Indirect effects of BSM physics at future colliders

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Workshop on Future Hadron Colliders at the Energy Frontier
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Why *not* indirect?

- Because direct is better (Pedro’s talk).

Why indirect?

- Can catch new physics by its tail

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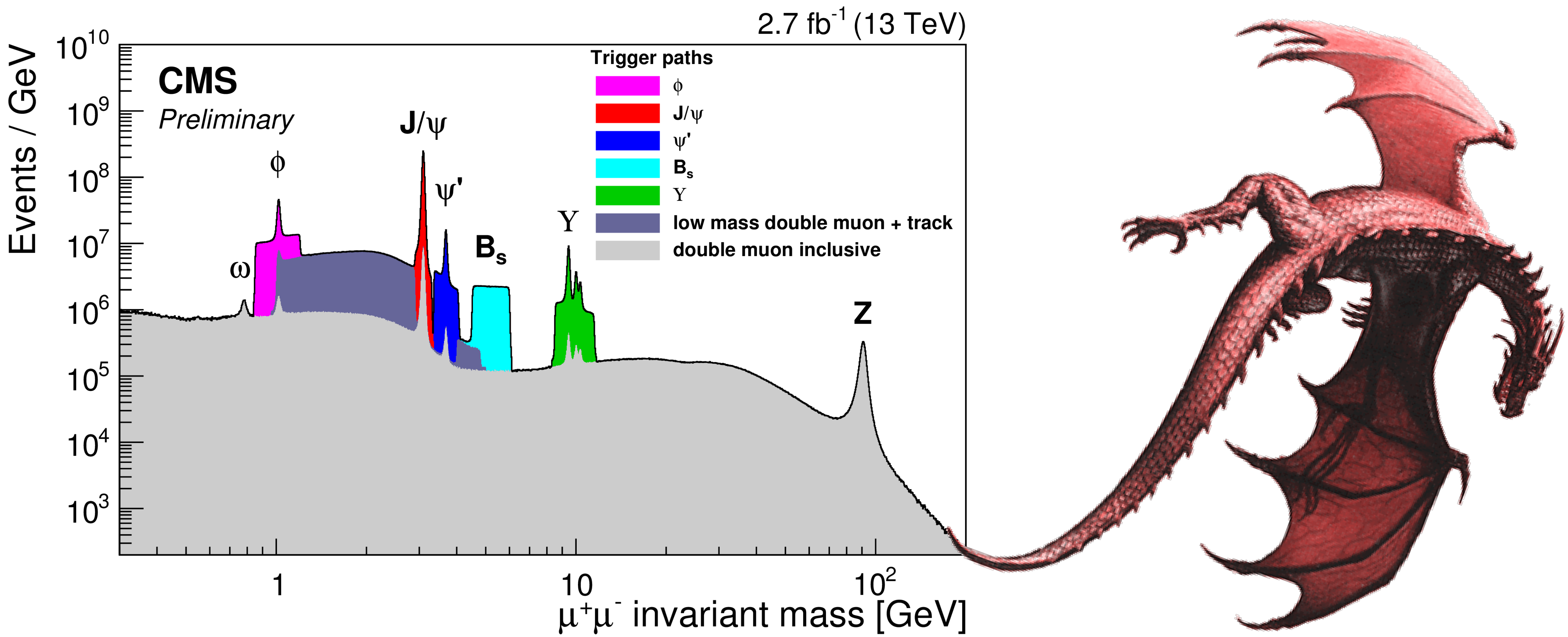


If scale of new physics beyond kinematic reach,
EFT systematically captures information about BSM
in a *model-independent* way. Easy to recast.

Only requirement: $\Lambda \gg E_{\text{experiment}}$

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \ldots$$

Not included here:

D=5 (or D=7) because they are **L** (or **B**) violating

D=8 and higher by assumption sub-leading.

EFT contains most general departure from SM at low-E,

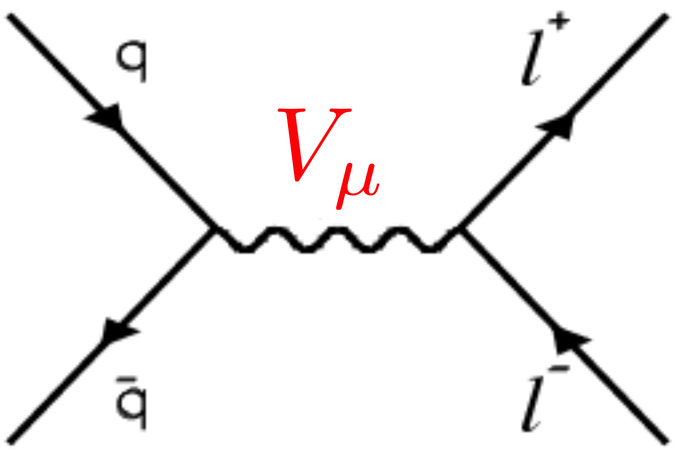
2499 distinct operators:

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

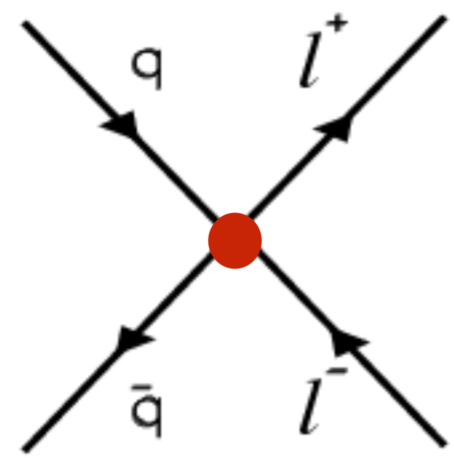
Buchmüller, Wyler ‘86
B. Grzadkowski et al’10, etc

Full theory



$$q^2 \ll m_V^2$$

EFT



$$g_q g_f \frac{-i g_{\mu\nu}}{q^2 - m_V^2 + i m \Gamma}$$

$$\tilde{c}\,(\bar{q}\gamma^\mu q)(\bar{l}\gamma_\mu l)$$

with $\tilde{c} = -\dfrac{g_q g_f}{m_V^2} = \dfrac{c}{\Lambda^2}$

Enormous reduction of complexity (loss of information)

Which operators are important?

- For a given process, only a small number of EFT operators contribute

- Ignore those already very constrained:
  LEP Z-Pole, low-energy precision experiments

- Find convenient parametrization which makes poorly constrained directions obvious

- Focus here: nature of EWSB

How can we test EFTs?

- Precision
- Energy

Precision

Measure at fixed energy scale:

- Higgs, Z, t decays
- Inclusive SM x-sec's

$$E \sim \mu_{\rm SM}$$

$$\frac{\sigma}{\sigma_{\rm SM}} = \left| 1 + c\,\frac{\mu_{\rm SM}^2}{\Lambda^2} \right|^2$$

Precision

Measure at fixed energy scale:
- Higgs, Z, t decays
- Inclusive SM x-sec's

$$E \sim \mu_{\rm SM} \qquad\qquad \frac{\sigma}{\sigma_{\rm SM}} = \left| 1 + c\,\frac{\mu_{\rm SM}^2}{\Lambda^2} \right|^2$$

If we can reach 1% precision in $\frac{\sigma}{\sigma_{\rm SM}}$, translates to

$$\delta \sim \left(\frac{m_h}{\Lambda}\right)^2 \longrightarrow \Lambda \sim 1.2\,{\rm TeV}$$

Ultimately limited by systematics, but useful for poorly constrained directions (e.g. HH).

Energy

Look into high-E tails of distributions, e.g. m_{ll}, $p_T(H)$, …

$$E \sim m_{ll} \gg \mu_{\mathrm{SM}}$$

$$\frac{\sigma}{\sigma_{\mathrm{SM}}} = \left| 1 + c\,\frac{E^2}{\Lambda^2} \right|^2$$

Energy

Look into high-E tails of distributions, e.g. m_{ll}, $p_T(H)$, …

$$E \sim m_{ll} \gg \mu_{\rm SM} \qquad\qquad \frac{\sigma}{\sigma_{\rm SM}} = \left|1 + c\,\frac{E^2}{\Lambda^2}\right|^2$$

Can reach large scales, even if precision is low,

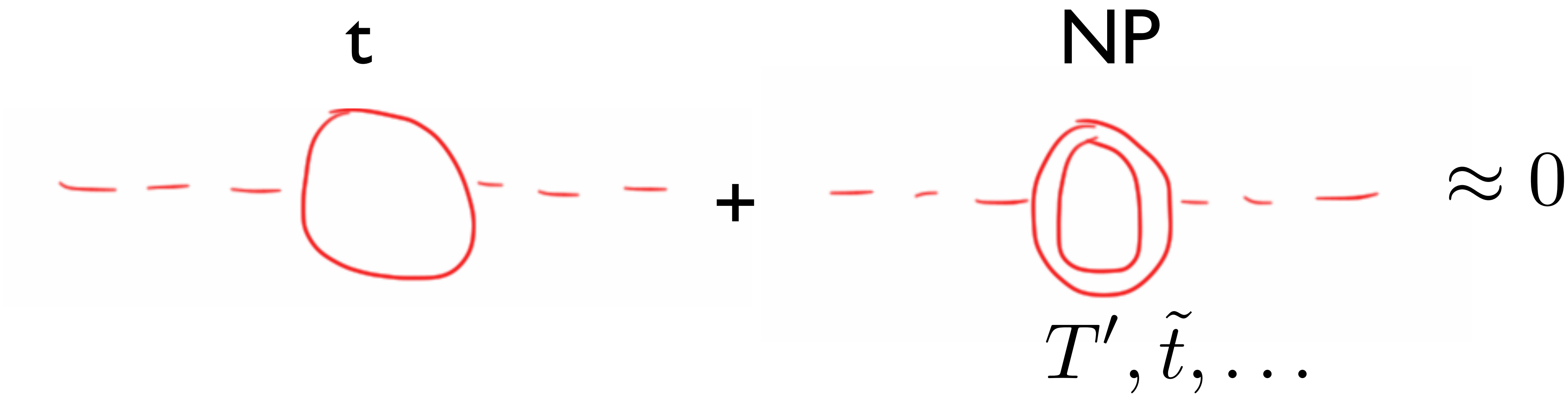
$$\delta \sim \left(\frac{E}{\Lambda}\right)^2 \quad \xrightarrow[E = 1\,\mathrm{TeV}]{\delta \sim 10\%} \quad \Lambda \sim 3\,\mathrm{TeV}$$

Additional benefit: often probes new directions

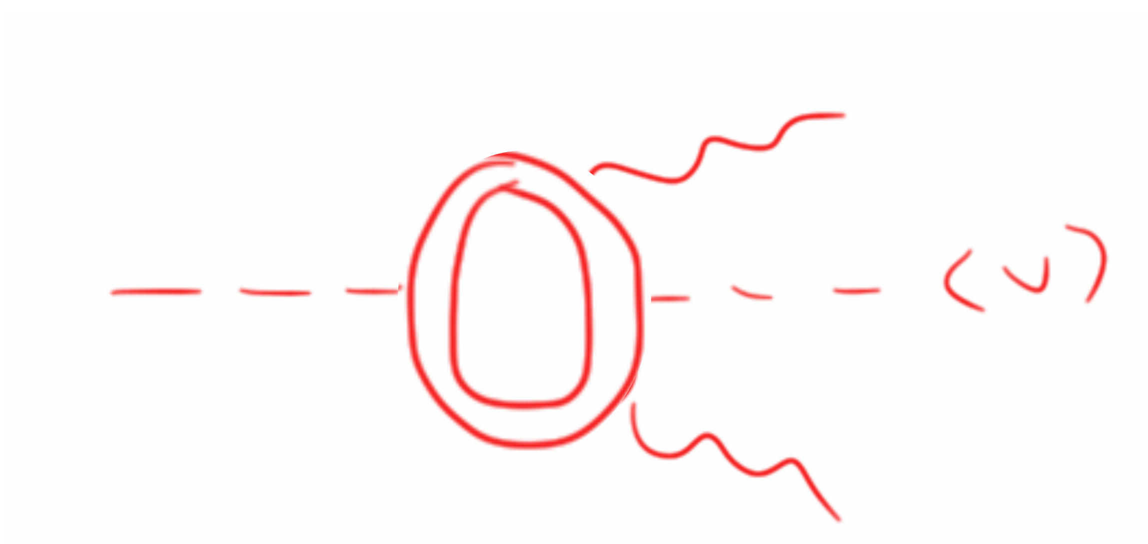
Example: single Higgs

$$\sigma(pp \to h + \boldsymbol{X})$$

The hierarchy problem…



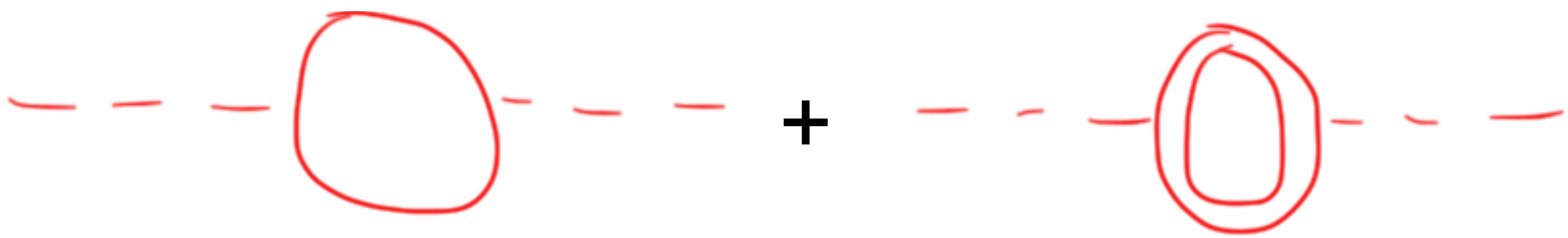
… motivates deviations in



see e.g. Low, Vichi, Rattazzi

The hierarchy problem…

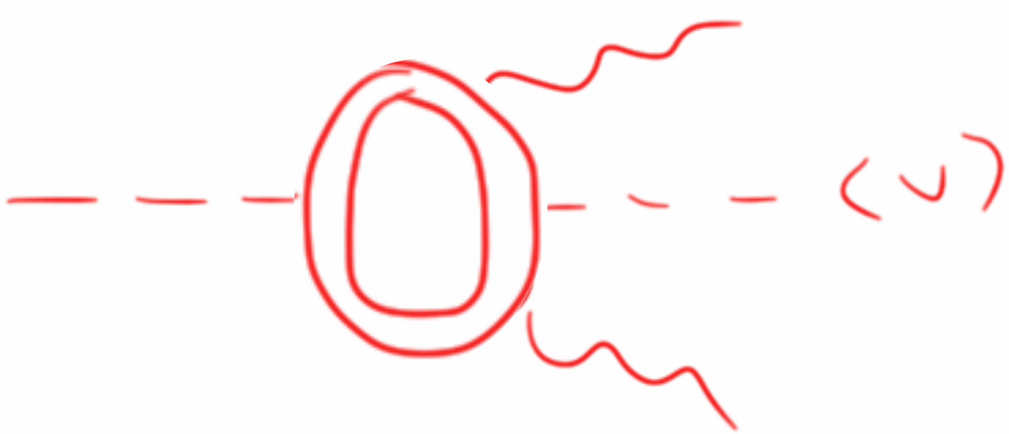
t **NP**



≈ 0

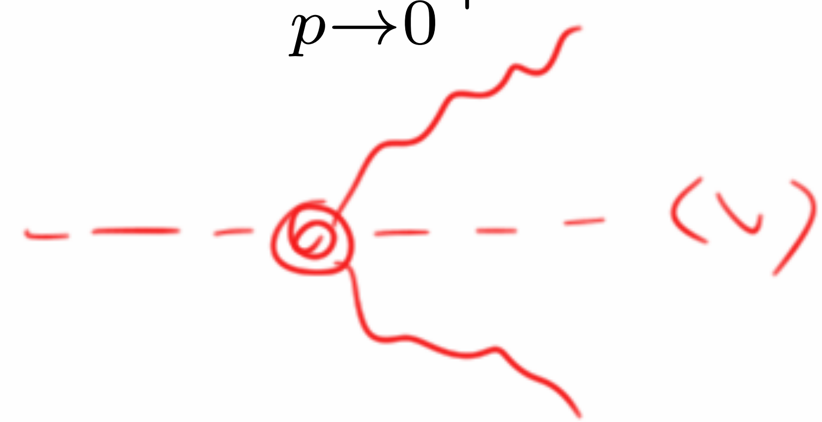
$T', \tilde{t}, \ldots$

… motivates deviations in



… but we actually measure:

$\propto \lim_{p \to 0} |\mathrm{SM} + \mathrm{NP}|^2$



see e.g. Low, Vichi, Rattazzi

Inclusive Higgs

$$\mathcal{O}_t = \frac{y_t}{v^2}|H|^2\bar{Q}_L\tilde{H}t_R\,, \qquad \mathcal{O}_g = \frac{\alpha_s}{12\pi v^2}|H|^2 G^a_{\mu\nu}G^{a\,\mu\nu}\,,$$

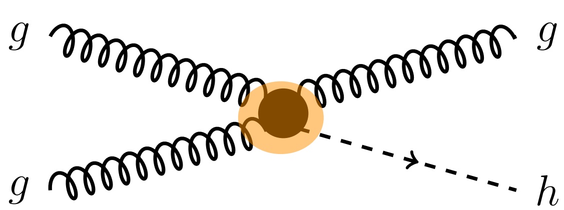
$$\mu_{\rm incl}(c_t,k_g) = \frac{\sigma^{\rm BSM}_{\rm incl}(c_t,k_g)}{\sigma^{\rm SM}_{\rm incl}} = (c_t+k_g)^2$$

Precision only : a degenerate direction!

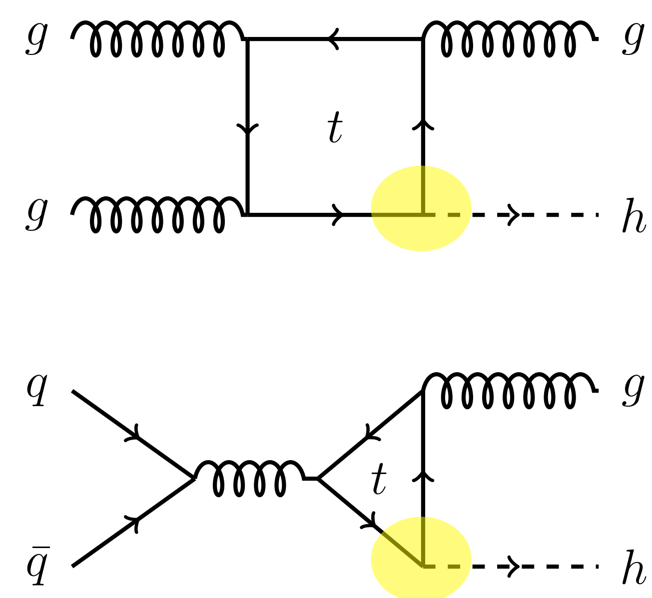
Composite Higgs predicts: $c_t \approx -k_g$

Use Energy: p_T(H)

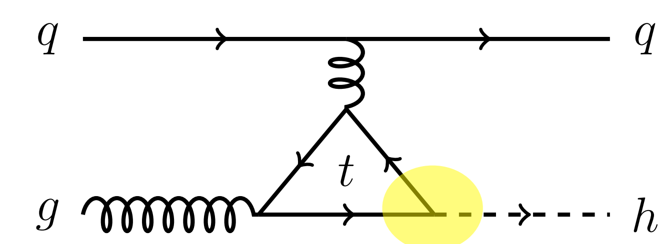
UV



vs.



IR



$$\hat{\sigma}_{p_T^{min}}(c_t, k_g, \hat{s}) \propto \frac{1}{16\,\pi\,\hat{s}^2} \int_{t_{min}}^{t_{max}} \mathrm{d}t \left| c_t \mathcal{M}_{IR} + k_g \mathcal{M}_{UV} \right|^2$$

$$t_{\substack{min \\ max}} = \frac{1}{2}\left(m_h^2 - \hat{s} \mp \sqrt{m_h^4 - 2\,\hat{s}\,(m_h^2 + 2\,(p_T^{min})^2) + \hat{s}^2} \right)$$

Grojean, Schlaffer, Salvioni, AW

Grojean, Schlaffer, Salvioni, AW

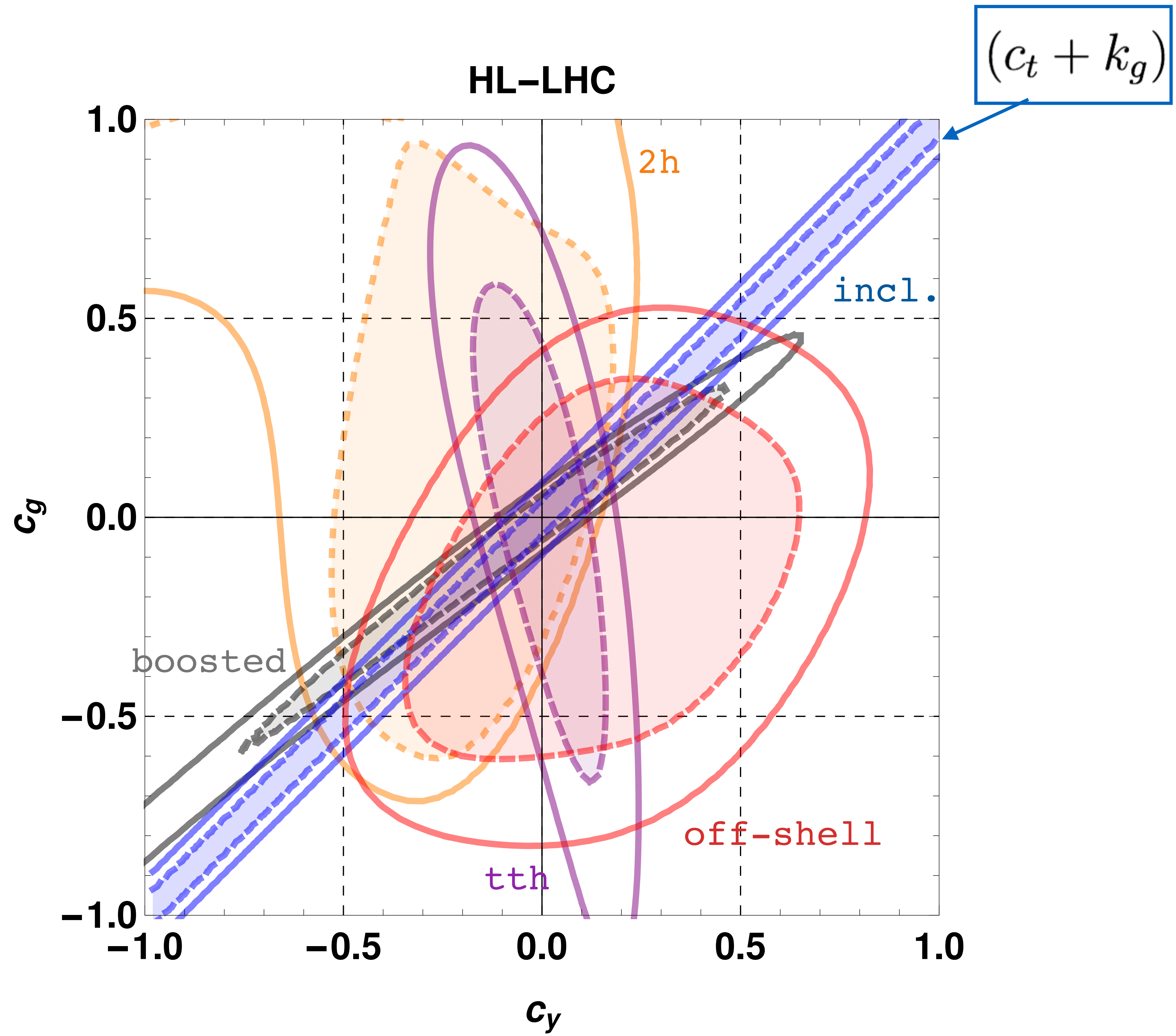
$$\frac{\sigma_{p_T^{min}}(c_t, k_g)}{\sigma^{SM}_{p_T^{min}}} = (c_t + k_g)^2 + \delta\, c_t\, k_g + \kappa\, k_g^2$$

degeneracy

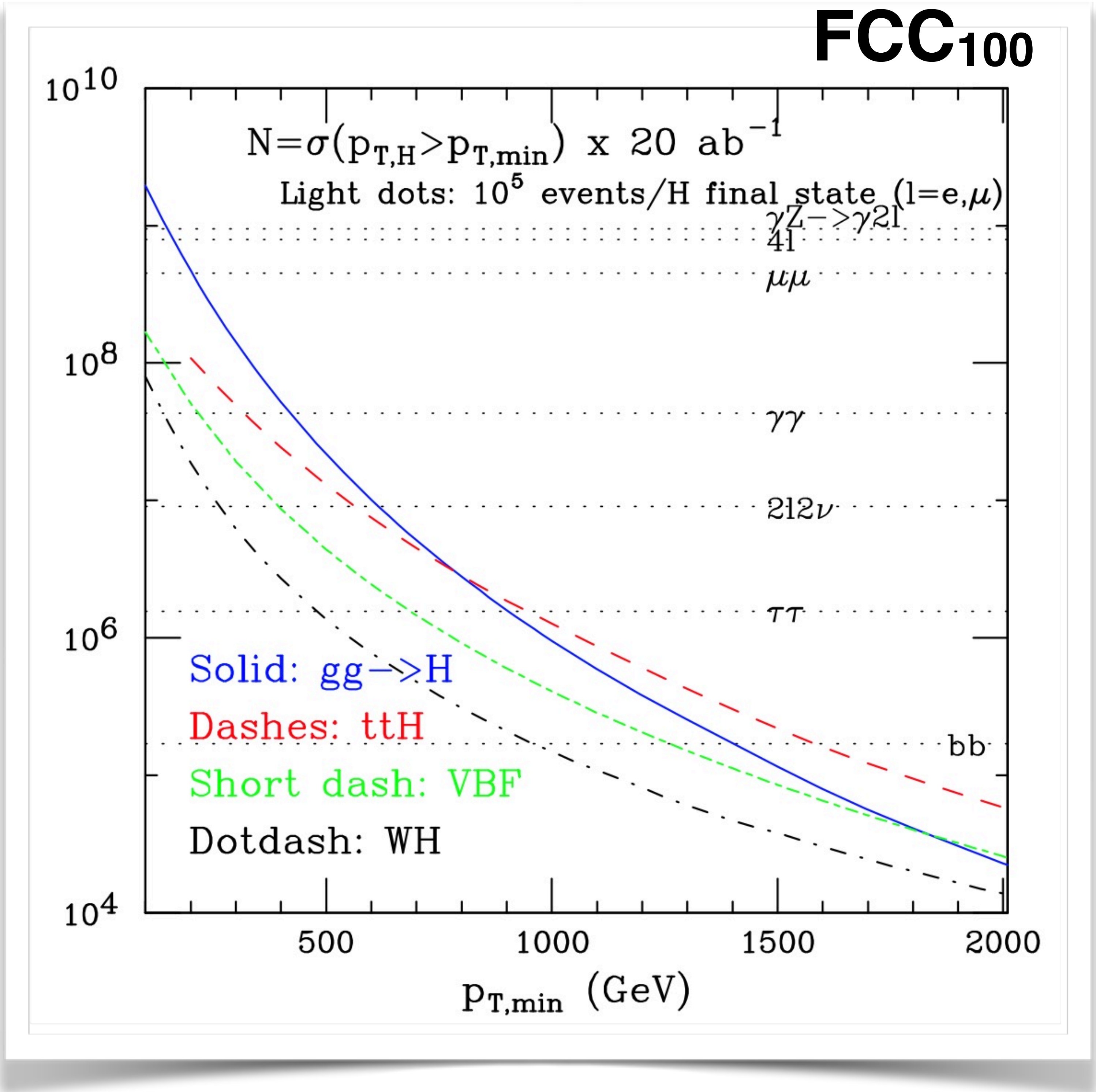
$$\sigma_{p_T^{min}}(c_t, k_g) = \int_{s_{min}/s}^{1} \mathrm{d}\tau\, \mathcal{L}_{part}(\tau)\, \hat{\sigma}_{p_T^{min}}(c_t, k_g, \tau\, s)$$

resolve UV vs IR

p_T^{min} [GeV]	$\sigma^{SM}_{p_T^{min}}$ [fb]	δ	κ
100	2200	0.016	0.023
150	840	0.069	0.13
200	350	0.20	0.31
250	160	0.39	0.56
300	75	0.61	0.89
350	38	0.86	1.3
400	20	1.1	1.8
450	11	1.4	2.3
500	6.3	1.7	2.9
550	3.7	2.0	3.6
600	2.2	2.3	4.4
650	1.4	2.6	5.2
700	0.87	3.0	6.2
750	0.56	3.3	7.2
800	0.37	3.7	8.4



Updated version of: Azatov, Grojean, Paul, Salvioni '16



Lesson: Hierarchy of production channels changes at large $p_T(H)$:

- $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
- $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

slide by M. Mangano

Probing the heart of EWSB with

$$\sigma(pp \to hh)$$

Higgs self-interaction

$$V_{\rm SM} = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$V_{\rm SM} = \frac{m_h^2}{2} h^2 + \lambda_3 v\, h^3 + \lambda_4\, h^4$$

SM predicts:

$$\lambda_3^{\rm SM} = m_h^2/(2v^2) \approx 0.13$$

$$\lambda_4^{\rm SM} = m_h^2/(8v^2) \approx 0.03$$

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SM predicts:

no need to measure this in absence of BSM

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$$\lambda_4^{\rm SM} = m_h^2/(8v^2) \approx 0.03$$

Di-Higgs production

	HL-LHC	HE-LHC$_3$	HE-LHC$_{15}$	FCC$_3$
$\sqrt{s}$ (TeV)	14	27	27	100
$L\,(\mathrm{ab}^{-1})$	3	3	15	3
σ_{hh} (fb)	40.2	162	162	1640
N_{hh}	$1.2 \cdot 10^5$	$4.9 \cdot 10^5$	$2.4 \cdot 10^6$	$4.9 \cdot 10^6$

hard possible easy-ish?

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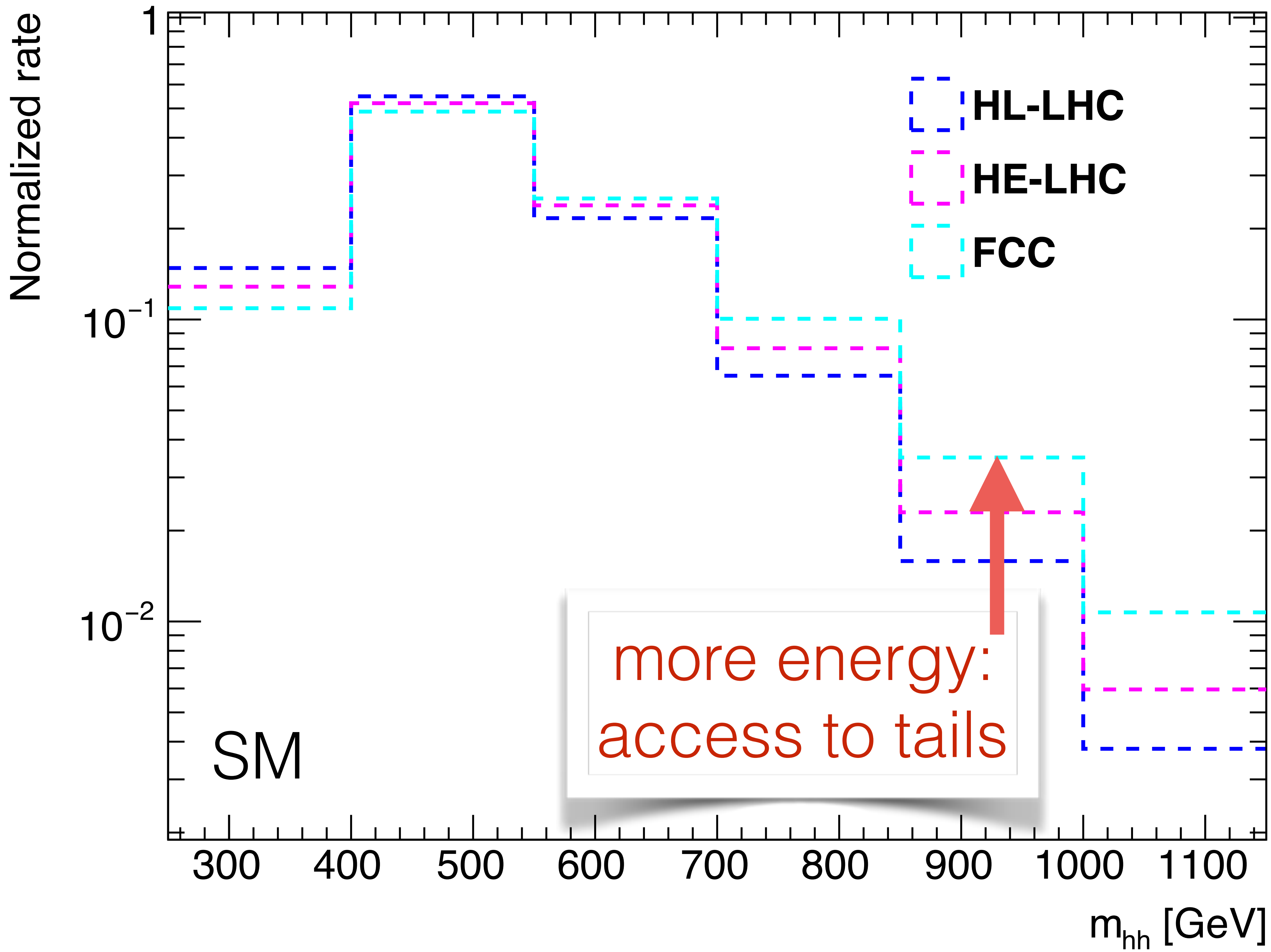
How well does HE-LHC$_{27}$ compared to FCC$_{100}$?

m_{hh} distribution (normalized)



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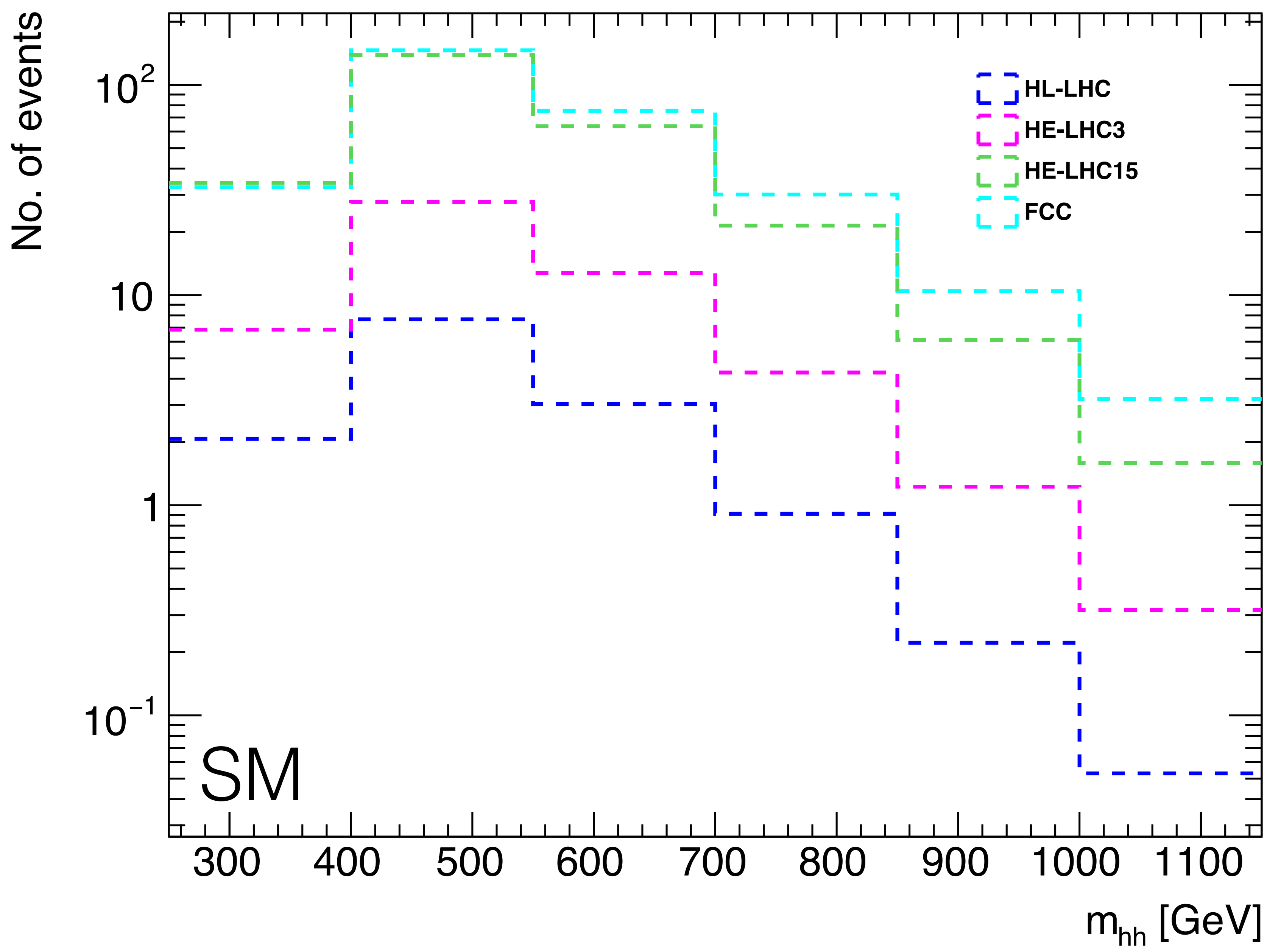
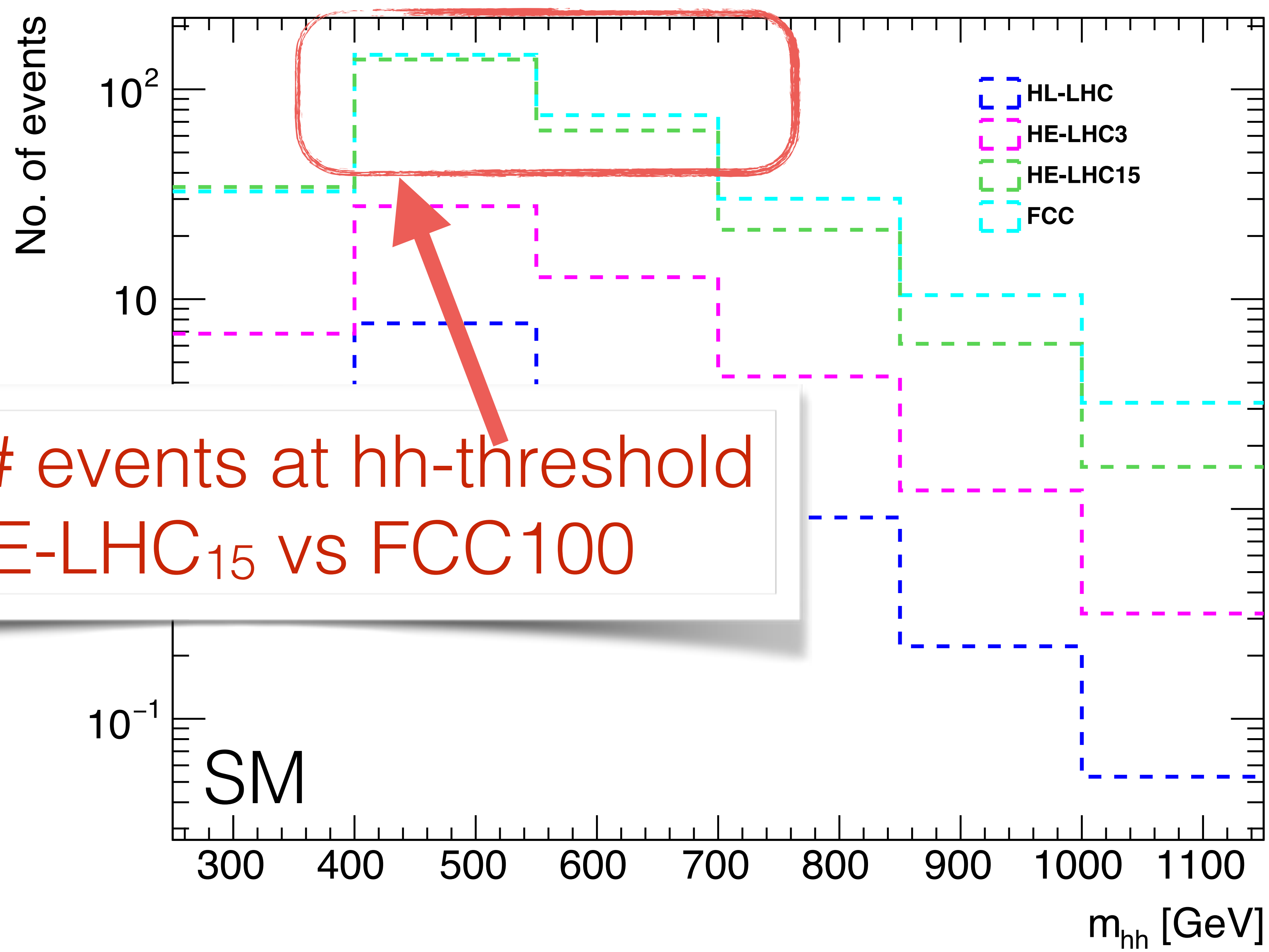


Liew, Sakurai, Salvioni, AW

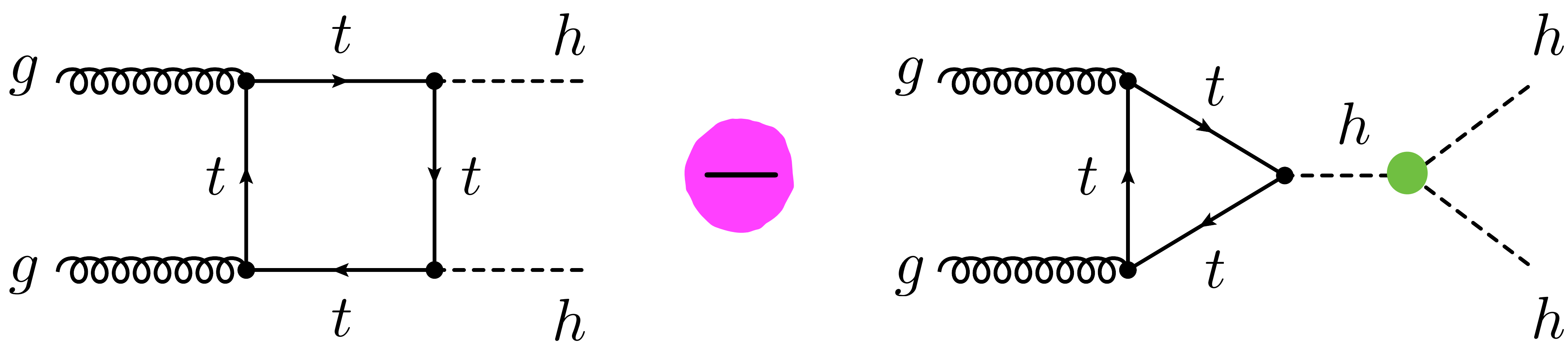
m_{hh} distribution



Similar # events at hh-threshold at HE-LHC$_{15}$ vs FCC100

Liew, Sakurai, Salvioni, AW

Anatomy of hh production

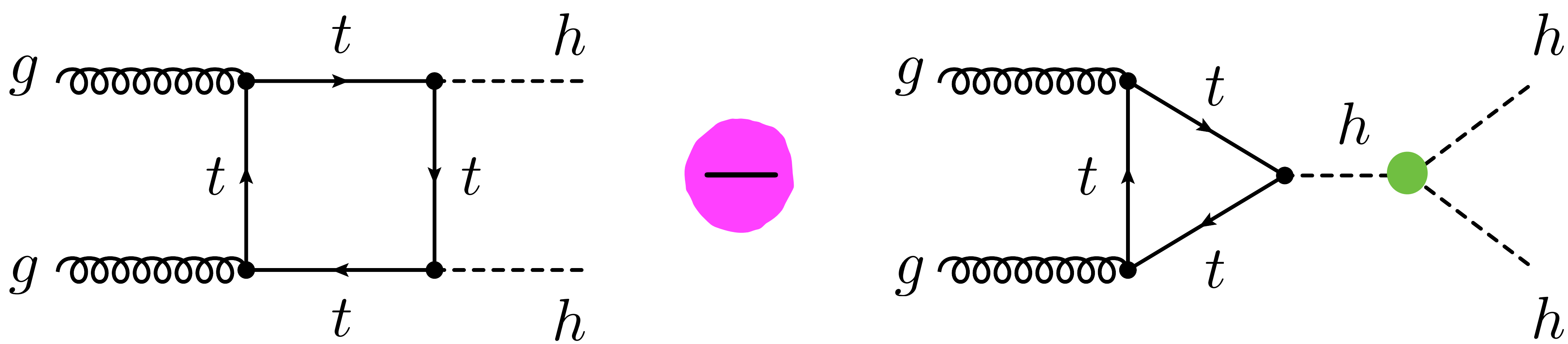


$$R = \frac{\sigma(pp \to hh)}{\sigma(pp \to hh)_{\text{SM}}} = 2.1 - 10.8\lambda + 17.2\lambda^2$$

$$R = 1 \implies \lambda_{1,2} = \{\lambda_{\text{SM}}, 3.8\lambda_{\text{SM}}\}$$

talk by U. Haisch at EWMoriond17

Anatomy of hh production



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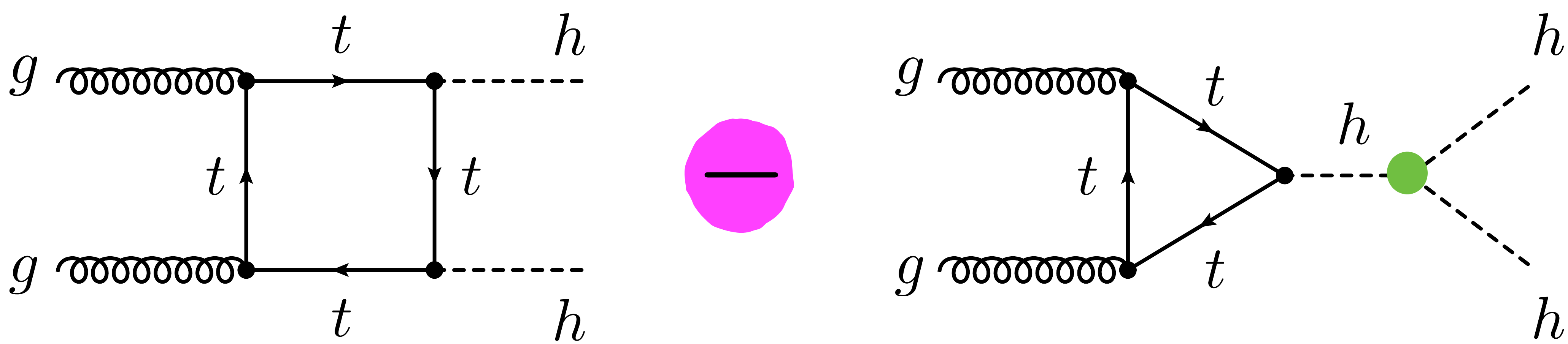
talk by U. Haisch at EWMoriond17, interesting indirect limits: many authors

Anatomy of hh production



Poorly constrained!

LHC Run II, 13.3 fb^{-1} → $\frac{\lambda}{\lambda_{\rm SM}} \in [\text{-}8.4,\ 13.4]$

4b, ATLAS-CONF-2016-049

HL-LHC, 3 ab^{-1} → $\frac{\lambda}{\lambda_{\rm SM}} \in [\text{-}0.8, 7.7]$

2γ2b, ATL-PHYS-PUB-2017-001

talk by U. Haisch at EWMoriond17, interesting indirect limits: many authors

- No BSM: modifying self-coupling clearly makes little sense.

- BSM: modifying only self-coupling not generic, expect effects in other couplings.

↑

Use EFT!

EFT contribution

$$\Delta\mathcal{L}_6 \supset \frac{\bar{c}_H}{2v^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) + \frac{\bar{c}_u}{v^2} y_t H^\dagger H(\bar{q}_L \widetilde{H} t_R + \text{h.c.})$$
$$- \frac{\bar{c}_6}{v^2}\frac{m_h^2}{2v^2}\left(H^\dagger H\right)^3 + \bar{c}_g \frac{g_s^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\,\mu\nu},$$

$$\mathcal{L}_{\text{nonlinear}} \supset -m_t \bar{t}t\left(c_t \frac{h}{v} + c_{2t}\frac{h^2}{v^2}\right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2}\left(c_g \frac{h}{v} + c_{2g}\frac{h^2}{2v^2}\right) G^a_{\mu\nu} G^{a\,\mu\nu},$$

$$c_t = 1 - \frac{1}{2}(\bar{c}_H + 2\,\bar{c}_u), \quad c_{2t} = -\frac{1}{2}(\bar{c}_H + 3\,\bar{c}_u), \quad c_3 = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6, \quad c_g = c_{2g} = \bar{c}_g\left(\frac{4\pi}{\alpha_W}\right)$$

Focus on $hh \to \gamma\gamma b\bar{b}$

$$p_T^{b_1}, p_T^{\gamma_1} > 50 \text{ GeV}\,, \quad p_T^{b_2}, p_T^{\gamma_2} > 30 \text{ GeV}\,,$$

$$\Delta R(b,b) < 2\,, \quad \Delta R(\gamma,\gamma) < 2\,, \quad \Delta R(b,\gamma) > 1.5\,, \qquad \text{(HL-LHC, HE-LHC)}$$

$$105 \text{ GeV} < m_{bb}^{\text{reco}} < 145 \text{ GeV}\,, \quad 120 \text{ GeV} < m_{\gamma\gamma}^{\text{reco}} < 130 \text{ GeV}\,.$$

m_{hh}^{reco} [GeV]	250-400	400-550	550-700	700-850	850-1000	1000-
hh	6.79	28.3	12.7	3.82	1.16	0.63
$\gamma\gamma b\bar{b}$	13.3	18.1	3.95	2.38	1.57	0.81
$t\bar{t}h$	9.89	22.8	7.7	1.85	0.56	0.22

TABLE II: Expected numbers of signal and background events at $\sqrt{s} = 27\,\text{TeV}$ assuming an integrated luminosity $L = 3\,\text{ab}^{-1}$. The last category is inclusive.

$$R = \frac{\sigma(pp \to hh)}{\sigma(pp \to hh)_{\rm SM}} = 2.1 - 10.8\lambda + 17.2\lambda^2$$

Parametrisation as in Azatov et al

$$\sigma = \sigma_{\rm SM}\Big[A_1\, c_t^4 + A_2\, c_{2t}^2 + A_3\, c_t^2 c_3^2 + A_4\, c_g^2 c_3^2 + A_5\, c_{2g}^2 + A_6\, c_{2t} c_t^2 + A_7\, c_t^3 c_3 + A_8\, c_{2t} c_t\, c_3 + A_9\, c_{2t} c_g c_3 + A_{10}\, c_{2t} c_{2g} + A_{11}\, c_t^2 c_g c_3 + A_{12}\, c_t^2 c_{2g} + A_{13}\, c_t c_3^2 c_g + A_{14}\, c_t c_3 c_{2g} + A_{15}\, c_g c_3 c_{2g} \Big].$$

Rate	SM	A_1	A_2	A_3	A_4	A_5	A_6	A_7
inclusive	162 fb	2.04	10.5	0.24	19.0	228	-8.47	-1.28
after-cut	17.8 ab	1.76	9.99	0.13	6.19	161	-7.54	-0.90

Rate	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}
inclusive	2.75	19.1	56.6	-9.31	-19.3	3.58	9.60	91.9
after-cut	1.99	11.5	41.6	-4.17	-18.5	1.12	9.90	50.2

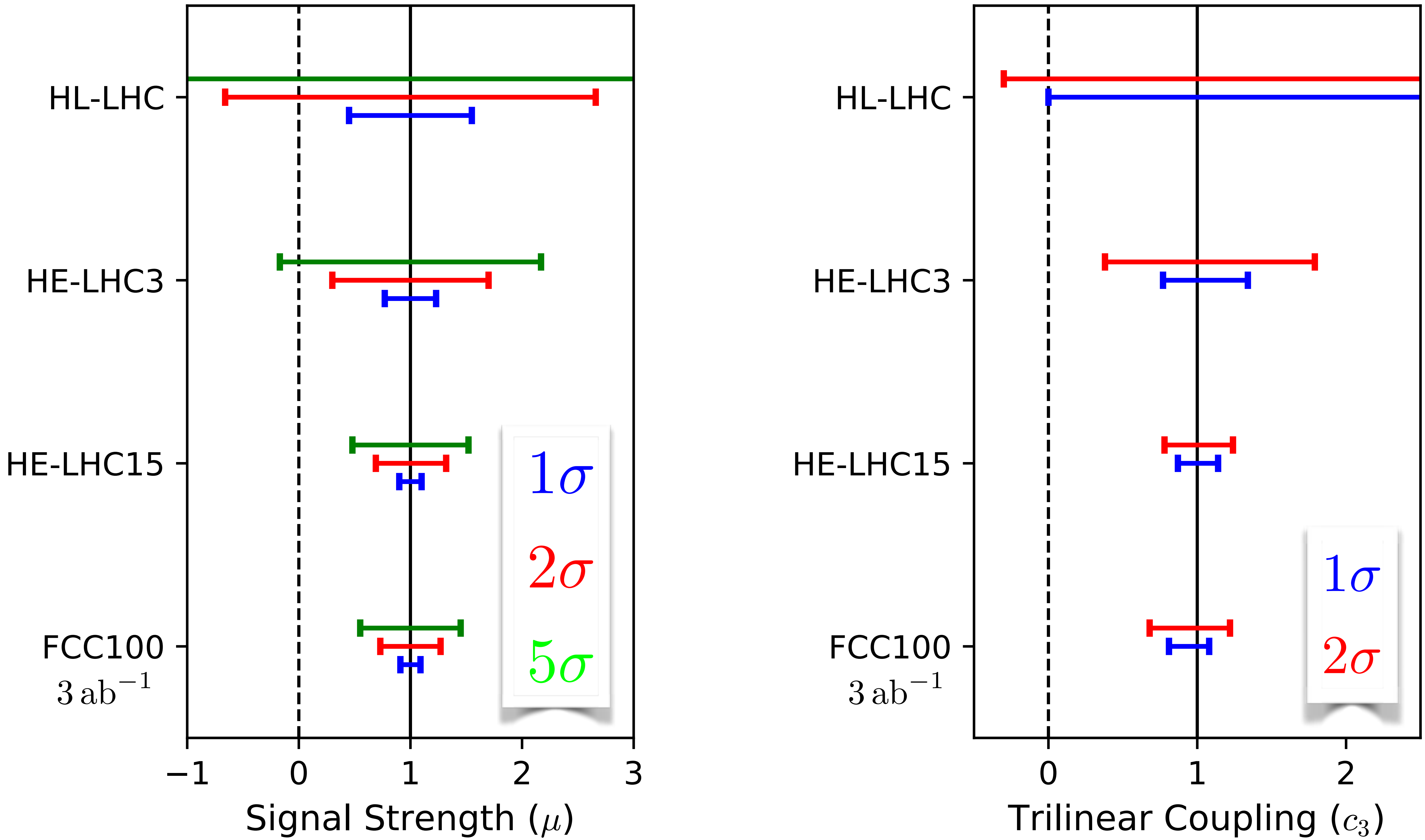
HE-LHC (27 TeV)

Liew, Sakurai, Salvioni, AW

Sensitivities

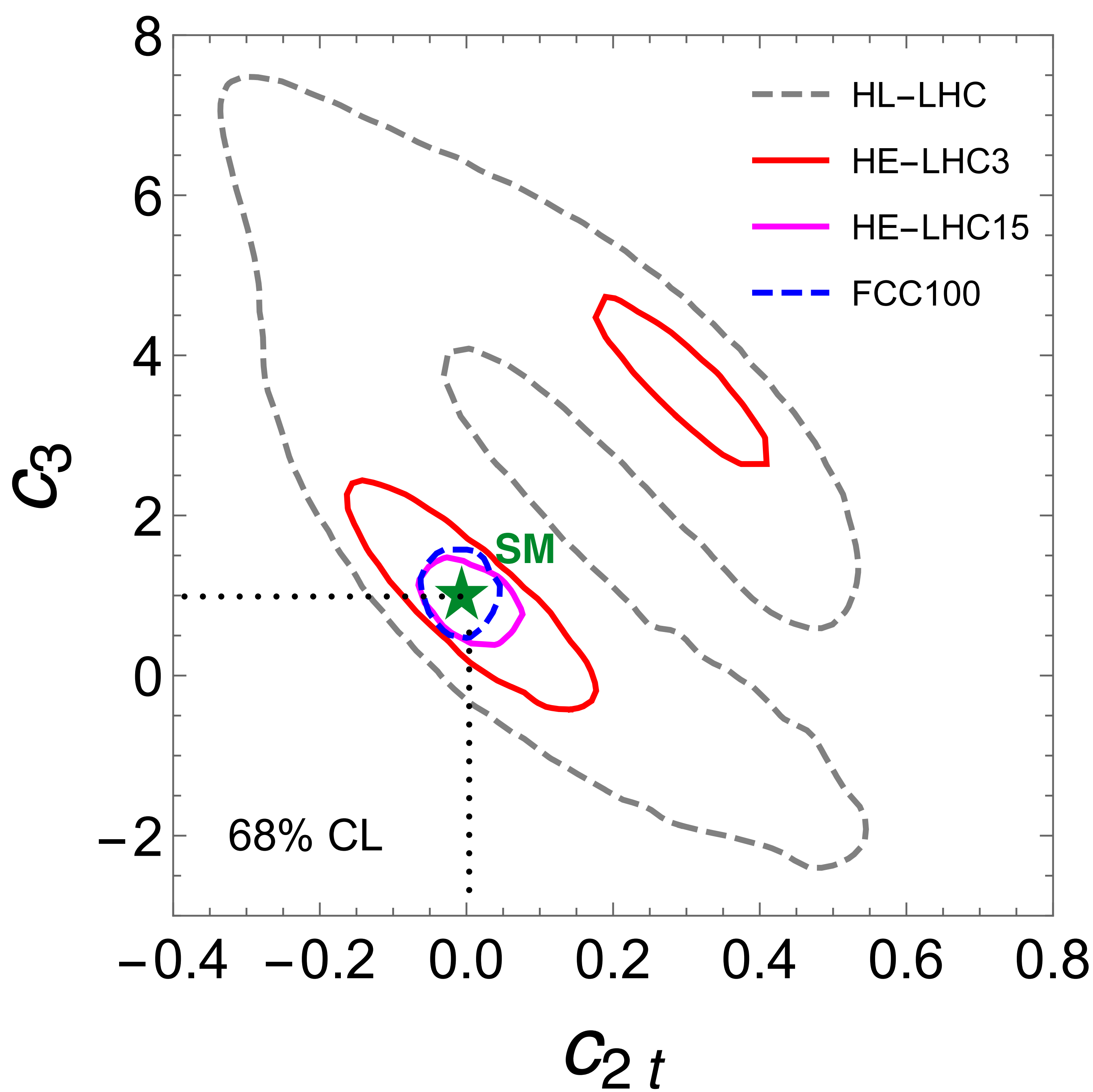
$$\mu = \frac{\sigma(pp \to hh)}{\sigma_{\rm SM}}$$

$$\mathbf{c_3} = \frac{\lambda^{\rm NP}}{\lambda^{\rm SM}}$$

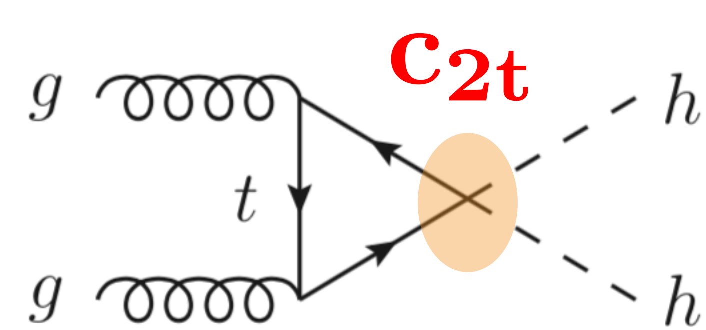


Liew, Sakurai, Salvioni, AW, see also Azatov et. al + many more

Higgs self-coupling vs. $\bar{t}thh$

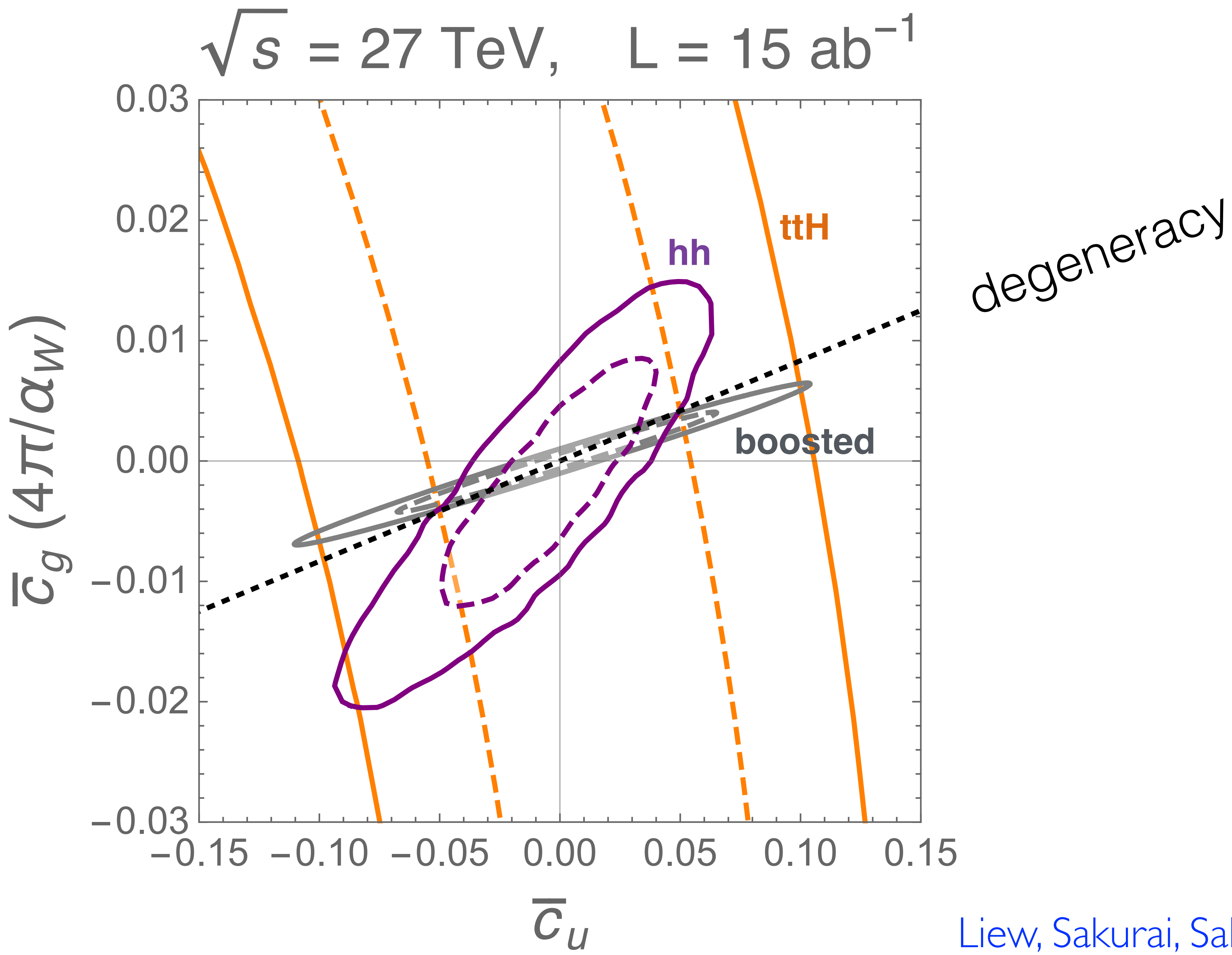


$$\mathbf{c_3} = \frac{\lambda^{\rm NP}}{\lambda^{\rm SM}}$$



Liew, Sakurai, Salvioni, AW

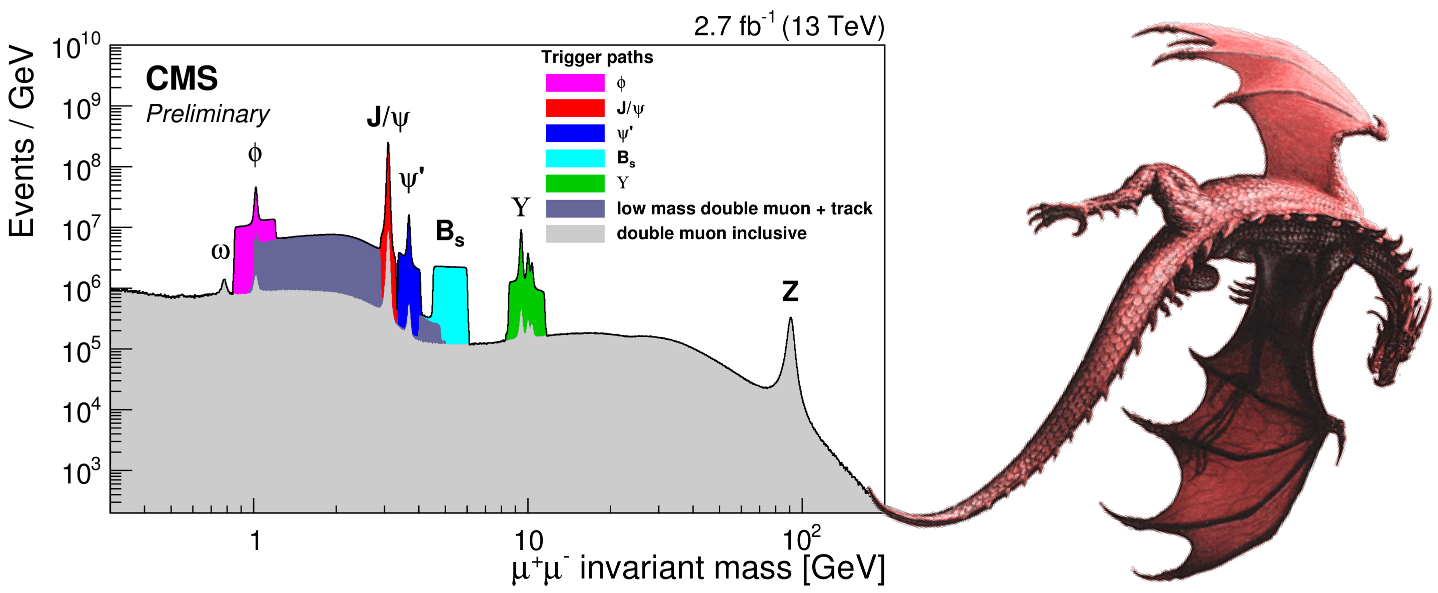
$\bar{c}_u$ vs. $\bar{c}_g$



Liew, Sakurai, Salvioni, AW

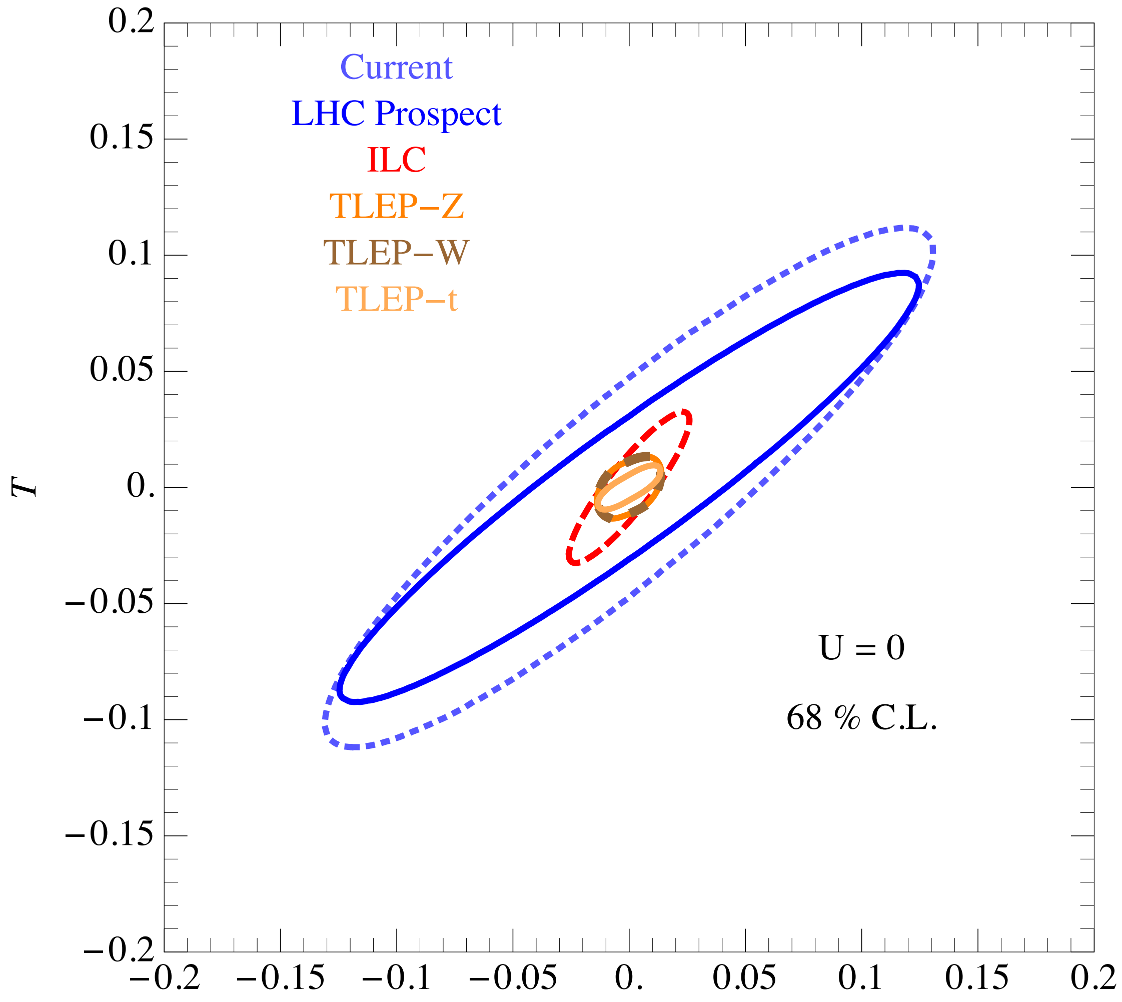
tth exclusions are based on a 10% determination of the tth(→ bb) signal strength

Catching the tails of EW resonances

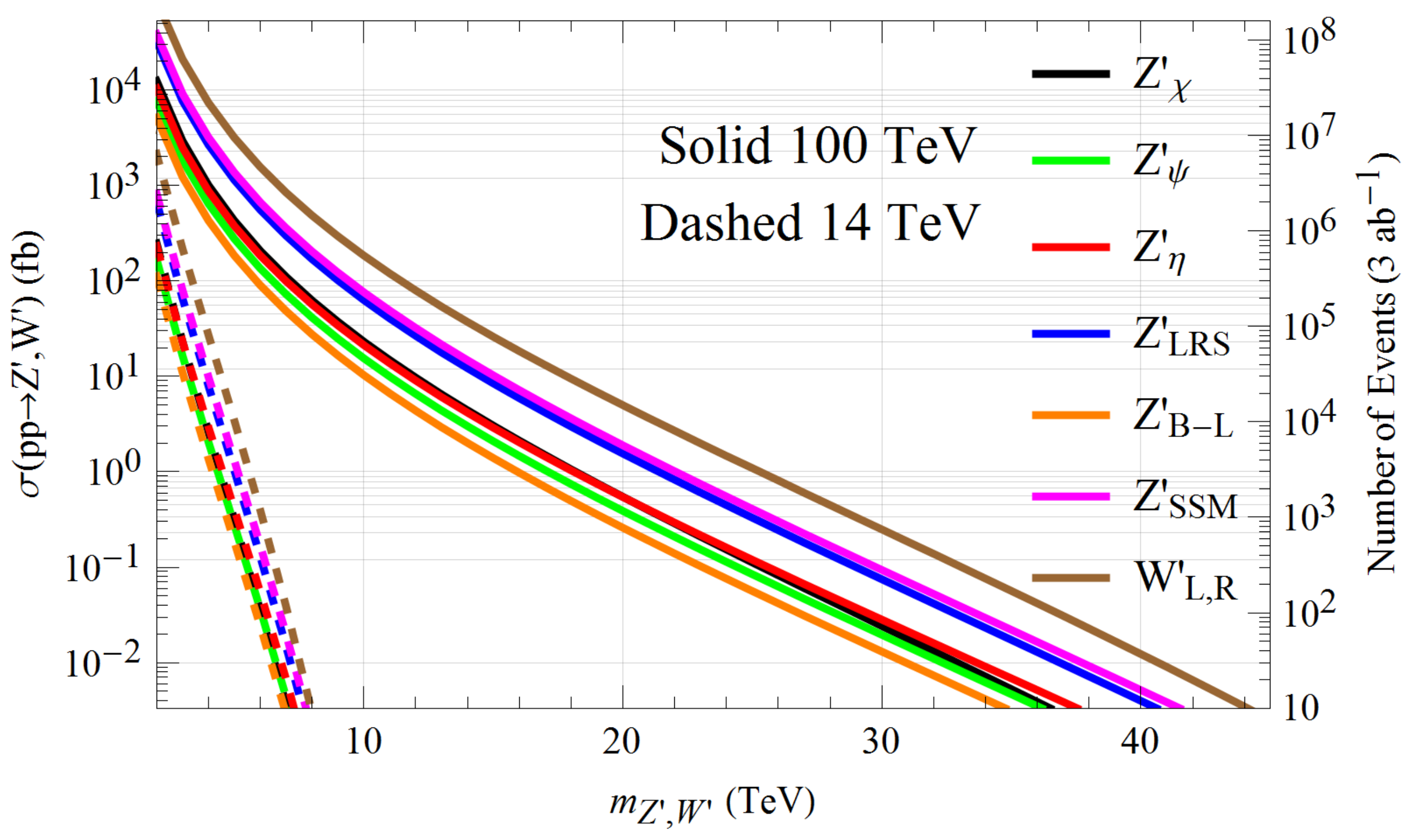


Conventional wisdom: Indirect vs. direct

FCC-ee: precision

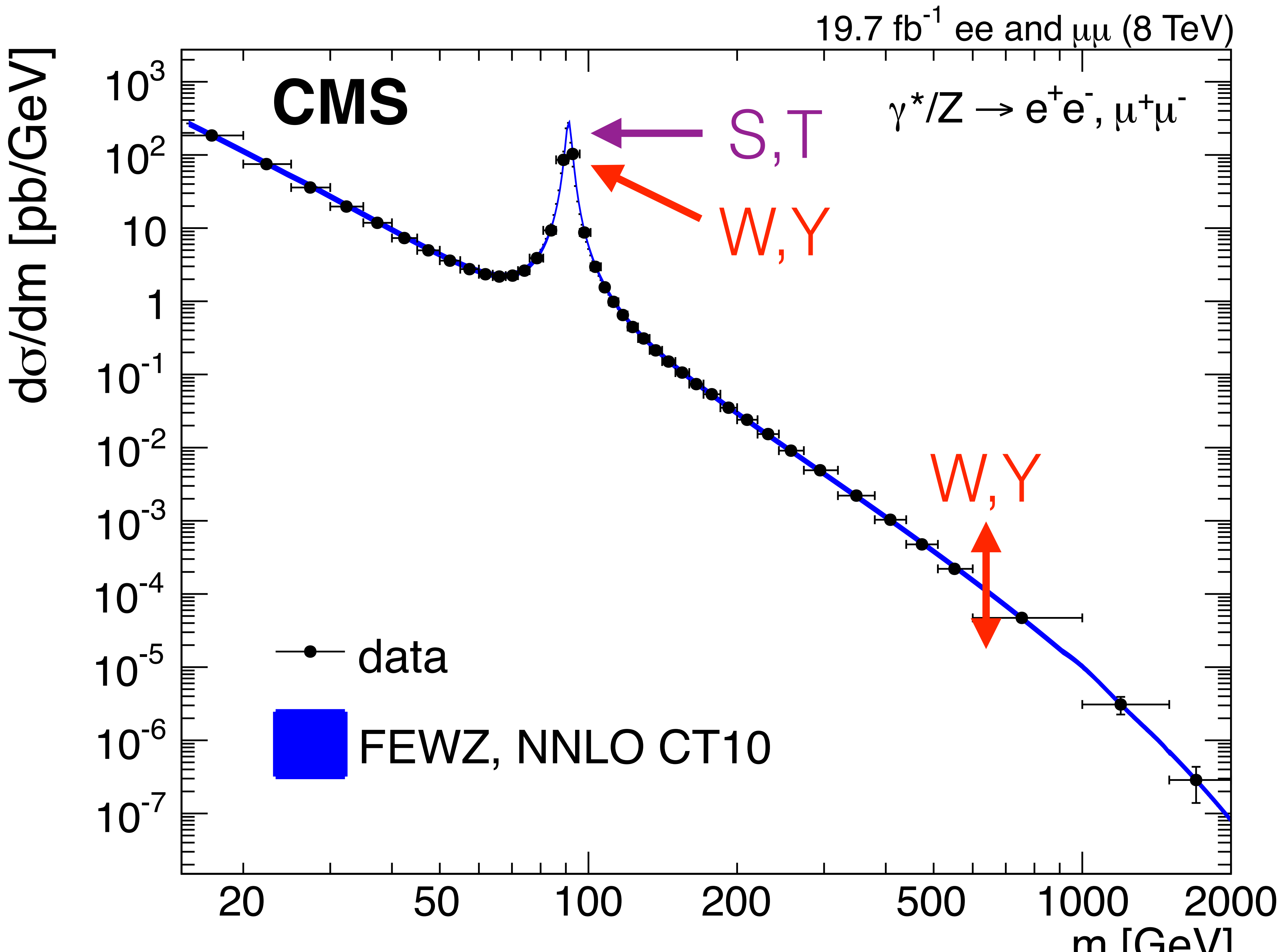


FCC-pp: direct production



Precision tests at FCC$_{100}$

$$\mathcal{L} \supset \frac{1}{\Lambda_S^2} H^\dagger W_{\mu\nu} H B_{\mu\nu} + \frac{1}{\Lambda_T^2} |H^\dagger D_\mu H|^2 + \frac{1}{\Lambda_W^2} (D_\rho W^a_{\mu\nu})^2 + \frac{1}{\Lambda_Y^2} (\partial_\rho B_{\mu\nu})^2$$

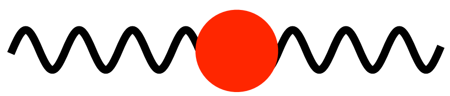


$$\frac{\delta\sigma}{\sigma} \propto \frac{q^2}{\Lambda_{W,Y}^2}$$

slide J Ruderman

Oblique Parameters

slide J Ruderman

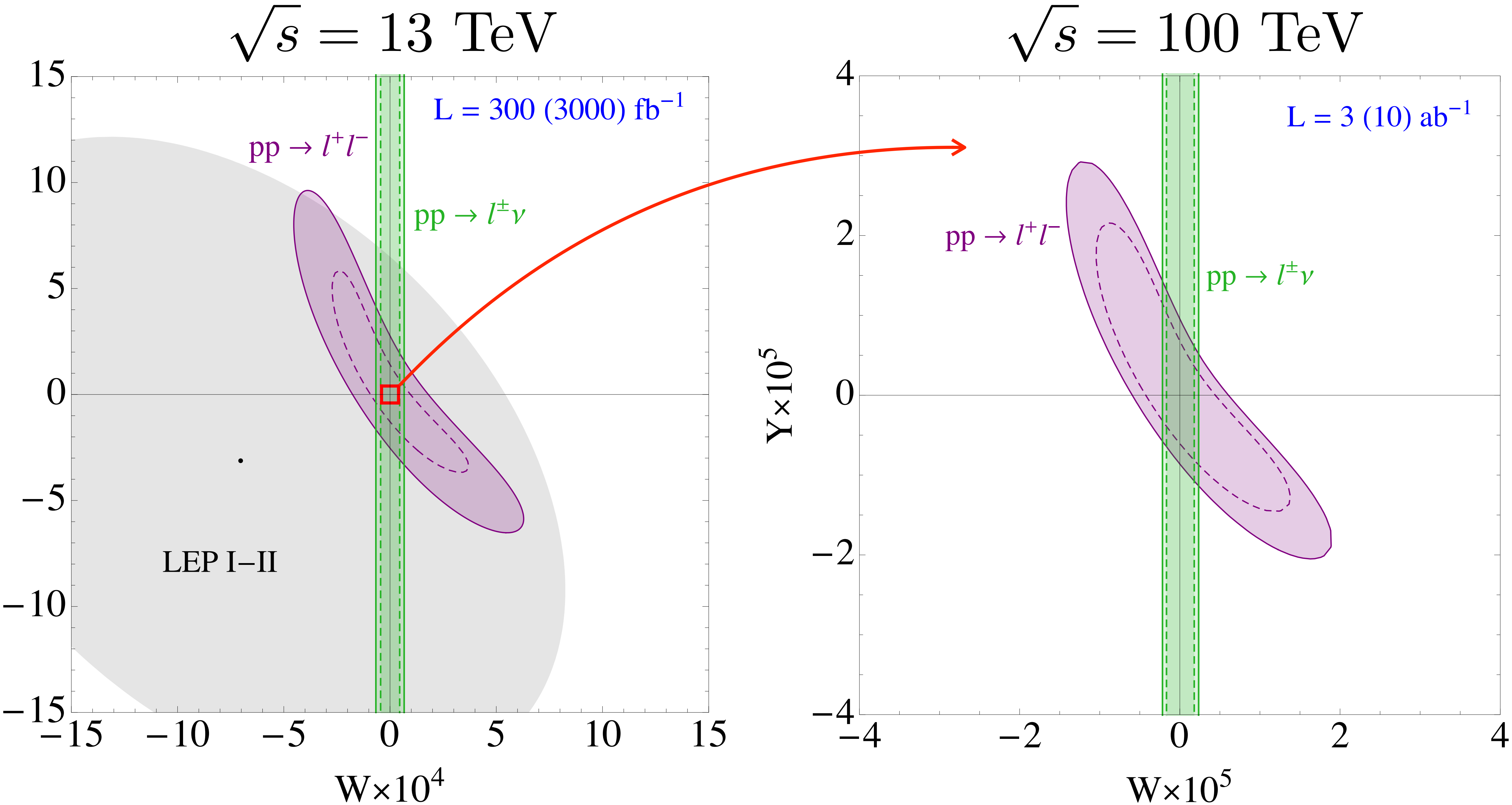
V_i  V_j $\qquad V = \gamma, Z, W^{\pm}$

$$\Pi_{V_iV_j}(q^2) = \Pi_{V_iV_j}(0) + q^2\Pi'_{V_iV_j}(0) + \frac{1}{2}q^4\Pi''_{V_iV_j}(0) + \ldots$$

form factor	operator	parameter
$\Pi'_{W_3B}(0)$	$\frac{1}{\Lambda_S^2}H^\dagger W_{\mu\nu}HB_{\mu\nu}$	$S = -\frac{16\sin(2\theta_W)}{g^2\alpha}\frac{m_W^2}{\Lambda_S^2}$
$\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$\frac{1}{\Lambda_T^2}\lvert H^\dagger D_\mu H\rvert^2$	$T = -\frac{2}{g^2\alpha}\frac{m_W^2}{\Lambda_T^2}$
$\Pi''_{W_3W_3}(0)$	$\frac{1}{\Lambda_W^2}(D_\rho W^a_{\mu\nu})^2$	$W = -4\frac{m_W^2}{\Lambda_W^2}$
$\Pi''_{BB}(0)$	$\frac{1}{\Lambda_Y^2}(\partial_\rho B_{\mu\nu})^2$	$Y = -4\frac{m_W^2}{\Lambda_Y^2}$

- Peskin, Takeuchi **1990**
- Barbieri, Pomarol, Rattazzi, Strumia **hep-ph/0405040**

Future W/Y Reach



$\Lambda_W \gtrsim 24$ TeV

$\Lambda_Y \gtrsim 15$ TeV

$\Lambda_W \gtrsim 110$ TeV

$\Lambda_Y \gtrsim 70$ TeV

Farina et al, Phys.Lett. B772 (2017) 210-215

comparing colliders

FCC-pp

		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		$2 \times 10^7\, Z$	$19.7\,\mathrm{fb}^{-1}$	$20.3\,\mathrm{fb}^{-1}$	$0.3\,\mathrm{ab}^{-1}$	$3\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$10^9\, Z$	$10^{12}\, Z$	$3\,\mathrm{ab}^{-1}$
NC	$\mathrm{W}\times 10^4$	$[-19, 3]$	$[-3, 15]$	$[-5, 22]$	± 1.5	± 0.8	± 0.04	± 3	± 0.7	± 0.3
	$\mathrm{Y}\times 10^4$	$[-17, 4]$	$[-4, 24]$	$[-7, 41]$	± 2.3	± 1.2	± 0.06	± 4	± 1	± 0.2
CC	$\mathrm{W}\times 10^4$	—	± 3.9		± 0.7	± 0.45	± 0.02	—	—	—

FCC-ee

Farina et al, Phys.Lett. B772 (2017) 210-215

Conclusions

- High-E machines can probe deep into the heart of EWSB, systematic approach via EFT

- HE-LHC can reach interesting pp -> hh benchmark

- Precision tests can catch new physics at its tail

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