THE HIGGS BOSON

at the FCC

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Overview

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- **FCC complex and FCC-ee first stage**

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- **Higgs production at FCC-ee**

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- **Higgs self-coupling**

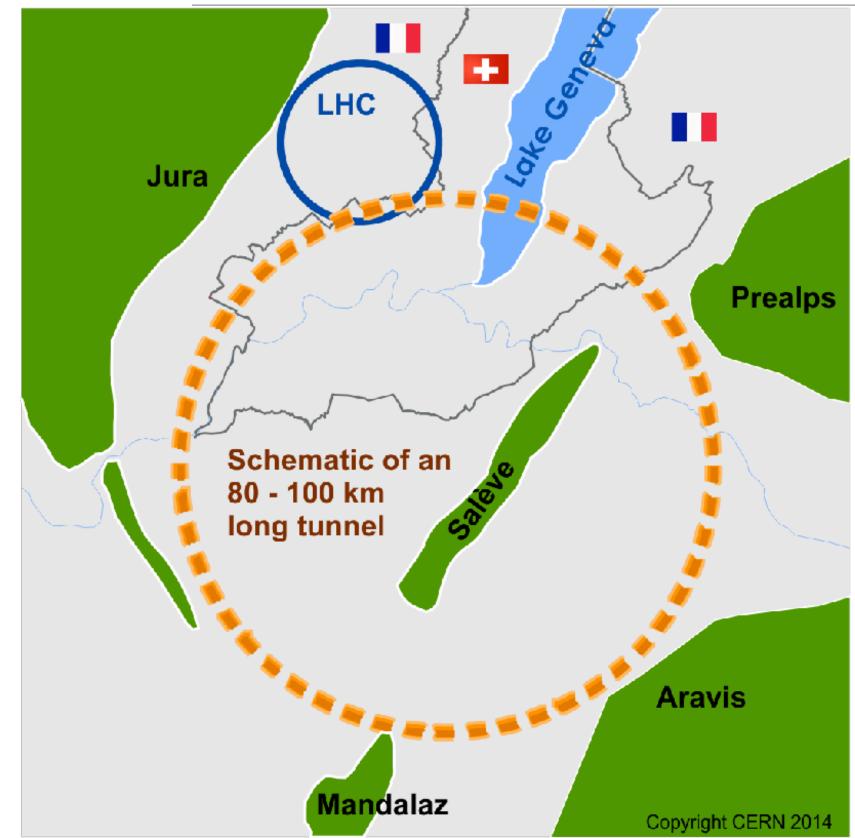- **Synergy with FCC-hh**

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- **Conclusions**

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- **BSM Higgs searches**

- **Higgs self-coupling**

- **Synergy with FCC-hh**

- **Conclusions**

FCC complex

Schematic of an 80 - 100 km long tunnel
Copyright CERN 2014

International FCC collaboration
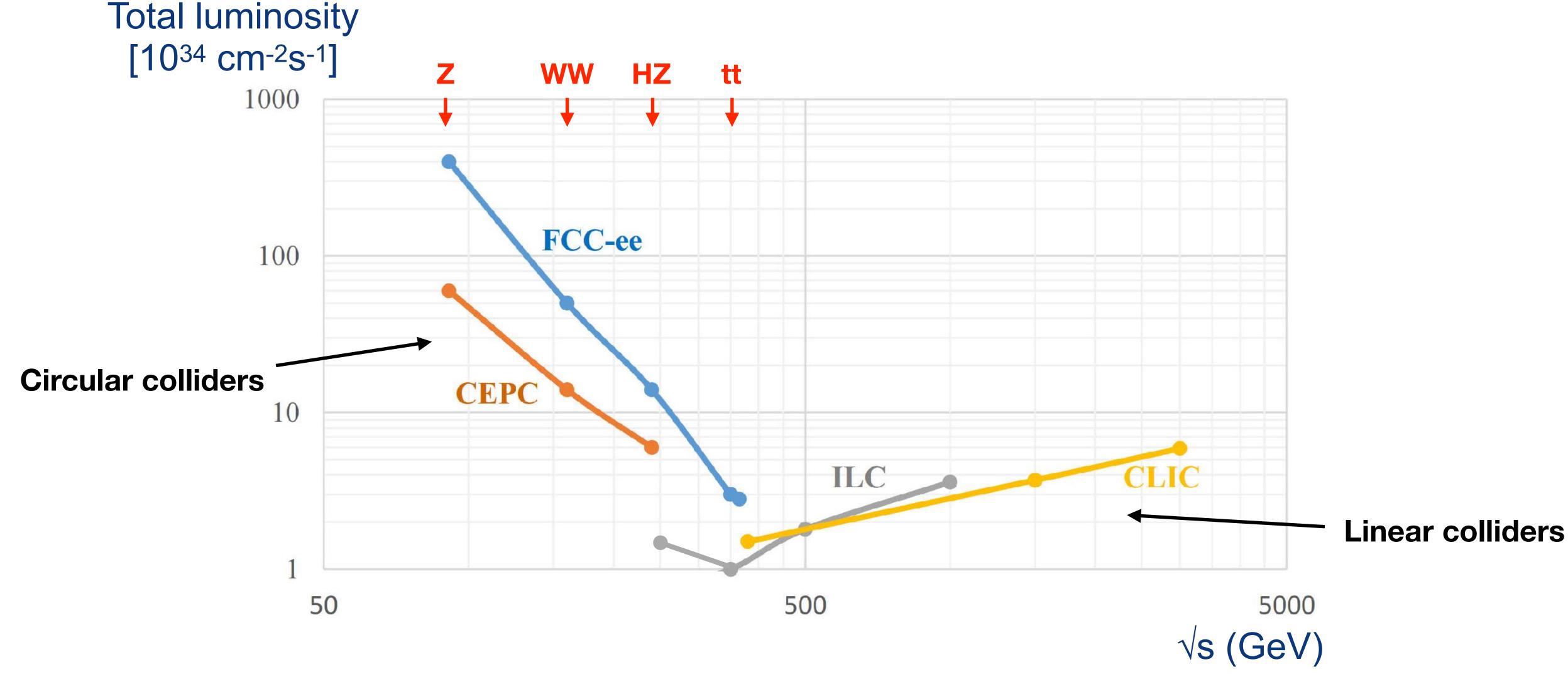
📌 **pp-collider** *(FCC-hh)*

➡ main emphasis, defining infrastructure requirements

- 16 T ⇒ 100 TeV pp, L~2x10^{35}, L_{int}=2 ab^{-1}/yr

📌 **~100 km tunnel infrastructure**

📌 **e^+e^- collider** *(FCC-ee)*, **√s=90-365 GeV, L~10^{35} - 4x10^{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, √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

Future lepton colliders luminosities

Total luminosity
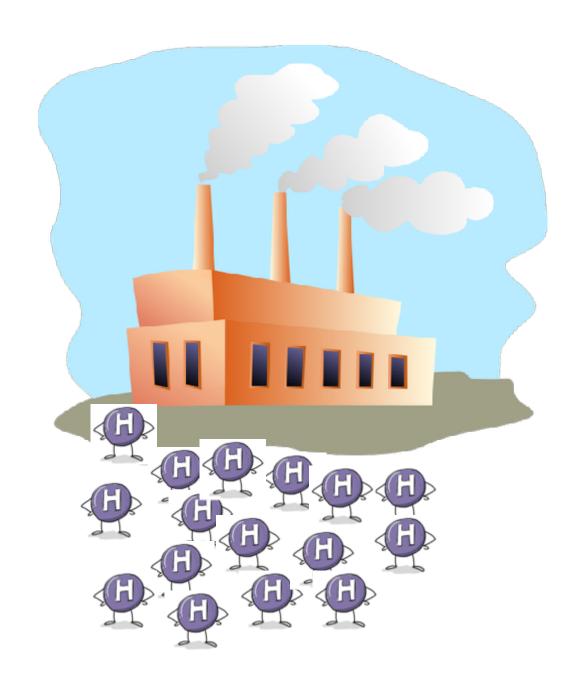$[10^{34}\ cm^{-2}s^{-1}]$

Significant advantage in luminosity for circular colliders vs. linear colliders, especially for FCC-ee. Linear colliders (esp. CLIC) have higher energy reach, but less than FCC-hh.
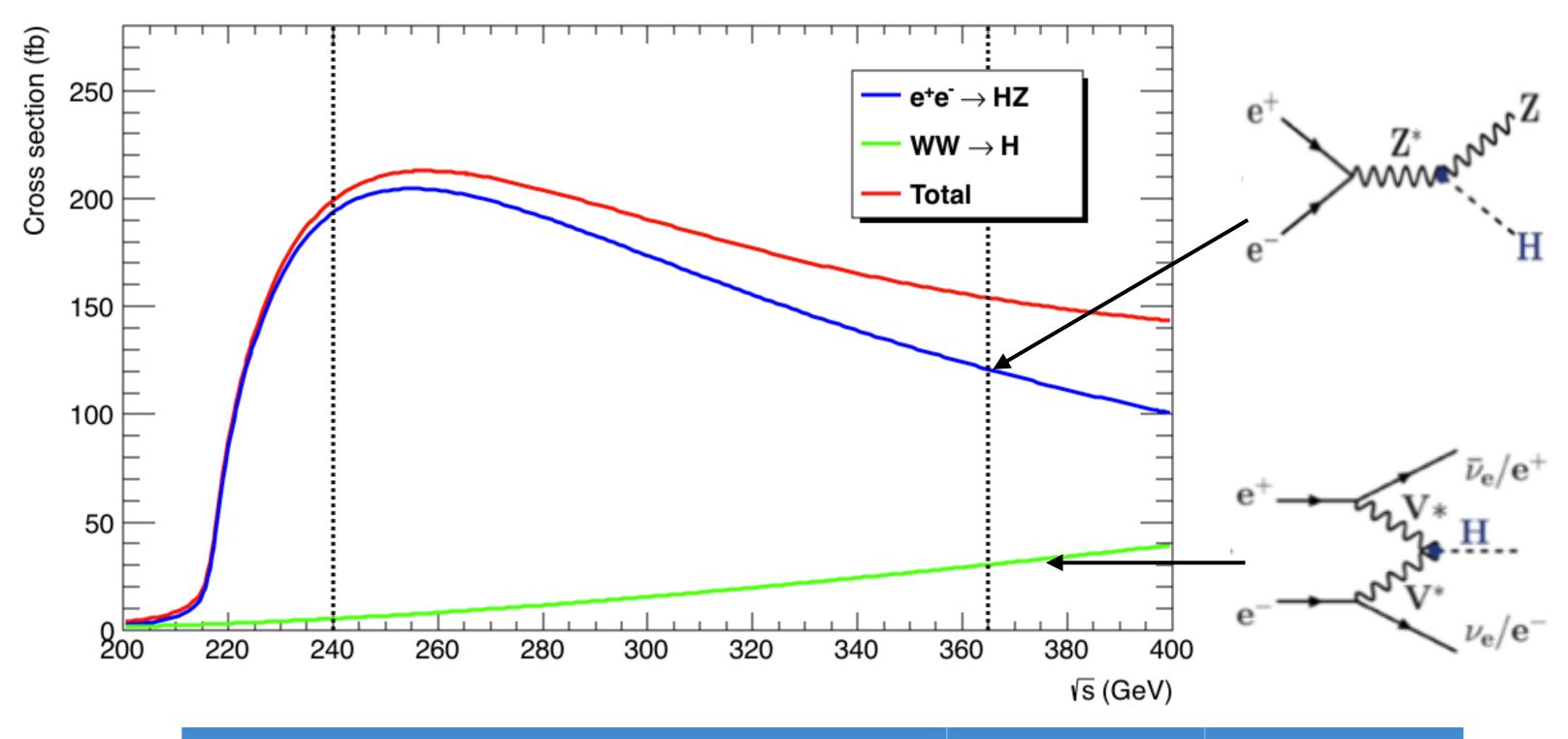
Higgs production at FCC-ee
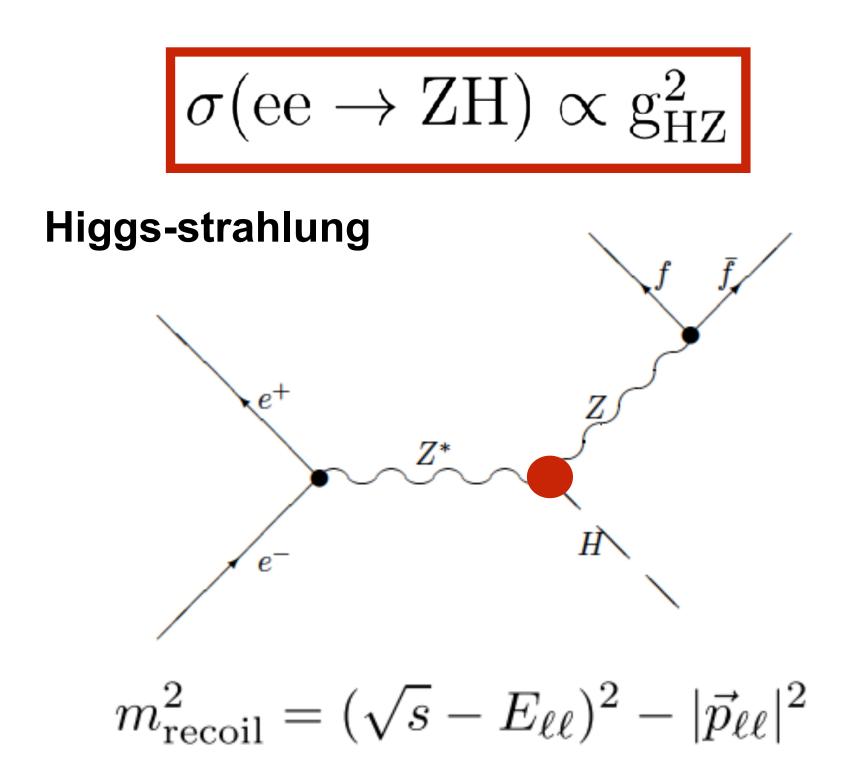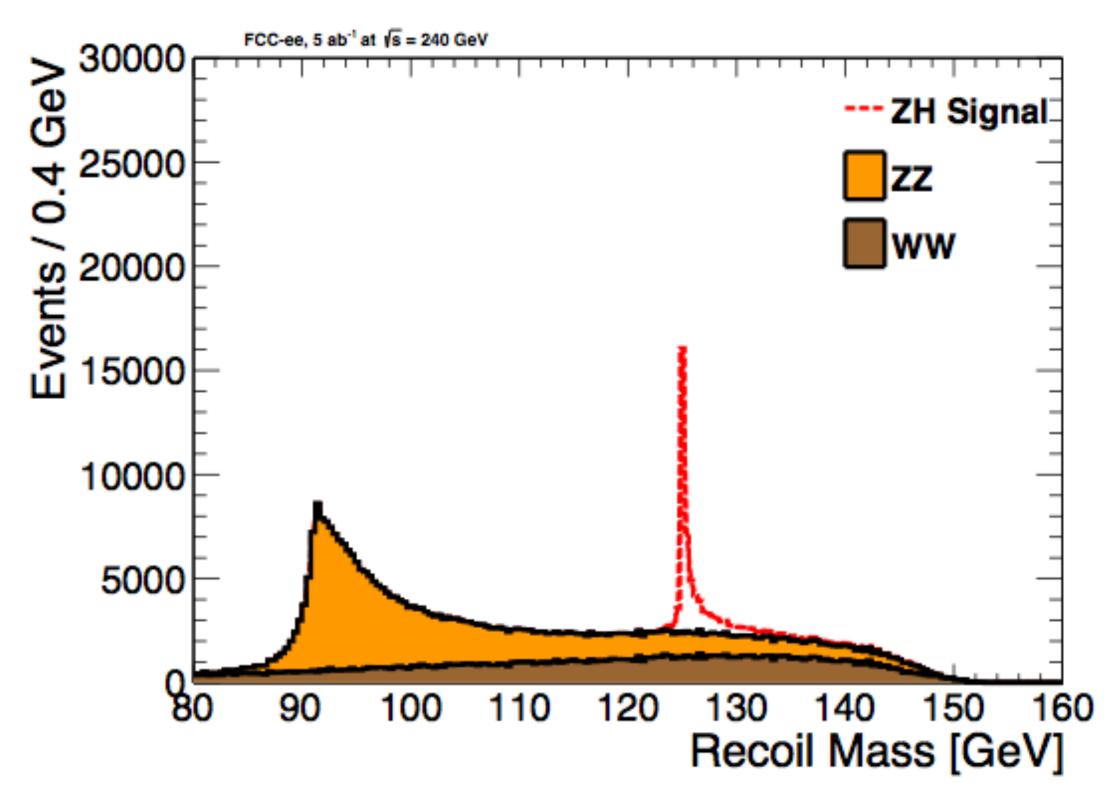
FCC-ee

5 ab^{-1}@240 GeV

~1.5 ab^{-1}@365 GeV

Higgs Factory!

	FCC-ee 240 GeV	FCC-ee 365 GeV
Total Integrated Luminosity (ab^{-1})	5	1.5
# Higgs bosons from e$^+$e$^-$→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 **0.5% at 240 GeV, 0.9% at 365 GeV** on the ZH cross section

- Using only leptonic Z decays

$$\sigma(ee \rightarrow ZH) \propto g_{HZ}^2$$

Higgs-strahlung

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

FCC-ee, 5 ab^{-1} at $\sqrt{s}$ = 240 GeV

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

$$\sigma(ee \rightarrow ZH) \cdot BR(H \rightarrow ZZ) \propto \frac{g_{HZ}^4}{\Gamma}$$

2) measurements of vector boson fusion production at 350-365 GeV

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

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

3) combination of all measurements

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

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

- 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 FCC-ee CDR)

  ◉ all measurements are under review / are being redone

Several couplings (g$_{H\mu\mu}$, g$_{H\gamma\gamma}$, g$_{Htt}$) improve further by doing a combined fit with HL-LHC.
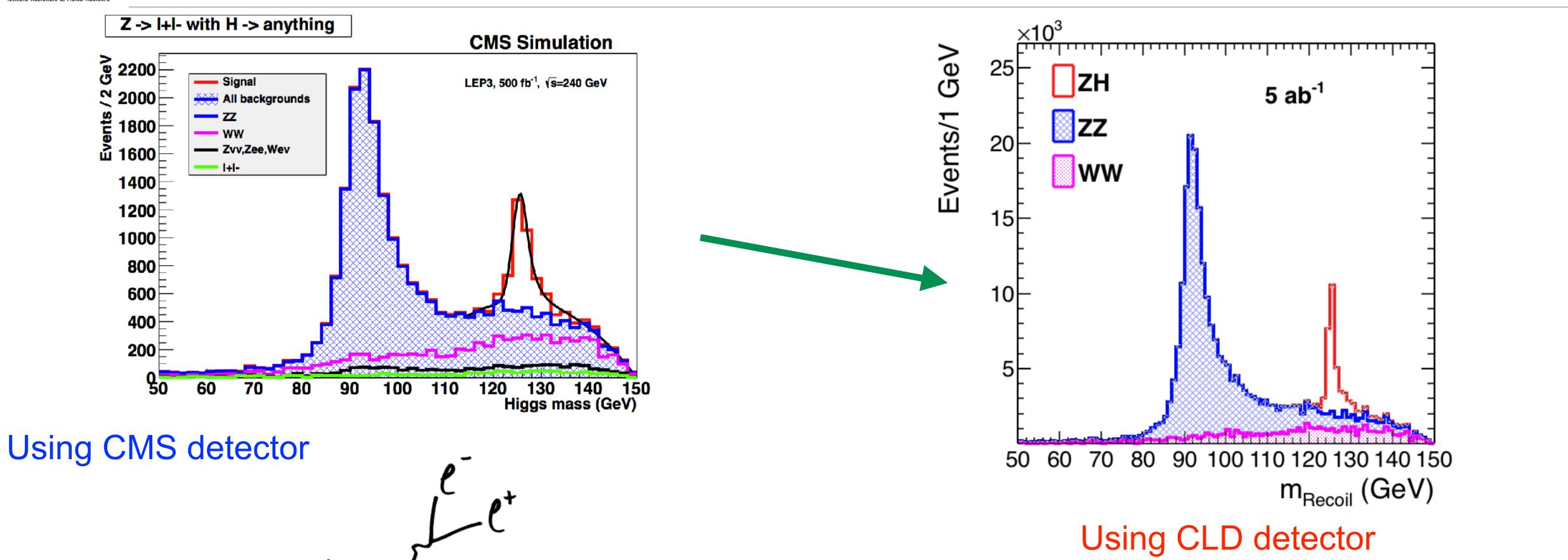**The combined fit makes the HL-LHC measurements model-independent.**

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

relative meas., e.g. $\delta g_H/g_H$

Higgs boson couplings, ZH→ℓℓX

Z → l+l- with H -> anything

CMS Simulation

LEP3, 500 fb⁻¹, √s=240 GeV

- Signal
- All backgrounds
- ZZ
- WW
- Zνν,Zee,Weν
- l+l-

Using CMS detector

Using CLD detector
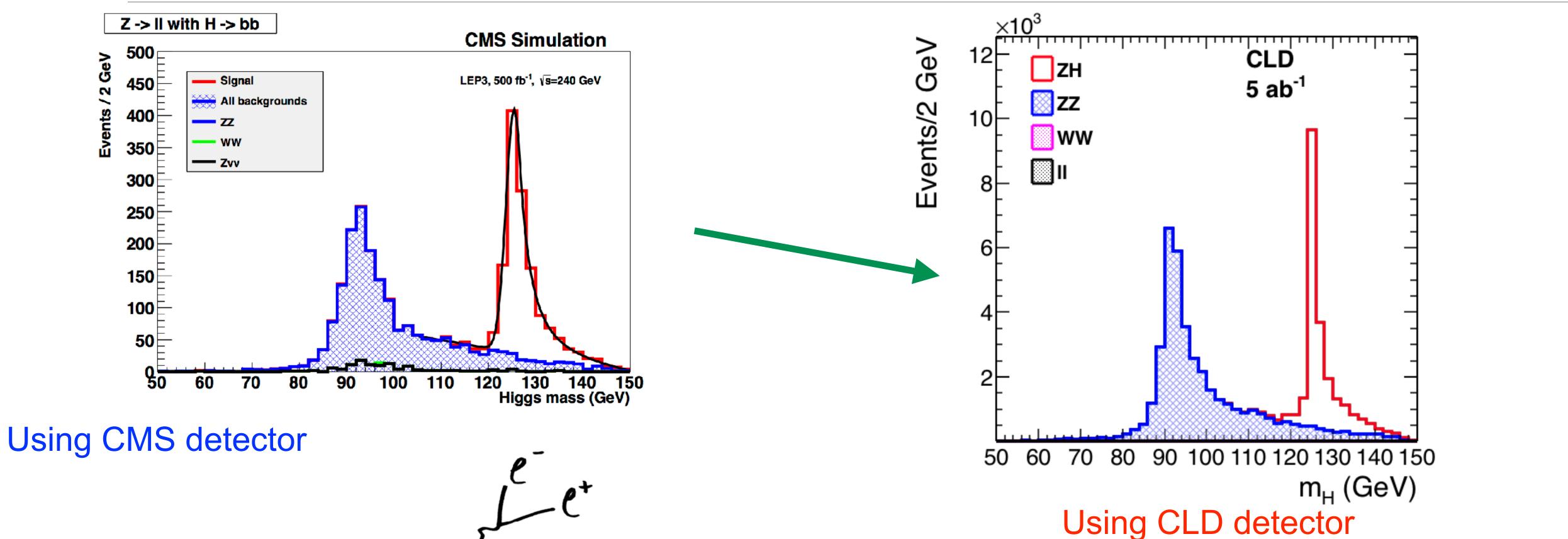
CLD: CLIC-inspired Lepton Detector, optimised for FCC-ee

C. Bernet
FCC week 2018

Higgs measurements at FCC - Paolo Giacomelli

9

Higgs boson couplings, ZH→$\ell\ell$bb
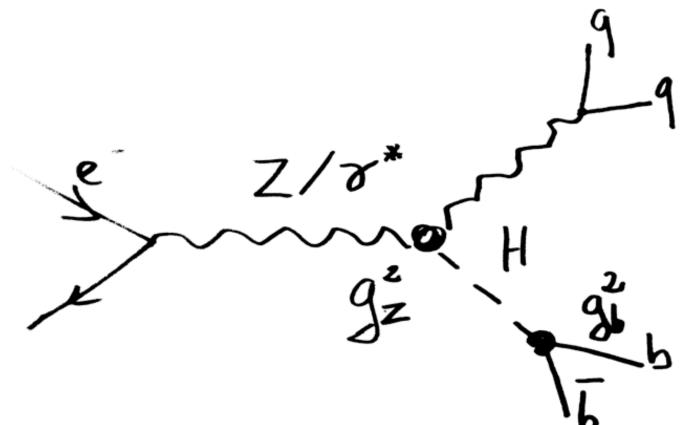

Using CMS detector

Using CLD detector
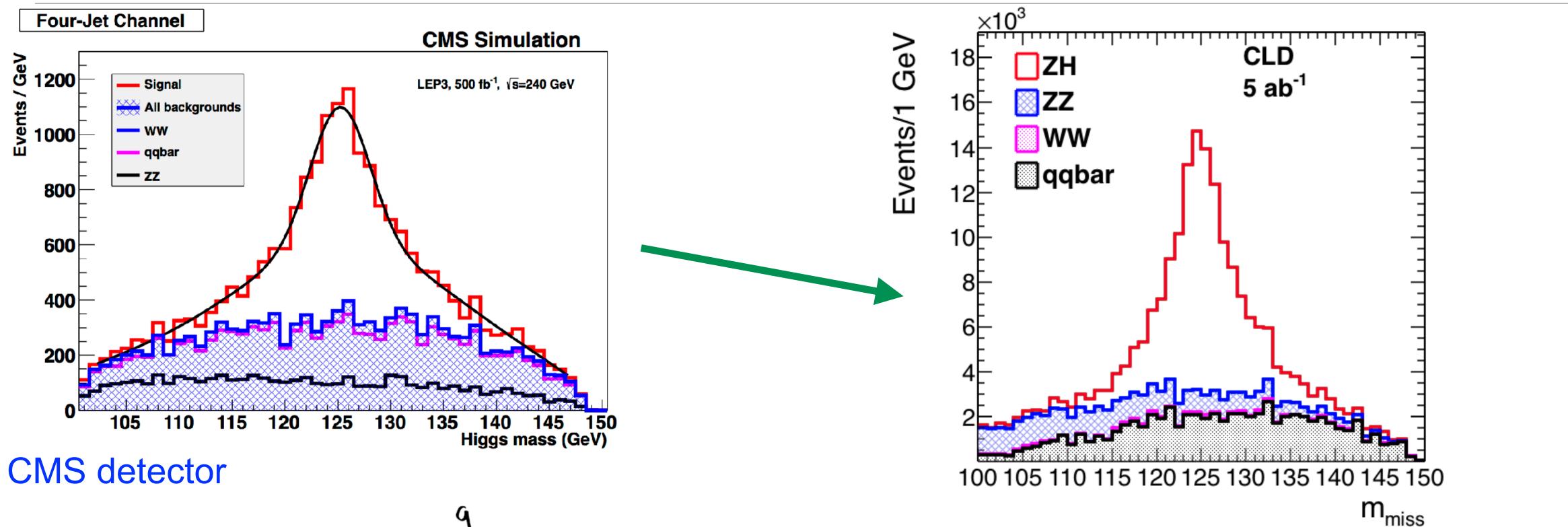
Higgs boson couplings, ZH→qqbb

Using CMS detector
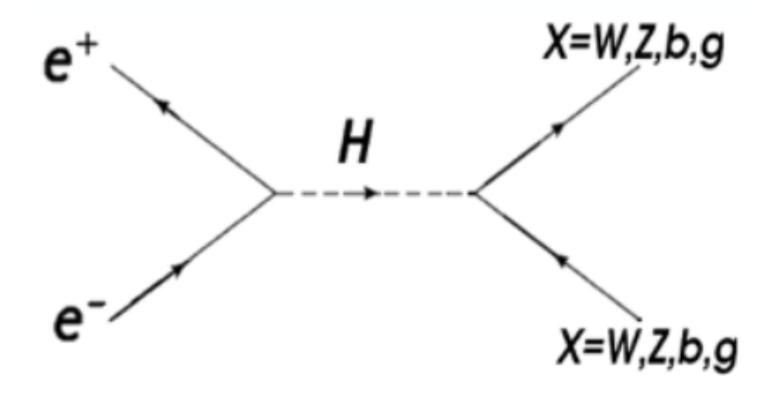
Using CLD detector
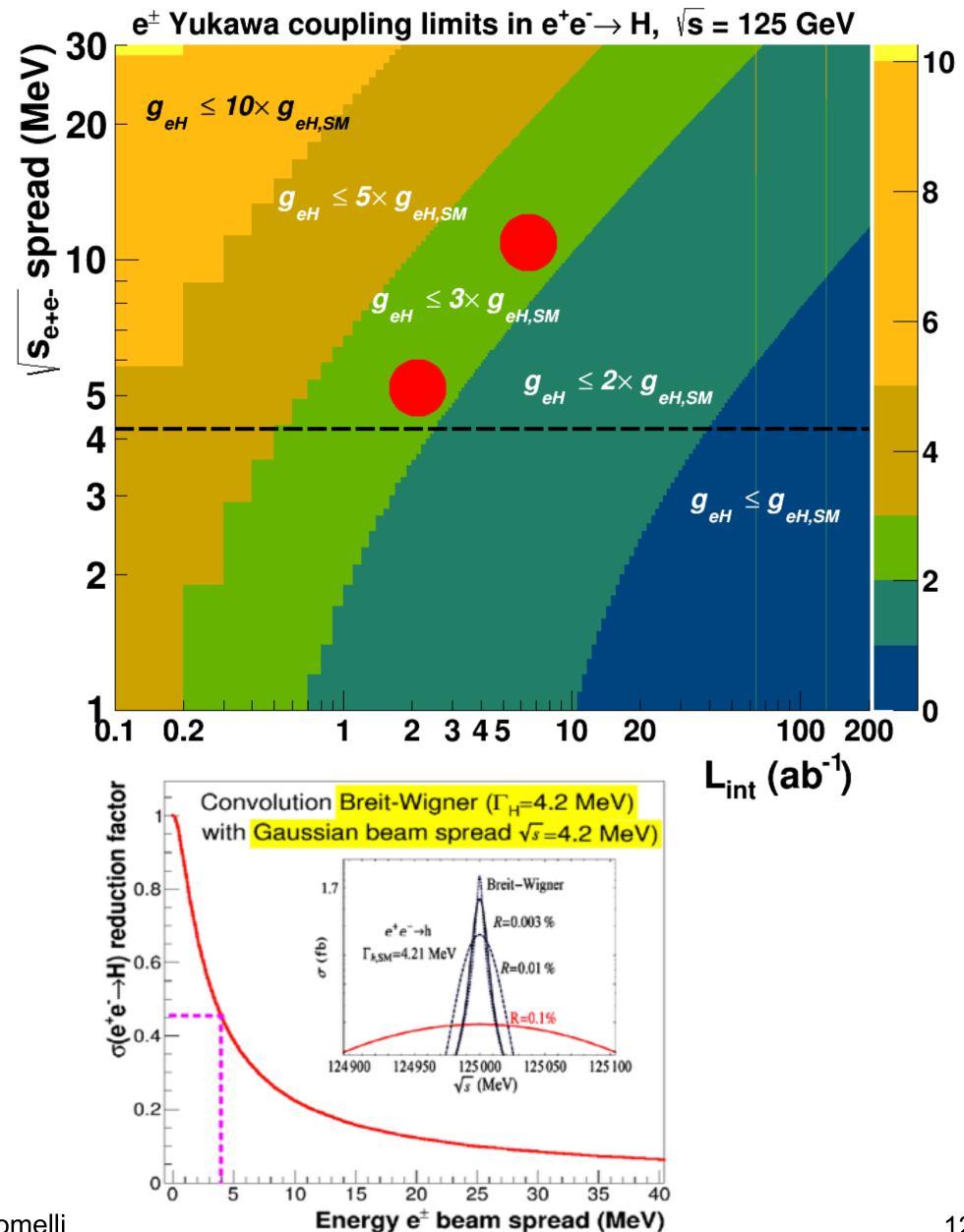
C. Bernet
FCC week 2018

electron Yukawa coupling

➡️ **s-channel Higgs production**

- ⦿ unique opportunity for measurement close to SM sensitivity

- ⦿ highly challenging; $\sigma(ee \to H) = 1.6$ 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}
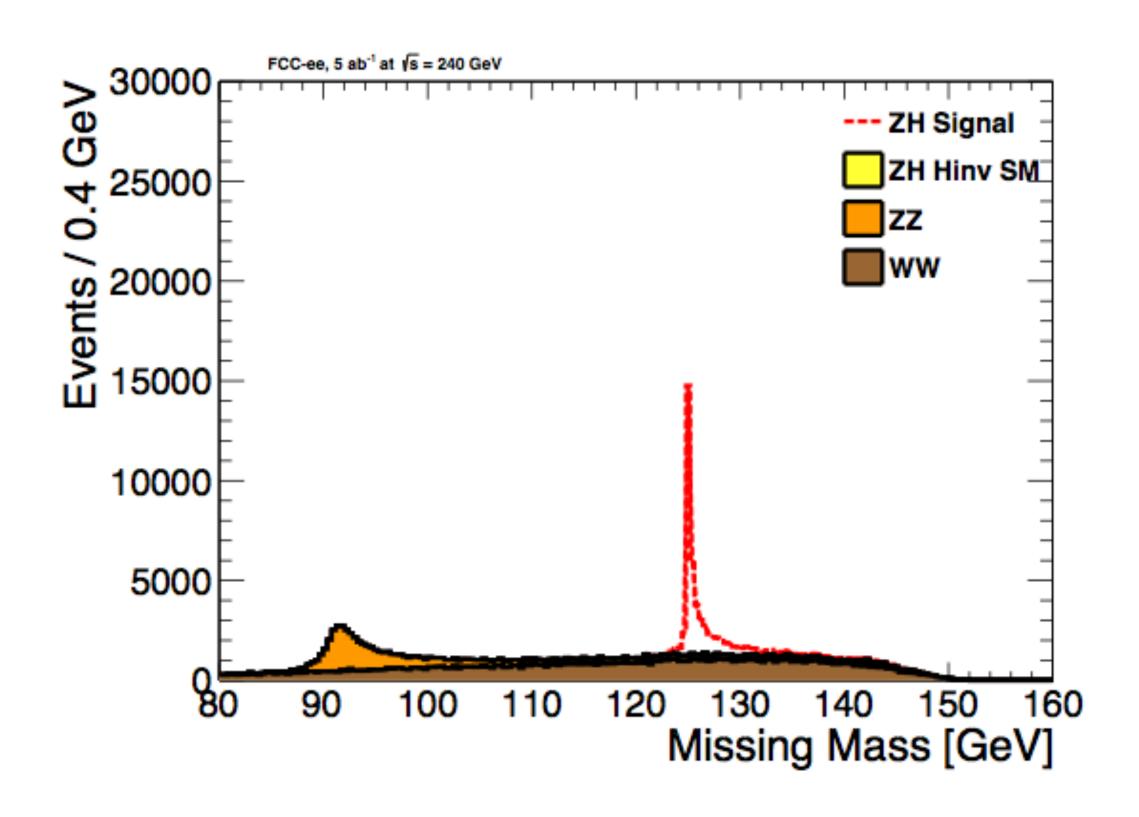
  - limit ~2.5 times SM in both cases

Higgs invisible decays

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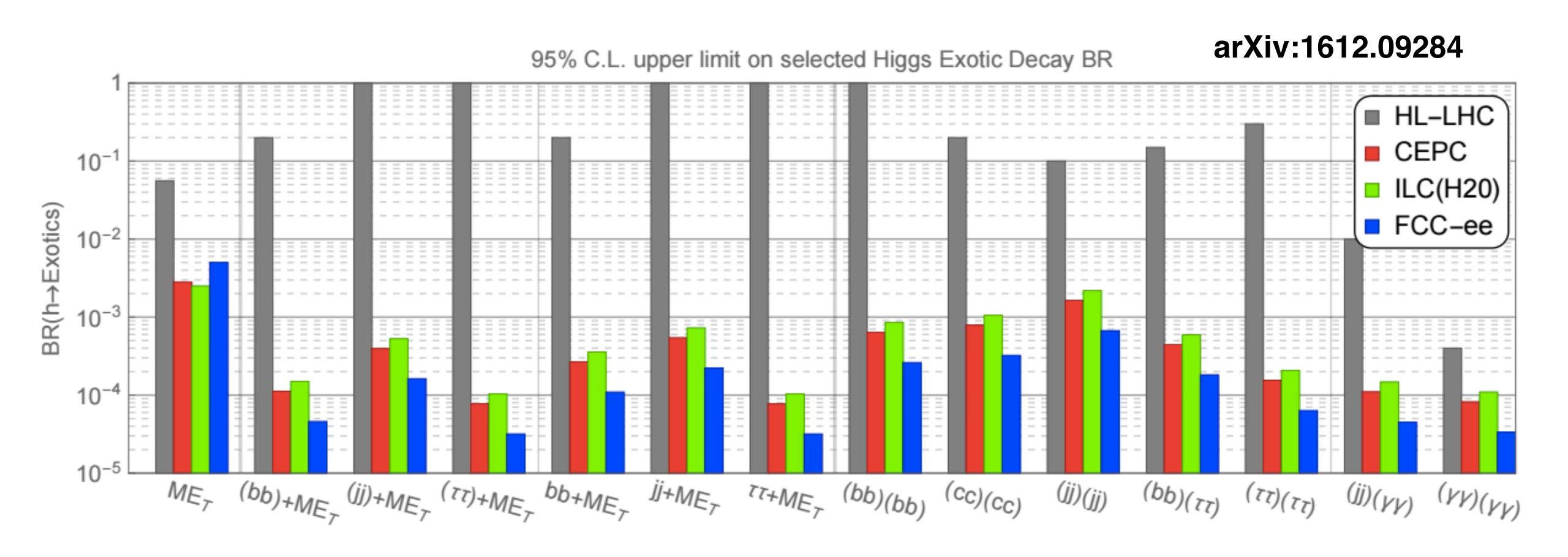

FCC-ee, 5 ab⁻¹ at √s = 240 GeV

- Follows FCC-ee ZH cross section measurement, events with a Z and nothing else are selected

- for visualization BR(H->inv) = 100%

- 95%CL upper limit using 5ab⁻¹ is 0.3% at 240 GeV, 0.6% with 1.5ab⁻¹ at 365 GeV

- Study using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
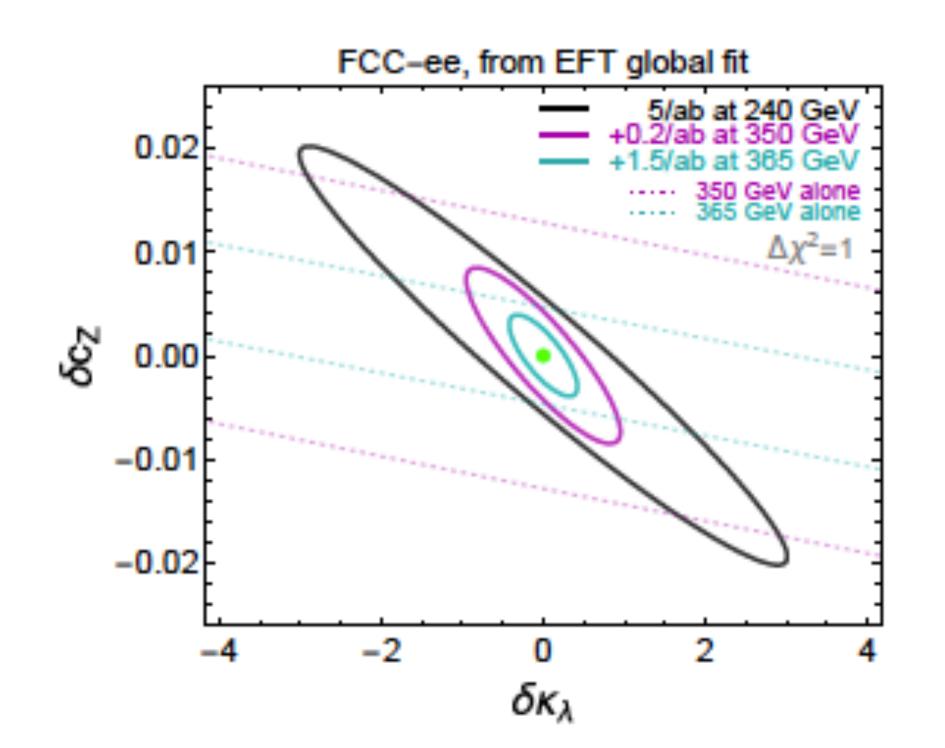
- Hadronic Z decays also included

➡ **Excellent opportunities for BSM Higgs searches**

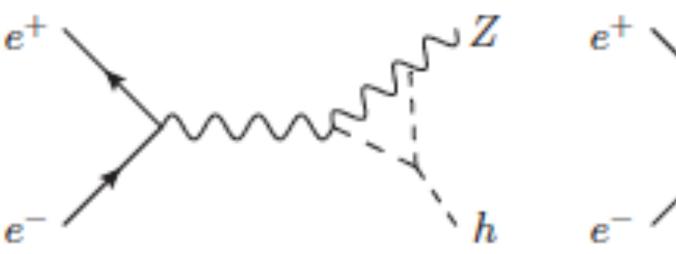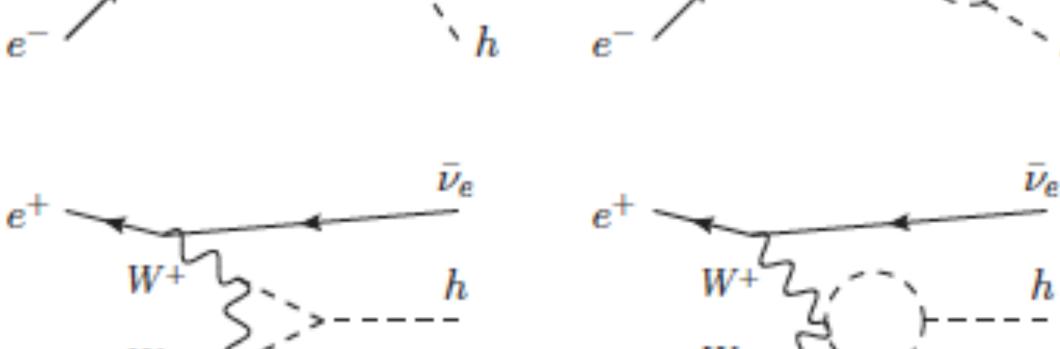arXiv:1612.09284

95% C.L. upper limit on selected Higgs Exotic Decay BR

Higgs self-coupling

➡ Very large HZ datasets allow σ_{ZH} and $\sigma_{\nu\nu H}$ measurements of extreme precision at $\sqrt{s}$ = 240, 350 and 365 GeV

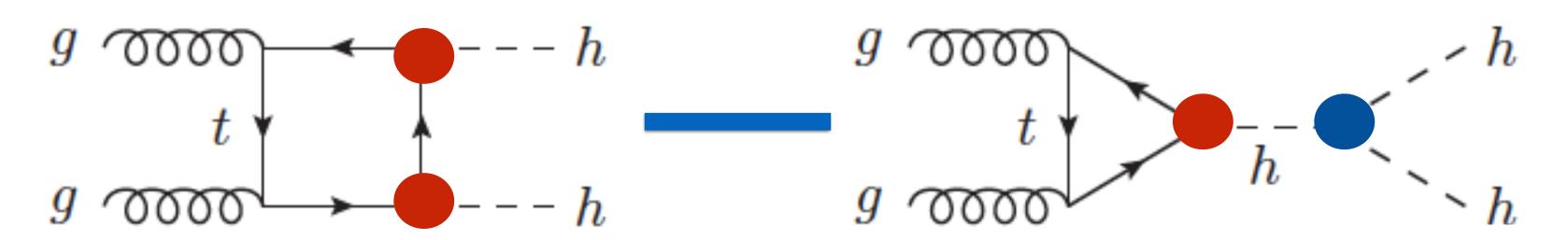➡ Model-independent bounds obtained from global-fit on Higgs self coupling κ_λ and the coupling to SM bosons c_Z

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

➡ **Enormous di-Higgs samples produced at FCC-hh**
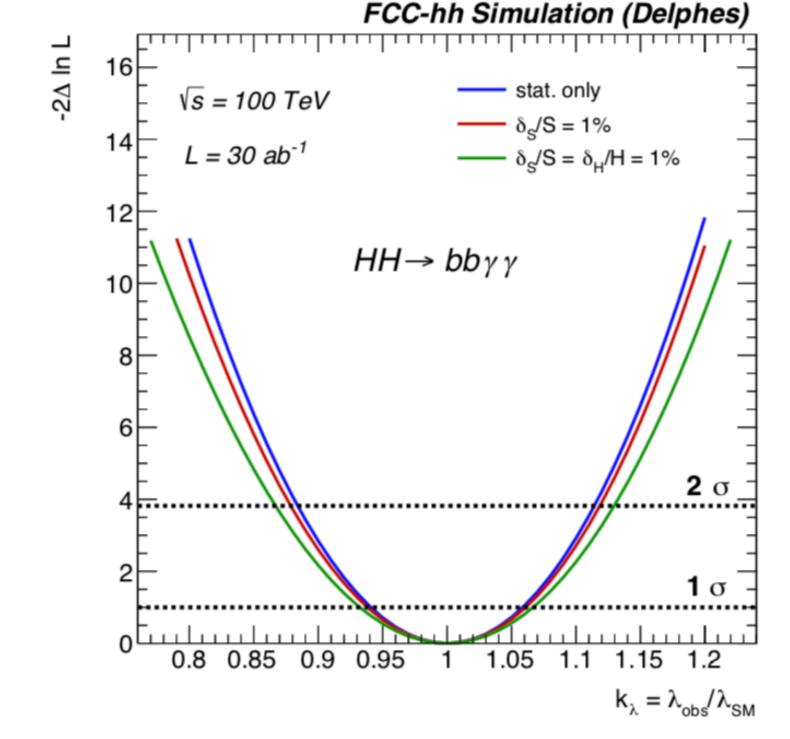
- ◉ σ(100 TeV) / σ(14 TeV) $\cong$ 40

- ◉ L (FCC-hh) / L (HL-LHC) $\cong$ 10

- ◉ Naively, factor 20 smaller statistical uncertainty

➡ **Studied a number of final states**

- ◉ bb$\chi\chi$ most sensitive channel

➡ **Per-cent level precision of HHH coupling**

- ◉ Only possible at a 100 TeV hadron machine

- ◉ $\delta\kappa$ 5% possible thanks also to precise BR measurements at FCC-ee

Details in arXiv:1606.09408 and arXiv1802.01607

$\delta\mu \cong$ **2-4%**

$\delta\kappa \cong$ **5%**

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- FCC-ee and FCC-hh will provide **by far** the best possible Higgs measurements of any accelerator.

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Stay tuned!

Backup

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
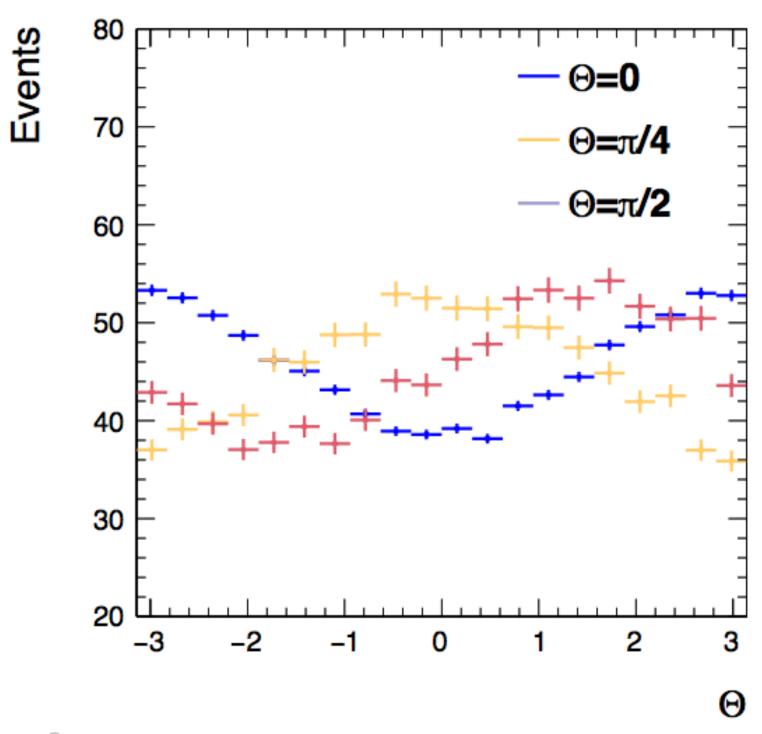
Higgs CP studies

➡ **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 $\tau^{\pm}\rightarrow\rho^{\pm}\nu_{\tau}\rightarrow\pi^{\pm}\pi^{0}\nu_{\tau}$

- exploring $\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5\sin\Delta)f$

- model using effective lagrangian

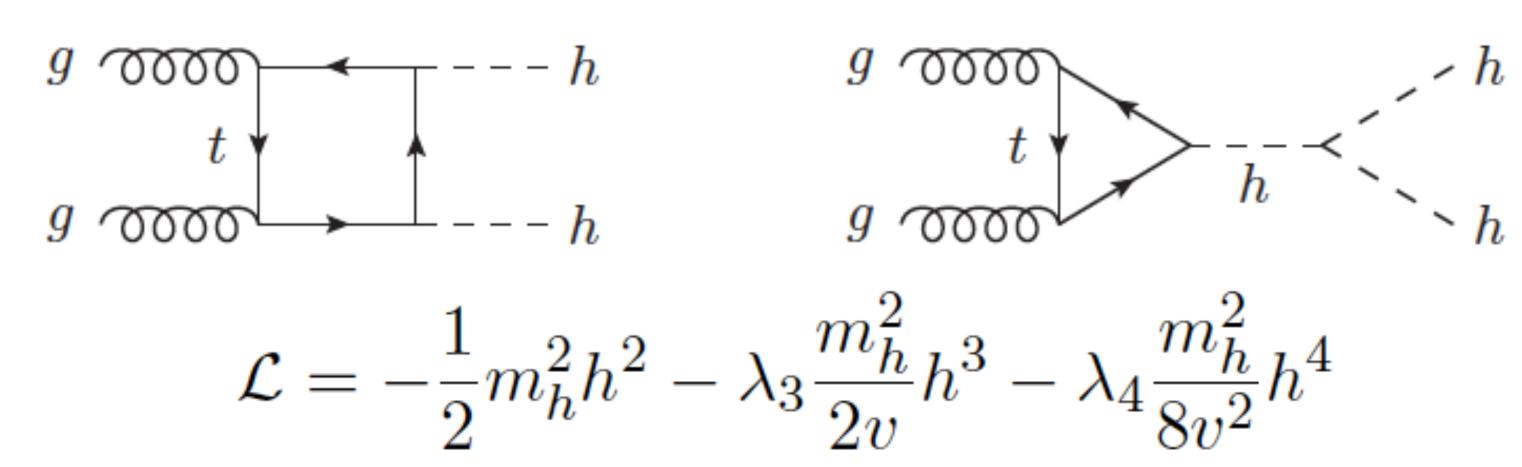**Andres Rios (MIT), Aram Apyan (FNAL)**
following arXiv:1308.1094

- 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