Higgs physics: a perspective on the long-term prospects

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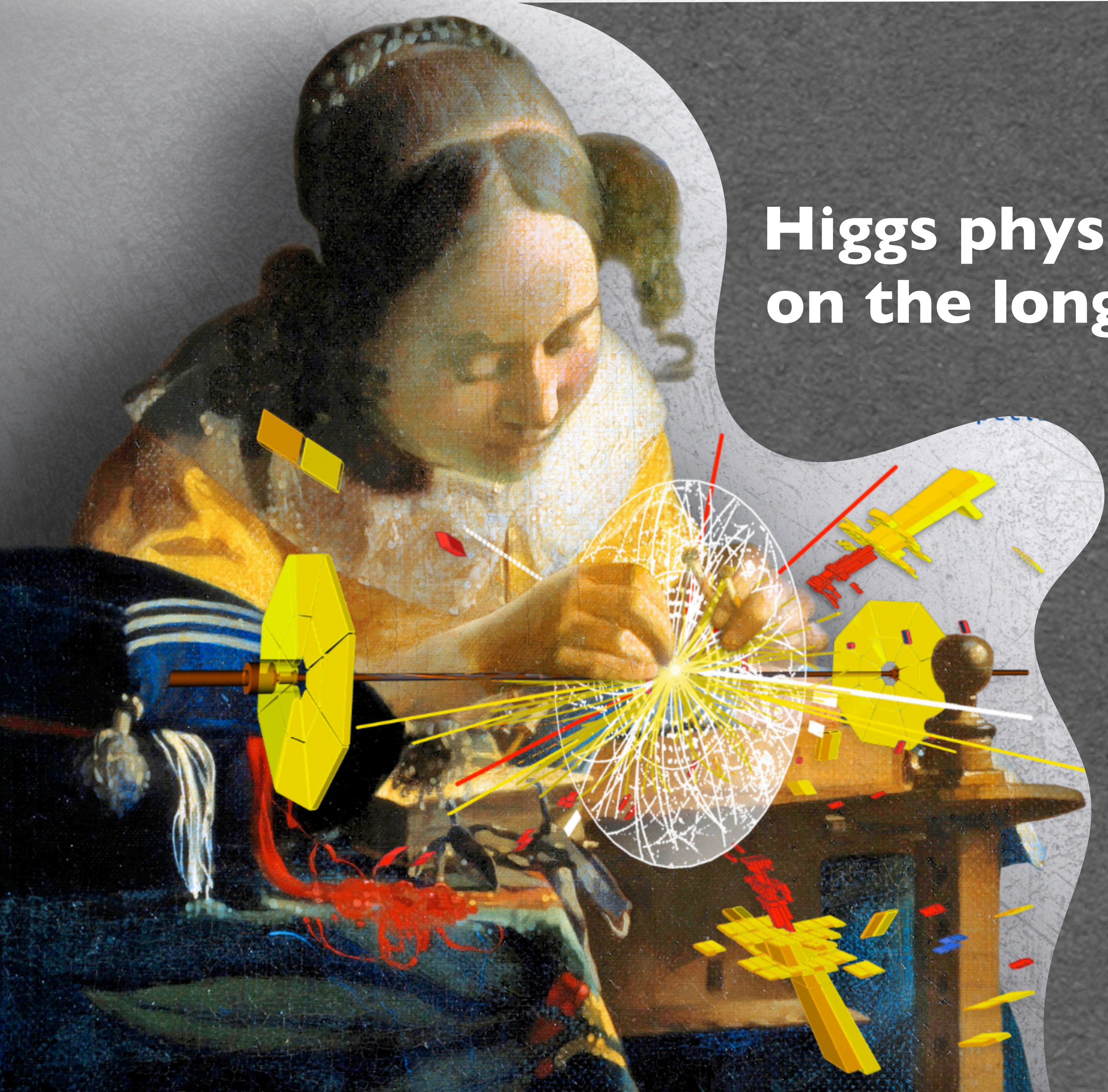

La Dentellière (1669-1671) - Johannes Vermeer
Musée du Louvre, Paris

10TH HIGGS HUNTING

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For the objective perspective:

EW/Higgs studies for the European Strategy review arXiv:1905.03764

Higgs Boson studies at future particle colliders

- Preliminary Version -

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ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects using uniform methodologies for all proposed machine projects of sufficient maturity. This report is still preliminary and is distributed for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019).

Anna Kaczmarska

Beyond the Standard Model Higgs Searches at ATLAS

Summary

- There is a plethora of searches for BSM physics in the Higgs sector at the LHC
- Only a small selection of results were presented here
- No evidence for any BSM Higgs Boson… yet
- Dedicated efforts in the combinations help improve sensitivity
- By now only impressive agreement with SM observed, instead of inspiring surprises
- But we have not yet finished! Much more Run2 data (140/fb) to analyse!

- We will turn every stone ☺ - but for now we need to wait a bit to tell an inspiring story to stimulate the HL-LHC and future experiments

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I think a story can be told already today ….

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  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …

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- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …

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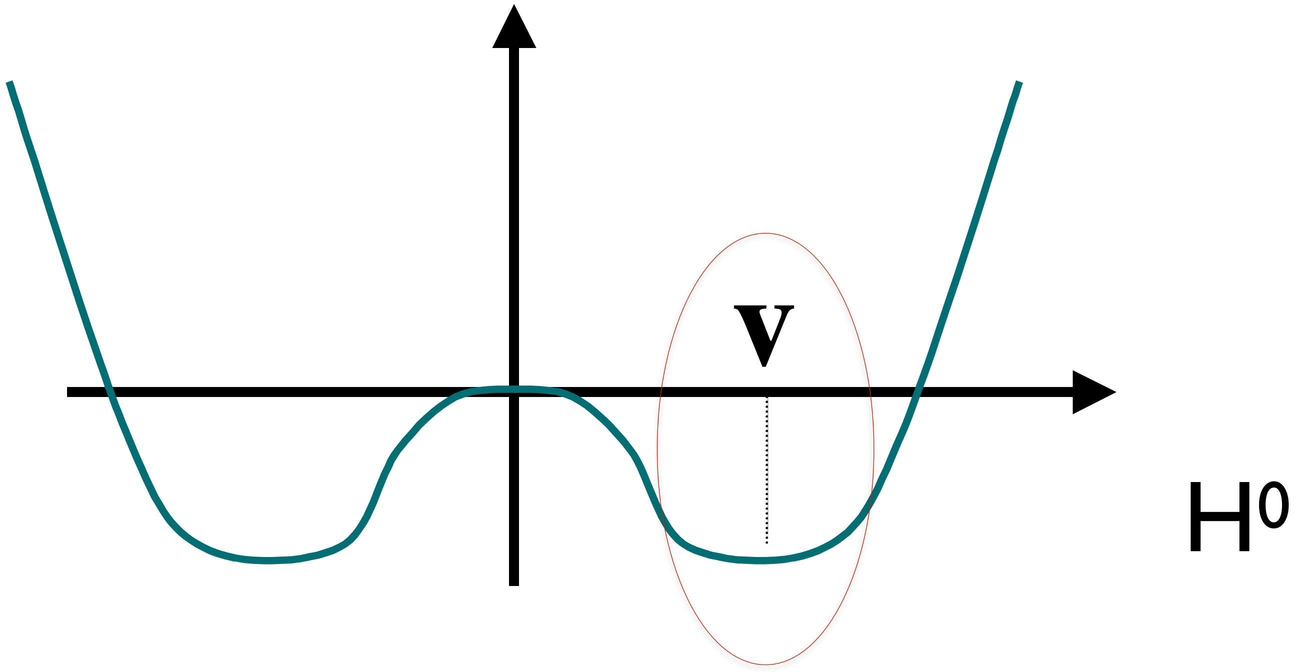
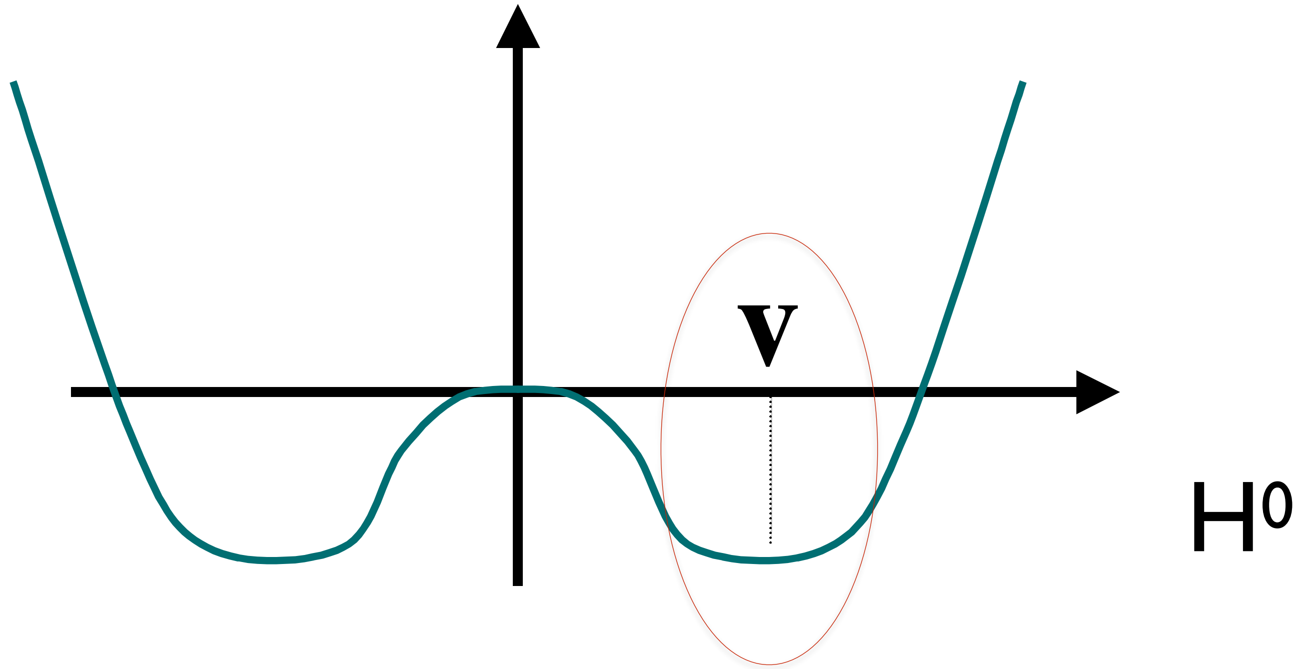
One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction….



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?



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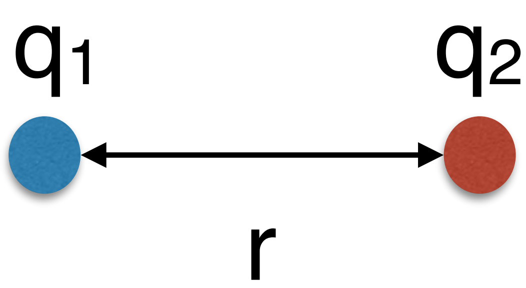
We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

Electromagnetic vs Higgs dynamics



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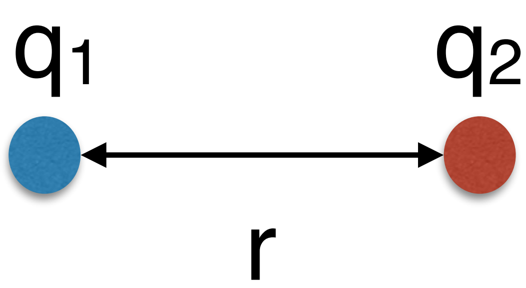

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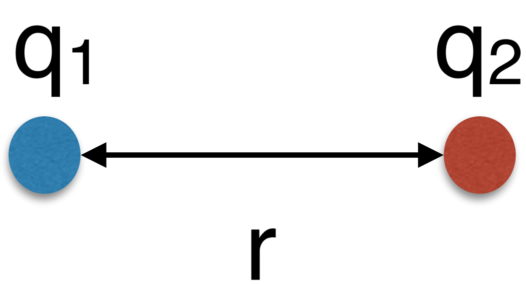

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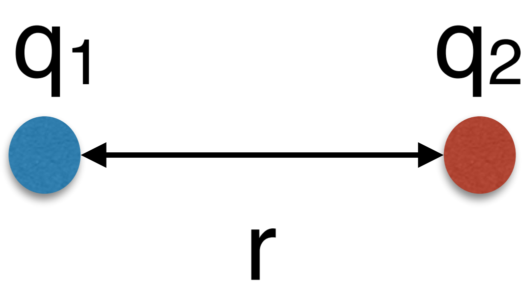

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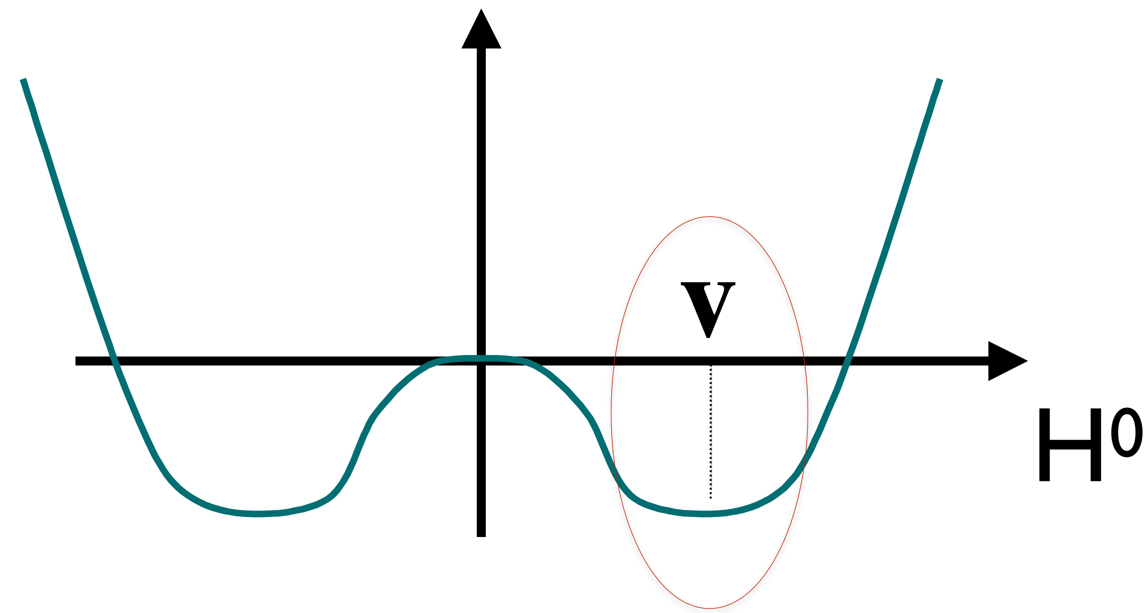

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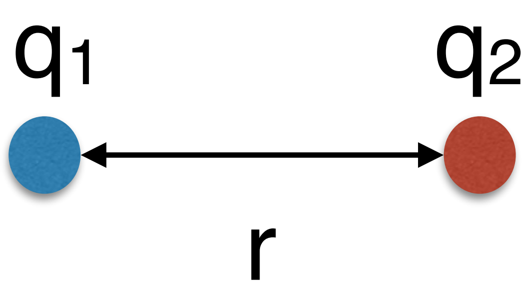

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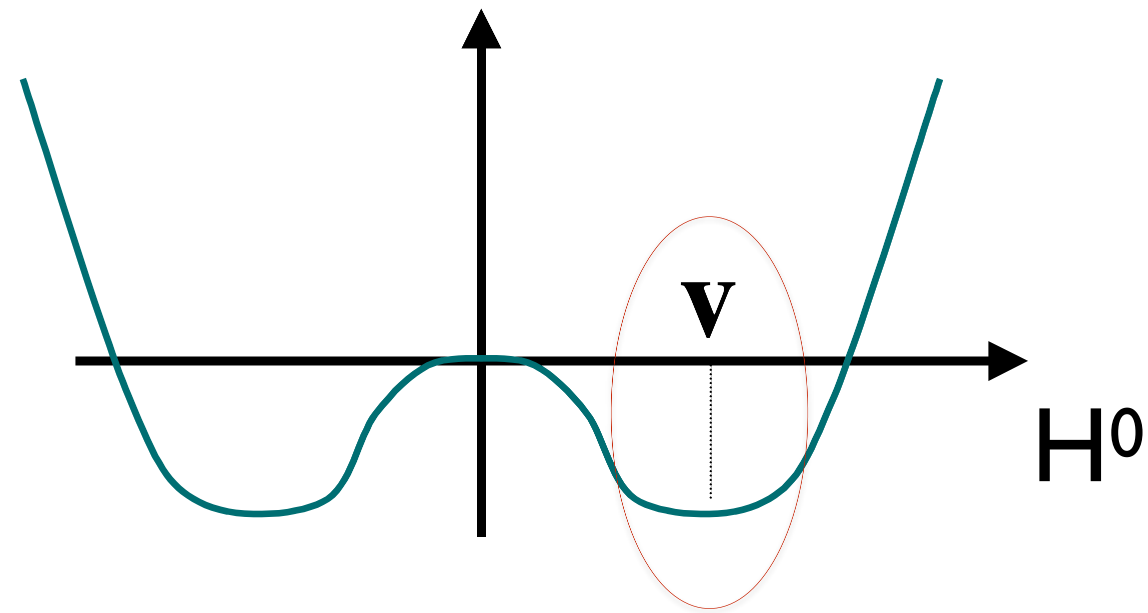

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both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

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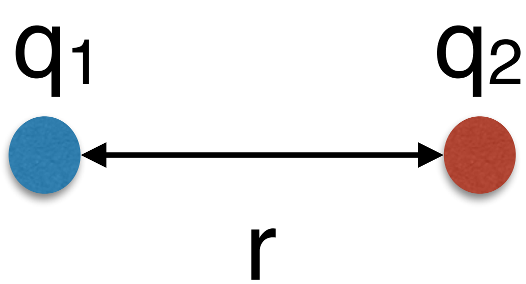

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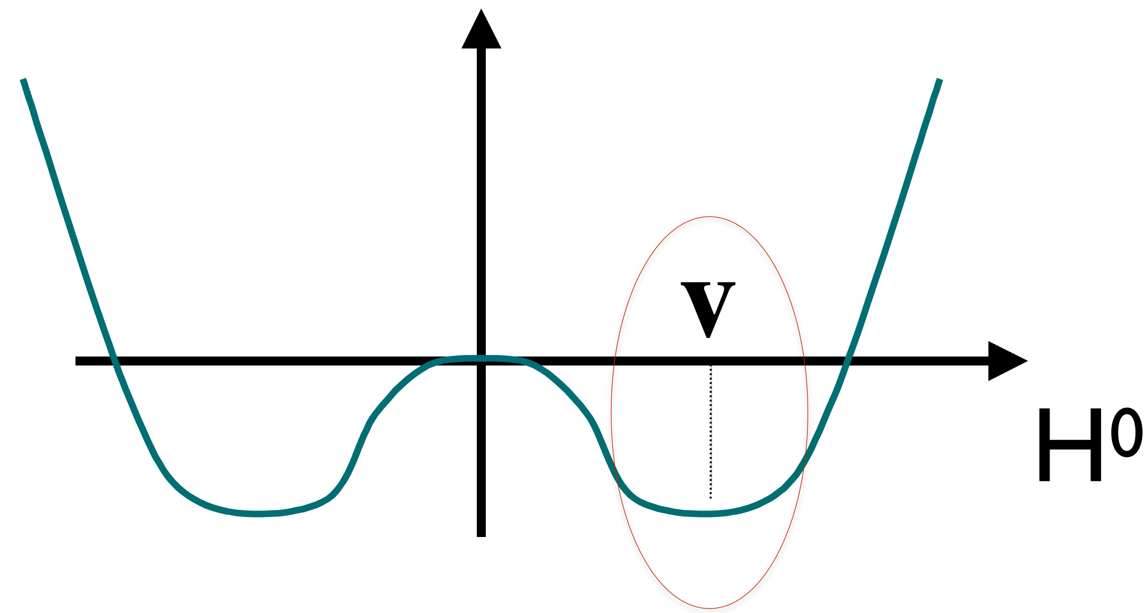

any function of $|H|^2$ would be ok wrt known symmetries

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a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

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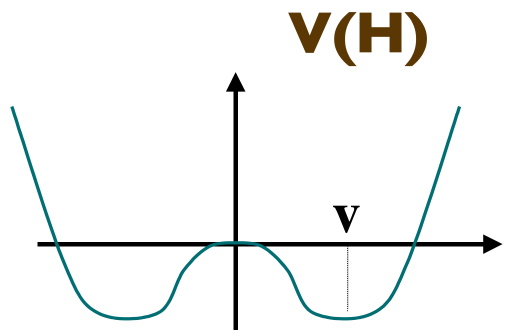
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either case we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

Example: an alternative *toy* Higgs potential



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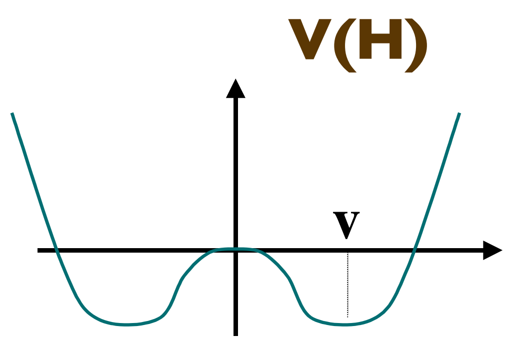

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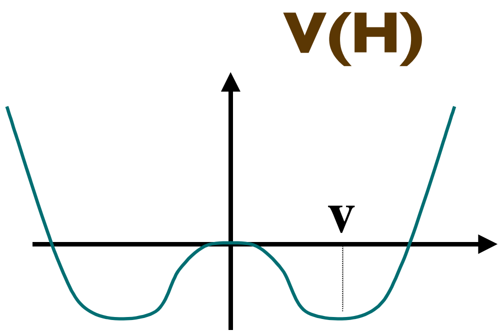

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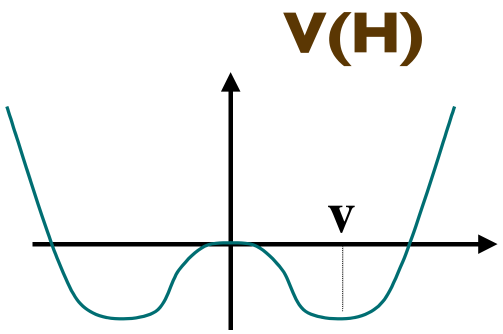

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If n=6, the Higgs self-coupling is modified by a factor of 5/3 wrt the SM relation. This is a big effect!
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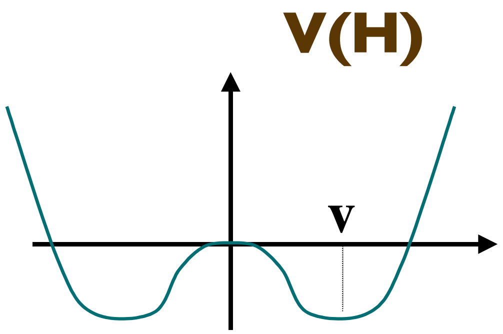

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$$m_\phi^2 = \frac{\lambda_{\phi\phi\phi}}{n-1} v$$

For all SM particles, m=gv, where g is their coupling to the Higgs. For the Higgs, the relation between self-coupling and mass is not universal, it depends on the detailed structure of the Higgs potential => ***until we test this relation, we cannot tell how the Higgs gets its mass ….***

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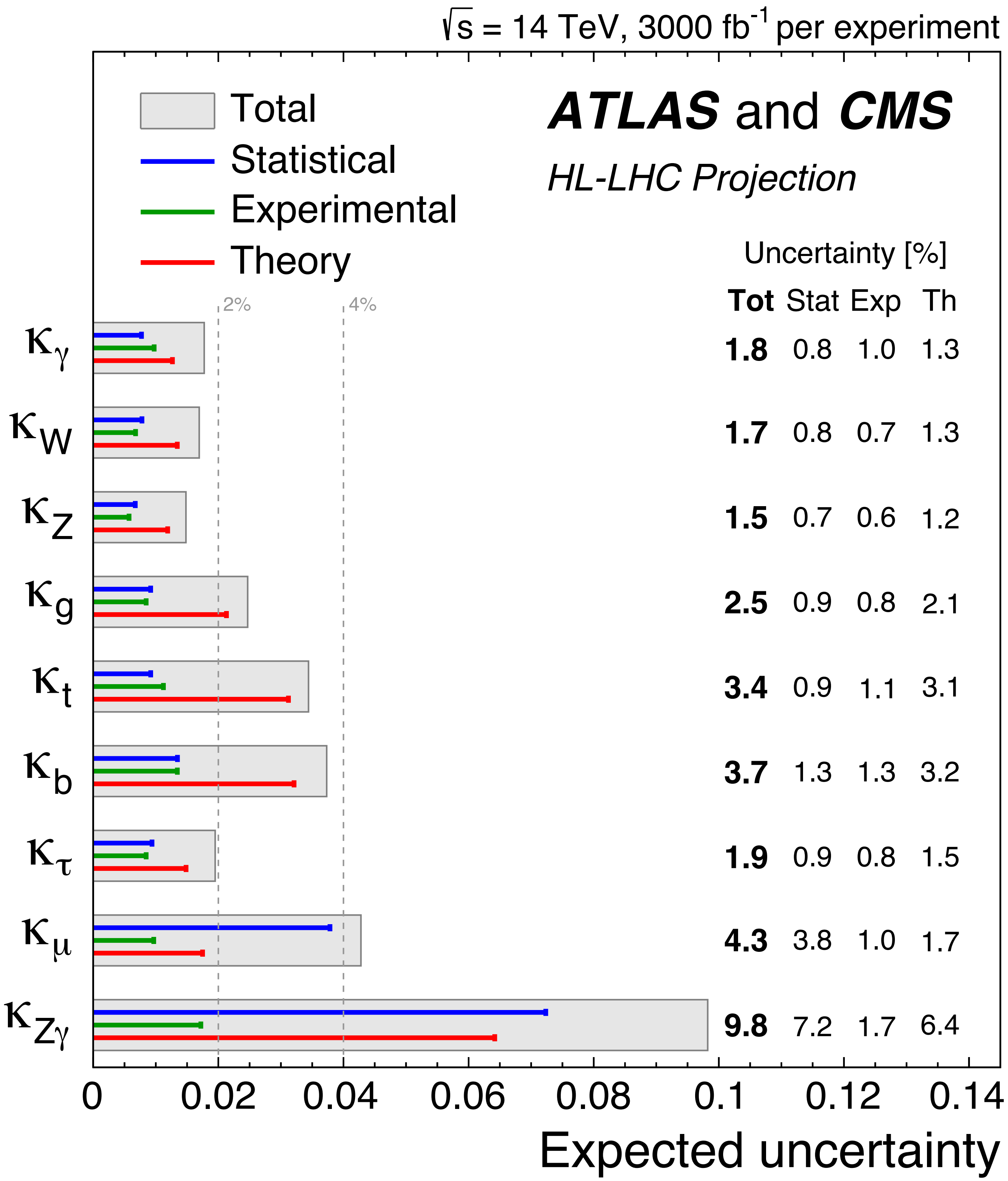
➡ *the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can* ***only*** *rely on a future generation of colliders*

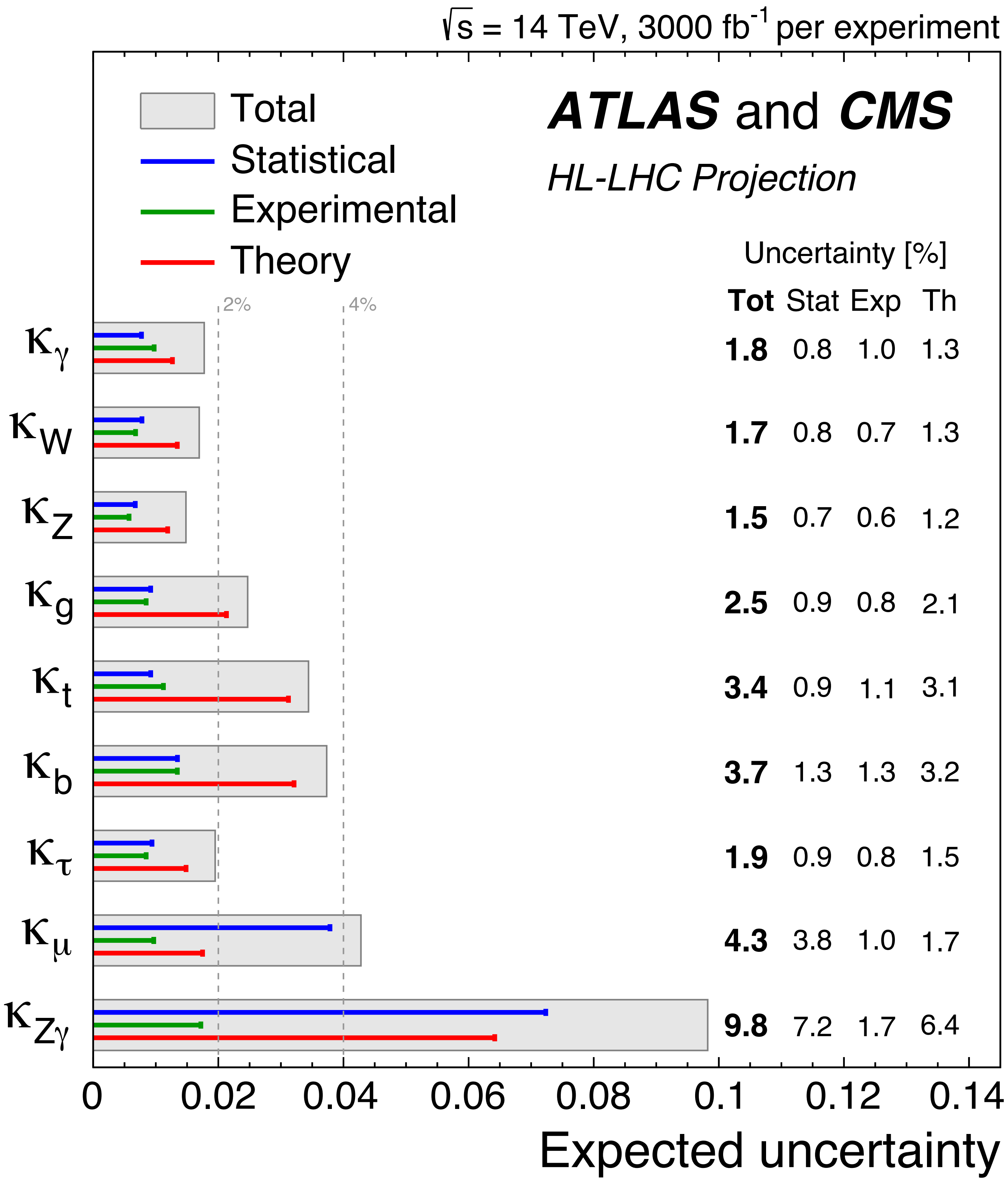
Higgs physics targets

HL-LHC



√s = 14 TeV, 3000 fb-1 per experiment
Total
Statistical
Experimental
Theory
ATLAS and CMS
HL-LHC Projection
Uncertainty [%]
Tot Stat Exp Th
κγ 1.8 0.8 1.0 1.3
κW 1.7 0.8 0.7 1.3
κZ 1.5 0.7 0.6 1.2
κg 2.5 0.9 0.8 2.1
κt 3.4 0.9 1.1 3.1
κb 3.7 1.3 1.3 3.2
κτ 1.9 0.9 0.8 1.5
κμ 4.3 3.8 1.0 1.7
κZγ 9.8 7.2 1.7 6.4
2%
4%
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14
Expected uncertainty

HL-LHC



	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

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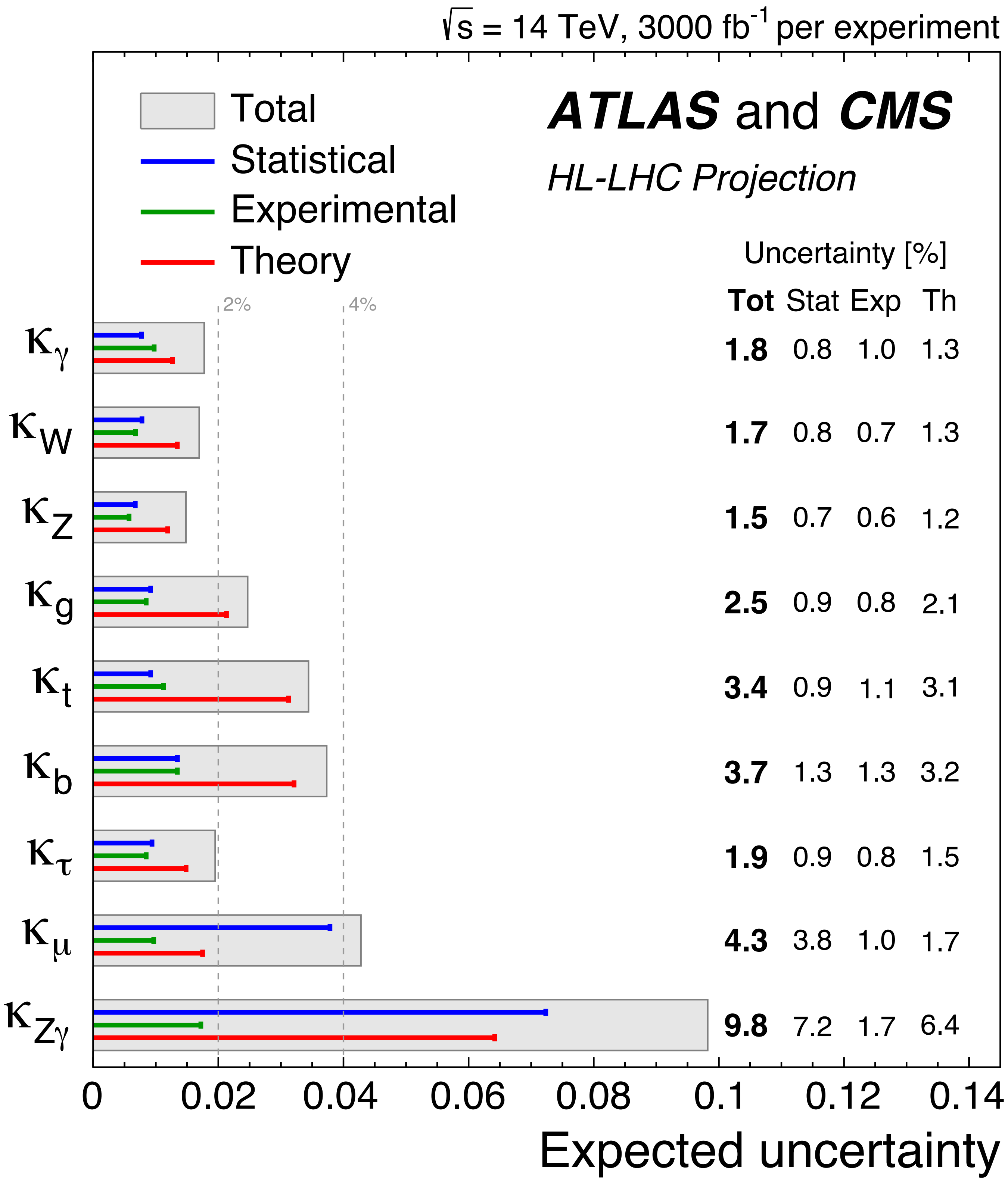
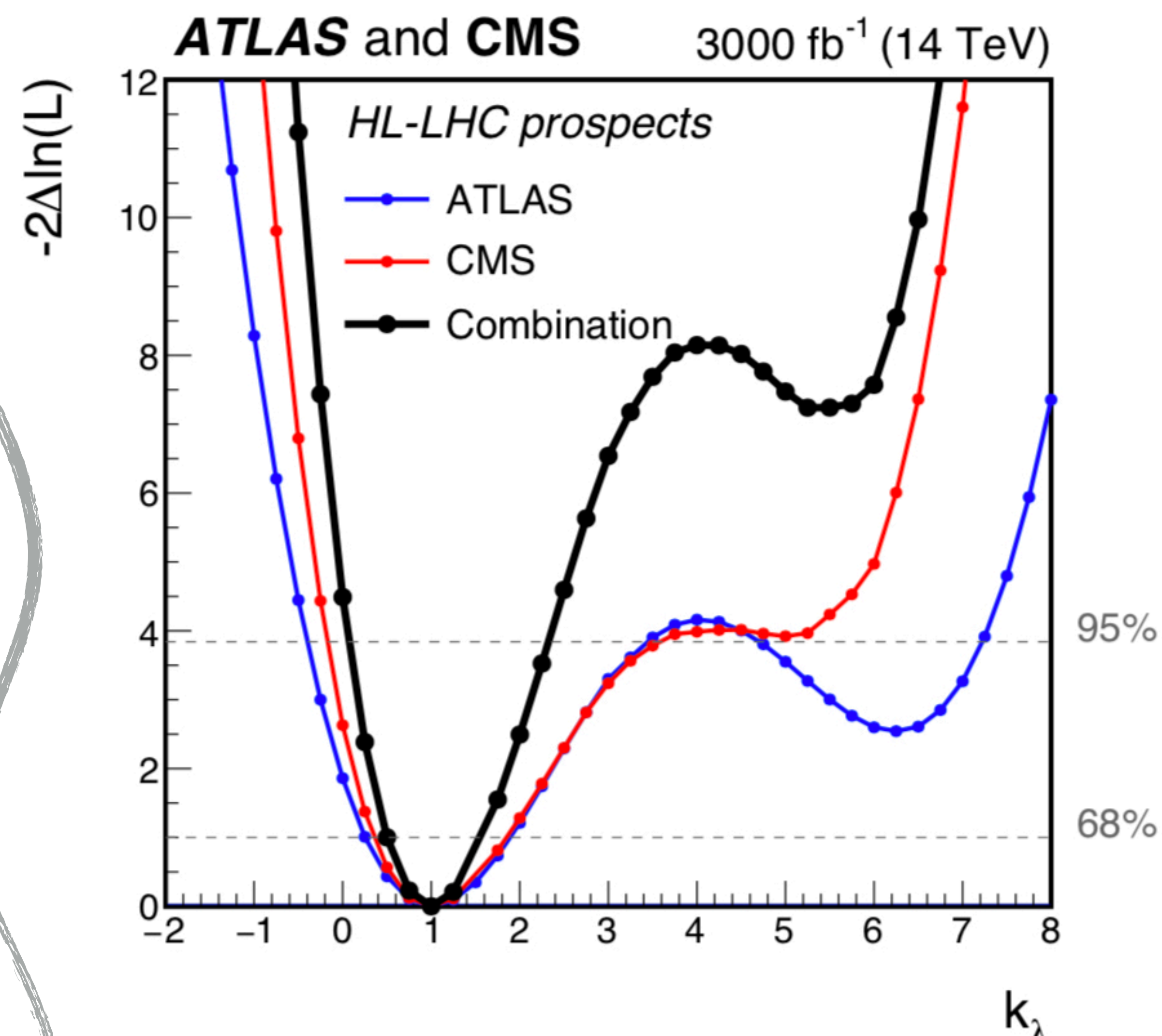


Higgs selfcoupling



$0.52 \leq k_\lambda \leq 1.5$ @ 68% CL

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

Remarks and messages

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
  - Projections will improve as **new** analyses, allowed by higher statistics, will be considered

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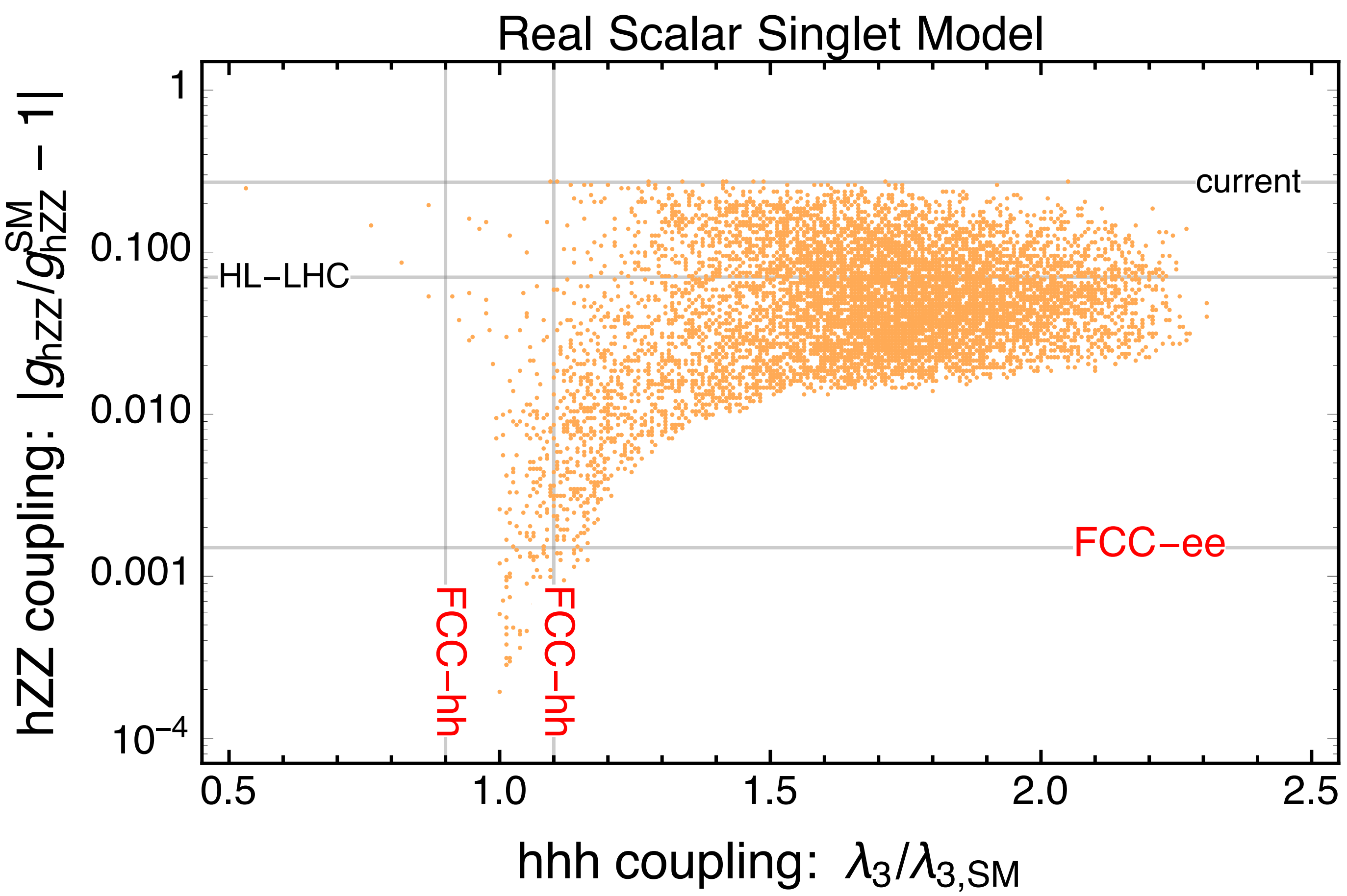
1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level
2. The Higgs selfcoupling will nevertheless remain far from being measured with any precision

Example of precision targets: constraints on models with 1st order phase transition

=> A.Glioti

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 .$$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

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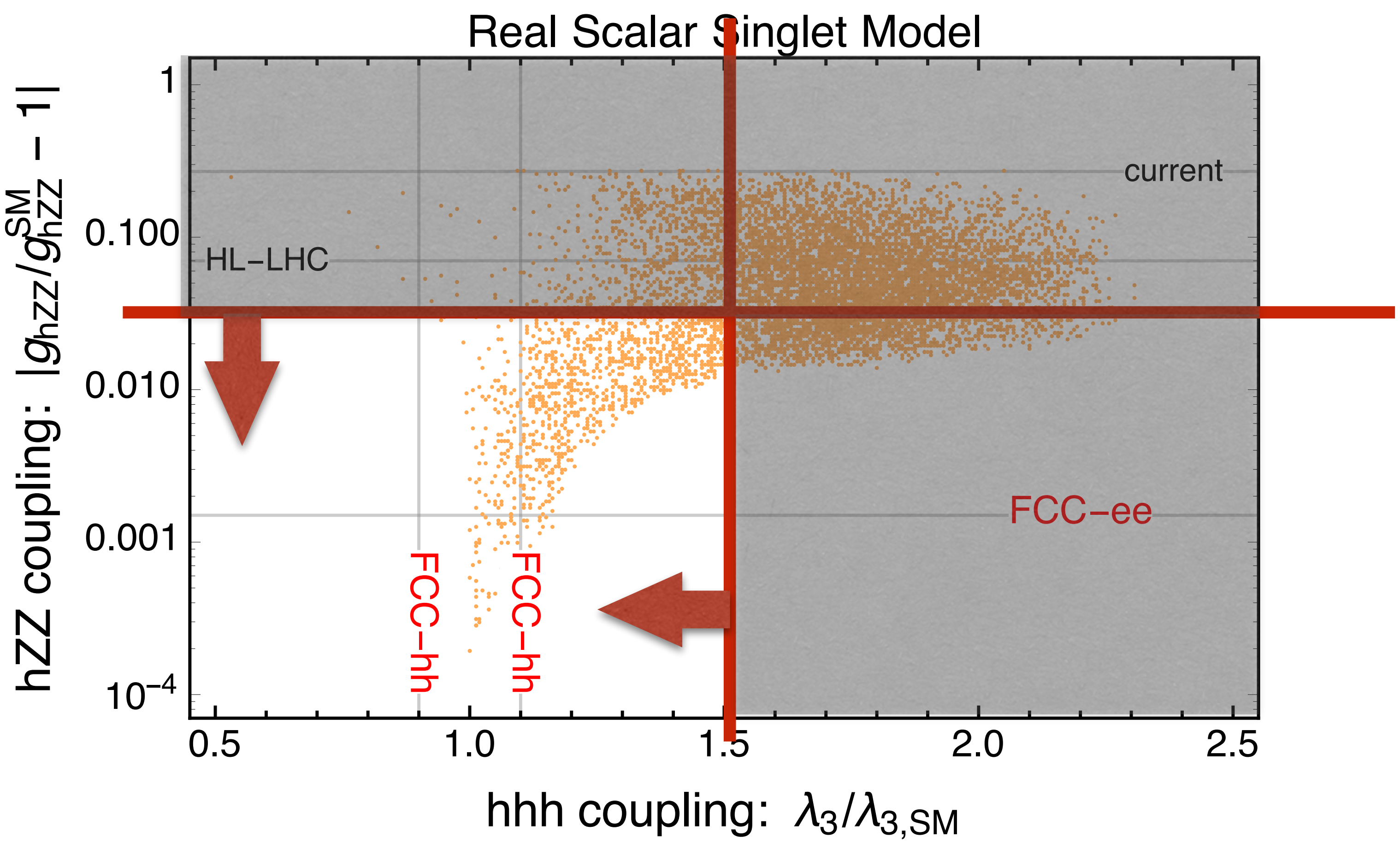
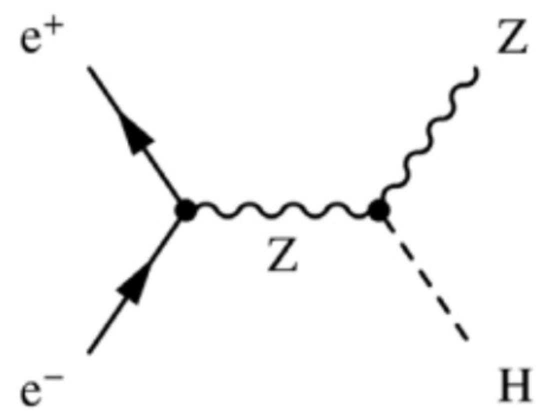


Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

g_{HZZ} to 0.02 and λ to 50% probe a good portion of parameter space, but not all

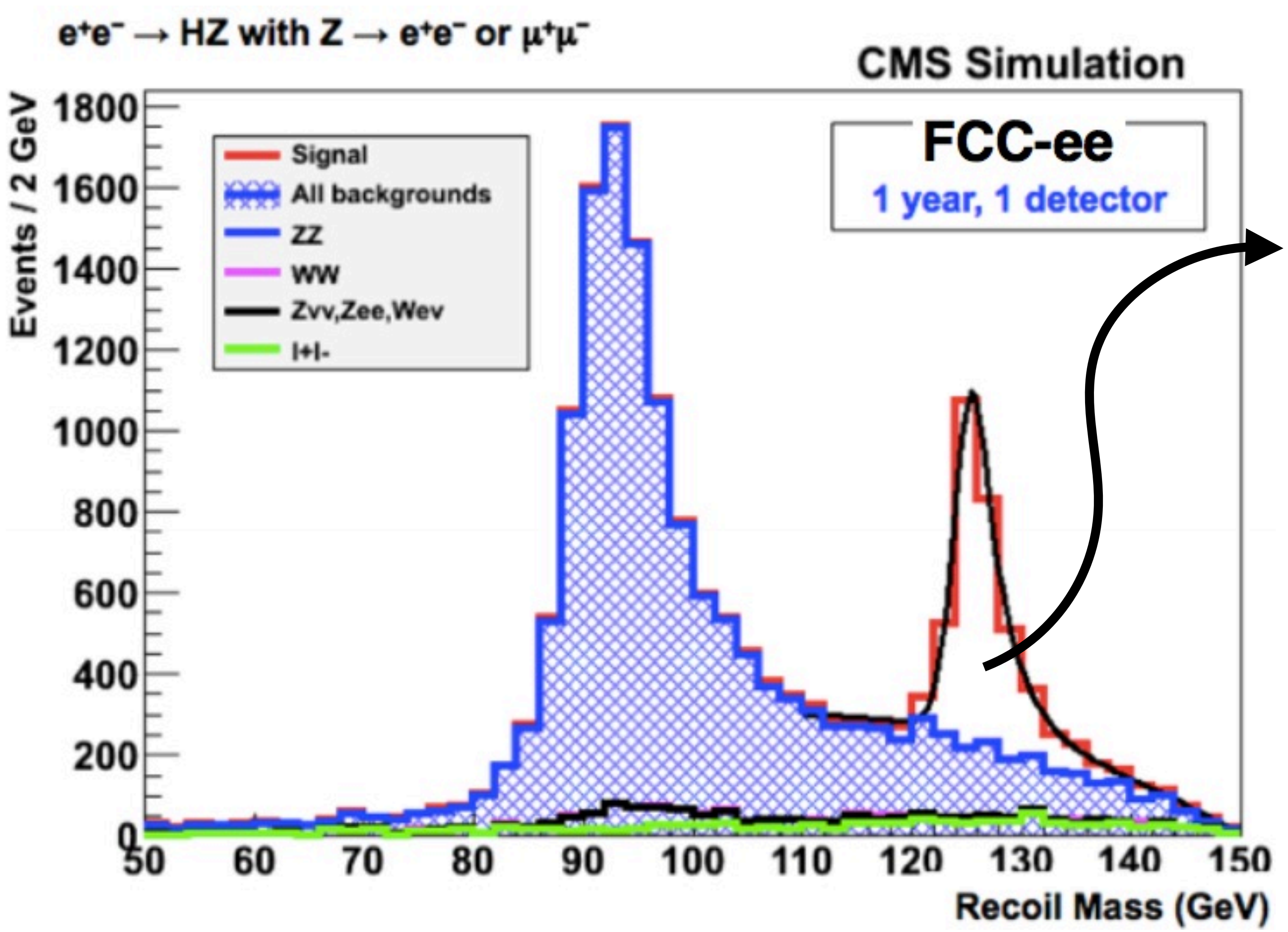
The necessity of $e^+e^- \to ZH$



$p(H) = p(e^-e^+) - p(Z)$

$\Rightarrow [\, p(e^-e^+) - p(Z) \,]^2$ peaks at $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!



$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

$N(ZH[\to ZZ]) \propto$

$\sigma(ZH) \times BR(H \to ZZ) \propto$

$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

$\Rightarrow$ absolute measurement of width and couplings

$m_{recoil} = \sqrt{[\, p(e^-e^+) - p(Z) \,]^2}$

Table 5. Expected relative precision (%) of the κ parameters in the kappa-3 (combined with HL-LHC) scenario described in Section 2 for future accelerators beyond the LHC era. The corresponding 95%CL upper limits on BR_{unt} and BR_{inv} and the derived constraint on the Higgs width (in %) are also given. No requirement on κ_V is applied in the combination with HL-LHC, since the lepton colliders provide the necessary access to the Higgs width. Cases in which a particular parameter has been fixed to the SM value due to lack of sensitivity are shown with a dash (−). An asterisk (∗) indicates the cases in which there is no analysis input in the reference documentation, and HL-LHC dominates the combination. The integrated luminosity and running conditions considered for each collider in this comparison are described in Table 1. Both the initial stage and the full program of the colliders is considered, with "ILC_{500}" corresponding to ILC_{250}+ILC_{350}+ILC_{500}, "$CLIC_{3000}$" to $CLIC_{380}$+$CLIC_{1500}$+$CLIC_{3000}$, and "FCC-ee_{365}" to FCC-ee_{240}+FCC-ee_{365}. FCC-ee/eh/hh corresponds to the combined performance of FCC-ee_{240}+FCC-ee_{365}, FCC-eh and FCC-hh.

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-0	fixed at 0	fixed at 0	no
kappa-1	measured	fixed at 0	no
kappa-2	measured	measured	no
kappa-3	measured	measured	yes

kappa-3 scenario	HL-LHC+							
	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-ee_{365}
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89
κ_γ (%)	1.3	1.2	1.5∗	1.3	1.1	1.2	1.3	1.2
$\kappa_{Z\gamma}$ (%)	11.∗	11.∗	11.∗	8.4	5.7	6.3	11.∗	10.∗
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64
κ_μ (%)	4.2	3.9	4.4∗	4.1	3.5	3.9	4.	3.9
κ_τ (%)	1.1	0.64	1.4	0.99	0.82	0.96	0.98	0.66
BR_{inv} (<%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19
BR_{unt} (<%, 95% CL)	1.8	1.4	2.7	2.4	2.4	1.1	1.2	1.

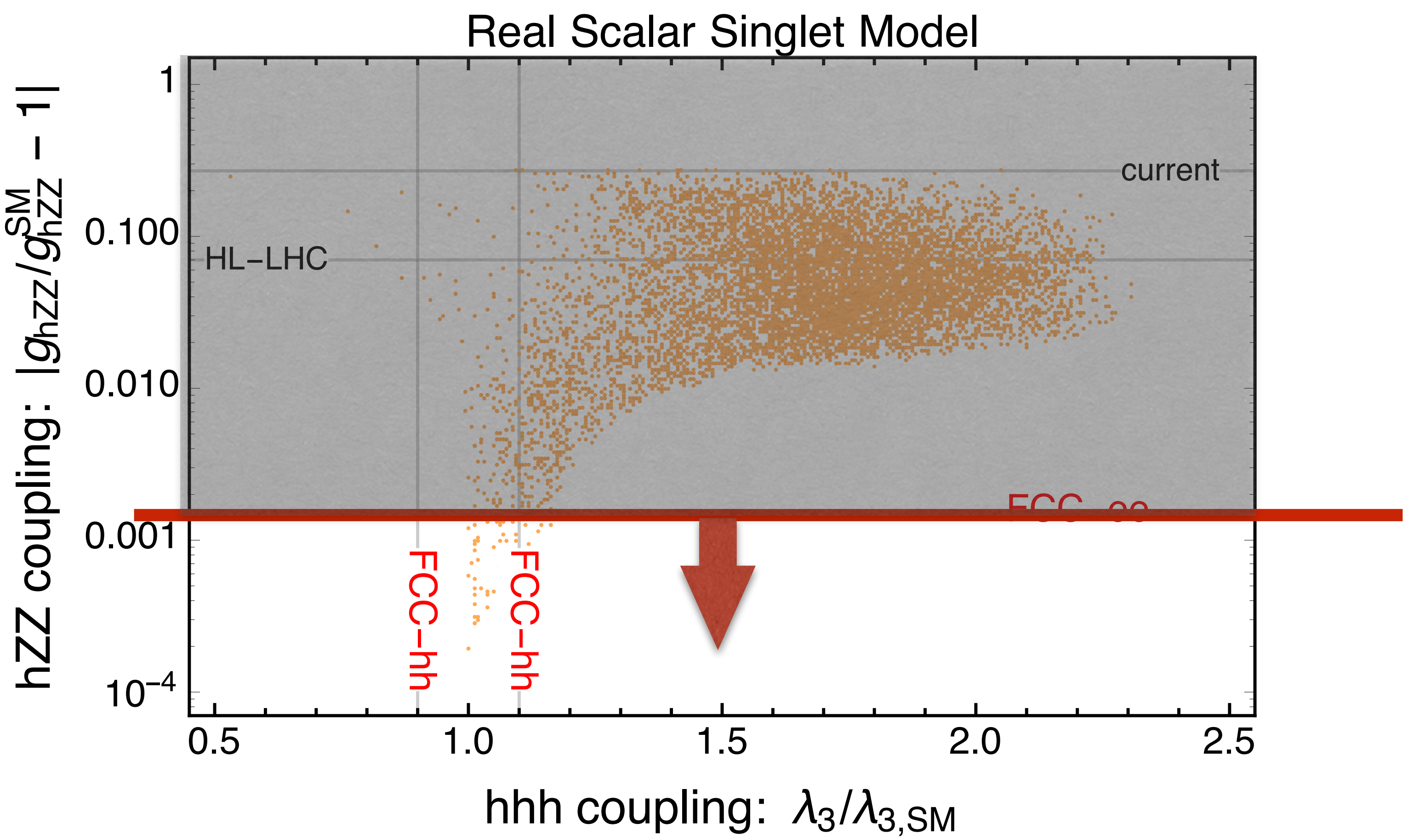
J. de Blas et al, http://arxiv.org/abs/arXiv:1905.03764

Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as Hγγ, Hμμ, HZγ, Htt

Example of precision targets: constraints on models with 1st order phase transition

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

g_{HZZ} to 10^{-3} allows to probe the ~full range of parameters

The sensitivity to the mass-scale of new physics, in terms of various EFT operators

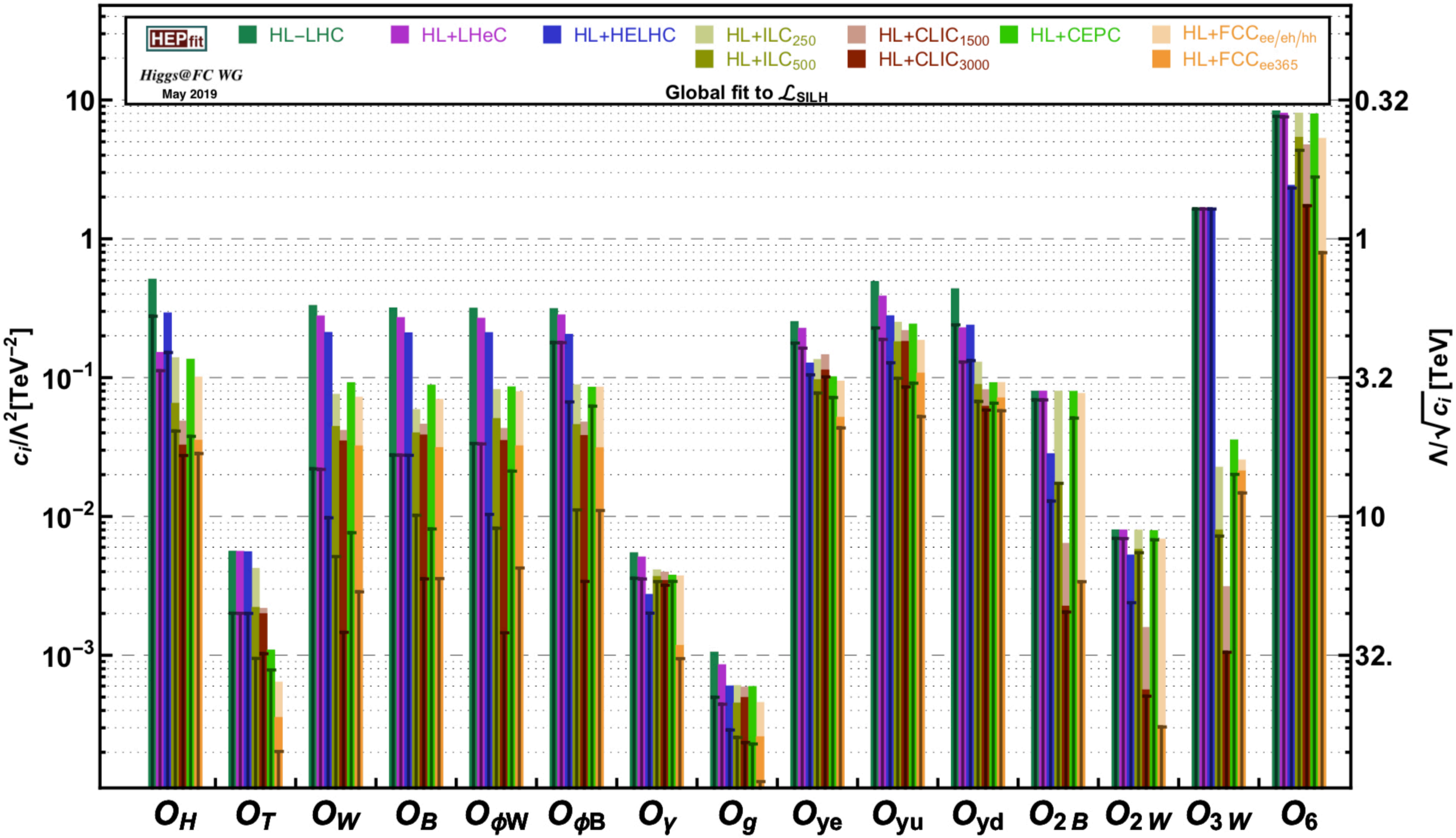


Figure 6. Global fit to the EFT operators in the Lagrangian (19). We show the marginalized 68% probability reach for each Wilson coefficient c_i/Λ^2 in Eq. (19) from the global fit (solid bars). The reach of the vertical lines indicate the results assuming only the corresponding operator is generated by the new physics.

We can spend hours discussing details of each limit, how each accelerator could improve their reach, etc. etc

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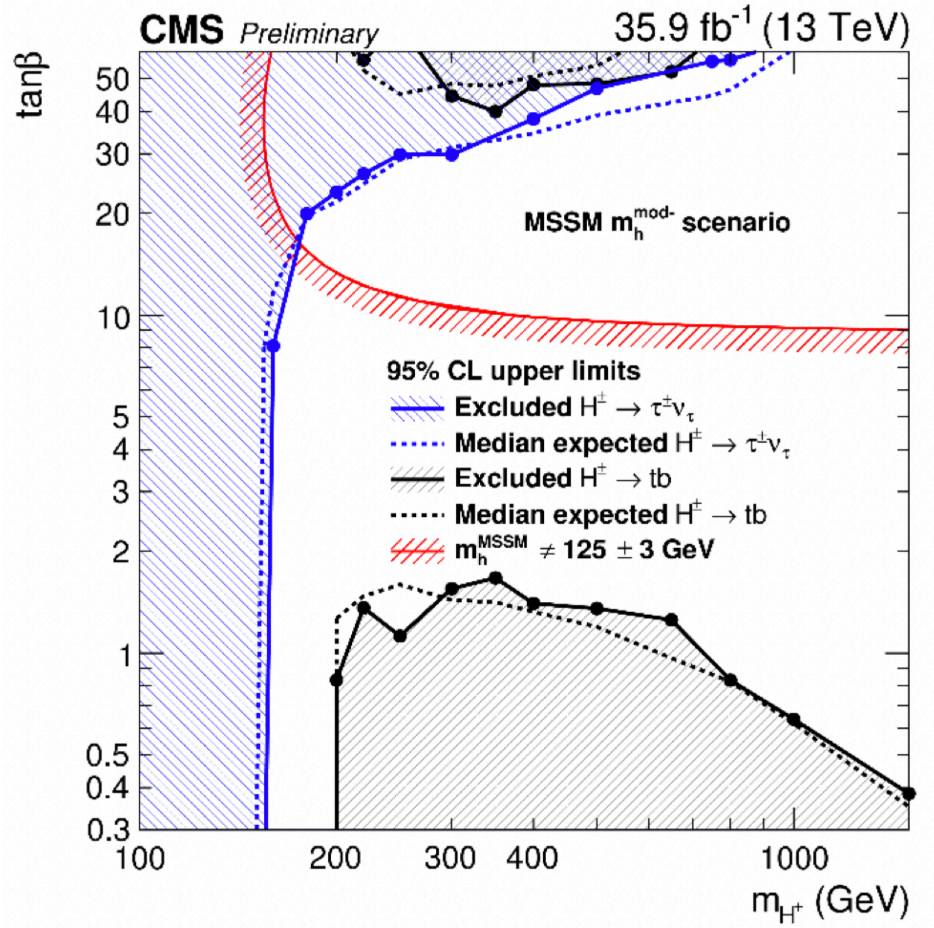
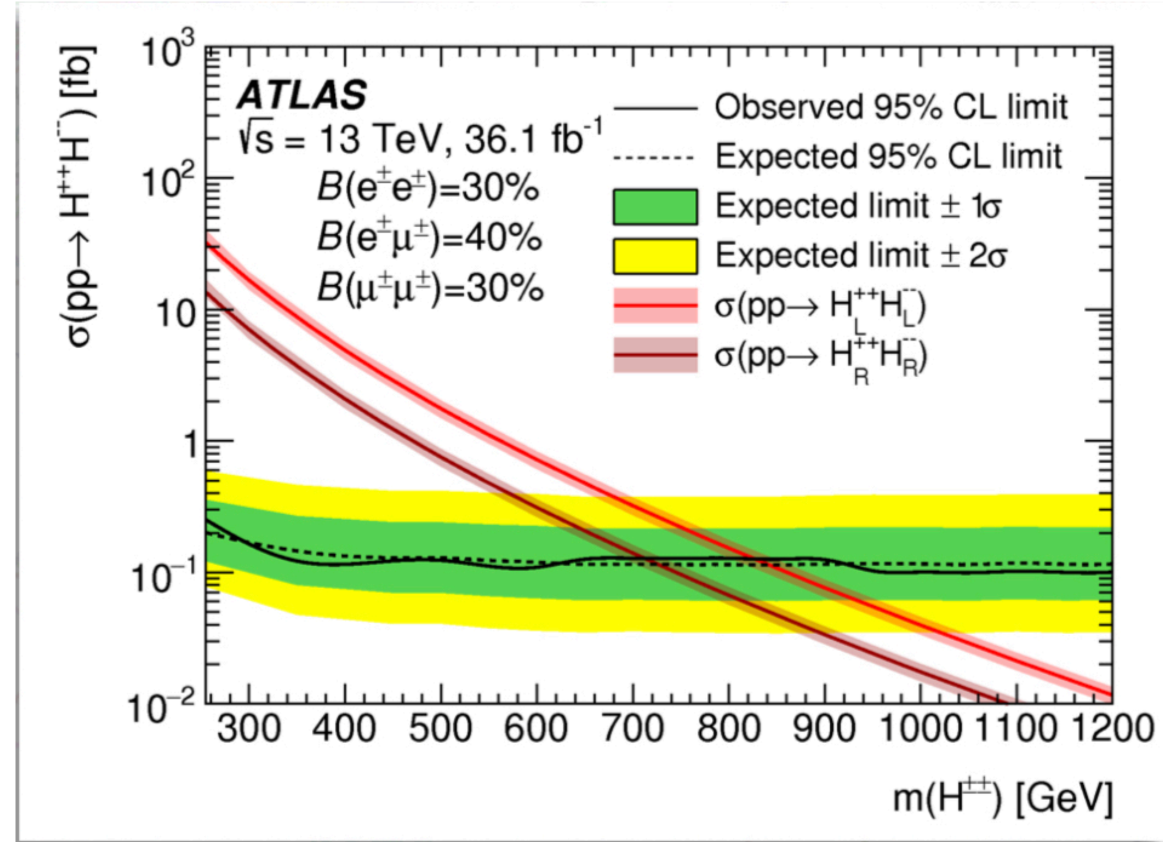
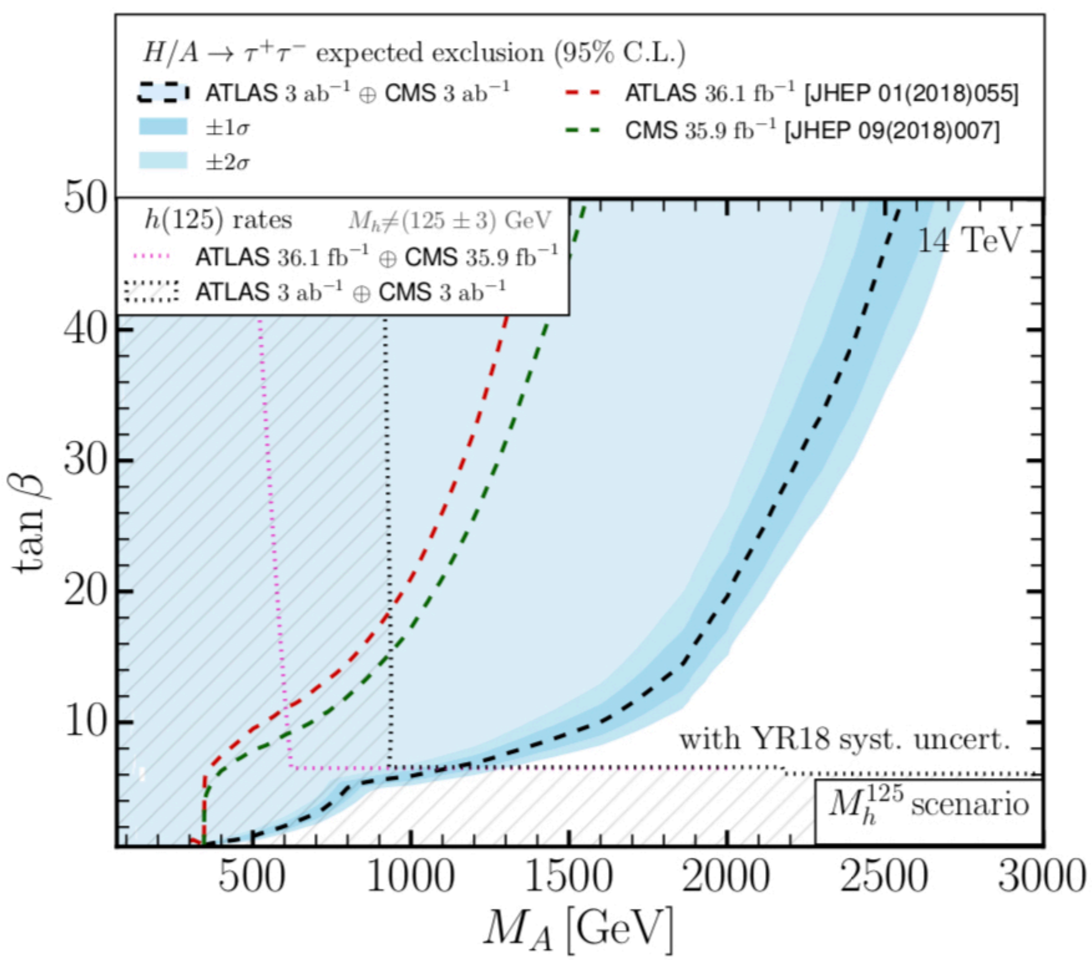
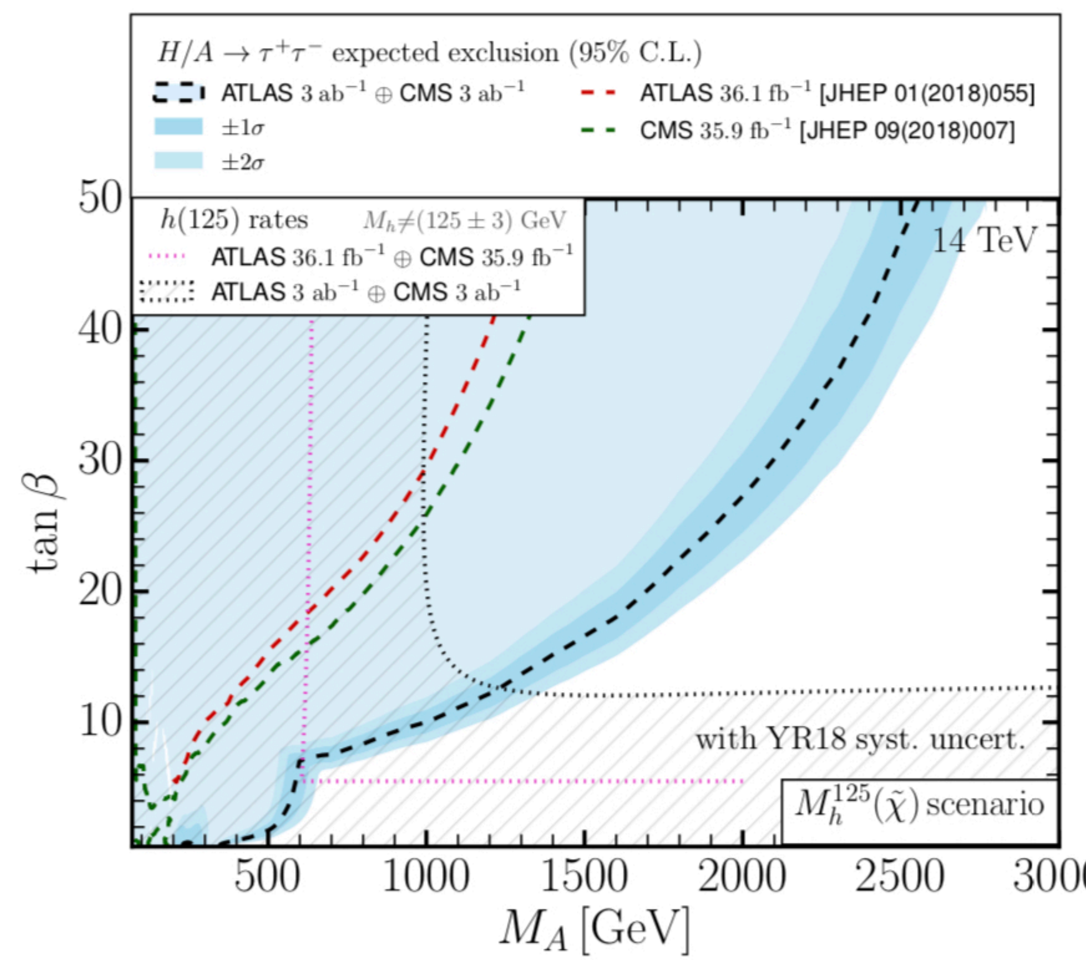
My main take-away message is that there is sensitivity to multi-TeV scales, and, if we want to directly access physics at those scales, we need a multi-TeV collider ….


CMS Preliminary
35.9 fb-1 (13 TeV)
tanβ
MSSM m_h^{mod-} scenario
95% CL upper limits
Excluded $H^{\pm} \to \tau^{\pm}\nu_{\tau}$
Median expected $H^{\pm} \to \tau^{\pm}\nu_{\tau}$
Excluded $H^{\pm} \to$ tb
Median expected $H^{\pm} \to$ tb
$m_h^{MSSM} \neq 125 \pm 3$ GeV
m_{H^+} (GeV)


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb-1
$B(e^{\pm}e^{\pm})$=30%
$B(e^{\pm}\mu^{\pm})$=40%
$B(\mu^{\pm}\mu^{\pm})$=30%
Observed 95% CL limit
Expected 95% CL limit
Expected limit ± 1σ
Expected limit ± 2σ
$\sigma(pp \to H_L^{++}H_L^{--})$
$\sigma(pp \to H_R^{++}H_R^{--})$
$\sigma(pp \to H^{++}H^{--})$ [fb]
$m(H^{\pm\pm})$ [GeV]


$H/A \to \tau^+\tau^-$ expected exclusion (95% C.L.)
ATLAS 3 ab^{-1} ⊕ CMS 3 ab^{-1}
±1σ
±2σ
ATLAS 36.1 fb^{-1} [JHEP 01(2018)055]
CMS 35.9 fb^{-1} [JHEP 09(2018)007]
$h(125)$ rates
$M_h \neq (125 \pm 3)$ GeV
ATLAS 36.1 fb^{-1} ⊕ CMS 35.9 fb^{-1}
ATLAS 3 ab^{-1} ⊕ CMS 3 ab^{-1}
14 TeV
with YR18 syst. uncert.
M_h^{125} scenario
$\tan\beta$
M_A [GeV]


$H/A \to \tau^+\tau^-$ expected exclusion (95% C.L.)
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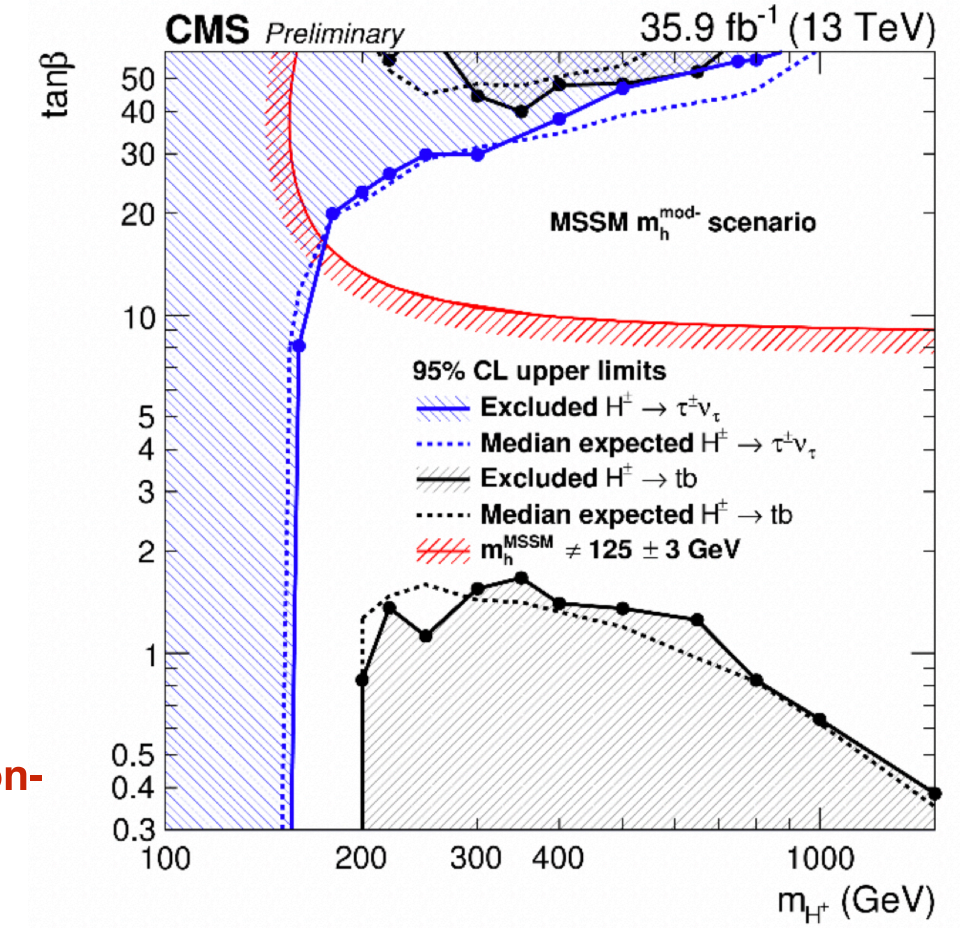
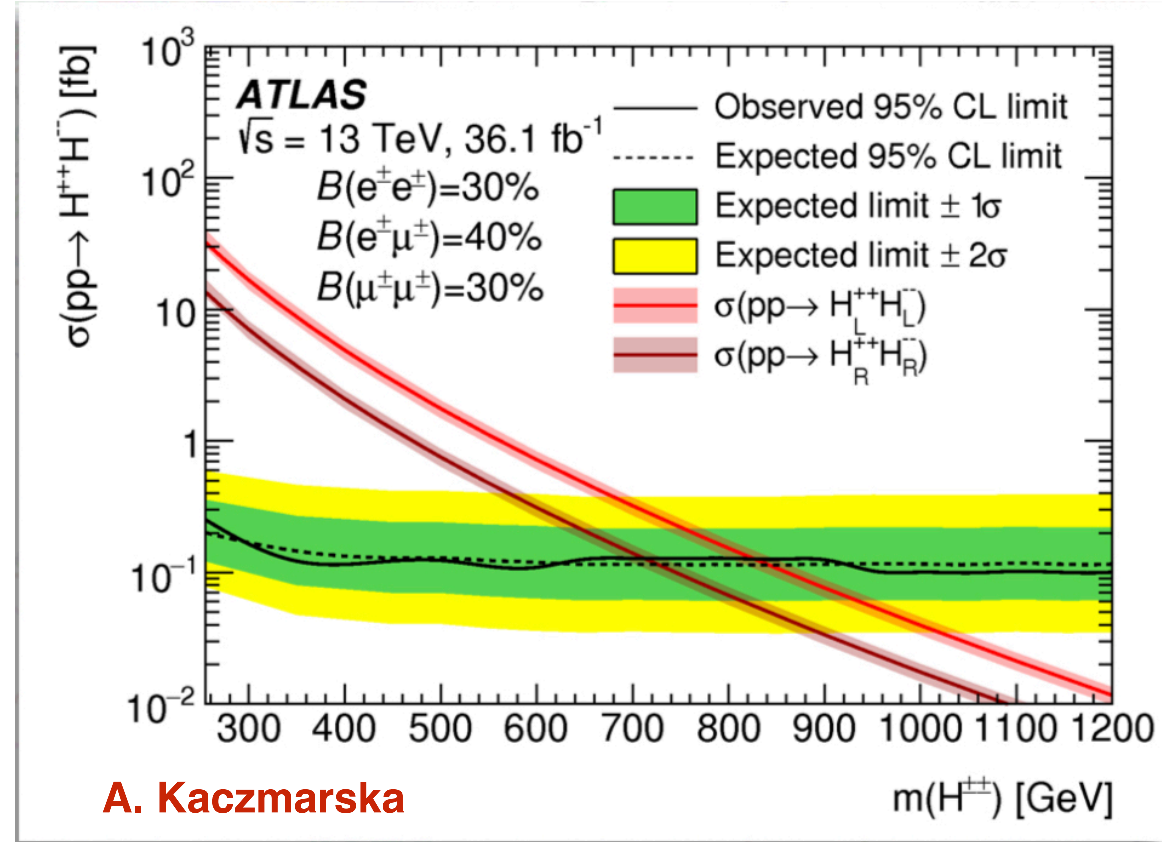
ATLAS 3 ab^{-1} ⊕ CMS 3 ab^{-1}
14 TeV
with YR18 syst. uncert.
$M_h^{125}(\tilde{\chi})$ scenario
$\tan\beta$
M_A [GeV]

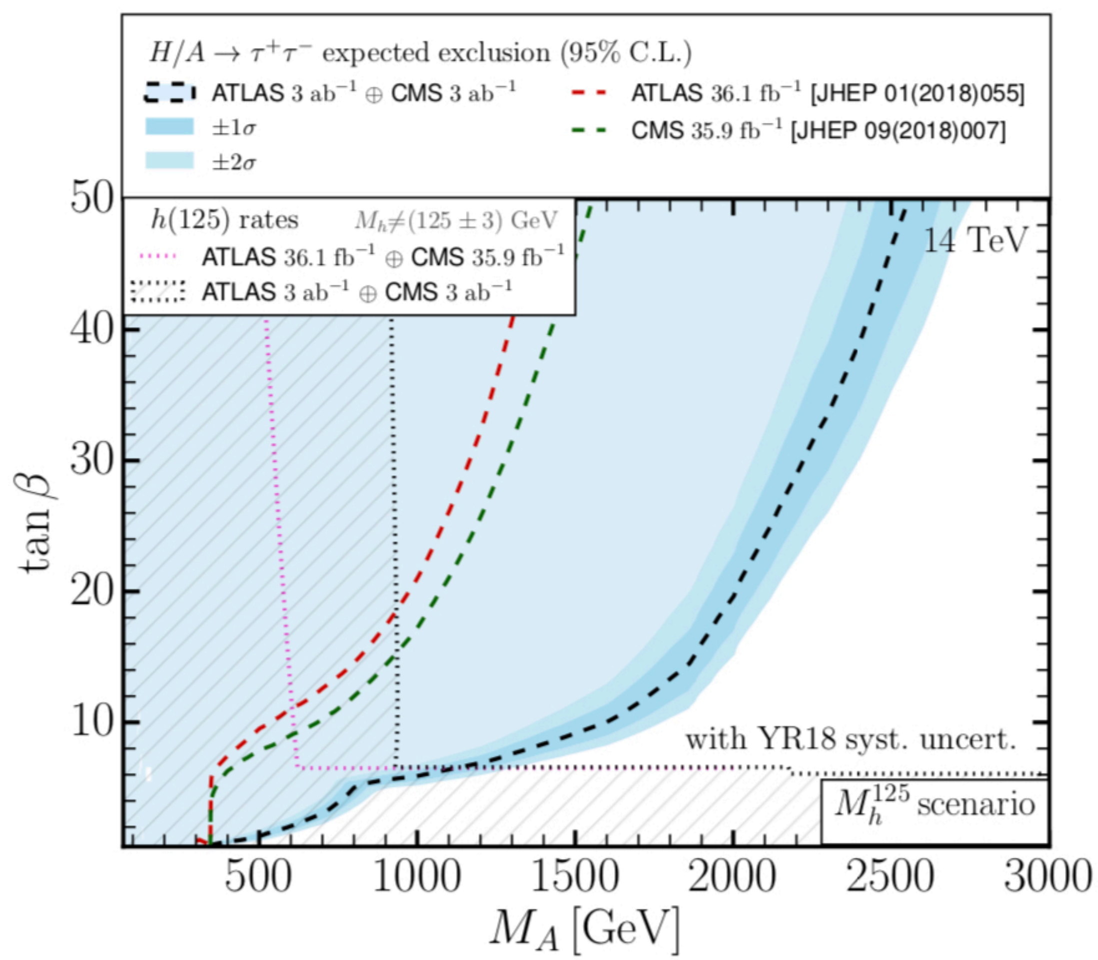


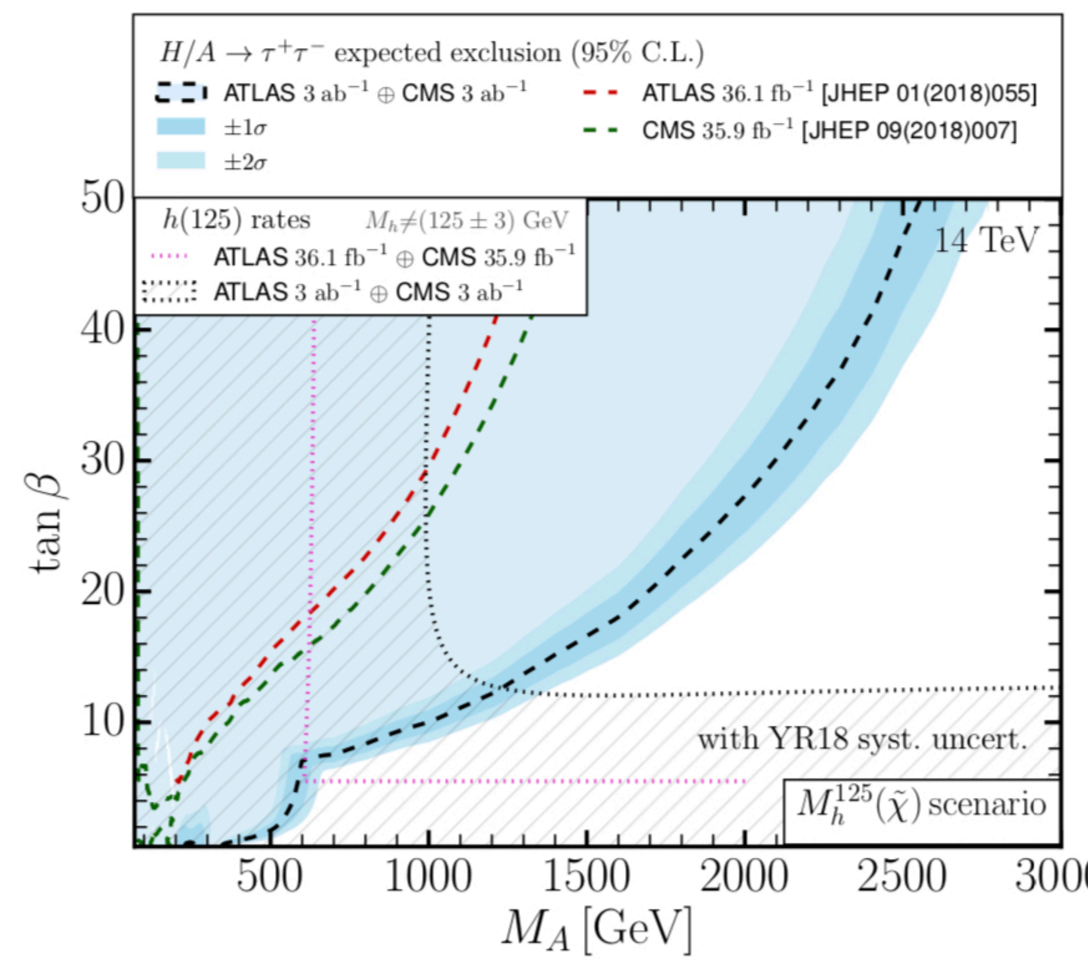
S. Gascon-Shotkin



A. Kaczmarska

* **Sven** et al, in *Higgs Physics at the HL-LHC and HE-LHC*, https://cds.cern.ch/record/2650162.





The exploration of BSM Higgs sectors at LHC is already pushing beyond the TeV region …
eventually need to be able to go beyond …

The unique contributions of a *100 TeV pp collider to Higgs physics*

- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision

- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition
    - …

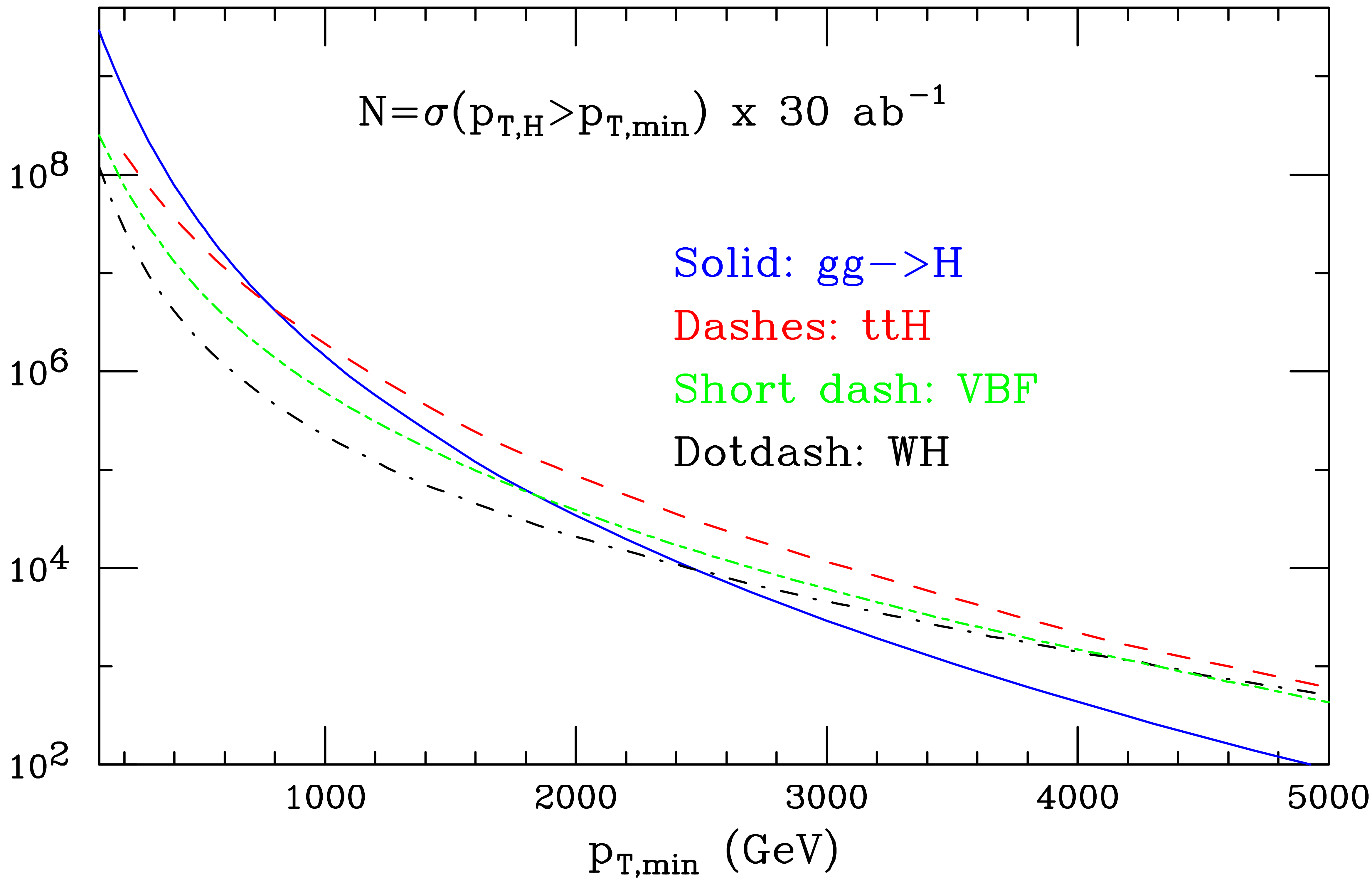
SM Higgs: event rates in pp@100 TeV

	$gg \to H$	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\text{TeV}} \times 30\ \text{ab}^{-1}$

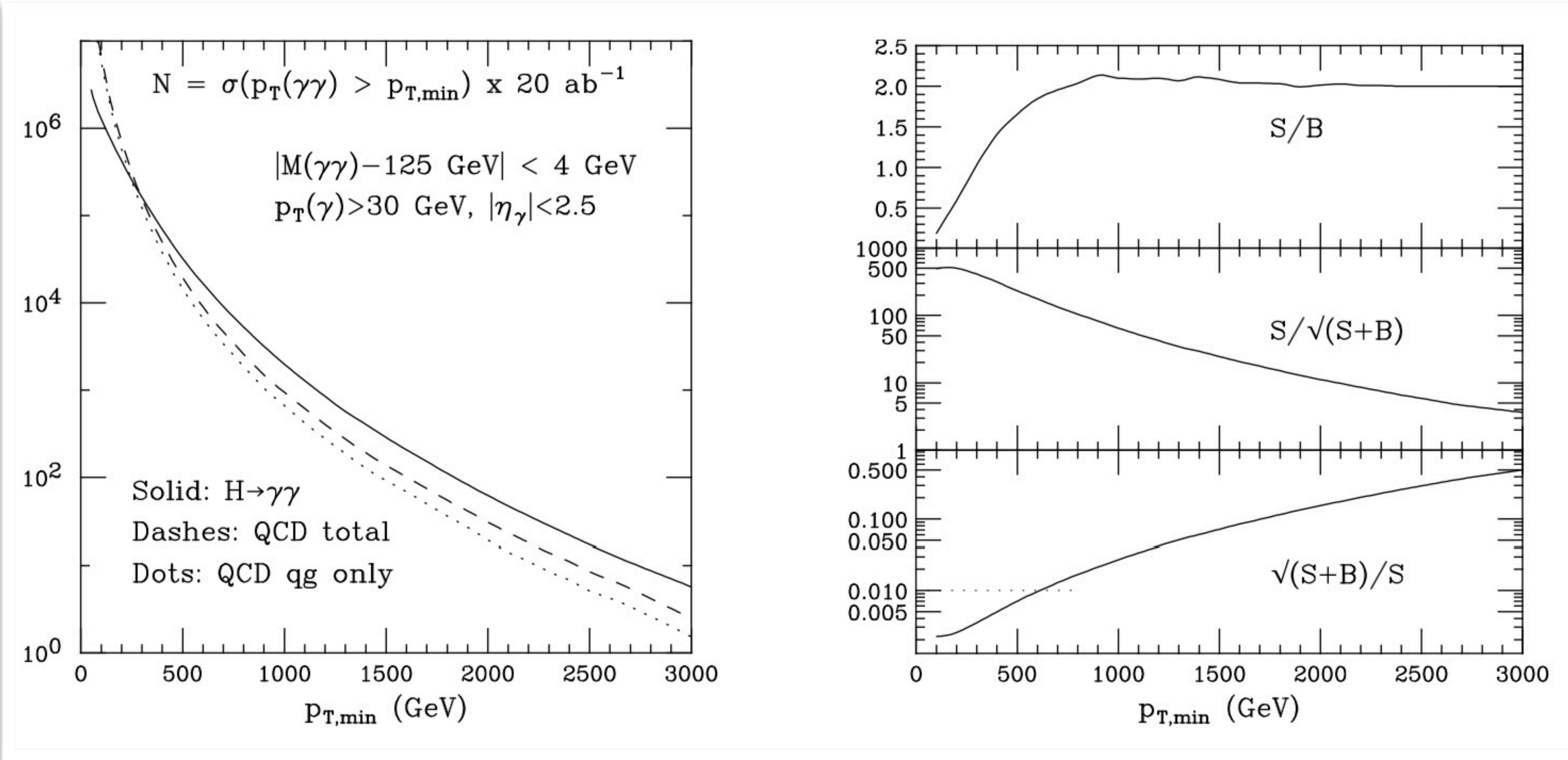
$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

H at large p_T



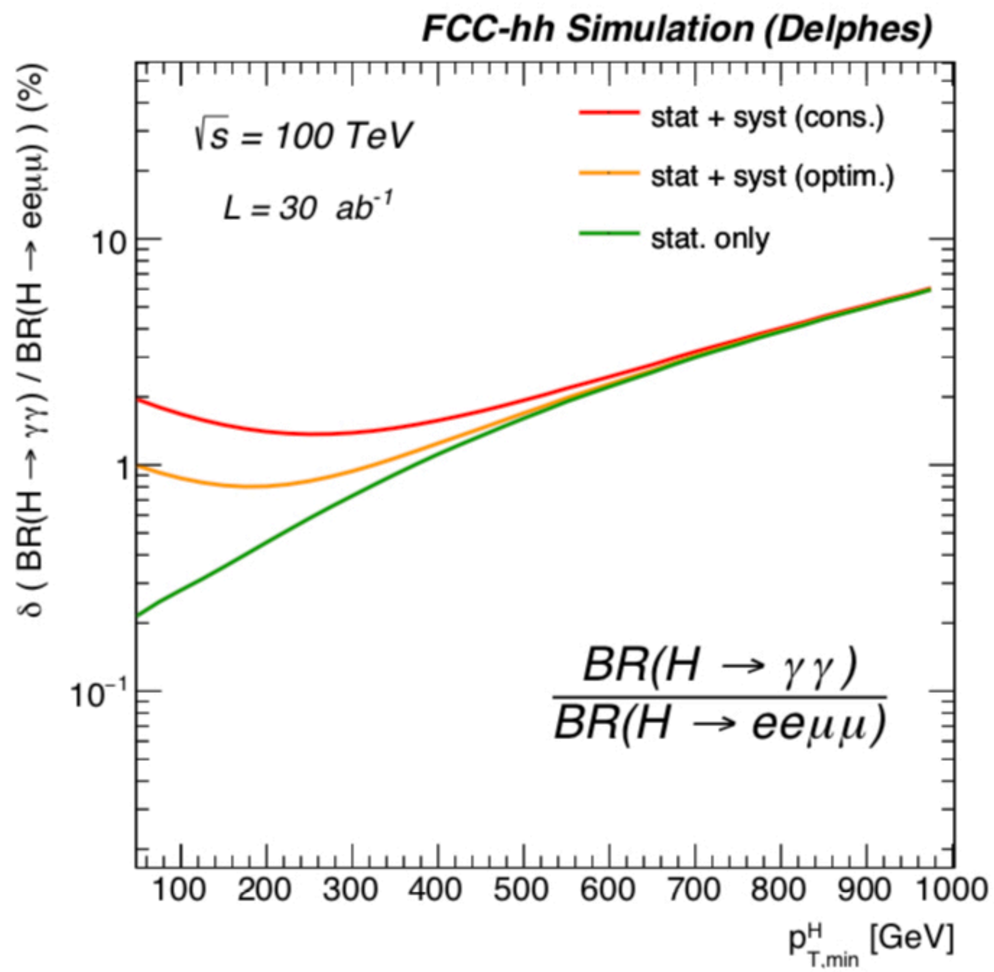
- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

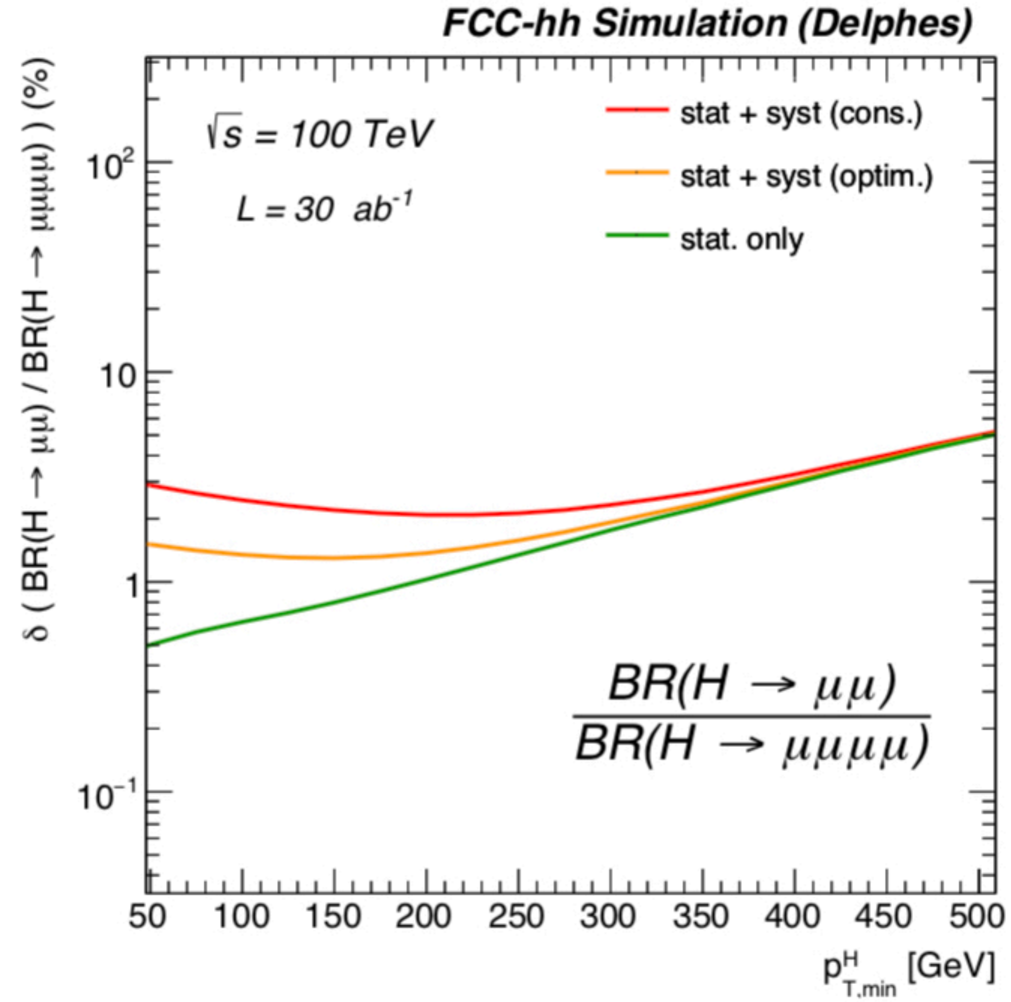
gg→H→γγ at large p_T



- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \gamma\gamma)}{BR(H \rightarrow ee\mu\mu)}$
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
$p_{T,min}^{H}$ [GeV]


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \mu\mu)}{BR(H \rightarrow \mu\mu\mu\mu)}$
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
$p_{T,min}^{H}$ [GeV]

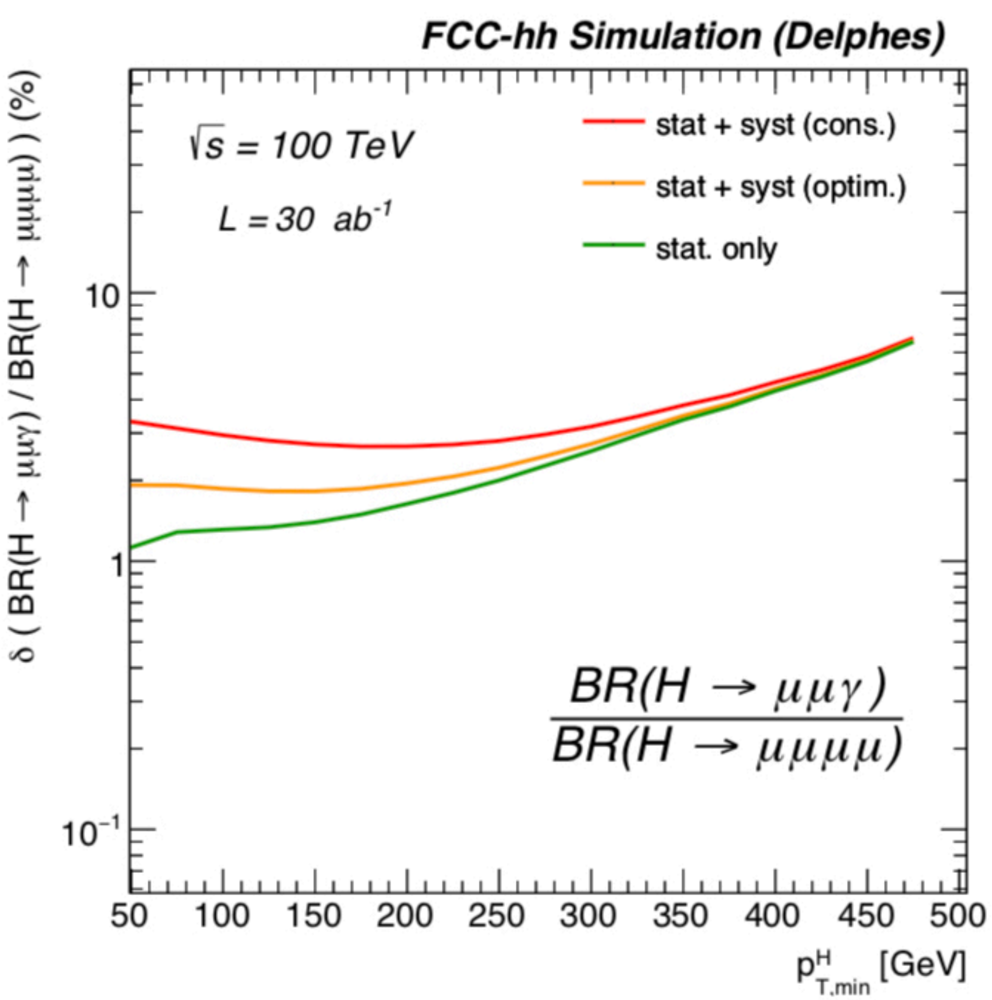

FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \mu\mu\gamma)}{BR(H \rightarrow \mu\mu\mu\mu)}$
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
$p_{T,min}^{H}$ [GeV]

Table 4.4: Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)\mathrm{B}(\mathrm{H} \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H} \to \mu\mu)/\mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H} \to \mu\mu\gamma)/\mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to b\bar{b})/\sigma(t\bar{t}\mathrm{Z}) \times \mathrm{B}(\mathrm{Z} \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H} \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Importance of standalone precise "ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

$BR(H\to\gamma\gamma)/BR(H\to ZZ^*)$

loop-level tree-level

$BR(H\to\mu\mu)/BR(H\to ZZ^*)$

2nd gen'n Yukawa gauge coupling

$BR(H\to\gamma\gamma)/BR(H\to Z\gamma)$

different EW charges in the loops of the two procs

$BR(H\to inv)/BR(H\to\gamma\gamma)$

tree-level neutral loop-level charged

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**6.5**
BR_{exo} (95%CL)	BR_{inv} < 2.5%	**< 1%**	**BR_{inv} < 0.025%**

* From BR ratios wrt B(H→4lept) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

Higgs self-coupling, gg→HH

From the detector performance studies: ←→ | Pheno-level studies: ←→

	bbγγ	bbZZ[→4l]	bbWW[→2jlν]	4b+j	2b2τ+j
$\delta\kappa_\lambda$ (%)	6.5	14	40	30	8

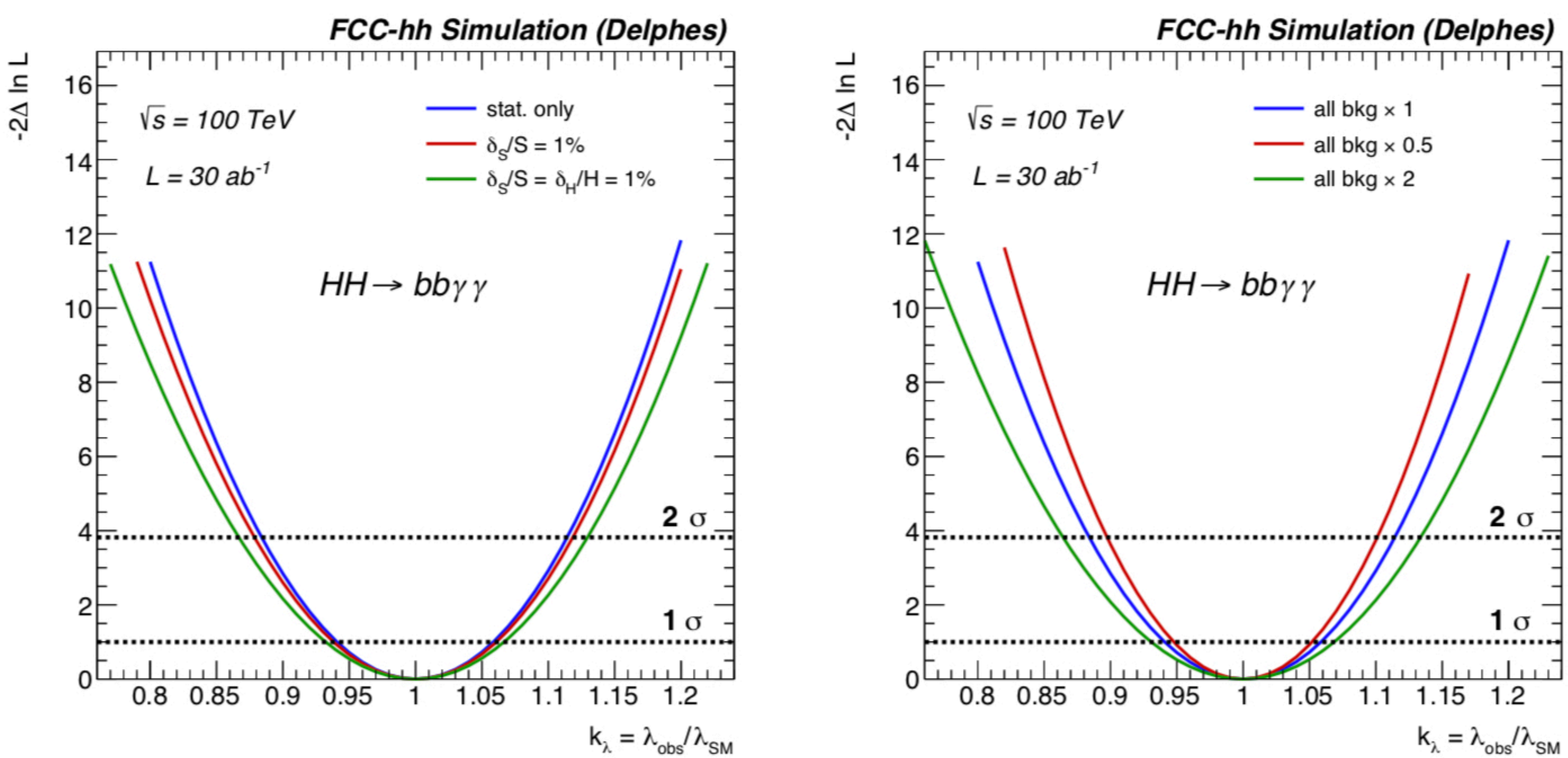
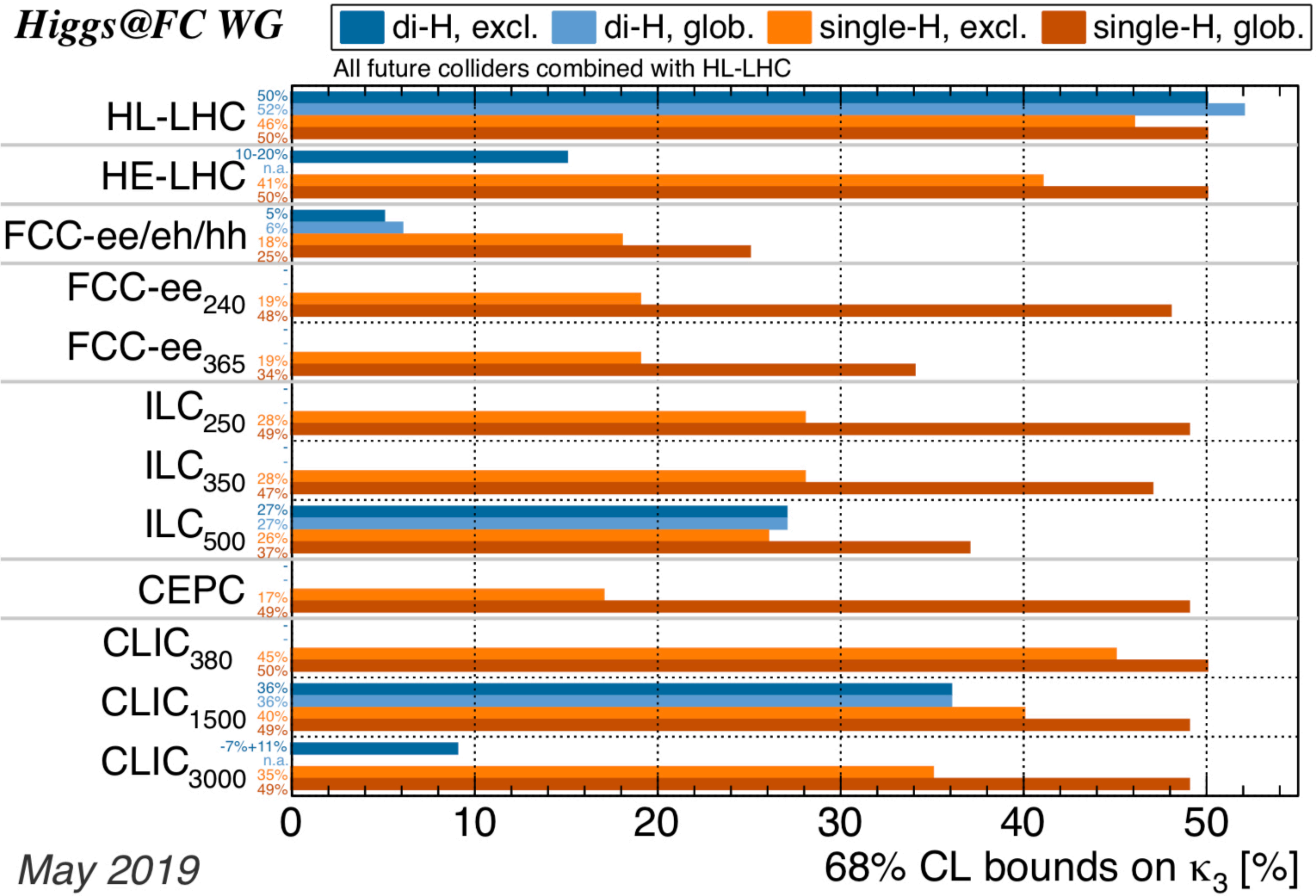


Figure 10.4: Expected precision on the Higgs self-coupling modifier κ_λ with no systematic uncertainties (only statistical), 1% signal uncertainty, 1% signal uncertainty together with 1% uncertainty on the Higgs backgrounds (left) and assuming respectively ×1, ×2, ×0.5 background yields (right).)

Higgs selfcoupling



J. de Blas et al, http://arxiv.org/abs/arXiv:1905.03764

Example of precision targets: constraints on models with 1st order phase transition

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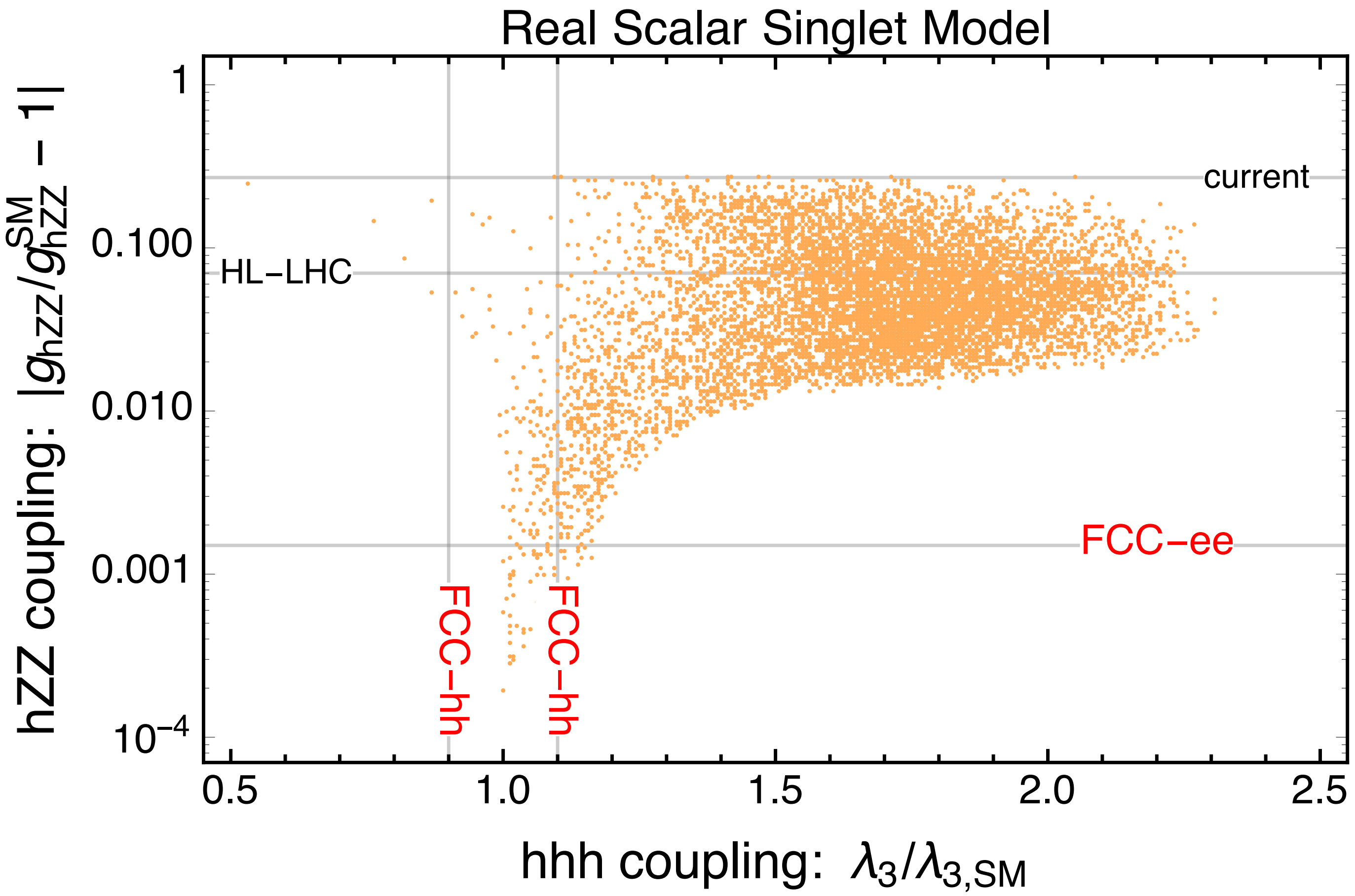
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

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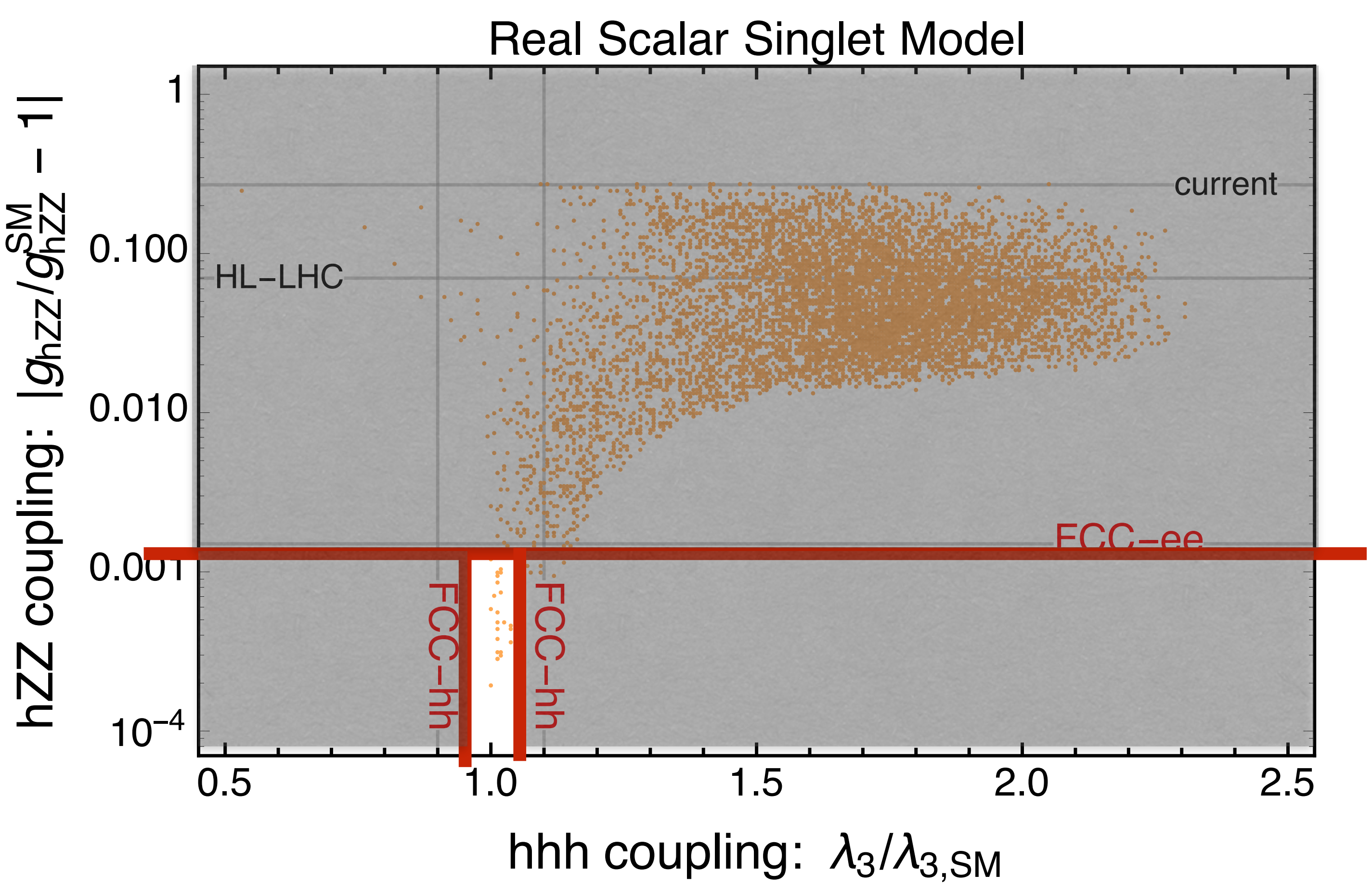

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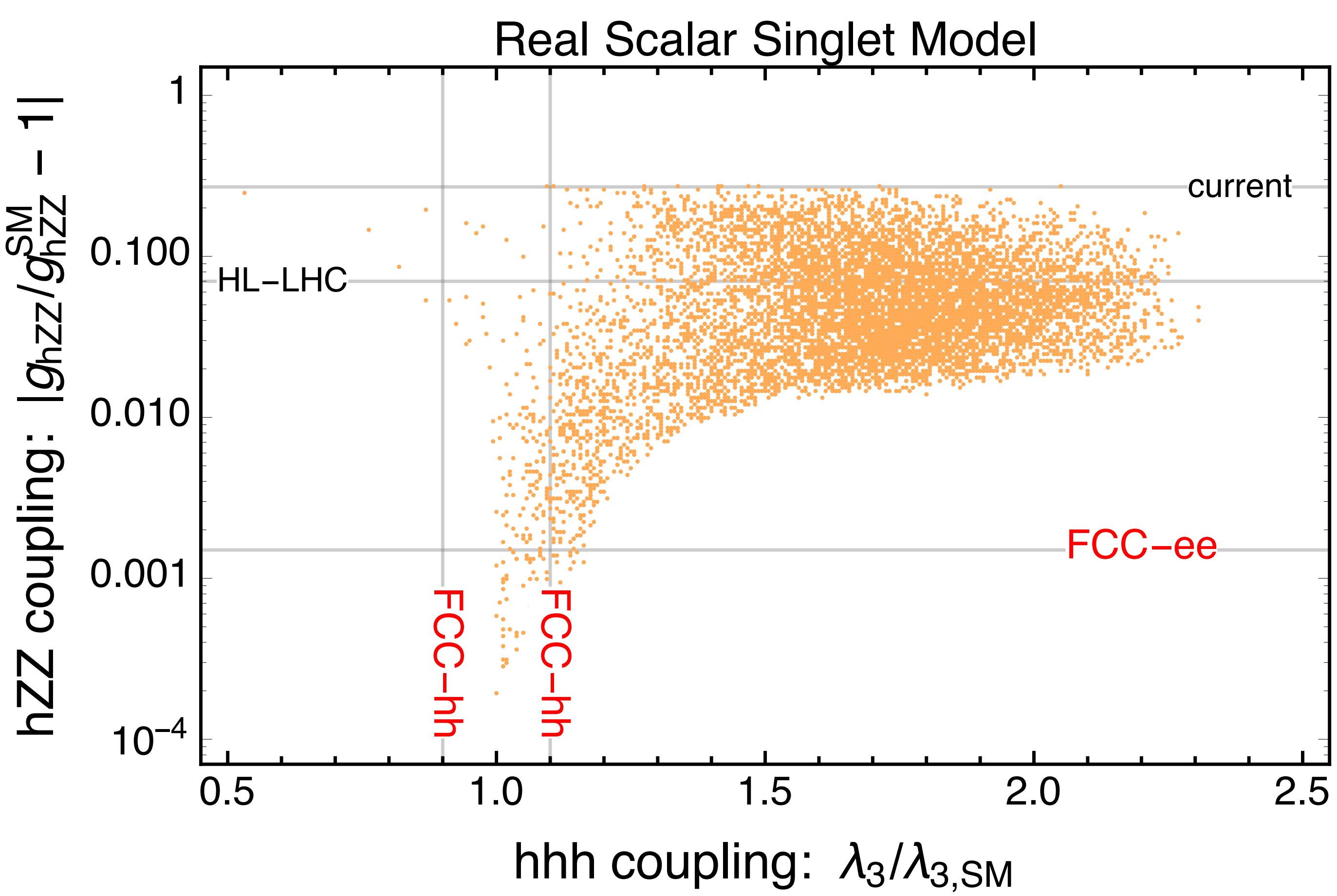

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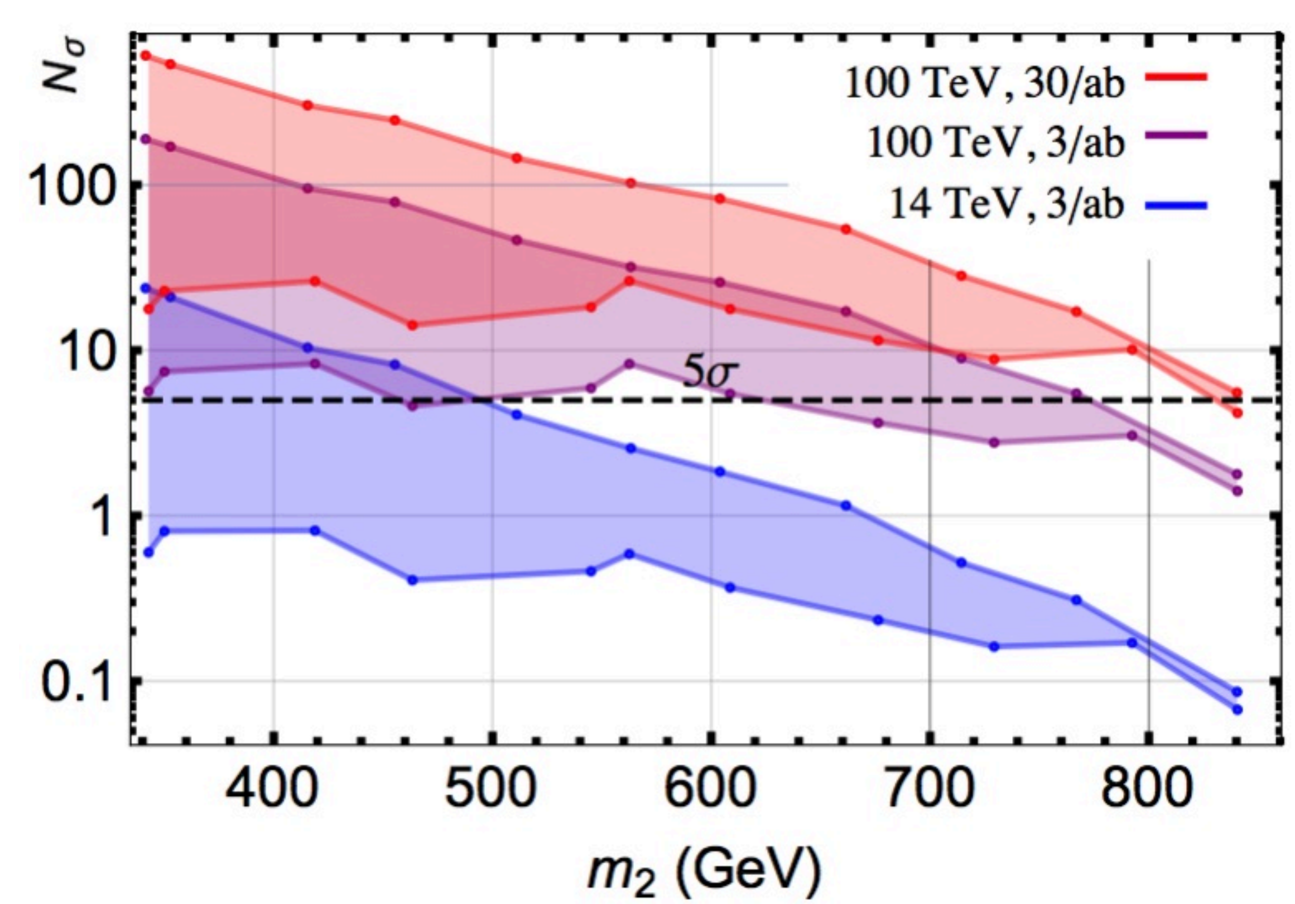
Direct detection of extra Higgs states at FCC-hh



$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

$(h_2 \sim S, \quad h_1 \sim H)$

The way to read the previous plots

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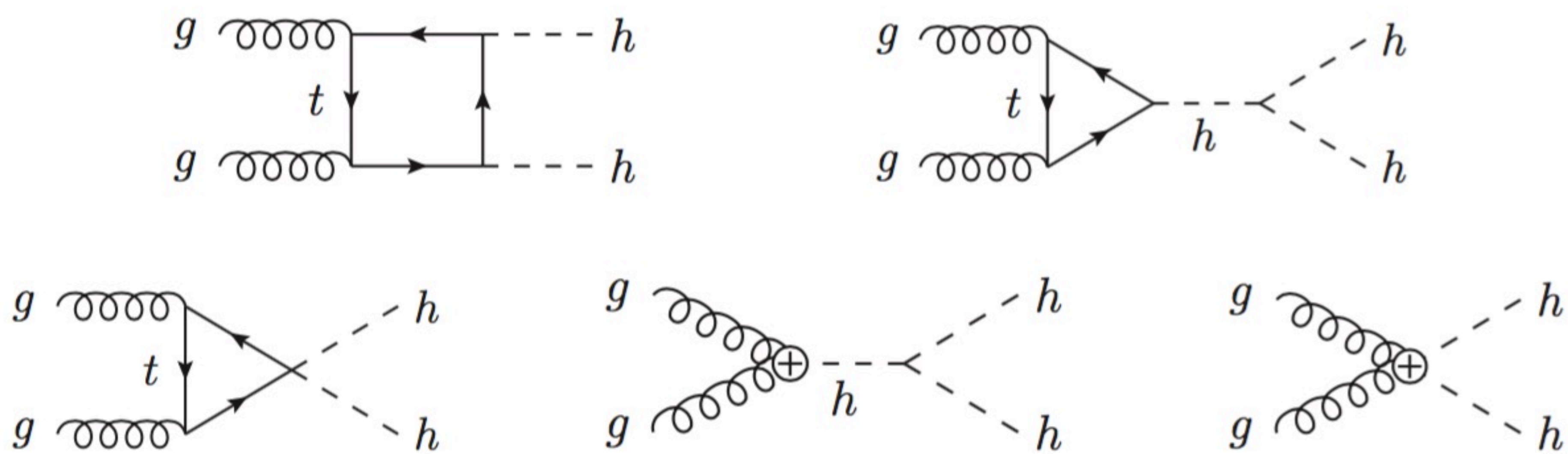
- Furthermore, if the purpose of precision Higgs measurements is to detect deviations, the natural continuation of this programme is to search for the microscopic origin of those deviations.

Example: extracting Higgs self-coupling from gg→HH at FCC-hh



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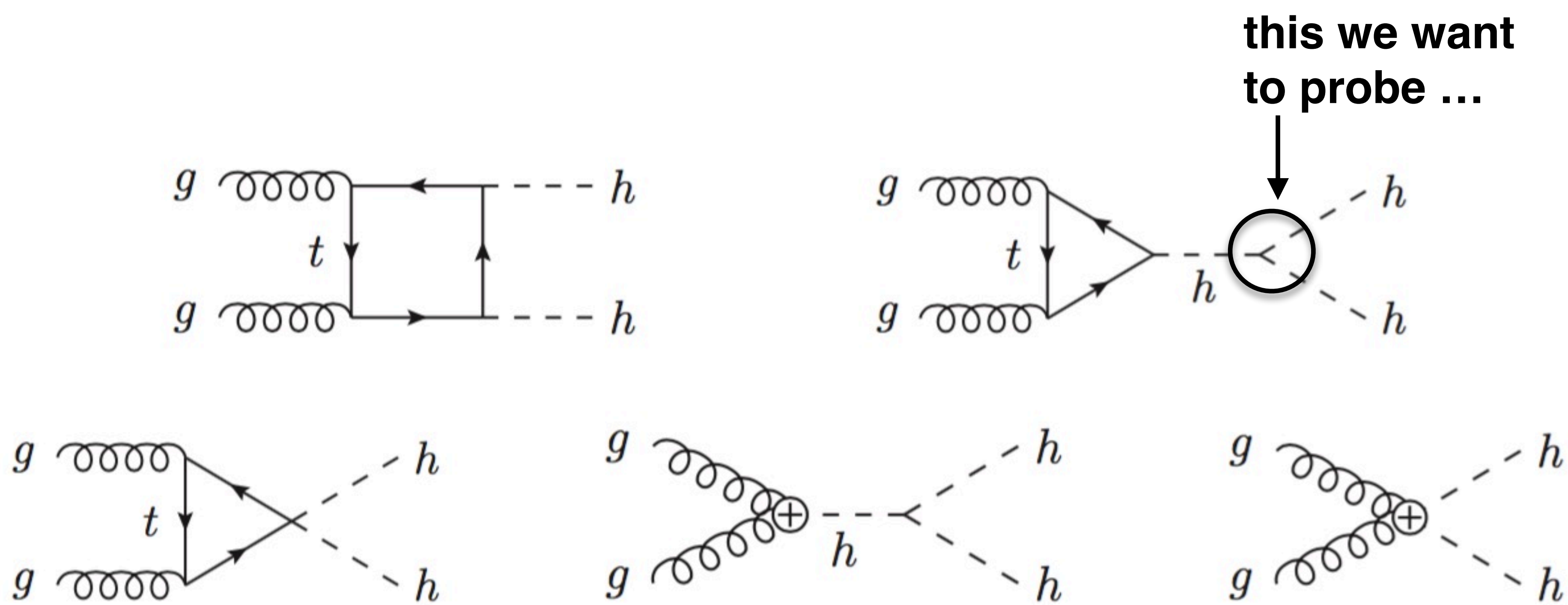

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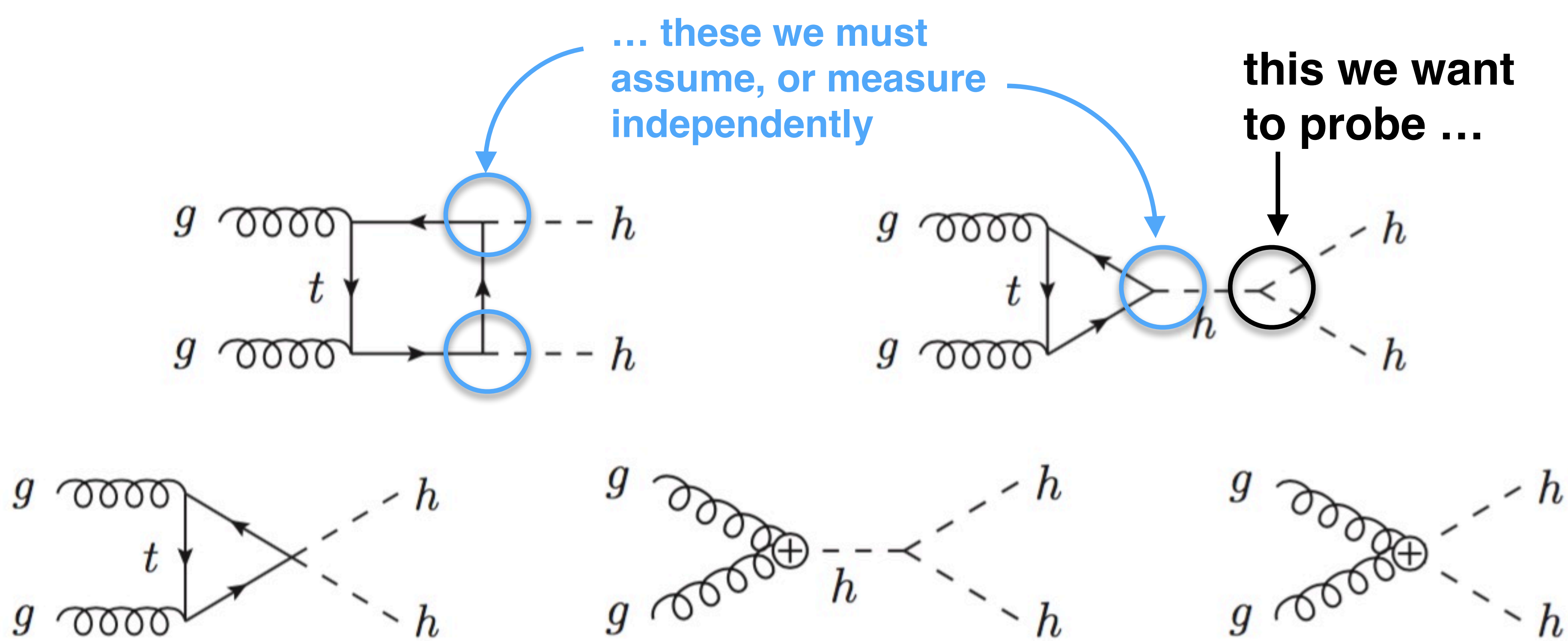

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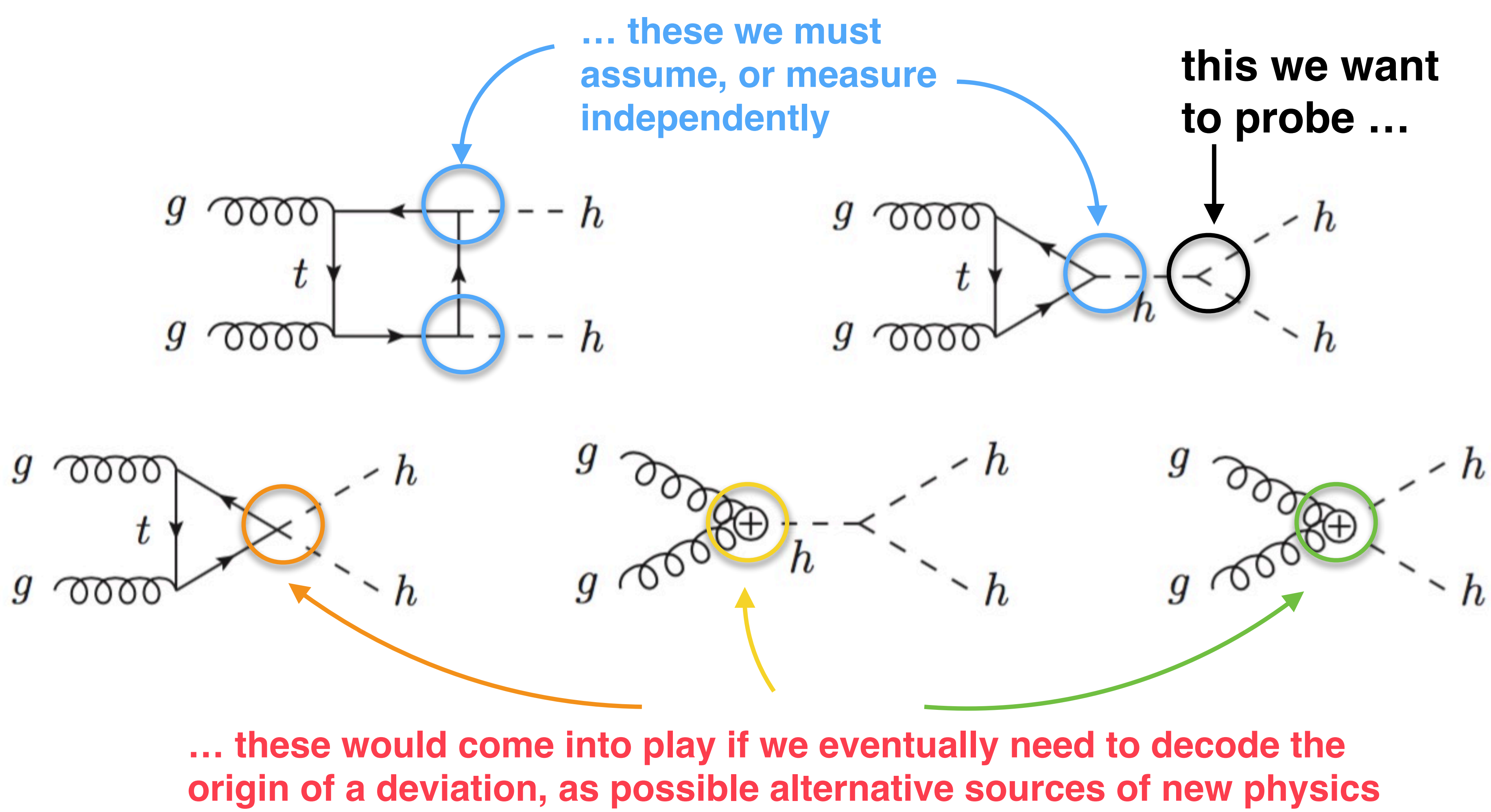
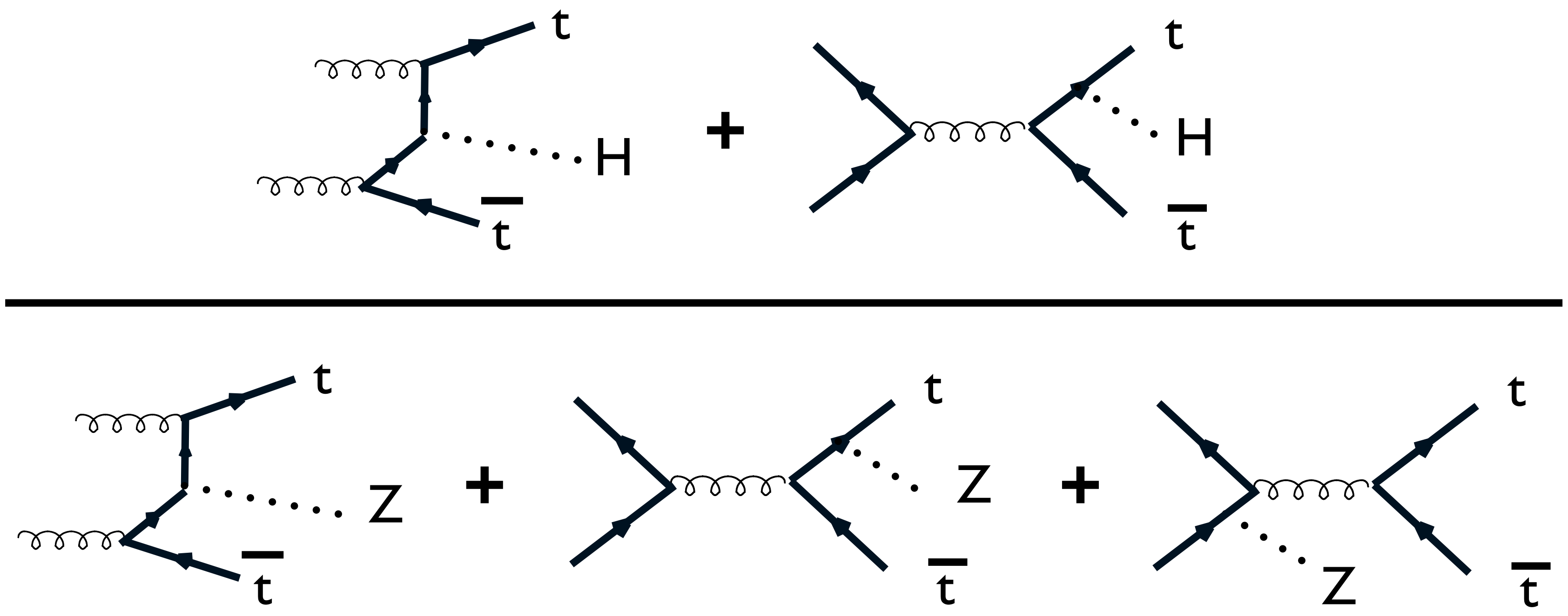


Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

FCC-hh can measure R_t with $\Delta R_t/R_t \sim 2\%$

R_t =



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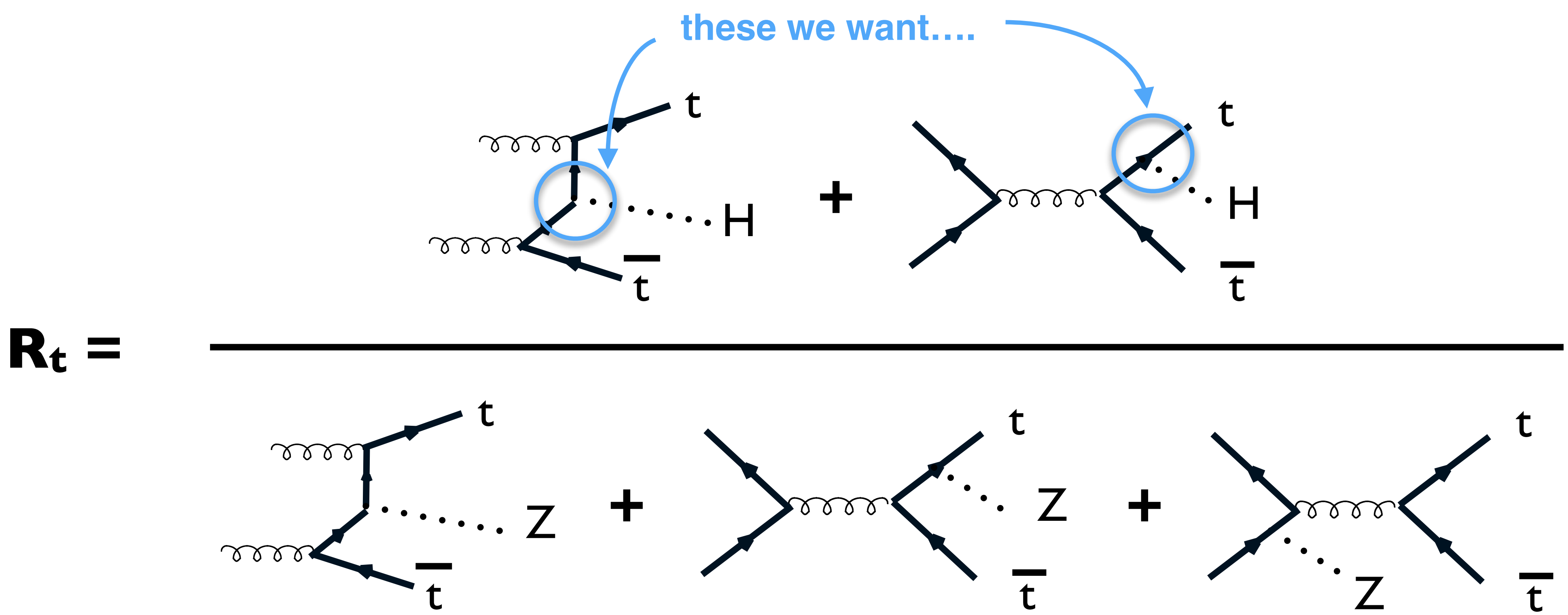

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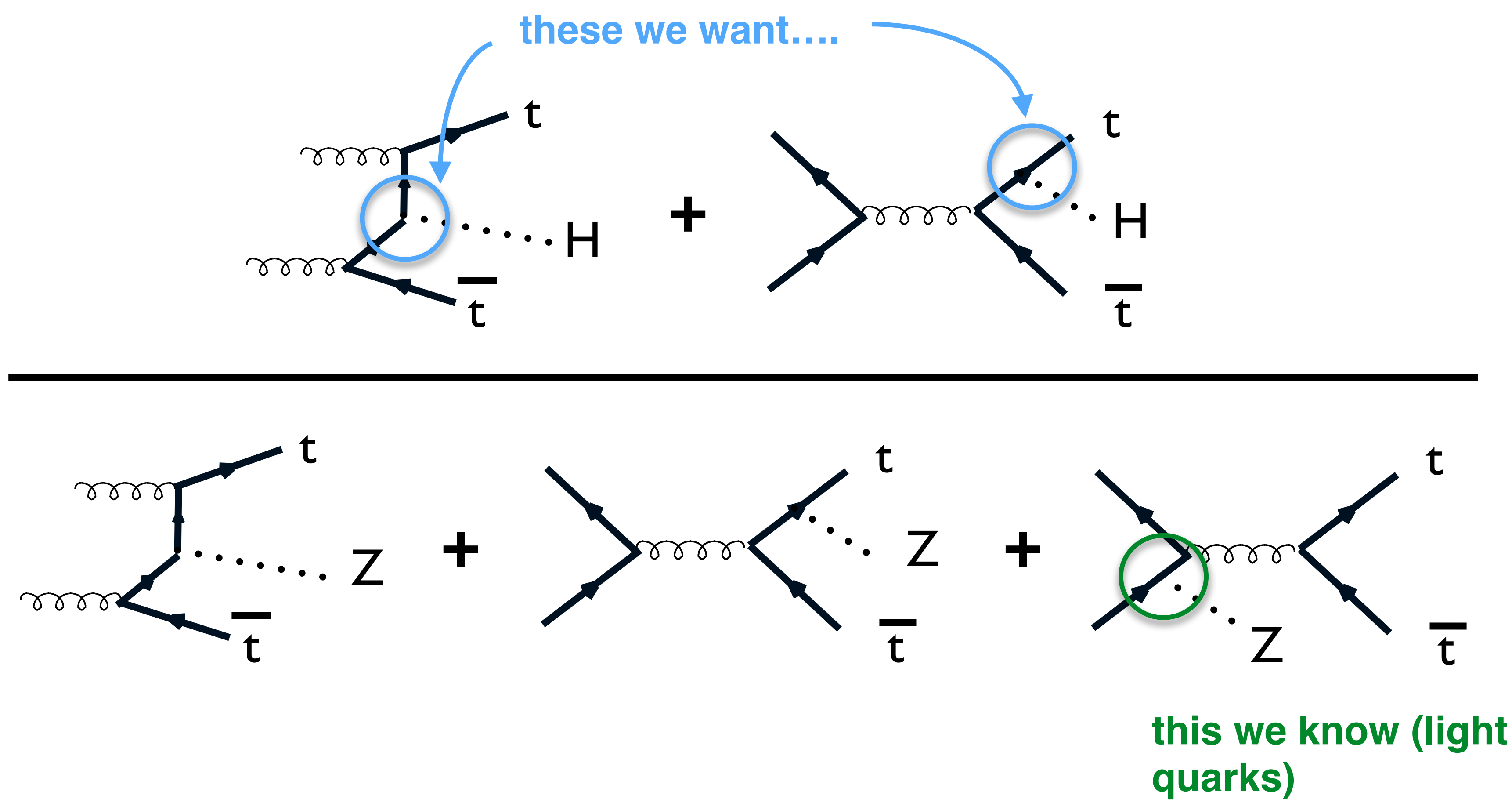

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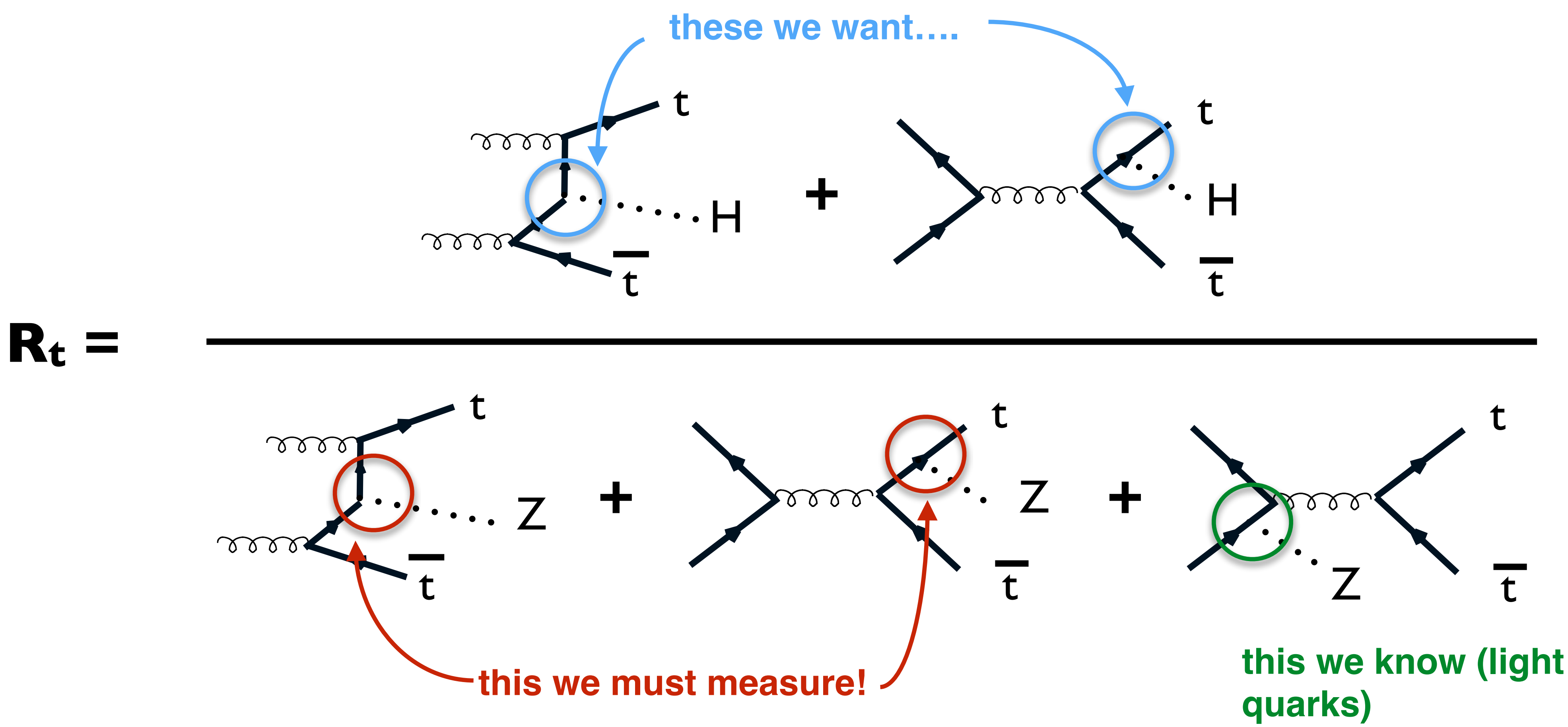

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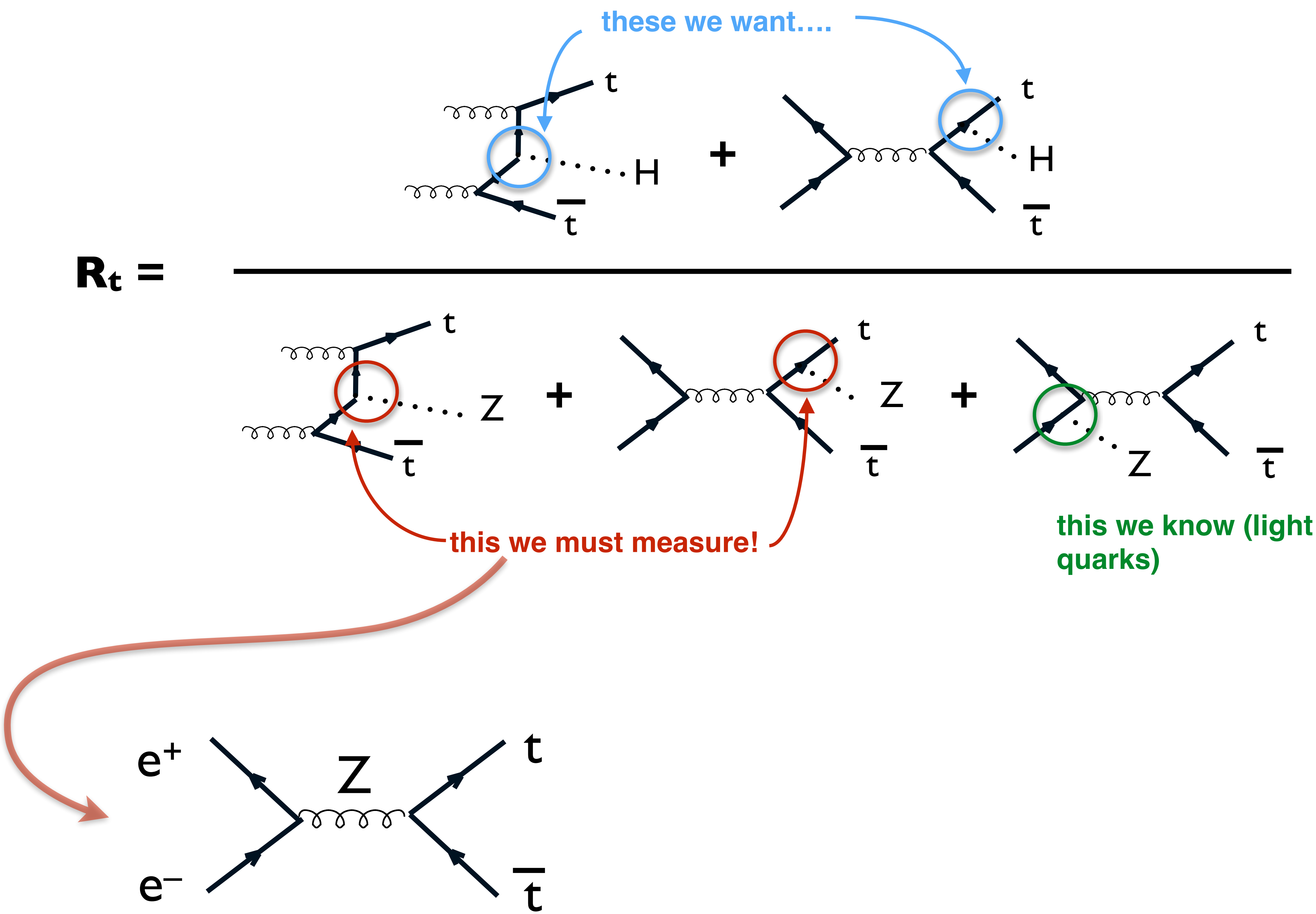

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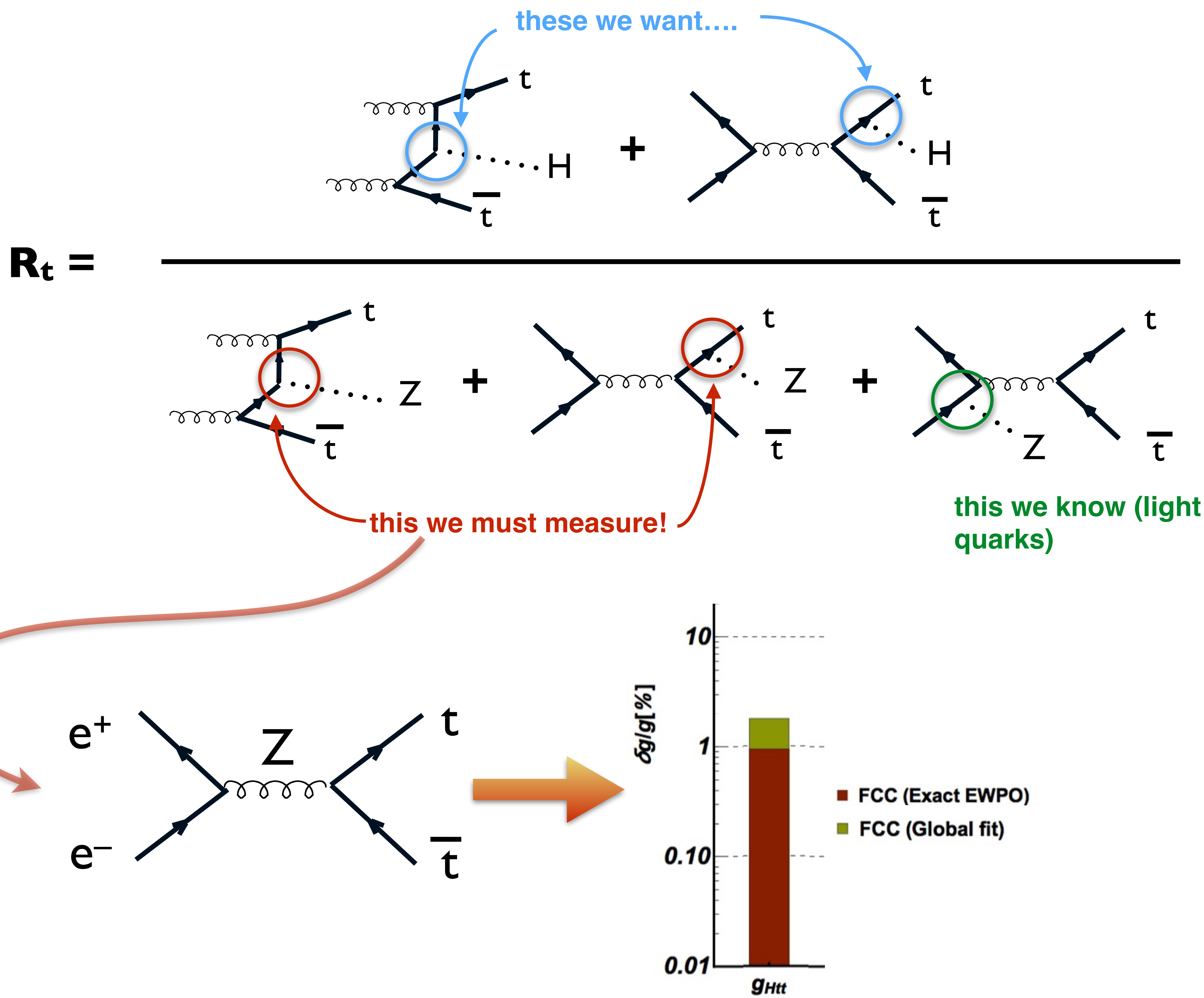

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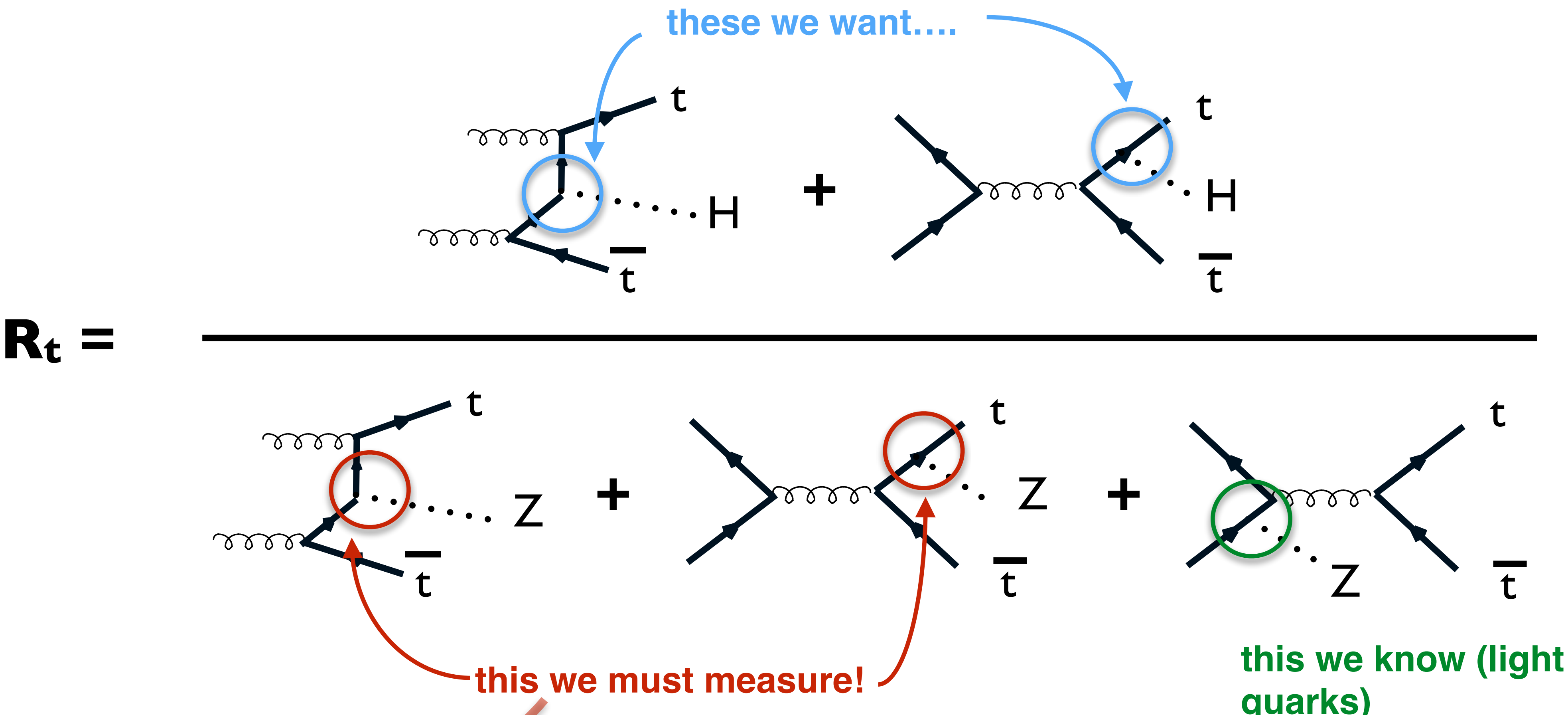
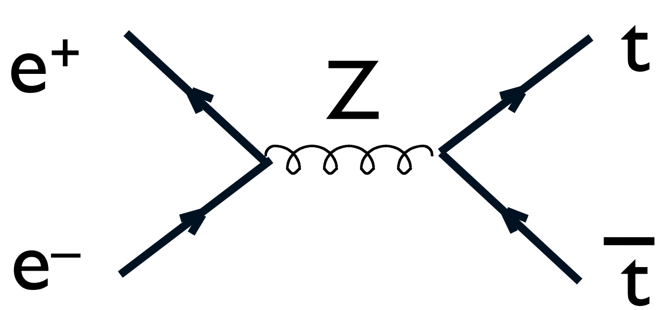
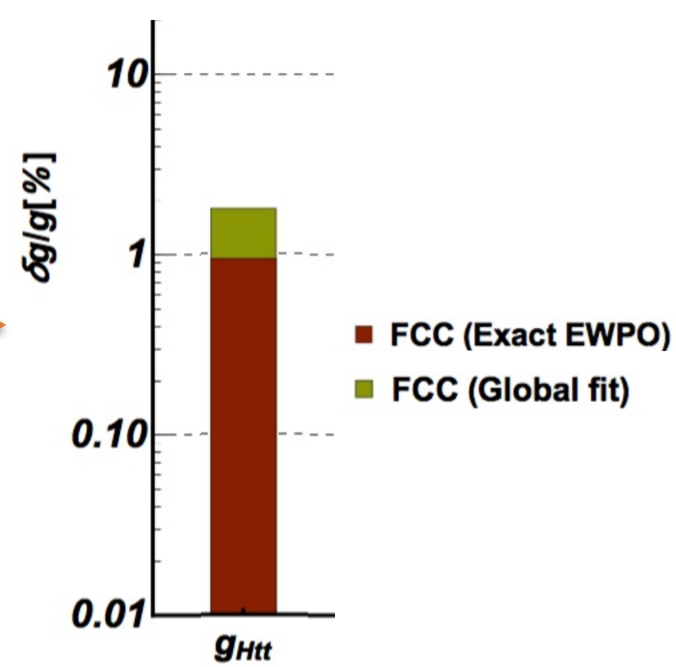






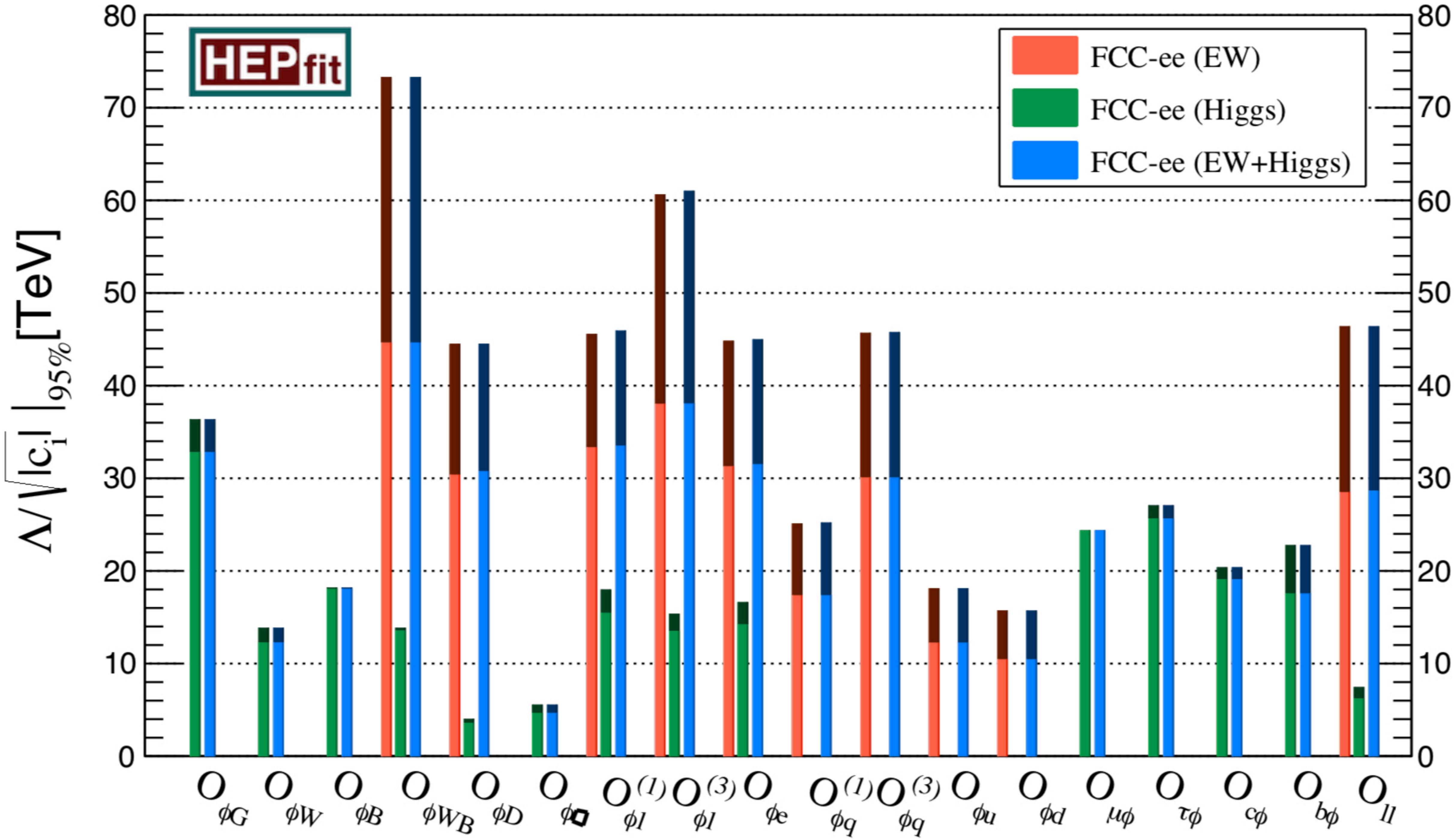
δλ/λ=5% from gg→HH assuming SM inputs

δλ/λ ~ 10% from global fit

EW parameters @ FCC-ee

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700±2200	5	100
Γ_Z (keV)	2495200±2300	8	100
R_l^Z ($\times10^3$)	20767±25	0.06	0.2-1.0
α_s (m_Z) ($\times10^4$)	1196±30	0.1	0.4-1.6
R_b ($\times10^6$)	216290±660	0.3	<60
σ^0_{had} ($\times10^3$) (nb)	41541±37	0.1	4
N_ν ($\times10^3$)	2991±7	0.005	1
$\sin^2\theta_W^{eff}$ ($\times10^6$)	231480±160	3	2-5
$1/\alpha_{QED}(m_Z)$ ($\times10^3$)	128952±14	4	Small
$A_{FB}^{b,0}$ ($\times10^4$)	992±16	0.02	1-3
$A_{FB}^{pol,\tau}$ ($\times10^4$)	1498±49	0.15	<2
m_W (MeV)	80350±15	0.6	0.3
Γ_W (MeV)	2085±42	1.5	0.3
α_s (m_W) ($\times10^4$)	1170±420	3	Small
N_ν($\times10^3$)	2920±50	0.8	Small
m_{top} (MeV)	172740±500	20	Small
Γ_{top} (MeV)	1410±190	40	Small
$\lambda_{top}/\lambda_{top}^{SM}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 – 1.5%	Small

Global EFT fits to EW and H observables at FCC-ee



Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

Remarks and key messages

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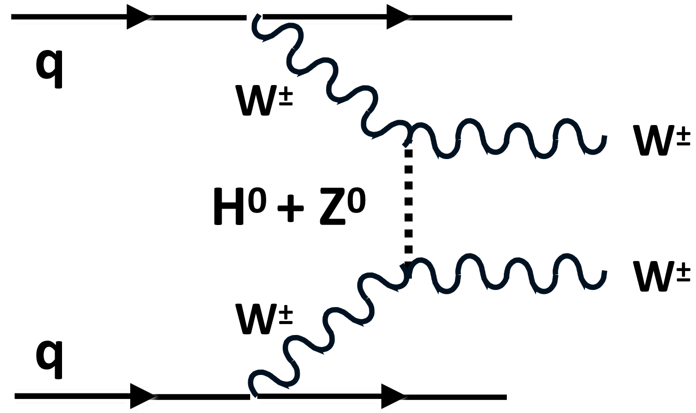
- EW&Higgs precision measurements at future ee colliders could probe scales as large as several 10's of TeV ($c_i \sim 1 \div 4\pi$)

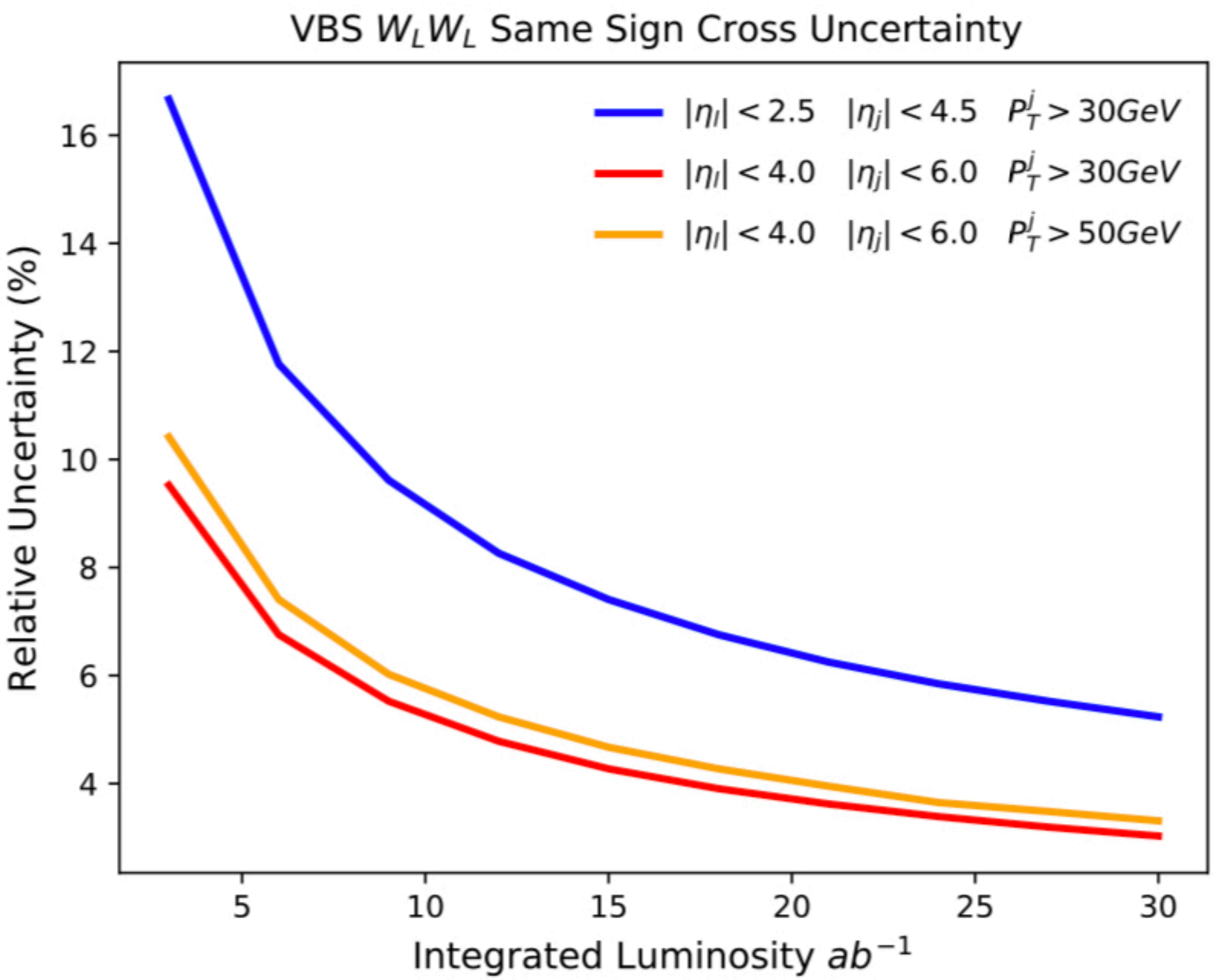
2. To directly explore the origin of possible discrepancies, requires collisions in the several 10s of TeV region

High energy probes of EW dynamics

$W_L W_L$ scattering



large m_{WW}



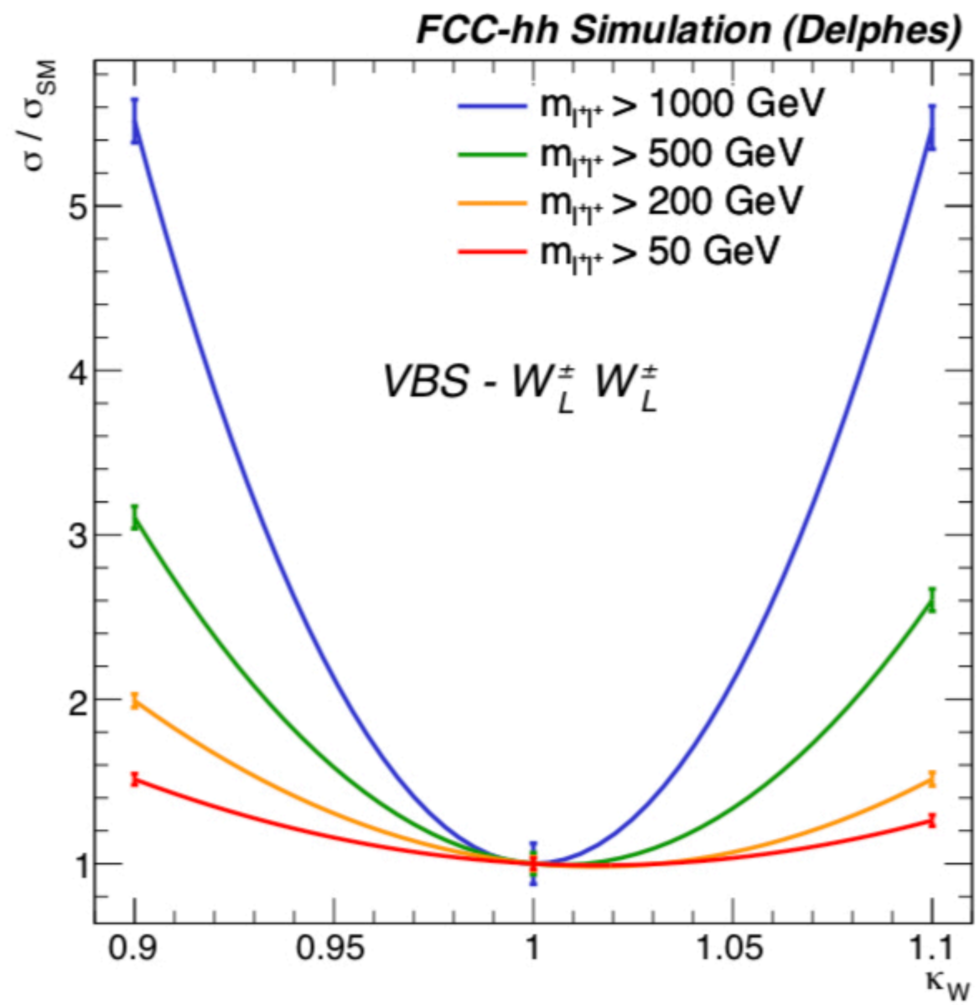
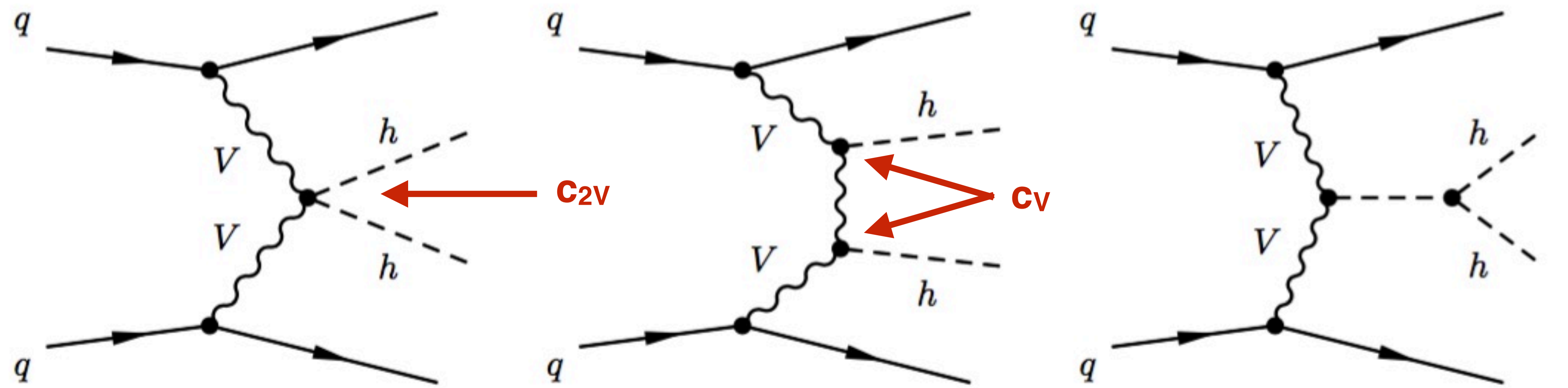


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass

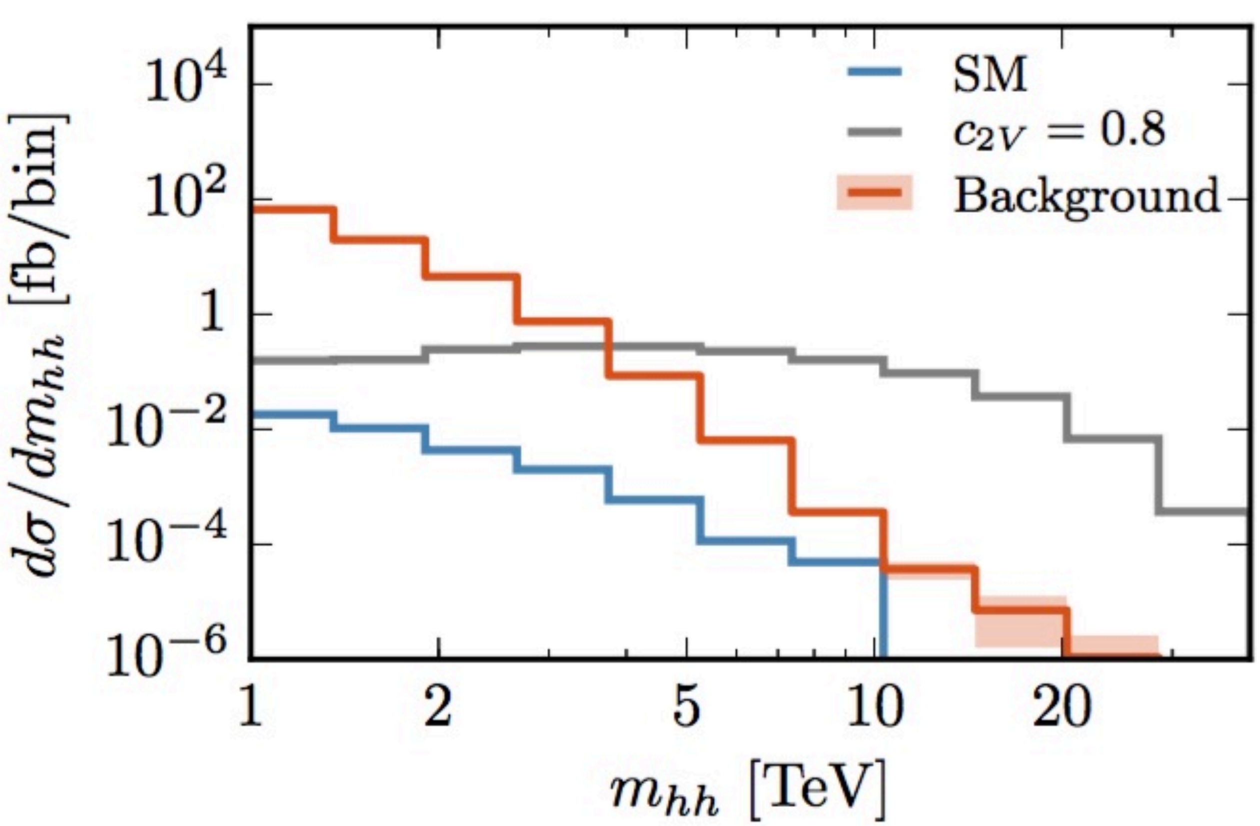
$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

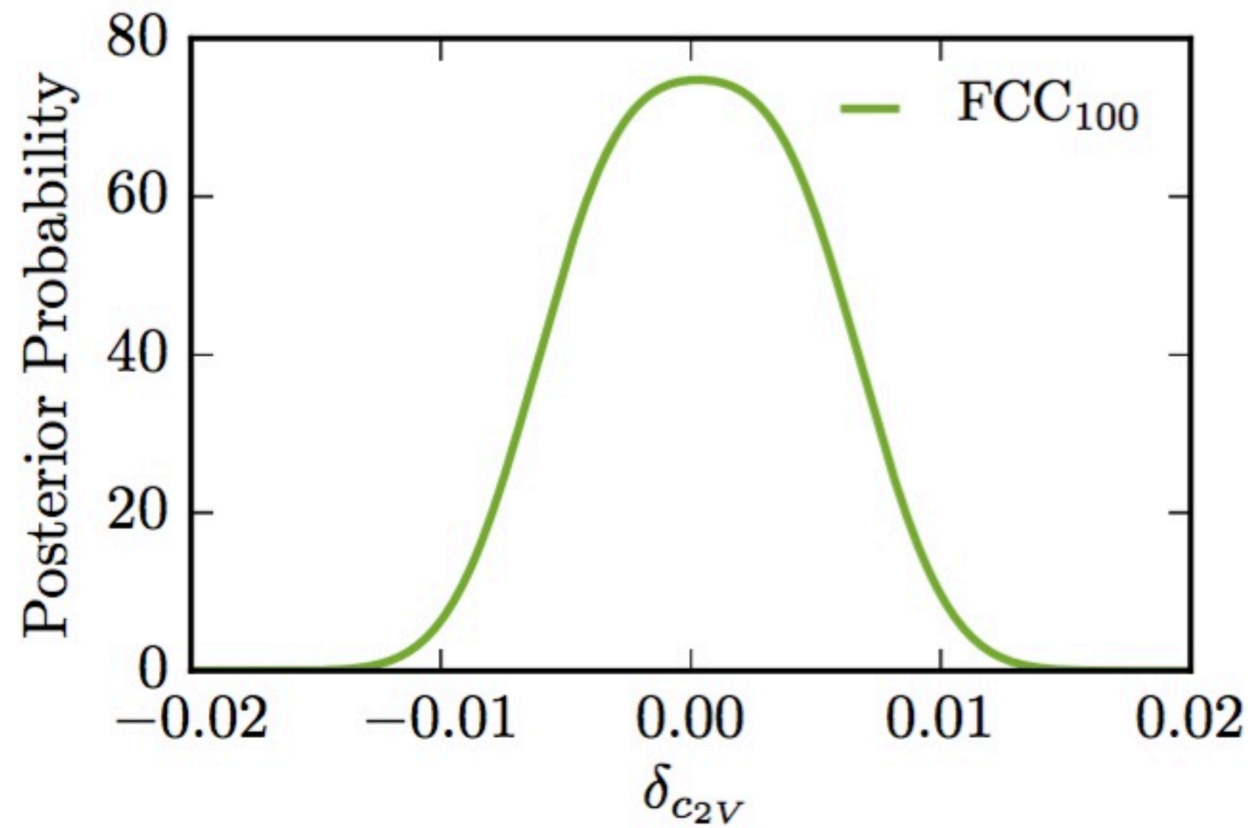
$$\kappa_W = \frac{g_{HWW}}{g_{HWW}^{SM}}$$

Example: high mass VV → HH

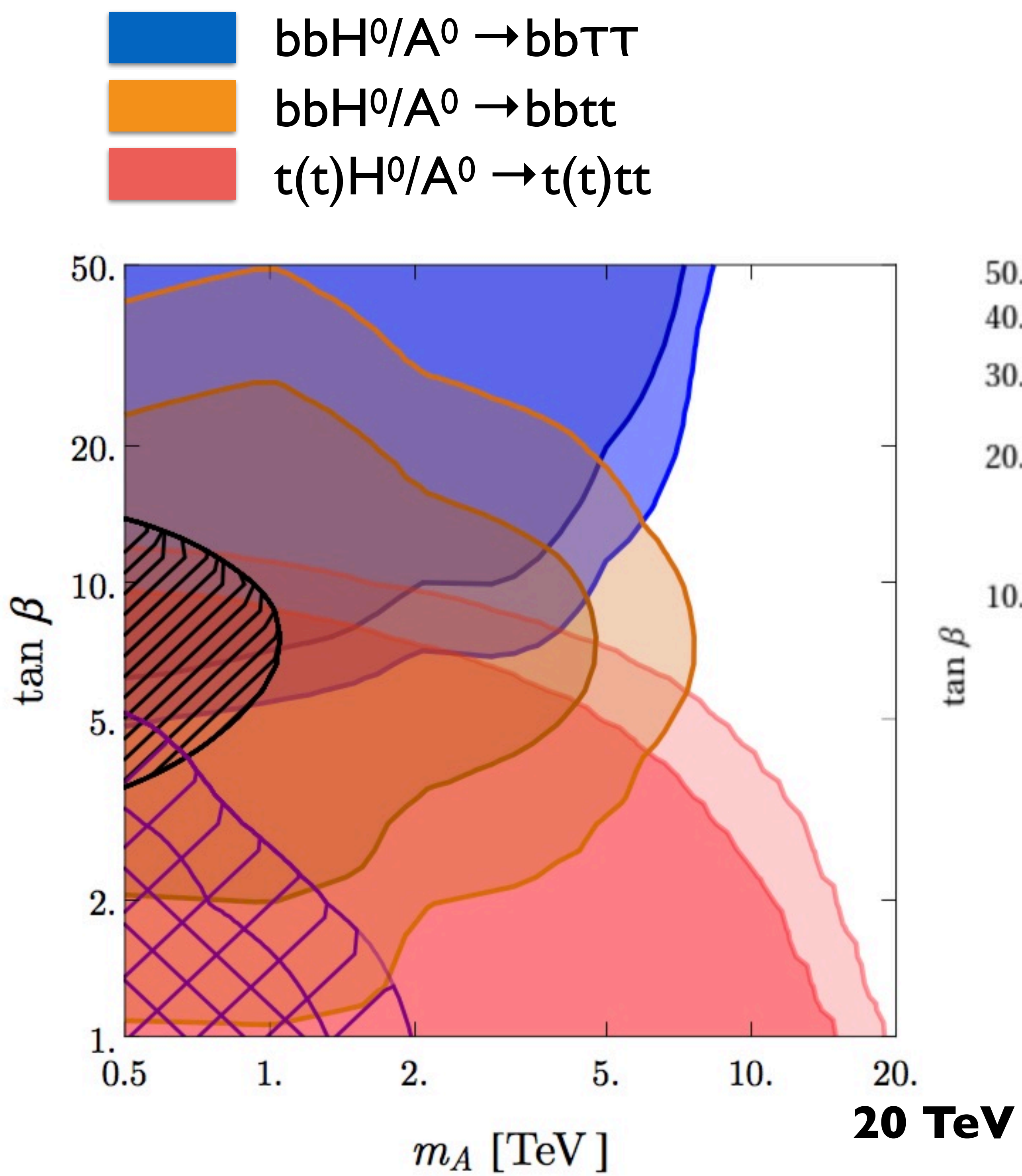


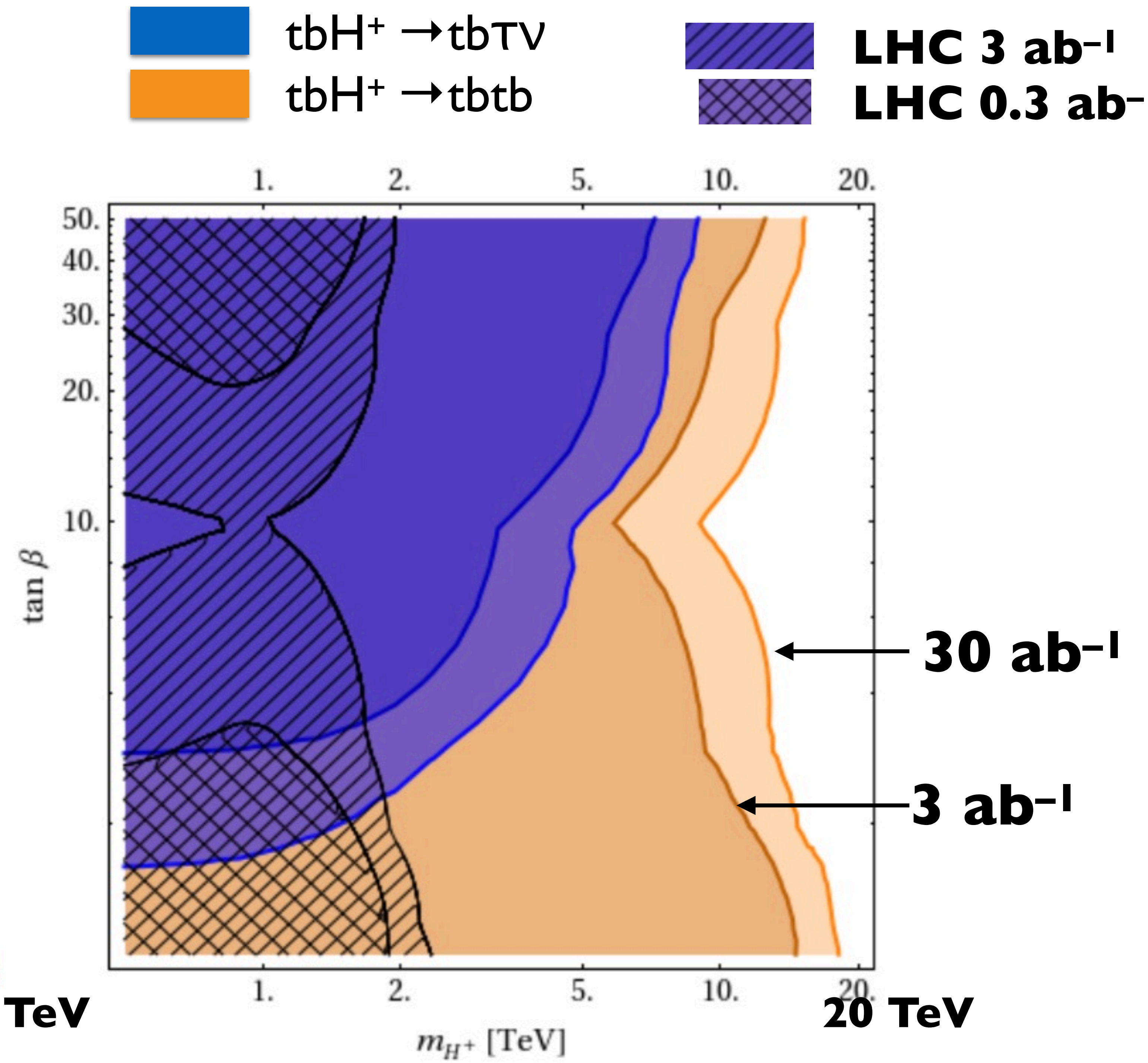
$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) \cdot$$ **where** $$\begin{cases} c_V = g_{HVV}/g_{HVV}^{SM} \\ c_{2V} = g_{HHVV}/g_{HHVV}^{SM} \end{cases} \Rightarrow \left(c_{2V} - c_V^2\right)_{SM} = 0$$





MSSM Higgs @ 100 TeV





N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

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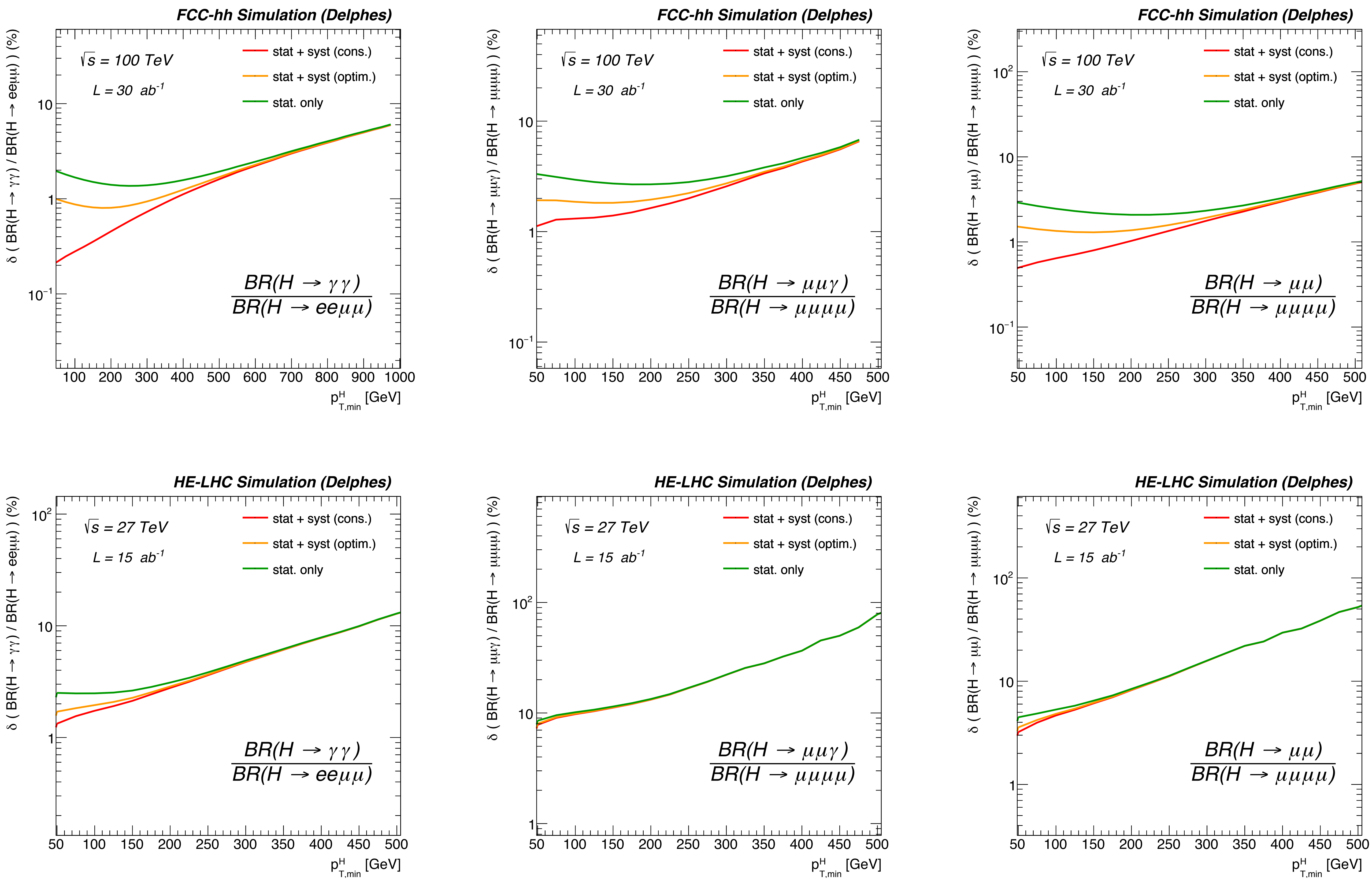
  - … from the direct search for the microscopic origin of deviations in precise measurements of Higgs/EW properties, to deeper probes of flavour phenomena
- In this perspective, the combination of a circular e^+e^- collider in the range 90-365 GeV, and its follow-up 100 TeV pp collider, appears like a uniquely powerful future facility !

Additional material

Higgs @ pp colliders of different energies

	$gg \to H$	VBF	WH	ZH	ttH	HH
σ(37.5 TeV) (pb)	230	19	5	3	5.8	0.26
27/14	2.7	2.7	2.3	2.4	4.8	3.8
37.5/14	4.2	4.4	3.3	3.5	9.5	7.0
100/14	15	16	10	13	53	34
37.5/27	1.6	1.6	1.5	1.5	2.0	1.8
100/37.5	3.6	3.6	3.0	3.7	5.6	4.9

100 vs 27 TeV


FCC-hh Simulation (Delphes)
√s = 100 TeV
L = 30 ab^-1
stat + syst (cons.)
stat + syst (optim.)
stat. only
BR(H → γγ) / BR(H → eeμμ)
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
p^H_T,min [GeV]
BR(H → μμγ) / BR(H → μμμμ)
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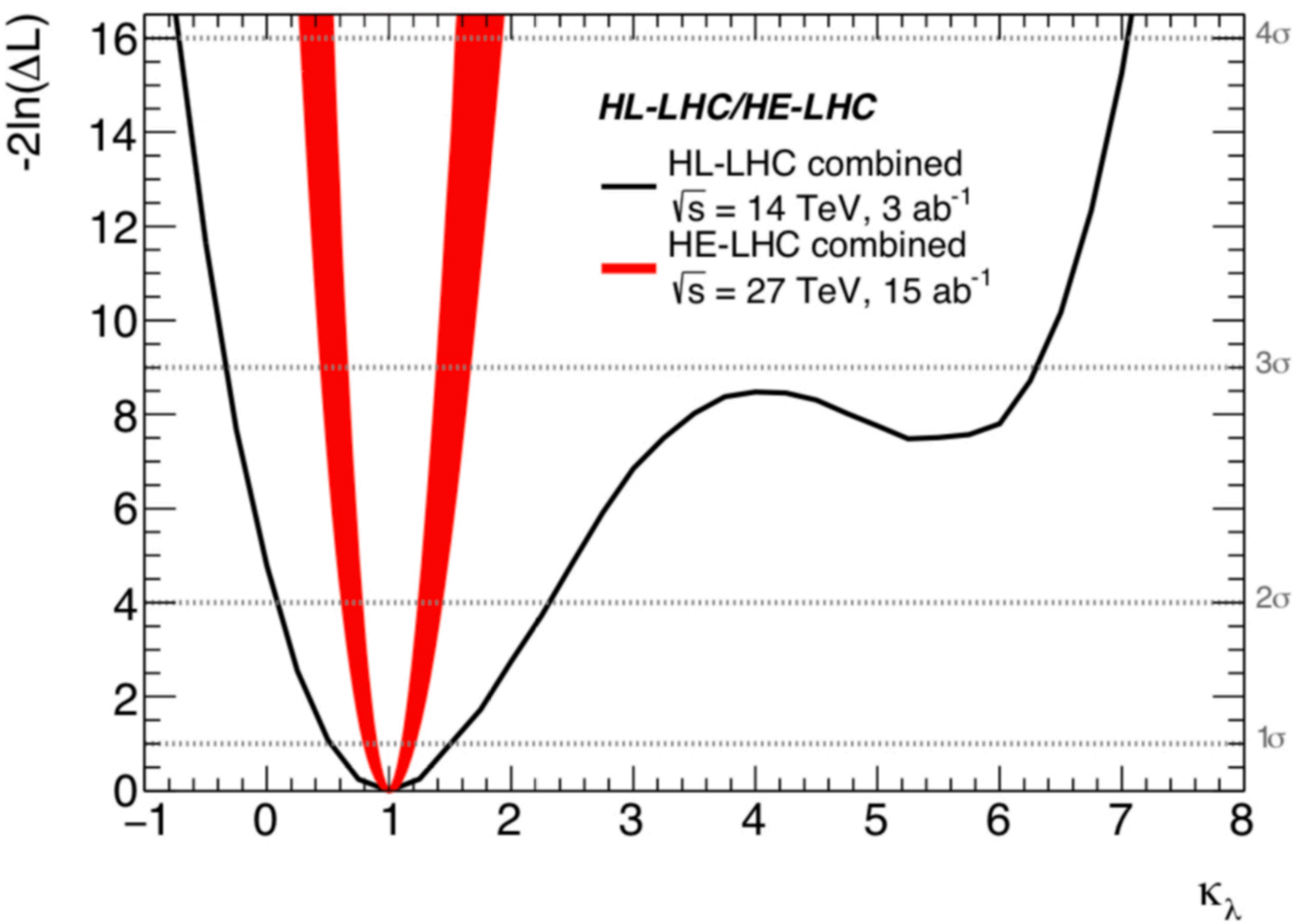
HE-LHC Simulation (Delphes)
√s = 27 TeV
L = 15 ab^-1

Higgs @ pp colliders of different energies

$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = B(H\to\gamma\gamma)/B(H\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = B(H\to\mu\mu)/B(H\to 4\mu)$	3.6%	2.9%	1.3%
$R = B(H\to\mu\mu\gamma)/B(H\to\mu\mu)$	8.4%	6%	1.8%
$R = B(H\to\gamma\gamma)/B(H\to 2\mu)$	3.5 %	2.8%	1.4%



HL-LHC: λ/λ_{SM}~1±0.5 (68%CL)

HE-LHC: λ/λ_{SM}~1±0.15 (68%CL)

Higgs @ pp colliders of different energies