Higgs physics opportunities at the Future Circular Collider

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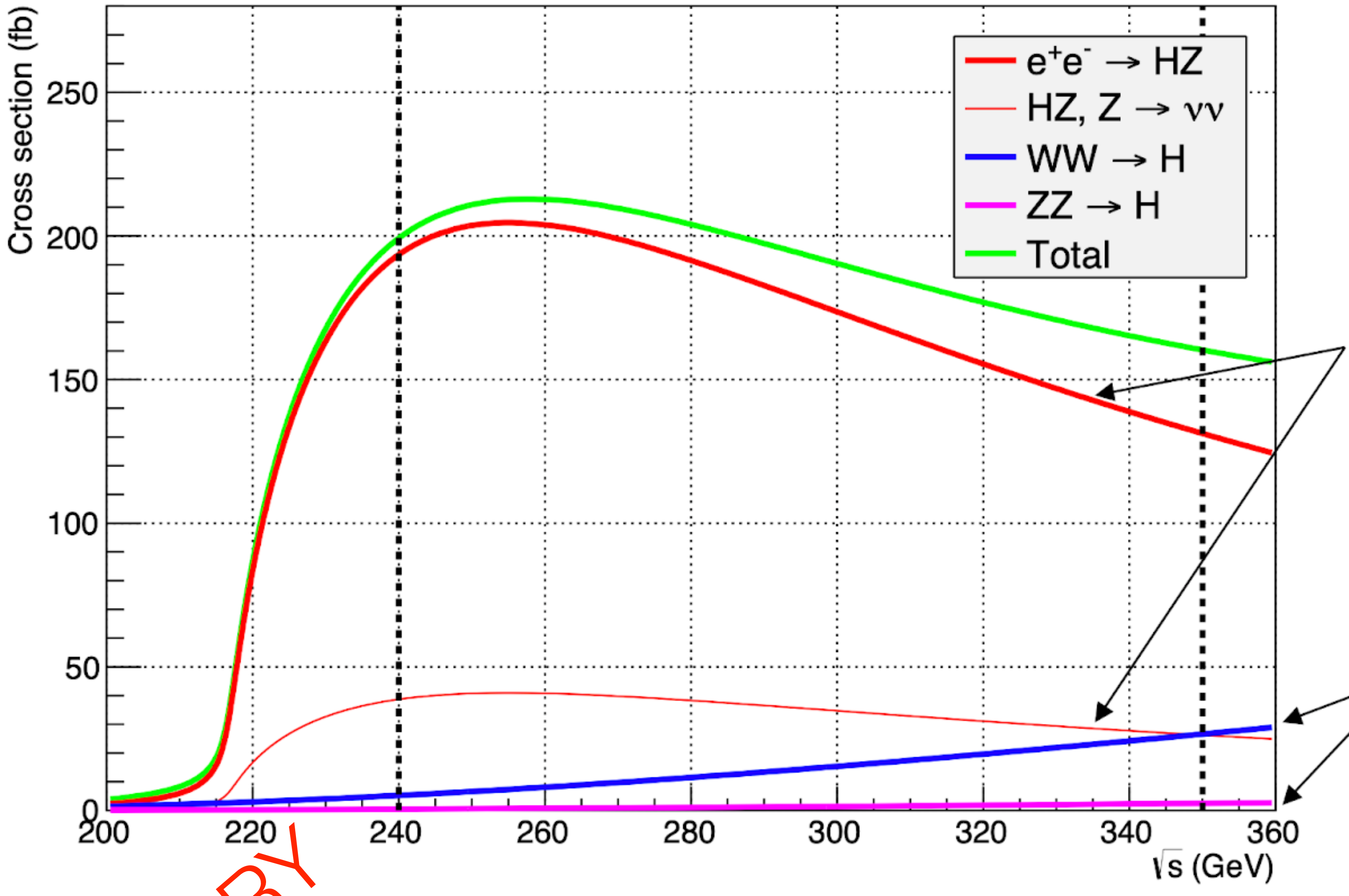
NUCLÉAIRE & PARTICULES

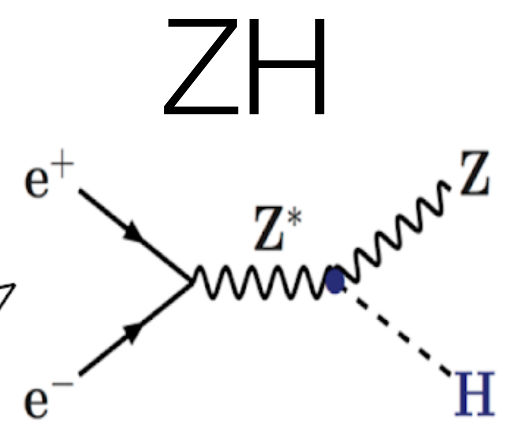
FCC

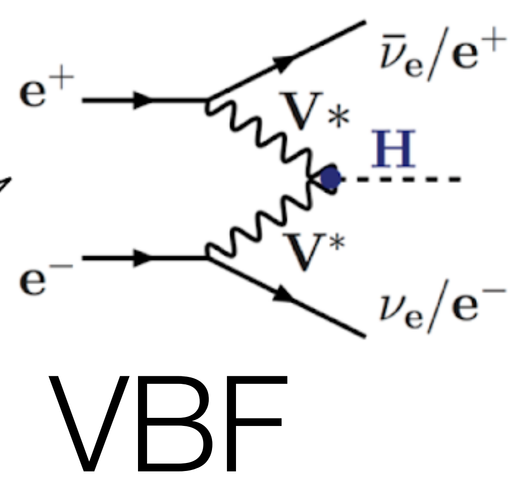
FCC : a great Higgs factory (and much more) for the future generations

- Future Circular Collider: proposed 91 km circular collider @CERN after HL-LHC, with 4 interaction points (IP), in two stages:
  - FCC-ee : e^+e^- $\sqrt{s}$=91—365 GeV (Z, WW, ZH, ttbar) 16 yrs, start around 2045 (and maybe $e^+e^- \to H$ at $\sqrt{s}$ = 125 GeV)
  - FCC-hh : pp $\sqrt{s}$=100 TeV 25 yrs, start around 2070
- Amazing potential for precision Higgs measurements

FCC-ee : ZH and VBF @ $\sqrt{s}$=240, 365 GeV



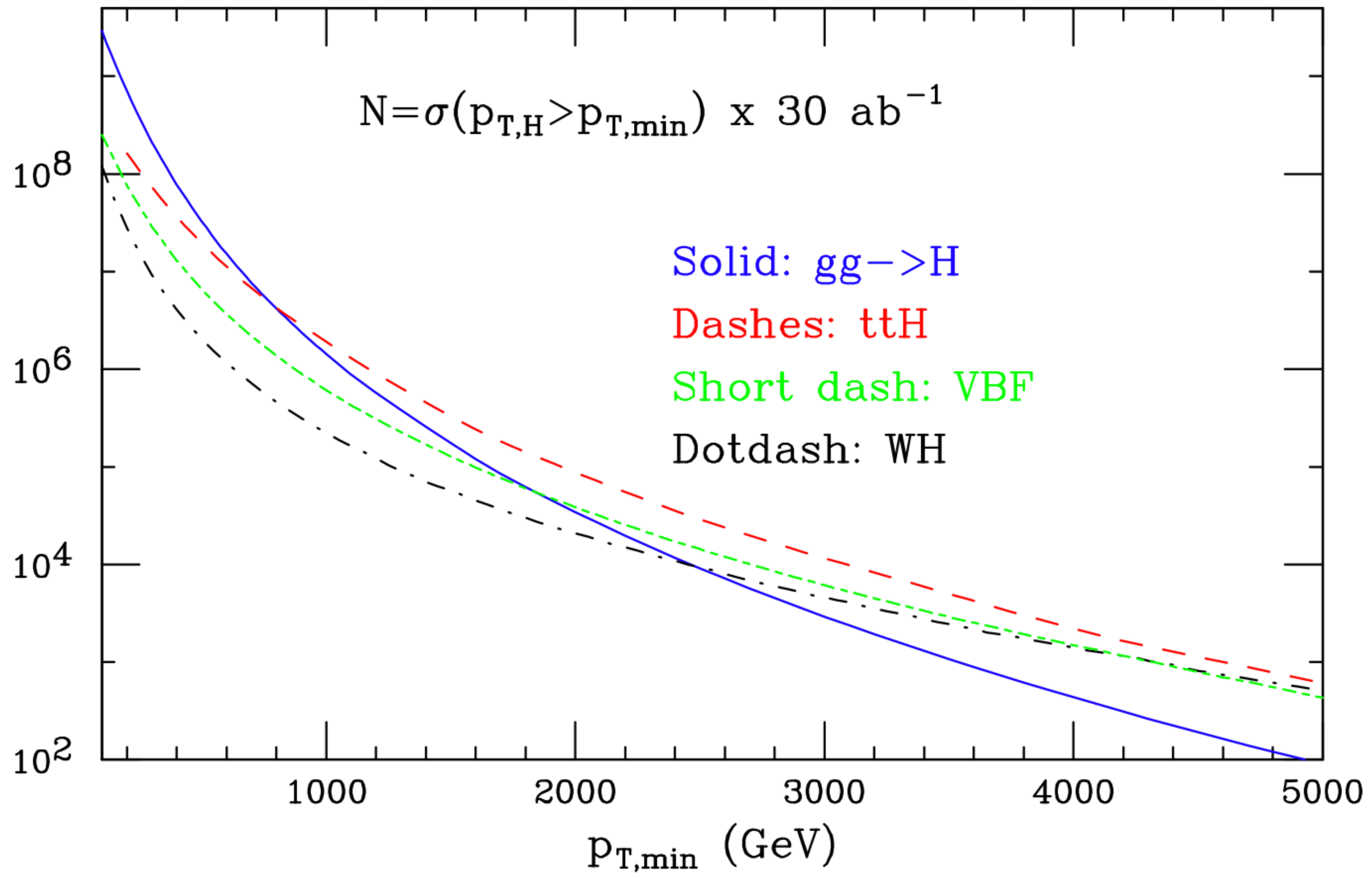




PRELIMINARY

$\sqrt{s}$	L (4IP)	yrs	N(ZH)	N(VBF)
240 GeV	10.8/ab	3	2.2M	67k
365 GeV	3/ab	5	330k	80k

FCC-hh : ggF, VBF, ttH, VH @ $\sqrt{s}$=100 TeV



	ggF	VBF	ttH	VH
σ(100TeV)(pb)	802	69	33	27
σ(100TeV)/σ(14TeV)(pb)	16	16	52	11
$N(\sqrt{s} = 100$ TeV, 30 ab^{-1})	25×10^9	2.5×10^9	10^9	7.5×10^8

Higgs physics at the FCC

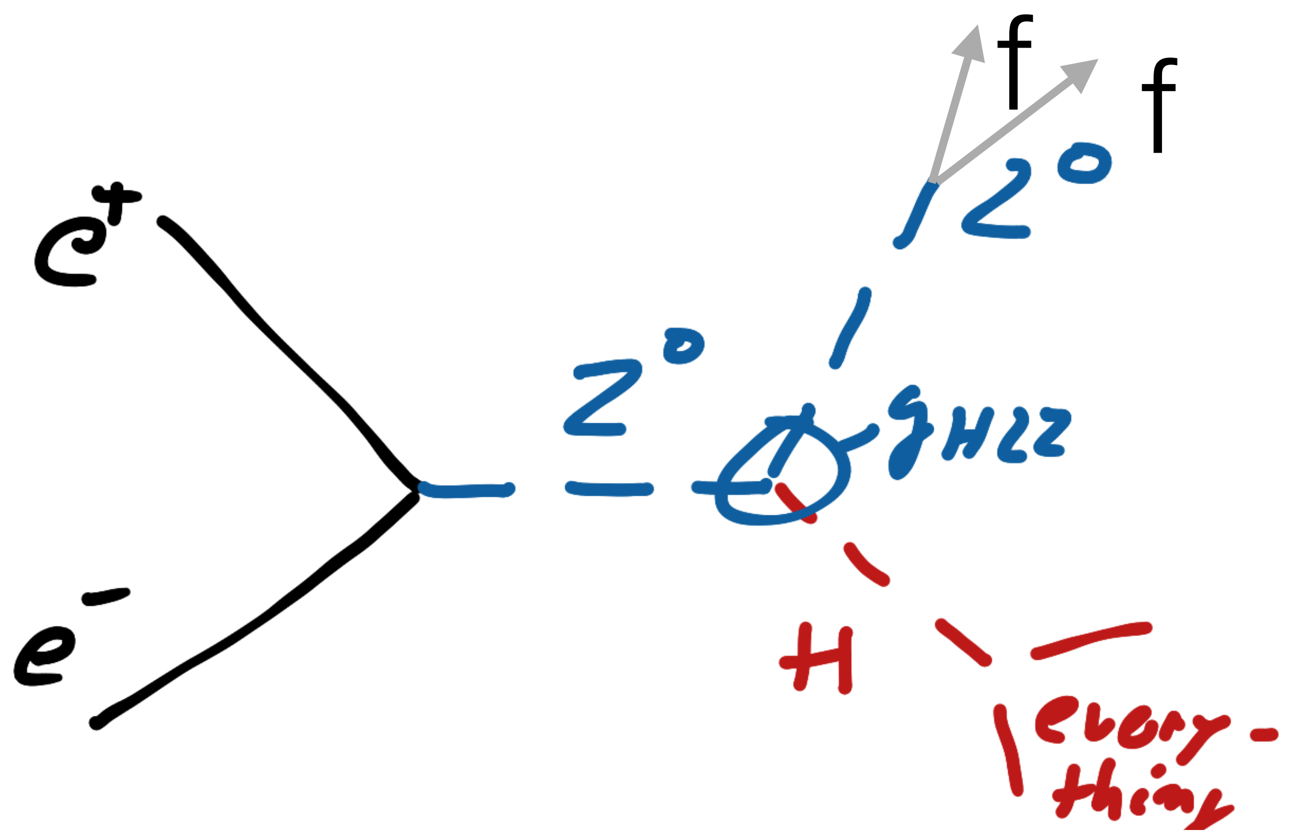
- Broad potential for Higgs measurements
  - FCC-ee:
    - Clean environment (e^+e^-), small backgrounds, high signal efficiency for most Higgs decays ⇒ large S/B
  - FCC-hh :
    - Hadronic environment and larger backgrounds, but huge yields ⇒ unprecedented accuracy for specific key measurements i.e. rare decays and multi-H production

- Wide experimental program summarised in the next slides
  - fundamental properties (mass, width)
  - total production cross-section
  - couplings to other particles (model-independent, absolute determination)
  - self-coupling

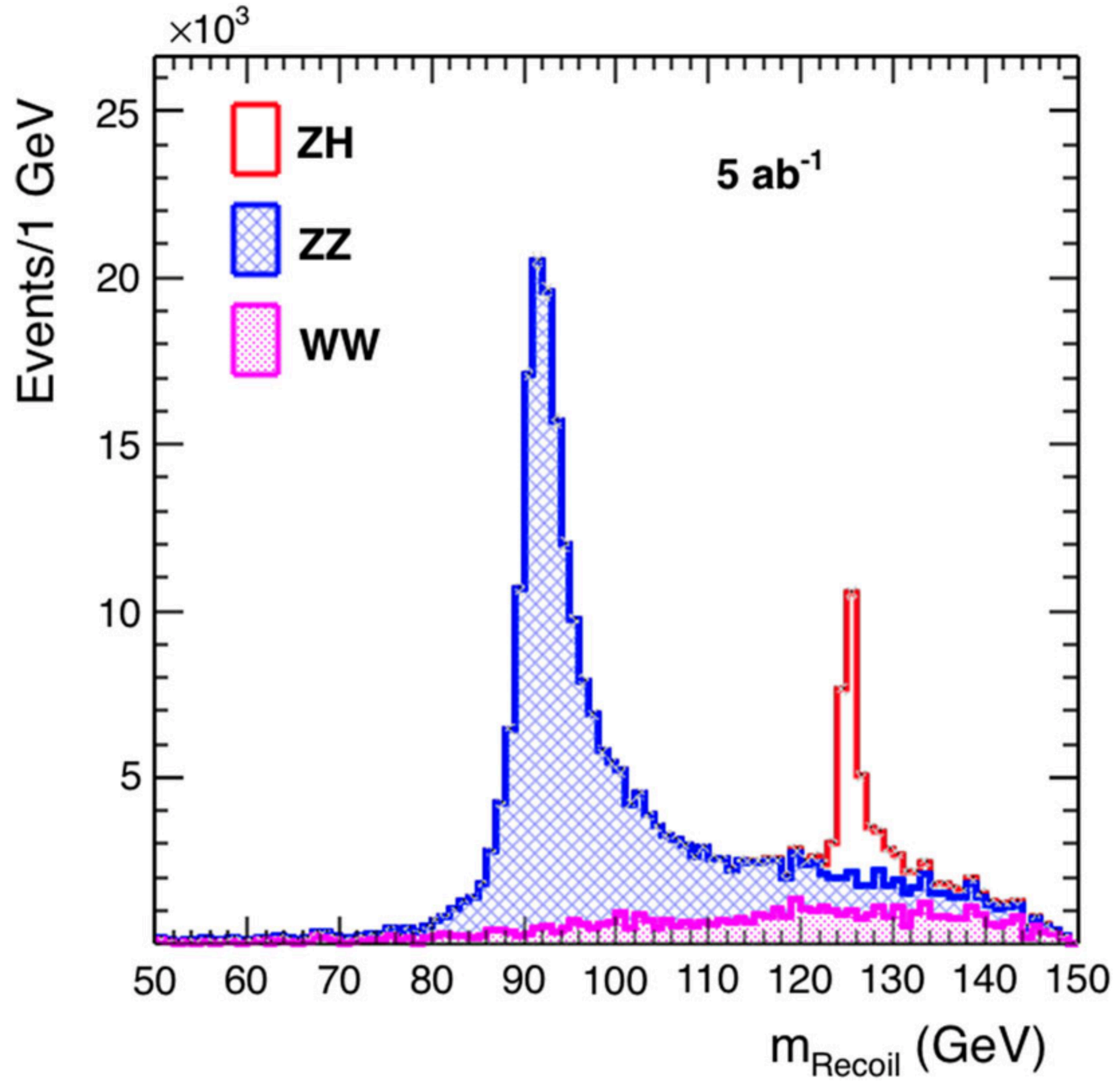
- Sensitivity studied with full analyses of parametrised detector simulations based on performance predicted by Geant4 simulations
  - Previous numbers for CDR in 2020 based on extrapolation of yields from ILC full simulations
- Most of the analyses limited by statistical uncertainty; precision depends on detector performance

Precision & model-independent Higgs physics at the FCC-ee

- “Recoil" technique allows tagging Z→ff and identifying in a clean, efficient, inclusive way ZH events ⇒ measure total ZH cross-section
- State-of-the-art next-gen detectors ⇒ reconstruct & identify efficiently many Higgs boson decays ⇒ measure BR ⇒ couplings, width



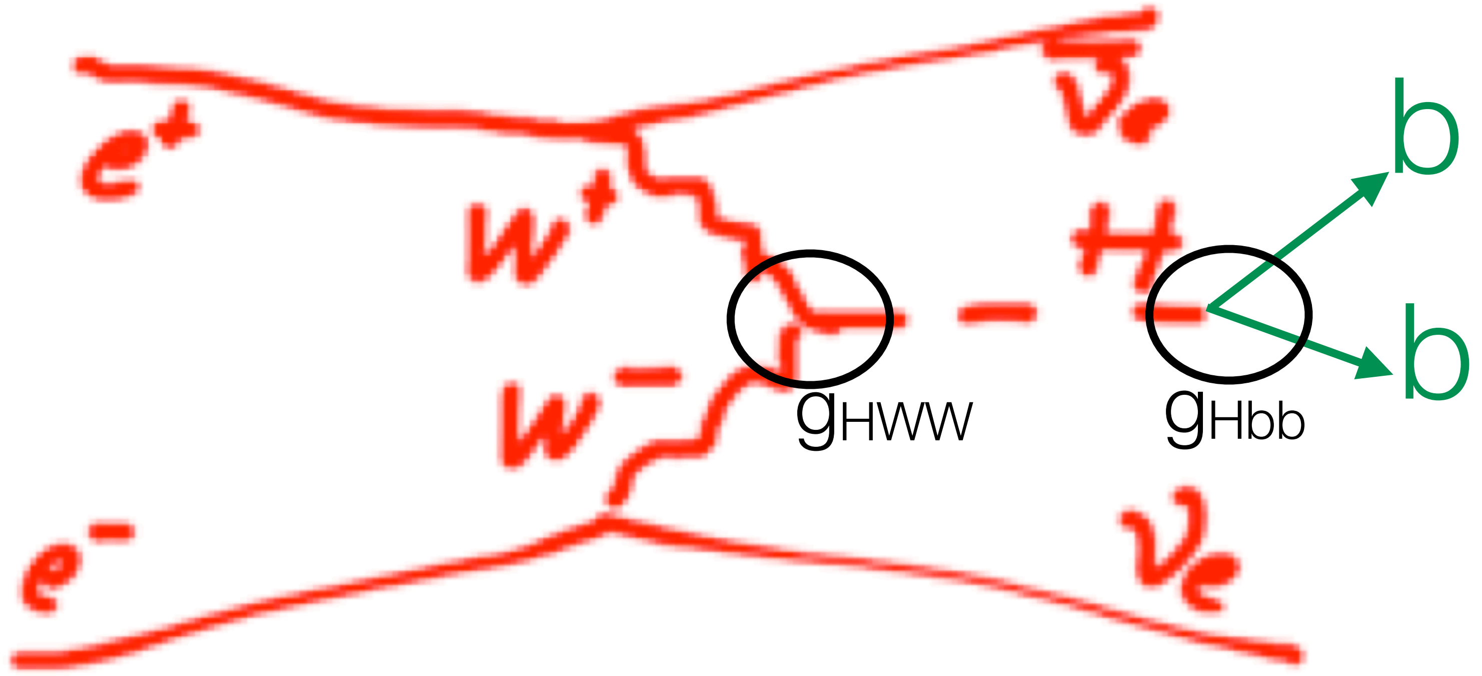
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}}$$



$$\Gamma_H \propto \frac{\sigma(e^+e^- \to ZH)^2}{\sigma(e^+e^- \to ZH, H \to ZZ)}$$

$$g^2_{HXX} \propto \frac{\sigma(ee \to ZH, H \to XX)\sigma(ee \to ZH)}{\sigma(ee \to ZH, H \to ZZ)}$$

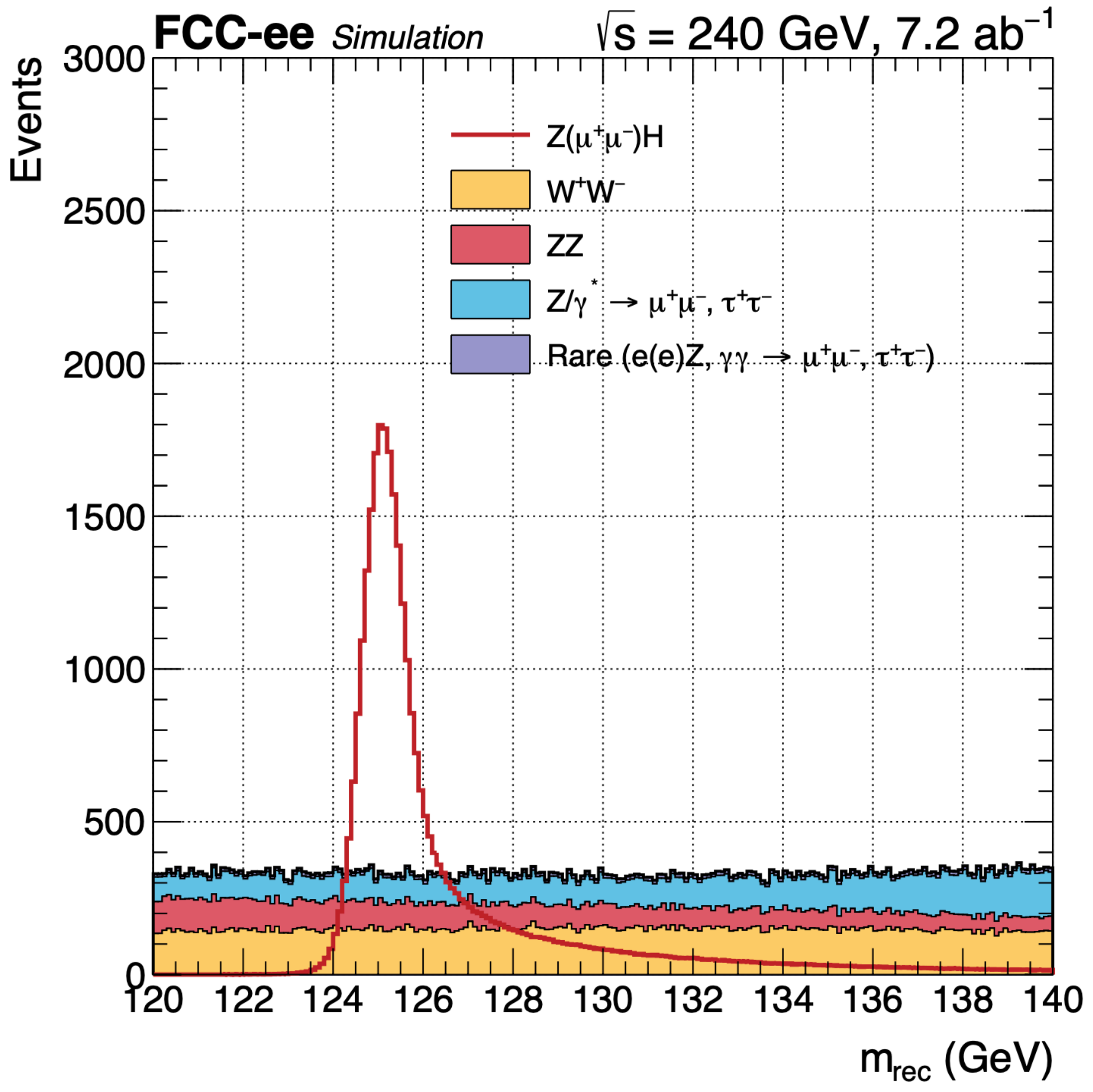
- VBF at 365 GeV provides essential additional information on couplings (g_{HWW}) and width

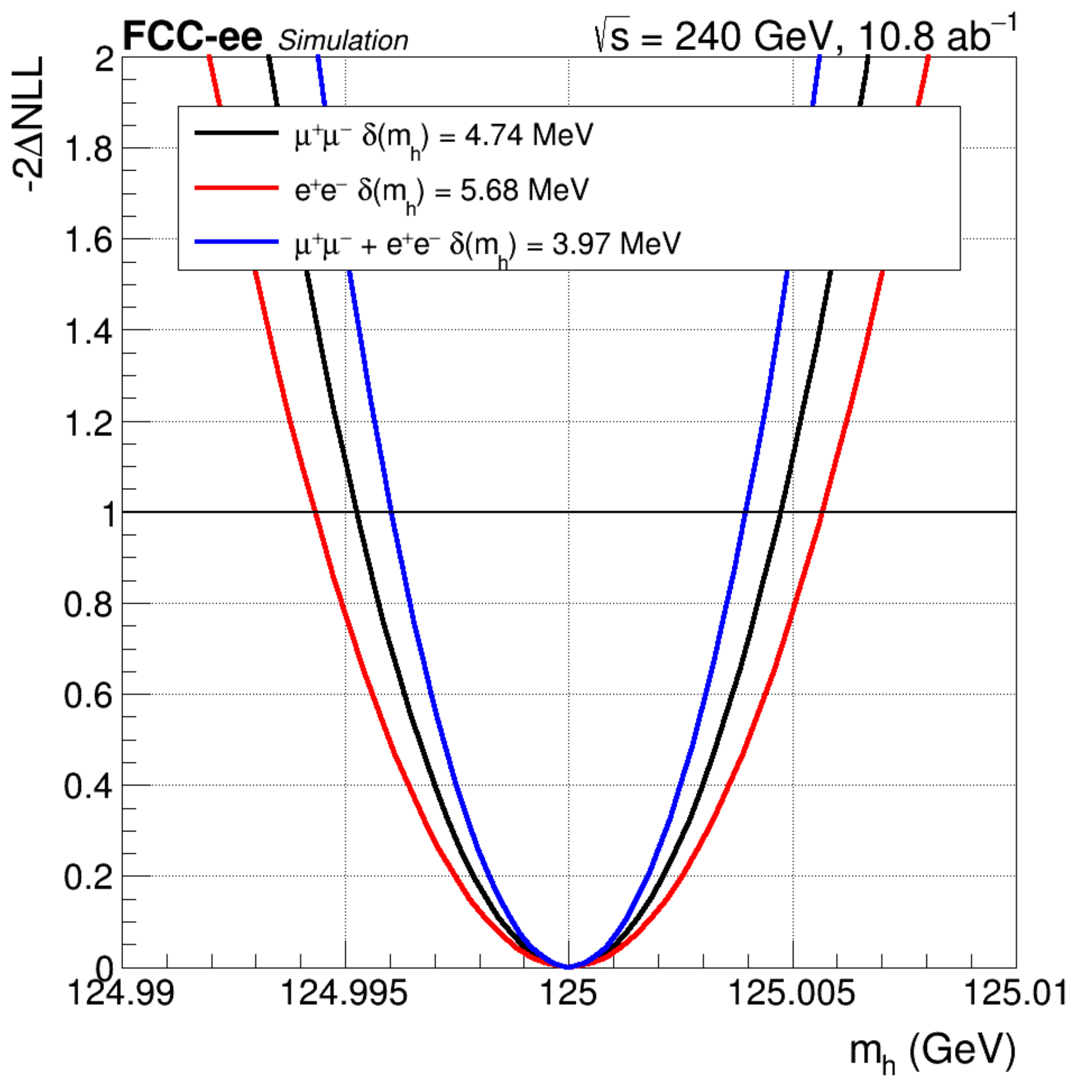


$$\Gamma_H \propto \frac{\sigma\left(e^+e^- \to \nu\bar{\nu}H, H \to bb\right)\sigma\left(e^+e^- \to ZH\right)^2}{\sigma\left(e^+e^- \to ZH, H \to bb\right)\sigma\left(e^+e^- \to ZH, H \to WW\right)}$$

Higgs mass @ FCC-ee

- Target <O(10) MeV uncertainty to control radiative corrections on σ and BR at <% level
- Higgs mass from position of peak of m_{recoil} distribution in Z(ll)H events (l=e, μ) — S~100k after selection (90k @ 240 GeV, 11k @ 365)
  - 2 leptons with opposite sign and same flavour, m_{ll}~mZ, p_{ll}~few tens of GeV
  - Fit performed in 2 lepton-flavour categories in m_{recoil} region around m_H
- Systematic uncertainties (beam energy spread, √s, lepton energy scales) ⇒ 2.5 MeV @ √s=240 GeV, dominant: √s, δm~2 MeV
- Sensitivity with baseline detector compared to alternative configurations





10.8/ab at 240 GeV

Final state	Muon 240 GeV	Electron 240 GeV	Combination 240 GeV
Nominal	3.92(4.74)	4.95(5.68)	3.07(3.97)
Inclusive	3.92(4.74)	4.95(5.68)	3.10(3.97)
Degradation electron resolution	3.92(4.74)	5.79(6.33)	3.24(4.12)
Magnetic field 3T	3.22(4.14)	4.11(4.83)	2.54(3.52)
Silicon tracker	5.11(5.73)	5.89(6.42)	3.86(4.55)
BES 6% uncertainty	3.92(4.79)	4.95(5.92)	3.07(3.98)
Disable BES	2.11(3.31)	2.93(3.88)	1.71(2.92)
Ideal resolution	3.12(3.95)	3.58(4.52)	2.42(3.40)
Freeze backgrounds	3.91(4.74)	4.95(5.67)	3.07(3.96)
Remove backgrounds	3.08(4.13)	3.51(4.58)	2.31(3.45)

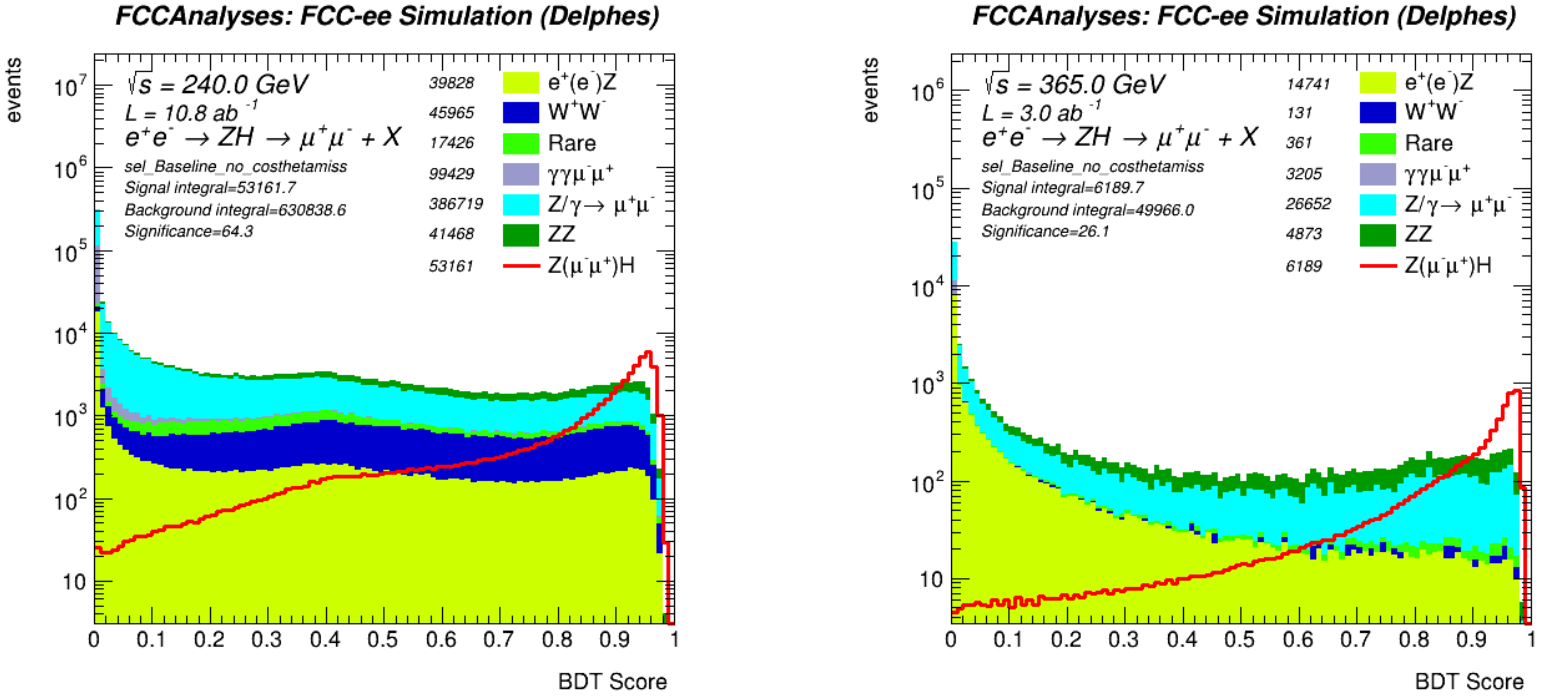
Nominal configuration → Nominal
Crystal ECAL to Dual Readout → Degradation electron resolution
Nominal 2 T → field 3 T → Magnetic field 3T
IDEA drift chamber → CLD Si tracker → Silicon tracker
Impact of Beam Energy Spread → BES 6% uncertainty / Disable BES
Perfect (=gen-level) momentum resolution → Ideal resolution

10.8/ab at √s=240 GeV : δm = 4 MeV (3.1 ⊕ 2.5)
Mildly affected (<15%) by detector scenario
<1% improvement on δm from combination with √s=365 GeV analysis. Other Z channels to be investigated

more details in G. Bernardi's talk

Total ZH cross section (and g_{HZZ}) @ FCC-ee

- Reconstruct Z(ll)+X events, train BDT to separate signal from backgrounds, and fit BDT score to determine signal cross-section
- Selection similar to m_H analysis (slightly looser for model independence), similar signal yields
- Analysis performed at both 240 and 365 GeV



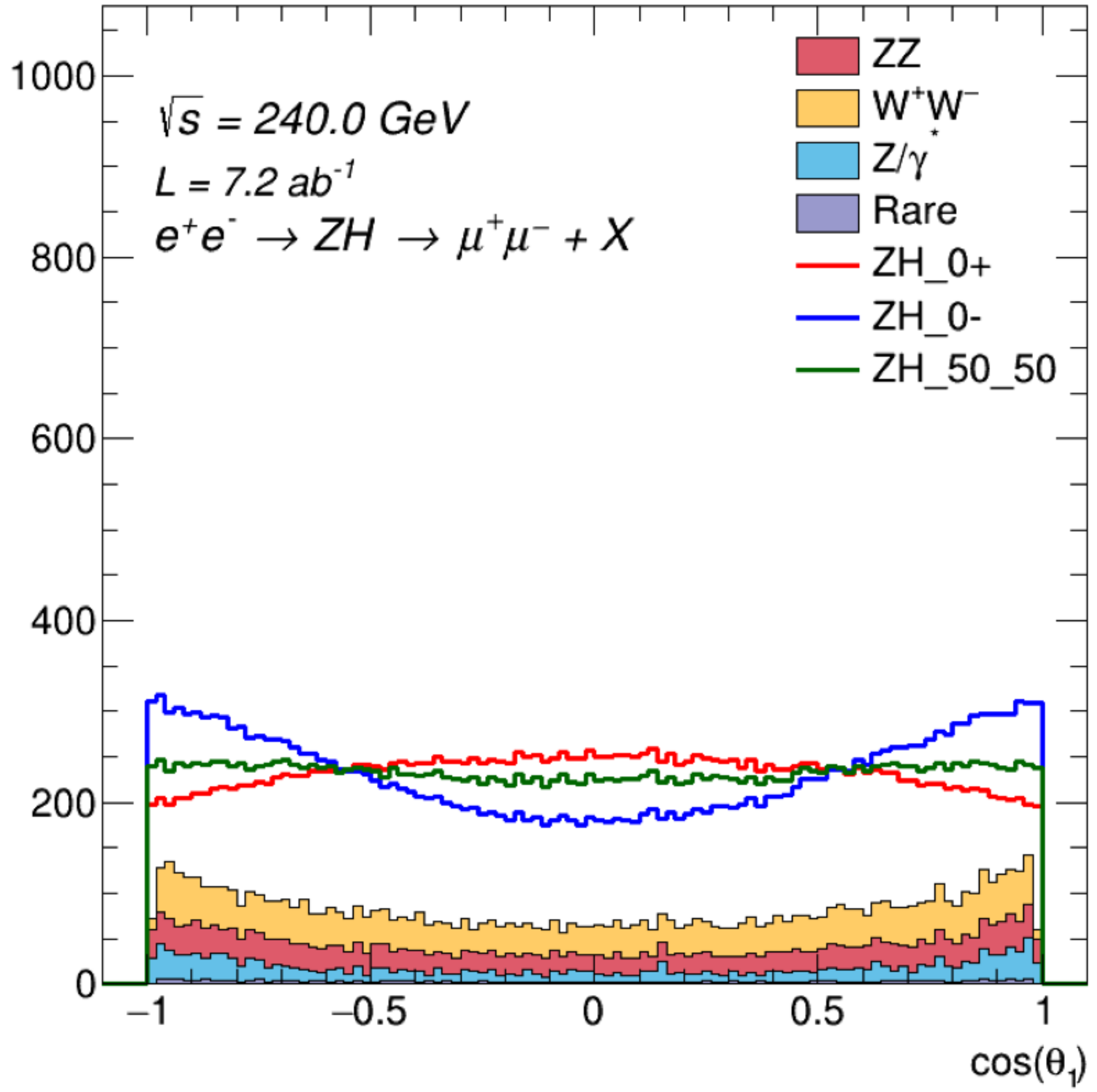
10.8/ab at $\sqrt{s}$=240 GeV : $\delta\sigma$ = 0.599% (0.592% stat-only)
3.0/ab at $\sqrt{s}$=365 GeV : $\delta\sigma$ = 1.48% (1.42% stat-only)

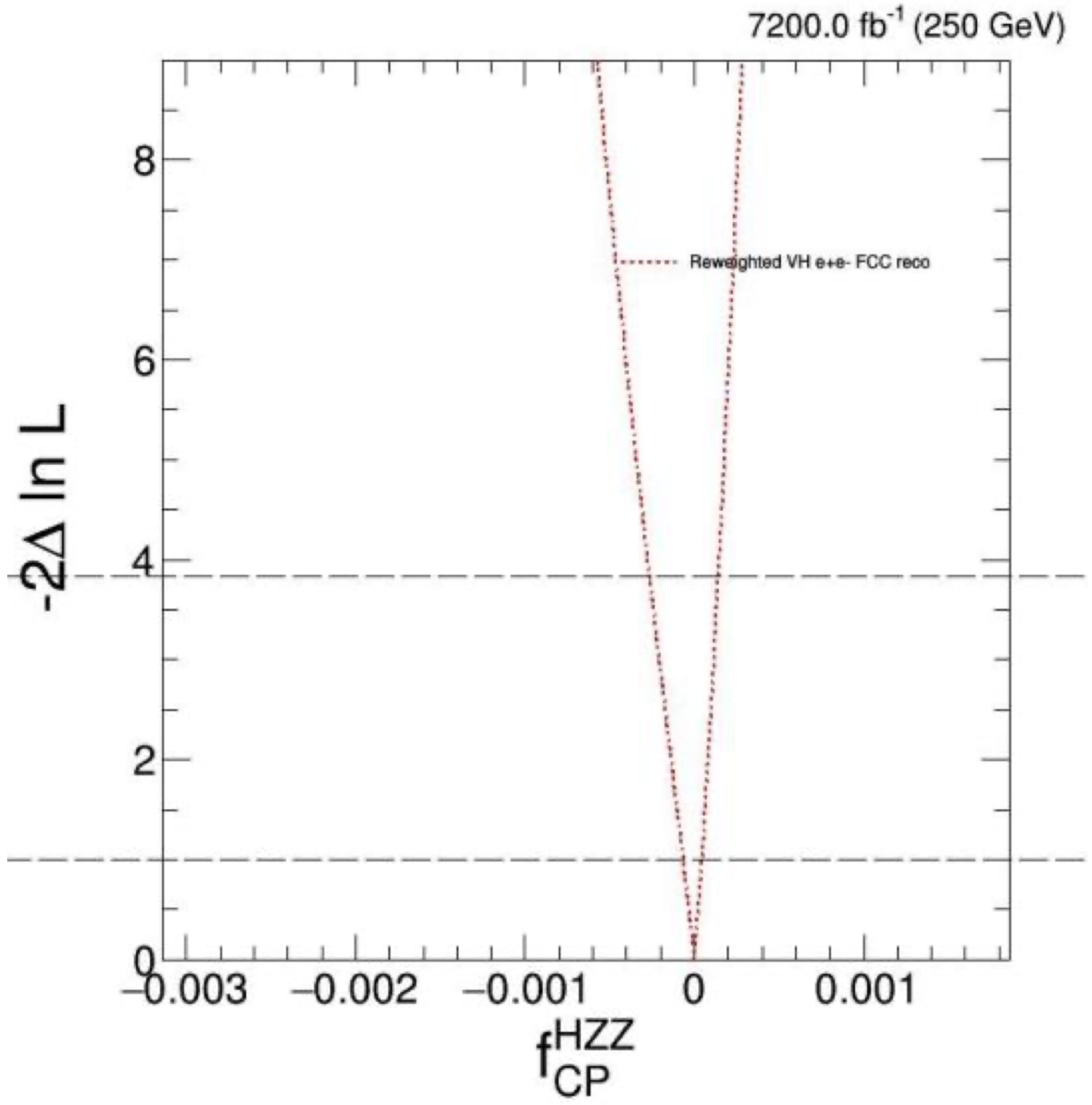
more details in G. Bernardi's talk

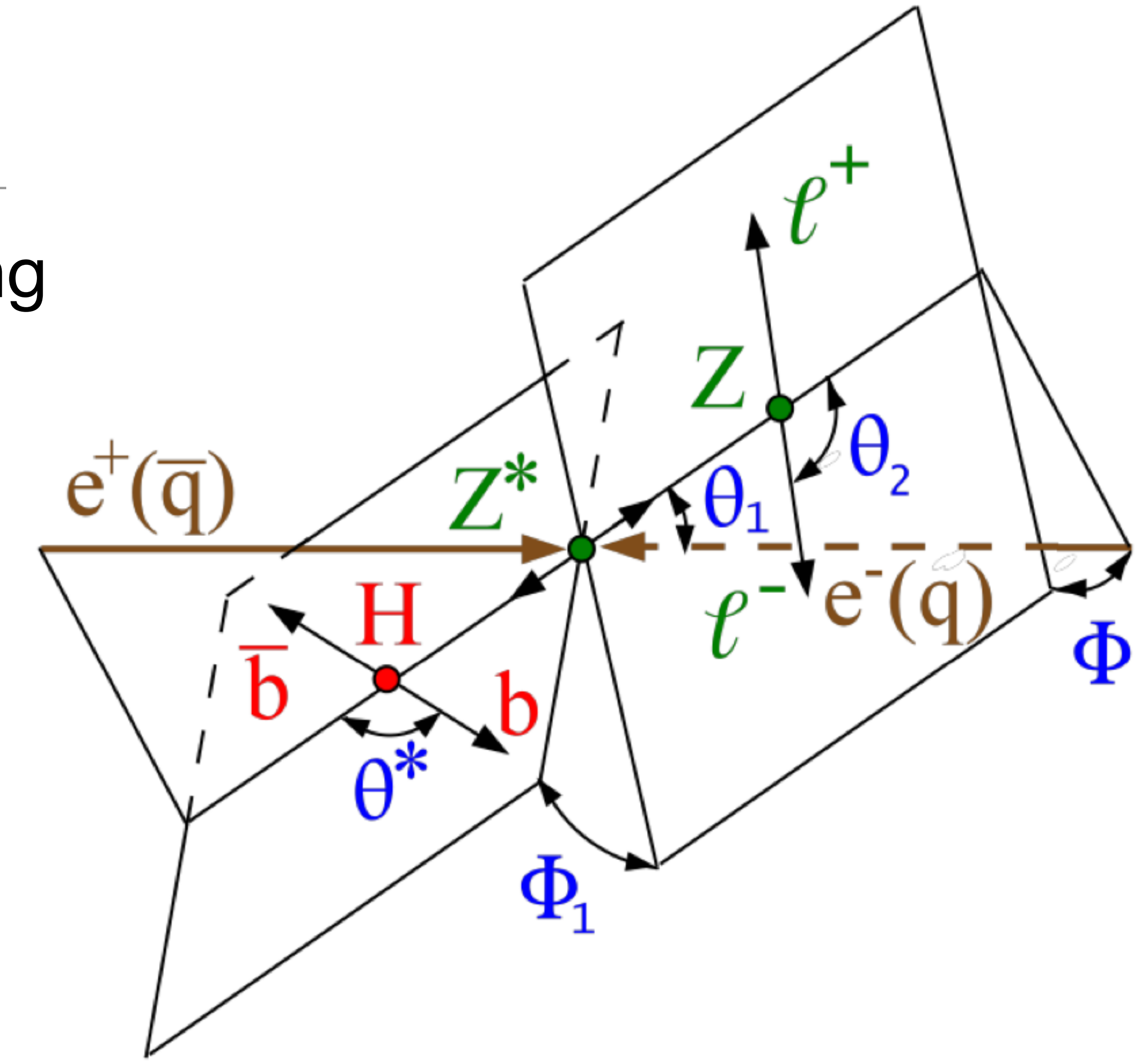
CP structure of the HZZ coupling @ FCC-ee

- Use angular distributions in Z(ll)H recoil analysis at 240 GeV to constrain anomalous CP-odd coupling
  - Tighter selection ⇒ S ~20k, S/B~3 for Z(μμ)H
  - Matrix-element reweighing of signal events to obtain templates for different CP-hypotheses, fit to extract f_{CP}

$$f_{CP}^{HX} \equiv \frac{\Gamma^{CP\,odd}_{H\to X}}{\Gamma^{CP\,odd}_{H\to X} + \Gamma^{CP\,even}_{H\to X}}$$







FCC-ee 10.8/ab @ 240 GeV : $\delta f_{CP}^{HZZ} \sim 4.4 \cdot 10^{-5}$

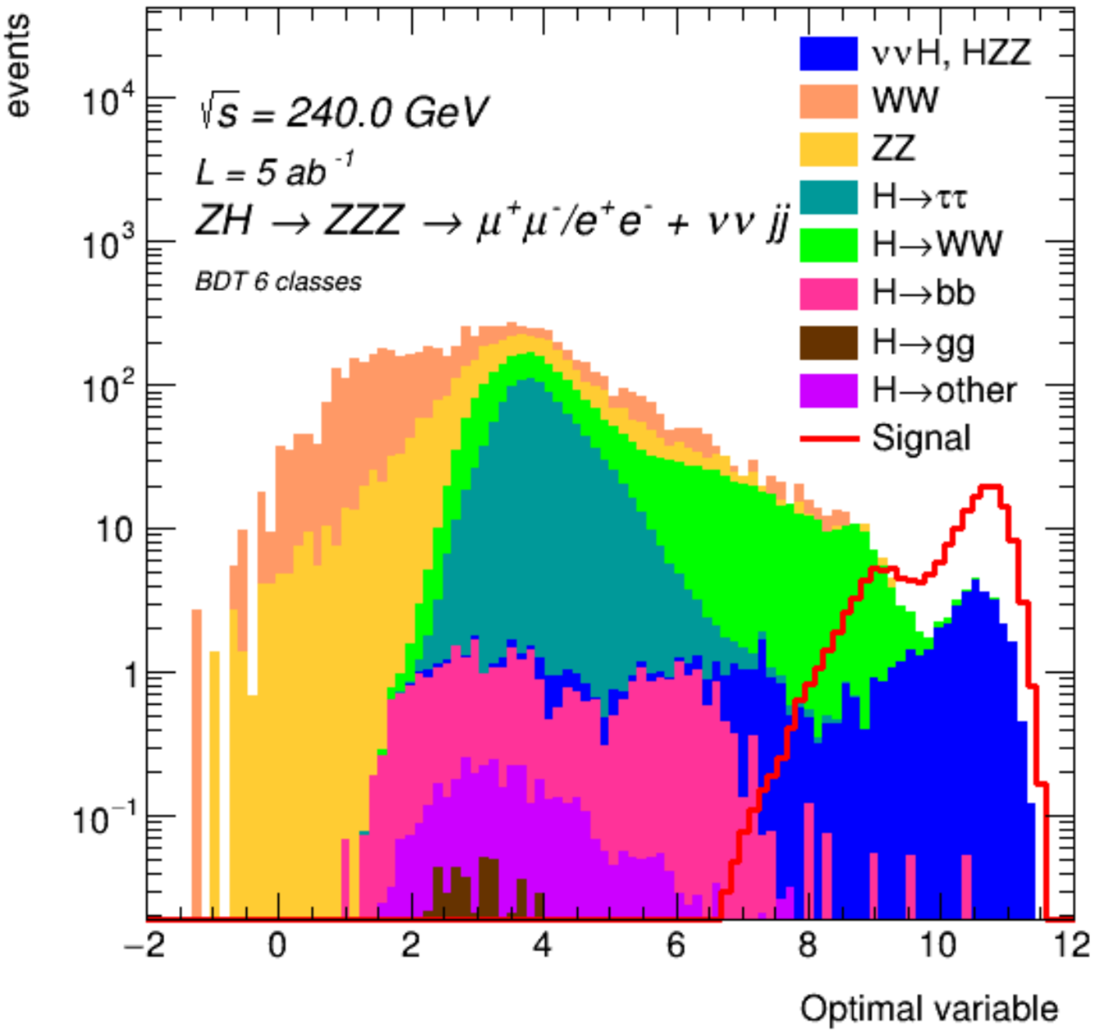
Developed tools & analysis strategy to be extended to more channels

Higgs width @ FCC-ee

- Γ_H determined from total σ_{ZH} and exclusive $\sigma_{ZH(ZZ^*)}$:

$$\Gamma_H \propto \frac{\sigma(e^+e^- \to ZH)^2}{\sigma(e^+e^- \to ZH, H \to ZZ)}$$

- Several final state configurations and signatures due to different Z boson decays (ll/vv/qq) and the Z boson they come from
- Analysis of 5 final states performed: Z(ll) + Z(vv)Z*(qq); Z(ll) + Z(qq)Z*(vv); Z(vv) + Z(ll)Z*(qq); Z(ll) + Z(qq)Z*(qq); Z(qq) + Z(qq)Z*(qq)
  - Preselections to identify Z→ll and remove from jet clustering; exclusive N=2,4,6 jet clustering depending on final state; orthogonality ensured by requirements on n(leptons) / missing energy / dijet mass / recoil mass
  - Multi-class BDTs trained for signal/background separation; $\sigma_{ZH(ZZ)}$ from template-fit or cut&count analysis using ZH(ZZ*) BDT score

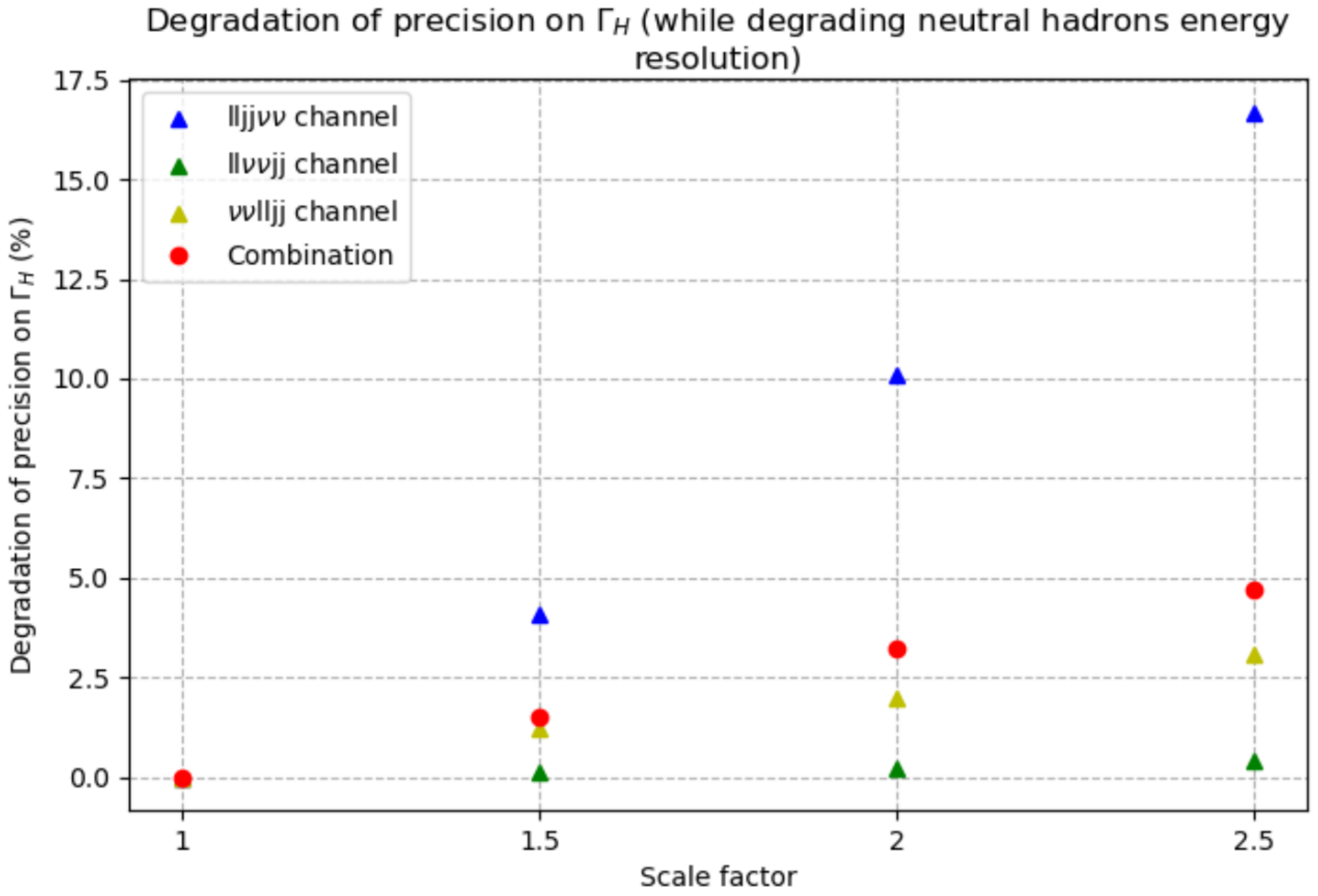


Uncertainties extrapolated to 10.8/ab at 240 GeV:

	ll + vvqq	ll + qqvv	vv + llqq	Combination
δσBR/σBR (%) Fit to BDT	5.0	7.3	4.7	3.1

	ll + qqqq
δσBR/σBR (%) Fit to BDT	8.4

	qqqqqq
δσBR/σBR (%) Cut & count	14



δΓ/Γ 2.9% — further optimisation ongoing on ll+4q, 6q analyses (llllqq: WIP)

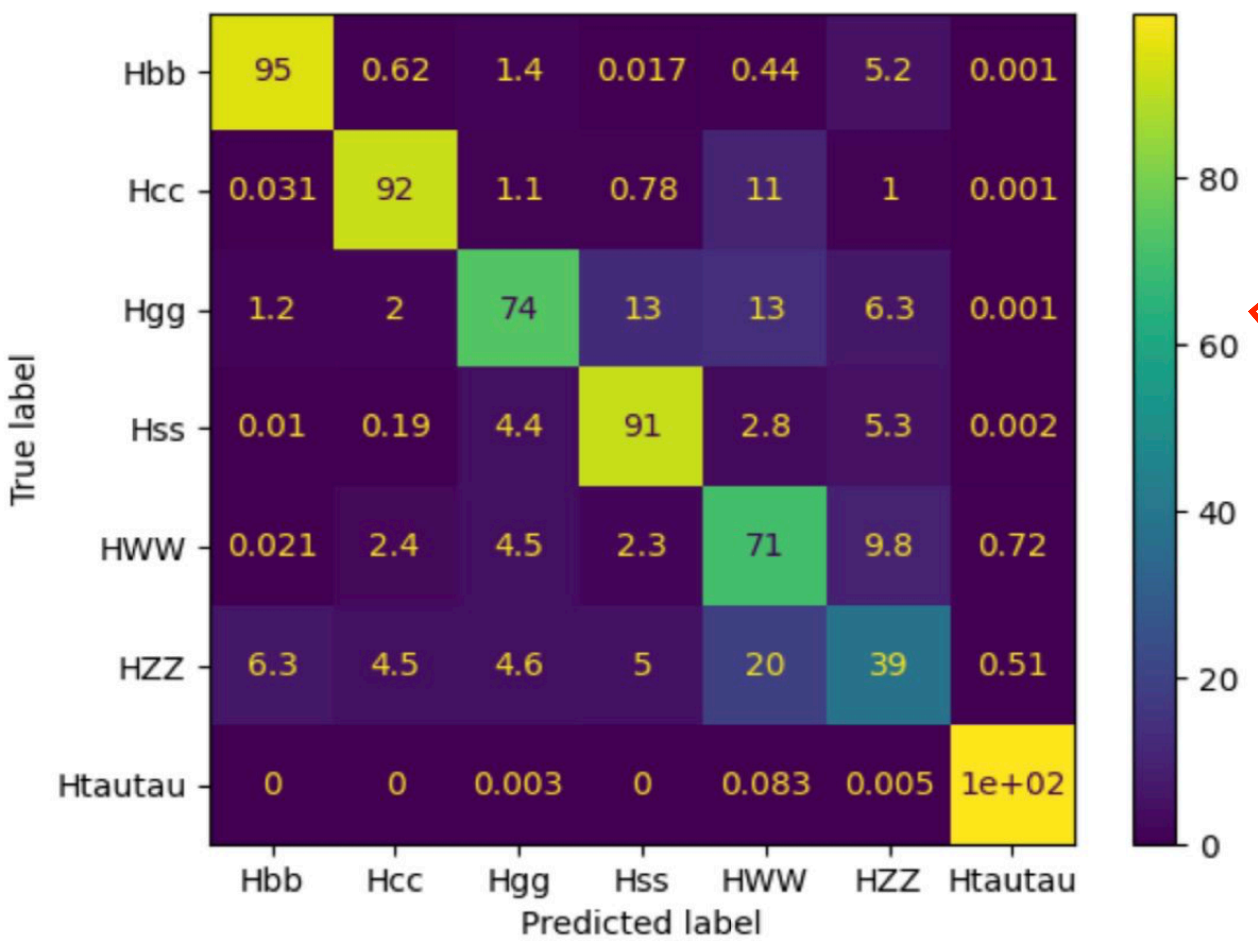
Impact of 2x worse neutral hadron energy resolution found small (3%) in ll + 4q analysis

Expect ~1% w/ WW→H→bb, WW @ 240+365 GeV :

$$\Gamma_H \propto \frac{\sigma(e^+e^- \to \nu\bar{\nu}H, H \to bb)\,\sigma(e^+e^- \to ZH)^2}{\sigma(e^+e^- \to ZH, H \to bb)\,\sigma(e^+e^- \to ZH, H \to WW)}$$

Hadronic Higgs decays @ FCC-ee (quark Yukawa and gluon couplings)

- Three analyses targeting Z(ll), Z(vv) and Z(qq) + H→qq/gg
  - Split according to Z decay based on number and flavour of leptons, missing momentum
  - All particles except leptons from Z clustered into 2 or 4 jets depending on final state
  - GNN-based jet-flavour tagging (b/c/s/u/d/g/τ) + kinematic features to classify events into H→bb/cc/…
  - Simultaneous fit to m_{recoil} (Z→ll), m_{vis} vs m_{miss} (vv), m_{recoil} vs m_{jj} (qq) in the categories to extract the BRs
- Also determine BRs of Higgs to ττ, WW and ZZ as byproduct (fully hadronic decays) - but can do better with dedicated analyses



PRELIMINARY

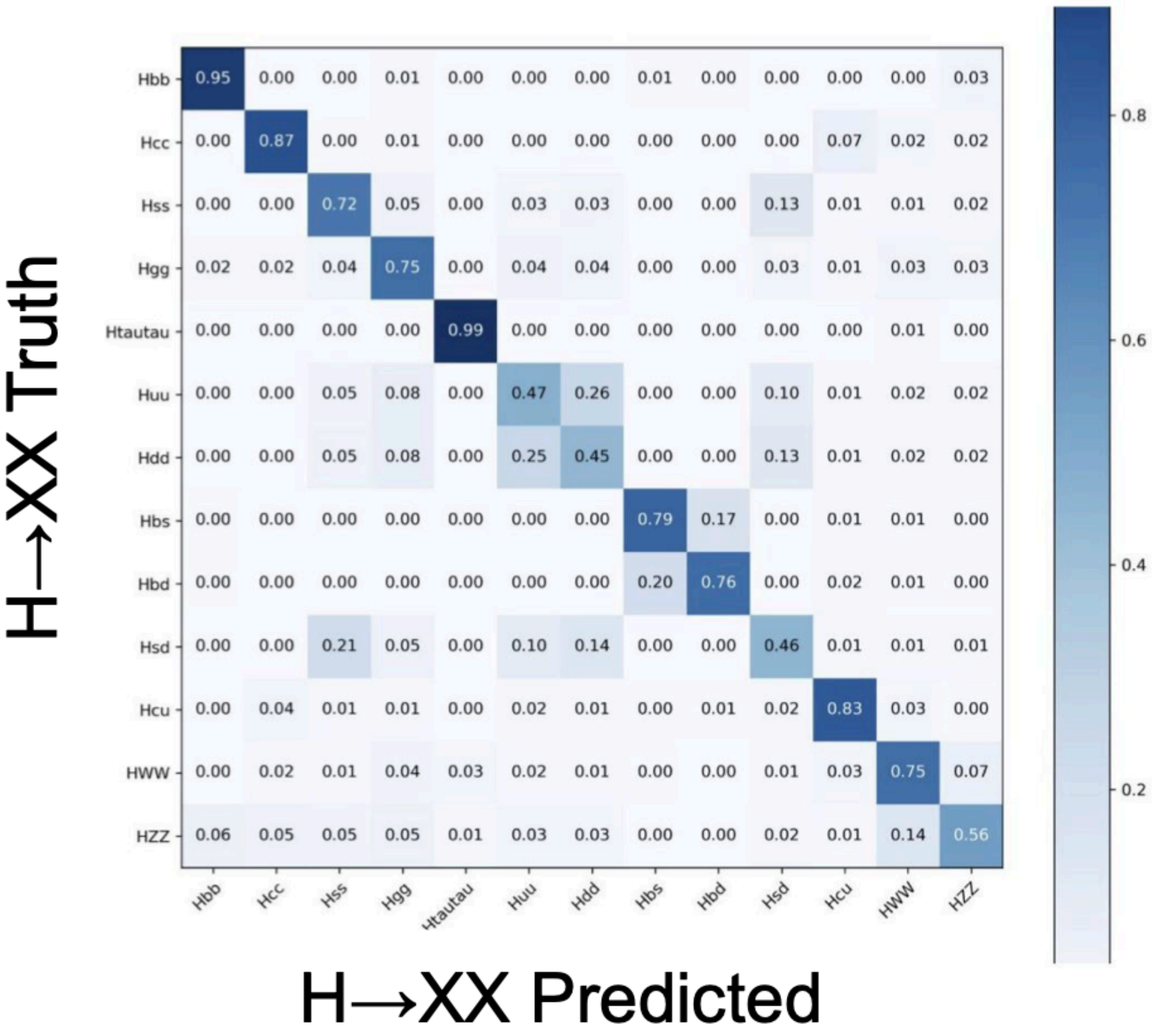
√s=240 GeV only

Final state	δσBR/σBR Z(ll)H(jj) %	δσBR/σBR Z(vv)H(jj) %	δσBR/σBR Z(qq)H(jj) %	BR(SM)
H→bb	0.7	0.4	0.3	58 %
H→cc	4.1	2.2	3.3	2.9 %
H→gg	2.2	1.1	3.1	8.6 %
H→ss	230	150	440	0.024 %
H→WW→had	1.8	1.1	8.7	10 %

10.8/ab at √s=240 GeV : δσBR/σBR = 0.22% (bb), 1.7% (cc), 0.9% (gg), 120% (ss), 1.1% (WW)
3/ab at √s=365 GeV : expect reduction of δBR/BR by ~10% in combination with 240 GeV

Higgs decays to quarks @ FCC-ee: 1st gen (uu, dd) and FCNC

- Extension of previous analysis using MVA with additional output classes (uu/dd/…) and floating freely in the final fit the normalisations of six additional Higgs decays



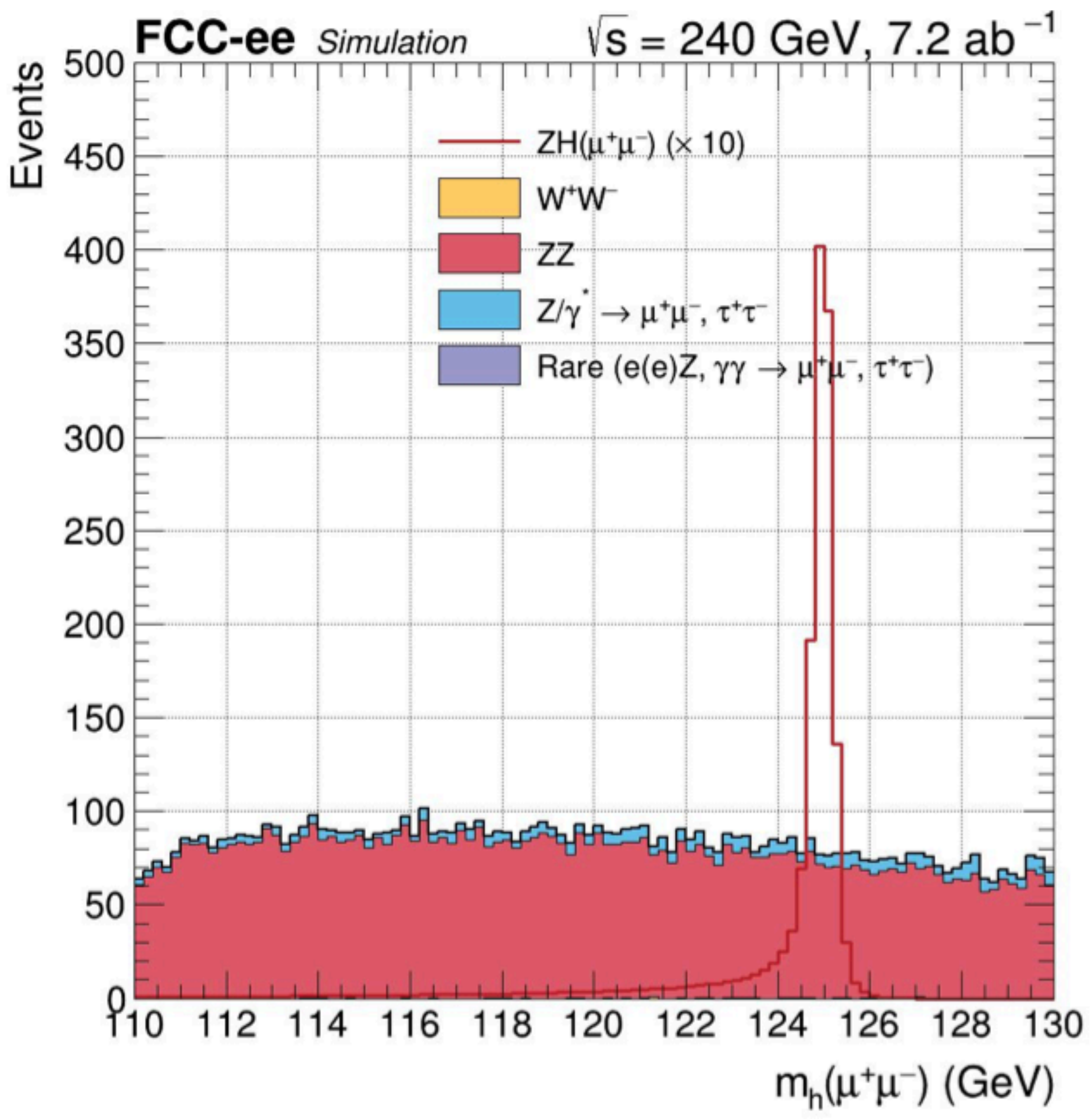
10.8/ab at 240 GeV, vvjj only

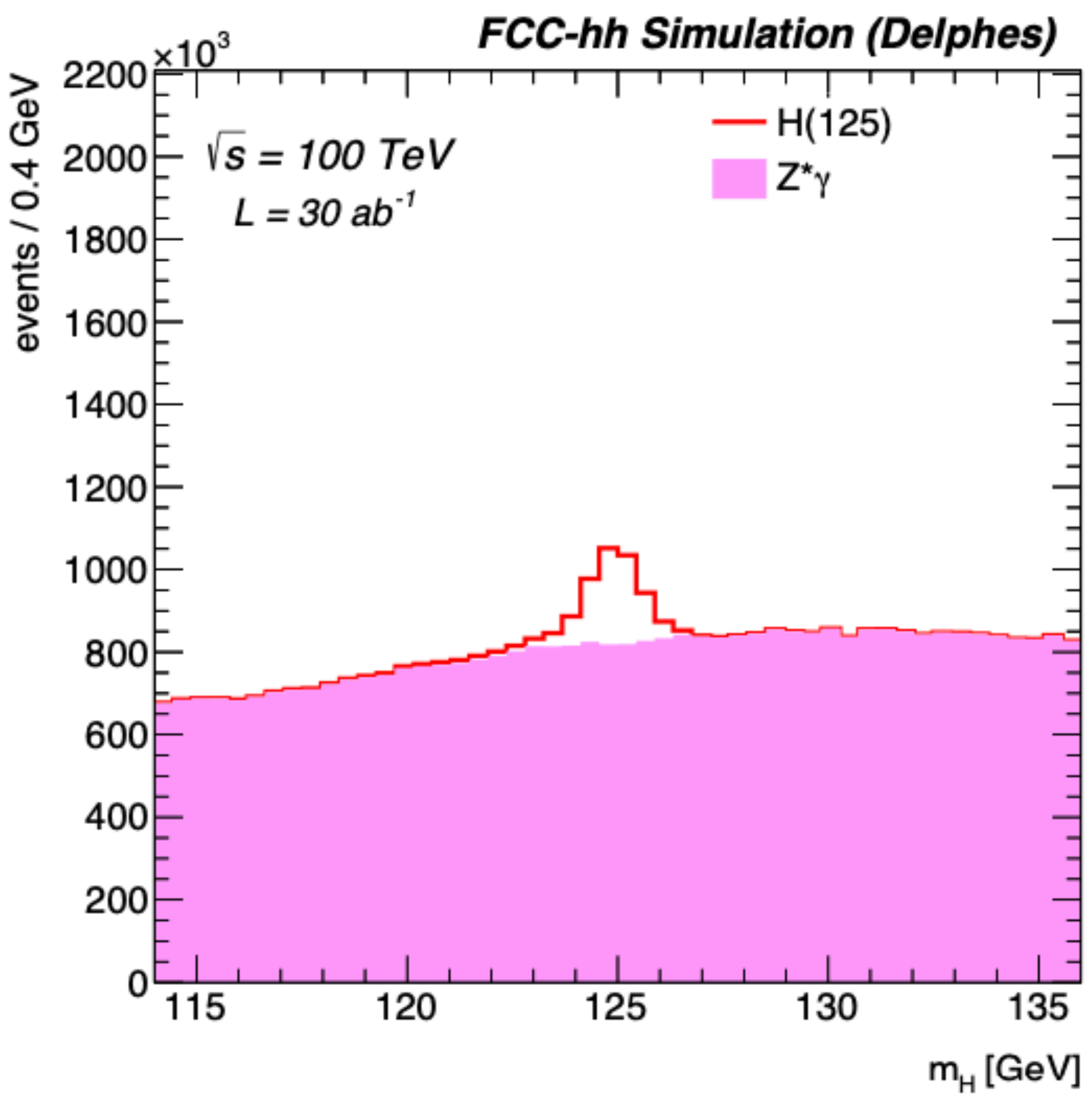
Final state	Upper limit on σBR @95% CL	BR(SM)
H→dd	1.4E-03	6E-07
H→uu	1.5E-03	1.4E-07
H→bs	3.7E-04	~1e-7
H→bd	2.7E-04	~1e-9
H→sd	7.7E-04	~1e-11
H→cu	2.5E-04	~1e-20

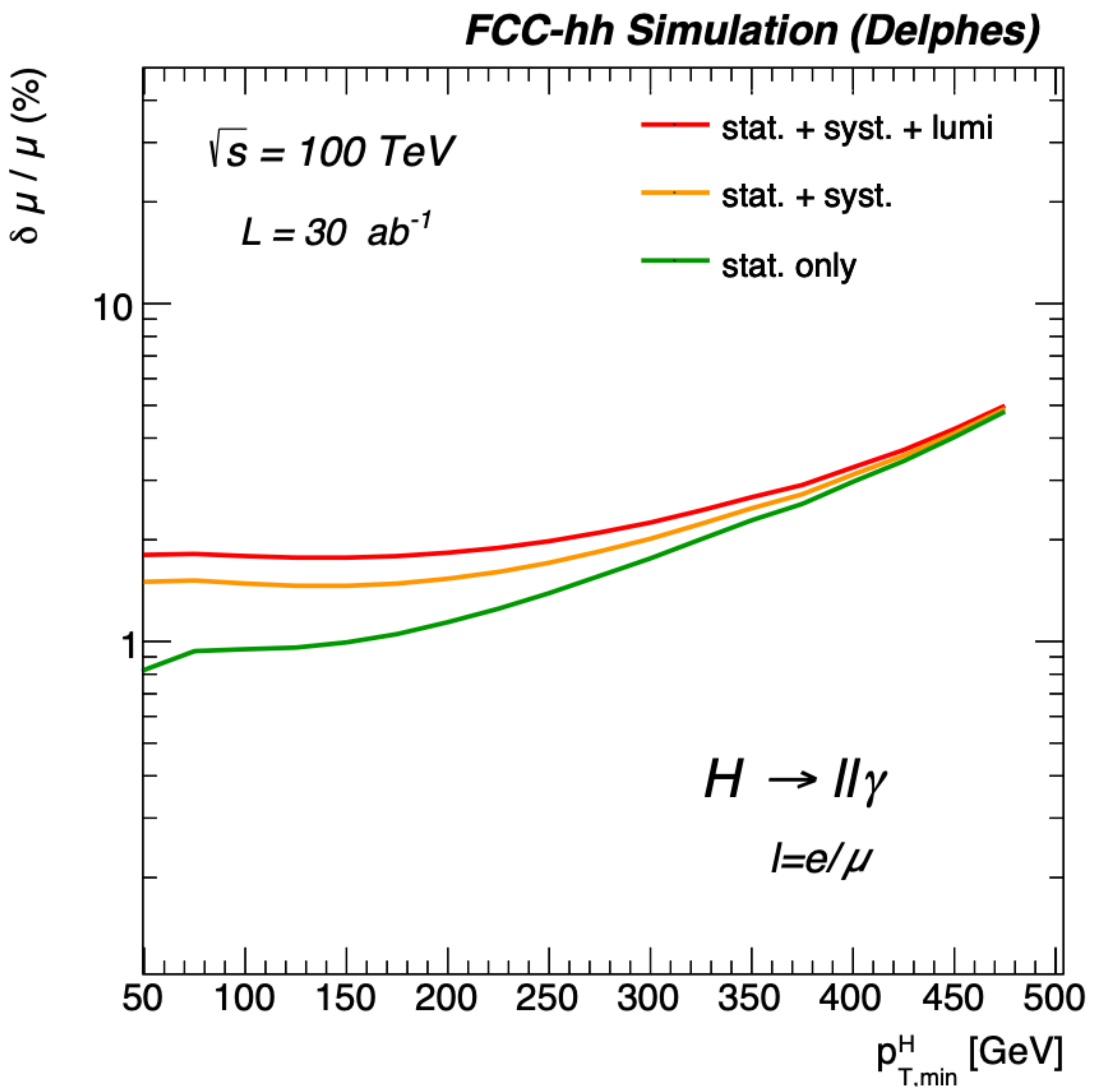
95% CL UL on σBR at 10^{-4} — 10^{-3} level with only vvjj final state at 240 GeV

Rare Higgs boson decays: μμ, γγ, Zγ

- @ FCC-ee, √s=240 GeV, H→μμ and γγ in ZH events
  - Select events with 2 high-momentum muons or photons, m_{inv}~m_H, recoil mass~m_Z (~300 H→μμ, 4000 H→γγ after selection in 10/ab)
  - Classify events into 4 categories (Z→ee, μμ, νν, qq) based on number and flavor of leptons, and missing momentum
  - Simultaneous fit to m_{inv} distributions in 4 categories. Largest sensitivity from Z(qq) (μμ) or Z(νν) (γγ)
- @ FCC-hh, √s=100 TeV GeV, H→μμ, γγ, Zγ
  - Huge yields (60M γγ, 40M Zγ, 6M μμ) & state-of-the art detectors to kill reducible backgrounds from mis-id
  - Measure σ*BR(H→X) normalised to σ*BR(H→4l) and scale by FCC-ee BR(H→4l) ⇒ BR(H→X)





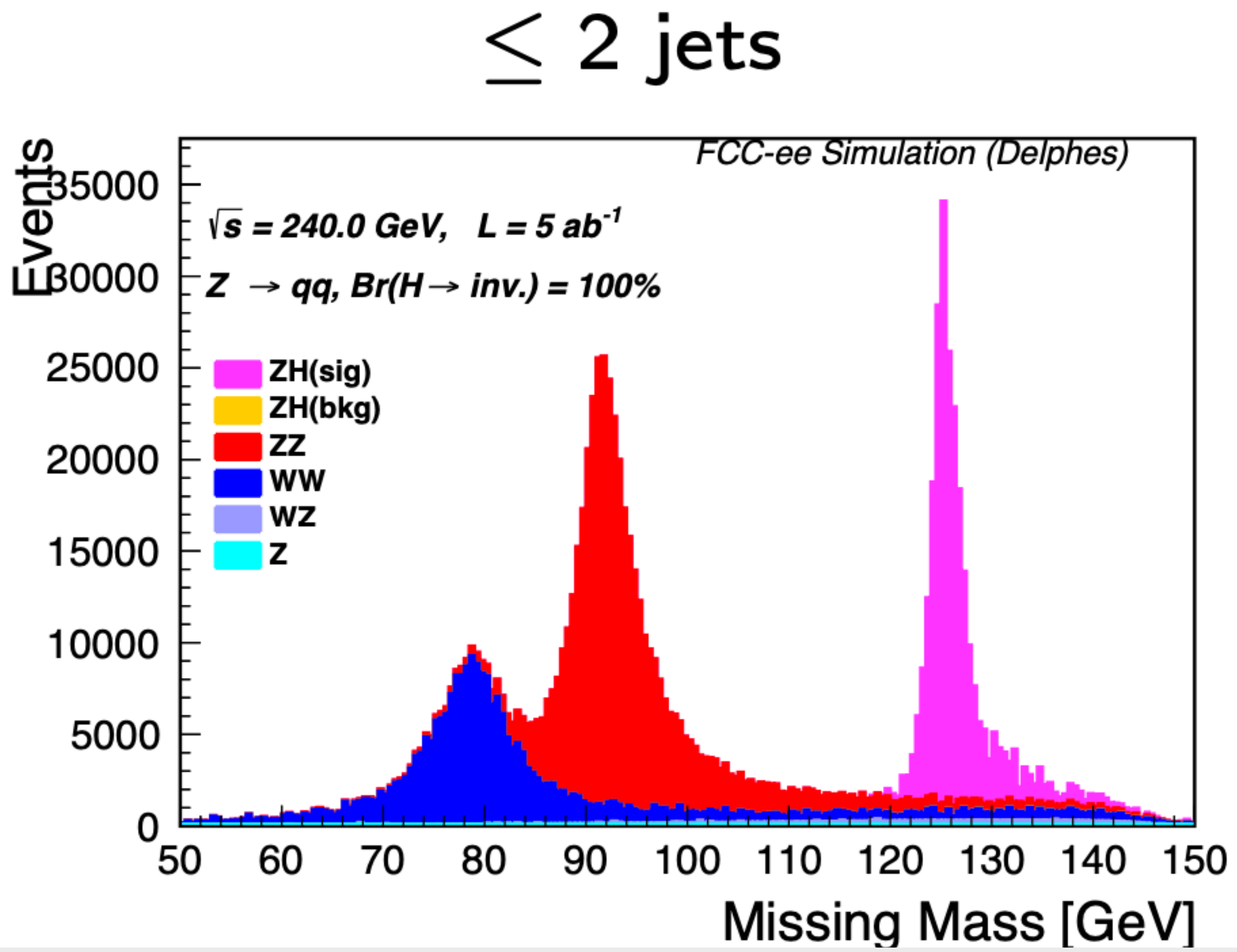


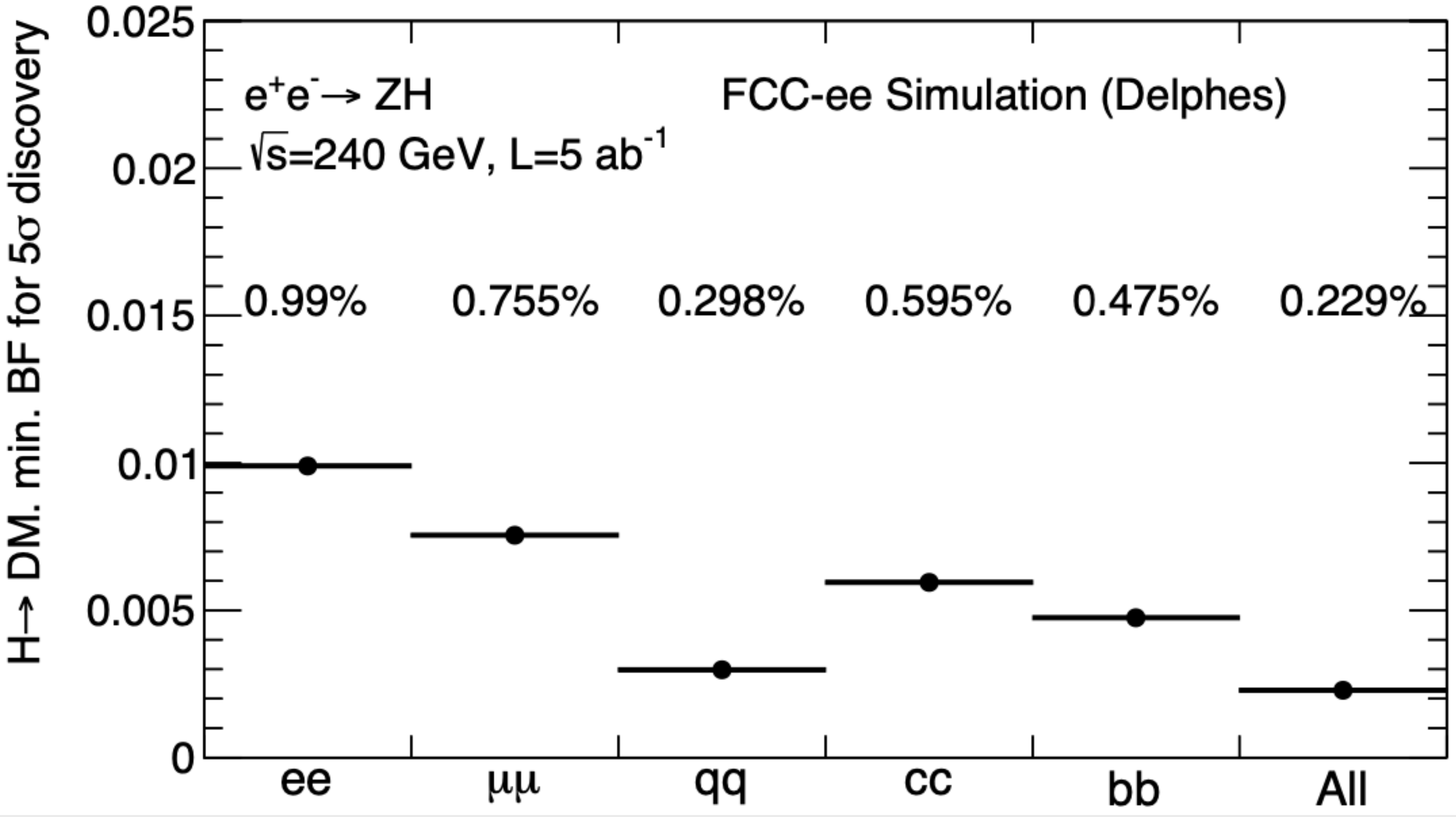
FCC-ee 10.8/ab @ 240 GeV : δσBR/σBR(μμ)=16% , δσBR/BR(γγ)=3.1%

FCC-hh (+ee) 30/ab @ 100 TeV : δBR/BR(μμ)=1.3% , δBR/BR(γγ)=0.8% , δBR/BR(Zγ)=1.8%

Higgs boson decays to invisible final states @ FCC-ee

- FCC-ee @ 240 GeV: search for H→invisible in ZH, Z→ll/qq
  - 5 final states/categories based on number of leptons (2e, 2μ, 0 e+μ) and, for 0-lepton, number of b- or c-tags (bb/cc/qq)
    - Further split of Z→qq category in jet-multiplicity categories (<=2, 3, >=4) (WW bkg ↑, dilepton bkg ↓ with N_{jet} ↑)
  - Z boson candidate formed by 2 leptons (Z(ll)) or all reconstructed particles (Z(qq)), m_{inv}~m_Z
  - p_{miss}> 10-20 GeV to suppress dilepton bkg
  - Signal yield and BR from fit to m_{miss} distribution (floating signal/WW/ZZ, constraining ZH(other) and dilepton background)



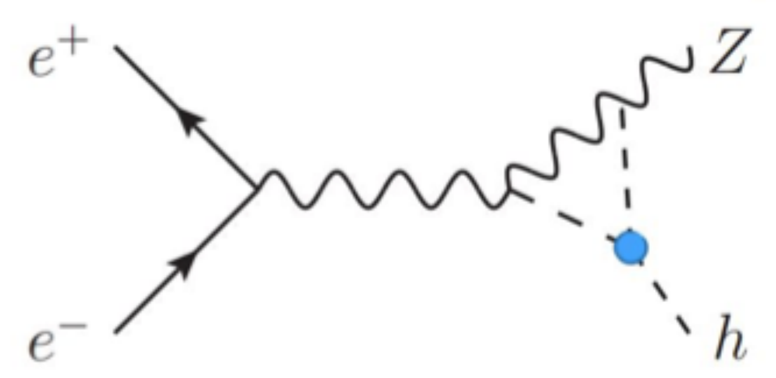


FCC-ee 10.8/ab @ 240 GeV : δσBR/BR=0.045% ⇒ 2σ measurement in SM case (BR≃0.1%)

Dominated by Z(qq) channel, limited by stat uncertainty

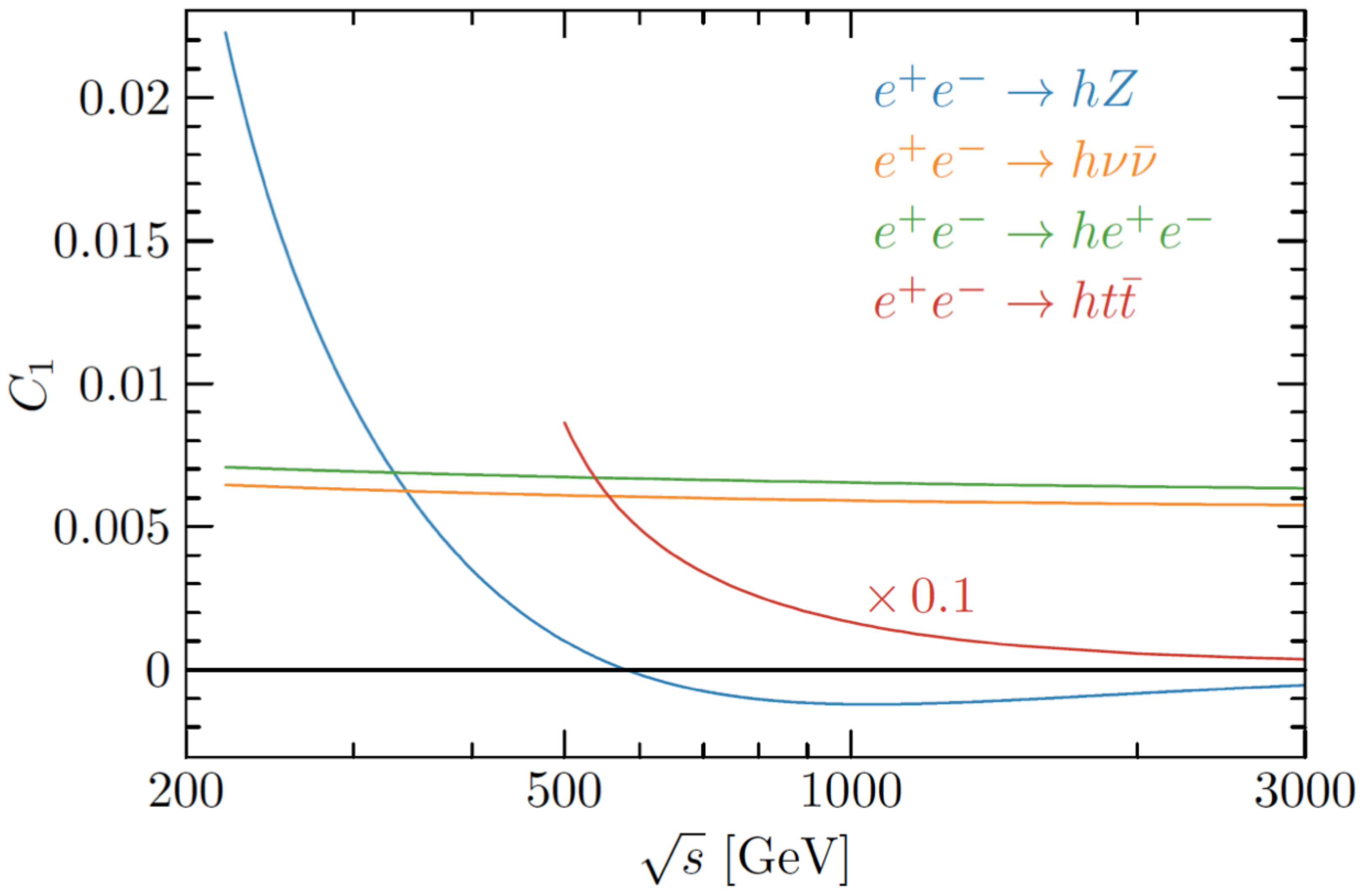
Higgs boson self-coupling

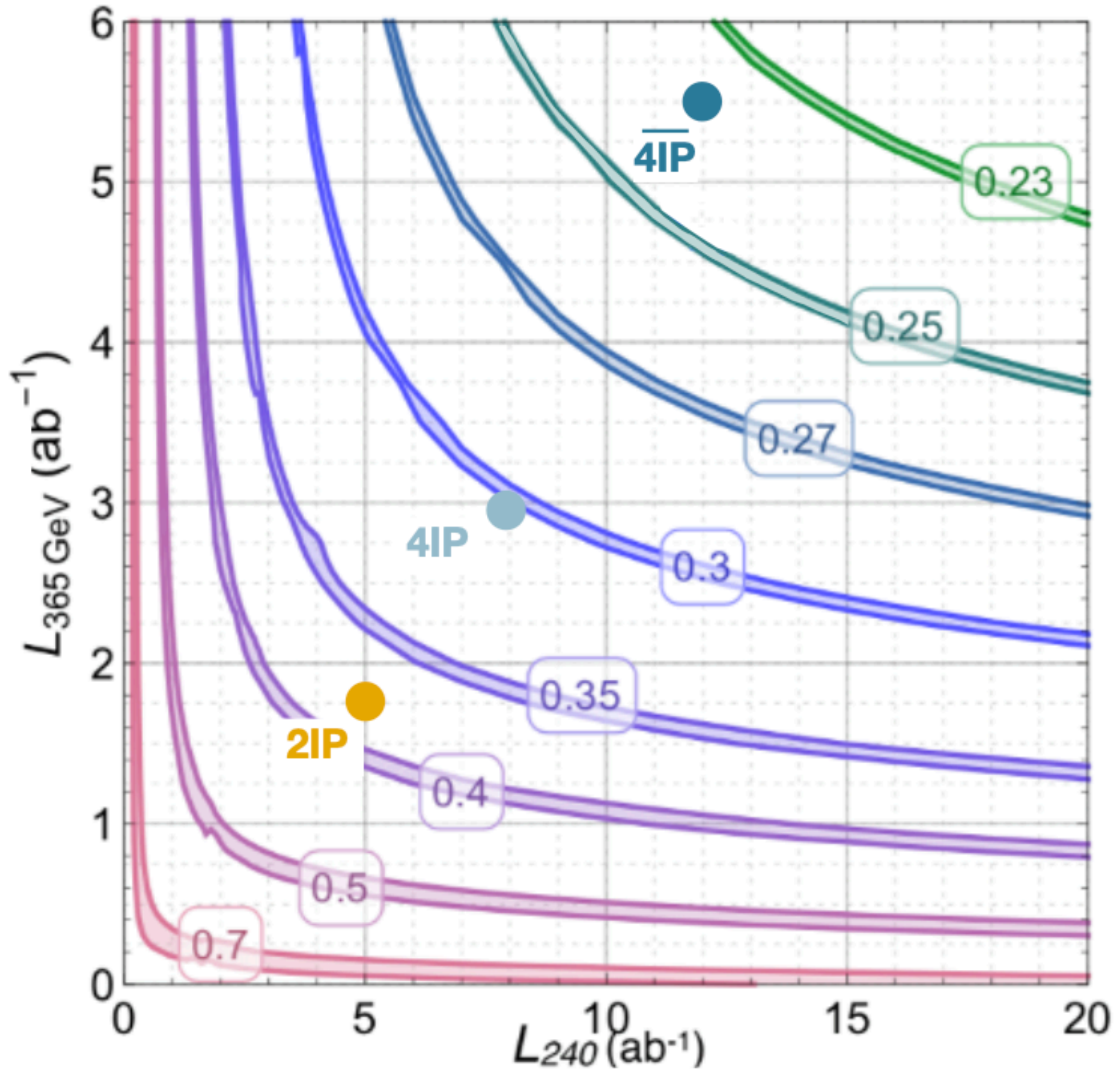
- FCC-ee: constrain $\kappa_\lambda = \lambda/\lambda_{SM}$ from single Higgs rate measurements, since κ_λ induces EW corrections to LO predictions



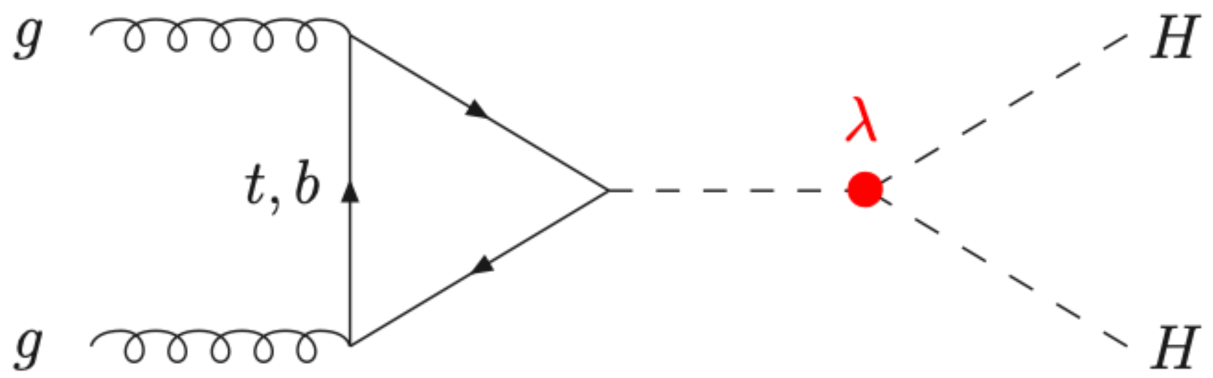
$$\sigma_{\mathrm{i,NLO}} = Z_H \sigma_{\mathrm{i,LO}} (1 + \kappa_\lambda C_{1,i}) \qquad Z_H = \frac{1}{1 - \kappa_\lambda^2 \delta Z_H} \qquad \delta Z_H \approx -0.00154$$

  - C_1 depends on $\sqrt{s}$ ⇒ use measurements at 240 and 365 GeV to lift degeneracy between two solutions
  - Expect $\delta\kappa_\lambda$ = 28% with 240 + 365 GeV runs





- At FCC-hh, constrain κ_λ from Higgs pair production



  - Sensitivity dominated by bbγγ, but several additional final states investigated (bbττ, bbWW, 4b)

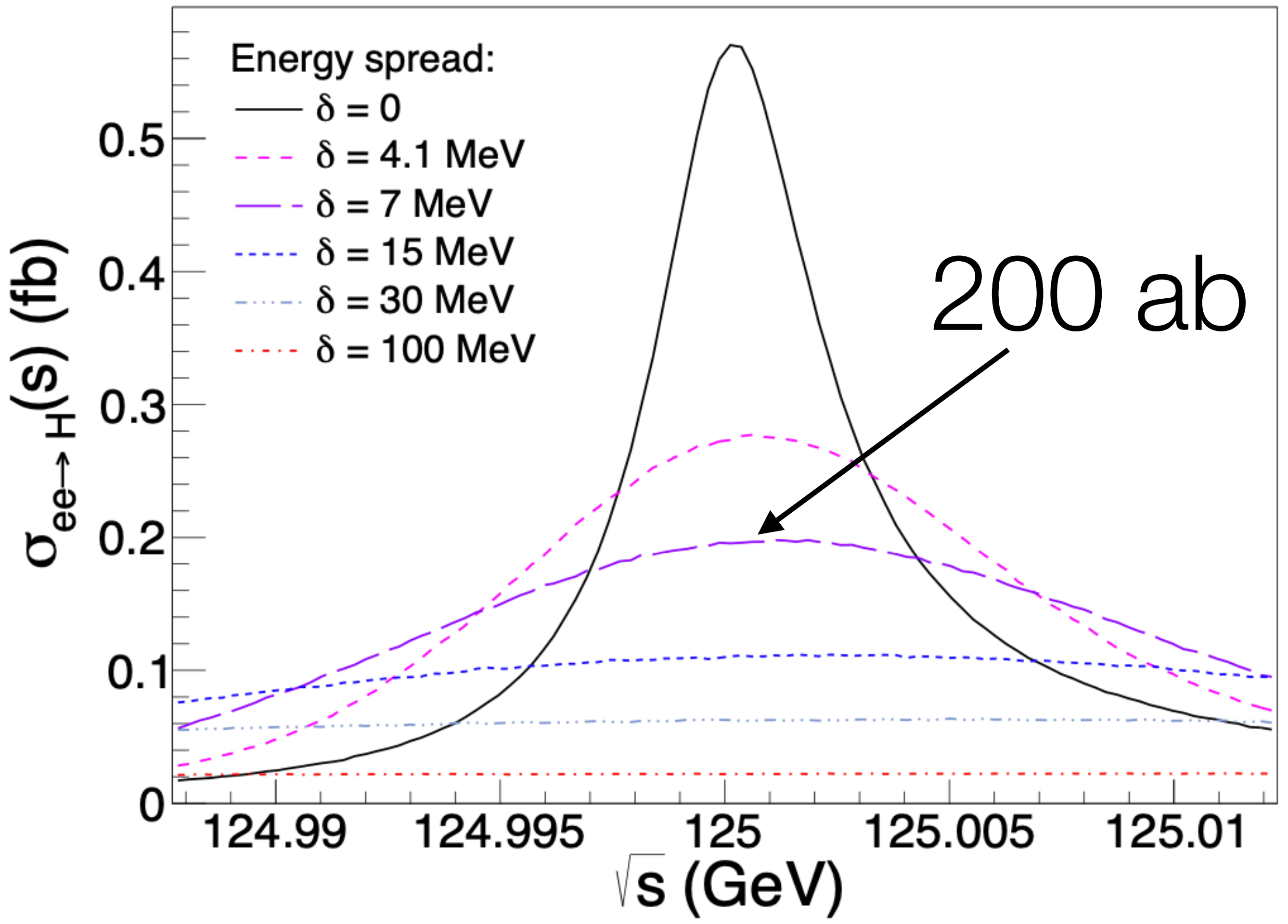
	Stat only	Syst 1
No assumption on $m_{\bar{b}b}$ resolution	3.2%	3.6%
10 GeV $m_{\bar{b}b}$ res	2.5%	2.7%
5 GeV $m_{\bar{b}b}$ res	2.0%	2.3%
3 GeV $m_{\bar{b}b}$ res	**1.8%**	**2.0%**

FCC-ee 240+365 GeV : $\delta\kappa_\lambda$ = 28%

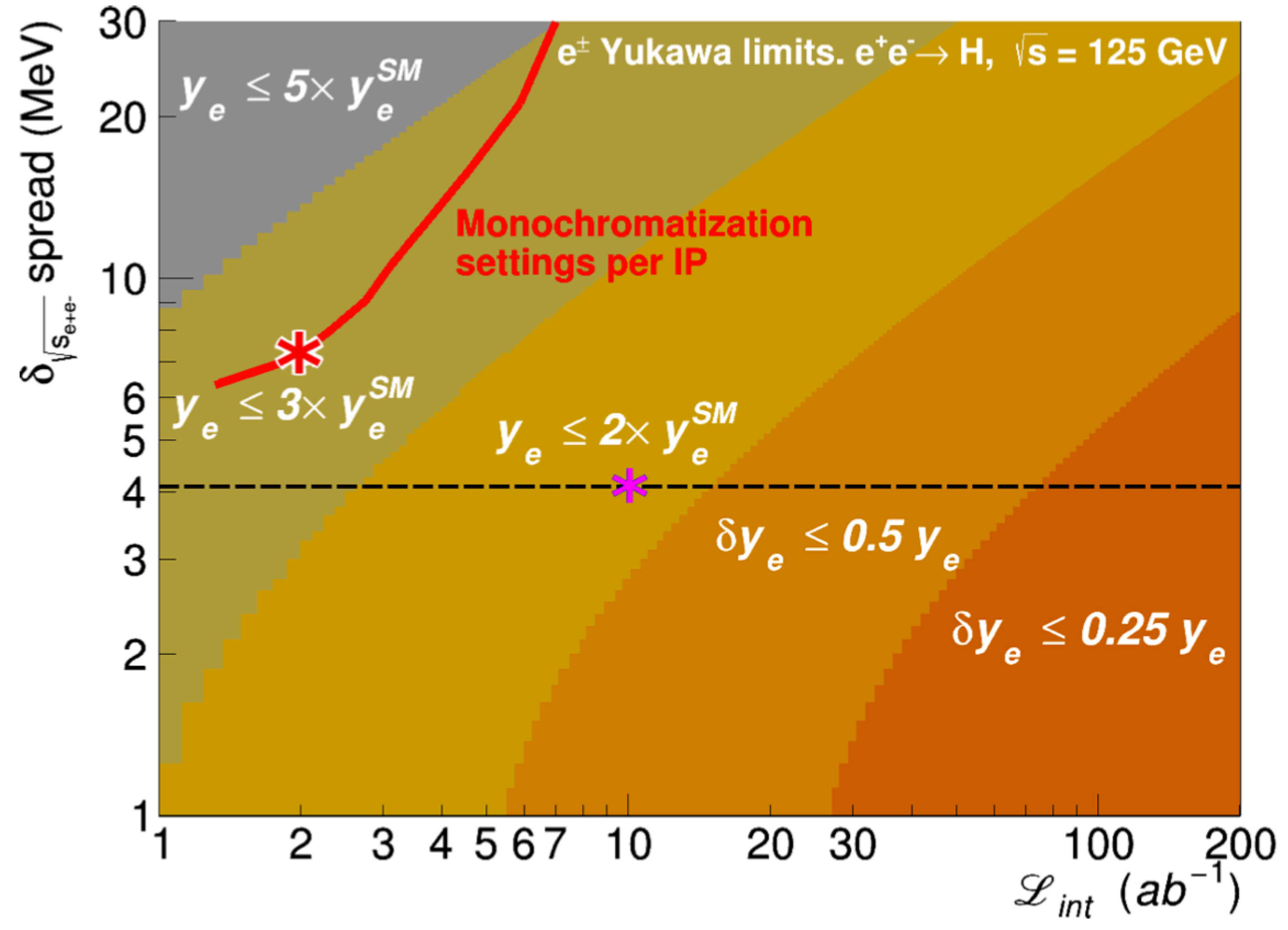
FCC-hh 100 TeV (30/ab) : $\delta\kappa_\lambda$ < 3% for m_{bb} resolution = 10 GeV

Higgs couplings to 1st gen fermions: the case for a run at $\sqrt{s_{ee}}$=125 GeV

- Dedicated run at $\sqrt{s}$=125 GeV could allow probing electron Yukawa coupling in s-channel (only way to access couplings to 1st gen)
  - Requires knowledge of Higgs mass to < 5 MeV, large luminosity, excellent beam chromatisation (energy spread ~ Γ_H)
  - Many Higgs decays considered, preselection followed by cut&count analysis on binary BDT classifier (signal vs background)



Target Higgs decay	Final state definition	Signal presel. efficiency
$H \to b\bar{b}$	2 (excl.) jets, 1 b-tagged jet, no τ_{had}	80%
$H \to gg$	2 (excl.) gluon-tagged jets, 0 isolated $\ell^{\pm}$	50%
$H \to \tau_{had}\tau_{had}$	Exactly 2 τ_{had}, 0 isolated $\ell^{\pm}$	65%
$H \to c\bar{c}$	2 (excl.) jets, 1 c-tagged jet, no τ_{had}	70%
$H \to WW^* \to \ell\nu 2j$	1 isolated $\ell^{\pm}$, $E_{miss} > 2$ GeV, 2 (excl.) jets	~100%
$H \to WW^* \to 2\ell 2\nu$	2 isolated opp.-charge $\ell^{\pm}$, $E_{miss} > 2$ GeV, 0 non-isol. $\ell^{\pm}$, 0 charged hadrons	~100%
$H \to WW^* \to 4j$	4 (excl.) jets, ≥ 1 c-tag jets, 0 b-,g-tag jets; jets with $m_{j1j2} \approx m_W$ not both c-tagged, 0 τ_{had}, 0 isolated $\ell^{\pm}$	70%
$H \to ZZ^* \to 2j2\nu$	2 (excl.) jets, $E_{miss} > 30$ GeV, 0 isolated $\ell^{\pm}$, 0 τ_{had}	~100%
$H \to ZZ^* \to 2\ell 2j$	2 isolated opposite-charge $\ell^{\pm}$, 2 (excl.) jets, 0 τ_{had}	~100%
$H \to ZZ^* \to 2\ell 2\nu$	2 isolated opp.-charge $\ell^{\pm}$, $E_{miss} > 2$ GeV, 0 non-isol. $\ell^{\pm}$, 0 charged hadrons	~100%
$H \to \gamma\gamma$	2 (excl.) isolated photons	~100%



arXiv:2107.02686

8/ab/yr (4 IP) with δ=7 MeV: 1600 ee→H/yr ⇒ $y_e < 1.6\, y_e^{SM}$ in 2 yrs

To reach sensitivity to SM need optics w/ excellent monochromatisation AND L_{inst}

Conclusion

- FCC provides exciting opportunities for wide Higgs physics program with unprecedented accuracy
- Sensitivity of many measurements studied with parametric simulations based on realistic performance of FCC detector concepts
  - L = 10.8/ab @240 GeV, 3/ab @365 GeV, 16/ab@125 GeV, 30/ab@100 TeV
- Impact of alternative detector scenarios or more conservative performance assumptions has so far shown limited impact on projections
- Analyses still being optimised, some not performed yet (esp. @ 365 GeV, separating ZH/VBF, and global combination+coupling fit)
- Lots of work ongoing to implement full simulation + reconstruction algorithms of the detector concepts for ultimate assessment of expected sensitivities
- TH effort needed to match experimental uncertainties in interpretation of results

everybody interested to join us is welcome!

Parameter	FCC-ee	FCC-hh
m_H	4 MeV	
Γ_H	2.9 %	
σ_{ZH}	0.6 % (240 GeV) 1.5 % (365 GeV)	
$\sigma BR(H\to ZZ)$	2.8 %	
$\sigma BR(H\to WW)$	1.1 %	
$\sigma BR(H\to gg)$	0.9 %	
$\sigma BR(H\to \gamma\gamma)$	3.1 %	0.8 %
$\sigma BR(H\to Z\gamma)$		1.8 %
$\sigma BR(H\to bb)$	0.2 %	
$\sigma BR(H\to \tau\tau)$	0.9 %	
$\sigma BR(H\to cc)$	1.7 %	
$\sigma BR(H\to ss)$	120 %	
$\sigma BR(H\to \mu\mu)$	16 %	1.3 %
$\sigma BR(H\to inv.)$	0.045 %	
y_e	$< 1.6\ y_e^{SM}$	
$\sigma BR(H\to uu, dd, FCNC)$	$< 10^{-4} - 10^{-3}$	
κ_λ	28 %	2.7 %

WORK in progress

More details

Latest FCC-ee parameters

FCC-ee parameters		Z	WW	ZH	ttbar
√s	GeV	88 - 94	157.2 - 162.5	240	350-365
Inst. Lumi / IP	10^{34} cm^2 s^{-1}	182	19.4	7.3	1.33
Integrated lumi / 4IP	ab^{-1} / yr	87	9.3	3.5	0.65
N bunches/beam	-	10 000	880	248	36
bunch spacing	ns	30	340	1 200	8 400
L*	m	2.2	2.2	2.2	2.2
crossing angle	mrad	30	30	30	30
vertex size (x)	µm	5.96	14.7	9.87	27.3
vertex size (y)	nm	23.8	46.5	25.4	48.8
vertex size (z)	mm	0.4	0.97	0.65	1.33
vertex size (t)	ps	36.3	18.9	14.1	6.5
Beam energy spread	%	0.132	0.154	0.185	0.221