Christoph Englert

Interference effects in (B)SM Higgs searches

LLR - Palaiseau

20.05.2015

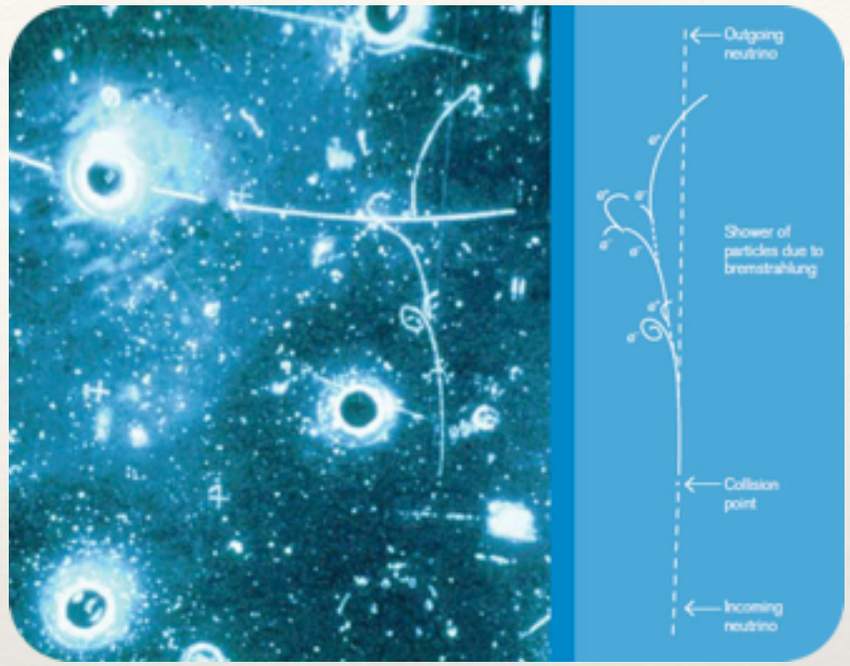
"Yang-Mills+Higgs had to be true"

`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 ?

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

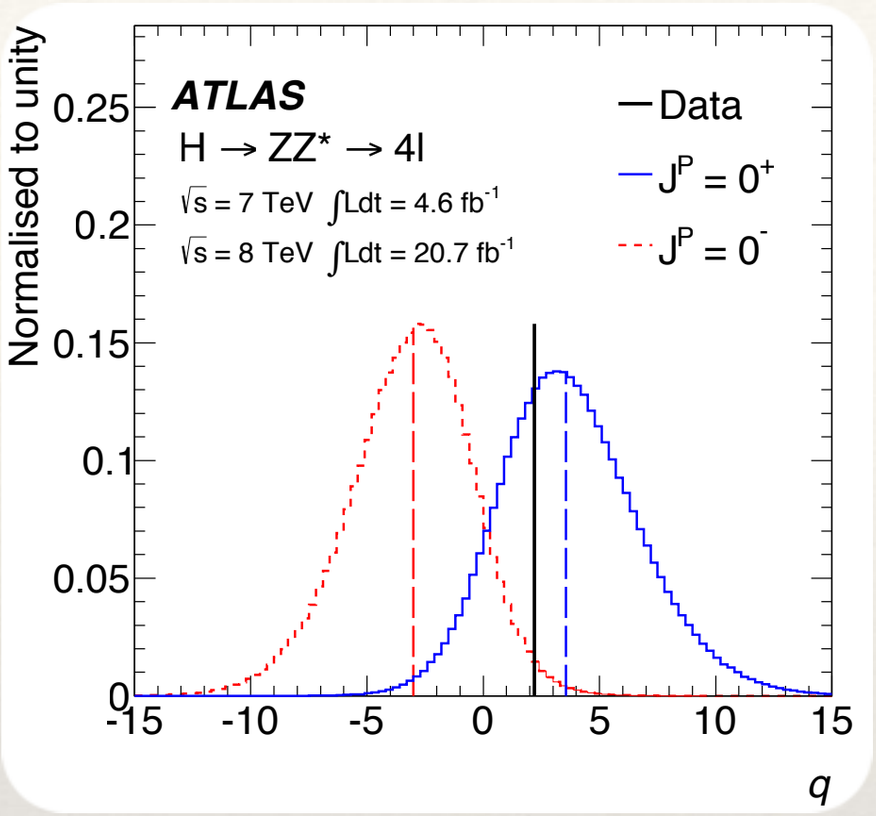
- non-linear realisation of gauge symmetry in a Yang Mills+scalar sector is compatible with $\langle H \rangle \neq 0$

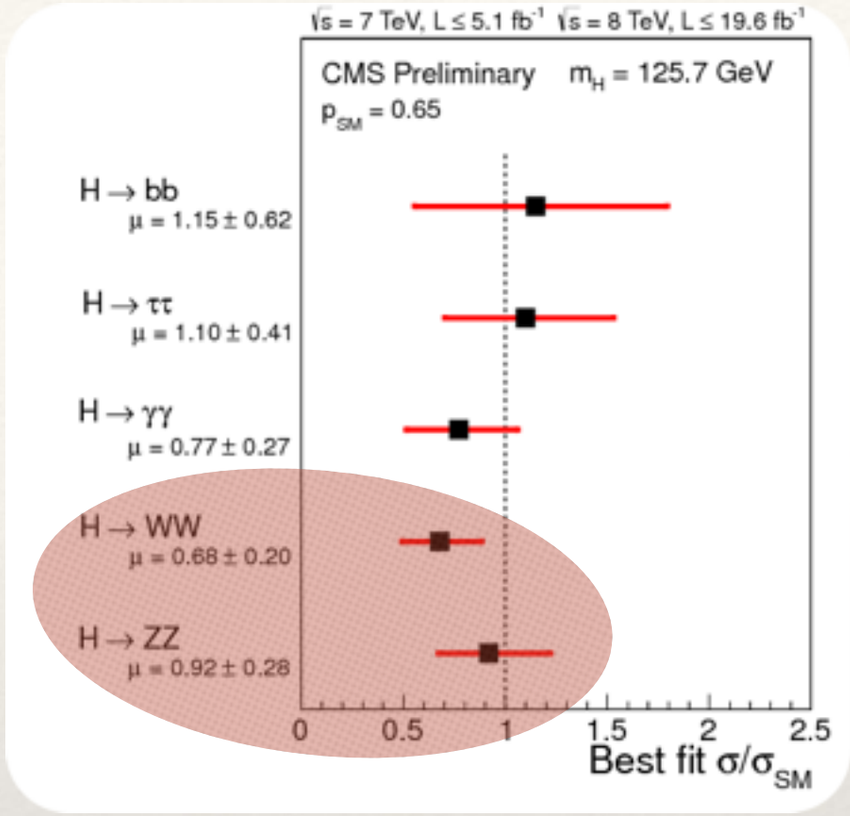
☛ "spontaneous" symmetry breaking

- 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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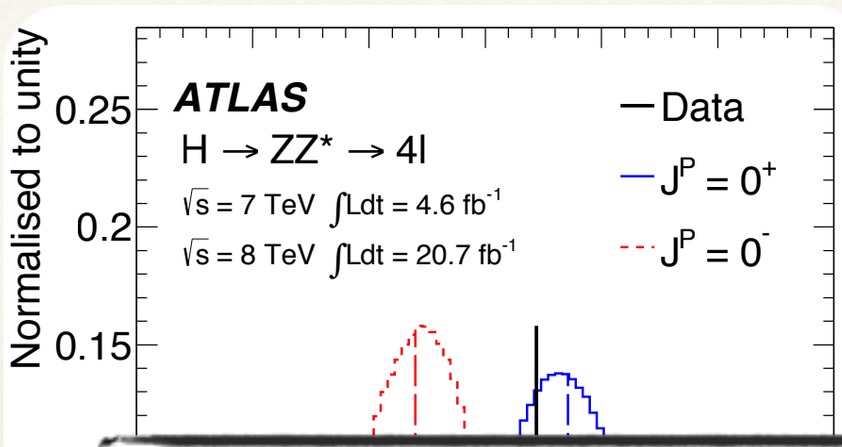
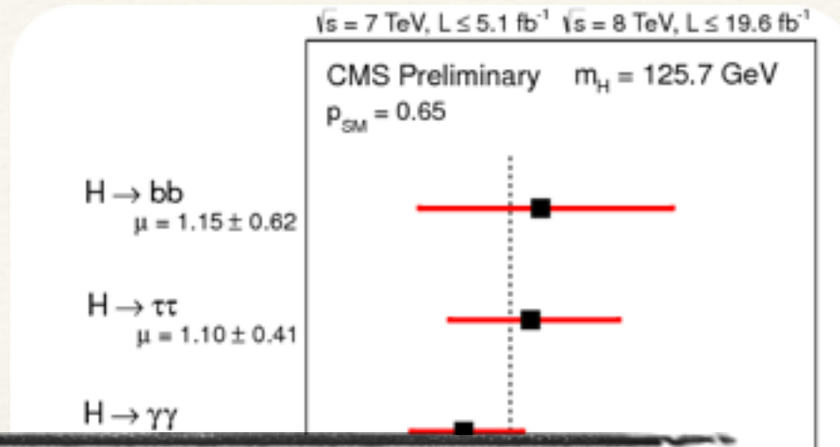
Higgs properties *sui generis*:

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

“Yang-Mills+Higgs had to be true”





“Yang-Mills+Higgs IS true”

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

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Higgs properties *sui generis*:

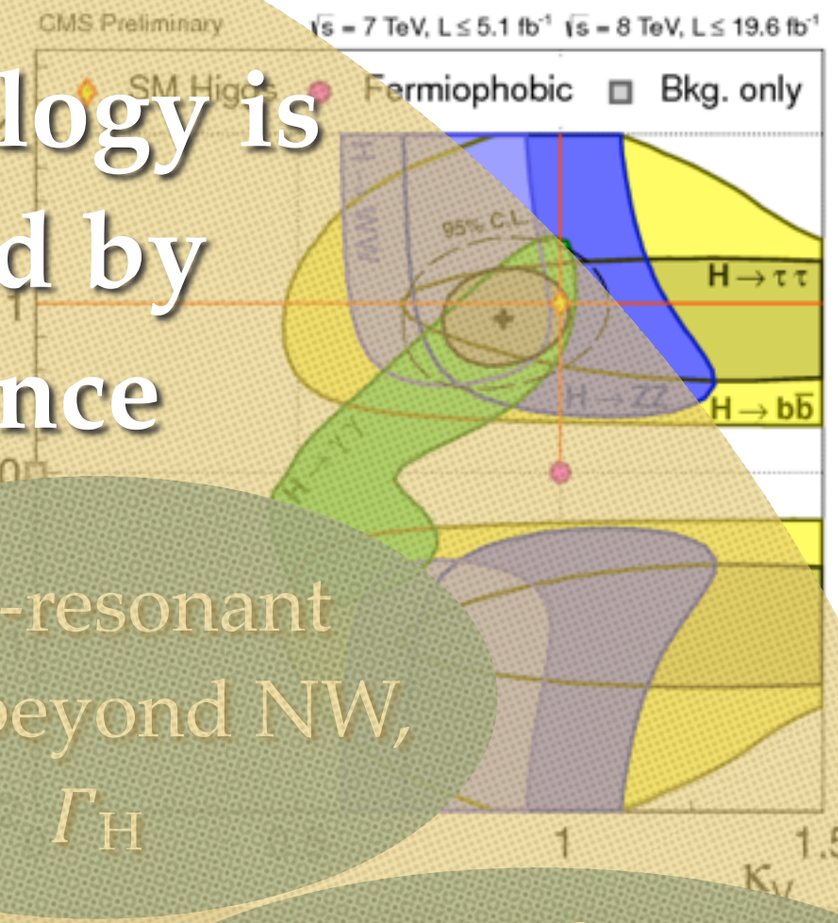
particle relates to unitarity conservation and an excitation of an isotropic and translationally invariant background field.

What's next? Where can new physics hide?

coupling measurements are determined by:

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

Phenomenology is dominated by interference



non-resonant
BSM beyond NW, Γ_H

EWSB
specific couplings, top interactions

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

naturalness
leaving footprints?

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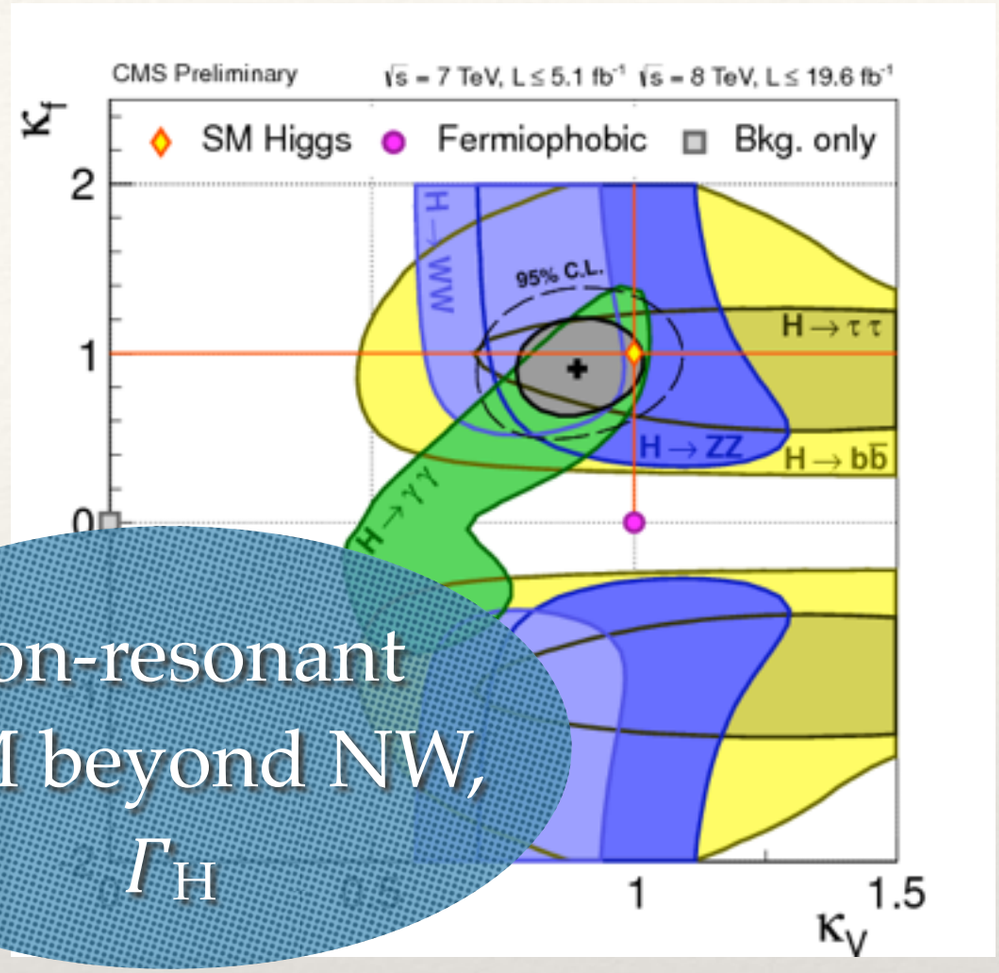
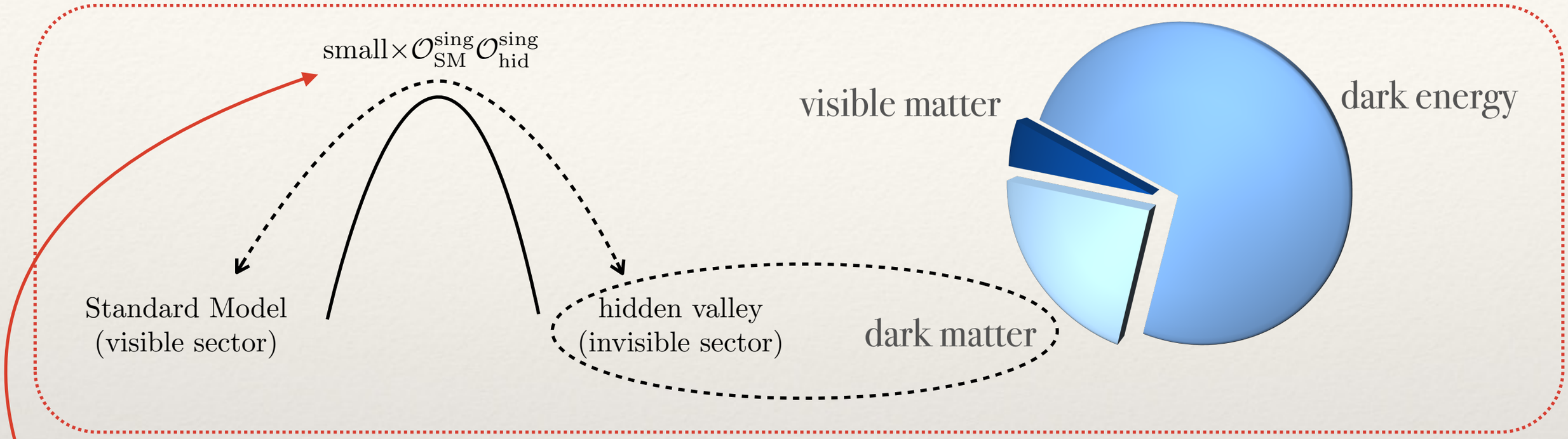


non-resonant BSM beyond NW, Γ_H

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]

The total Higgs width

Why is this important ?



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

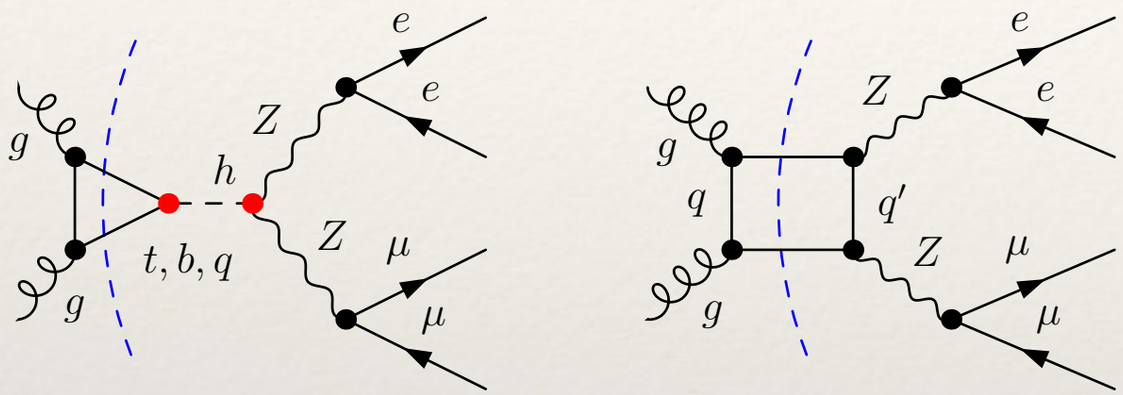
$$\Gamma_H = \Gamma_H^{\rm SM} + \Gamma_{\rm inv}$$

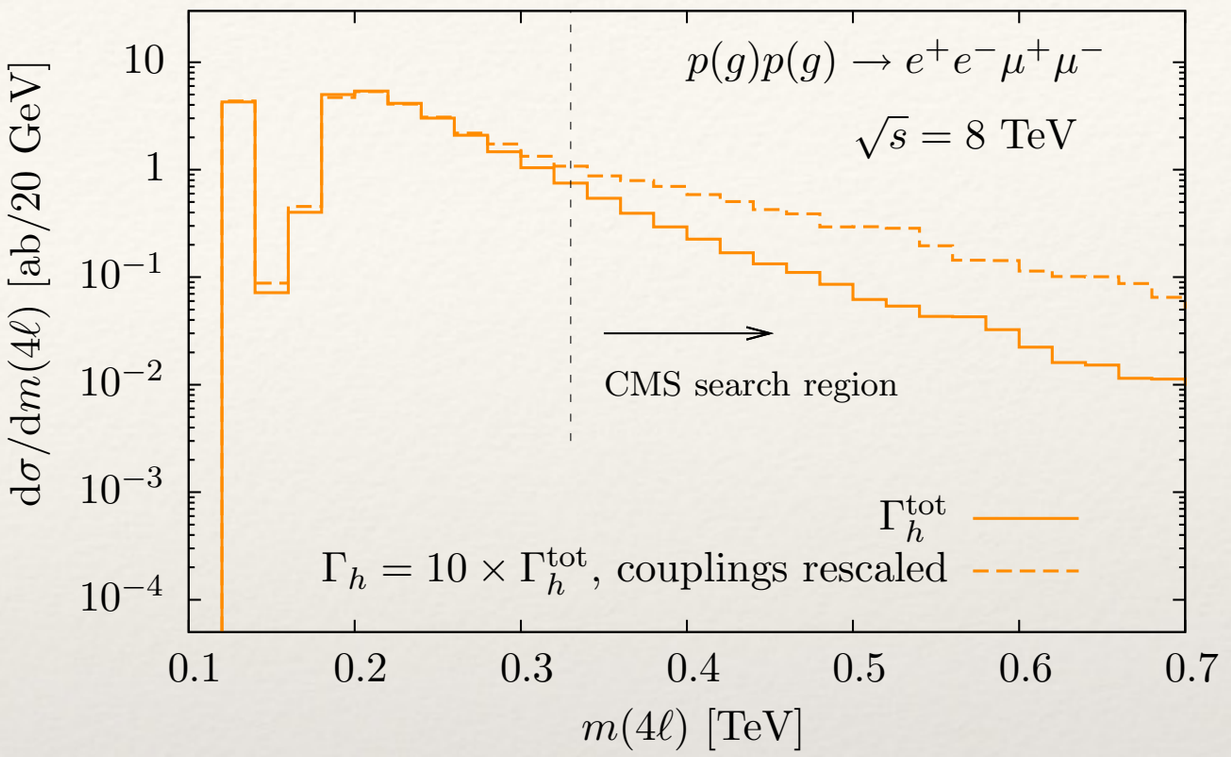
→ a **model-independent constraint** on the total Higgs decay width is a **game changer for particle physics and cosmology** !

The total Higgs width

A two-step programme in ZZ

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





The total Higgs width

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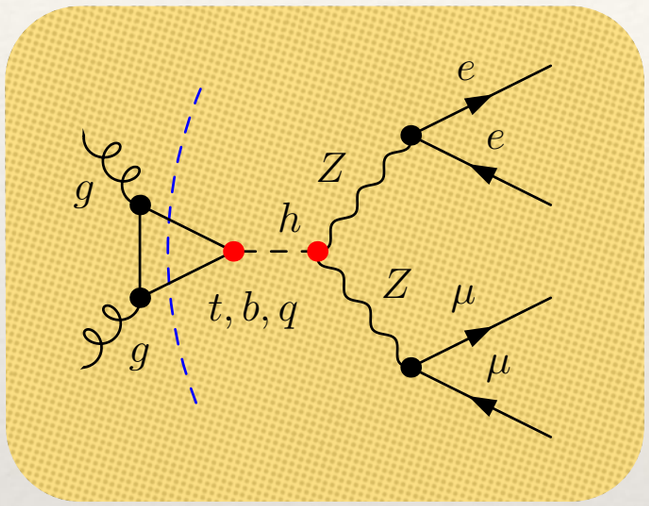

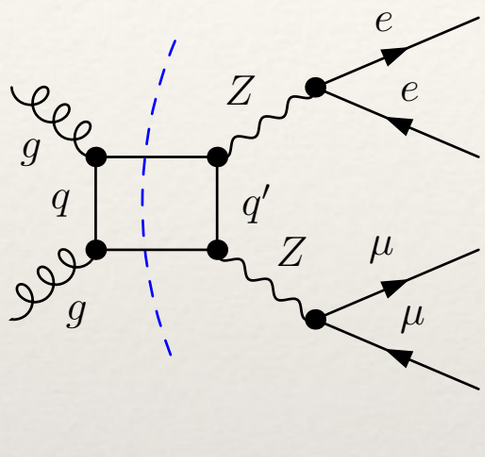

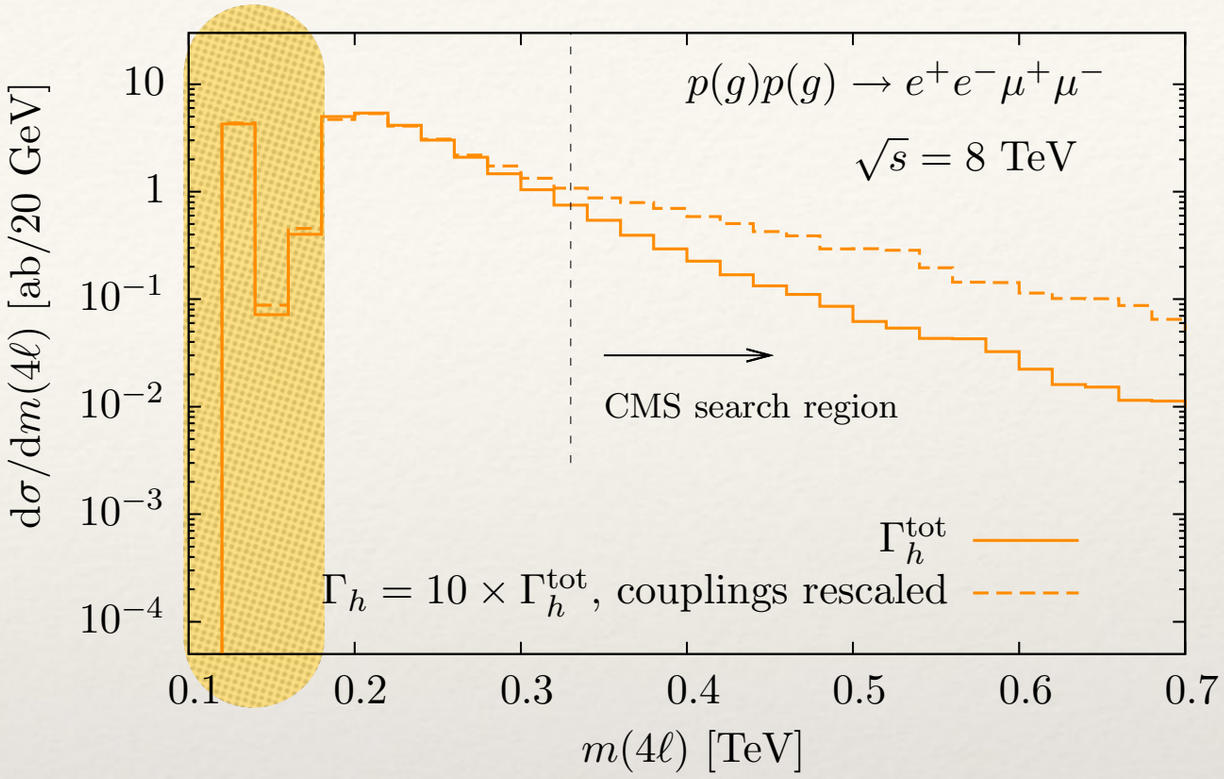

1. on-shell measurement

dominated by h signal

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

The total Higgs width

A two-step programme in ZZ

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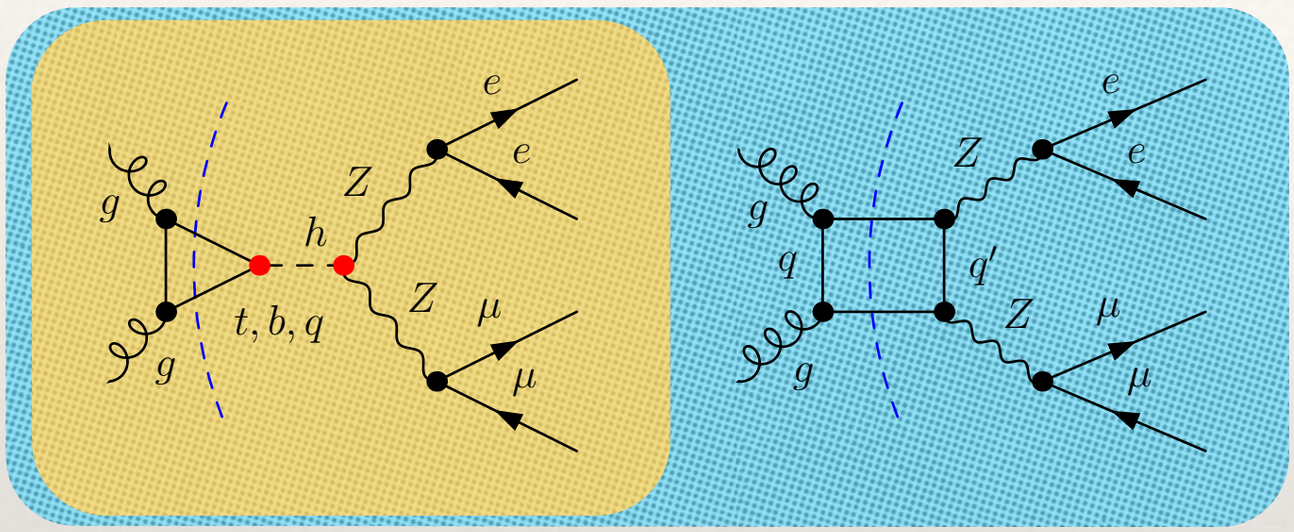
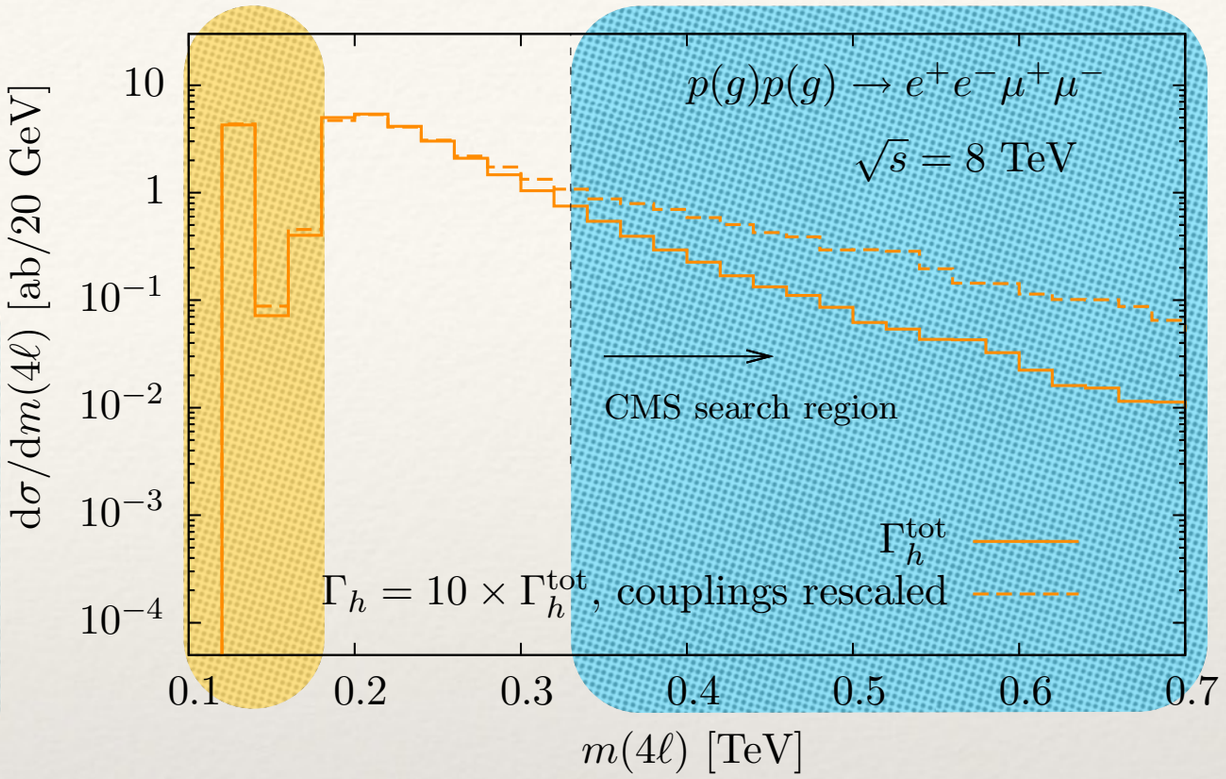




1. on-shell measurement

dominated by h signal

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

2. off-shell measurement

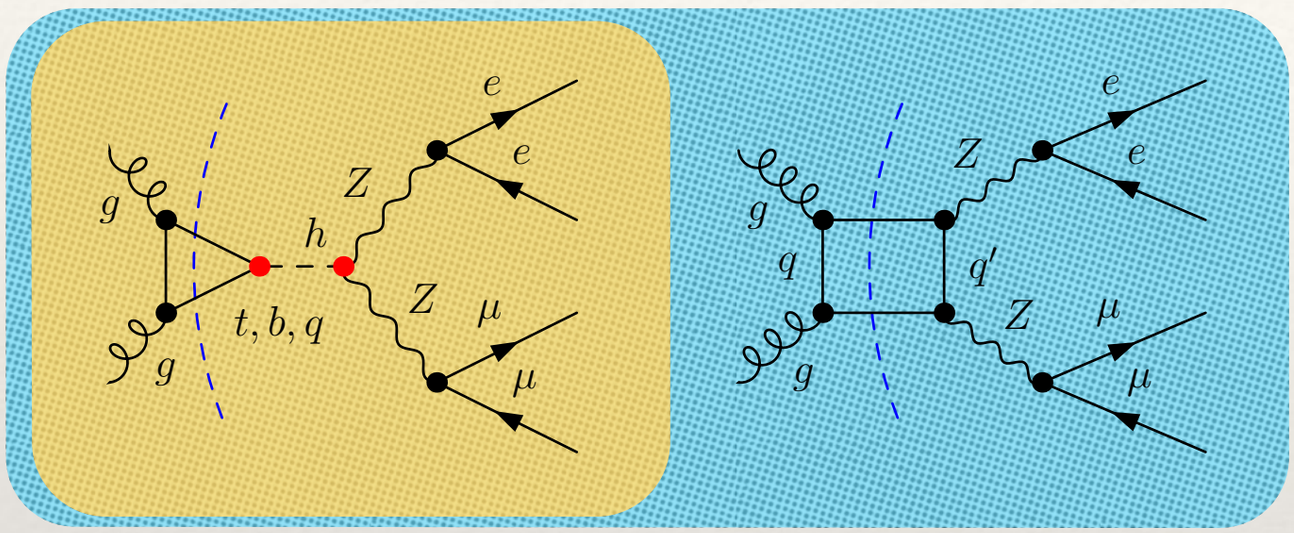
threshold effects and unitarity driven interference, but de-coupling of width parameter $\sim i/(s - m_h^2 + i\Gamma_h m_h)$

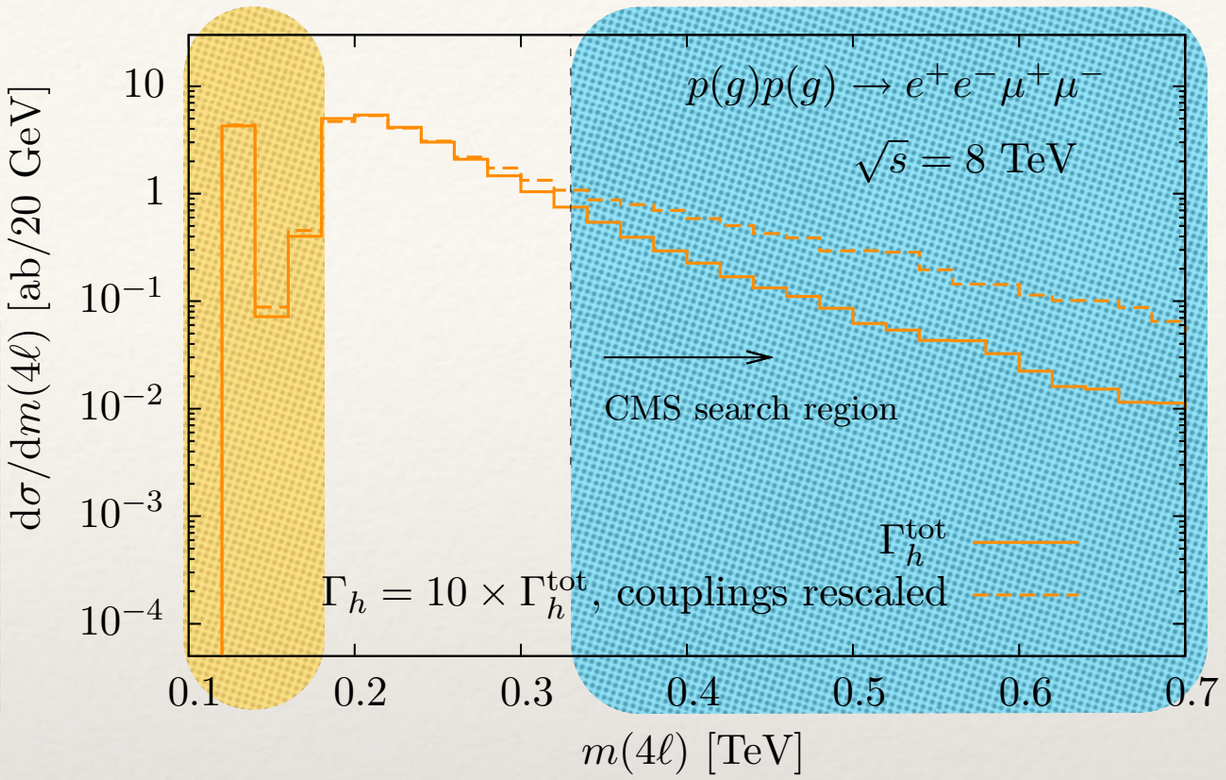
$$\mathrm{d}\overline{\sigma}_h \sim \frac{g^2_{ggh}(\sqrt{s})\, g^2_{hZZ}(\sqrt{s})}{s}\ \mathrm{dLIPS}\times\mathrm{pdfs}$$

The total Higgs width

A two-step programme in ZZ

[Caola, Melnikov `13]
[CMS-HIG-14-002] [ATLAS-CONF-2014-042]





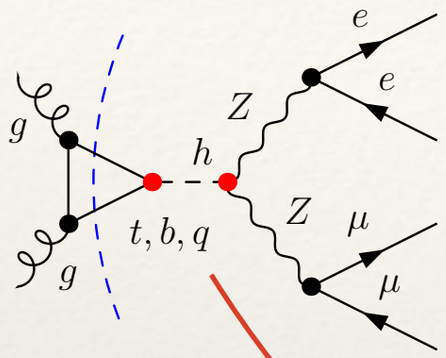
correlate measurements

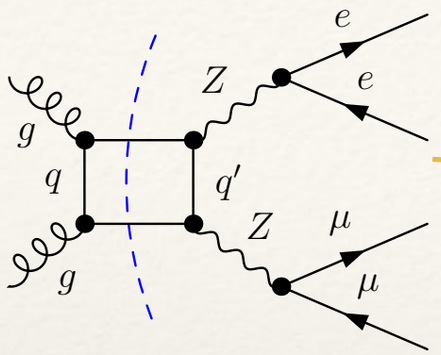
for off-shell an on-shell Higgs couplings are correlated:

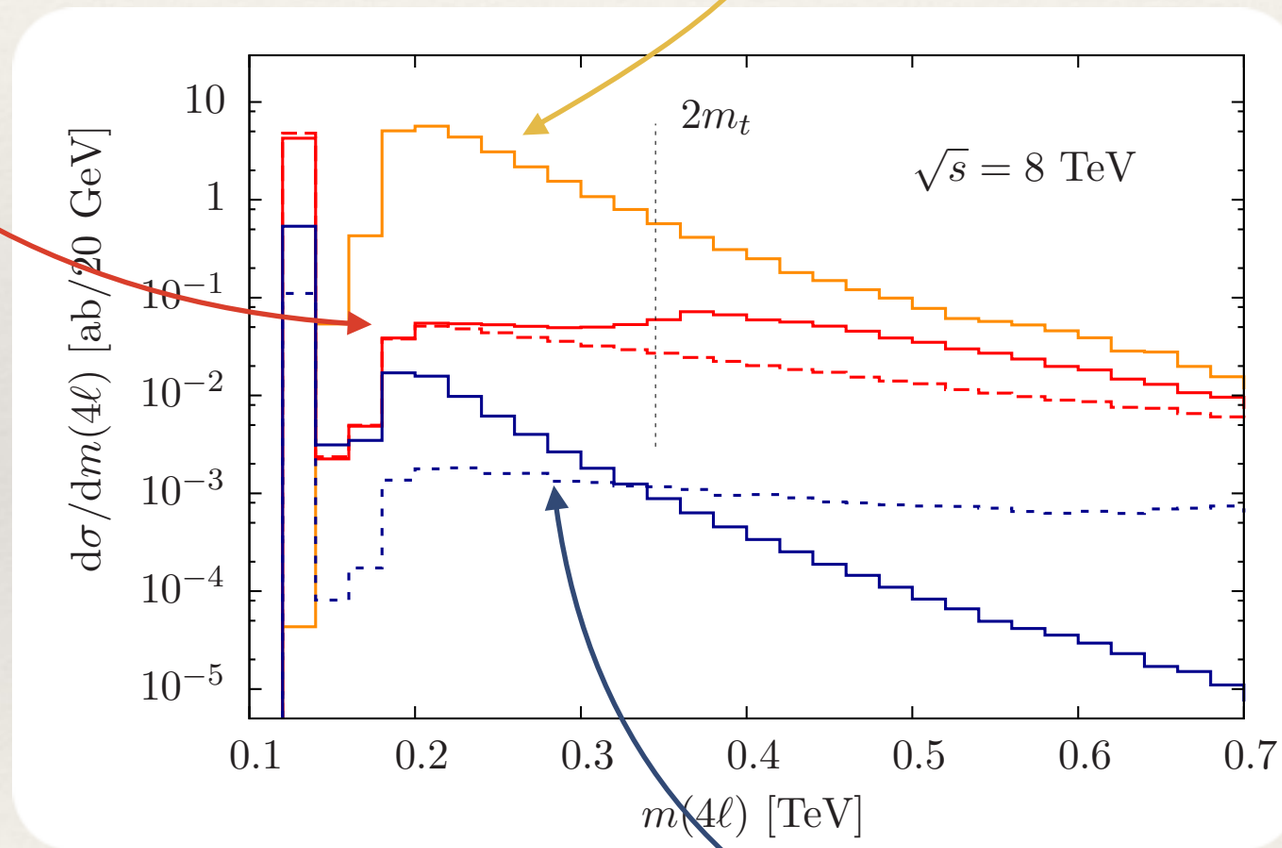
$$\Gamma_h > \Gamma_h^{\rm SM}, \quad \sigma \times {\rm BR} \simeq [\sigma \times {\rm BR}]^{\rm SM} \iff g_{ggh} g_{hZZ} > [g_{ggh} g_{hZZ}]^{\rm SM} \iff \overline{\sigma} > \overline{\sigma}^{\rm SM}$$

The total Higgs width

… is there a loophole?

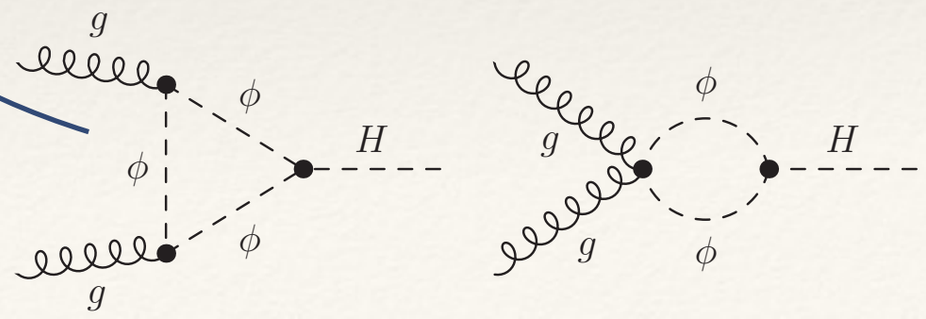






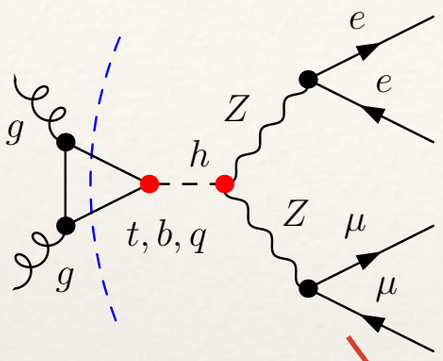
light (non-chiral) masses:

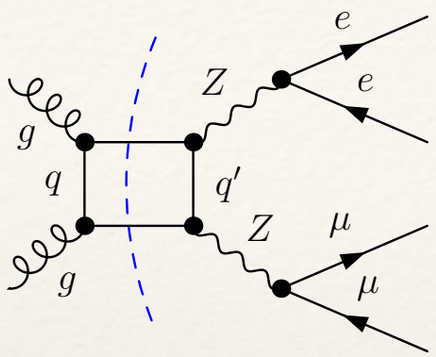
$$\mathcal{L} = |D_\mu \phi|^2 - m^2 \phi + \lambda |H|^2 |\phi|^2$$



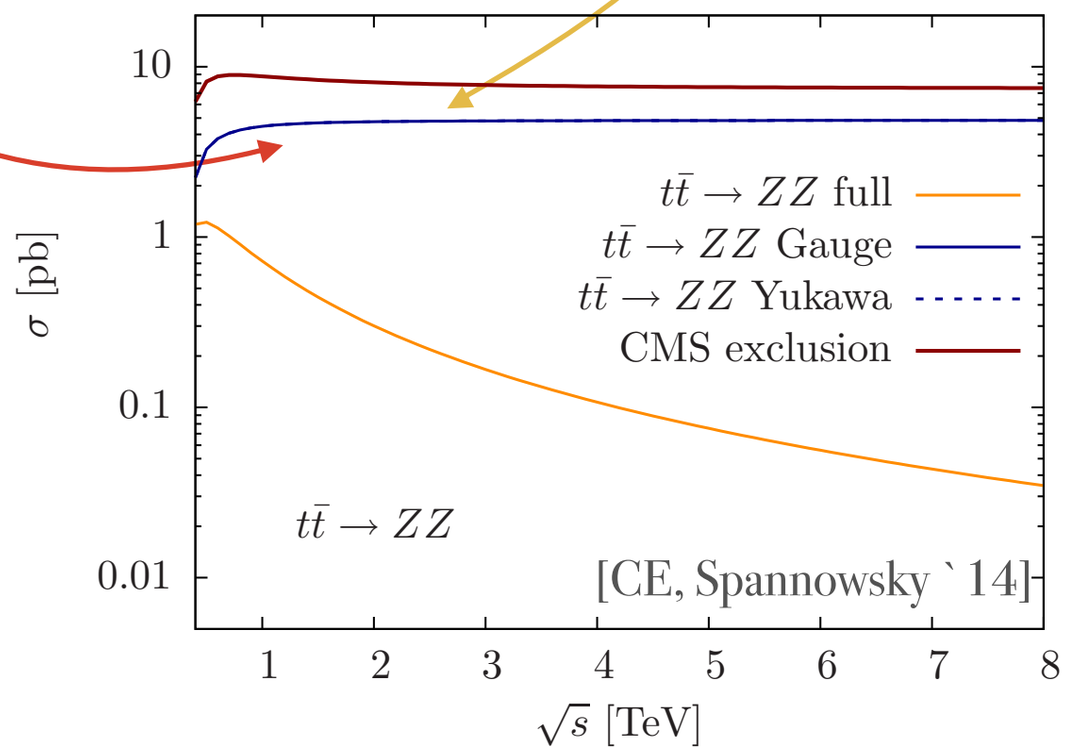
Higgs "off-shell" measurements

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





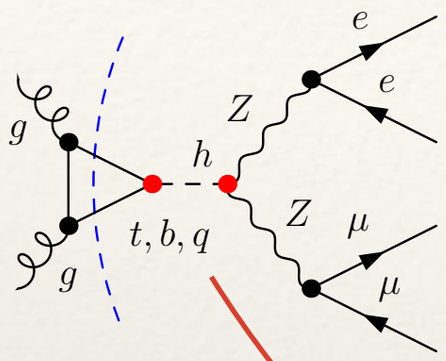
nested top scattering!

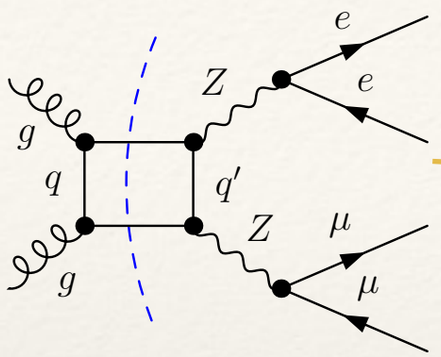


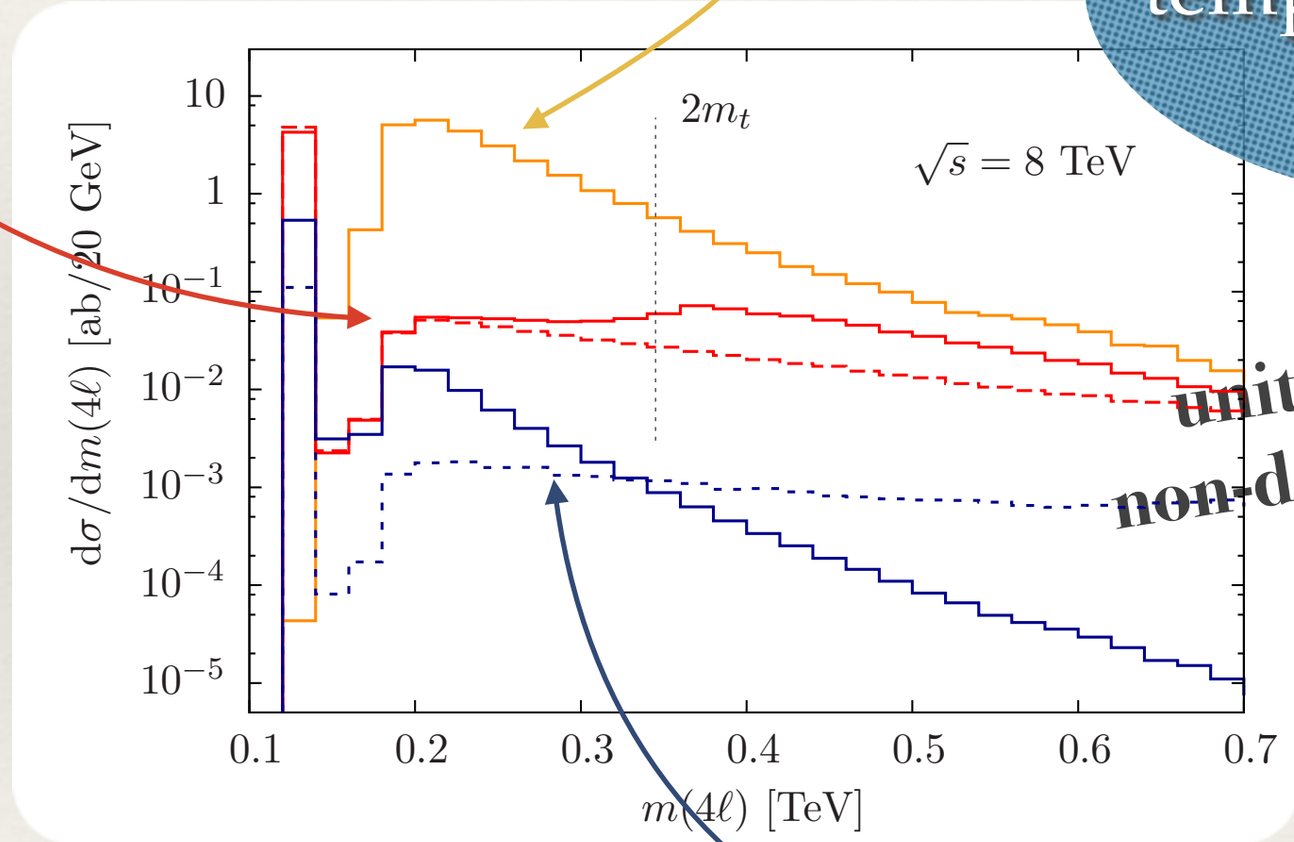
Naive and inconsistent rescaling arguments violate unitarity in the 100 GeV region where the measurement picks up the sensitivity. We constrain unphysical models.

Higgs "off-shell" measurements

…nonetheless rescaling arguments should not be a guiding principle!

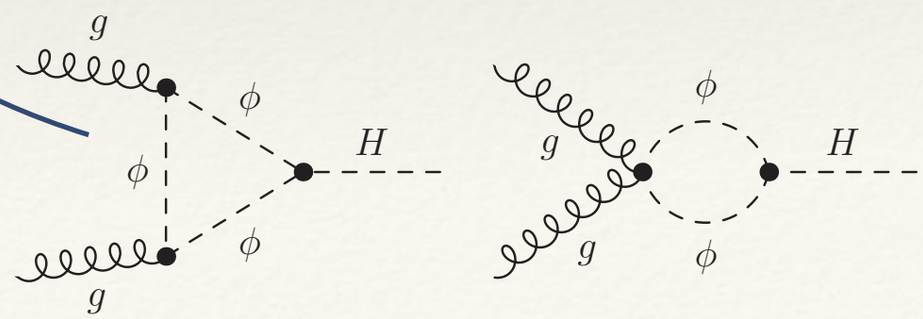






cannot template individual topologies!

unitarity & non-decoupling



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	$\simeq 1.0$	$\simeq 4.7$	$+80\%$
170 GeV	$\simeq 1.0$	$\simeq 1.7$	$+6\%$

- **cannot control loop contributions in QCD processes at hadron colliders**
- **width interpretation not possible in BSM scenarios without uniform convergence to the SM template, statistical pull always from σBR!**

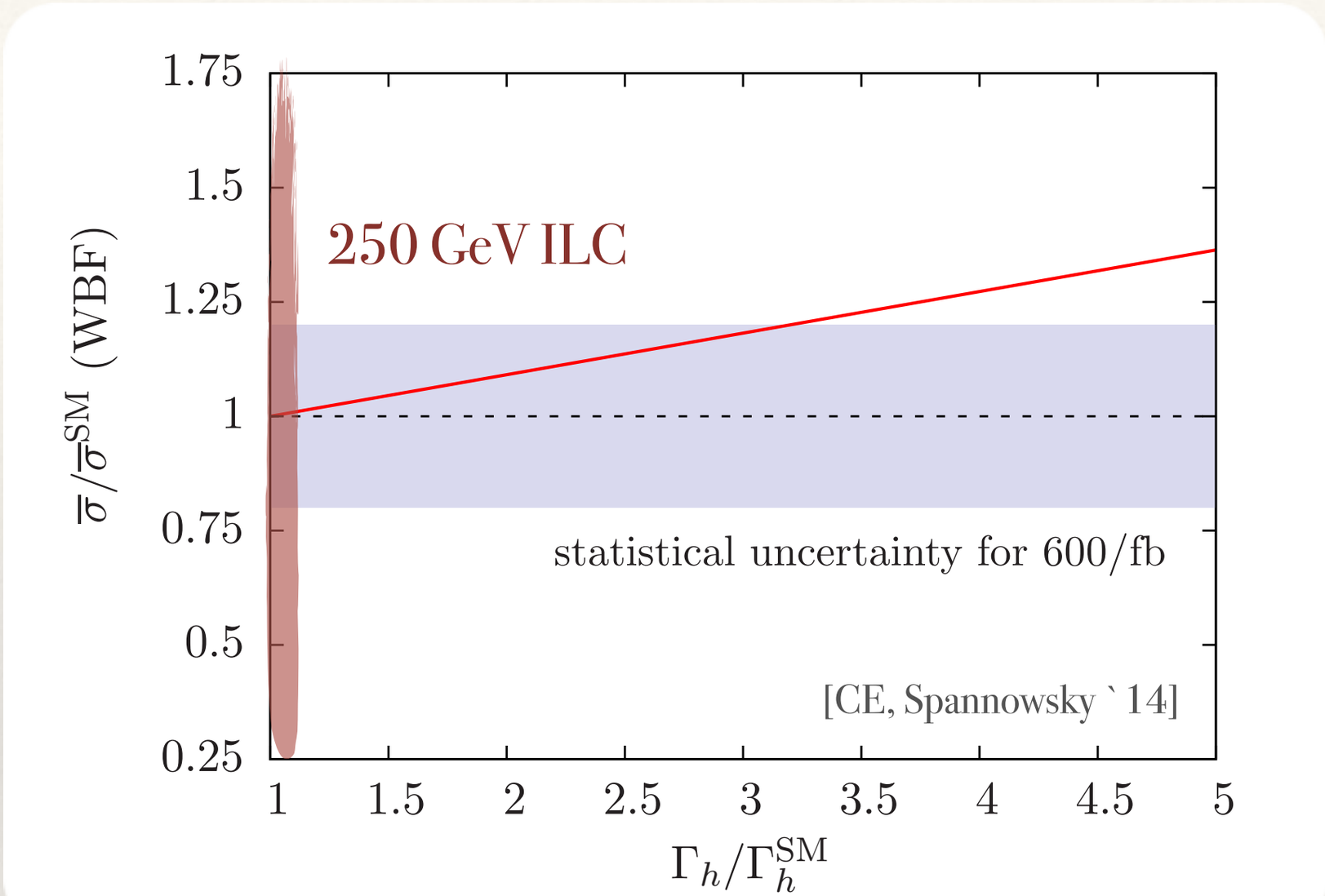
[CE, Spannowsky, Soreq ` 14]

- new contributions to continuum ZZ suppressed and bound to be small in light of electroweak precision constraints

- interpreted SM-like width measurement this analysis is not competitive: **2**-like WWh coupling and zero hidden width bias gave $\Gamma_{\rm H}<1.4\,\Gamma_{\rm H}^{\rm SM}$ already with very early data!

[Dobrescu, Lykken ` 14]

The total Higgs width

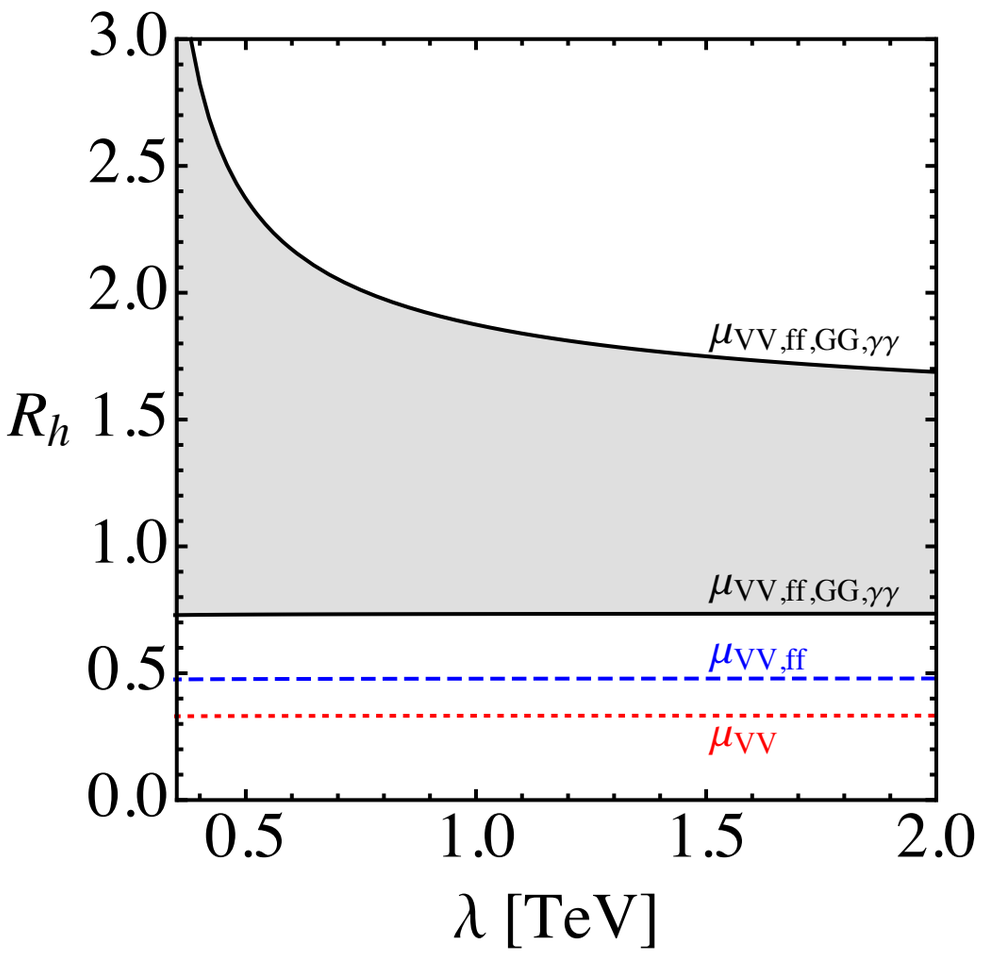


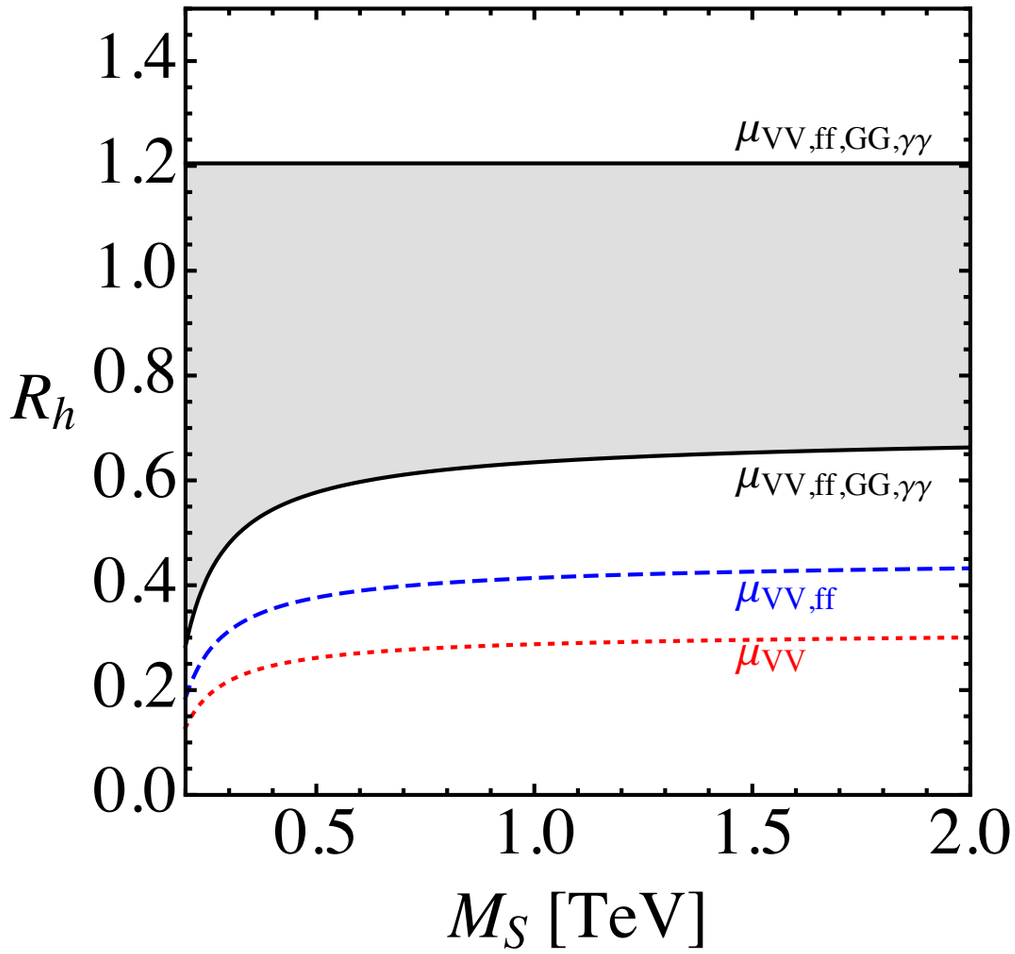
- **remove loop argument with WBF:** adapt to weak boson fusion + custodial isospin (small interference with GF, GF can be suppressed, H couplings to ZZ and WW directly reflect electroweak properties) [Kauer, Passarino `12]

LEP as a off-shell Higgs factory

[CE, McCullough, Spannowsky `15]

- in models that allow a width interpretation, we can use LEP measurements as an input to break the on-shell signal strength degeneracy
- "UV off-shell" measurement is replaced by "IR off-shell+UV sensitivity"





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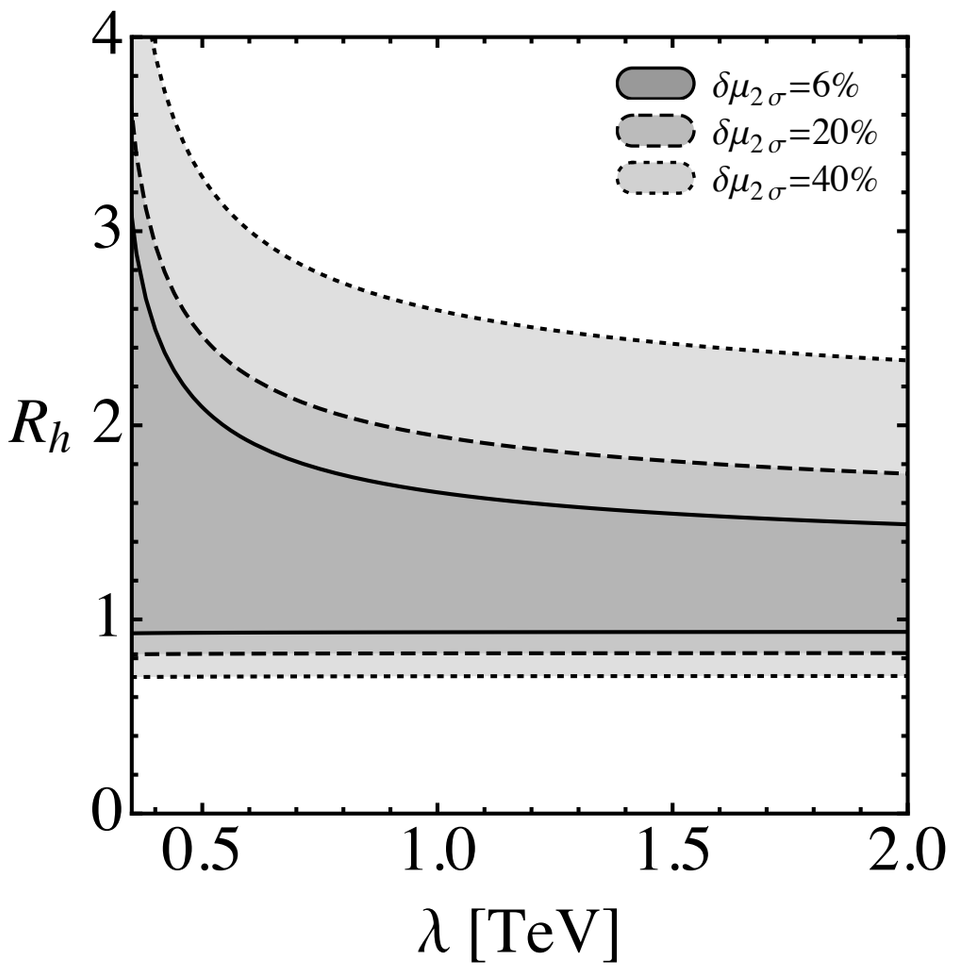
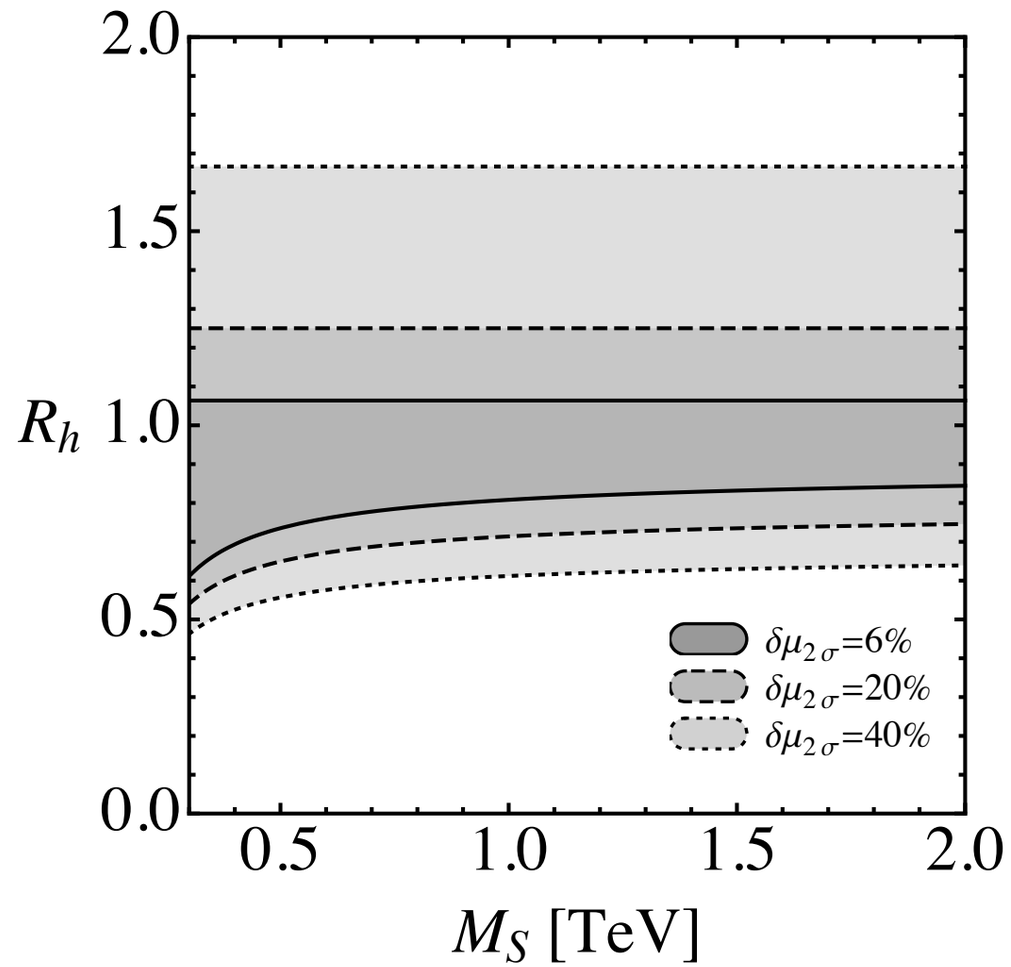




Guidelines for Run II and after

[following the HXSWG]

Is there evidence for new degrees of freedom?

No.

Yes.

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, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

concrete models

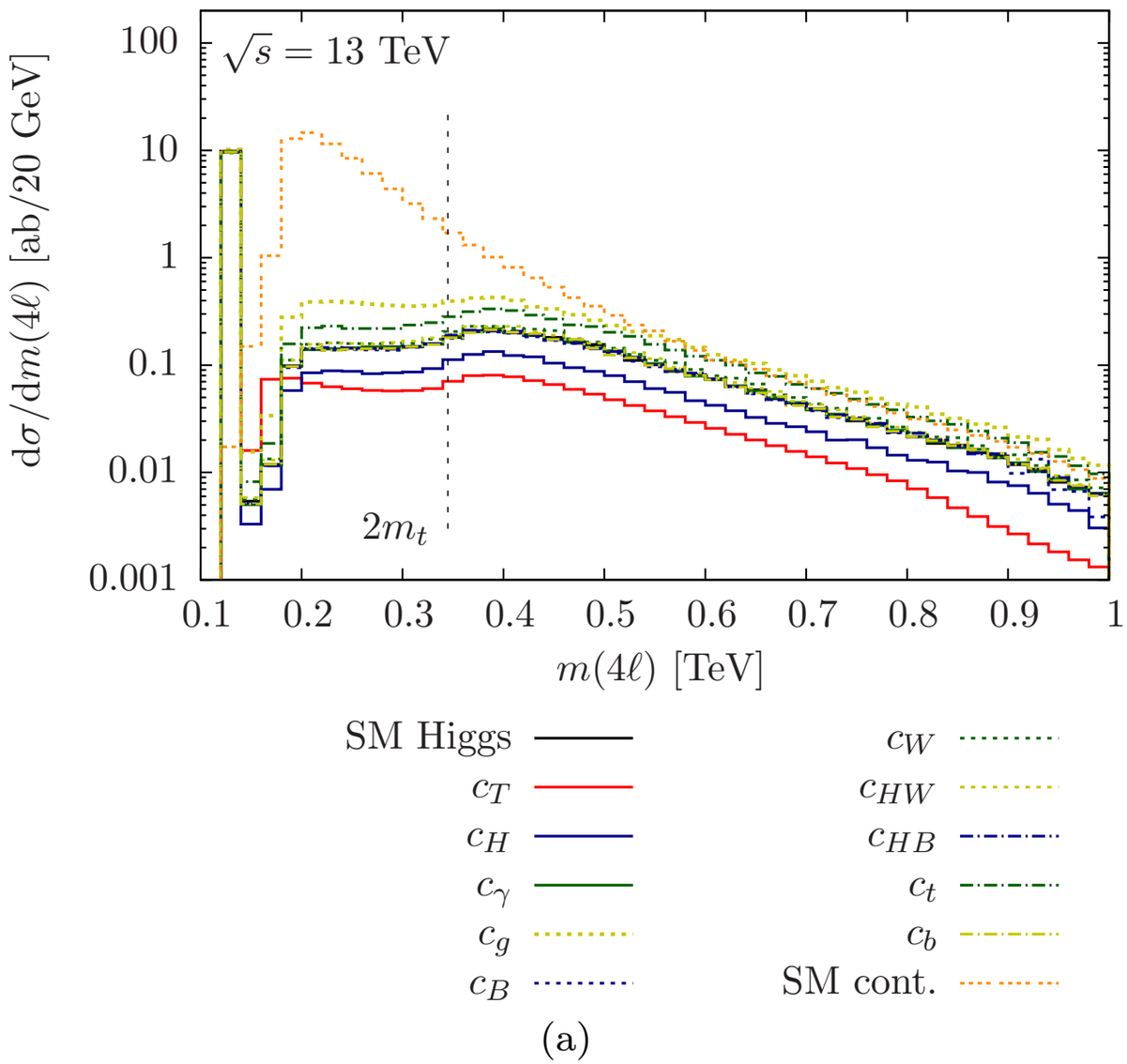
- **Higgs portals**
- (N)MSSM
- compositeness
- …

Guidelines for Run II and after

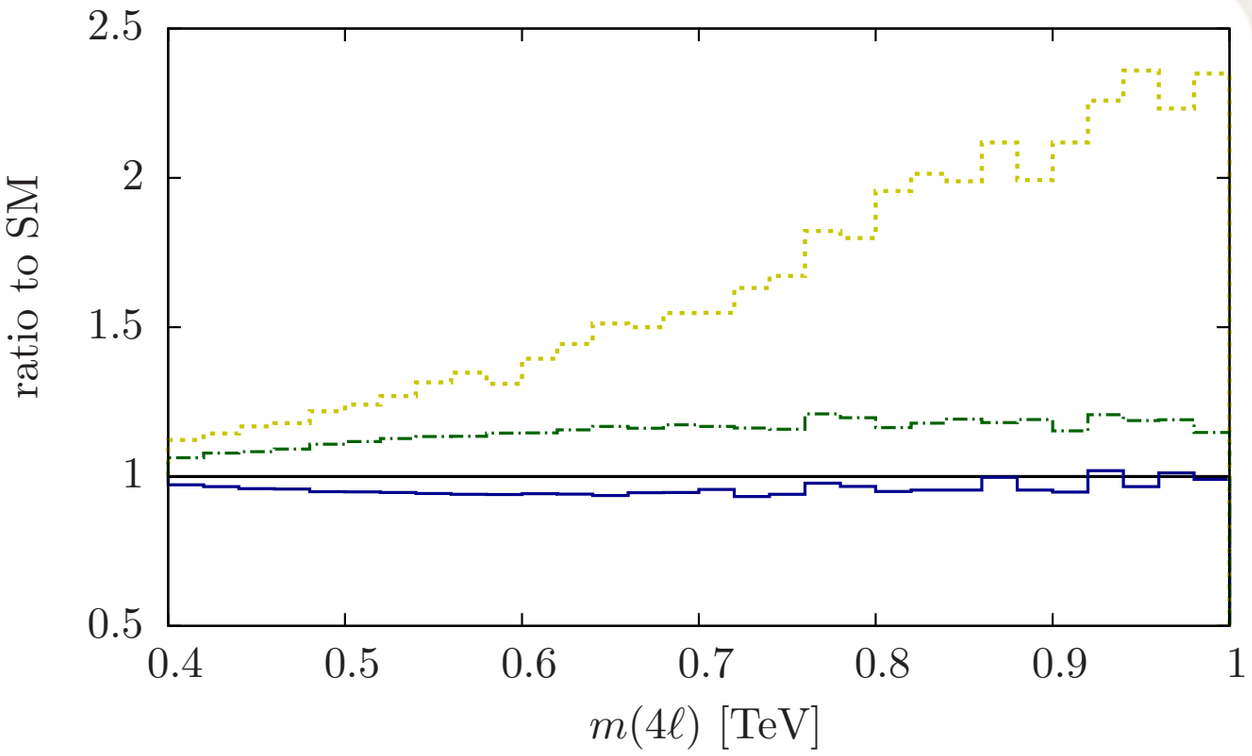
Higgs Effective Field Theory

[following the HXSWG]

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



(a)



(b)

[CE, Spannowsky, Soreq `14]

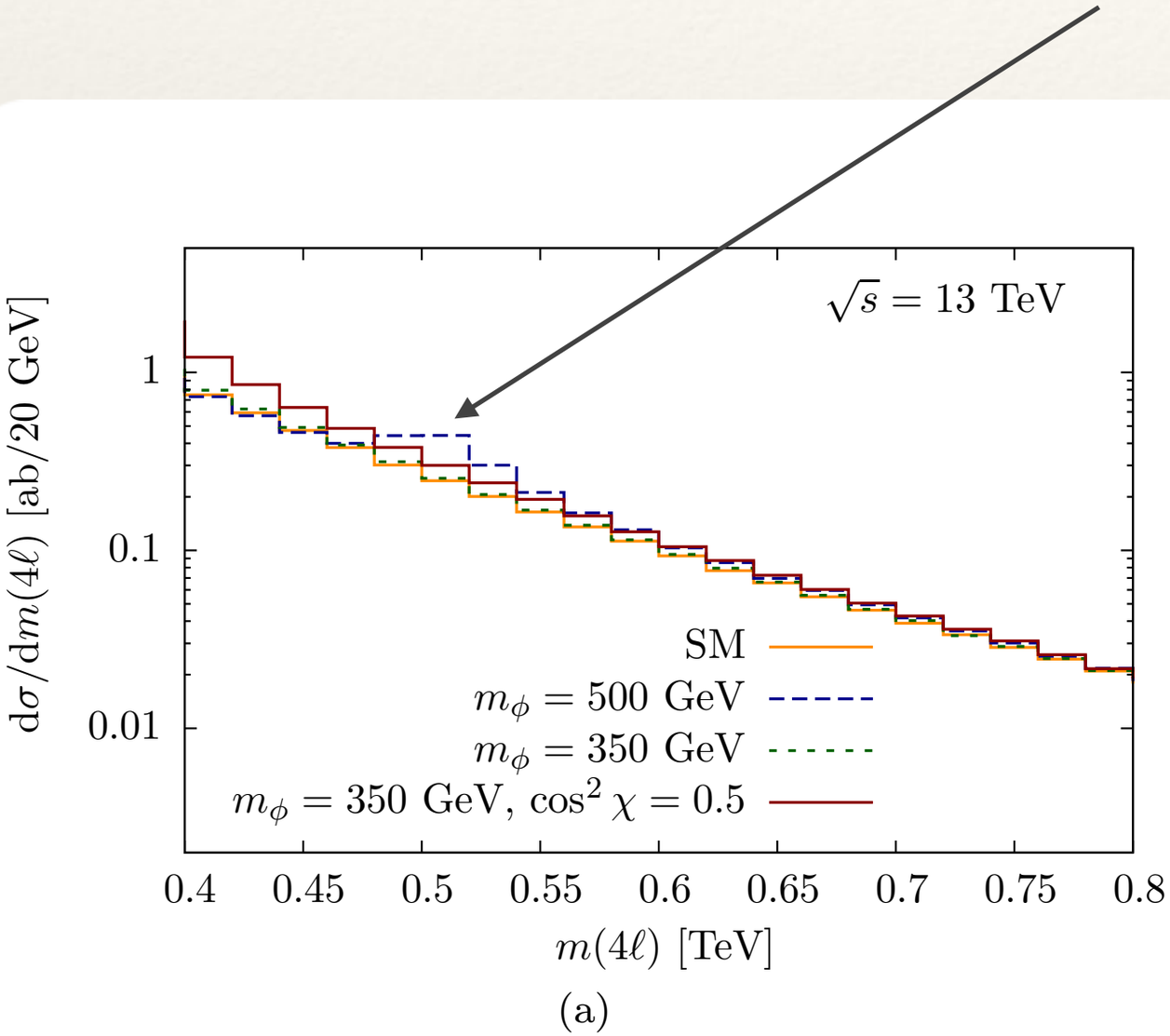
Guidelines for Run II and after

[following the HXSWG]

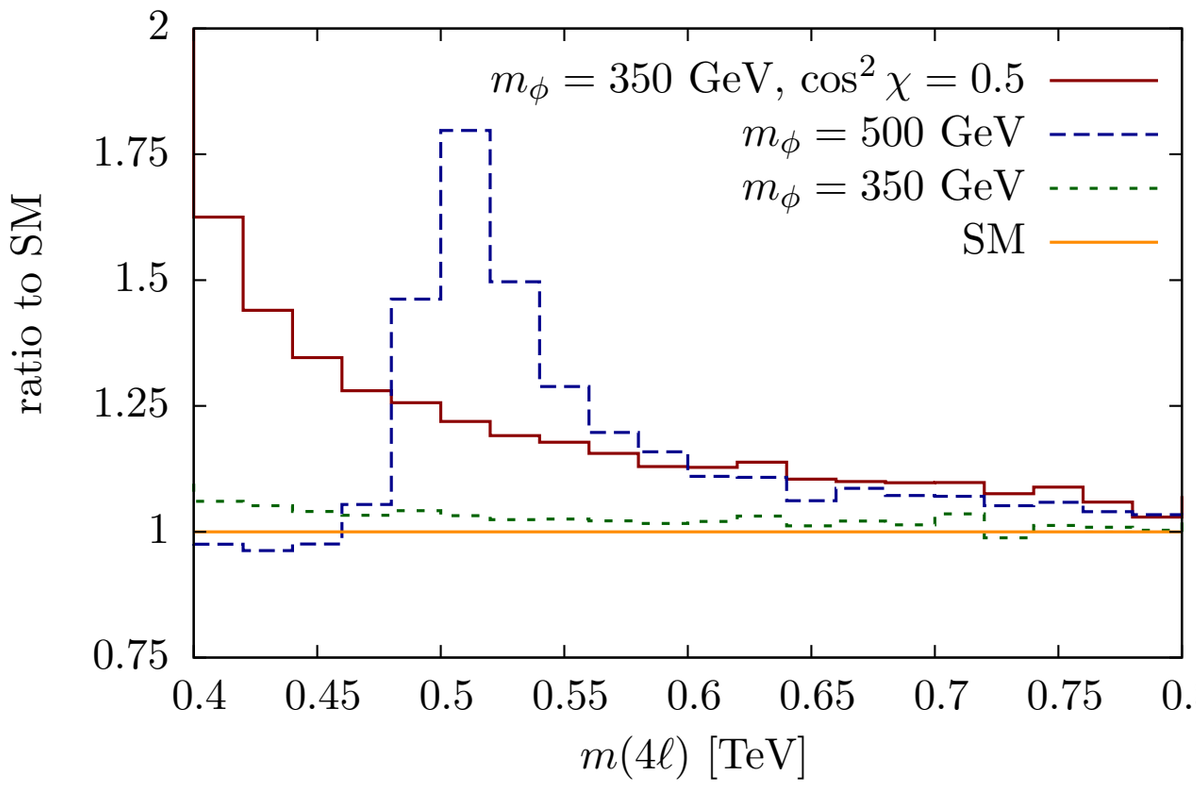
concrete models

- **extra Higgs-like states**

additional (wide) resonance in the TeV regime



(a)



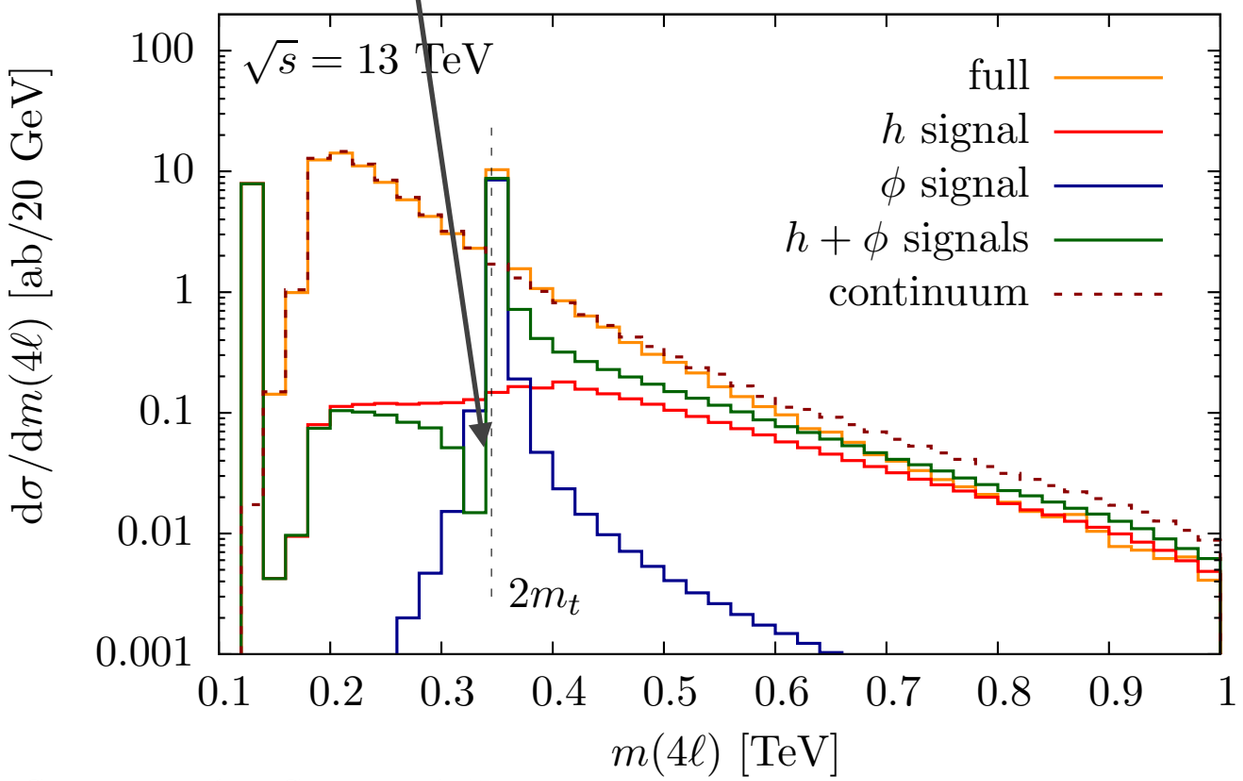
(b)

[CE, Spannowsky, Soreq `14]

Impact of width modelling

dip structure is sensitive to width and propagator modelling

how do we treat a systematic resummation in theory?



[CE, Spannowsky, Soreq `14]

(a)

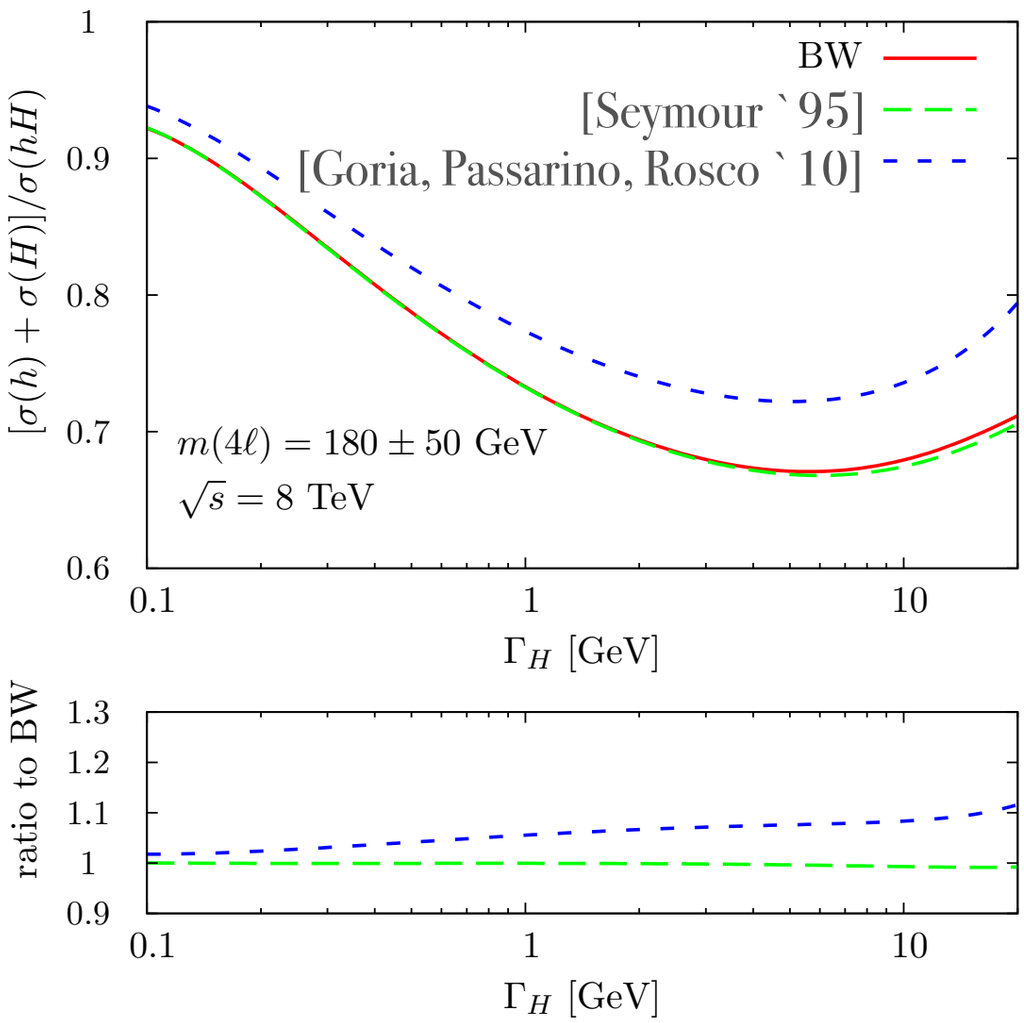
$$\Delta = \frac{i}{s - m^2 + im\Gamma_m}$$

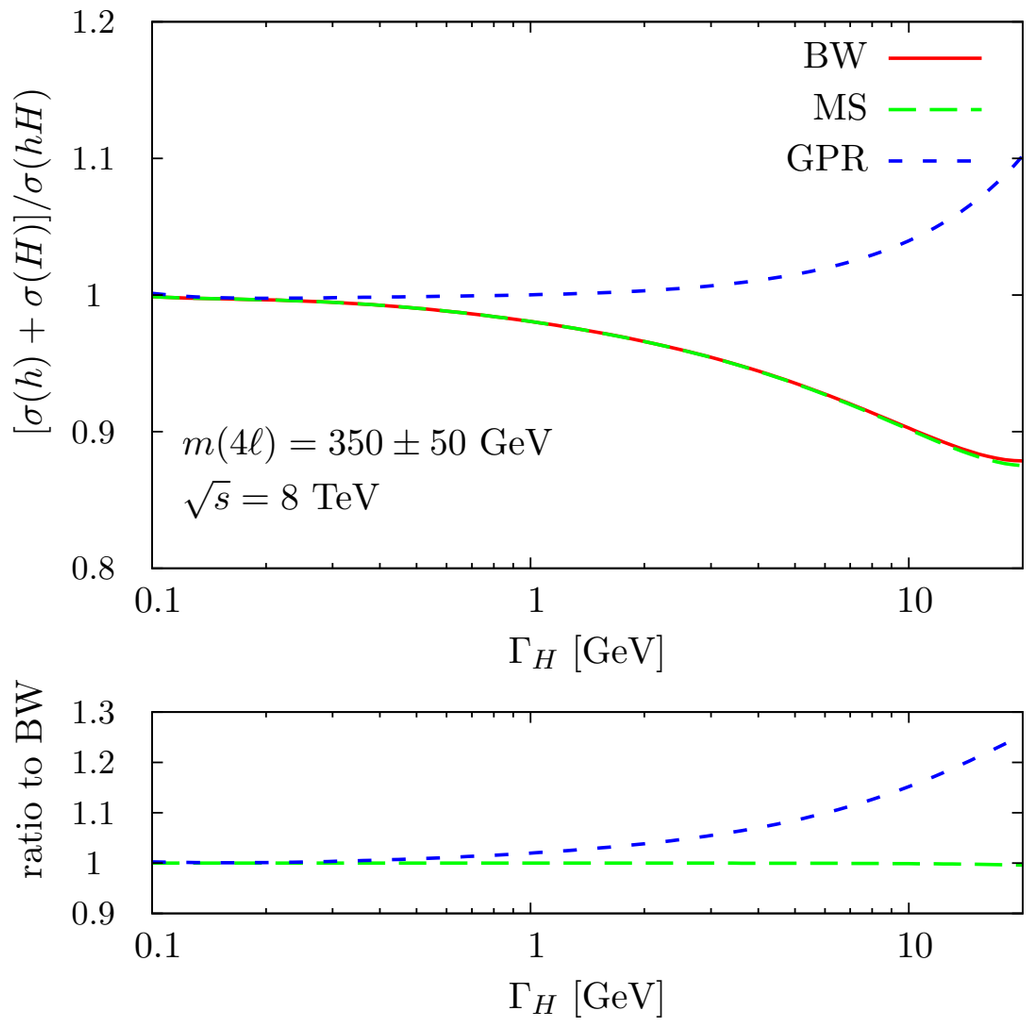
Impact of width modelling

dip structure is sensitive to width and propagator modelling

how do we treat a systematic resummation in theory?

[CE, Low, Spannowsky ` 15]

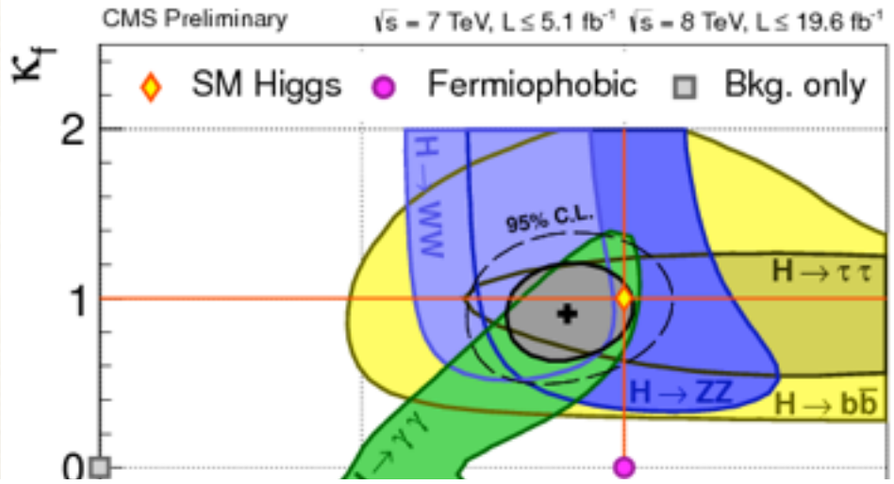




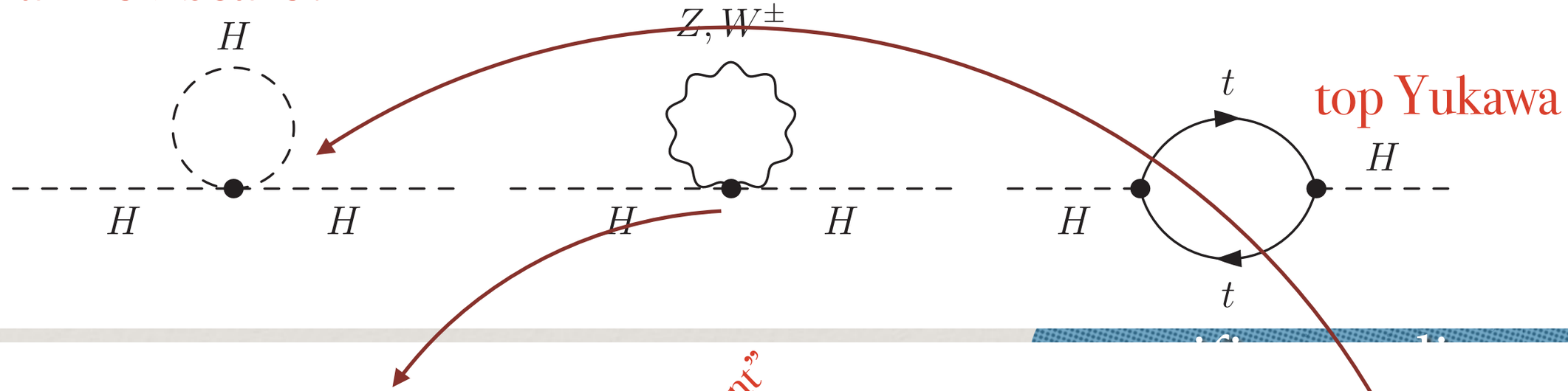
A bottom-up (B)SM Higgs programme

coupling measurements are determined by

1. unitarity



Natural TeV scale?



$$\mathcal{L}_H = (D_\mu H)^\dagger D^\mu H - V(\langle H\rangle) - V'(\langle H\rangle)(H - \langle H\rangle)$$

"unimportant"

$$= 0$$

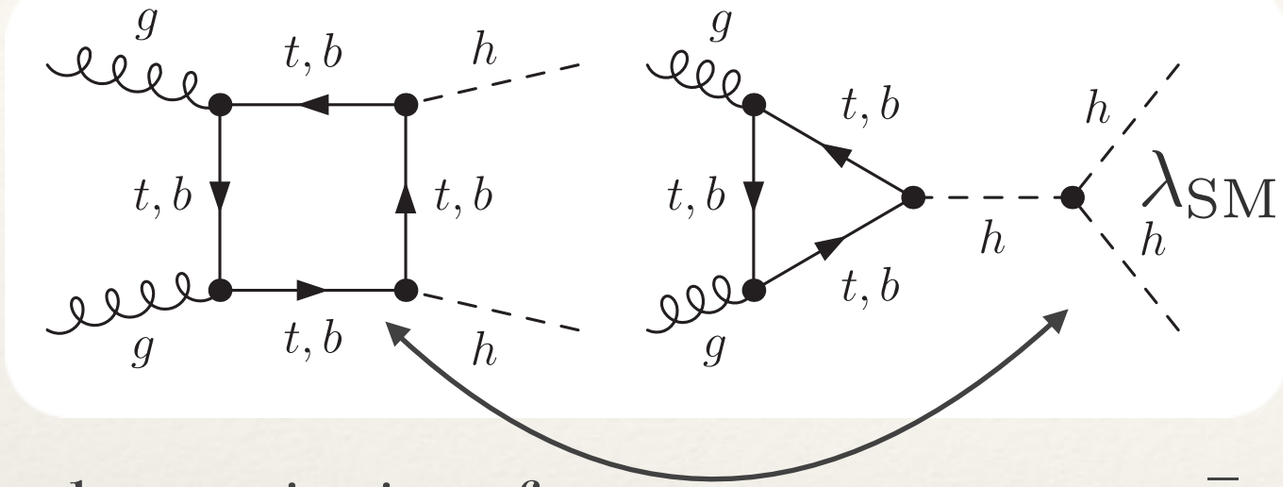
$$-\frac{1}{2}V''(\langle H\rangle)(H - \langle H\rangle)^2 - \ldots$$

$$\sim m_H^2$$

gauge-Higgs couplings ?

self-couplings ?

The Higgs trilinear coupling

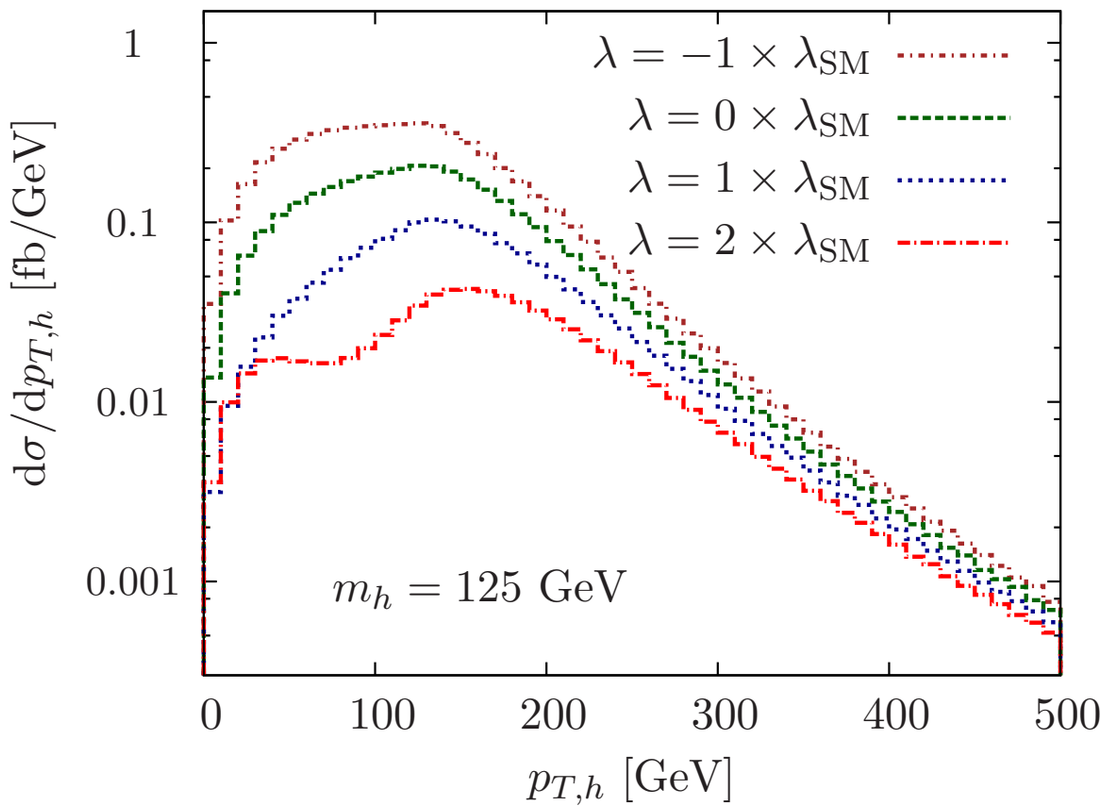


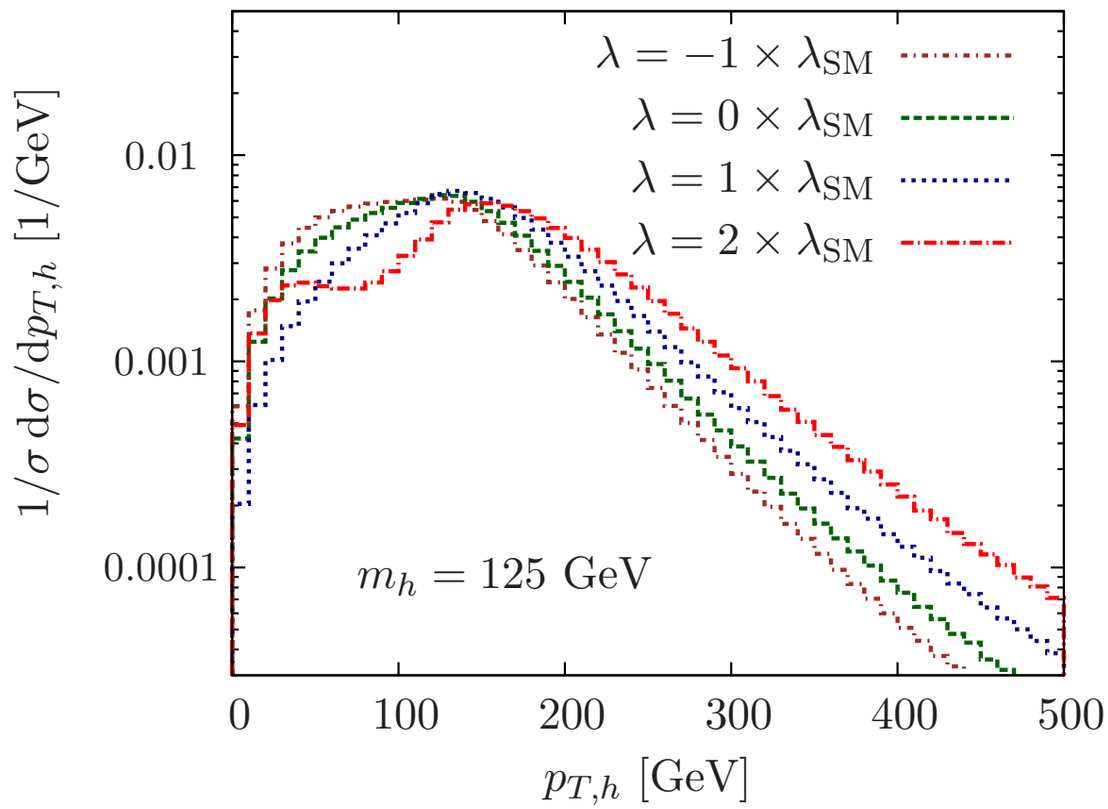
[Plehn, Baur, Rainwater `03]
[Dolan, CE, Spannowsky `12]
[Papaefstathiou, Yang, Zurita `13]
[Barr, Dolan, CE, Spannowsky `13]
[Dolan, CE, Greiner, Spannowsky `13]

destructive interference
sensitive to modifications of

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

[ATLAS PHYS-PUB 2014-19]



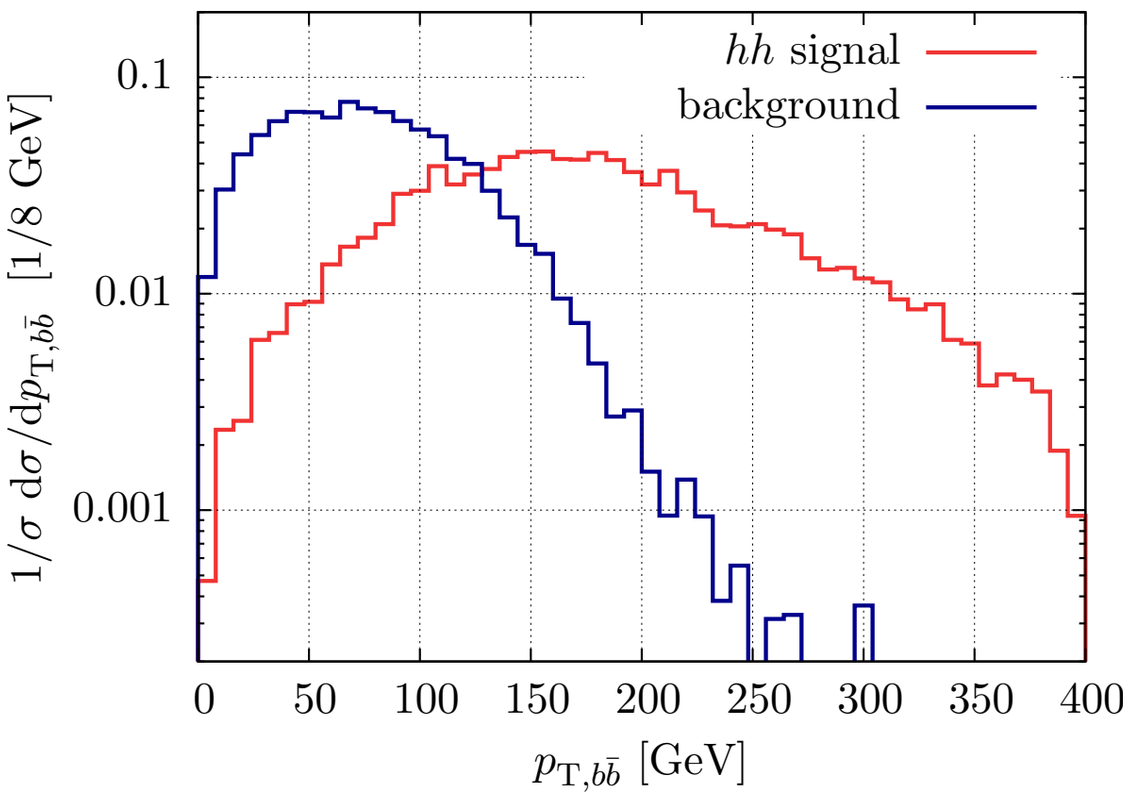


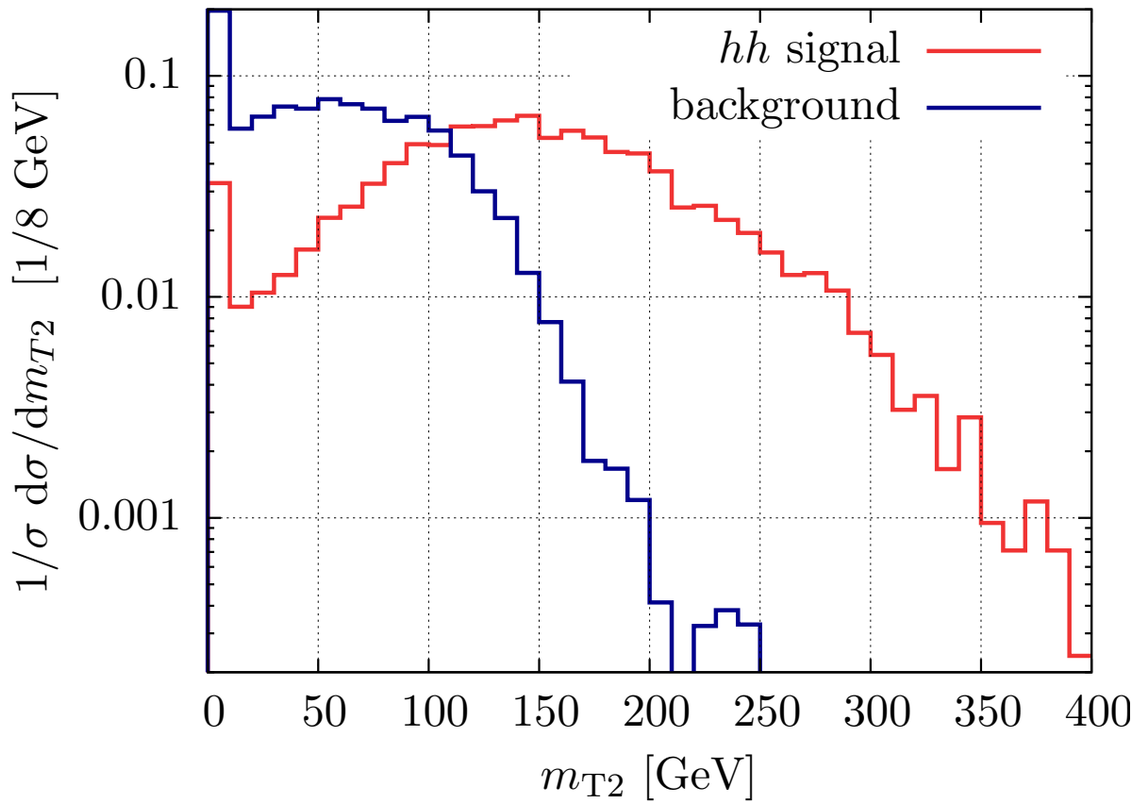
The Higgs trilinear coupling

- large backgrounds, small signal, but feasible in $b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$?
- boosted regime unavoidable for $b\bar{b}\tau\tau$
- use complementarity of MT2 to tackle $t\bar{t}$

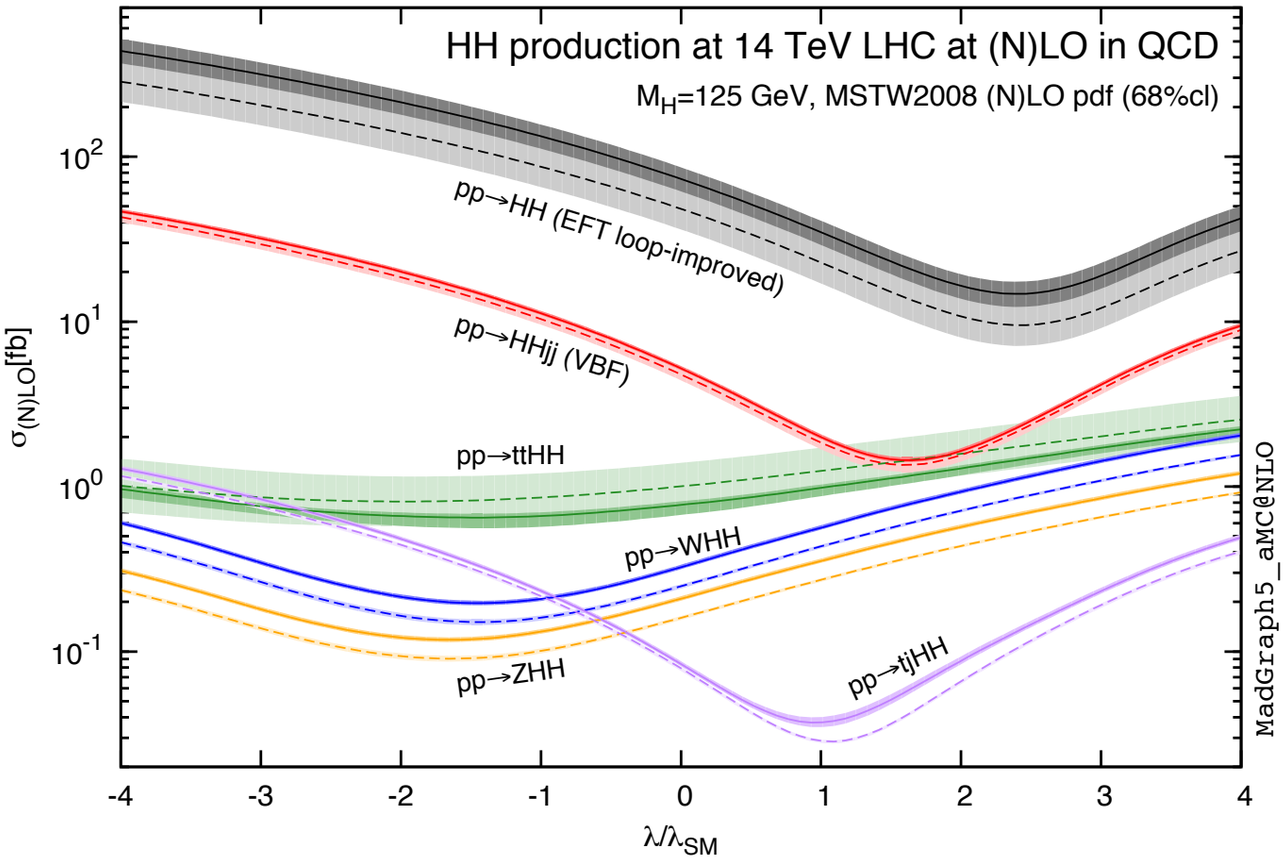
[Dolan, CE, Spannowsky `12]
[Barr, Dolan, CE, Spannowsky `13]
[Dolan, CE, Greiner, Spannowsky `13]

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





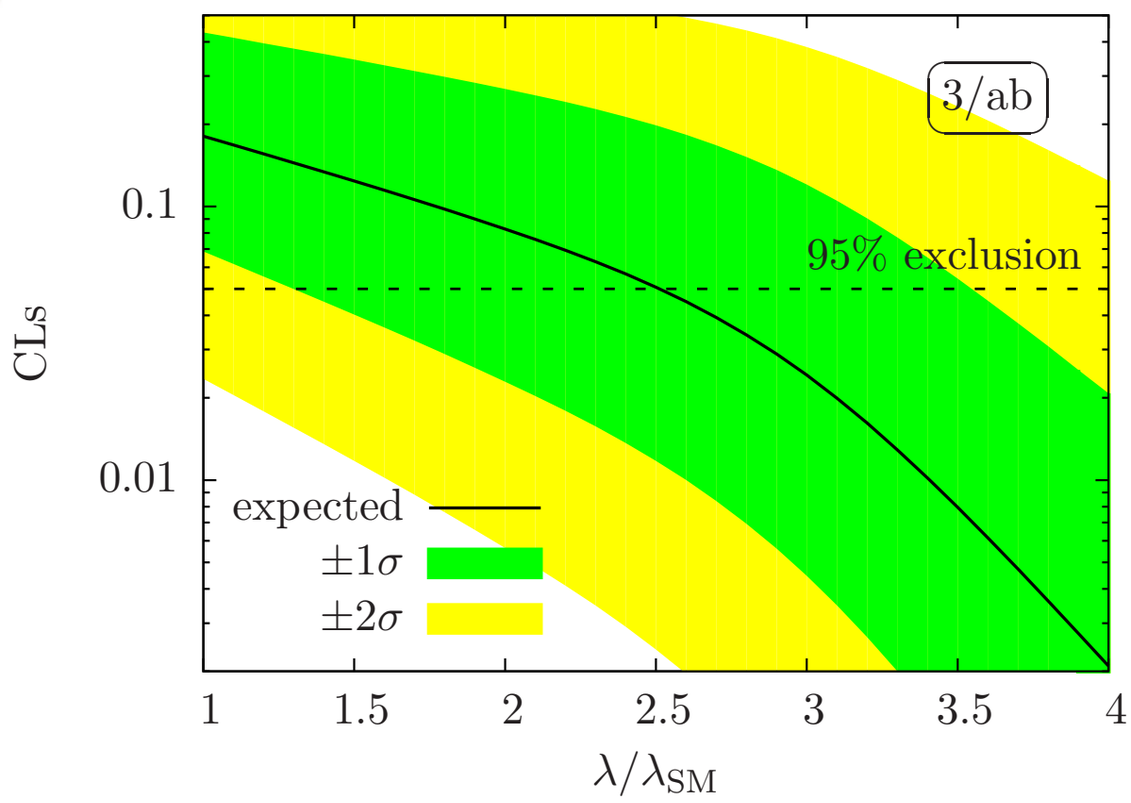
The Higgs trilinear coupling



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

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

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

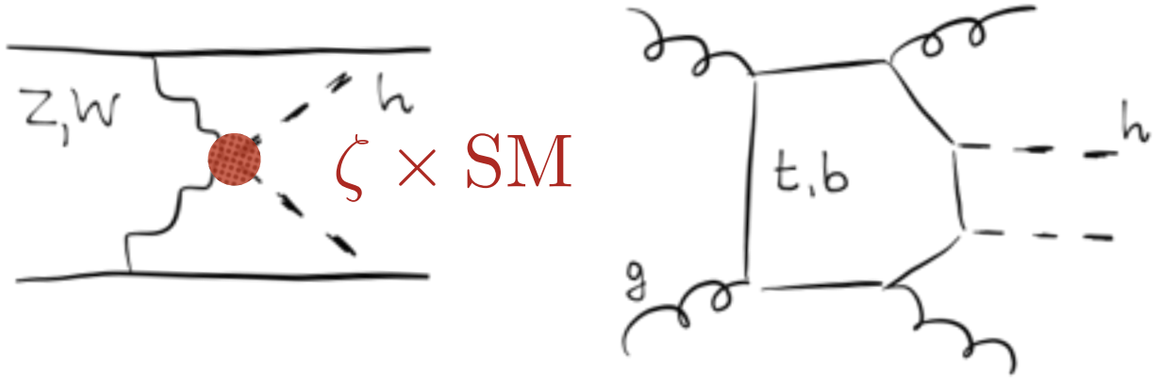


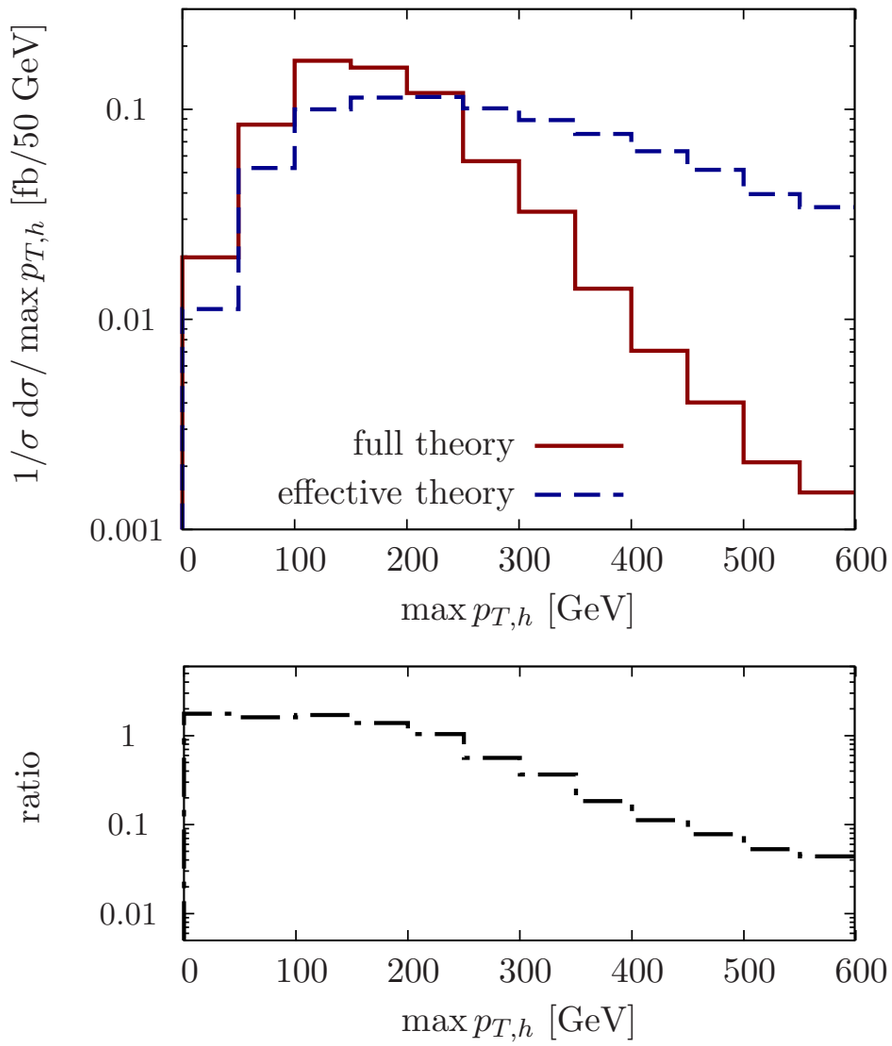
[CE, Krauss, Spannowsky, Thompson `14]

The Higgs quartic gauge couplings

- directly accessible in WBF $pp \to hhjj$, $\mathcal{O}(\text{fb})$ cross section

[Figy `08]
[Baglio, Djouadi, Gröber et al. `13]





[Dolan, CE, Greiner, Spannowsky` 13]

- gluon fusion contribution beyond EFT is **key to this channel,** legacy of trilinear!

$b\bar{b}\tau\tau$	Signal with $\zeta \times \{g_{WWhh}, g_{ZZhh}\}$			Background	
	$\zeta = 0$	$\zeta = 1$	$\zeta = 2$	$t\bar{t}jj$	Other BG
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
Higgs rec. from b jets	0.321	0.016	0.207	7.444	0.303
2 tag jets/re-weighting	0.184	0.010	0.126	5.284	0.236
incl. GF after cuts/re-weighting	0.273	0.099	0.214	5.284	0.236

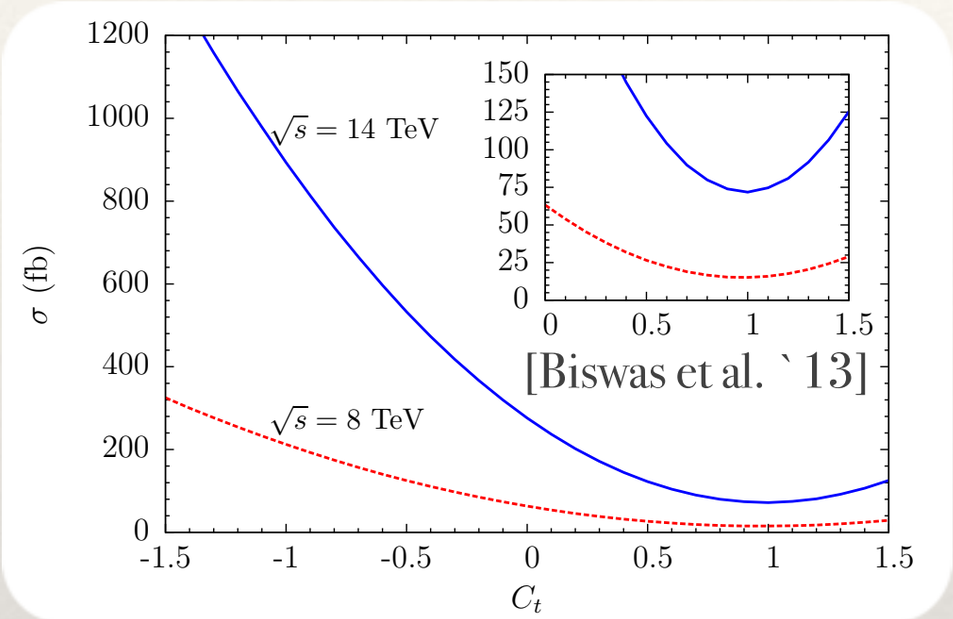
[Dolan, CE, Greiner, Spannowsky` 13]

1/50...but can be improved significantly... **1/4**

[Dolan, CE, Greiner, Nordstrom, Spannowsky in prep.]

model-independent top-Yukawa constraints

- of course $t\bar{t}h$ production [Plehn, Salam, Spannowsky `10] [Soper, Spannowsky `12,`14] [Artoisenet et al. `13]
- but also thj production [Farina et al. `12] [Biswas et al. `13] [Ellis et al. `13]



- angular observables!

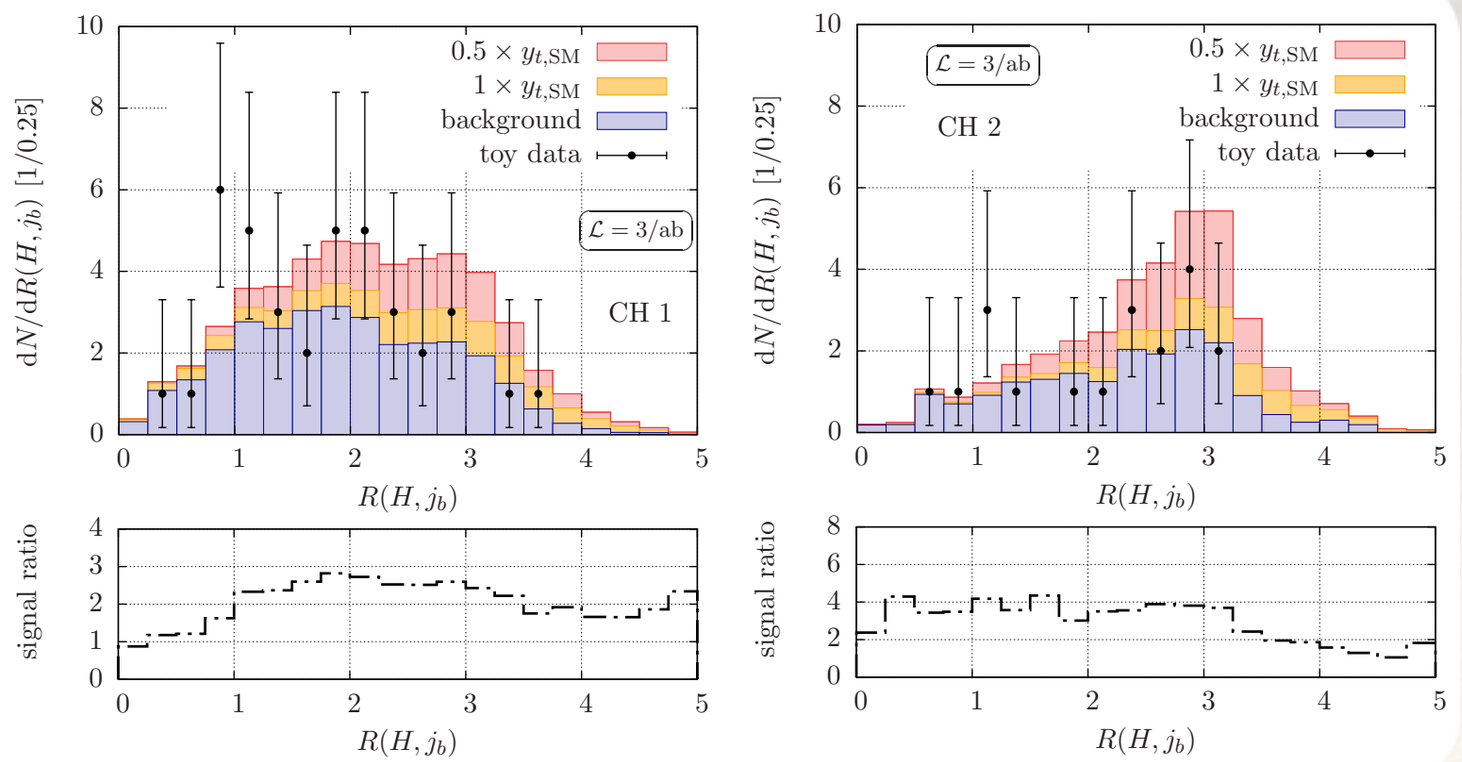
[CE, Re `14]

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

- cross sections are small but highly sensitive through interference

[Fisher, Becker, Kirkby `95]

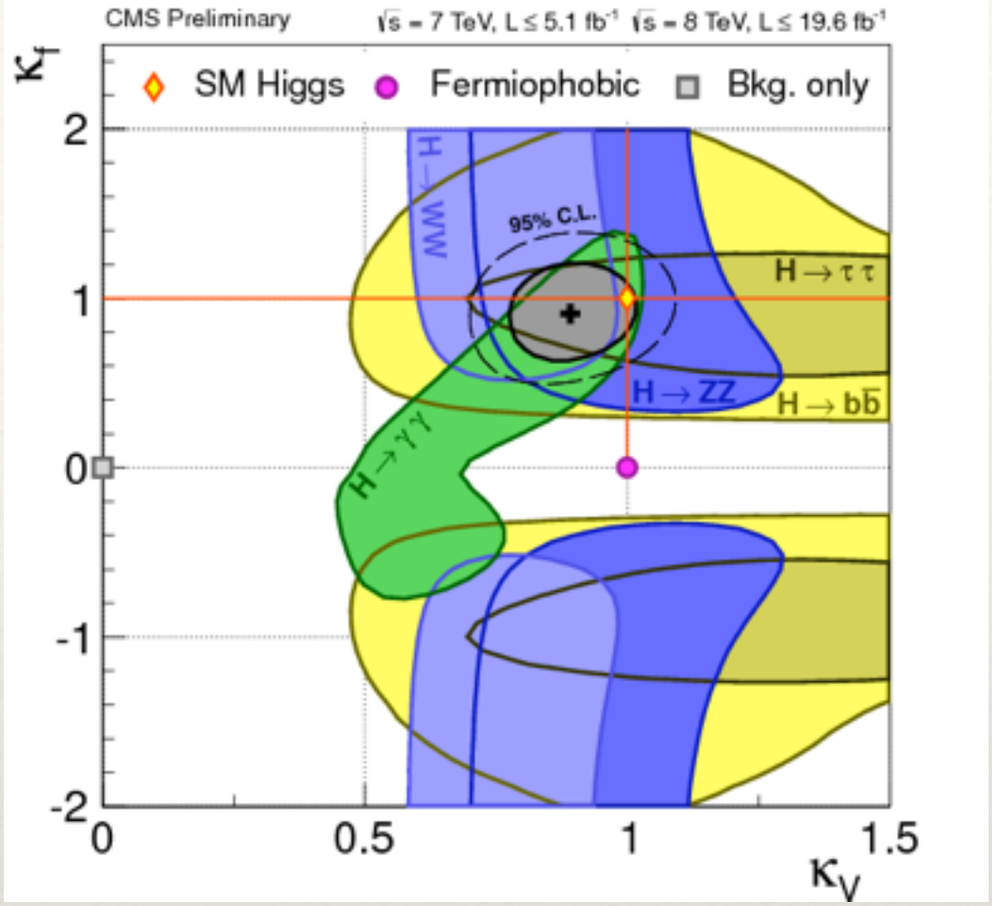
- *somewhat* reminiscent of radiation zeros in $W^{\pm}\gamma \rightsquigarrow \Delta y(tH) \sim 0$



A bottom-up (B)SM Higgs programme

coupling measurements are determined by

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

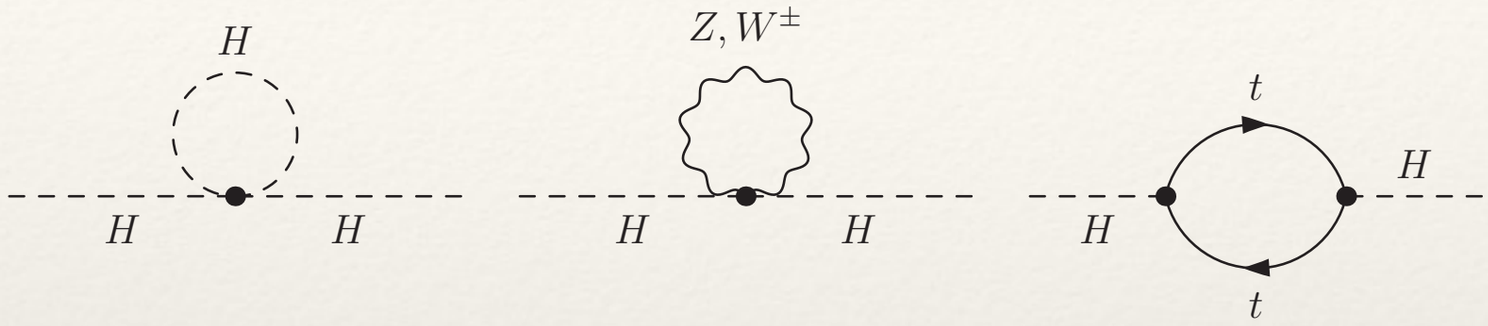


similar analyses by [Ellis, You `12]
[Masso, Sanz `12]
[Carmi, Falkowski, Kuflik, Volansky `12]
[Klute, Lafaye, Plehn, Rauch, Zerwas `12]
[Corbett, Eboli, Gonzalez-Fraile, et al. `12]
[Espin[illegible] Trott `12]

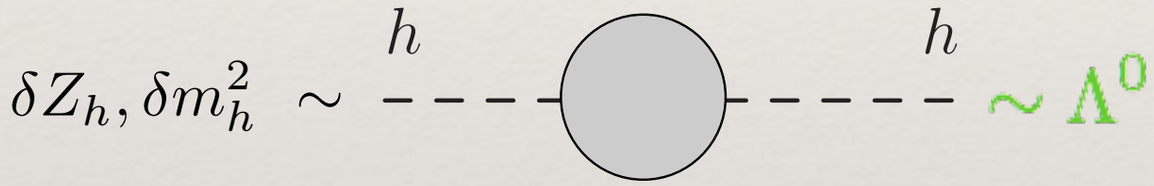
naturalness
leaving footprints?

Higgs couplings: a probe of naturalness

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



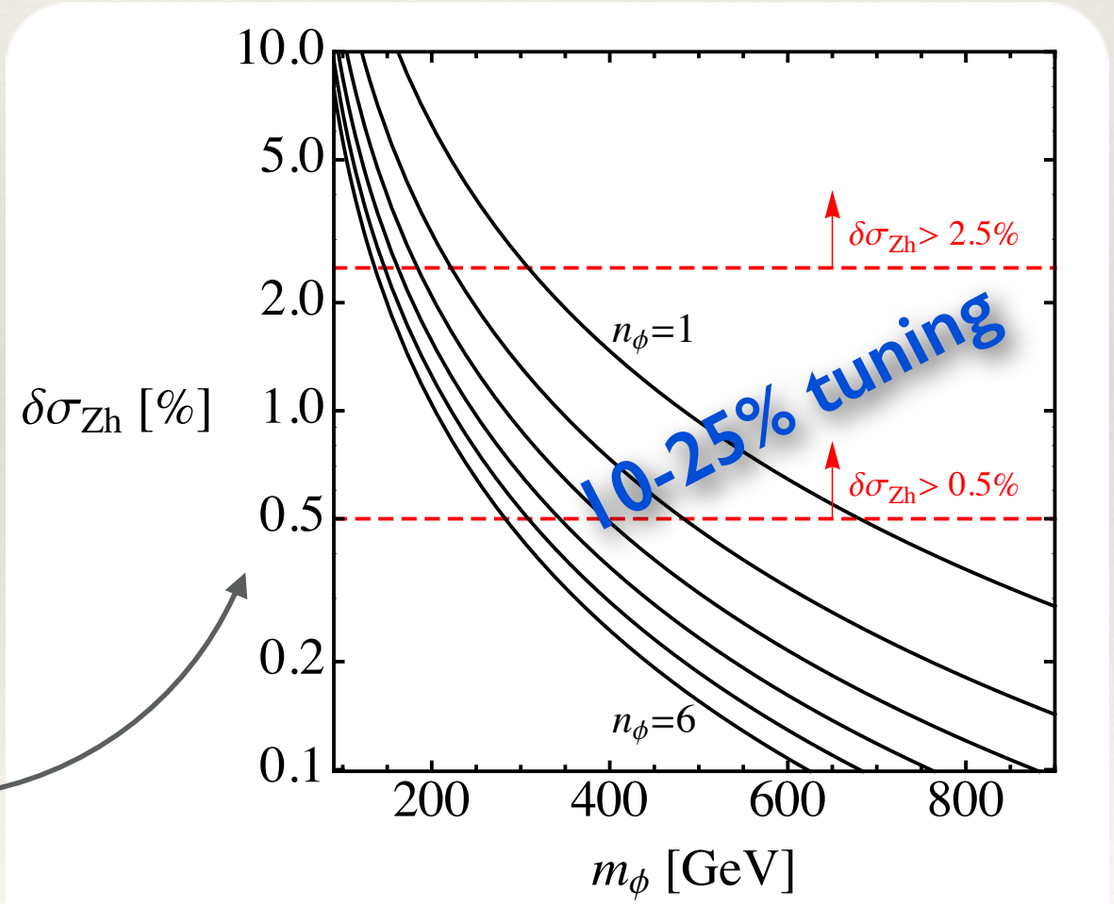
- don't forget the B_0 functions !



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

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

250 GeV linear collider
full EW corrections



[Craig, CE, McCullough `13]

Summary & Conclusions

- The Higgs sector and the Higgs interactions are the best places to look for BSM physics, there's a lot left to do
- **run II** & HL-LHC will give us more insights into the SM-likeness of the Higgs
  - exploit interference-induced sensitivity in fully differential measurements
  - high momentum transfers with reasonable statistics
  - more sensitive new resonance searches
  - there is already a case for 250 GeV linear collider for Higgs spectroscopy! (→ width & naturalness)