SM Higgs measurements at FCC-ee

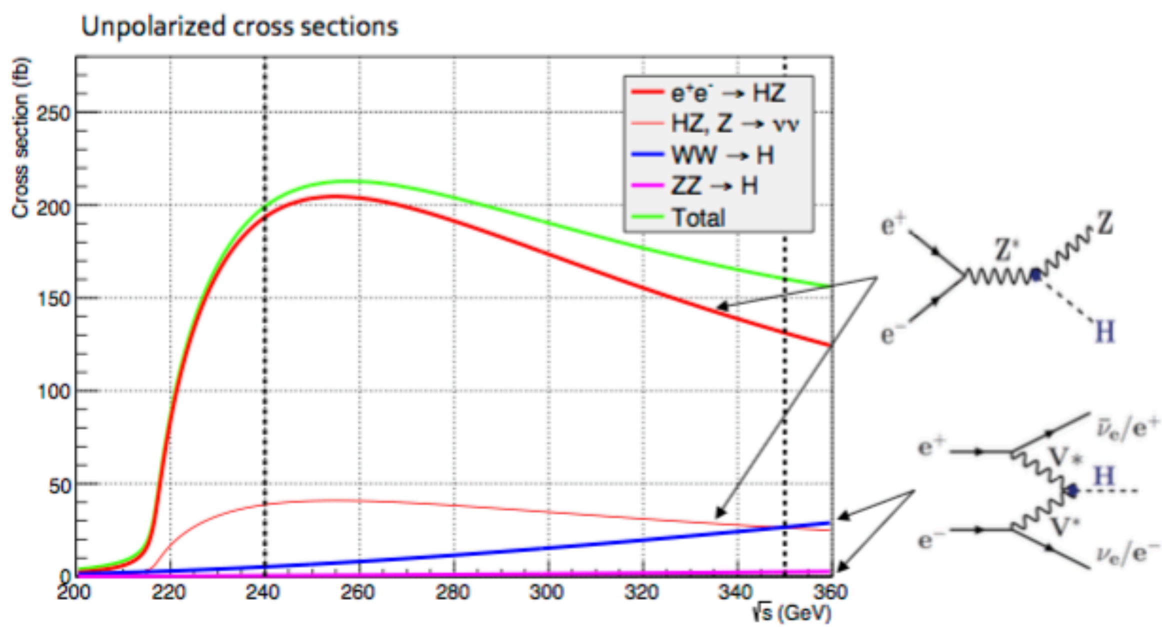
1st FCC Physics Workshop, 2017

Aram Apyan

Higgs production at FCC-ee

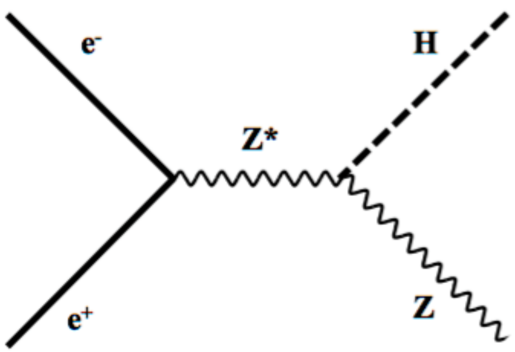
- FCC-ee Higgs boson program
- Exploiting very large Higgs boson sample
    - Precise Higgs studies and very rare decays

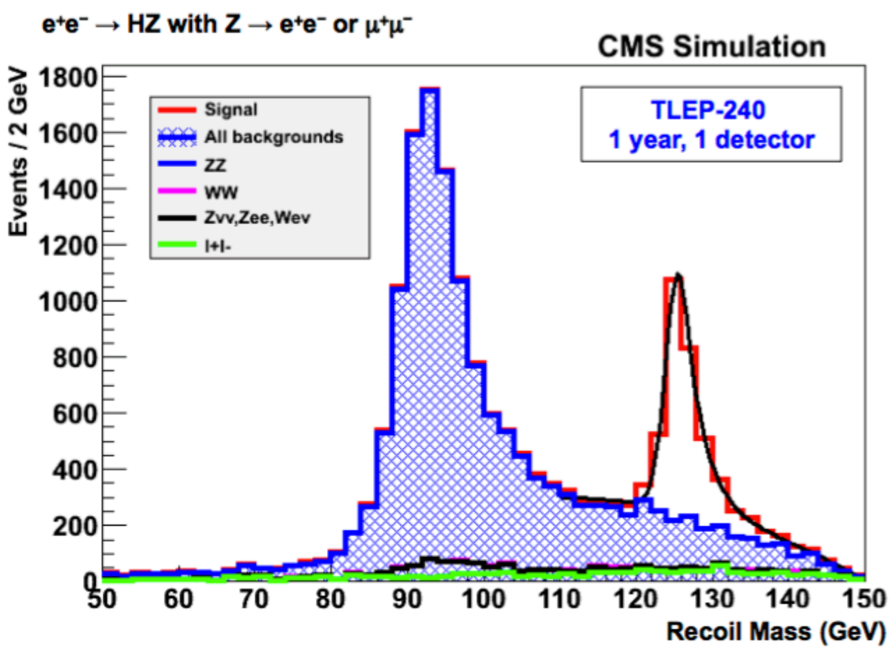
	FCC-240	FCC-350
Total Integrated Luminosity (ab^{-1})	**10**	**2.6**
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**	**340,000**
Number of Higgs bosons from boson fusion	**50,000**	**70,000**



Recoil method

- Recoil method unique to lepton colliders
  - No information from the Higgs decay is used
- Measurement of $\sigma(ee \to ZH) \propto g_{HZ}^2$
  - Model-independent
  - Precision measurement (0.4%)





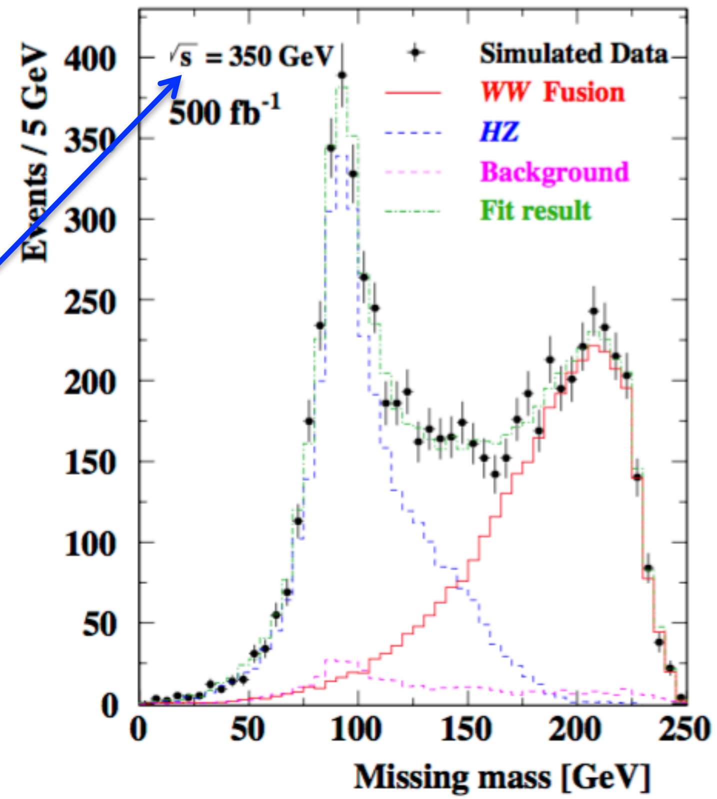
$$m_R^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

Total width

- Higgs total width from combination of measurements
  - Tagging of the Higgs decay final states

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

  - BR(H->X) obtained from √s=240 GeV
  - Precision of 0.6% on: $\sigma(ee \to \nu\nu H) \cdot BR(H \to bb)$



$e^+e^- \to$ HZ with $H \to ZZ$	**3.1%**
WW $\to$ H with $H \to b\bar{b}$ at 240 GeV	**2.4%**
WW $\to$ H with $H \to b\bar{b}$ at 350 GeV	**1.2%**
Combined	**1.0%**

Higgs precision couplings

- Precision better than 1% for most of the couplings
  - Model independent fit for the couplings
  - Branching fraction to invisible tested directly to 0.19% at 95% CL

	FCC-240	FCC	FCC (2IP)
g_{HZZ}	0.16%	**0.15%**	(0.18%)
g_{HWW}	0.85%	**0.19%**	(0.23%)
g_{Hbb}	0.88%	**0.42%**	(0.52%)
g_{Hcc}	1.0%	**0.71%**	(0.87%)
g_{Hgg}	1.1%	**0.80%**	(0.98%)
$g_{\mathrm{H}\tau\tau}$	0.94%	**0.54%**	(0.66%)
$g_{\mathrm{H}\mu\mu}$	6.4%	**6.2%**	(7.6%)
$g_{\mathrm{H}\gamma\gamma}$	1.7%	**1.5%**	(1.8%)
$\mathrm{BR_{exo}}$	0.48%	**0.45%**	(0.55%)

Higgs precision couplings

- Comparison with LHC and HL-LHC (model-dependent)
- Factor >10 improvement for many of the couplings
- Sensitive to new physics at multi-TeV scale

Parameter	Current* 7+8+13 TeV $\mathcal{O}$ (70 fb^{-1})	HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)
σ(HZ)	–	–	0.4%
g_{ZZ}	10%	2–4%	0.15%
g_{WW}	11%	2–5%	0.2%
g_{bb}	24%	5–7%	0.4%
g_{cc}	–	–	0.7%
$g_{\tau\tau}$	15%	5–8%	0.5%
$g_{t\bar{t}}$	16%	6–9%	13%
$g_{\mu\mu}$	–	8%	6.2%
$g_{e^+e^-}$	–	–	<100%
g_{gg}	–	3–5%	0.8%
$g_{\gamma\gamma}$	10%	2–5%	1.5%
$g_{Z\gamma}$	–	10–12%	
Δm_H	200 MeV	50 MeV	11 MeV
Γ_H	<26 MeV	5–8%	1.0%
Γ_{inv}	<24%	<6–8%	<0.45%

d'Enterria
arXiv:1701.02663

Detector requirements

- Detector requirements for the high precision Higgs measurements
    - Muon momentum resolution
    - Jet resolution, 50, 30, and 20%
    - Photon separation for tau identification
    - b and c-tagging with a high granularity vertex detector
    - …

- Ongoing effort to analyze the impact of detector performance
    - Subset of Higgs studies is used

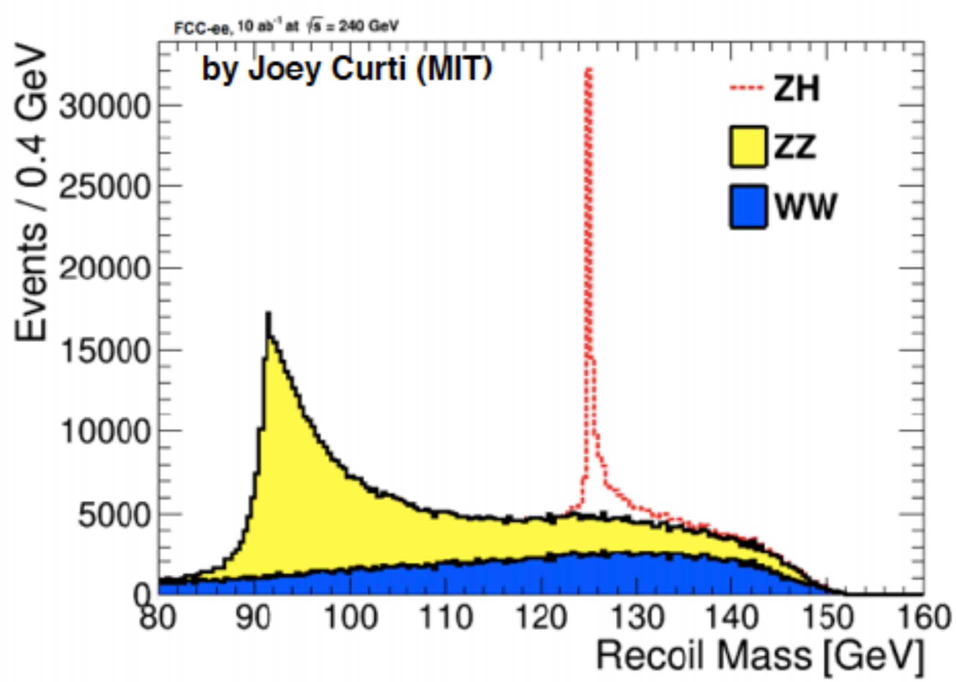
ZH cross section

- Selecting two leptons, electrons and muons of opposite charge
- Impact of electron and muon resolution

$$\frac{\Delta P}{P} = 0.001 + B * \frac{P_T}{10^5}, \text{ for } |\eta| \leq 2.4$$

$$\frac{\Delta E}{E} = 0.011 + A * \frac{0.166}{\sqrt{E}}, \text{ for } |\eta| \leq 2.4$$

  - Also check with no constant term

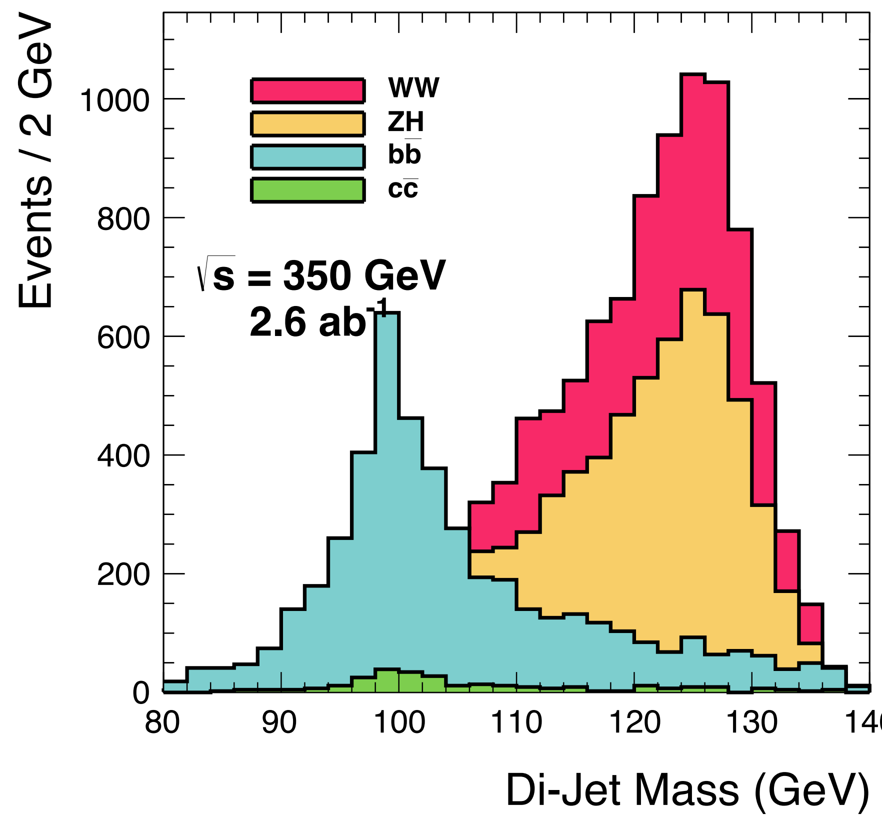


- No changes in results
  - A, B: 1,2, and 4

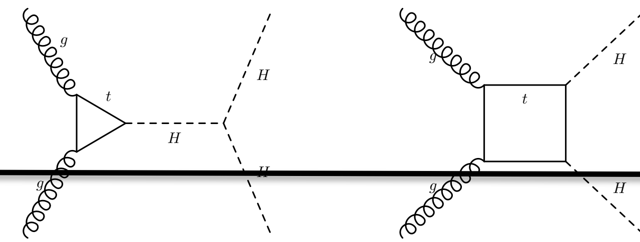
Detector requirements

- Investigating VBF production
- Impact of jet resolution on di-jet and missing mass
  - Jet reconstruction
  - Charm and gluon tagging
- Other ongoing studies
  - H->γγ (Kevin Tang, MIT)
  - H->μμ (Aimane Ahmed, Saclay)
  - H->ττ (Molly Kaplan, MIT)
  - Z{->hadronic}H (MIT)

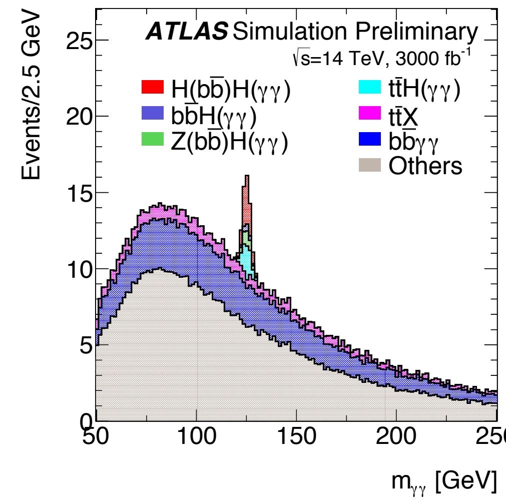
by Alexander Andriatis (MIT)



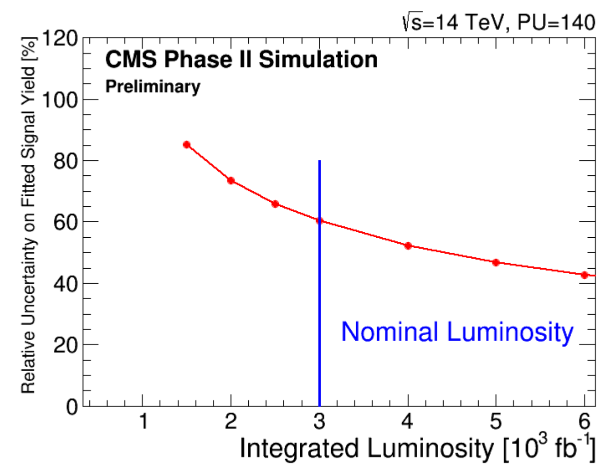
Higgs self coupling



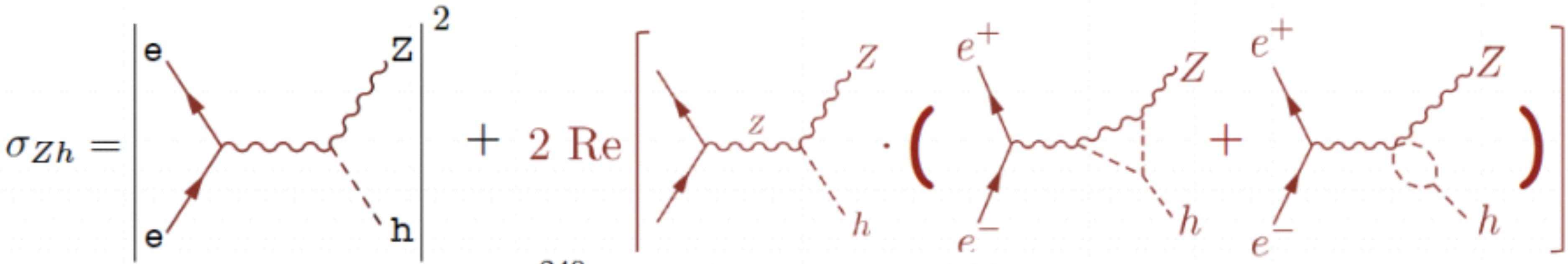
- One of the exciting prospects of HL-LHC
  - Higgs pair production
- Most interesting final states
  - bbγγ [320 expected events at HL-LHC, 3000fb^{-1}]
  - bbττ [8900 expected]
  - bbWW [30000 expected]
  - bbbb [40k expected (2K VBF)]



- Goal is to reach minimum sensitivity of 3σ for SM production and with that to BSM scenarios



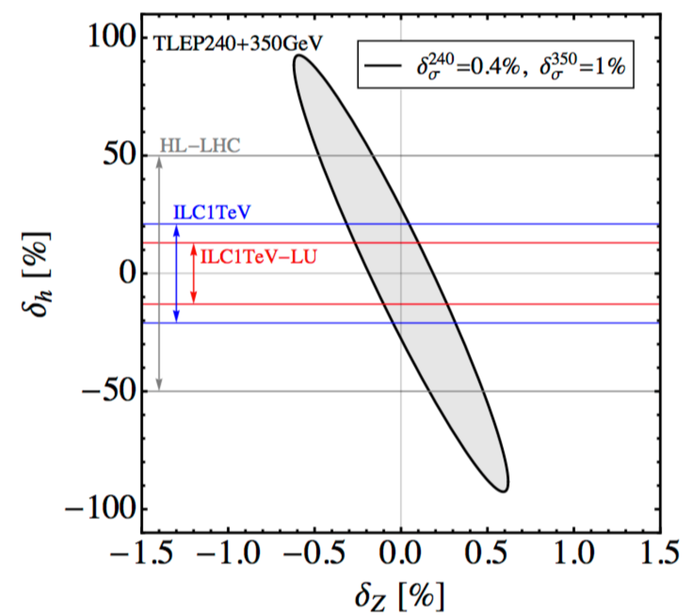
Higgs self coupling



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

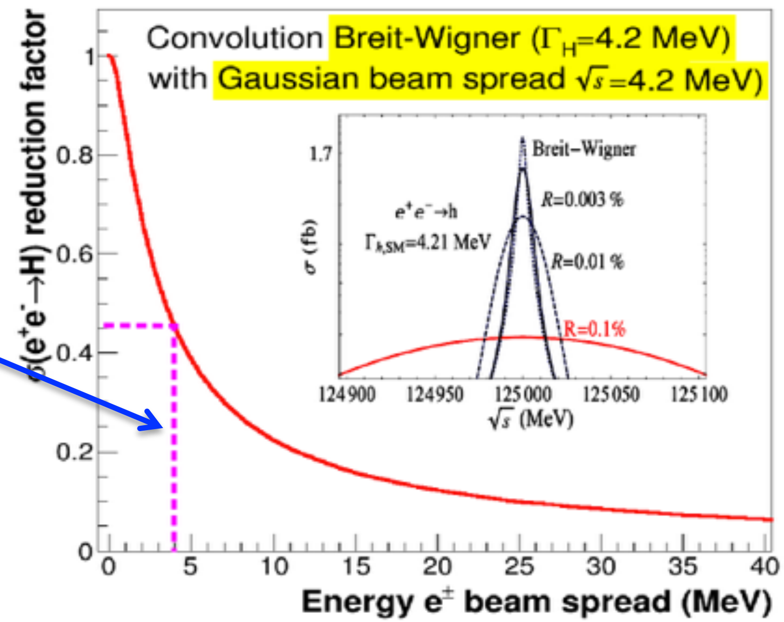
- Indirect and model dependent probe of Higgs self coupling
    - Utilizing excellent precision g_{ZH} measurements
- The NLO self coupling correction is energy dependent
- Indirect constrain in δ_Z-δ_h parameter space under specific model assumptions

Matthew McCullough
Phys. Rev. D 92, 039903



First generation couplings

- s-channel Higgs production
  - Extract electron Yukawa coupling
- Very challenging: $\sigma(ee \rightarrow H) = 1.6$ fb
- Beams ISR and finite energy spread reduce it to σ~290 ab (for √s spread~Γ_H)
- Can energy yield spreads of Higgs width or smaller be achieved?
  - Monochromatization is required
  - What is the cost for luminosity?
- Polarization enhances σ
  - What is the cost for luminosity?
  - x2 for P=70%

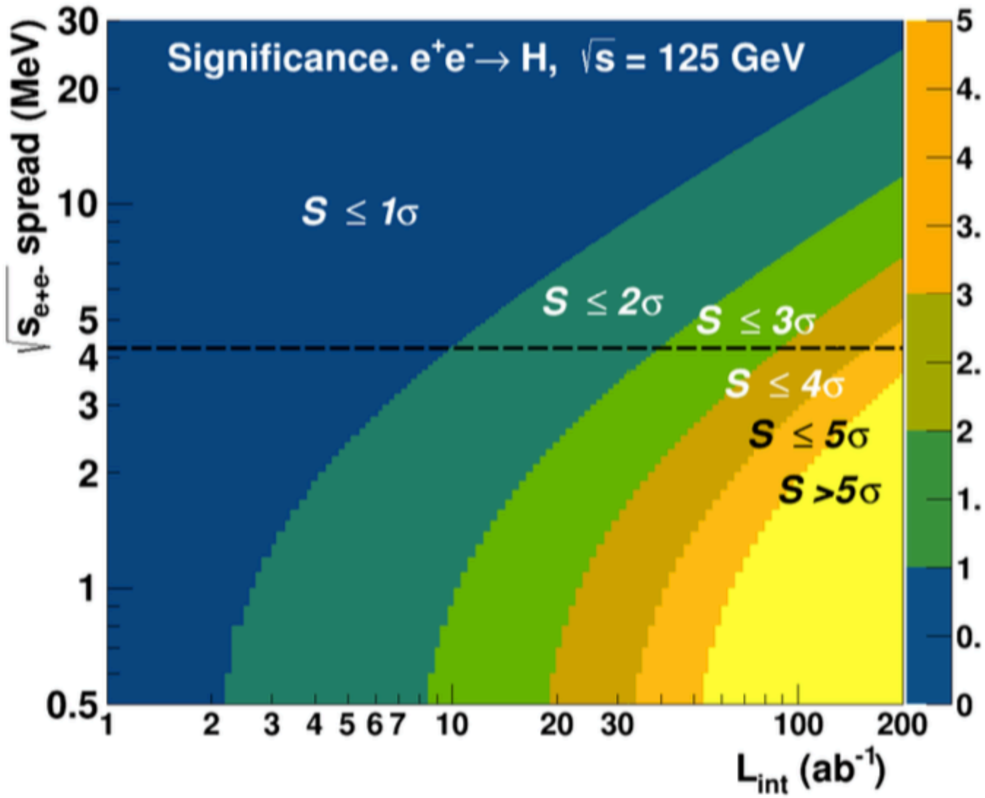


d'Enterria-Wojcik-Aleksan
arXiv:1701.02663

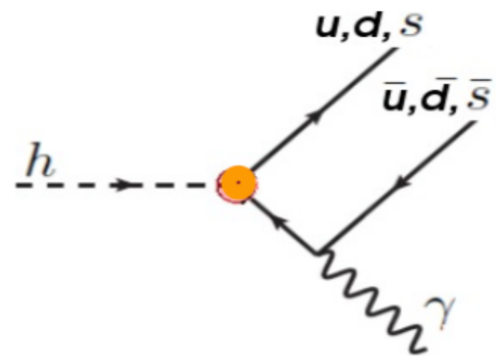
Electron Yukawa coupling

- Ten Higgs final-state decay channels
  - Significance and limits on e-Yukawa
  - 3σ observation requires 90 ab^{-1}

d'Enterria-Wojcik-Aleksan
arXiv:1701.02663

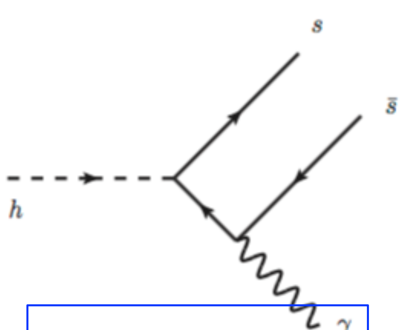


First generation couplings 2

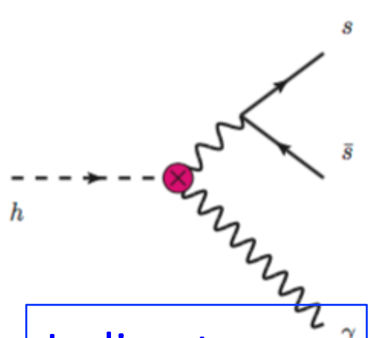


- Exclusive Higgs boson decays
  - First and second generation accessible
  - ρ(ππ)γ decay is the most promising
    - BR=1.9x10^{-7}
    - About 50 events expected
    - Sensitivity to u/d Yukawa couplings

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]\cdot 10^{-5}}{0.57\bar{\kappa}_b^2}$$



Vector meson



Indirect

A.L.Kagan, et. al.
PhysRevLett.114.101802

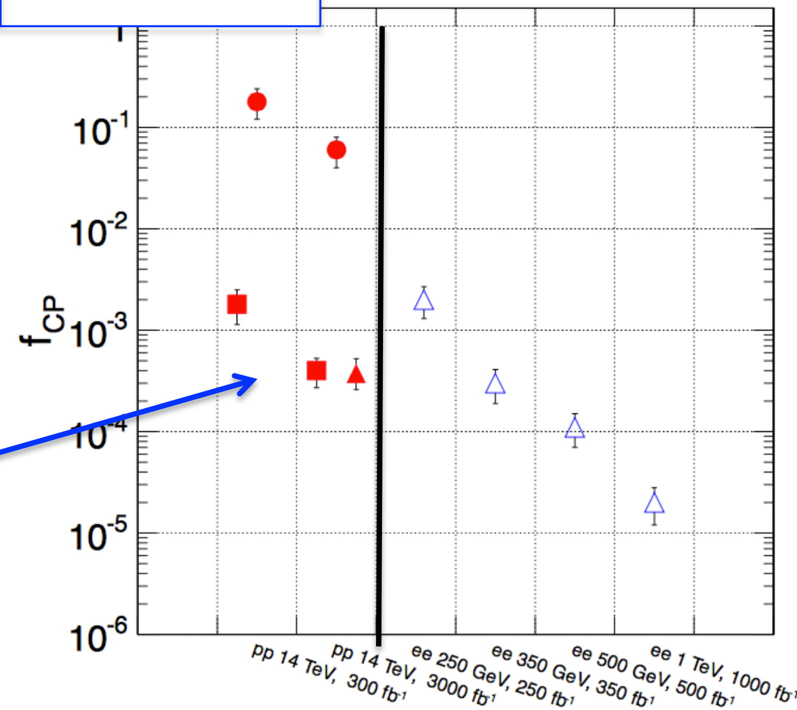
Higgs CP measurement

- CP violation can be searched by searching for CP odd contributions

$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

- Fraction of CP-odd contribution

$$f_{CP} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$$



- Snowmass Higgs Paper [1310.8361]
  - Circles: H->VV
  - Triangles: HZ
  - Squares: VBF

Higgs CP measurement 2

- H->ττ decay is a promising channel to study the CP violation
- Tree level couplings to quarks and leptons
  - CP-even and CP-odd couplings induced at the same order

$$\mathcal{L}_{h\bar{f}f} = \cos\alpha y_f \bar{\Psi}_f \Psi_f h + \sin\alpha \tilde{y}_f \bar{\Psi}_f i\gamma_5 \Psi_f h.$$

- CP violation can be probed through τ polarization
  - τ decays clean enough that the spin information is not washed out by hadronization effects
  - Pion is preferably emitted in the direction of the τ spin in rest frame

$\sqrt{s}$=250 GeV
1 ab^{-1} integrated lum.

$\sigma_{e^+e^-\to hZ}$	0.30 pb
$\mathrm{Br}(h \to \tau^+\tau^-)$	6.1%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%
$\mathrm{Br}(Z \to \text{visibles})$	80%
N_{events}	990
Accuracy	4.4°

arxiv:1308:1094

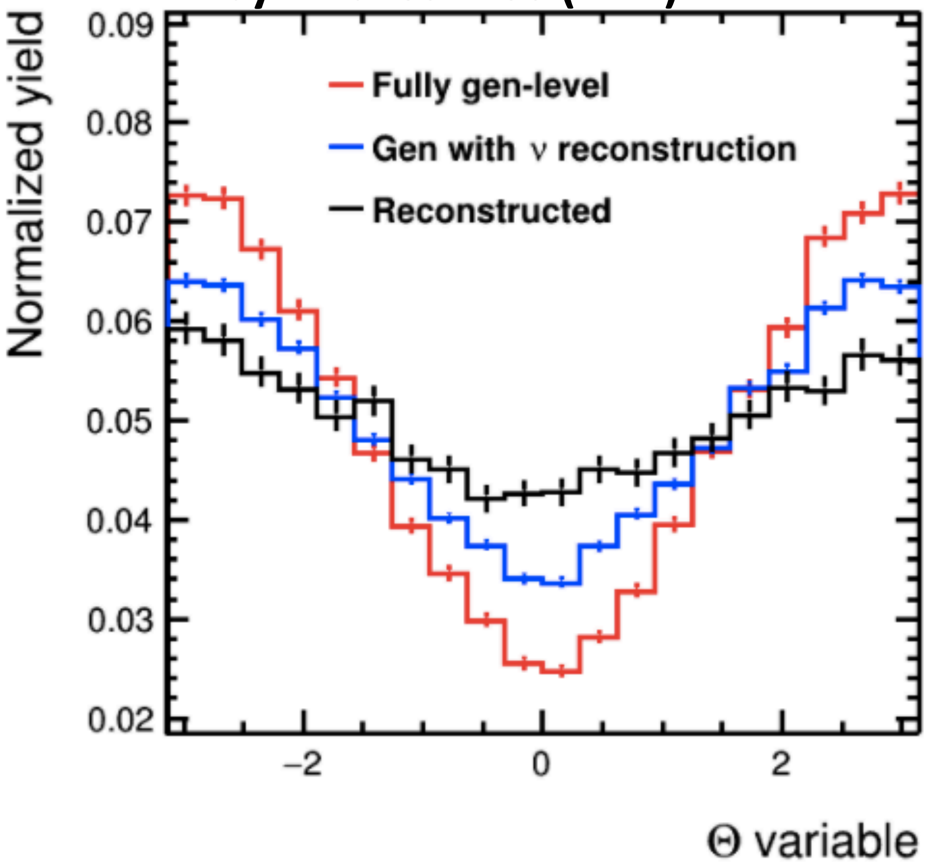
Theta variable

- The approach is to explore

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

- Detector performance has large impact on the analysis
  - Impact on selection efficiency and performance of the Θ variable
  - ILC-like detector with Delphes
- Mass resolution is leading followed by the tau selection
- Work in progress to map this to detector performance

by Andres Rios (MIT)



Summary

- Precise Higgs measurements
- Exploring the physics potential beyond TLEP physics case studies
    - Exciting FCC-ee Higgs program
- Investigating requirements and constraints on detector
    - Impact of detector performance on Higgs measurements
    - Ongoing work
- Unique constraints on first generation Yukawa and Higgs trilinear self couplings at FCC-ee