Higgs Physics at the FCC:

the stunning complementarity between ee and pp

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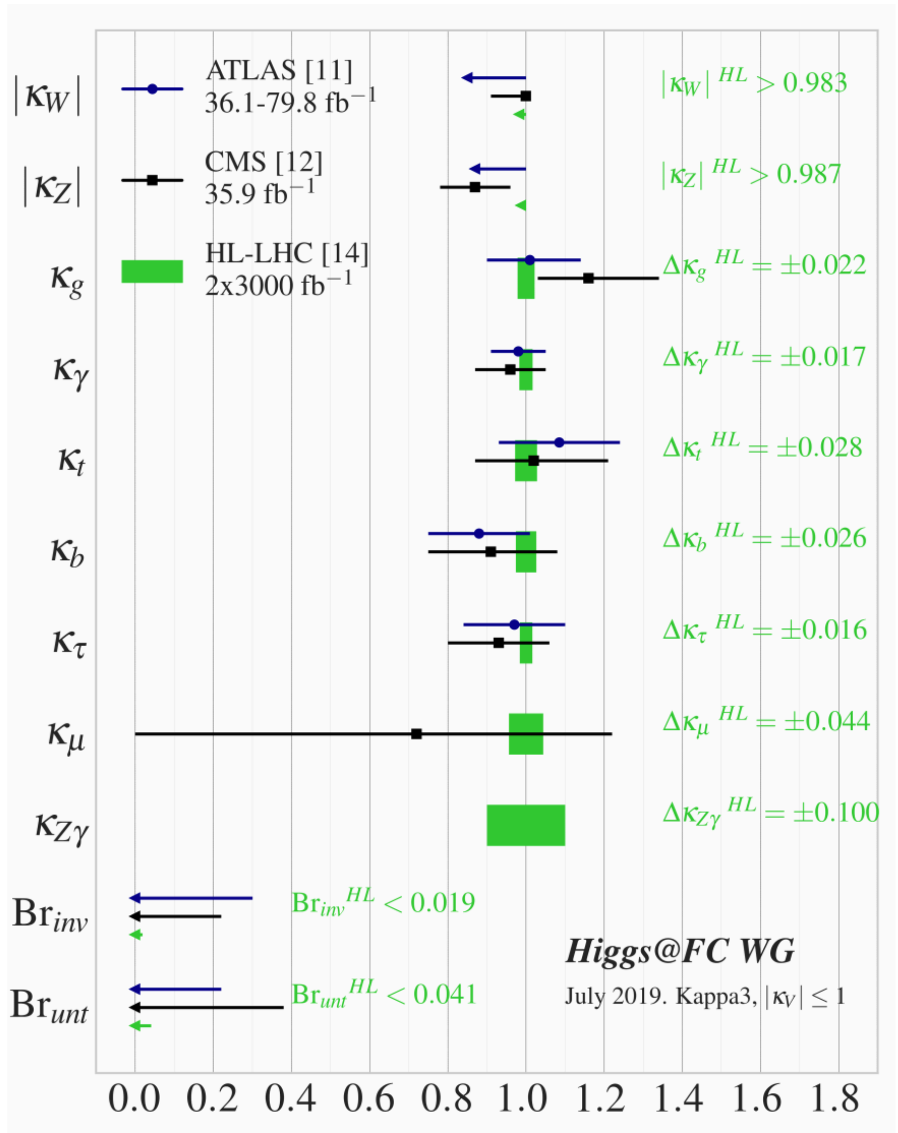
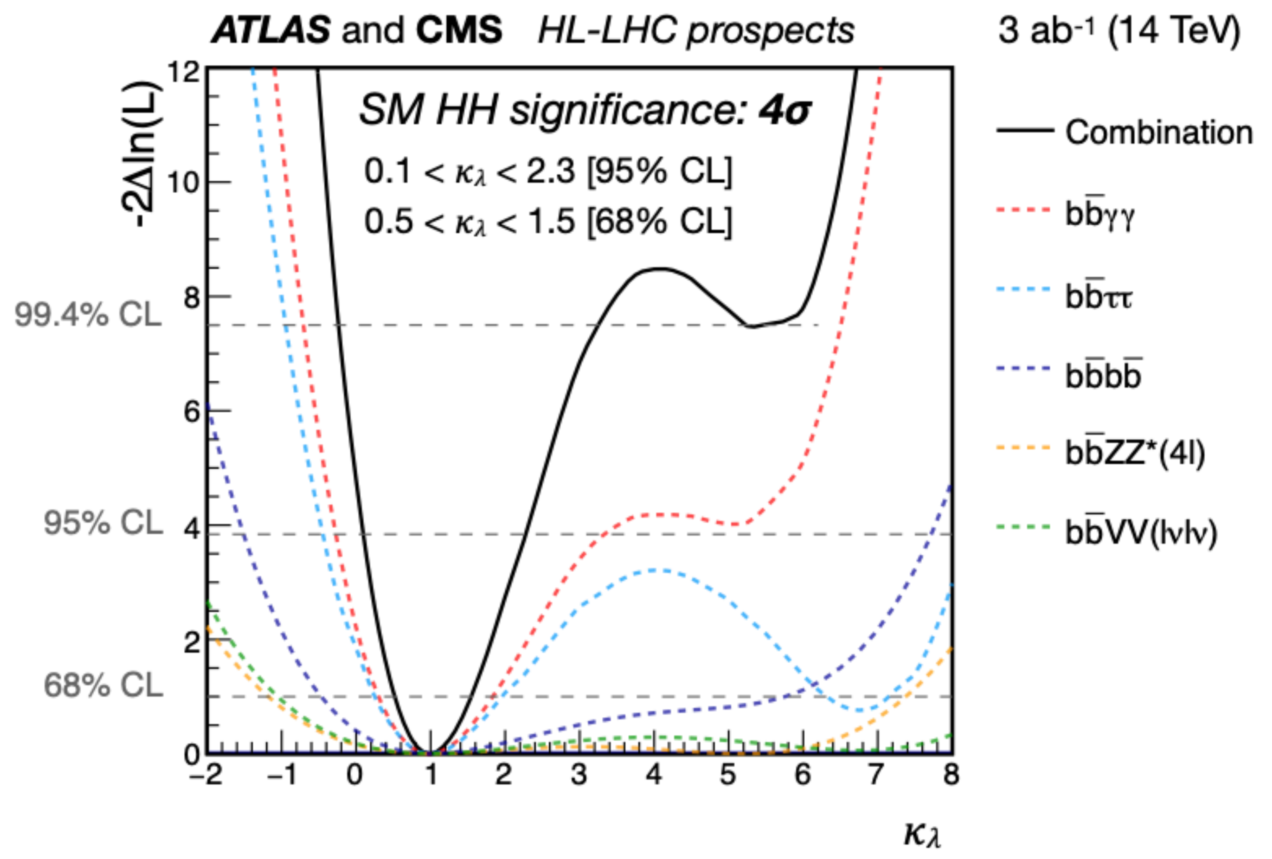
Why Higgs precision?



After Higgs discovery, still many open questions:

- Is the Higgs composite or fundamental?
  - Is there more than 1 Higgs
- Does it generate light fermion masses? What about neutrino masses?
- does it couple to dark matter?
- nature of the Higgs potential
  - and its relation to the EWPT

	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

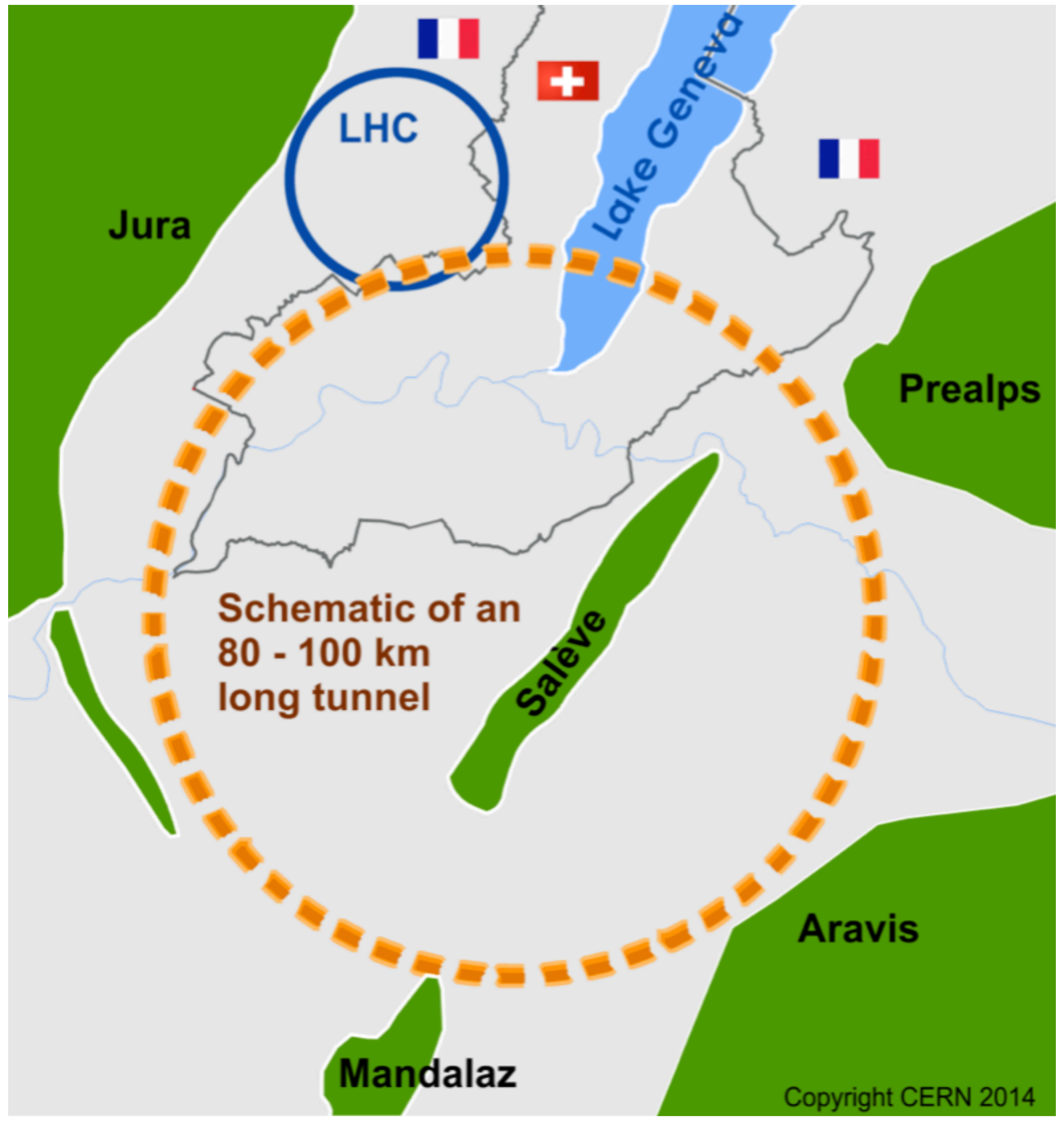


Need to go beyond the LHC precision measurements:

- Model independence, Higgs width
- Light couplings (charm, muon)
- Invisible decays

- Self-coupling(s)
- BSM Higgs

The FCC project



- ee-collider (FCC-ee) (2/4 IPs):
  - as an EWK factory:
    - $\sqrt{s}$ = 90 GeV (5 10^{12} Z' - 4 yrs)
    - $\sqrt{s}$ = 160 GeV (10^{8} W - 2 yrs)
    - $\sqrt{s}$ = 240 GeV (10^{6} H - 3 yrs)
    - $\sqrt{s}$ = 365 GeV (5 10^{12} top - 5 yrs)

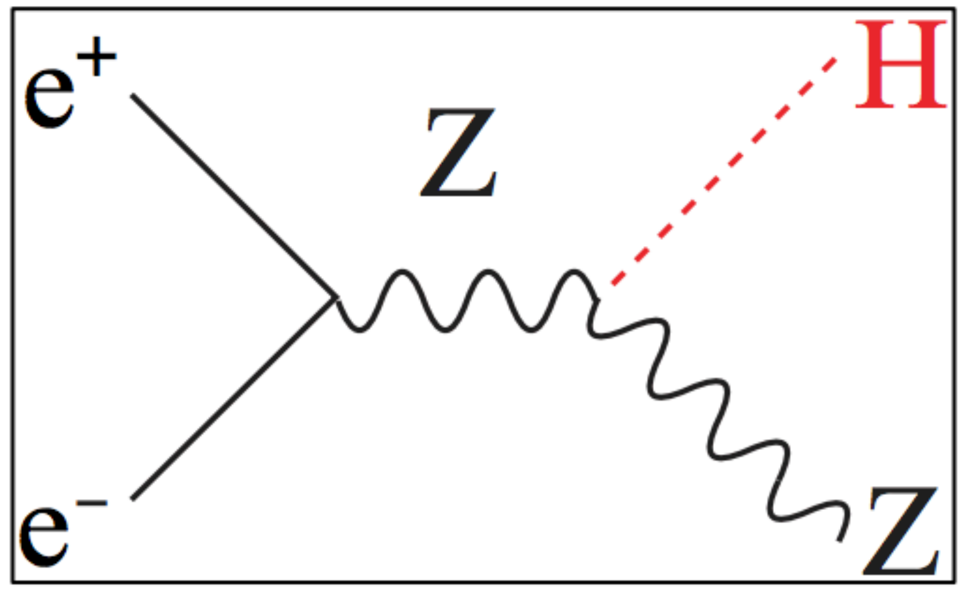
- pp-collider (FCC-hh):
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunnel
    - 30 ab^{-1} integrated lumi
      - 2 10^{10} Higgs (200x LHC)
      - 3 10^{7} Higgs pairs (400x LHC)

CDRs and European Strategy documents have been made public in Jan. 2019
https://fcc-cdr.web.cern.ch/

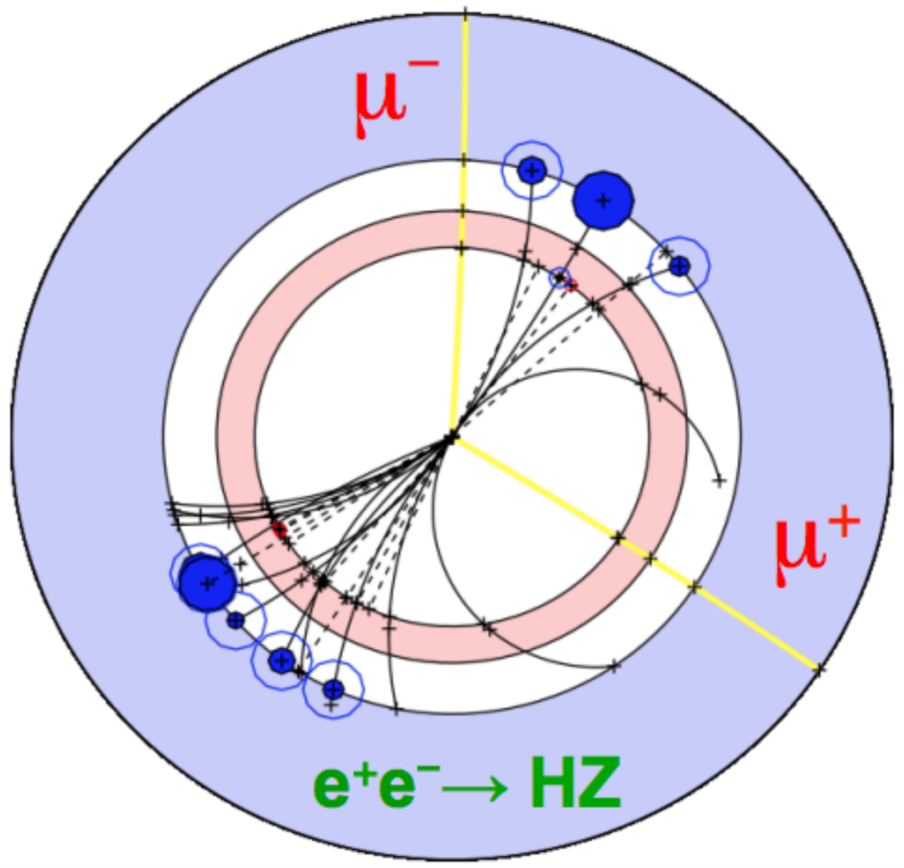
CERN-FCC-PHYS-2019-0001

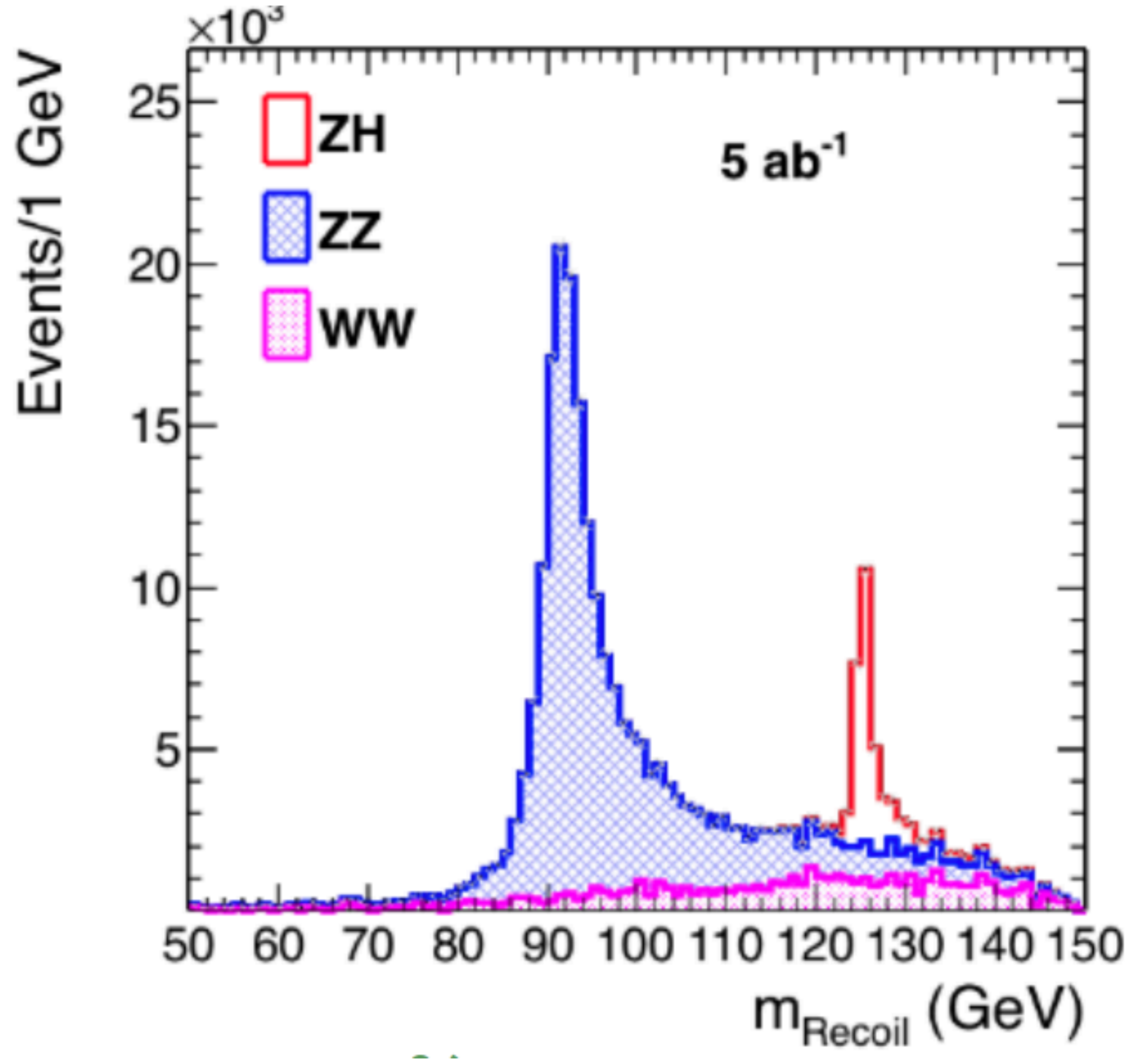
FCC-ee Higgs couplings (part I)

Precise knowledge of center of mass allows for:



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





Higgs recoil mass measurement → production cross section:

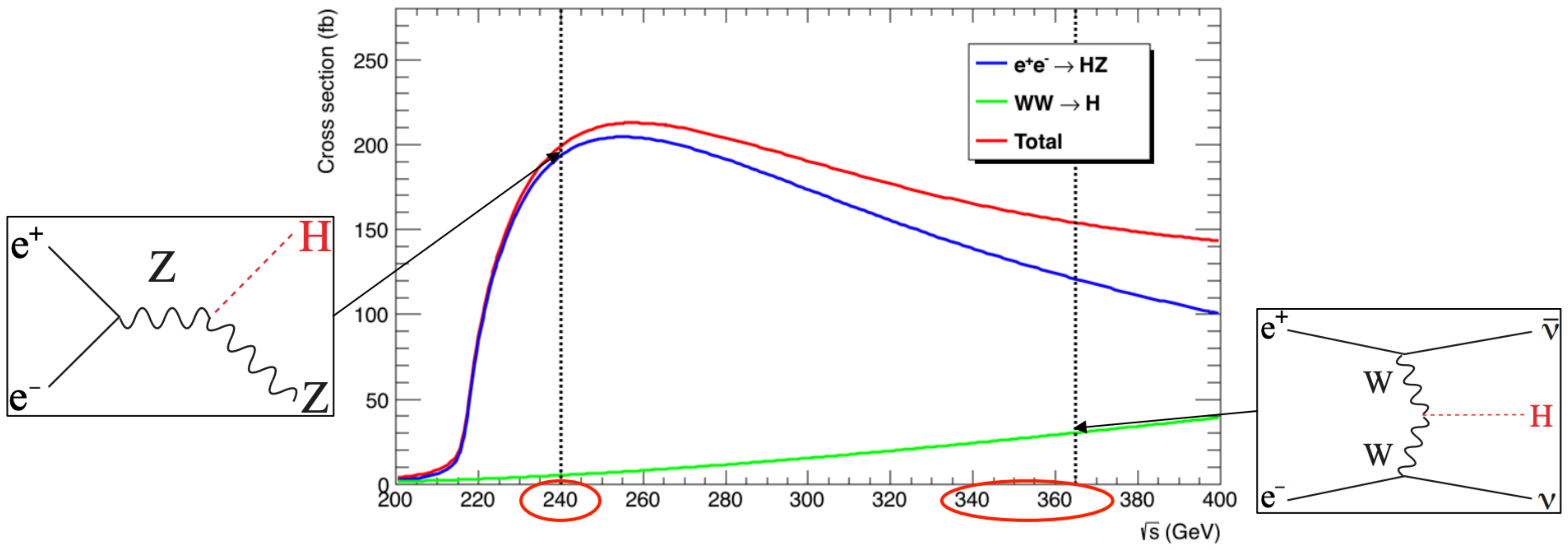
- 10^6 Higgs produced @ FCC-ee
- rate ~ $g_Z{}^2$ → $\delta g_Z/g_Z$ ~ 0.2 %

- Then measure ZH → ZZZ
- rate ~ $g_Z{}^4 / \Gamma_H$ → $\delta\Gamma_H / \Gamma_H$ ~ 1 %

- Then measure ZH → ZXX
- rate ~ $g_Z{}^2 g_X{}^2 / \Gamma_H$ → $\delta g_X/g_X$ ~ 1 %

Provides absolute and model independent measurement of g_Z coupling in e+e-

FCC-ee Higgs couplings (part II)



WW fusion added value

- $\nu\nu H \rightarrow \nu\nu bb \sim g_W^2\, g_b^2 / \Gamma_H$
  - $\nu\nu bb$ / (ZH(bb) ZH(WW) $\sim g_Z^4 / \Gamma_H = R$
    - Γ_H precision at 1%
- Then do $\nu\nu H \rightarrow \nu\nu WW \sim g_W^4 / \Gamma_H$
  - $R / \nu\nu WW \sim g_W^4 / g_Z^4$
    - g_W precision to few permil

Running at the top does not simply add statistics
it exploits complementary production mode to improve constraints

BR expected precision with 2 IPs

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \rightarrow$ any	±0.5		±0.9	
$H \rightarrow b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \rightarrow c\bar{c}$	±2.2		±6.5	±10
$H \rightarrow gg$	±1.9		±3.5	±4.5
$H \rightarrow W^+W^-$	±1.2		±2.6	±3.0
$H \rightarrow ZZ$	±4.4		±12	±10
$H \rightarrow \tau\tau$	±0.9		±1.8	±8
$H \rightarrow \gamma\gamma$	±9.0		±18	±22
$H \rightarrow \mu^+\mu^-$	±19		±40	
$H \rightarrow$ invis.	< 0.3		< 0.6	

For 4 IPs, expect:
x 1.7 luminosity / statistics
x 1.3 in expected precision

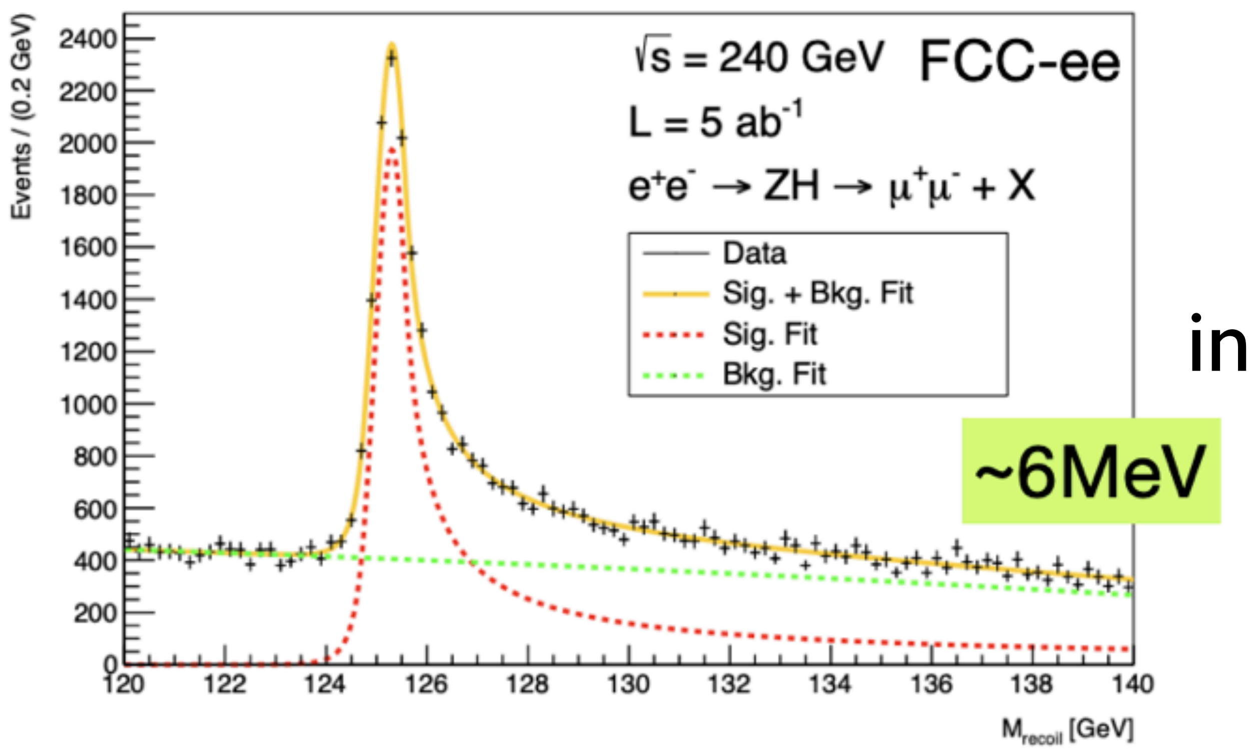
Abundant statistics and high precision for:
- bb/cc/gg/WW

Limited for:
- rare decays μμ,γγ, Zγ
- HH

Mass, cross-section and Higgs self-coupling and electron Yukawa

Higgs recoil method for simultaneous extraction of Higgs mass and ZH cross-section

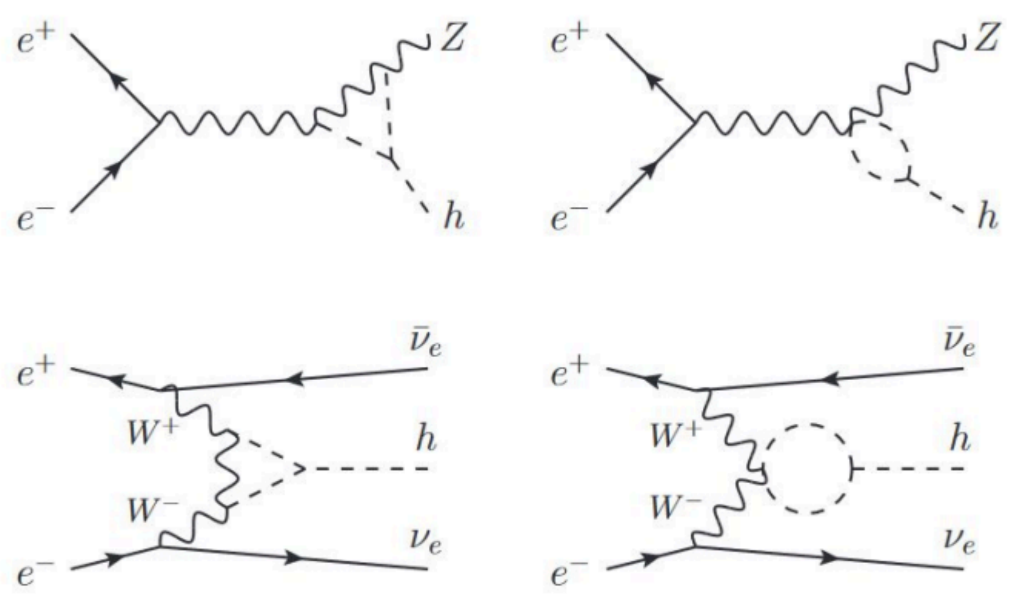
- Why measure Higgs mass:
  - O(10 MeV) need for permil precision of g_Z and g_W
  - O(Γ_H = 4 MeV) can constrain electron Yukawa
- Defines stringent detector constraints

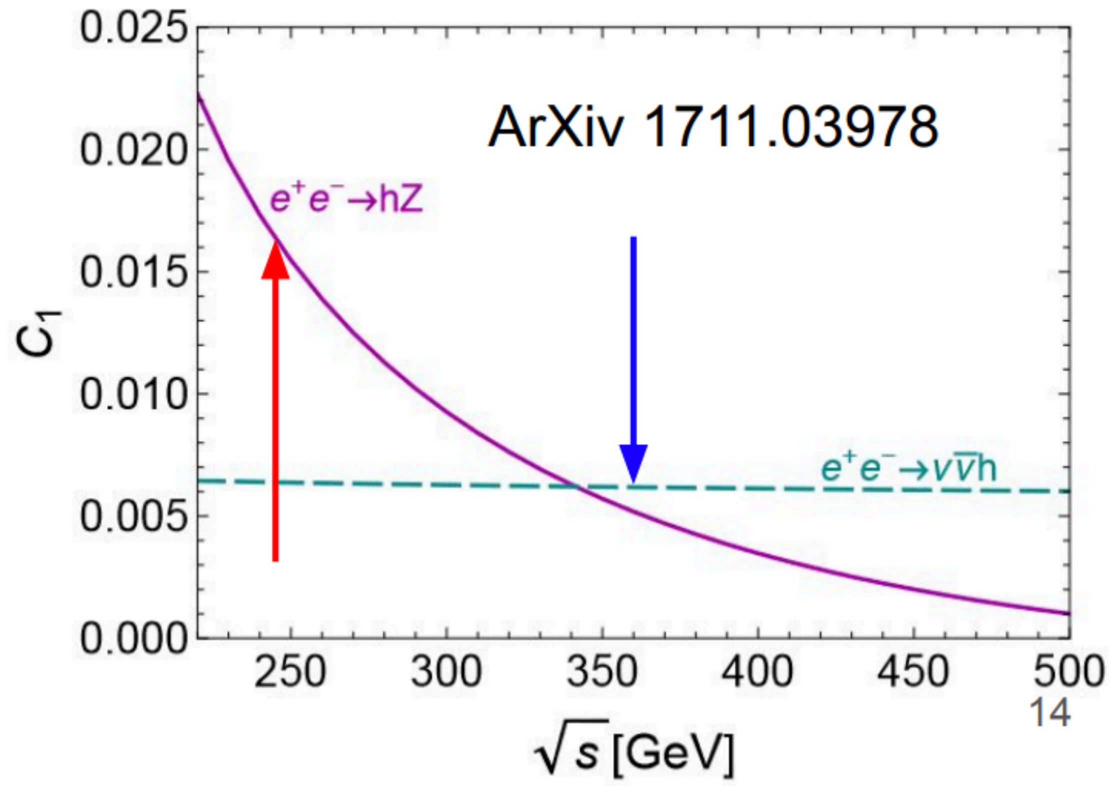


~150 MeV
in ATLAS/CMS

Stat-only results

IDEA	Δm_H (MeV)	$\Delta\sigma$ (%)
Nominal	**6.70**	**1.07**
FullSilicon	**9.01**	**1.12**
3T	**5.78**	**1.06**

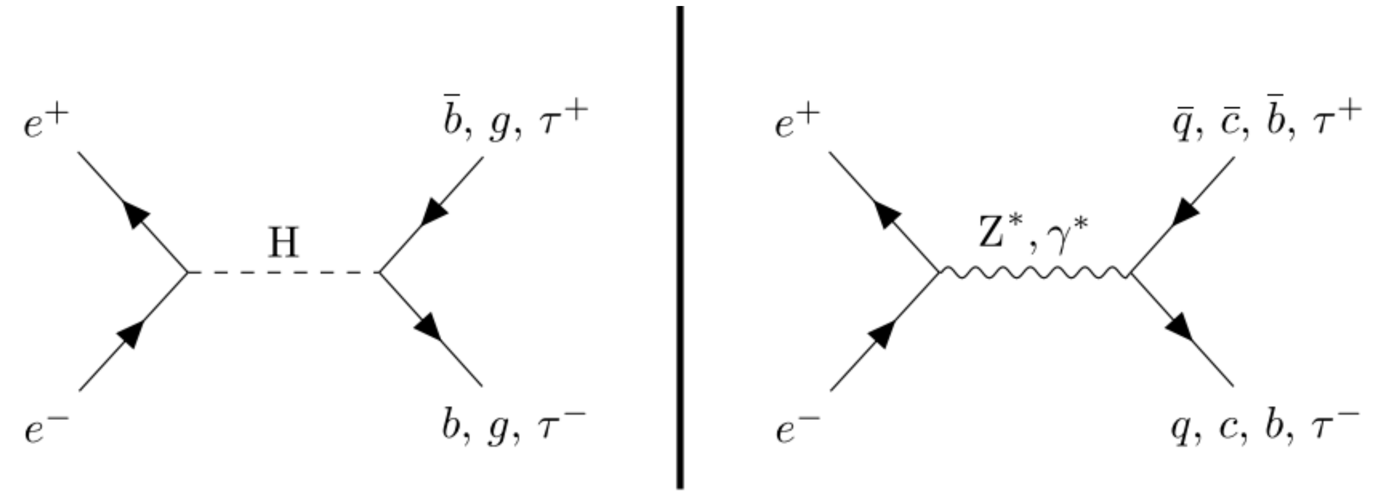




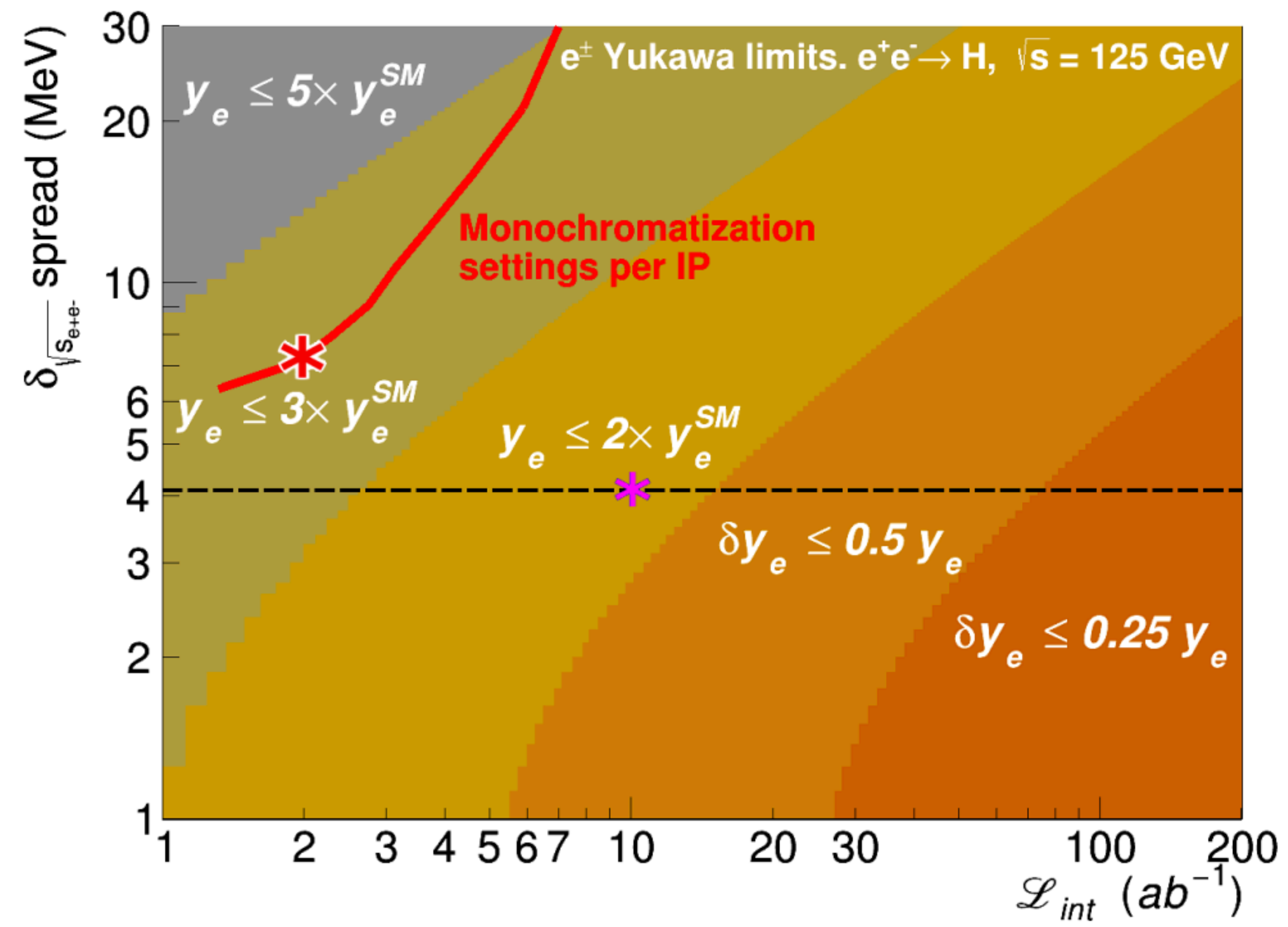
also allows to indirectly measure the Higgs self-couplings

with 2 IPs, can reach $\delta\kappa_\lambda$ ~ 40% (33% if combined to HL-LHC)

- could reach $\delta\kappa_\lambda$ ~ 25% with 4IPs



- s-channel production with beam mono-chromatisation at $\sqrt{s}$ = 125 GeV
  - ISR+FSR leads to 40% + with beam spread ~ Γ_H another 45%
    - plus potentially uncertainty on the Higgs mass
  - can hope for y_e < 1.6 y_e (SM) with 4 (2) years of running with 2 (4) IPs



Complementarity FCC-ee/hh

Large rates for rare modes and HH production at FCC-hh

- Higgs **self-coupling**
- **top Yukawa**
- **Higgs → invisible**
- **rare decays** (BR(μμ), BR(Zγ), ratios, ..) measurements will be **statistically limited** at FCC-ee

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

Need to improve

At pp colliders very large rates, but we can only measure:

$$\sigma_{prod}\, BR(i) = \sigma_{prod}\, \Gamma_i / \Gamma_H$$

→ we do not know the total width

In order to perform global fits, we have to make **model-dependent assumptions**

Measurements of ratios of BRs at hadron colliders:

from e^+e^-

$$BR(H\to XX) / BR(H\to ZZ) \approx g_X{}^2 / g_Z{}^2$$

We can "convert" **relative measurements into absolute** via g_Z thanks to e^+e^- measurement

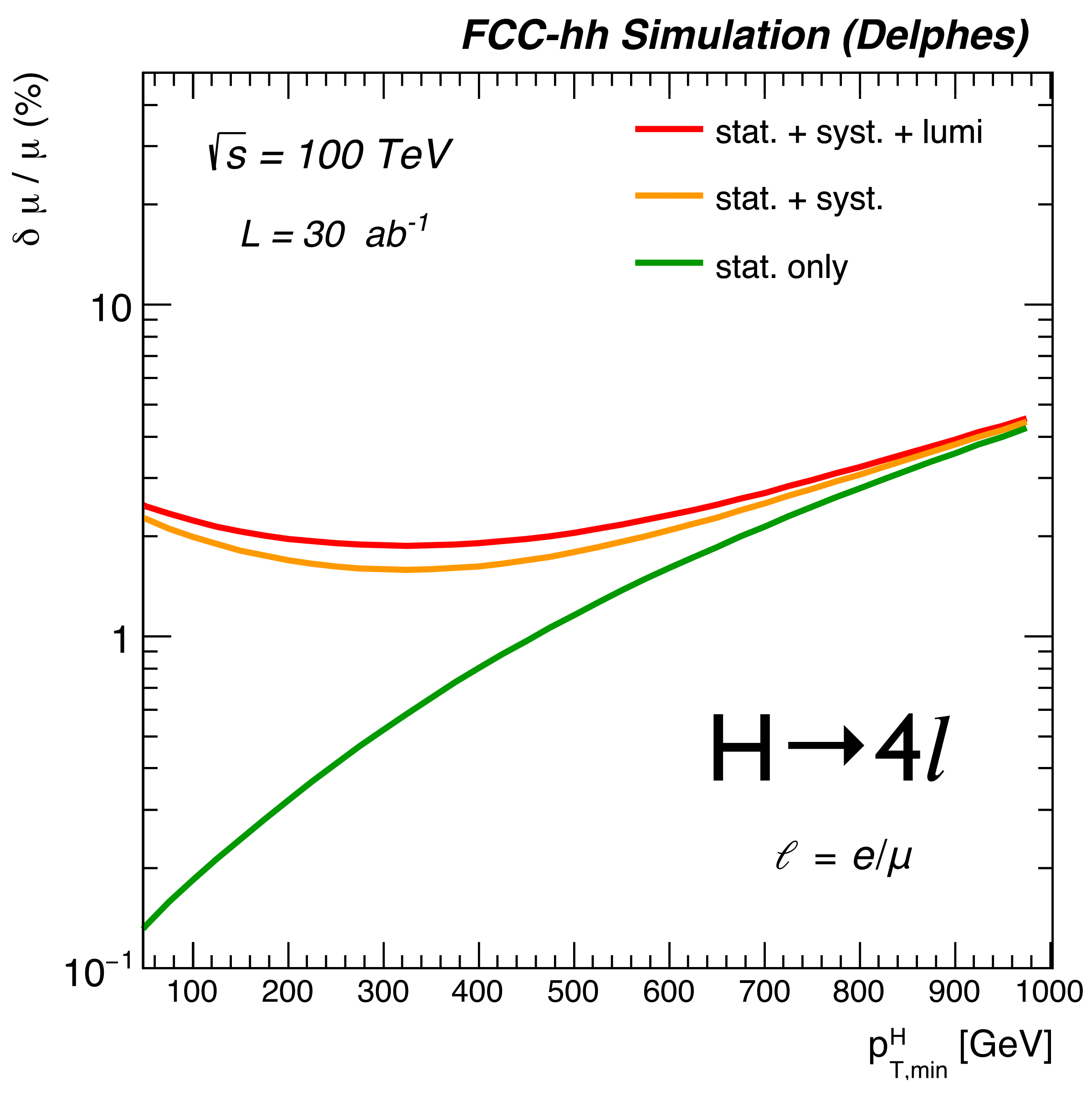
Ratios of BR(H→XX) / BR(H→ZZ)

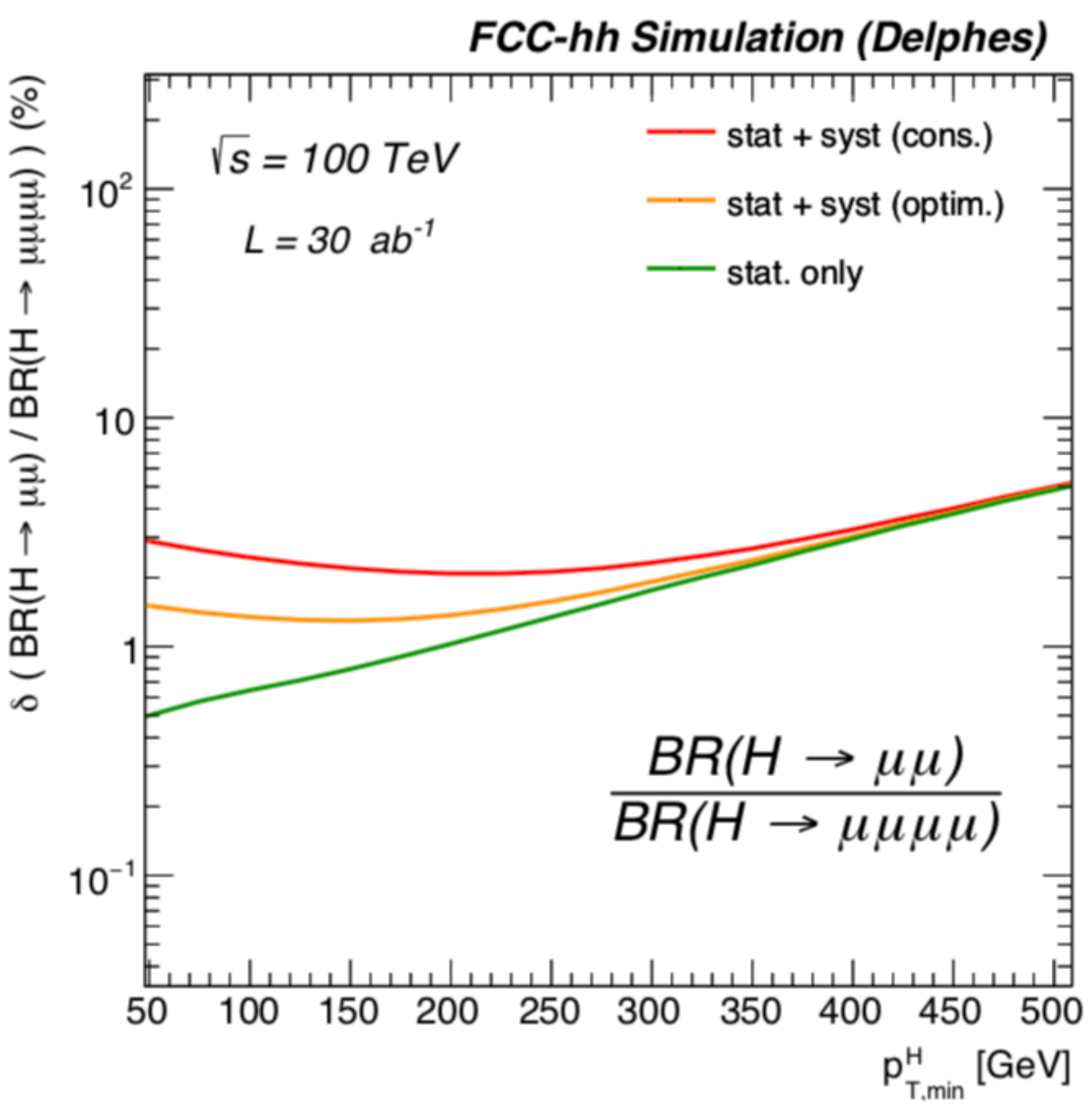
	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55

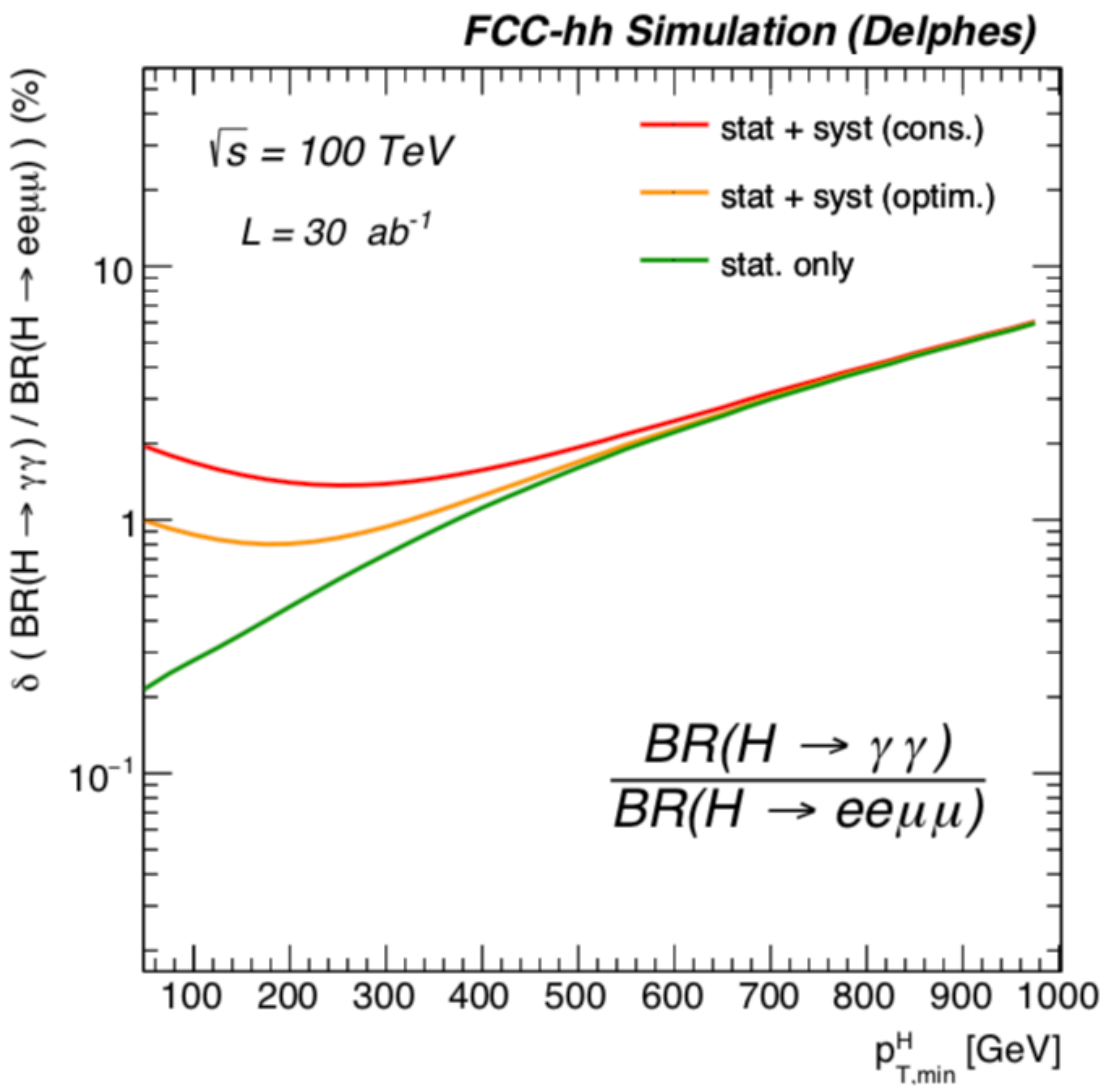
N = 20 Billions Higgs at threshold
N = 1 Million Higgs with p_T > 1 TeV

- measure **ratios of BRs** to cancel correlated sources of systematics:
- Becomes **absolute precision** measurement in particular if combined with **H→ZZ** e^+e^- (at 0.2%)
- Exploit large Higgs rate rate at large p_T

<1% precision on μμ,γγ, Zγ couplings combining FCC-ee/hh

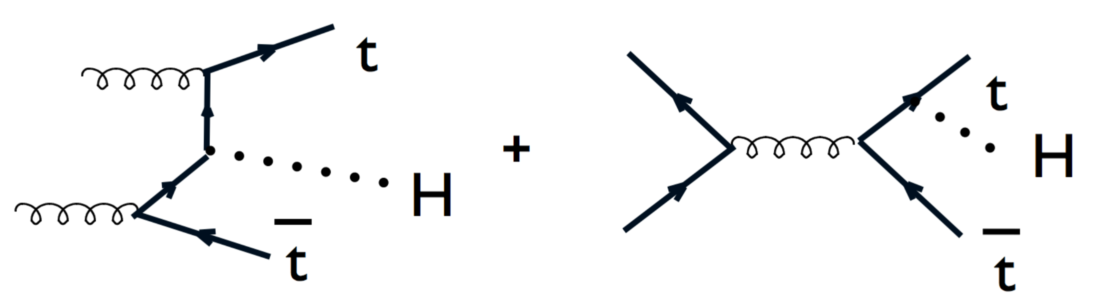


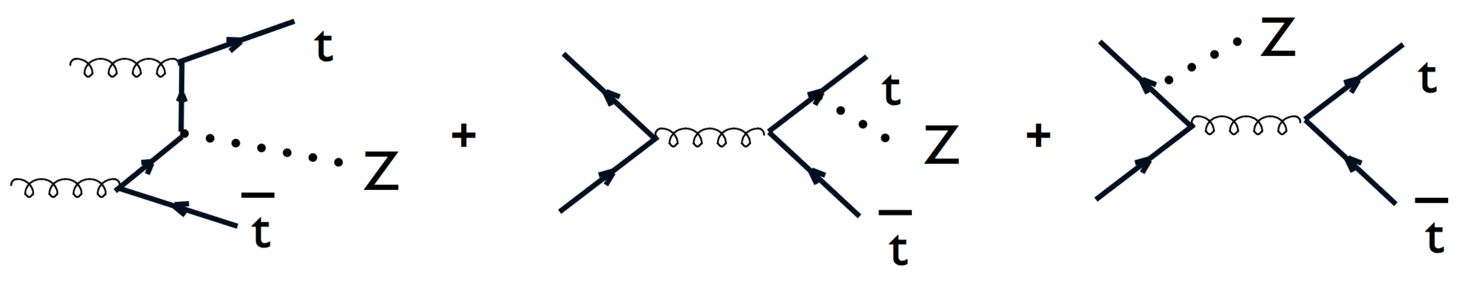




Top Yukawa (production) and Higgs invisible

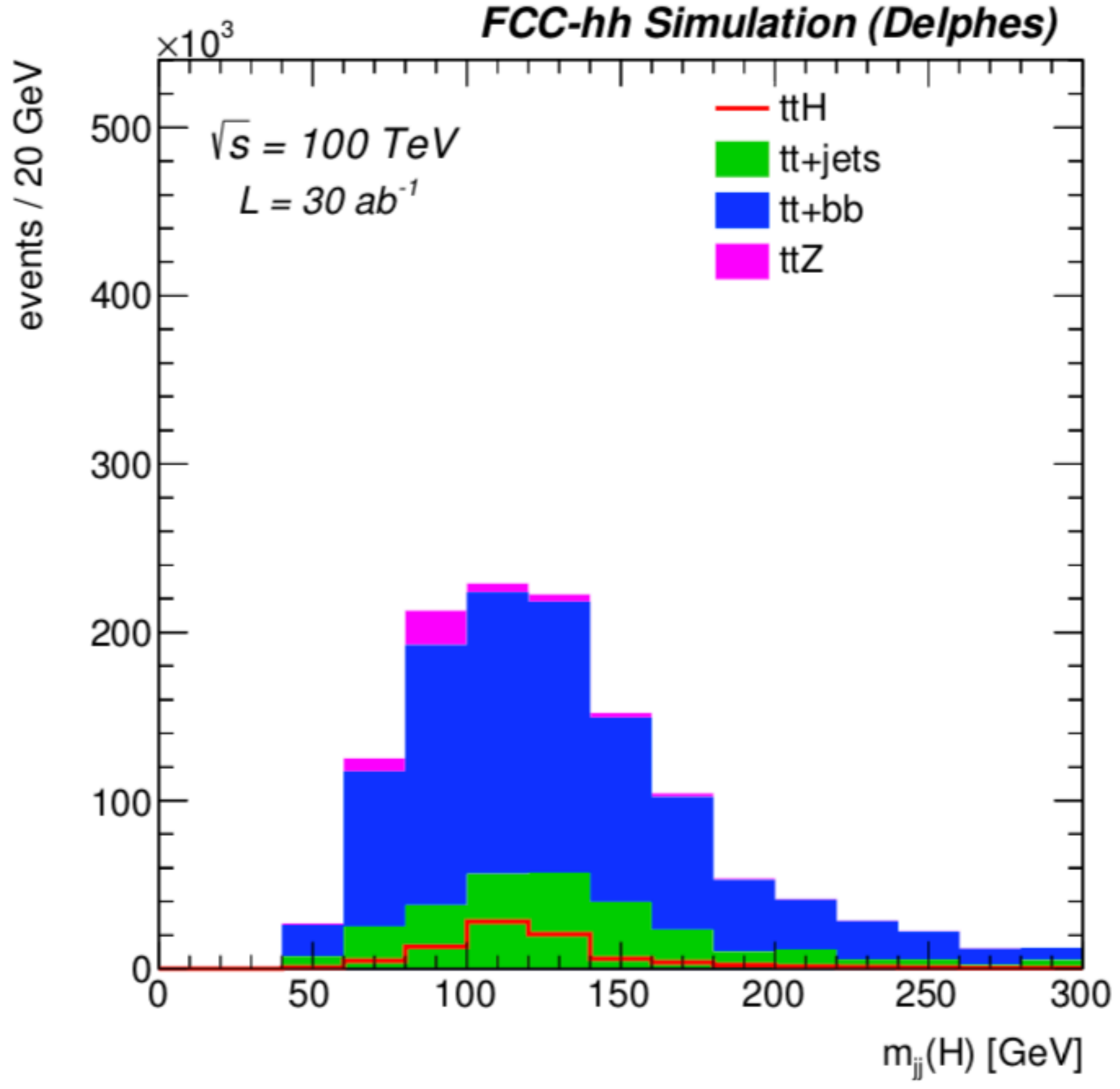
ttH ttZ



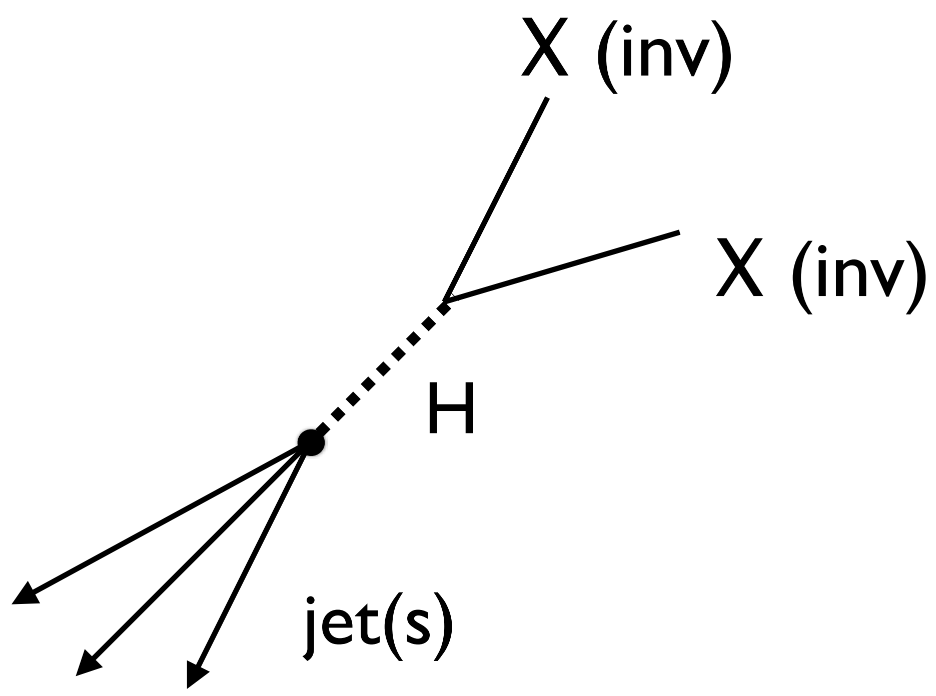


- production ratio **σ(ttH)/σ(ttZ)** ≈ $y_t^2\ y_b^2 /\ g_{ttZ}^{\ 2}$
- measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio

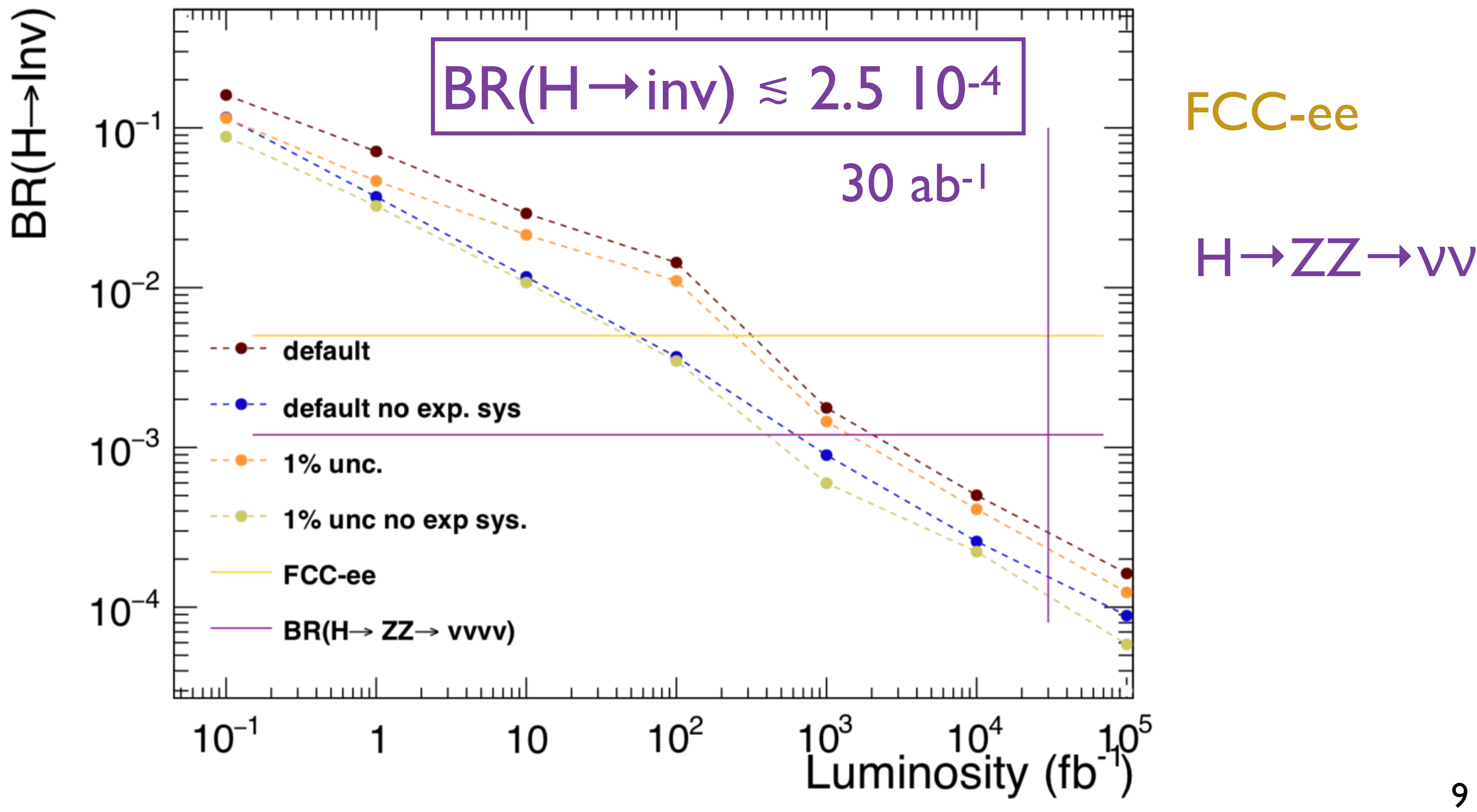
- assuming $\mathbf{g_{ttZ}}$ and $\boldsymbol{\kappa_b}$ known to 1% (from FCC-ee),



$\delta y_t / y_t \lesssim 1\ \%$

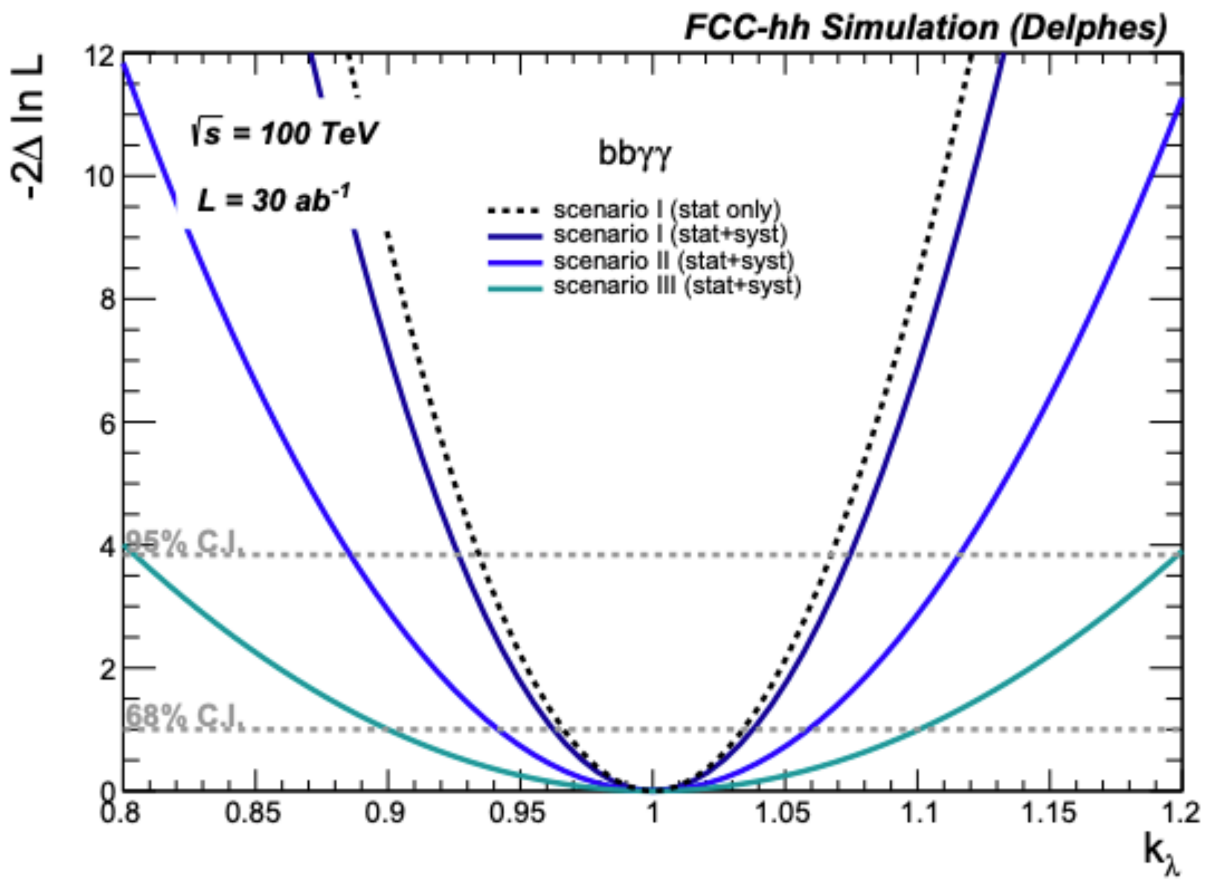


- Measure it from H + X at **large p_T(H)**
- Fit the $\mathbf{E_T^{miss}}$ spectrum
- Constrain background p_T spectrum from **Z→νν** to the % level using NNLO QCD/EW to relate to measured Z, W and γ spectra (low stat)
- Estimate Z→νν (W→lν) from Z→ee/μμ (W→lν) control regions (high stat).

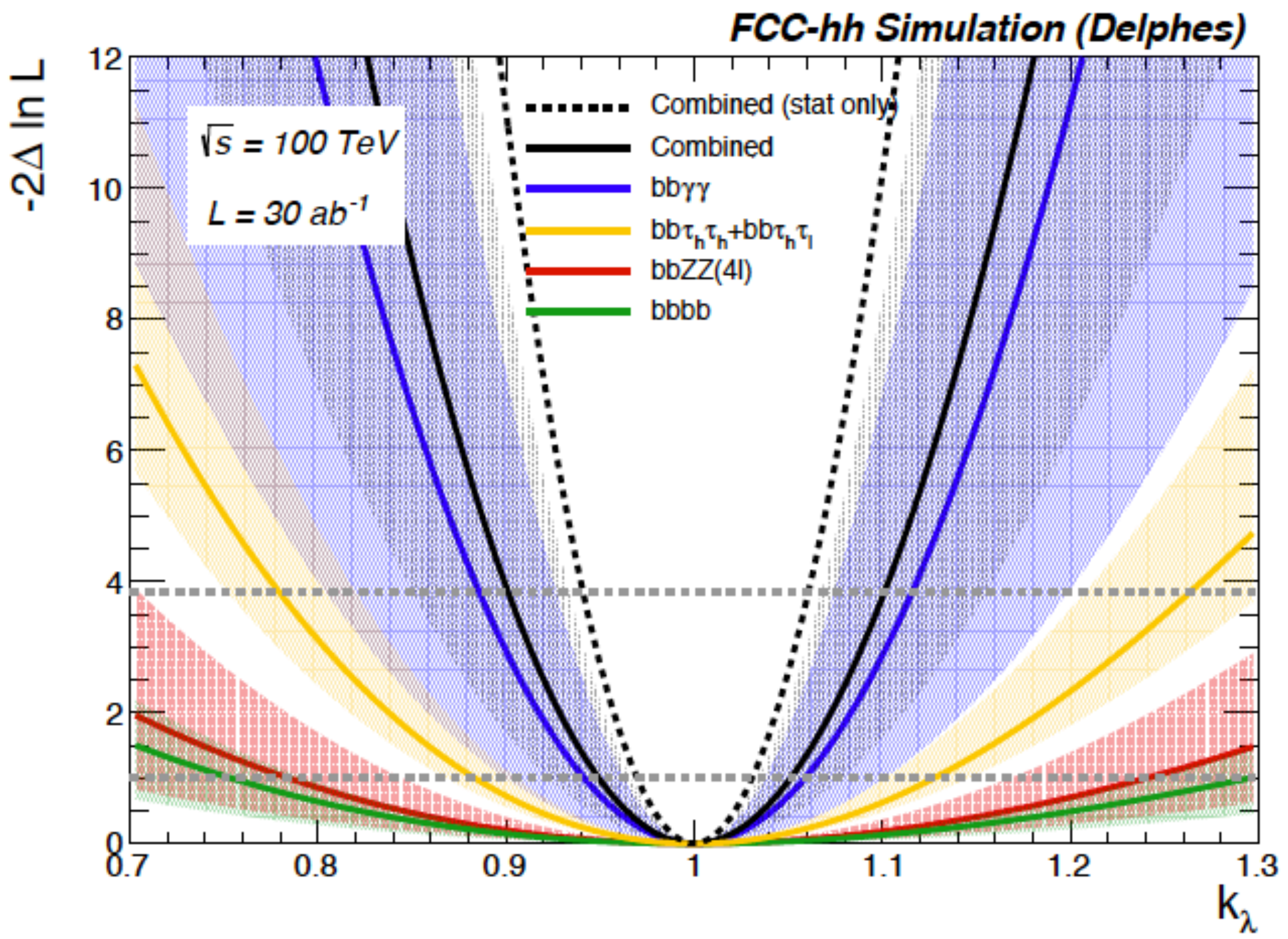


Self-coupling at the FCC-hh

2004.03505 [hep-ph]

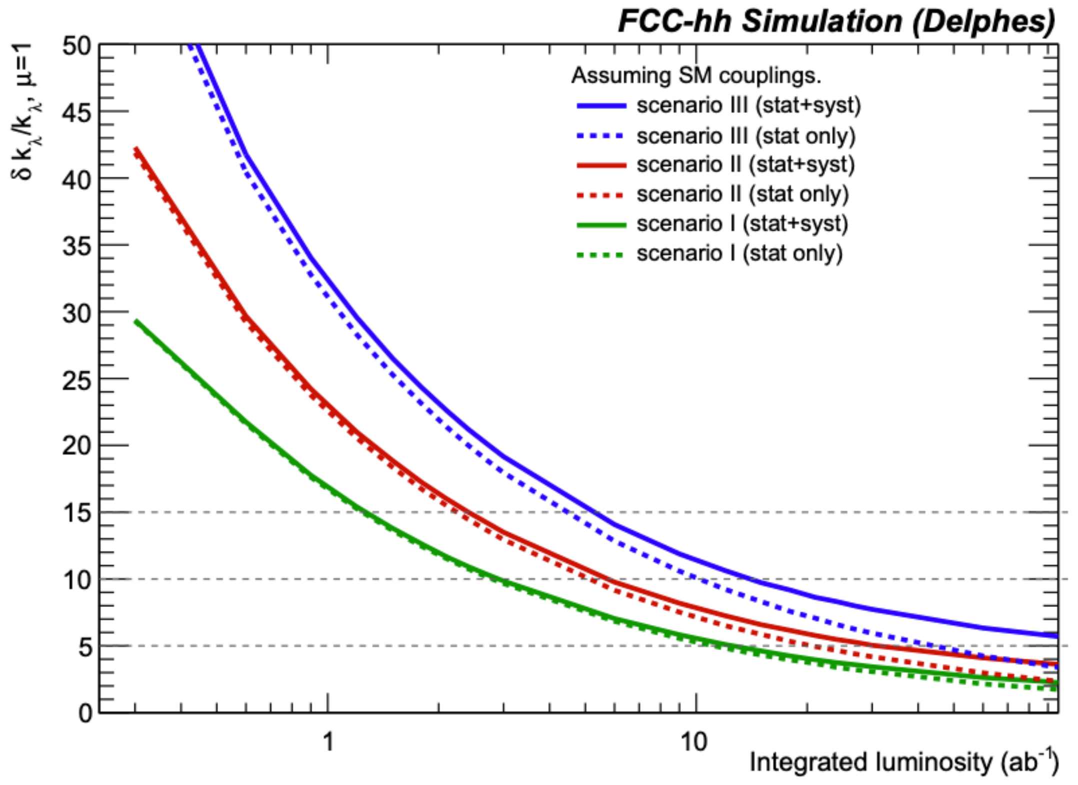


parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\to \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

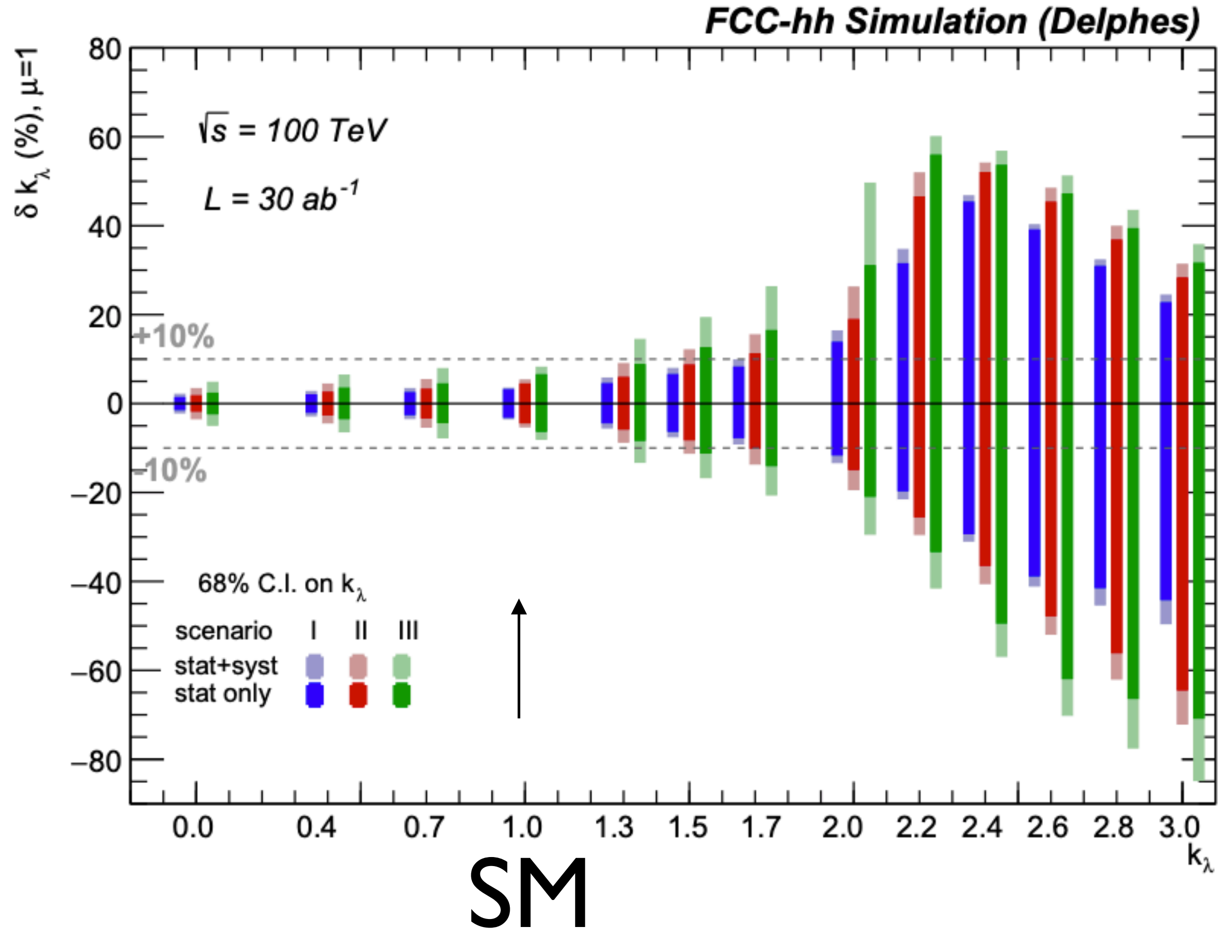


- Expected precision:

@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8



- Combined precision:
  - 3.5-8% for SM (3% stat. only)
  - **10-20%** for $\lambda_3 = 1.5 * \lambda_3^{SM}$



Summary direct measurements

	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	–	0.95 (**)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	0.91 (*)
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	5
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%	$BR_{inv} < 0.025\%$

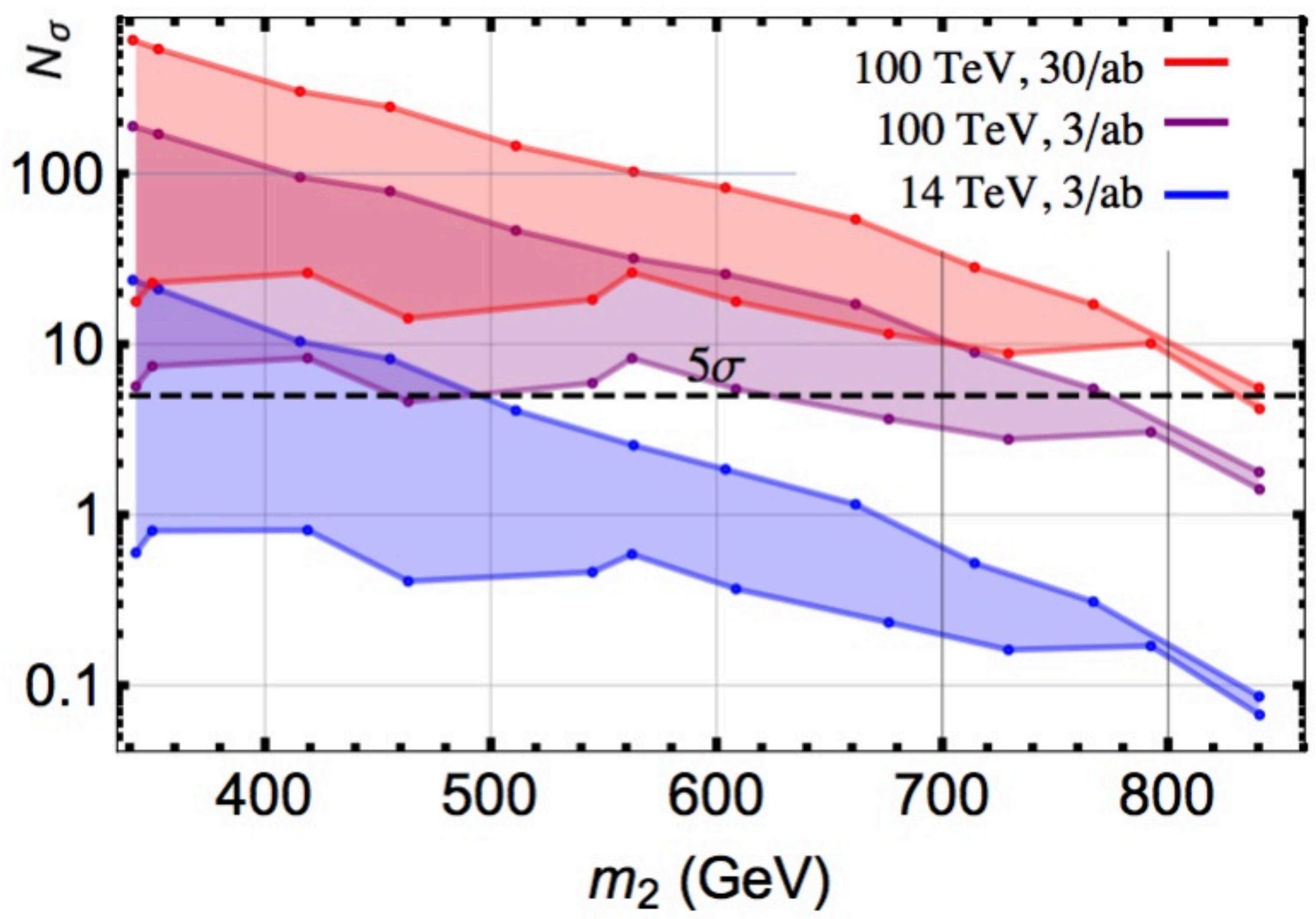
* From BR ratios wrt B(H→4l) @ FCC-ee

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

Higgs Self-coupling and constraints on models with 1st order EWPT

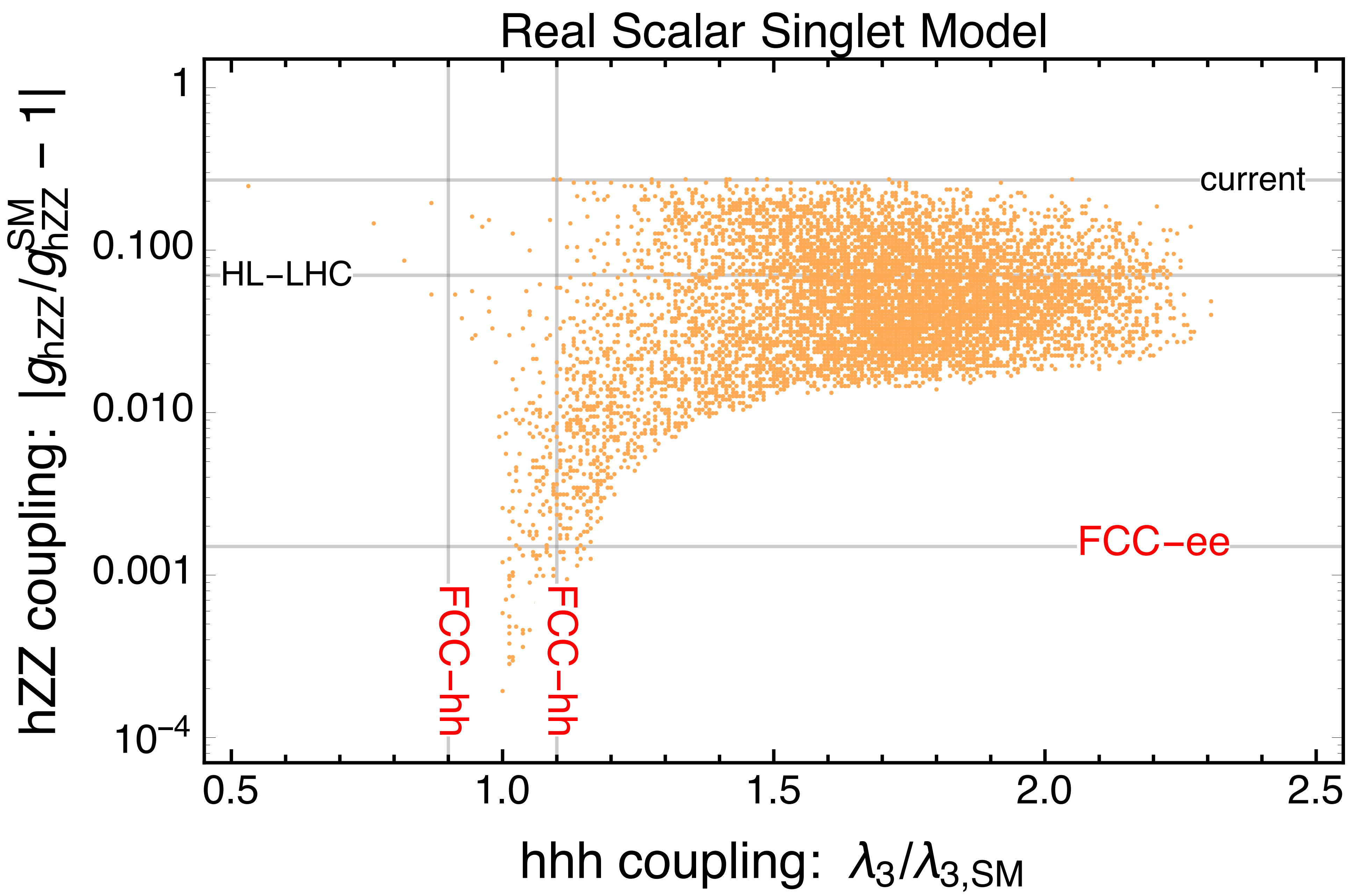
- **Strong 1st order electroweak phase transition** (and CP violation) needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

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.

Conclusions & outlook

- The integrated FCC program allows for ultimate precision in the Higgs sector
  - among all proposed future facilities, it is the natural next step for Higgs (and BSM) exploration
  - **Higgs precision is a guaranteed deliverable for the FCC**

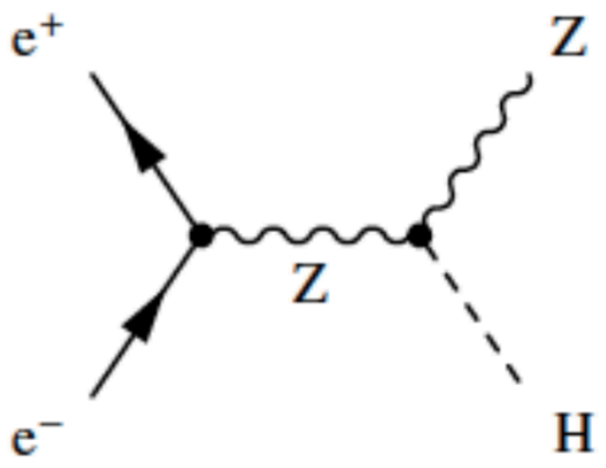
- The FCC-ee will produce 1-2 millions Higgs in a clean environment (low systematics):
  - allows for model independent measurement of Higgs couplings
  - exquisite precision in abundant Higgs decay channels

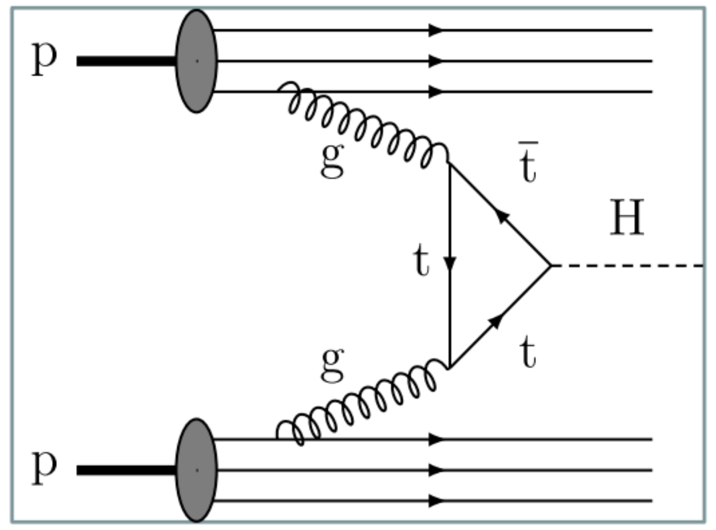
- The FCC-hh will produce 20B Higgs and 30M Higgs pairs
  - In synergy with the FCC-ee will provide percent level precision on most Higgs couplings
    - very rare decays ($H \to \mu\mu$, $Z\gamma$)
    - ttH (with ttZ from FCC-ee)
  - <5% on the Higgs self-coupling

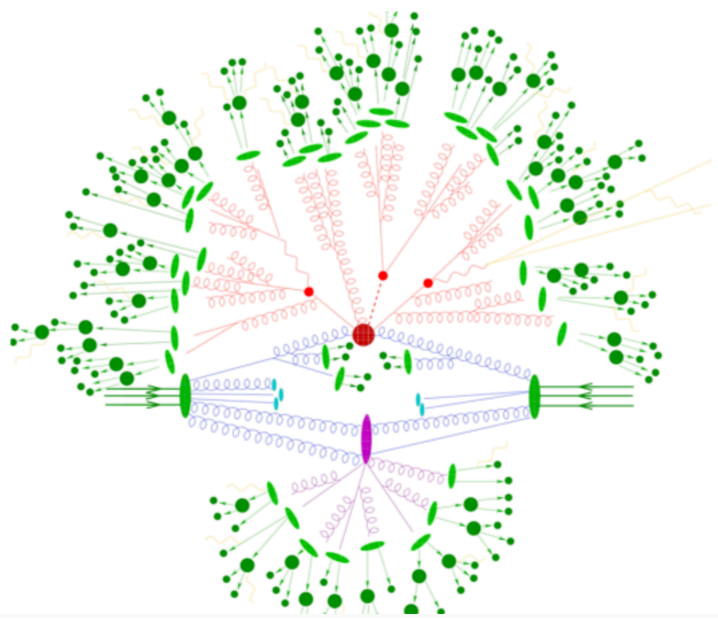
Join the effort for an exciting future !

Backup

e+e- vs p p







e^+e^- collisions

e^+/e^- are point-like
→ Initial state well defined (*E*, ***p***), polarisation
→ High-precision measurements

Clean experimental environment
→ (Almost) Trigger-less readout
→ Low radiation levels
Superior sensitivity for **electro-weak states**

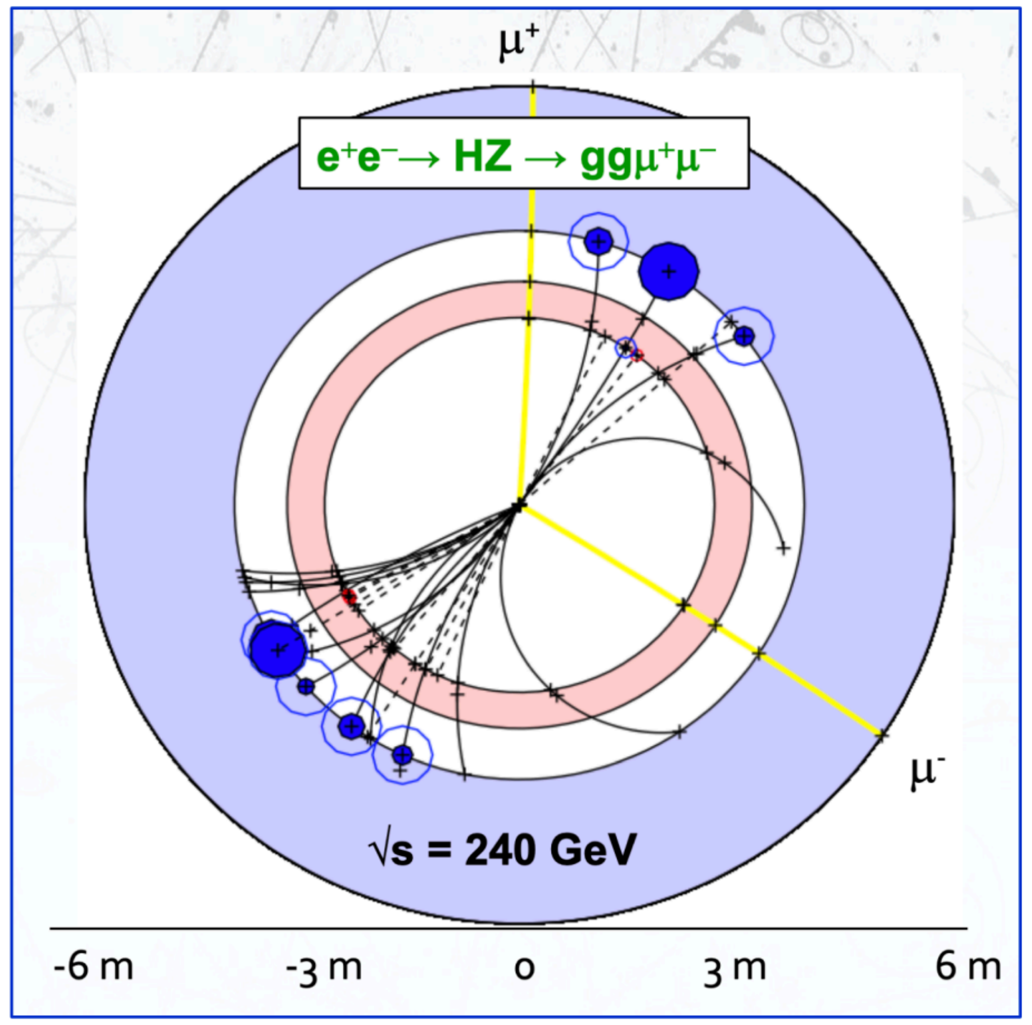
- **Circular** e^+e^- colliders can deliver **very large luminosities**
- **Linear** collider can reach higher energies (>1TeV)

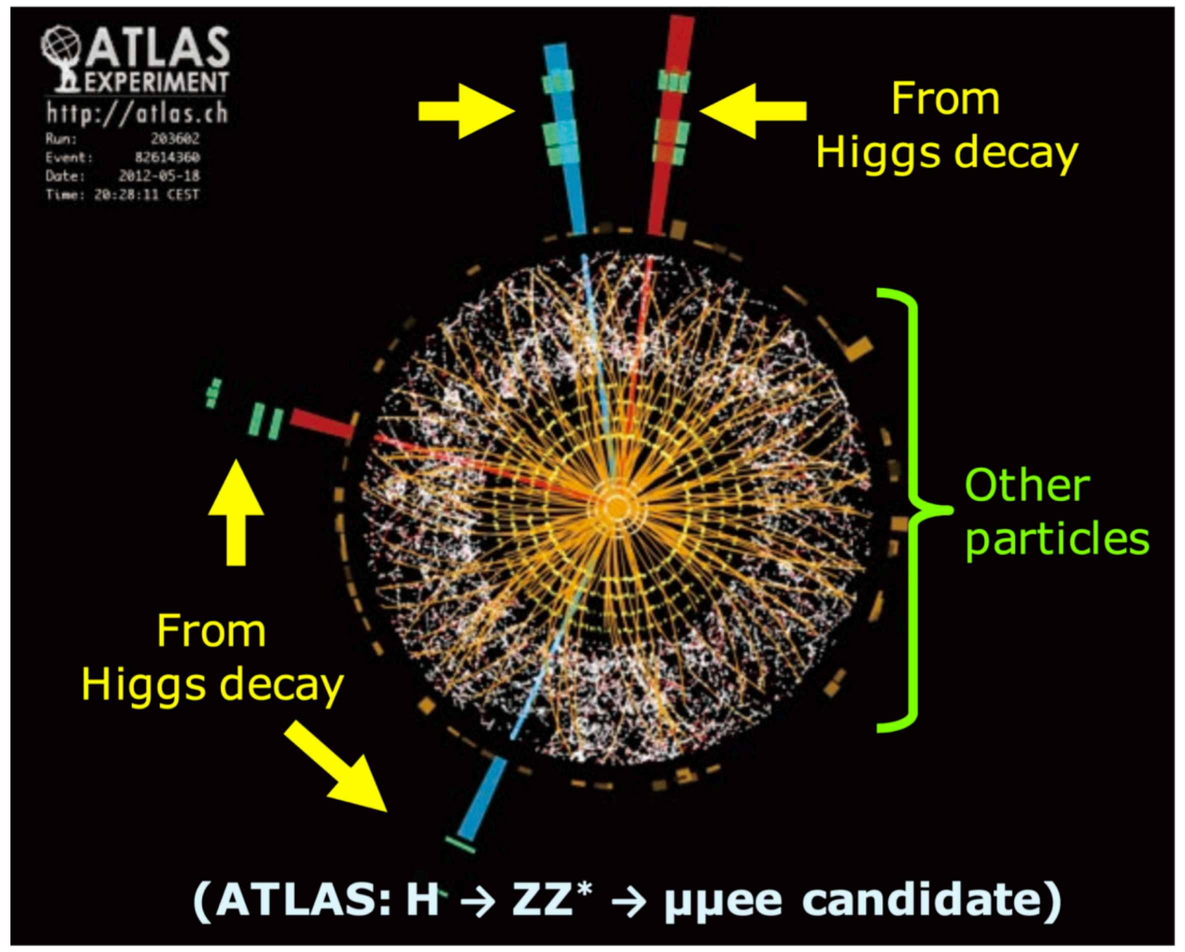
pp collisions

Proton is compound object
→ Initial state not known event-by-event
→ Limits achievable precision

High rates of QCD backgrounds
→ Complex triggering schemes
→ High levels of radiation
High cross-sections for **colored-states**

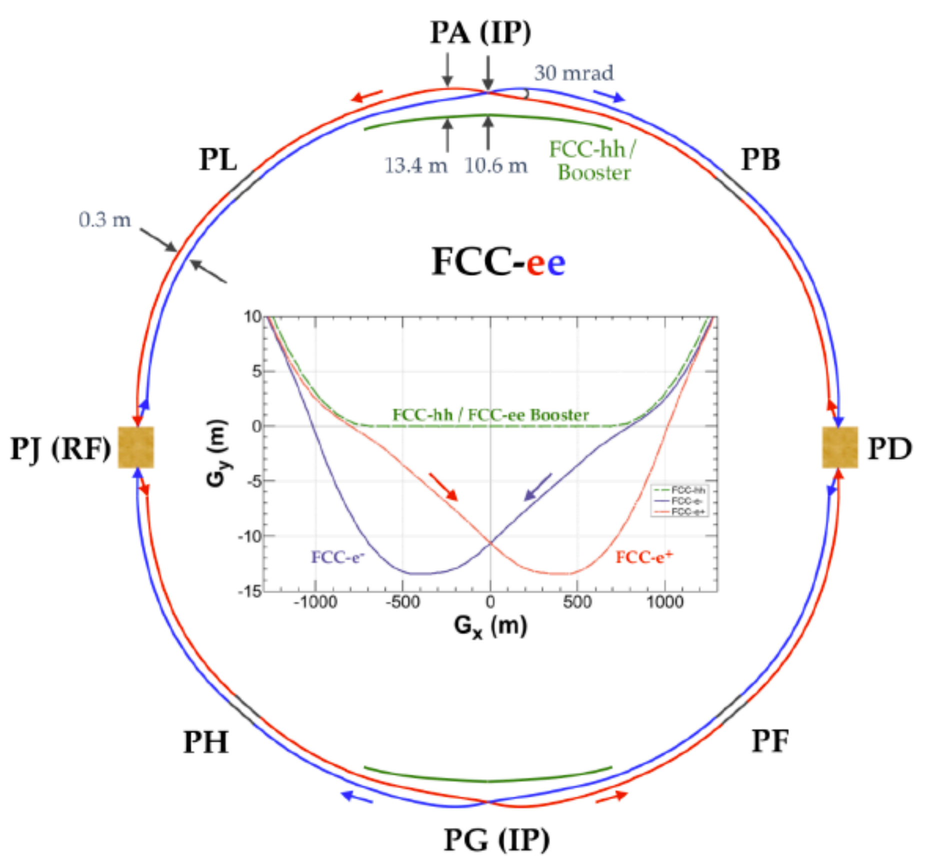
High-energy **circular** pp colliders feasible.
R&D on high field magnets needed.



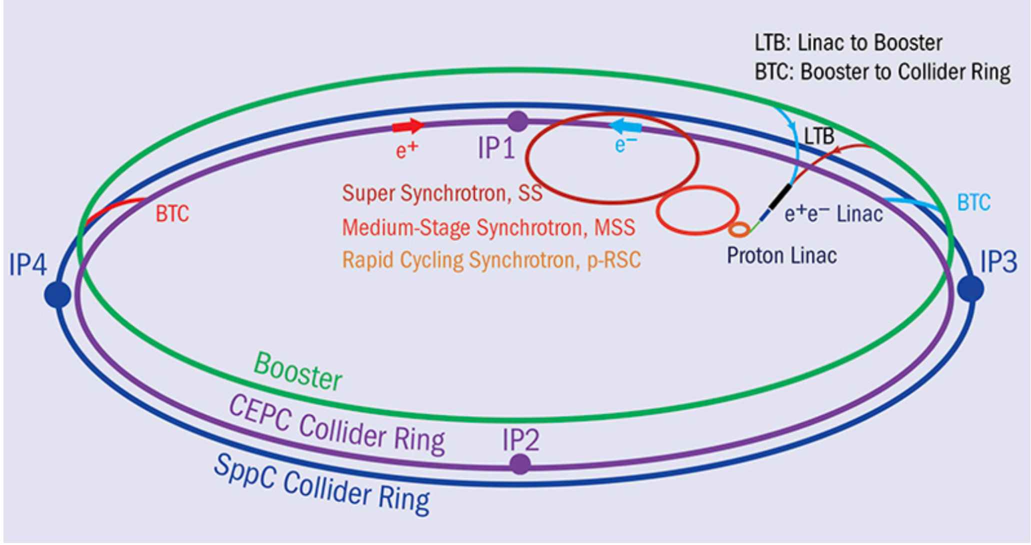


Future e+e- machines

FCC-ee



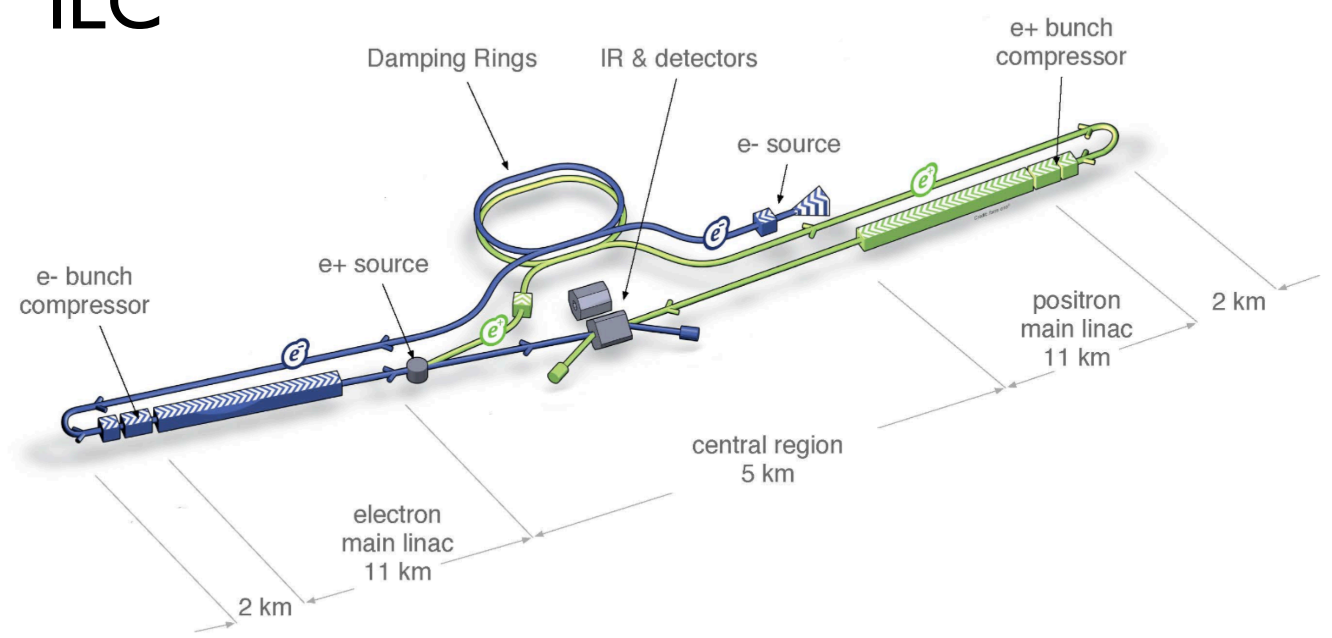
CEPC



- Maximum E_{CM} ~ 350 GeV (limited by synchrotron radiation)
- Very high luminosity at low energy (Z > W > H > t)
- Allows multiple experiments

Parameter	Z	W	H	t
Cm E [GeV]	91.2	160	240	350
FCC-ee				
L [10^{34} cm^{-2}s^{-1}]	200	28	8.5	1.8
Years op.	4	2	3	5
Int. L / 2 IP [ab^{-1}]	150	10	5	1.5
CEPC				
L [10^{34} cm^{-2}s^{-1}]	32	10	3	
Years op.	2	1	7	
Int. L / 2 IP [ab^{-1}]	16	2.6	5.6	

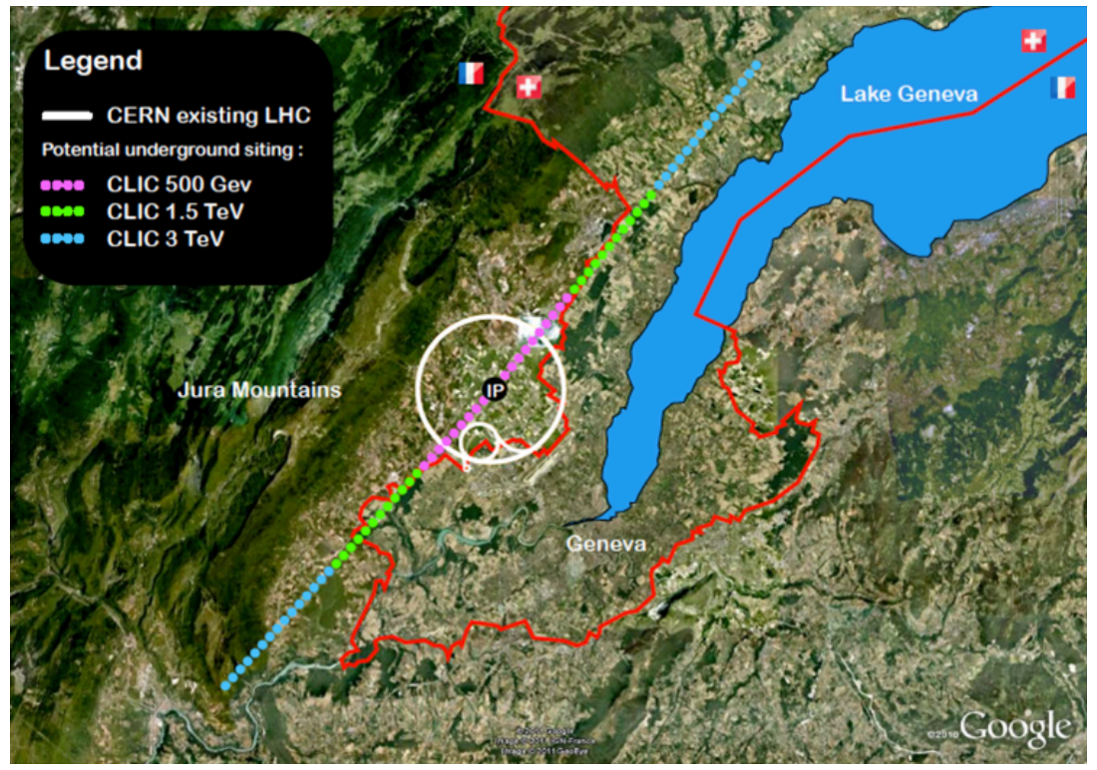
ILC



sqrt(s)	500 GeV	1 TeV
Lumi	4 ab^{-1}	8 ab^{-1}

- Can reach high energies
- High lumi at high energies (ttH, HH, H …)

CLIC



sqrt(s)	1.5 TeV	3 TeV
Lumi	2.5 ab $^{-1}$	5 ab $^{-1}$

Machine specs and detector requirements

lumi & pile-up

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\vert_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta\vert_{\eta=5}$	GeV	316	316	427	765
$dP/d\eta\vert_{\eta=5}$	kW	0.04	0.2	1.0	4.0

→ x6 HL-LHC

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

but also x10 integrated luminosity w.r.t to HL-LHC

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

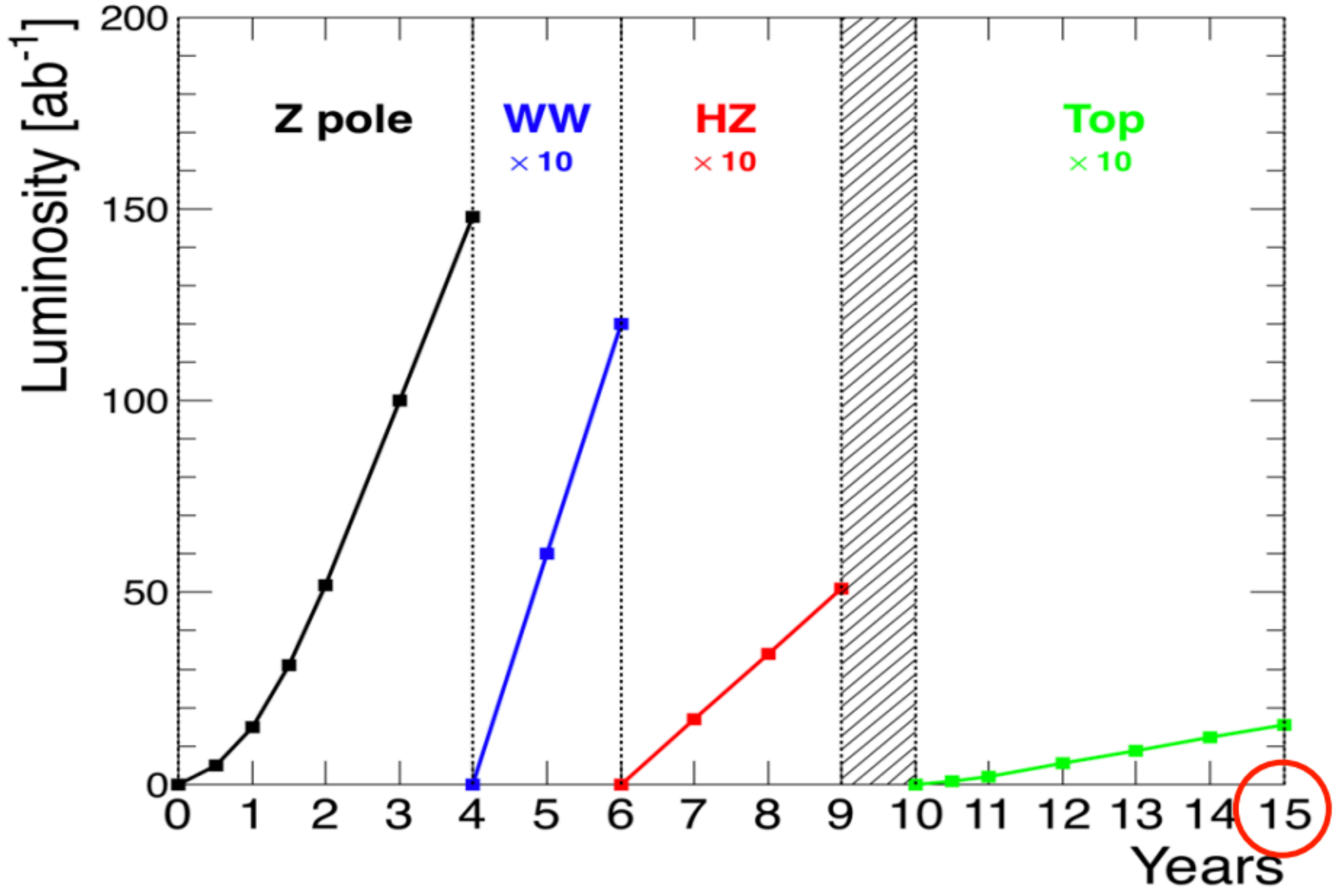
FCC-ee run plan

- 185 physics days / year, 75% efficiency, 10% margin on luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold…	… and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

nty

Total : 15 years



Event statistics

5×10^{12} $e^+e^- \rightarrow Z$
10^8 $e^+e^- \rightarrow W^+W^-$
10^6 $e^+e^- \rightarrow HZ$
10^6 $e^+e^- \rightarrow t\bar{t}$

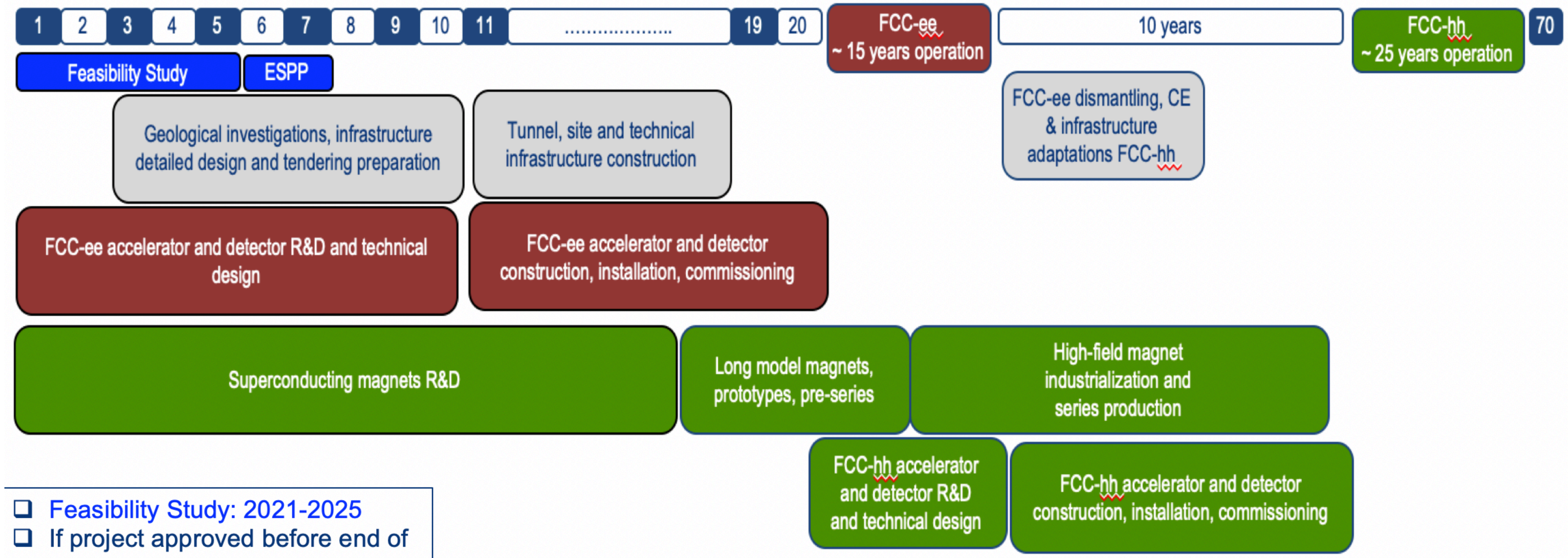
√s precision

100 keV
300 keV
2 MeV
5 MeV

Transverse polarization (E_{beam} calib.),
No longitudinal polarization.

For 4 IPs x 1.7 luminosity / statistics

Timeline of the integrated FCC project

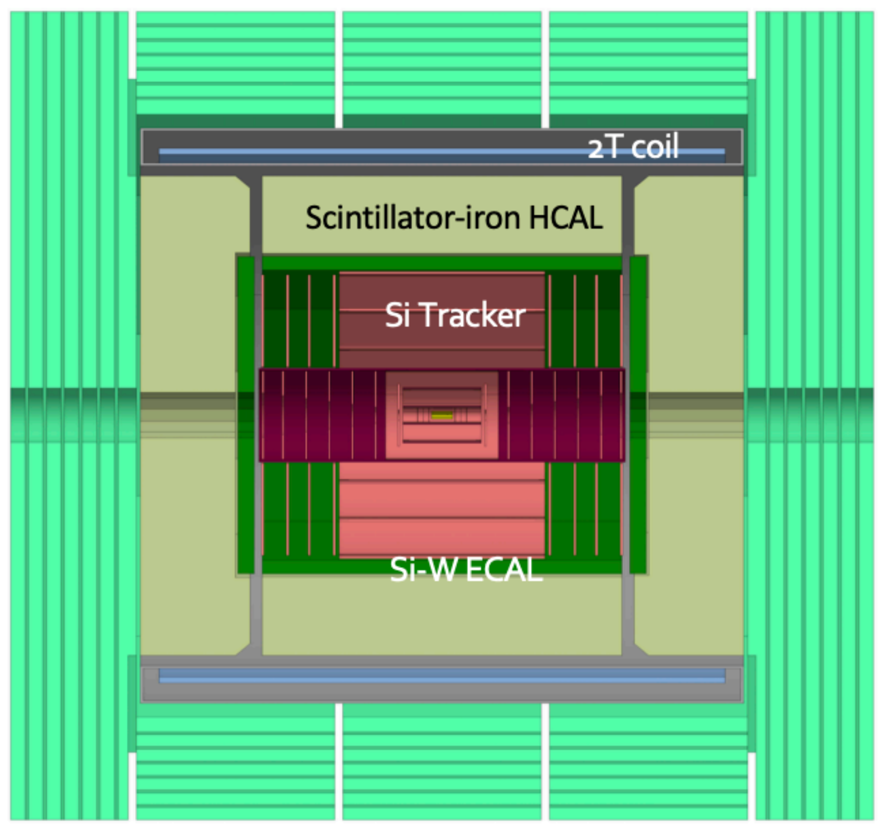


- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

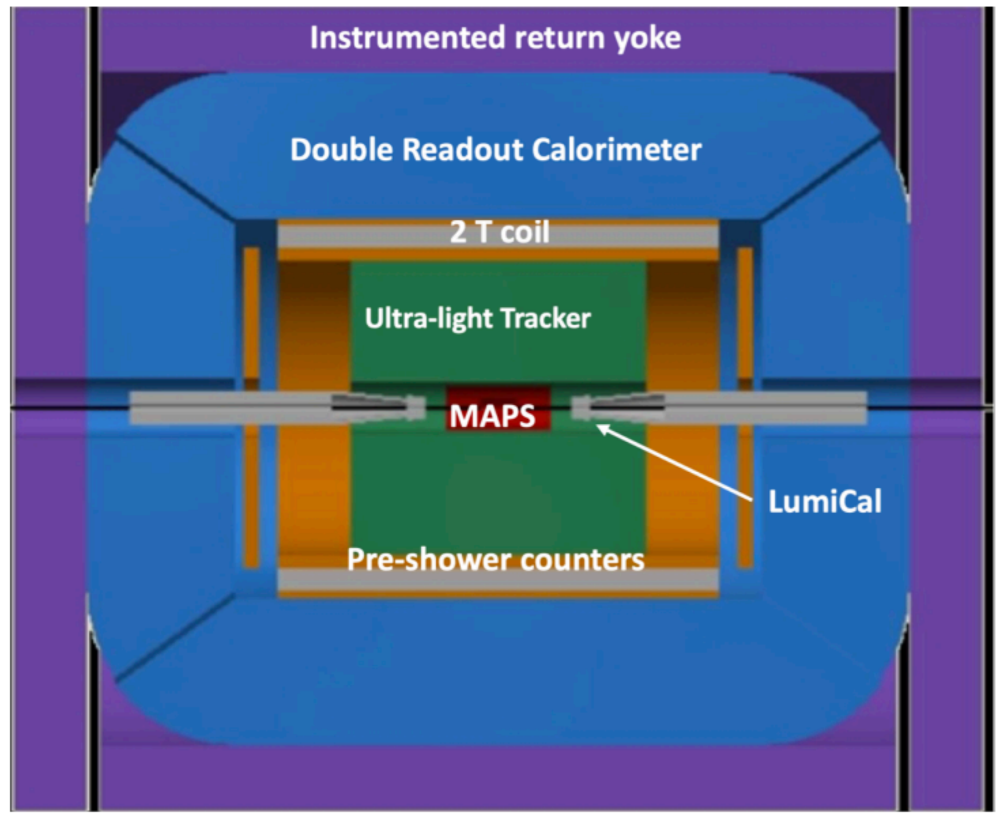
Detector designs

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)



CLD

- Consolidated option based on the detector design developed for CLIC
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil outside calorimeter system
- Proven concept, understood performance



IDEA

- New, innovative, possibly more cost-effective design
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil inside calorimeter system

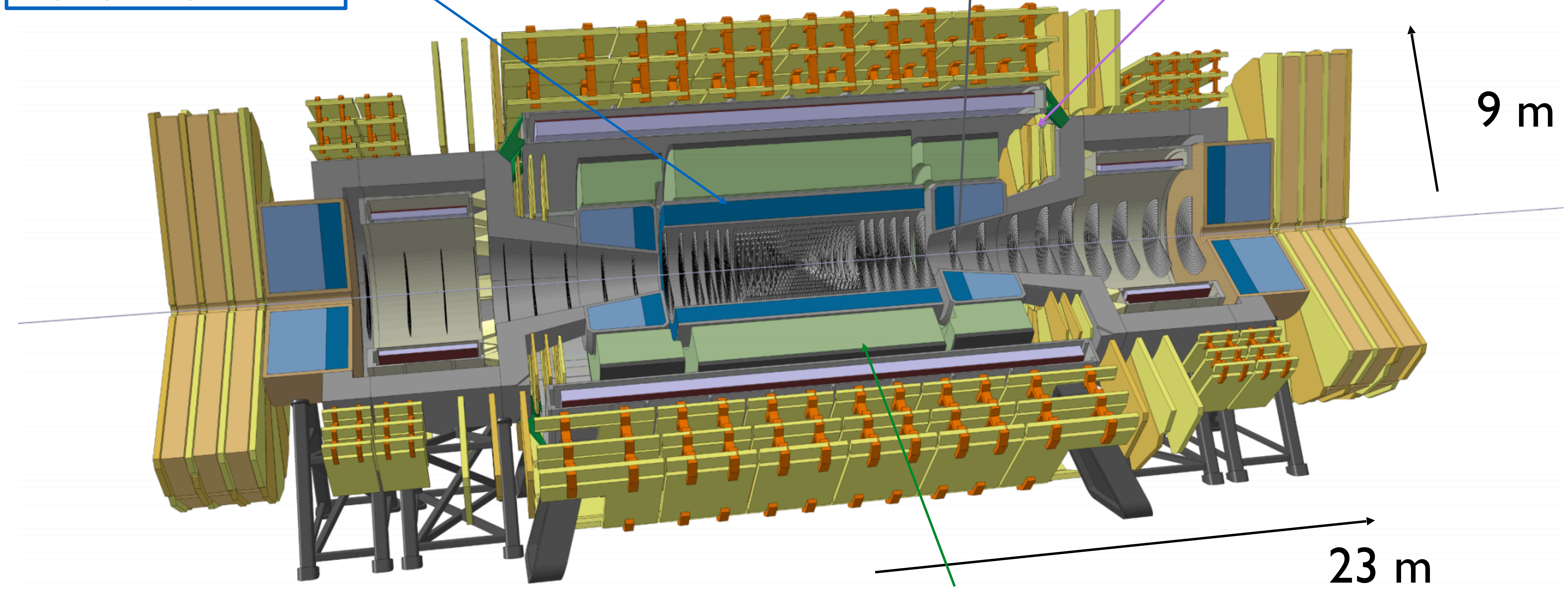
A third concept based on highly granular LAr being proposed as well …

The FCC-hh detector

Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
$30\ X_0$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

Tracker: $\sigma_{p_T}/p_T \sim 20\%$
at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids

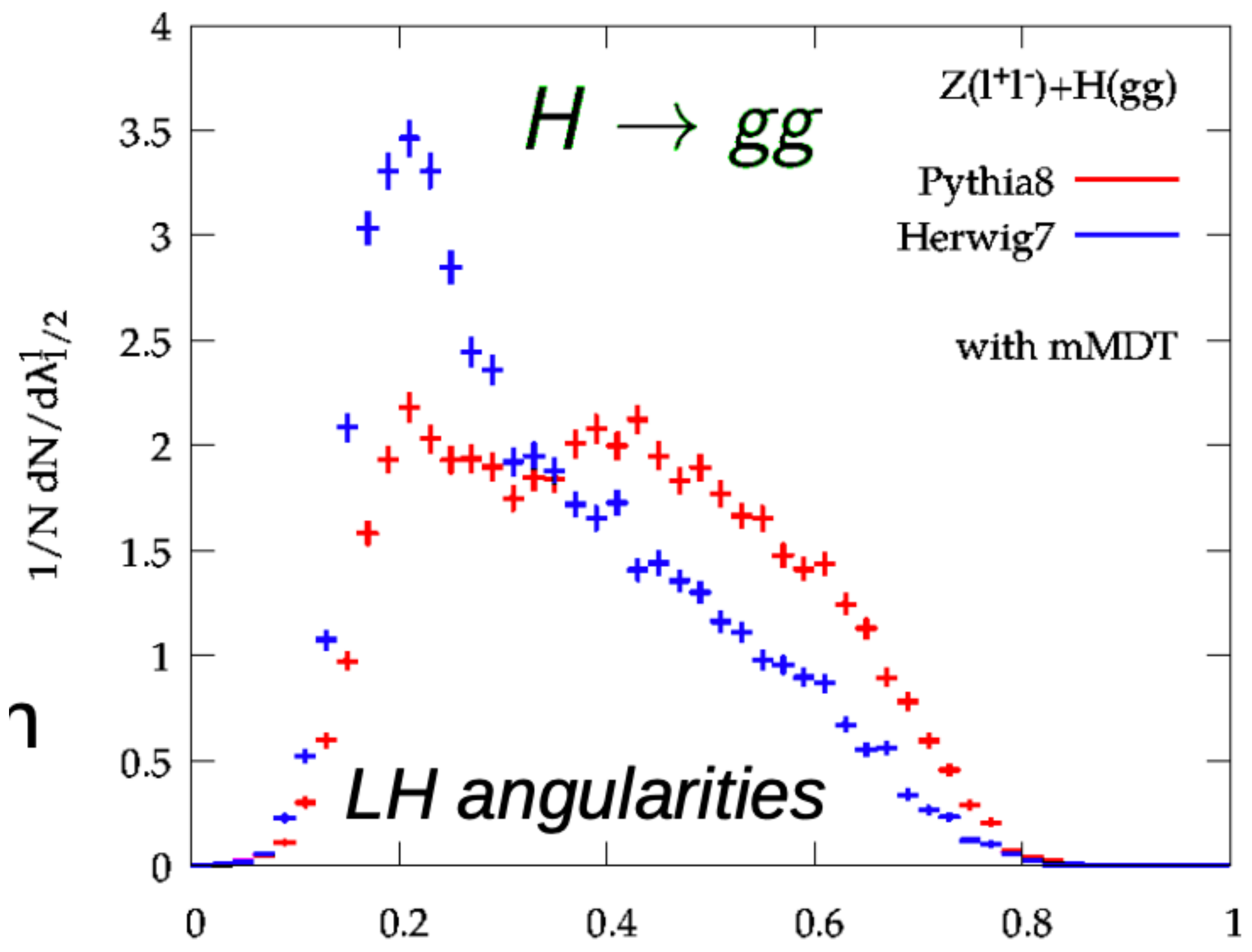


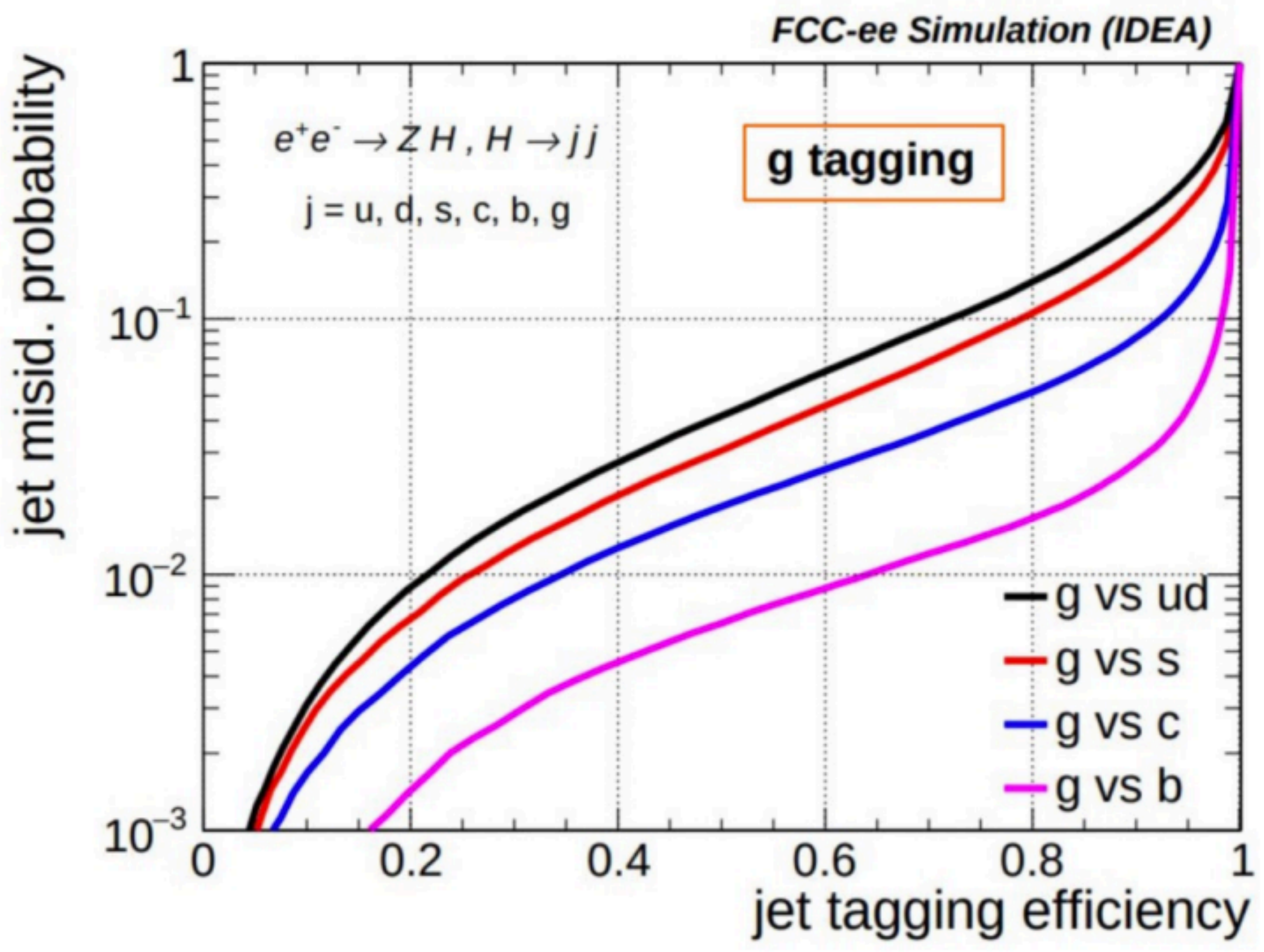
Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
$11\ \lambda$ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

H→gluons





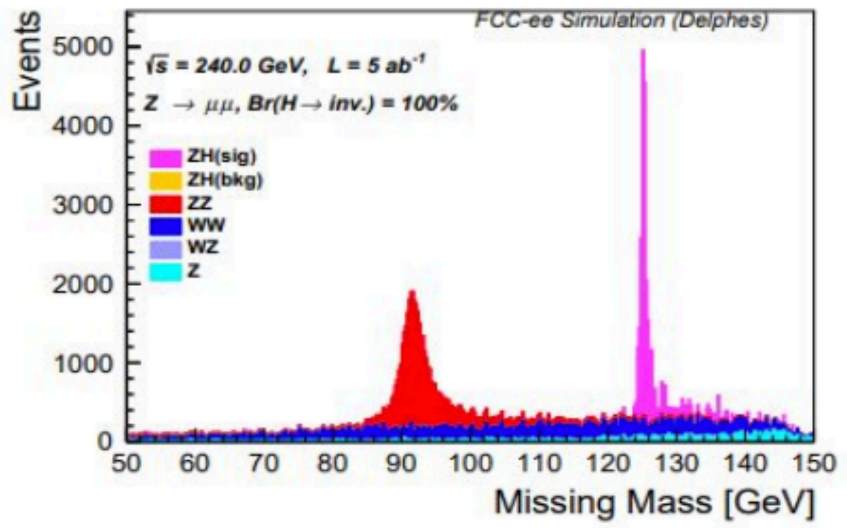
40% H → gg for 0.1% H → cc

0.01% H → bb

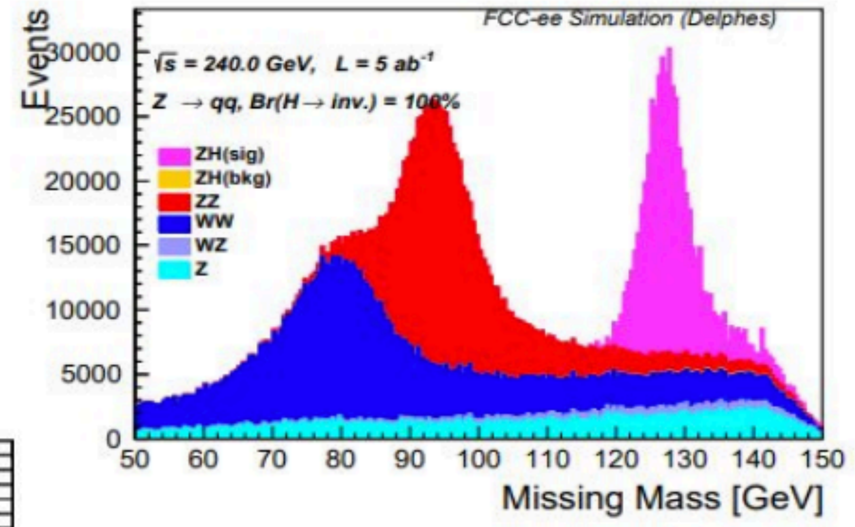
- with powerful gluon taggers:
  - measure Higgs to gluon coupling
  - exploit it as a gluon factory
    - 100k extra clean gluon events
    - study gluon radiation and jet properties

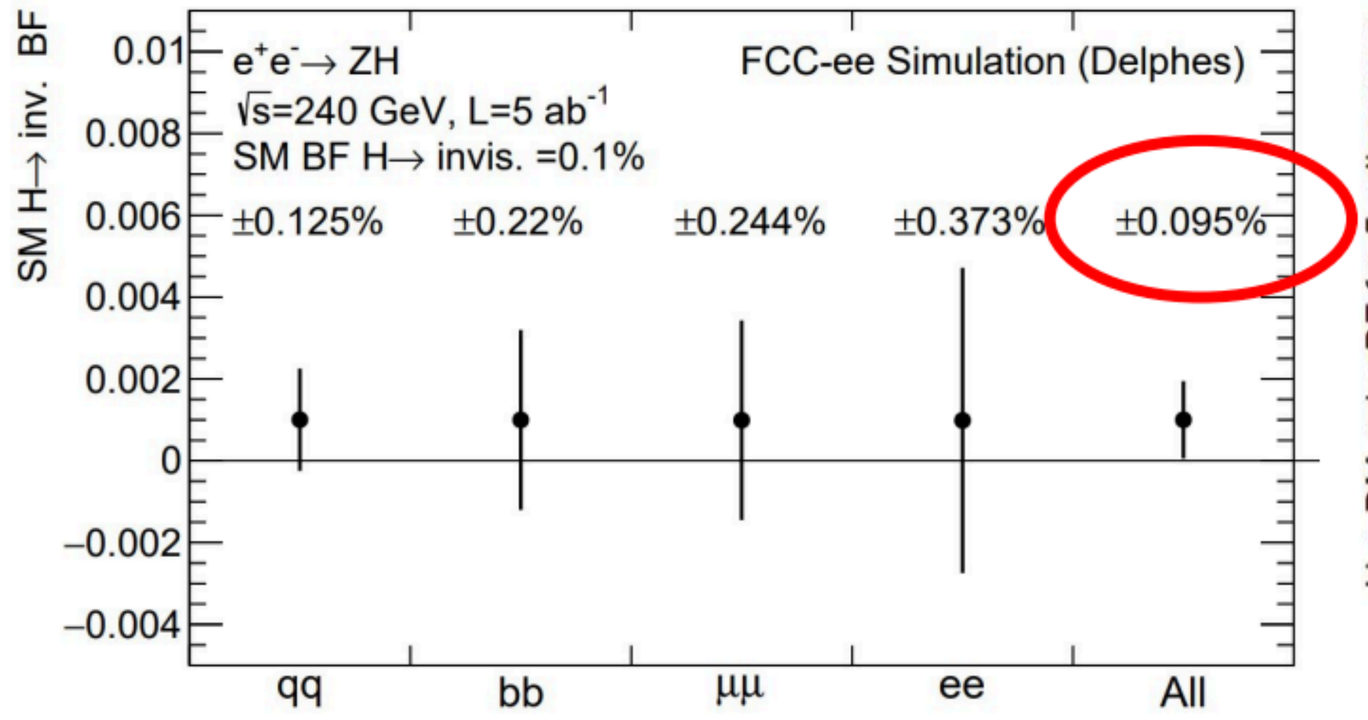
H → invisible

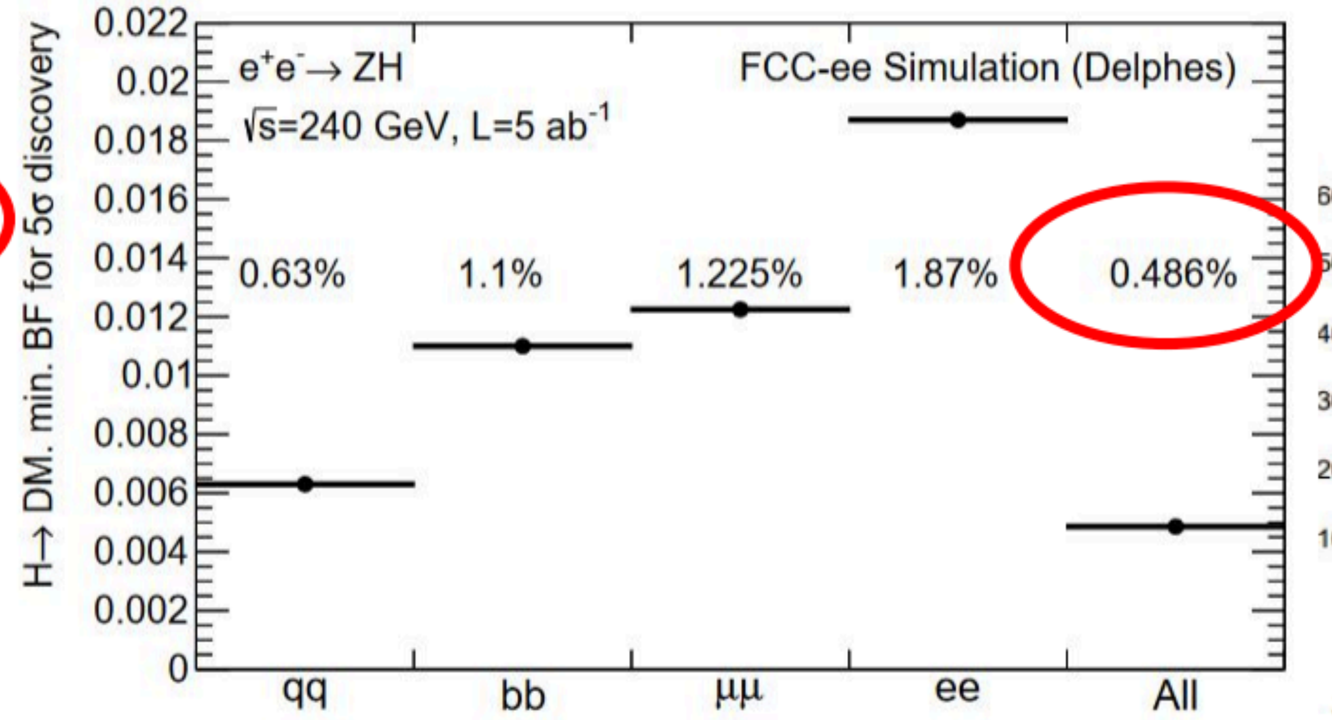
- Higgs could be a portal to dark matter or other new physics
- In the SM B(H→inv) ~ 10^{-3}
- Use recoil method to reconstruct the Higgs
  - potential to improve 1 order of magnitude compared to LHC

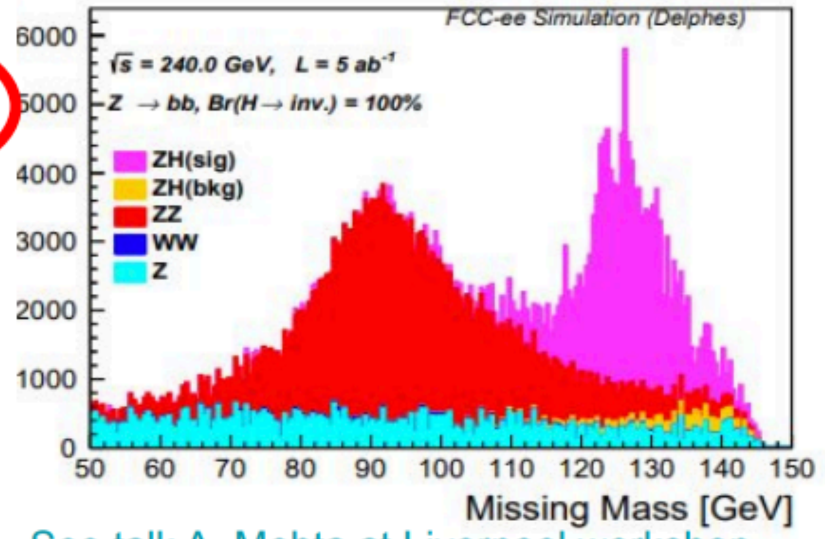


- Using Z→ee/μμ/bb/qq channels
  - stat. only uncertainty reaches SM sensitivity at the FCC-ee
    - in the SM B(H→inv) ~ 10^{-3}
- Potential for discovery for H→X(inv) with BR ~ 0.5%



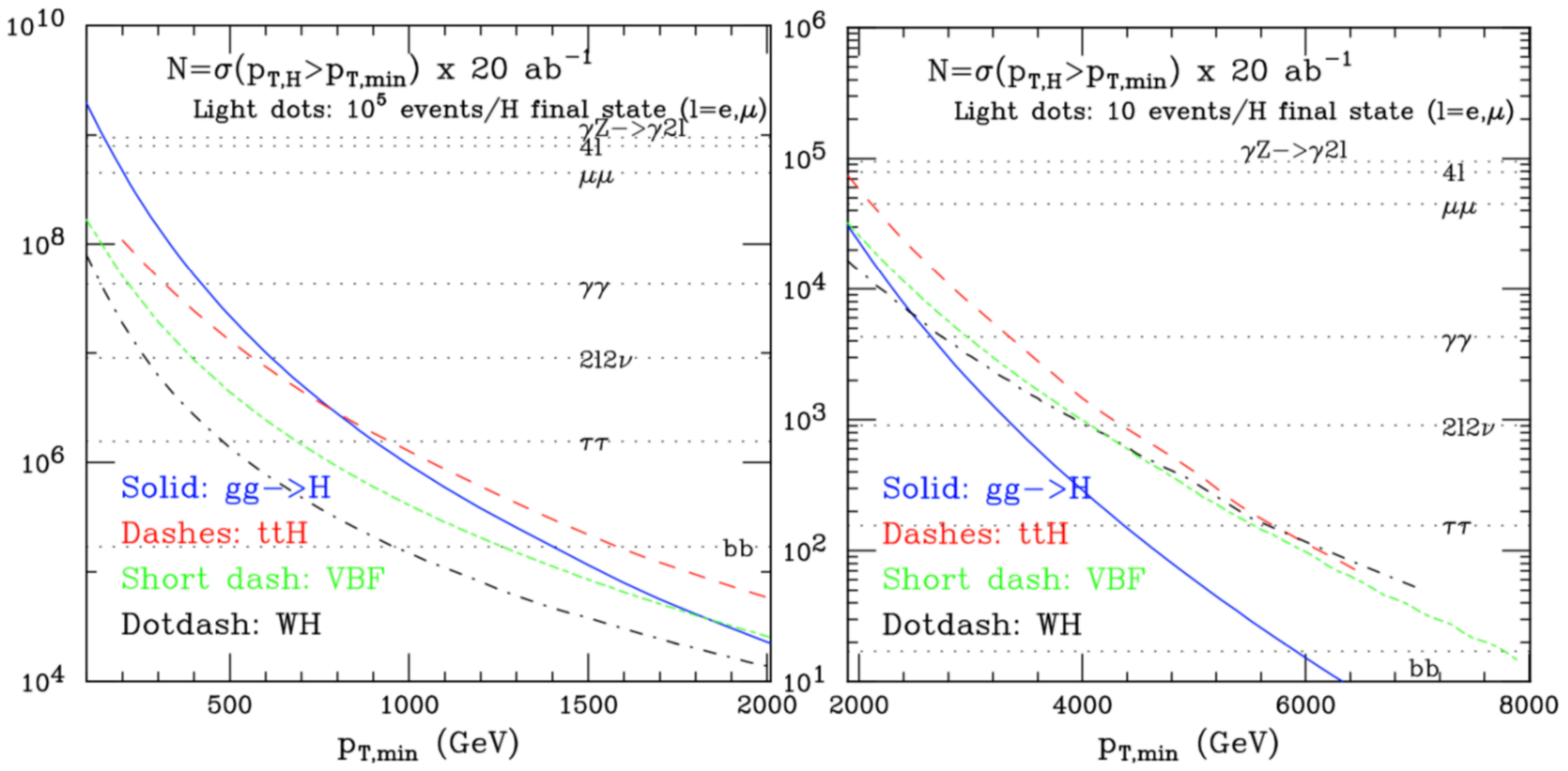




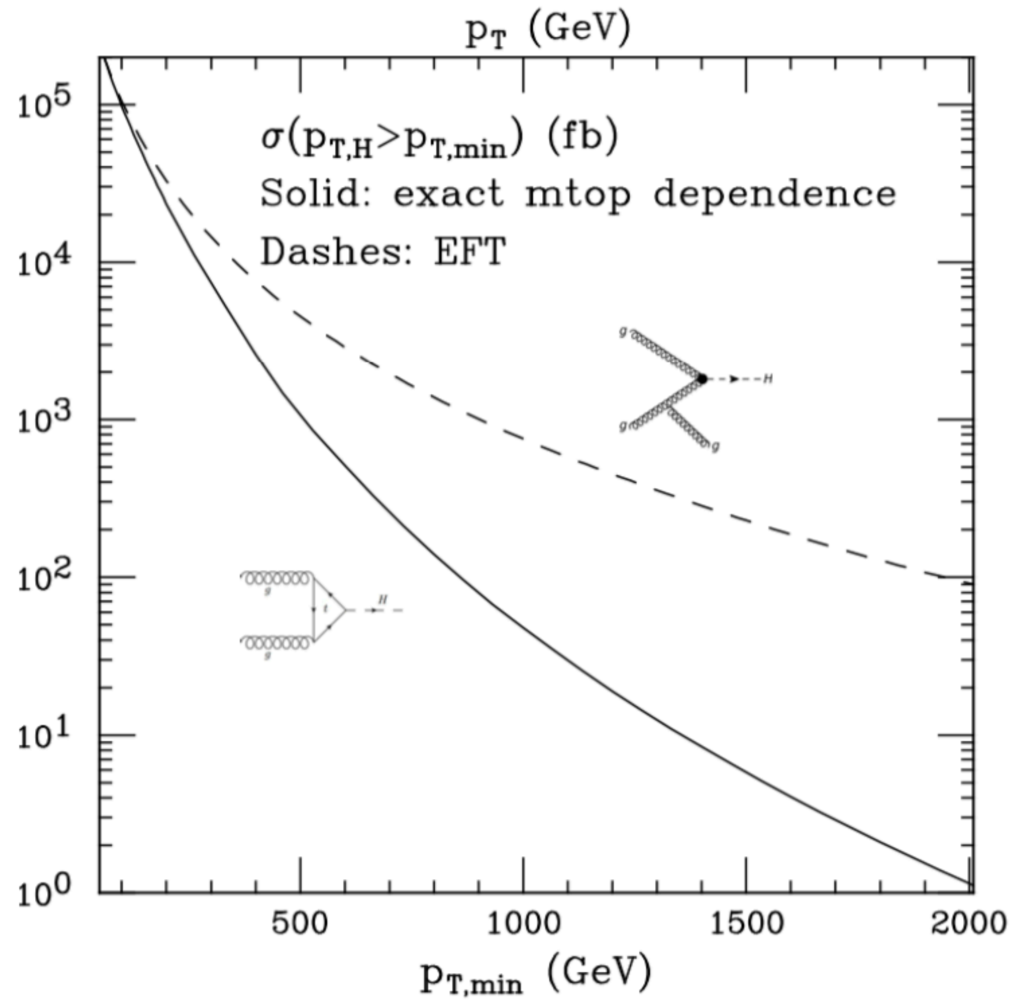


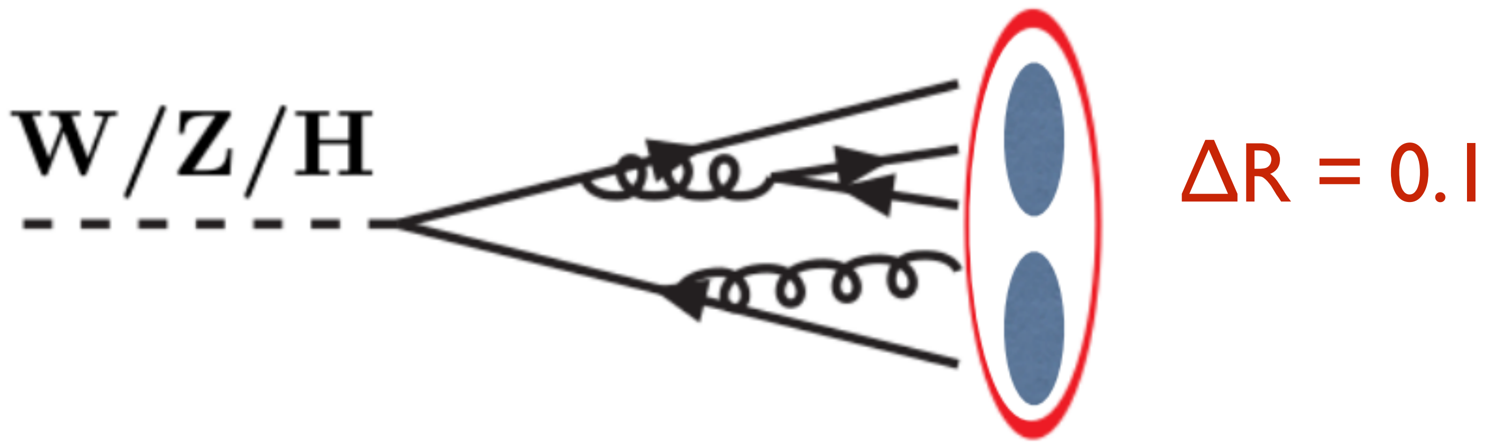
See talk A. Mehta at Liverpool workshop

Higgs at large p_T



$N(p_T > p_{T,\,min})$





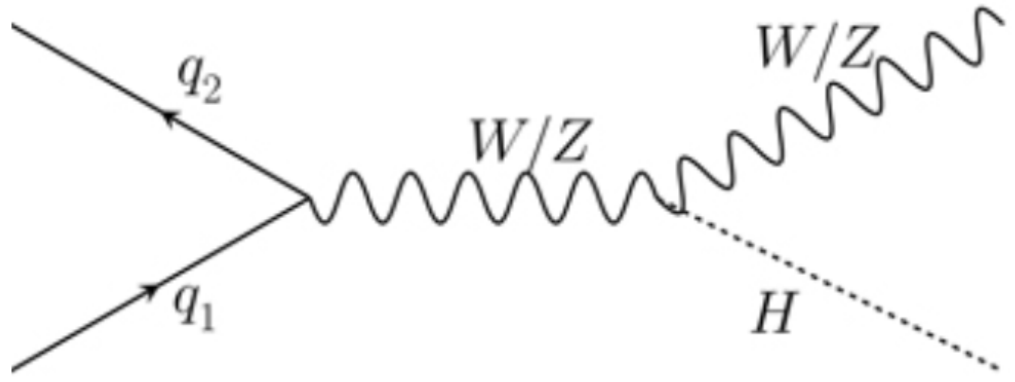
- Huge rates at large p_T :
  - **> 10^6 Higgs** produced with p_T > 1 TeV
  - Higher probability to produce large p_T Higgs from ttH/VBF/VH at large
  - Even rare decay modes can be accessed at large p_T
- Opportunity to measure the Higgs **in a new dynamical regime**
  - Higgs p_T spectrum highly sensitive to new physics.

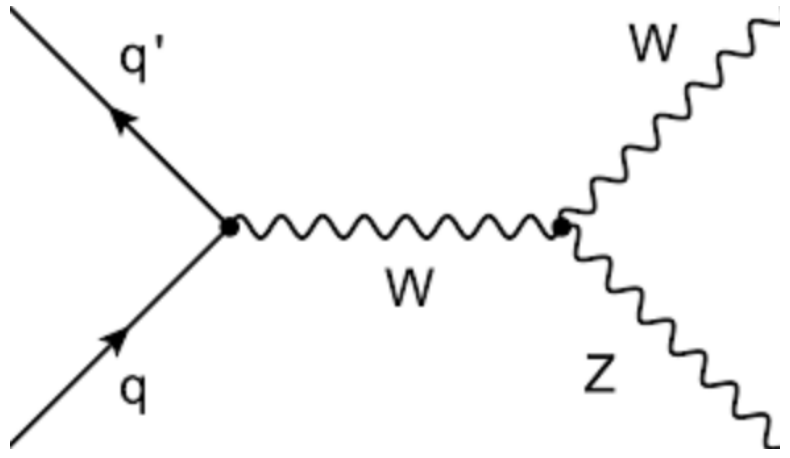
- highly granular sub-detectors:
  - Tracker - pixel:10 μm @ 2cm → $\sigma_{\eta\times\varphi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\times\varphi} \approx$ 10 mrad
- good energy/p_T resolution at large p_T:
  - σ_p / p = 2% @ 1 TeV

Standalone 100 TeV Higgs measurements

MLM

- Following the principle of **reducing** as much as possible **the impact of systematics** assumptions on future measurements, additional **ratio measurements**:





$\sigma(WH[\to\gamma\gamma])\ /\ \sigma(WZ[\to e^+e^-])$ $\longrightarrow$ $G_W = g^2_{HWW} \times BR(H \to \gamma\gamma)$

$\sigma(WH[\to\tau\tau])\ /\ \sigma(WZ[\to\tau\tau])$ $\longrightarrow$ $G_\tau = g^2_{HWW} \times BR(H \to \tau\tau)$

$\sigma(WH[\to bb])\ /\ \sigma(WZ[\to bb])$ $\longrightarrow$ $G_b = g^2_{HWW} \times BR(H \to bb)$

parton level study

p_T^{min} (GeV)	W[e]Z[e] (pb)	W[e]H (pb)	W[ℓ]Z[e] $\times$ L	W[ℓ]H[γγ] $\times$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E6	1.4E4	8.5E−3
150	1.0E-2	6.3E-2	6.0E5	8.7E3	1.1E−2
200	5.6E-3	3.8E-2	3.4E5	5.2E3	1.4E−2
300	2.1E-3	1.6E-2	1.3E5	2.2E3	2.1E−2

p_T^{min} (GeV)	W[e]Z[τ] (pb)	W[e]H (pb)	W[ℓ]Z[τ] $\times\varepsilon_\tau$ L	W[ℓ]H[ττ] $\times\varepsilon_\tau$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E5	3.8E4	5.9E−3
150	1.0E-2	6.3E-2	6.0E4	2.4E4	7.7E−3
200	5.6E-3	3.8E-2	3.4E4	1.4E4	1.0E−2
300	2.1E-3	1.6E-2			
400	9.8E-4	7.9E-3			

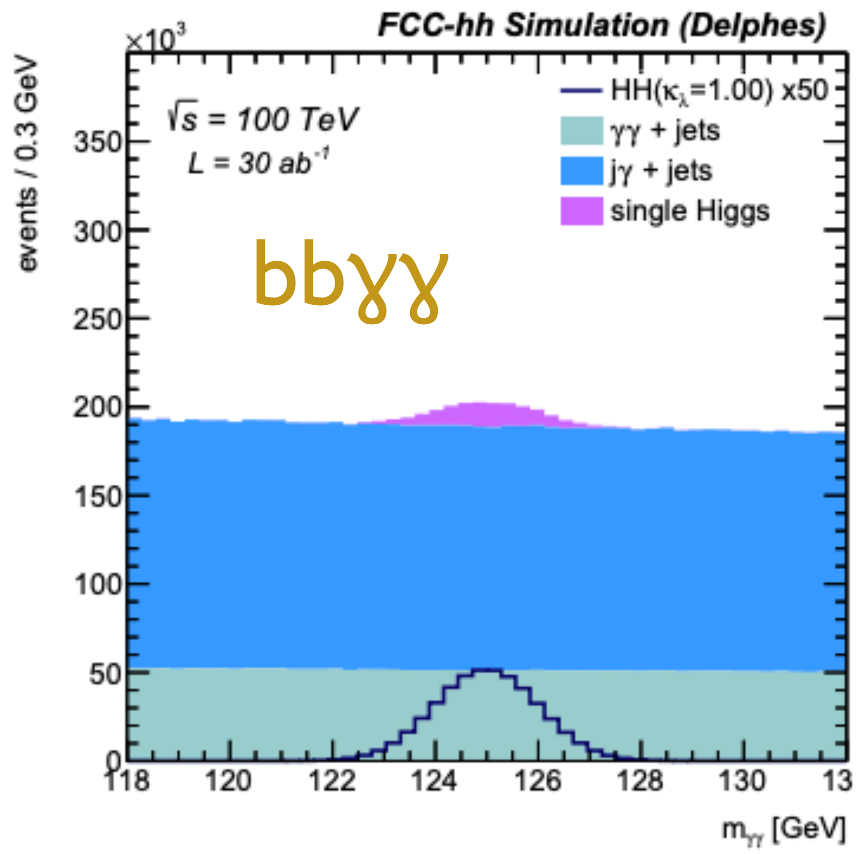
$\delta G/G < 1\%$

p_T^{min} (GeV)	W[e]+bb (pb) $m[bb] \in m_Z$	W[e]Z[bb] (pb)	W[e]+bb (pb) $m[bb] \in m_H$	W[e]H (pb)	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_Z$	W[ℓ]Z[bb] $\times\varepsilon_b$ L	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_H$	W[ℓ]H[bb] $\times\varepsilon_b$ L	$\delta R/R$
200	3.3E−2	2.5E−2	2.3E−2	3.8E−2	9.9E5	7.5E4	6.9E5	6.6E5	2.5E−3
300	1.2E−2	9.2E−3	8.8E−3	1.6E−2	3.6E5	5.5E4	2.6E5	2.8E5	3.2E−3
400	5.5E−3	4.3E−3	4.1E−3	7.9E−3	1.7E5	2.6E5	1.2E5	1.4E5	4.5E−3
600	1.7E−3	1.4E−3	1.3E−3	2.6E−3	5.1E4	8.4E4	3.9E4	4.5E4	7.8E−3
800	6.8E−4	6.2E−4	5.0E−4	1.2E−3	2.0E4	3.7E4	1.5E4	2.1E4	1.1E−2

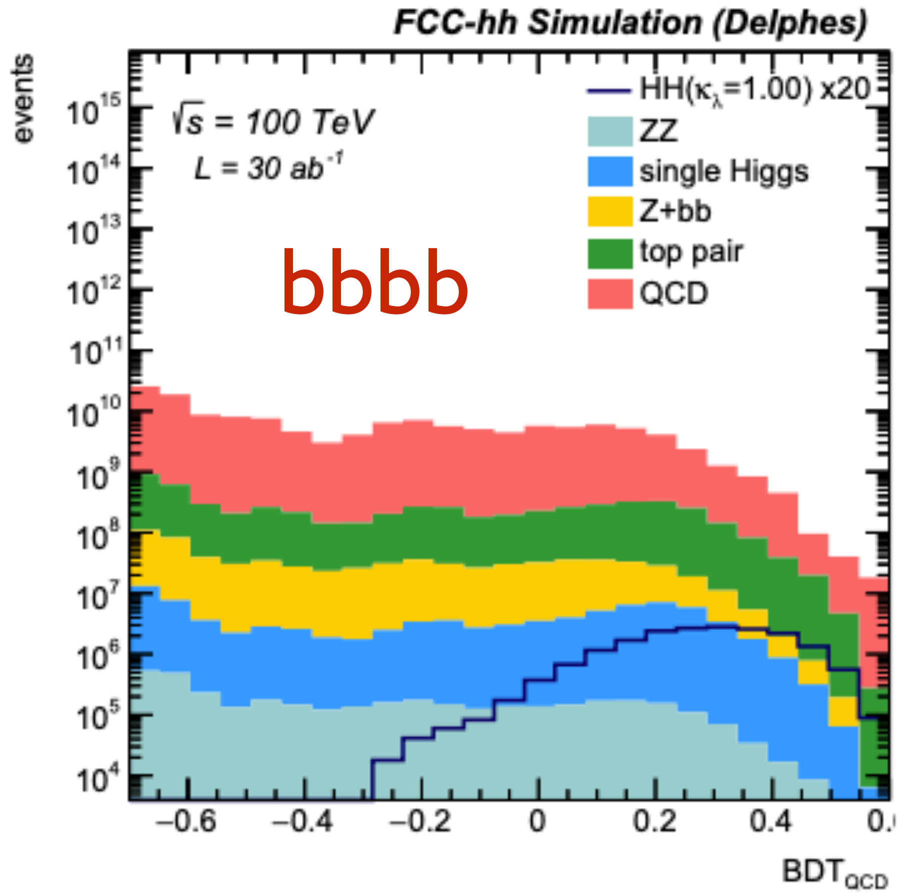
also: $\sigma(Z[\nu\nu]H[\to\gamma\gamma])\ /\ \sigma(Z[\nu\nu]Z[\to e^+e^-])$

Self-coupling at the FCC-hh

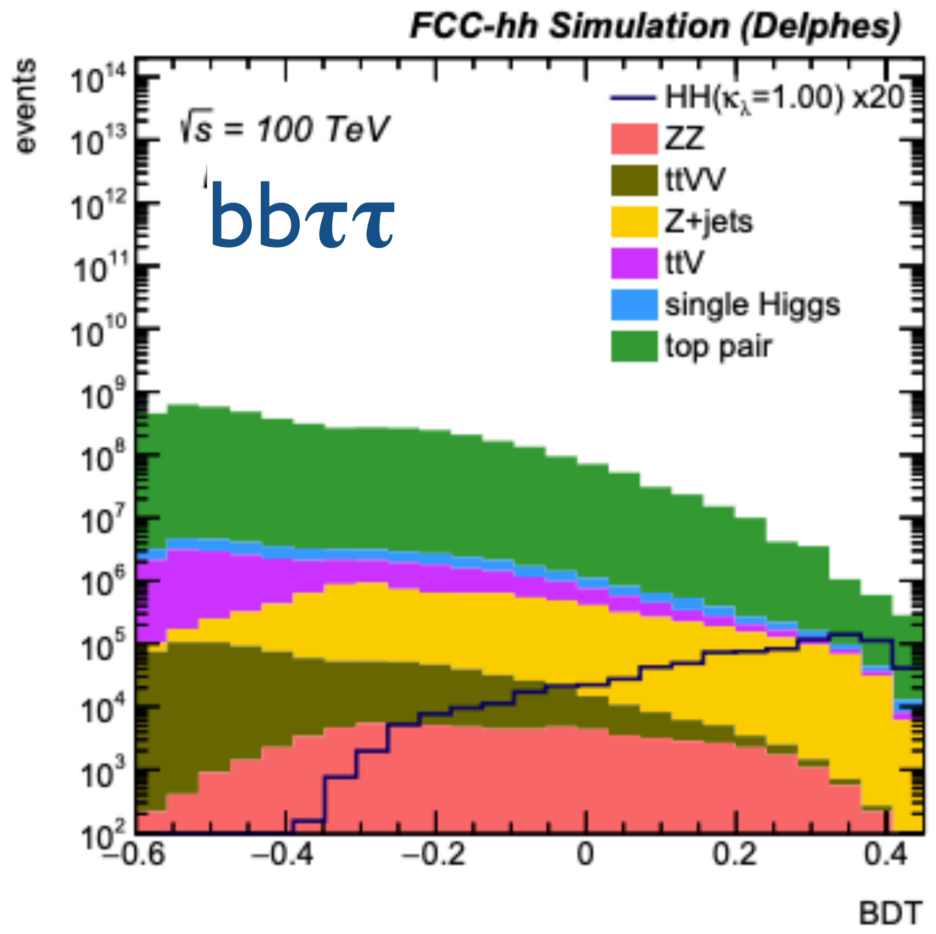
2004.03505 [hep-ph]



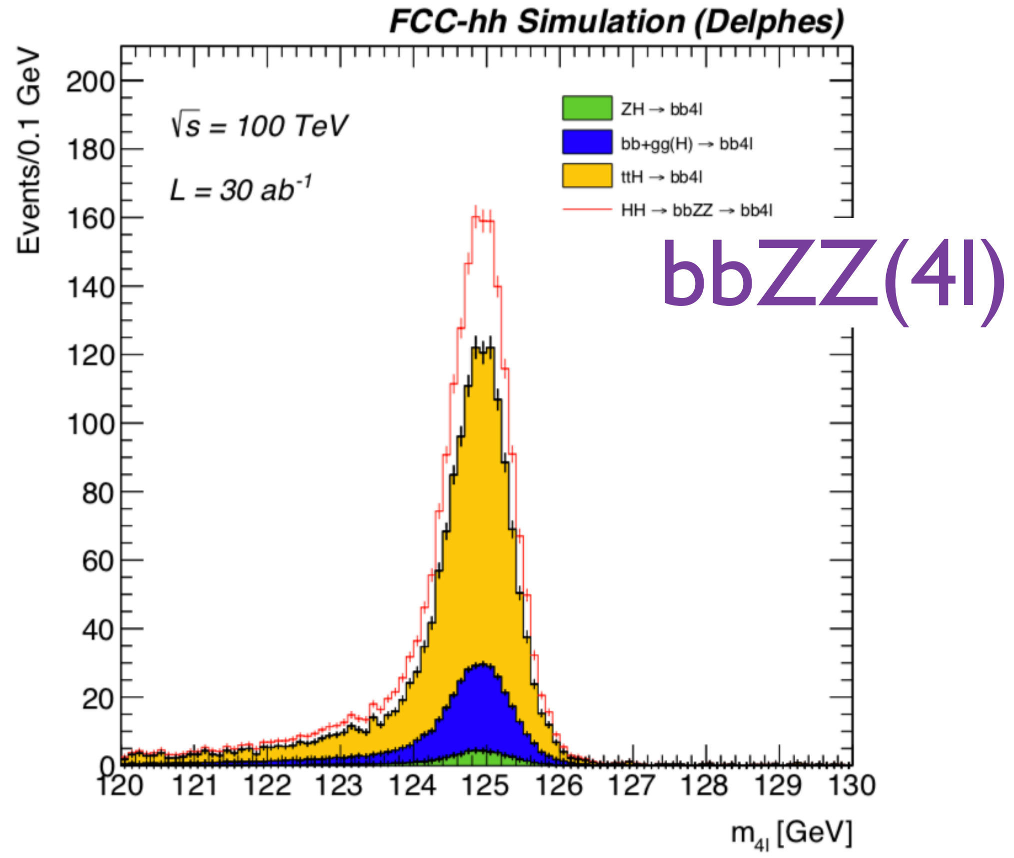
- Channels:
  - bbɣɣ (golden channel)
  - bbττ
  - bbbb
  - bbZZ(4l)



- Defined 3 scenarios with various detector assumptions and systematics:



parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\rightarrow \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20



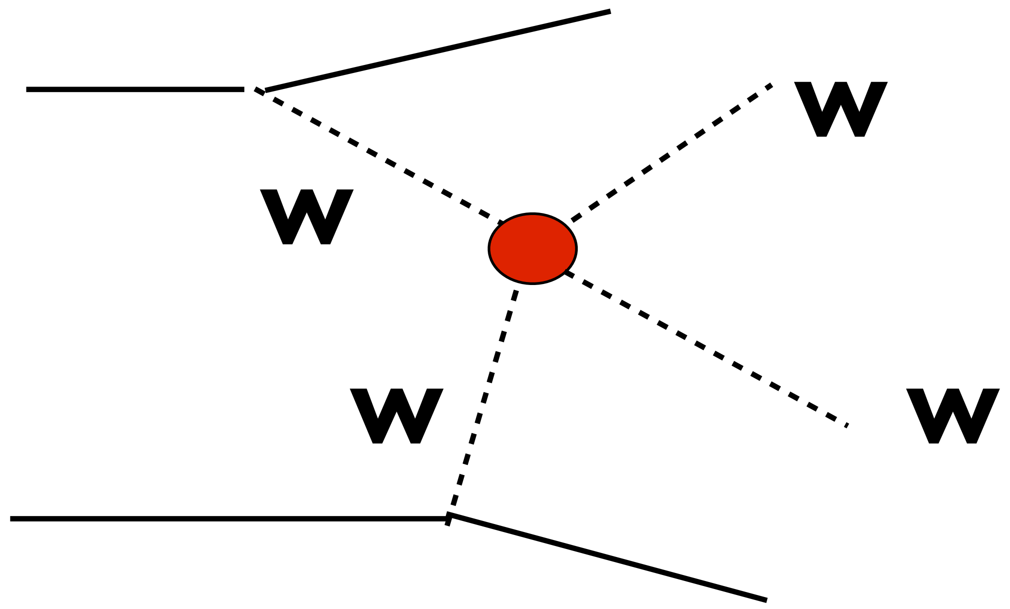
Summary of Higgs direct measurements

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

$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = B(H\to\gamma\gamma)/B(H\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = B(H\to\mu\mu)/B(H\to4\mu)$	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%

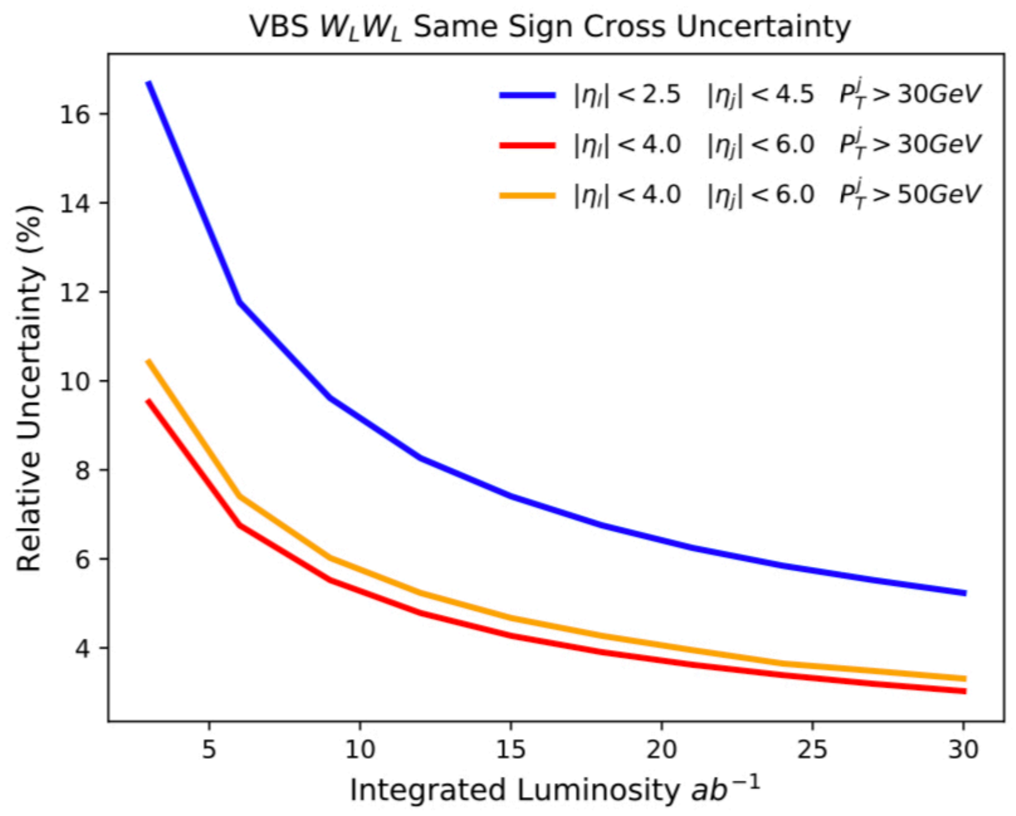
- **Percent level precision on σ x BR** in most rare decay channels achievable only at 100 TeV
- **Percent level precision on couplings** if HZZ coupling known from FCC-ee (to 0.2%)

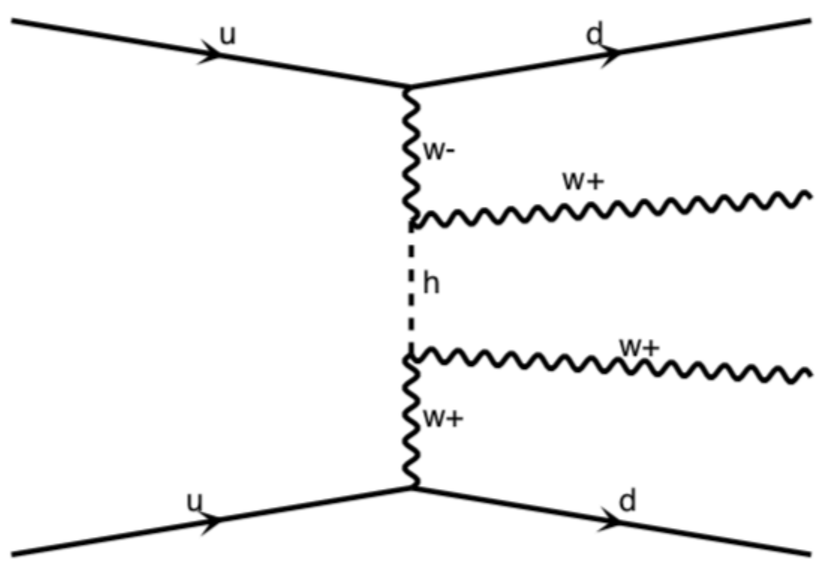
Vector Boson Scattering



large m_{WW}

- Sets constraints on **detector acceptance** (fwd jets at **$\eta \approx 4$**)
- Study **$W^{+/-}W^{+/-}$ (same-sign)** channel
- **Large WZ** background at FCC-hh
- **3-4% precision on $W_L W_L$ scattering** xsec. achievable with full dataset (only 3σ HL-LHC)
- Indirect measurement of HWW coupling possible, **$\delta\kappa_W / \kappa_W \approx 2\%$**





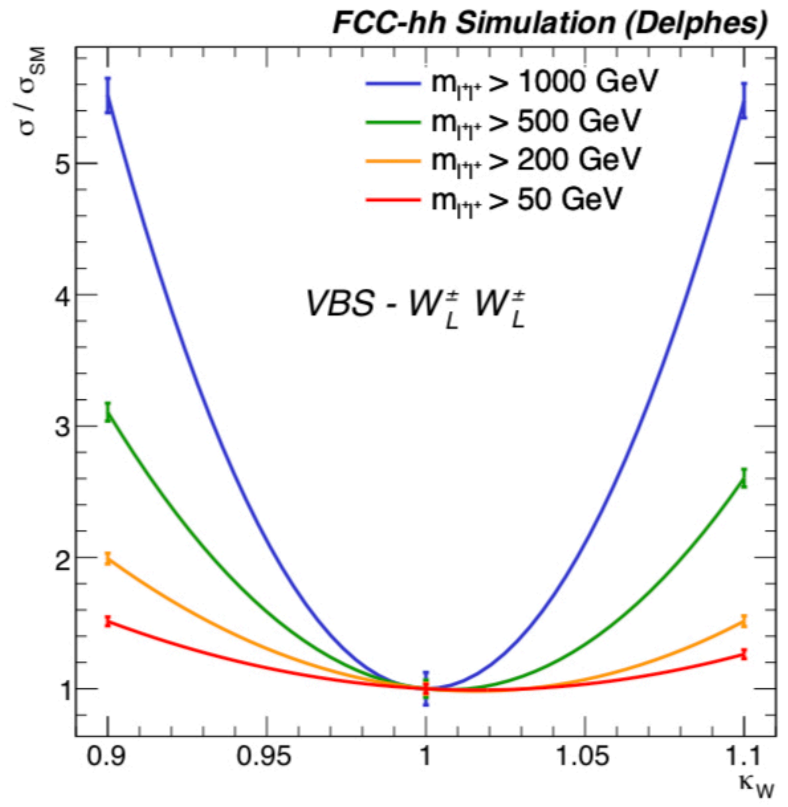
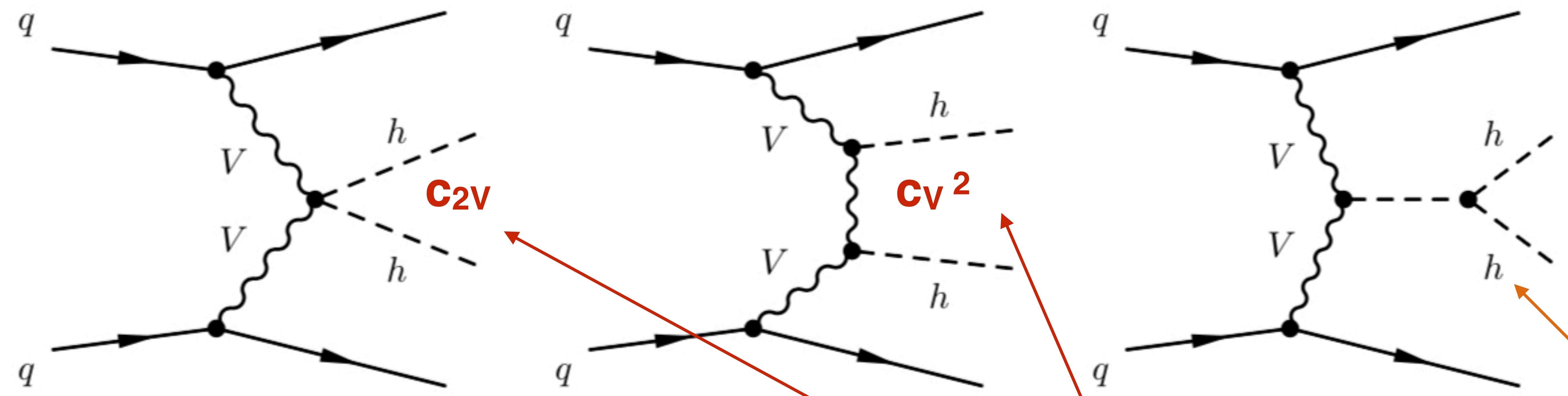


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

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

$W_L W_L \to HH$

F. Bishara, R. Contino, J. Rojo



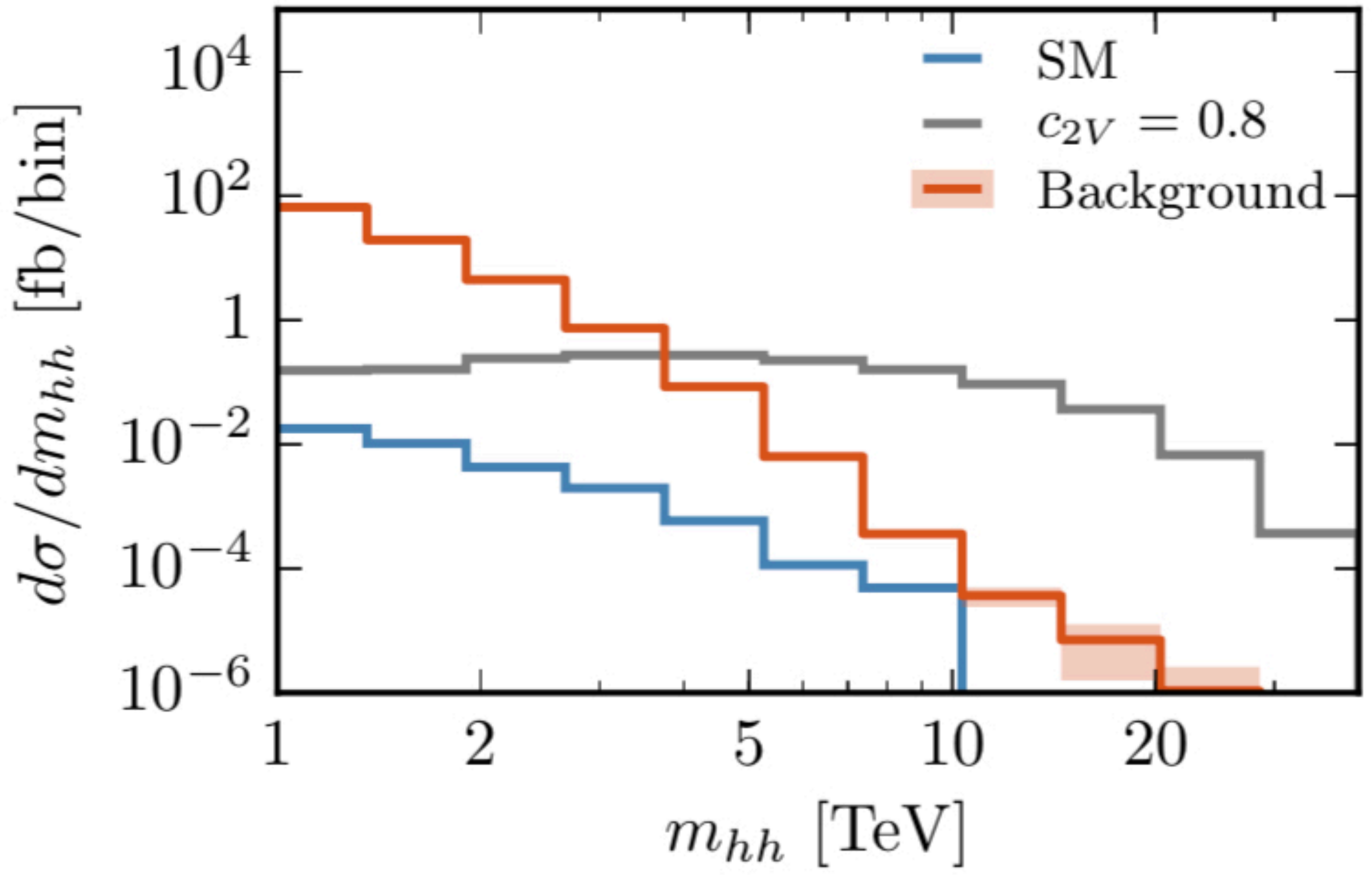
c_{2V}

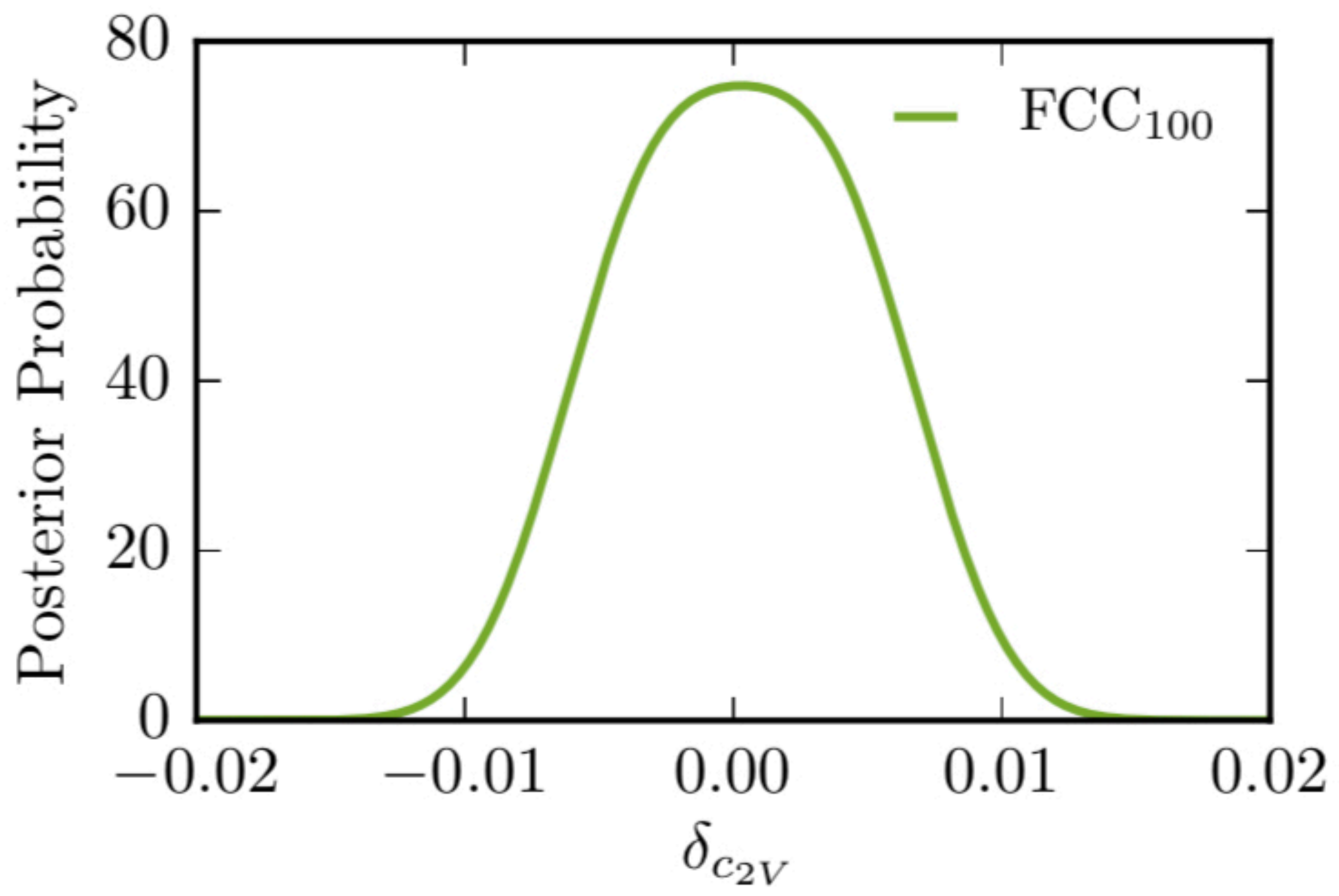
$c_V{}^2$

negligible at large m_{HH}

$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2} \underbrace{(c_{2V} - c_V^2)}_{\text{0 in the SM}} + \mathcal{O}(m_W^2/\hat{s}),$$

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E





With c_V from FCC-ee, $\delta c_{2V} < 1\%$