University of Glasgow

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Three avenues for Higgs phenomenology

Particle Physics Seminar

Warwick

17/01/2019

Overview

- *Improving the expected: SM-like Higgs couplings*
  - lifting degeneracies in coupling space for expected uncertainties with adversarial machine learning
  - .....

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  - .....
- *Closing in on new physics in the Higgs sector*
  - *di-Higgs production as a probe of new physics*
  - .....

"Yang-Mills theories had to be right"

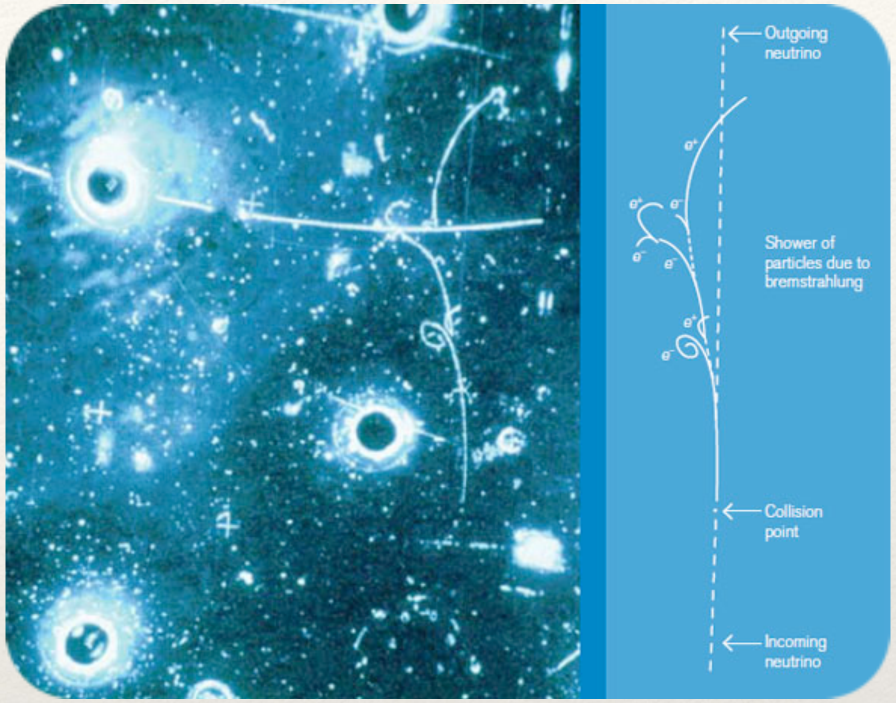
\`t Hooft, "Under the Spell of the Gauge Principle"

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 ?



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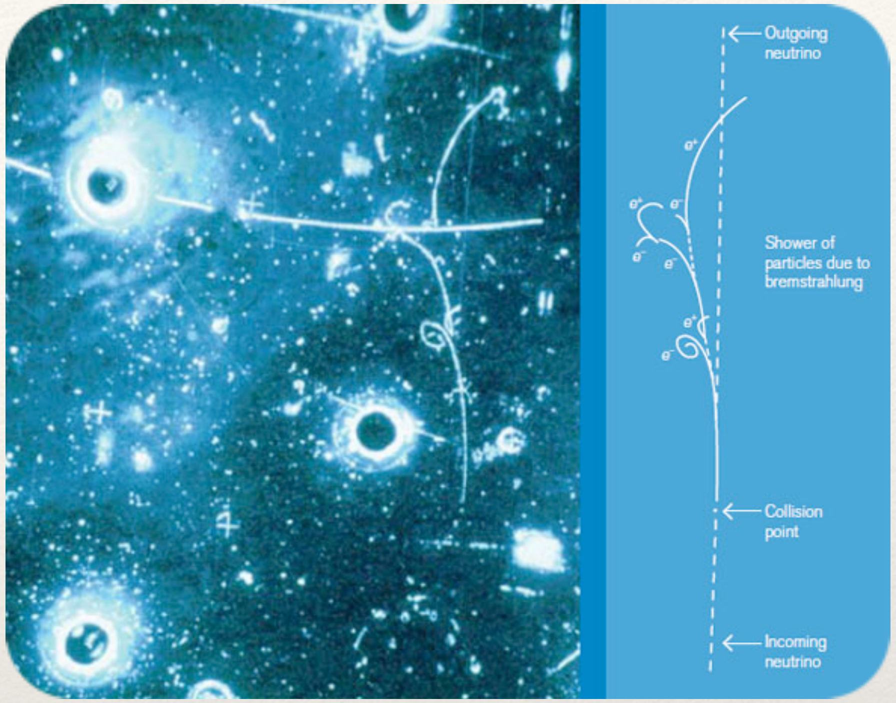

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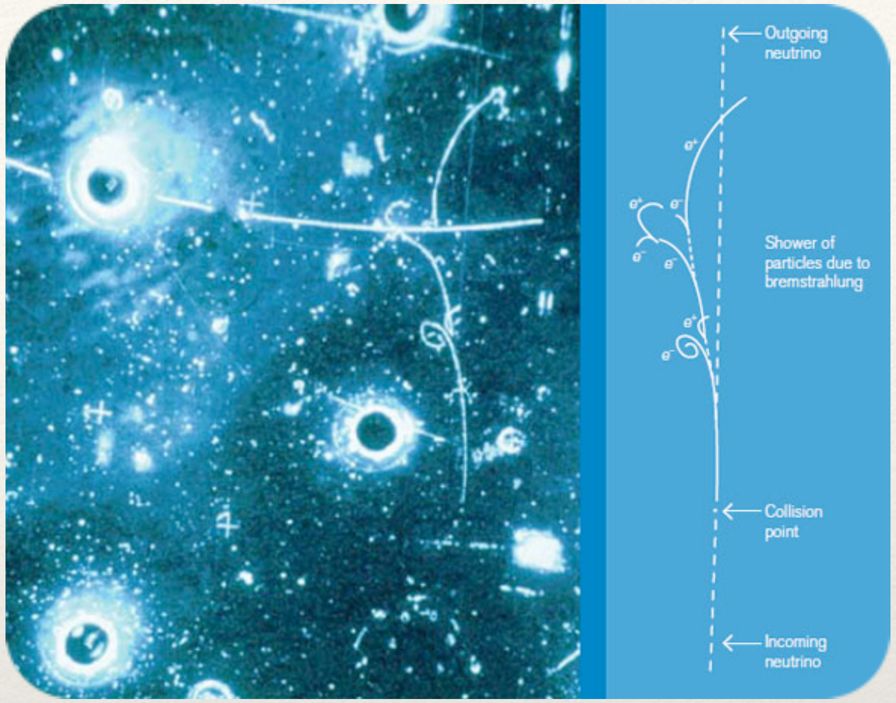

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☛ ″spontaneous″ symmetry breaking

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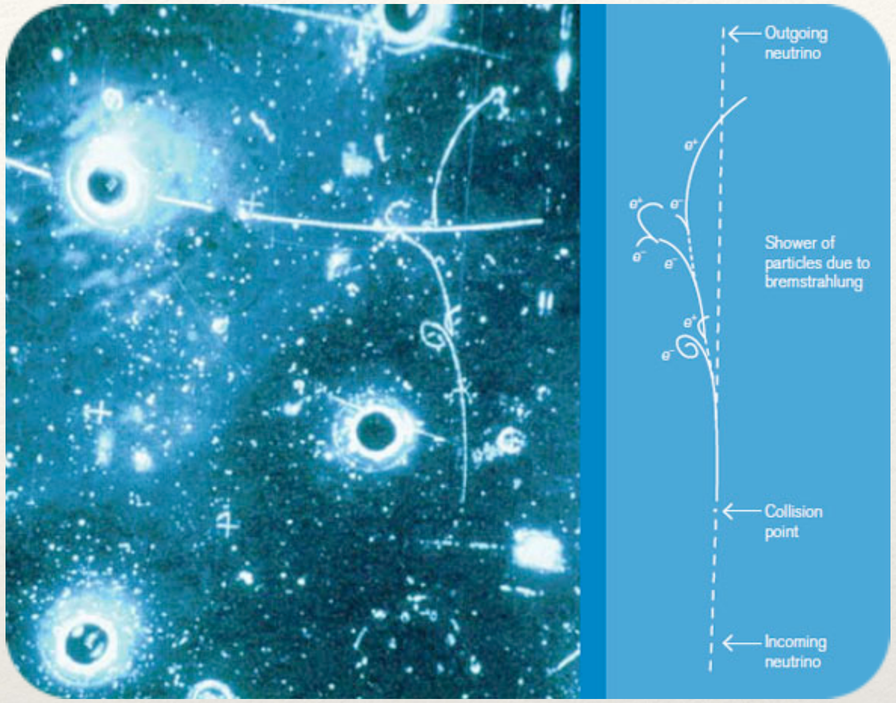

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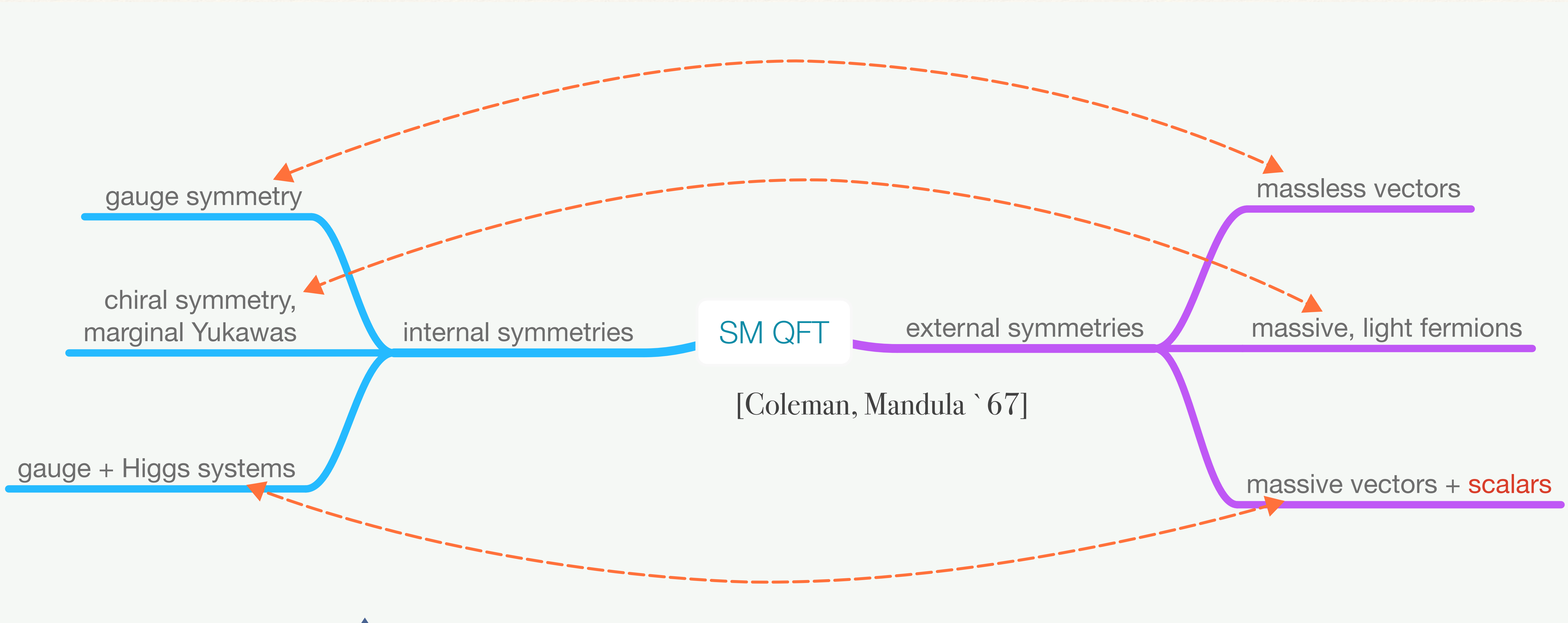
- non-linear realisation of gauge symmetry in a Yang Mills+scalar sector is compatible with $\langle H \rangle \neq 0$

  ☛ "spontaneous" symmetry breaking

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

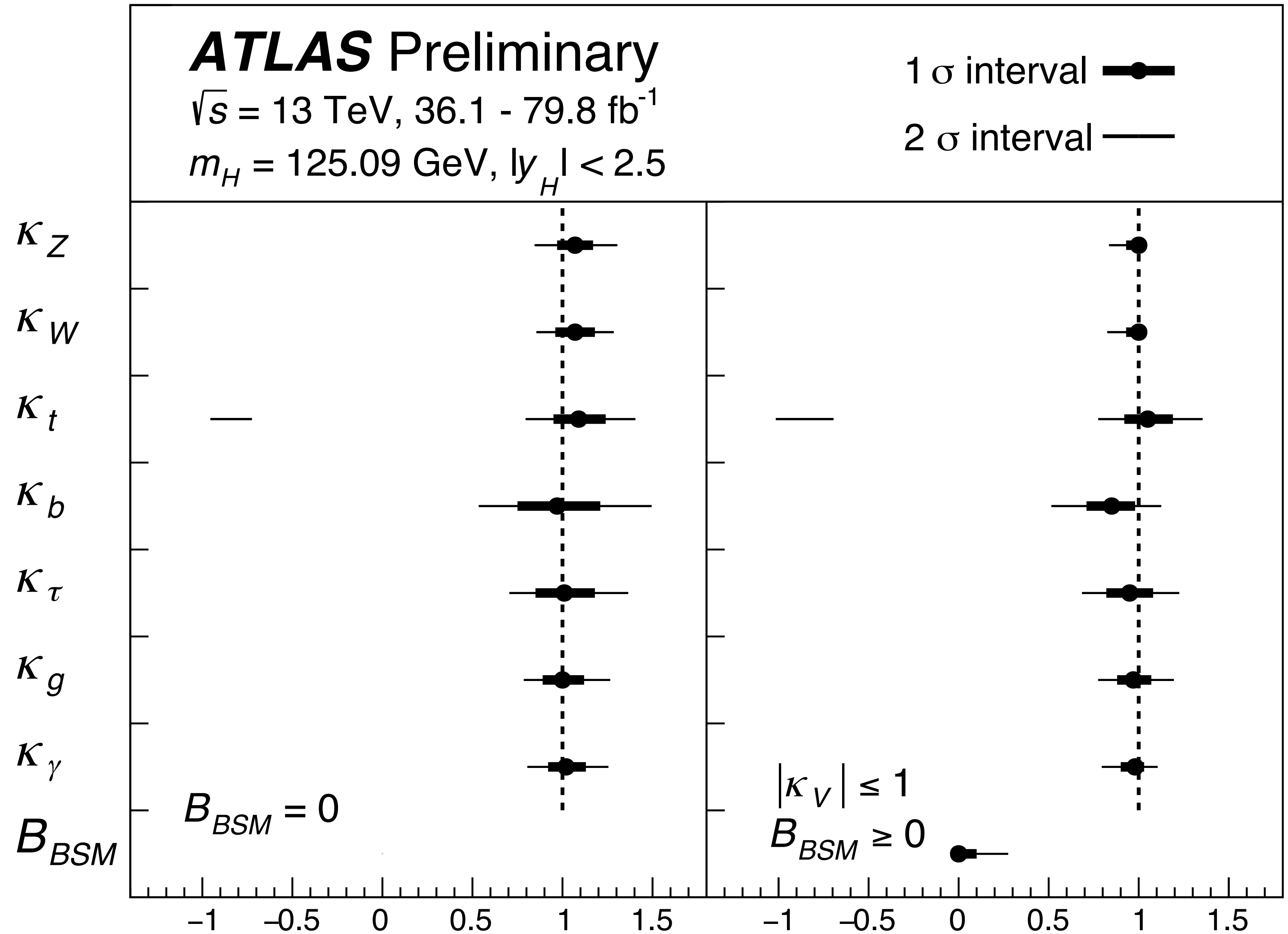
  ☛ renormalizability, probability conservation

The Standard Model: taking stock



"What's next at the LHC ?"

Status of LHC measurements



[ATLAS `18]

☛ everything is consistent with the SM Higgs hypothesis (so far) but what are the implications for new physics?

Fingerprinting the lack of new physics

the SM is flawed

no evidence for exotics

coupling/scale separated BSM physics

Effective Field Theory

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

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

59 B-conserving operators $\otimes$ flavor $\otimes$ h.c., d=6
2499 parameters (reduces to 76 with N_f=1)

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concrete models

- extended SMEFT
- ($\mathbb{C}$) Higgs portals
- 2HDMs
- (N)MSSM
- compositeness….

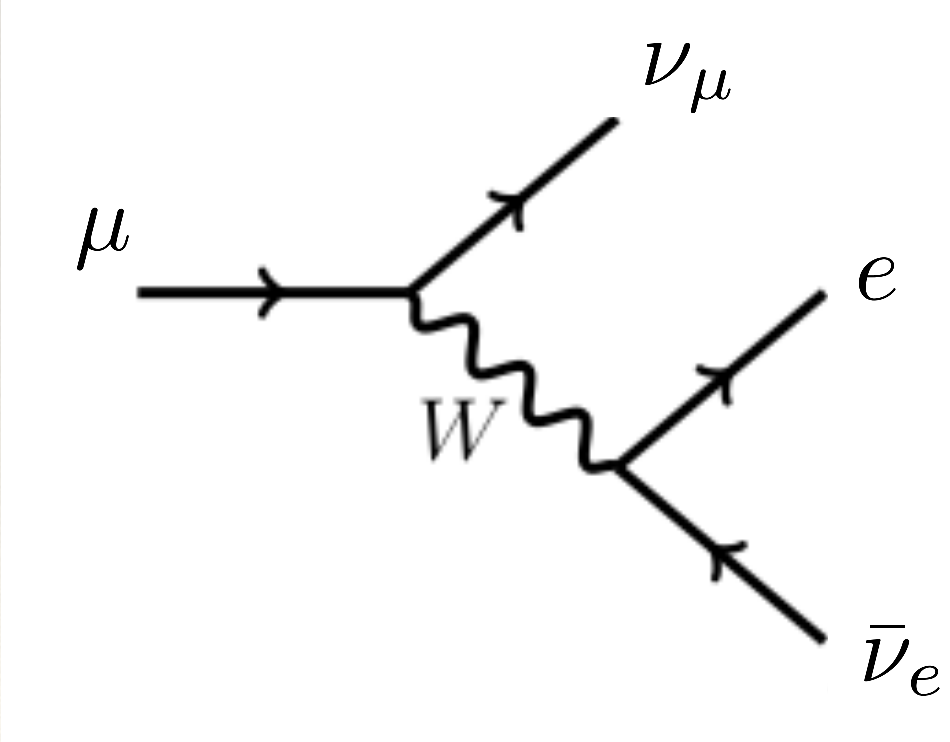
Effective theory

data

effective field theory

interpretation

Weak decay



Effective theory

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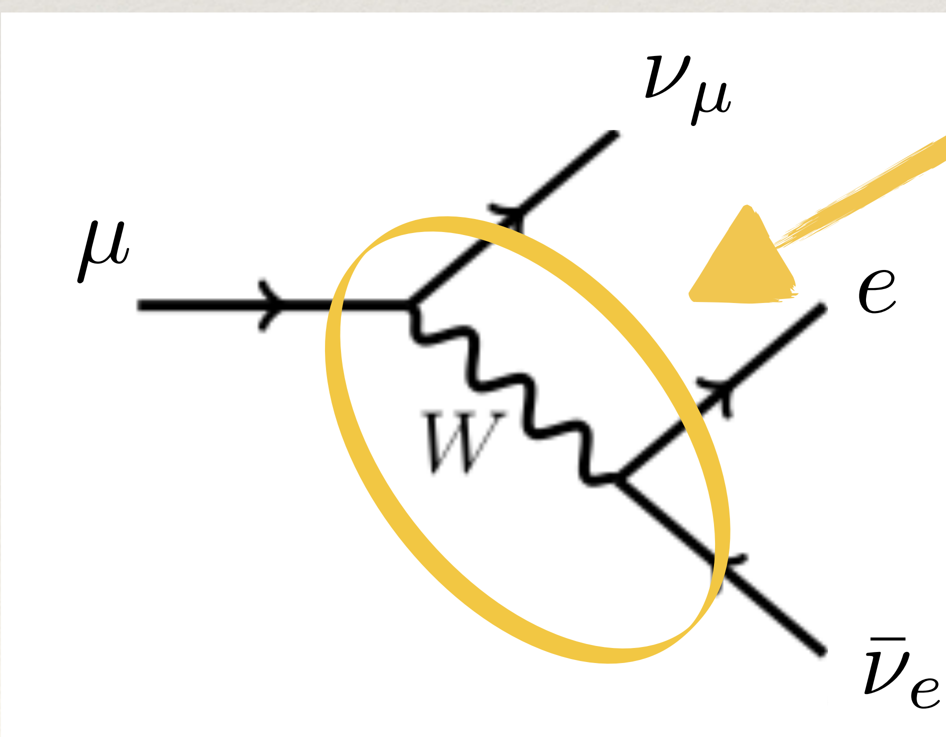
Weak decay

$$m_\mu^2 \sim |t| \ll m_W^2$$

$$\frac{1}{t - m_W^2} = -\frac{1}{m_W^2} - \frac{t}{m_W^4} + \dots$$



Effective theory

data → effective field theory → interpretation

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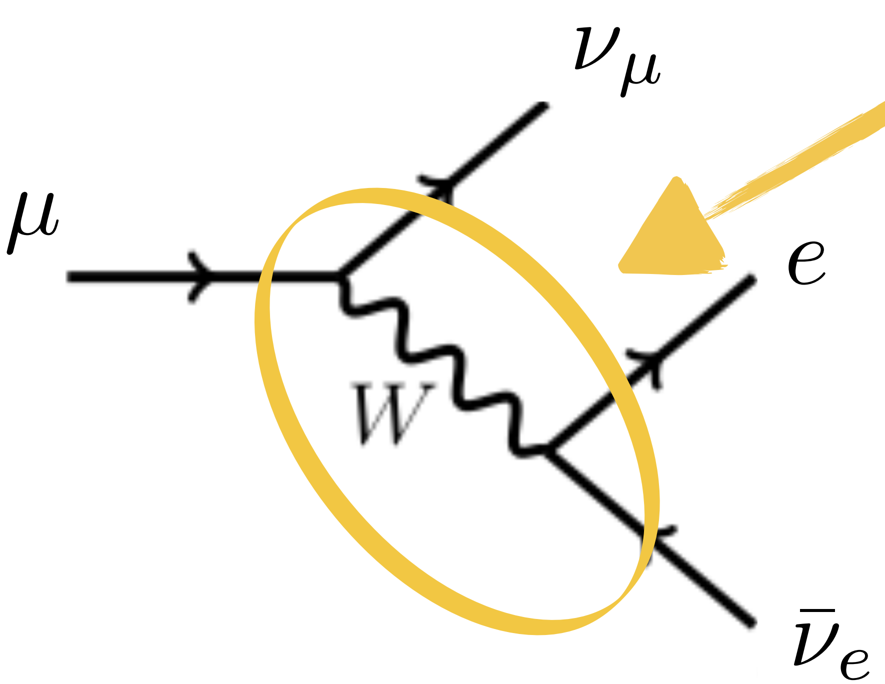
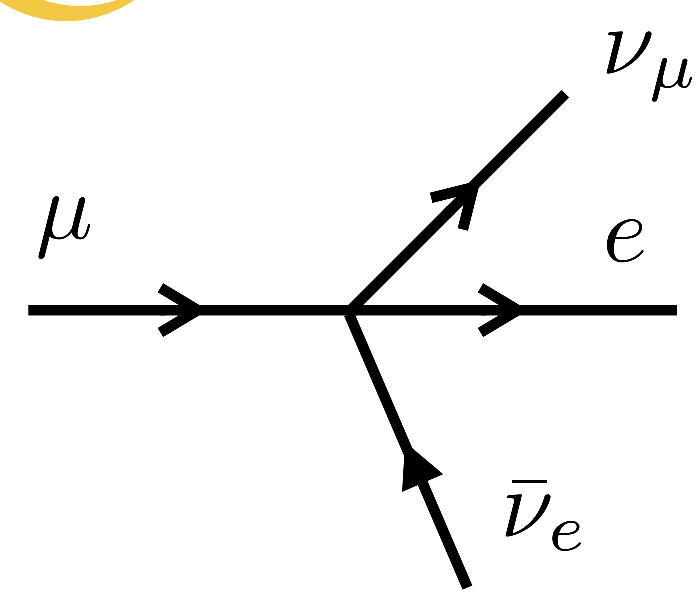


$$\simeq -\frac{1}{m_W^2} \times$$



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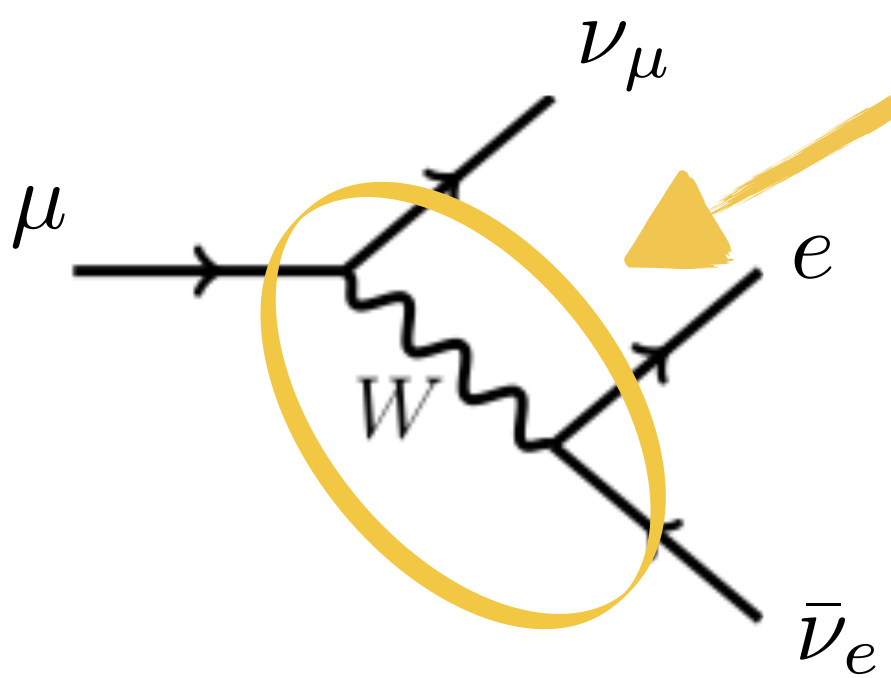

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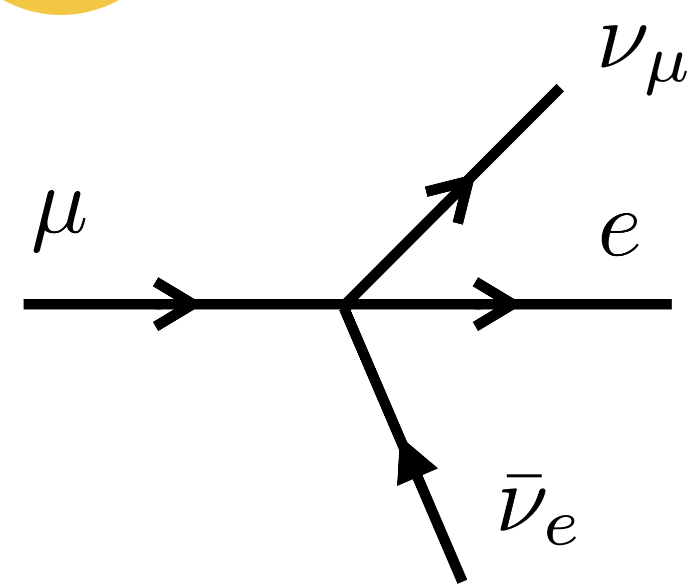
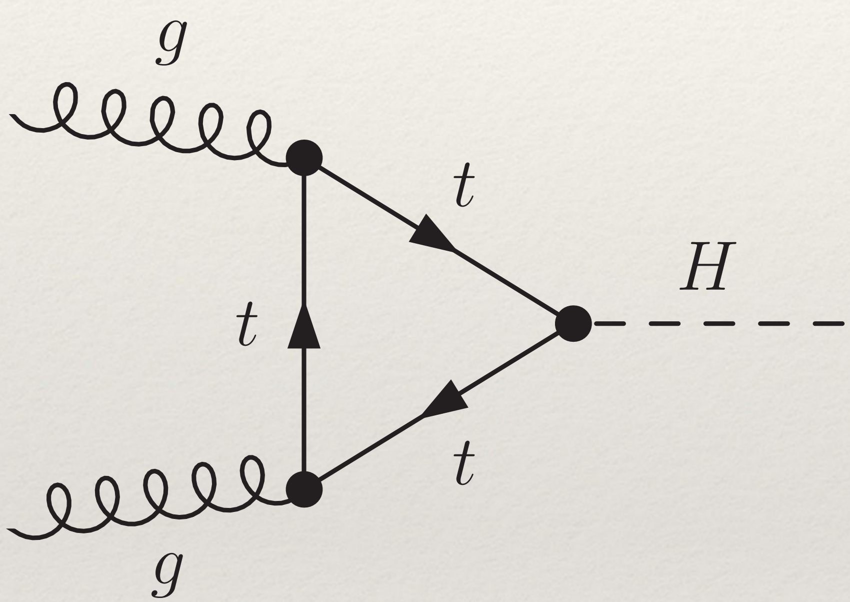


effective theory below m_W

SM-like couplings

- large number of unconstrained EFT parameters lead to phenomenological degeneracies = "blind directions"
- one of the most prominent an relevant for Higgs physics

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



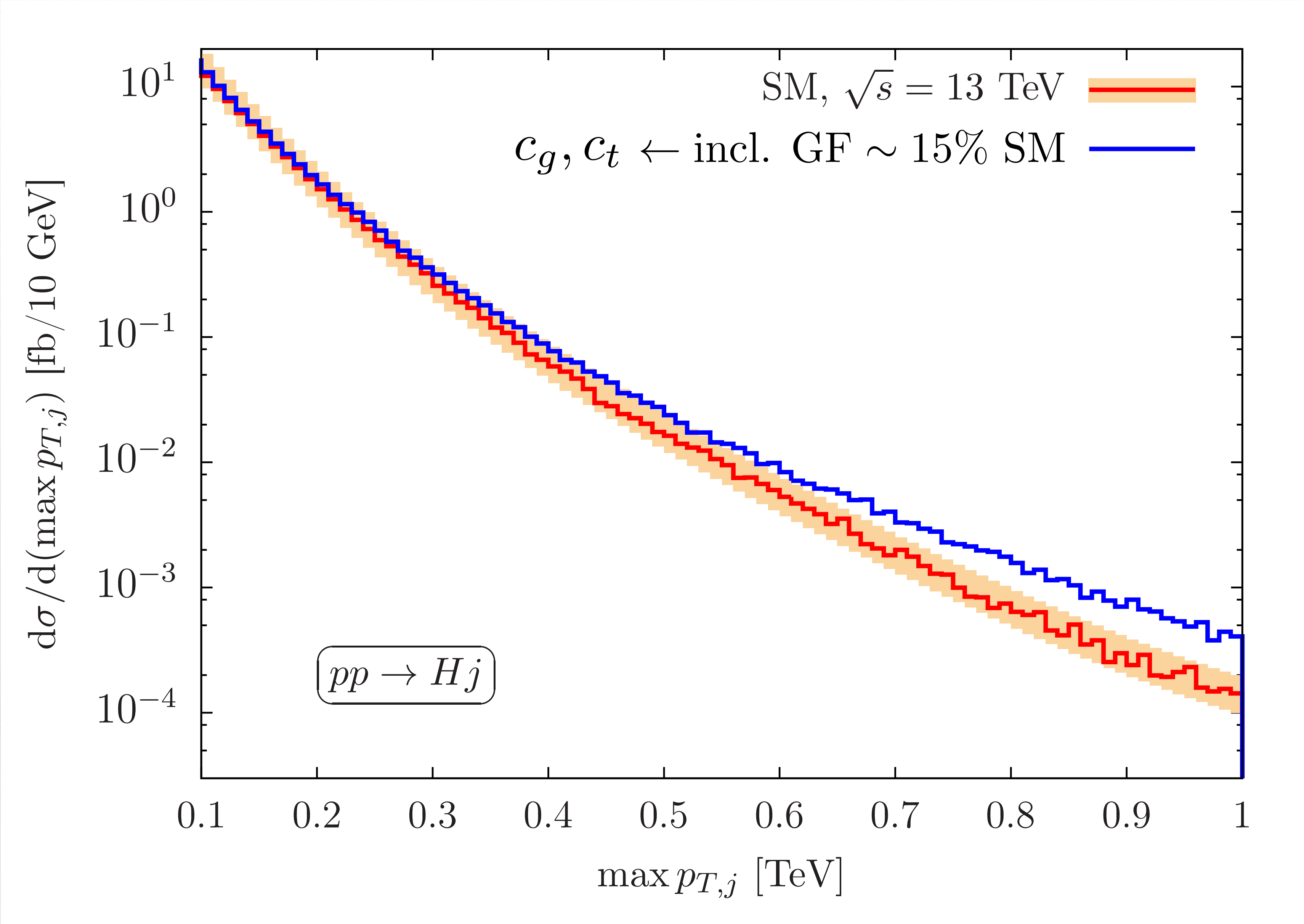
$$\xrightarrow{m_t \to \infty} \quad \subset \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v}$$

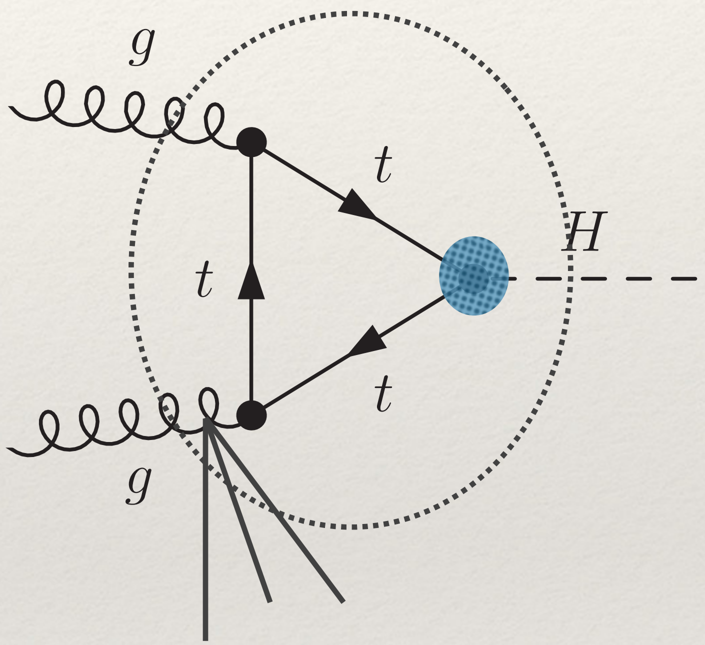
contact ggH interactions mask top Yukawa measurements

- way out: resolve C_0 function 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]

A word of caution





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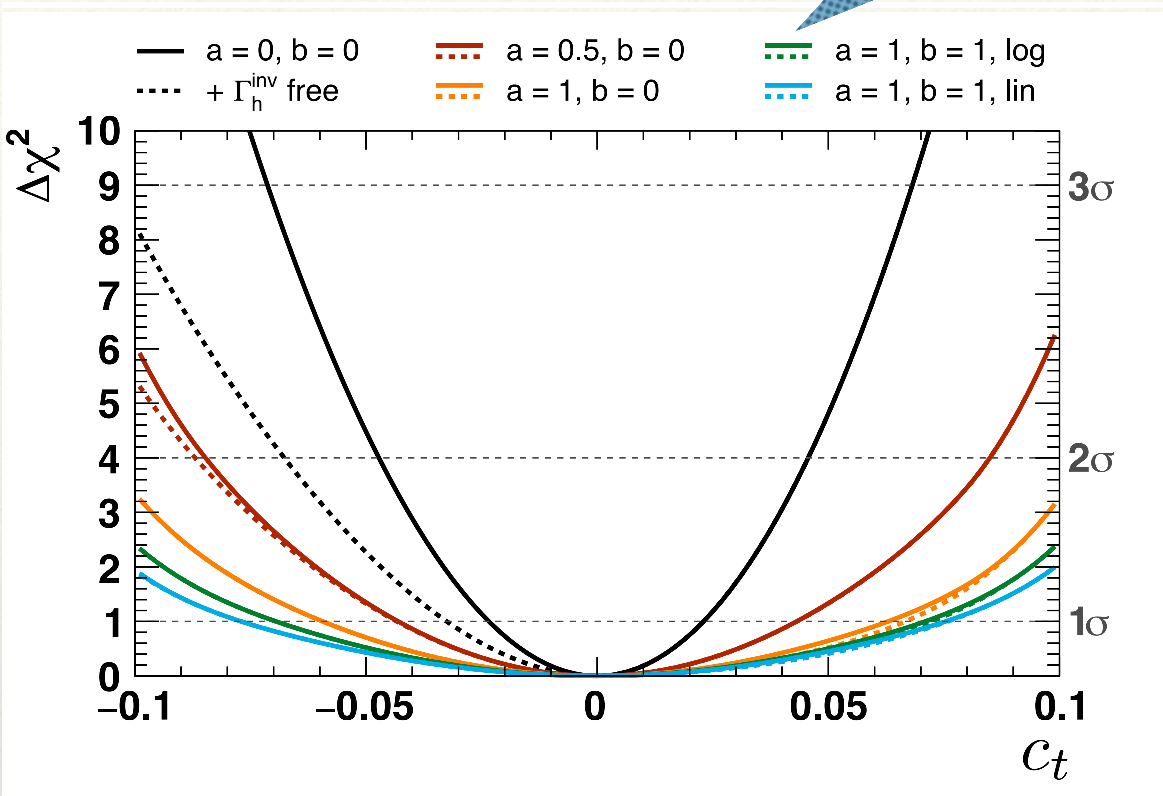
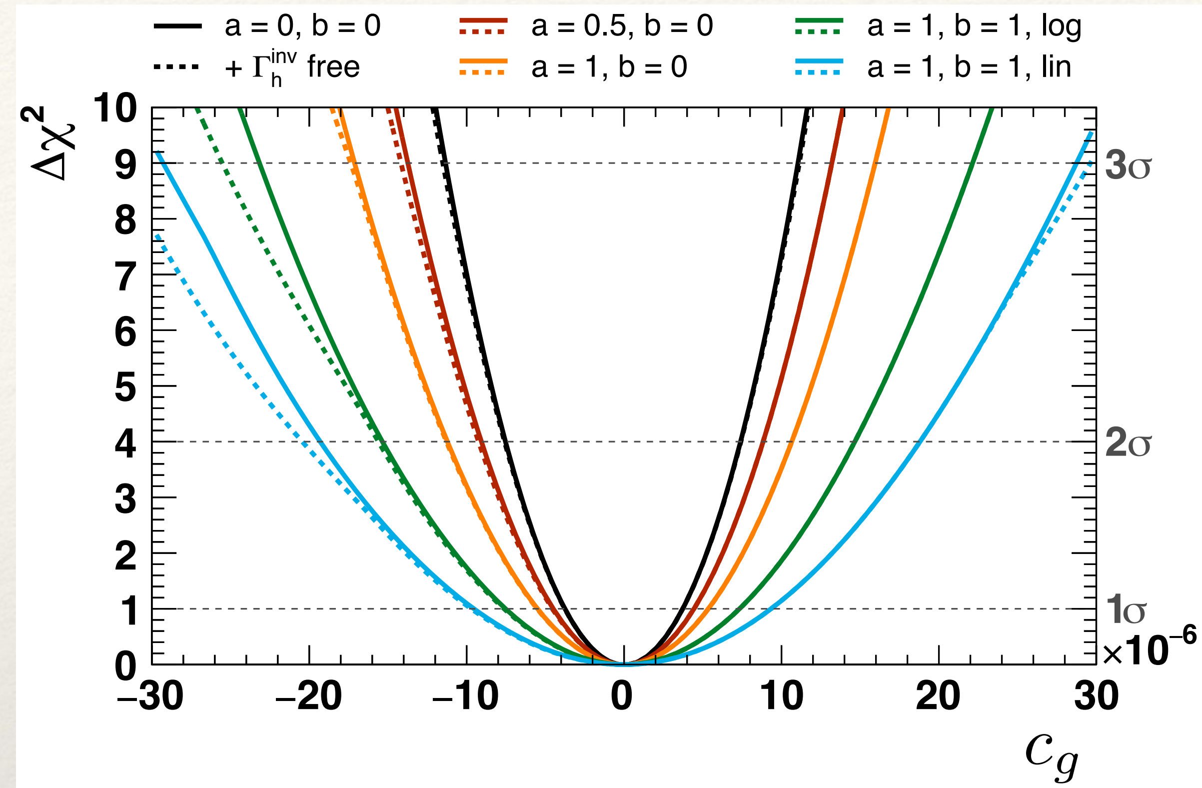
Role of uncertainties

[CE, Kogler, Schulz, Spannowsky ` 17]

steer $p_T(H)$ shape uncertainty



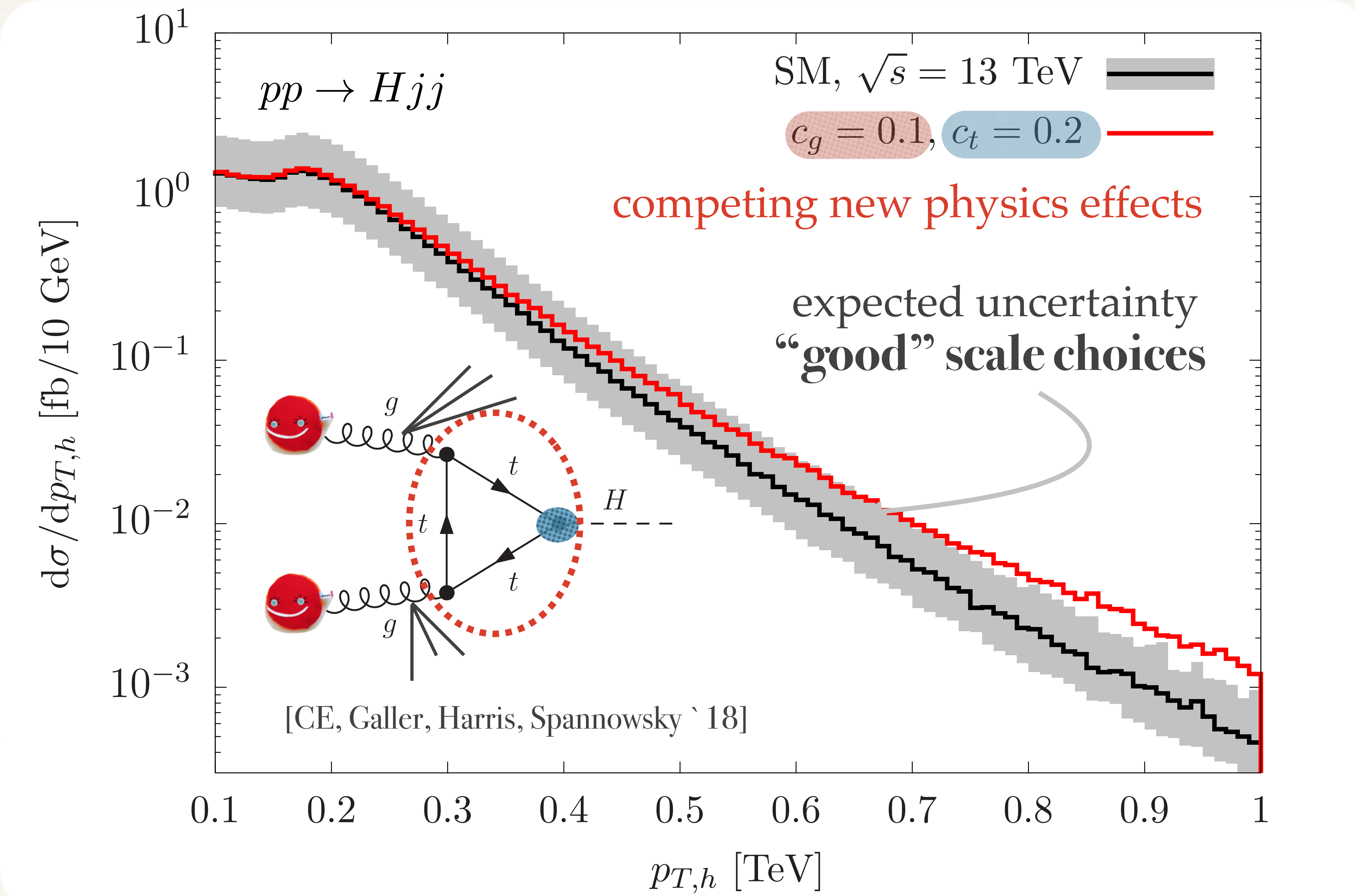


- comparably small impact of tail uncertainties (lin vs log ~ 35% different shape uncertainty at 150 GeV p_T
- **decoupled (non-resonant) new physics perturbatively constrained at relatively low transverse momentum**

large stats!

SM-like couplings

- more kinematic information for H+2j, which is particularly promising, unfortunately $m_t=\infty$ SM limit accidentally good [Del Duca et al. `03] ...



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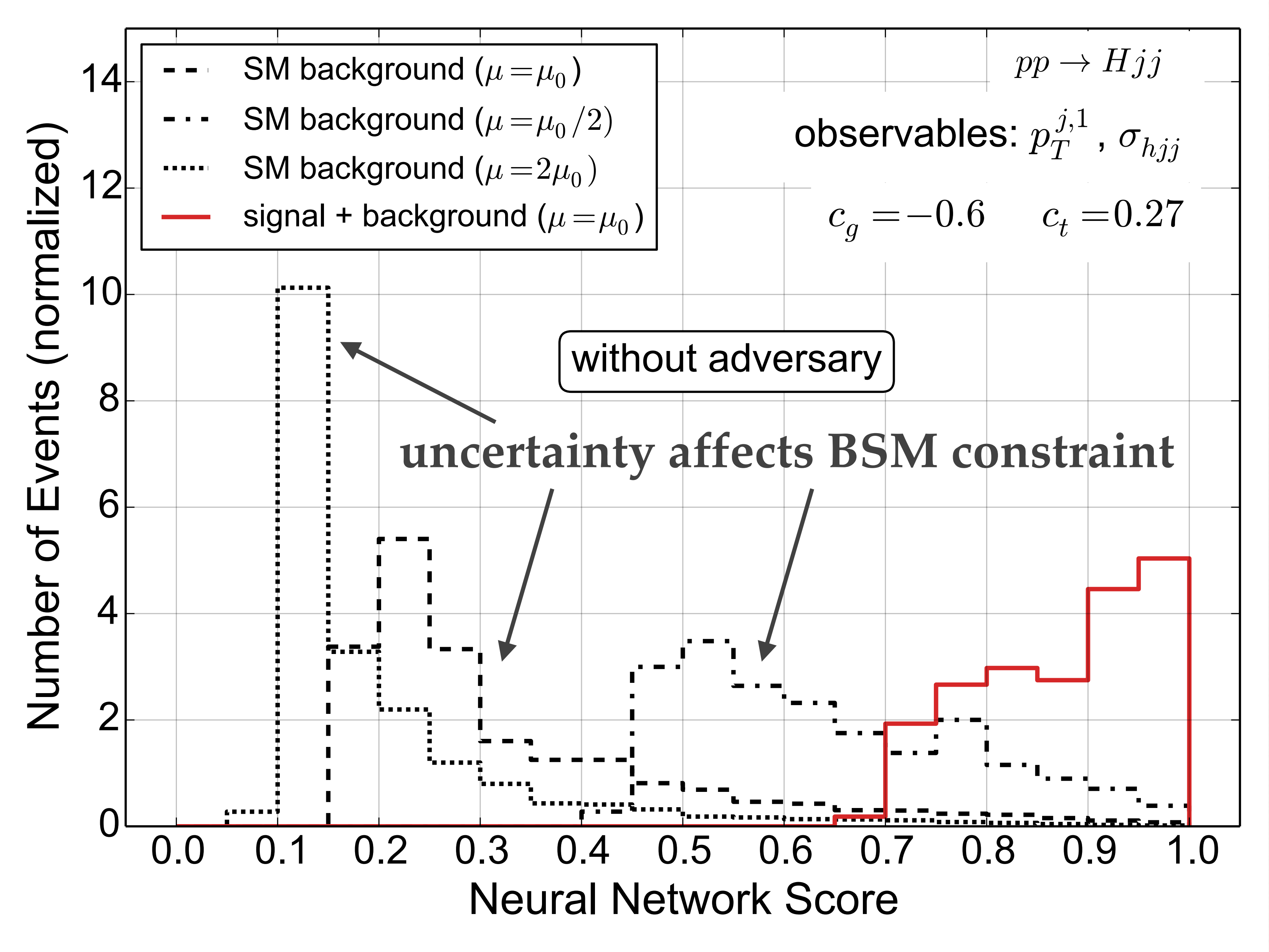

neural net learns regions that are sensitive to uncertainty….

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

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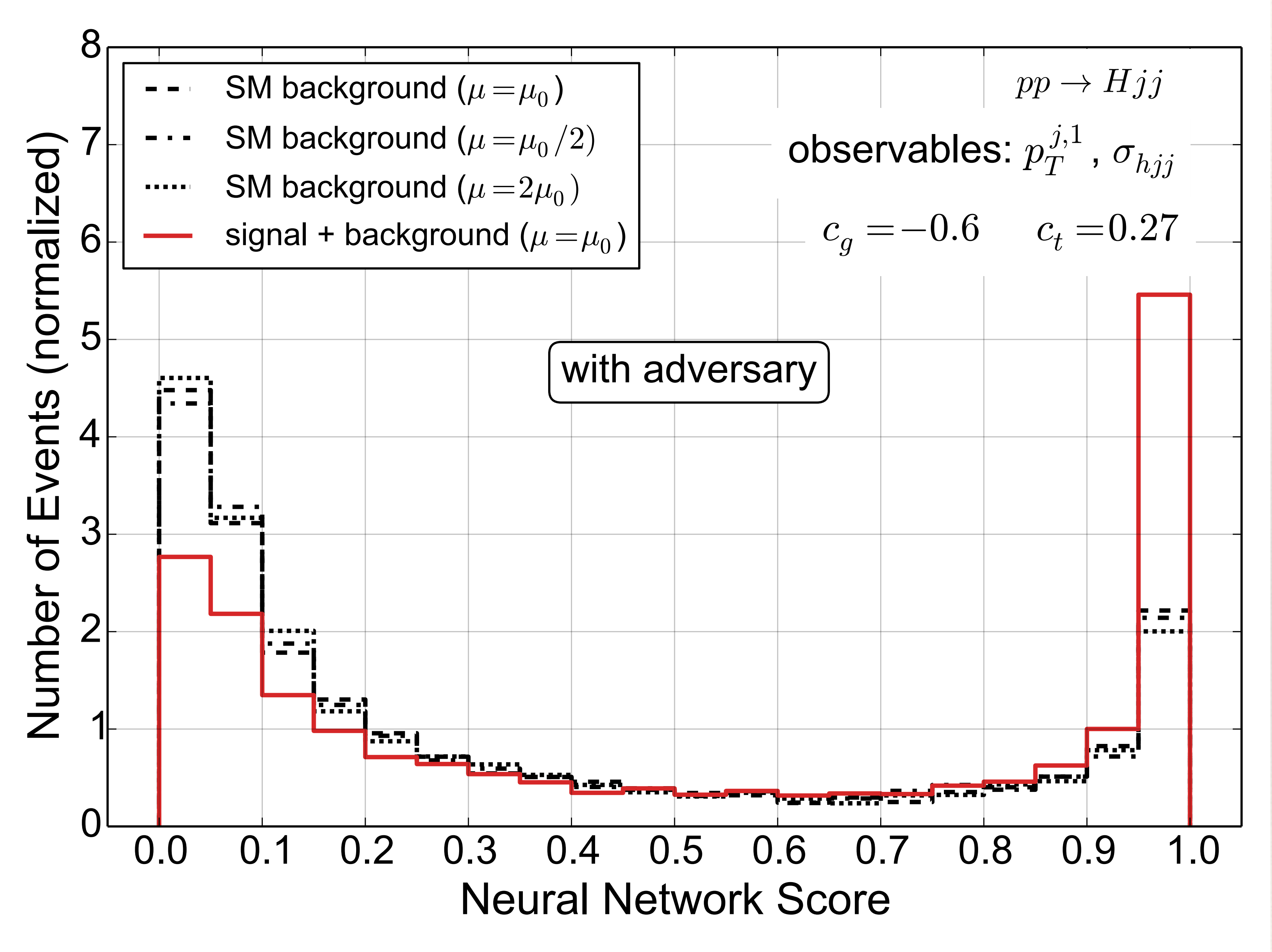

… and can be forced to avoid them → **most robust constraints**

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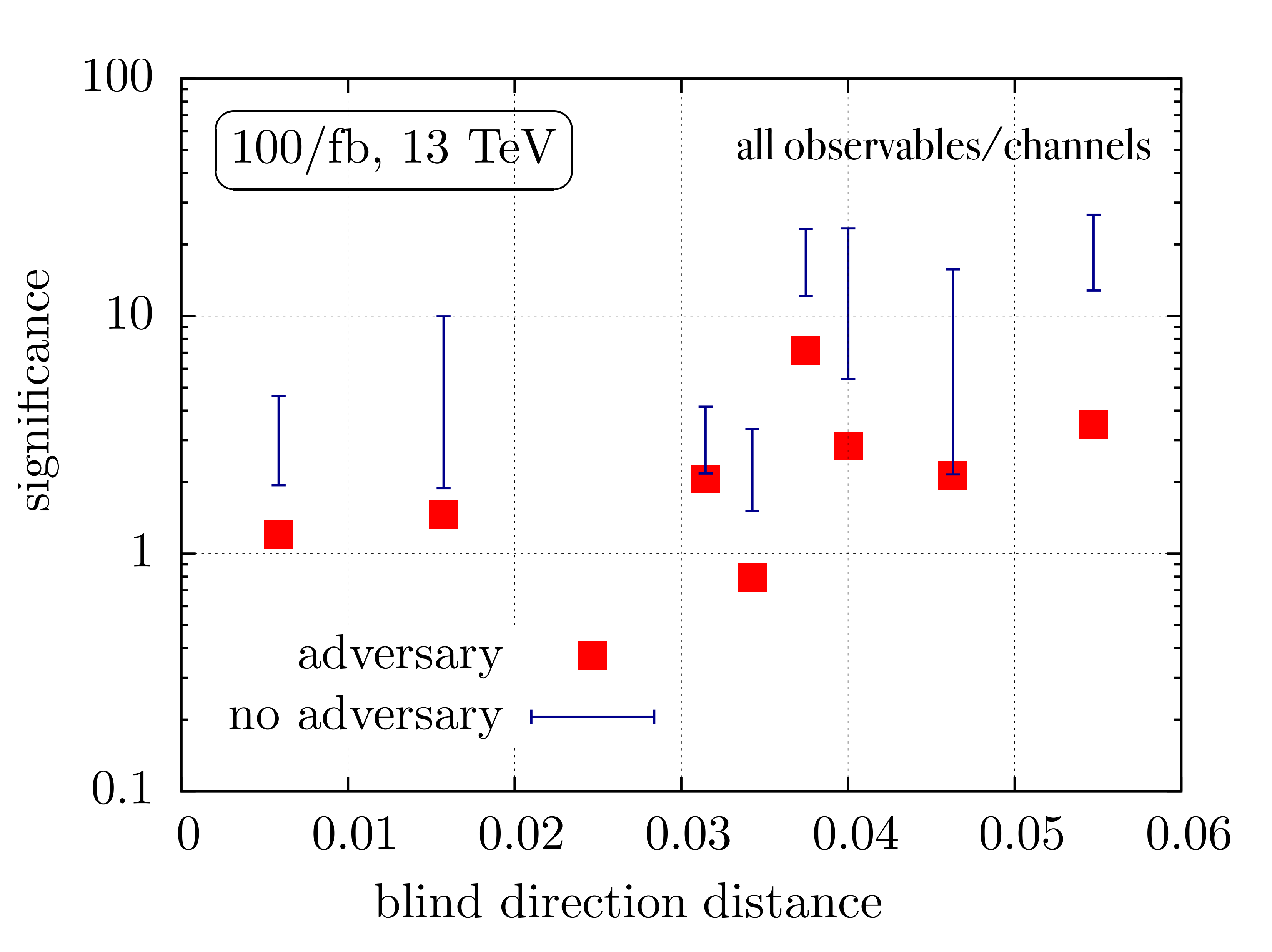

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CP violation

- a repeating point of argument is inclusion of (dim 6)^2 as there is no clear right or wrong

matching

MC perturbativity

unitarity…

$$d\sigma \sim \underbrace{|\mathcal{M}_{\rm SM}|^2}_{\sim \Lambda^0} + \underbrace{2{\rm Re}\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{\rm d6}\}}_{\sim \Lambda^{-2}} + \underbrace{|\mathcal{M}_{\rm d6}|^2}_{\sim \Lambda^{-4}}$$

dim 8…

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- qualitatively different for CP-violation:

naive perturbative power counting

$\frac{c_i}{\Lambda^2}$ **~ dim 6** $\longrightarrow$ **~ (dim 6)^2** $\frac{c_i^2}{\Lambda^4}$

- only genuinely CP-sensitive observables carry information

signed $\Delta\phi_{jj}$, asymmetries, ….

- every CP-even observable carries information

cross sections, widths, p_T spectra…

…[Figy, Hankele, Klämke, Zeppenfeld `06]…

CP violation

[Bernlochner, CE, Hays, Lohwasser, Mildner, Pilkington, Price, Spannowsky ` 18]

- the linearised upshot

$$O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$
$$O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu}\tilde{W}^a_{\mu\nu}\,,$$
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$$O_{H\tilde{W}B} = H^\dagger \tau^a H B_{\mu\nu}\tilde{W}^{a\mu\nu}$$

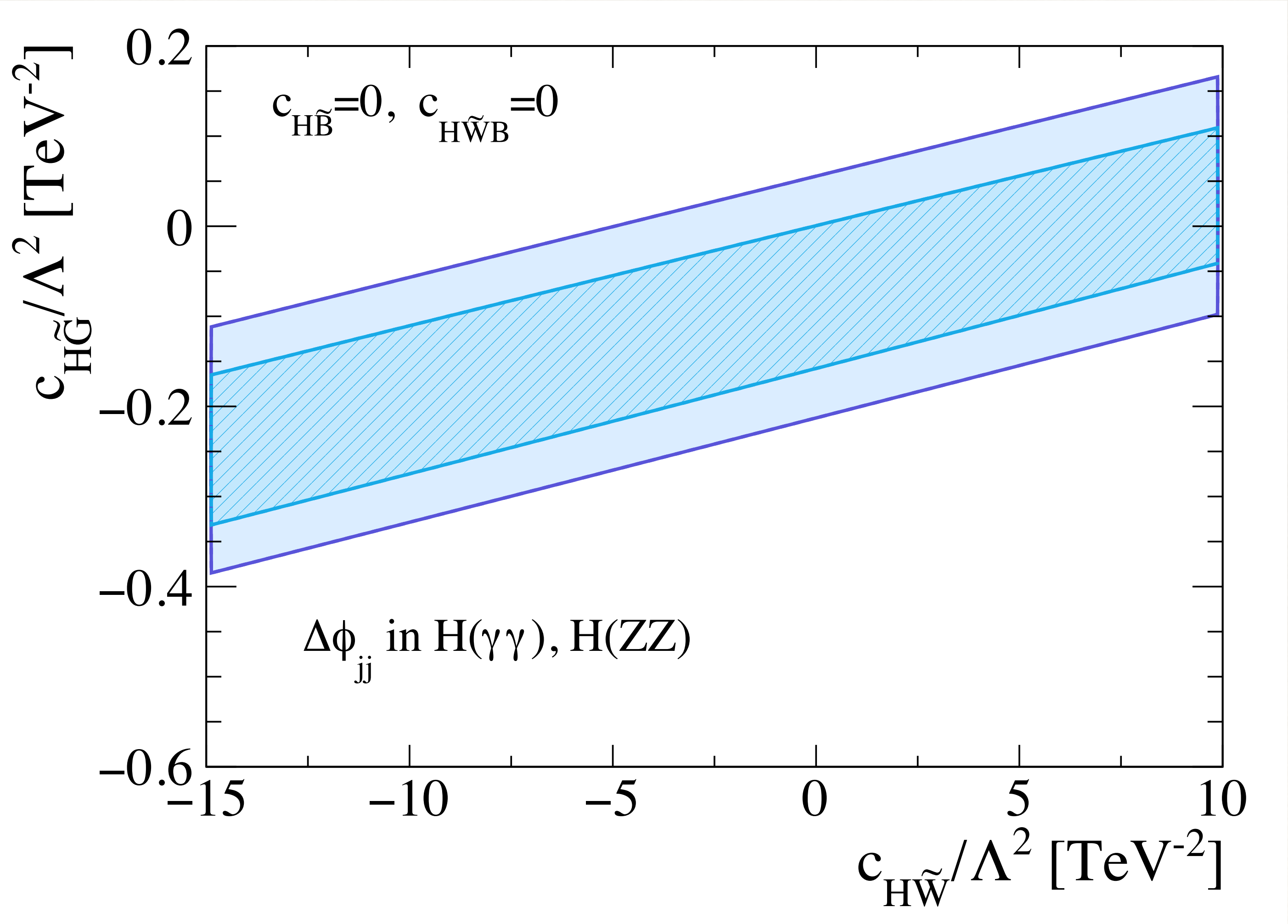
+

$\boxed{\text{Yukawa phases}}$

top quark

$$\sim \frac{\alpha_s}{8\pi v} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} h \;=\tilde{O}_G$$

...ignore them for now...



- fit uses ATLAS results for 4 leptons, $\gamma\gamma$

[ATLAS 1708.02810; 1802.04146]

- small stats/observables = blind directions for decay vs production
- non-significant asymmetry **0.3±0.2**

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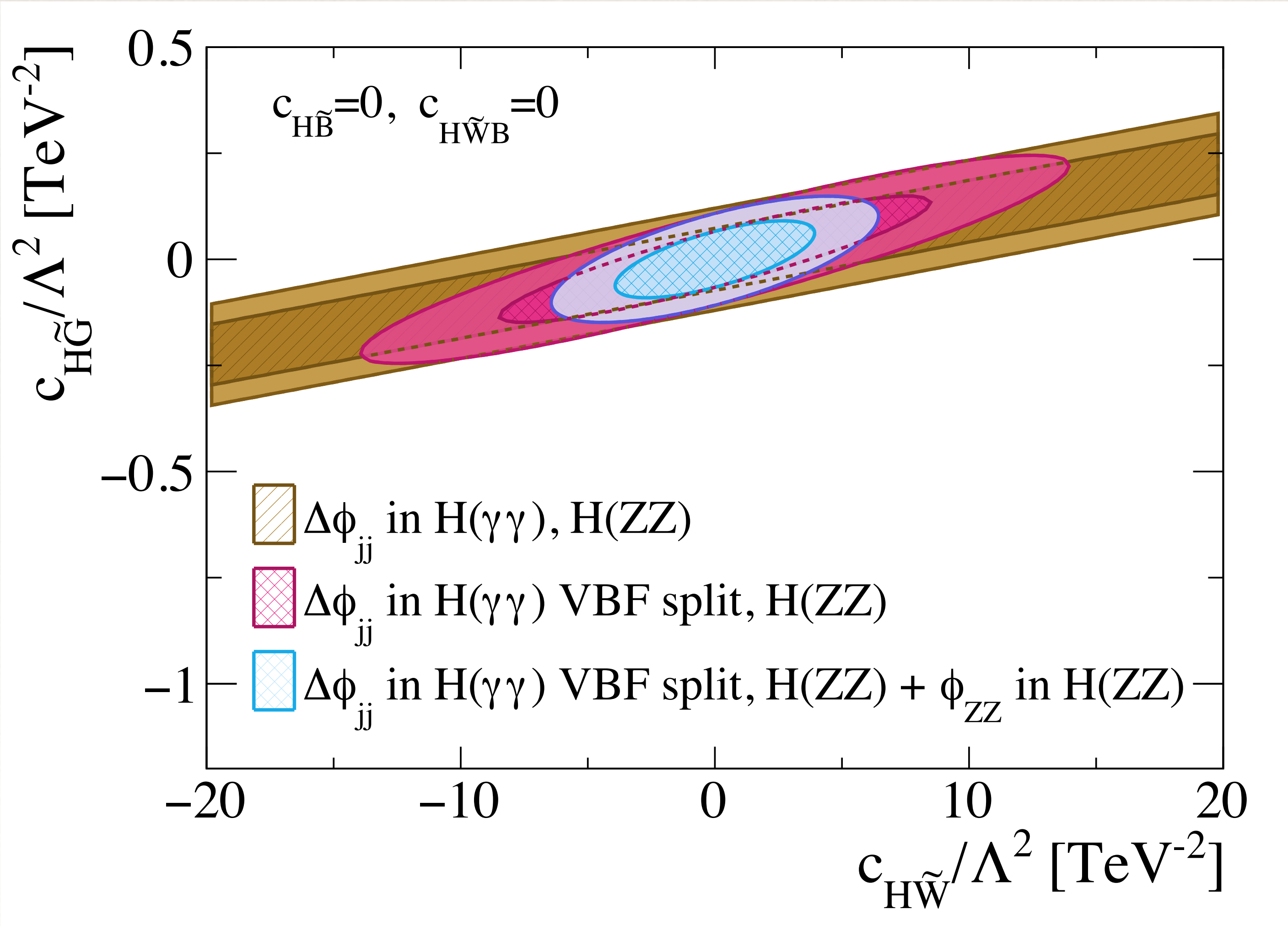

- can already narrow this down with 36/fb by using
  - GF vs VBF selections
  - lepton decay plane angles

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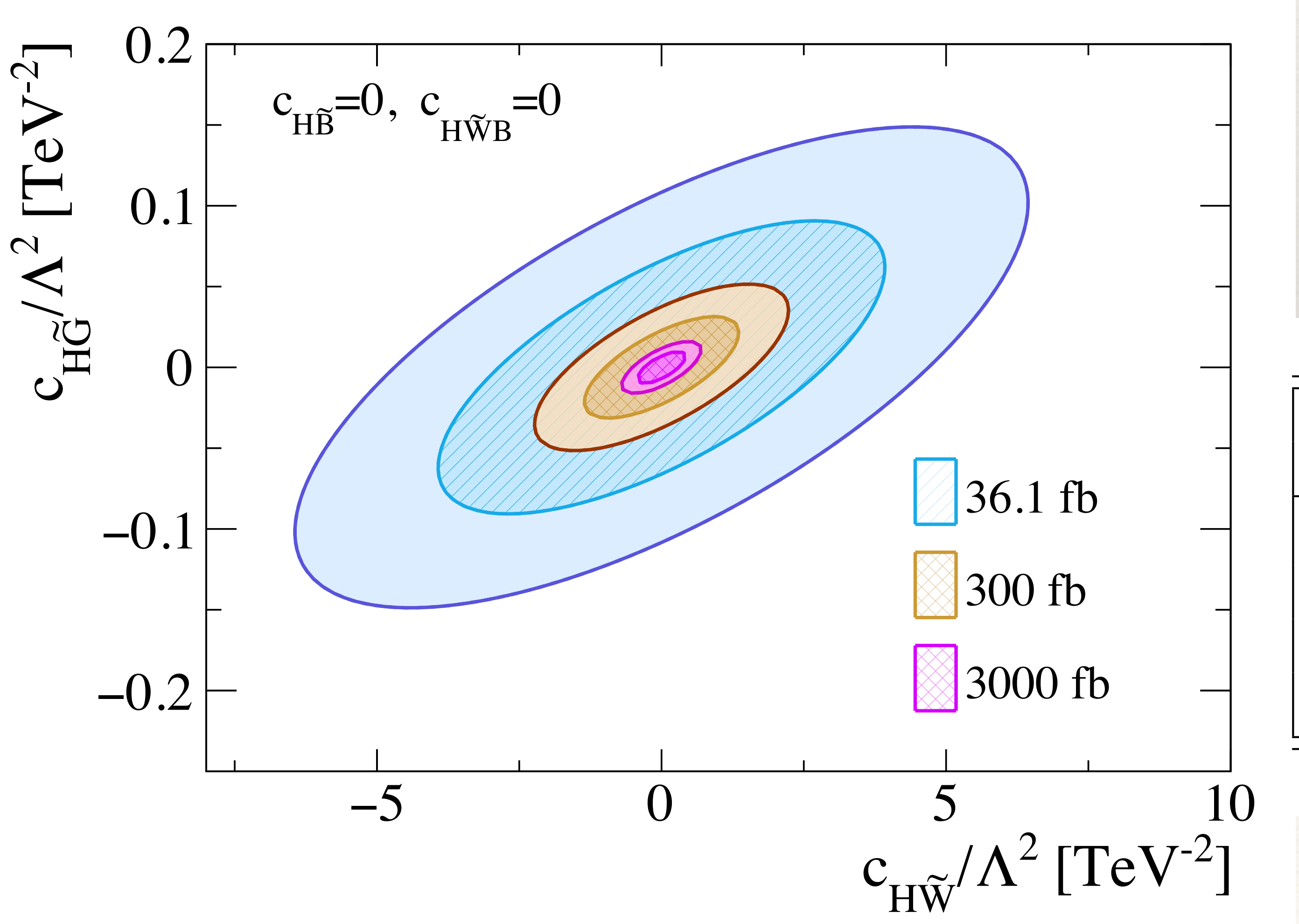

LHC and HL-LHC extrapolations

Coefficient [TeV^{-2}]	36.1 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
$c_{H\tilde{G}}/\Lambda^2$	$[-0.19, 0.19]$	$[-0.067, 0.067]$	$[-0.021, 0.021]$
$c_{H\tilde{W}}/\Lambda^2$	$[-11, 11]$	$[-3.8, 3.8]$	$[-1.2, 1.2]$
$c_{H\tilde{B}}/\Lambda^2$	$[-5.9, 5.9]$	$[-2.1, 2.1]$	$[-0.65, 0.65]$
$c_{H\tilde{W}B}/\Lambda^2$	$[-14, 14]$	$[-4.9, 4.9]$	$[-1.5, 1.5]$

CP violation

[CE, Galler, Pilkington, Spannowsky in prep.]

- lifting top-specific blind directions

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[Del Duca et al. `03]

- $m_t = \infty$ SM limit accidentally good

large stats / kin. coverage necessary

- split GF selection into m_t-related Higgs p_T threshold ~ 150 GeV

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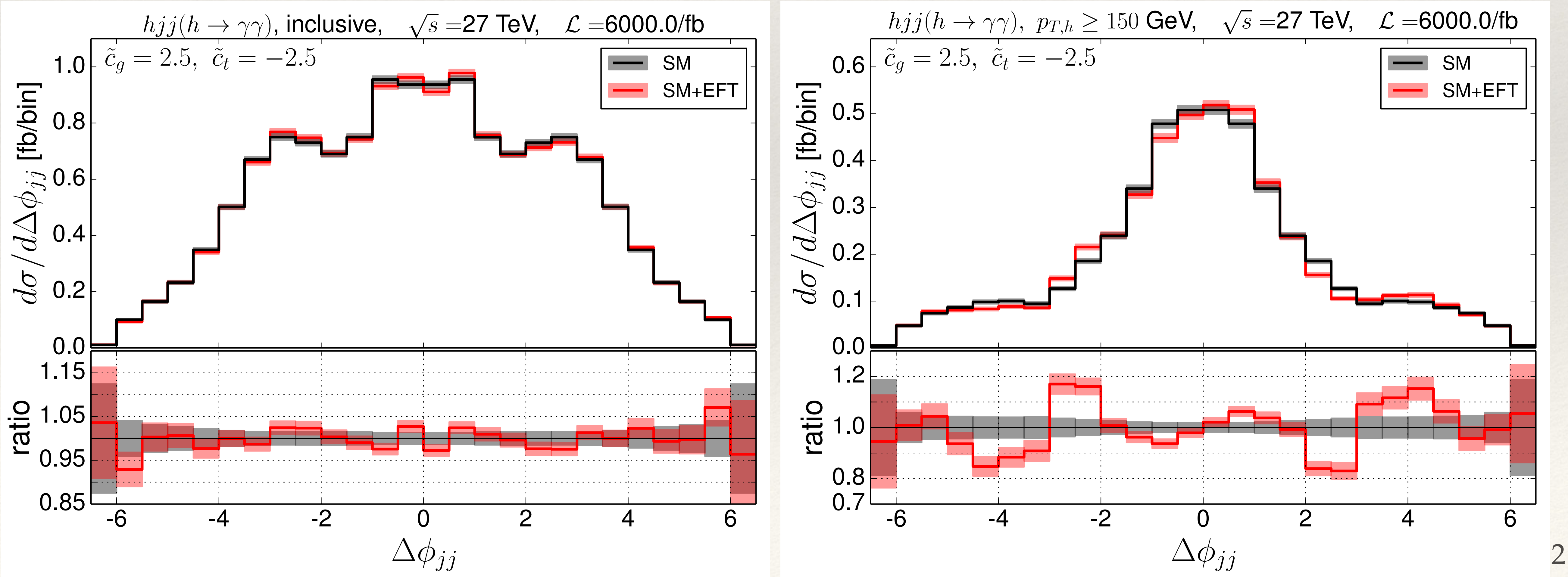

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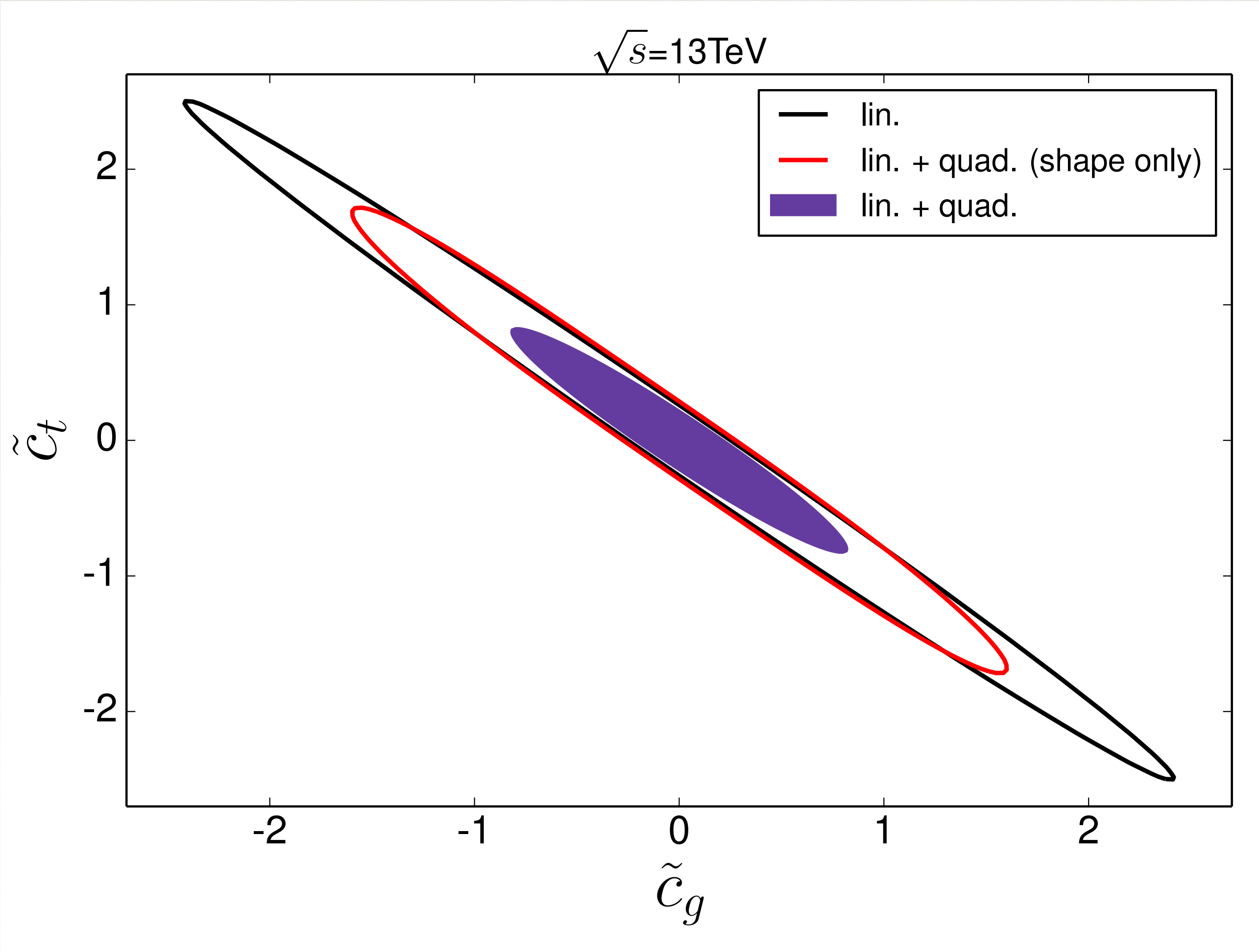

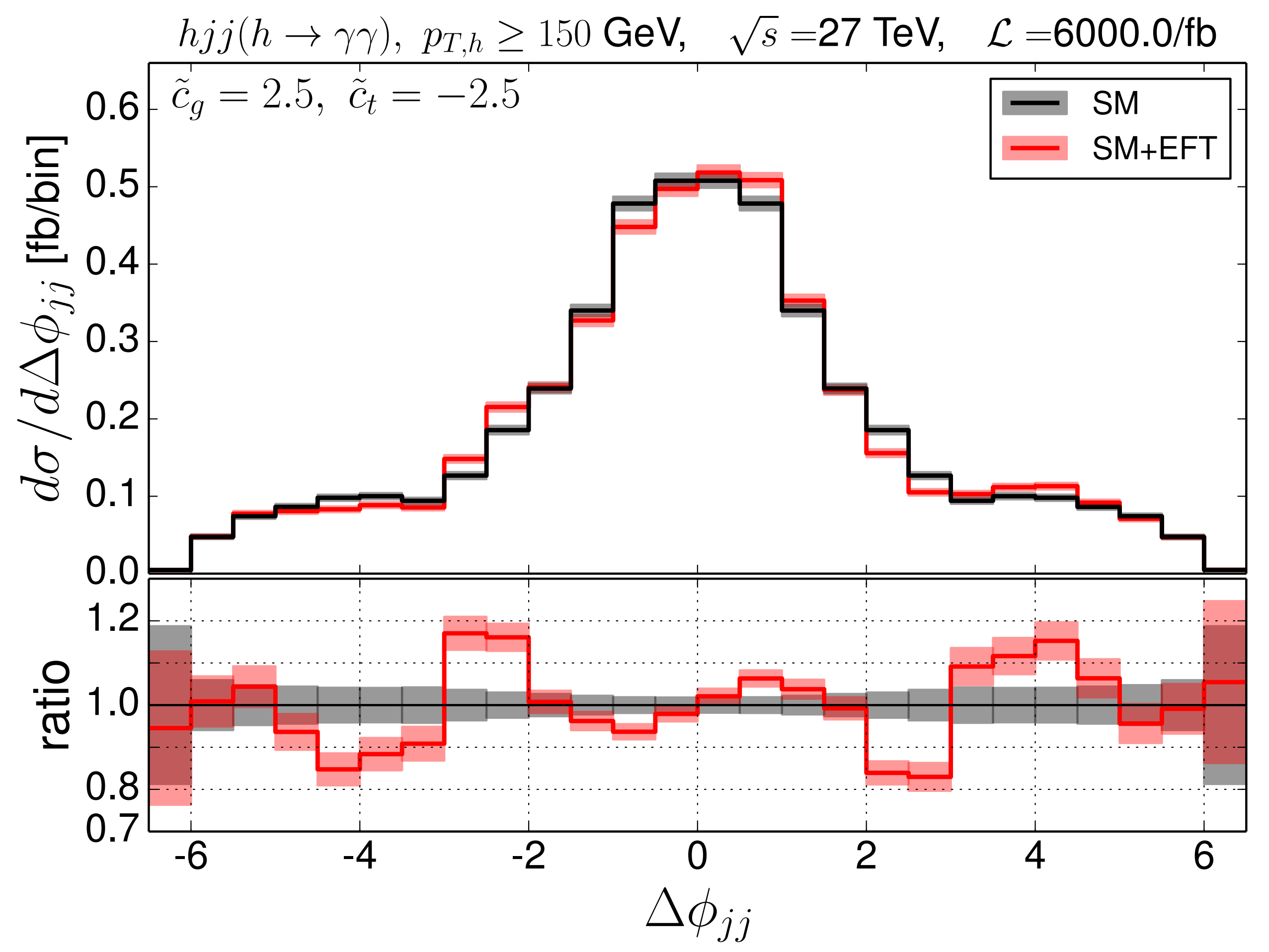

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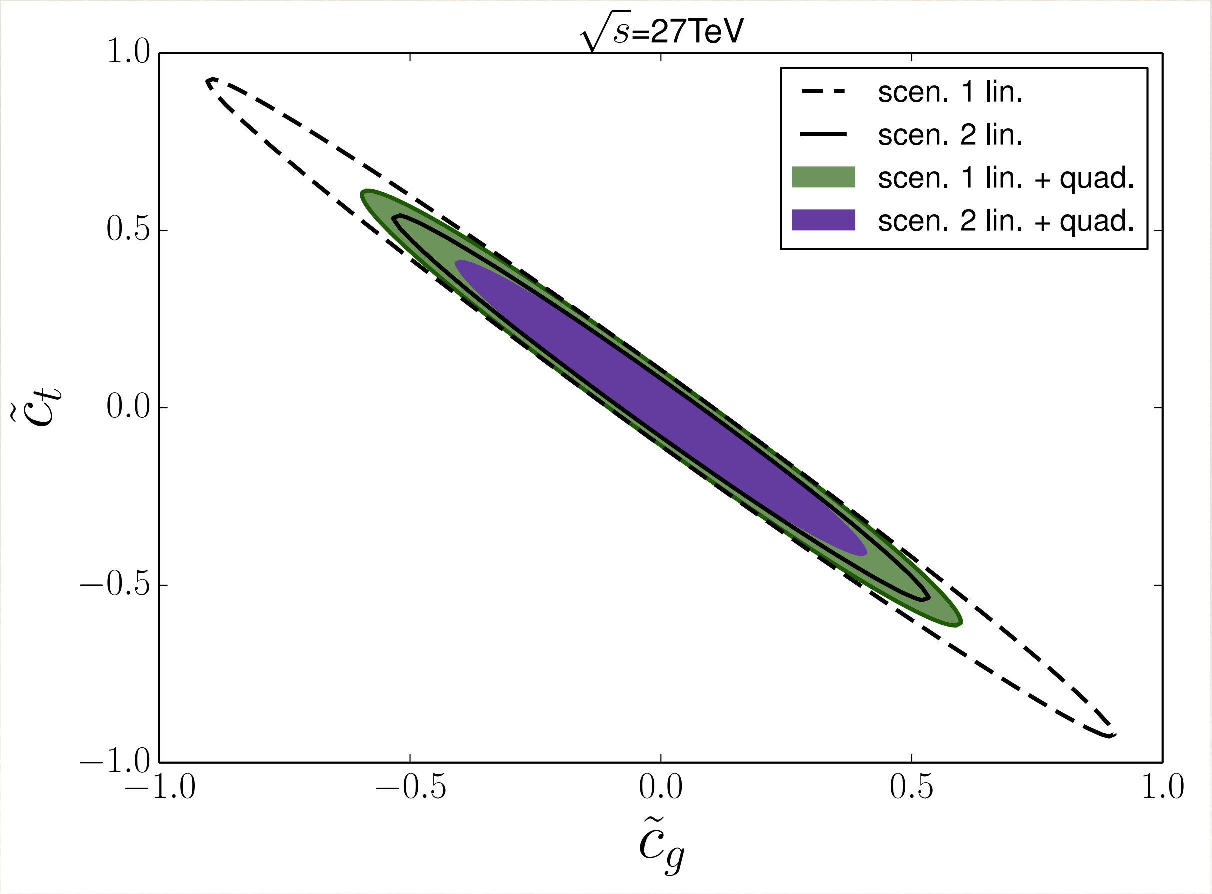
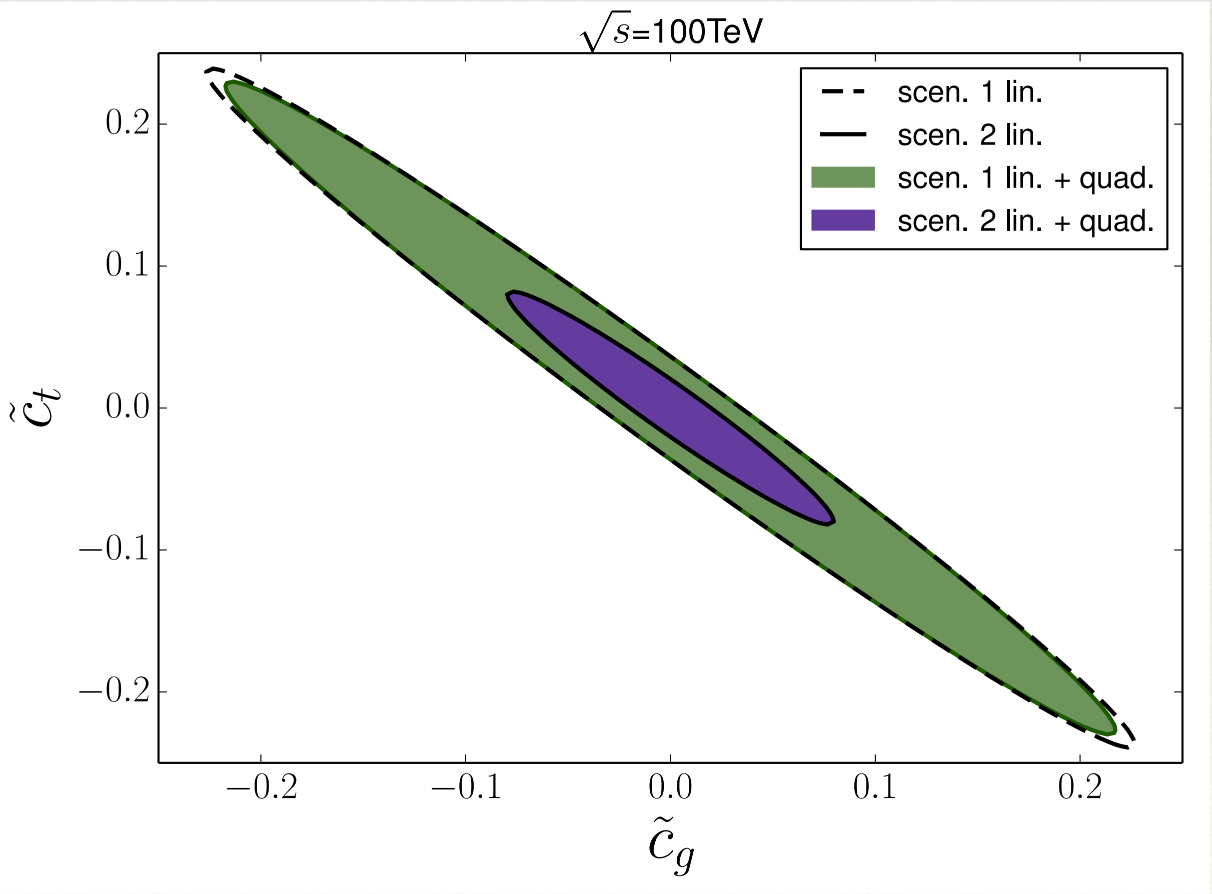




HH pheno

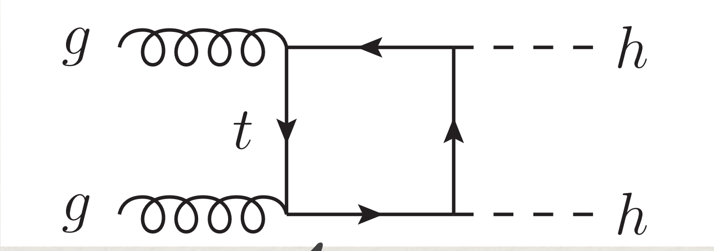
LHC blind spots: Higgs potential

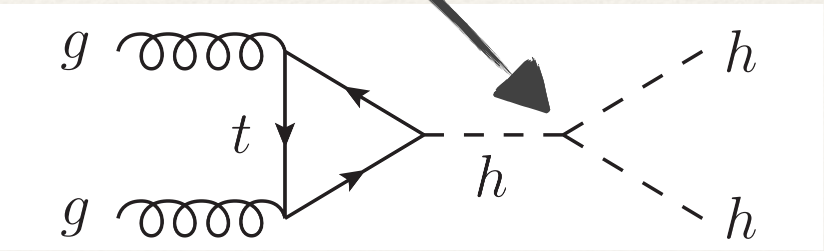
- dimension 6 deformations of the Higgs potential

$$V(H^\dagger H)_6 \supset c_6/\Lambda^2 (H^\dagger H)^3$$

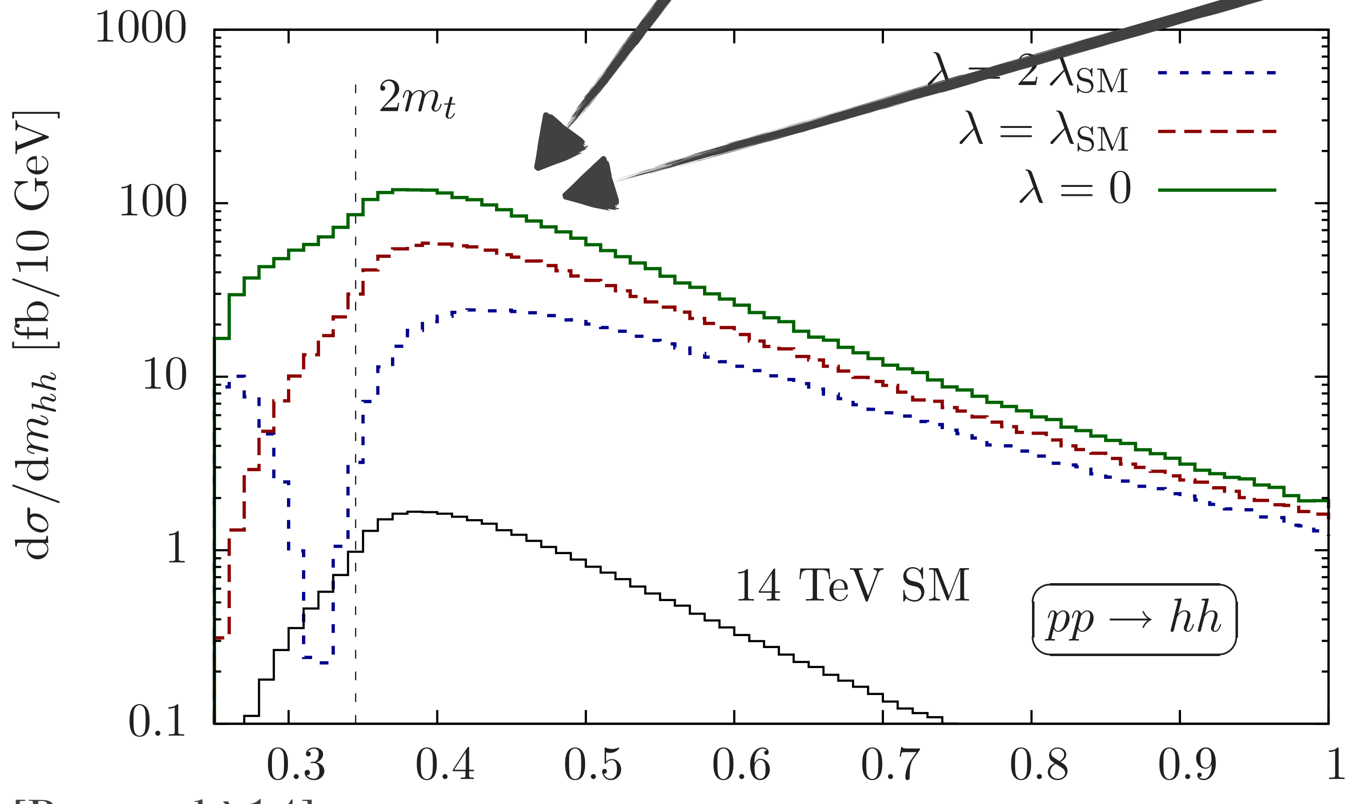
e.g.
[Giudice, Grojean, Pomarol, Rattazzi `07]

modify Higgs self-interactions. Large top-threshold interference.



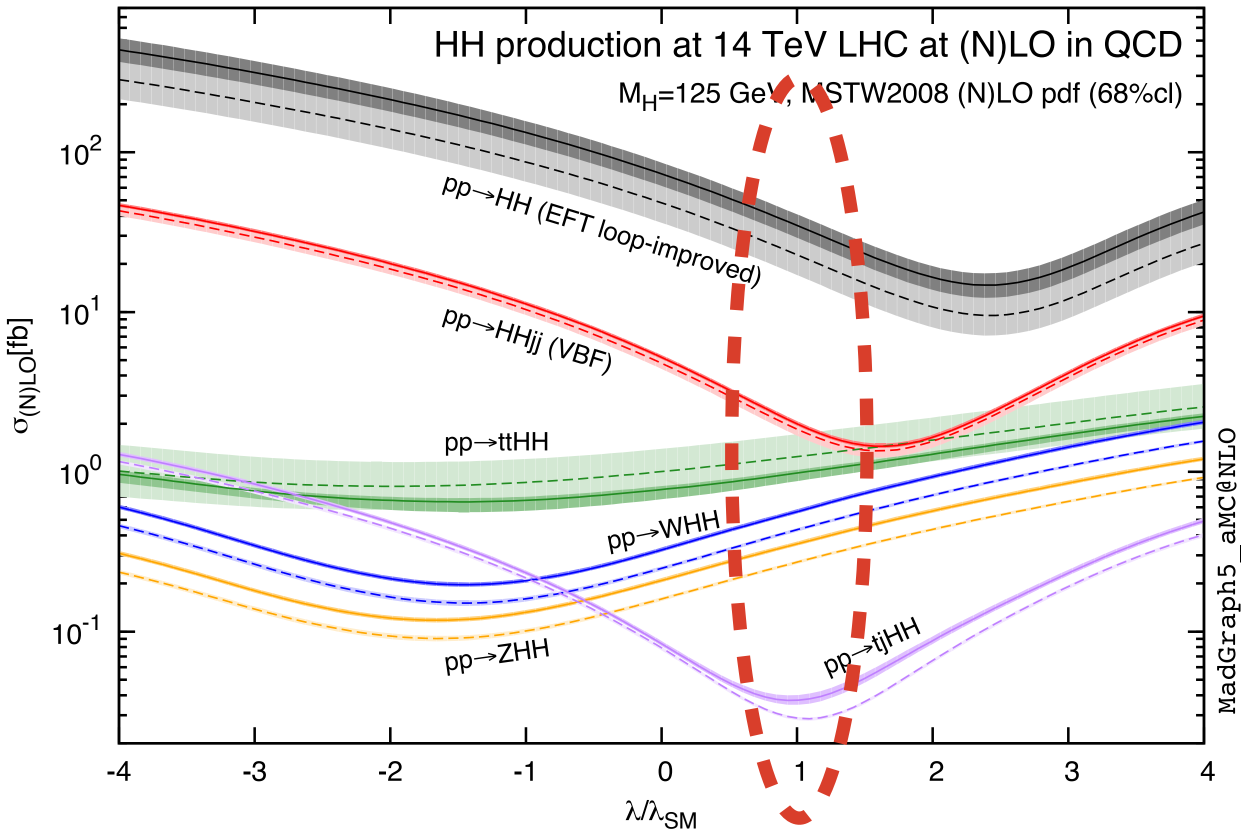


e.g.
[Glover, van der Bij `88]

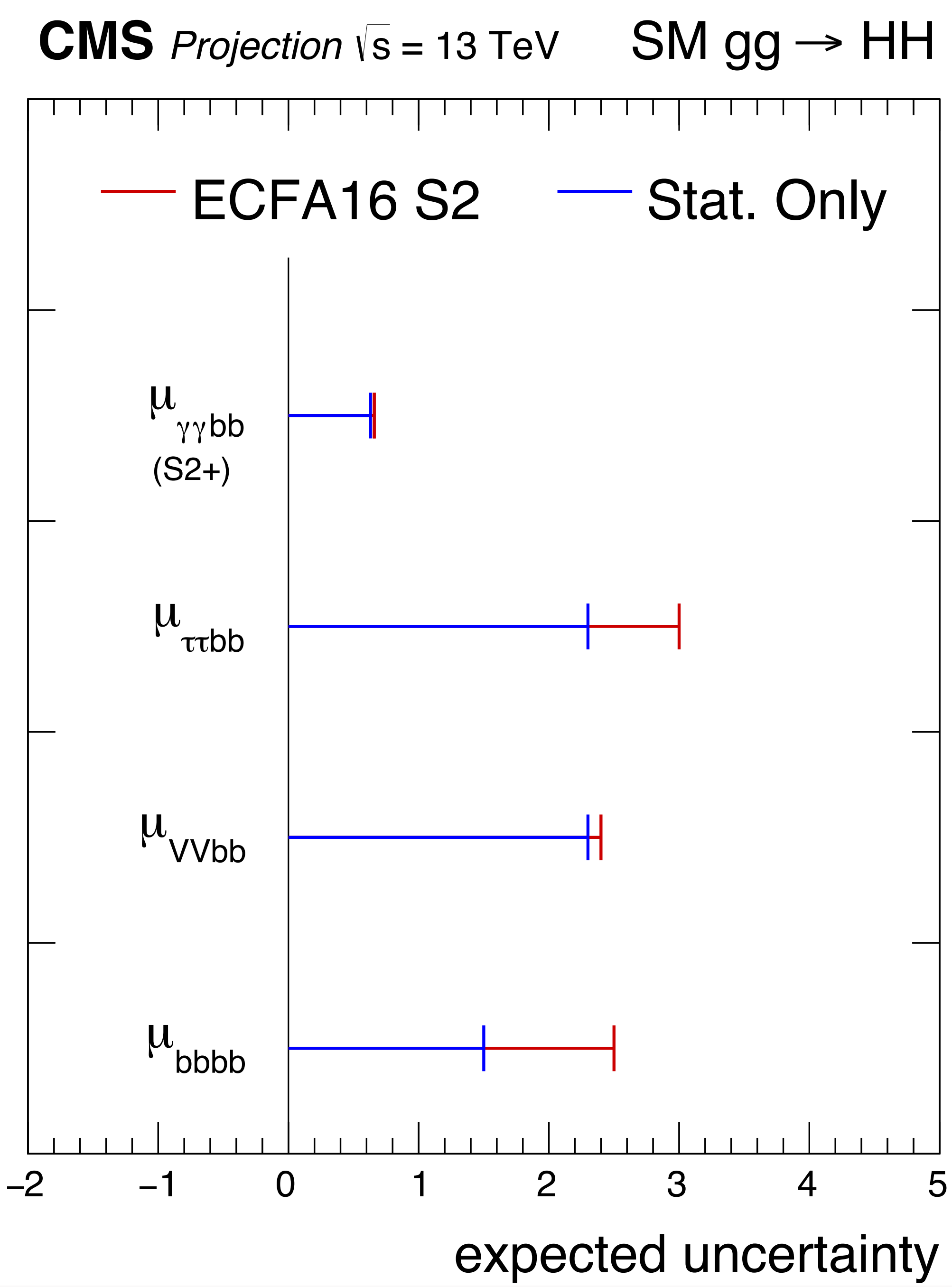


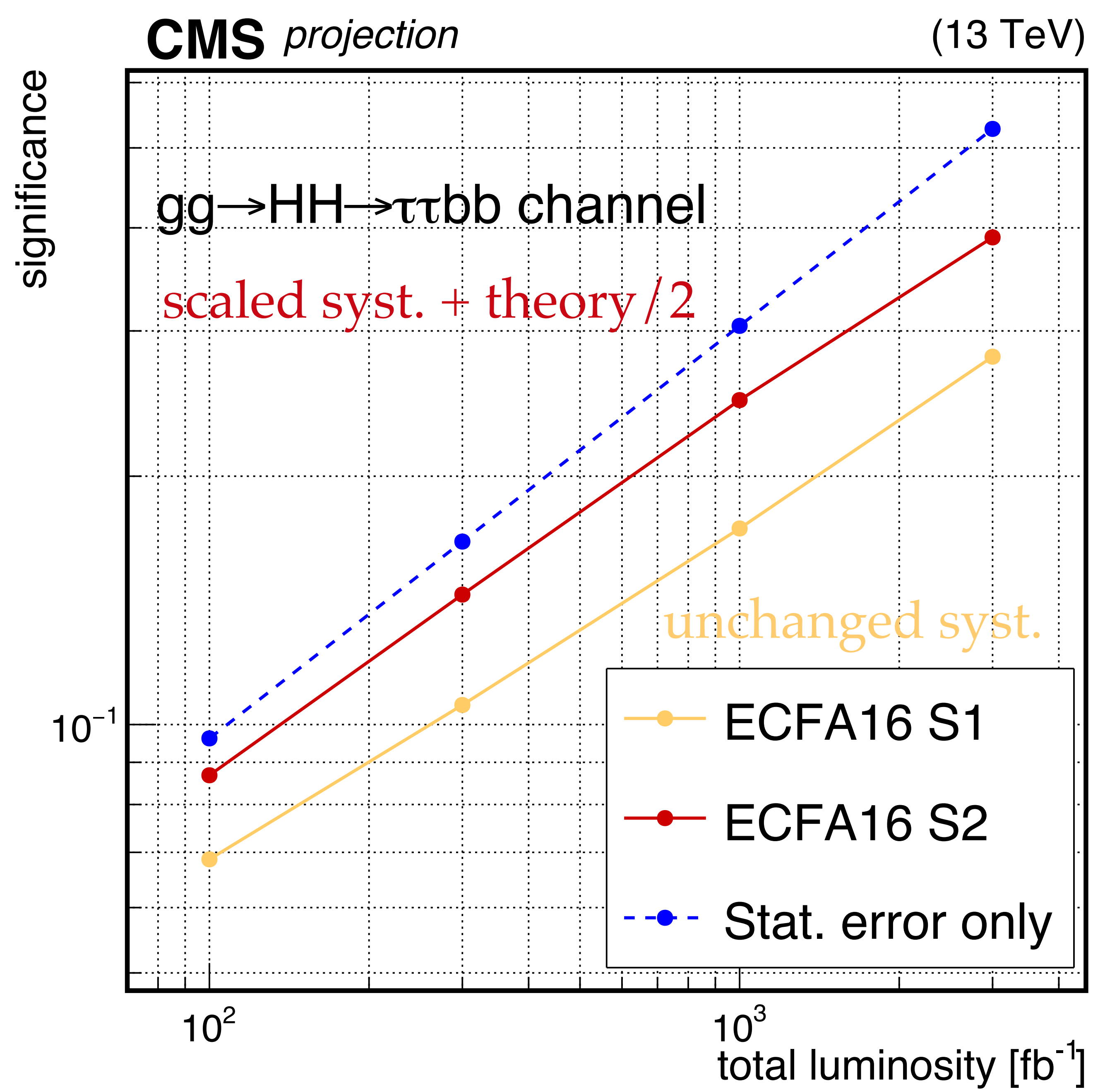
[Barr et al `14]

[Frederix et al `14]



LHC blind spots: Higgs potential





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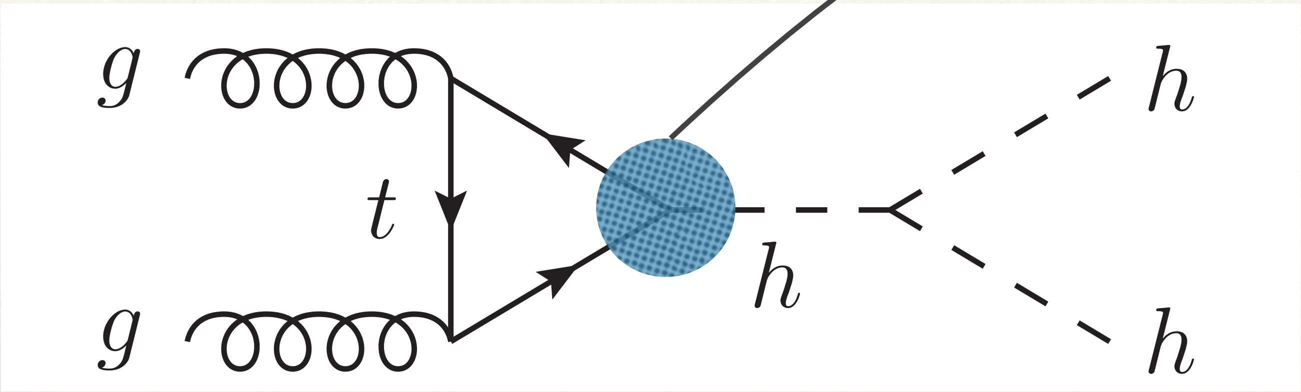
- however…

correlated with on-shell Higgs phenomenology



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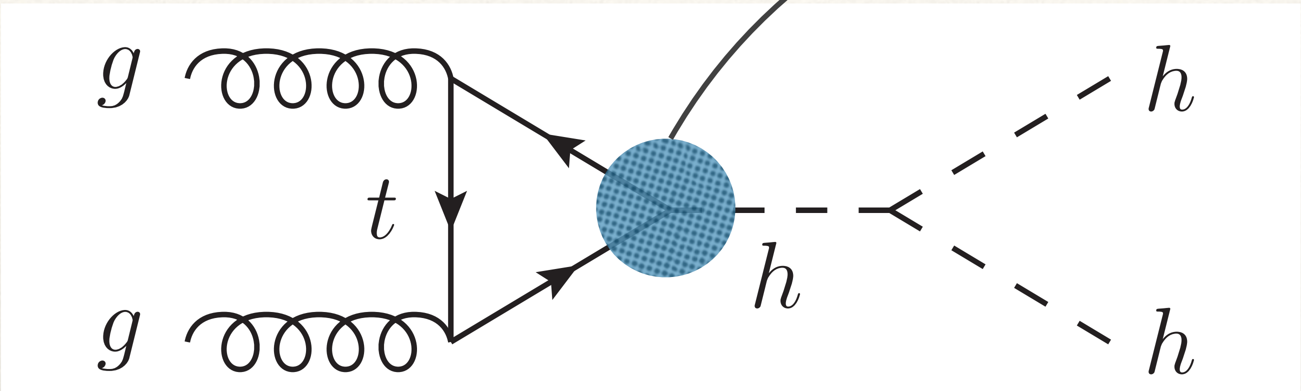
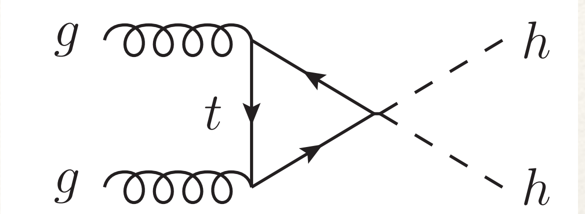
broken by $\sim \bar{t}th^2/\Lambda$….





[Gröber, Mühlleitner `10]

- easy to arrange EFT coefficients in a way to get spectacular rates, but can doubt physical relevance of such limits ($\rightarrow$ matching)

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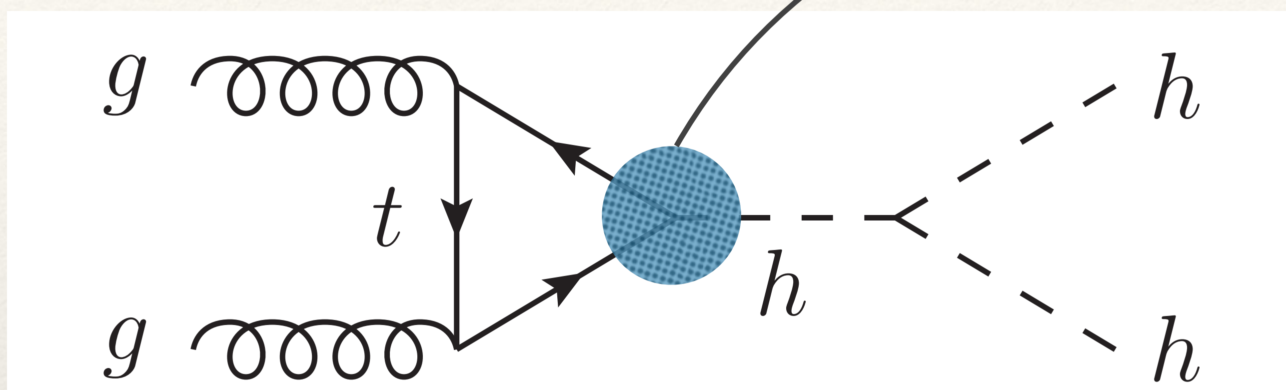

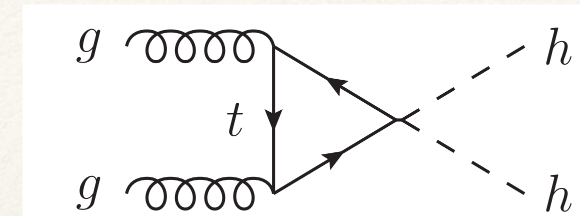

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- bit what about concrete Higgs sector extensions?
  - extrapolate 125 GeV signal strengths
  - extrapolate exotic Higgs searches
  - additional constraints (*electron EDMs, flavor, perturbativity, …*)

HH pheno

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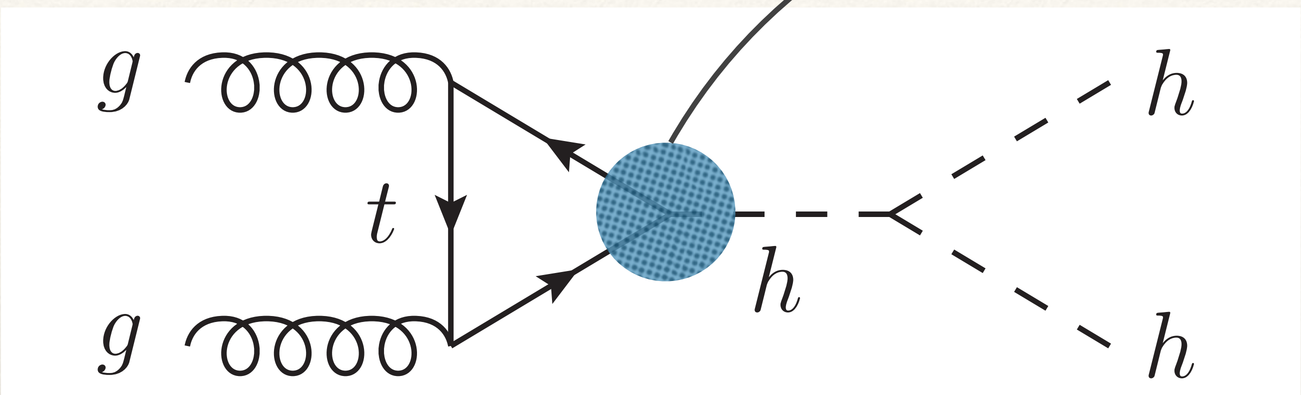

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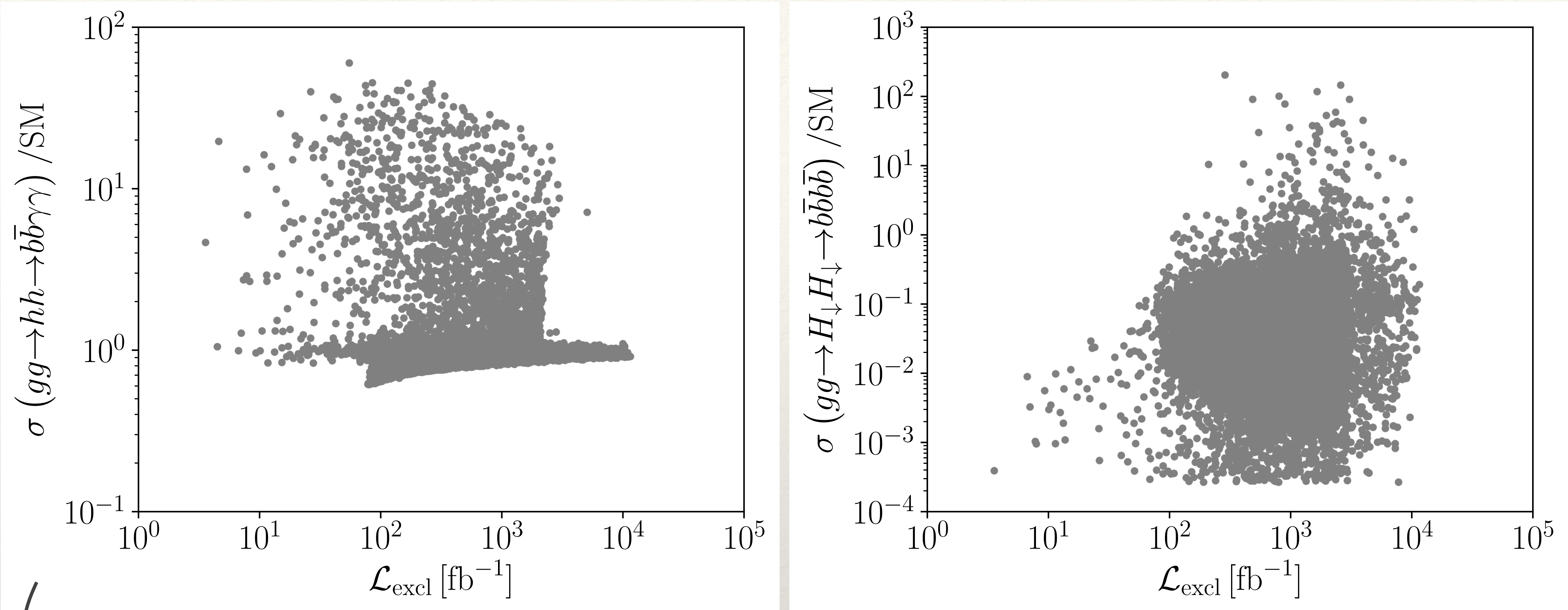
in how far are di-Higgs final states still relevant at 3/ab?

C2HDM & NMSSM

[Basler, Dawson, CE, Mühlleitner ` 18]



SM-like measurements can show a plethora resonant anomalies
diHiggs final states important for BSM discovery

…diHiggs final states quickly lose relevance when approaching EFT limit

C2HDM & NMSSM

[Basler, Dawson, CE, Mühlleitner ` 18]

above Higgs pair threshold

- (multi) resonant diHiggs production (hh, hH,…)

opportunity for diHiggs

Higgs interactions dominant

exotics with large couplings to tops

top interactions dominant

above top pair threshold

- tt final states preferred
- analysis highly model-dependent due to dedicated S-B interference

below top pair threshold

- compressed spectra
- single Higgs competitive except b-final states (*trigger etc…*)

opportunity for diHiggs

- *Advances have been extremely rapid*
  - good understanding of EFT
  - simulation
  - limit setting - machine learning

- *Opportunity to link the Higgs sector to new physics*
  - cure SM shortcomings (CP violation…)
  - multi-Higgs production as a chance for BSM
  - LHC probably not be enough to achieve this in full glory