Higgs Physics
experimental overview

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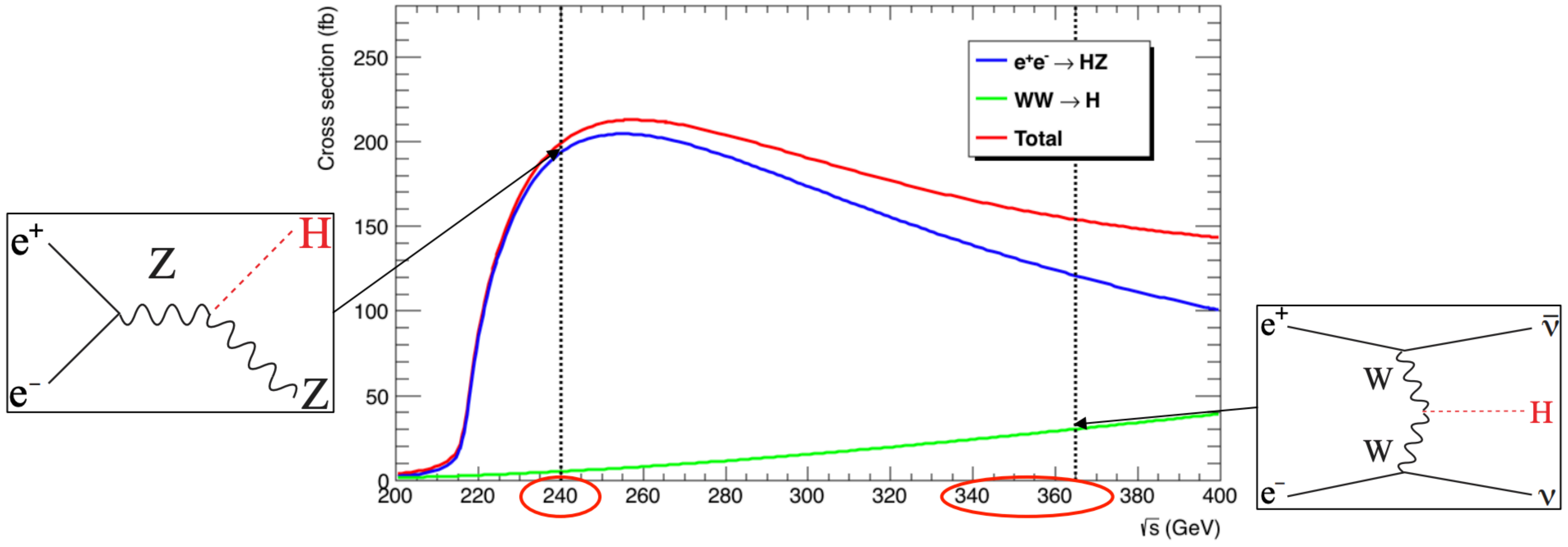
FCC Physics Workshop ’23 Krakow

FCC-ee program

- ee-collider (FCC-ee) (2/4 IPs):
  - $\sqrt{s}$ = 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)

- FCC-ee offers ideal environment for Higgs physics
  - large rates (> 1e6)
  - clean exp. environment (no UE, Pile-up, low event rate)
  - Large S/B (no QCD background)

- Production mechanisms
  - Higgs-strahlung
  - VBF



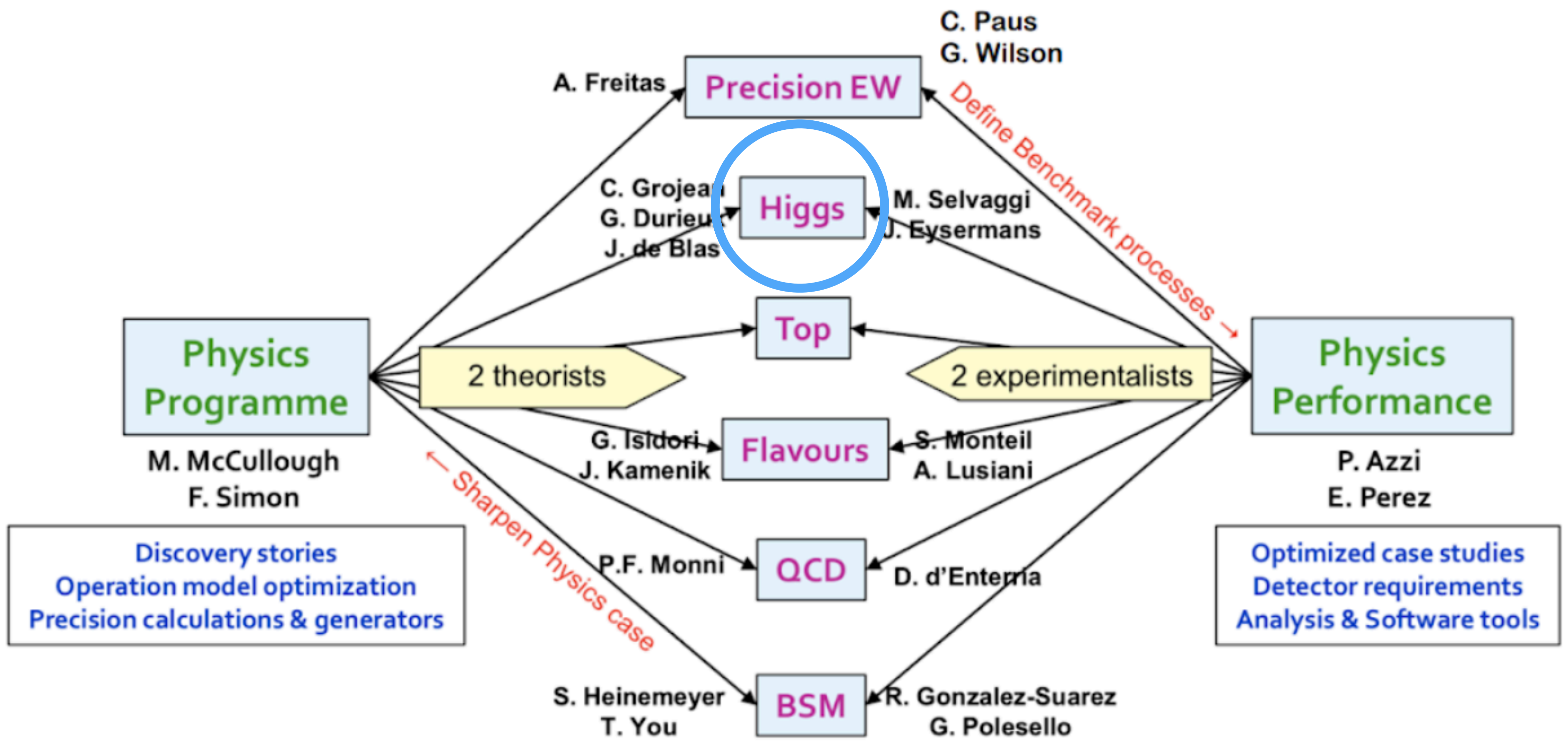
2IP

	L = 5 ab^{-1}	L = 1.5 ab^{-1}
	ZH = 10^{6}	ZH = 2.5×10^{5}
	VBF = 2×10^{4}	VBF = 5×10^{4}

Overview of Higgs analyses

- Intrinsic properties
  - mass
  - ZH cross section (decay mode independent)
  - width
  - self-coupling (FCC-ee/hh)

- Higgs couplings
  - vector bosons
  - jets
    - bb/cc/gg/ss
  - electron (production)
  - taus
  - rare (μμ/γγ/Zγ)



Goal: establish the detector requirements that maximise the Higgs physics potential

- as part of the FCC Feasibility Study, to be completed by the end of 2025
- Mid-term review of feasibility study in 2023

Overview of Higgs analyses

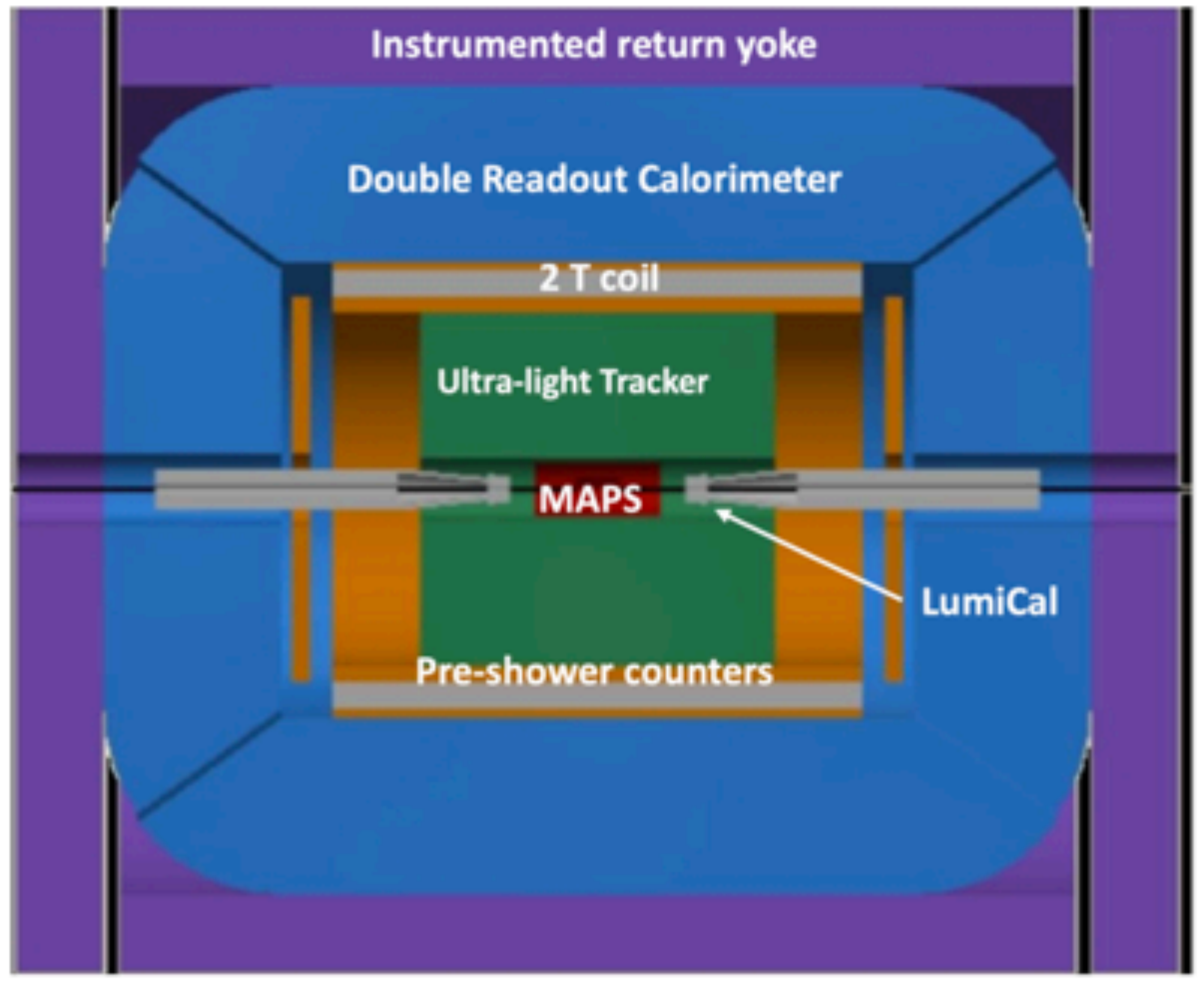
- $H\rightarrow$ hadrons
  - Z(ll) H (Marchiori, Maloizel - Paris, CERN)
  - Z(vv)H (Del Vecchio, Gouskos, MS - CERN)
  - Z(jj) H (Aly, Bari)
- $Z \rightarrow X$ $H\rightarrow$ anything (recoil)
  - $Z\rightarrow$ ll/jj :
    - xsec, mass (Eysermans, Bernardi, Li - MIT, Paris)
    - Self coupling (Salerno/Portales, Lemmon - LLR/Liverpool/Brookhaven)
- $H\rightarrow$ invisible (Mehta, Rompotis - Liverpool)
- $H\rightarrow \tau\tau$ and BSM (Cepeda Madrid, KIT)
- $ee\rightarrow$ H (d'Enterria, Guntam - CERN/Hamburg)
- FCC-hh - HH combination (MS, Taliercio, Caputo, Stapf, Gallo - CERN, NWU, DESY)

Detector description and samples

- Detector simulation baseline:
  - IDEA with Delphes
    - full track covariance reconstruction
    - Jet tagging using Weaver/Particle NET
      - Flavors: g/b/c/s/light

Bedeschi, MS

Del Vecchio, Garcia Marti, Gouskos, MS

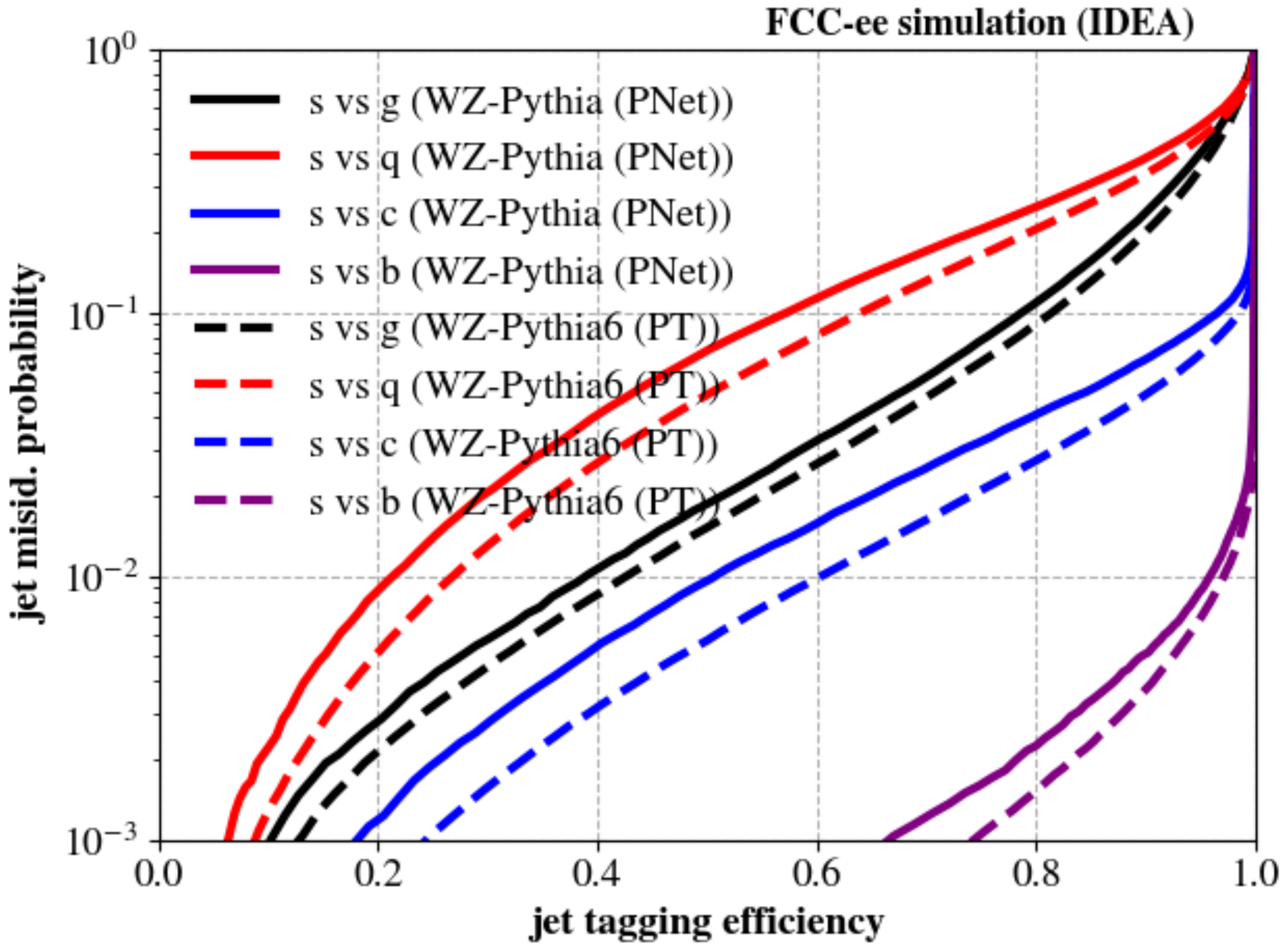


IDEA

- Recent updates:
  - "Realistic" electron description
    - including brem recovery
  - smaller beampipe
  - ECAL crystal for better ele/photon performance

Perez, MS

L. Gouskos (Thursday)

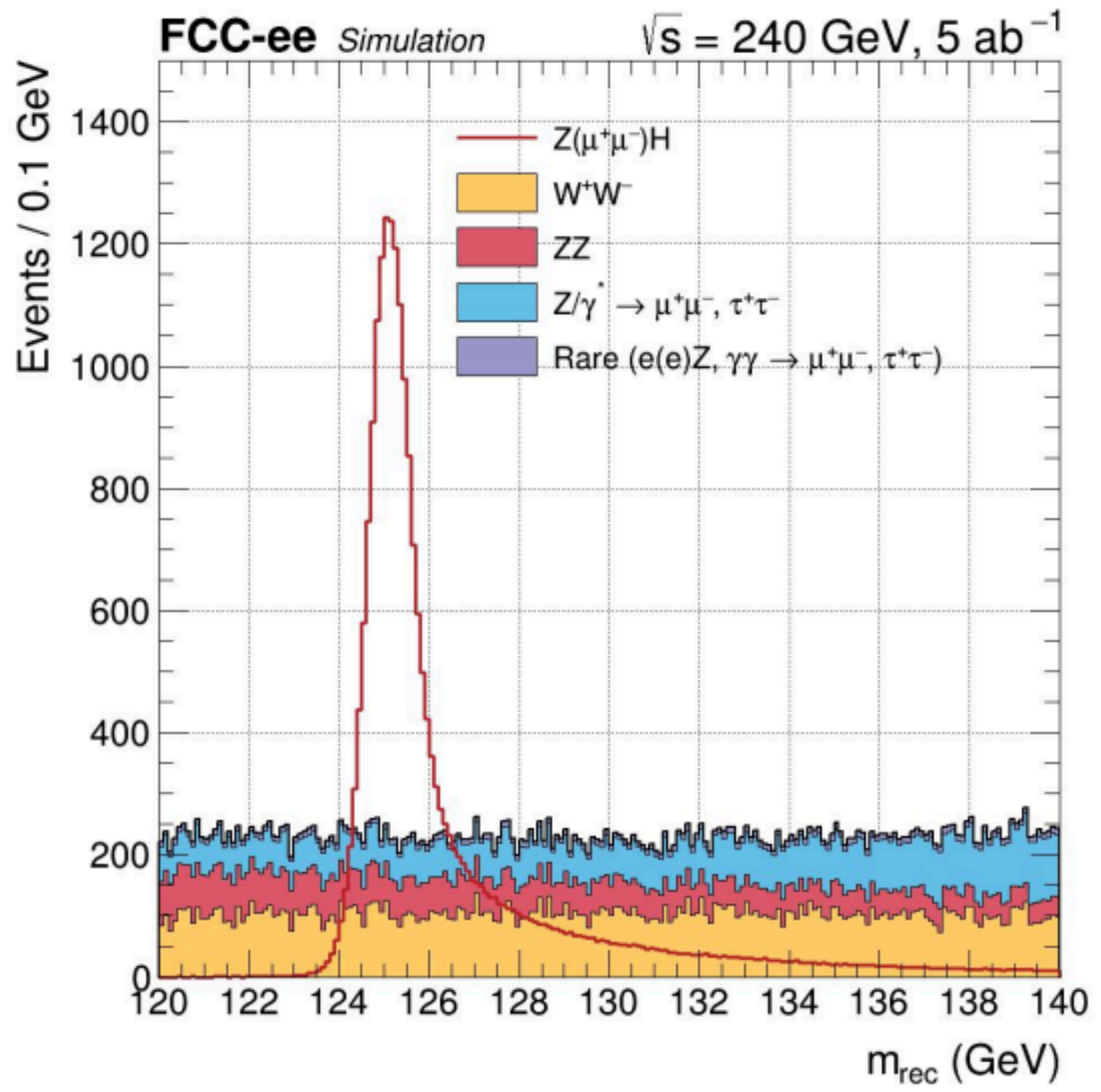


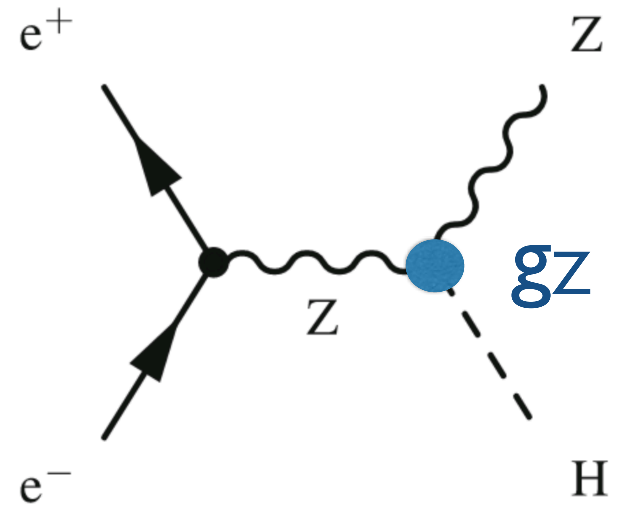
- Samples:
  - Wizard3+ Pythia6
  - Pythia8

Portales

http://fcc-physics-events.web.cern.ch/fcc-physics-events/FCCee/winter2023/Delphesevents_IDEA.php

FCC-ee recoil





Higgs recoil mass measurement → ZH production cross section:

- 10^6 Higgs produced @ FCC-ee
  - rate ~ $\mathbf{g_Z}^{2}$ → $\delta g_Z/g_Z$ ~ 0.2 %
- Then measure ZH → ZZZ
  - rate ~ $\mathbf{g_Z}^{4} / \mathbf{\Gamma_H}$ → $\delta\Gamma_H / \Gamma_H$ ~ 1 %
- Then measure ZH → ZXX
  - rate ~ $\mathbf{g_Z}^{2}\,\mathbf{g_X}^{2} / \mathbf{\Gamma_H}$ → $\delta\, g_X/g_X$ ~ 1 %

Precise knowledge of center of mass allows for:

- tag the Z by reconstructing pair of leptons
- reconstruct the the recoil mass

$$m^2_{\text{recoil}} = s - 2\sqrt{s}E_{\text{di-lepton}} + m^2_{\text{di-lepton}}$$

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

Bernardi, Li

Z(ll)H cross-section measurement

Goals:

- O(<%) on cross-section

Event selection:

- at least 2 leptons
- tight m_Z selection [86,96] GeV
- $p(\mu\mu)$ > 20,70 GeV
- $\cos(\theta miss)$

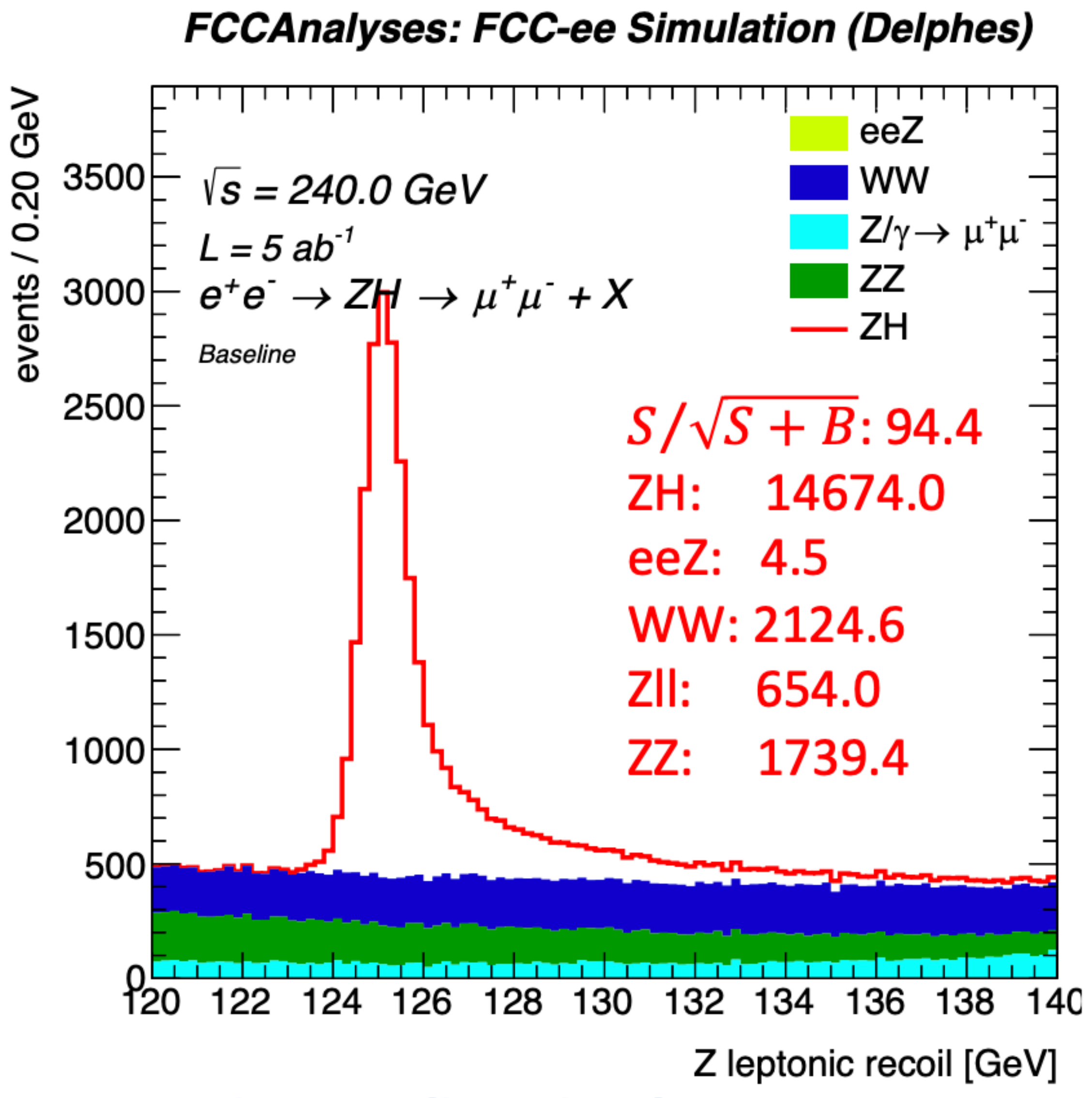
A. Li's talk (Friday)

Cross-section:

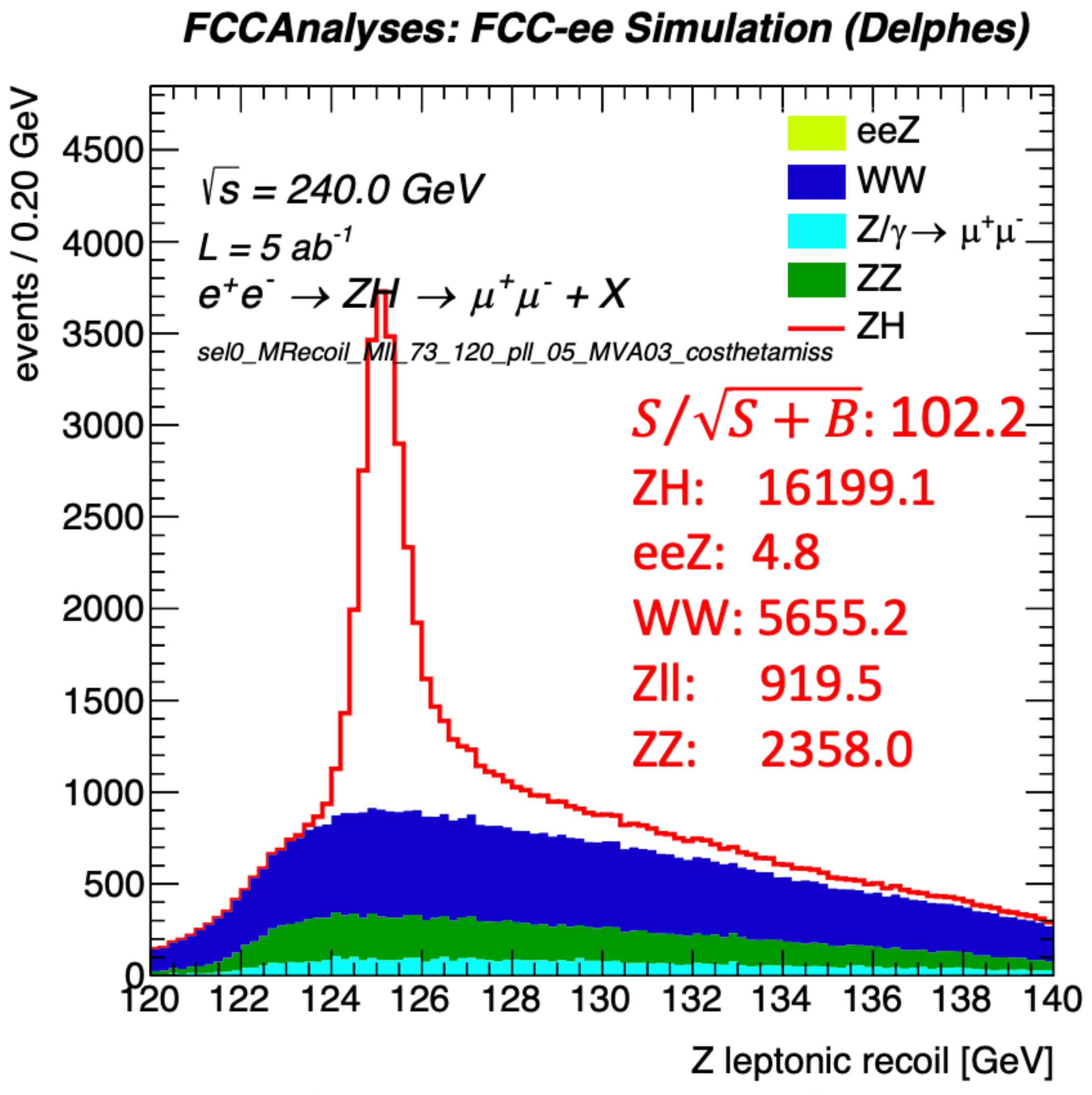
- Cut-based only μμ
  - $\delta\sigma_{ZH}$ ~ 0.95% (model dep.)
  - $\delta\sigma_{ZH}$ ~ 1.43% (model indep.)
- BDT:
  - $\delta\sigma_{ZH}$ ~ 1.28% (model indep.)

- Next: combined with ee;
  - $\delta\sigma_{ZH}$ ~ 0.9-1.0?

cut-based



bdt



Higgs mass measurement

Jan Eysermans

Goals:

- O(few MeV) precision on m_H

Event selection (common with sec):

- at least 2 leptons
- tight m_Z selection [86,96] GeV
- p(μμ) > 20,70 GeV
- measurement differential in θ

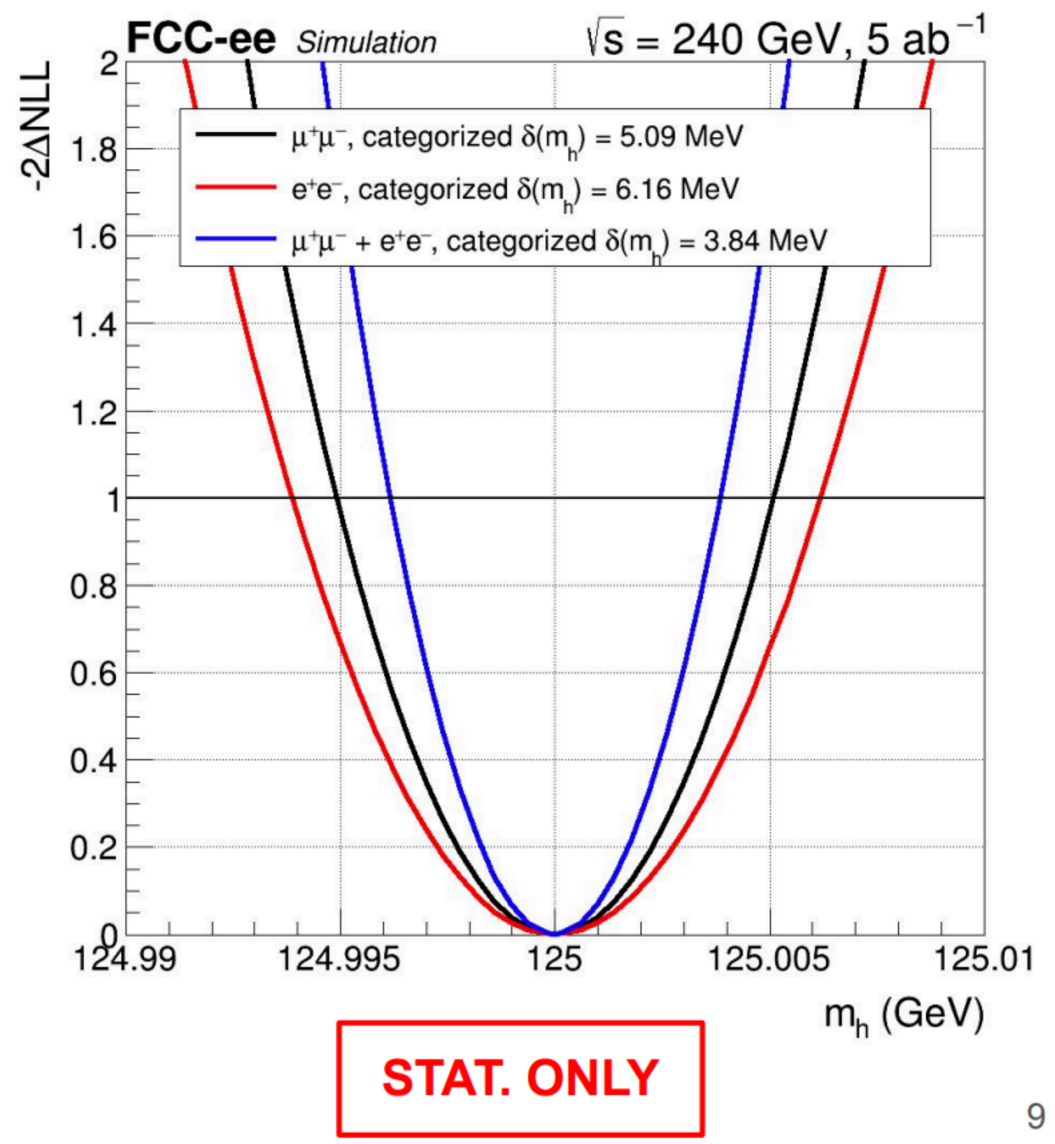
Systematics:

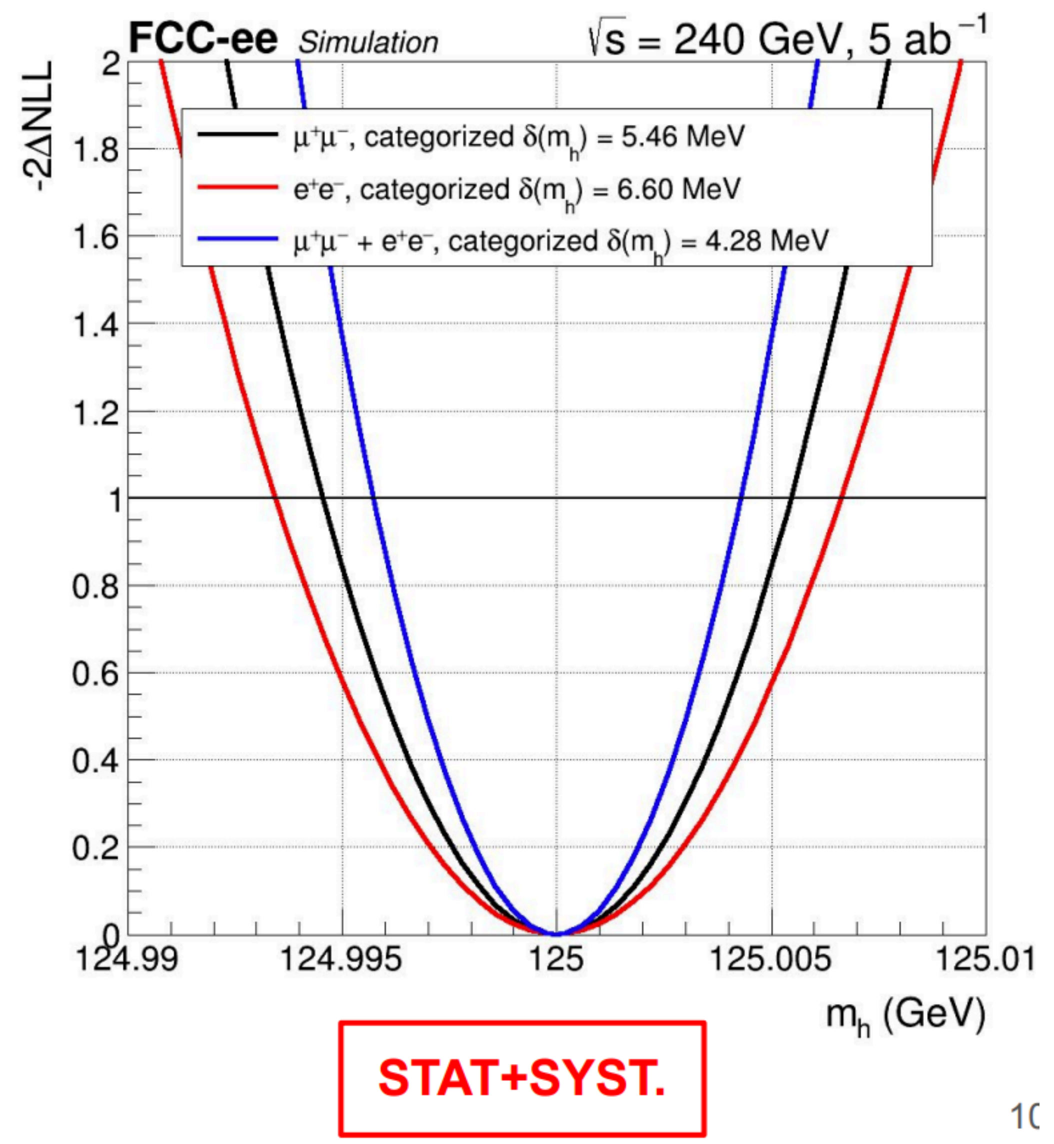
- Beam energy spread ~ **2e-03**
- C.O.M energy ~ **2e-05**
- Lepton scale ~ **2e-05**
- ISR ~ t.b.d

A. Li's talk (Friday)

m_H precision:

- Muon channel:
  - 5.1 MeV
- Electron channel:
  - 6.2 MeV
- Combined:
  - 3.8 MeV (stat. only)
  - 4.3 MeV (stat+syst)



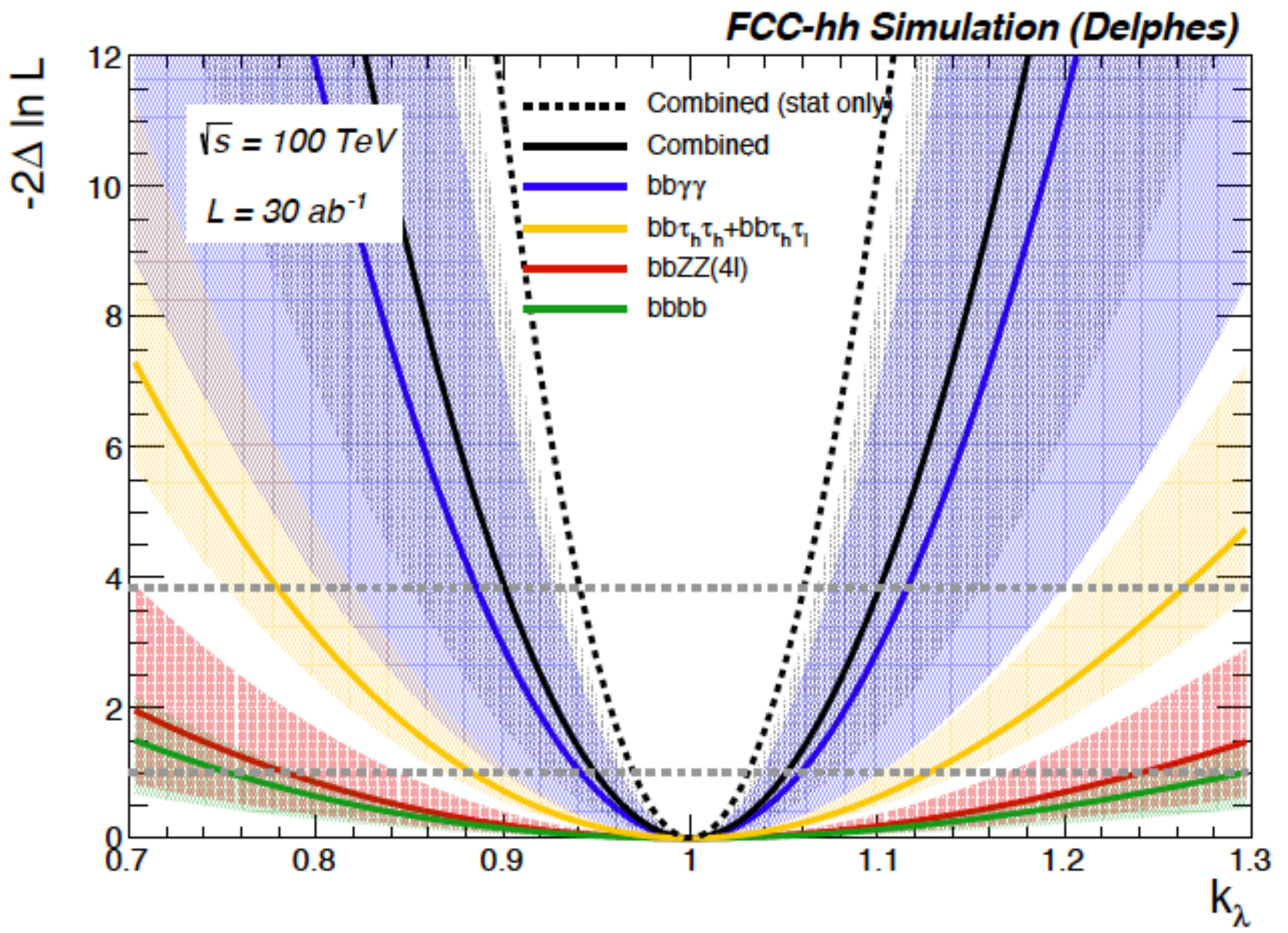


Higgs self-coupling

MS, MLM, Ortona

%-level precision only at the FCC-hh

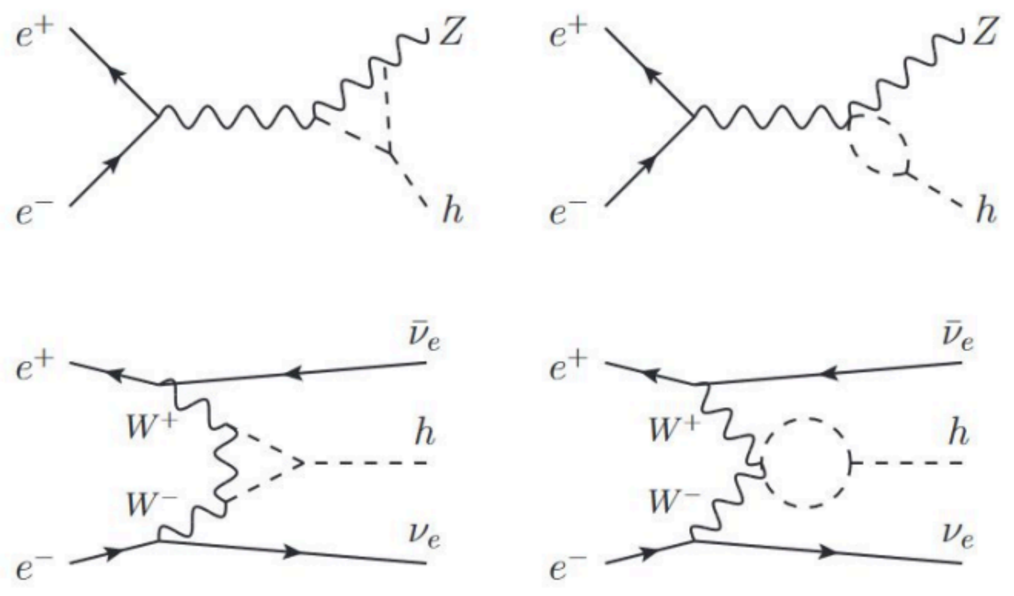
@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8

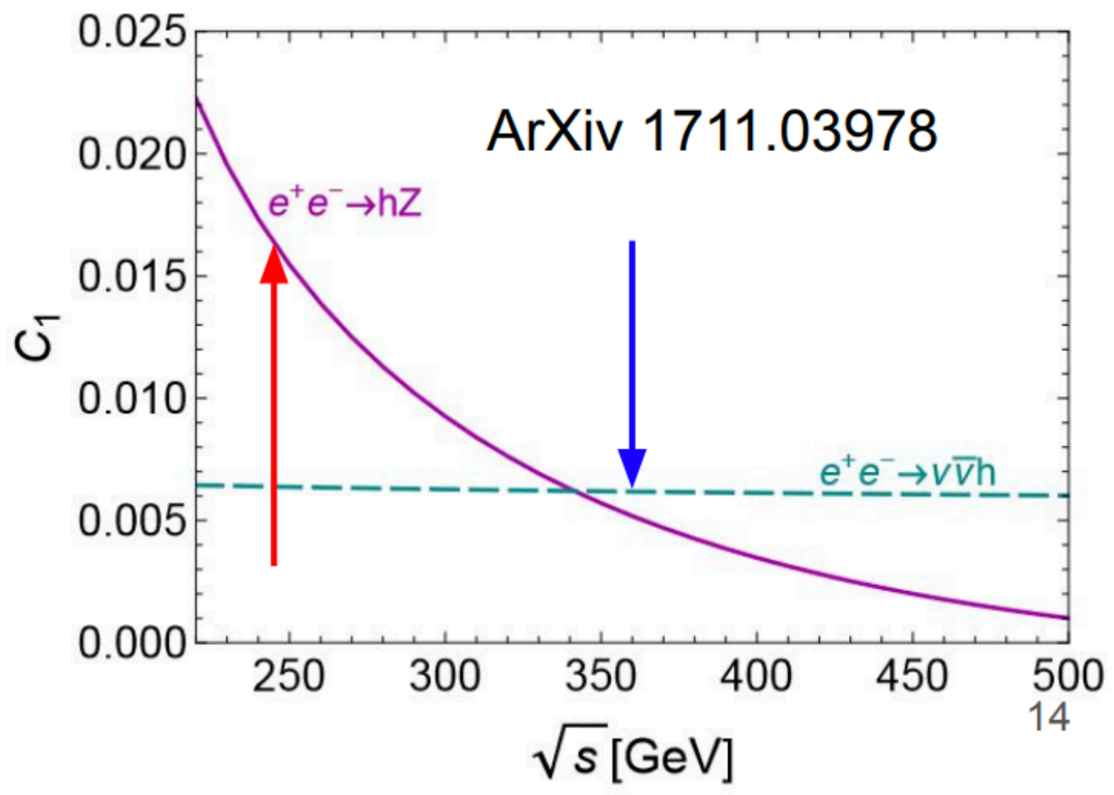


New effort started (new channel/extended parameter space/ revisited detector performance)

Salerno, Harringer, Lemmon, Portales

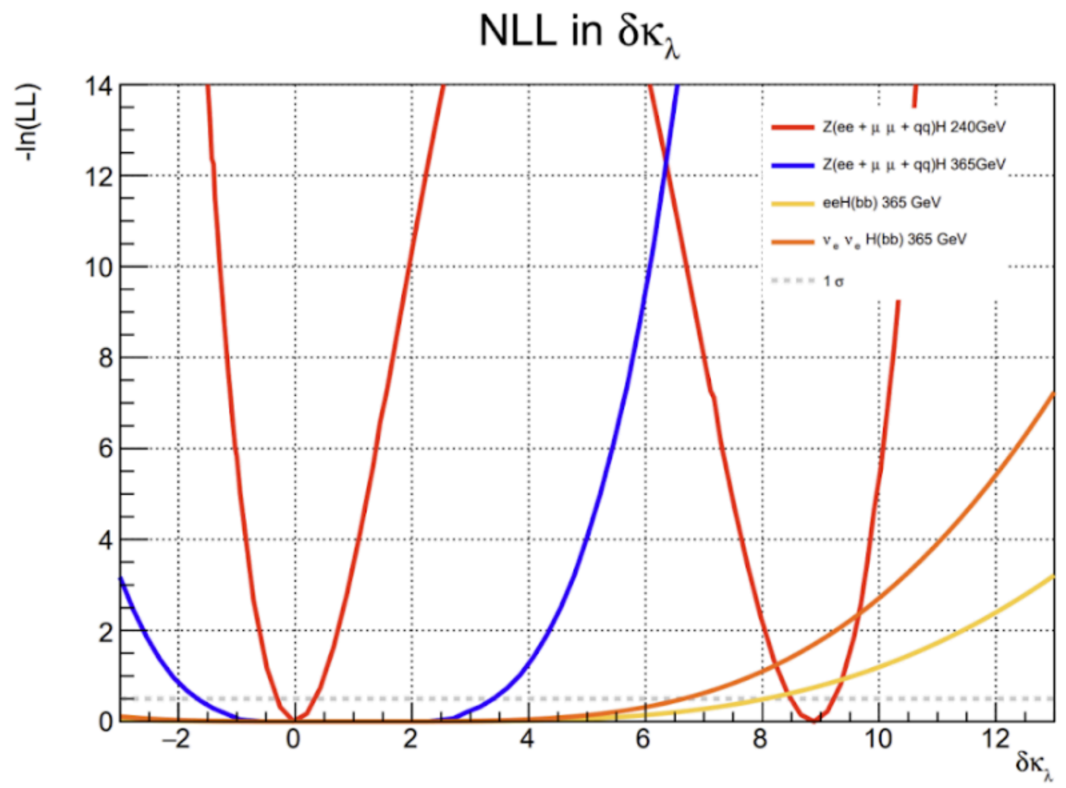
FCC-ee:
from radiative corrections to ZH/VBF single H production
($\sqrt{s}$=240, 365 GeV)





A. Li's talk (Friday)

experimental analysis

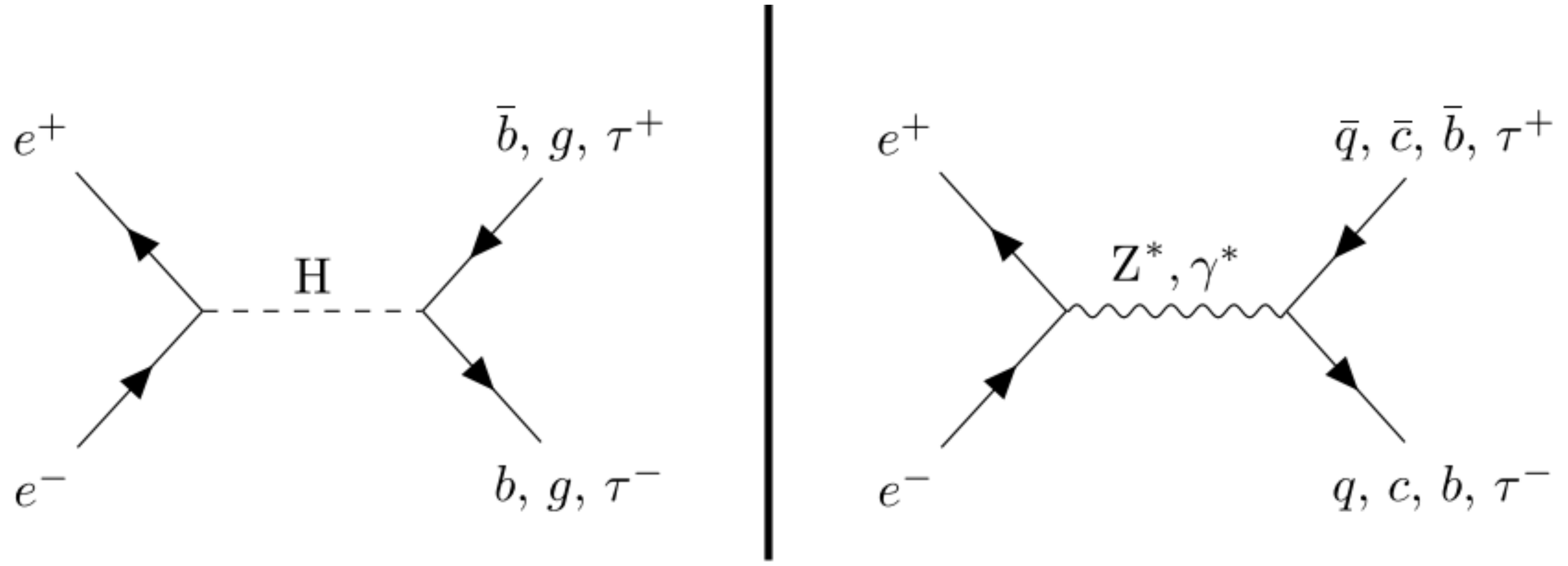


- state of the art fit to self-coupling precision:
  - 19% kl alone vs 33% full (EFT projected) with 2IPs
  - 14% kl alone vs 24% full (EFT projected) with 4IPs

J. De Blas (today)

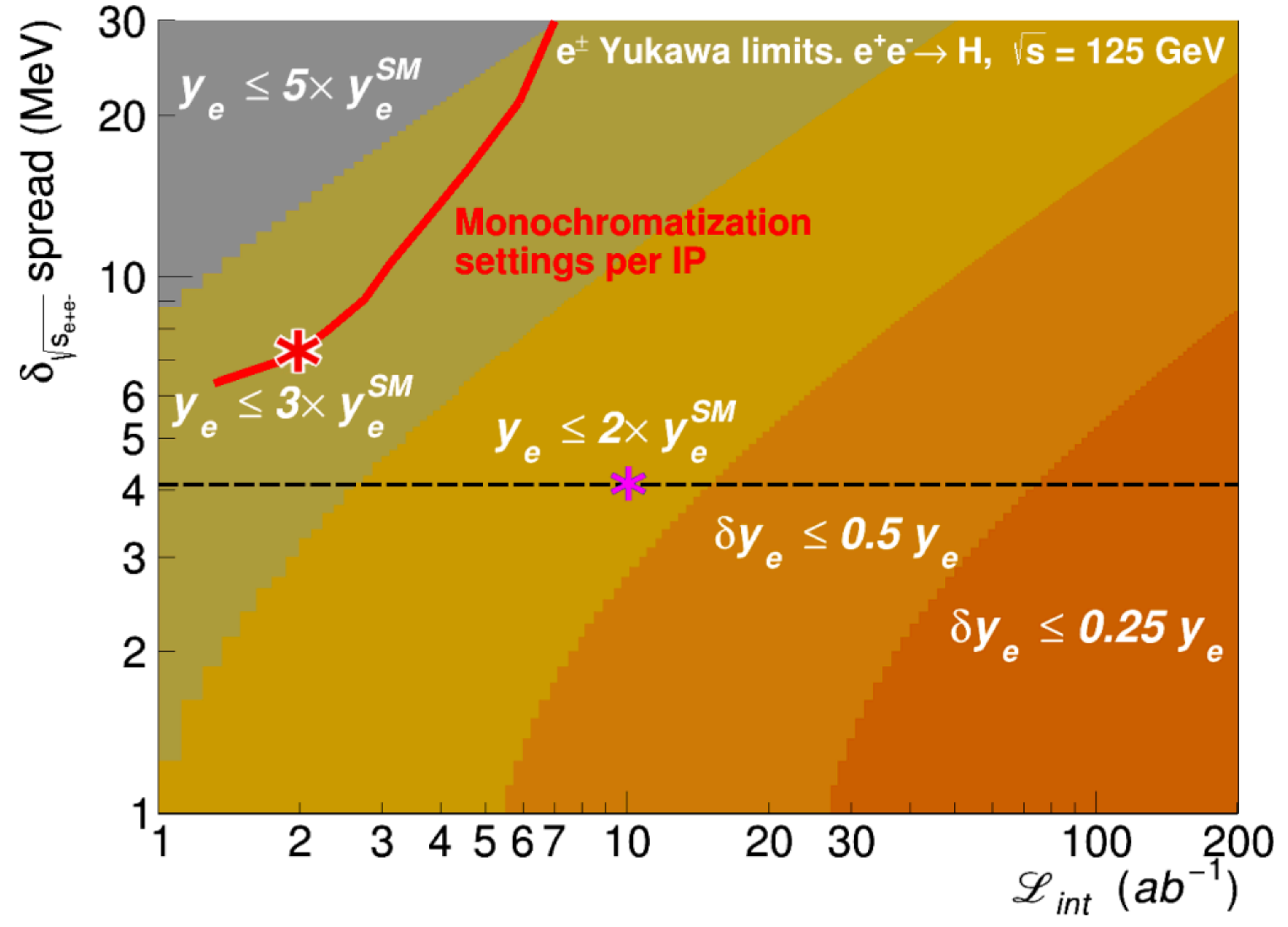
Electron Yukawa

D'Enteria

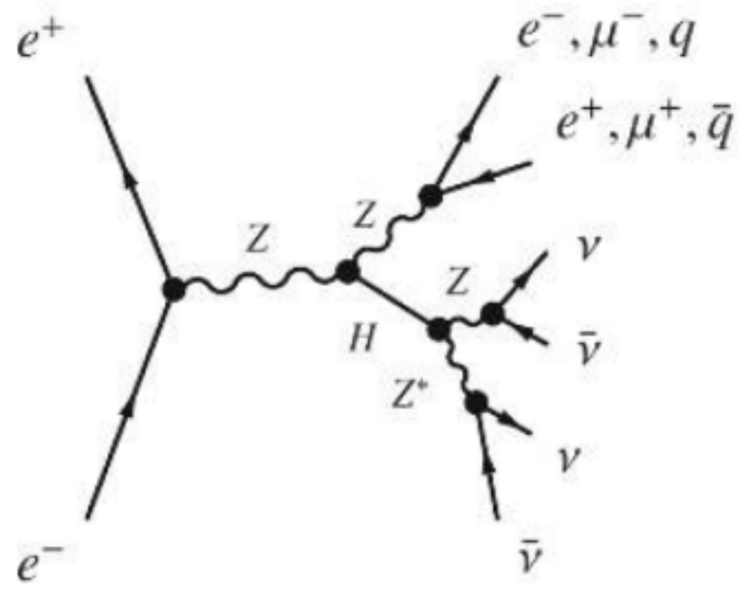


Higgs decay channel	BR	$\sigma\times$ BR (ISR⊗spread incl.)
$H\to b\bar{b}$	58.2%	164 ab
$H\to gg$	8.2%	23 ab
$H\to\tau\tau$	6.3%×60%×60%	6.5 ab
$H\to c\bar{c}$	2.9%	8 ab
$H\to WW\to\ell\nu\,2j$	21.4%×67.6%×32.4%×2	26 ab
$H\to WW\to 2\ell\,2\nu$	21.4%×32.4%×32.4%	6.3 ab
$H\to WW\to 4j$	21.4%×67.6%×67.6%	28 ab
$H\to ZZ\to 2j\,2\nu$	2.6%×70.%×20.%×2	2 ab
$H\to ZZ\to 2\ell\,2j$	2.6%×70.%×10.%×2	1 ab
$H\to ZZ\to 2\ell\,2\nu$	2.6%×20.%×10.%×2	0.3 ab
$H\to\gamma\gamma$	0.23%	0.65 ab

- s-channel production with beam mono-chromatisation at $\sqrt{s}$ = 125 GeV
  - ISR+FSR leads to 40% + with beam spread ~ Γ_H another 45% (σ ~ 280 ab^{-1})
    - 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
    - potentially improve with exclusive ee→gg(cc)

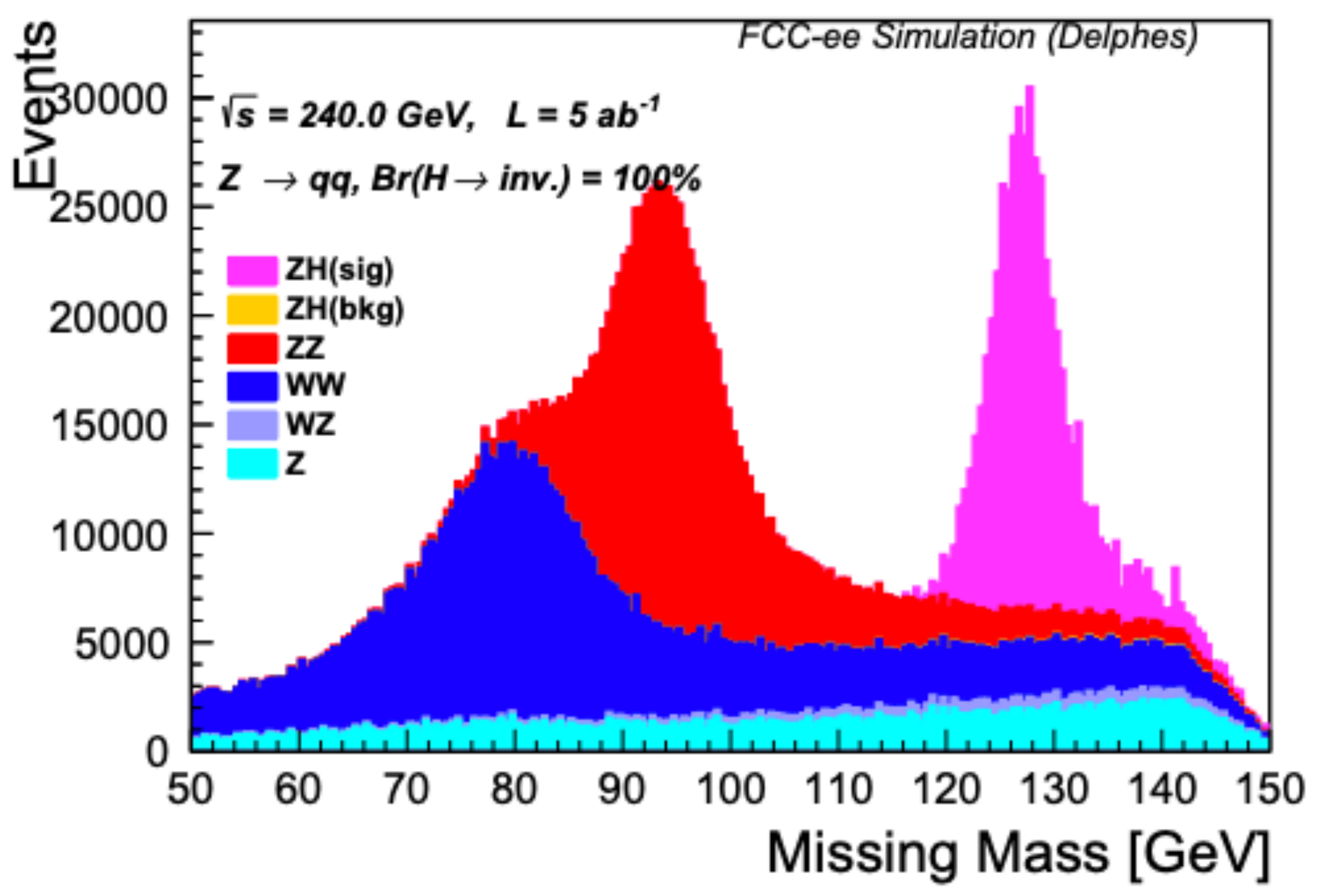


Higgs to invisible

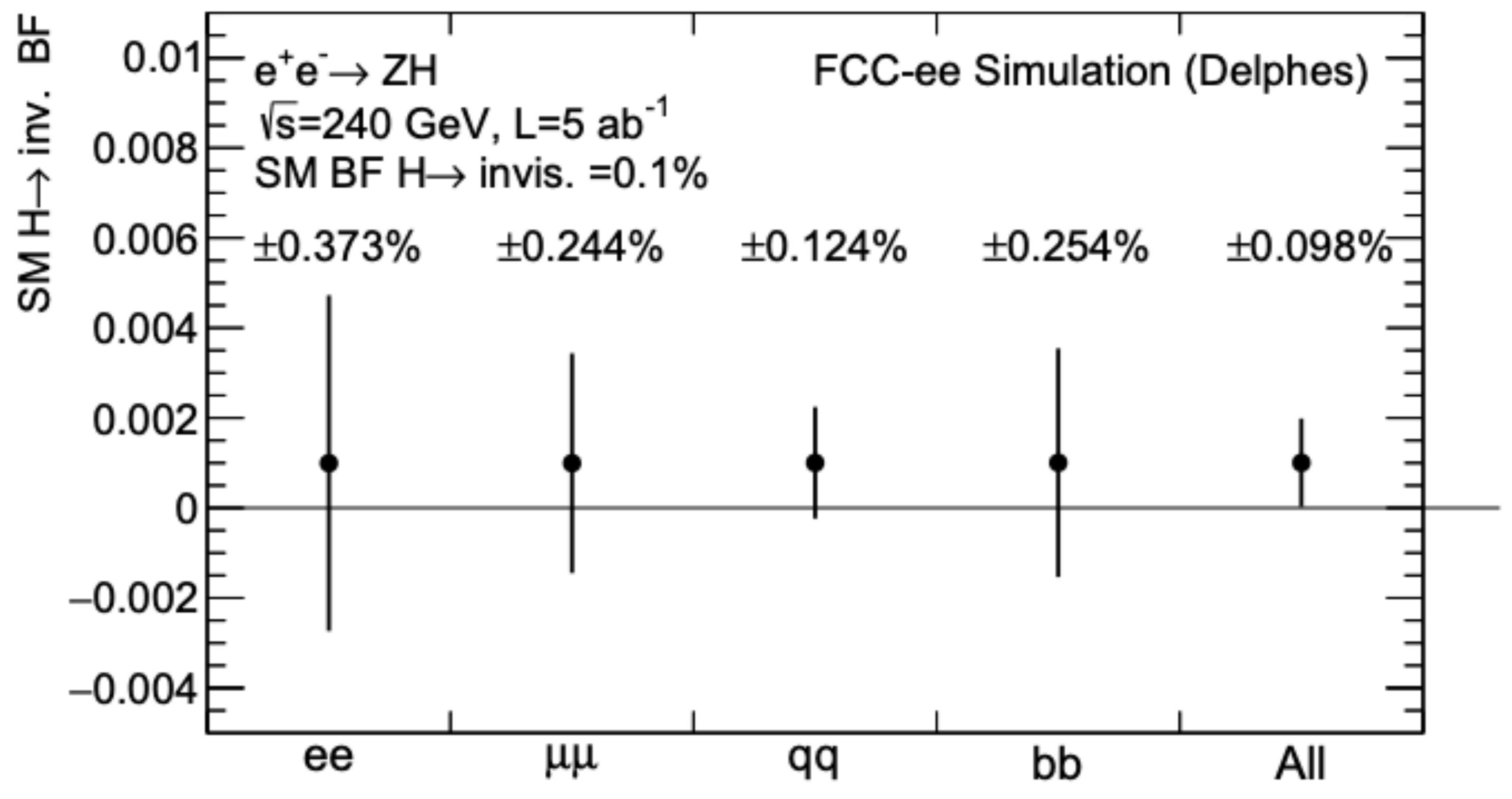


A. Mehta (today)

Mehta, Rompotis



- 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



- Event selection:
  - Split events into exactly 2e, 2μ and 0 e+μ (bb/qq)
  - Reconstruct Z from 2 leptons or M_{vis}
  - Reconstruct M_{miss} from all visible particles
  - Use distribution of M_{miss} in likelihood fit

~ 100% sensitivity on SM BR(H→inv)

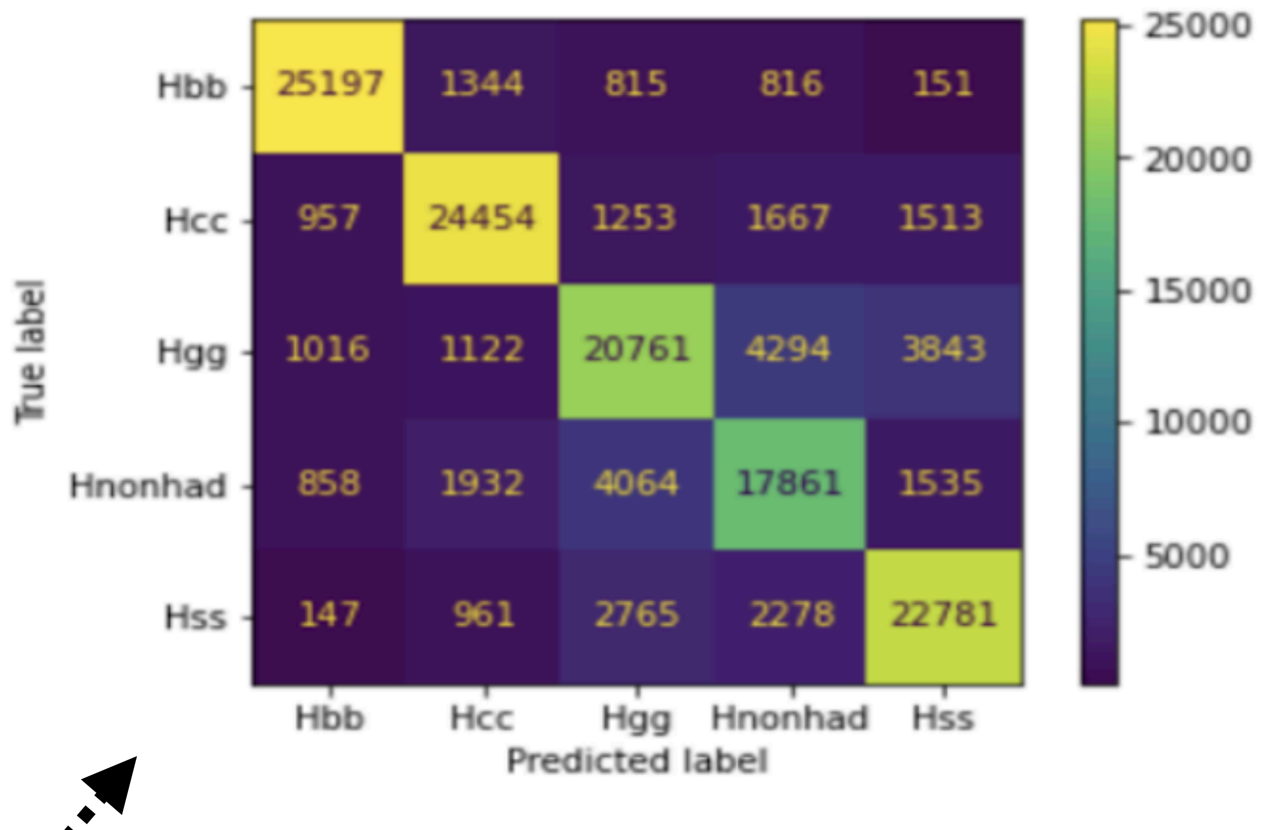
Higgs to hadrons (Z(LL))

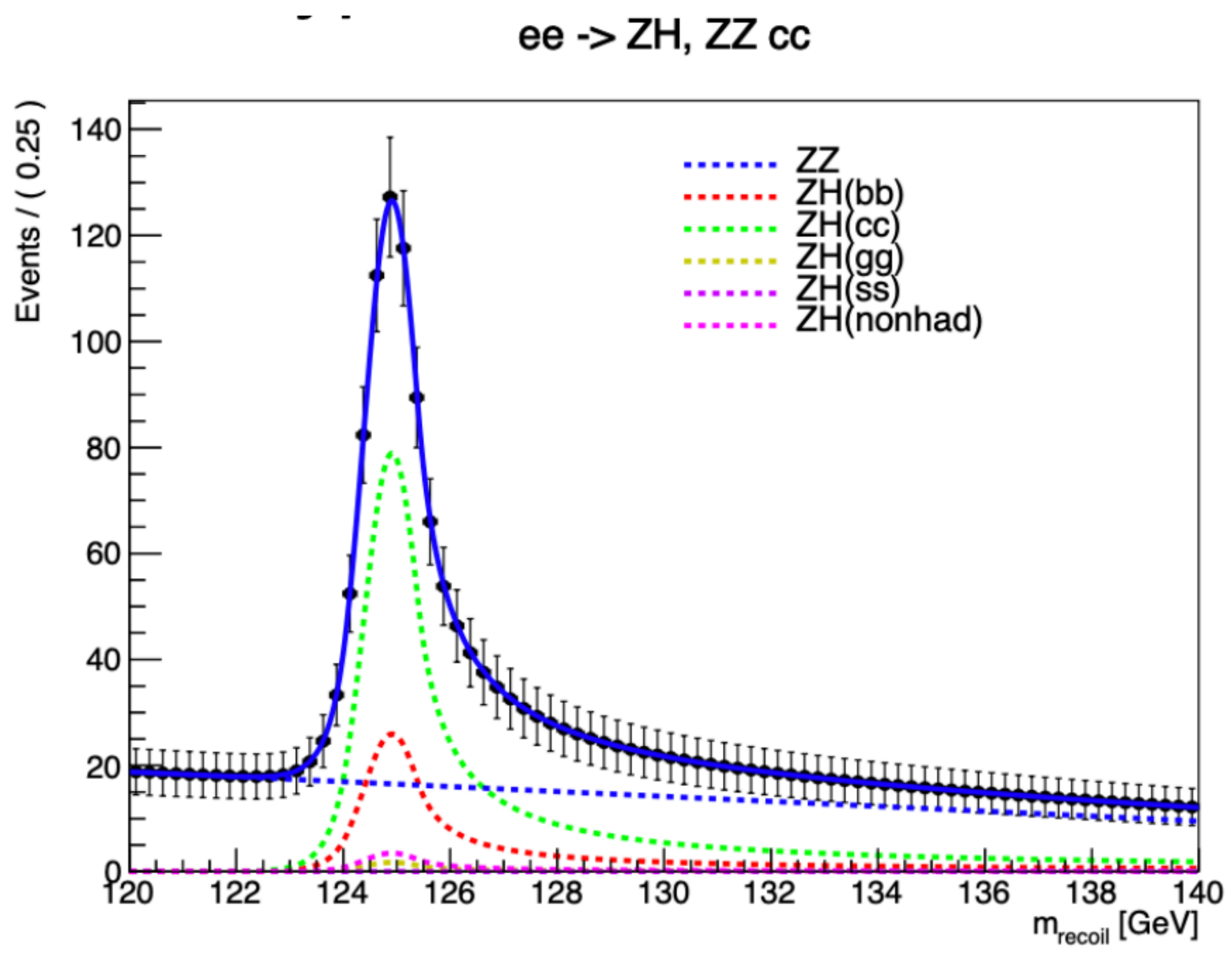
G. Marchiori (Friday)

Marchiori, Maloizel

- ee → ZH → l l j j
  - j = b, c, s, g
- Event pre-selection:
  - build recoil mass

one $Z(\ell\ell)$ candidate
$m_{\ell\ell}$ in 81–101 GeV
$|\cos\theta_{\ell\ell}| < 0.8$
m_{recoil} in 120–140 GeV
m_{jj} in 100–140 GeV
$p_{\text{miss}} < 30$ GeV
no leptons with $p > 25$ GeV
$d_{23} > 2,\ d_{34} > 1.5,\ d_{45} > 1.0$





- Final selection and signal extraction:
  - multi-score BDT using jet tagger output to maximise purity in
    - bb/cc/ss/gg/other final states
  - simultaneous un-binned fit on m_{recoil} on 4/5 signal strength modifiers POIs

Signal strength	Uncertainty (%)		
	5 POIs	4 POIs	3 POIs
$b\bar{b}$	0.86	0.86	0.86
$c\bar{c}$	6.44	6.45	6.43
gg	3.50	3.47	3.20
other	3.08	3.09	-
$s\bar{s}$	540	-	-

Higgs to hadrons (Z(νν))

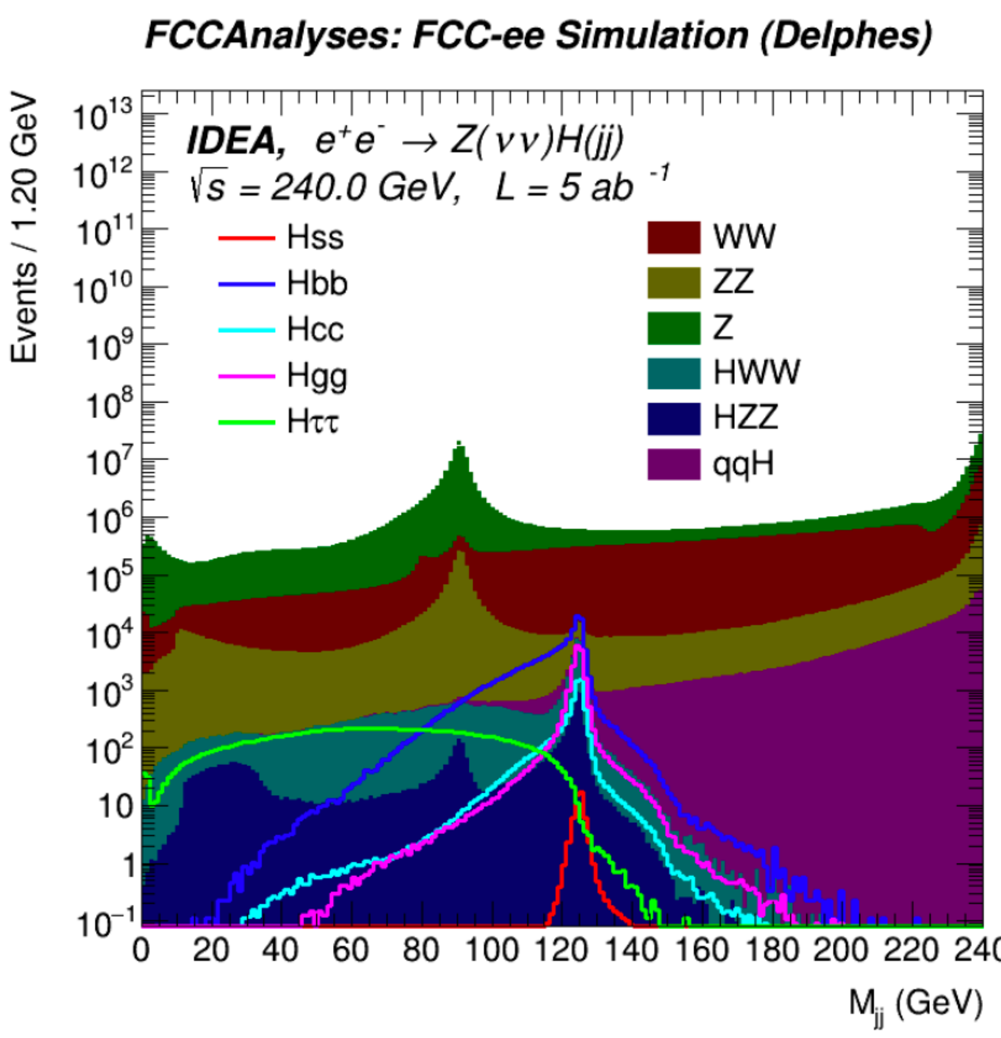
[G. Marchiori (Friday)](#)

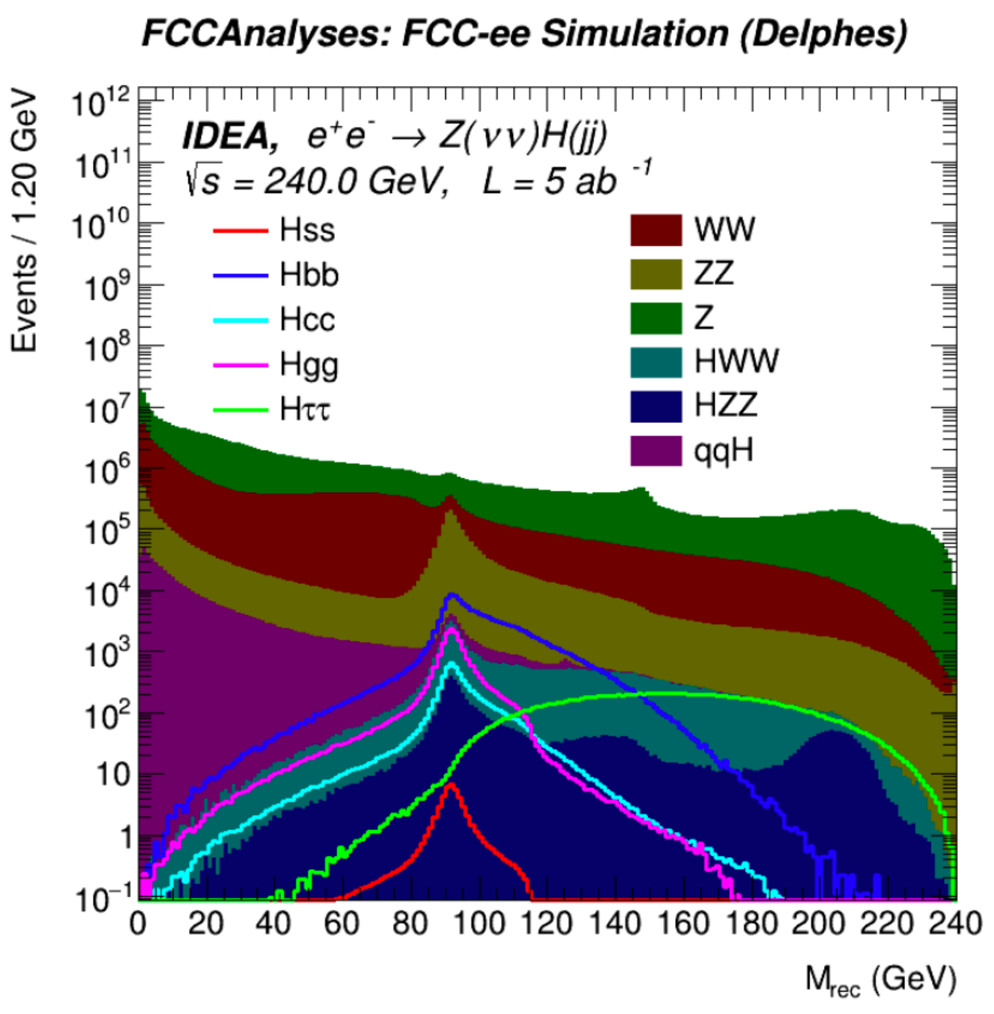
Del Vecchio, Gouskos, MS

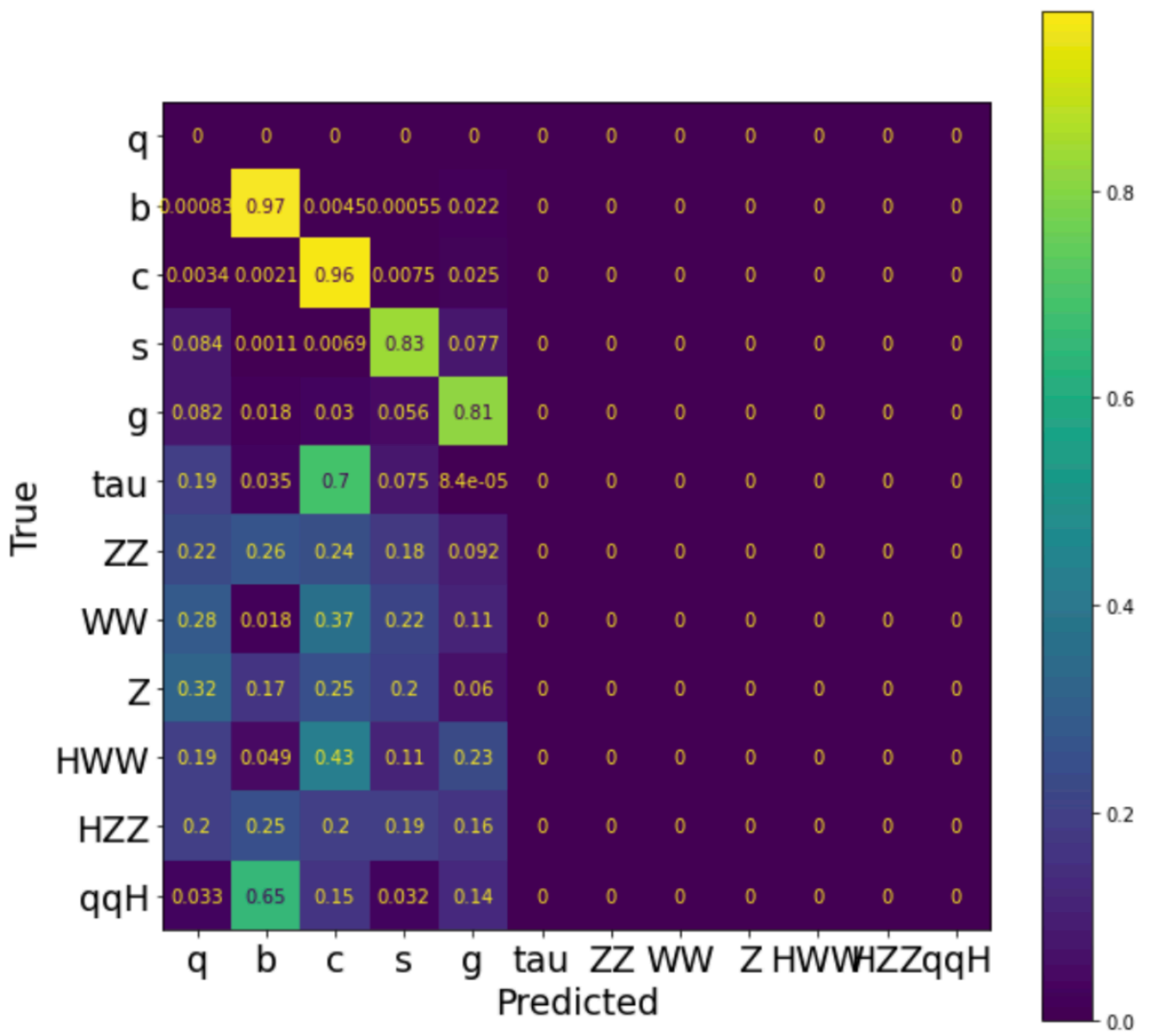
- ee → ZH → νν j j
  - j = b, c, s, g

Final States	Cross-section [pb]	BR(H)	BR(Z)	Expected Yields
signal				
$Z(\nu\nu)H(uu/dd)$	0.201868		0.2	
$Z(\nu\nu)H(bb)$	0.201868	0.571	0.2	$1.34 \cdot 10^5$
$Z(\nu\nu)H(cc)$	0.201868	0.0291	0.2	$6.68 \cdot 10^3$
$Z(\nu\nu)H(ss)$	0.201868	$2.50 \cdot 10^{-4}$	0.2	55
$Z(\nu\nu)H(gg)$	0.201868	0.0853	0.2	$1.89 \cdot 10^4$
$Z(\nu\nu)H(\tau\tau)$	0.201868	0.0626	0.2	$1.45 \cdot 10^4$
background				
ZZ	1.35899	-	-	$6.79 \cdot 10^6$
WW	16.4385	-	-	$8.22 \cdot 10^7$
Z	52.6539	-	-	$2.63 \cdot 10^8$
$Z(\nu\nu)H(WW)$	0.201868		0.2	$4.97 \cdot 10^4$
$Z(\nu\nu)H(ZZ)$	0.201868		0.2	$6.10 \cdot 10^3$
$Z(q\bar{q})H$	0.201868			$6.82 \cdot 10^5$

- Strategy:
  - Event preselection
    - lepton veto (orthogonalise)
  - build bb/cc/ss/gg orthogonal enriched categories using max sum of jet scores







Higgs to hadrons (Z(νν))

G. Marchiori (Friday)

Del Vecchio, Gouskos, MS

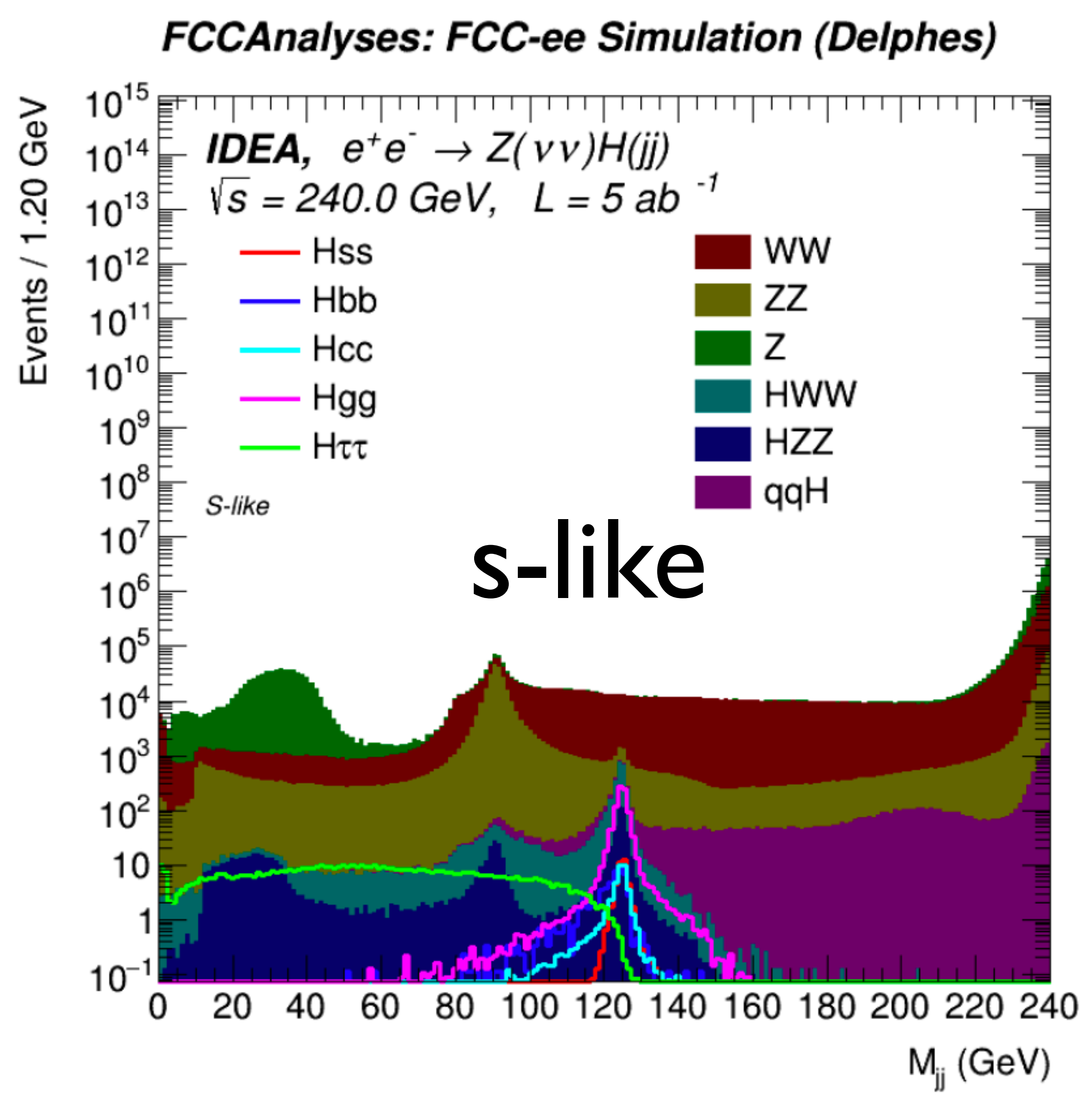
- ee → ZH → νν j j
  - j = b, c, s, g

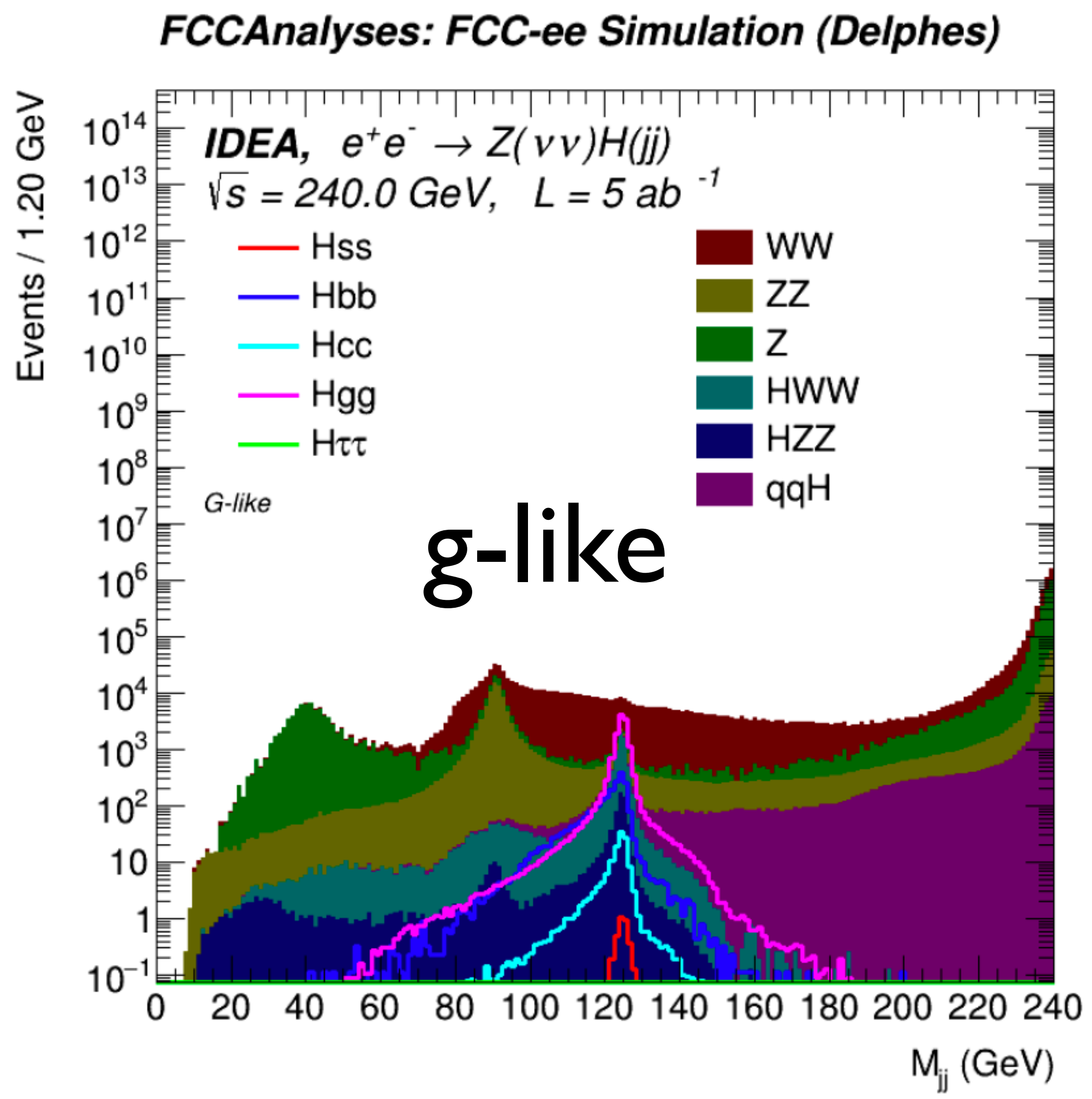
- Strategy (continued):
  - for each signal category (bb/cc/ss/gg)
    - define LP/MP/HP categories based on $s(j_1) + s(j_2)$
  - perform a 2D (m_{jj}, m_{recoil}) template fit on each of the 3x4 categories

Achievable precision:

decay	δμ/μ (%)
bb	0.4
gg	1.2
cc	2.8
ss	160

~ almost reaching SM sensitivity for H→ss





Conclusions & outlook

- Higgs activities are gaining in momentum
- Contact us if interested to join the effort
- Monthly informal meetings
- Many uncovered areas:
  - Higgs rare decays (μμ/γγ/Zγ)
  - Higgs Width (HWW/HZZ)
    - Higgs @365 GeV
  - Higgs to taus (polarisation/CP)
  - ....

FCC-ee Higgs conveners

Performance

Michele Selvaggi, Jan Eysermans

Programme

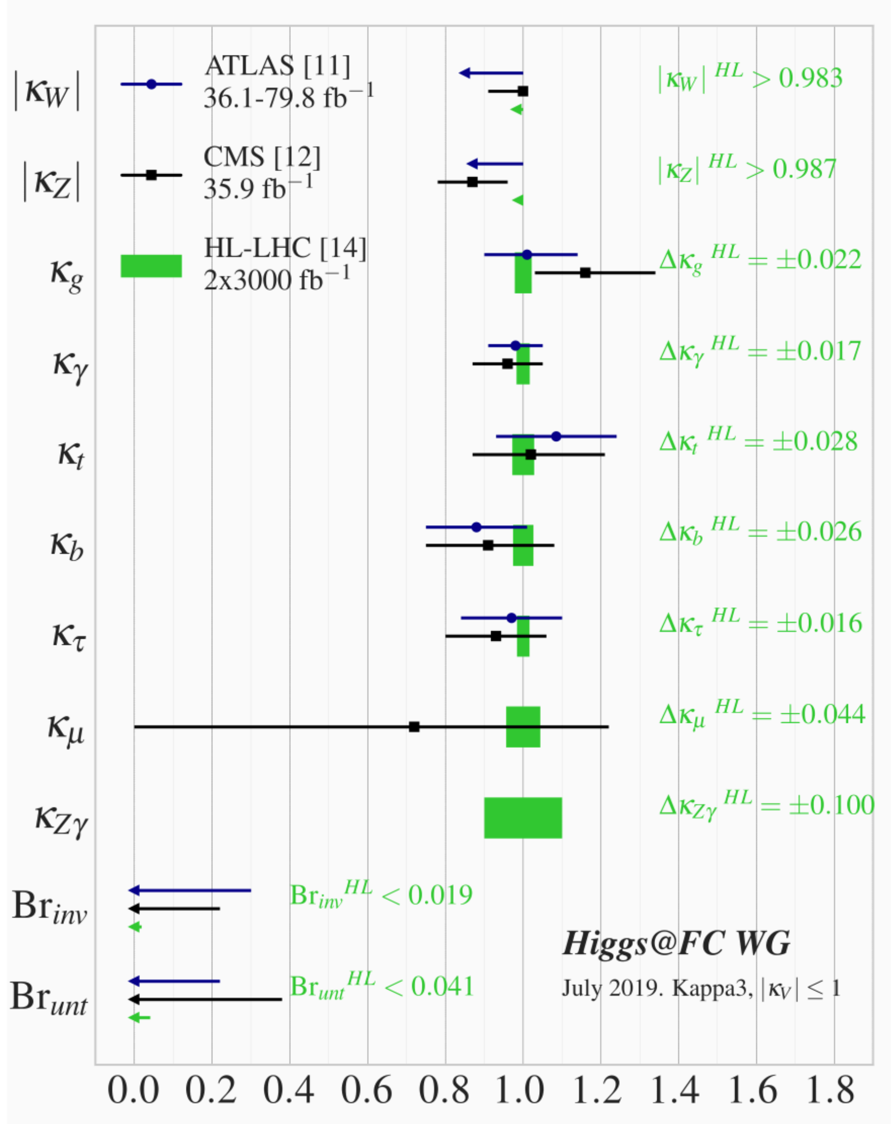
Gauthier Durieux, Christophe Grojean, Jorge De Blas Mateo

FCC-PED-PhysicsGroup-Higgs@cern.ch

Join the effort for an exciting future !

Backup

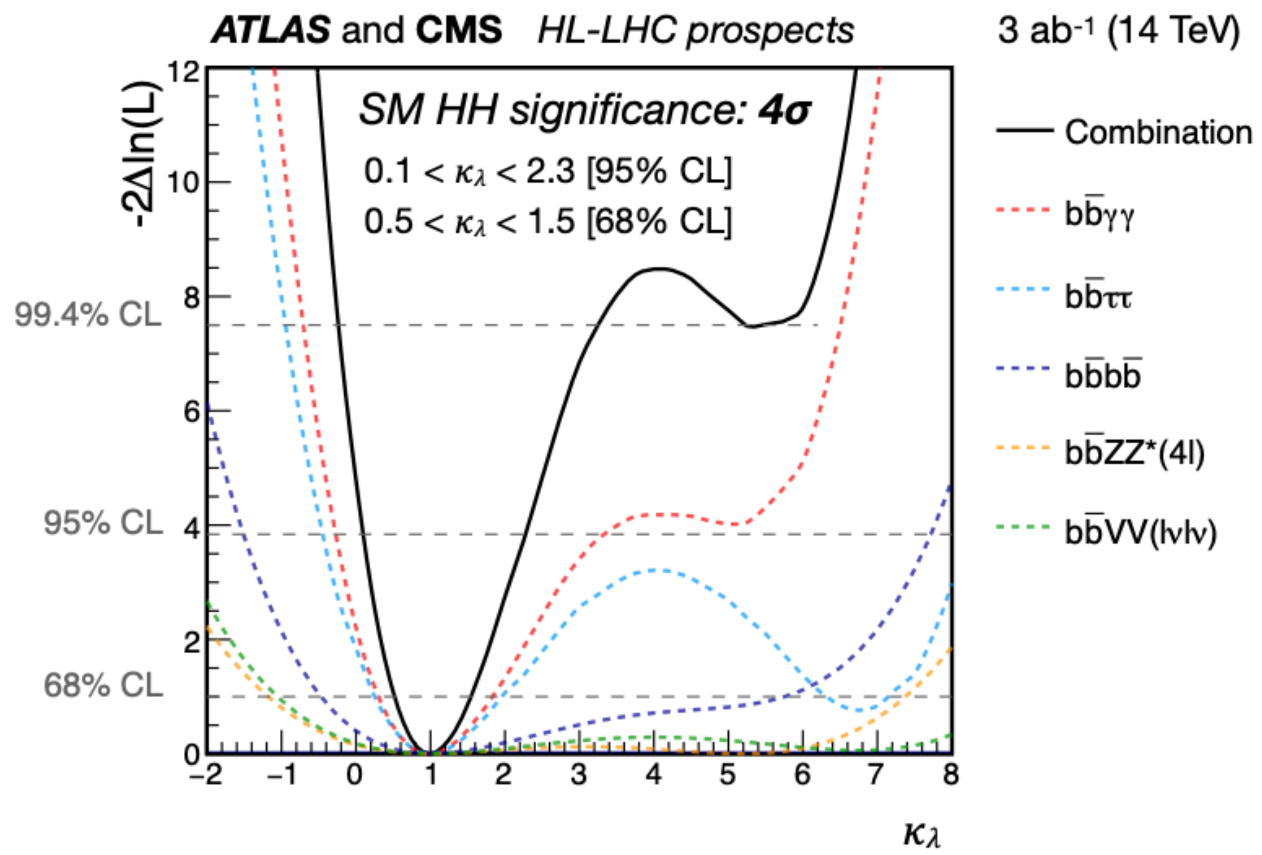
Why Higgs precision?



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

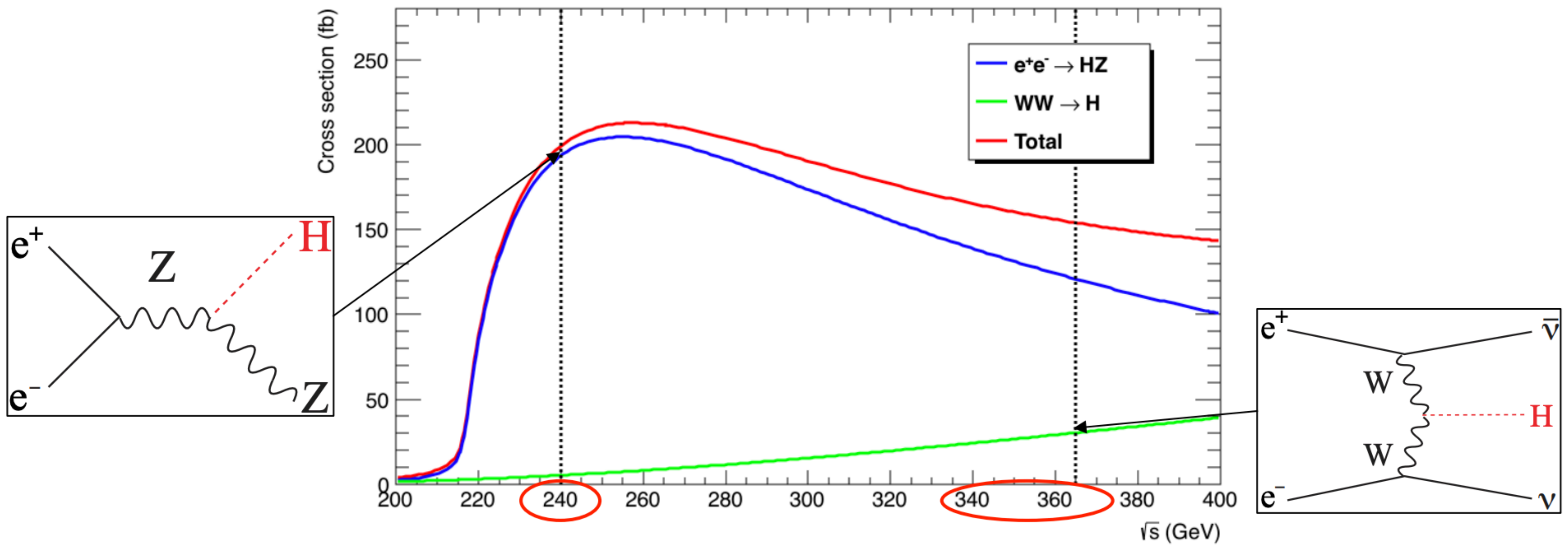


Need to go beyond the LHC precision measurements:

- model independence, Higgs width
- light couplings (charm, muon)
- invisible decays

- self-coupling(s)
- BSM Higgs

FCC-ee Higgs couplings (part II)



WW fusion added value

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

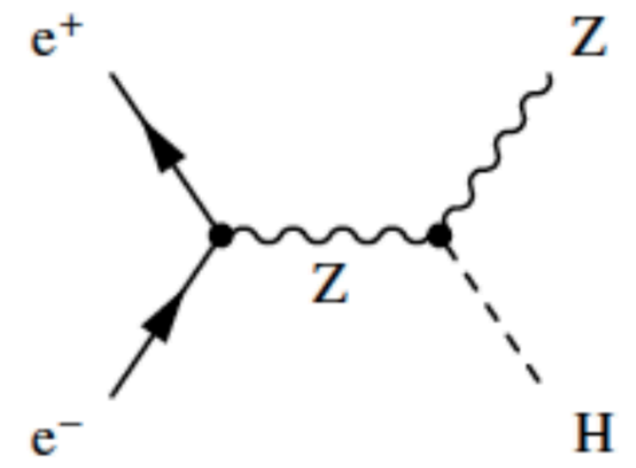
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to ZZ$	±4.4		±12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

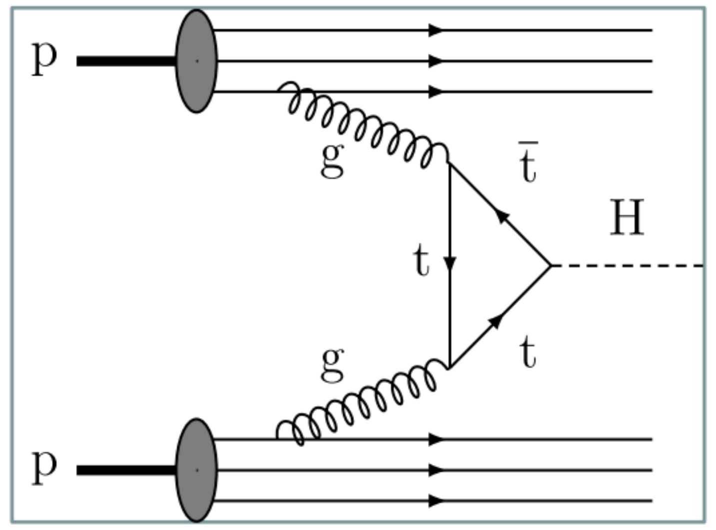
For 4 IPs, expect:
x 1.7 luminosity / statistics
x 1.3 in expected precision

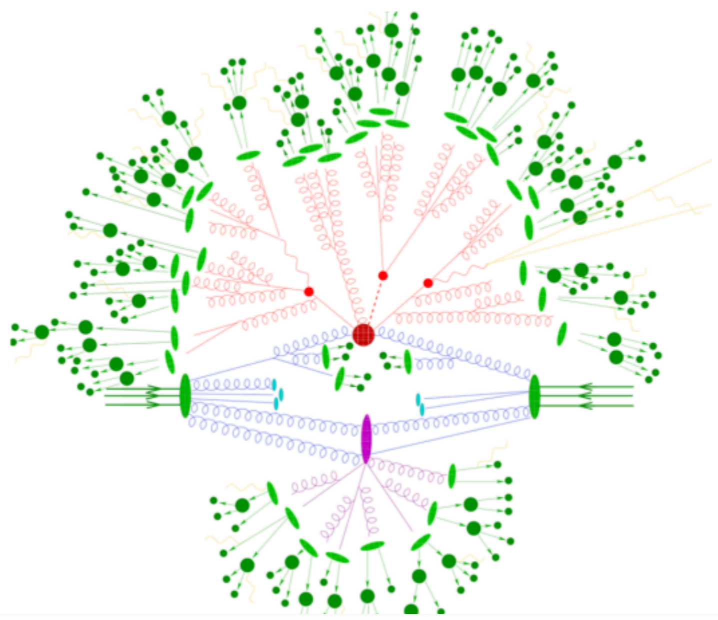
Abundant statistics and high precision for:
- bb/cc/gg/WW

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

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

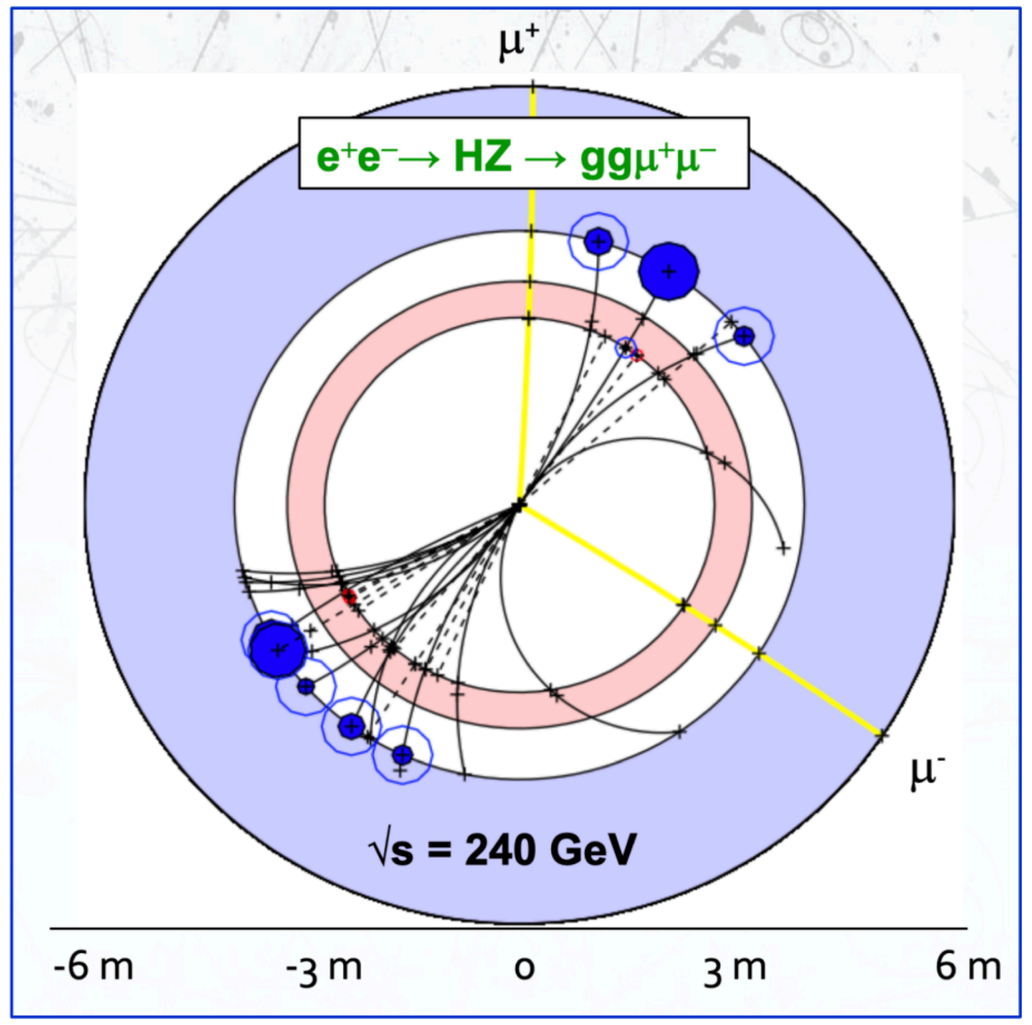
High rates of QCD backgrounds

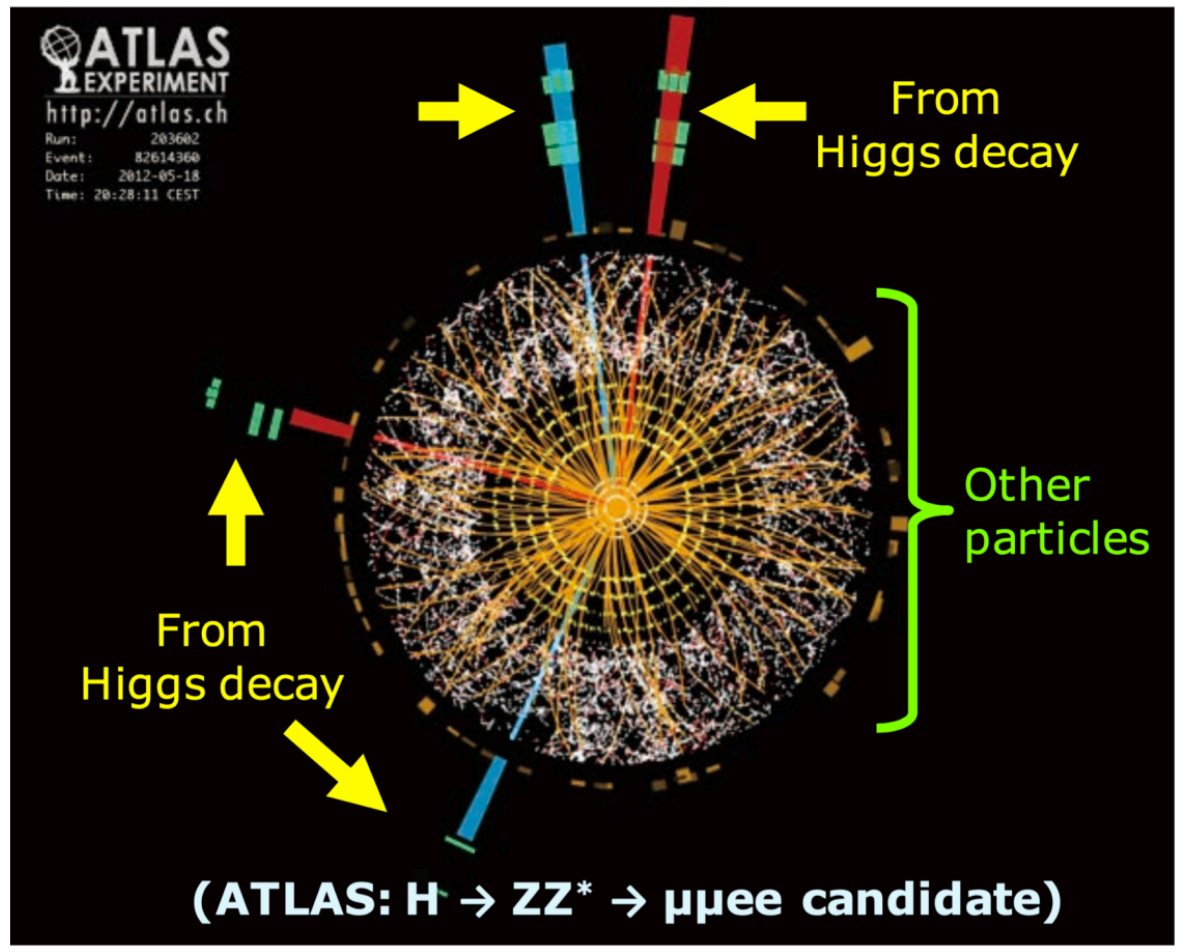
→ Complex triggering schemes

→ High levels of radiation

High cross-sections for **colored-states**

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





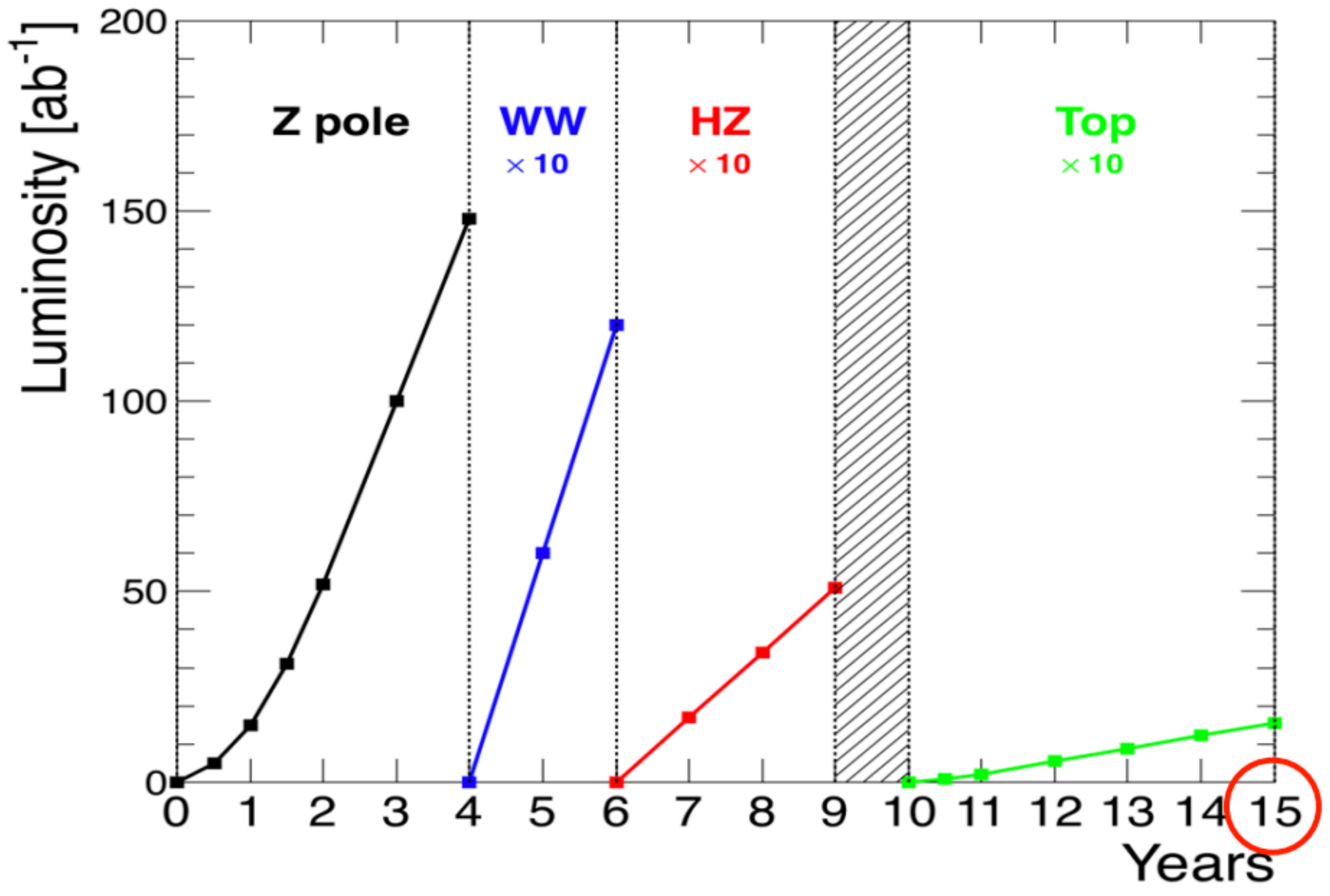
FCC-ee run plan

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

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold…	… and above
$\sqrt{s}$ (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 $e^+e^- \rightarrow t\bar{t}$

$\sqrt{s}$ precision

100 keV

300 keV

2 MeV

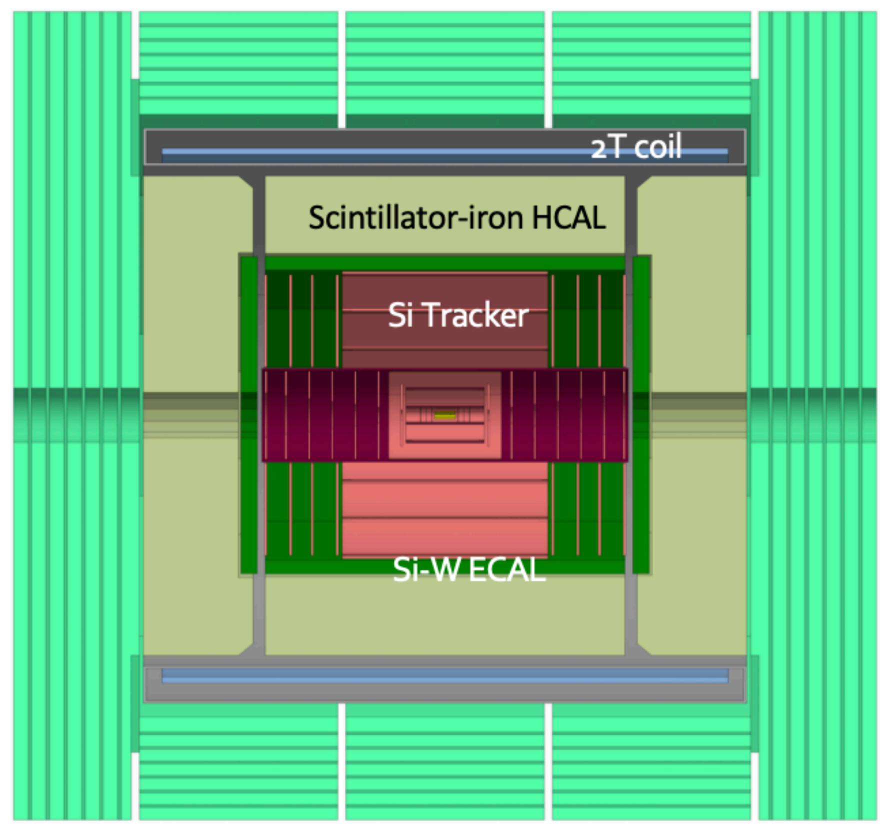
5 MeV

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

For 4 IPs x 1.7 luminosity / statistics

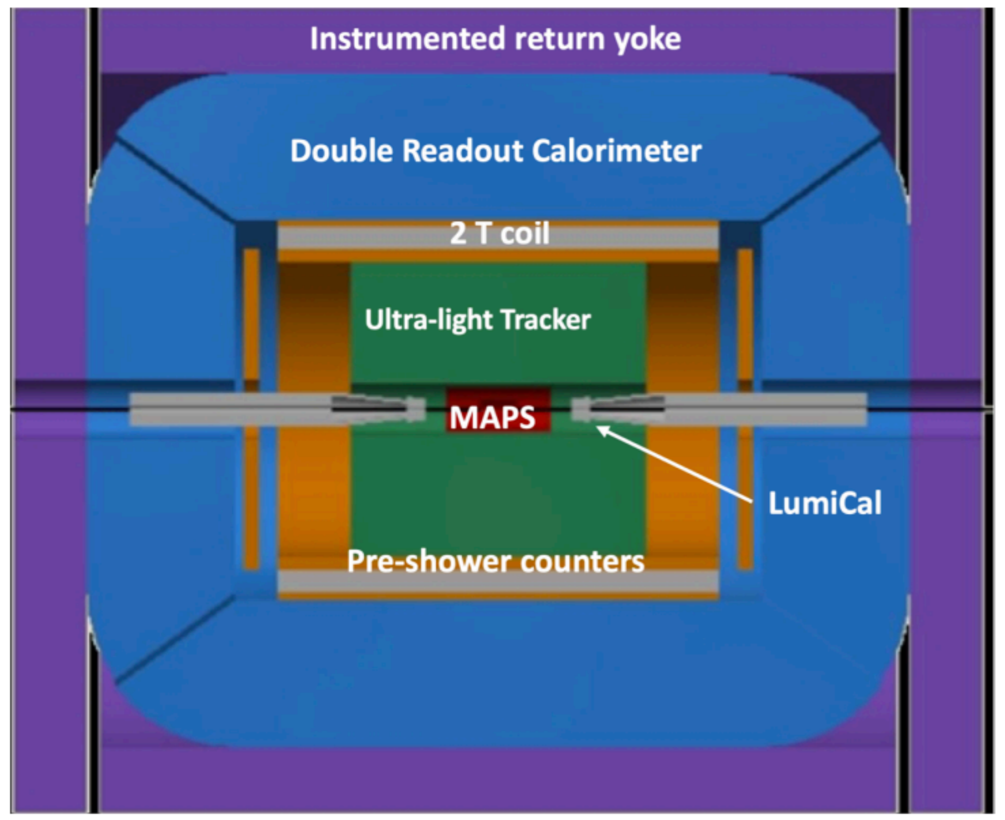
Detector designs

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