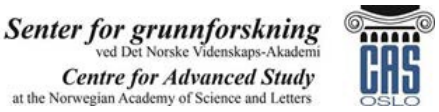

# 7th General Advanced Mathematical Methods in Finance and Swissquote Conference 2015

**September 7-10, 2015**

**SwissTech Convention Center, EPFL, Switzerland**







## Plenary Speakers

Beatrice Acciaio (London School of Economics)
Francesca Biagini (University of Munich)
Rene Carmona (Princeton University)
Darrell Duffie (Stanford University)
Kay Giesecke (Stanford University)
Jan Kallsen (University of Kiel)
Constantinos Kardaras (London School of Economics)
Alex Lipton (Bank of America and Oxford University)
Chris Rogers (University of Cambridge)
Alexander Schied (University of Mannheim)

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Damir Filipovic
Hans Föllmer
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## Administrative Assistance

Sophie Cadena

# Program

## Monday September 7

| | | | |
|---|---|---|---|
| 09:30 – 10:30 | Registration and welcome coffee | | |
| 10:30 – 11:00 | Welcome | | |
| **11:00 – 12:00** | **Darrell Duffie: Improving the efficiency of over-the-counter financial markets** p. 1 | | |
| **12:00 – 13:00** | **Alexander Schied: Robust strategies, pathwise Itô calculus, and generalized Takagi functions** p. 3 | | |
| 13:00 – 14:00 | Lunch break & poster session | | |
| **14:00 – 15:30** | **Credit Risk**<br>Room 5ABC, chair: Wolfgang Runggaldier, p. 4 | **Insurance**<br>Room 4BC, chair: Constantinos Kardaras, p. 5 | **Random Fields and Stochastic Analysis**<br>Room 3BC, chair: Giulia Di Nunno, p. 6 |
| 14:00 – 14:30 | **Agostino Capponi**<br>*Arbitrage-free pricing of XVA* | **Catherine Donnelly**<br>*How to pool mortality risk* | **Salvador Ortiz-Latorre**<br>*A pricing measure for non-tradable assets with mean-reverting dynamics* |
| 14:30 – 15:00 | **Nathalie Packham**<br>*Asymptotic behaviour of multivariate default probabilities and default correlations under stress* | **Thorsten Rheinländer**<br>*Risk-minimization for life insurance liabilities with basis risk* | **Francesco Russo**<br>*BSDEs, càdlàg martingale problems and mean-variance hedging under basis risk* |
| 15:00 – 15:30 | **Thorsten Schmidt**<br>*Dynamic term structure modelling beyond the intensity paradigm* | **Griselda Deelstra**<br>*Contingent claim evaluation in the setting of stochastic mortality and interest rates with dependence* | **Michèle Vanmaele**<br>*Discretisation of FBSDEs driven by càdlàg martingales and applications* |
| 15:30 – 16:00 | Coffee break & poster session | | |
| **16:00 – 17:30** | **Interest Rates**<br>Room 5ABC, chair: Zorana Grbac, p. 7 | **Model Risk and Robustness**<br>Room 4BC, chair: Thorsten Rheinländer, p. 8 | **Portfolio Optimization**<br>Room 3BC, chair: Jan Kallsen, p. 9 |
| 16:00 – 16:30 | **Alessandro Gnoatto**<br>*Hybrid FX-interest rate models: a tale of two risks* | **Andreas Tsanakas**<br>*Model risk cultures* | **Paolo Guasoni**<br>*Nonlinear price impact and portfolio choice* |
| 16:30 – 17:00 | **Wolfgang Runggaldier**<br>*Derivative pricing for a multicurve extension of the Gaussian, exponentially quadratic short rate model* | **Claudia Ravanelli**<br>*Ambiguity aversion in standard and extended Ellsberg frameworks: alpha-maxmin versus maxmin preferences* | **Johannes Muhle-Karbe**<br>*Information and inventories in high-frequency trading* |
| 17:00 – 17:30 | **Stefan Tappe**<br>*Affine realizations with affine state processes for the HJMM equation* | **Ruodu Wang**<br>*Robustness of regulatory risk measures in aggregation* | **Christoph Czichowsky**<br>*Portfolio optimisation: shadow prices and fractional Brownian motion* |

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| | | | |
|---|---|---|---|
| 08:30 – 09:00 | Coffee | | |
| **09:00 – 10:00** | **Kay Giesecke: Modeling correlated mortgage risk** p. 2 | | |
| **10:00 – 11:00** | **Alexander Lipton: Modern monetary circuit theory, stability of interconnected banking network, and balance sheet optimization for individual banks** p. 2 | | |
| 11:00 – 11:30 | Coffee break & poster session | | |
| **11:30 – 13:00** | **Econometrics**<br>Room 5ABC, chair: Robert Stelzer, p. 9 | **Functional and Pathwise Calculus**<br>Room 4BC, chair: Rama Cont, p. 10 | **Multicurve Models**<br>Room 3BC, chair: Martin Keller-Ressel, p. 12 |
| 11:30 – 12:00 | **Mathias Vetter**<br>*Change-point analysis of volatility* | **Pierre Blacque-Florentin**<br>*Functional Itô calculus and martingale representation formula for integer-valued random measures* | **Zorana Grbac**<br>*No-arbitrage conditions in HJM multiple curve term structure models* |
| 12:00 – 12:30 | **Vicky Fasen**<br>*Estimation of marginal expected shortfall under asymptotic independence* | **Giovanni Zanco**<br>*Infinite dimensional methods for path-dependent equations* | **Christa Cuchiero**<br>*Affine multiple yield curve models* |
| 12:30 – 13:00 | **Imma Curato**<br>*The Fourier estimator of the stochastic leverage effect* | **Yi Lu**<br>*Weak approximation of martingale representations* | **Stéphane Crépey**<br>*Rational multi-curve models with counterparty-risk valuation adjustments* |
| 13:00 – 14:00 | Lunch break & poster session | | |
| **14:00 – 15:30** | **Swissquote Practitioners' Session**<br>Room 5ABC, chair: Serge Kassibrakis, p. 13 | **Functional and Pathwise Calculus**<br>Room 4BC, chair: Rama Cont, p. 10 | **BSDEs**<br>Room 3BC, chair: Stéphane Crépey, p. 14 |
| 14:00 – 14:30 | **14:00 – 14:45**<br>**Damien Challet**<br>*Predicting investment fluxes from implicit lead-lag investor networks* | **Candia Riga**<br>*Pathwise analysis and robustness of hedging strategies for path-dependent options* | **Thomas Kruse**<br>*Minimal supersolutions for BSDEs with singular terminal condition and application to optimal position targeting* |
| 14:30 – 15:00 | **14:45 – 15:30**<br>**Filippo Passerini**<br>*Managing inventory with proportional transaction costs* | **Andrea Cosso**<br>*Functional versus Banach space stochastic calculus, and strong-viscosity solutions to semilinear parabolic path-dependent PDEs* | **Thibaut Mastrolia**<br>*Utility maximization with random horizon: a BSDE approach* |
| 15:00 – 15:30 | | **David Prömel**<br>*Pathwise Tanaka formula and local times for typical price paths* | **Romuald Elie**<br>*Optimal incentives for a system of interacting agents* |
| 15:30 – 16:00 | Coffee break & poster session | | |
| **16:00 – 17:30** | **Panel discussion "Future directions and challenges for Mathematics in Finance"**<br>Rene Carmona, Darrell Duffie, Alexander Lipton, Chris Rogers, moderator: Damir Filipovic | | |

## Wednesday September 9

| | | | |
|---|---|---|---|
| 08:30 – 09:00 | Coffee | | |
| **09:00 – 10:00** | **Beatrice Acciaio: Robust pricing by informed investors** p. 1 | | |
| **10:00 – 11:00** | **Francesca Biagini: The long-term swap rate and a general analysis of long-term interest rates** p. 1 | | |
| 11:00 – 11:30 | Coffee break & poster session | | |
| **11:30 – 13:00** | **Polynomial Models in Finance**<br>Room 5ABC, chair: Damir Filipovic, p. 14 | **Long-Memory Models**<br>Room 4BC, chair: Yuliya Mishura, p. 17 | **Systemic Risk**<br>Room 3BC, chair: Hans Föllmer, p. 18 |
| 11:30 – 12:00 | **Paul Krühner**<br>*Affine processes with compact state space and counter-examples for polynomial processes* | **José Manuel Corcuera**<br>*A long-range dependence model in fixed income markets* | **Svetlana Borovkova**<br>*Interbank payment and repo networks and what can we learn from them* |
| 12:00 – 12:30 | **Martin Larsson**<br>*Polynomial preserving jump-diffusions on the unit interval* | **Ehsan Azmoodeh**<br>*Pathwise volatility in a long-memory pricing model: estimation and asymptotic behavior* | **Luitgard Veraart**<br>*A Bayesian methodology for systemic risk assessment in financial networks* |
| 12:30 – 13:00 | **Martin Keller-Ressel**<br>*Affine processes with stochastic discontinuities* | **Christian Bender**<br>*Simple arbitrage* | **Stefan Weber**<br>*Measures of systemic risk* |
| 13:00 – 14:00 | Lunch break & poster session | | |
| **14:00 – 15:30** | **Polynomial Models in Finance**<br>Room 5ABC, chair: Sergio Pulido, p. 14 | **Partial and Insider Information**<br>Room 4BC, chair: Christian Bender, p. 20 | **Systemic Risk**<br>Room 3BC, chair: Hans Föllmer, p. 18 |
| 14:00 – 14:30 | **Damien Ackerer**<br>*Linear credit risk models* | **Luca Di Persio**<br>*Polynomial chaos expansion approach to financial modeling* | **Rama Cont**<br>*Fire sales, endogenous risk and price-mediated contagion* |
| 14:30 – 15:00 | **Elise Gourier**<br>*Option pricing in a quadratic variance swap model* | **Yuliya Mishura**<br>*On mean-variance hedging under partial observations* | **Eric Schaanning**<br>*Price-mediated contagion and systemic risk: indirect exposures, macroprudential tools and modeling issues* |
| 15:00 – 15:30 | **Paul Schneider**<br>*(Almost) Model-free recovery* | **Lukasz Stettner**<br>*Asymptotics of utilities from terminal wealth under partial information* | **Christoph Aymanns**<br>*Taming the Basel leverage cycle* |
| 15:30 – 16:00 | Coffee break & poster session | | |
| **16:00 – 17:30** | **Polynomial Models in Finance**<br>Room 5ABC, chair: Martin Larsson, p. 14 | **Optimal Transport in Mathematical Finance**<br>Room 4BC, chair: Francesco Russo, p. 21 | **Limit Order Markets**<br>Room 3BC, chair: Julius Bonart, p. 22 |
| 16:00 – 16:30 | **Eberhard Mayerhofer**<br>*Existence and regularity of densities for affine processes* | **Luciano Campi**<br>*On the support of extremal martingale measures with given marginals: the countable case* | **Mathieu Rosenbaum**<br>*The microstructural foundations of rough volatility models* |
| 16:30 – 17:00 | **Sergio Pulido**<br>*The Jacobi stochastic volatility model* | **Alex Cox**<br>*Model-independent bounds for Asian options: a dynamic programming approach* | **Thibault Jaisson**<br>*Estimation of slowly decreasing Hawkes kernels: Application to high frequency order book modelling* |
| 17:00 – 17:30 | **Anders Trolle**<br>*Linear-rational term structure models* | **Martin Huesmann**<br>*Model independent finance, Vovk's outer measure, and insider trading* | **Ryan Donnelly**<br>*Algorithmic trading under the effects of volume order imbalance* |
| 18:00 – 22:00 | Olympic Museum visit and conference dinner at the Olympic Museum | | |

## Thursday September 10

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|---|---|---|---|
| 08:30 – 09:00 | Coffee | | |
| **09:00 – 10:00** | **Constantinos Kardaras: Incomplete stochastic equilibria with exponential utilities close to Pareto optimality** p. 2 | | |
| **10:00 – 11:00** | **Rene Carmona: Models of bank runs and mean field games of timing** p. 1 | | |
| 11:00 – 11:30 | Coffee break & poster session | | |
| **11:30 – 13:00** | **Numerical Methods**<br>Room 5ABC, chair: Robert Stelzer, p. 23 | **Energy Finance**<br>Room 4BC, chair: Salvador Ortiz-Latorre, p. 24 | **Liquidity Risk**<br>Room 3BC, chair: Luitgard Veraart, p. 25 |
| 11:30 – 12:00 | **Andreas Neuenkirch**<br>*Discretising the Heston model: an analysis of the weak convergence rate* | **Jocelyne Bion-Nadal**<br>*Path-dependent second order PDEs and dynamic risk measures* | **Monika Trapp**<br>*Time-varying credit risk and liquidity premia in bond and CDS markets* |
| 12:00 – 12:30 | **Antonia Mayerhofer**<br>*Derivative pricing using a reduced basis method for parameter functions* | **Bernt Øksendal**<br>*Stochastic differential insider games and applications to finance* | **Simone Scotti**<br>*Optimal exit strategies for investment projects* |
| 12:30 – 13:00 | **Blanka Horvath**<br>*Dirichlet forms and finite element methods for the SABR model* | **Barbara Rüdiger**<br>*Exponential ergodicity of jump-diffusion CIR processes* | **Julius Bonart**<br>*Latent liquidity in limit order driven markets* |
| 13:00 – 14:00 | Lunch break & poster session | | |
| **14:00 – 15:00** | **Jan Kallsen: Are American options European after all?** p. 2 | | |
| **15:00 – 16:00** | **Chris Rogers: Bermudan options by simulation** p. 3 | | |
| 16:00 – 16:30 | Closing | | |

# Poster sessions (p. 26)

## Monday September 7

**Sühan Altay**
*Term structure of defaultable bonds, an approach with Jacobi processes*

**Zvonko Kostanjčar**
*Does bargaining dynamics inherently cause market bubbles and crashes?*

**Yaroslav Melnyk**
*Stochastic impulse control with regime-switching dynamics*

**Markus Scholz**
*Cointegrated multivariate continuous-time autoregressive moving average (MCARMA) processes*

**Shih-Hau Tan**
*An efficient solver for multidimensional nonlinear Black-Scholes equation with Newton-like method*

**Fabian Woebbeking**
*Tail-risk-protection trading strategies*

## Tuesday September 8

**Francesco Cordoni**
*A representation theorem for stochastic functional delay differential equations with jumps and applications to option pricing*

**Ola Mahmoud**
*The two dimensions of drawdown: magnitude and duration*

**Georg Mikus**
*Estimation of credit models via likelihood transformation and filtering*

**Jakub Rojček**
*High-frequency trading in limit order markets: equilibrium impact and regulation*

**Paola Pederzoli**
*Valuing American options using fast recursive projections*

**Dariusz Zawisza**
*Monotone mean-variance portfolio choice in a continuous time market models*

## Wednesday September 9

**Anne Balter**
*Sets of indistinguishable models for robust optimisation*

**David Krief**
*An asymptotic approach for the pricing of options on realized variance*

**Steven Kou**
*Asset pricing with spatial interaction*

**Agnieszka Rygiel**
*Arbitrage for simple strategies on the market with bid and ask prices*

**Anna Sulima**
*Optimal portfolio selection for Markov regime-switching Lévy market with additional impulses on changing economical environment*

**Hanlin Yang**
*$L^p$ solutions of quadratic BSDEs*

## Thursday September 10

**Xuecan Cui**
*Option pricing model with underlying time-varying Lévy processes*

**Fabien Heuwelyckx**
*Lookback options in the binomial model*

**Stefan Waldenberger**
*Affine LIBOR models driven by real-valued affine processes*

# Abstracts

## Contents

# 1 Plenary Talks

**Beatrice Acciaio** (London School of Economics)

Robust pricing by informed investors

*based on joint work with Martin Larsson*

In a model-independent framework, where semi-static trading opportunities are available to all market participants, we study super-hedging prices for agents having access to different information. A crucial role is played by the notion of semi-static completeness, which is the natural extension in this context of the predictable representation property. Under structural assumptions, we find that informed agents compute super-hedging prices using only those martingale measures that render the additional information inconsequential.

**Francesca Biagini** (University of Munich)

The long-term swap rate and a general analysis of long-term interest rates

*based on joint work with Alessandro Gnoatto and Maximilian Härtel*

We introduce here for the first time the long-term swap rate, characterised as the fair rate of an overnight indexed swap with infinitely many exchanges. The long term swap rate can be characterized explicitly in terms of a model-free formula and is always finite and non-monotonic. As a contribution to the ongoing debate on suitable discounting factors for investments over long time horizons, we analyse the relationship between the long-term swap rate, the long-term yield and the long-term simple rate. We finally compute these long-term rates in two term structure methodologies, the Flesaker-Hughston model and the linear-rational model.

**Rene Carmona** (Princeton University)

Models of bank runs and mean field games of timing

We introduce mean field games of timing to capture some of the features of recent continuous time models of bank runs. We present abstract results for the existence of Nash equilibria and we discuss the challenges posed by the lack of constructive proofs and numerically implementable approximations.

**Darrell Duffie** (Stanford University)

Improving the efficiency of over-the-counter financial markets

The most important ingredients of efficient financial market design are price transparency and trade protocols that promote low-cost matching and competition. I will review concepts, evidence, and open research problems regarding these elements of market efficiency in over-the-counter (OTC) markets. Most OTC trade is intermediated by dealers, who rarely compete directly with each other through simultaneously executable quotes. Trade is often conducted through one-on-one negotiation. Price transparency, search costs, and buyer-seller matching efficiency are therefore often relatively low. In some cases, however, there is a limited degree of direct competition on multilateral trading platforms. I will discuss the design of these OTC platforms from the viewpoint of market efficiency. Relative to exchanges, OTC price transparency tends to be relatively low, but can be improved by quotes posted on trading platforms, with post-trade data repositories such as TRACE, and via the publication of accurate fixings of financial benchmarks. However, the most heavily used OTC price benchmarks, including those for currencies, commodities, and interest rates, have been manipulated.

**Kay Giesecke** (Stanford University)

Modeling correlated mortgage risk

*based on joint work with Justin Sirignano and Apaar Sadhwani*

An unprecedented number of mortgage defaults in 2007 precipitated one of the greatest financial crises in recent memory. Financial institutions grossly underestimated loan-to-loan correlations, leading to inaccurate evaluations of risk exposures. Although it is now recognized that loan-to-loan correlation was a key factor, little attention has been directed towards developing and testing concrete mortgage risk models accounting for this correlation. Understanding loan-to-loan correlation is essential for banks, investors, and rating agencies to analyze the risk of loan portfolios such as mortgage-backed securities. We propose a dynamic model for mortgage delinquency and prepayment in the US which captures loan-to-loan correlation due to geographic proximity and exposure to common risk factors. The model is estimated using highly detailed zip code level data on mortgage performance for 120 million prime and subprime borrowers as well as local economic factors. It also exploits nonlinear relationships between covariates and loan risk to attain additional accuracy. Using multiple performance metrics, the model is shown to provide accurate multi-period forecasts of loan- and pool-level risk of mortgage delinquency and prepayment.

**Jan Kallsen** (University of Kiel)

Are American options European after all?

Christensen (Mathematical Finance 24, 2014, 156-172) has introduced an efficient numerical approach for obtaining upper bounds of American option prices in diffusion models. It relies on approximating the initial value of the American option by European options whose price dominates the American payoff at any time. In this talk we discuss the question whether the value of an American option actually coincides in the continuation region with that of a properly chosen European payoff. Or, in the language of financial engineering: can an American option be hedged statically with European calls/puts of all strikes? In analytical terms this boils down to the question whether a harmonic function solving a free boundary problem can be extended to a harmonic function on the whole space.

**Constantinos Kardaras** (London School of Economics)

Incomplete stochastic equilibria with exponential utilities close to Pareto optimality

*based on joint work with Hao Xing and Gordan Žitković*

We study existence and uniqueness of continuous-time stochastic Radner equilibria in an incomplete markets model. An assumption of "smallness" type – imposed through the new notion of "closeness to Pareto optimality" – is shown to be sufficient for existence and uniqueness. Central role in our analysis is played by a fully-coupled nonlinear system of quadratic BSDEs.

**Alexander Lipton** (Bank of America and Oxford University)

Modern monetary circuit theory, stability of interconnected banking network, and balance sheet optimization for individual banks

A modern version of Monetary Circuit Theory with a particular emphasis on stochastic underpinning mechanisms is developed. Existing theories of money creation are compared and contrasted. It is explained how money is created by the banking system as a whole and by individual banks. The role of central banks as system stabilizers and liquidity providers is elucidated. It is shown that in the process of money creation banks become naturally interconnected. A novel Extended Structural

Default Model describing the stability of the Interconnected Banking Network is proposed. The purpose of banks' capital and liquidity is explained. Multi-period constrained optimization problem for banks' balance sheet is formulated and solved in a simple case. Both theoretical and practical aspects are covered.

**Chris Rogers** (University of Cambridge)

Bermudan options by simulation

The aim of this study is to devise numerical methods for dealing with very high-dimensional Bermudan-style derivatives. For such problems, we quickly see that we can at best hope for price bounds, and we can only use a simulation approach. We use the approach of Barraquand & Martineau which proposes that the reward process should be treated as if it were Markovian, and then uses this to generate a stopping rule and hence a lower bound on the price. Using the dual approach introduced by Rogers, and Haugh & Kogan, this approximate Markov process leads us to hedging strategies, and upper bounds on the price. The methodology is generic, and is illustrated on a number examples of varying levels of difficulty. Run times are largely insensitive to dimension.

**Alexander Schied** (University of Mannheim)

Robust strategies, pathwise Itô calculus, and generalized Takagi functions

In mainstream finance, the price evolution of a risky asset is usually modeled as a stochastic process defined on some probability space and hence is subject to model uncertainty. In a number of situations, however, it is possible to construct continuous-time strategies on a path-by-path basis and without making any probabilistic assumptions on the asset price evolution. In the first part of this talk, we will present several examples in which this program can be carried out by means of the pathwise Itō calculus introduced by Föllmer (1981). In the second part, we will address the issue of finding a suitable set of test integrators for pathwise Itō calculus. We will present one class of such test integrators which is closely related to the celebrated Takagi function and has a number of appealing mathematical properties.

## 2 Credit Risk (Mo, 14:00 – 15:30, Room 5ABC)

### Agostino Capponi (Columbia University)

Arbitrage-free pricing of XVA

The recent financial crisis has highlighted the importance to account for counterparty risk and funding costs in the valuation of over-the-counter portfolios of derivatives. When managing their portfolios, traders face costs for maintaining the hedge of the position, posting collateral resources, and servicing their collateral requests. Due to the interdependencies between these operations, such costs cannot be separated and attributed to different business units (CVA, DVA and FVA desks).

In this talk, we introduce a unified framework for computing the total costs, referred to as XVA, of an European style derivative transaction traded between two risky counterparties. We use no-arbitrage arguments to derive the nonlinear backward stochastic differential equations (BSDEs) associated with the portfolios which replicate long and short positions in the claim.

This leads to defining buyer's and seller's XVAs which in turn identify a no-arbitrage band. When borrowing and lending rates coincide, our framework recovers a generalized version of Piterbarg's model. In this case, we provide a fully explicit expression for the uniquely determined price of XVA. When they differ, we derive the semi-linear partial differential equations (PDEs) associated with the non-linear BSDEs and show that they admit a unique classical solution. We use these solutions to conduct a numerical analysis showing high sensitivity of the no-arbitrage band and replicating strategies to funding spreads and collateral levels.

### Nathalie Packham (Frankfurt School of Finance & Management)

Asymptotic behaviour of multivariate default probabilities and default correlations under stress

We investigate default probabilities and default correlations of Merton-type credit portfolio models in stress scenarios where a common risk factor is truncated. For elliptically distributed asset variables, the asymptotic limits of default probabilities and default correlations depend on the max-domain of attraction of the asset variables. In the regularly varying case, we derive an integral representation for multivariate default probabilities, which turn out to be strictly smaller than 1. Default correlations are in (0,1). In the rapidly varying case, asymptotic multivariate default probabilities are 1 and asymptotic default correlations are 0.

### Thorsten Schmidt (University of Freiburg)

Dynamic term structure modelling beyond the intensity paradigm

We extend the Heath-Jarrow-Morton approach to bond markets by allowing for events which take place at predictable times. This introduces a discontinuity in the term structure which requires a suitable generalization of the setup.

It turns out, that previously considered models lead to arbitrage possibilities. The chosen generalization of the forward-rate approach contains an additional stochastic integral with atoms at predictable times and necessary and sufficient conditions for an appropriate no-arbitrage condition (NAFL) are given.

In the view of efficient implementations we develop a new class of affine models which do not satisfy the standard assumption of stochastic continuity. Examples include interest rate models and credit risky models.

## 3 Insurance (Mo, 14:00 – 15:30, Room 4BC)

**Griselda Deelstra** (Université Libre de Bruxelles)

CONTINGENT CLAIM EVALUATION IN THE SETTING OF STOCHASTIC MORTALITY AND INTEREST RATES WITH DEPENDENCE

*based on joint work with Martino Grasselli and Christopher Van Weverberg*

In this paper, we consider affine models where mortality and interest rates remain positive and we assume that the interest rate and the mortality dynamics are not independent of each other. We concentrate in particular upon two cases: The first one assumes that the dynamics of the mortality and interest rate processes are driven by a multi-dimensional CIR process and the second one uses a Wishart process.

Our main goal consists in studying the influence in pricing of the dependence structure for some common insurance contracts. It is worth recalling that in general, in the actuarial literature, mortality risk and interest risk are assumed to be independent, which simplifies the valuation problem. However, especially in the long term, it seems reasonable that demographic changes can affect the economy. In this setting, we start by deriving pricing formulae for some insurance contracts such as Guaranteed Annuity Options (GAOs). We follow a methodology introduced by Jalen and Mamon (2009), who were the first to introduce a pricing framework in which a correlation between the mortality and the interest rates is modelled. By a change of measure, we simplify the valuation expressions for the insurance contracts under consideration. Next, we study the sensitivity of the pricing with respect to the dependence between the mortality and interest rate processes. We observe that in a general affine model like the Wishart model where a non-trivial dependence between the mortality and the interest rates can be reproduced, the value of these insurance contracts cannot only be explained in terms of the initial pairwise linear correlation. Indeed, thanks to the ability of the Wishart process to allow for a richer structure of dependence, several behaviors can be reproduced.

**Catherine Donnelly** (Heriot-Watt University)

HOW TO POOL MORTALITY RISK

*based on joint work with Montserrat Guillen, Jens Perch Nielsen and John Young*

Pooling mortality risk can provide many of the benefits of a life annuity contract without locking in to an irrevocable contract, or having to pay for longevity risk. It can give people a higher return than they would have without pooling.

We show one way in which people can pool their mortality risk, while retaining individual investment freedom and the ability to leave the pool without cost before death. We discuss the advantages and disadvantages of pooling, the difficulties in applying it practically as well as some potential applications.

**Thorsten Rheinländer** (Vienna University of Technology)

RISK-MINIMIZATION FOR LIFE INSURANCE LIABILITIES WITH BASIS RISK

*based on joint work with Francesca Biagini and Irene Schreiber*

We study the hedging of typical life insurance payment processes in a general setting by means of the well-known risk-minimization approach. We find the optimal risk-minimizing strategy in a financial market where we allow for investments in a hedging instrument based on a longevity index, representing the systematic mortality risk. Thereby we take into account and model the basis risk that arises due to the fact that the insurance company cannot perfectly hedge its exposure by investing in a hedging

instrument that is based on the longevity index, not on the insurance portfolio itself. We also provide a detailed example within the context of unit-linked life insurance products where the dependency between the index and the insurance portfolio is described by means of an affine mean-reverting diffusion process with stochastic drift.

## 4 Random Fields and Stochastic Analysis (Mo, 14:00 – 15:30, Room 3BC)

**Salvador Ortiz-Latorre** (University of Oslo)

A pricing measure for non-tradable assets with mean-reverting dynamics

In this talk we present a new class of parametrised pricing measures that is suitable for markets where the underlying or primary asset is non-tradable and has a mean-reverting dynamics. Typical examples of application are energy related markets: commodities, electricity and weather derivatives. This class of pricing measures can be seen as an extension of the Esscher transform and allow for a simultaneous change of the level and rate of mean reversion in the driving factors. We use these pricing measures to compute the theoretical forward price curve and its associated risk premium. It is demonstrated that we can provide theoretical risk premium shapes similar to the ones observed in energy markets, which cannot be obtained using the Esscher transform. In particular, the risk premium allows for a stochastic change of sign and it can attain positive values in the short end of the forward market and negative values in the long end.

**Francesco Russo** (ENSTA-ParisTech)

BSDEs, càdlàg martingale problems and mean-variance hedging under basis risk

*based on joint work with Ismail Laachir*

The aim of this talk consists in introducing a new formalism for the deterministic analysis associated with backward stochastic differential equations driven by general càdlàg martingales. When the martingale is a standard Brownian motion, the natural deterministic analysis is provided by the solution of a semilinear PDE of parabolic type. A significant application concerns the hedging problem under basis risk of a contingent claim $g(X_T, S_T)$, where $S$ (resp. $X$) is an underlying price of a traded (resp. non-traded but observable) asset, via the celebrated Föllmer-Schweizer decomposition. We revisit the case when the couple of price processes $(X, S)$ is a diffusion and we provide explicit expressions when $(X, S)$ is an exponential of additive processes.

**Michèle Vanmaele** (Ghent University)

Discretisation of FBSDEs driven by càdlàg martingales and applications

We study the discretisation of forward backward stochastic differential equations (FBSDEs) driven by càdlàg martingales. We prove that under certain conditions imposed on the parameters of the FBSDE the time-discrete scheme we consider converges to the time-continuous equation in the $L^2$-sense. Moreover, we show that the $L^2$-norm of the error is of the order of the time step. The type of FBSDE in this paper naturally appears for example in quadratic hedging problems in finance and insurance. As an application we study the quadratic hedging of vanilla, spread and basket options via FBSDEs.

## 5 Interest Rates (Mo, 16:00 – 17:30, Room 5ABC)

**Alessandro Gnoatto** (University of Munich)

Hybrid FX-interest rate models: a tale of two risks

The valuation of long-dated foreign-exchange products can be reliably performed by means of frameworks where exchange and interest rates are jointly modelled. In a multi-currency setting, analytical tractability can be granted if the functional form of the FX dynamics is invariant with respect to the inversion of the spot and the construction of FX triangles via suitable products/ratios of FX rates. We provide examples of models driven by multifactor affine stochastic volatility models in a standard risk-neutral setting which fulfill the aforementioned requirement. In the second part, we consider a new stochastic volatility model that includes as special cases the square root Heston model and the 3/2 model. The new model is analytically tractable and the computation of the characteristic function of asset prices involves a non trivial extension of known results in probability. We will use this model as a building block in order to develop a multifactor version that considerably extends the model investigated in [1] and [2], including stochastic interest rates. The new methodology does not require the existence of a risk neutral probability measure.


[1] Baldeaux, J., Grasselli, M., and Platen, E. (2015) Pricing Currency Derivatived Under the Benchmark Approach, *Journal of Banking and Finance, 53(0):34–48.*

[2] De Col, A., Gnoatto, A., and Grasselli, M. (2013) Smiles all around: FX joint calibration in a Multi-Heston model, *Journal of Banking and Finance, 37(10):3799–3818.*

[3] Gnoatto, A., and Grasselli, M. (2014) An affine multi-currency model with stochastic volatility and stochastic interest rates, *SIAM Journal on Financial Mathematics, 5(1):493–531.*


**Wolfgang Runggaldier** (University of Padova)

Derivative pricing for a multicurve extension of the Gaussian, exponentially quadratic short rate model

*based on joint work with Z. Grbac and L. Meneghello*

We consider post-crisis multicurve extensions of pre-crisis short rate models where, for each possible tenor, a spread is added to the short rate itself. The specific extension concerns a factor model where short rate and spreads are second order polynomials of Gaussian factor processes. This leads to a Gaussian, exponentially quadratic model class, for which we study the pricing of linear and optional interest rate derivatives.

**Stefan Tappe** (Leibniz Universität Hannover)

Affine realizations with affine state processes for the HJMM equation

The goal of this presentation is to clarify when the HJMM (Heath-Jarrow-Morton-Musiela) equation with an affine realization admits affine state processes. This includes a characterization of the set of initial curves of the realization. Several examples illustrate our results.

## 6 Model Risk and Robustness (Mo, 16:00 – 17:30, Room 4BC)

**Claudia Ravanelli** (University of Zurich)

Ambiguity aversion in standard and extended Ellsberg frameworks: alpha-maxmin versus maxmin preferences

We study optimal portfolio choice and equilibrium asset prices induced by alpha-maxmin utility models. We find that in the standard Ellsberg framework ambiguity averse alpha-MEU and maxmin preferences coincide. We derive novel theoretical implications for equilibrium asset prices, and revisit the laboratory experimental findings in Bossaerts et al. (2010). Only when there are three or more ambiguous states, the alpha-MEU and maxmin models are not observational equivalent and induce different attitudes toward ambiguity. In particular, the search for ambiguity exposure peculiar to alpha-MEU agents may prevent the existence of equilibrium. Our theoretical results enhance the empirical findings that ambiguity aversion matters for portfolio choice and does not wash out in equilibrium.

**Andreas Tsanakas** (City University London)

Model risk cultures

*based on joint work with M. Bruce Beck and Michael Thompson*

Model risk can be understood as the risk to a decision maker arising from specific ways of (not) using a quantitative model. Model risks range from basing decisions on flawed calculations, to impacts on perception, behaviour and accountability. Building on anthropological theories of risk, we stipulate that there are four distinct perceptions of models and their legitimate use. Each such perception is justified by, but also generates, concern for a different type of uncertainty. Furthermore, each distinct way of perceiving and (not) using models, when deployed on its own, generates a different sort of model risk. This argument has normative implications. First, it highlights the required pluralism of stakeholders involved in model governance and validation. Second, it expands the space of legitimate challenges to quantitative models from a purely technical critique, in order to also reflect operational and commercial criteria. In particular, legitimising the concerns of a wide variety of stakeholders creates transparency about models' strengths and limitations, improving accountability and risk management. The authors acknowledge the feedback and contribution of the Model Risk Working Part of the Institute and Faculty of Actuaries.

Keywords: Model Risk, Model Uncertainty, Risk Culture, Cultural Theory, Solvency II.

**Ruodu Wang** (University of Waterloo)

Robustness of regulatory risk measures in aggregation

*based on joint work with Paul Embrechts and Bin Wang*

In risk aggregation, marginal risks and their dependence structure are often modeled separately, leading to uncertainty arising at the level of a joint model. In this talk, we introduce a notion of qualitative robustness for risk measures, concerning the sensitivity of a risk measure to the uncertainty of dependence in risk aggregation. It turns out that coherent risk measures, such as Expected Shortfall (ES), are more robust than Value-at-Risk (VaR) according to the new notion of robustness. We also give approximations and inequalities for aggregation and diversification of VaR under dependence uncertainty, and derive an asymptotic equivalence for worst-case VaR and ES under general conditions. We obtain that for a portfolio of a large number of risks VaR generally has a larger uncertainty spread compared to ES. The results warn that unjustified diversification arguments for VaR used in

risk management need to be taken with much care, and potentially support the use of ES in risk aggregation.

## 7 Portfolio Optimization (Mo, 16:00 – 17:30, Room 3BC)

**Christoph Czichowsky** (London School of Economics)

Portfolio optimisation: shadow prices and fractional Brownian motion
*based on joint work with Walter Schachermayer*

While absence of arbitrage requires price processes to be semimartingales in frictionless financial markets, non-semimartingales can be used to model prices in an arbitrage-free way, if transaction costs are taken into account. In this talk, we show, for a class of non-semimartingale price processes, the existence of a solution to utility maximisation problems on the whole real line under transaction costs by establishing a so-called shadow price. This is a semimartingale price process such that frictionless trading for that price leads to the same optimal strategy and utility as in the original problem under transaction costs. Our results combine arguments from convex duality and dynamic programming with the stickiness condition introduced by Paolo Guasoni. They apply in particular to exponential utility and fractional Brownian motion.

**Paolo Guasoni** (Dublin City University)

Nonlinear price impact and portfolio choice
*based on joint work with Marko Weber*

In a market with price-impact proportional to a power of the order flow, we derive optimal trading policies and their implied welfare for long-term investors with constant relative risk aversion, who trade one safe asset and one risky asset that follows geometric Brownian motion. These quantities admit asymptotic explicit formulas up to a structural constant that depends only on the price-impact exponent. Trading rates are finite as with linear impact, but they are lower near the target portfolio, and higher away from the target. The model nests the square-root impact law and, as extreme cases, linear impact and proportional transaction costs.

**Johannes Muhle-Karbe** (ETH Zurich)

Information and inventories in high-frequency trading
*based on joint work with Kevin Webster*

We propose an equilibrium model for the short-term informational advantages crucial in high-frequency trading. In this setting, risk-neutral insiders hold martingale inventories. In contrast, inventory aversion leads to autoregressive positions. These vanish in the continuous-time limit while still yielding approximately the same returns. This suggests that high-frequency trading allows to monetize information with very little inventory risk.

## 8 Econometrics (Tu, 11:30 – 13:00, Room 5ABC)

**Imma Curato** (Ulm University)

The Fourier estimator of the stochastic leverage effect

We define a non-parametric estimator of the leverage effect by means of the covariance between the log price and its corresponding volatility. The data are assumed to follow a general stochastic volatility model driven by two continuous semi-martingales. The novelty of this paper is estimating the

high frequency leverage effect using only a pre-estimation of the Fourier coefficients of the volatility. This procedure overcomes the bias due to the latency of the spot volatility process by moving the analysis in the frequency domain. The Fourier methodology used in this work allows to obtain a consistent estimation without any manipulation of the data set in the time domain. The analysis of the asymptotic confidence interval along with a simulation study investigate the finite sample properties of the estimator in the presence of microstructure contaminations and of irregular trading leading to non-equidistant observations of the price process.

**Vicky Fasen** (Karlsruhe Institute of Technology)

ESTIMATION OF MARGINAL EXPECTED SHORTFALL UNDER ASYMPTOTIC INDEPENDENCE

Systemic risk attempts to measure the amount of risk contagion in large networks in finance, banking, insurance, and many other large scale systems. Suppose $Z = (Z_1, Z_2)$ denotes risk pertaining to two components of some system. In the context of systemic risk we can think of $Z_1$ as the risk of a stock we are interested in and $Z_2$ that of the entire market. It is often observed that the joint risk vector $Z = (Z_1, Z_2)$ is asymptotically independent, meaning that it is highly unlikely that both risks are large together. We study the behavior of $E(Z_1|Z_2 > t)$ which is the expected shortfall of one risk given that the other risk is high under assumptions of multivariate and hidden regular variation. This quantity called Marginal Expected Shortfall (MES) is an important component in the study of systemic risk. Under asymptotic independence of the variables a naive estimate for MES is $E(Z_1)$. In this talk we present an extrapolation method to estimate MES which provides sharper estimates and show that our estimator is consistent. The estimates are verified in both simulated and real data sets.

**Mathias Vetter** (University of Kiel)

CHANGE-POINT ANALYSIS OF VOLATILITY

*based on joint work with Markus Bibinger and Moritz Jirak*

We discuss change-point methods for the volatility of an Ito semimartingale, which is discretely observed over a fixed time horizon. We construct a minimax-optimal test to discriminate different smoothness classes of the underlying stochastic volatility process. In a high-frequency framework we prove weak convergence of the test statistic under the hypothesis to an extreme value distribution. As a key example, under extremely mild smoothness assumptions on the stochastic volatility we thereby derive a consistent test for volatility jumps.

## 9 Functional and Pathwise Calculus (Tu, 11:30 – 15:30, Room 4BC)

**Pierre Blacque-Florentin** (Imperial College London)

FUNCTIONAL ITÔ CALCULUS AND MARTINGALE REPRESENTATION FORMULA FOR INTEGER-VALUED RANDOM MEASURES

*based on joint work with Rama Cont*

We develop a calculus for functionals of integer-valued measures, which extends the Functional Itô calculus to functionals of Poisson random measures in a pathwise sense. We show that smooth functionals in the sense of this pathwise calculus are dense in the space of square-integrable (compensated) integrals with respect to a large class of integer-valued random measures. As a consequence, we obtain an explicit martingale representation formula for all square-integrable martingales with respect to the filtration generated by such integer-valued random measures. Our representation formula extends beyond the Poisson framework and allows for random and time-dependent compensators.

**Andrea Cosso** (Université Paris-Diderot)

Functional versus Banach space stochastic calculus, and strong-viscosity solutions to semilinear parabolic path-dependent PDEs

In the first part of the talk we revisit the basic theory of functional Itō calculus, using the regularization approach. This allows us to explore its relations with the corresponding Banach space stochastic calculus. In the second part of the talk, we introduce a viscosity type solution for path-depenendent partial differential equations, called strong-viscosity solution, with the peculiarity that it is a purely analytic object. We discuss its properties and we present an existence and uniqueness result for strong-viscosity solutions to semilinear parabolic path-dependent partial differential equations.

**Yi Lu** (Université Pierre & Marie Curie-Paris VI)

Weak approximation of martingale representations

We present a systematic method for computing explicit approximations to martingale representations for a large class of Brownian functionals. The approximations are based on a notion of pathwise functional derivative and yield a consistent estimator for the integrand in the martingale representation formula for any square-integrable functional of the solution of an SDE with path-dependent coefficients. Explicit convergence rates are derived for functionals which are Lipschitz-continuous in the supremum norm. The approximation and the proof of its convergence are based on the Functional Ito calculus, and require neither the Markov property, nor any differentiability conditions on the coefficients of the stochastic differential equations involved.

**David Prömel** (Humboldt University of Berlin)

Pathwise Tanaka formula and local times for typical price paths
*based on joint work with Nicolas Perkowski*

Starting from the pathwise Föllmer-Ito formula, we provide a pathwise Tanaka formula for absolutely continuous functions with weak derivative of finite $q$-variation provided the local time is of finite $p$-variation with $1/p + 1/q > 1$. To justify the assumption on the local time, we follow Vovk's hedging based approach to model free financial mathematics. We prove that it is possible to make an arbitrarily large profit by investing in those one-dimensional paths which do not possess a local time. The local time is constructed from discrete approximations and it is shown that it is of finite $p$-variation for every $p > 2$.

**Candia Riga** (University of Zurich)

Pathwise analysis and robustness of hedging strategies for path-dependent options
*based on joint work with Rama Cont*

We develop a pathwise framework for analyzing the performance and robustness of delta hedging strategies for path-dependent derivatives across a given set of scenarios. Our setting allows for general path-dependent payoffs and does not require any probabilistic assumption on the dynamics of the underlying asset, thereby extending previous results on robustness of hedging strategies in the setting of diffusion models. We obtain a pathwise formula for the hedging error for a general path-dependent derivative and provide sufficient conditions ensuring the robustness of the delta hedge. We show in particular that robust hedges may be obtained in a large class of continuous exponential martingale models under a directional convexity condition on the payoff functional. Under the same conditions, we

show that discontinuities in the underlying asset always deteriorate the hedging performance. These results are illustrated in the case of Asian options.

**Giovanni Zanco** (Università di Pisa)

Infinite dimensional methods for path-dependent equations

*based on joint work with Franco Flandoli and Francesco Russo*

Path-dependent stochastic differential equations are intrinsecally infinite dimensional objects, even when the state space is finite dimensional. I will show how path-dependent SDEs can be studied in a infinite dimensional product space framework (inspired by the theory for delay equations) using standard differential and topological structures. This framework is helpful to prove existence and uniqueness of classical solutions to path-dependent Kolmogorov-type PDEs on the space of continuous paths, to obtain probabilistic representation formulae for such solutions and moreover to prove Ito-type formulae for functionals of paths of continuous semimartingales, thus providing a counterpart of the functional Ito calculus developed by Dupire, Cont and Fournié. It also provides an insight on the role and the analytical structure of the so-called horizontal derivative, which is a key object in the study of path-dependent equations.

## 10 Multicurve Models (Tu, 11:30 – 13:00, Room 3BC)

**Stéphane Crépey** (Evry University)

Rational multi-curve models with counterparty-risk valuation adjustments

*based on joint work with Andrea Macrina, Tuyet Mai Nguyen and David Skovmand*

We develop a multi-curve term structure setup in which the modelling ingredients are expressed by rational functionals of Markov processes. We calibrate to LIBOR swaptions data and show that a rational two-factor lognormal multi-curve model is sufficient to match market data with accuracy.

We elucidate the relationship between the models developed and calibrated under a risk-neutral measure and their consistent equivalence class under the real-world probability measure. The real-world probability measure is used for computing the risk exposures which may be required to comply with regulatory obligations. In order to compute counterparty-risk valuation adjustments, such as CVA, we show how default intensity processes with rational form can be derived. We flesh out our study by applying the results to a basis swap contract.

**Christa Cuchiero** (University of Vienna)

Affine multiple yield curve models

*based on joint work with Claudio Fontana and Alessandro Gnoatto*

We propose a flexible and tractable specification based on affine processes to model multiple yield curves, which can be embedded in the HJM approach considered in [2]. More precisely, we model the OIS short rate and logarithmic multiplicative spreads between LIBOR rates and simply compounded OIS rates as affine functions of a common affine process. This approach thus constitutes a natural extension of classical affine short rate models, which allows for the possibility of ordered spreads (with respect to the tenor's length) and tractable pricing formulas also in the multi-curve setting. In order to exactly fit the initial term structure of OIS bonds and spreads, we also provide a deterministic shift extension in the spirit of [1]. Finally, we show how our approach is related to other multi-curve models based on affine processes.

[1] Brigo D., and Mercurio F. (2001) A deterministic-shift extension of analytically-tractable and time- homogeneous short-rate models, *Finance and Stochastics, 5(3):369-387.*

[2] Cuchiero C., Fontana C., and Gnoatto A. (2015) A general HJM framework for multiple yield curve modeling, *to appear in Finance and Stochastics.*

**Zorana Grbac** (Université Paris-Diderot)

No-arbitrage conditions in HJM multiple curve term structure models
*based on joint work with Wolfgang Runggaldier*

We study post-crisis modeling of the term structure of interest rates in the HJM framework. One of the most significant consequences of the financial crisis for fixed-income markets was divergence of various interest rate curves which followed each other closely before the crisis, thus creating a need for new models referred to as multiple curve models. In this work we discuss several possible extensions of the classical HJM setup to include multiple curves and the corresponding no-arbitrage drift conditions, as well as their relationship.

## 11 Swissquote Practitioners' Session (Tu, 14:00 – 15:30, Room 5ABC)

**Damien Challet** (Centrale Supélec France and Encelade Capital SA, Switzerland)

Predicting investment fluxes from implicit lead-lag investor networks
*based on joint work with Mehdi Lallouache and Rémy Chicheportiche*

Investors using the same kind of trading strategies are likely to be active or inactive in a coordinated way. This defines an implicit investor network. Applying community detection methods from network theory yields groups of traders which are remarkably stable in time. We then build lead-lag networks between such groups and find surprisingly many statistically valid lead-lag relationships. In other words the actions (or inaction) of one group predicts those of some other groups. In turn, this implies that the investment flux is predictable. Using machine learning methods, we show that this is indeed the case.

**Filippo Passerini** (Swissquote)

Managing inventory with proportional transaction costs
*based on joint work with Remy Chicheportiche, Florent Gallien, Julien Hugonnier, Serge Kassibrakis and Semyon Malamud*

Efficient inventory management is pivotal for market making activities. Market makers and broker/dealers typically need to hold large inventories of risky assets and face the natural trade-off between the directional risk for holding inventories and transaction costs implied by the offloading of the inventories. We study this problem for a CARA market-maker who faces proportional transaction costs and marking to market. We derive an inventory management policy that optimally accounts for the distribution of client orders that the dealer anticipates to receive in the future. Clients' orders are assumed to arrive according to a compound Poisson process with an arbitrary distribution of order sizes. We show that the optimal inventory policy is characterized by a no-trade region (a band) around the Merton efficient portfolio. We characterise the boundaries of the band explicitly through the distribution of order sizes and show that they may exhibit surprising, non-monotonic behaviour. We test our model with simulated data and real data of Forex clients of Swissquote bank..

## 12 BSDEs (Tu, 14:00 – 15:30, Room 3BC)

**Romuald Elie** (Université Paris-Est)

Optimal incentives for a system of interacting agents
*based on joint work with Dylan Possamaï*

We consider a model where a principal requires to contract separately with a large number of agents. In this framework, each agent will be in charge of one project, whose stochastic dynamics can be influenced by all the agents. More specifically, each agent can choose to make efforts towards managing his own project, but can also decide to impact (positively or negatively) the projects of the other agents. Considering agents with relative performance concerns, we look towards the optimal way for the principal to contract with the system of interacting agents and discuss in particular the role of competition in this framework. BSDES play a central role in our study.

**Thomas Kruse** (Université d'Evry)

Minimal supersolutions for BSDEs with singular terminal condition and application to optimal position targeting
*based on joint work with Stefan Ankirchner, Monique Jeanblanc and Alexandre Popier*

We study the existence of a minimal supersolution for backward stochastic differential equations when the terminal data can take the value $+\infty$ with positive probability. We deal with equations on a general filtered probability space and with generators satisfying a monotonicity assumption. With this minimal supersolution we then solve a stochastic control problem related to portfolio liquidation problems. We generalize the existing results in several directions: For example we relax the terminal liquidation constraint and allow for a random time horizon.

**Thibaut Mastrolia** (Dauphine Université Paris)

Utility maximization with random horizon: a BSDE approach
*based on joint work with Monique Jeanblanc, Dylan Possamaï and Anthony Réveillac*

We study a utility maximization problem with random horizon and reduce it to the analysis of a specific BSDE, which we call BSDE with singular coefficients, when the support of the default time is assumed to be bounded. We prove existence and uniqueness of the solution for the equation under interest. Our results are illustrated by numerical simulations

## 13 Polynomial Models in Finance (We, 11:30 – 17:30, Room 5ABC)

**Damien Ackerer** (EPFL)

Linear credit risk models
*based on joint work with Damir Filipovic*

We introduce a novel class of reduced form models for the term-structure of credit default risk where the survival probability of a firm is a linear function of the risk factors. The hazard-rate has a static compact support and the background stochastic process has a dynamic compact support. We present a canonical multi-names specification built upon an extension of the multivariate Jacobi process. This approach is analytically more tractable than the affine hazard-rate models as, for example, the price of a credit-default-swap contract is available in exact closed-form. Finally, we show that the single-name model is able to empirically capture the dynamics of selected individual CDS term-structures.

**Elise Gourier** (Princeton University)

Option pricing in a quadratic variance swap model

We present a novel method to price European options in a quadratic variance swap model. In this model, the multivariate state process is characterized by a quadratic diffusion function. The variance swap curve is quadratic in the state variable and available in closed form. Our pricing method relies on the polynomial preserving property of quadratic jump-diffusion processes, which allows us to approximate the conditional moments of the log price. The characteristic function is obtained using an Edgeworth expansion, and option prices are recovered with standard Fourier inversion.

**Martin Keller-Ressel** (Technische Universität Dresden)

Affine processes with stochastic discontinuities

*based on joint work with Thorsten Schmidt*

Motivated by applications in finance, such as credit risk, we study affine processes without the common assumption of stochastic continuity. Such processes are semimartingales, but usually not quasi-left-continuous and may exhibit jumps at pre-determined times. We derive the associated Riccati equations that determine the characteristic function of the process and discuss some results on existence.

**Paul Krühner** (Vienna University of Technology)

Affine processes with compact state space and counter-examples for polynomial processes

A polynomial preserving process (PPP) is a strong Markov process whose (extended) generator maps polynomials to polynomials of at most the same degree. They somewhat generalise the popular class of affine process. The key feature of PPP are the tractable formulas how polynomials are mapped to polynomials by their transition semigroups. One advantage of the PPP-class over affine processes is the greater flexibility. Additionally, it seemed to be believed that affine process, unlike PPP, with compact state space are deterministic – which, however, is not the case. In this talk we classify all affine processes with compact state spaces. If the state space is compact, then the power moments of the marginals determine the law of the PPP. In case of unbounded state spaces it is still unknown which properties a PPP needs in addition to the polynomial structure – i.e. how polynomials transition to polynomials – so that those determine the law of the PPP. In this talk we provide examples that show that the law of a PPP on the real line can fail to be determined by their polynomial structure.

**Martin Larsson** (ETH Zurich)

Polynomial preserving jump-diffusions on the unit interval

*based on joint work with Christa Cuchiero and Sara Svaluto-Ferro*

Polynomial preserving processes have recently been recognized as a useful basis for financial modeling. While their general behavior is relatively well understood in the diffusion case, much less is known in the presence of jumps. In this talk I will present some results on the properties of polynomial preserving jump-diffusions, focusing on the case where the state space is the unit interval. Some applications will be discussed, as well as a curious open question.

**Eberhard Mayerhofer** (Dublin City University)

Existence and regularity of densities for affine processes

*based on joint work with Christa Cuchiero*

In this talk, I present an analytical method for deriving existence and regularity of transition densities of affine jump-diffusions. This method is a refinement of a previous one developed by Filipovic, M., and Schneider (2014), and it allows refined conclusions, in particular for models with a regularising jump component, and with degenerate stochastic drivers such as typical in interest rate or credit risk models.

**Sergio Pulido** (ENSIIE)

The Jacobi stochastic volatility model

*based on joint work with Damien Ackerer and Damir Filipovic*

We introduce a novel stochastic volatility model, where the squared volatility could be bounded and follows a Jacobi process. This model comprises the Heston model as a limiting case. The price of a European call option admits a closed form series representation. This representation involves the moments of the log price of the asset, which are given in terms of a linear ordinary differential equation. We demonstrate that the numerical computations are robust and perform particularly well. In addition, we present theoretical bounds for the error in the price approximation. The proposed pricing method has important implications as it could be applied to a wide range of European type claims.

**Paul Schneider** (Boston University and Swiss Finance Institute)

(Almost) Model-free recovery

We recover conditional physical moments of the S&P 500 from mild economic restrictions and a polynomial projection of the pricing kernel which attains the kernel's conditional expectation given S&P 500 returns. Similar to the multitude of possible martingale measures in incomplete markets these conditional moments identify a set of feasible physical probability measures. The moments predict realizations out-of-sample in particular for long maturities and yield refined Hansen-Jagannathan-type bounds from the nonlinear projection along with a corresponding trading strategy. The coefficients of the projection reveal that the true conditional pricing kernel is likely very far from being globally monotonic and convex as suggested by expected utility theory, but rather convex in negative, and concave in positive S&P 500 returns.

**Anders Trolle** (EPFL)

Linear-rational term structure models

*based on joint work with Damir Filipovic and Martin Larsson*

We introduce the class of linear-rational term structure models, where the state price density is modeled such that bond prices become linear-rational functions of the current state. This class is highly tractable with several distinct advantages: i) ensures nonnegative interest rates, ii) easily accommodates unspanned factors affecting volatility and risk premiums, and iii) admits semi-analytical solutions to swaptions. A parsimonious model specification within the linear-rational class has a very good fit to both interest rate swaps and swaptions since 1997 and captures many features of term structure, volatility, and risk premium dynamics – including when interest rates are close to the zero lower bound.

## 14 Long-Memory Models (We, 11:30 – 13:00, Room 4BC)

**Ehsan Azmoodeh** (University of Luxembourg)

Pathwise volatility in a long-memory pricing model: estimation and asymptotic behavior

Inspired by a substantial contribution due to Bender. et al. [3] that pricing by hedging and no arbitrage can extend beyond semimartingales if the quadratic variation of stock price follows as the classical Black–Scholes model, we consider the *long-memory* price process

$$S_t := s_0\, e^{X_t - \frac{1}{2}t}, \quad t \in [0, T],$$

where $X_t = W_t + B_t^H$ is a mixed Brownian–fractional Brownian motion with Hurst parameter $H > 1/2$ and Brownian motion $W$ and fractional Brownian motion $B^H$ are independent. In this talk, we show that the so called *randomized periodogram* provides a consistent estimator for quadratic variation $[X, X]_T$. Moreover, using Malliavin calculus techniques, we prove that the estimator enjoys the *asymptotic normality* property if and only if $H \geq 3/4$, i.e. in the semimartingales world. The talk is based on references [1, 2].


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[2] Azmoodeh, E., Valkeila, E. (2013) Characterization of the quadratic variation of mixed Brownian–fractional Brownian motion. *Stat. Inference Stoch. Process*. 16 (2), 97-112.

[3] Bender, C., Sottinen, T., Valkeila, E. (2008) Pricing by hedging and no-arbitrage beyond semimartingales. *Finance Stoch*. 12 (4), 441-468.


**Christian Bender** (Saarland University)

Simple arbitrage

We characterize absence of arbitrage with simple trading strategies in a discounted market with a constant bond and several risky assets. We show that, if there is a simple arbitrage, then there is a 0-admissible one or an obvious one, i.e., a simple arbitrage which promises a minimal riskless gain, if the investor trades at all. For continuous stock models we provide an equivalent condition for absence of 0-admissible simple arbitrage in terms of a property of the fine structure of the paths, which we call 'two-way crossing'. This property can be verified for many models by the law of the iterated logarithm. As an application we show that the mixed fractional Black-Scholes model with Hurst parameter bigger than a half is free of simple arbitrage on a compact time horizon. More generally, we discuss absence of simple arbitrage for stochastic volatility models and local volatility models which are perturbed by an independent 1/2-Hölder continuous process.

**José Manuel Corcuera** (Universitat de Barcelona)

A long-range dependence model in fixed income markets

In this talk we study a long-range dependence model for the short rates in a bond market. In spite of the fact that the process modelling the instantaneous short rate is not a semimartingale, the proposed model is quite tractable in comparison to other alternatives in the literature.

## 15 Systemic Risk (We, 11:30 – 15:30, Room 3BC)

**Christoph Aymanns** (University of Oxford)

Taming the Basel leverage cycle

*based on joint work with Fabio Caccioli, J. Doyne Farmer, Vincent W. C. Tan*

Effective risk control must make a tradeoff between the microprudential risk of exogenous shocks to individual institutions and the macroprudential risks caused by their systemic interactions. We investigate a simple dynamical model for understanding this tradeoff, consisting of a bank with a leverage target and an unleveraged fundamental investor subject to exogenous noise with clustered volatility. The parameter space has three regions: (i) a stable region, where the system always reaches a fixed point equilibrium; (ii) a locally unstable region, characterized by cycles and chaotic behavior; and (iii) a globally unstable region. A crude calibration of parameters to data puts the model in region (ii). In this region there is a slowly building price bubble, resembling a "Great Moderation", followed by a crash, with a period of approximately 10-15 years, which we dub the "Basel leverage cycle". We propose a criterion for rating macroprudential policies based on their ability to minimize risk for a given average leverage. We construct a one parameter family of leverage policies that allows us to vary from the procyclical policies of Basel II or III, in which leverage decreases when volatility increases, to countercyclical policies in which leverage increases when volatility increases. We find the best policy depends critically on three parameters: The average leverage used by the bank; the relative size of the bank and the fundamentalist, and the amplitude of the exogenous noise. Basel II is optimal when the exogenous noise is high, the bank is small and leverage is low; in the opposite limit where the bank is large or leverage is high the optimal policy is closer to constant leverage. We also find that systemic risk can be dramatically decreased by lowering the leverage target adjustment speed of the banks.

**Svetlana Borovkova** (University of Amsterdam)

Interbank payment and repo networks and what can we learn from them

We build a series of daily interbank payment networks on the basis of the transactions data from the so-called Target II system. Target II is the real-time gross settlement system owned and operated by the Eurosystem. We investigate how this network and its characteristics have evolved through time, from 2008 until the present day. We identify central and most critical nodes and study the stability of the payment network by means of various measures. Another dynamic interbank network is build using repo transactions. The dynamic characteristics of this network are studied as well and related to changes in macroeconomic variables.
We find that the nature and the dynamic evolution of large interbank networks can differ significantly, depending on what types of links (payments or loans) are considered.

**Rama Cont** (Imperial College London)

Fire sales, endogenous risk and price-mediated contagion

*based on joint work with Eric Schaanning*

Large-scale deleveraging of assets by distressed financial institutions have been recognized as an important channel for the contagion of losses during the recent financial crisis. Building on previous work of (Cont & Wagalath, 2013), we propose a model for analyzing the impact of fire sales on system-wide losses in a system with multiple financial institutions subject to a macroeconomic stress scenario affecting asset values. Our model emphasizes the nonlinear threshold nature of de-leveraging, as a result of which the volume of de-leveraging is a convex function of initial asset losses, and enables to quan-

tify the magnitude of spillover effects due to price-mediated contagion in terms of liquidity-weighted overlaps of institutional asset holdings. We illustrate these observations on European bank data from the European Banking Authority.

A key concept which emerges from the model is the notion of indirect exposure of a financial institution to an asset class: we show that, when the impact of of fire sales is taken into account, the effective exposure of an institution to an asset class may be found to be much larger than the apparent exposure as revealed by the portfolio holdings alone. These results illustrate the importance of system-wide stress testing, which can provide a completely different perspective than stress tests performed on individual bank portfolios.

**Eric Schaanning** (Imperial College London)

Price-mediated contagion and systemic risk: indirect exposures, macroprudential tools and modeling issues

*based on joint work with Rama Cont*

Fire sales and price-mediated contagion have been identified as important vectors of contagion during the last financial crisis. We introduce a multi-asset, multi-institution, multi-timestep model to study these phenomena, and use balance sheet data from the European Banking Authority to reconstruct the network of overlapping portfolios of European banks. Depending on certain characteristics of this network, the aggregate response of banks to an initial shock can propagate in the form of fire sales and price-mediated contagion as a new endogenous shock through the financial market. We quantify how losses originating in a specific sector spread across asset classes and institutions as a function of the liquidity weighted overlap of the banks' portfolios. The potential for such contagion leads to the concept of indirect exposures: Contingent mark to market losses in a stress scenario, expose banks indirectly to risk factors that are not apparent on their balance sheet. A consequence of such indirect exposures is that the risk of a given portfolio cannot be inferred from its constituent assets alone, but depends on the aggregate configuration of the system. This highlights the role of macroprudential regulation in reducing the systemic risk stemming from fire sales and price-mediated contagion. We show how targeted risk weights for systemic asset classes can be calibrated towards this goal and significantly outperform a benchmark policy of uniform capital increases.

By introducing a threshold-based model of fire sales, we complement the current literature on linear "leverage targeting" models. While, especially for small shocks, linear models tend to overestimate the significance of fire sales, threshold-based models seem to deliver more plausible results. Despite losing analytical tractability, such models can therefore offer an interesting complement to linear models of fire sales in future research.

**Luitgard Veraart** (London School of Economics)

A Bayesian methodology for systemic risk assessment in financial networks

*based on joint work with Axel Gandy*

We develop a Bayesian methodology for systemic risk assessment in financial networks such as the interbank market. Nodes represent participants in the network and weighted directed edges represent liabilities. Often, for every participant, only the total liabilities and total assets within this network are observable. However, systemic risk assessment needs the individual liabilities. We propose a model for the individual liabilities, which, following a Bayesian approach, we then condition on the observed total liabilities and assets. We construct a Gibbs sampler to generate samples from this conditional distribution. These samples can be used in stress testing, giving probabilities for the outcomes of interest. As one application we derive default probabilities of individual banks and

discuss their sensitivity with respect to prior information included to model the network. An R-package implementing the methodology is provided.

**Stefan Weber** (Leibniz Universität Hannover)

Measures of systemic risk

*based on joint work with Zachary G. Feinstein and Birgit Rudloff*

Systemic risk refers to the risk that the financial system is susceptible to failures due to the characteristics of the system itself. The tremendous cost of this type of risk requires the design and implementation of tools for the efficient macroprudential regulation of financial institutions. We propose a novel approach to measuring systemic risk.

Key to our construction is a rigorous derivation of systemic risk measures from the structure of the underlying system and the objectives of a financial regulator. The suggested systemic risk measures express systemic risk in terms of capital endowments of the financial firms. Their definition requires two ingredients: first, a random field that assigns to the capital allocations of the entities in the system a relevant stochastic outcome. The second ingredient is an acceptability criterion, i.e. a set of random variables that identifies those outcomes that are acceptable from the point of view of a regulatory authority. Systemic risk is measured by the set of allocations of additional capital that lead to acceptable outcomes. The resulting systemic risk measures are set-valued and can be studied using methods from set-valued convex analysis. At the same time, they can easily be applied to the regulation of financial institutions in practice.

We explain the conceptual framework and the definition of systemic risk measures, provide an algorithm for their computation, and illustrate their application in numerical case studies. We apply our methodology to systemic risk aggregation as described in Chen, Iyengar & Moallemi (2013) and to network models as suggested in the seminal paper of Eisenberg & Noe (2001), see also Cifuentes, Shin & Ferrucci (2005), Rogers & Veraart (2013), and Awiszus & Weber (2015).

## 16 Partial and Insider Information (We, 14:00 – 15:30, Room 4BC)

**Luca Di Persio** (University of Verona)

Polynomial chaos expansion approach to financial modeling

The Polynomial Chaos Expansion (PCE) technique allows to recover the finite second order moment of a random variable exploiting suitable linear combinations of orthogonal polynomials, functions of a given stochastic quantity, acting as a kind of random basis. The PCE methodology has been developed as a mathematically rigorous Uncertainty Quantification (UQ) method aiming at providing reliable numerical estimates for given uncertain physical quantities characterizing specific engineering simulations. We exploit the PCE approach to analyse some well known financial models, e.g. the ones based on the Geometric Brownian Motion, the Vasicek model and the CIR model. In particular we present theoretical, as well as related concrete numerical approximations results, providing both an efficiency and an accuracy study of our approach by comparing its outputs with the ones obtained by mean of the Monte Carlo technique in its standard as well as in its enhanced version. Latter comparisons show how the PCE outperforms the Monte Carlo based simulations.

**Yuliya Mishura** (Taras Shevchenko National University of Kyiv)

On mean-variance hedging under partial observations

*based on joint work with with A. Melnikov and V. Makogin*

We study a mean-square minimization hedging or superhedging problem with partial observations. The problem is naturally connected to the mean-variance hedging problem under incomplete information, however, the new approach to solving this problem is proposed. We provide a solution when the underlying price process is a square-integrable martingale and extend the results to a semimartingale case too. The results are illustrated and supported by examples with two correlated Wiener processes.

**Lukasz Stettner** (Polish Academy of Sciences)

Asymptotics of utilities from terminal wealth under partial information

In the paper we present we are looking for asymptotics of utility $U$ from terminal wealth $W_T$ i.e. we are looking for $\lambda$ such that optimal value of $E\{U(X_T)\}$ is of order $U(e^{\lambda T})$ for $T$ large. We consider the case when the asset prices depend on economic factors, which are observed only through the asset prices. We study the problem both in discrete with or without transaction costs and in continuous time with proportional transaction costs. The presentation in discrete time is based on the paper [1], while the continuous time problem is a generalization to partially observed case of the papers [2] and [3].


[1] L. Stettner (2012) Asymtotics of utility from terminal wealth for partially observed portfolios, *Applicationes Math. 39(4), 445–461.*

[2] T. Duncan, B. Pasik Duncan, L. Stettner (2011) Growth optimal portfolio selection under proportional transaction costs with obligatory diversification, *Appl. Math. Optim. 63, 107–132.*

[3] L. Stettner (2011) Asymptotics of HARA utility from terminal wealth under proportional transaction costs with decision lag or execution delay and obligatory diversification, *in Advanced Mathematical Methods for Finance, ed. G. di Nunno, B. Øksendal, Springer 2011, 509–536.*


## 17 Optimal Transport in Mathematical Finance (We, 16:00 – 17:30, Room 4BC)

**Luciano Campi** (London School of Economics)

On the support of extremal martingale measures with given marginals: the countable case

*based on joint work with Claude Martini*

After discussing some characterisations of extremal measures with given marginals available in the literature, going from functional analysis to combinatorics, we will turn to their martingale counterparts whose study is related to robust pricing and hedging. In particular, we will give some sufficient and necessary conditions with a geometric and combinatorial flavour for a given set to be the support of an extremal martingale measure with pre-specified discrete marginals. Some open problems will be discussed as well.

**Alex Cox** (University of Bath)

Model-independent bounds for Asian options: a dynamic programming approach
*based on joint work with S. Källblad*

We consider the problem of finding model-independent bounds on the price of an Asian option, when the call prices at the maturity date of the option are known. Our methods differ from most approaches to model-independent pricing in that we consider the problem as a dynamic programming problem, where the controlled process is the conditional distribution of the asset at the maturity date. By formulating the problem in this manner, we are able to determine the model-independent price through a PDE formulation. Notably, this approach does not require specific constraints on the payoff function (e.g. convexity), and would appear to be generalisable to many related problems.

**Martin Huesmann** (Universität Bonn)

Model independent finance, Vovk's outer measure, and insider trading
*based on joint work with B. Acciaio, M. Beiglboeck, A. Cox, N. Perkowski, D. Prömel*

Model-independent finance has grown into a sizable field within mathematical finance during the last two decades. We present a natural and flexible continuous-time framework based on a combination of ideas of optimal transport and Vovk's outer measure that is well suited to incorporate various constraints in the market and allows to consider rather complicated setups in a model independent way. To illustrate the power of this approach I will present two examples: a general multi-marginal duality result and a model independent approach to insider trading.

## 18 Limit Order Markets (We, 16:00 – 17:30, Room 3BC)

**Ryan Donnelly** (EPFL)

Algorithmic trading under the effects of volume order imbalance
*based on joint work with Sebastian Jaimungal and Alvaro Cartea*

Shortcomings of continuous microstructure models are noted with motivation provided by data from the NASDAQ. The influence of volume order imbalance on microstructure dynamics is incorporated into a model which allows the agent to adjust their strategy based on an easily observable quantity. The predictive power of order imbalance allows the agent to decide when they should trade more aggressively to take advantage of beneficial price movements, and when they should trade more conservatively to protect against adverse selection effects. High imbalance results in a stronger inclination to place limit buy orders with the opposite effect on limit sell orders. We attempt to quantify the value of accurately observing imbalance through historical simulations.

**Thibault Jaisson** (École Polytechnique, Paris)

Estimation of slowly decreasing Hawkes kernels: Application to high frequency order book modelling
*based on joint work with Emmanuel Bacry and Jean-François Muzy*

We present a modified version of the non parametric Hawkes kernel estimation procedure studied in [1] that is adapted to slowly decreasing kernels. We show on numerical simulations involving a reasonable number of events that this method allows us to estimate faithfully a power-law decreasing kernel over at least 6 decades. We then propose a 8-dimensional Hawkes model for all events associated with the first level of some asset order book. Applying our estimation procedure to this model, allows us to

uncover the main properties of the coupled dynamics of trade, limit and cancel orders in relationship with the mid-price variations.

[1] Barcy E., and Muzy J.-F. (2014) Second order statistics characterization of Hawkes processes and non-parametric estimation. *arXiv preprint arXiv:1401.0903.*

**Mathieu Rosenbaum** (Universite Pierre et Marie Curie, Paris)

The microstructural foundations of rough volatility models

*based on joint work with Thibault Jaisson*

It has been recently shown that rough volatility models reproduce very well the statistical properties of low frequency financial data. In such models, the volatility process is driven by a fractional Brownian motion with Hurst parameter of order 0.1. The goal of this talk is to explain how such fractional dynamics can be obtained from the behaviour of market participants at the microstructural scales. Using limit theorems for Hawkes processes, we show that a rough volatility naturally arises in the presence of high frequency trading combined with metaorders splitting.

## 19 Numerical Methods (Th, 11:30 – 13:00, Room 5ABC)

**Blanka Horvath** (ETH Zurich)

Dirichlet forms and finite element methods for the SABR model

*based on joint work with Oleg Reichmann*

We propose a deterministic numerical method for pricing vanilla options under the SABR stochastic volatility model, based on a finite element discretization of the Kolmogorov pricing equations via non-symmetric Dirichlet forms. Our pricing method is valid both in moderate interest rate environments and in the currently prevalent low interest rate regimes and is consistently applicable under very mild assumptions on parameter configurations of the process, which are easily met in all practical scenarios. The parabolic Kolmogorov pricing equations for the SABR model are degenerate at the origin, yielding nonstandard partial differential equations, for which conventional pricing methods — designed for non-degenerate parabolic equations — break down. We derive here the appropriate analytic setup to handle the degeneracy of the model at the origin. That is, we construct an evolution triple of suitably chosen Sobolev spaces with singular weights, consisting of the domain of the SABR-Dirichlet form- its dual spaceand the pivotal Hilbert space. We show well-posedness of the variational formulation of the SABR-pricing equations for vanilla and barrier options on this triple. Furthermore, we present a concrete finite element discretization scheme based on a (weighted) multiresolution wavelet approximation in space and a $\theta$-scheme in time and provide an error analysis for the finite element discretization.

**Antonia Mayerhofer** (Universität Ulm)

Derivative pricing using a reduced basis method for parameter functions

*based on joint work with Robert Stelzer and Karsten Urban*

For derivative pricing, one needs to calculate the conditional expectation of the discounted payoff under a risk neutral measure. To this end one can equivalently solve the associated parabolic partial differential equation in diffusion based models.

Solving a parabolic partial differential equation for different parameters leads to an enormous computational effort. With the reduced basis method, cf. [1] and references therein, one obtains a good

approximation for the solution of a parameter-dependent partial differential equation by solving a very small linear equation system.

For solving the parabolic partial differential equation we use a space time approach, generalising [2]. For different payoff functions, we usually have to construct a new reduced basis for each function. To avoid this effort we develop a strategy to handle functions as parameters, [3]. This leads to the possibility of pricing with the reduced basis method by constructing only one reduced basis offline and using it for different payoff functions online. Furthermore, we are discussing the application of the reduced basis method in a calibration process.


[1] A.T. Patera, G. Rozza (2008) Reduced basis approximation and a posteriori error estimation for parametrized partial differential equations, *MIT Pappalardo monographs in mechanical engineering (to appear), available at http://augustine.mit.edu*

[2] K. Urban, A.T. Patera (2013) An improved error bound for reduced basis approximation of linear parabolic problems, *Mathematics of Computation.*

[3] A. Mayerhofer, K. Urban (to appear) An improved error bound for reduced basis approximation of linear parabolic problems, *Journal of Comp. Finance.*



**Andreas Neuenkirch** (University of Mannheim)


Discretising the Heston model: an analysis of the weak convergence rate

We analyze the weak convergence rate of a discretisation scheme for the Heston model. Under mild assumptions on the smoothness of the payoff and on the Feller index of the volatility process, respectively, we establish a weak convergence rate of order one. Moreover, under almost minimal assumptions we obtain weak convergence without a rate. These results are accompanied by several numerical examples. Our error analysis relies on a classical technique from Talay and Tubaro, a recent regularity estimate for the Heston PDE by Feehan and Pop and Malliavin calculus.

## 20 Energy Finance (Th, 11:30 – 13:00, Room 4BC)


**Jocelyne Bion-Nadal** (CNRS - CMAP, Ecole Polytechnique)


Path-dependent second order PDEs and dynamic risk measures

We introduce new notions of regular solutions and viscosity solutions for path dependent second order partial differential equations (PDE). In contrast with the classical setting, the notion of regular solution for a path dependent PDE needs to deal with càdlàg paths. In order to have a Polish space we consider the Skorokhod topology on the set of càdlàg paths. Making use of the martingale problem approach to path-dependent diffusion processes, we construct explicitely families of time-consistent dynamic risk measures on the set of càdlàg paths $IR^n$ valued. These risk measures are shown to have regularity properties. We prove then that these time-consistent dynamic risk measures provide viscosity supersolutions and viscosity subsolutions for path dependent semi-linear second order partial differential equations.

This talk is based on the paper "Dynamic Risk Measures and Path-Dependent Second Order PDEs" to appear in the CAS-SEFE (Stochastics in Environmental and Financial Economics, Centre for Advanced Study, Olso) proceedings.

**Bernt Øksendal** (University of Oslo)

Stochastic differential insider games and applications to finance
*based on joint work with Olfa Draouil*

We study stochastic differential games of jump diffusions, where the players have access to inside (possibly asymmetric) information. Our approach is based on anticipative stochastic calculus, white noise, Hida-Malliavin calculus, forward integrals and the Donsker delta functional. We obtain a characterization of Nash equilibria of such games in terms of the corresponding Hamiltonians. This is used to study applications to insider games in finance.

**Barbara Rüdiger** (Bergische Universität Wuppertal)

Exponential ergodicity of jump-diffusion CIR processes
*based on joint work with Peng Jin and Chiraz Trabelsi*

We analyse exponential ergodicity of jump -diffusion CIR processes. In the case of a basic affine jump diffusion we determine also the density and prove Harris recurrence properties.

## 21 Liquidity Risk (Th, 11:30 – 13:00, Room 3BC)

**Julius Bonart** (Imperial College London)

Latent liquidity in limit order driven markets

The ideal human marketplace is often conceptualized with the help of the Walrasian paradigm: Repeated auctions lead to market clearing at the equilibrium price defined by the intersection of the aggregate demand and supply curves. Limit order driven markets, however, implement an asymmetry between liquidity providers and takers: Transactions can only take place after the prior submission of a limit order, regarded as a commitment to trade without any guarantee of execution. This institutionalized asymmetry inhibits the massive use of limit orders and a large fraction of trading intentions remains latent. We develop a framework which takes into account the effects of this latent liquidity on the price dynamics. Applications to non-linear price impact and optimal execution schedules are presented.

**Simone Scotti** (Université Paris-Diderot)

Optimal exit strategies for investment projects
*based on joint work with Etienne Chevalier, Vathana Ly Vath and Alexandre Roch*

We study the problem of an optimal exit strategy for an investment project which is unprofitable and for which the liquidation costs evolve stochastically. The firm has the option to keep the project going while waiting for a buyer, or liquidating the assets at immediate liquidity and termination costs. The liquidity and termination costs are governed by a mean-reverting stochastic process whereas the rate of arrival of buyers is governed by a regime-shifting Markov process. We formulate this problem as a multidimensional optimal stopping time problem with random maturity. We characterize the objective function as the unique viscosity solution of the associated system of variational Hamilton-Jacobi-Bellman inequalities. We derive explicit solutions and numerical examples in the case of power and logarithmic utility functions when the liquidity premium factor follows a mean-reverting CIR process.

**Monika Trapp** (University of Cologne)

Time-varying credit risk and liquidity premia in bond and CDS markets

We develop a reduced-form model that allows us to decompose bond spreads and CDS premiums into a pure credit risk component, a pure liquidity component, and a component measuring the relation between credit risk and liquidity. CDS liquidity has important consequences for the bond credit risk and liquidity components. Besides the credit risk link, we document a liquidity link between the bond and the CDS market. Liquidity in both markets dries up as credit risk increases, and higher bond market liquidity leads to lower CDS market liquidity. Ignoring CDS liquidity results in partly negative liquidity premiums, particularly when CDS liquidity is low.

## 22 Poster Sessions

**Sühan Altay** (Vienna University of Technology)

Term structure of defaultable bonds, an approach with Jacobi processes

*based on joint work with Uwe Schmock*

This study provides a novel defaultable term structure model that is capable of capturing negative instantaneous correlation between credit spreads and risk-free rate documented in empirical literature while sustaining the positivity of the default intensity and risk-free rate. Given a multivariate Jacobi (Wright-Fisher) process and a certain functional, we are able to compute the zero-coupon bond prices, both defaultable and default-free, in a relatively tractable way by using the exponential change of measure technique with the help of "carré du champ" operator as well as by using the transition density function obtained from the dual representation of the Jacobi process. The resulting formula involves series involving ratios of gamma functions and fast converging exponential decay functions. The main advantage of the proposed reduced form model is that it provides a more flexible correlation structure between state variables governing the (defaultable) term structure within a relatively tractable framework for bond and derivative pricing. Moreover, in higher dimensions one does not need to rely on numerical schemes related to the differential equations, which may be difficult to handle (e.g multi-dimensional Riccati equations in affine and quadratic term structure frameworks), because transition density function of the state variables are known. We also illustrate how one can use the proposed model for credit default swap pricing and in a multi-curve setting.

**Anne Balter** (Maastricht University)

Sets of indistinguishable models for robust optimisation

*based on joint work with Antoon Pelsser*

Models can be wrong and recognising their limitations is important in financial and economic decision making under uncertainty. Finding the explicit specification of the uncertainty set has been difficult so far. We develop a method that provides a credible set of models to use in robust decision making. The choice of the specific size of the uncertainty region is what we will focus on. We use the Neyman-Pearson Lemma to characterise a set of models that cannot be distinguished statistically from a "baseline" model. The set of indistinguishable models can explicitly be obtained for a given probability for the Type I and II error.

**Francesco Cordoni** (University of Trento)

A representation theorem for stochastic functional delay differential equations with jumps and applications to option pricing

*based on joint work with Luca Di Persio and Immacolata Oliva*

We consider a stochastic process $X$ solution to a given stochastic functional delay differential equation (SFDDE) with jumps taking values in $R^d$.

Exploiting the notion of segment at time $t$ of the process $X$, i.e. the path of the process $X$ in the interval $[t-r, t]$, where $r$ is a positive constant which represents the length of the memory, the aforementioned problem can be lifted in a suitable infinite dimensional space of Lebesgue square integrable function $L^2$, showing that the related solution is an $L^2$-valued Markov process whose uniqueness can be shown, see, e.g. [1], under standard assumptions of locally Lipschitzianity and linear growth for the coefficients.

Taking then into account a backward stochastic differential equation with delay and exploiting the Malliavin calculus we provide a non linear Feynman-Kac representation theorem for the delayed forward-backward system under mild assumptions on differentiability of the coefficients, in particular the coefficients are required to satisfy only Lipschitz continuity and polynomial growth at infinity, see, e.g. [2].

Eventually, previous results will be applied to the option pricing problem for pathdependent claims, such as Asian options, in some notable stochastic volatility models with jumps.


[1] Banos D., Cordoni F., Di Nunno G., Di Persio L., and Rose E. (work in progress) A note on the computation of the delta in a market with memory driven by Lévy noise.

[2] Cordoni F., Di Persio L., and Oliva I. (work in progress) Stochastic delay differential equations with jumps.


**Xuecan Cui** (University of Luxembourg)

Option pricing model with underlying time-varying Lévy processes

*based on joint work with Jang Schiltz*

We develop an equilibrium asset and option pricing model in a production economy under Itô-Lévy processes with time-varying drift, volatility and jump intensity. We derive equity premium and general pricing kernel in this model, and give pricing formulas for an European call. Empirically we will use Hodrick-Prescott Filter and Particle Filter methods to separate the time series of three time-varying variables from S&P500 Index and its option data.

**Fabien Heuwelyckx** (University of Mons)

Lookback options in the binomial model

*based on joint work with Karl Grosse-Erdmann*

This poster presents how to obtain the price of European lookback options at any time between emission and maturity using trees. We look at the price for calls and puts for any nonnegative spot rate. The levels in these trees denote the difference between the current value and the lowest (or highest) value of the underlying since emission [1]. We study the speed of convergence of such a modelisation to its evaluation by the Black-Scholes model [2] when the length of the tree increases. We show as expected that this convergence is of order $1/\sqrt{n}$. To prove this we write the price as an asymptotic expansion in powers of $1/\sqrt{n}$ for which we obtain the precise value of the first two coefficients.

[1] Cheuk T.H.F., and Vorst T.C.F. (1997) Currency lookback options and observation frequency: a binomial approach, *J. Int. Money Finance 16,173–187.*

[2] Goldman M.B., Sosin H.B., and Gatto M.A. (1979) Path dependent options: buy at low, sell at the high, *J. Finance 34, 1111-1127.*

**Zvonko Kostanjčar** (University of Zagreb)

Does bargaining dynamics inherently cause market bubbles and crashes?
*based on joint work with Stjepan Begušić, H. E. Stanley and Boris Podobnik*

Estimating a current stock price requires estimating future cash flows and cost of capitals. The accuracy of estimates can then be checked against the actual data, which emerge with the passage of time. Bad predictions are time-limited and case of overestimation can induce abrupt adjustments in the form of market crashes. The question is: Can we predict the time of market crashes?! Here, we propose a bargaining model based on a complex networks, where agents on the supply side of the market cooperate with agents on the demand side of the market, but agents who are on the same side of the market compete with each other. We demonstrate that the competition clustering in the networks directly affects the bargaining outcome, where bargaining dynamics strongly influence the emergence of market bubbles and the occurrence of market crashes. We propose a dynamical free cash flow model to estimate the intrinsic (fundamental) value of a financial index. When a bargaining process pushes market values to levels that are above intrinsic values, the uncertainty in market dynamics increases, and this increase in uncertainty could be used as an early warning indicator for market crashes. We illustrate the applicability and forecasting power of the network model for the S&P500 index by estimating a probability of market crash occurrence in period from April 2015 to December 2016. We demonstrate how our market crash predictions are in good agreement with the S&P500 index market crashes in the past.

**Steven Kou** (National University of Singapore)

Asset pricing with spatial interaction
*based on joint work with Xianhua Peng and Haowen Zhong*

We propose a spatial capital asset pricing model (S-CAPM) and a spatial arbitrage pricing theory (S-APT) that extend the classical asset pricing models by incorporating spatial interaction. We then apply the S-APT to study the co-movements of Eurozone stock indices (by extending the Fama-French factor model to regional stock indices) and the futures contracts on S&P/Case-Shiller Home Price Indices; in both cases spatial interaction is significant and plays an important role in explaining cross-sectional correlations.

**David Krief** (Université Paris Diderot)

An asymptotic approach for the pricing of options on realized variance
*based on joint work with Zorana Grbac, Archil Gulisashvili and Peter Tankov*

We propose a method for the approximate pricing of options on realized variance in stochastic volatility models where the instantaneous volatility process $(Z_t)$ is a diffusion process with general drift coefficient and constant diffusion coefficient:

$$dZ_t = b(Z_t)dt + \sigma dW_t,\ Z_0 = z_0.$$

This can be seen as an extension of the Stein-Stein model. The price of a call on realized variance with strike K is then given by

$$E\Big[\Big(\int_0^T Z_t^2 dt - K\Big)^+\Big].$$

Our method for computing this price is based on the asymptotic expansion of the density of the integrated variance in the spirit of [1] and [2]. We then integrate the payoff of the option against the asymptotic expression of the density to obtain an approximation of the option price using Laplace's method.


[1] Deuschel J. D., Friz P. K., Jacquier A., and Violante S. (2014) Marginal density expansions for diffusions and stochastic volatility I: theoretical foundations, *Communications on Pure and Applied Mathematics, 67.*

[2] Deuschel J. D., Friz P. K., Jacquier A., and Violante S. (2014) Marginal density expansions for diffusions and stochastic volatility II: applications, *Communications on Pure and Applied Mathematics, 67.*



**Ola Mahmoud** (University of St Gallen and University of California at Berkeley)


The two dimensions of drawdown: magnitude and duration

Multi-period measures of risk account for the path that the value of an investment portfolio takes. The most widely used such path-dependent indicator of risk is drawdown, which is a measure of decline from a historical peak in cumulative returns. In the context of probabilistic risk metrics, the focus has been on one particular dimension of drawdown, its magnitude, and not on its temporal dimension, its duration. In this paper, the concept of temporal path-dependent risk measure is introduced to capture the risk associated with the time dimension of a stochastic process. We formulate drawdown duration, which measures the length of excursions below a running maximum, and liquidation stopping time, which denotes the first time drawdown duration exceeds a subjective liquidation threshold, as temporal path-dependent risk measures and show that they, unlike drawdown magnitude, do not satisfy any of the axioms for coherent risk measures. Despite its non-coherence, we illustrate through an empirical example some of the insights gained from analyzing drawdown duration in the investment process. Remarks on the challenges of path-dependent risk estimation in practice are given in the conclusion.


**Yaroslav Melnyk** (EPFL)


Stochastic impulse control with regime-switching dynamics

*based on joint work with Ralf Korn and Frank Thomas Seifried*

We investigate dynamic optimal control problems that feature both intervention costs with a fixed component and partially controlled regime shifts. We analyze the associated coupled systems of quasi-variational inequalities in suitable Sobolev spaces and establish a direct approach to construct the value function and optimal strategies. Our results in particular yield a numerical procedure that converges to the value function. We also provide a corresponding verification theorem that relies on minimal regularity conditions and illustrate our results and methodology using an application in optimal product management.

**Georg Mikus** (Frankfurt School of Finance and Management)

Estimation of credit models via likelihood transformation and filtering

*based on joint work with Wolfgang Schmidt*

We consider the estimation of a structural credit default model, which is based on an exponential jump-diffusion firm value process. This process is not directly measurable, only derivatives such as credit default swap spreads provide noisy information. A likelihood transformation concept can be applied to estimate the parameters of the model. We describe how to implement such a method and the estimation success in view of model complexity. The framework builds on maximum likelihood estimation, with the parameters entering both transition density and transformation function. To capture broader characteristics of the data, we also describe how a filtering approach can be used to arrive at estimates for the state of the firm and the model parameters. Since our valuation function of the credit default swap from a certain credit quality is highly nonlinear already due to the involvement of inverse Laplace transforms, we use a non-linear particle filtering approach simulating trial states, and set up a tailored state space to capture the jump component efficiently. We show results for specific cases of the jump size distribution, such as the double exponential Kou model and the one-sided spectrally negative Kou model, and illustrated challenges and advantages of the approach.

**Paola Pederzoli** (University of Geneva and Swiss Finance Institute)

Valuing American options using fast recursive projections

*based on joint work with Antonio Cosma, Stefano Galluccio, and Olivier Scaillet*

This paper introduces a new numerical option pricing method by fast recursive projections. The projection step consists in representing the payoff and the state price density with a fast discrete transform based on a simple grid sampling. The recursive step consists in transmitting coefficients of the representation from one date to the previous one by an explicit recursion formula. We characterize the convergence rate of the computed option price. Numerical illustrations with different American and Bermudan payoffs with discrete dividend paying stocks in the Black Scholes and Heston models show that the method is fast, accurate, and general. As an application, we characterise the early exercise boundary of an American call option on a dividend paying stock. The boundary is higher under the Merton and Heston model than under Black Scholes if the dividend is discrete, and lower in the case of a continuous dividend yield. We apply our method to study a sample of call options on stocks with quarterly dividends during the period January 1996 through December 2012. We illustrate that the choice of the model for the underlying asset is important for both the early exercise decision and for the quantification of the dollar amount that the buyer of the option forgoes when he fails to optimally exercise to the advantage of the seller. By using stochastic volatility, jumps and a mixture of these processes in modelling the stock price, the cash amount foregone by call holders is lower than what found using the Black Scholes model.

**Jakub Rojček** (University of Zurich)

High-frequency trading in limit order markets: equilibrium impact and regulation

*based on joint work with Alexandre Ziegler*

We investigate the impact of high-frequency trading (HFT) on market quality and investor welfare using a general limit order book model. We find that while the presence of HFT always improves market quality under symmetric information, under asymmetric information this is the case only if competition between high-frequency traders is sufficiently strong. While HFT does not negatively

impact investor welfare, it reduces the welfare of slow speculators. The flexibility of the model allows investigating the effect of the main recent regulatory initiatives designed to curb HFT on market quality and investor welfare. We consider time-in-force rules, cancellation fees, transaction taxes, rebate fee structures, and speed bumps. While some of these regulations lead to improvements in a number of market quality measures, this generally does not translate into higher welfare for long-term investors. Rather, the main effect of such regulations is to generate wealth transfers from high-frequency traders to slow speculators. These regulations therefore appear inadequate to enhance investor welfare in the presence of HFTs. Of the different measures, transaction taxes are the least harmful; while they reduce welfare roughly by the amount of the tax, they do not significantly worsen market quality. The common practice by exchanges of granting rebates to limit orders is detrimental to market quality and investor welfare, causing both higher effective spreads and longer execution times.

**Agnieszka Rygiel** (Cracow University of Economics)

ARBITRAGE FOR SIMPLE STRATEGIES ON THE MARKET WITH BID AND ASK PRICES

*based on joint work with Łukasz Stettner*

We study markets with bid and ask prices over finite time horizon. We consider two kinds of simple strategies: simple strategies consisting of at most deterministic number of transactions and almost simple strategies consisting of finite but random number of transactions. In both cases we are looking for a necessary and sufficient conditions for absence of arbitrage. In particular we study the notion of obvious arbitrage, which is an arbitrage consisting of two transactions (buying and selling). We investigate the relationship between obvious simple and almost simple absences of arbitrage. We also show results concerning absence of arbitrage under shortselling constrains. The results in some sense generalize papers [1] – [4].

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[2] BENDER C. (2012) Simple arbitrage, *Annals of Applied Probability 22 (5), pp. 2067–2085.*

[3] ROLA P. (submitted) Arbitrage in markets with bid-ask spreads.

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**Markus Scholz** (Karlsruhe Institute of Technology)

COINTEGRATED MULTIVARIATE CONTINUOUS-TIME AUTOREGRESSIVE MOVING AVERAGE (MCARMA) PROCESSES

*based on joint work with Vicky Fasen*

The well known vector-ARMA models are commonly used as linear stochastic models in discrete time. The concept of cointegration, which was introduced by Engle and Granger [1], describes the phenomena, that two or more non-stationary processes, which are integrated, can have a stationary linear combination. Cointegration models therefore stochastic trends of some or all the variables. There is empirical evidence that cointegration arises e.g. in financial data. For example exchange rates or the relation between long-term and short-term interest rates show such a common stochastic behaviour. The obvious extension of this framework to a continuous-time setting are cointegrated MCARMA processes.

First of all we introduce our multivariate cointegrated model in continuous-time and examine a characterization for cointegration. We are going to extend the results in [2]. A question arising in this context is how to estimate the cointegrated MCARMA model.


[1] Engle R. F., and Granger C. W. J. (1987) Co-integration and Error Correction: Representation, Estimation, and Testing. *Econometrica, 55(2), 251–76.*

[2] Comte F. (1999) Discrete and continuous time cointegration. *Journal of Econometrics, vol. 88, no. 2, pp. 207–226.*



**Anna Sulima** (Jagiellonian University in Kraków)


Optimal portfolio selection for Markov regime-switching Lévy market with additional impulses on changing economical environment

*based on joint work with Z. Palmowski and Ł. Stettner*

We analyze a portfolio selection problem in a continuous-time Markovian regime-switching Lévy Black-Scholes-Merton model. The market in this model is, in general, incomplete. We use a power-jump assets and Markov additive assets to complete this market. We solve some investment problems of maximizing the expected utility of the terminal wealth in the enlarged market for a power utility and a logarithmic utility.


**Shih-Hau Tan** (University of Greenwich)


An efficient solver for multidimensional nonlinear Black-Scholes equation with Newton-like method

*based on joint work with Choi-Hong Lai and Konstantinos Skindilias*

Spread option pricing is an important problem in commodity market and when concerning about the liquidity, useful solvers are always desired for solving the multidimensional nonlinear Black-Scholes equation. In this poster presentation, a comparison of using different linearisation techniques combined with ADI method is provided to show the advantage of using Newton-like method. Essentially the main idea is to reduce the number of iterations while allowing the possibility of doing GPU computing. The proposed methodology may easily be applied to a number of instruments that appear in commodity markets.


**Stefan Waldenberger** (Graz University of Technology)


Affine LIBOR models driven by real-valued affine processes

*based on joint work with Wolfgang Müller*

The class of affine LIBOR models is appealing since it satisfies three central requirements of interest rate modeling. It is arbitrage-free, interest rates are nonnegative and caplet and swaption prices can be calculated analytically. In order to guarantee nonnegative interest rates affine LIBOR models are driven by nonnegative affine processes, a restriction, which makes it hard to produce volatility smiles. We modify the affine LIBOR models in such a way that real-valued affine processes can be used without destroying the nonnegativity of interest rates. Numerical examples show that in this class of models pronounced volatility smiles are possible.

**Fabian Woebbeking** (Goethe University Frankfurt)

TAIL-RISK-PROTECTION TRADING STRATEGIES

*based on joint work with Natalie Packham, Jochen Papenbrock and Peter Schwendner*

Classical tail risk protection strategies, such as protective put and CPPI, can be costly or fail to generate adequate positive returns. We develop dynamic portfolio protection trading strategies while taking into account different aspects of time-variation and dynamics of distributional parameters of financial time series. As a criterion for riskiness we consider the evolution of the Value-at-risk spread from a GARCH model with normal innovations relative to a GARCH model with generalized innovations. These generalised innovations may for example follow a Student t, a Generalised hyperbolic, an alpha-stable or a Generalised Pareto (GP) distribution.

First, accounting for the time-dependent dynamics of distributional parameters via a GARCH process allows to incorporate volatility clustering and autoregressive behaviour in volatility, both of which are well-documented stylized facts of financial time series (e.g. [1]). Second, by fitting the GARCH residuals (innovations) to flexible distribution families incorporating both normal and extreme behavior allows to determine whether, in a given time period, extreme events are more likely to occur than suggested by e.g. normal innovations. This information can be used in several ways, for example as an early warning indicator, but also for robust portfolio building.

Our preliminary results indicate that the GP distribution provides the strongest signals for avoiding tail risks. This is not surprising as the GP distribution arises as a limit of tail behaviour in extreme value theory and therefore is especially suited to deal with tail risks. This research indicates a great potential of tail-risk protection strategies. Although a strategy based on a historical time-series will fail for totally surprising extreme events, it is very well capable of detecting risk build-up. This suggests an alternative to classic risk-protection strategies such as CPPI and protective put that may be too expensive in times of small risk premia.

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**Hanlin Yang** (University of Zurich)

$L^p$ SOLUTIONS OF QUADRATIC BSDES

We study a general class of quadratic BSDEs with terminal value in $L^p$ for $p > 1$. We prove a $L^p$-type estimate, existence, comparison theorem, uniqueness and stability result. In order to construct a solution, we use a combination of the localization procedure developed by Briand and Hu [1] and the monotone stability result. We point out that our existence result relies on rather weak assumptions on the generators. By additionally assuming monotonicity and convexity, we deduce the comparison theorem, uniqueness and stability result via $\theta$-technique developed by Briand and Hu [2]. The Krylov estimate is used throughout to derive some auxiliary results. We point out that our results extend (sometimes partially) [1], [2], etc. Finally, we derive a probabilistic representation for the viscosity solution to the associated quadratic PDEs.

Keywords: quadratic BSDEs, Krylov estimate, convexity, FBSDEs, quadratic PDEs

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**Dariusz Zawisza** (Jagiellonian University in Kraków)

MONOTONE MEAN-VARIANCE PORTFOLIO CHOICE IN A CONTINUOUS TIME MARKET MODELS
*based on joint work with Jakub Trybuła*

We consider an investment problem based on continuous time modification of a monotone mean-variance functional first proposed in [1]. We assume that an investor has access to the market, where he can freely buy and sale a riskless bond and a risky asset. We consider both diffusion and jump-diffusion models. The problem is formulated as a stochastic differential game problem and Hamilton-Jacobi-Bellman-Isaacs equations are used to derive the optimal investment strategy. Finally, solution to our models are compared with the solution to classical Markowitz problem.

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