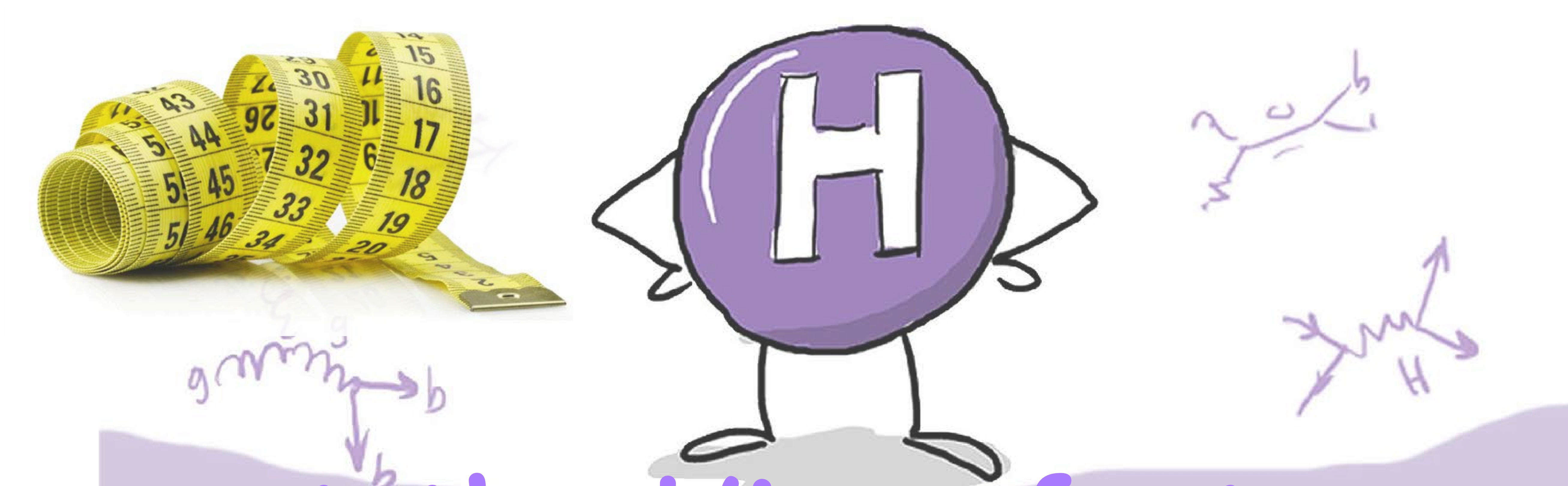
eeFACT2018
Hong Kong, 24/09/2018

THE HIGGS BOSON



at the Higgs factory

and complementarity with hadron colliders

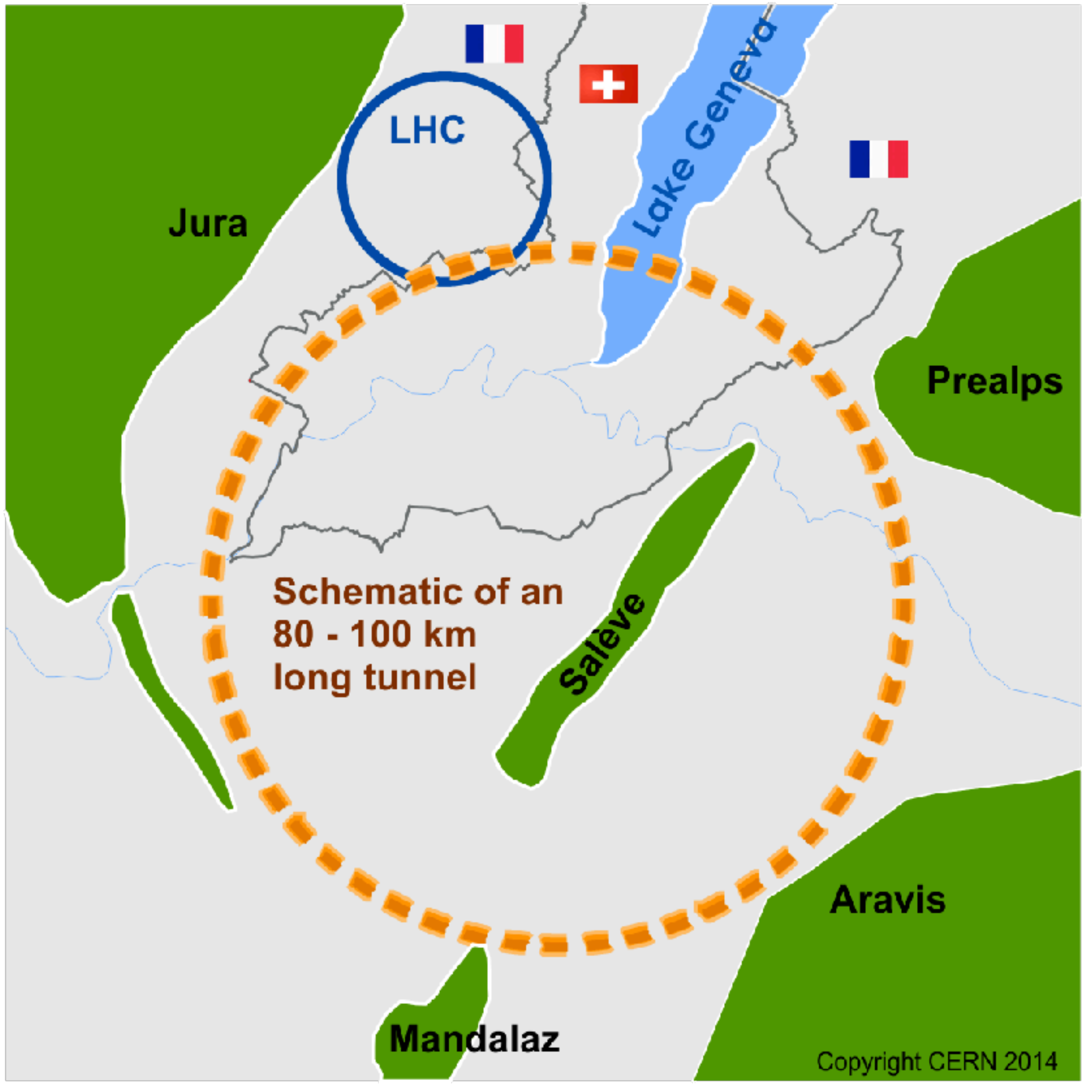
P. Giacomelli
INFN Bologna

Overview

- FCC complex and FCC-ee first stage
- CepC
- Higgs production at an e^+e^- collider
- Higgs width measurement
- Higgs couplings
- Higgs CP studies
- s-channel Higgs production
- BSM Higgs searches
- Higgs self-coupling
- Synergy with hadron colliders
- Conclusions

Acknowledgments
M. Klute and P. Janot for material and useful discussions

FCC complex



International FCC collaboration

- **pp-collider *(FCC-hh)***
  ➡ main emphasis, defining infrastructure requirements
  - **16 T $\Rightarrow$ 100 TeV pp, L~2×10^{35}, L_{int}=2 ab^{-1}/yr**
- **~100 km tunnel infrastructure**
- **e^+e^- collider *(FCC-ee)*,$\sqrt{s}$=90-365 GeV, L~10^{35}-4×10^{36}, L_{int}=1-48 ab^{-1}/yr for H, Z**
  as potential first step
- **HE-LHC** with *FCC-hh* technology
- **p-e *(FCC-he)*** option, $\sqrt{s}$=3.5 TeV, L~10^{34}

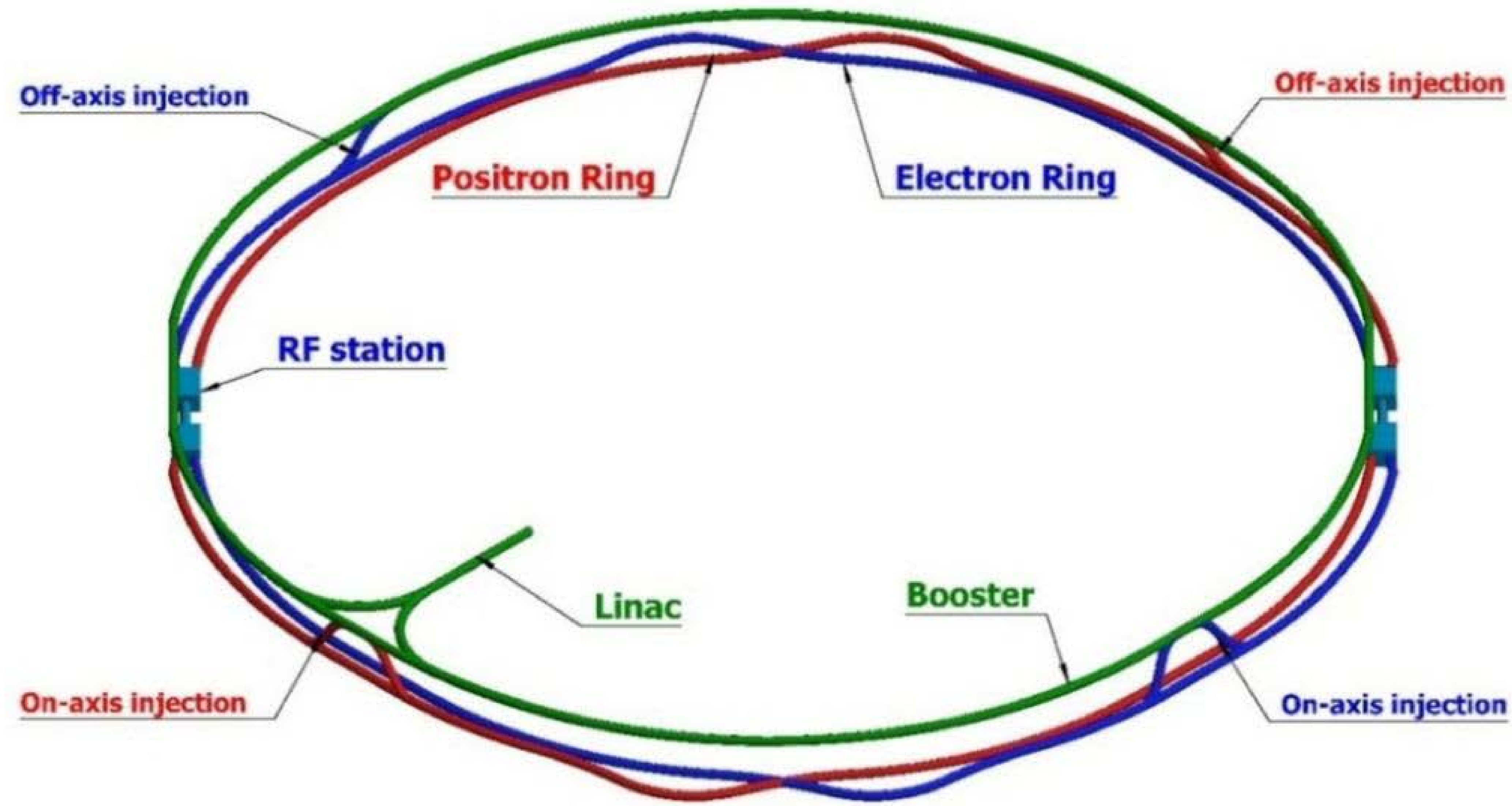
FCC-ee operation model

working point	nominal luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr half luminosity in first two years (Z) and first year (ttbar) to account for initial operation	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	10 ab^{-1}	1 - 2
H	7.0	1.7 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.34 ab^{-1}/year	1.5 ab^{-1}	4

FCC-ee parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

CepC

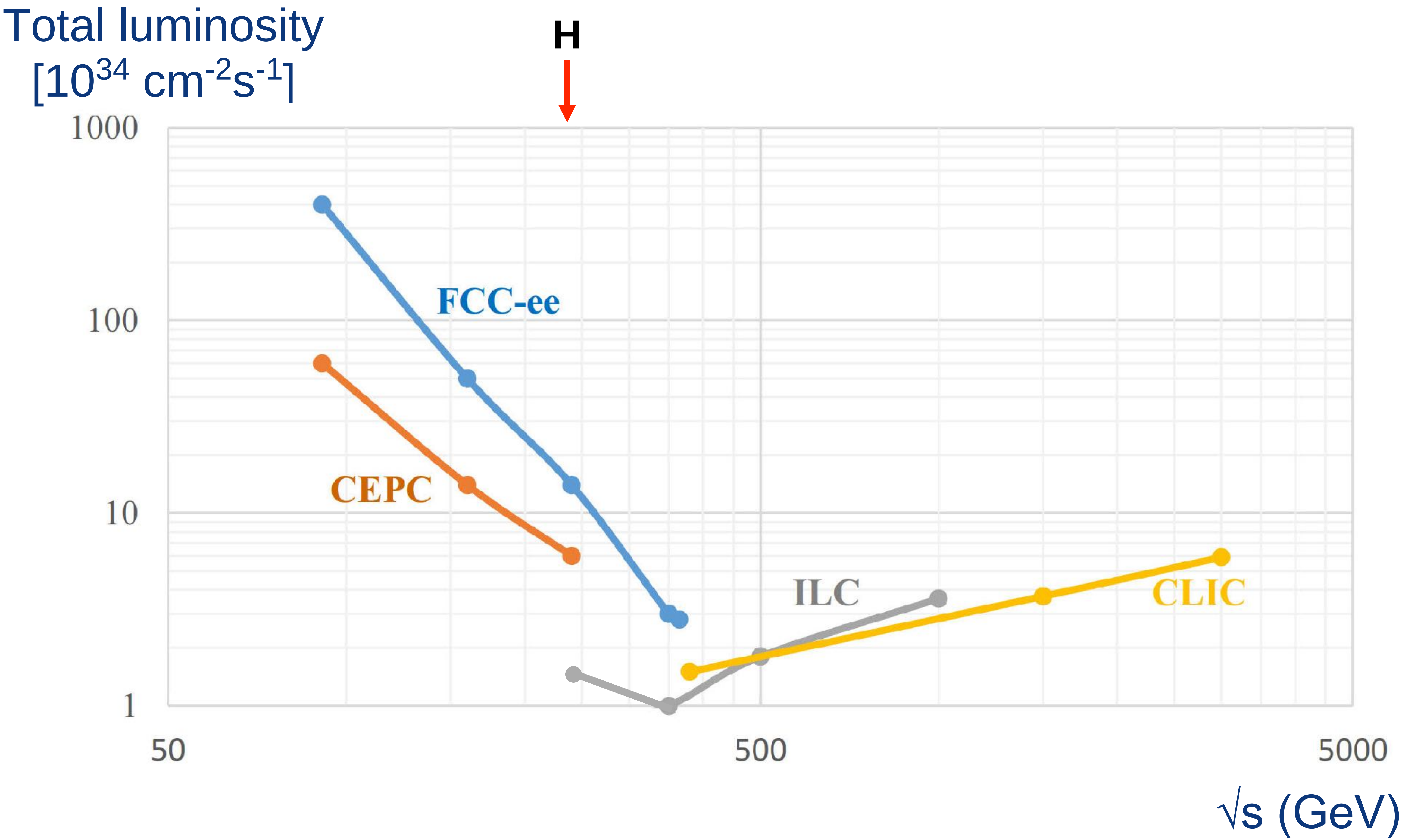


- Double ring e^+e^- collider with 2 IPs
- Compatible with the geometry of SPPC

□$\sqrt{s}$ 90-240 GeV

- L=2.93x10^{34} $cm^{-2}s^{-1}$ at $\sqrt{s}$=240 GeV

Future lepton colliders luminosities



Clear advantage in luminosity for circular colliders vs. linear colliders.

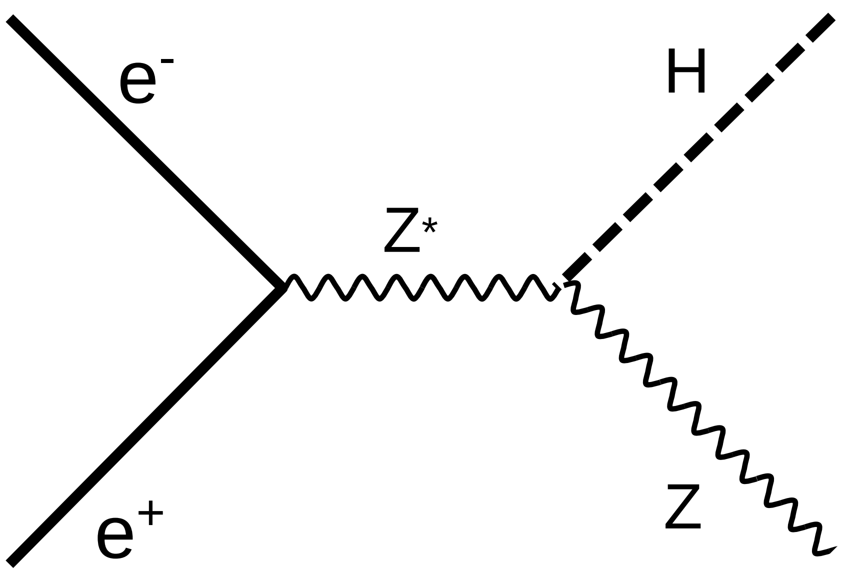
Linear colliders (esp. CLIC) have higher energy reach, but less than FCC-hh.

Higgs production at an e^+e^- collider

"Higgstrahlung" process close to threshold

Production cross section has a maximum at near threshold ~200 fb

$10^{34}/cm^2/s$ ❾ 20'000 HZ events per year.



Z – tagging
by missing mass

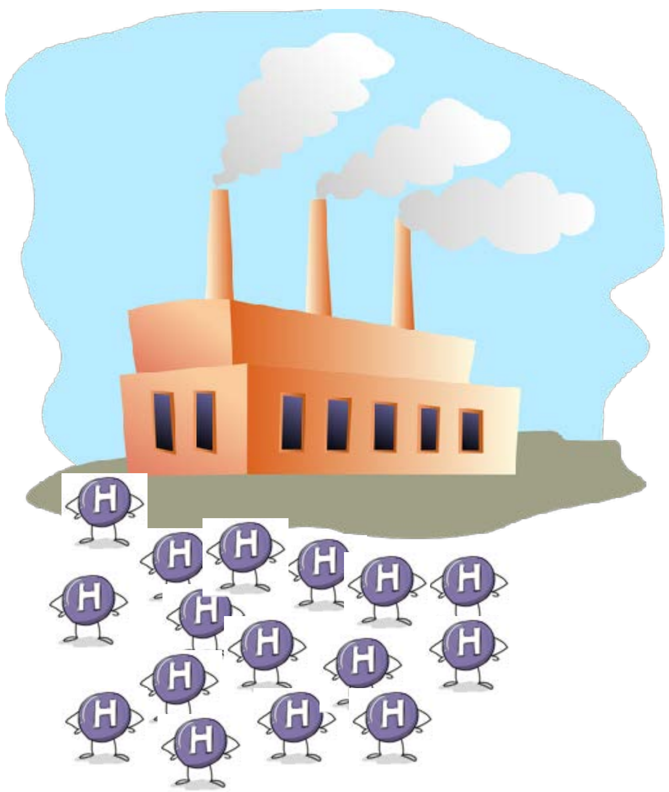
For a Higgs of 125GeV, a centre of mass energy of 240-250 GeV is optimal
❾ kinematical constraint near threshold for high precision in mass, width, selection purity

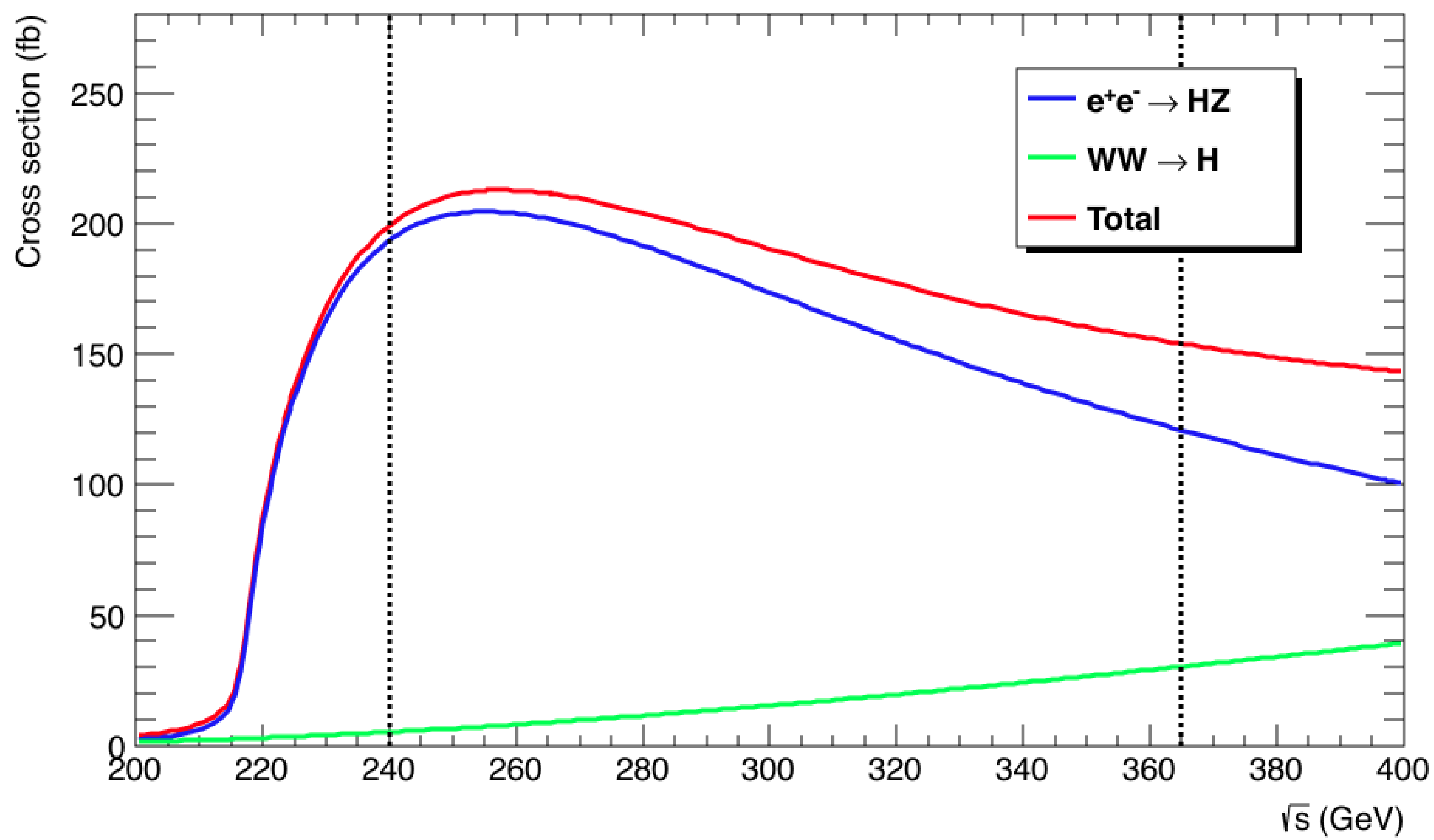
Higgs production at FCC-ee

FCC-ee

5 ab-1@240 GeV

~1.5 ab^{-1}@365 GeV





Higgs Factory!

	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab^{-1})	5	1.5
# Higgs bosons from $e^+e^- \rightarrow HZ$	1,000,000	180,000
# Higgs bosons from fusion process	25,000	45,000

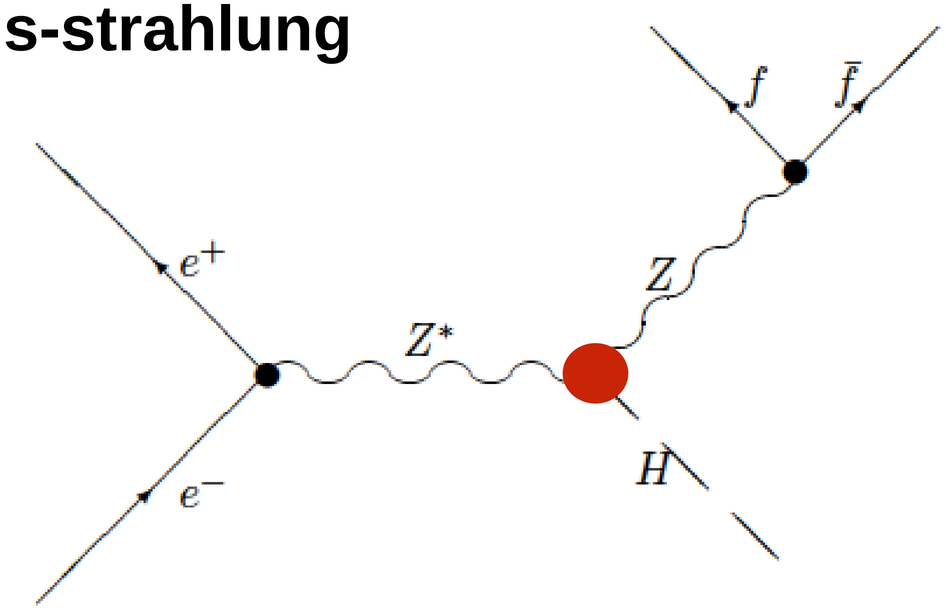
Higgs couplings to Z

➡ **Recoil method provides a unique opportunity for a decay-mode independent measurement of the HZ coupling**

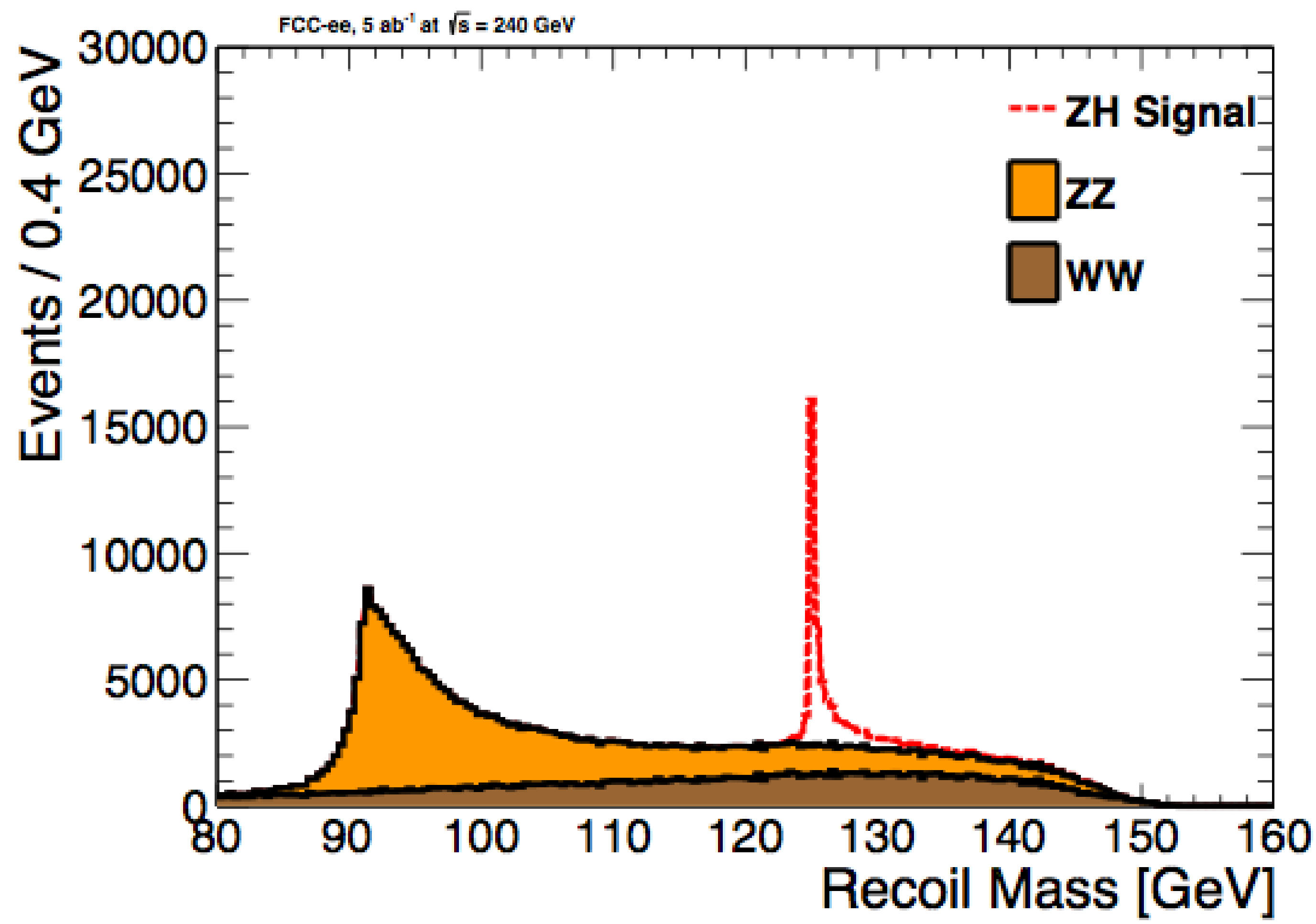
- Higgs events are tagged with the Z boson decays, independently of Higgs decay mode, $m_{recoil} = m_H$
- Expected precision **0.7%** on the ZH cross section
- Using only leptonic Z decays and only a measurement at 240 GeV so far

$$\boxed{\sigma(\mathrm{ee} \to \mathrm{ZH}) \propto \mathrm{g}^2_{\mathrm{HZ}}}$$

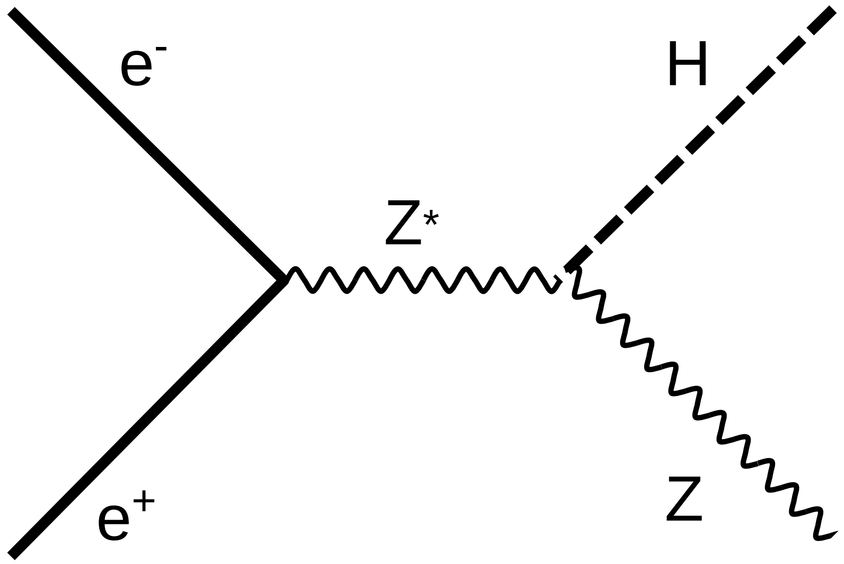
Higgs-strahlung



$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

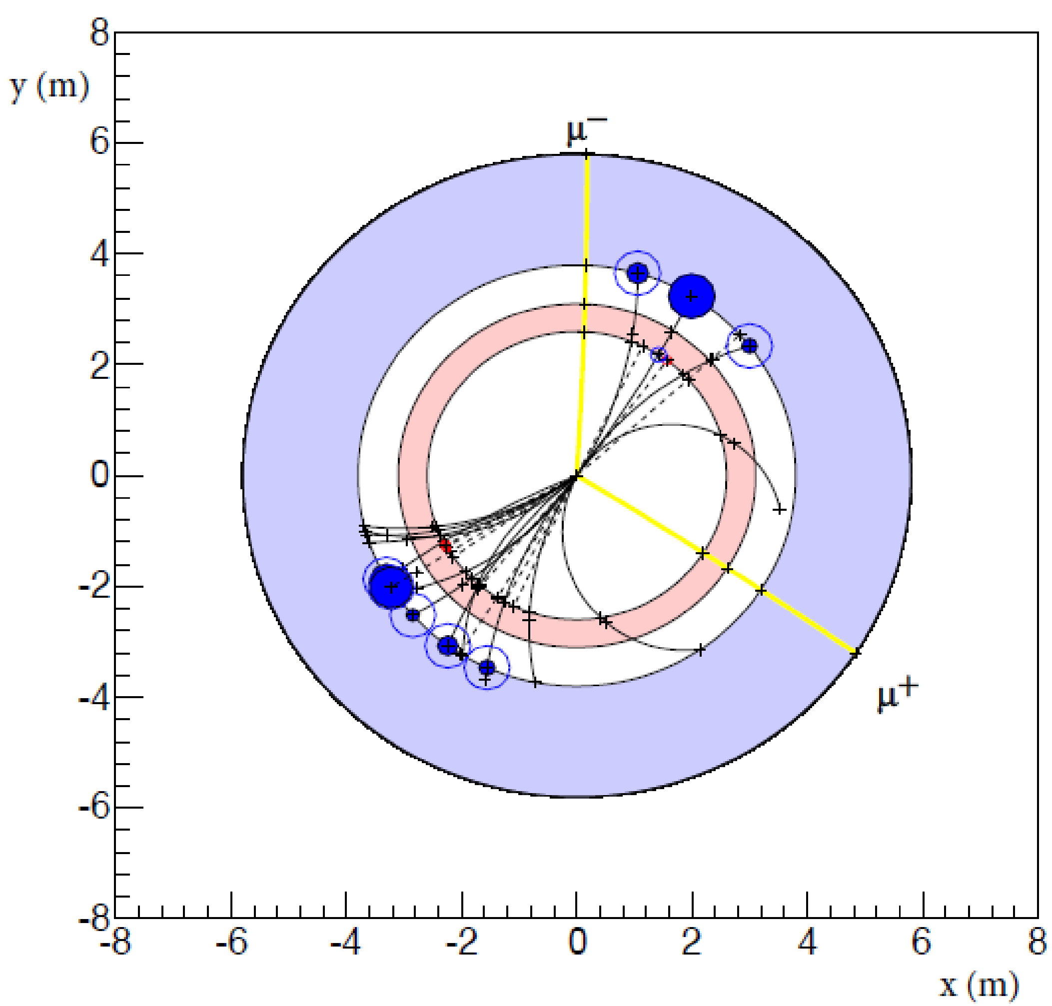


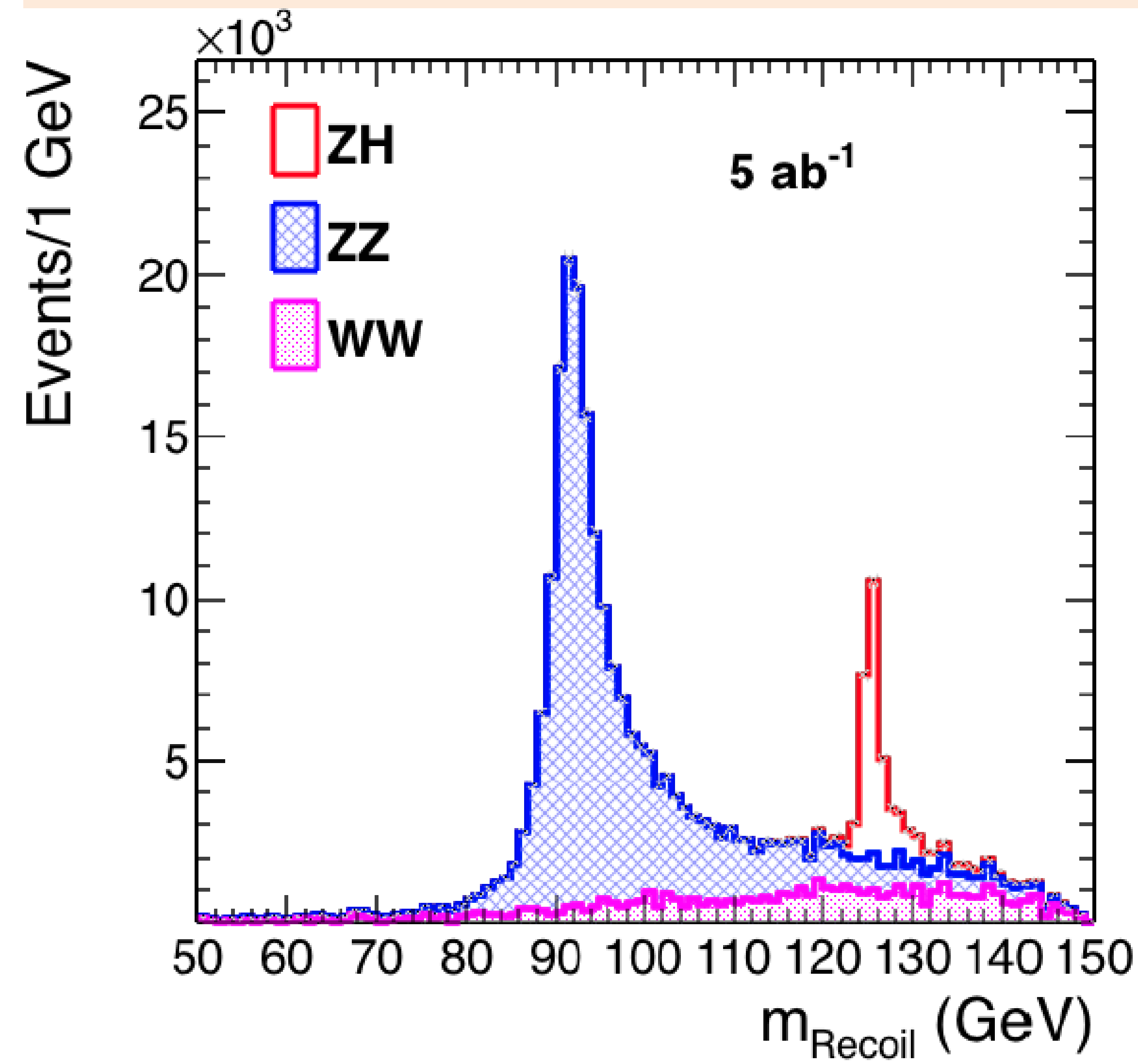
Z-tagging by missing mass



total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ **measure total width** Γ_H

g_{HZZ} to ±0.2% and many other partial widths
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below threshold





Higgs boson width

➡ **Total Higgs boson width can be extracted from a combination of measurements in a model independent way**

- **1) tagging Higgs final states**

$$\sigma(\mathrm{ee} \to \mathrm{ZH}) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$

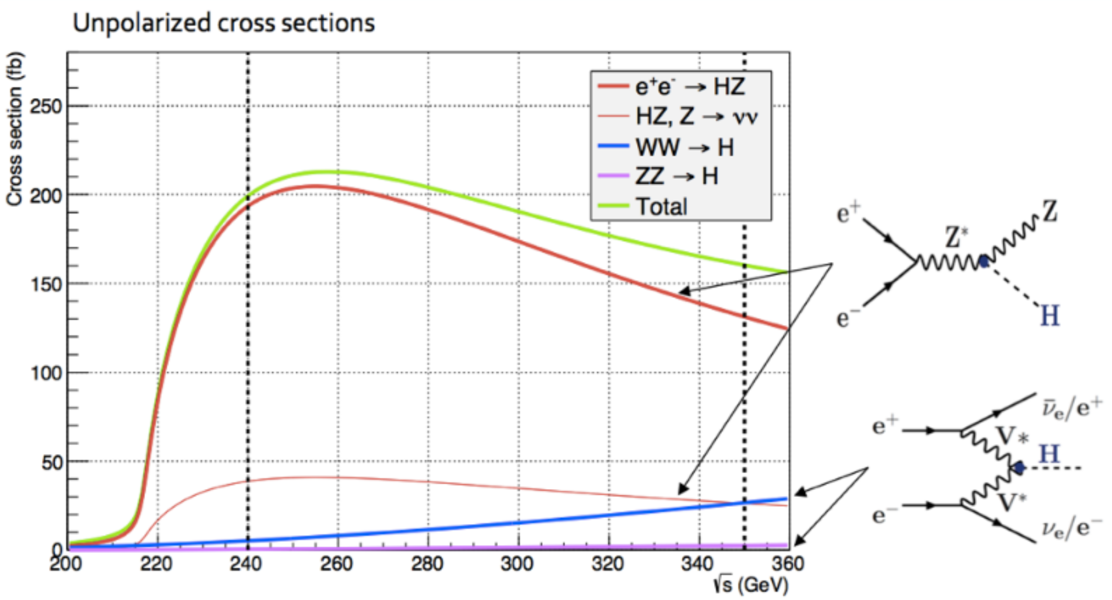
- **2) measurements of vector boson fusion production at 365 GeV**

$$\frac{\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{WW})\cdot\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}{\sigma(\mathrm{ee}\to\nu\nu\mathrm{H})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}$$

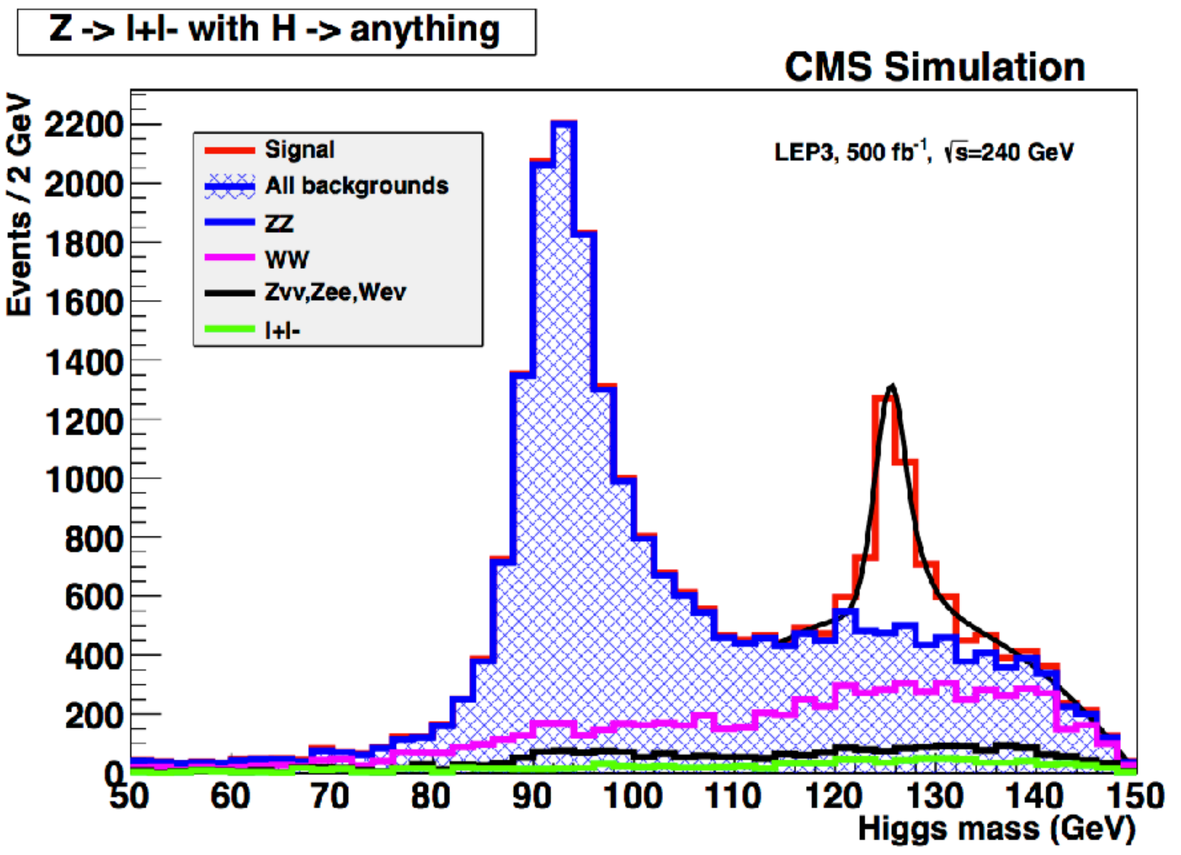
$$\propto \frac{g^2_{\mathrm{HZ}}\cdot \cancel{g^2_{\mathrm{HW}}}}{\Gamma} \cdot \frac{g^2_{\mathrm{HZ}}\cdot \cancel{g^2_{\mathrm{Hb}}}}{\cancel{\Gamma}} \cdot \frac{\cancel{\Gamma}}{\cancel{g^2_{\mathrm{HW}}}\cdot \cancel{g^2_{\mathrm{Hb}}}} = \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$

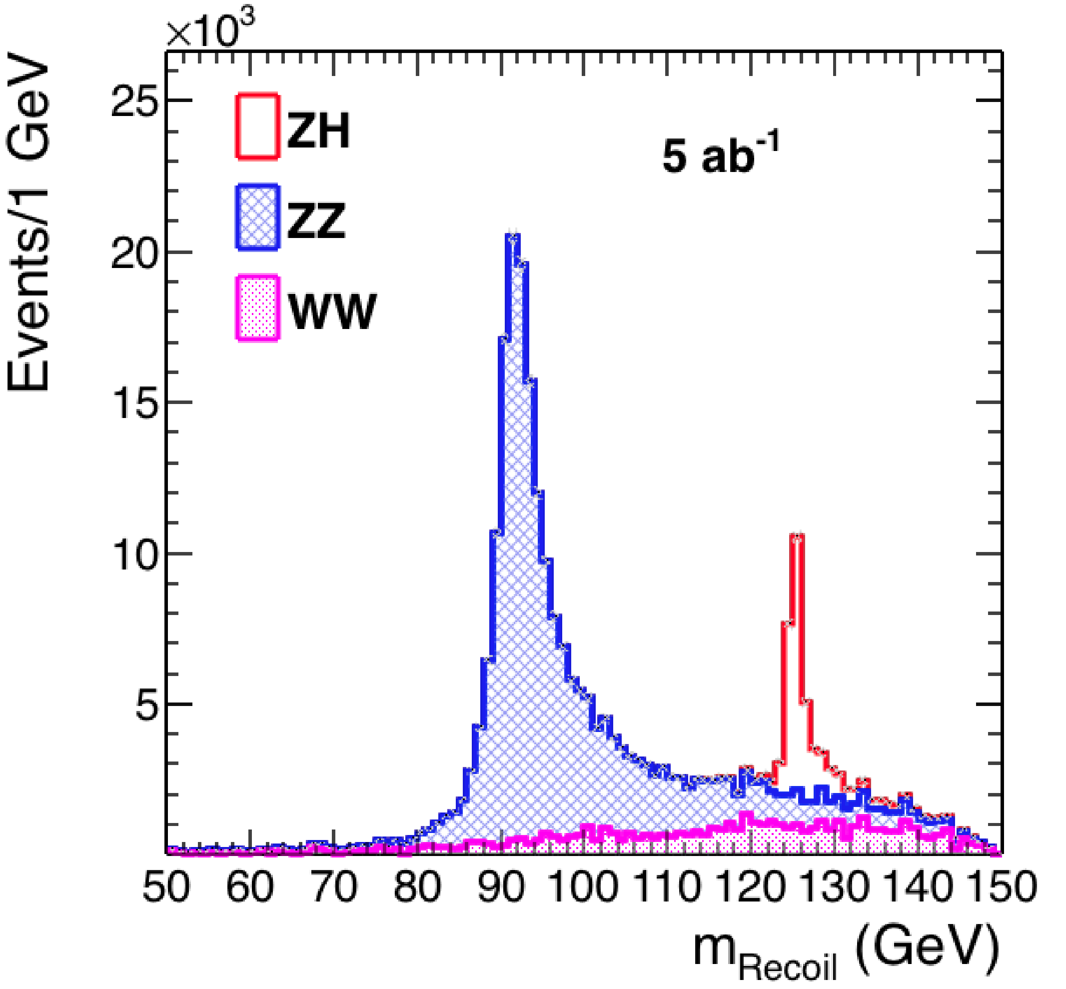
- **3) combination of all measurements**

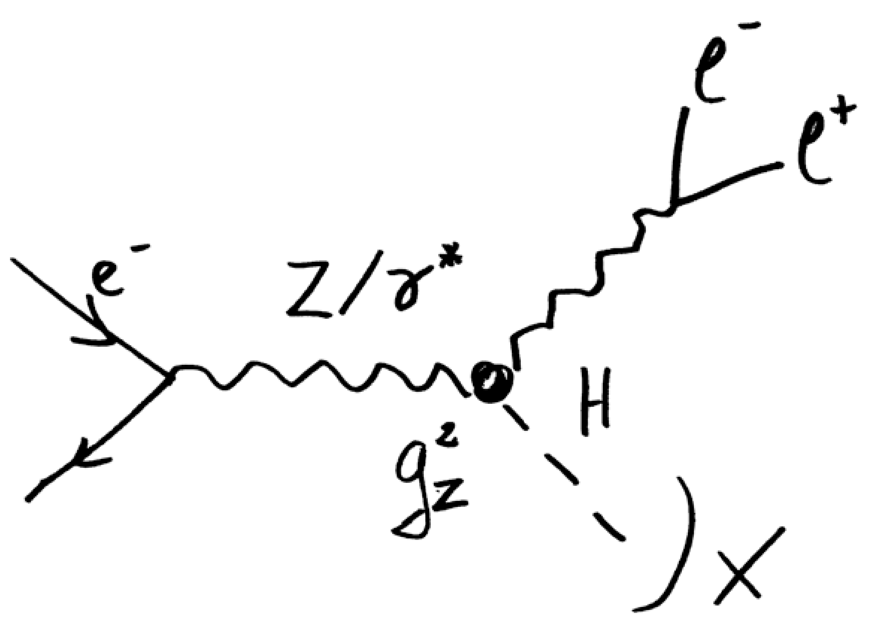
Precision obtainable on $\delta\Gamma_H/\Gamma_H$ ~ 1.6%



Higgs boson couplings, ZH→ℓℓX





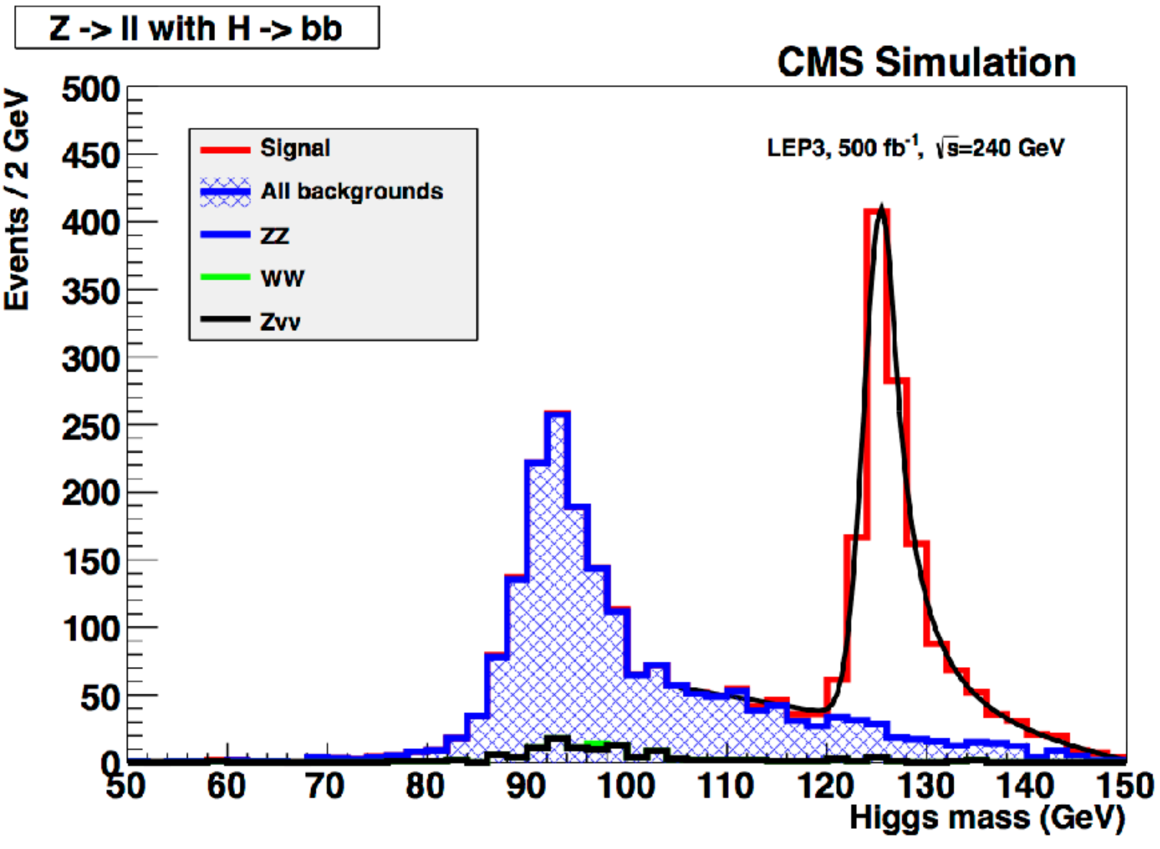


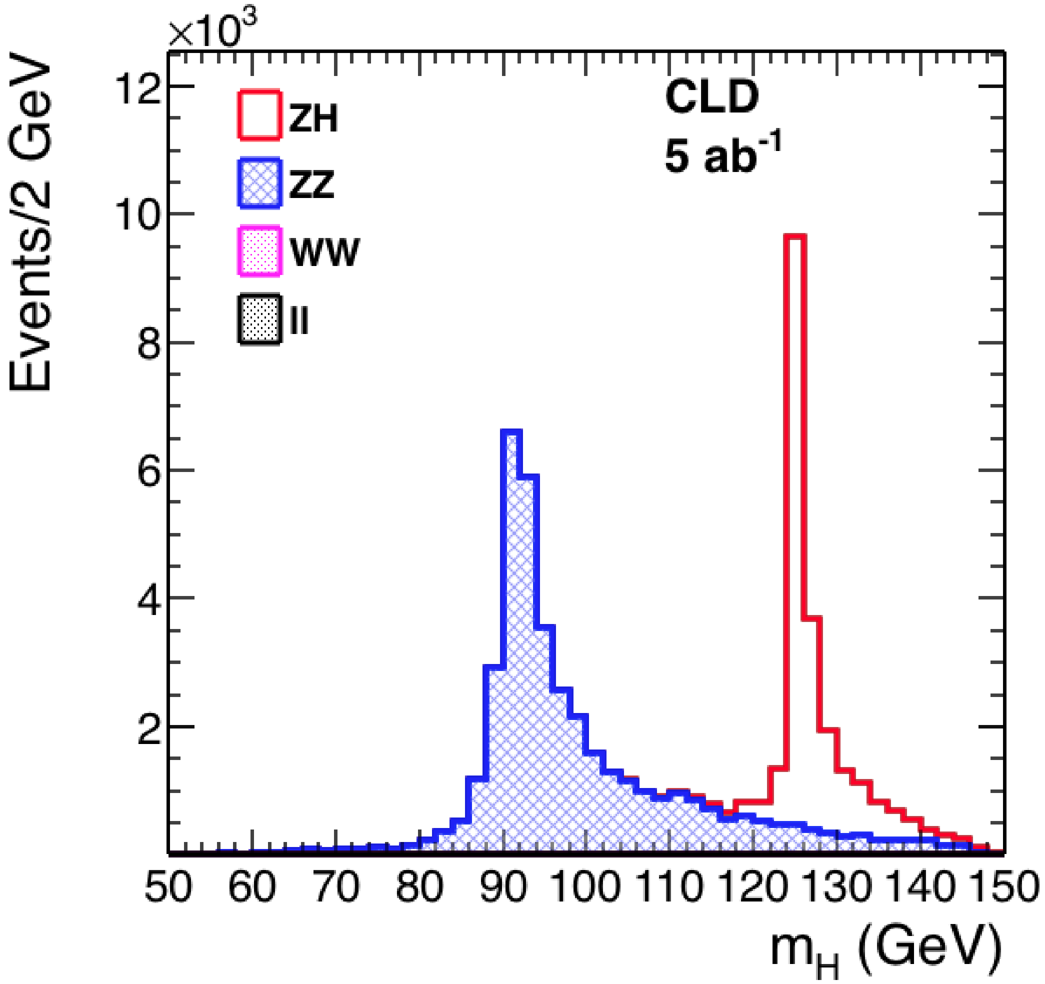
C. Bernet
FCC week 2018

Ongoing work, should lead to better results in TDR

CLD: 15% improvement due to higher lepton efficiency

Higgs boson couplings, ZH→ℓℓbb





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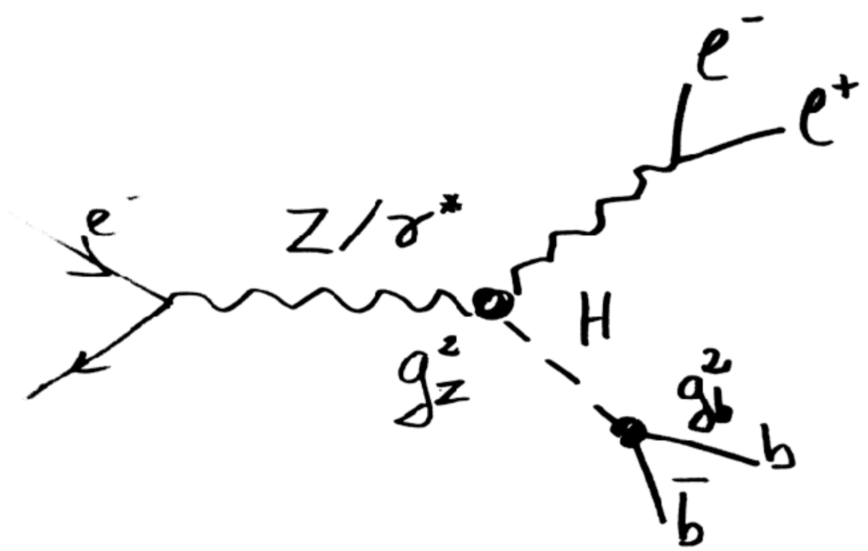
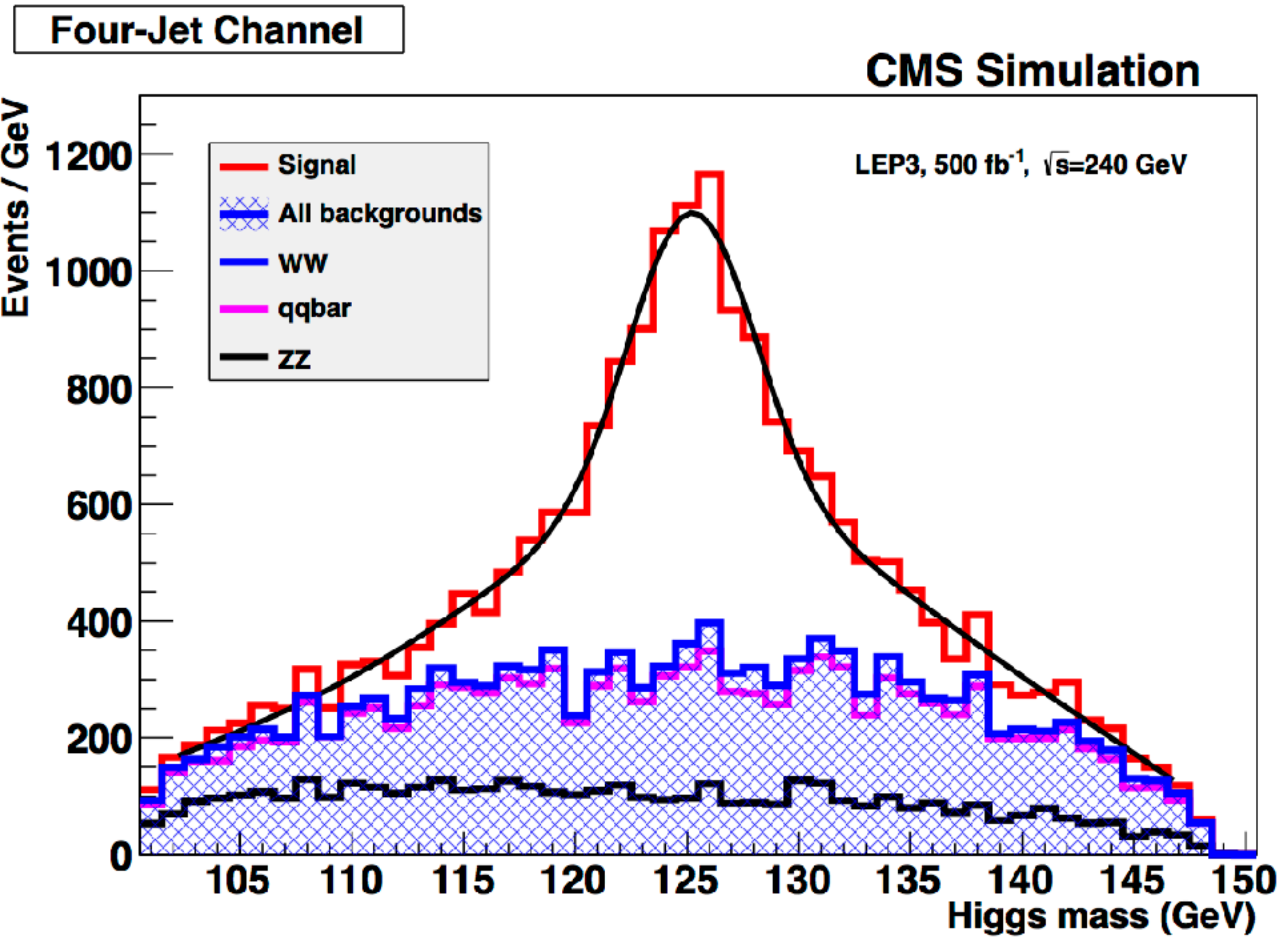
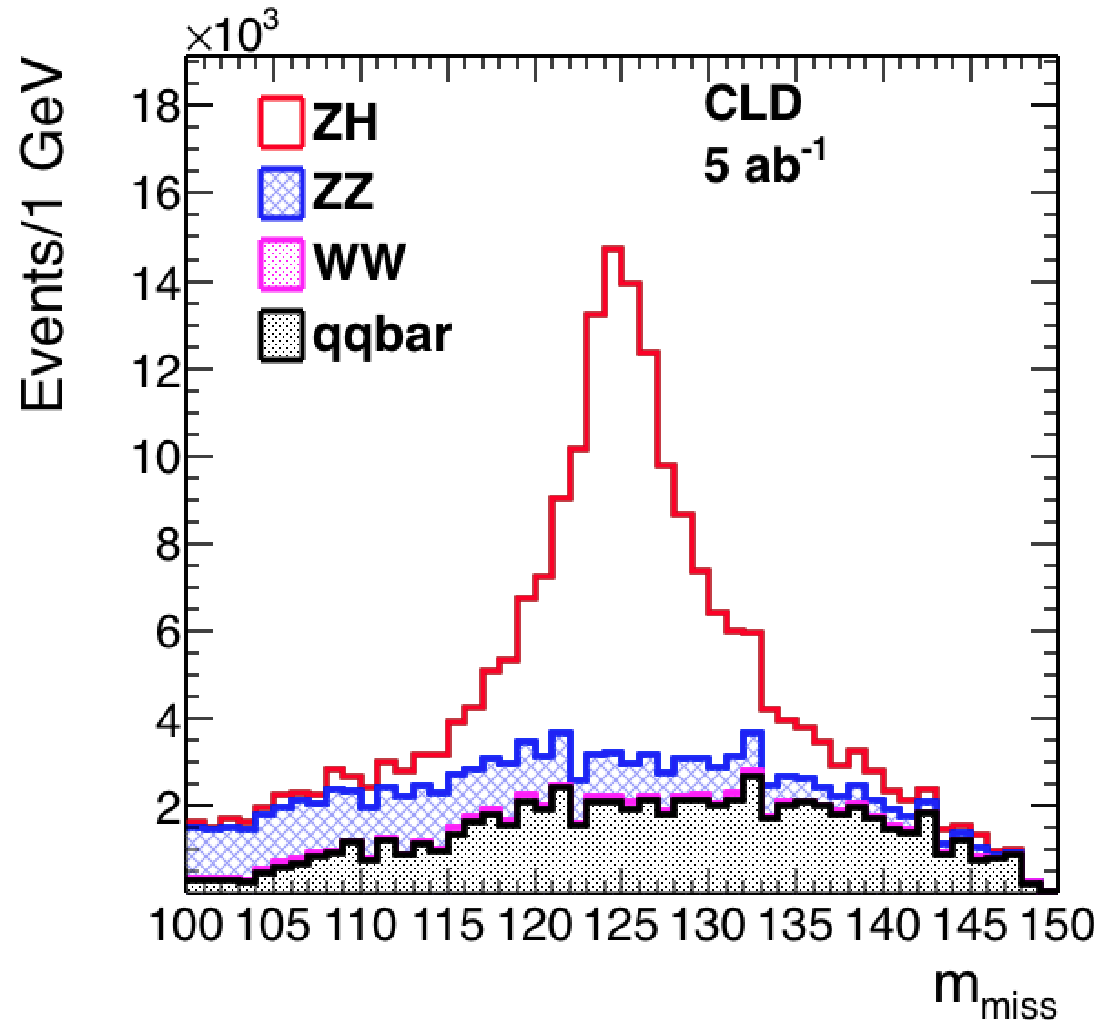


Ongoing work, should lead to better results in TDR

CLD: 20% improvement due to higher lepton efficiency and better b tagging

Higgs boson couplings, ZH→qqbb





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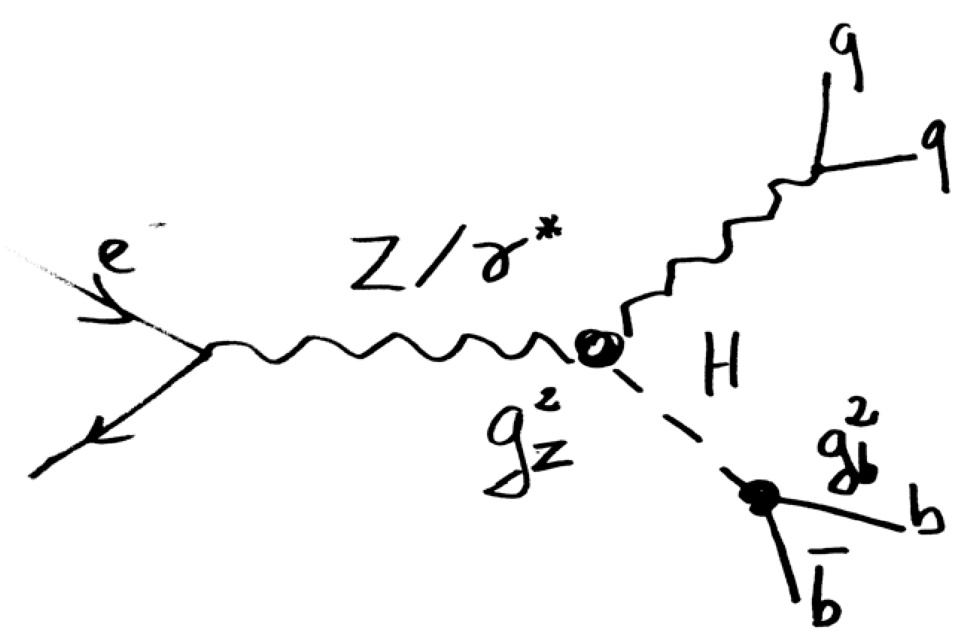


Ongoing work, should lead to better results in TDR

CLD: 35% improvement due to better b tagging and particle flow

Higgs boson couplings

➡ **Precision Higgs coupling measurements**

- Absolute coupling measurements enabled by HZ cross section and total width measurement
- Data at 365 GeV constrain total width
  - only used $H \to bb$ in fusion production so far
- Tagging individual Higgs final states to extract various Higgs couplings
- Couplings extracted from model-independent fit
- Statistical uncertainties are shown for 5 ab^{-1}@240 GeV and 1.5 ab^{-1}@365 GeV (from arXiv:1308.6176)
  - all measurements are under review / are being redone
  - possible improvements of 10-35% on cross section measurements

in %	FCC-ee 240 GeV	+FCC-ee 365 GeV	+HL-LHC
δg_{HZZ}	0.25	0.22	0.21
δg_{HWW}	1.3	0.47	0.44
δg_{Hbb}	1.4	0.68	0.58
δg_{Hcc}	1.8	1.23	1.20
δg_{Hgg}	1.7	1.03	0.83
$\delta g_{H\tau\tau}$	1.4	0.8	0.71
$\delta g_{H\mu\mu}$	9.6	8.6	3.4
$\delta g_{H\gamma\gamma}$	4.7	3.8	1.3
δg_{Htt}			3.3
$\delta \Gamma_H$	2.8	1.56	1.3

Several couplings improve further by doing a combined fit with HL-LHC

Comparison with other e^+e^- colliders

Collider	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	7	6	7	3	[illegible]
Lumi (ab^{-1})	0.005	2	0.5	3	5	[illegible]	1.5
δm_H (MeV)	0.1	14	110	10	[illegible]	7	6
$\delta\Gamma_H / \Gamma_H$ (%)	6.1	3.8	6.3	[illegible]	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	[illegible]	1.8	1.3	1.4	0.68
$\delta g_{HW} / g_{HW}$ (%)	3.9	[illegible]	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$ (%)	[illegible]	1.9	4.2	1.9	1.4	1.4	0.80
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	3.8
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2

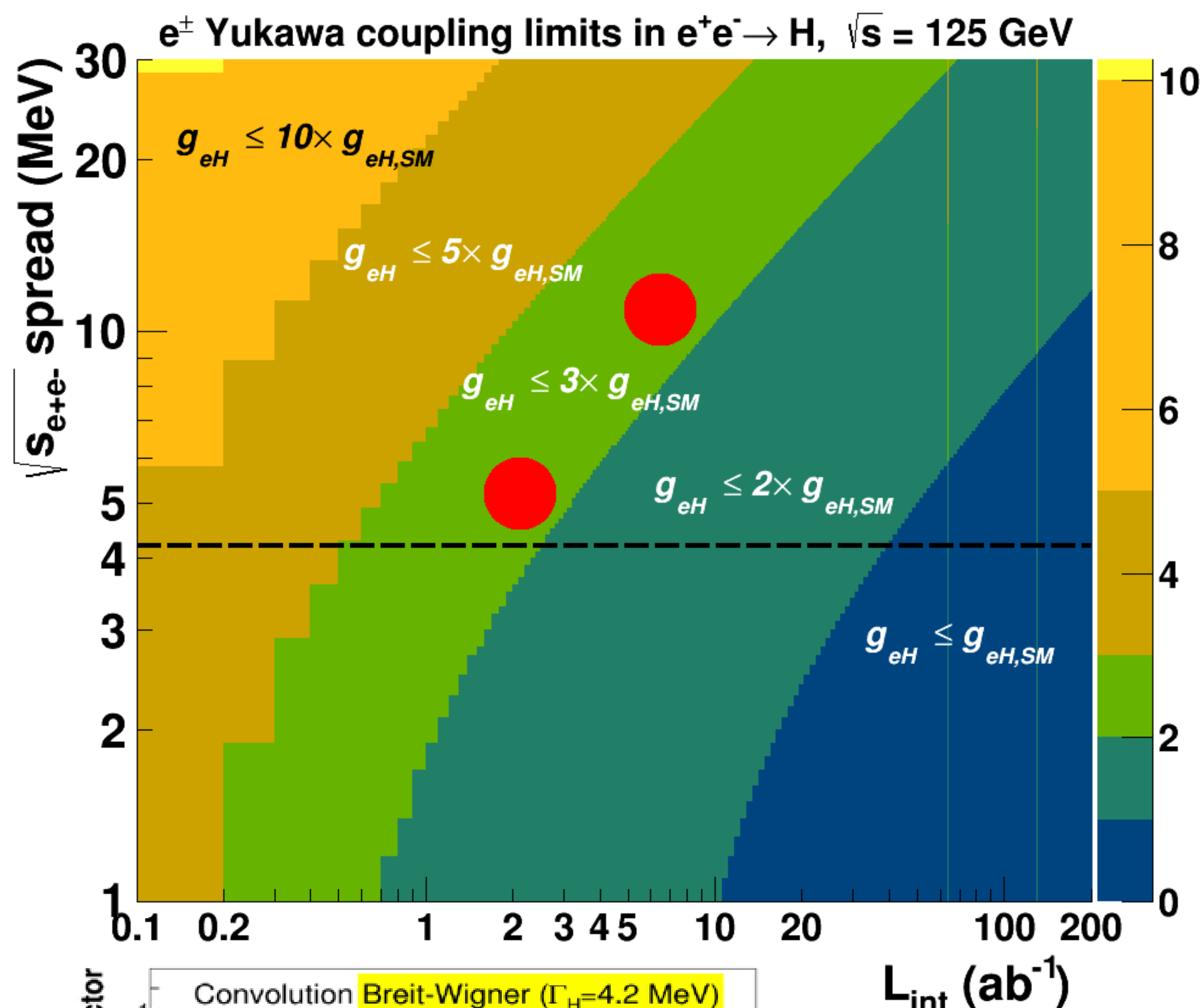
FCC-ee and CepC have a clear edge over linear colliders

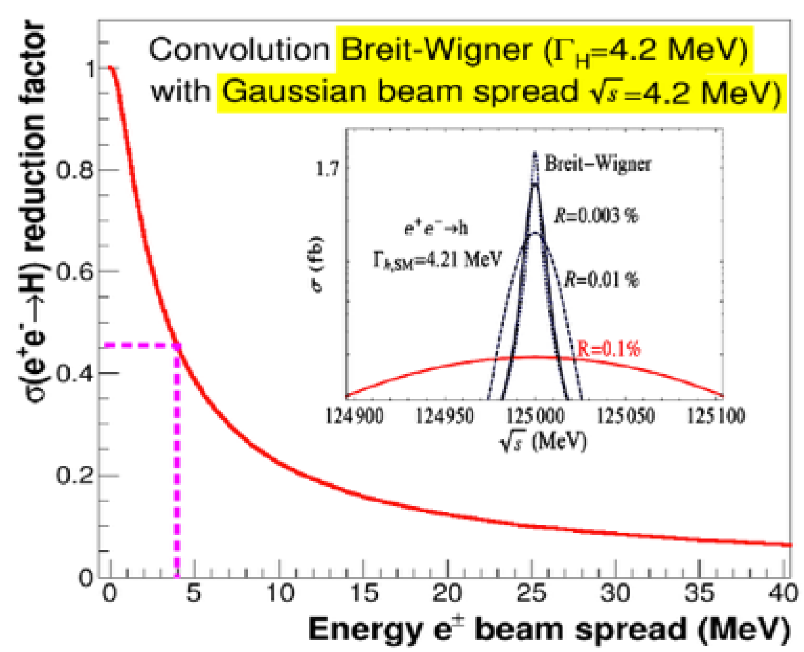
Green = best
Red = worst

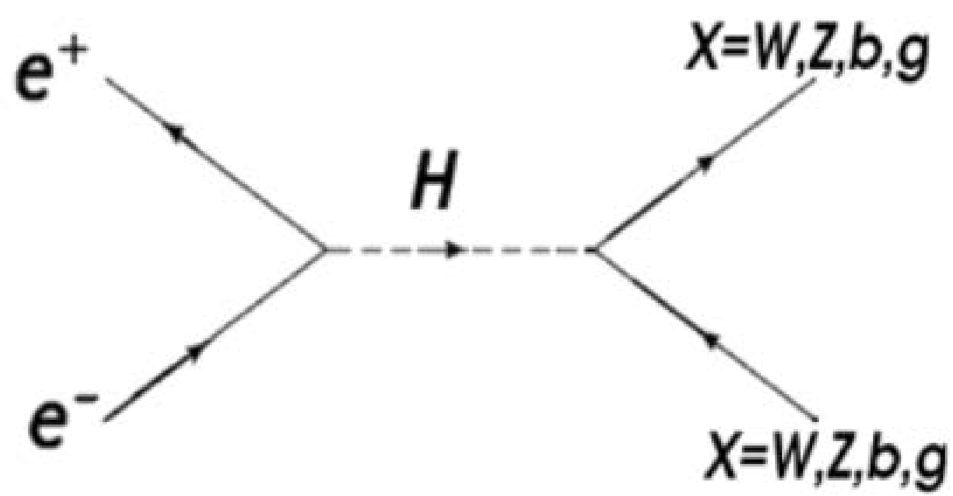
electron Yukawa coupling

➡**s-channel Higgs production**

- unique opportunity for measurement close to SM sensitivity
- highly challenging; σ(ee→H) = 1.6 fb;
- various Higgs decay channels studied
- studied monochromatization scenarios
  - baseline: 6 MeV energy spread, L = 2 ab^{-1}
  - optimized: 10 MeV energy spread, L = 7 ab^{-1}
  - limit ~3.5 times SM in both cases

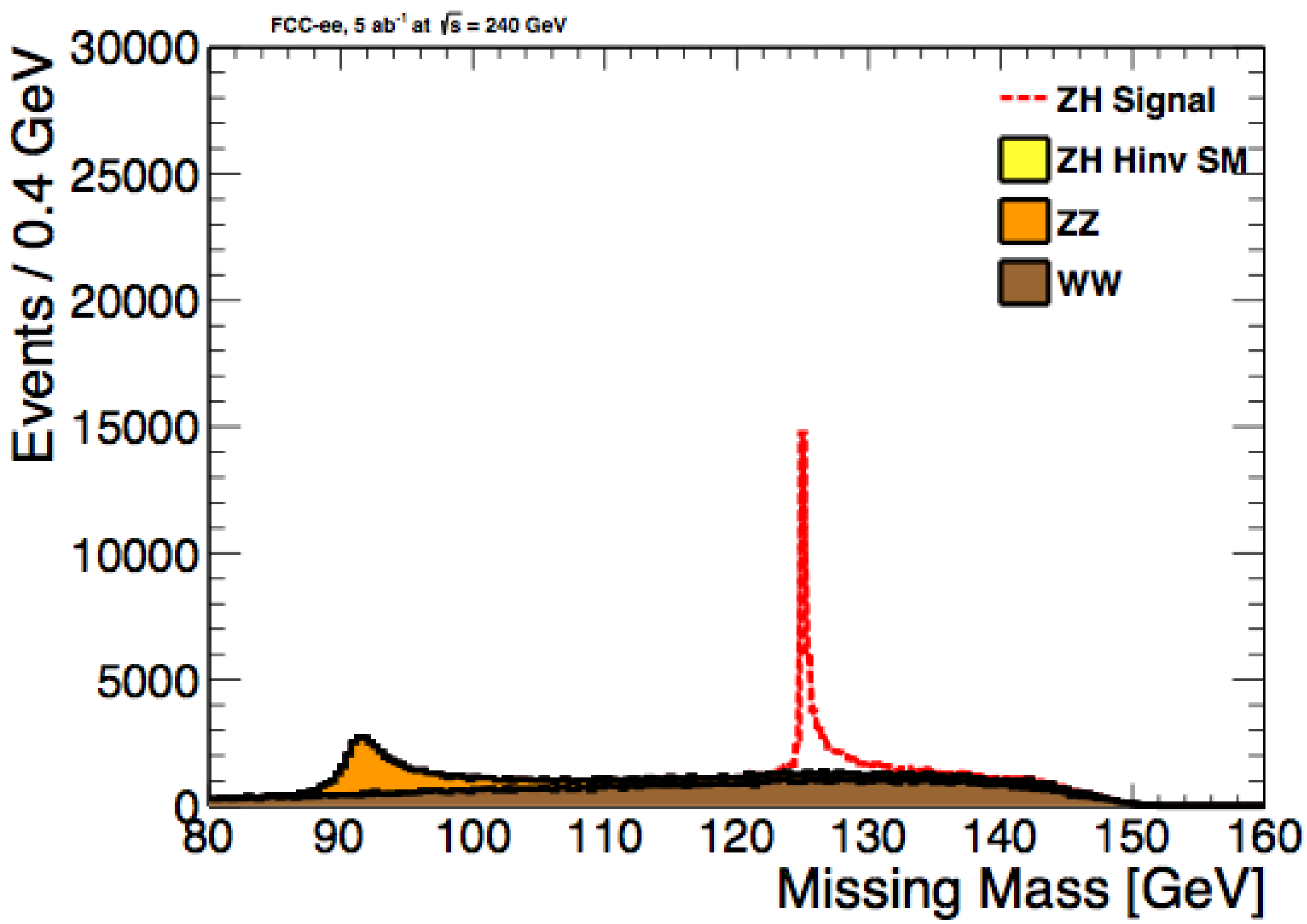






Higgs invisible decays

Higgs boson to invisible decays are predicted for instance in the Higgs-portal model of Dark Matter.

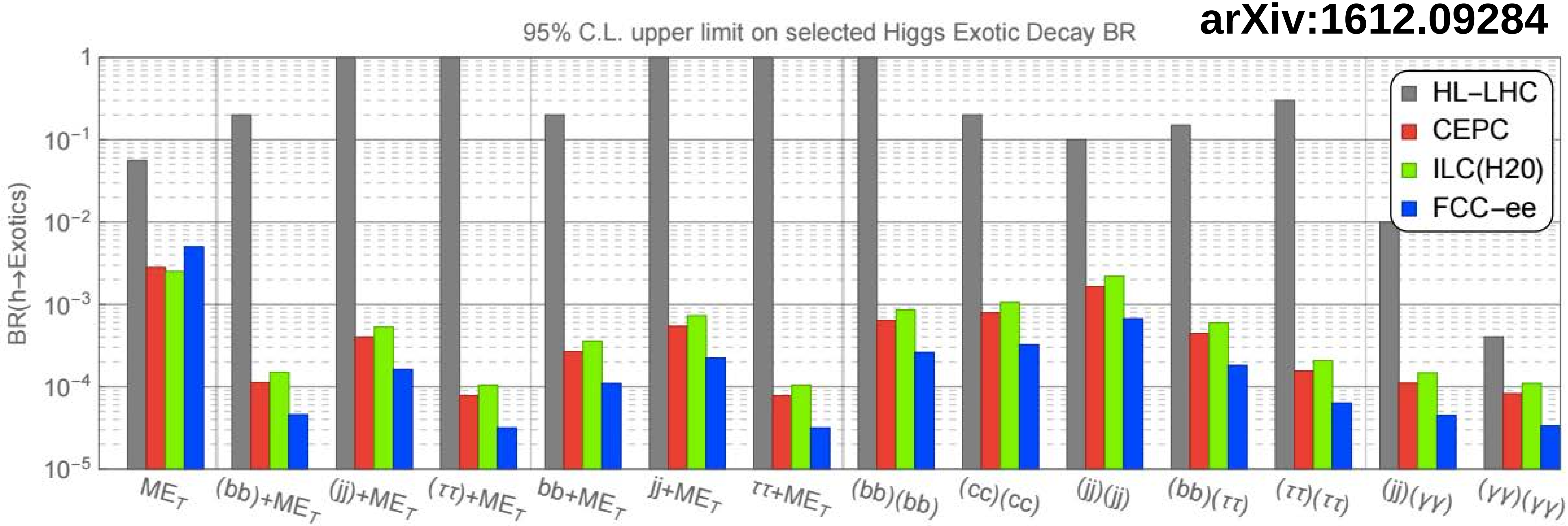


- Follows FCC-ee ZH cross section measurement
- for visualization BR(H->inv) = 100%
- 95%CL upper limit using $5ab^{-1}$ is 0.47%
- Study using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
- Hadronic Z decays under study. Show similar performance

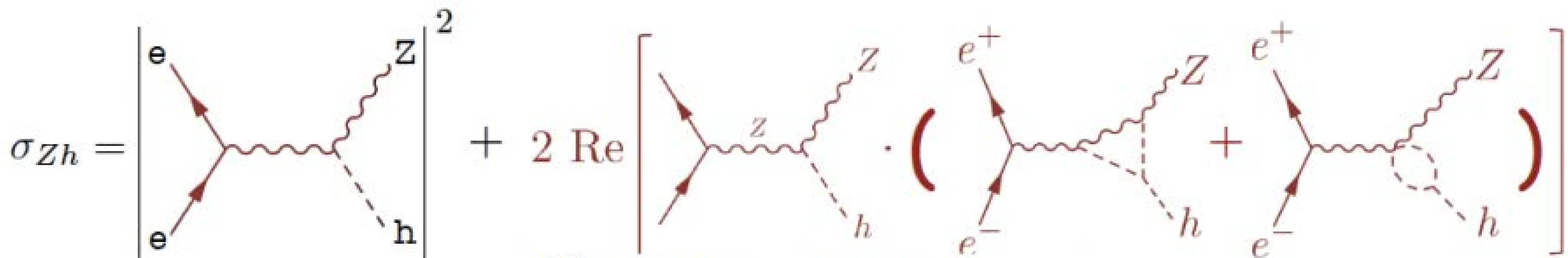
BSM Higgs

➡**Excellent opportunities for BSM Higgs searches**

arXiv:1612.09284



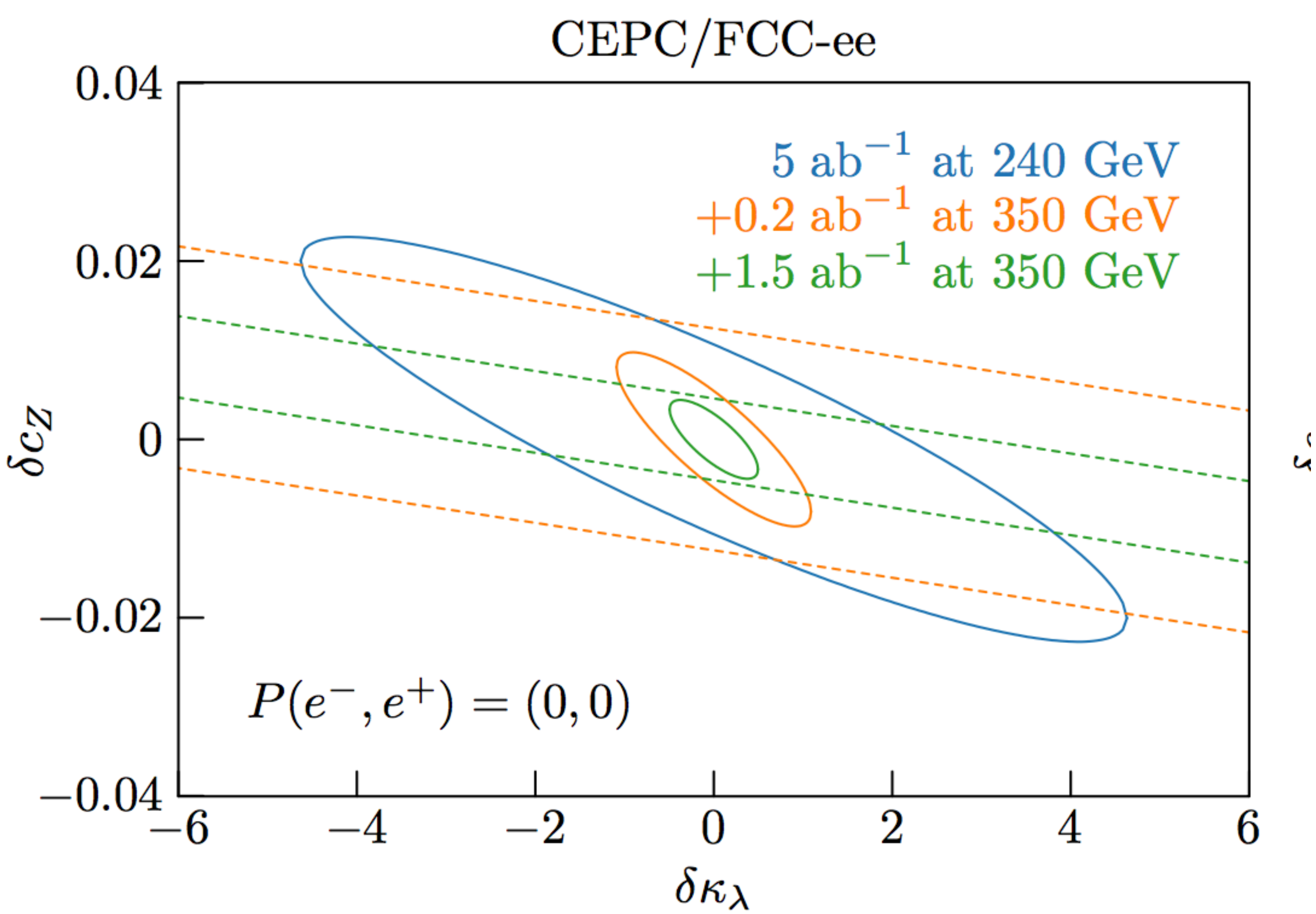
Higgs self-coupling



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

➡ Very large HZ datasets allow g_{ZH} measurements of extreme precision

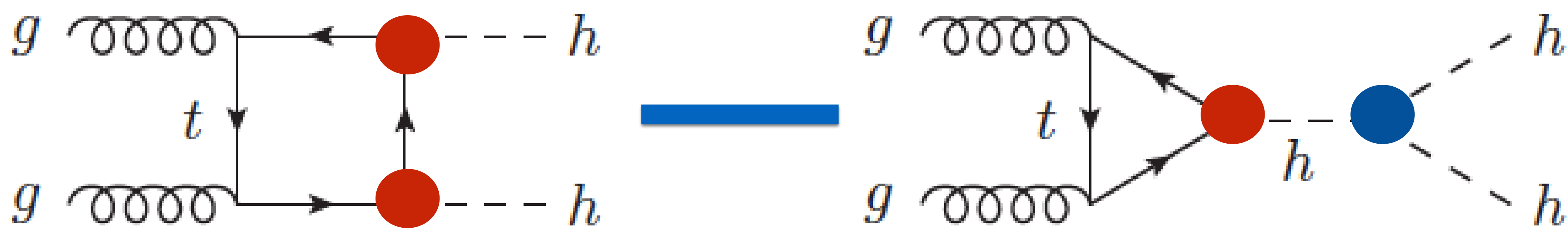
➡ Indirect and model-dependent probe of Higgs self-coupling



A precision on $\delta\kappa_\lambda$ of ±40% can be achieved, and of ±35% in combination with HL-LHC.

If c_Z if fixed to its SM value, then the precision on $\delta\kappa_\lambda$ improves to ±20%

Higgs self-coupling at FCC-hh



$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

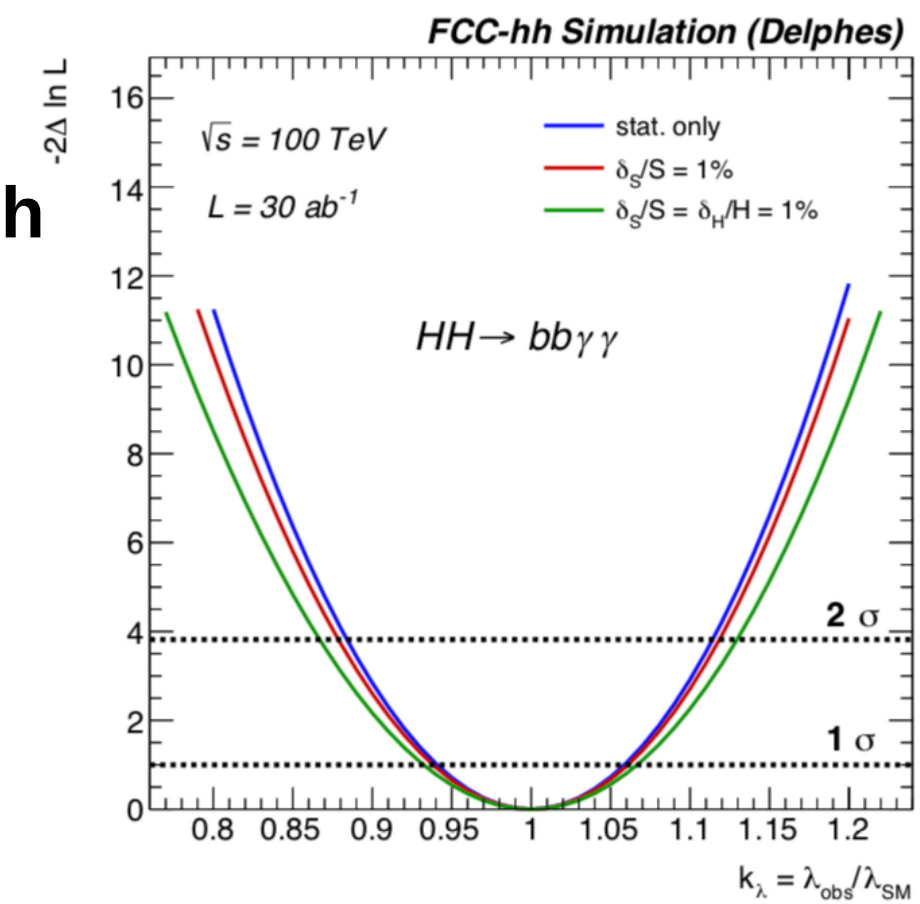
EFT Lagrangian

➡ **Enormous di-Higgs samples produced at FCC-hh**

- σ(100 TeV) / σ(14 TeV) ≅ 40
- L (FCC-hh) / L (HL-LHC) ≅ 10
- Naively, factor 20 smaller statistical uncertainty

➡ **Studied a number of final states**

- bbχχ most sensitive channel



δμ ≅ 2-4%

δ□ ≅ 5%

Details in arXiv:1606.09408 and arXiv1802.01607

Complementarity

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume SM or ee measurements
FCC-hh : H→ ZZ to serve as cross-normalization

for ttH, combination of ±4% (model dependent)HL-LHC with FCC-ee will lead to ttH coupling to ± 3%... model independent!

for g_{HHH} investigating now : the possibility of reaching 5σ observation at FCC-ee:
4 detectors
+ recast of running scenario

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.22 %**	**< 1%** *	
WW	**0.47%**		
Γ_H	**1.6%**		
$\gamma\gamma$	4.2%	**<1%**	
$Z\gamma$	--	**1%**	
ttH	13%	**1%**	
bb	**0.7%**		0.5%
$\tau\tau$	**0.8%**		
cc	**0.7%**		1.8%
gg	**1.0%**		
$\mu\mu$	8.6%	**1-2%**	
uu,dd	H→ $\rho\gamma$?	H→ $\rho\gamma$?	
ss	H→ $\phi\gamma$?	H→ $\phi\gamma$?	
ee	**ee → H**		
HH	40%	**~3-5%**	20%
inv, exo	<0.55%	**10^{-3}**	5%

Conclusions

➡**Fantastic prospects to probe the Higgs sector with FCC**

- Large Higgs samples open new possibilities
- Model-independent measurements of g_{ZH} and total width with FCC-ee
- Precision measurements of Higgs boson couplings, including self couplings, mass, CP
  - **sub-percent precision** on several Higgs couplings only possible with FCC-ee
- BSM Higgs physics through direct and indirect measurements
- Synergy between FCC-ee and FCC-hh Higgs physics
- More precise Higgs measurements are foreseen for the FCC TDR.
- FCC-ee and FCC-hh (or CepC + SppC) will provide **by far** the best possible Higgs measurements of any accelerator.

Higgs CP studies

➡ **H→ττ decay is a promising channel to study CP violation**

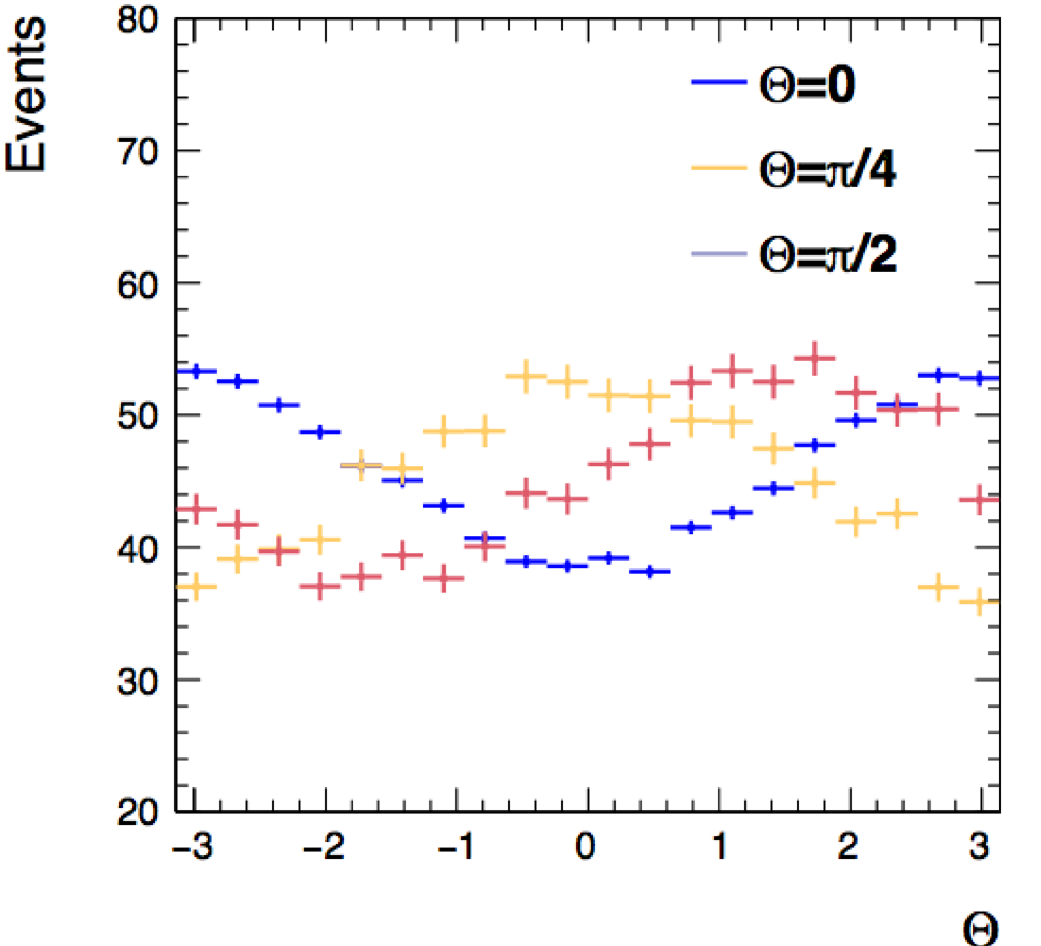
- Tree level couplings to quarks and leptons
- CP-even and CP-odd couplings induced at the same order

➡ **CP violation can be probed through τ polarization**

- **τ** decays clean enough that the spin information is not washed out by hadronization effects
- pion emission preferred in the direction of the **τ** spin in rest frame
- exploring $\tau^{\pm} \rightarrow \rho^{\pm}\nu_{\tau} \rightarrow \pi^{\pm}\pi^{0}\nu_{\tau}$
- model using $\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$

Andres Rios (MIT), Aram Apyan (FNAL)

following arXiv:1308.1094

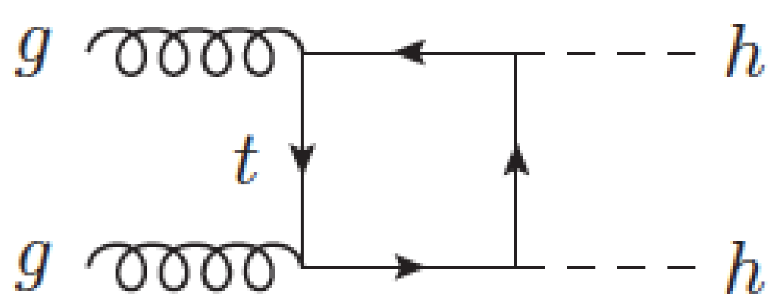


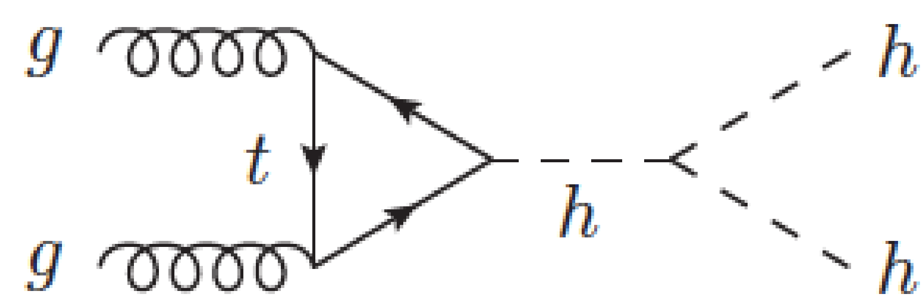
- 920 signal event in 5 ab^{-1}
- expected 68% CL
  - ❖ 0.17 radian (0.05 in GEN level study)
  - ❖ 9.7 degree (2.9 in GEN level study)

Higgs self-coupling at hadron colliders

➡Probing triple-Higgs coupling with double Higgs production

- Consistency of check of EWSB
- Reconstructing the Higgs potential
- Sensitivity through yields and kinematics
- Large enhancement through BSM possible
- Exhaustive program at the (HL-)LHC





$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

EFT Lagrangian