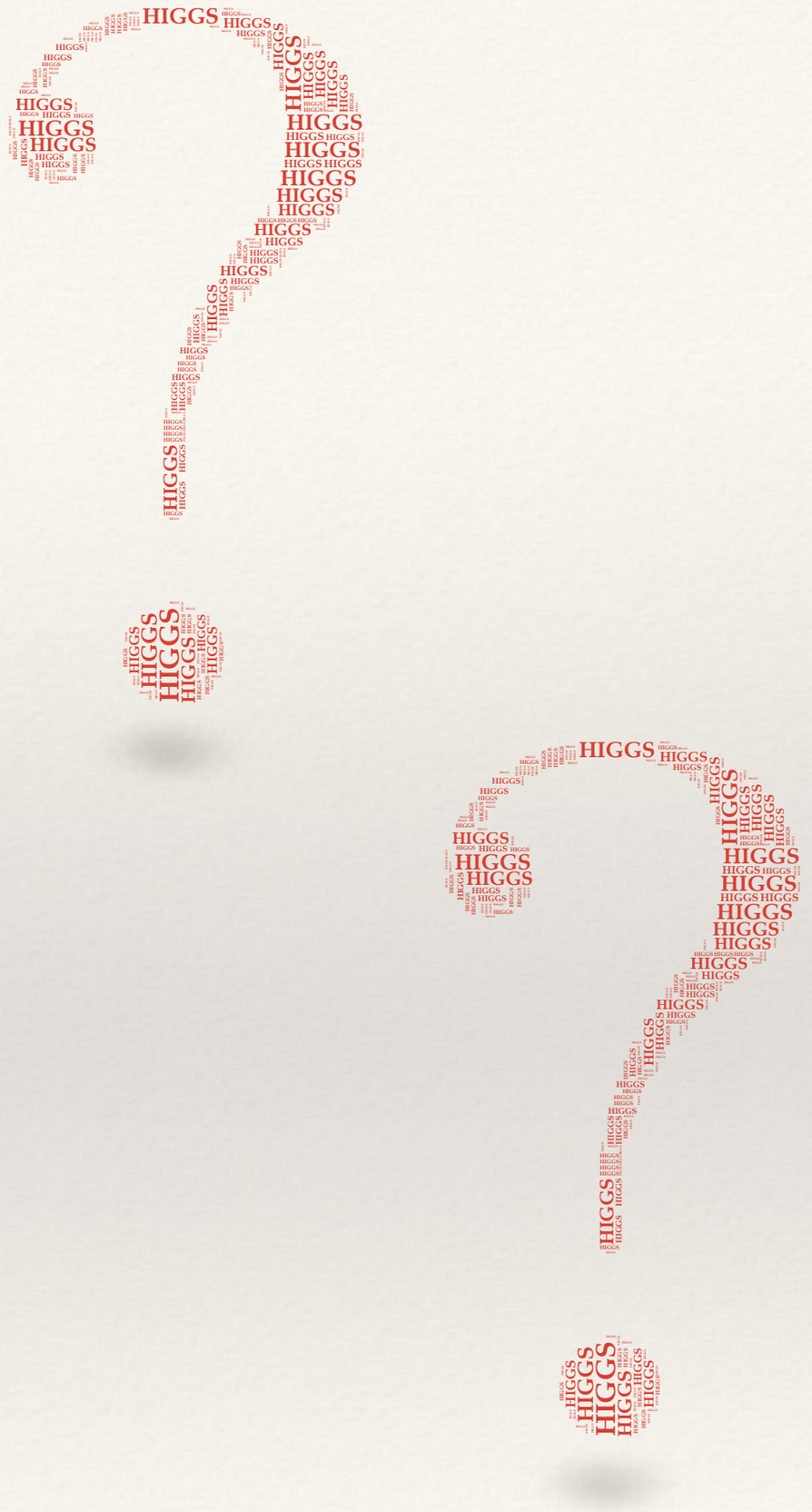
Christoph Englert

Open issues in Higgs physics

UK HEP Forum
"Future Colliders"

13.11.2014



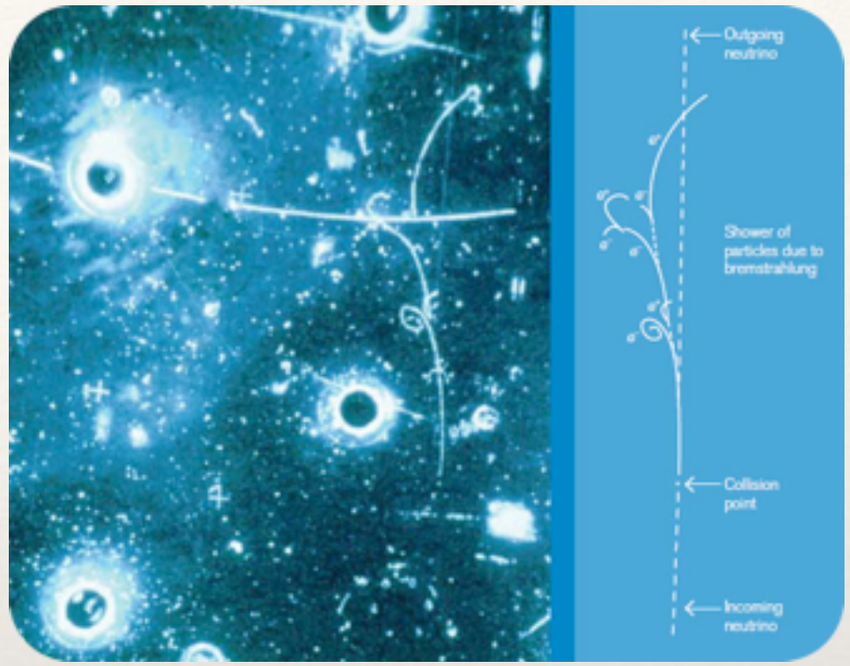
"Yang-Mills+Higgs had to be true"

`t Hooft, "Under the Spell of the Gauge Principle"

Ws and Zs in 1983 at UA1/UA2

$$m_W \simeq 80.42 \text{ GeV}$$

$$m_Z \simeq 91.19 \text{ GeV}$$



How do you accommodate this in QFT ?

[Weinberg `67]

☛ answer to this in 1964 [Higgs `64] [Brout, Englert `64] [Guralnik, Hagen, Kibble `64]

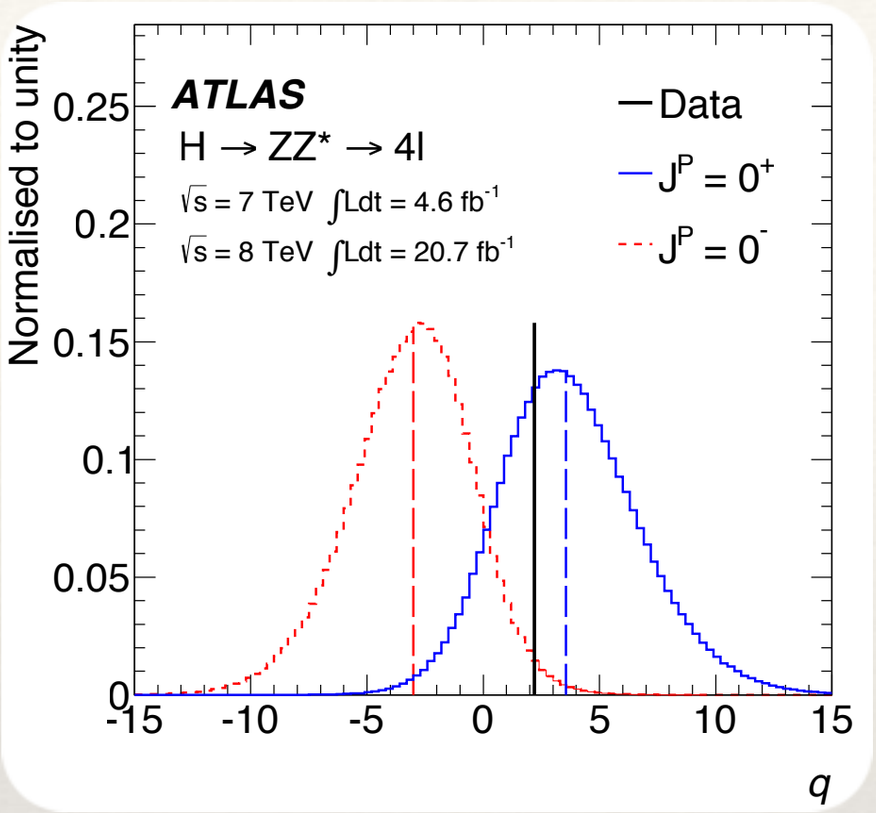
- non-linear realisation of gauge symmetry in a Yang Mills+scalar sector is compatible with $\langle H \rangle \neq 0$

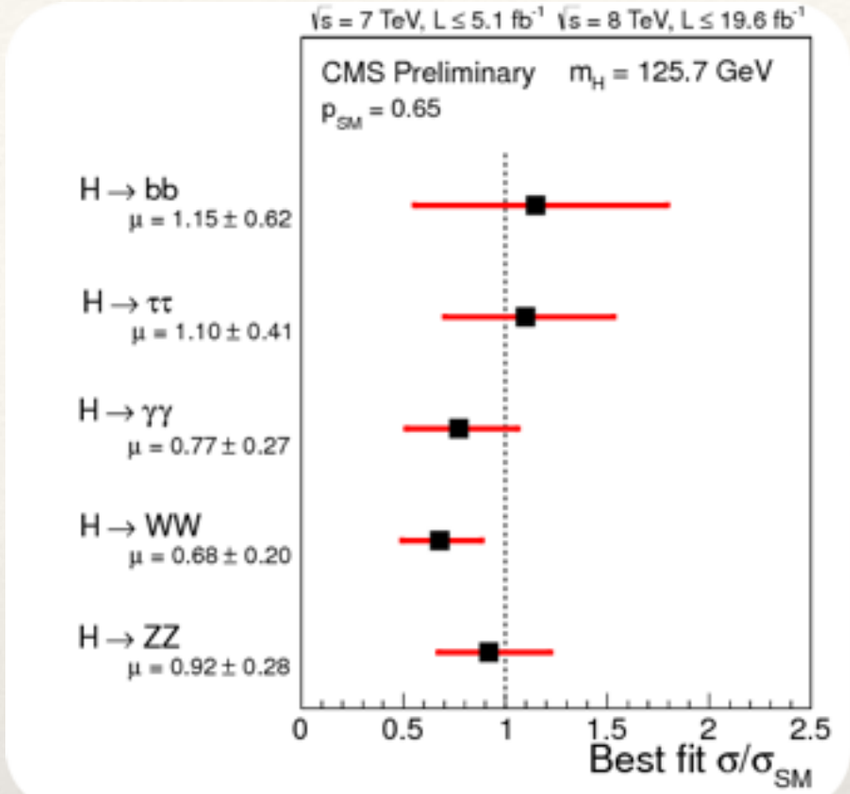
☛ "spontaneous" symmetry breaking

- massive gauge bosons, but no ghost problems at small distances

☛ renormalizability, unitarity

“Yang-Mills+Higgs had to be true”





SM seemingly complete after July 4th 2012, evidence for $J^{CP} = 0^+$ and couplings to (longitudinal) massive gauge bosons

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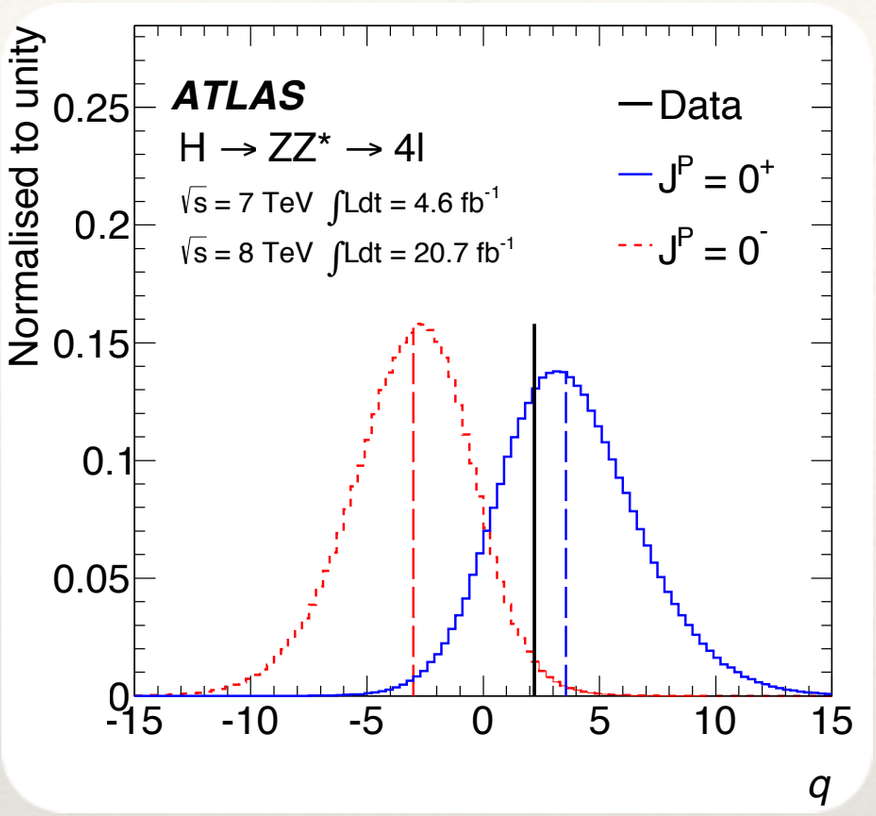

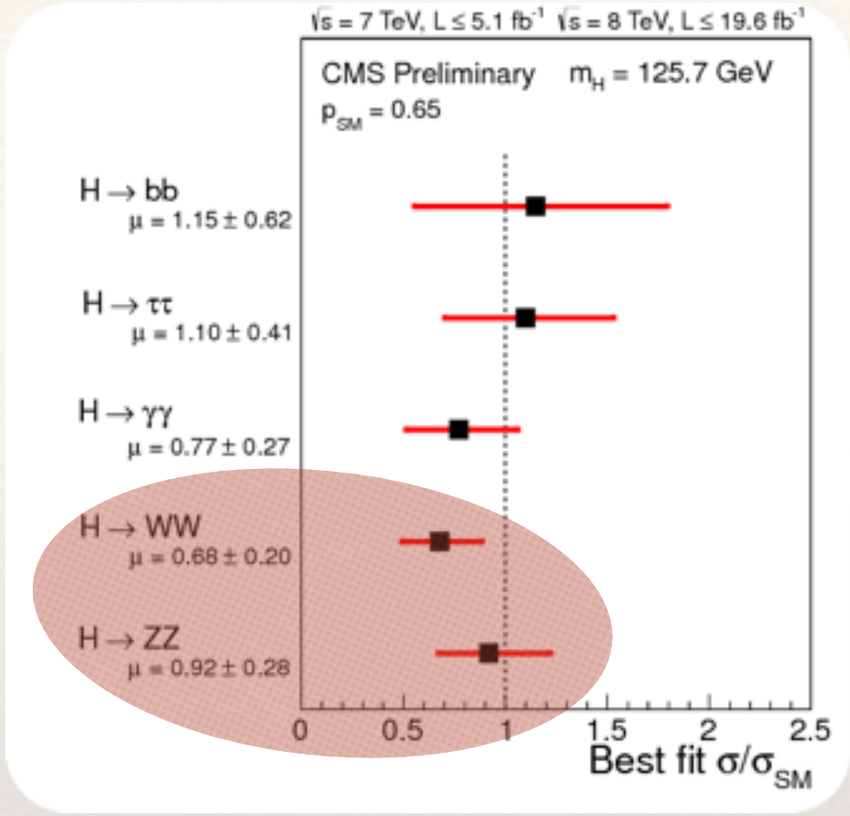

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Higgs properties *sui generis*:

particle relates to unitarity conservation and an excitation of an isotropic and translationally invariant background field.

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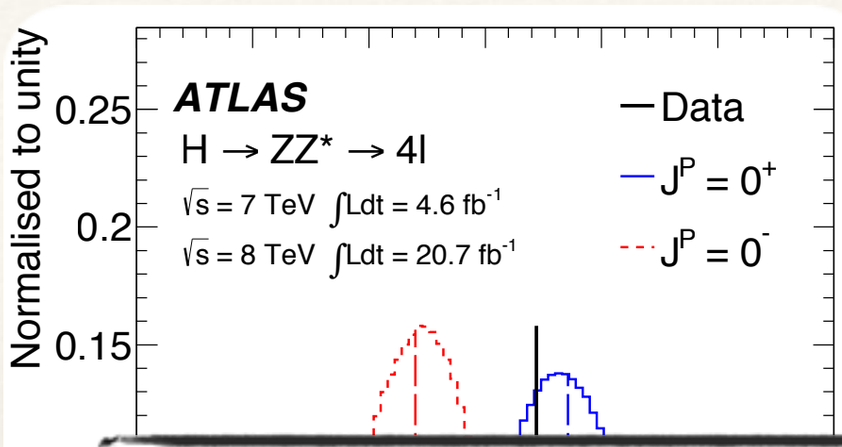

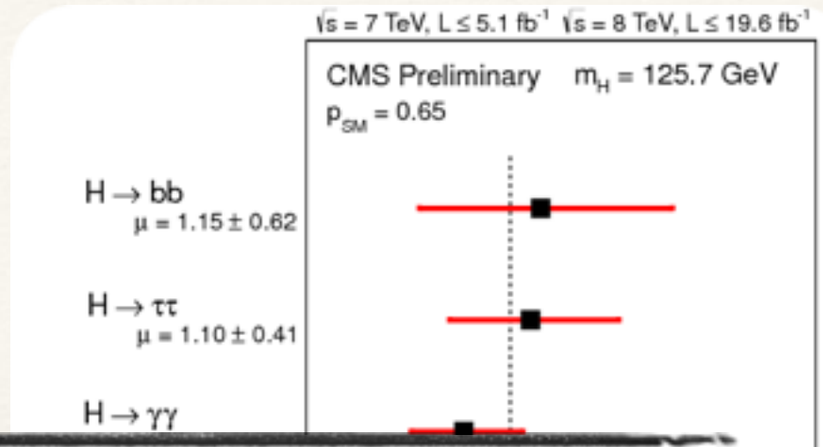

"Yang-Mills+Higgs IS true"

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Higgs properties *sui generis*:

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What's the Higgs we are dealing with??

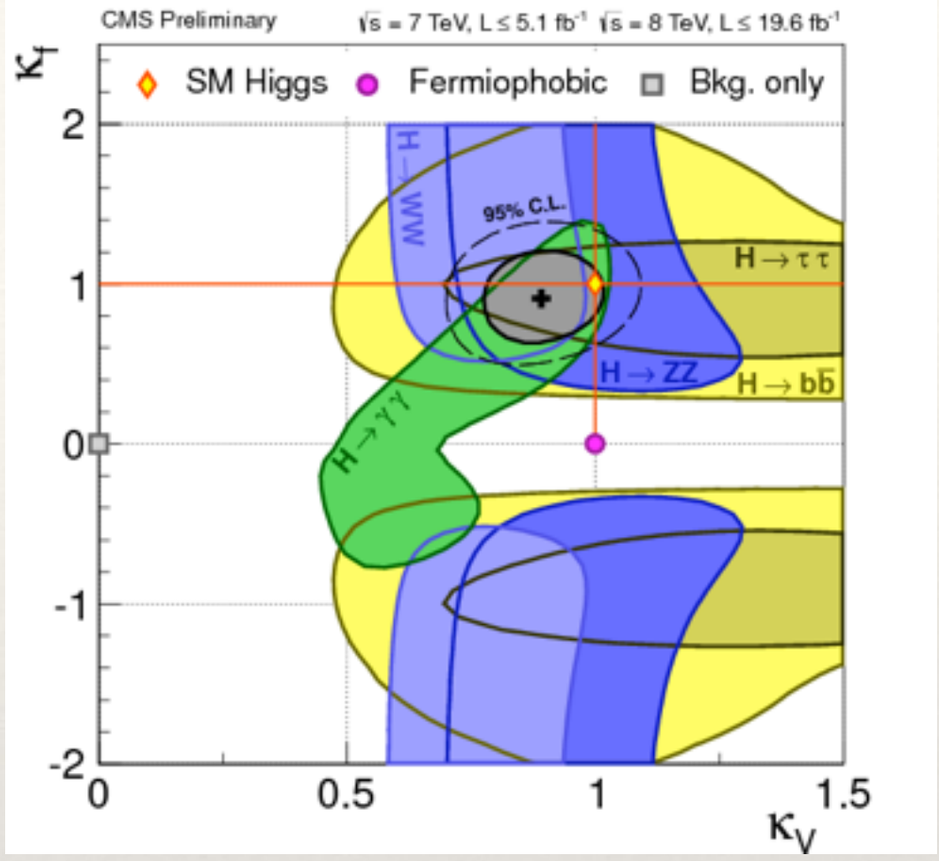
Is it a doublet?

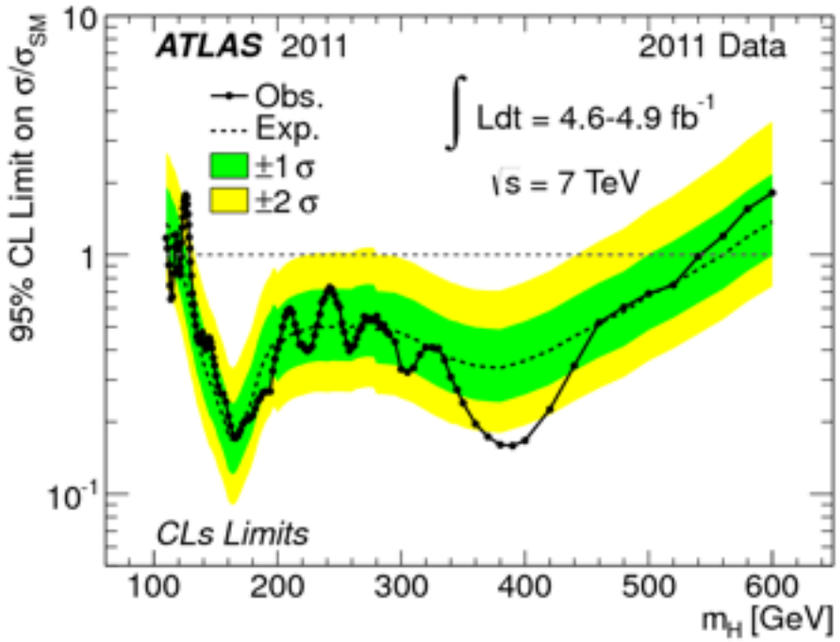
Is there more than just a (SM) Higgs?

Is there a relation with dark matter?

What triggers symmetry breaking?

What can we say about all that at the end of the high luminosity phase and how can future colliders help us?





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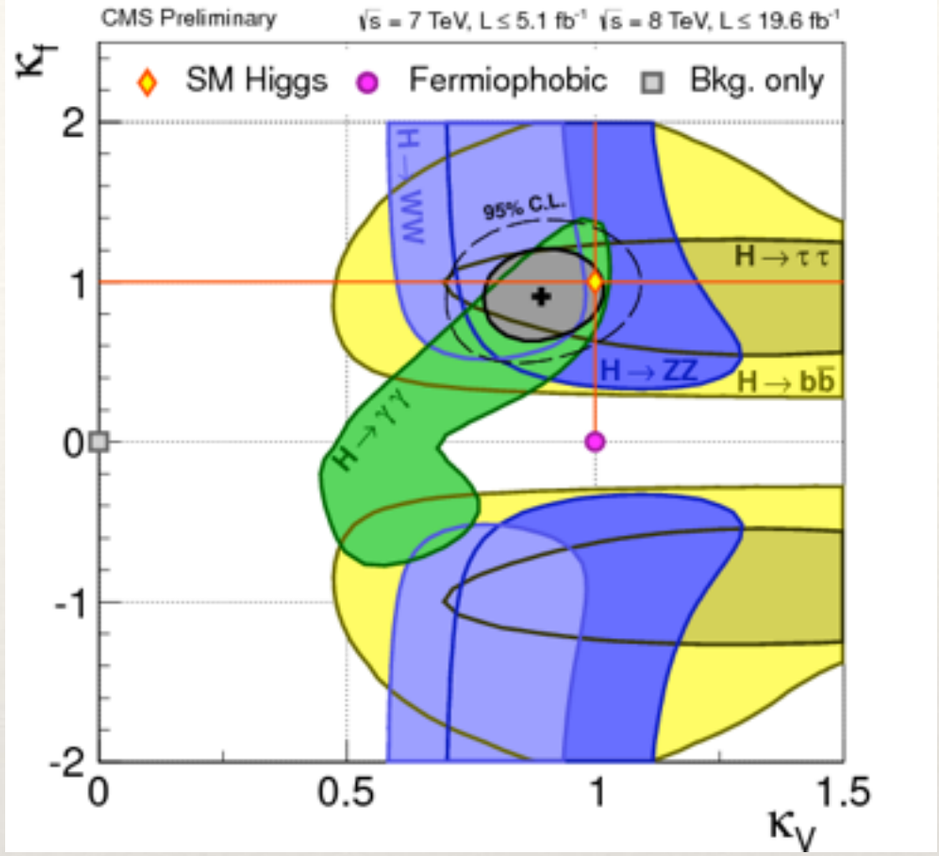

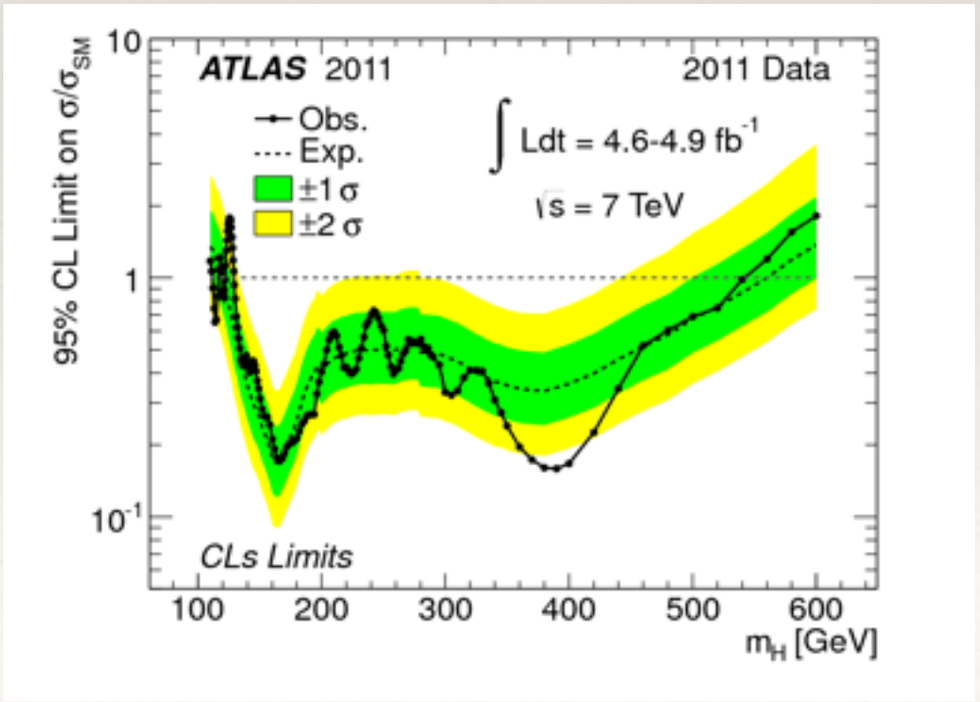

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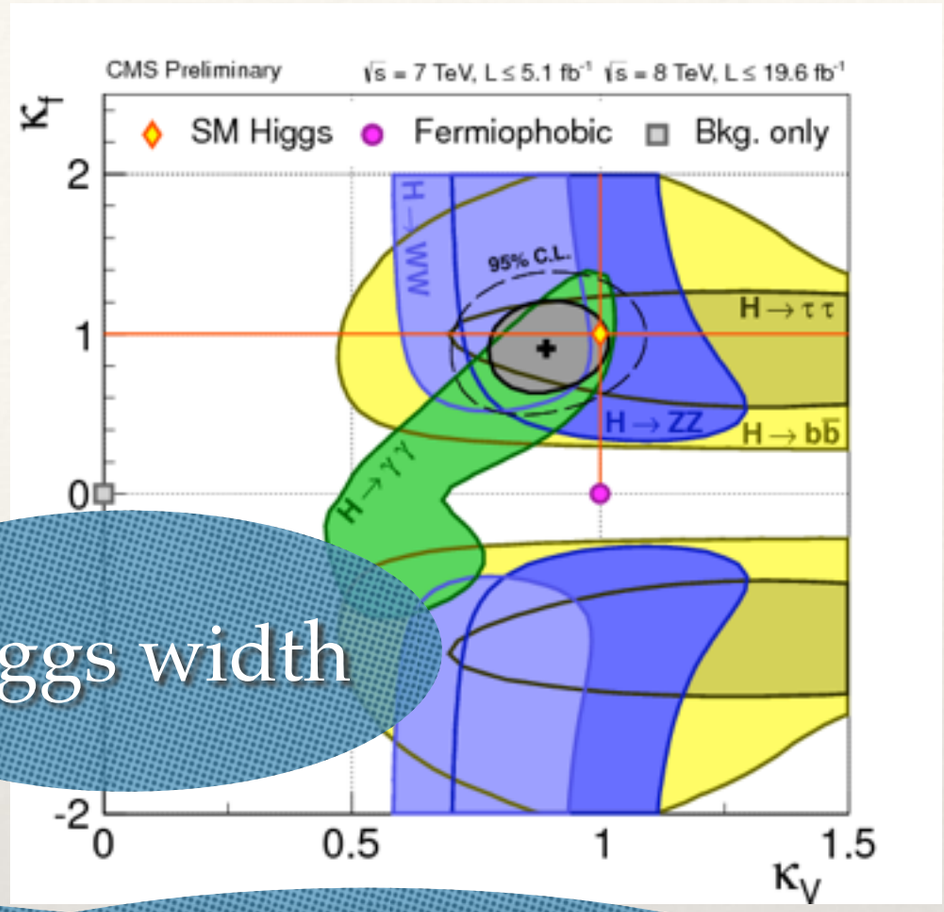
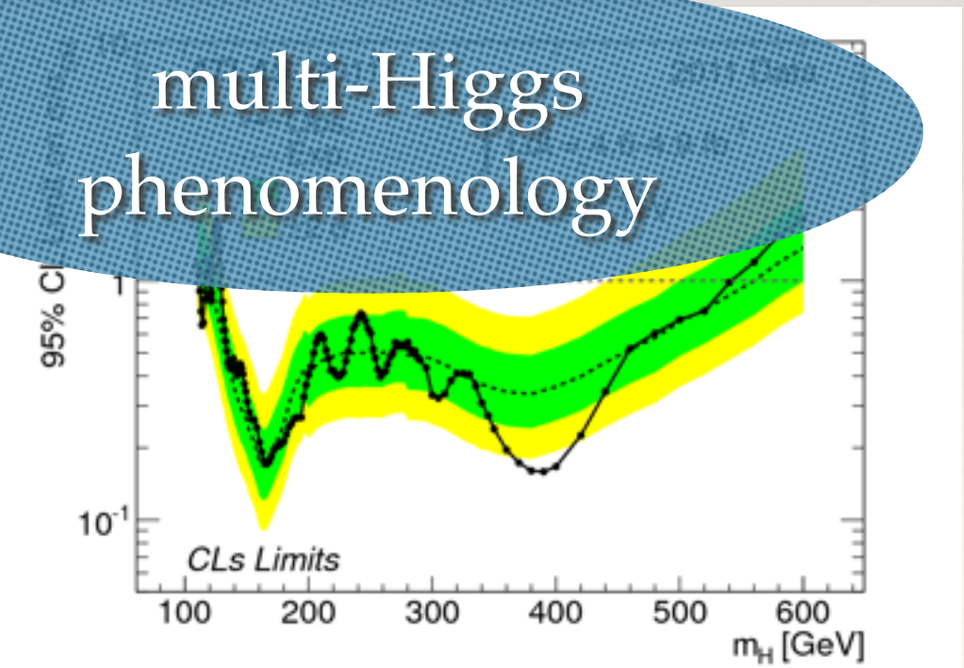
Higgs EFT

Higgs width

multi-Higgs phenomenology





Fingerprinting the Higgs

Is there evidence for new degrees of freedom?

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→ *Verónica's talk*

No.

Yes.

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Higgs Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

[Buchmüller, Wyler `87] [Hagiwara, Peccei, Zeppenfeld `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

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concrete models

- **Higgs portals**
- (N)MSSM
- compositeness
- …

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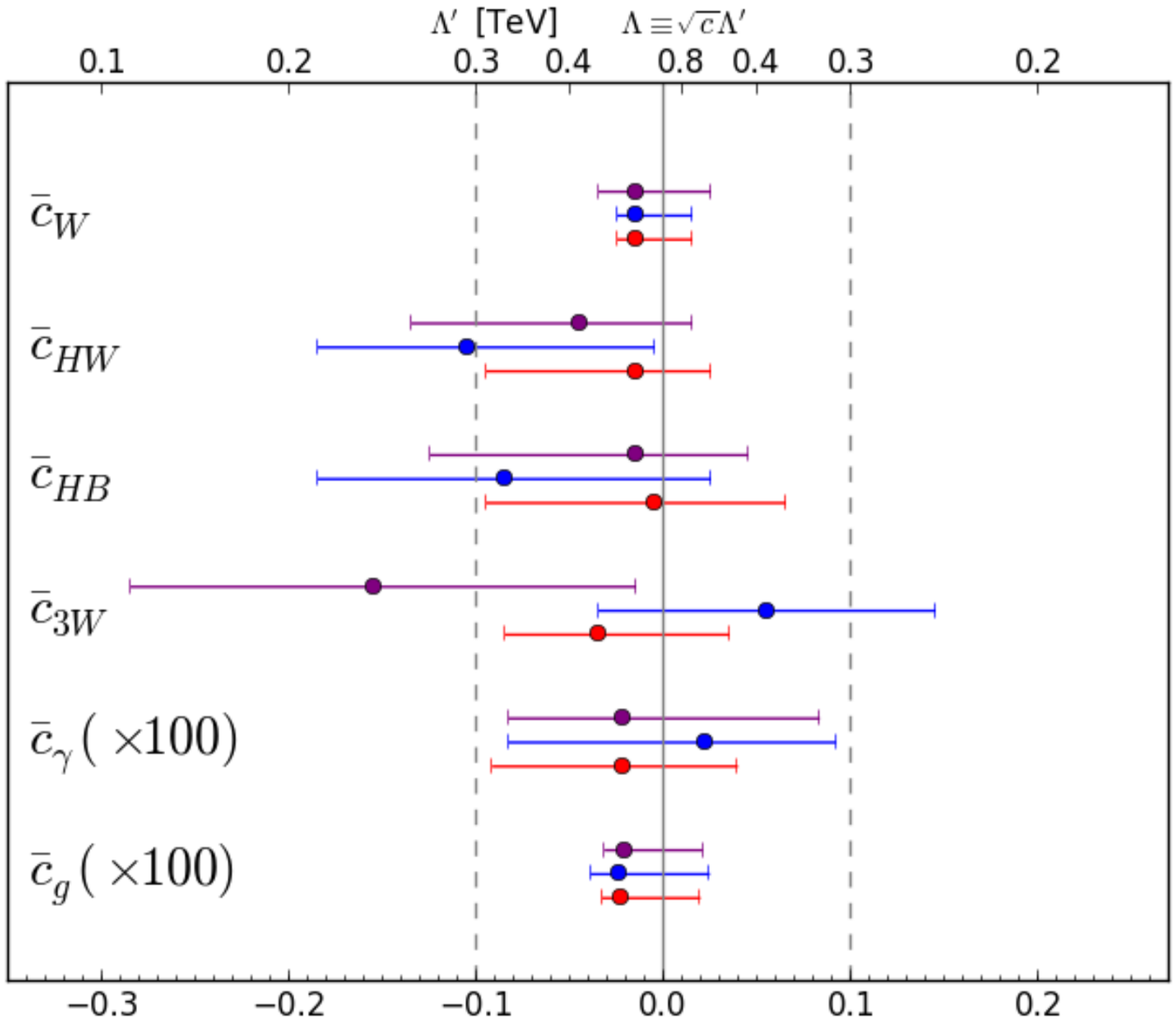

[Ellis, Sanz, You ` 14]

see also [Ellis, You ` 12][Masso, Sanz ` 12]
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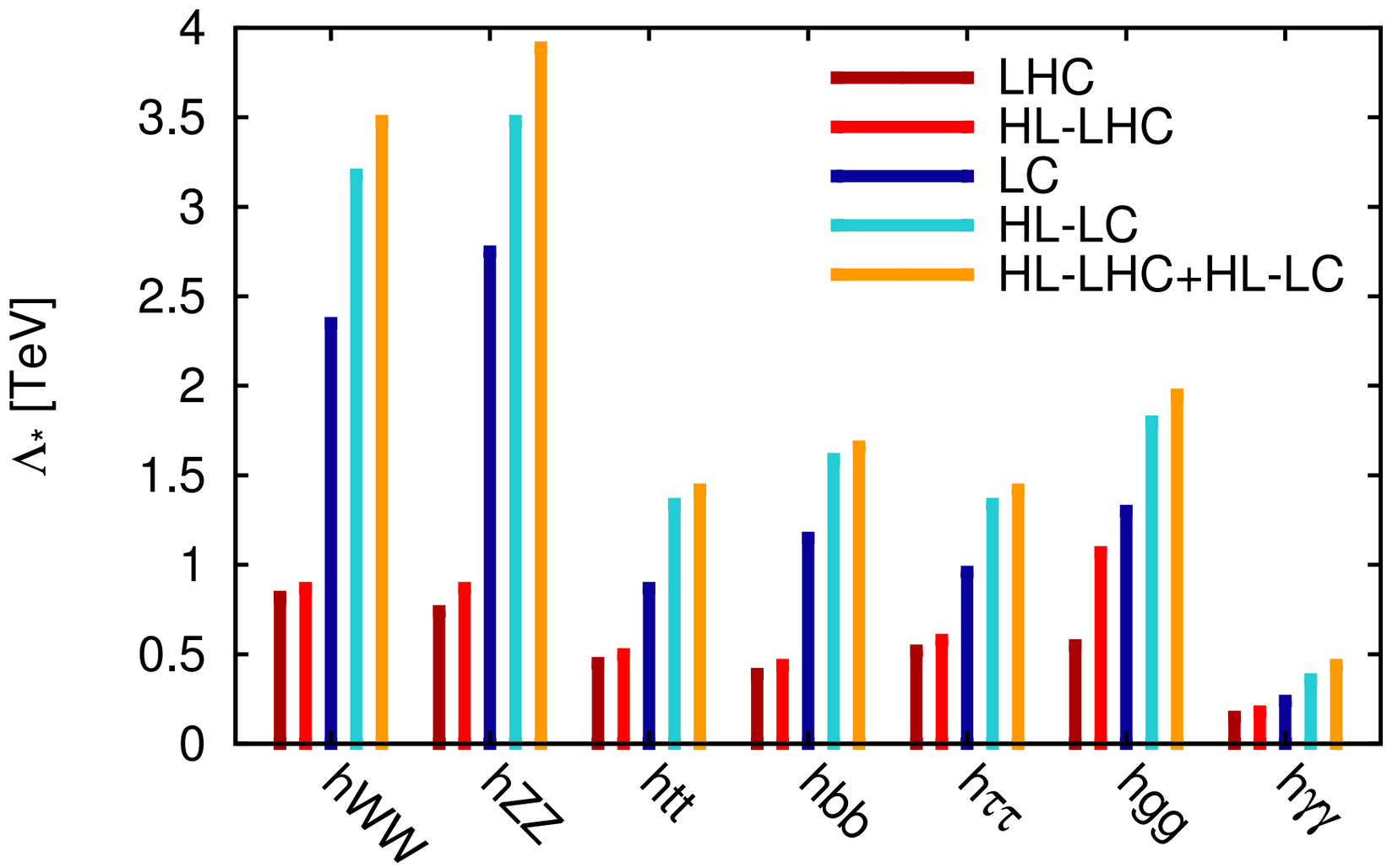
[Espinosa, Grojean, Mühlleitner, Trott ` 12]

How high can we go?

$\mathcal{O} \sim v^2/\Lambda_*^2$



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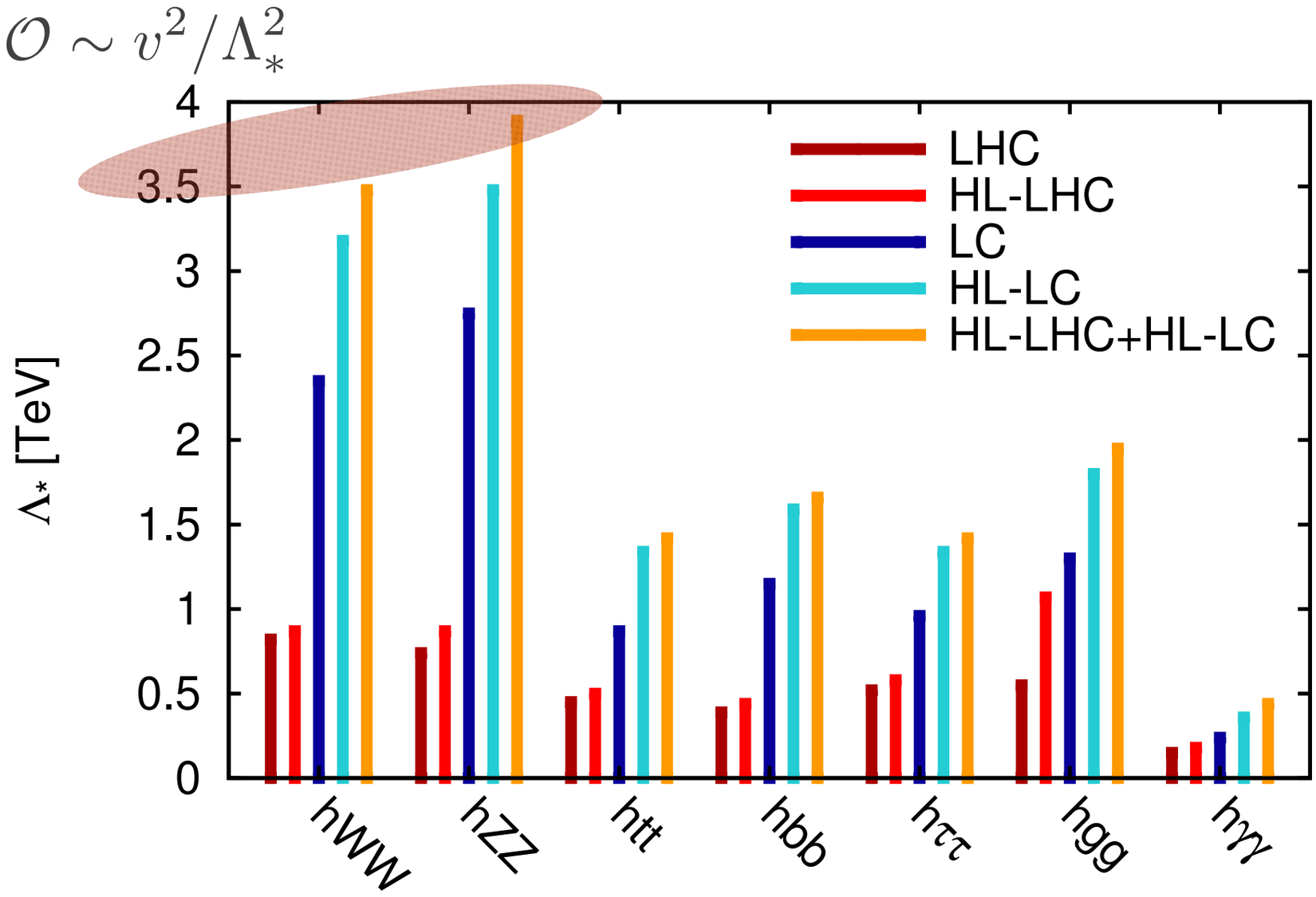

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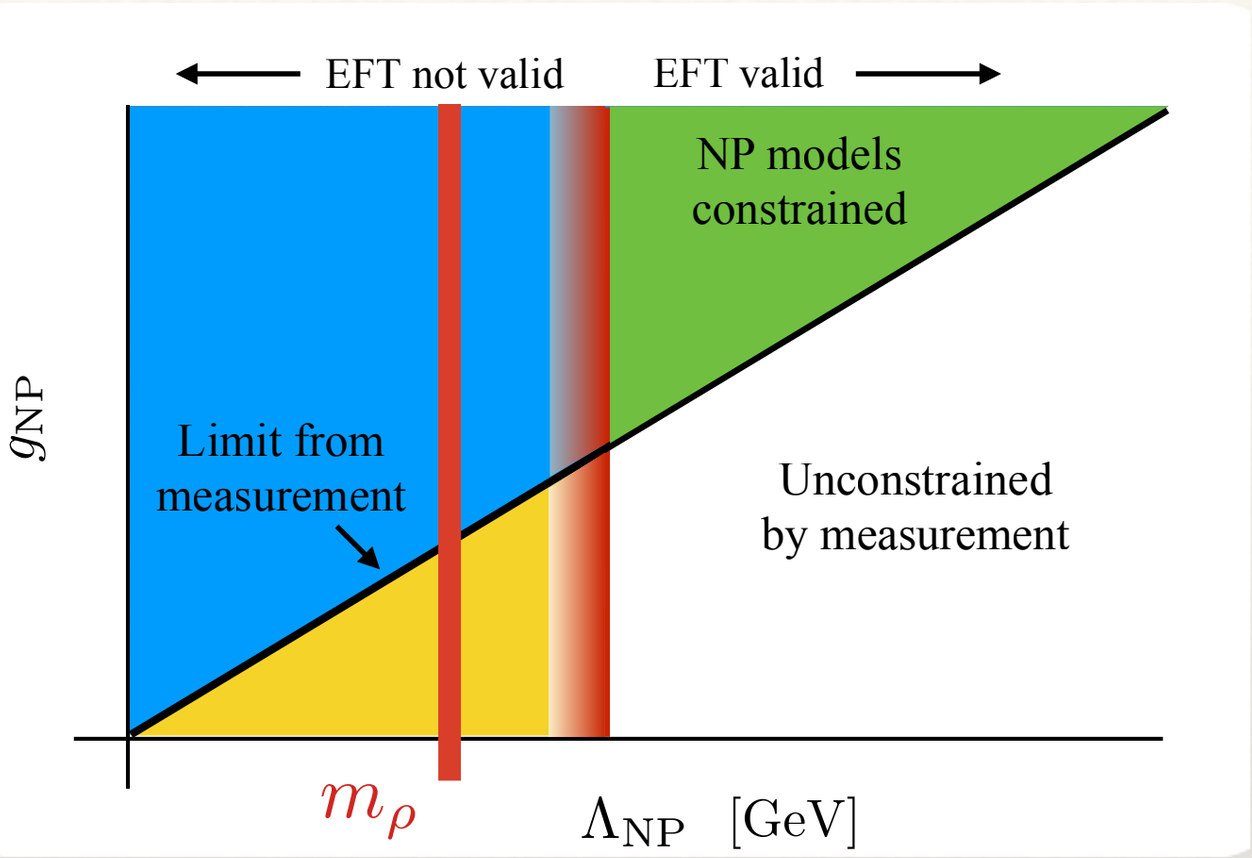

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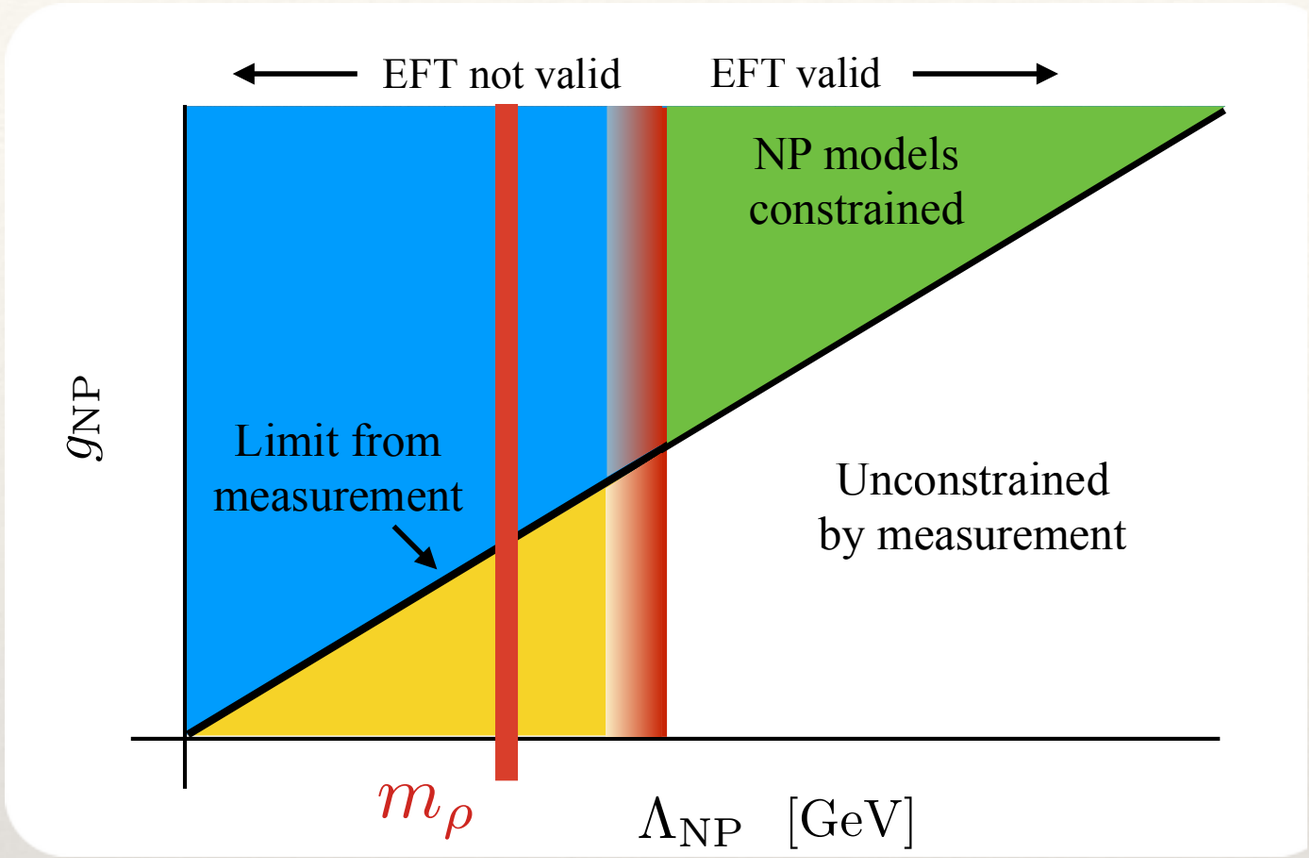

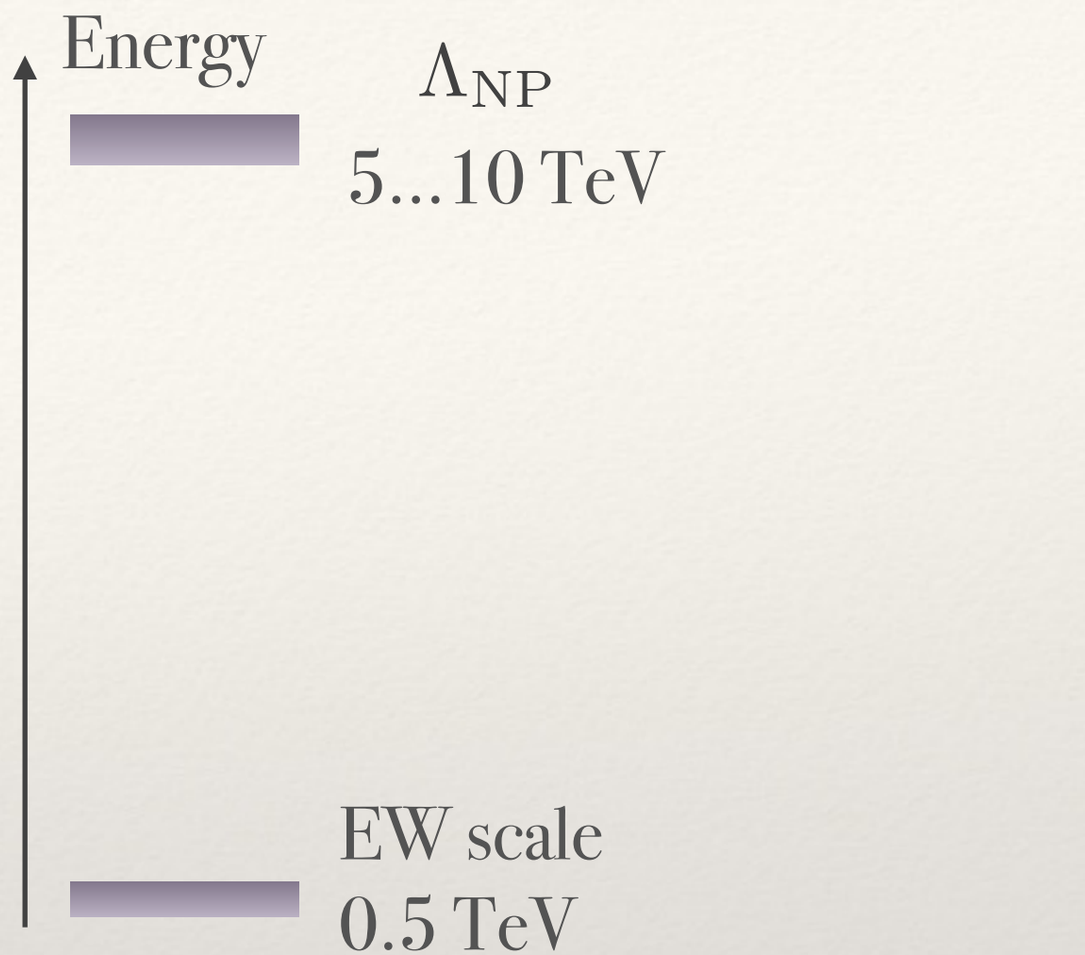

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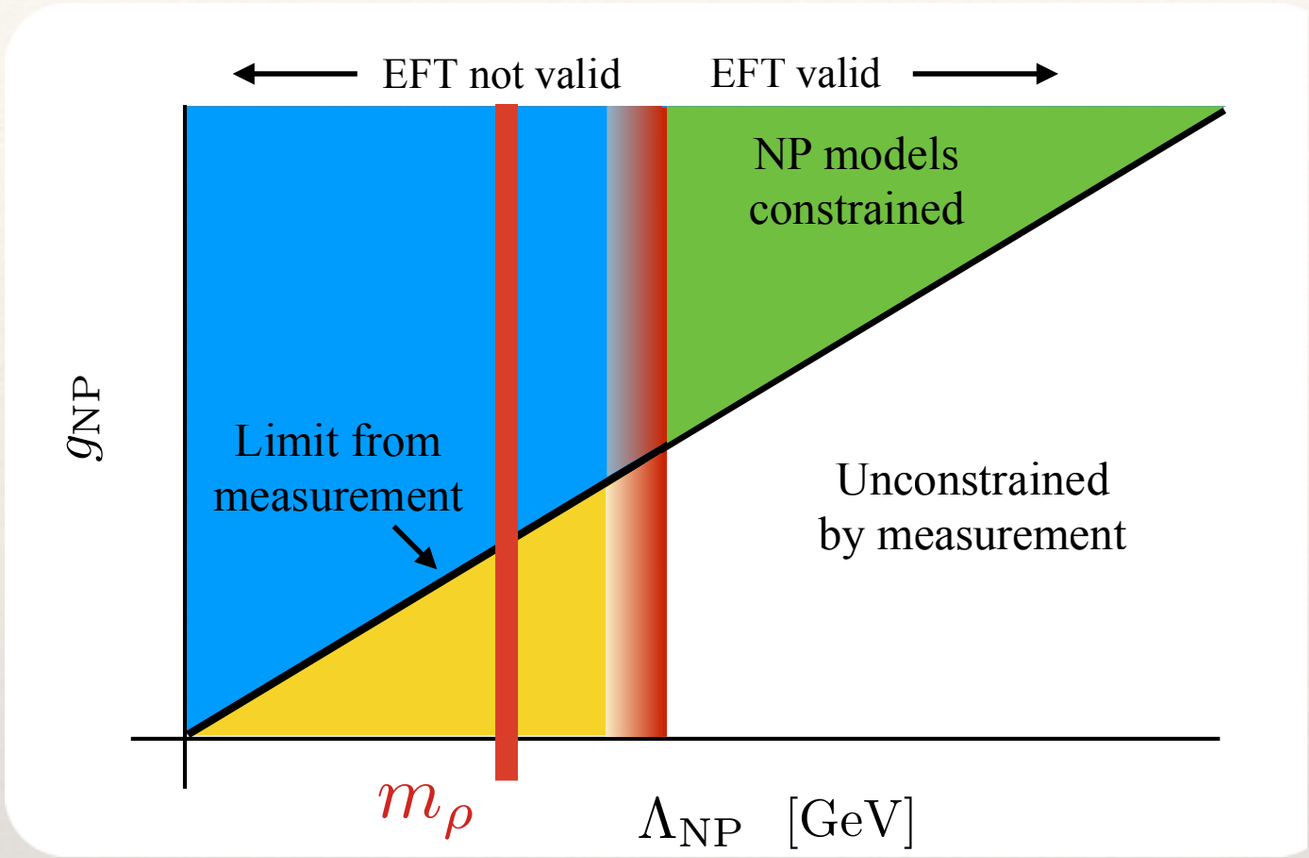

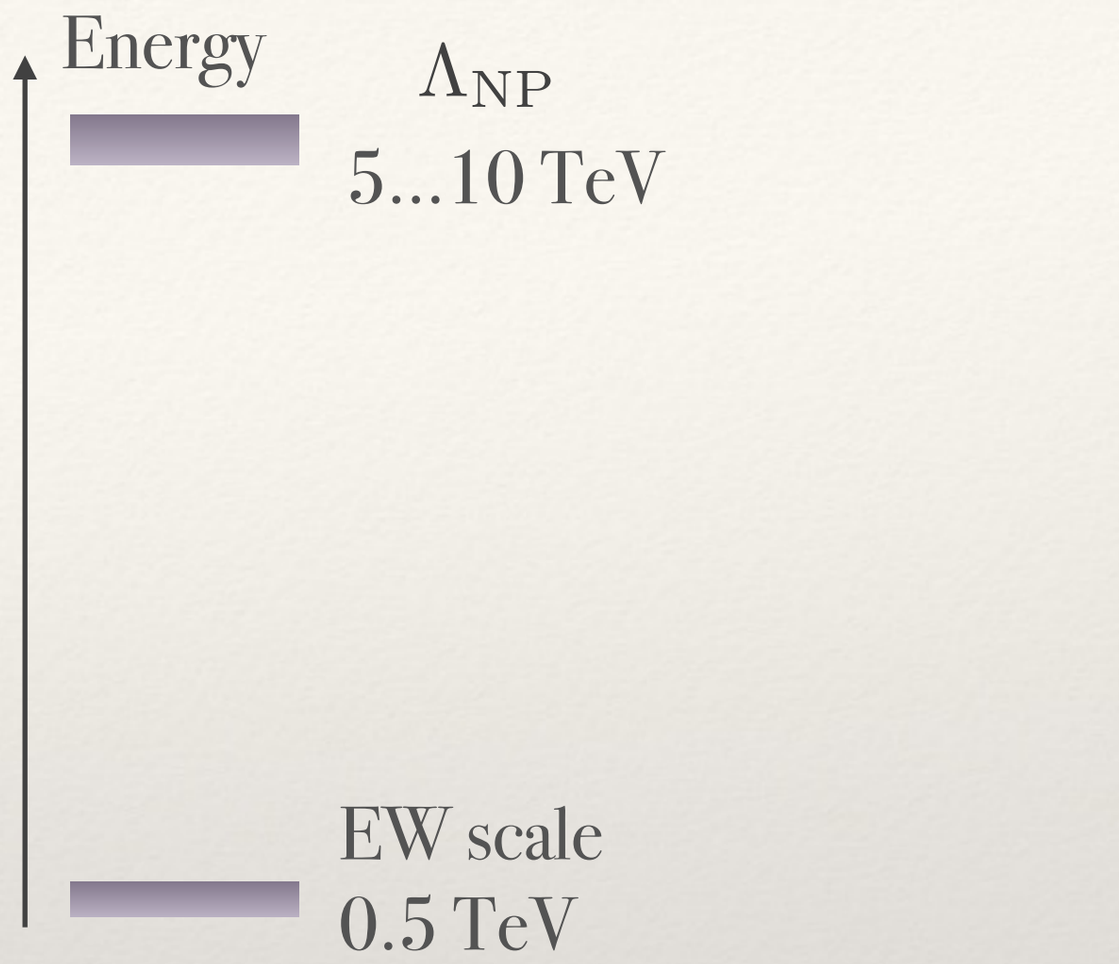

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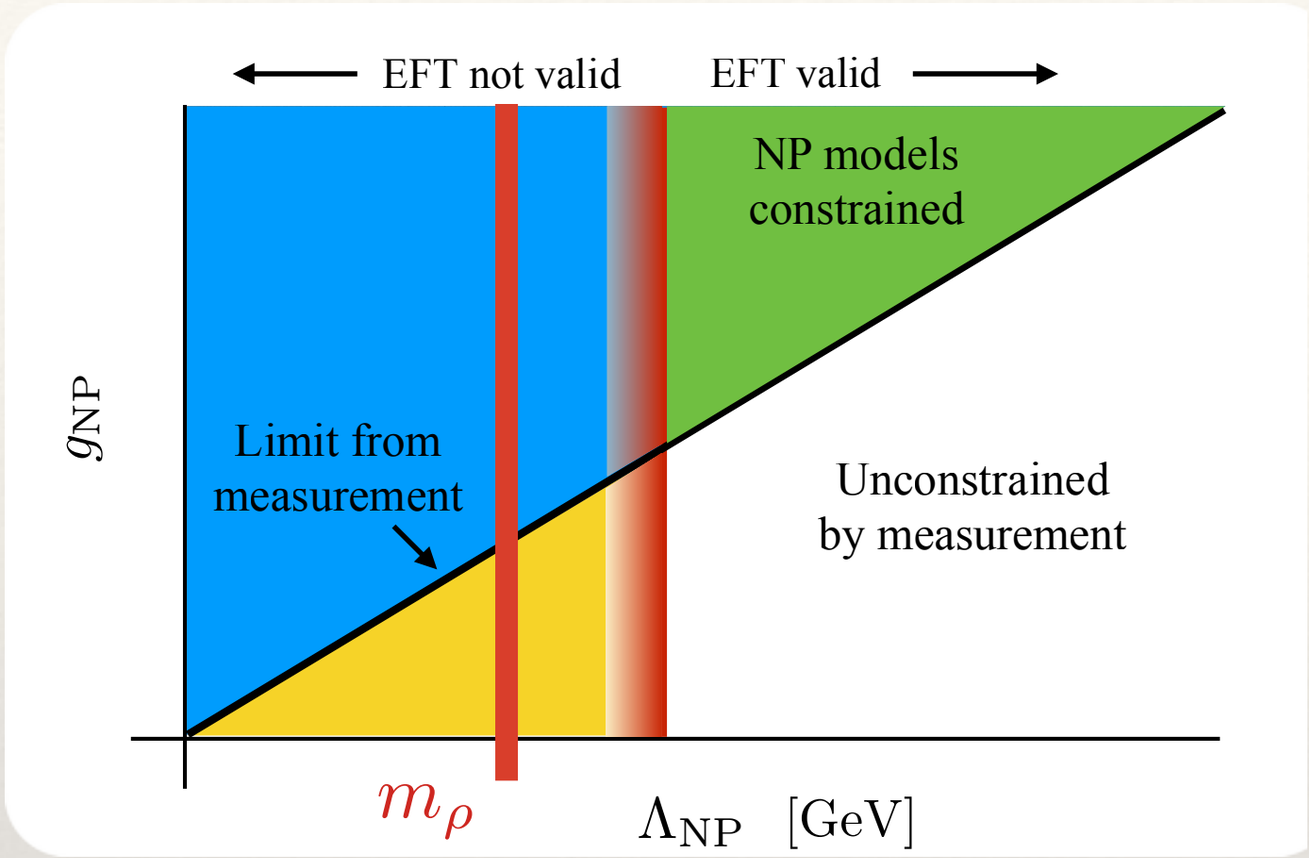

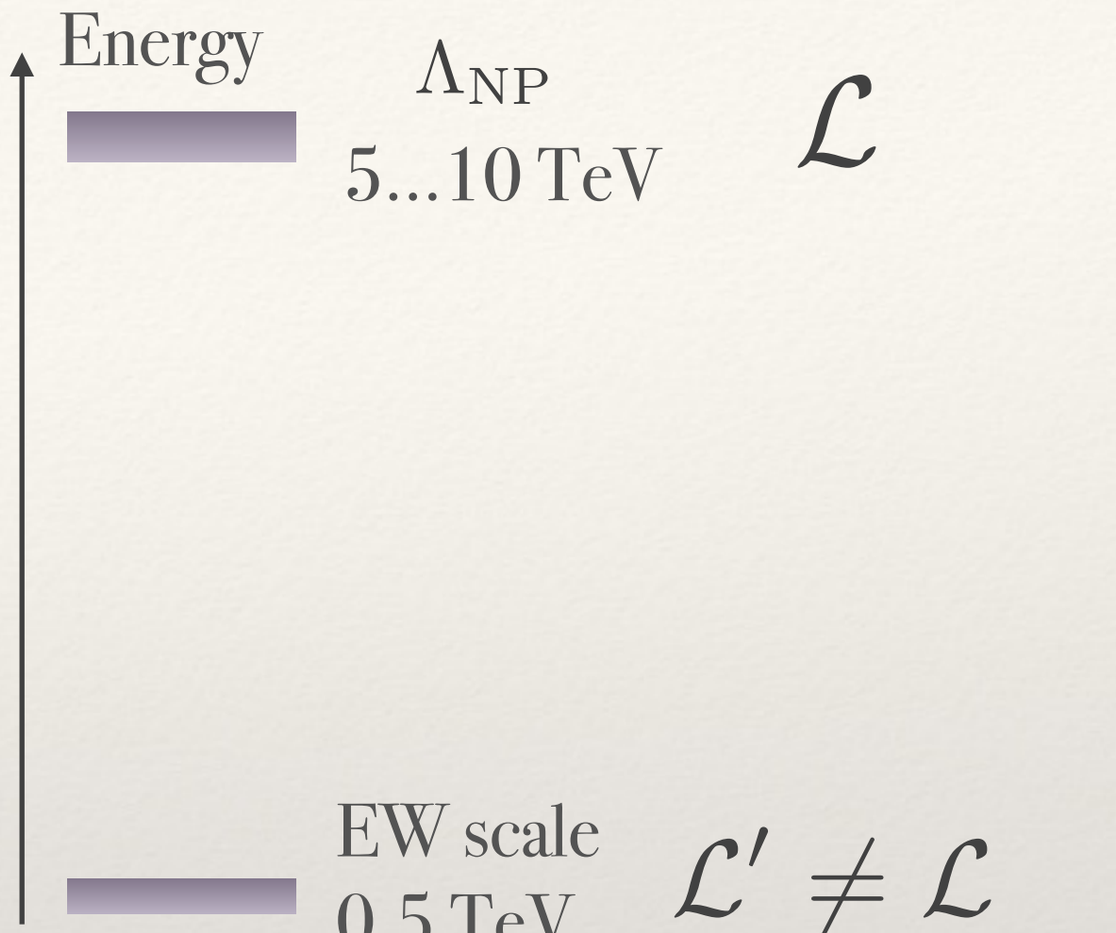

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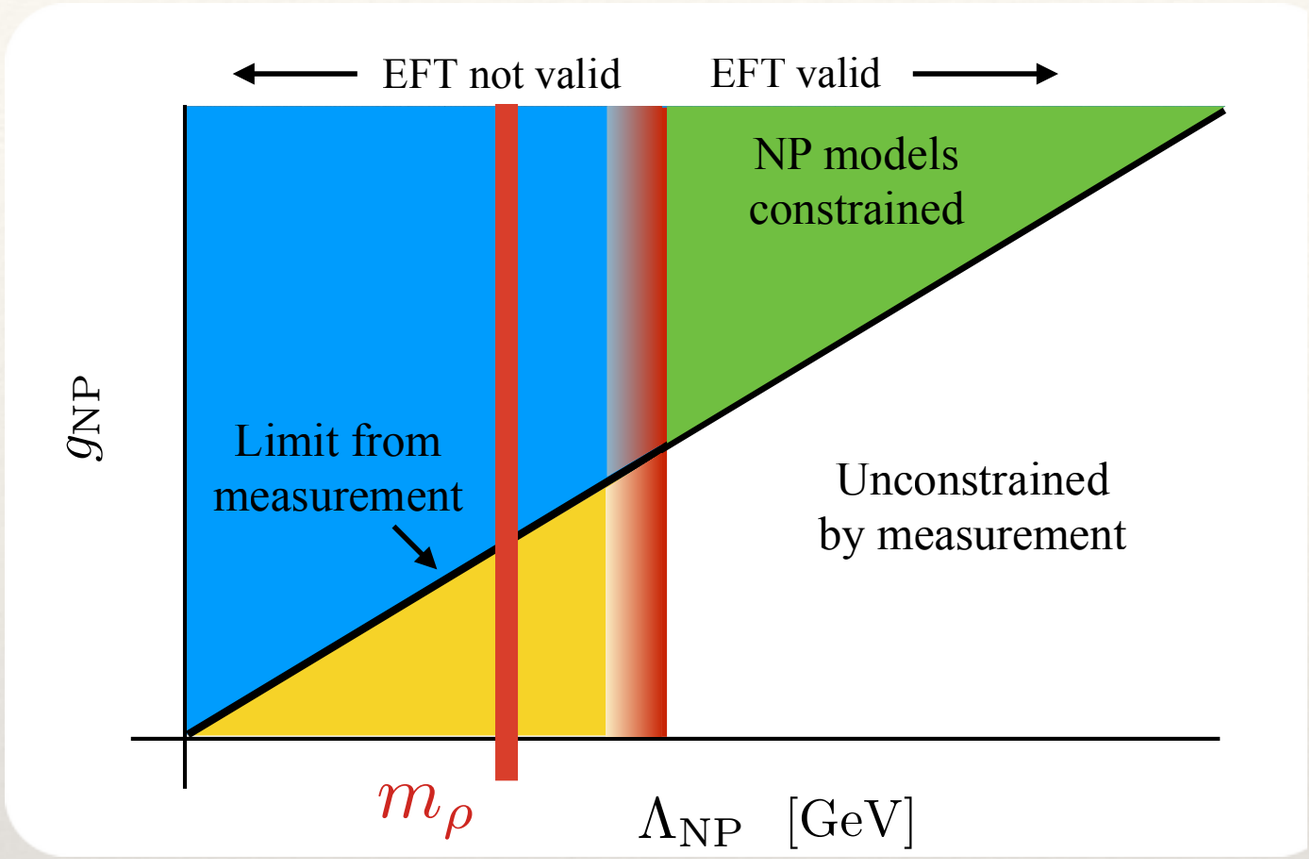

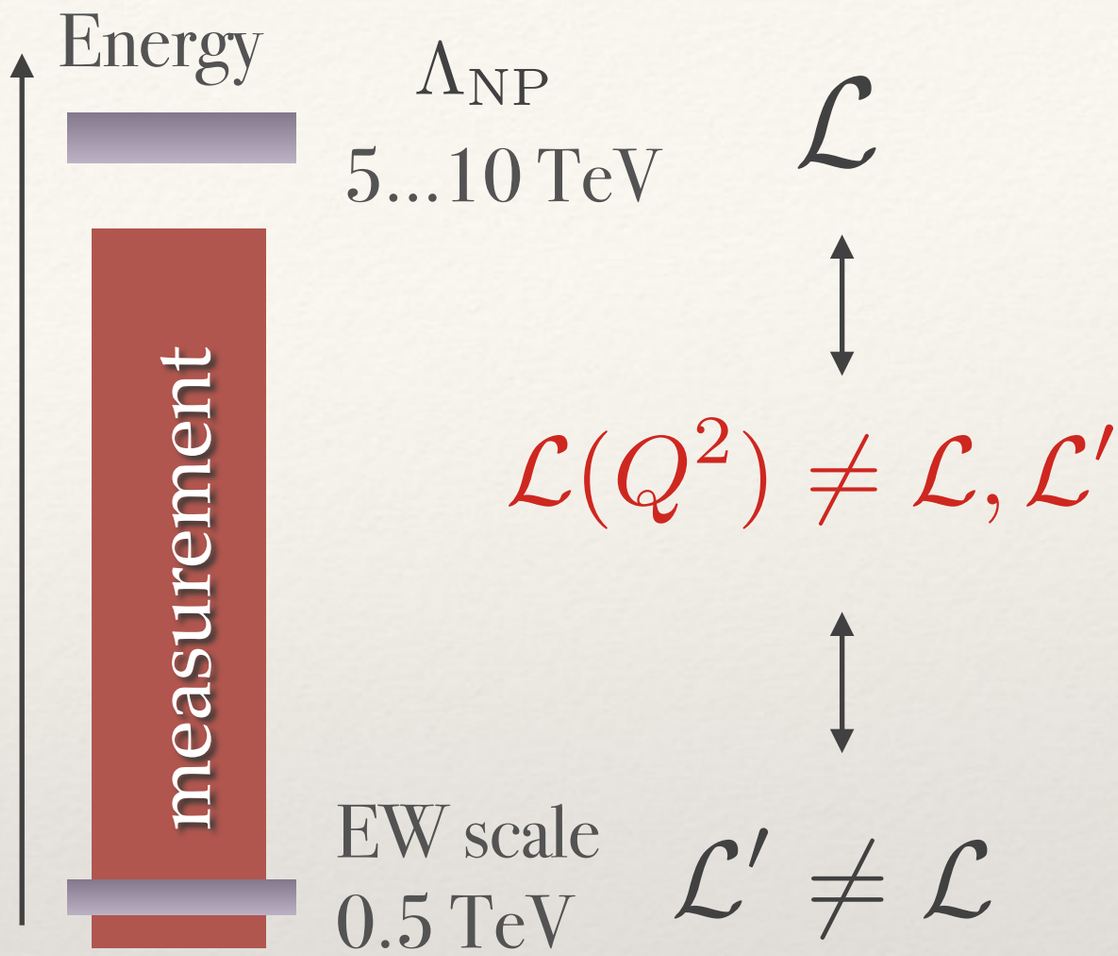

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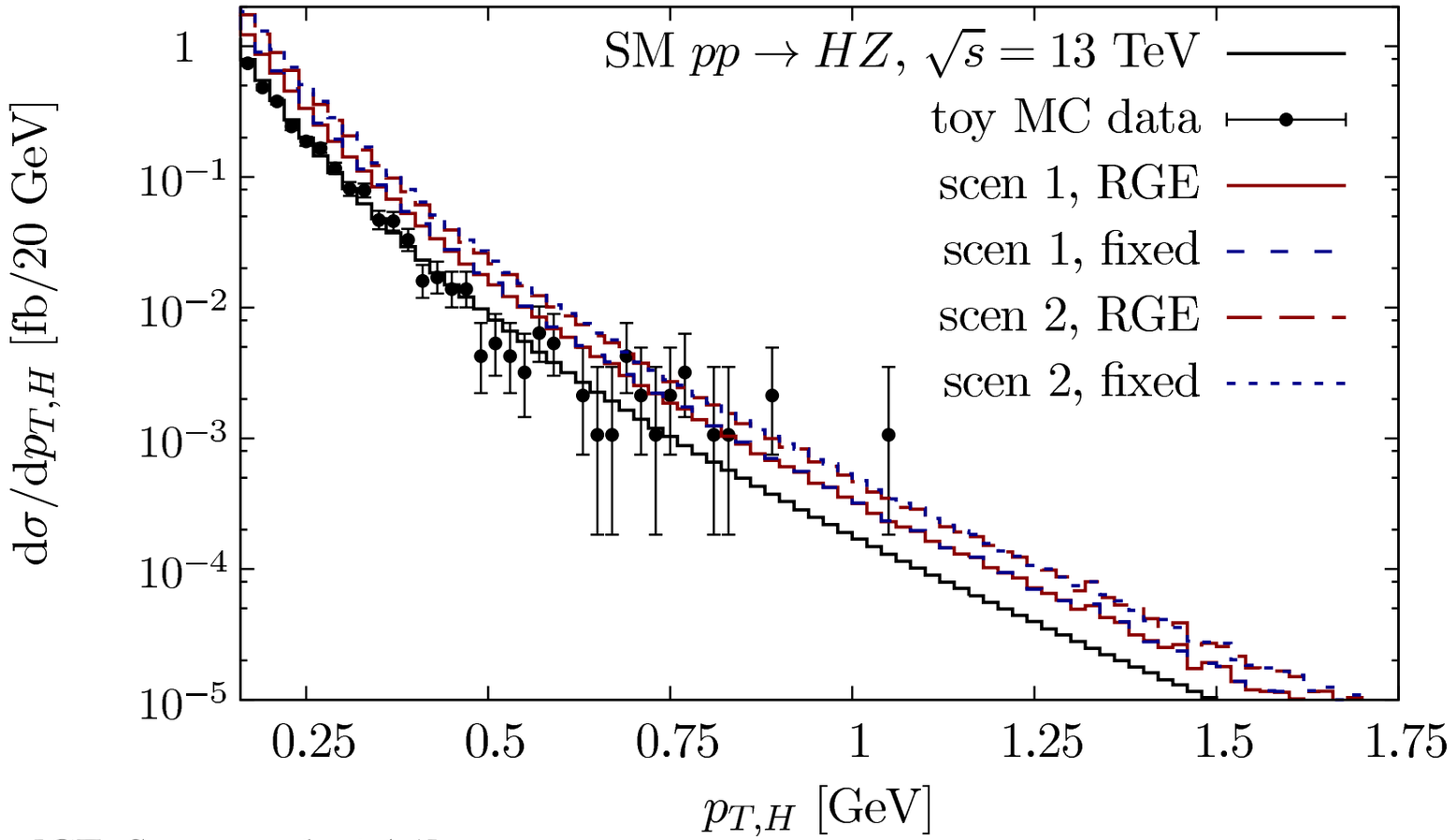

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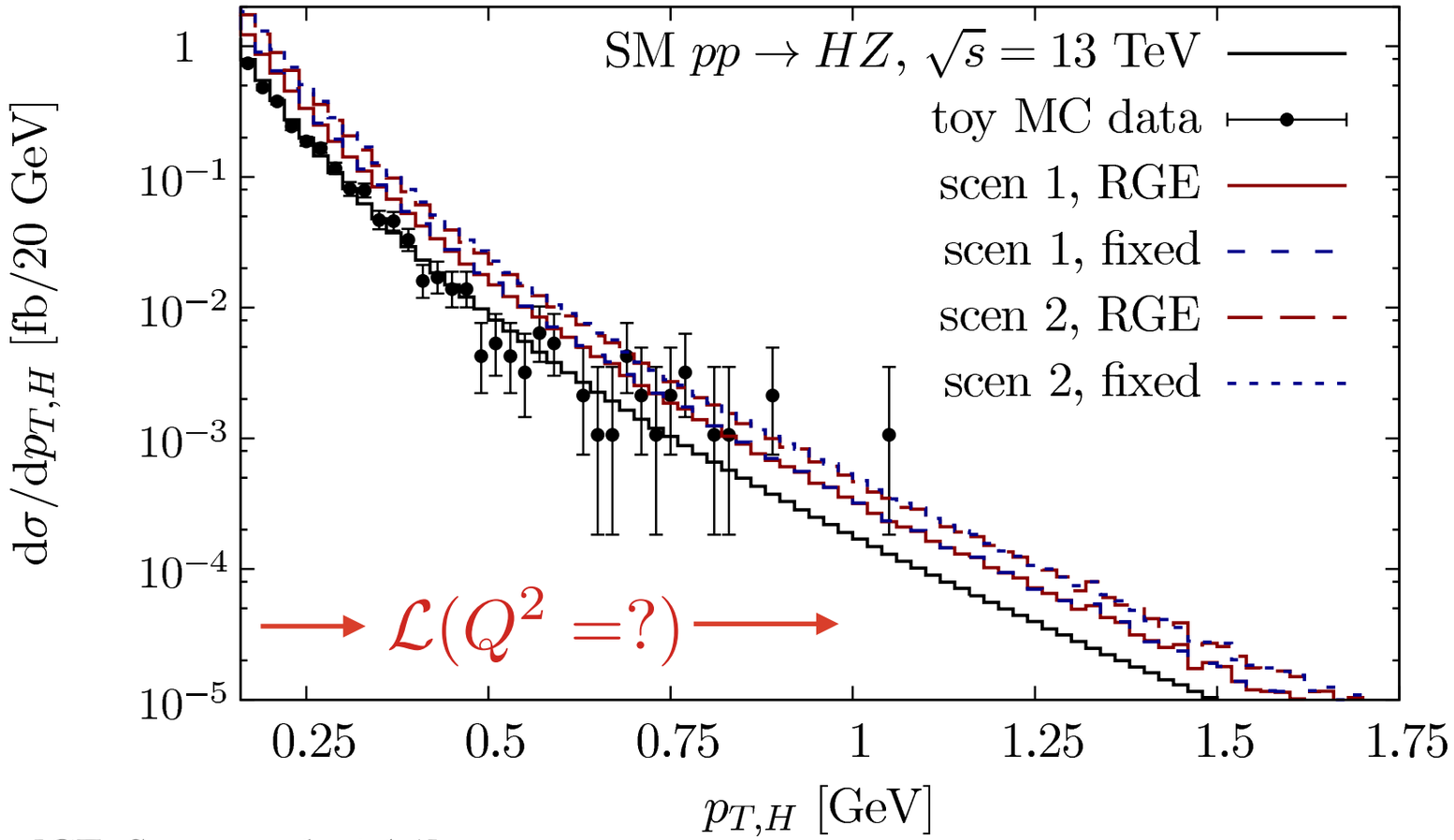

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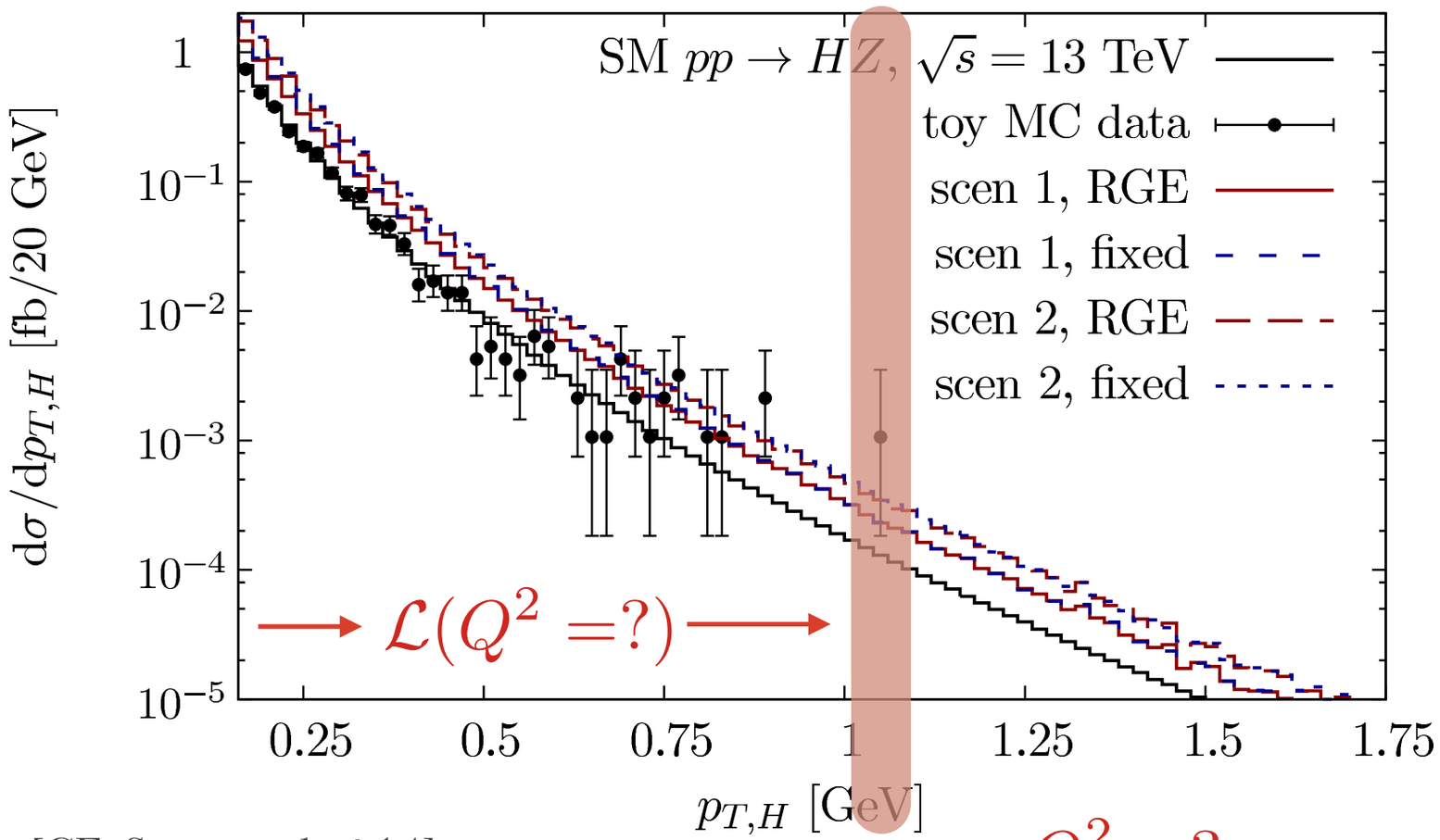

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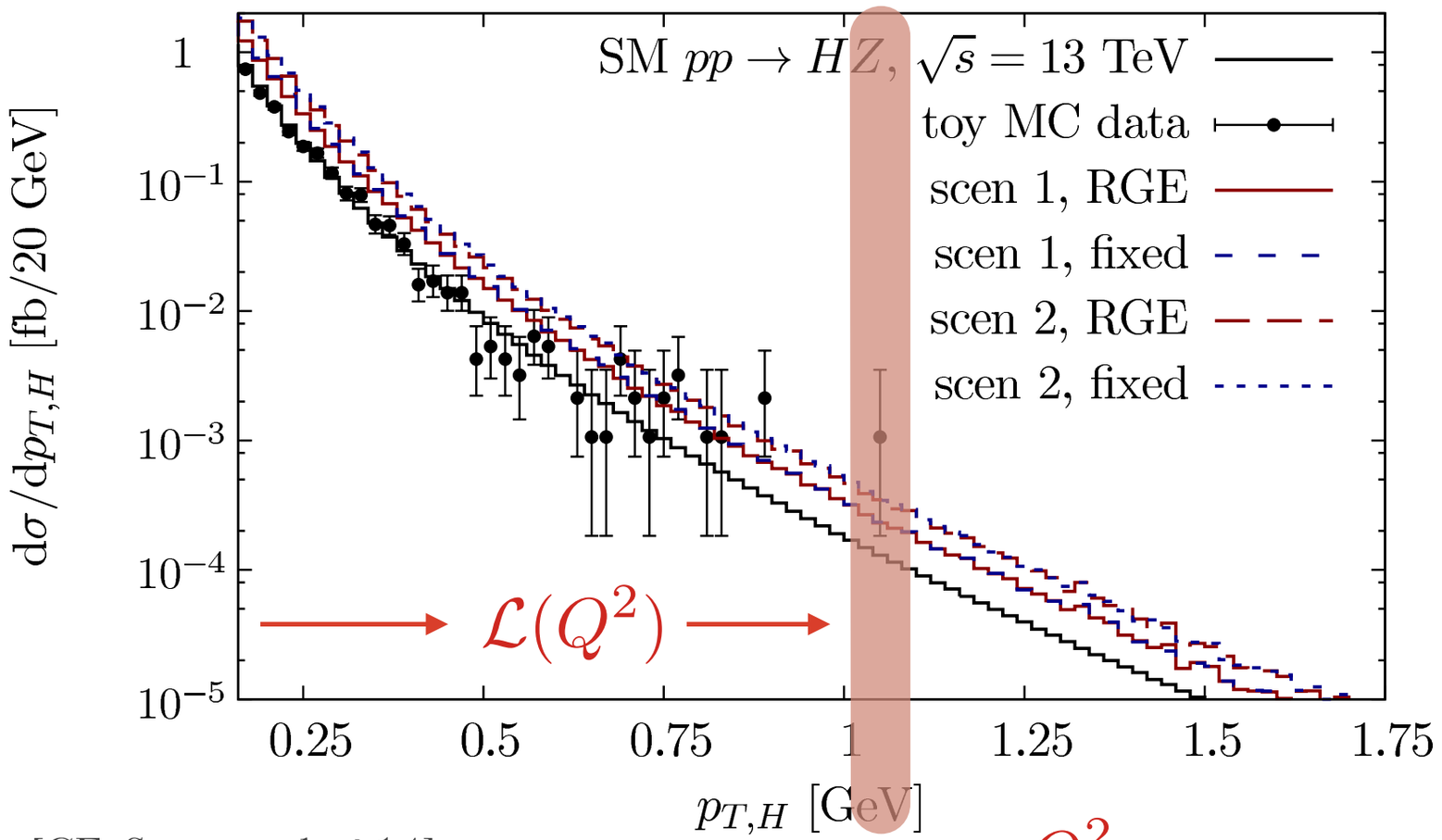

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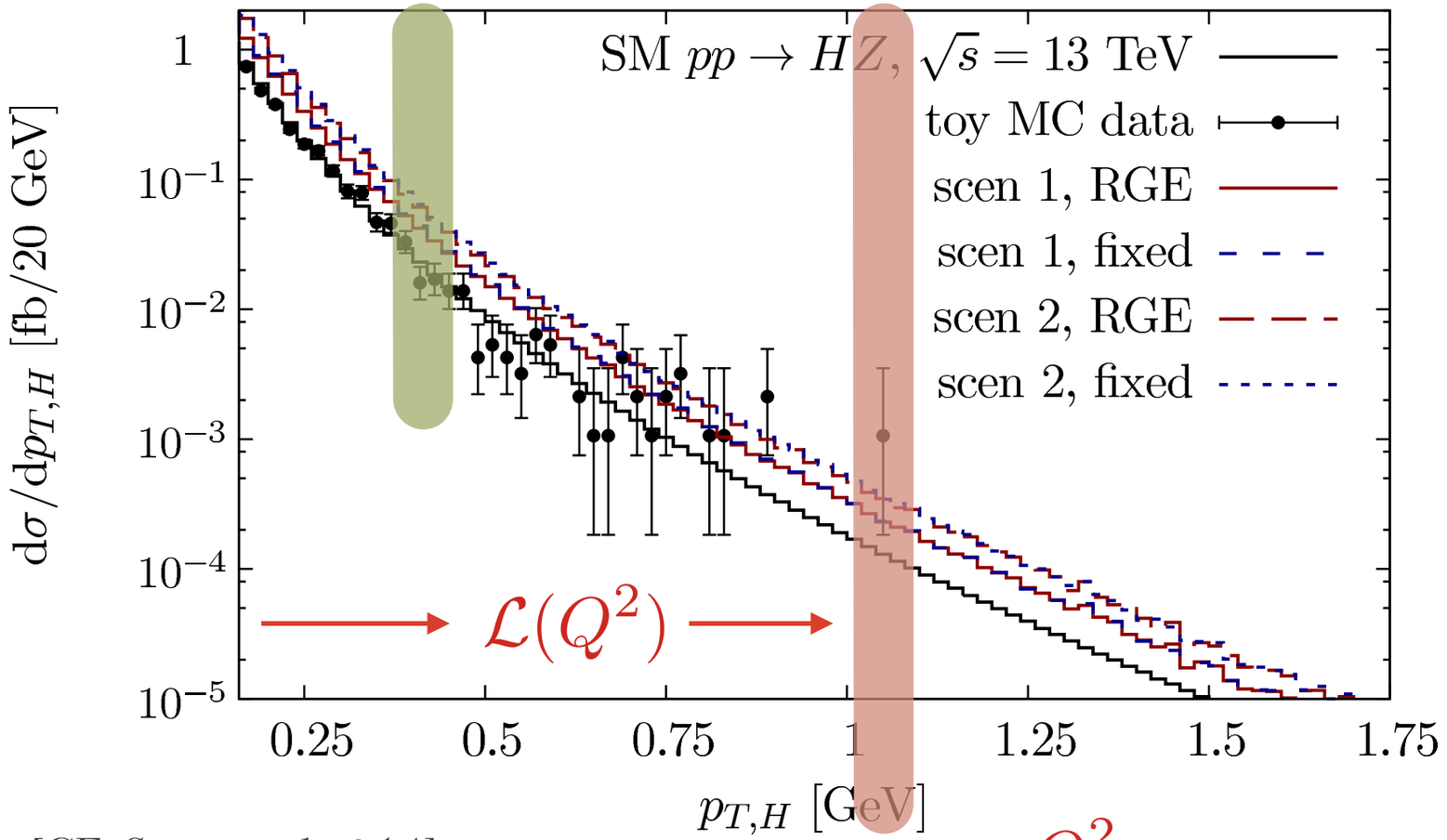

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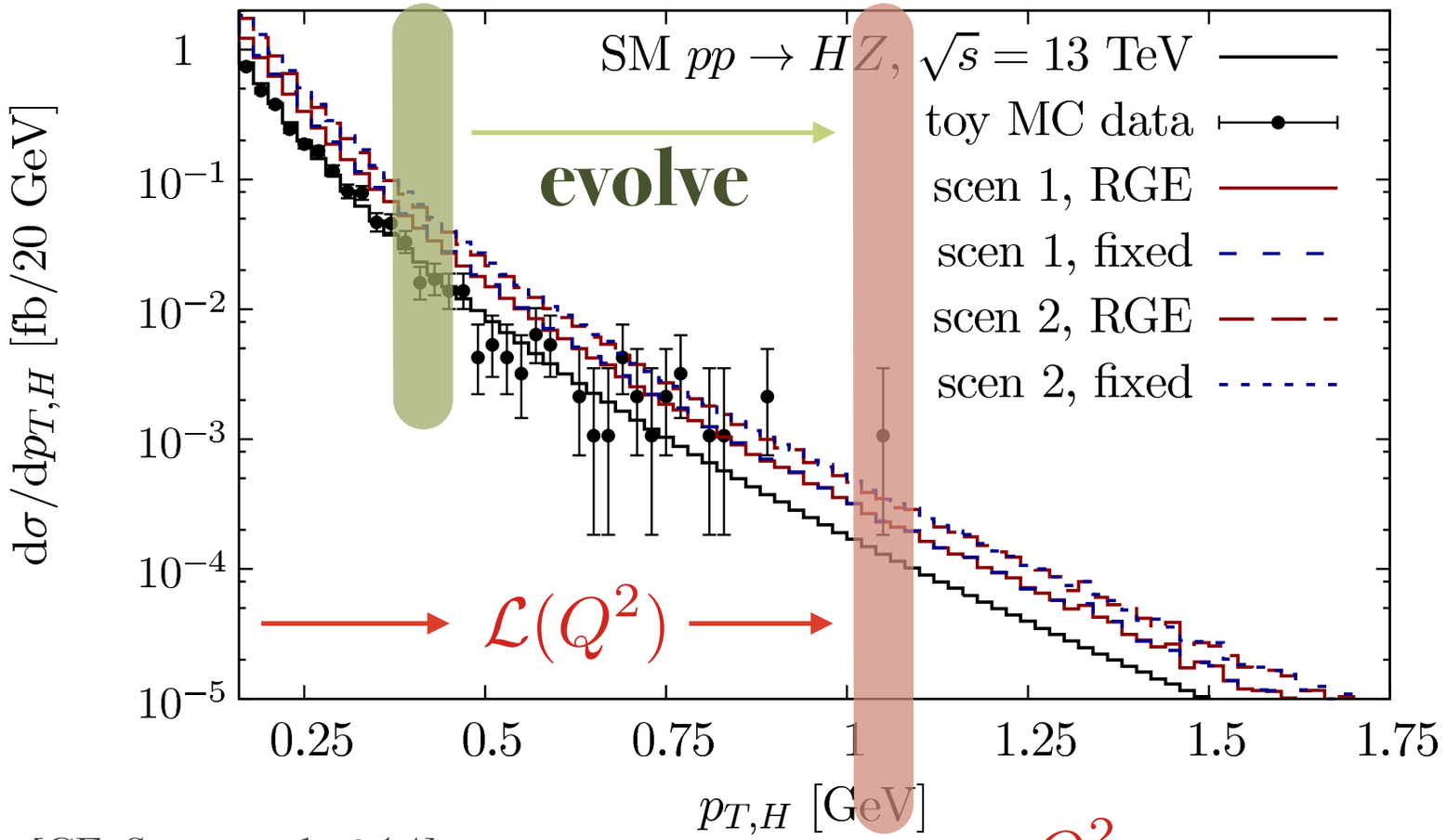

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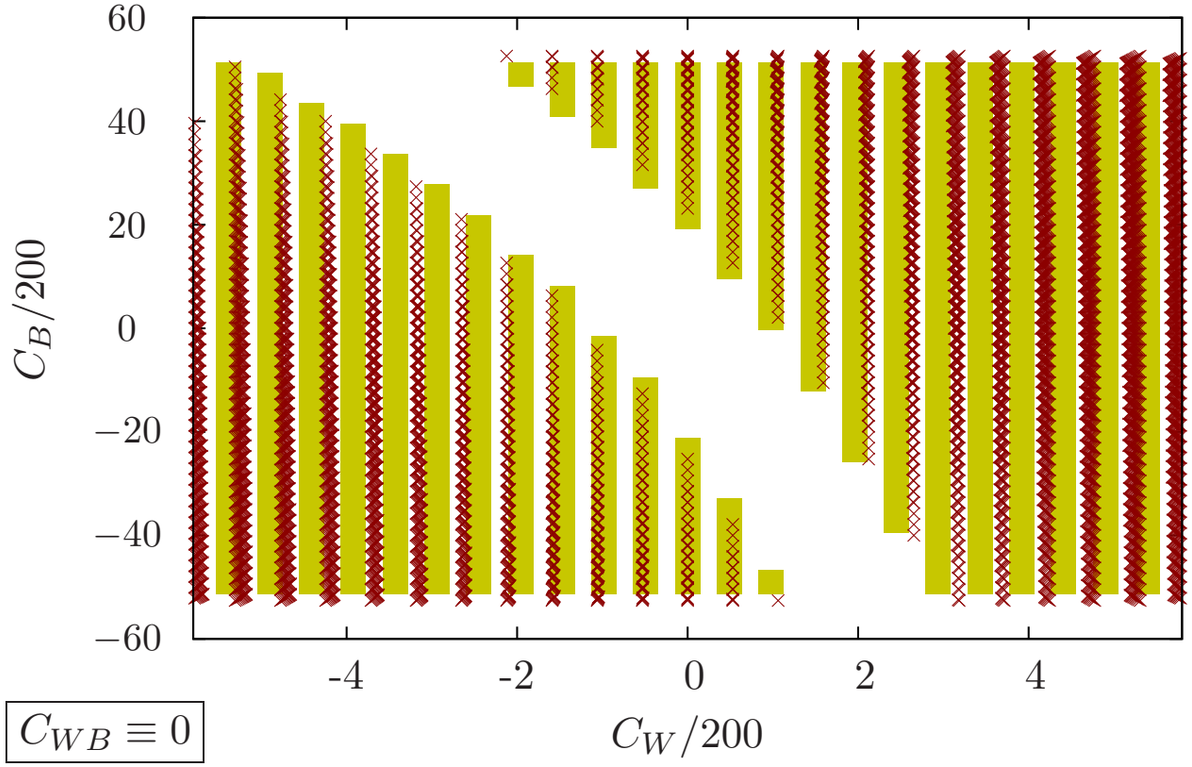
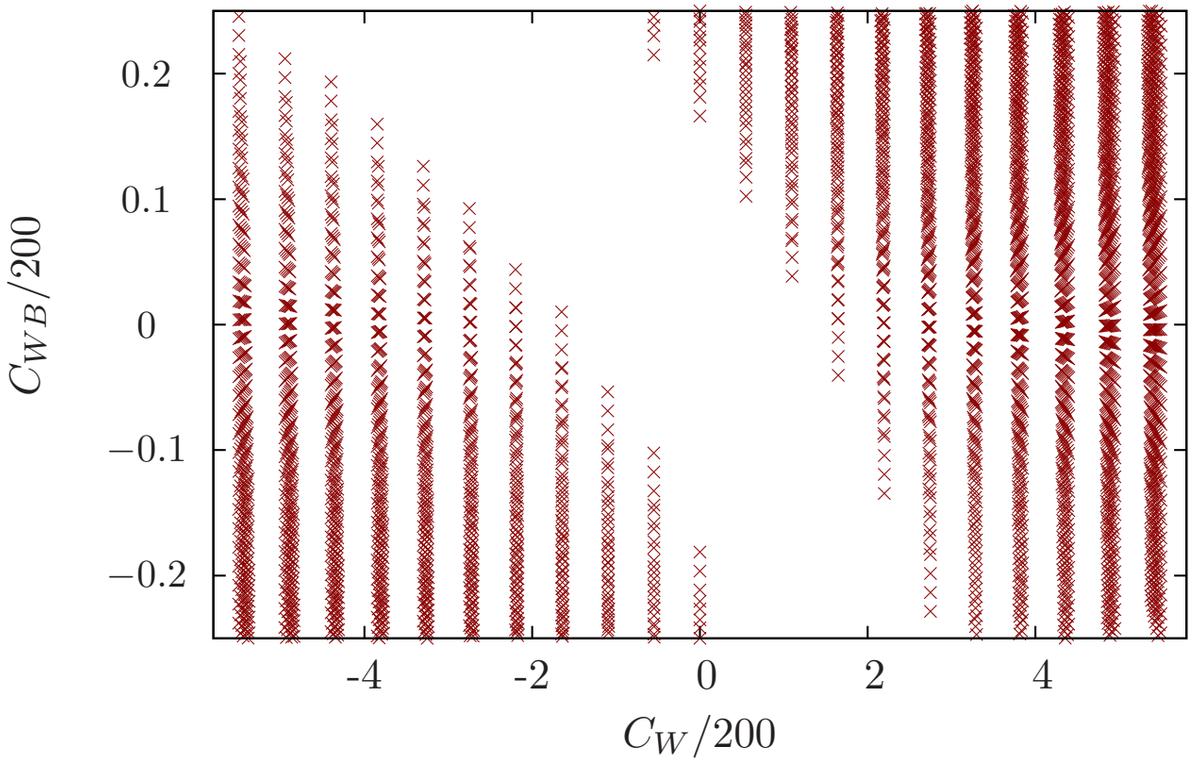


$C_{WB} \equiv 0$



$$\max Q^2 = 2.4 \text{ TeV} \Longrightarrow \mathcal{L}^{\text{BSM}}(2.4 \text{ TeV})$$

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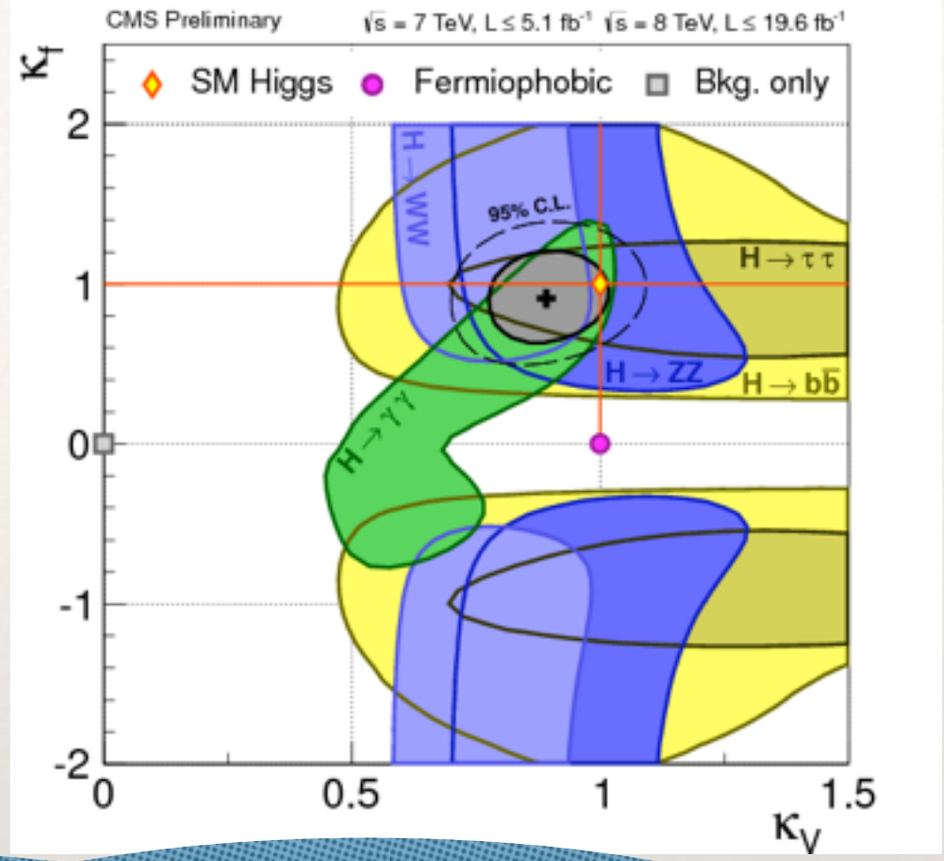
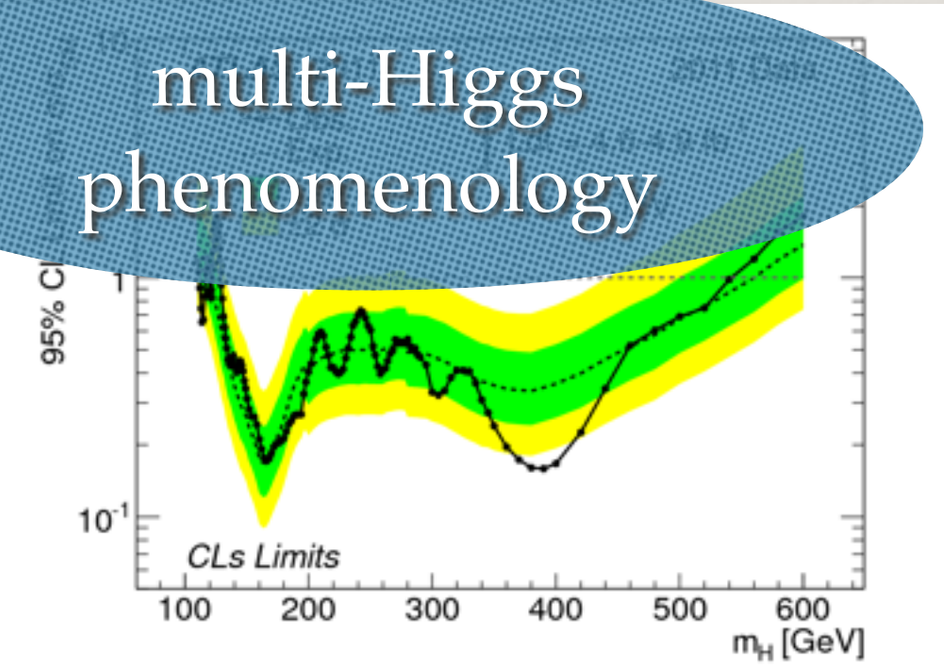
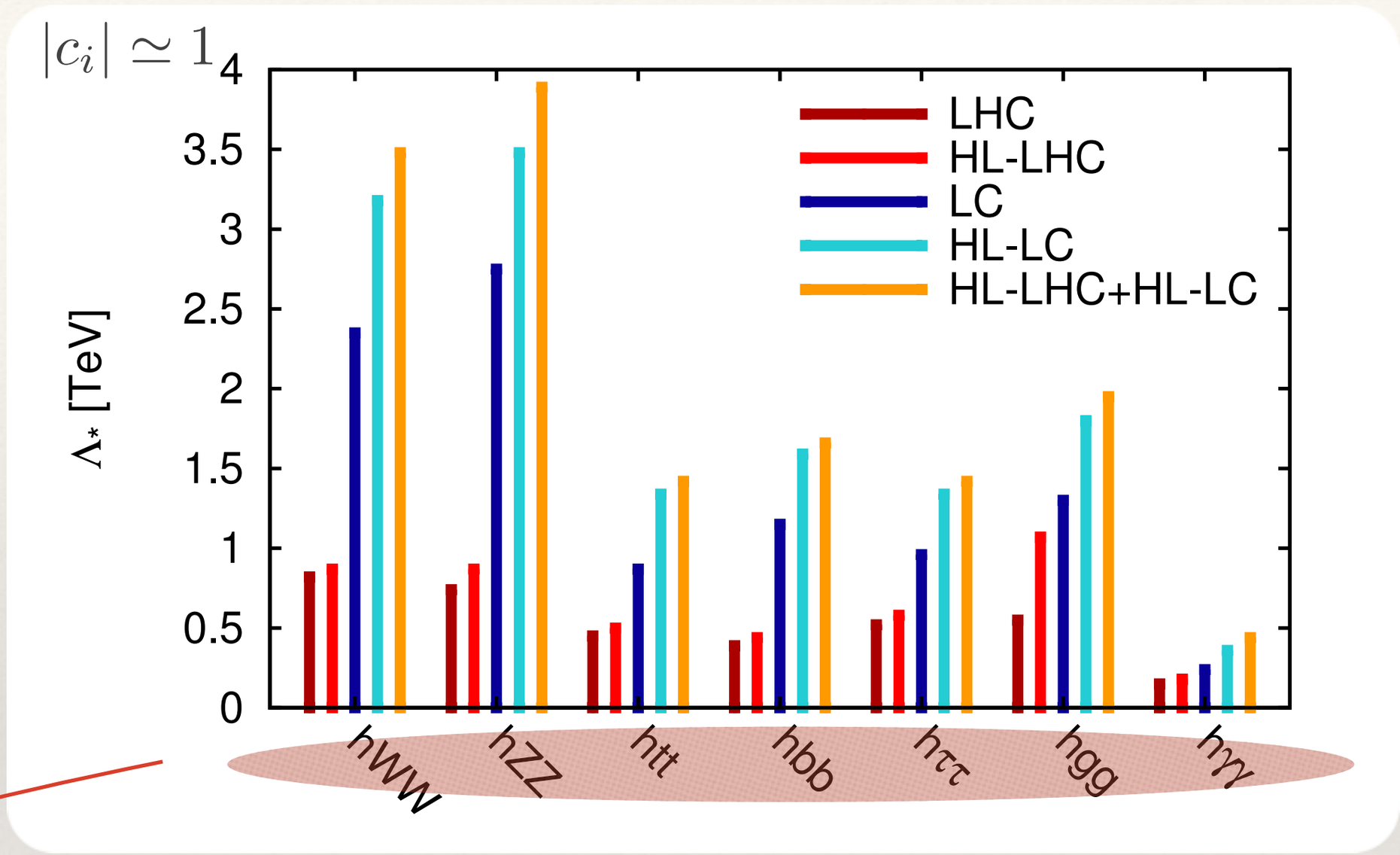


multi-Higgs phenomenology



Why is multi-Higgs pheno important ?



no eminent implication for EWSB !

$$V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2$$
$$\supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$

$$\hat{\mathcal{O}}_6 = \frac{c_6}{\Lambda^2} (\hat{H}^\dagger \hat{H})^3$$

single EFT direction!

The Higgs trilinear coupling

The Higgs trilinear coupling

- large backgrounds, small signal, but feasible in $b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$?
- boosted regime unavoidable for $b\bar{b}\tau\tau$

[Glover, van der Bij `88]
....[Plehn, Baur, Rainwater `03]
[Dolan, CE, Spannowsky `12]
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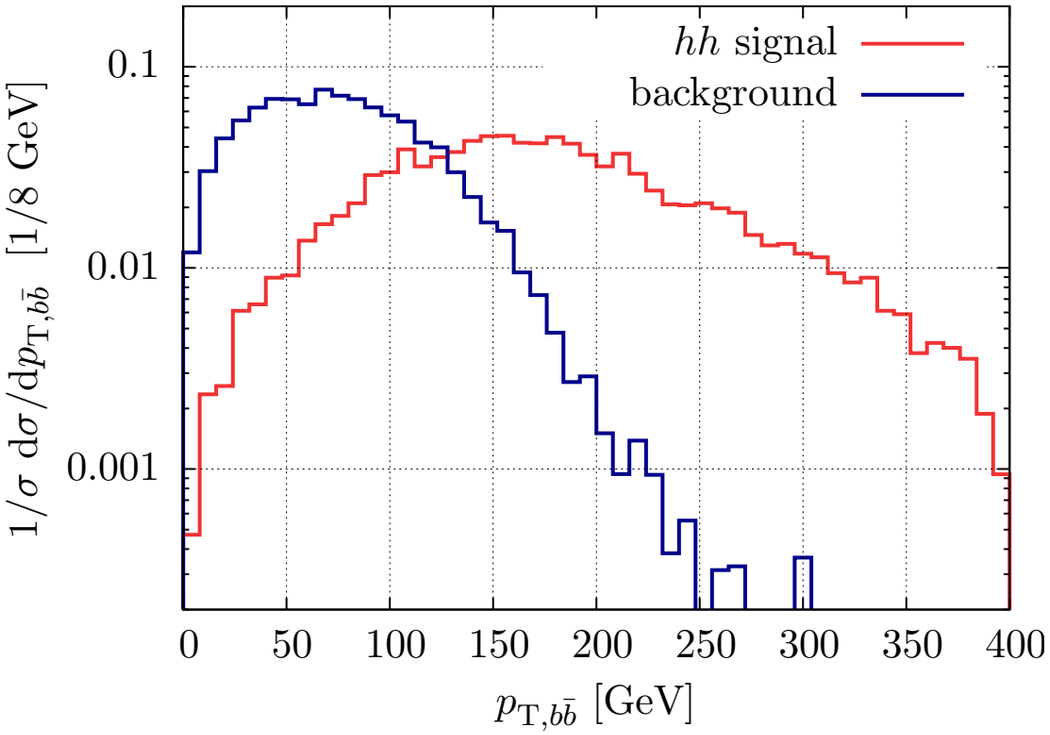

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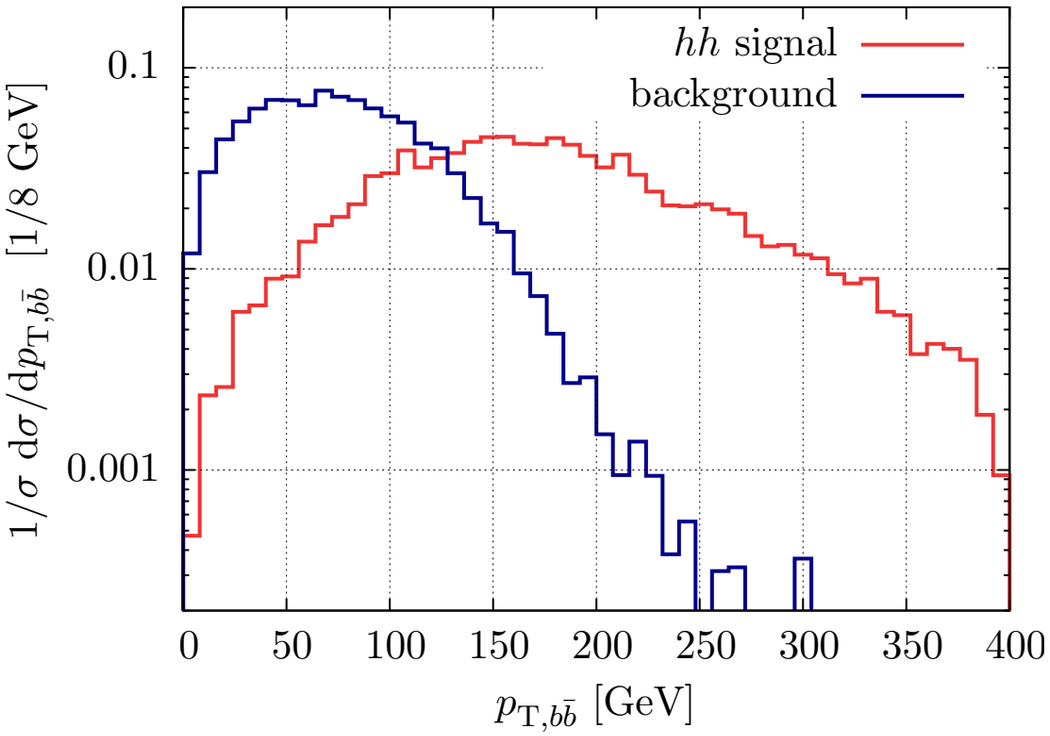

- $b\bar{b}\gamma\gamma$: 1.3σ at 3/ab, limited statistics

[ATLAS PHYS-PUB 2014-19]

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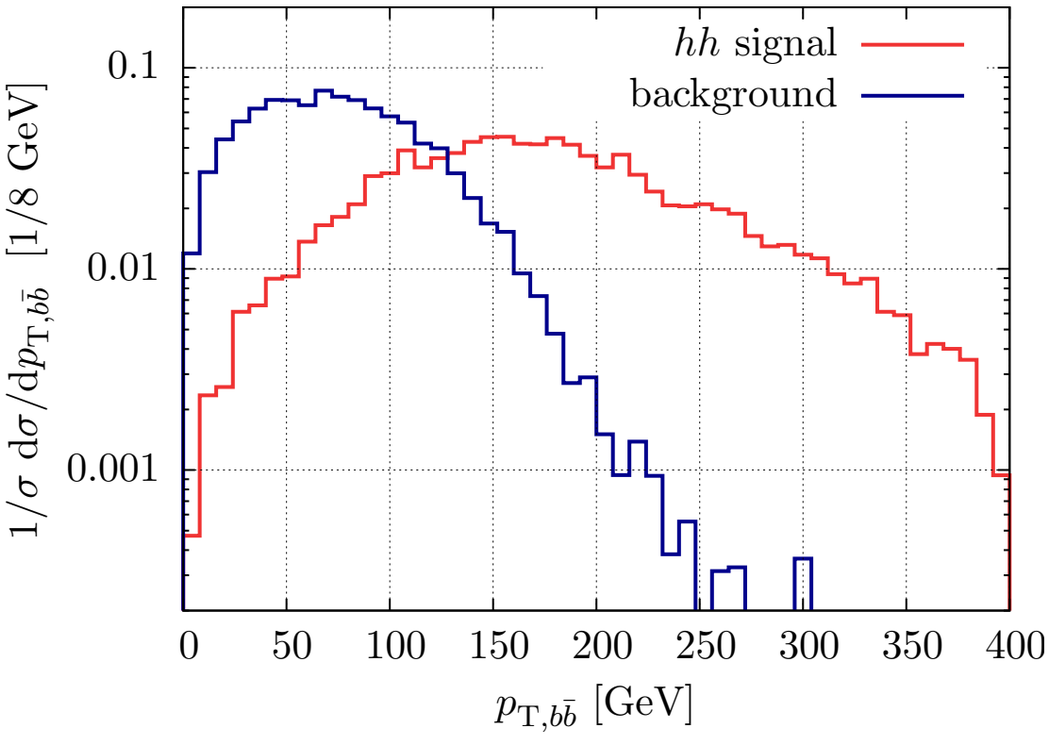

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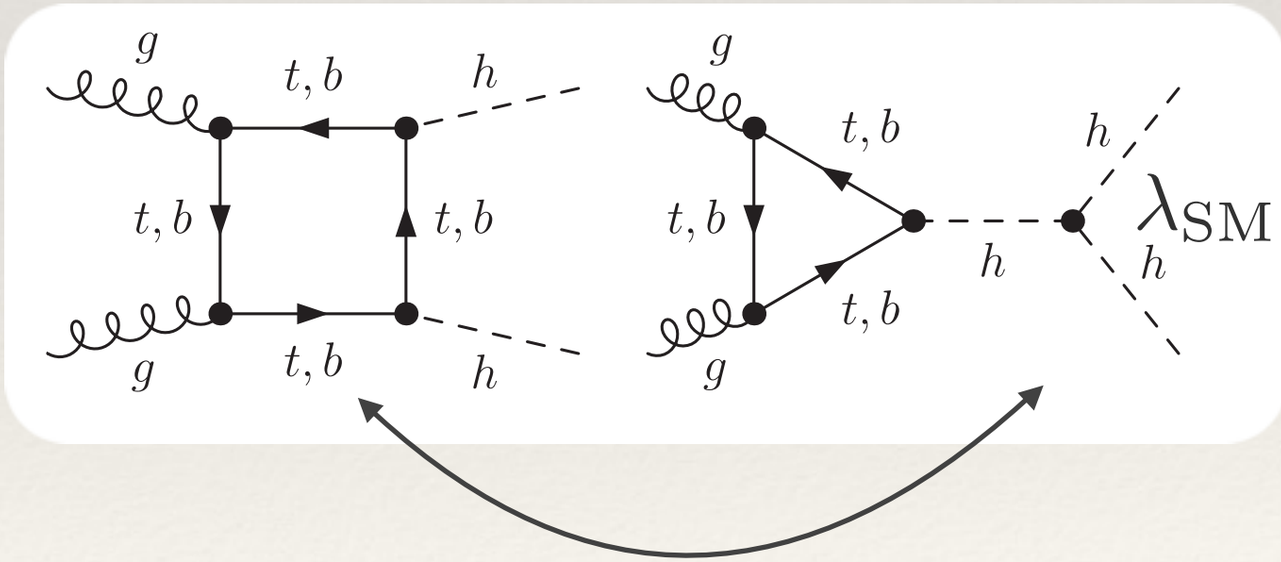

destructive interference
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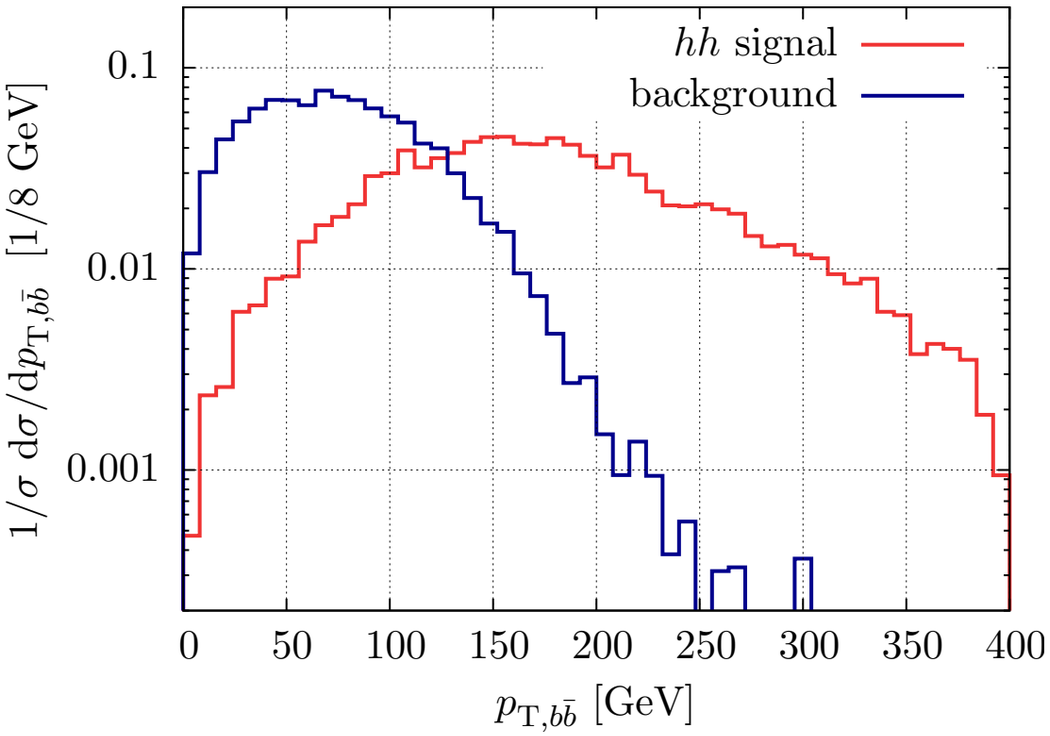
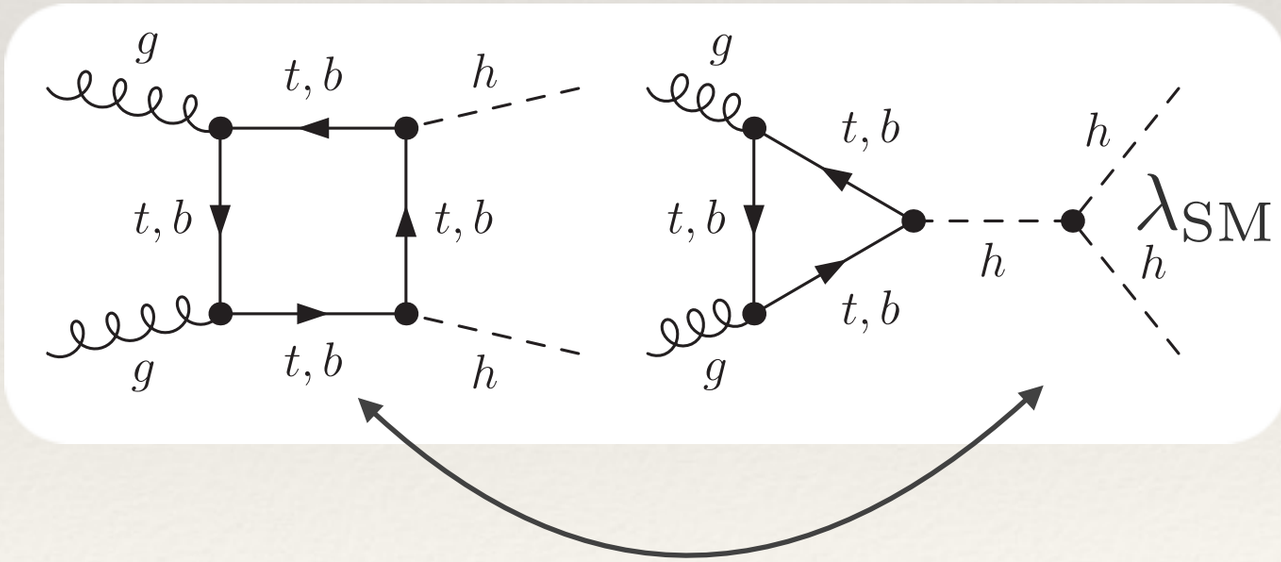


$\lambda > 1 \ldots 3\,\lambda_{\mathrm{SM}}$ in $b\bar{b}\tau^+\tau^-$ for 3/ab

- $b\bar{b}\gamma\gamma$: 1.3σ at 3/ab, limited statistics

[ATLAS PHYS-PUB 2014-19]



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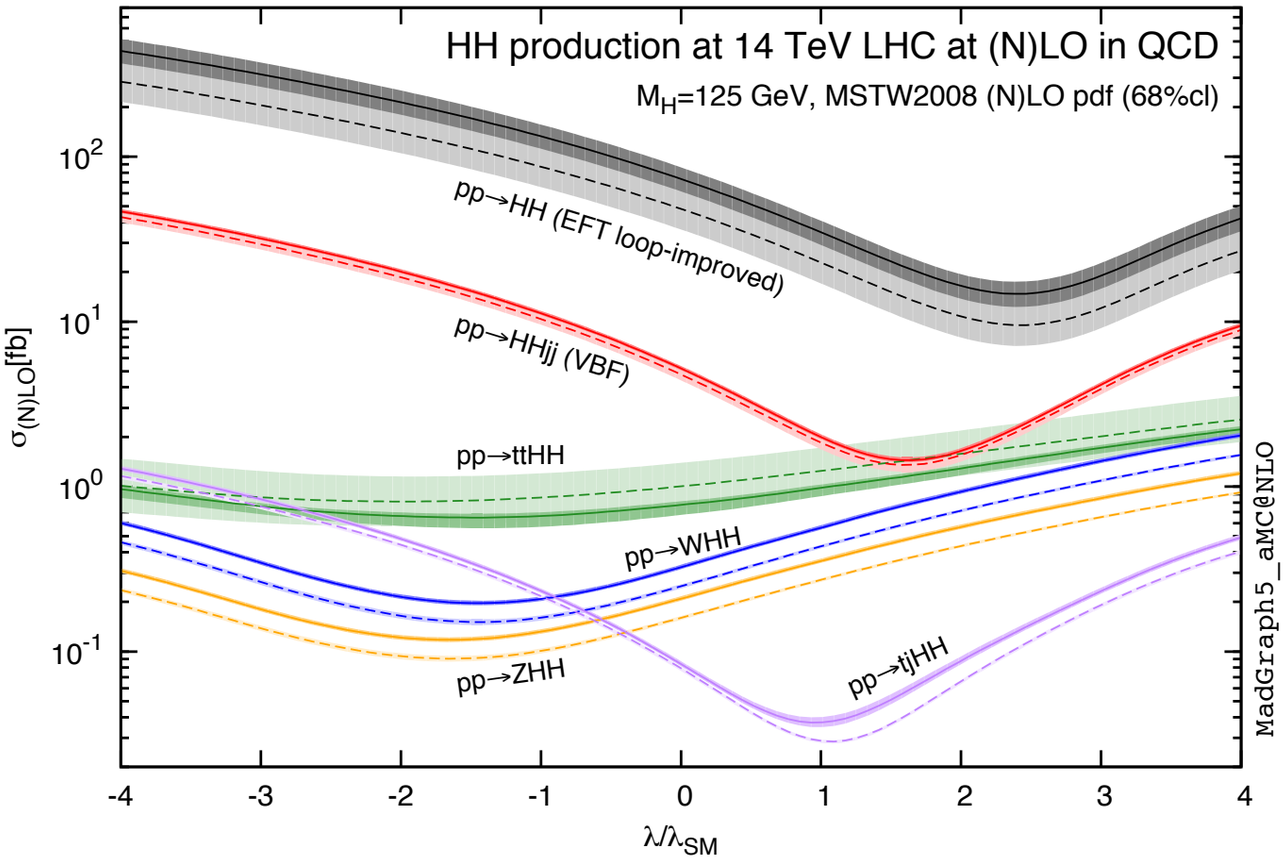
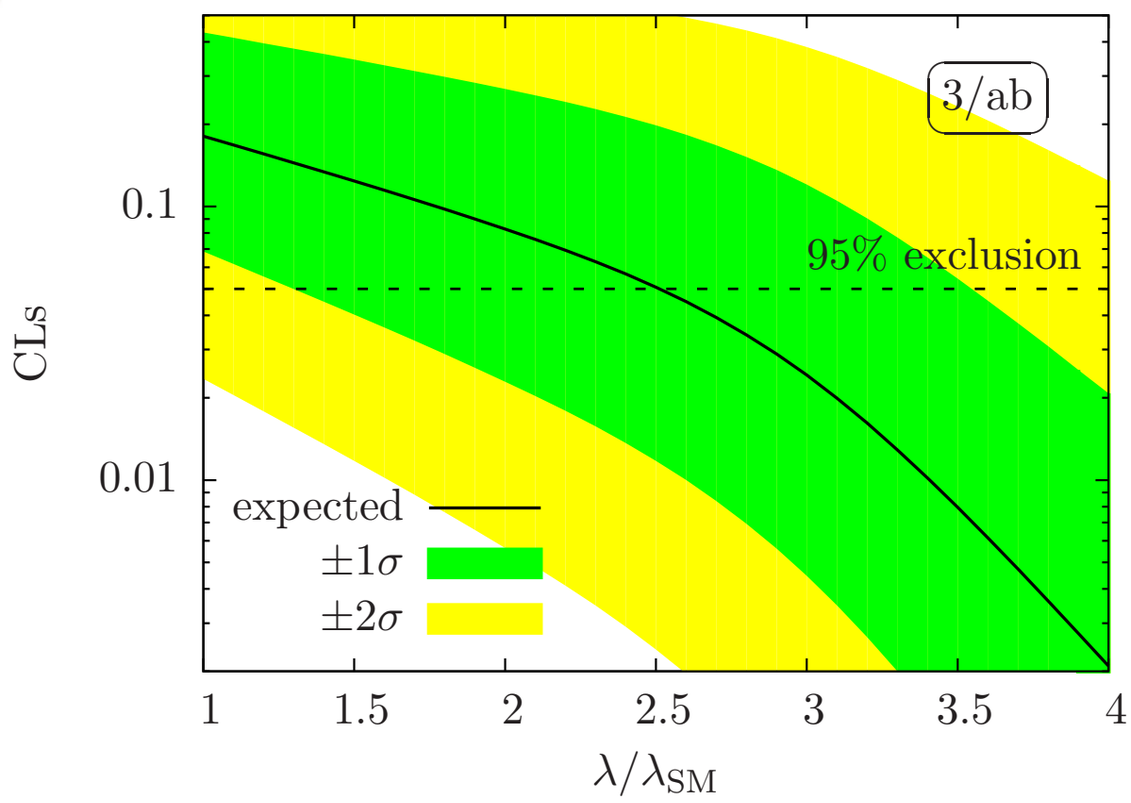


[Frederix, Frixione, Hirschi, Maltoni, et al. ` 14]

- multi-top and multi-Higgs adds complementary information !

[CE, Krauss, Spannowsky, Thompson ` 14]
[Liu, Zhang ` 14]



[CE, Krauss, Spannowsky, Thompson ` 14]

What's the Higgs we are dealing with??

Is it a doublet?

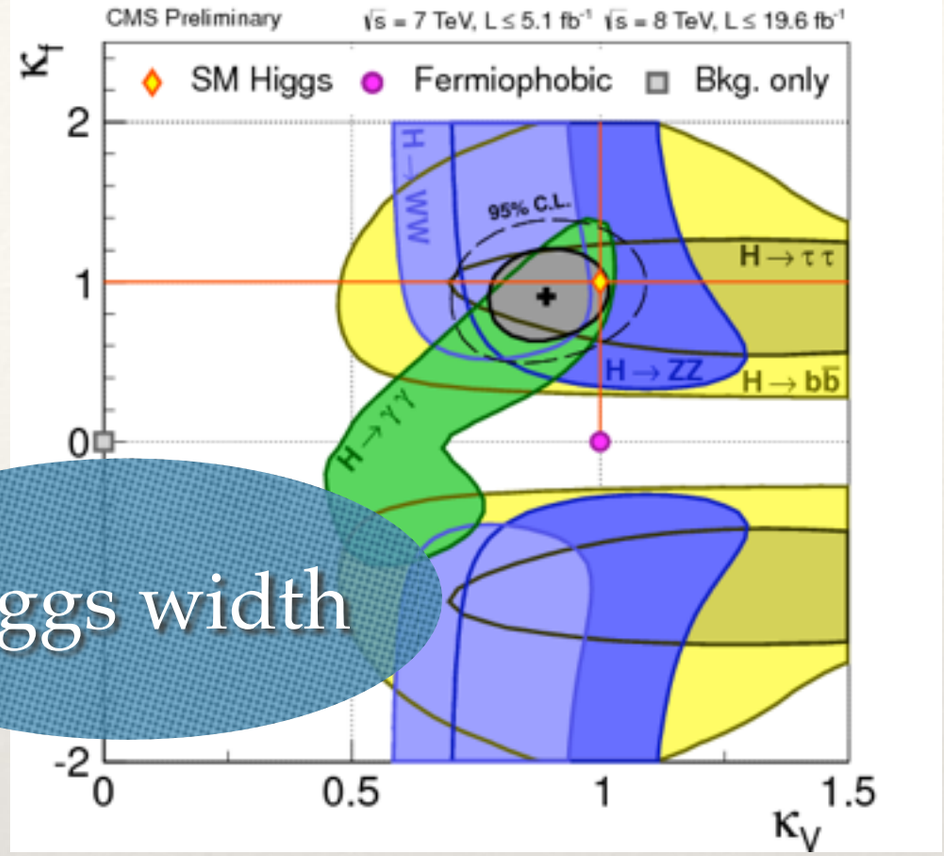
Is there more than just a (SM) Higgs?

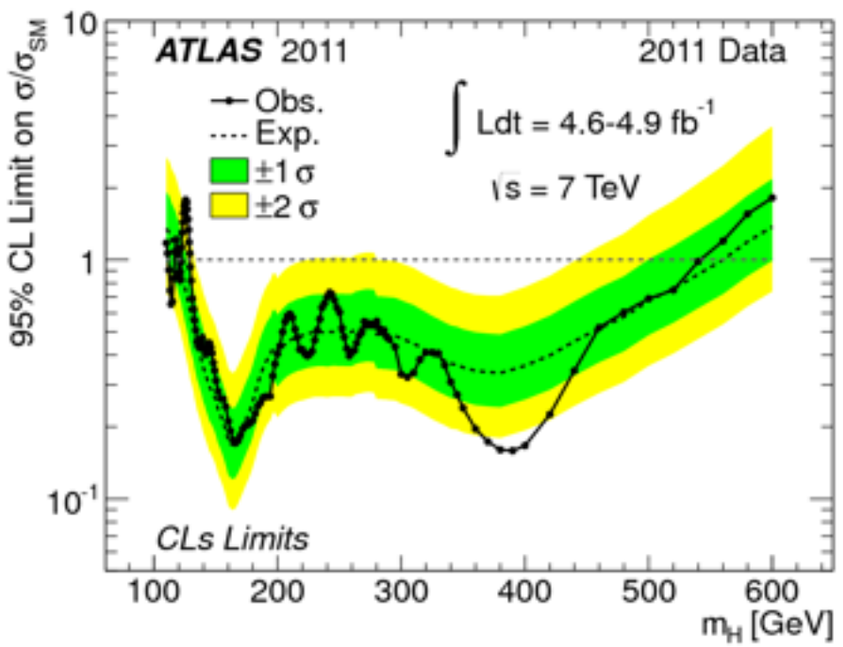
Is there a relation with dark matter?

What triggers symmetry breaking?

What can we say about all that at the end of the high luminosity phase and how can future colliders help us?

Higgs width





The total Higgs width

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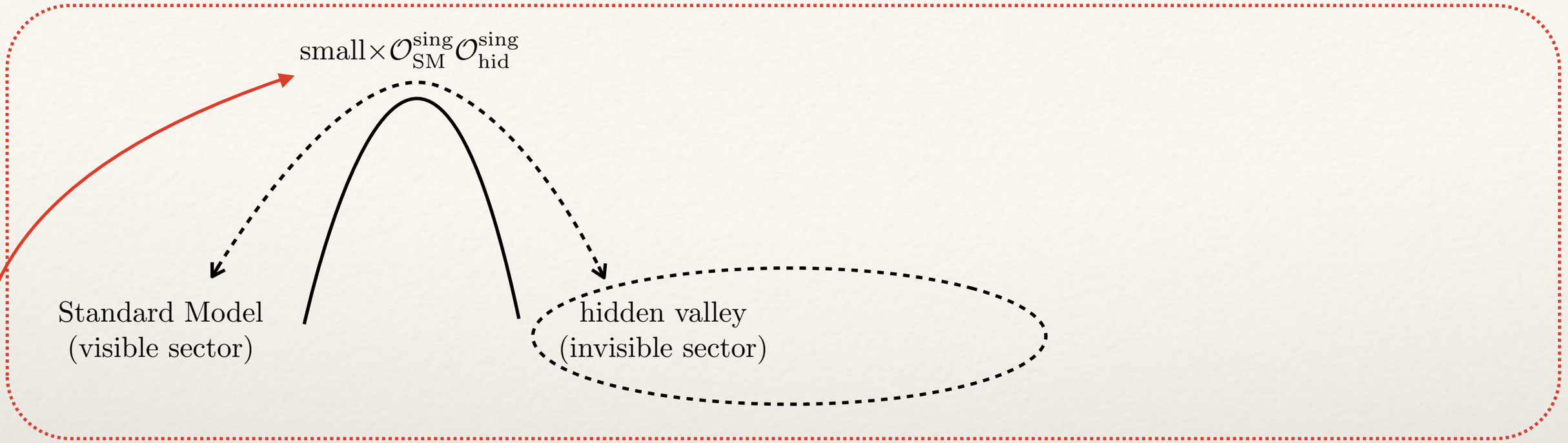
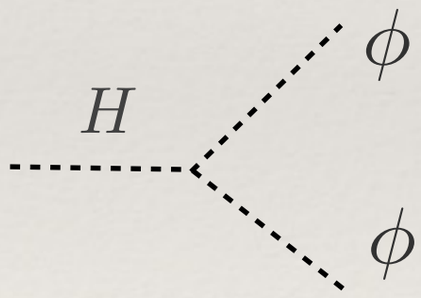


Higgs Portals $\sim \lambda|H|^2|\phi|^2$



$$\Gamma_H = \Gamma_H^{\rm SM} + \Gamma_{\rm inv}$$

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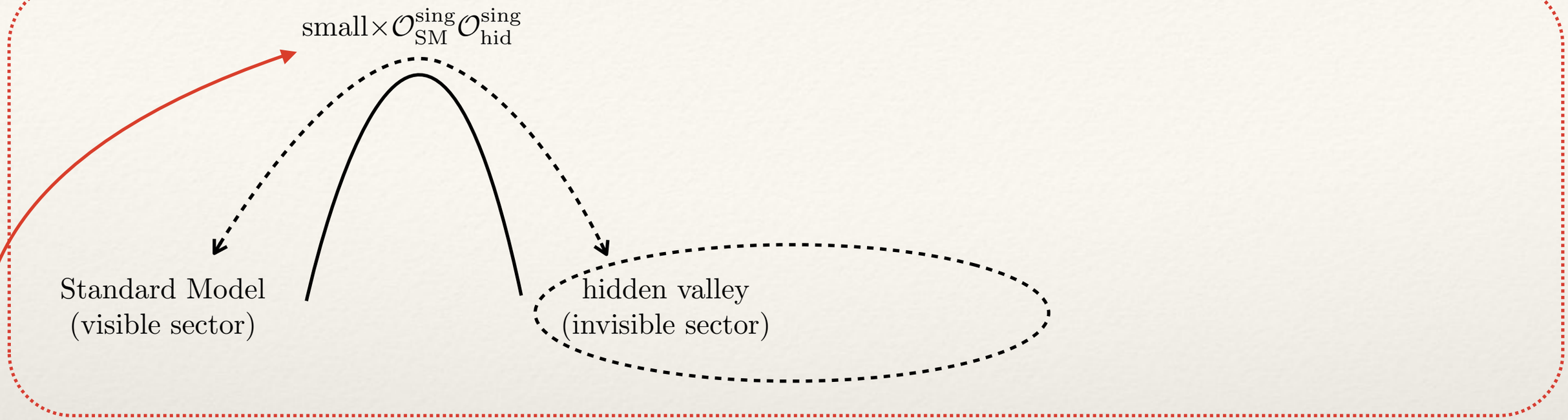

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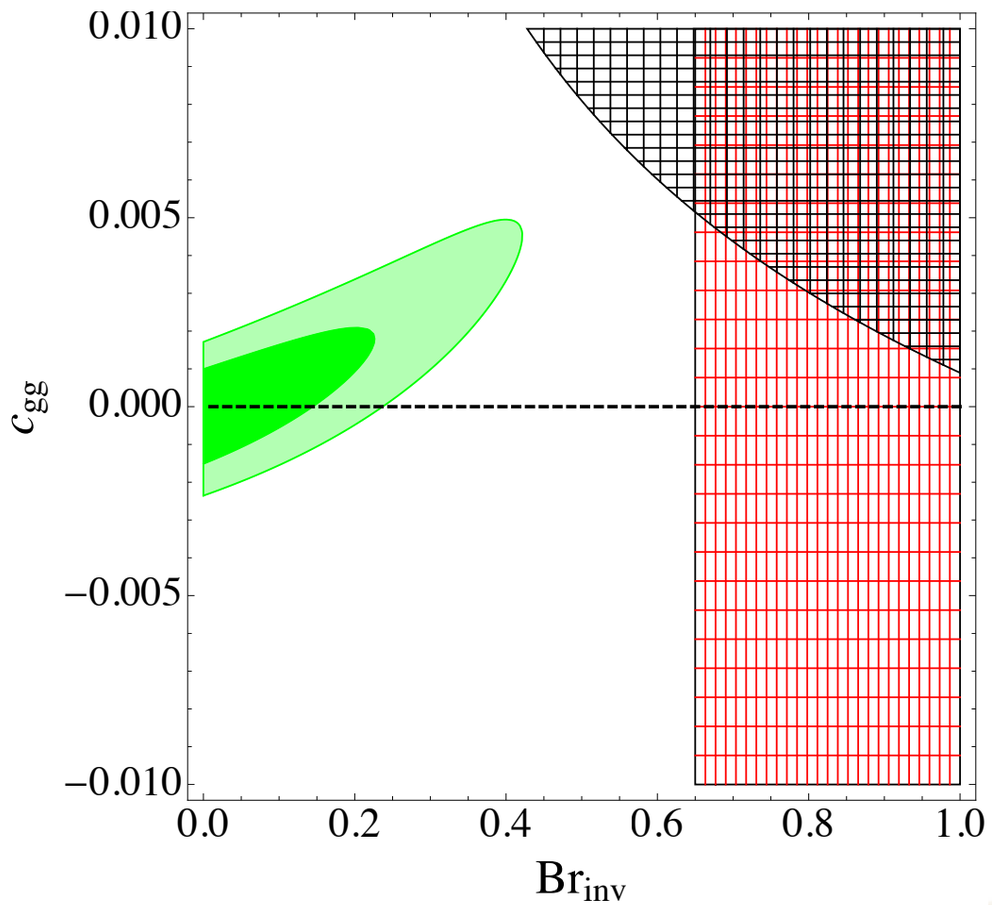
$$\Gamma_H = \Gamma_H^{\rm SM} + \Gamma_{\rm inv}$$

→ a model-independent constraint on the total Higgs decay width is a game changer for particle physics and cosmology !

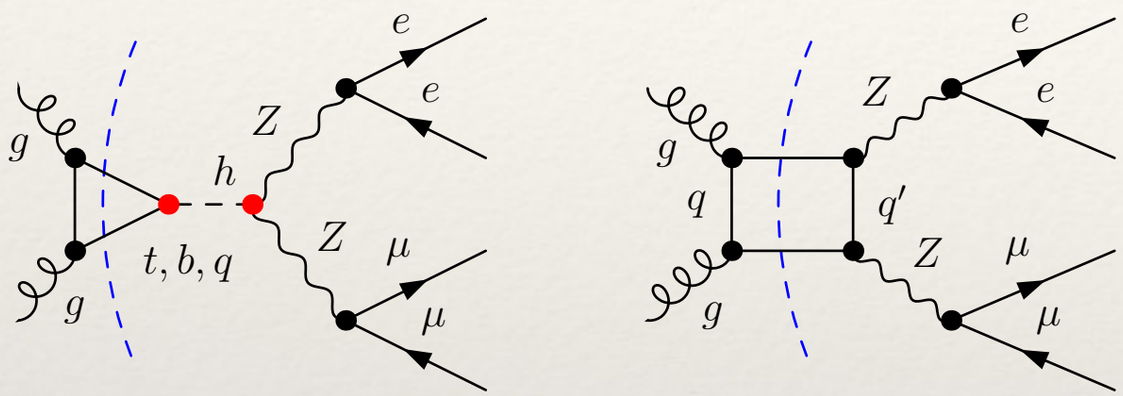
[Djouadi, Falkowski, Mambrini, Quevillon `12]

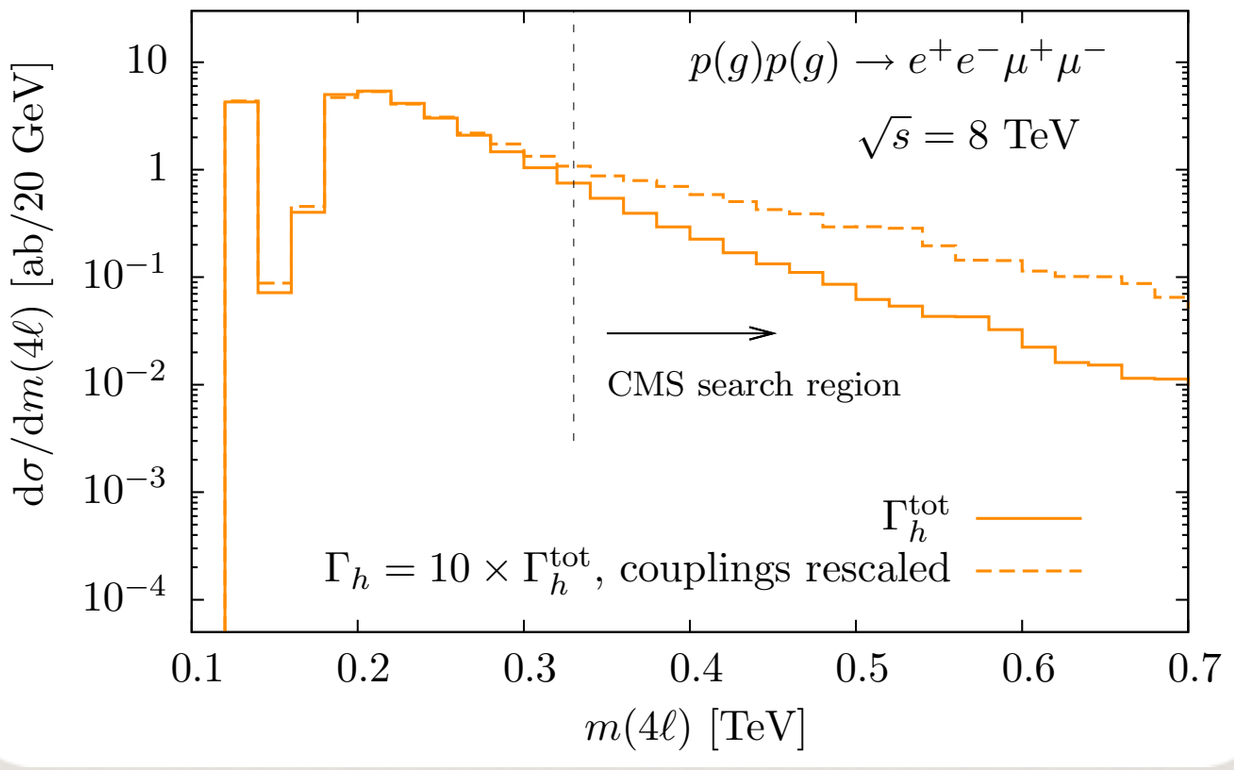


The total Higgs width at the LHC?

A two-step programme in ZZ

[Kauer, Passarino ` 12][Caola, Melnikov ` 13]
[Campbell, Ellis, Williams ` 13]





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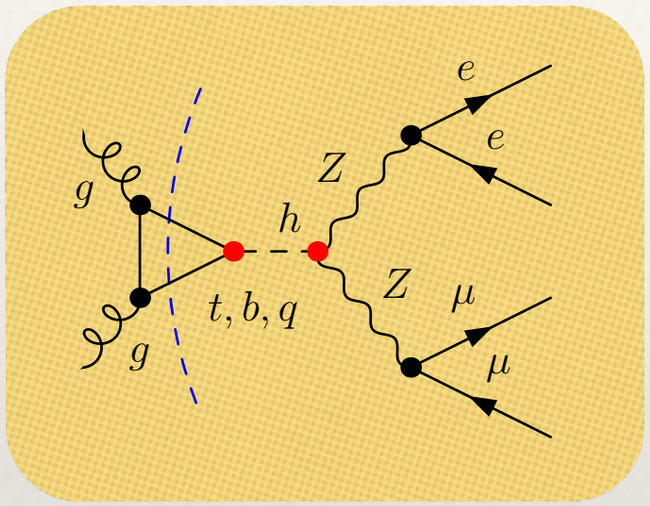
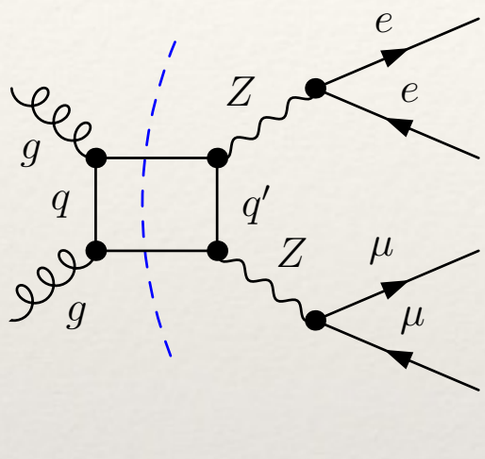


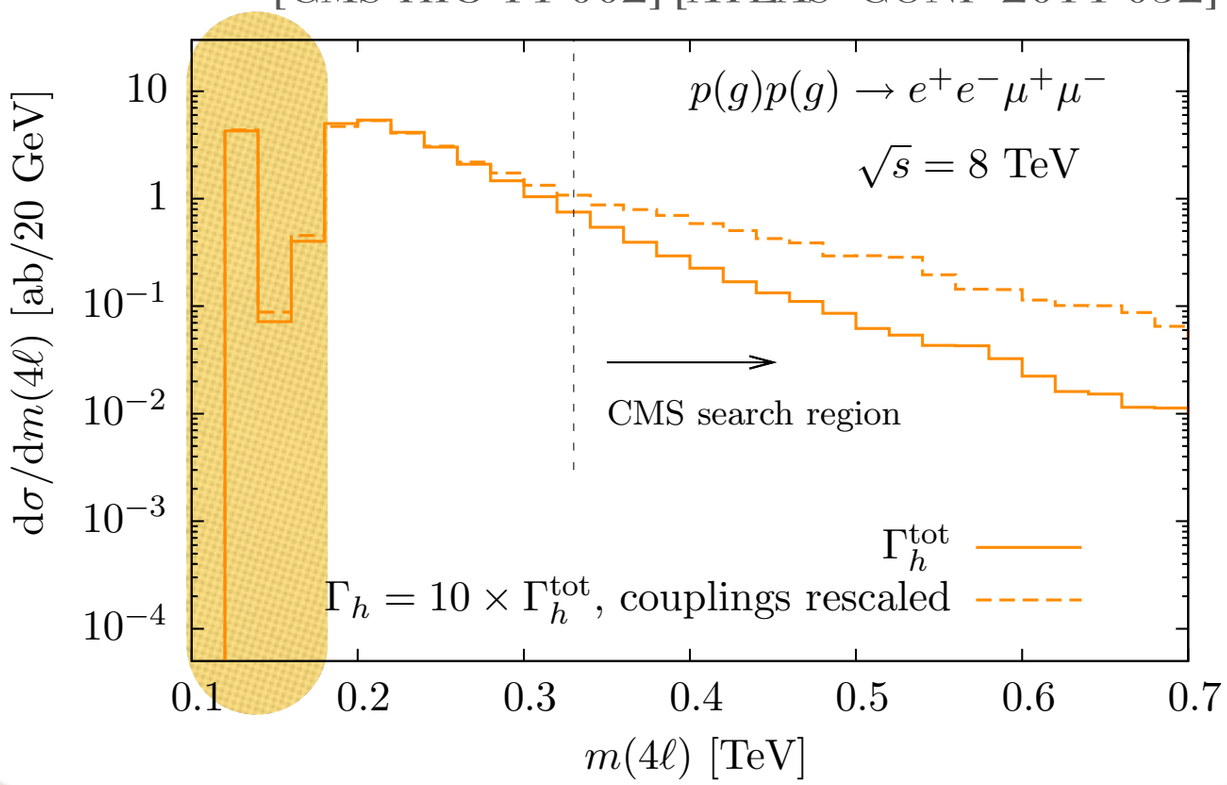


1. on-shell measurement

dominated by Higgs signal

$$\sigma_{h,g} \times \mathrm{BR}(H \to ZZ \to 4\ell) \sim \frac{g^2_{ggh}\, g^2_{hZZ}}{\Gamma_h}$$

[CMS-HIG-14-002] [ATLAS -CONF-2014-052]



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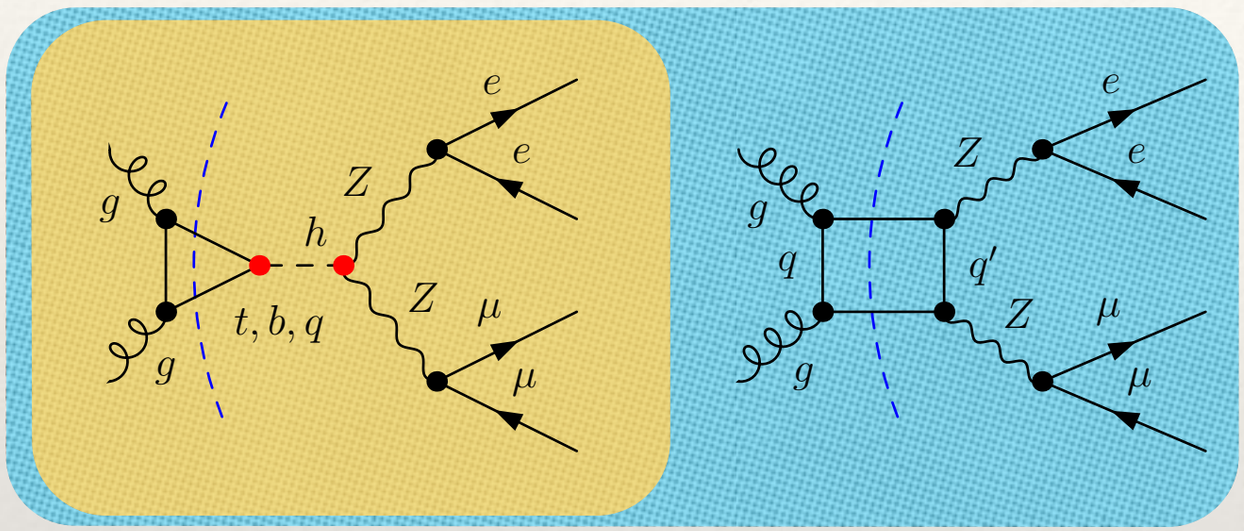

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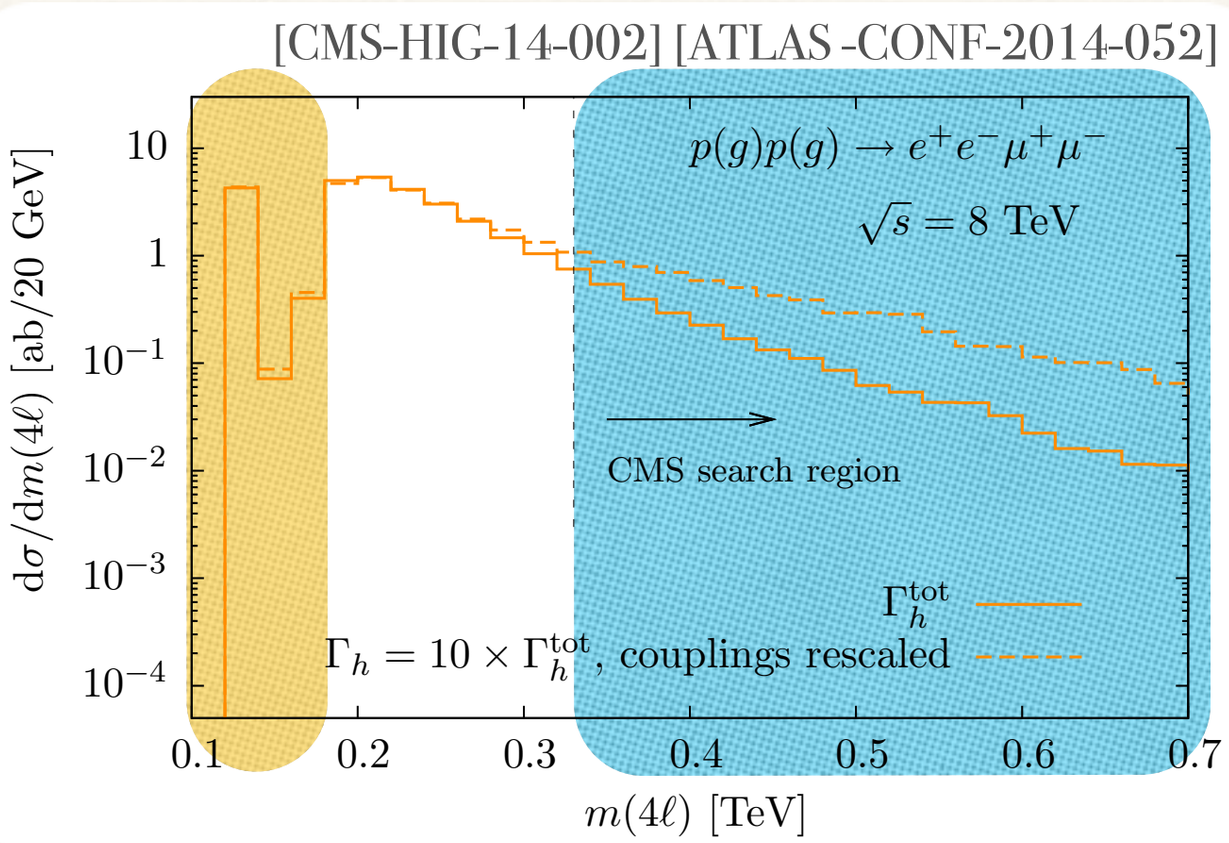

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2. off-shell measurement

threshold effects and unitarity driven interference, but de-coupling of width parameter $\sim i/(s - m_h^2 + i\Gamma_h m_h)$

$$\mathrm{d}\overline{\sigma}_h \sim \frac{g^2_{ggh}(\sqrt{s})\, g^2_{hZZ}(\sqrt{s})}{s}\ \mathrm{dLIPS}\times\mathrm{pdfs}.$$

The total Higgs width

A two-step programme in ZZ

[Kauer, Passarino ` 12][Caola, Melnikov ` 13]
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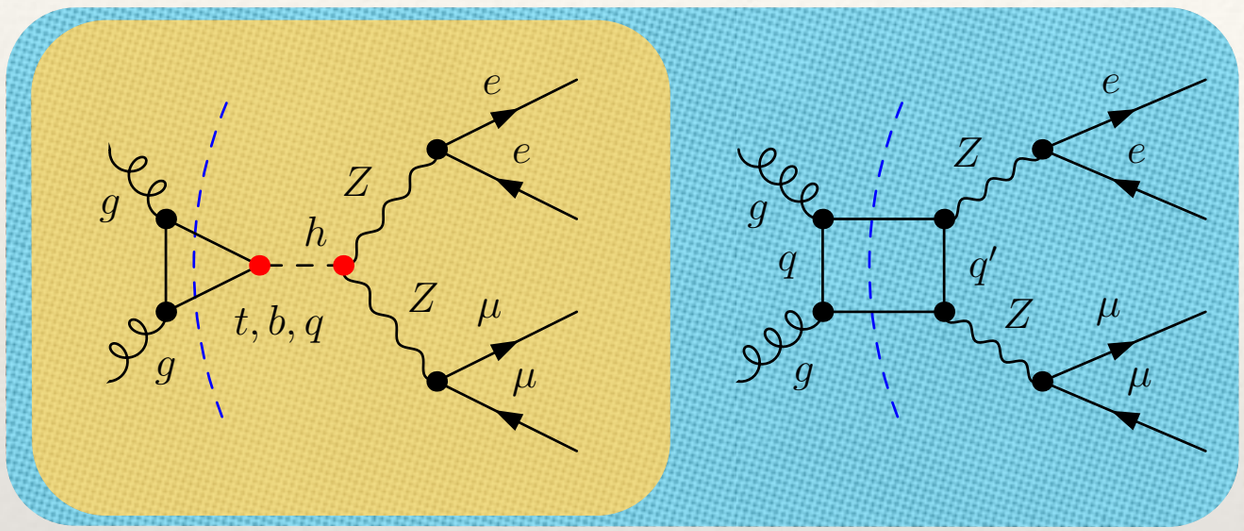

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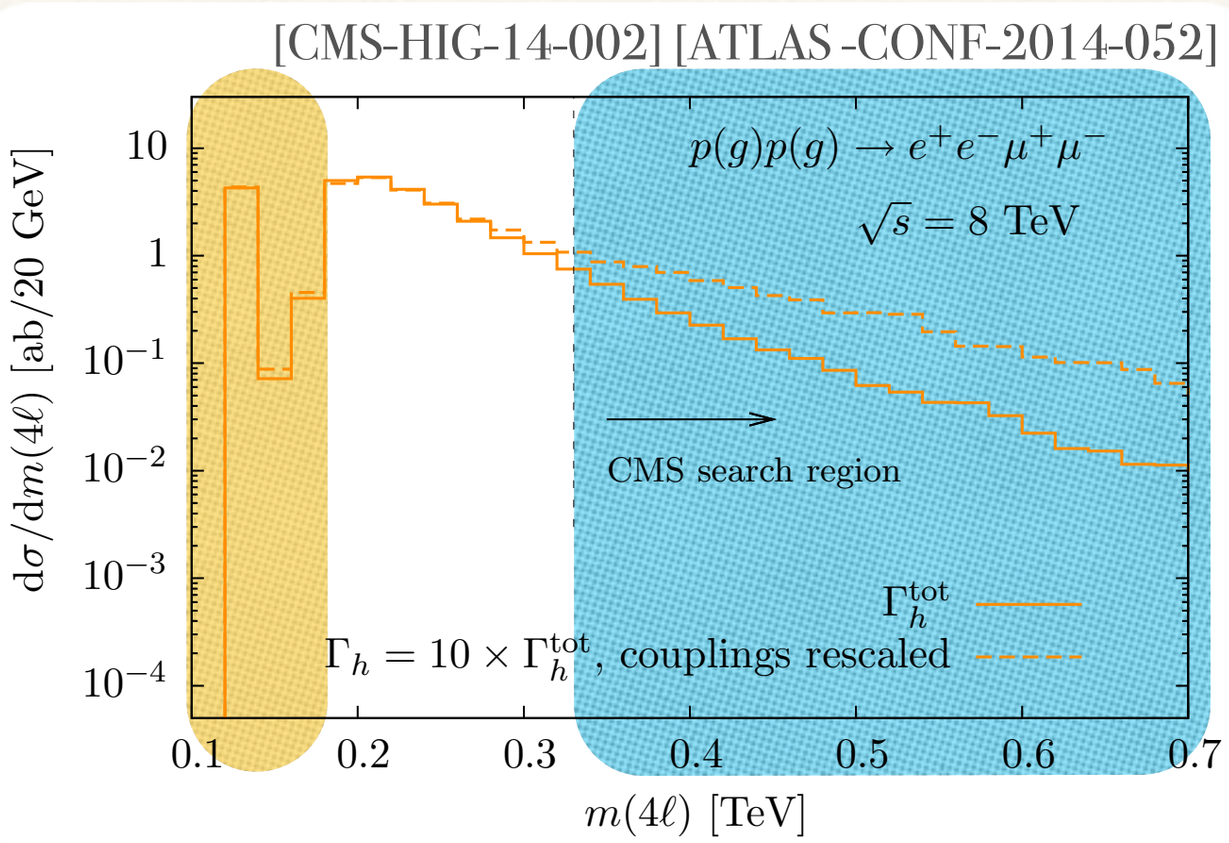

correlate measurements

for off-shell an on-shell Higgs couplings are correlated:

$$\Gamma_h > \Gamma_h^{\rm SM}, \quad \sigma \times \mathrm{BR} \simeq [\sigma \times \mathrm{BR}]^{\rm SM} \iff g_{ggh} g_{hZZ} > [g_{ggh} g_{hZZ}]^{\rm SM} \iff \overline{\sigma} > \overline{\sigma}^{\rm SM}$$

The total Higgs width

- cannot control loop contributions in QCD processes at hadron colliders

m_ϕ	μ (h peak)	$\Gamma_h/\Gamma_h^{\rm SM}$	$\overline{\sigma}/\overline{\sigma}^{\rm SM}$ $[m(4\ell) \geq 330$ GeV$]^a$
70 GeV	$\simeq 1.0$	$\simeq 5$	-2%
170 GeV	$\simeq 1.0$	$\simeq 4.7$	$+80\%$
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[CE, Spannowsky ` 14]

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- little appeal in introducing a SM-bias into such a measurement

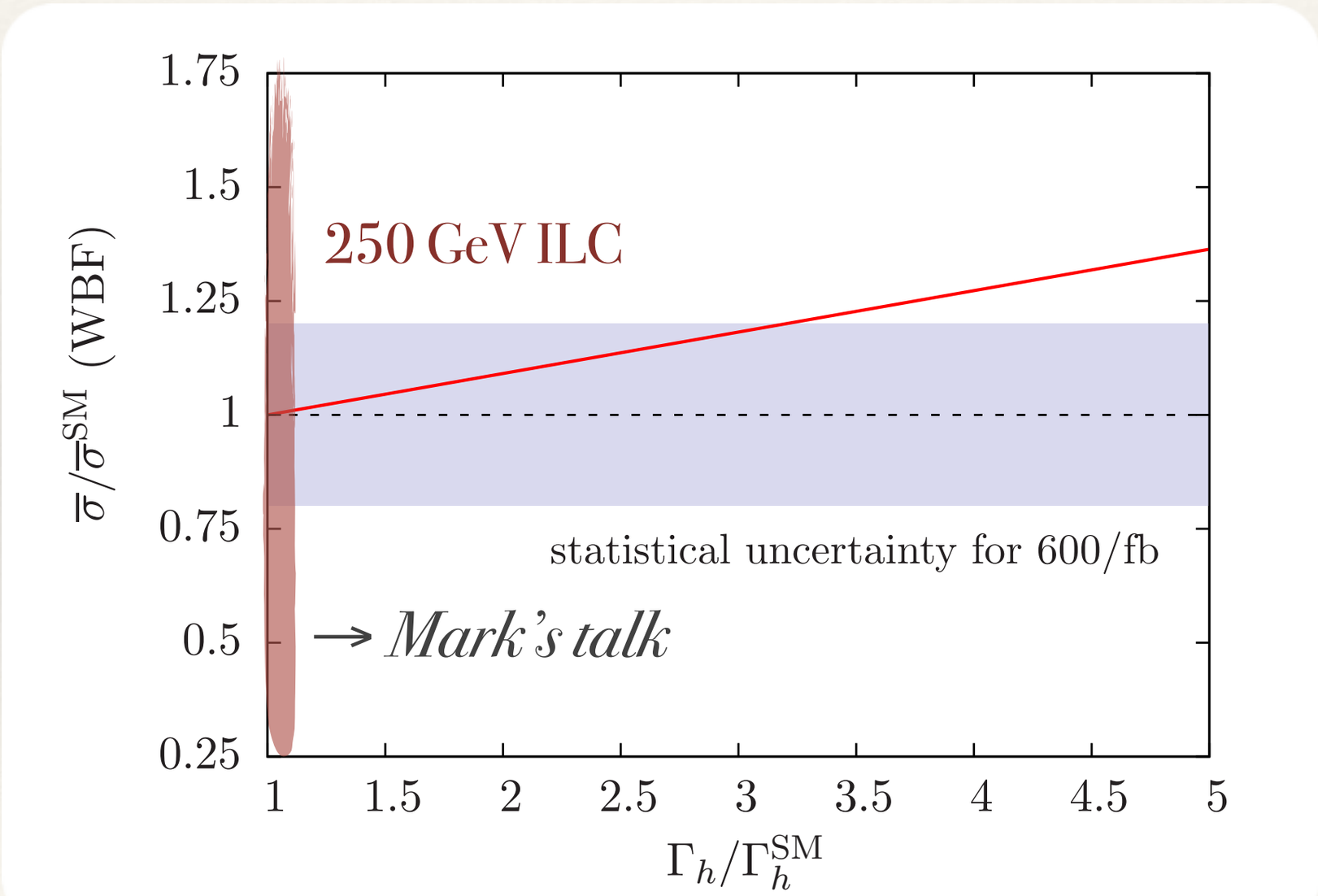
  – in a QFT the Higgs width is not a free parameter

  – interpreted SM-like width measurement this analysis is never competitive: **2**-like VVH coupling and zero hidden width bias already yields $\Gamma_{\rm H}<1.4\,\Gamma_{\rm H}^{\rm SM}$ with small statistics

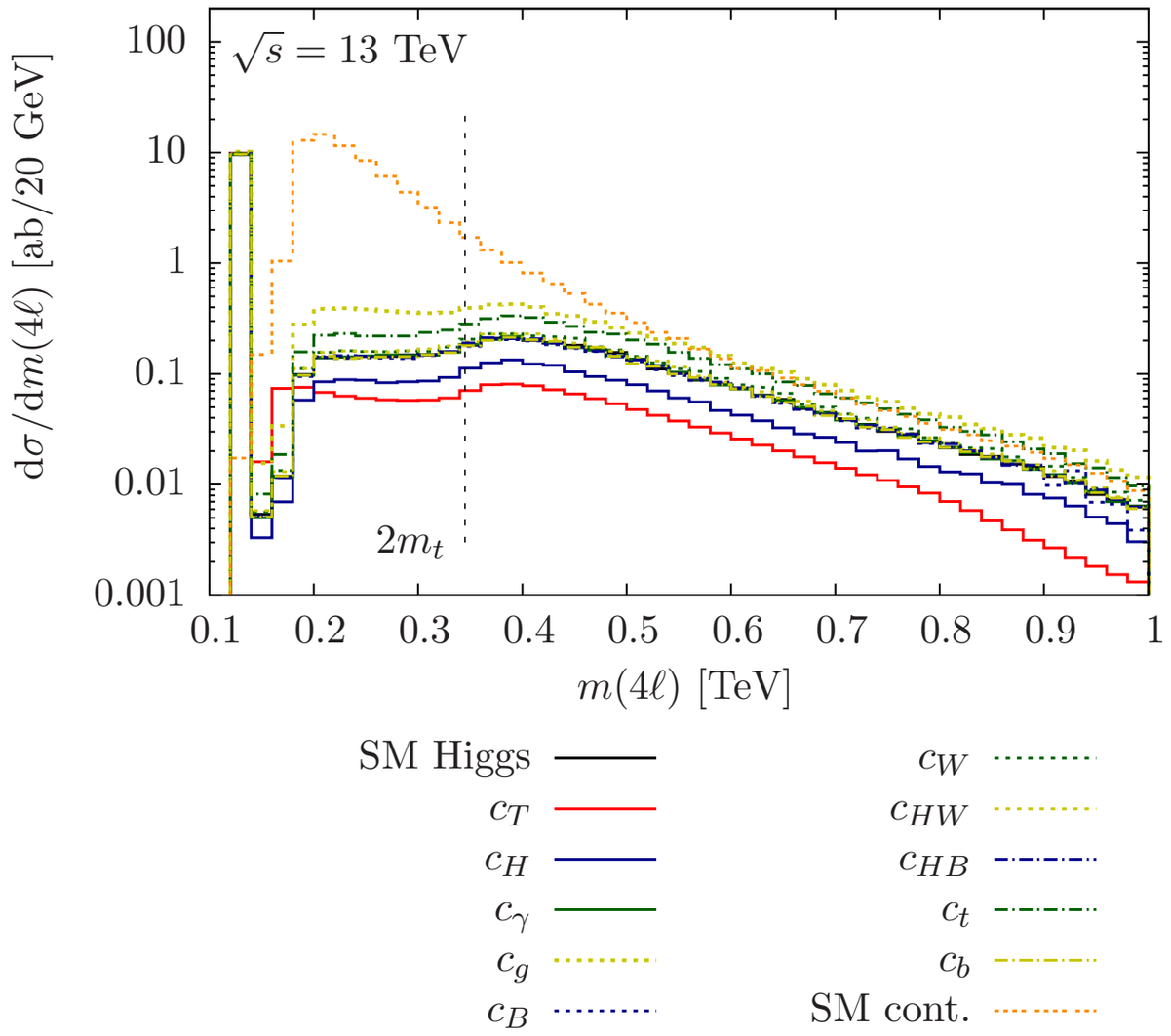
[Dobrescu, Lykken ` 12]
[Bechtle, Heinemeyer, Stål, Stefaniak, Weiglein ` 14]

The total Higgs width

- **can remove loop issues:** adapt to weak boson fusion + custodial isospin (small interference with GF, GF can be suppressed, H couplings to ZZ and WW directly reflect electroweak properties)

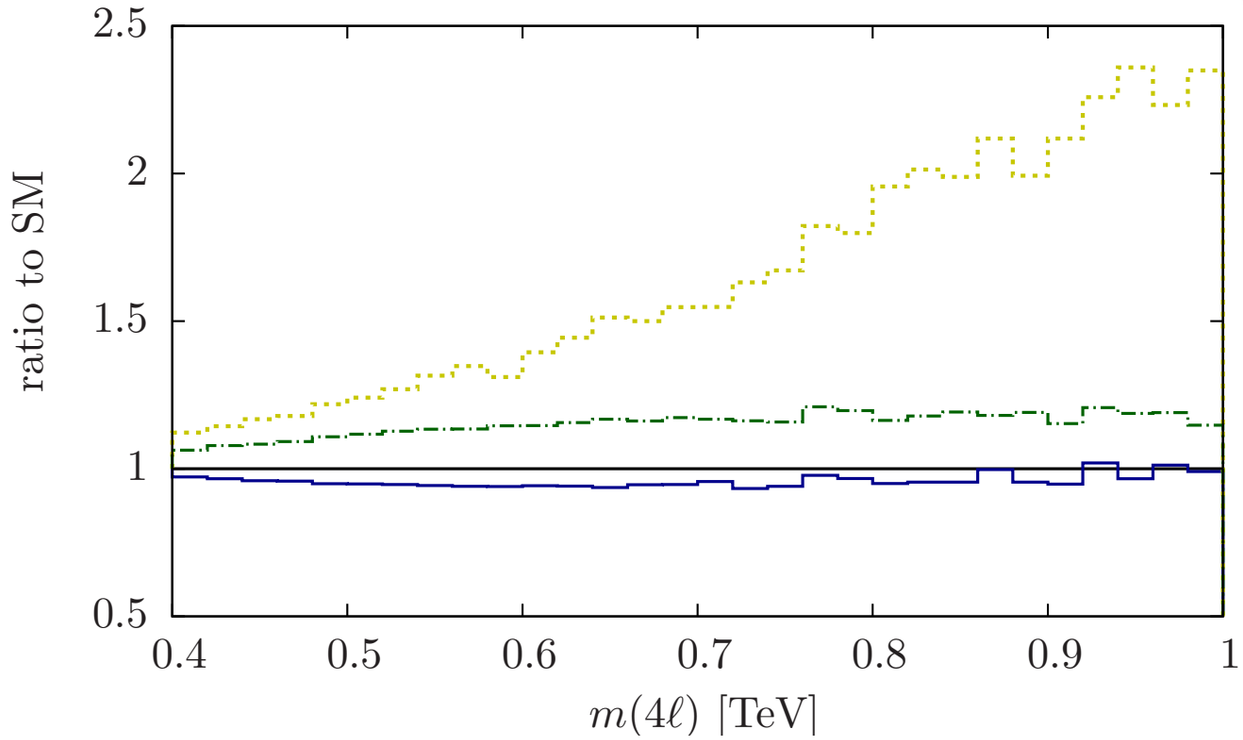


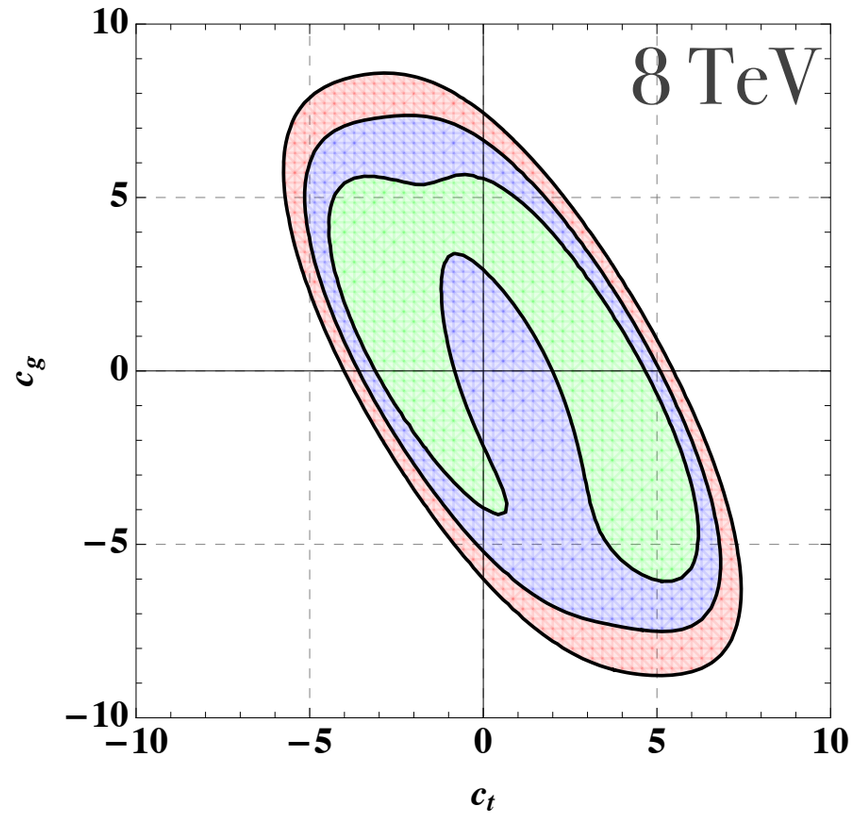
Large momentum transfers → BSM



[CE, Soreq, Spannowsky `14]

see also [Coleppa, Mandal, Mitra `14]
[Azatov, Grojean, Paul, Salvioni `14]





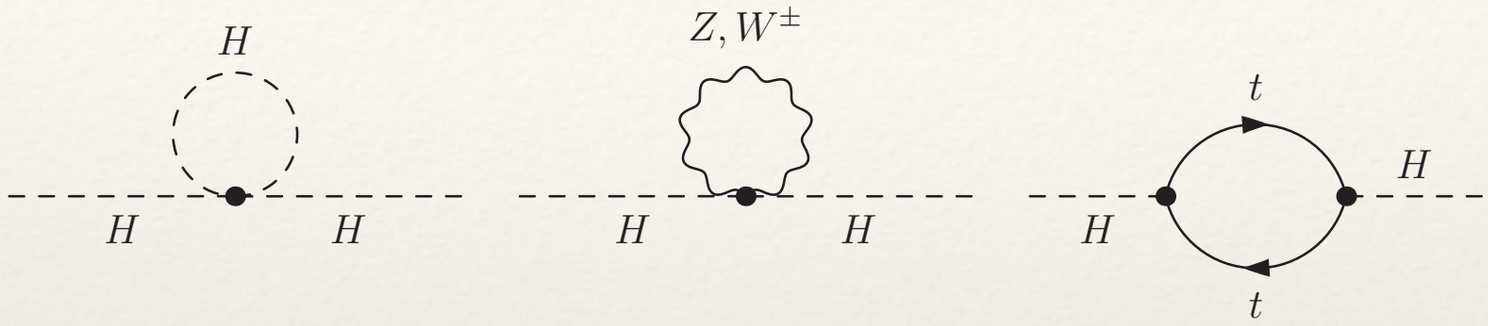
[Cacciapaglia, Denandrea, La Rochelle, Flament `14]

Summary & Conclusions

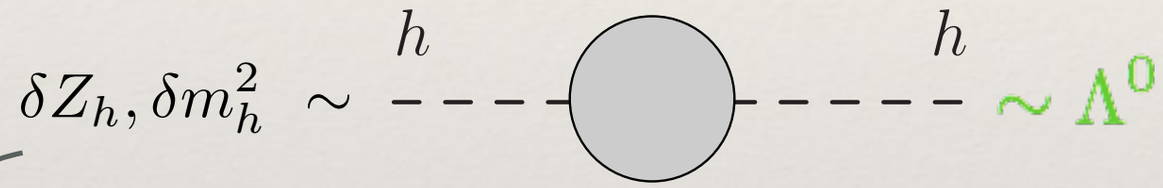
- there are more questions than answers….
- run II & HL-LHC will give us more insights into the SM-likeness of the Higgs
  - high momentum transfers with reasonable statistics
  - fully-differential EFT-based approaches
  - **new analysis strategies, new channels**
  - there is already a case for 250 GeV linear collider for Higgs spectroscopy! (→ non-resonant naturalness!)
- say something about the self-interactions at 3/ab? → FCC-ee/hh?

Benefits of precision: Higgs naturalness

- obviously direct LHC measurements will have their sensitivity saturated by systematics ⇒ lepton collider physics



- don't forget the B_0 functions !

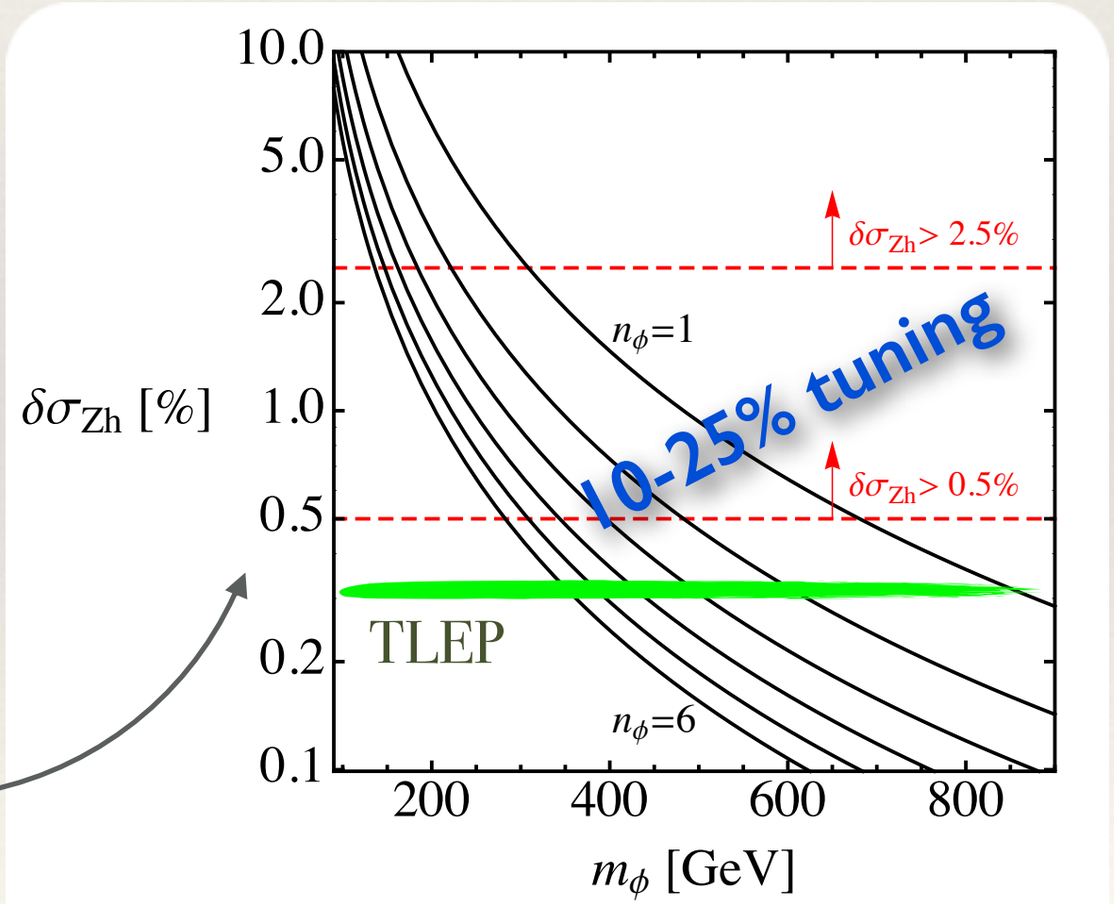


<u>worst case:</u> dark sector enforces naturalness, e.g. twin Higgs models

[Chako, Gho, Harnik `05]

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\delta Z_h (\partial_\mu h)^2 + \ldots$$

250 GeV linear collider
full EW corrections



[Craig, CE, McCullough `13]