IAS HKUST workshop

10/01/2019

Christoph Englert

Three avenues for Higgs phenomenology

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

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  - .....
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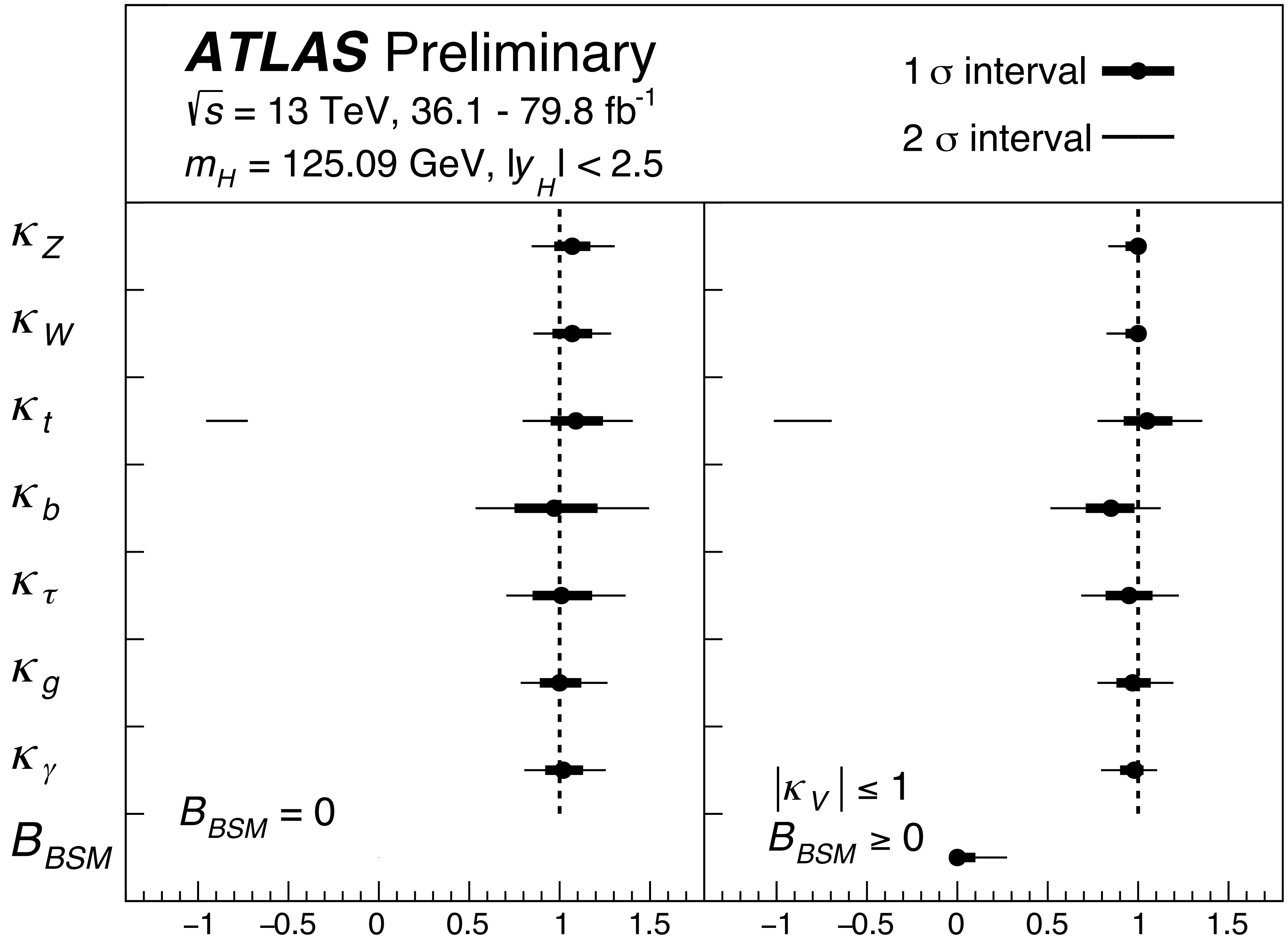
  - .....
- *Constraining/observing the unexpected:*
  - Higgs sector CP violation
  - .....
- *Closing in on new physics in the Higgs sector*
  - *di-Higgs production as a probe of new physics*
  - .....

Status of LHC Higgs 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 ⊗ flavor ⊗ h.c., d=6
2499 parameters (reduces to 76 with N_f=1)

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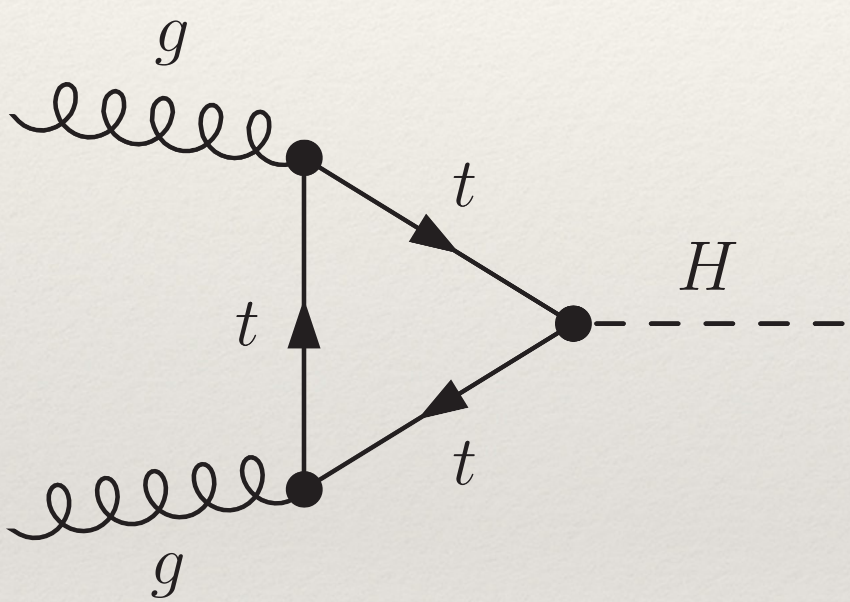
concrete models

- extended SMEFT
- (ℂ) Higgs portals
- 2HDMs
- (N)MSSM
- compositeness….

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]
....

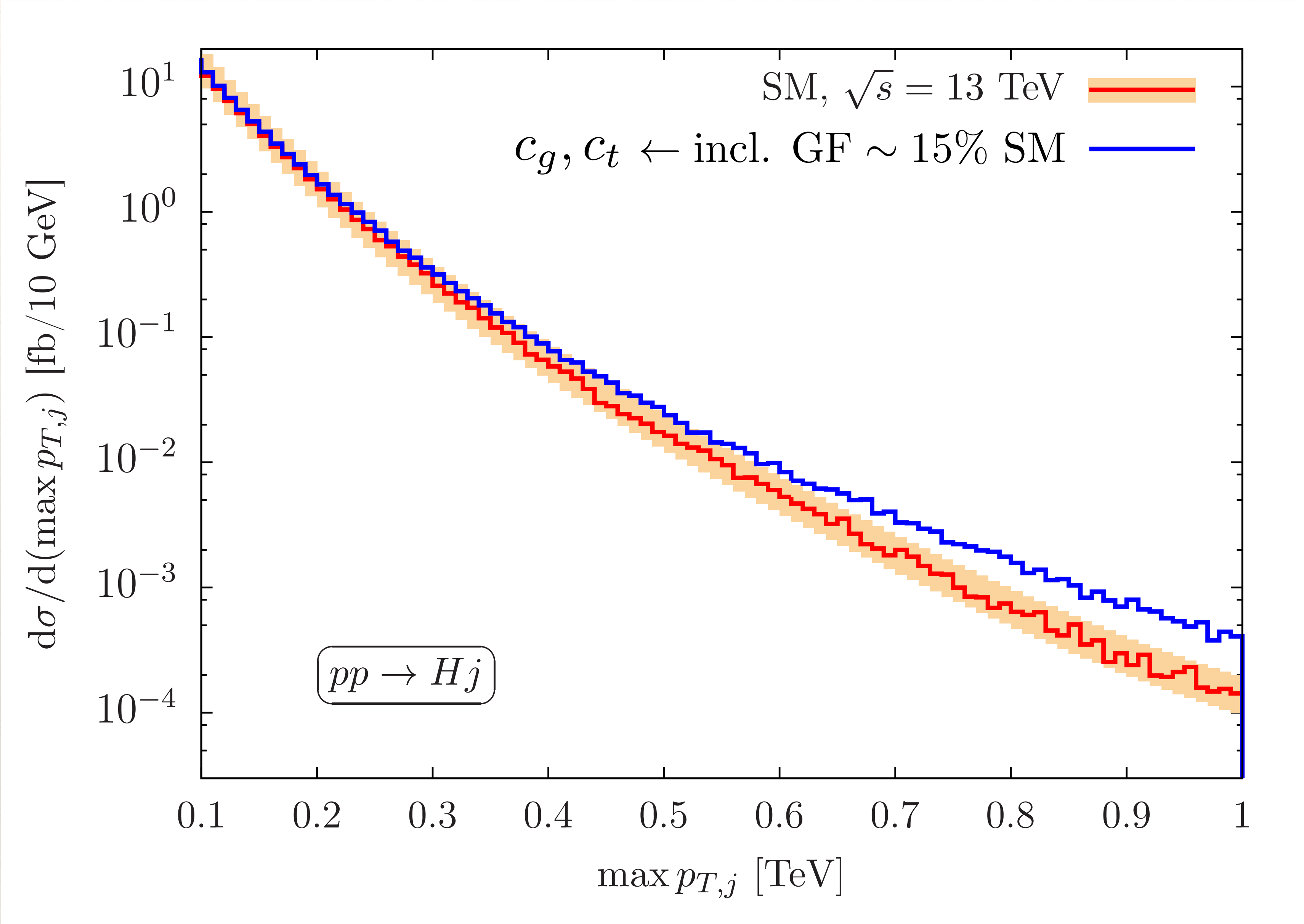


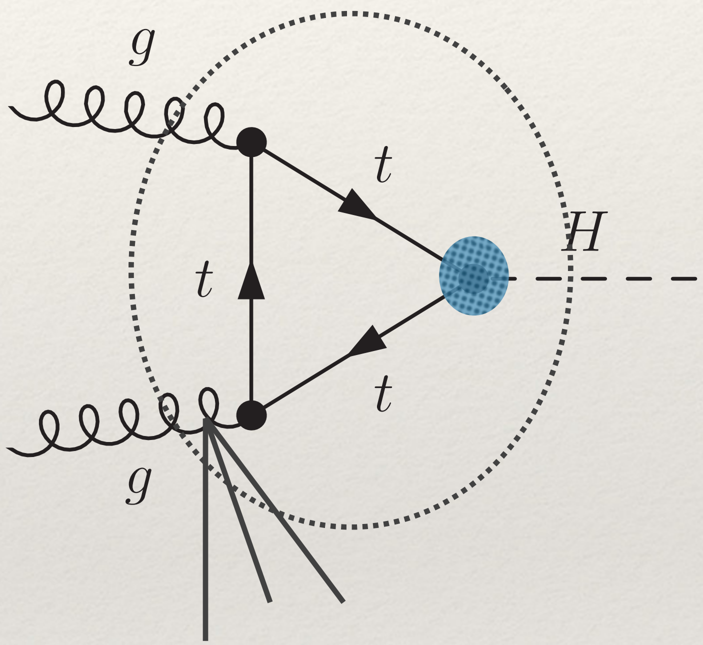
$$\xrightarrow{m_t \to \infty} \quad \subset \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v}$$

contact ggH interactions vs. 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]





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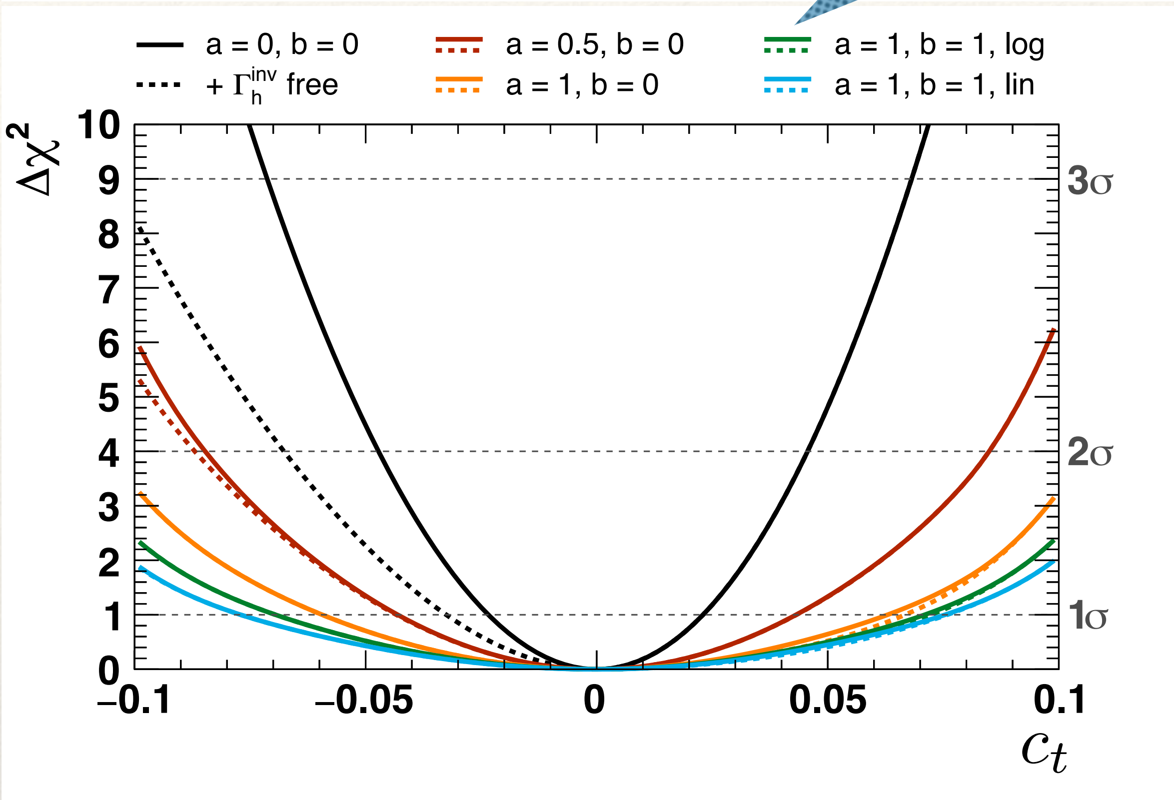
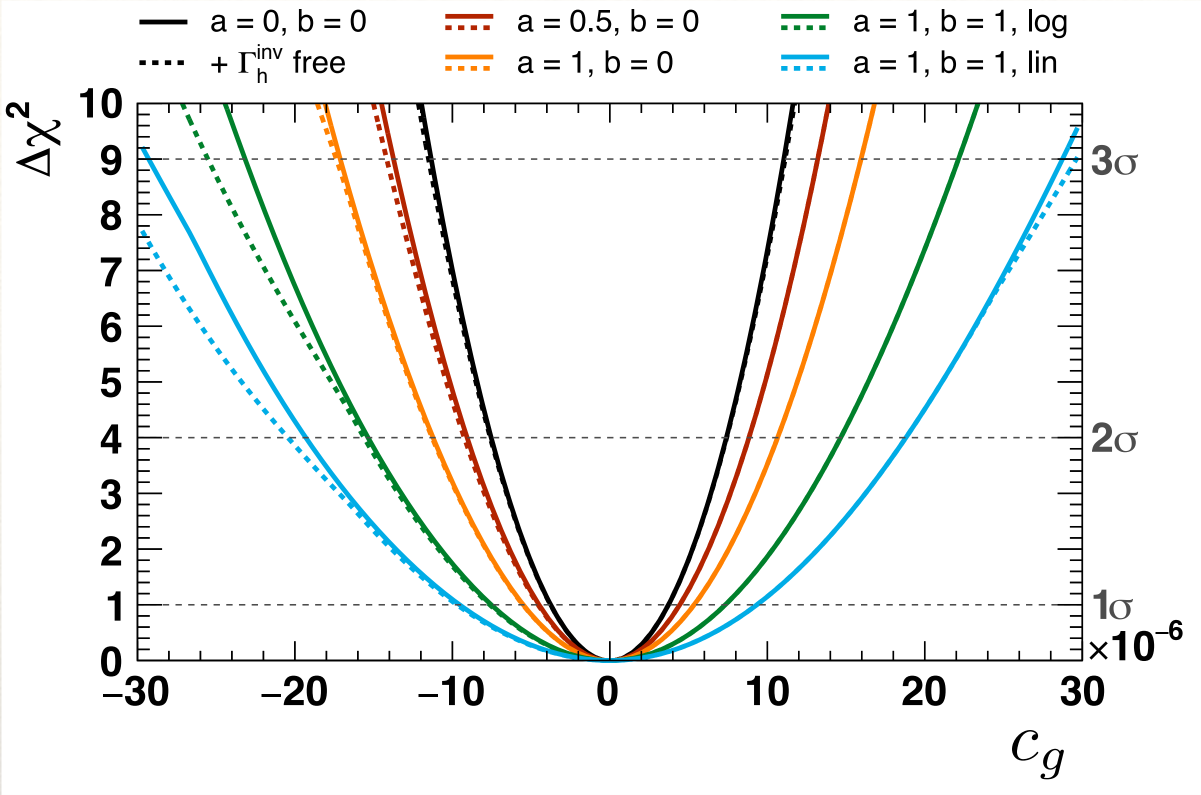
Role of uncertainties

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!

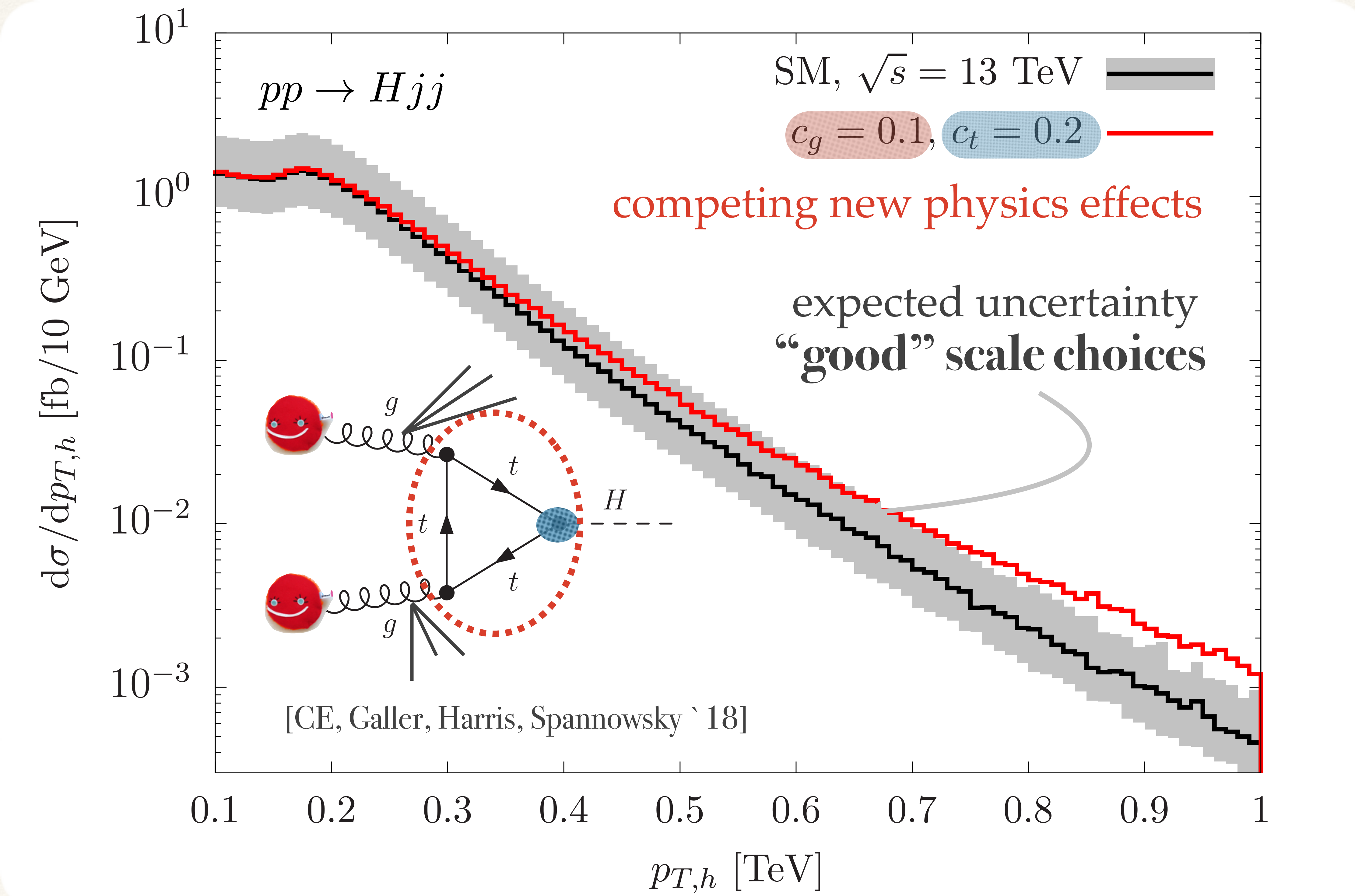
"fit will always pick region where null hypothesis is under good control"

similar conclusion hold for more abundant top final states

[CE, Moore, Nordstrom, Russell ` 16]

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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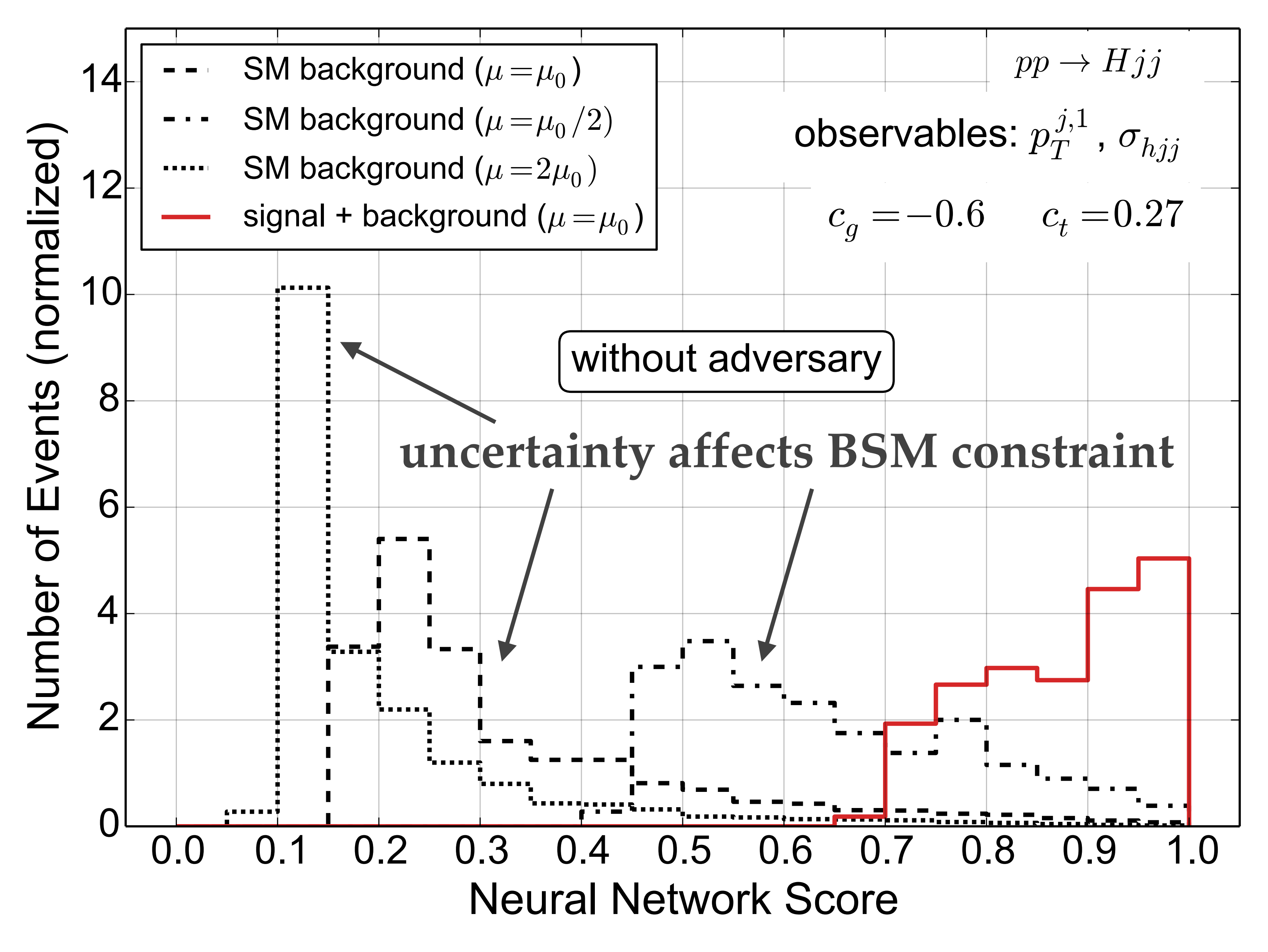

neural net learns regions that are sensitive to uncertainty….

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

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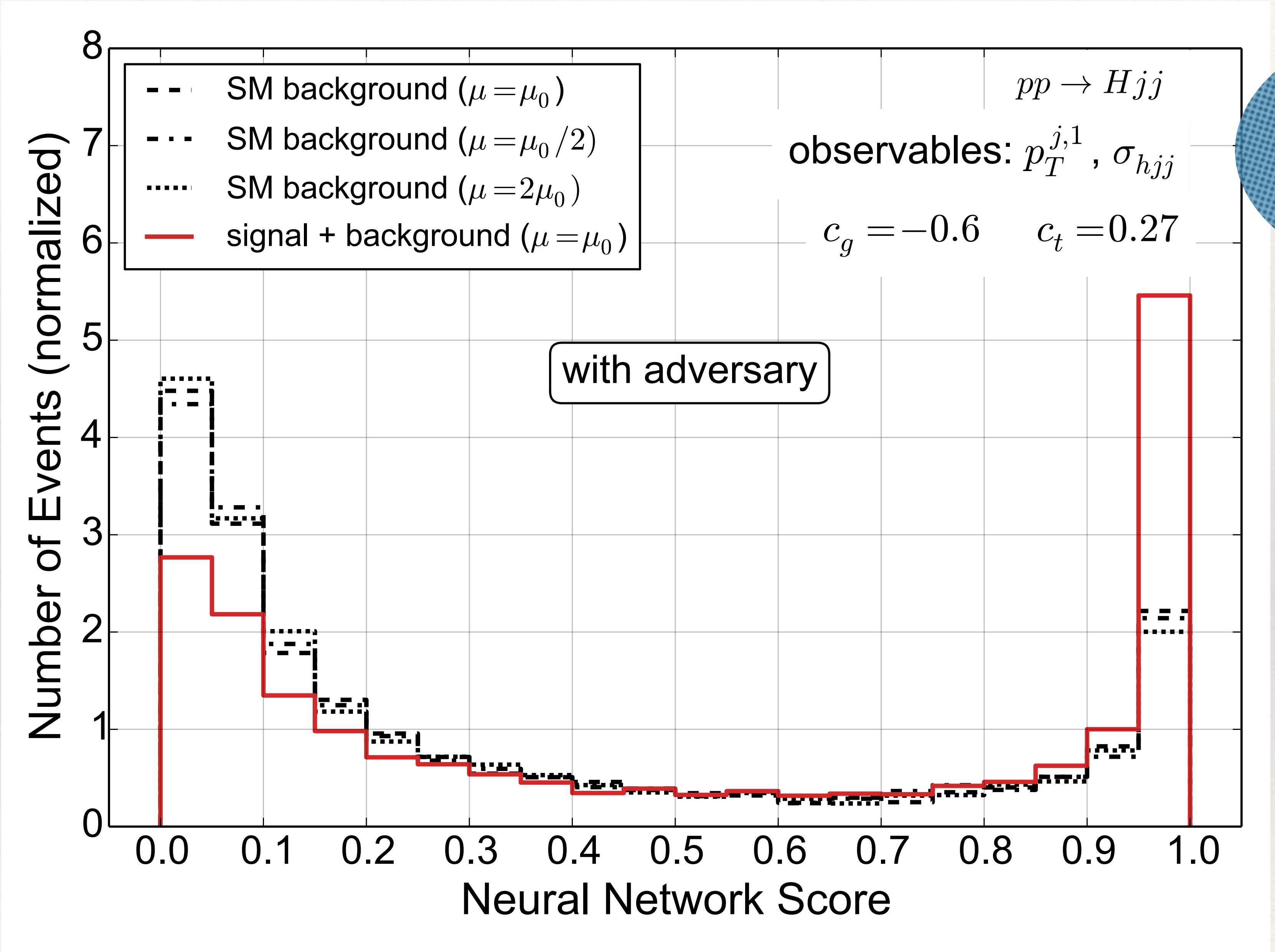

Friday afternoon

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

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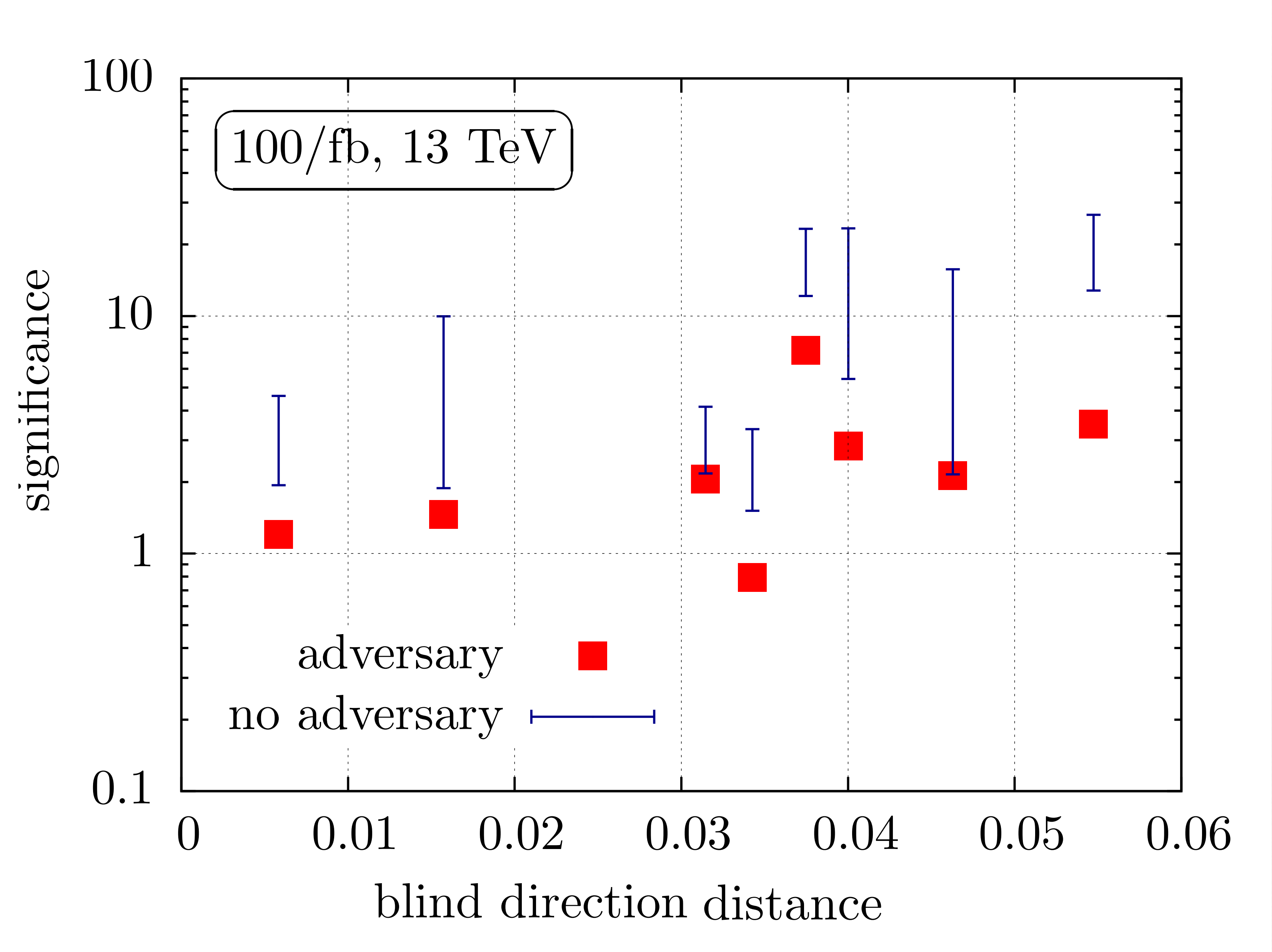

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CP violation

Matthias' talk yesterday

- a repeating point of argument is inclusion of (dim 6)^2 as there is no clear right or wrong $\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{SM}} + \mathrm{d}\sigma^{\{O_i\}}/\Lambda^2$

$$\mathrm{d}\sigma^{\{O_i\}} \sim 2\,\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{d=6}\}$$

matching

MC perturbativity

unitarity…

CP violation

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- qualitatively different for CP-violation:

naive perturbative power counting

$\frac{c_i}{\Lambda^2}$ ~ dim 6

~ (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

xsections, widths, pT spectra…

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

- every C… carrie…

  xsectio…

early Higgs characterisation programme

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

CP violation

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

see also [Brehmer, Plehn, Tait `17]

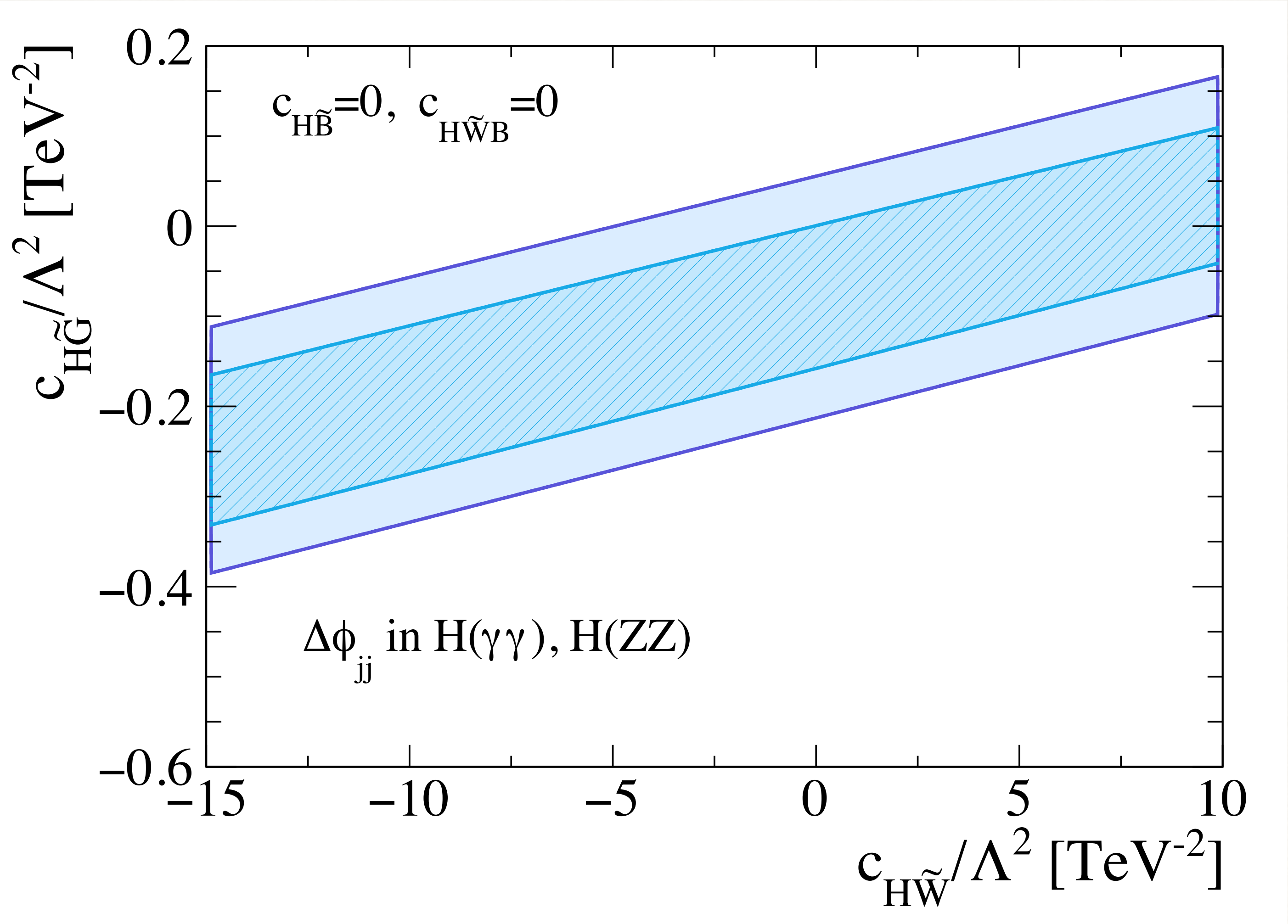
- the linearised upshot

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

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

\+ Yukawa phases (top quark)

...ignore them for now...



- fit uses ATLAS results for 4 leptons, γγ

[ATLAS 1708.02810; 1802.04146]

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

CP violation

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

see also [Brehmer, Plehn, Tait `17]

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$+$

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top quark

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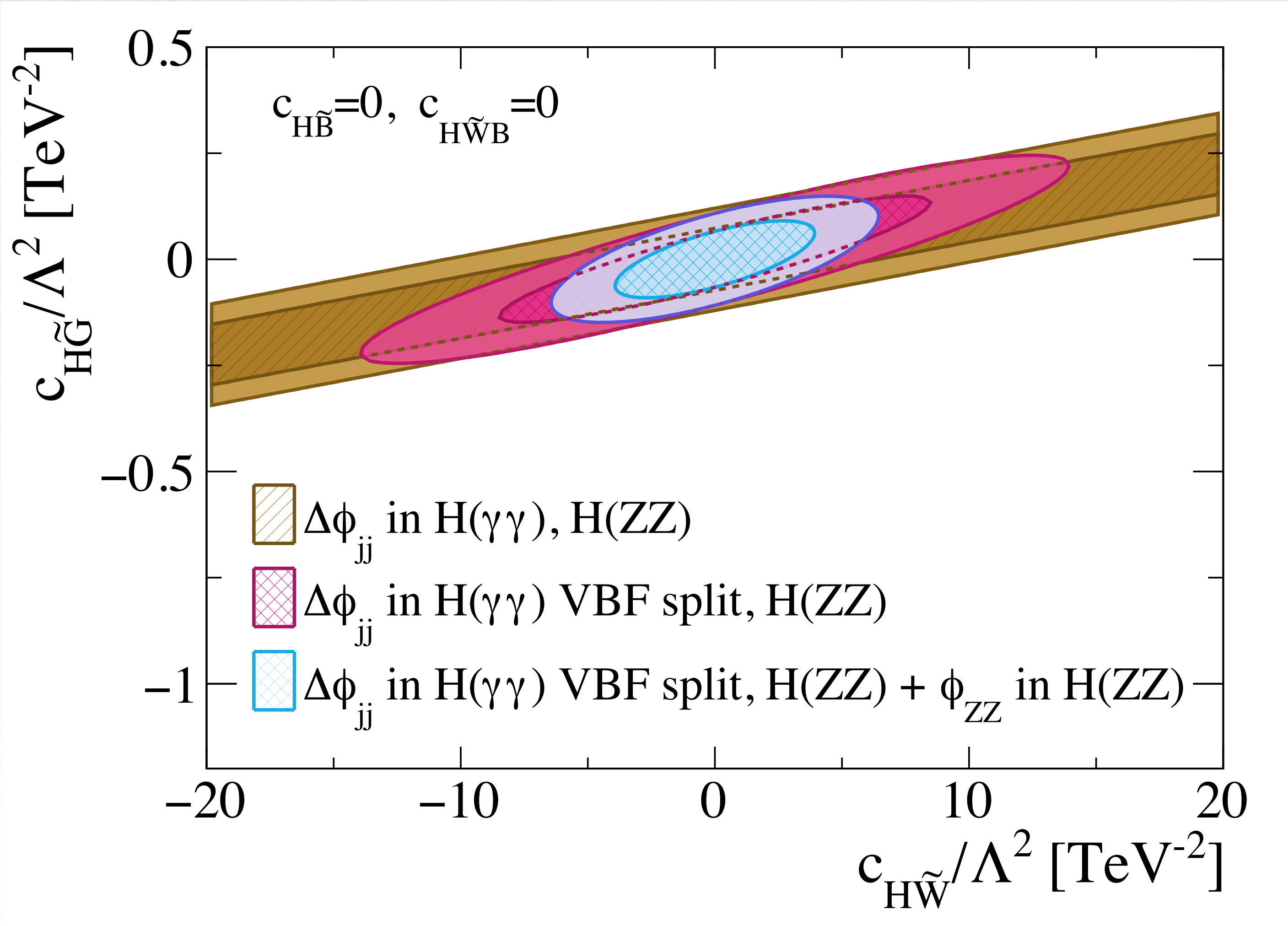

- <u>could already narrow this down at 36/fb by using</u>
  - GF vs VBF selections
  - lepton decay plane angles

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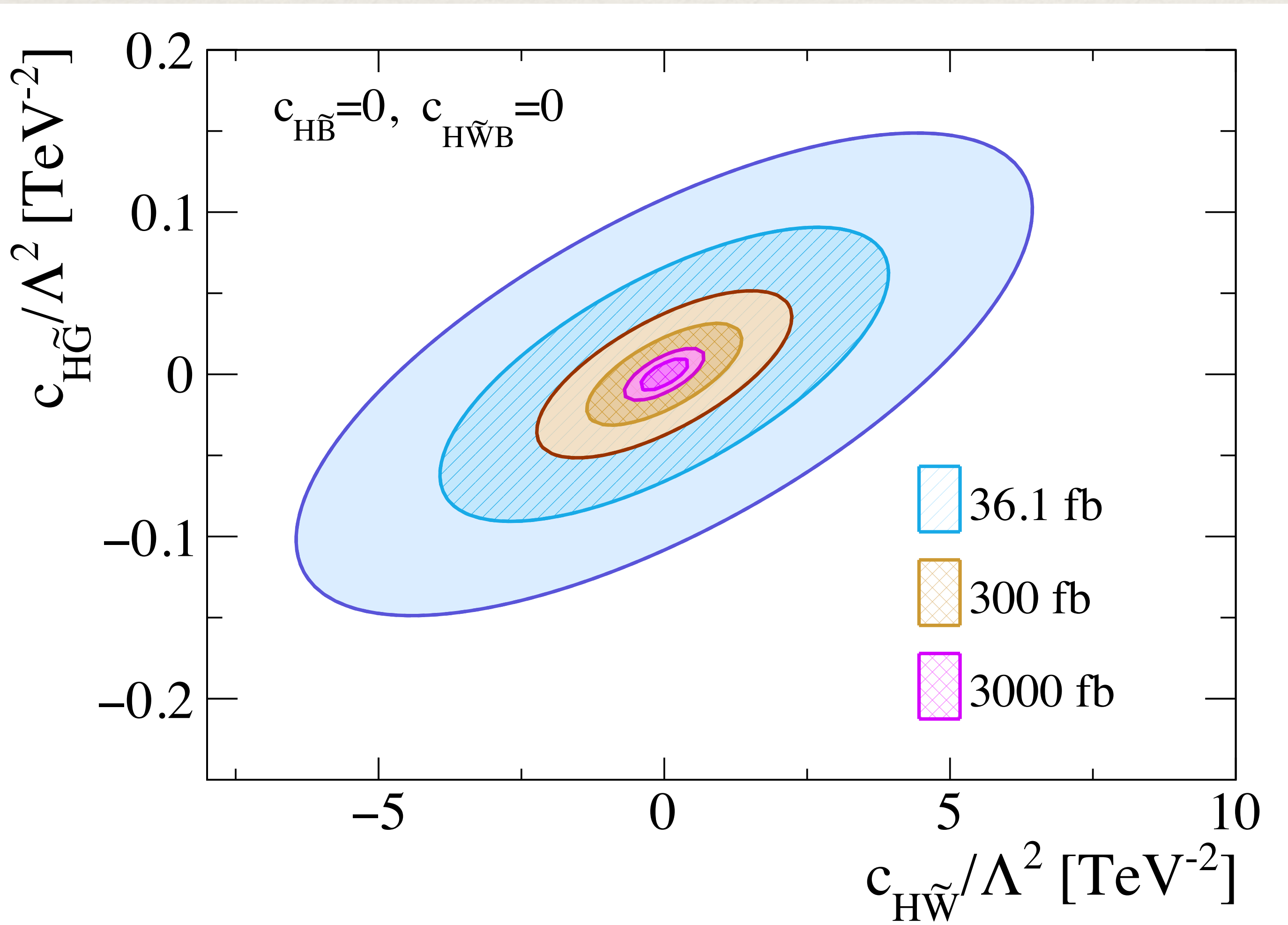

LHC and HL-LHC extrapolations

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

top quark

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$$O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \qquad + \qquad \text{top Yukawa phase}$$

[Del Duca et al. `03]

- $m_t = \infty$ SM limit accidentally good
- split GF selection into m_t-related Higgs p_T threshold ~ 150 GeV

large stats / kin. coverage necessary

CP violation

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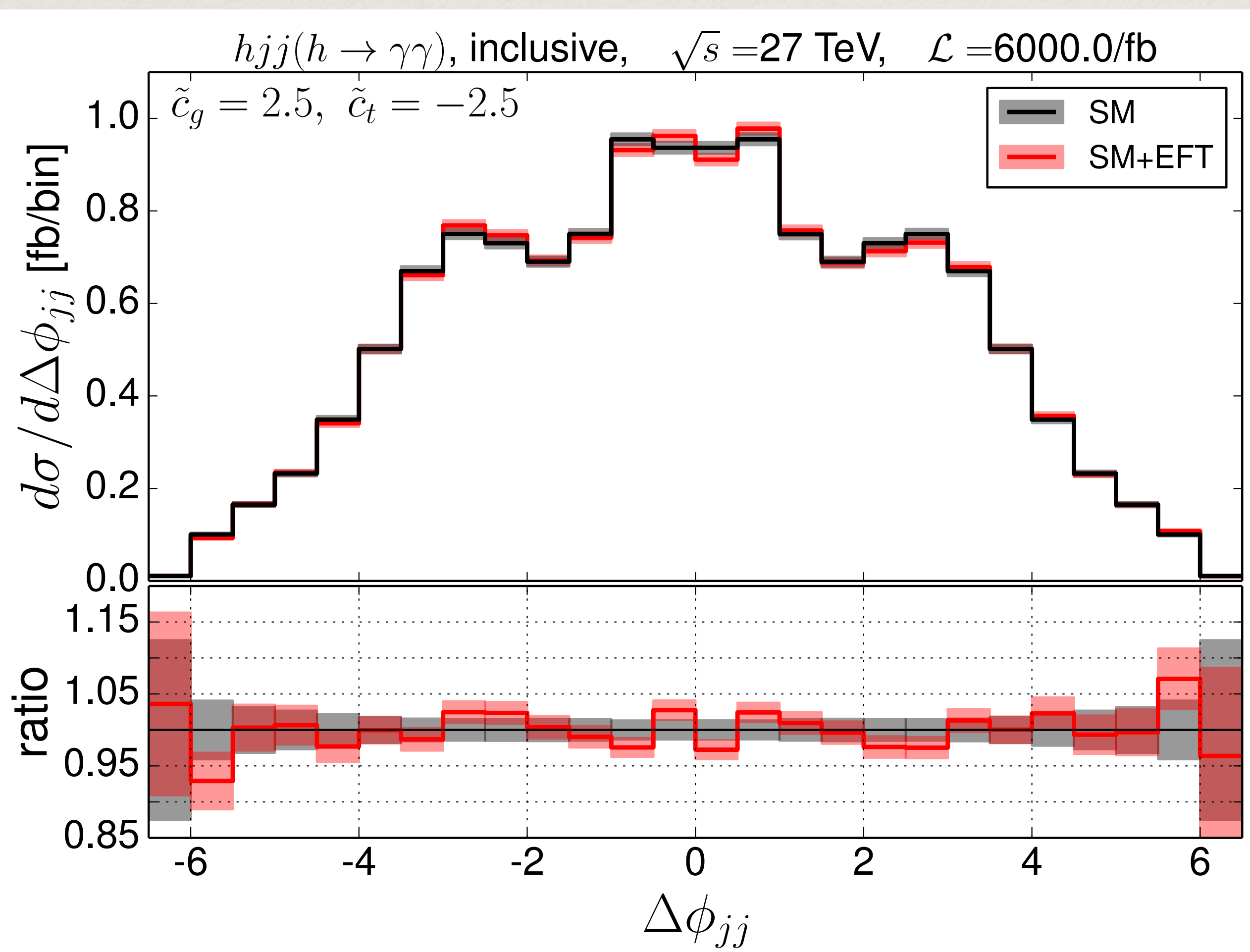

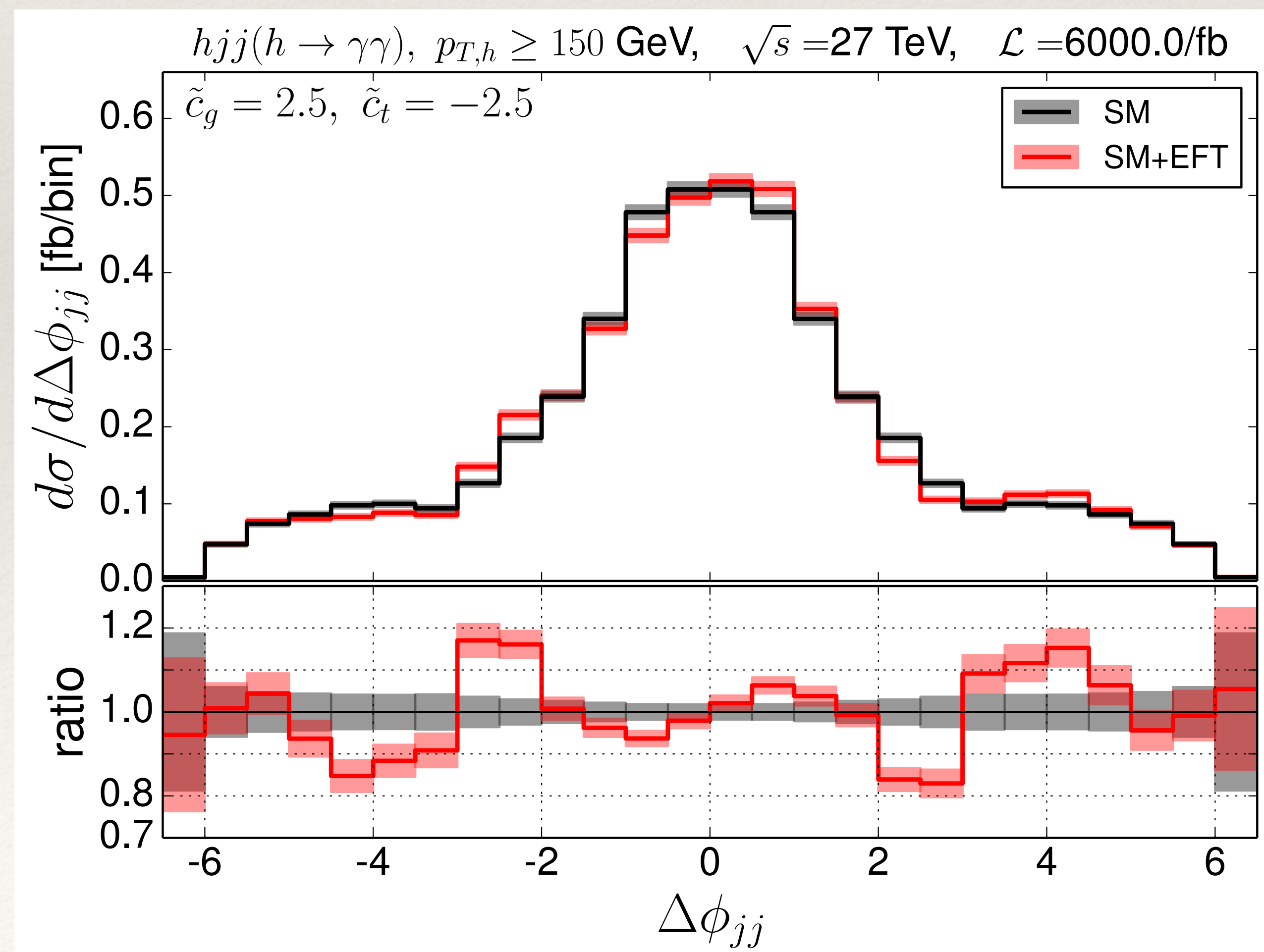

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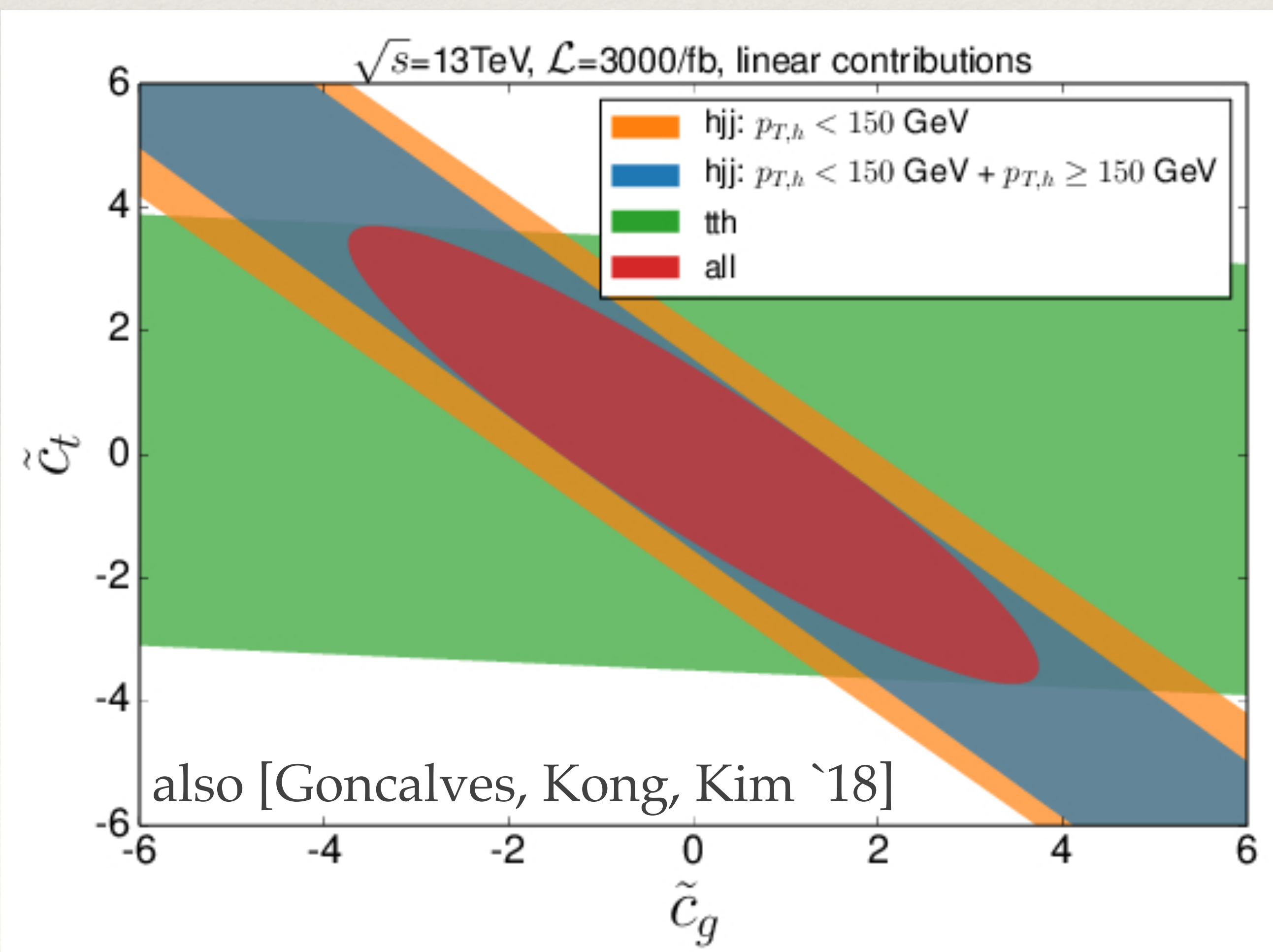
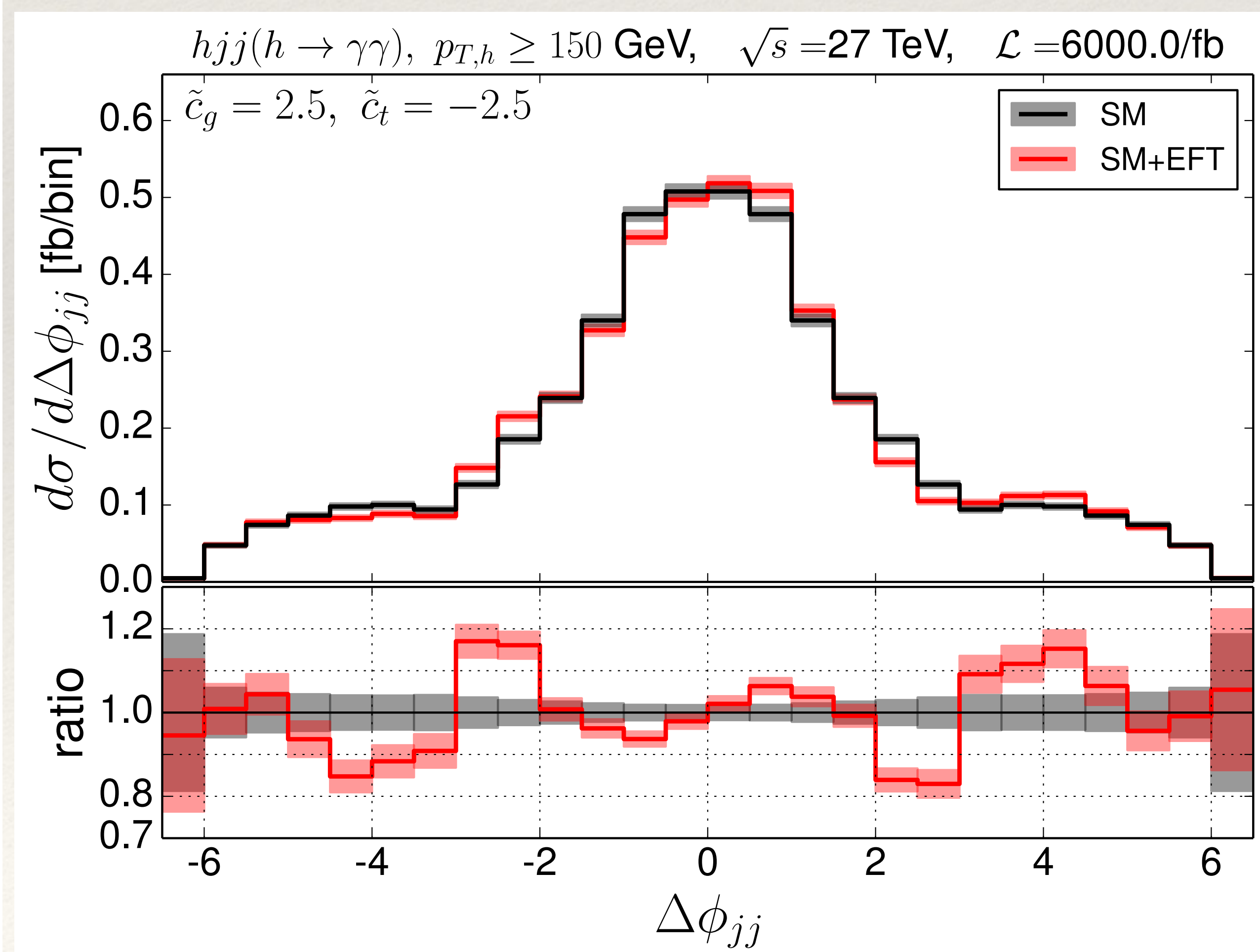




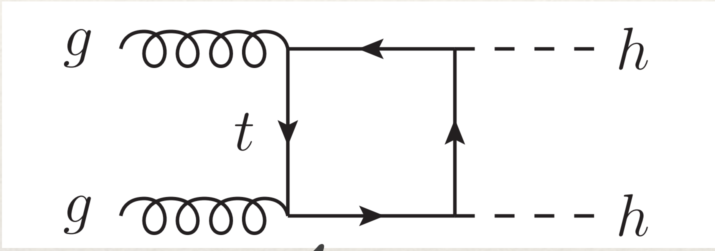
LHC blind spots: Higgs potential

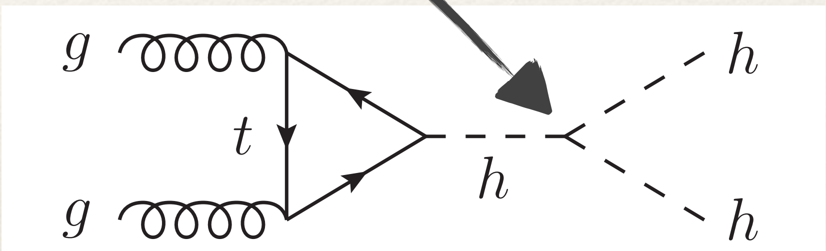
- dimension 6 deformations of the Higgs potential

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

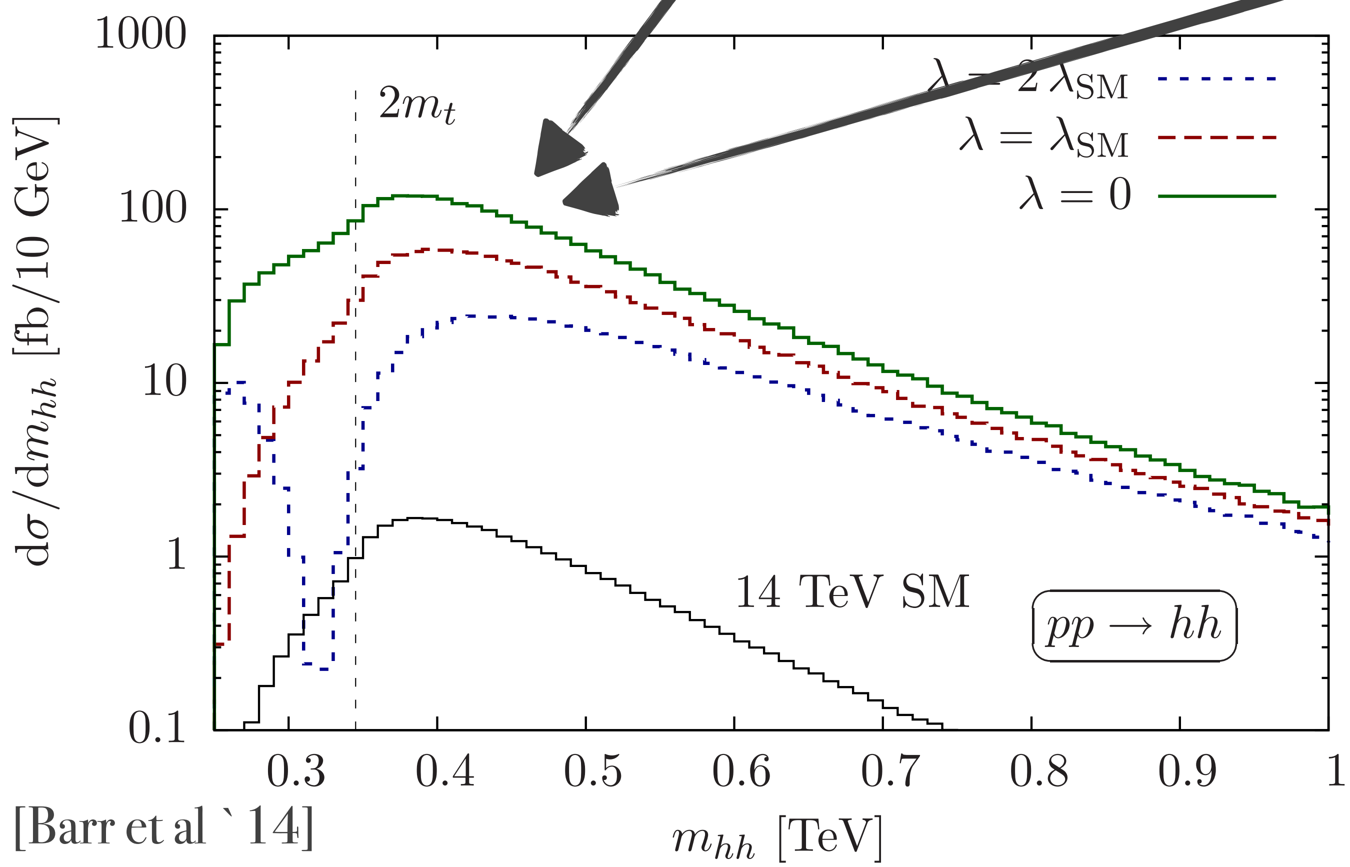
e.g. [Giudice, Grojean, Pomarol, Rattazzi `07]

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



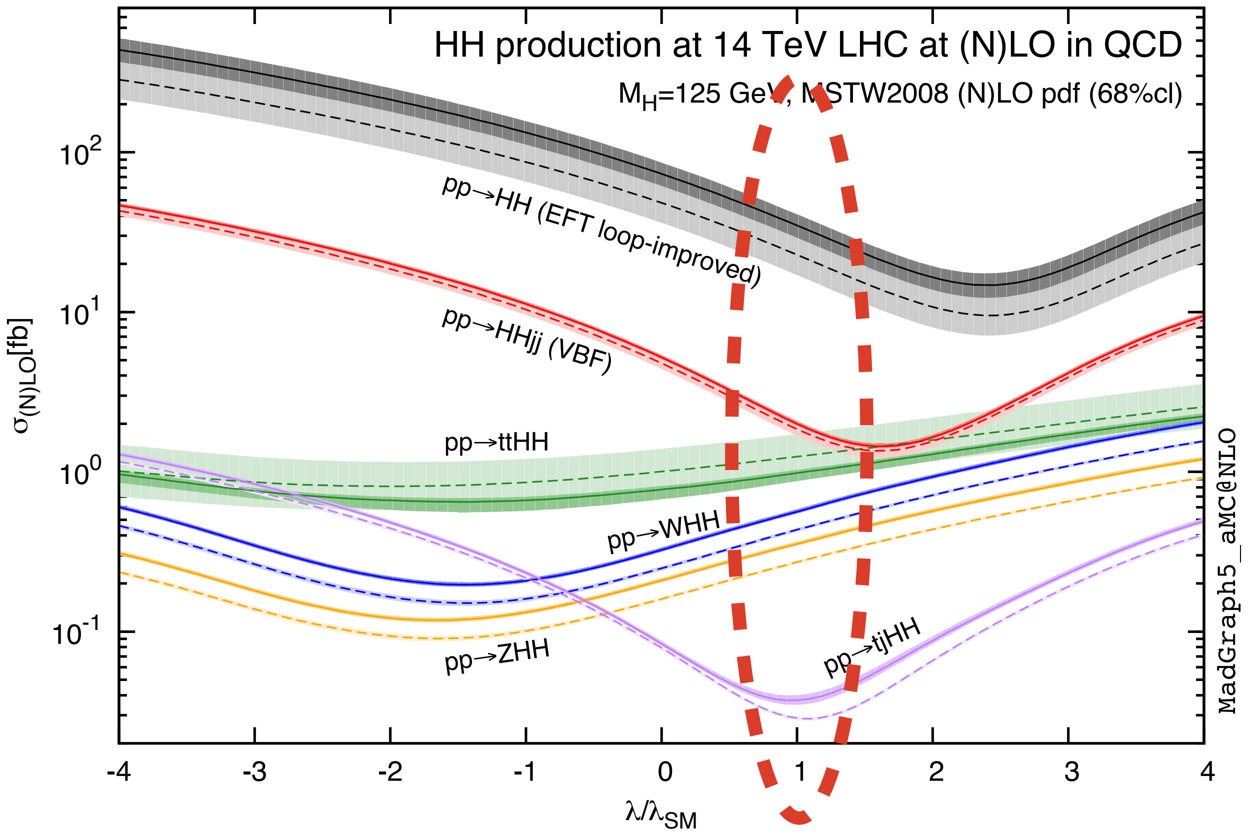


e.g. [Glover, van der Bij `88]



[Barr et al `14]

[Frederix et al `14]



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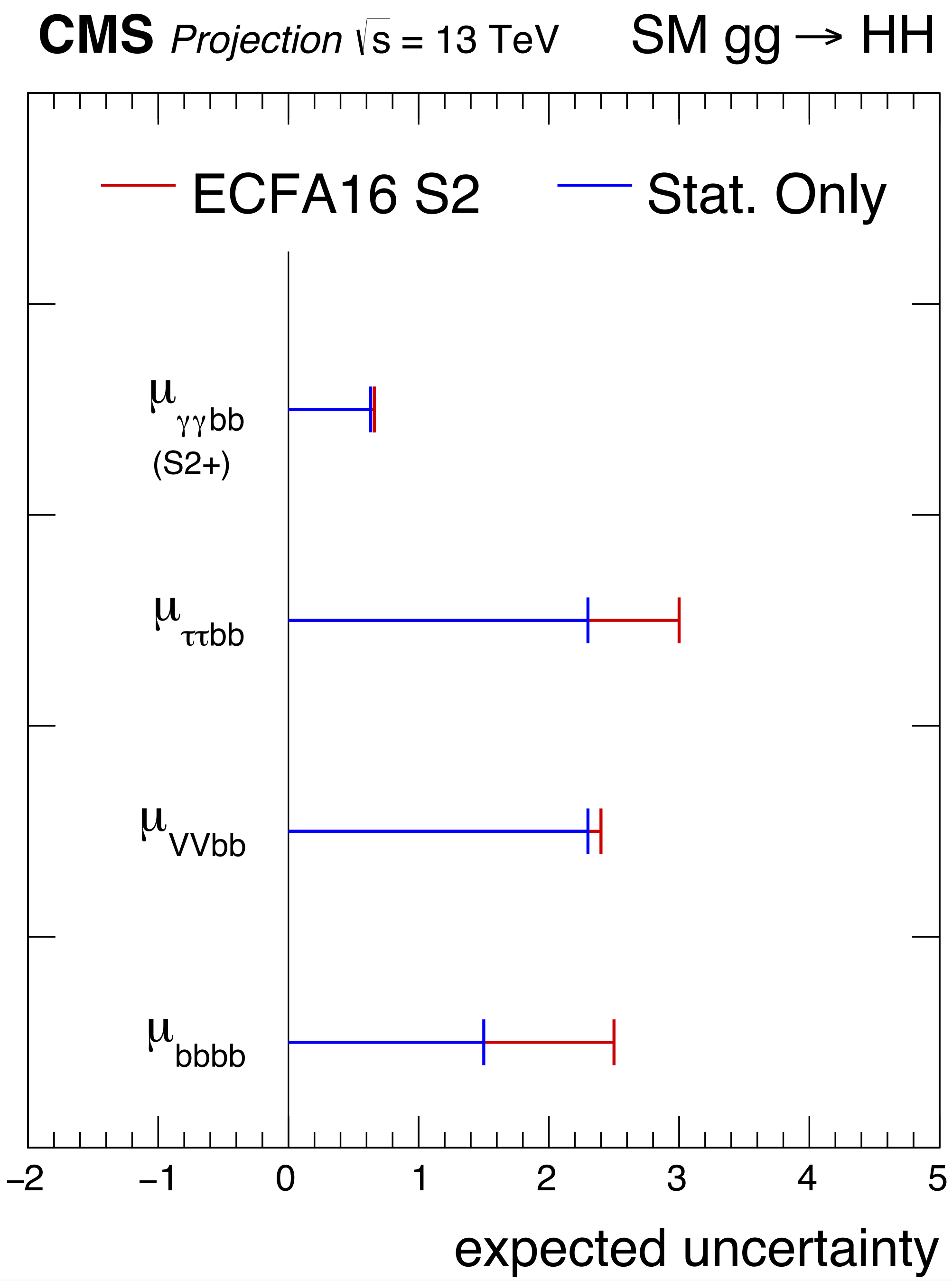
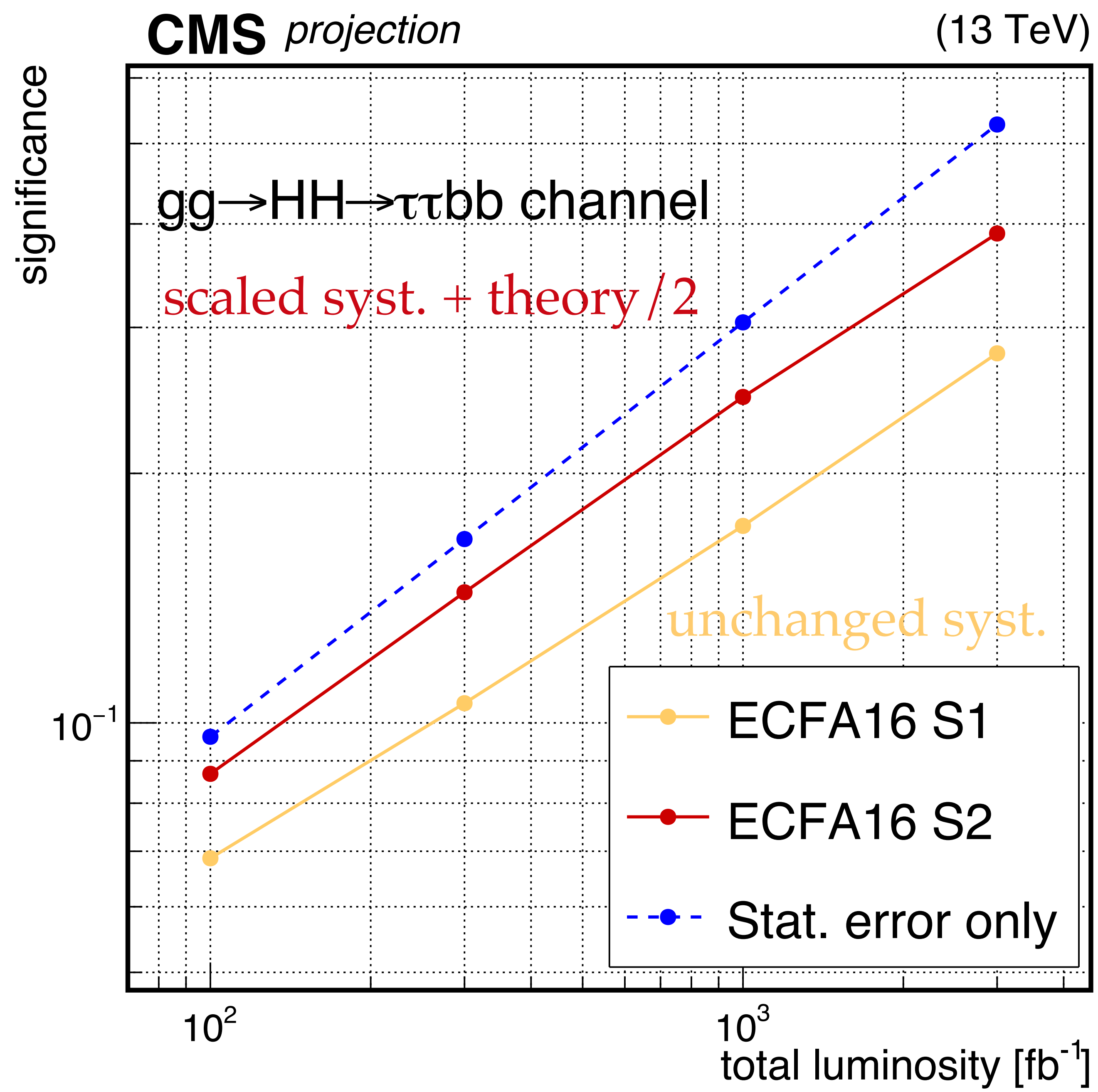
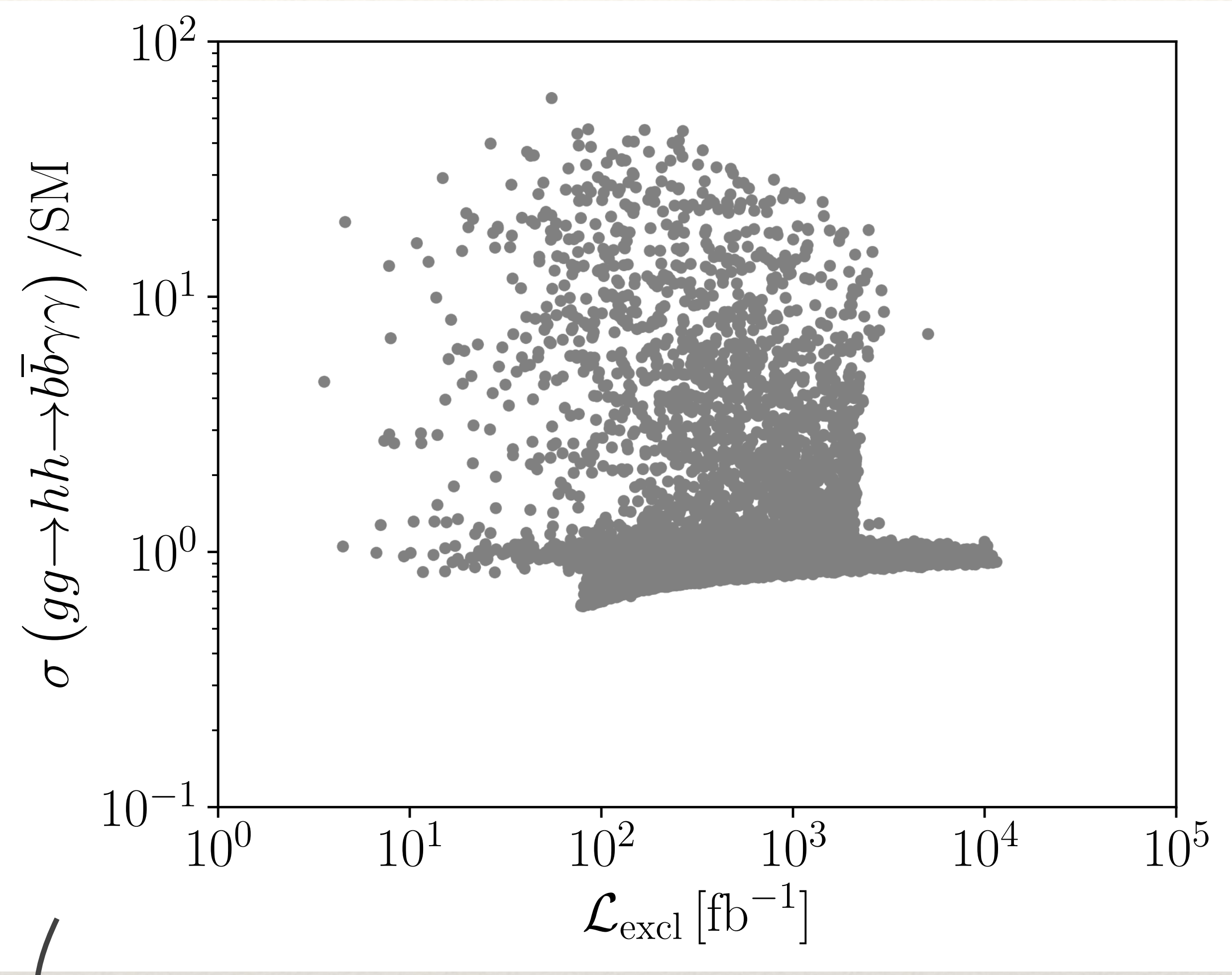
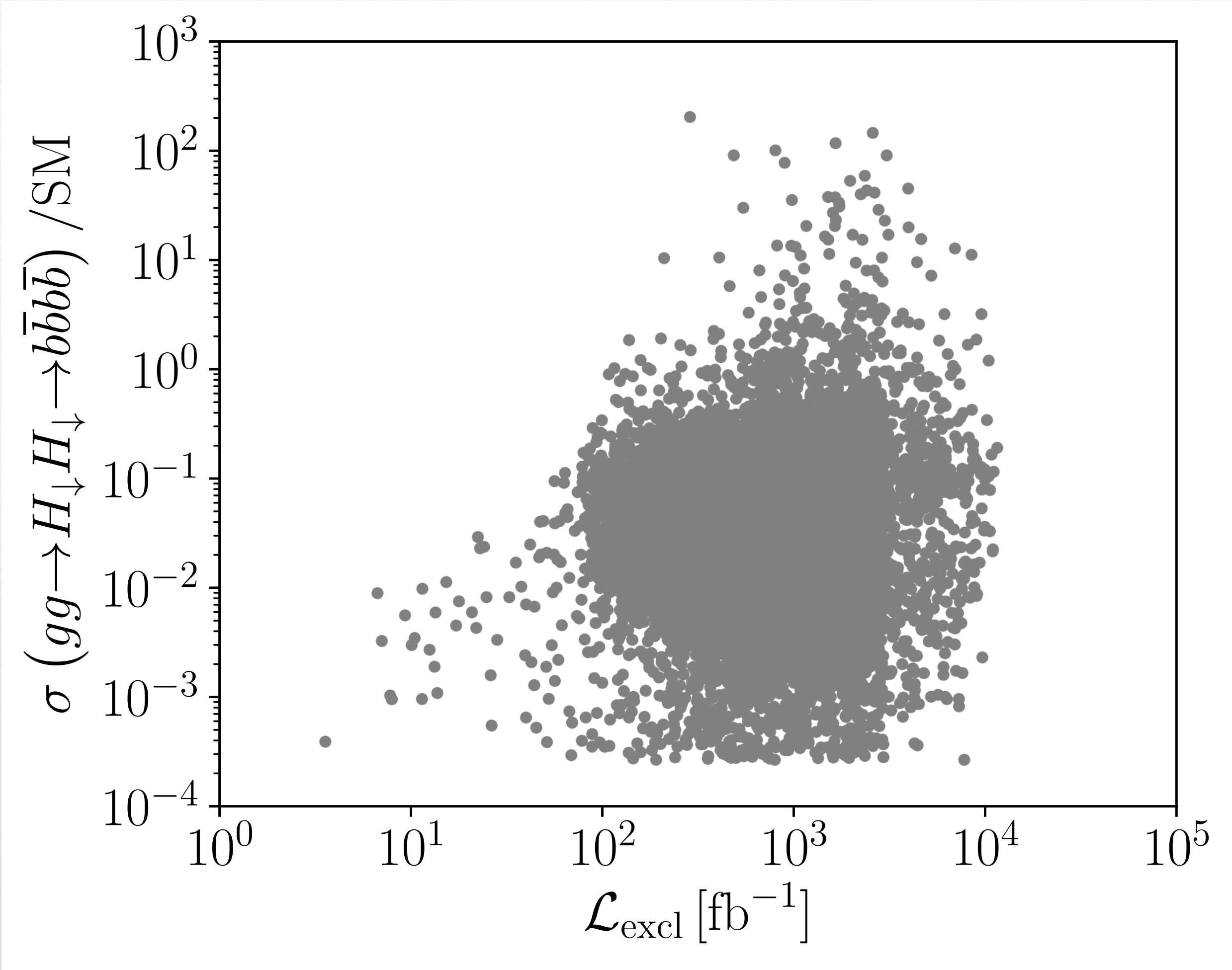




C2HDM & NMSSM

[Basler, Dawson, CE, Mühlleitner ` 18]





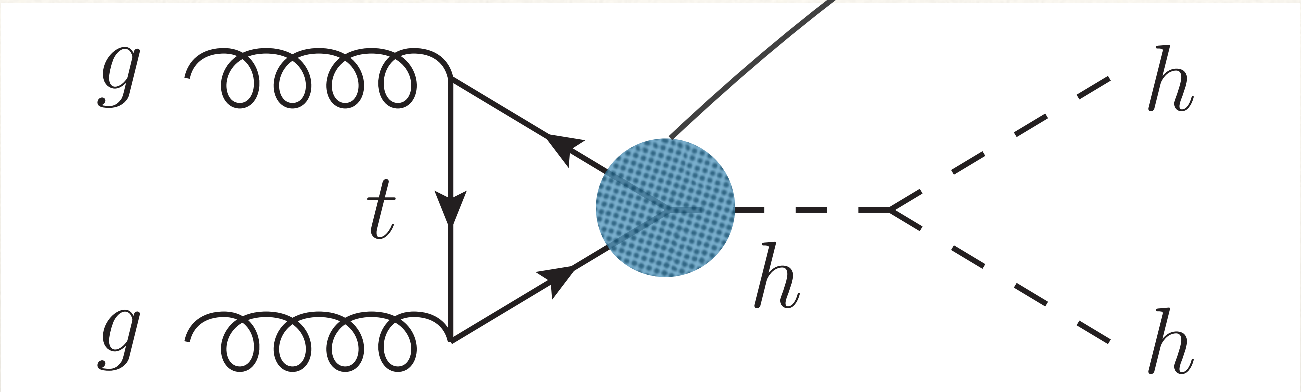
SM-like measurements can show a plethora resonant anomalies
diHiggs final states important for BSM discovery

…diHiggs final states quickly lose relevance when approaching EFT limit

LHC blind spots: Higgs potential

- however…

correlated with on-shell Higgs phenomenology



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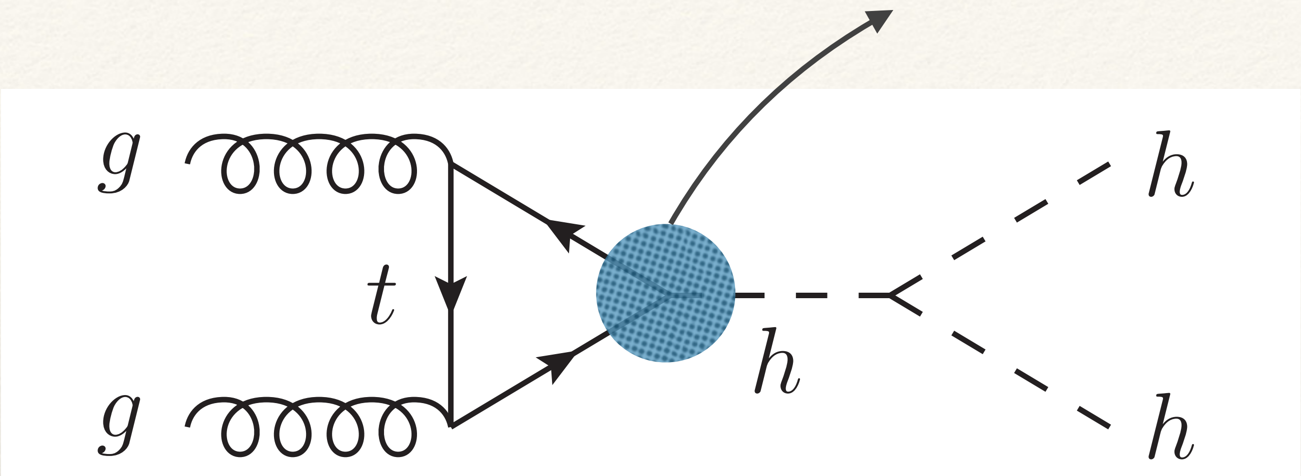

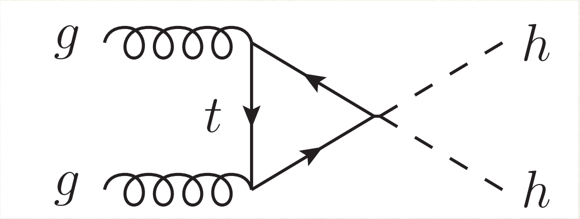

[Gröber, Mühlleitner `10]

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

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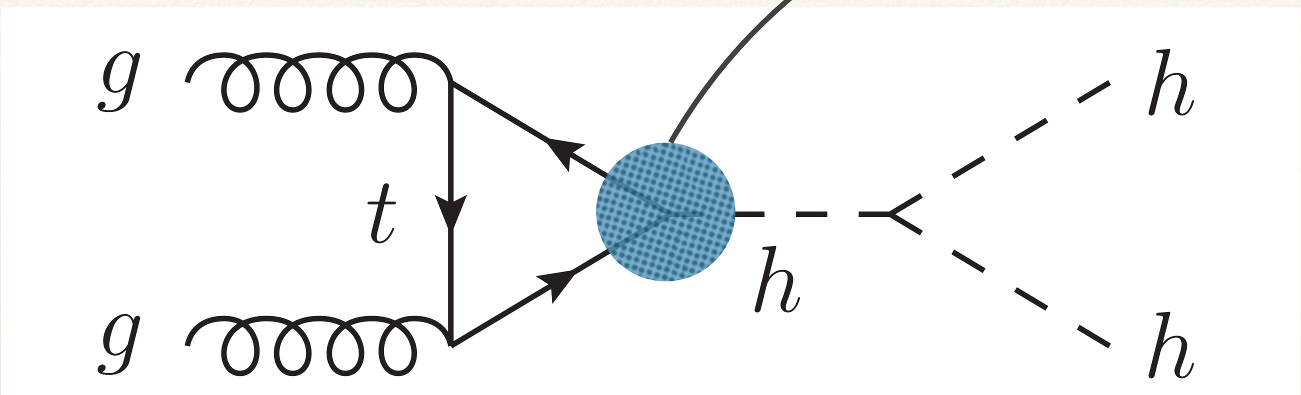
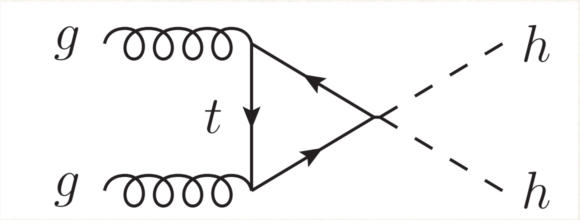




[Gröber, Mühlleitner `10]

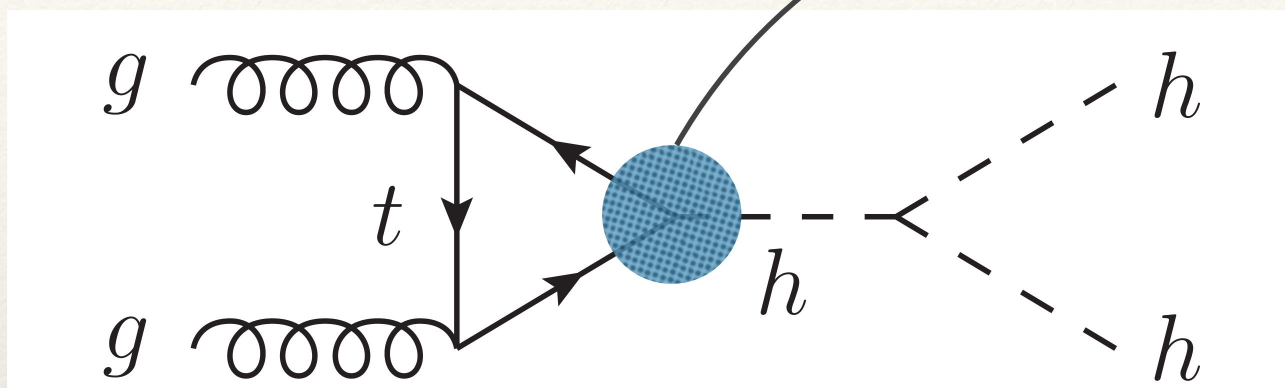
- easy to arrange EFT coefficients in a way to get spectacular rates, but can doubt physical relevance of such limits ($\longrightarrow$ matching)

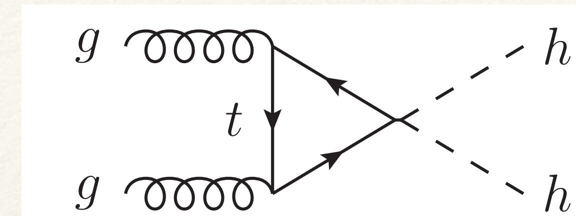
- use concrete Higgs sector extensions
  - extrapolate 125 GeV signal strengths
  - extrapolate exotic Higgs searches
  - additional constraints (*electron EDMs, flavor, perturbativity, …*)

LHC blind spots: Higgs potential

- however…

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





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

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

- *Technical advances have been extremely rapid*
  - matrix elements
  - jets
  - machine learning
  - coupling extraction

Friday afternoon

- *Opportunity to link the Higgs sector to new physics*
  - cure SM shortcomings
  - LHC probably not be enough to achieve this
  - multi-Higgs production as a chance for BSM

Today/Friday