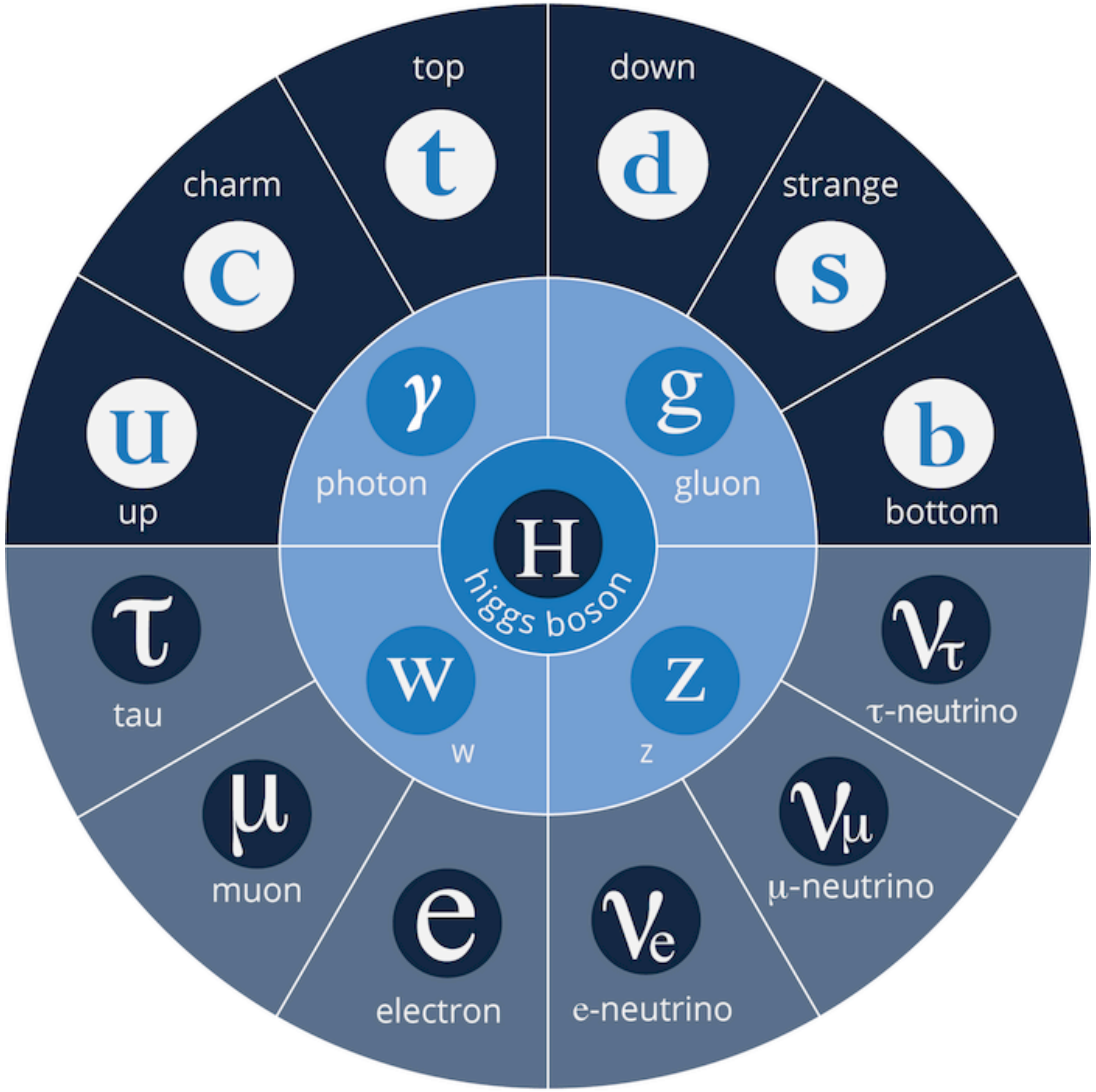
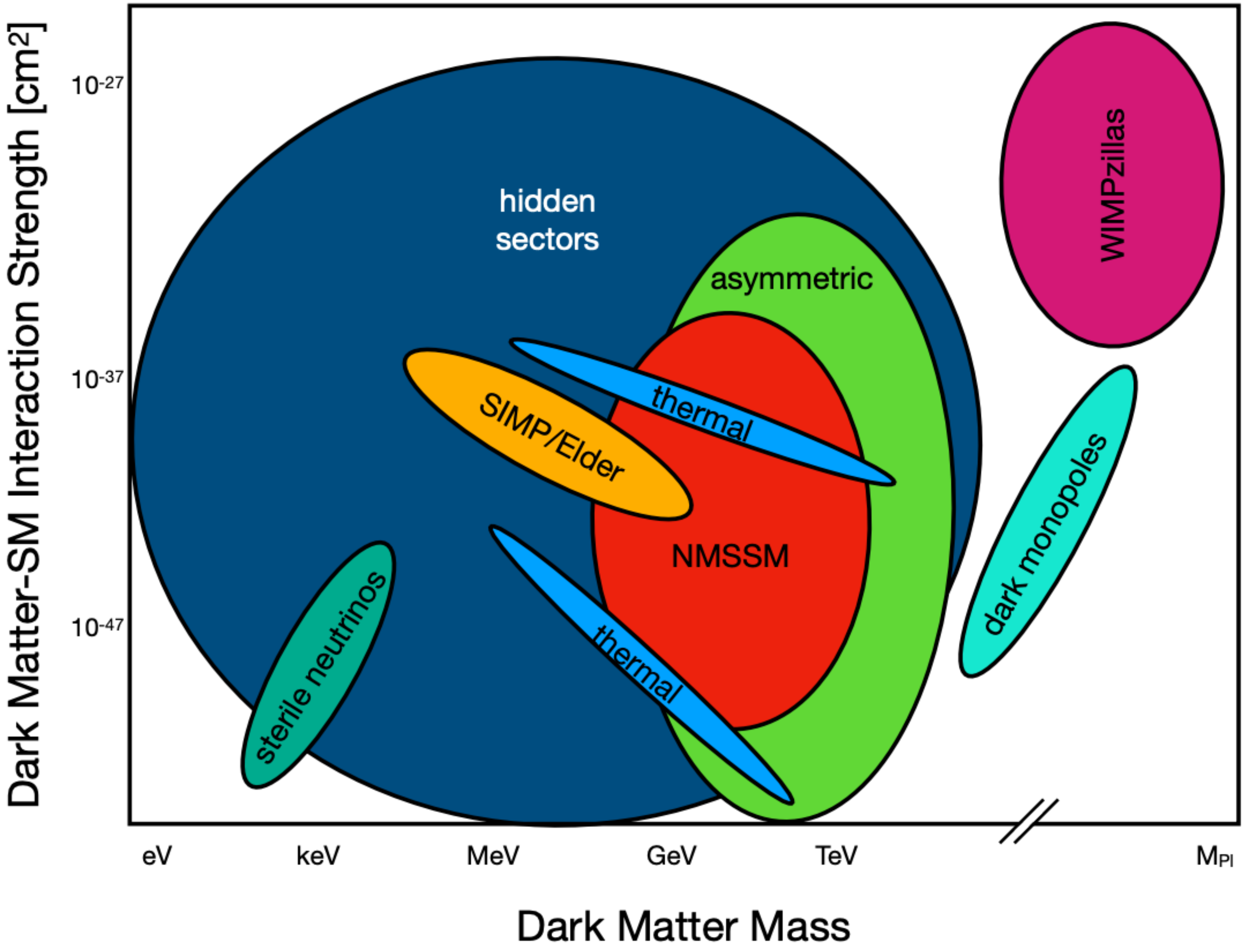
Physics Potential at Future Circular Colliders

Alexander von Humboldt-Professor Dr. Markus KLUTE (markus.klute@kit.edu)
Institute of Experimental Particle Physics (ETP)

Particle Physics Today

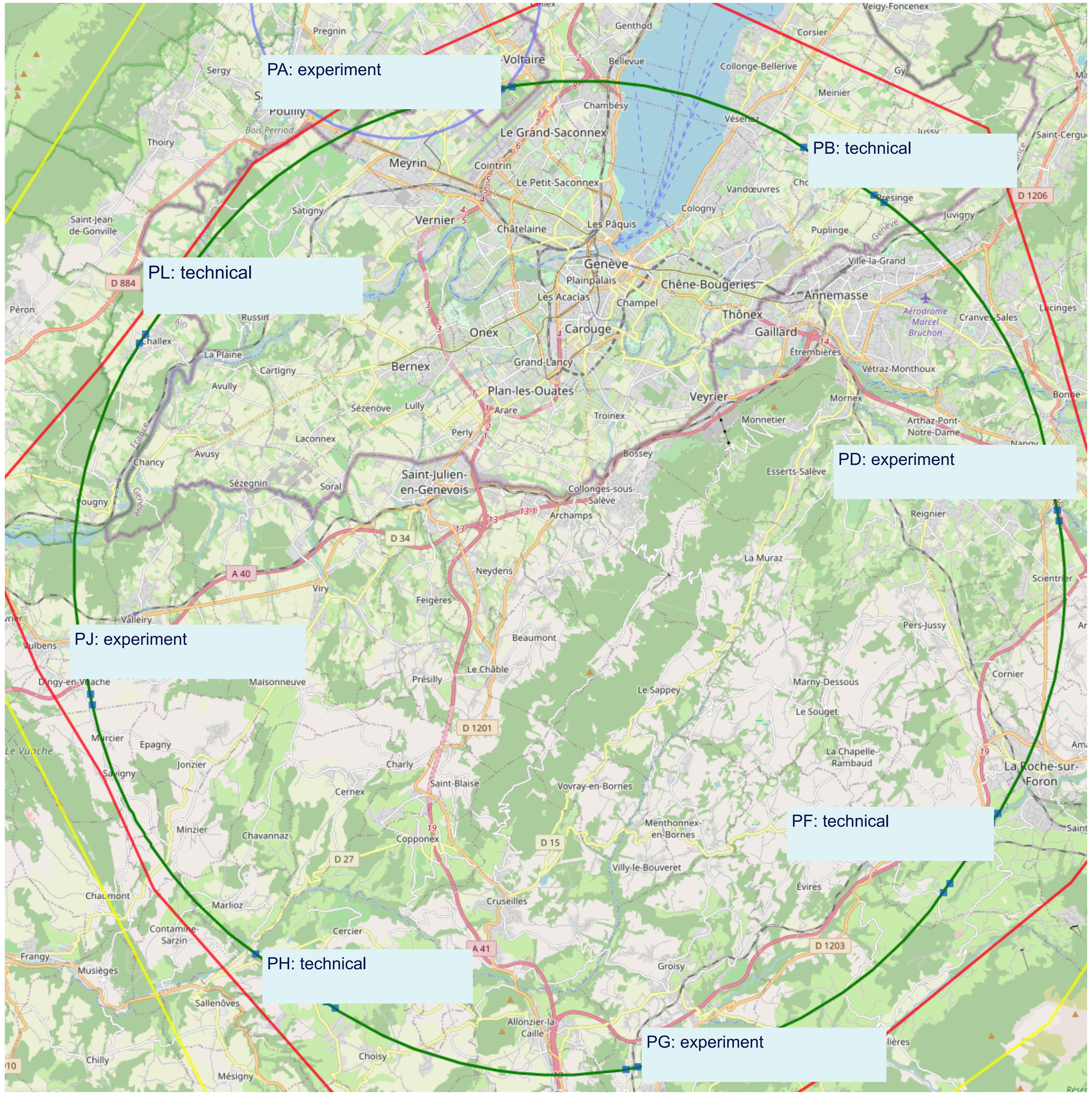


arXiv:2209.07426



Future Circular Collider

- CERN Plan-A beyond HL-LHC
- New infrastructure
  - 90.7km, 8 surface points
  - 4 experimental areas
  - Deepest shaft 400m
  - Average shaft depth 240m
- Recycling current accelerator chain
- Stage 1: **FCC-ee “Higgs Factory”**
- Stage 2: FCC-hh



Historic Timeline

First Look at the Physics Case of TLEP

TLEP Design Study Working Group • M. Bicer (Ankara U.) Show All(128)

Aug 28, 2013

49 pages

Part of Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics: Snowmass on the Mississippi (CSS2013) : Minneapolis, MN, USA, July 29-August 6, 2013

Published in: *JHEP* 01 (2014) 164

Contribution to: CSS2013

Published: Jan 29, 2014

e-Print: 1308.6176 [hep-ex]

DOI: 10.1007/JHEP01(2014)164

View in: HAL Science Ouverte, ADS Abstract Service, CERN Document Server

pdf   links   cite   claim   reference search   695 citations

- 2012 Discovery of the Higgs boson at m_H = 125 GeV
- 2012-13 Papers on LEP3 and TLEP with case for a circular e^+e^- collider
- 2014-18 FCC Conceptual Design Study
- 2021-25 FCC Feasibility Study

European Strategy, Snowmass, P5

To stay at the forefront of particle physics, 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

European Strategy, Snowmass, P5

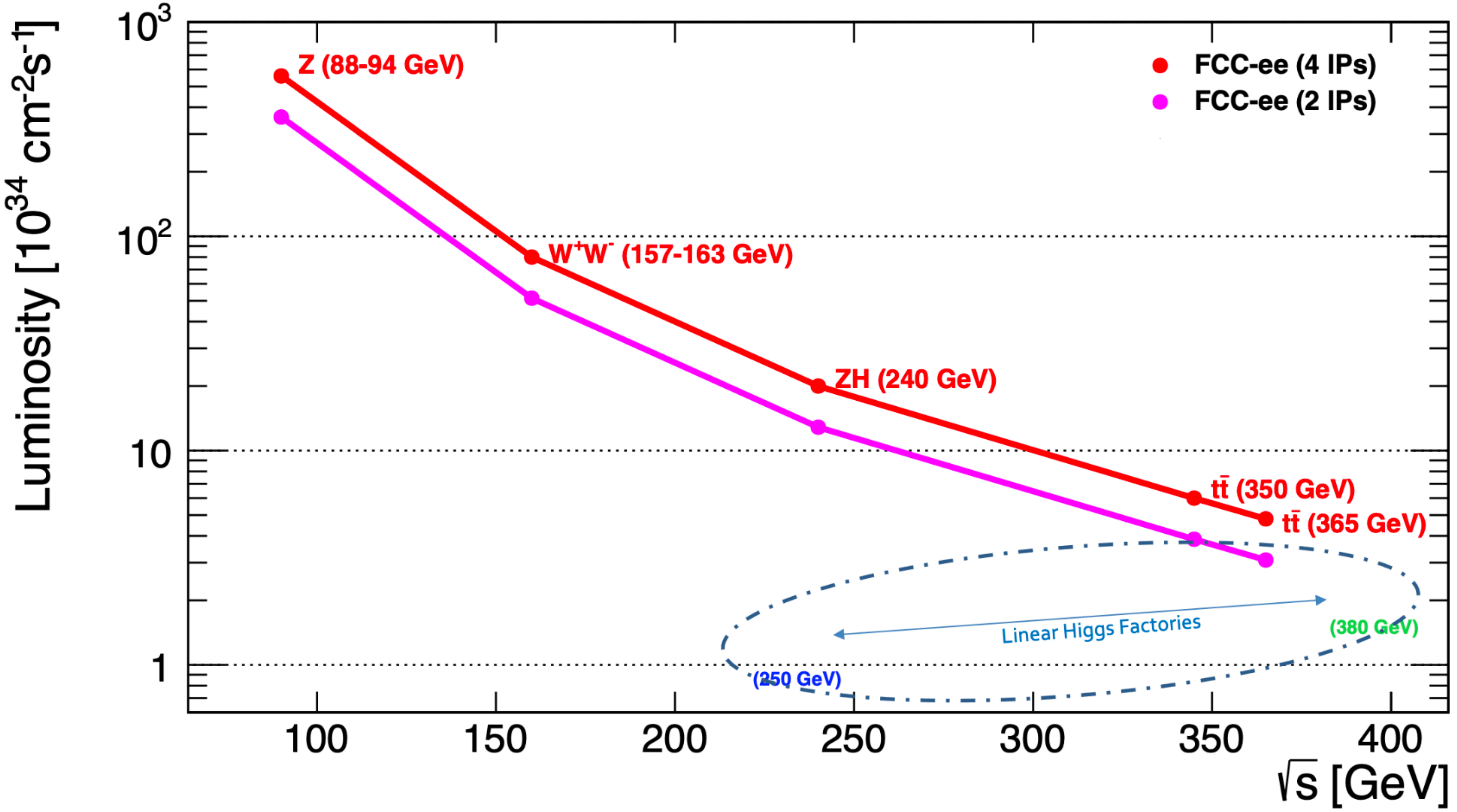
An **electron-positron Higgs factory is the highest-priority next collider.** For the longer term, the European particle physics community has the **ambition to operate a proton-proton collider** at the highest achievable energy.

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.

FCC Feasibility Study 2021-2025

- **Main deliverable**
  - Demonstration of geological, technical, environmental, and administrative feasibility of the tunnel and surface areas including optimisation of the layout
  - Prepare potential project approval
  - Elaborate operational model for the machine and experiments
  - Optimise the design of the colliders supported by R&D
  - Develop a consolidated cost estimate and identify resources
  - Consolidate the physics case, detector concept and technologies
- **Midterm review submitted end of 2023**
  - Executive summary (46 pages) and main document (702 pages)
  - No showstopper found

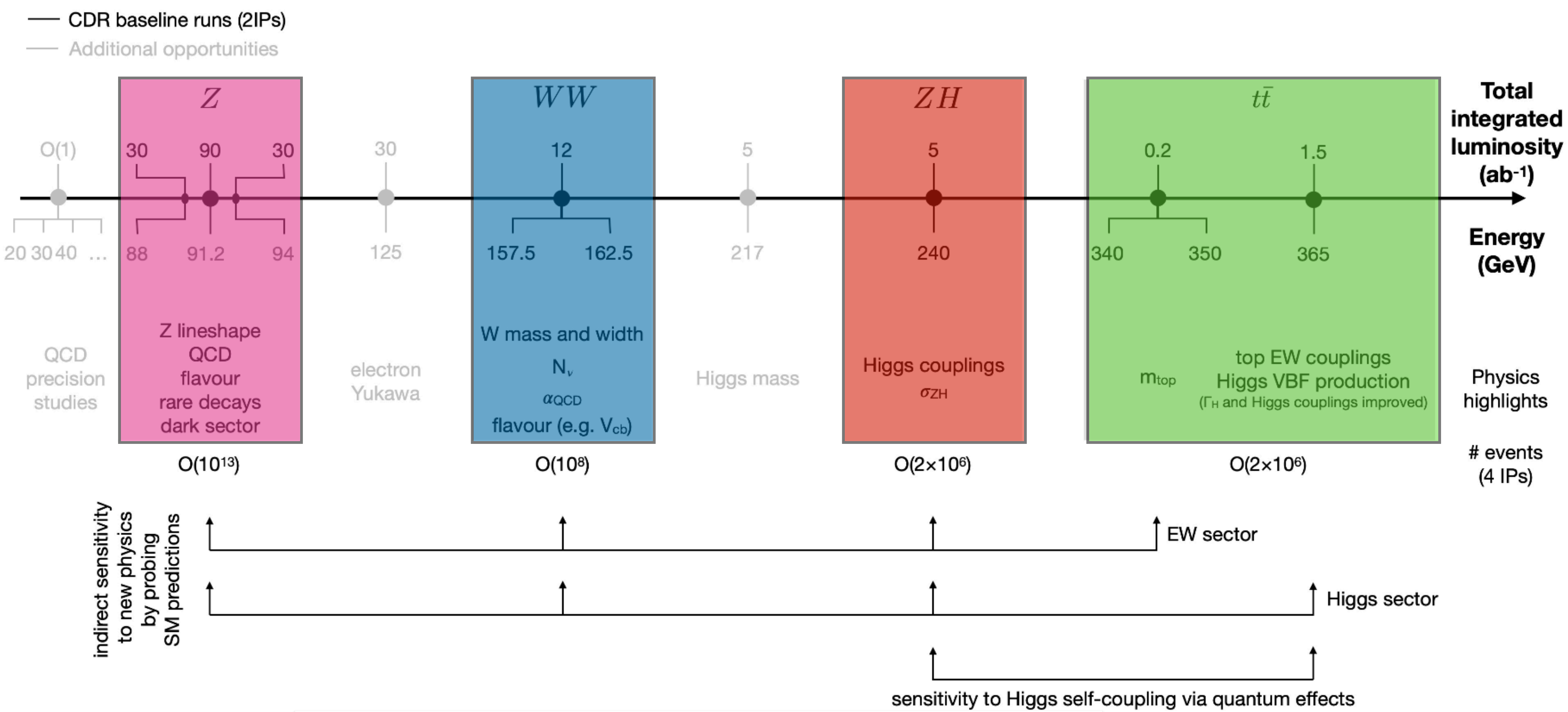
Baseline Design Luminosity



in each detector:

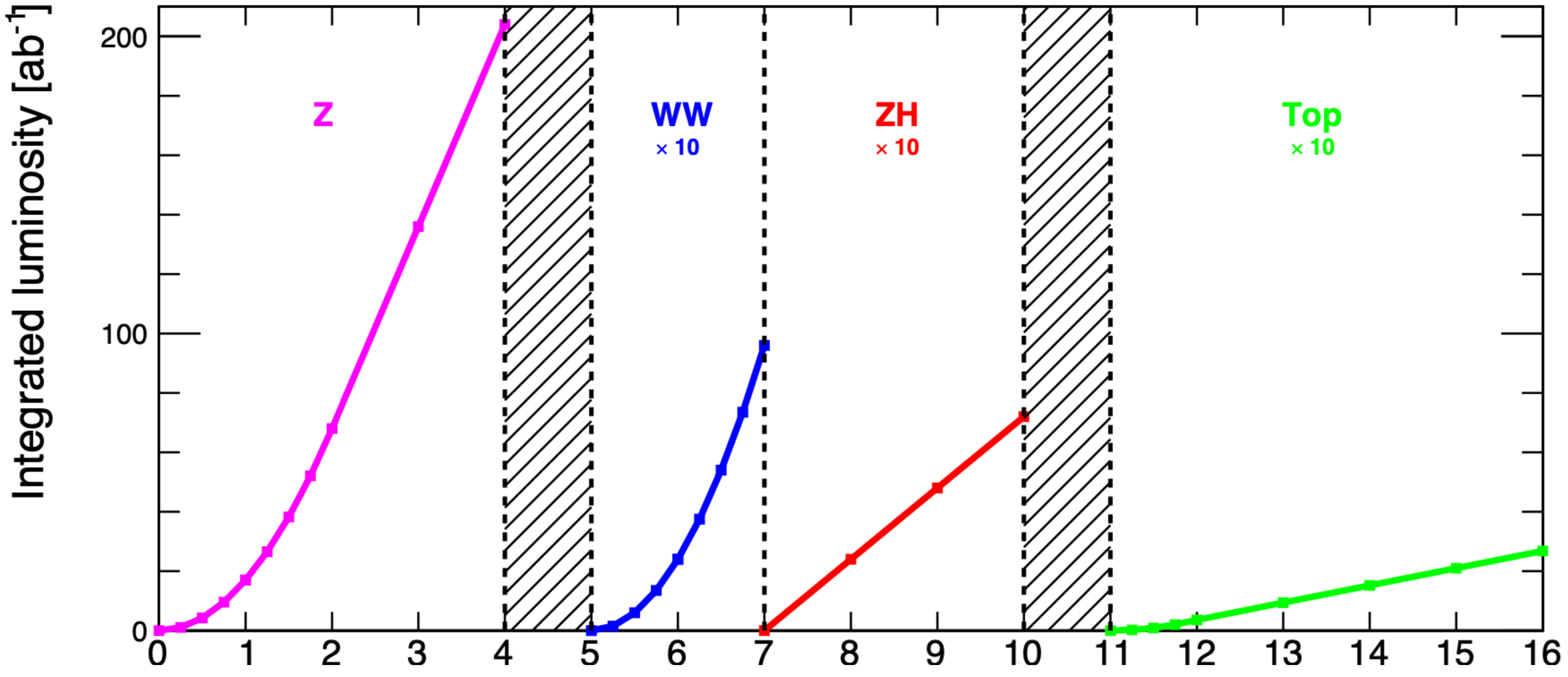
- 10^5 Z / sec
- 10^4 W pairs / hour
- 1500 H / day
- 1500 top pairs / day

FCC-ee Runs Ordered by Energy



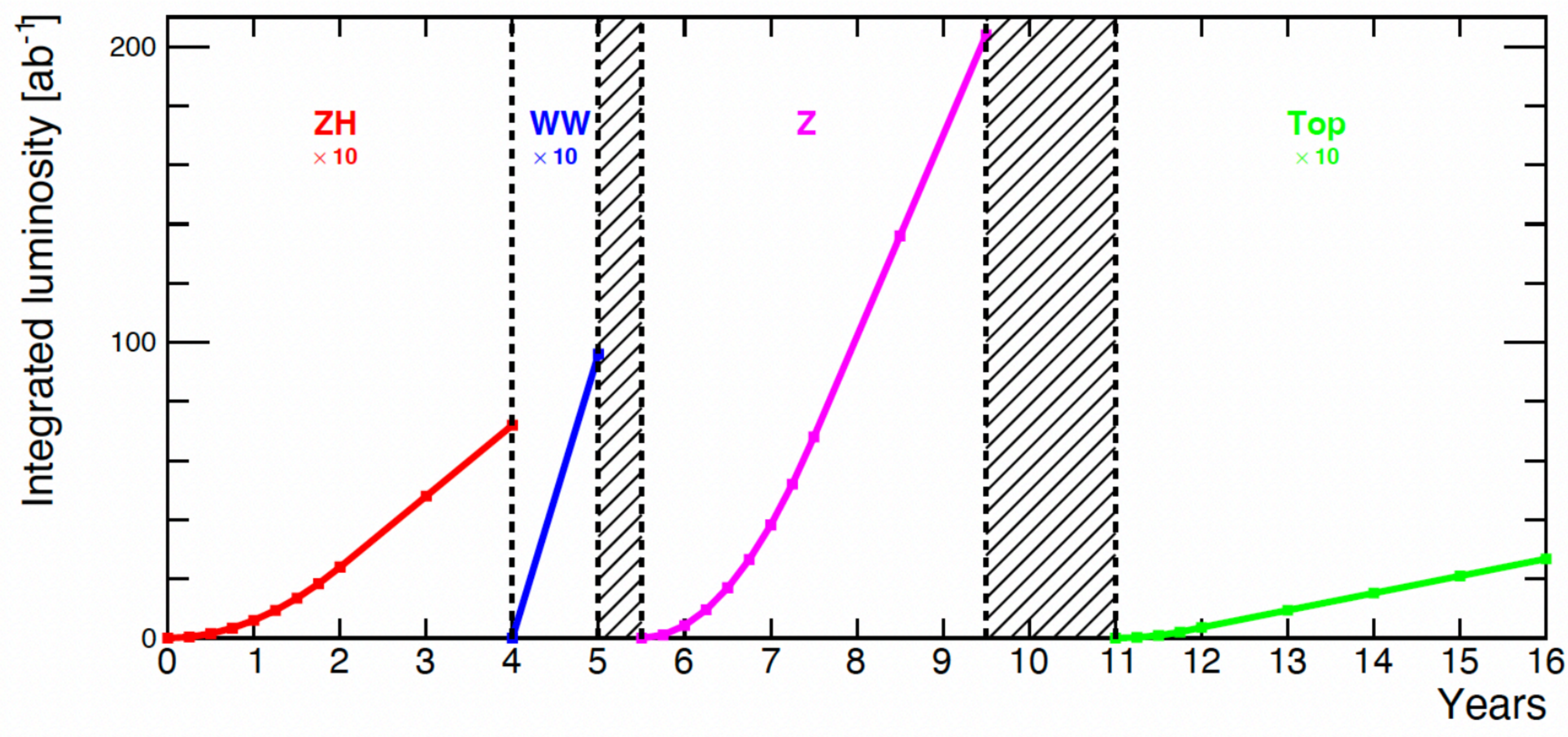
- **Opportunities** beyond the baseline plan (√s below Z, 125GeV, 217GeV; larger integrated lumi…)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
  - using the electrons from the injectors for beam-dump experiments,
  - extracting electron beams from the booster,
  - reusing the synchrotron radiation photons.

FCC-ee Runs Time Ordered

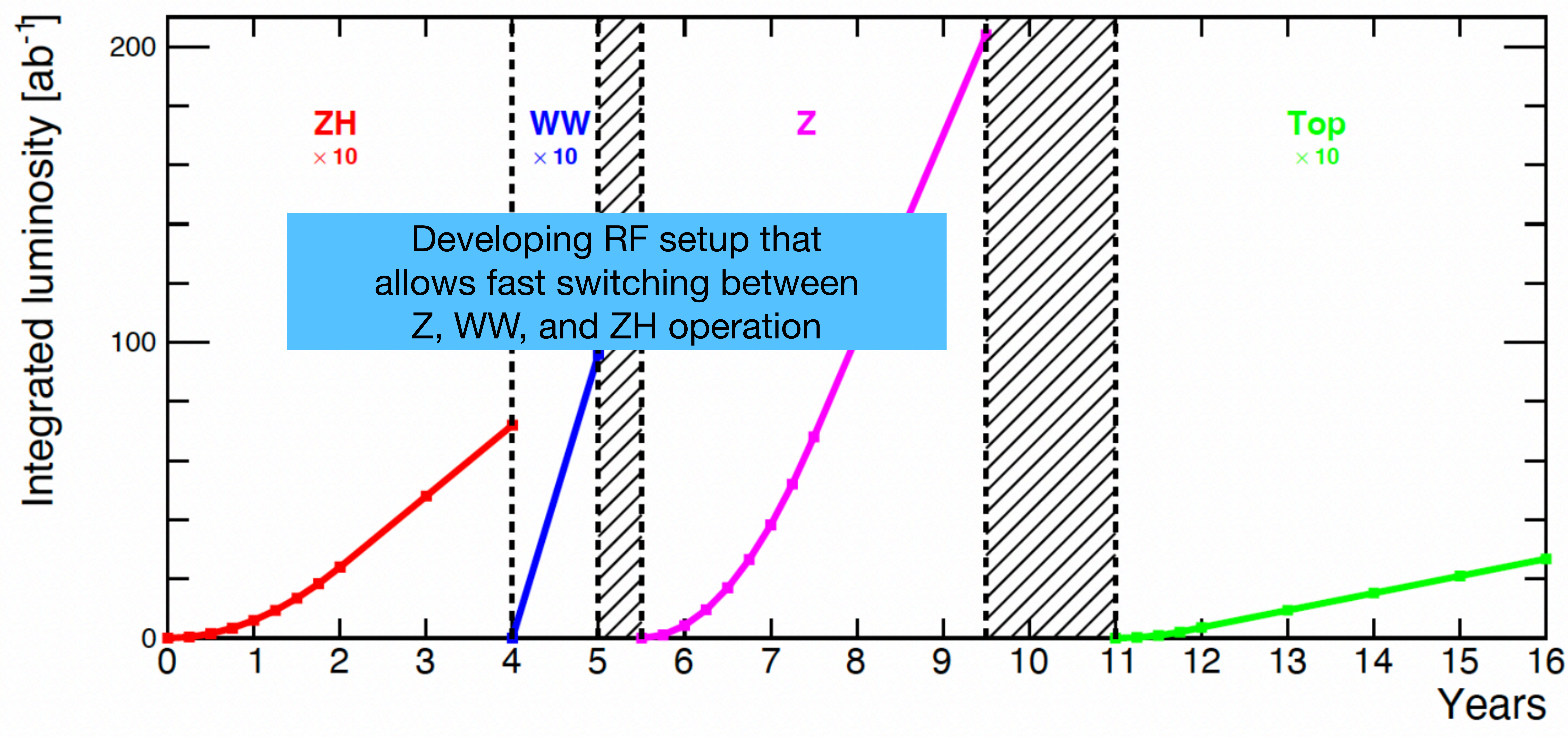


Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm^{-2}s^{-1}}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year ($\mathrm{ab^{-1}}$)	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events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

Operation Models

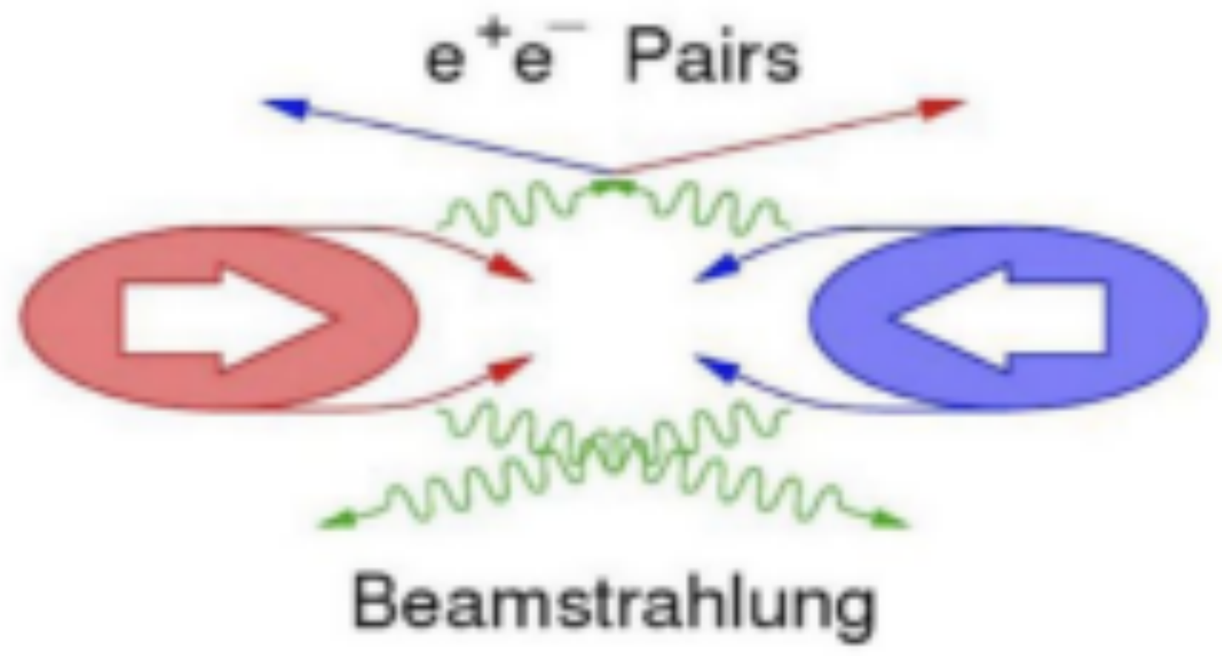


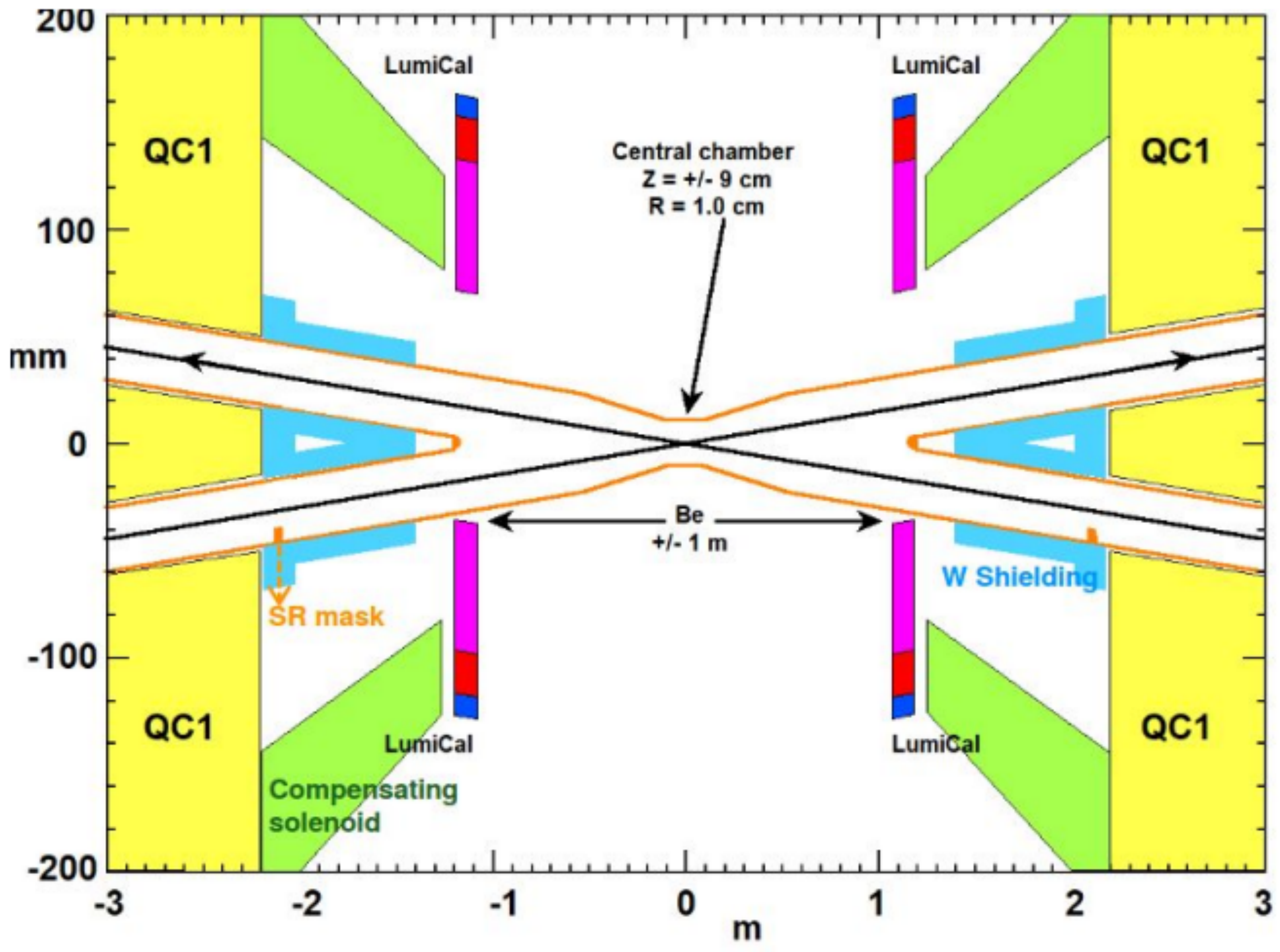
Operation Models



Detector Requirements

- Requirements for Higgs physics studied in detail by LC community
- Detector capable of dealing with energy and luminosity range
- Limitations imposed by Z pole run
  - ~33MHz collision rate
  - High occupancy for inner layers and forward region
  - Beamstrahlung
- Complex machine detector interface

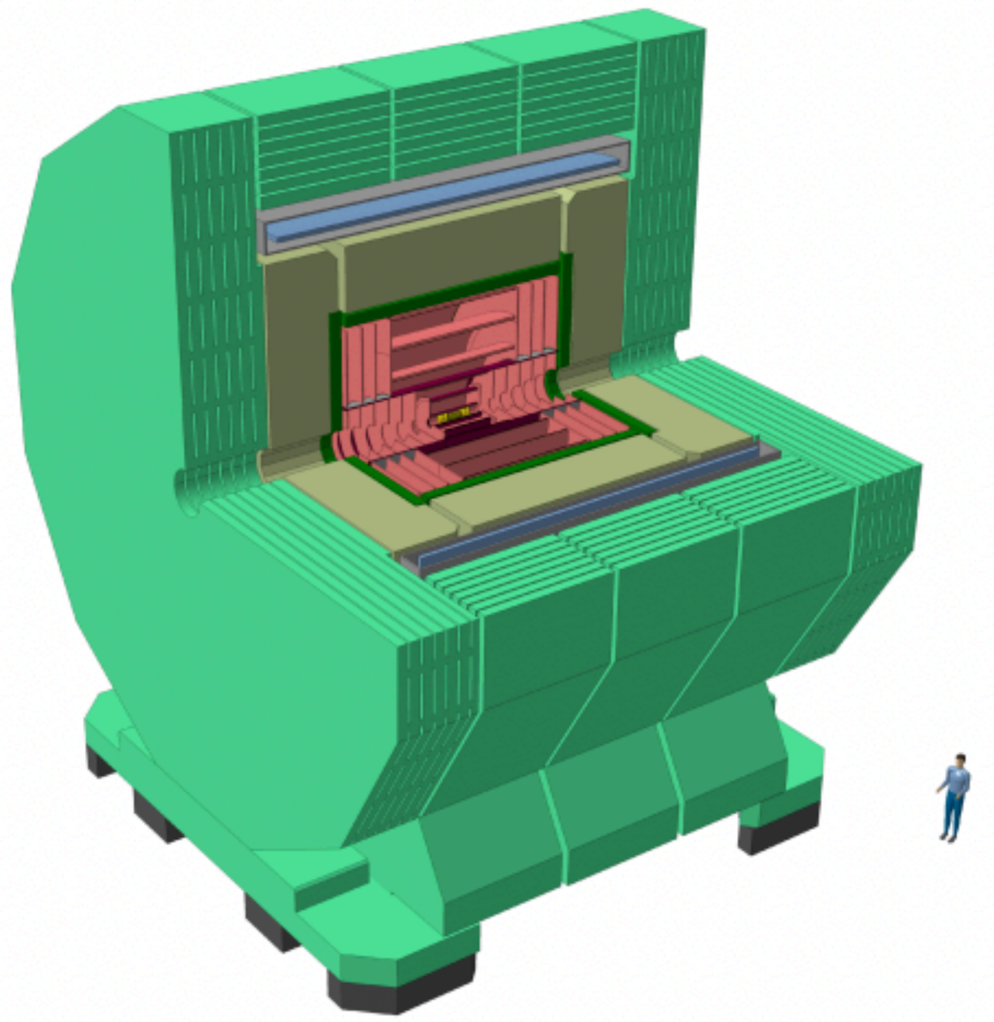




Detector Concepts

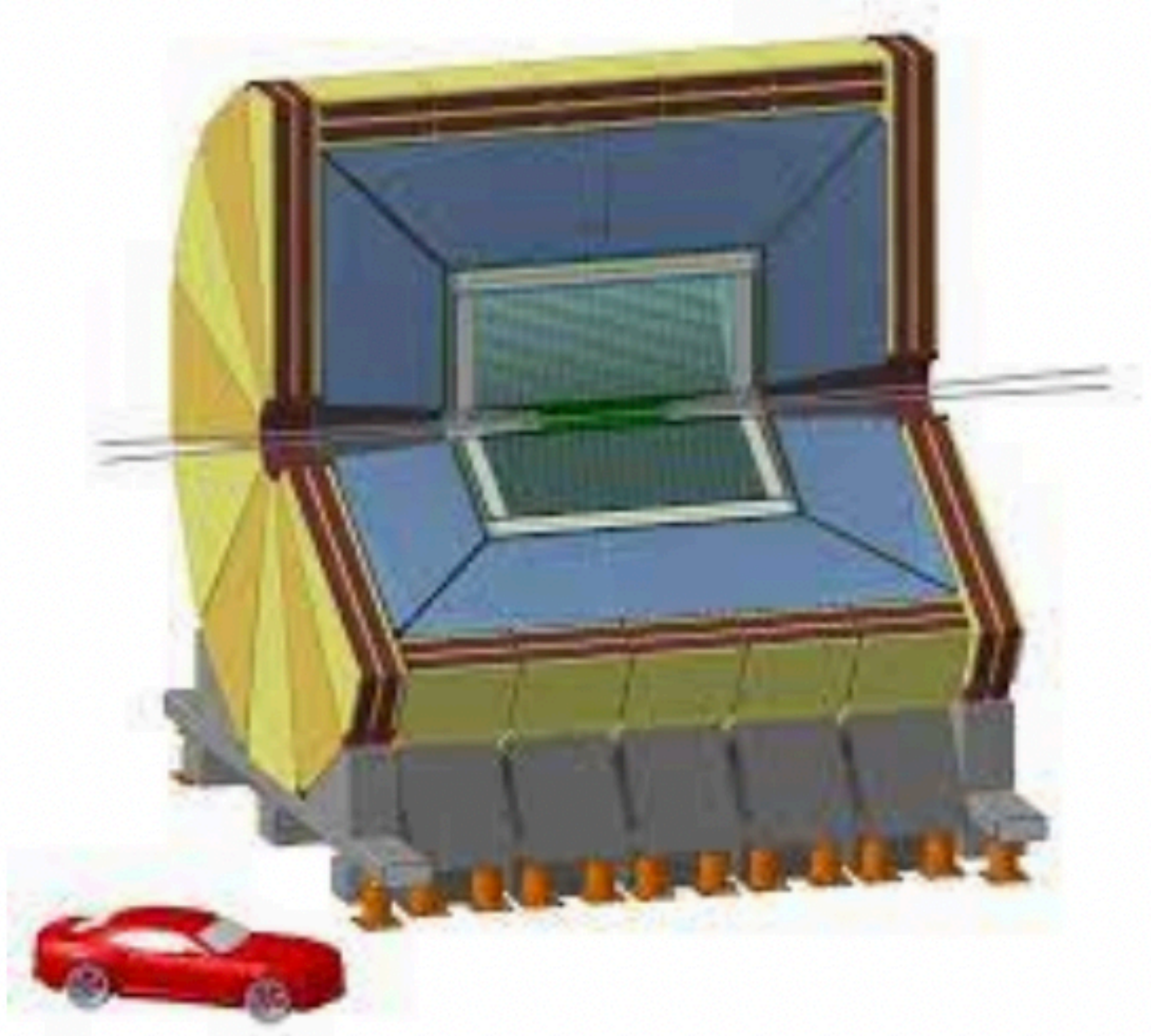
CLIC-like Detector (CLD)

- Full silicon vertex-detector + tracker
- 3D high-granularity calorimeter
- Solenoid outside calorimeter



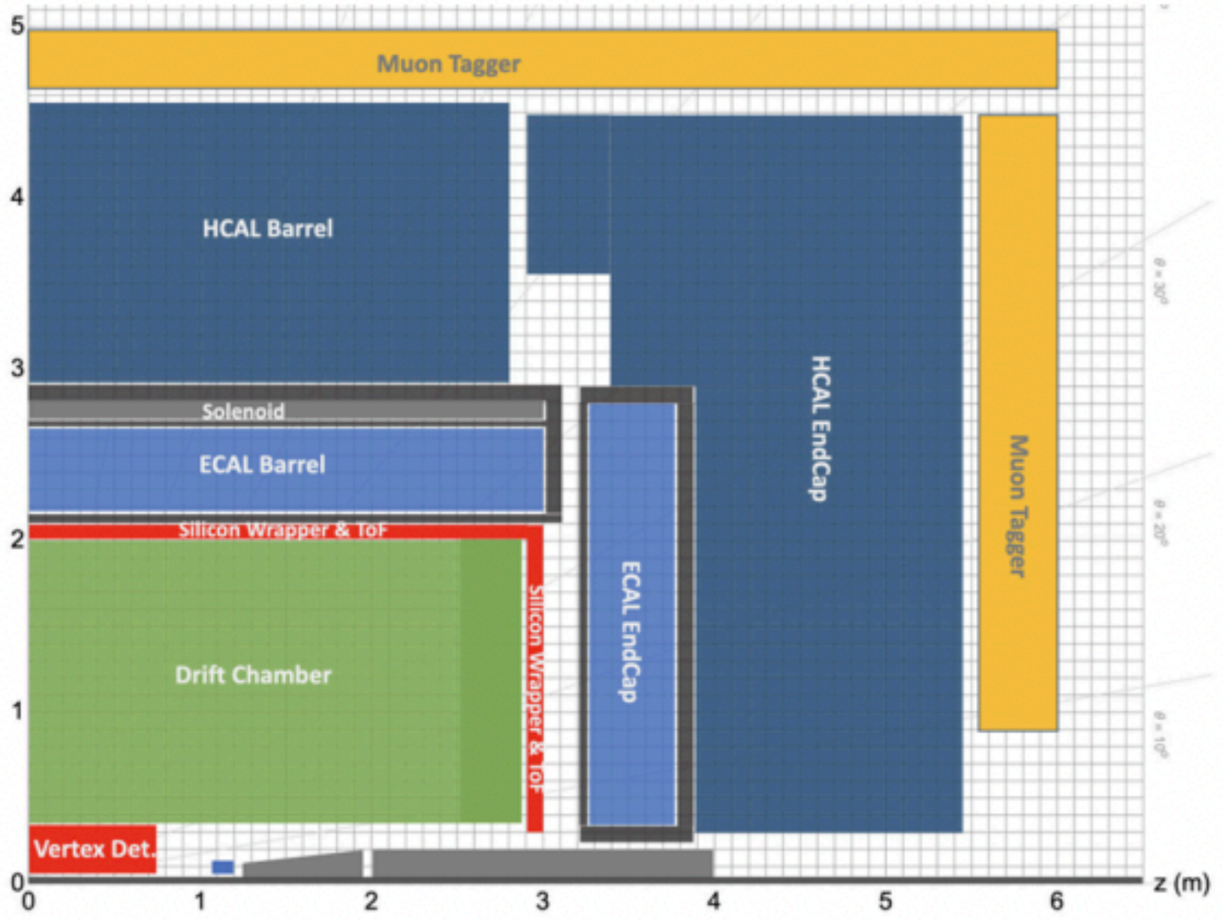
Innovative Detector for an Electron-Positron Accelerator (IDEA)

- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter (solenoid inside)



ALLEGRO

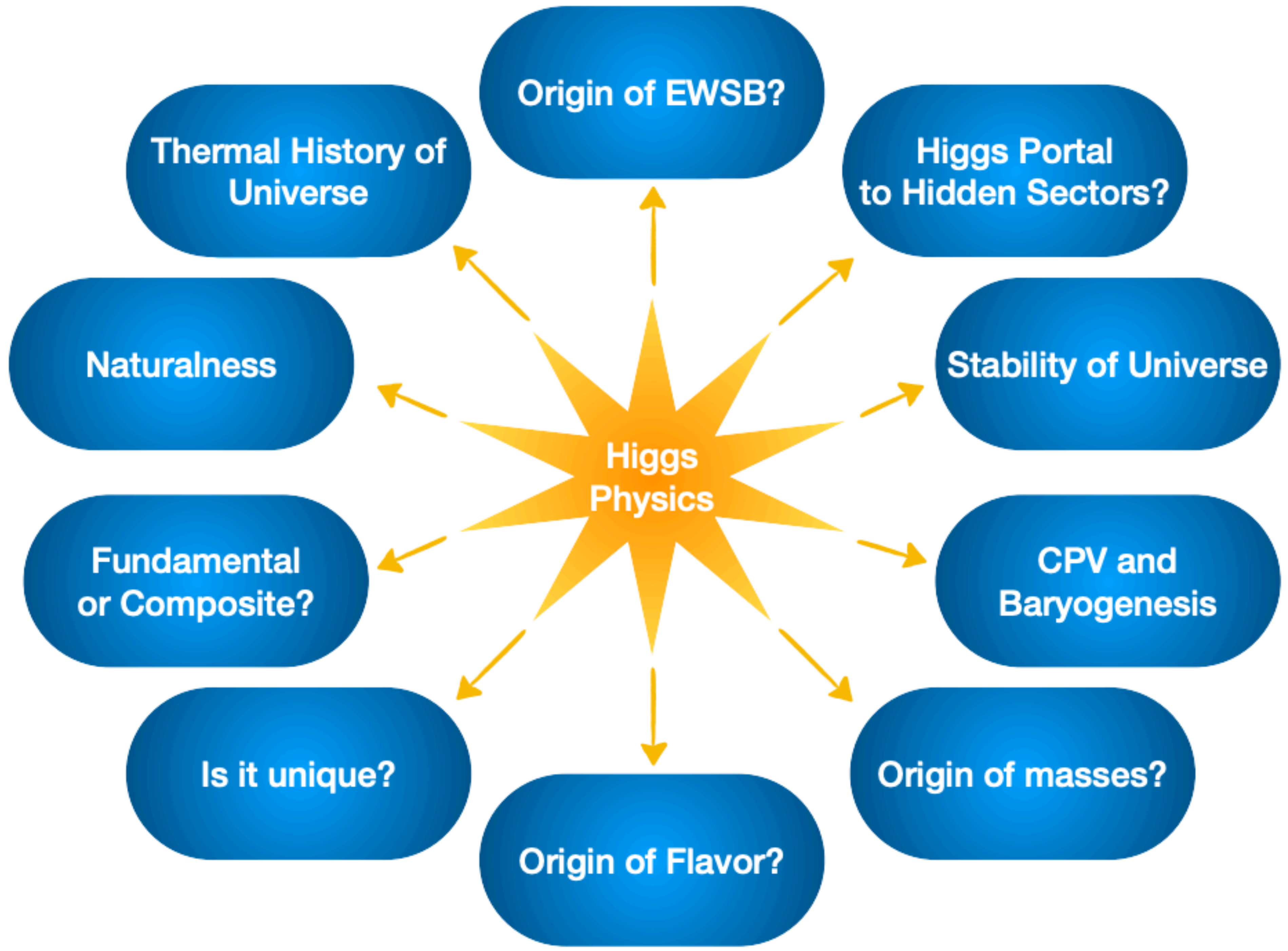
- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal



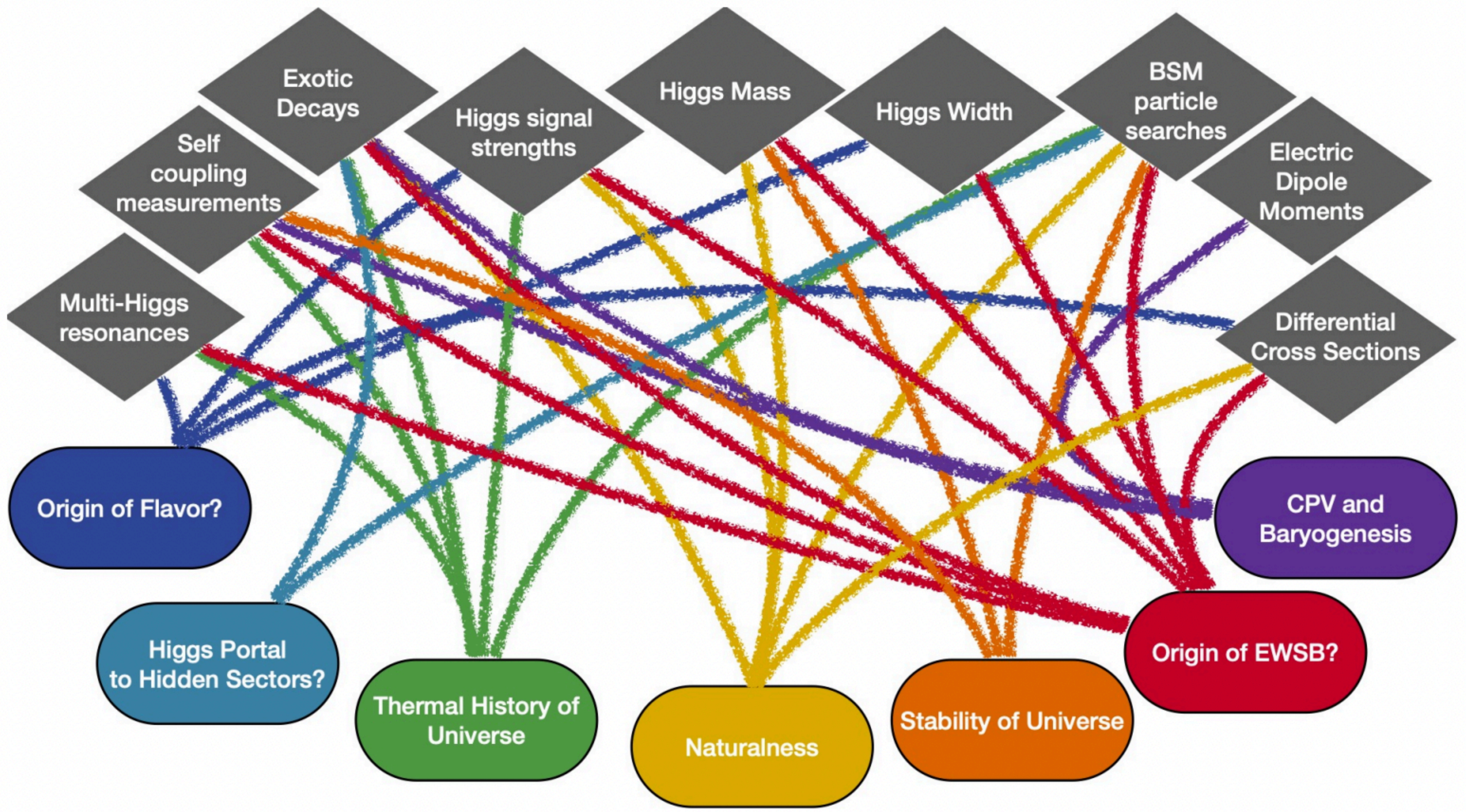
Ideas for specialised detectors

Physics Program: Higgs Physics

- Higgs connected to most relevant questions in HEP
- BSM scenarios introduce modifications of Higgs properties



arXiv:2209.07510

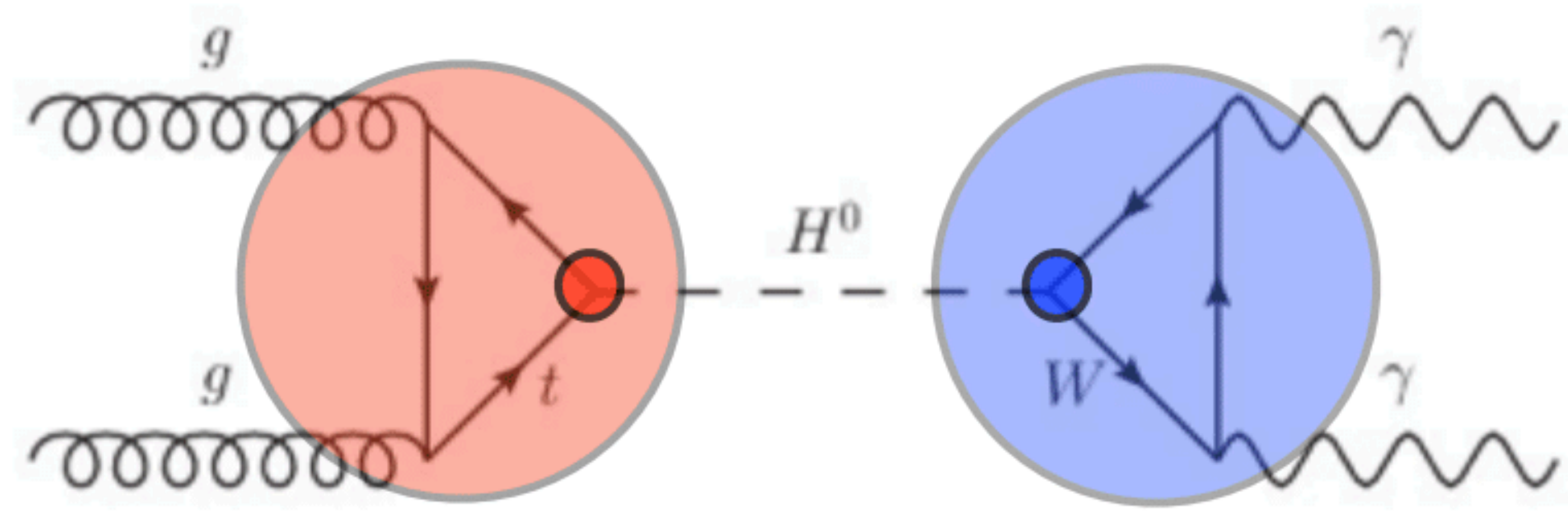


CERN @ 100

CERN @ 100

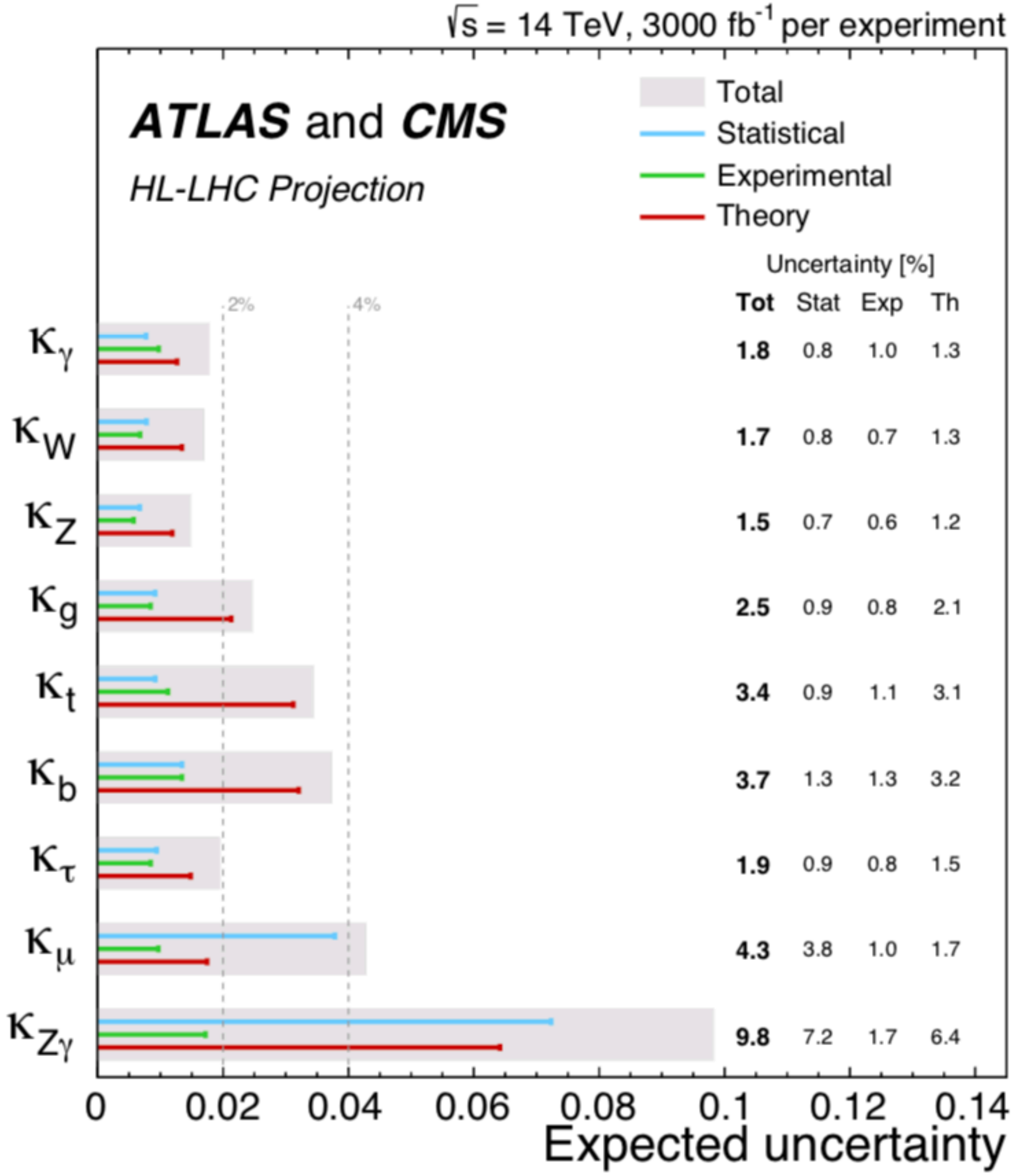
Physics Program: Higgs Physics

- HL-LHC Higgs Legacy



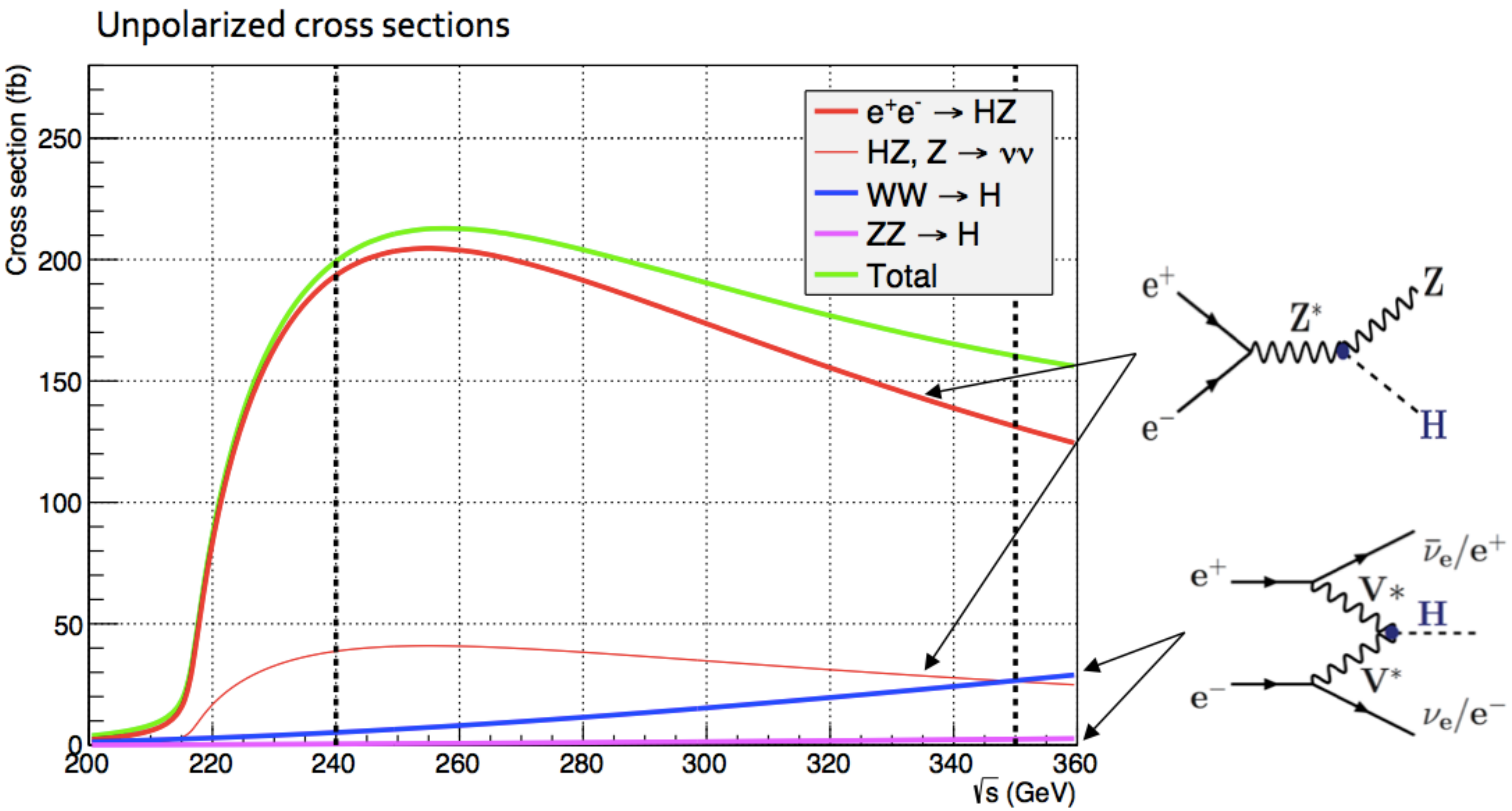
$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



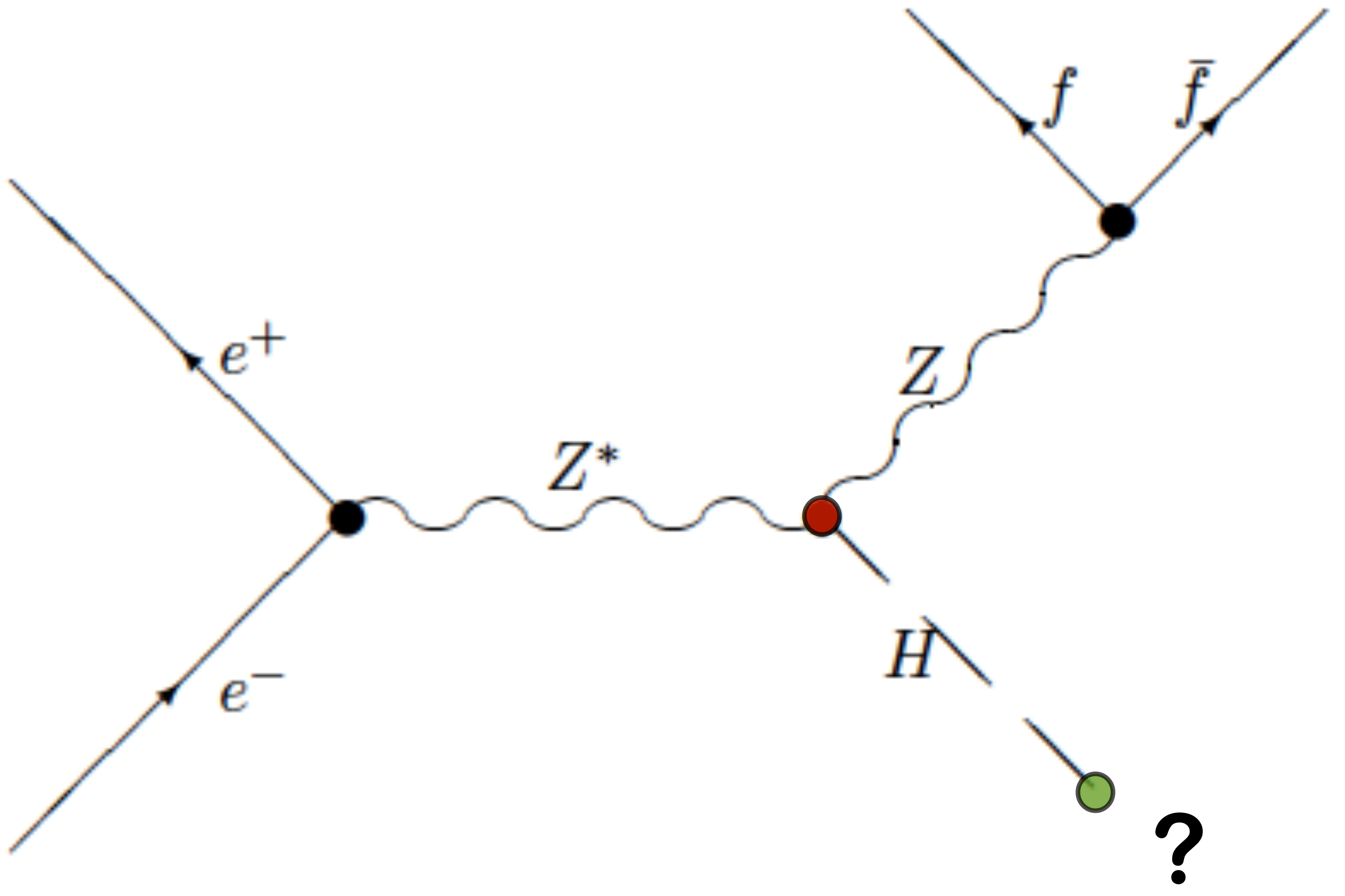
Physics Program: Higgs Physics

- **Cross section:** σ_{ZH} (240) ~200fb
- **Statistics:** $2*10^6$ (ZH) and $2*10^5$ (WWH) Higgs bosons in 4 IPs
- **Clean environment:** no pileup, beam background under control, E & p constraints

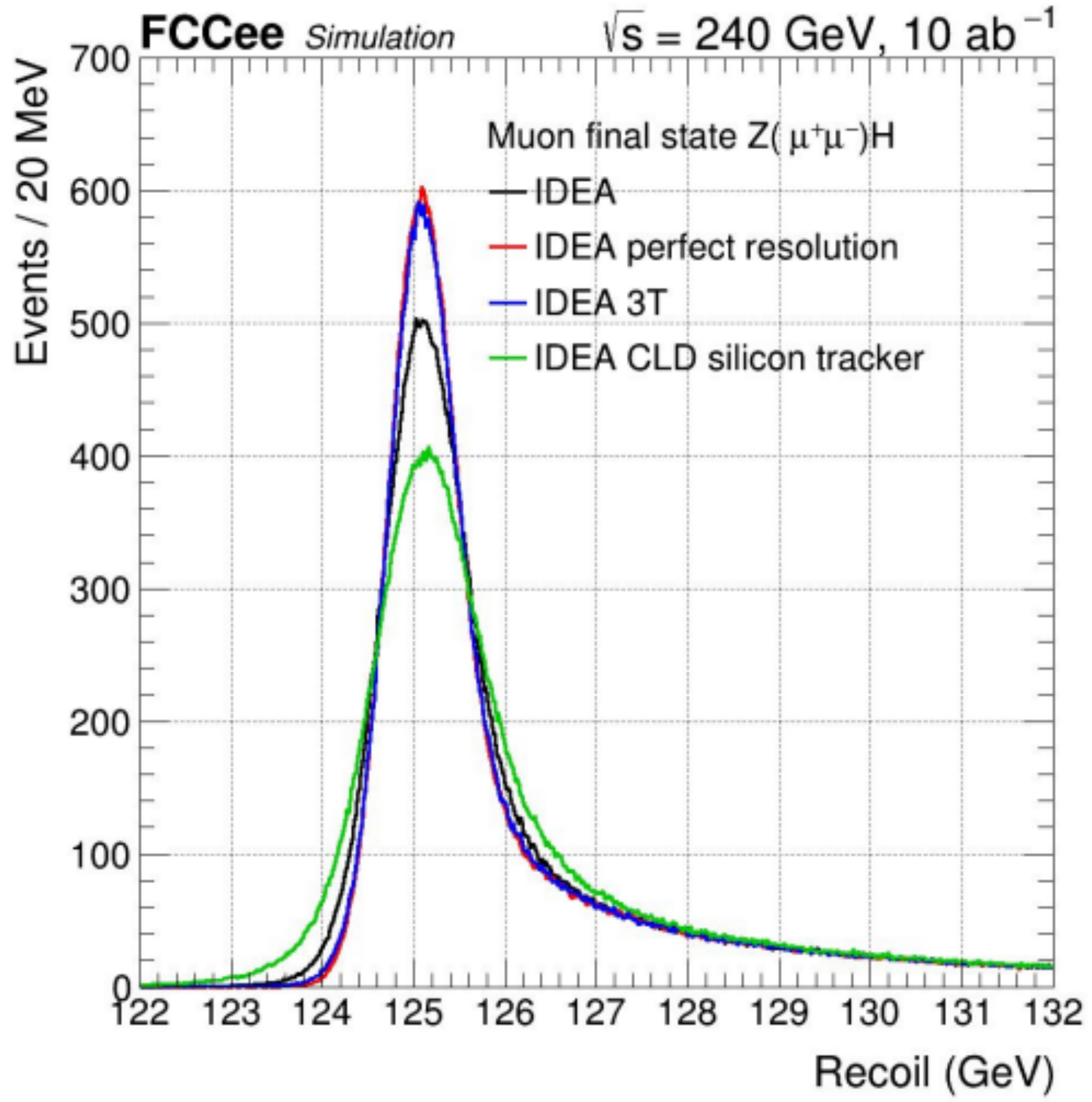


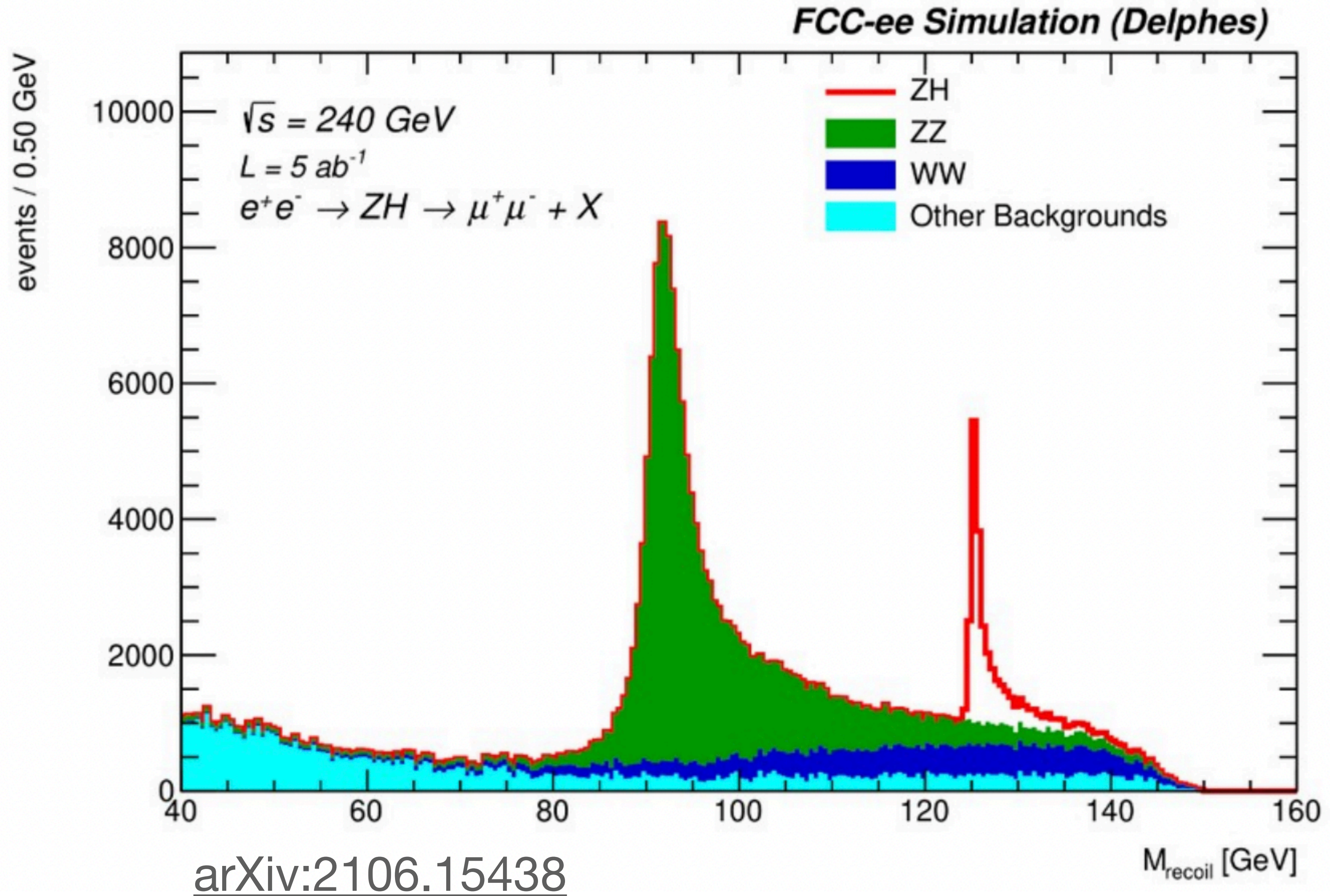
Physics Program: Higgs Physics

- Measurement of σ_{ZH} and m_H



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



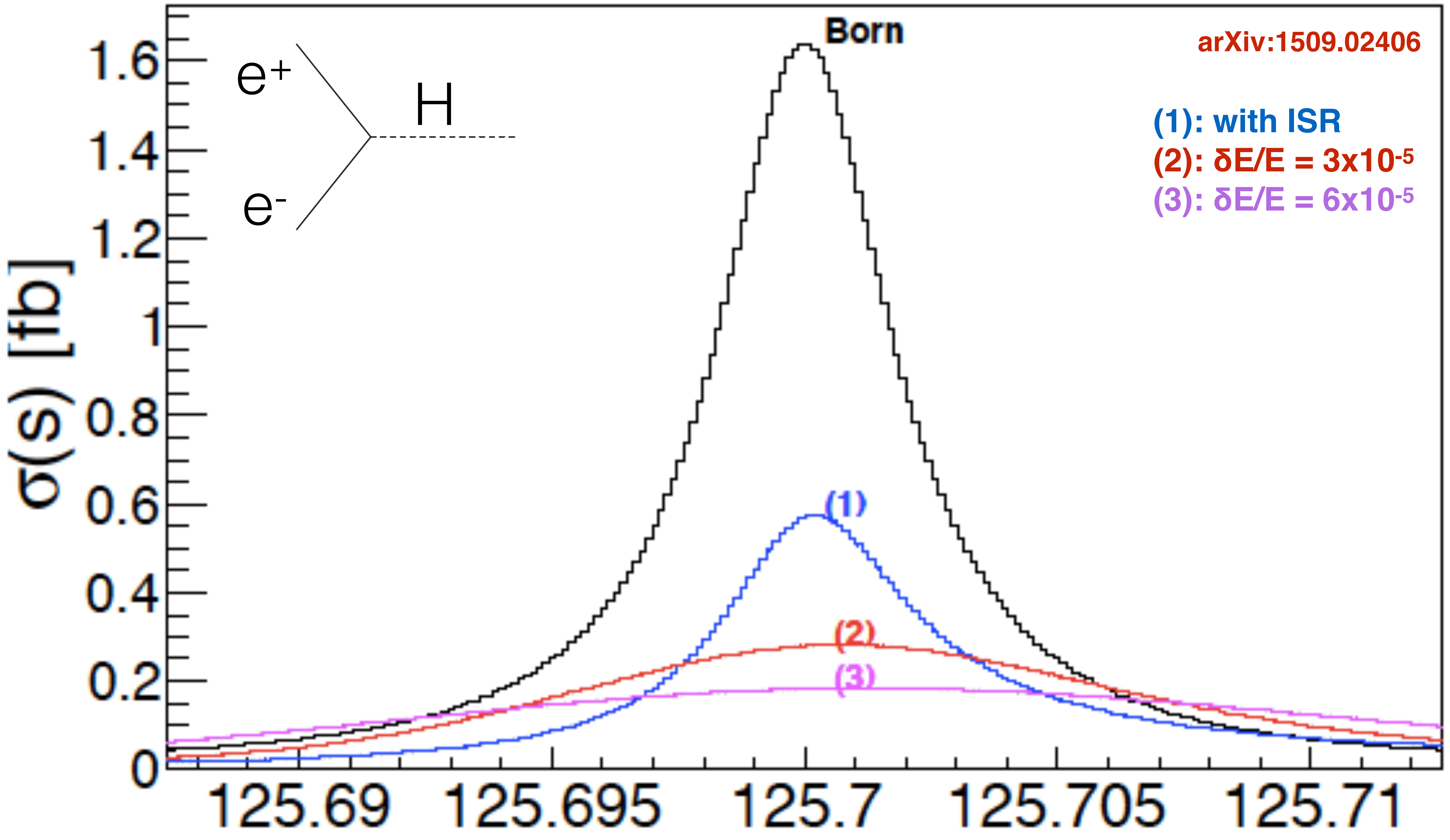


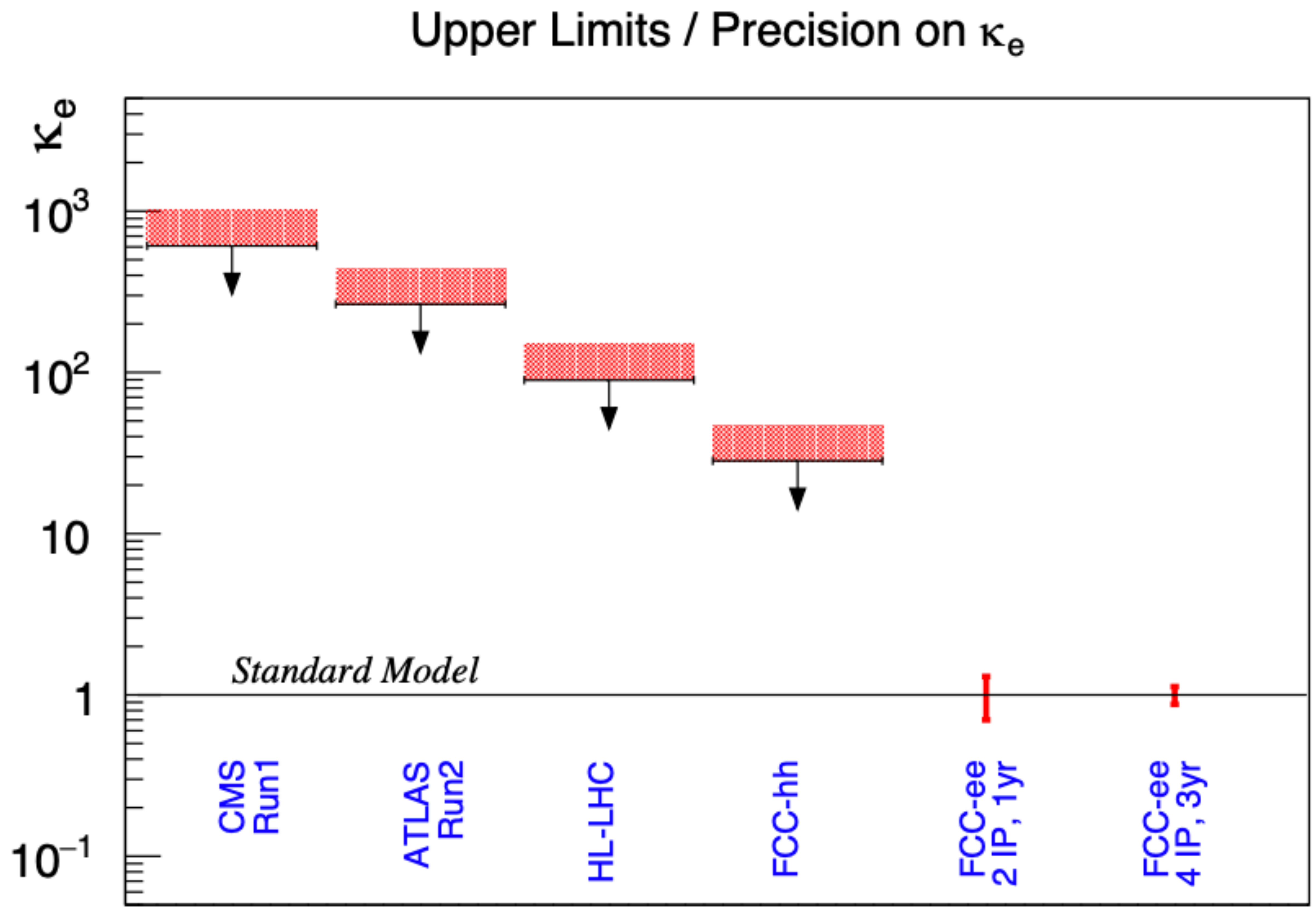
tracking system	Δm_H (MeV) stat.only	Δm_H (MeV) stat + syst
IDEA 2T	**3.49**	**4.27**
Perfect	**2.67**	**3.44**
IDEA 3T	**2.89**	**3.97**
CLD 2T	**4.56**	**5.32**

arXiv:2106.15438

Physics Program: Higgs Physics

- S-channel production to probe electron Yukawa coupling
  - Very small cross section reduced by ISR and beam spread



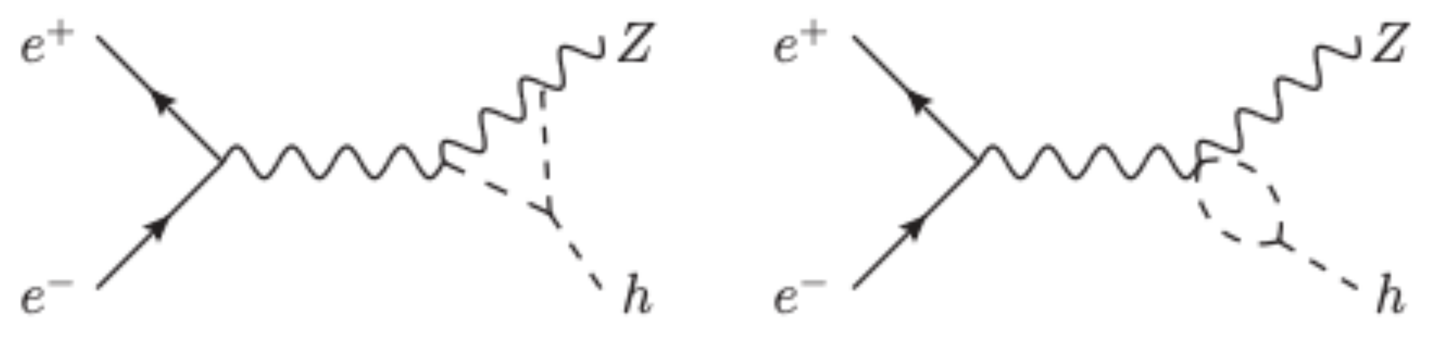


Physics Program: Higgs Physics

- Higgs total width and couplings measurements
  - σ(ee→ZH) * BR (H→X) by identifying X
  - Example: σ(ee→ZH) * BR (H→ZZ) $\propto g_{HZZ}^4/\Gamma_H$

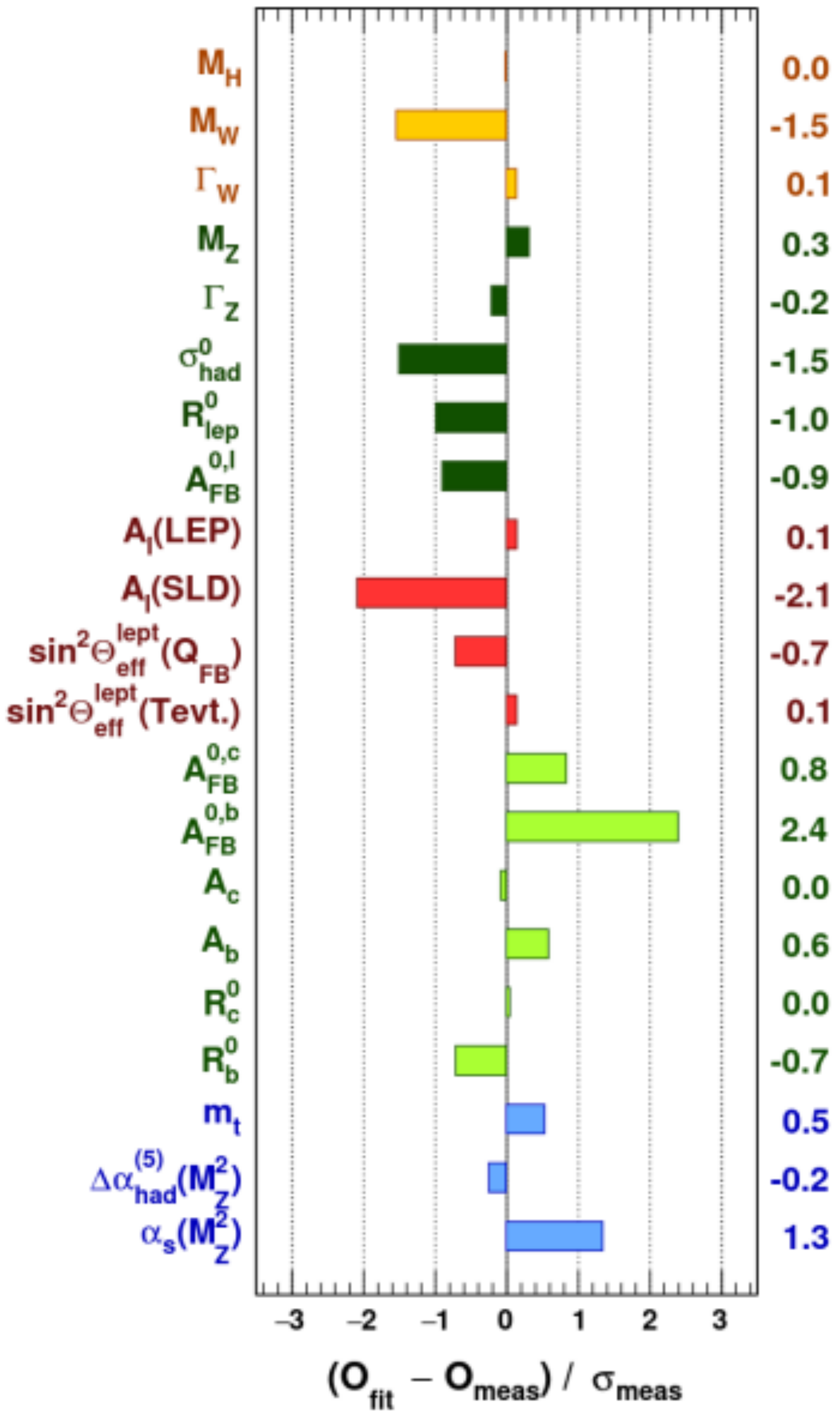
Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88

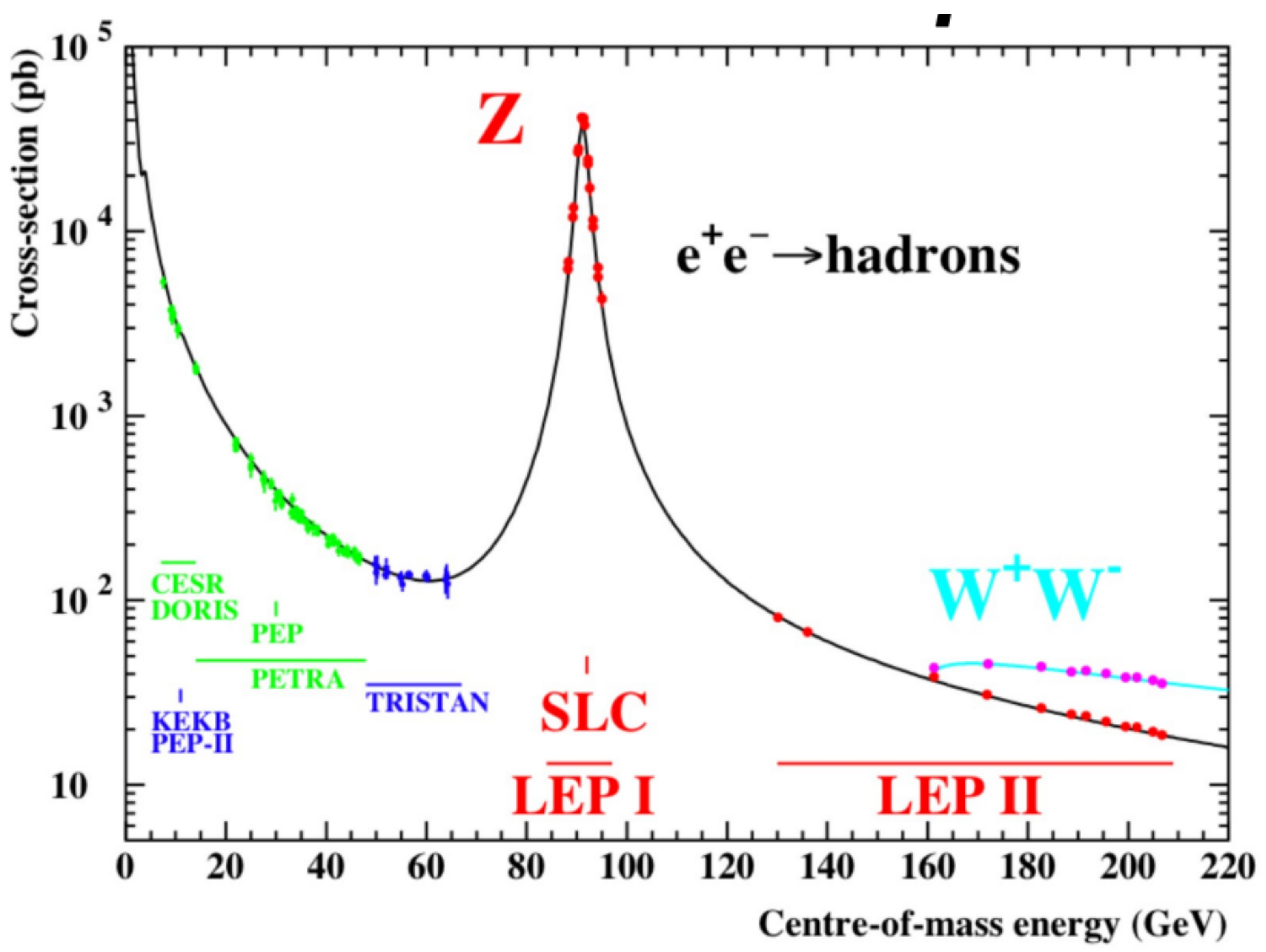
- Results not limited by experimental systematics
- Total width uncertainty at ~1%
- Testing quantum corrections in the Higgs sector, probing Higgs self coupling

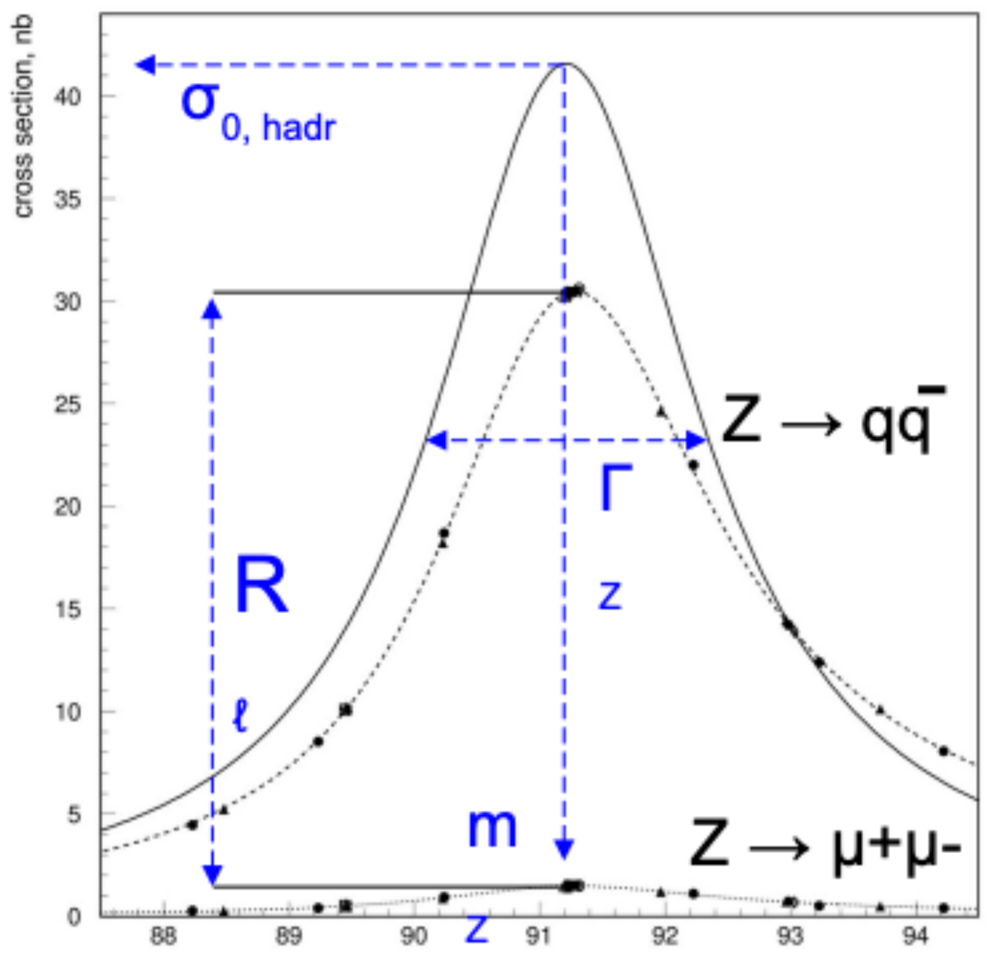


Physics Program: EW Precision

- LEP Legacy
  - Measurements of crucial and fundamental parameters of the standard model
  - Z & W boson masses, number of light neutrinos, α_s, α_{QED}, …
  - Constrain m_{top} and m_H indirectly
- FCC-ee
  - All LEP1 data in minutes
  - All SM parameter known
  - Study consistencies > 3 orders of magnitude more stringently
  - Inconsistencies will invoke new physics



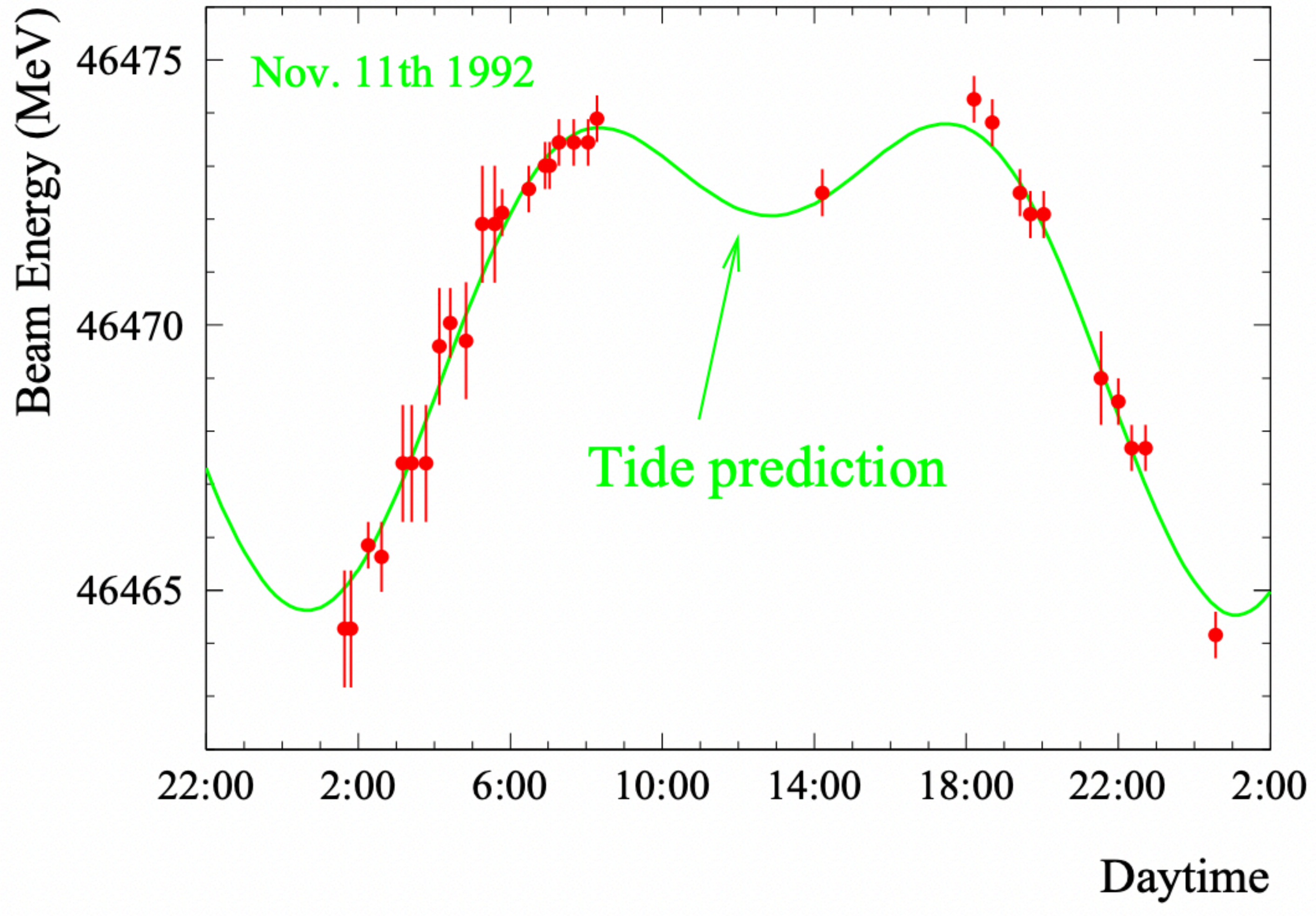


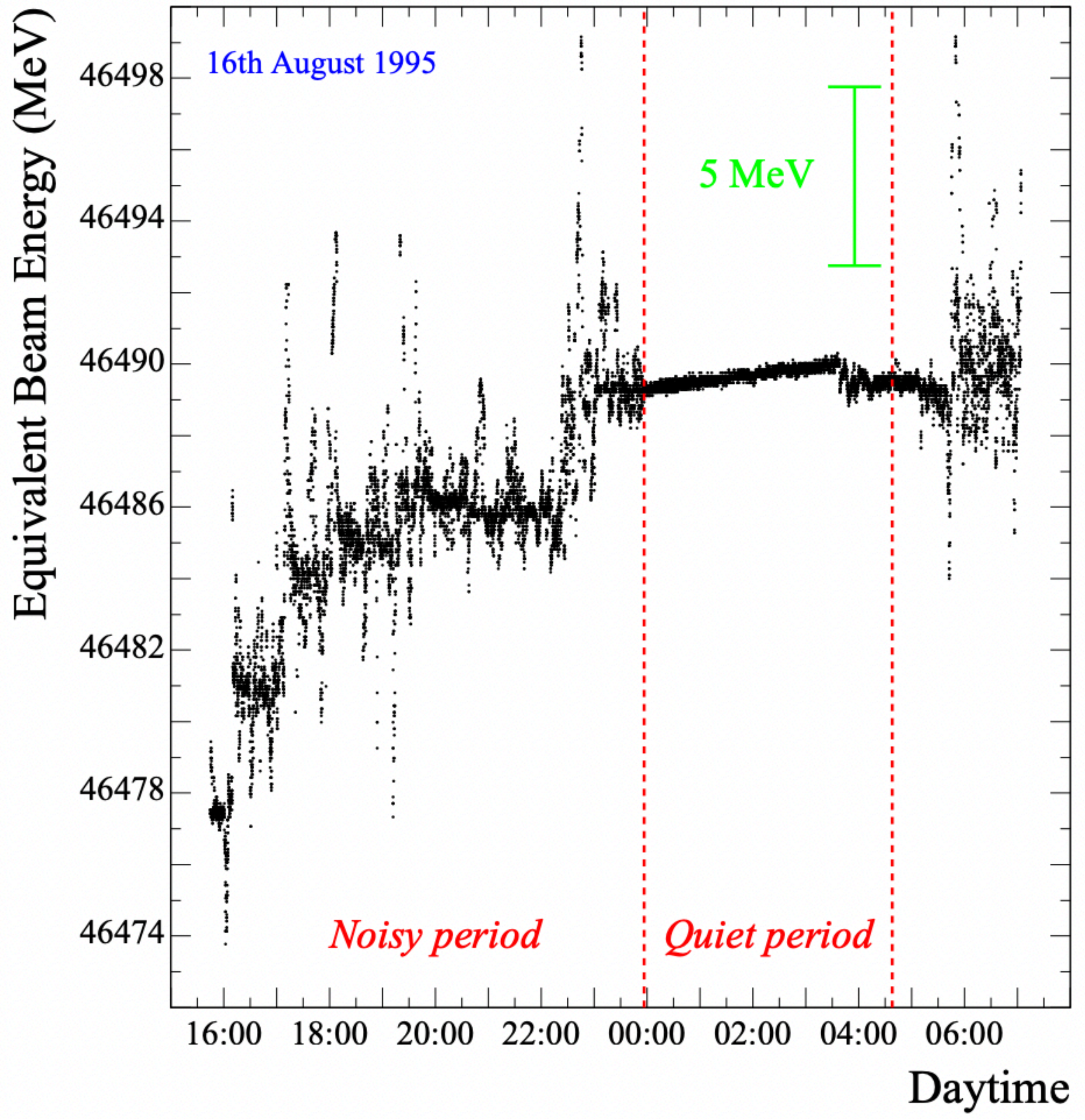


Physics Program: EW Precision

- Uncertainties: energy calibration
  - In-situ calibration during data taking with non-colliding pilot bunches
  - Beam energy spread from di-lepton events
  - Methods need to be improved. Work in progress!
  - LEP measurements of beam energy

arXiv:1909.12245

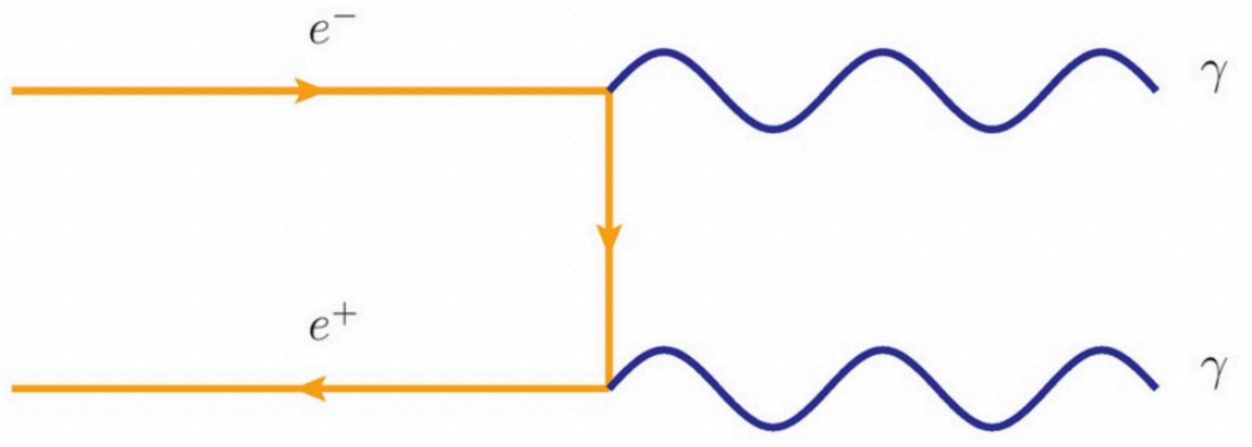




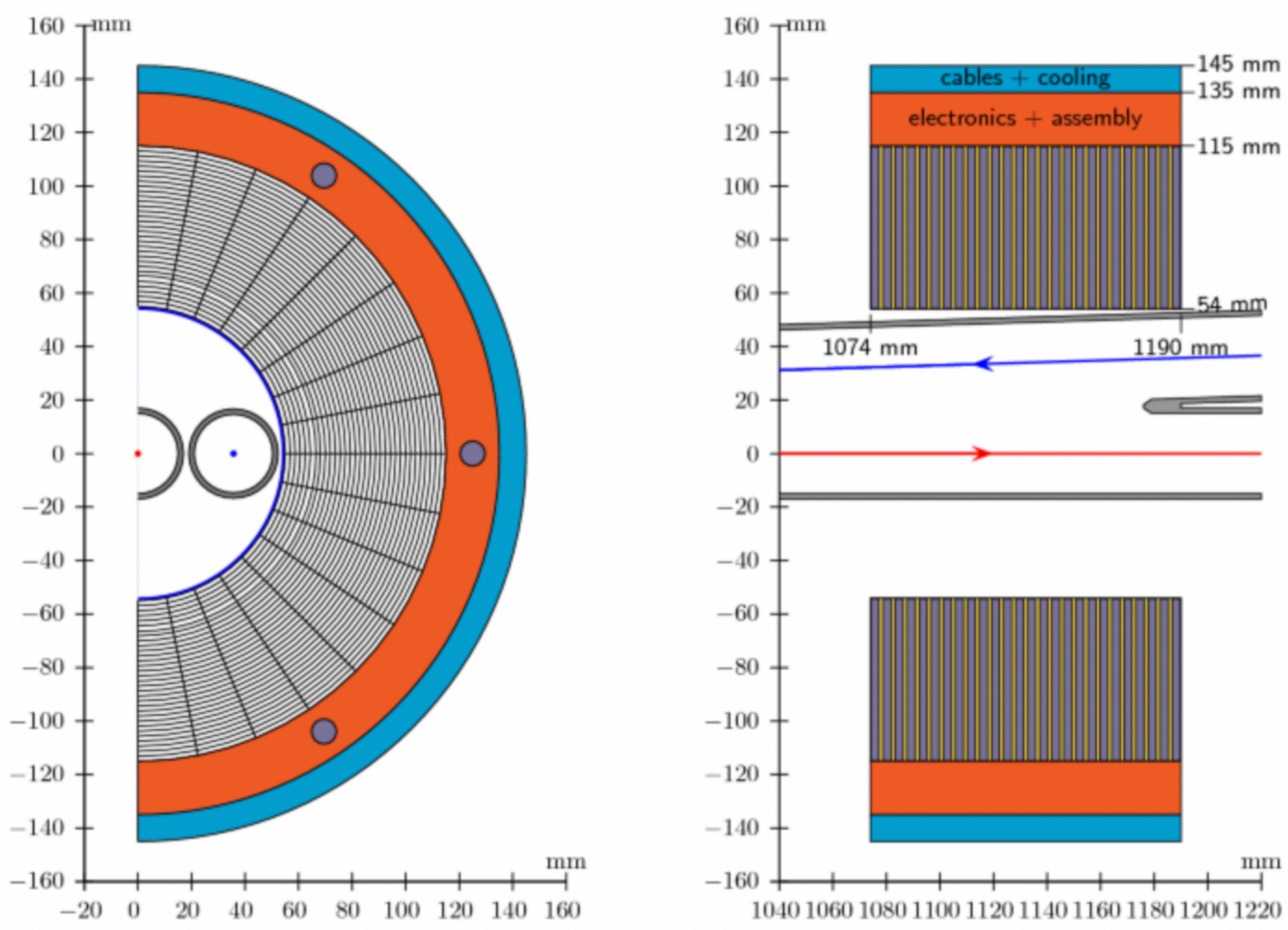
Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV**	calib. stats. $200\,\mathrm{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV
$\mathrm{m_Z}$ (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_\mathrm{W}^{\mathrm{eff}} \times 10^6$ from $A_{\mathrm{FB}}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{\mathrm{QED}}(\mathrm{m_Z^2})}{\alpha_{\mathrm{QED}}(\mathrm{m_Z^2})} \times 10^5$	3	0.1	**0.9**	–	**0.1**

Physics Program: EW Precision

- Uncertainties: luminosity
  - Small angle **Bhabha scattering** used at LEP
    - Very large cross section (78nb)
    - Excellent control of geometry needed: O(10^{-5}) precision, Δr ~1 μm
    - Theory prediction 0.037% but far from statistical precision
  - **Di-photon production** excellent probe
    - Clean events, but lower, accuracy O(10^{-4})

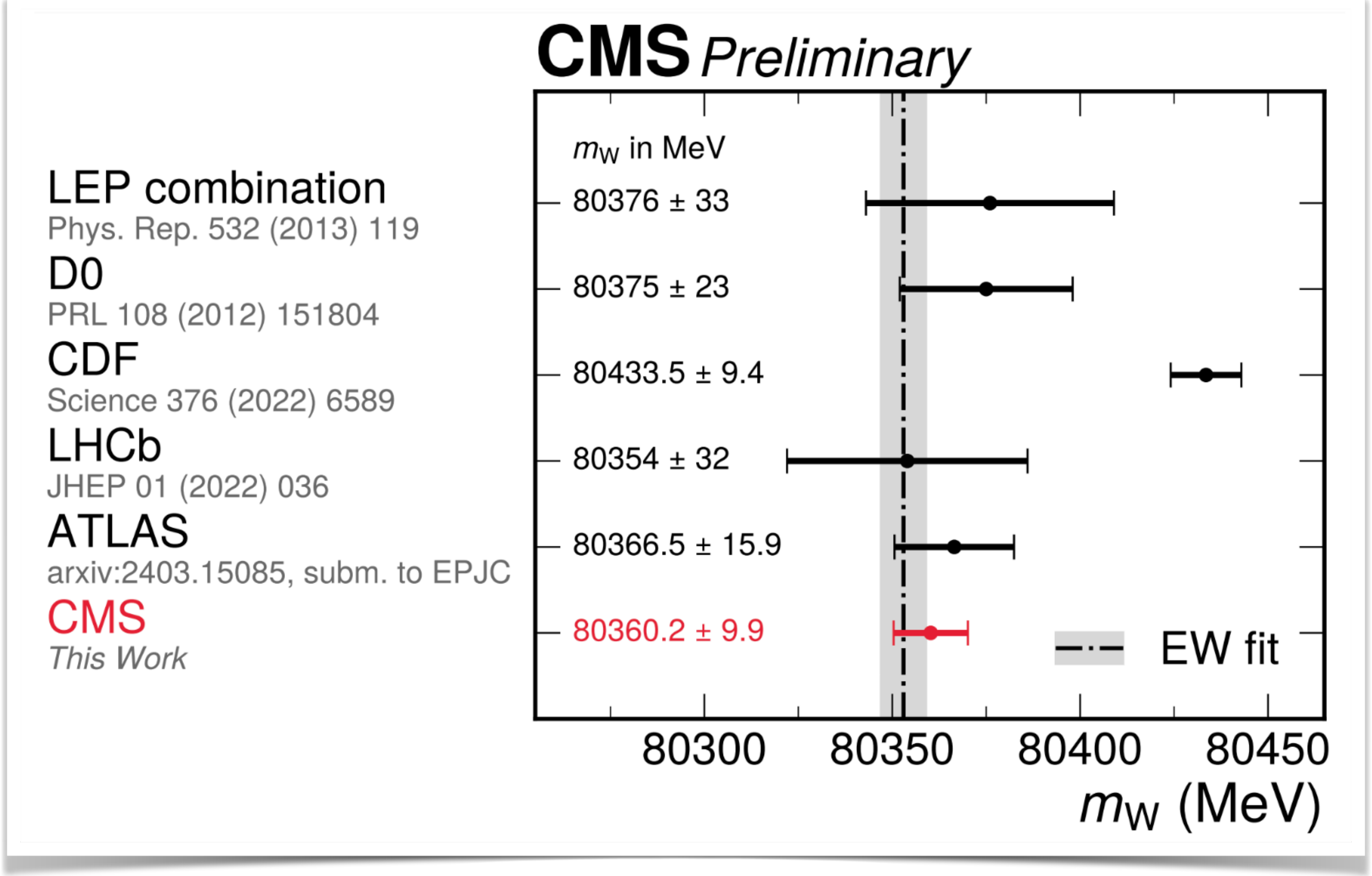


Eur.Phys.J.Plus (2022) 137:81

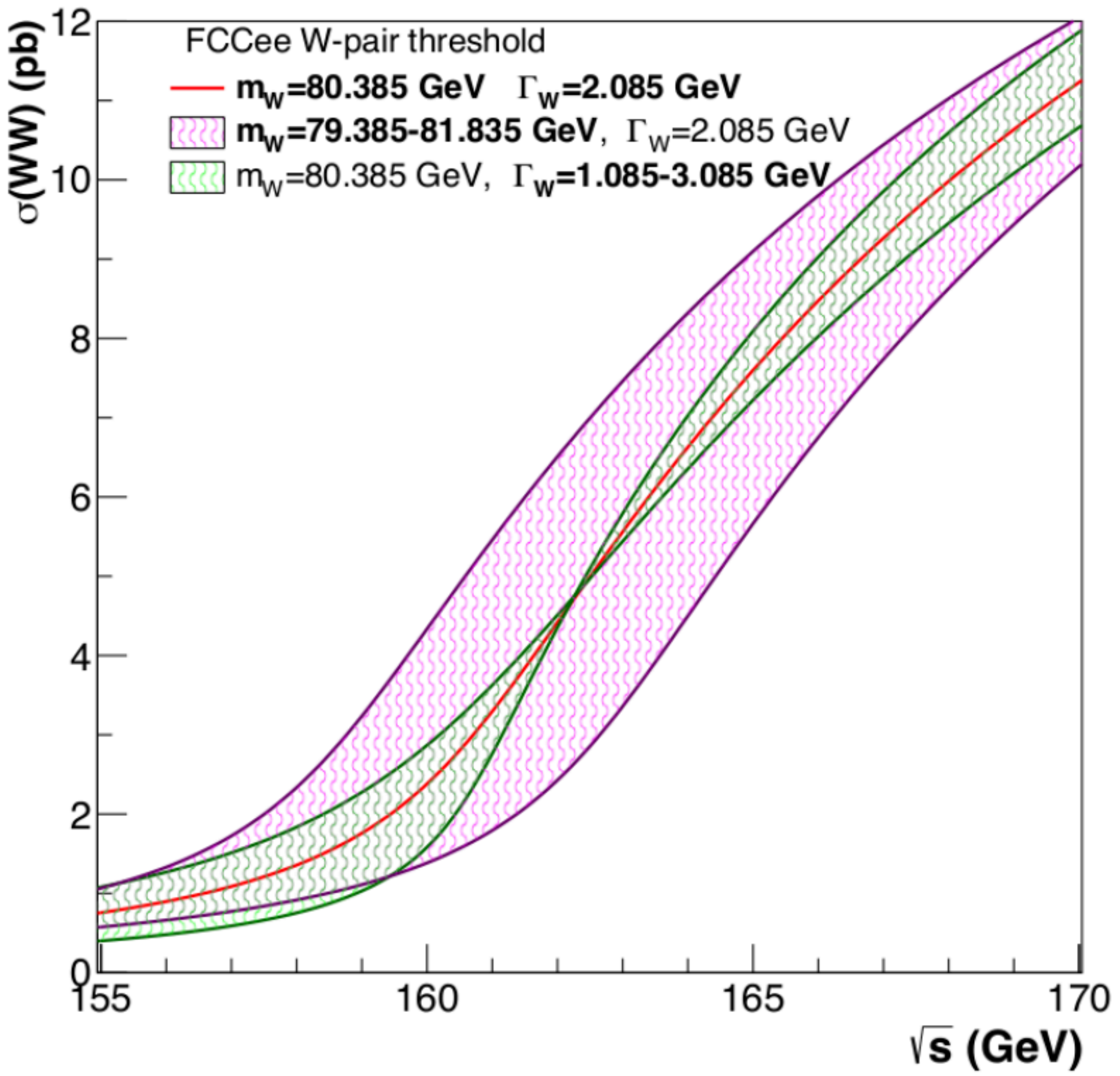


Physics Program: EW Precision

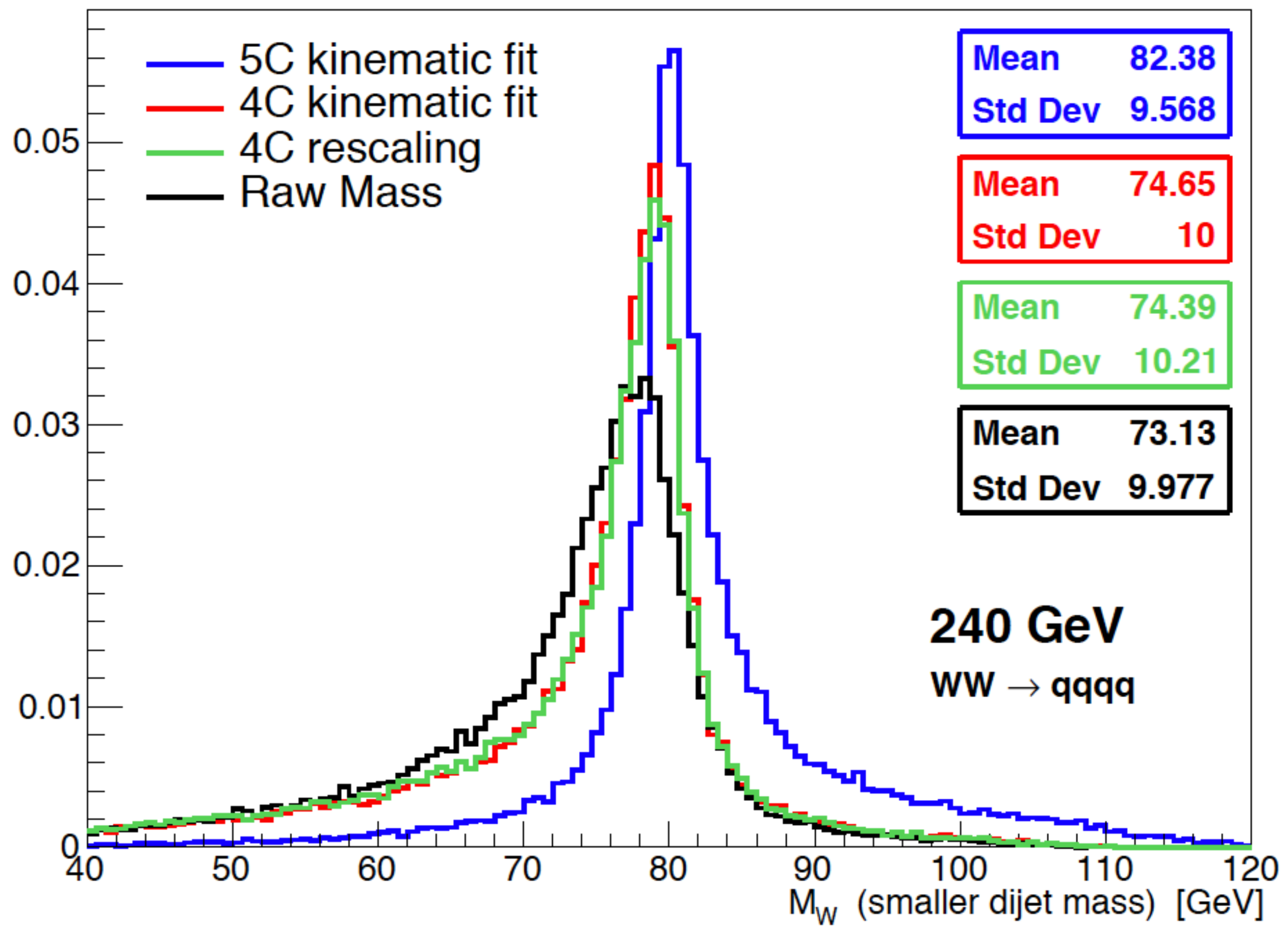
- W mass measurement



Threshold scan
Statistical uncertainty ~0.45 MeV
Lead systematics: beam energy

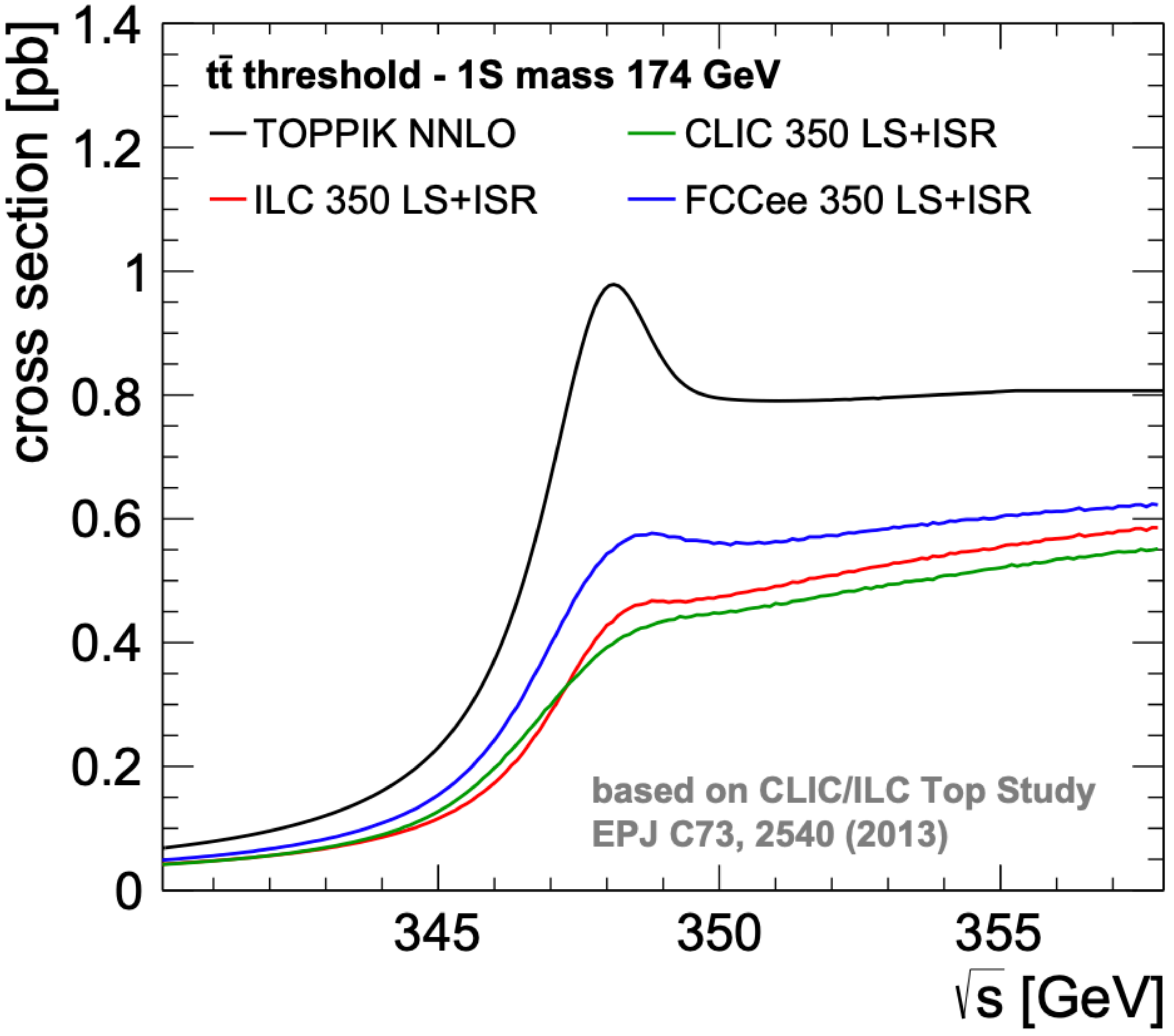


Direct mass reconstruction
Statistical uncertainty ~0.22 MeV
Lead systematics: theoretical



Physics Program: Top Precision

- Top mass and width can be measured directly with an accurate top cross section threshold scan
- Uncertainties
  - Statistics: mt (Γ_t) is ~**17 (45) MeV**
  - 3 MeV from center-of-mass energy
  - 5 MeV from α_s
  - ~40 MeV from theoretical uncertainties (NNNLO)



Physics Program: EW Precision

- Summary of results

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2 – 1.0	Ratio of hadrons to leptons; acceptance for letpons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	0.4 – 1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2 \theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

Theoretical Calculations

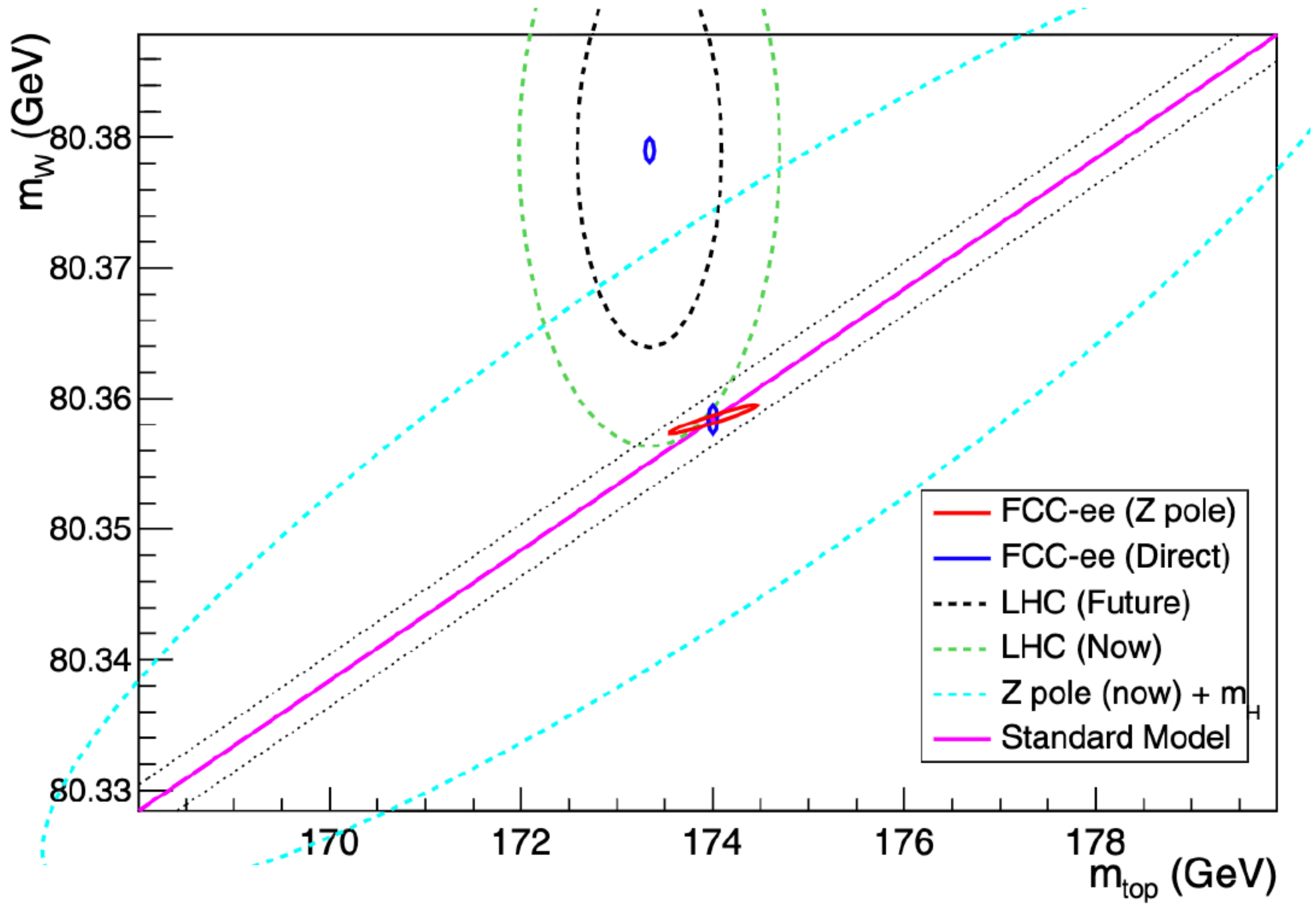
- Theoretical predictions and tools need to match experimental precision

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement†
m_Z Γ_Z $\sin^2\theta^{\ell}_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT framework)	NNLO for $ee\to WW$, $W\to ff$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak
$m_{\rm top}$	100 MeV	17 MeV	threshold scan $e^+e^-\to t\bar{t}$	N^3LO QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

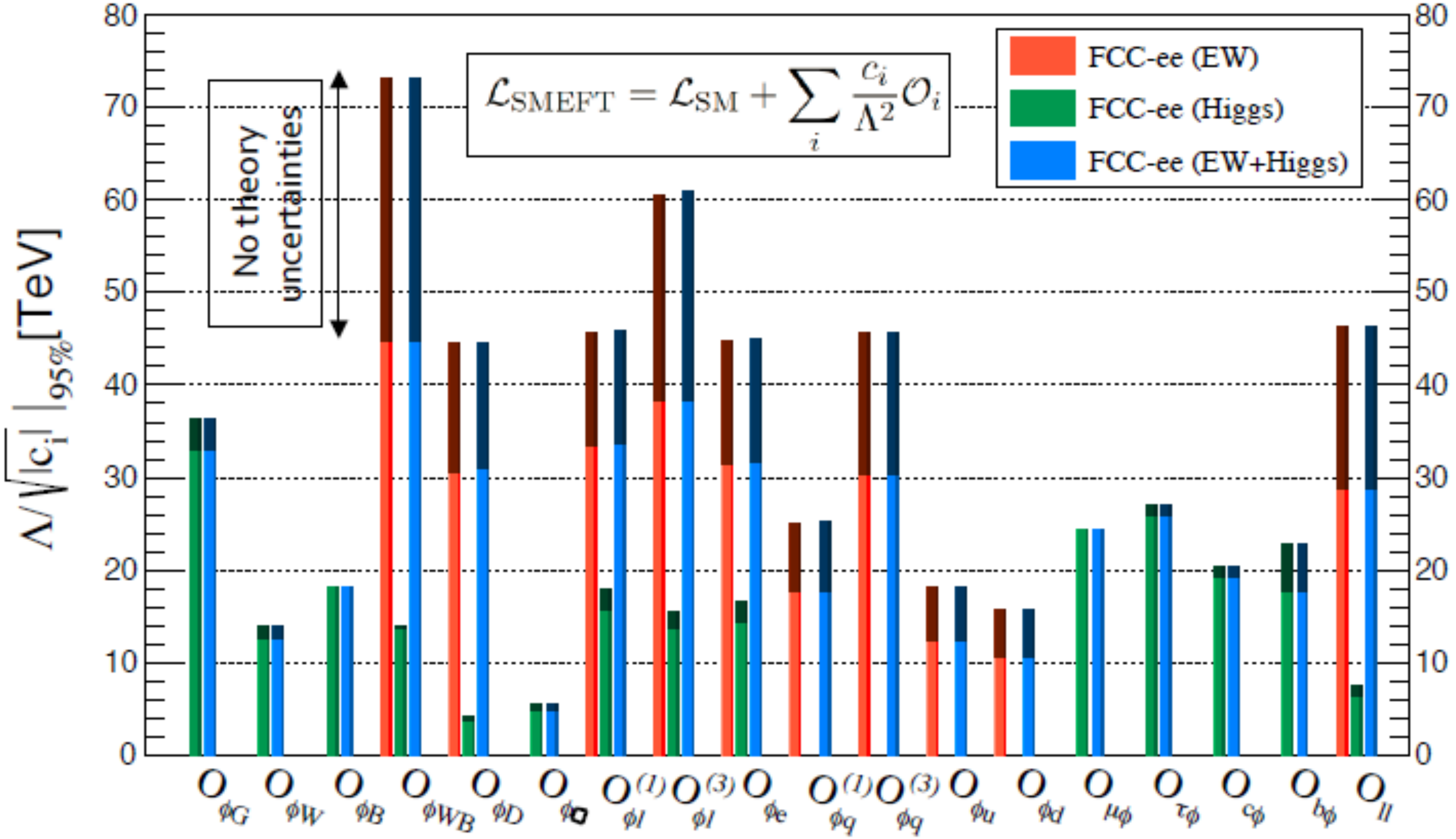
†The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.

- Recent progress on a number of techniques and tools
  - e.g. Two-Loop Electroweak Corrections with Fermion Loops to $e^+e^-\to ZH$
- Plan is emerging but significant advancement are needed

Physics Program: EW and Top Precision



Physics Program: New Physics Searches



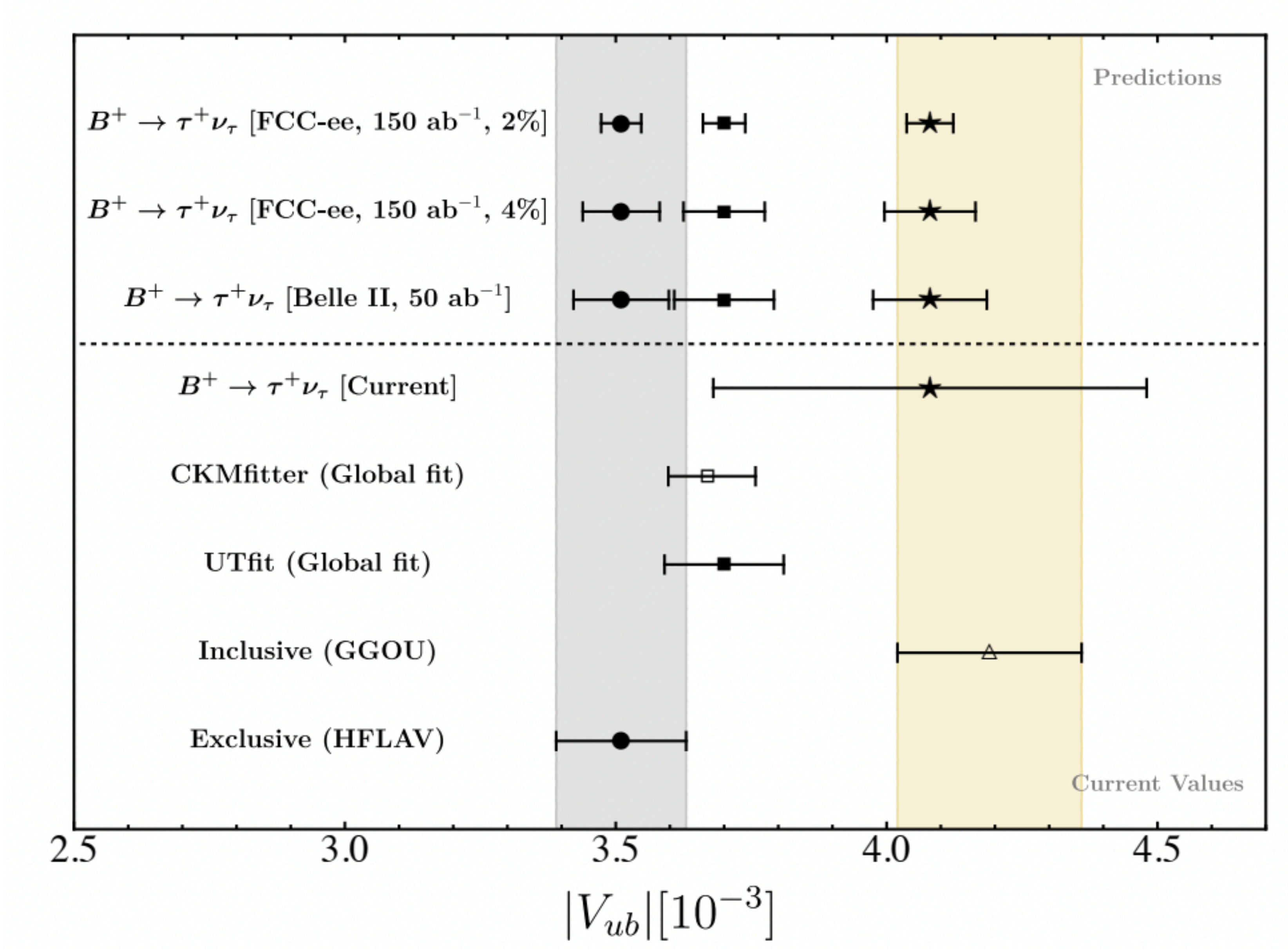
- EFT D6 operators (some assumptions)
- ***Higgs and EWPOs are complementary***

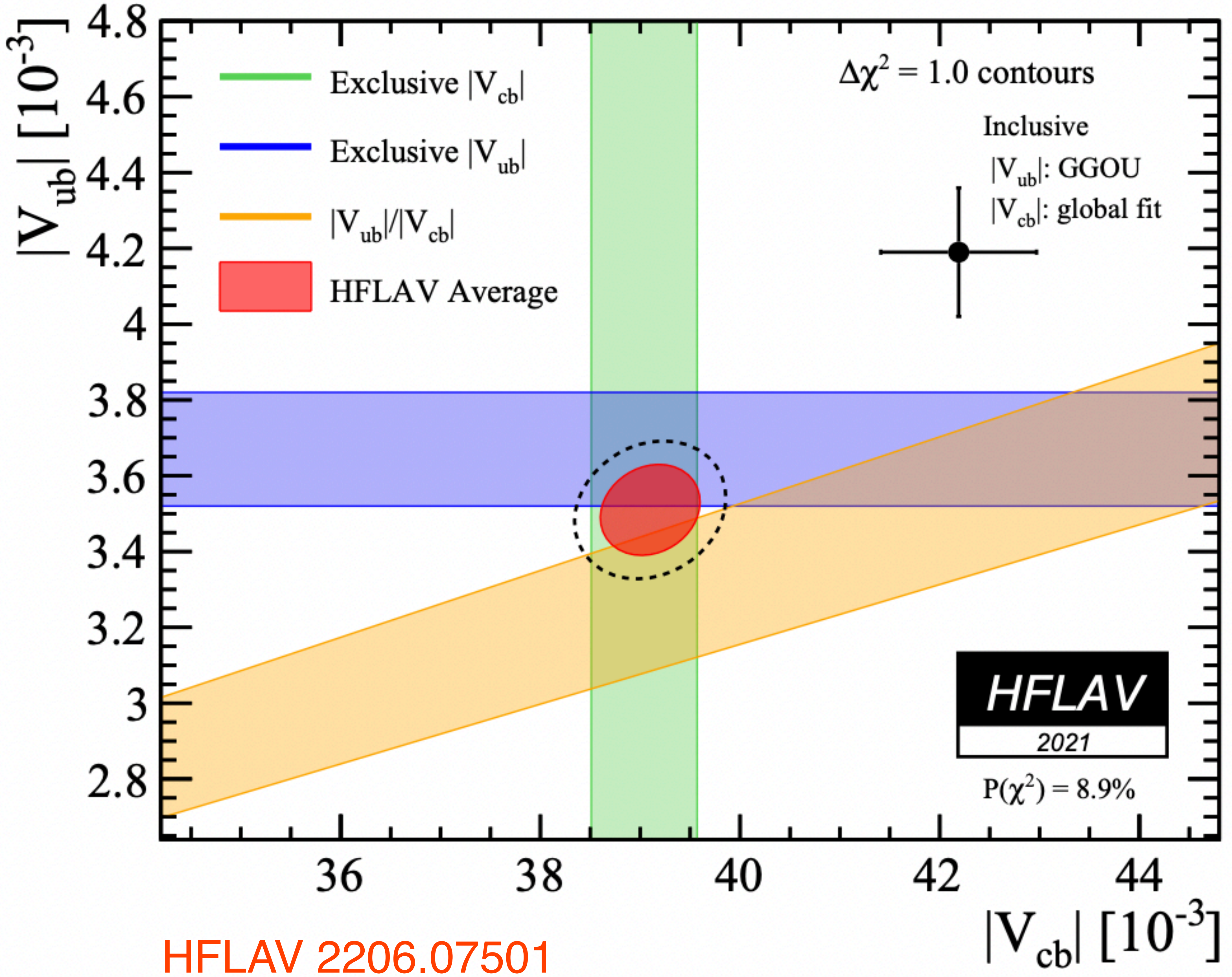
Physics Program: Flavor Physics

Particle count (10^9)	$B^0(\bar{B}^0)$	$B^\pm$	$B_s^0(\bar{B}_s^0)$	$B_c^\pm$	$\Lambda_b(\bar{\Lambda}_b)$	$c(\bar{c})$	$\tau^\pm$
Belle-II	55	55	0.6	N.A.	N.A.	130	90
FCC-ee	770	770	170	7	150	1400	400

- Precise determination of $|V_{ub}|$ and $|V_{cb}|$ CKM elements
- Long standing tension between inclusive and exclusive extractions
- Extreme precision at FCC-ee
- Independent probe using B_c^+ and $B^+ \to \tau^+\nu_\tau$

arxiv:2305.02998





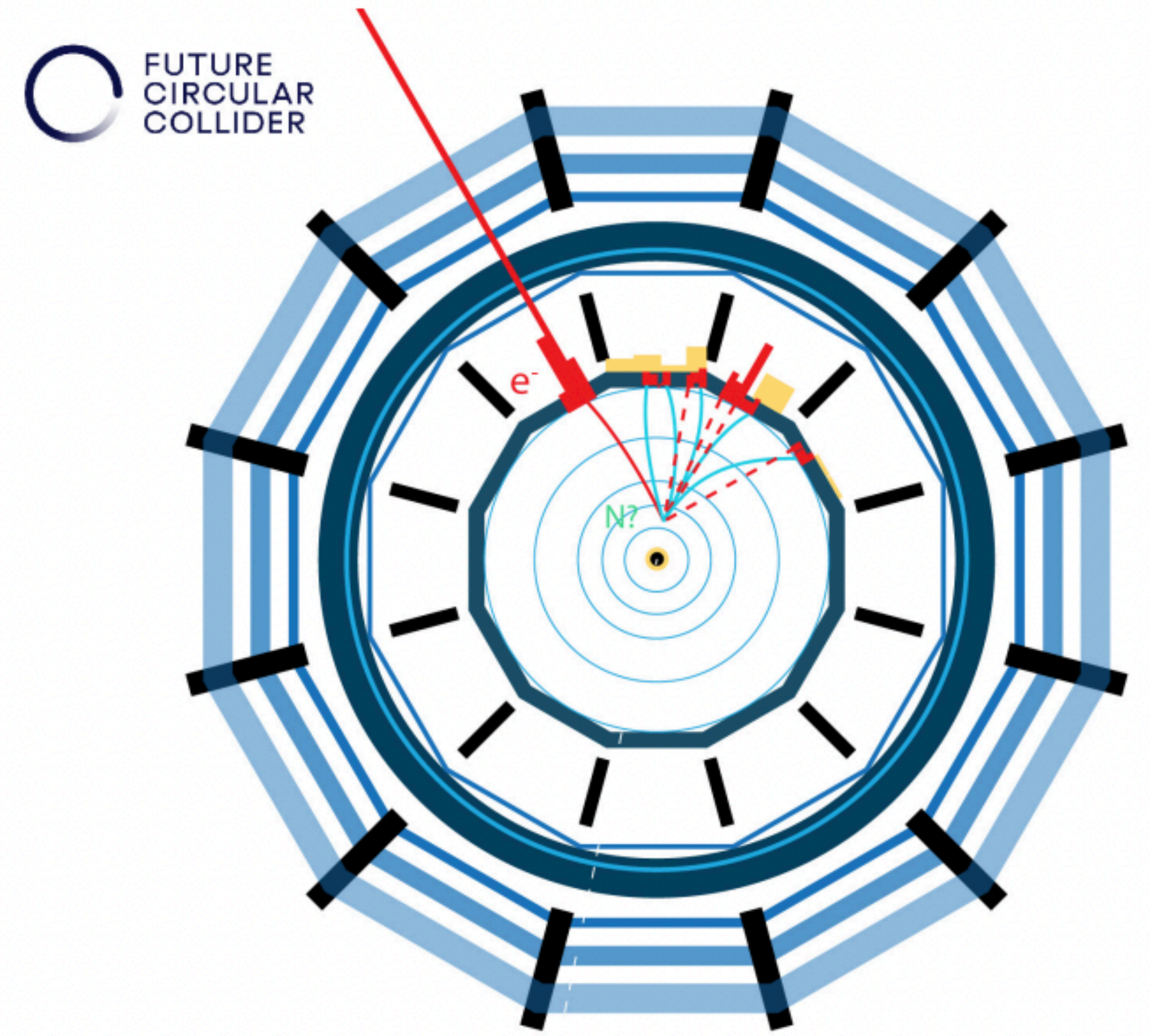
HFLAV 2206.07501

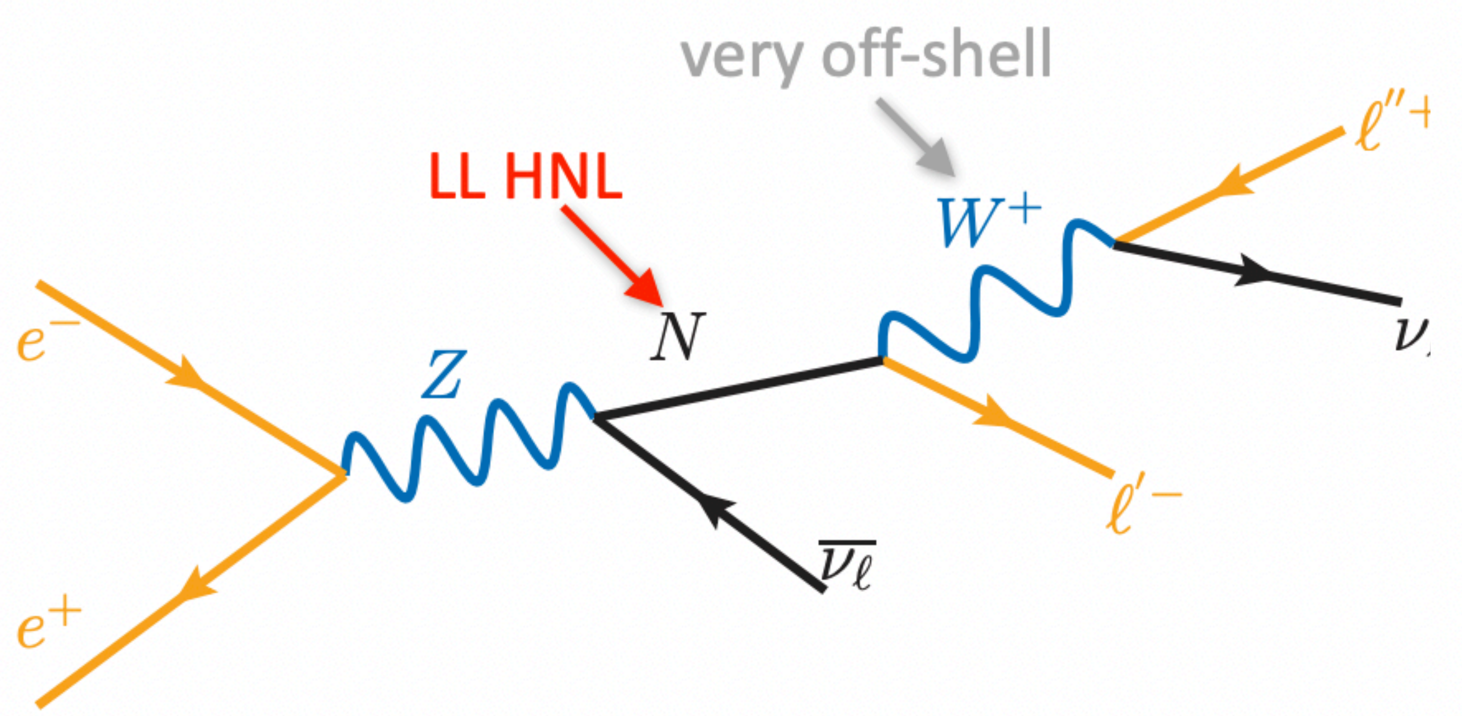
Physics Program: New Physics Searches

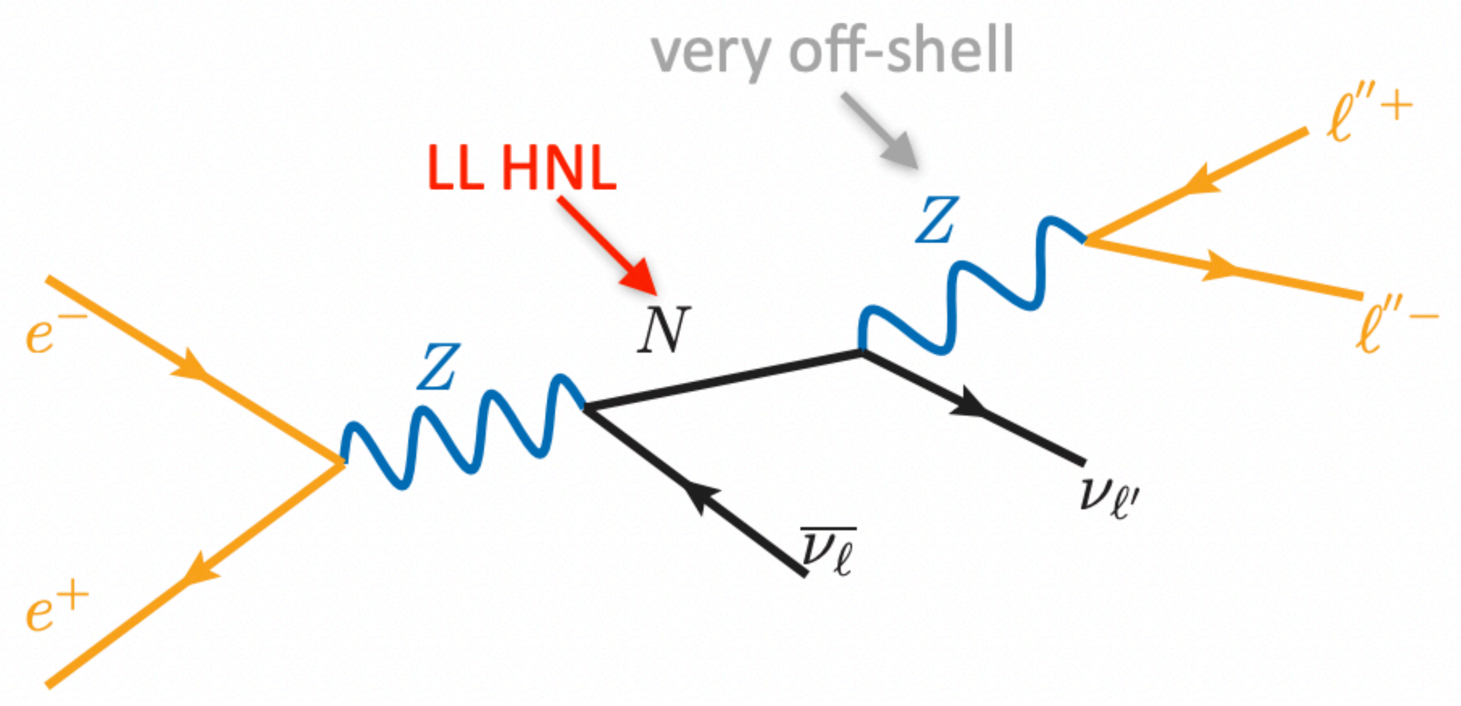
- Heavy neutral leptons
  - Sterile neutrinos
  - Can be long-lived

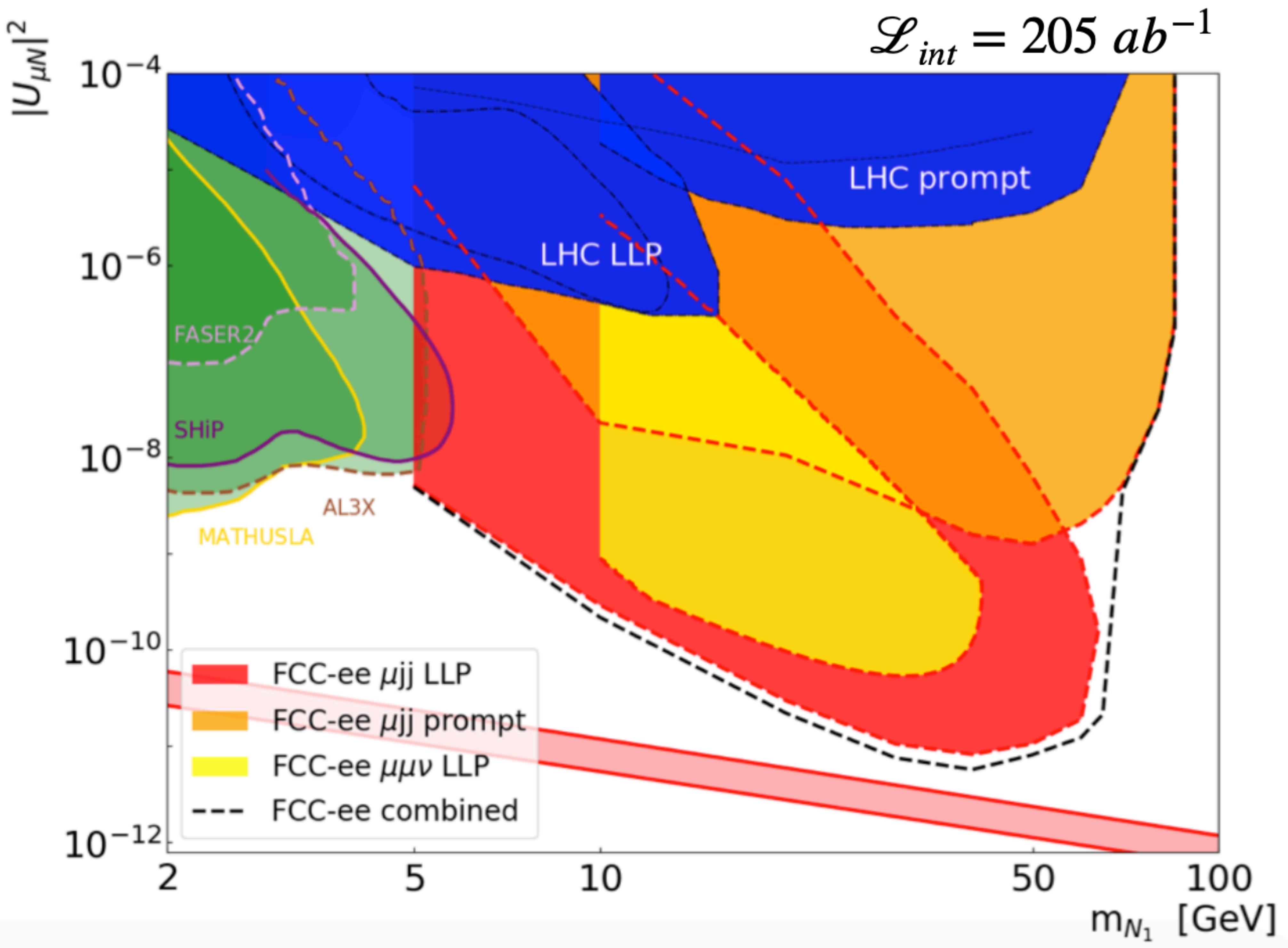
e+e- → Z→ vN

N→ e- + {W+* →jj}

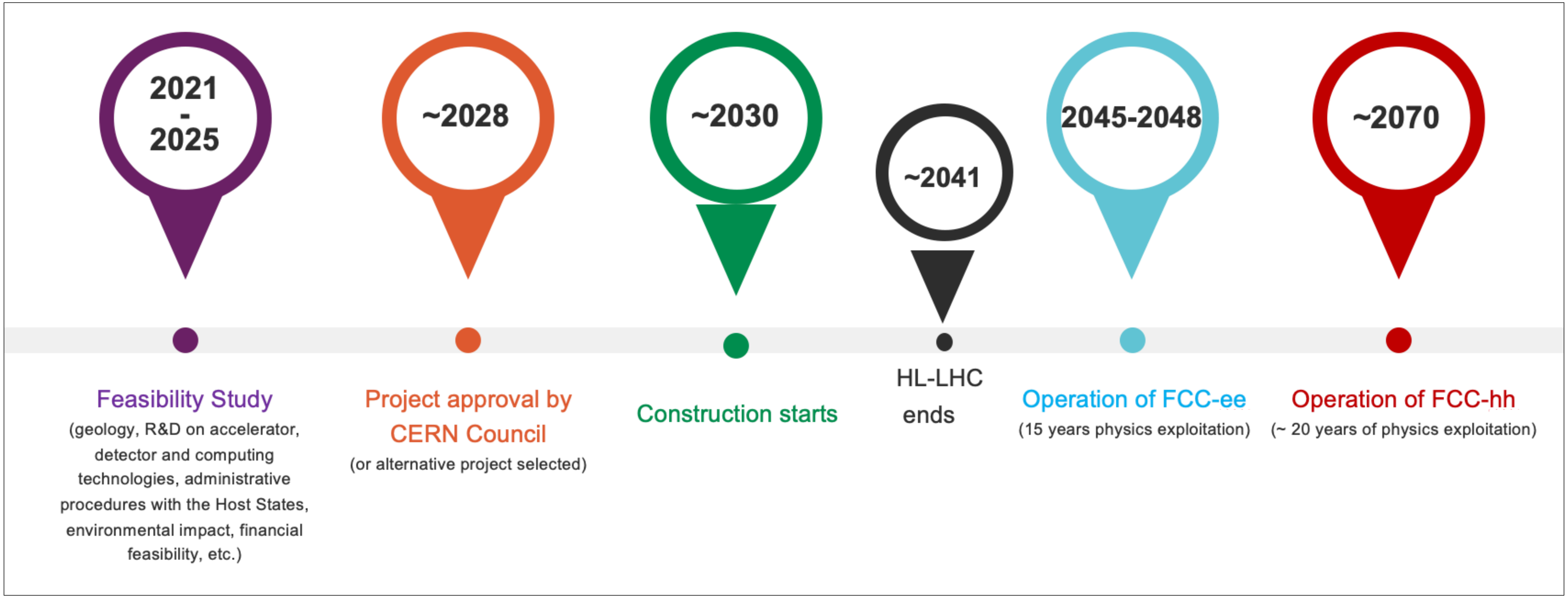








FCC Schedule



- Schedule considers past experience, approval timelines, and that the HL-LHC will run until 2041
- Accelerated scenarios are under study

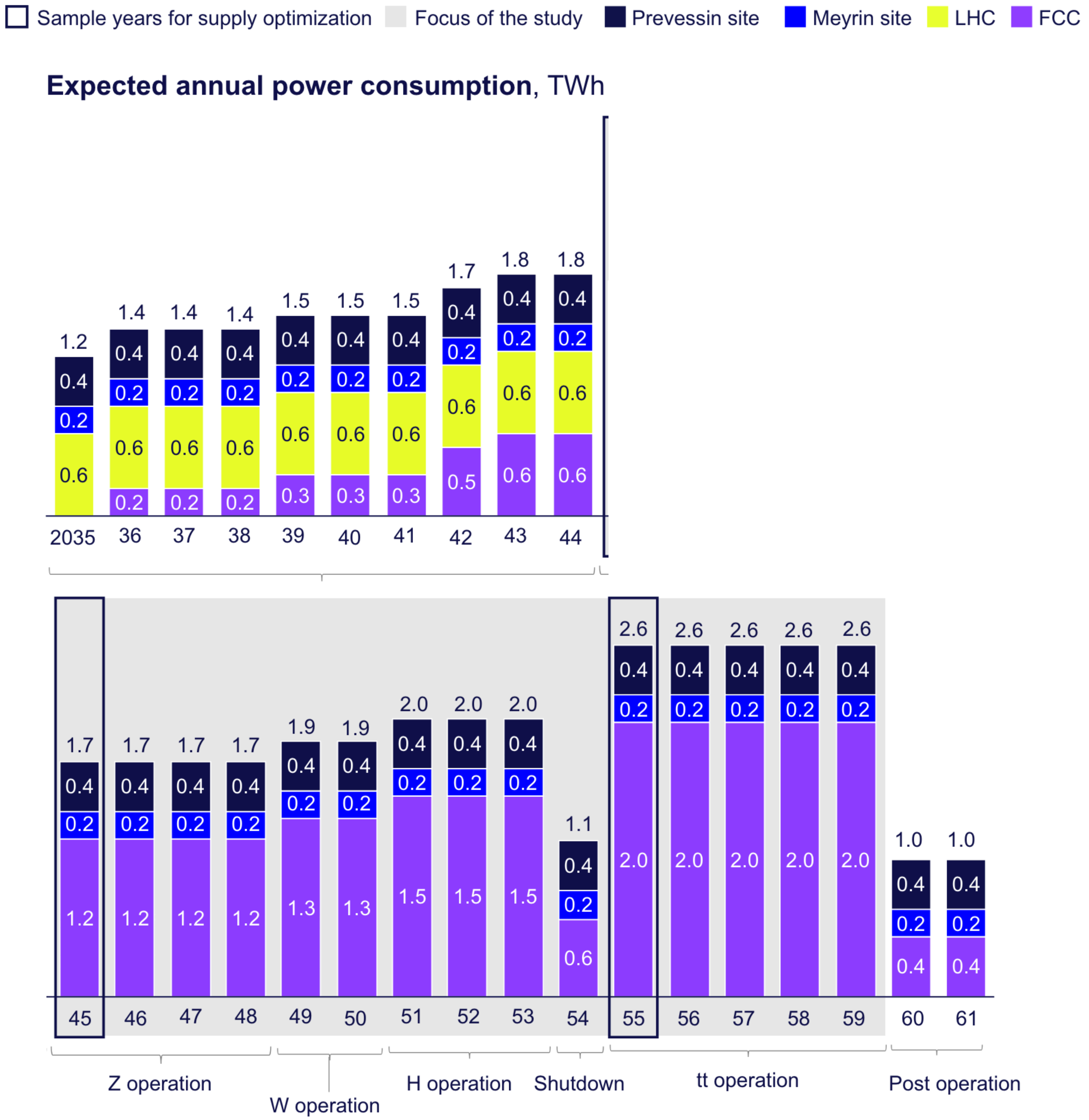
FCC Feasibility Study Midterm Cost Estimate

- Total cost for Z, W, and ZH run with two IPs estimated to 12,801 MCHF
  - Accelerator: 3,847 MCHF
  - Injector & transfer lines: 585 MCHF
  - Civil engineering: 5,538 MCH
  - Technical infrastructure: 2,490 MCHF
  - Territorial development 191 MCHF
  - CERN contribution to experiments: 150 MCHF

- Additional cost for two further IPs is estimated to 710 MCHF
- To operate FCC-ee at the top-pair threshold would require an additional investment in RF equipment and cryogenics of 1,465 MCHF

Sustainable - Energy Supply

- Analysis for the supply from renewable sources
- Carried out in collaboration with two experienced consulting companies (McKinsey, Accenture) and report prepared
- Findings
  - FCC and CERN can be supplied with renewable energy sources
  - Requires detailed planning, implementation, and operation of power purchasing agreements
  - Mix of wind and solar power most recommended technology complemented with battery storage
  - Providing FCC with renewable energy is an incentive for an accelerated energy transition and can lead to lower prizes



Conclusion

- Higgs factory as the highest-priority next collider
- FCC-ee delivers ambitious, unbiased, high precision exploration of the Higgs Boson and so much more
- Integrated FCC program offers unparalleled exploration potential over the widest physics frontier through precision and direct searches
- Feasibility study reached mid-point and will conclude in 2025
- Many opportunities to engage in all areas of the project

created by OpenAI's DALL-E