Christoph Englert

Higgs under the Hood ?

University of Sussex

15.05.2014

"Yang-Mills+Higgs had to be true"

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

Ws and Zs in 1983 at UA1/UA2

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

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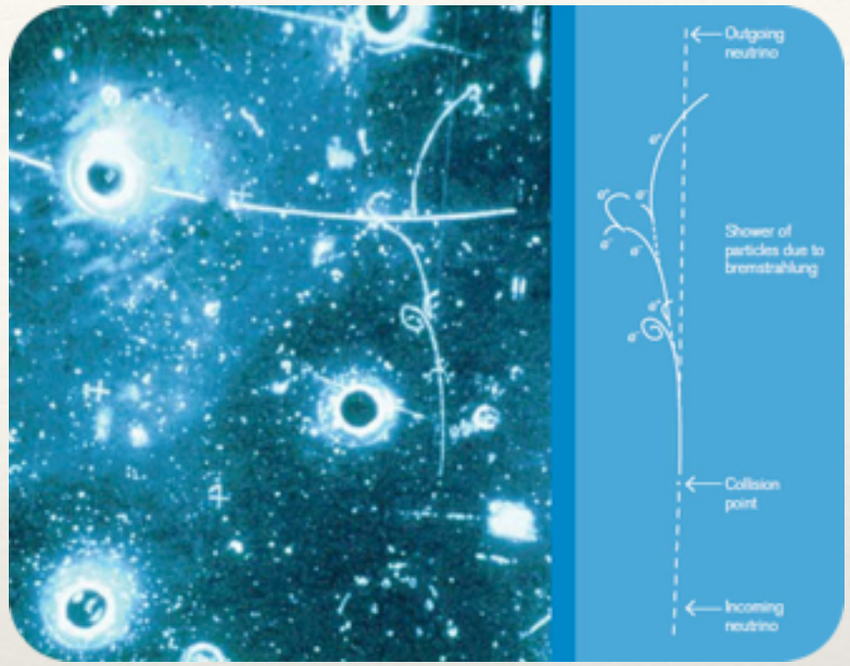

How do you accommodate this in QFT ?

[Weinberg `67]

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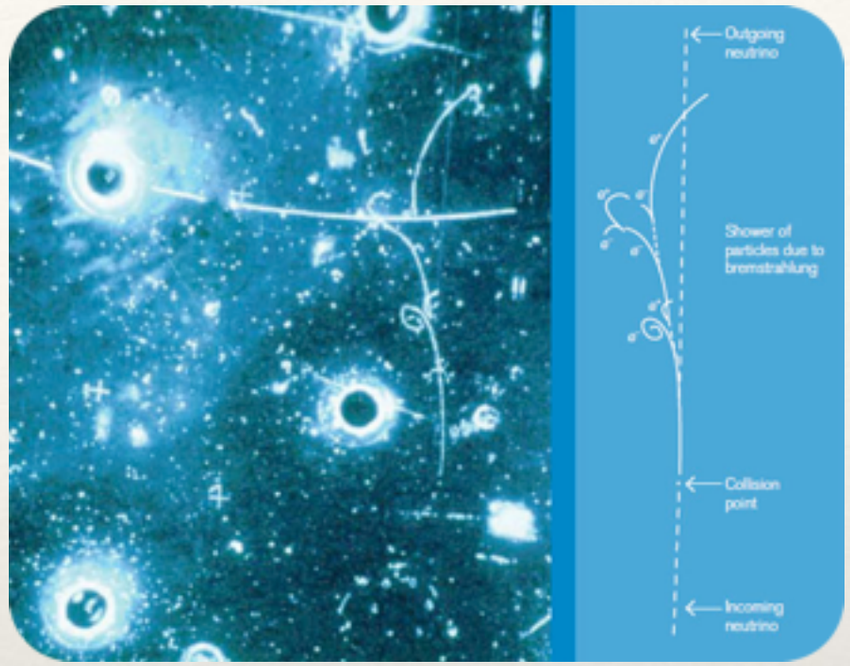

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[Higgs `64] [Brout, Englert `64] [Guralnik, Hagen, Kibble `64]

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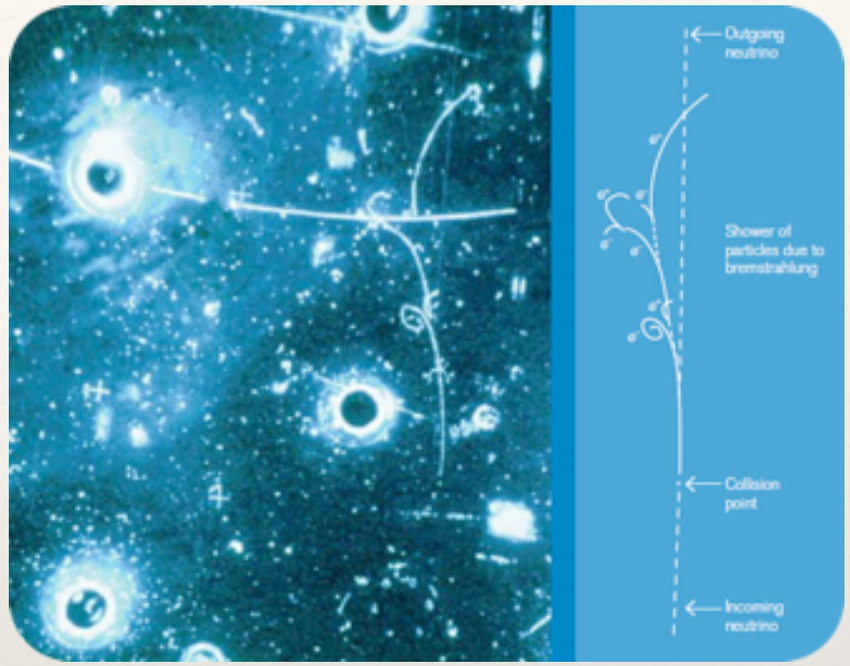

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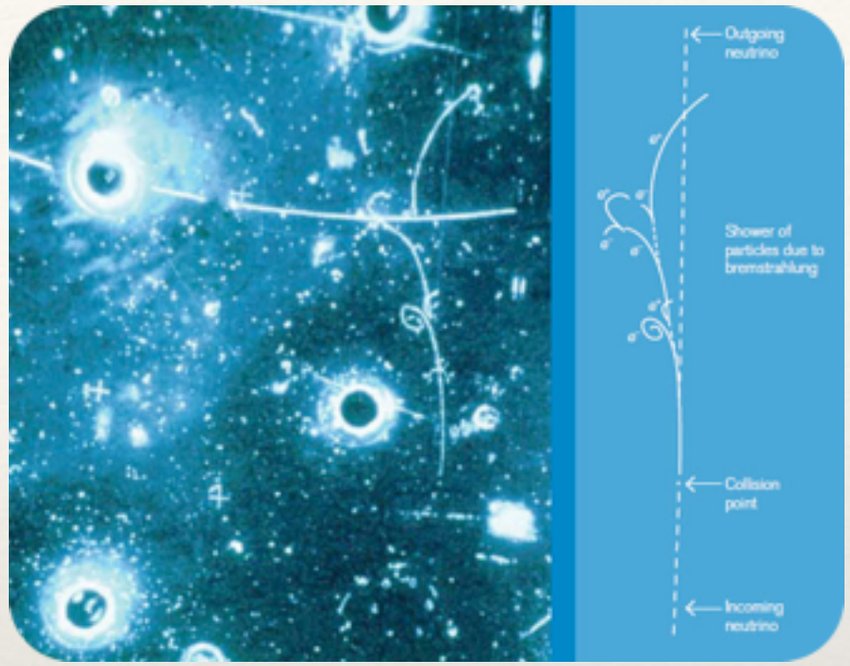

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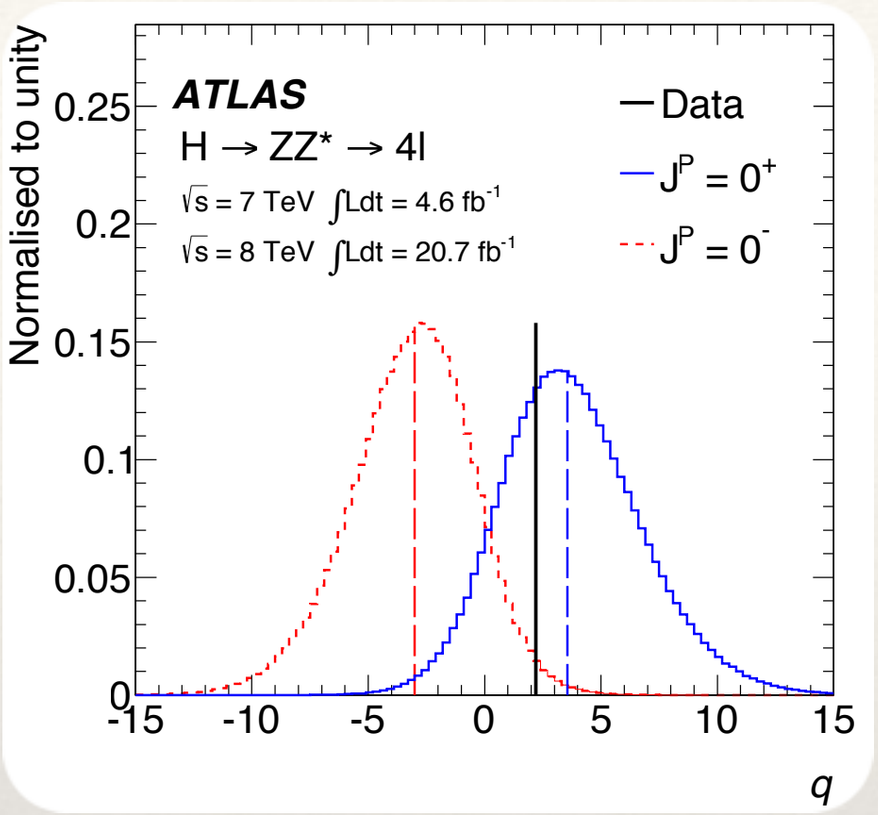
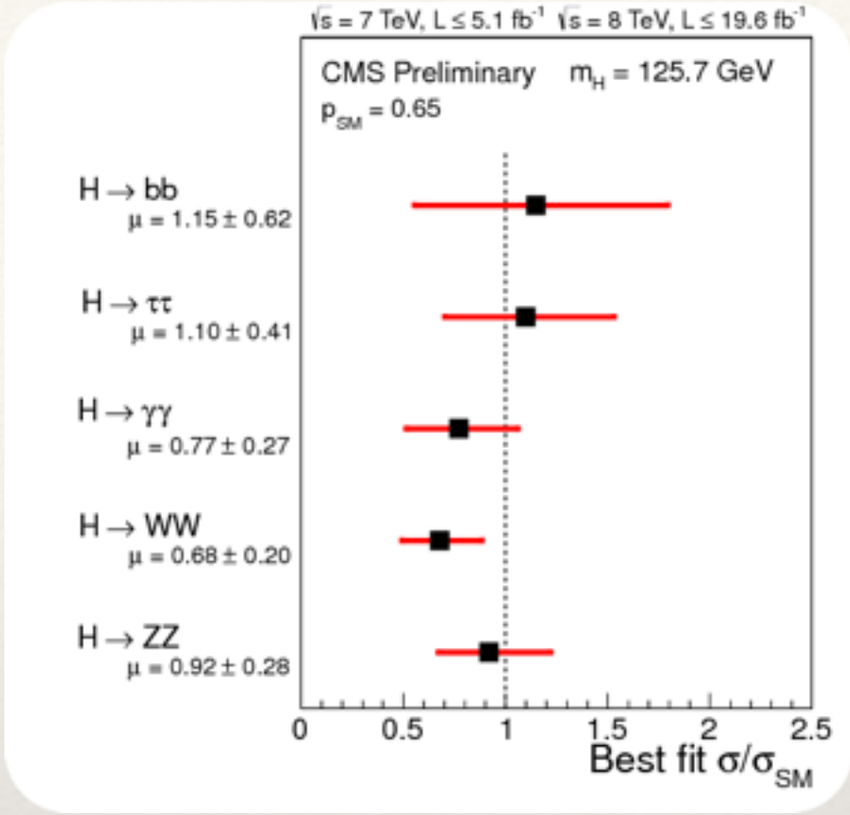
- massive gauge bosons, but no ghost problems at small distances

☛ 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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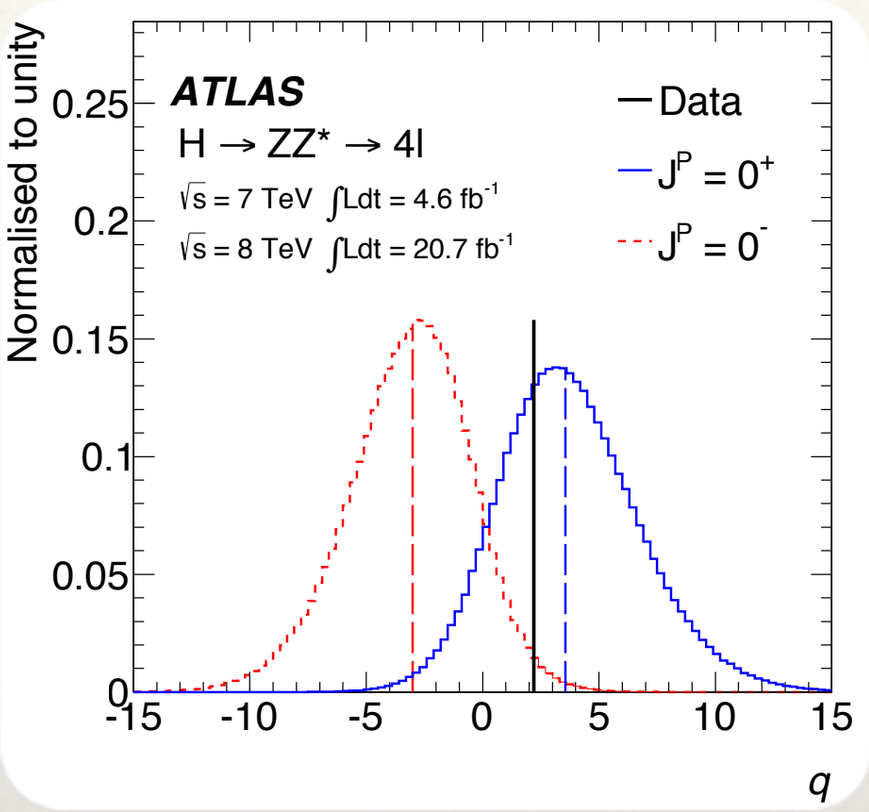

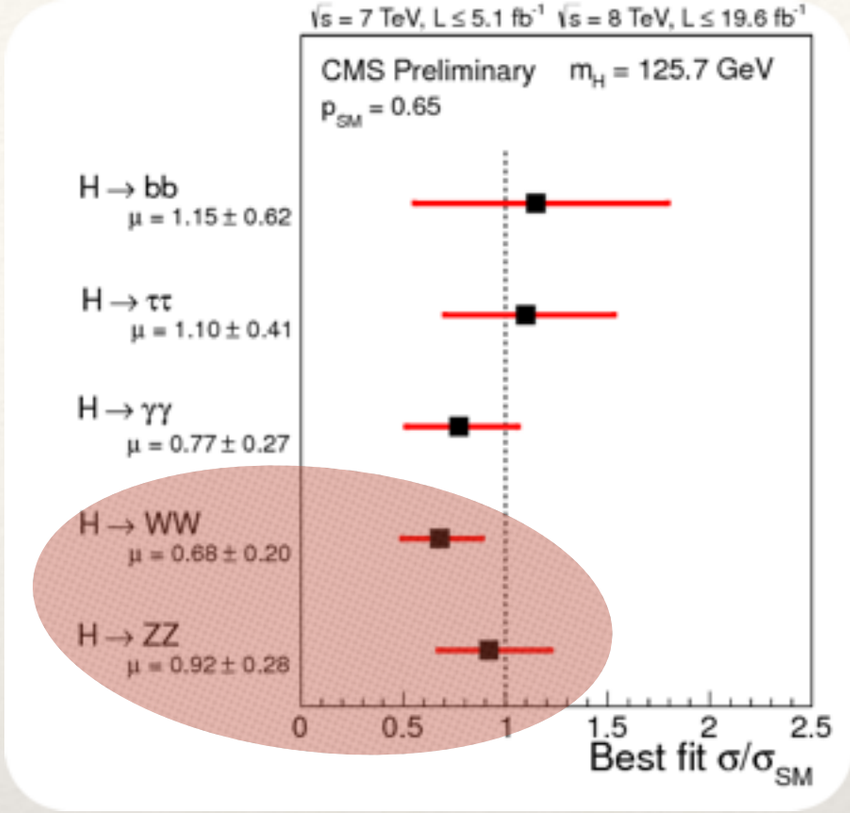

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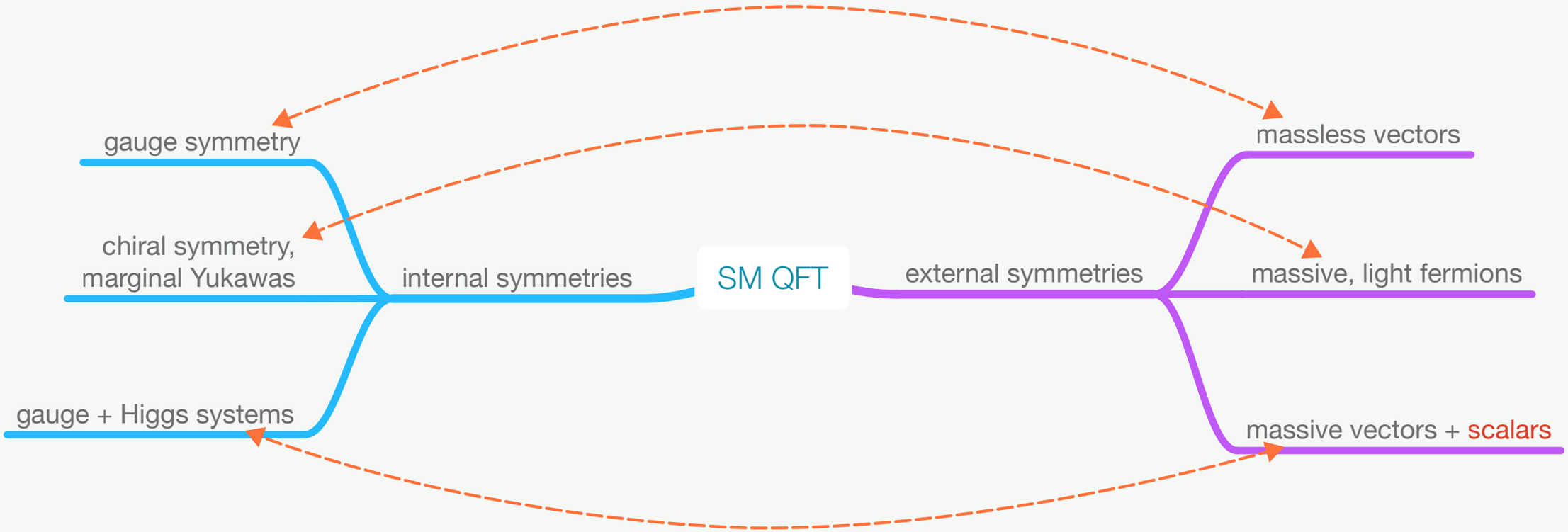
Higgs properties *sui generis*:

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

The Standard Model: taking stock



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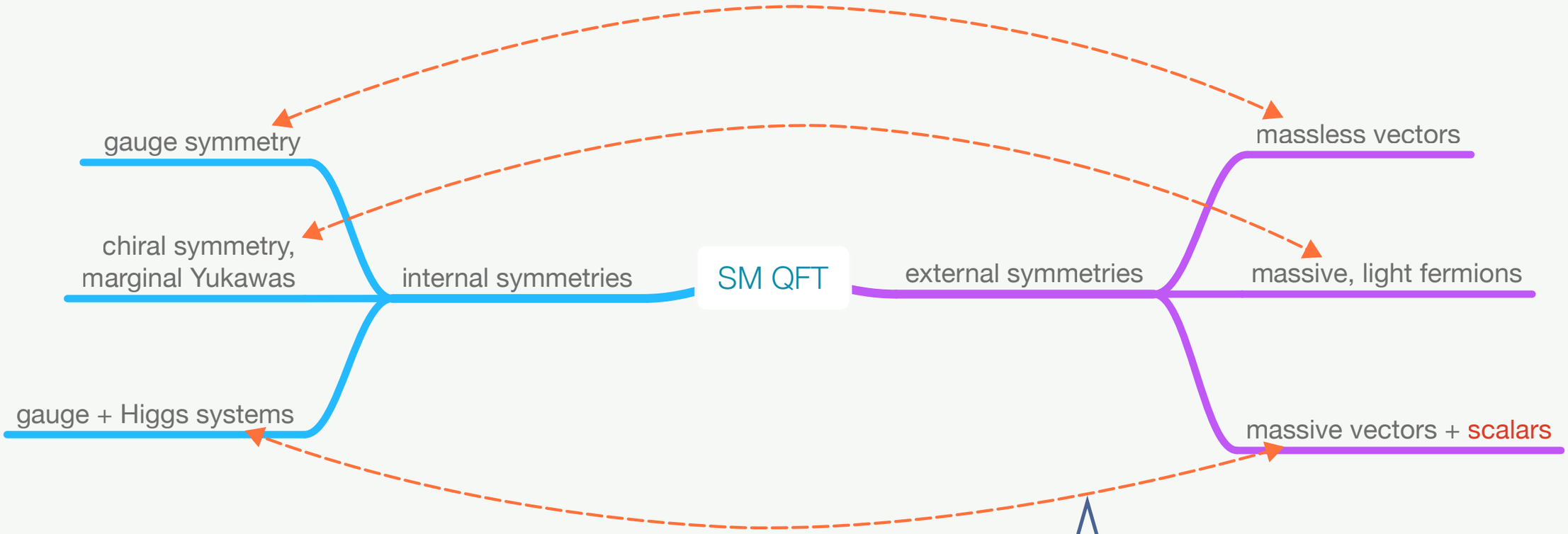

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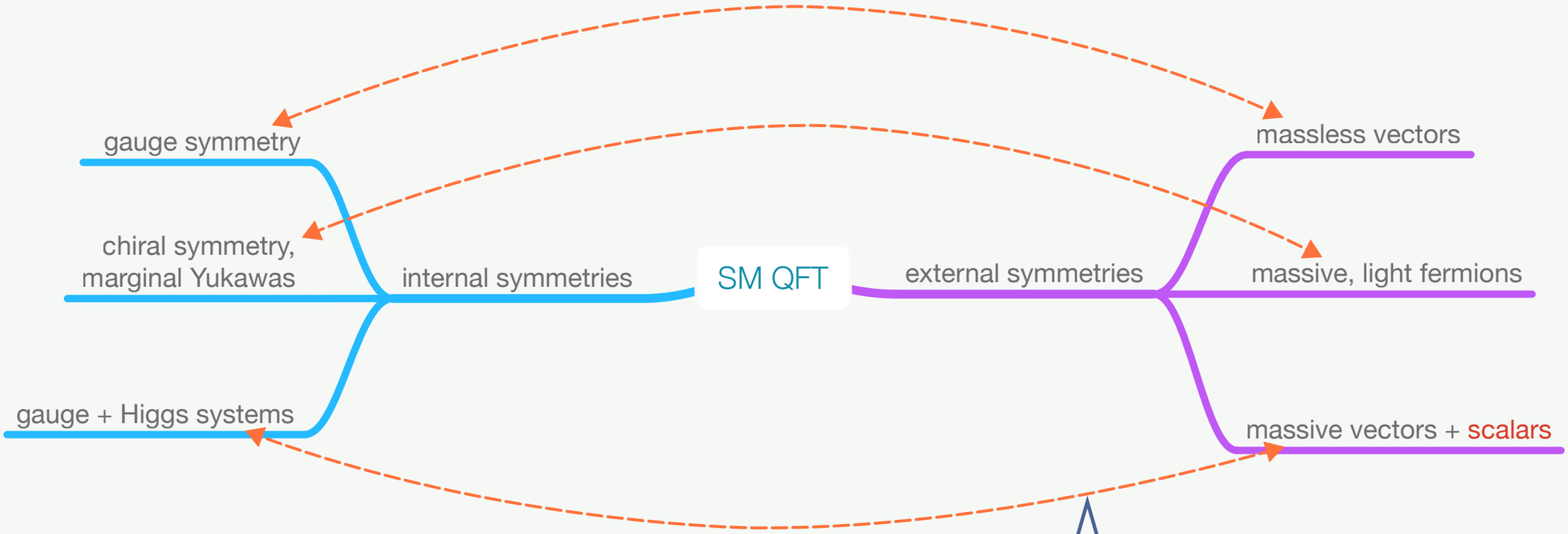

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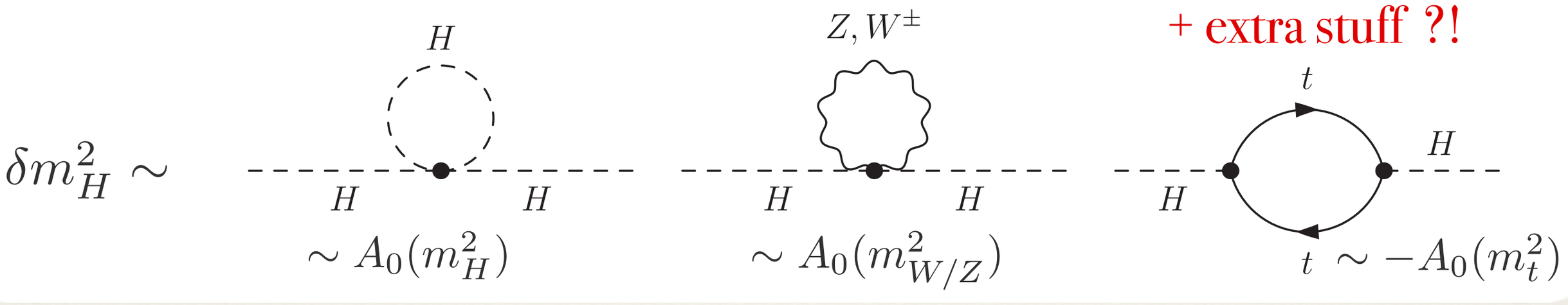
☛ ultraviolet catastrophe of the 21st century

Higgs physics: 21st century's UV catastrophe?



$$\delta m_H^2 \sim \text{UV cutoff/threshold(s)}$$

$$\sim \underbrace{(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2)}_{=0\ ?} \times \frac{\Lambda^2}{\langle H \rangle^2}$$

[Veltman `81]

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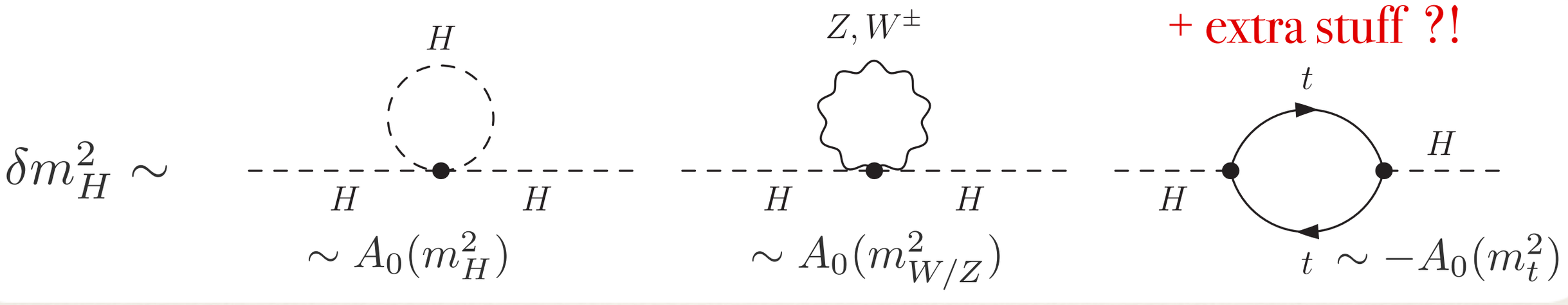

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- bosonic and fermionic thresholds enter differently, RS dependent
- it is a relation of couplings rather than masses $m \sim \text{coupling} \times \langle H \rangle$

Stabilizing Hierarchies: SUSY

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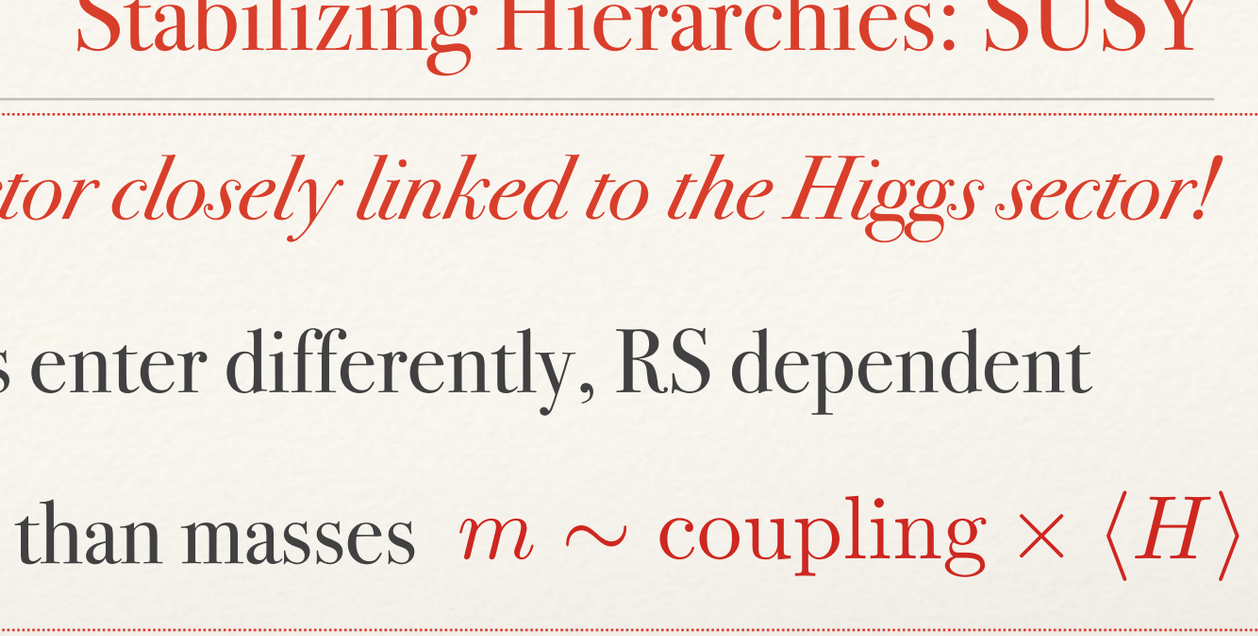
☛ what are the ways out ?

- Supersymmetry: "play with particle content"

enhanced external symmetry removes sensitivity to the UV,

good properties persist when SUSY is softly broken, only logarithmic sensitivity to UV scales reintroduced



light colored partners: not observed (yet)...

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☛ what are t …

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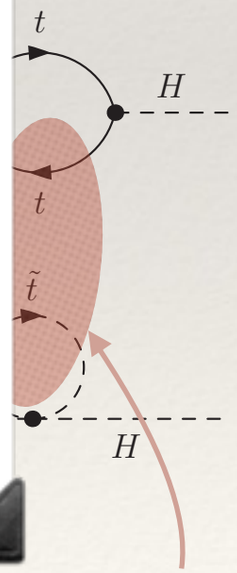
How will we know?

- Higher Energy !!
  - * Find Something! → End of discussion!
  - * Find Nothing → Tuning $\propto E^2_{\text{machine}}$

[Arkani-Hamed `13]



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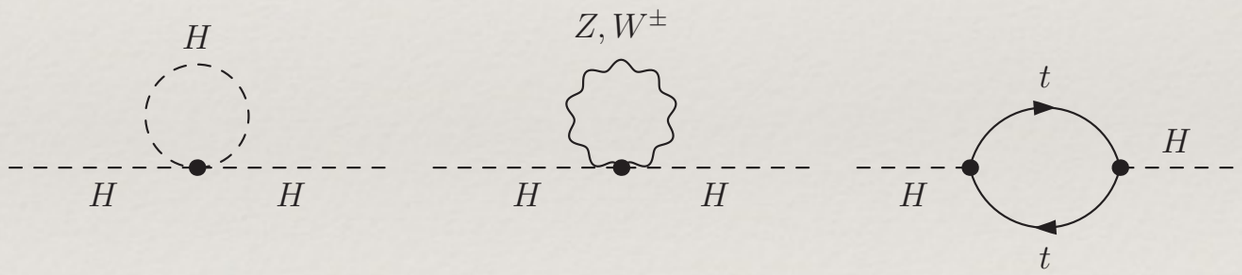
- Conformal UV dynamics: "Dilaton" and/or "hierarchies are spurious"

vanishing explicit mass terms due to a UV conformal fix point

Coleman-Weinberg sector generates scale dynamically and transmits it via marginal couplings



+ **"resummation"**

[Hempfling `96]
Meissner, Nicolai `08]
[CE, Jaeckel, Khoze Spannowsky `13]
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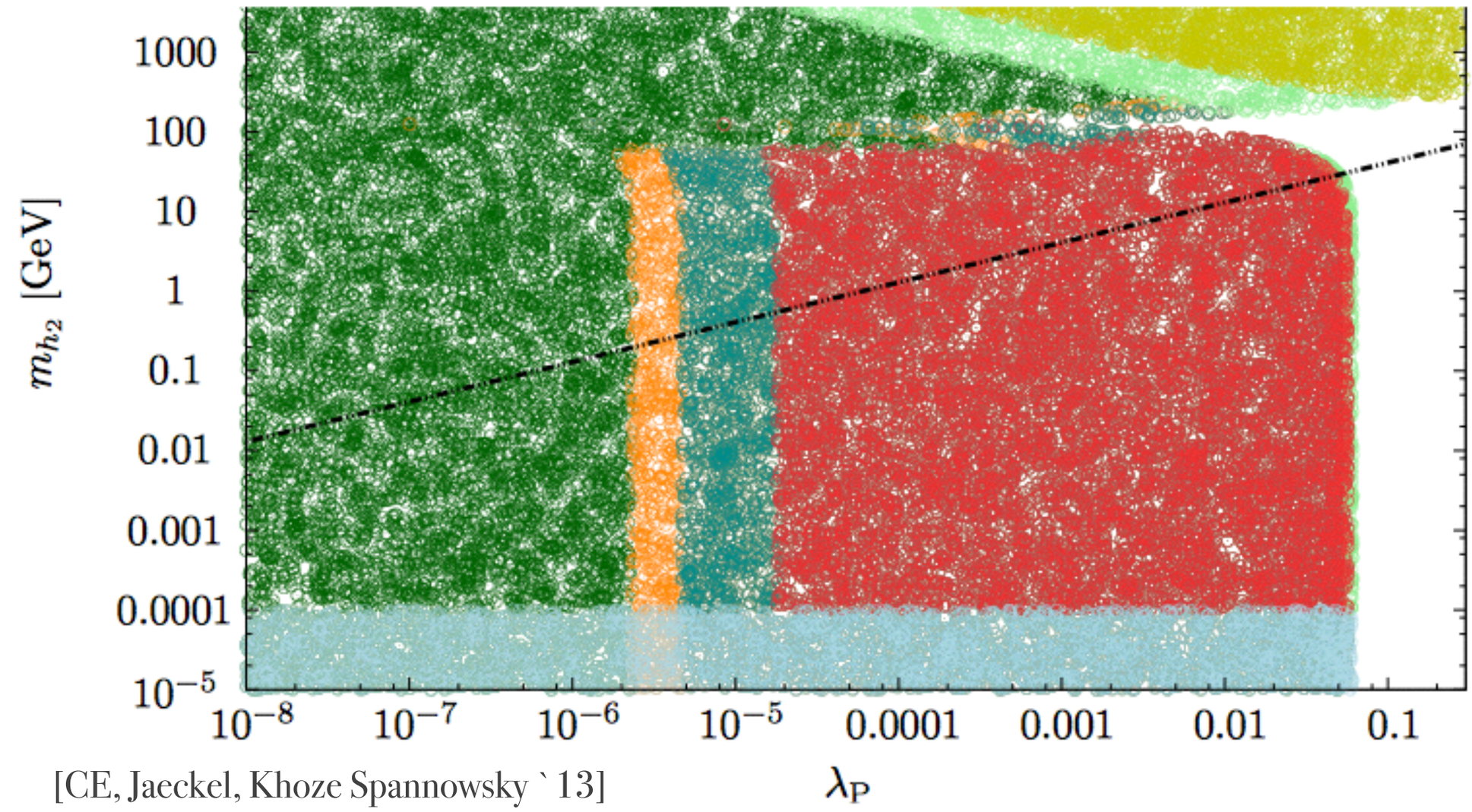

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$\langle H \rangle$

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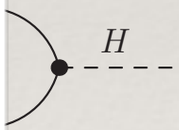

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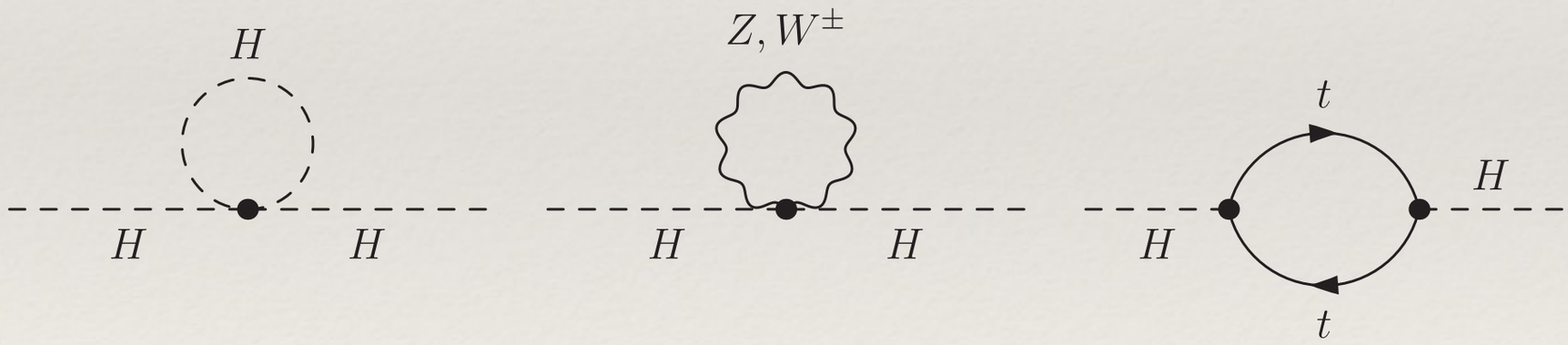

+ top partners

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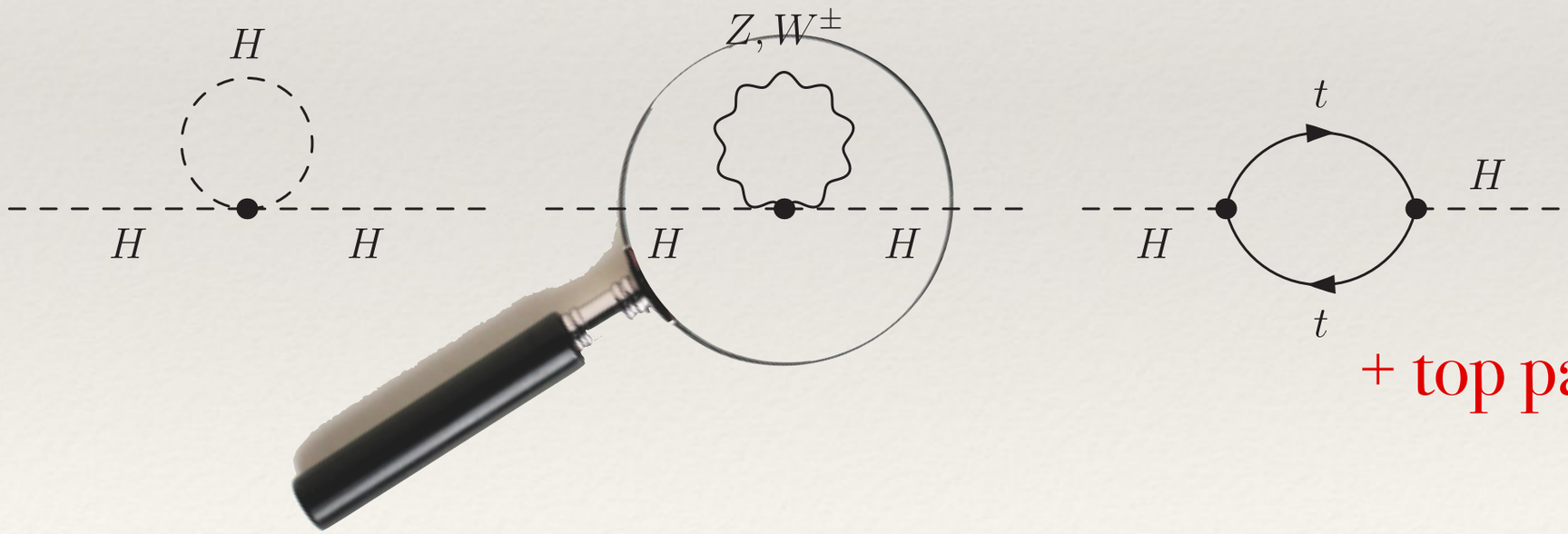

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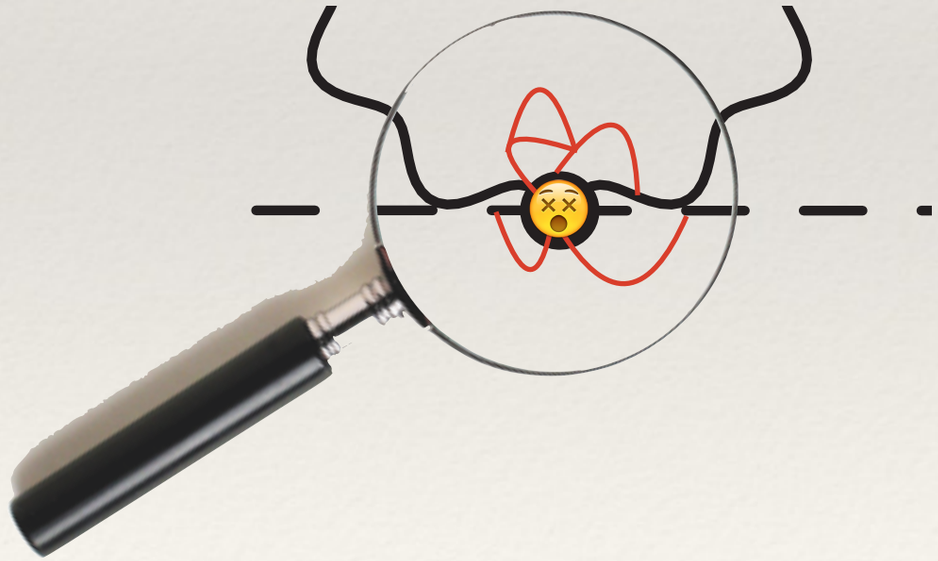

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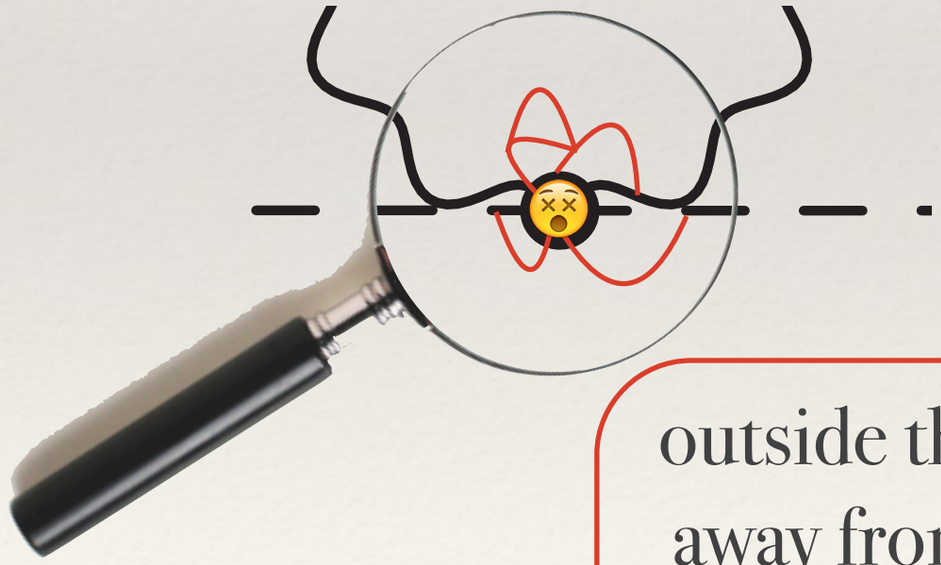

outside the perturbative regime?
away from conformal fix points?
away from large-N?

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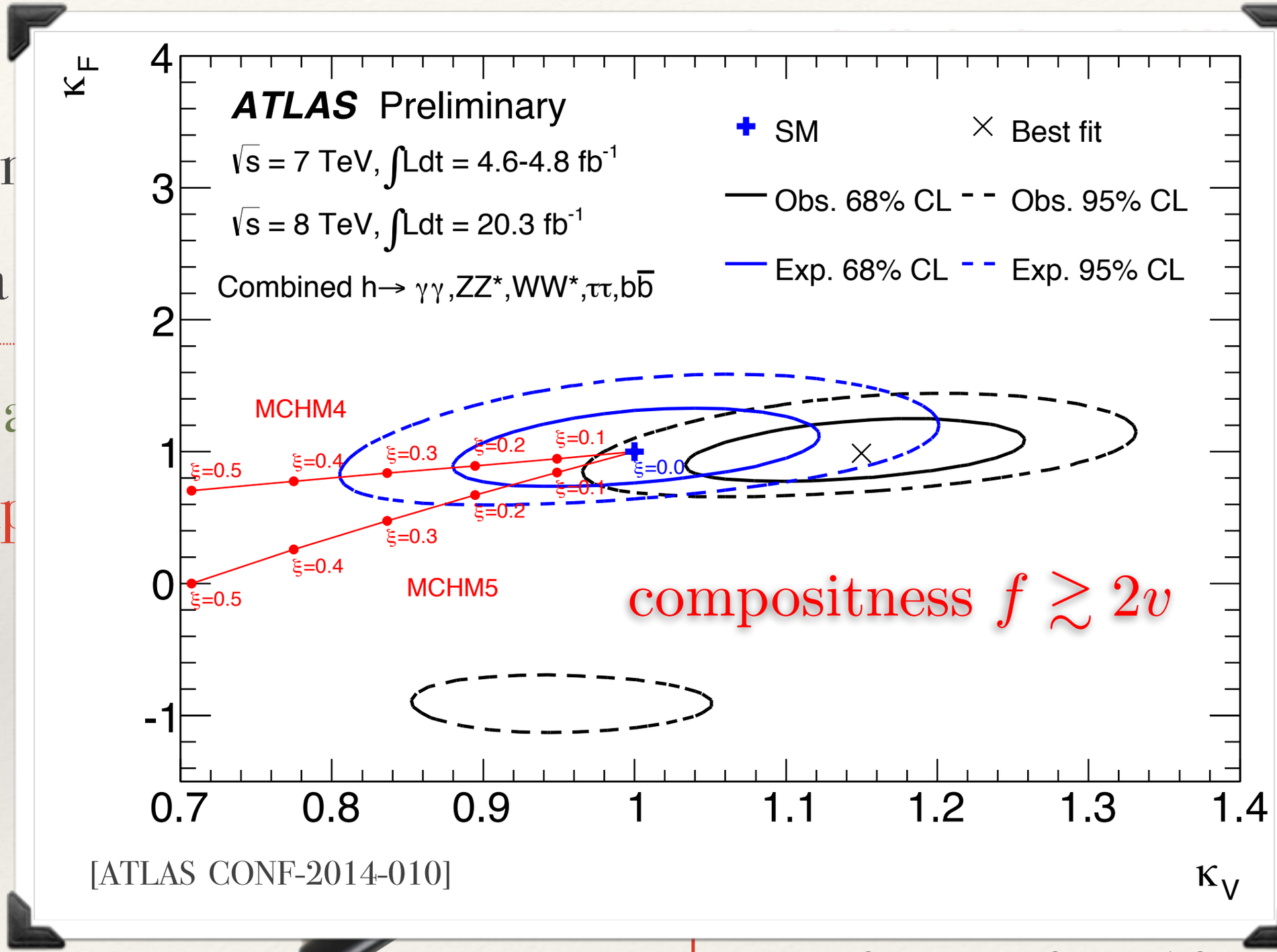
- it is a …

☛ what a…

- Comp…



[ATLAS CONF-2014-010]

…sector!

[Georgi `84]
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[Rattazzi `07]

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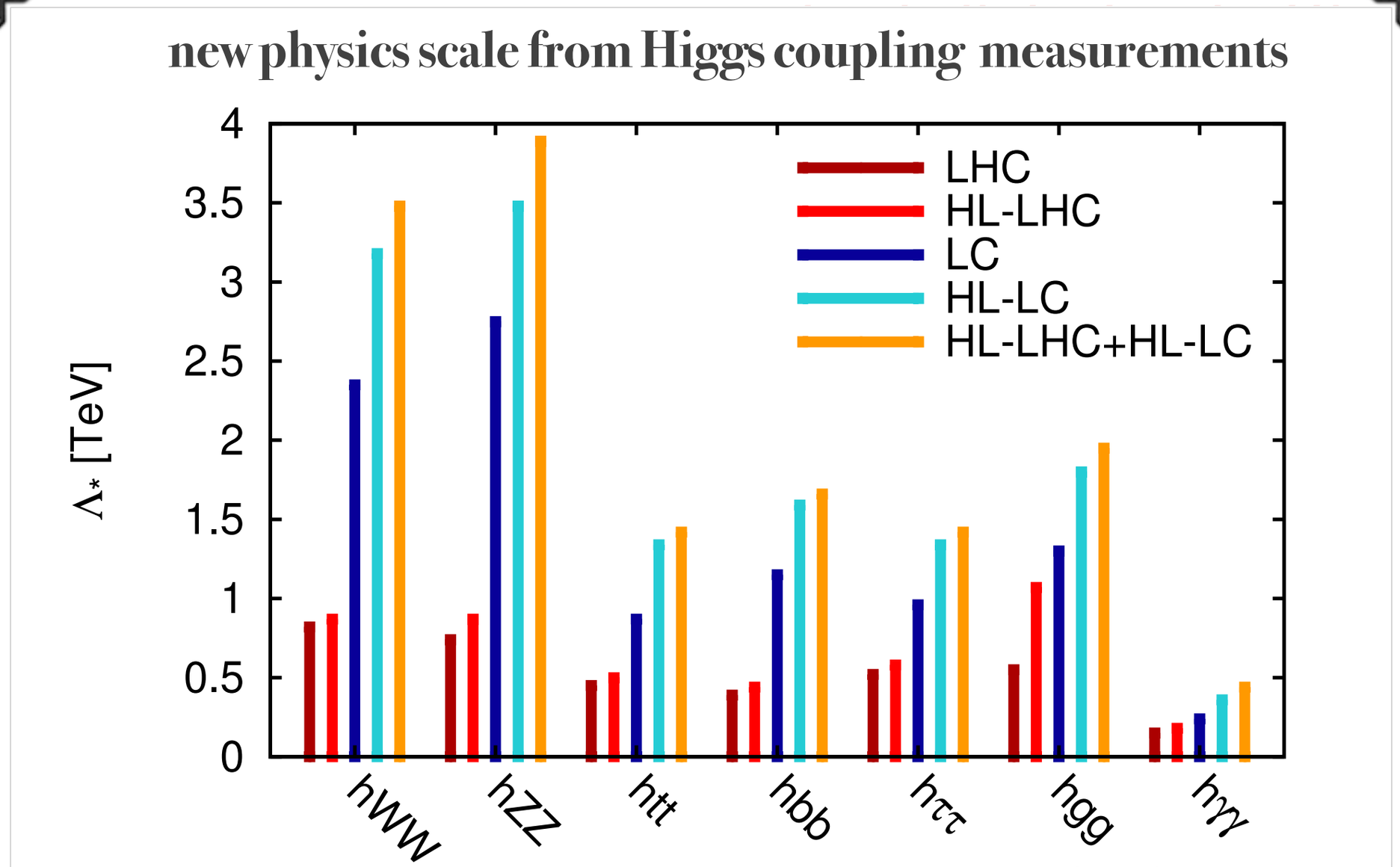

[CE, Freitas, Mühlleitner, Plehn, Rauch, Spira, Walz `14]

$$f \gtrsim \begin{matrix}(3.5)_{\text{LHC}} \\ (20)_{\text{ILC}}\end{matrix} \; v$$

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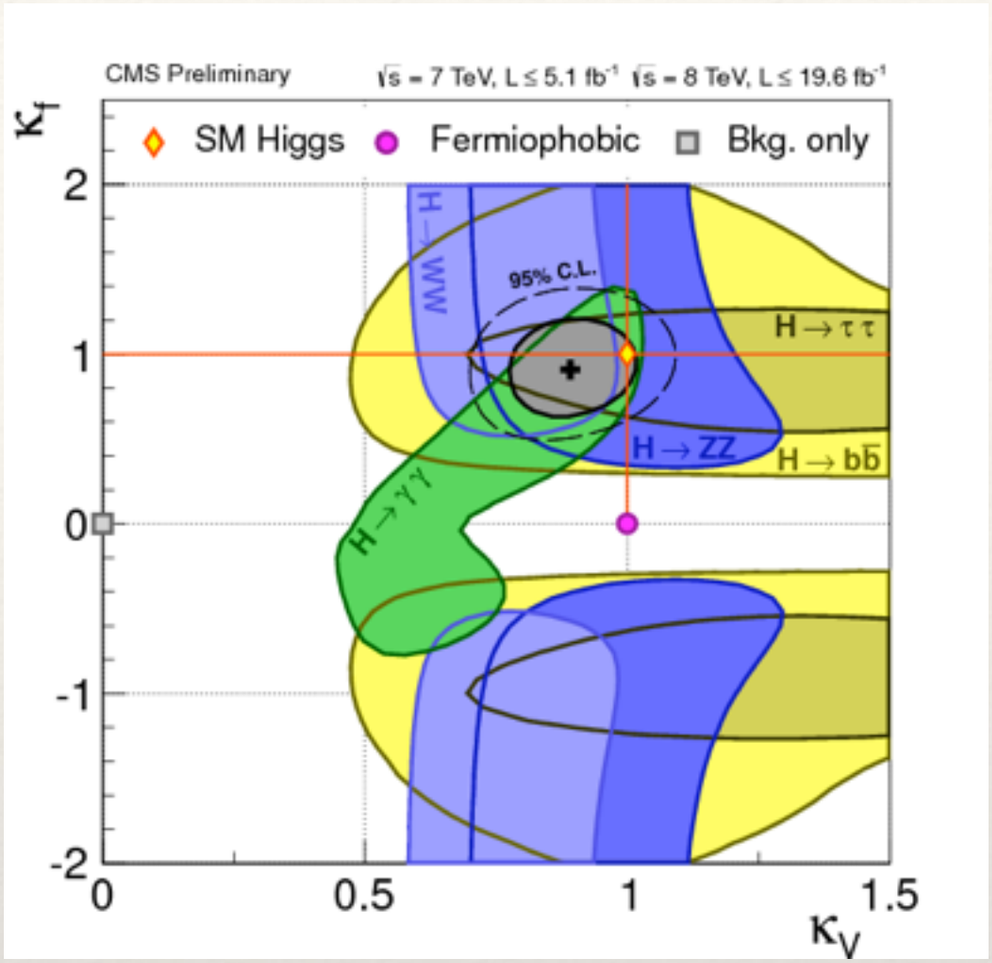
A bottom-up (B)SM Higgs programme

coupling measurements are determined by

1. unitarity
2. number of Higgs fields
3. **gauge representation**
4. **experimental extraction**
5. **mechanism of ELW symmetry breaking**
6. **spectrum through quantum effects**



similar analyses by [Ellis, You `12]
[Masso, Sanz `12]
[Carmi, Falkowski, Kuflik, Volansky `12]
[Klute, Lafaye, Plehn, Rauch, Zerwas `12]
[Corbett, Eboli, Gonzalez-Fraile, et al. `12]
[Espinosa, Grojean, Mühlleitner, Trott `12]

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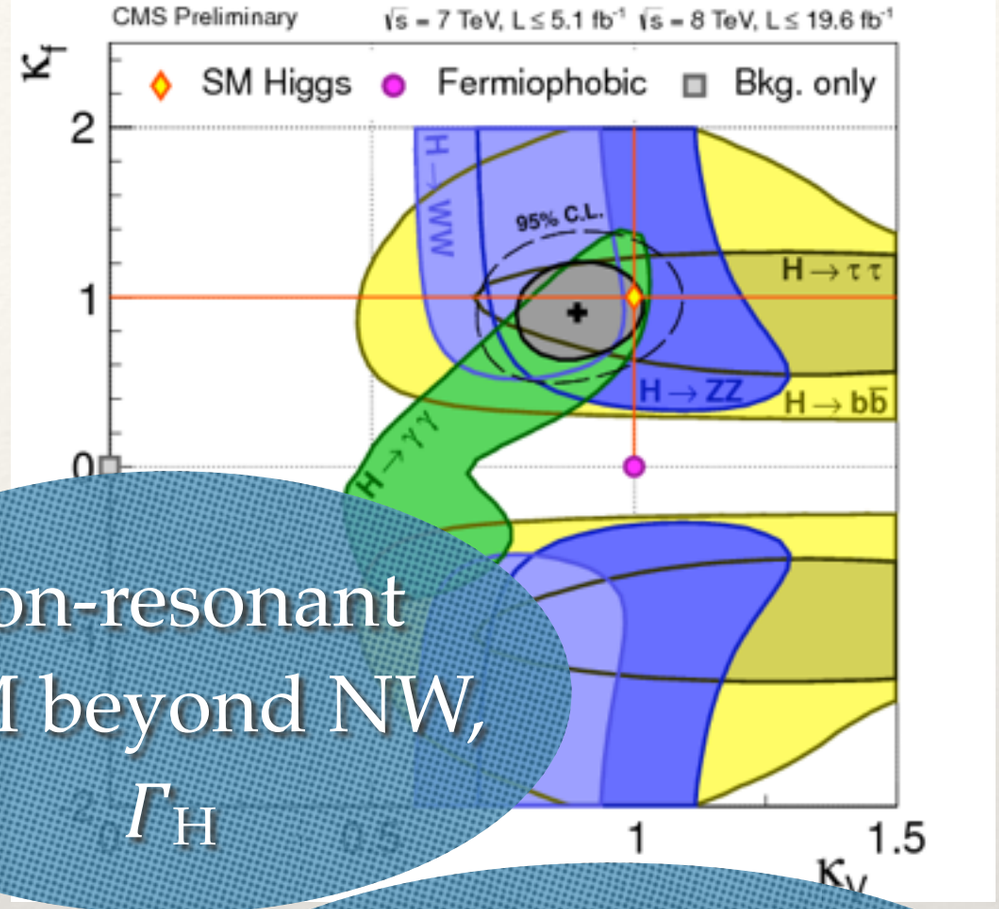
exotics

non-resonant
BSM beyond NW,
Γ_H

EWSB
specific couplings, top
interactions

naturalness
leaving footprints?



[Corbett, Eboli, González-Fraile, et al. `12]
[Trott `12]

Higgs couplings: gauge representation

Let's try an additional **3** under $SU(2)_w$

...there's a price to pay in the rho parameter:

$$\left[\frac{m_W}{m_Z}\right]_{(3,1)} \neq \left[\frac{m_W}{m_Z}\right]_{(2,1)}$$

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$$(3,3)\otimes(2,2)\simeq 5\oplus 3\oplus 3\oplus 1\oplus 1$$

heavy gauge
phobic

fermiophobic
$H^{\pm\pm}$

lightest state
125 GeV

$$c_{f,H_0} = \frac{c_q}{c_H}\,,$$

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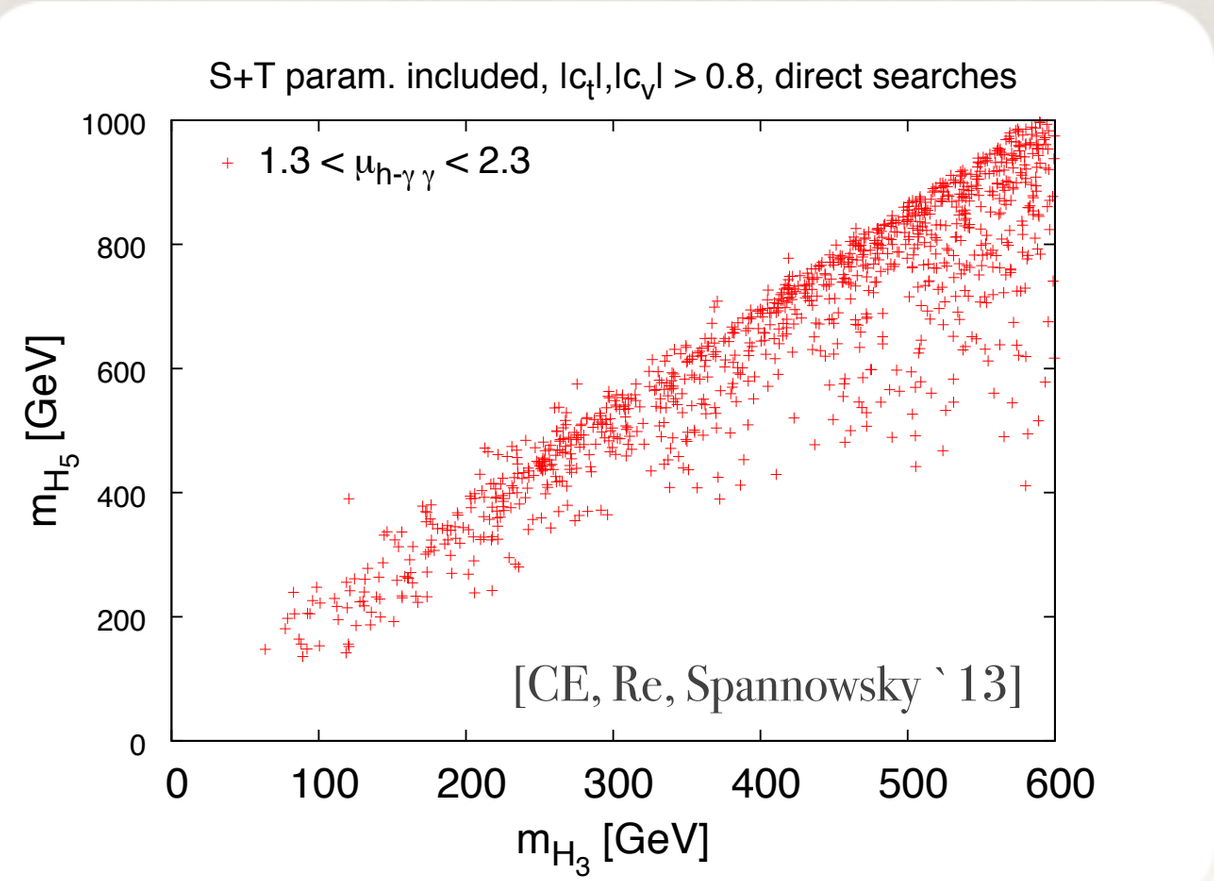
singlet mixing vev mixing

- 125 GeV state needs to be more triplet like. Otherwise severe issues with EWPD & pheno

$$m_{H_0'} = 125\ \text{GeV}$$



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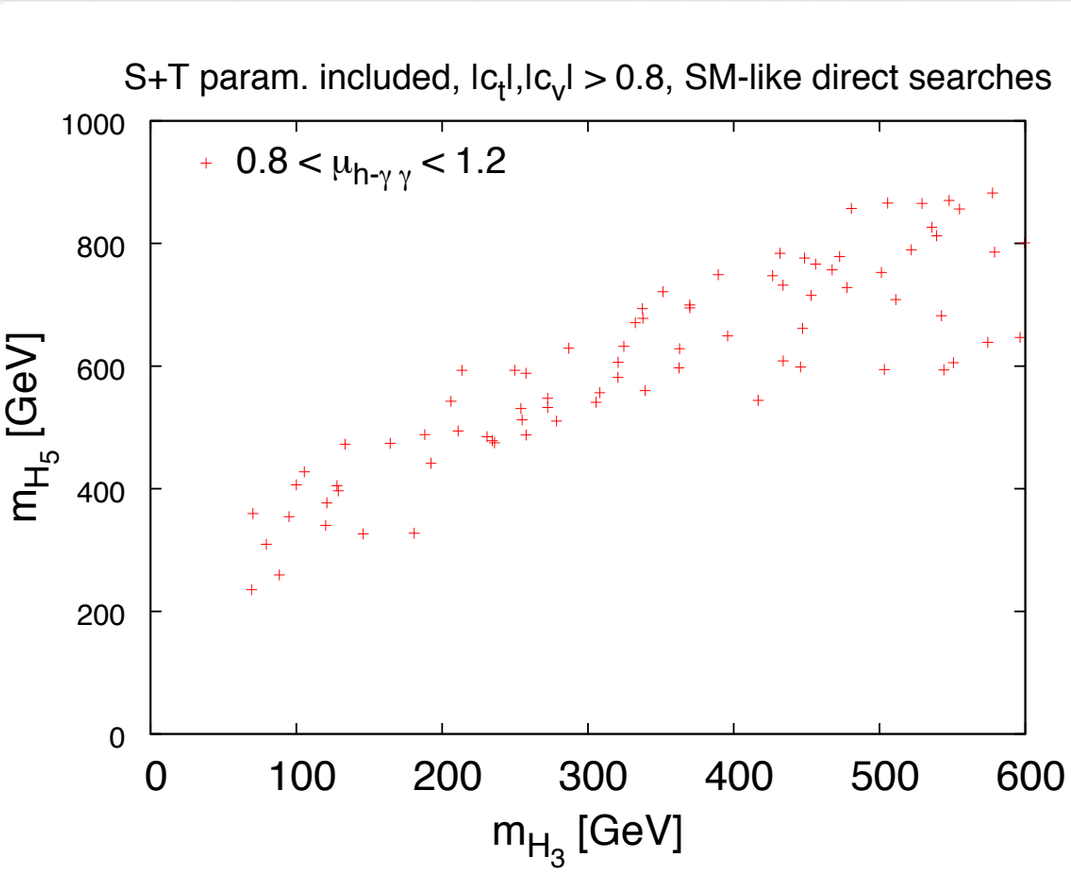

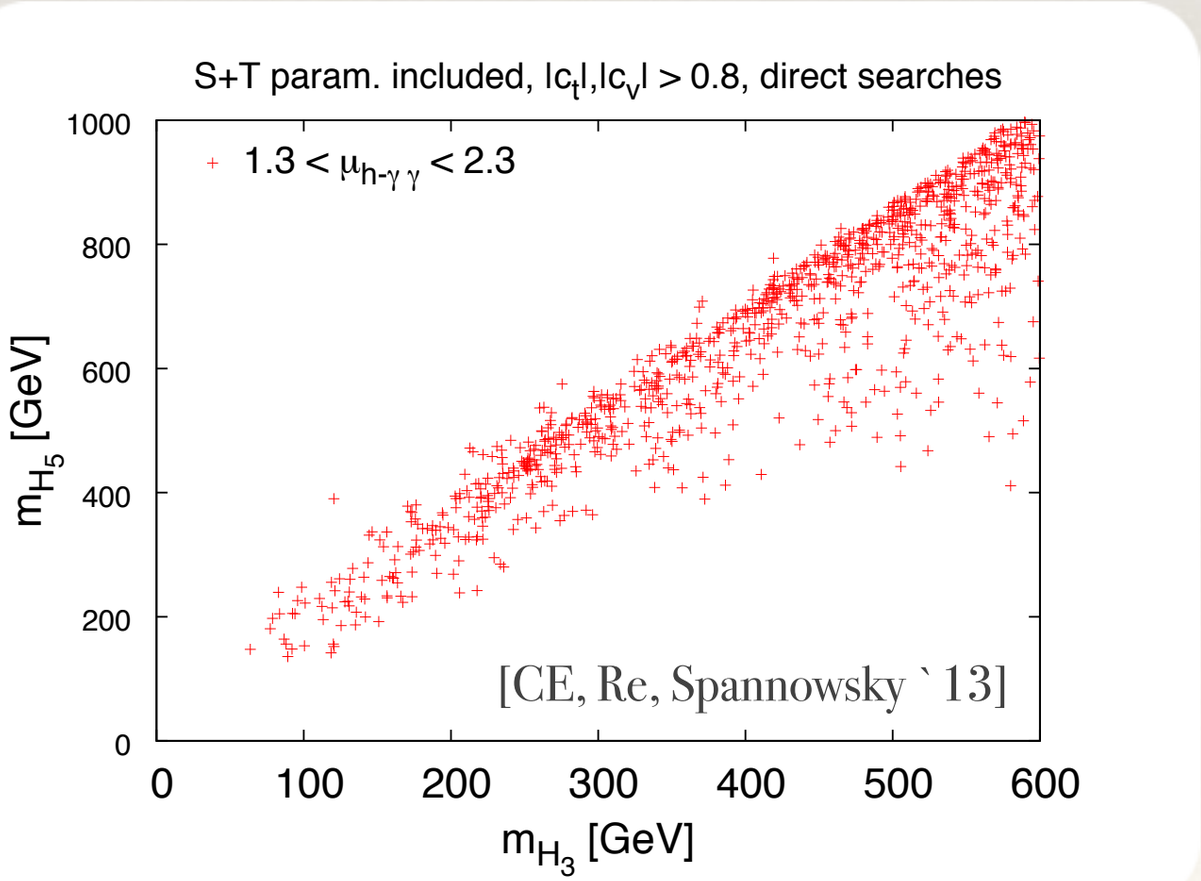

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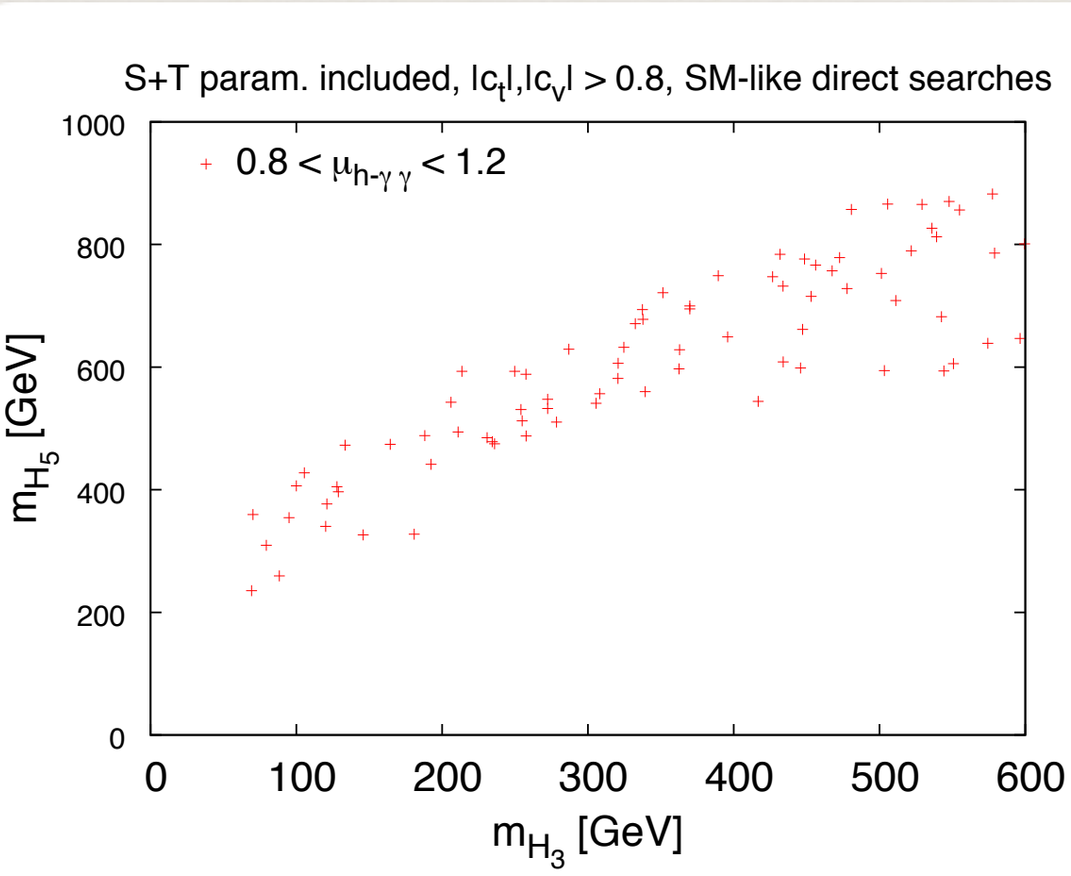
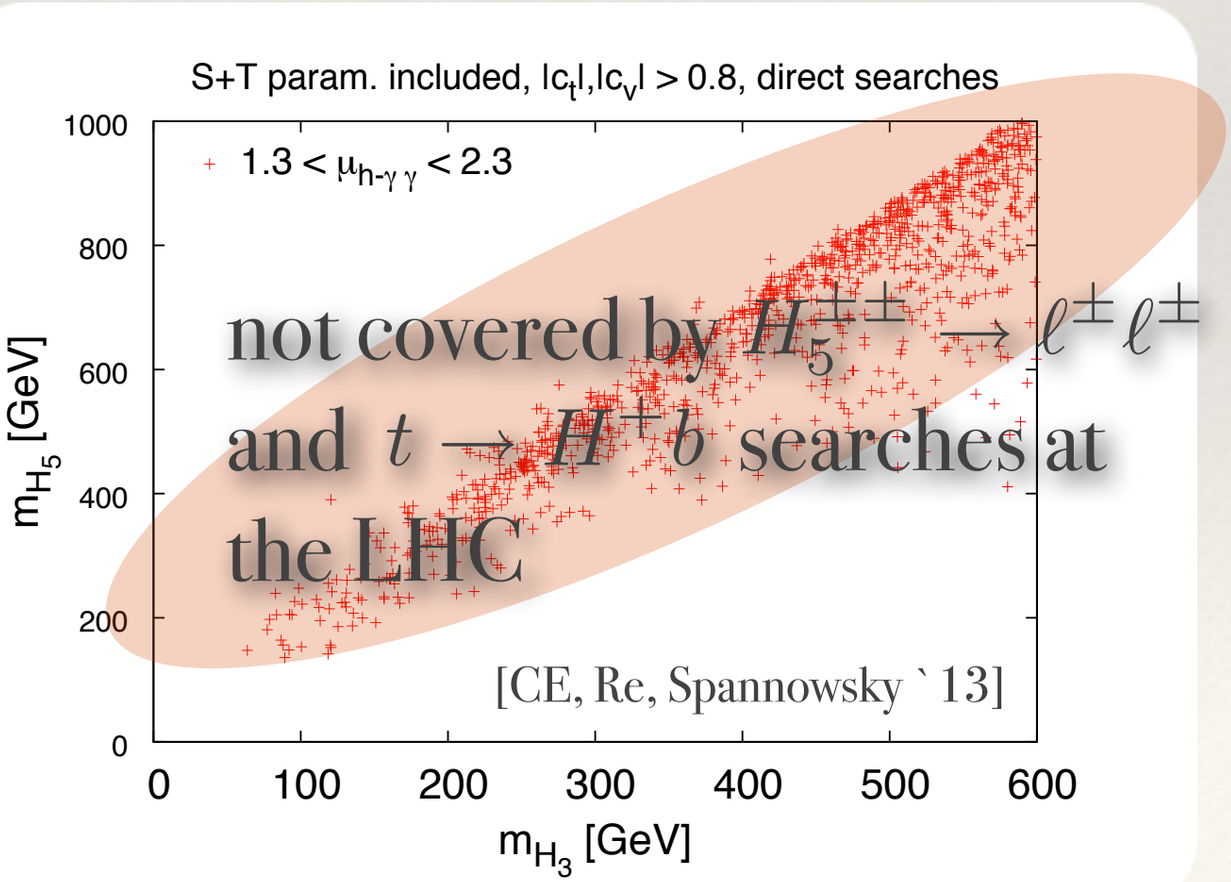
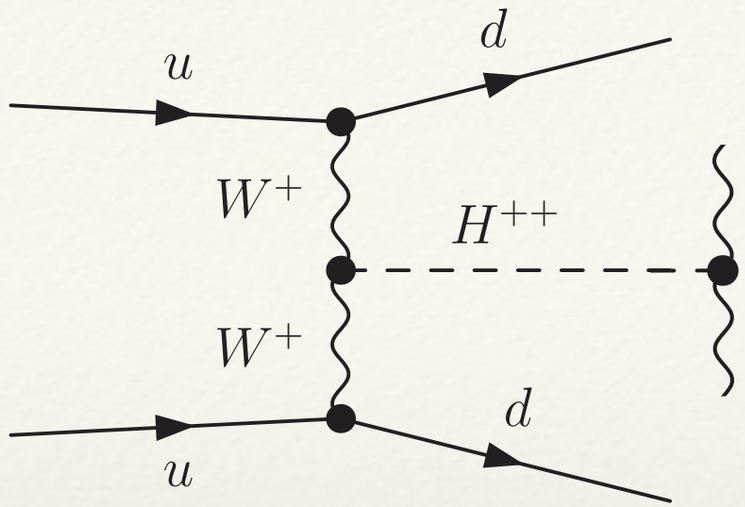
singlet mixing vev mixing





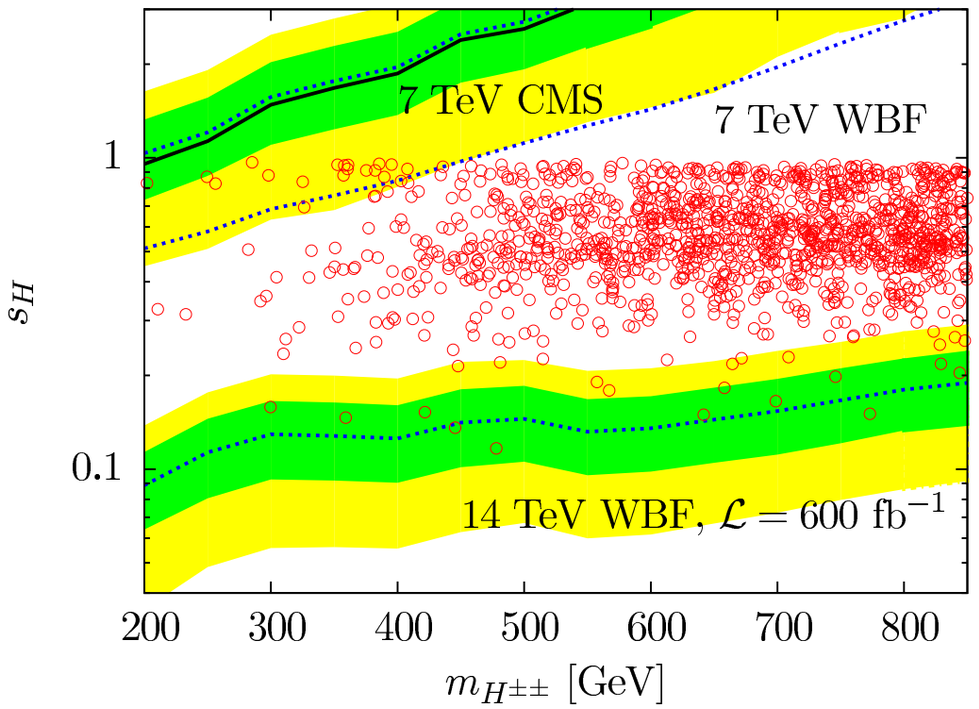
gauge representation: exotics



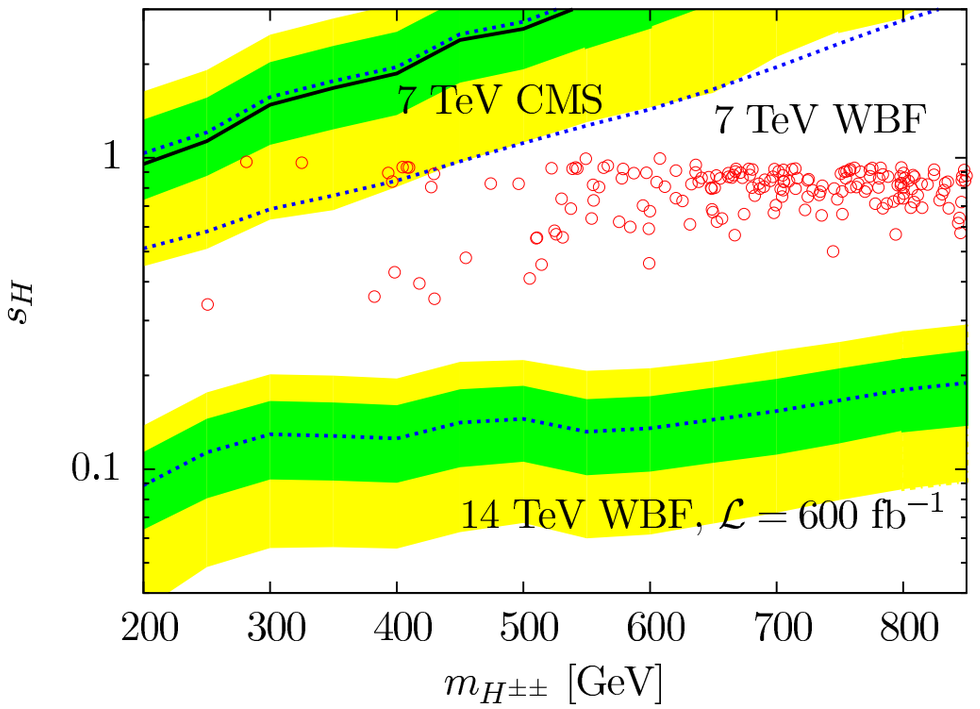
unitarity!

[Logan, Roy `10]
[Godfrey, Moats `10] [Chiang, Nomura, Tsumura `12]
[CE, Re, Spannowsky `13, `13] [Chiang, Yagyu `13]

[on-going in ATLAS and CMS]



(a) Higgs to diphoton branching ratio enhanced:
$1.3 \leq \xi_{H\to\gamma\gamma} \leq 2.3$

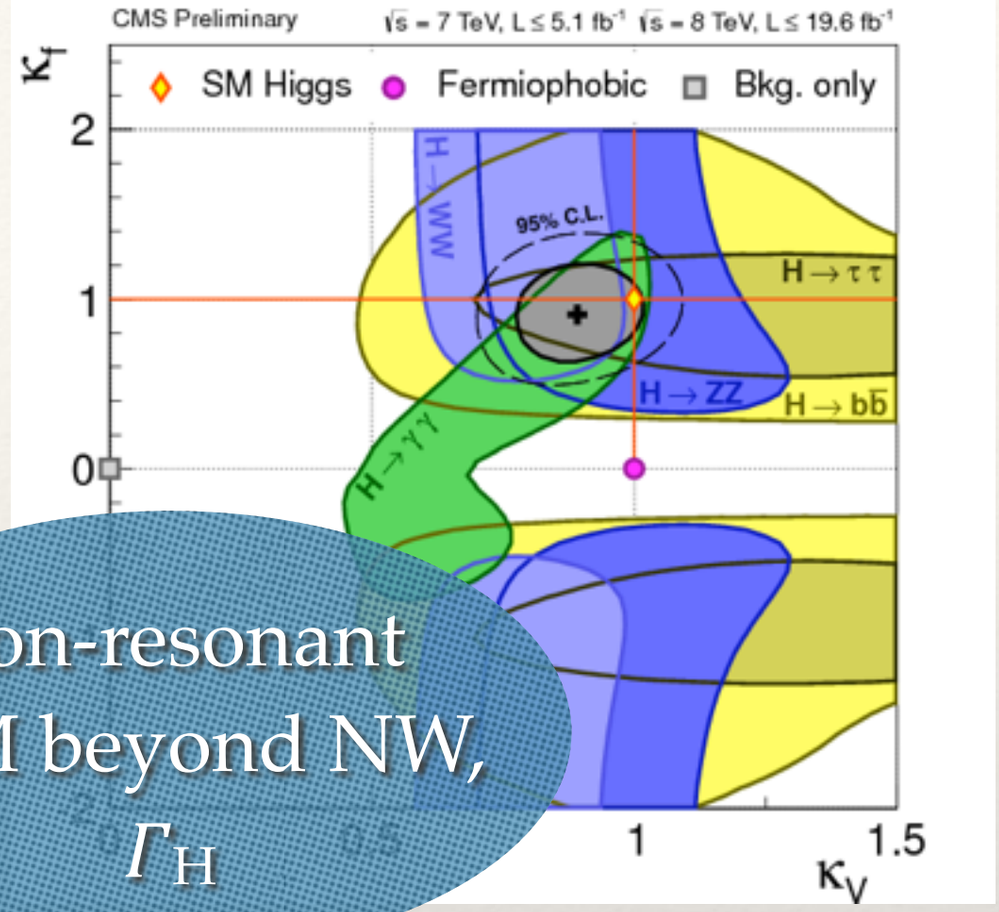


(b) Higgs to diphoton branching ratio SM-like:
$0.8 \leq \xi_{H\to\gamma\gamma} \leq 1.2$

A bottom-up (B)SM Higgs programme

coupling measurements are determined by

1. unitarity
2. number of Higgs fields
3. **gauge representation**
4. **experimental extraction**
5. **mechanism of ELW symmetry breaking**
6. **spectrum through quantum effects**



non-resonant
BSM beyond NW,
Γ_H

similar analyses by [Ellis, You ` 12]
[Masso, Sanz ` 12]
[Carmi, Falkowski, Kuflik, Volansky ` 12]
[Klute, Lafaye, Plehn, Rauch, Zerwas ` 12]
[Corbett, Eboli, Gonzalez-Fraile, et al. ` 12]
[Espinosa, Grojean, Mühlleitner, Trott ` 12]

(B)SM Higgs couplings: experimental extraction

- new contributions become relevant at high luminosity & energy

[Banfi, Martin, Sanz `13], [CE, McCullough, Spannowsky `13]

- quantum interference is your friend, and can be sizable in analyses of tails

- e.g. BDRS-like analyses of hZ production: our only shot at $h \to b\bar{b}$! Massive $t\bar{t}$ backgrounds, but manageable when the Higgs is boosted!

[Butterworth, Davison, Rubin, Salam `08]

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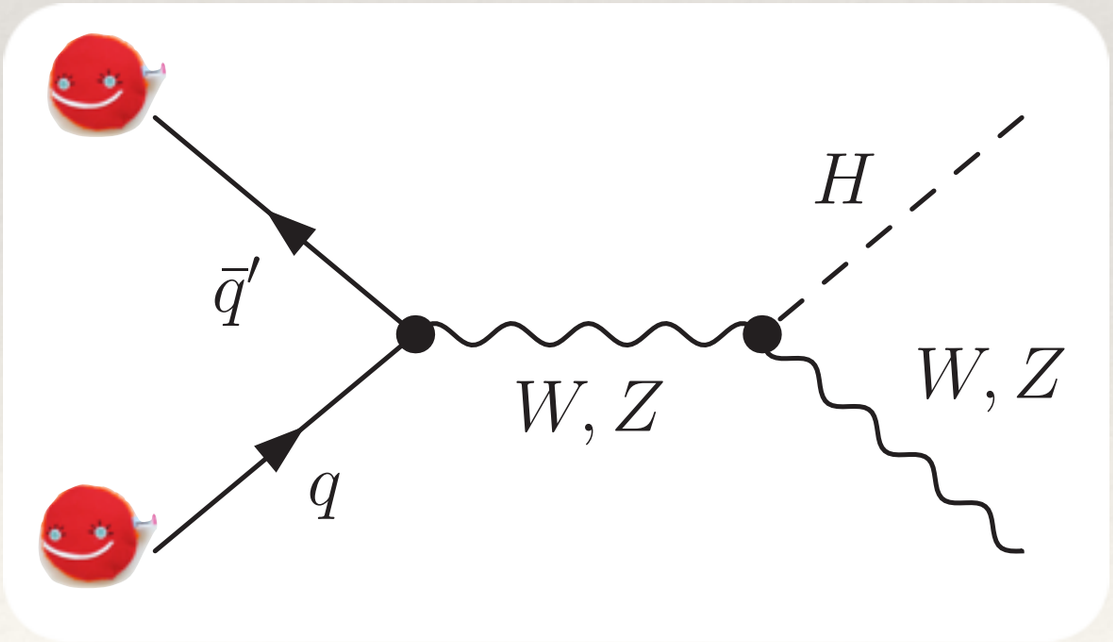

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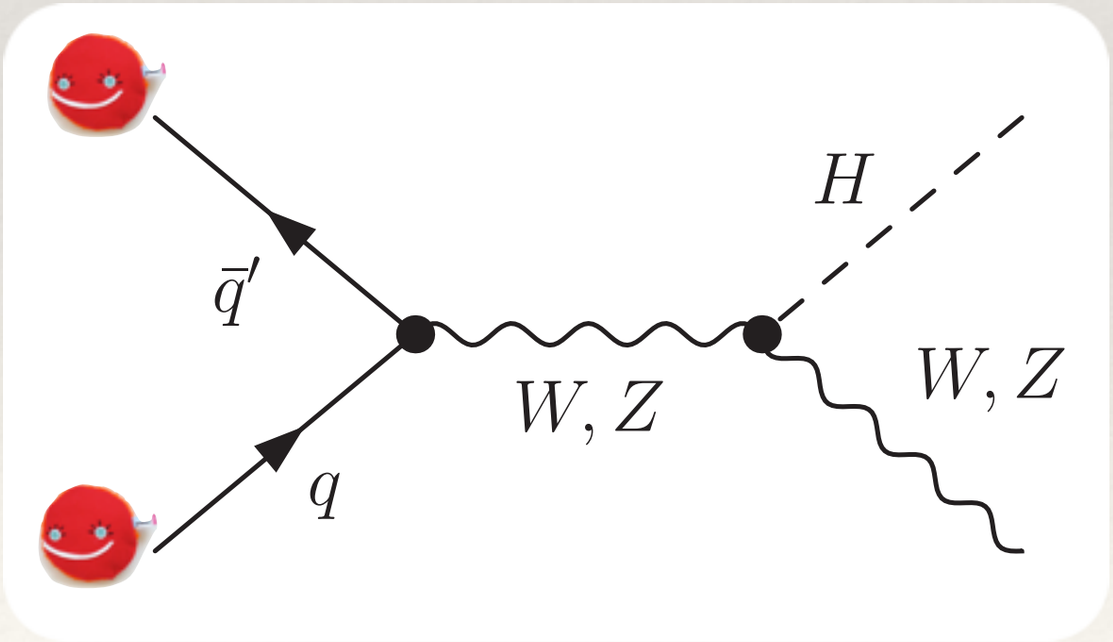

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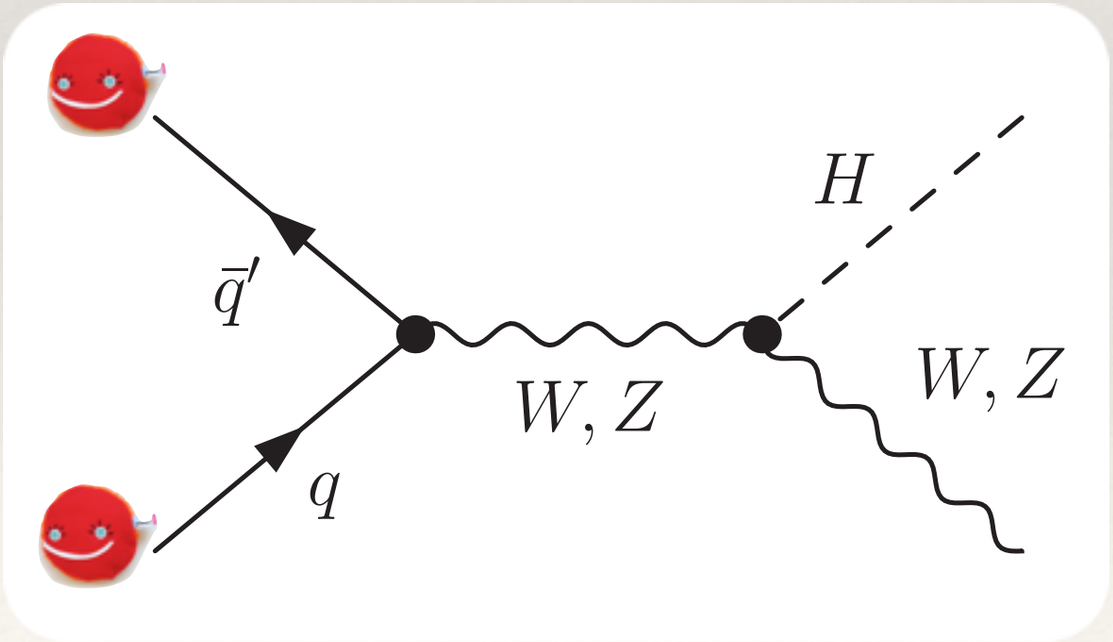

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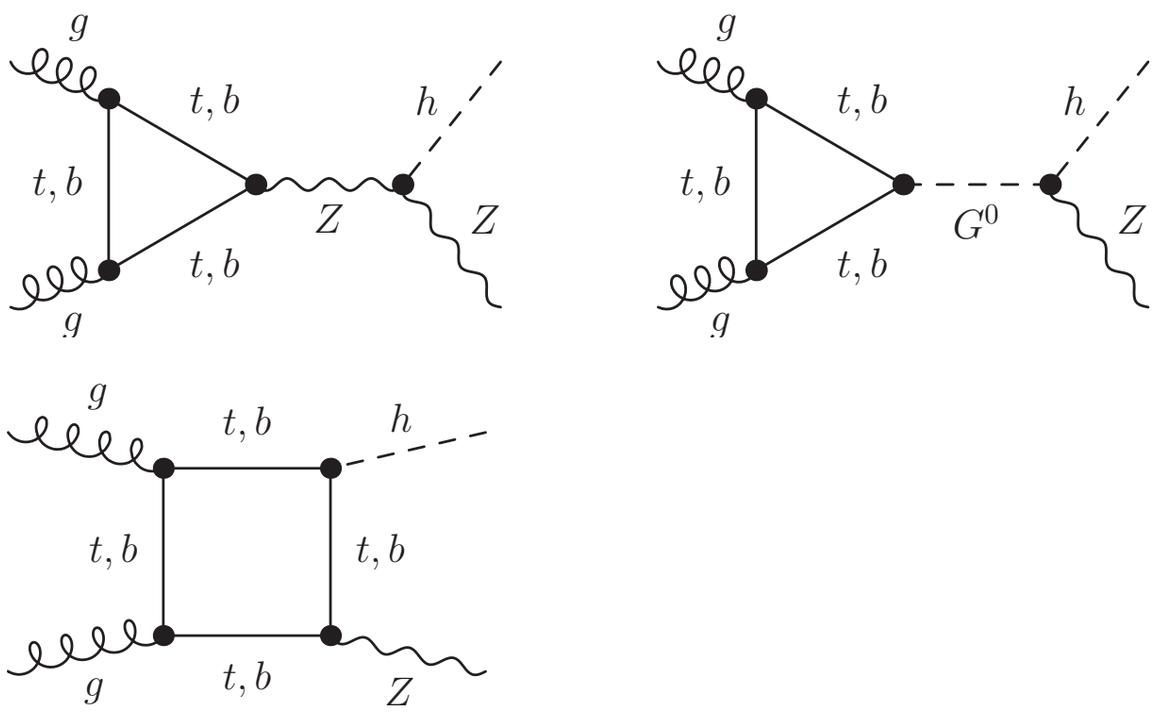

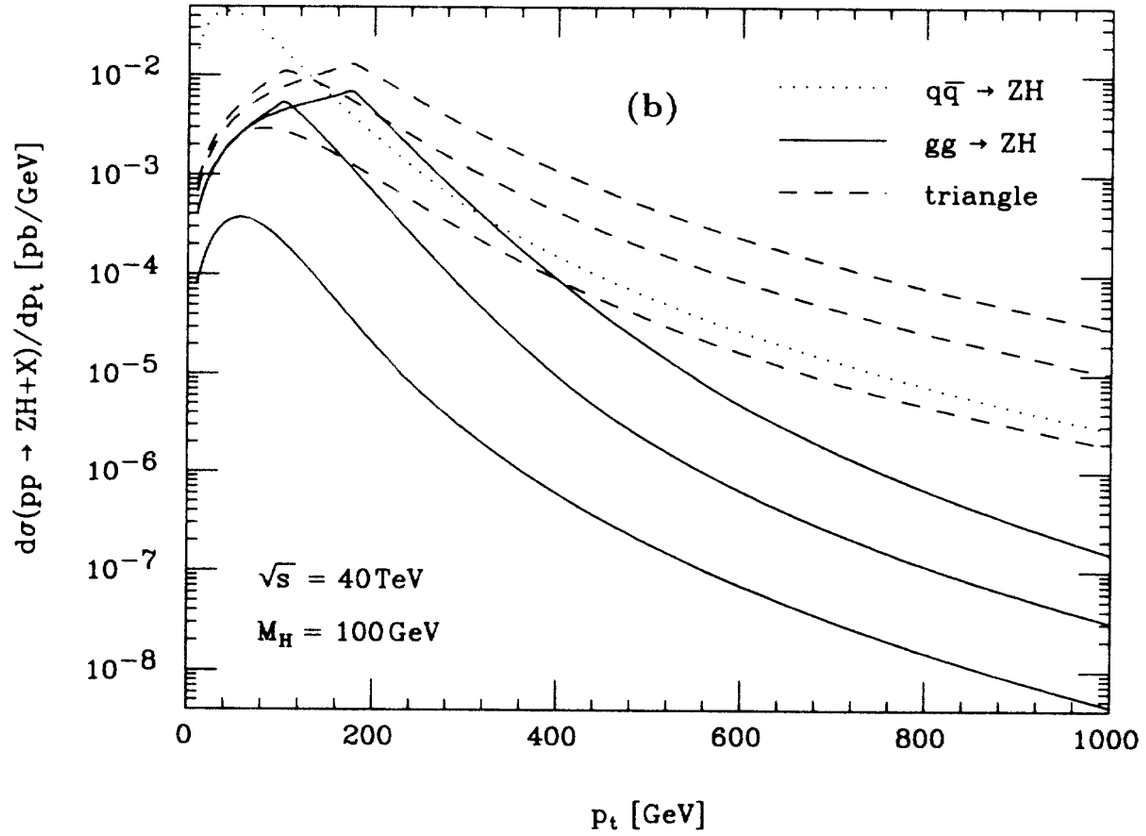

[Kniehl `90] [Matsuura, Hamberg, van Neerven `90]

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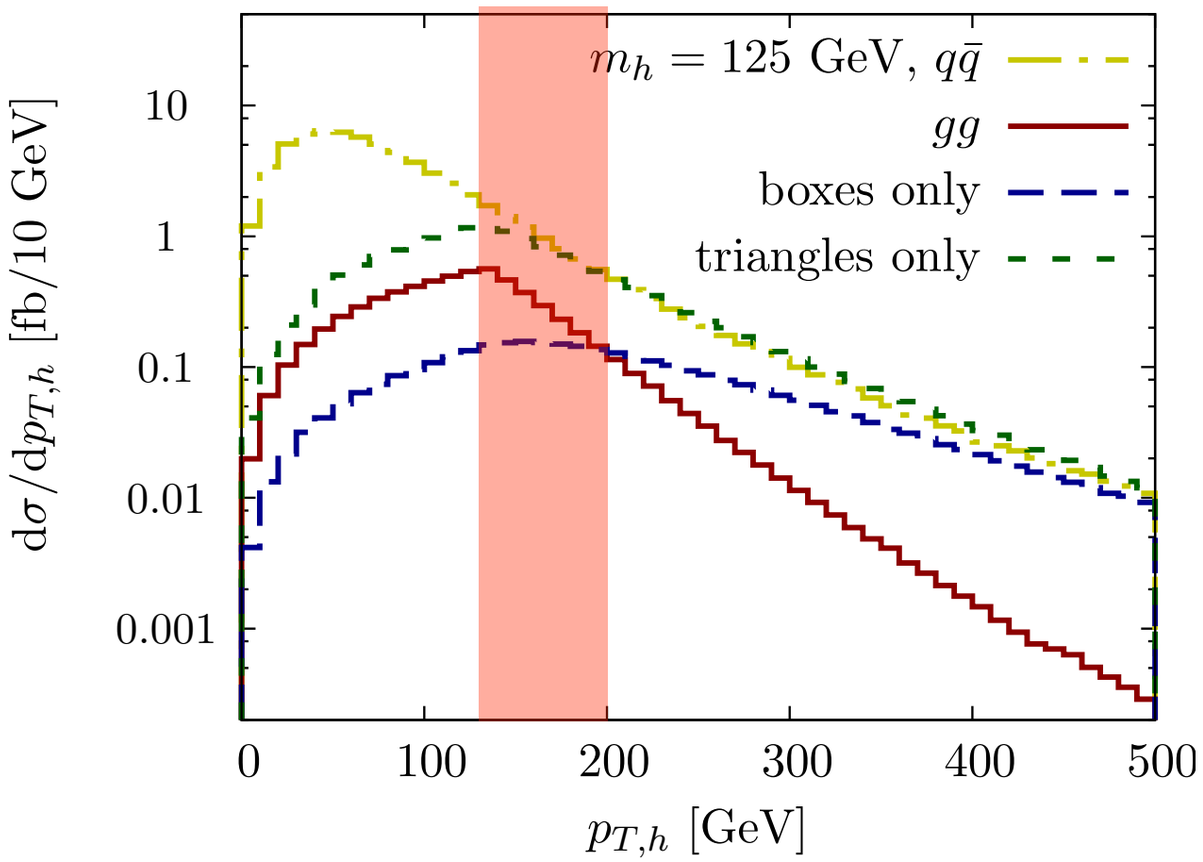

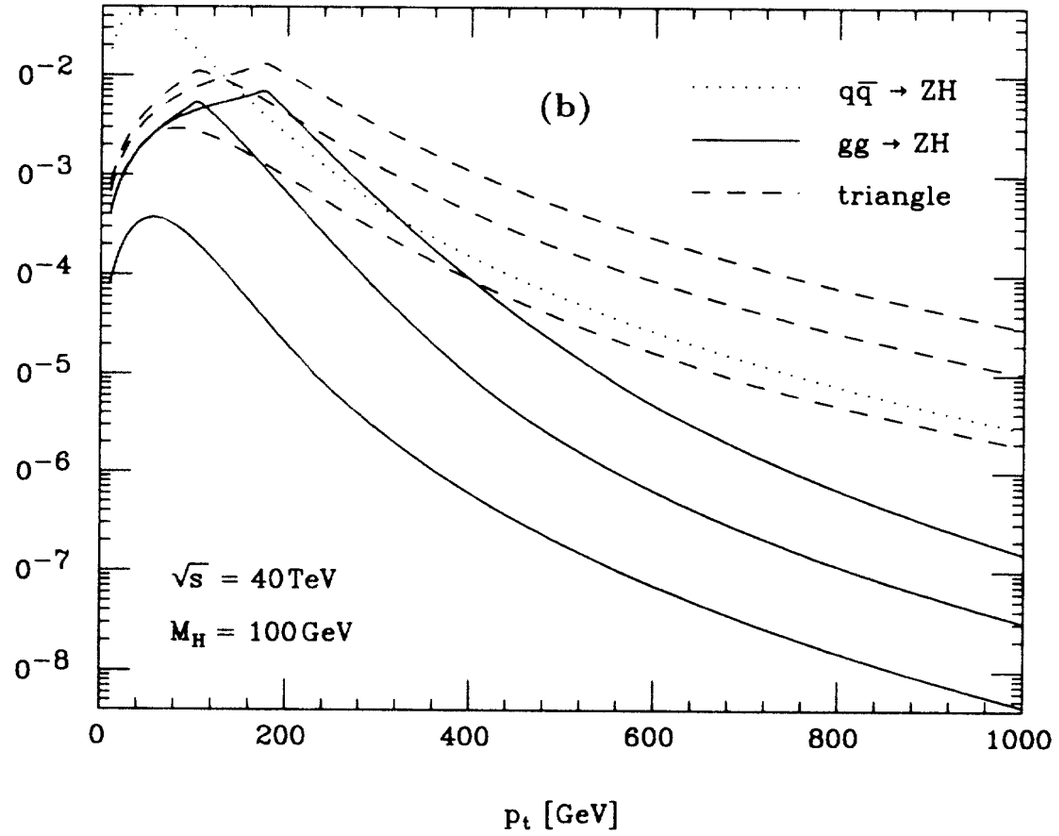

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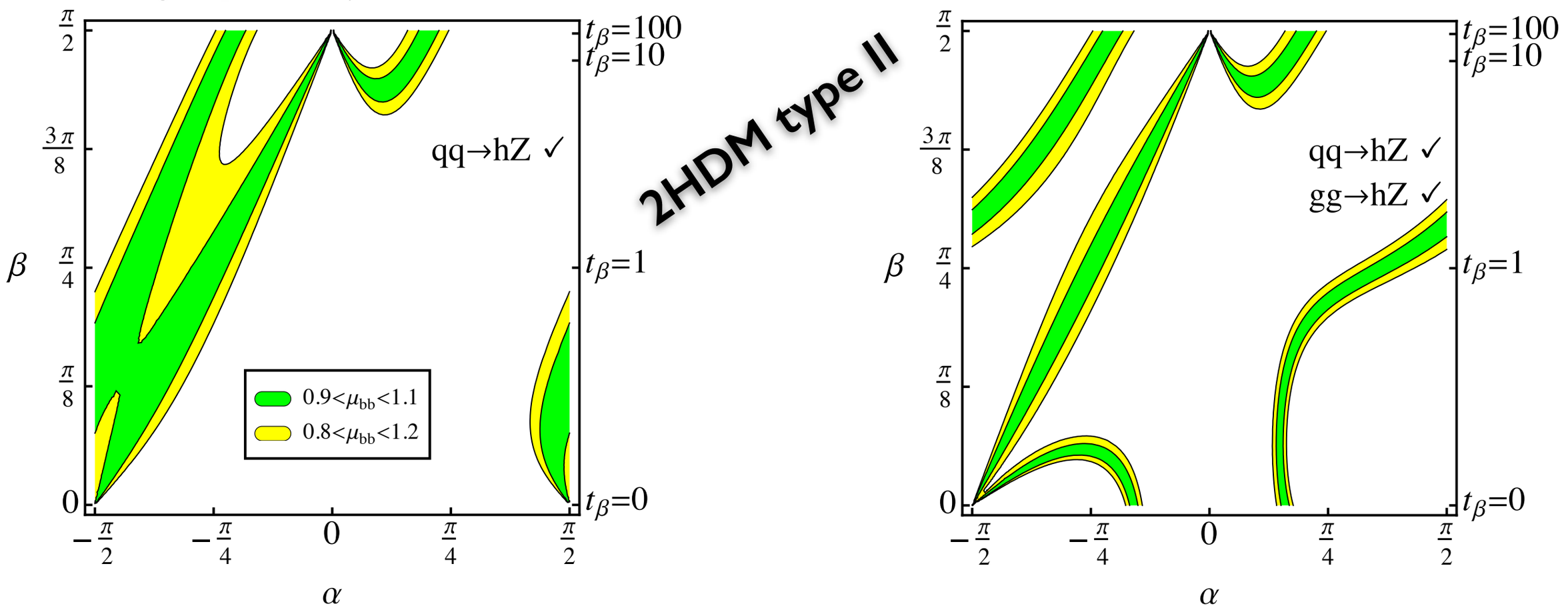

The total Higgs width

Why is this important ?

The total Higgs width

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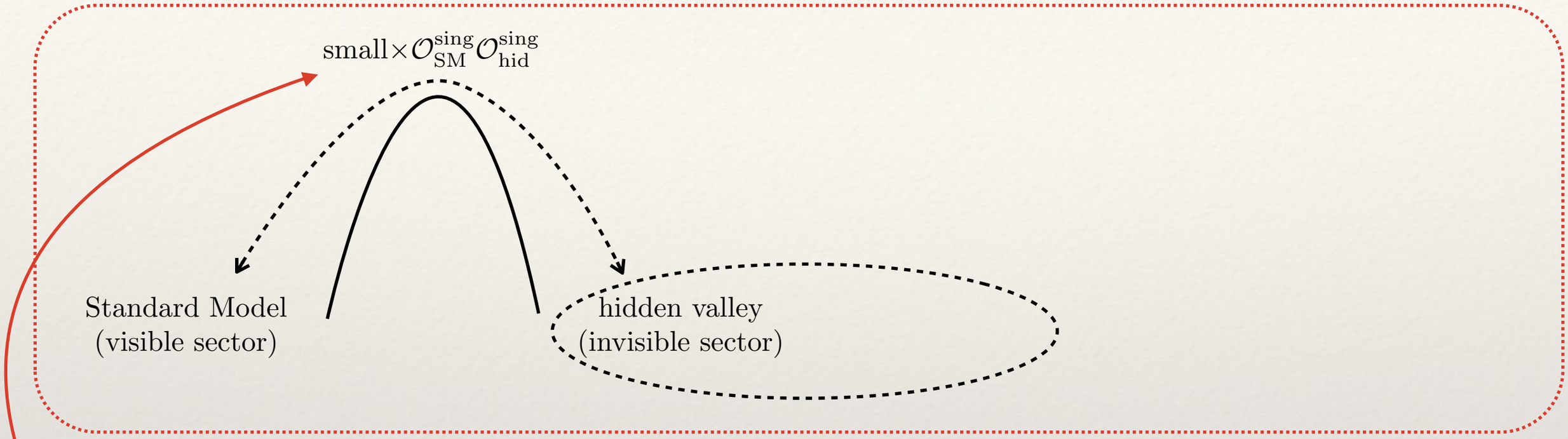

only U(1) and sterile neutrino mixing + **Higgs Portals** $\sim \lambda|H|^2|\phi|^2$

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

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

The total Higgs width

[CMS, Pheno 2014]

Theoretical Background

- As suggested in a recent paper[2], we can make a *model-independent* measurement of the Higgs width

$$\sigma^{\text{on-peak}}_{gg\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma} \qquad \sigma^{\text{off-peak}}_{gg\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

Conclusions

[CMS, Moriond 2014]

- First experimental constraint on Higgs total width using H*(126) → ZZ events has been presented
- Mild model-dependence
  - Just based on Higgs propagator structure
  - Assumptions on gg → ZZ continuum production beyond LO
  - Assumption of SM production of $q\bar{q} \to ZZ$ and, in general, no other BSM sources enhancing high-mass ZZ yields

$$\Gamma_H < 4.2\,\Gamma_H^{\text{SM}}$$

[CMS PAS HIG-14-002]

The total Higgs width

QUANTUM DIARIES

Thoughts on work and life from particle physicists from around the world.

Tevatron and LHC experiments so far. The week went on to include a spectacular CMS result on the Higgs width.

LIFEANDPHYSICS
JONBUTTERWORTH
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Previous Blog home

How wide is a Higgs?

In accord with Heisenberg's uncertainty principle, short-lived particles have uncertain mass. So the Higgs boson, which gives mass to other particles, is uncertain about its own mass. New results from the CMS experiment at the CERN LHC have started to tell us how uncertain

ATLAS Experiment Blog

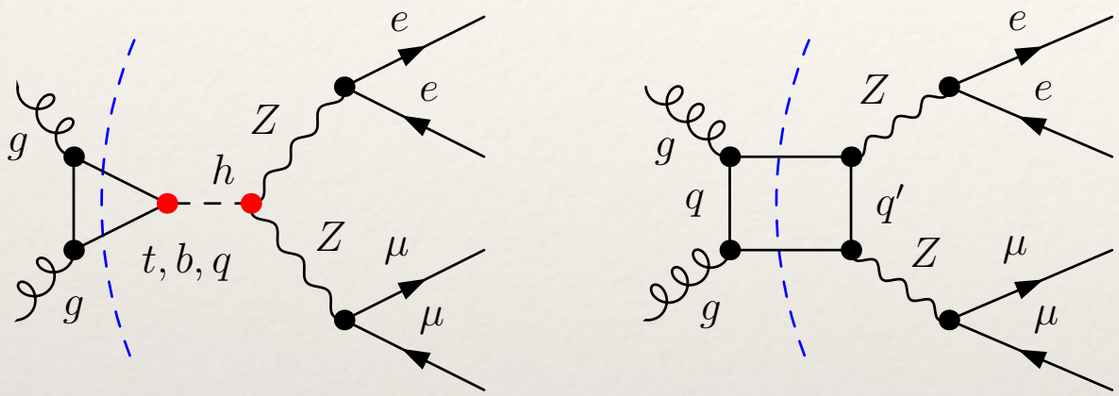
Mapping the Secrets of the Universe

boson width.) This new measurement shows a remarkable sensitivity and constrains the Higgs boson width to be below 17 MeV, more than two orders of magnitude better than the previous limits! Standard Model 2.5 : New Physics 0. Only half a point here, as the Higgs boson is still allowed to decay into invisible new particles, less than 50% of the time, but this still leaves enough room for new physics to sneak in. It maybe the only place, actually.

The total Higgs width

A two-step programme in ZZ

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



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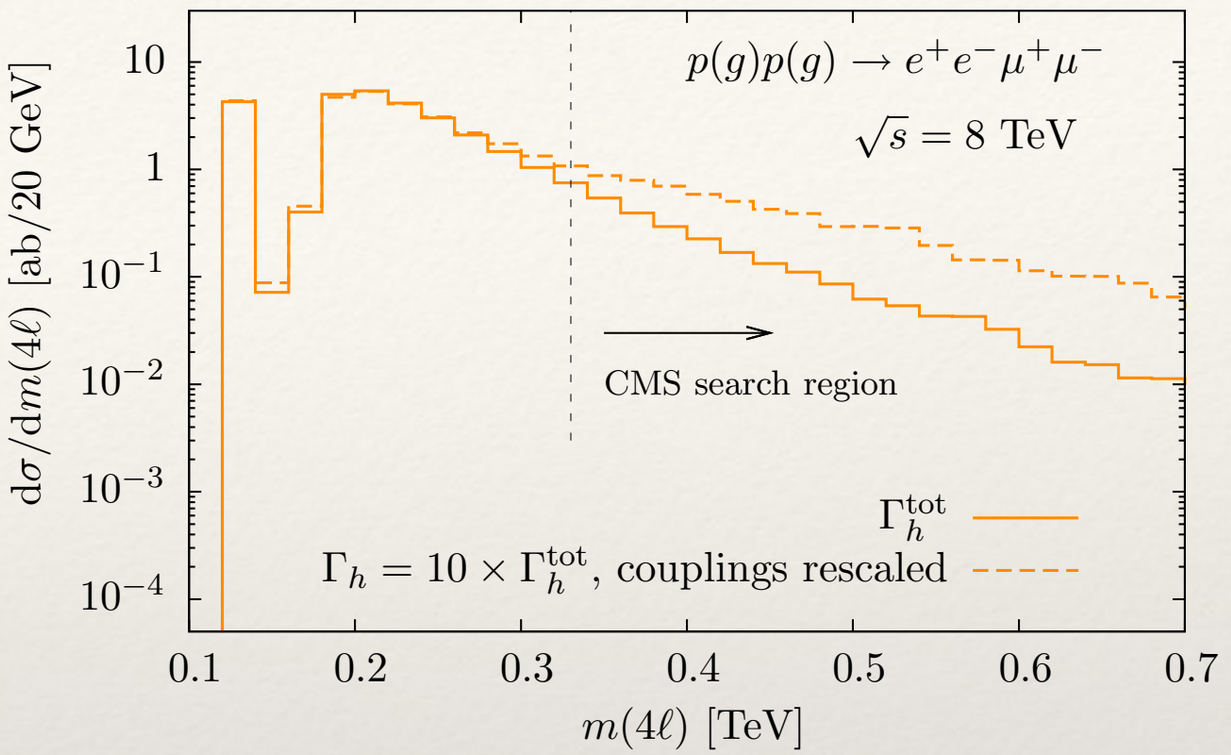

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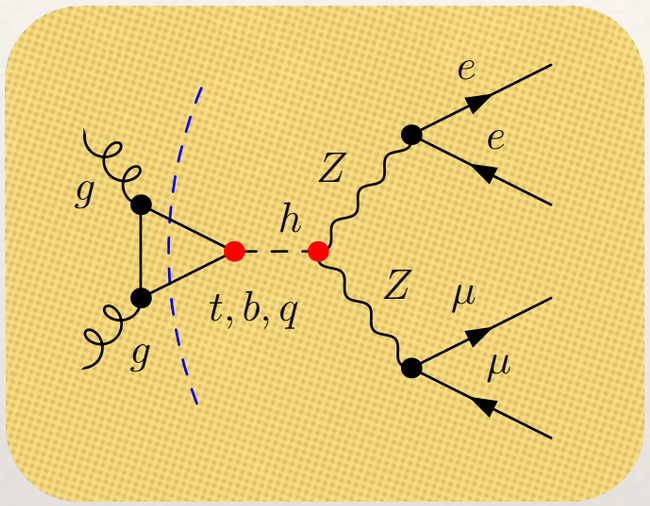
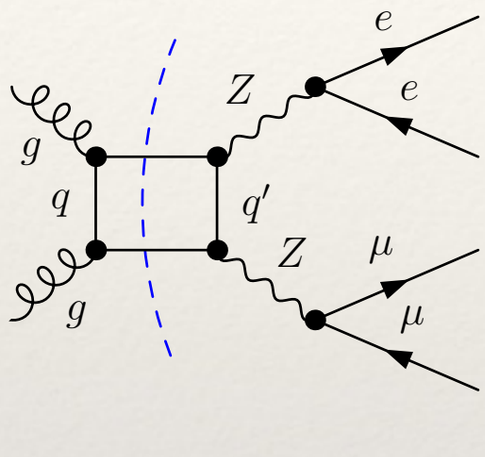


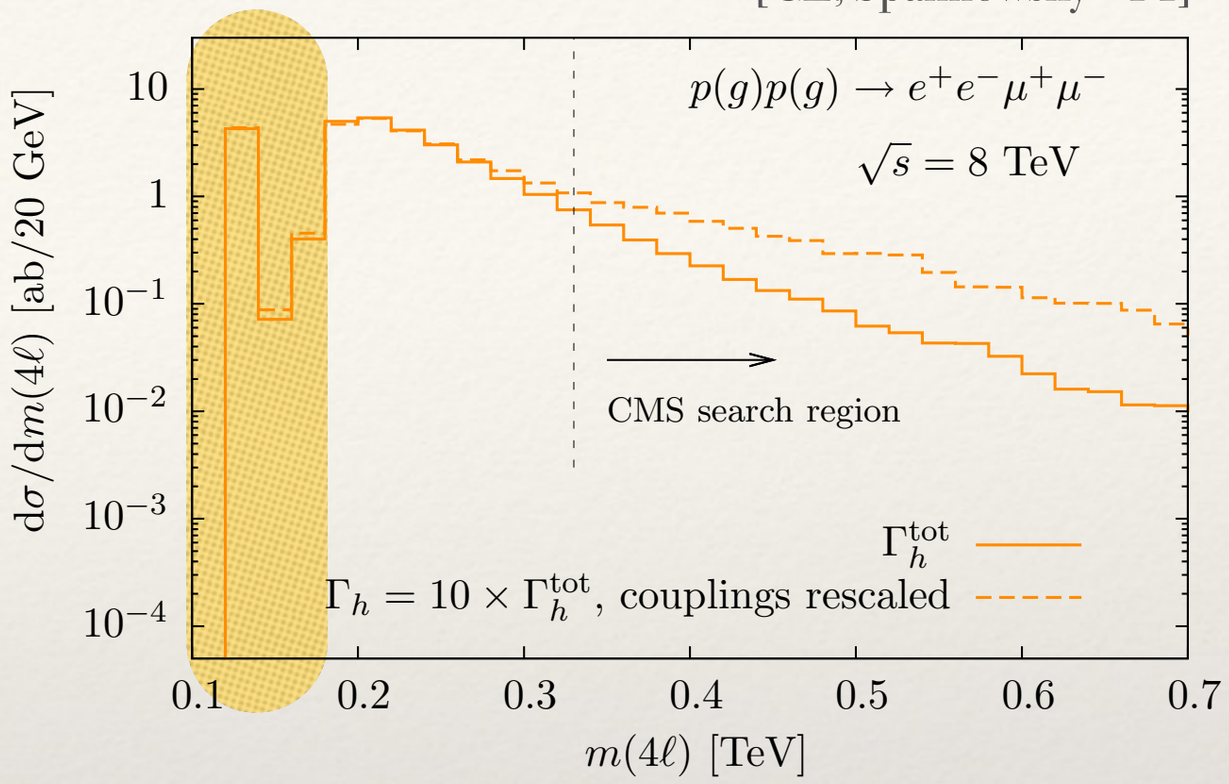


1. on-shell measurement

dominated by h signal

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

[CE, Spannowsky ` 14]



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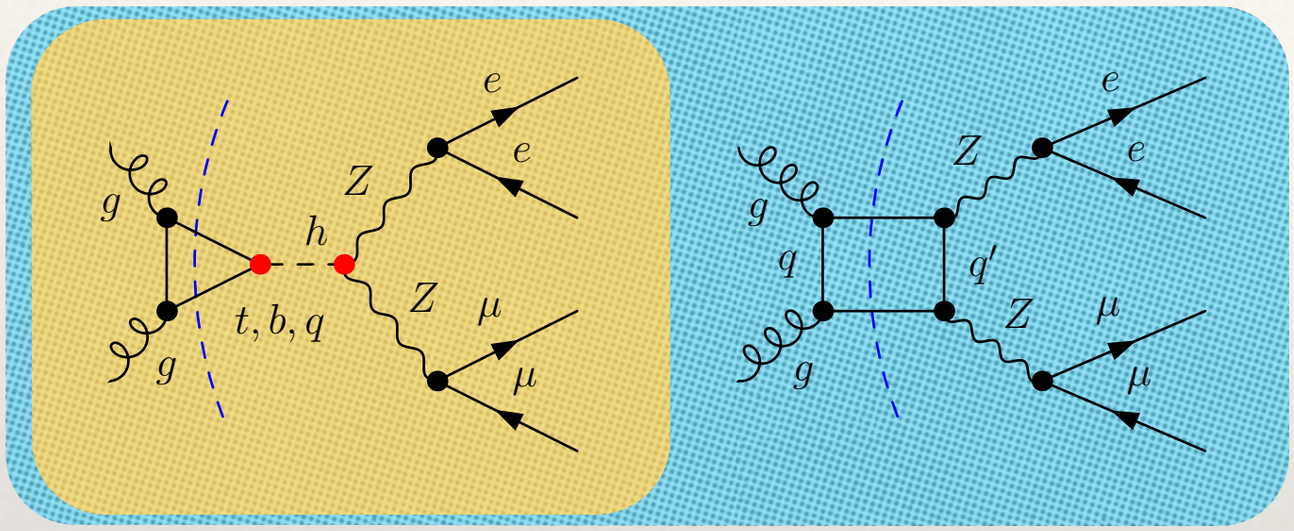

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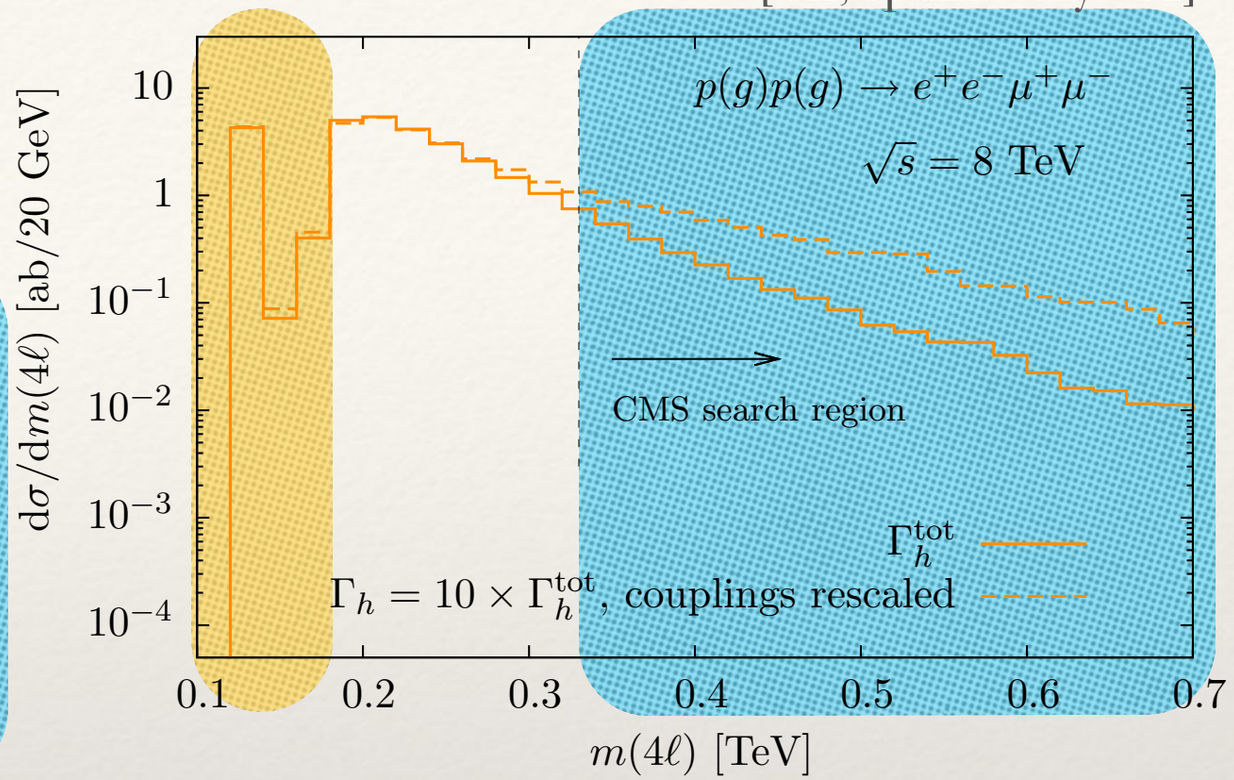

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2. off-shell measurement

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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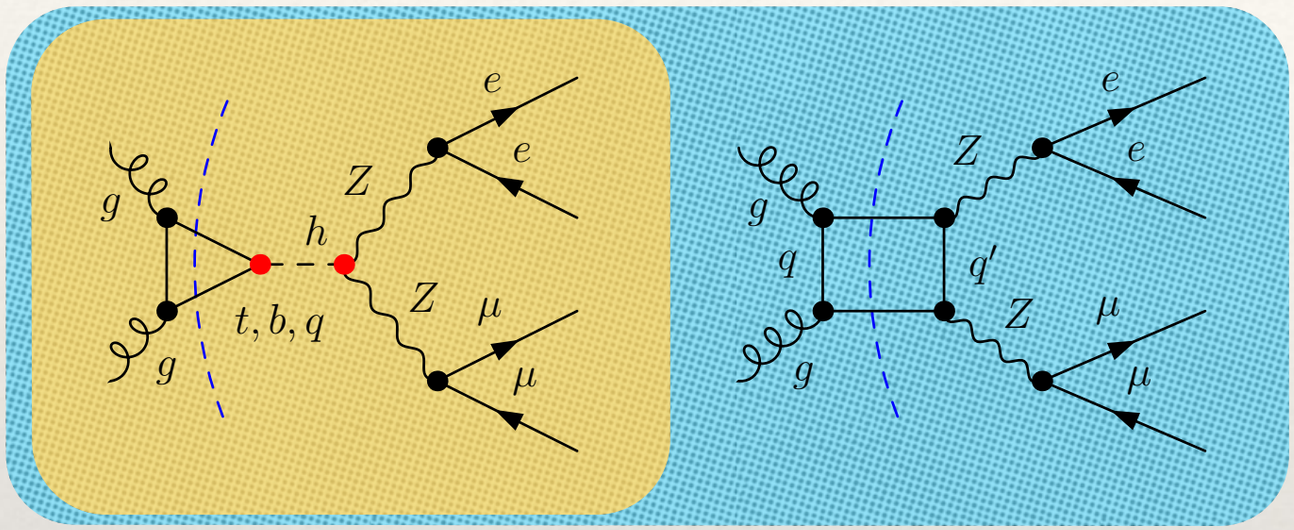

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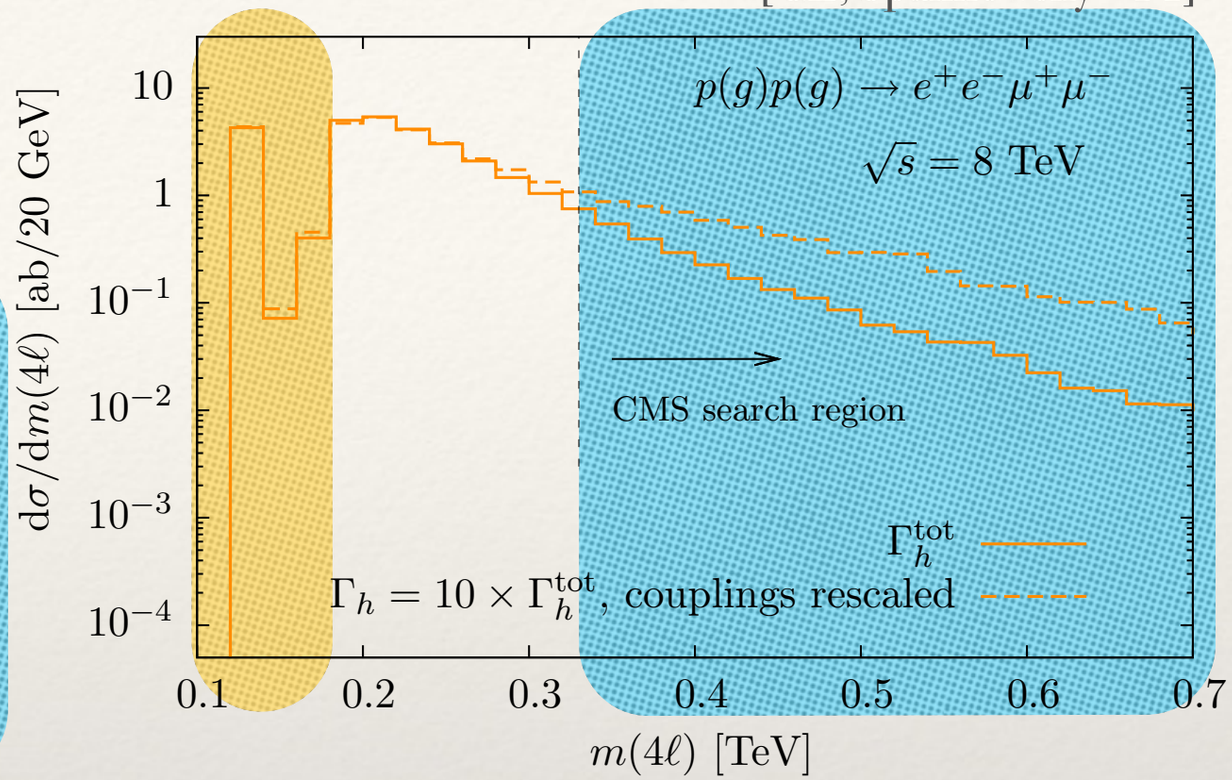

correlate measurements

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

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

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…so much for the theory, but is this really a measurement of the width?

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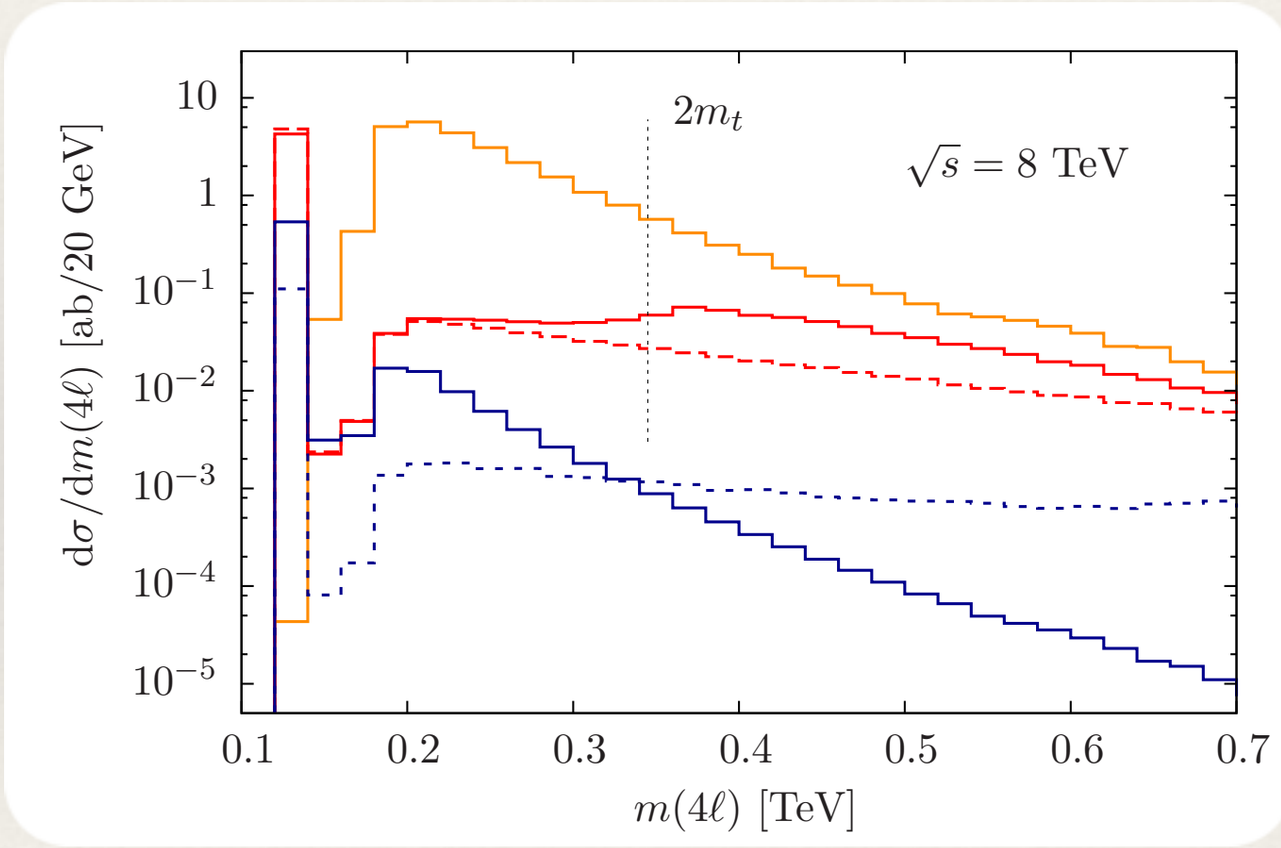

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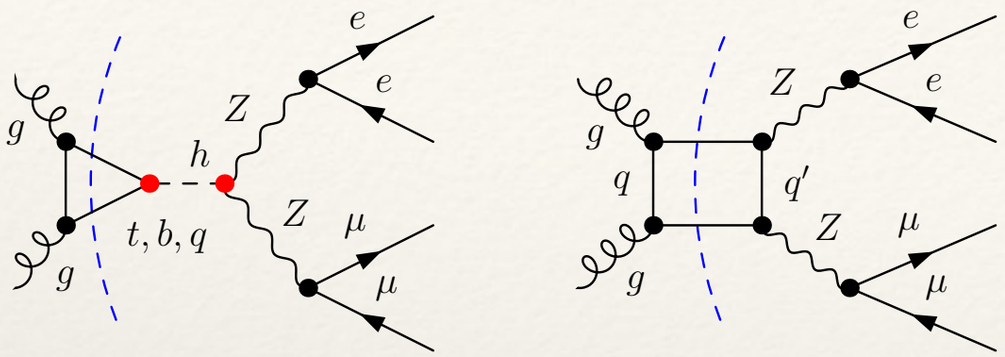

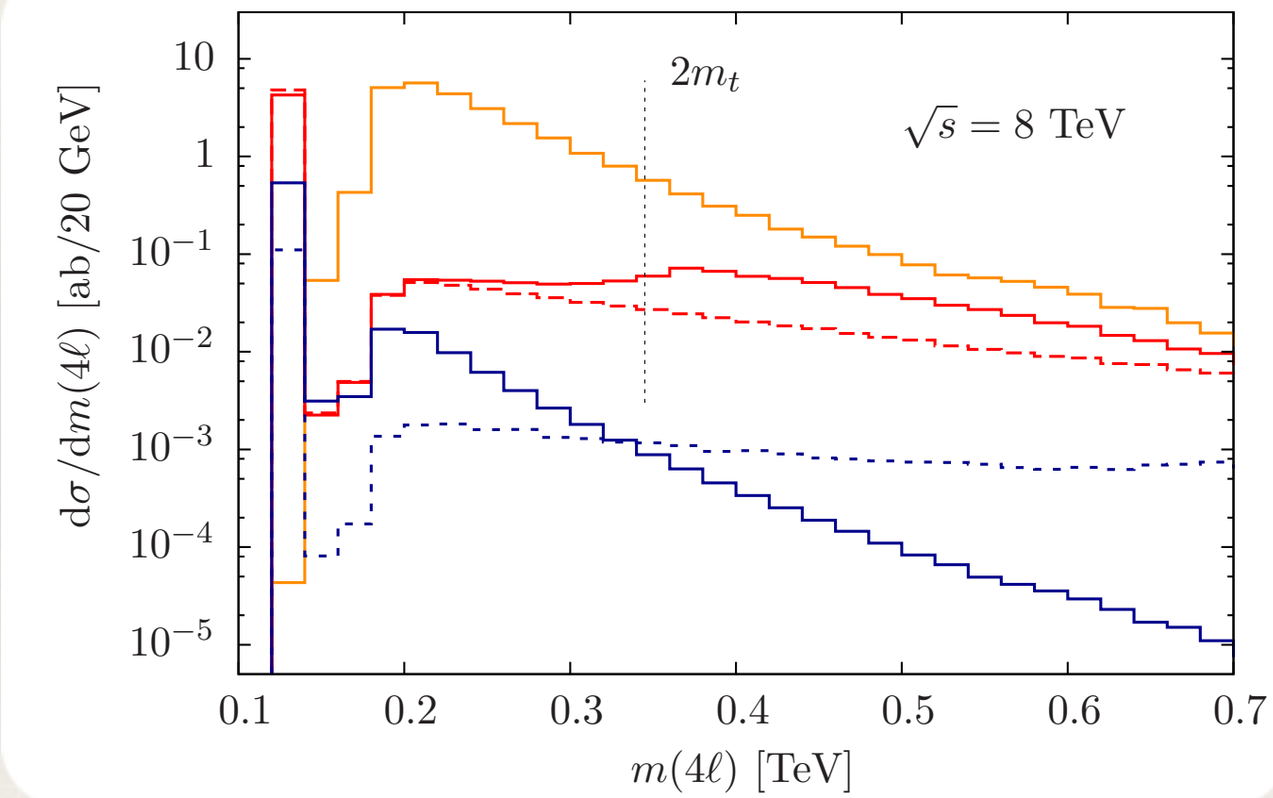

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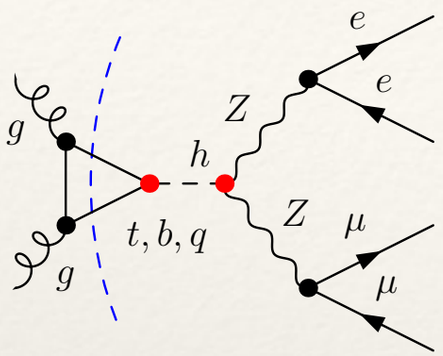

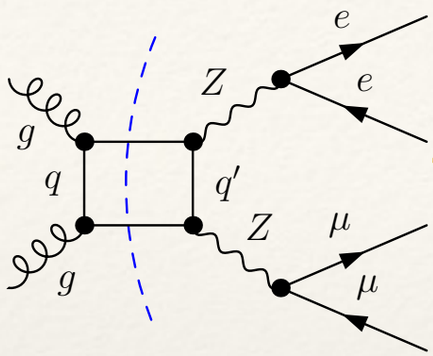

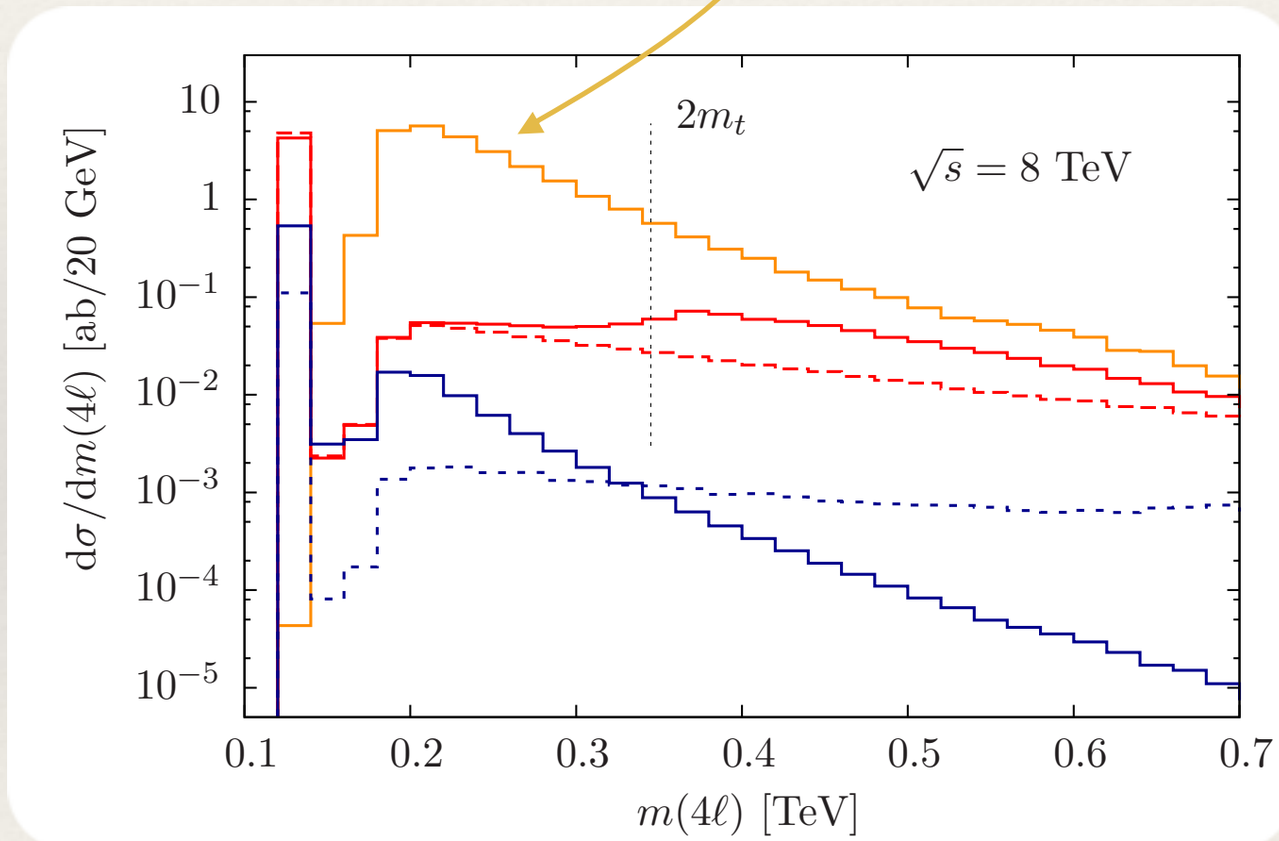

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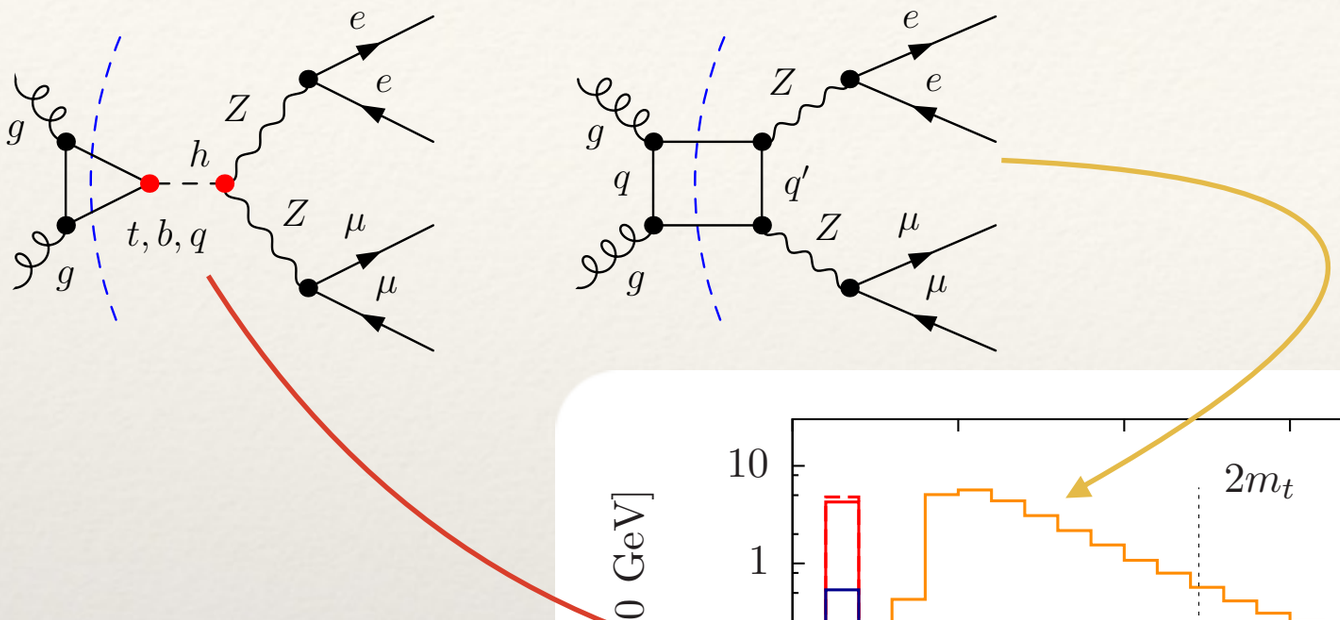

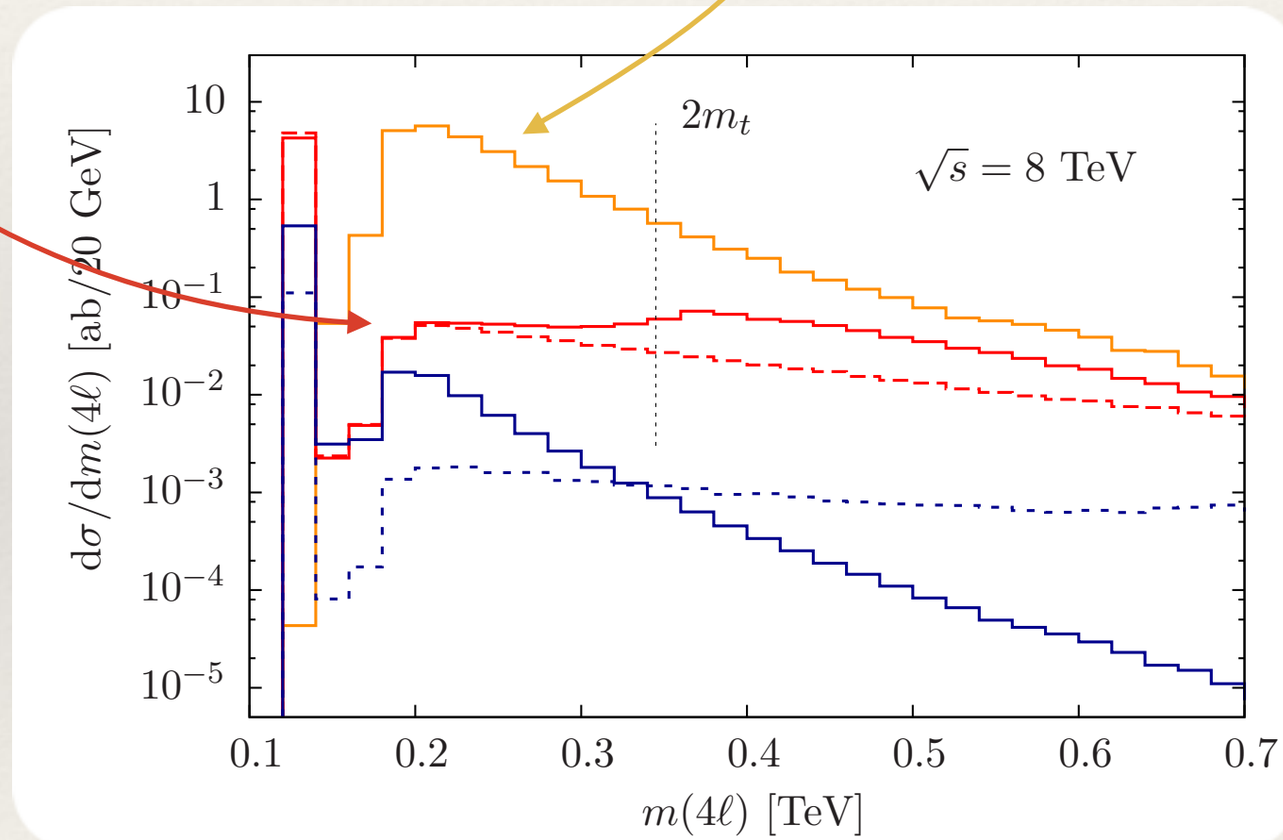

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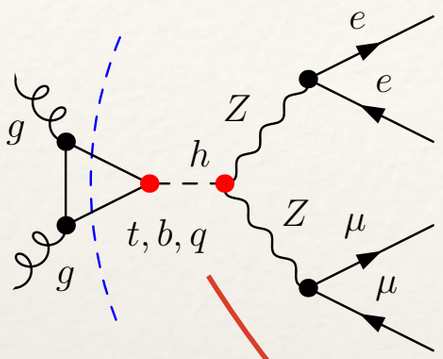

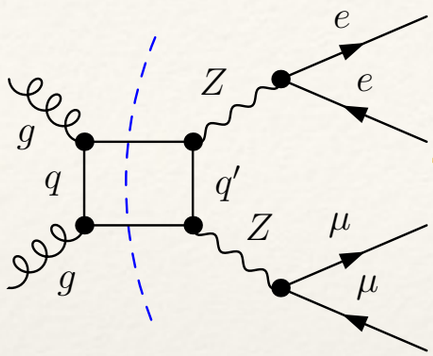

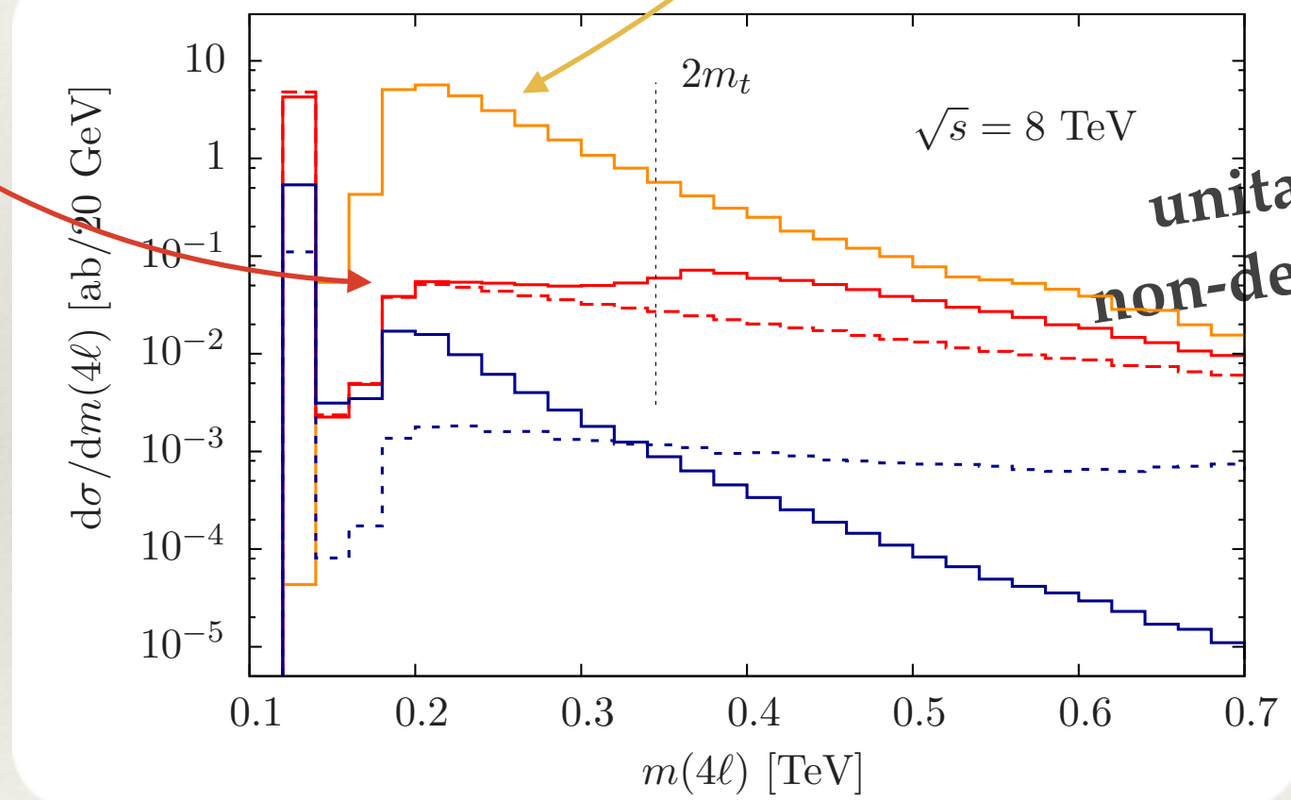

unitarity & non-decoupling

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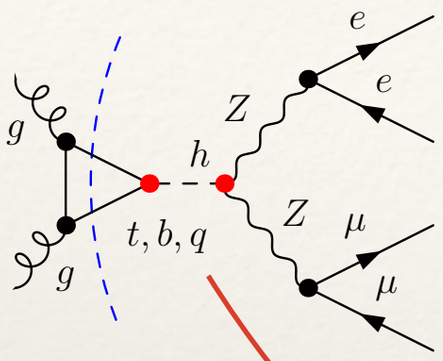

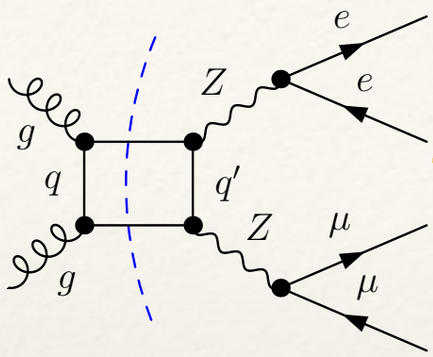

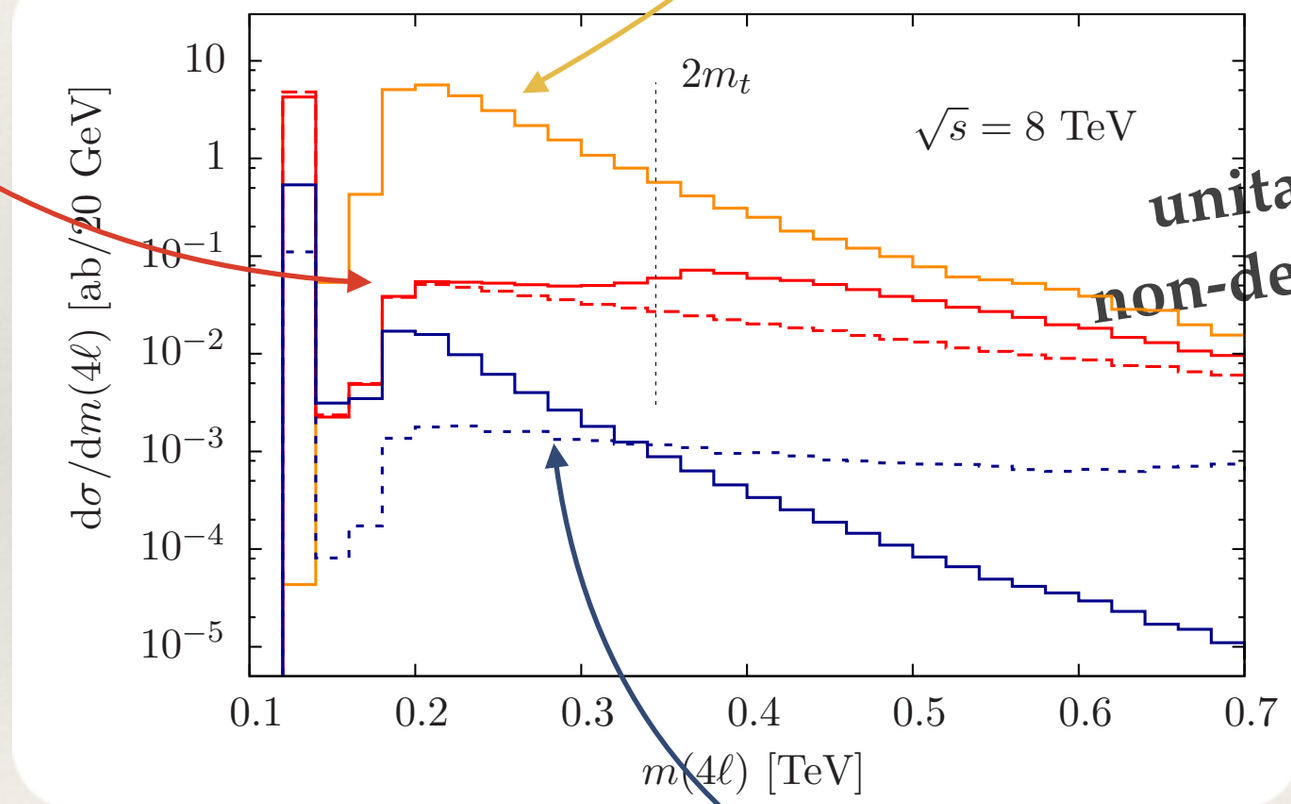

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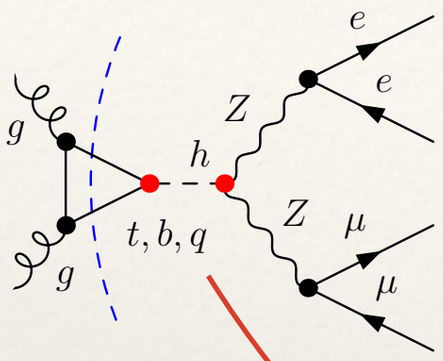

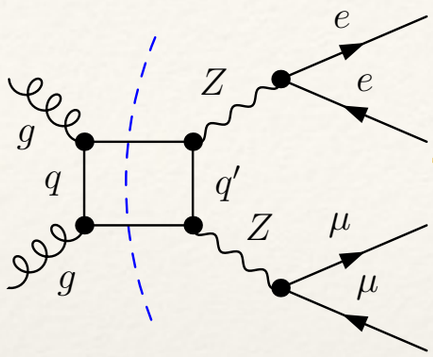

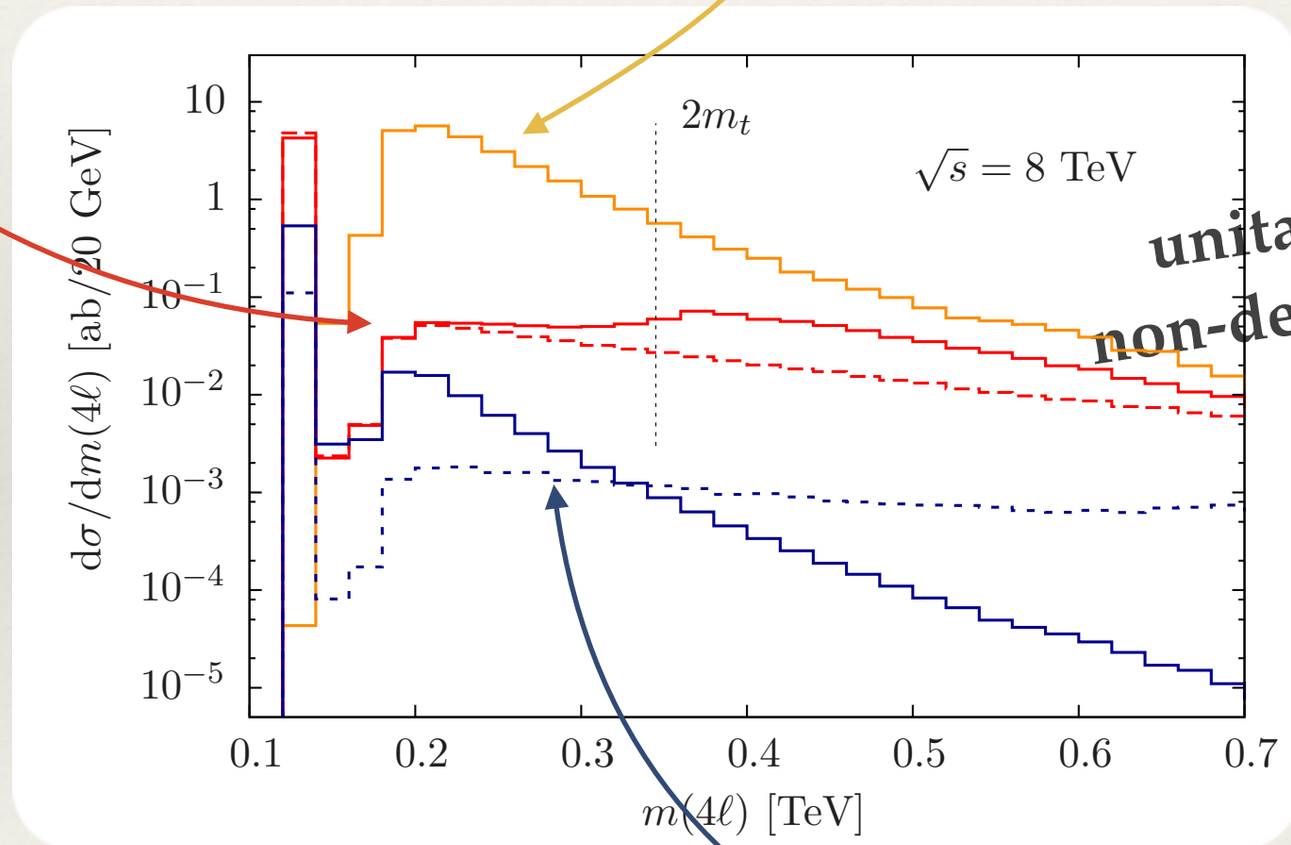

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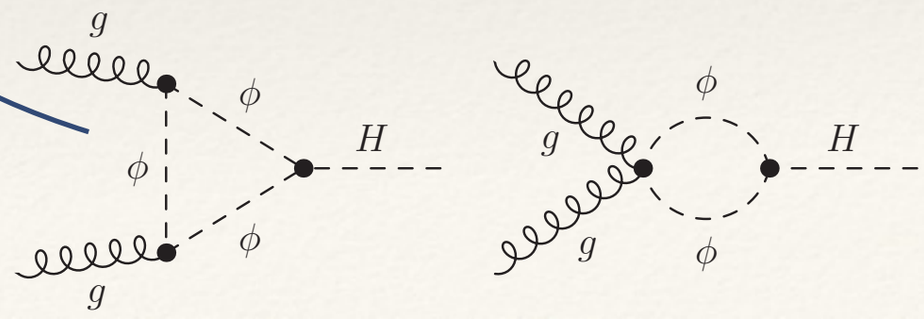

The total Higgs width

[CE, Spannowsky `14]

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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- interpreted SM-like width measurement this analysis is never competitive: **2**-like WWh coupling and zero hidden width bias gave $\Gamma_H < 1.4\ \Gamma_H^{SM}$ already yesterday

  [Dobrescu, Lykken ` 14]

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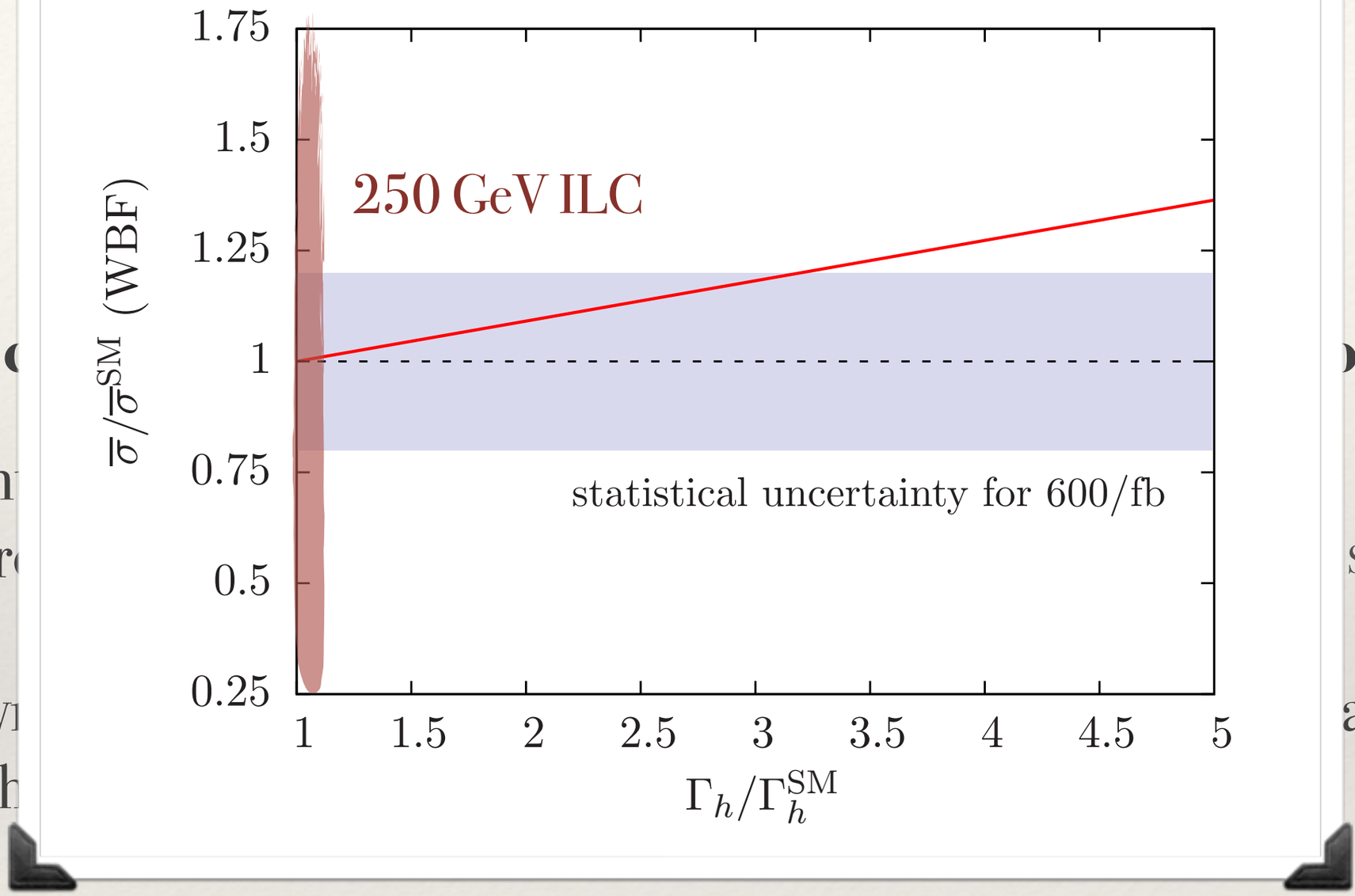
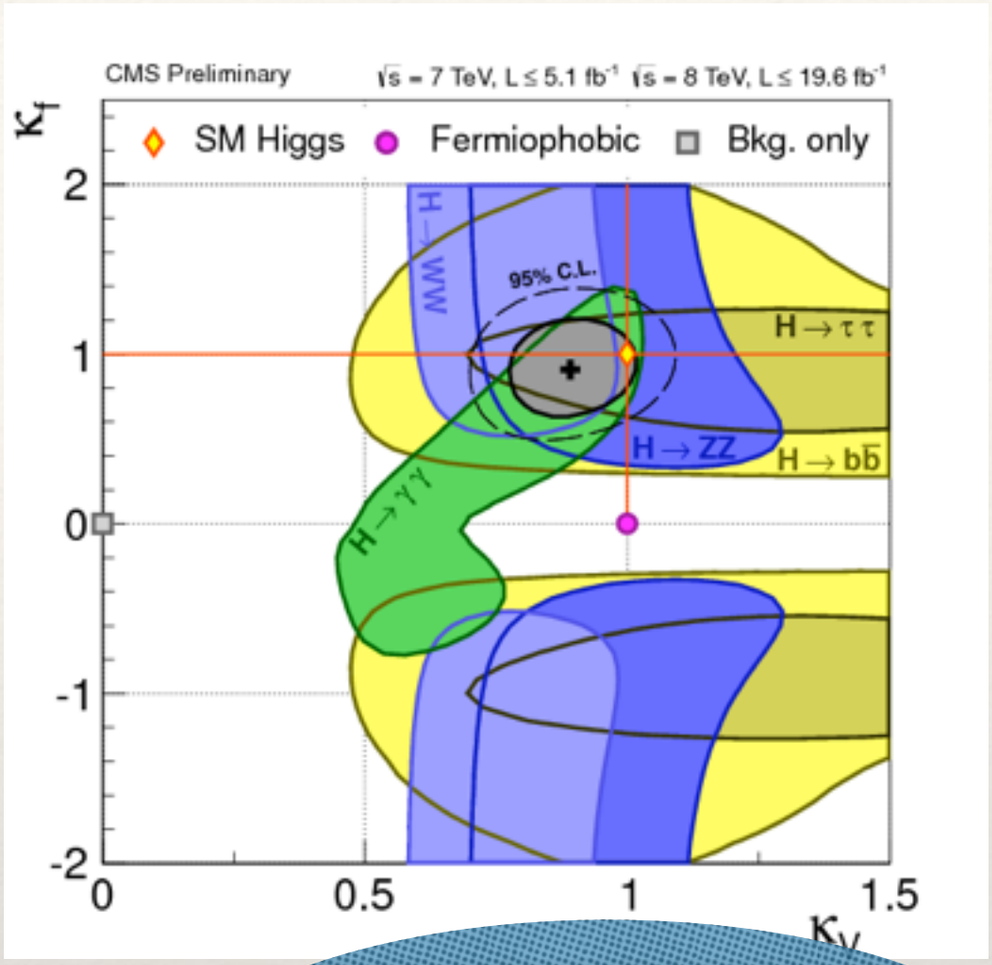


- **cannot c** **on colliders**
- new con small in light of electr Spannowsky `14]
- unknow approaching the SM h
- **nothing wrong with the generic strategy:** adapt to weak boson fusion + custodial isospin (small interference with GF, GF can be suppressed, H couplings to ZZ and WW directly reflect electroweak properties)

A bottom-up (B)SM Higgs programme

coupling measurements are determined by

1. unitarity
2. number of Higgs fields
3. **gauge representation**
4. **experimental extraction**
5. **mechanism of ELW symmetry breaking**
6. **spectrum through quantum effects**



EWSB
specific couplings, top interactions

[Klute, … `12]
[Corbett, Eboli, Gonzalez-Fraile, et al. `12]
[Espinosa, Grojean, Mühlleitner, Trott `12]

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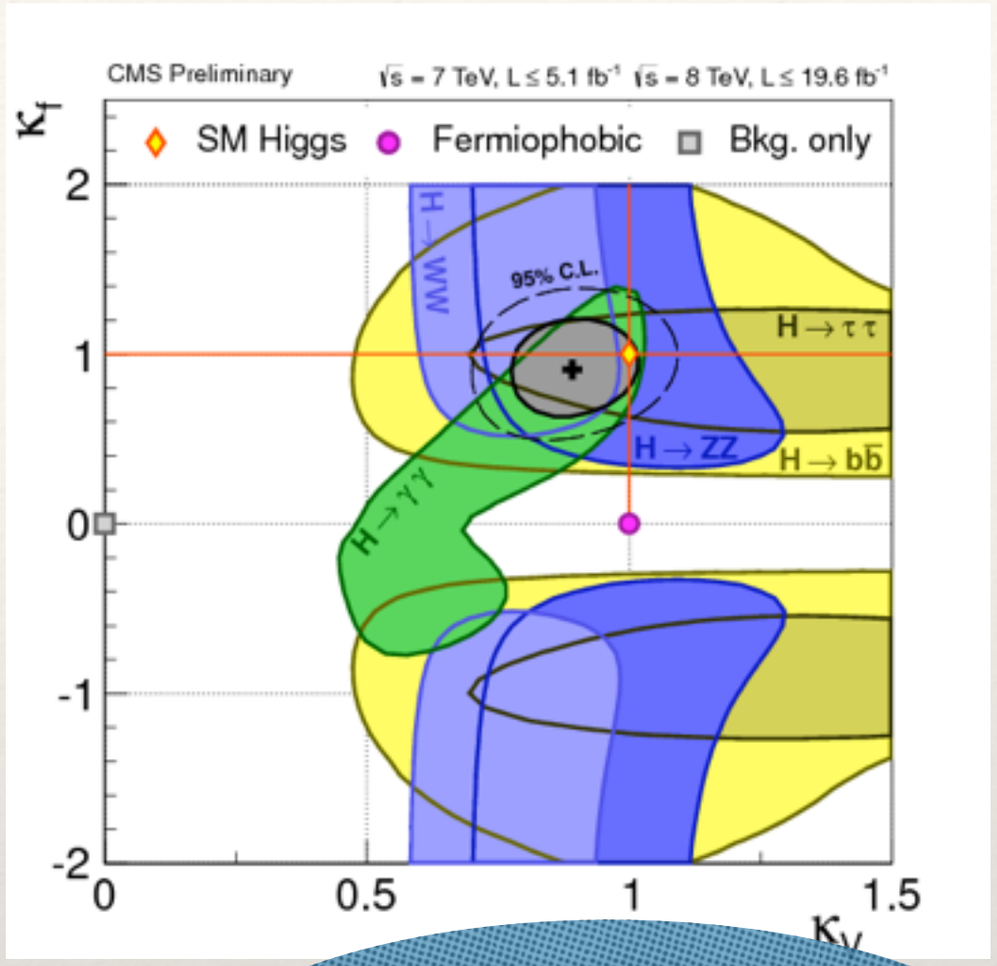

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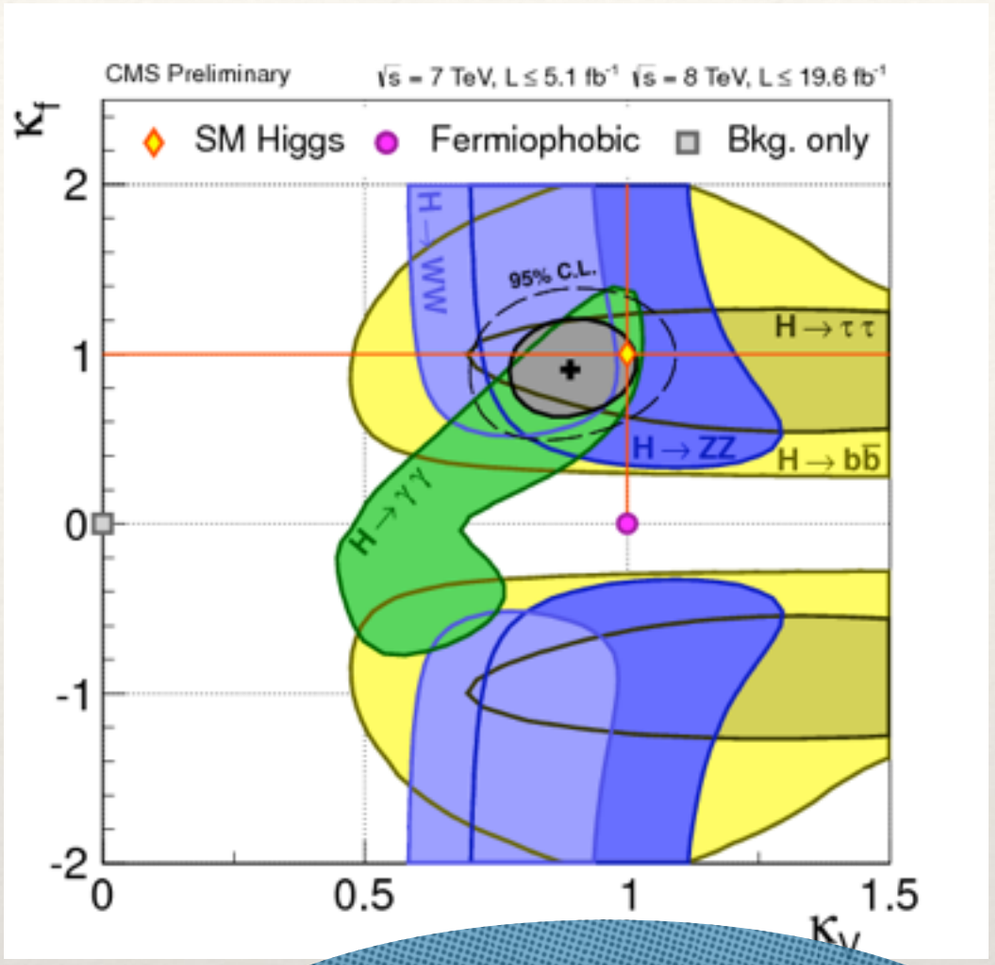

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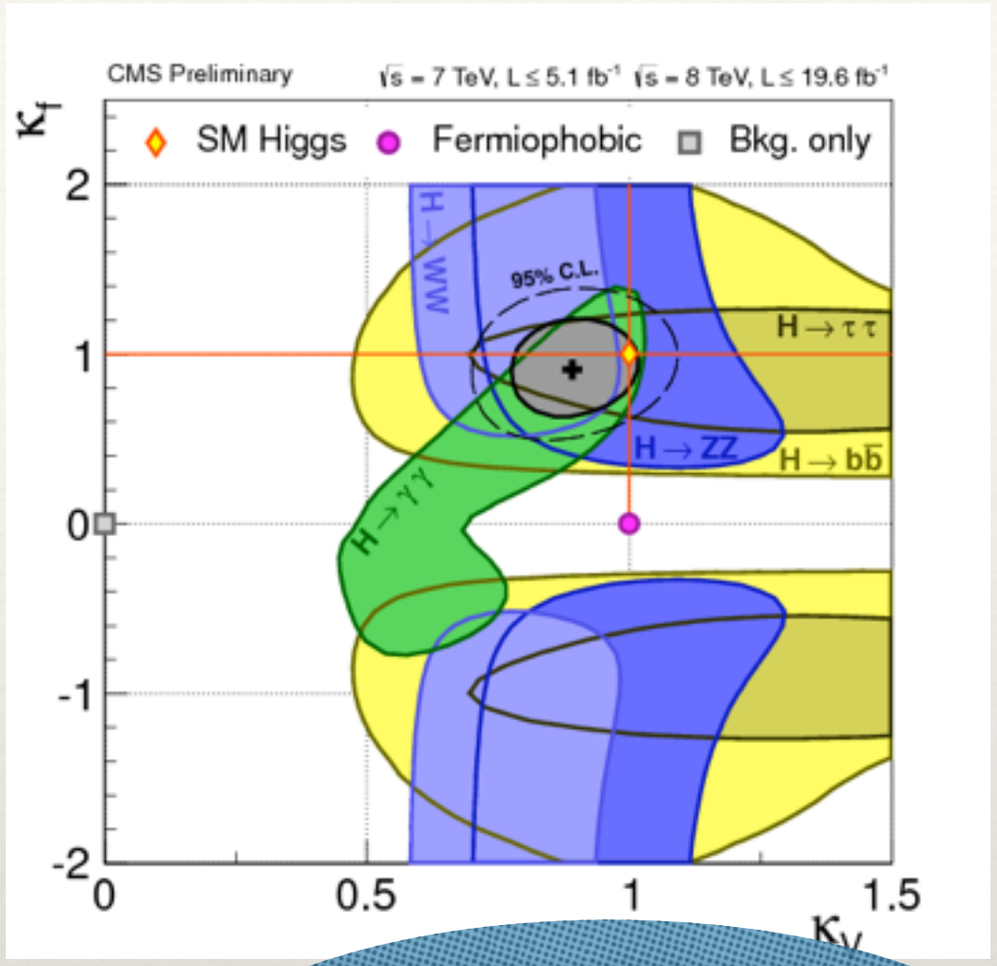

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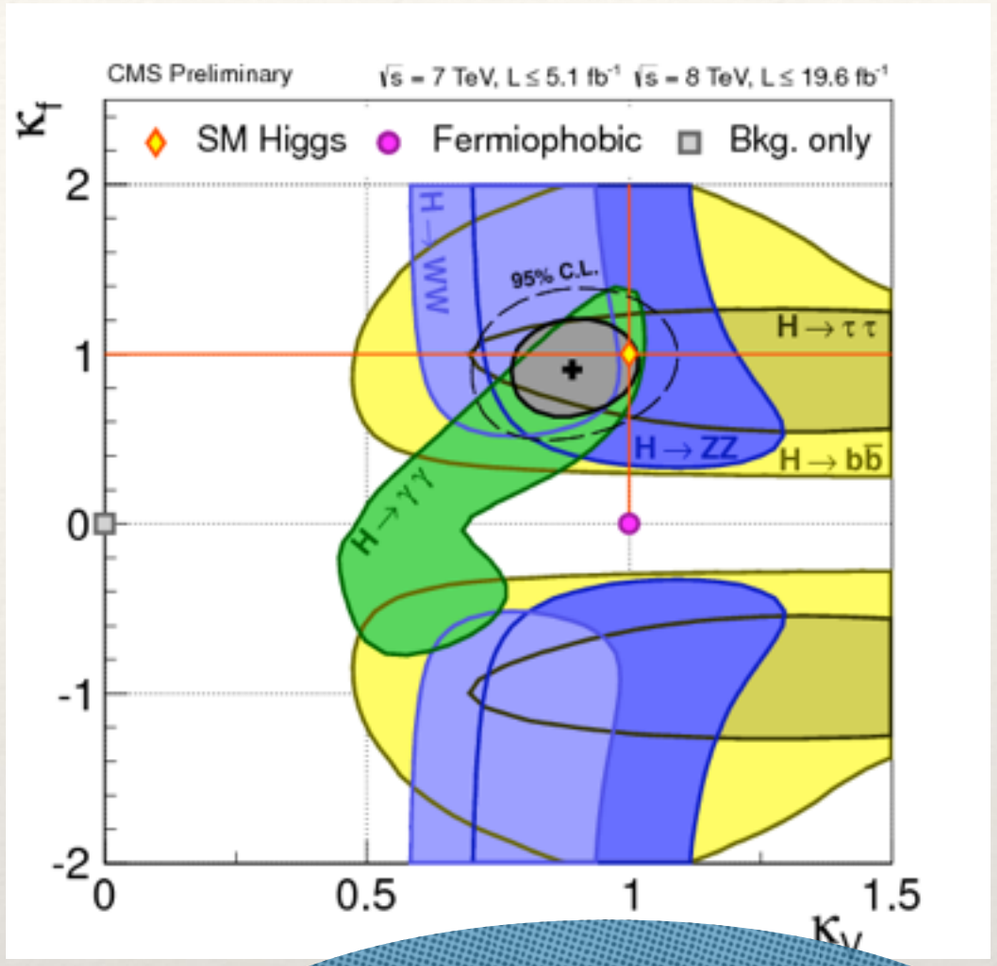

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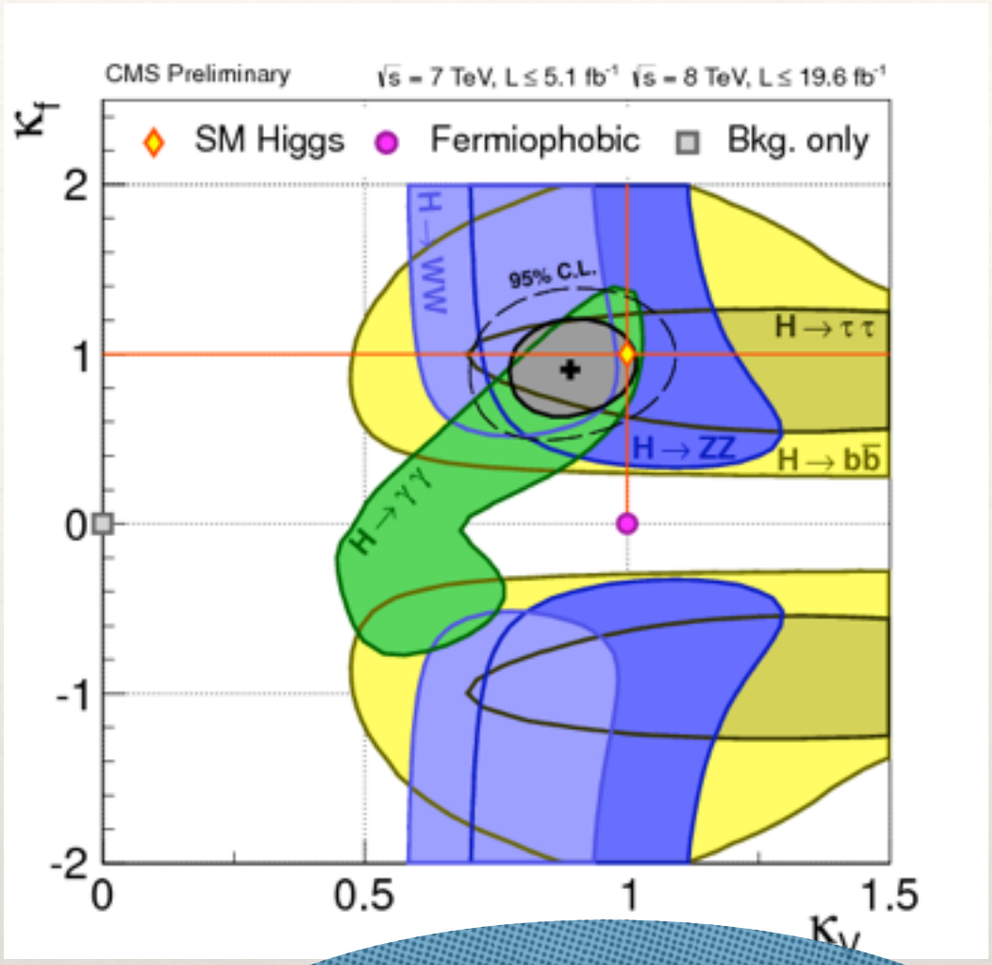

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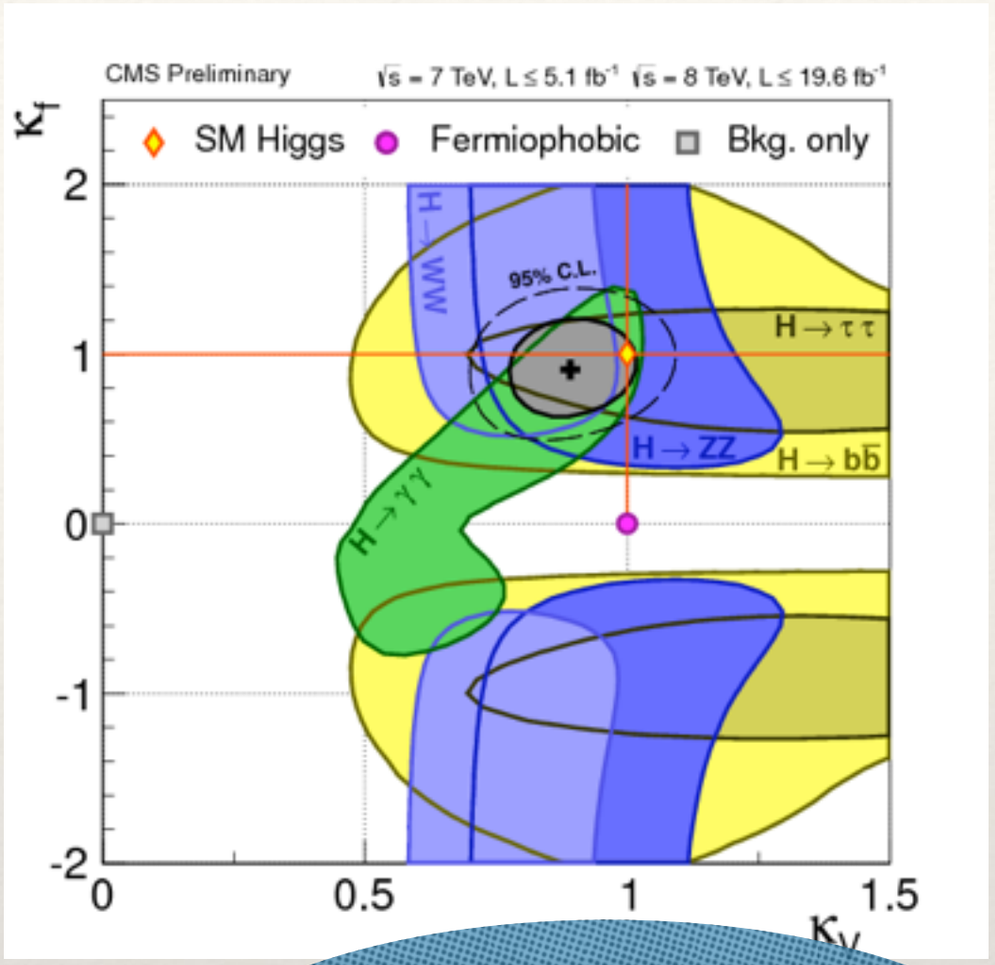

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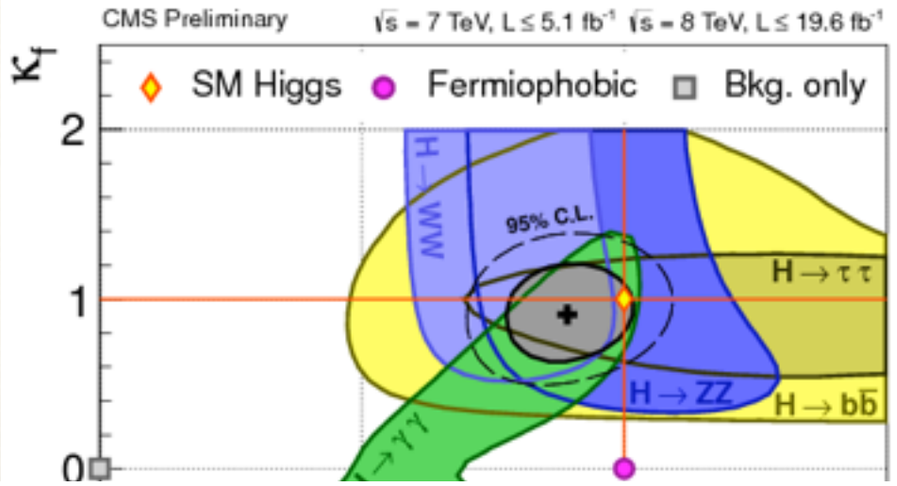

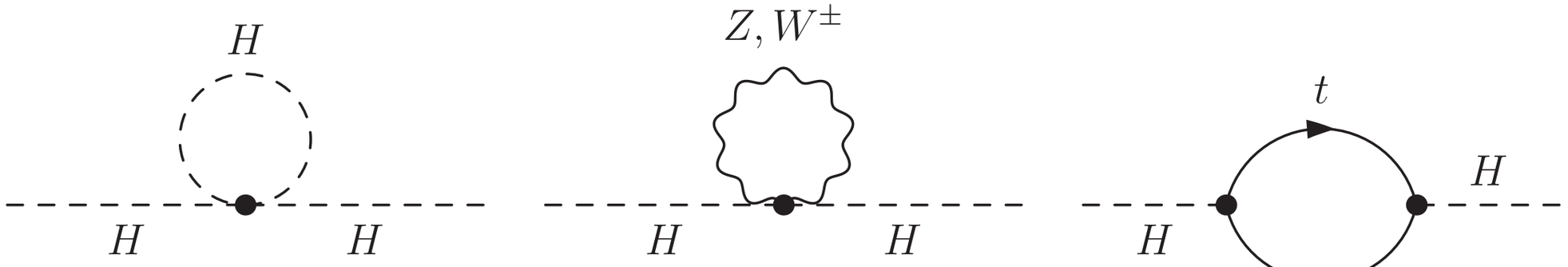

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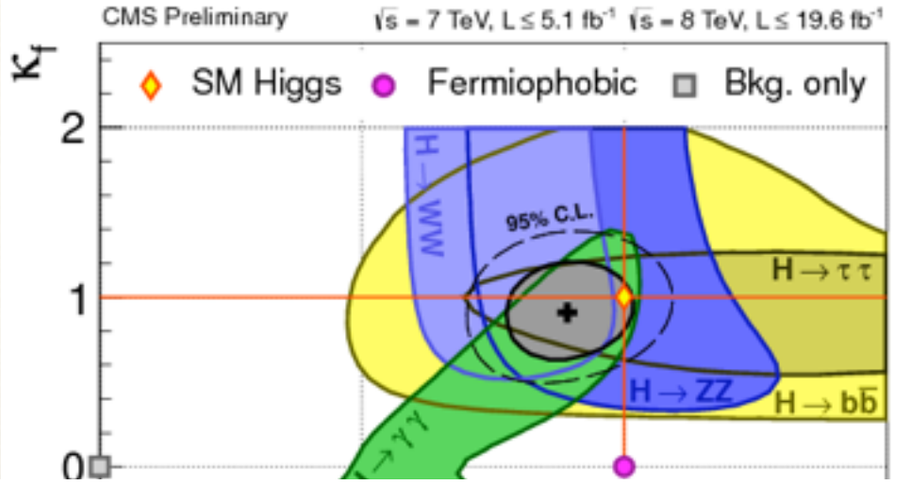

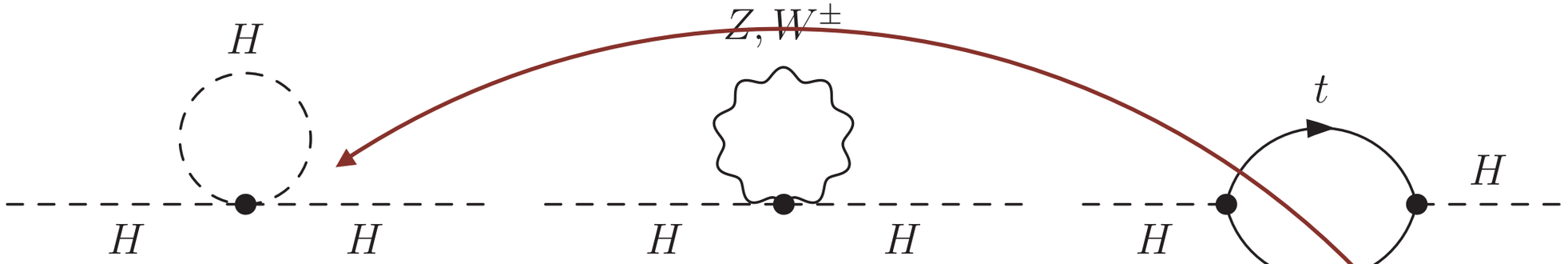

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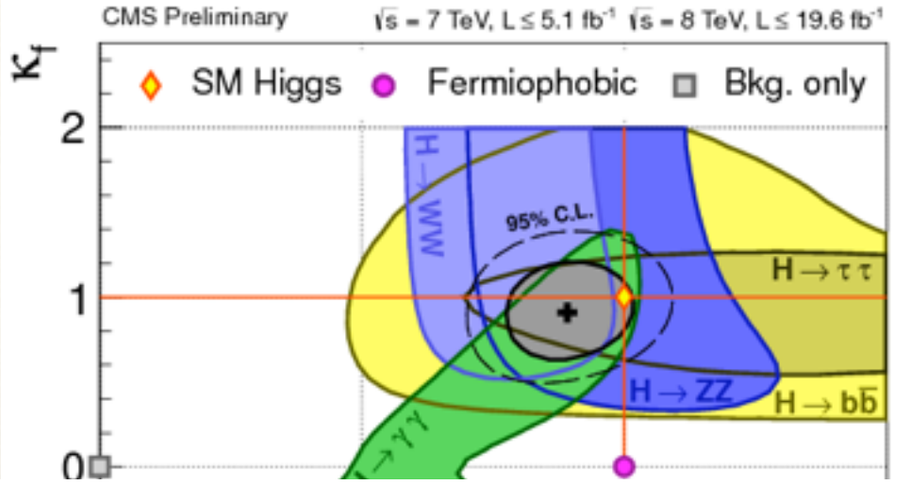

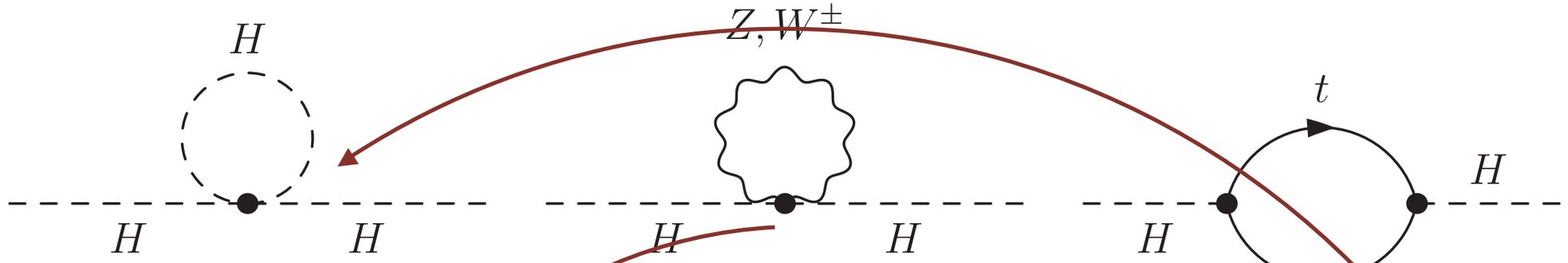

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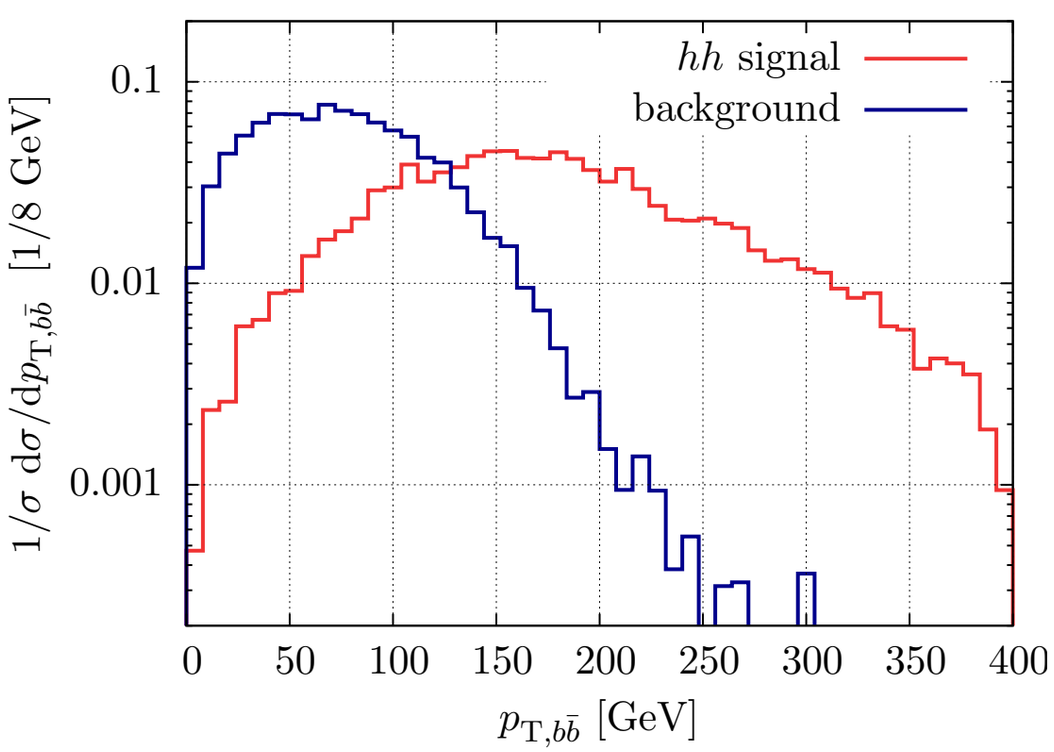

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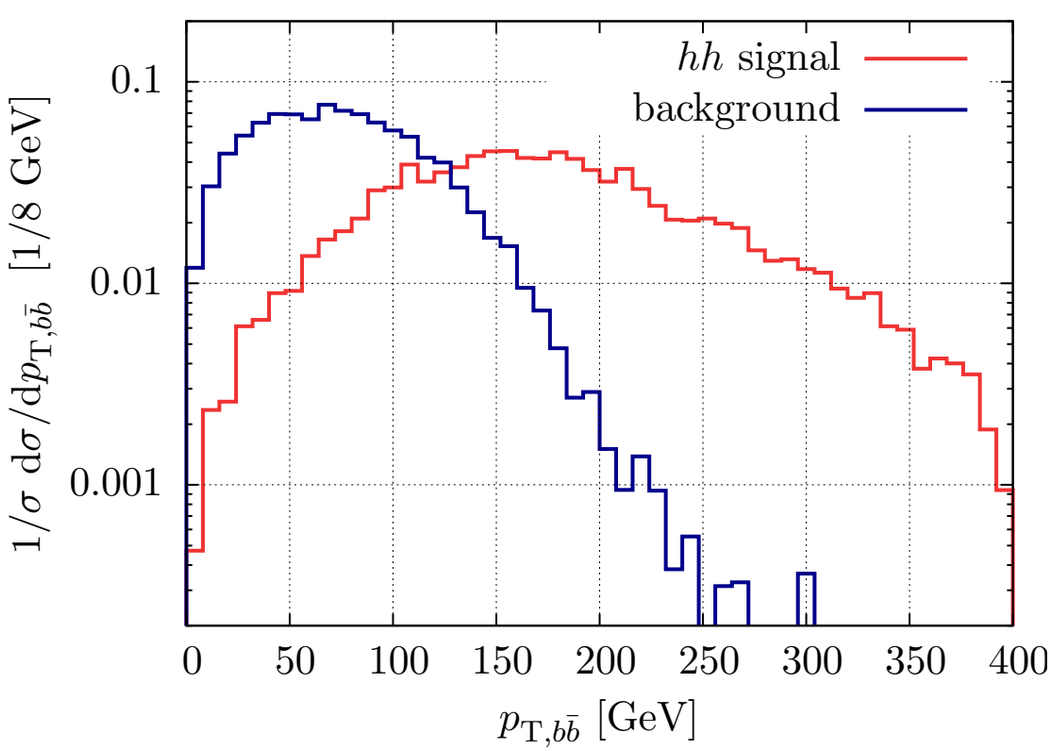

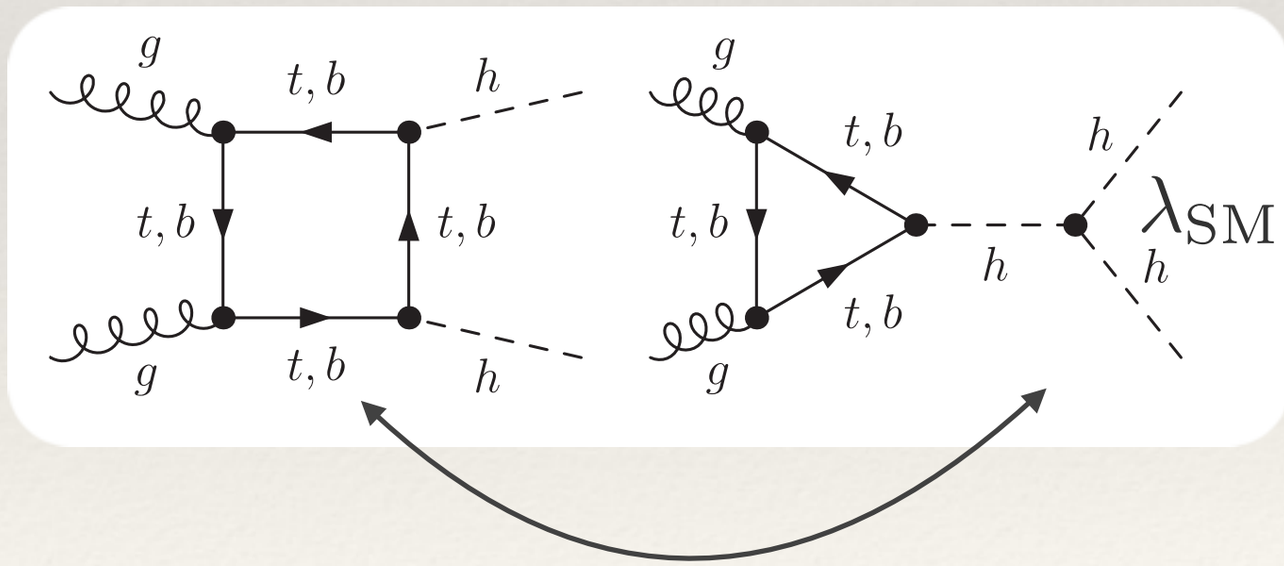

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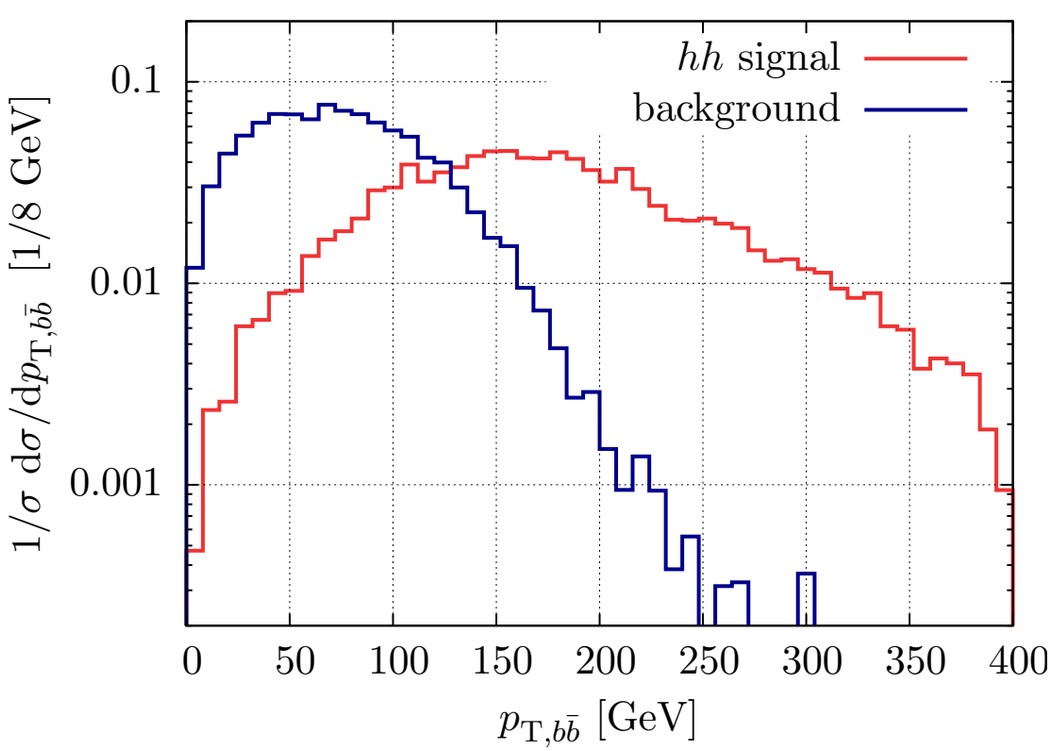

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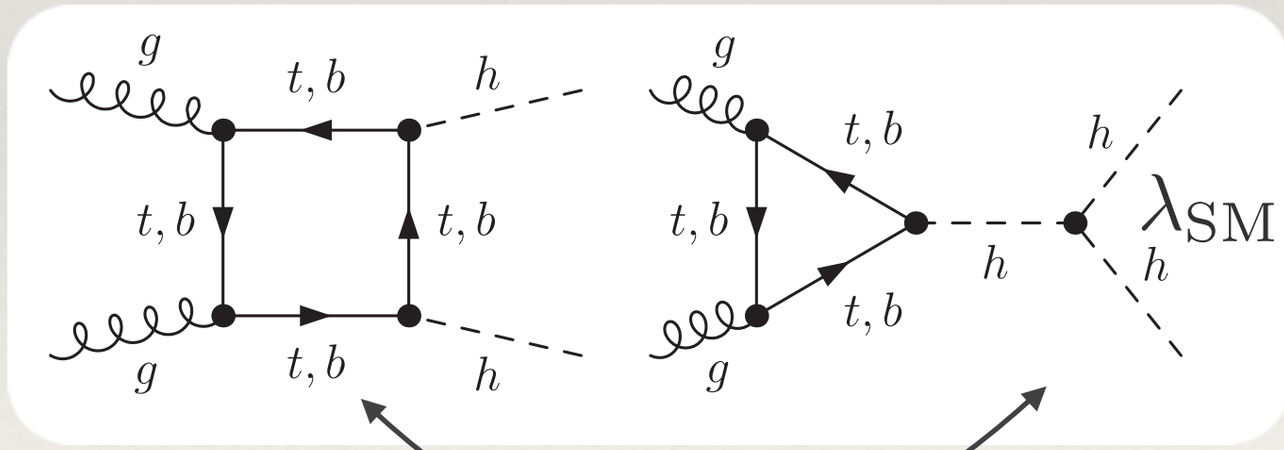

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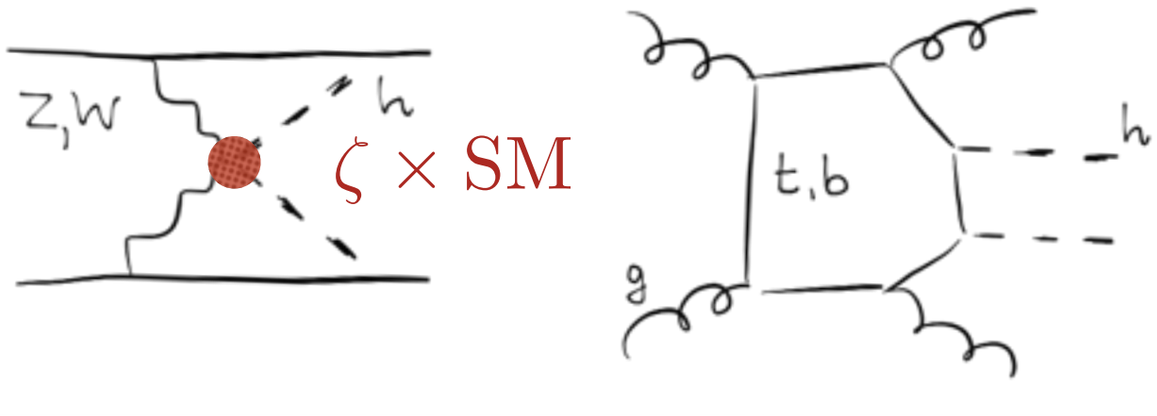

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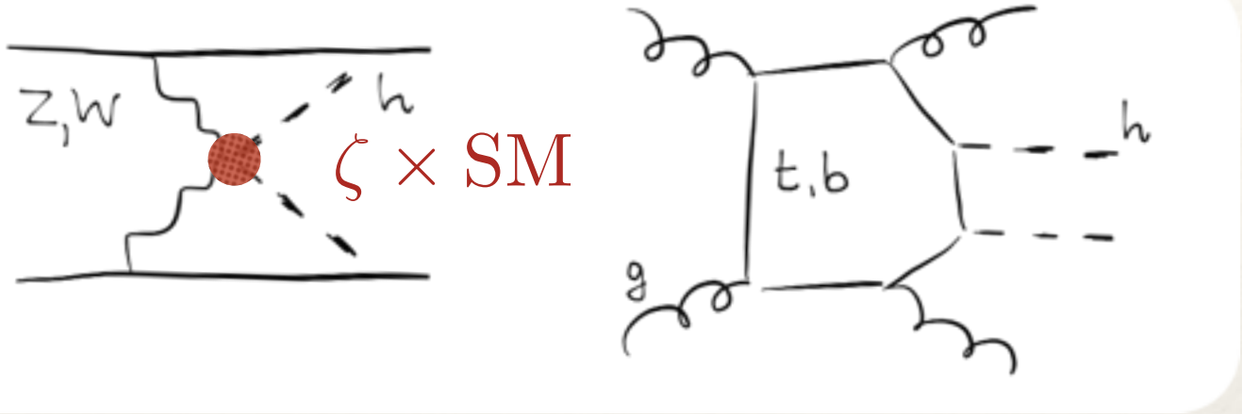

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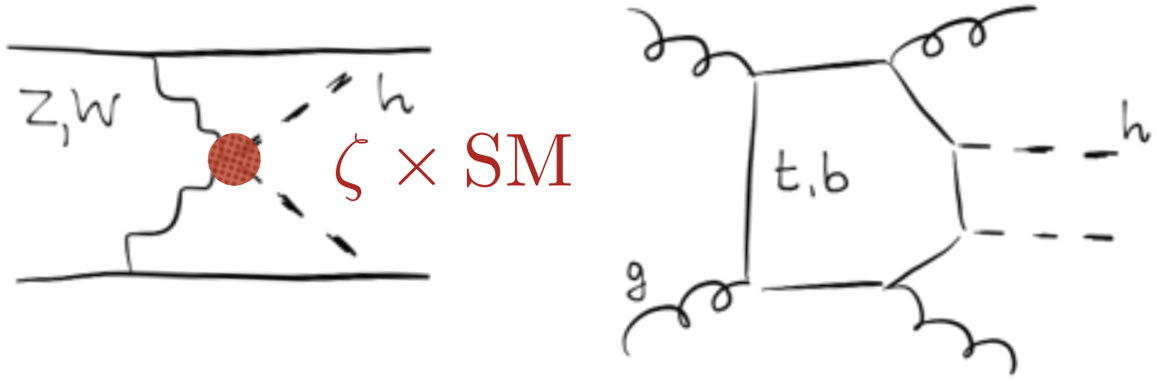

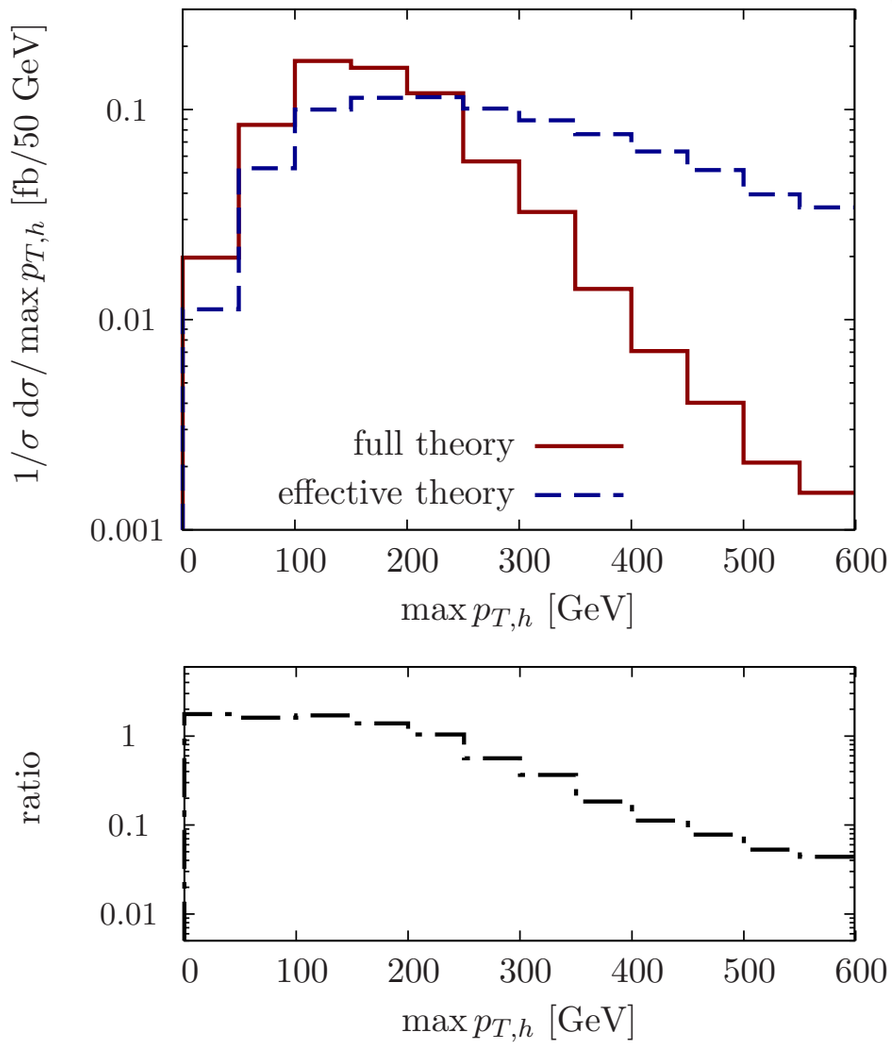

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tau selection cuts	1.353	0.091	0.841	3101.0	57.06
Higgs rec. from taus	1.352	0.091	0.840	683.5	31.92
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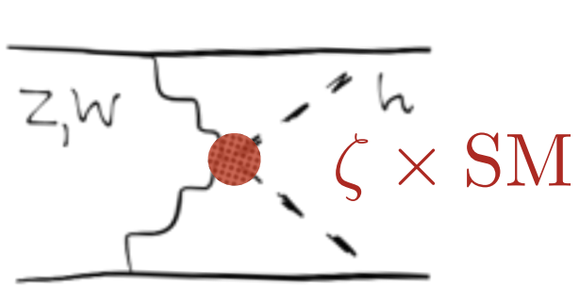

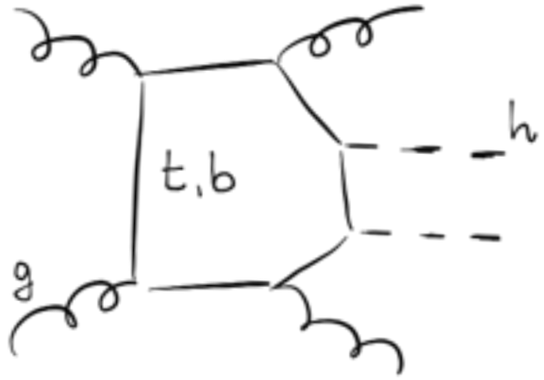

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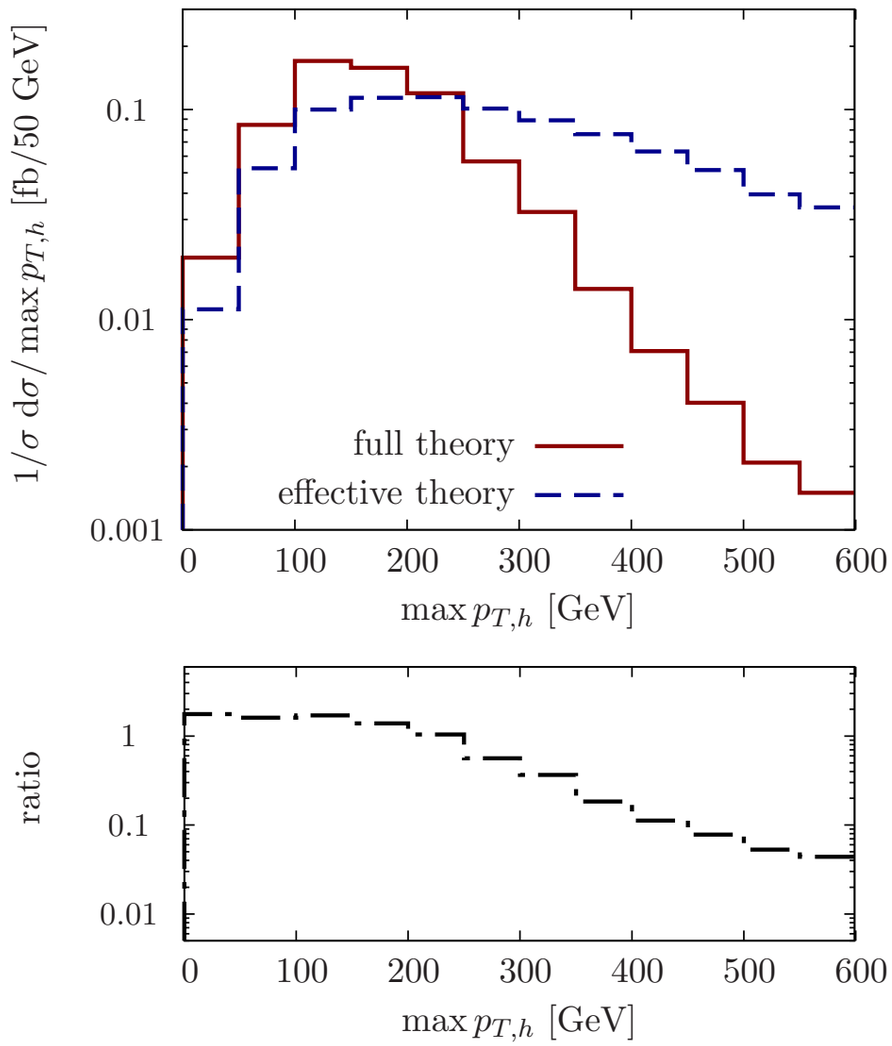

[Dolan, CE, Greiner, Spannowsky` 13]

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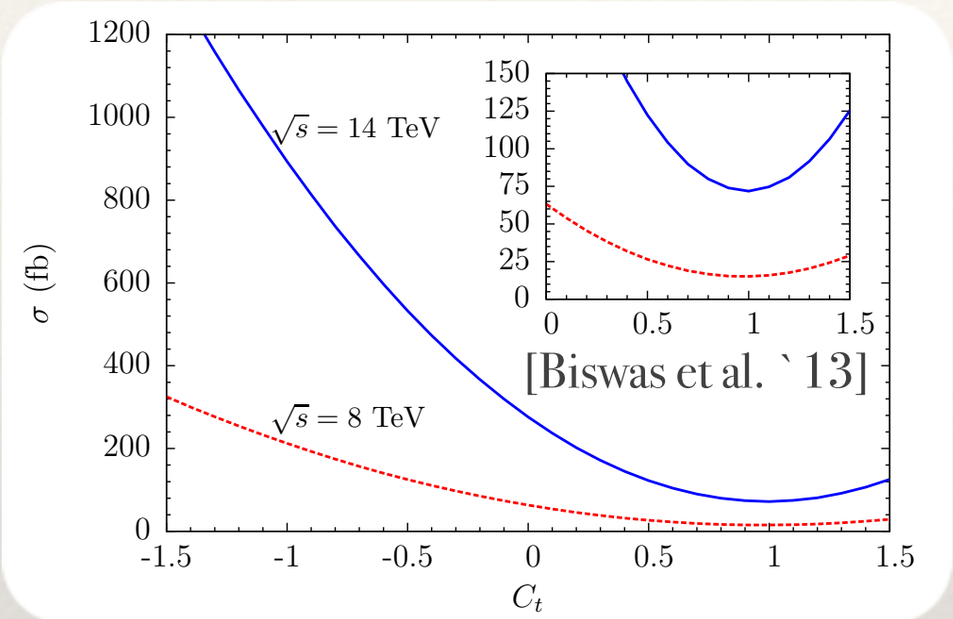

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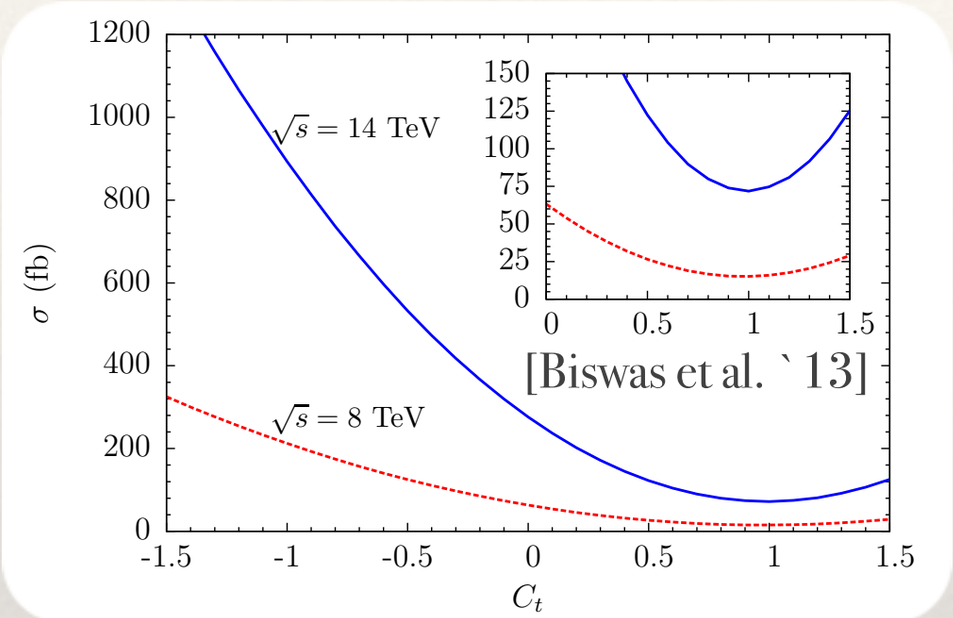

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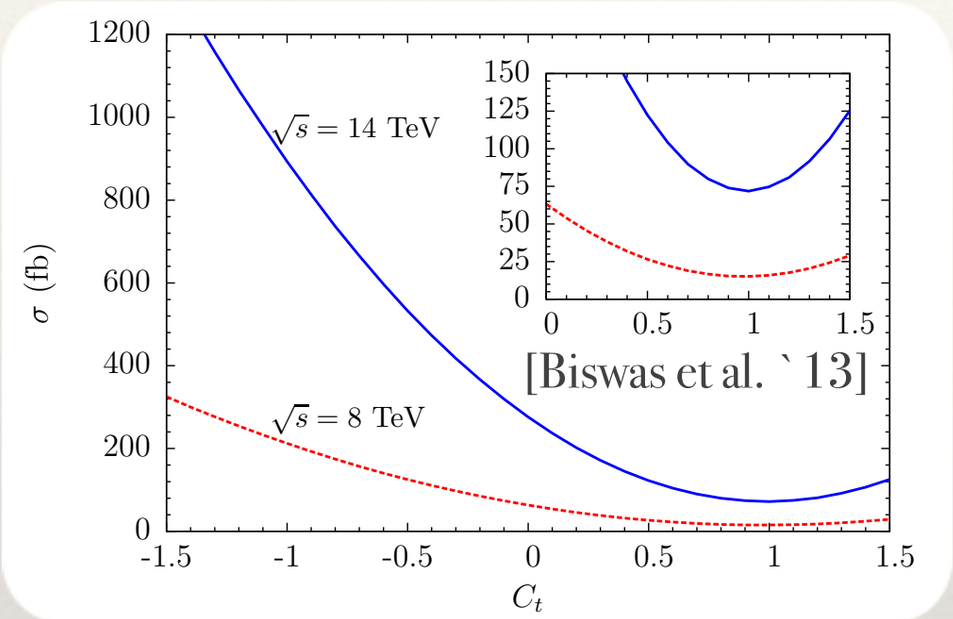

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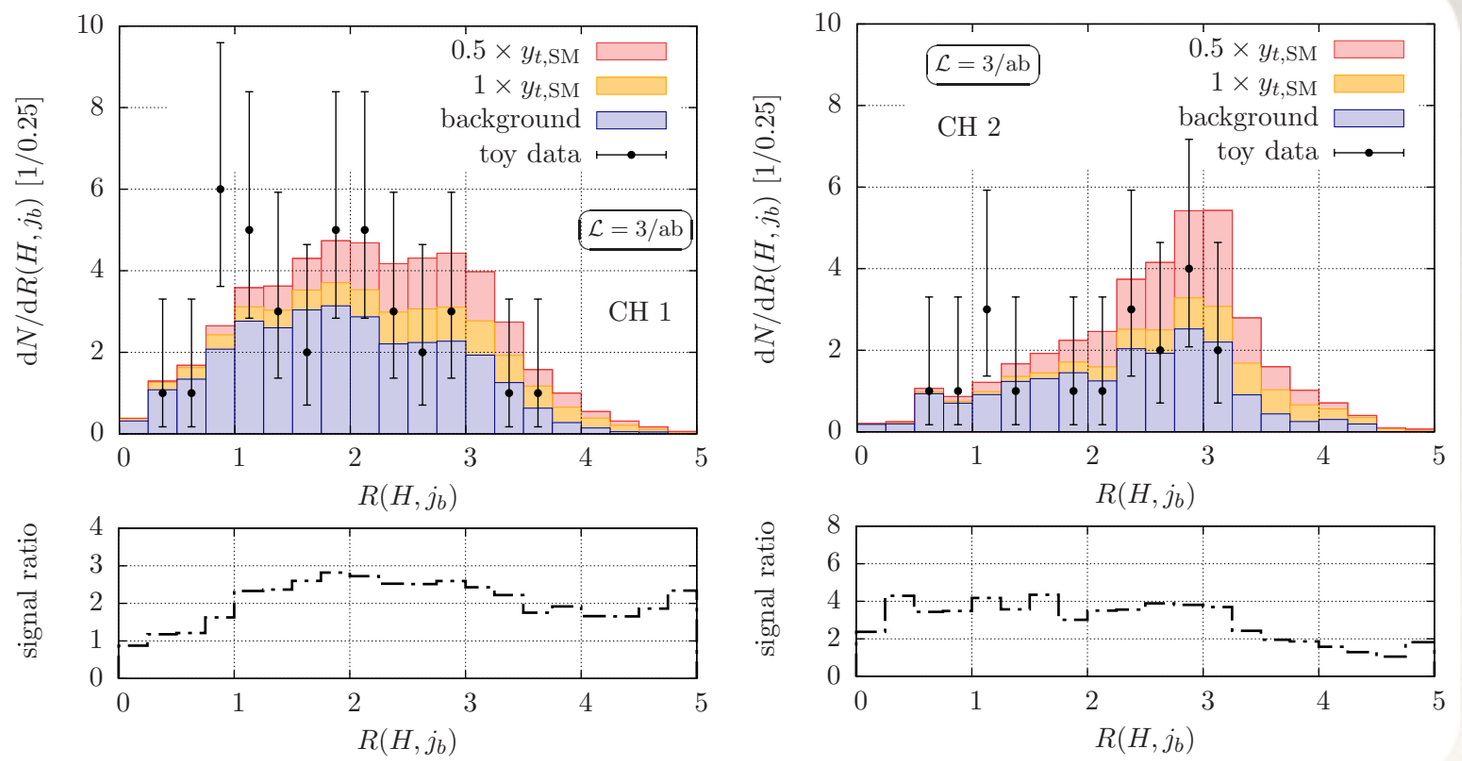

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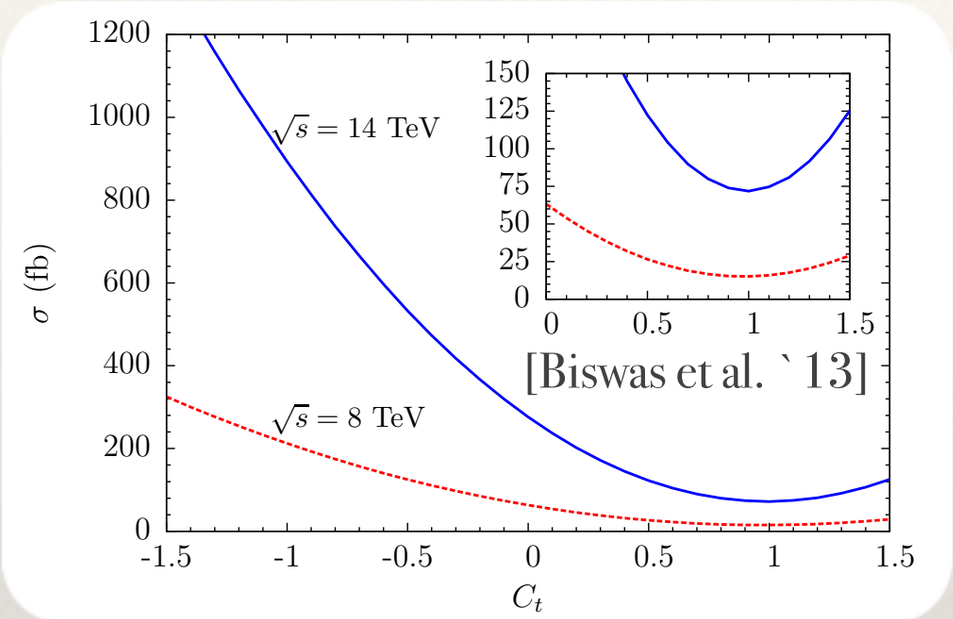

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- even in rare (but clean!) final states $c_t \gtrsim 0.5$ at 95..99% confidence level

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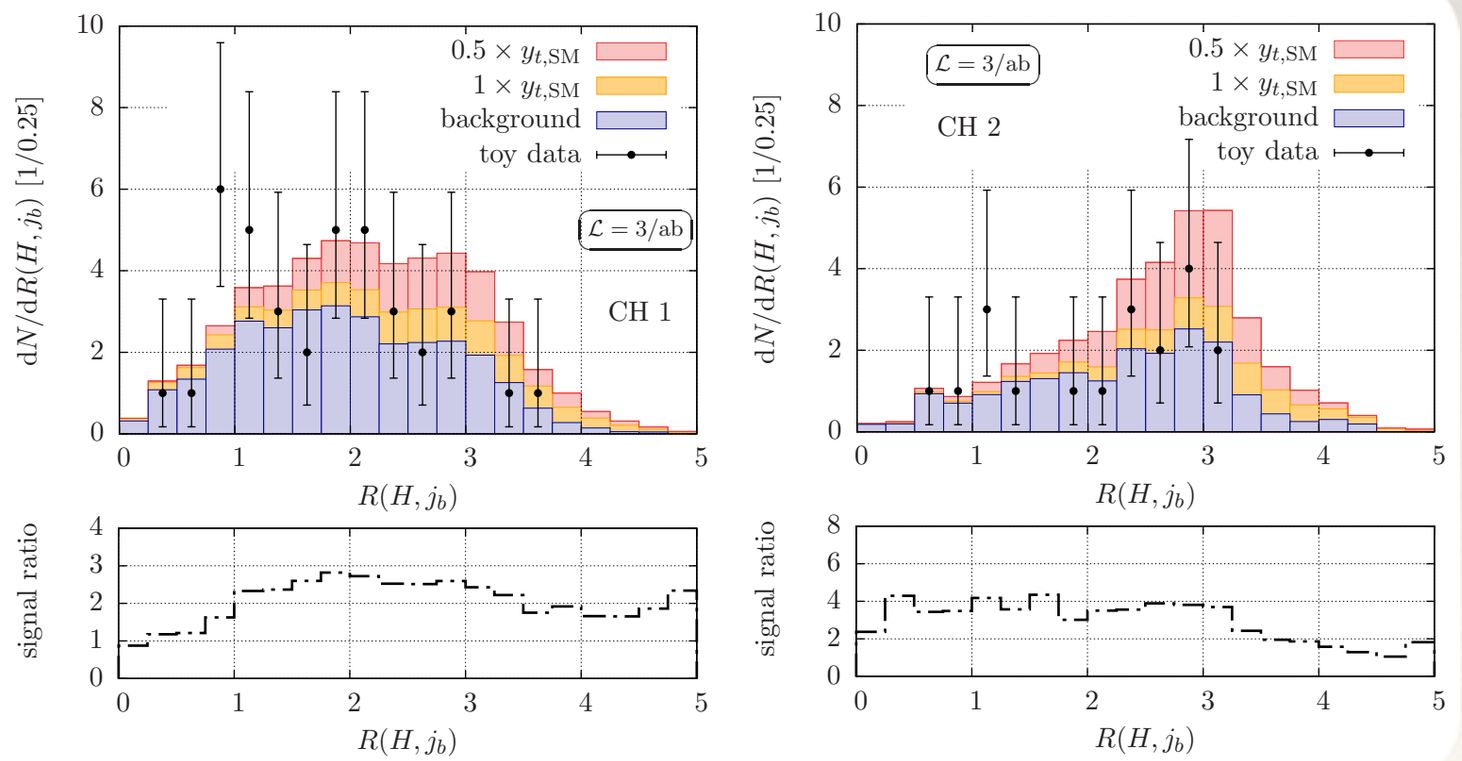
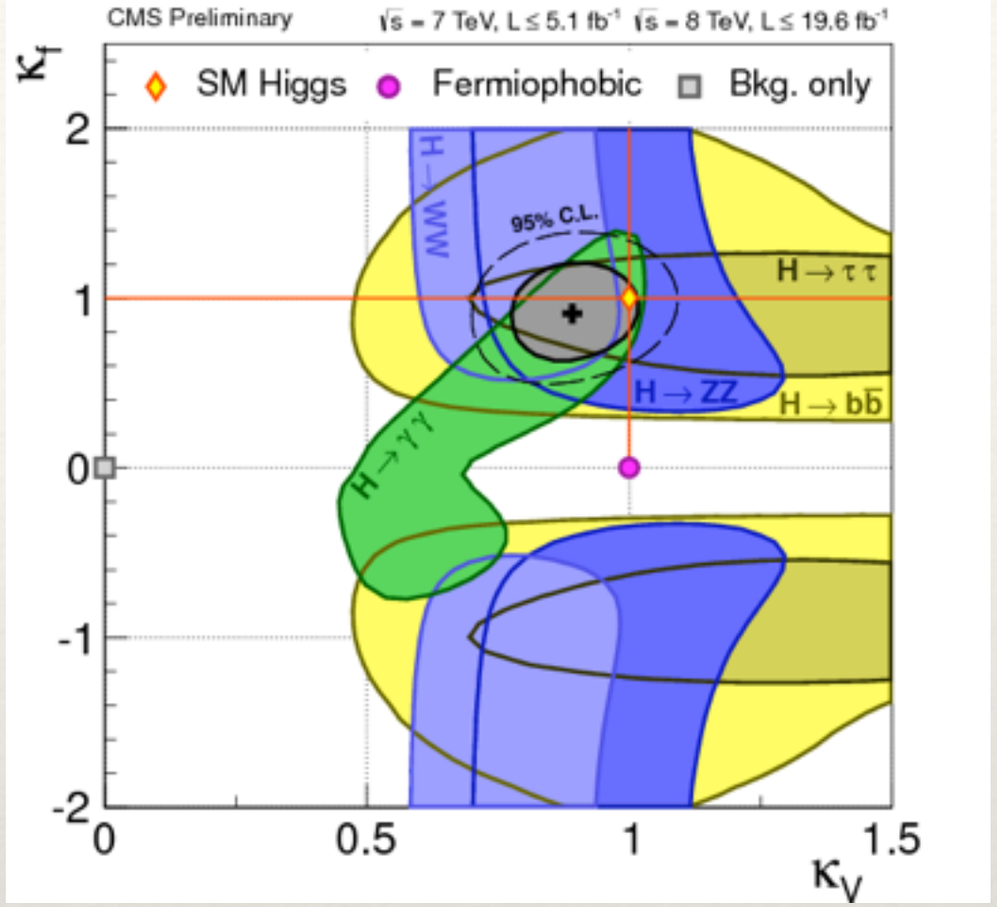


A bottom-up (B)SM Higgs programme

coupling measurements are determined by

1. unitarity
2. number of Higgs fields
3. **gauge representation**
4. **experimental extraction**
5. **mechanism of ELW symmetry breaking**
6. **spectrum through quantum effects**



similar analyses by [Ellis, You `12]
[Masso, Sanz `12]
[Carmi, Falkowski, Kuflik, Volansky `12]
[Klute, Lafaye, Plehn, Rauch, Zerwas `12]
[Corbett, Eboli, Gonzalez-Fraile, et al. `12]
[Espin… …er, Trott `12]

naturalness
leaving footprints?

Higgs couplings: a probe of naturalness

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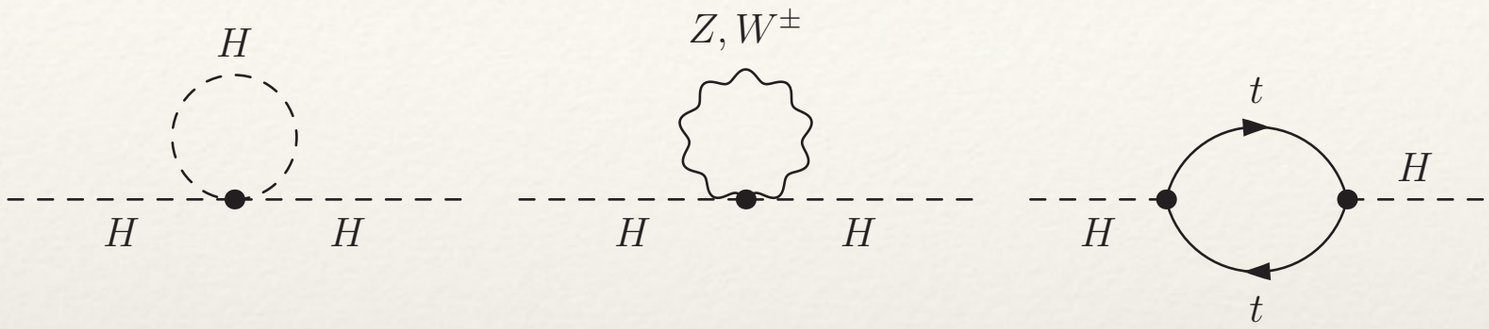

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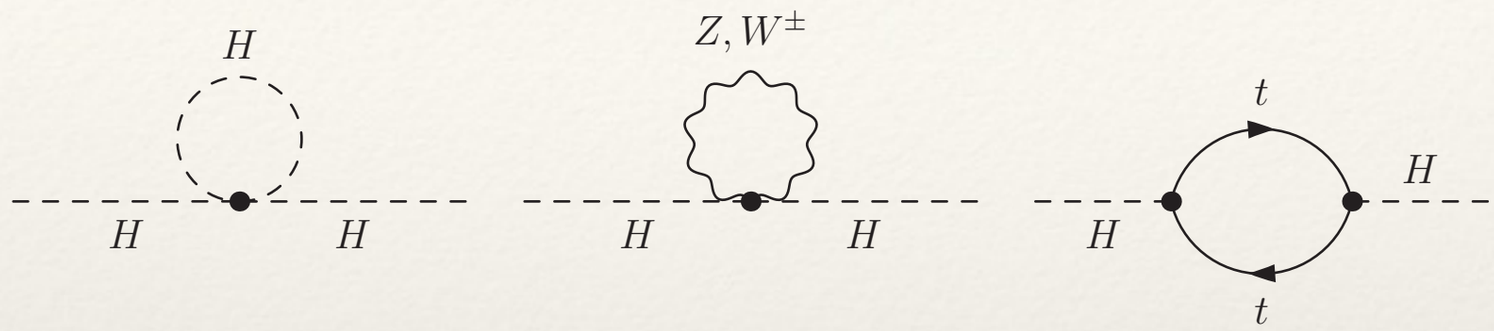

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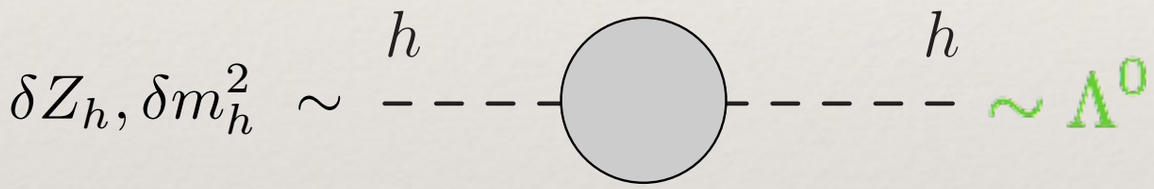

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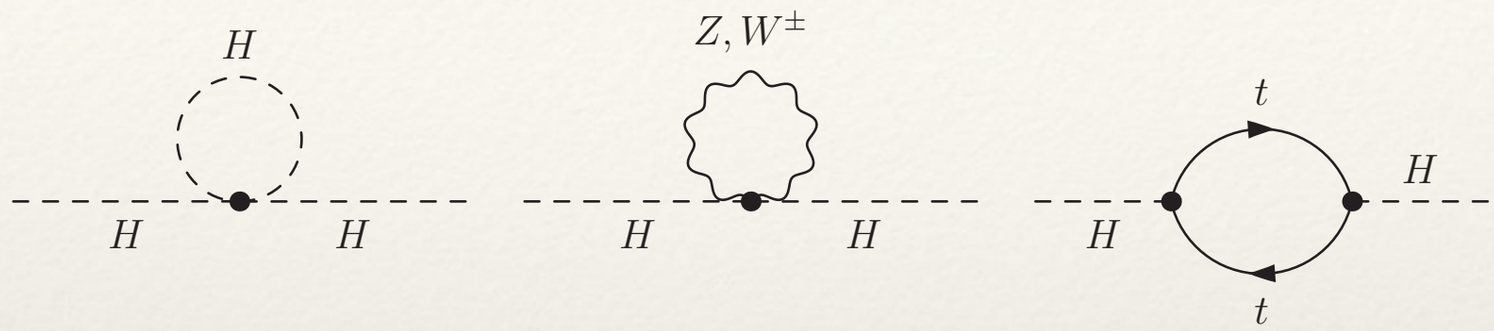

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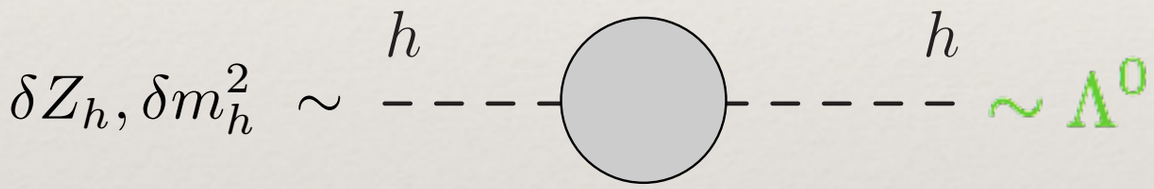

worst case: dark sector enforces naturalness

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

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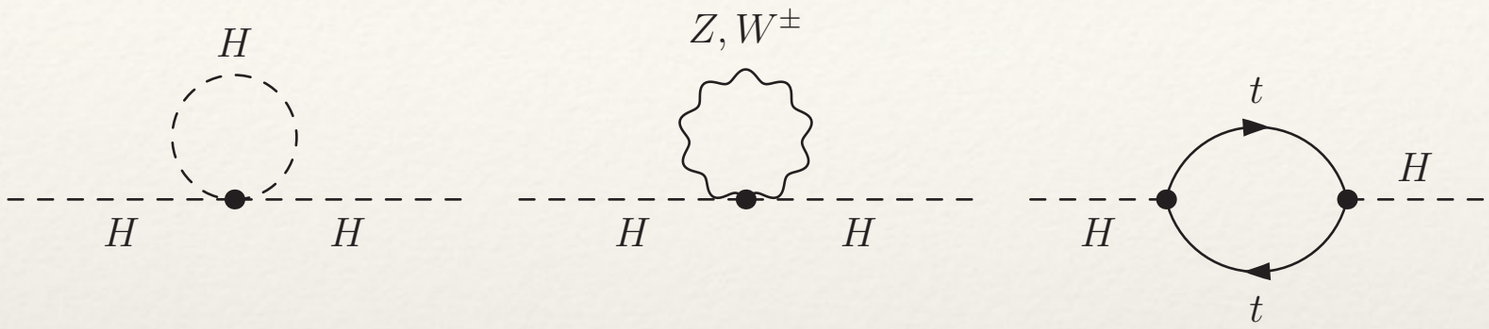

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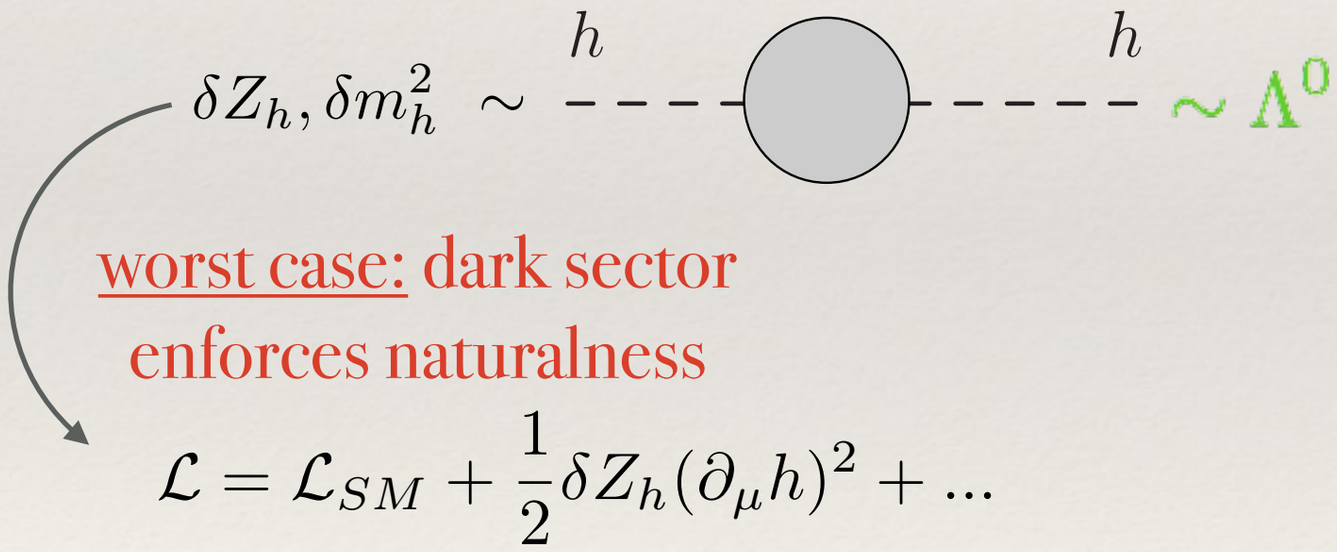

250 GeV linear collider
full EW corrections

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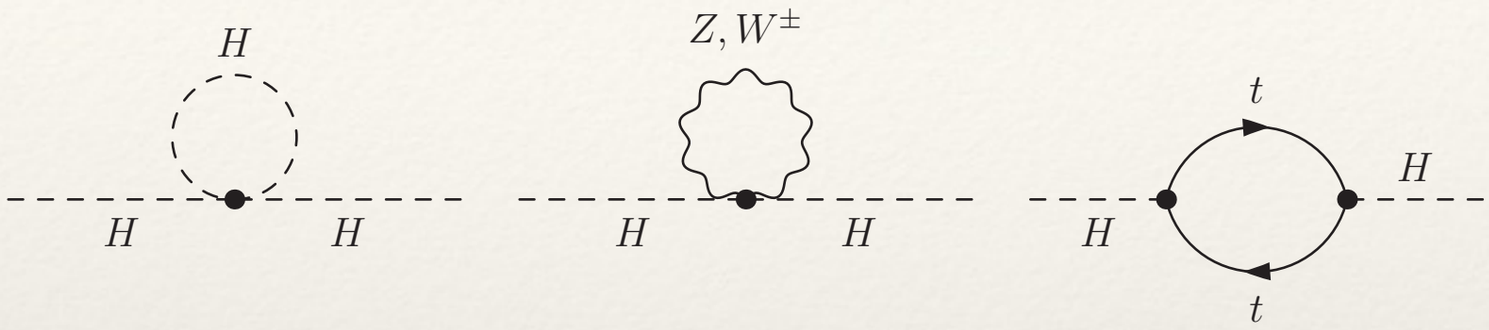

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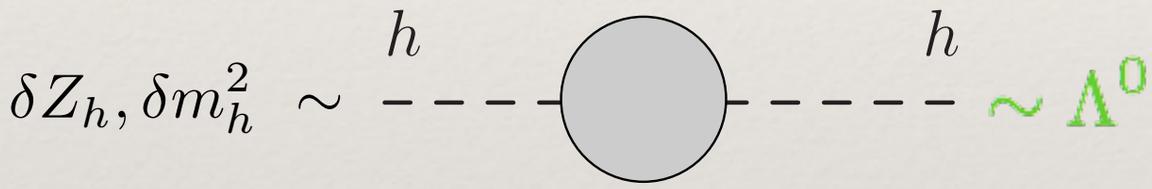

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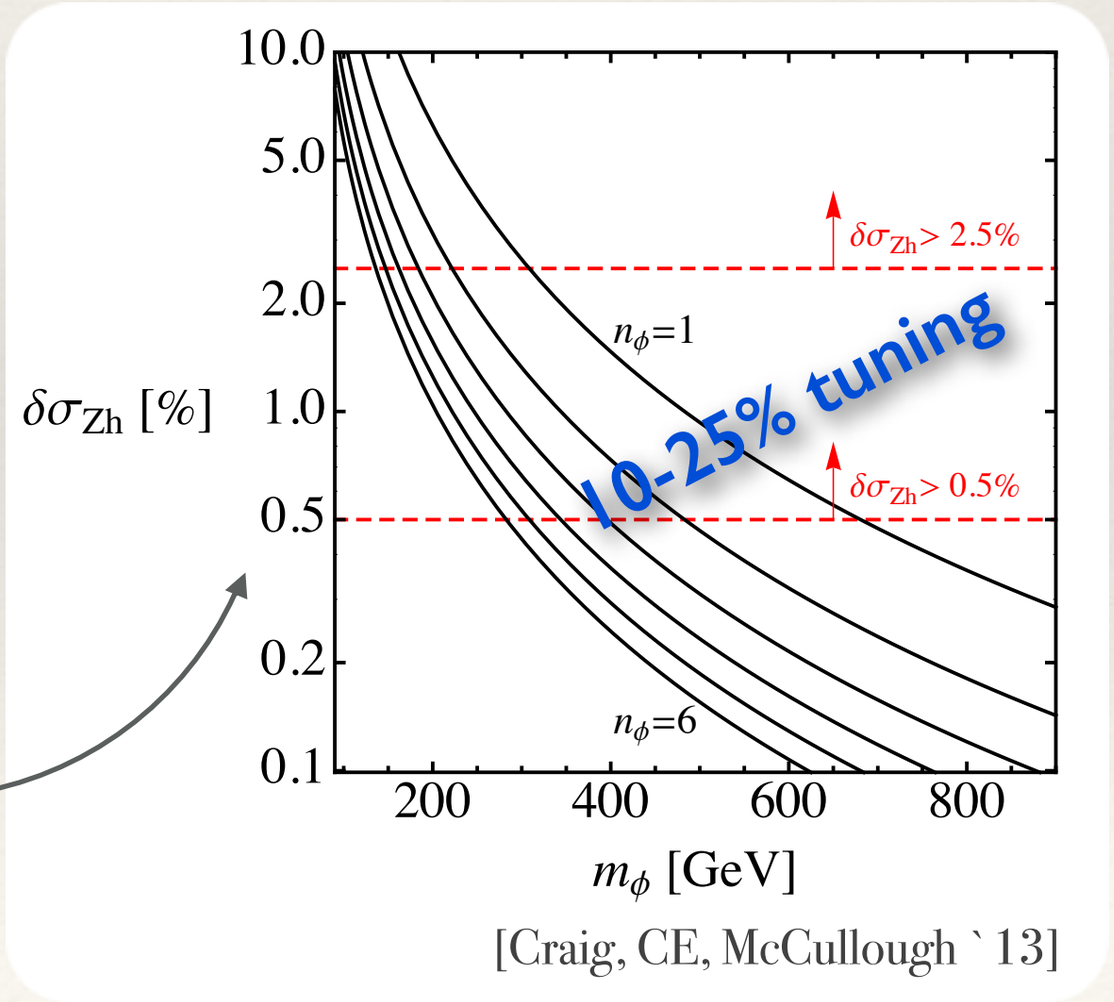

[Craig, CE, McCullough `13]

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