Absolute Higgs cross section, mass, and width at FCC-ee

EPS-HEP 2025

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on behalf of FCC Higgs study group

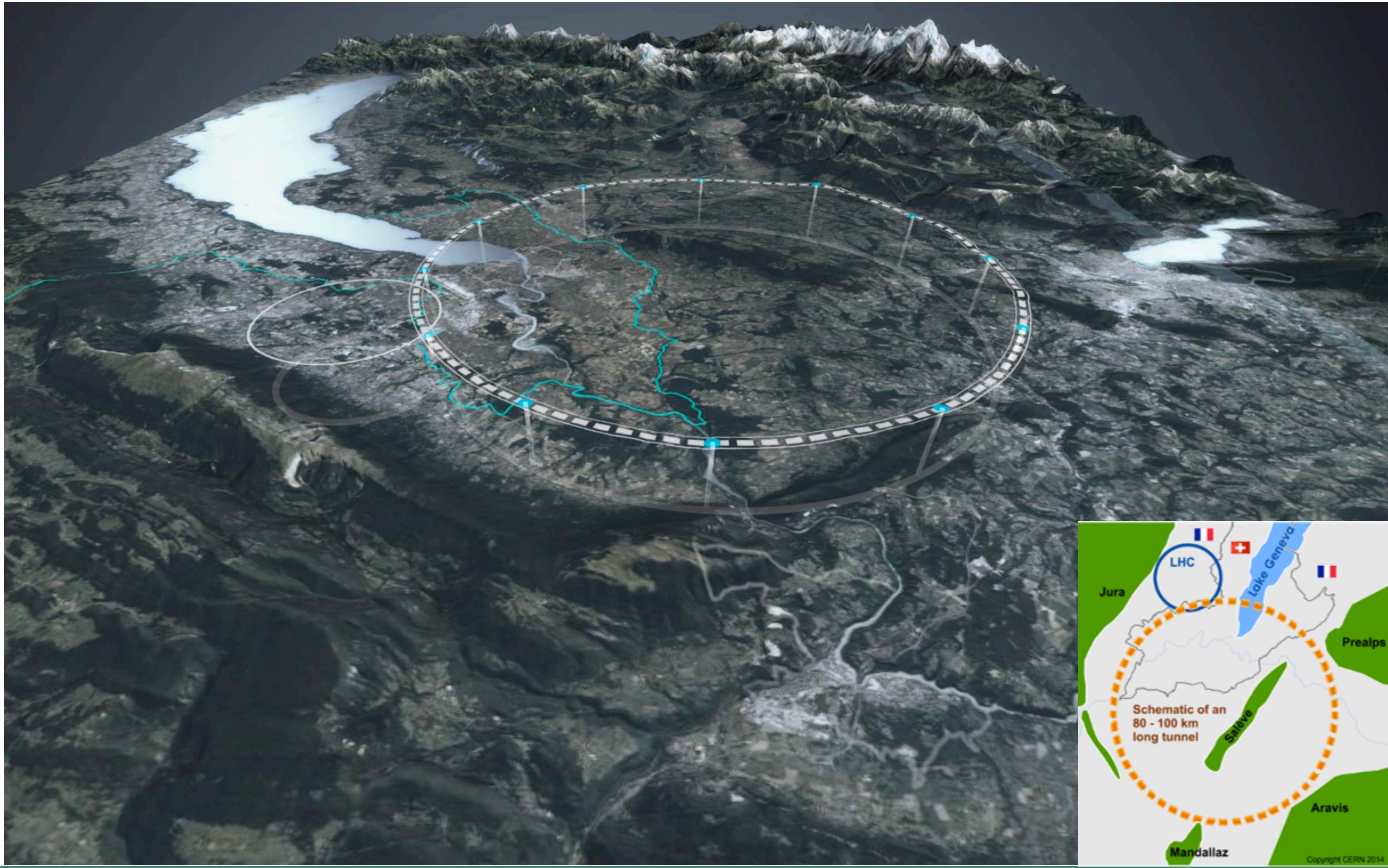
FCC project

New infrastructure

- 90.7 km tunnel
- 8 surface points
- 4 experimental sites
- Deepest shaft 400 m, average 240 m

Two stages

- FCC-ee (~15 years)
- FCC-hh (>20 years)



Historic timeline

1st European strategy

"Europe needs to be in a position to **propose** an ambitious **post-LHC accelerator project** at CERN by the time of the next Strategy update"

2nd European strategy

Europe, together with its international partners, should investigate the **technical and financial feasibility** of a **future hadron collider** at CERN with a center-of-mass energy of at least 100 TeV and with an **electron-positron Higgs and electroweak factory** as a possible first stage.

3rd European strategy

March 31, 2025: Contribution submission complete

January 2026: ESPP draft to CERN council

May 29 2026: council decision

Higgs discovery

2012

2013

2019

2026

❖2012-2013

Early concepts

- TLEP concept

❖2014-2019

FCC conceptual design study

- FCC CDRs

❖2021-2025

FCC feasibility study

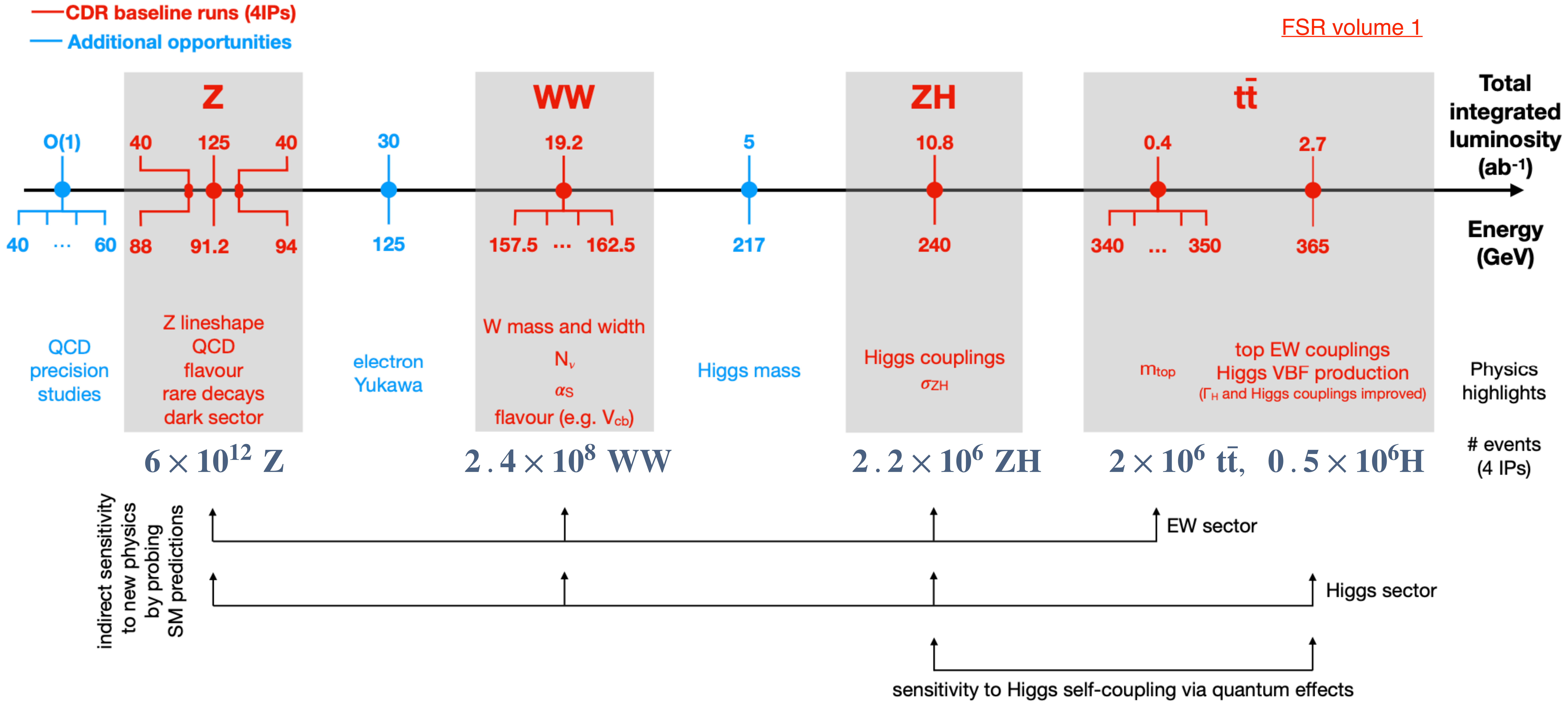
- Feasibility study reports

❖2025-2027

pre-TDR

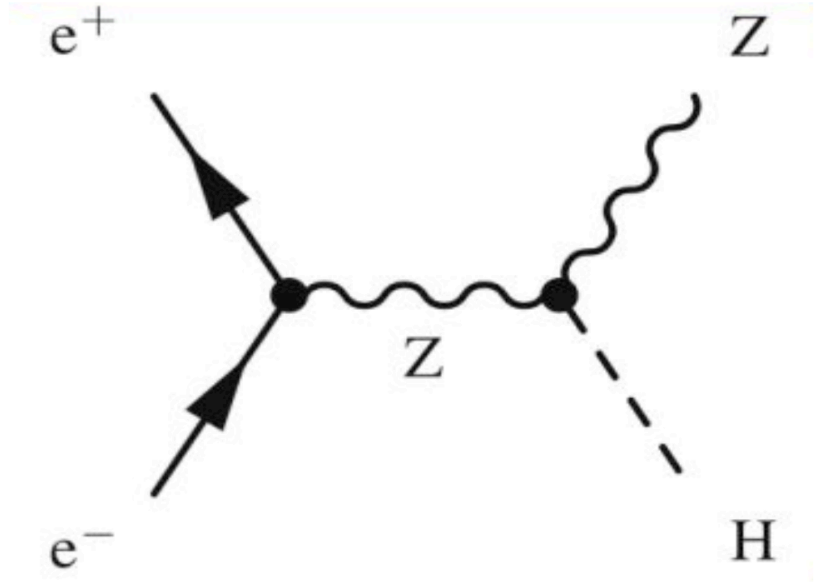
Decision around 2028

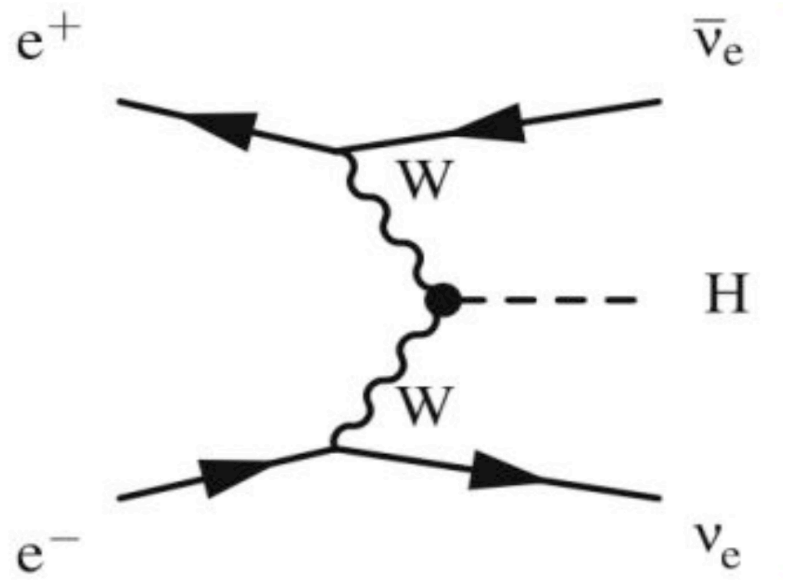
FCC-ee physics runs



Overview of Higgs program

- Two main production modes





2.2M events at 240 GeV
379k events at 365 GeV

65k events at 240 GeV
92k events at 365 GeV

- ~ 20 dedicated analysis notes
  - public at CERN CDS
- Summary submitted to ESPPU
  - Comprehensive coverage of Higgs properties
  - Model-independent coupling determination
  - Unrivaled precision

See more from A. Maloizel

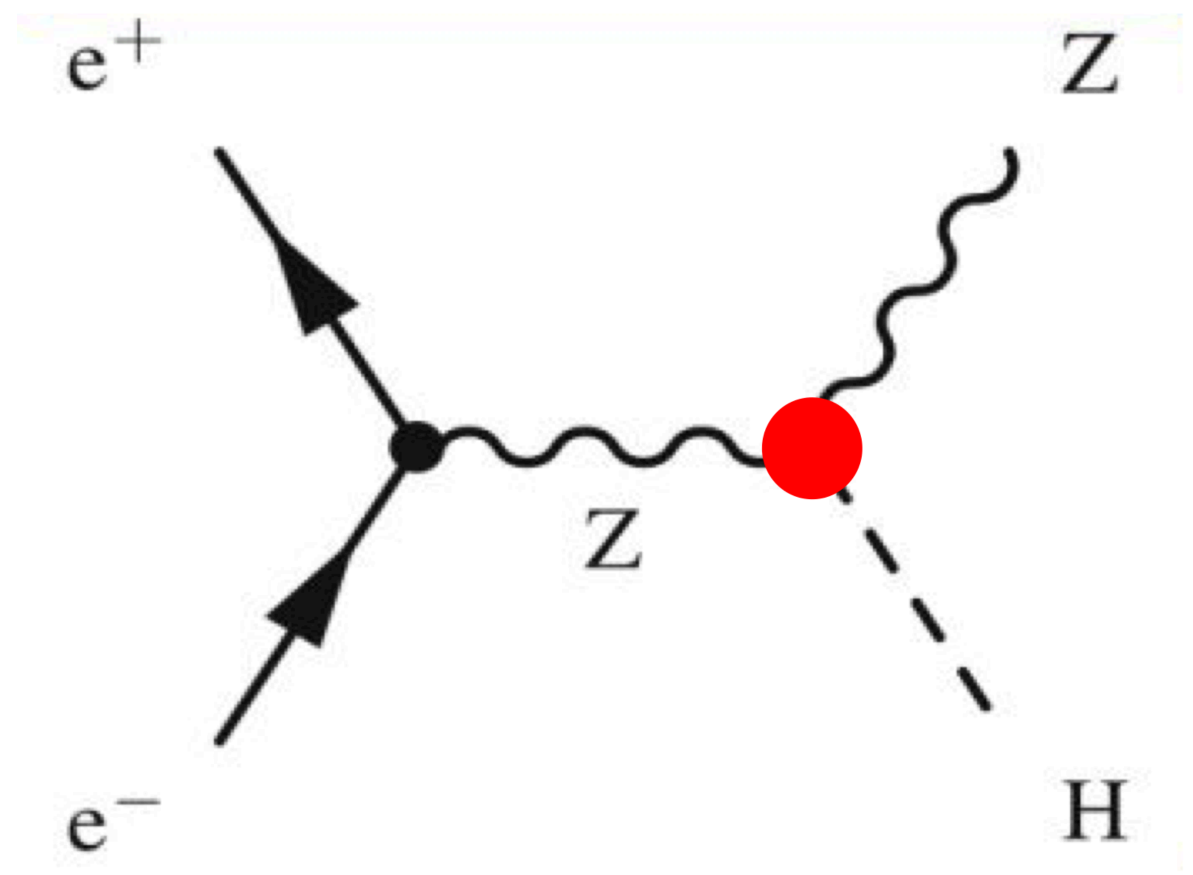
relative precision on BR, in percent

$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
$H \to \tau\tau$	±0.58		±1.2	±5.6 (*)
$H \to \mu\mu$	±11		±25	
$H \to WW^*$	±0.80		±1.8 (*)	±2.1 (*)
$H \to ZZ^*$	±2.5		±8.3 (*)	±4.6 (*)
$H \to \gamma\gamma$	±3.6		±13	±15
$H \to Z\gamma$	±11.8		±22	±23
$H \to \nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

HEWT summary

(*) analyses ongoing, results scaled from FCC CDR

Recoil method



In lepton collisions

✓ Initial energy known

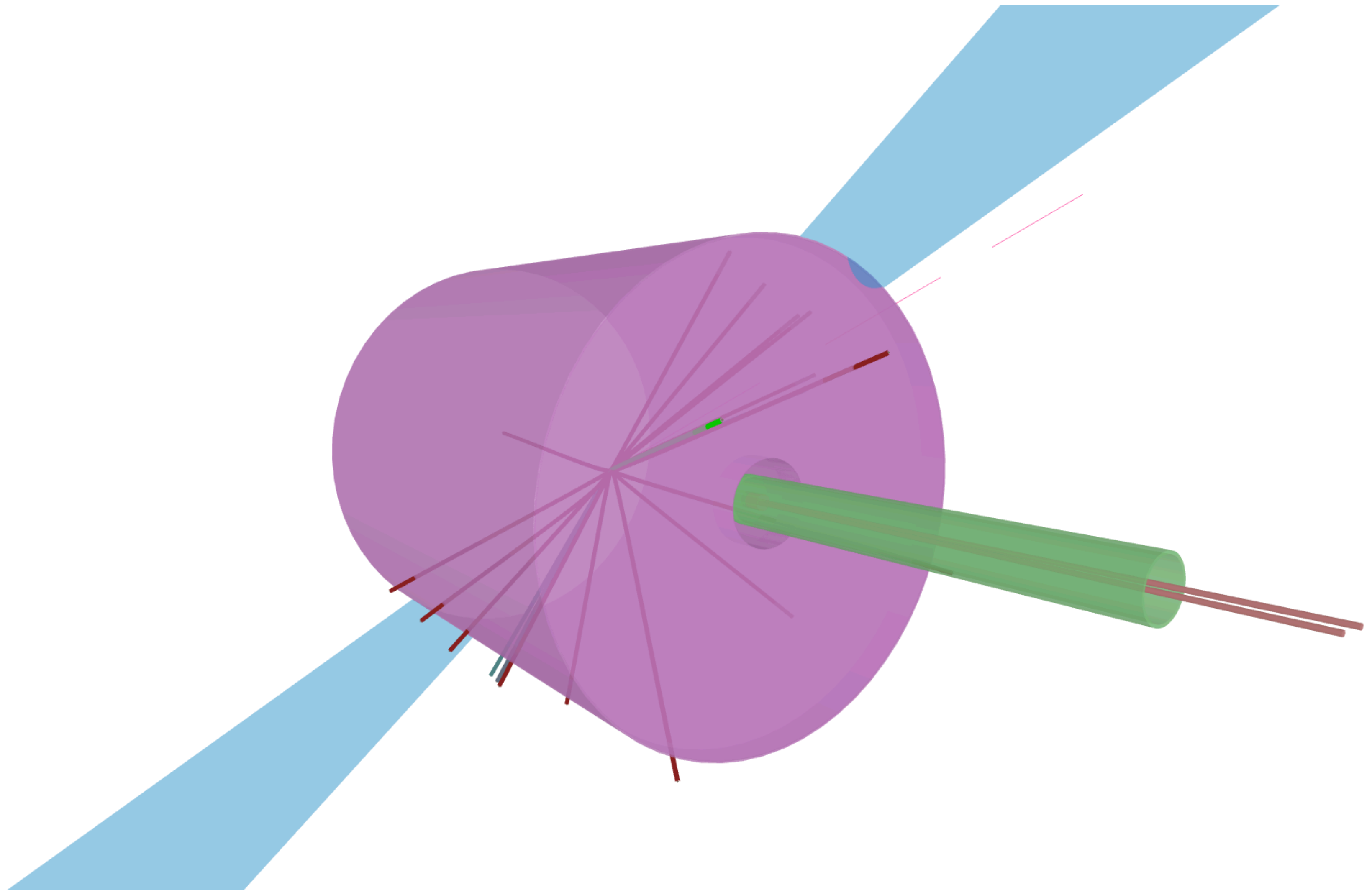
✓ Z system well understood

✓ No additional particle expected

Recoil from Z: $m^2_{recoil} = s + m^2_Z - 2E_Z\sqrt{s}$

- Inclusive Higgs decay
- Basis for the self coupling, width, mass and many other measurements

Jet clustering

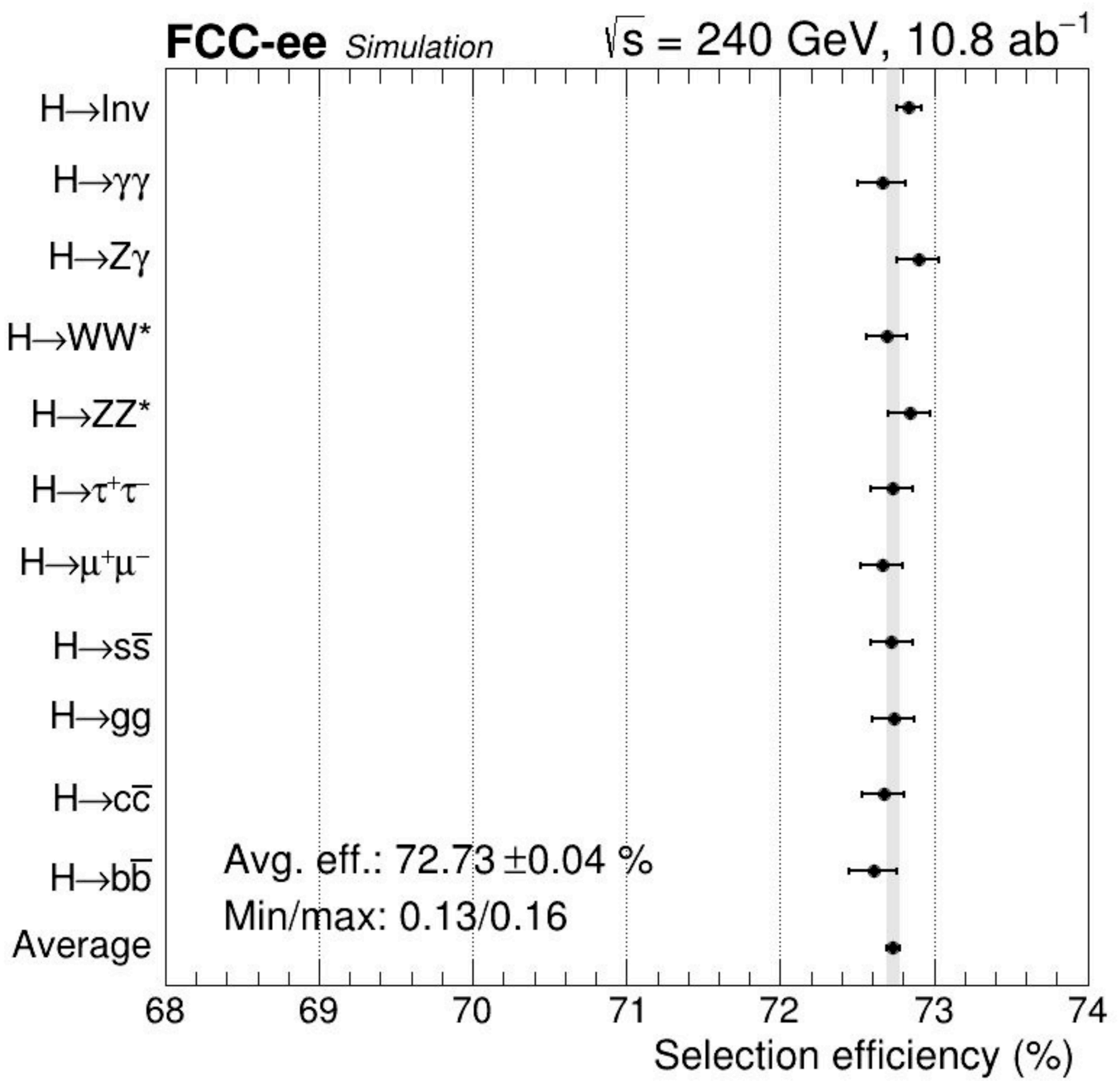


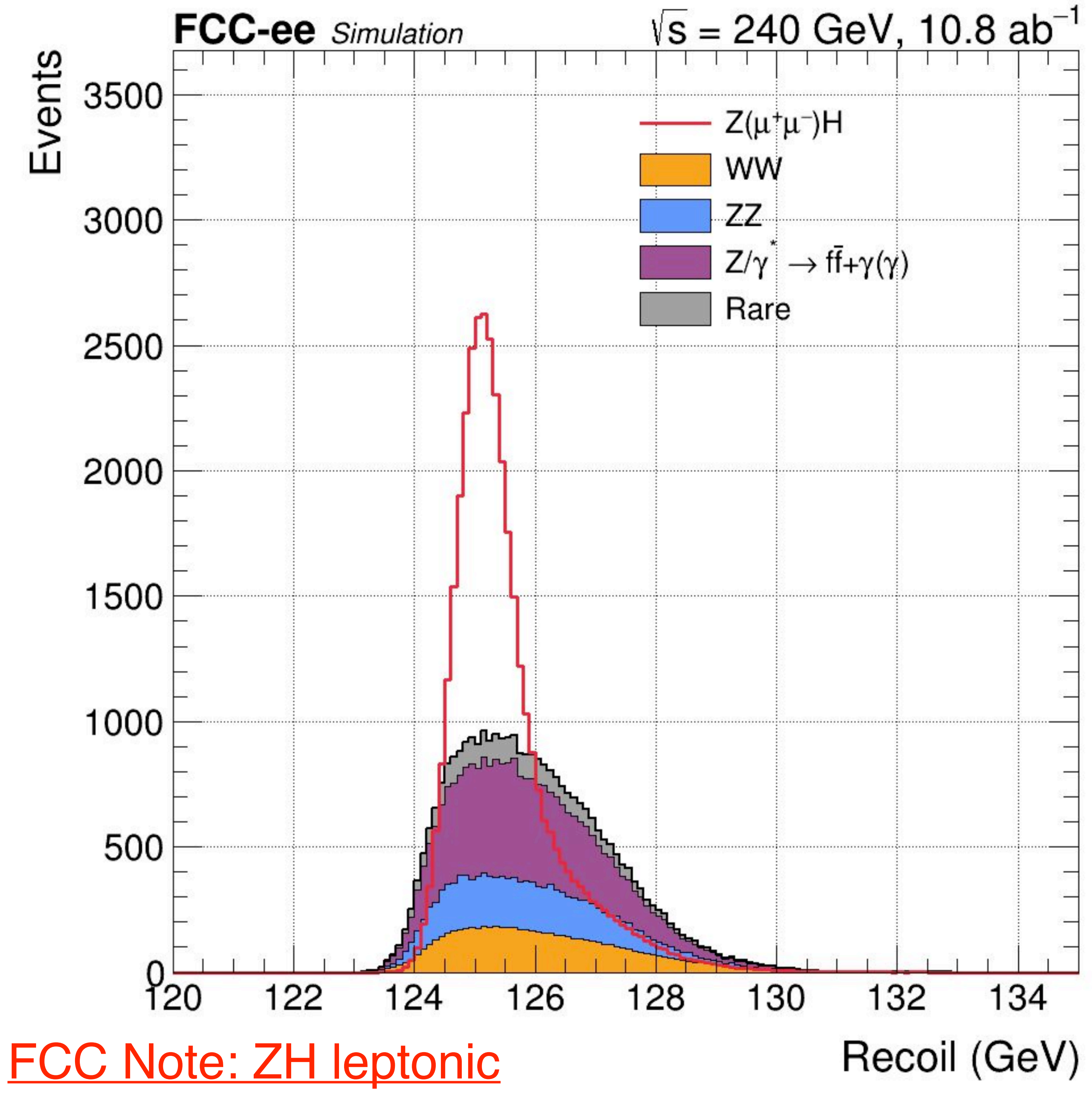
Durham kt algorithm

- Predefine number of jets n_j in event
- All particles clustered into n_j jets

ZH cross section: $Z \to \ell\ell$ channels

- Focus on kinematics of $Z \to ee, \mu\mu$
- Crucial to stay **agnostic to Higgs decays**
- Model-independence achieved at 0.2% level
- BDT based on $Z \to ee, \mu\mu$ kinematics to suppress backgrounds
- Fit recoil mass in 2 bins of MVA discriminator





FCC Note: ZH leptonic

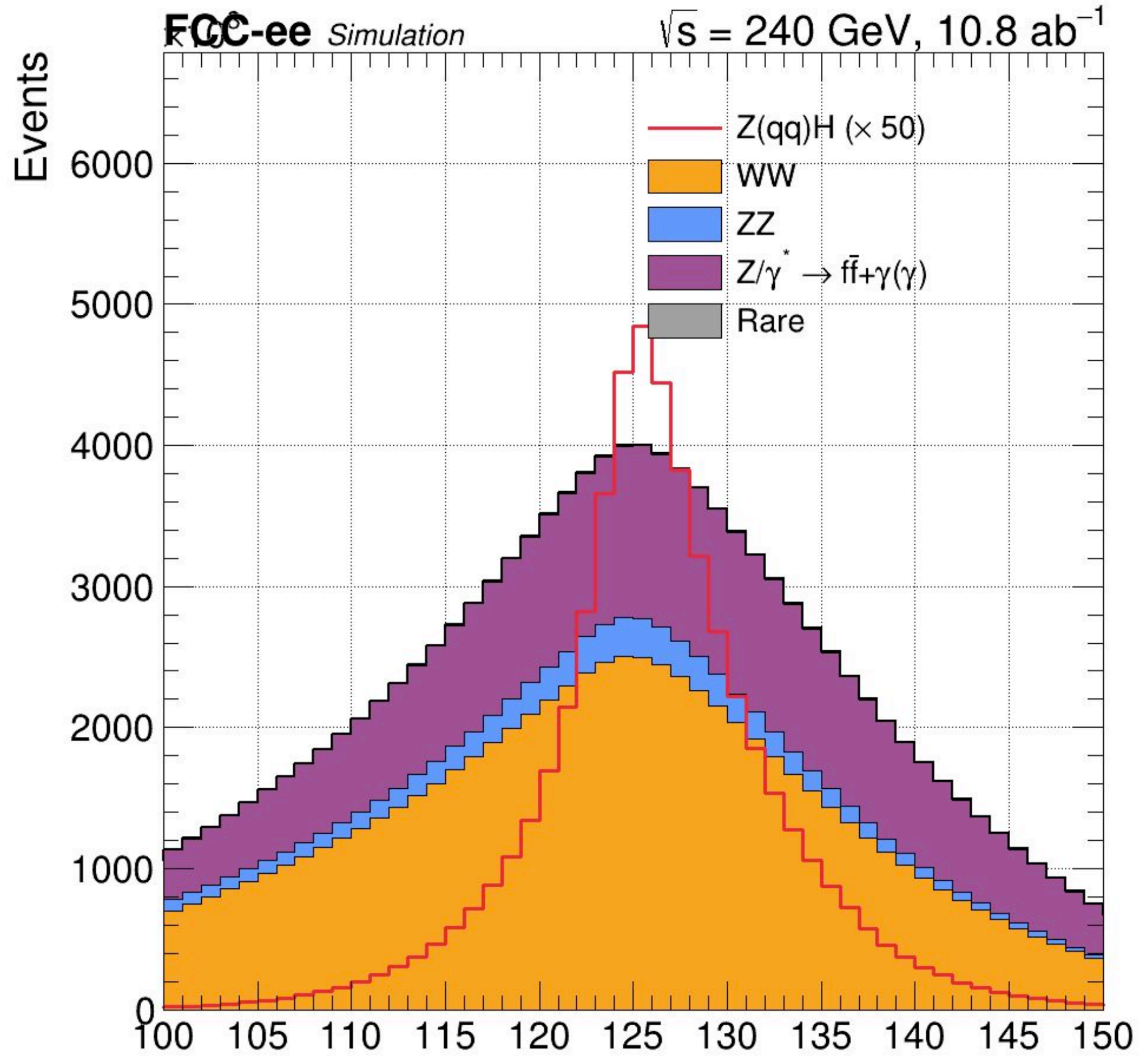
Combined uncertainty of 0.52(1.35)% at 240(365) GeV

Uncertainty on ZH (%)		
√s (GeV)	240 GeV	365 GeV
Muon	0.68	1.83
Electron	0.81	1.95
Combination	0.52	1.35

ZH cross section: $Z \to q\bar{q}$ channels

Consider all $Z \to q\bar{q}$ decays

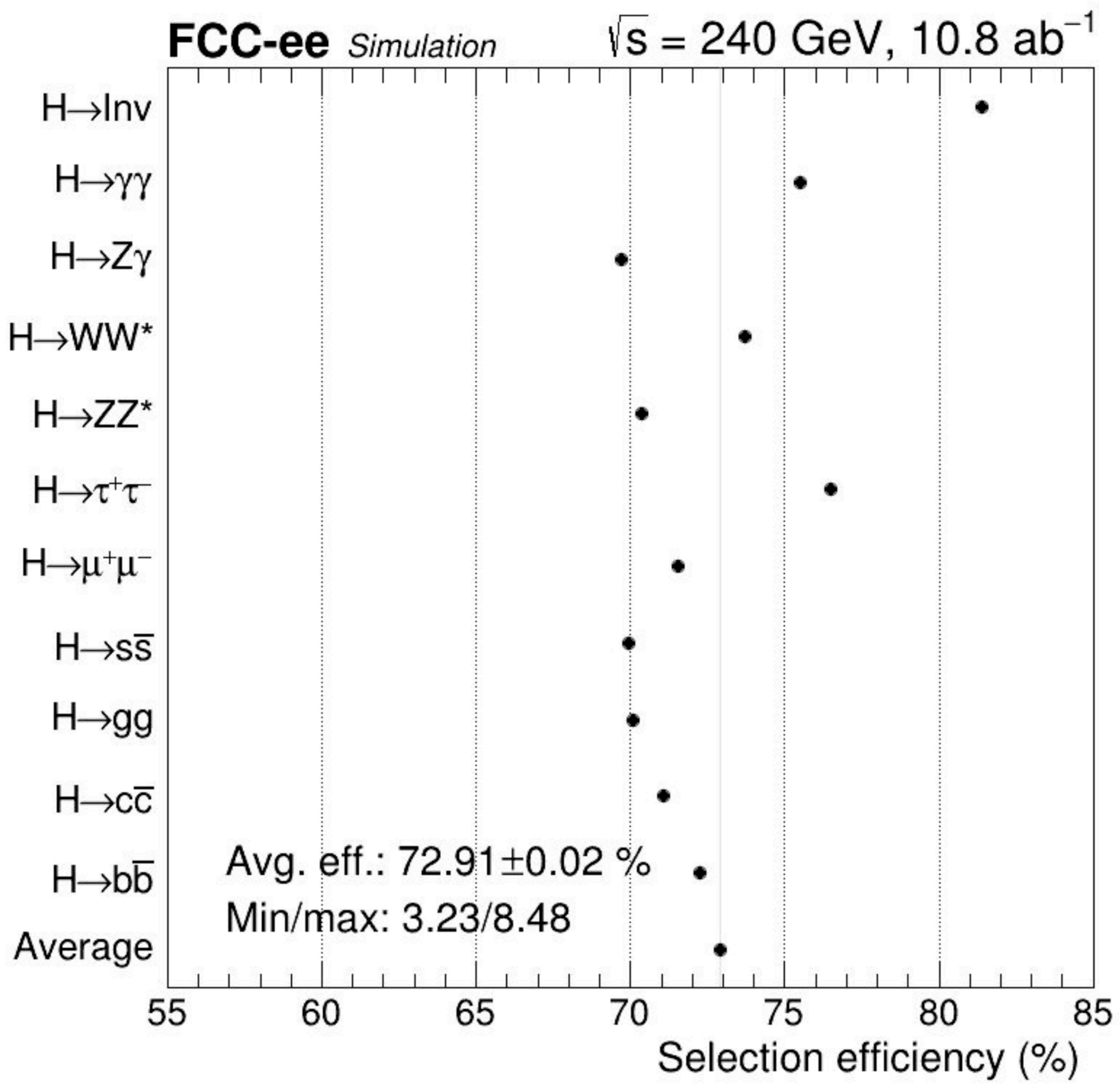
- High statistics: $\mathscr{B}(Z \to q\bar{q})$ = 70% vs $\mathscr{B}(Z \to ee, \mu\mu)$ = 7%
- Multi-jet final state depends on Higgs decay (several clustering schemes test, n_j = 2,4,6)
- Select pairing to match ZH, minimize $\chi^2 = (m_{jj} - m_Z)^2 + (m_{recoil} - m_H)^2$
- BDT to suppress WW and Z/γ backgrounds
    - Inputs: dijet kinematics, angular correlations
- 2D fit of $m_{recoil} - m_{jj}$ in 2 bins of MVA discriminator



FCC Note: ZH hadronic

Selection no longer agnostic to decay modes, need to evaluate impact

ZH cross section: $Z \to q\bar{q}$ channels



Selection efficiency ~10% spread

Bias test to evaluate impact (arXiv 1509.02853):

- Pseudo-data by perturbing each BR independently to yield a deviation δZH = x% (prior)
- Bias = μ^{fit} - 1 - x%, needs to be smaller than expected uncertainty

FCC Note: ZH hadronic

Bias on σ(ZH) (%)			
Channel	Leptonic	Hadronic	Combination
Bias prior	5%	1%	1%
bb	-0.011	0.027	0.02
cc	-0.013	-0.085	-0.063
gg	-0.013	-0.024	-0.018
ss	-0.016	-0.168	-0.124
$\mu\mu$	0.095	0.149	0.115
$\tau\tau$	-0.008	-0.072	-0.054
ZZ	0.487	0.023	0.042
WW	-0.023	-0.039	-0.03
Zγ	0.545	-0.132	-0.069
γ	-0.007	0.285	0.209
inv	0.002	0.362	0.267

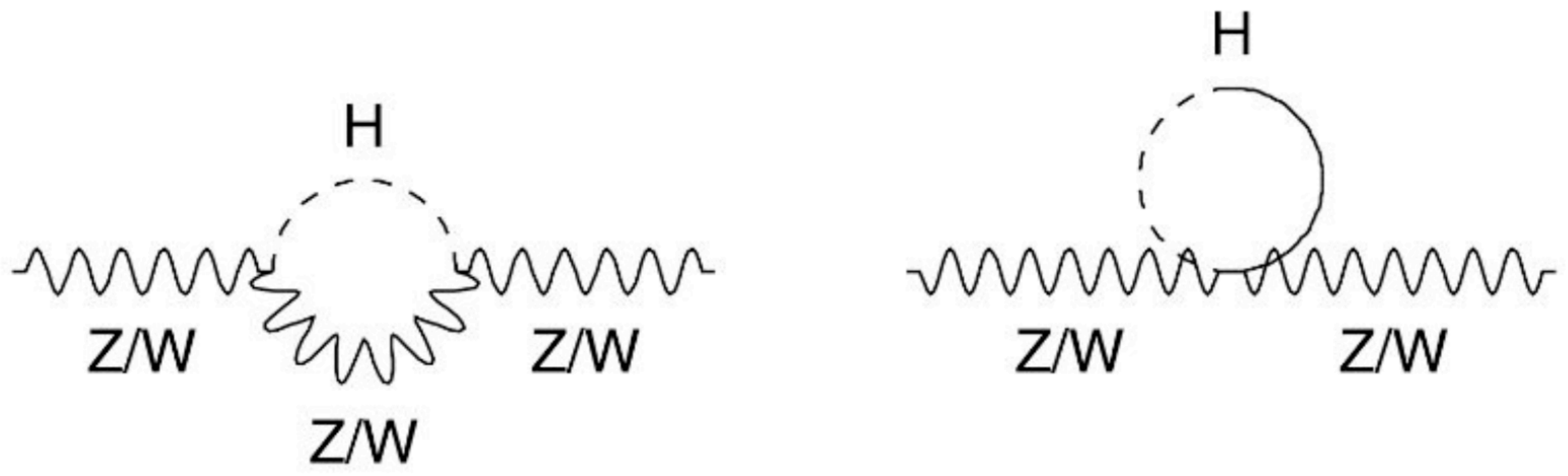
Uncertainty of hadronic measurement: 0.38(0.57)% at 240(365) GeV

Combined with leptonic channels: 0.31(0.52)% at 240(365) GeV

Higgs mass

Fundamental parameter in SM, connected to other measurements

- EWK radiative corrections depend on m_H
- FCC-ee demands sub-percent precision on cross section and BRs
- Translates to $\delta(m_H)$ < O(10) MeV requirement

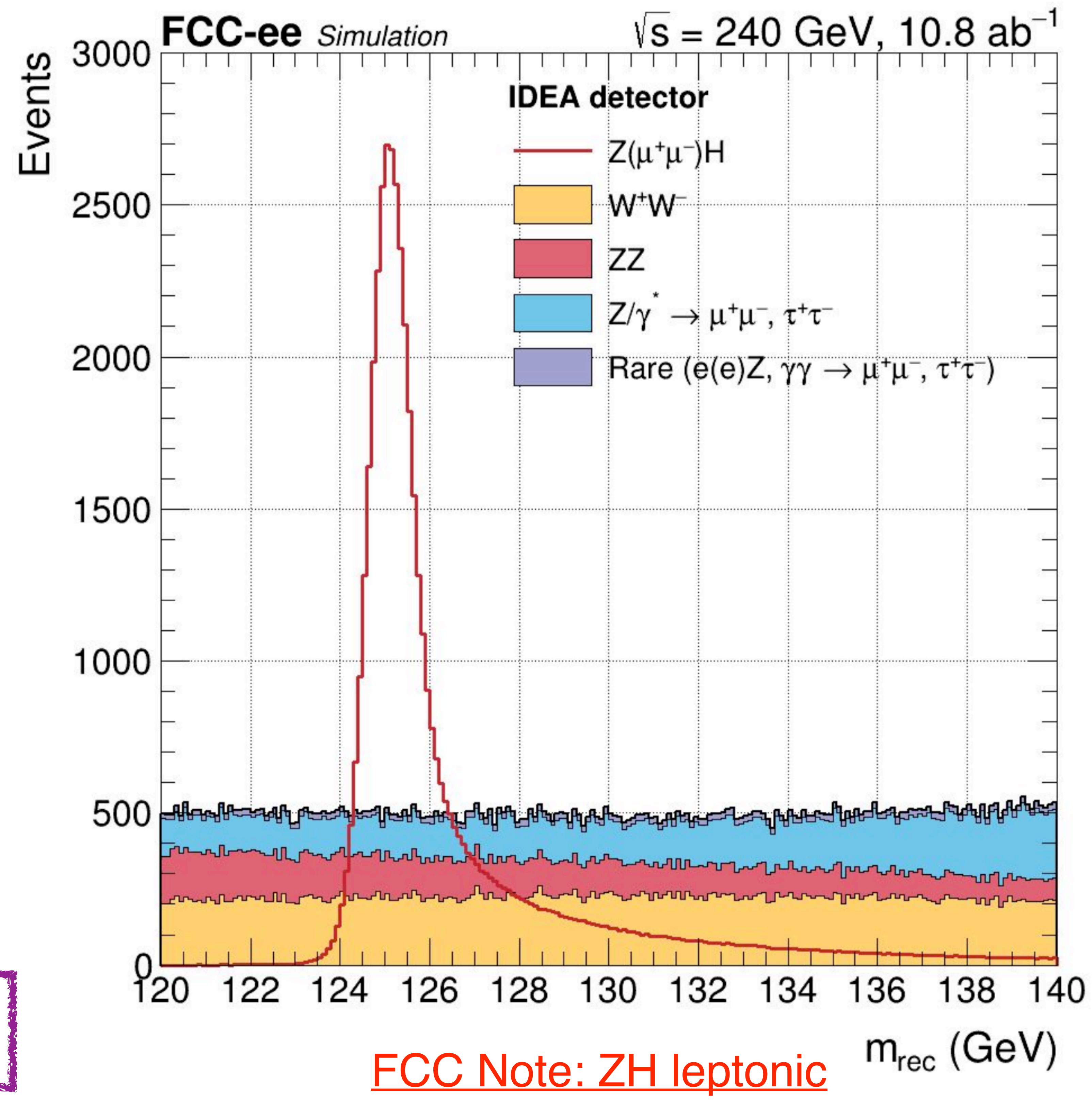


Higgs mass analysis

- Tight selection on $Z \to ee, \mu\mu$ decays, m_H from m_{recoil}
- Sensitivity driven by 240 GeV data
- Rely on excellent tracking resolution

Total uncertainty of 4 MeV, statistically dominated

- Systematic uncertainty of $\sqrt{s}$ taken as 2 MeV (but 1 MeV achievable)
- Useful for potential $e^+e^- \to H$ operation



FCC Note: ZH leptonic

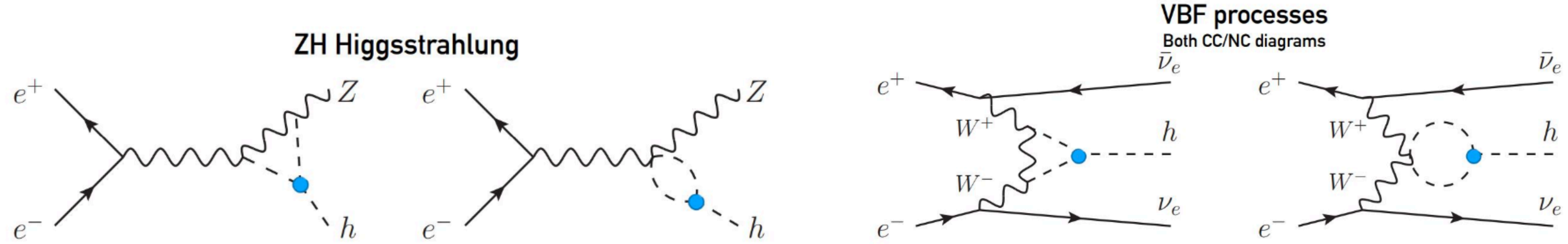
Today ~150 MeV → HL-LHC ~20 MeV → FCC-ee ~4 MeV

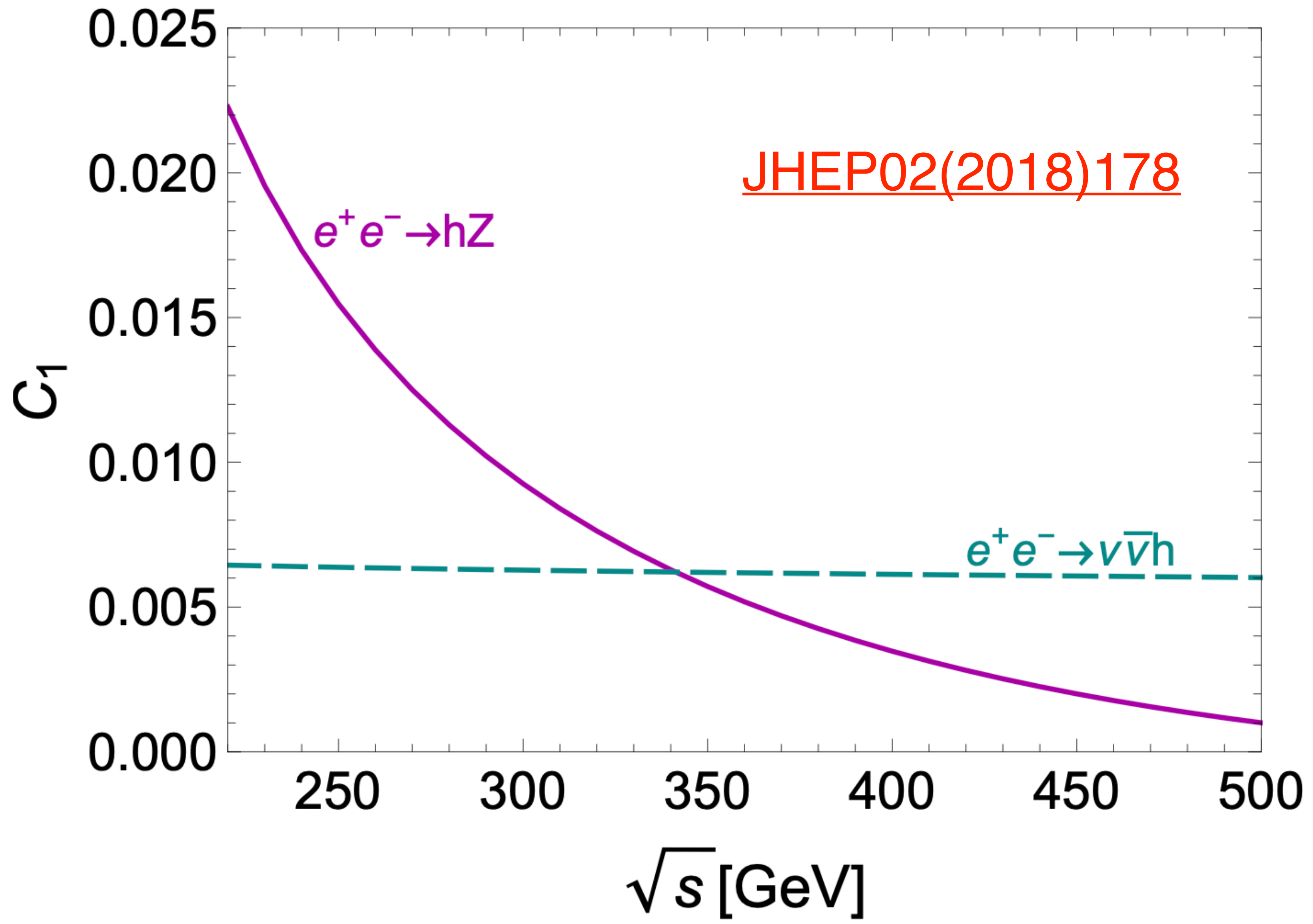
Higgs width

FCC Note: Higgs width

- Measurements of Higgs total width, and all Higgs couplings, at LHC are model-dependent
- Model-independent measurement at e^+e^- colliders
- Based on $\sigma(e^+e^- \to ZH)$ determination
  - $\sigma(ZH) \times \mathscr{B}(H \to XX) \propto g_{HZZ}^2 \times \frac{g_{HXX}^2}{\Gamma_H}$ $\Longrightarrow$ $\Gamma_H \propto \frac{\sigma(ZH)^2}{\sigma(ZH, H \to ZZ)}$
- Similarly, for VBF mode
  - $\sigma(\nu_e \nu_e H) \times \mathscr{B}(H \to YY) \propto g_{HWW}^2 \times \frac{g_{HYY}^2}{\Gamma_H}$ $\Longrightarrow$ $\Gamma_H \propto \frac{\sigma(ZH)^2 \sigma(\nu_e \nu_e H, H \to YY)}{\sigma(ZH, H \to YY)\sigma(ZH, H \to WW)}$
- Combining these relations in kappa fit leads to **$\delta\Gamma_H$ = 0.78%**
  - Crucial to measure $H \to ZZ, WW$ to high precision
- With Γ_H determined, each $\mathscr{B}(H \to XX)$ measurement becomes a model-independent determination of g_{HXX} coupling.

Higgs self coupling





Probe of λ_3 through NLO contributions to single Higgs production

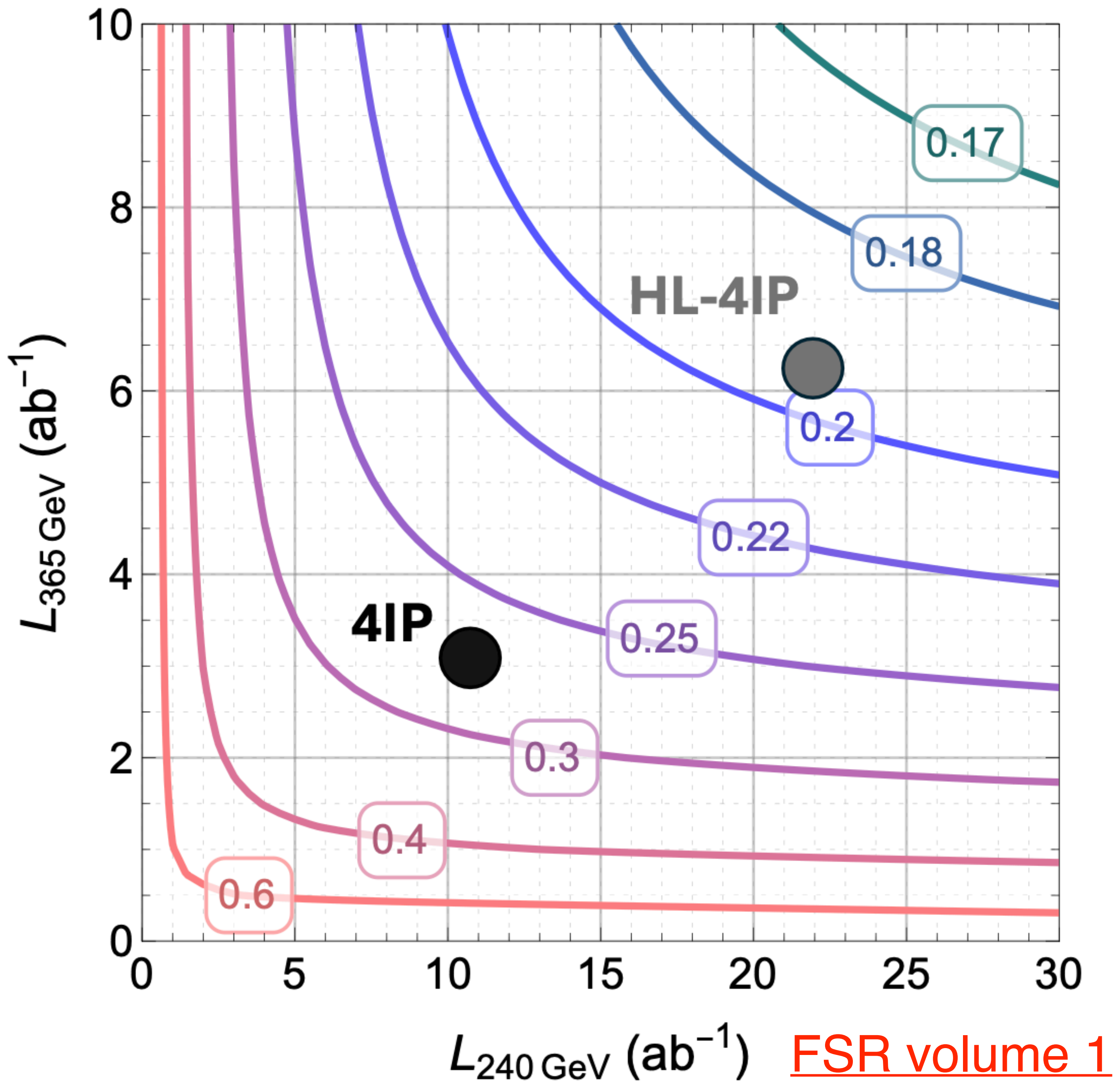
- $\Sigma_{NLO} = Z_H \Sigma_{LO}(1 + \kappa_\lambda C_1)$
- where $Z_H = 1/(1 - \kappa_\lambda^2 \delta Z_H)$, $\quad \delta Z_H \approx -0.00154$

C_1 shows dependence on $\sqrt{s}$

- Measure ZH xsec at different energies to resolve correlation between κ_λ and other operators, like trilinear Z coupling λ_Z and correction to HZZ coupling δc_Z

With 0.3% precision on $\sigma(ZH)$, expect **27% precision on κ_λ**

- 18% if combined with HL-LHC
- Ultimate precision to be achieved at FCC-hh

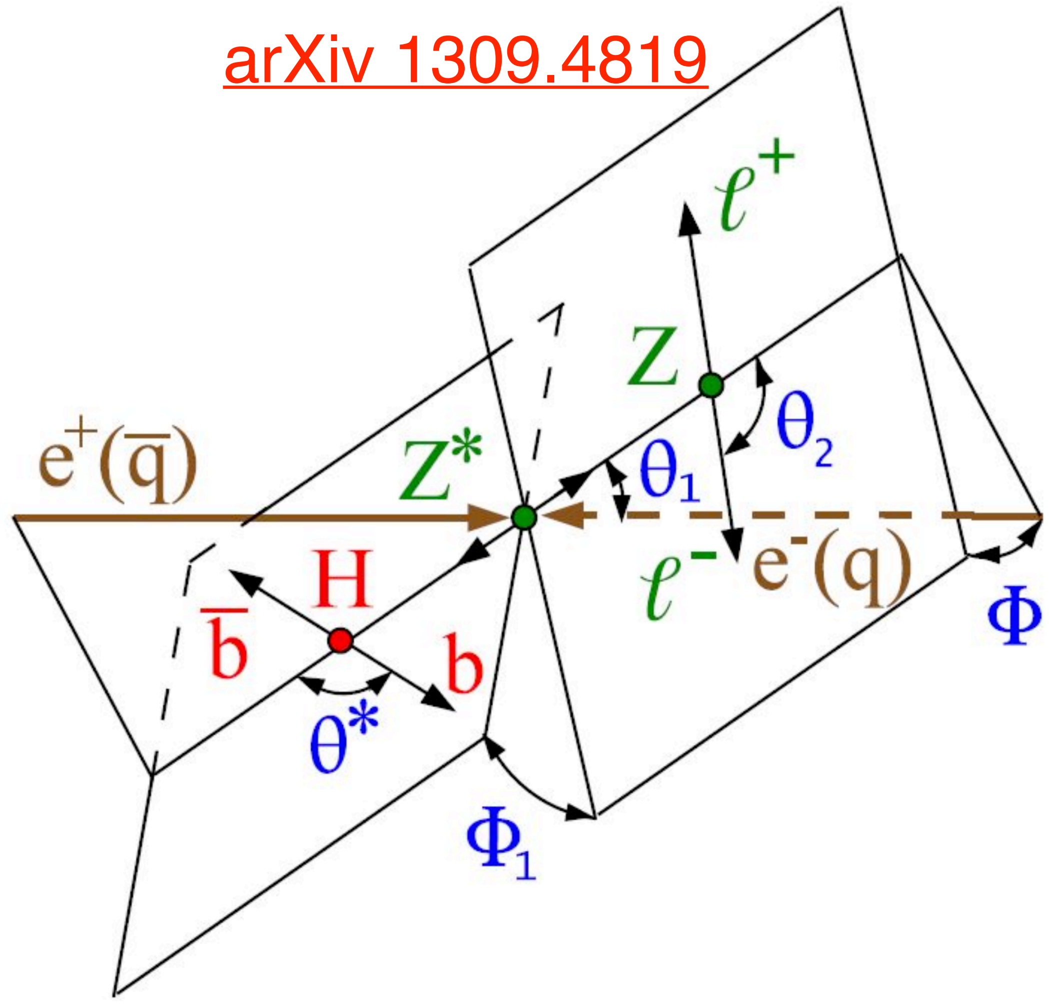


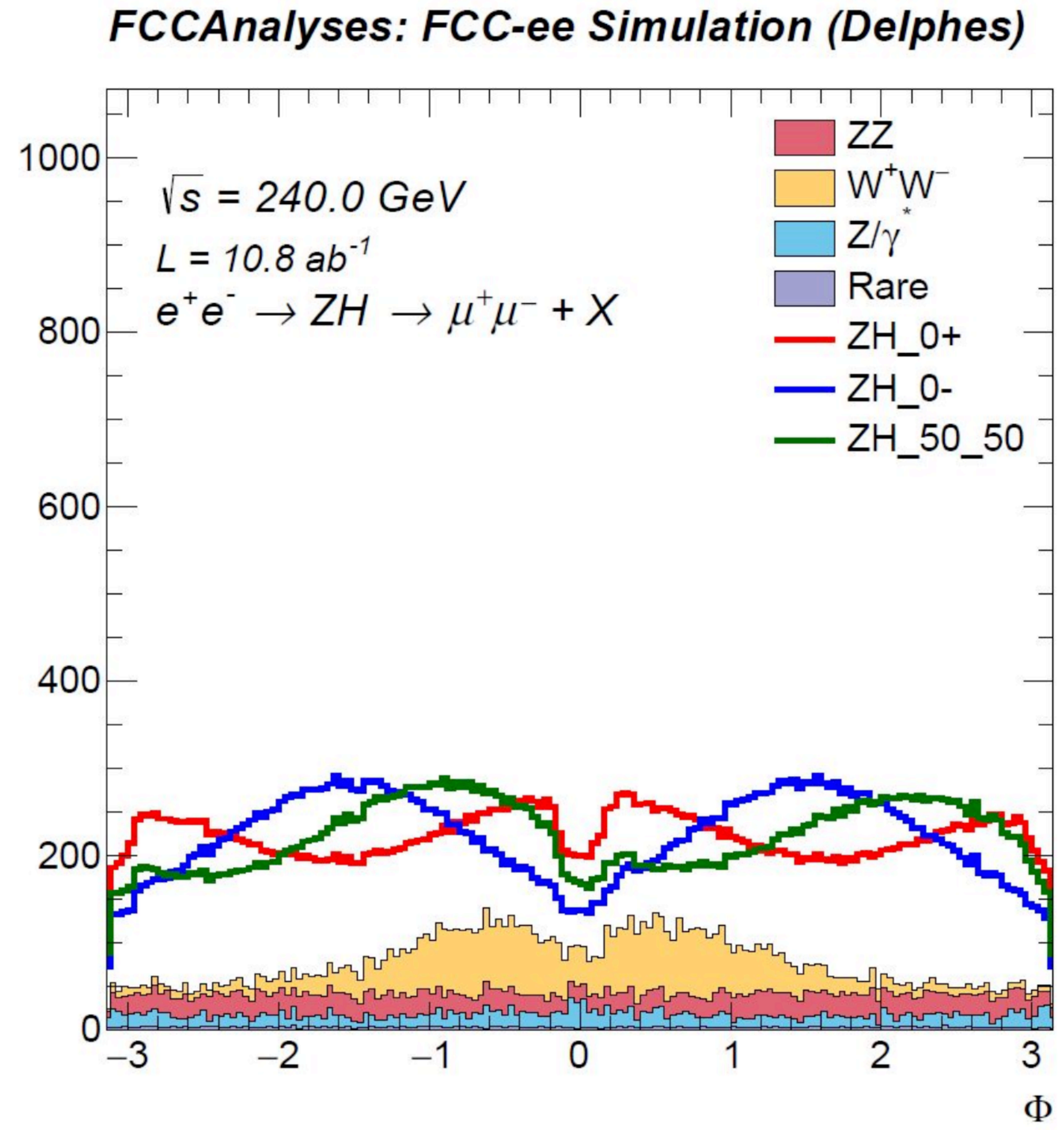
FSR volume 1

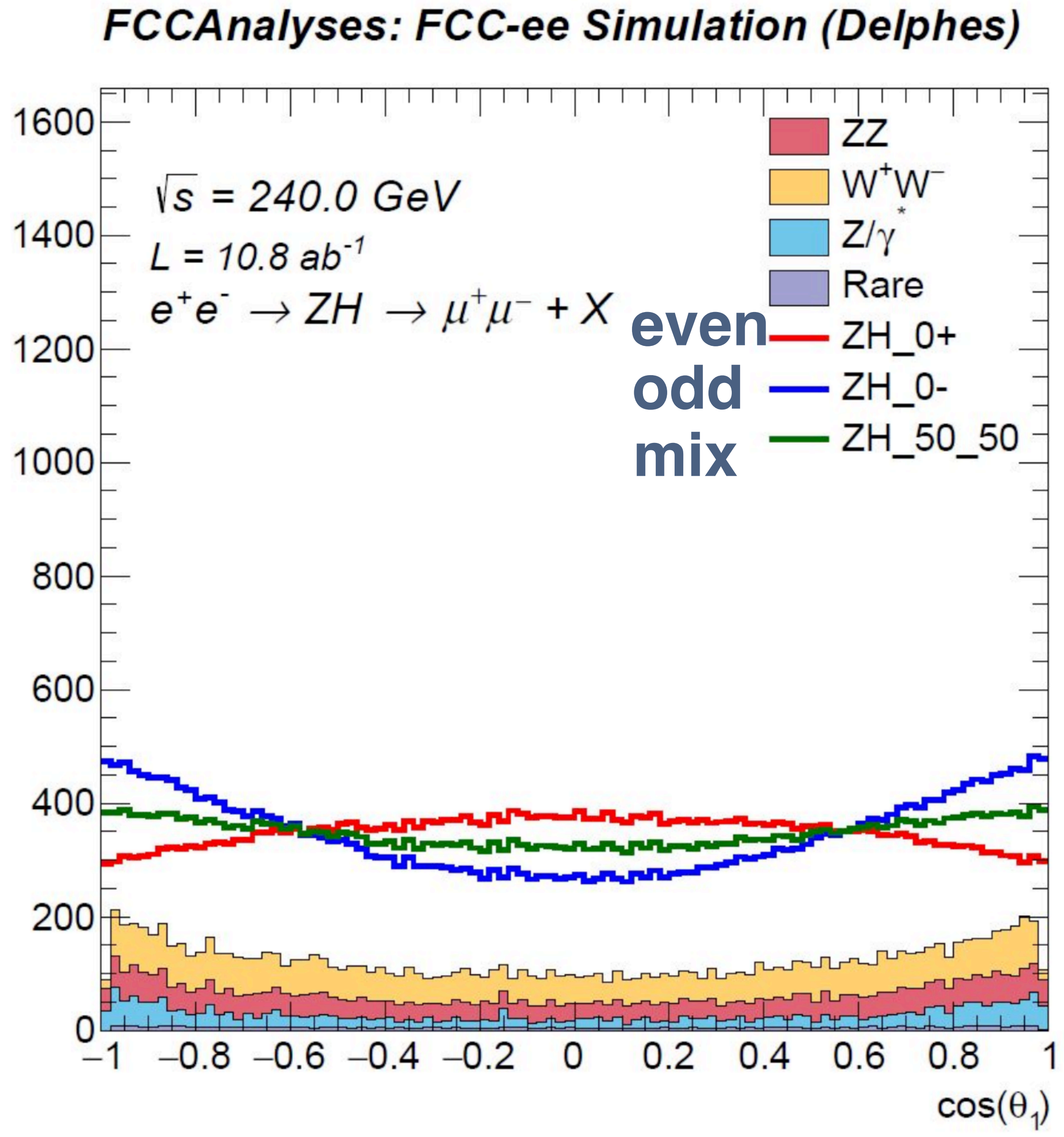
CP of g_{HZZ} coupling

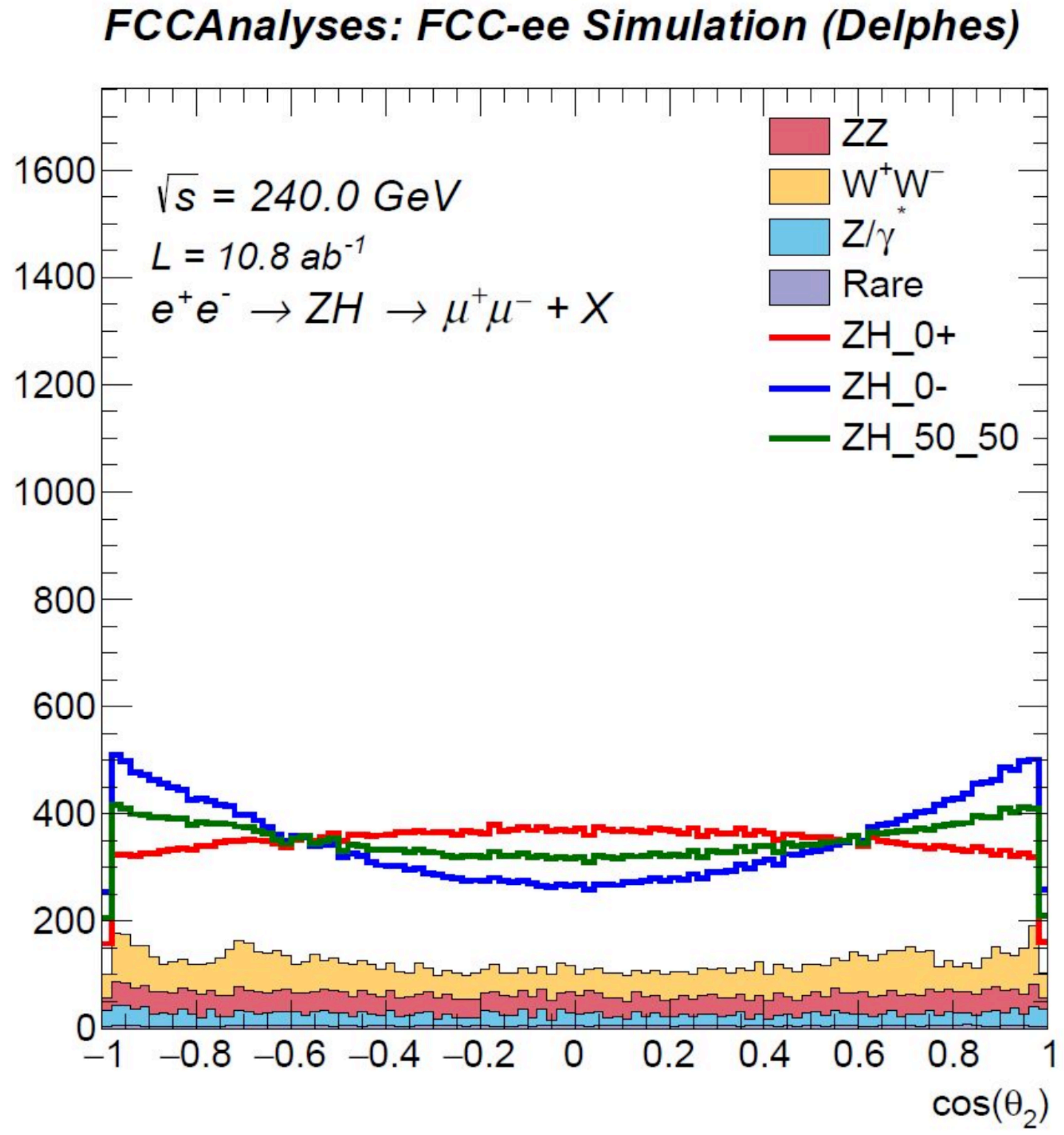
- Consider $Z \to \ell\ell, qq$, $H \to$ inclusive
- Reconstruct CP-sensitive variables via Z decay
- 3-dimensional fit (m_{recoil} and optimal observables $\mathscr{D}_{0-}, \mathscr{D}_{CP}$ for leptonic channel, anglular variables ϕ, $\cos(\theta_1)$, $\cos(\theta_2)$ for hadronic channel)
- Constrain CP fraction $f_{CP}^{HX} = \dfrac{\Gamma_{H\to X}^{\text{CP odd}}}{\Gamma_{H\to X}^{\text{CP odd}} + \Gamma_{H\to X}^{\text{CP even}}} < 1.2 \times 10^{-5}$ (68% CL)

arXiv 1309.4819









FCC note: Higgs CP

Summary

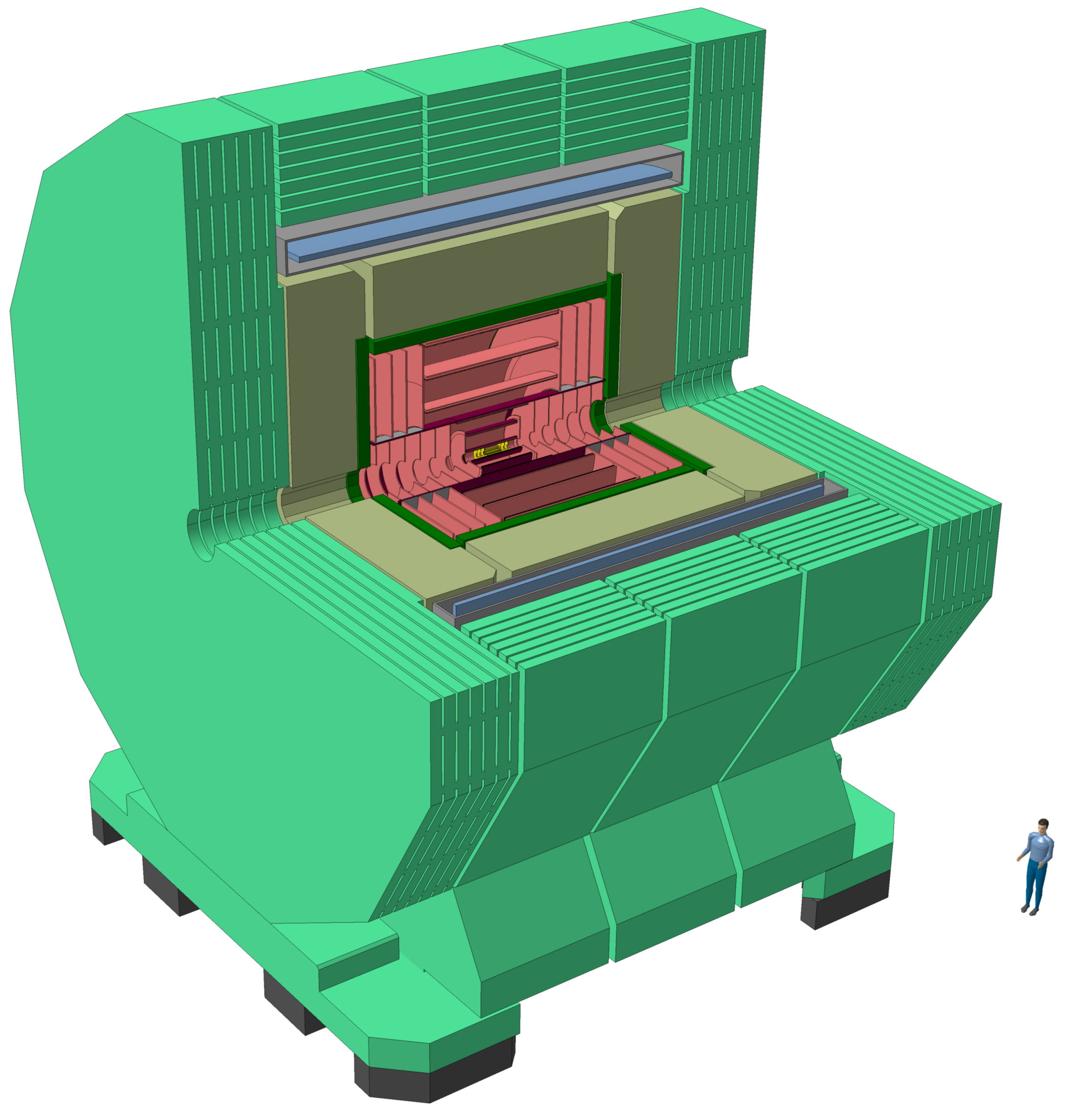
- Model independent measurements of Higgs boson properties
  - 0.31% relative precision on ZH total cross section
  - 4 MeV uncertainty on Higgs mass
  - 0.78% relative precision Higgs total width
- Core piece for other Higgs studies
  - Indirect constraint on scalar-coupled BSM physics
  - Inputs to high order EW calculations
  - Input for electron Yukawa measurement via $e^+e^- \rightarrow H$ direct production
  - Foundation for all model-independent Higgs coupling measurements
  - Complimentary measurements (self-coupling, rare decays) accessible at FCC-hh

Backups

Detector concepts

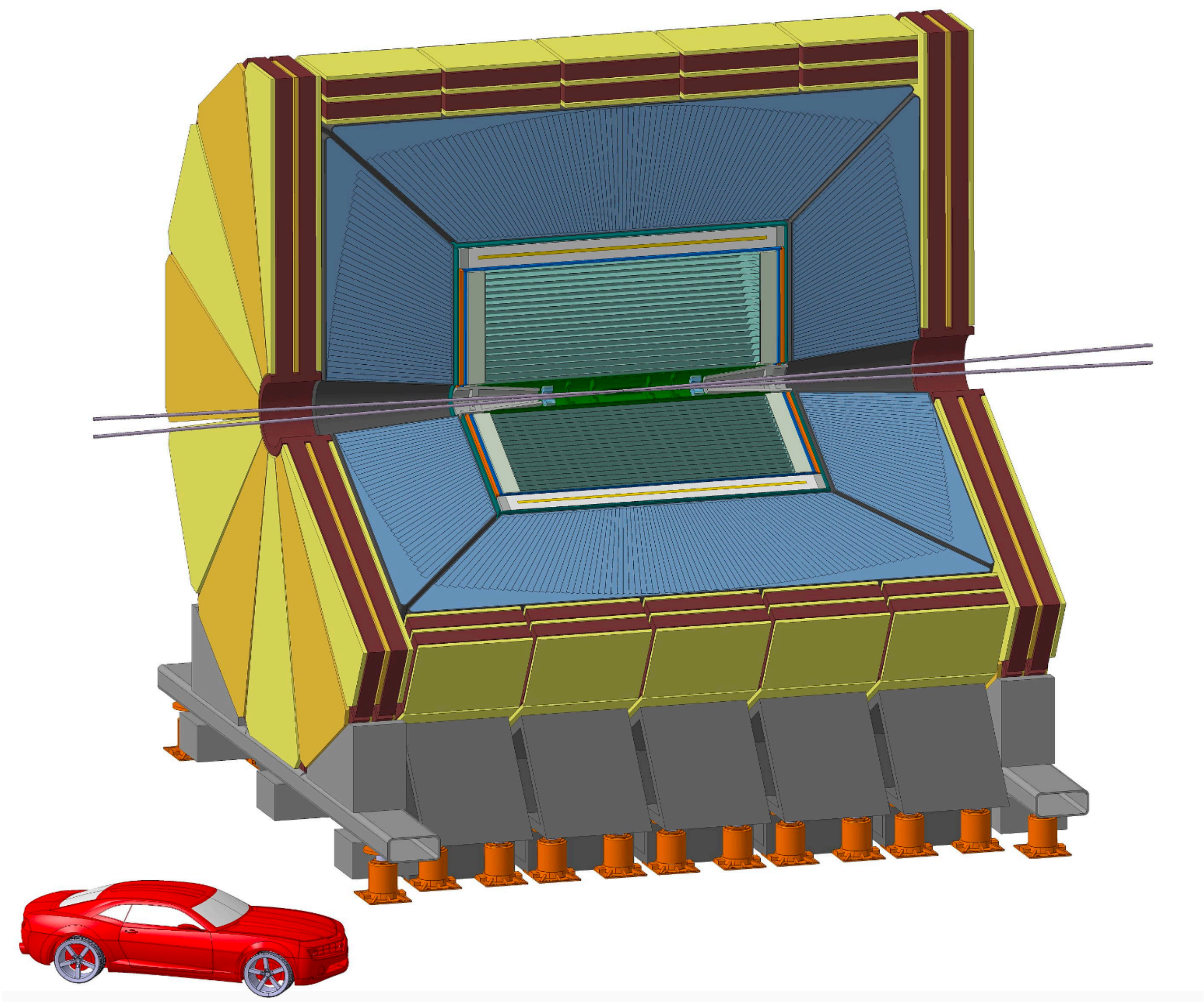
CLD (CLIC-like detector)

- Full silicon vertex detector and tracker
- High granularity silicon-tungsten ECAL + scintillator-steel HCAL
- Solenoid outside of calorimeter



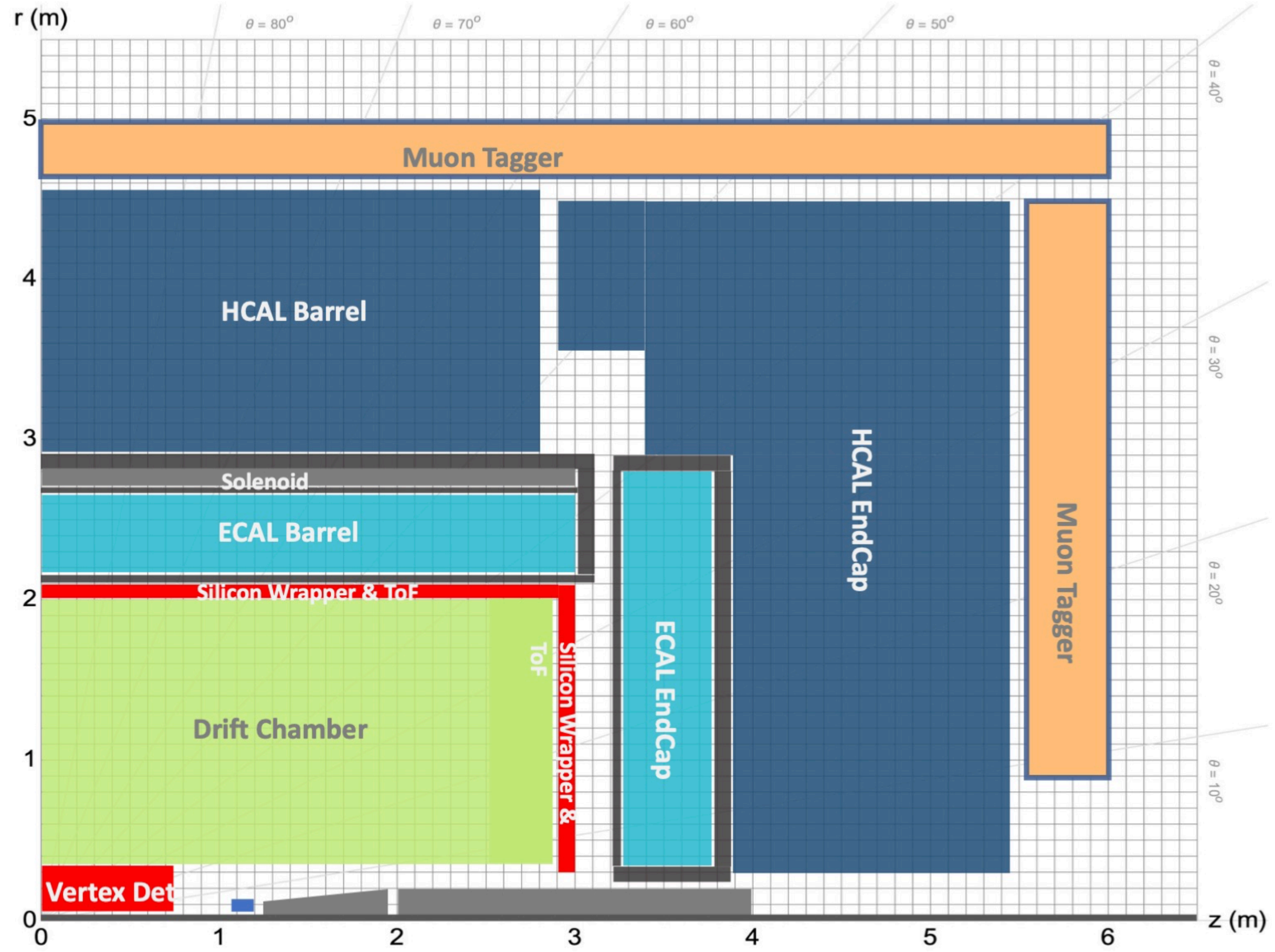
IDEA (Innovative detector for an electron-positron accelerator)

- Silicon vertex detector
- Low mass drift chamber
- Thin solenoid inside of duel-readout calorimeter (Cherenkov and scintillator)



ALLEGRO (A Lepton-Lepton collider Experiment with Granular Read-Out)

- Silicon vertex detector + silicon or gaseous tracker
- Noble liquid + Pb/W ECAL
- Solenoid between ECAL and HCAL



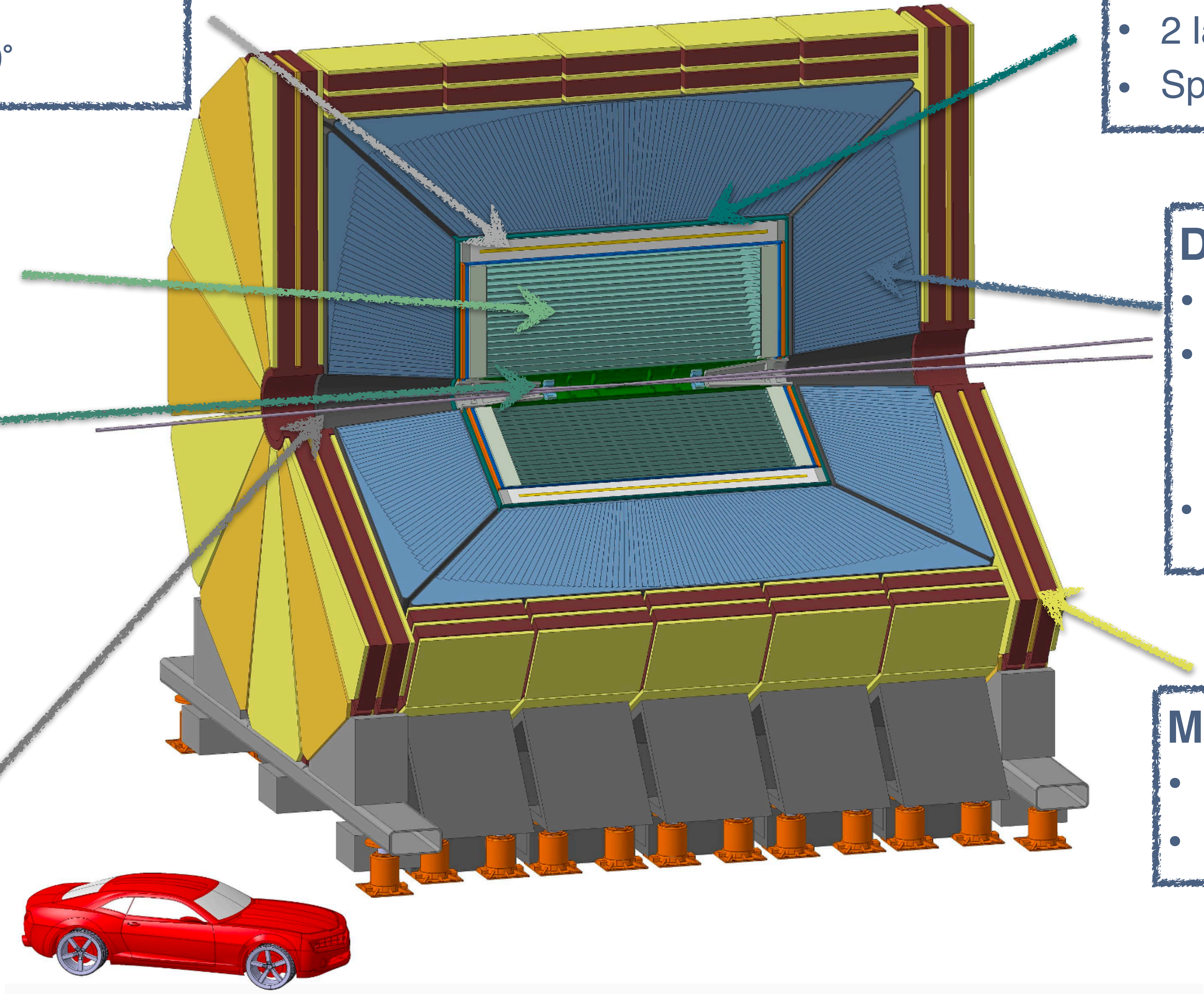
IDEA detector

Superconducting solenoid
- 2 T, R = 2.0 - 2.4 m
- $0.74\ X_0,\ 0.16\ \lambda\ @90^{\circ}$

Wire drift chamber
- 112 layers, R = 35 - 200 cm
- $0.016\ X_0 @90^{\circ}$

Silicon vertex detector
- 5 layers, R = 1.7 - 34 cm
- Pixel $20 \times 20\ \mu\mathrm{m}^2$

Beam pipe
- R ~ 1.5 cm



Preshower
- 2 layers, gas detector
- Spatial reso < 100 μm

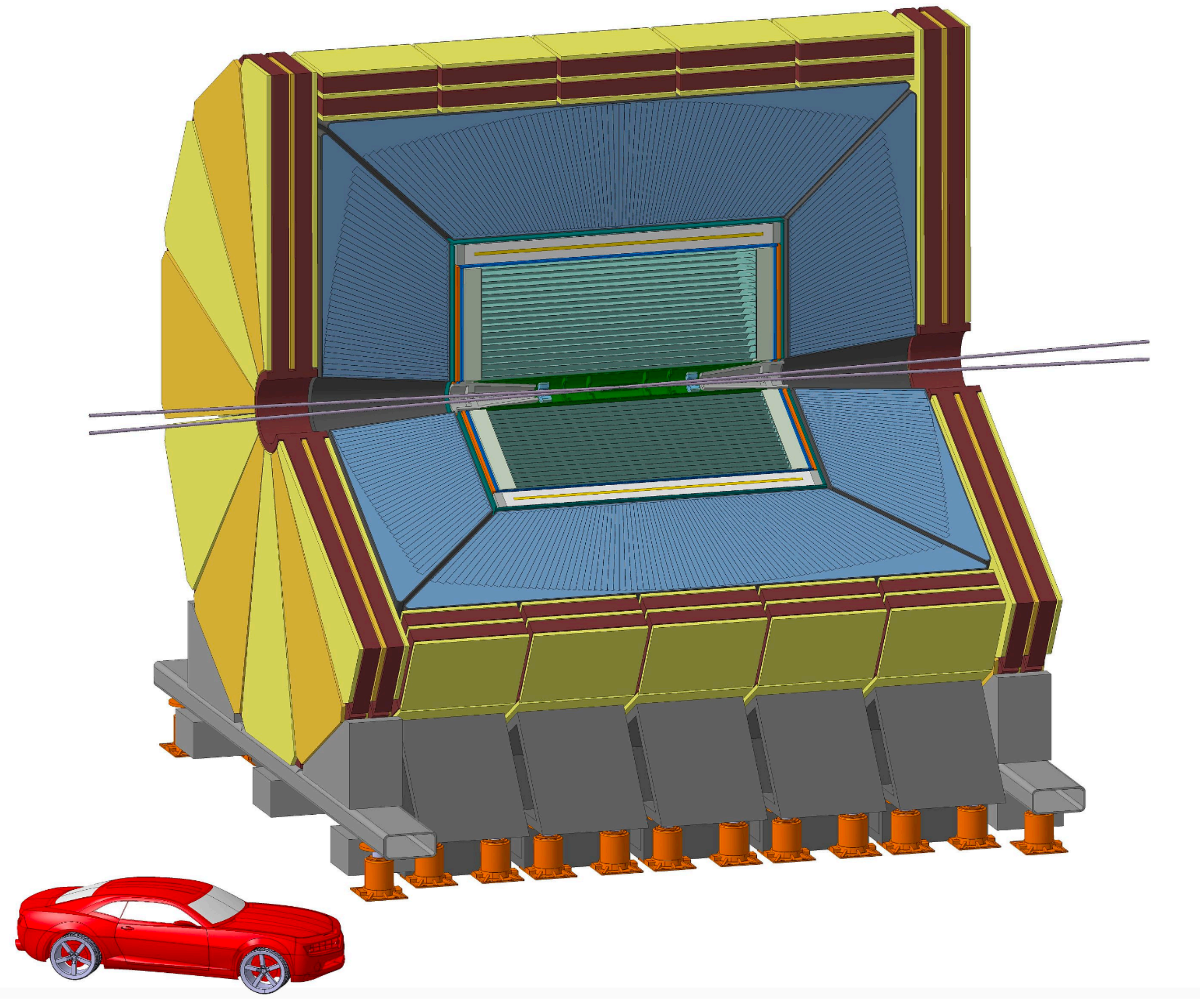
Dual-readout calorimeter
- 2 m capillaries
- Alternate Cherenkov and scintillation fibers
- $\sigma_{EM} \approx \frac{10\,\%}{\sqrt{E}}$, $\sigma_{had} \approx \frac{30\,\%}{\sqrt{E}}$

Muon chambers
- 3 layers, gas detector
- Spatial reso < 400 μm

Analysis framework

Abundant centrally-produced simulation

- Generators: Pythia 8, Whizard + Pythia 6
- Simulation: Delphes fastsim based on IDEA concept
- 400+ MC samples, a few billion events (more than expected data)



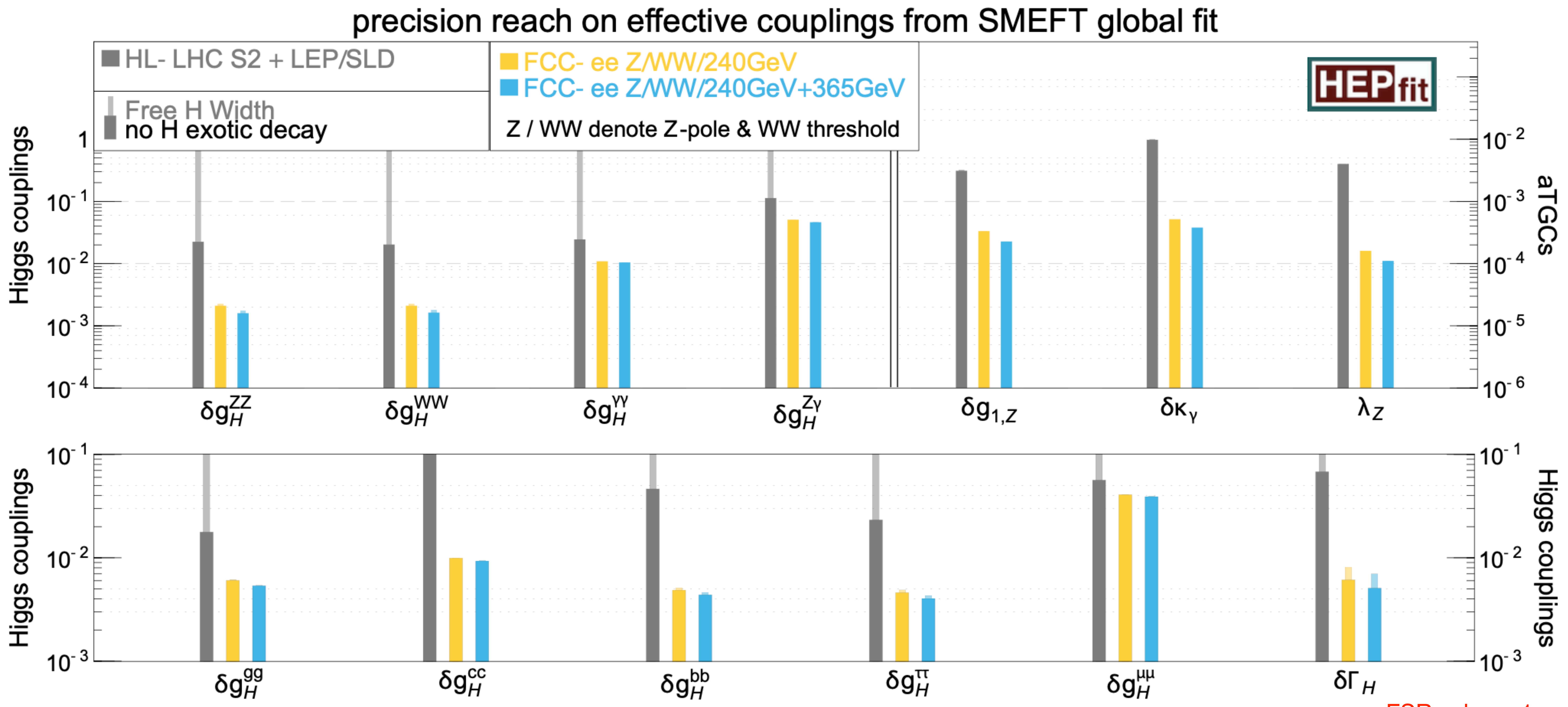
Common analysis tools

- RDataFrame-based common workflow
- Jet reconstruction: FastJet, exclusive Durham kT algorithm for most cases
- Flavor tagging: Particle Net, considering properties of all constituents (full track info, dN/dx, mTOF)
- Statistical analysis: CMS combine tool

Dedicated analyses to cover all Higgs properties

- ~ 20 dedicated analysis notes
- Centrally coordinated and reviewed

Higgs SMEFT fit



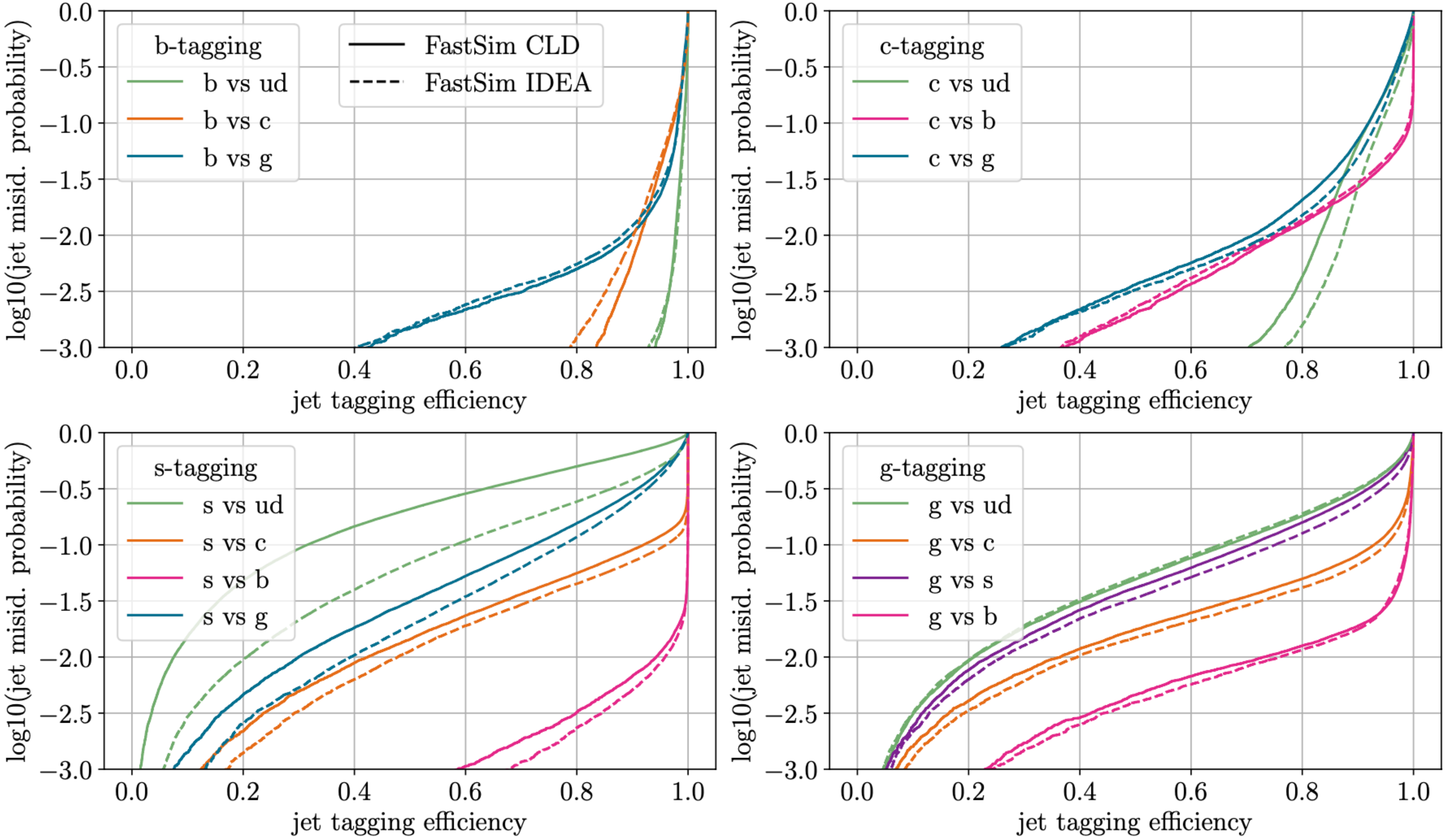
FSR volume 1

kappa fit

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

FSR volume 1

tagging performance



FCC Note: jet tagging performance

Higgs mass and detector variation

Nominal configuration → Nominal

Crystal ECAL to Dual Readout → Degradation electron resolution

Nominal 2 T → field 3 T → Magnetic field 3T

IDEA drift chamber → Si tracker → Silicon tracker

Impact of Beam Energy Spread → BES 6% uncertainty / Disable BES

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

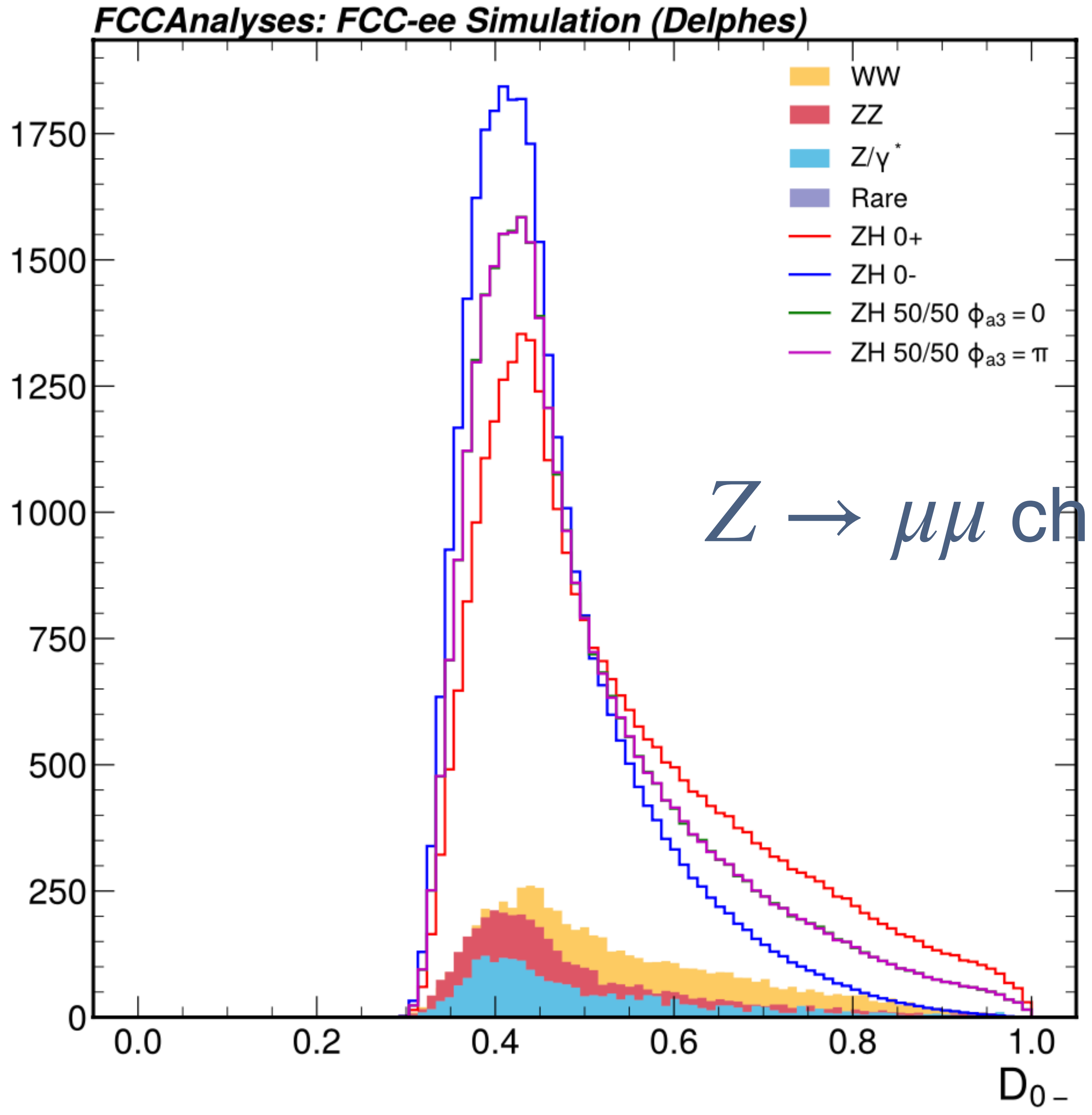
stats (stats+syst)

Final state	Muon	Electron	Combination
Nominal	3.92(4.74)	4.95(5.68)	3.07(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)

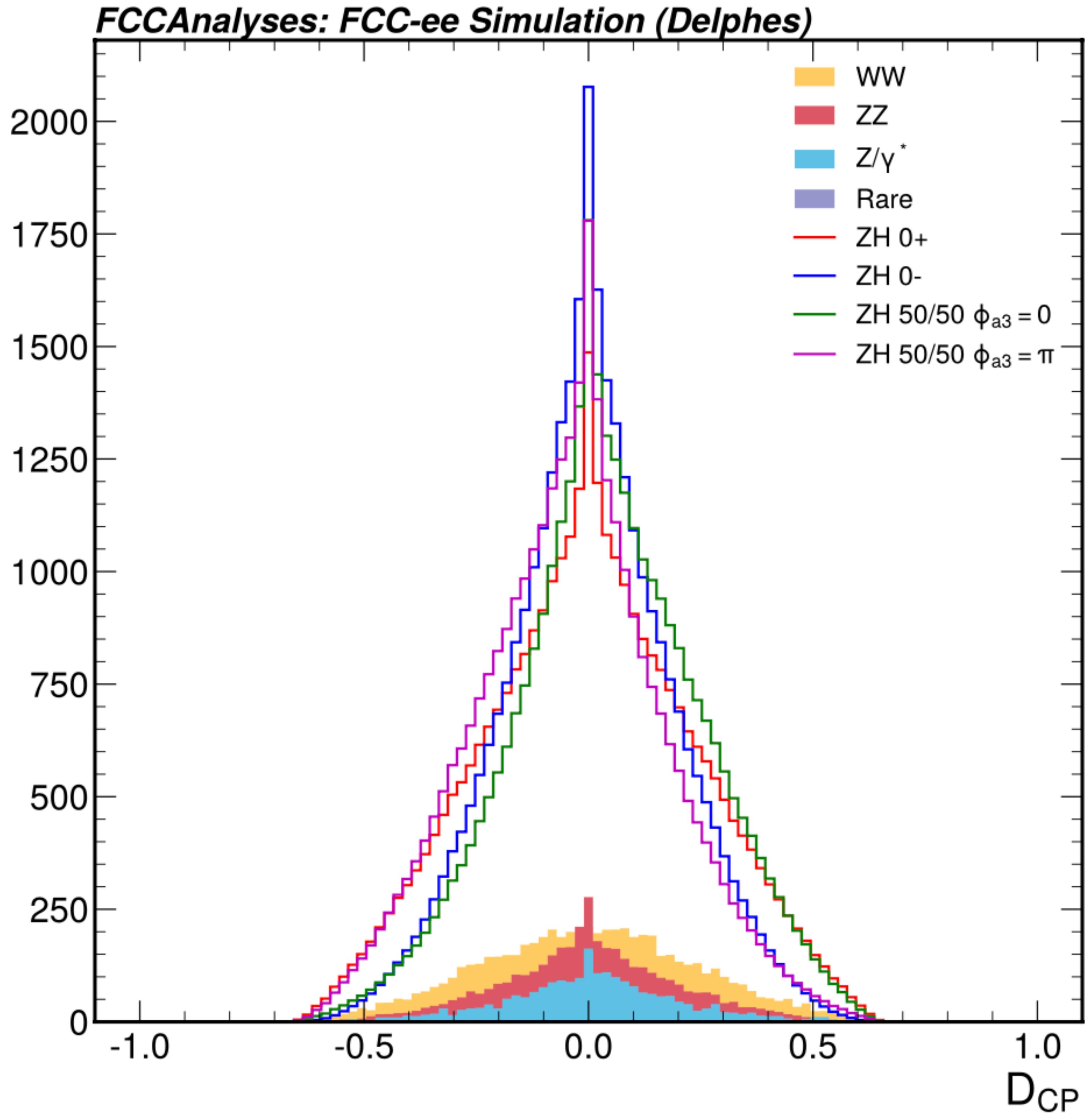
CP optimal observables

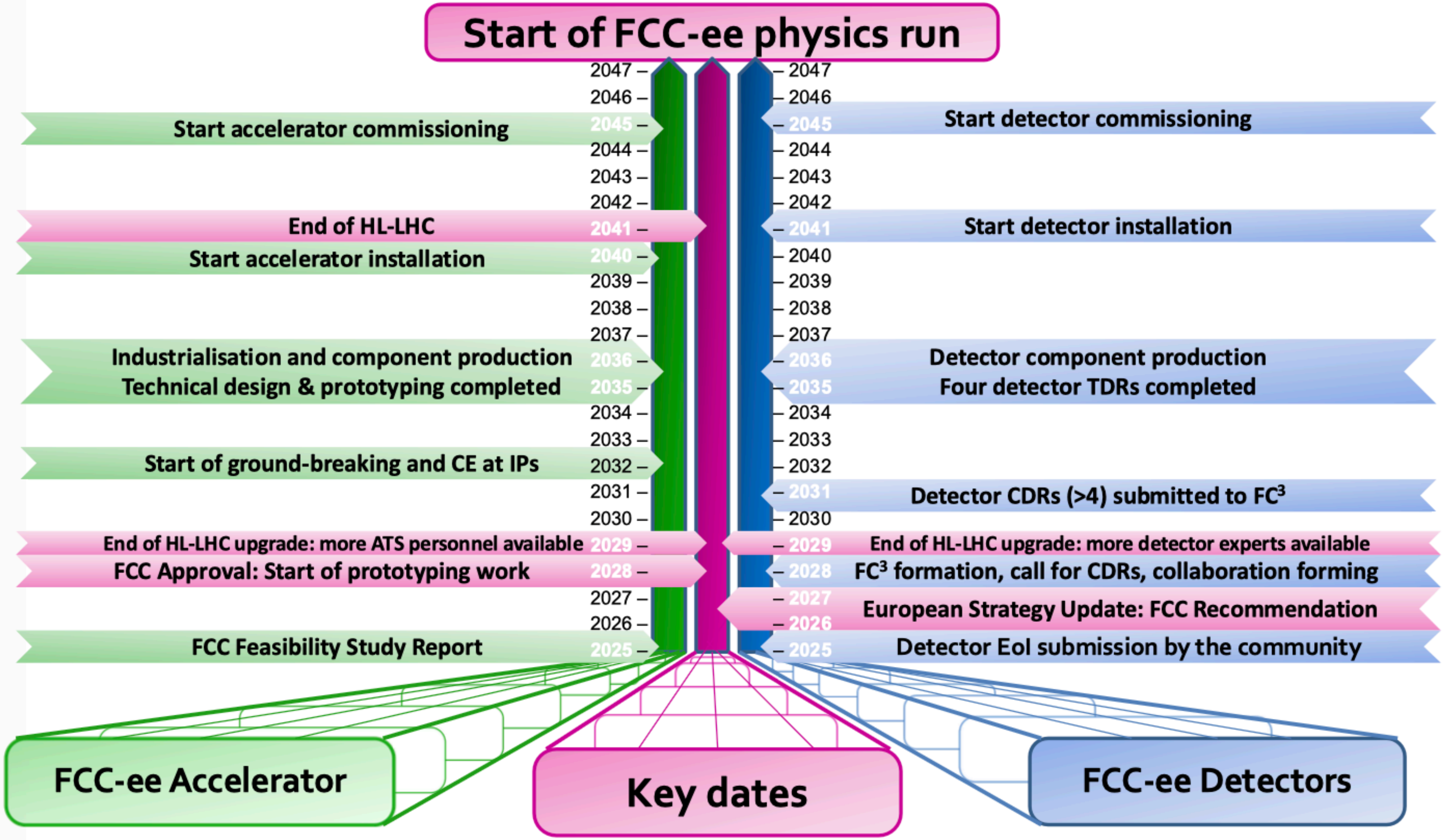
- $\mathscr{D}_{0-}$ sensitive to CP-odd amplitude
- $\mathscr{D}_{CP}$ sensitive to even-odd interference

FCC note: Higgs CP



$Z \rightarrow \mu\mu$ channel




Start of FCC-ee physics run
Start accelerator commissioning
Start detector commissioning
End of HL-LHC
Start accelerator installation
Start detector installation
Industrialisation and component production
Technical design & prototyping completed
Detector component production
Four detector TDRs completed
Start of ground-breaking and CE at IPs
Detector CDRs (>4) submitted to FC³
End of HL-LHC upgrade: more ATS personnel available
End of HL-LHC upgrade: more detector experts available
FCC Approval: Start of prototyping work
FC³ formation, call for CDRs, collaboration forming
European Strategy Update: FCC Recommendation
FCC Feasibility Study Report
Detector EoI submission by the community
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FCC-ee Accelerator
Key dates
FCC-ee Detectors

Rescaled LCF results (from ESPPU document) to match FCC-ee luminosity

- Additional scaling of √1.24 to remove effects due to beam polarization
  - ZH cross section increase with longitudinal polarisation: $1 - P^{-}P^{+} - A_e(P^{-} - P^{+})$
  - Results in 1.394 and 1.086 for LR and RL combination of 80% and 30% respectively with an average of 1.24

Comparison only valid with equal luminosity

- Running times are significantly different: 3y@10.8ab^{-1} for FCC-ee vs. 8y@2.7ab^{-1} for ILC/LCF

Collider	FCC CDR	FCC ESPPU	LCF ESPPU	LCF	LCF $\times\sqrt{1.2}$
Integrated luminosity	10.8 ab^{-1}	10.8 ab^{-1}	2.7 ab^{-1}	10.8 ab^{-1}	10.8 ab^{-1}
$H \to$ any	±0.36	±0.31	±0.62	±0.31	±0.34
$H \to bb$	±0.20	±0.21	±0.41	±0.21	±0.22
$H \to cc$	±1.5	±1.6	±2.5	±1.25	±1.37
$H \to gg$	±1.3	±0.8	±2.1	±1.05	±1.15
$H \to W^+W^-$	±0.8	±0.8	±1.4	±0.70	±0.77
$H \to ZZ$	±3.0	±2.5	±5.5	±2.75	±3.01
$H \to \tau^+\tau^-$	±0.6	±0.58	±0.95	±0.48	±0.52
$H \to \gamma\gamma$	±6.1	±3.6	±10	±5.00	±5.48