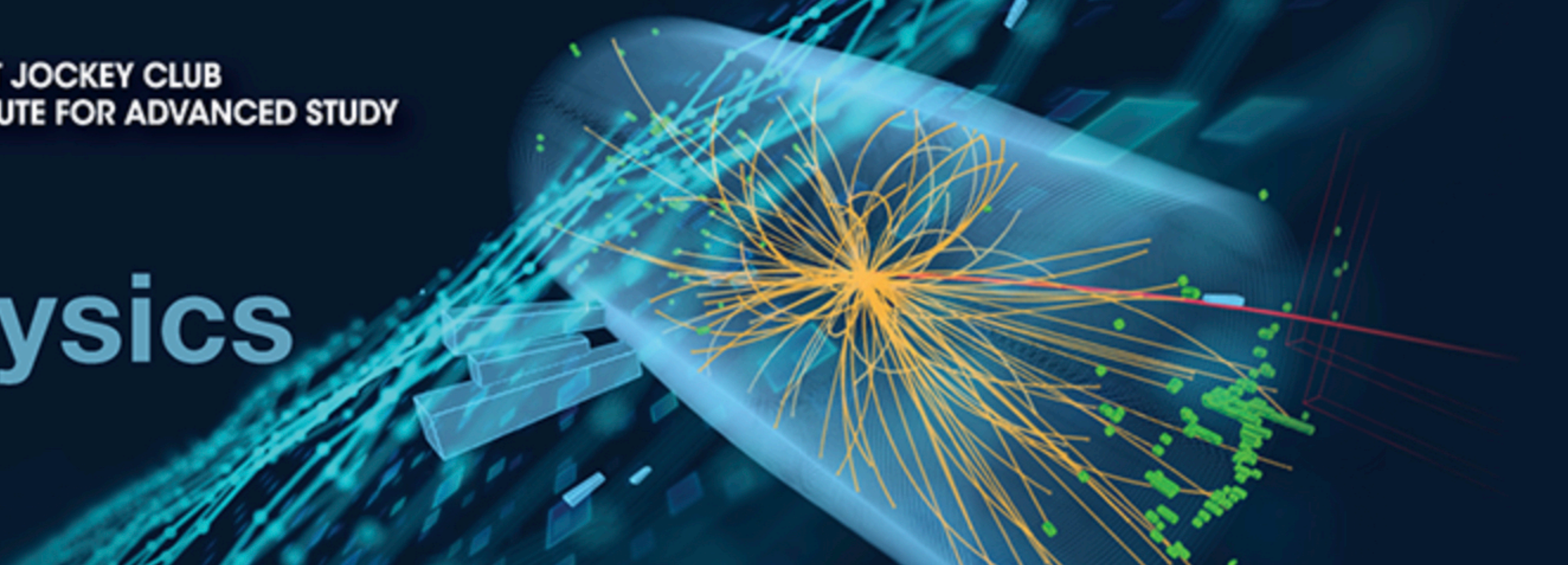
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY | IAS HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

IAS PROGRAM

High Energy Physics

January 7-25, 2019



Status of HE-LHC and FCC-hh

Michelangelo L. Mangano
Theory Department, CERN, Geneva

Outline

- For the general status of the FCC project and CDR, see M.Koratzinos talk
- Will focus on status of physics studies for FCC-hh & HE-LHC
- Will briefly review aspects of the HE-LHC project (challenges, schedule, cost)

General remarks for FCC-hh

- CDR implementation plan now affirms that the first step is the construction and operation of FCC-ee
- Important implications for FCC-hh:
  - adds 15 yrs to the timeline to develop the high-field magnets. Go directly to HTS @ 24T (~150 TeV)?
  - adds 15 yrs to the timeline to design and build detectors: implications for ultimate performance, triggers, etcetc??
  - ensures that the interpretation of FCC-hh data can rely on the knowledge acquired by FCC-ee, increasing its value
- Stretches the whole FCC programme to a period of ~70 years:
  - dilution of costs makes it more financially credible
  - guaranteed CERN presence for extended period might justify additional effort by CH and FR to support project
- Staging of the costs (ee first) could facilitate an early decision?

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  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

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  - **enhanced mass reach** for direct exploration
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

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    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

Higgs properties

Higgs couplings after HL-LHC & FCC-ee (κ fit)

	HL-LHC (*)	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM (**)	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**4.3**	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**1.8**	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	**3.4**	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–
$\delta g_{HHH} / g_{HHH}$ (%)	**50**	~40 (indirect)
BR_{exo} (95%CL)	BR_{inv} < 2.5%	**< 1%**

Need to improve

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, Higgs Physics at the HL-LHC and HE-LHC, Version 1, CERN-LPCC-2018-04

** SM width assumed in the global fit. Will be measured to ~20% (68%CL) via off-shell H->4l, to ~5% (95%CL) from global fit of Higgs production cross sections.

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

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

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

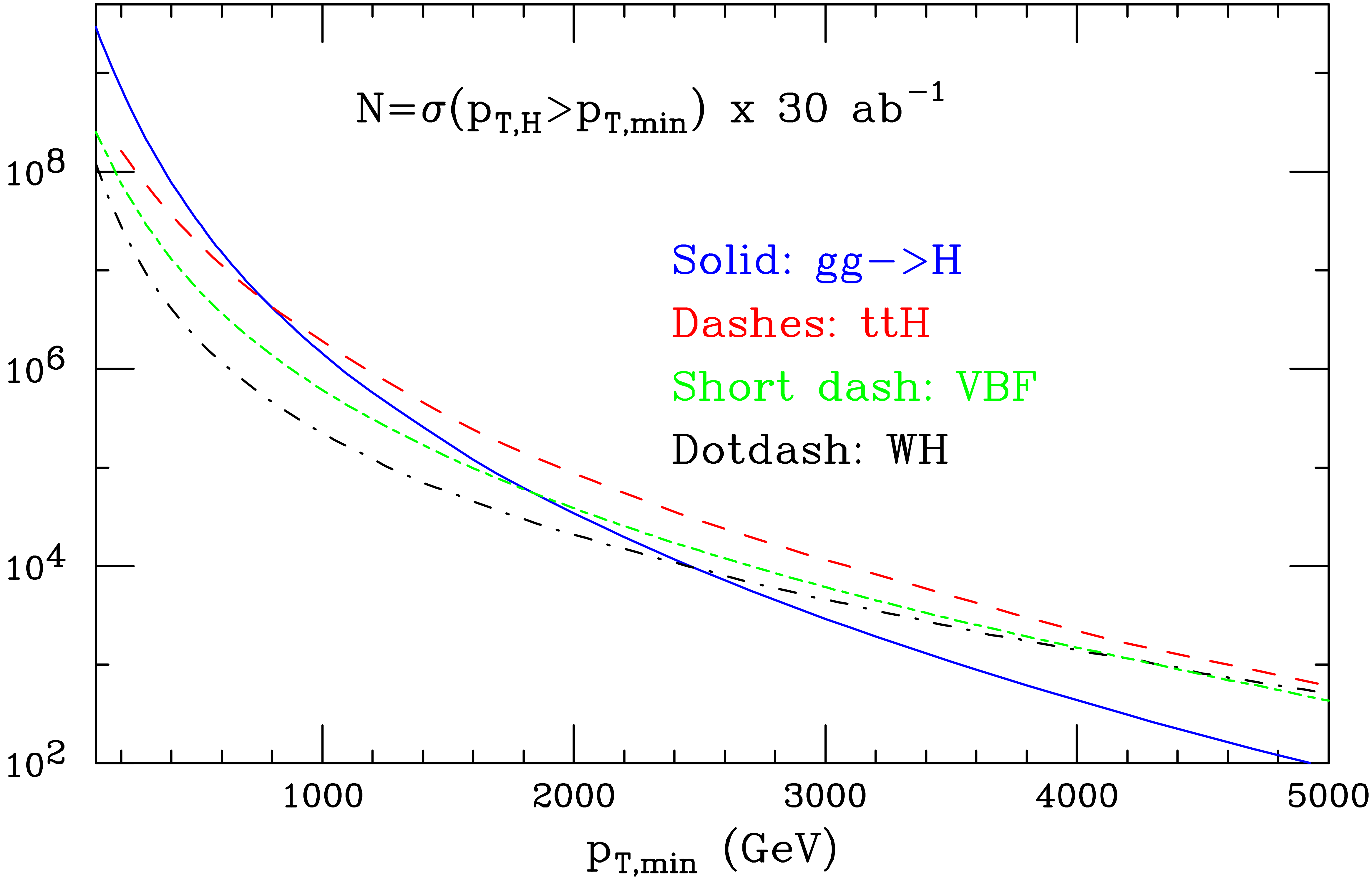
The unique contributions of a *100 TeV pp collider to Higgs physics*

- 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
    - …

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

Delphes-based projections

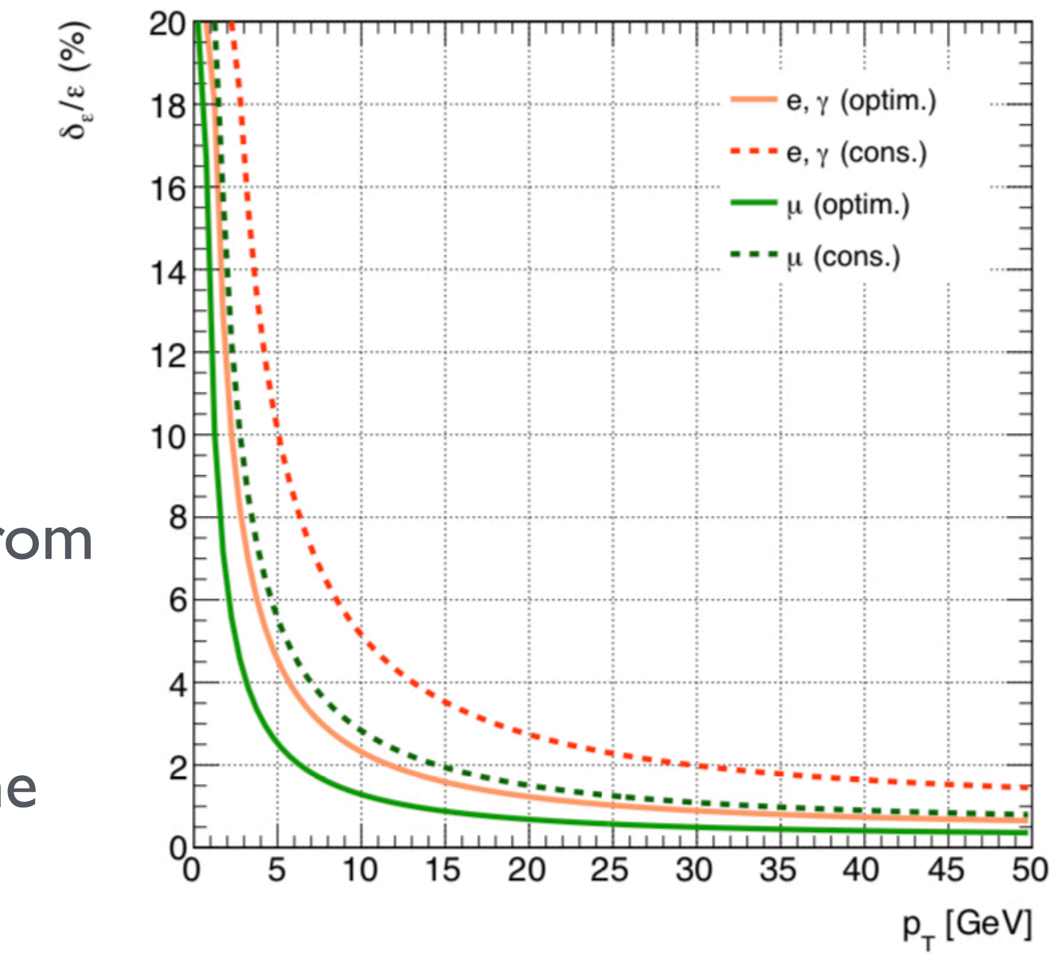
M.Selvaggi

All **signal and background samples** have been generated via the following chain (using the FCCSW): http://fcc-physics-events.web.cern.ch/fcc-physics-events/LHEevents.php

- **MG5aMC@NLO + Pythia8**
  - LO (MLM) matched samples (up to 1/2/3 jets) and global K-factor applied to account for $N^{2/3}LO$ corrections
  - full list of signal prod. modes simulated (ggH with finite m_{top})
- **Delphes-3.4.2** with baseline FCC-hh detector

Consider the following categories of uncertainties:

- δ_{stat} = statistical
- δ_{prod} = production + luminosity systematics
- $\delta_{eff}^{(i)}(p_T)$ = object reconstruction (trigger+isolation+identification) systematics
- $\delta_B = 0$, background (assume to have ∞ statistics from control regions)



Assume (un-)correlated uncertainties for (different) same final state objects

Following scenarios are considered:

- δ_{stat} → stat. only (I)
- δ_{stat} , δ_{eff} → stat. + eff. unc. (II)
- δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + eff. unc. + prod (III)

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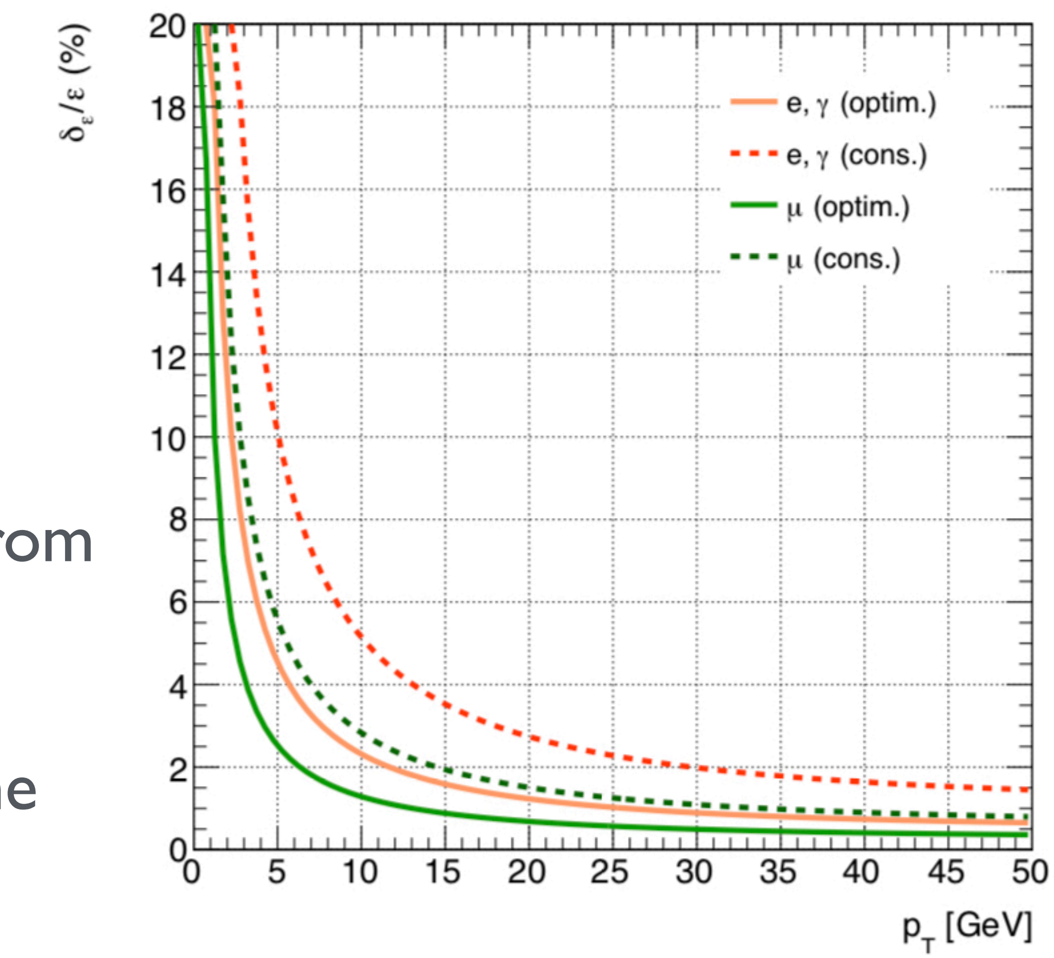

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could be seen as syst in the normalization of production*lumi wrt standard candles such as pp→Z→ee

Remarks

- 1% systematics on (production x luminosity) is meant as a reference target.
  - Reasonably justified by foreseen theoretical progress over the next few decades. Few % is already achievable **today** for channels such as VH or VBF:

14 TeV	σ[fb]	Δ_{scale} (%)	$\Delta_{PDF+\alpha S}$ (%)
pp -> lν H	66.6	$^{+0.52}_{-0.64}$	±1.9
pp -> l⁺ l⁻ H	33.1	$^{+3.6}_{-2.9}$	±1.9
VBF	4260	$^{+0.45}_{-0.34}$	±2.1

see next slides for future evolution

Dominated by gg->ZH systematics

(VH and VBF statistics at FCC by itself will allow for sub-% statistical precision in the relevant decay channels)

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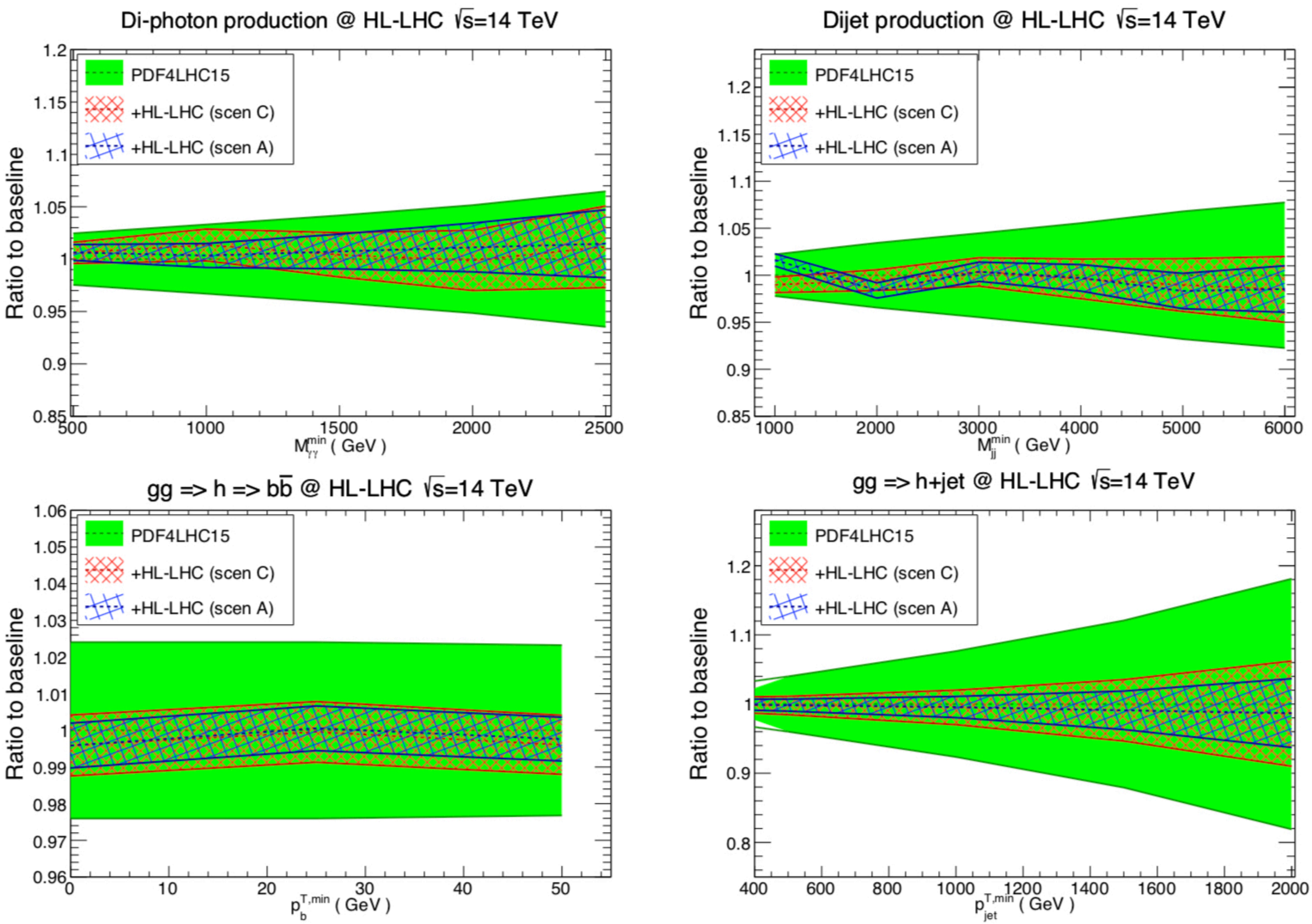
- All final states considered here rely on reconstruction of mH to within few GeV. All bg's (physics and instrumental) to be determined with great precision from sidebands
- Impact of pile-up: hard to estimate with today's analyses. Expect that focus on high-pT objects will mitigate the issue

PDF uncertainty: HL-LHC projections



PDF uncertainty: FCC-eh projections

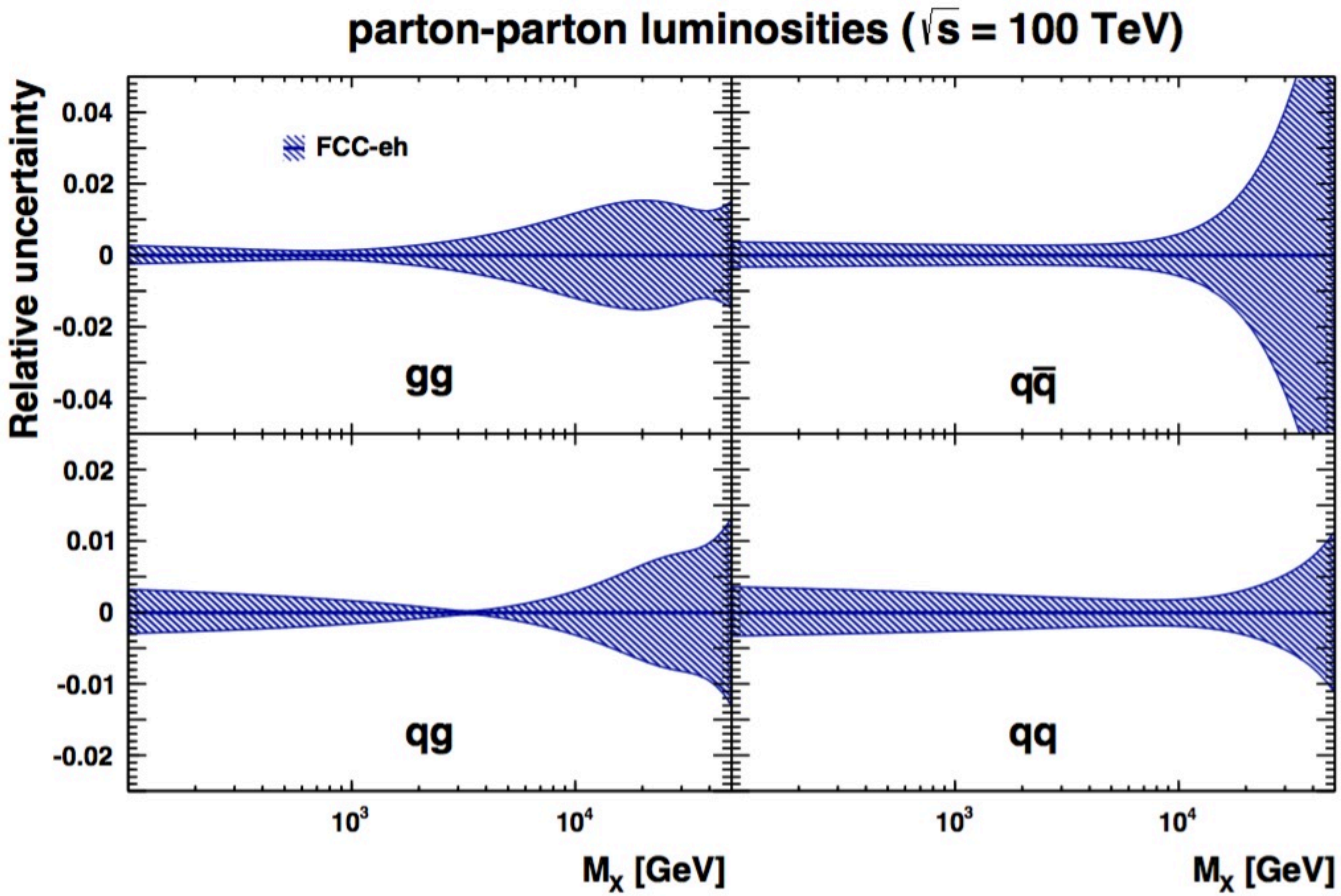
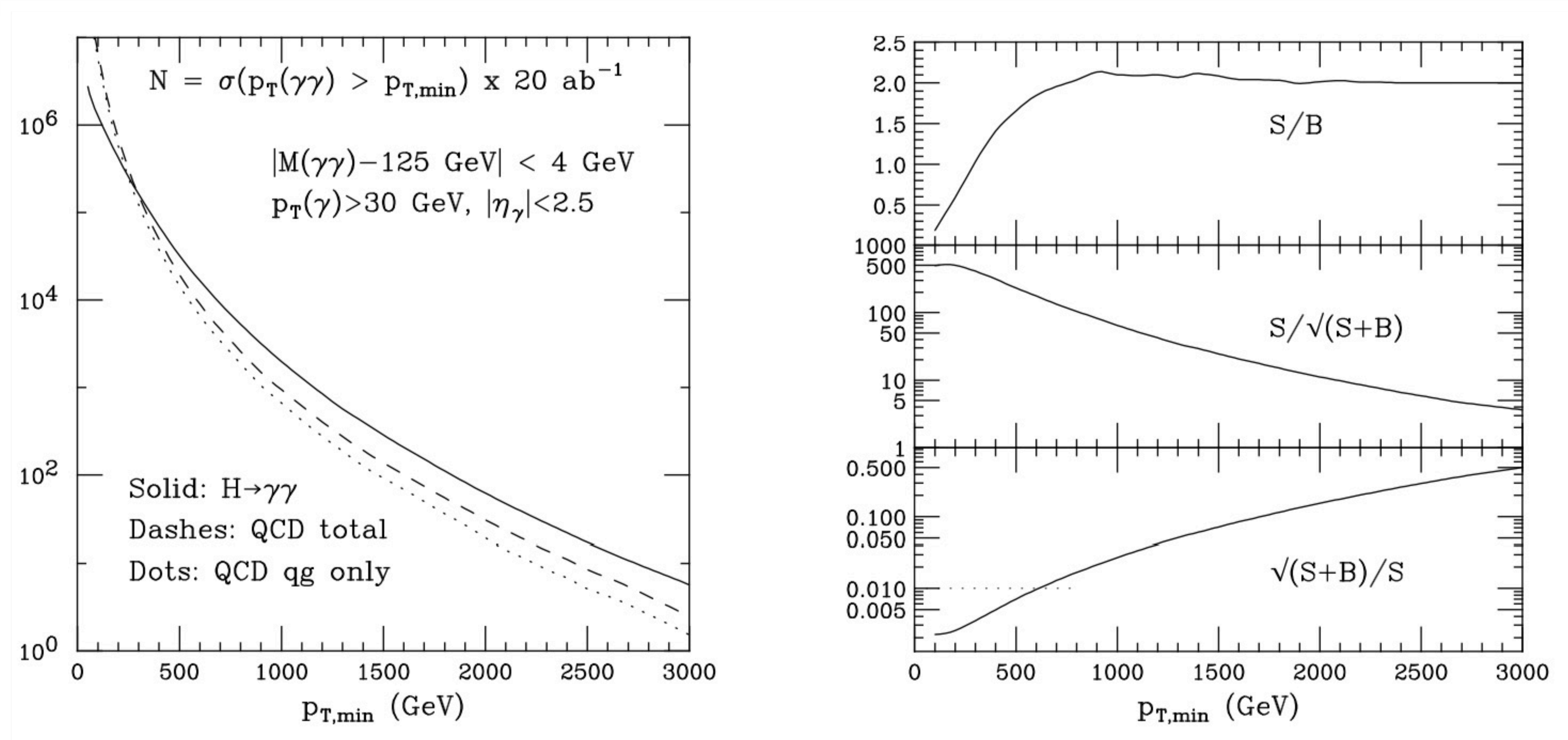


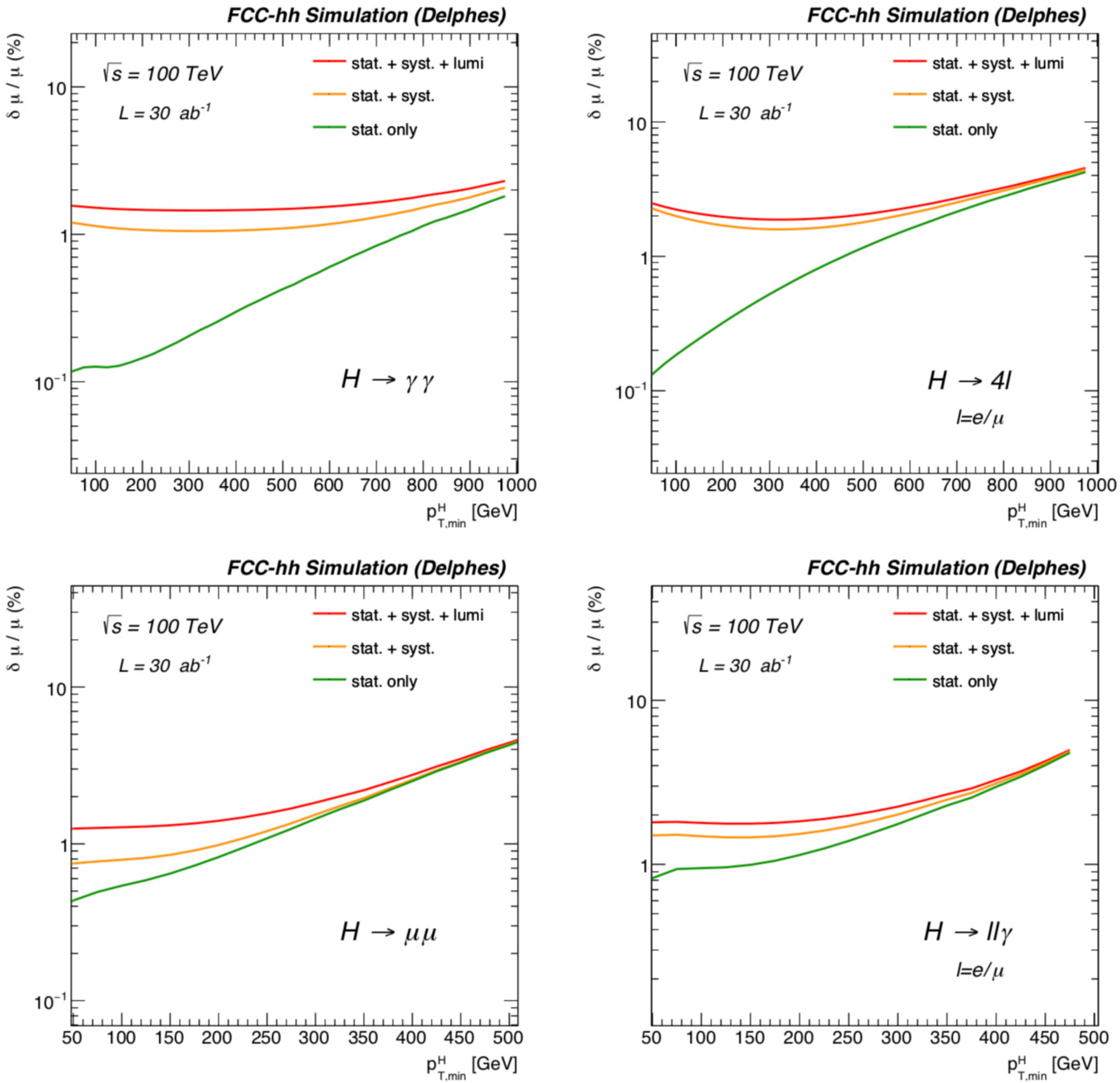
Figure 5.14: Relative PDF uncertainties on parton-parton luminosities from the FCC-eh PDF set, as a function of the mass of the produced heavy object, M_X, at $\sqrt{s} = 100$ TeV. Shown are the gluon-gluon (top left), quark-antiquark (top right), quark-gluon (bottom left) and quark-quark (bottom right) luminosities.

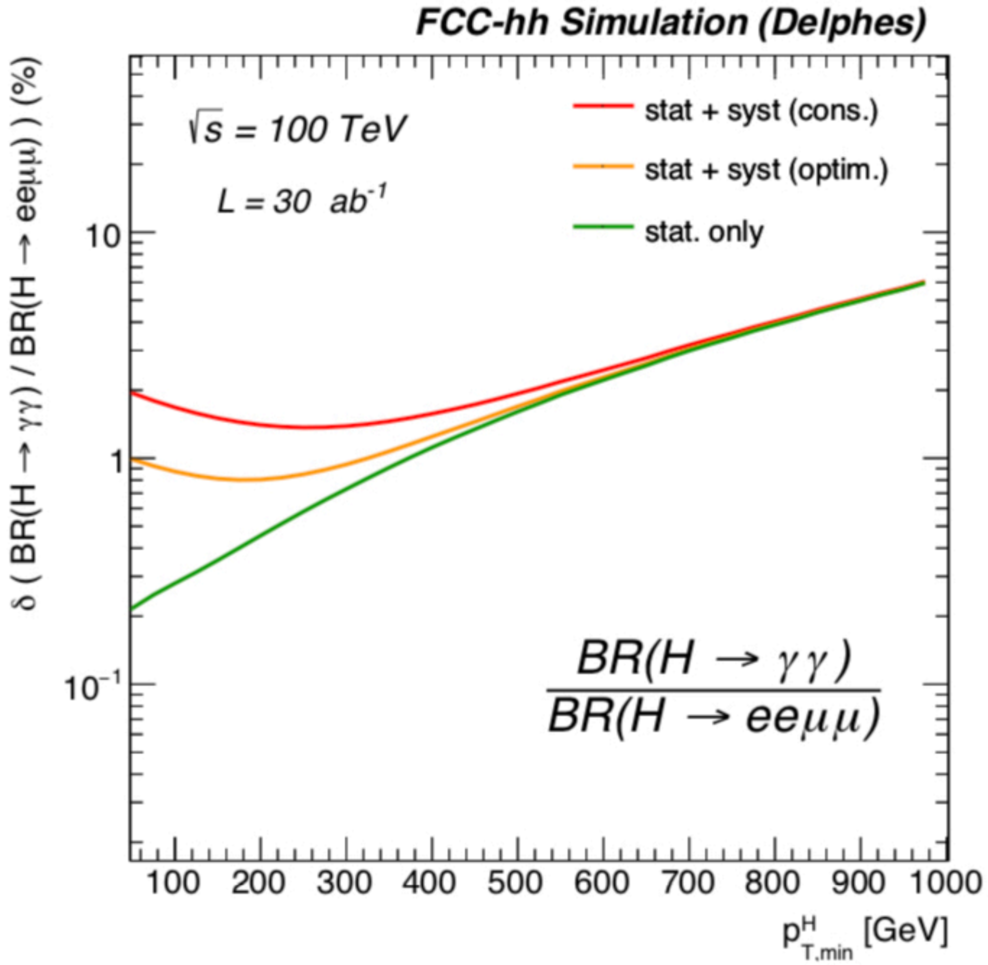
$gg \to H \to \gamma\gamma$ at large p_T



- 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%


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat. + syst. + lumi
stat. + syst.
stat. only
$H \rightarrow \gamma\gamma$
$H \rightarrow 4l$
$l=e/\mu$
$H \rightarrow \mu\mu$
$H \rightarrow ll\gamma$
$l=e/\mu$
$\delta\mu / \mu$ (%)
$p^H_{T,min}$ [GeV]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stat + syst (cons.)
stat + syst (optim.)
stat. only
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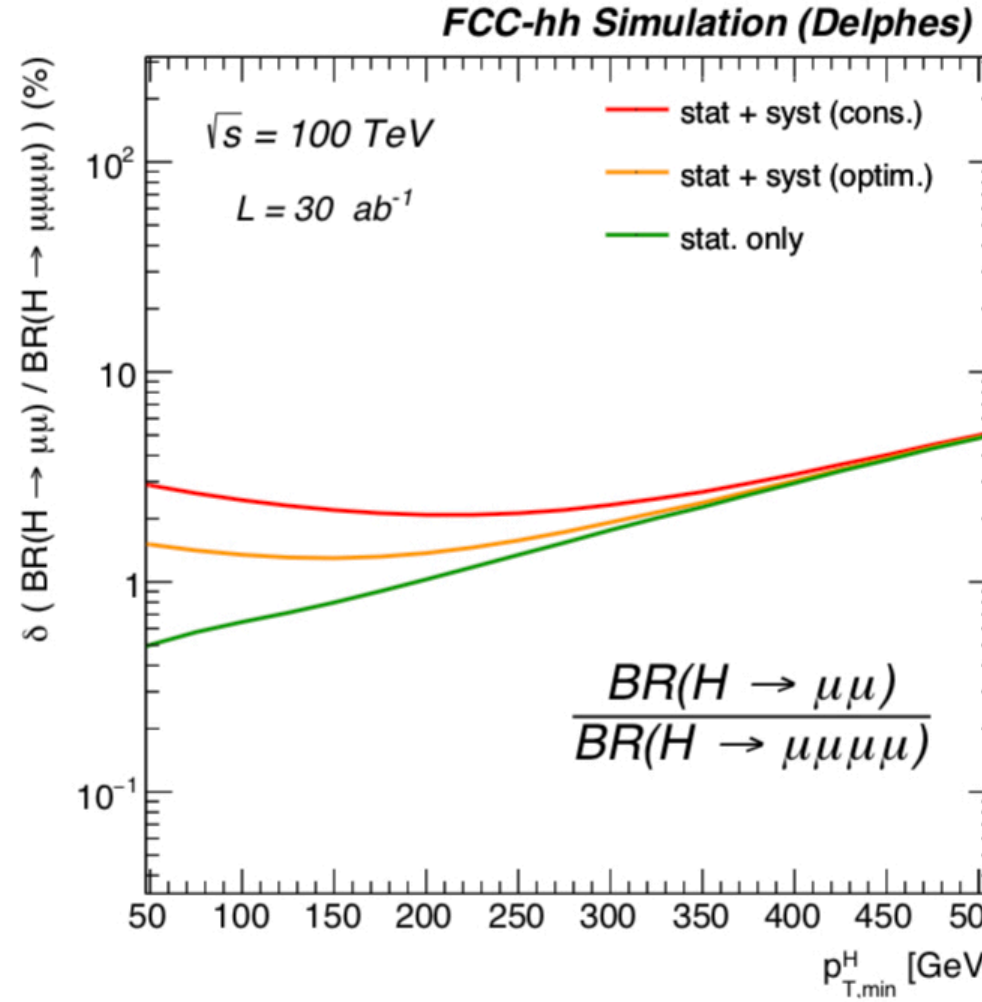
$p_{T,min}^{H}$ [GeV]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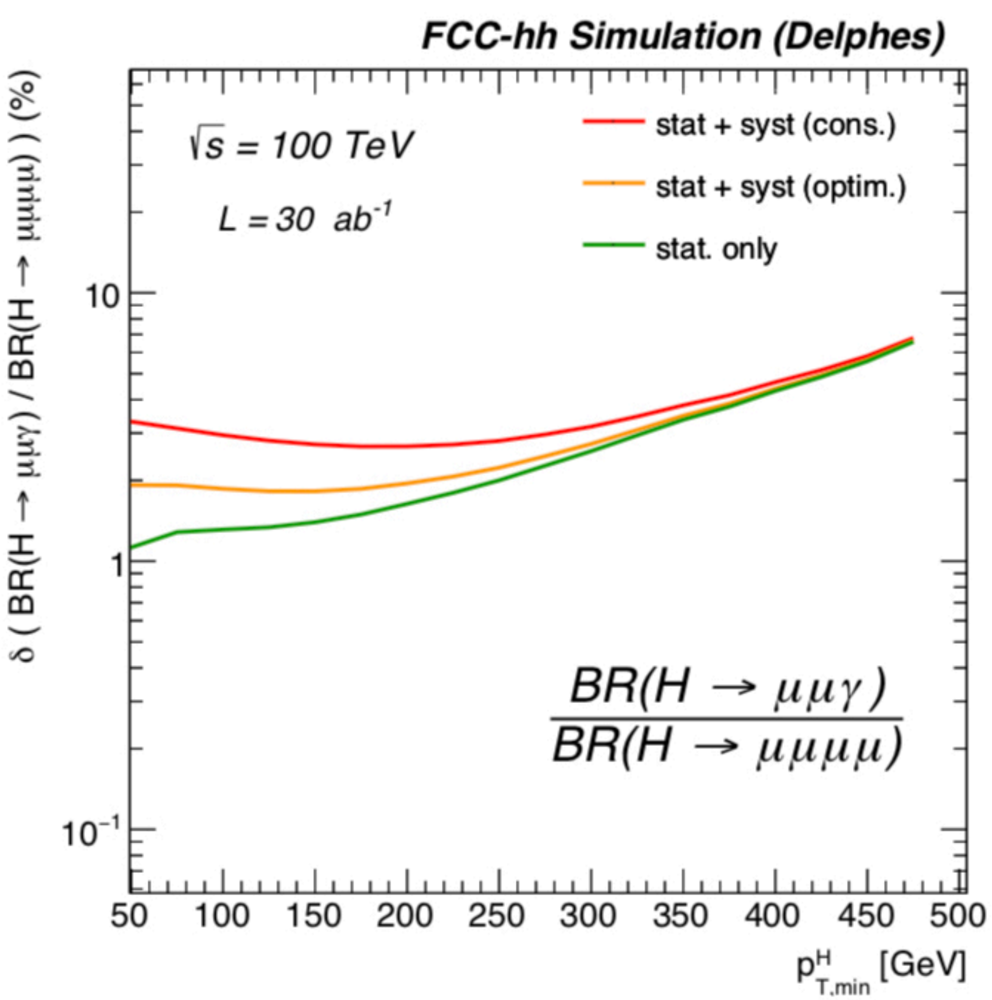
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Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
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$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
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$\delta g_{Hgg} / g_{Hgg}$ (%)	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	–	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (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

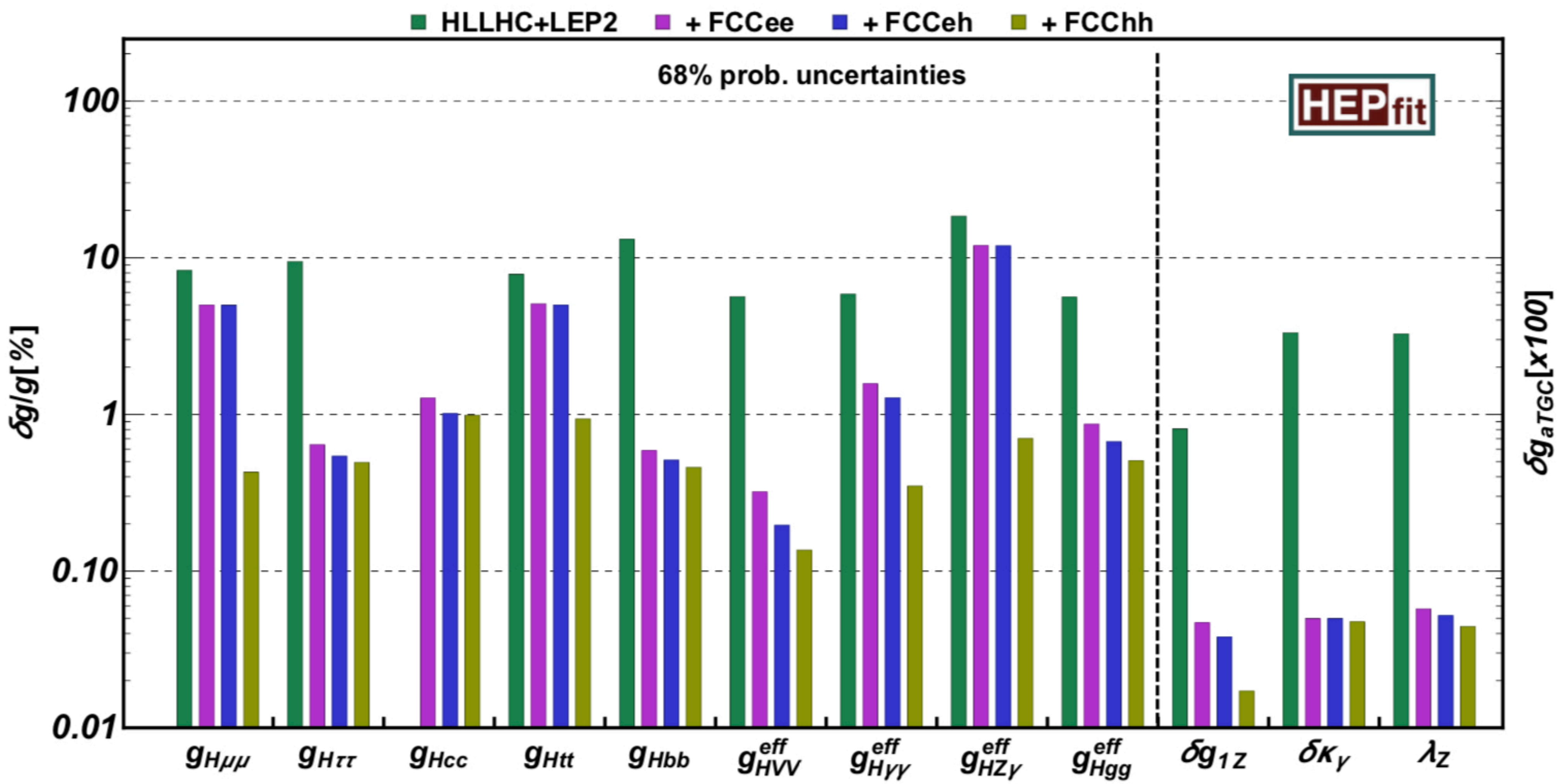


Figure 8.4: One-sigma precision reach at the FCC on the 12 effective single Higgs couplings and aTGC. An absolute precision in the EW measurements is assumed. The different bars illustrate the improvements that would be possible by combining each FCC stage/collider with the previous knowledge at that time (the precisions, not reported here, at each FCC stage/collider considered individually would obviously be quite different). Note that, without a run above the $\mathrm{t\bar{t}H}$ threshold, circular $\mathrm{e^+e^-}$ colliders alone do not directly constrain the g_{Hgg}^{eff} and g_{Htt} couplings individually. The combination with LHC measurements however resolves this flat direction.

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

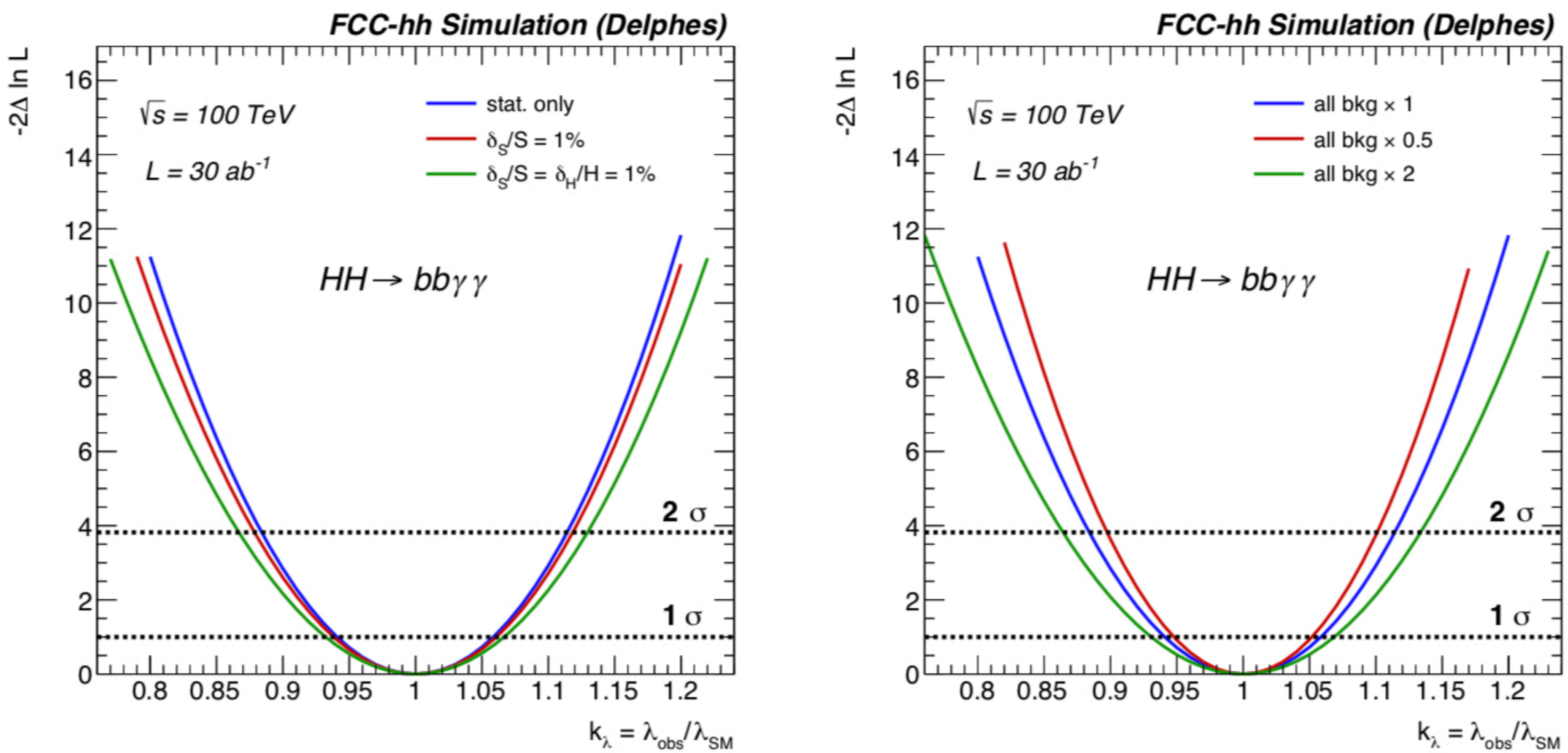
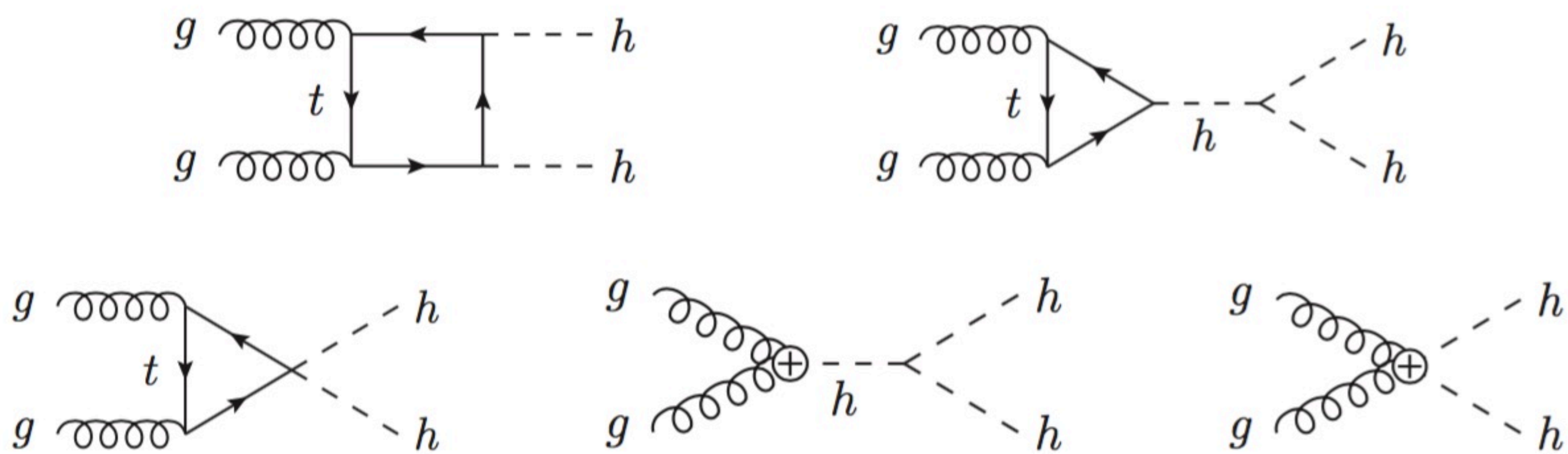


Figure 10.4: Expected precision on the Higgs self-coupling modifier κ_λ with no systematic uncertainties (only statistical), 1% signal uncertainty, 1% signal uncertainty together with 1% uncertainty on the Higgs backgrounds (left) and assuming respectively ×1, ×2, ×0.5 background yields (right).)

Extracting Higgs self-coupling from gg→HH at FCC-hh



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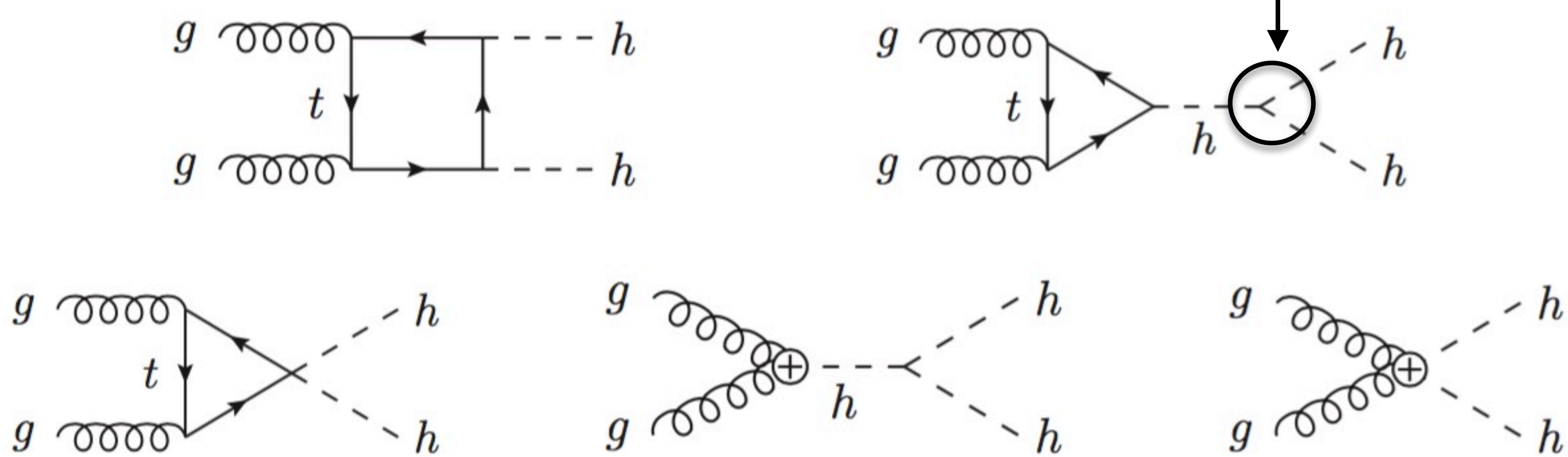
to probe …



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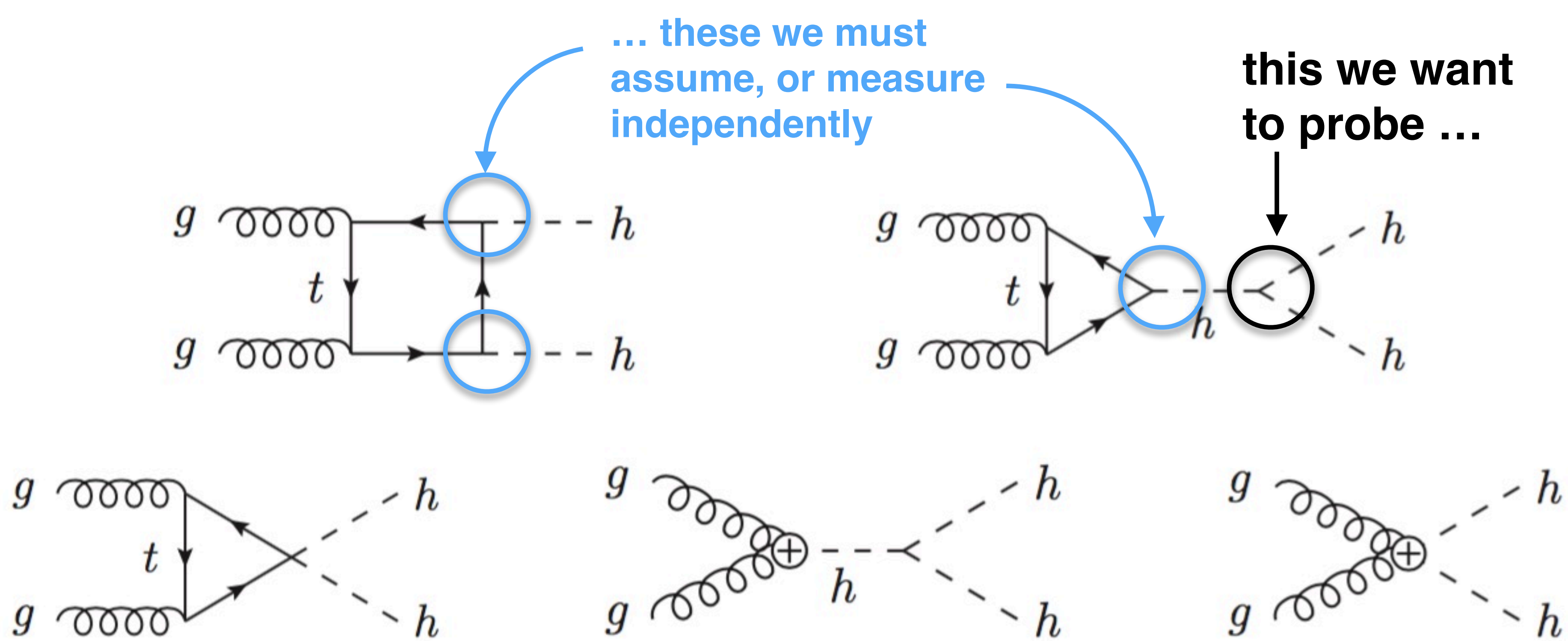
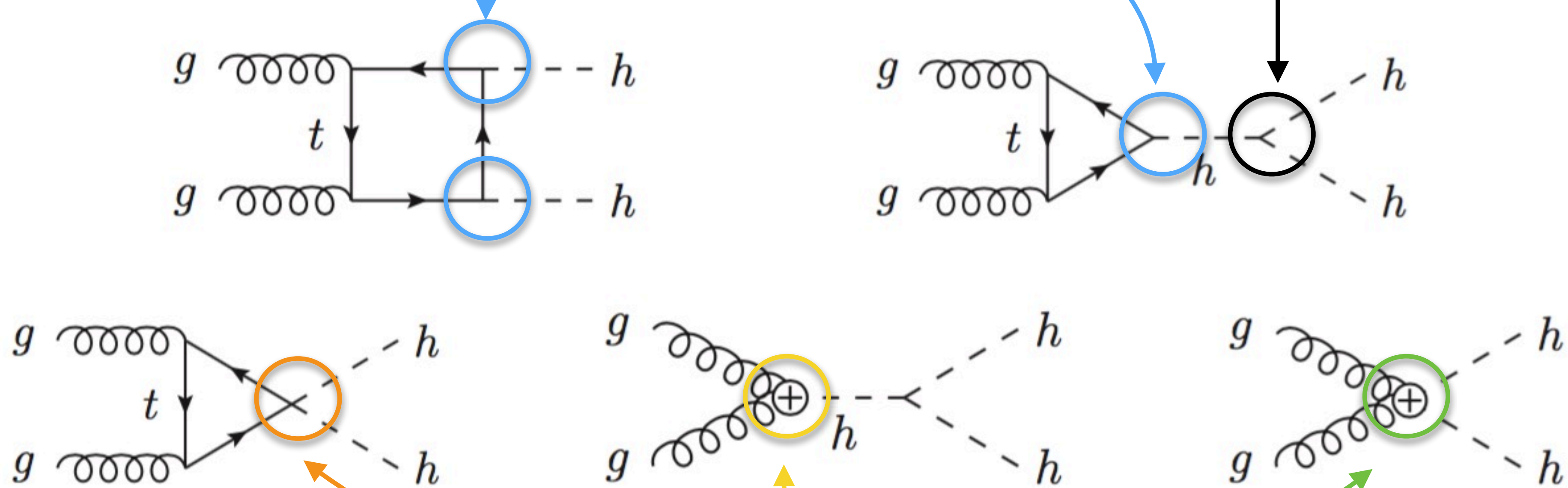


Extracting Higgs self-coupling from gg→HH at FCC-hh

… these we must assume, or measure independently

this we want to probe …

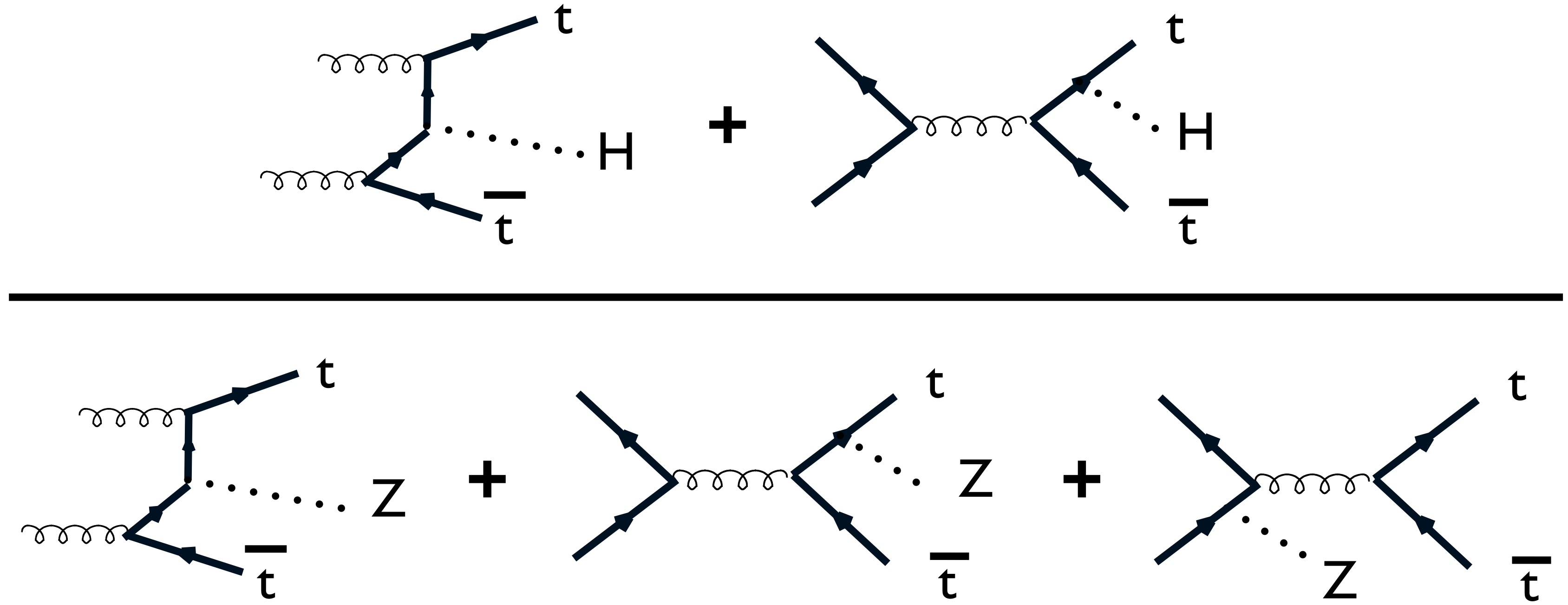


… these would come into play if we eventually need to decode the origin of a deviation, as possible alternative sources of new physics

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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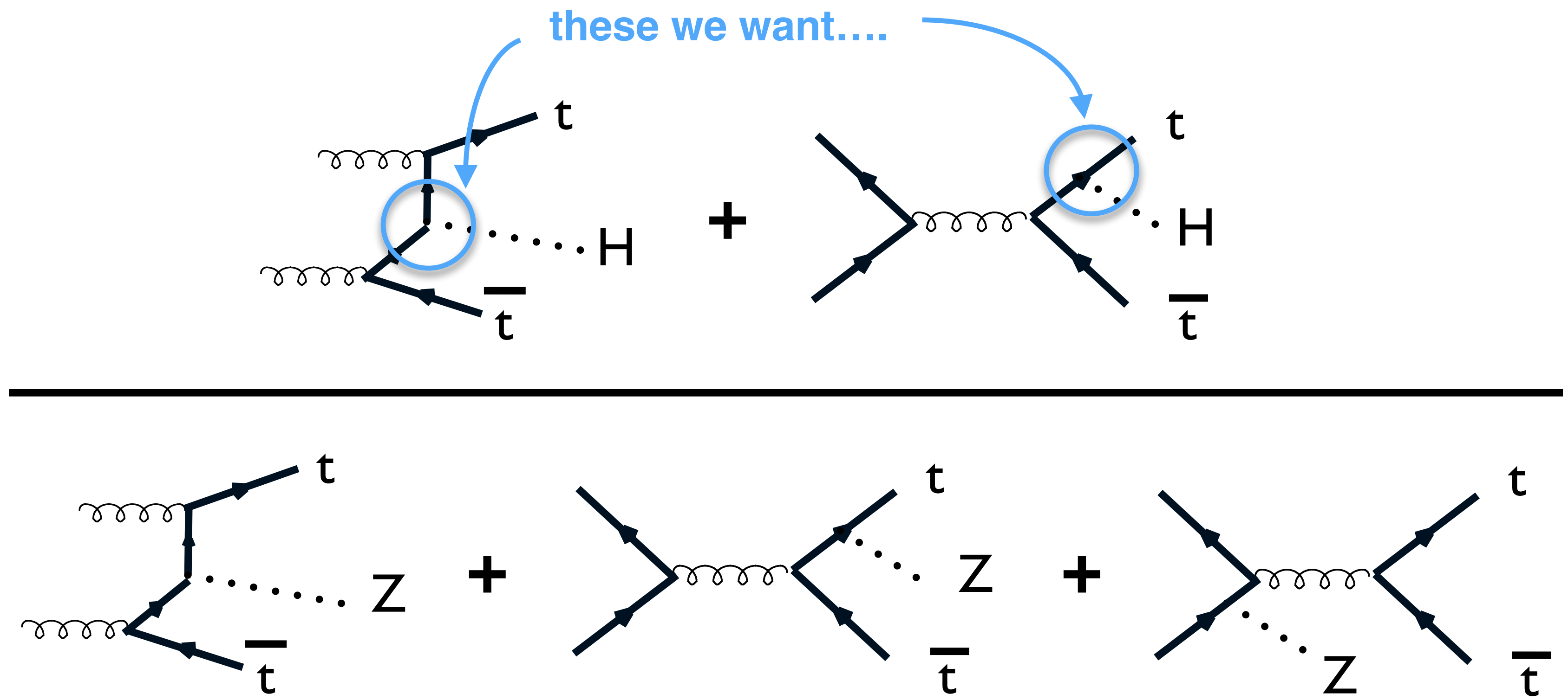

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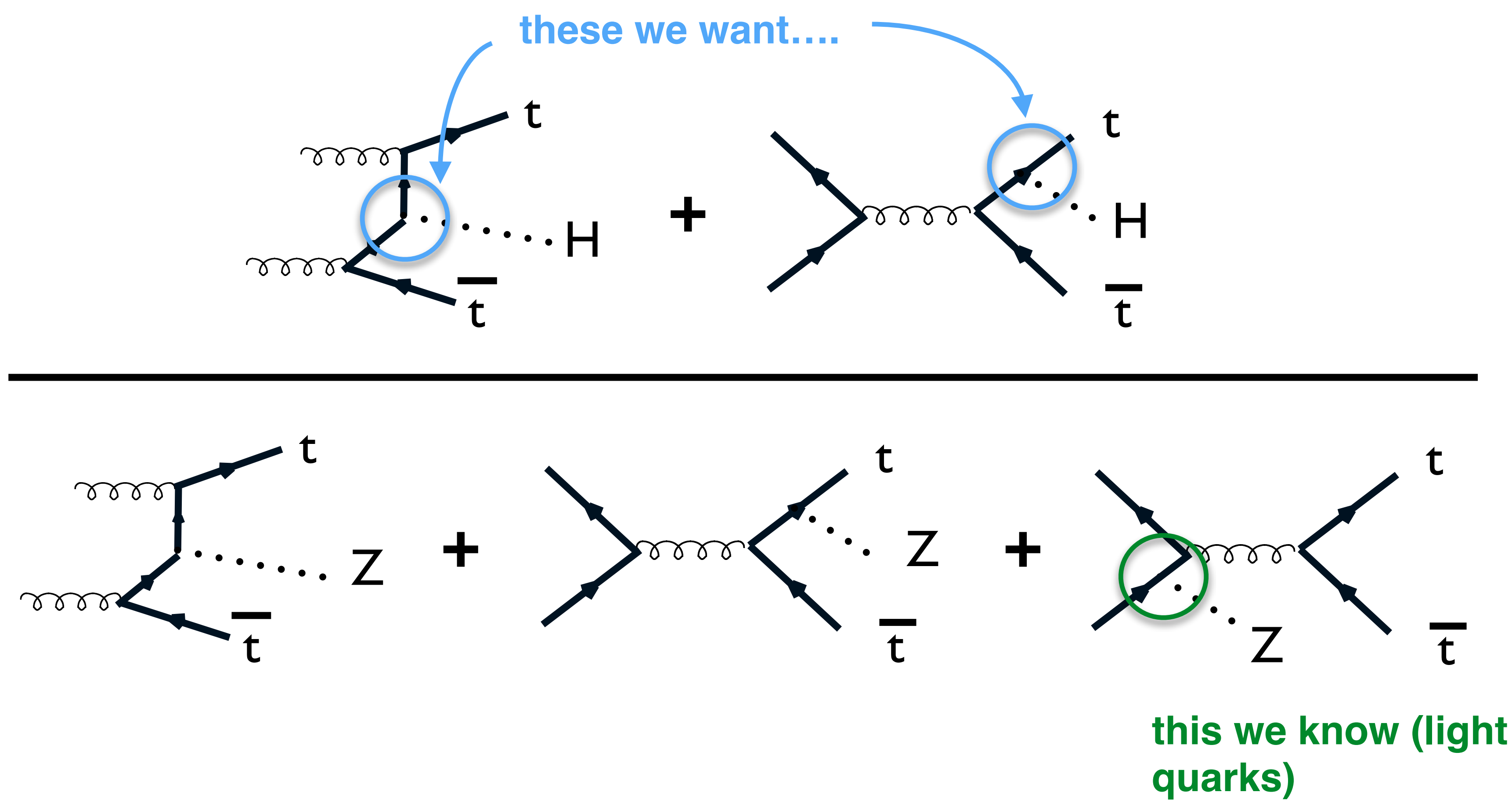

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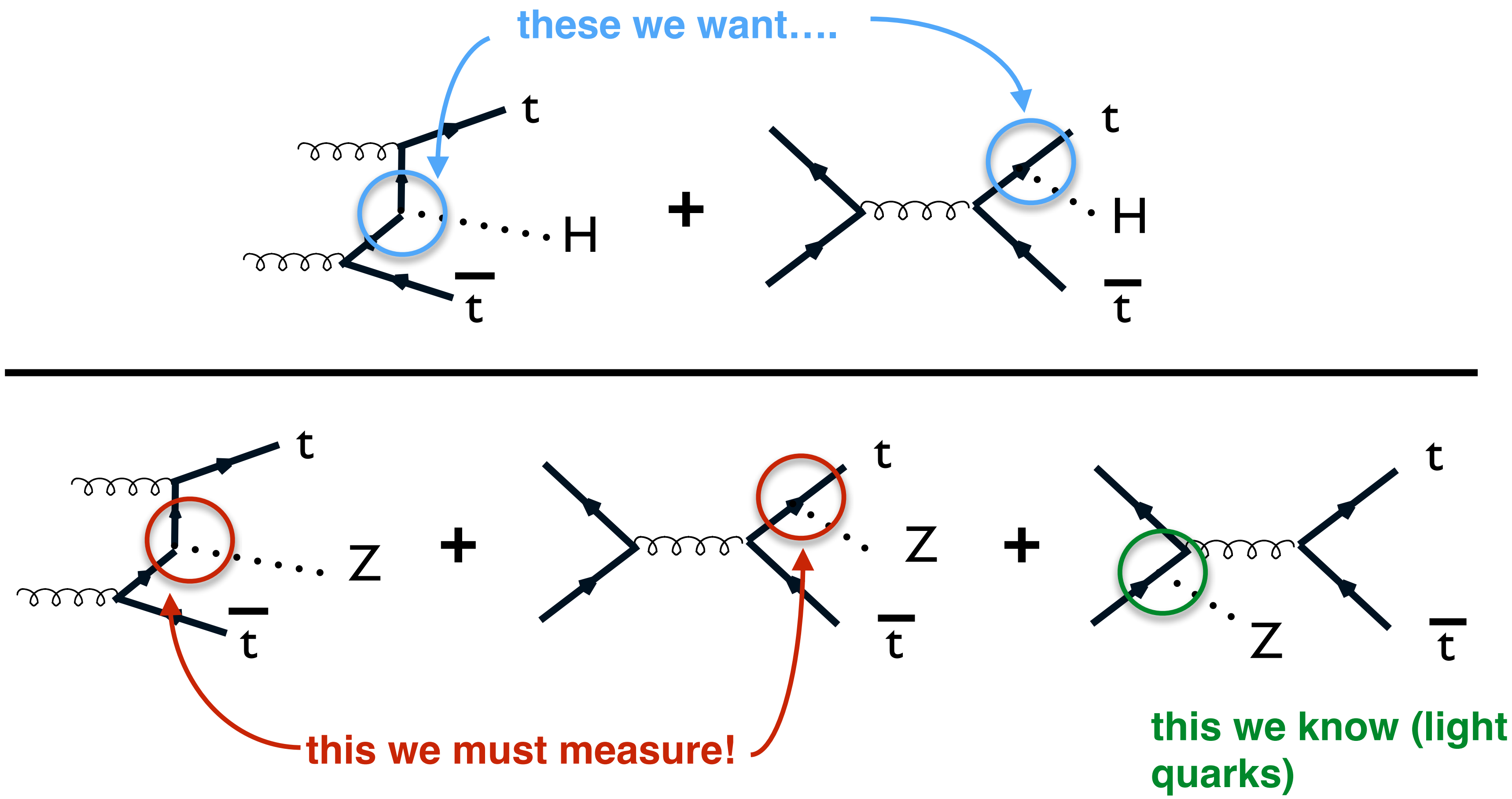

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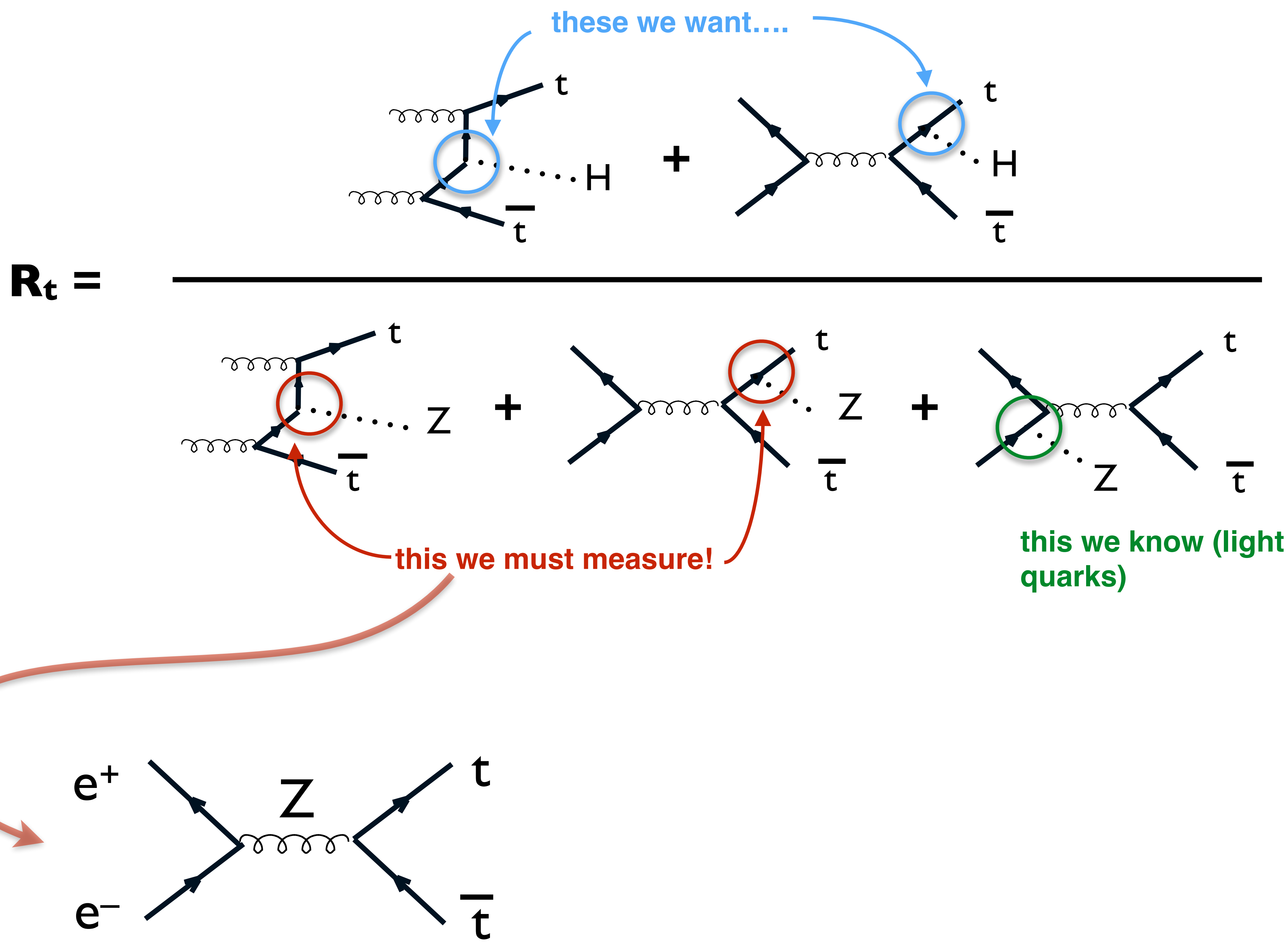

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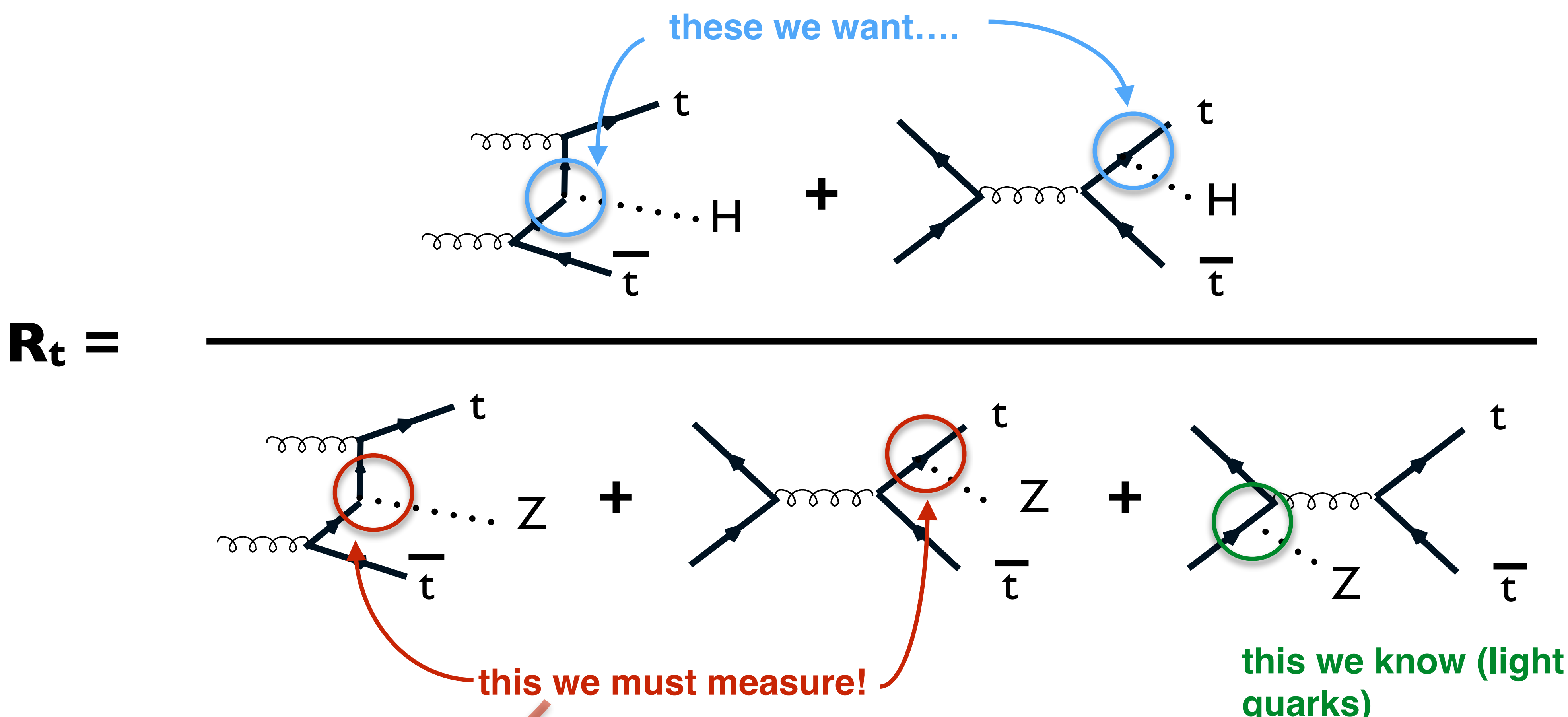
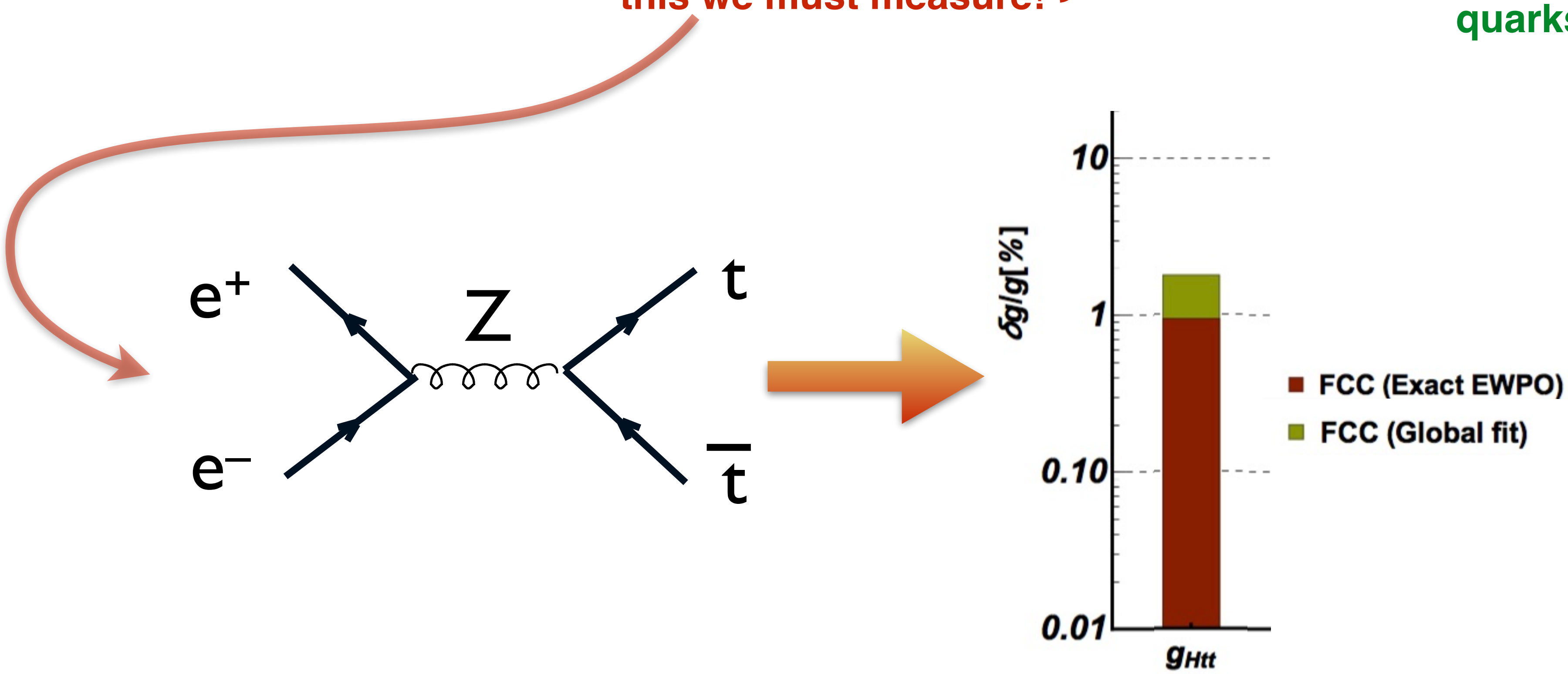
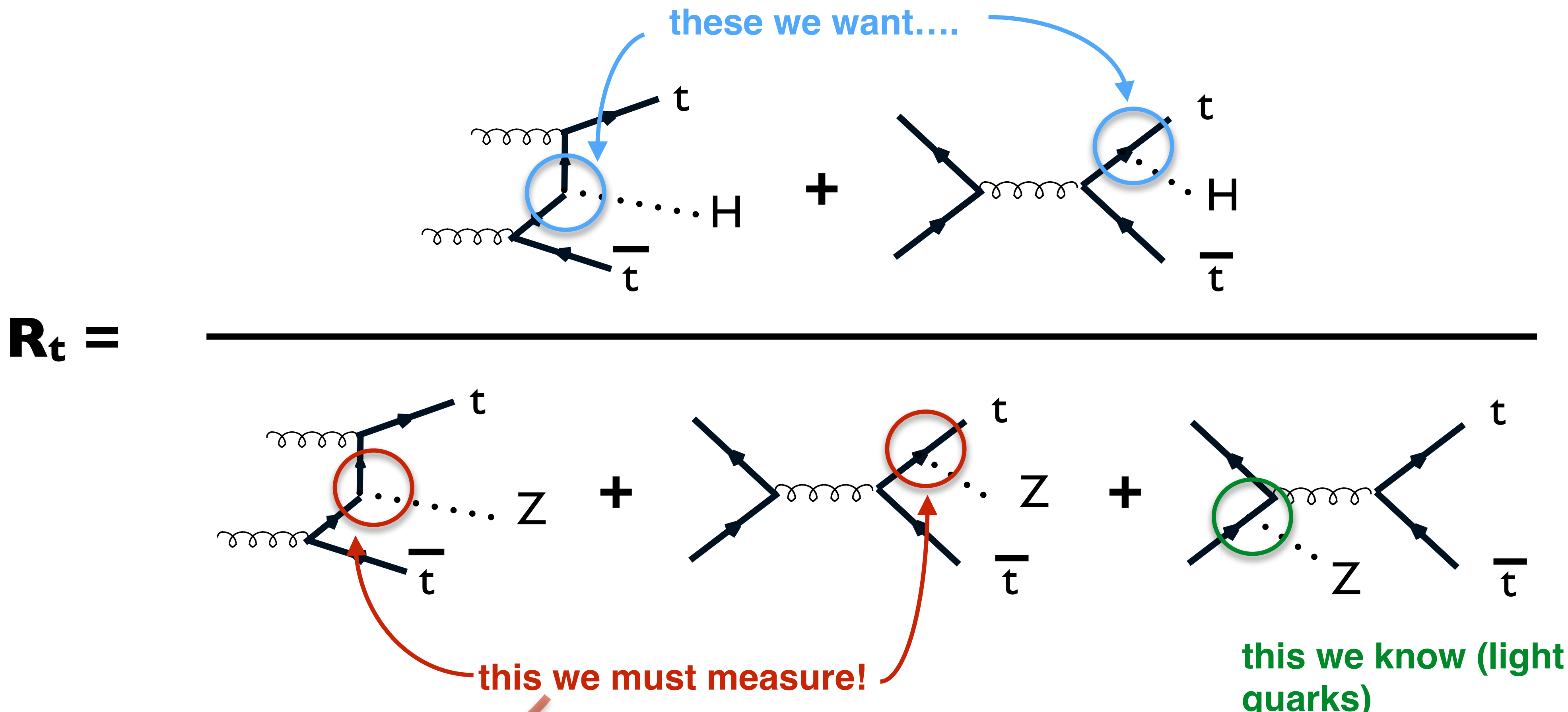
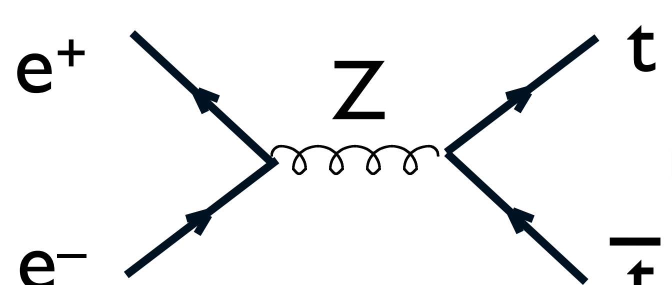


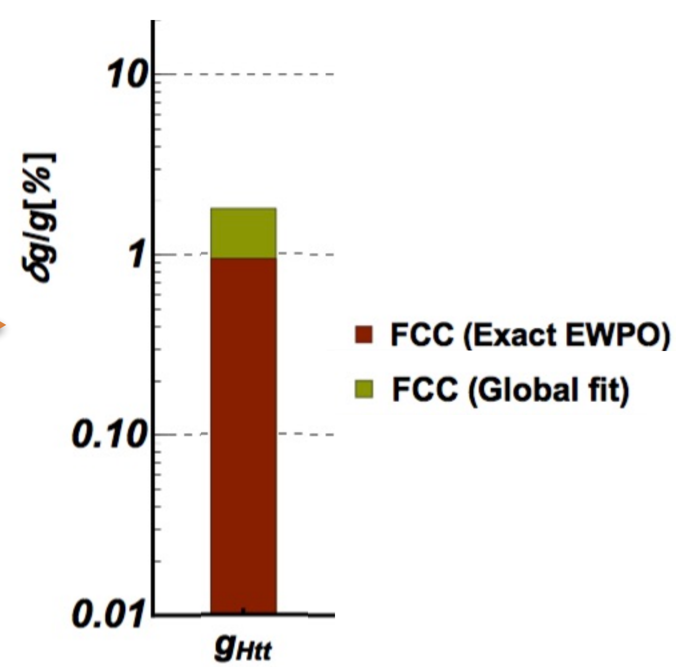


Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

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



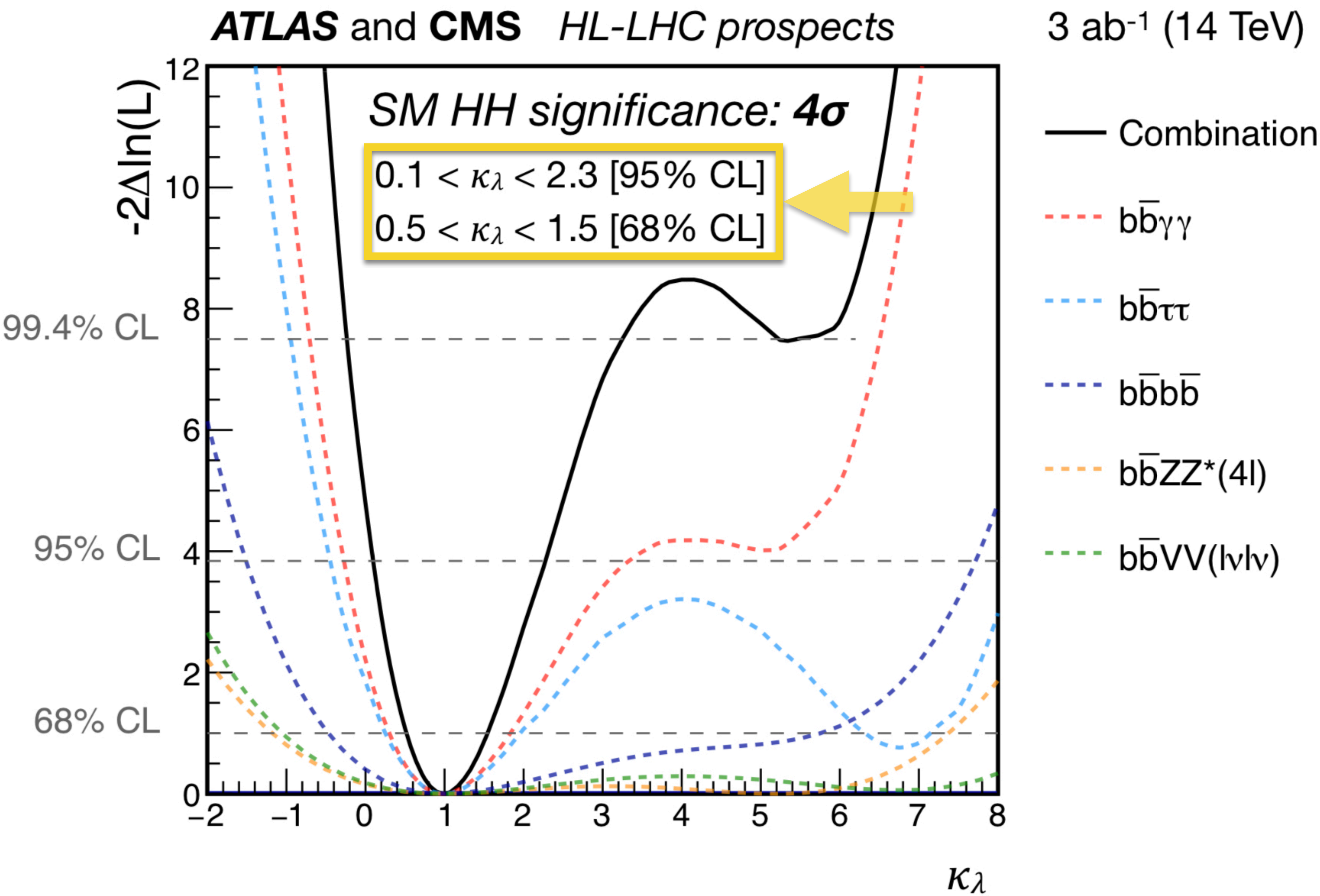




$\delta\lambda/\lambda$=5% from gg→HH assuming SM inputs

$\delta\lambda/\lambda$ ~ 10% from global fit

FYI: Higgs self-coupling projections @ HL-LHC *

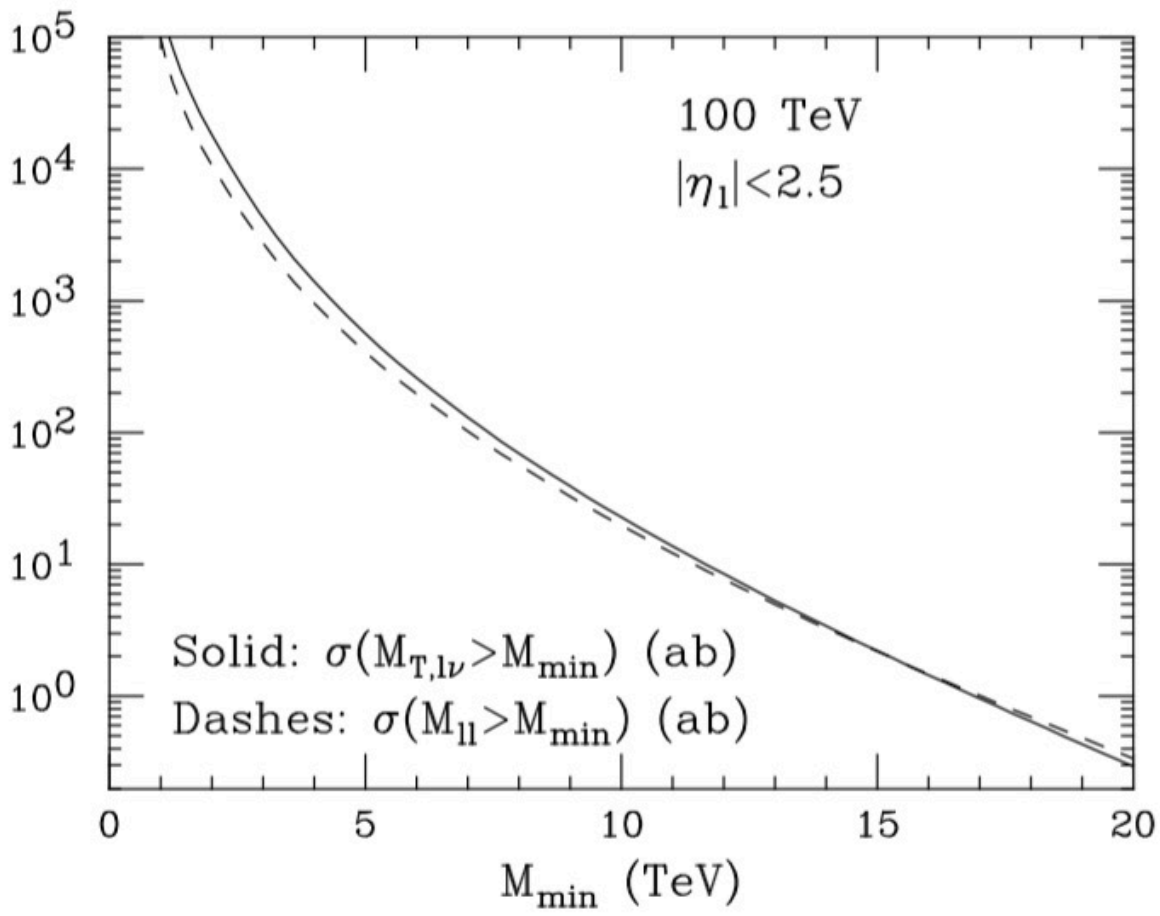


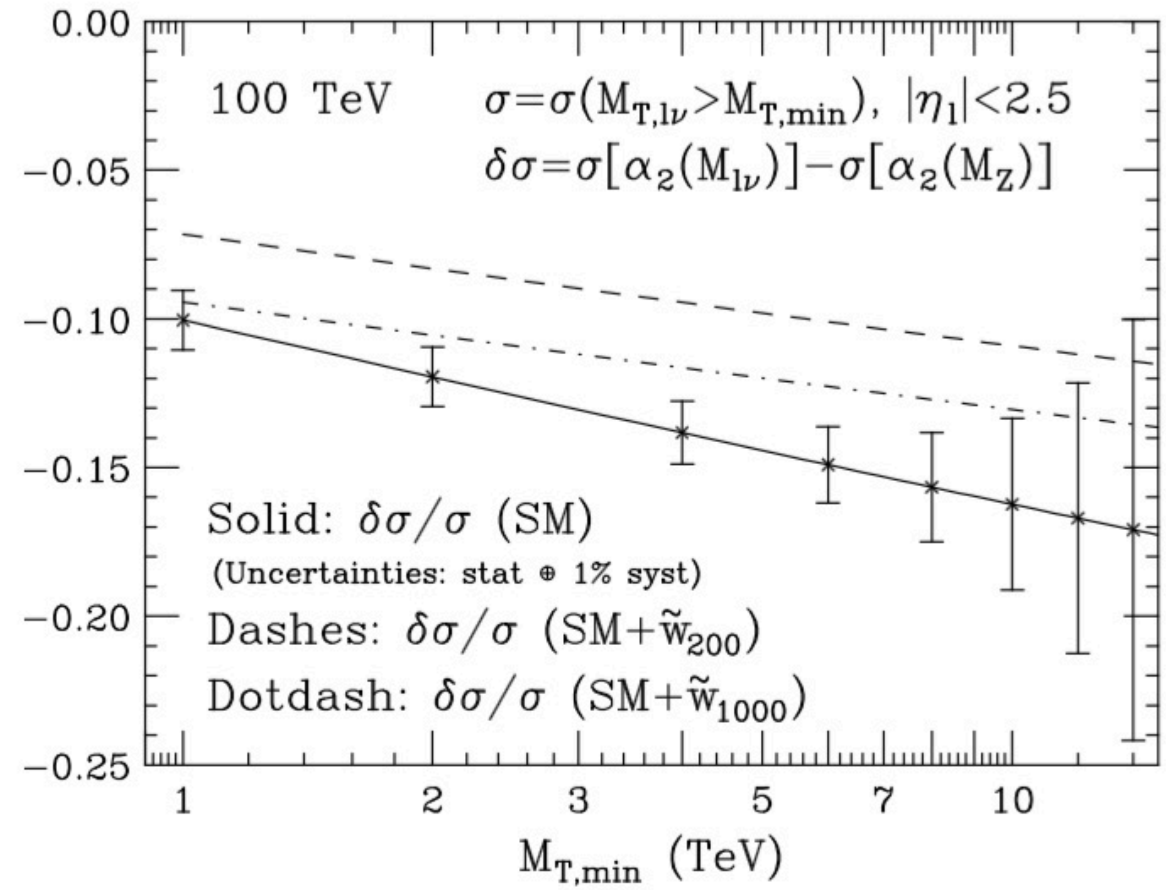
* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

High-Q^2 probes of EW dynamics & EWSB

Example: high mass DY

α_W running and sensitivity to new EW particles





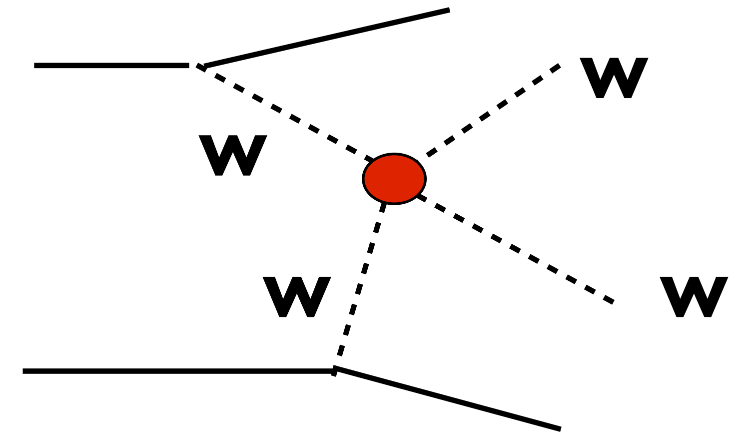
Constraints on Higher-dim op's

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

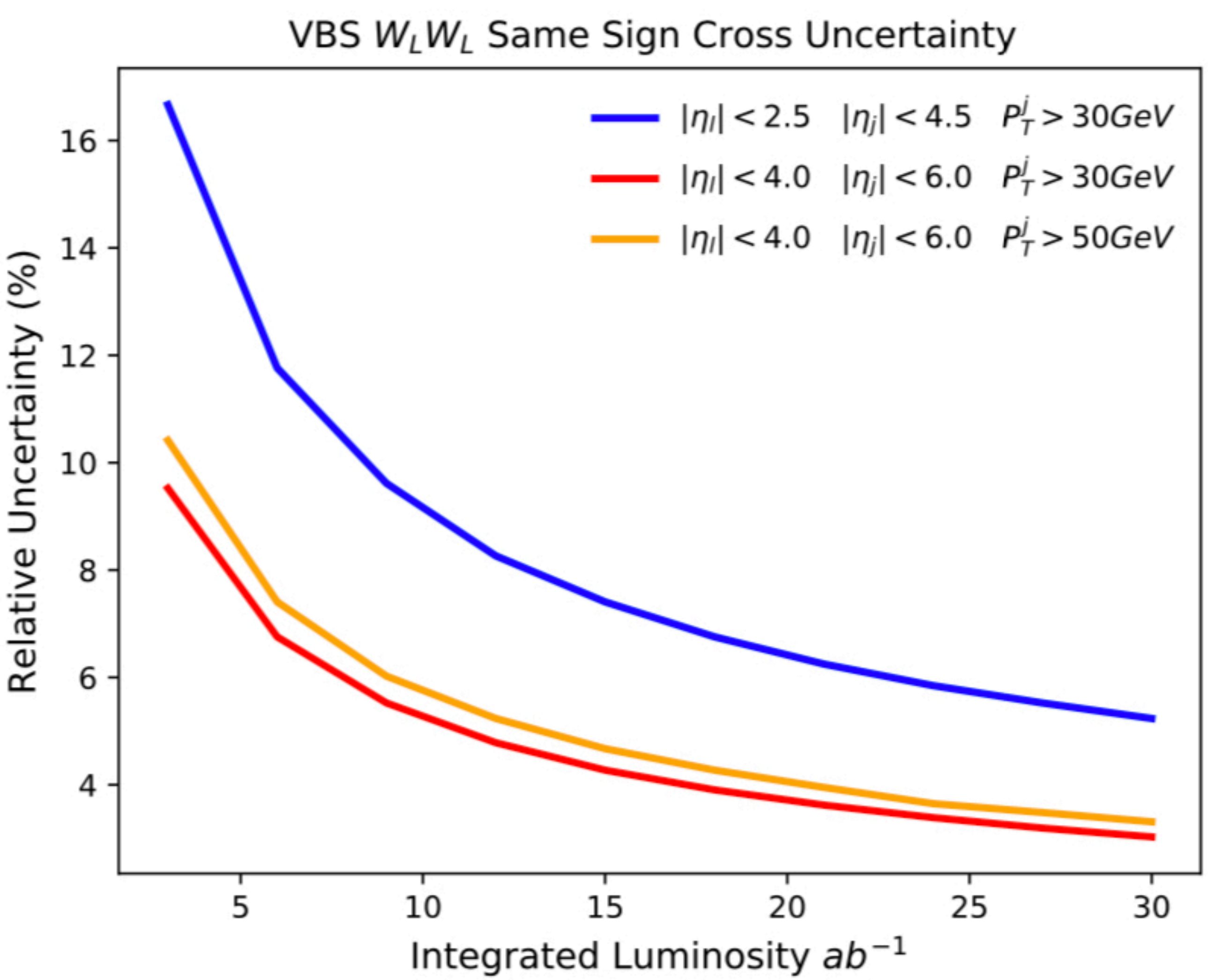
		LEP	ATLAS 8	CMS 8	LHC 13		FCC-hh	FCC-ee
	luminosity	$2\times10^7\,Z$	$19.7\,\mathrm{fb}^{-1}$	$20.3\,\mathrm{fb}^{-1}$	$0.3\,\mathrm{ab}^{-1}$	$3\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$10^{12}\,Z$
NC	W $\times10^4$	[−19, 3]	[−3, 15]	[−5, 22]	±1.5	±0.8	±0.04	±1.2
	Y $\times10^4$	[−17, 4]	[−4, 24]	[−7, 41]	±2.3	±1.2	±0.06	±1.5
CC	W $\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—

$W / 4m_W^2 \;<\; 1/(100\ \mathrm{TeV})^2$

$W_L W_L$ scattering



large m_{WW}



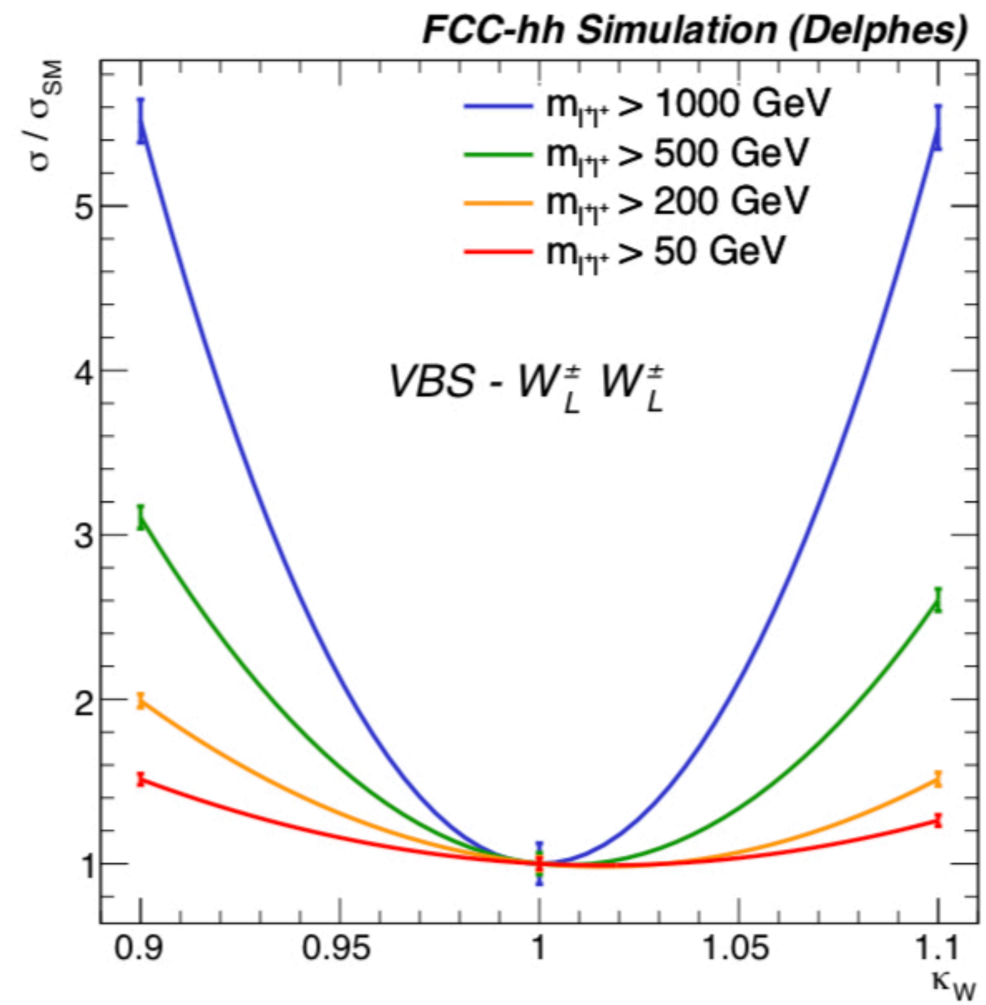


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

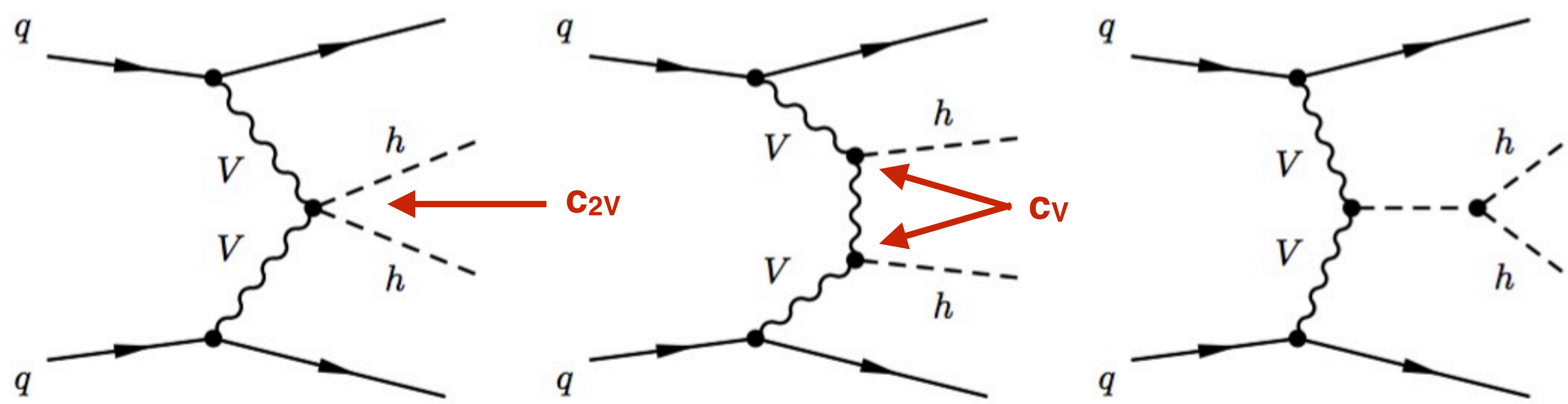
$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

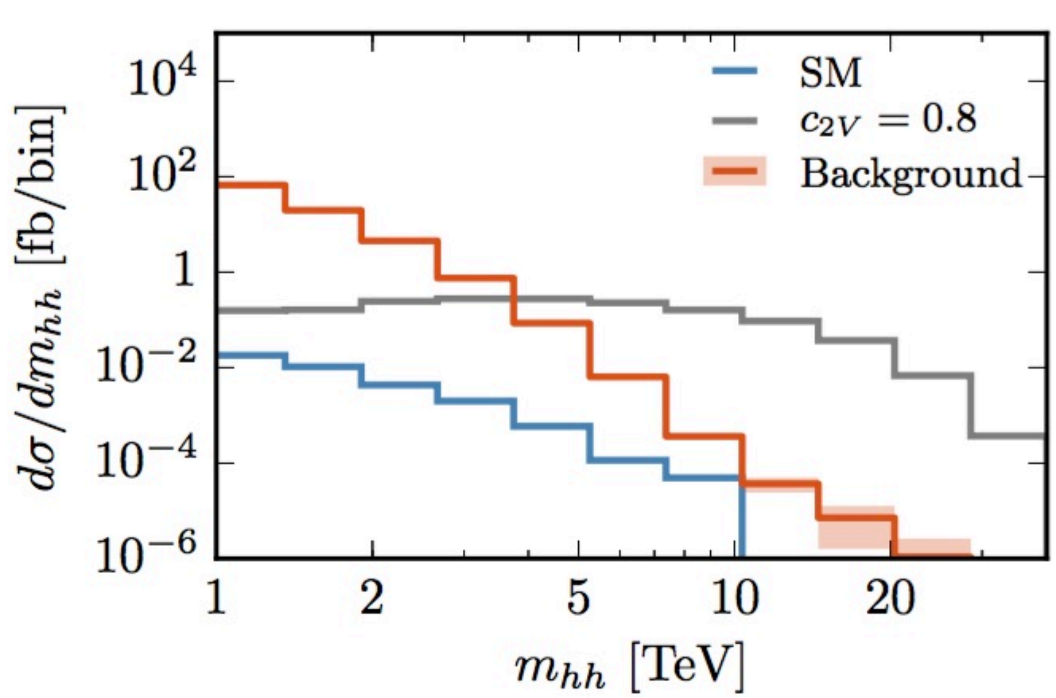
Example: high mass VV → HH

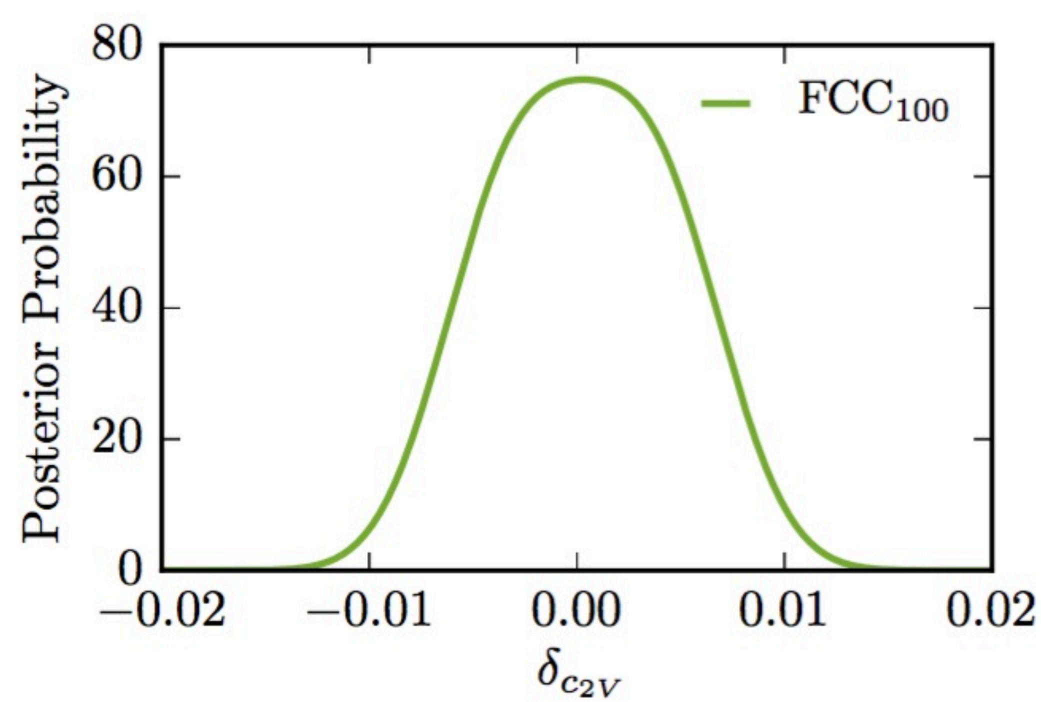
see also I.Low talk in // session

$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)\,.$$

$c_{2V} = c_V^2$ in the SM

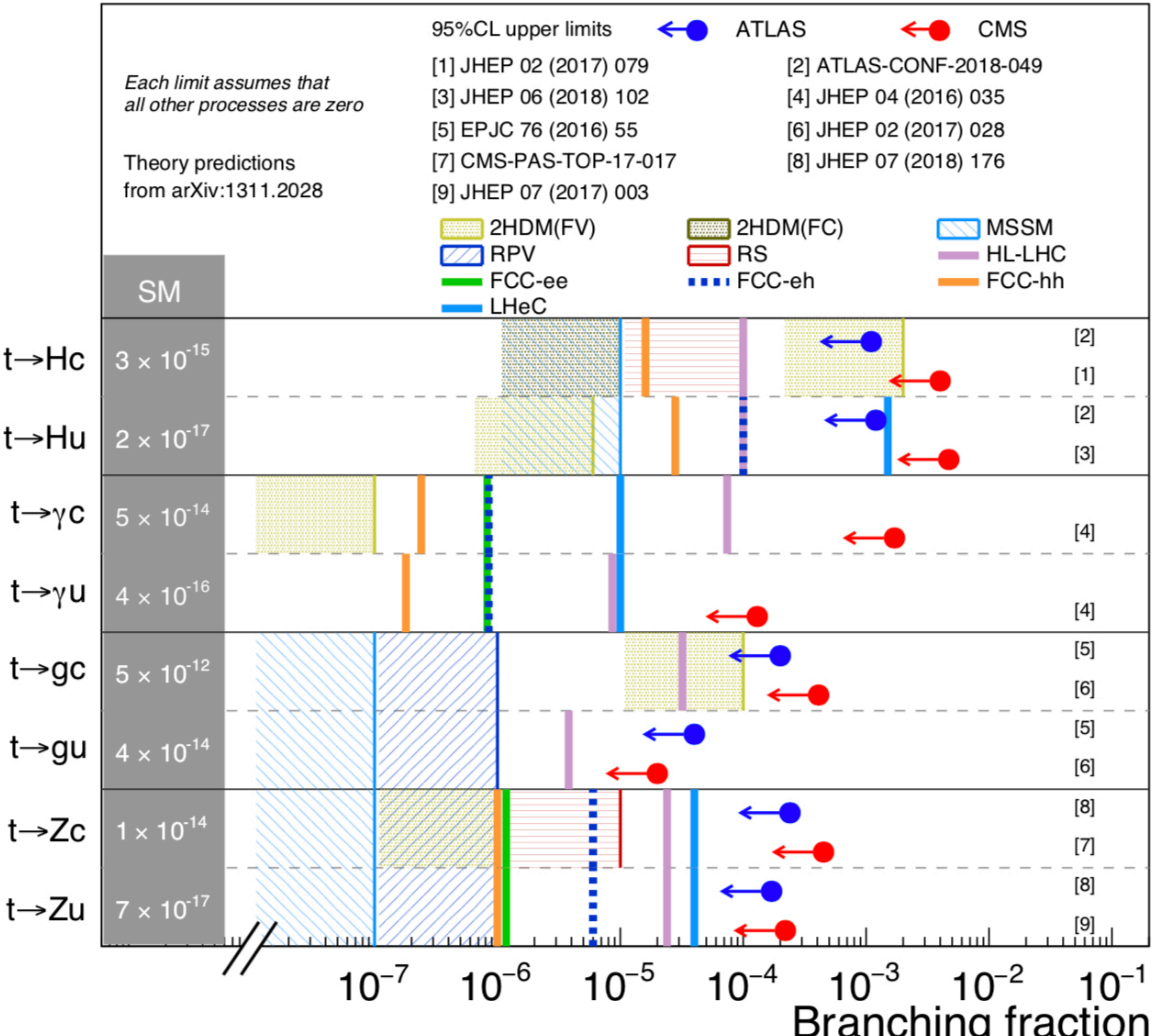






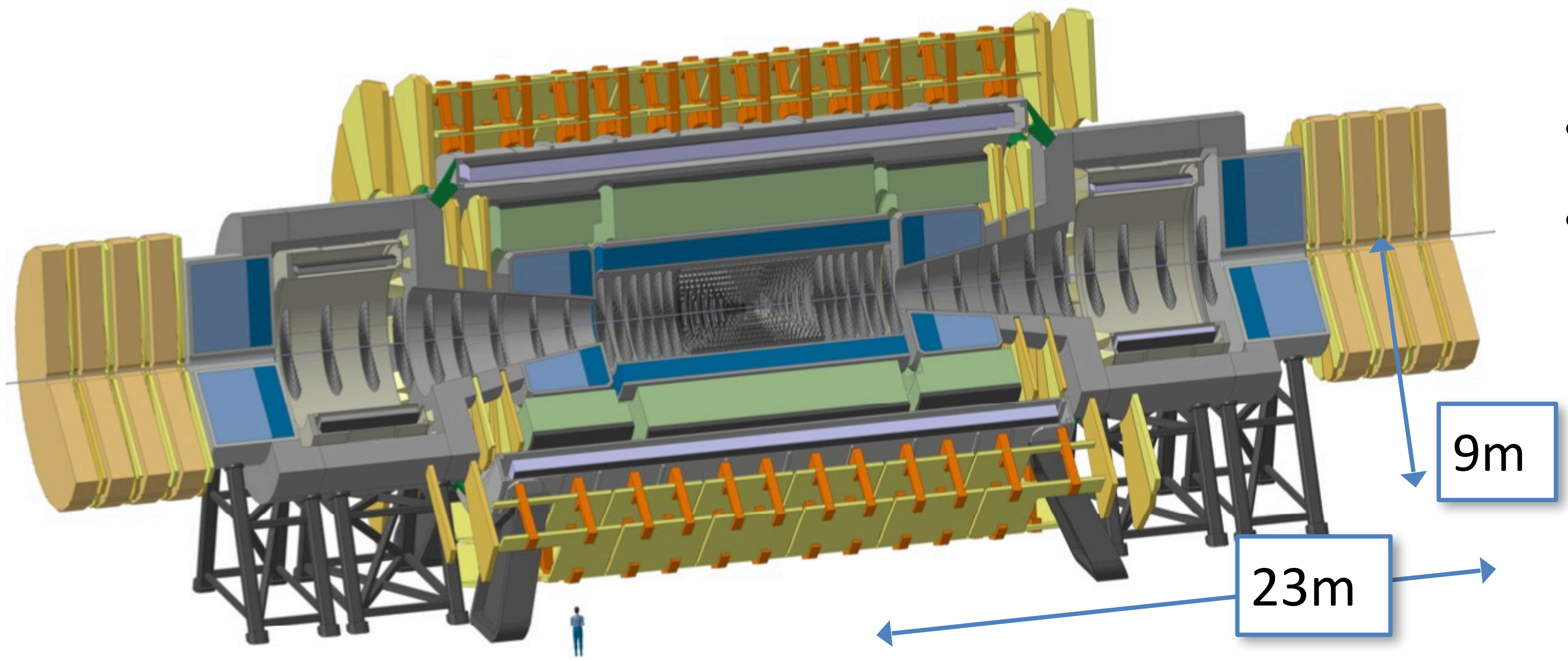
F. Bishara, R. Contino, and J. Rojo, *Higgs pair production in vector-boson fusion at the LHC and beyond*, Eur. Phys. J. **C77** (2017) no. 7, 481, arXiv:1611.03860 [hep-ph].

FCNC top quark decays



Direct discovery reach: the power of 100 TeV

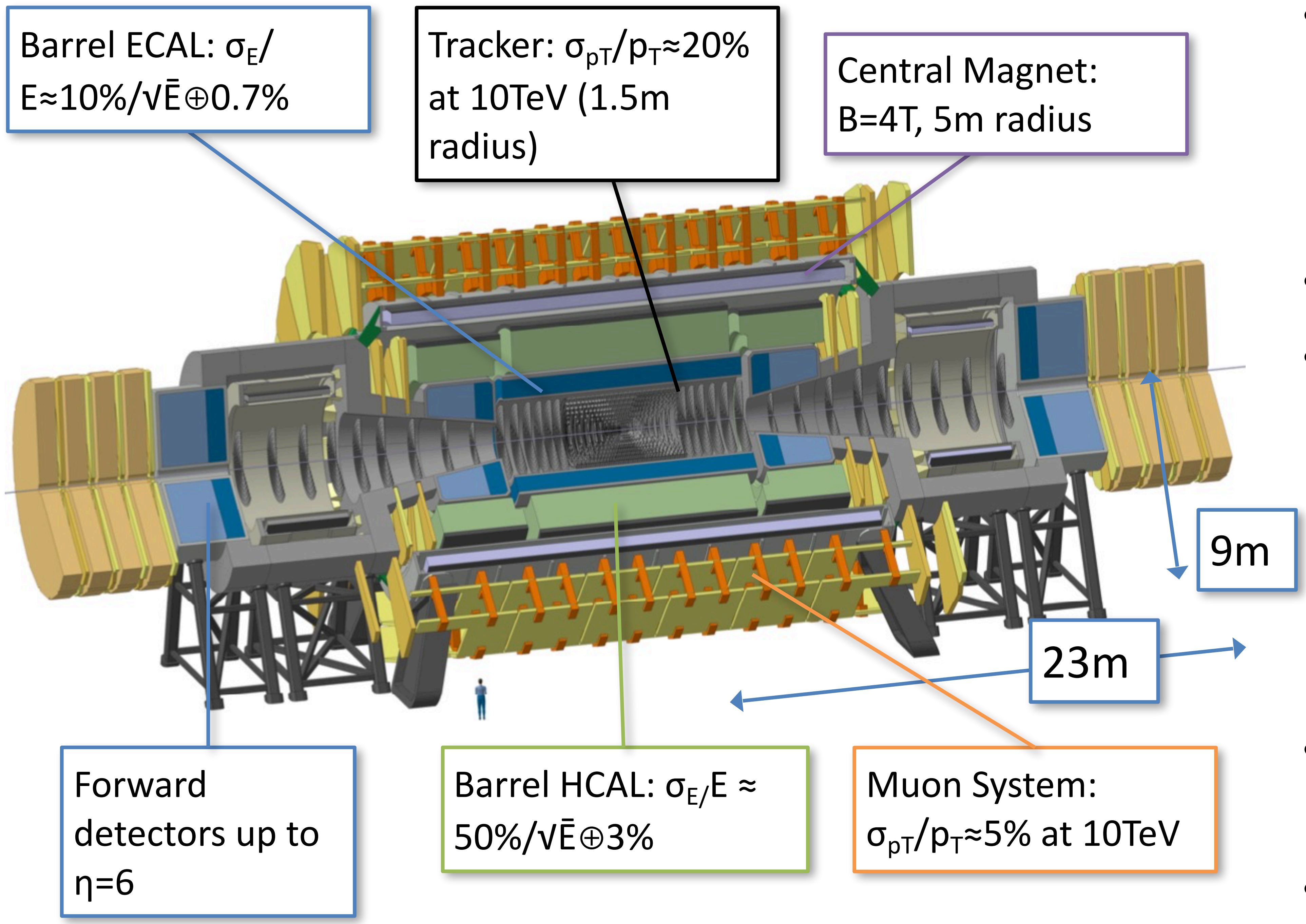
FCC-hh Detector – Reference Design for CDR



- During last years converged on **reference design for an FCC-hh experiment**
- **Radiation simulations**
- Demonstrate in the CDR document, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
- → **Input for Delphes physics simulations**
- Room for other ideas, other concepts and different technologies

See FCC CDR Volume 3, Chapter 7

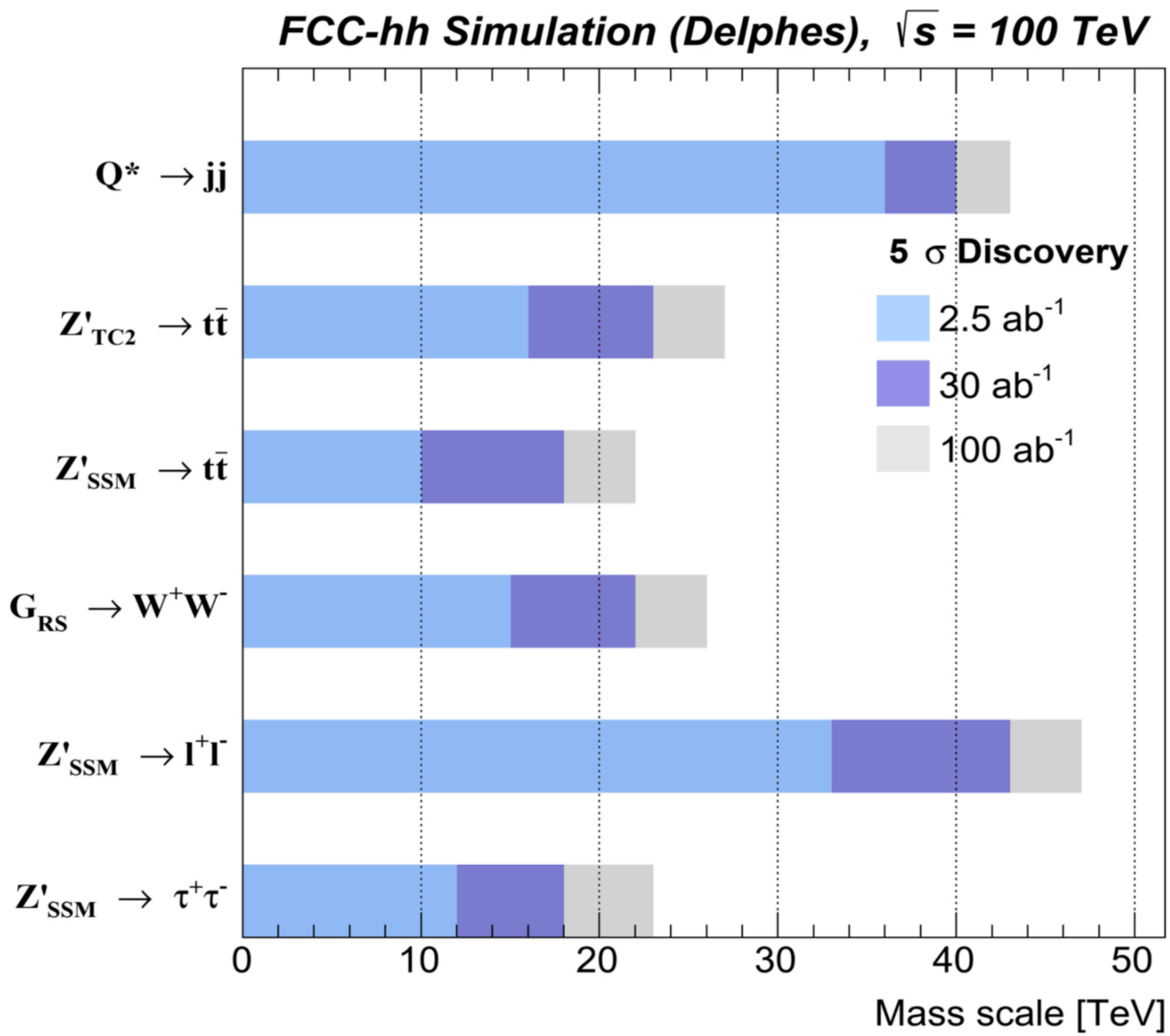
FCC-hh Detector – Reference Design for CDR



- During last years converged on **reference design for an FCC-hh experiment**
- **Radiation simulations**
- Demonstrate in the CDR document, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
- → **Input for Delphes physics simulations**
- Room for other ideas, other concepts and different technologies

See FCC CDR Volume 3, Chapter 7

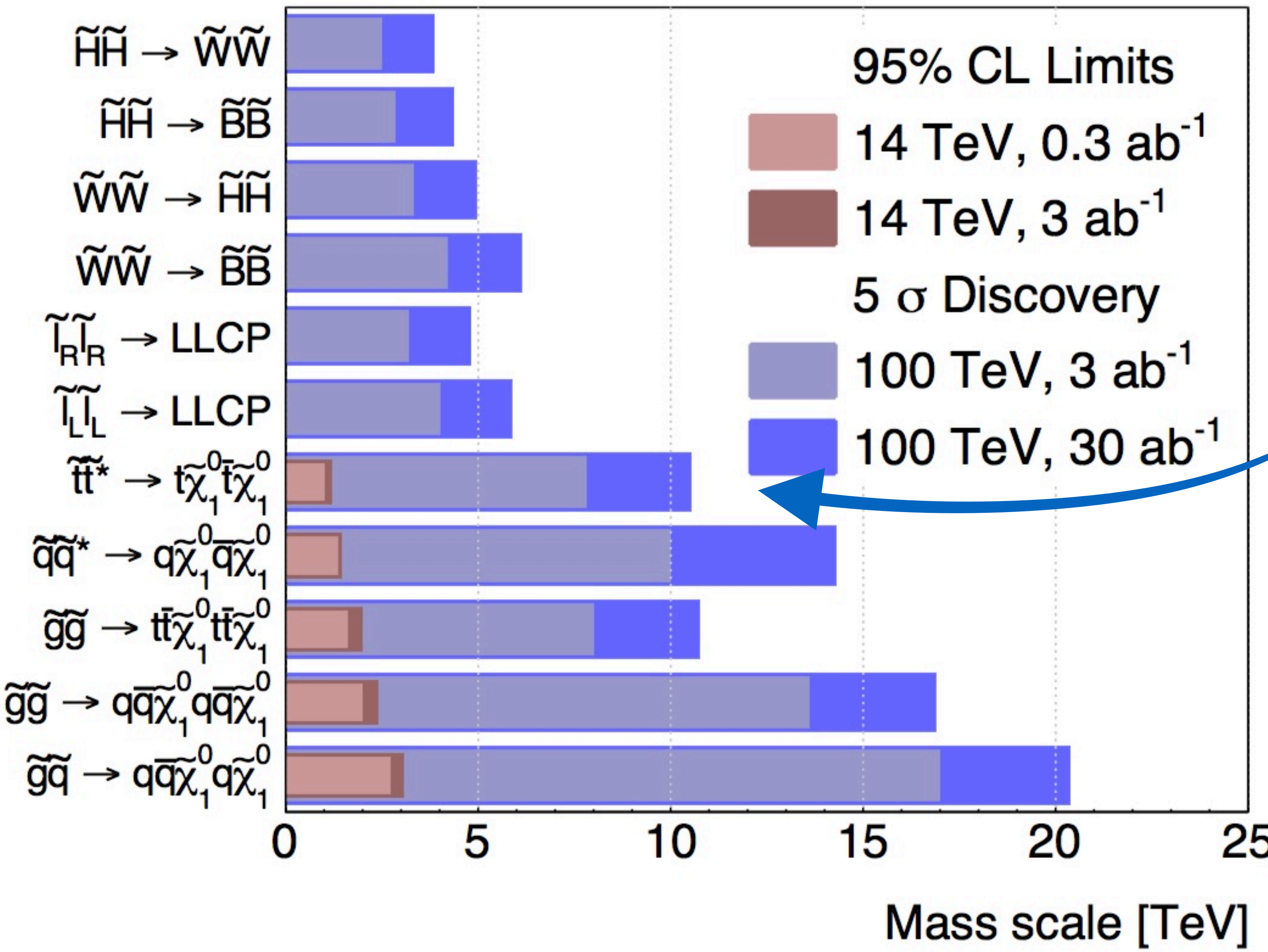
s-channel resonances



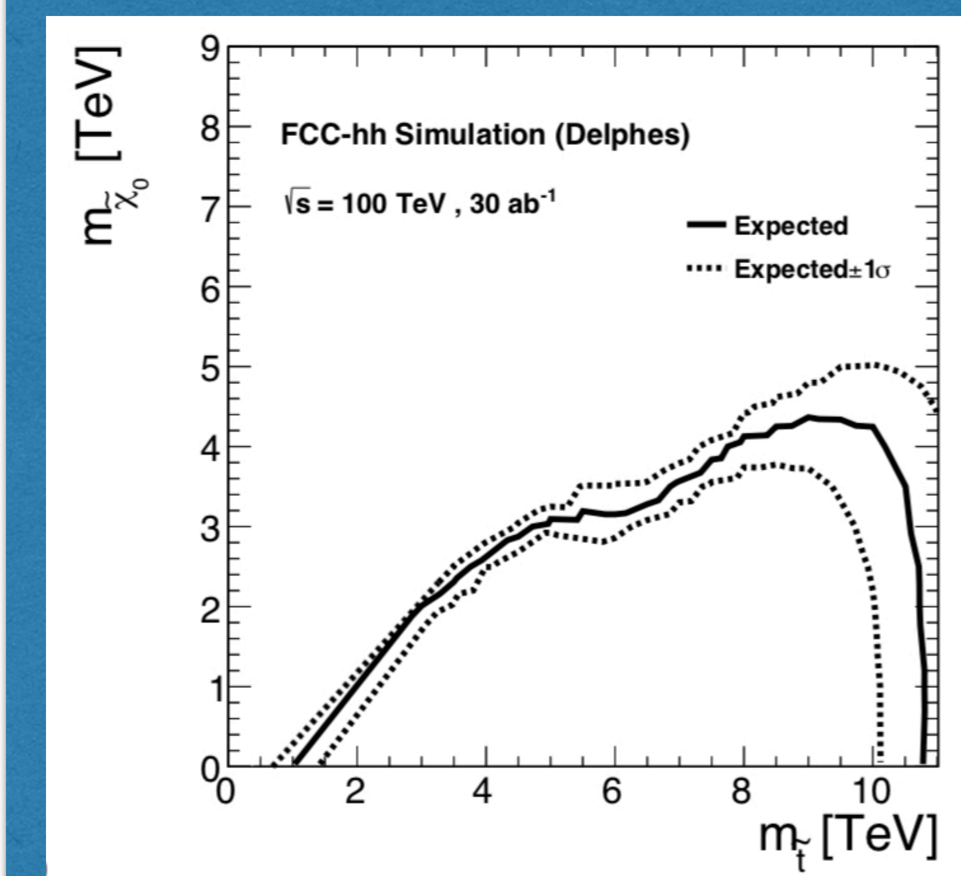
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies

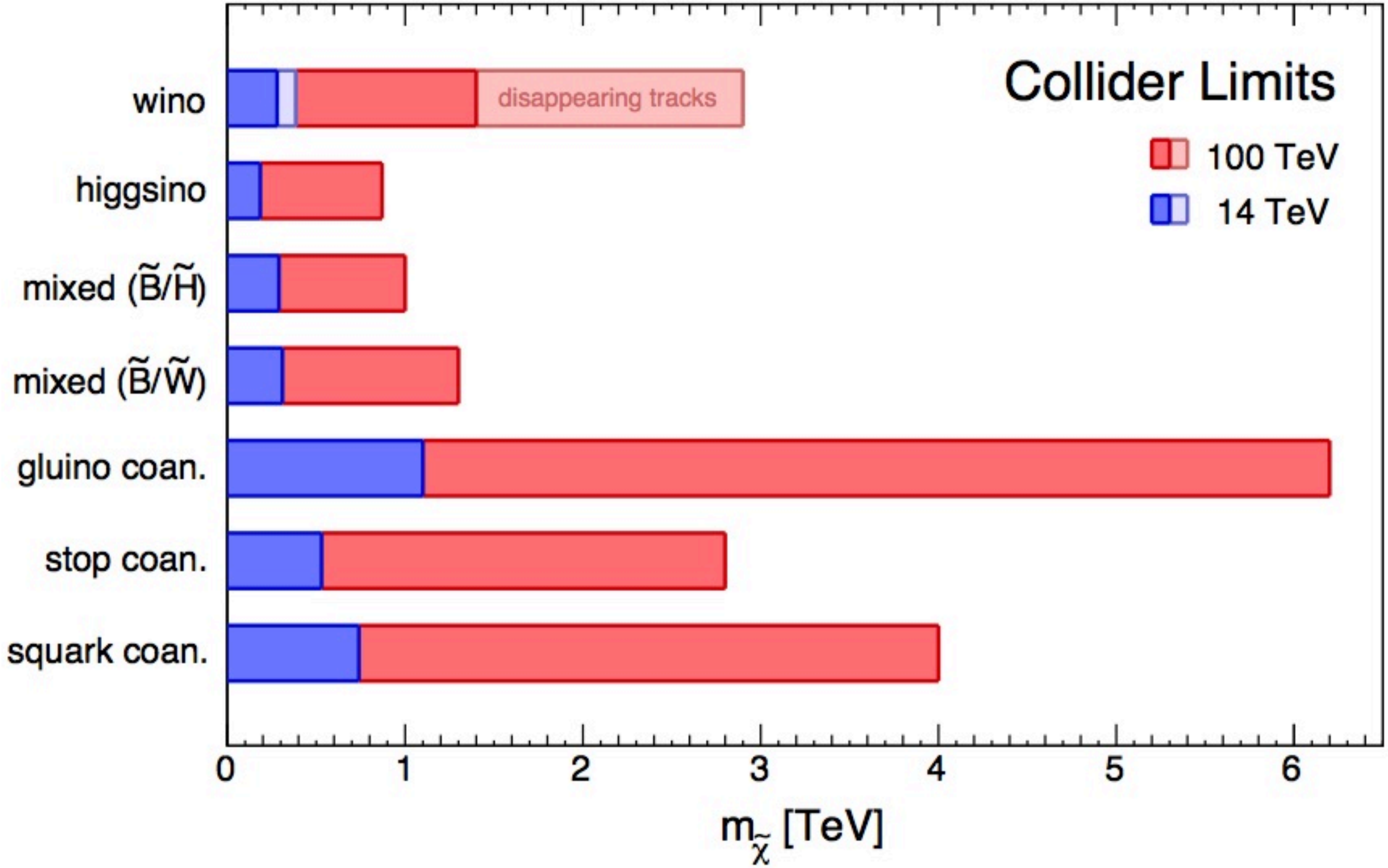


New detector performance studies



DM reach at 100 TeV

Early phenomenology studies

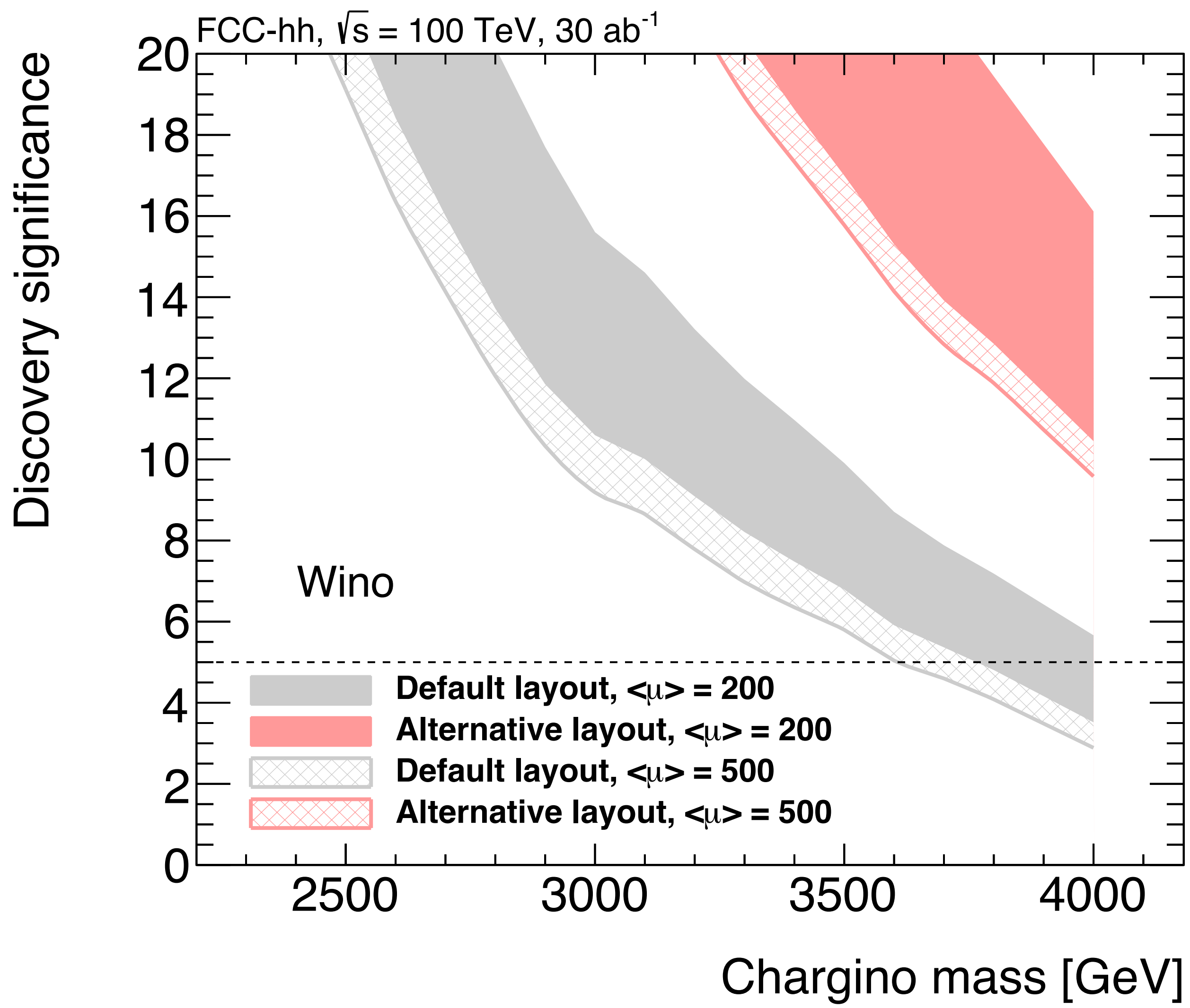


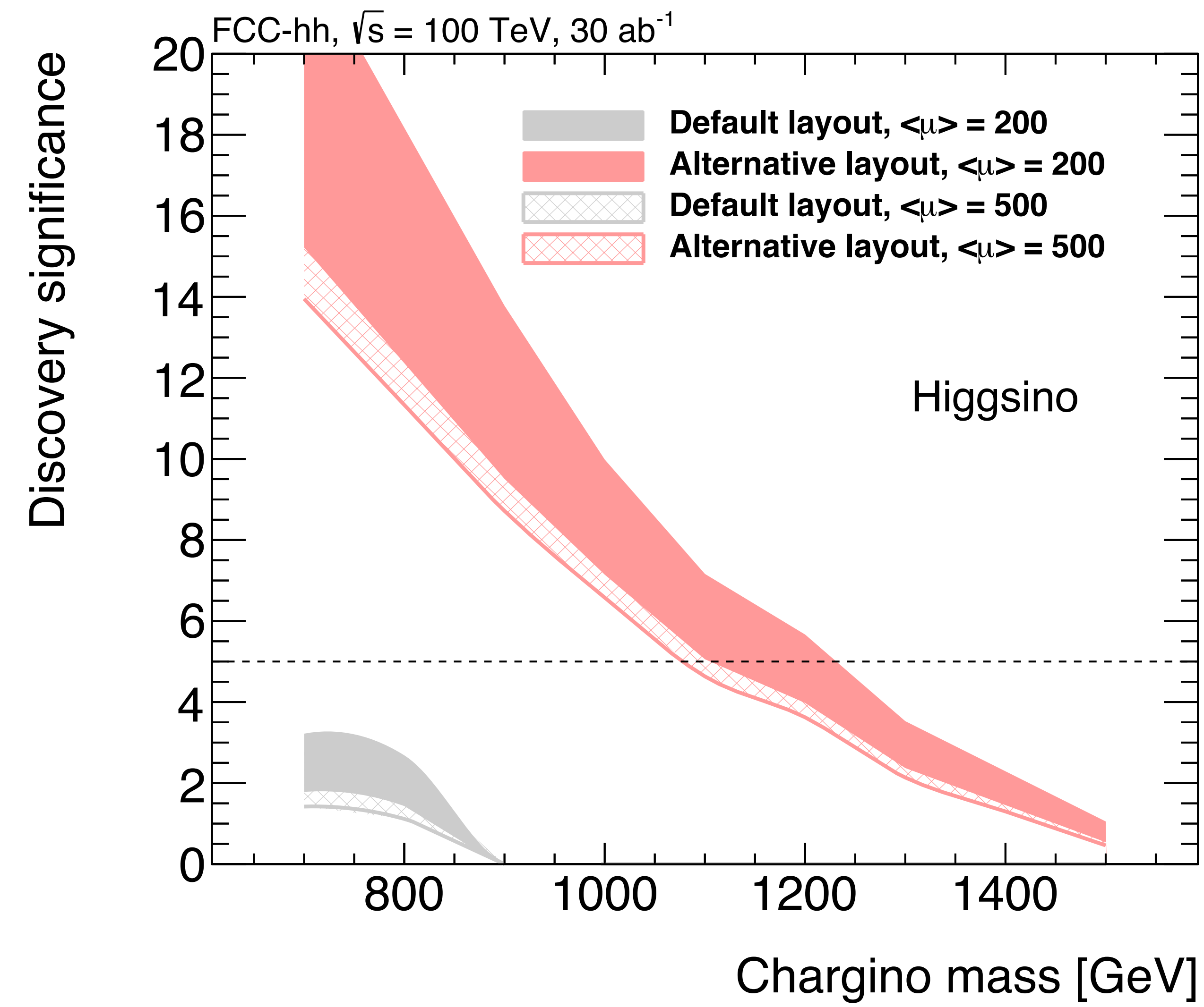
K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

(at ~full pileup)

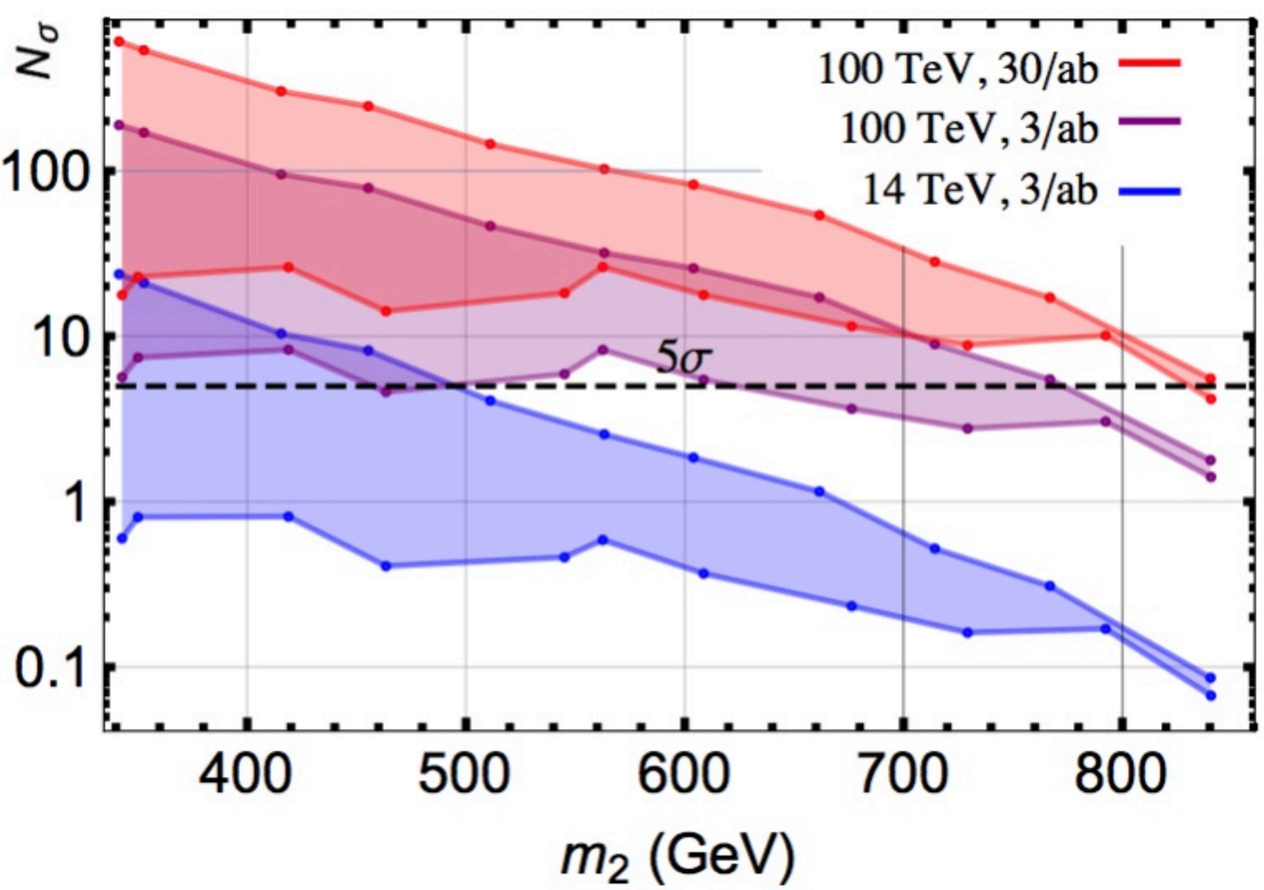




=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

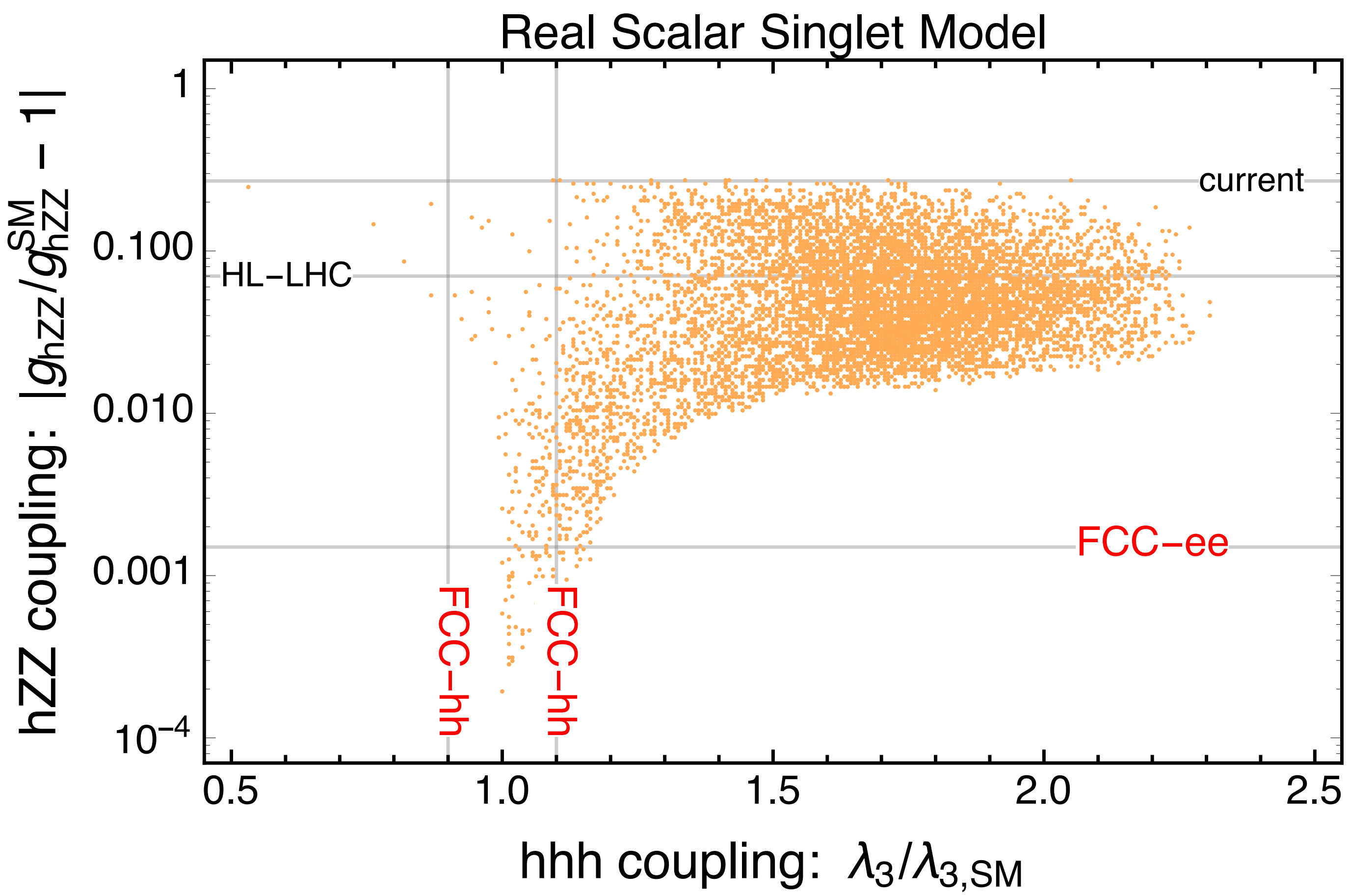
H selfcoupling measurements: constraints on models with 1st order phase transition

Direct detection of extra Higgs states



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

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.

HE-LHC physics potential: domains to be evaluated

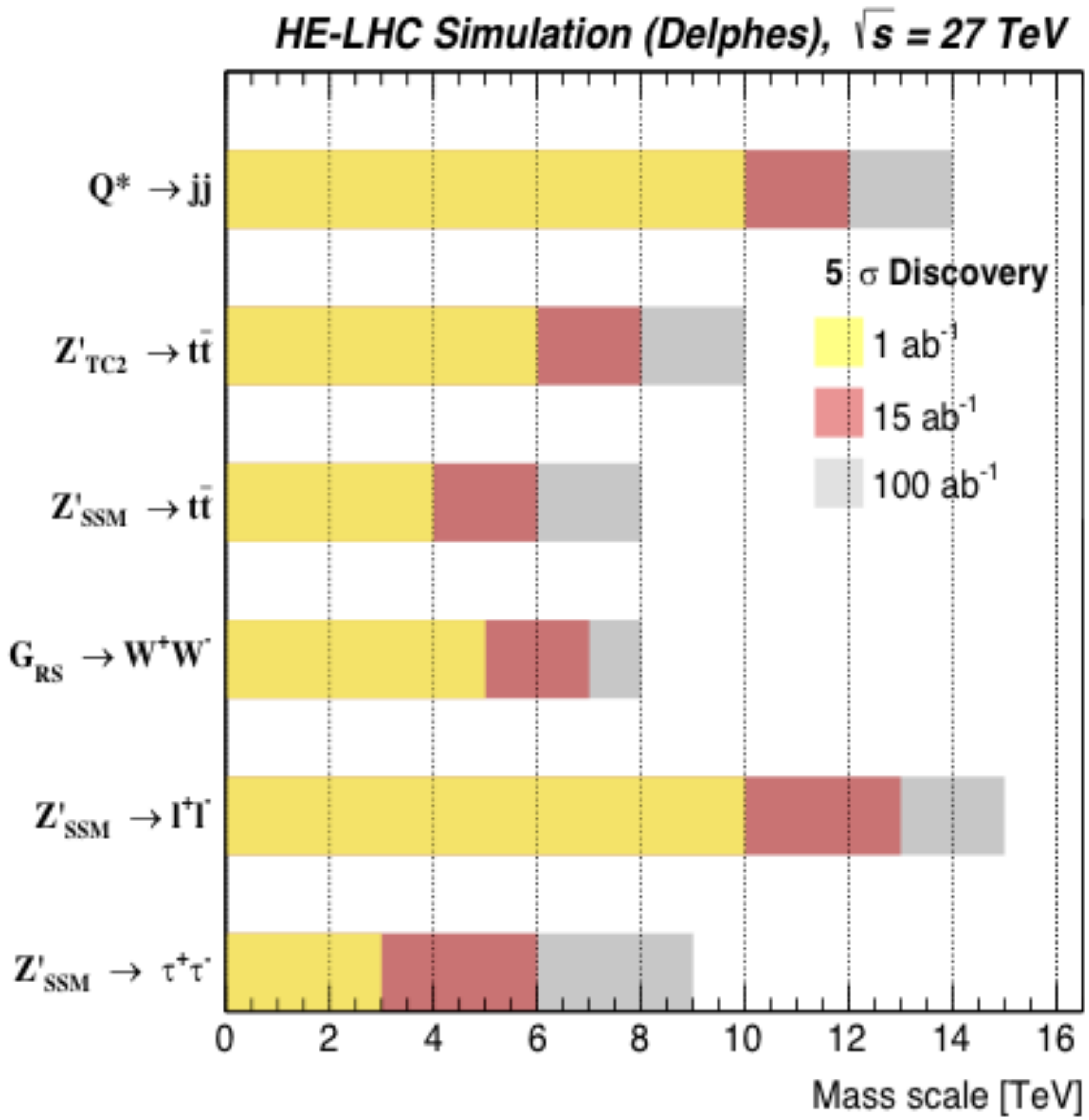
(1) extension of the LHC direct search for new particles (approximately doubling its mass reach);

(2) the Higgs self-coupling: establishing the structure of the symmetry-breaking Higgs potential;

(3) increased precision in the measurements made by the LHC, and the consequent increased sensitivity to new physics (indirectly to high mass scales, and, directly, to elusive final states such as dark matter);

(4) exploration of future LHC discoveries, confirmation of preliminary signs of discovery from the LHC, or the search for the underlying origin of new phenomena revealed indirectly **(e.g. the flavour anomalies under discussion nowadays)** or in experiments other than the LHC ones (e.g. dark matter or neutrino experiments).

(I) extension of mass reach for discovery: s-channel resonances



(I) extension of mass reach for discovery: "natural" supersymmetry examples

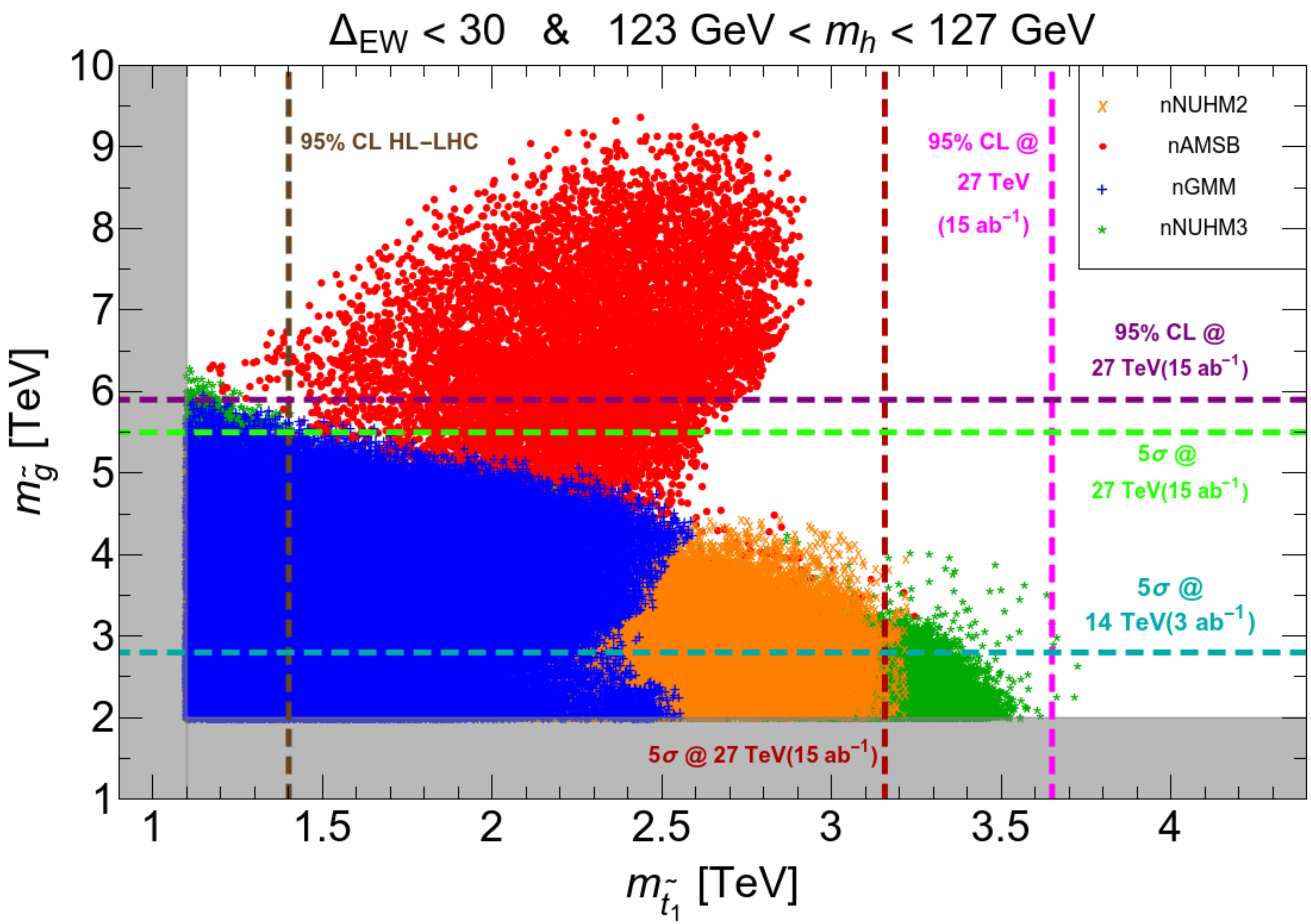
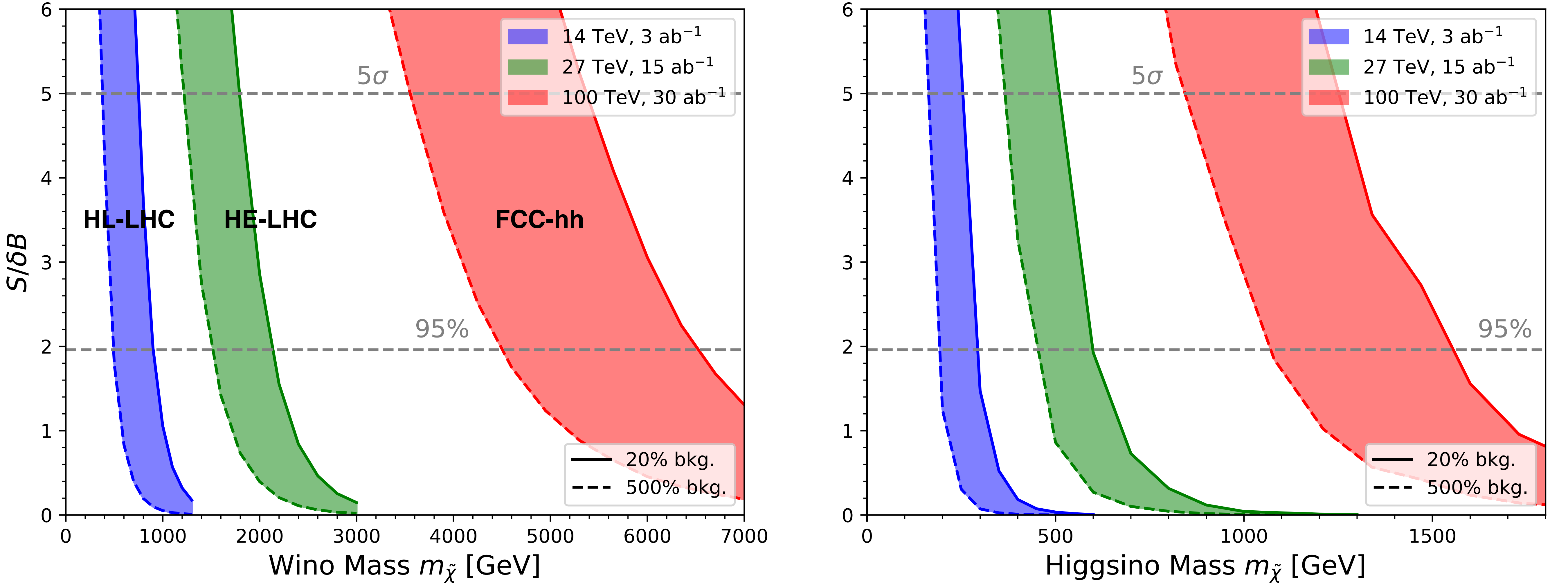


Figure 1.2: Discovery reach at the HE-LHC for gluinos and stops in various, compared to the HL-LHC reach and to the expectations of a several classes of natural supersymmetric models.

H. Baer, *talk at the Fermilab Workshop on HL-HE/LHC Physics, April 2-4 2018*, `https://indico.fnal.gov/event/16151/session/4/contribution/46/`.

(I) EW-ino DM searches



T. Han, S. Mukhopadhyay, and X. Wang, *Electroweak Dark Matter at Future Hadron Colliders*, `arXiv:1805.00015 [hep-ph]`.

(II+III) precision measurements and EWSB probes: Higgs observables

Examples of goals in the Higgs sector:

(a) improve the sensitivity to the Higgs self-coupling

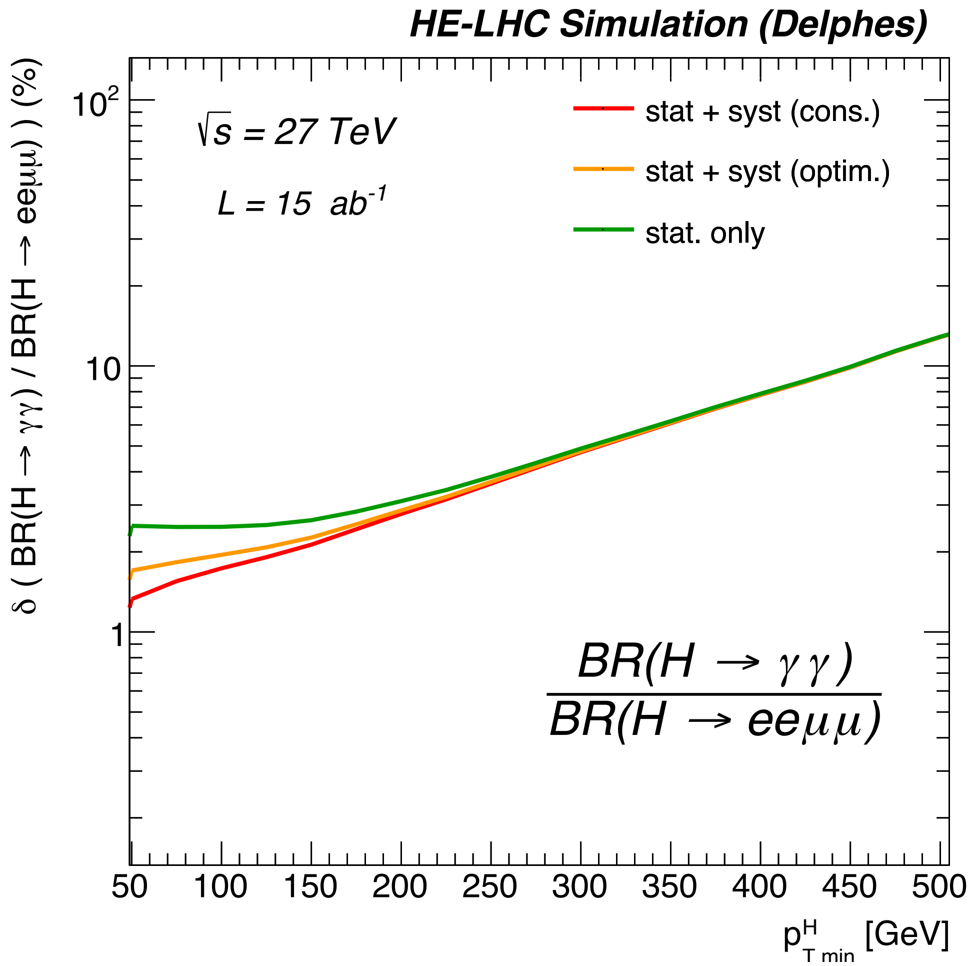
(b) reduce to the few percent level all major Higgs couplings

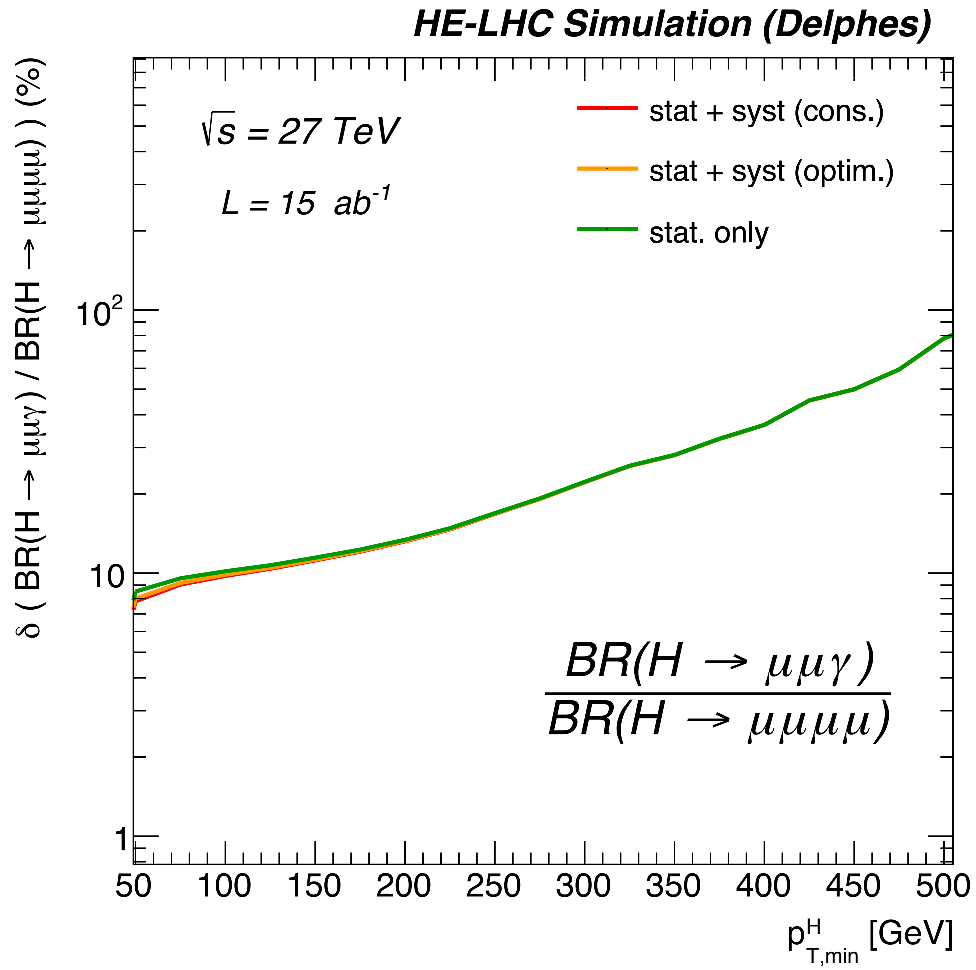
(c) improve the sensitivity to possible invisible Higgs decays

(d) measure the charm Yukawa coupling

	$gg \to H$	WH	ZH	ttH	HH
N_{27}	2.2×10^9	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

$N_{27}=\sigma(27\ \text{TeV}) * 15\ \text{ab}^{-1}$ $N_{14}=\sigma(14\ \text{TeV}) * 3\ \text{ab}^{-1}$


HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \gamma\gamma)}{BR(H \to ee\mu\mu)}$
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
$p^{H}_{T\ min}$ [GeV]


HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 ab^{-1}
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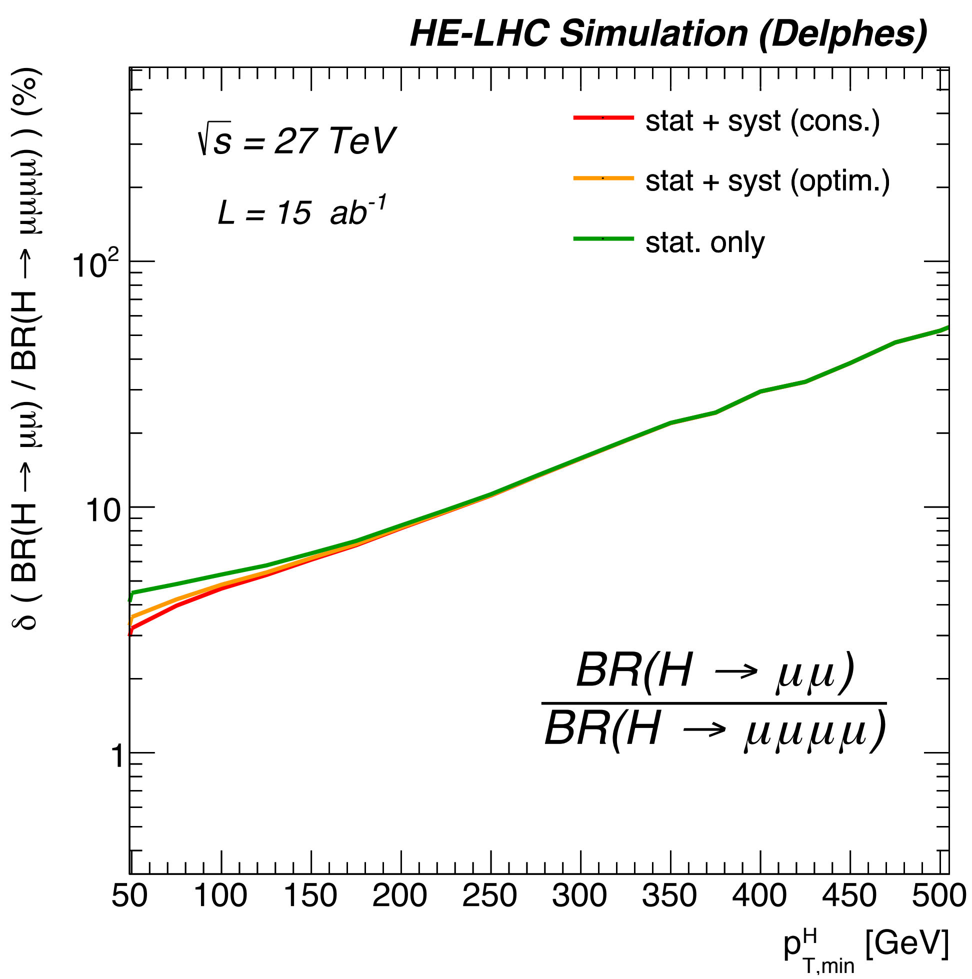
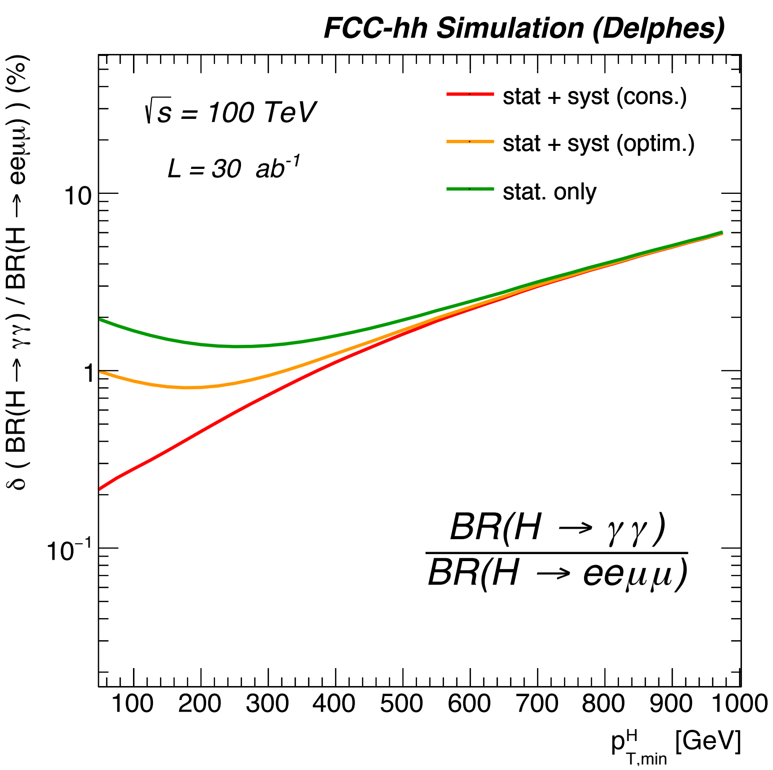
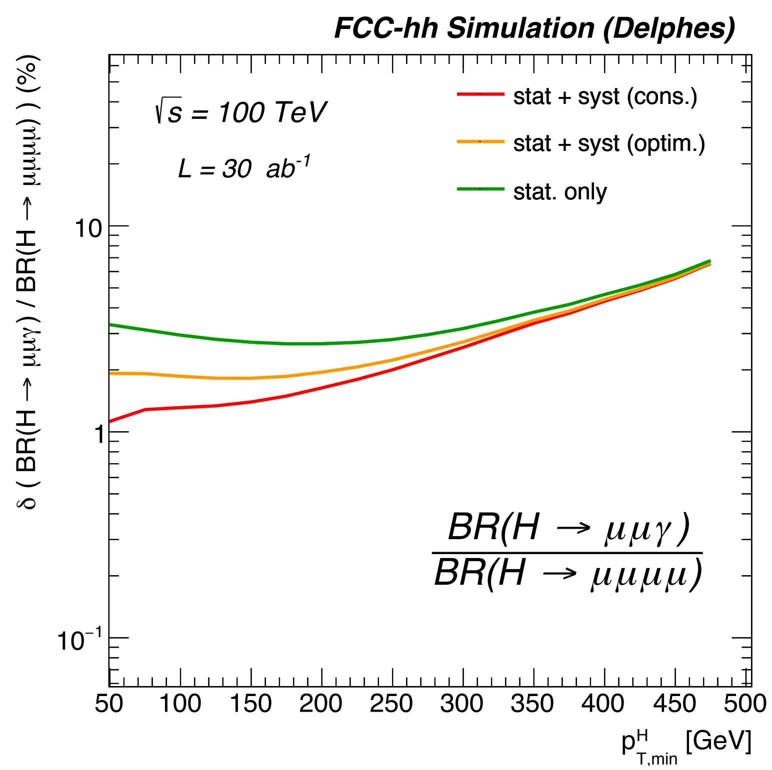
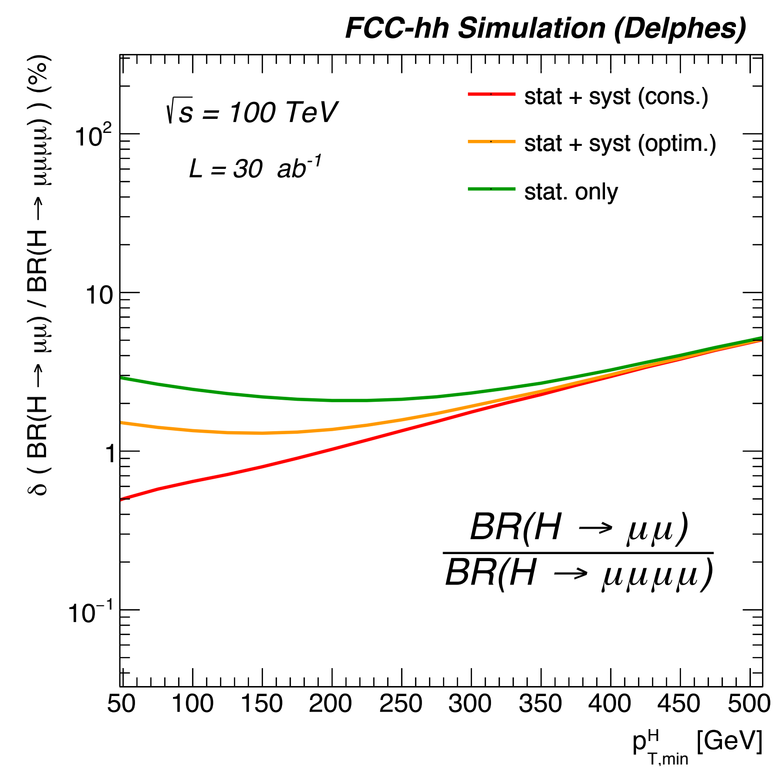
$\frac{BR(H \to \mu\mu\gamma)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
$p^{H}_{T,min}$ [GeV]

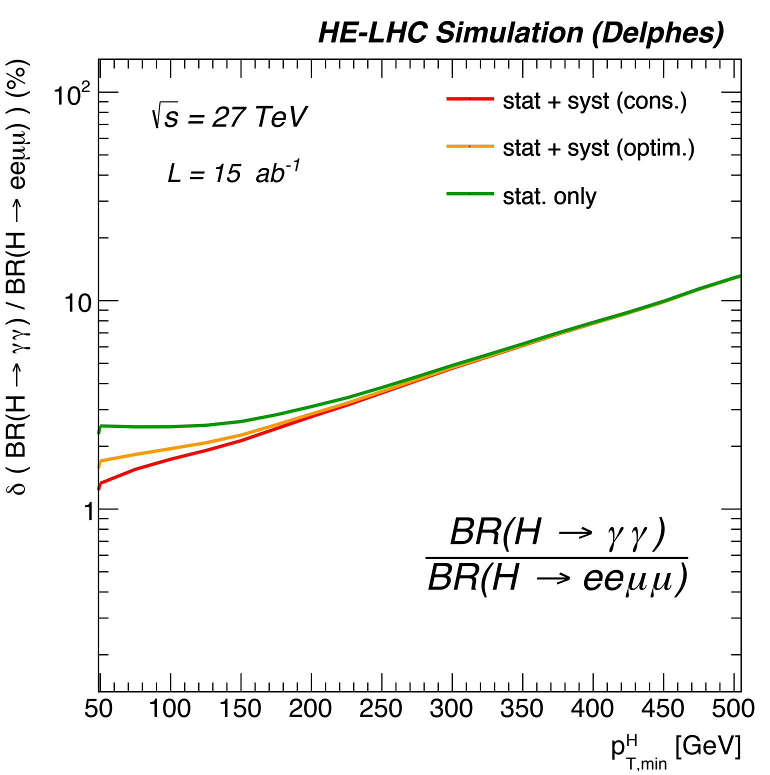

HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \mu\mu)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
$p^{H}_{T,min}$ [GeV]

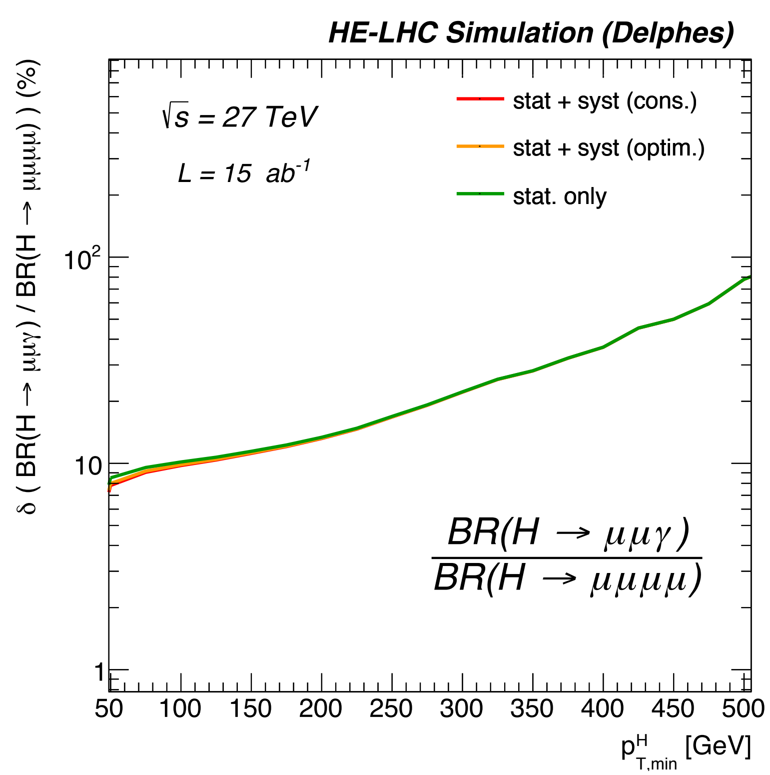
100 vs 27 TeV

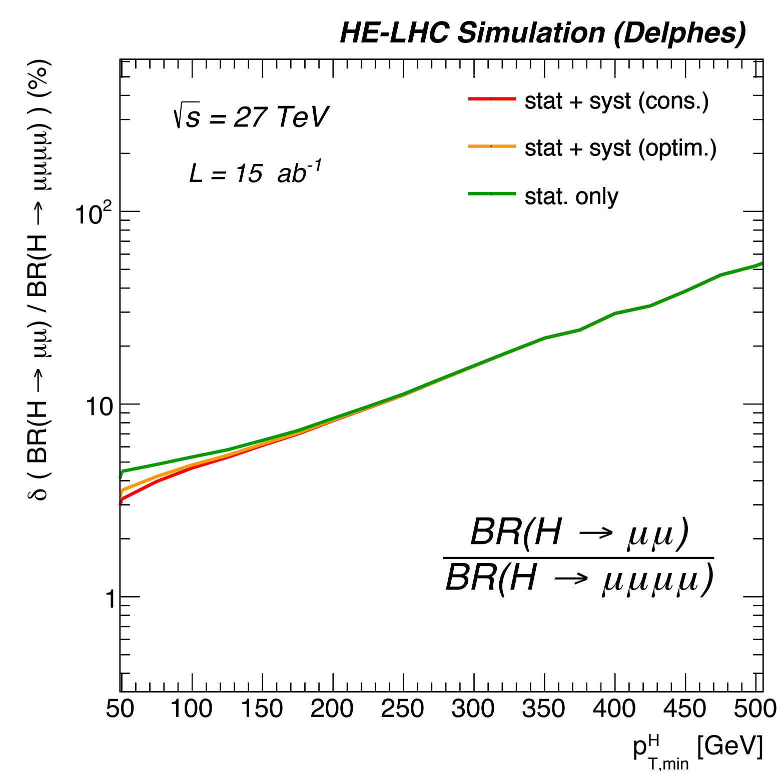

FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \gamma\gamma)}{BR(H \rightarrow ee\mu\mu)}$
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
$p_{T,min}^{H}$ [GeV]


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


HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 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]

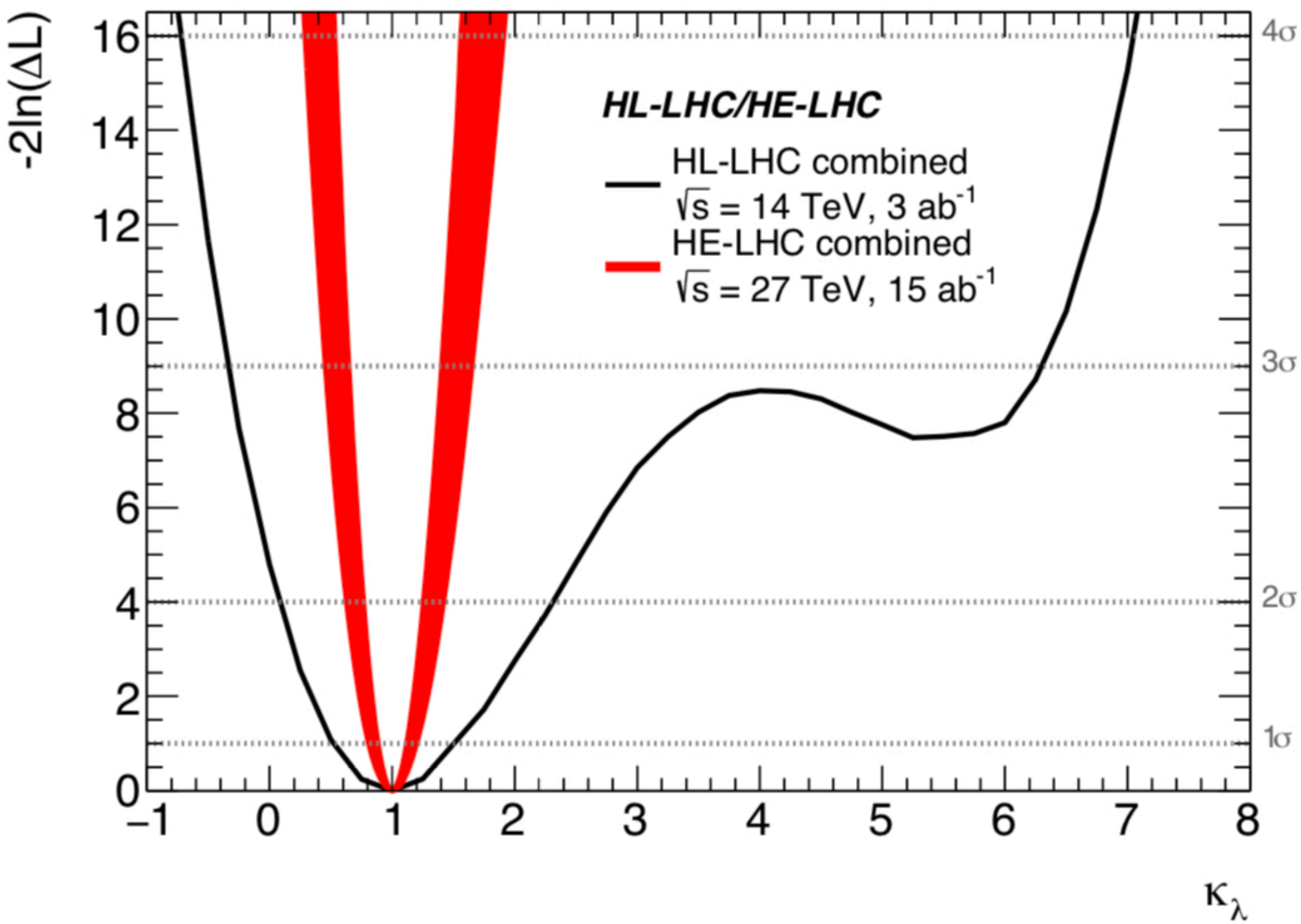

HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \mu\mu\gamma)}{BR(H \rightarrow \mu\mu\mu\mu)}$
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
$p_{T,min}^{H}$ [GeV]


HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 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]

Higgs self-coupling at HE-LHC vs HL-LHC

HL-LHC: λ/λ_{SM} ~1±0.5 (68%CL)

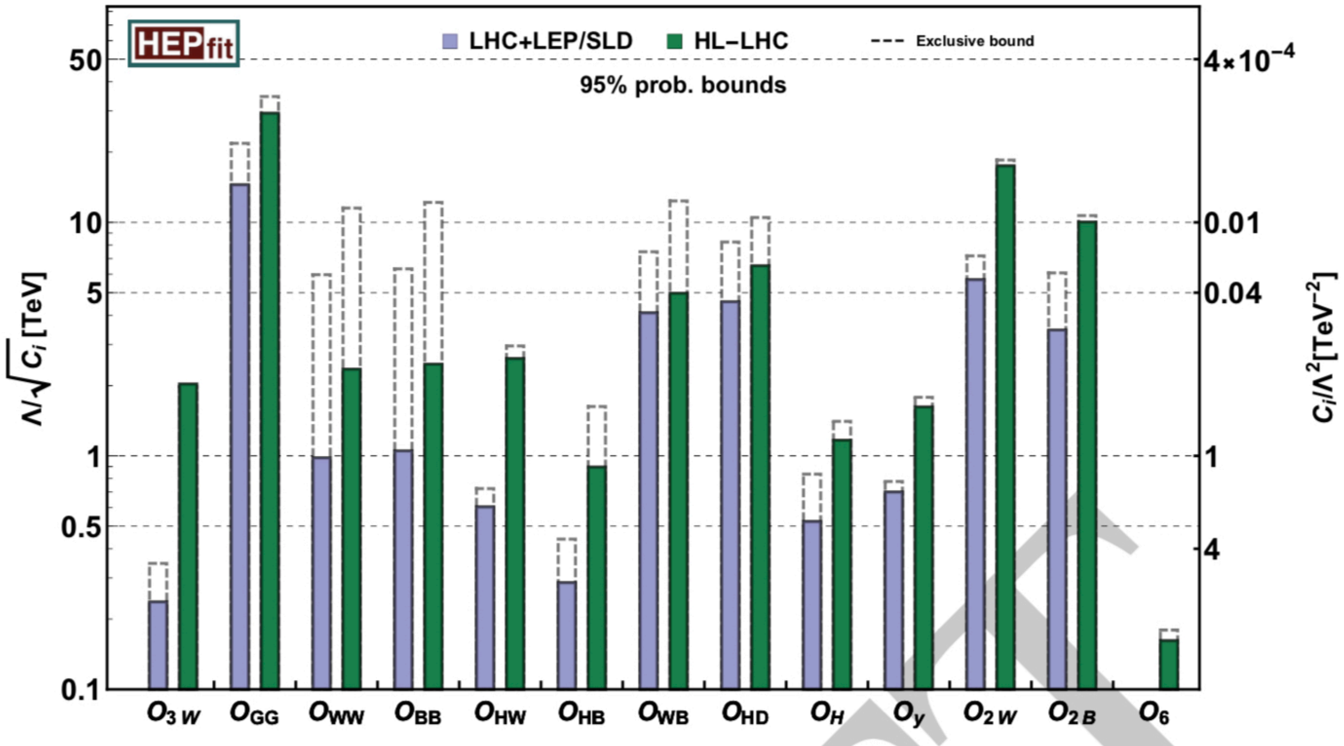
HE-LHC: λ/λ_{SM} ~1±0.15 (68%CL)



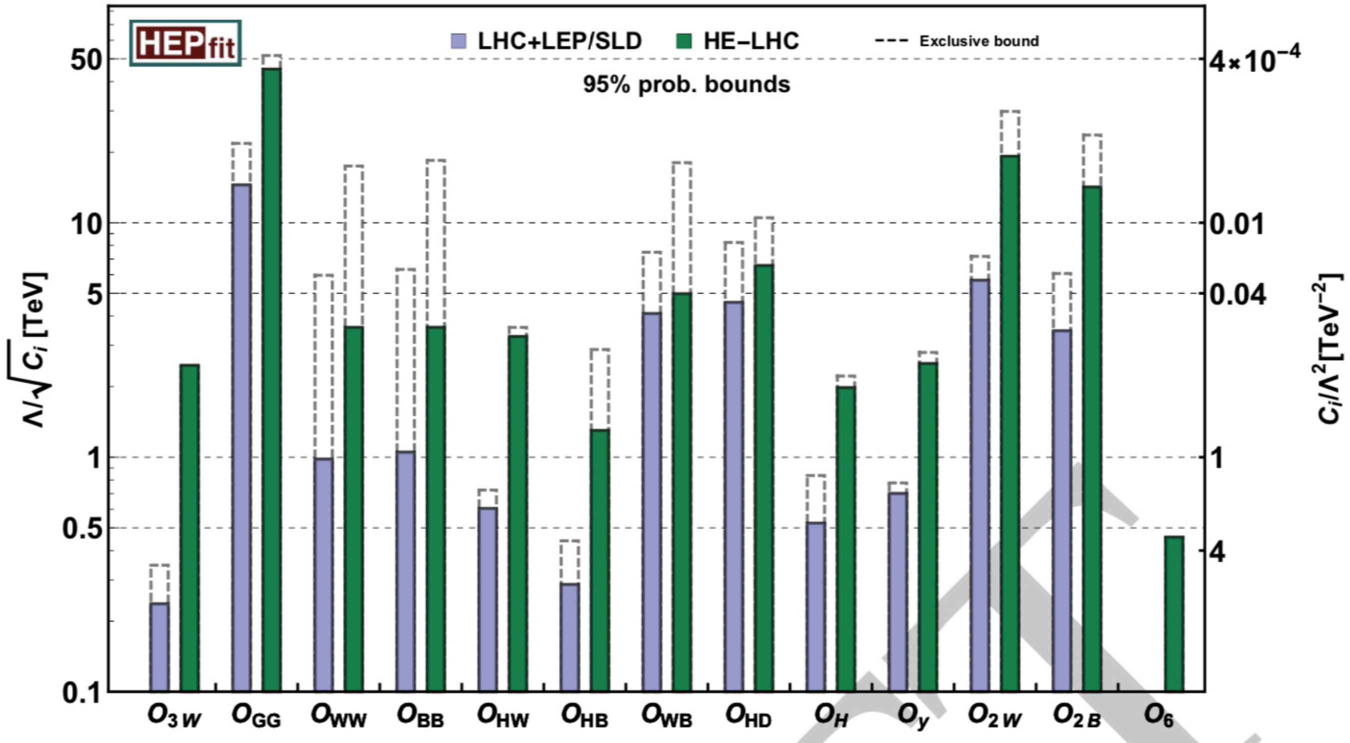
See also:

D. Gonçalves, T. Han, F. Kling, T. Plehn, and M. Takeuchi, *Higgs Pair Production at Future Hadron Colliders: From Kinematics to Dynamics*, `arXiv:1802.04319 [hep-ph]`.

SMEFT fits

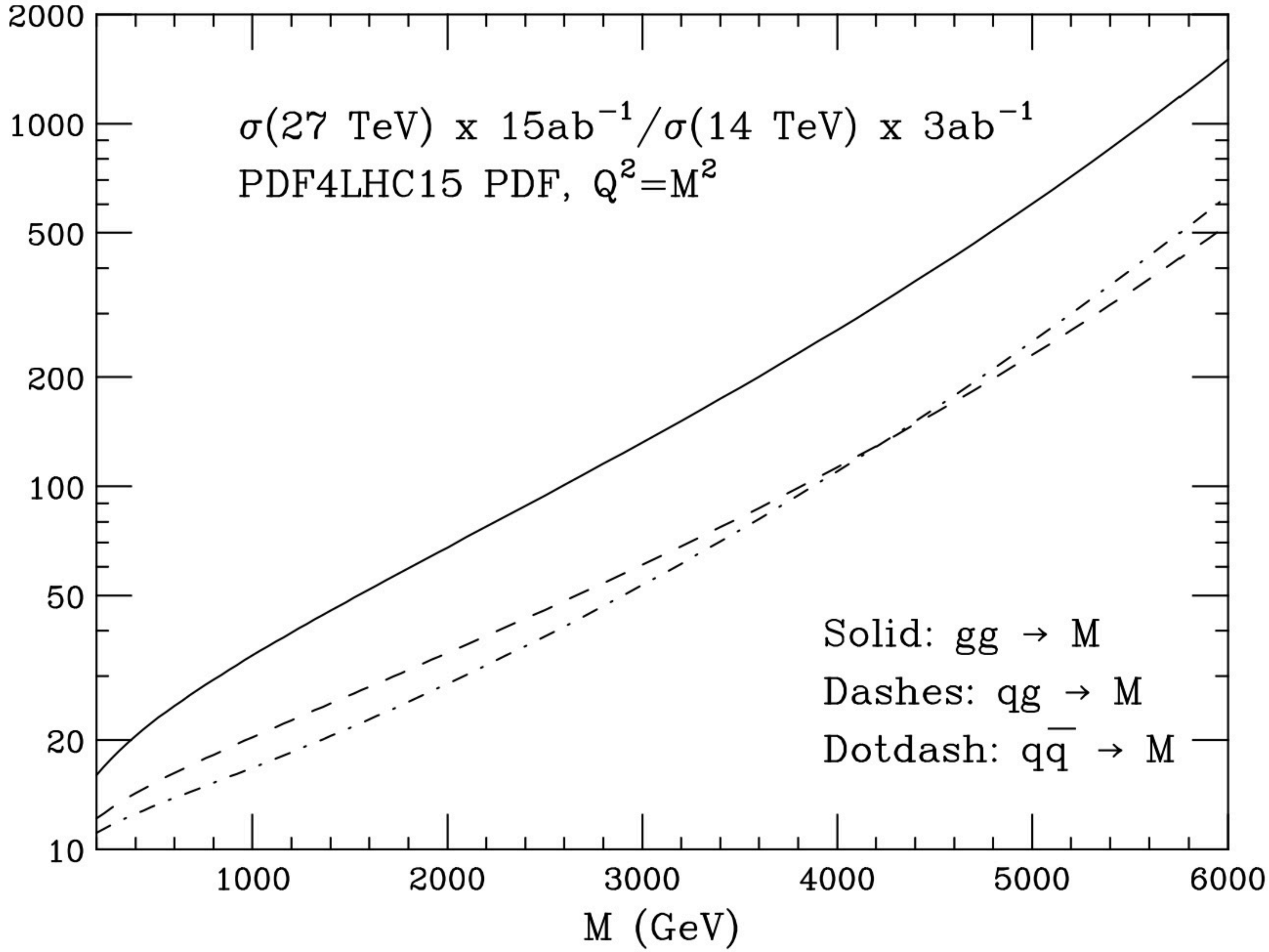


HL-LHC



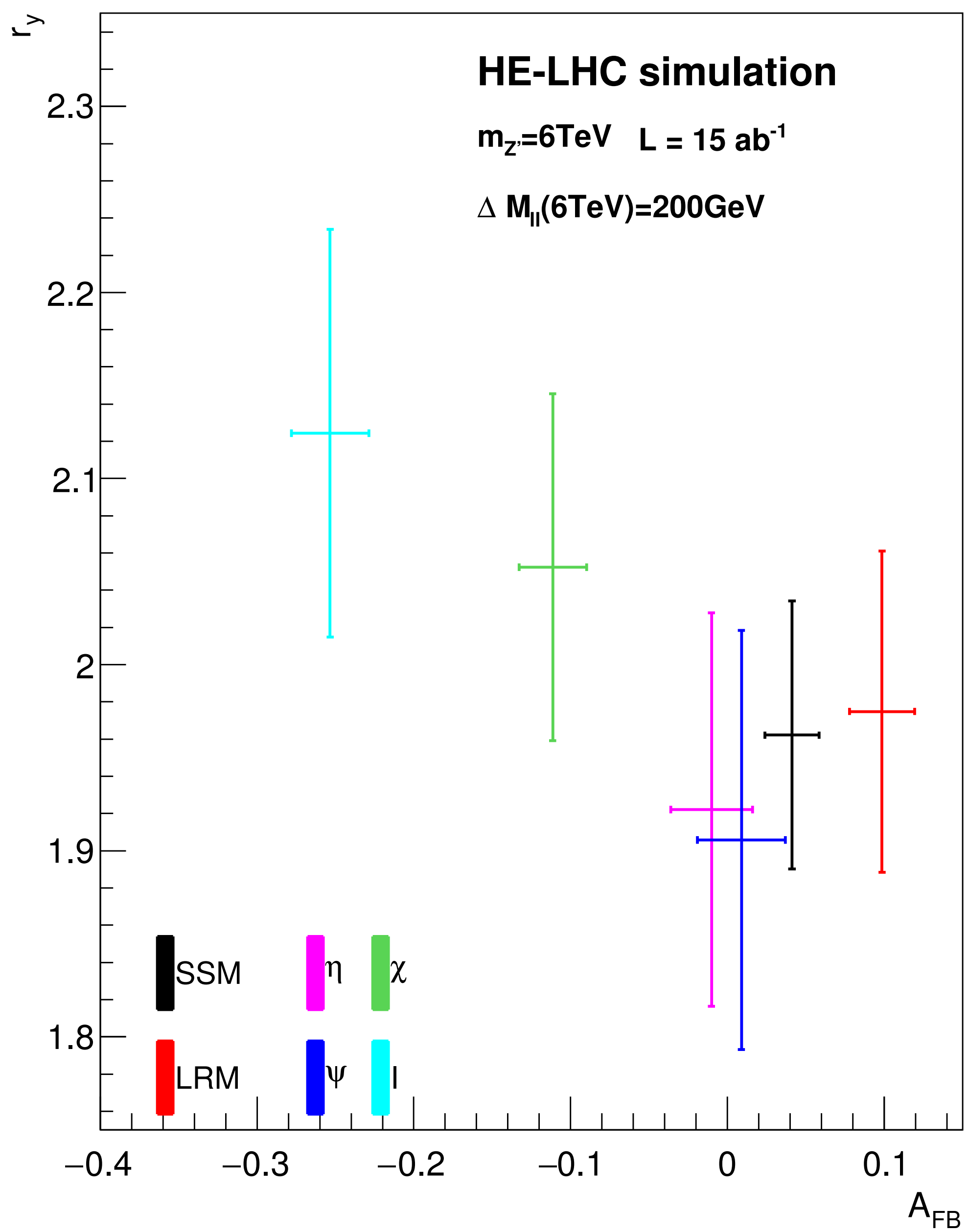
HE-LHC

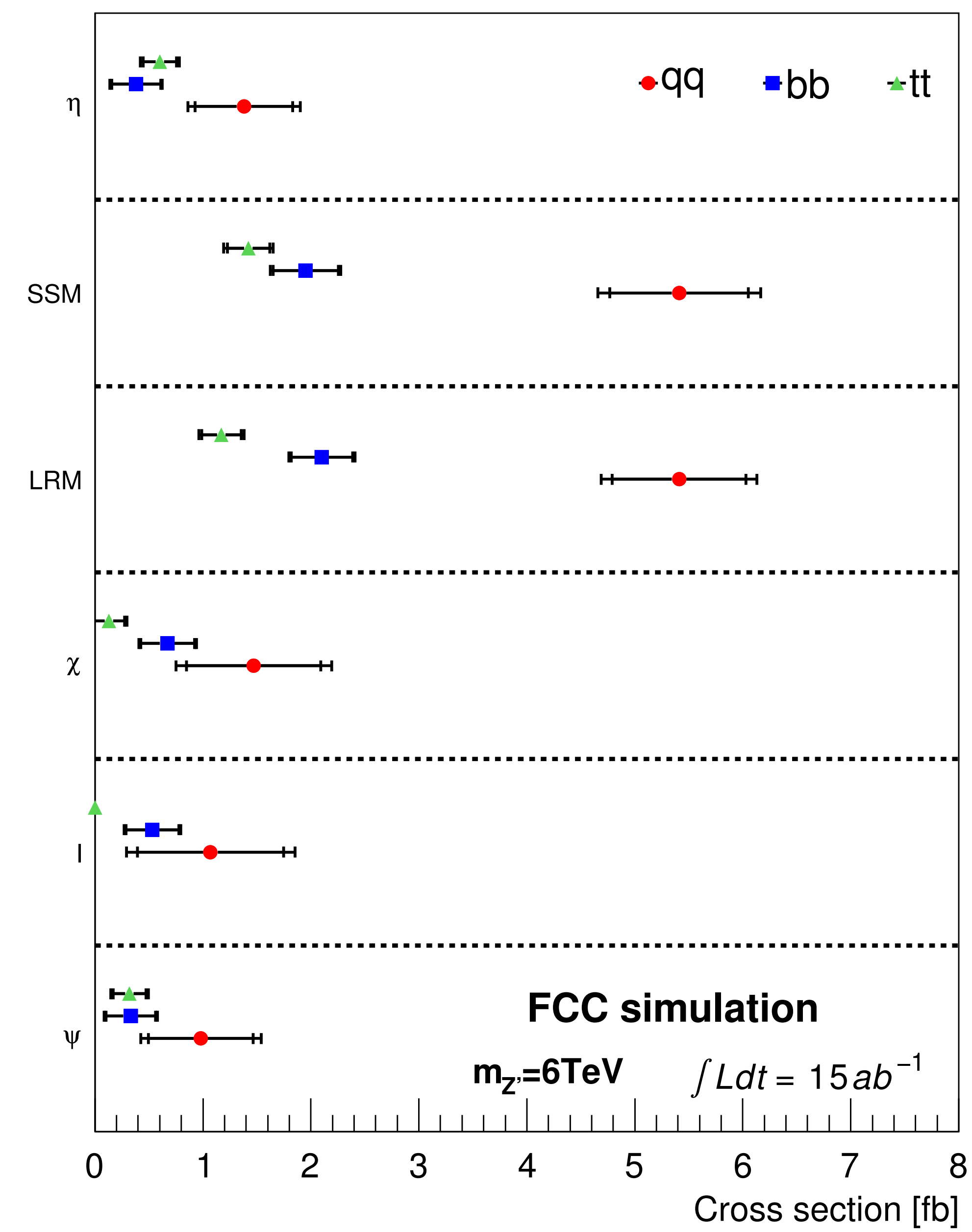
(IV) Exploration at 27 TeV of LHC discoveries: generic results



(IV) Exploration at 27 TeV of LHC discoveries: characterization of Z' models within reach of LHC observation

NB: uncertainty bars reflect very conservative syst assumptions



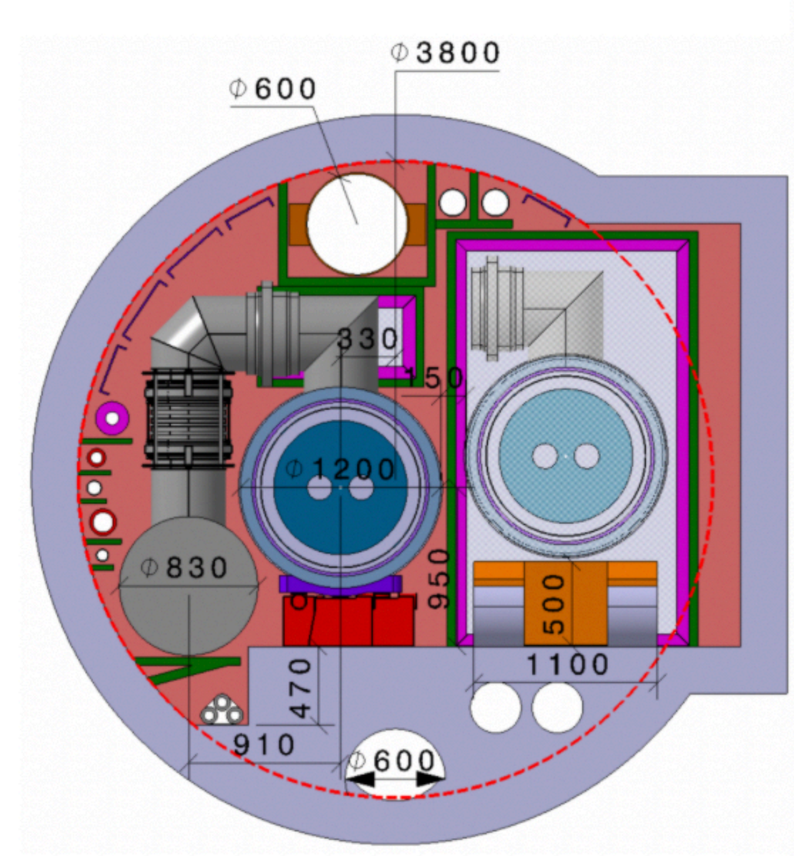


Colours: different Z' models, leading to observation at HL-LHC in Z'->dilepton decay for m(Z')=6 TeV

T. G. Rizzo, *Exploring new gauge bosons at a 100 TeV collider*, Phys. Rev. **D89** (2014) no. 9, 095022, arXiv:1403.5465 [hep-ph].

HE-LHC: the challenges

- 16T Nb_3Sn magnets: more challenging than for FCC-hh, due to reduced space in the tunnel (requires dedicated R&D)



- SPS upgrade, to SC technology, to allow injection at 0.9-1.3 TeV
- Full replacement and strengthening of all infrastructure on the surface and underground cryogenics
- Significant civil engineering work both on the surface and in the tunnel (new SPS transfer lines, new caverns for cryogenics, 2 new shafts, …)
- Overhaul/full replacement of detectors (radiation damage after HL-LHC, limited lifetime of key systems like magnets, use of new technologies, …)
- …

HE-LHC, project timeline

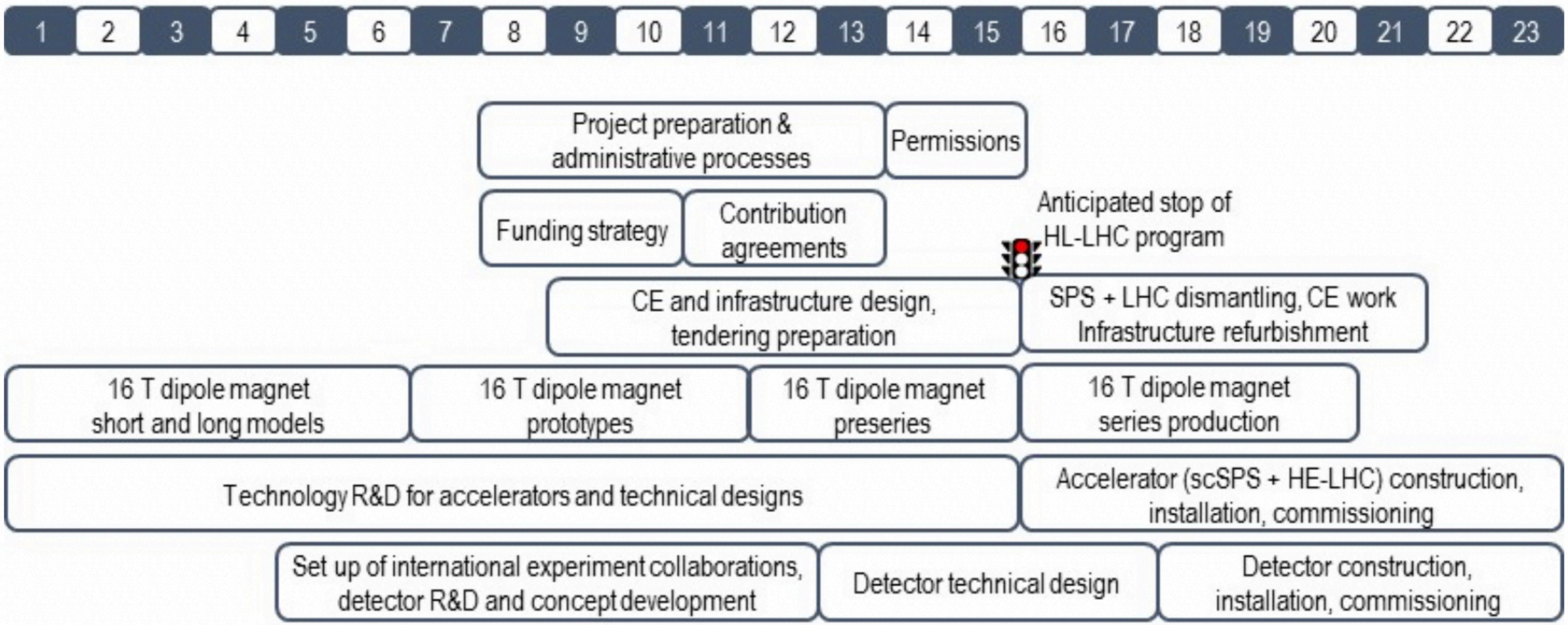


Figure 7: Overview of implementation timeline for the HE-LHC project starting in 2020. Numbers in the top row indicate the year. Physics operation would start in the mid 2040ies.

HE-LHC, preliminary cost estimates

Domain	Cost in MCHF
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil Engineering	300
TOTAL cost	**7,200**

Table 2: Summary of capital cost for implementation of the HE-LHC project.

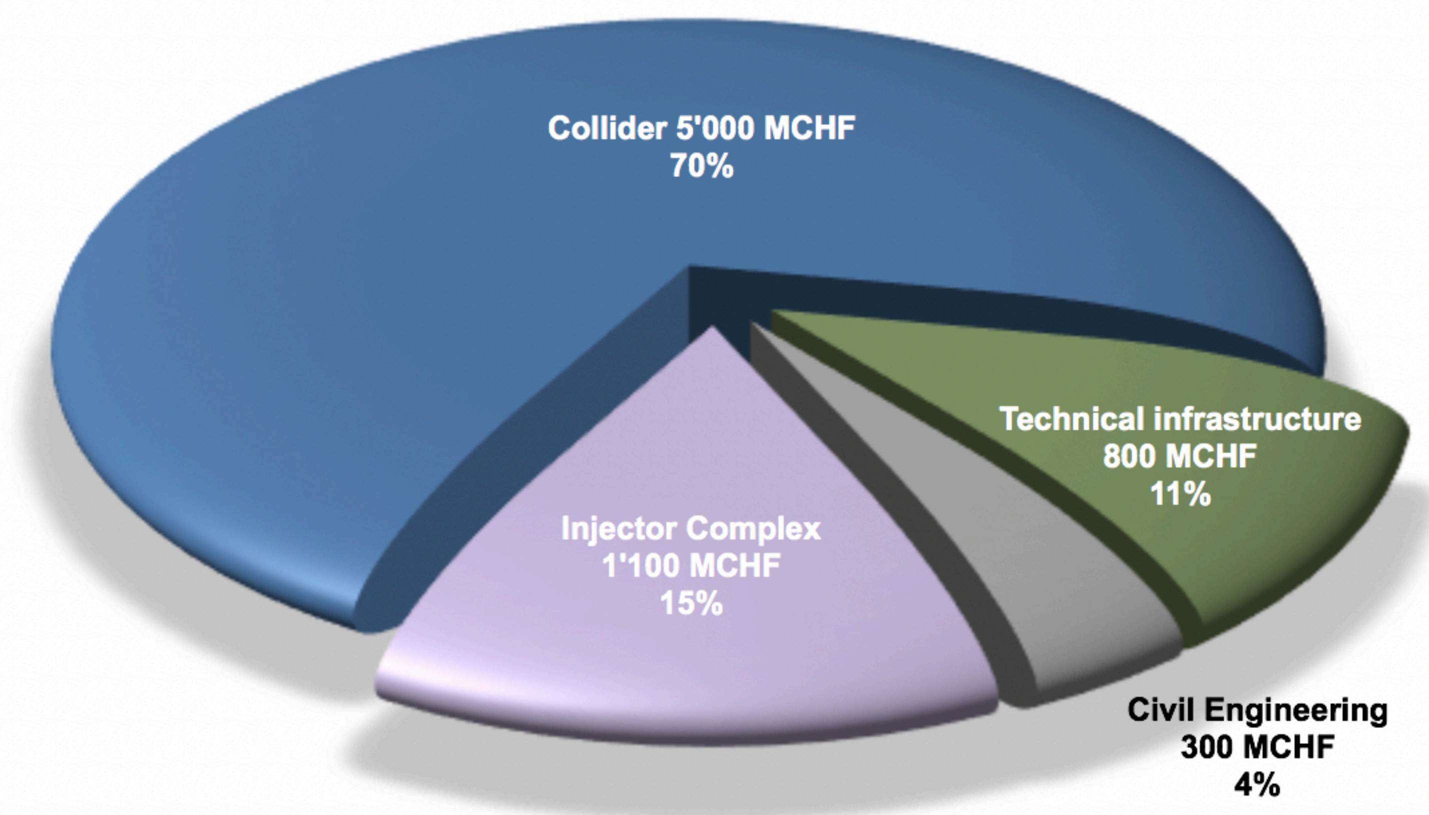


Figure 8: HE-LHC capital cost per project domain.

March 4-5 2019

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Physics at FCC: overview of the Conceptual Design Report

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In preparation for the discussions at the European Strategy meeting in Granada, this Conference will review the main findings of the physics studies carried out in the context of the FCC CDR. The physics discussion will be accompanied by a status report of the overall project, reviewing the technological challenges for both accelerator and detectors, the ongoing actions to address them, the project implementation strategy, and the cost estimates.

This Conference is meant to help all colleagues, interested in the future of high energy physics in Europe, become familiar with the extraordinary progress made in the past 5 years in defining a realistic plan to meet the ambitious physics targets of the FCC.