Naturalness
&
Compositeness
2014

Riccardo Rattazzi, EPFL

In QM whatever is *possible* is also *compulsory*

selection rules

$$\mathcal{O} = \sum_i \mathcal{O}_i \qquad \underbrace{\mathcal{O}_i}_{\text{dim } = \Delta} = c_i \underbrace{\lambda_1^{n_{1i}} \ldots \lambda_k^{n_{ki}}}_{\text{dim } = \Delta}$$

If $\quad \mathcal{O}|_{\text{exp}} \ll \max|\mathcal{O}_i| \quad$ it seems we are missing something

Un-Naturalness = failure of dimensional analysis and selection rules

Mass Hierarchies

Λ_{UV}

$\sim$ scale invariant dynamics

$\mathcal{L} \sim$ fixed point of RG

Λ_{IR}

Naturalness of $\Lambda_{IR} \ll \Lambda_{UV}$ ⟷ stability of fixed point

3 options

1. Marginality

Λ_{UV}

the fixed point theory does not possess scalar operators with dimension strictly less than 4

Λ_{IR}

$$\mathcal{L}_{\text{mass}} = c\,\Lambda_{UV}^{\epsilon}\,\mathcal{O}_{4-\epsilon}$$

$$\Lambda_{IR}^{\epsilon} = c\,\Lambda_{UV}^{\epsilon} \qquad\qquad \Lambda_{IR} = c^{1/\epsilon}\,\Lambda_{UV}$$

algebraically small c and ϵ is enough to produce hierarchy

see Strassler arXiv:hep-th/0309122

Ex: Yang-Mills, TechniColor, Randall-Sundrum model

2. Symmetry

Λ_{UV}

$$\mathcal{L}_{\rm mass} = \epsilon\, \Lambda_{UV}^2\, \mathcal{O}_2$$

small parameter protected by symmetry

Λ_{IR}

$$\Lambda_{IR} = \sqrt{\epsilon}\, \Lambda_{UV}$$

- ϵ must be *hierarchically* small
- how does this smallness originate?

Ex: QCD, Supersymmetry

3. Sequestering

Λ_{UV}

Λ_{IR}

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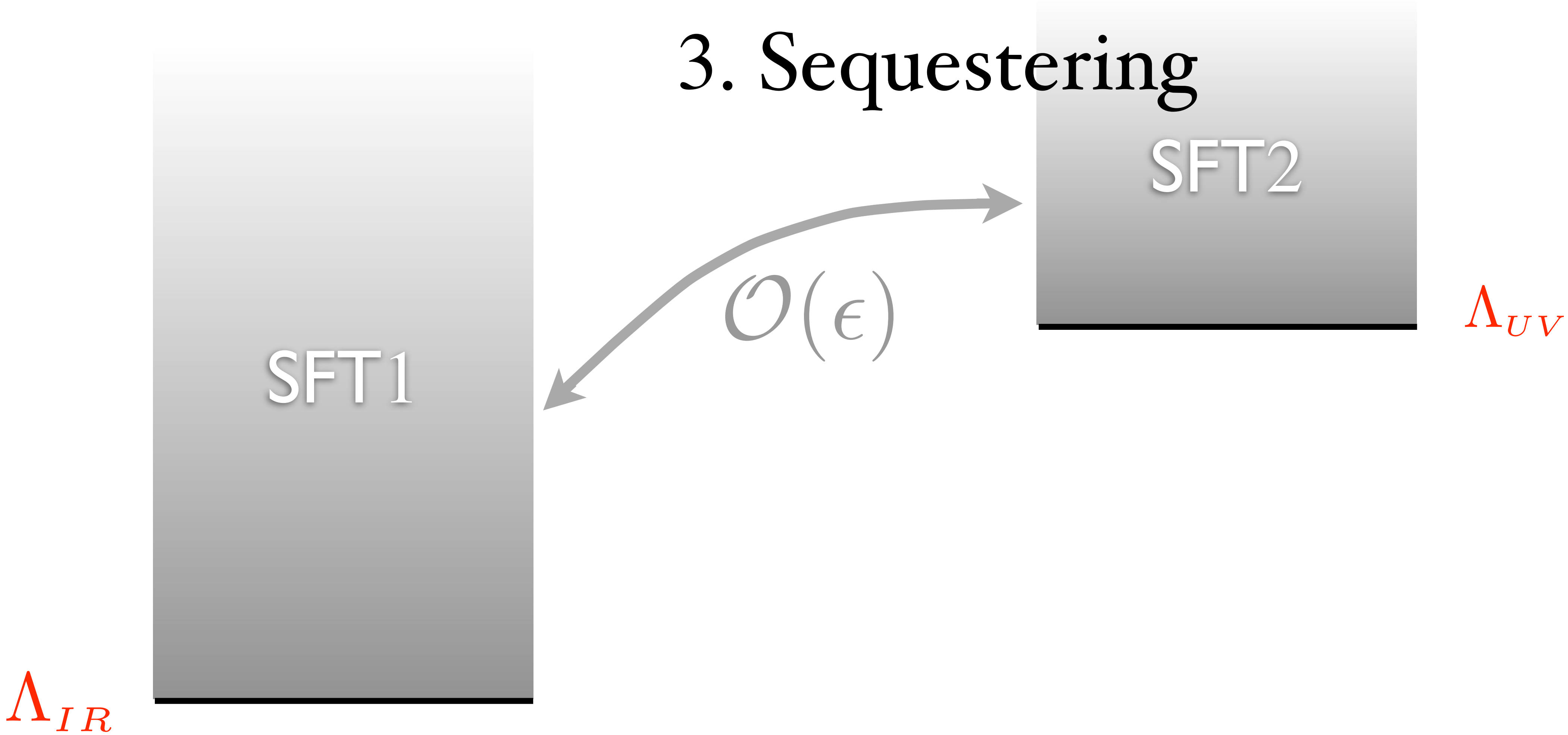
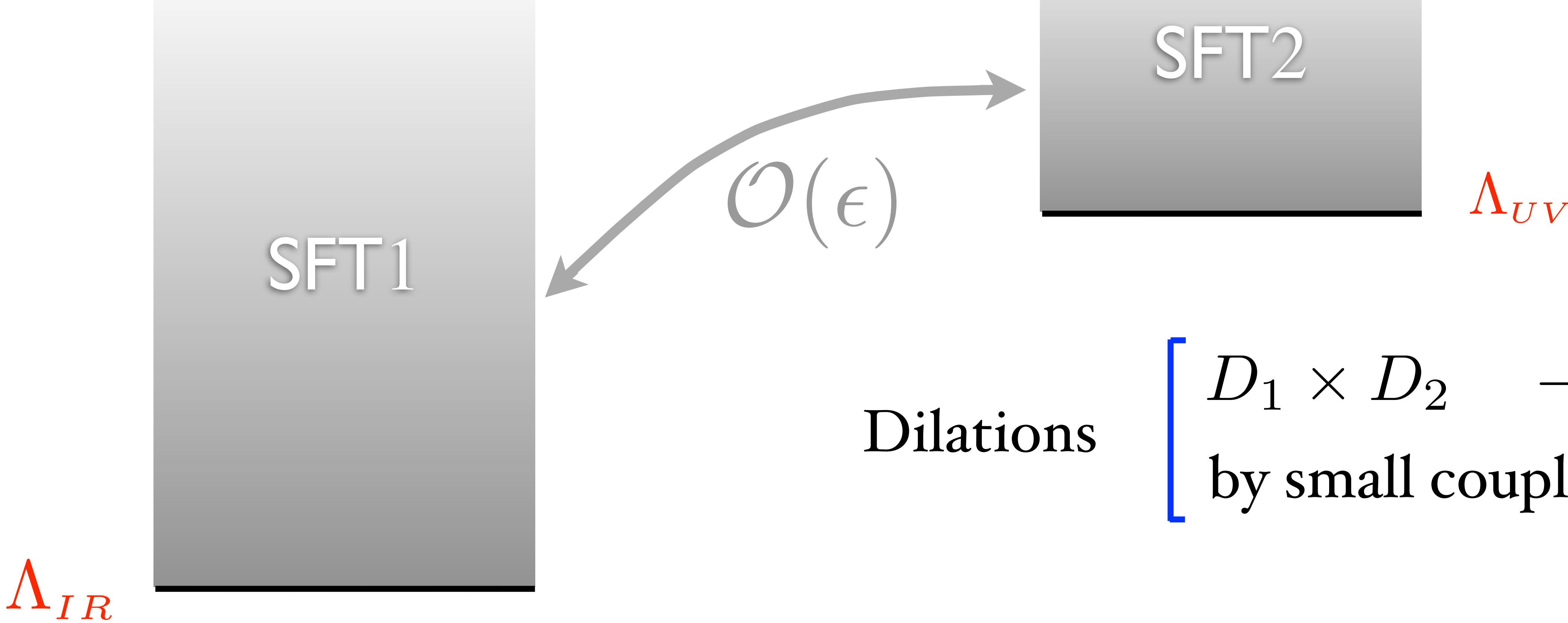


3. Sequestering



Dilations $\left[\begin{array}{l} D_1 \times D_2 \quad \to \quad D_{1+2} \\ \text{by small coupling} \quad \epsilon \end{array}\right.$

$$\Lambda_{IR} \sim \epsilon\,\Lambda_{UV}$$ technically natural

- SFT2 = 'UV completion of gravity' $\quad \epsilon = \Lambda_{UV}/M_P$
- not clearly compatible with basic principles
- but imagine we find a gorgeous candidate for SFT1?

Ex. a-gravity by a-strumia

Salvio, Strumia 2012

The Standard Model

Λ_{UV}

$$\mathcal{L}_{SM} \sim \mathcal{L}_{free} \quad \equiv \text{ fixed point}$$

$$H^\dagger H \quad \equiv \text{ relevant and unprotected}$$

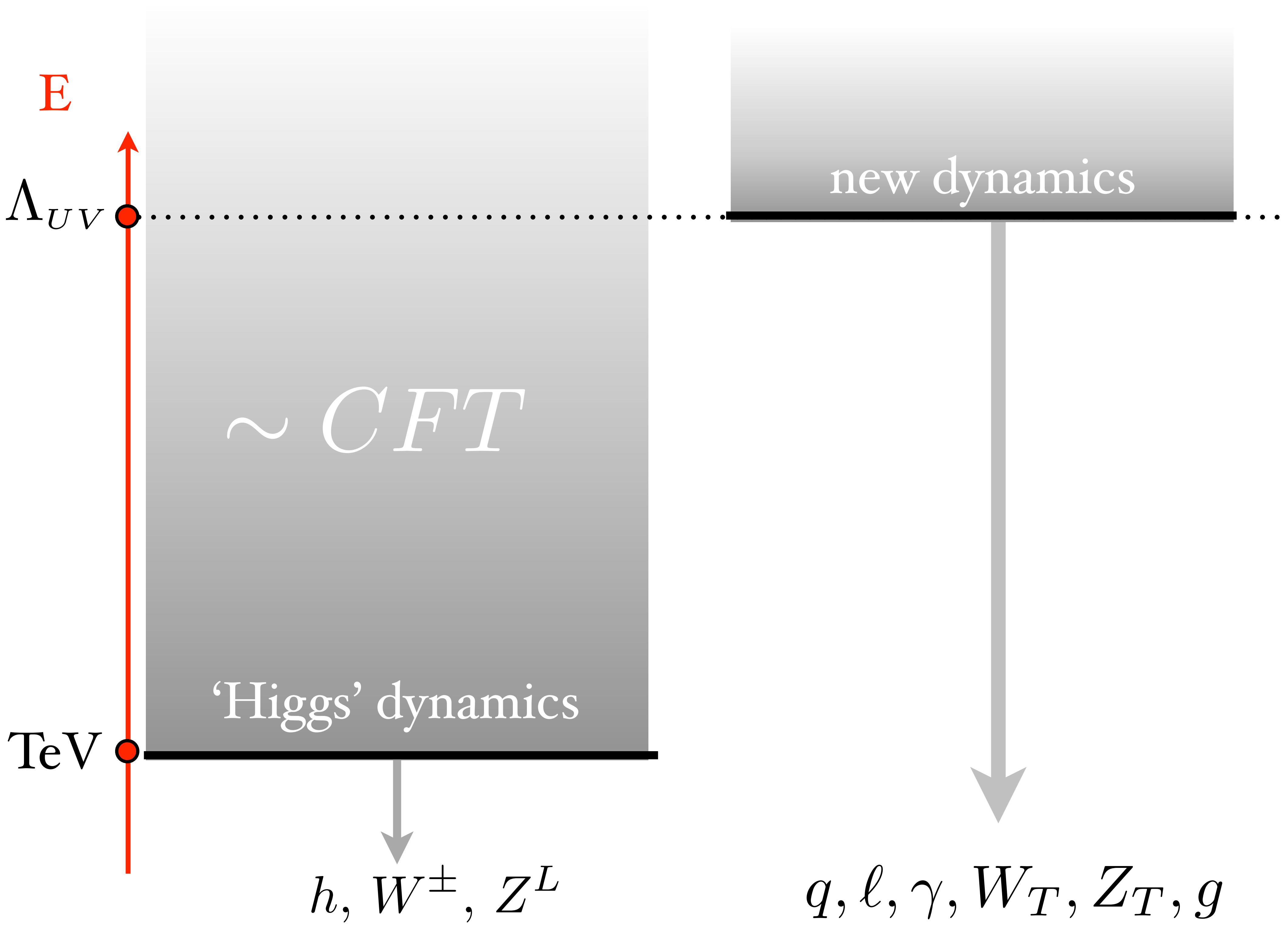
$\Lambda_{IR} \sim m_W$

but tuning comes with a bonus

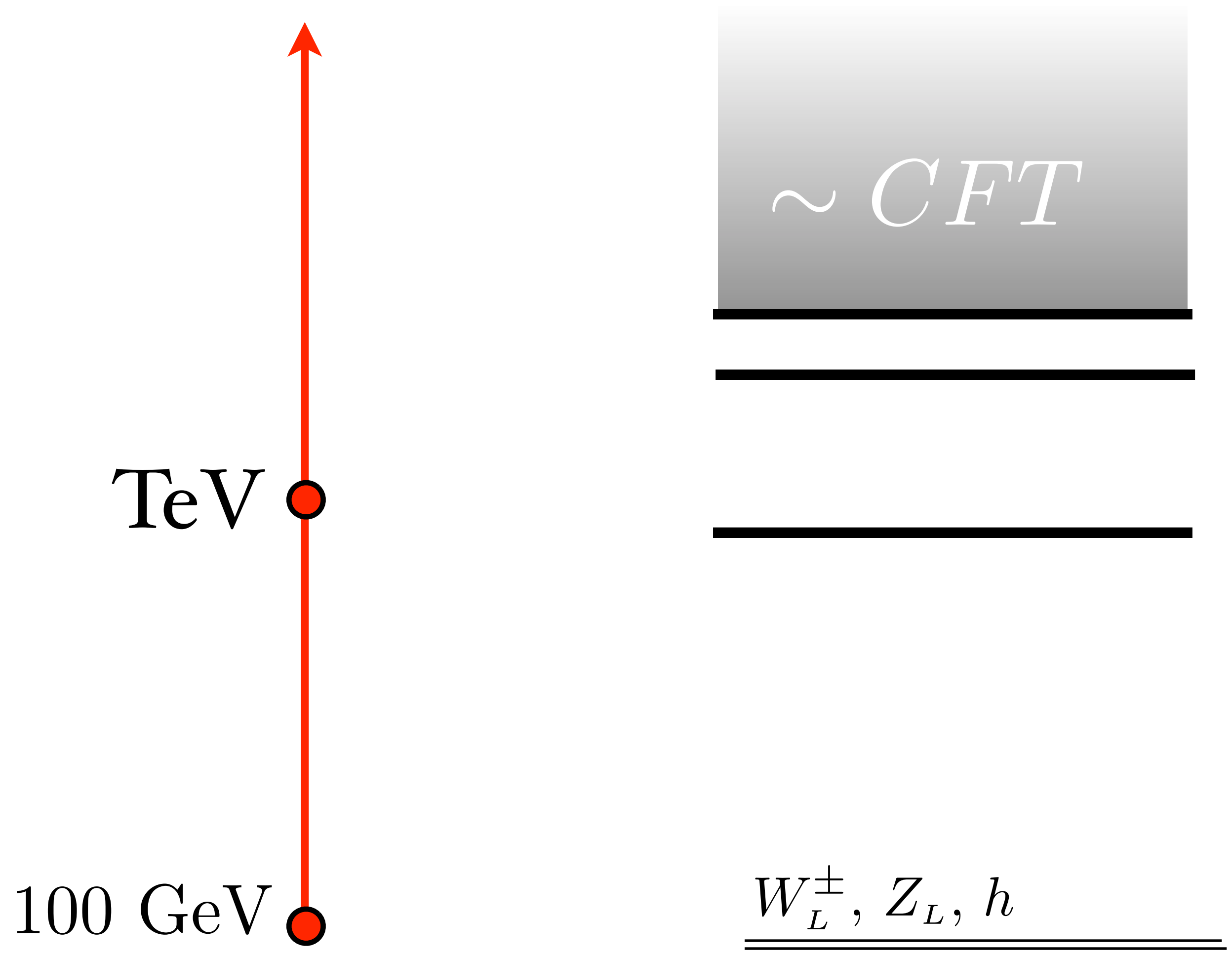
$$\mathcal{L}_{SM} \;=\; \mathcal{L}^{(d\leq 4)} + \frac{1}{\Lambda_{UV}}\mathcal{L}^{(5)} + \frac{1}{\Lambda_{UV}^2}\mathcal{L}^{(6)} + \ldots$$

- *Accidentally* possesses all the symmetries we observe in Nature: B, L, Flavor,...
- Not the case in any natural completion of the SM

Composite Higgs Scenario



Weak scale structure



$$H = \begin{pmatrix} h_1 + ih_2 \\ h + ih_3 \end{pmatrix}$$

must be a pseudo-Golstone multiplet

Ex.: $H \in SO(5)/SO(4)$

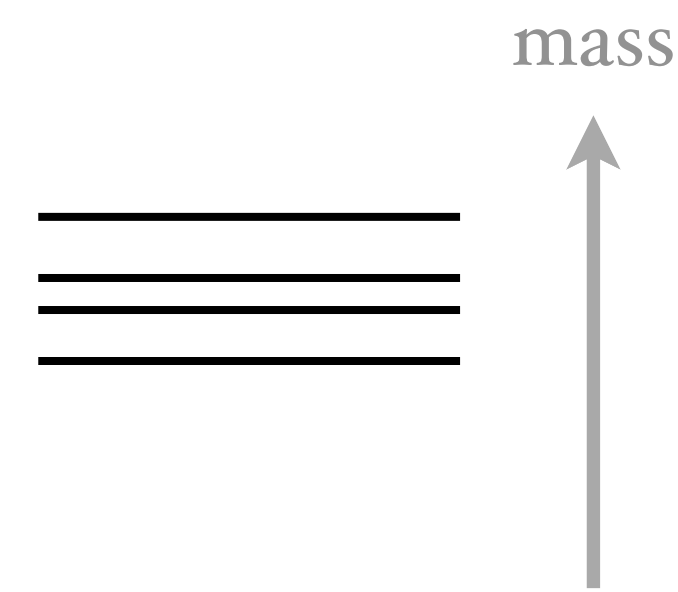
Georgi, Kaplan '84
Banks '84

Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

EWSB is *broadly* described by

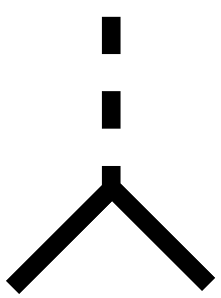
✦ one mass scale m_*

$\sim m_*$ {

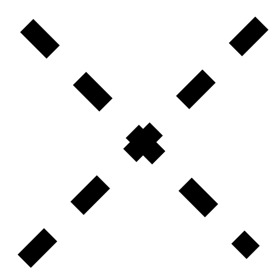


✦ one coupling g_*

Ex.: $g_* \sim \frac{4\pi}{\sqrt{N}}$



$g_* \, \bar{\Psi}\Psi\Phi$



$$\frac{g_*^2}{m_*^2}\,(\pi\partial\pi)^2$$

$h \in \pi =$ pseudo-NG

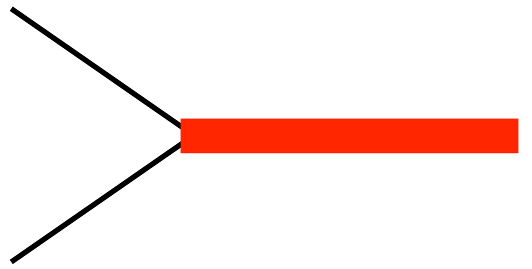
$$\frac{g_*}{m_*} \equiv \frac{1}{f}$$

Flavor

The two ways to Flavor

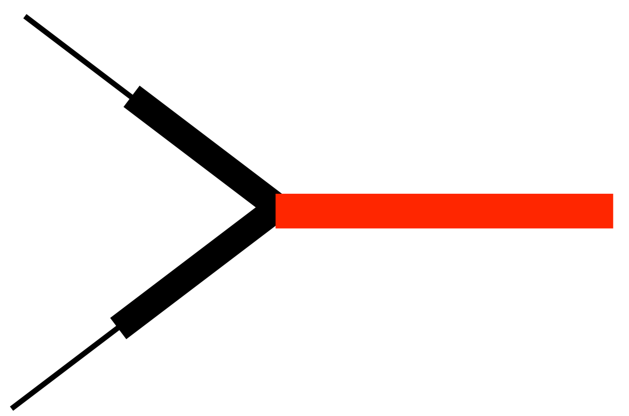
Bilinear: ETC, conformalTC

Dimopoulos, Susskind
Holdom
....
Luty, Okui



Linear: partial compositeness

D.B. Kaplan
....
Huber
RS with bulk fermions



The two ways to Flavor

Bilinear: ETC, conformal TC

Dimopoulos, Susskind
Holdom
....
Luty, Okui

disfavored by CFT ‘theorems’
Rychkov, Rattazzi, Tonni, Vichi 2008
Poland, Simmons-Duffin, Vichi 2011

Linear: partial compositeness

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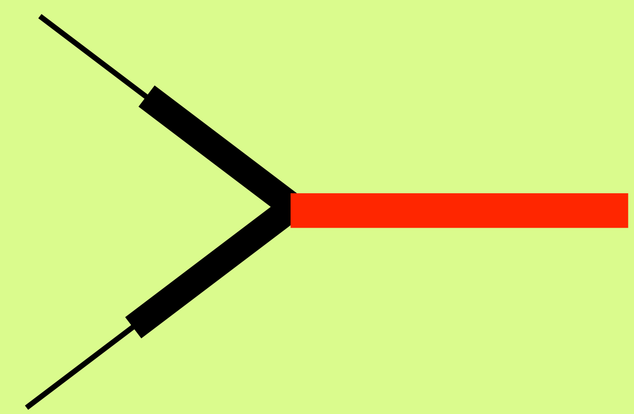
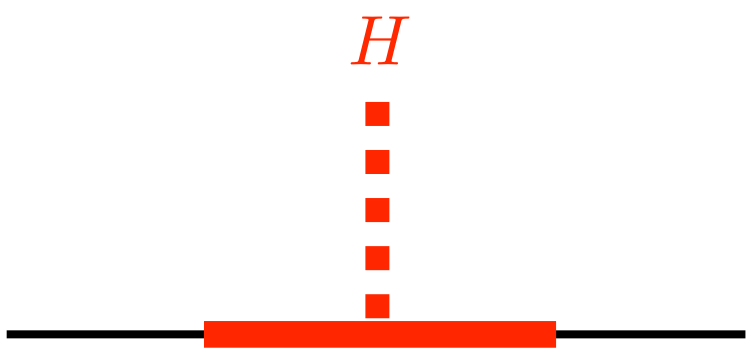


Flavor from partial compositeness

D.B. Kaplan '91
....
Huber, Shafi '00
RS with bulk fermions

$$\mathcal{L}_{Yukawa} = \epsilon_q^i q_L^i \Psi_q^i + \epsilon_u^i u_L^i \Psi_u^i + \epsilon_d^i d_L^i \Psi_d^i$$



$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_*$$

$$Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_*$$

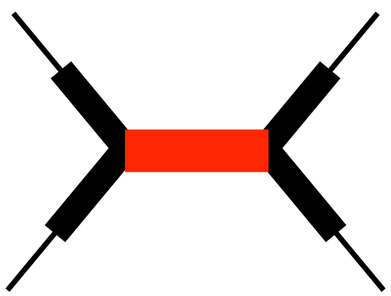
Ψ = composite with dimension $\sim \frac{5}{2}$ ⇒ $\epsilon_q^i,\ \epsilon_u^i,\ \epsilon_d^i$ = dimensionless

- Hypothesis seems a bit wishful, but no other option is in sight
- Problems of minimal technicolor greatly alleviated, but not eliminated

Flavor transitions controlled by selection rules

(accidental non-compact $U(1)^9$ flavor symmetry)

ΔF=2



$$\epsilon_q^i \epsilon_d^j \epsilon_q^k \epsilon_d^\ell \times \frac{g_*^2}{m_*^2} \; (\bar{q}^i \gamma^\mu d^j)(\bar{q}^l \gamma_\mu d^\ell)$$

ΔF=1

$$\epsilon_q^i \epsilon_u^j g_* \times \frac{v}{m_*^2} \times \frac{g_*^2}{16\pi^2} \; \bar{q}^i \sigma_{\mu\nu} u^j G_{\mu\nu}$$

Flavor and CP bounds

Keren-Zur et al., 2012

	$\Delta F=2$ (ϵ_K, ...)	$\Delta F=1$ (Δc^D_{CP}, ϵ'/ϵ, , $b \to s\gamma$)	edms	$\mu \to e\gamma$
$m_* >$ (TeV)	15	$\frac{g_*}{4\pi} \times (10-15)$	$\frac{g_*}{4\pi} \times (50-200)$	$\frac{g_*}{4\pi} \times 200$

Partial compositeness is likely not the full story

Flavor and CP symmetry must be assumed

Range of possibilities

$U(1)_e$ x $U(1)_\mu$ x $(1)_\tau$

. . . .

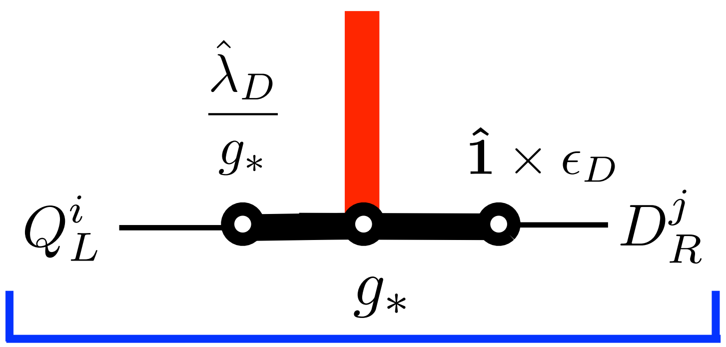
SU(3) x SU(3) x ...

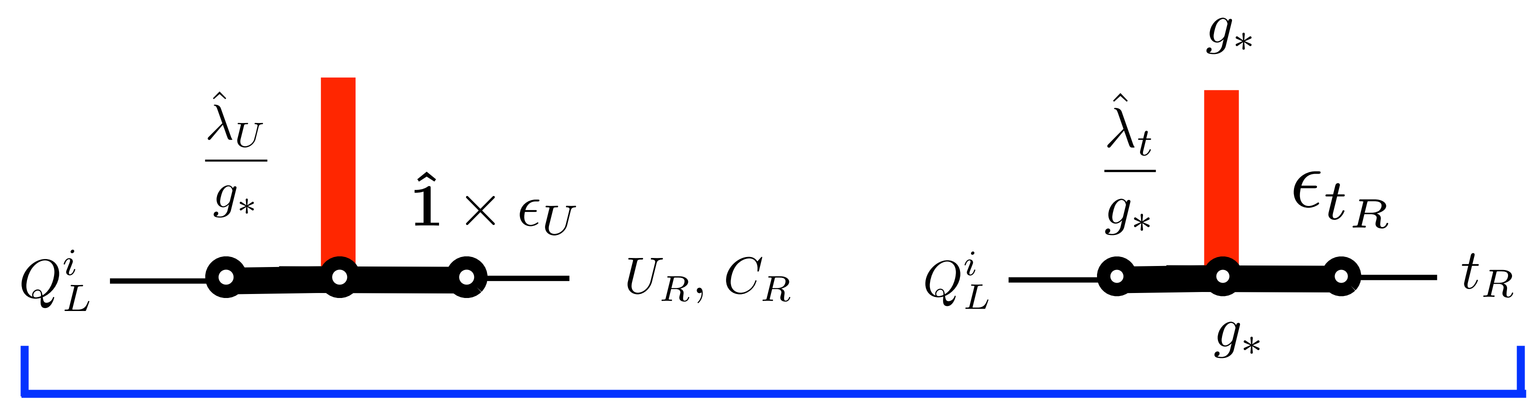
Redi, Weiler ’11
Barbieri et al. ’12

The most *clever* set up

$$SU(3)_{comp} \times SU(3)_Q \times SU(3)_D \times SU(2)_U$$

Redi 2012





$$\hat{Y}_D = \hat{\lambda}_D \, \epsilon_D$$

$$\hat{Y}_U = \hat{\lambda}_U \epsilon_U + \hat{\lambda}_t \epsilon_{t_R}$$

$\epsilon_{U,D}$ [sufficiently small to satisfy bounds from light quark compositeness

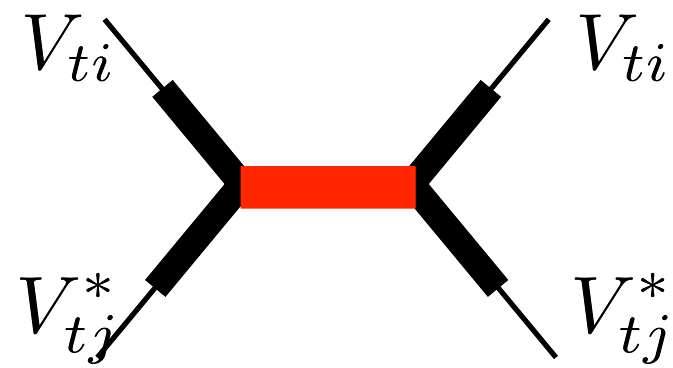
sufficiently large to avoid sizeable flavor violation from $\hat{\lambda}_{U,D}$

ϵ_{t_R} [sufficiently large to confortably account for top Yukawa $y_t = |\hat{\lambda}_t| \epsilon_{t_R}$

CP conserving strong dynamics phase alignment controls edms

$\epsilon_U \sim 0.2 - 0.5$ constrainst from compositeness and $\hat{\lambda}_U$ subdominant

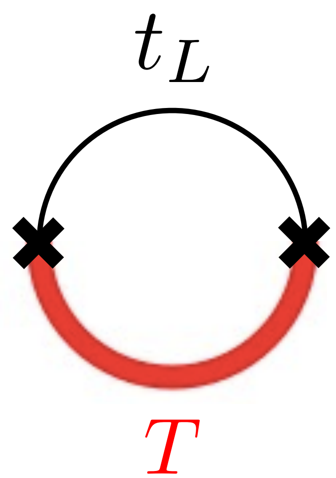
Uneliminable effect via the top doublet

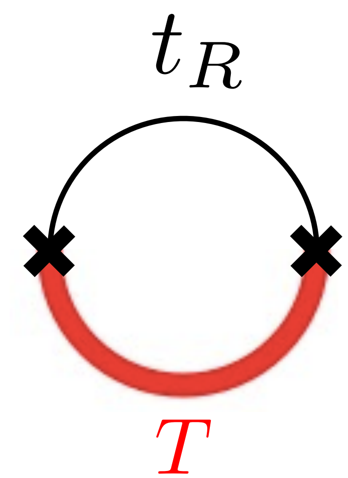


$\epsilon_K, \ \Delta m_{B_d, B_s}$

$$m_* g_* > \frac{5 \text{ TeV}}{\epsilon^2_{t_R}} \geq 5 \text{ TeV}$$

Higgs's mass versus top-partners'

$V(h) =$ 

$+$ 

$+ \ldots$

$\propto g_*^2 \epsilon_{t_L}^2$ $\qquad$ $\propto g_*^2 \epsilon_{t_R}^2$

$$y_t \sim \epsilon_{t_L} \epsilon_{t_R} g_*$$

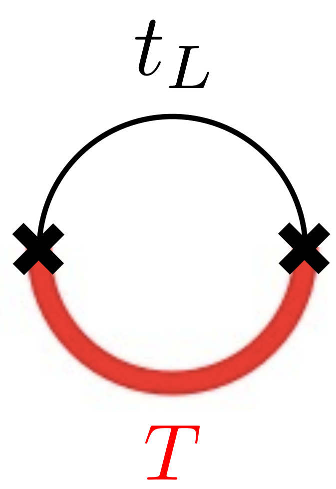
best option t_R is fully composite SO(5) singlet

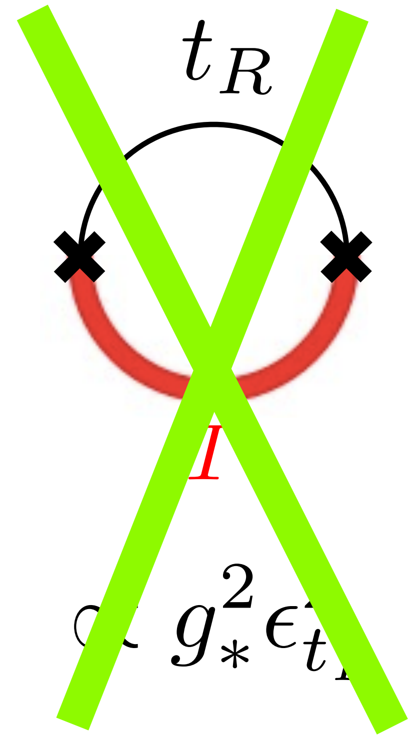
$$\epsilon_{t_R} = 1$$
$$\epsilon_{t_L} g_* = y_t$$

Mrazek et al, '11
Panico, Wulzer '11
Pomarol, Riva '12

$$V(h) = \frac{m_*^4}{g_*^2} \times \frac{y_t^2}{16\pi^2} \times F(h/f)$$

Higgs's mass versus top-partners'

$V(h) =$ 

$+$ 

$+ \ldots$

$\propto g_*^2 \epsilon_{t_L}^2$

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Mrazek et al, '11
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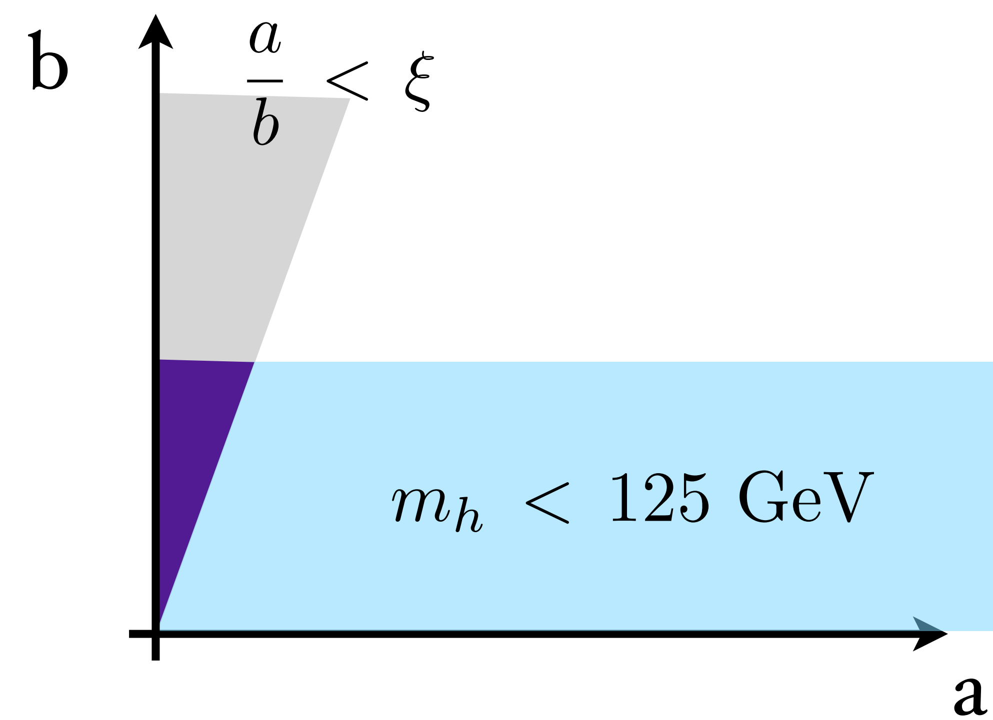
The connection between $g_*,\ m_*,\ m_t$ and m_h

$$V = \frac{3y_t^2 m_*^2}{16\pi^2}\left(ah^2 + bh^4/f^2 + \dots\right)$$



$$\begin{cases} \xi \equiv \dfrac{v^2}{f^2} = \dfrac{a}{b} \\ m_h^2 = b\,\dfrac{3g_*^2}{2\pi^2}\,m_t^2 \sim (125\ \text{GeV})^2\,\dfrac{g_*^2 b}{4} \end{cases}$$

Total tuning **~** area **=** $a\,b = \left(\dfrac{430\,\text{GeV}}{m_*}\right)^2 \times \dfrac{4}{g_*^2}$

De Simone, Matsedonskyi, RR, Wulzer 2012

Notice impact of 125 GeV Higgs

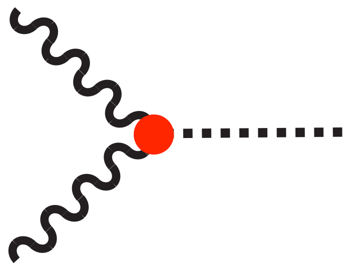
$$m_h = 125\,\mathrm{GeV} \quad \Longrightarrow \quad a\,b = \left(\frac{430\,\mathrm{GeV}}{m_*}\right)^2 \times \frac{4}{g_*^2}$$

weakly strong EWSB sector and light resonances preferred

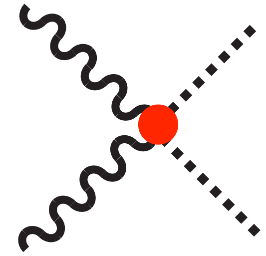
$$m_h = 250\,\mathrm{GeV} \quad \Longrightarrow \quad a\,b = \left(\frac{860\,\mathrm{GeV}}{m_*}\right)^2 \times \frac{16}{g_*^2}$$

moderately strong and heavy EWSB sector

Higgs couplings



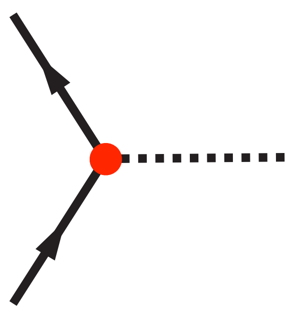
$a \times \frac{2m_V^2}{v}$



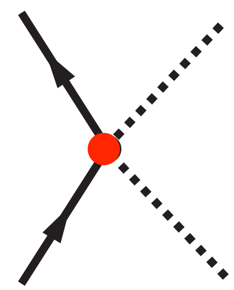
$b \times \frac{m_V^2}{v^2}$

$b = a^2 = 1 - \frac{v^2}{f^2} \equiv 1 - \xi < 1$

robust consequence of coset structure



$c_i \times \frac{m_i}{v}$



$\propto \frac{m_i}{f^2}$

New!

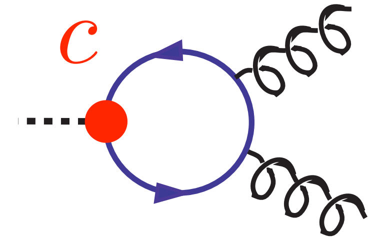
$c_i \simeq 1 + O(\frac{v^2}{f^2}) < 1$

generic but not theorem

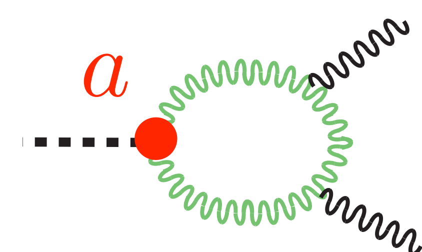
No other parameter at

leading order in g_{SM}^2/g_*^2

c



a



EWPT

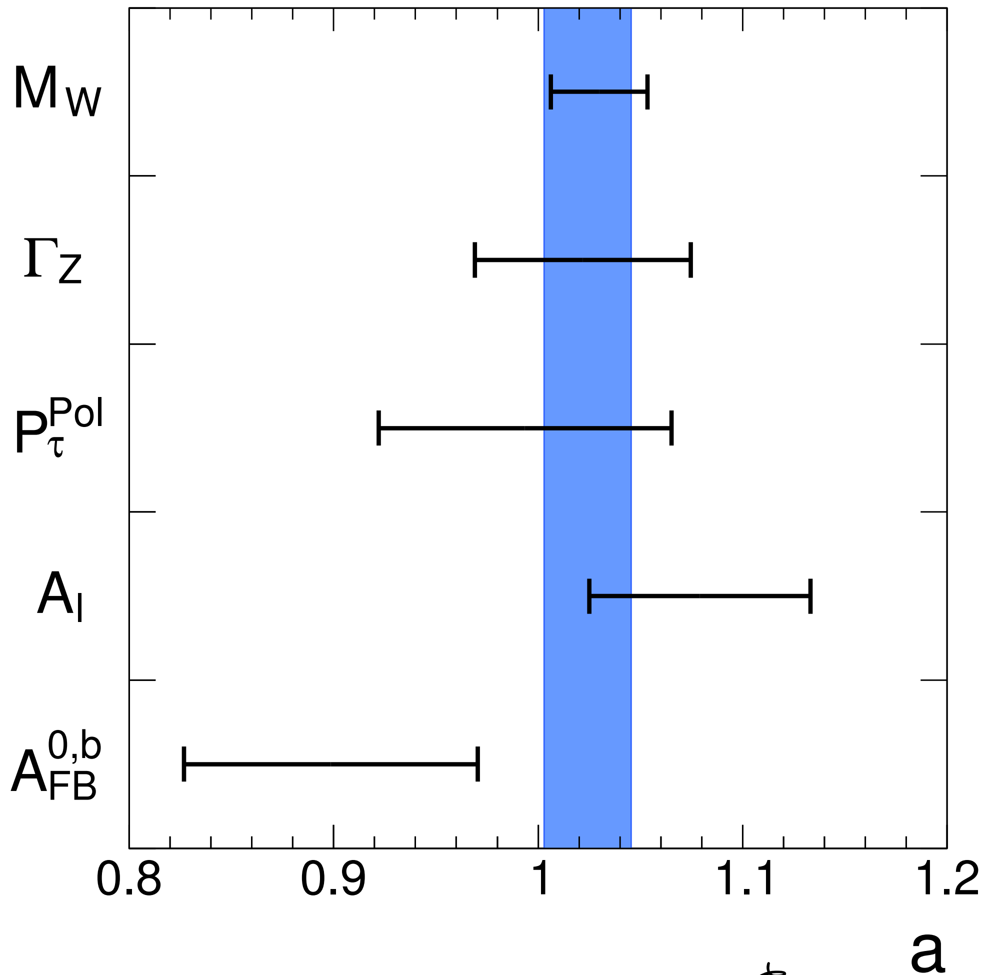
$$\Delta\epsilon_3 \quad = \quad O(1) \times \frac{m_W^2}{m_*^2} + \frac{g^2}{96\pi^2}\frac{v^2}{f^2}\ln(m_*/m_h)$$

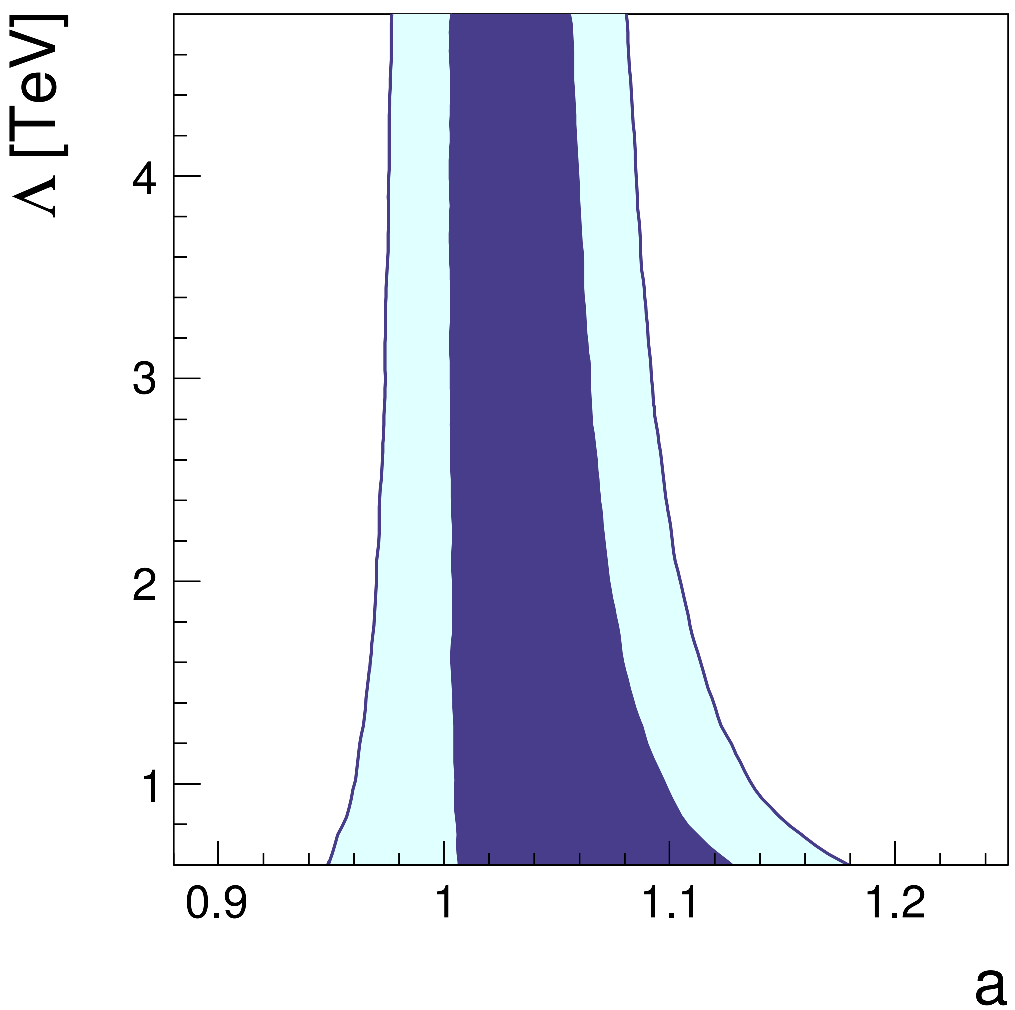
$$m_* \gtrsim 2 \text{ TeV}$$

$$\Delta\epsilon_1 \quad = \quad \delta\rho_{SM} \times \frac{m_t^2}{m_*^2} - \frac{3g^2\tan\theta_W^2}{32\pi^2}\frac{v^2}{f^2}\ln(m_*/m_h)$$

in principle very strong bound : $\xi \equiv \frac{v^2}{f^2} \lesssim 0.05$

in practice it could be relaxed by short distance contribution





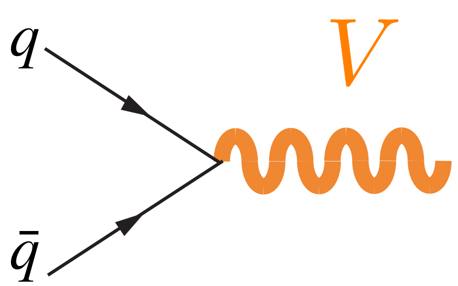
$$a = 1 - \frac{\xi}{2}$$

Franco, Mishima, Silvestrini 2013

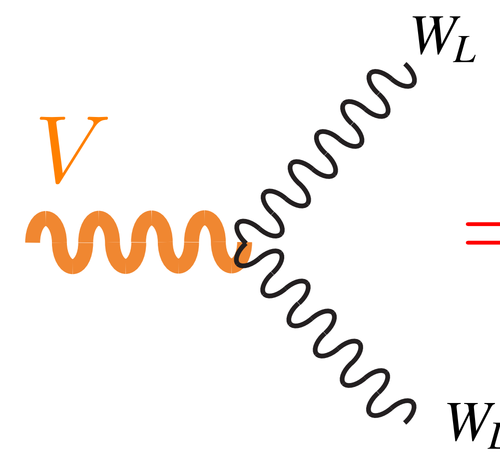
Direct searches (LHC 8TeV)

- Top partners (Q=-1/3, 2/3, 5/3) $m_* \gtrsim 1\,\text{TeV}$

- Vector resonances



$$= \frac{g_W^2}{g_*} < g_W$$



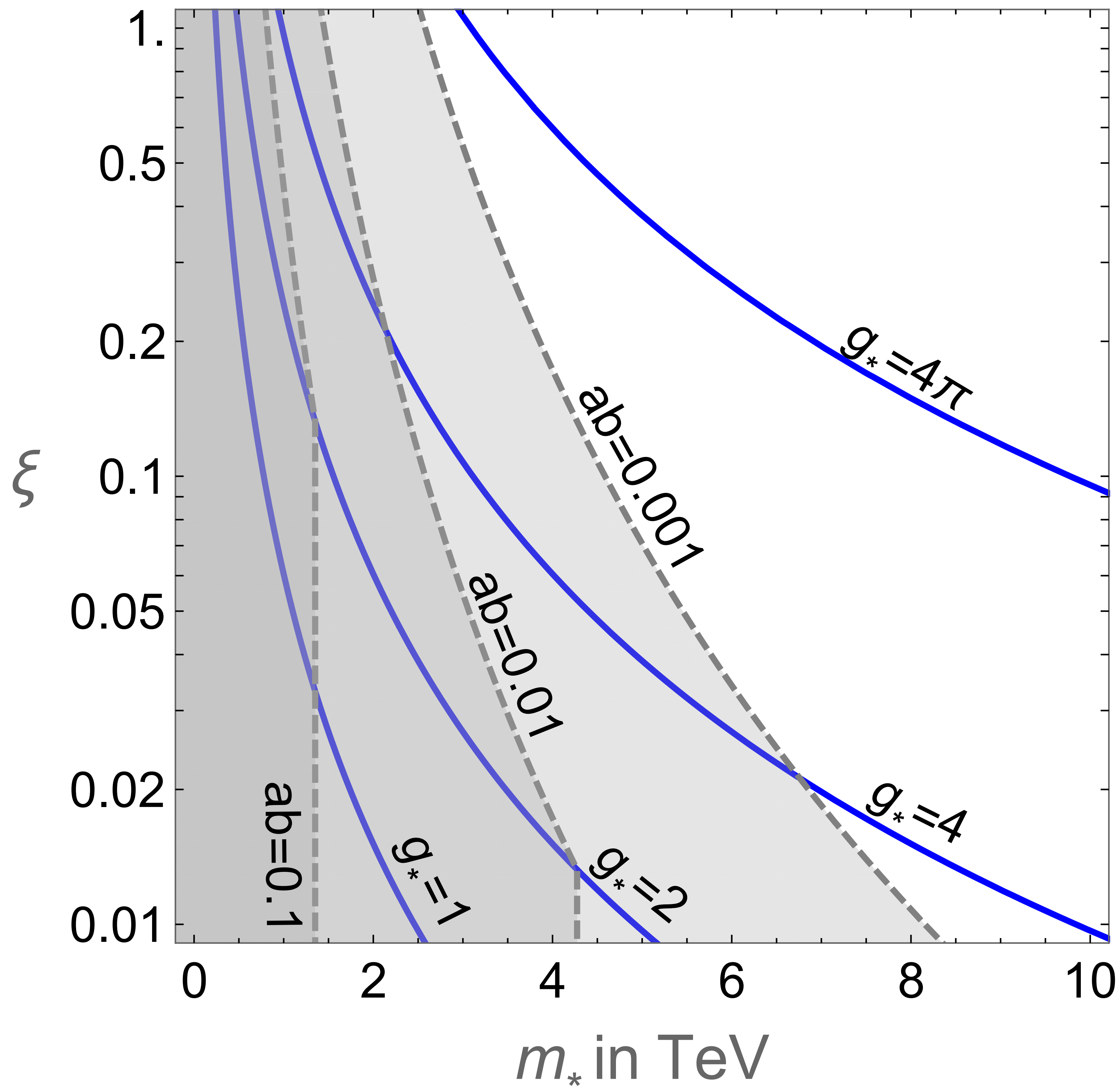
$$= g_*$$

CMS data
Pappadopulo, Thamm, Torre, Wulzer 2014

$$\begin{cases} g_* = 1 & m_* > 3\,\text{TeV} \\ g_* = 3 & m_* > 2\,\text{TeV} \end{cases}$$

$$m_*^2 \xi = g_*^2 v^2$$

A. Thamm 2014



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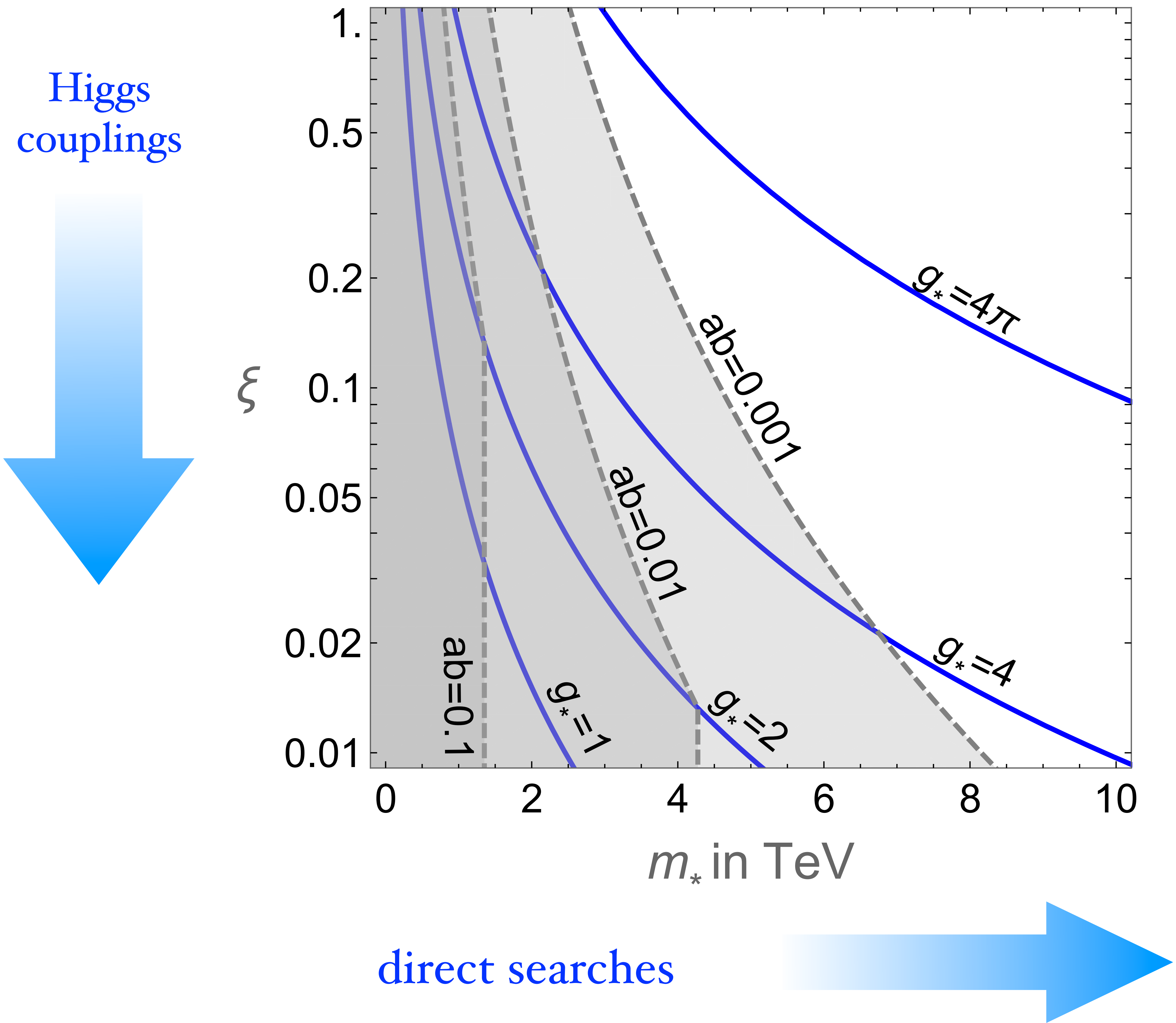
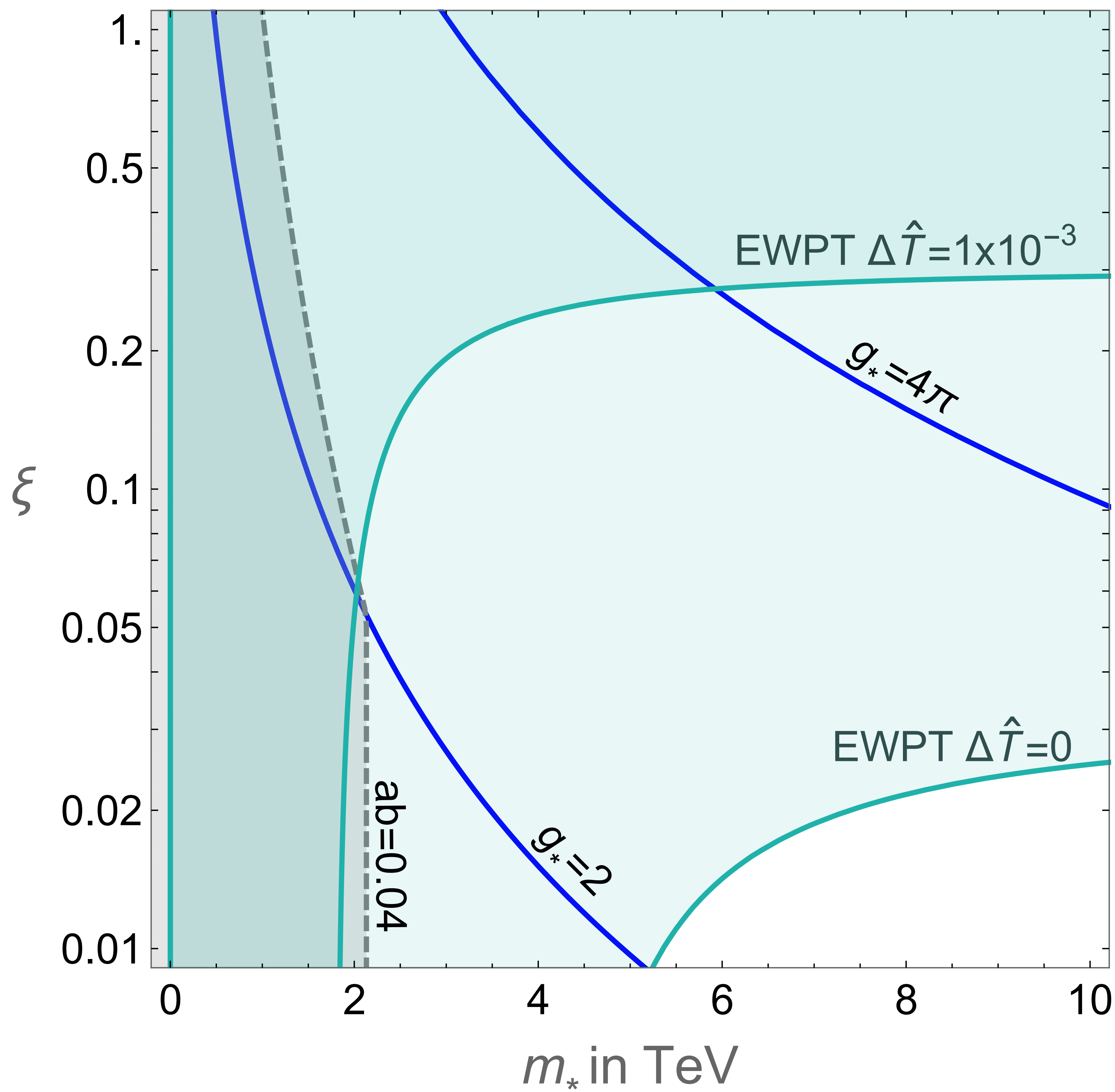
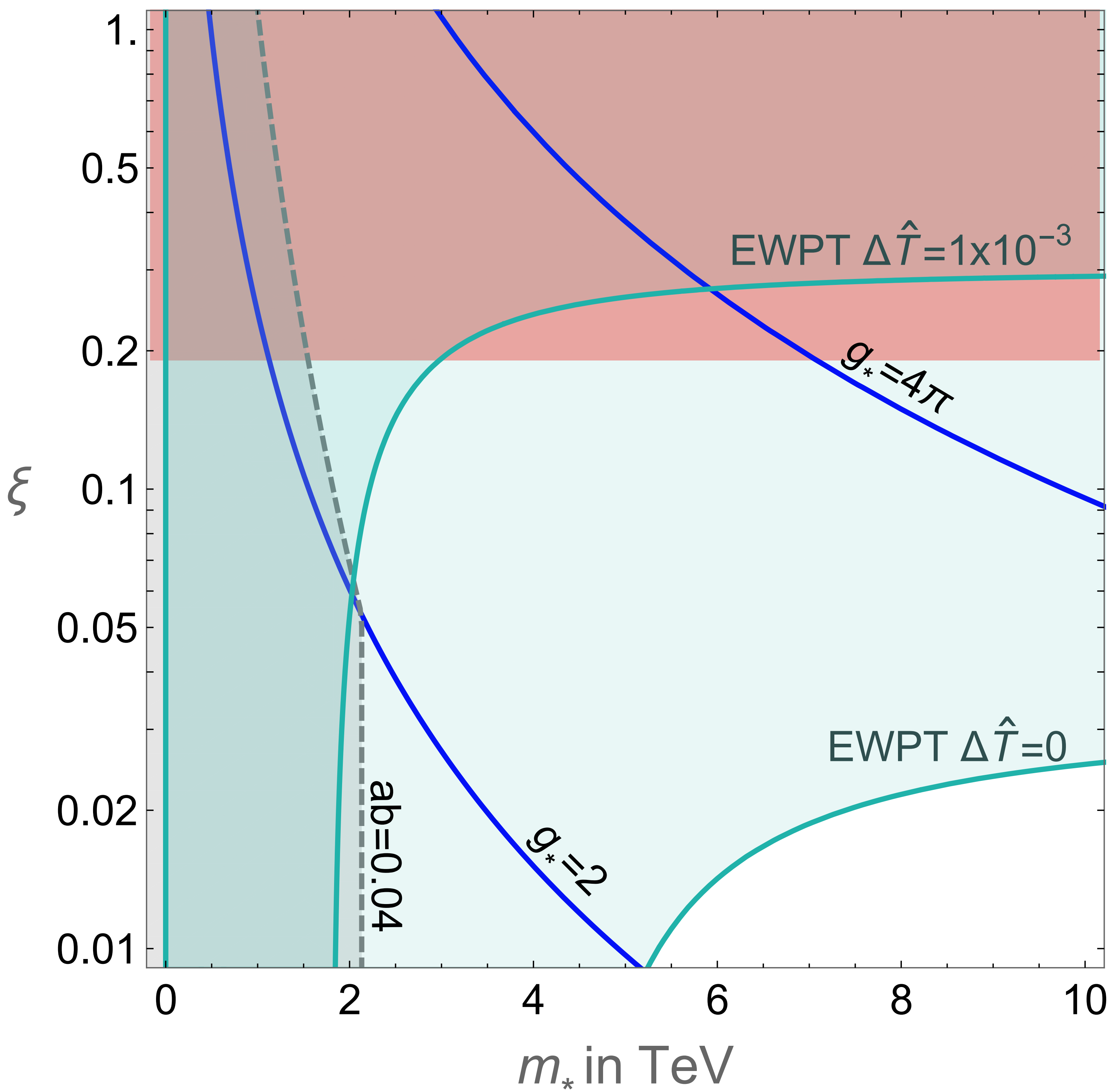
A. Thamm 2014




EWPT $\Delta\hat{T}$=1x10^{-3}
g_*=4π
g_*=2
ab=0.04
EWPT $\Delta\hat{T}$=0
1.
0.5
0.2
0.1
0.05
0.02
0.01
ξ
0
2
4
6
8
10
m_* in TeV

A. Thamm 2014



1.
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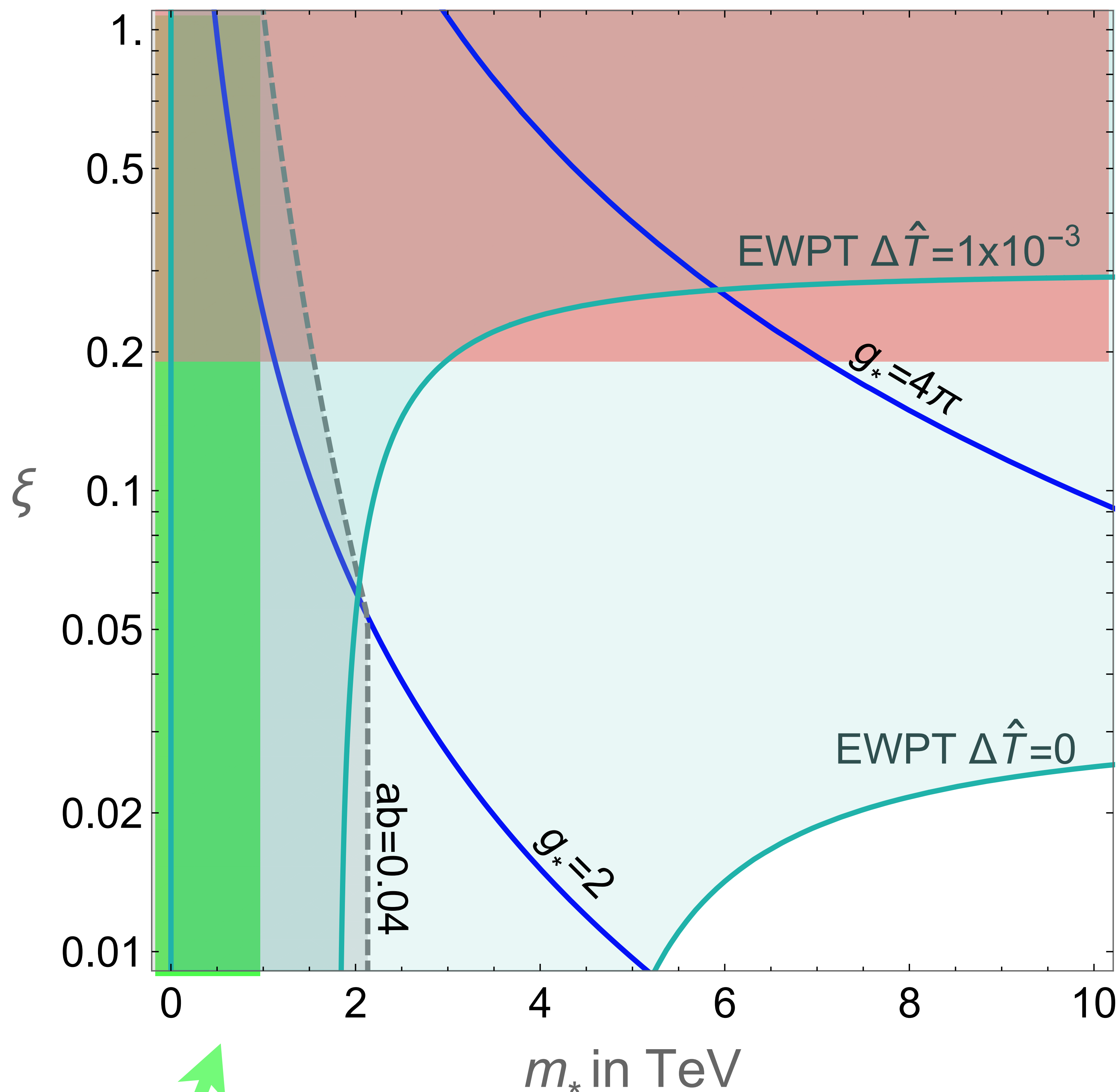
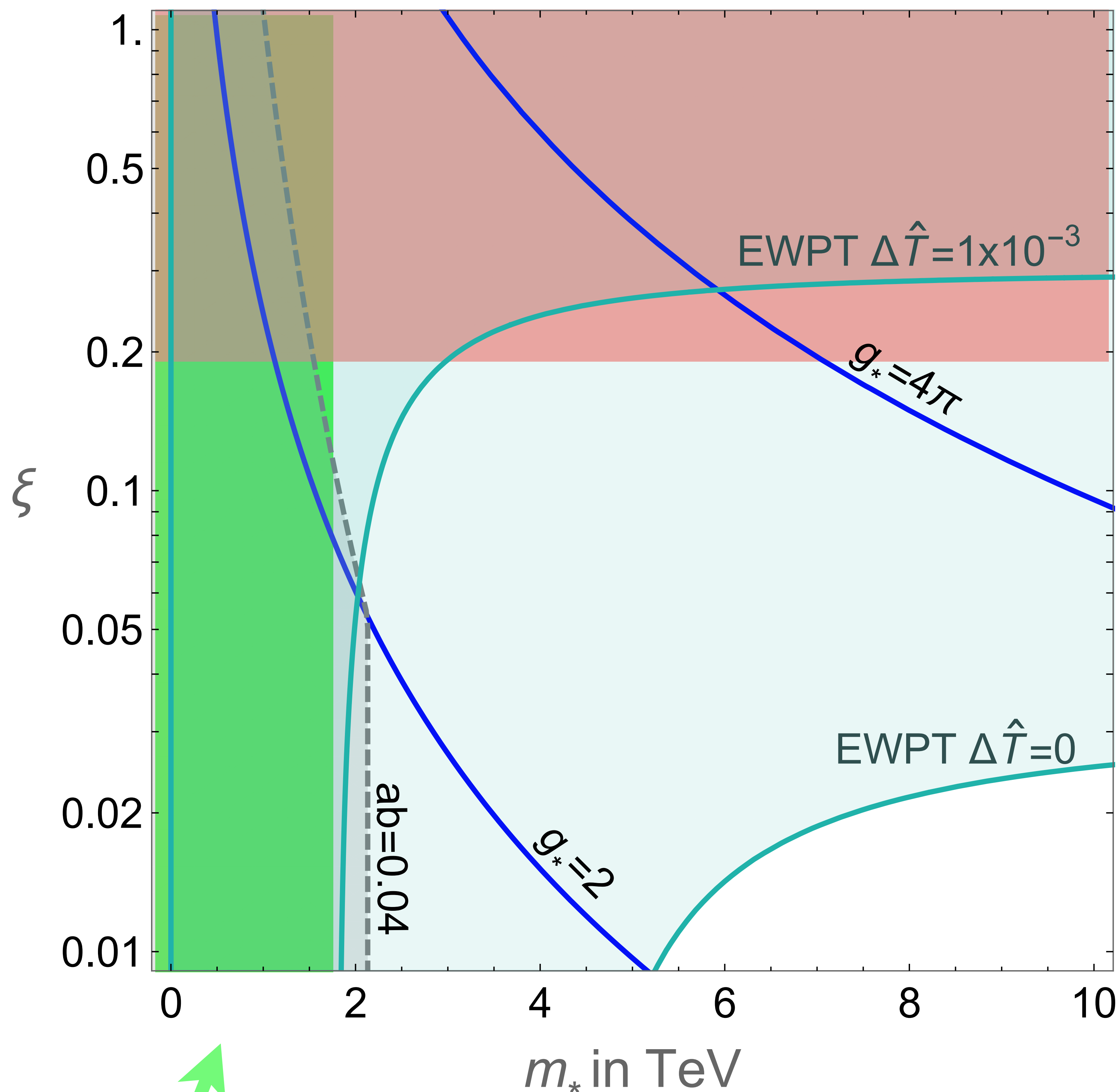


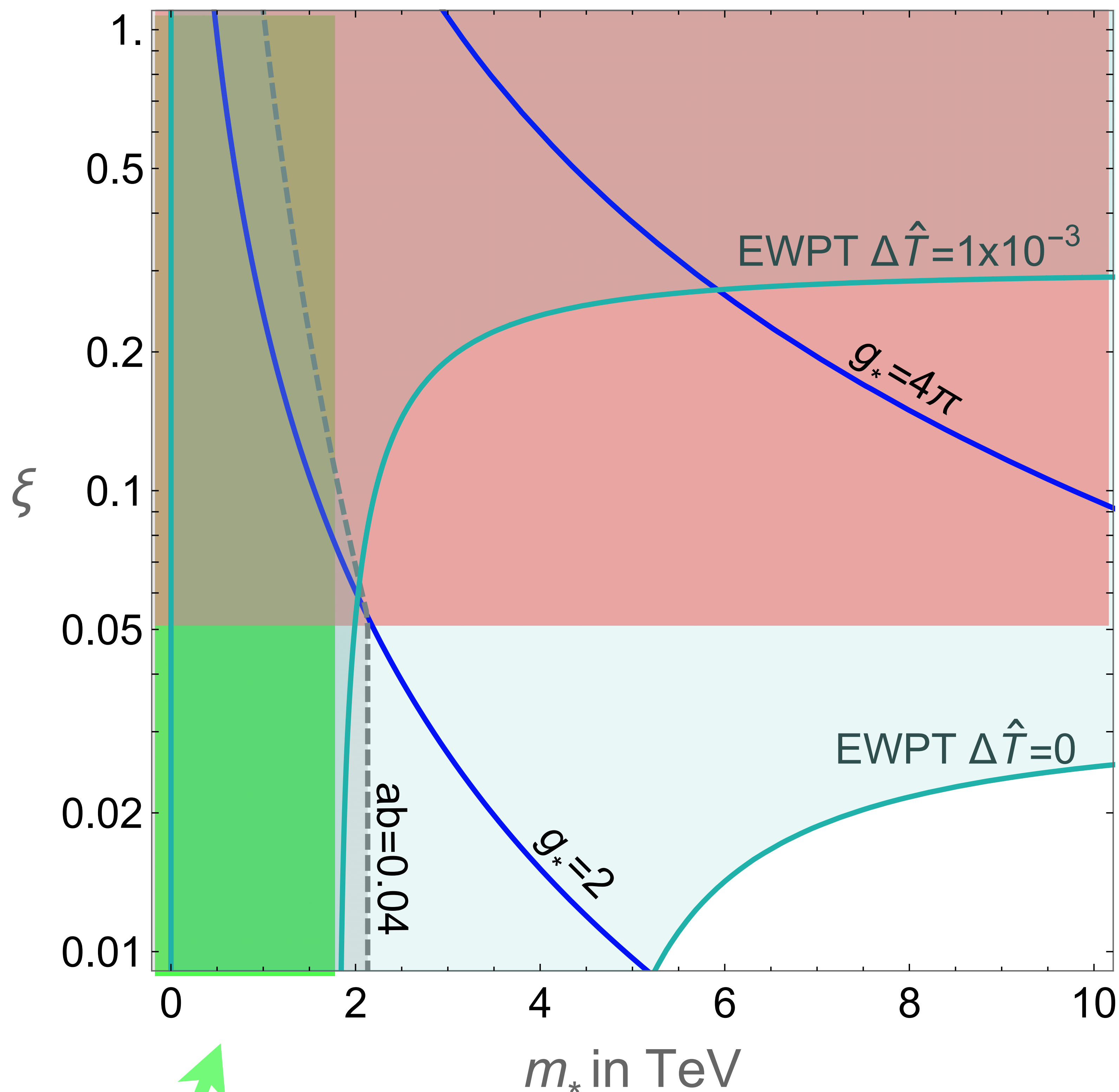
Top partners LHC8

A. Thamm 2014

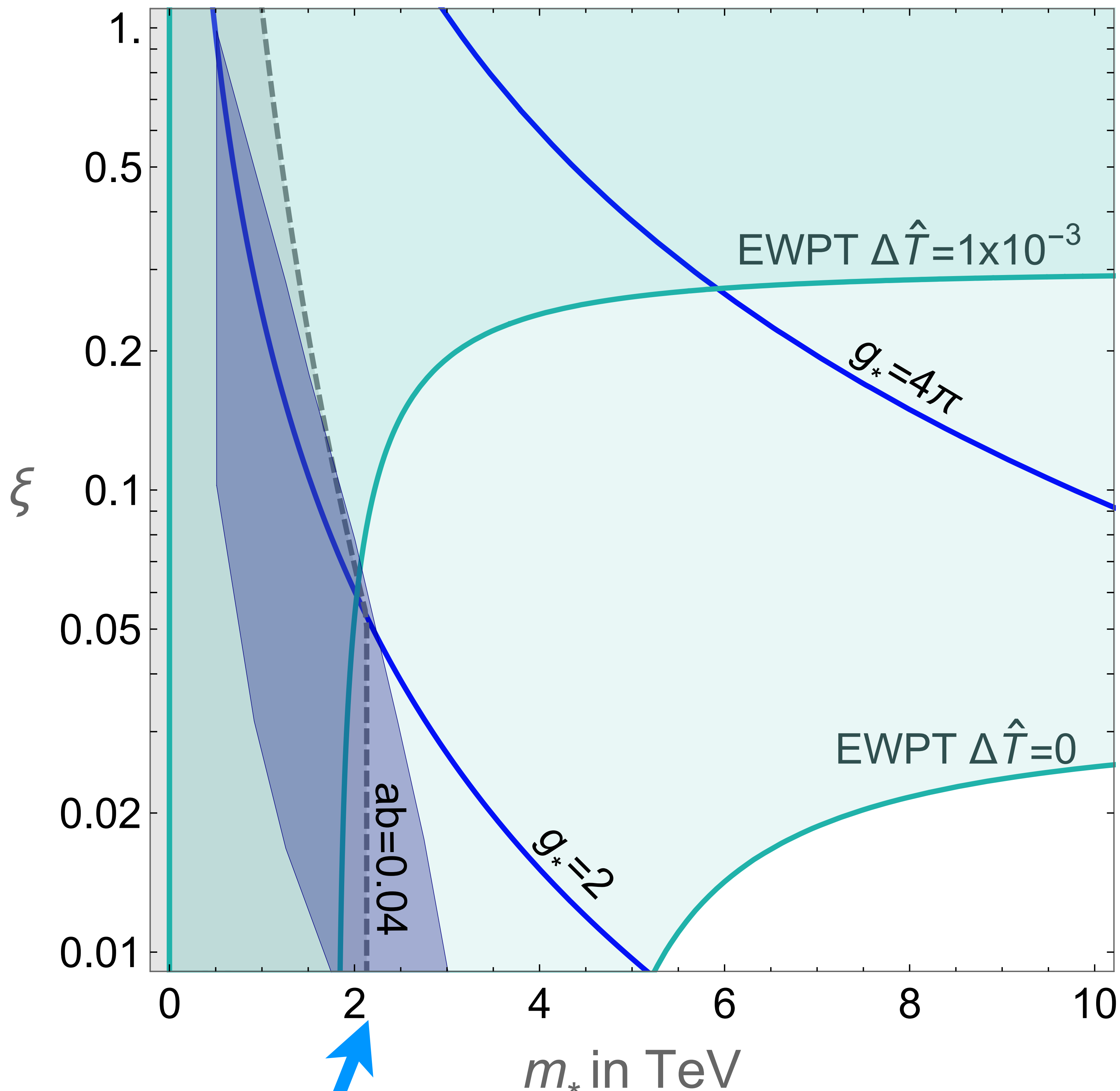


Top partners LHC13

A. Thamm 2014



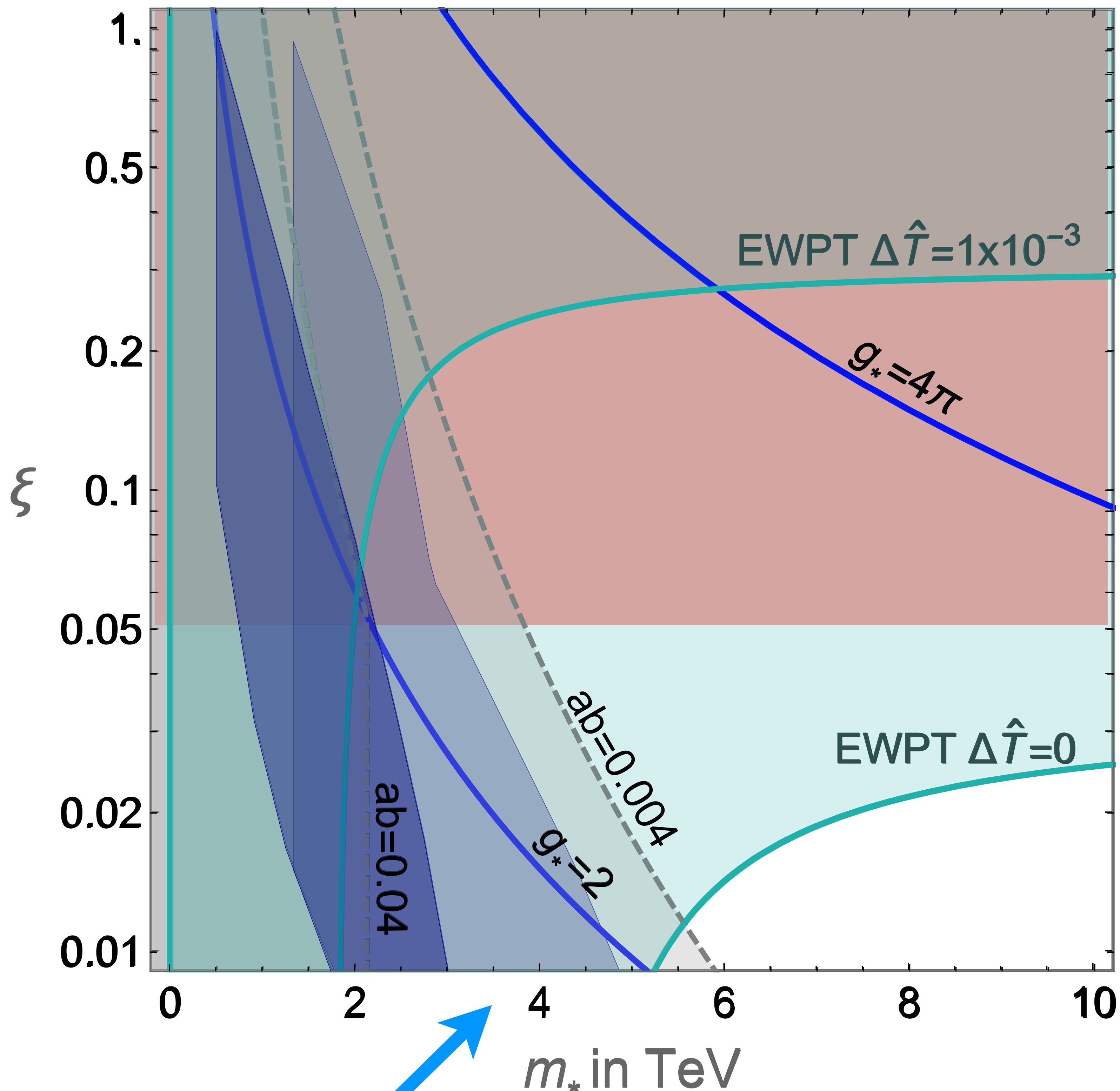
Top partners LHC13



Vectors LHC8

Pappadopulo, Thamm, Torre, Wulzer 14

A. Thamm 2014



Vectors LHC13

Pappadopulo, Thamm, Torre, Wulzer 14

In my opinion

- Compositeness remains a comparatively viable option to solve the hierarchy problem.
- It also forces us to think more and better about QFT
- Flavor is its major structural drawback
- Flavor and EWPT make the outcome of LHC8 unsurprising
- LHC13 and HL-LHC will definitely break new grounds