DIS 2016

Simplify your life

Towards more model-independent new physics searches

Michael Krämer (RWTH Aachen University)

Outline

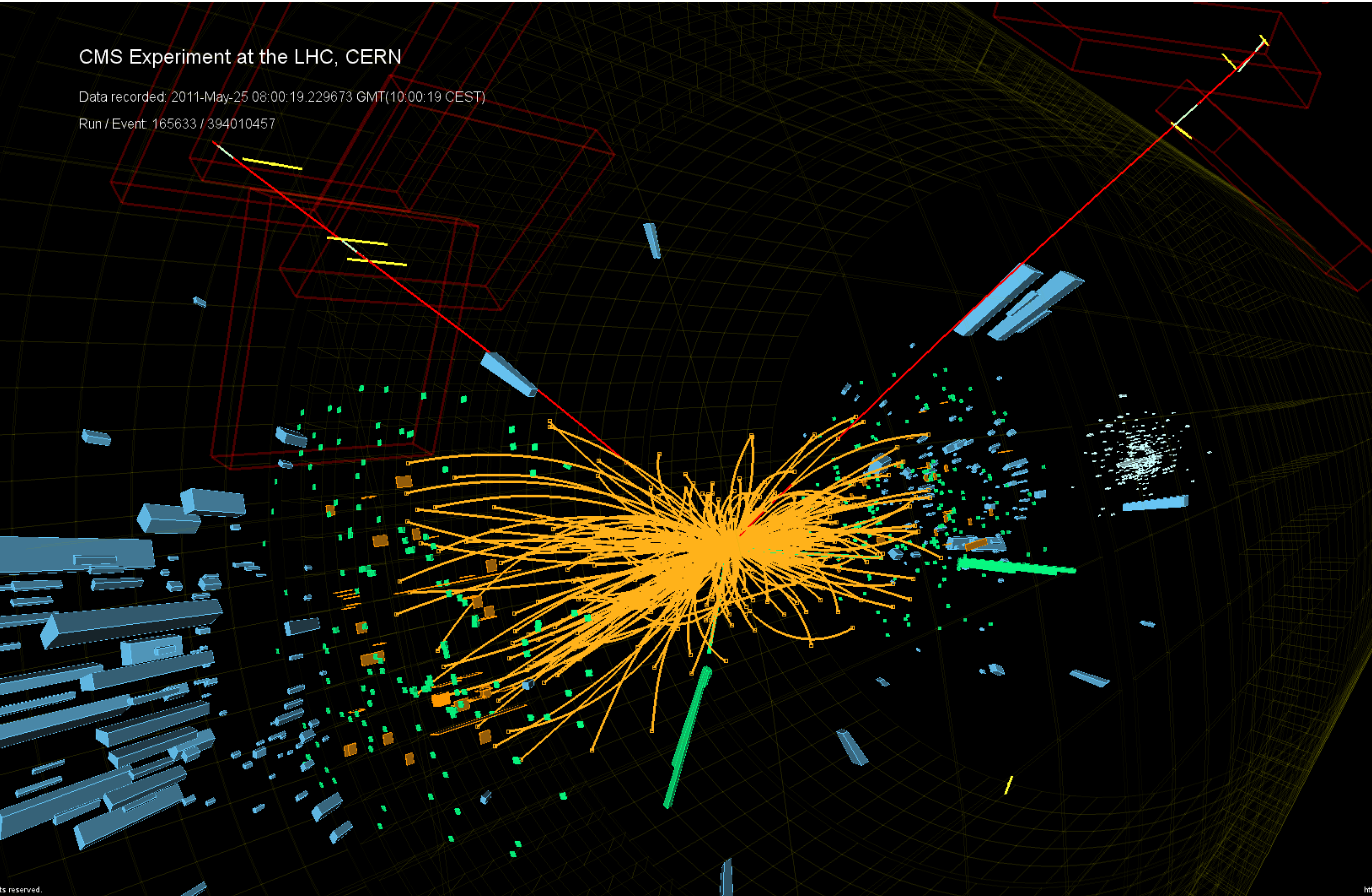
- Lessons from the 1st phase of the LHC

- Towards more model-independent searches:
  effective field theories and simplified models

- Simplified models for BSM Higgs physics

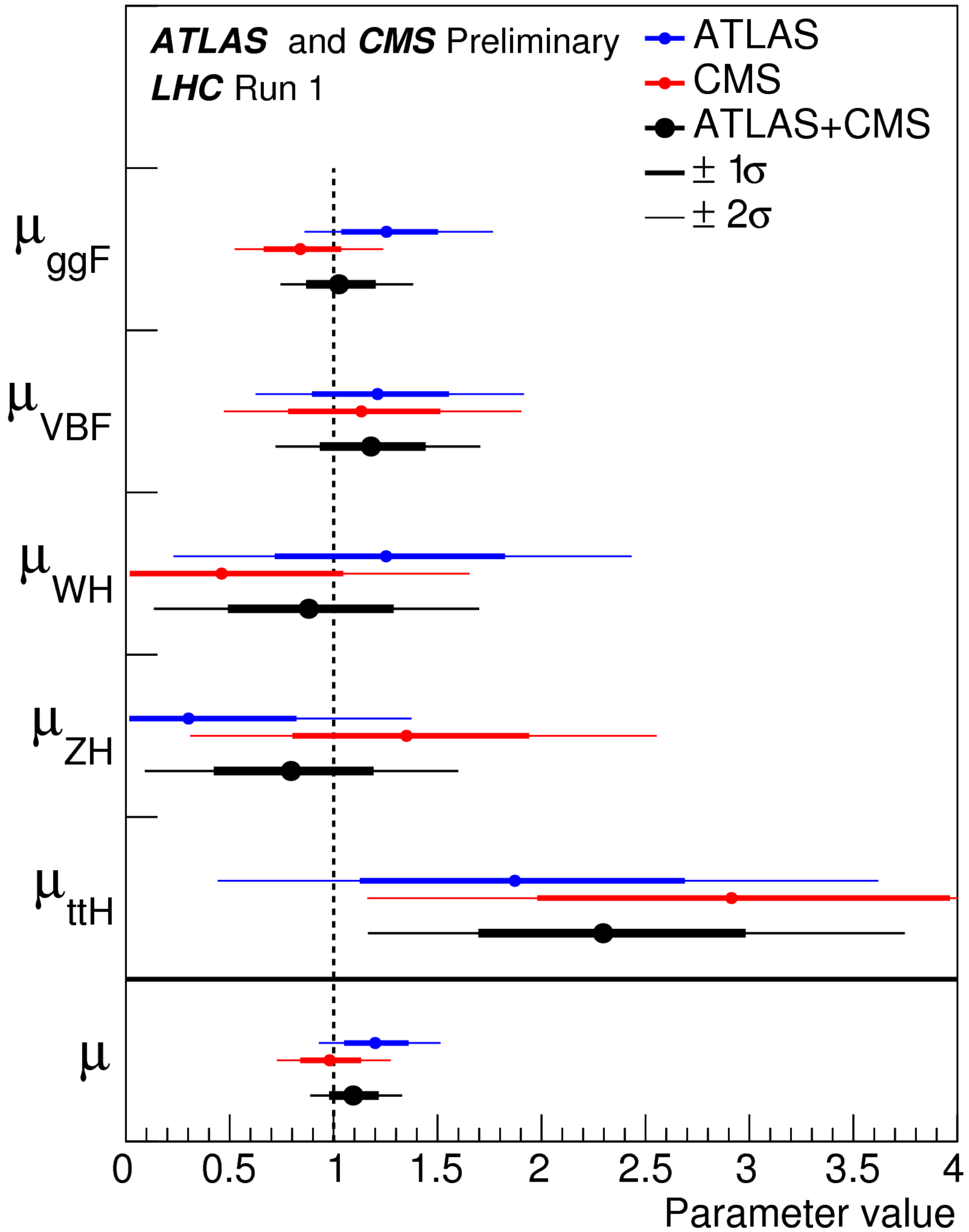
- Summary & conclusion

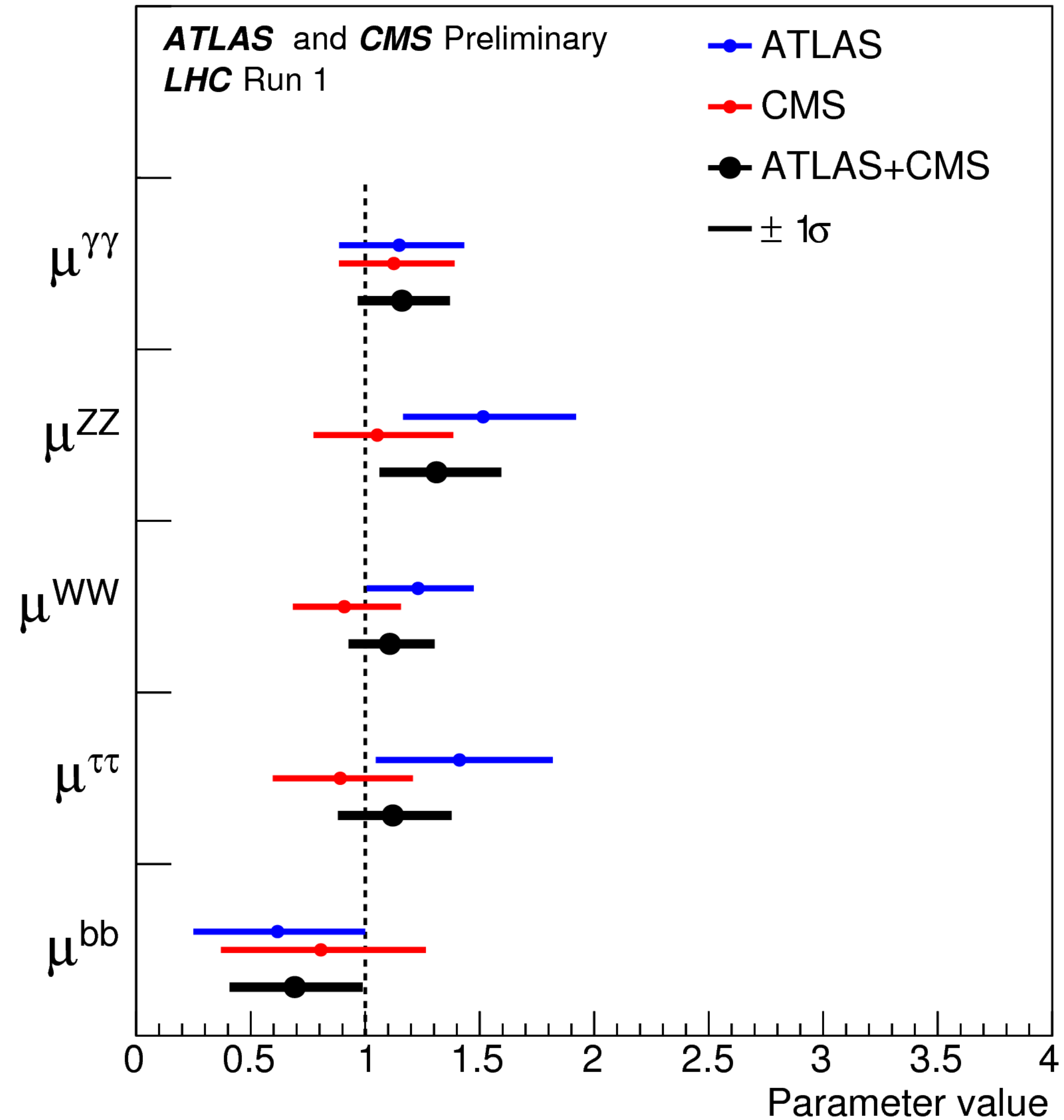
Lessons from LHC run1: a Higgs boson has been found



Lessons from LHC run1: a Higgs boson has been found

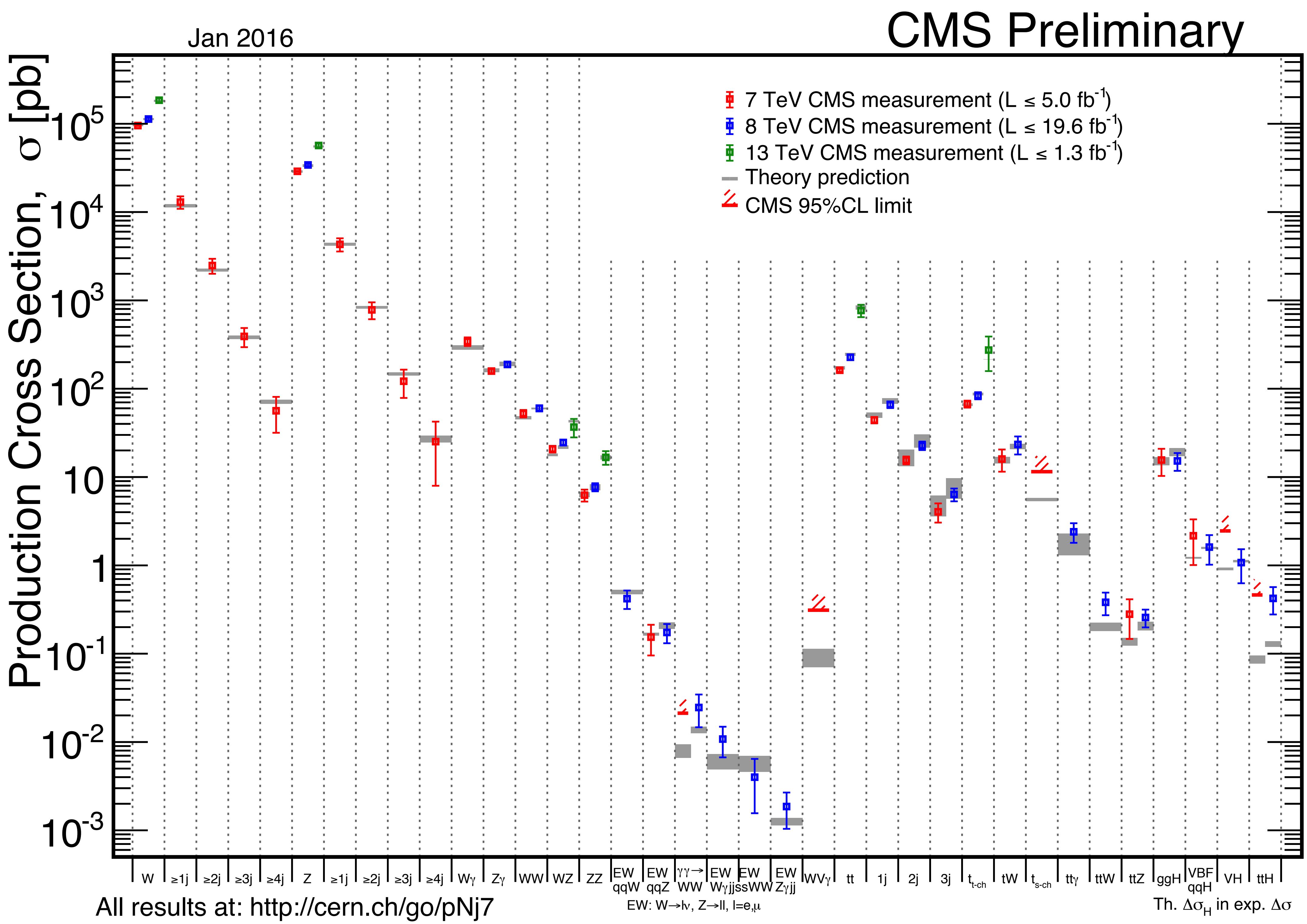
…and it looks like the Standard Model Higgs





Lessons from LHC run1:

the SM has passed most tests with flying colours



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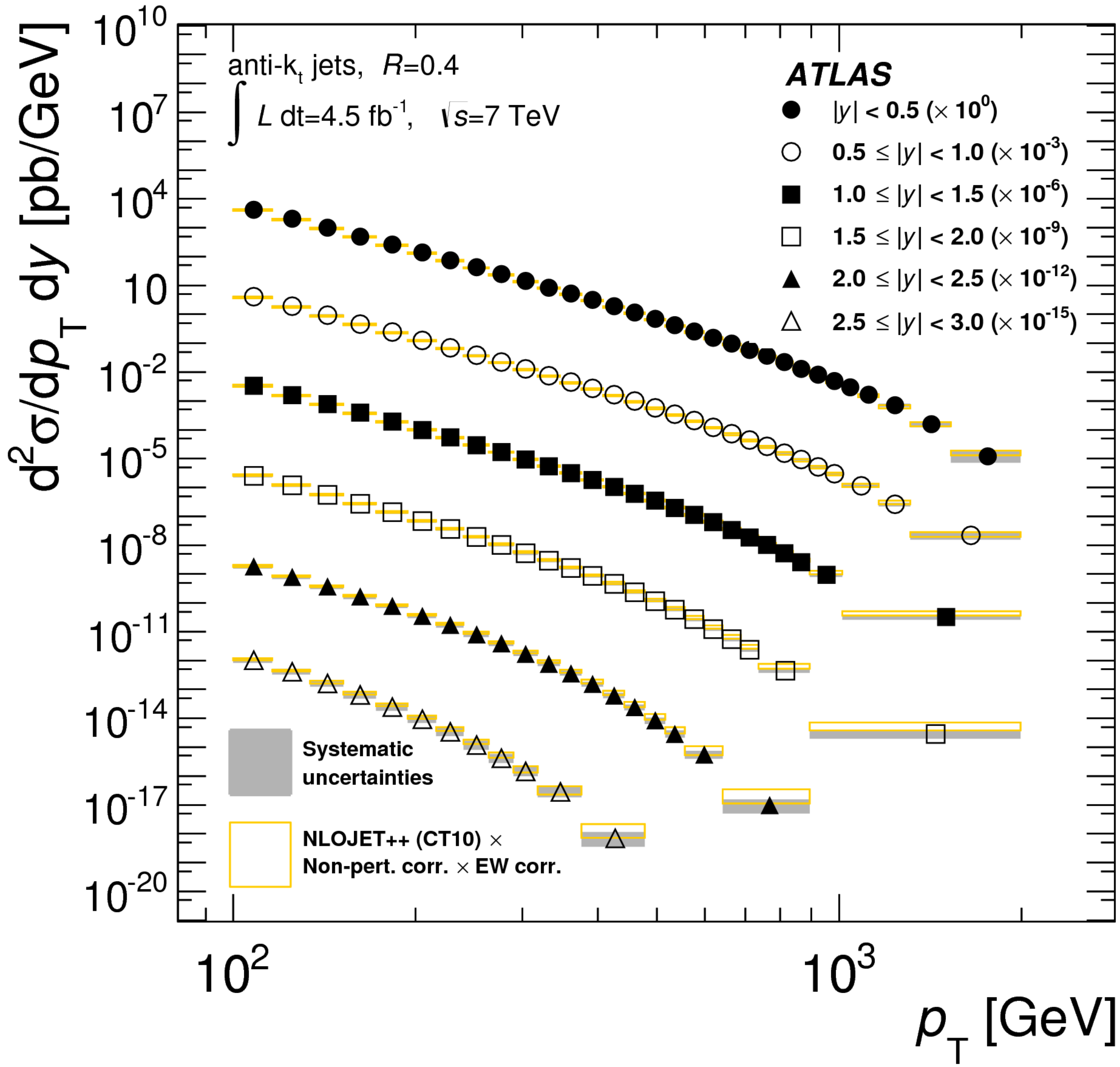
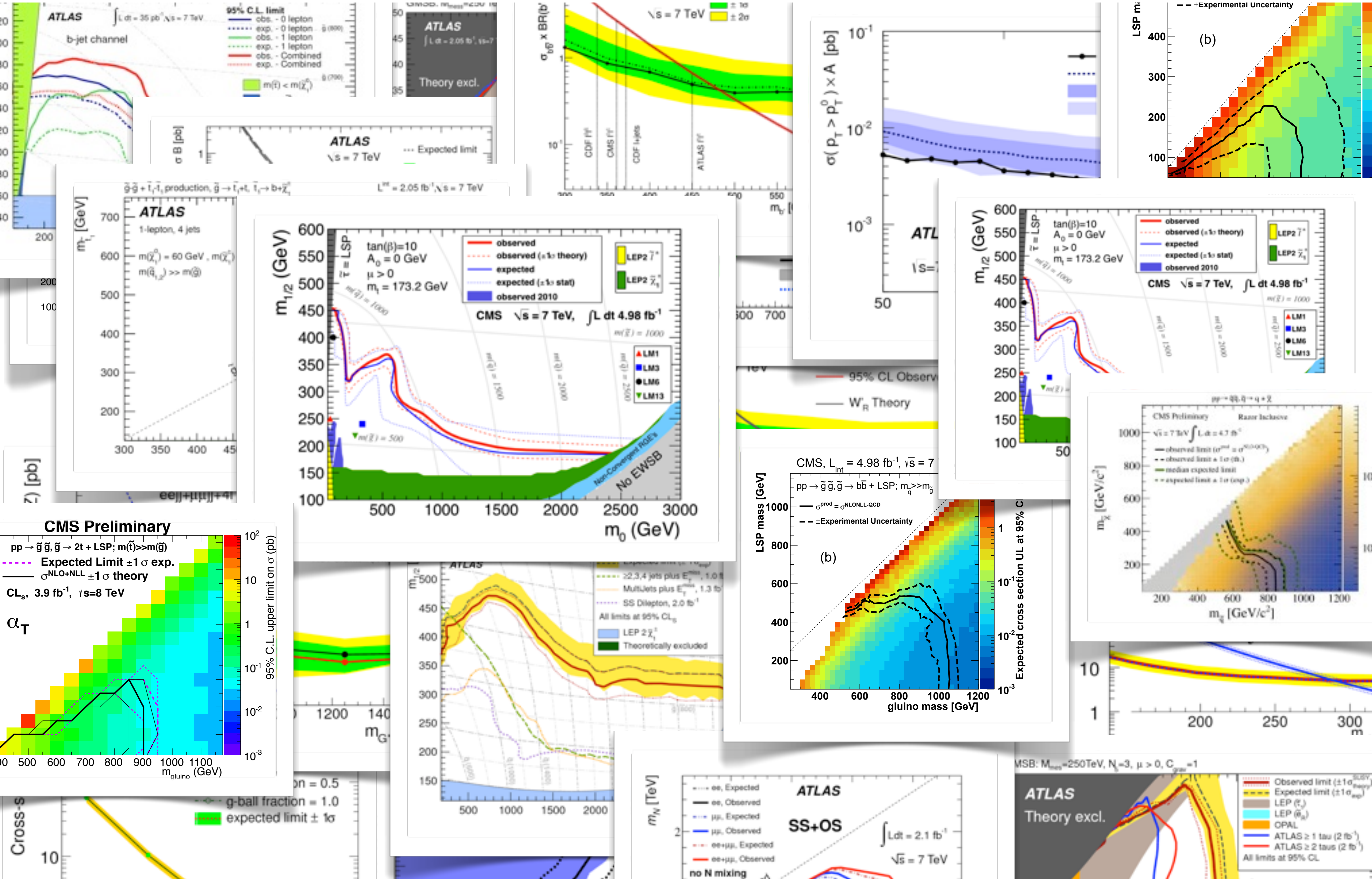


Lessons from LHC run1: no clear sign of new physics



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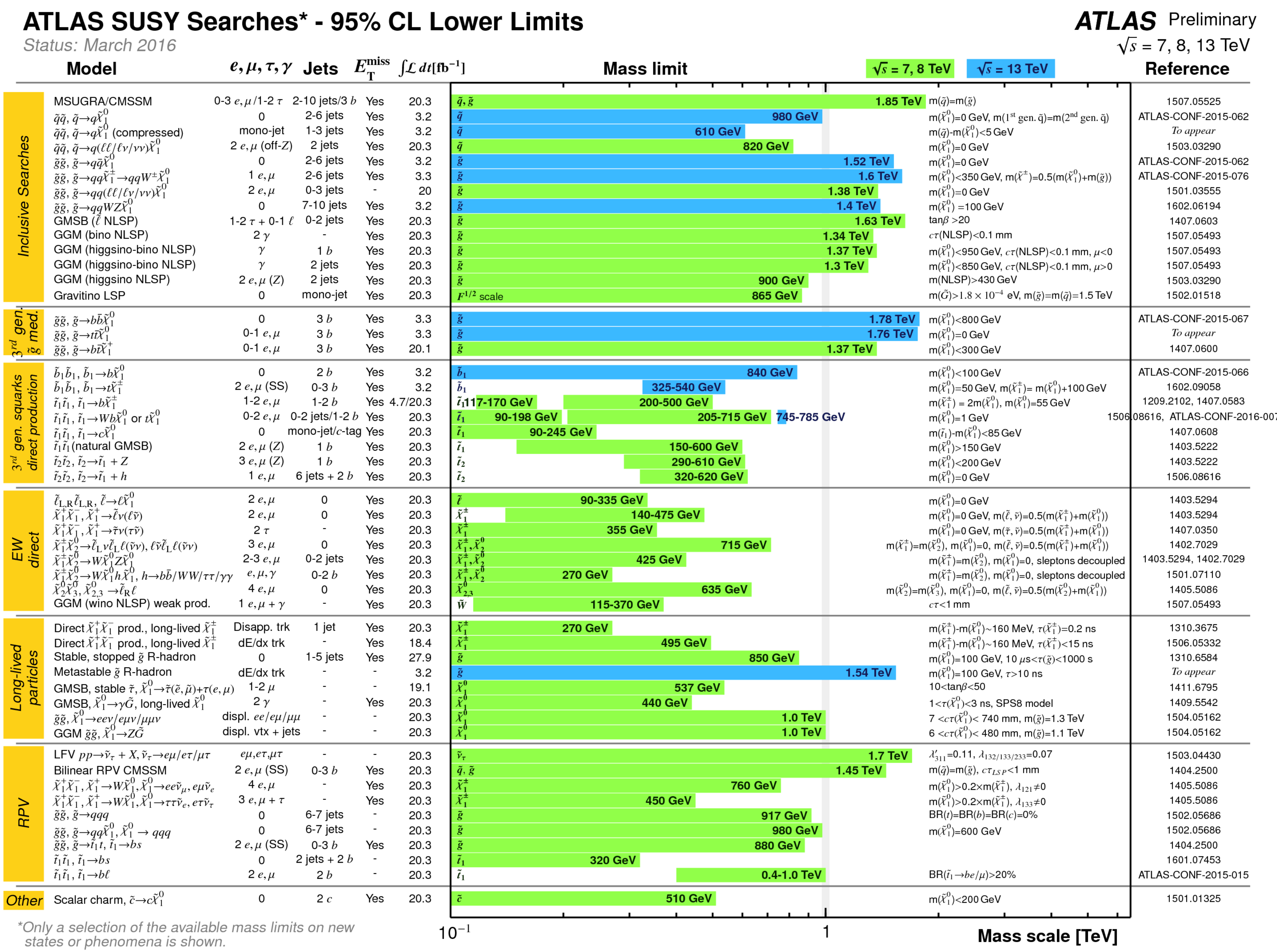

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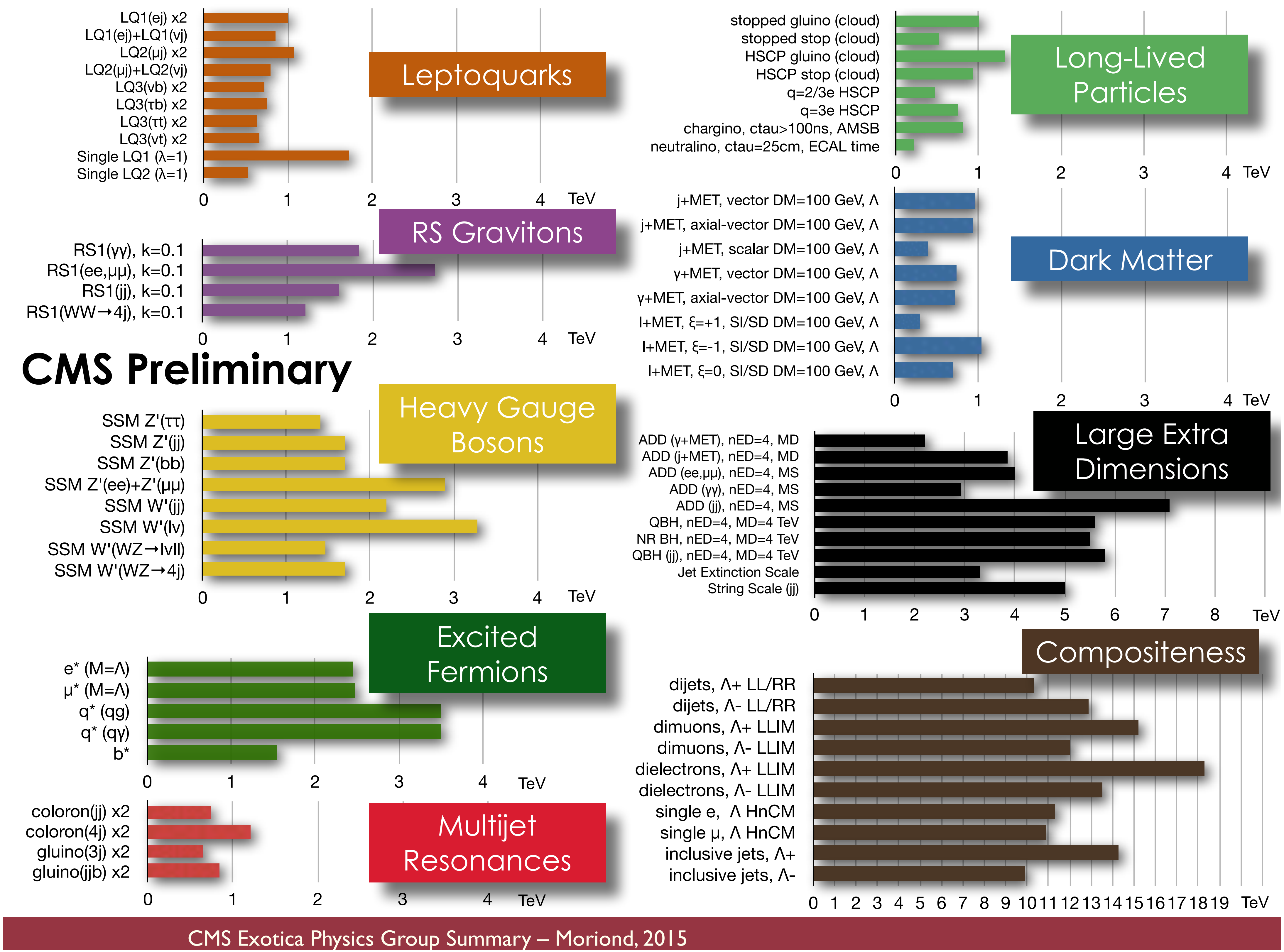

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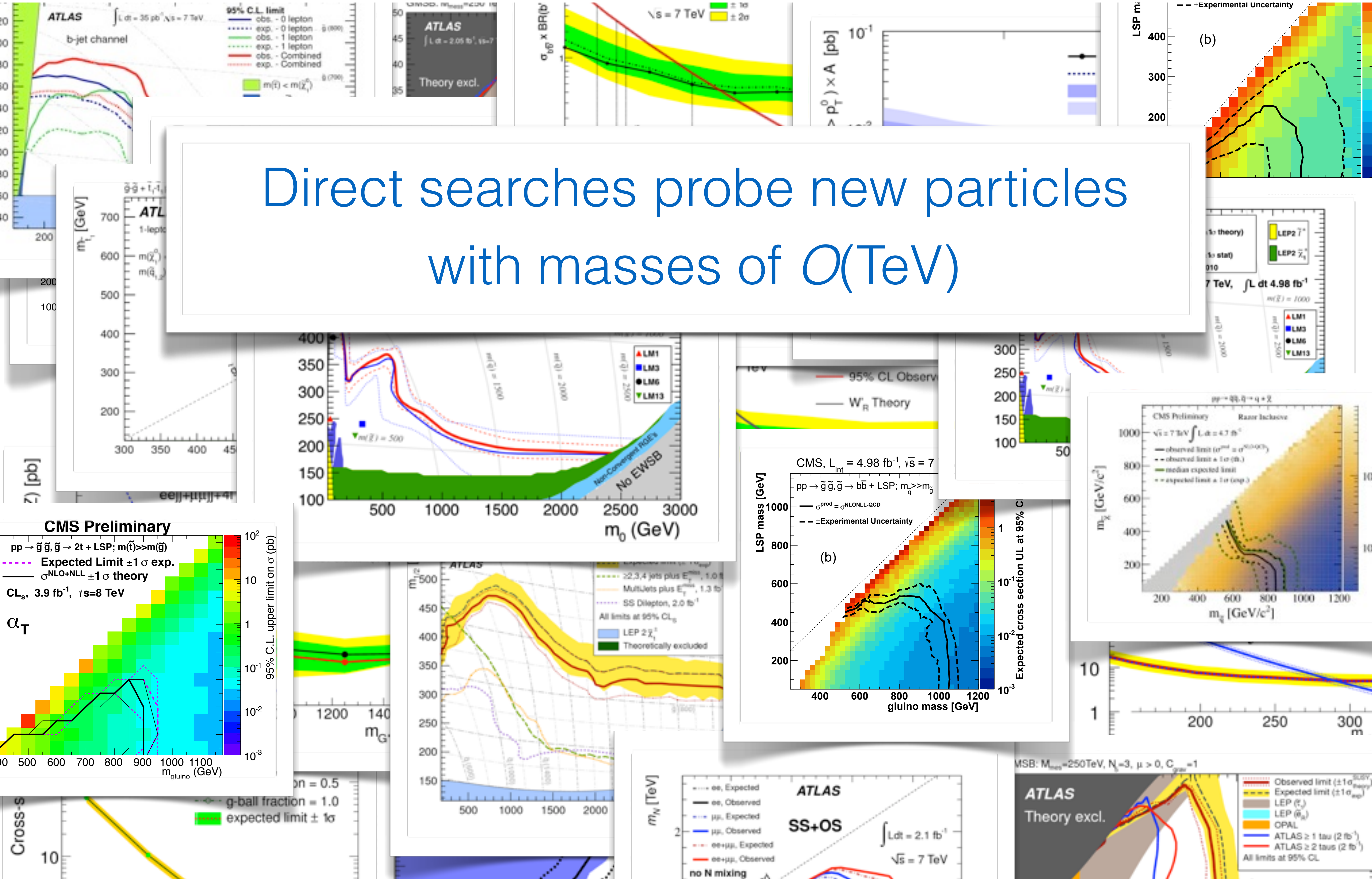

Direct searches probe new particles with masses of O(TeV)

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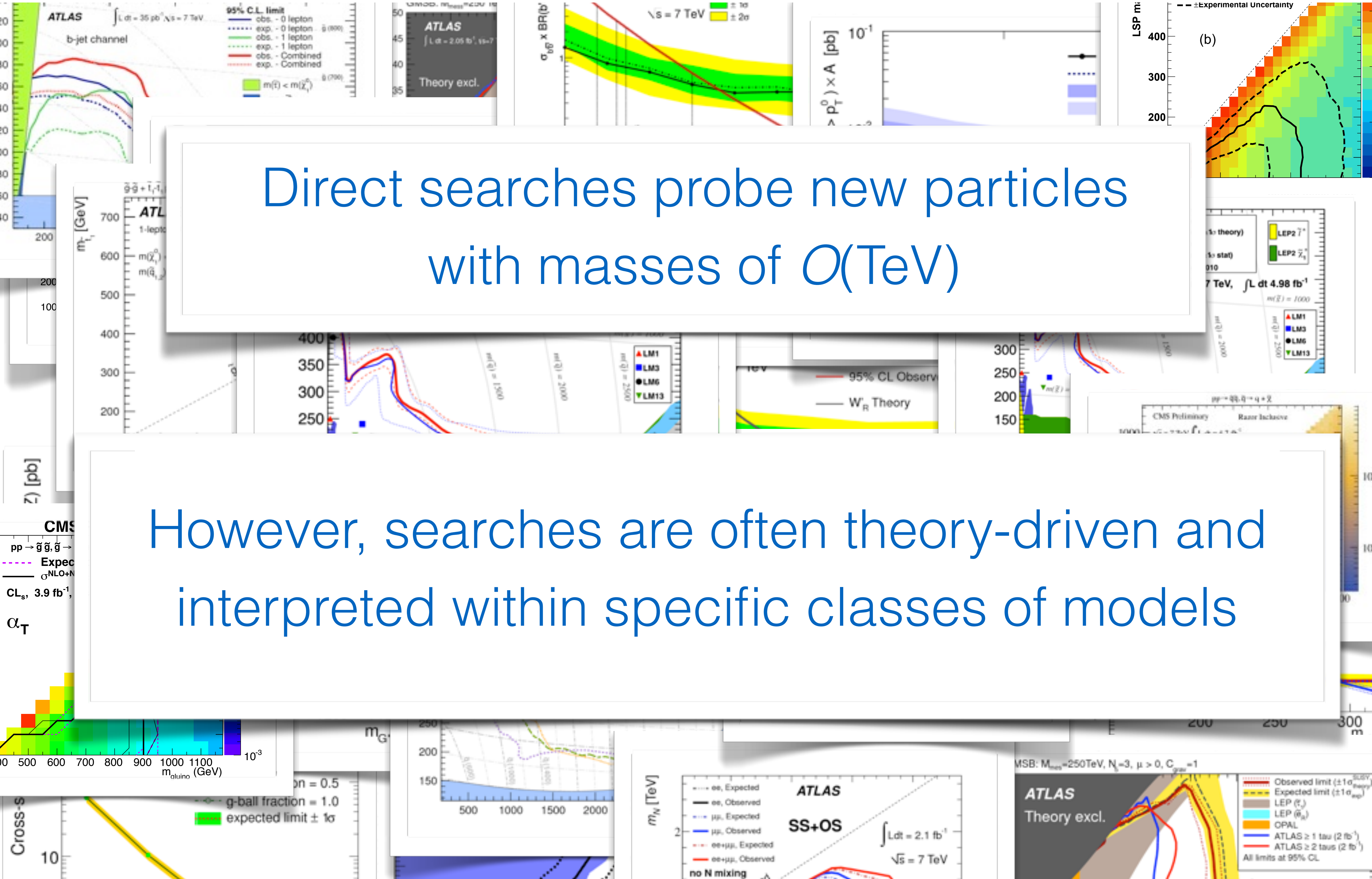
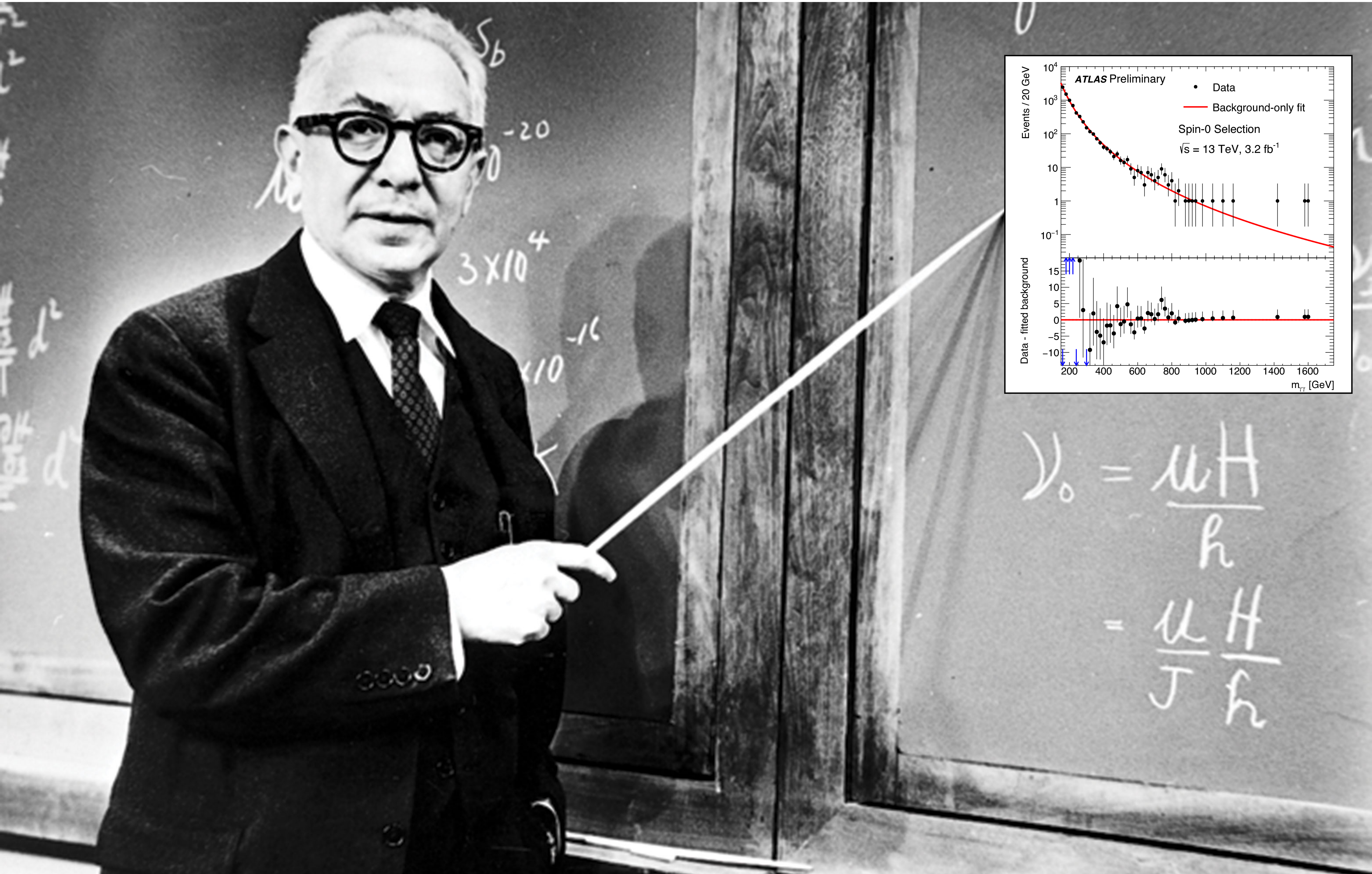


Direct searches probe new particles with masses of O(TeV)

However, searches are often theory-driven and interpreted within specific classes of models

Lessons from the LHC: “Who ordered that?”



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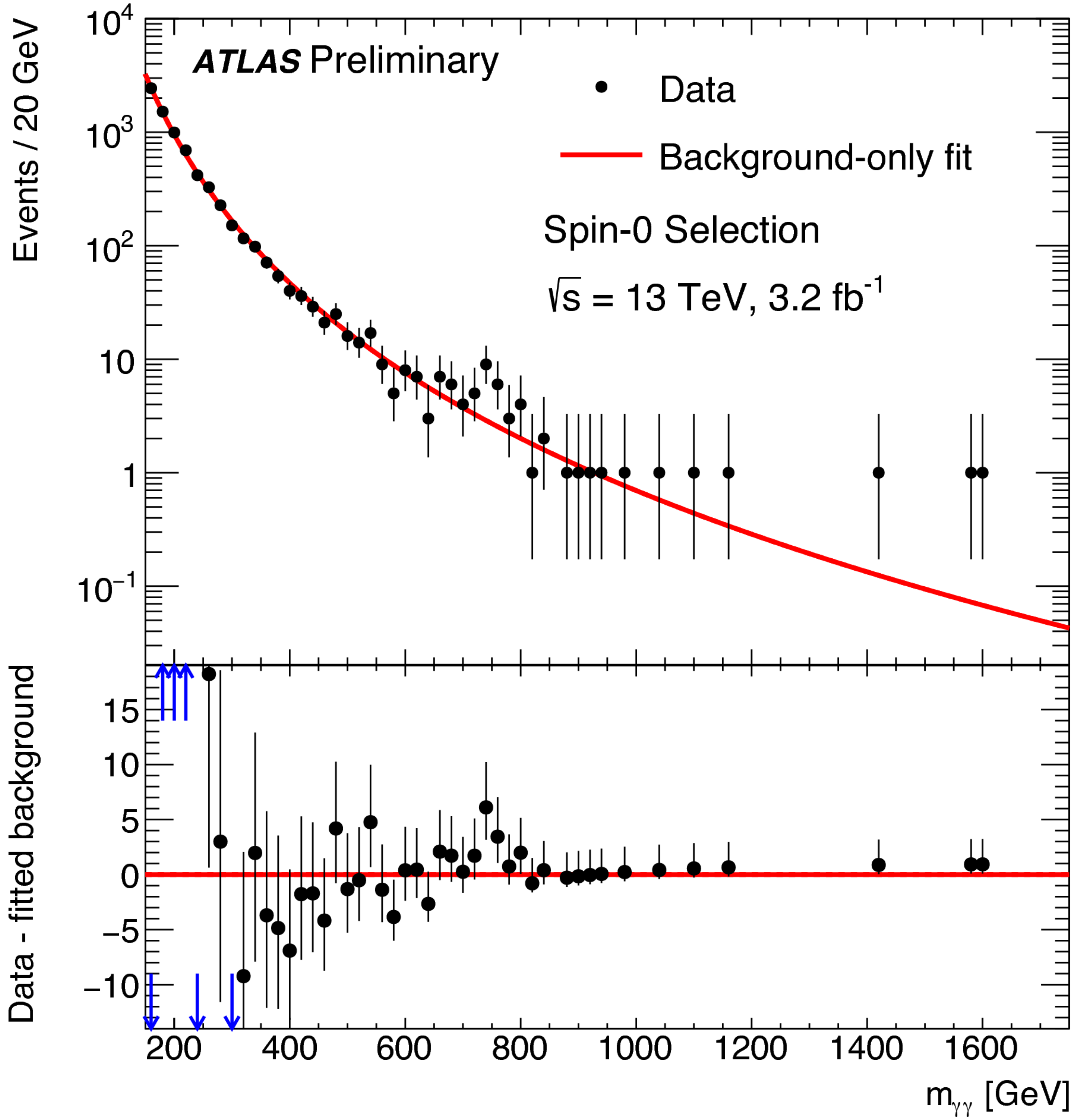

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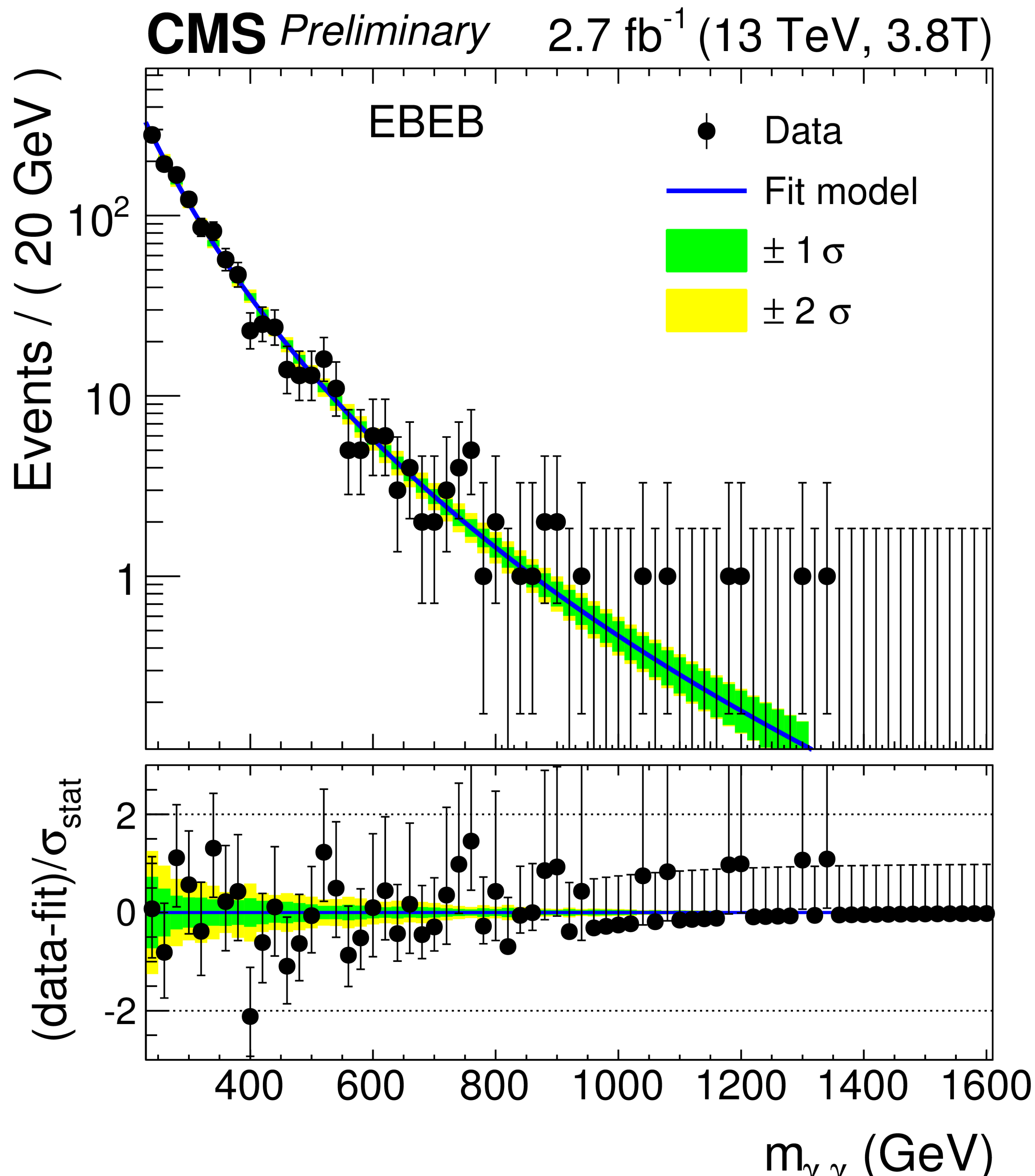
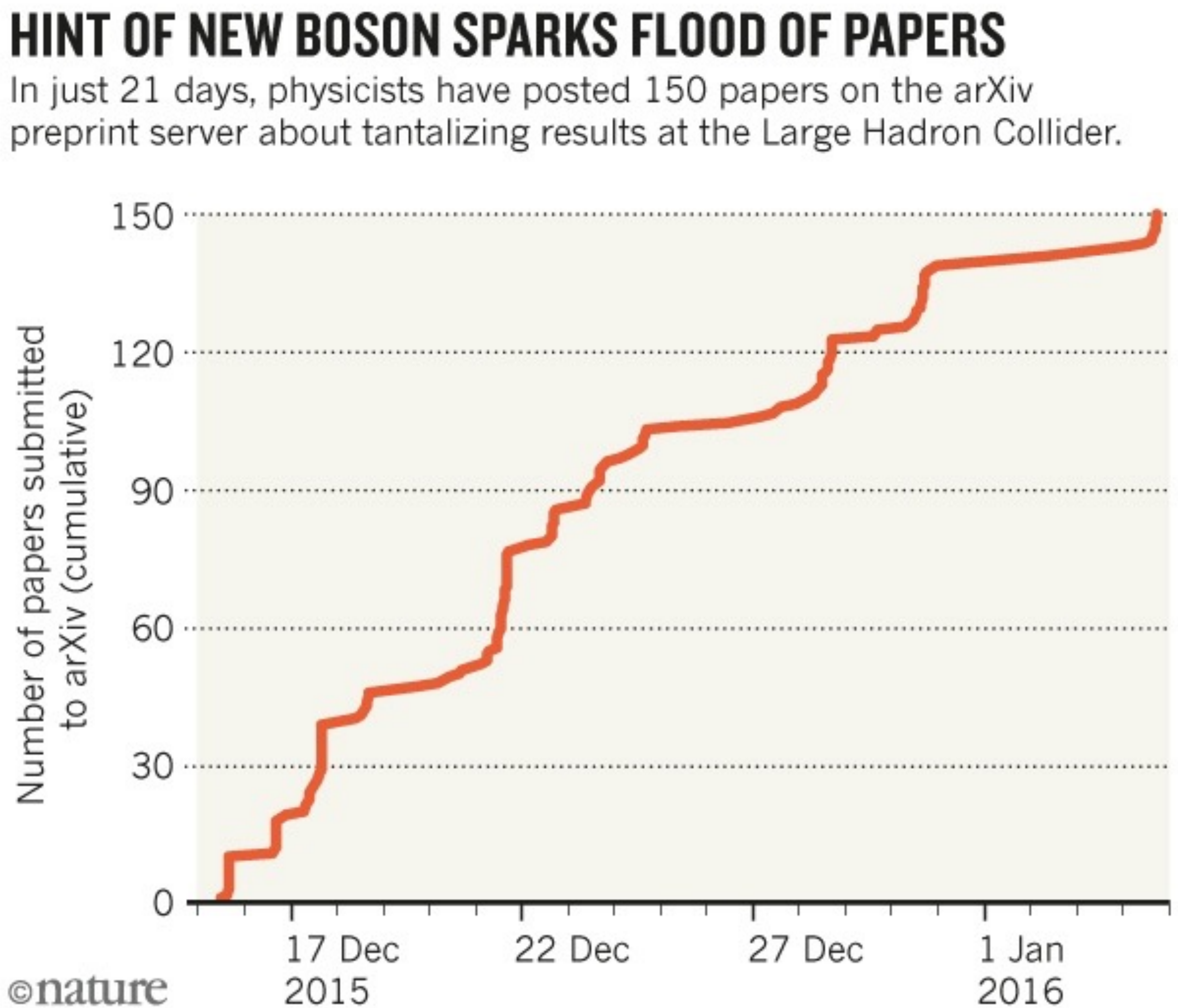


The sociology of ambulance chasing



Key questions for LHC run 2

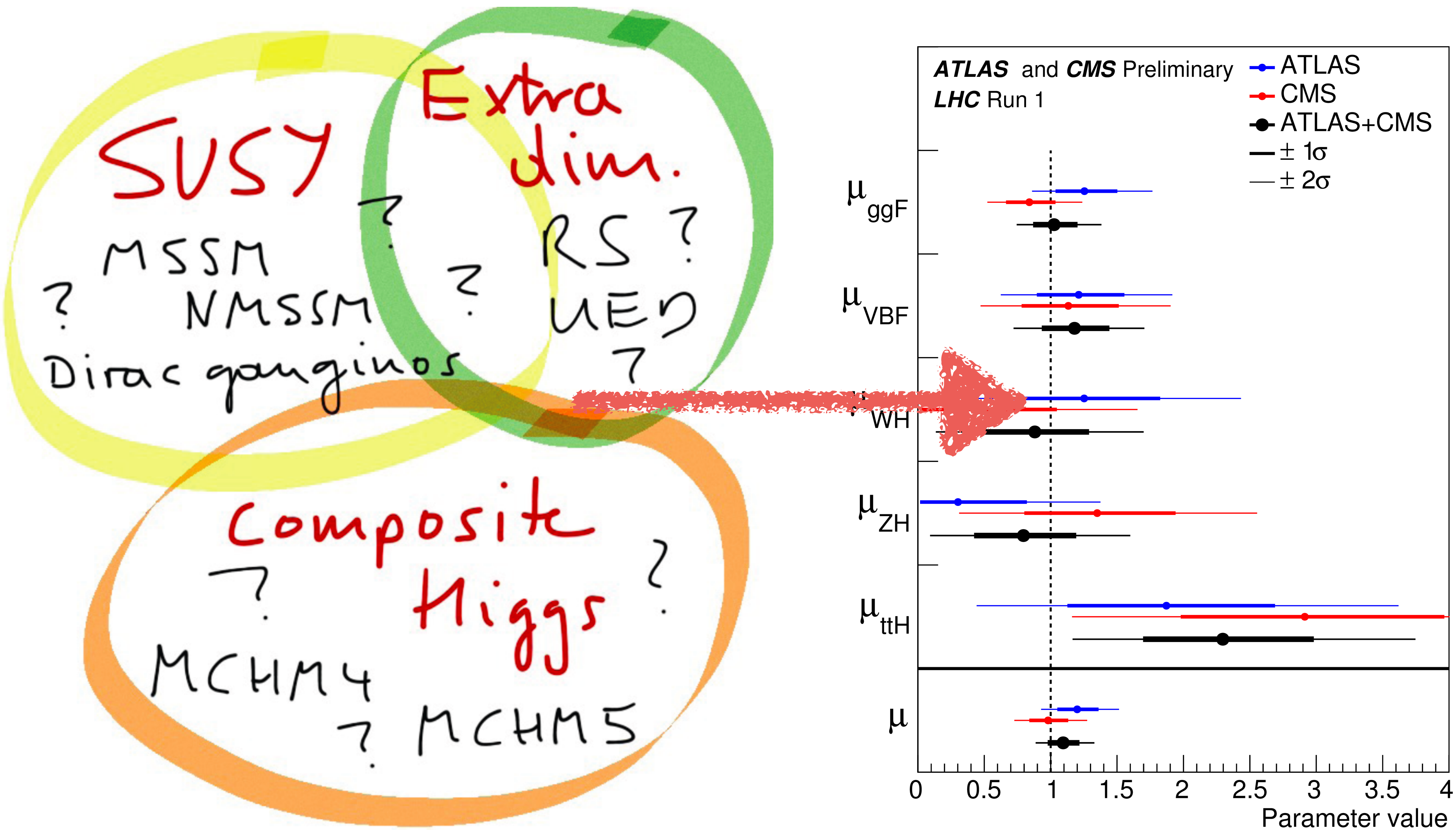
What is the mechanism of electroweak symmetry breaking?

→ Precision studies of Higgs boson properties

Is there physics beyond the Standard Model at the TeV scale (SUSY, dark matter, …)?

→ Searches for new particles

BSM models for Higgs physics: top-down



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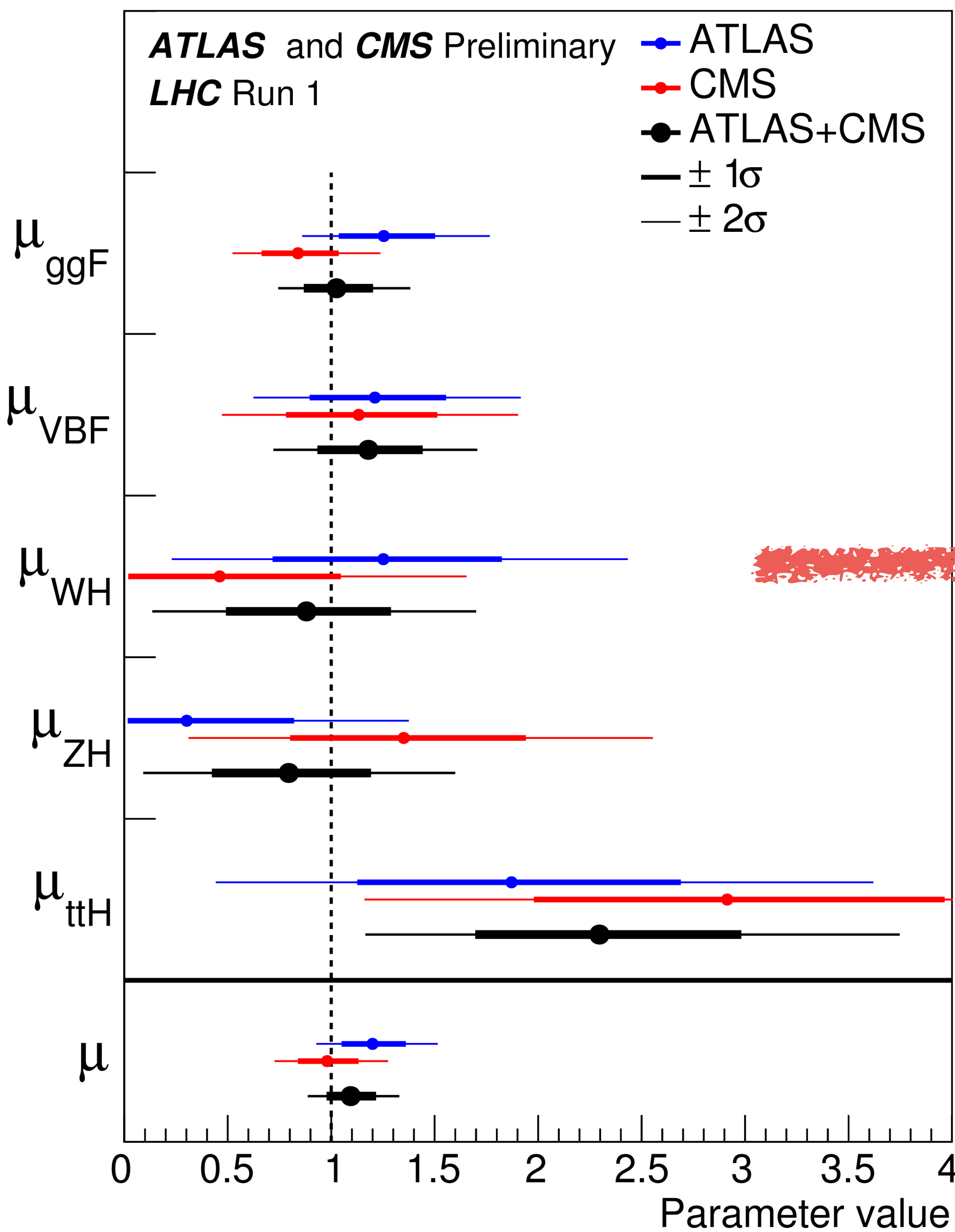

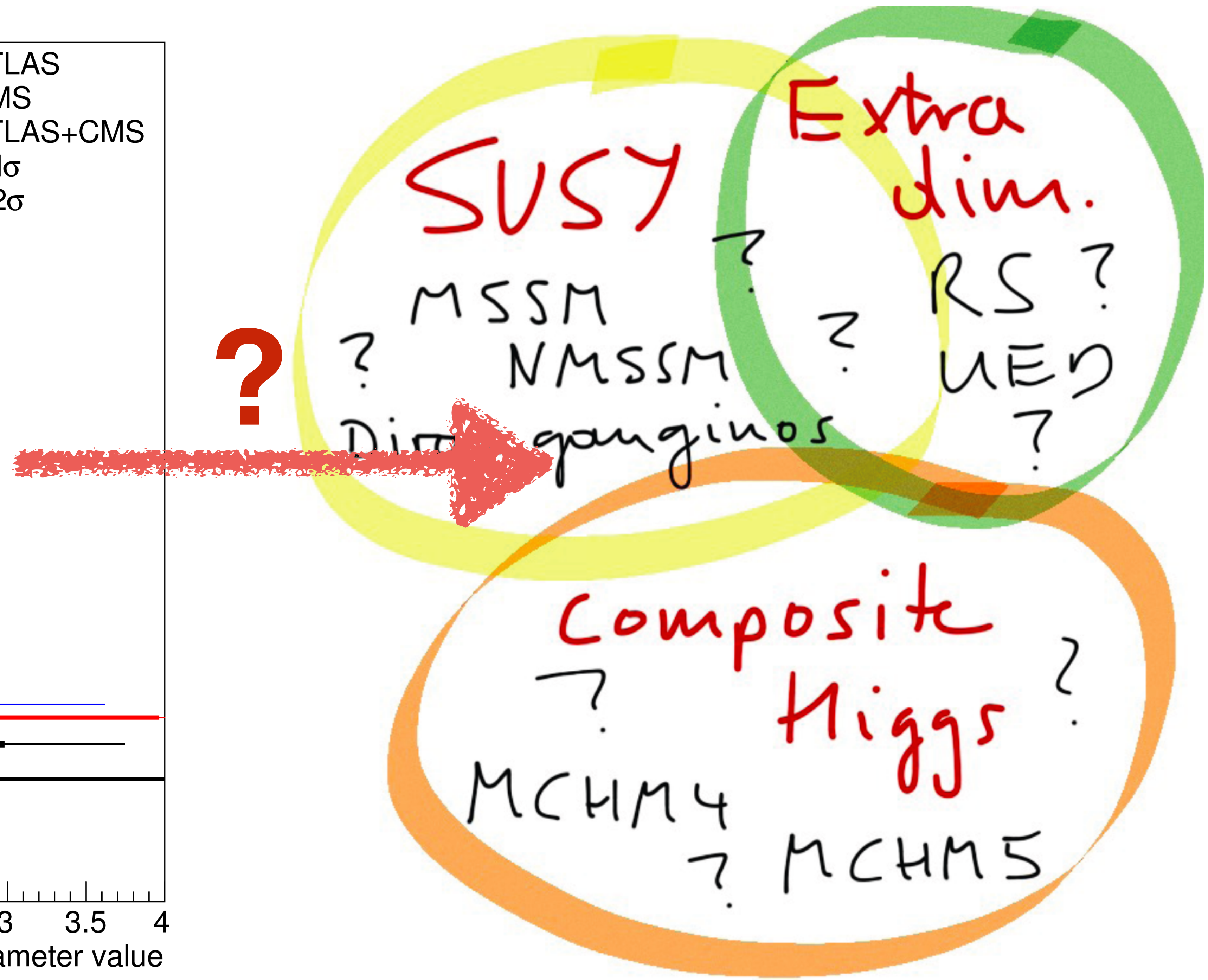

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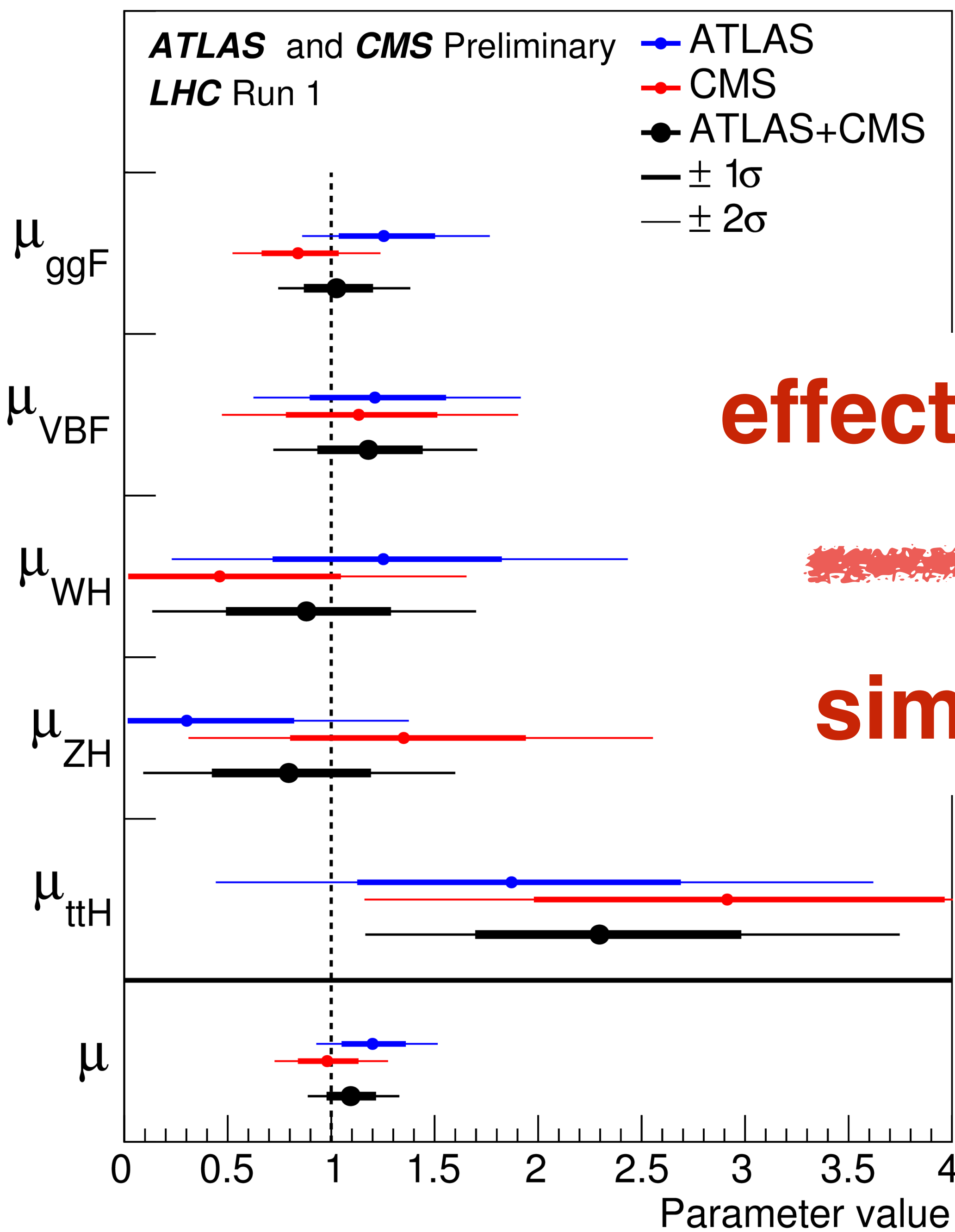
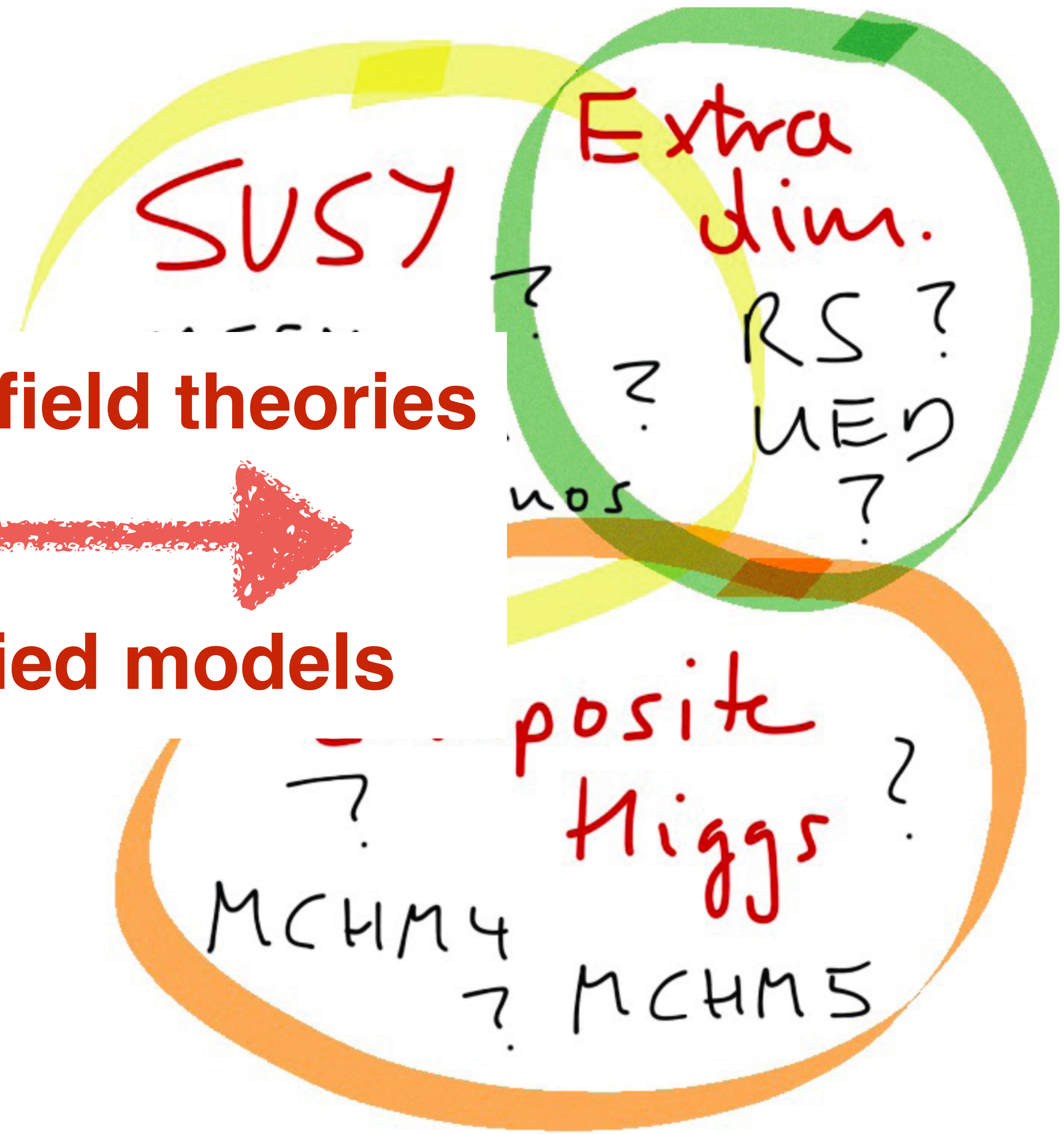


effective field theories

simplified models



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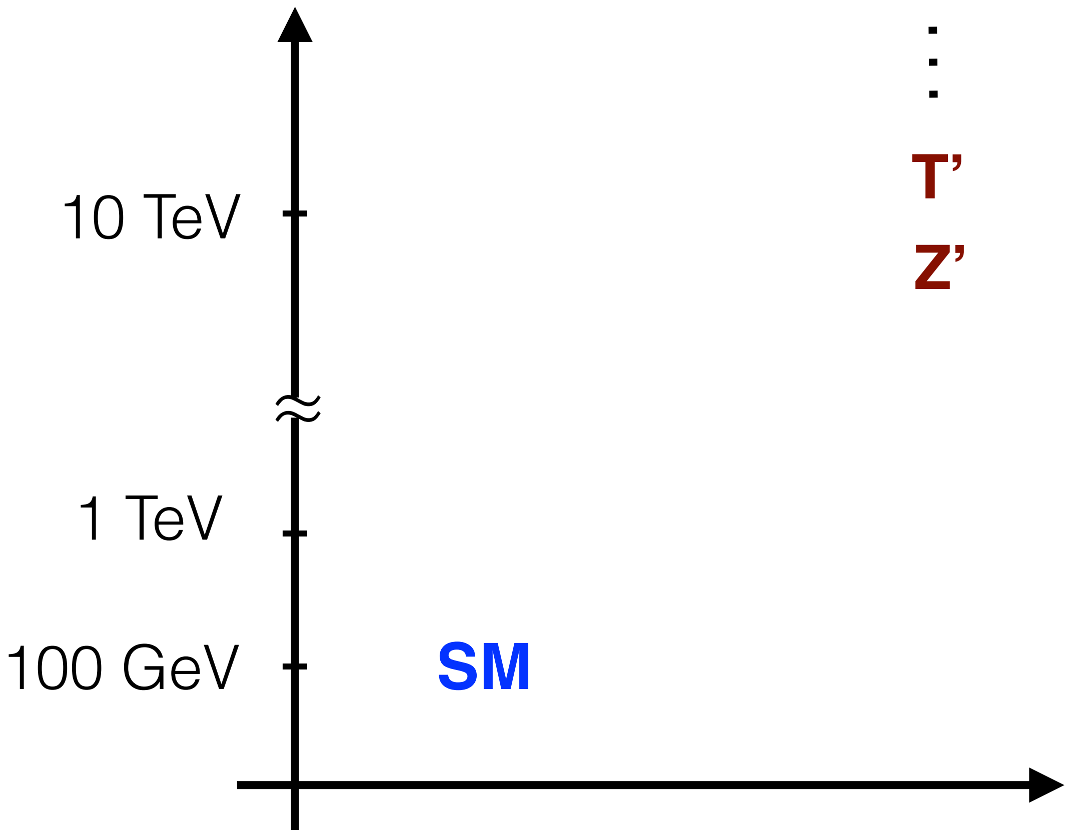

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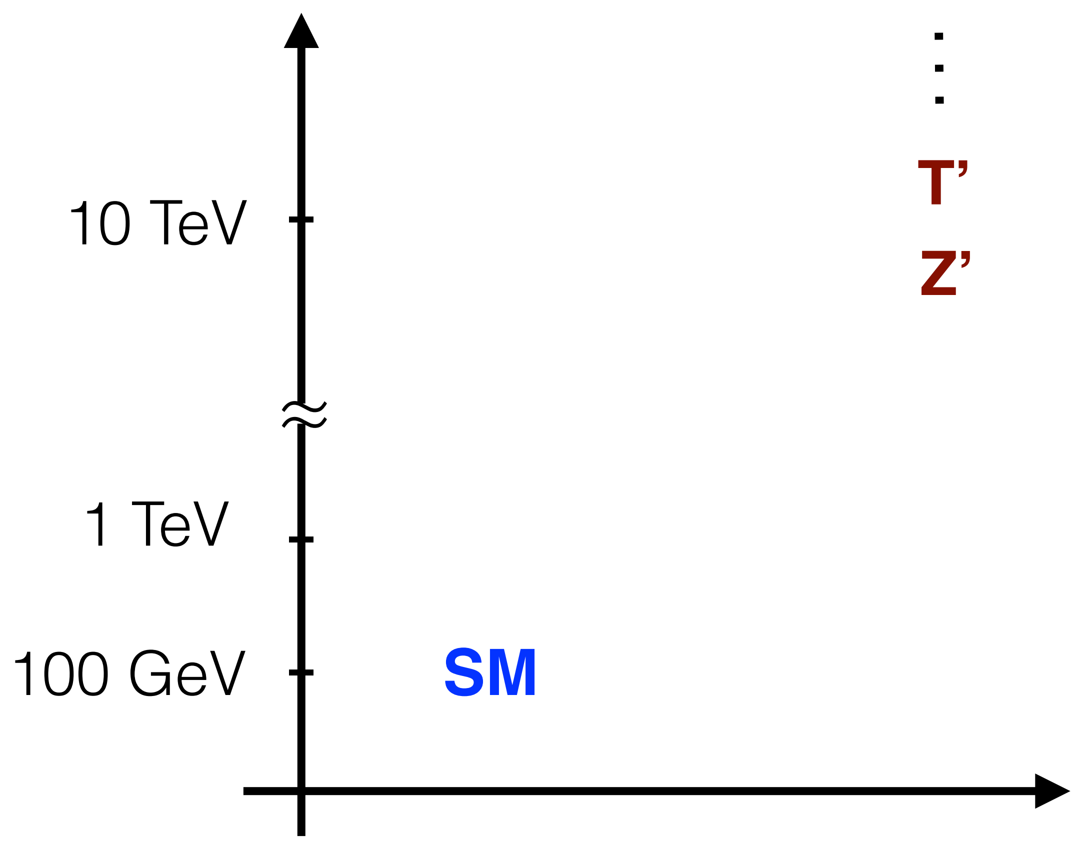

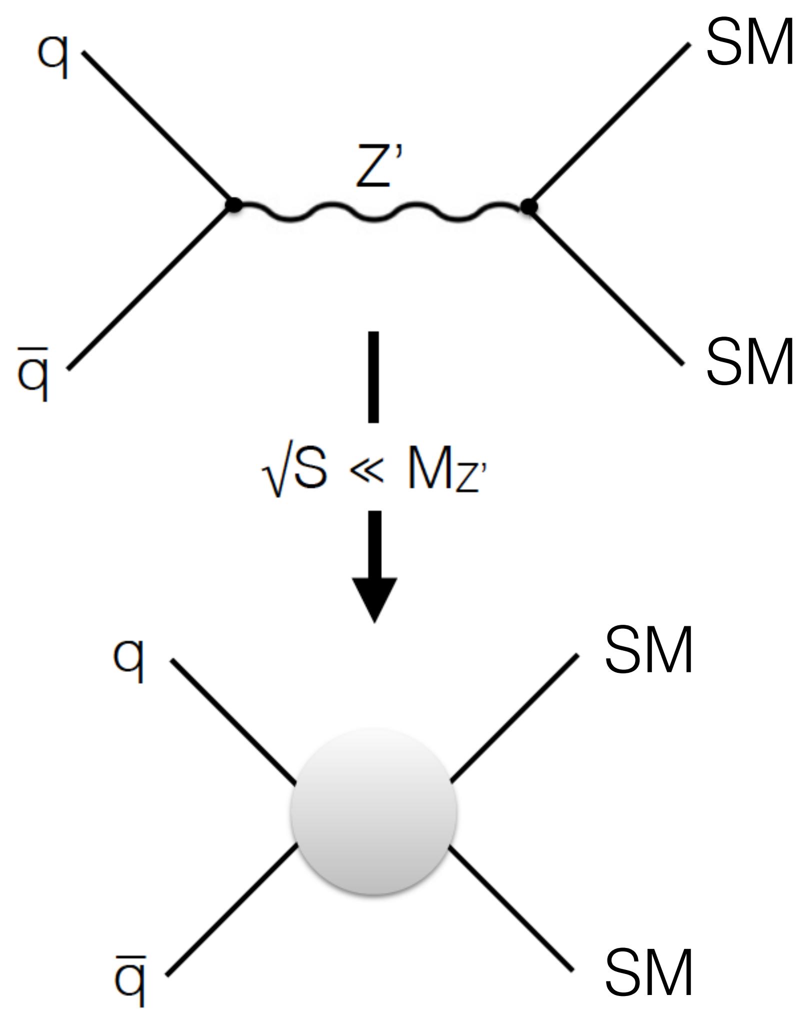

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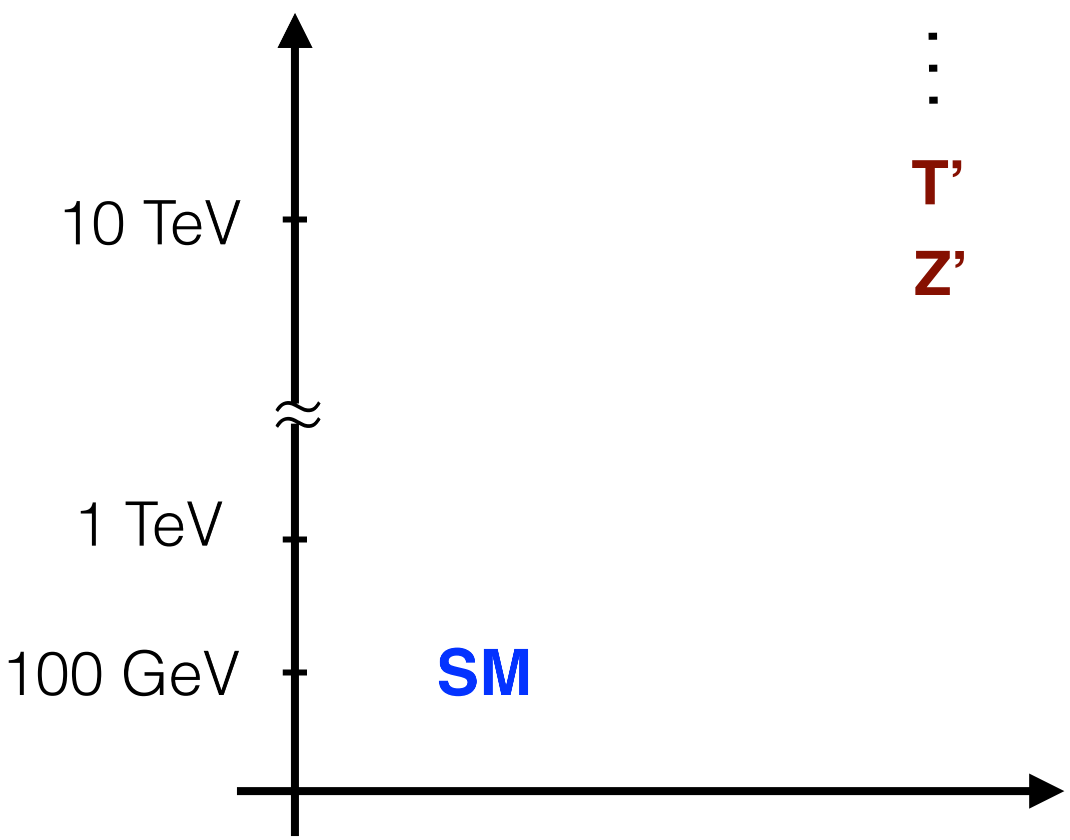

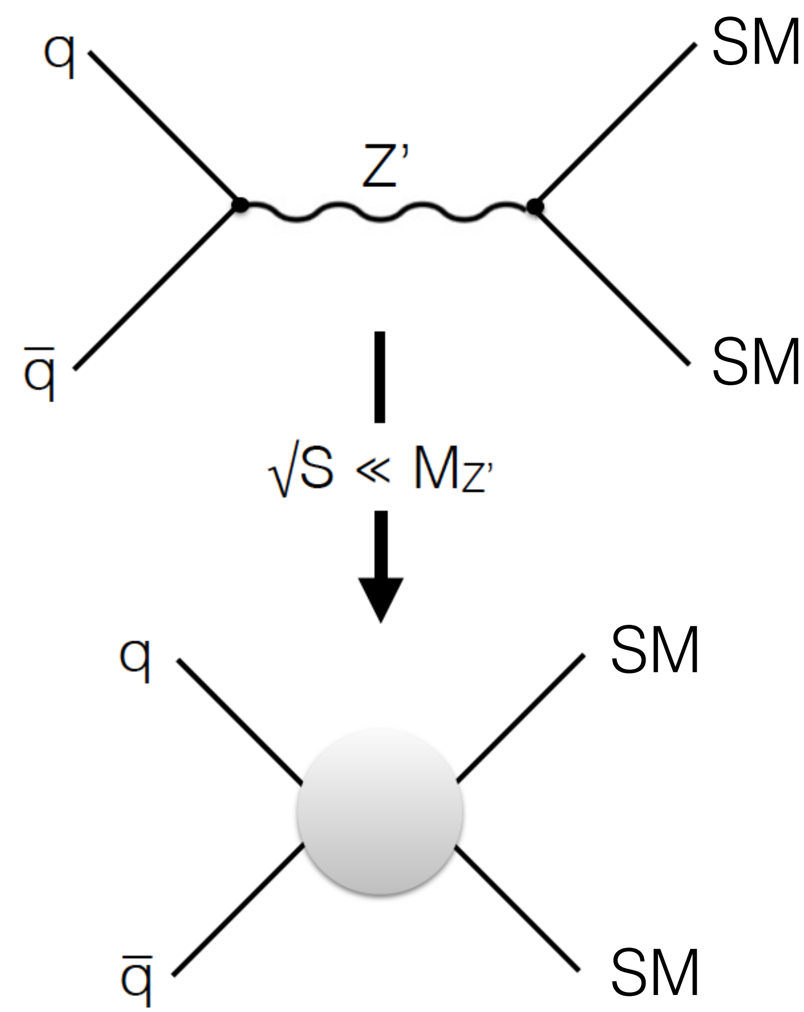

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{g^2}{M_{Z'}^2}(\bar{q}\Gamma q)(\bar{l}\Gamma l) + \ldots$$

Buchmüller, Wyler; Grazdkowski et al.

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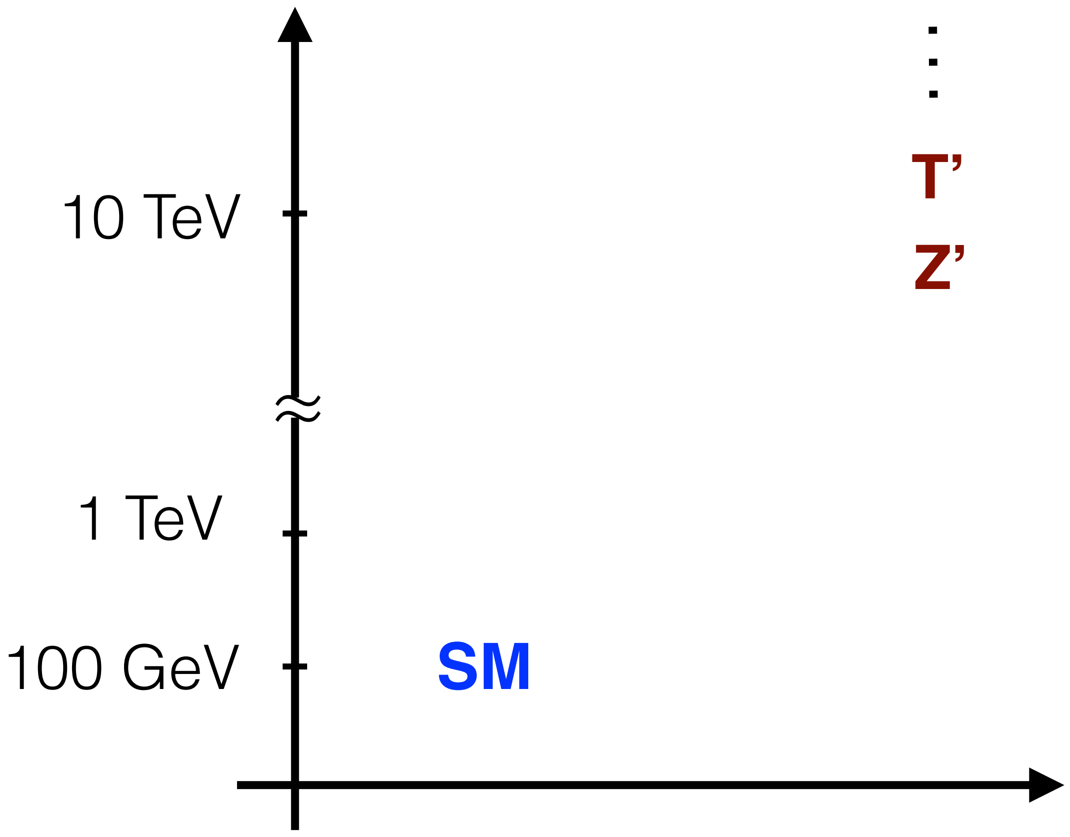

Higgs physics at the LHC:

$$\left| \frac{\sigma \times \mathrm{BR}}{\sigma \times \mathrm{BR}|_{\mathrm{SM}}} - 1 \right| \sim \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 0.1$$

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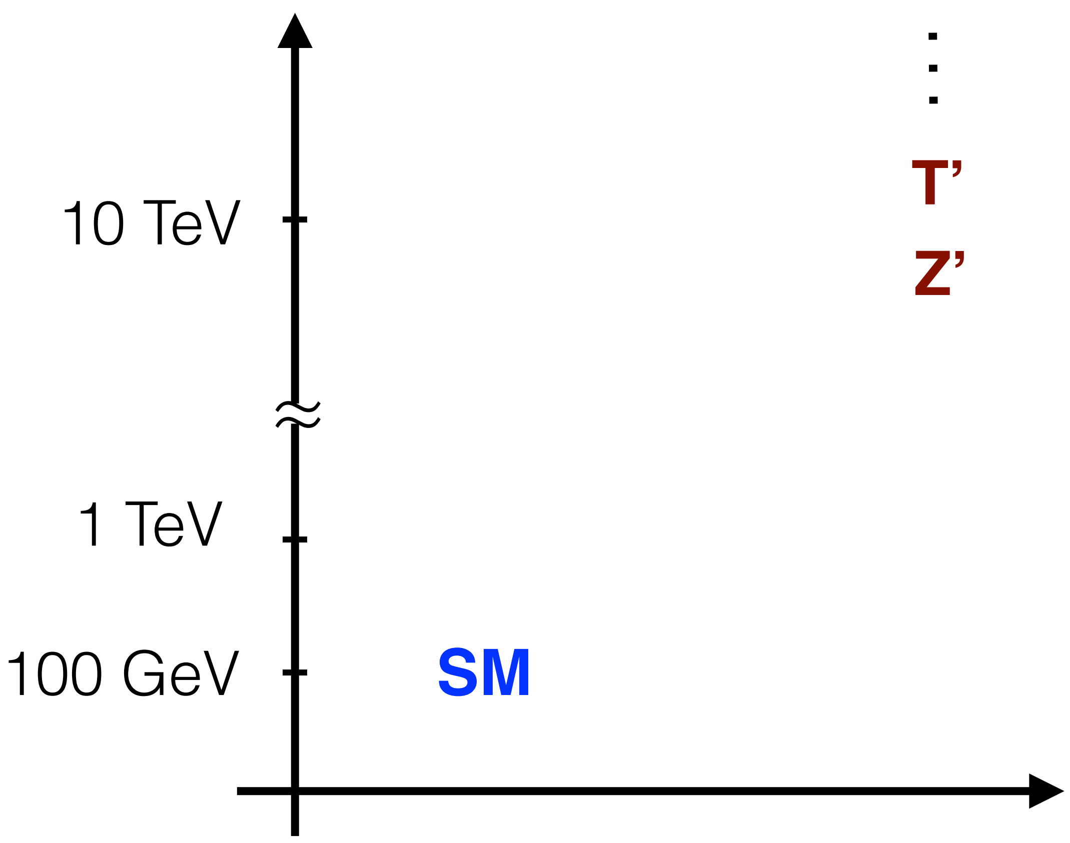

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$$\Leftrightarrow \Lambda \lesssim 500\,\mathrm{GeV}$$

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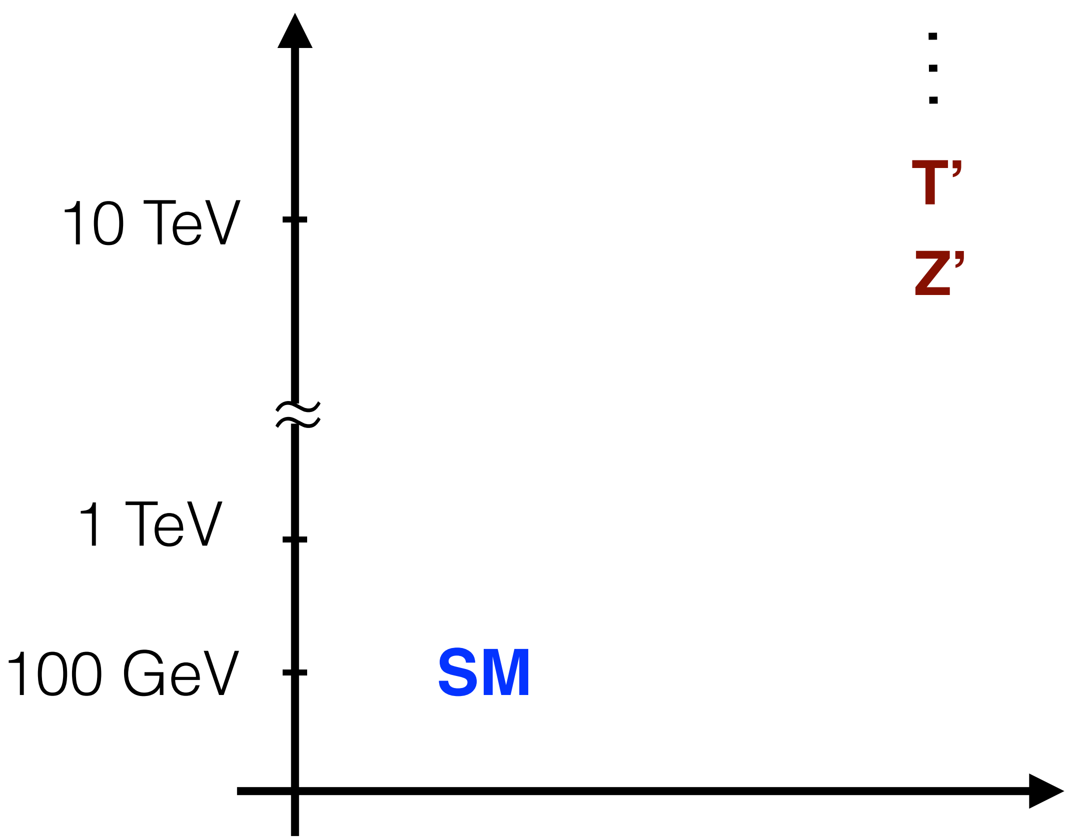

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→ expect to find new particles

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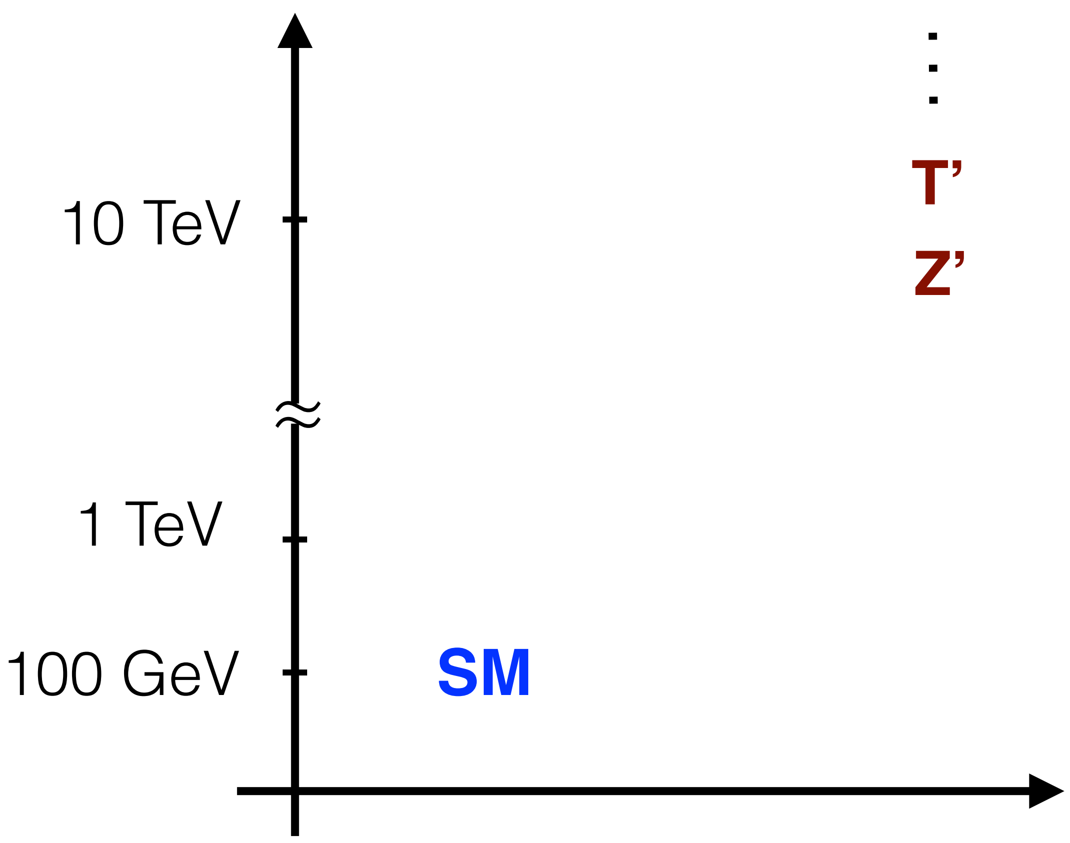
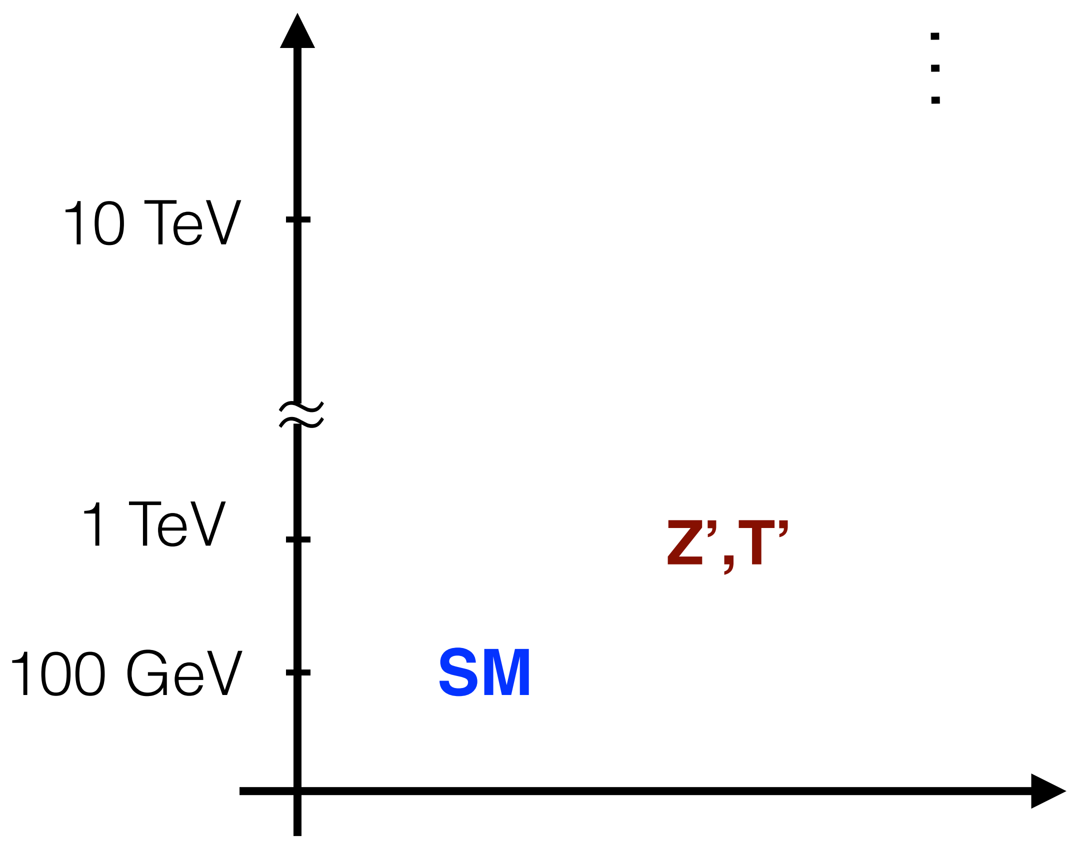


simplified models



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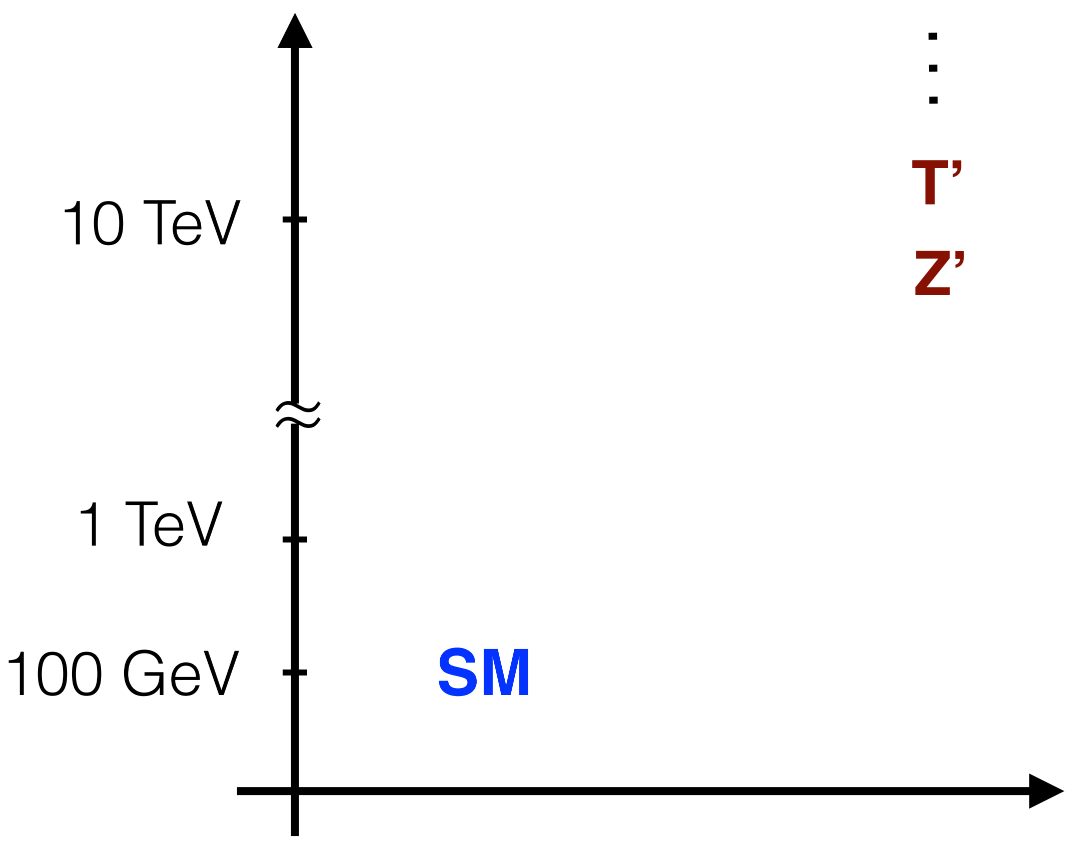

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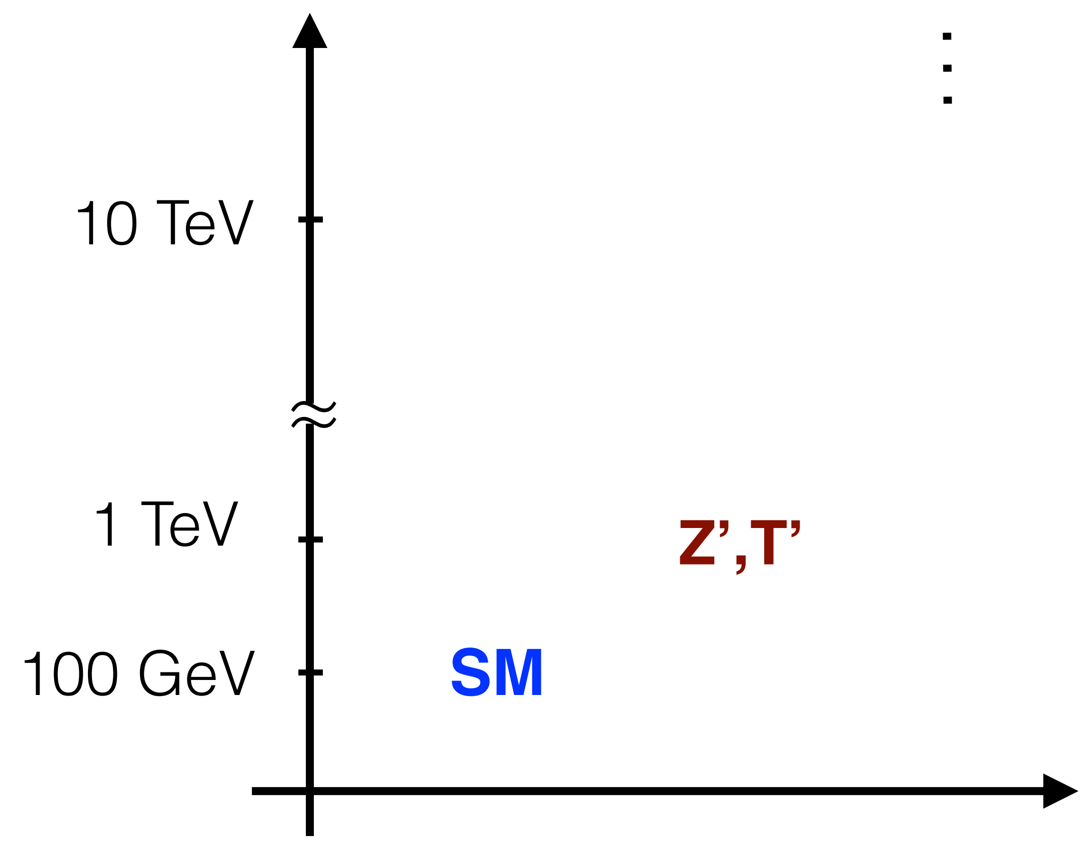

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{T',Z'} + \mathcal{L}_6 + \ldots$$

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- mediate between theory and data
- allow to explore the space of theories and signatures
- connect direct and indirect searches for new physics

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Simplified models have become standard for SUSY and dark matter searches at the LHC. We want to construct simplified models for Higgs physics to

- explore BSM theories that affect the Higgs sector;
- connect measurements of Higgs properties and direct searches for new physics.

A simplified model for Higgs physics

Dolan, Hewett, MK, Rizzo (arXiv:1601.07208 [hep-ph])

We take the SM and add

- a scalar singlet S
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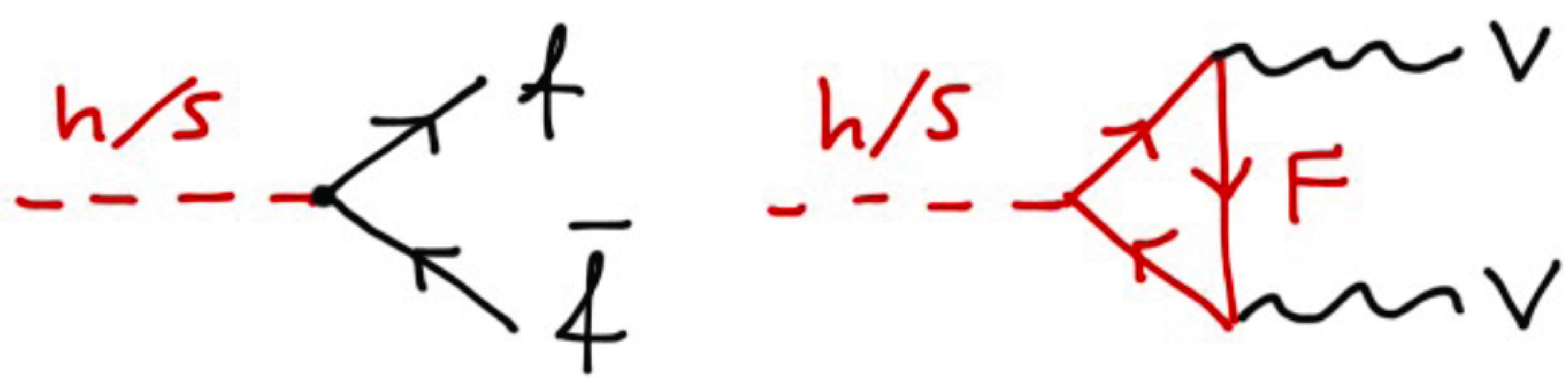
S aquires a vev, $S = (s + v_S)$, and provides mass for the fermion, $m_F = y_F\, v_S$. The Higgs and new scalar fields mix, $\lambda_{HS}\, H^\dagger H\, S^2$, and thus we generate new physics effects in all SM Higgs couplings:



A simplified model for Higgs physics

The simplest simplified model with F = T has 5 free and 3 fixed parameters. We choose:

$\mathbf{m_2}$, θ, $\mathbf{v_S}$, $\mathbf{m_T}$ and θ_L

and set m_1 = 125 GeV, v_H = 246 GeV and m_t = 173 GeV.

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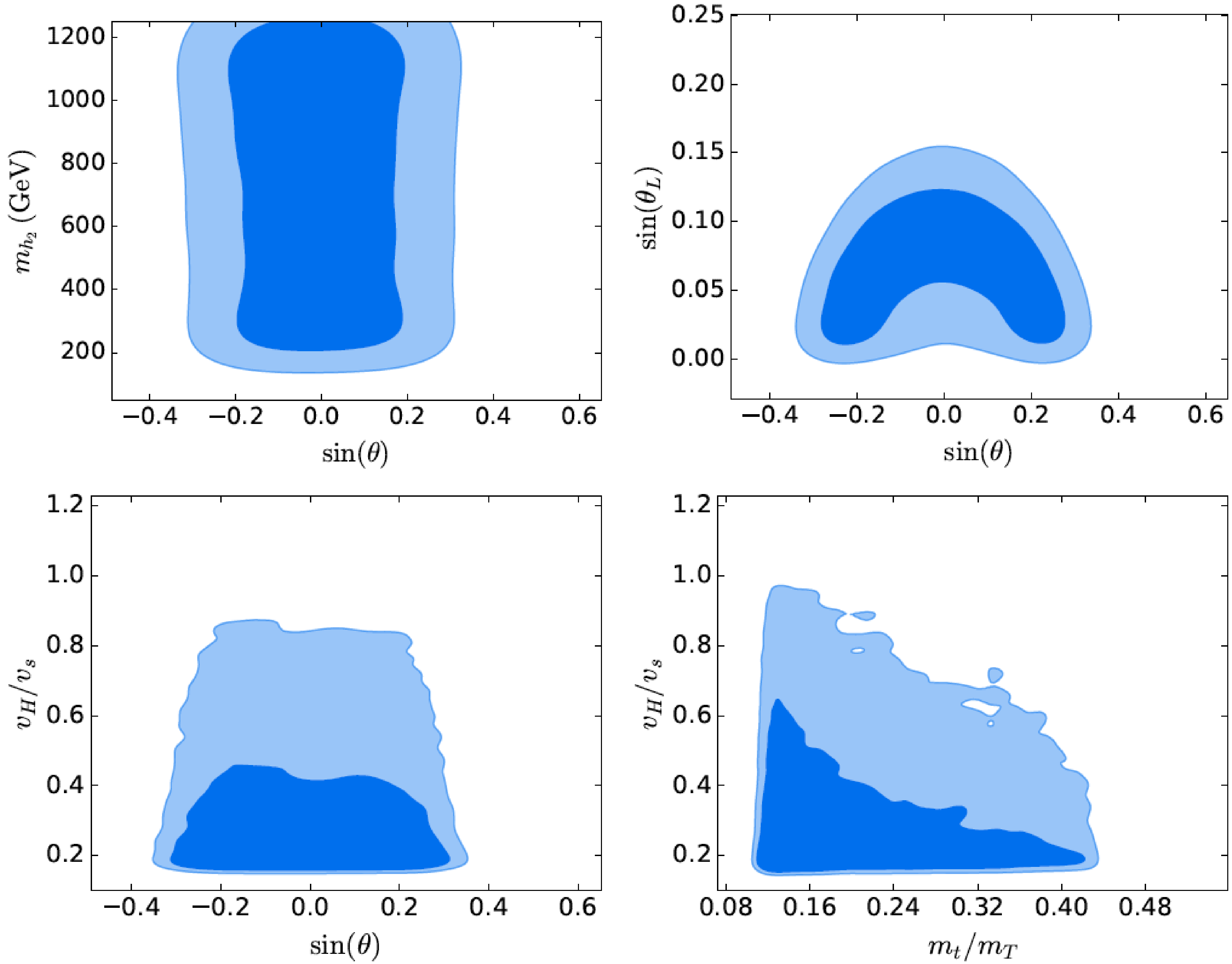
The parameters are constrained by

- perturbative unitary
- precision EW data: S, T and U
- Higgs cross sections and branching ratios

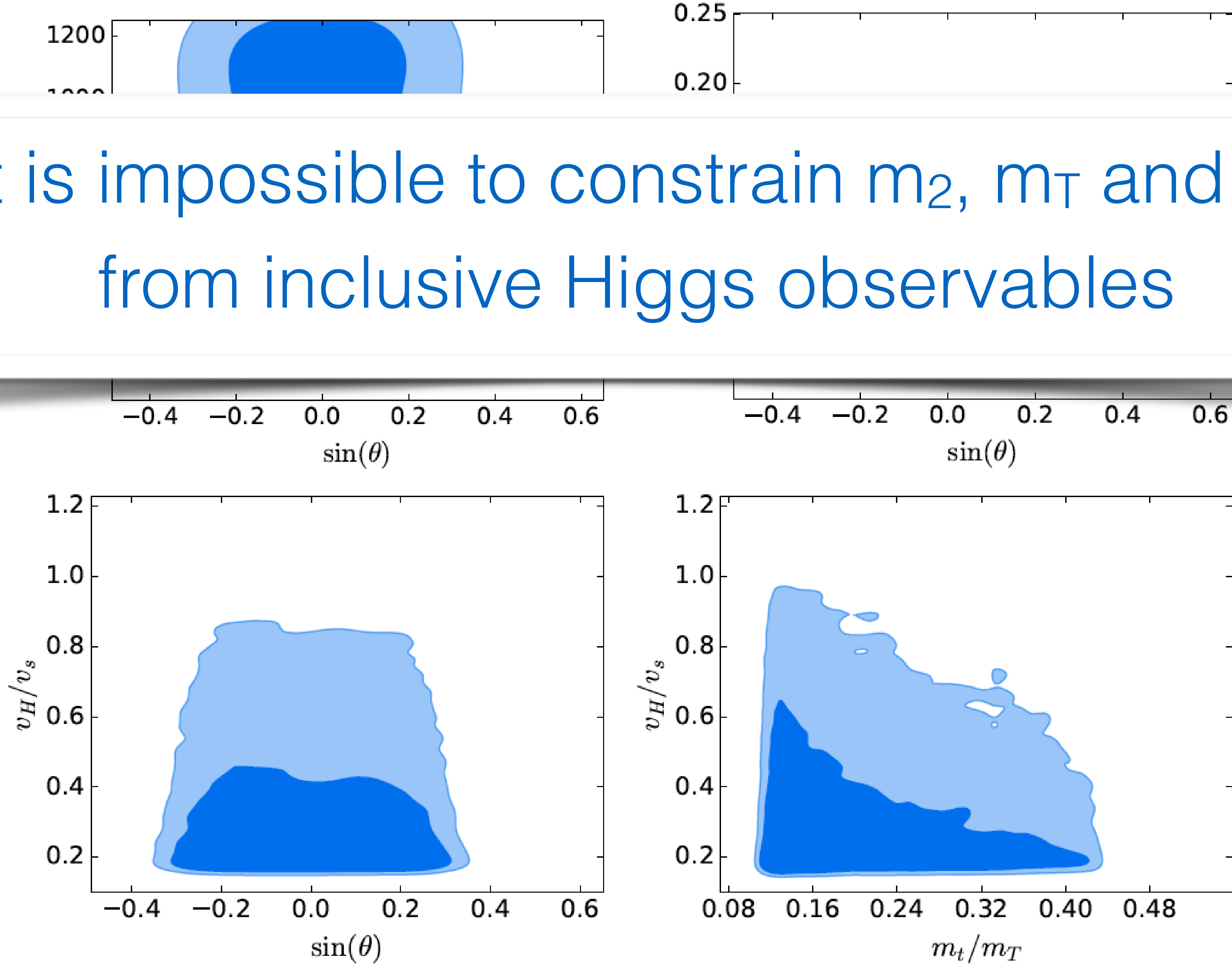
A fit to the Higgs cross sections and BRs



HiggsSignals/HiggsBounds

A fit to the Higgs cross sections and BRs

It is impossible to constrain m_2, m_T and v_S from inclusive Higgs observables



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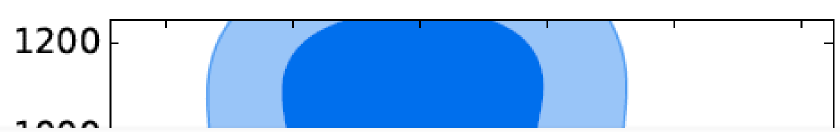

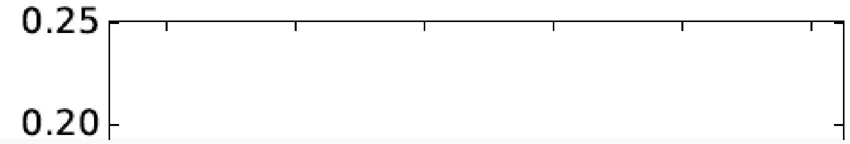

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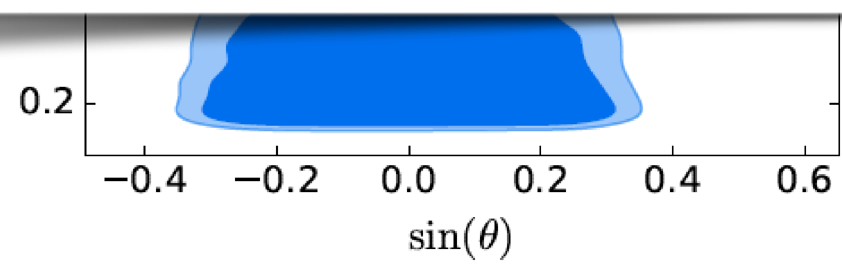
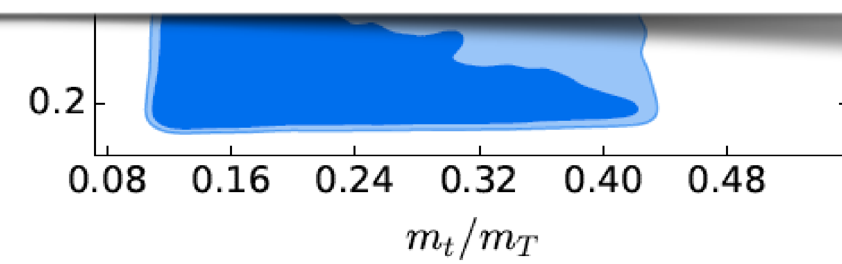
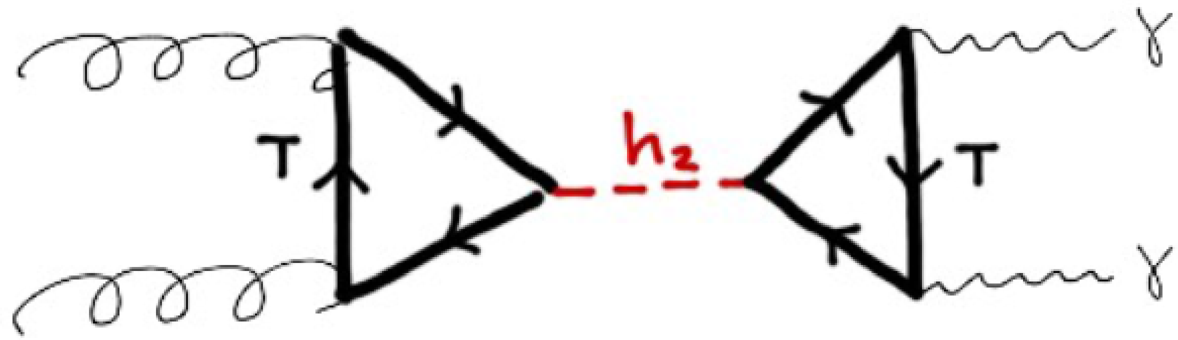
Need to consider more exclusive Higgs observables and direct searches for h_2 and T.





HiggsSignals/HiggsBounds

Is the new the scalar h_2 the 750 GeV resonance?



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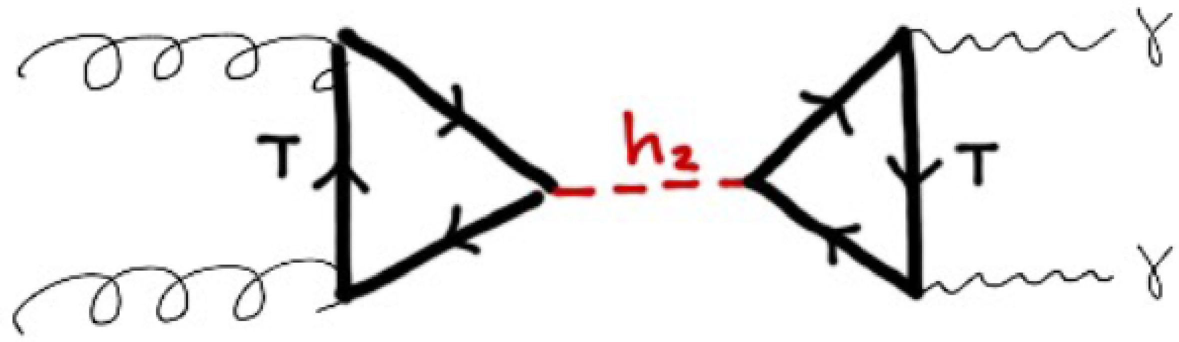

Need $\sigma(pp \to h_2) \times \mathrm{BR}(h_2 \to \gamma\gamma) \sim \mathcal{O}(\text{few fb})$

With $\mathrm{BR}(h_2 \to \gamma\gamma) \approx \dfrac{\Gamma(h_2 \to \gamma\gamma)}{\Gamma(h_2 \to gg)} = \dfrac{8}{9}\left(\dfrac{\alpha}{\alpha_\mathrm{s}}\right)^2 \approx 0.5\%$

this corresponds to $\sigma(pp \to h_2) \approx 1\,\mathrm{pb}$

and thus $y_T = \dfrac{m_T}{v_S} \gg 1$

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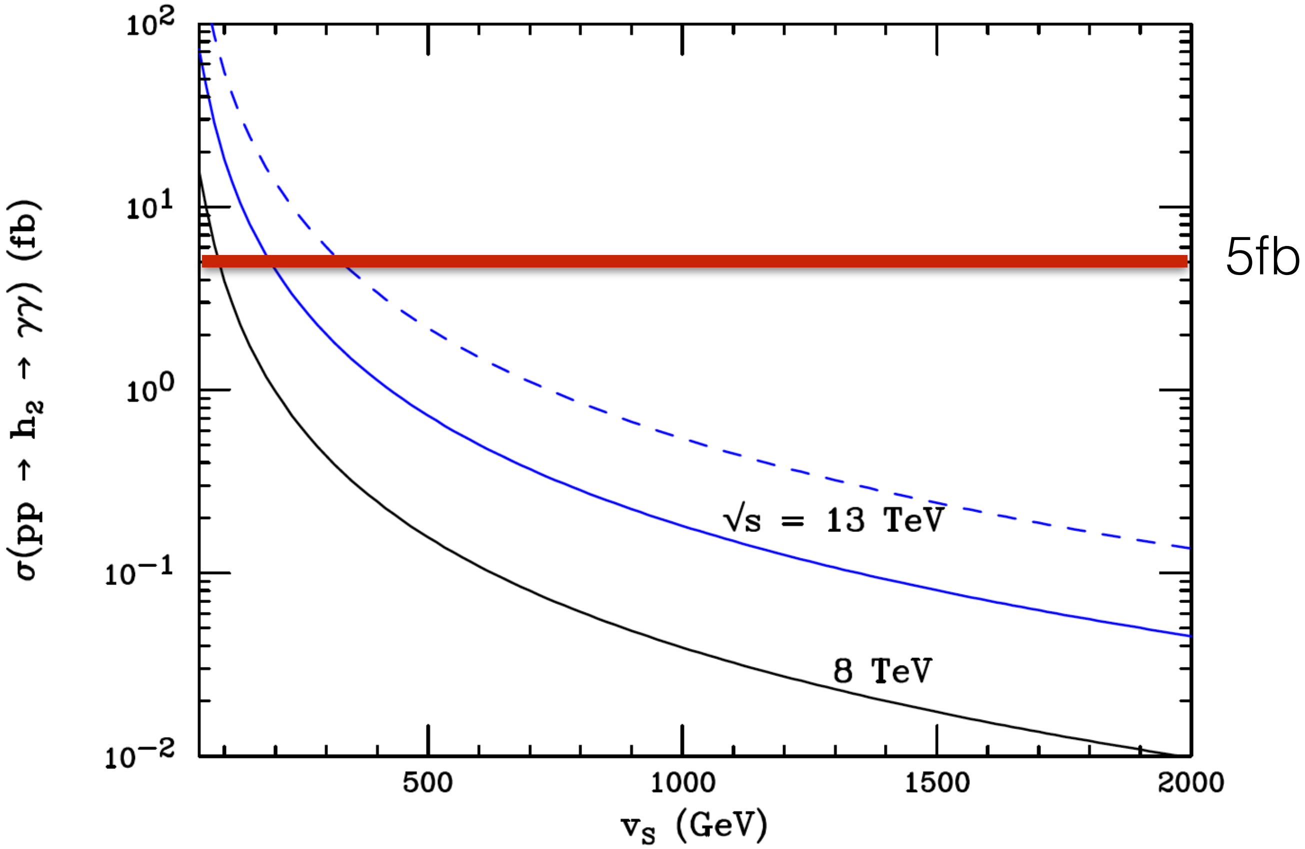

A small $v_s \approx$ 100 GeV implies a large $y_T = m_T / v_S$

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Can restore perturbativity by adding more generations of new fermions.

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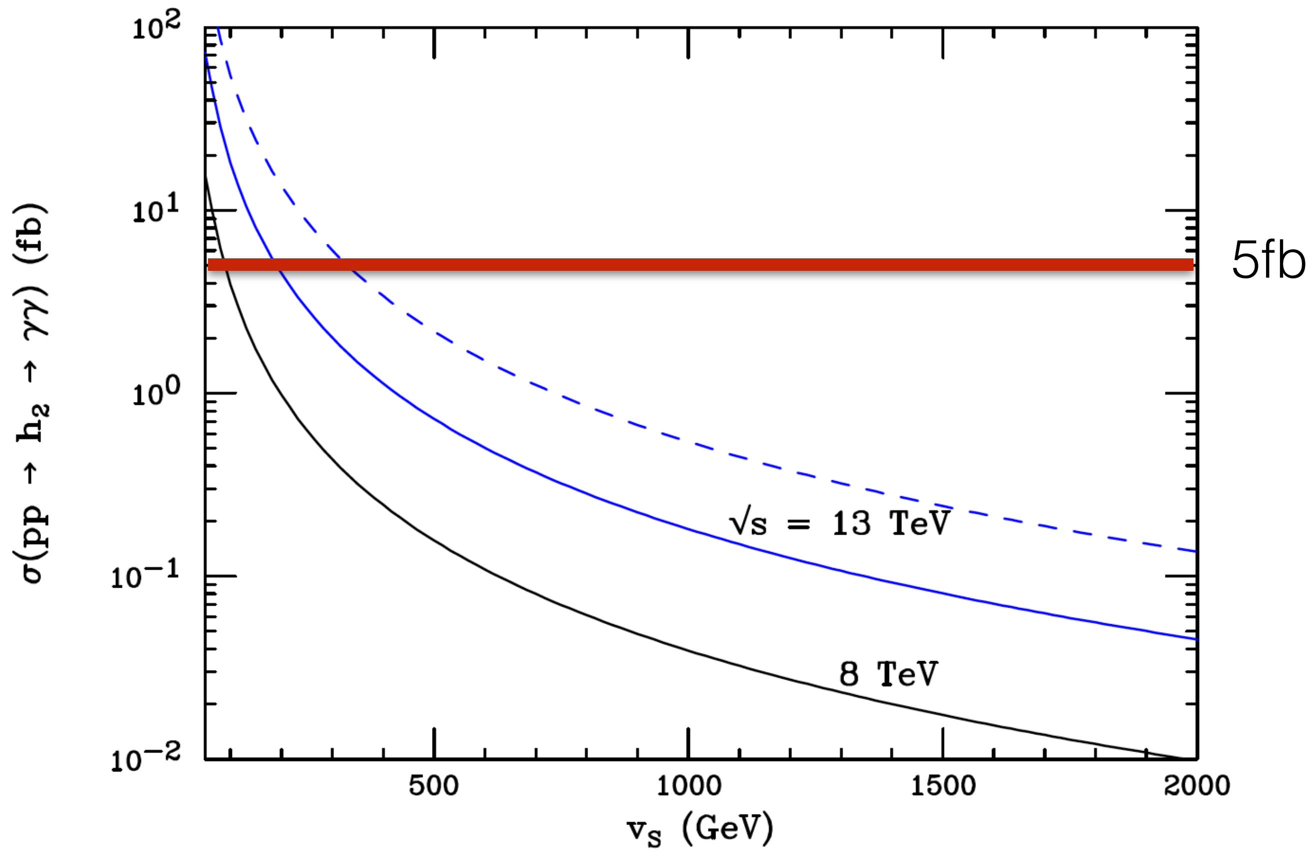

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However, a large width $\Gamma_{h_2} \approx 45\,\mathrm{GeV}$ as favoured by ATLAS, would most likely imply non-perturbative dynamics. (See e.g. 1512.04933)

Summary

Searches for new physics are increasingly designed and interpreted in terms of simplified models rather than specific top-down models

Simplified models

- mediate between theory and data
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Summary

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However

- how do we choose the right simplified model?
- do simplified models provide an explanation?
- how to simplified models connect to theory?

Conclusions

The Higgs boson mass and profile, and the limits from direct searches tend to push the new physics scale beyond TeV.

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The Higgs boson mass and profile, and the limits from direct searches tend to push the new physics scale beyond TeV.

New physics is either natural and somewhat elaborate, or simple and unnatural.

For the LHC-13 we need to

- explore a wider range of BSM models
- move towards more model-independent searches: effective field theories, simplified models.

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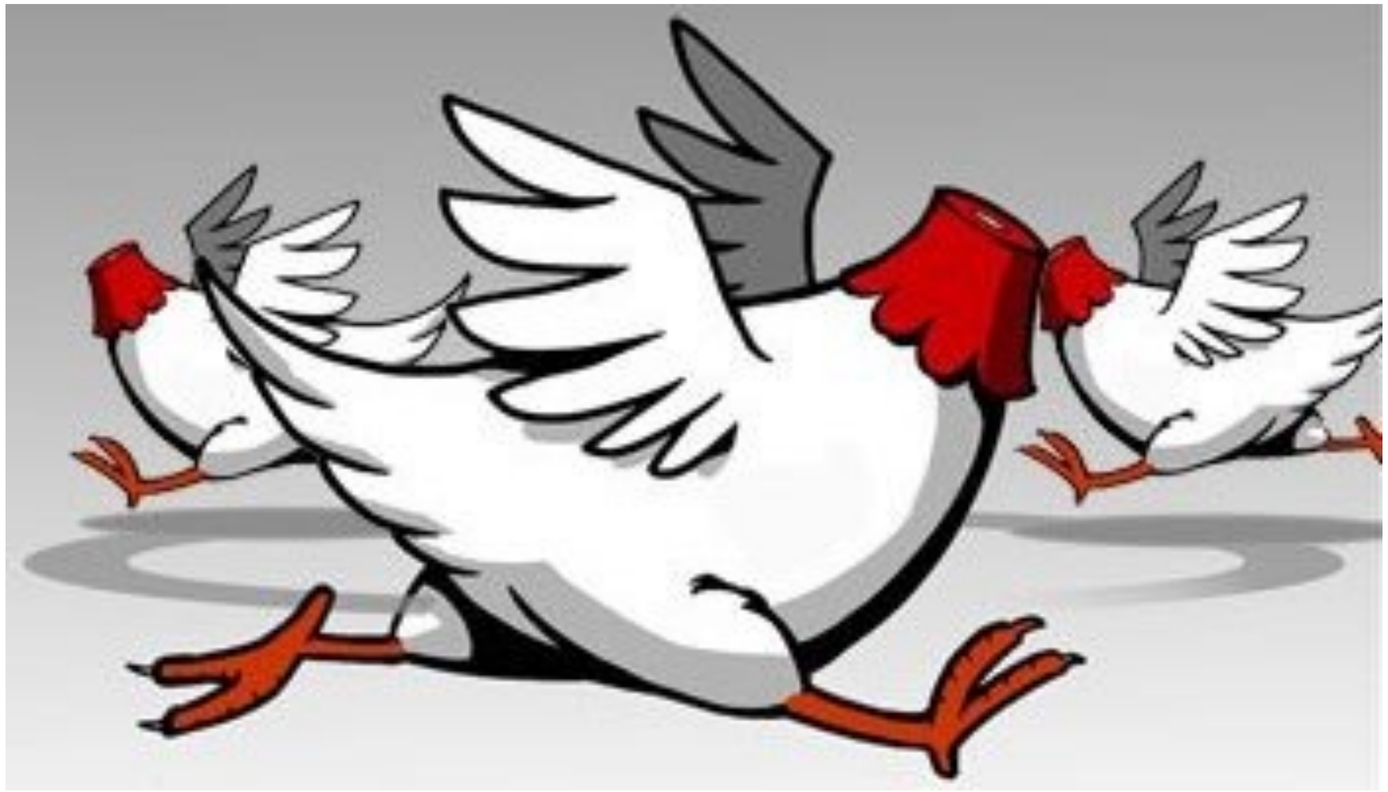

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Experiment has to tell!

Thank you!

Backup

A simplified model for Higgs physics

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Consider the Higgs gauge boson coupling ~ h $V_{\mu\nu}V^{\mu\nu}$

$$\gamma\gamma: \quad \epsilon_\gamma \frac{\alpha}{\pi}\frac{1}{v}\left(\frac{\lambda_{\mathrm{HS}} v^2}{m_S^2}\right)$$

$$G_a G^a: \quad \epsilon_g \frac{\alpha_s}{\pi}\frac{1}{v}\left(\frac{\lambda_{\mathrm{HS}} v^2}{m_S^2}\right)$$

$$BB: \quad \epsilon_B \frac{g'^2}{\pi^2}\frac{1}{v}\left(\frac{\lambda_{\mathrm{HS}} v^2}{m_S^2}\right)$$

$$W_i W^i: \quad \epsilon_W \frac{g^2}{\pi^2}\frac{1}{v}\left(\frac{\lambda_{\mathrm{HS}} v^2}{m_S^2}\right)$$

F	ϵ_γ	ϵ_g	ϵ_B	ϵ_W
$\begin{pmatrix} T' \\ B' \end{pmatrix}_{L+R}$	$\frac{5}{18}$	$-\frac{1}{6}$	$\frac{1}{144}$	$\frac{1}{16}$
Q_{L+R}	$\frac{1}{2}Q^2$	$-\frac{1}{12}$	$\frac{1}{8}Q^2$	0
$\begin{pmatrix} N \\ E \end{pmatrix}_{L+R}$	$\frac{1}{6}$	0	$\frac{1}{48}$	$\frac{1}{48}$
L_{L+R}	$\frac{1}{16}Q^2$	0	$\frac{1}{24}$	0

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$$\mathcal{L}_{\text{Yukawa}} = y_T S \overline{T}_L^{\text{int}} T_R^{\text{int}} + y_t \overline{Q}_L^{\text{int}} \widetilde{H} t_R^{\text{int}} + y_b \overline{Q}_L^{\text{int}} H b_R + \lambda_T \overline{Q}_L^{\text{int}} \widetilde{H} T_R^{\text{int}}$$

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After SSB the SM top quark $\mathbf{t}^{\text{int}}$ and the vector quark $\mathbf{T}^{\text{int}}$ mix to form the mass eigenstates **t** and **T**:

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$$\mathcal{L}_{\text{Yukawa}} = y_T S \overline{T}_L^{\text{int}} T_R^{\text{int}} + y_t \overline{Q}_L^{\text{int}} \widetilde{H} t_R^{\text{int}} + y_b \overline{Q}_L^{\text{int}} H b_R + \lambda_T \overline{Q}_L^{\text{int}} \widetilde{H} T_R^{\text{int}}$$

After SSB the SM top quark **t^int^** and the vector quark **T^int^** mix to form the mass eigenstates **t** and **T**:

$$m_t^2 = \tfrac{1}{2} v_H^2 y_t^2 \left(1 - \frac{\lambda_T^2}{2y_T^2}\frac{v_H^2}{v_S^2}\right) \qquad m_T^2 = v_S^2 y_T^2 \left(1 + \frac{\lambda_T^2}{2y_T^2}\frac{v_H^2}{v_S^2}\right)$$

$$\tan(2\theta_L) = \frac{2}{\sqrt{2}} \frac{\lambda_T}{y_T} \frac{v_H}{v_S}$$

A simplified model for Higgs physics

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{Yukawa}} + \mathcal{L}_{\mathrm{gauge}} - \boxed{V(H,S)}$$

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$$+ \frac{a_2}{2} H^\dagger H\, S^2 \ + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

with $\quad H = \begin{pmatrix} i\phi^+ \\ \frac{1}{\sqrt{2}}(h + v_H + i\phi^0) \end{pmatrix} \quad \text{and} \quad S = (s + v_S)$

For simplicity, we assume a Z_2-symmetry and set $a_1 = b_1 = b_3 = 0$.

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For simplicity, we assume a Z_2-symmetry and set $a_1 = b_1 = b_3 = 0$.

H and **S** mix, to form mass eigenstates **h_1** and **h_2**:

$$m_1^2 = 2\lambda v_H^2 \left(1 - \frac{a_2^2}{4\lambda b_4}\right) \qquad m_2^2 = 2 b_4 v_S^2 \left(1 + \frac{a_2^2}{4 b_4^2} \frac{v_H^2}{v_S^2}\right)$$

$$\tan(2\theta) = \frac{a_2}{b_4} \frac{v_H}{v_S}$$

A simplified model for Higgs physics

It is straightforward to calculate the couplings of the 125-Higgs to SM particles:

$$\kappa_W = \kappa_Z = \kappa_b = \kappa_\tau = \cos\theta \quad \text{and} \quad \kappa_t = c_L^2 c_\theta - s_L^2 s_\theta \frac{v_H}{v_S}$$

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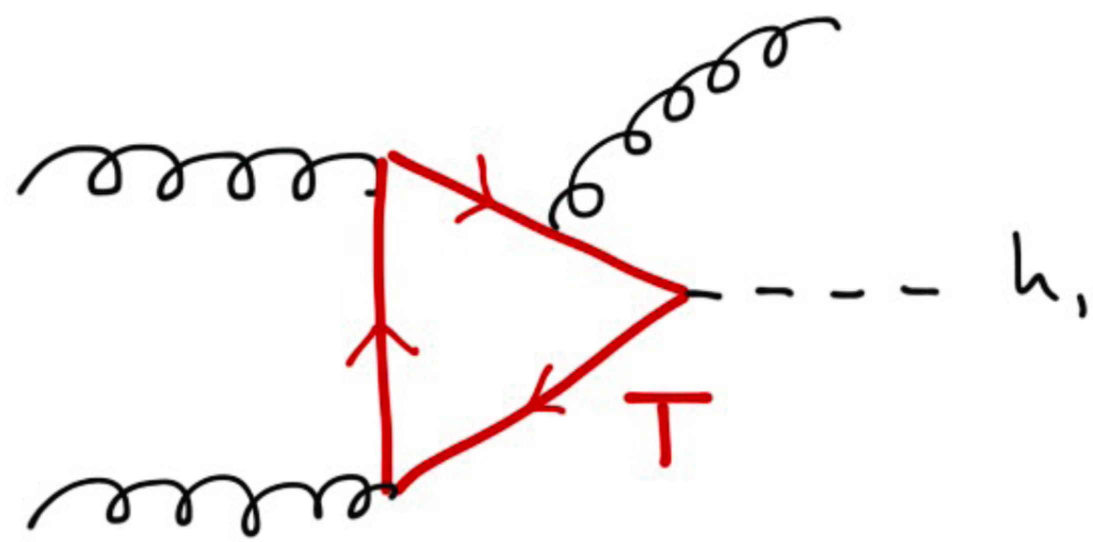
For the loop-induced couplings one has

$$\boxed{g_{hgg}} = \frac{g_s^2}{4\pi^2}\left(\sum_f \frac{g_{hff}}{m_f} A_{1/2}(\tau_f) + \frac{g_{hTT}}{m_T} A_{1/2}(\tau_T)\right) \quad \approx \quad \boxed{g_{hgg}^{\mathrm{SM}}\left(c_\theta - s_\theta \frac{v_H}{v_S}\right)}$$

$$g_{h\gamma\gamma} = \frac{e^2}{4\pi^2}\left(\frac{g_{hWW}}{m_W^2} A_1(\tau_W) + \sum_f 2N_C^f Q_f^2 \frac{g_{hff}}{m_f} A_{1/2}(\tau_f) + \frac{8}{3}\frac{g_{hTT}}{m_T} A_{1/2}(\tau_T)\right)$$

The Higgs P_T distribution

One can try to resolve the heavy new fermion in the loop through Higgs + jet production:



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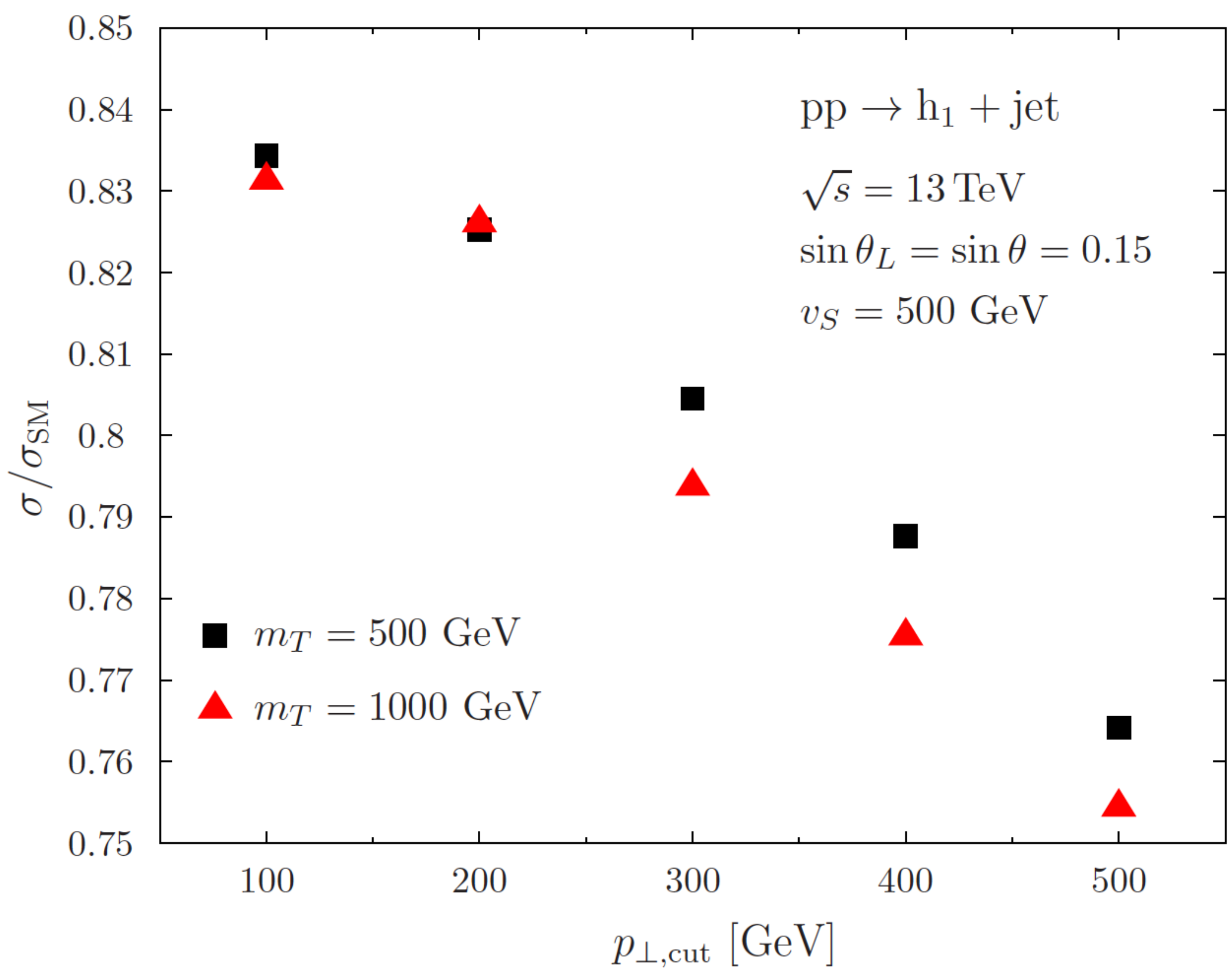
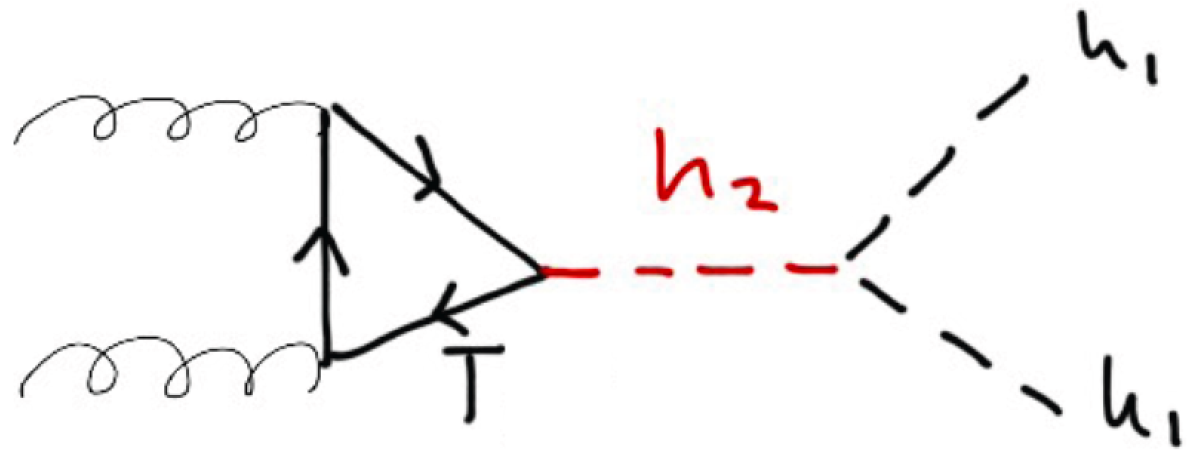


Madgraph5@NLO

Higgs pair production

One can try to learn something about the new scalar sector through Higgs pair production:



$$\mathcal{L} \supset g_{tty}^{\rm SM}\left(\bar{t}th_1 + \frac{m_T}{m_t}\frac{v_H}{v_S}\bar{T}Th_2\right)$$ for $\sin\theta = \sin\theta_L = 0$

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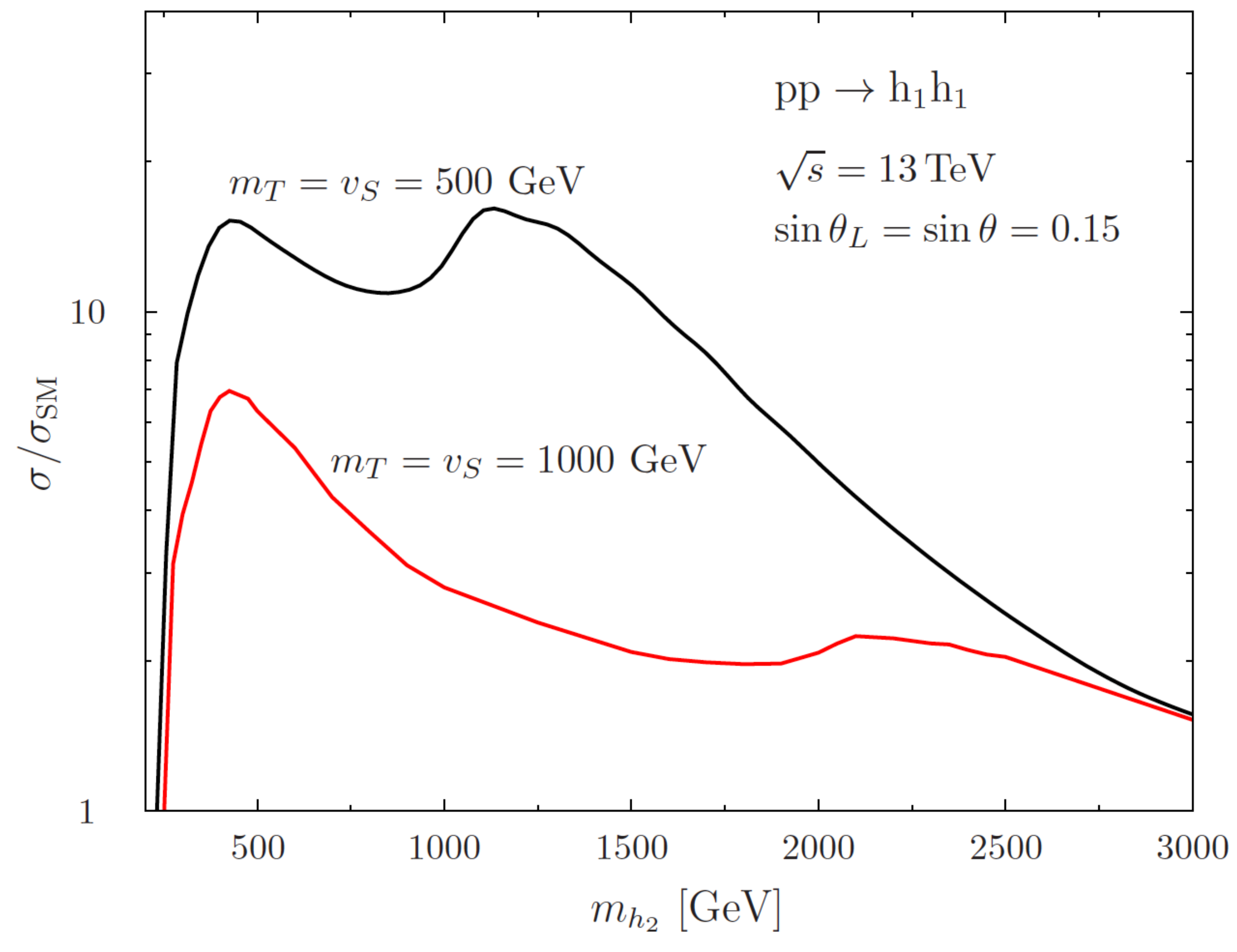
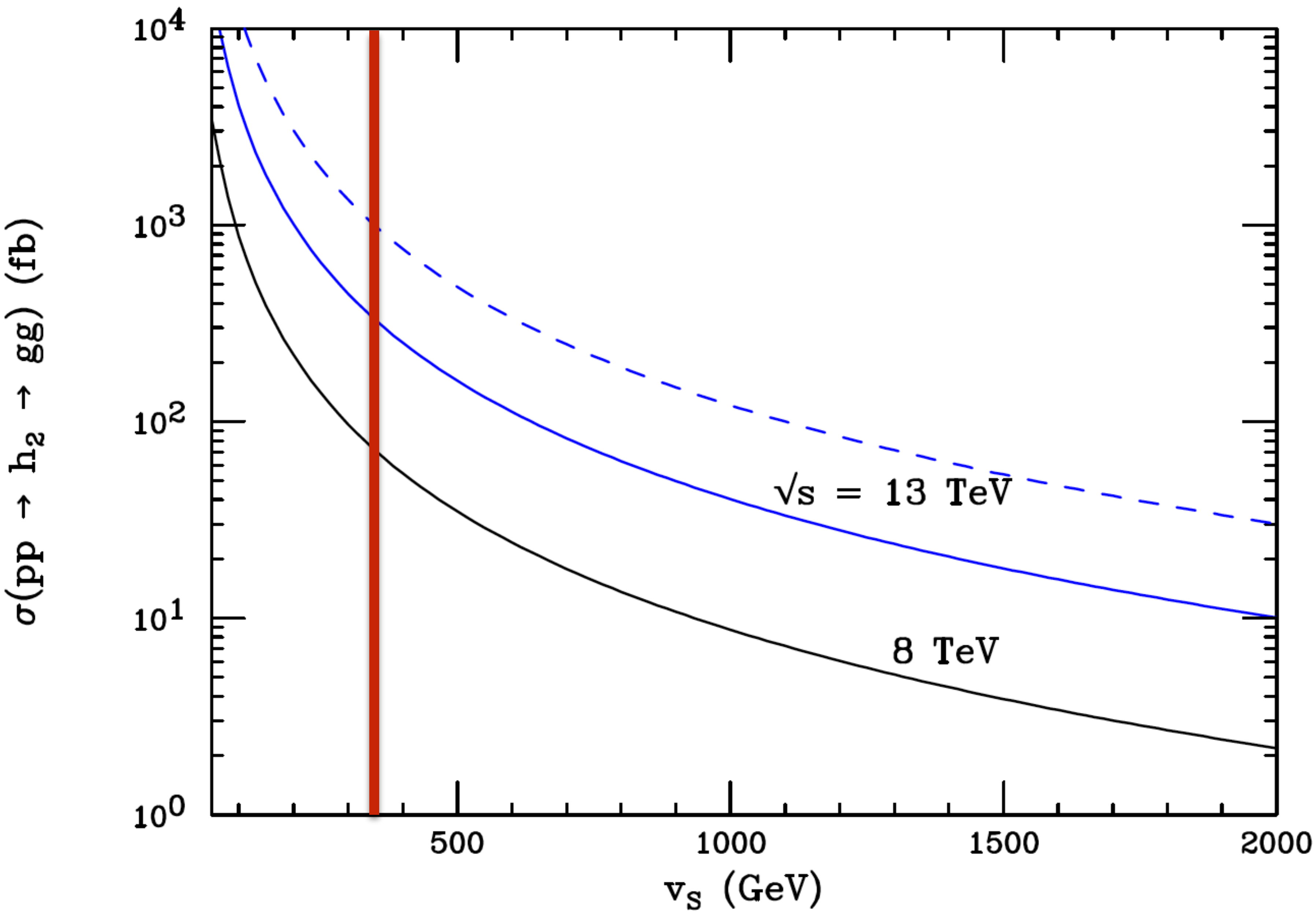


$\sin\theta = \sin\theta_L = 0.15$

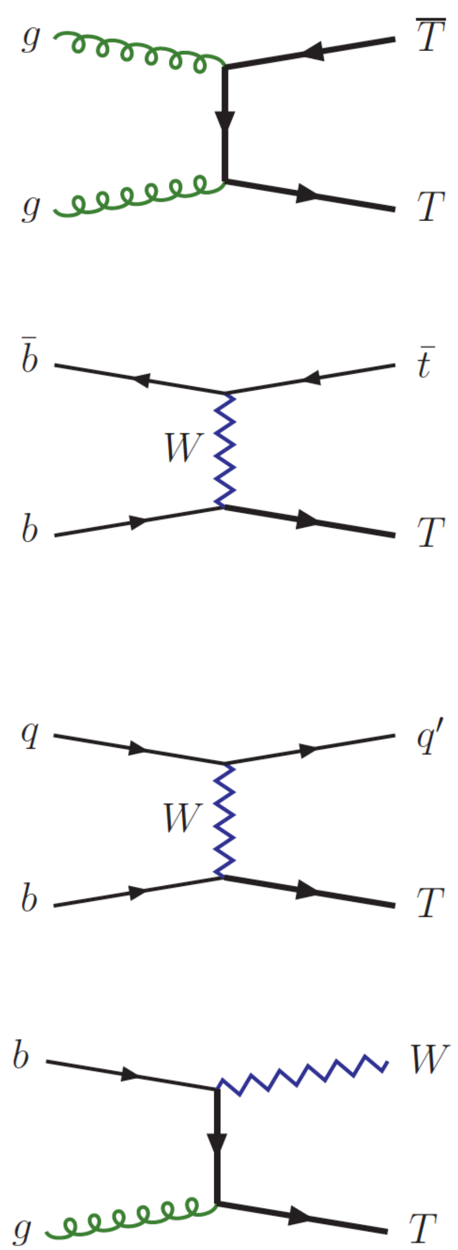
Madgraph5@NLO

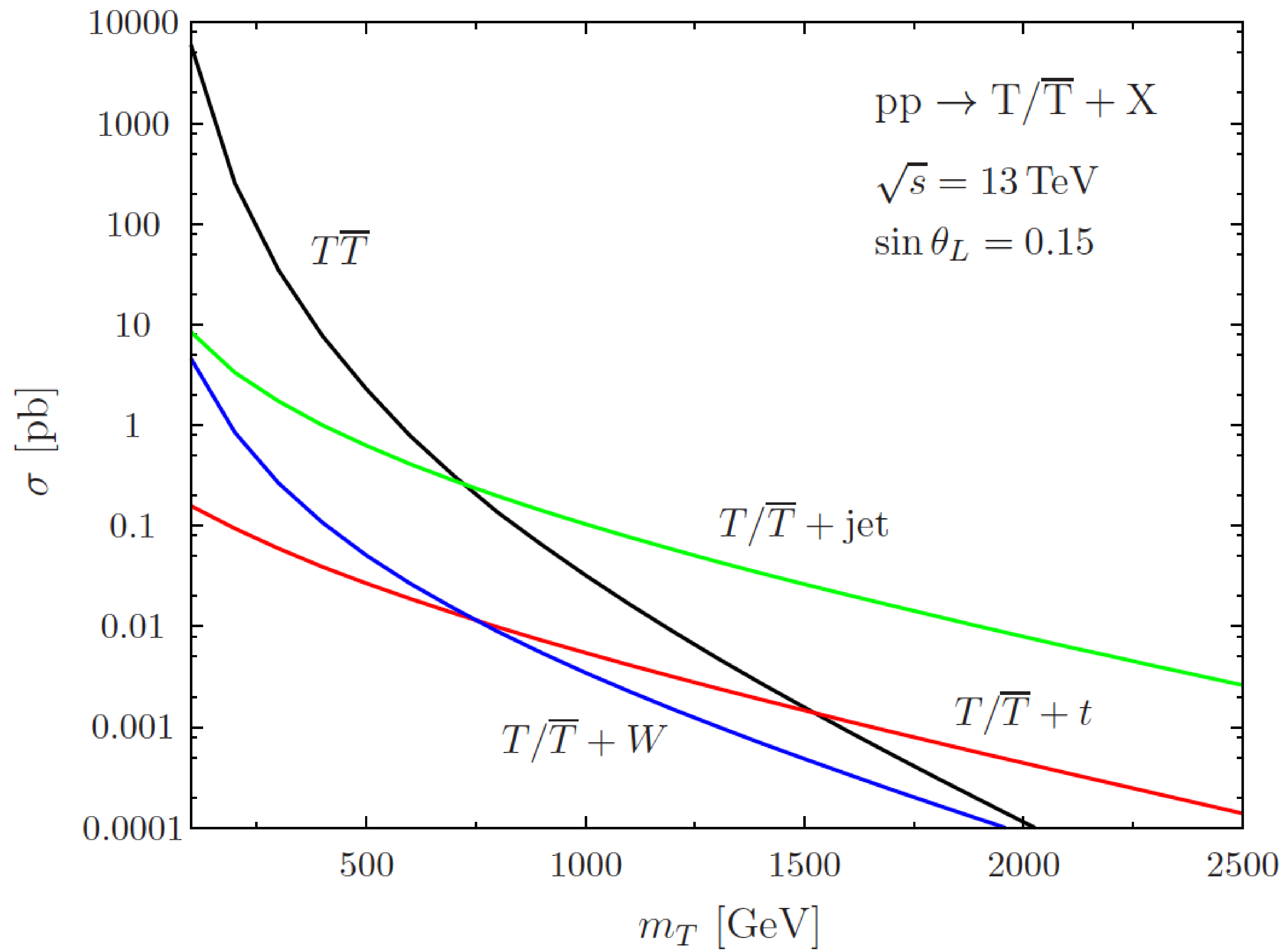
Is the new the scalar h_2 the 750 GeV resonance?

Straightforward test: di-jet searches



Direct searches for S and T





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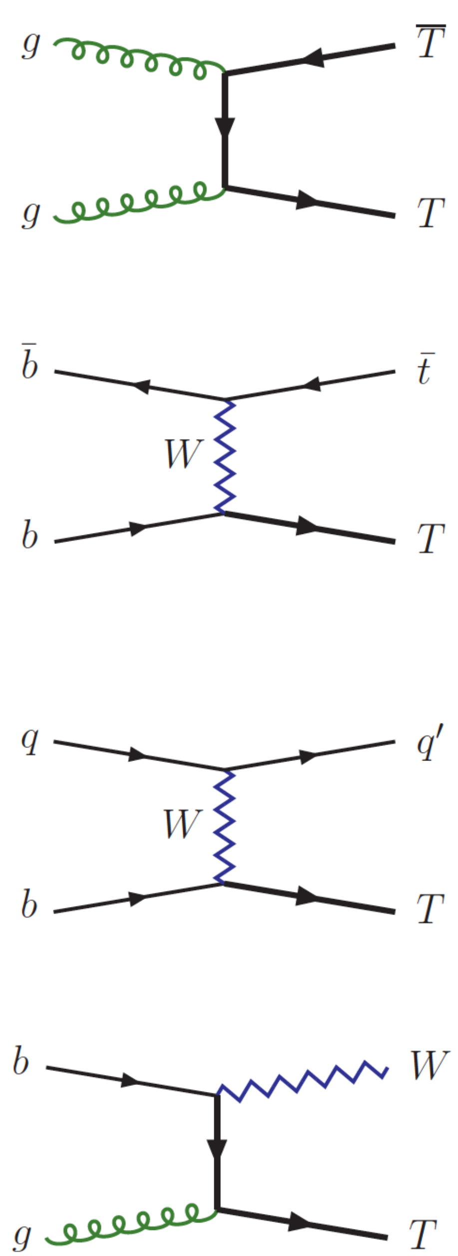

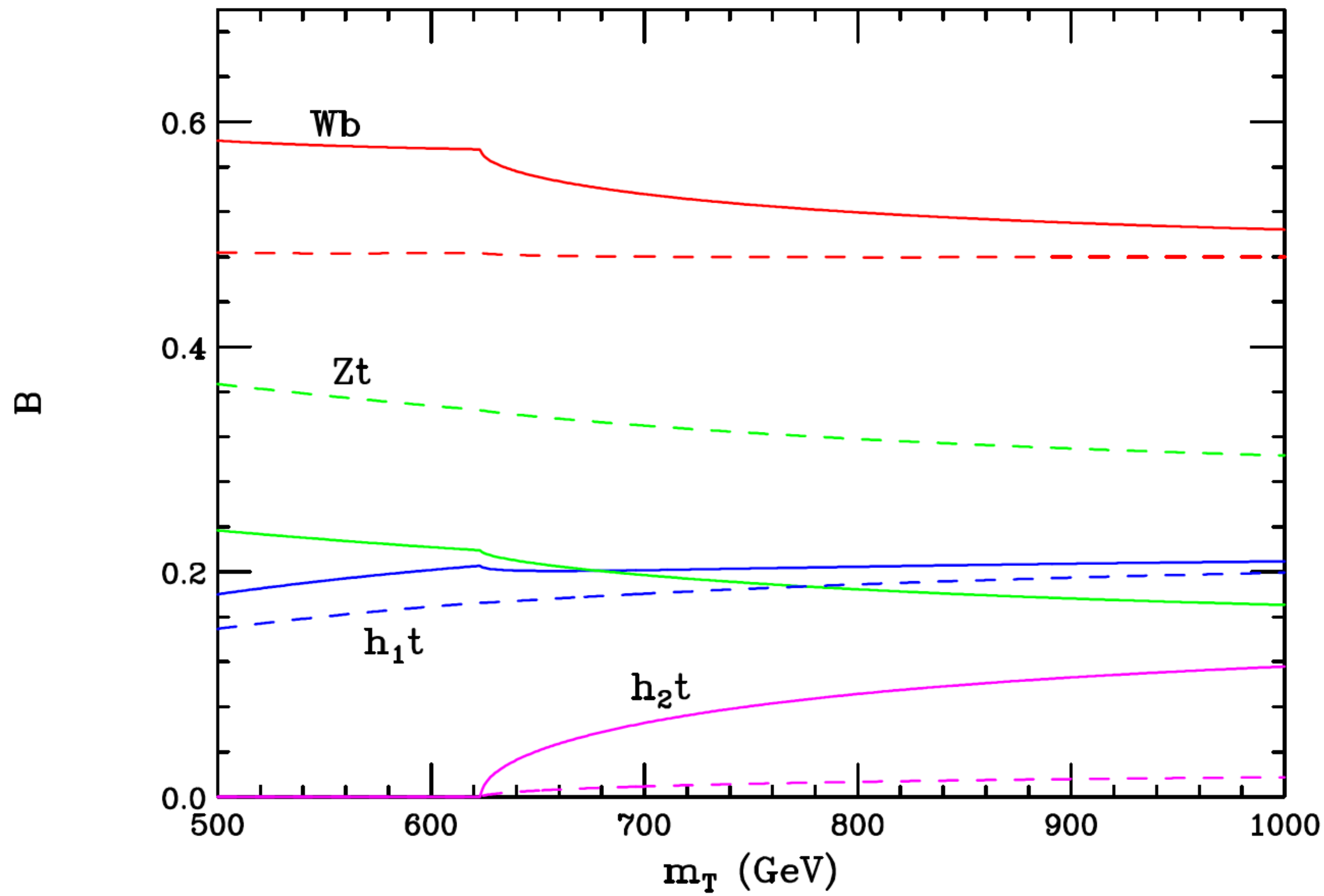

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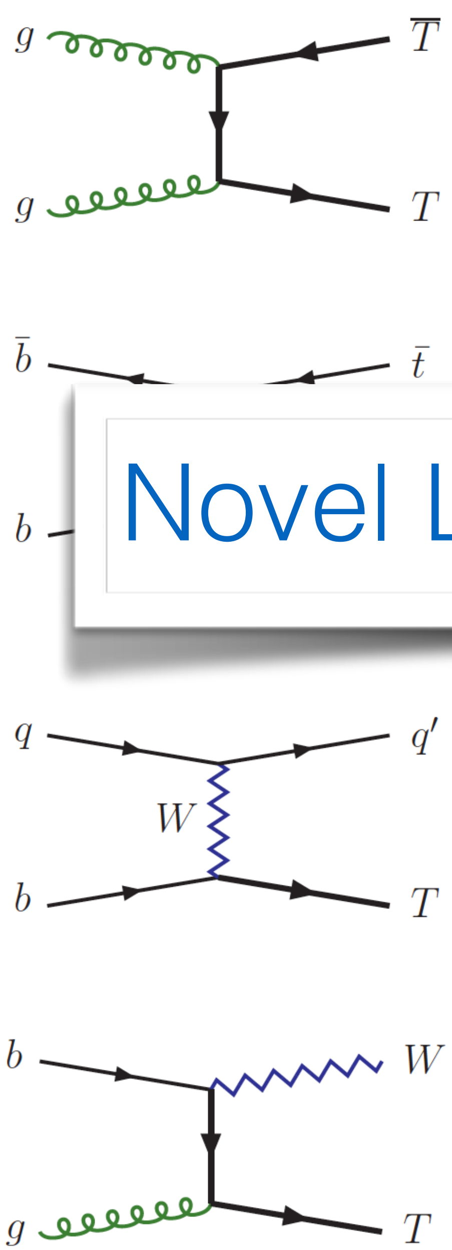

Novel LHC phenomenology for T searches