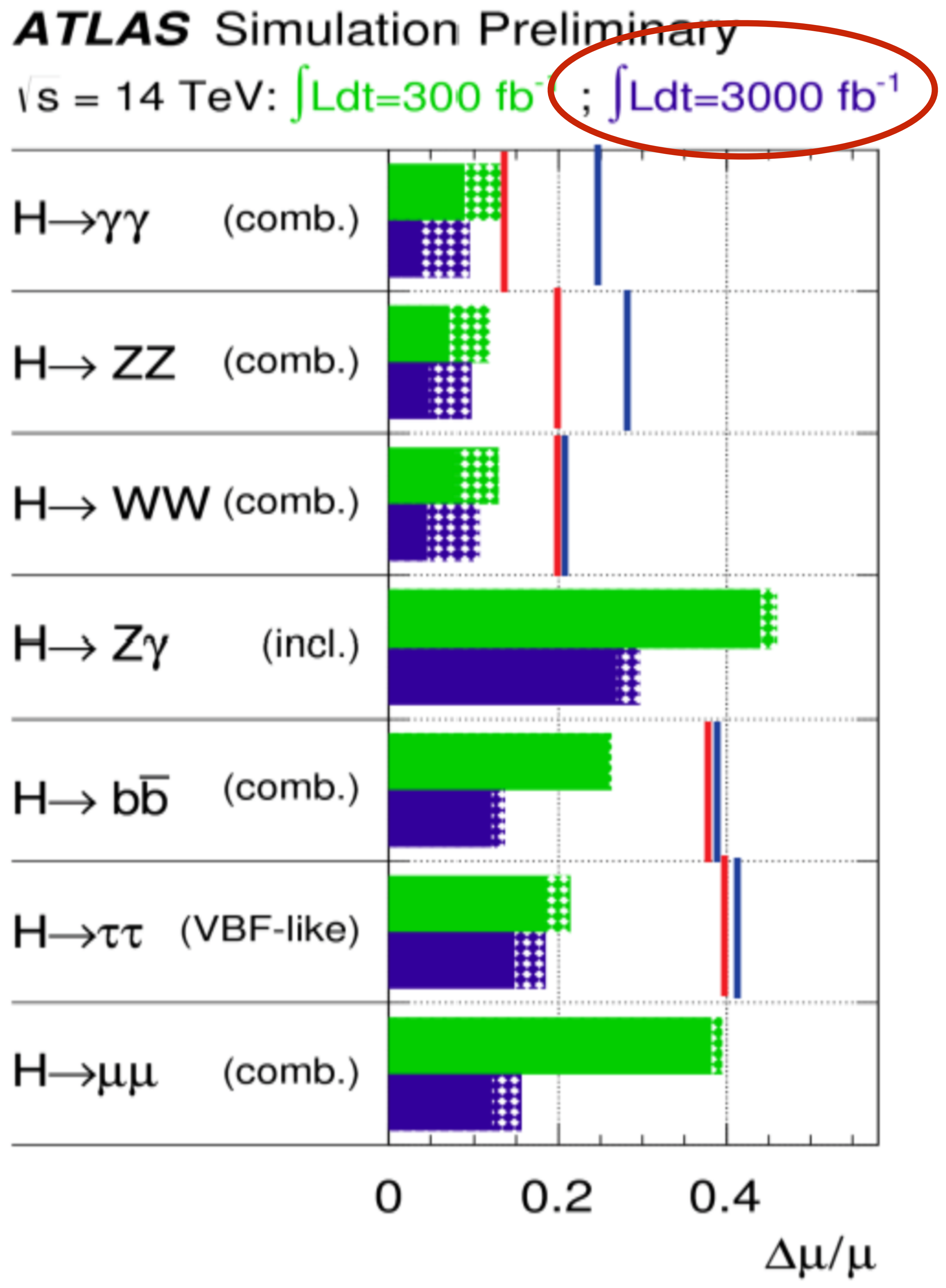
Higgs physics at the FCC

Krisztian Peters (DESY)

HC2018, Tokyo, Nov. 28, 2019

Main Higgs physics goals



Typical precision: 5 to 10%

(mainly to boson couplings and 3rd gen. fermions)

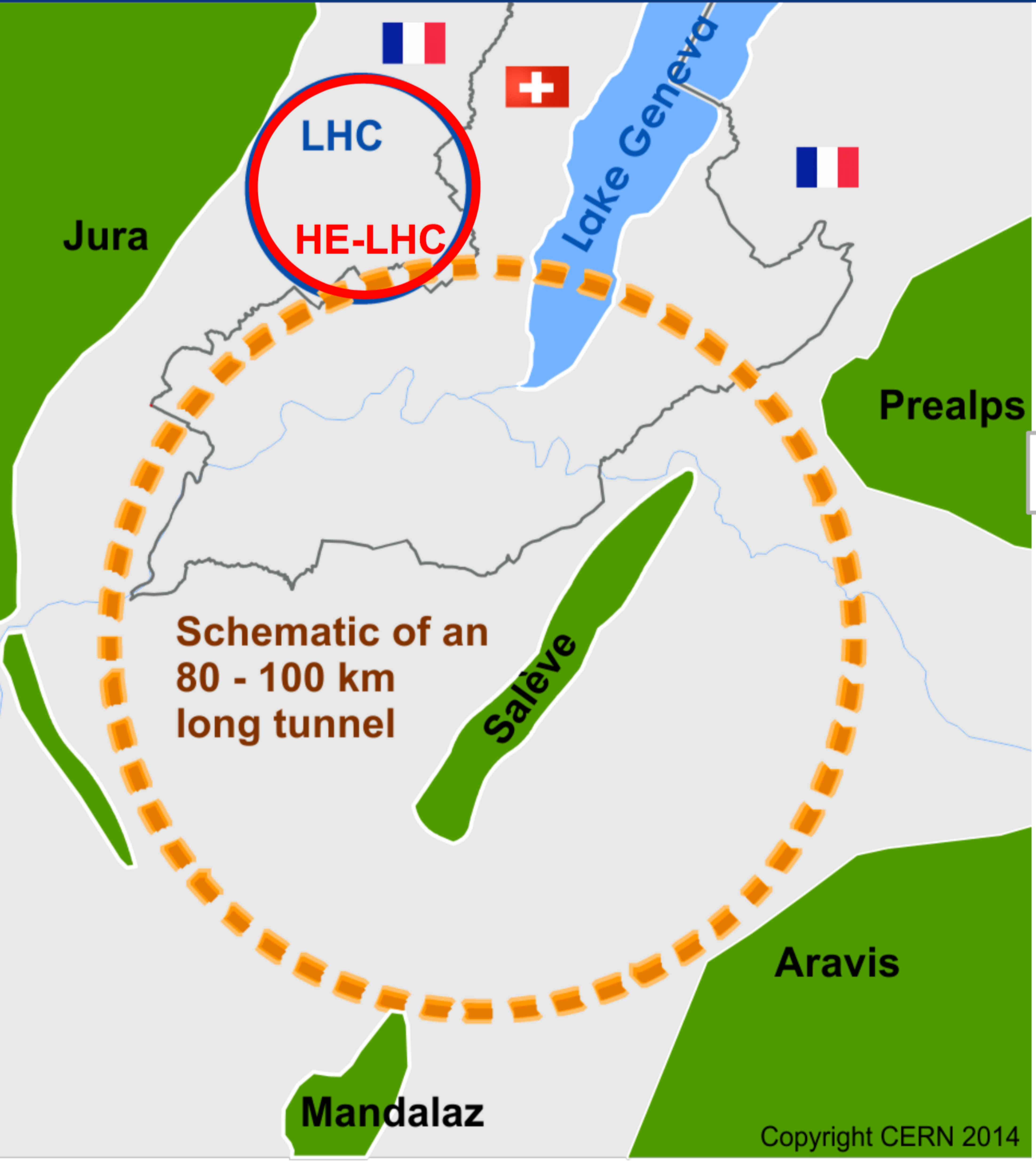
LHC experiments discovered the Higgs boson and will leave a legacy of precision measurements and constraints on new physics

To capture quantum corrections that modify the Higgs properties requires that measurements be pushed significantly further

- Model independent, (sub-)percent level measurements (including 2nd. gen. fermions, other rare decays, width,…)
- Test a large dynamic range for Higgs production
- Higgs self-coupling measurement

Broad range of goals well covered with the combination of future e^+e^- and *pp* colliders (such as the FCC project)

Future Circular Collider (FCC) Study

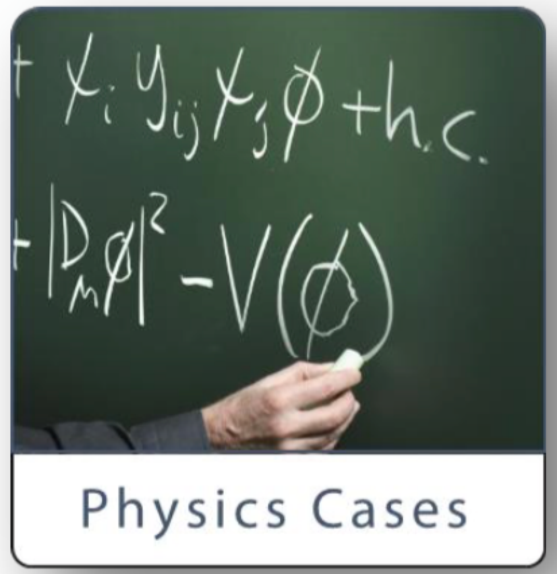


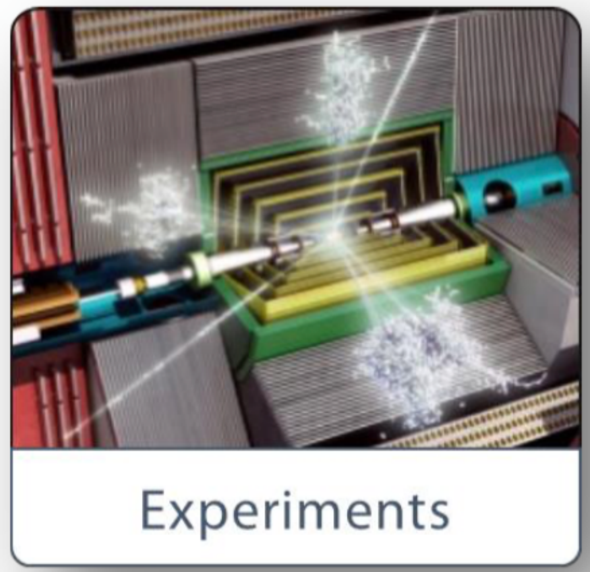
International FCC collaboration (CERN as host lab) to study:

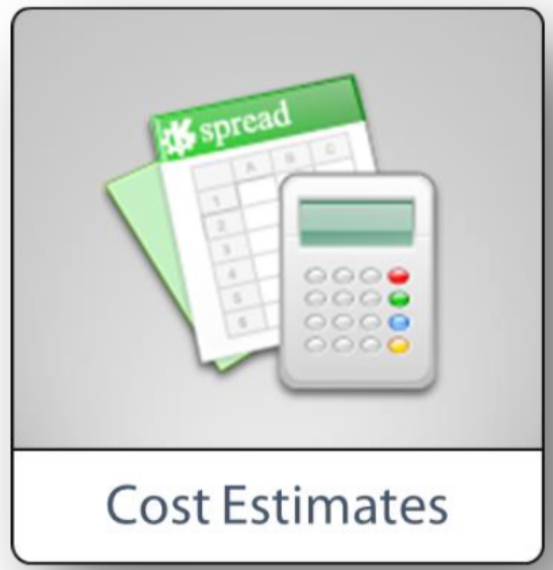
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from ERL

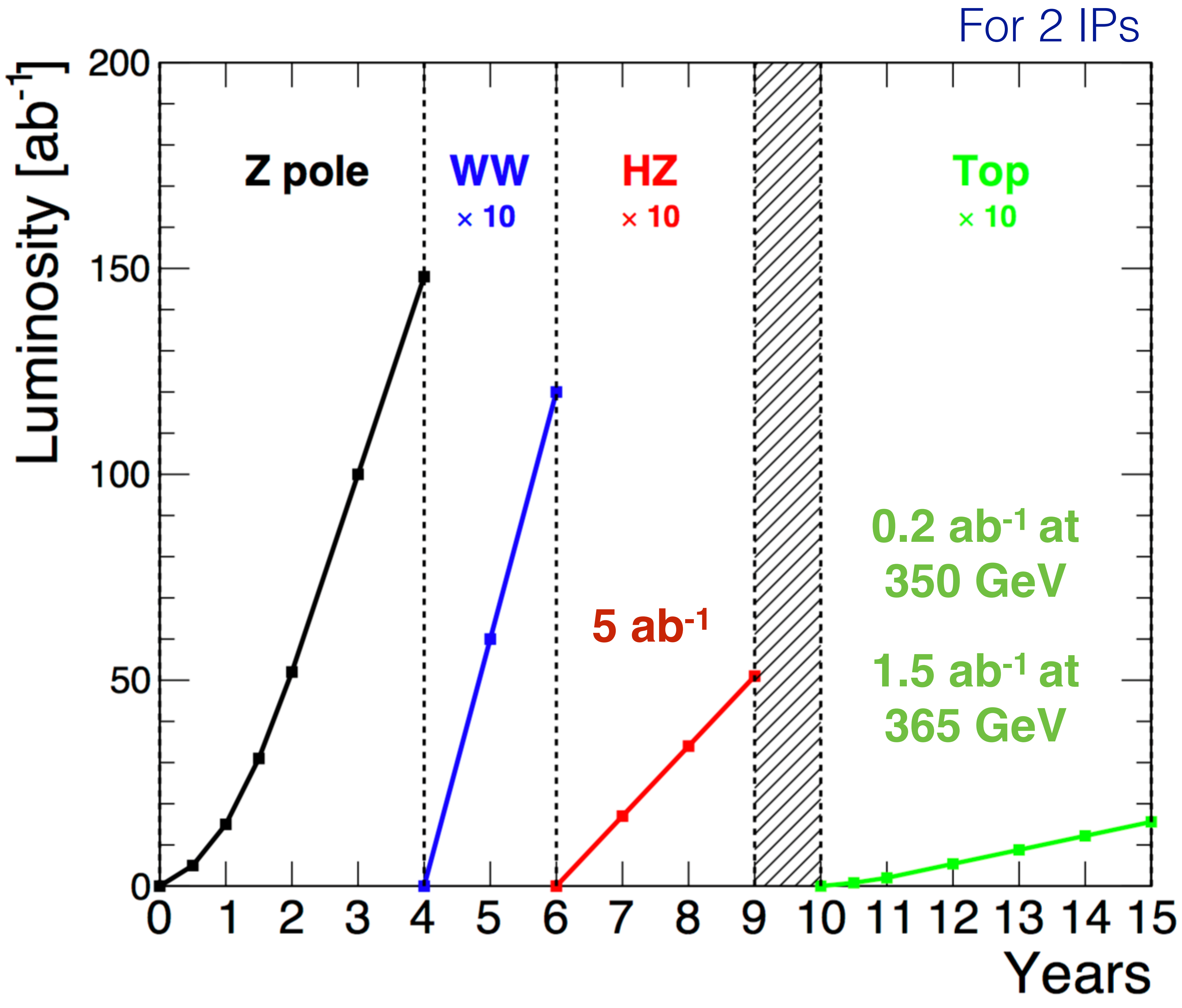


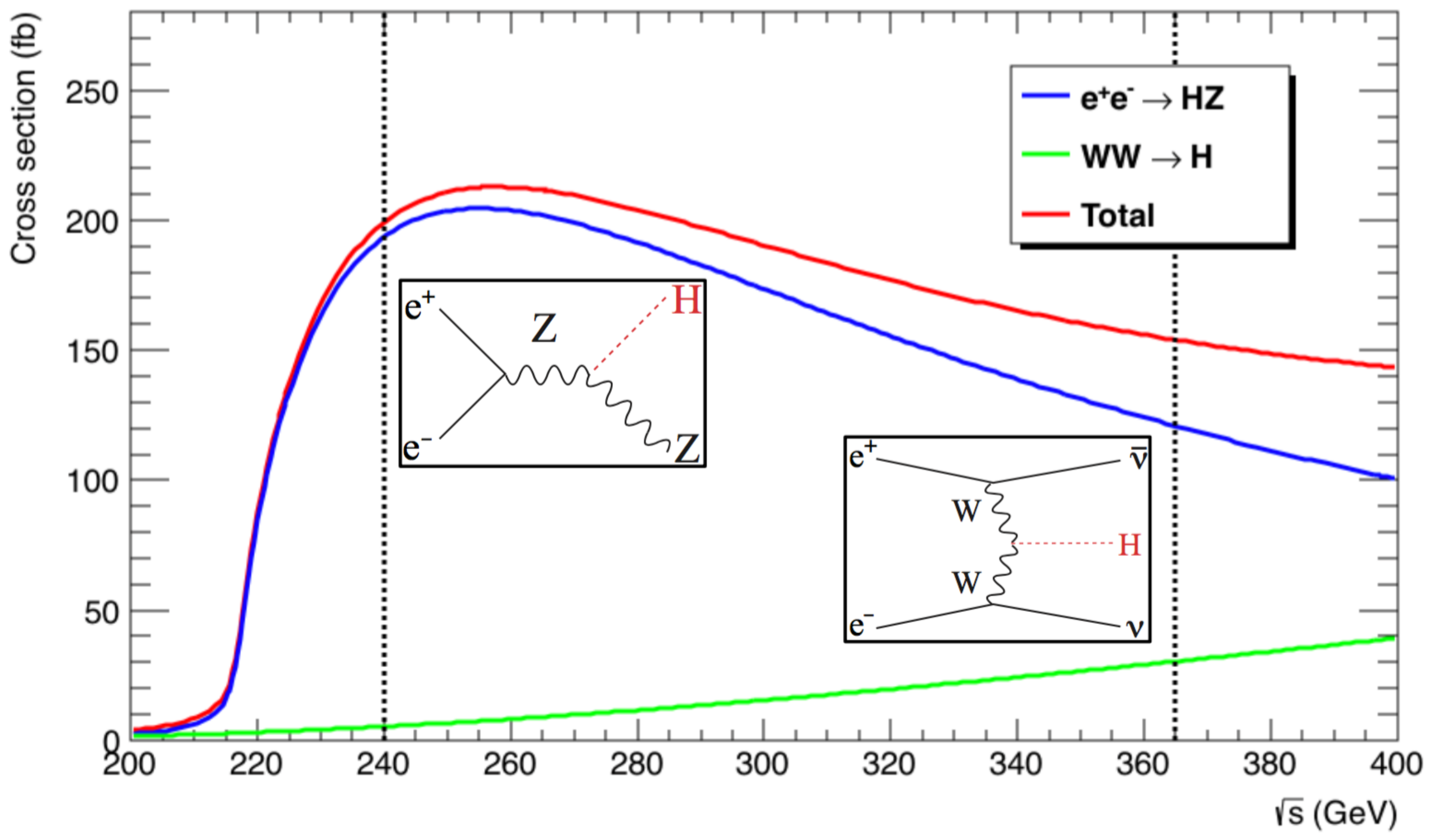




https://indico.cern.ch/event/750953/

Higgs boson production at the FCC-ee



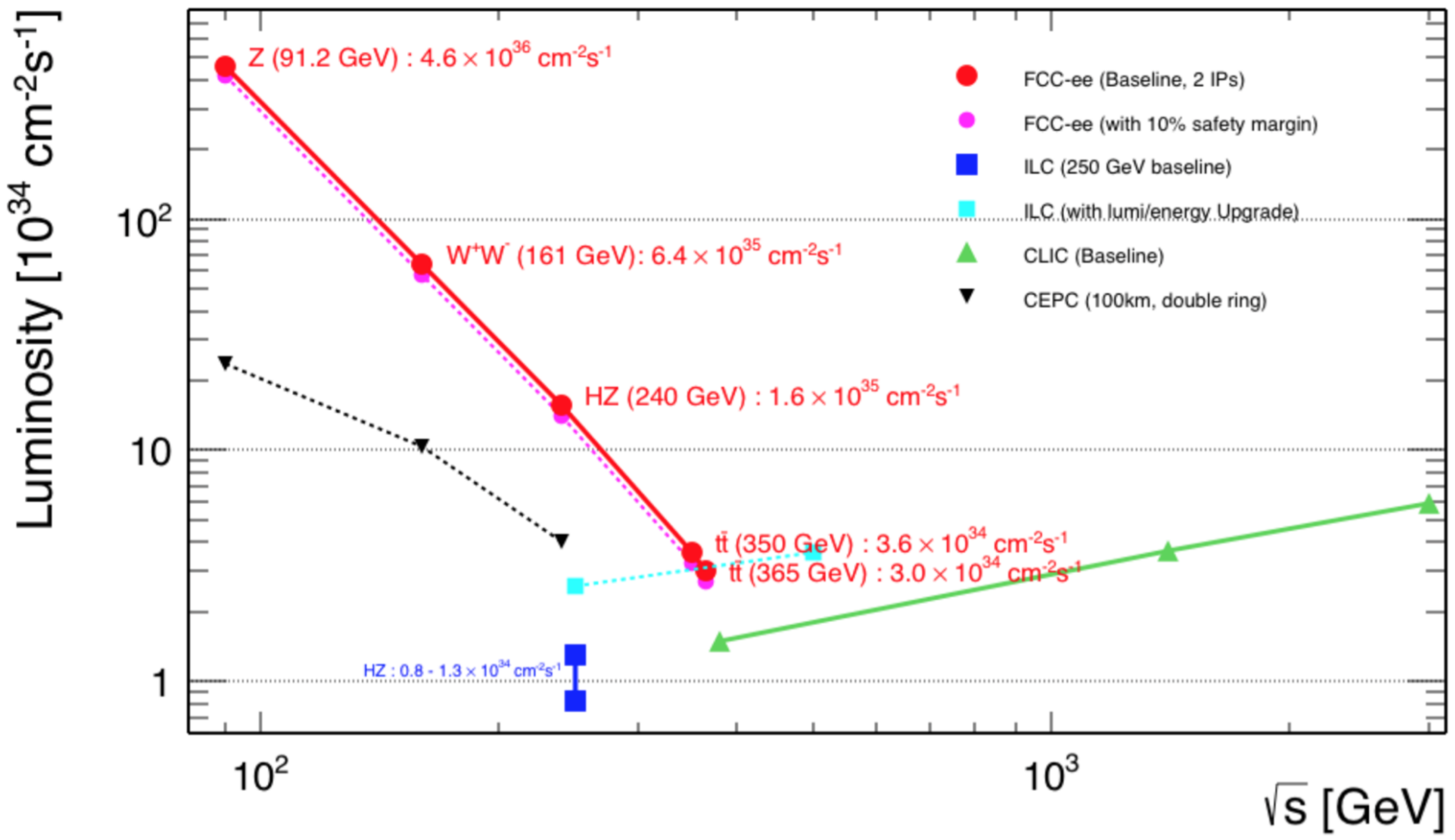


Total programme duration 15 years - including machine modifications

	5 ab^{-1} at 240 GeV	1.5 ab^{-1} at 365 GeV
# Higgs from HZ	1,000,000	180,000
# Higgs from VBF	25,000	45,000

FCC-ee: coupling measurements

Main advantage: large luminosity at circular collider



Factor ~10 improvement for most couplings compared to HL-LHC

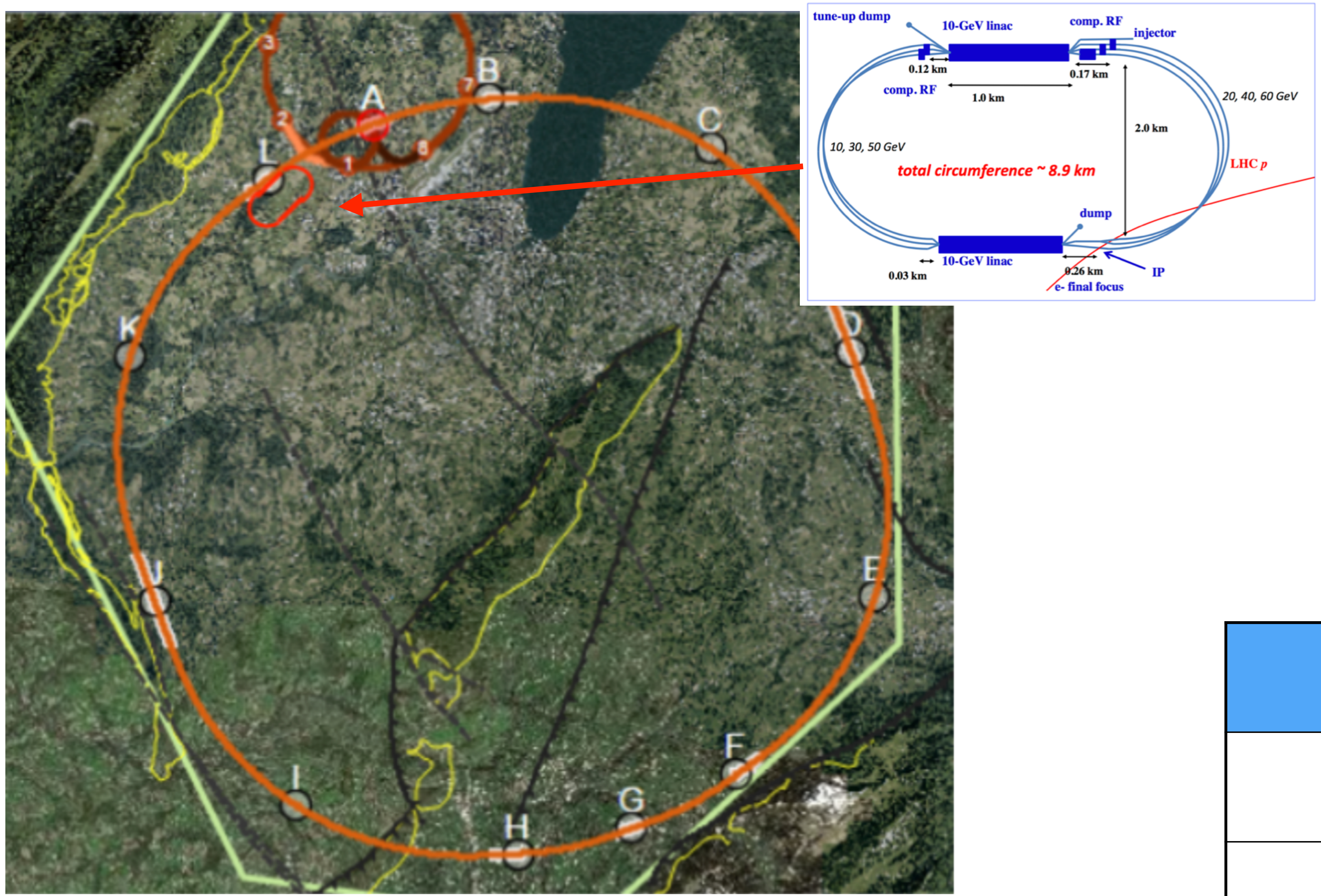
For more details, see Frank Simon's presentation

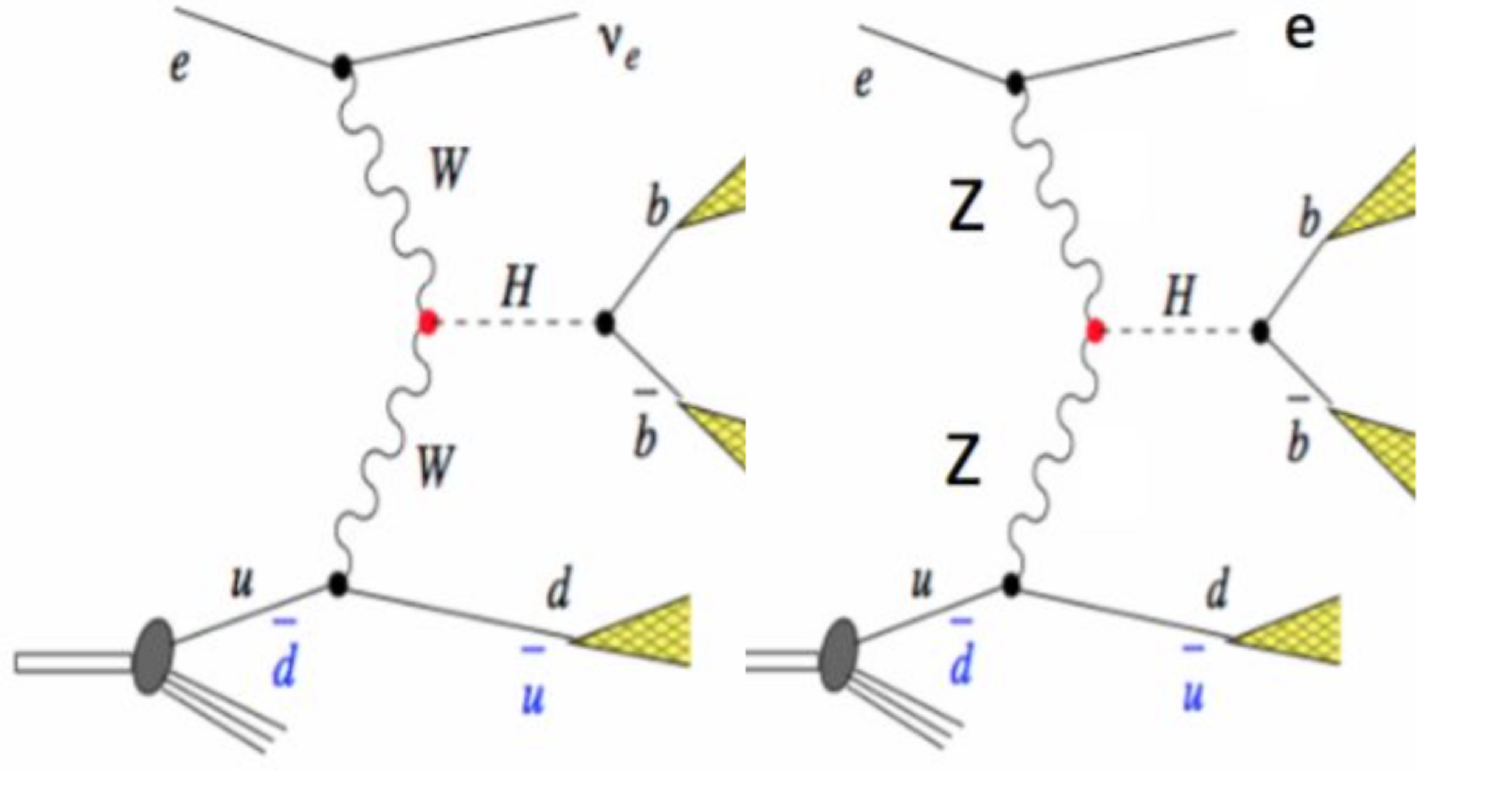
	5/ab at 240 GeV	***+1.5/ab at 365 GeV***
$\delta\Gamma_H/\Gamma_H$ (%)	2.8	**1.6**
$\delta g_{HZZ}/g_{HZZ}$ (%)	0.25	**0.22**
$\delta g_{HWW}/g_{HWW}$ (%)	1.3	**0.47**
$\delta g_{Hbb}/g_{Hbb}$ (%)	1.4	**0.68**
$\delta g_{Hcc}/g_{Hcc}$ (%)	1.8	**1.23**
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.7	**1.03**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.4	**0.80**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	9.6	**8.6**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	4.7	**3.8**
$\delta g_{Htt}/g_{Htt}$ (%)	–	–
BR_{EXO} (%)	< 1.2	$\mathbf{< 1.1}$

Model-independent fit, statistical uncertainties only

Higgs boson production at the FCC-eh

Runs concurrently with FCC-hh!





σ = 1 pb   σ = 0.15 pb

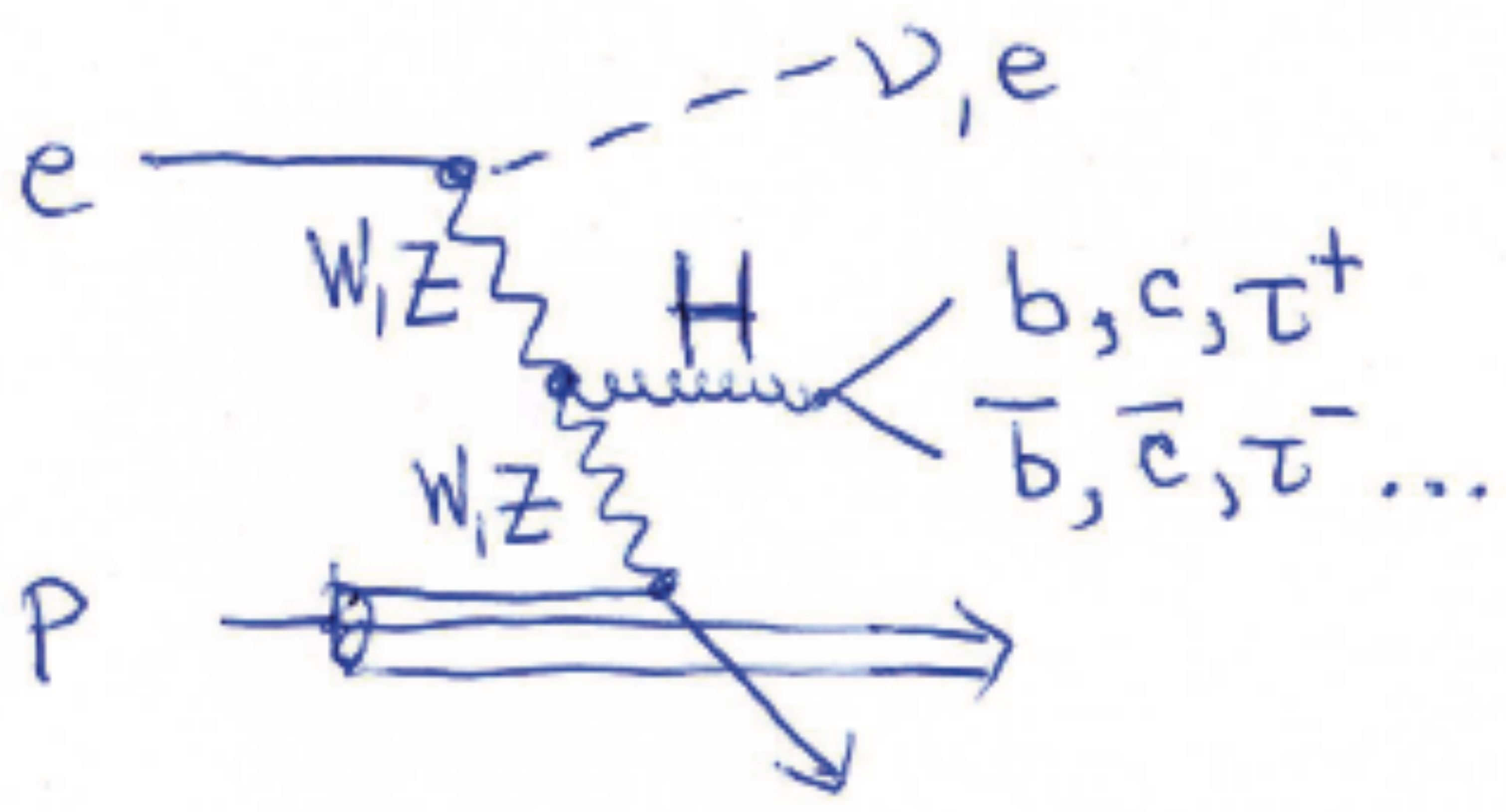
	2 ab^{-1} at 3.5 TeV
# Higgs from CC [LO]	2.000.000
# Higgs form NC [LO]	300.000

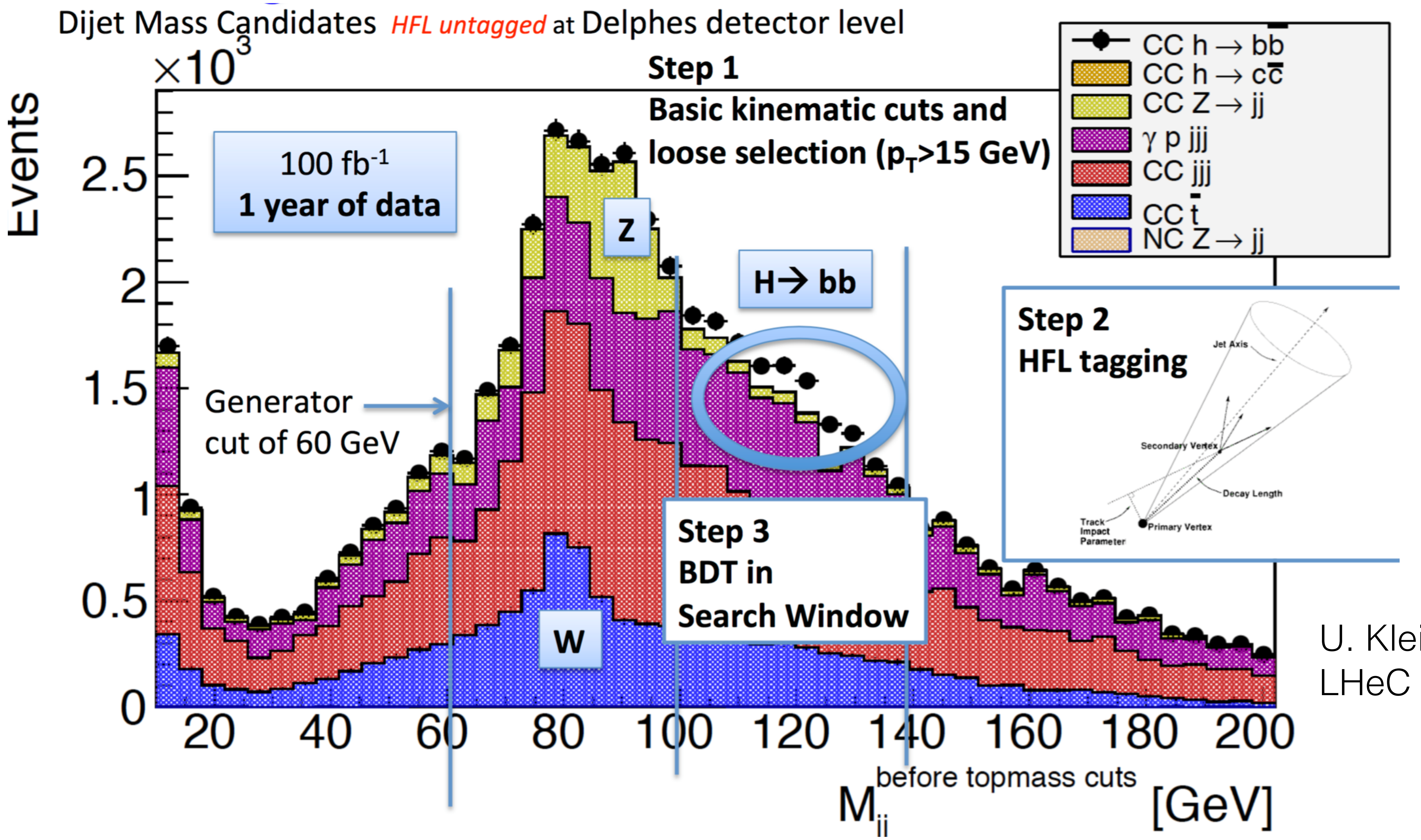
with 80% e polarisation

E_p = 50 TeV , E_e = 60 GeV

$\sqrt{s}$ = 3.5 TeV , Lumi = 15E33

FCC-eh: coupling measurements



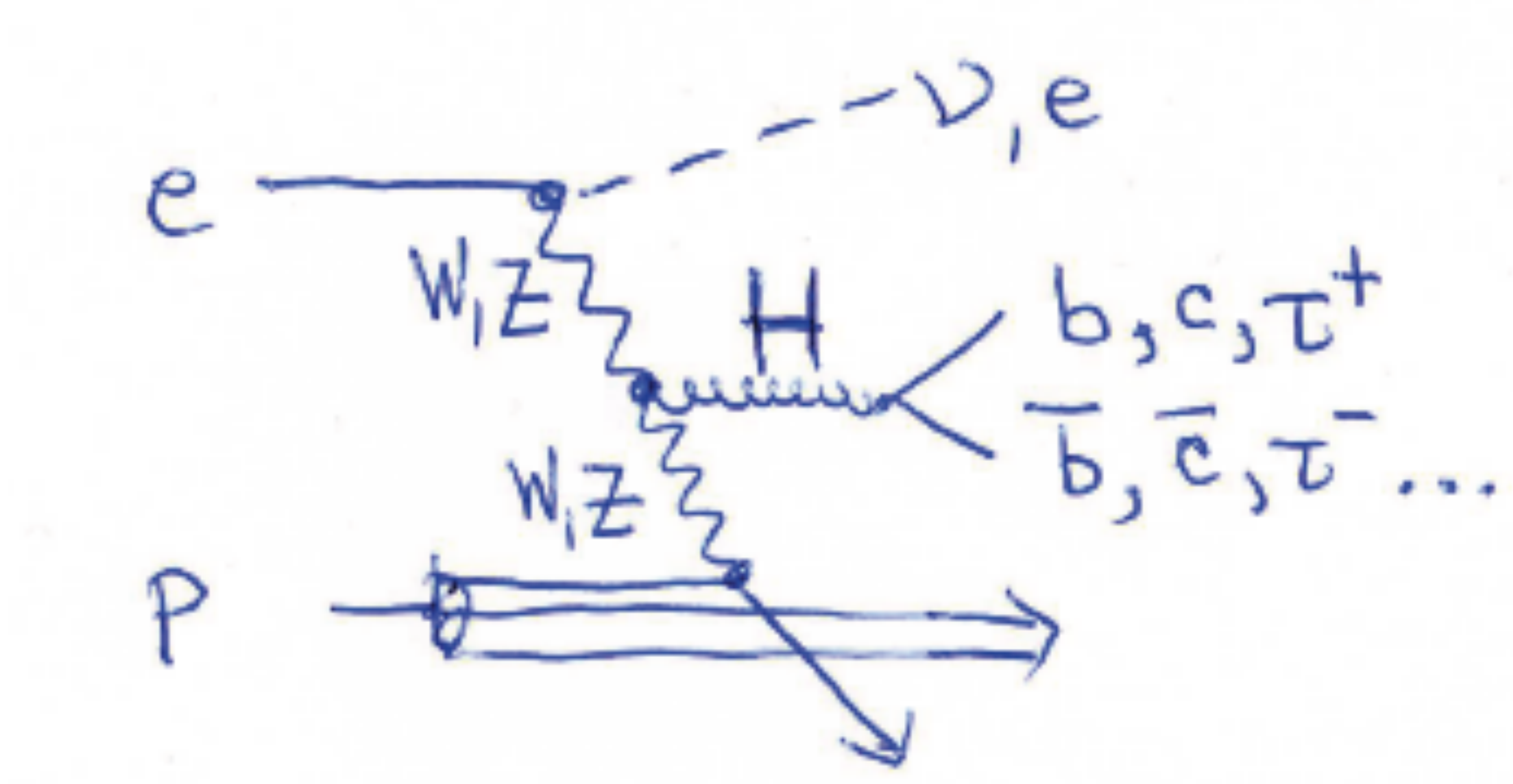


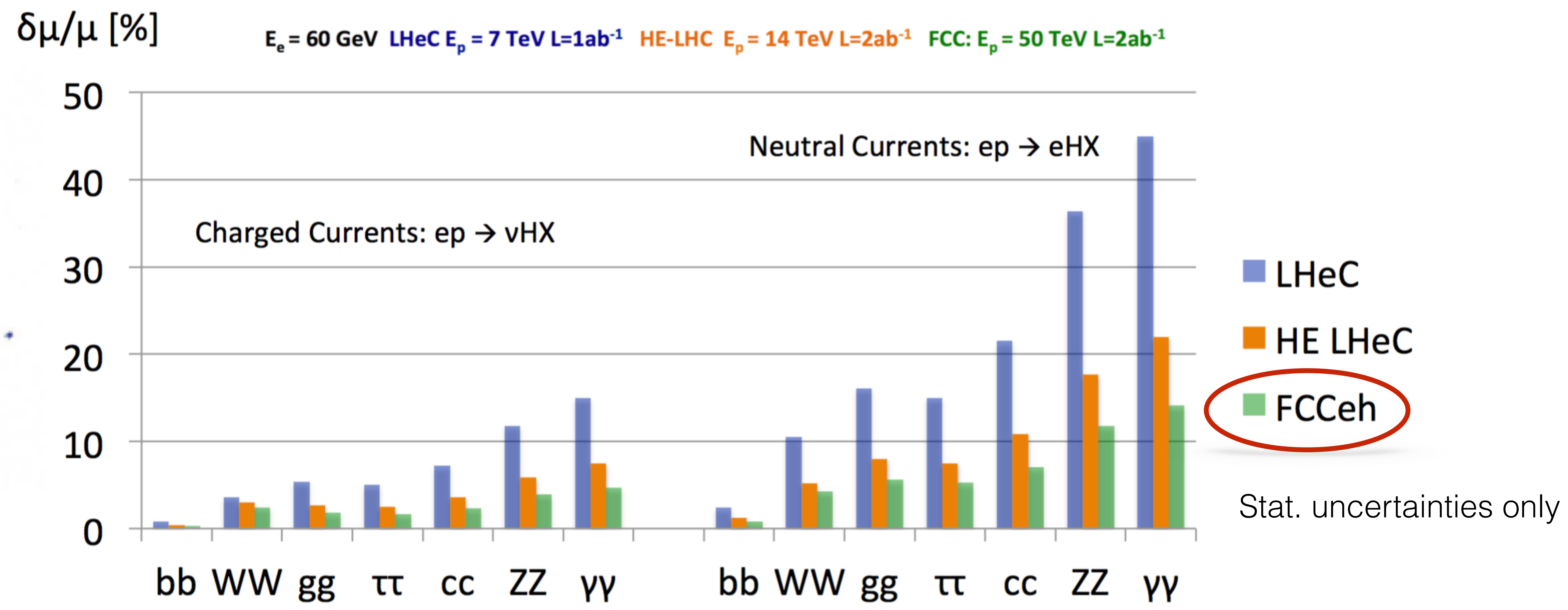
U. Klein
LHeC

Pile-up estimated to be just 1

Good S/B in most channels, e.g. S/B > 1 for bb mode

FCC-eh: coupling measurements





Signal strengths precision 0.5% for the most abundant channel and up to 5% for γγ

Model independent coupling measurements enabled by FCC-ee total width measurement

Critically improve Higgs measurements at FCC-hh, with very precise PDF determination

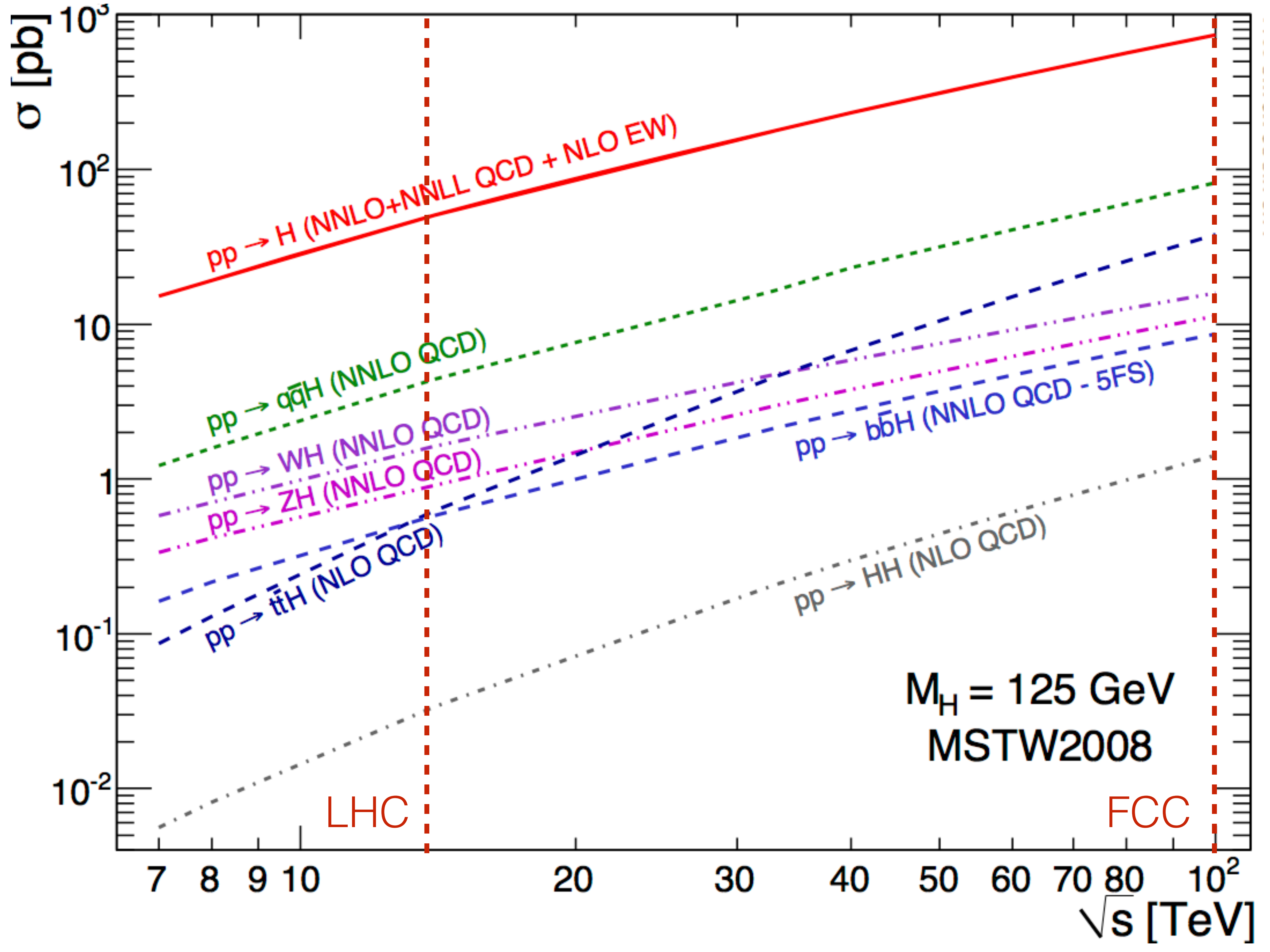
Higgs boson production at the FCC-hh

$\sqrt{s}$ = 100 TeV

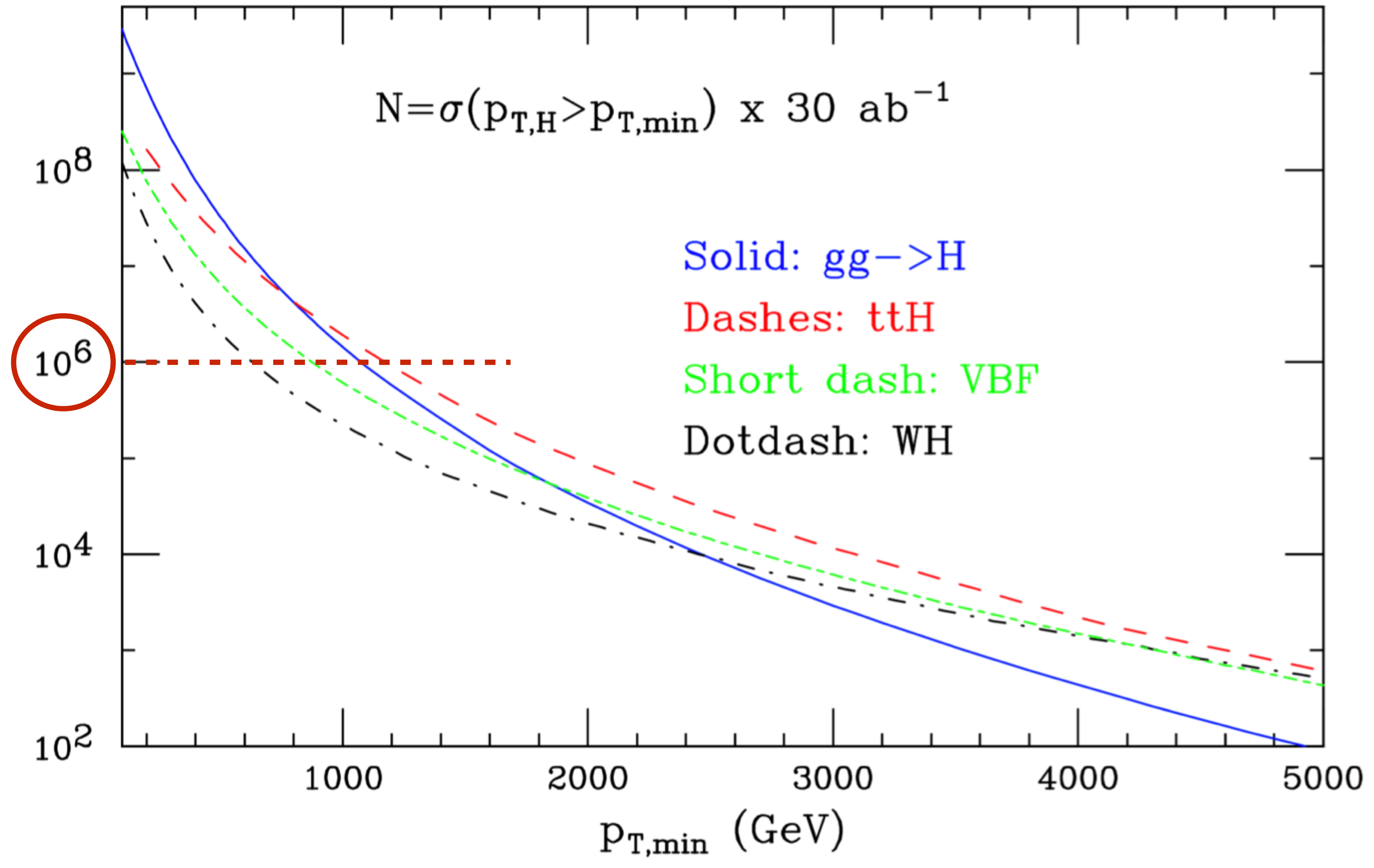
L = 20 ab^{-1} in 25y

Higgs boson rates (also relative to HL-LHC):

	gg→H	VBF	WH	ZH	$t\bar{t}H$	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



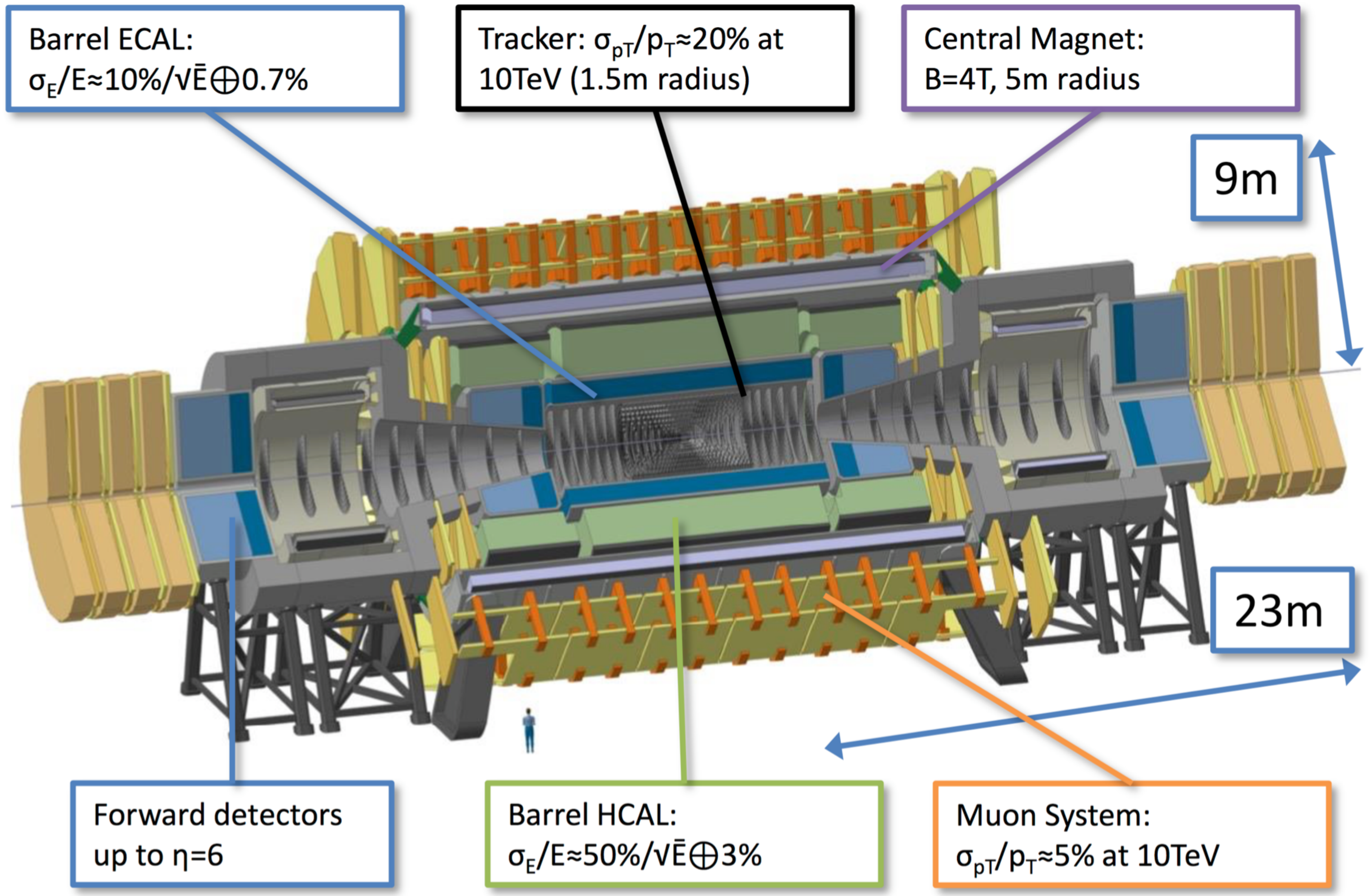
The ultimate Higgs Factory!



Probe high scales with precise measurements at high Q^2!

Collider and detectors

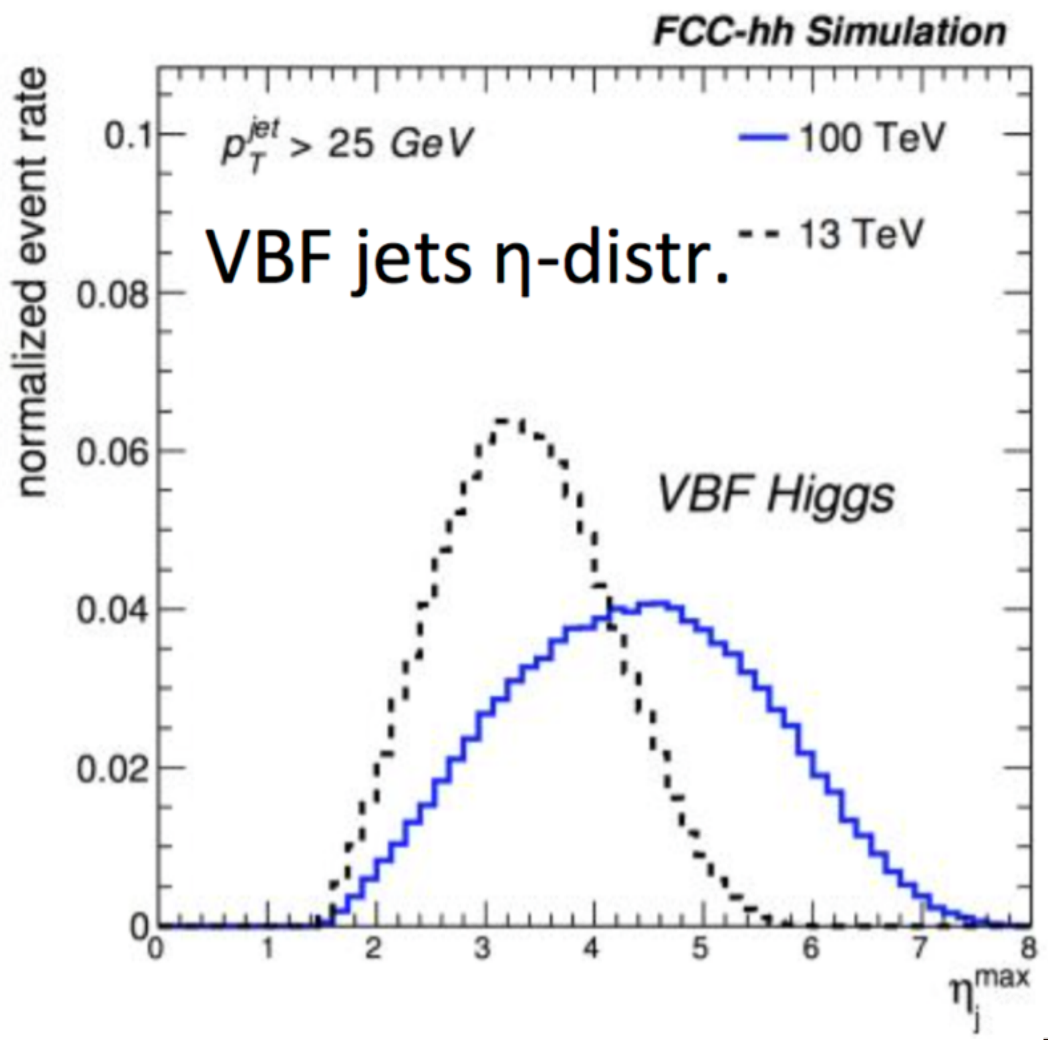
parameter	FCC-hh		HE-LHC	HL-LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	1.1
bunch intensity [10^{11}]	1	1	2.2	2.2
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3
SR power / length [W/m/ap.]	28.4		4.6	0.33
long. emit. damping time [h]	0.54		1.8	12.9
beta* [m]	1.1	0.3	0.45	0.15 (min.)
normalized emittance [μm]	2.2		2.5	2.5
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	16	5 (lev.)
events/bunch crossing	170	1000	460	132
stored energy/beam [GJ]	8.4		1.3	0.7

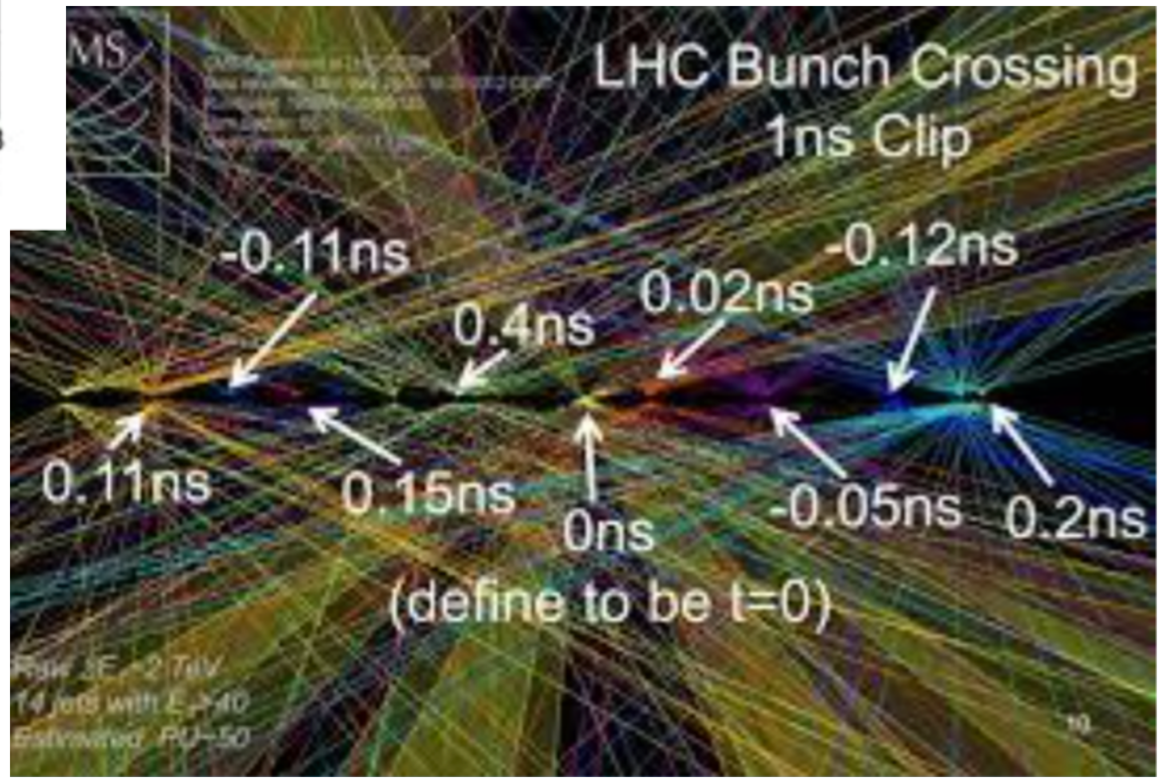


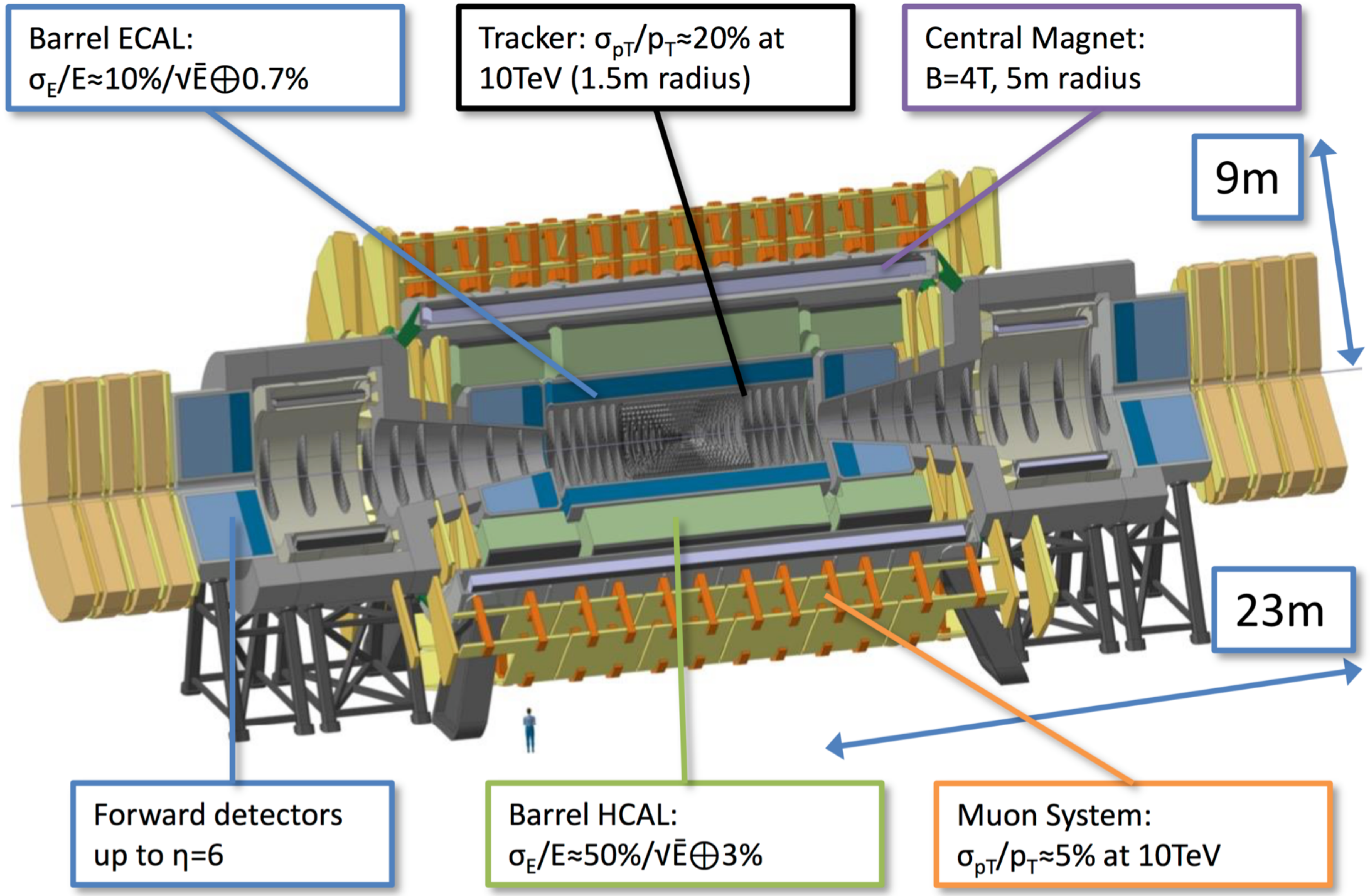
Schedule constrained by 16T magnets and CE, possible physics operation 2043

Extended pseudorapidity (η) coverage, granularity and timing (pileup up to 1000!)

Collider and detectors







Schedule constrained by 16T magnets and CE, possible physics operation 2043

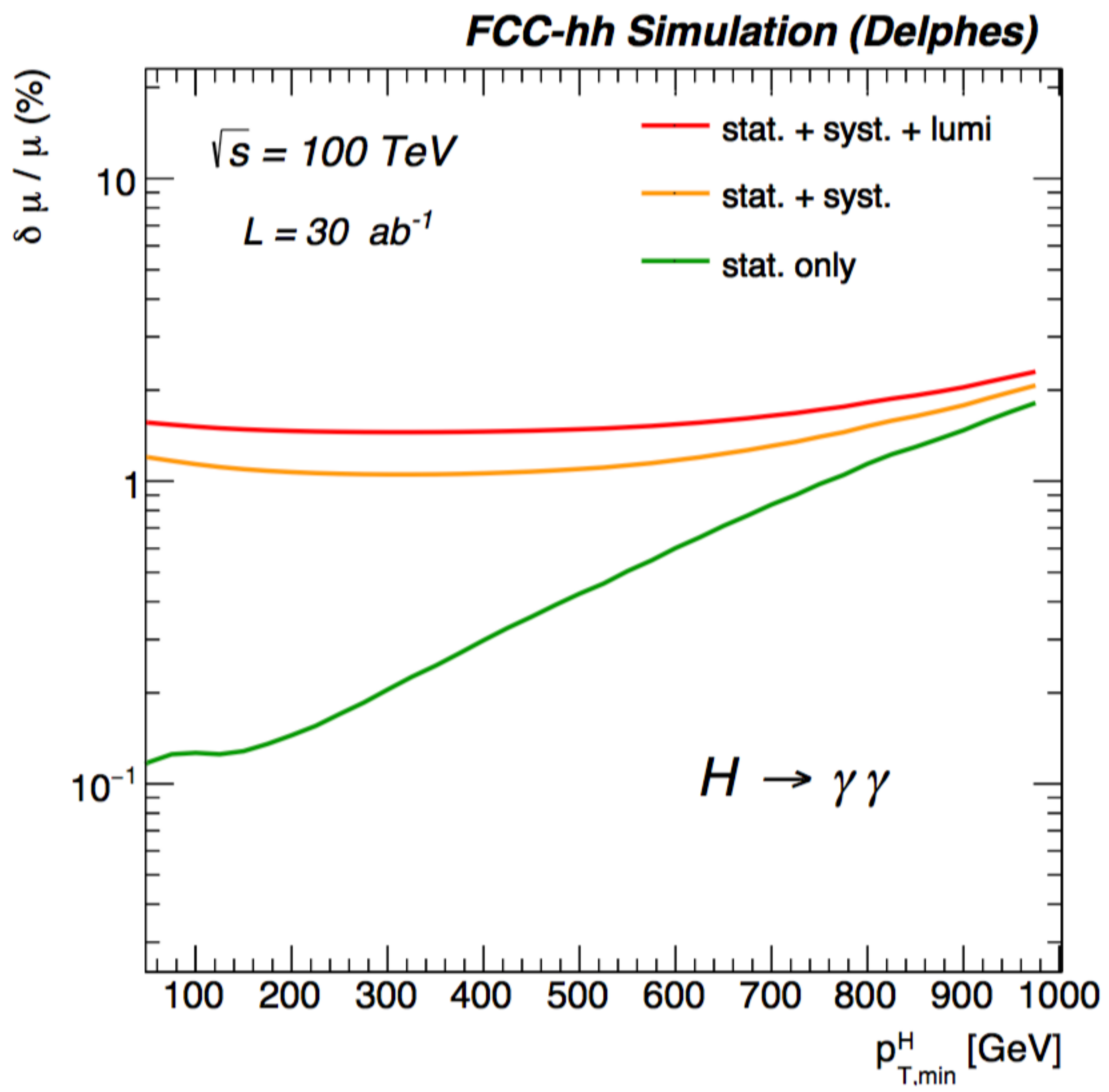
Extended pseudorapidity (η) coverage, granularity and timing (pileup up to 1000!)

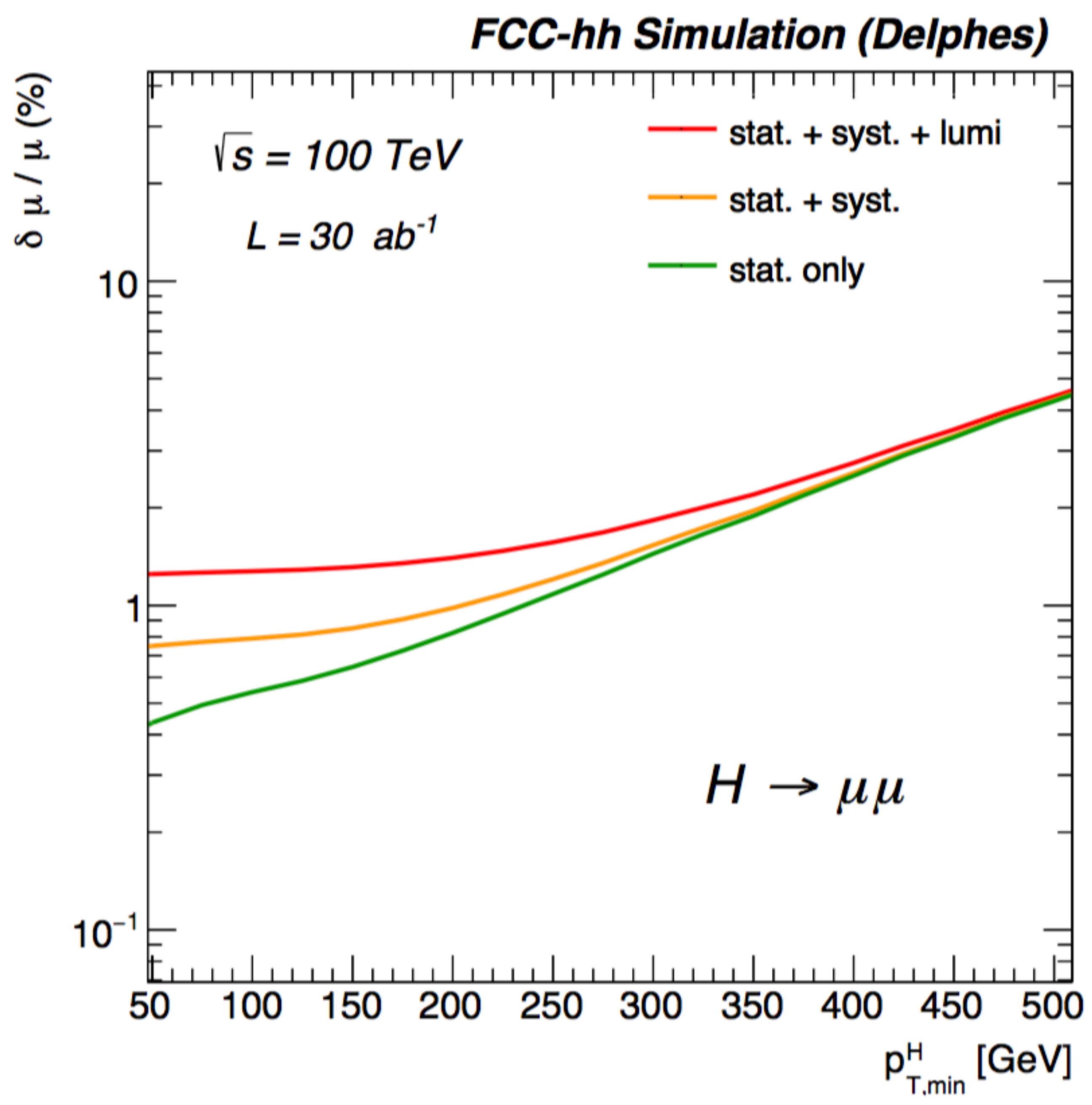
Higgs physics at FCC-hh

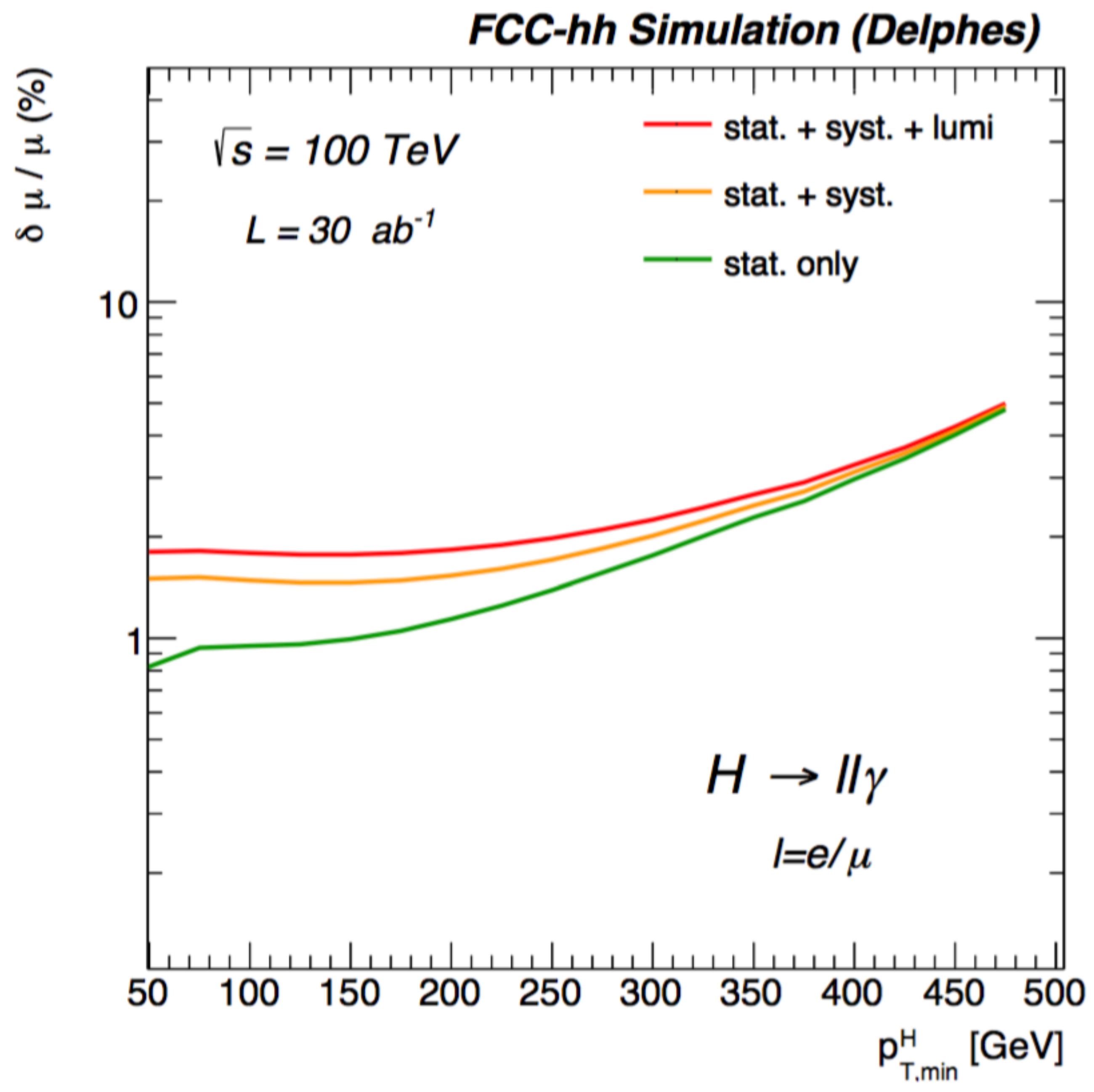
Rare Higgs decays statistically limited at FCC-ee/eh

Large dynamic range for Higgs production (pT, m(H+X),…)

- Ease challenges by triggers and reconstruction in the high pileup environment
- Improve signal-to-background ratios
- Increase sensitivity to higher-dimension operators affecting Higgs dynamics

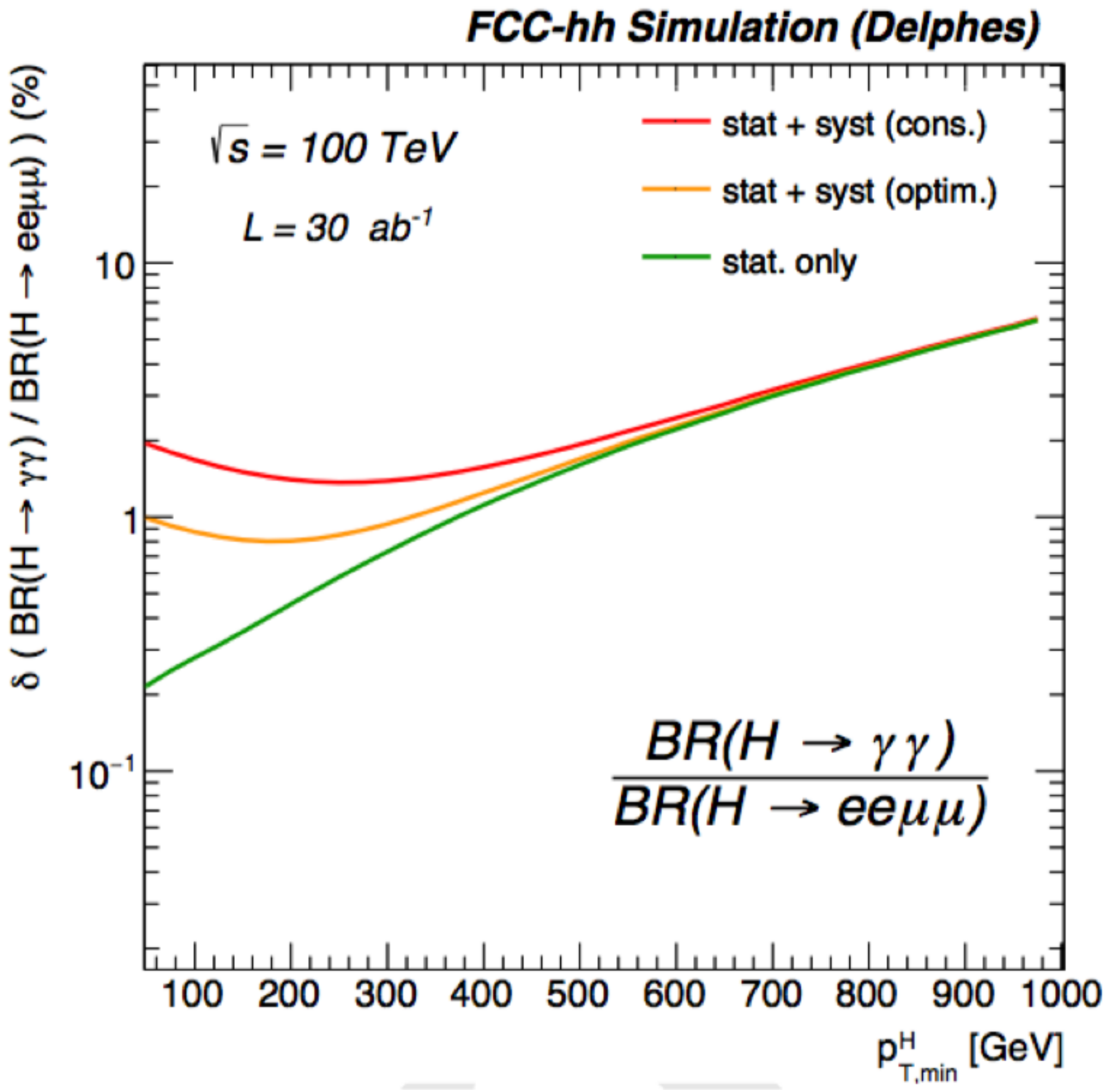


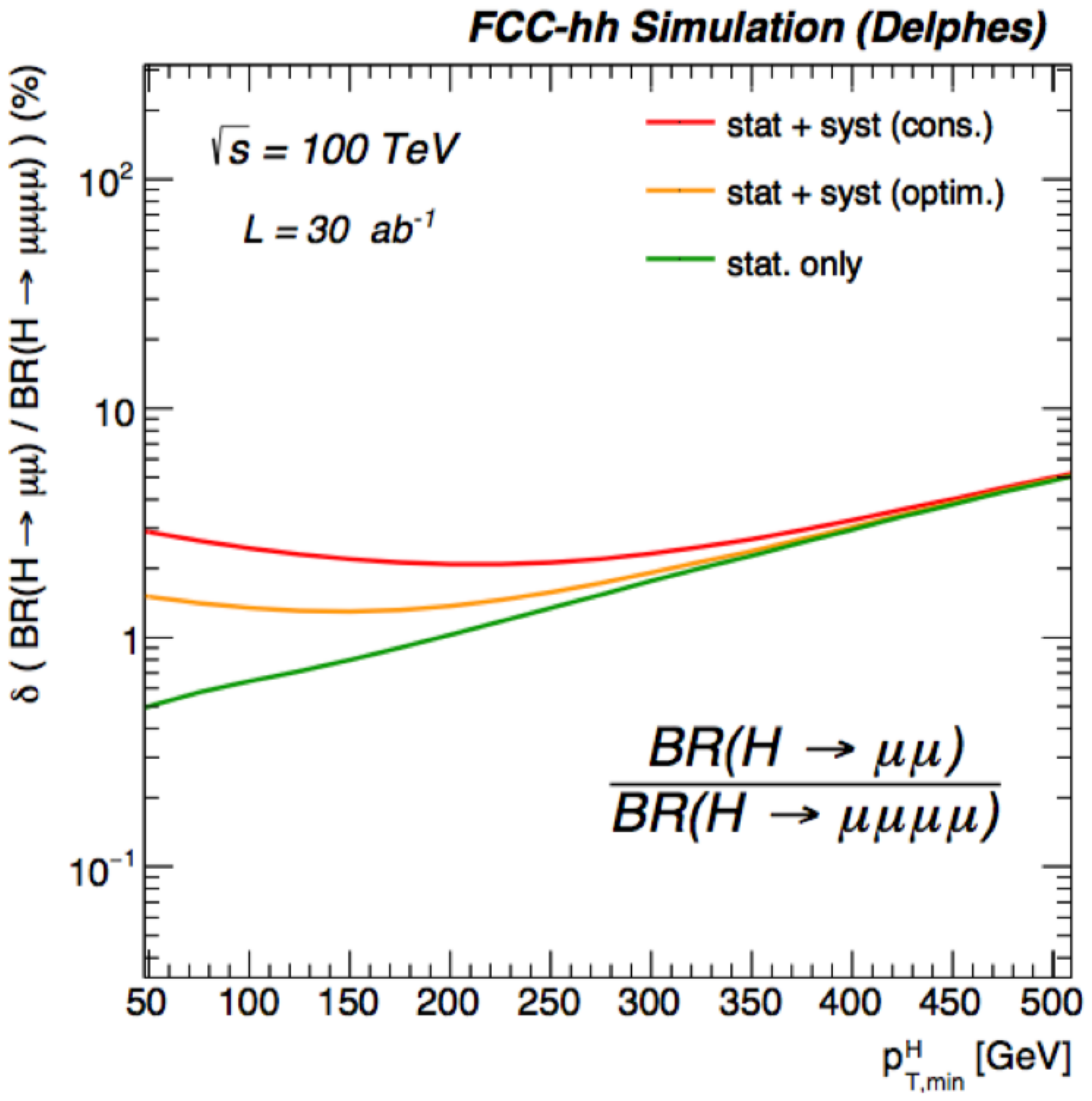


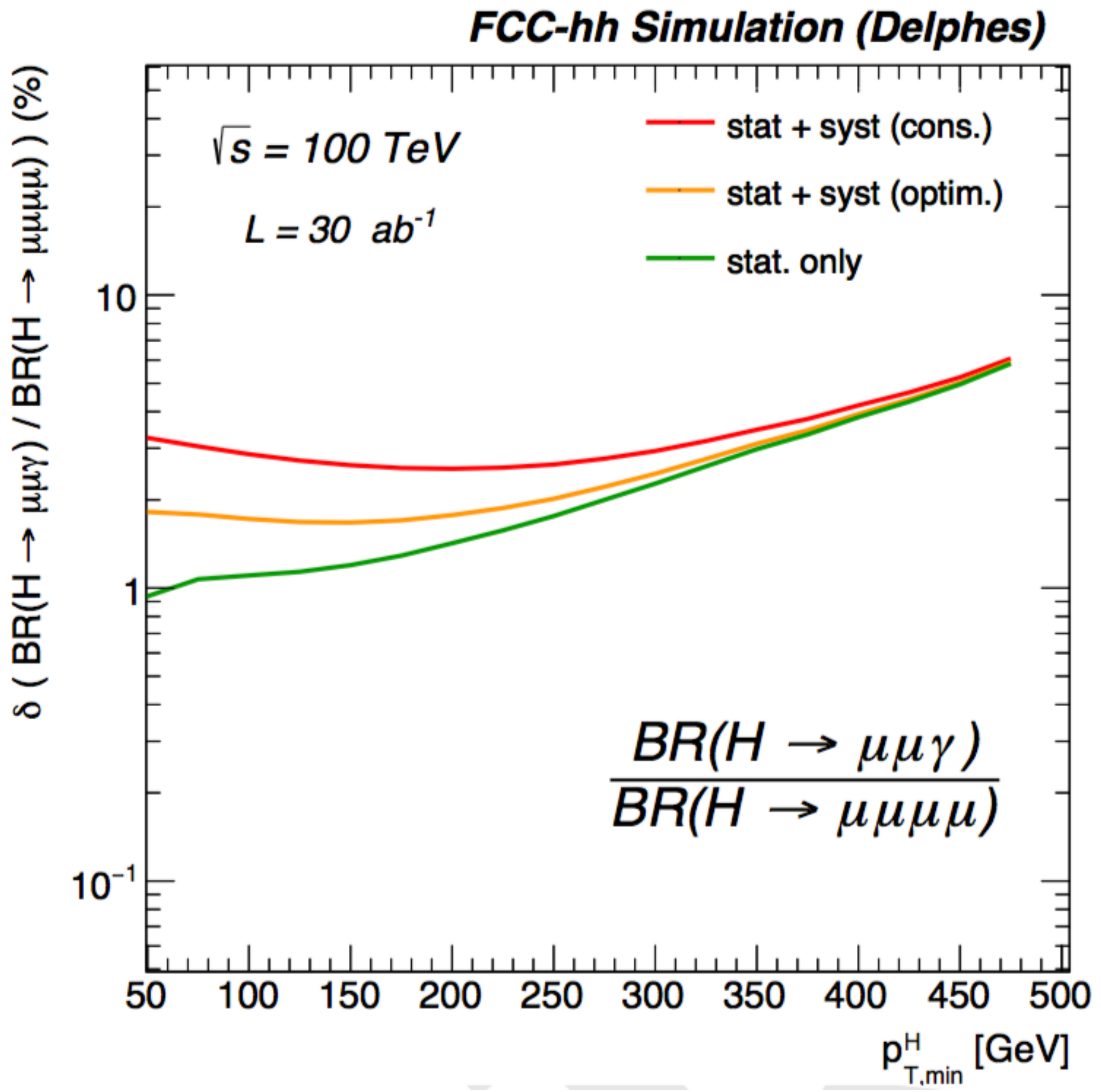


Ratio measurements

Uncertainties due to production modelling and luminosity cancel in the ratio of different decay modes



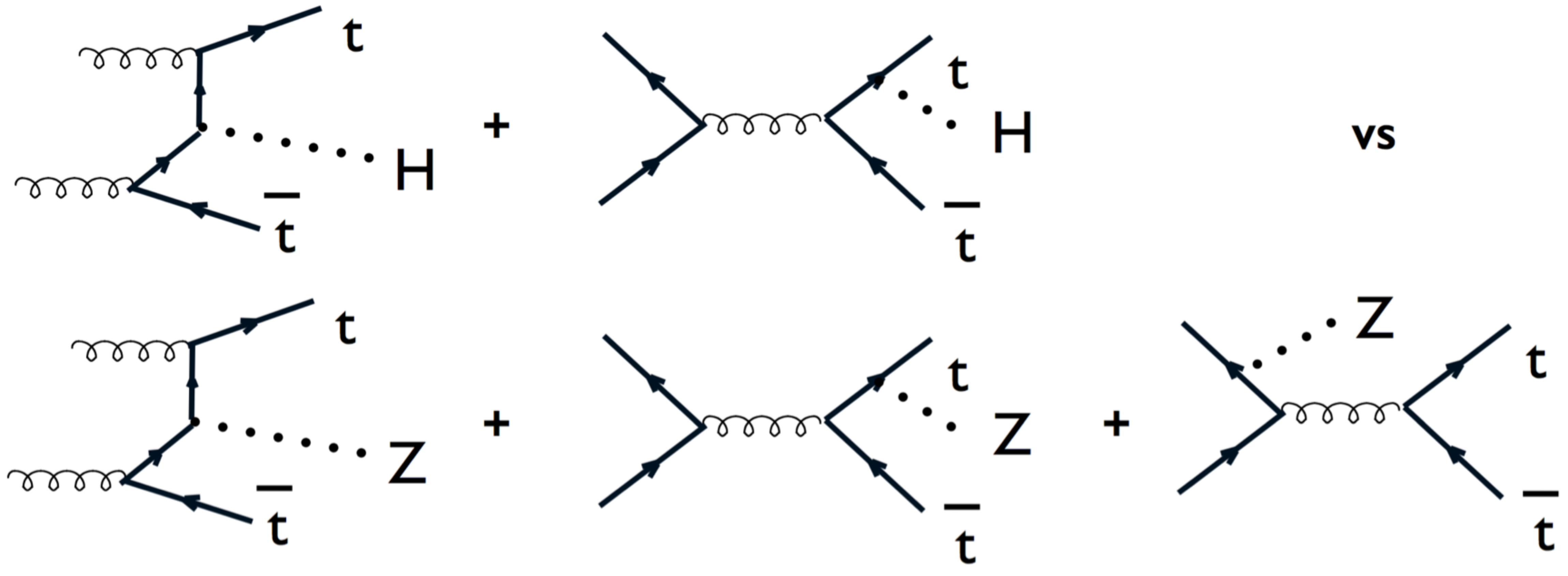


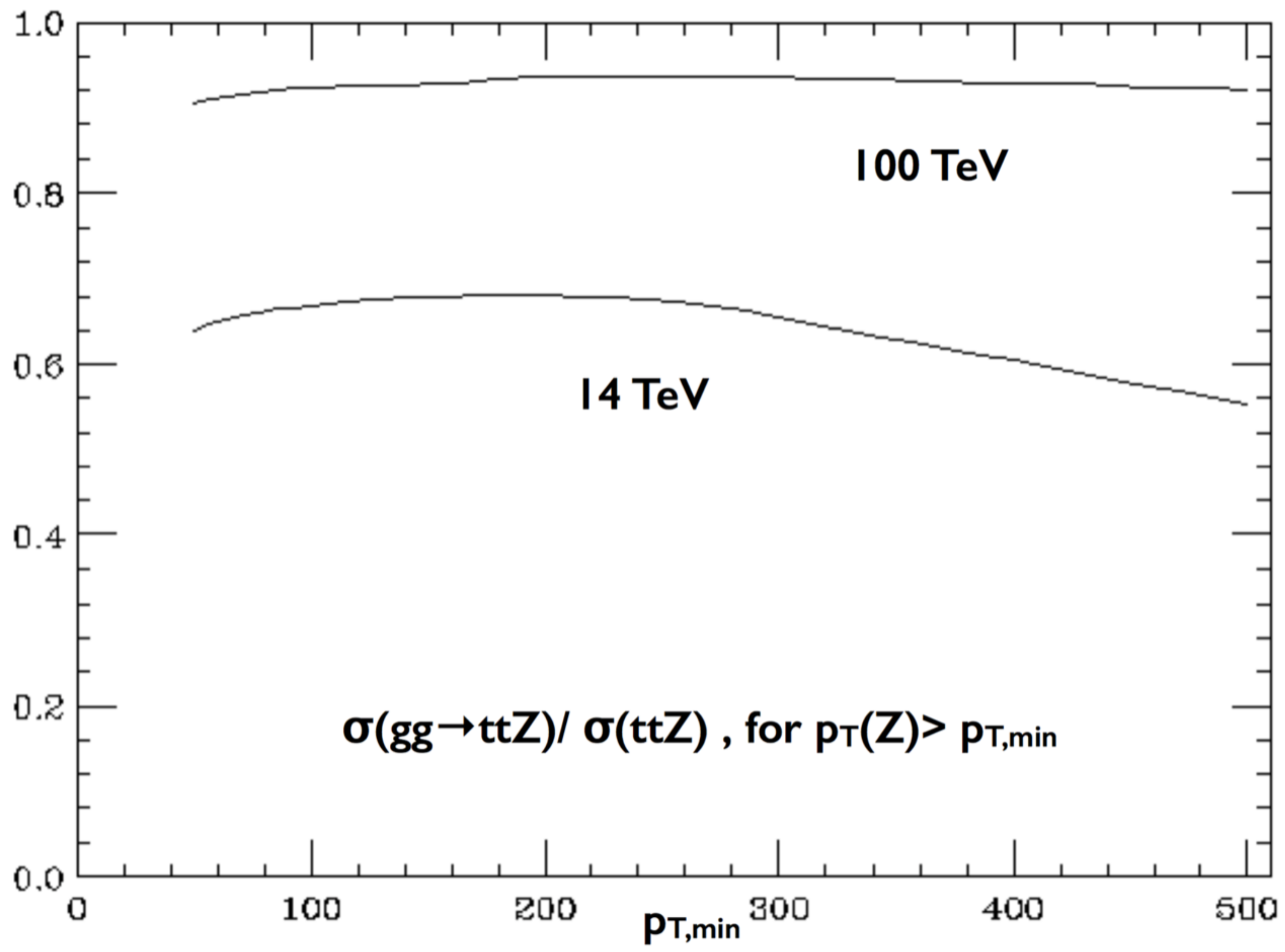


With the *BR*(H→4l) accuracy from FCC-ee, from the FCC-hh ratios it could be possible to extract the absolute couplings of the Higgs to γγ (0.4%), μμ (0.7%) and Zγ (0.9%)

Top Yukawa coupling at FCC-hh

Extract top-quark Yukawa coupling from σ(ttH) / σ(ttZ)





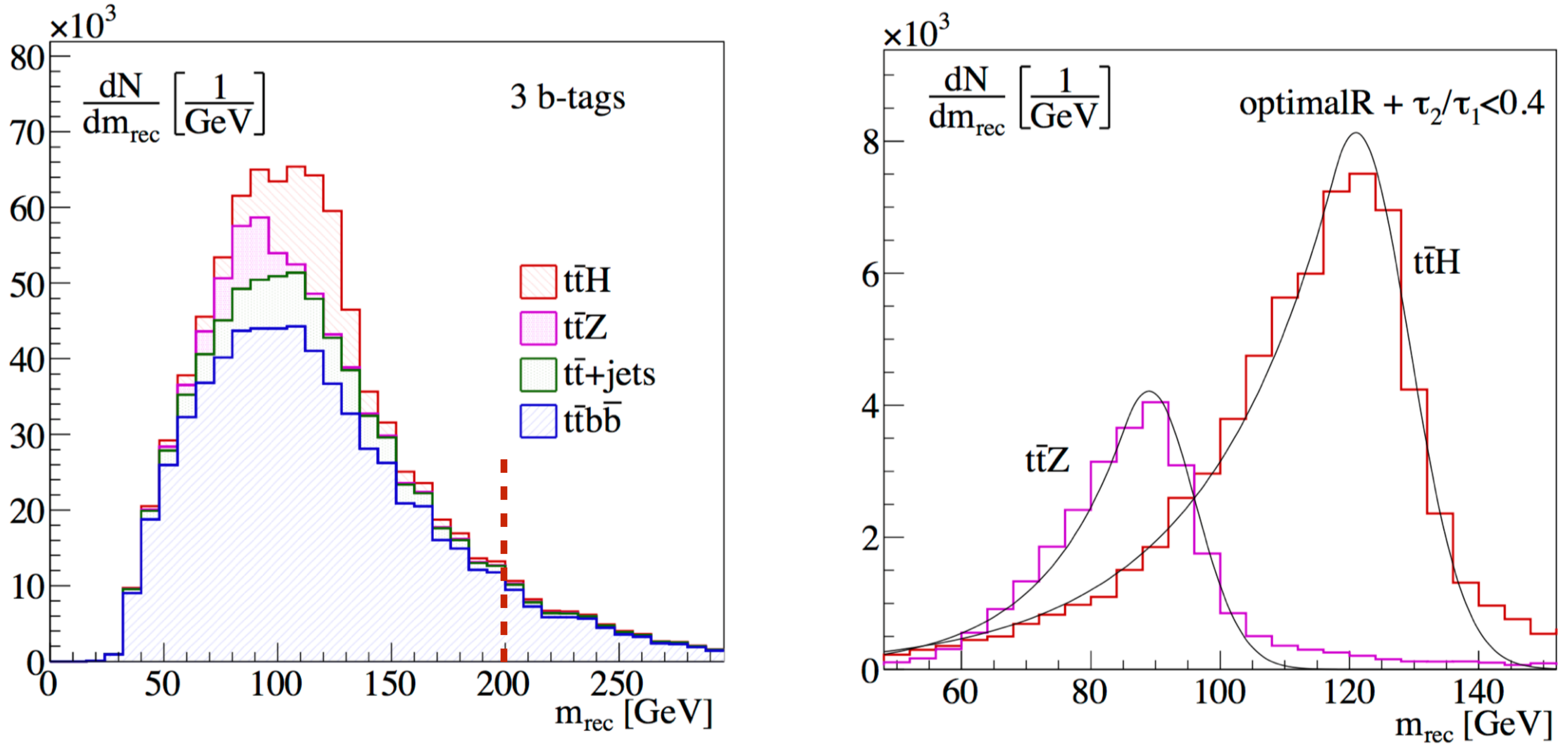
To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:
  - o correlated QCD corrections, correlated scale dependence
  - o correlated α_S systematics
- $m_Z \sim m_H$ ⇒ 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

Top Yukawa coupling at FCC-hh

Extract top-quark Yukawa coupling from σ(ttH) / σ(ttZ)



M.L. Mangano et al., arXiv: 1507.08169 [hep-ph]

Select semi-leptonic tt and boosted topology to reduce combinatorial backgrounds

Constrain backgrounds by m_J > 200 GeV

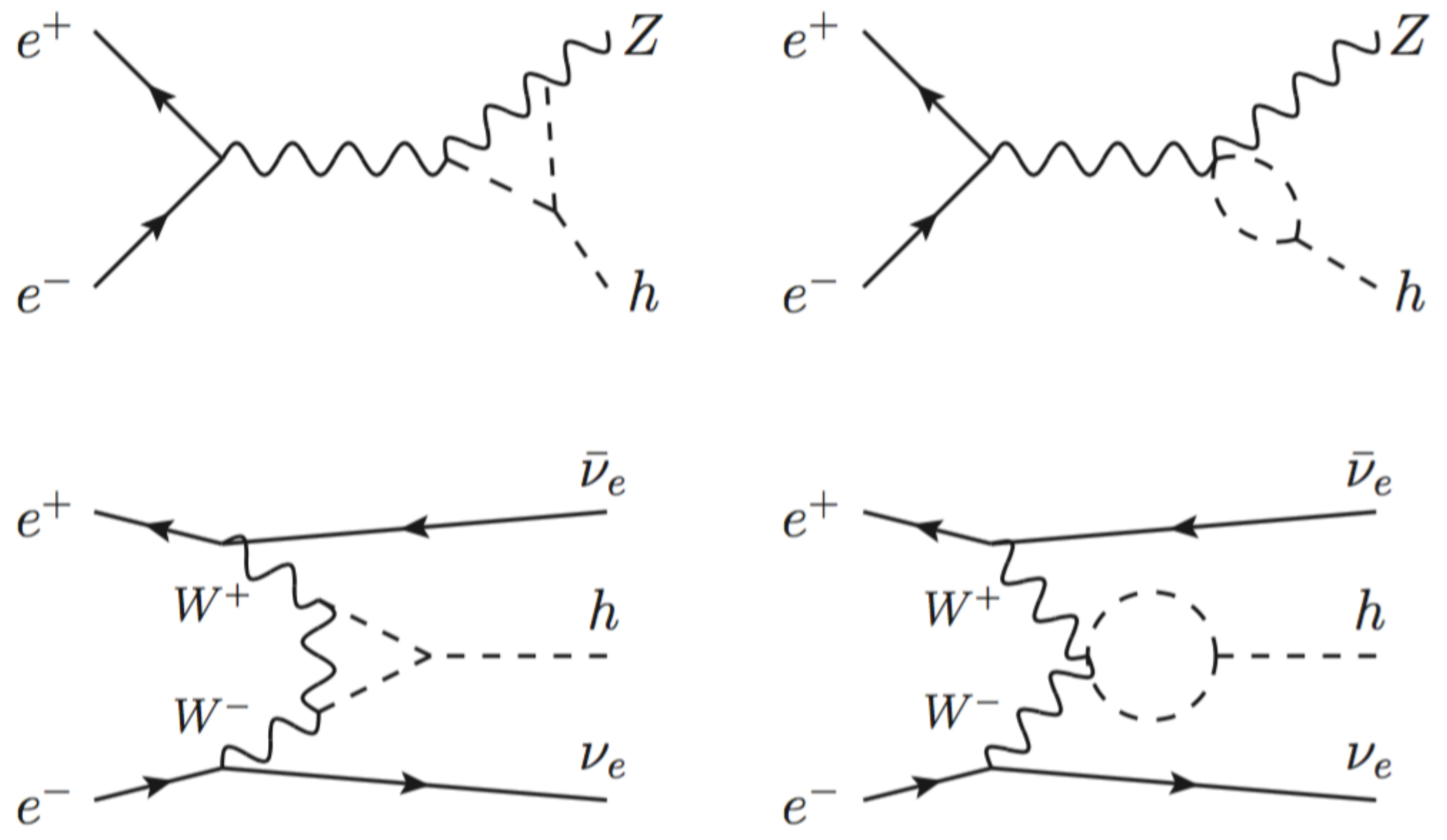
Extract ttH and ttZ contribution simultaneously from m_J fit

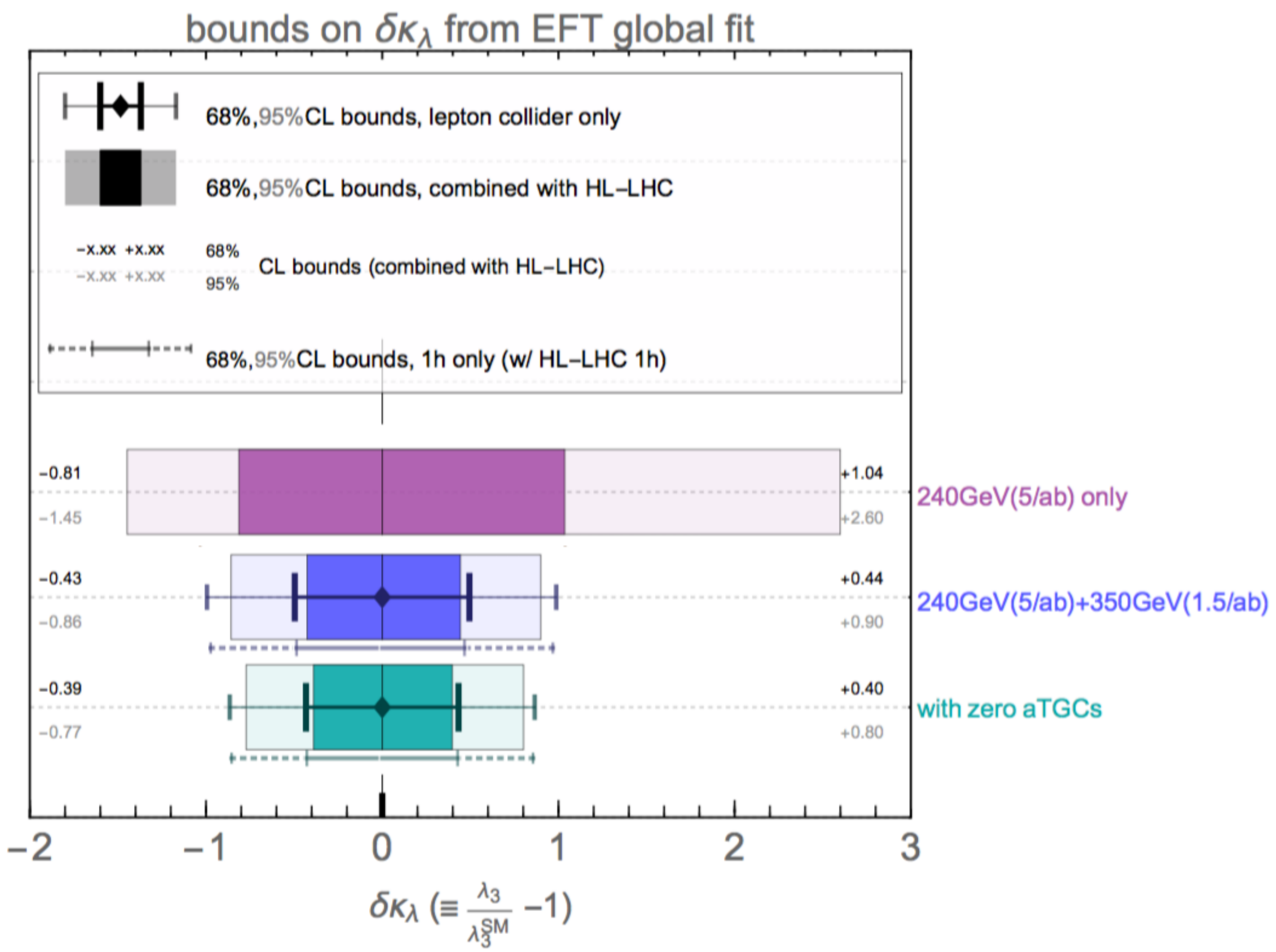
Precision measurement of top-Z coupling and *BR*(H→bb) from FCC-ee/eh

Overall precision on the top Yukawa coupling ~1%

Higgs potential - indirect probe at FCC-ee

In single Higgs production self-coupling enters via processes at loop level



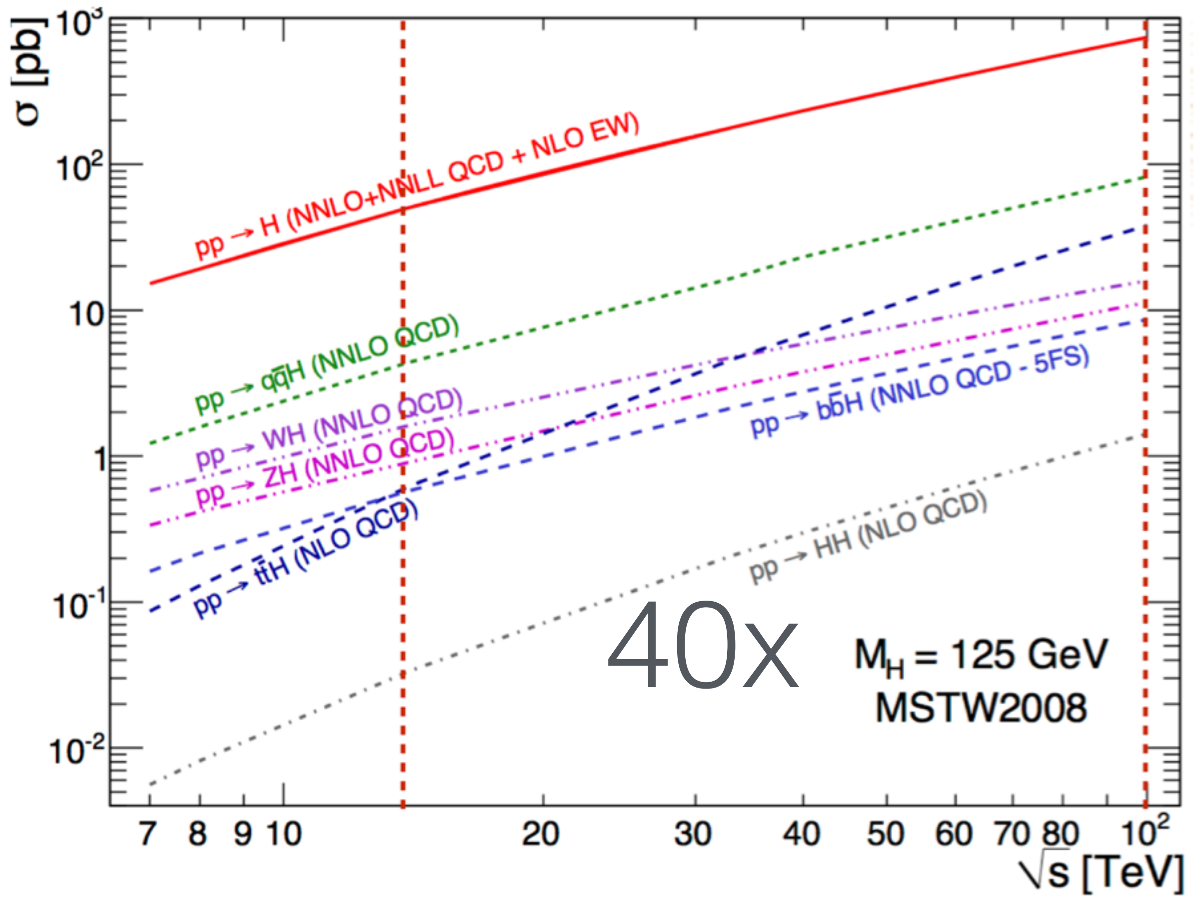


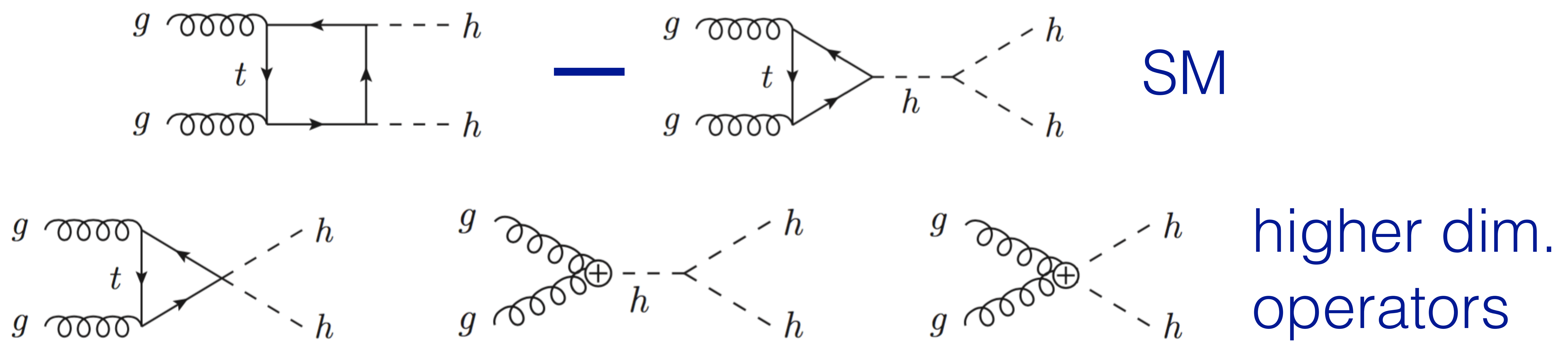
arXiv:1711.03978v1

Global analysis, allows for all dim-6 operators, model-independent description of Higgs self-coupling

Measure $\delta\kappa_\lambda$ with 40% precision

Higgs potential - direct probe at FCC-hh





~400x more HH events compared to HL-LHC

Interference suppresses SM rate, but higher sensitivity to deviations from SM couplings

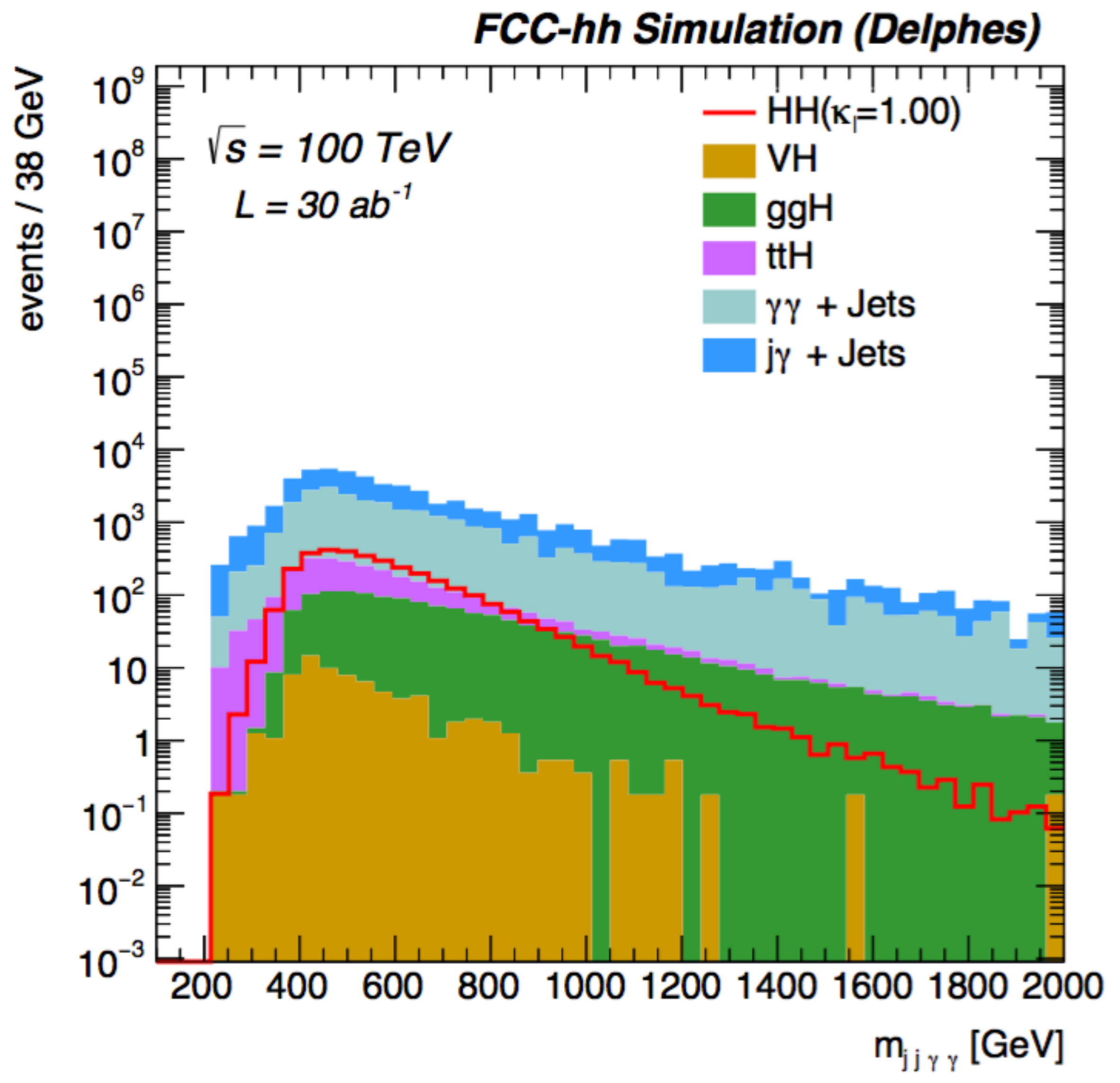
Direct constraint on $\delta\kappa_\lambda$ requires inclusion of other higher dim. operators, which can be measured at FCC-ee/eh/hh with 1% precision

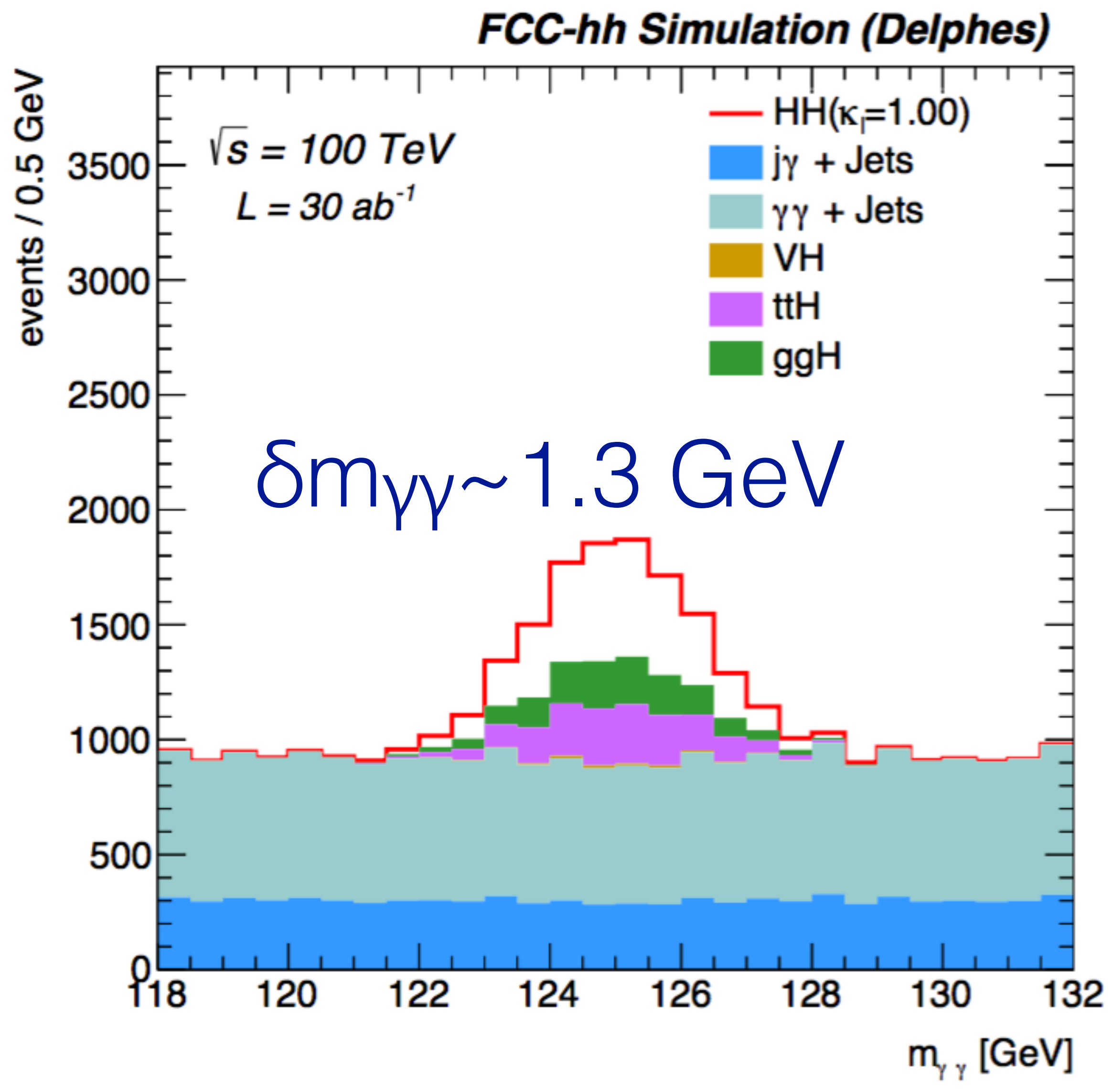
→ Global FCC fit for robust estimates

Most promising channel HH → γγbb

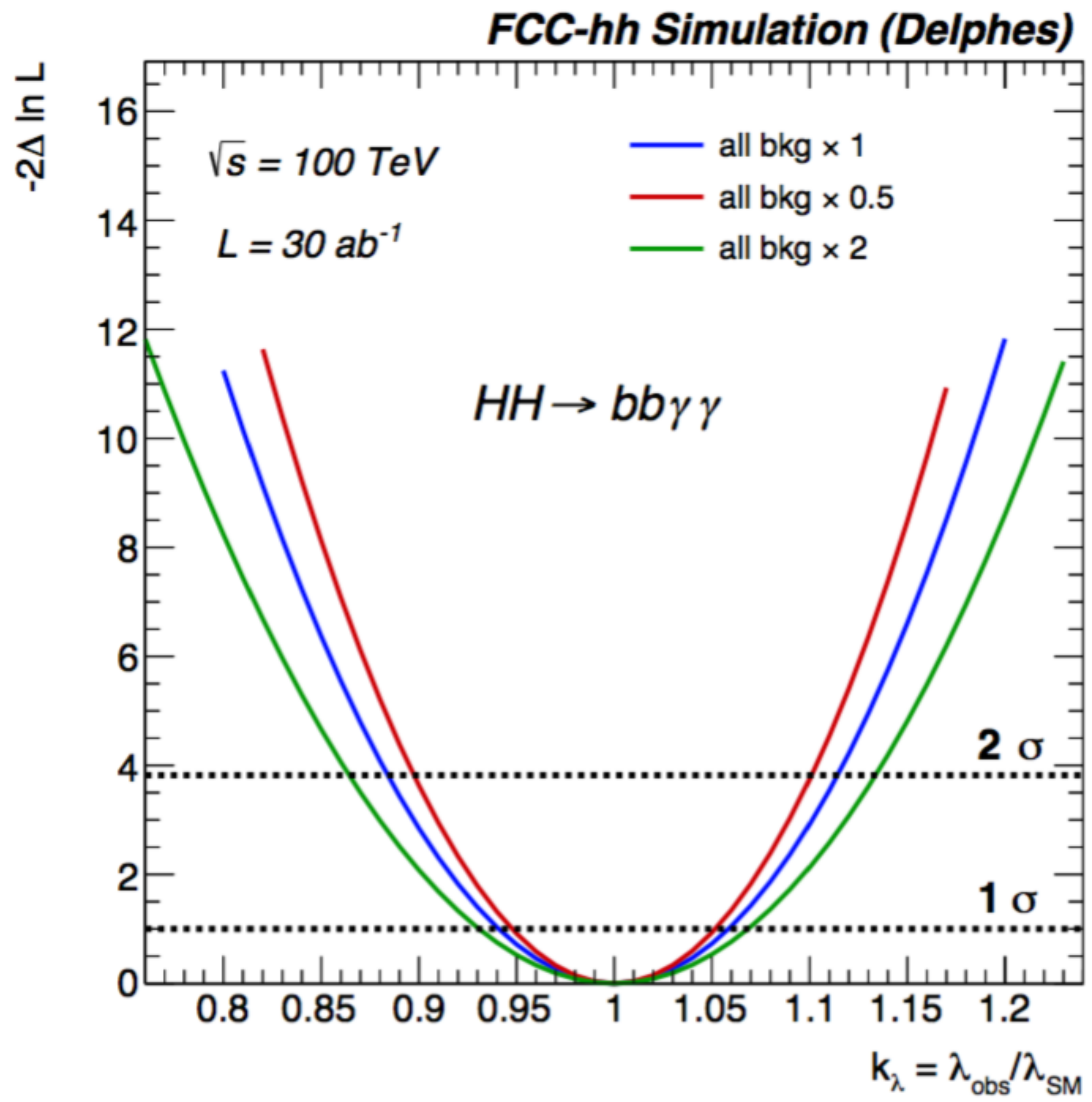
Backgrounds:

- QCD (extrapolated from high-stat sideband)
- Single Higgs prod. (assume 1% uncertainty)





→ 6.5% precision on Higgs self-coupling



Varying background rates or detector performance gives only 1-2% degradation

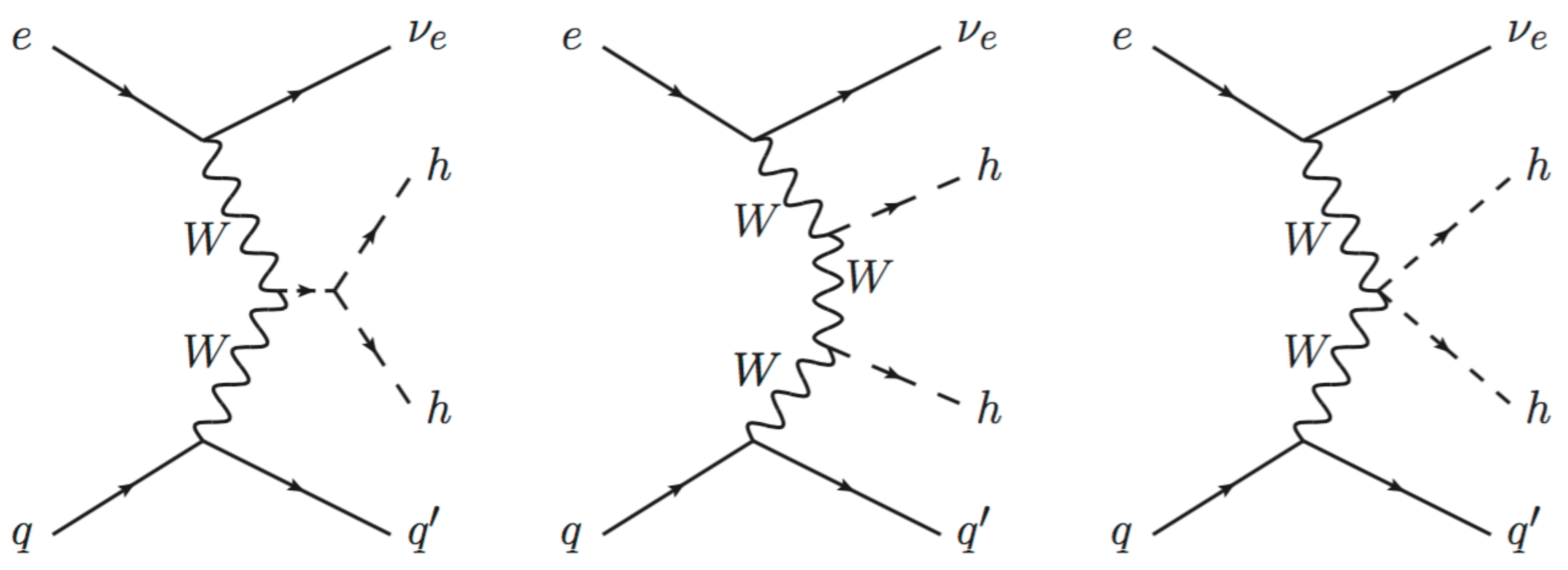
Higgs potential - direct probe

	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\rightarrow 4\ell]$	$b\bar{b}WW^*[\rightarrow 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

For further details, talk from Clement Helsens

Electroweak loop corrections *O*(few%), FCC will start to probe quantum structure of the Higgs potential

FCC-eh

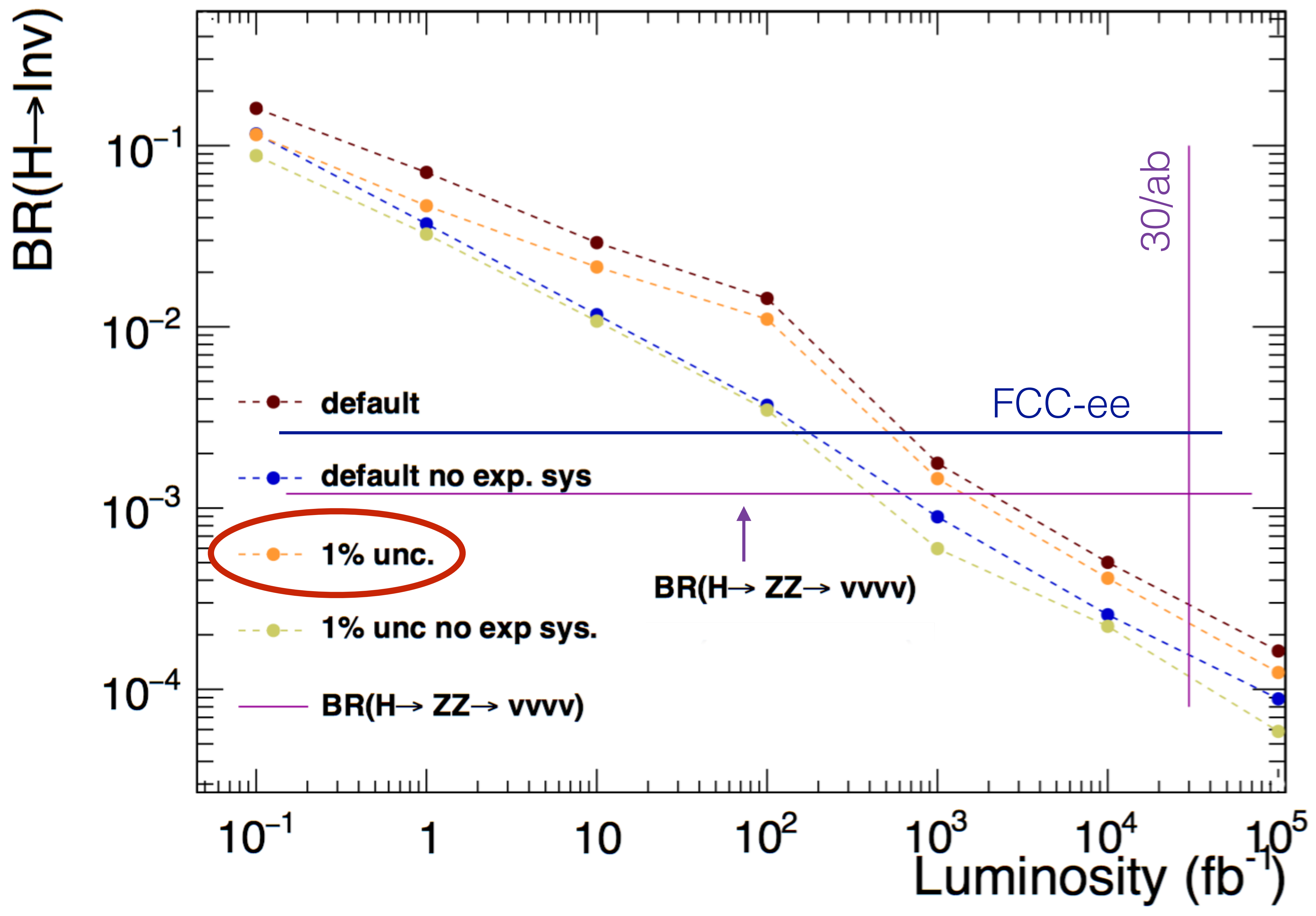


Clean final state in a low pile-up environment
Access to HHWW and Higgs self-coupling

Complementary measurement from FCC-eh at the 10% level

Invisible Higgs decay

FCC-ee with 5 ab^{-1}: BR(H→inv)$_{95\%CL}$ < 0.25%



FCC-hh: BR(H→inv) in H+X production

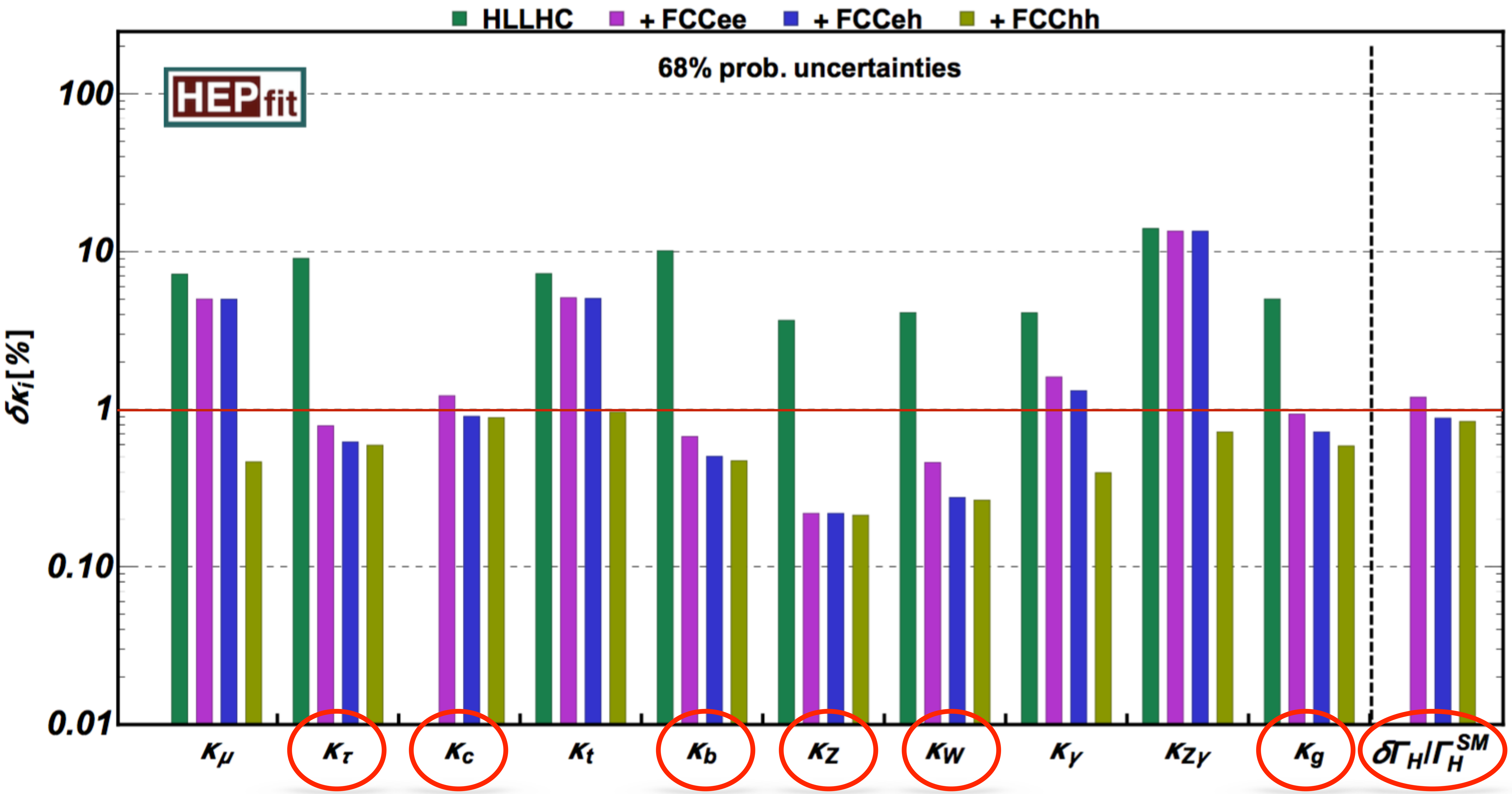
- Production at large Higgs pT
- Main sensitivity from gluon-fusion and ttH production
- Constrain Z→νν pT spectrum to the % level

  → Use NNLO QCD/EW calculations to relate to measured Z→ll,W and γ spectra

SM sensitivity with 1 ab^{-1}, can reach few $x10^{-4}$ with 30 ab^{-1}

FCC Higgs coupling fit

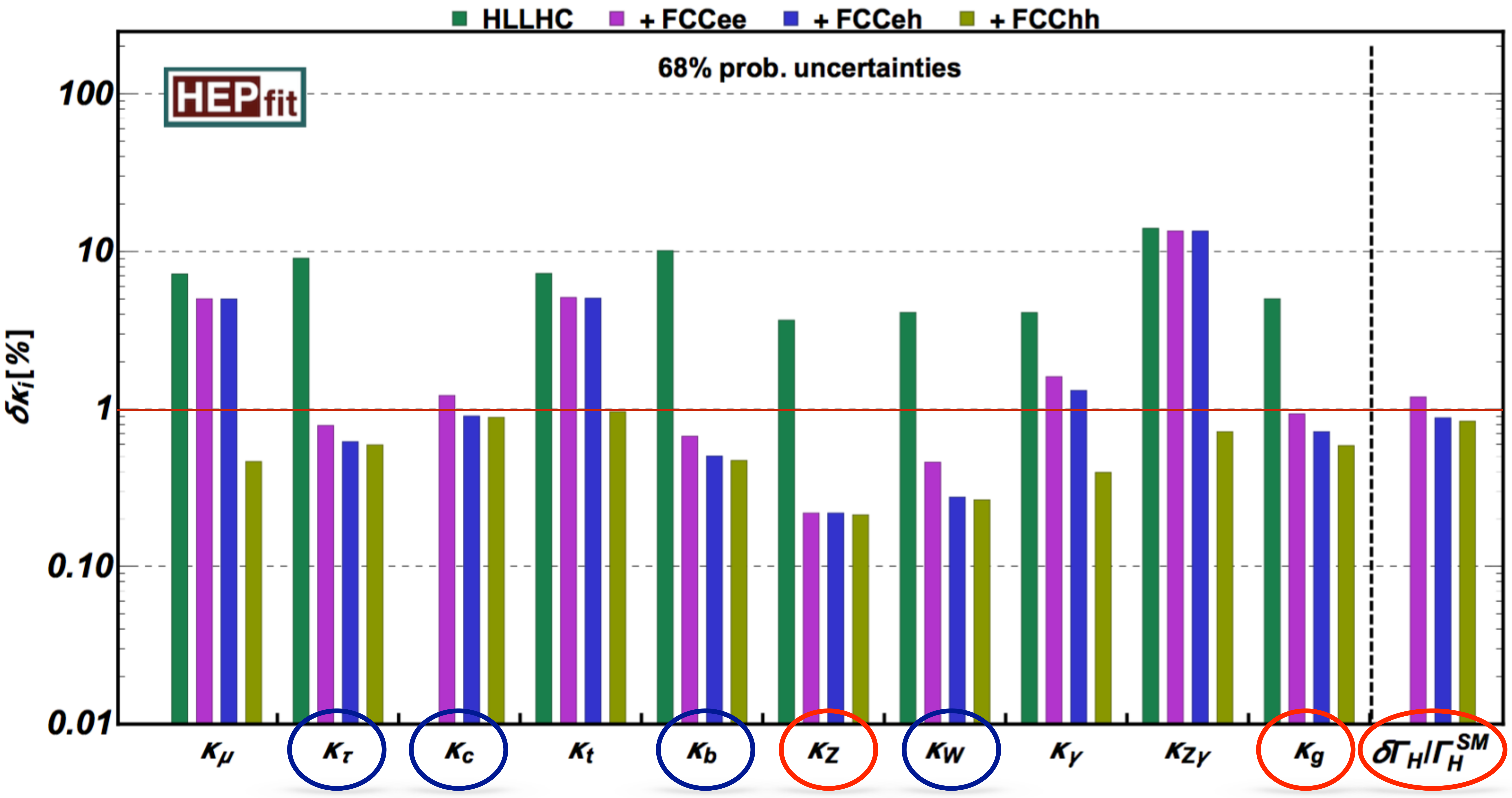
Coupling scale factors (κ-framework) (EFT fit in the backup slides)



All single Higgs couplings below per-cent level

FCC Higgs coupling fit

Coupling scale factors (κ-framework) (EFT fit in the backup slides)



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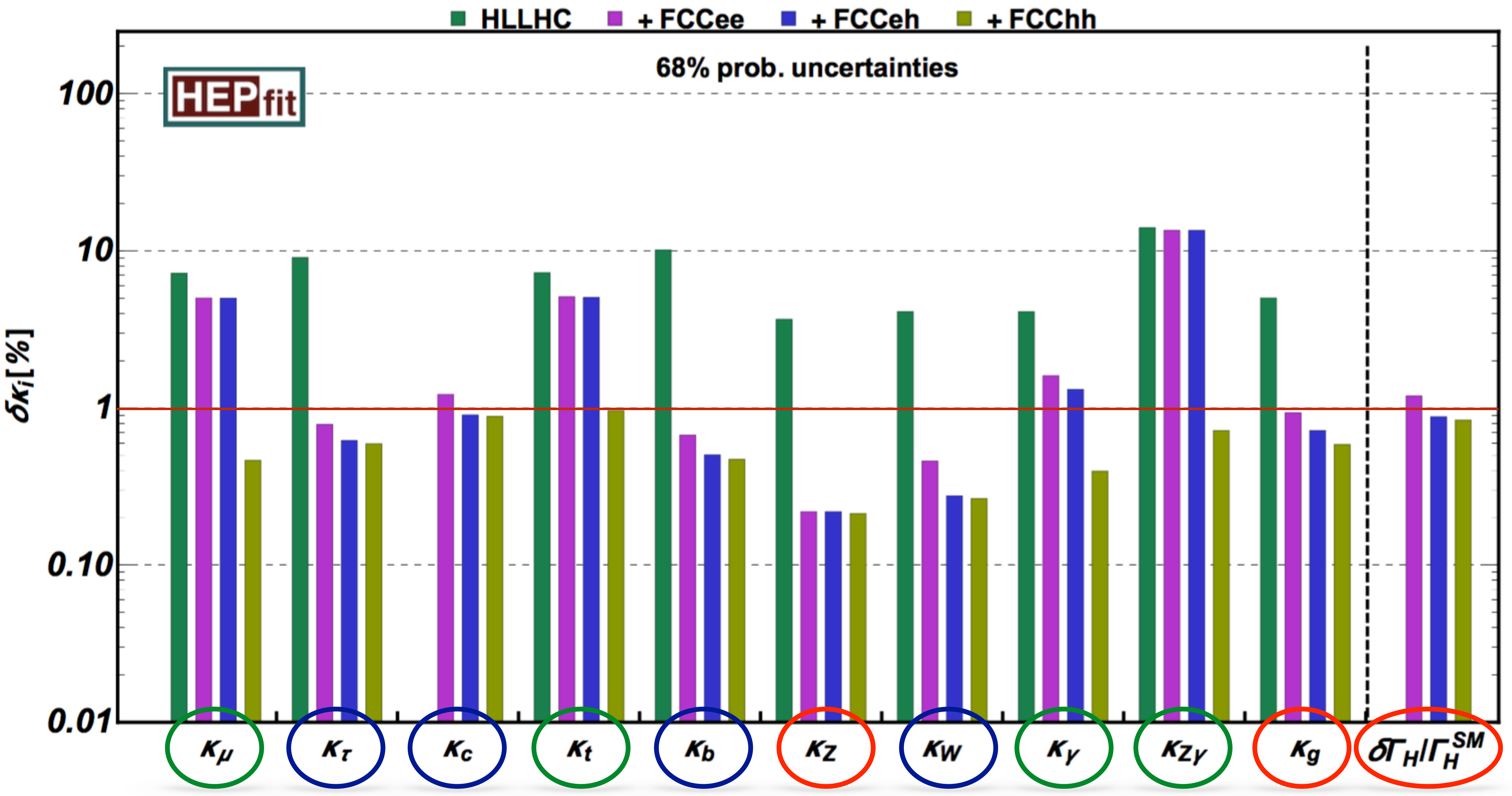


All single Higgs couplings below per-cent level

Conclusions

The large number of Higgs bosons produced at the FCC in the different environments of ee/eh/hh colliders bring unprecedented opportunities

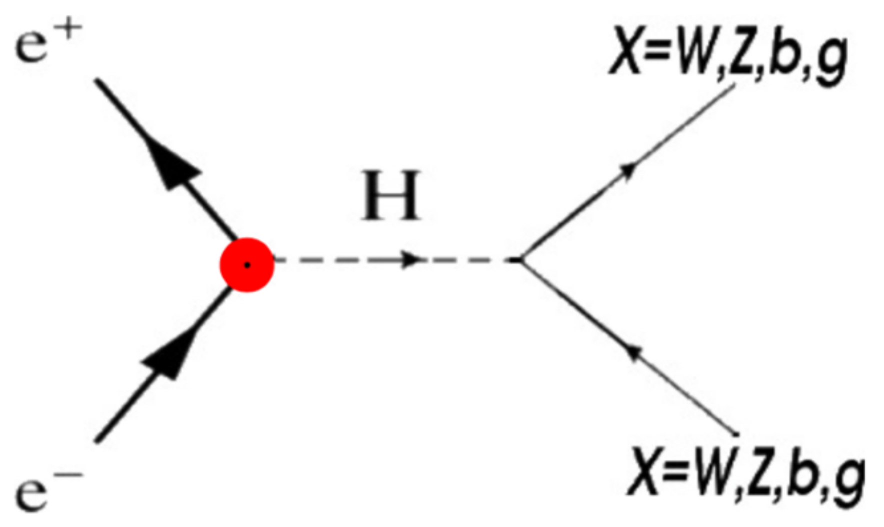
- Sub-percent level measurement of Higgs couplings to most SM particles
- Probe the quantum structure of the Higgs potential
- Access to extreme regions of phase space: probe Higgs couplings away from its mass-shell
- Study of rare production and decay channels, e.g. couplings to new particles of a dark sector
- …

Large synergy and complementarity between lepton and hadron collider Higgs physics

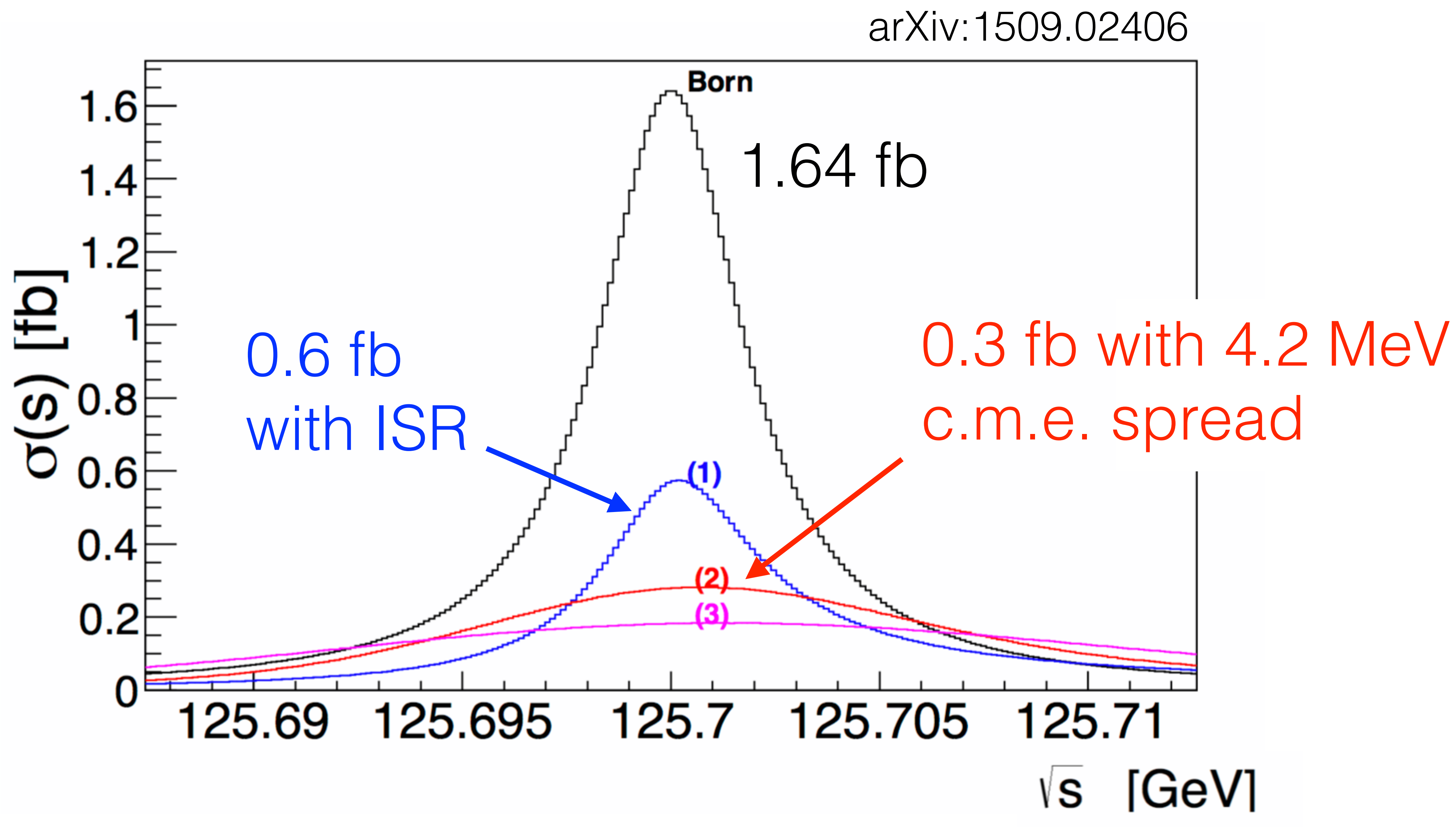
Close to final version of the CDR summary documents https://indico.cern.ch/event/750953/

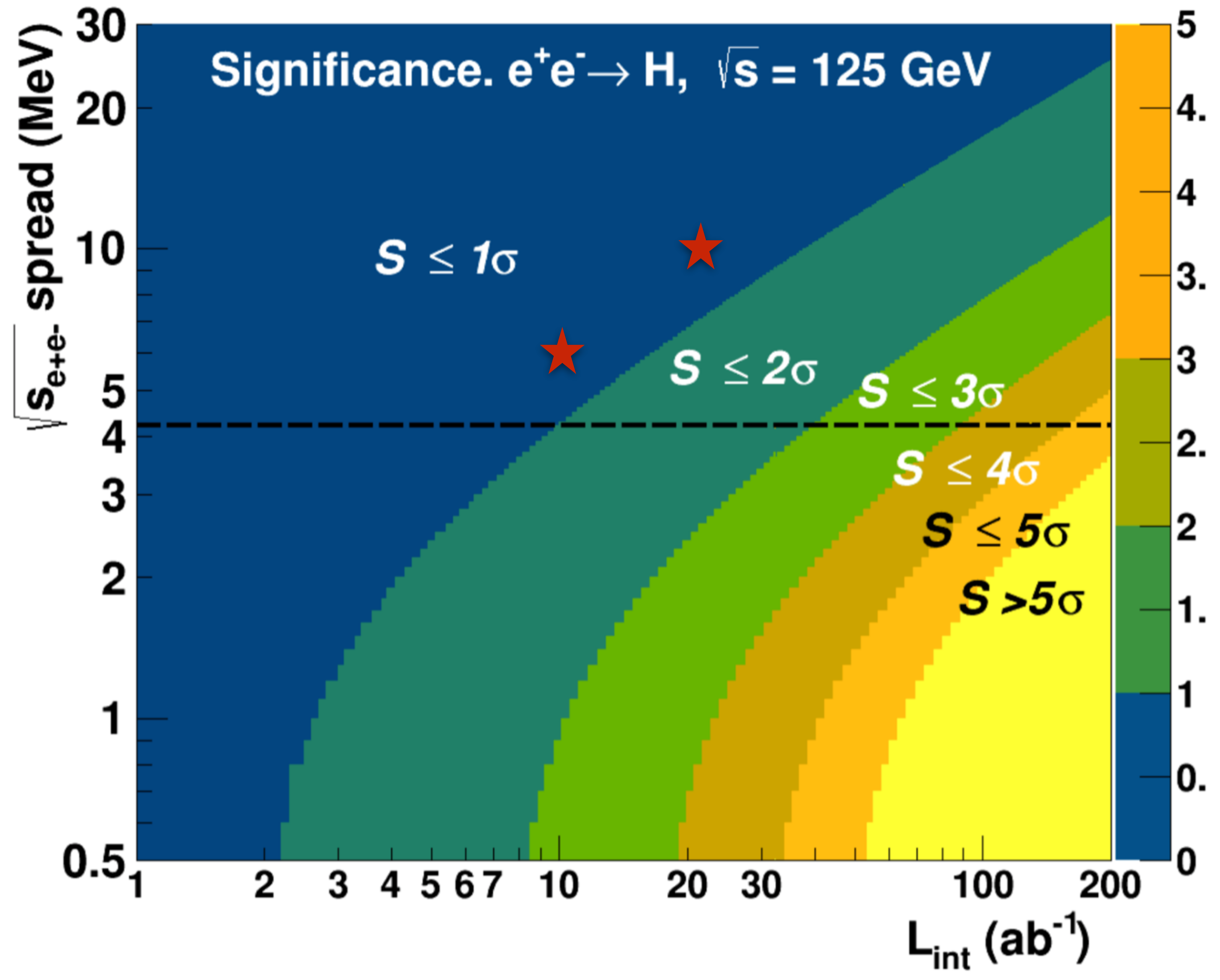
Electron Yukawa coupling

Resonant Higgs production



10 decay channels analysed





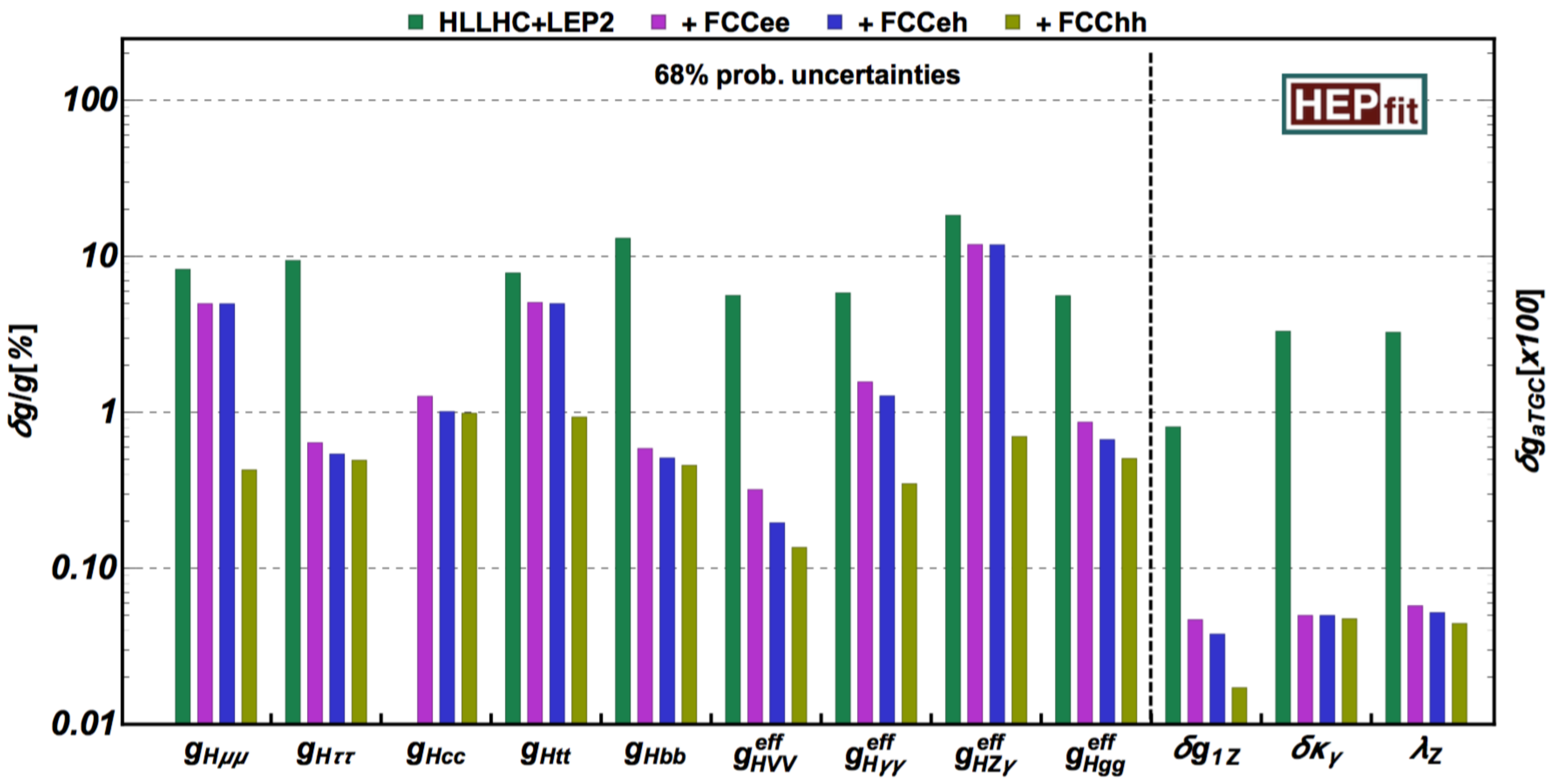
Reduce energy spread by mono-chromatisation (https://cds.cern.ch/record/2159683)

2(7) ab^{-1} per year with c.m.e spread of 6 (10) MeV

0.4σ sensitivity per year, upper limit on e-Yukawa coupling $\sigma/\sigma_{SM} = 2.5$

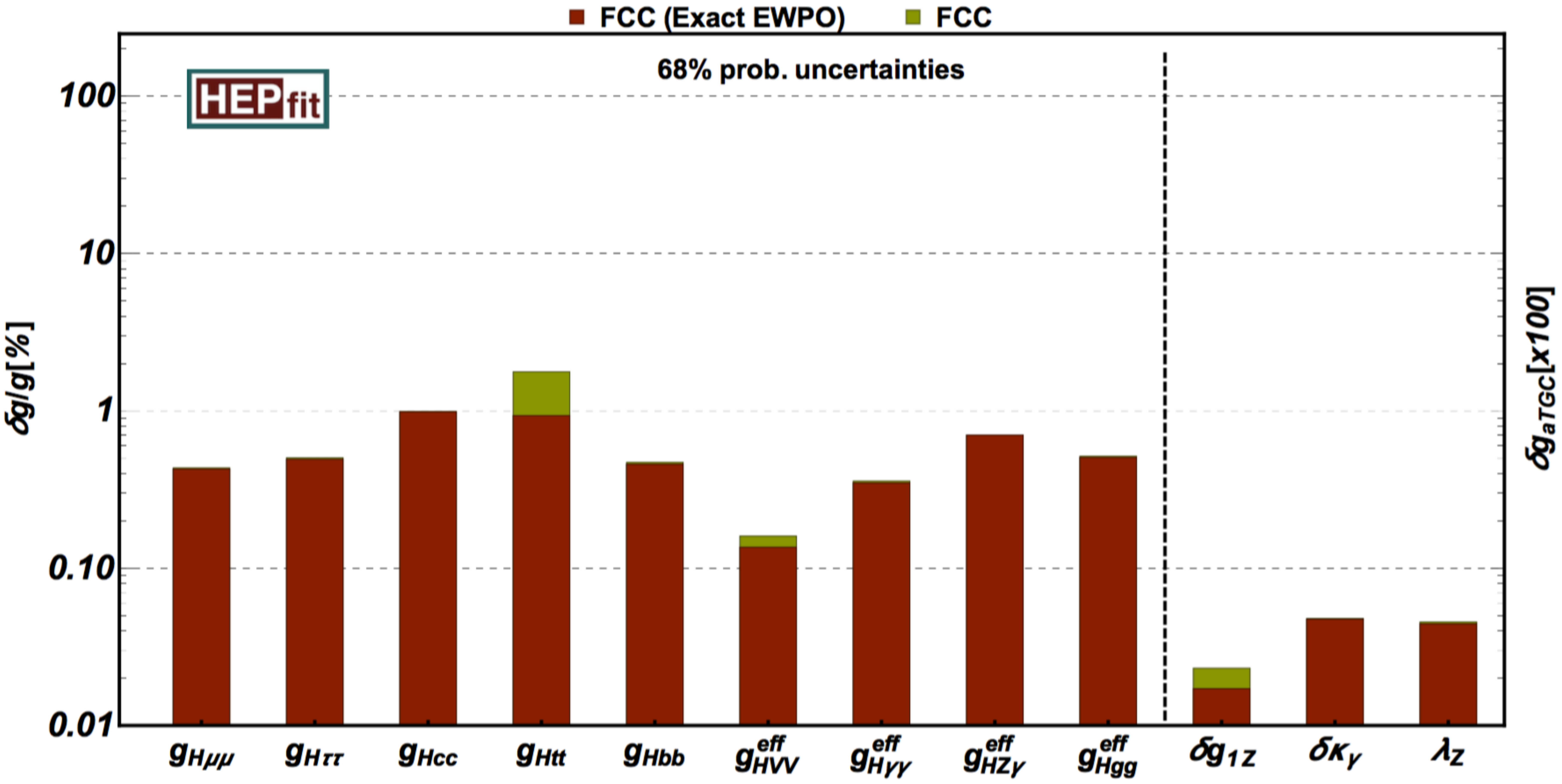
SM sensitivity in 5 years

EFT fit



HLLHC+LEP2
+ FCCee
+ FCCeh
+ FCChh
68% prob. uncertainties
HEPfit
100
10
1
0.10
0.01
δg/g[%]
δg_aTGC[x100]
g_Hμμ
g_Hττ
g_Hcc
g_Htt
g_Hbb
g^eff_HVV
g^eff_Hγγ
g^eff_HZγ
g^eff_Hgg
δg_1Z
δκ_γ
λ_Z

Global fit

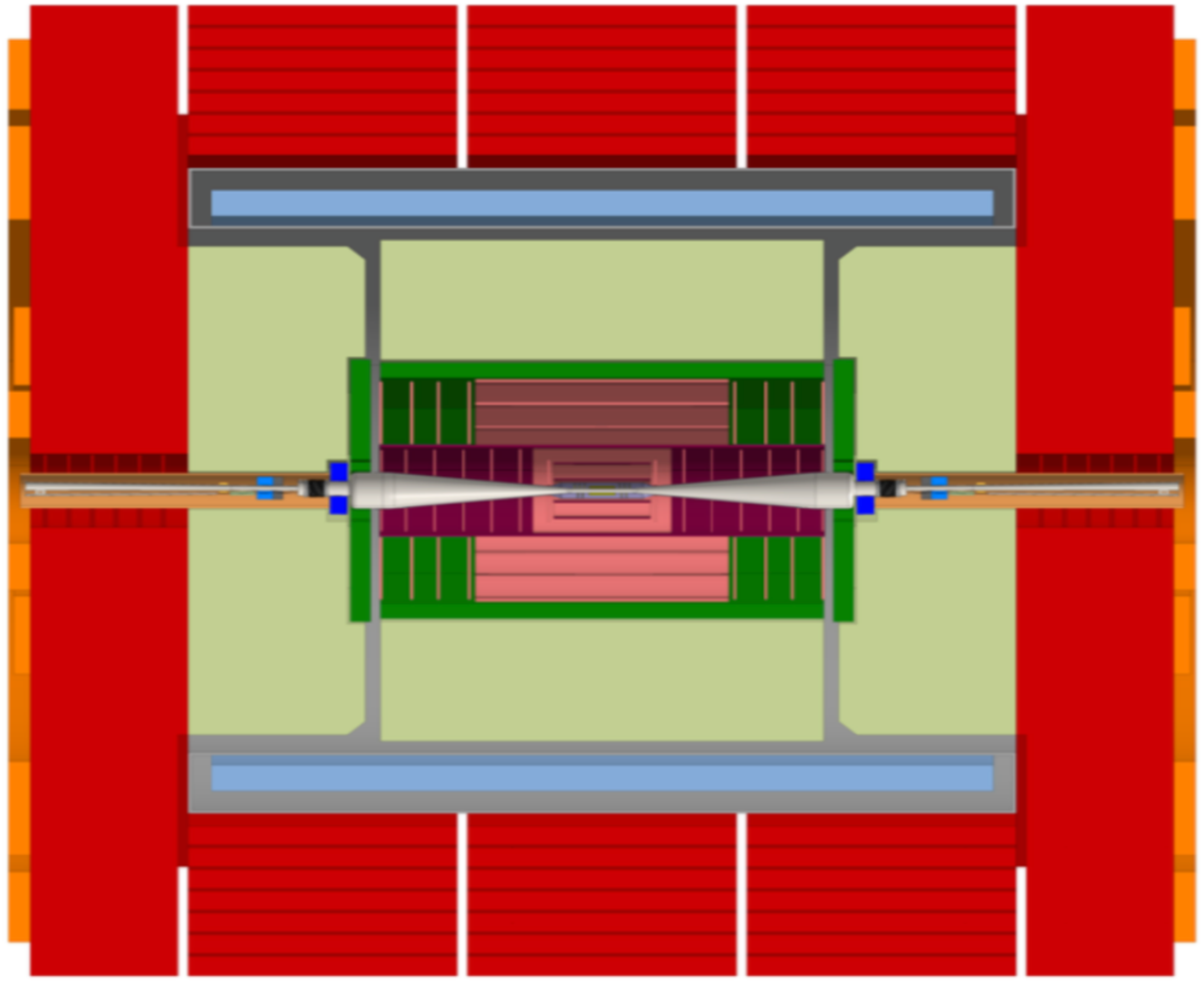


FCC (Exact EWPO)
FCC
68% prob. uncertainties
HEPfit
100
10
1
0.10
0.01
δg/g[%]
δg_aTGC[x100]
g_Hμμ
g_Hττ
g_Hcc
g_Htt
g_Hbb
g^eff_HVV
g^eff_Hγγ
g^eff_HZγ
g^eff_Hgg
δg_1Z
δκ_γ
λ_Z

FCC-ee detector

The CLIC detector is being adapted for FCC-ee

- Smaller beam pipe radius (15mm)
  - Inner pixel layer closer to IP
- Not instrumented from 0 to 150 mrad
- Smaller B field
  - Larger tracker radius (1.5 → 2.2m)
- Smaller energies
  - Thinner HCAL (4.2m → 3.7m)
- Continuous operation
  - Increased cooling
  - Thicker pixel/tracker layers
  - Reduced calorimeter granularity



Further detector concept dedicated for FCC-ee (with light wire drift chamber and dual readout fibre calorimeter)