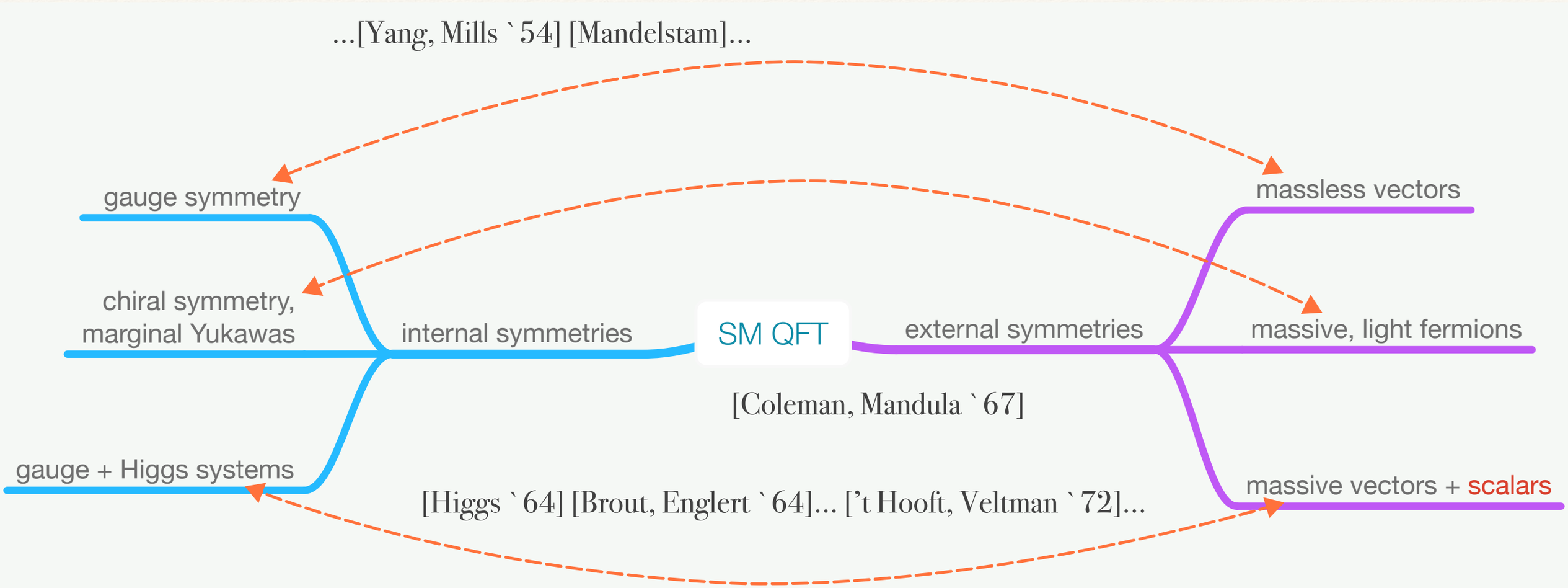
*Christoph Englert*

# Higgs phenomenology: An opportunity for new physics

*NCTS Annual Theory Meeting*

*12/12/2019*

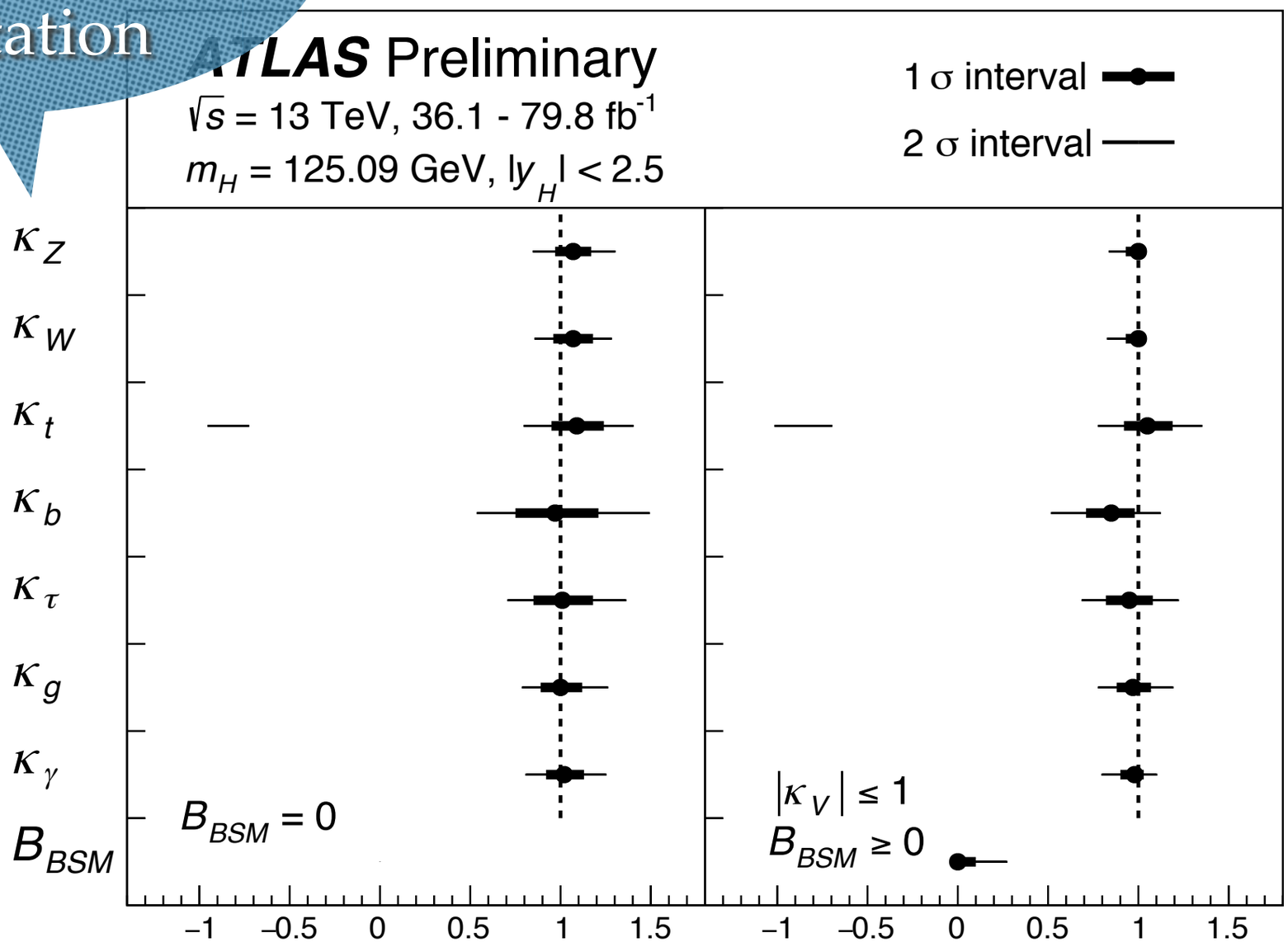
# The Standard Model: taking stock




"What's next ?"

# Status of LHC measurements

Higgs coupling/SM expectation




[ATLAS `18]

☛ lack of CP violation, hierarchy,.... Where's the new physics?

# Status of LHC measurements

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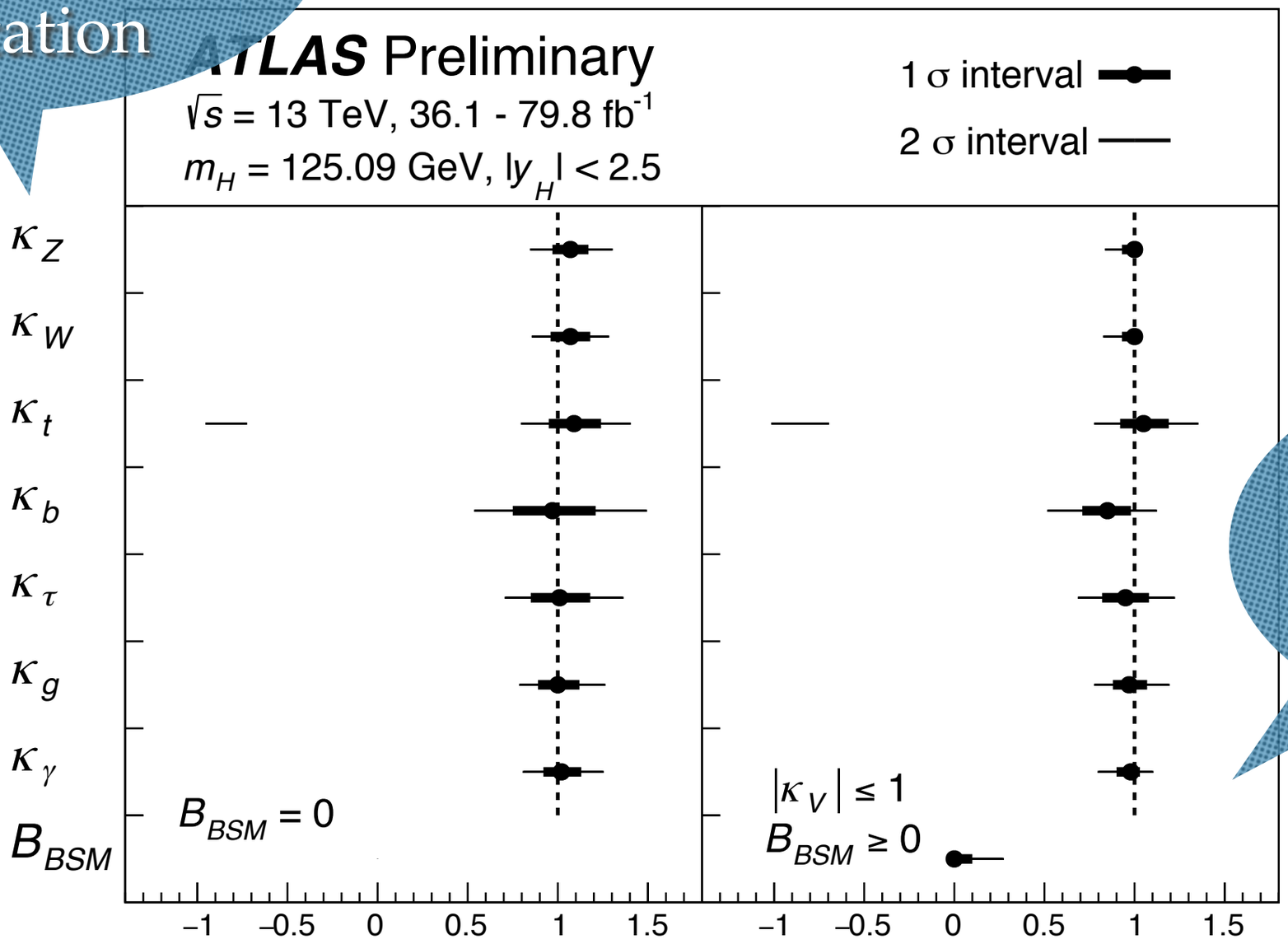


[ATLAS `18]

Higgs self-coupling missing...

☛ lack of CP violation, hierarchy,.... Where's the new physics?

# Higgs physics as a probe of (B)SM physics

- Can Higgs phenomenology pinpoint BSM solutions?

**Why have we not seem them yet?**

**New Physics Benchmarking for 3/ab**

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**Why have we not seem them yet?**

**New Physics Benchmarking for 3/ab**

Positive outcome depends on 3 ingredients

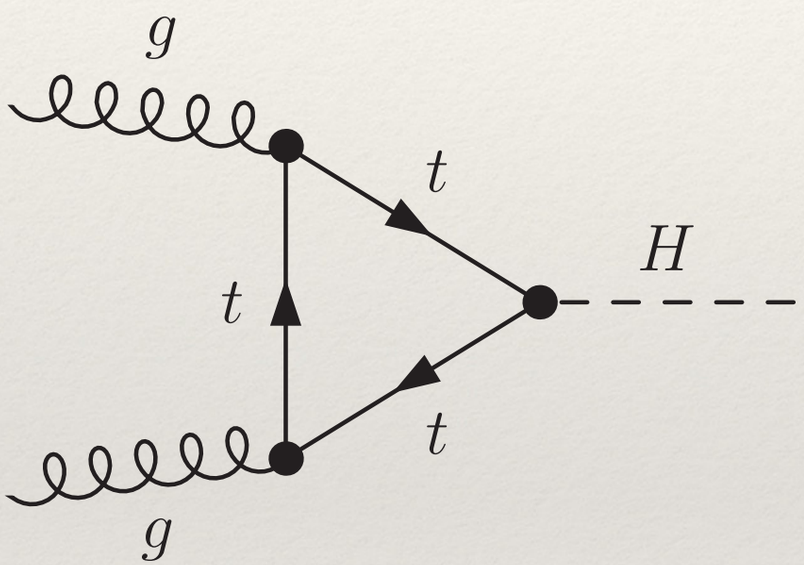
1. precision of Higgs coupling extraction
2. sensitivity of exotic Higgs searches
3. sensitivity to rare SM processes (e.g. di-Higgs)

**future collider roadmap**

# SM couplings

- Higgs coupling extraction is made difficult by “blind directions”
- one of the most prominent an relevant for Higgs physics

[Ellis et al. `76]
[Vainstein et al. `70]
....

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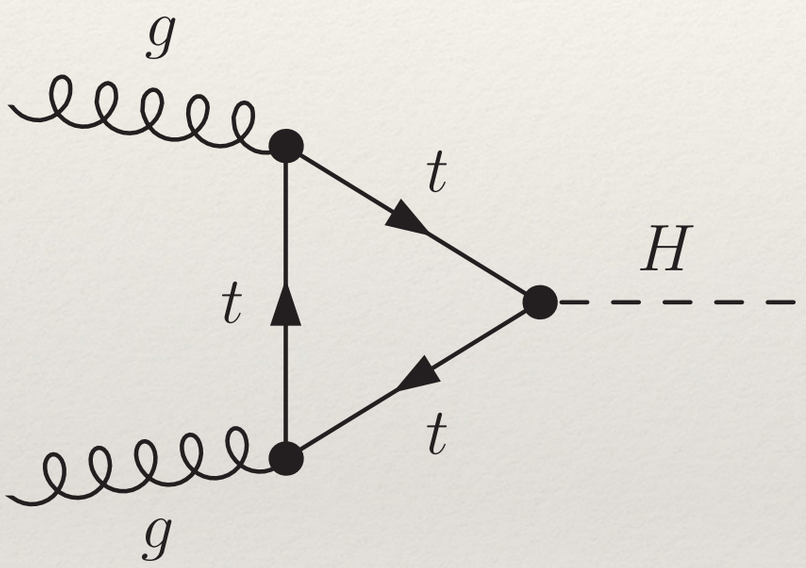



$$\xrightarrow{m_t \to \infty} \subset \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v}$$

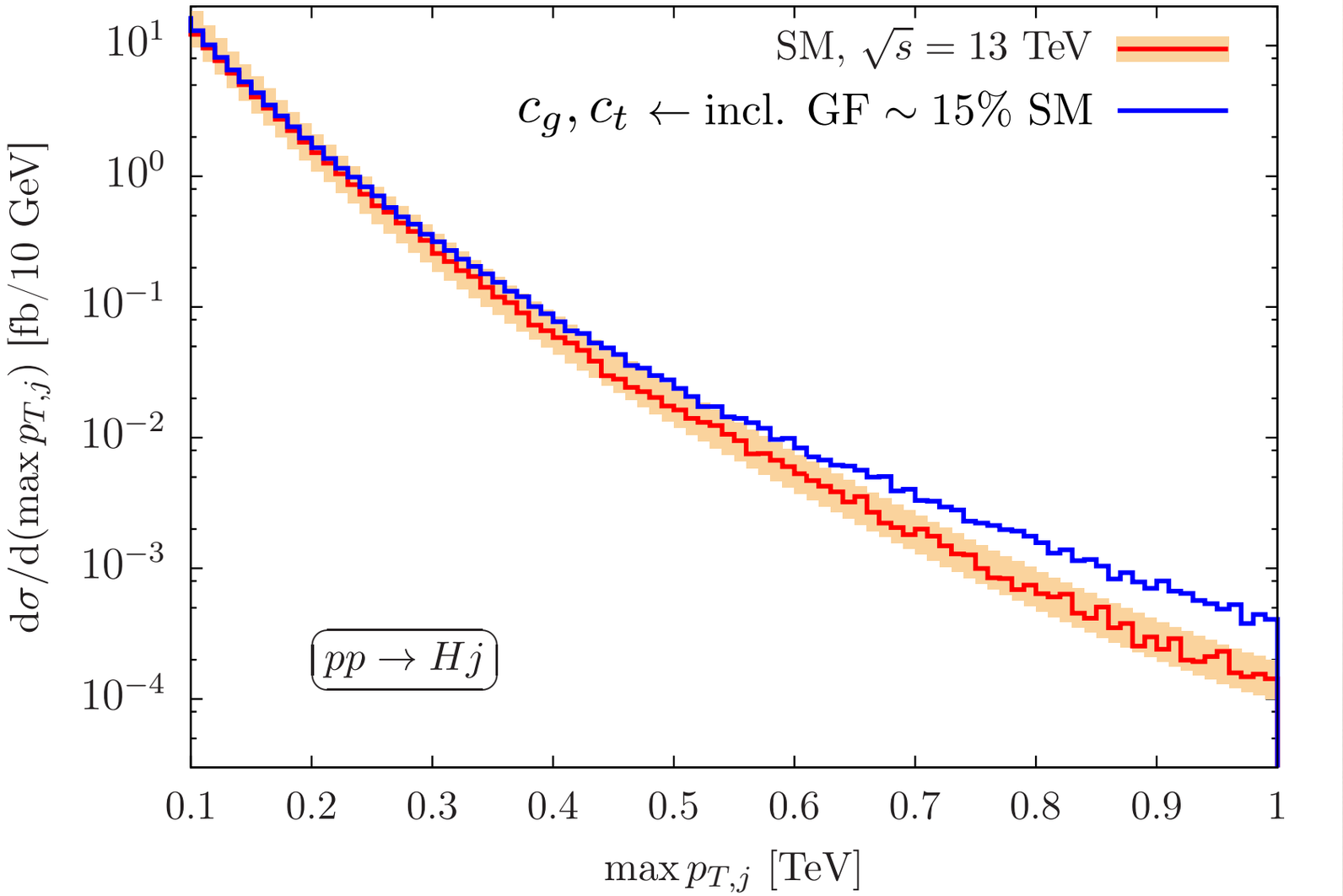
contact ggH interactions mask top Yukawa measurements

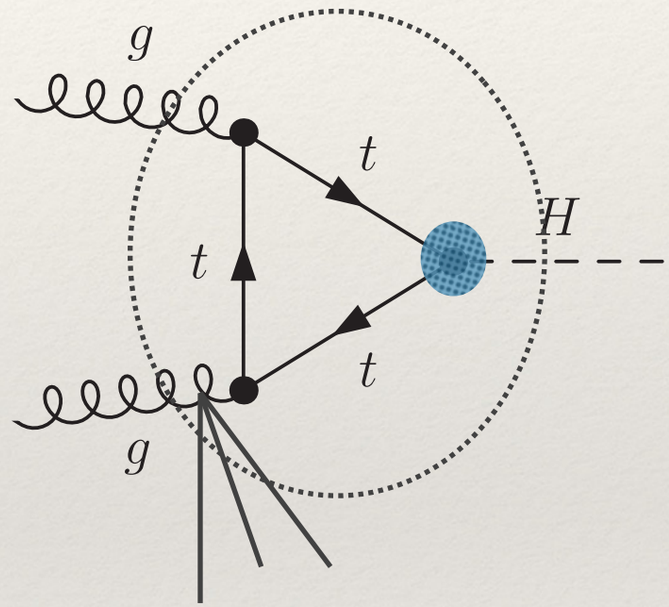
- way out: resolve loop for $p_T(H) \gtrsim m_t$ with one or more jets

[Banfi, Martin, Sanz `13] [Grojean, Salvioni, Schalffer, Weiler `13]
[Schalffer et al` 14] [Buschmann et al. `14] [Buschmann et al. `14]

# SM couplings

## Hadron collider systematics

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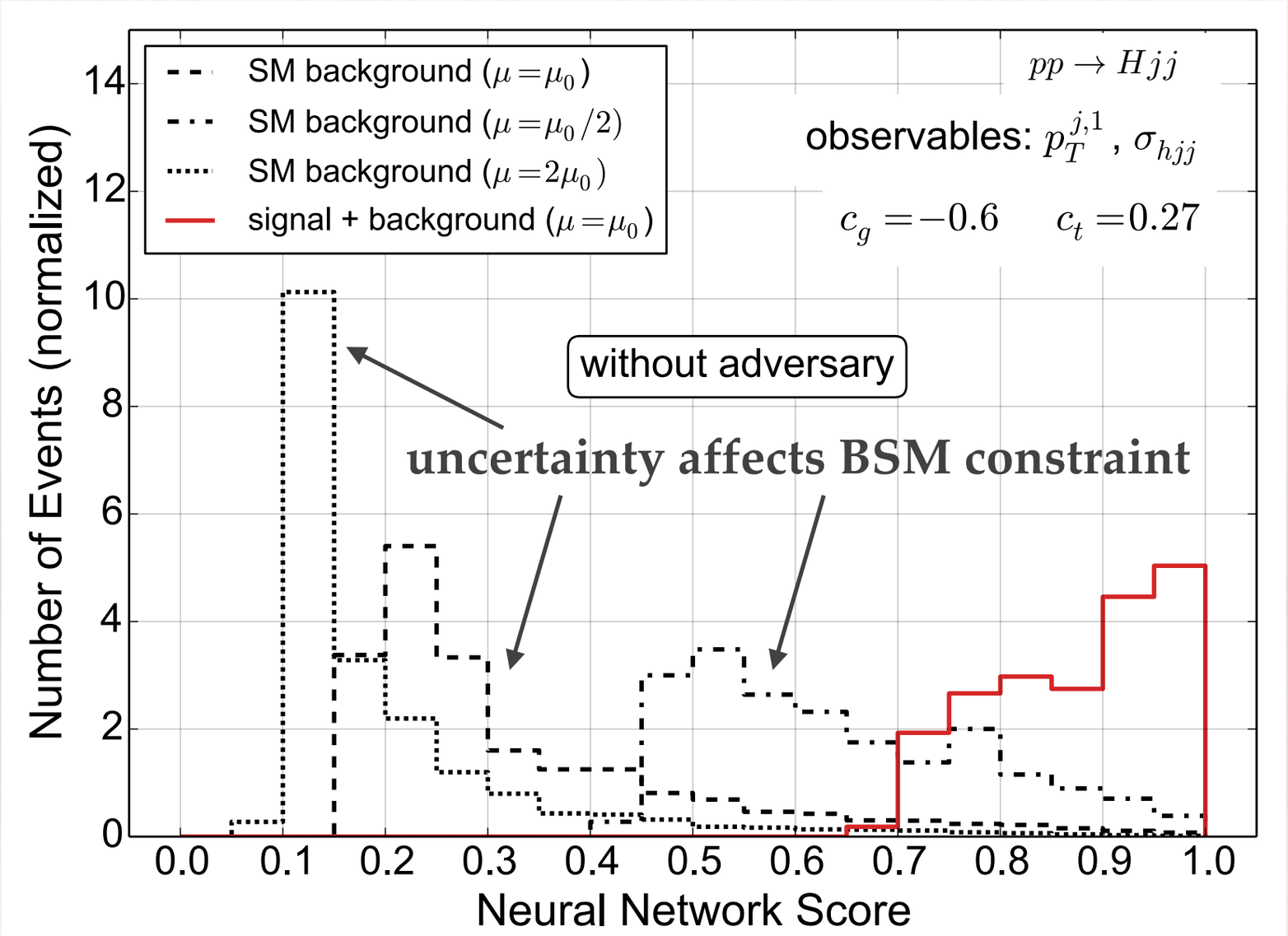
# SM couplings

- more kinematic information for H+2j, which is particularly promising, unfortunately $m_t=\infty$ SM limit accidentally good [Del Duca et al. `01]




[CE, Galler, Harris, Spannowsky `18]

**neural net learns** regions that are sensitive to uncertainty....

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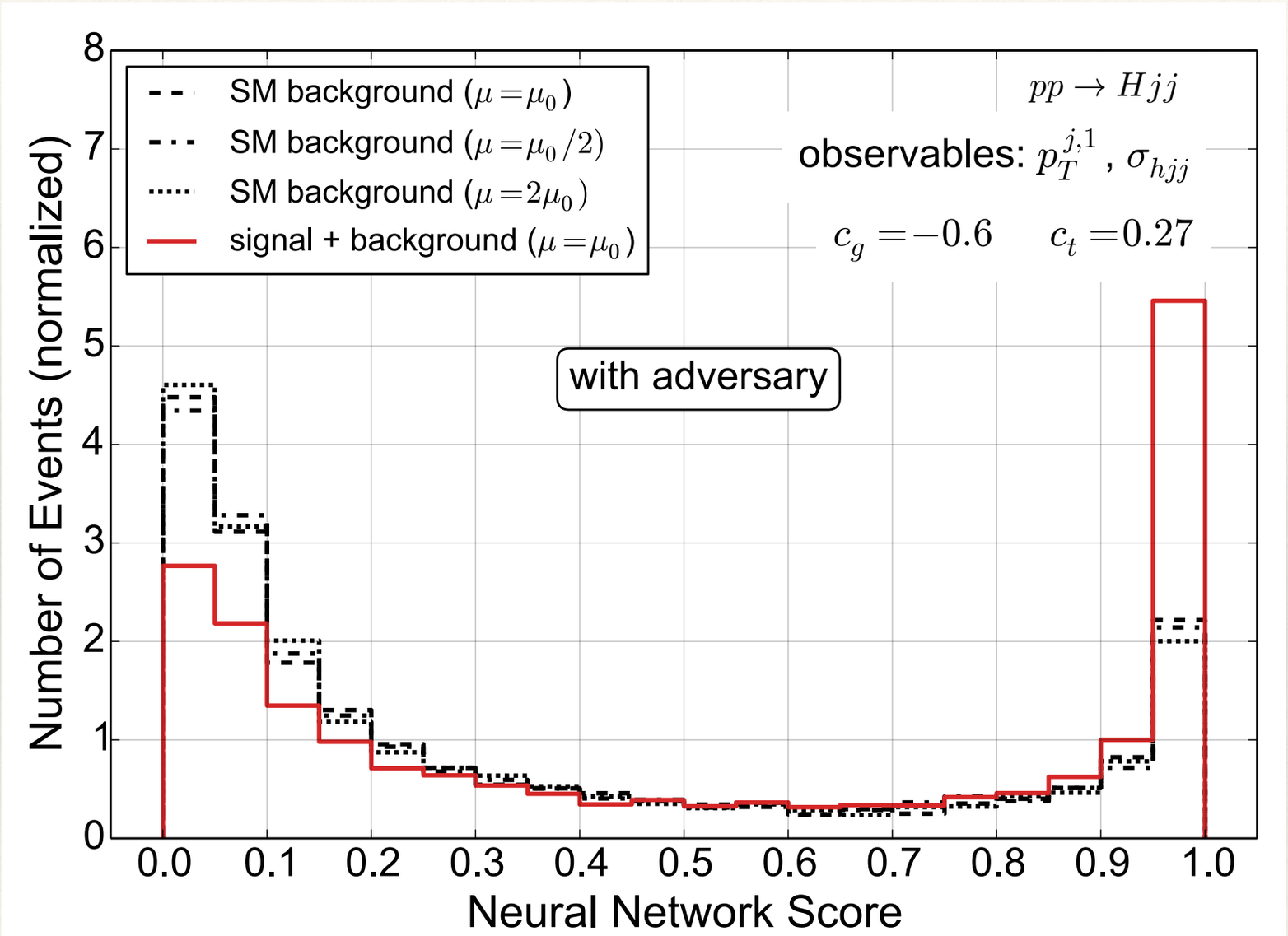


[CE, Galler, Harris, Spannowsky ` 18]

… and can learn to avoid them → **robustness at highest sensitivity**

see also [Goodfellow et al. ` 14] [Louppe, Kagan, Cranmer ` 16] …

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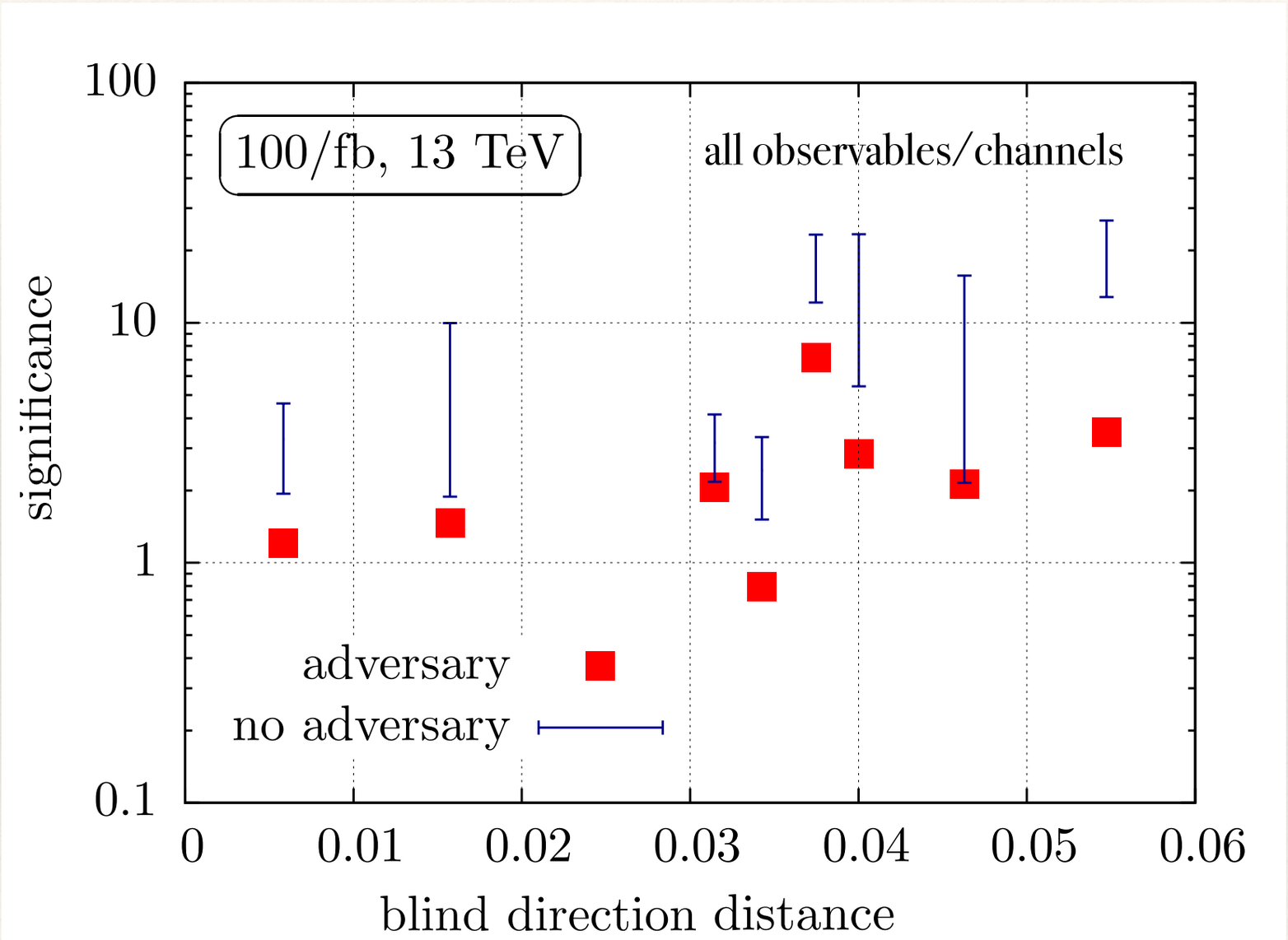


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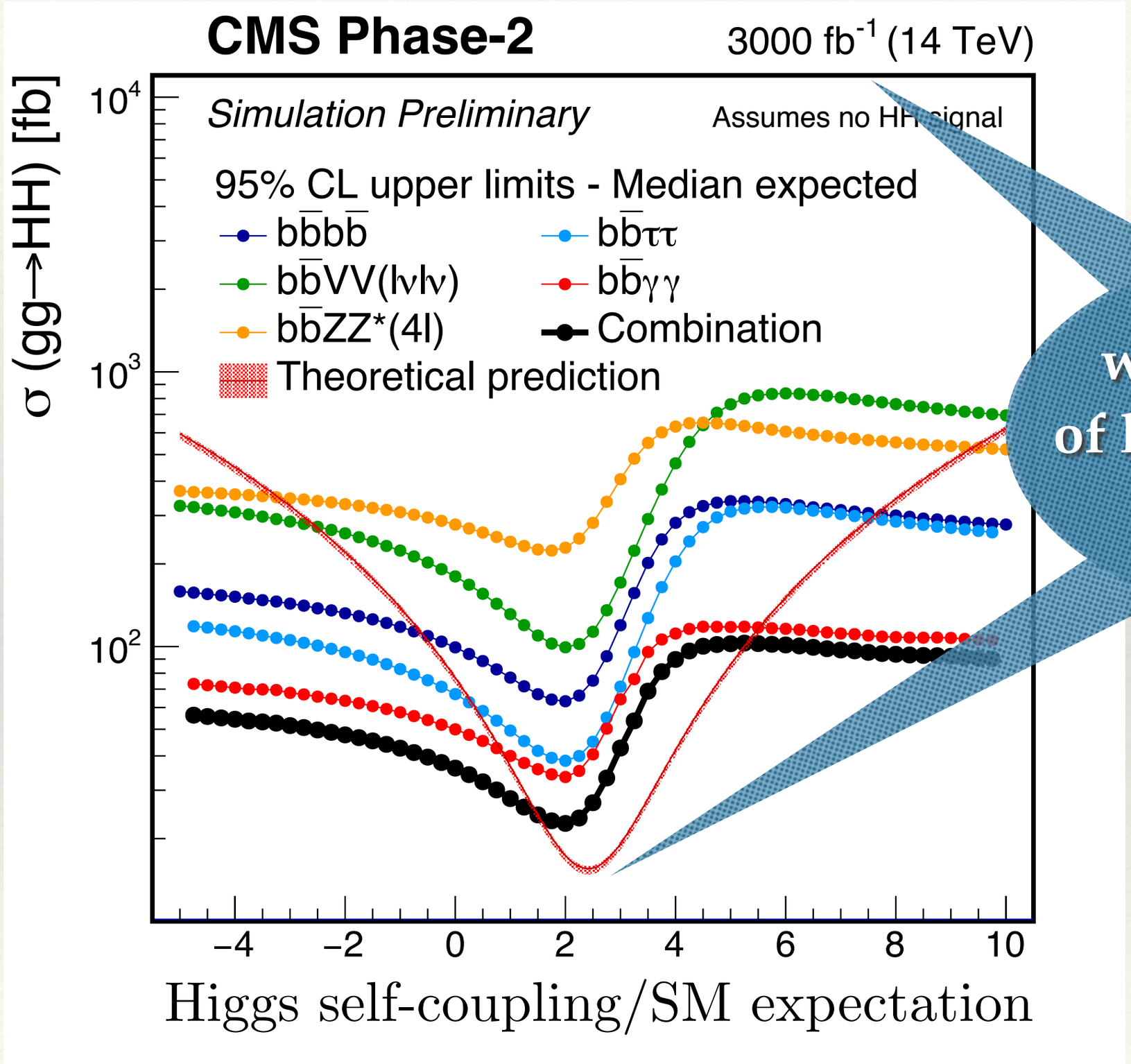
# di-Higgs final states

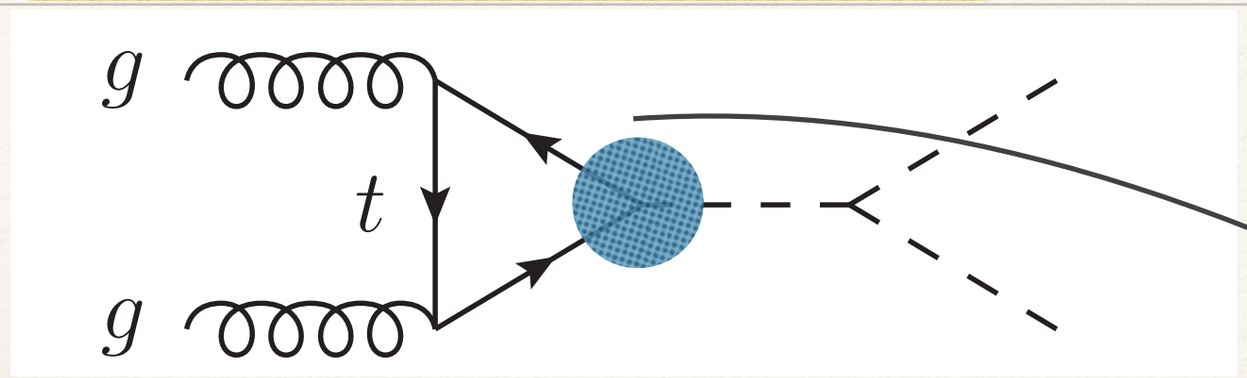
rare final states = large statistics

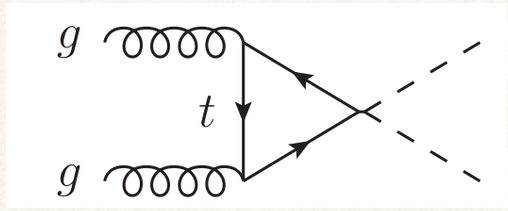



we are in the domain of large (end-of-lifetime) LHC luminosity

# di-Higgs final states

## di-Higgs anatomy at 3/ab




e.g. [Gröber, Mühlleitner `10]

correlated with on-shell Higgs phenomenology broken by $\sim \bar{t}th^2/\Lambda$....

- easy to arrange ad-hoc EFT in a way to get spectacular rates, but can doubt physical relevance of such limits (→ matching)

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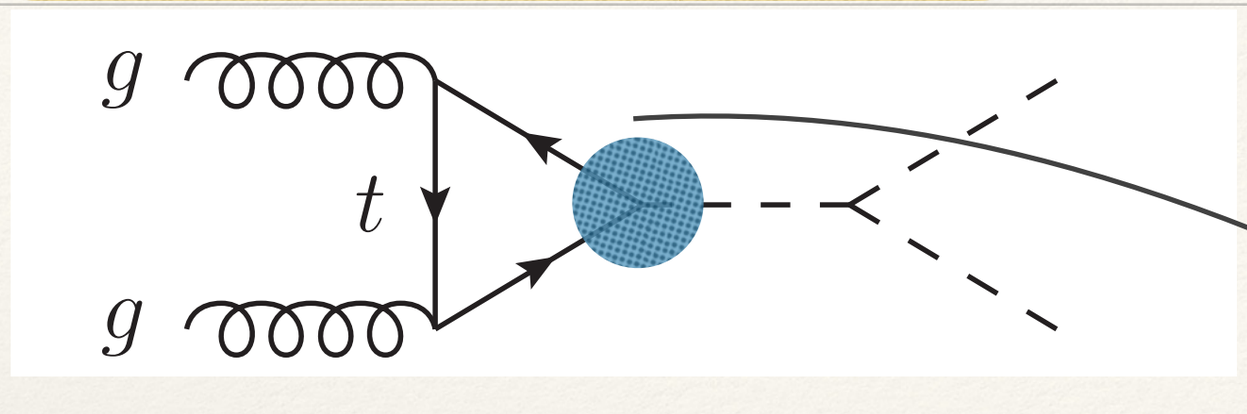


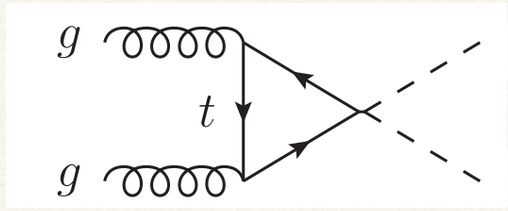


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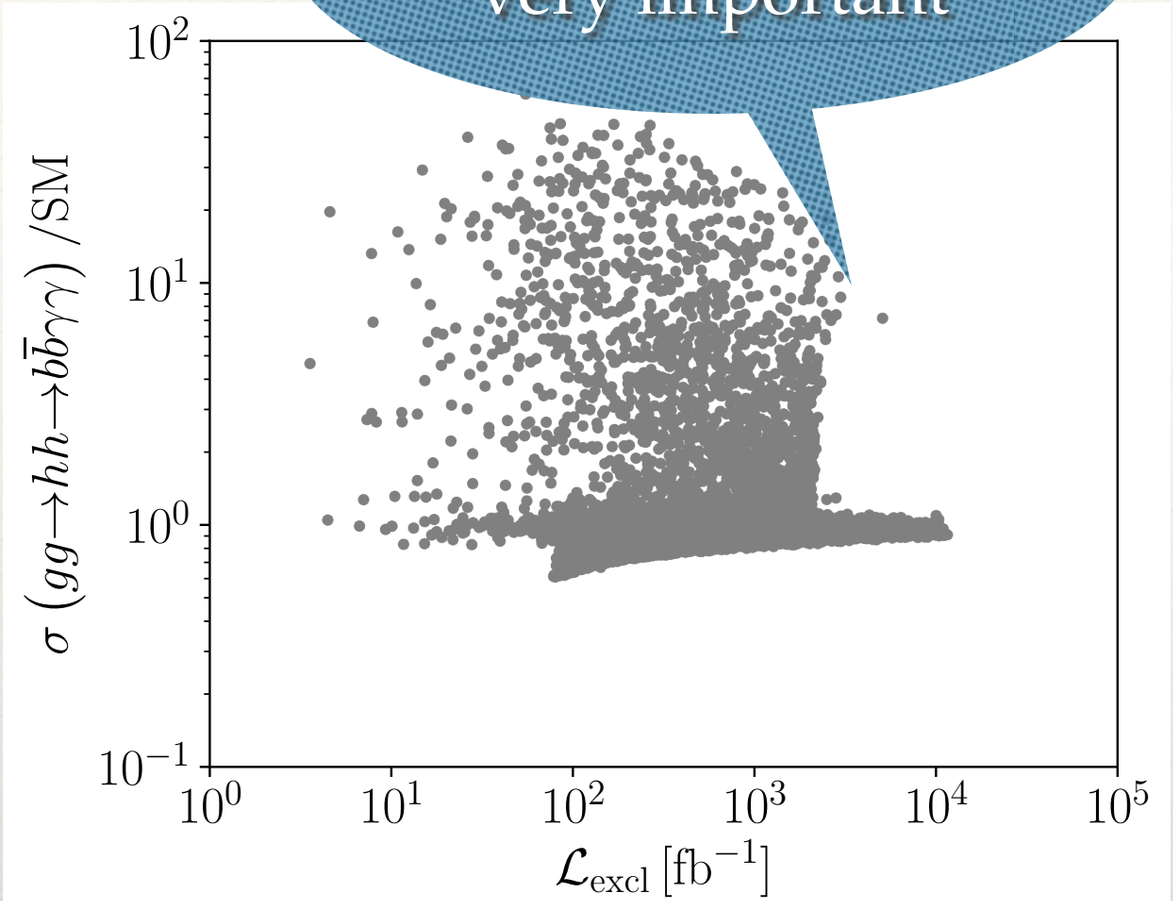
[Basler, Dawson, CE, Mühlleitner `18]

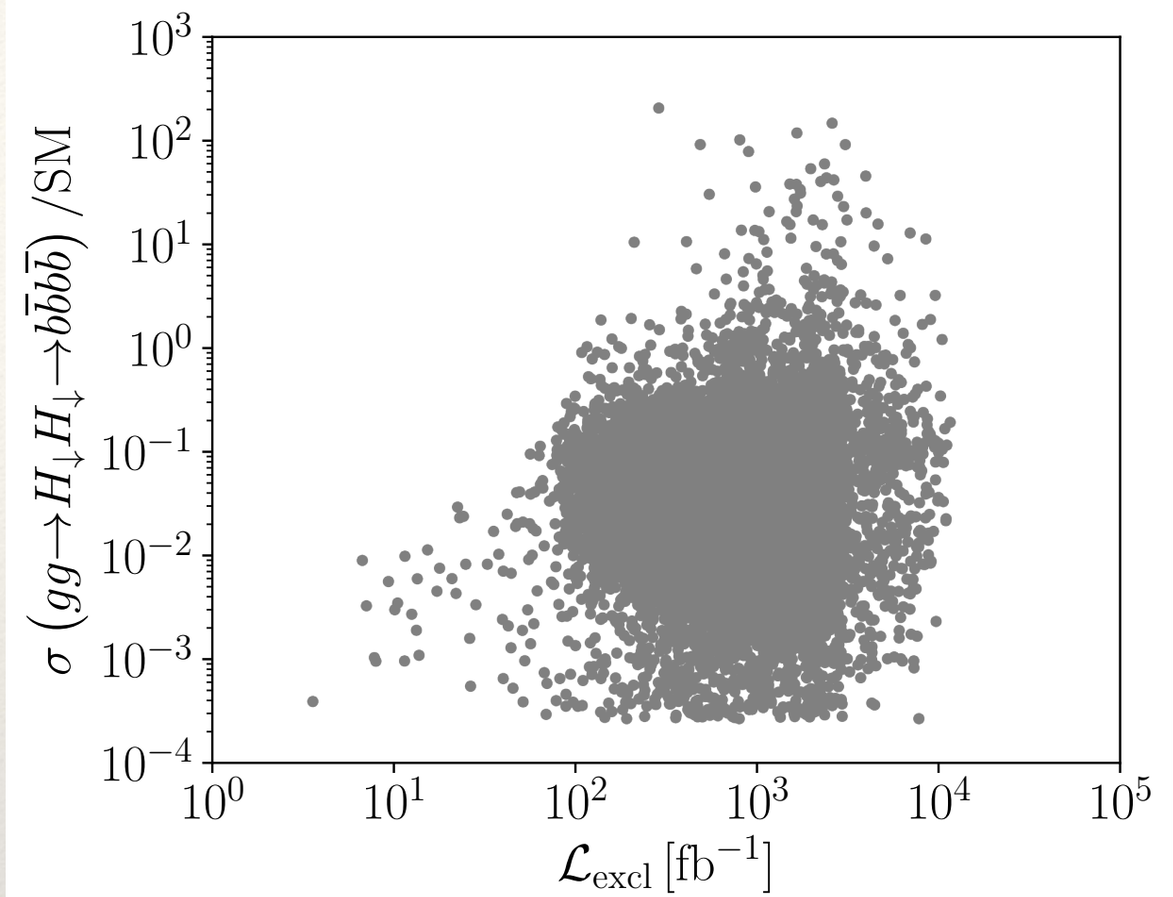
- use concrete Higgs sector extensions (C2HDM/CxSM/...)
  - extrapolate 125 GeV signal strengths
  - extrapolate exotic Higgs searches
  - more constraints (*electron EDMs, flavor, perturbativity, strong PS, CP viol.*)

What's left for HH?

# e.g. C2HDM

tt resonance searches very important




[Basler,Dawson, CE, Mühlleitner `18]

luminosity at which non-HH searches become sensitive

SM-like measurements can show a plethora resonant anomalies

diHiggs final states important for BSM discovery

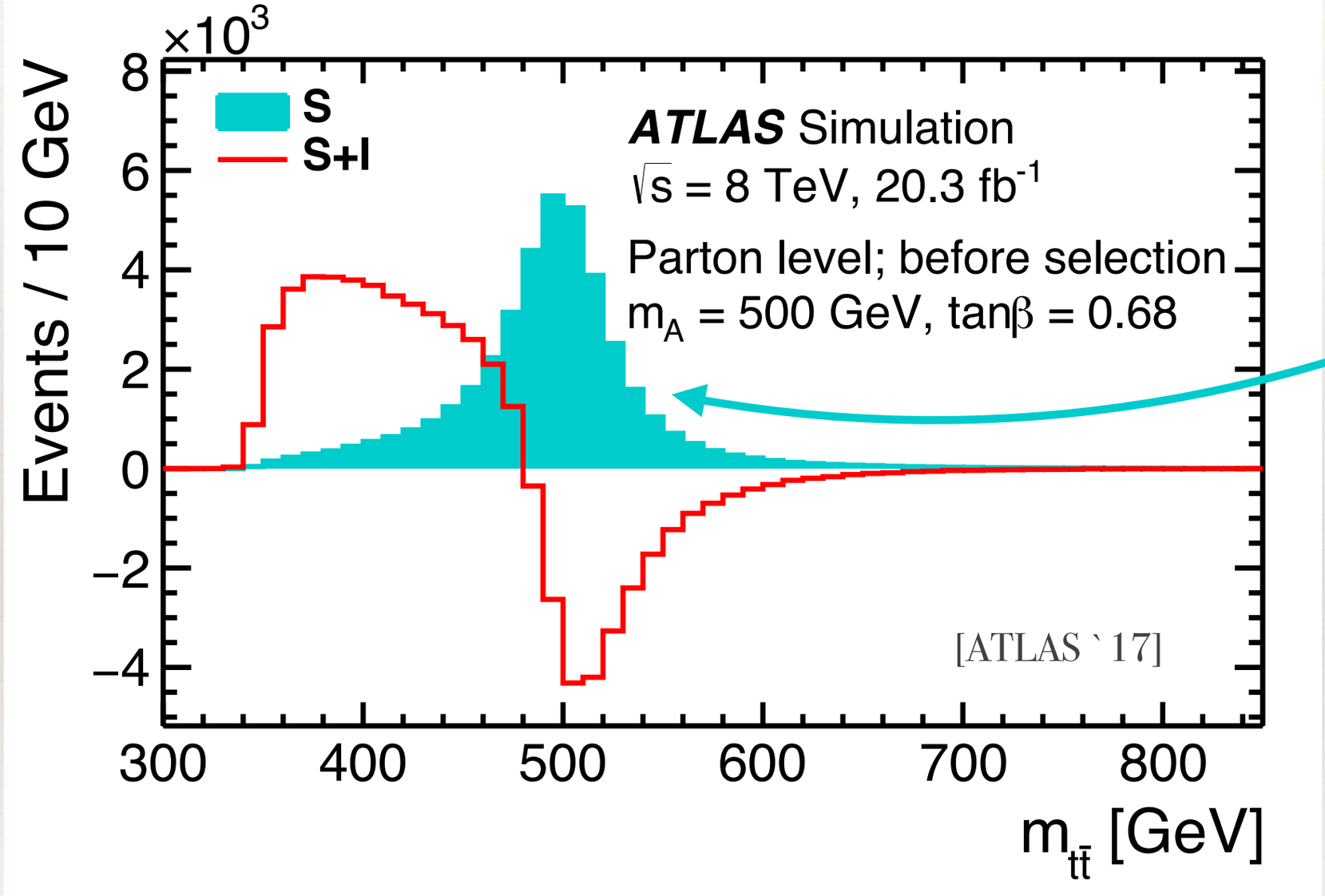
…di Higgs final states quickly lose relevance when approaching EFT limit

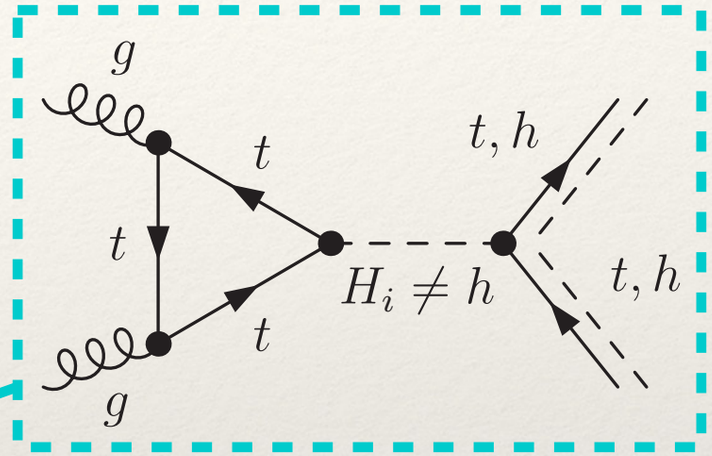
# di-Higgs final states

## special role of tops

- large interference effects of Higgs "signal" with QCD background

[Gaemers, Hoogeveen `84] [Dicus et al. `94]....



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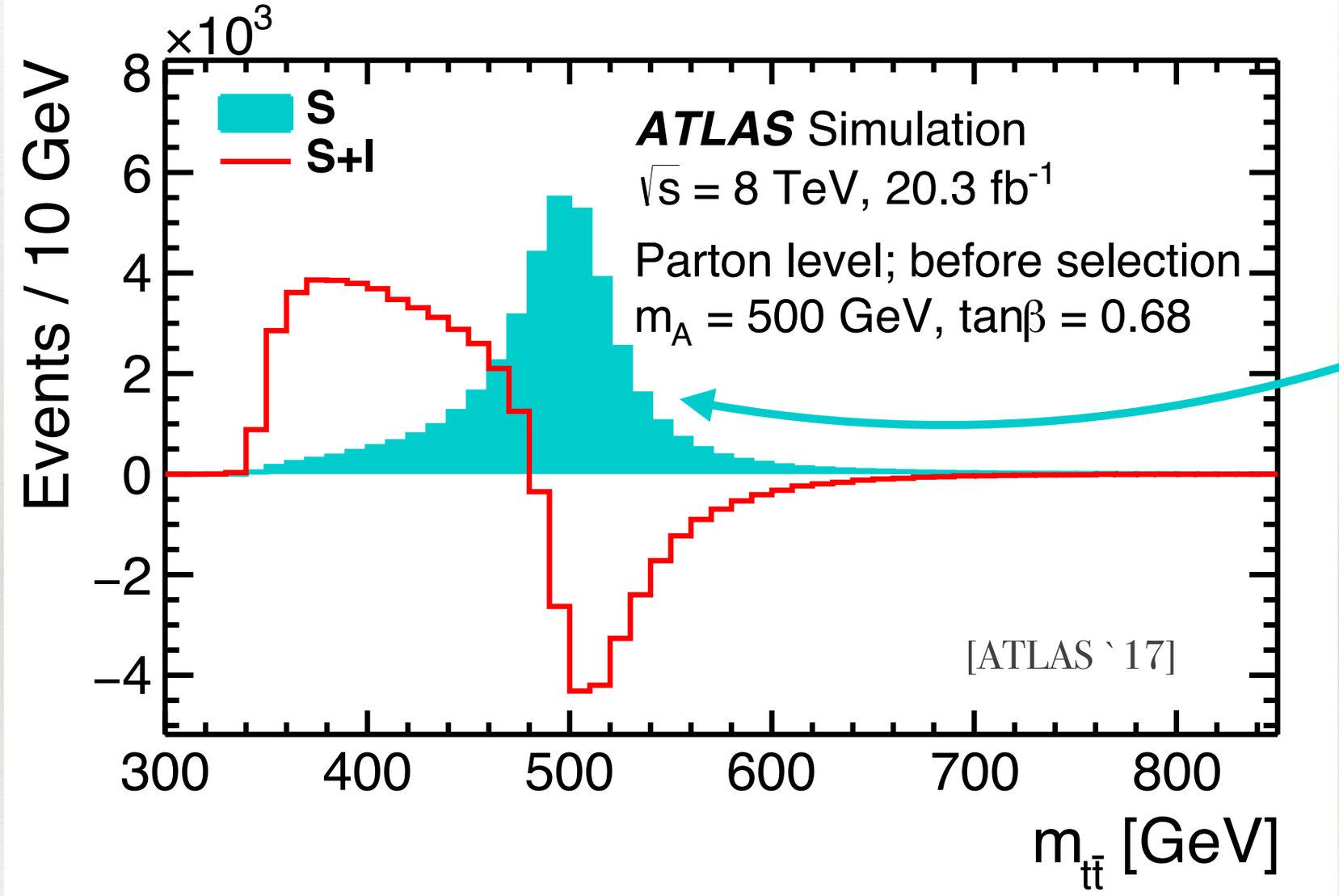
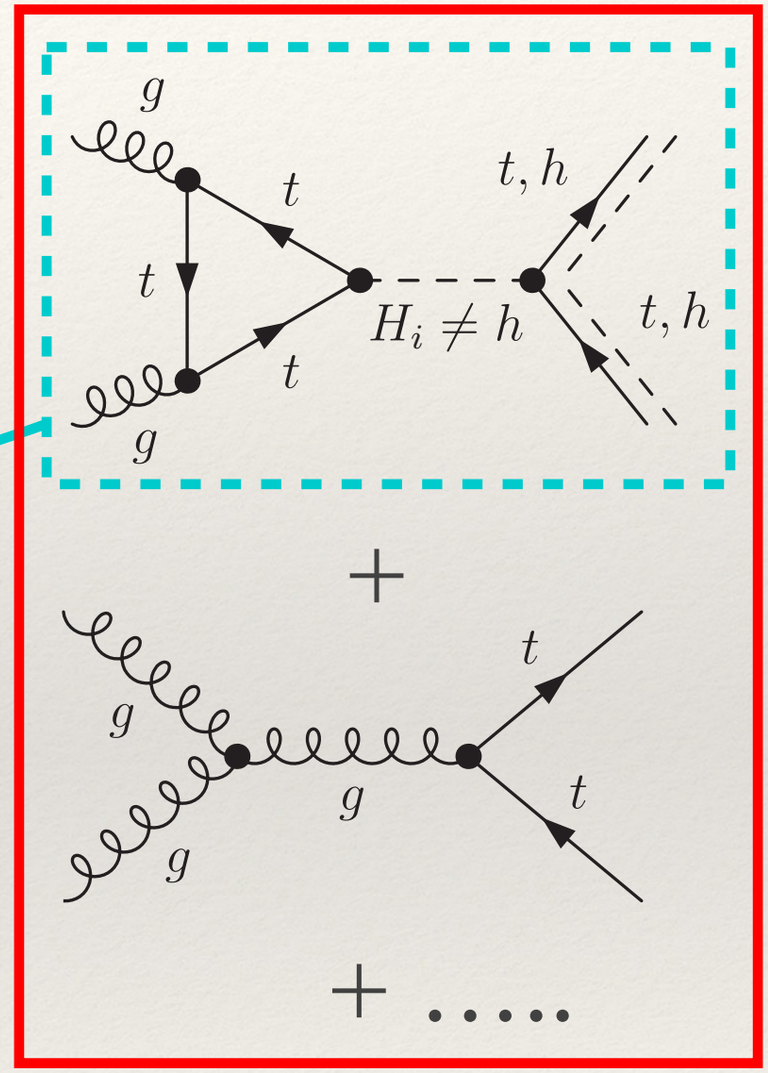
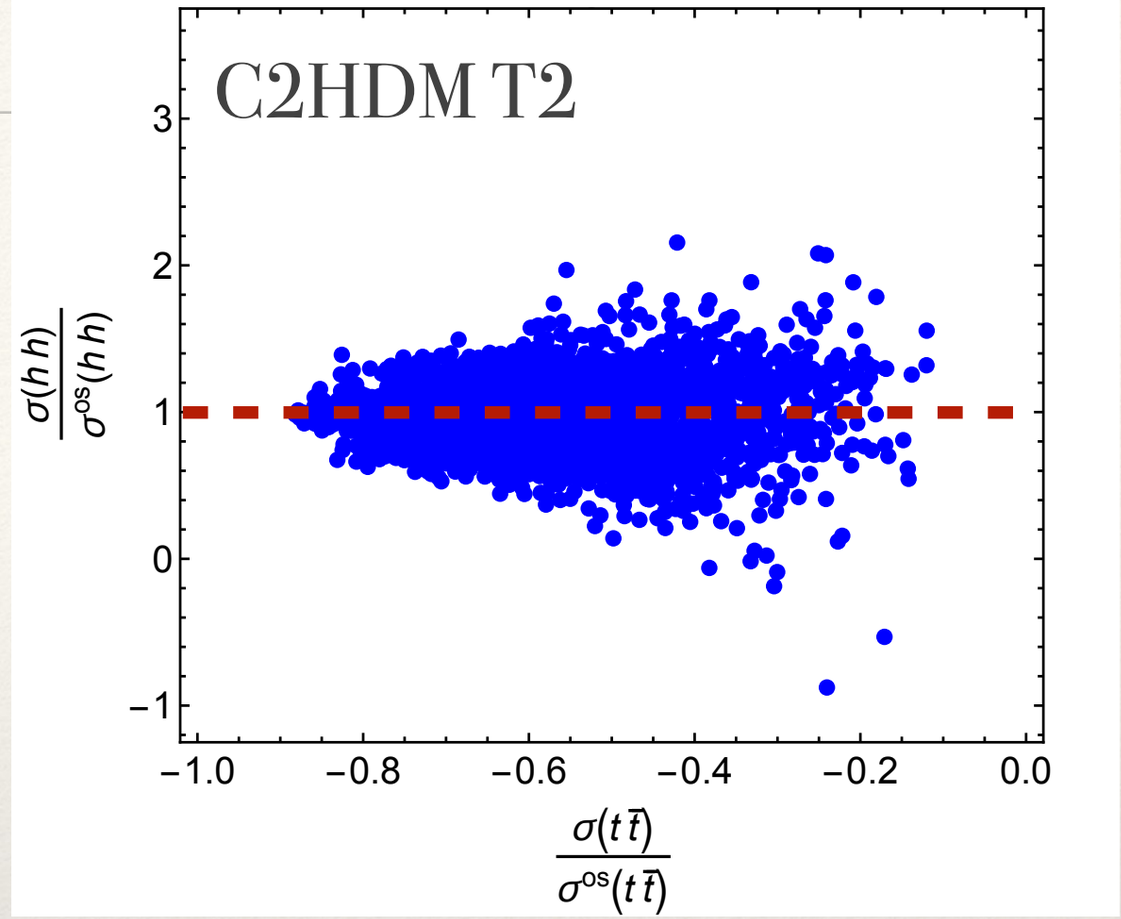



- top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!

# special role of tops

- destructive interference in top final states can be correlated with excess in HH - how ?



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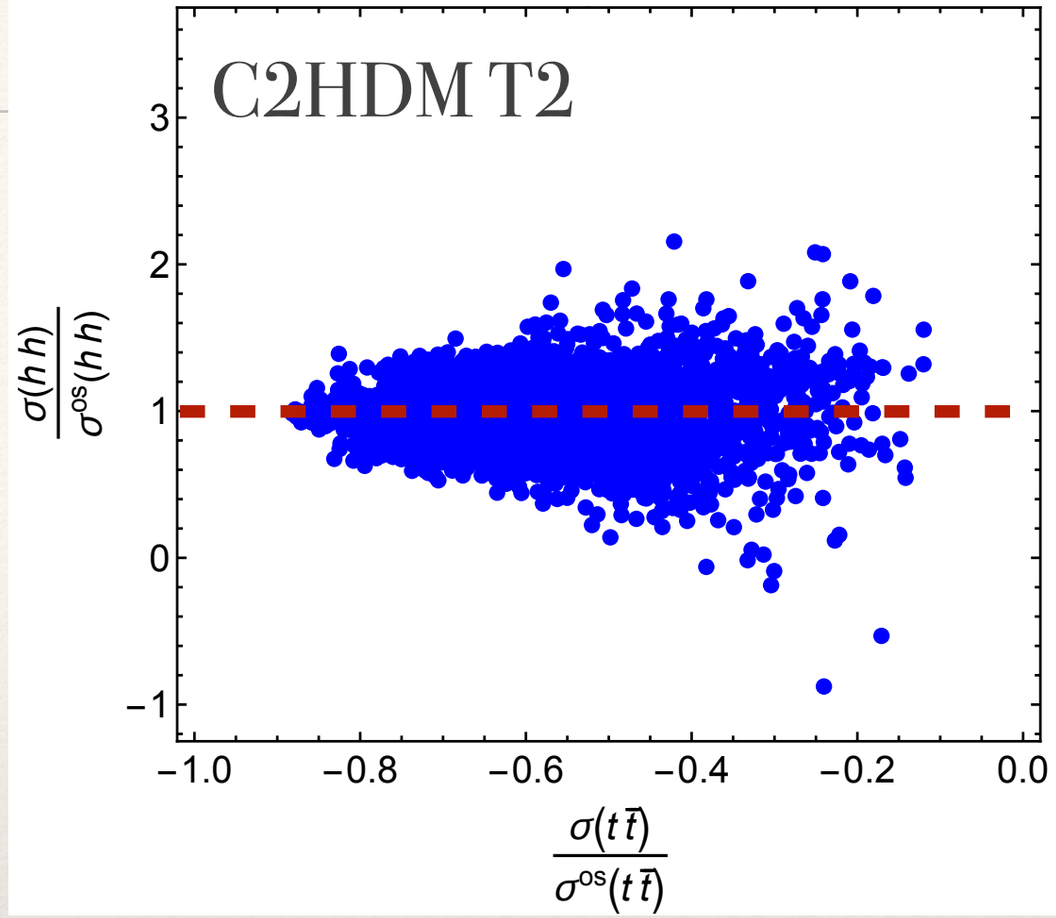
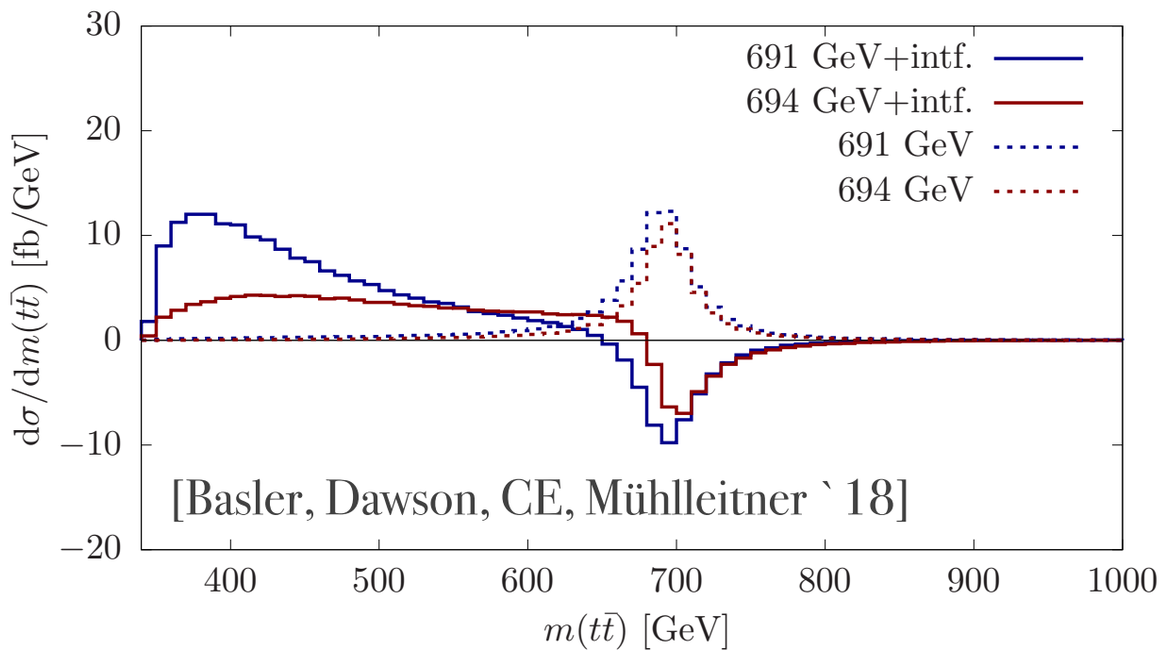
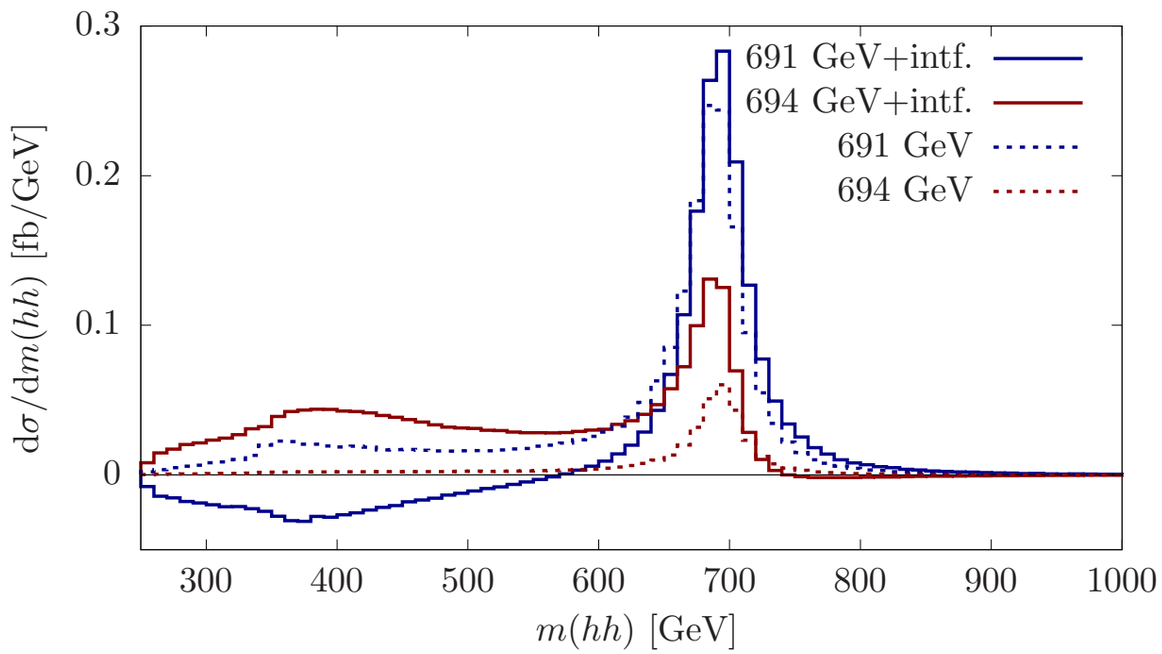
- phenomenologically viable regions exhibit compressed spectra: **signal-signal interference**



# future colliders

[CE, Jaeckel `19]

- straw man scenario: the $\mathbb{Z}_2$-symmetric Higgs portal

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

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- Higgs physics modifications via loop- or kinematics-suppressed effects

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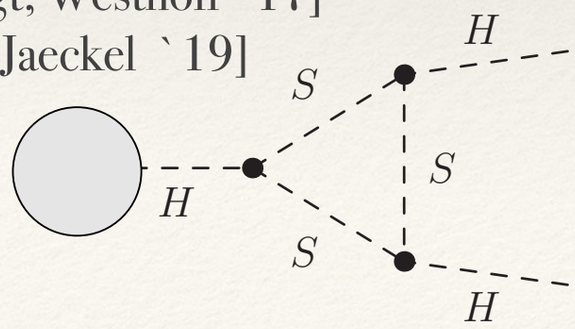
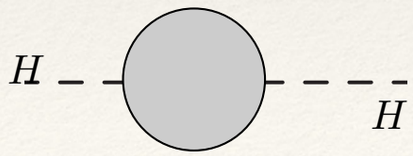
Trilinear Higgs coupling modifications

[He, Zhu `16]
[Voigt, Westhoff `17]
[CE, Jaeckel `19]



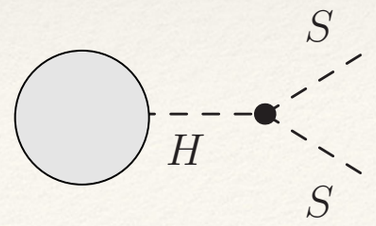

Higgs precision studies at colliders

[CE, McCullough `13]
[Craig, CE, McCullough `13]
[Goncalves, Han, Mukhopadhyay `18]

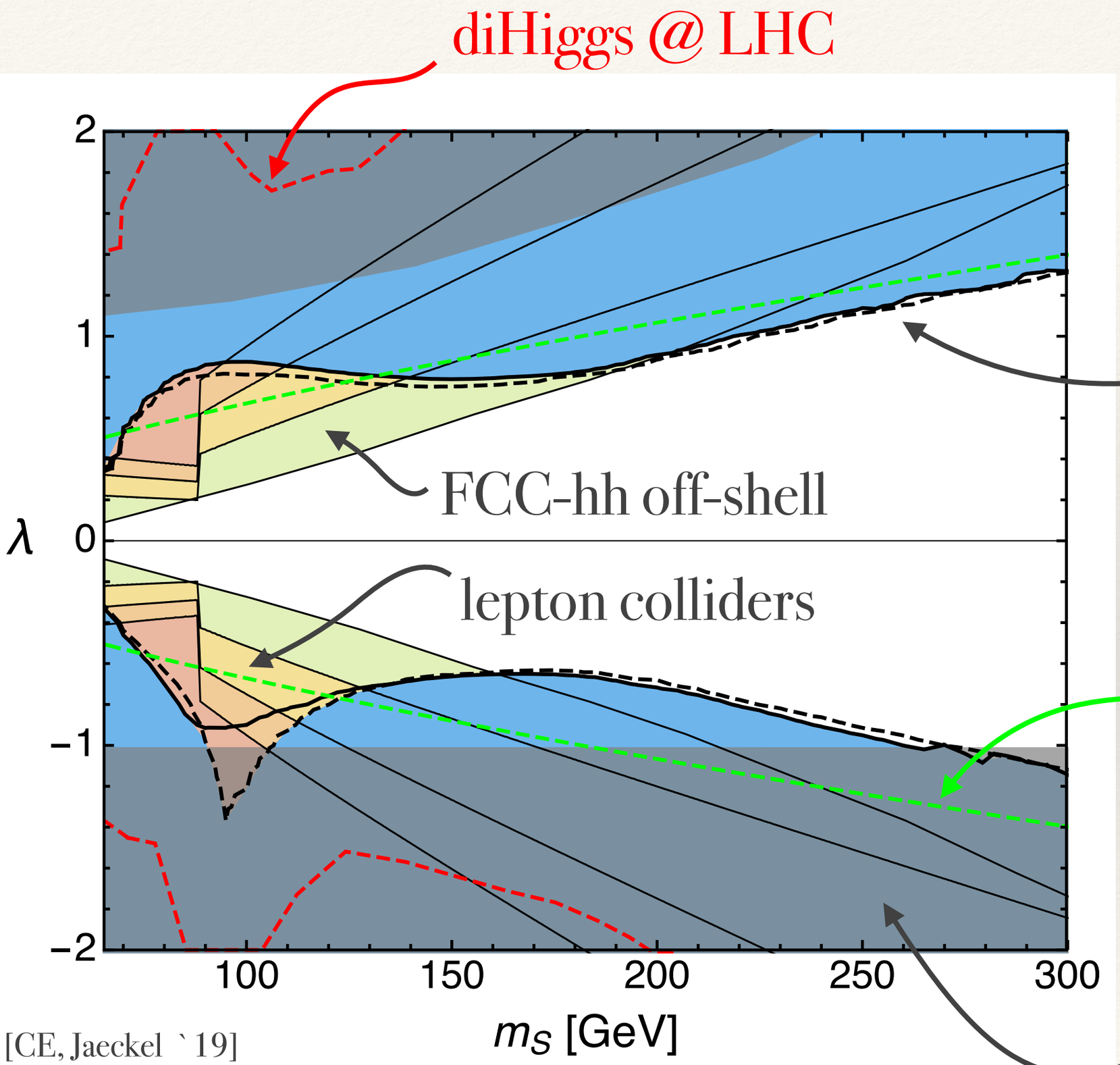



off-shell production

[Craig , Lou. et al. `14]
[Ruhdorfer, Salvioni, Weiler `19]



# enhanced sensitivity




[CE, Jaeckel `19]

diHiggs @ FCC-hh

[Contino et al. `17]

Coleman-Weinberg approximation for diHiggs

electroweak potential unstable

[Curtin , Meade. Yu` 14]

# Summary

- *Higgs physics sits at the heart of our BSM efforts good way*
  - enhancing theoretical predictions
  - limit setting tailored to minimise systematics polutions

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  - limit setting tailored to minimise systematics polutions

- *Opportunity to link the Higgs sector to new physics*
  - cure SM shortcomings (CP violation…)
  - multi-Higgs is a hard case for BSM sensitivity
  - new collider concepts can maximise precision vs energy reach in complementary ways