THE HIGGS, THE SM & BEYOND

Incontri di Fisica delle Alte Energie - IFAE 2014

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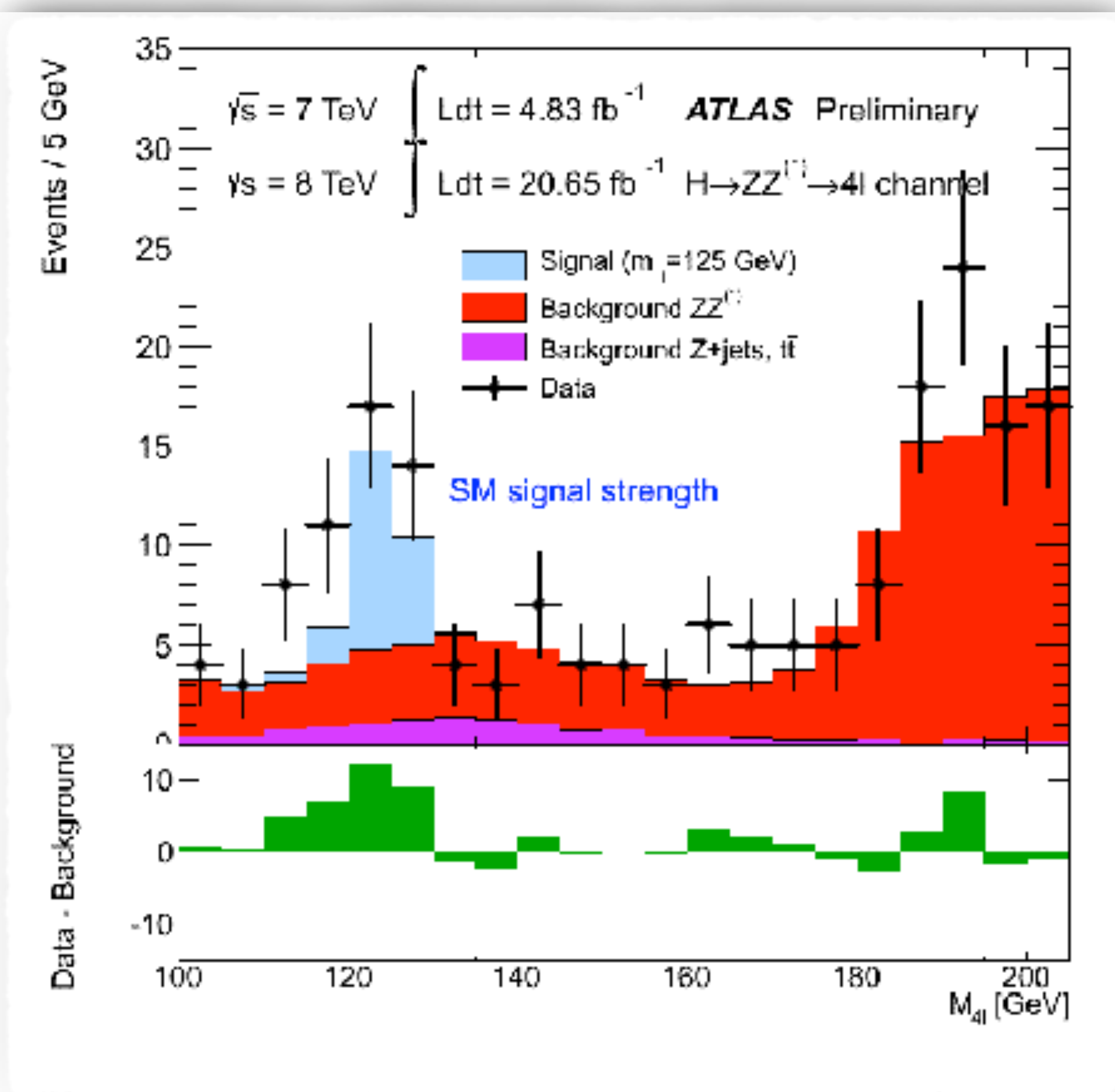
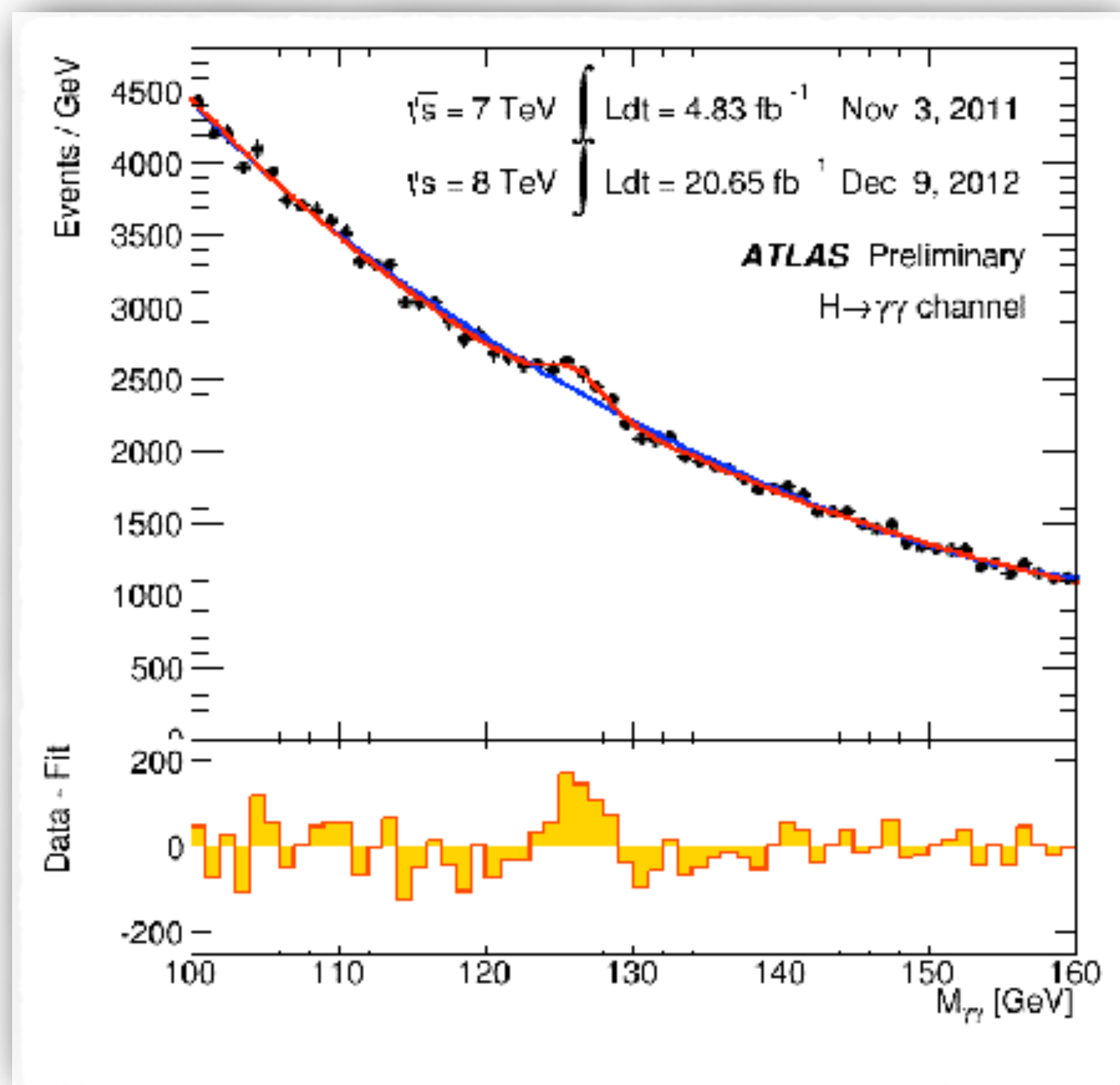
The SM Higgs

The Naturalness paradigm

THE SM-LIKE HIGGS

A 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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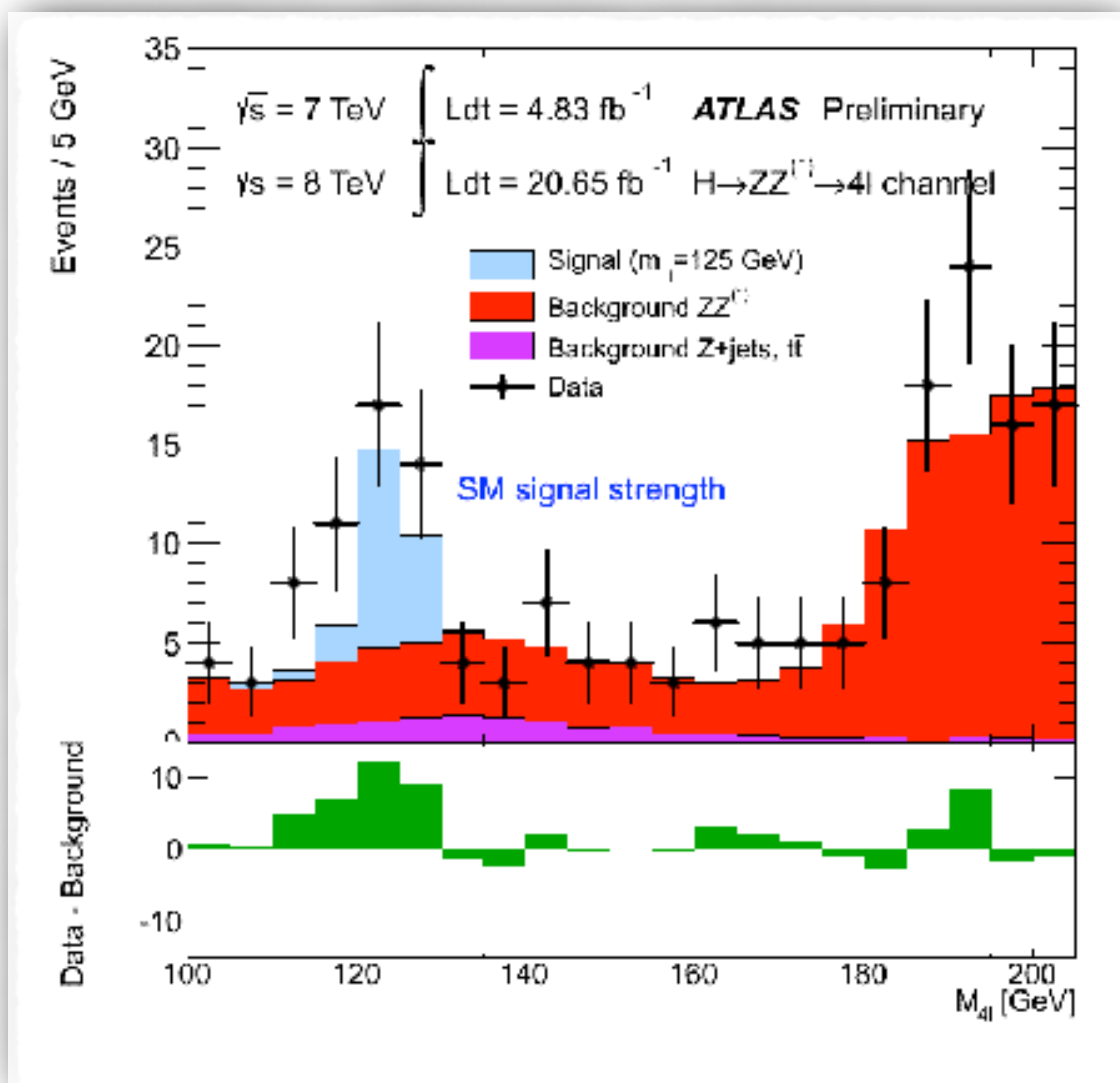

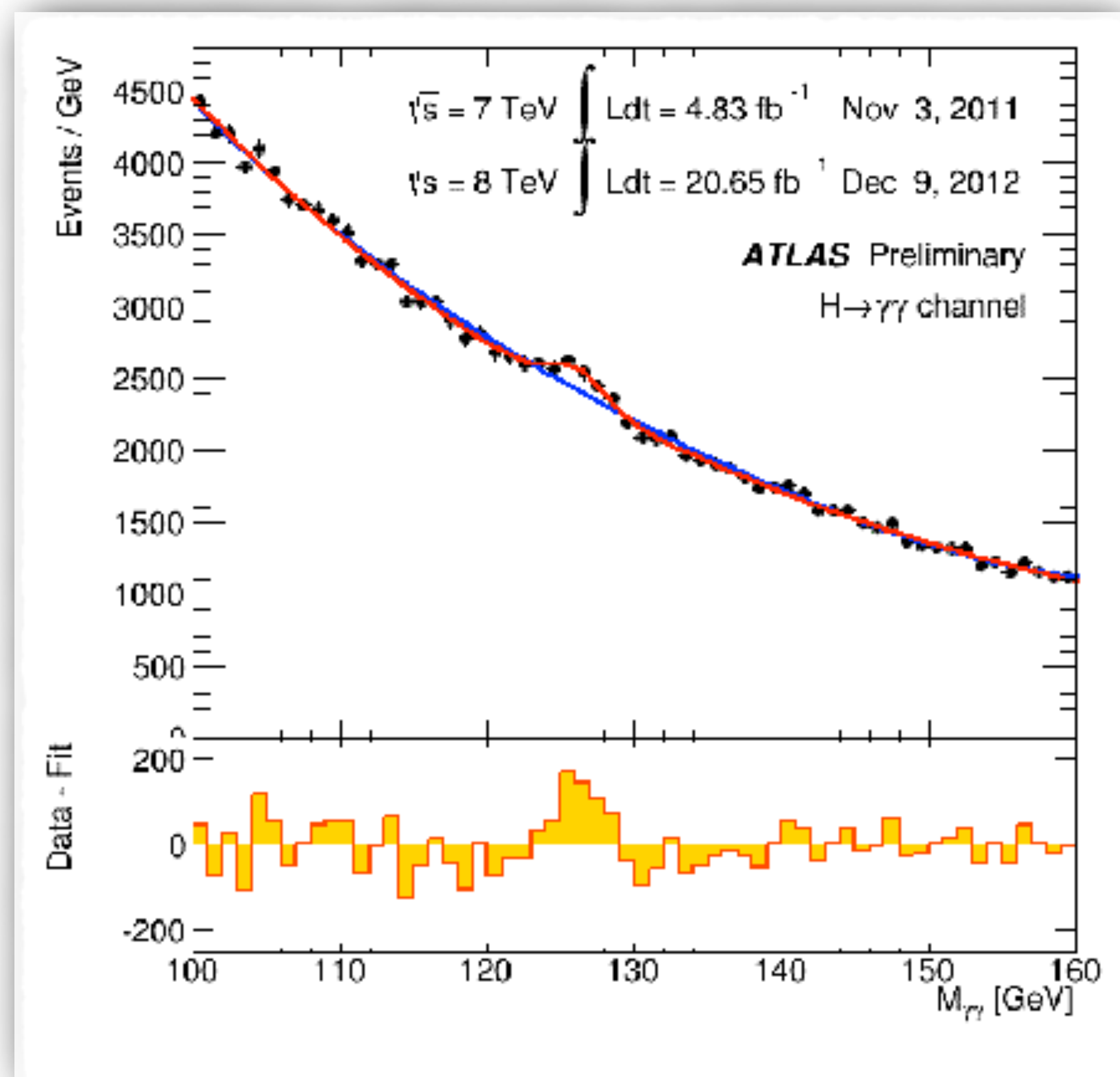

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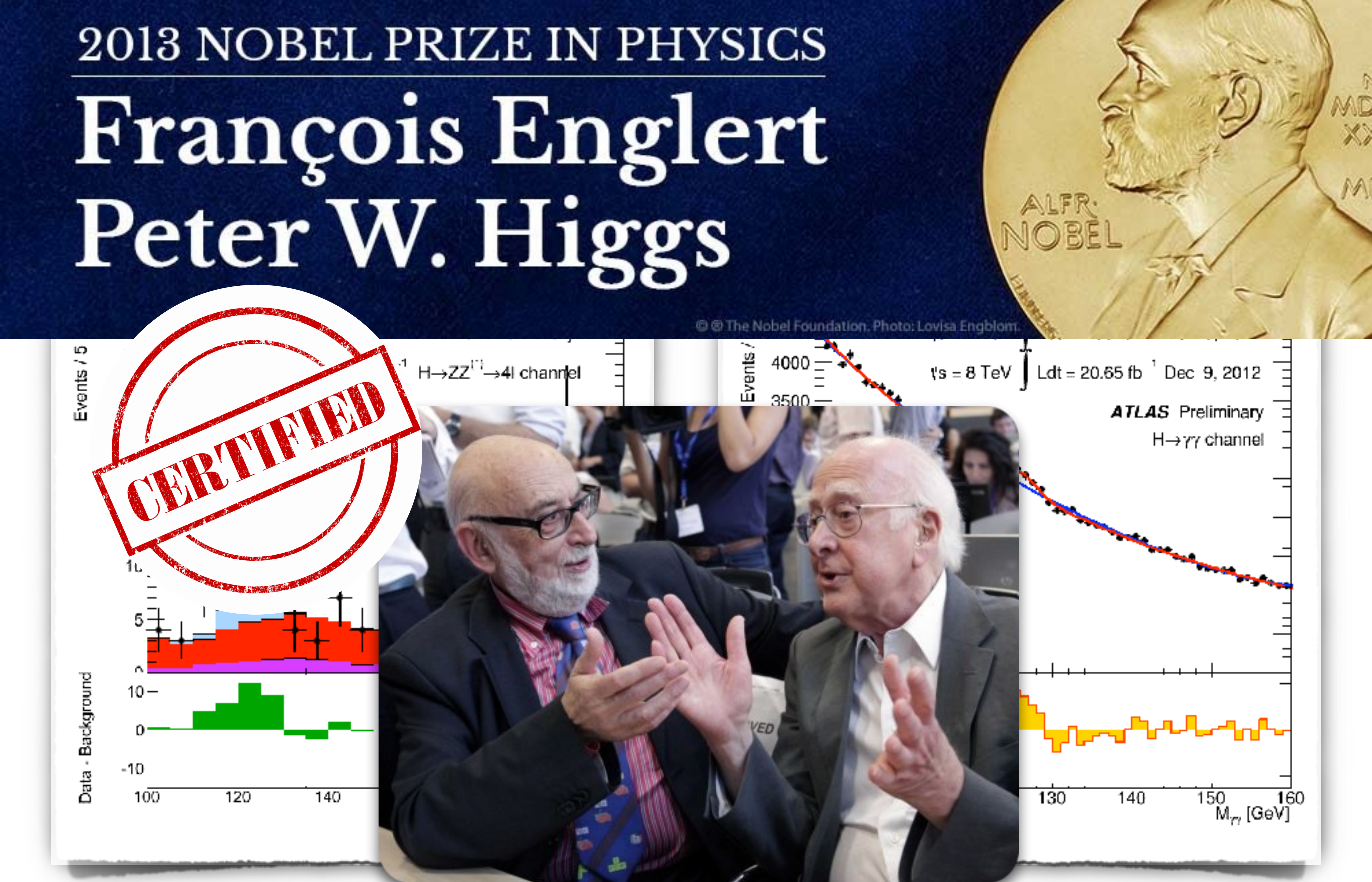

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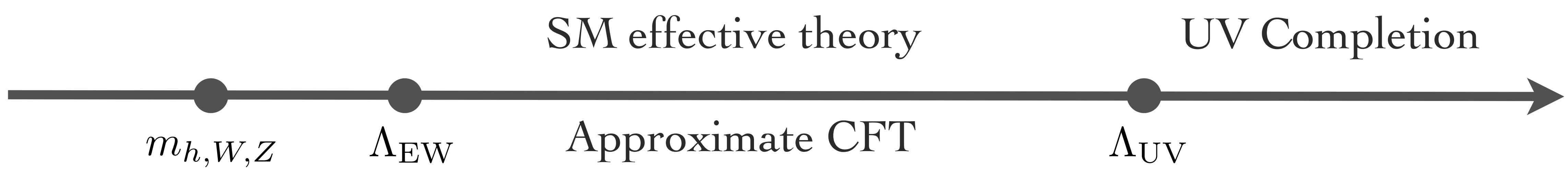
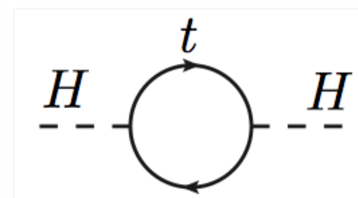
NATURALNESS IN THE SM



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 ($1/\Delta$ is called the fine tuning)

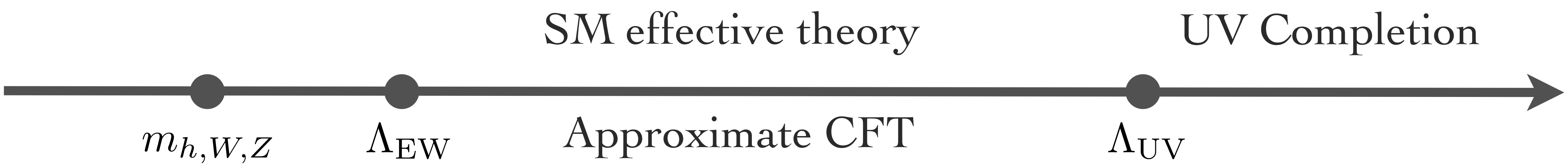
$$\Delta \gtrsim \left(\frac{125\ \text{GeV}}{m_h}\right)^2 \left(\frac{\Lambda_{\rm UV}}{400\ \text{GeV}}\right)^2$$

- If we believe in some “naturalness”, e.g.

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

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

NATURALNESS IN THE SM



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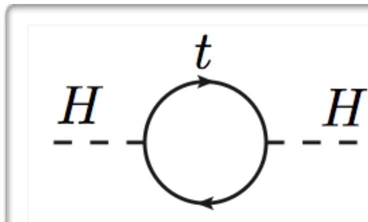

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Natural CH $\Downarrow$ Light top partners

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Natural SUSY $\Downarrow$ Light stops

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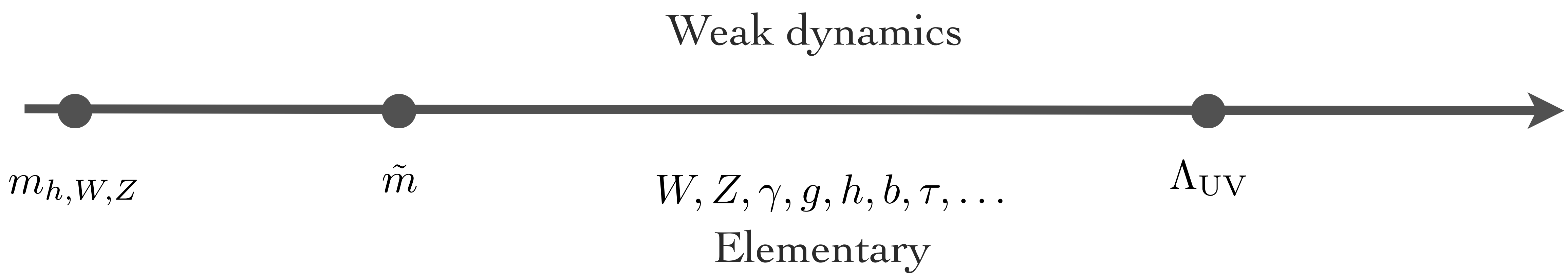
TWO POSSIBLE SOLUTIONS

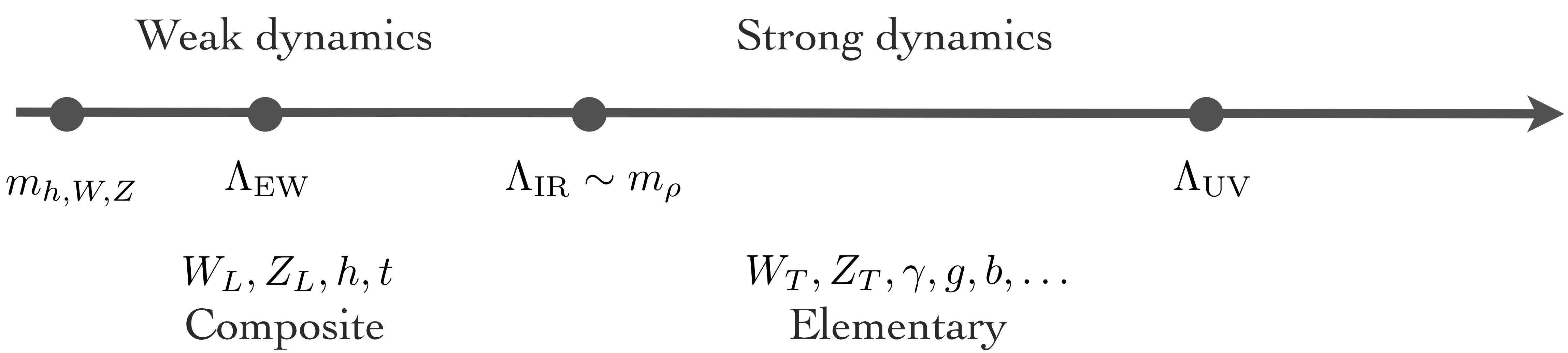
1. Weak dynamics (Supersymmetry)



- In the UV an enhanced symmetry, supersymmetry, prevents the scalar masses to have quadratic sensitivity on the UV scale
- Supersymmetry is broken softly, i.e. only by relevant operators
- The breaking disappears in the UV
- New degrees of freedom, i.e. superpartners of the SM fields are expected to be present close to the EW scale
- A large separation between SM particles and sparticles generally requires large fine-tuning

TWO POSSIBLE SOLUTIONS

2. Strong dynamics (Compositeness)



- The IR scale $\Lambda_{\rm IR}$ 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
- Again a large separation between the 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)

First solution: Supersymmetry

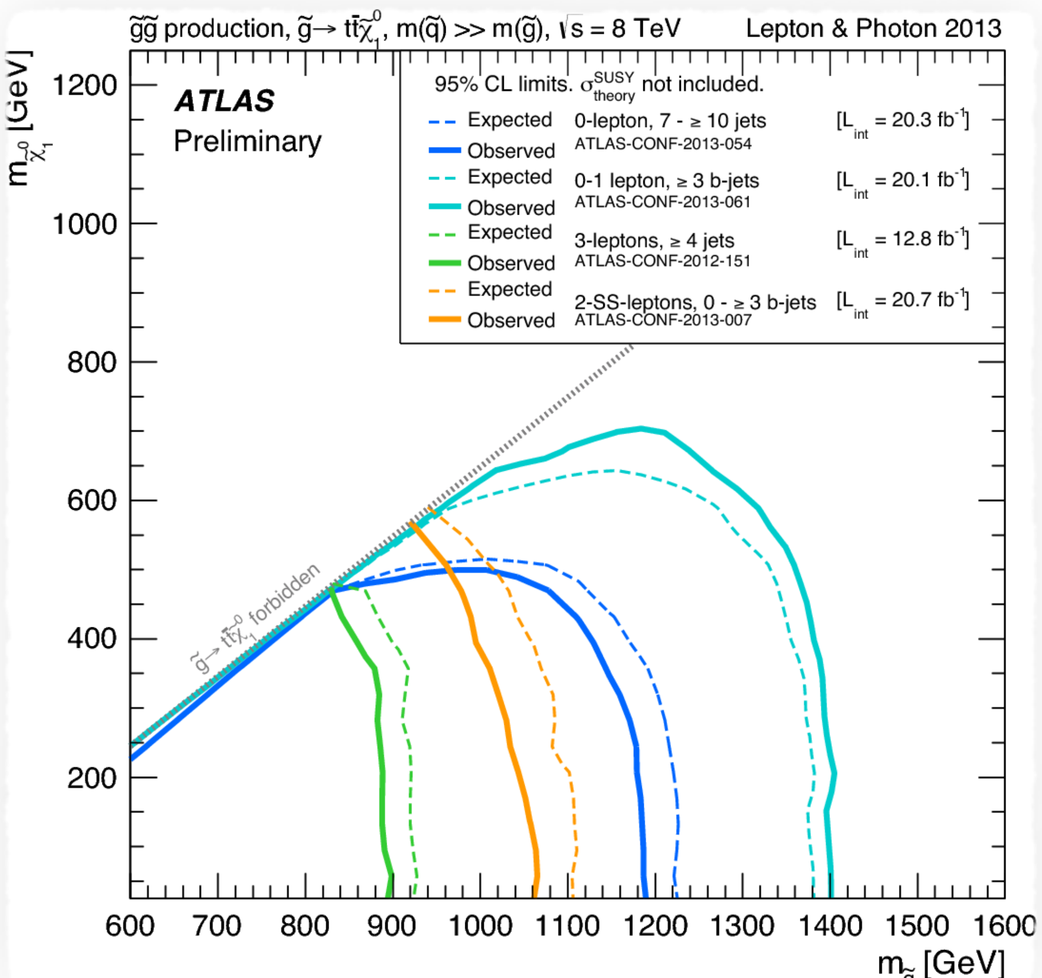
Status of SUSY

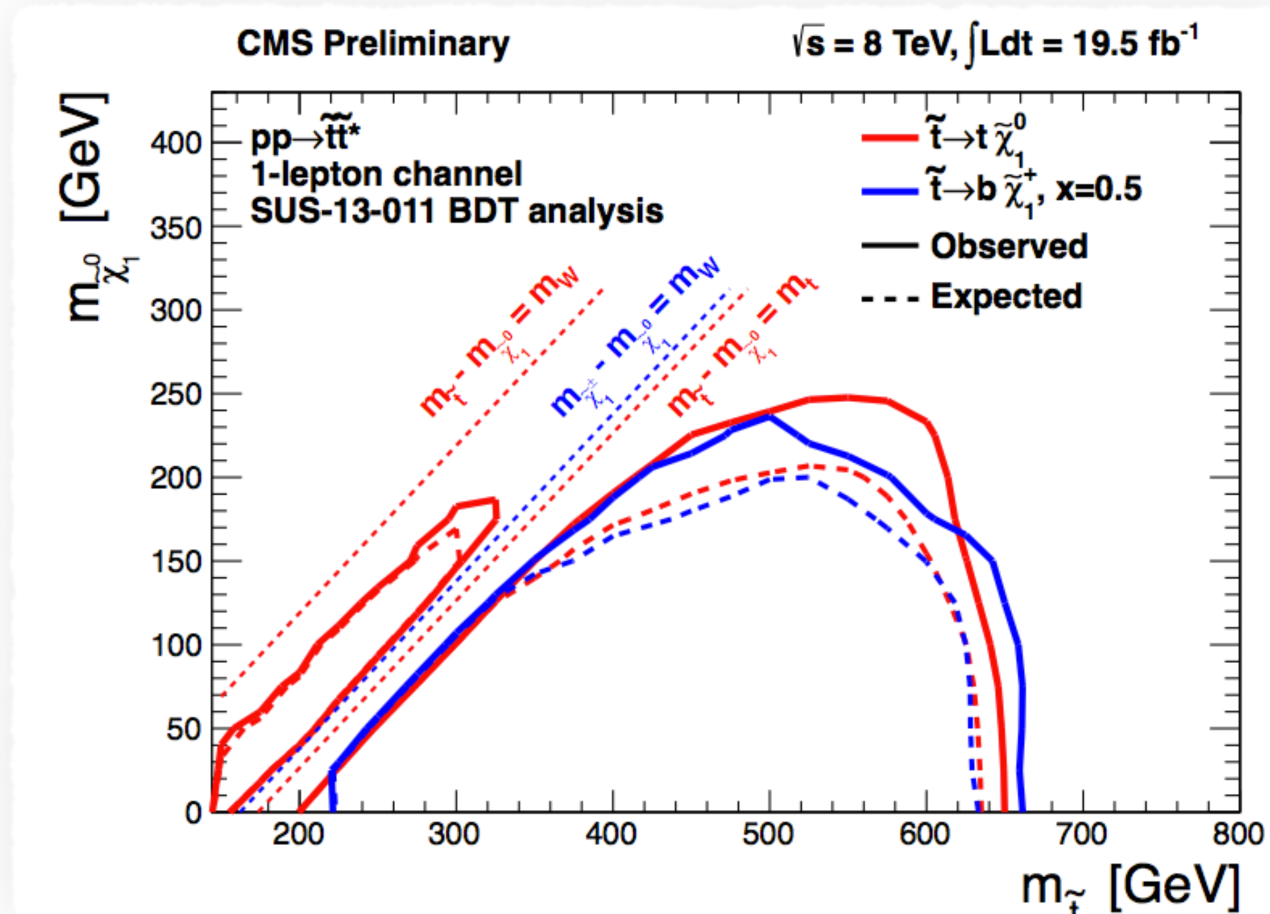
The MSSM & beyond

STATUS OF SUSY

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

- Here Λ_{UV} is related to the masses of the colored particles contributing to the Higgs mass radiative corrections (stops and gluinos)





- Putting the correct factors into the formula we get a very general estimate of the fine-tuning in SUSY theories of the order of

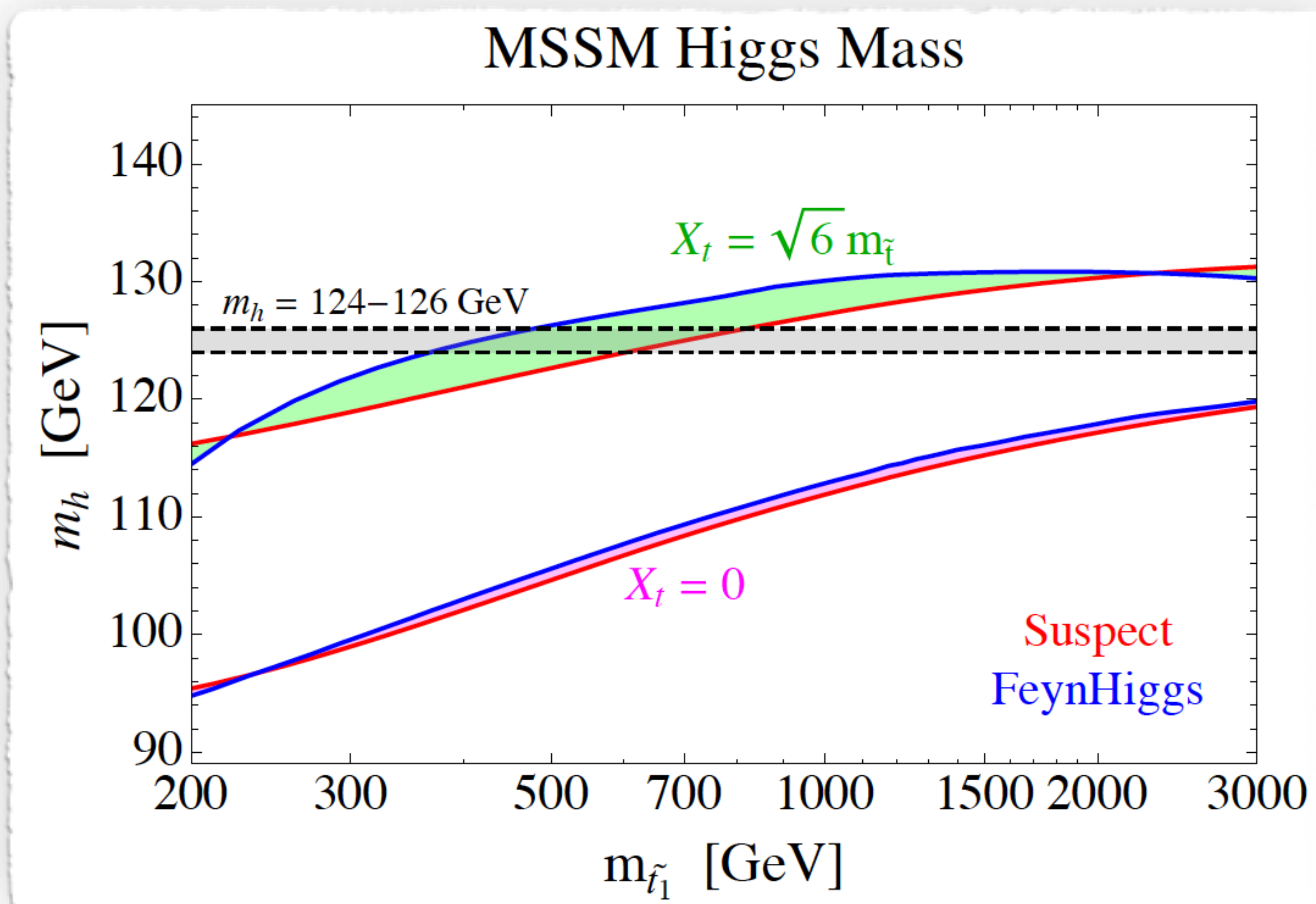
$$\Delta \gtrsim 20 - 100$$

THE MSSM & THE HIGGS

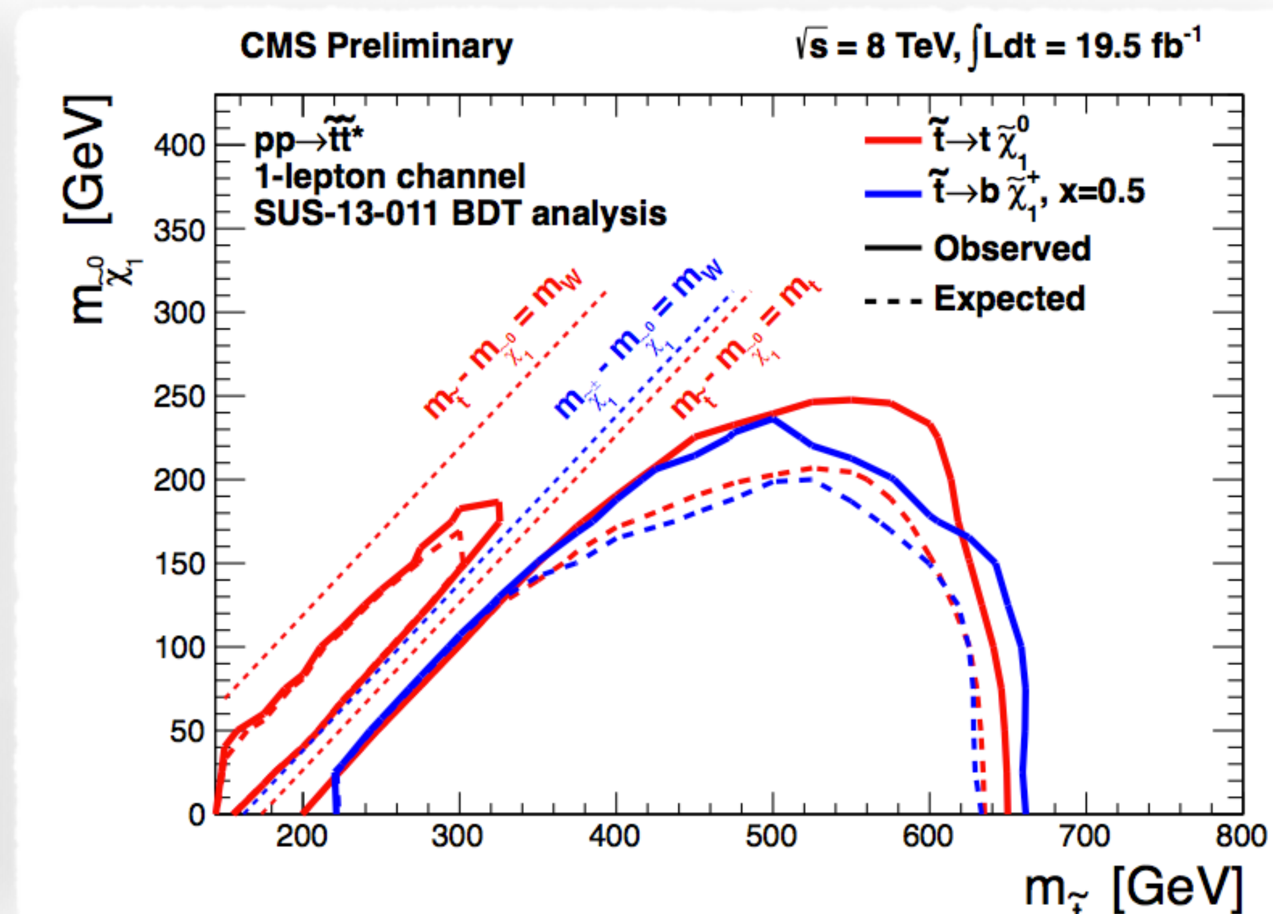
- The lightest CP-even Higgs mass in the MSSM is

$$m_h^2 = m_Z^2 \cos^2 2\beta$$

- The measured value of the Higgs boson mass exacerbates the fine-tuning of the MSSM with respect to general SUSY



Hall, Pinner, Ruderman 1112.2703 [hep-ph]



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$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right] \qquad \begin{array}{c} X_t = A_t - \mu/\tan\beta \\ m_{\tilde{t}}^2 = m_{Q_3} m_{U_3^c} \end{array}$$

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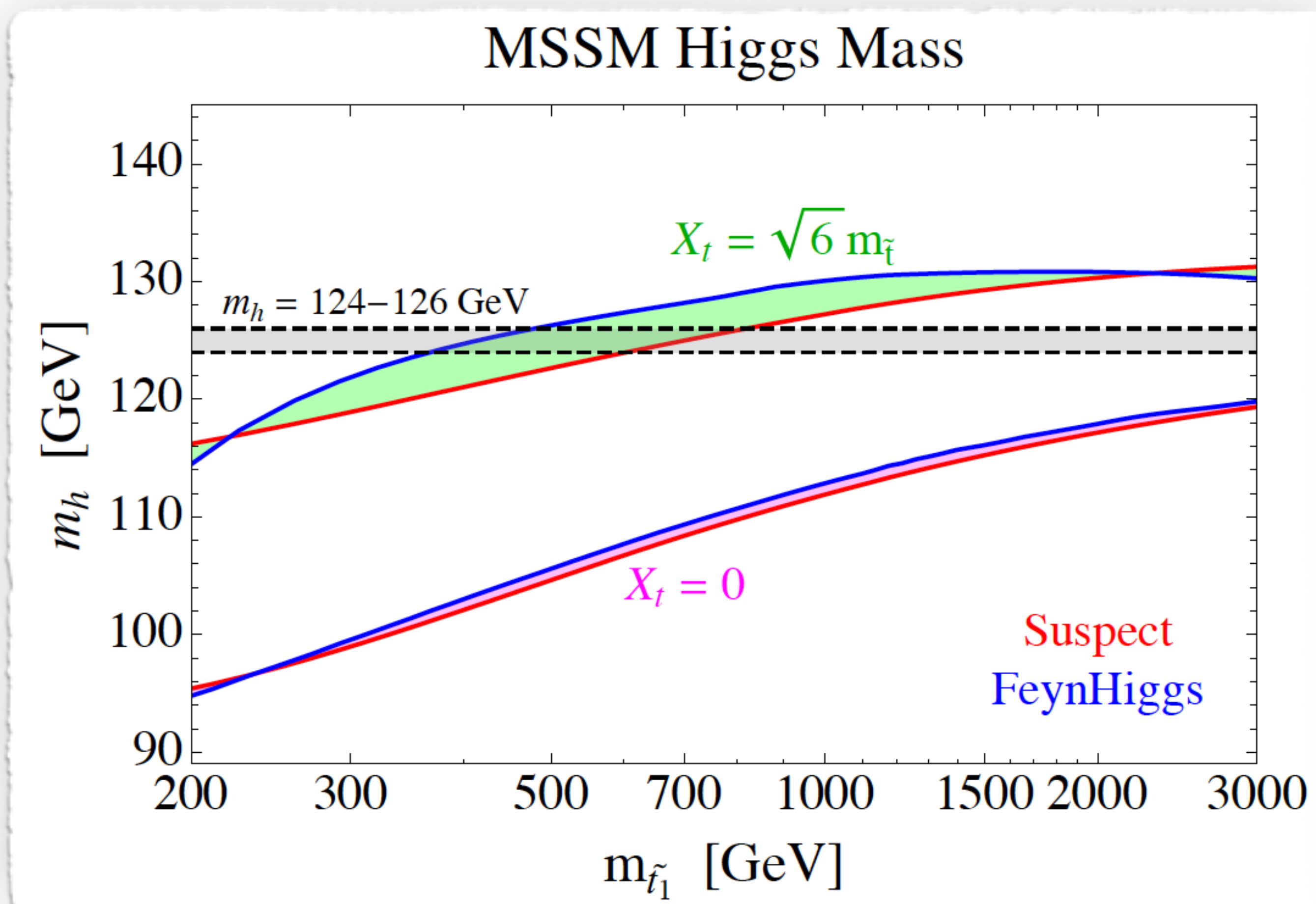

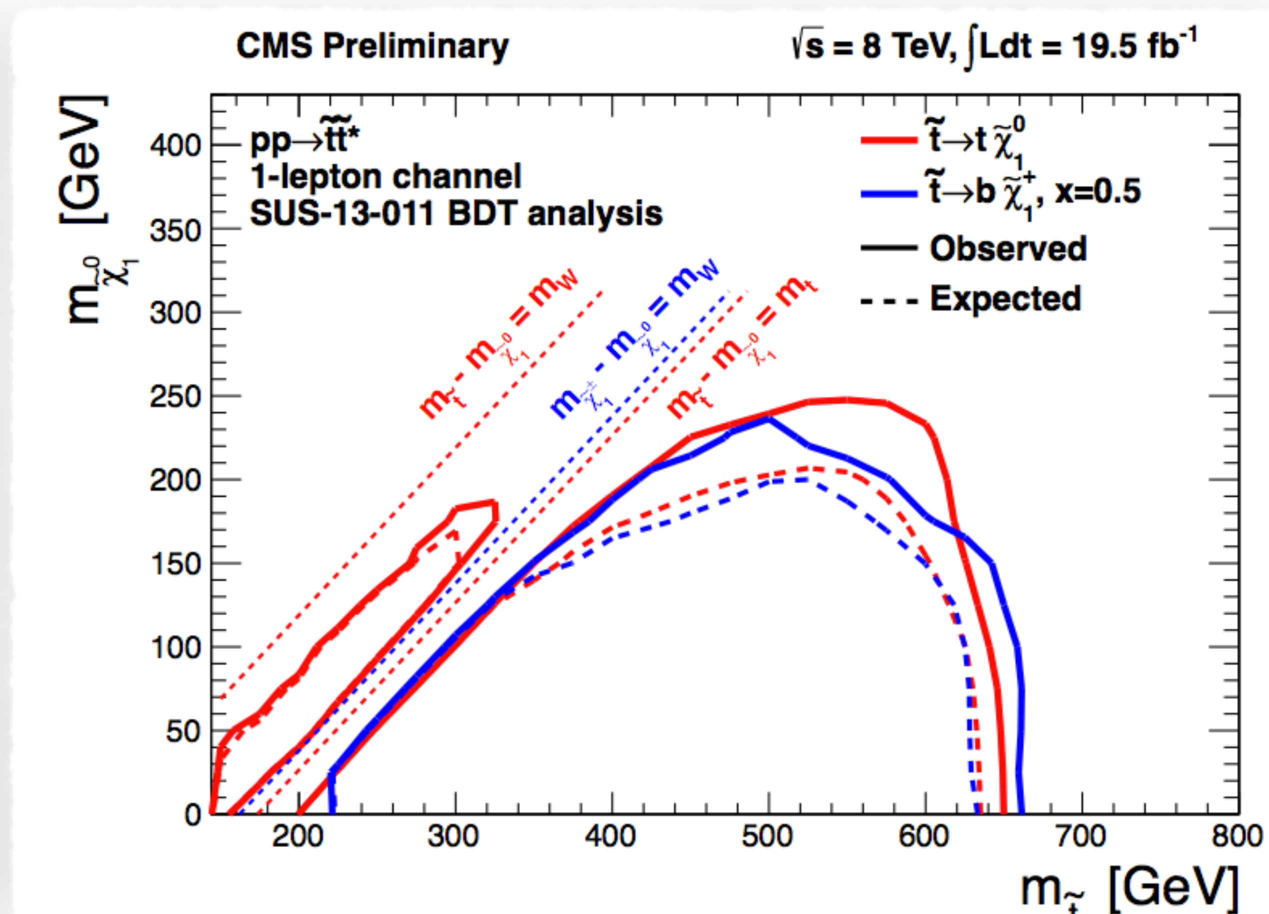

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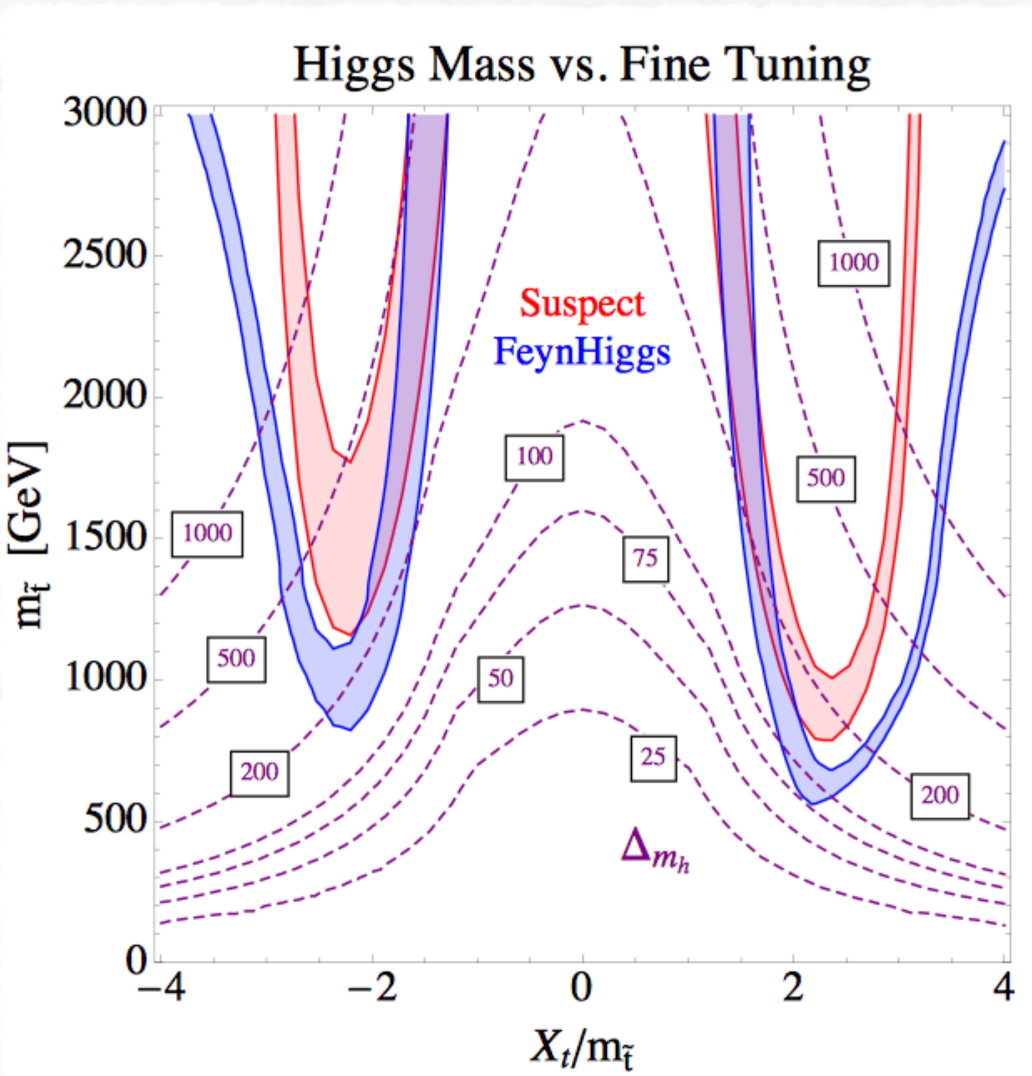

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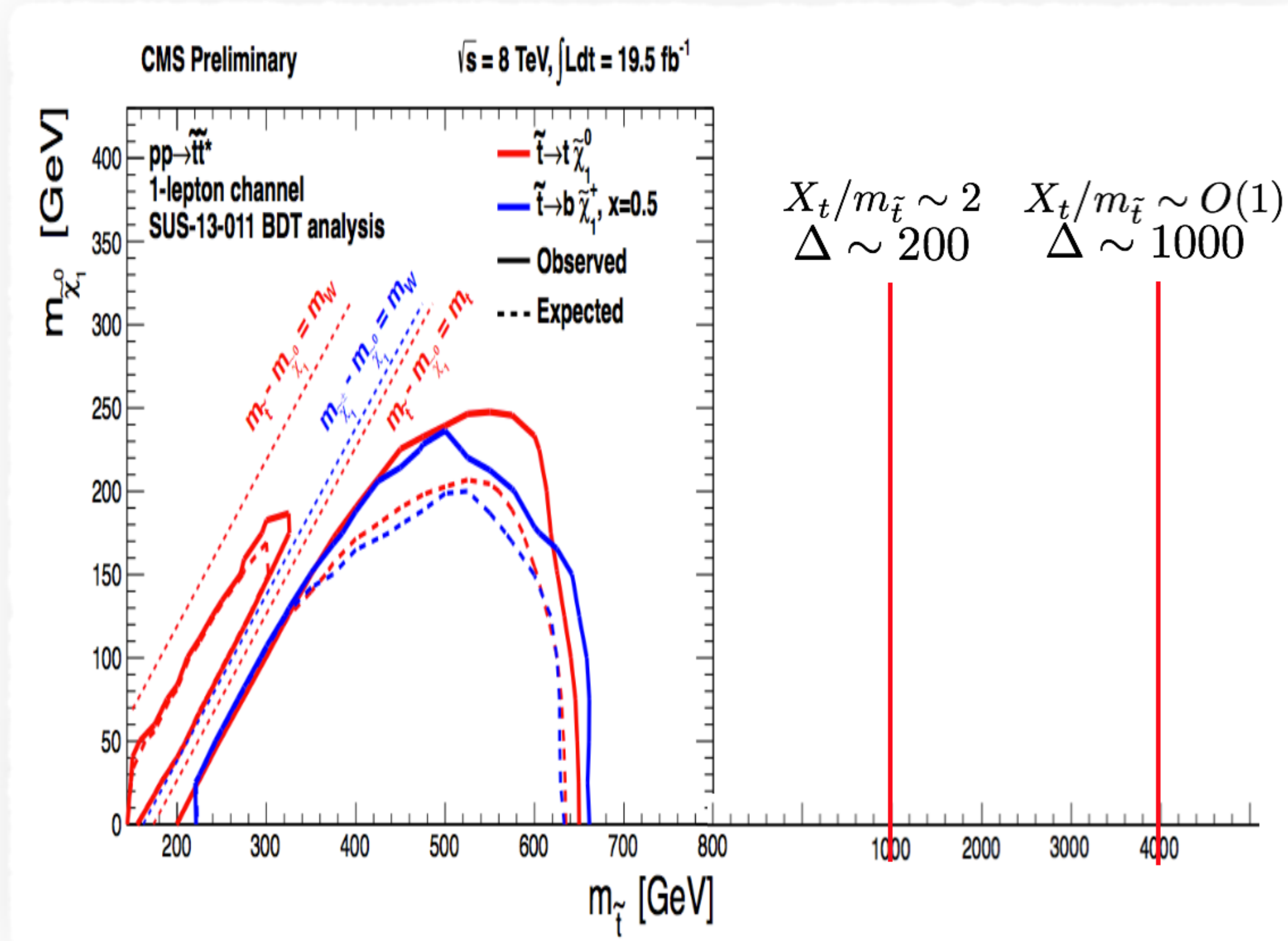


$$\Delta \gg 100$$

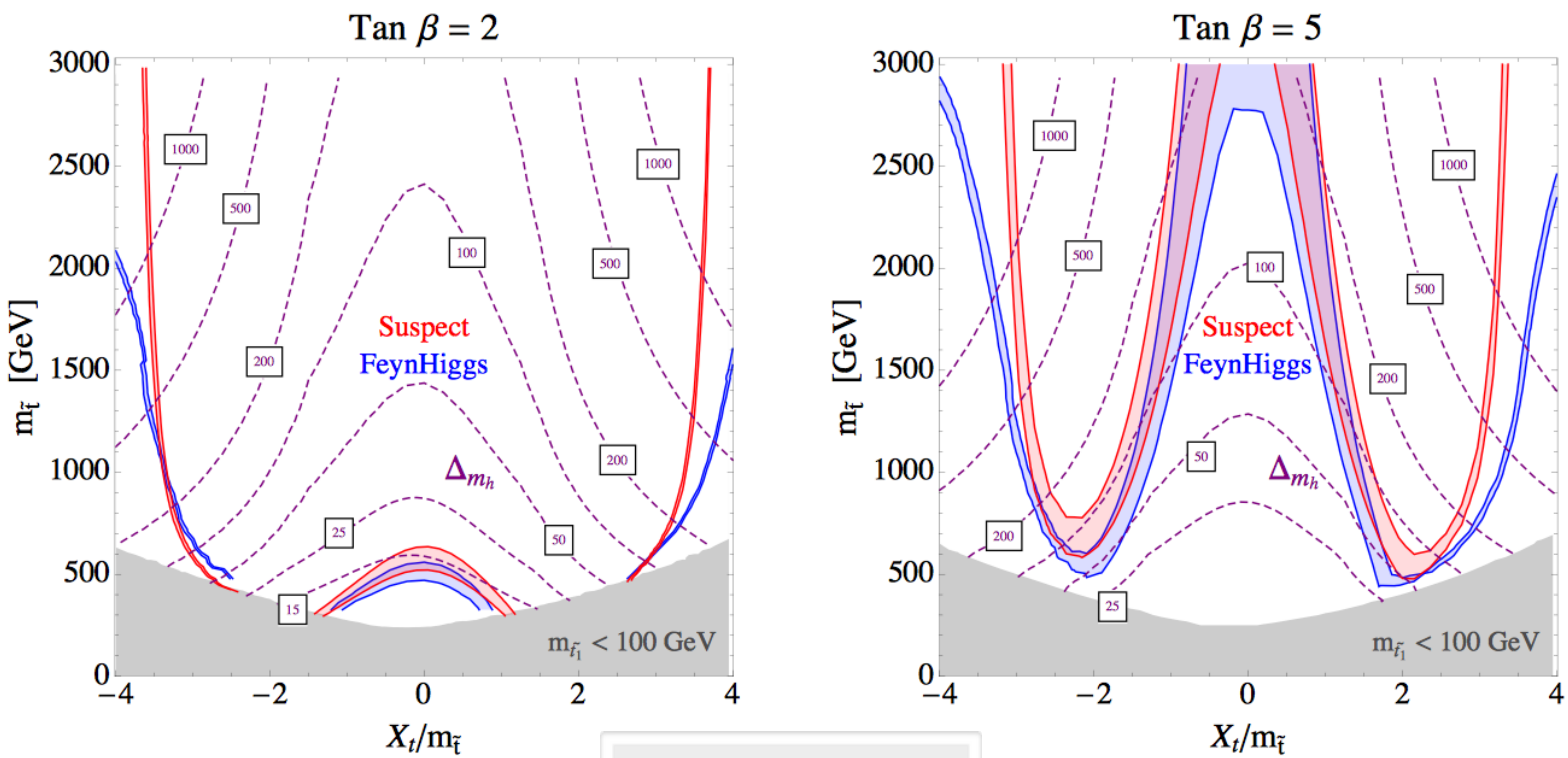
THE NMSSM & THE HIGGS

- There is a new contribution to the tree level Higgs mass from D-terms

$$m_h^2 = m_Z^2 \cos^2 2\beta$$

- The fine-tuning is better than in MSSM for intermediate values of tan beta

Hall, Pinner, Ruderman 1112.2703 [hep-ph]



$$\Delta \gtrsim 50 - 100$$

THE NMSSM & THE HIGGS

- There is a new contribution to the tree level Higgs mass from D-terms

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{\lambda^2 v^2}{2} \sin^2(2\beta) + \text{rad. corr.}$$

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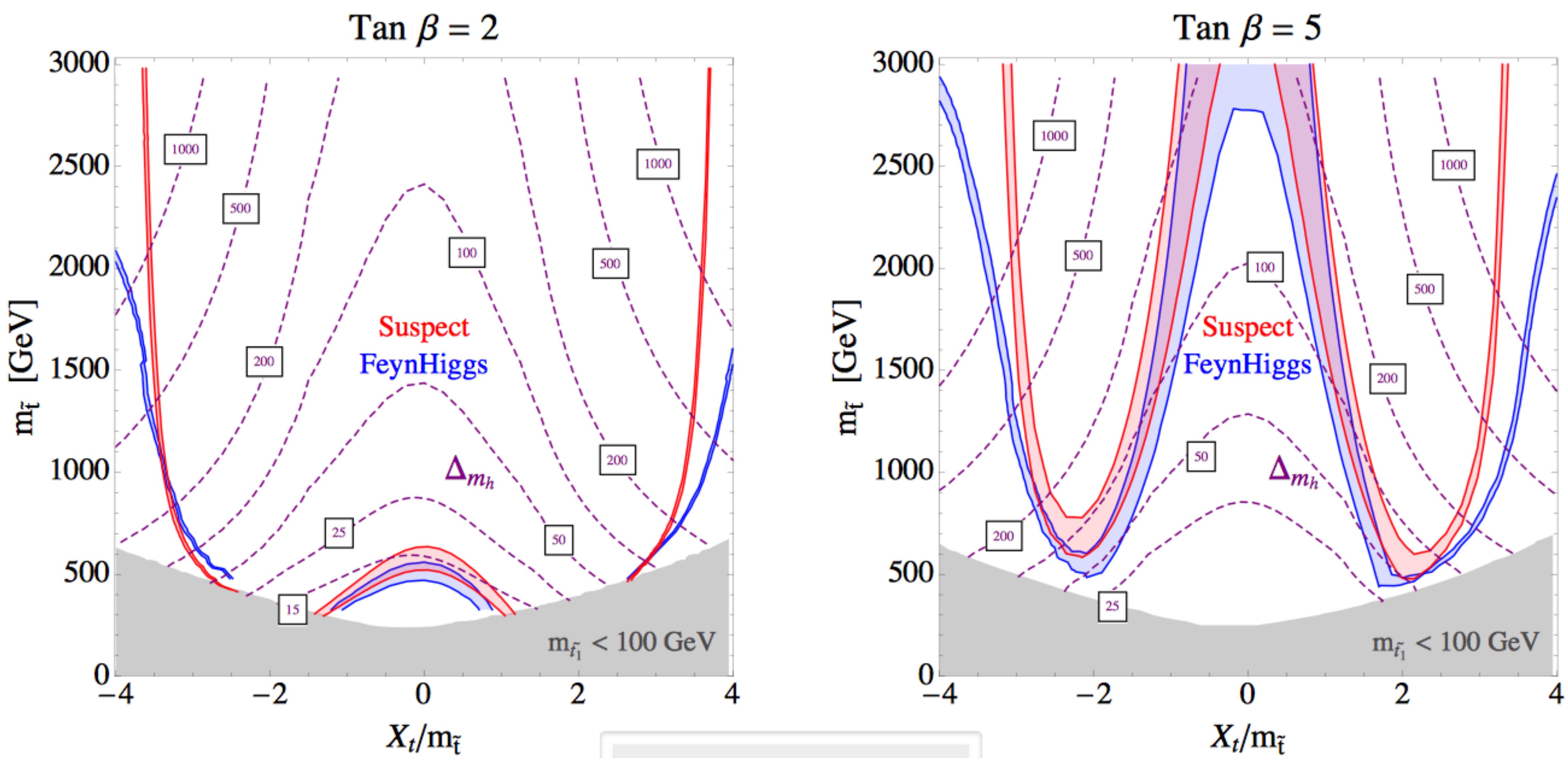
Hall, Pinner, Ruderman 1112.2703 [hep-ph]



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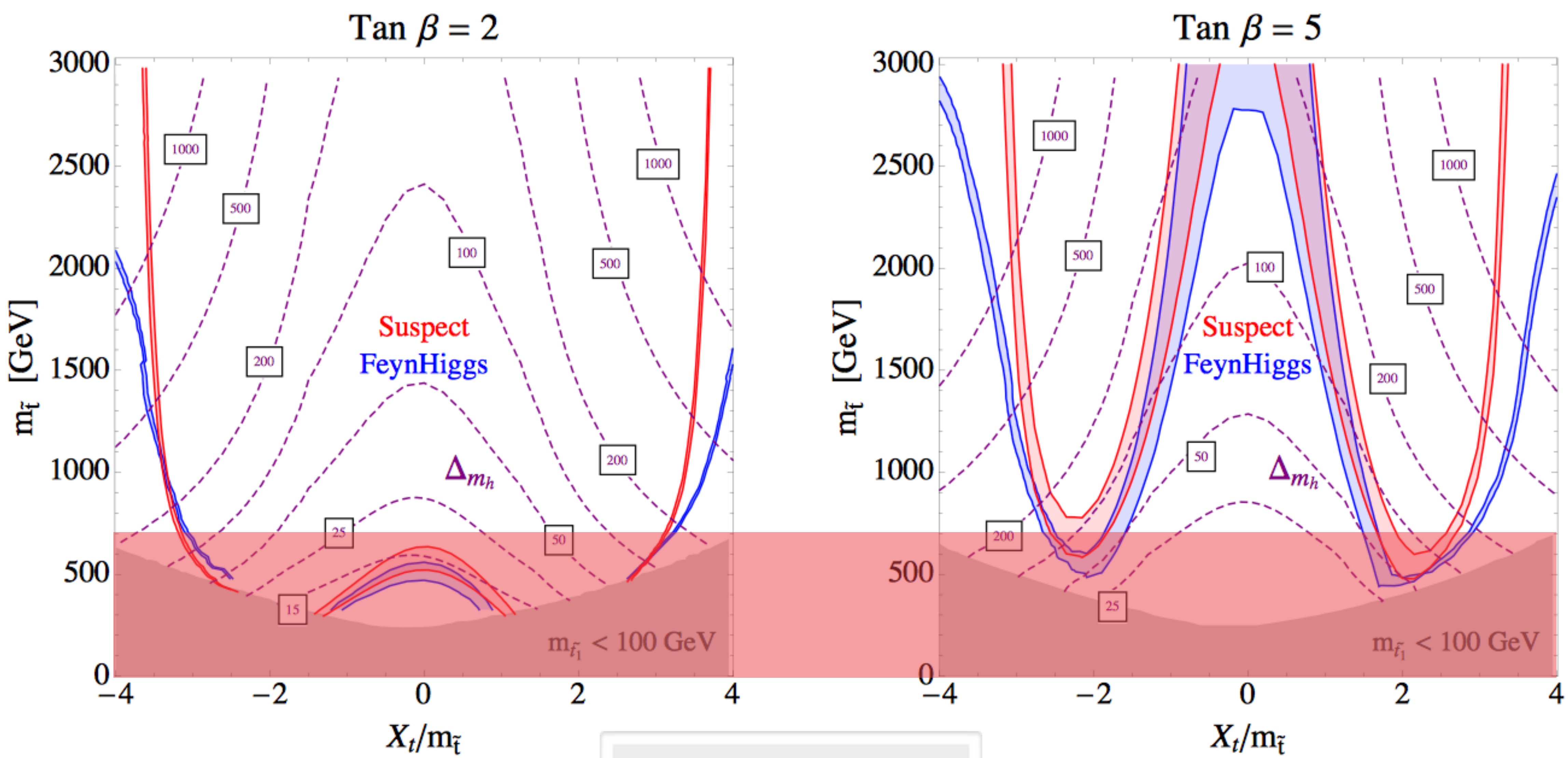

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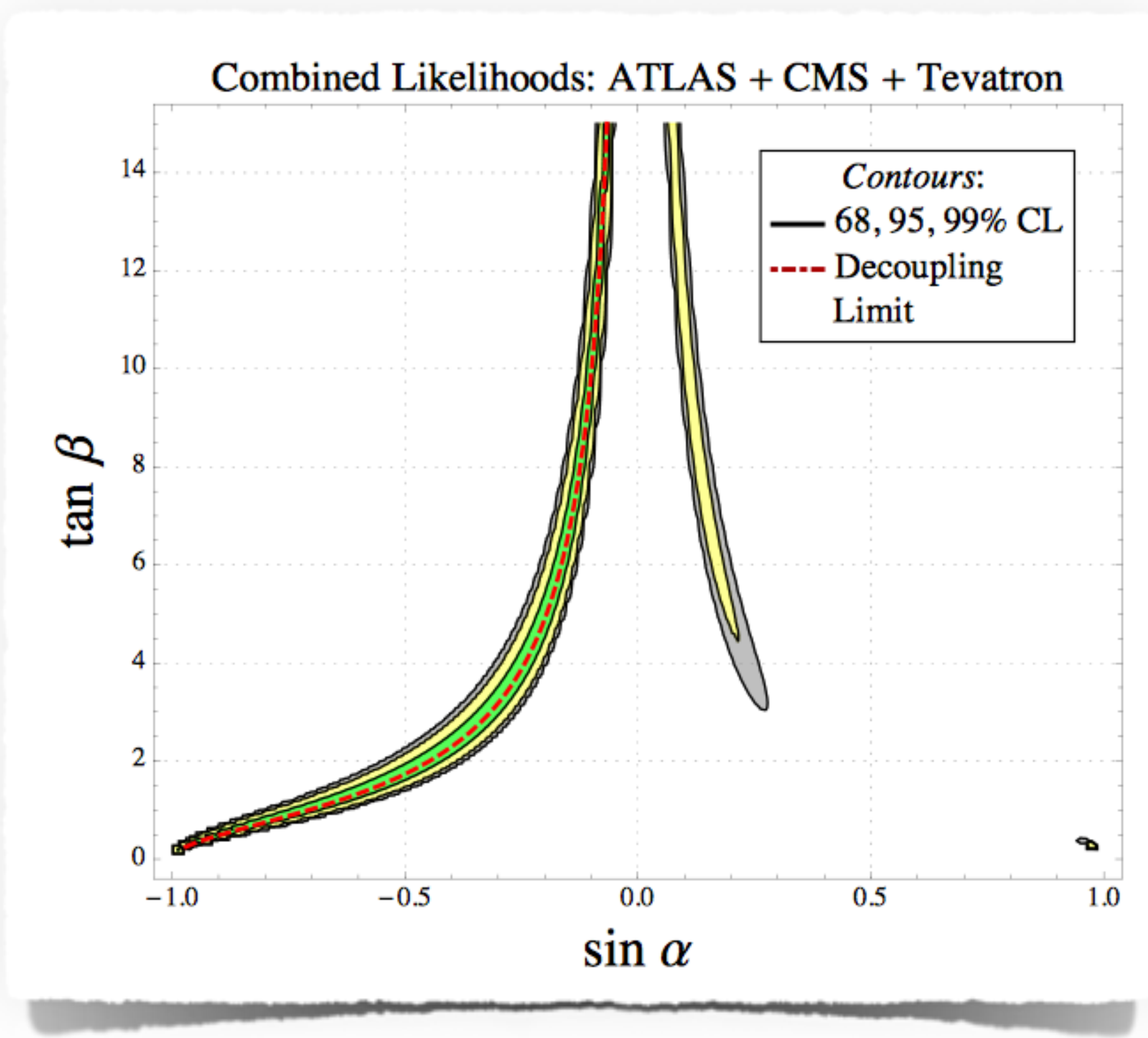
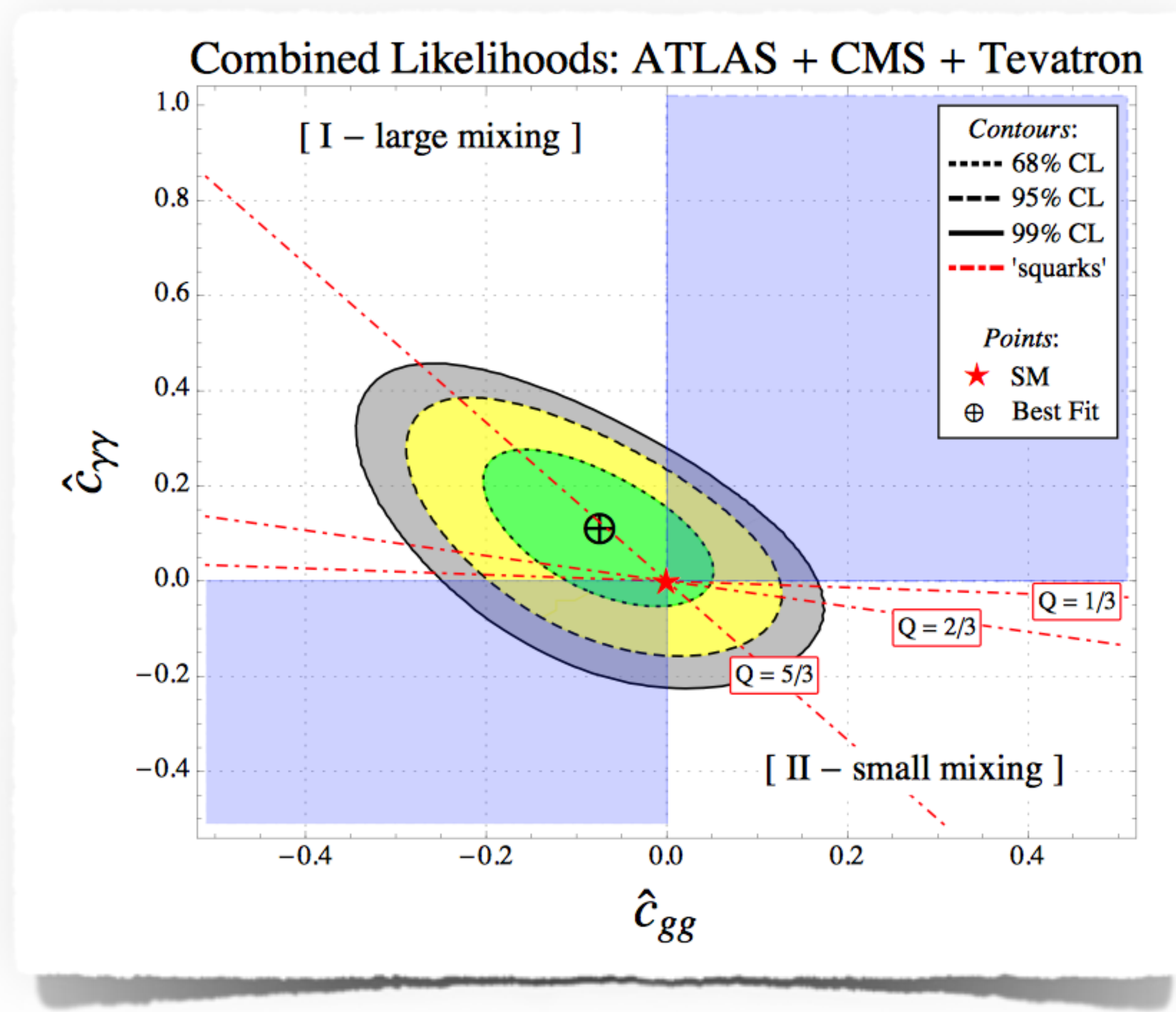
SUSY AND HIGGS COUPLINGS

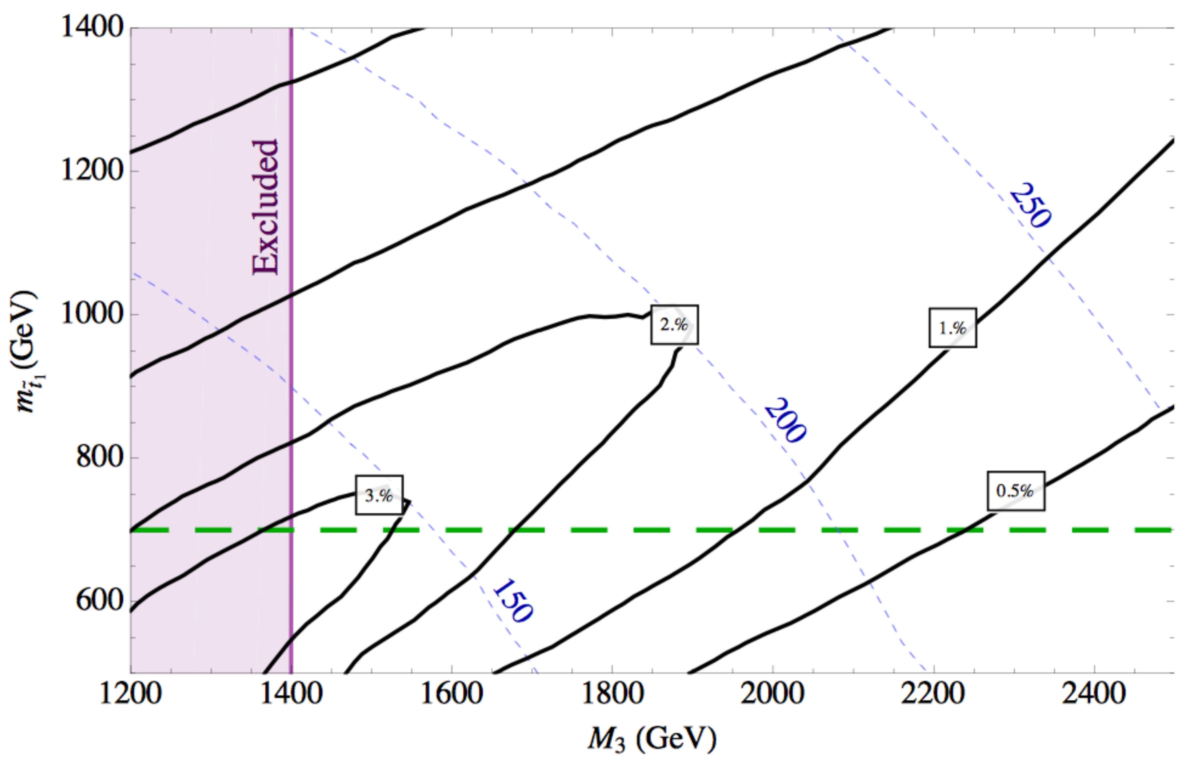
- The lightest CP-even Higgs looks very SM-like and this pushes the MSSM to live in a region very close to the decoupling limit $m_A \gg m_Z$
- New light colored particles (stops, sbottoms, etc.) are expected to contribute to loop induced Higgs couplings

Azatov, Galloway 1212.1380 [hep-ph]

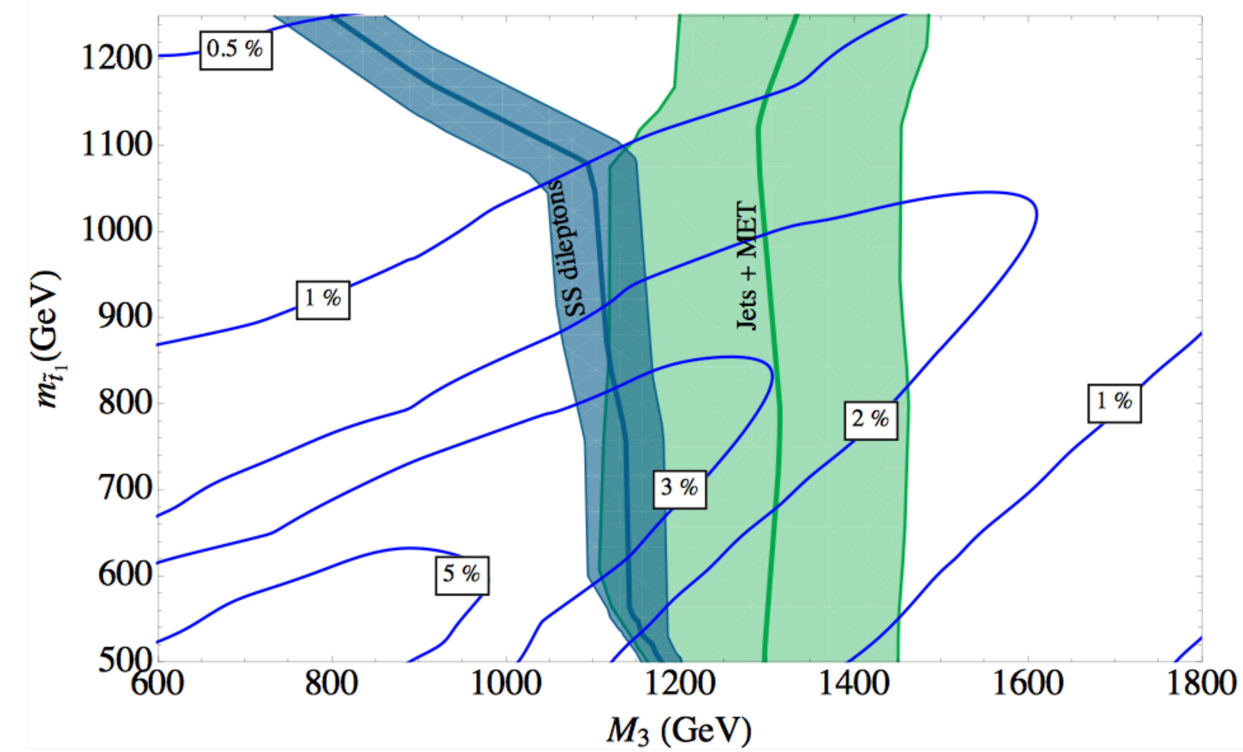




MOST NATURAL SUSY



Natural SUSY



bRPV

Model	FT
Mini-Split	$\lesssim$0.05%
MSSM	0.3–1%
NMSSM	2%
Split Families	3%
bRPV	2–3%
Dirac Gauginos	($\lesssim$1%).

After the first run of the LHC we can conclude that SUSY survives, in non minimal models with a fine tuning at the level of

$$\Delta \gtrsim 20 - 100$$

Arvanitaki, Baryakhtar, Huang, van Tilburg, Villadoro 1309.3568 [hep-ph]

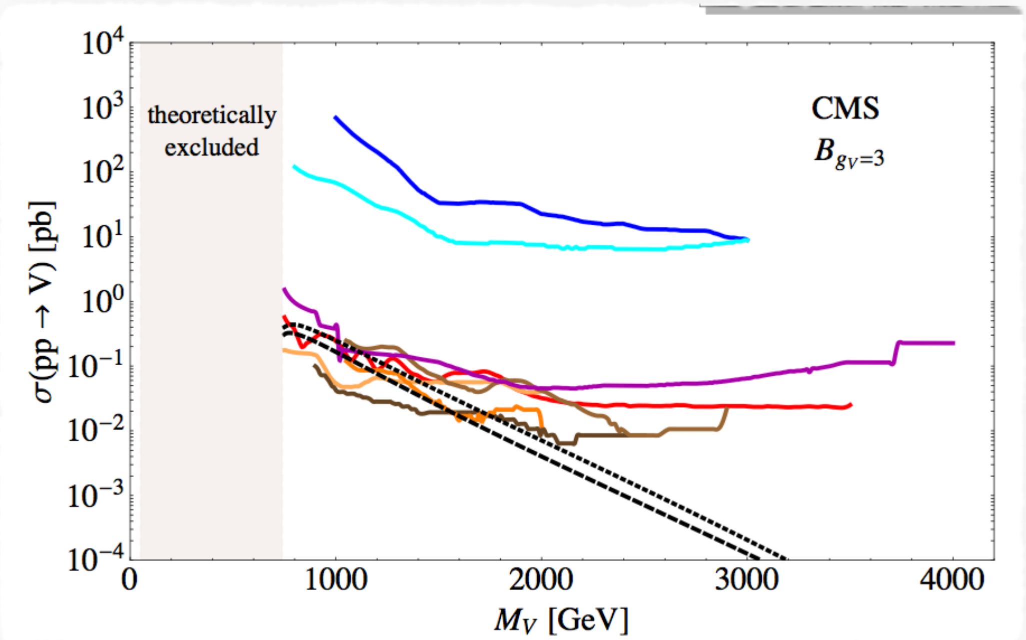
Second Solution: Strong dynamics

The Composite Higgs

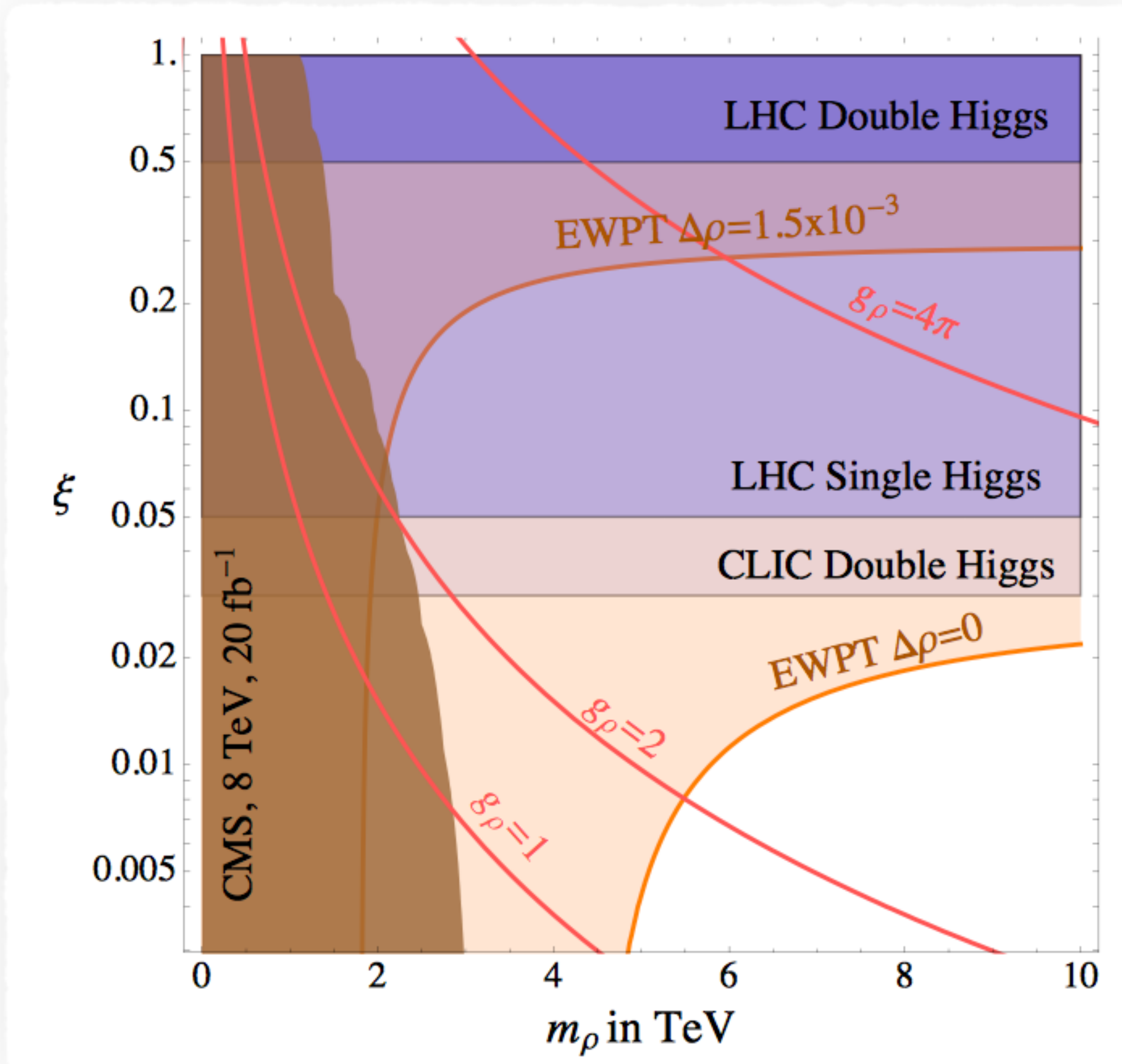
Predictions

STATUS OF COMPOSITE HIGGS

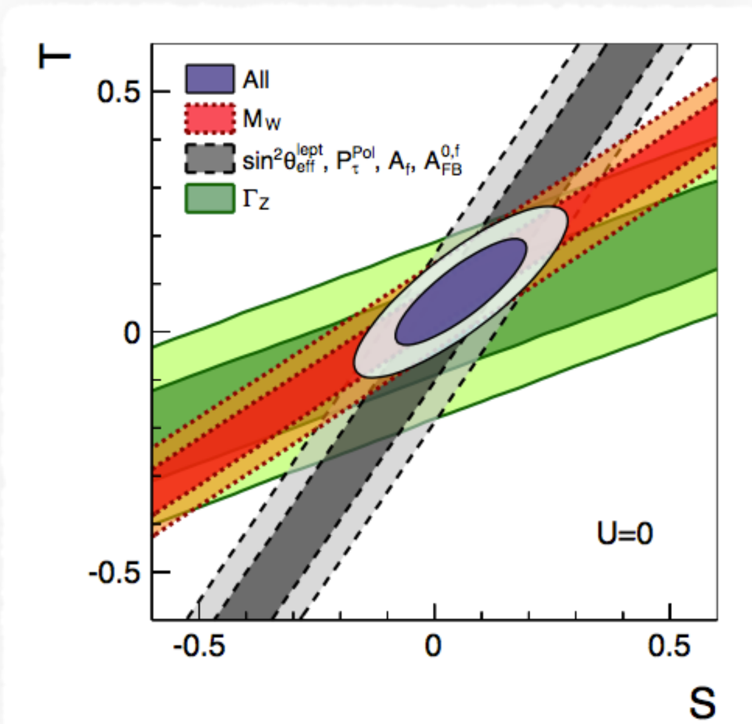
- EWPT and direct searches set a bound in the (m_ρ, ξ) plane



Pappadopulo, Thamm, Torre, Wulzer 1402.4431 [hep-ph]



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



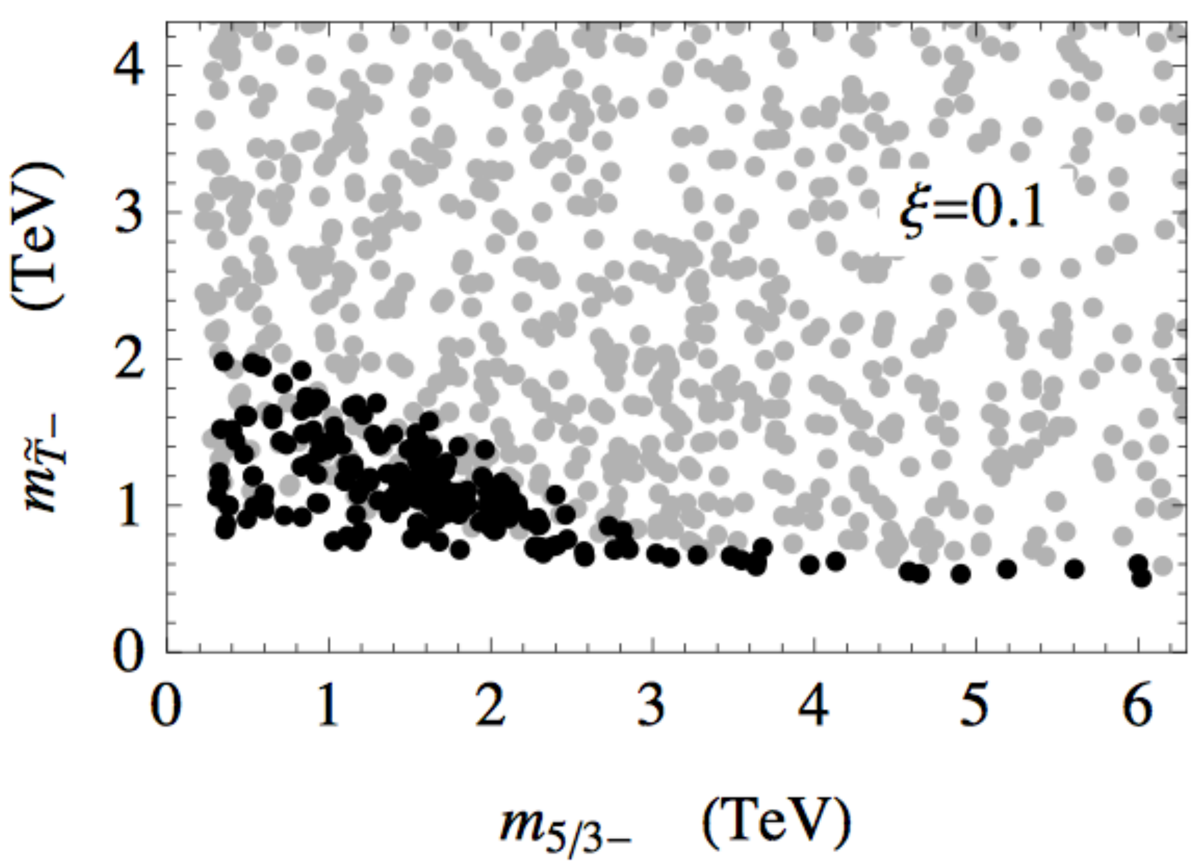
Ciuchini, Franco, Mishima, Silvestrini 1306.4644 [hep-ph]

$$\Delta \gtrsim 5 - 20$$

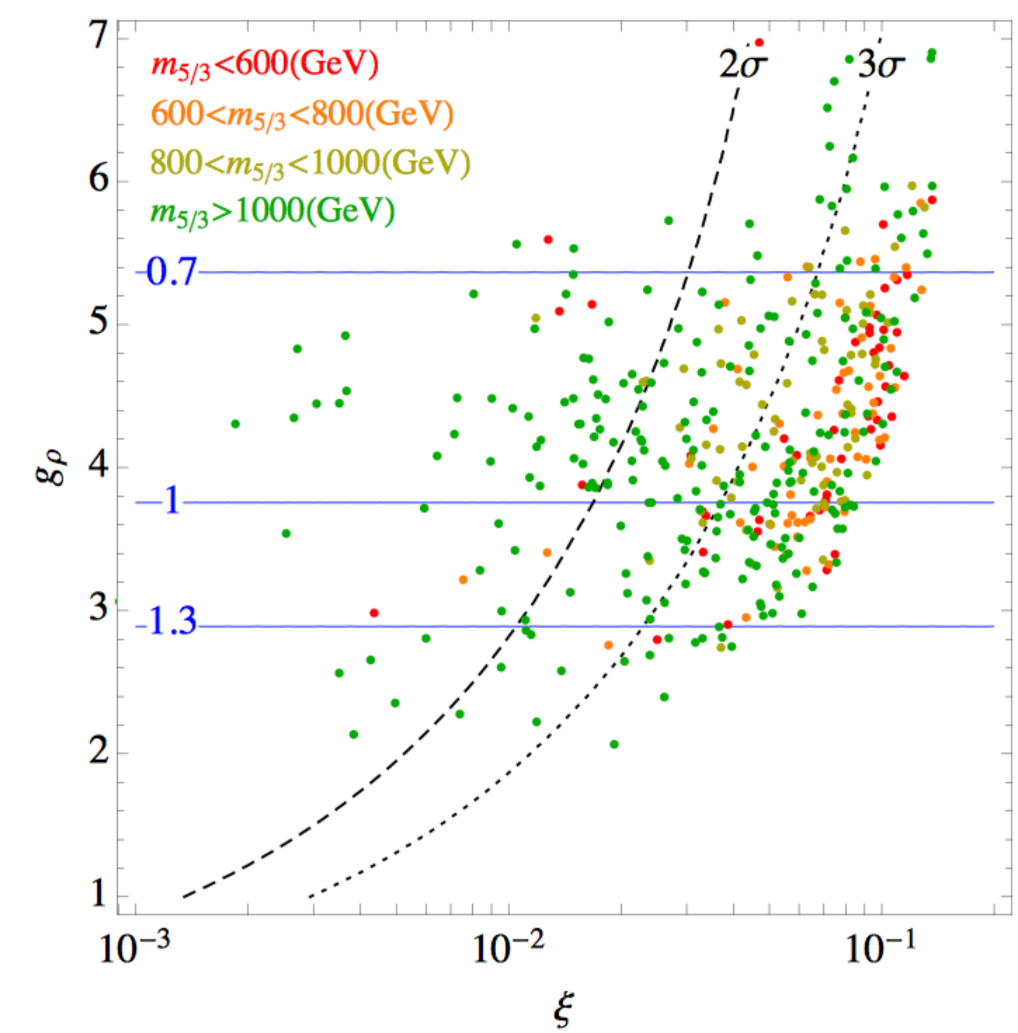
THE HIGGS MASS

- Composite Higgs have the opposite problem of SUSY: the Higgs tends to be too heavy
- Reproducing the observed Higgs mass generally needs light fermionic resonances

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



Matsedonskyi, Panico, Wulzer 1204.6333 [hep-ph]



Pappadopulo, Torre, Thamm 1303.3062 [hep-ph]

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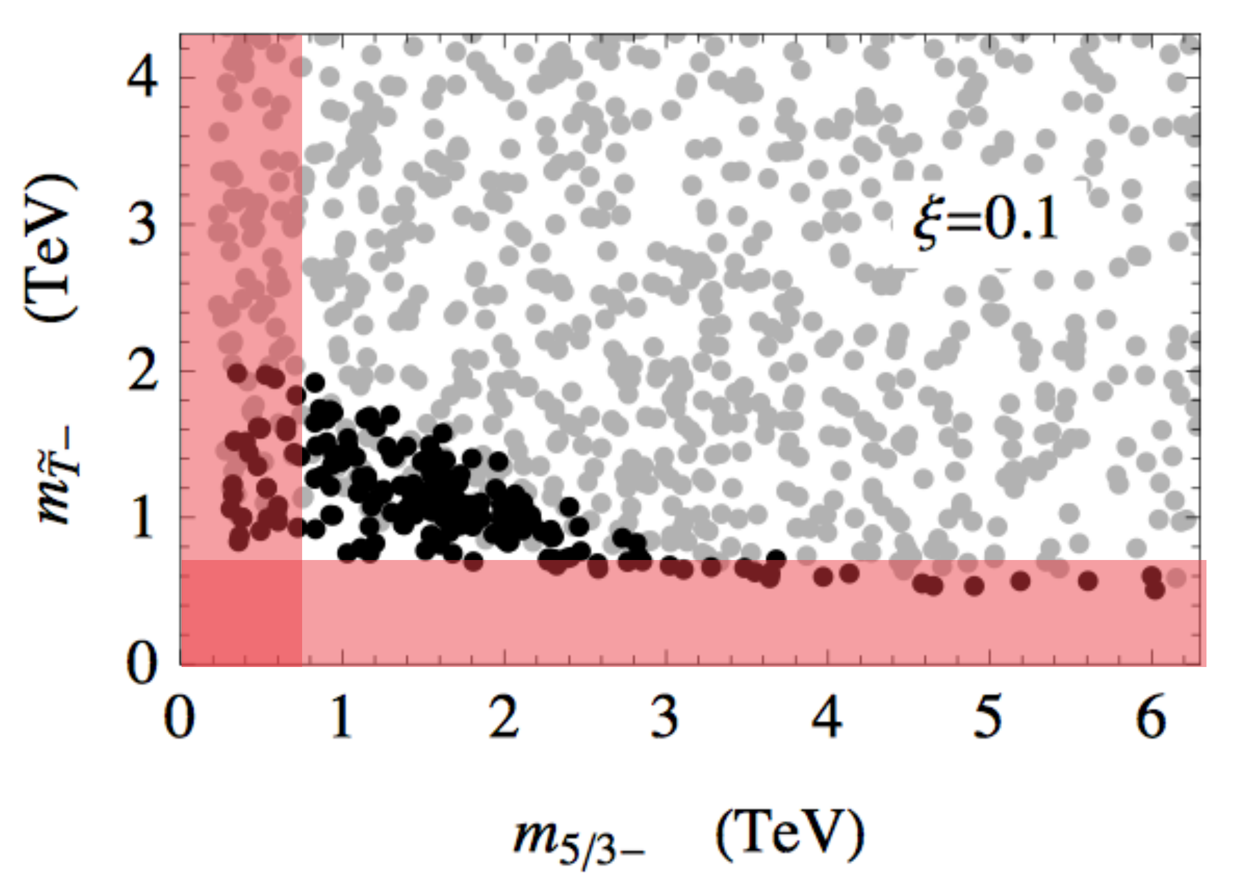
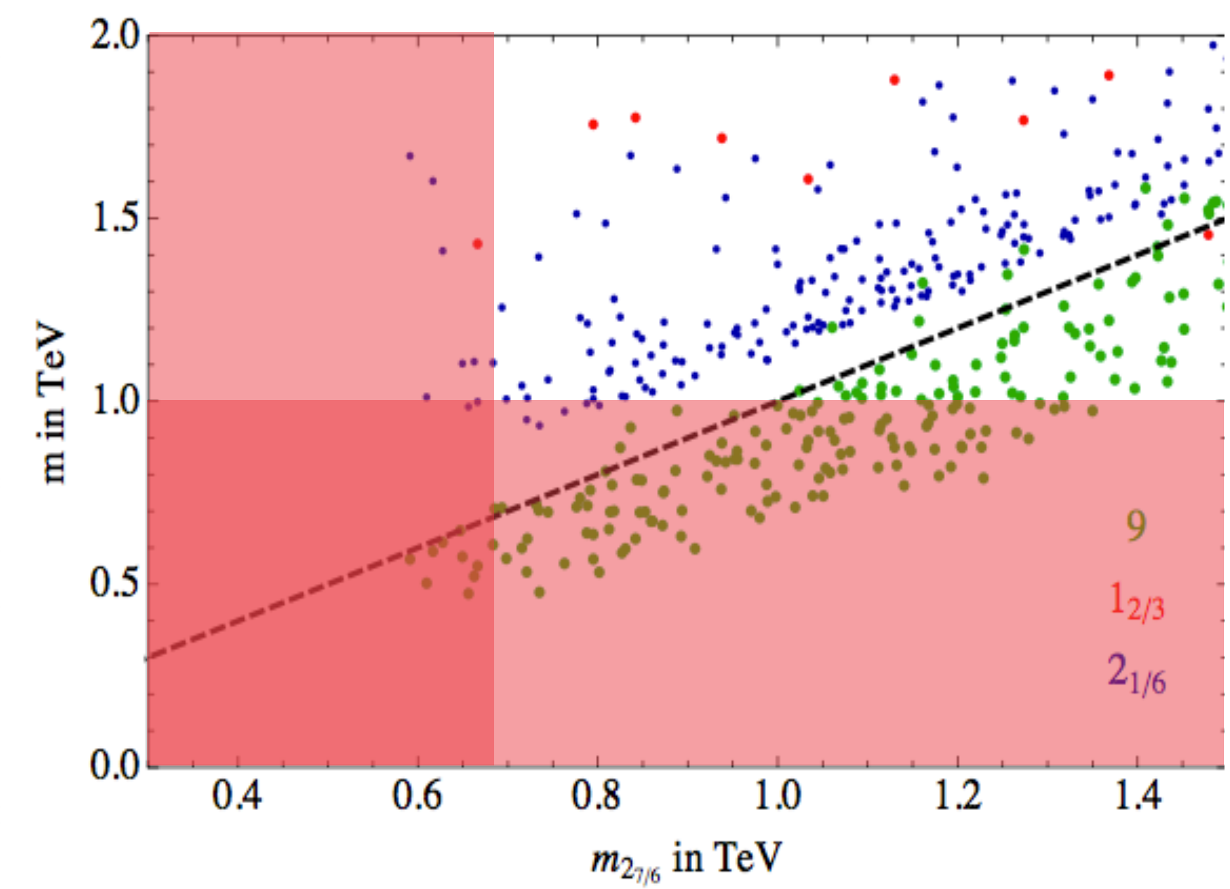


Matsedonskyi, Panico, Wulzer 1204.6333 [hep-ph]



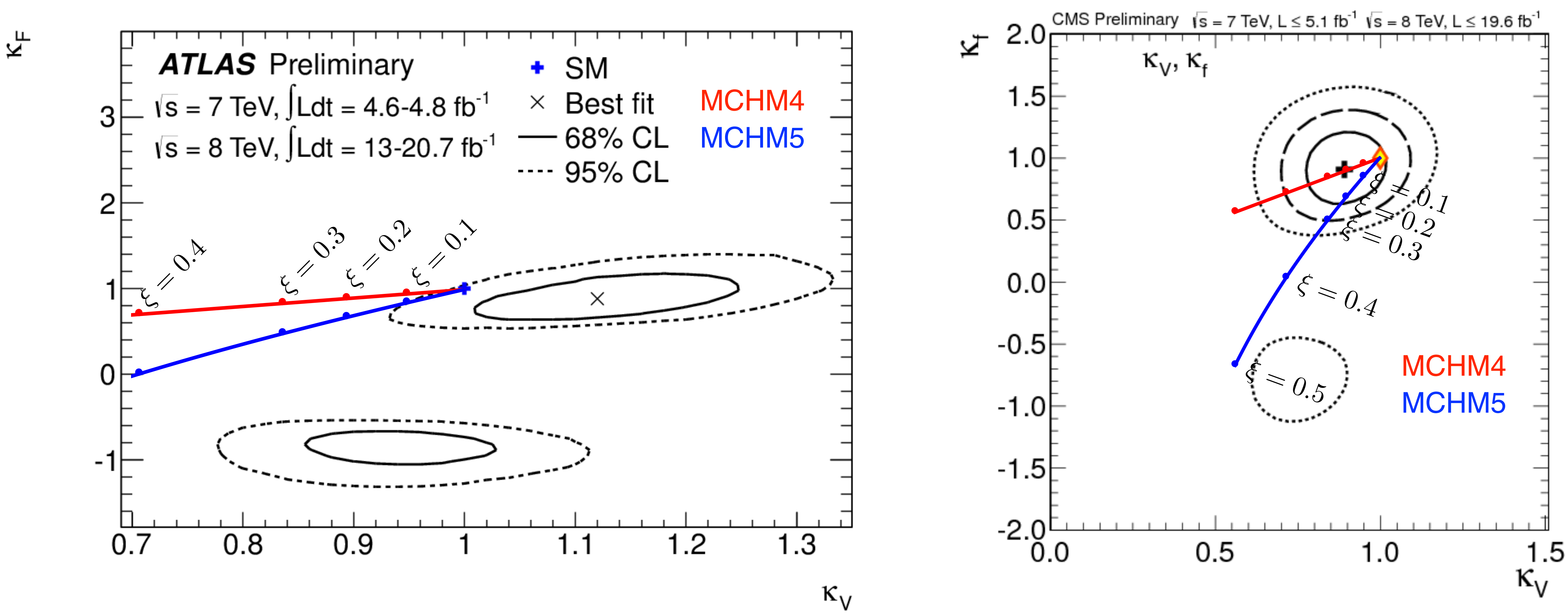
Pappadopulo, Torre, Thamm 1303.3062 [hep-ph]

$$\Delta \gtrsim 20 - 100$$

TREE LEVEL HIGGS COUPLINGS

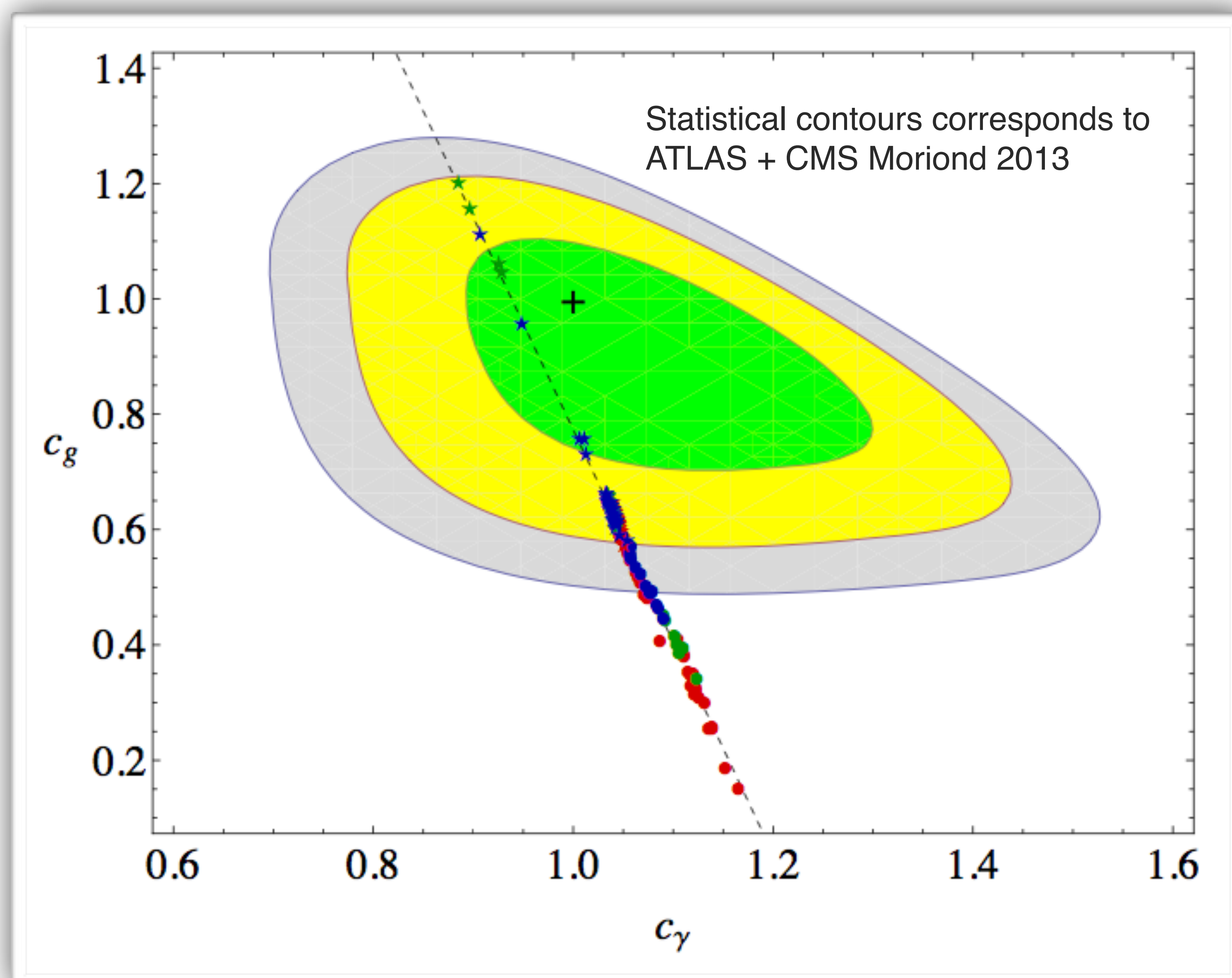
- In composite Higgs models where the Higgs is a pGB the Higgs couplings to SM particles are in general rescaled by functions of ξ .
- For particular fermion representations the universal rescaling with ξ can be accompanied by a dependence on the resonances spectrum
- Higgs coupling measurements can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

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



LOOP INDUCED HIGGS COUPLINGS

- The coupling to photons is a combination of the part induced by loops of fermions and the one induced by loops of EW gauge bosons
- The relation between c_g and c_γ can be compared in explicit models
- In the MCHM14+14 (minimal tuning) for example one has



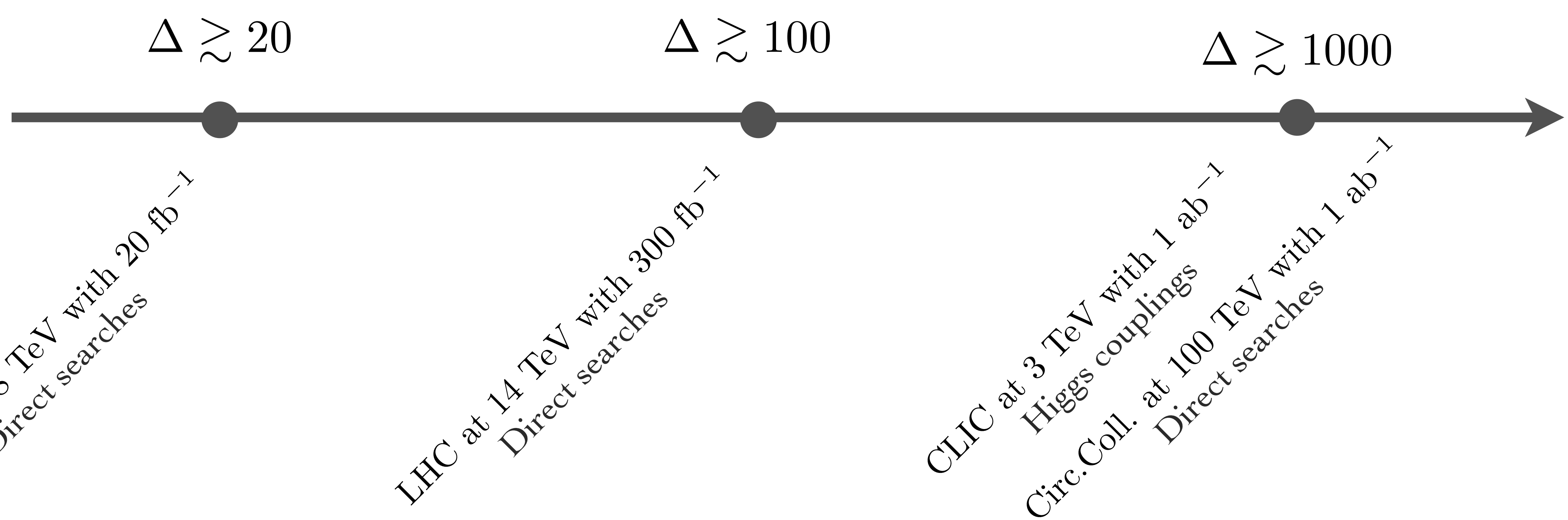
Montull, Riva, Salvioni, RT 1308.0559 [hep-ph]

STATUS OF BSM & THE FUTURE

- After the first run of the LHC both SUSY and CH minimal models are strongly disfavored $\Delta \gg 100$
- Non-minimal models are also pushed in the percent region fine tuning
- The LHC at 14 TeV with $300\ \mathrm{fb}^{-1}$ could cover all the region $\Delta \lesssim 100$ in most of the non minimal models

and then?

- Future colliders could completely rule out the idea of naturalness and put under discussion our reductionistic way of thinking



- It's absolutely necessary to not stop the direct and indirect exploration of EW physics at colliders!

CONCLUSIONS

- The observation of a SM-like Higgs boson is yet another success of the SM picture of particle physics
- The stability of the Higgs potential under radiative corrections strongly suggests the existence of new physics at the energy scale within the reach of the LHC
- Indirect tests at LEP and direct searches at the Tevatron and LHC1 already disfavored minimal models (MSSM, MCHM5 etc.)
- But Nature does not need to be minimal, at least in our mathematical descriptions
- Non minimal models can be highly constrained by the next run of the LHC, which is of fundamental importance for our understanding of particle physics
- Future colliders can test naturalness to an even higher level both by direct searches (proton circular colliders) and indirect measurements (electron linear colliders)
- Still time is needed before drawing any final conclusion about naturalness

THANK YOU