COMPOSITE HIGGS STATUS

3rd KIAS Phenomenology Workshop

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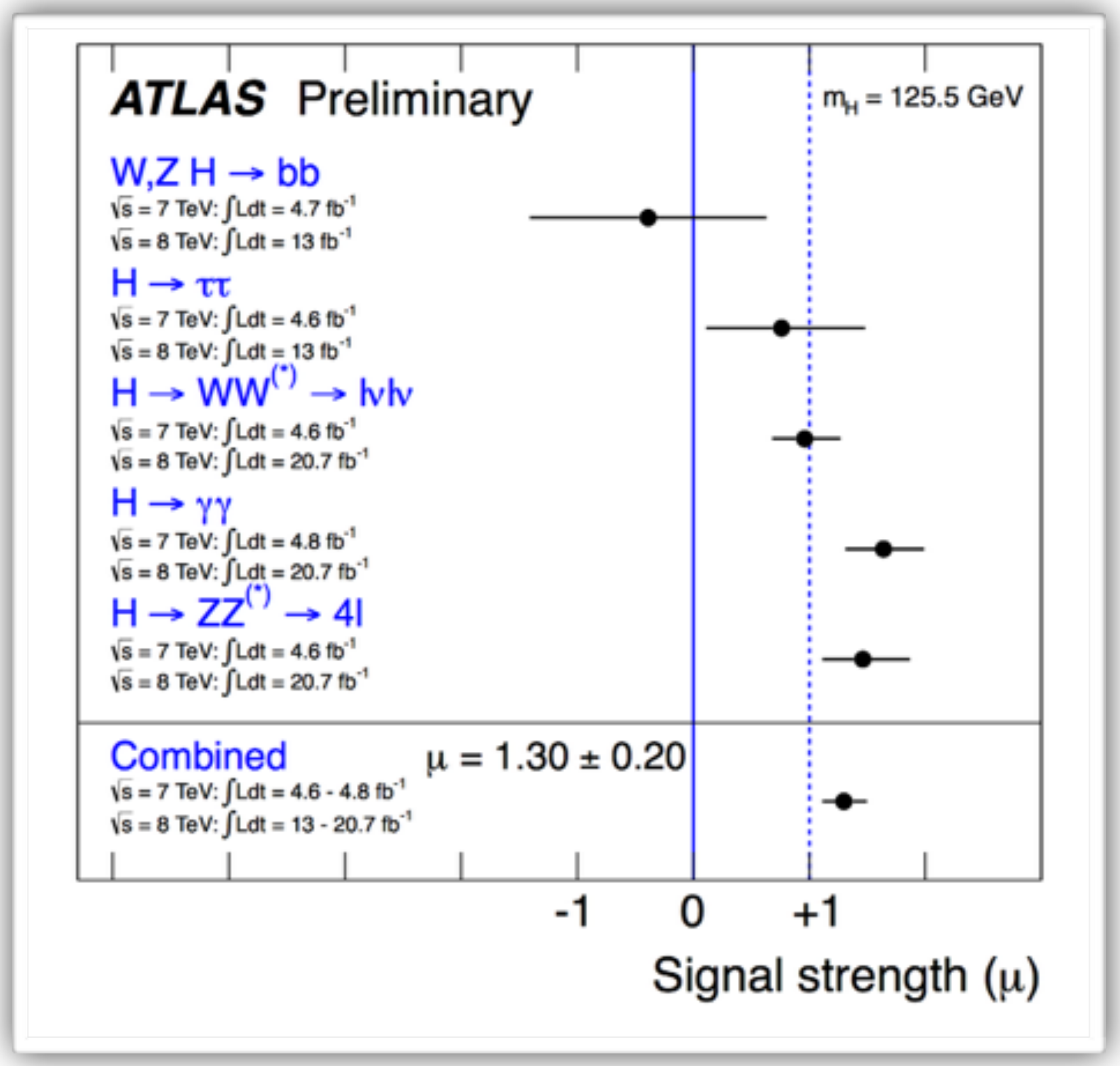
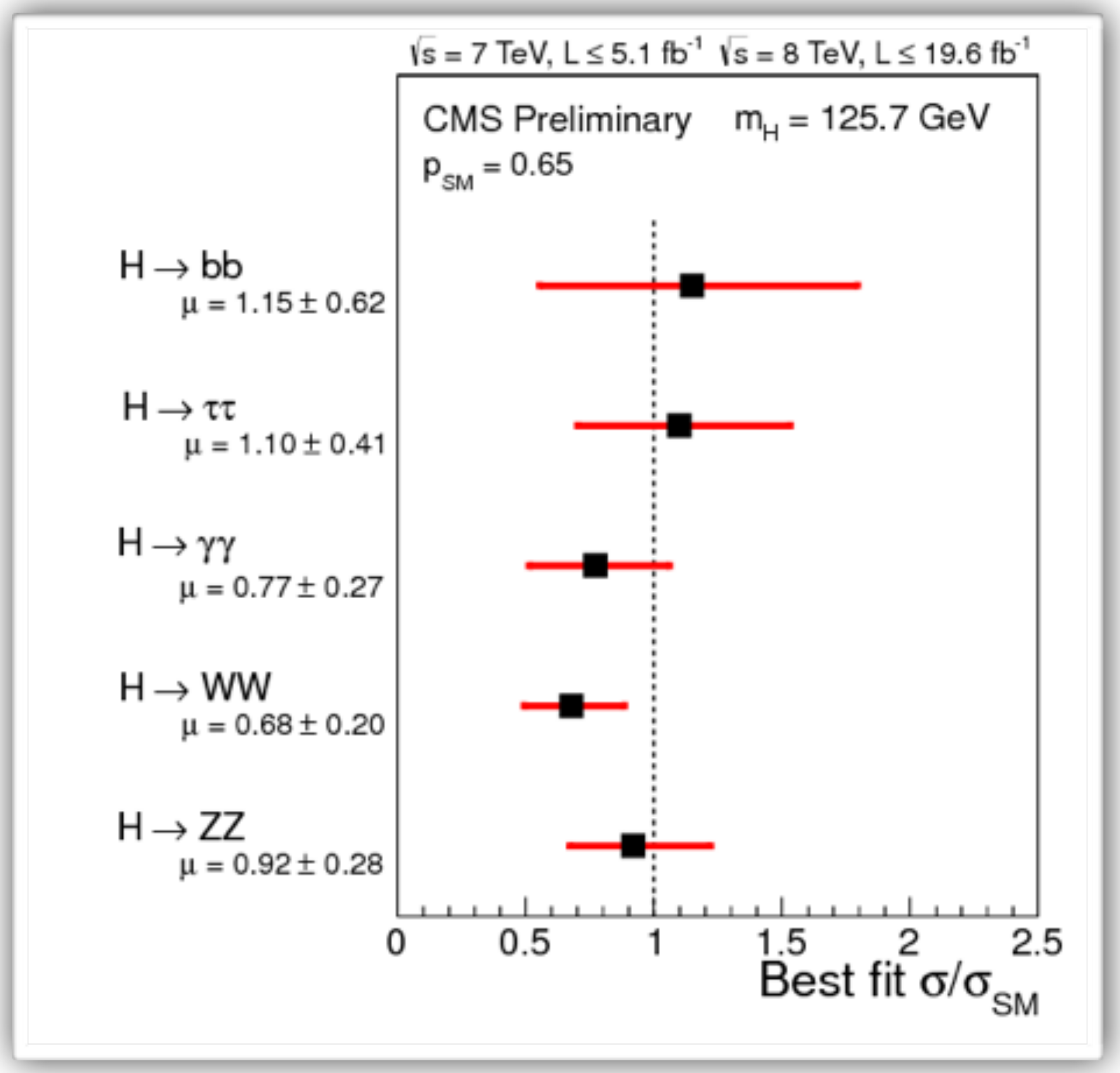
The SM-like Higgs

One possible solution to the hierarchy problem

THE SM-LIKE HIGGS

A Brout-Englert-Higgs boson is there, has a mass of ~126 GeV and looks very SM-like (at least for another couple of years!)





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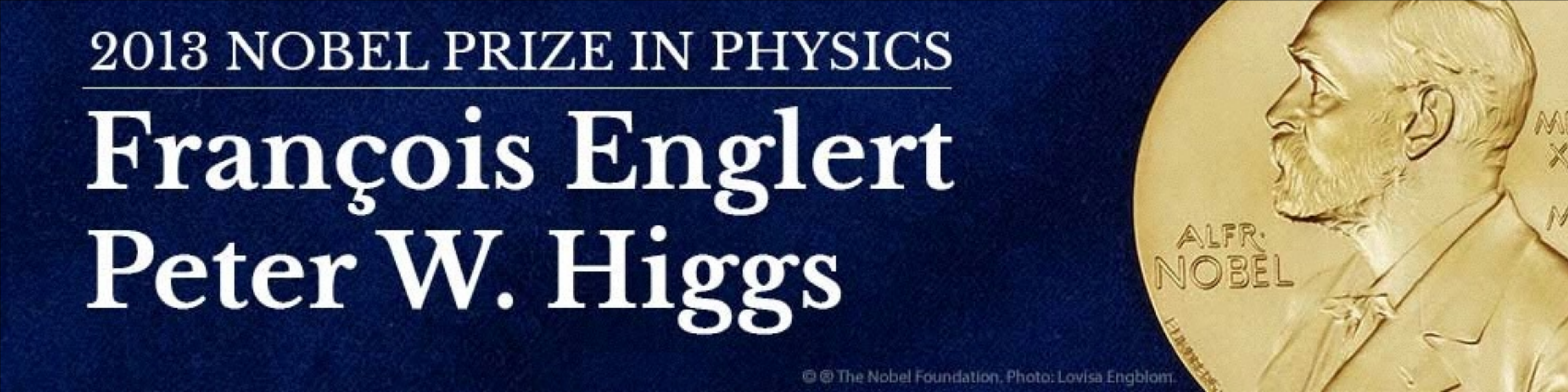

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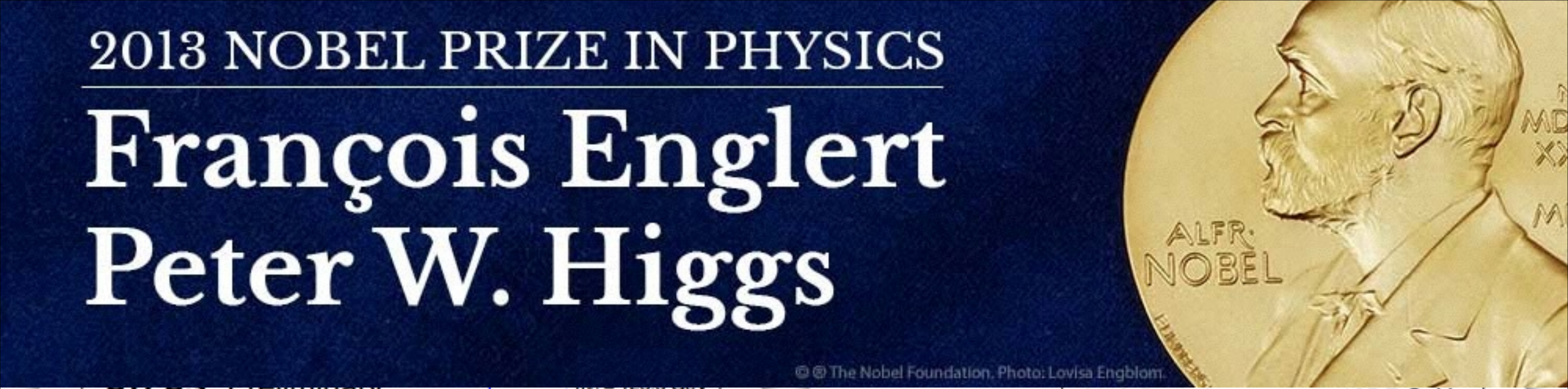

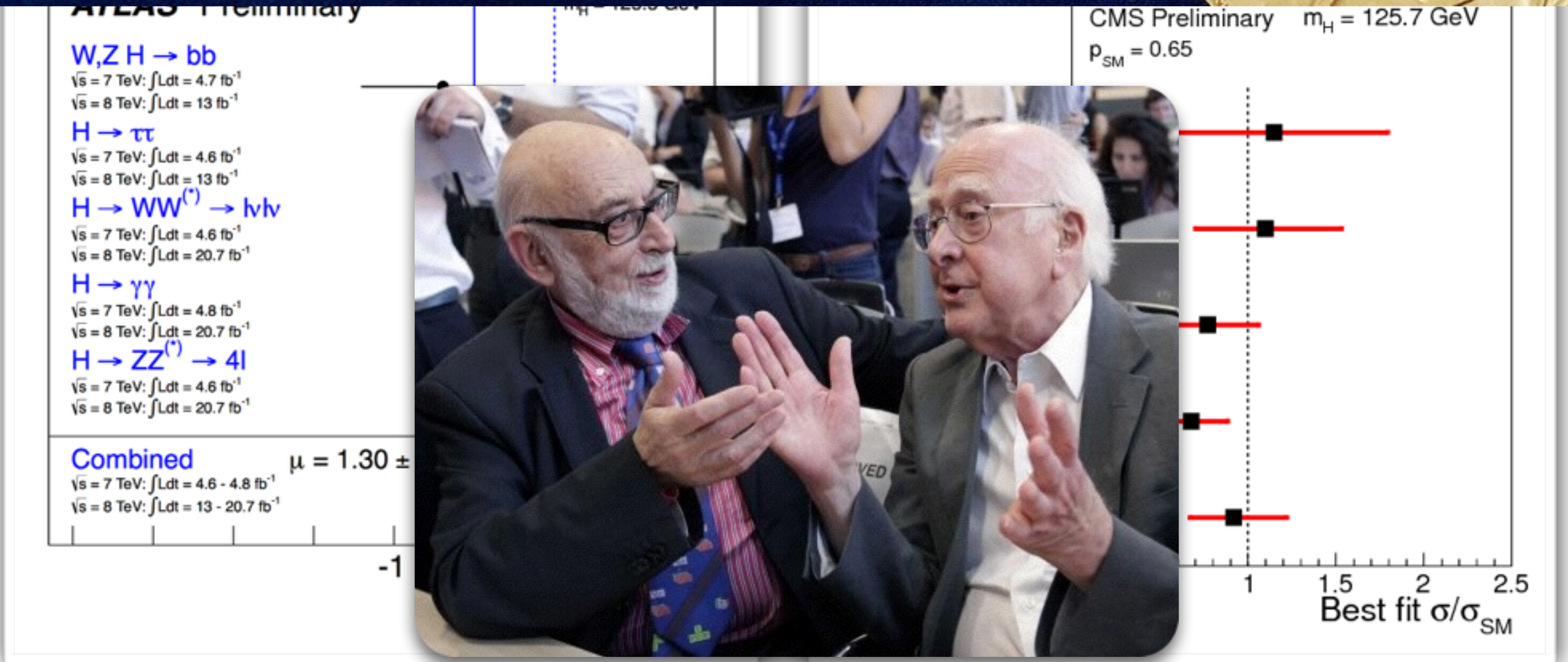

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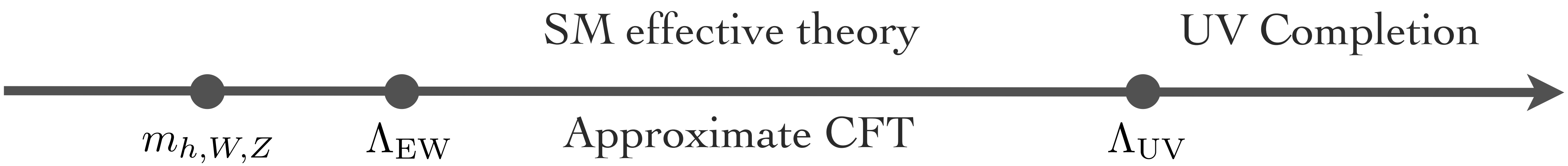
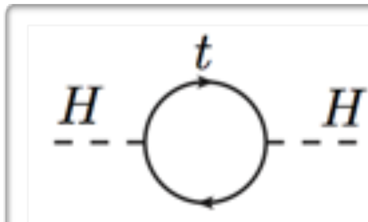
NATURALNESS IN THE SM



1. All deformations of the CFT are either irrelevant, marginal or very close to marginal (e.g. QCD)
2. The relevant deformations can be forbidden by symmetries (e.g. fermion masses forbidden by chiral symmetry)
3. The relevant deformations are tuned to be small

$$\Delta\mathcal{L}_{\rm SM}^{\rm rel} = c\Lambda_{\rm UV}^2 H^\dagger H$$

$$m_h^2 = c\Lambda_{\rm UV}^2 + \delta m_h^2$$



$$\delta m_h^2 = -\frac{y_t^2}{16\pi^2}\Lambda_{\rm UV}^2$$

- The sensitivity of the Higgs mass on physics at the scale $\Lambda_{\rm UV}$ is given by

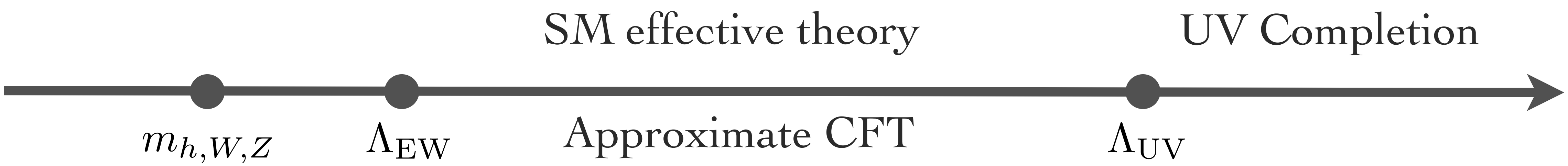
$$\Delta \gtrsim \left(\frac{125\ \text{GeV}}{m_h}\right)^2 \left(\frac{\Lambda_{\rm UV}}{400\ \text{GeV}}\right)^2$$

- If we believe in some “naturalness”

$$\Delta \lesssim 100 \quad \Longrightarrow \quad \Lambda_{\rm UV} \lesssim 4\ \text{TeV}$$

- This is the ONLY argument to expect new physics related to EWSB at the TeV scale!

NATURALNESS IN THE SM



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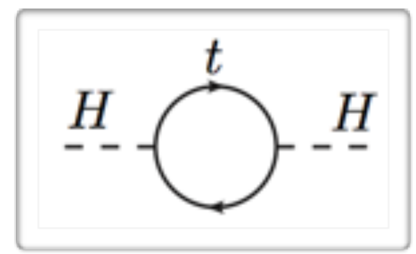

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Natural CH $\Downarrow$ Light top partners

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Natural SUSY $\Downarrow$ Light stops

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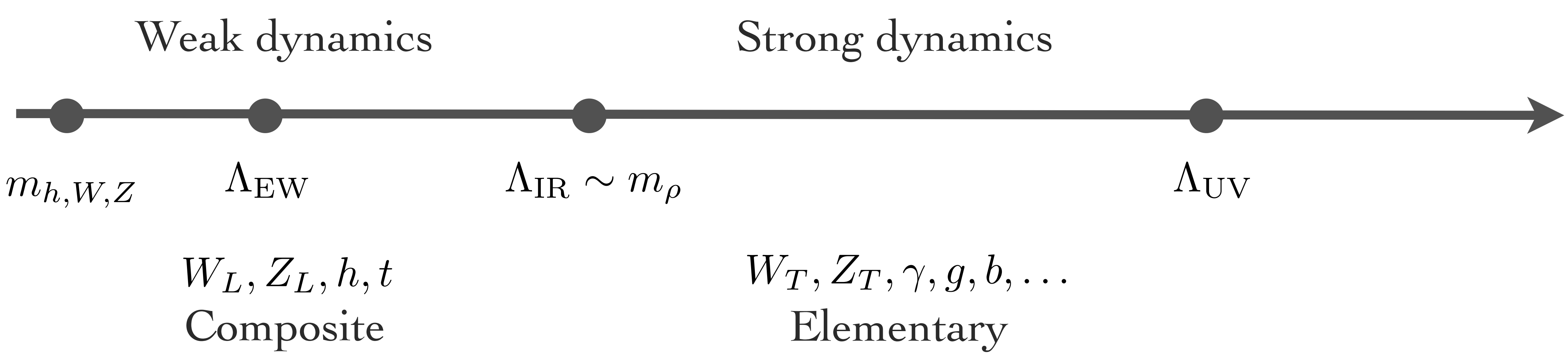
A POSSIBLE SOLUTIONS

Strong dynamics (Compositeness)



- The IR scale Λ_{IR} is dynamically generated (like in QCD)
- Above the IR scale the Higgs mass term is irrelevant (4 fermion operator) and the big hierarchy is therefore stabilized
- Heavy resonances are expected at the TeV scale
- A large separation between SM particles and the new heavy sector requires fine tuning
- A light Higgs can be present accidentally (e.g. a light dilaton) or related to the longitudinal polarizations of the gauge bosons (pGB Higgs)

The Higgs as a pseudo-Goldstone boson

Symmetry breaking by vacuum misalignment

Partial compositeness

The Minimal Composite Higgs Model (MCHM)

see also the talks by Thomas Flacke and Hisaki Hatanaka

STRONG EWSB

- A strong sector with a given global symmetry containing the SM gauge group is present
- Dynamical breaking of this symmetry at some scale f delivers as many Goldstone Bosons (GBs) as the broken generators (we need at least 3 to have EWSB)
- Three GBs are eaten by the W/Z providing their longitudinal polarizations and breaking spontaneously the EW symmetry
- Additional GBs (if present) can be identified with the Higgs and other physical scalars

Georgi, Kaplan, Galison, Dimopoulos, Dugan, '84-'85

- SM gauging and Yukawa couplings explicitly break the global symmetry and a radiative potential is generated for the additional GBs which acquire a mass and a vev (vacuum misalignment)

Coleman, Weinberg PRD7 '73

- The pseudo-GB nature of these scalars guarantees their lightness
- Notice that the Higgs does not need to be a pGB and can arise from other mechanisms, e.g. it can be a light dilaton or even a mixture of pGB and dilaton

Bellazzini, Csaki, Hubisz, Serra, Terning 1209.3299 [hep-ph]
Bellazzini, Franceschini, Martucci, RT 13xx.xxxx [hep-ph]

THE MAIN INGREDIENTS

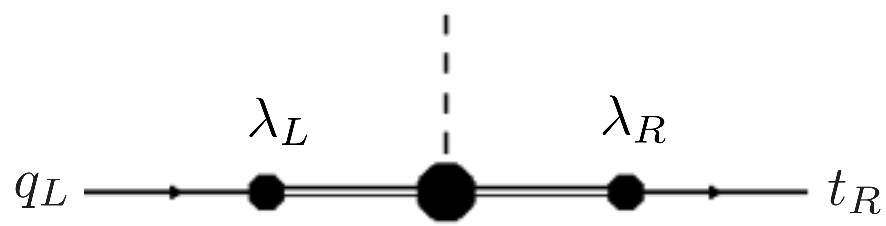
- The old problems of Technicolor (TC) can be avoided if the scale of compositeness can be taken parametrically larger than the EW scale

Georgi, Kaplan, Galison, Dimopoulos, Dugan, '84-'85
Contino, Nomura, Pomarol, hep-ph/0306259
Agashe, Contino, Pomarol, hep-ph/0412089
Agashe, Contino, hep-ph/0510164
Contino, Da Rold, Pomarol, hep-ph/0612048
Barbieri, Bellazzini, Rychkov, Varagnolo, 0706.0432[hep-ph]

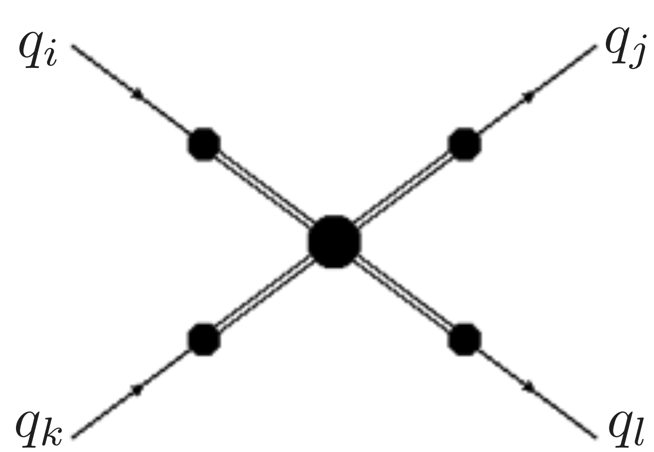
$$f > v$$

- This can be achieved using the mechanism of vacuum misalignment
- Since we need custodial symmetry the simplest compact coset is $SO(5)/SO(4)$
- The flavor problem of TC theories can be improved if the Yukawa couplings arise through mixings of elementary quarks with fermionic operators of the strong sector
- This idea is called Partial Compositeness

Kaplan, NPB 365 '91
Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi, 1205.5803 [hep-ph]



$$y_t \sim \frac{\lambda_L \lambda_R}{g_\psi} \equiv \epsilon_L \epsilon_R g_\psi$$



$$\sim \frac{\lambda_i \lambda_j \lambda_k \lambda_l}{g_\psi^2 f^2} \equiv \frac{\epsilon_i \epsilon_j \epsilon_k \epsilon_l g_\psi^2}{f^2}$$

FINE TUNING

- The scalar potential can be written, according to Naive Dimensional Analysis (NDA)

$$
\begin{aligned}
V(h) &= V^{(1\,\text{loop})}(h/f) + V^{(2\,\text{loop})}(h/f) + \dots \\
&= f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^2 \left(\epsilon^2 \mathcal{F}_1^{(1)}(h/f) + \epsilon^4 \mathcal{F}_2^{(1)}(h/f) + \dots\right) \\
&\quad + f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^4 \left(\epsilon^2 \mathcal{F}_1^{(2)}(h/f) + \dots\right) + \dots
\end{aligned}
$$

- The functions $\mathcal{F}$ are given by linear combinations of non-linear G invariants

$$
\mathcal{F} = \sum_i c_i I_i \left(\frac{h}{f}\right)
$$

- The c_i are expected to be $O(1)$ couplings and some degree of cancellation among them is necessary to get a small enough ratio $\xi = v^2/f^2$
- In absence of additional cancellations ξ provides a measure of the cancellation
- However, when only one invariant is generated at a given order in ϵ an additional cancellation is needed to tune $\xi \ll 1$ and we expect a tuning of the order of $\xi \times \epsilon^2$(this is what happens, e.g. in the MCHM5)
- These models are said to be "doubly tuned"

Panico, Redi, Tesi, Wulzer 1210.7114 [hep-ph]

MINIMAL TUNING: THE MCHM14

- We can compute the 1-loop Coleman-Weinberg potential in the MCHM14

$$V(h) = \alpha c_h^2 + \beta s_h^2 c_h^2 = (\beta - \alpha) s_h^2 - \beta s_h^4$$

- The corresponding vev and mass are given by

Panico, Redi, Tesi, Wulzer 1210.7114 [hep-ph]
Pappadopulo, Thamm, RT 1303.3062 [hep-ph]

$$\xi = \frac{\beta - \alpha}{2\beta} \qquad\qquad m_h^2 = -\frac{8\beta}{f^2}\xi(1-\xi)$$

- The size of α and β can be estimated using the spurionic symmetry and NDA

$$V(h) \approx N_C \frac{m_\psi^4}{16\pi^2}\frac{\lambda_L^2}{g_\psi^2}(a_1 I_1 + a_2 I_2)$$

$$\hat{S} \approx \frac{g^2}{3 g_\rho^2}\xi \approx 10^{-3}\left(\frac{\xi}{0.1}\right)\left(\frac{4}{g_\rho}\right)^2$$

$$m_h^2 \sim N_C \frac{g_\psi^2}{2\pi^2}\frac{g_\psi^2}{\lambda_R^2} y_t^2 v^2 |a_2|(1-\xi) \approx (380\ \text{GeV})^2 \frac{1}{\epsilon_R^2}\left(\frac{g_\psi}{4}\right)^2 |a_2|$$

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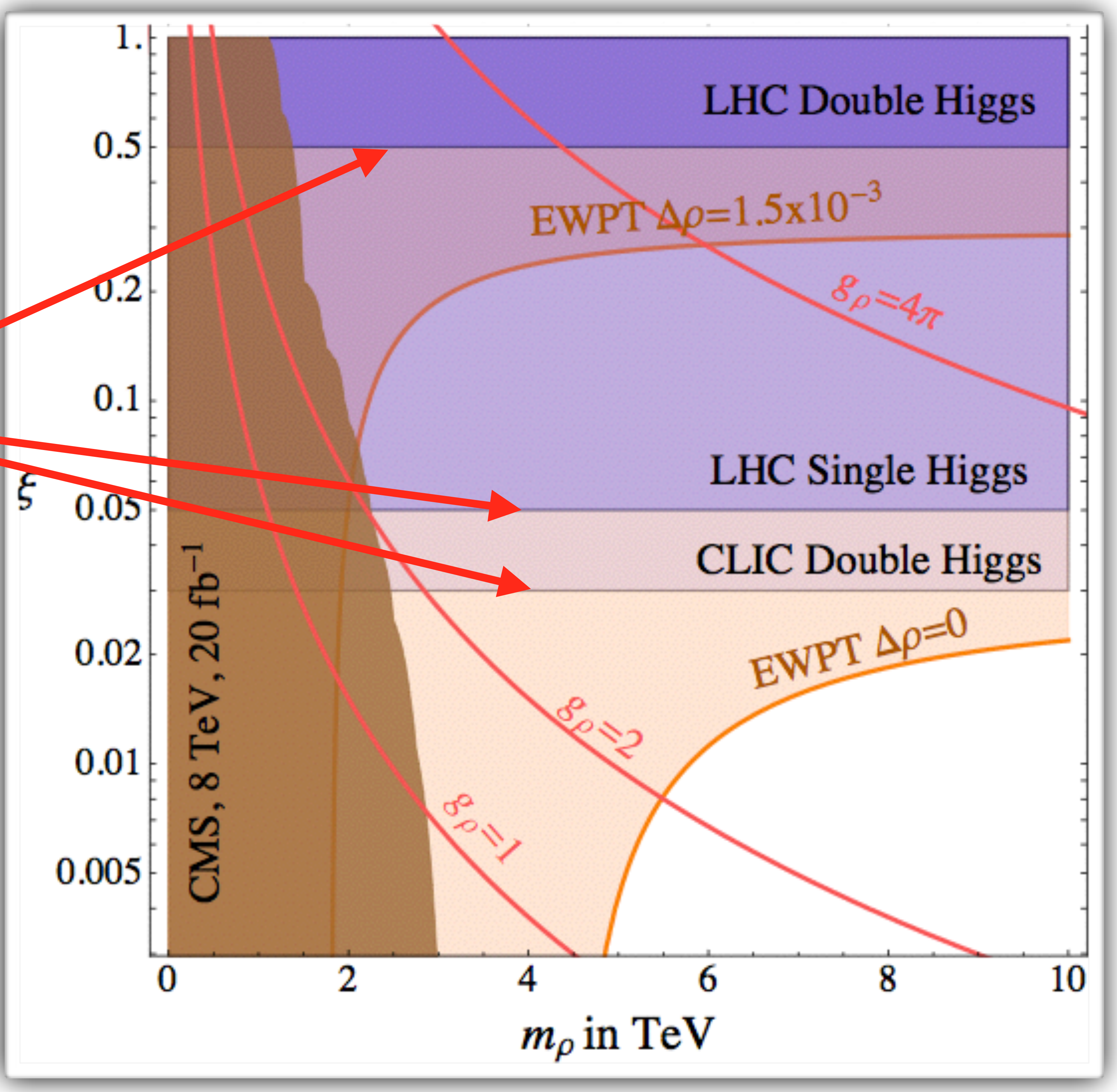
5D
$g_\psi = g_\rho$

4D
$g_\psi \neq g_\rho$

BOUNDS

- EWPT and direct searches set a bound in the (m_ρ, ξ) plane

1σ contours



Contino, Grojean, Pappadopulo, Rattazzi, Thamm 1309.7038 [hep-ph]

Higgs couplings

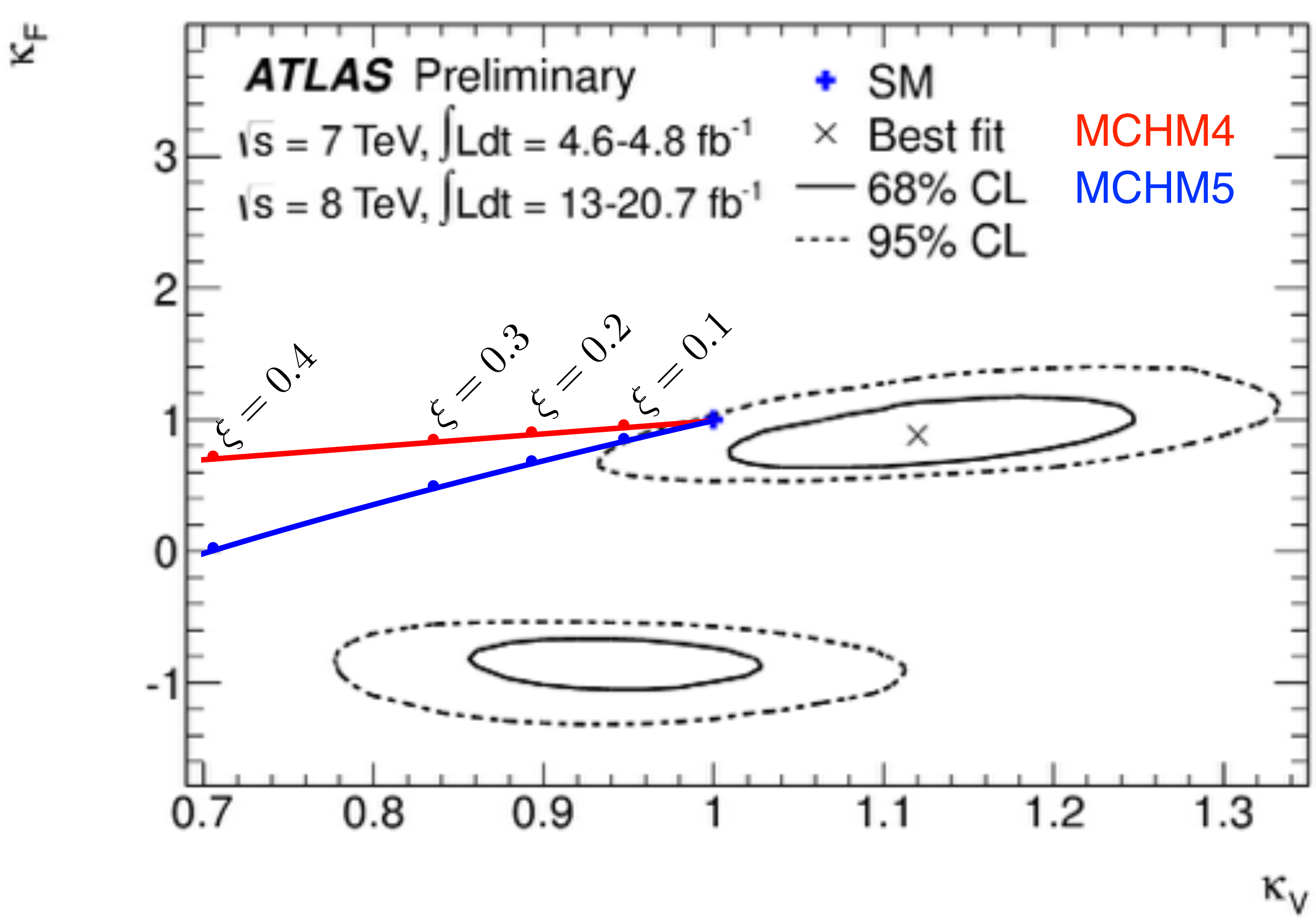
Tree level Higgs couplings

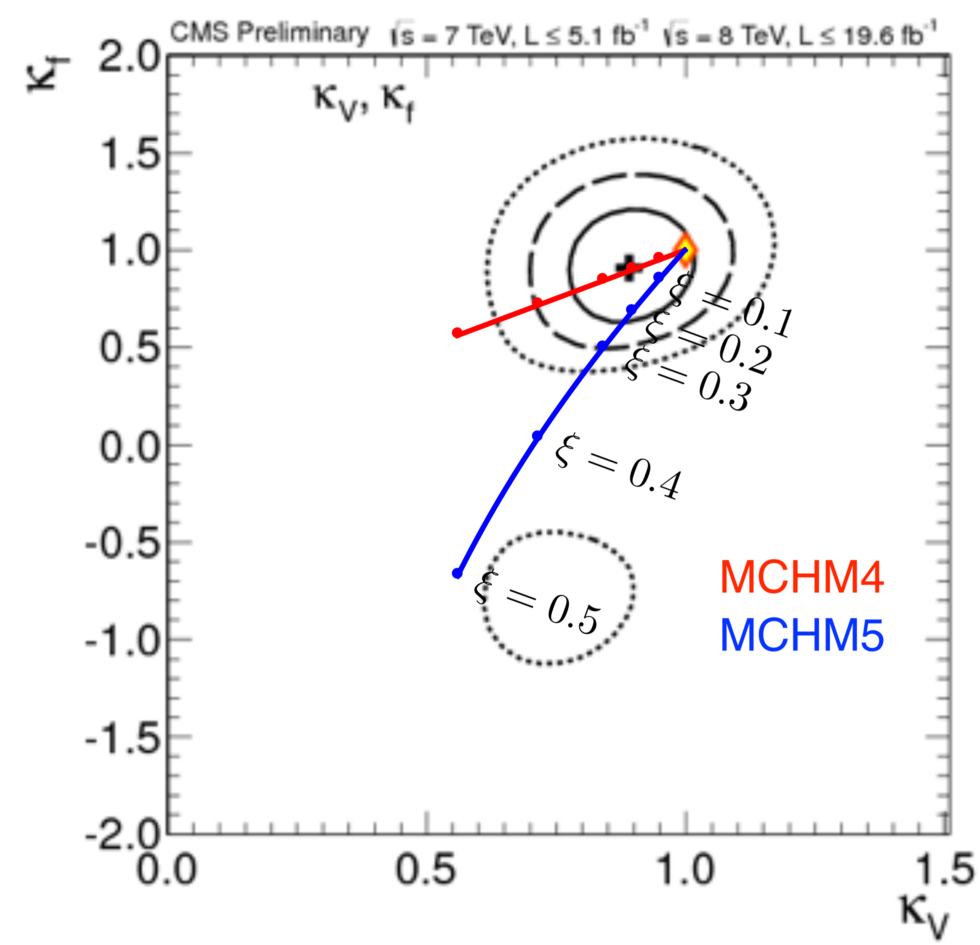
Loop induced Higgs couplings

TREE LEVEL HIGGS COUPLINGS

- In composite Higgs models where the Higgs is a pGB the Higgs couplings to SM particles are in general rescaled by functions of ξ .
- For particular fermion representations the universal rescaling with ξ can be accompanied by a dependence on the resonances spectrum
- Higgs coupling measurements can therefore be used to constrain ξ
- In the MCHM for example one has

$$c_V = \sqrt{1-\xi} \qquad c_f^{(\mathbf{4})} = \sqrt{1-\xi} \qquad c_f^{(\mathbf{5})} = \frac{1-2\xi}{\sqrt{1-\xi}} \qquad c_f^{(\mathbf{14})} = f(\xi)g(M_\psi) \qquad \ldots$$





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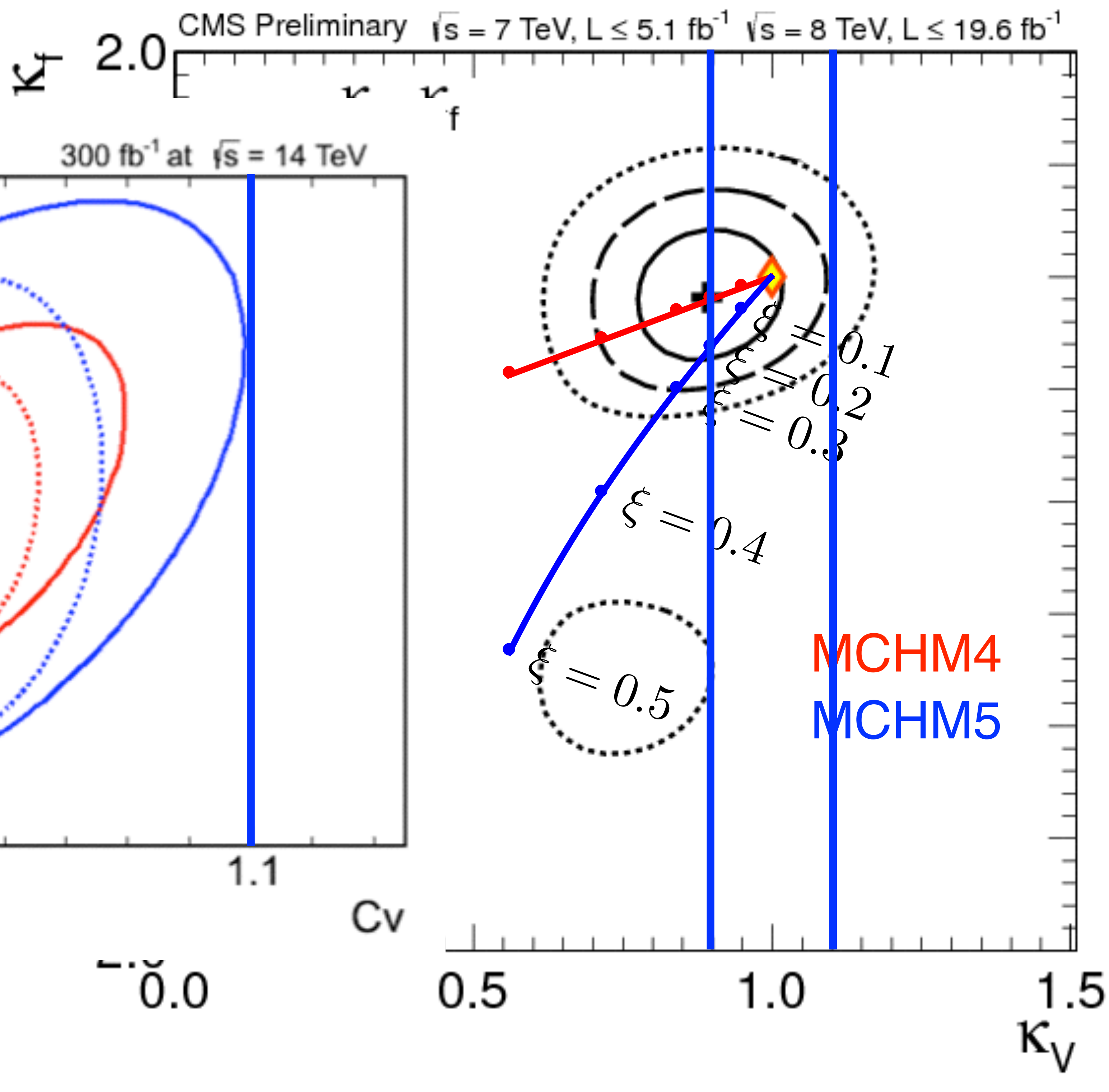
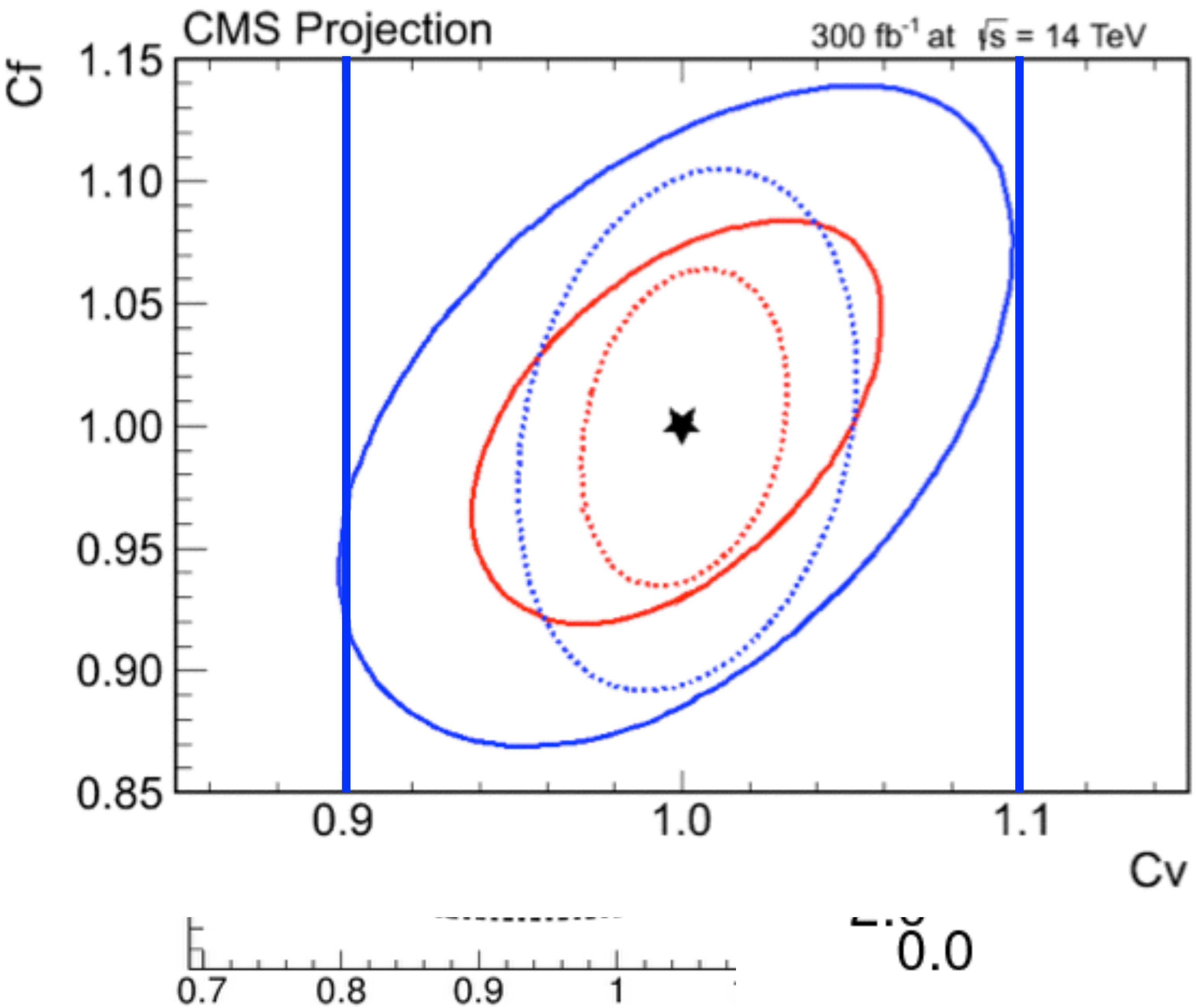




LOOP INDUCED COUPLINGS: GENERAL RESULT

- Partial Compositeness implies the form of the mass matrix

$$\mathcal{M}_t(h) = \left(\begin{array}{c|c} 0 & \mathbf{F}_L^T(h) \\ \hline \mathbf{F}_R(h) & \mathbf{M}_c \end{array}\right)$$

- General properties of block matrices imply

$$\det \mathcal{M}_t(h) = m_t^0(h) \times \det \mathbf{M}_c \qquad m_t^0(h) = -\mathbf{F}_L^T(h)\mathbf{M}_c^{-1}\mathbf{F}_R(h)$$

- This parameter can be obtained from the low energy effective action

$$\mathcal{L}_{\text{eff}} = -m_t^0(h)\bar{t}_L t_R + \text{h.c.} + iZ_{t_L}(h)\bar{t}_L \partial\!\!\!/ t_L + iZ_{t_R}(h)\bar{t}_R \partial\!\!\!/ t_R$$

$$m_t(h) = \frac{m_t^0(h)}{\sqrt{Z_{t_L}(h)Z_{t_R}(h)}} \qquad Z_{t_{L,R}}(h) \sim 1 + \epsilon_{L,R}^2 f_{L,R}(h)$$

- Higgs couplings to gluons and tops can then be simply obtained using LET

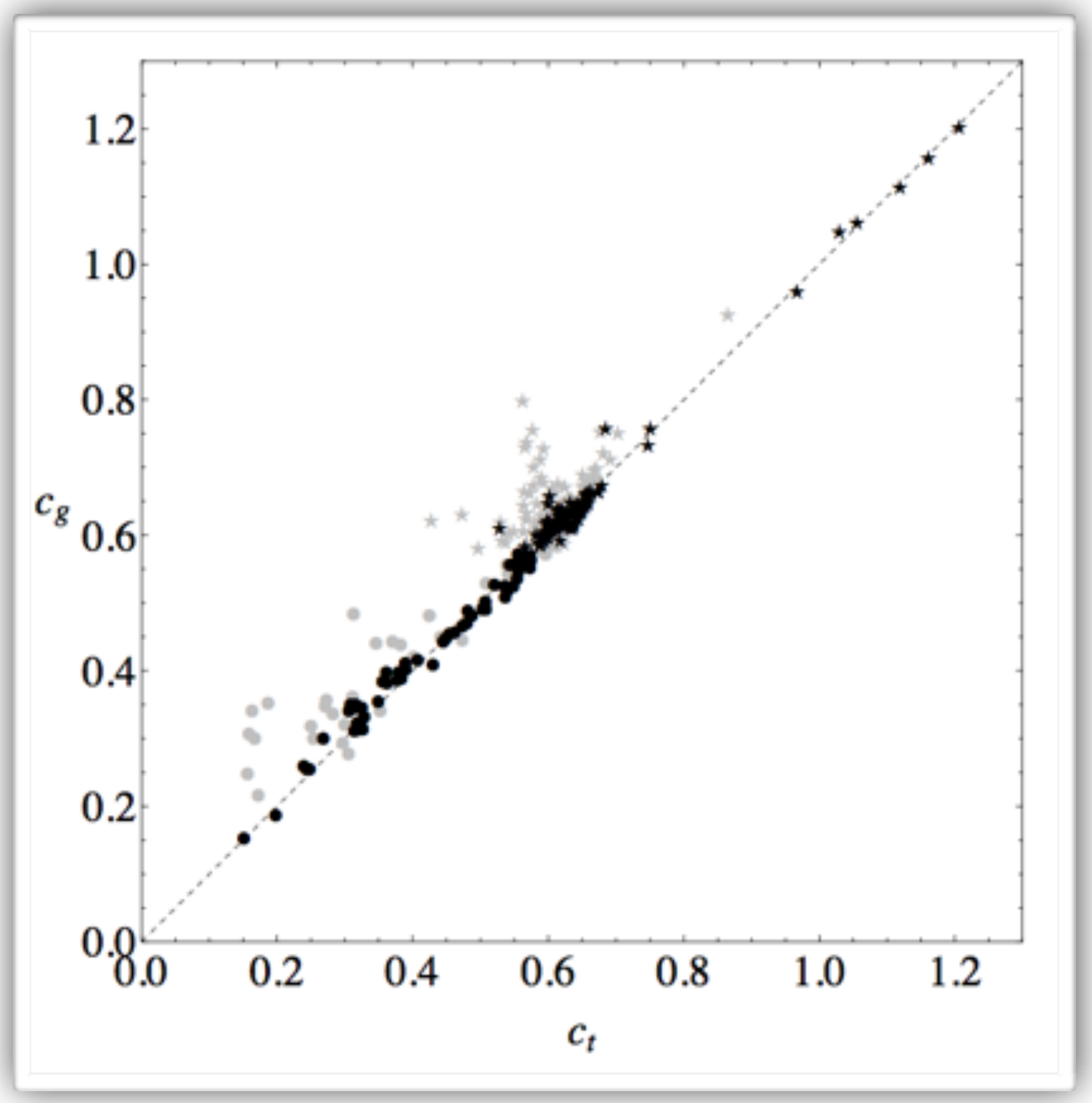
$$c_g^{(t)} = v\left[\frac{\partial}{\partial h}\log m_t^0(h)\right]_{\langle h\rangle} \qquad c_t = v\left[\frac{\partial}{\partial h}\log m_t(h)\right]_{\langle h\rangle}$$

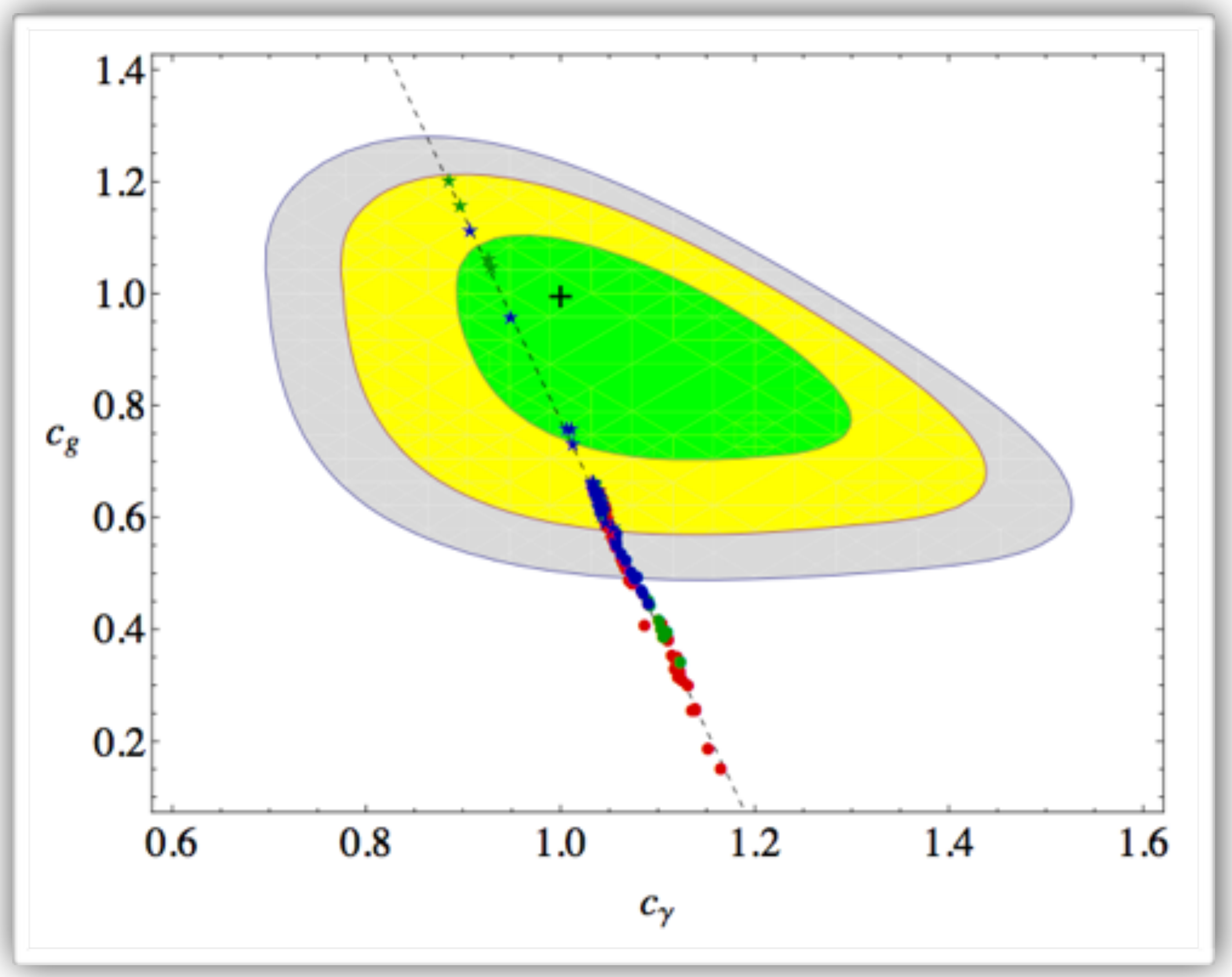
- They differ only for subleading terms of order ϵ^2

Montull, Riva, Salvioni, RT 1308.0559 [hep-ph]

COUPLING TO GLUONS AND TO TOPS

- The difference between $c_g^{(t)}$ and c_t is generated by mixings effects
- Large mixings in general correspond to light top partners and direct searches already set a constraint on the strength of the mixings
- For example in a model with q_L and t_R mixing with a single vector-like 14 we have



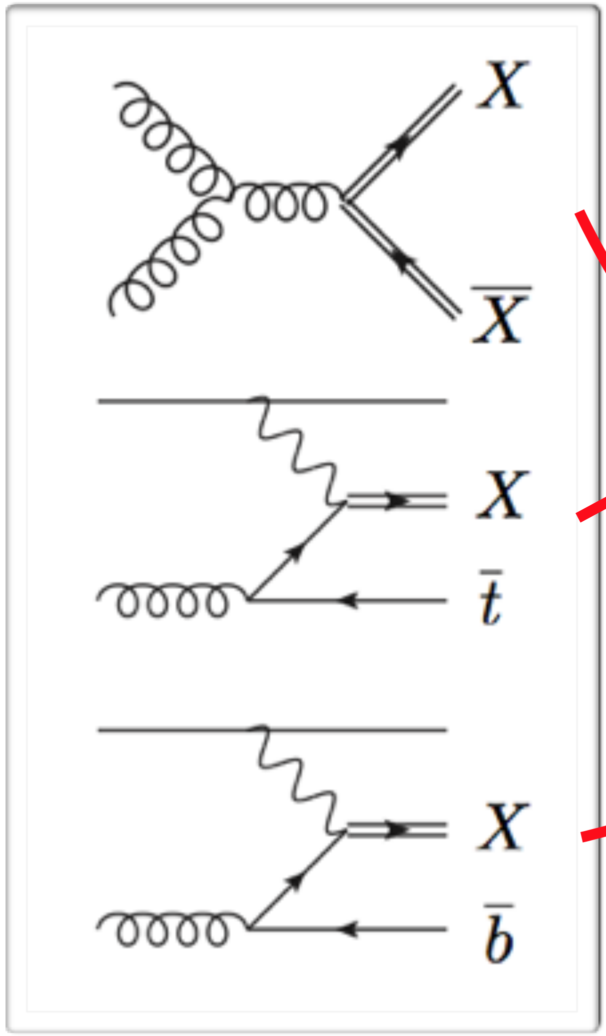


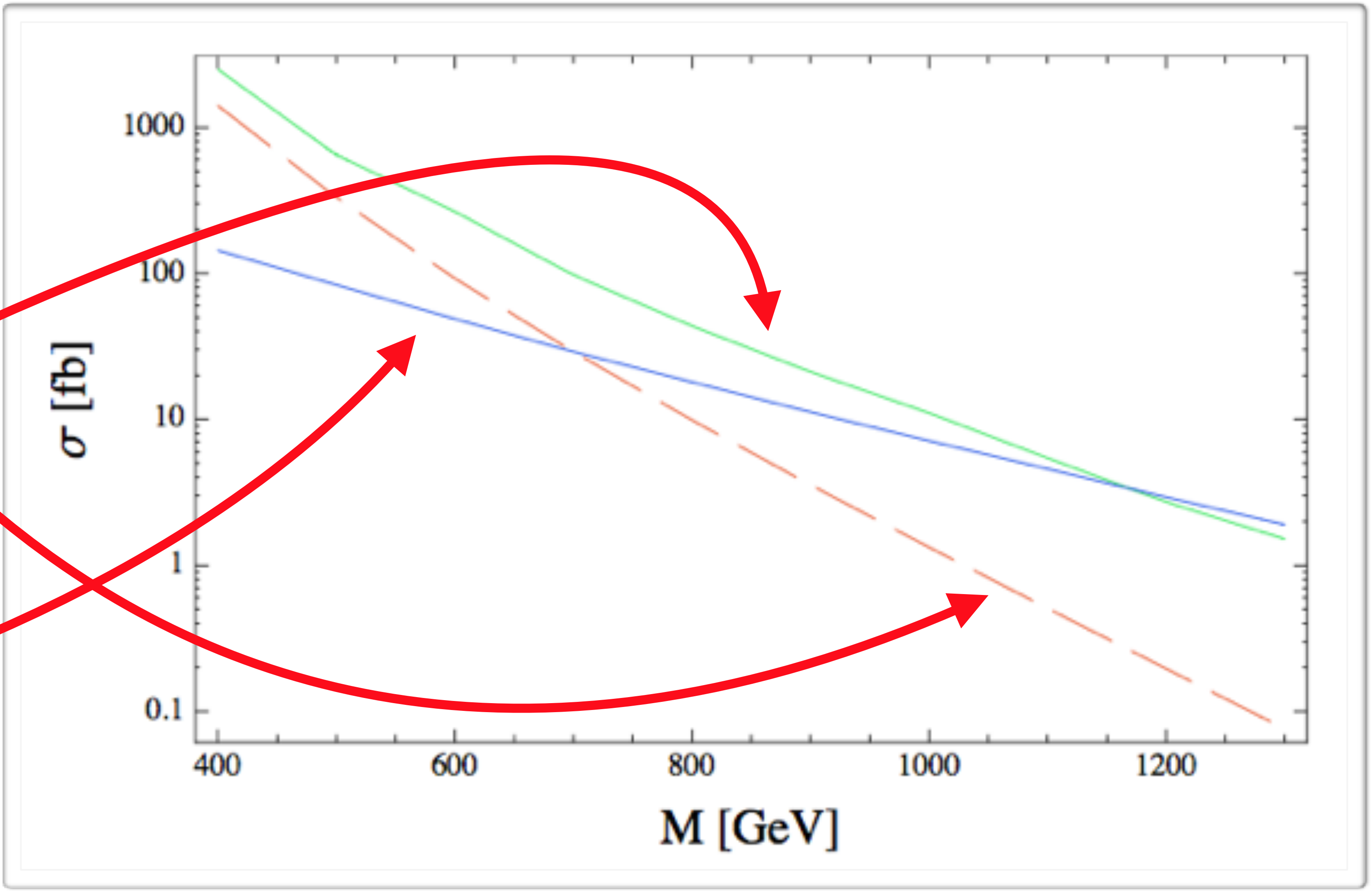
Top partners

Top partner searches and bounds

TOP PARTNERS: PRODUCTION

- New vector-like colored fermions are expected around the TeV scale (for light quarks partners see Thomas Flacke's talk)
- In the minimal case we have a heavy top-like state and a heavy charge 5/3 colored state
- In non-minimal cases (e.g. MCHM14) there are many new states: top and bottom-like states and charge -4/3, 5/3 and 8/3 states
- One can study the phenomenology of these resonances by means of an effective low energy theory containing only a small number of new states

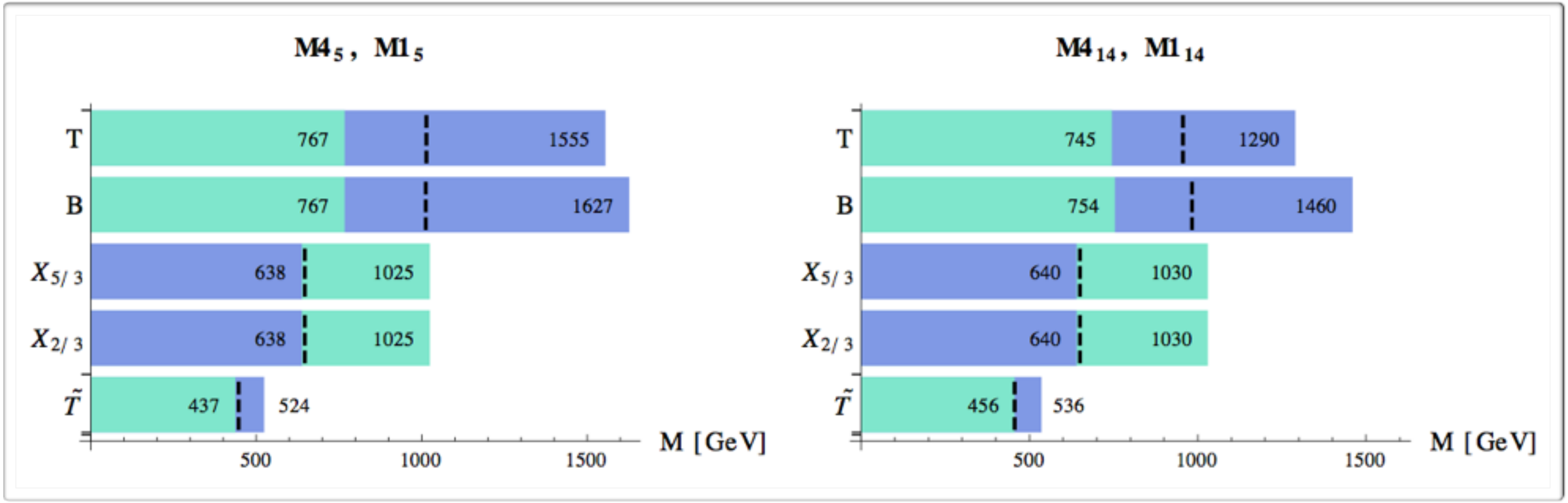




De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663 [hep-ph]

TOP PARTNERS: BOUNDS

- Searches for heavy quarks and also some SUSY searches with same-sign di-leptons or tri-leptons are already testing the interesting mass region



- If nothing is found with a few hundreds of inverse fb at the 14 TeV LHC we expect the level of tuning to decrease much below the 1% level, excluding the model from a naturalness point of view

De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663 [hep-ph]

Conclusion

CONCLUSIONS

- Composite Higgs models provide a motivated and well established alternative to weakly coupled BSM theories like SUSY deserving particular attention from the experimental community

- These theories still provide a possible "natural" solution to the HP: $1/\Delta \sim 1 \div 10\%$

- There are two main predictions: modifications of the Higgs couplings and the existence of fermionic resonances at or below 1 TeV

- Measuring Higgs couplings at the percent level at LHC is challenging (need a Linear Collider!) and the search for the top partners is therefore the primary task

- Excluding new colored fermionic resonances up to a few TeV would rule out the Composite Higgs idea pushing it in a region of unacceptable fine tuning

THANK YOU