HIGGS PROPERTIES AT THE FCC-ee

MARÍA CEPEDA (CIEMAT)

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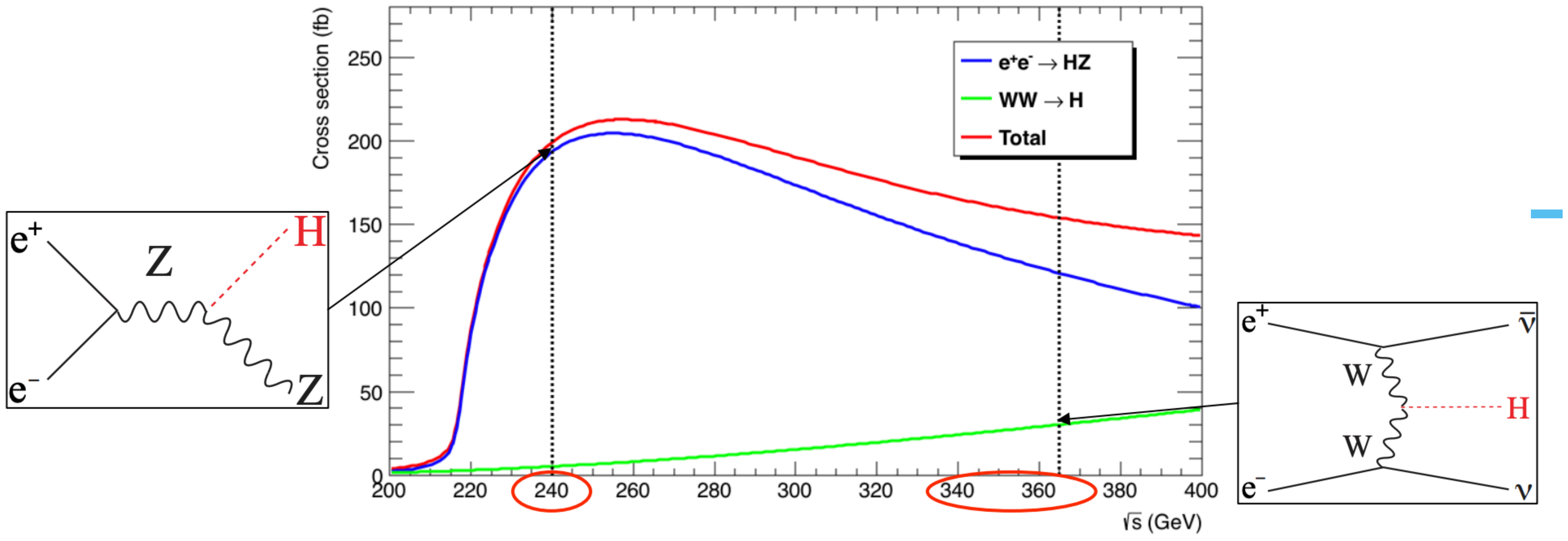
Higgs 2024, Uppsala

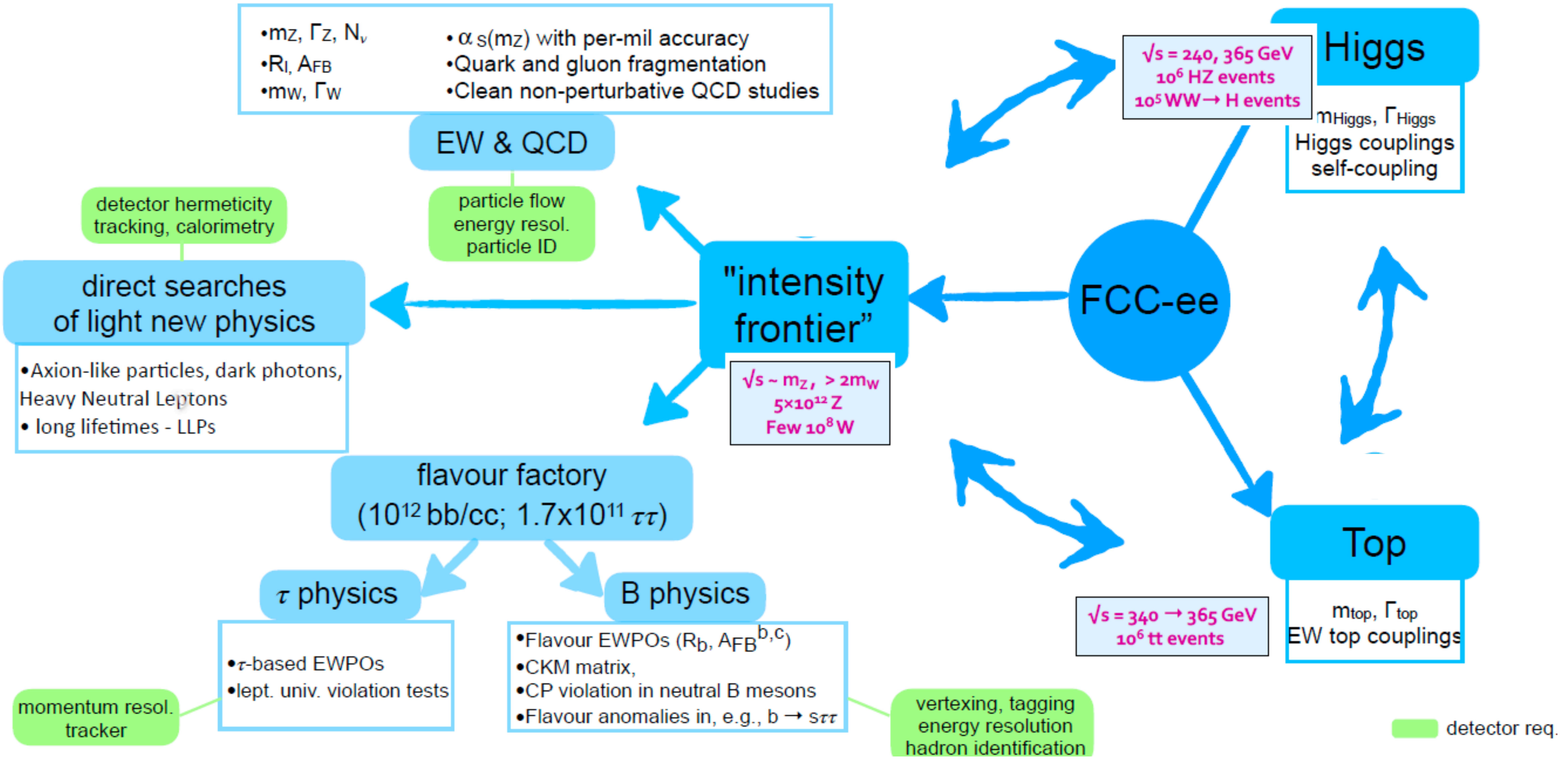
HIGGS @ FCC-ee



- **Production of millions of Higgs bosons in a clean environment**
- Baseline (4IP):
  - 240 GeV / 10.8 ab^{-1} : 2.2M ZH / 67k VBF
  - 365 GeV / 3 ab^{-1}: 330k ZH / 80k VBF
- Systematics:
  - integrated lumi ~ 0.01%
  - tagging efficiency, BES < 1%
  - TH < 1% (no PDFs, QCD corrections are small)

- **Fundamental properties:** model-independent ZH cross section, mass, width, self-coupling, CP
- **Brs/Couplings:** ZZ&WW, Hadrons (bb,cc,ss), Leptons ($\tau\tau$), Rare ($\gamma\gamma$, Zγ,$\mu\mu$), Exotic (BSM/invisible), First Generation (ee, uu/dd?)
- **And more…** Differential measurements, Angular observables, Anomalous Couplings, BSM searches (FCNC, Additional Scalars)

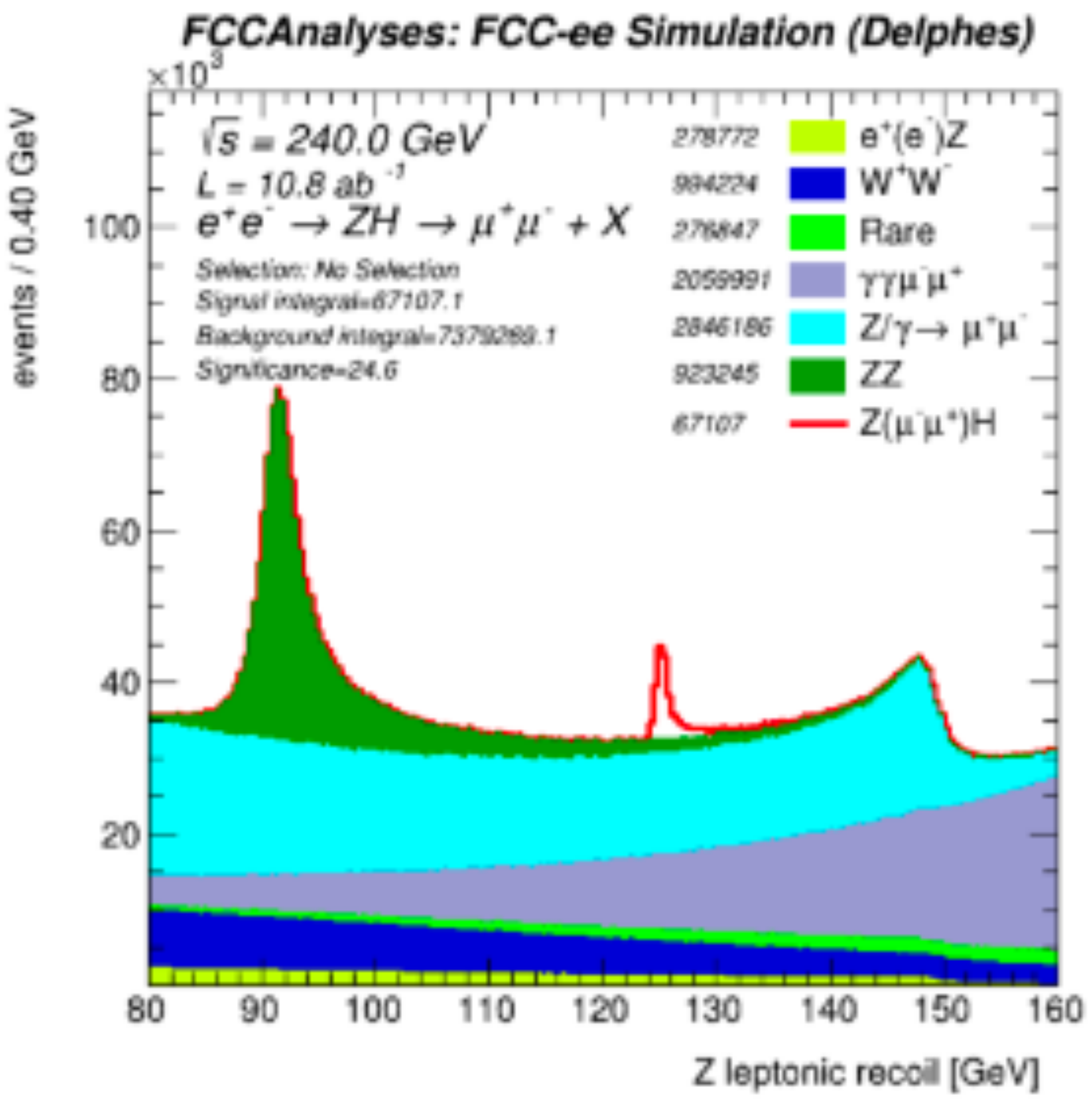
RICH PHYSICS PROGRAM: DETECTOR IMPLICATIONS

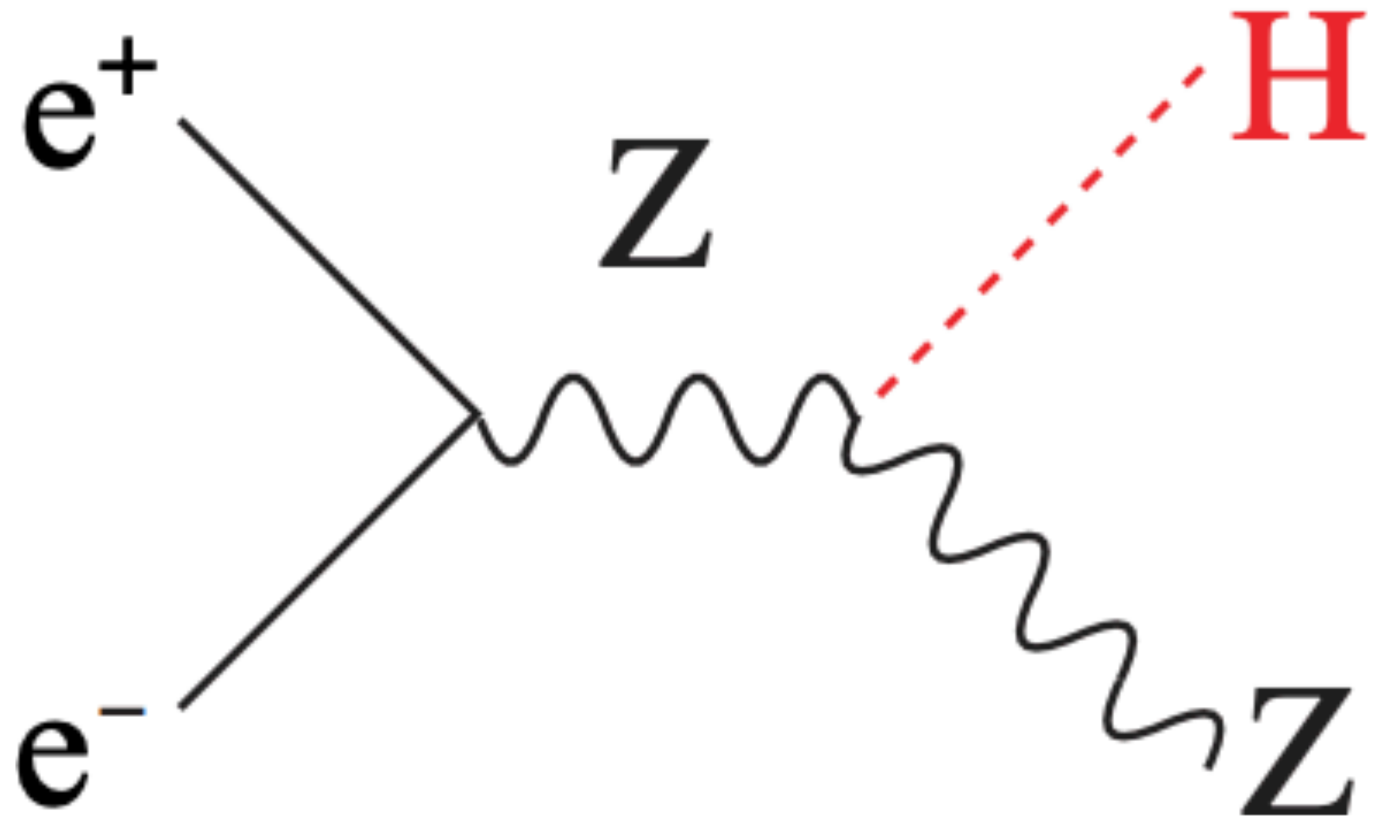


ZH MODEL-INDEPENDENT MEASUREMENTS

- **Precise inclusive measurement of σ_{ZH}, mass, width,...**
- **Recoil method in ZH: unbiased reconstruction of the Higgs**
  - Known initial state. Not possible in a hadron collider
  - Tag Z: lepton&jet decays, tight invariant mass constraints→ Higgs Recoil
  - Dominated by detector resolution
  - Backgrounds: Vector Boson pair production (ZZ,WW) and Z/gamma

$$m_{recoil}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2$$
$$= s + m_Z^2 - 2E_{ff}\sqrt{s} \approx m_H^2$$

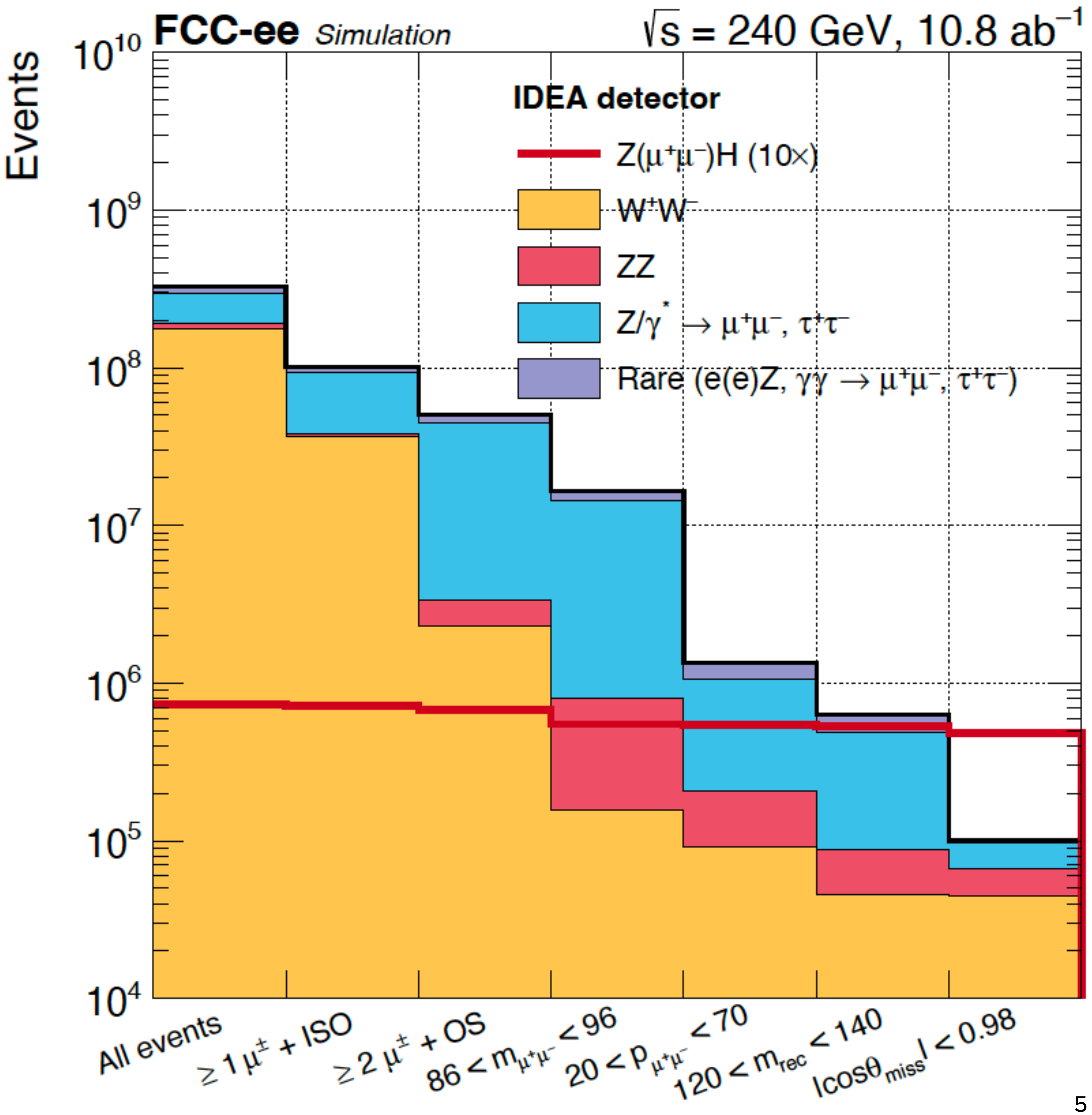




- **Studied at 240 and 365 GeV. Sensitivity driven by $\sqrt{s} = 240$ GeV (larger statistics)**
- **Challenges for the Higgs program (see Andreas' talk!):**
  - Detector Performance (tracking, vertexing, timing, angular)
  - Hadronic states: Flavour Tagging, Jet clustering

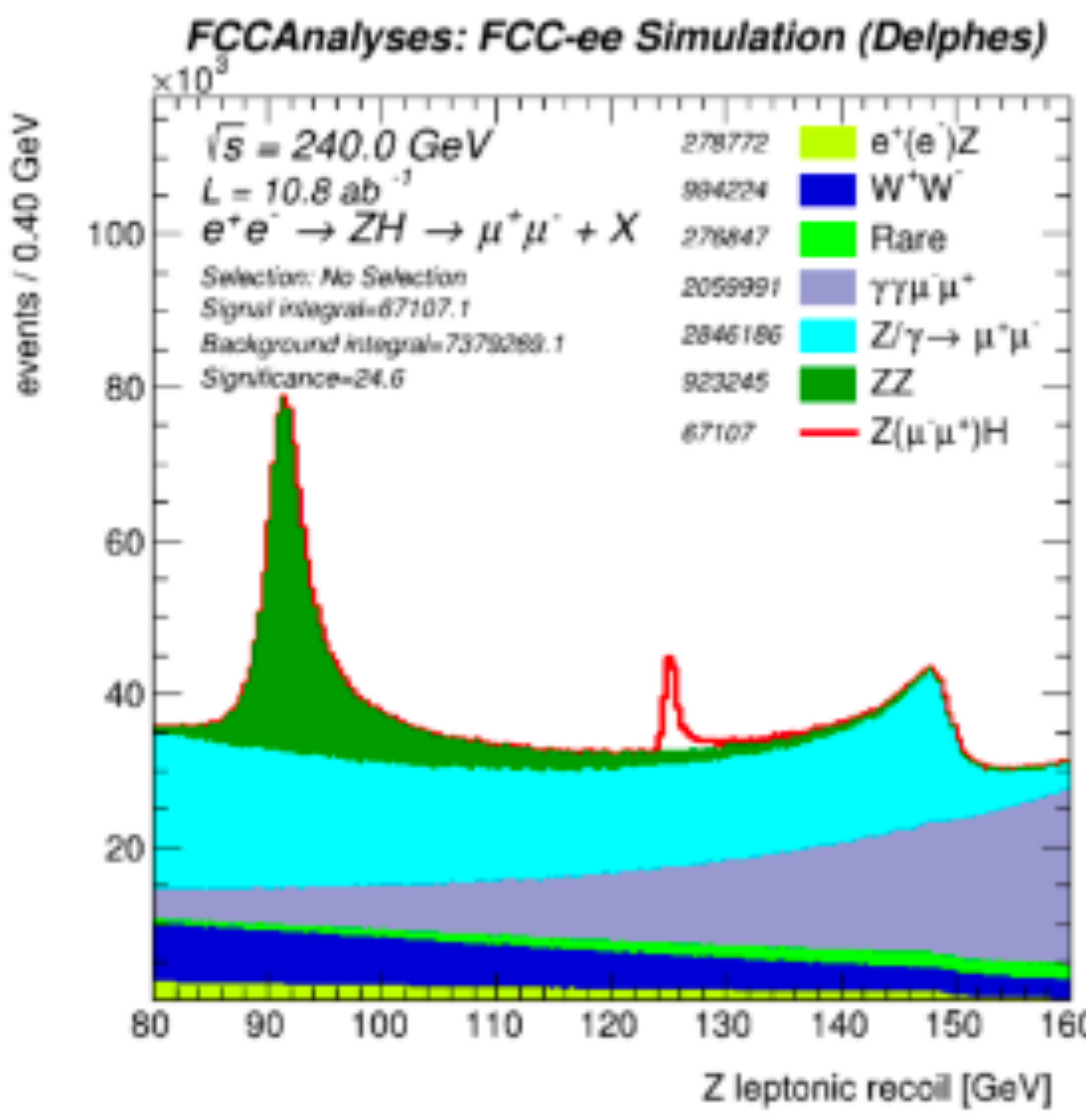
ZH MODEL-INDEPENDENT MEASUREMENTS

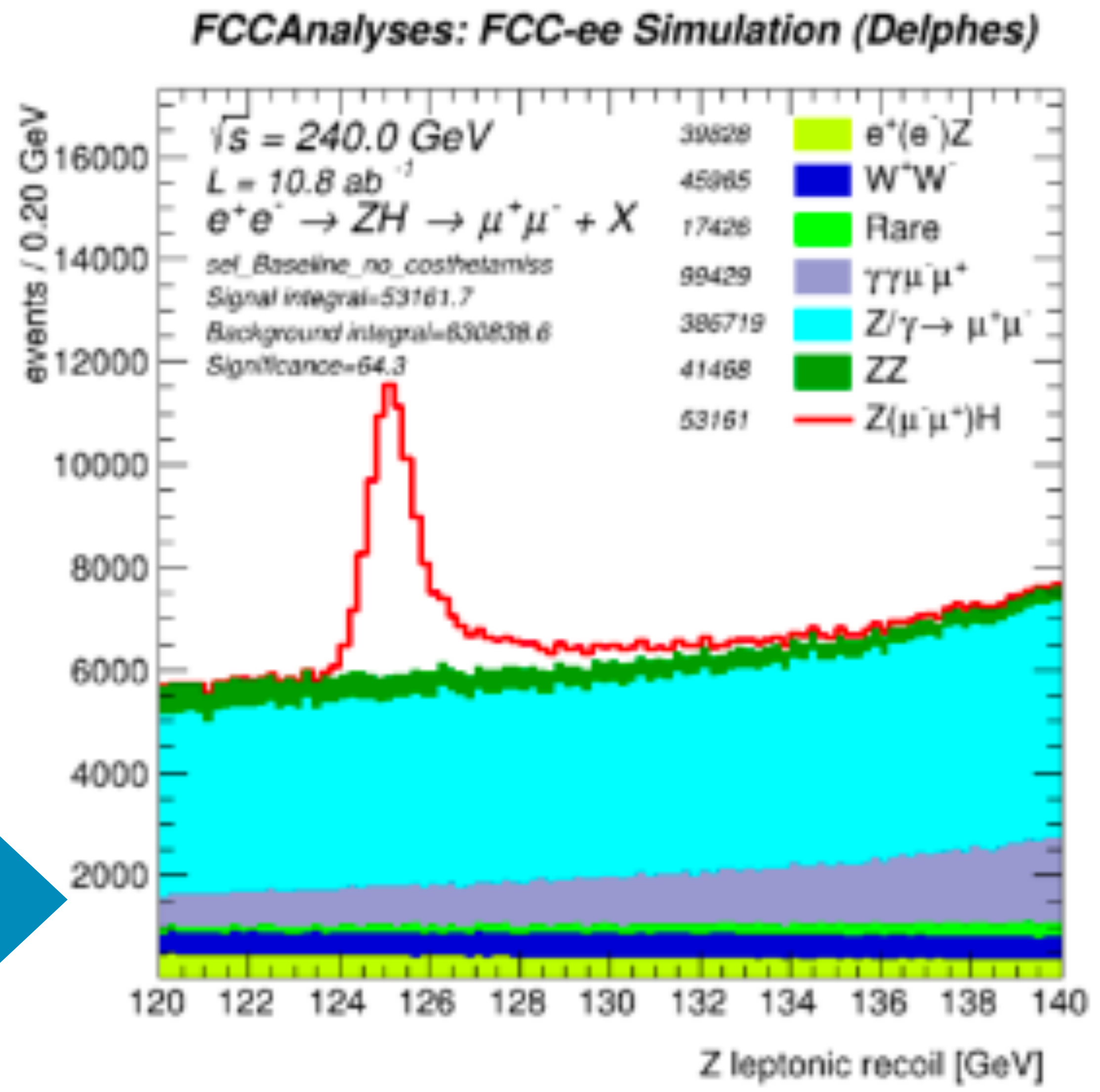
- **Cross section measurement driven by leptonic Z decays: clean and sharp recoil distribution, reduced backgrounds, minimized model dependency**
- ZH signal modeled with Whizard in DELPHES (IDEA)
- Backgrounds (Whizard/Pythia):
  - Main: ZZ, WW, $Z/\gamma*$, eeZ
  - Rare: other ZH, $Z \to qq$, $\gamma\gamma \to e^+e^-$, $\gamma\gamma \to \mu^+\mu^-$, $\gamma\gamma \to \tau^+\tau^-$
- Basic selection:
  - 2 OS leptons, at least one isolated
  - $m_{ll} \in [86{,}96]$ GeV
  - $p_{ll} \in [20{,}70]$ GeV at $\sqrt{s} = 240$ GeV,
  - $p_{ll} > 20$ GeV at $\sqrt{s} = 365$ GeV
  - $m_{recoil} \in [120{,}140]$ GeV



$Z(\mu^+\mu^-)H$: 240 GeV vs 365 GeV

240 GeV

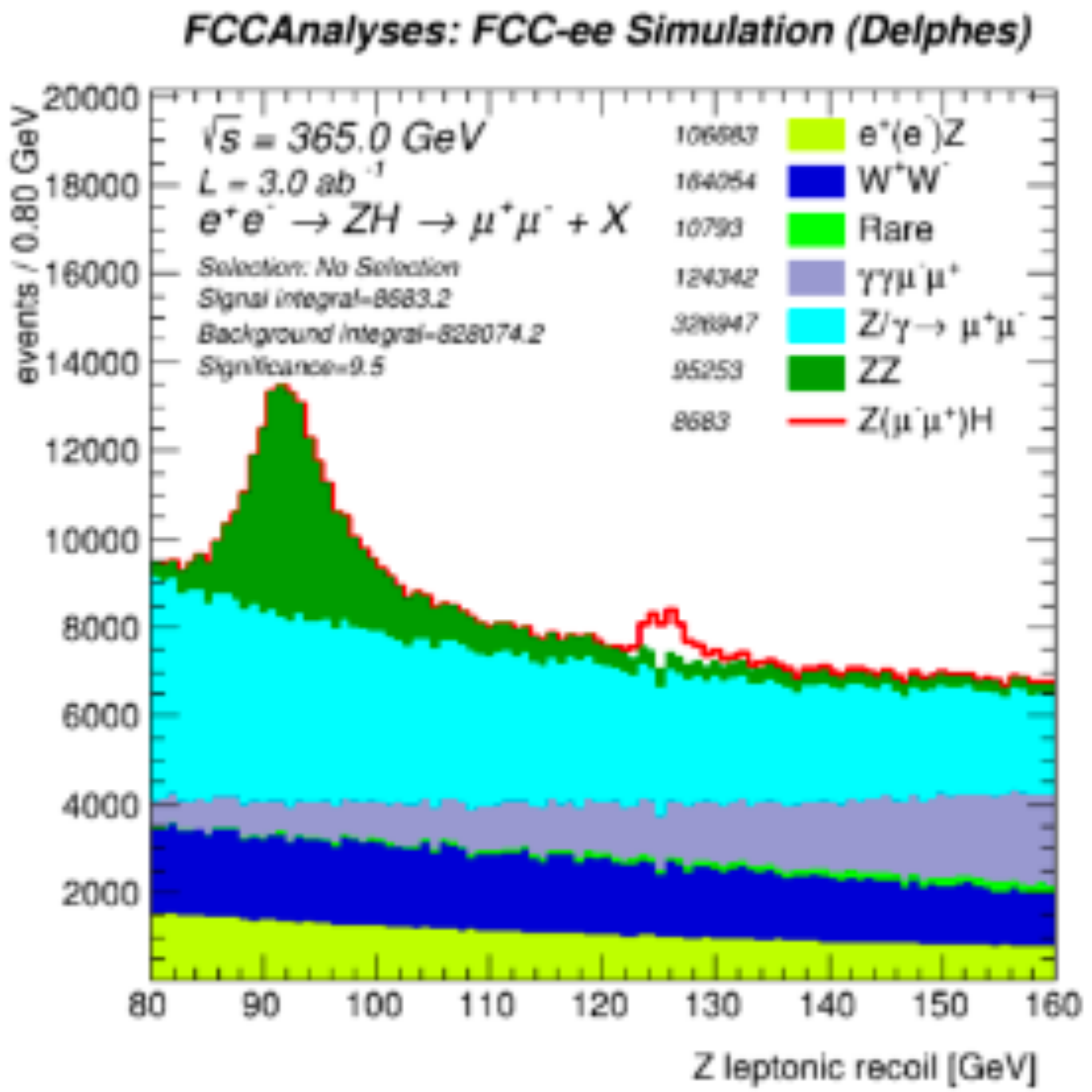


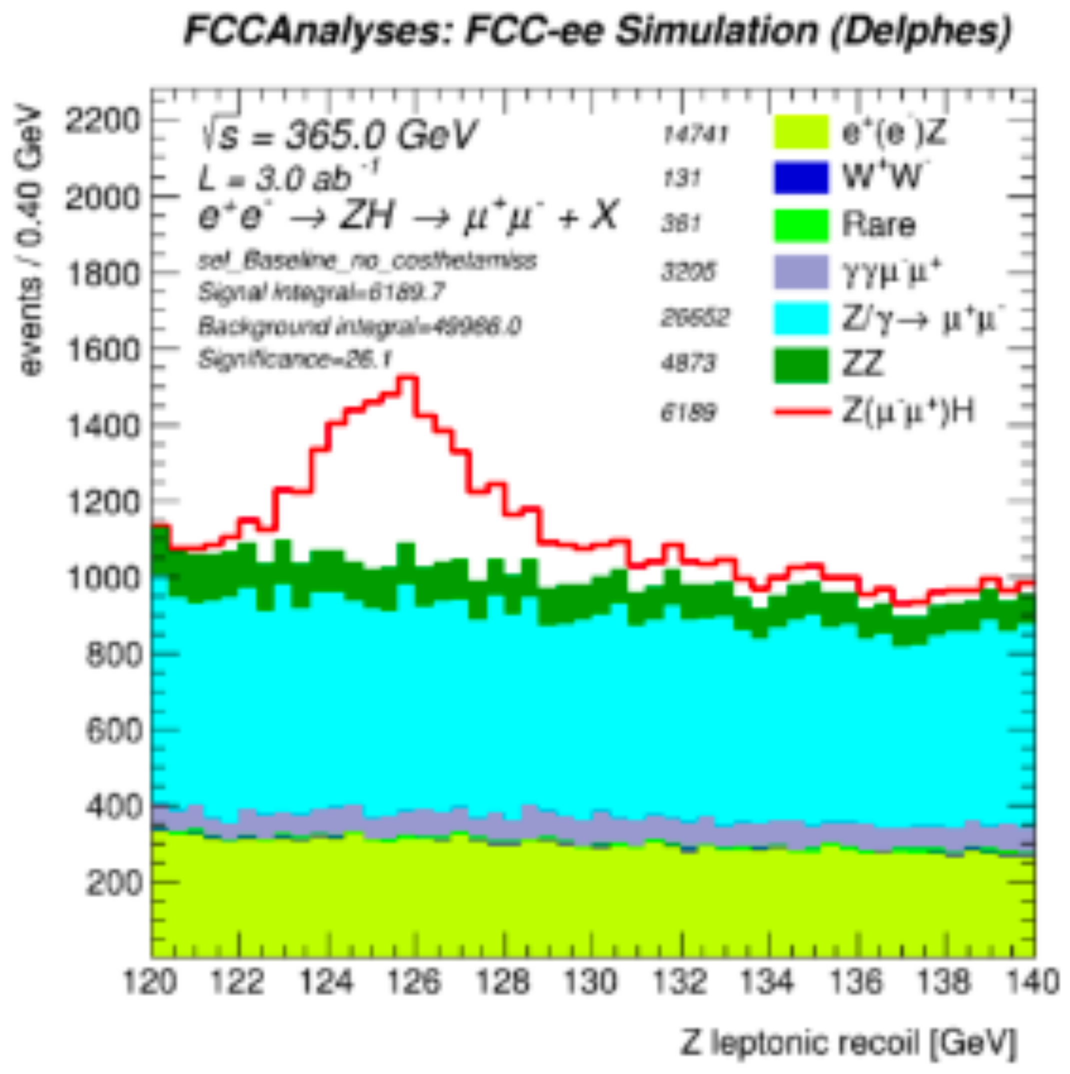


selection

(kin cuts)

365 GeV



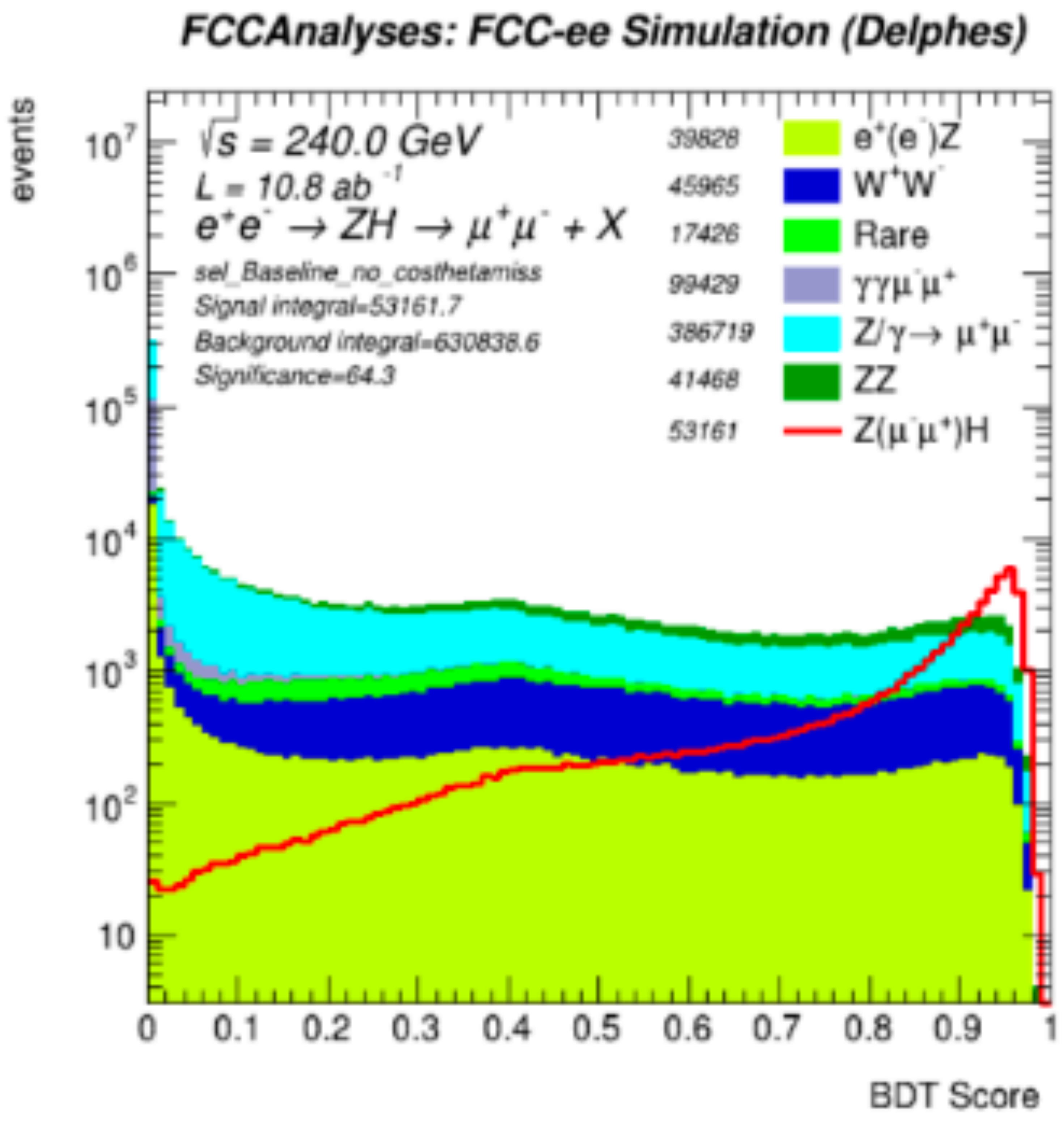


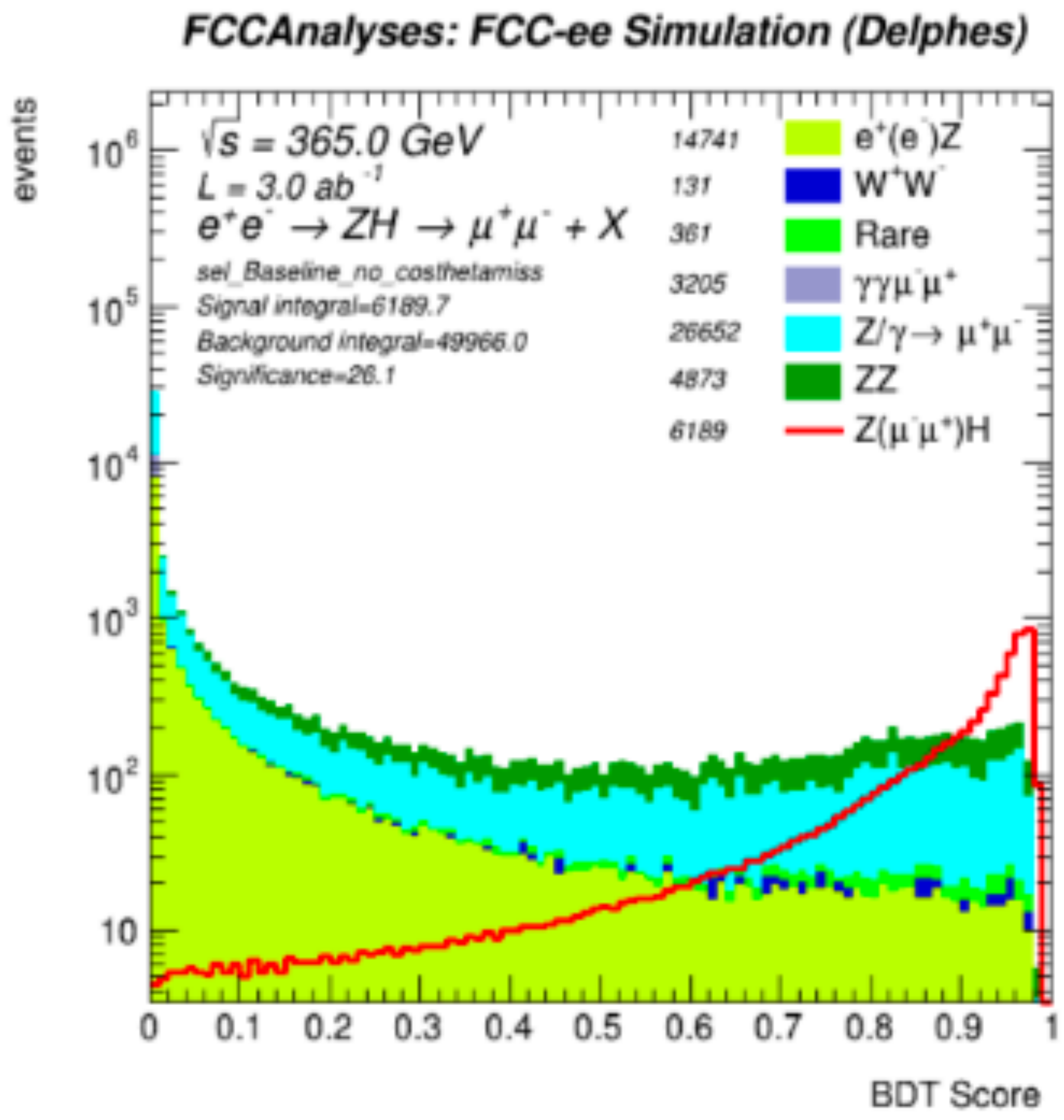
- Luminosity: 10.8 ab^{-1} at 240 GeV, 3.0 ab^{-1} at 365 GeV
- **Different shapes of the background before selection cuts**
- **Signal peak has lower resolution but also less background at 365 GeV**
  - WW becomes negigible at 365 GeV (removed by Z mass selection)
  - Resolution ~2.3 wider at 365 GeV
- Further S/B optimization:
  - BDT for model independent ZH cross section measurement
  - $|\cos\theta_{\mathrm{miss}}| < 0.98$ for Higgs mass analysis

FURTHER OPTIMIZATION FOR CROSS SECTION ANALYSIS

- BDT discriminator trained with variables from the Z decay to ensure model-independent result
- ZH cross section measurement obtained from a fit to the BDT distribution

Variable	Description
$p_{\ell^+\ell^-}$	Lepton pair momentum
$\theta_{\ell^+\ell^-}$	Lepton pair polar angle
$m_{\ell^+\ell^-}$	Lepton pair invariant mass
$p_{l_{\text{leading}}}$	Momentum of the leading lepton
$\theta_{l_{\text{leading}}}$	Polar angle of the leading lepton
$p_{l_{\text{subleading}}}$	Momentum of the subleading lepton
$\theta_{l_{\text{subleading}}}$	Polar angle of the subleading lepton
$\pi - \Delta\phi_{\ell^+\ell^-}$	Acoplanarity of the lepton pair
$\Delta\theta_{\ell^+\ell^-}$	Acolinearity of the lepton pair

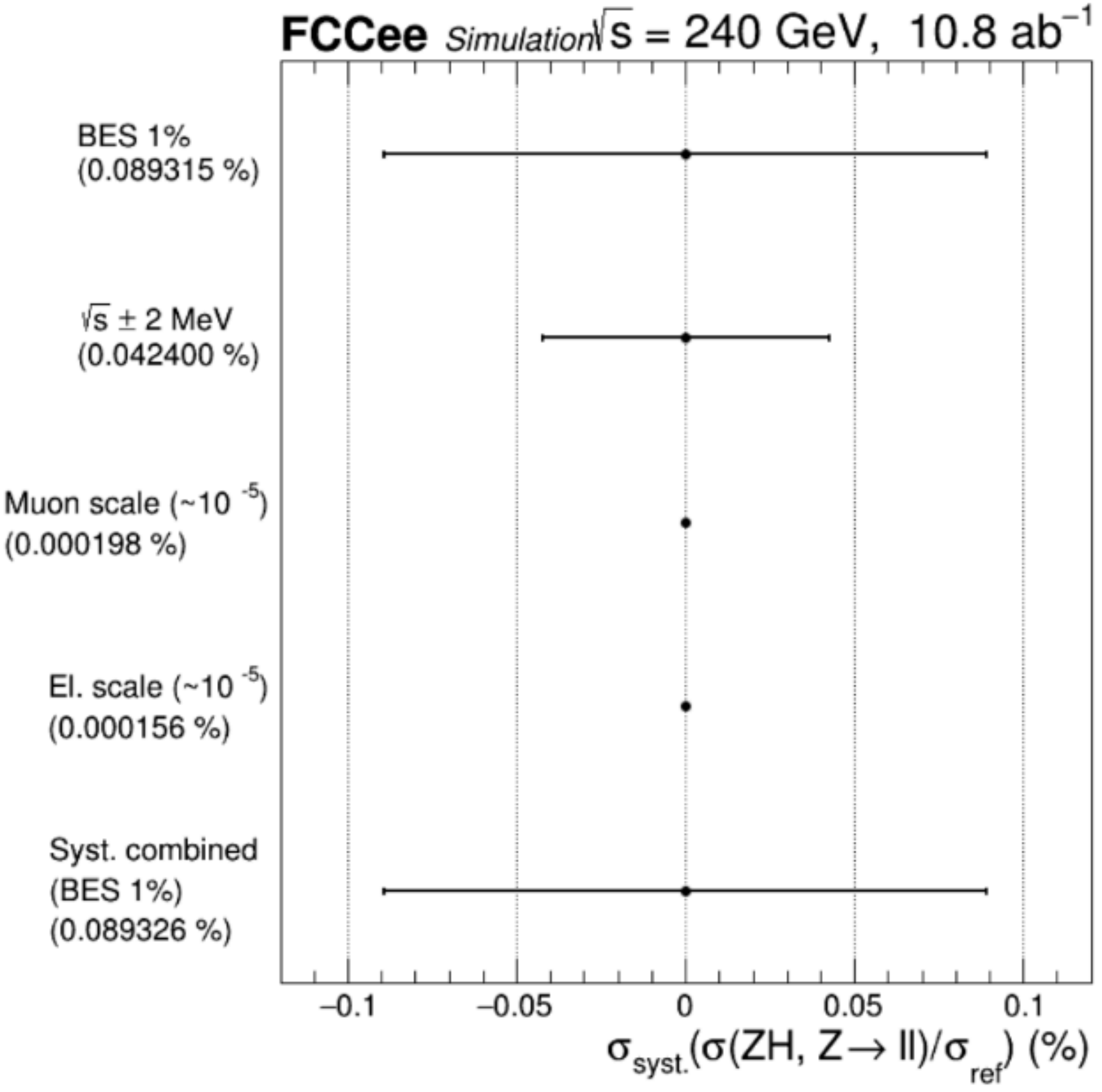




IMPACT OF THE SYSTEMATIC UNCERTAINTIES ON ZH

- **Beam energy spread:** dependent on the beam energy
  - At a center-of-mass energy of 240 (365) GeV, the beam energy spread (BES) is ±0.185% (±0.221%) per beam, i.e. ±222 (±403) MeV
  - **Uncertainty assumed on the BES value: ~1% at 240 GeV and ~10% at 365 GeV**
- **Center of mass ($\sqrt{s}$) uncertainty:** assumed 2 MeV both at 240 GeV and 365 GeV
- **Lepton energy scale:** assumed 10^{-5} precision both at 240 GeV and 365 GeV
- ISR: not yet estimated, expected to be smaller

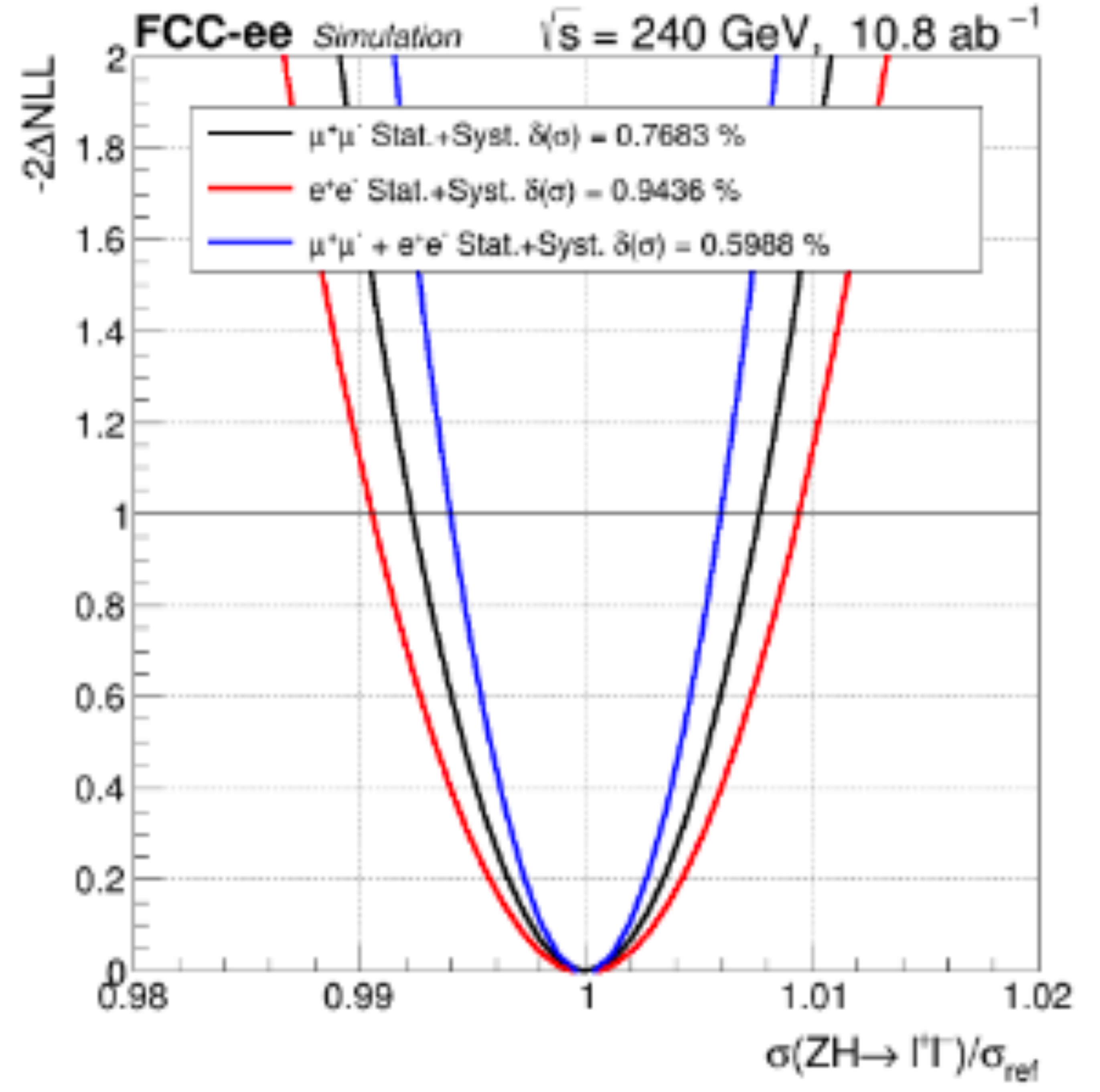
- **Combined systematic uncertainty: 0.09% at 240 GeV and 0.40% at 365 GeV (driven by BES!)**

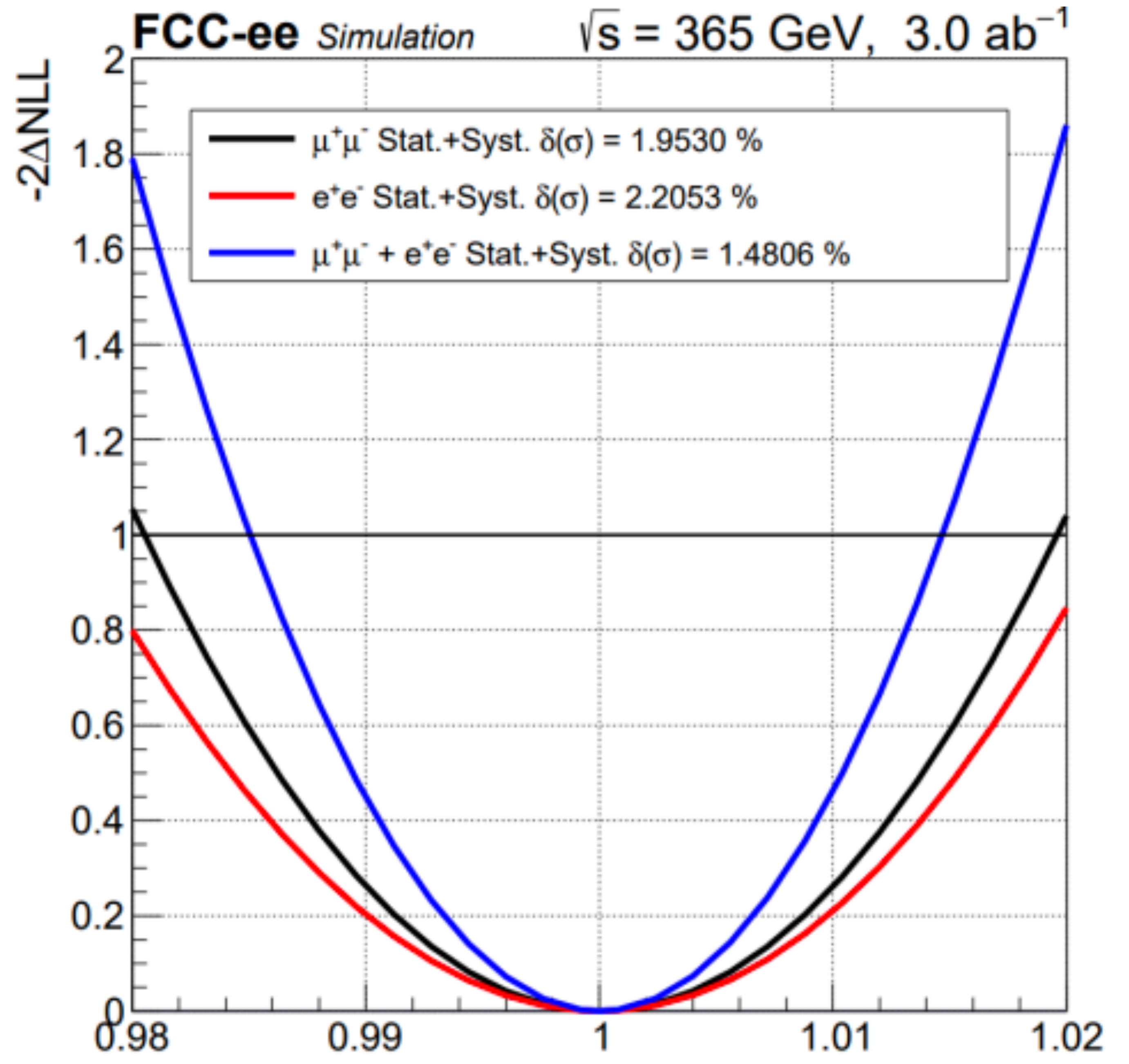


INCLUSIVE CROSS SECTION RESULTS

ee+mumu ZH Cross Section	240 GeV	365 GeV
Stat Only	0.59%	1.42%
Stat + Syst	0.60%	1.48%

- Better sensitivity for mumu channel (~20% better at 240 GeV)
- Systematics larger at 365 GeV, but ZH cross section precision still dominated by statistics
- Intrinsic sensitivity is similar (~25% larger) at 365 GeV vs. 240 GeV for ZH cross section





FROM CROSS SECTION TO WIDTH (AND COUPLINGS)

- Once σ_{ZH} is known, g_Z coupling can be determined in a model-independent way
  - Individual decay channel measurements lead to measurement of total width
  - Measure HZZ in all its possible final states to bring down the uncertainty on the width
- Complementary way to extract the width by measuring the absolute kW coupling at 365 (instead of kZ)
- **Expected width precision: $\delta\Gamma_H / \Gamma_H$ ~ 1 %**

$$\sigma\left(e^+e^- \to ZH\right) \propto g^2_{HZZ}$$

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

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

See talk on Higgs Couplings by A. Sciandra

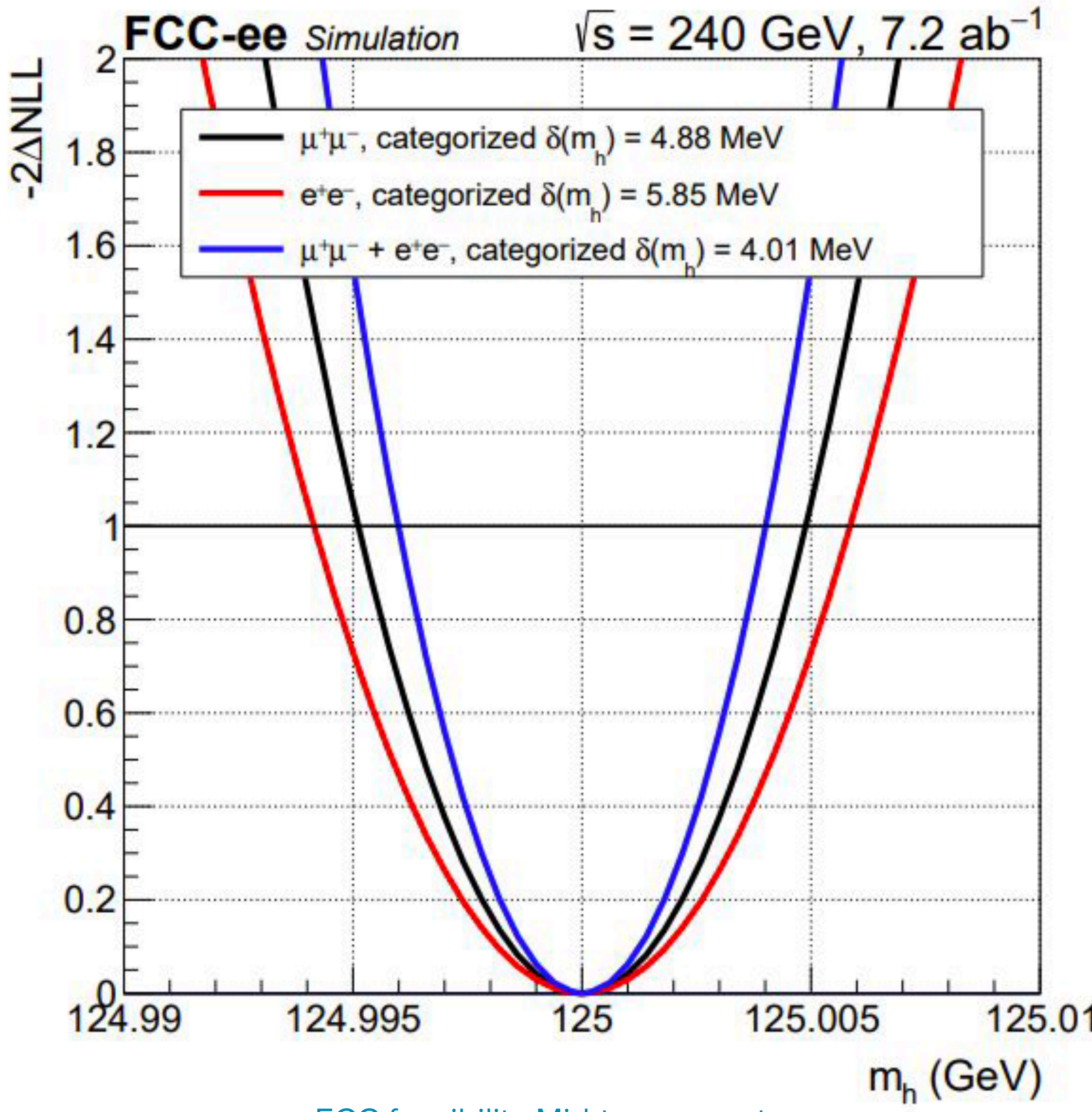
HIGGS MASS

- m_H enters SM EWK parameters via radiative corrections
- Current LHC experimental precision ~0.1%. HL-LHC reach: ~20/30 MeV possible

$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?

- **In lepton colliders, m_H needs be improved to around 10 MeV to avoid any limitation on cross sections and branching fraction measurements.**
- **For the potential run at $\sqrt{s}$ = 125 GeV (to probe the electron-Yukawa coupling): m_H precision equal or better to its width (4 MeV)**
- Detailed study of systematics and detector/acelerator effects done for the Midterm report
- Stringent test of the Standard Model, together with precise Top and W/Z masses

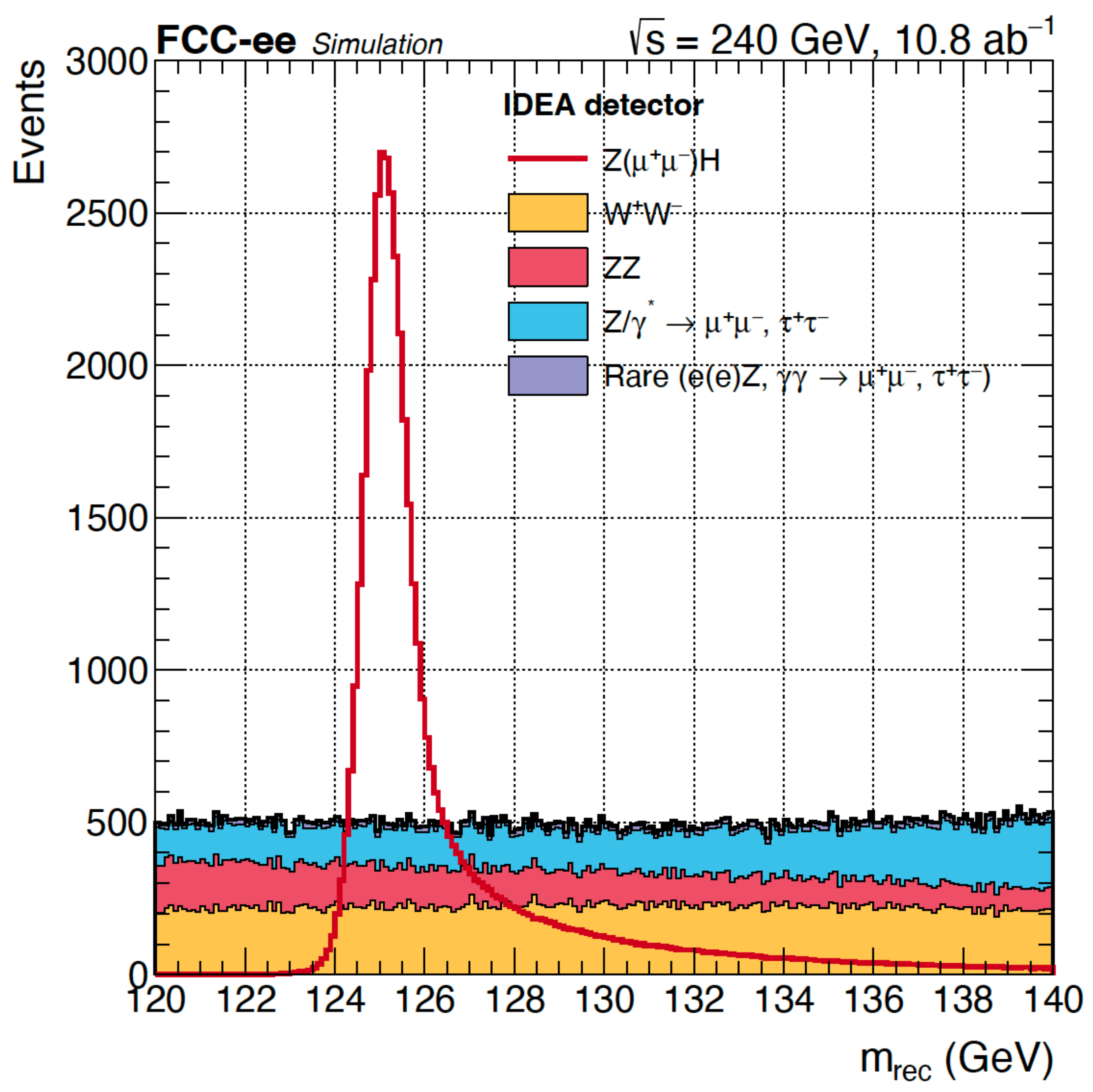


FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

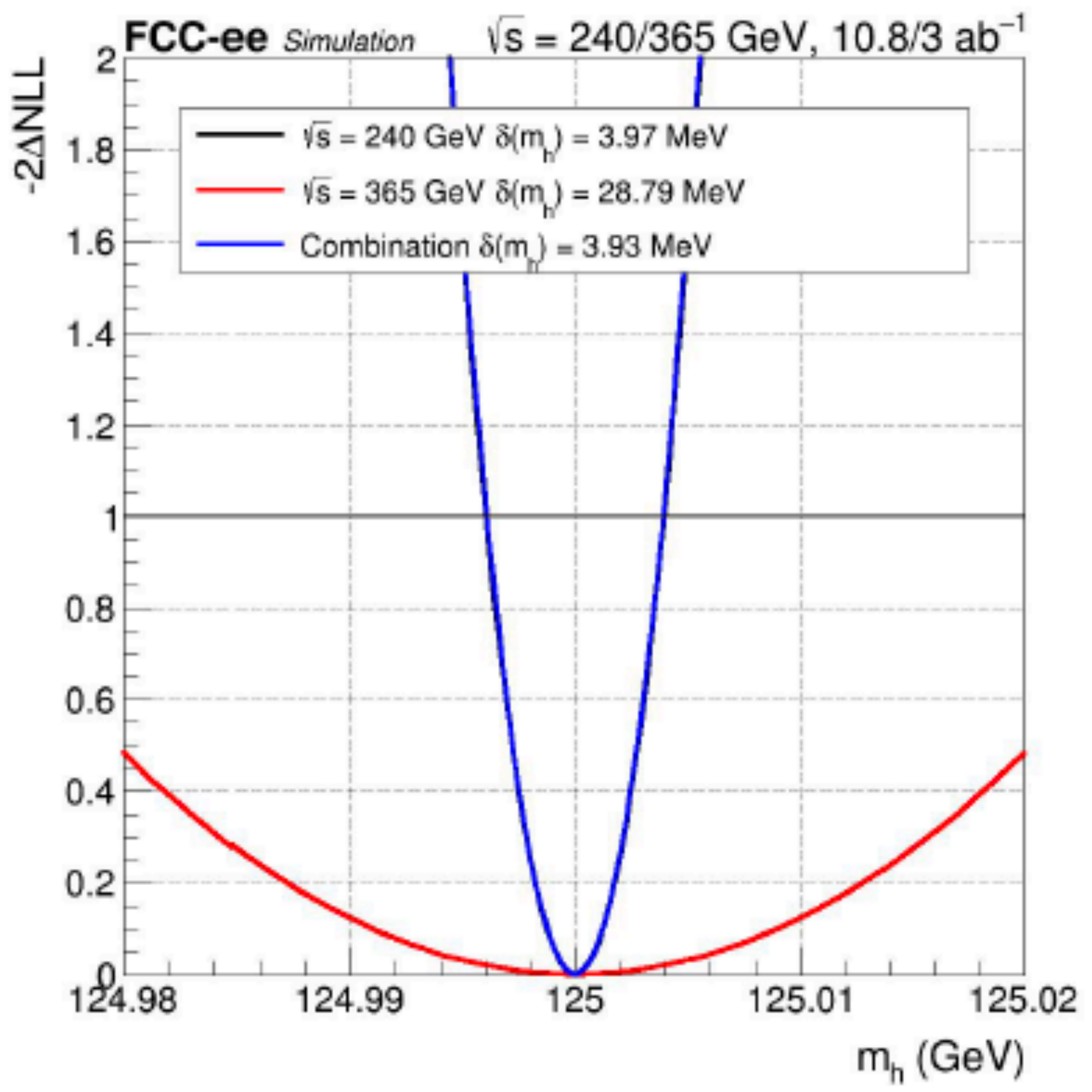
Recoil method: **4 MeV @ FCC-ee**

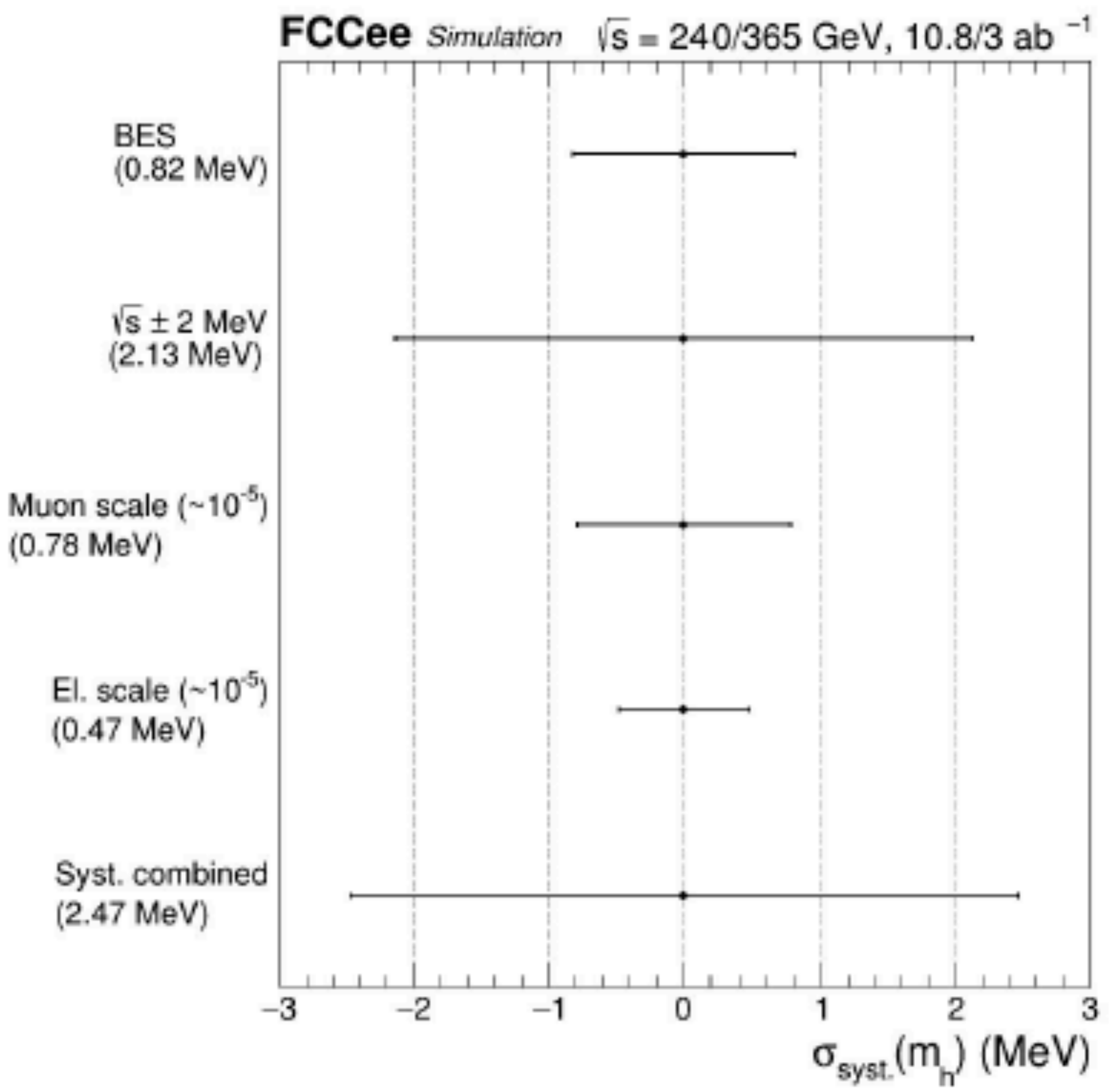
HIGGS MASS EXTRACTION

- **Fit to recoil distribution in muon and electron final states**
- Tighter selection, including $|\cos\theta_{miss}| < 0.98$
- 3 categories by detector regions to account for different material budget (central: 0.8 < θ < 2.34 rad or forward)
- Driven by 240 GeV. Improvement from adding 365 GeV: 1%
- Systematics dominated by ECM uncertainty (2 MeV)



$$M^2_{recoil} = \left(\sqrt{s} - E_{ll}\right)^2 - p^2_{ll} = s - 2E_{ll}\sqrt{s} + m^2_{ll}$$



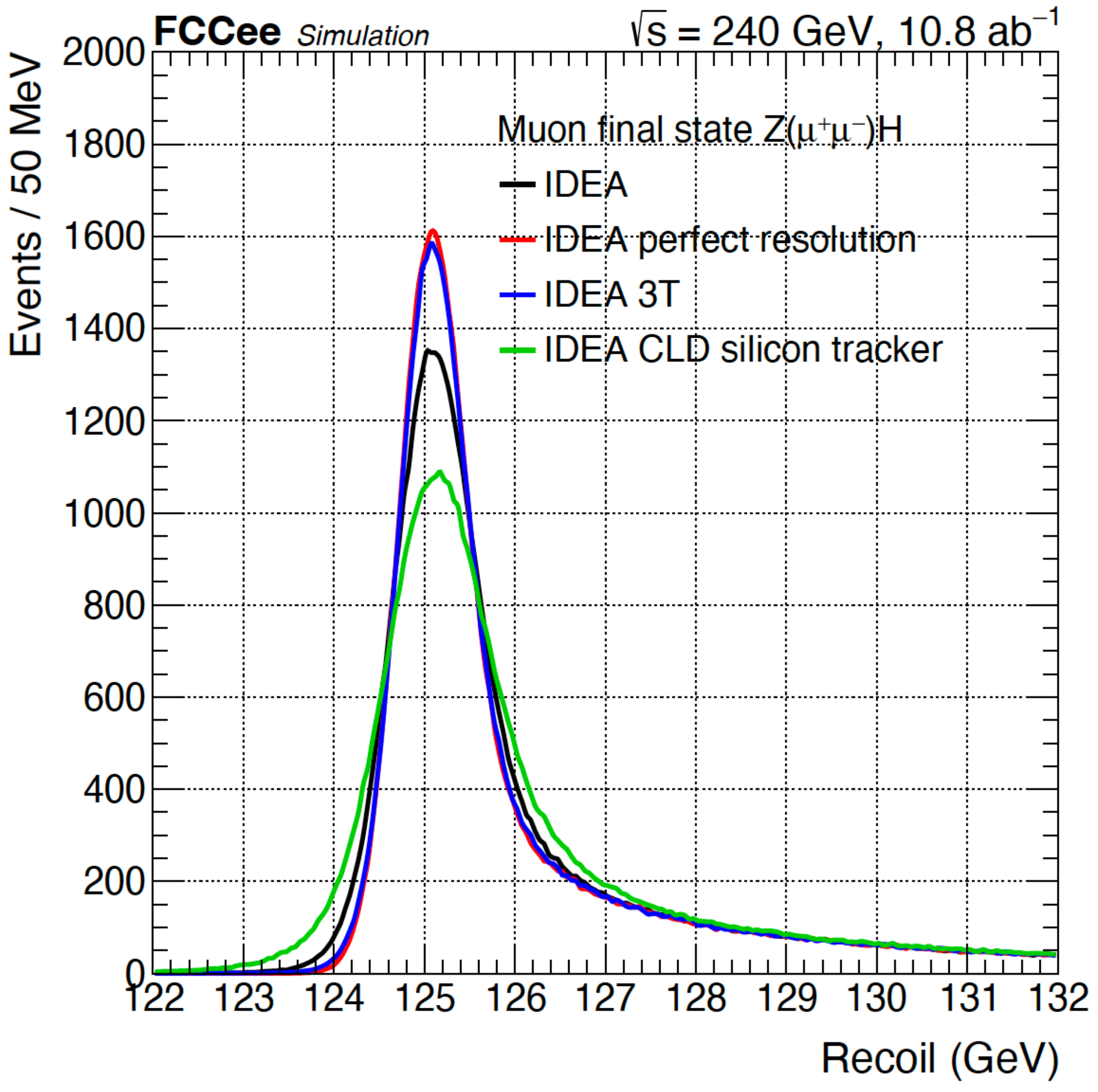


Updated result for 10.8 ab^{-1} at 240 GeV + 3.0 ab^{-1} at 365 GeV:

$$\Delta m_H = 3.93 \text{ MeV}$$

$$\left(3.05 \text{ stat only}\right)$$

EXPERIMENTAL CONSTRAINTS FROM HIGGS MASS SENSITIVITY



- Reaching $\Delta m_H \sim \Gamma_H \sim 4$ MeV requires outstanding detector performance
- Extended studies for key detector effects: feedback to detector design
- Tracking resolution highly impacts m_H precision
- Light tracker / high magnetic field preferable

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 → CLD 2T (silicon tracker)

Impact of Beam Energy Spread → BES 6% uncertainty / No beam energy spread

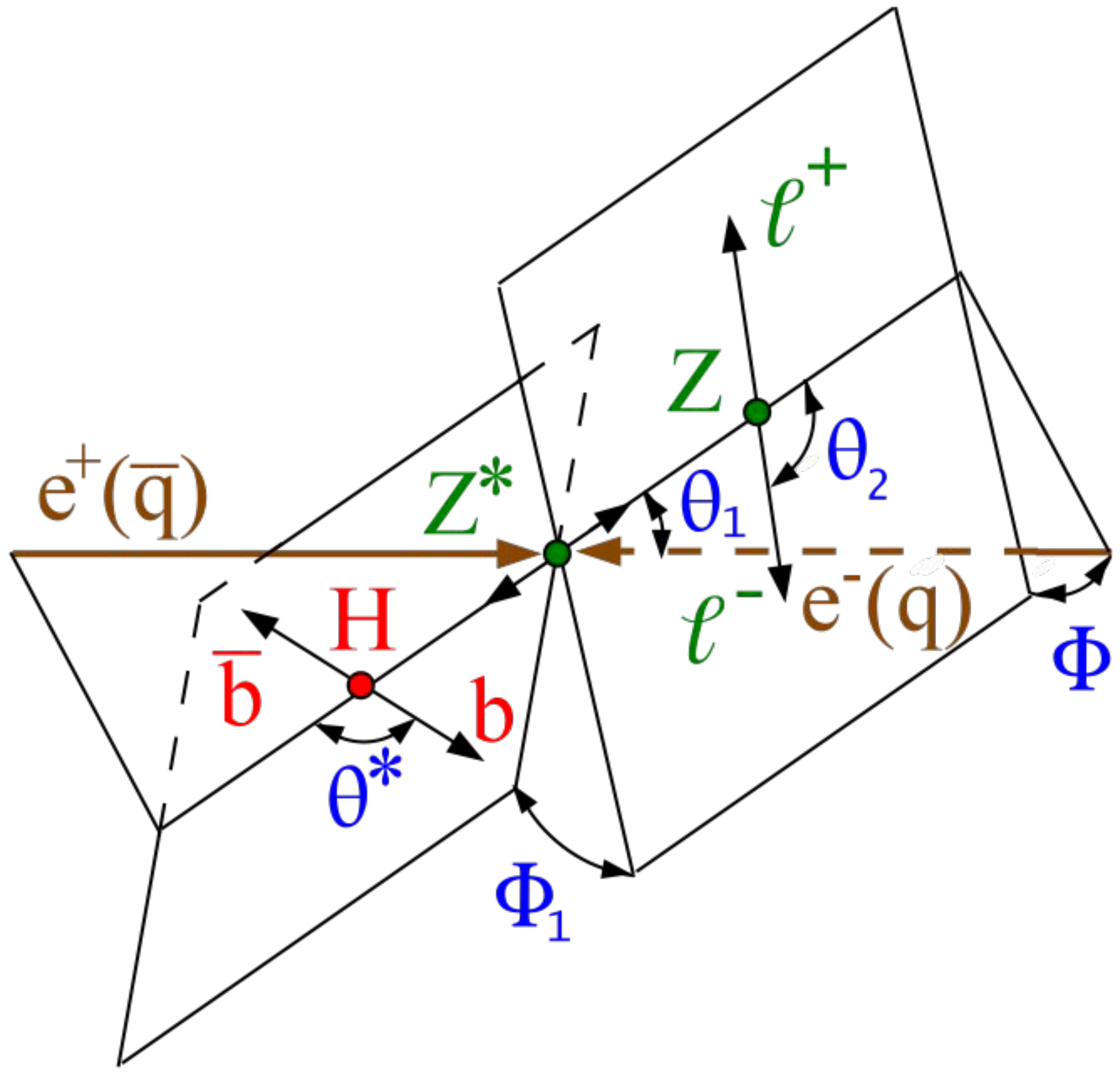
Perfect (=gen-level) momentum resolution → Ideal resolution

Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
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)
CLD 2T (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)
No beam energy spread	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)

HIGGS & CP?

- Exploring the tensor structure of Higgs couplings can bring surprises in years to come. There is still a lot to know!
- CP properties of fermion interactions (taus, tops) only start to be within reach now for LHC: Very important to follow in Run3/HL-LHC and beyond

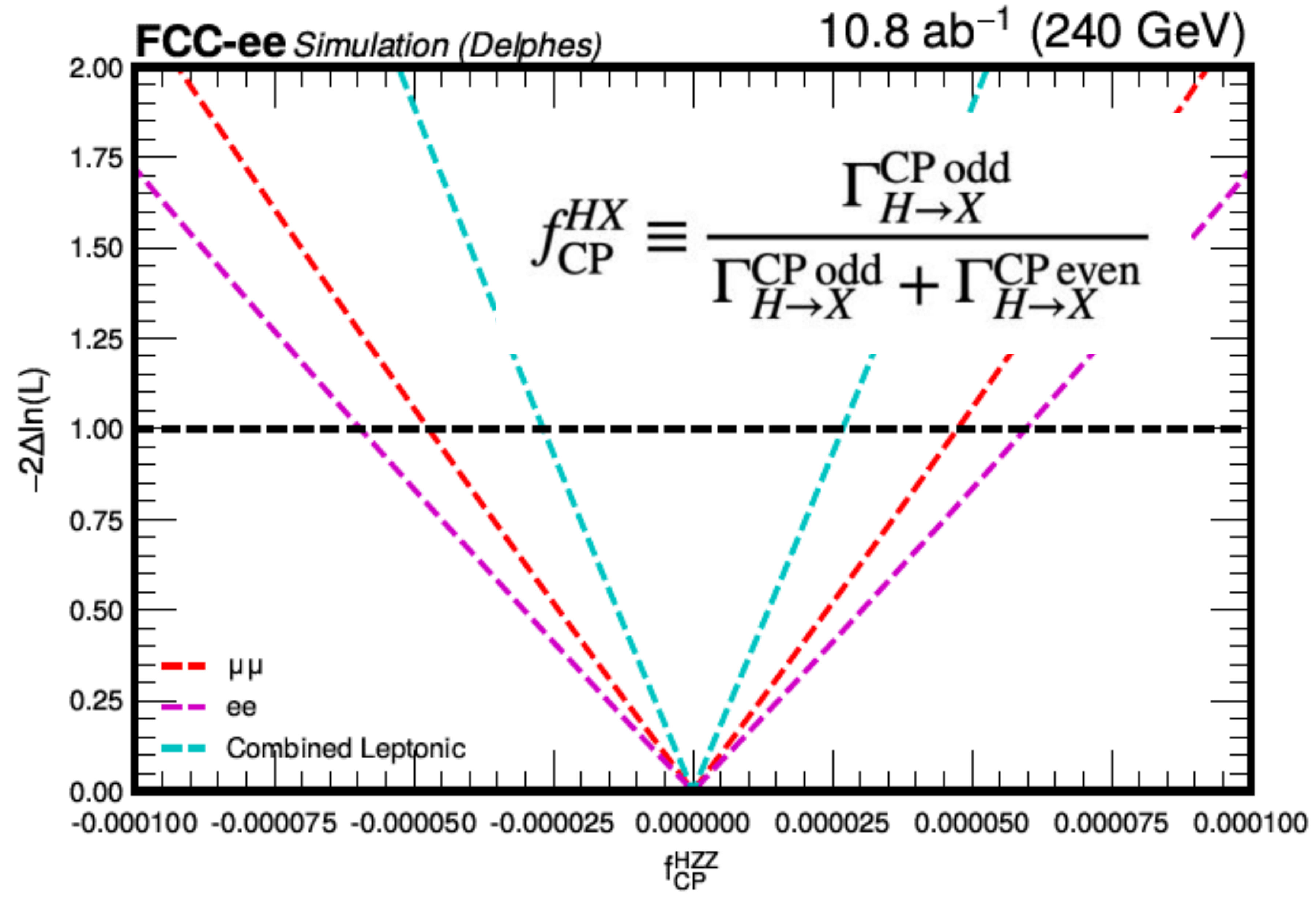
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000		125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000		250			
hZZ/hWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.4\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$h\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$hZ\gamma$	–	~ 1	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	–	✓	$< 10^{-2}$
$h\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$h\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

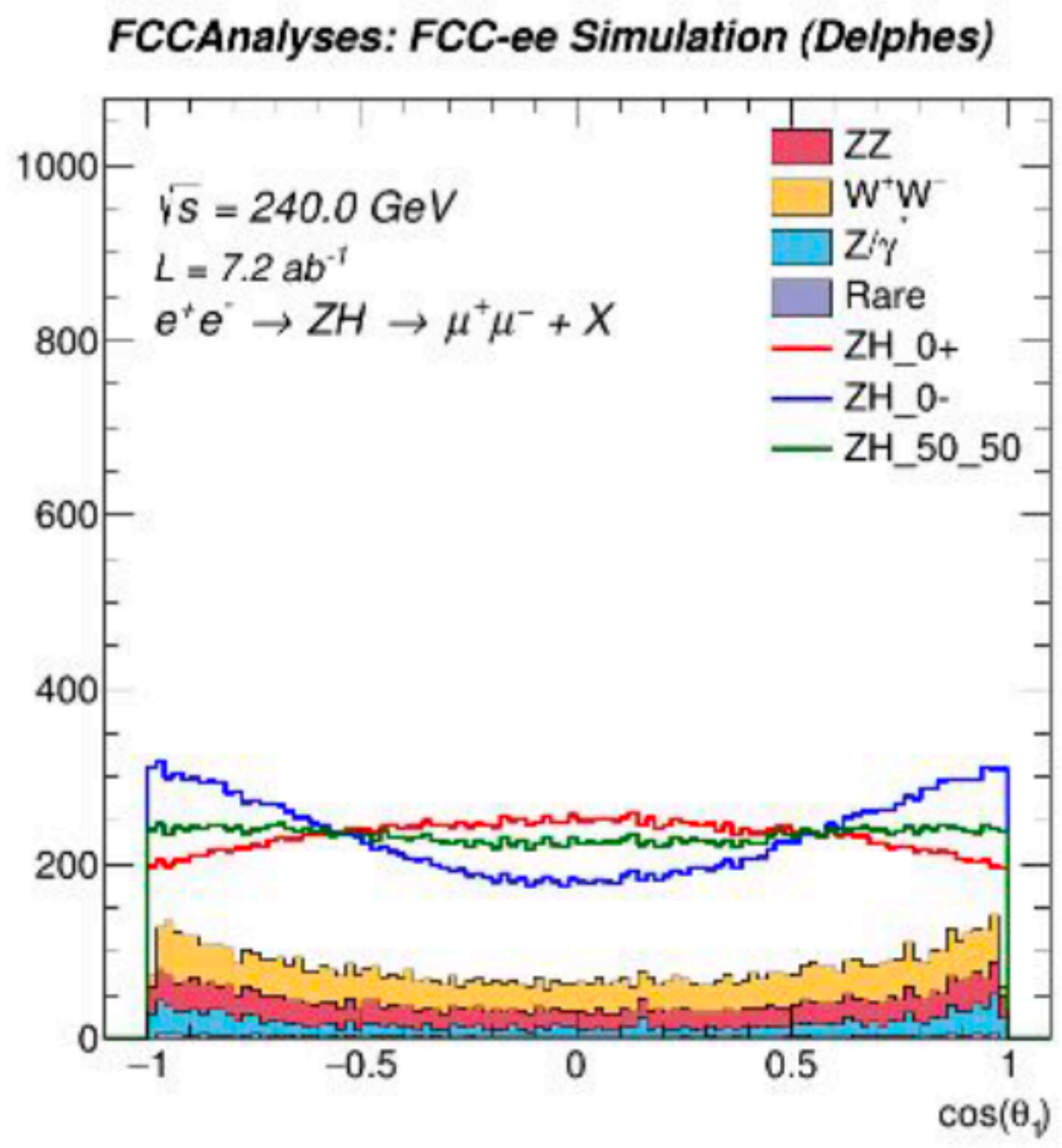


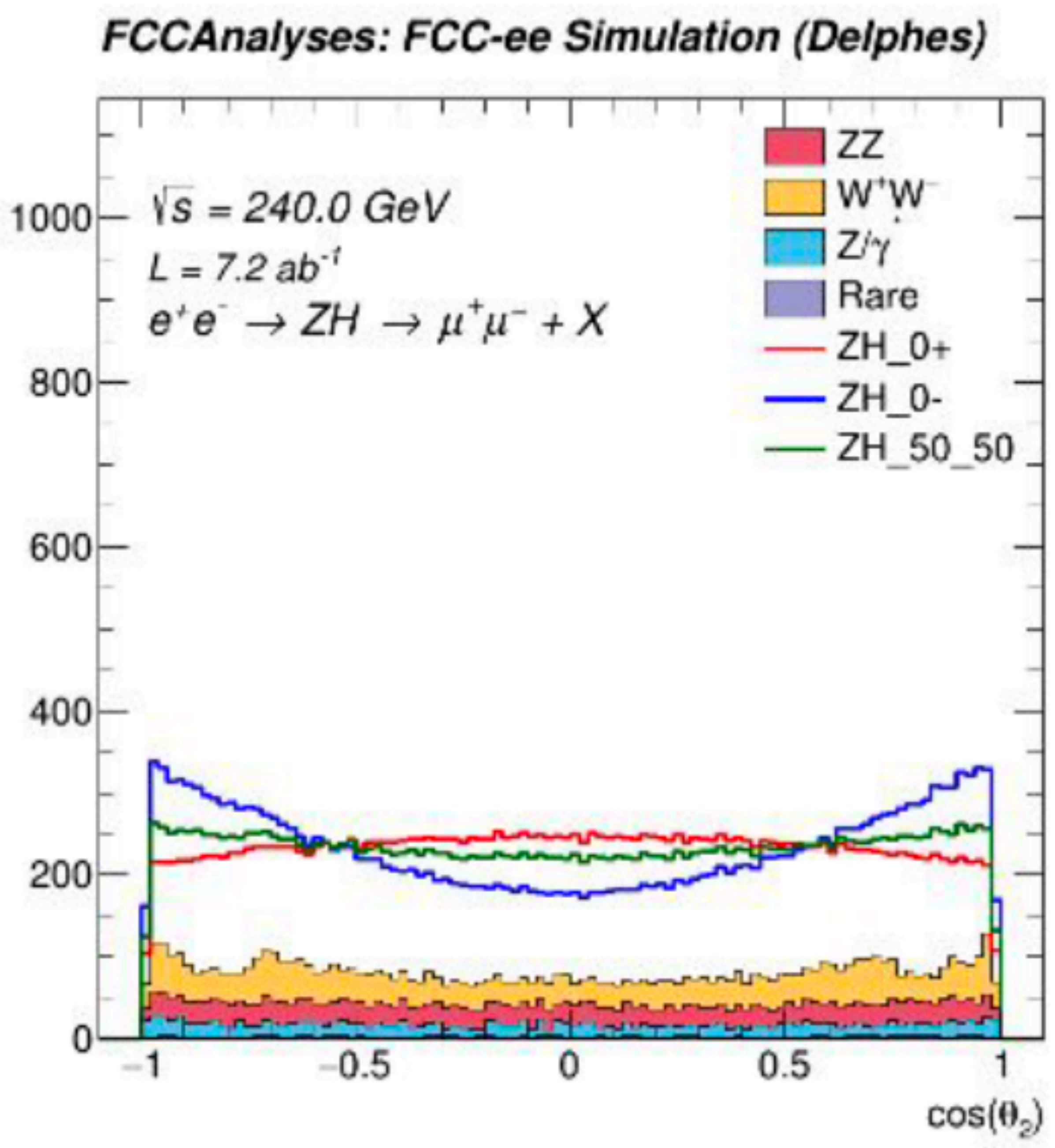
[hep-ex/2205.07715, Snowmass]

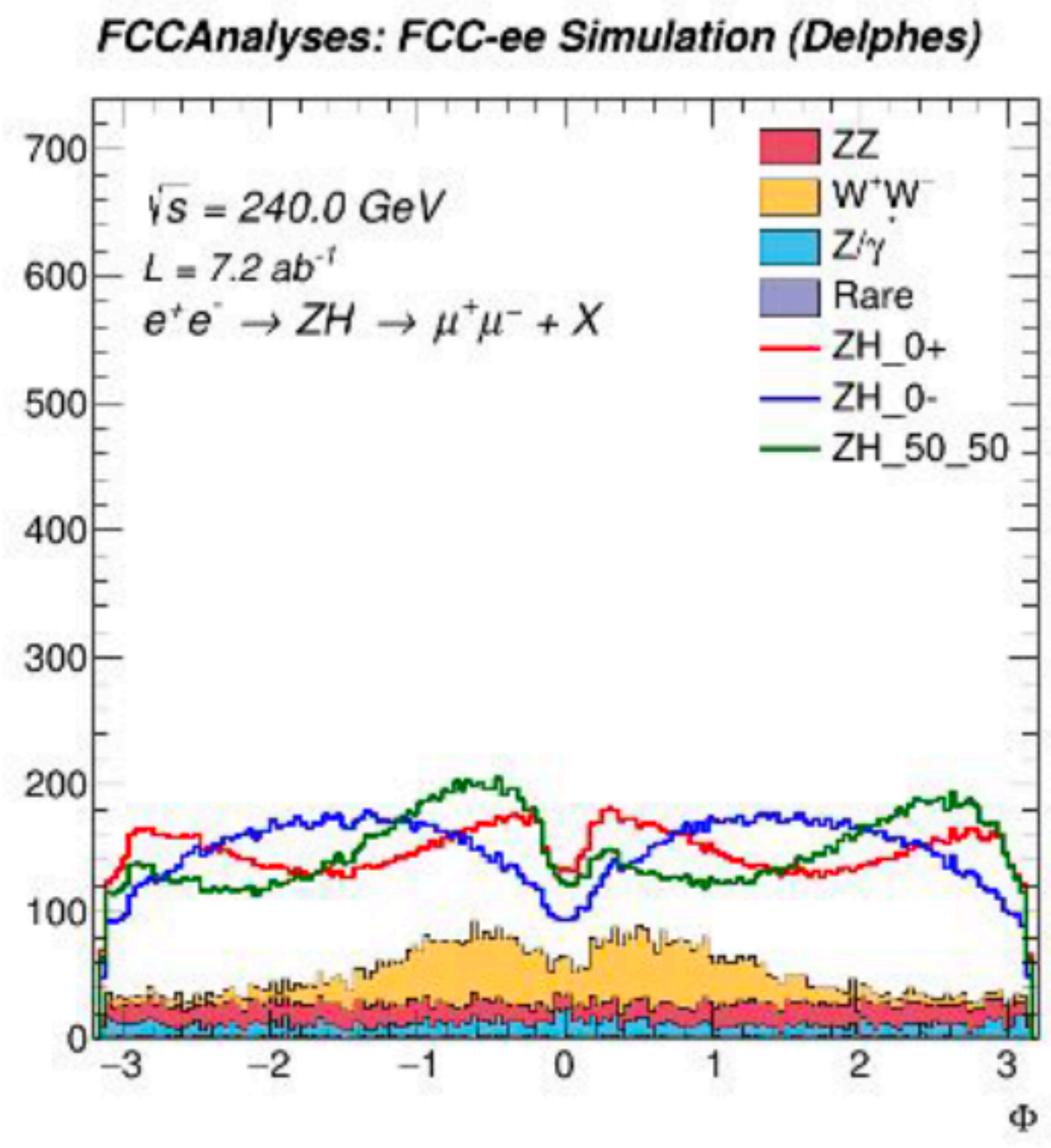
HIGGS & CP?

- MELA-based study of anomalous couplings
  - Construct CP even/odd templates to fit for CP-odd hypothesis
- First results HVV: $\delta f_{CP}^{HZZ} \sim 2.5 \times 10^{-5} (68\,\%\ CL)$
  - Z→$\mu\mu$ and Z→ee, selection very similar to the cross-section analysis
- Work for H→$\tau\tau$ ongoing









SUMMARY

- A deep study of the Higgs sector, together with an exploration of what is beyond the SM, is a priority for the field. And the FCCee is a unique machine for this purpose.

- Extreme precision in the measurement of the properties of the Higgs:

  - **ZH cross section down to 0.6% at 240 GeV (1.5 % at 365 GeV), which paves the way to precise Higgs coupling measurements and to the Total Higgs Width $\Delta\Gamma_H/\Gamma_H$~1%**

  - **Higgs Mass measurement with 4 MeV accuracy at 240 GeV (3.9 MeV adding 365 GeV)**

  - **Large potential for CP measurements**

- All these measurements place constraints on detector design: interplay between detector R&D and physics key going forward.

THANKS!

MINISTERIO
DE CIENCIA, INNOVACIÓN
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Cofinanciado por
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AGENCIA
ESTATAL DE
INVESTIGACIÓN

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Consolidación Investigadora 2023: CNS2023-144781

DETECTOR DESIGN

4 IPs! Ample opportunities for detector design & optimization

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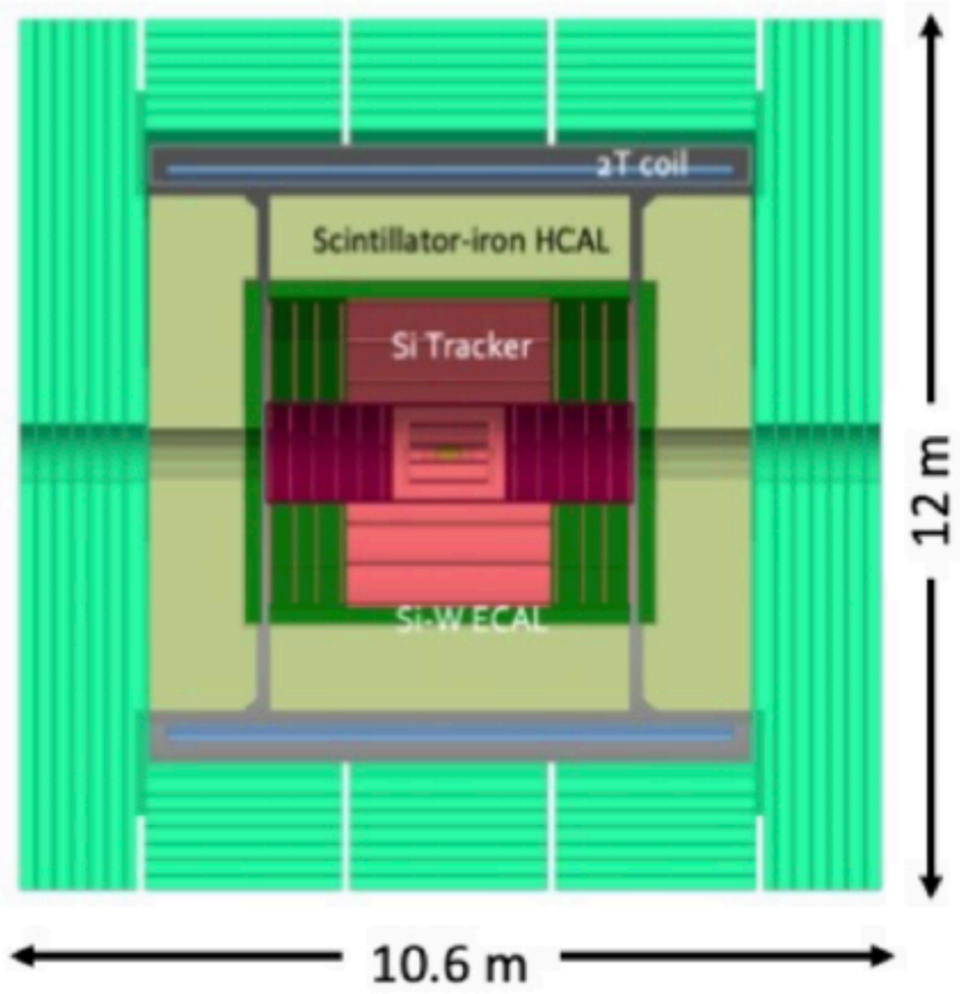
<td>
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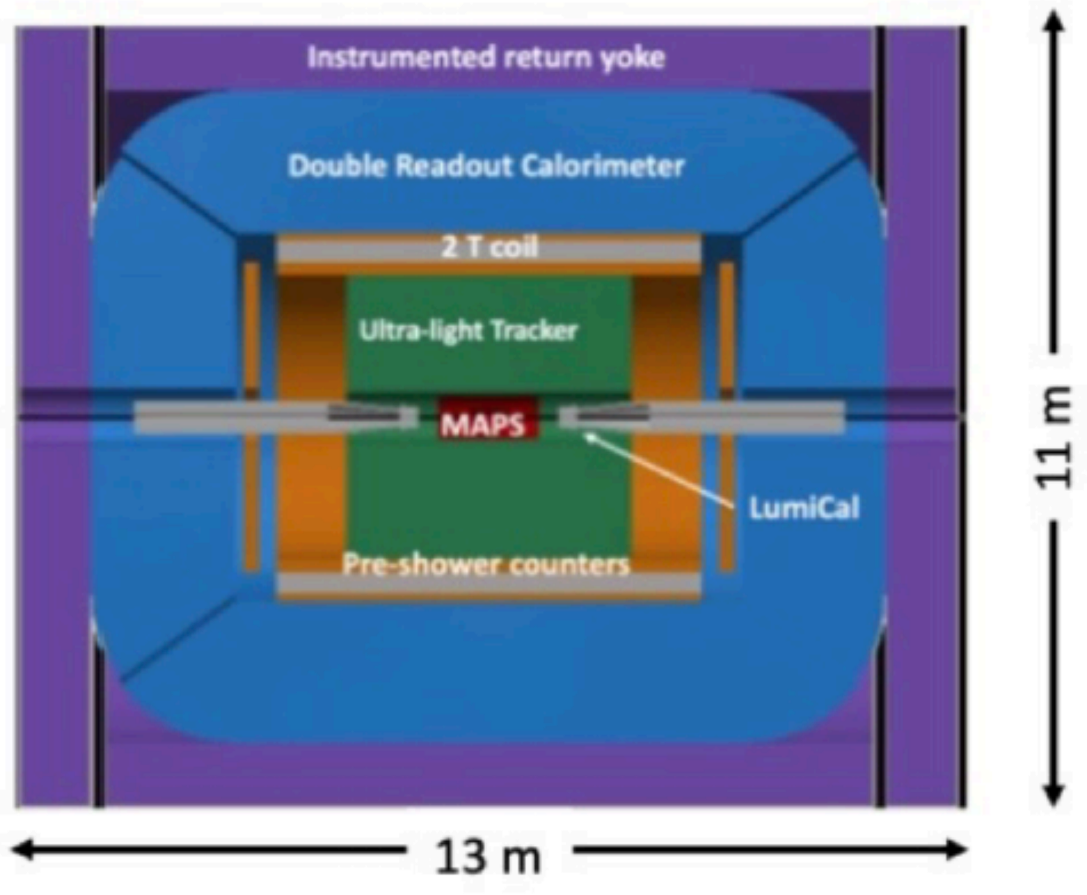
<td>
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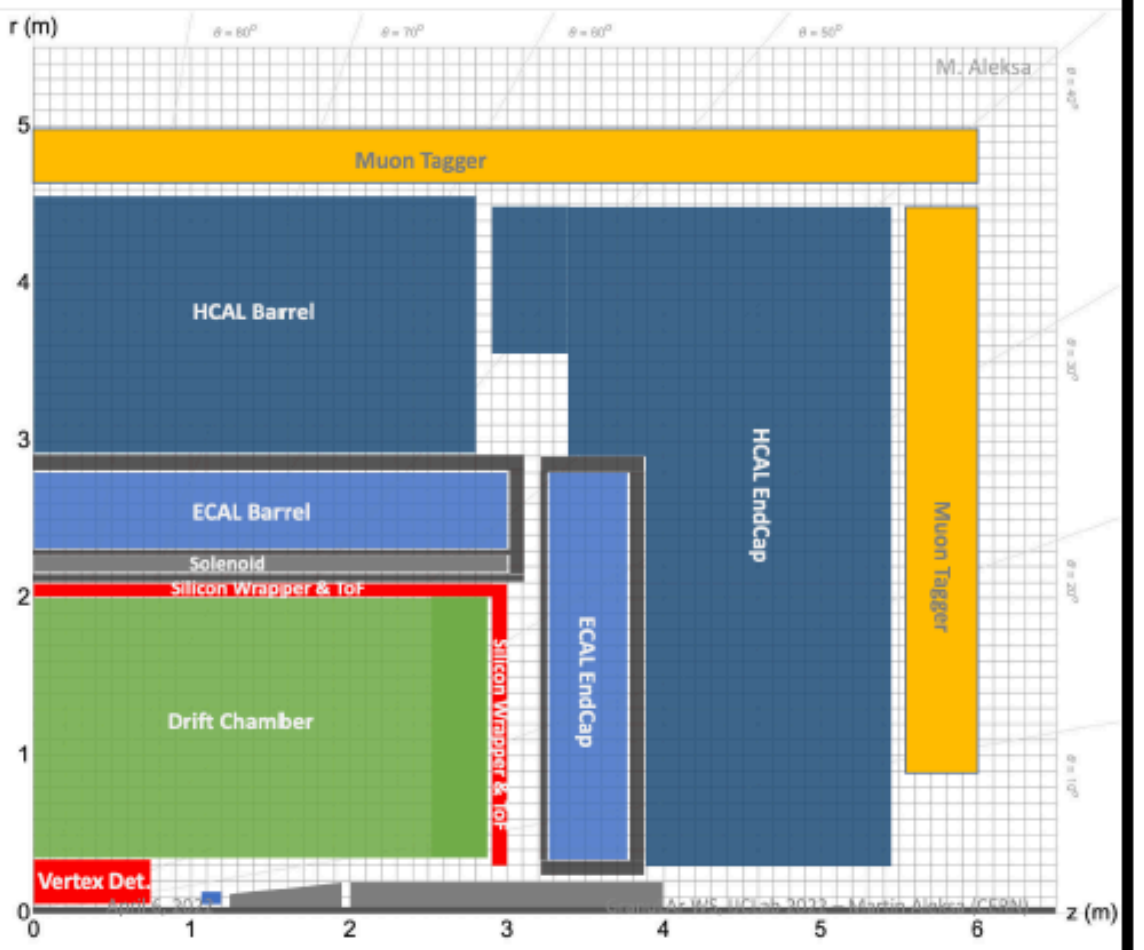
<td>
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<td>Based on CLIC detector design, arXiv:1911.12230

Full silicon vertex detector and tracker
3D-imaging highly-granular calorimeter system
Coil outside calorimeter system</td>
<td>Innovative, possibly cheaper than CLD
https://pos.sissa.it/390/819
Baseline in many ongoing studies

Silicon vertex detector
Short-drift, ultra-light wire chamber
Dual-readout calorimeter
Thin and light solenoid coil inside calorimeter system</td>
<td>GranuLAr WS, IJCLab 2022 – Martin Aleksa

Highly granular noble-liquid calorimeter
Thin 2T solenoid in the calorimeter cryostat.</td>
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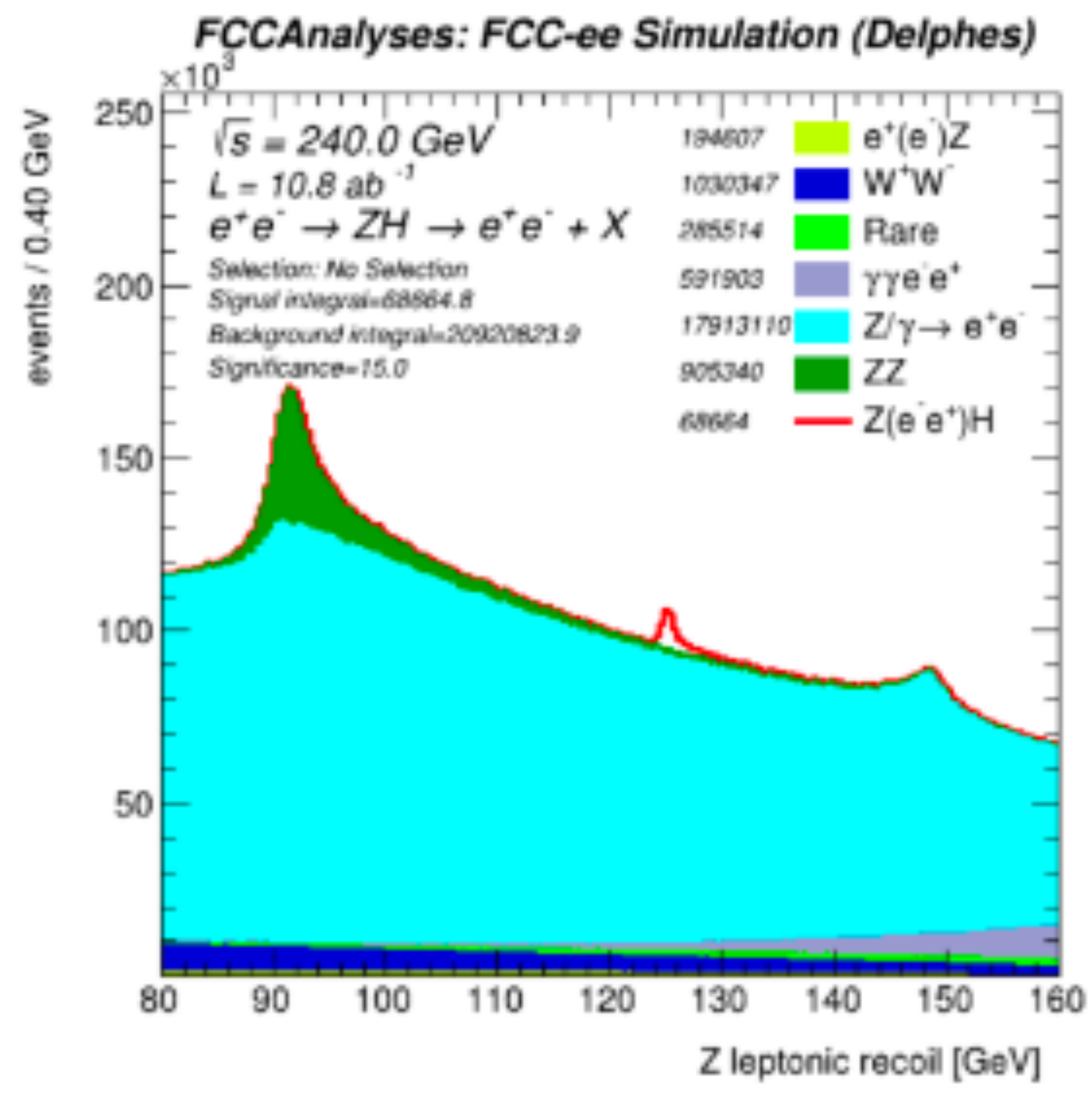
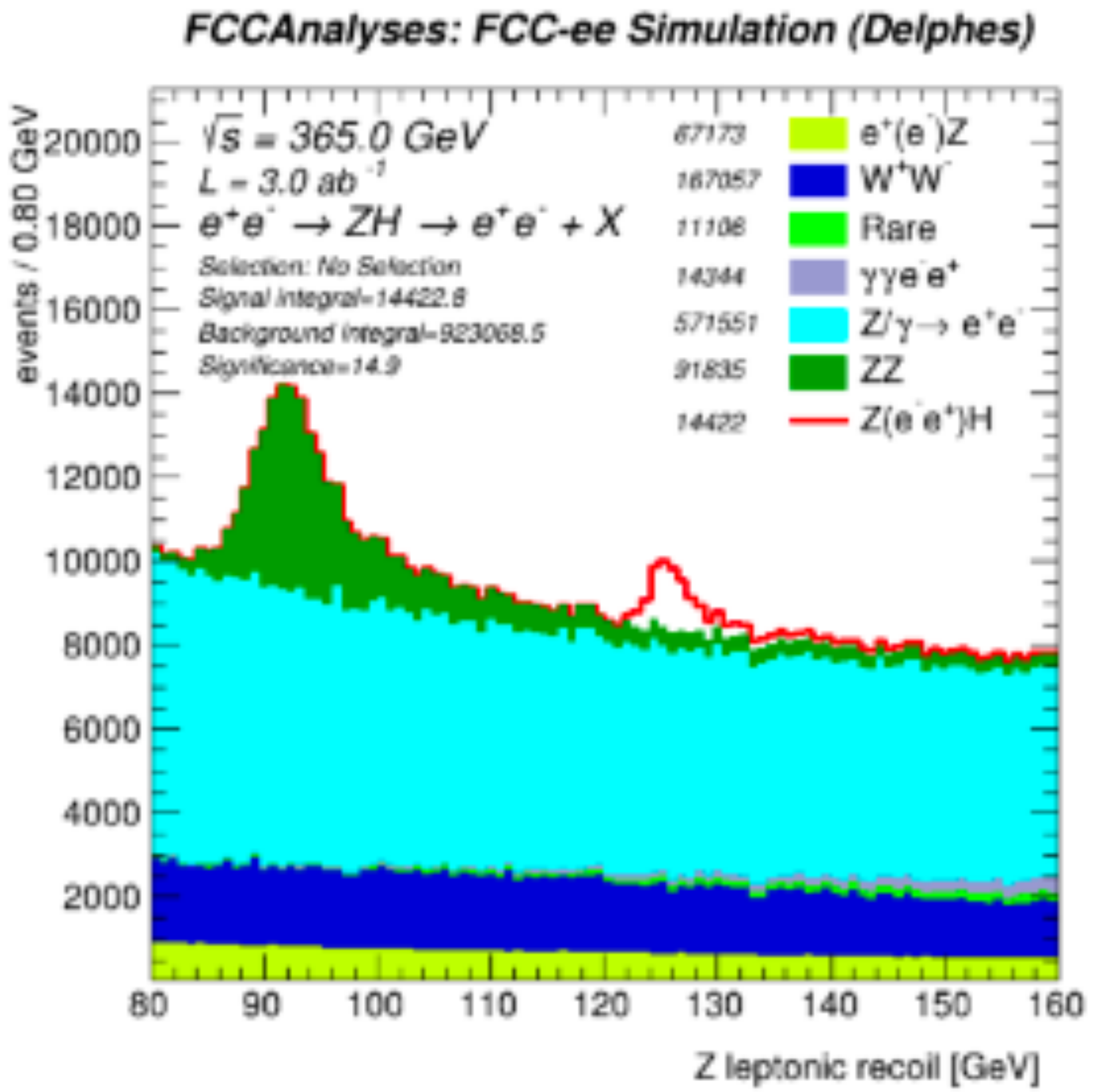
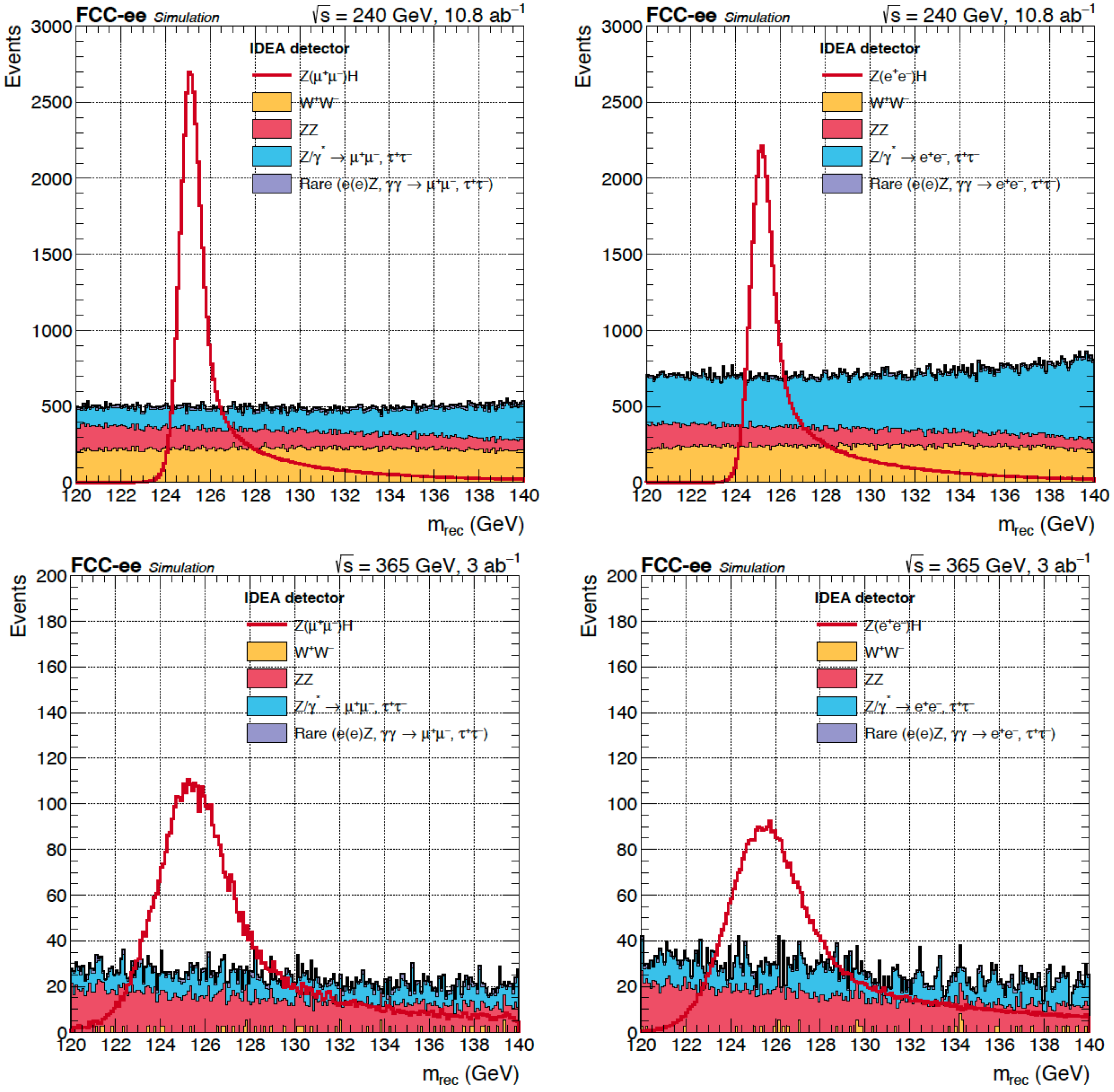
$Z(e^+e^-)H$: 240 GeV vs 365 GeV





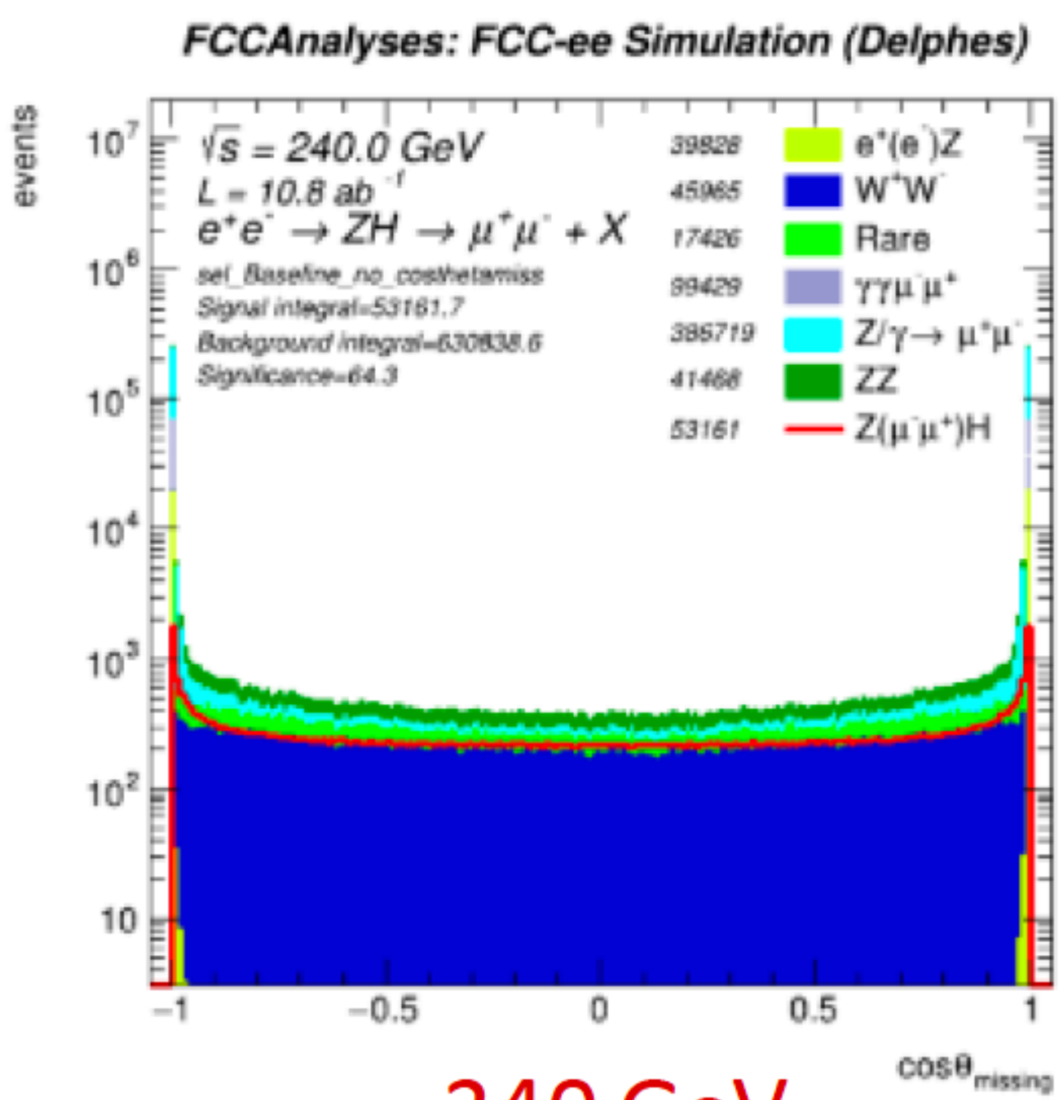
- Different shapes of the background before selection cuts
- Luminosity: 10.8 ab^{-1} at 240 GeV, 3.0 ab^{-1} at 365 GeV
- Signal peak has lower resolution but also less background at 365 GeV

HIGGS RECOIL AFTER MASS MEASUREMENT SELECTION

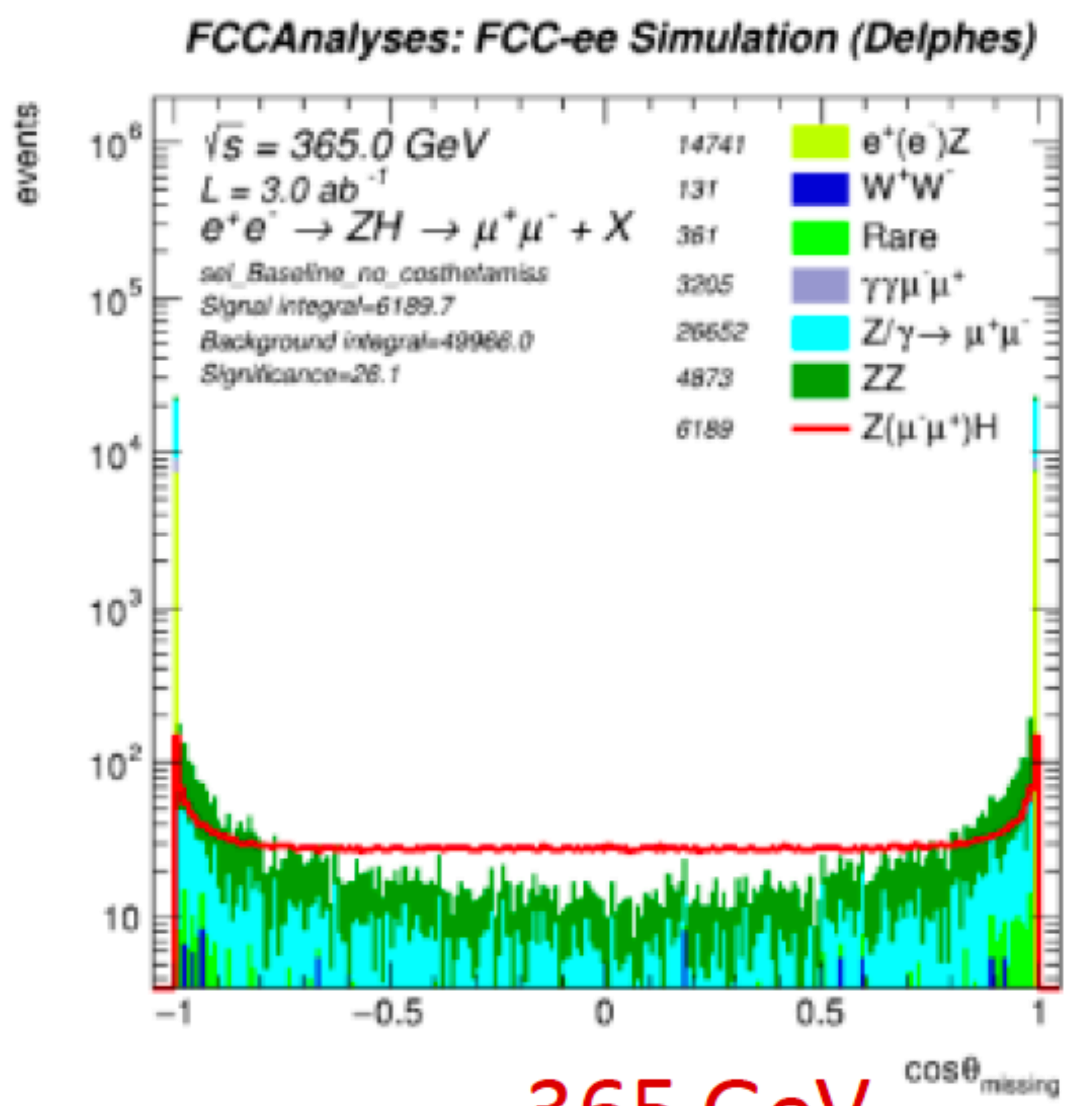


SELECTION PER DECAY MODE : IMPAC OF $\cos\theta_{miss}$

Cos θ$_{missing}$ Distribution ⇒



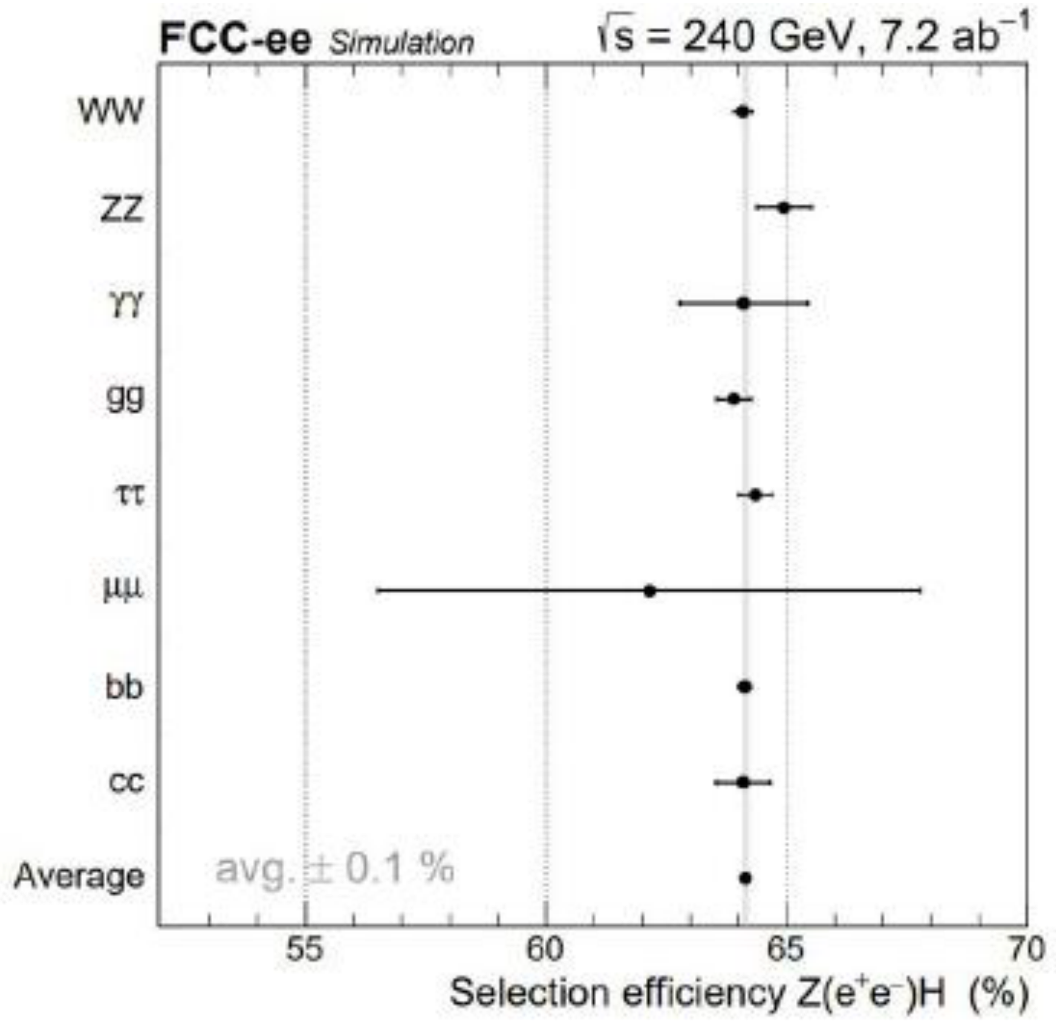
240 GeV

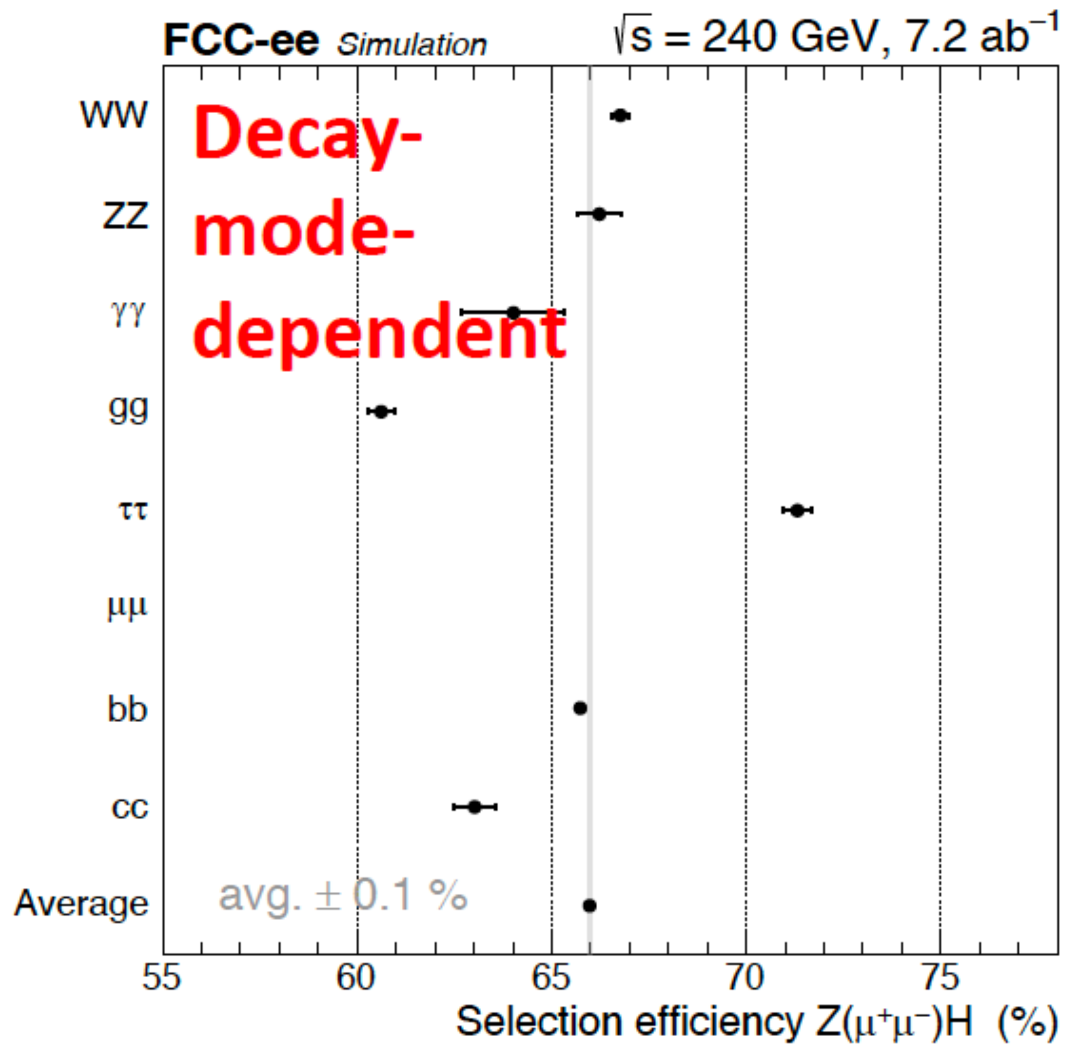


365 GeV

The $\cos\theta_{miss}$ cut introduces a bias towards Higgs decays involving neutrinos (or any non-Standard Model invisible decays): cannot be used in the ZH cross section analysis (OK for the mass)

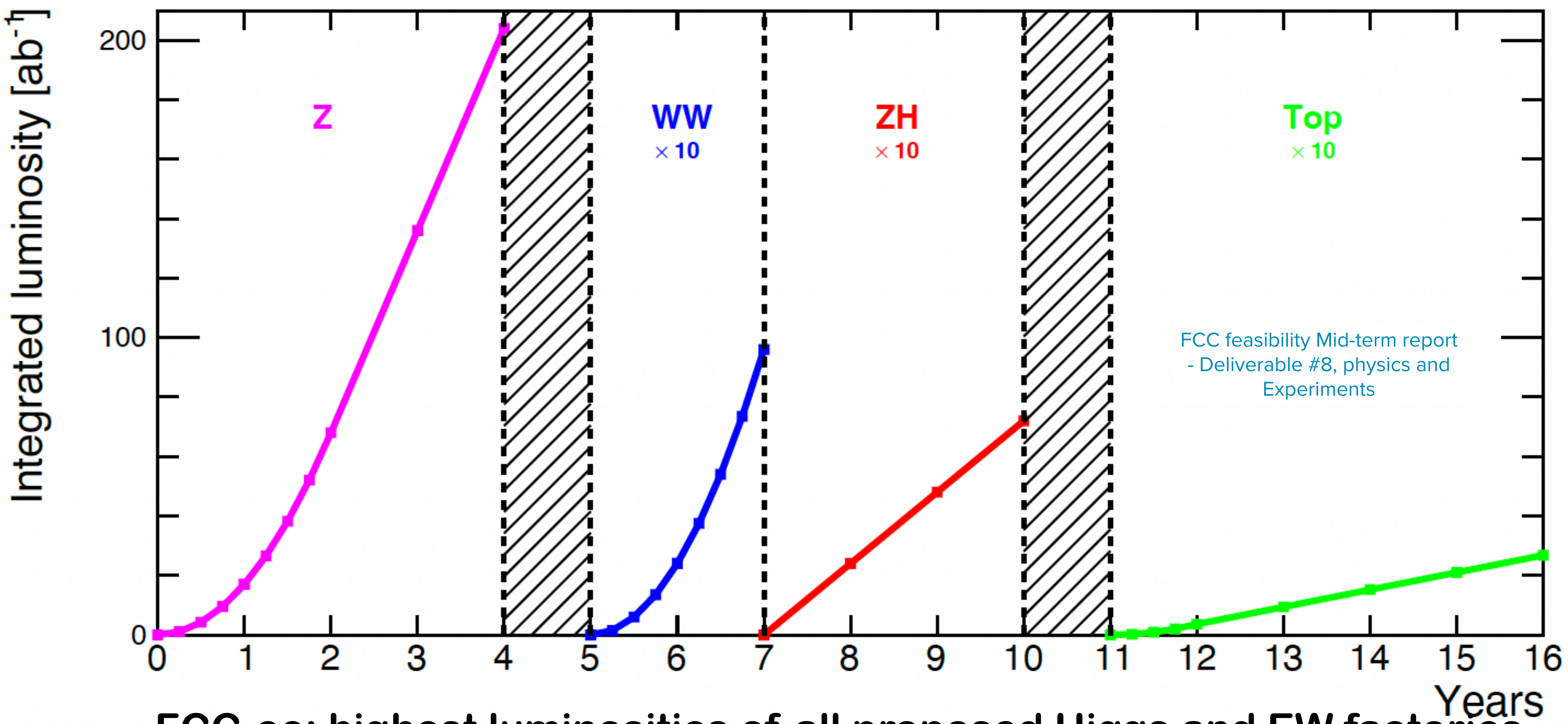
Without $\cos\theta_{miss}$ (ZH cross section)





With $\cos\theta_{miss}$ (Mass measurement)

FCCEE: HUGE STATISTICS & PRECISION

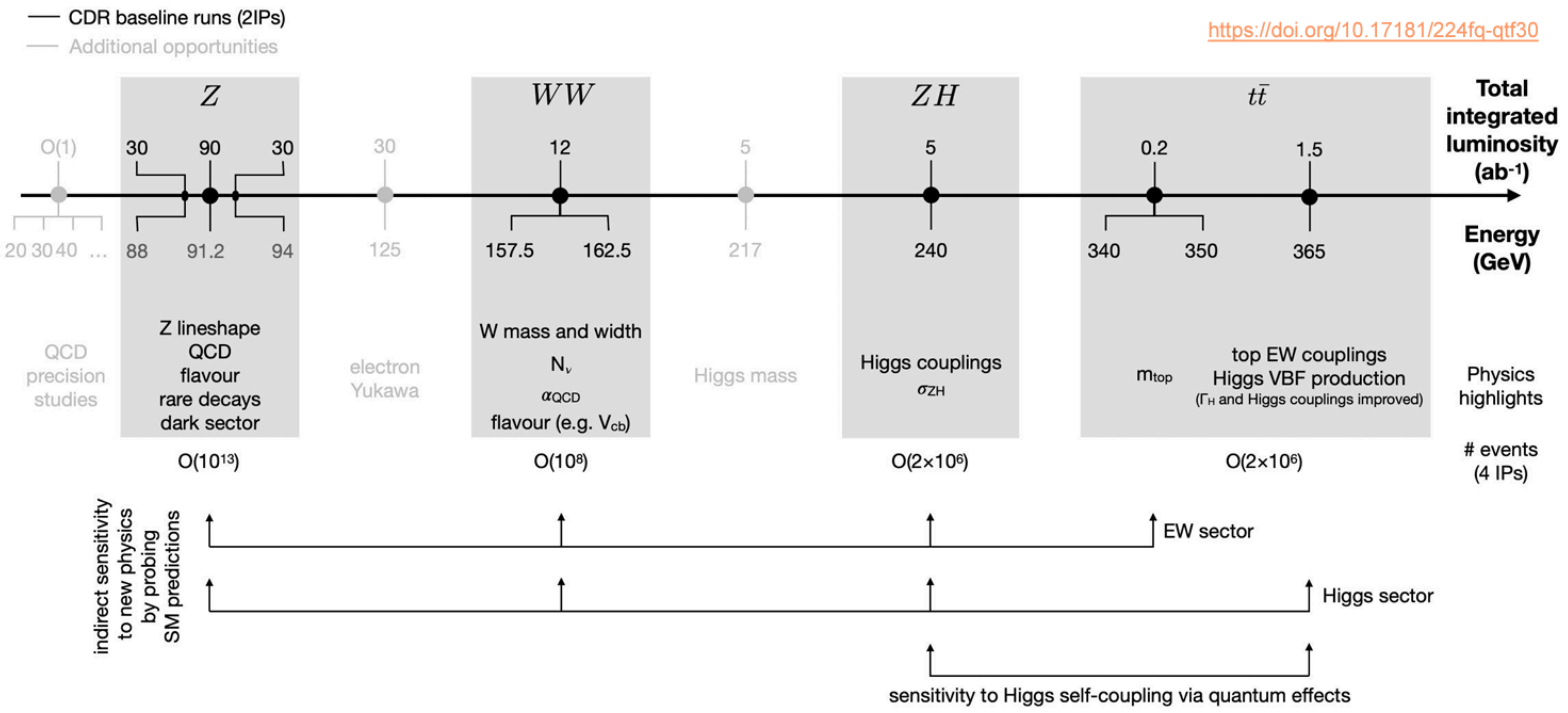


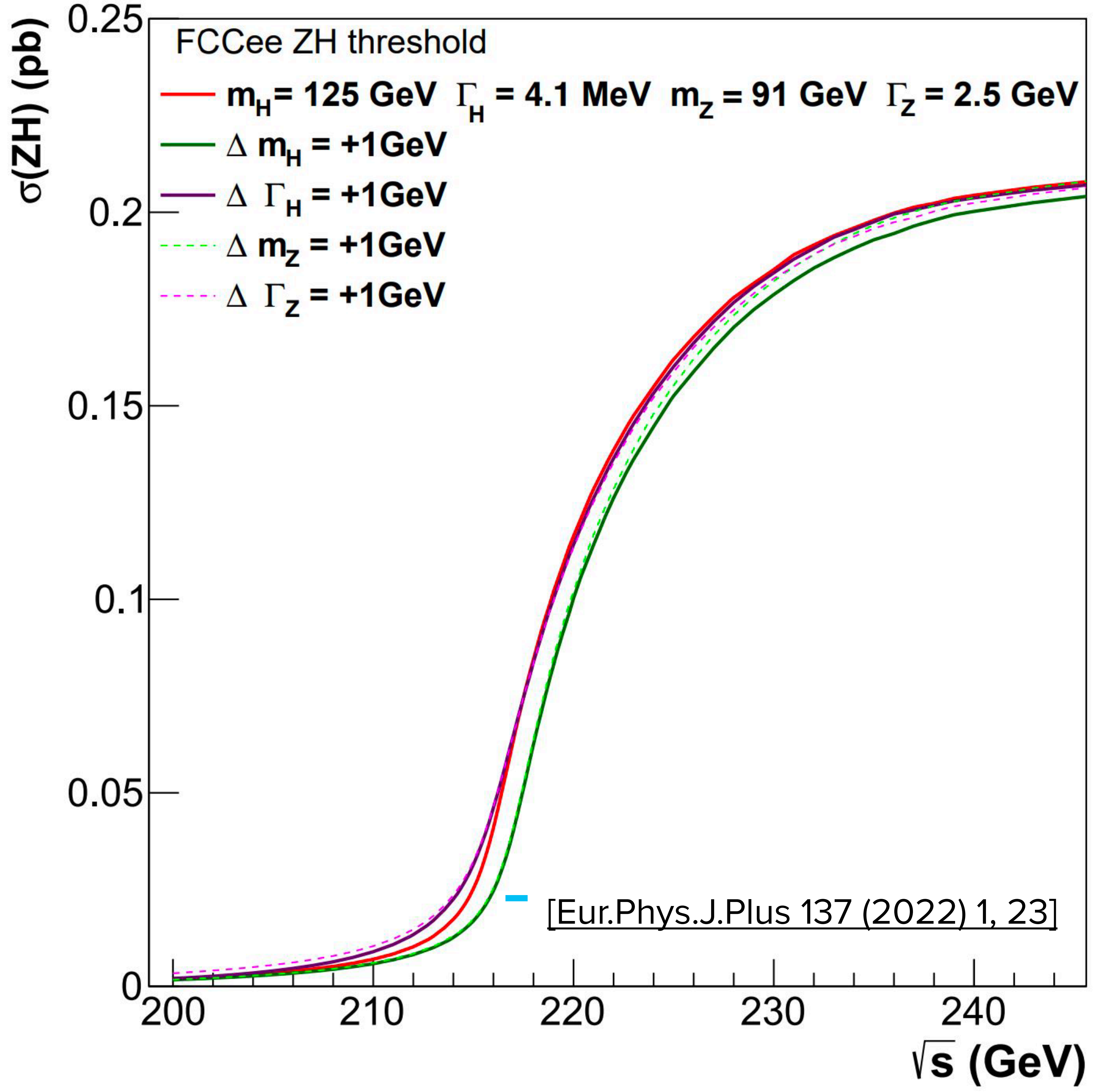
FCC-ee: highest luminosities of all proposed Higgs and EW factories

Range of energies that cover Z, WW, ZH, and tt

DEDICATED HIGGS MASS RUN?

- **Alternative proposal to reach <5 MeV with a dedicated √s= 217 GeV run**
  - Higgs mass dependency on the total cross section as a function of √s
  - Rely on accurate measurements of Z mass&width at the Z-pole
  - Ratio between 217 and 240 GeV: experimental and theoretical uncertainties cancel —> reach sensitivity of 5 MeV, (estimate, real analysis to come)
- **Not in the baseline!**





- [Eur.Phys.J.Plus 137 (2022) 1, 23]

FCCEE: HUGE STATISTICS & PRECISION

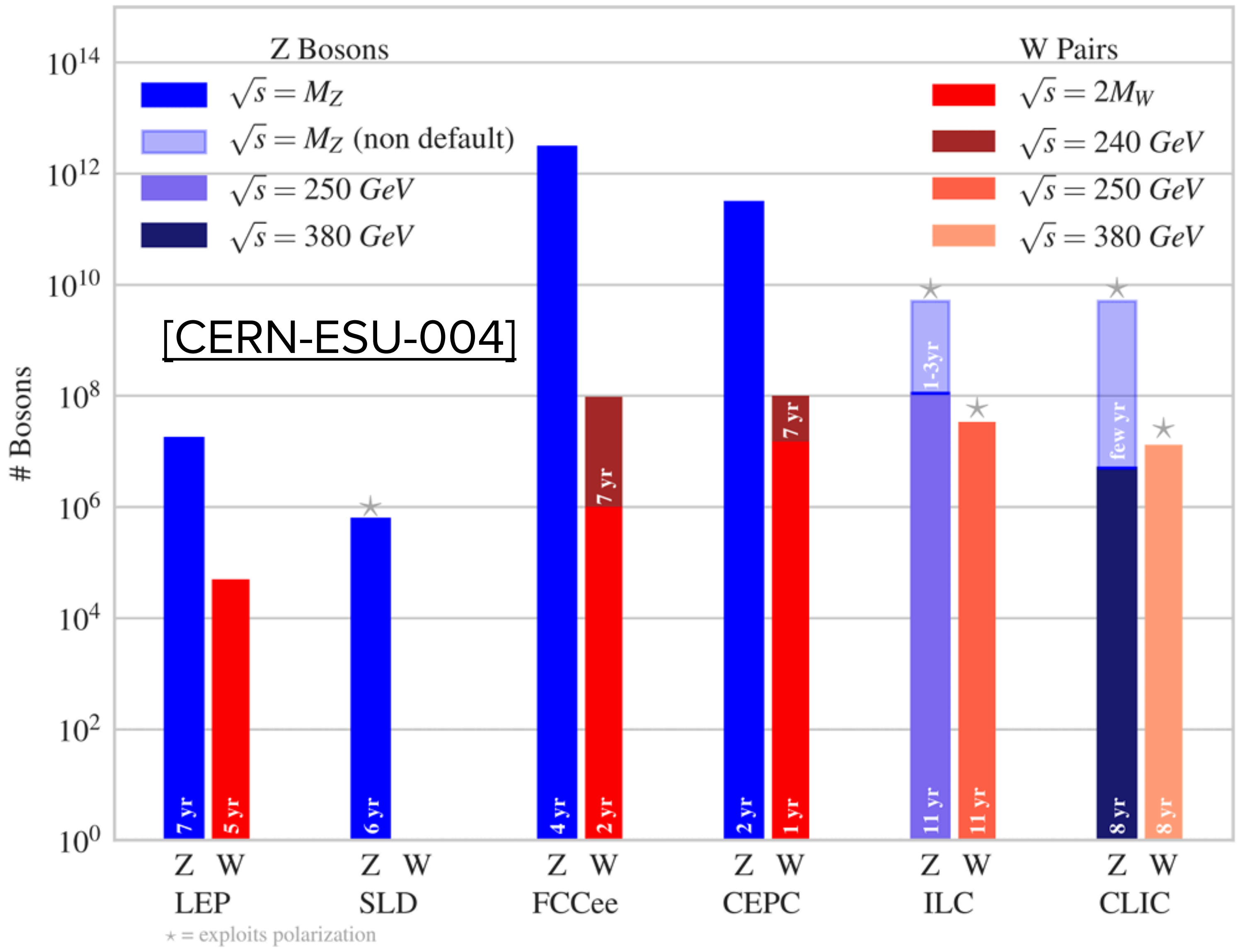
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

NOT ONLY HIGGS...

FCC feasibility Mid-term report -
Deliverable #8, physics and Experiments

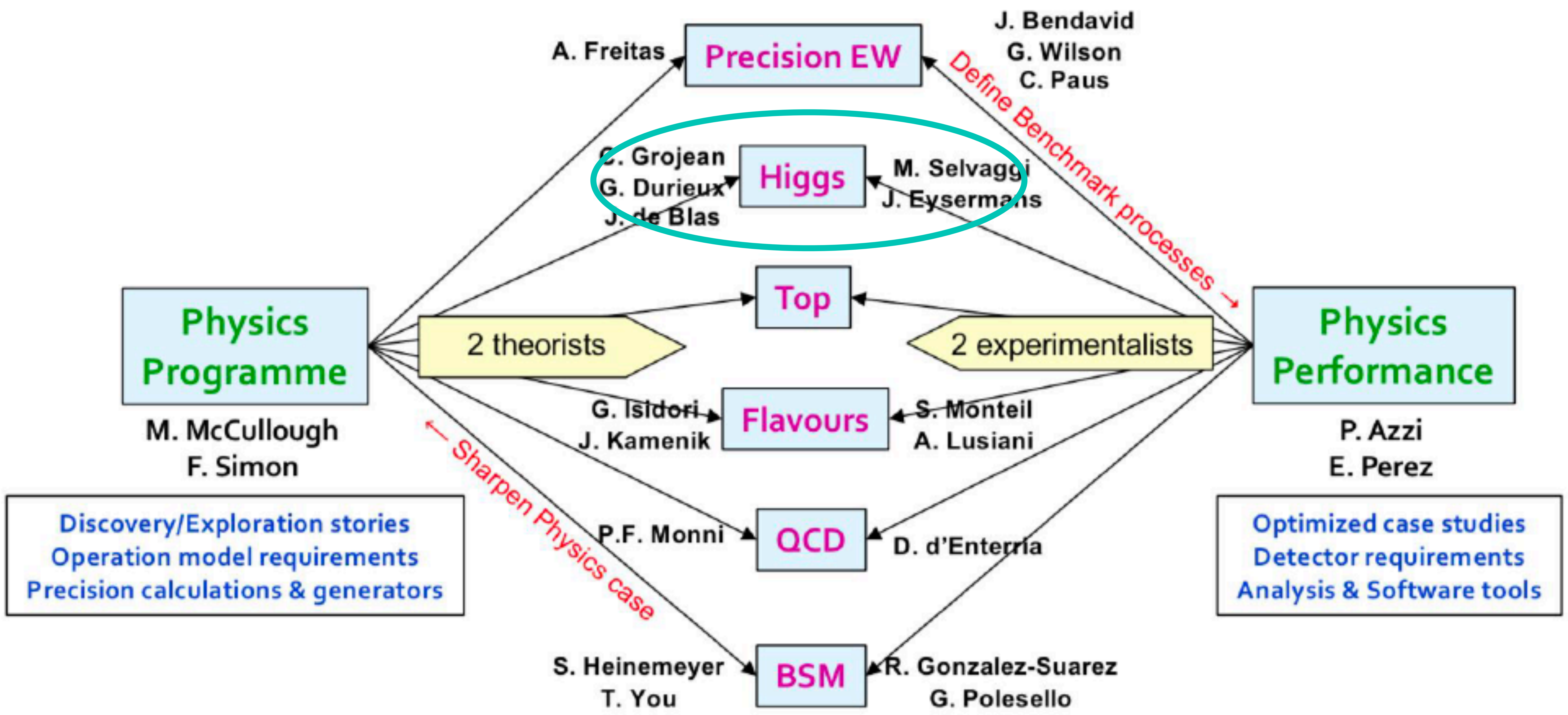
FUTURE CIRCULAR COLLIDER

- Dedicated W and Z runs with unprecedented statistics
- Z pole run → LEP Statistical uncertainties divided by ~1000
- Comprehensive measurements of the Z lineshape and many Electroweak Precision Observables
- Direct and uniquely precise determinations of α_{QED}(mZ) (for the first time) and α_S(mZ)



Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ^0_{had} $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration

EXPERIMENTAL PROGRAMME



- Analysis statistically driven, but high precision requires excellent detector performance —> optimizing the detector requirements for Higgs studies for the FCC Feasibility studies (end 2025).
  - Mid-term report (2023, soon to be made public) already includes the base for key Higgs performance.