University of Glasgow

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Future colliders

UK Input to European Particle Physics Strategy Update

Durham, 04/04/2018

2026-2037

proton-proton 14 TeV [3/ab]

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electron-positron

top threshold [100/fb]
380 GeV [500/fb]
1.5 TeV [1.5/ab]
3 TeV [3/ab]

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electron-positron

250 GeV [2/ab]
350 GeV [200/fb]
500 GeV [4/ab]

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proton-proton 100 TeV [30/ab], HE-LHC 27 TeV [15/ab]

electron-positron 91 [5.6/ab/yr], 160 [1.6/ab/yr], 240 [2.5/ab], 365 GeV [130/fb/yr]

electron-proton e(60 GeV) p(50 TeV)

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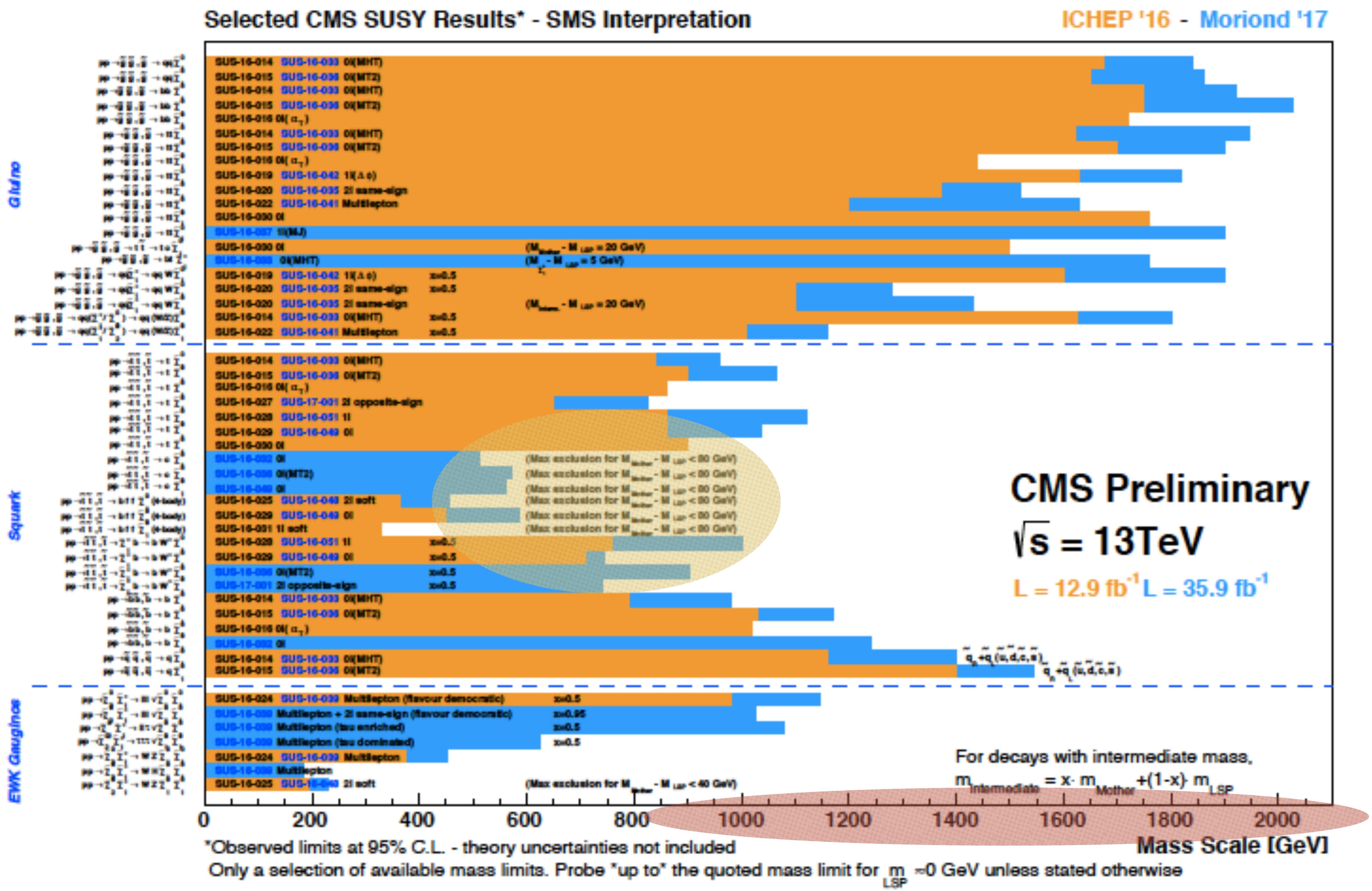
proton-proton 100 TeV as SPPC

electron-positron 91 ["10 x LEP"], 240 GeV [5/ab]

electron-proton e(60 GeV) p(35 TeV)

HiLumi HL-LHC PROJECT — proton-proton	14 TeV [3/ab]	2026-2037
CLIC — electron-positron	top threshold [100/fb] 380 GeV [500/fb] 1.5 TeV [1.5/ab] 3 TeV [3/ab]	CDR `12 update `16
ILC — electron-positron	250 GeV [2/ab] 350 GeV [200/fb] 500 GeV [4/ab]	TDR 2013
FCC hh ee he — proton-proton electron-positron electron-proton	100 TeV [30/ab], HE-LHC 27 TeV [15/… 91 [5.6/ab/yr], 160 [1.6/ab/yr], 240 [2.5/ab], 365 G… e(60 GeV) p(50 TeV)	TLEP `13, YRs `16 CDR end `18?
CEPC — proton-proton electron-positron electron-proton	100 TeV as SPPC 91 ["10 x LEP"], 240 GeV [5/ab] e(60 GeV) p(35 TeV)	preCDR `15 CDR spring `18?

☛ LHC has entered the TeV scale sensitivity range



Status of LHC measurements

☛ early stage: constraints can be avoided in non-minimal scenarios

e.g. [Costa, Mühlleitner, Sampaio, Santos ` 15] scenarios for run-2

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
$\star\ m_{h_1}$ (GeV)	125.1	125.1	57.83	86.79	33.17
m_{h_2} (GeV)	260.6	228	125.1	125.1	64.99
$\star\ m_{h_3}$ (GeV)	449.6	311.3	299	291.8	125.1
$\star\ \alpha_1$	-0.04375	0.05125	-1.102	-1.075	1.211
$\star\ \alpha_2$	0.4151	-0.4969	1.136	0.8628	-1.319
$\star\ \alpha_3$	-0.6983	-0.5059	-0.02393	-0.0184	1.118
$\star\ v_S$ (GeV)	185.3	52.3	376.9	241.9	483.2
v_A (GeV)	371.3	201.6	236.3	286.1	857.8
λ	1.148	1.018	0.869	0.764	0.5086
δ_2	-0.9988	1.158	-0.4875	-0.4971	0.01418
d_2	1.819	3.46	0.6656	0.9855	0.003885
m^2 (GeV^2)	5.118×10^4	-5.597×10^4	2.189×10^4	1.173×10^4	-2.229×10^4
b_2 (GeV^2)	-3.193×10^4	-5.147×10^4	-3.484×10^4	-3.811×10^4	1362
b_1 (GeV^2)	9.434×10^4	5.864×10^4	1.623×10^4	1.599×10^4	3674
a_1 (GeV^3)	-1.236×10^7	-2.169×10^6	-4.325×10^6	-2.735×10^6	-1.255×10^6
$\mu^C_{h_1}/\mu^T_{h_1}$	0.0127	0.0407	0.365	0.117	0.687
μ_{h_1}	0.836	0.771	0.0362	0.0958	0.00767
$\sigma_1 \equiv \sigma(gg \to h_1)$	36.1 [pb]	33.3 [pb]	6.42 [pb]	8.03 [pb]	4.61 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	7.55 [pb]	6.96 [pb]	0.345 [fb]	10.3 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	[illegible]	[illegible]	[illegible]	2.44 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to b\bar{b})$	21.3 [pb]	19.6 [pb]	5.48 [pb]	6.6 [pb]	[illegible].01 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	2.29 [pb]	2.11 [pb]	501 [fb]	659 [fb]	323 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	83.7 [fb]	77.2 [fb]	2.87 [fb]	9.13 [fb]	0.617 [fb]

⊕ exotic (rare) signatures

- Conclusions for HEP ? **No guaranteed discoveries. Best case(s)?**

the SM is flawed

no evidence for exotics yet

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Higgs/top properties are central to BSM and a clear deliverable of any future collider

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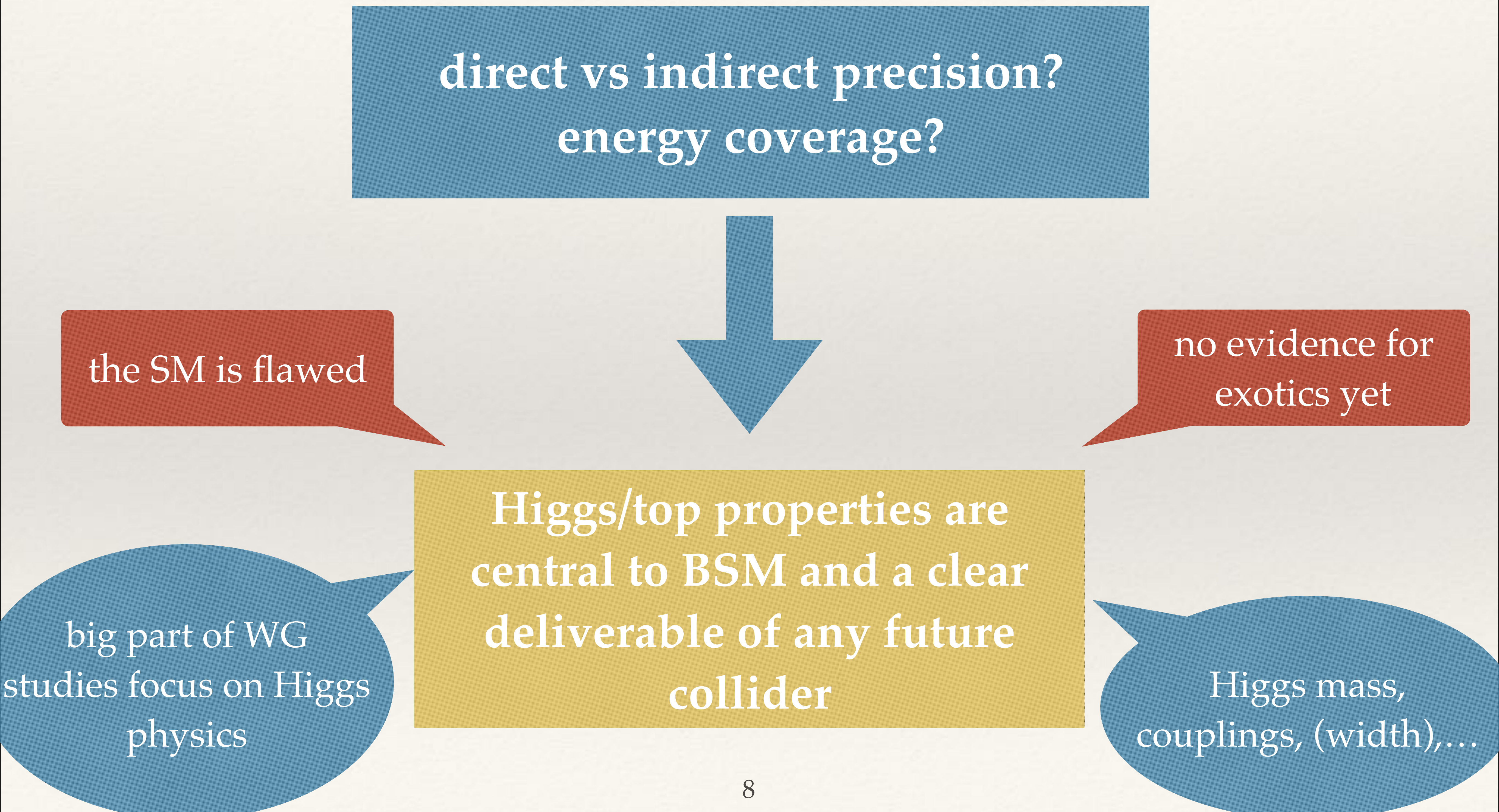


Physics Baseline

☛ Conclusions for HEP ? **No guaranteed discoveries. Best case(s)?**

direct vs indirect precision?
energy coverage?

Higgs properties are central to BSM and a clear deliverable of any future collider

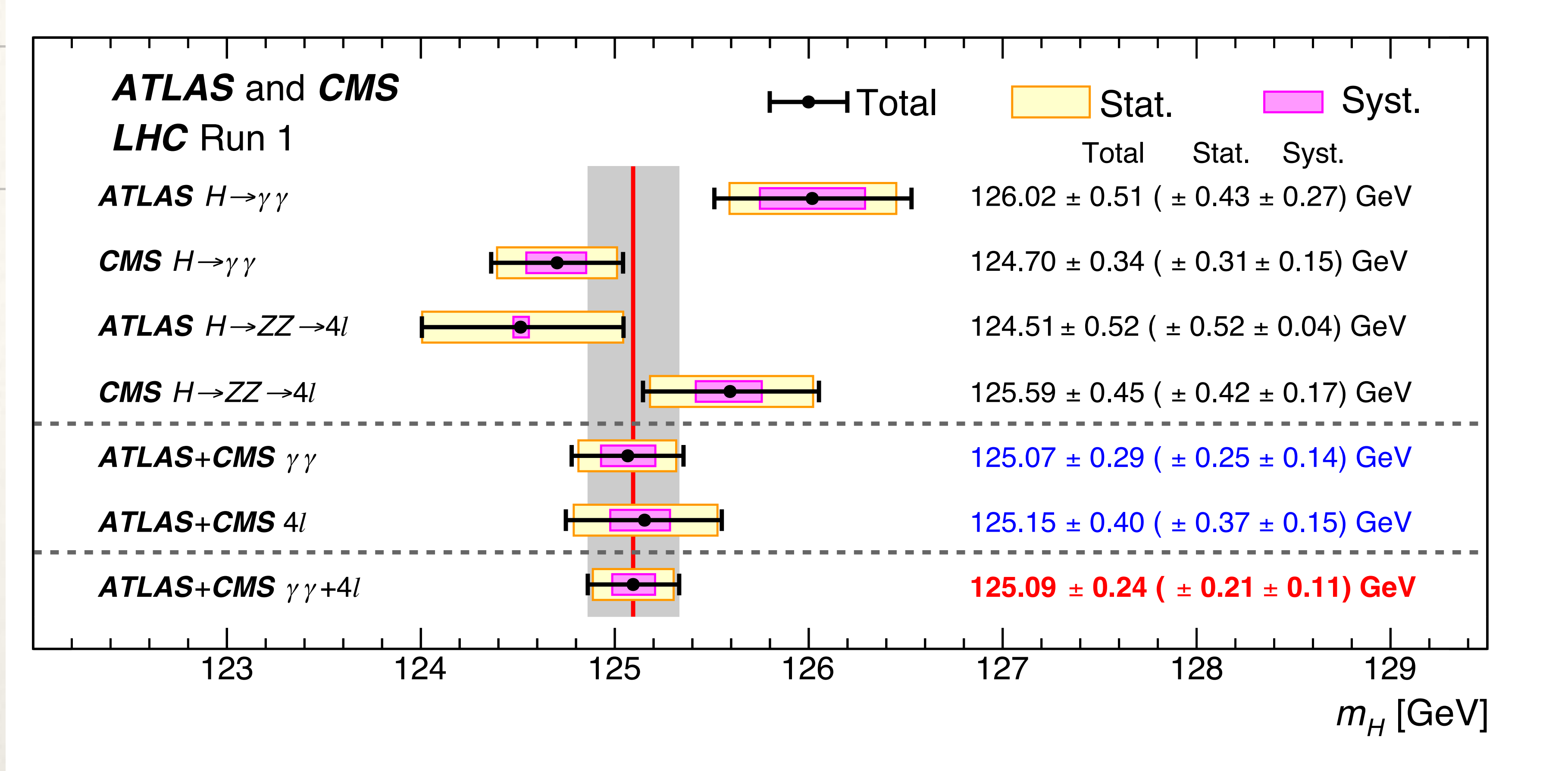
Effective Field Theory

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

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

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

Higgs mass

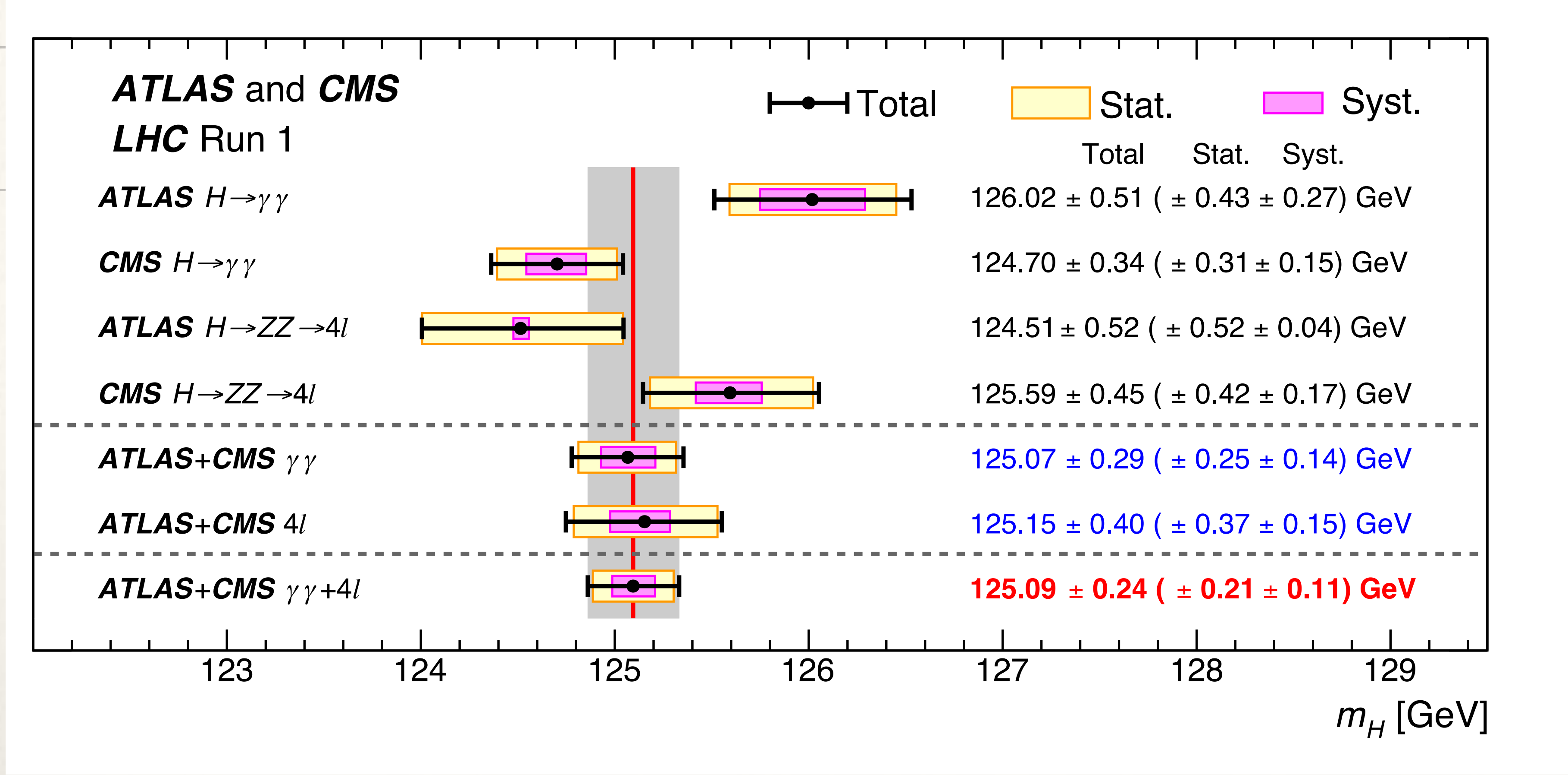


- Higgs mass precision can be limitation of coupling fit precision

$$\delta_W = 6.9 \cdot \delta m_h, \qquad \delta_Z = 7.7 \cdot \delta m_h$$

[Almeida, Lee, Pokorski, Wells ` 13]

Higgs mass



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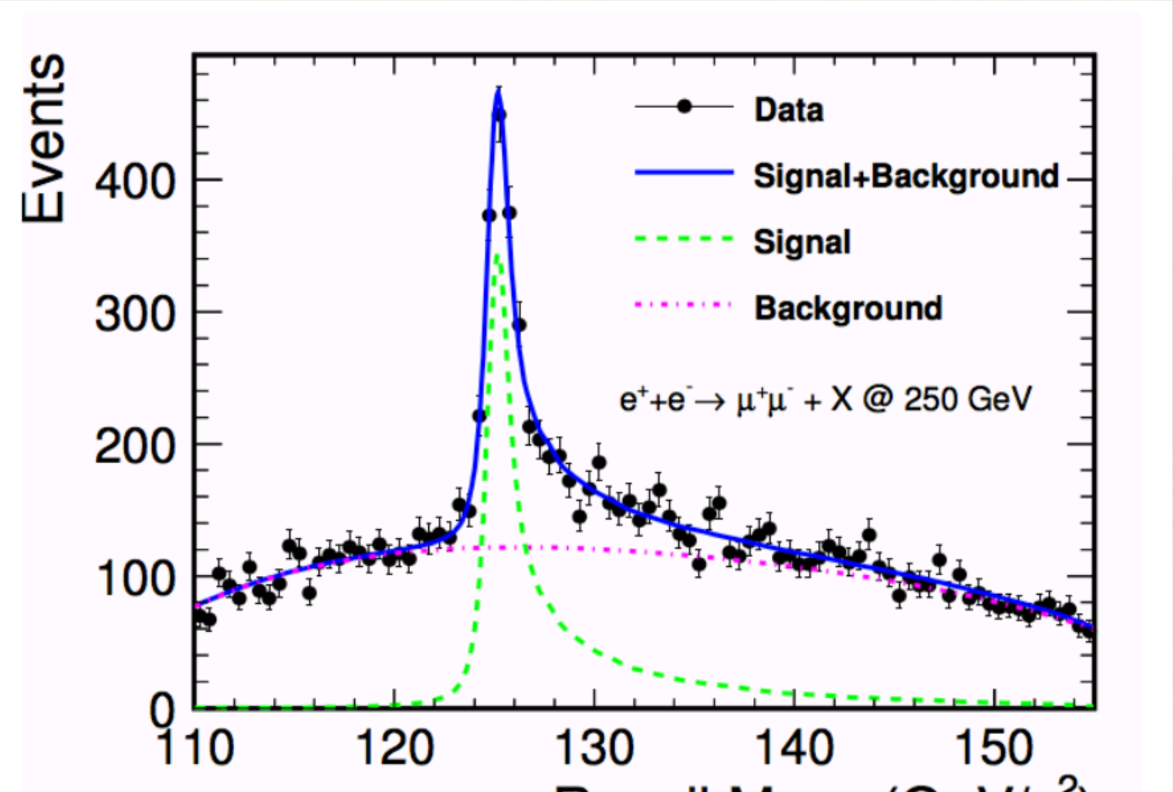
[Almeida, Lee, Pokorski, Wells `13]

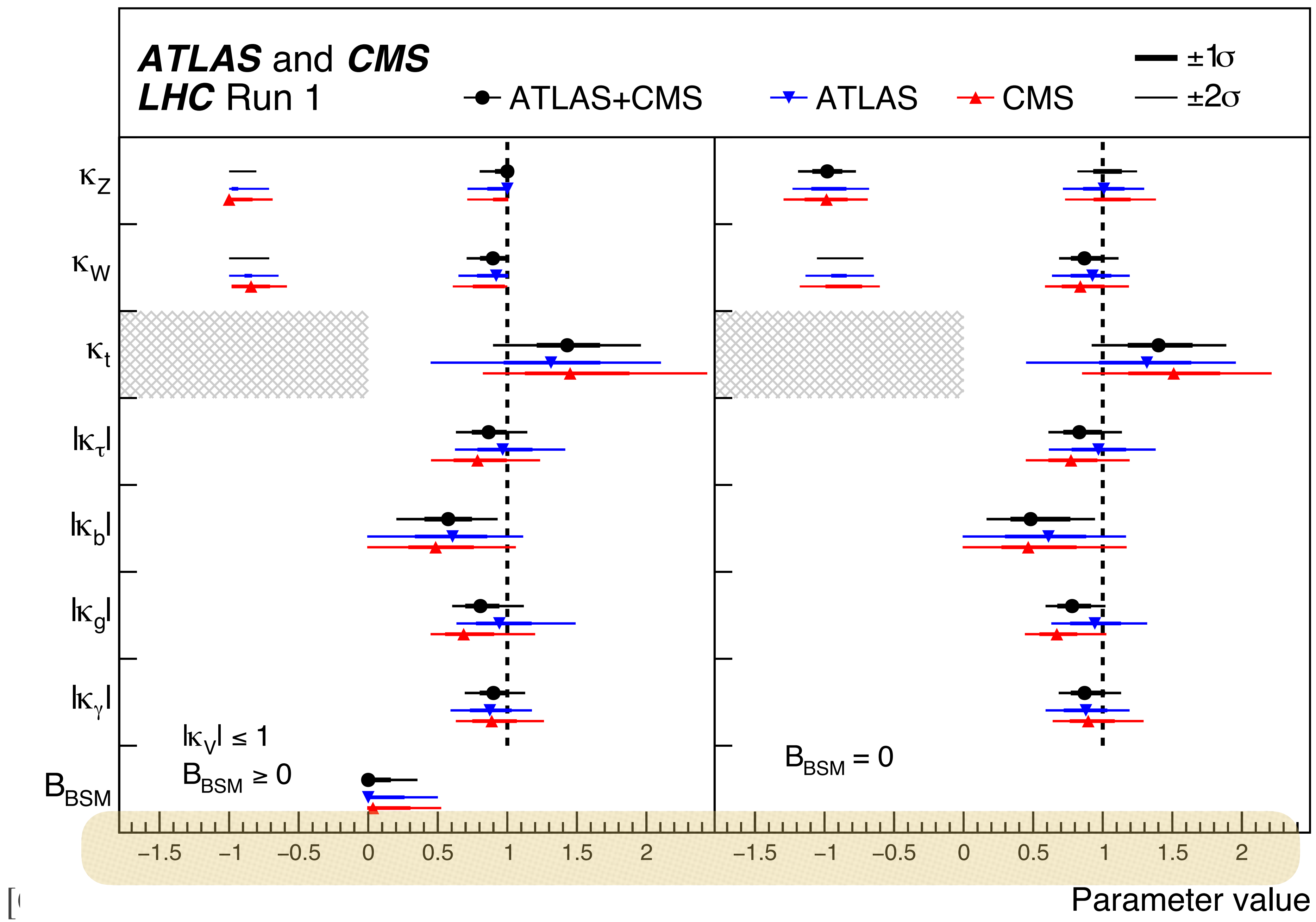
- through leptonic recoil in $Z \to \mu^+\mu^-$ the Higgs mass can be constrained to 14 MeV [LCC Physics Working Group `18]

- impact on Z/W couplings ~0.1%



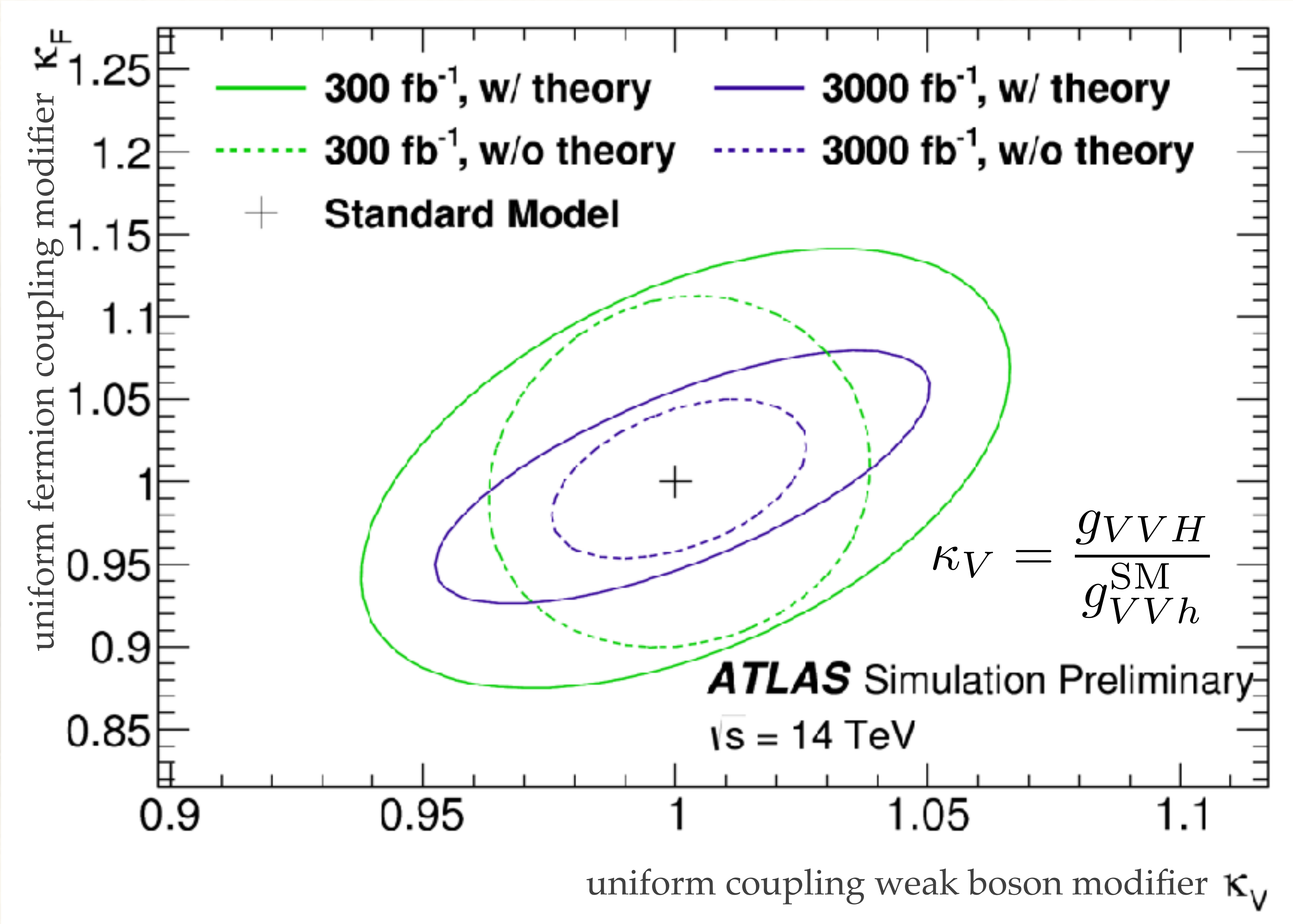
[Yan et al. `16]

Status of LHC measurements



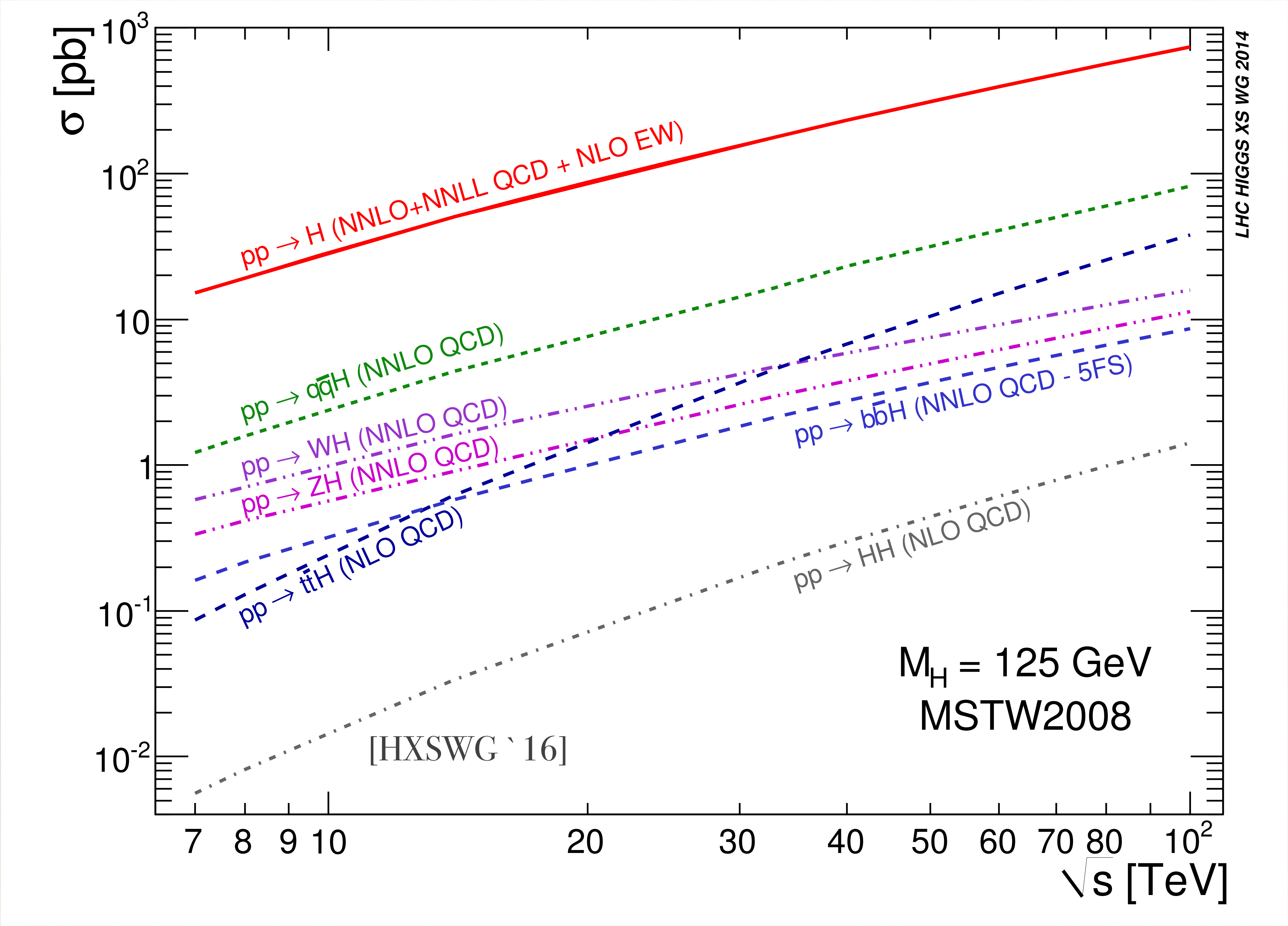
☛ everything is consistent with the SM Higgs hypothesis (so far) but what are the implications for new physics/future colliders?

HL-LHC projections



$$\kappa_V = \frac{g_{VVH}}{g_{VVh}^{\rm SM}}$$

FCC-hh projections



☛ large relative improvement for ttH (pdfs & phasespace)

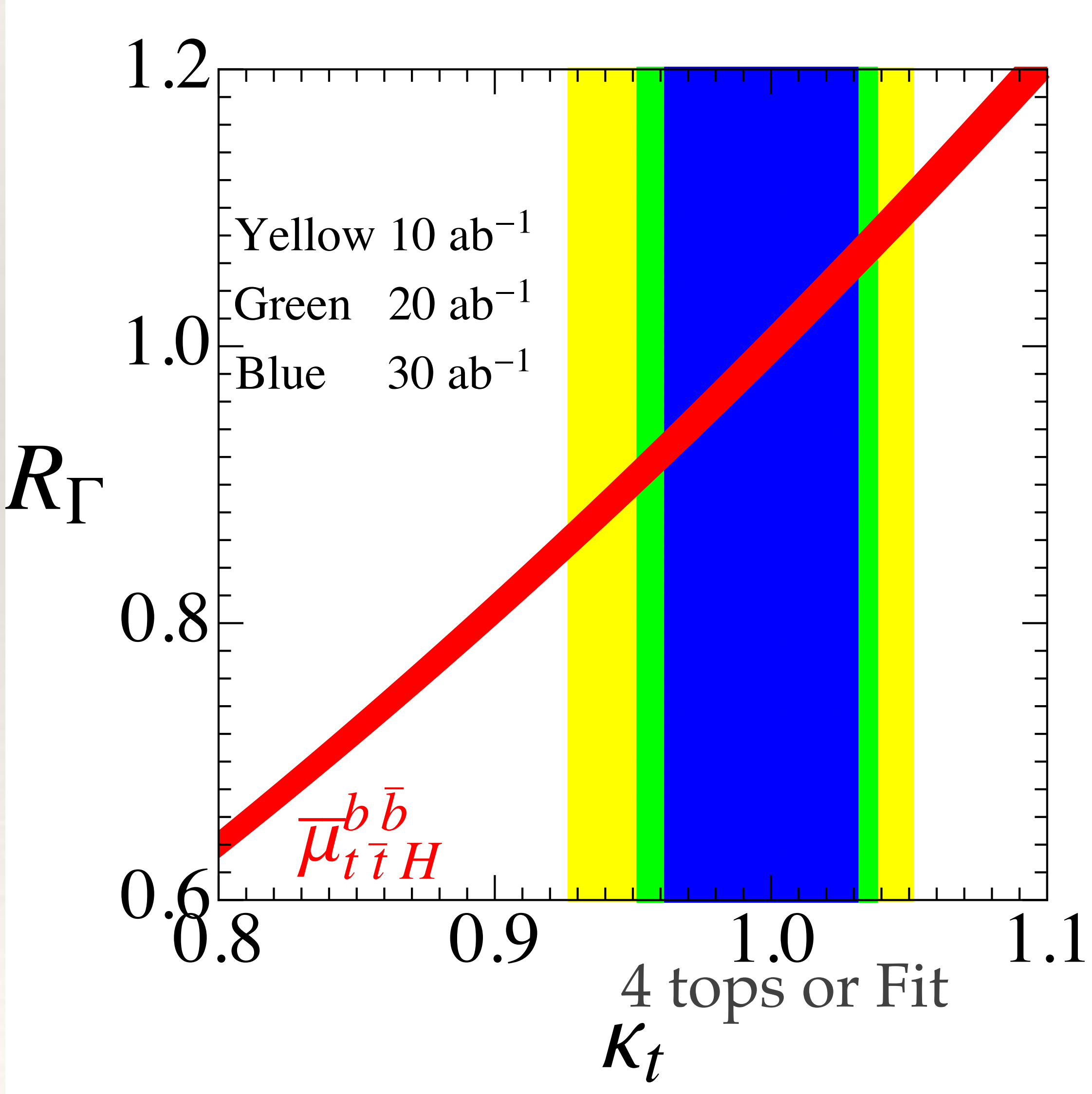
	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

[Mangano, Plehn, Reimitz, Schell, Shao` 15]

$$\mu^{bb}_{t\bar{t}H} = \frac{\kappa_t^2 \kappa_b^2}{R_\Gamma} \qquad \text{with} \qquad R_\Gamma \equiv \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$\sim 1.00 \pm 0.01 \text{ @ } 20/\text{ab}$$

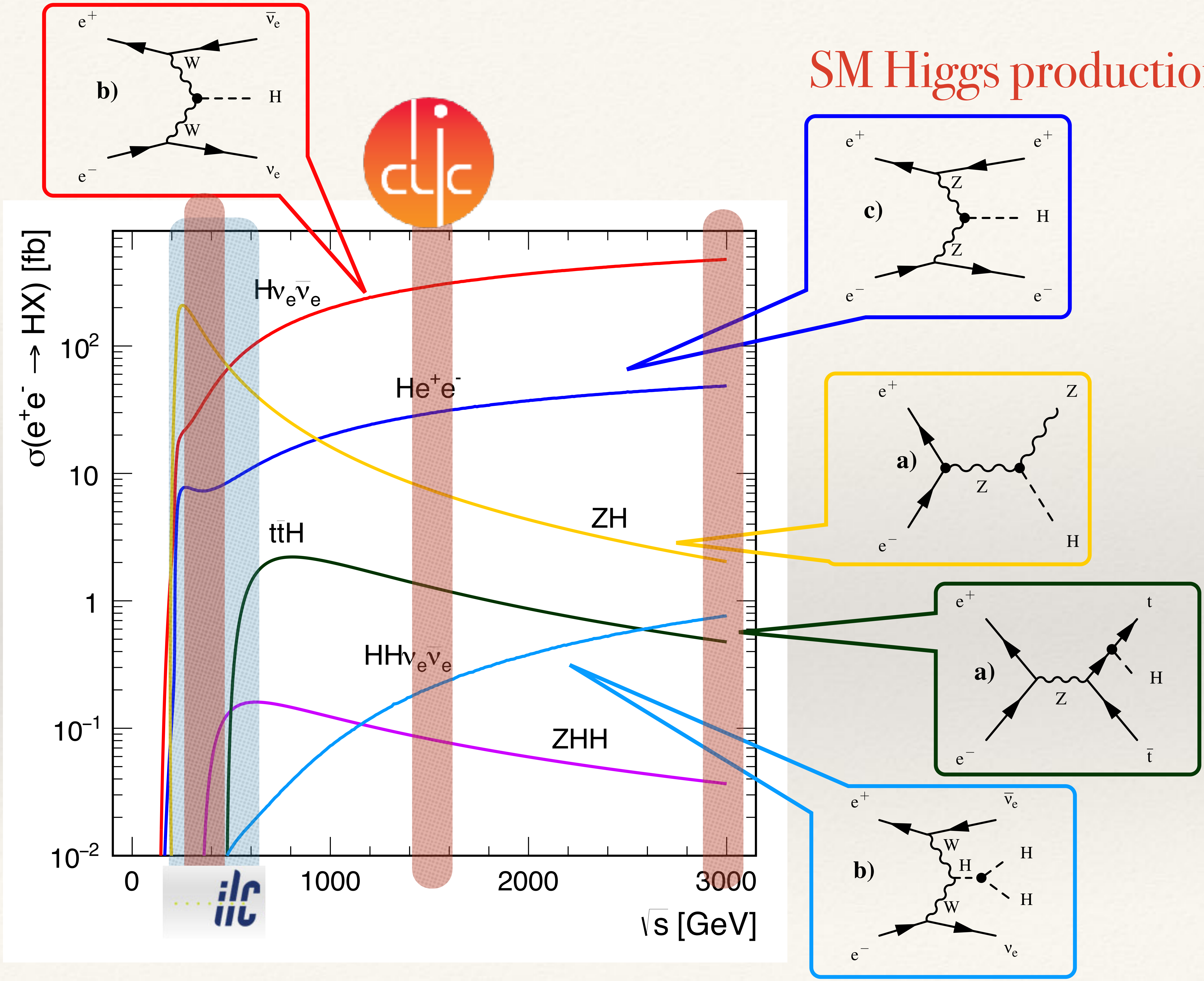
- Precise extraction of top/Higgs properties possible at 100 TeV including rare final states



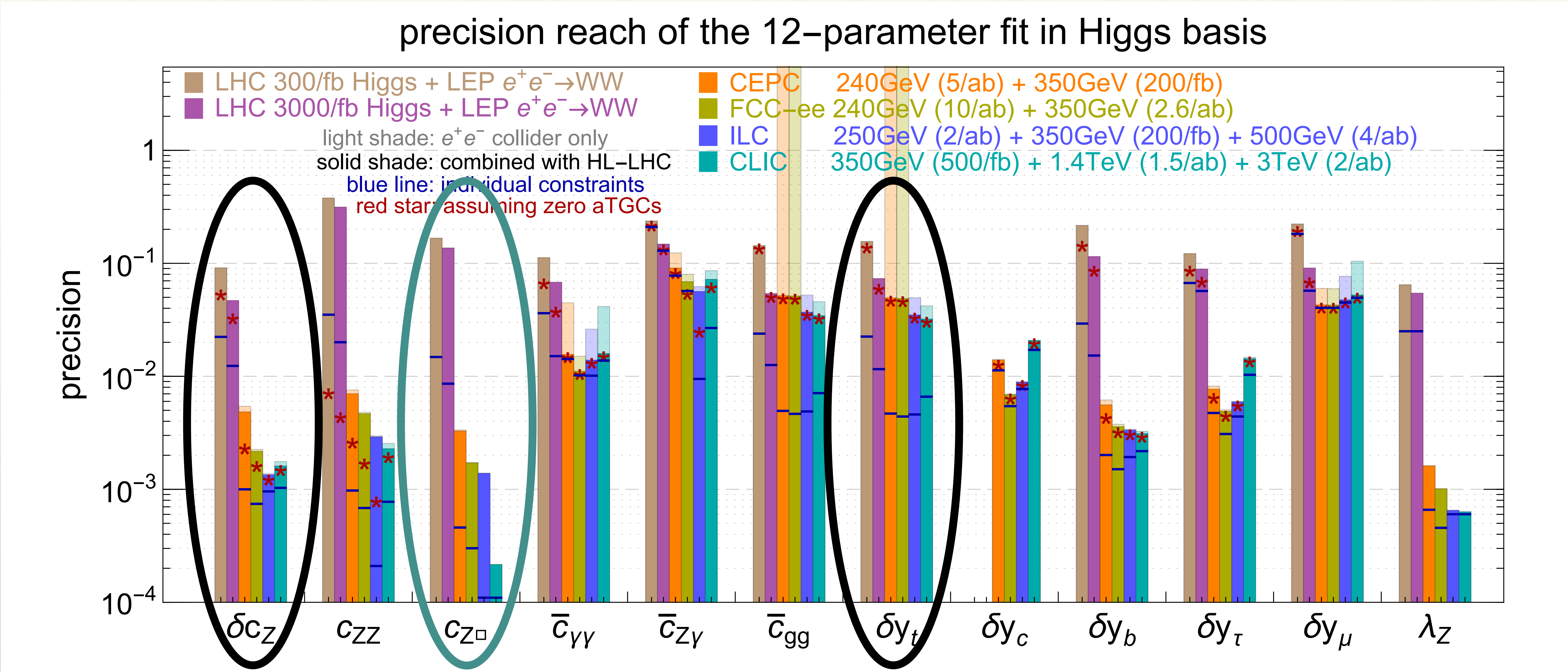
[Cao, Chen, Liu ` 16]

[Contino et al. CERN YR ` 16]

SM Higgs production



Coupling projections: HL-LHC

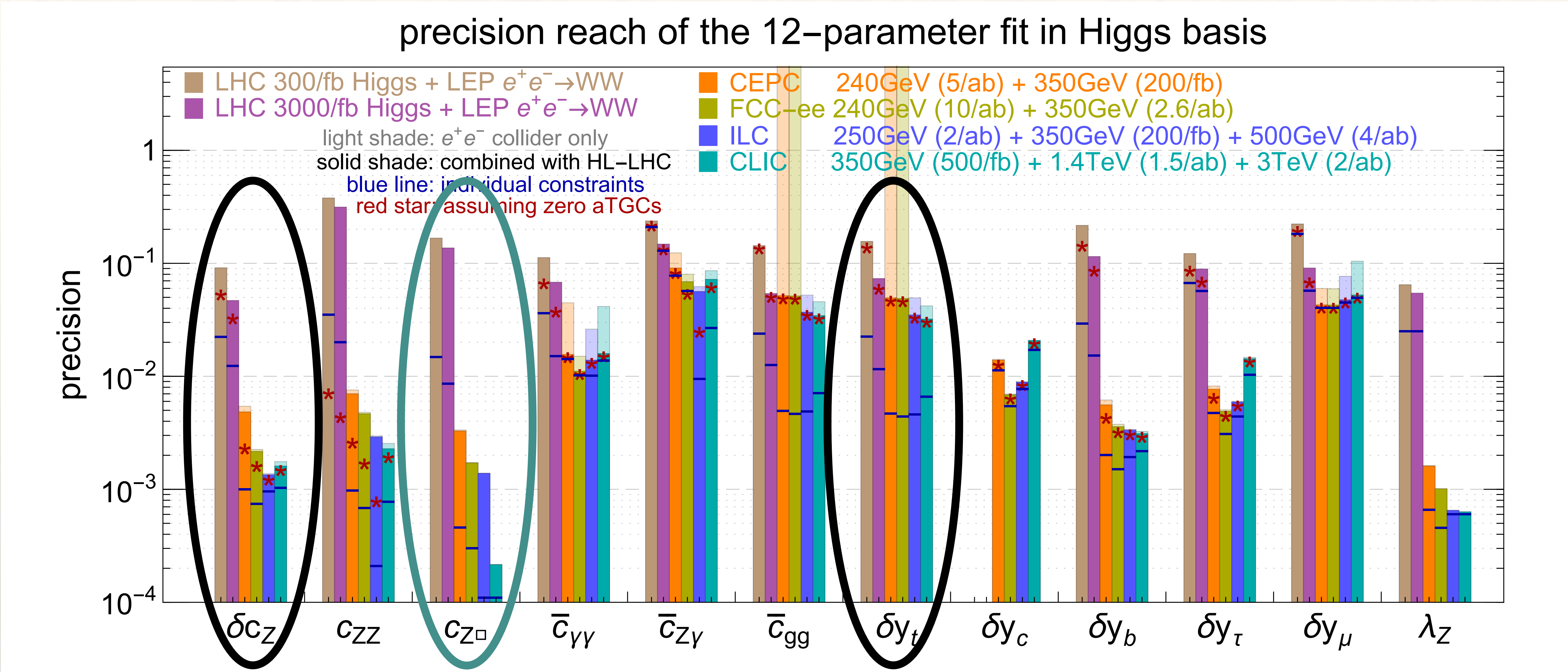


see also [LCC working group ` 18], [CEPC working group ` 17]

- Precision environment of a lepton colliders allows to pin down gauge-Higgs sector at the per mille level in case of the Z

[Durieux, Grojean, Gu, Wang ` 17]

Coupling projections: HL-LHC



see also [LCC working group ` 18], [CEPC working group ` 17]

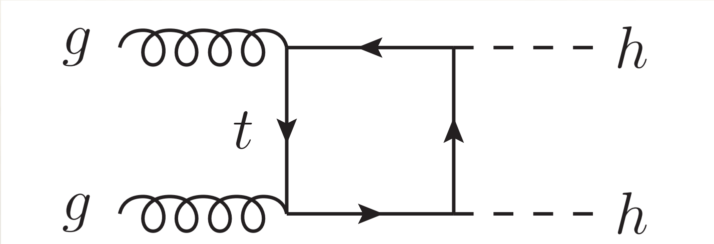
- Precision environment of a lepton colliders allows to pin down gauge-Higgs sector at the per mille level in case of the Z
- CLIC energy coverage beneficial to pin down high energy behavior of electroweak sector e.g. $c_{Z\Box}\, g^2 Z_\mu \partial_\nu Z_{\mu\nu}$

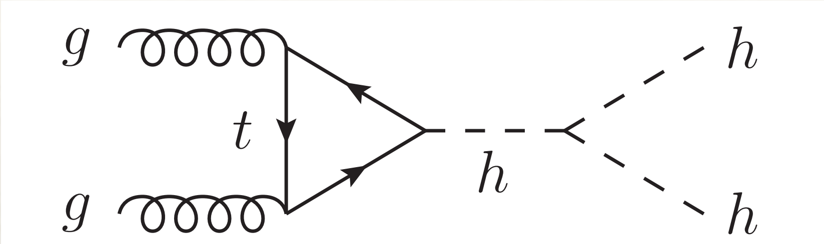
LHC blind spots: Higgs potential

☛ dimension 6 deformations of the Higgs potential

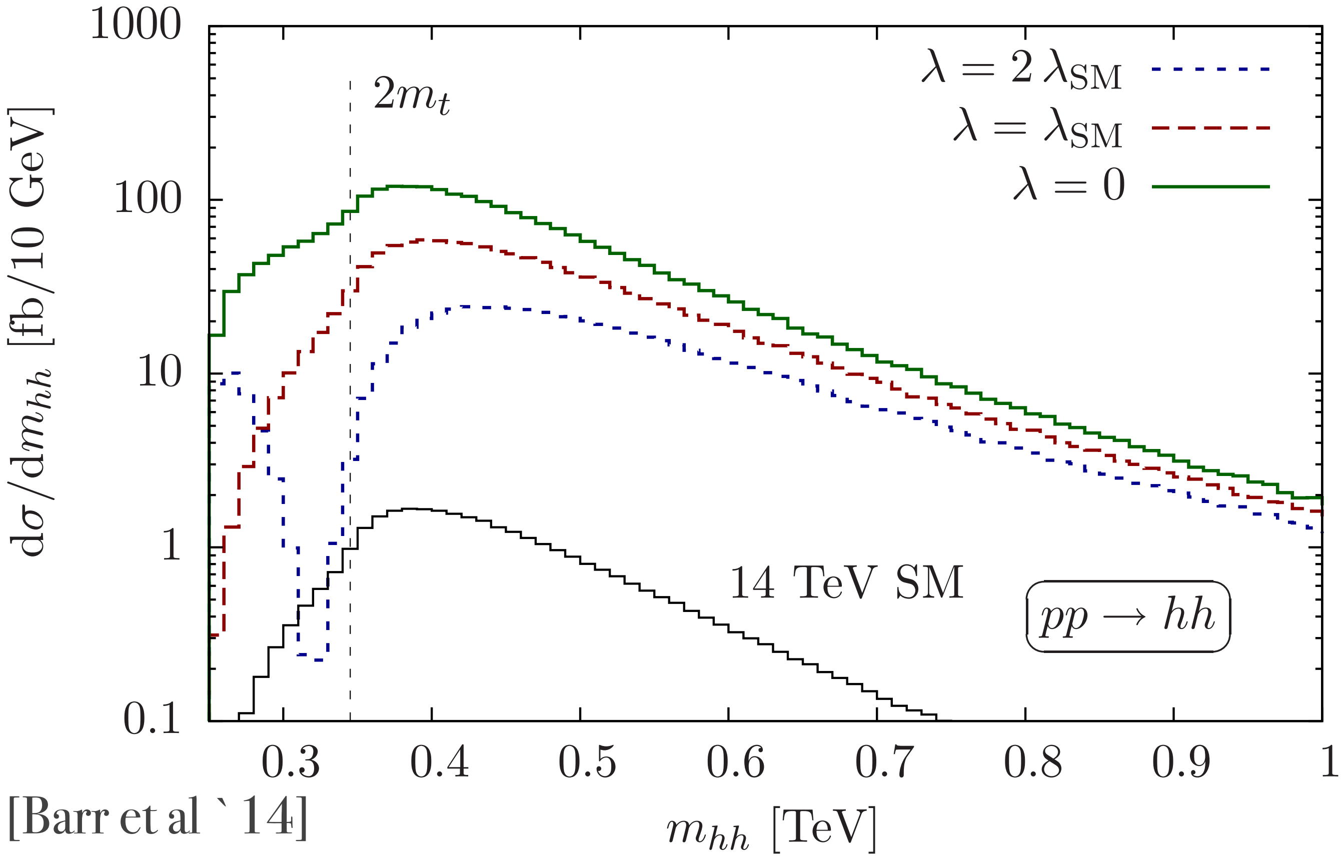
$$V(H^\dagger H)_6 \supset c_6/\Lambda^2 (H^\dagger H)^3$$

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



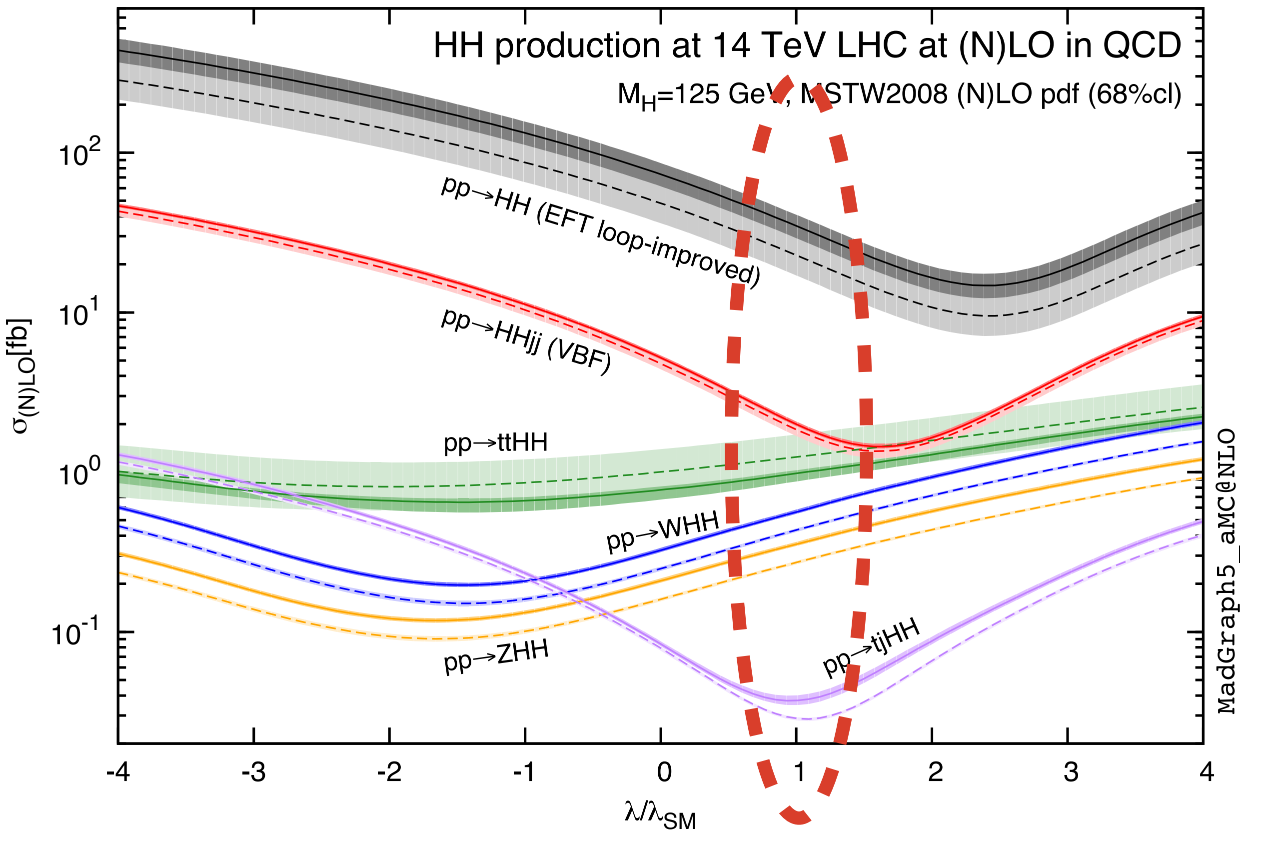


[Glover, van der Bij ` 88]



[Barr et al ` 14]

[Frederix et al ` 14]



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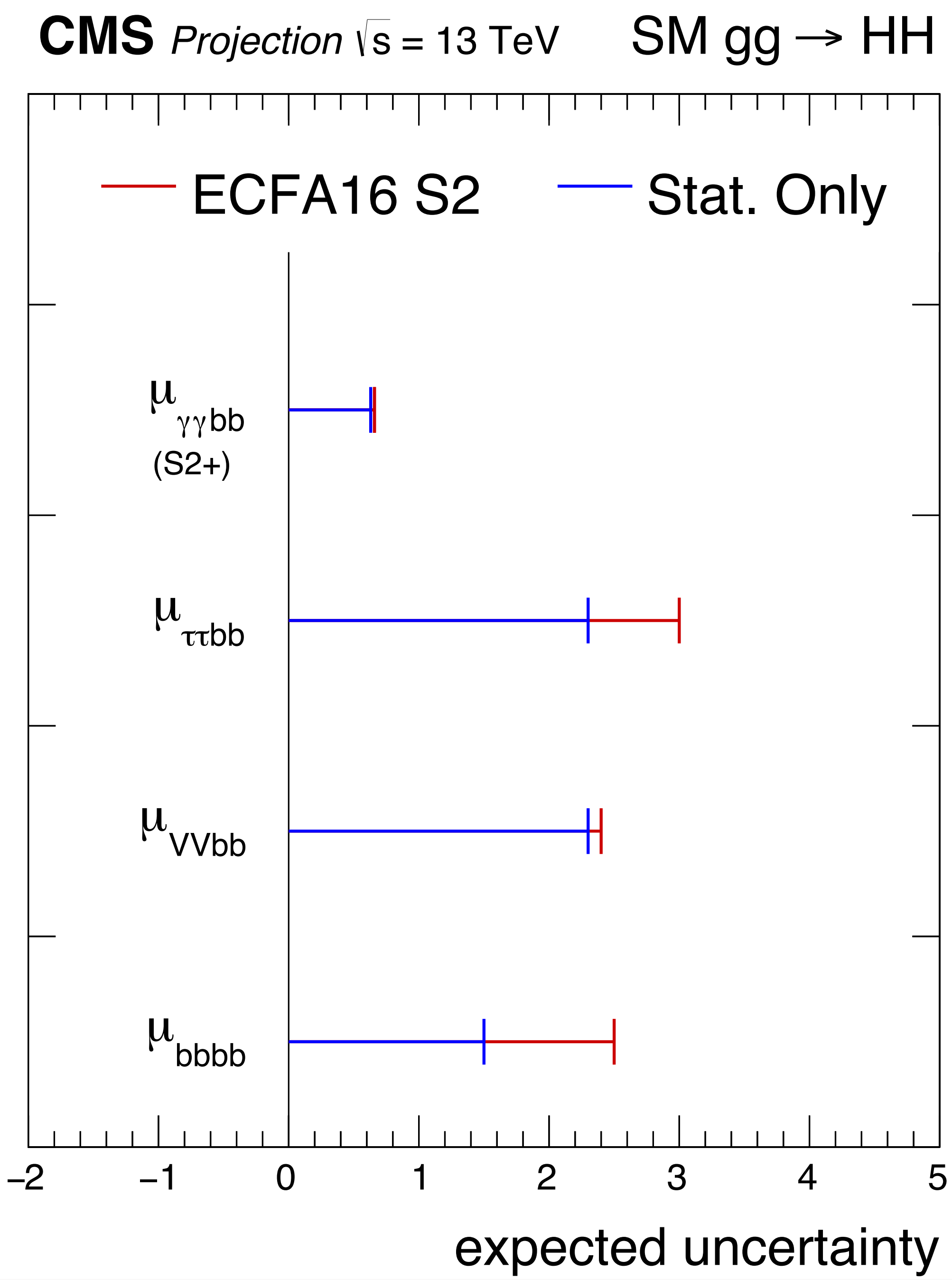
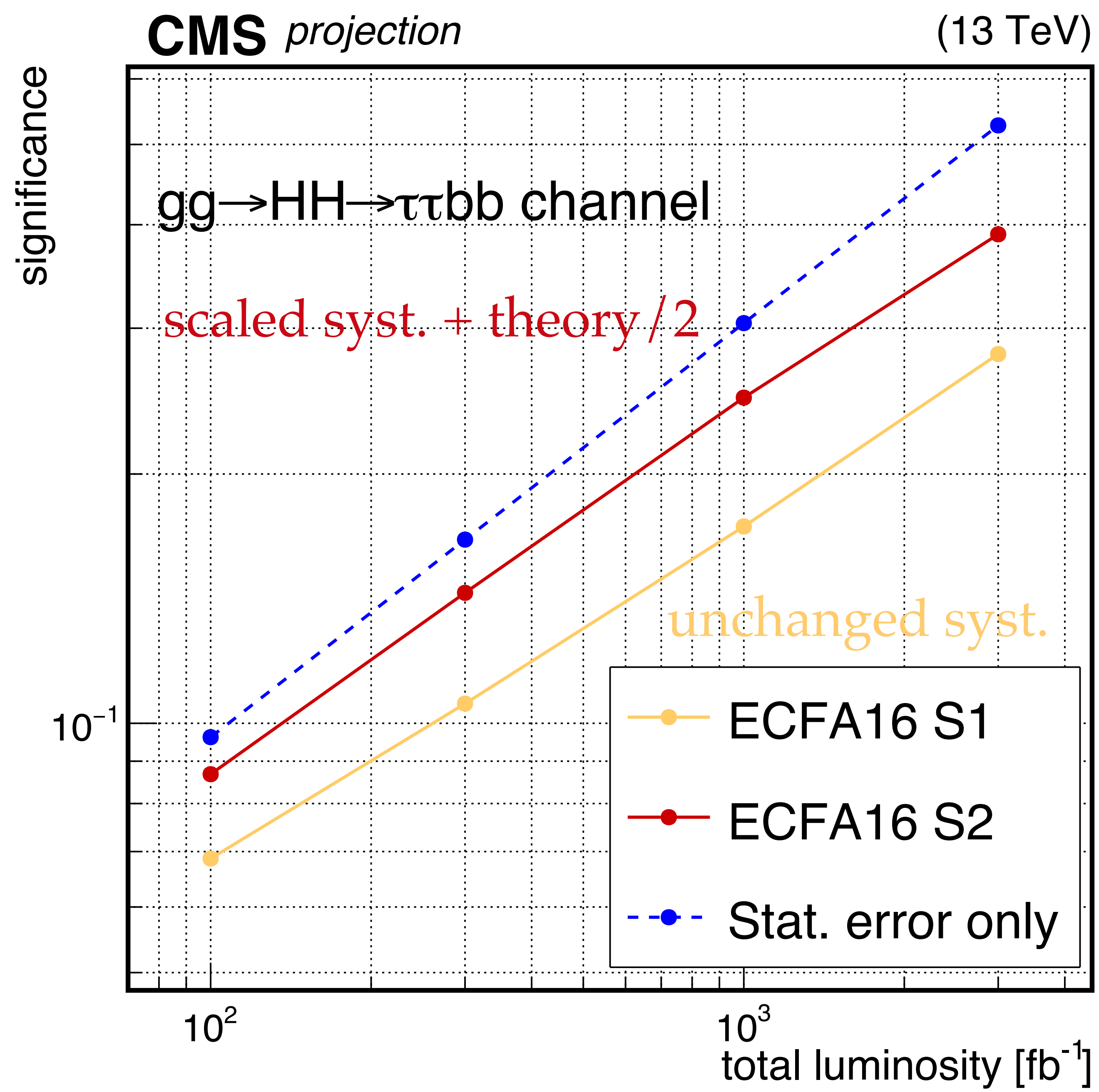
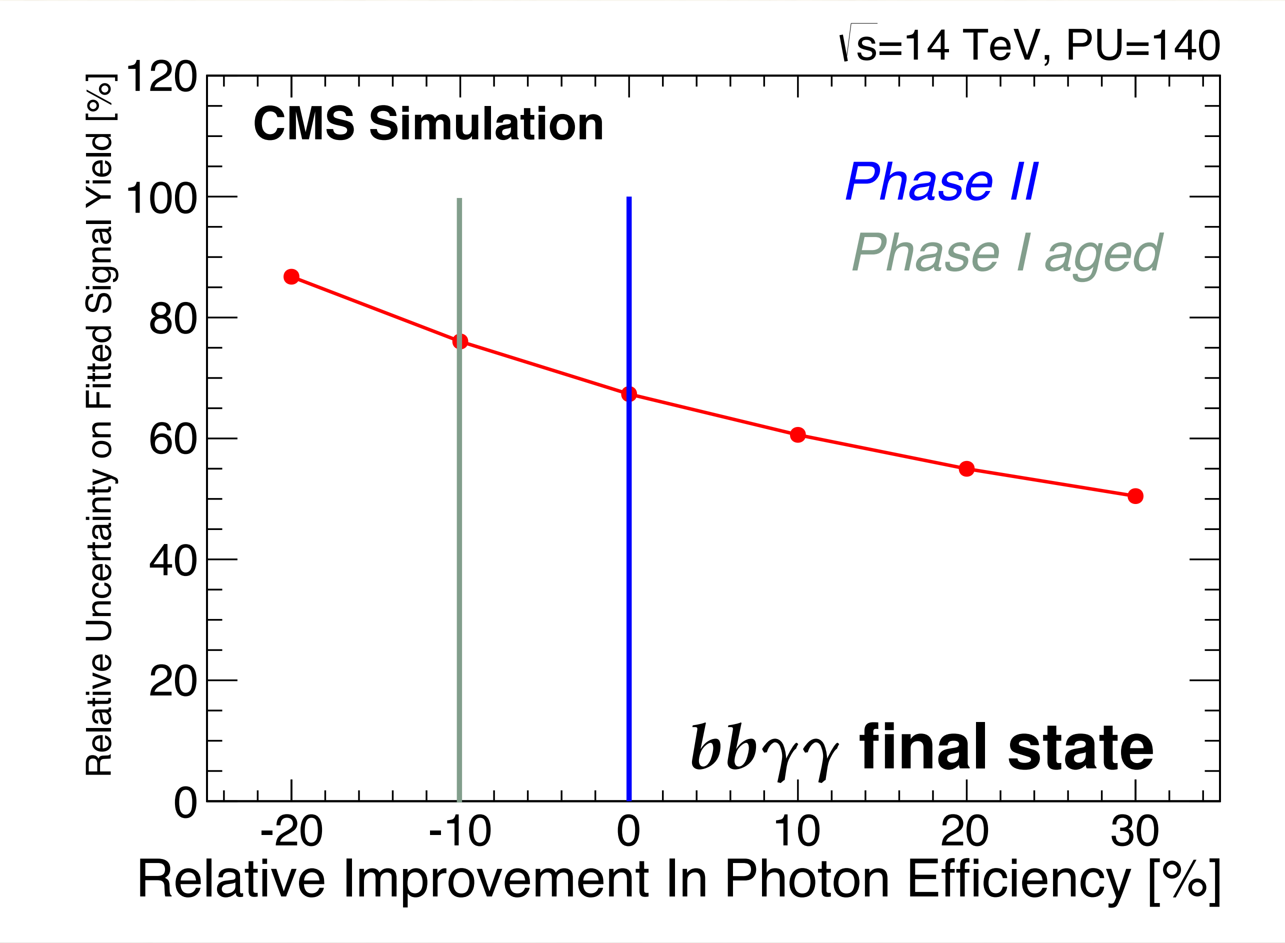
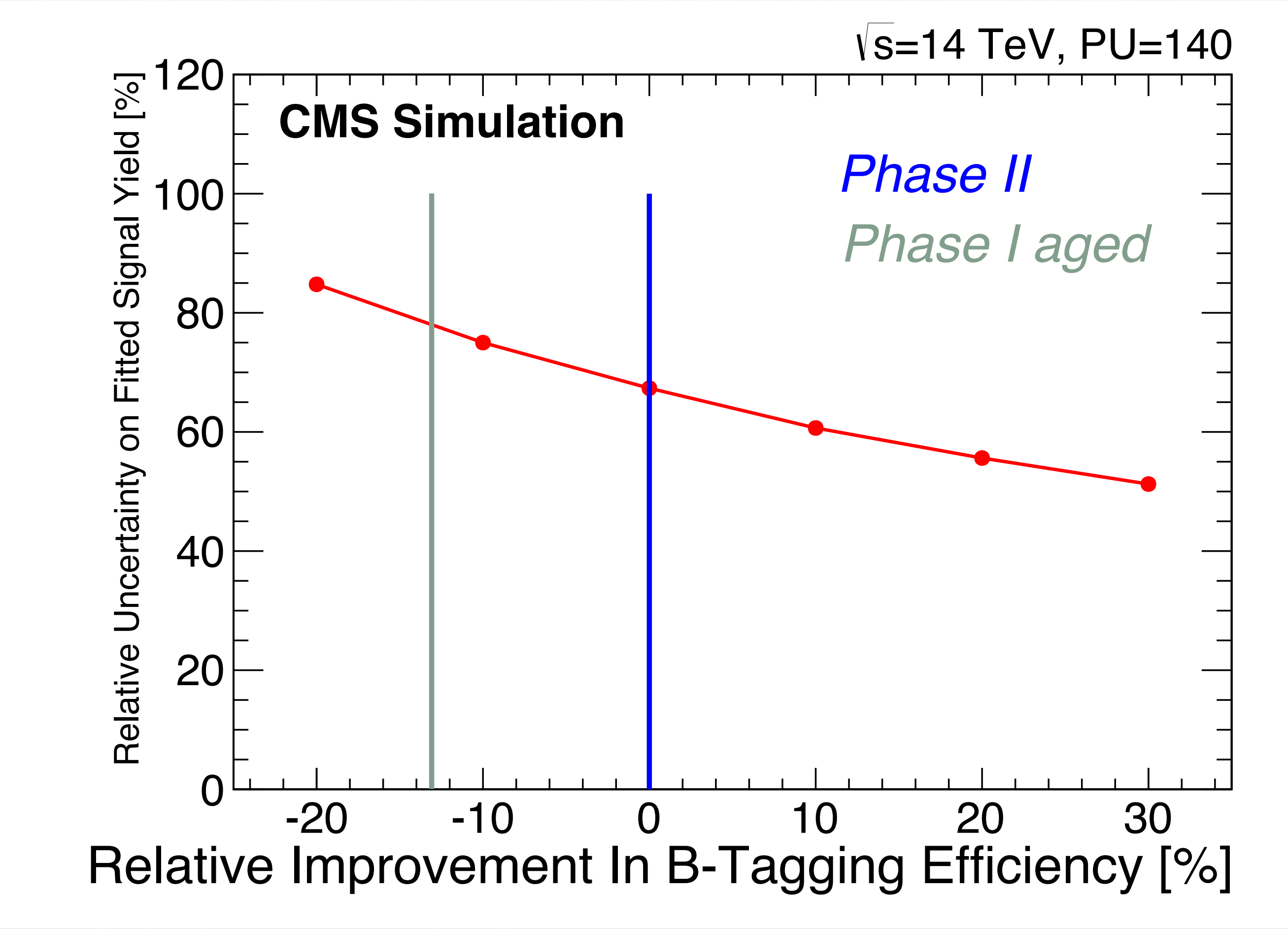




LHC blind spots: HH @ 100 TeV





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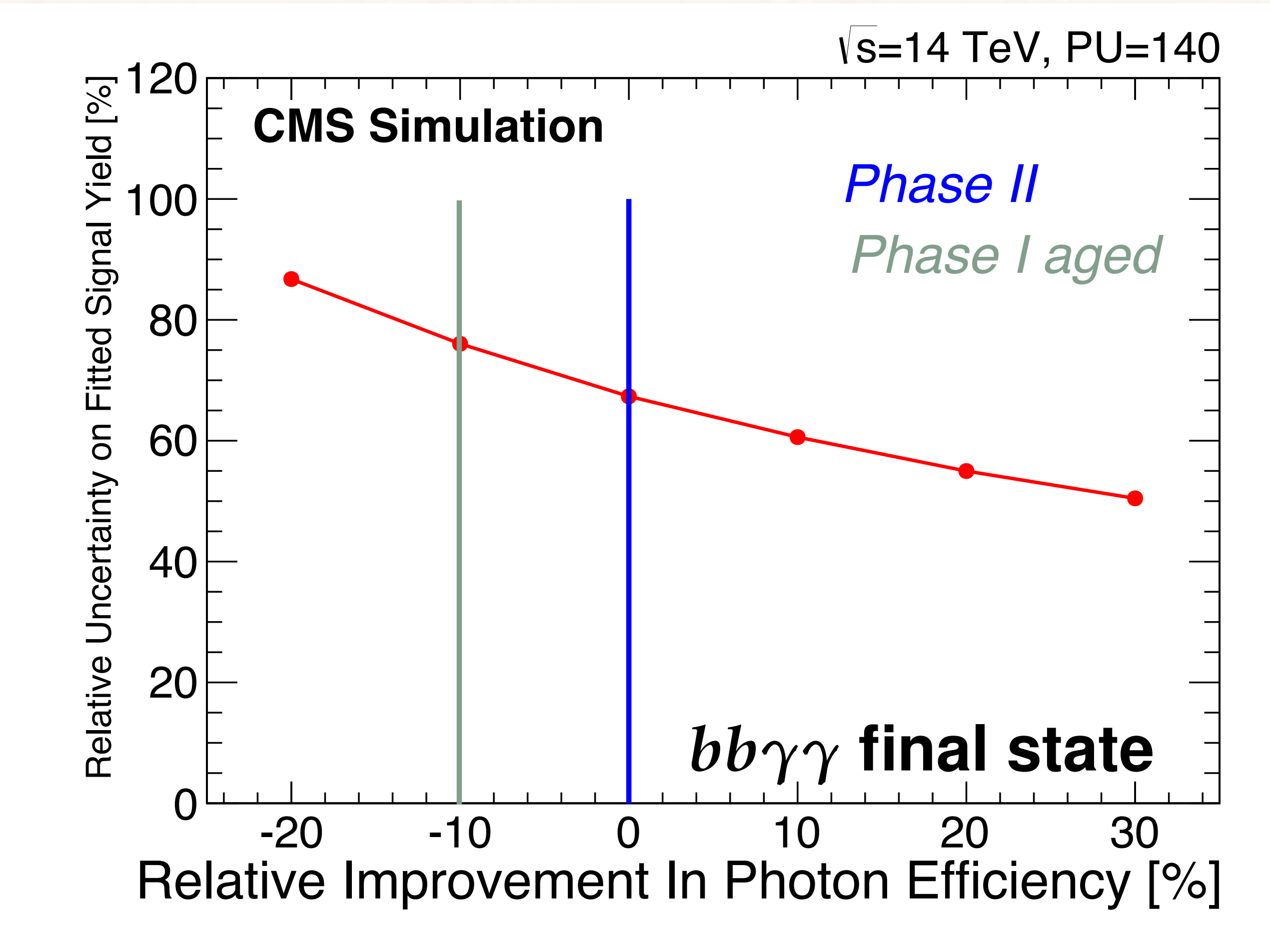
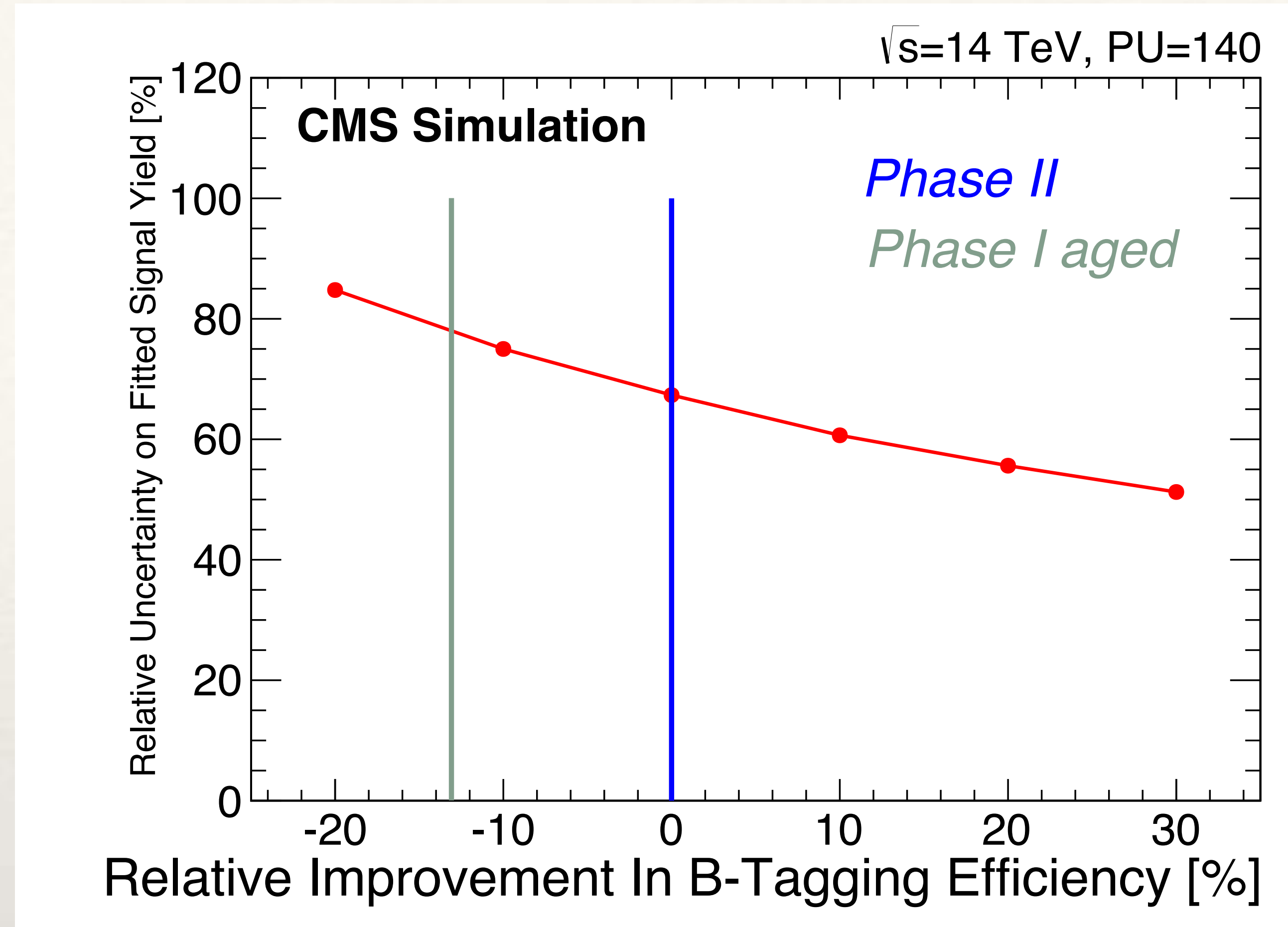




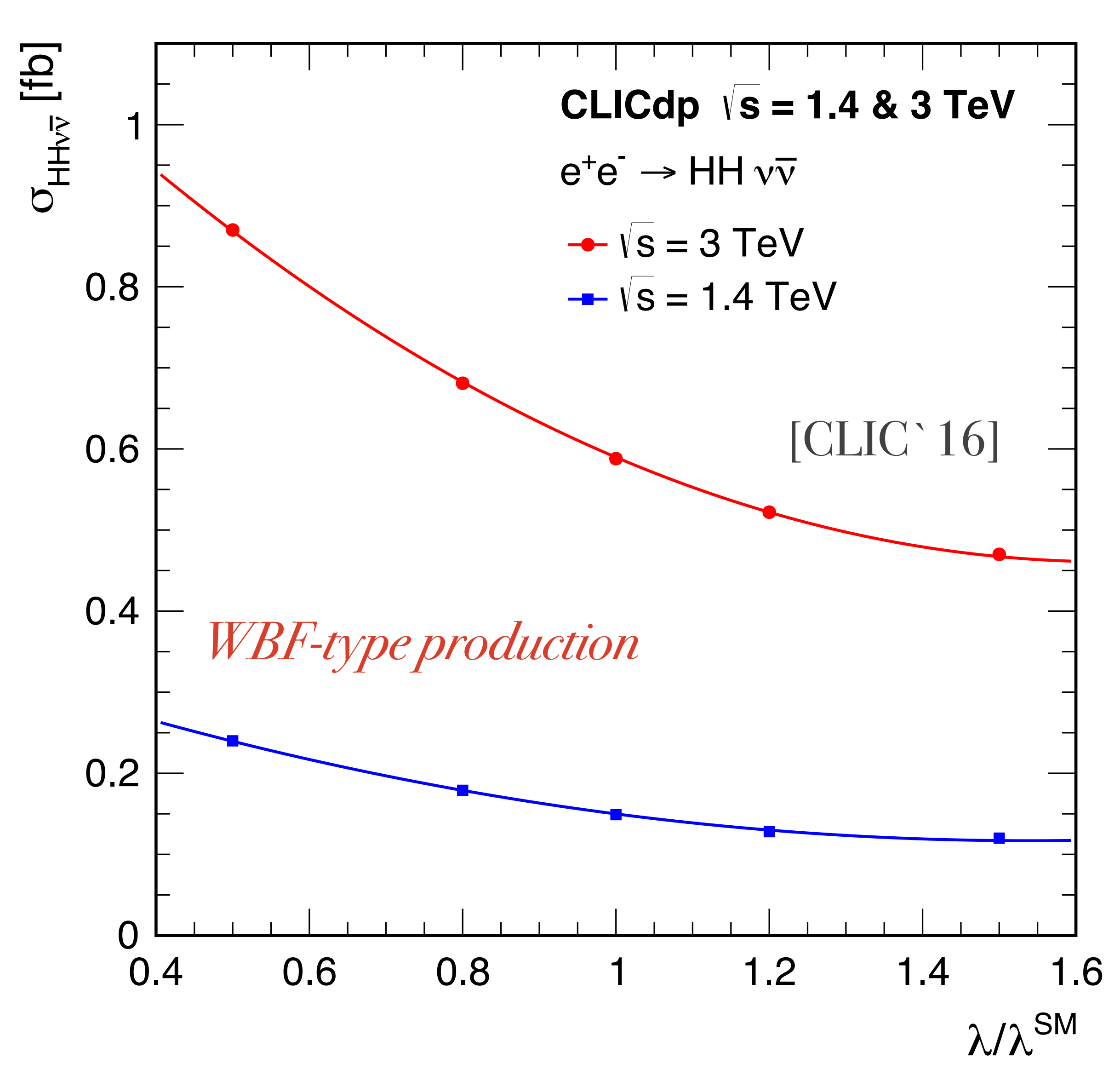
process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

$\mathcal{O}(\pm 3\%)$

FCC-hh @ 100 TeV

[Contino et al. CERN YR `16]

LHC blind spots: HH @ $e^+ e^-$



- direct probe of Higgs self interactions possible for higher energies

$$\Delta\lambda/\lambda = 40\,\% \;\text{ at } \sqrt{s} = 1.4\,\text{TeV}\,,$$
$$\Delta\lambda/\lambda = 22\,\% \;\text{ at } \sqrt{s} = 3\,\text{TeV}\,.$$

- recent EFT fit to Zh(h) production show sensitivity to $e^+e^- \to Zhh$

$$[\langle(\delta\sigma)^2\rangle]^{1/2} = 2.4\% \oplus 5\% \;\text{ EFT systematics,} \quad \sigma/(SM) = 1 + 0.56 c_6 + \cdots$$

self-coupling extraction becomes possible at 500 GeV at ~14%

[Barklow, Fujii, Jung, Peskin, Tian ` 17]

Summary

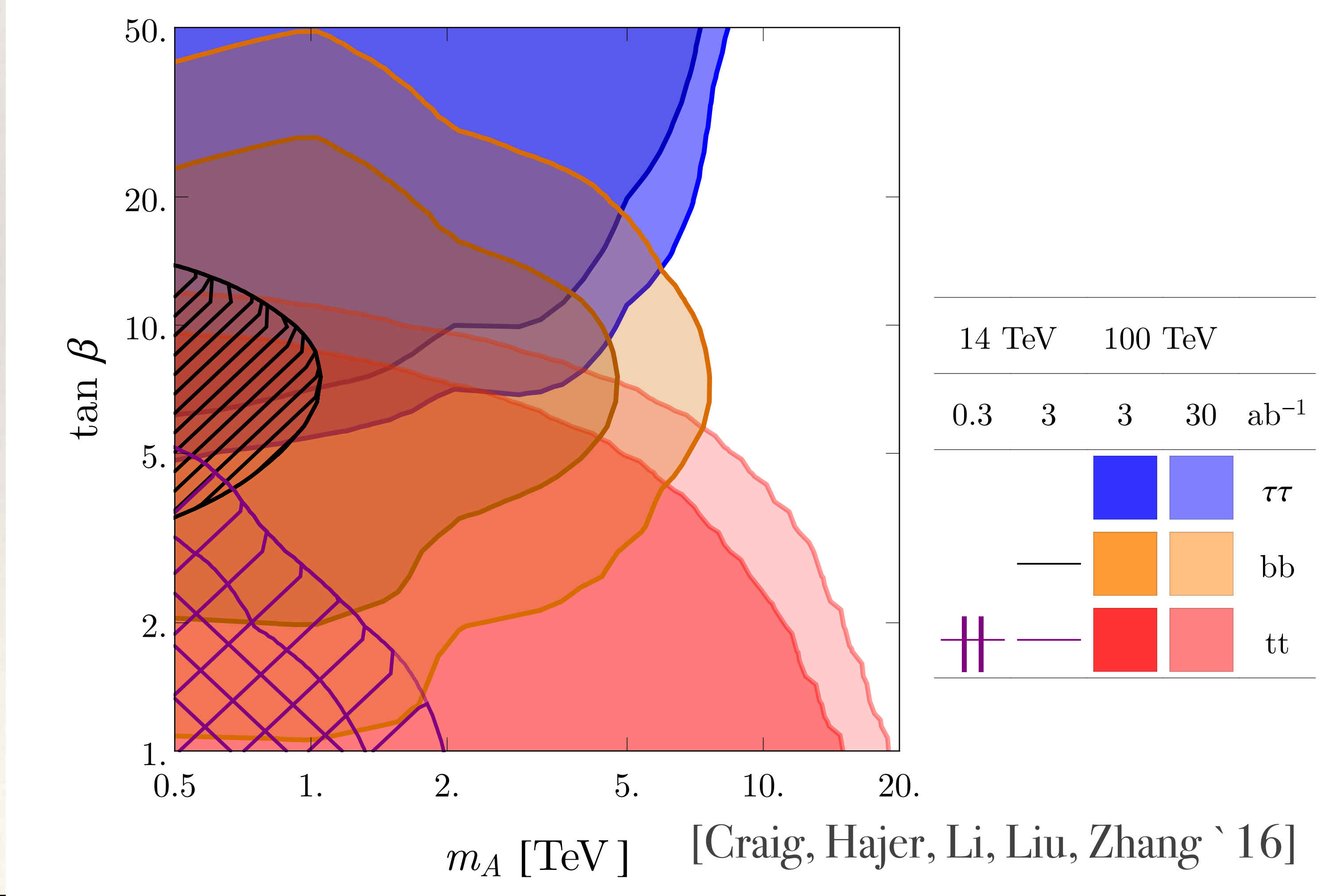
- community is active in making the case for the next generation of colliders
- (HL-)LHC input to strategy is crucial

complementarity in searches for light resonances/dark matter

constrain blind directions vice versa

identify BSM parameter space after LHC

- FCC(hh)/... although at an early stage in planning clearly has the highest energy reach



[Craig, Hajer, Li, Liu, Zhang ` 16]