Higgs properties at Future Colliders

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From the Planck scale to the Electroweak scale
Planck 2021

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linear…

e^+e^- @ 250, 350, 500 GeV

TDR 2012,
decision pending

TDR: Technical Design Report

e^+e^- @ 380 GeV, 1.5 & ~3 TeV

CDR 2012+
update '16

CDR: Conceptual Design Report

… circular

HiLumi
HL-LHC PROJECT

pp @ 14 TeV, $3ab^{-1}$

✓Approved
2027-38

FCC
hh ee he

- e^+e^- @ 91, 160, 240, 365 (& possibly 125) GeV
- pp @ 100 TeV
- $e_{60GeV}\, p_{50TeV}$ @ 3.5 TeV

link to CDR

in a 100km tunnel around CERN

CEPC

- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and $e_{60GeV}\, p_{35TeV}$

link to CDR

in a 100km tunnel in China

Plan

- Will address the measurement opportunities and projections for the next generation of future colliders (ILC, CLIC, FCC), with a focus on the complementarity and synergy between ee and hh programmes

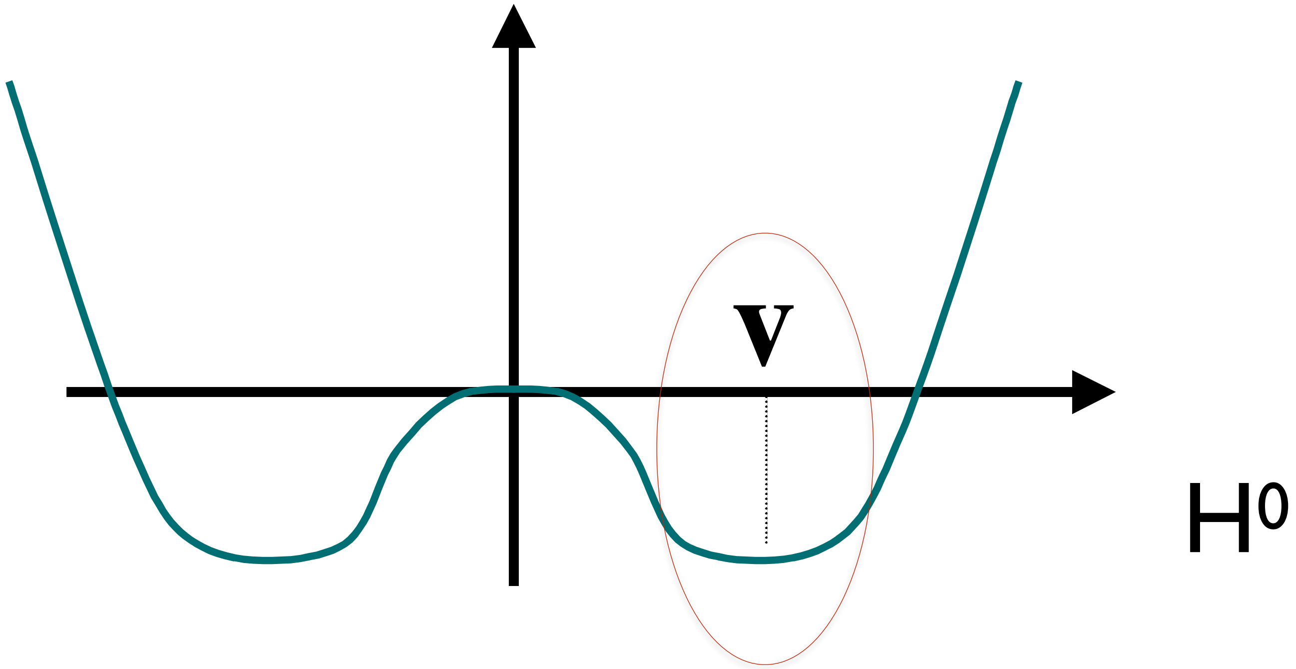
- For BSM interpretations in the context of EFT: see Ilaria’s talk

- Beyond the next generation: see Roberto’s talk

Why focus on the Higgs when discussing future colliders?

Dark matter, neutrino masses, CP violation, … they all require a broad and diverse experimental programme, since we still have no clue as to where the next hint to the solution of the puzzles they raise will come from.

But there is one question that can only be addressed by colliders, and future collider efforts must focus on its thorough exploration



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

Where does this come from?

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.

- 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 both cases 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.**

- The search for the origin of the Higgs and EW symmetry breaking is justified independently of prejudice on the relevance of theoretical puzzles like the hierarchy problem

- It is reasonable to expect that the dynamics underlying the Higgs phenomenon sits nearby the EW scale, justifying the yet unfulfilled hope that new physics should be seen by LHC…

- .. thus many theoretical ideas are emerging, postponing to much higher energies or to alternative scenarios the framework to understand the origin of the weak scale

- The detailed experimental investigation of Higgs properties remains nevertheless a sine qua non condition to make progress no matter what is our bias

Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^\pm$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do **Higgs couplings conserve flavour?** $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

➡ *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*

- The precision measurement of Higgs properties is a guaranteed deliverable of all future colliders

- Whether the measurements will challenge or confirm the SM properties, these measurements are a key ingredient in exploration of physics beyond the SM.

- Should they show deviations from the SM, the hint to BSM will be explicit, and the correlations among the various deviations will guide the interpretation of their origin

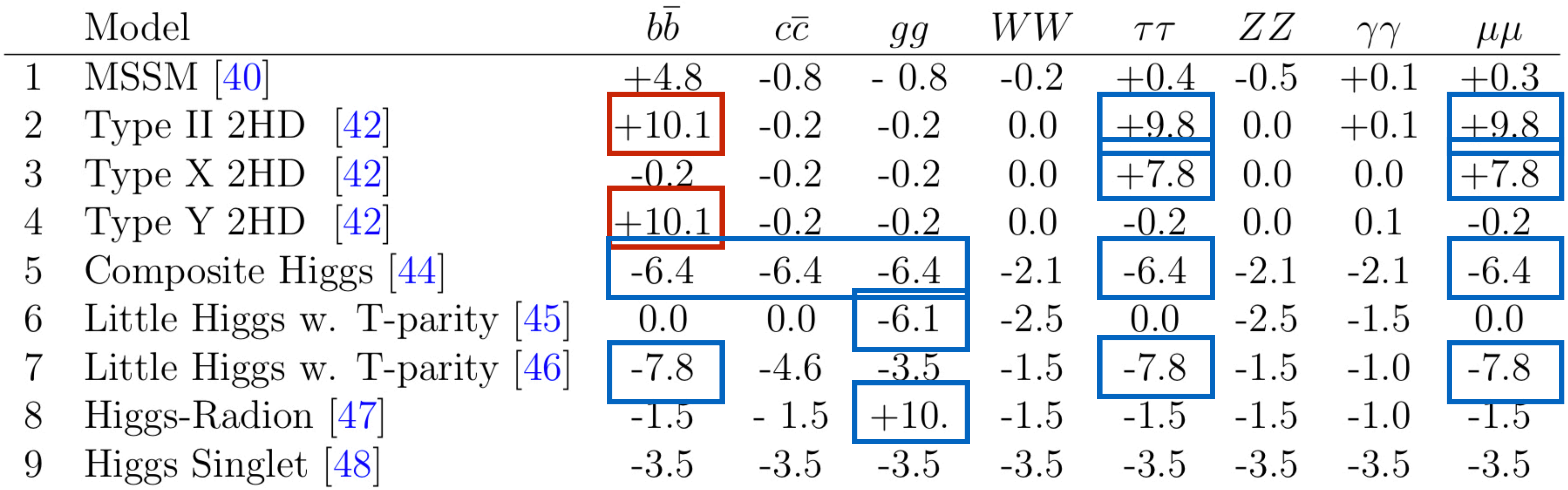
- Should they agree with the SM, the more accurate the measurements, the more constraining their power in identifying the microscopic origin of possible BSM effects observed in other parts of the programme

    - *The LEP precision measurements are still today an essential constraint in evaluating BSM models proposed whenever some anomaly is detected in the data*

What are the Higgs precision targets?

Coupling deviations for various BSM models, likely to remain unconstrained by direct searches at HL-LHC

T. Barklow et al, https://arxiv.org/pdf/1708.08912.pdf



	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

🟦 5 – 10 %

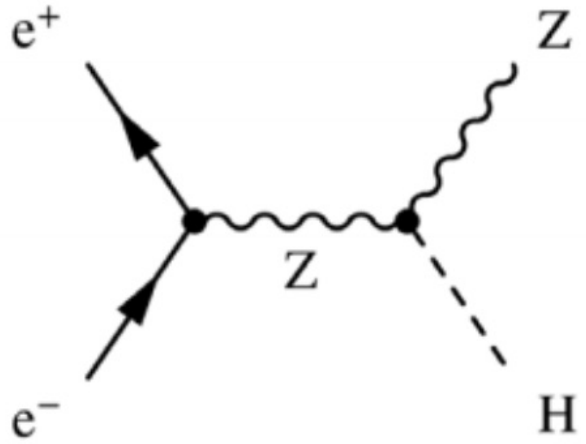
🟥 > 10%

NB: when the b coupling is modified, BR deviations are smaller than the square of the coupling deviation. Eg in model 5, the BR to b, c, tau, mu are practically SM-like

(sub)-% precision must be the goal to ensure 3-5σ evidence of deviations, and to cross-correlate coupling deviations across different channels

The absolutely unique power of $e^+e^- \to ZH$ (circular or linear):

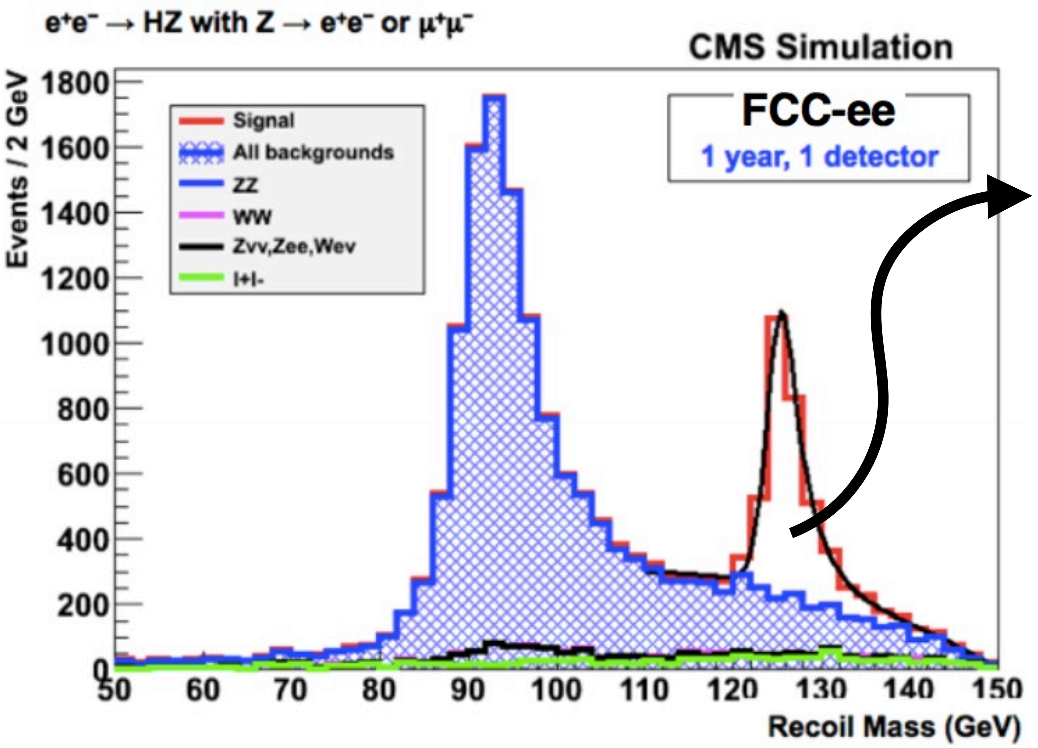
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

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

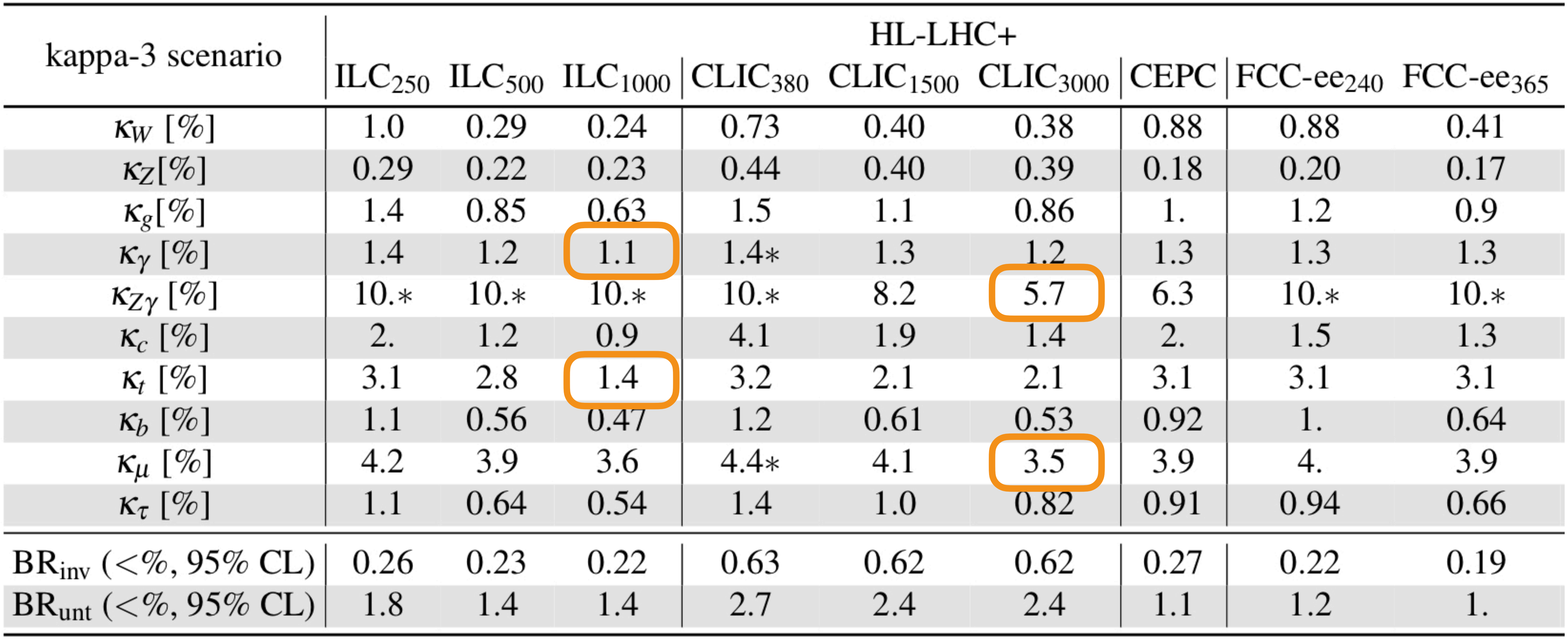
$N(ZH[\to ZZ]) \propto$
$\sigma(ZH) \times BR(H\to ZZ) \propto$
$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

$\Rightarrow$ absolute measurement of width and couplings

Higgs@FC: Higgs subgroup of the Physics Preparatory Group of the ESPP, J. De Blas et al, https://arxiv.org/abs/1905.03764

κ-3 scenario:

$\kappa_X = g_{HXX} / g^{SM}_{HXX}$
$\kappa_{XY} = g_{HXY} / g^{SM}_{HXY}$
$BR_{inv,unt}$ measured



kappa-3 scenario	HL-LHC+ ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCC\text{-}ee_{240}$	$FCC\text{-}ee_{365}$
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	0.9
κ_γ [%]	1.4	1.2	1.1	1.4∗	1.3	1.2	1.3	1.3	1.3
$\kappa_{Z\gamma}$ [%]	10.∗	10.∗	10.∗	10.∗	8.2	5.7	6.3	10.∗	10.∗
κ_c [%]	2.	1.2	0.9	4.1	1.9	1.4	2.	1.5	1.3
κ_t [%]	3.1	2.8	1.4	3.2	2.1	2.1	3.1	3.1	3.1
κ_b [%]	1.1	0.56	0.47	1.2	0.61	0.53	0.92	1.	0.64
κ_μ [%]	4.2	3.9	3.6	4.4∗	4.1	3.5	3.9	4.	3.9
κ_τ [%]	1.1	0.64	0.54	1.4	1.0	0.82	0.91	0.94	0.66
BR_{inv} (<%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19
BR_{unt} (<%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.

NB Even the runs at the highest energies do not allow ee colliders to break the % goal for several Higgs couplings

The absolutely unique power of pp → H+X:

- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ≲5% measurement of the Higgs trilinear selfcoupling

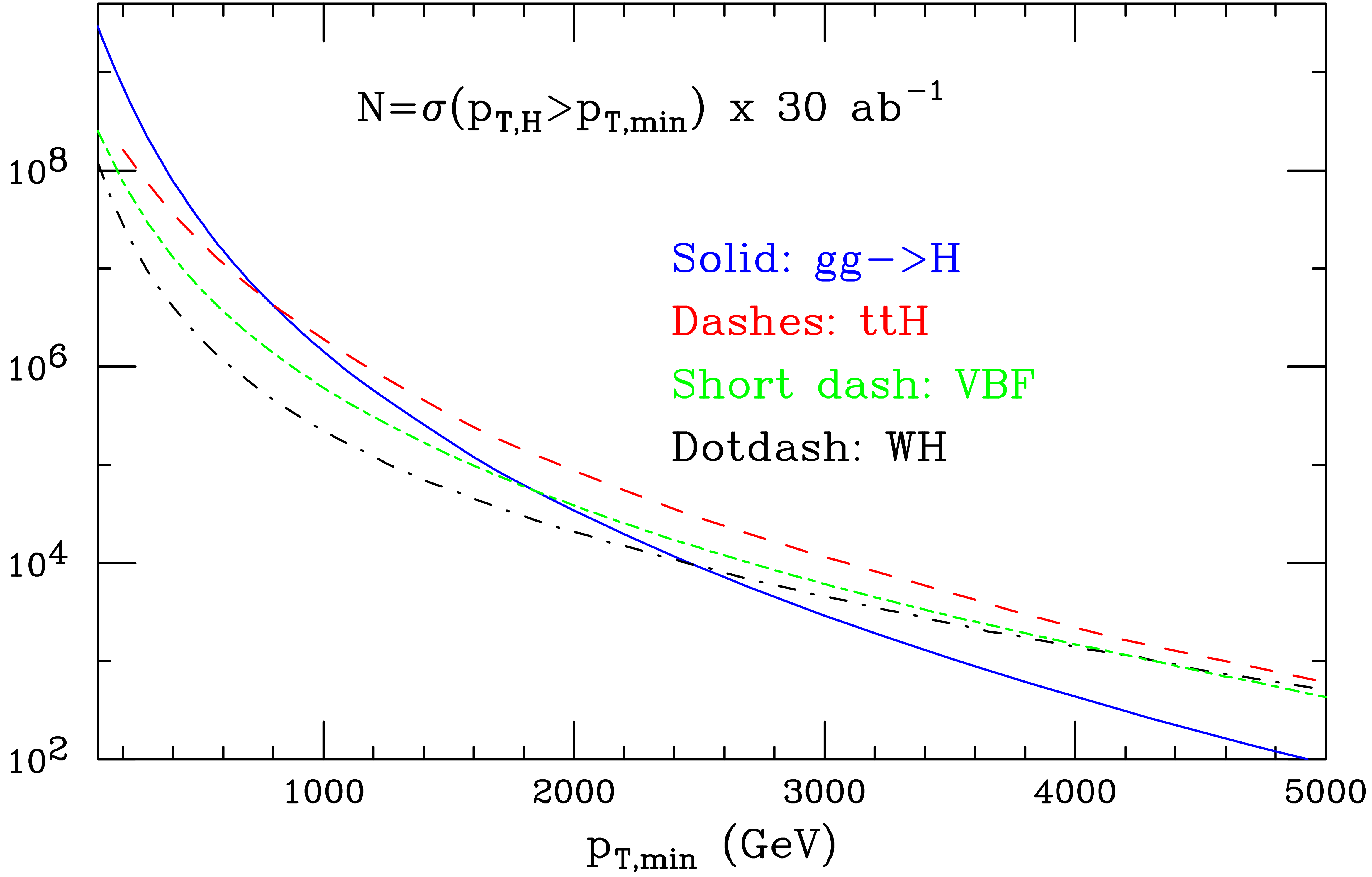
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4 EFT operators up to scales of several TeV
  - search for multi-TeV resonances decaying to H, or extensions of the Higgs sector

	gg→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

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

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

H at large p_T



- Hierarchy of production channels changes at large p_T(H):
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

Three kinematic regimes

- Inclusive production, $p_T > 0$:
  - largest overall rates
  - most challenging experimentally:
    - triggers, backgrounds, pile-up ⇒ low efficiency, large systematics

  ➡ det simulations challenging, likely unreliable ⇒ regime not studied so far

- $p_T \gtrsim 100$ GeV :
  - stat uncertainty ~few × 10^{-3} for $H \to 4l$, $\gamma\gamma$, …
  - improved S/B, realistic trigger thresholds, reduced pile-up effects ?

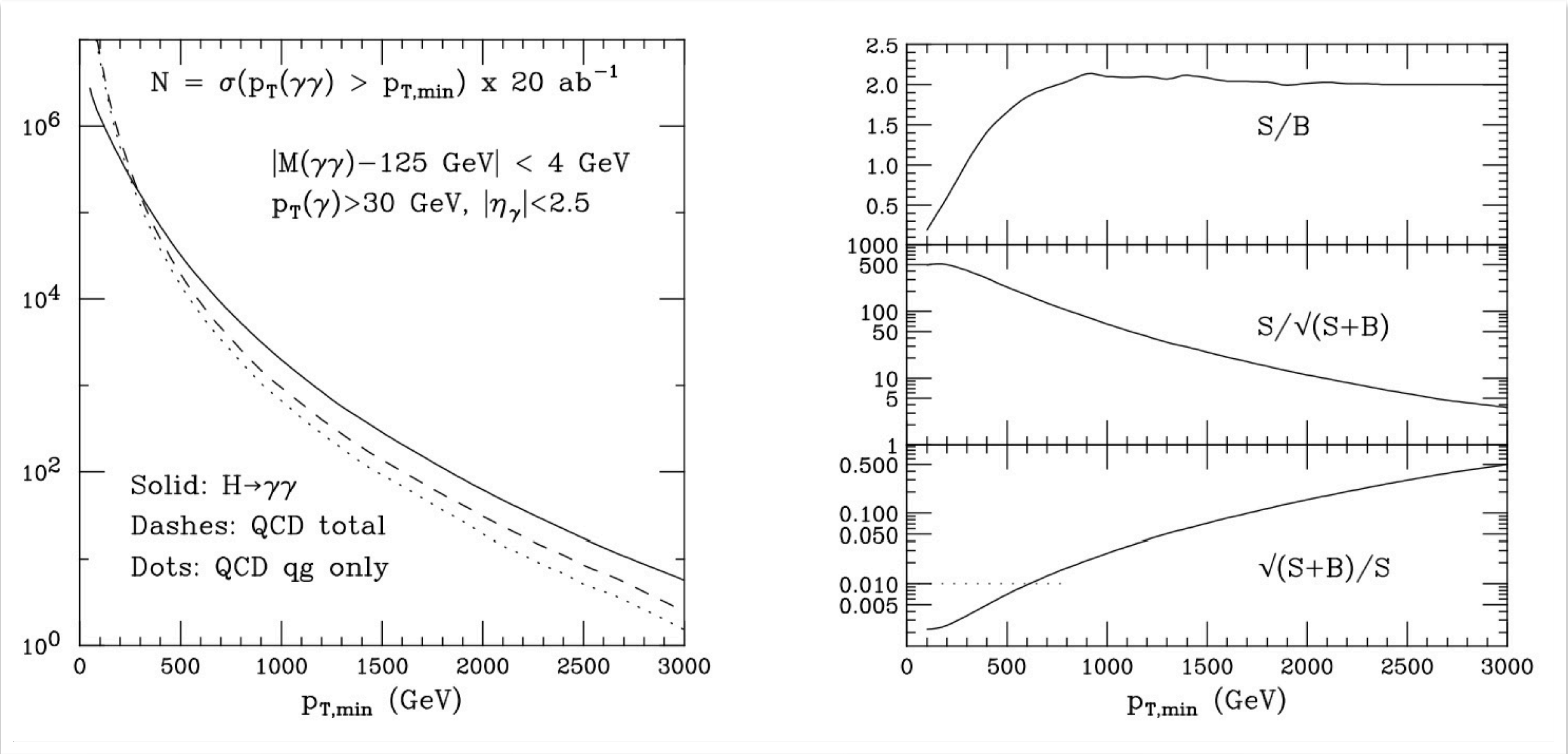
  ➡ current det sim and HL-LHC extrapolations more robust

  ➡ focus of FCC CDR Higgs studies so far

  ➡ sweet-spot for precision measurements at the sub-% level

- $p_T \gtrsim$ TeV :
  - stat uncertainty O(10%) up to 1.5 TeV (3 TeV) for $H \to 4l$, $\gamma\gamma$ ($H \to bb$)
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

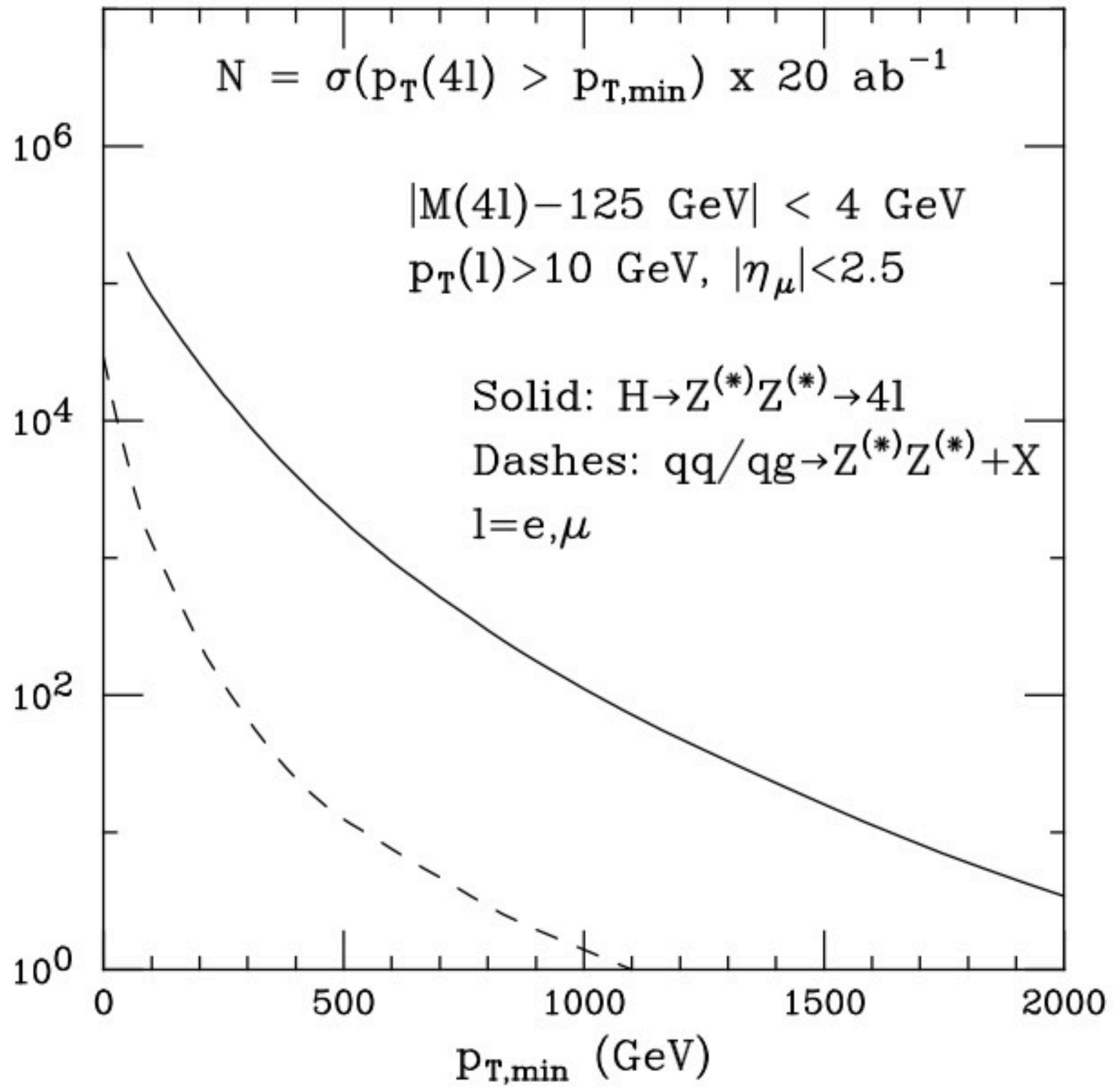
$gg \to H \to \gamma\gamma$ at large p_T

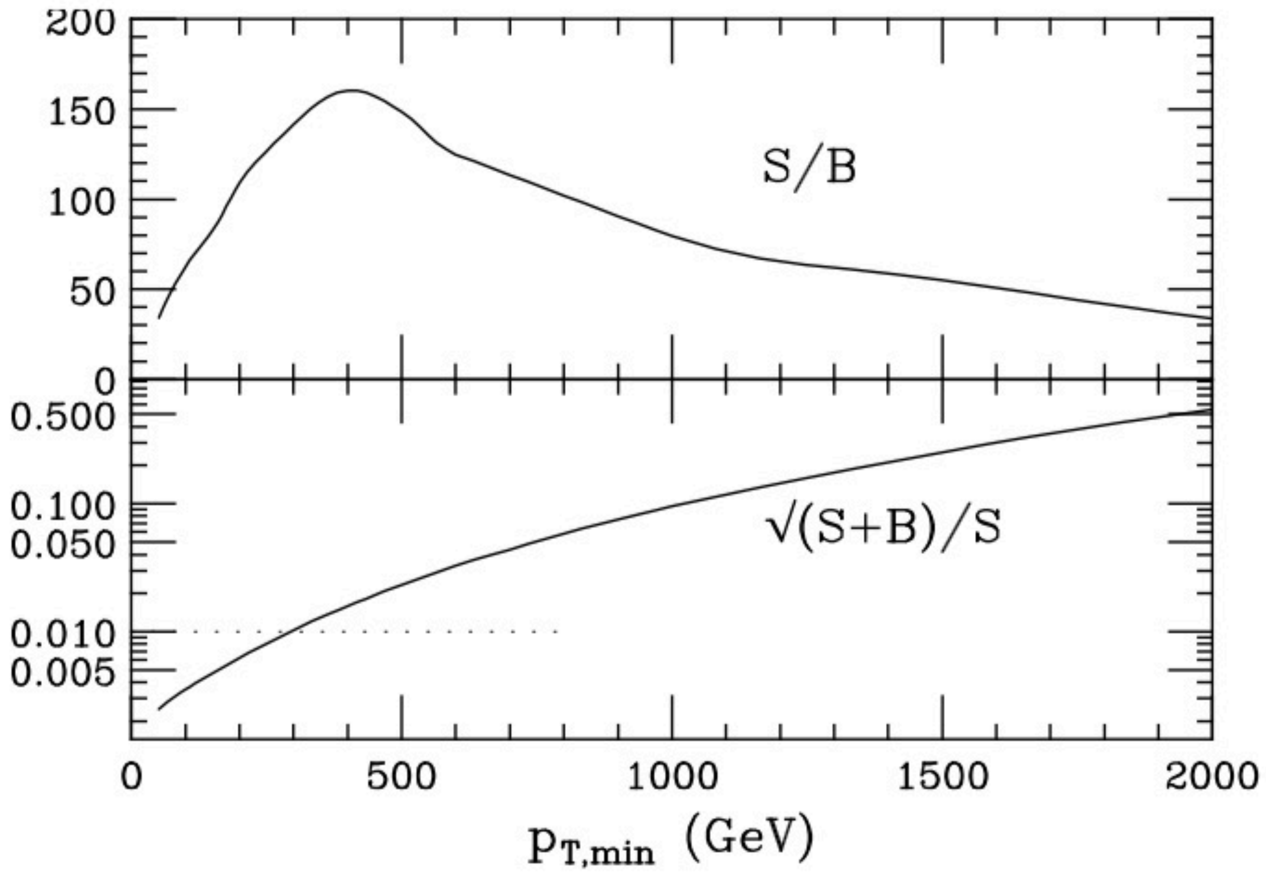


- At LHC, S/B in the $H \to \gamma\gamma$ channel is O(few %)
- At FCC, for $p_T(H) > 300$ GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

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

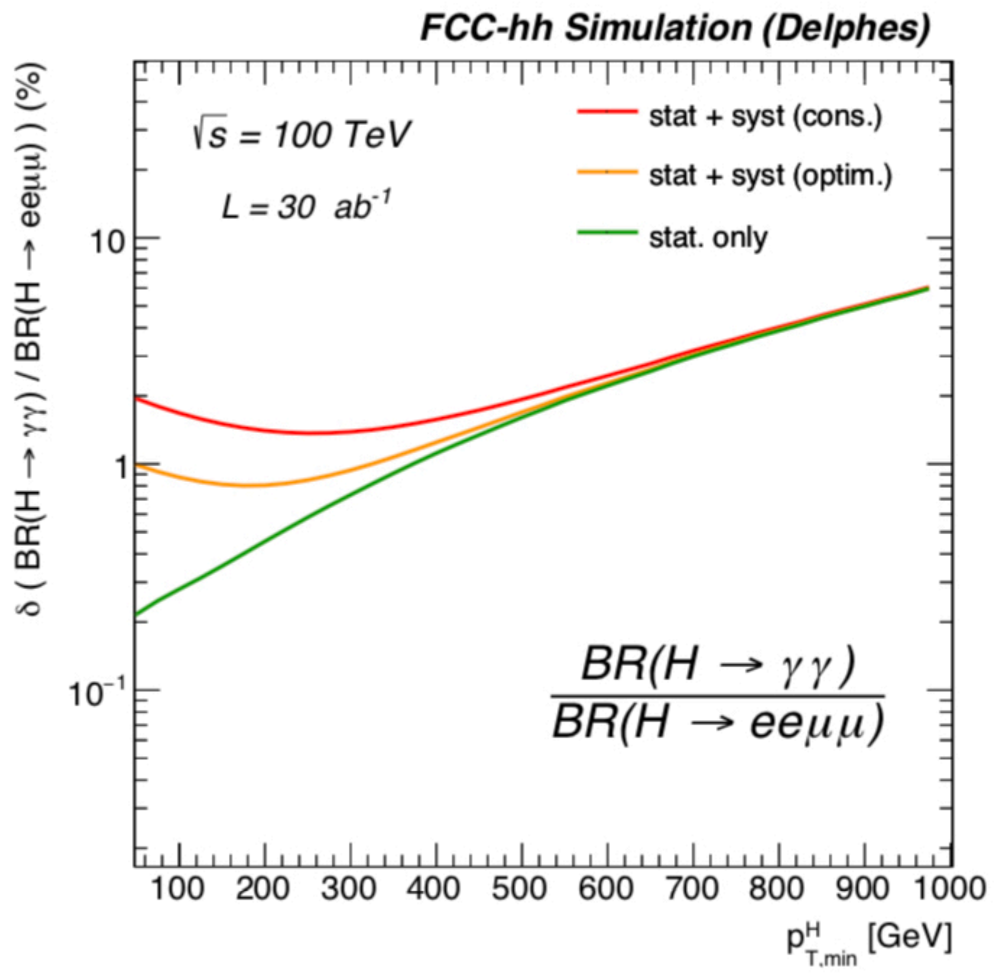
gg→H→ZZ*→4l at large p_T

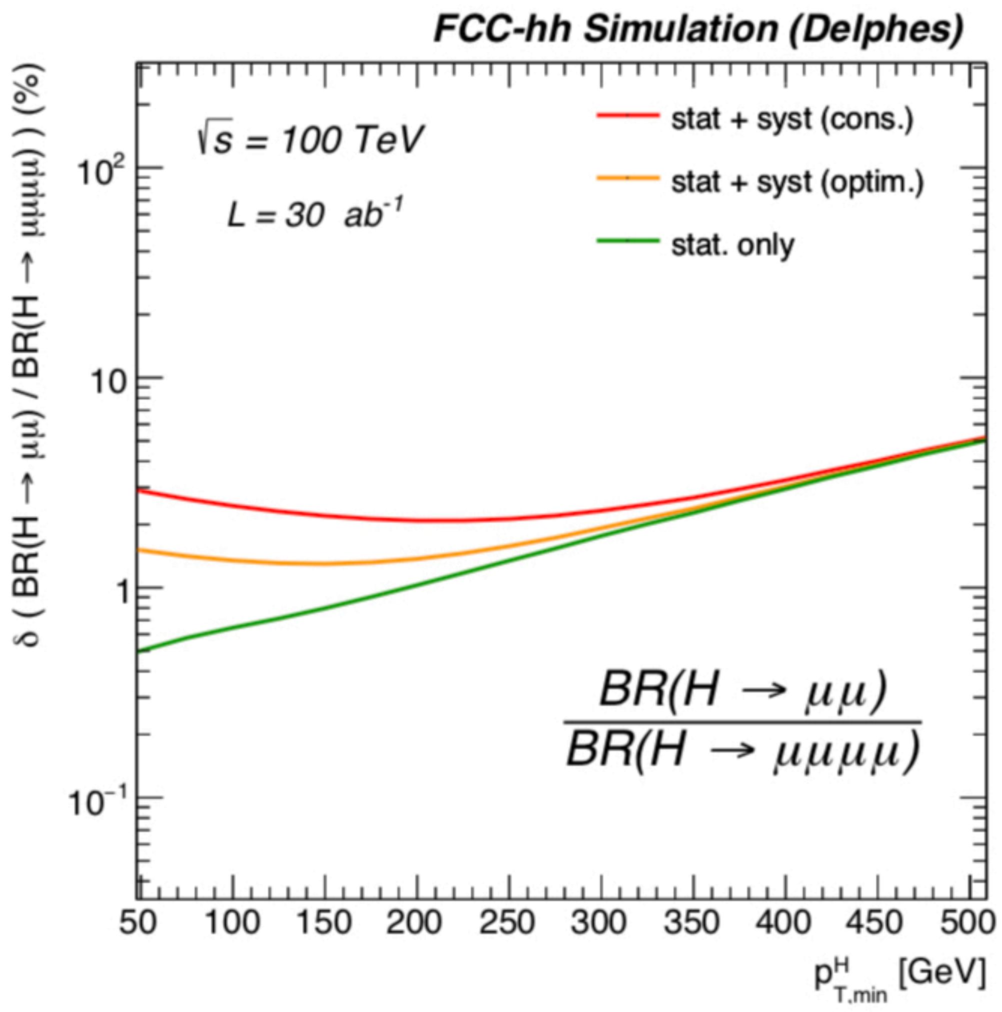


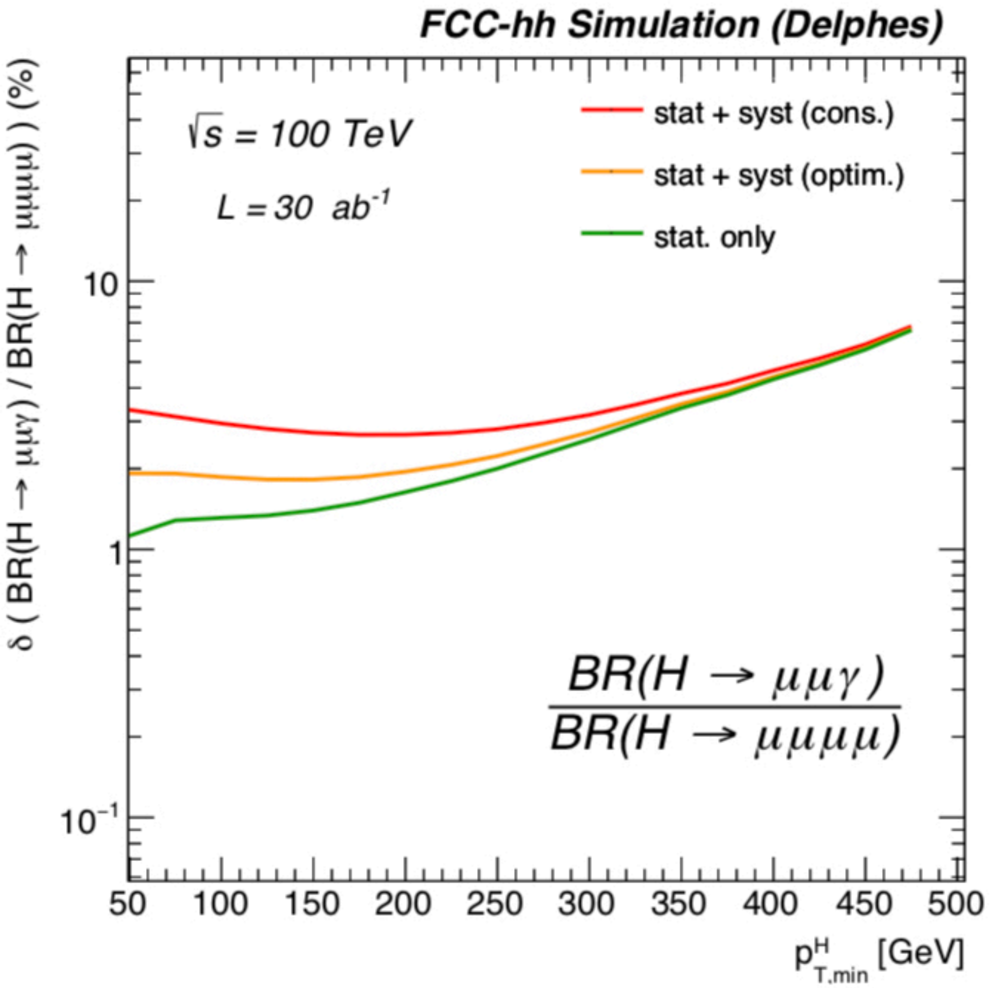


- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.3%**
300	**1%**
1000	10%





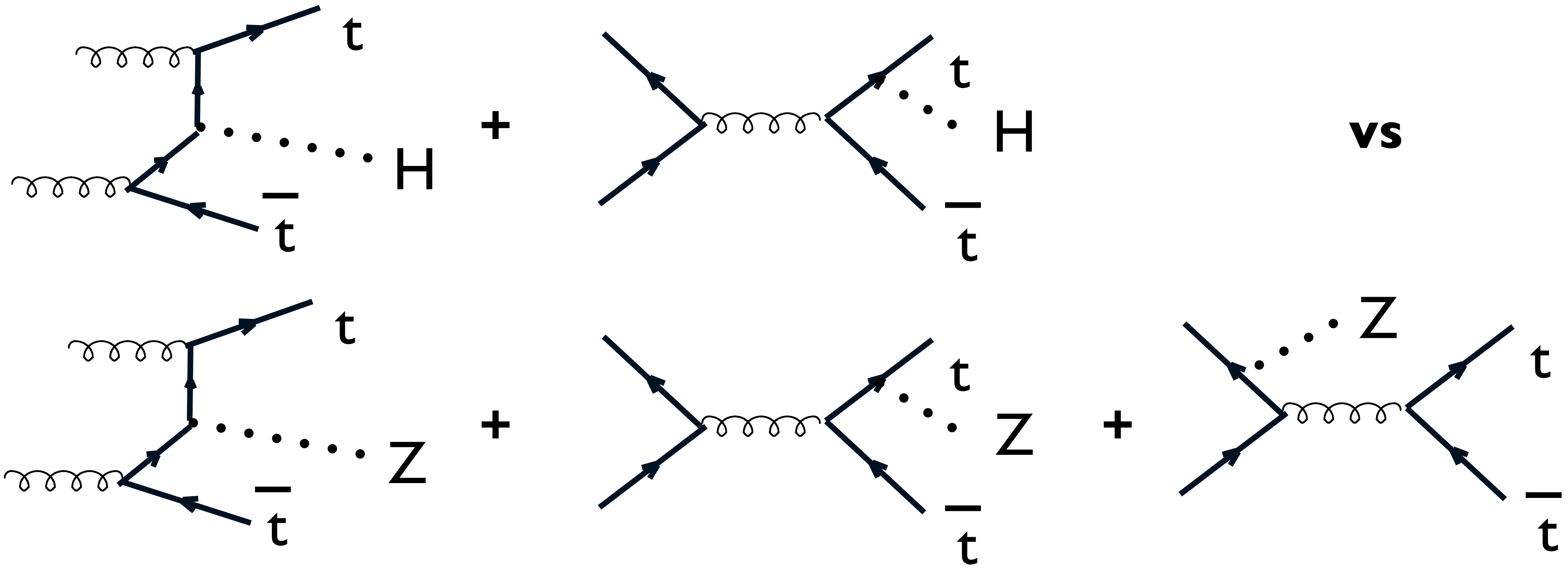


Normalize to BR(4l) from ee => sub-% precision for absolute couplings

Future work: explore in more depth data-based techniques, to validate and then reduce the systematics in these ratio measurements, possibly moving to lower pt's and higher stat

Top Yukawa coupling from σ(ttH)/σ(ttZ)

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**

  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**

  o correlated PDF systematics
  o correlated m_{top} systematics

For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

Analysis in arXiv:1507.08169 used boosted H/Z→bb decays (large stat, reduced combinatoric bg, correlated b-tagging efficiencies, …)
Reloaded with FCC-hh det sim in https://cds.cern.ch/record/2642471

- ttjj and ttbb bgs “measured” with data at mjj>200 with negligible δ_{stat} . Syst to be assessed for shape modeling under mH peak systematics
- ttZ kinematics validated with Z→leptons
- N(ttH)/N(ttZ) = 1.64 ± 0.01 (stat.) after perfect bg subtraction

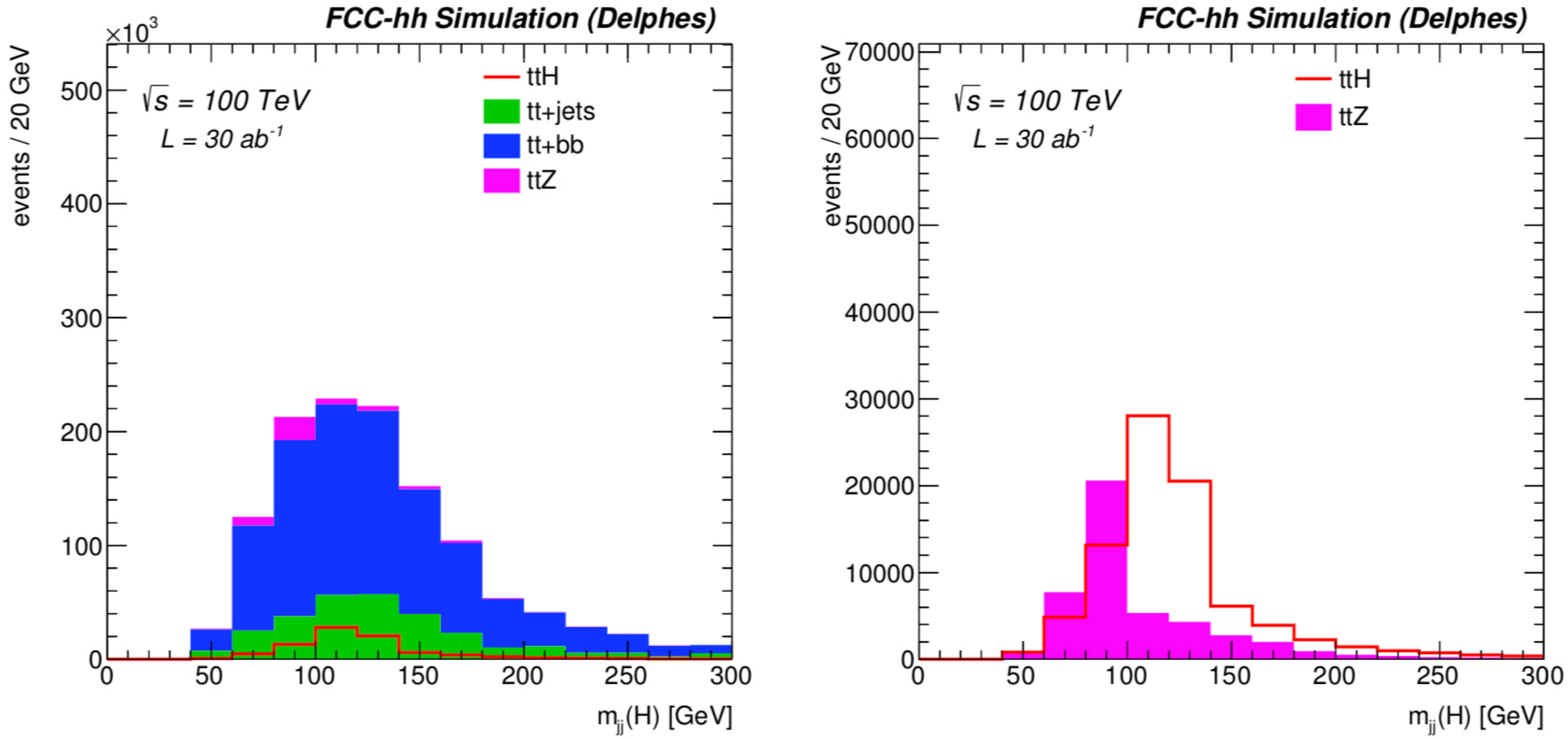
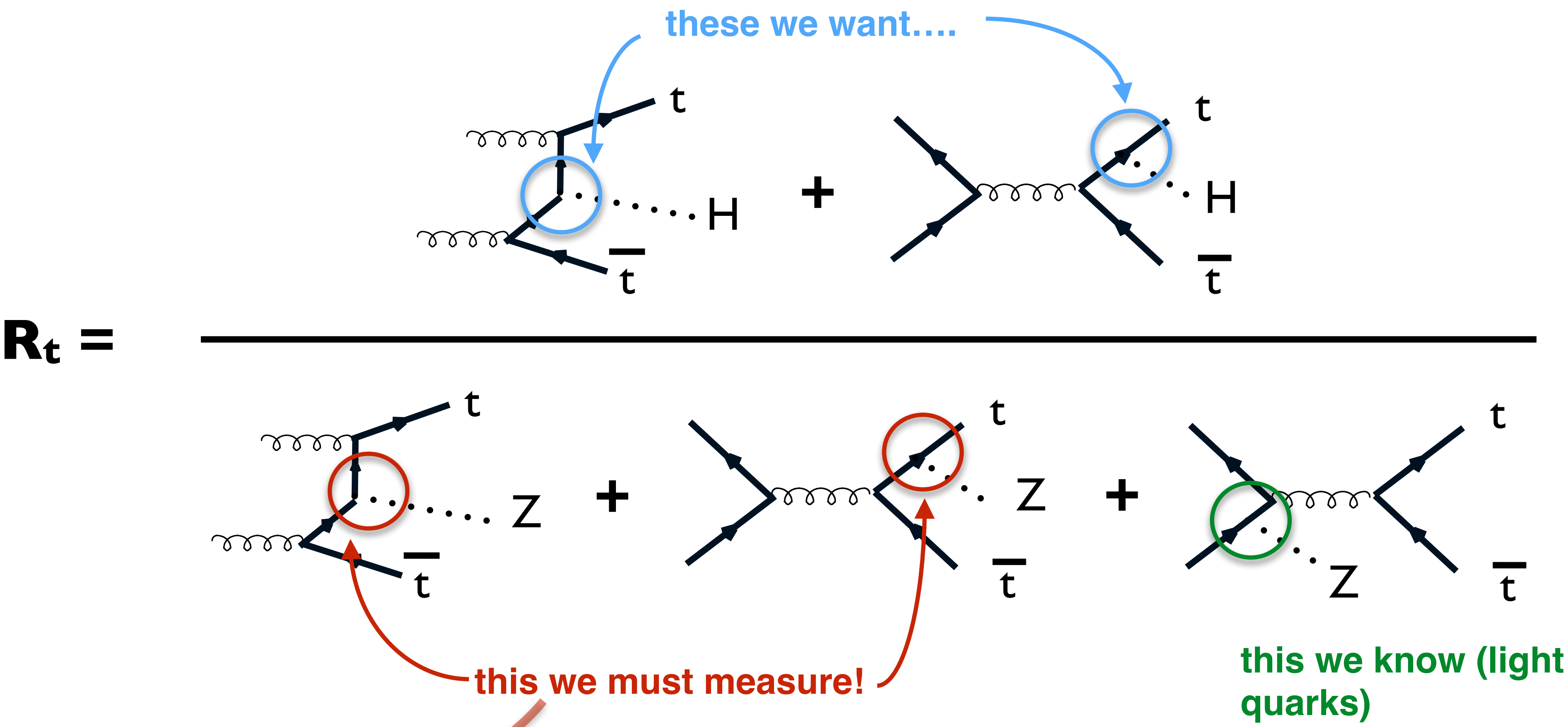


Figure 7: Invariant mass the di-jet pair forming the Higgs candidate including all backgrounds (left) and after (perfect) background subtraction as input for measuring the ttH/ttZ fraction (right).

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

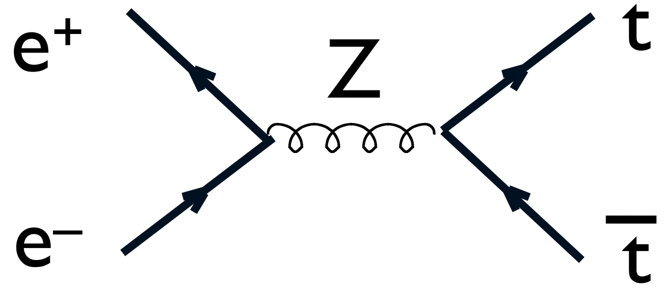
FCC-hh can measure R_t with $\Delta R_t/R_t \sim 2\%$

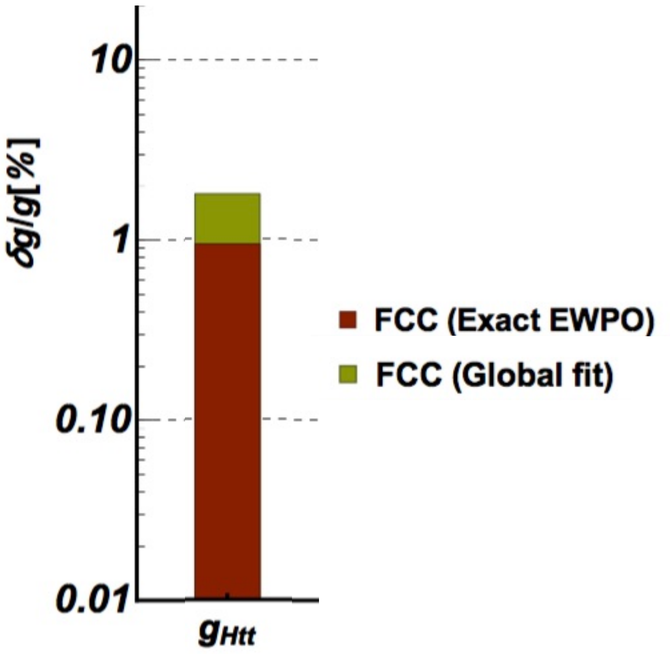


these we want....

this we must measure!

this we know (light quarks)



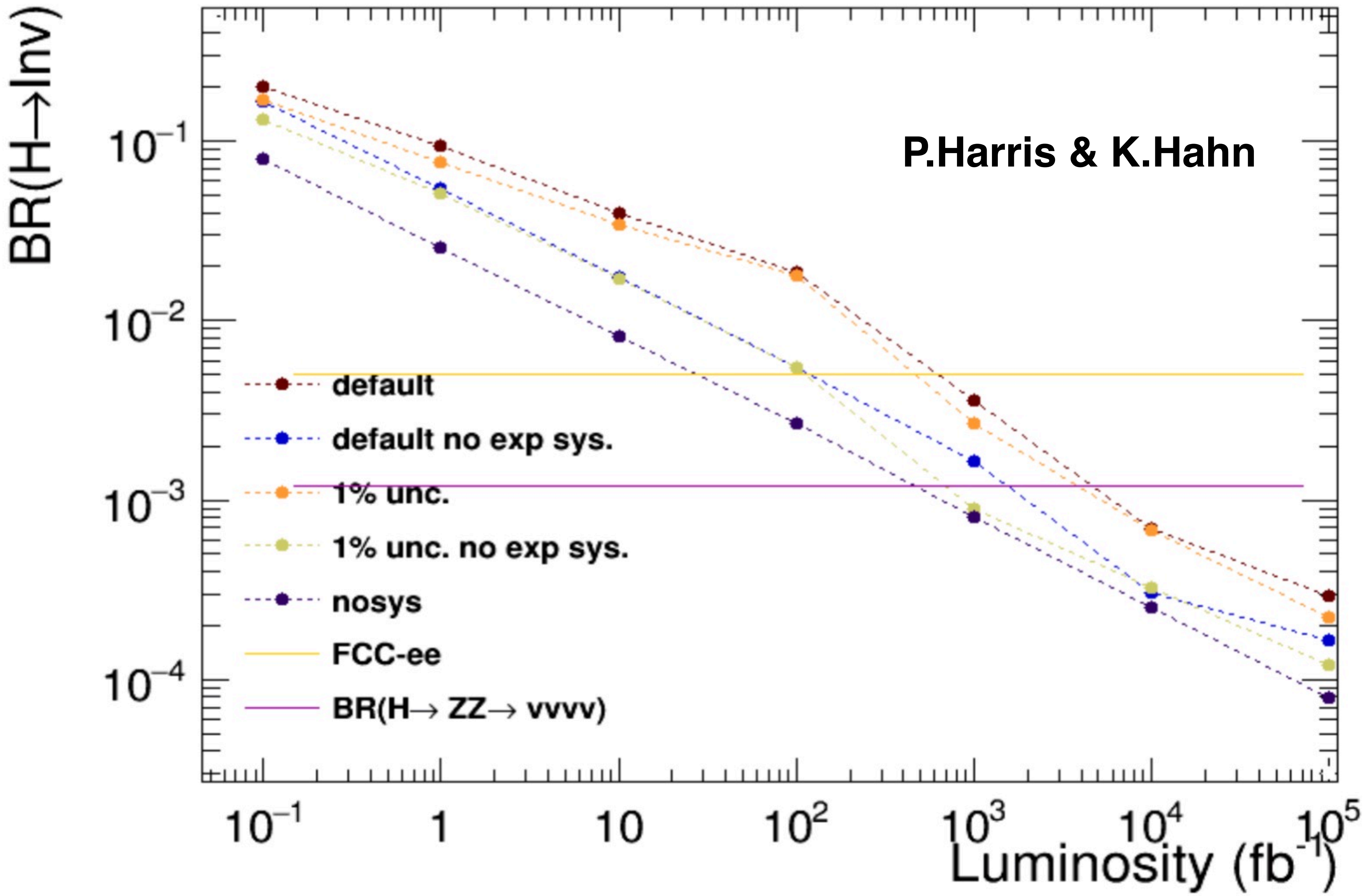


δλ/λ=5% from gg→HH assuming SM inputs

δλ/λ ~ 10% from global fit

BR(H→inv) in H+X production at large p_T(H)

Constrain bg pt spectrum from Z→νν to the % level using
NNLO QCD/EW to relate to measured Z→ee, W and γ spectra



SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

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)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

$BR(H \to Z\gamma, \gamma\gamma) \sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ evts for $\Delta_{stat} \sim \%$**

$BR(H \to \mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for $\Delta_{stat} \sim \%$**

pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

* From BR ratios wrt $B(H \to ZZ^*)$ @ FCC-ee

** From pp→ttH / pp→ttZ, using $B(H \to bb)$ and ttZ EW coupling @ FCC-ee or other ee LC

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→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

2nd gen’n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

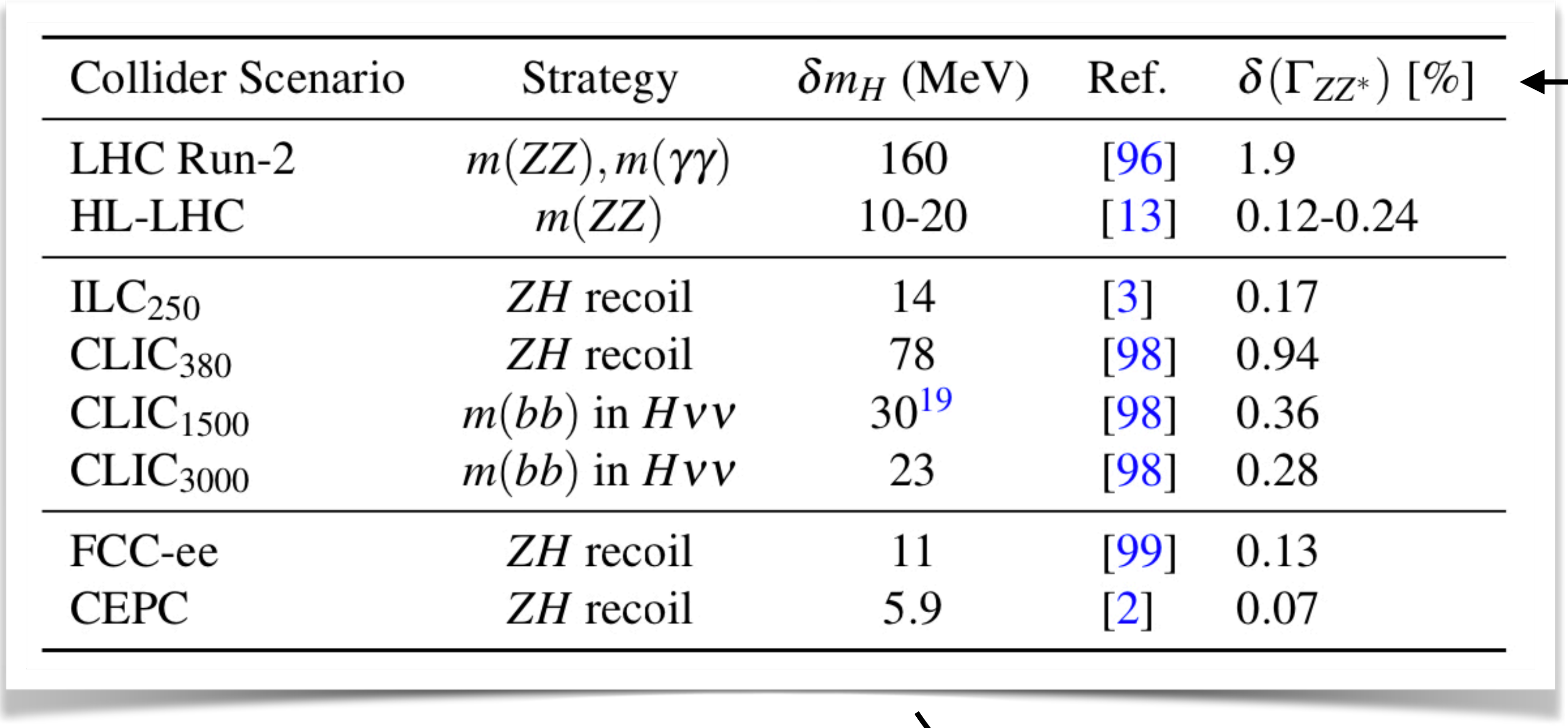
different EW charges in the loops of the two procs

BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

Mass and width

Higgs @ FC

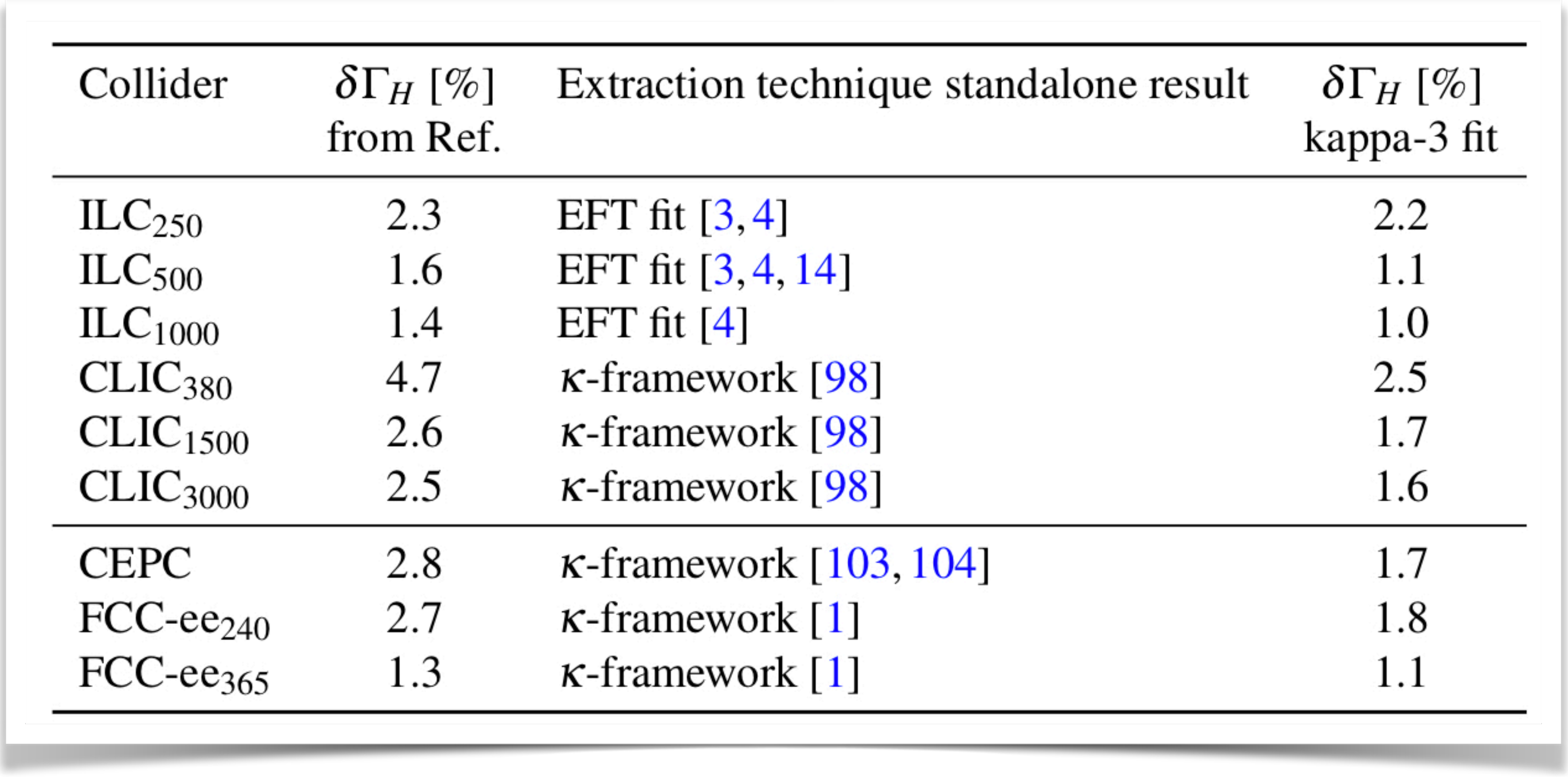


Collider Scenario	Strategy	δm_H (MeV)	Ref.	$\delta(\Gamma_{ZZ^*})$ [%]
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	[96]	1.9
HL-LHC	$m(ZZ)$	10-20	[13]	0.12-0.24
ILC$_{250}$	ZH recoil	14	[3]	0.17
CLIC$_{380}$	ZH recoil	78	[98]	0.94
CLIC$_{1500}$	$m(bb)$ in $H\nu\nu$	30[19]	[98]	0.36
CLIC$_{3000}$	$m(bb)$ in $H\nu\nu$	23	[98]	0.28
FCC-ee	ZH recoil	11	[99]	0.13
CEPC	ZH recoil	5.9	[2]	0.07

Impact of δm_H on the SM value of Γ_{ZZ^*}

Important improvements wrt these results reported in new internal preliminary analyses by the groups

Projected experimental precision on Γ_H

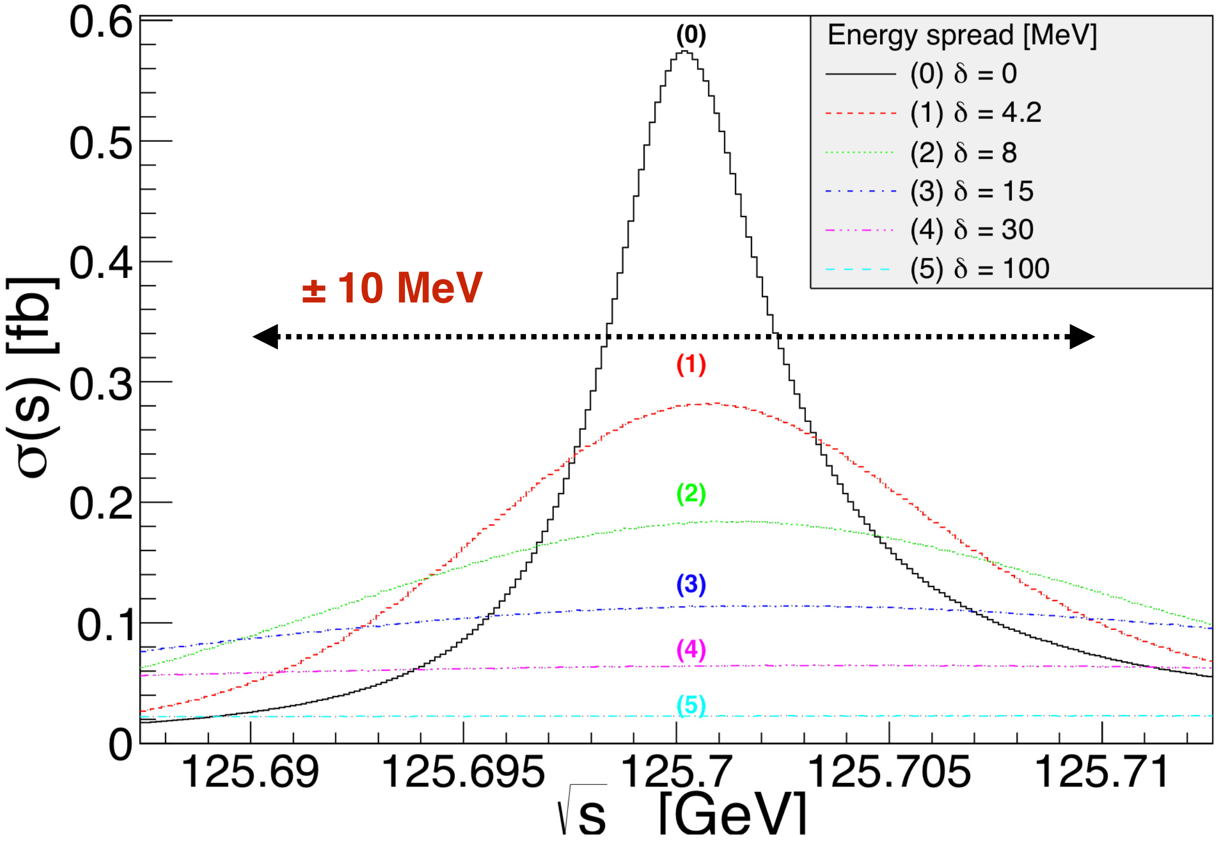


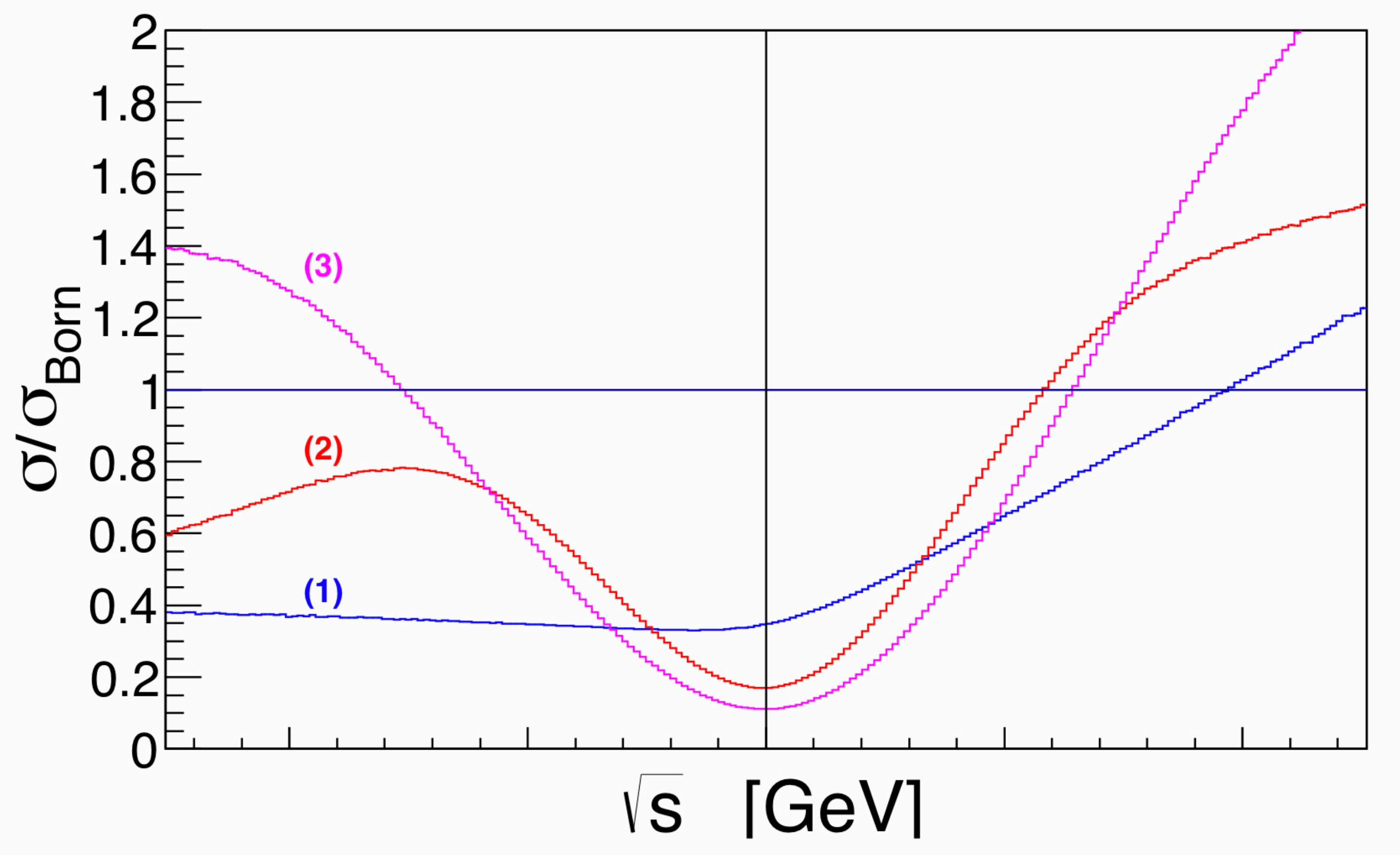
Collider	$\delta\Gamma_H$ [%] from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
ILC$_{250}$	2.3	EFT fit [3, 4]	2.2
ILC$_{500}$	1.6	EFT fit [3, 4, 14]	1.1
ILC$_{1000}$	1.4	EFT fit [4]	1.0
CLIC$_{380}$	4.7	κ-framework [98]	2.5
CLIC$_{1500}$	2.6	κ-framework [98]	1.7
CLIC$_{3000}$	2.5	κ-framework [98]	1.6
CEPC	2.8	κ-framework [103, 104]	1.7
FCC-ee$_{240}$	2.7	κ-framework [1]	1.8
FCC-ee$_{365}$	1.3	κ-framework [1]	1.1

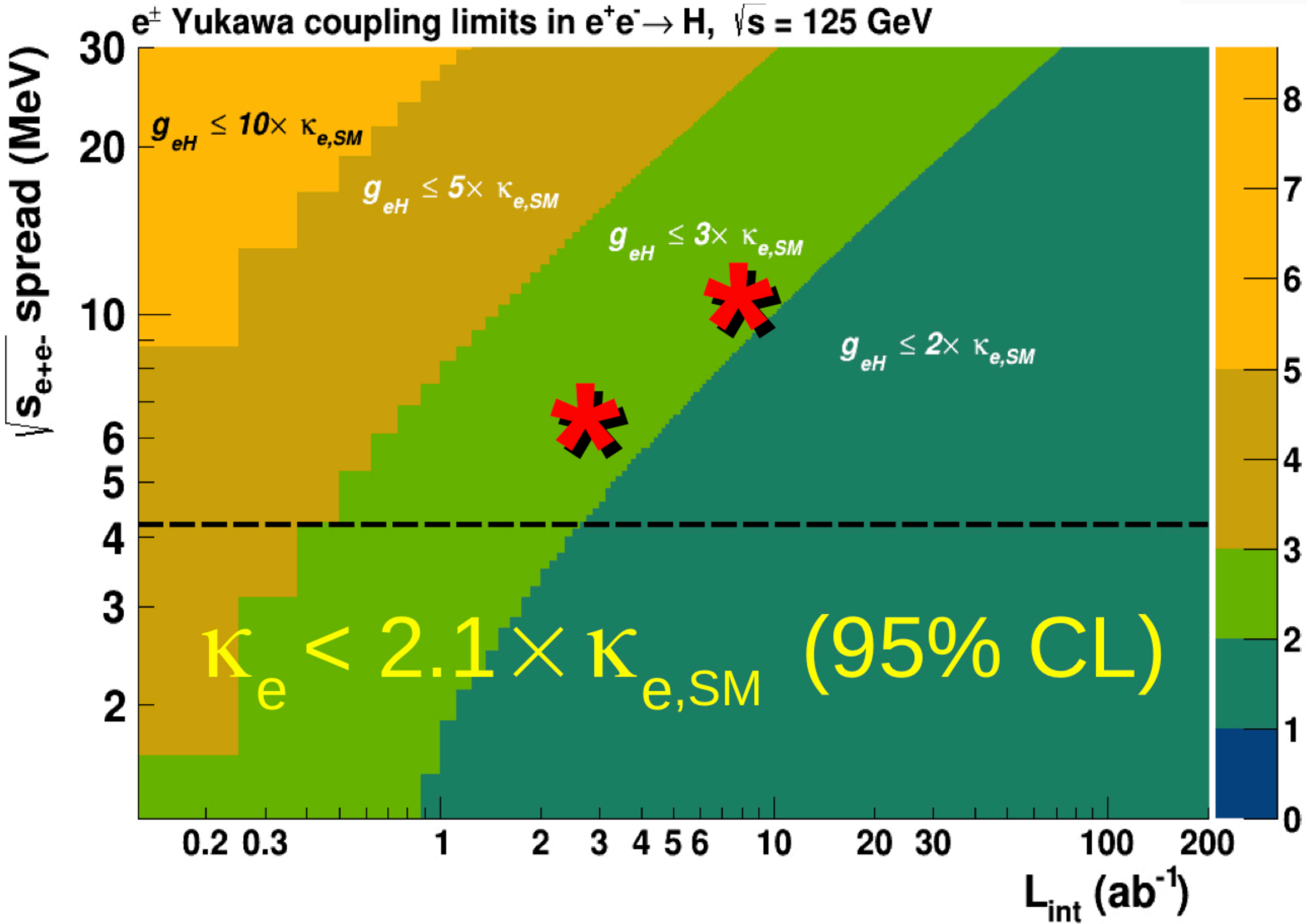
ee→H at $\sqrt{s}=m_H$: Hee coupling

Impact of ISR + beam energy spread on σ(ee→H)

Jadach and Kycia, https://arxiv.org/abs/1509.02406

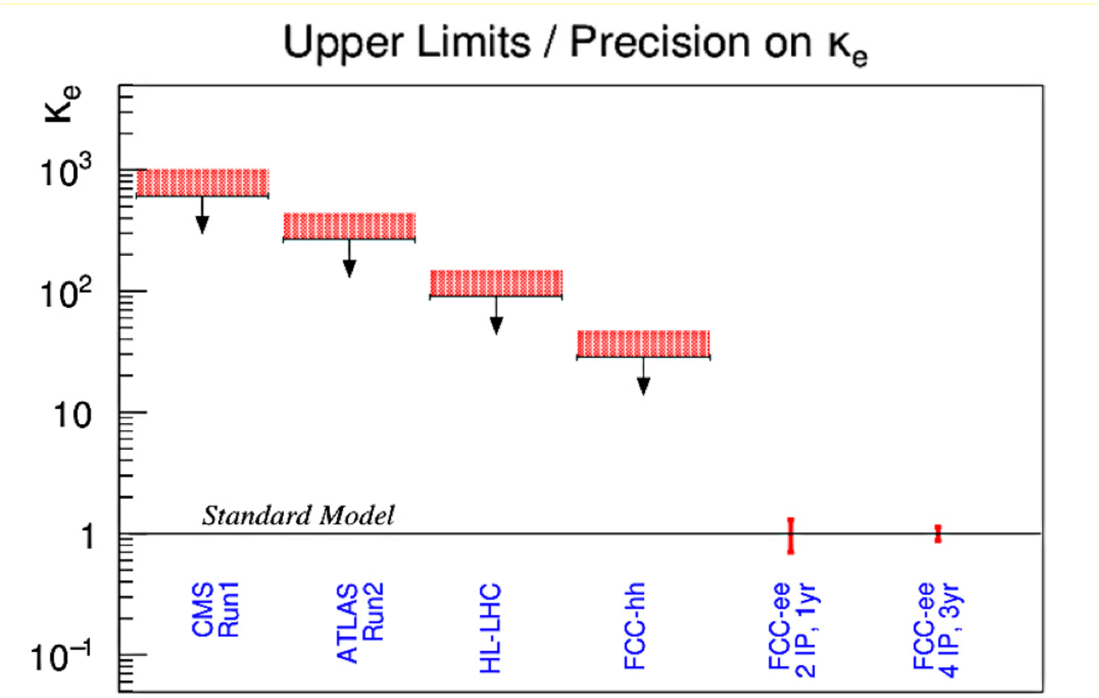




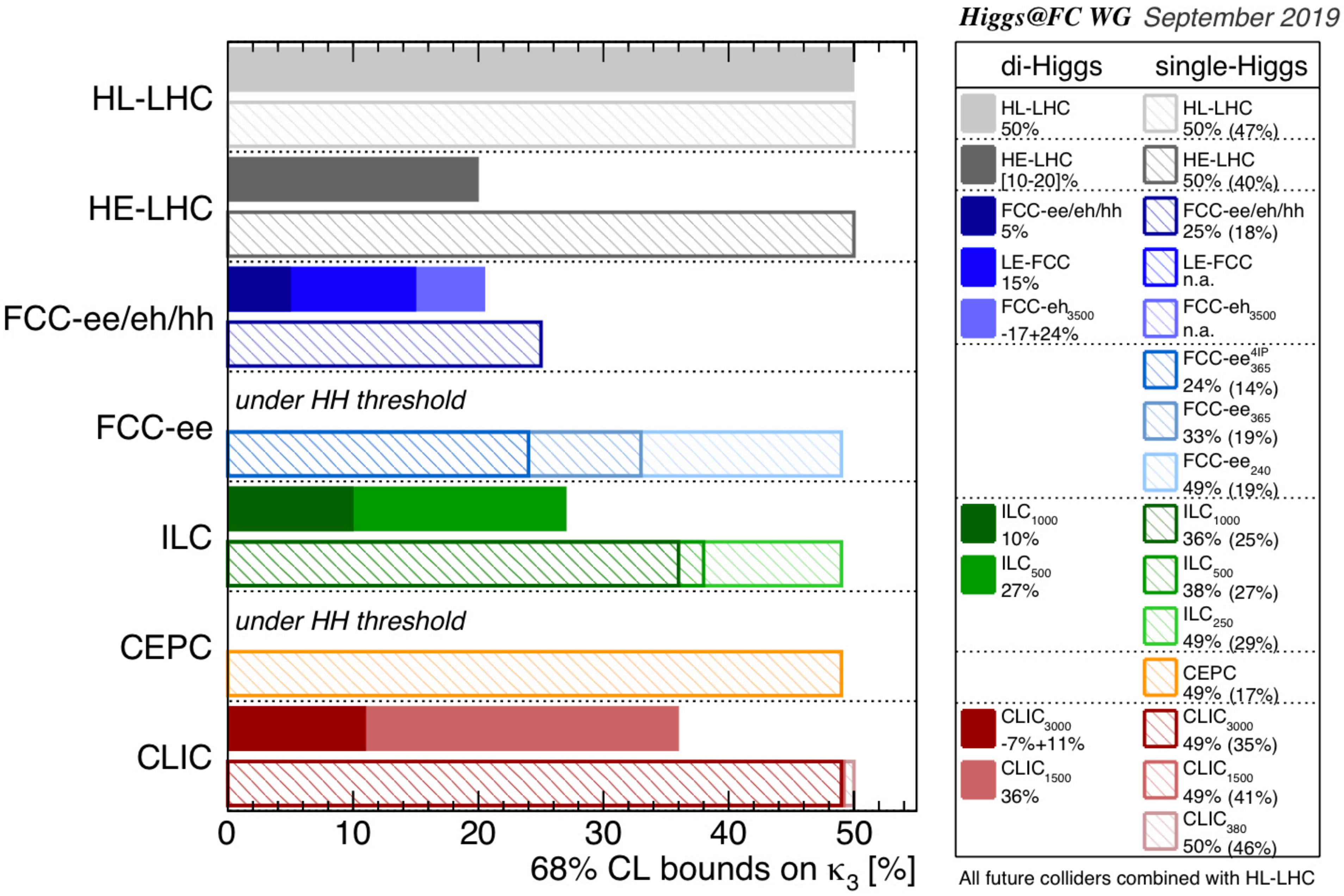


$\kappa_e < 2.1 \times \kappa_{e,SM}$ (95% CL)

D'Enterria, A. Poldaru, Wojcik, at 4th FCC physics workshop, slides

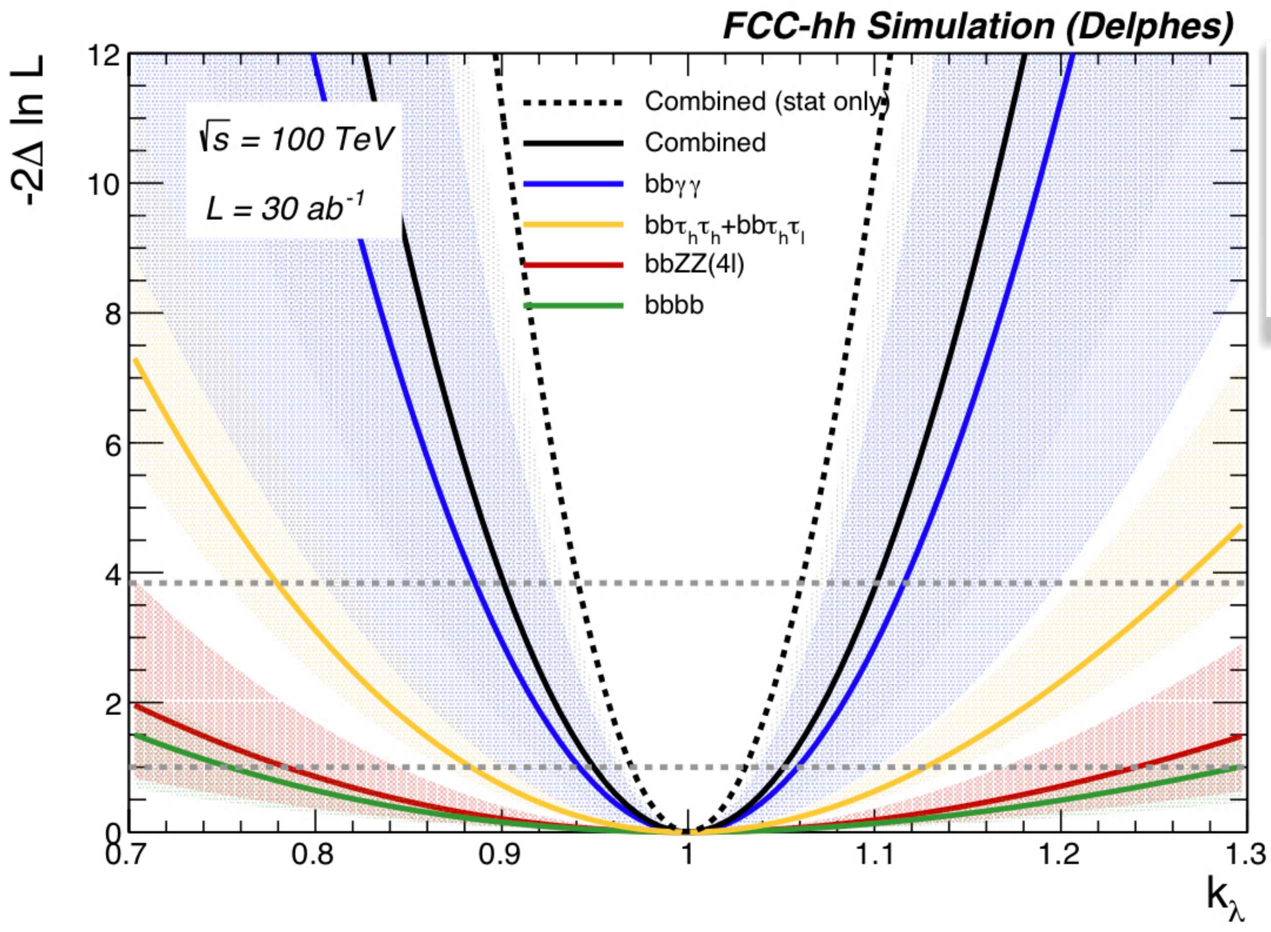


The Higgs self-coupling



The Higgs self-coupling at FCC-hh

https://arxiv.org/abs/2004.03505



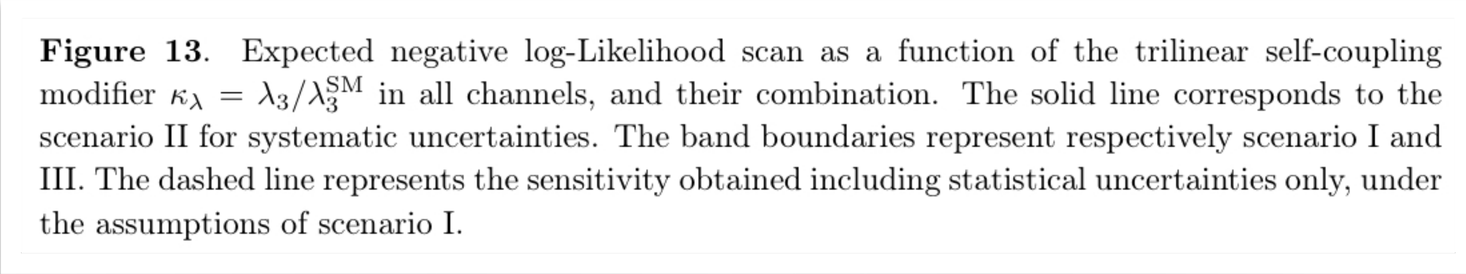


Figure 13. Expected negative log-Likelihood scan as a function of the trilinear self-coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{\rm SM}$ in all channels, and their combination. The solid line corresponds to the scenario II for systematic uncertainties. The band boundaries represent respectively scenario I and III. The dashed line represents the sensitivity obtained including statistical uncertainties only, under the assumptions of scenario I.

Syst scenarios

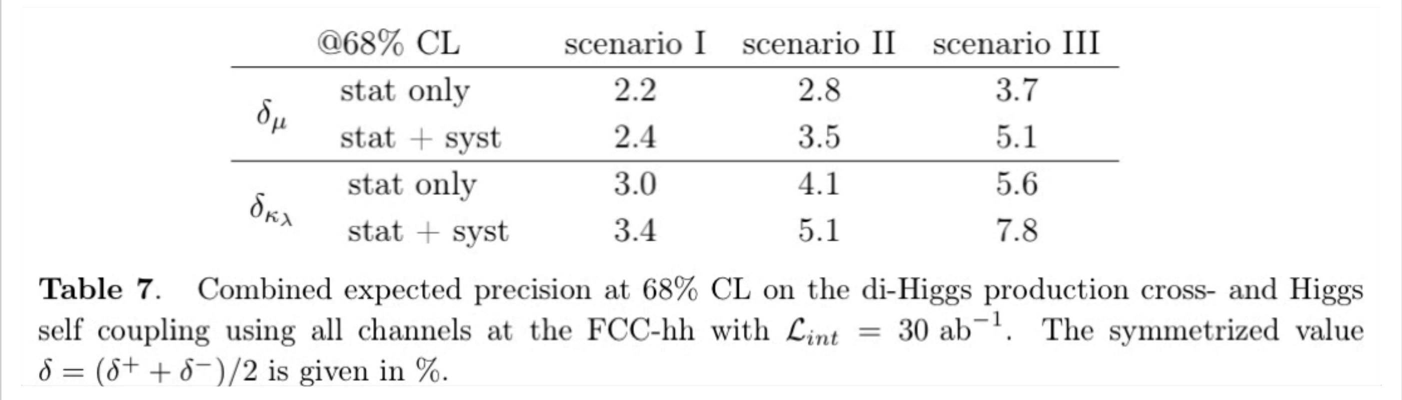
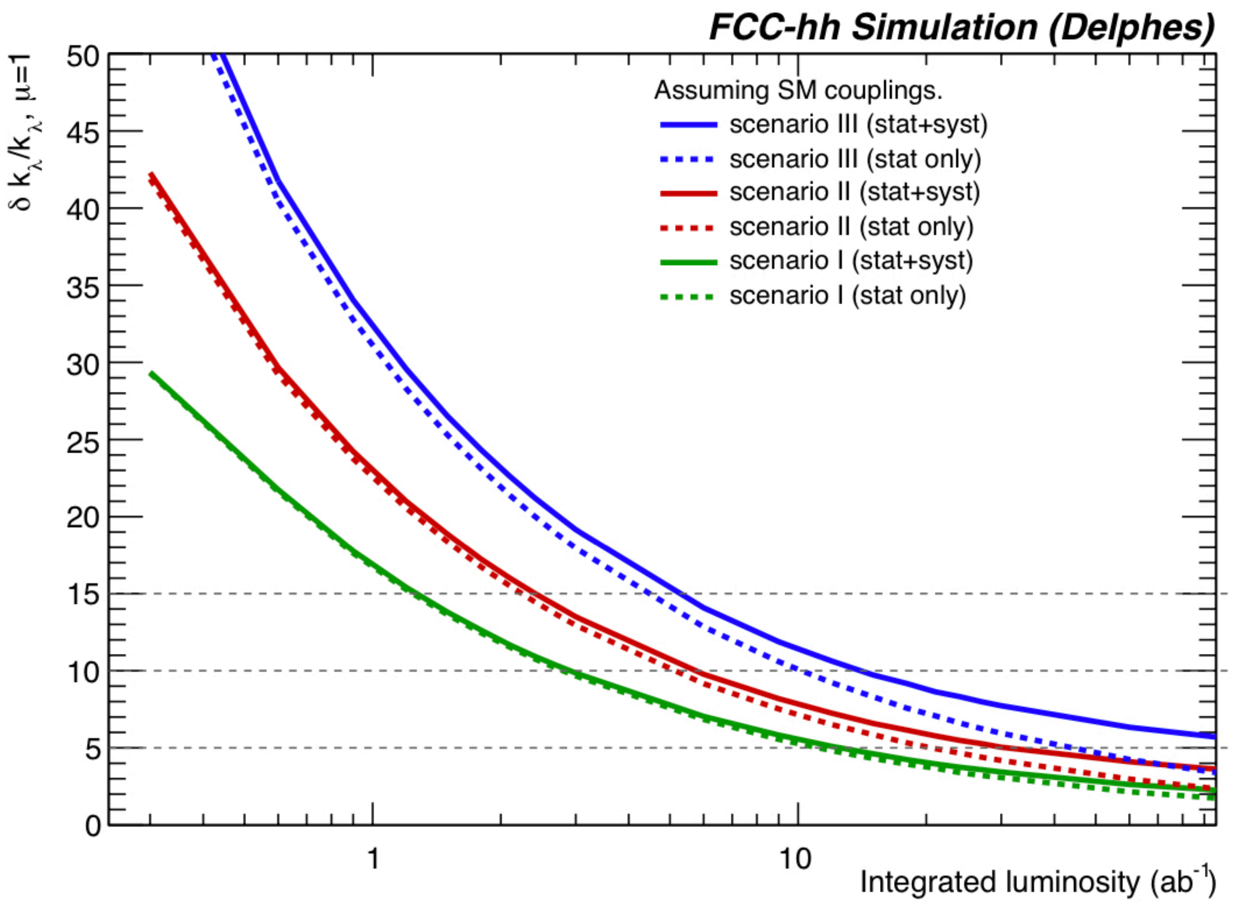

@68% CL		scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8

Table 7. Combined expected precision at 68% CL on the di-Higgs production cross- and Higgs self coupling using all channels at the FCC-hh with $\mathcal{L}_{int}$ = 30 ab^{-1}. The symmetrized value $\delta = (\delta^+ + \delta^-)/2$ is given in %.

I. Target det performance: LHC Run 2 conditions
II. Intermediate performance
III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)



Expected precision on the Higgs self-coupling as a function of the integrated luminosity.

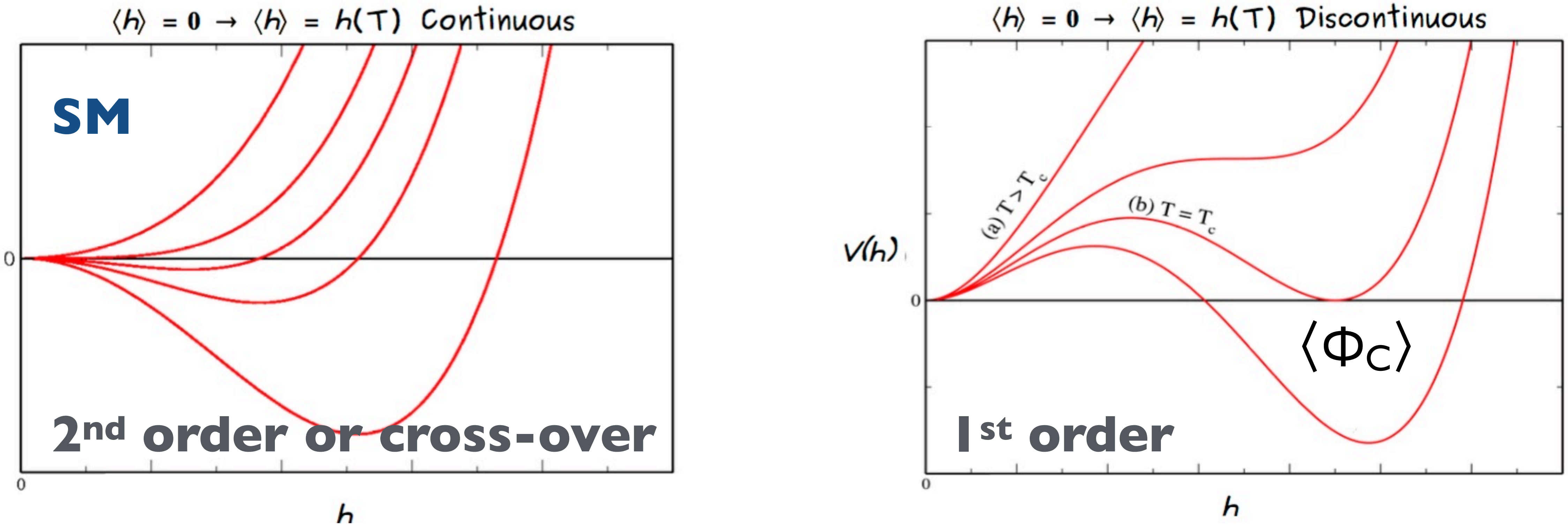
3-5 ab^{-1} are sufficient to get below the 10% level

=> within the reach of the first 5yrs of FCC-hh running,

in the "low" luminosity / low pileup phase

=> compatible with the timescale for a similar precision measurement by CLIC @ 3 TeV

Implications: the nature of the EW phase transition



Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim$ 80 GeV, else transition is a smooth crossover.

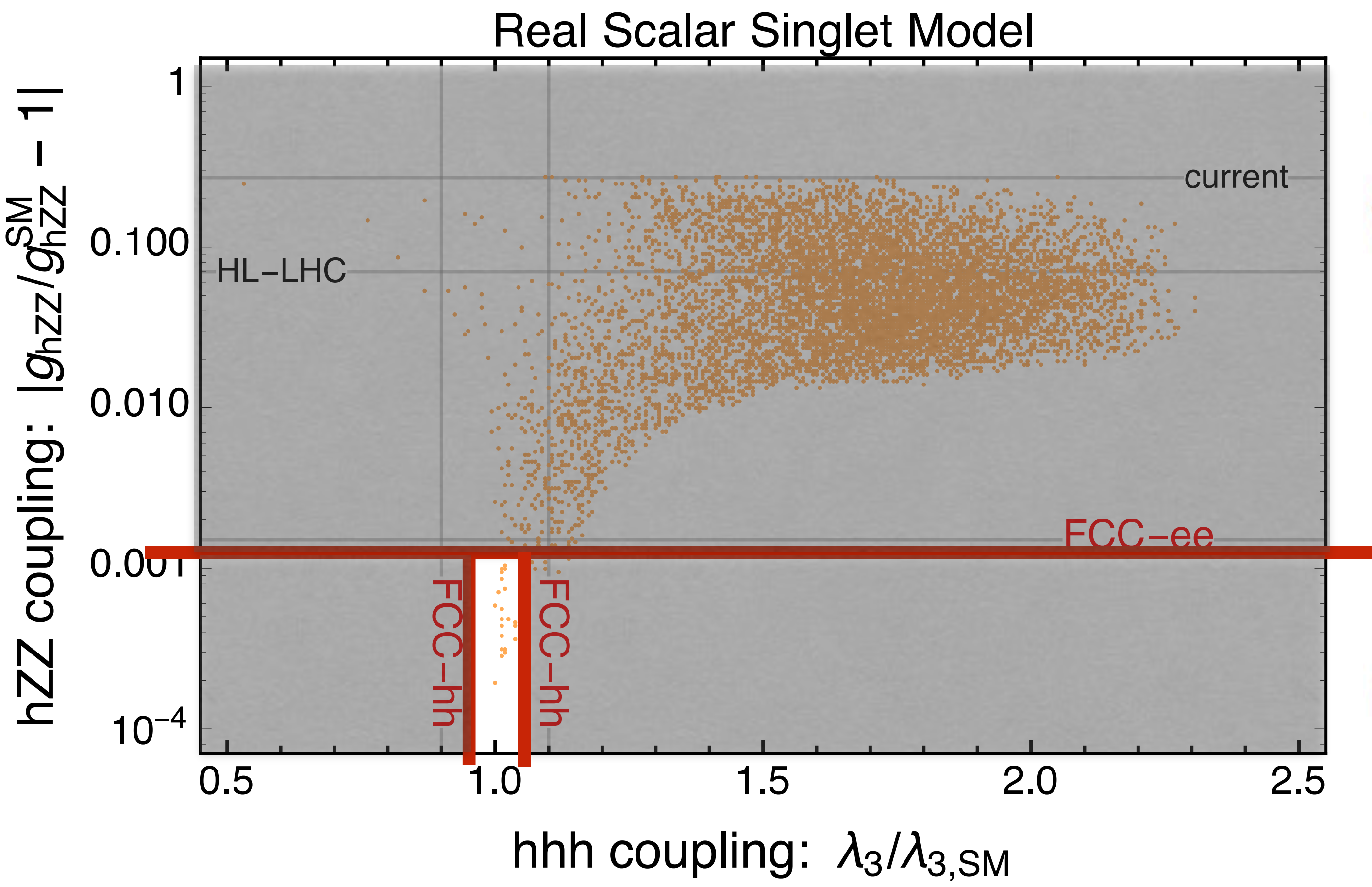
Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

Constraints on models with 1st order phase transition at the FCC

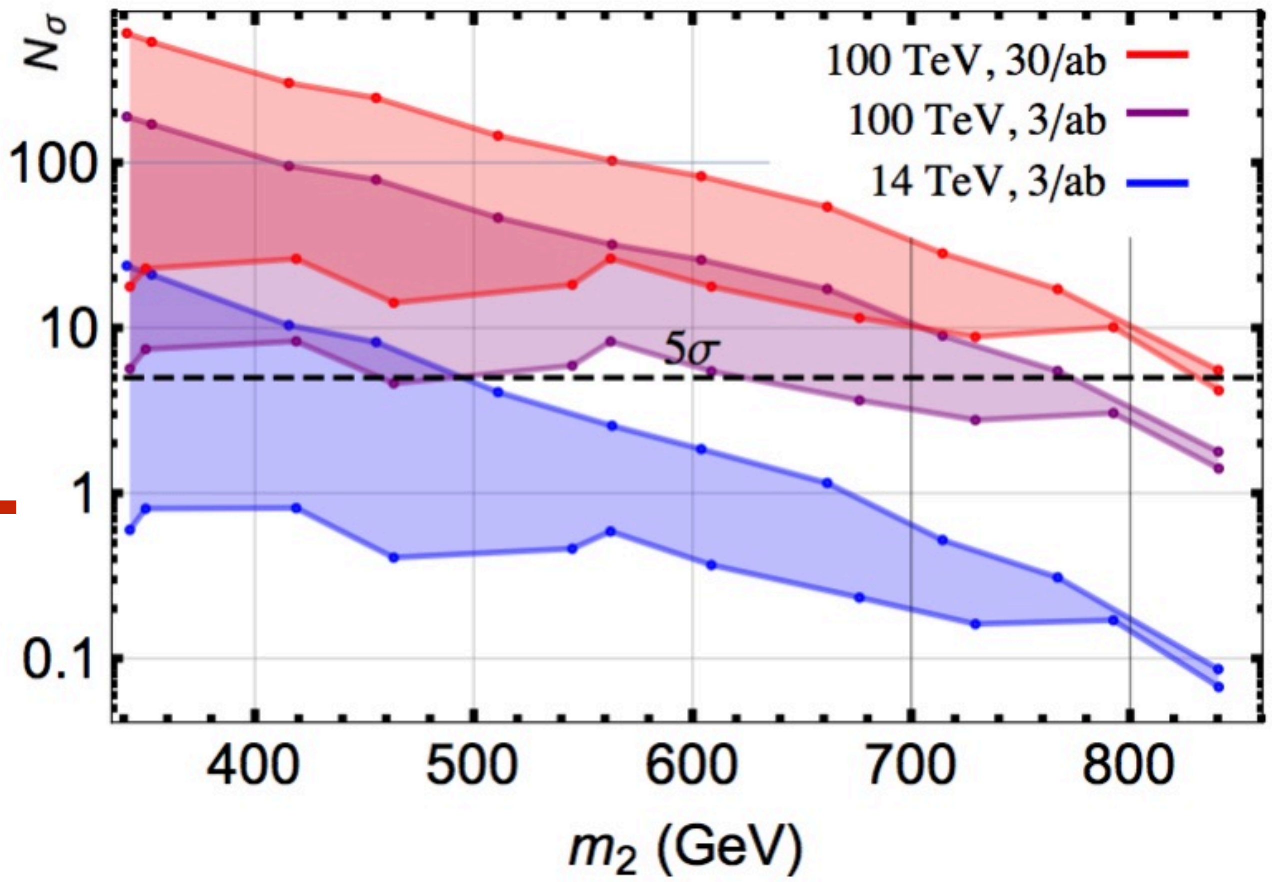
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

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.

Direct detection of extra Higgs states at FCC-hh

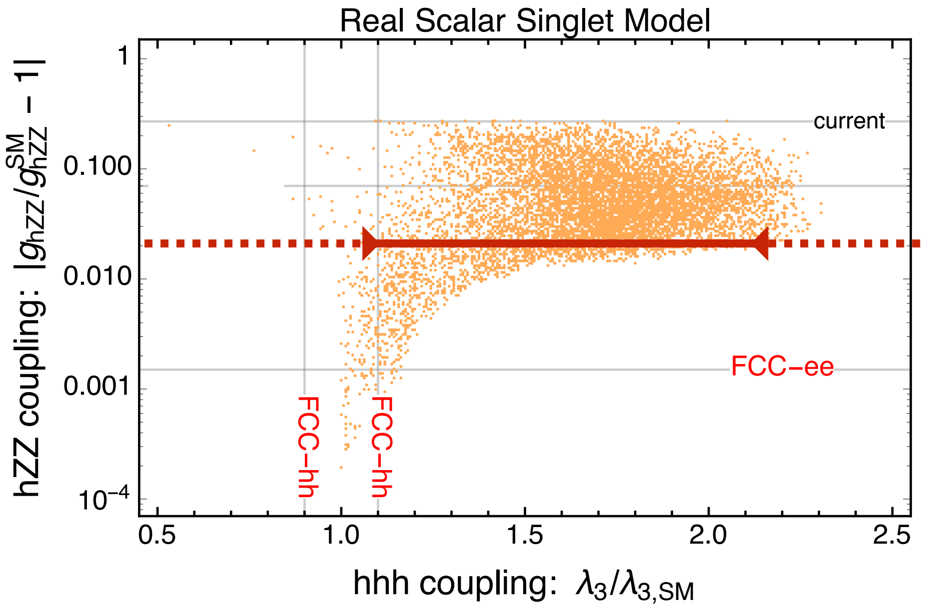


$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

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

Remarks

- Apparently, adding the self-coupling constraint does not add much in terms of exclusion power, wrt the HZZ coupling measurement …
- … BUT, should HZZ deviate from the SM, λ_{HHH} is necessary to break the degeneracy among all parameter sets leading to the same HZZ prediction



- The concept of *“which experiment sets a better constraint on a given parameter”* is a very limited comparison criterion, which looses value as we move from *“setting limits”* to *“diagnosing observed discrepancies”*
- Likewise, it’s often said that some observable sets better limits than others: “all known model predict deviations in X larger than deviations in Y, so we better focus on X”. But once X is observed to deviate, knowing the value of Y could be absolutely crucial ….
- Redundancy and complementarity of observables is of paramount importance

Higgs as a BSM probe: precision vs dynamic reach

$$\boxed{L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots}$$

$$O = | \langle f|L|i\rangle |^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, μ~O(v,m_H)

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. δO=1% ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, μ~O(Q)

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

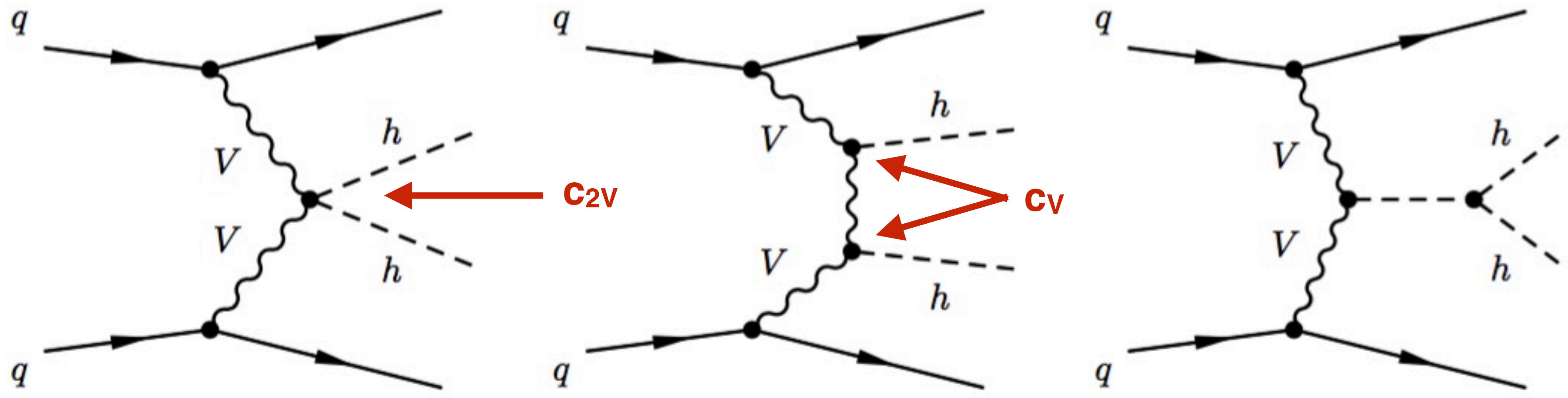
⇒ **kinematic reach** probes

large Λ even if precision is low

e.g. δO=15% at Q=1 TeV ⇒ Λ~2.5 TeV

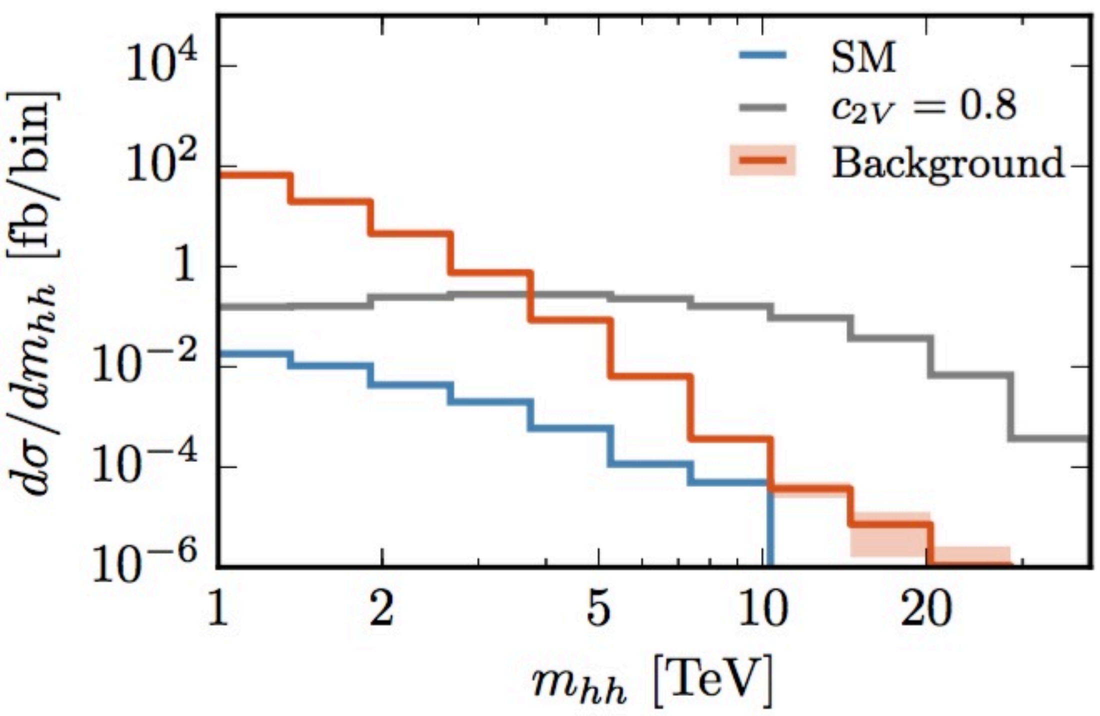
Precision and extensive kinematic reach provide unique complementarity and redundancy, crucial to interpret possible SM deviations manifest in either of these observabes

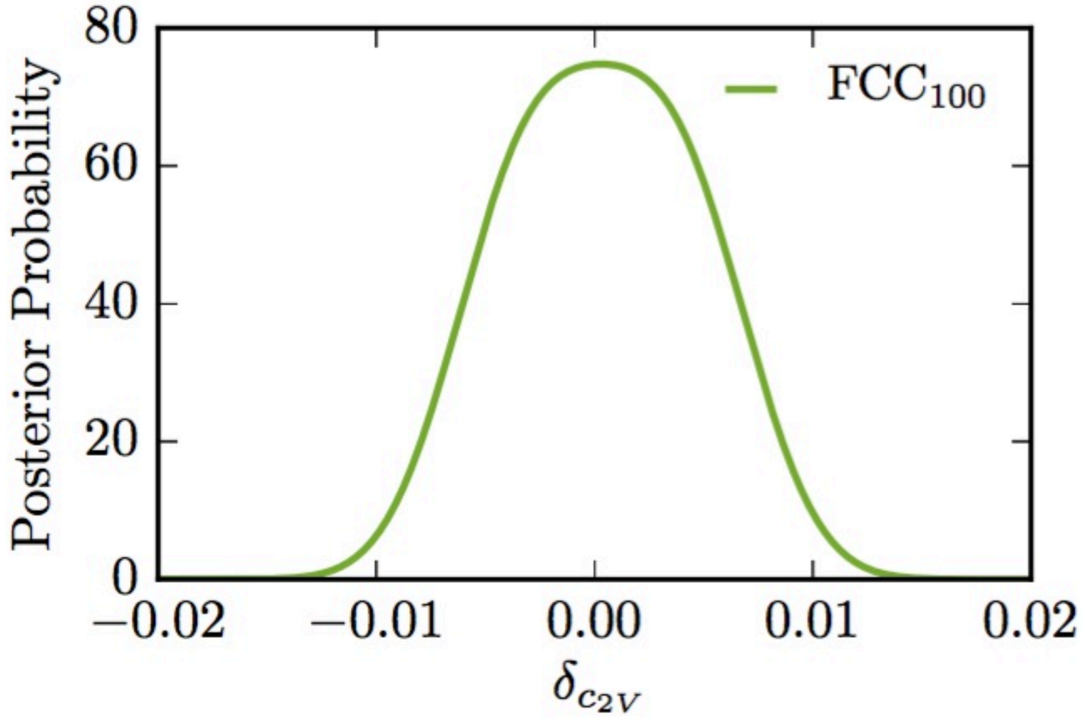
Example: high mass VV → HH



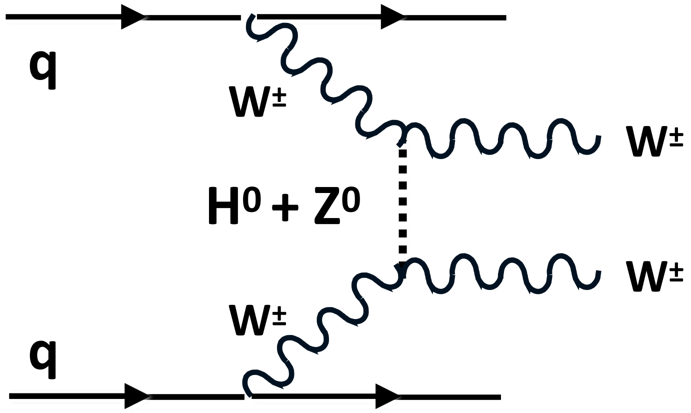
$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) \cdot$$ **where** $$\begin{cases} c_V = g_{HVV}/g^{SM}_{HVV} \\ c_{2V} = g_{HHVV}/g^{SM}_{HHVV} \end{cases} \Rightarrow \left(c_{2V} - c_V^2\right)_{SM} = 0$$

$c_{2V} \neq c_V^2$ probes custodial symmetry breaking, extended Higgs sectors, …

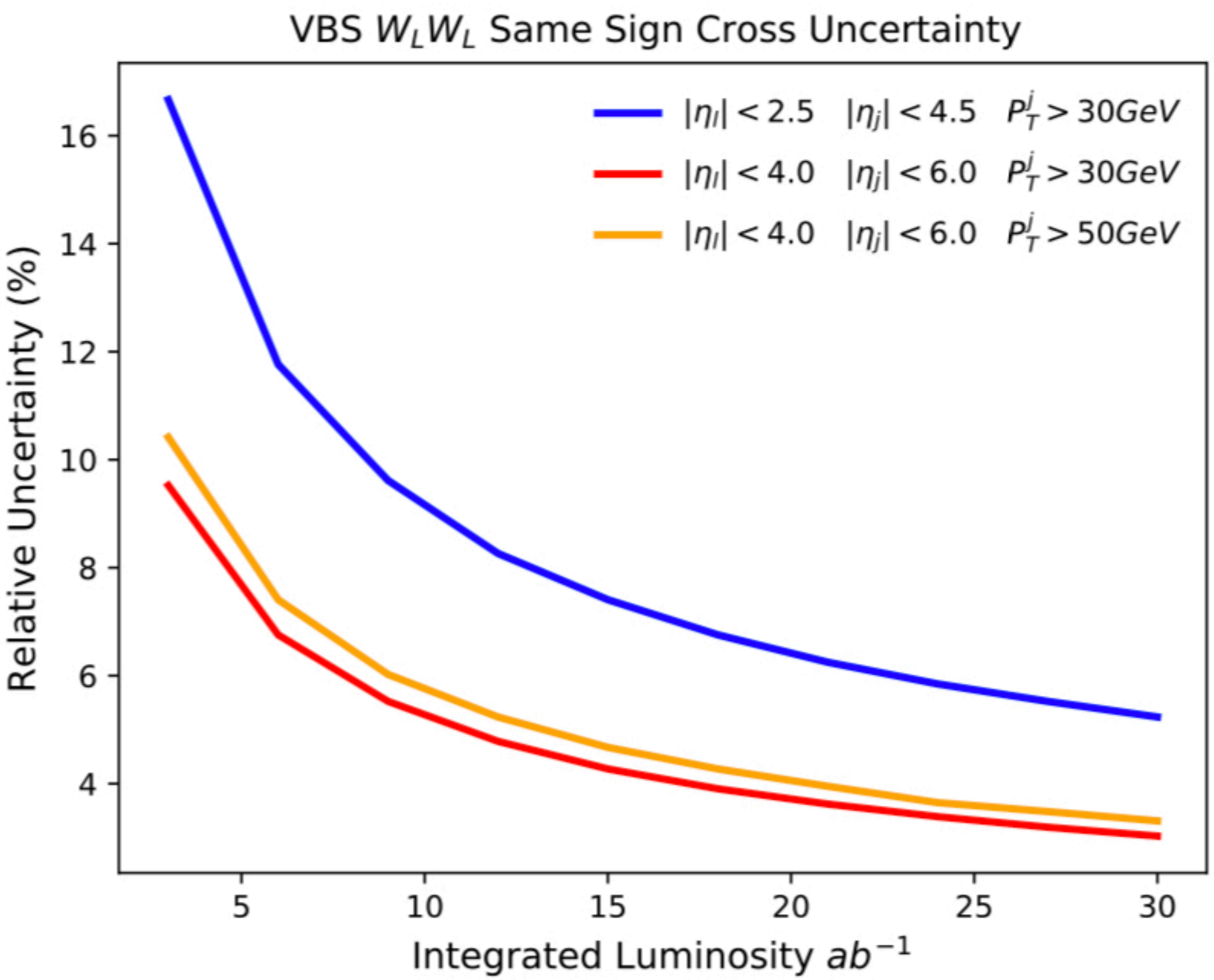




W_LW_L scattering



large m_{WW}



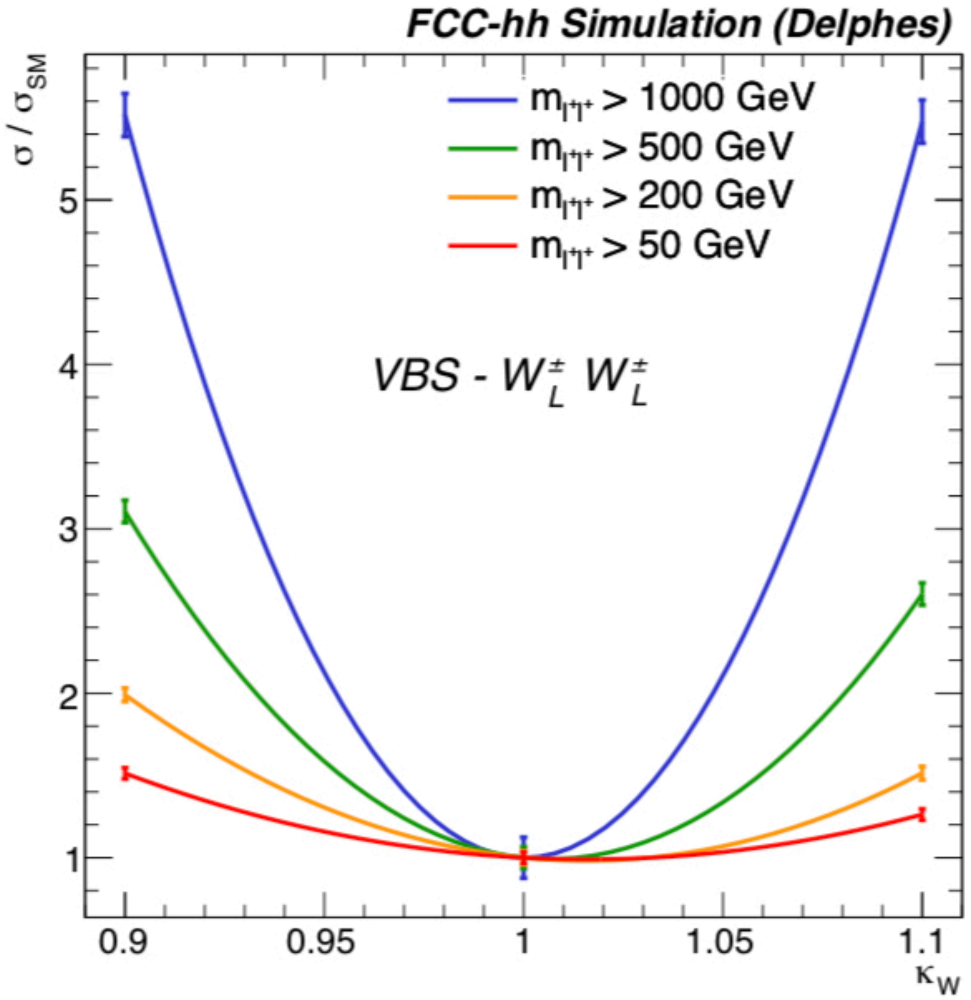
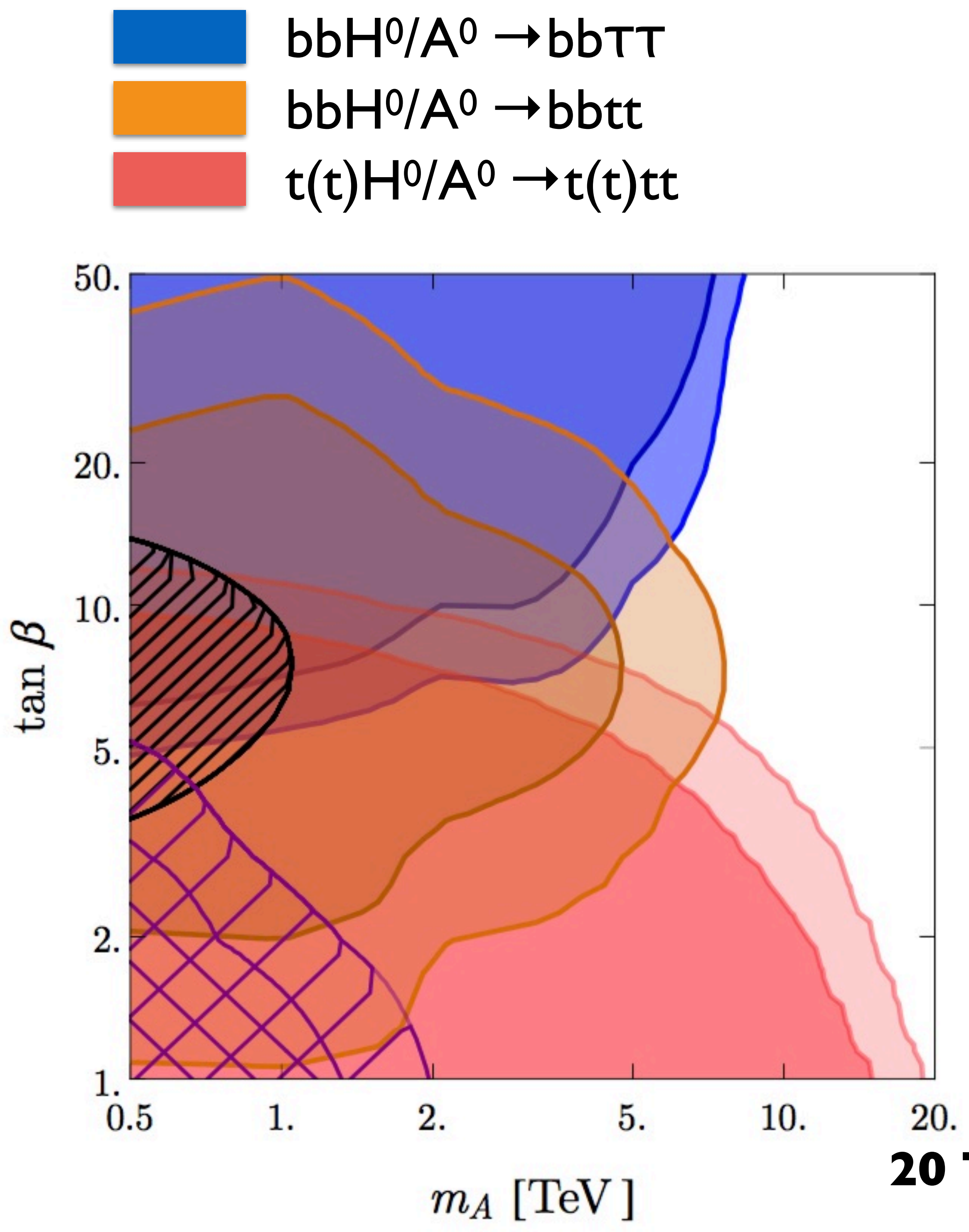


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \rightarrow HH$ process.

$m_{l^+l^+}$ 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]

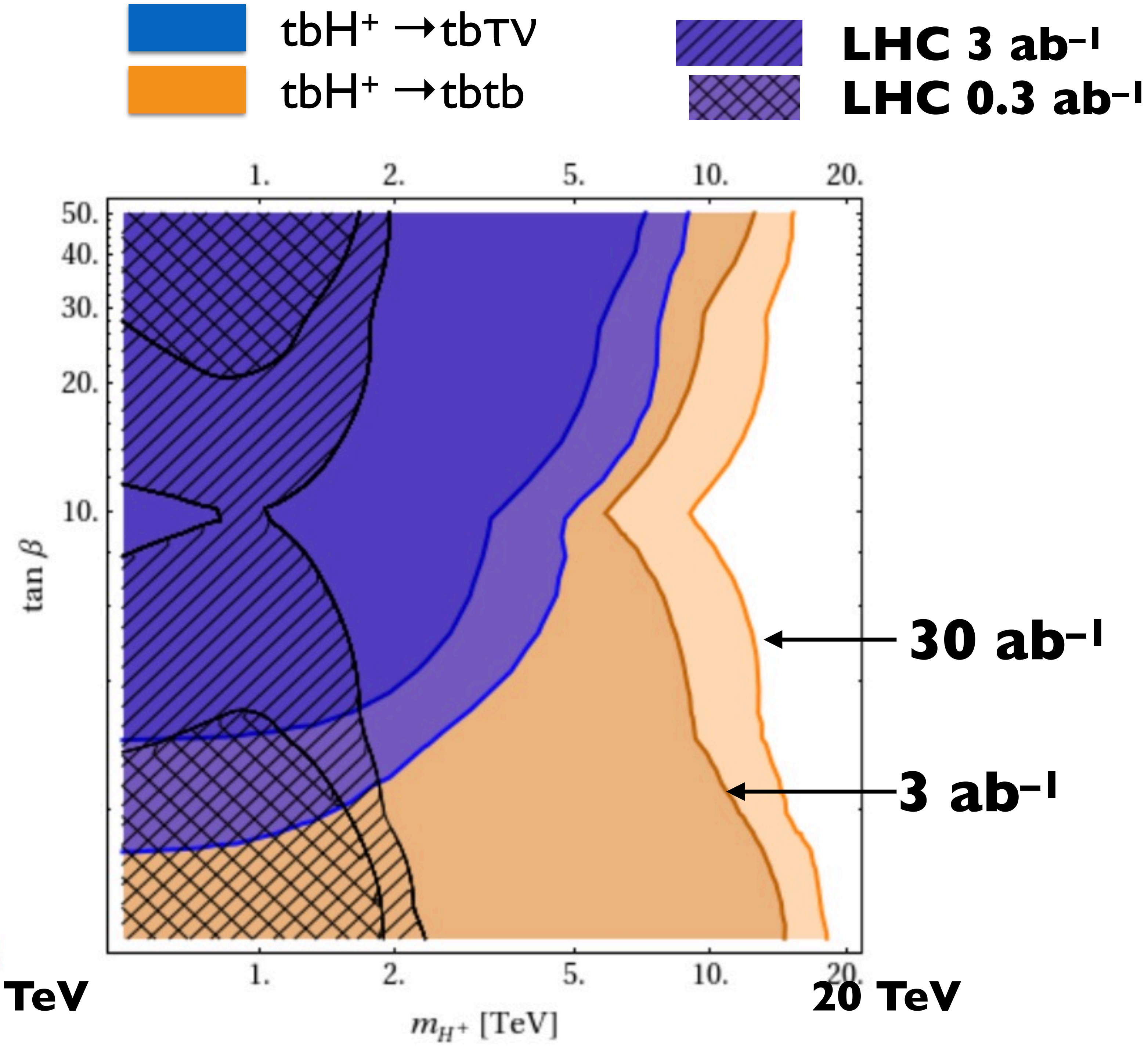
$$\kappa_W = \frac{g_{HWW}}{g_{HWW}^{SM}}$$

MSSM Higgs @ 100 TeV



20 TeV

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



30 ab⁻¹

3 ab⁻¹

20 TeV

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

Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- Future colliders provide the only experimental approach to expand and improve our knowledge of Higgs properties
- The synergy and complementarity between ee and pp colliders remains the most powerful exploratory tool that HEP has available
- The technological, financial and sociological challenges are immense, and will test our community ability to build and improve on the experience of similar challenges in the past.
- The next 5-6 years, before the next review of the European Strategy for Particle Physics, will be critical to reach the scientific consensus and political support required to move forward