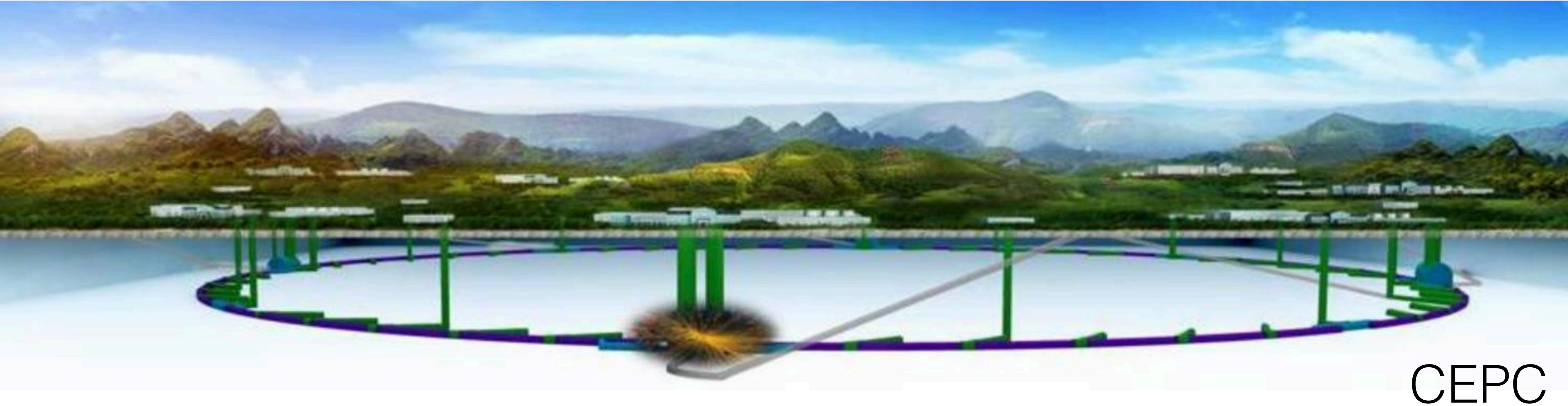
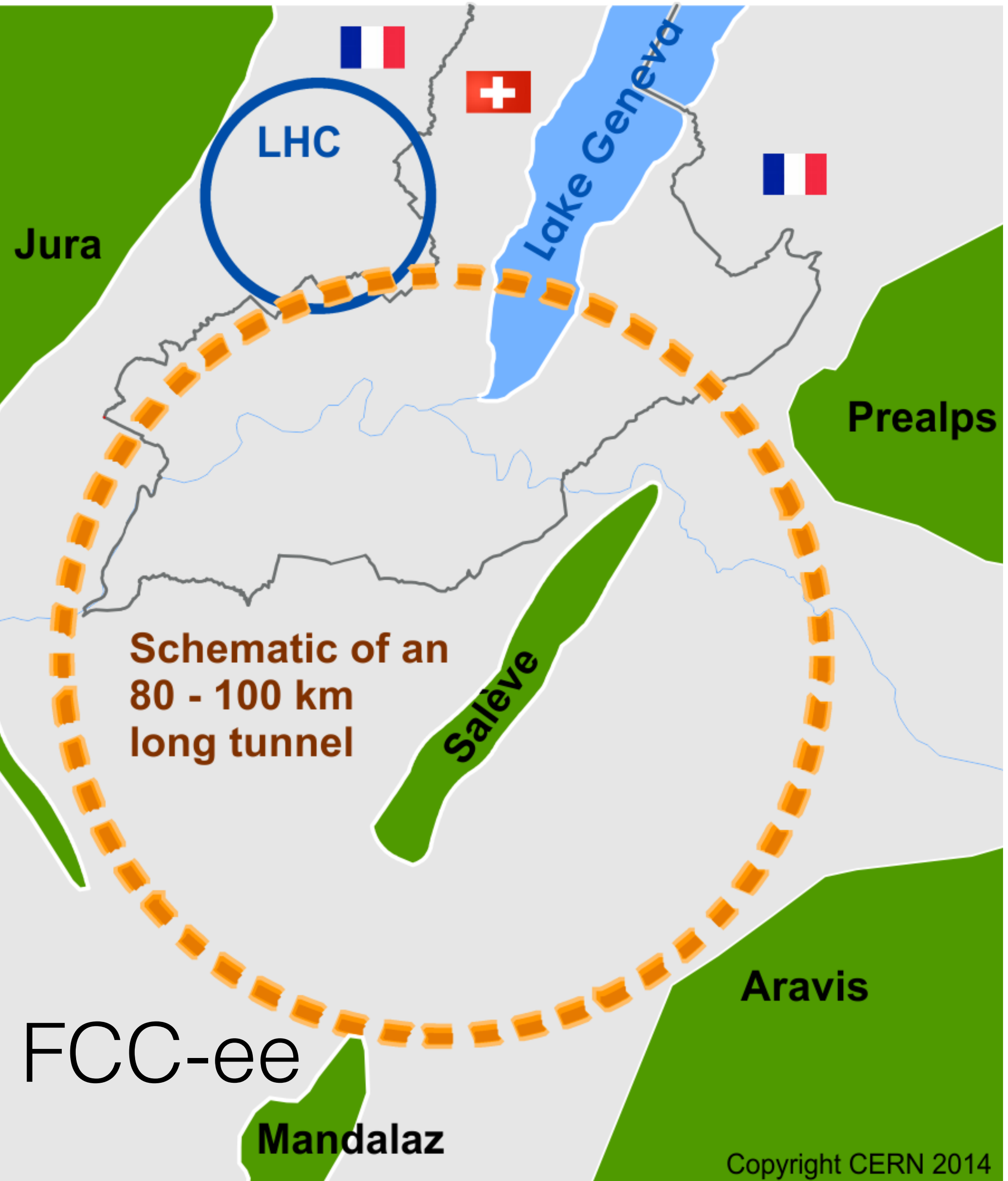


CEPC



Future Circular e^+e^- Colliders

Markus Klute (MIT)

November 5th, 2020
Korean Physical Society Meeting

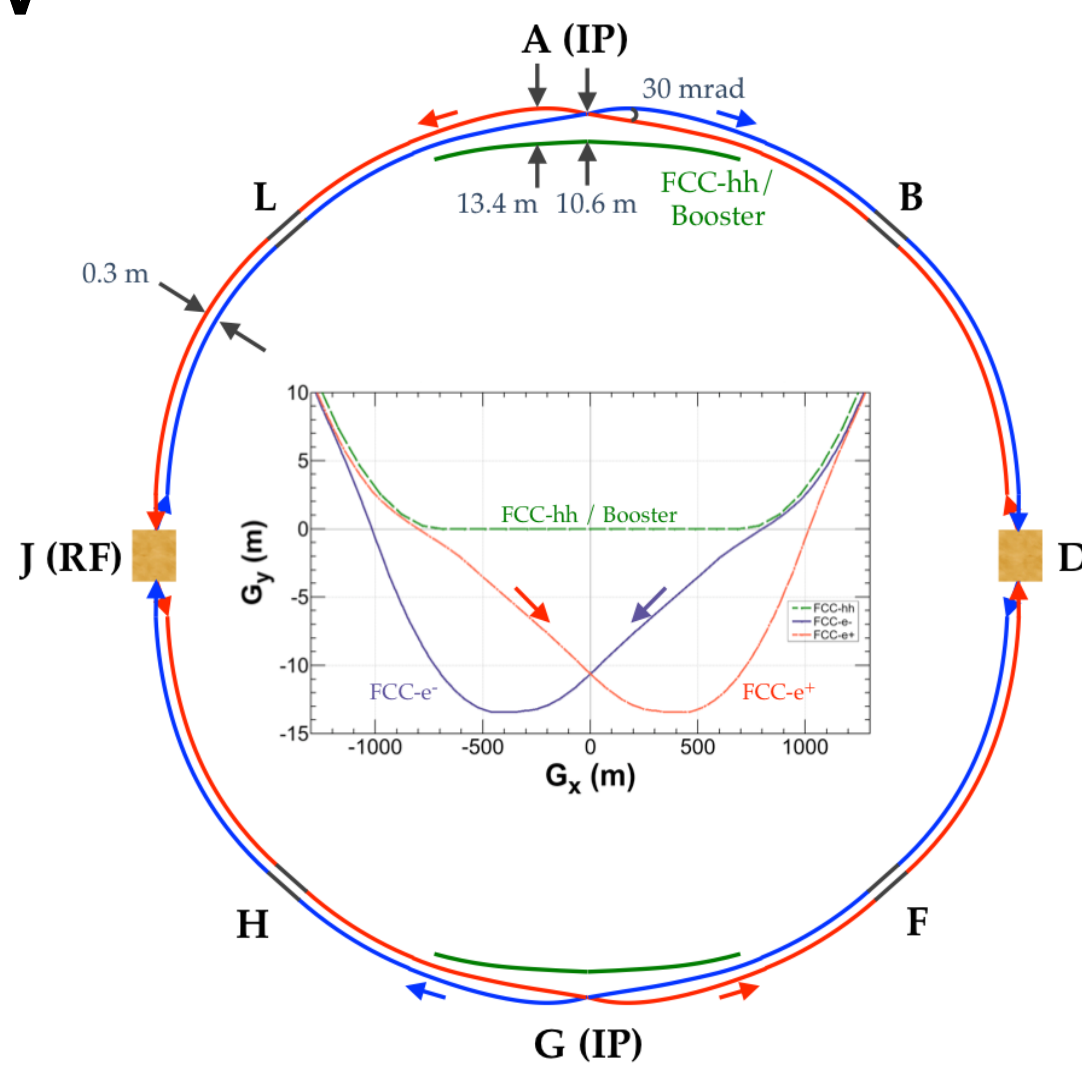
Circular Lepton Colliders

- **FCC-ee and CEPC** are electron-positron collider sharing infrastructure with a subsequent hadron collider (FCC-hh / SppC)

- Beam energies range from **45.6 to 182.5 GeV** covering the Z-pole, W-pair threshold, ZH production and the top-pair production

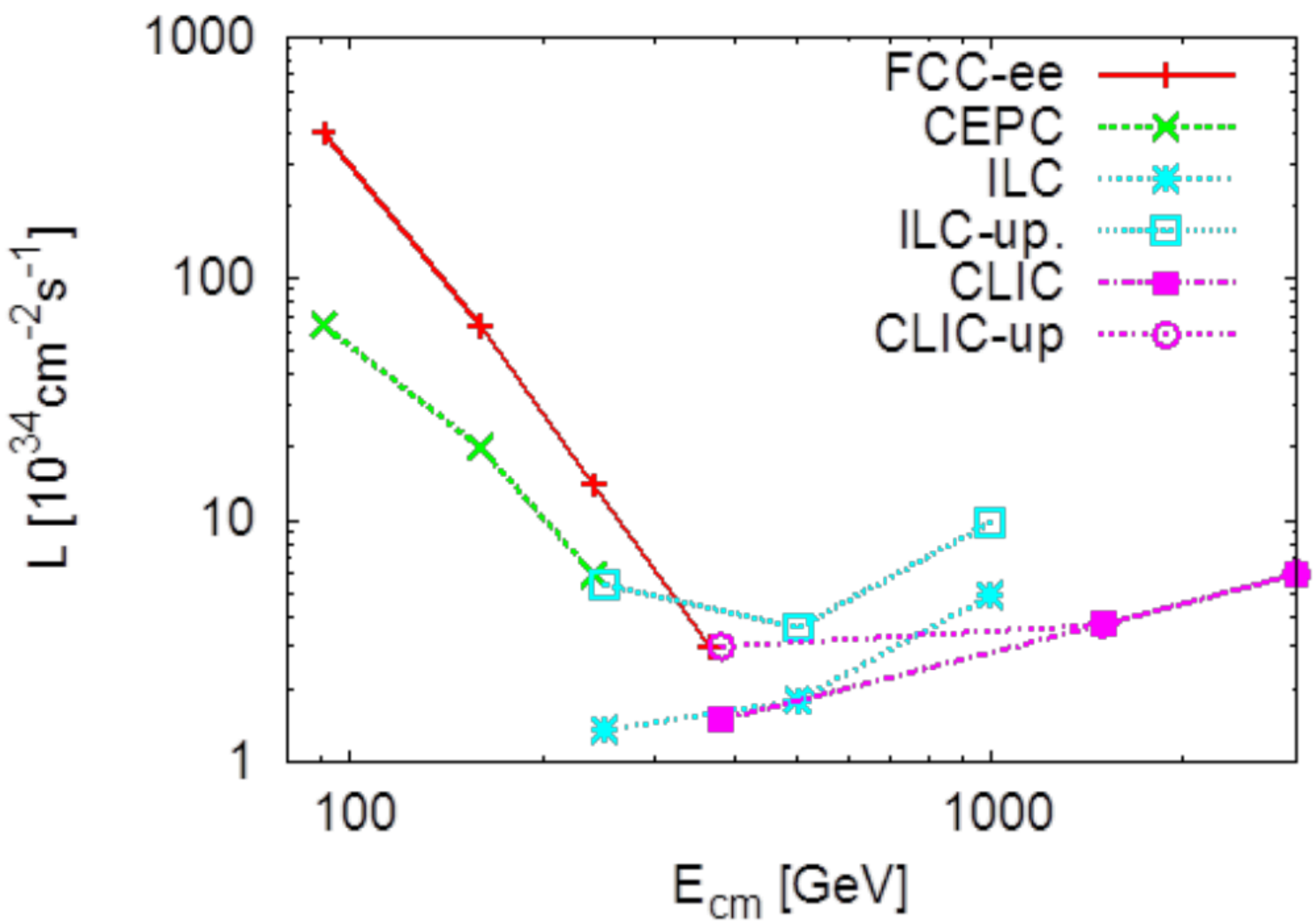
- Double-ring collider with 2 (or 4) interaction regions and a booster synchrotron in a ~100km tunnel

- Injector complex with linac, pre-booster, and e+ source with damping ring



Future Circular Collider Study. Volume 2: The Lepton Collider (FCC-ee) Conceptual Design Report, December 2018. Published in Eur. Phys. J. ST.
Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020, arXiv:1910.11775 ; CERN-ESU-004

Physics Results Landscape



(4y)	Z peak	E_{cm} = 91 GeV	$5\ 10^{12}$	e+e- → Z
(2y)	WW threshold	E_{cm} = 161 GeV	10^{8}	e+e- → WW
(3y)	ZH threshold	E_{cm} = 240 GeV	10^{6}	e+e- → ZH
(4y)	$t\bar{t}$ threshold	E_{cm} = 350 GeV	10^{6}	e+e- → $t\bar{t}$
(ny)	H(optional)	E_{cm} = 125 GeV	10^{4}	e+e- → $\bar{H}$

LEP x 10^{5}
LEP x 2.10^{3}
Never done
Never done
Never done
Never done

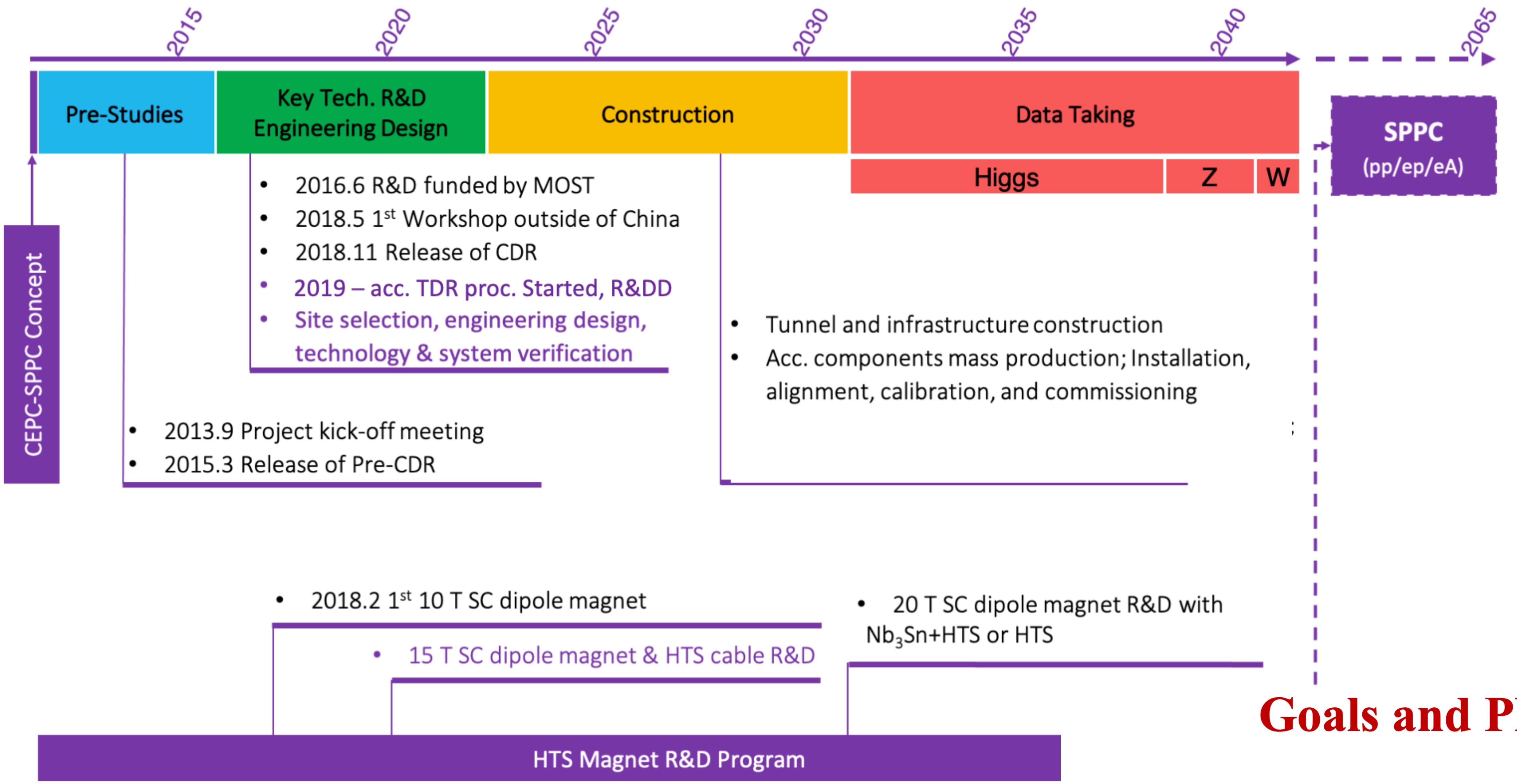
E_{CM} errors:

100 keV
300 keV
2 MeV
5MeV
<1 MeV

Great energy range for the heavy particles of the Standard Model.
Complementarity with hadron colliders (LHC, FCC-hh/SppC) and also with linear colliders

Timelines

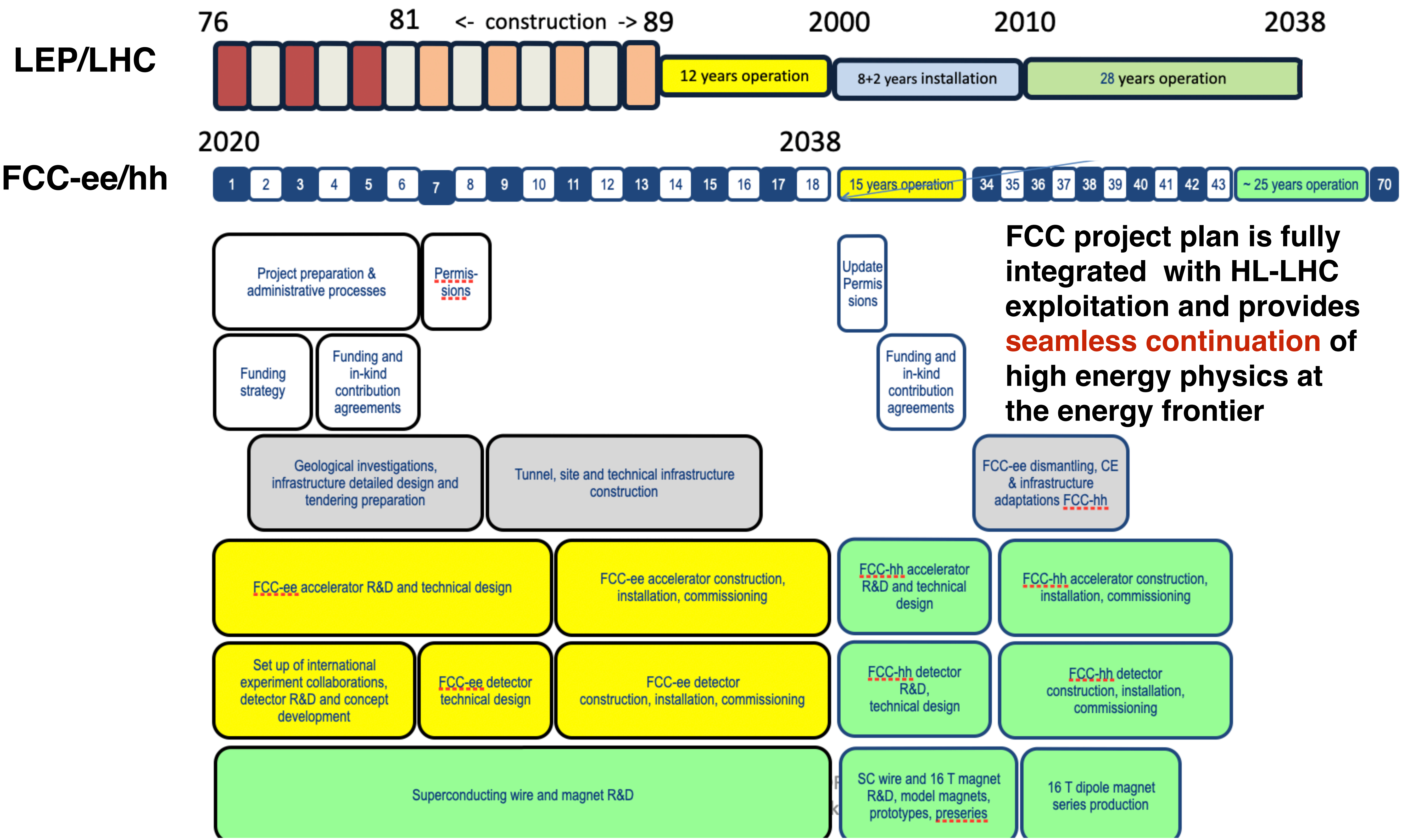
CEPC Project Timeline



Goals and Plan

- **Design enhancement + R&D**
- **Validation, & industrial preparation**
- **Best prepare CEPC for national government's approval**
- **Realization of the CEPC project, the experimental program and pursue the science**
- **International collaboration and coordination**

Timelines



FCC project plan is fully integrated with HL-LHC exploitation and provides seamless continuation of high energy physics at the energy frontier

European Strategy

Preamble: The particle physics community is ready to take the next step towards even higher energies and smaller scales. The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

High-priority future initiatives

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. Accomplishing these compelling goals will require innovation and cutting-edge technology:

the particle physics community should ramp up its R&D effort focused
· on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

· Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

FCC Main Goals (2020-2026)

Overall goal

- Perform all necessary steps and studies to enable a definitive project decision by 2026, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2029.

This requires successful completion of the following four main activities

- Develop and establish a governance model for project construction and operation
- Develop and establish a financing strategy
- Prepare and successfully complete all required project preparatory and administrative processes with the host states (debat public, EIA, etc.)
- Perform site investigations to enable CE planning and to prepare CE tendering.

In parallel development preparation of TDRs and physics/ experiment studies

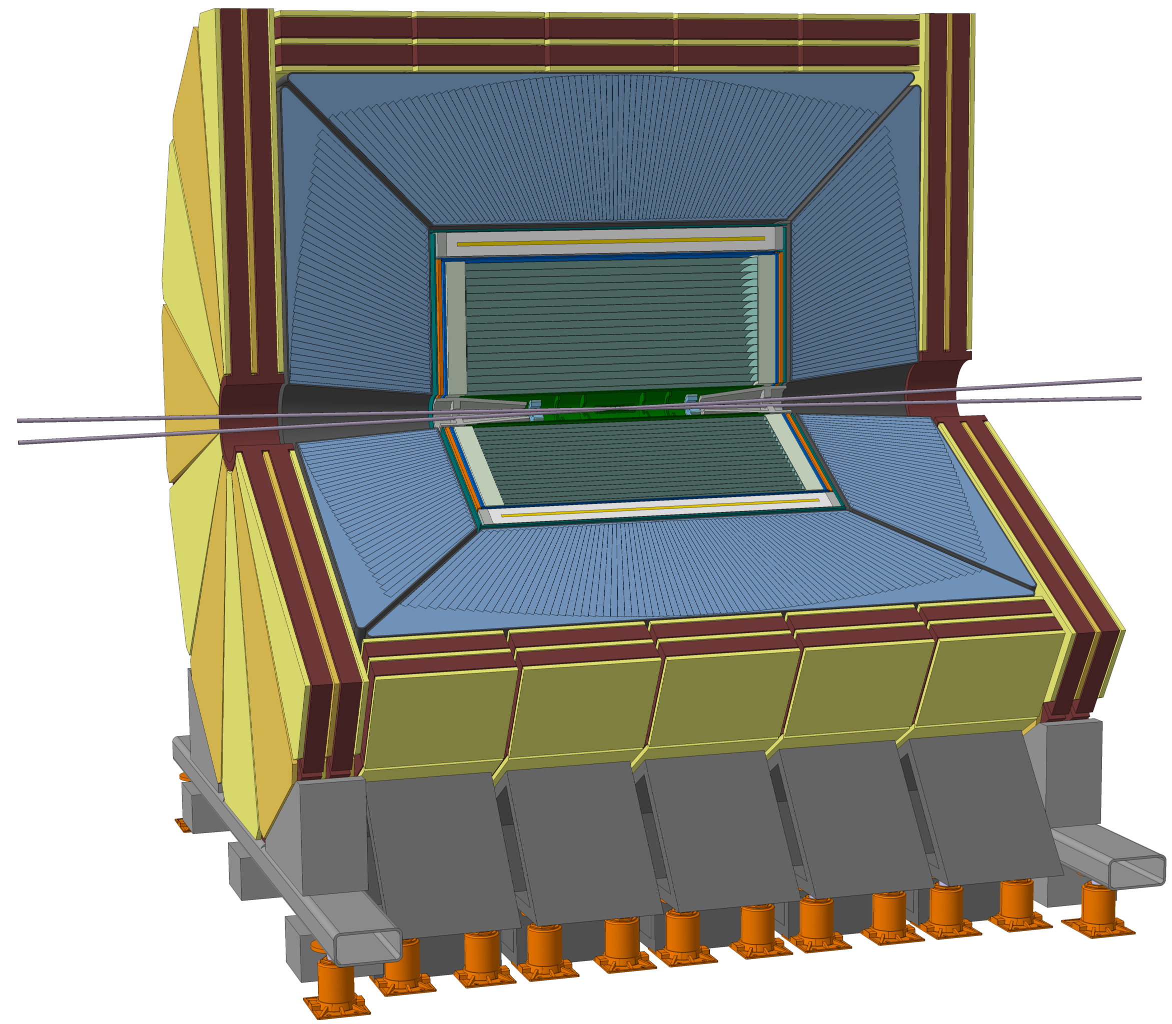
- Machine designs and main technology R&D lines
- Establish user communities, work towards proto-experiment collaborations by 2025.

Detectors

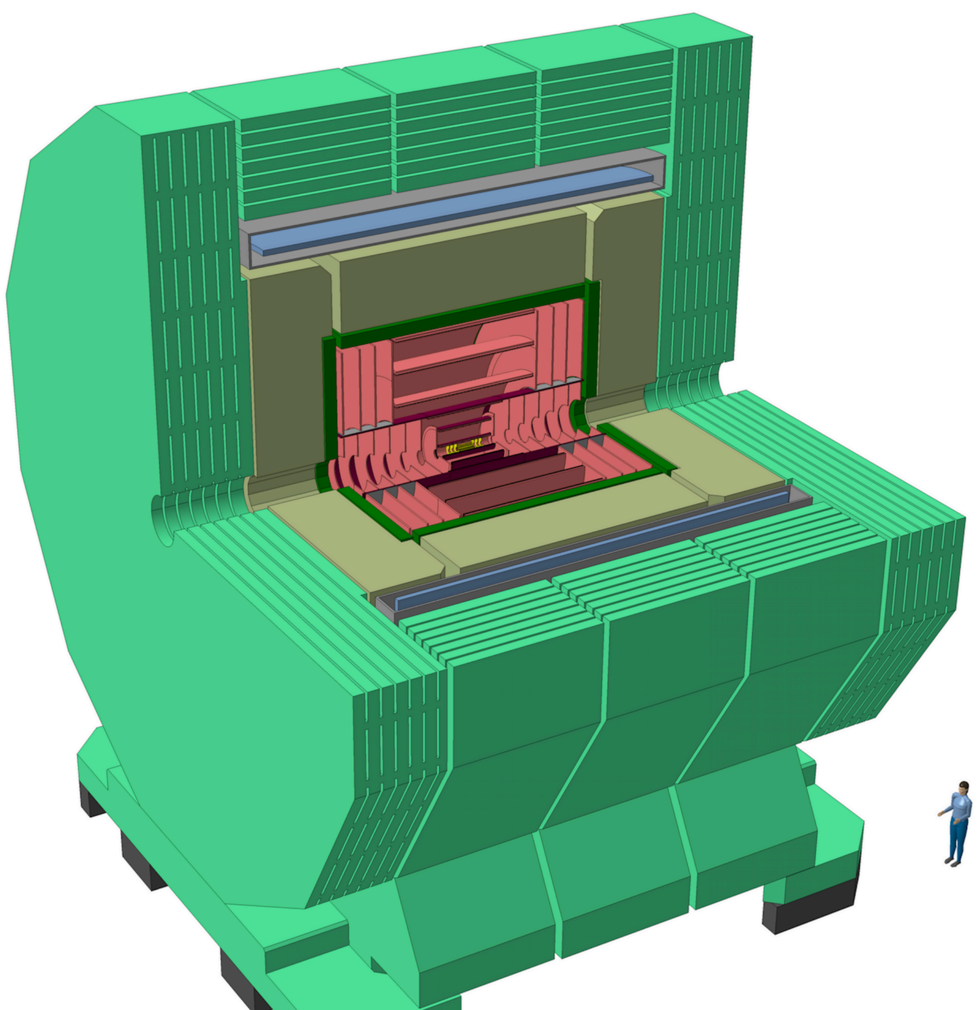
Two detector concepts used for integration, basic performance and cost estimates:

- Linear Collider Detector group at CERN has undertaken the adaption of a detector for FCC-ee
- IDEA, detector specifically designed for FCC-ee (and CEPC)

IDEA design



CERN adapted design



Next step is to design detectors for physics

Opportunity to design multiple collider detector

Detectors Requirements

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

All requirements need to be re-evaluated

- Excellent PID, for π/K separation up to ~20 GeV.
- High precision luminosity measurement, $\delta L / L \sim 10^{-4}$.

from CEPC Workshop Talk by Jianchun Wang

The Higgs Factory

(4y)	Z peak	E_{cm} = 91 GeV	5 10^{12}	e+e- → Z
(2y)	WW threshold	E_{cm} = 161 GeV	10^{8}	e+e- → WW
(3y)	ZH threshold	E_{cm} = 240 GeV	10^{6}	e+e- → ZH
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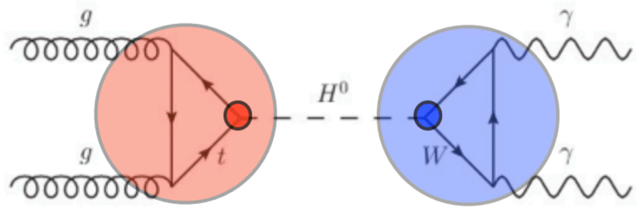
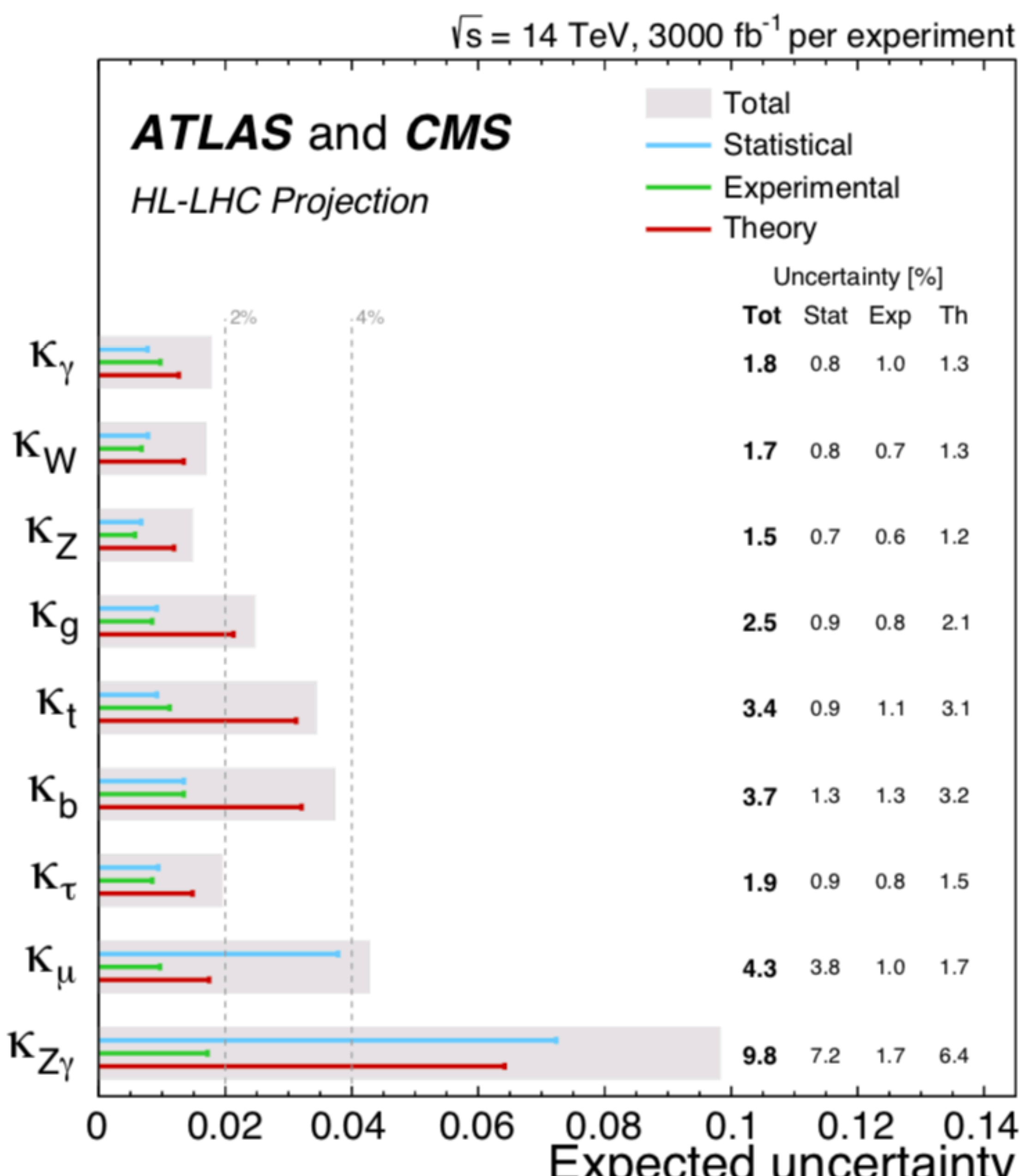
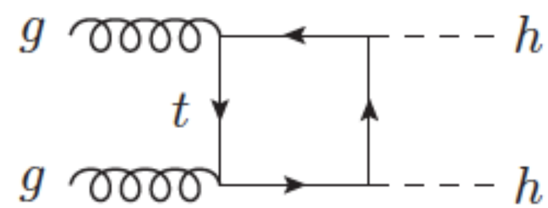
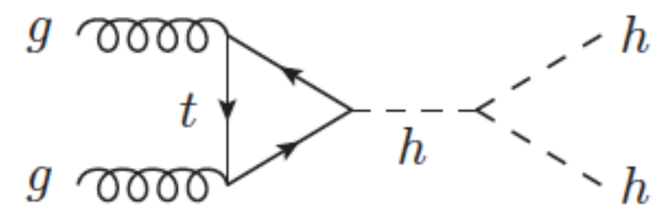
HL-LHC Higgs Legacy

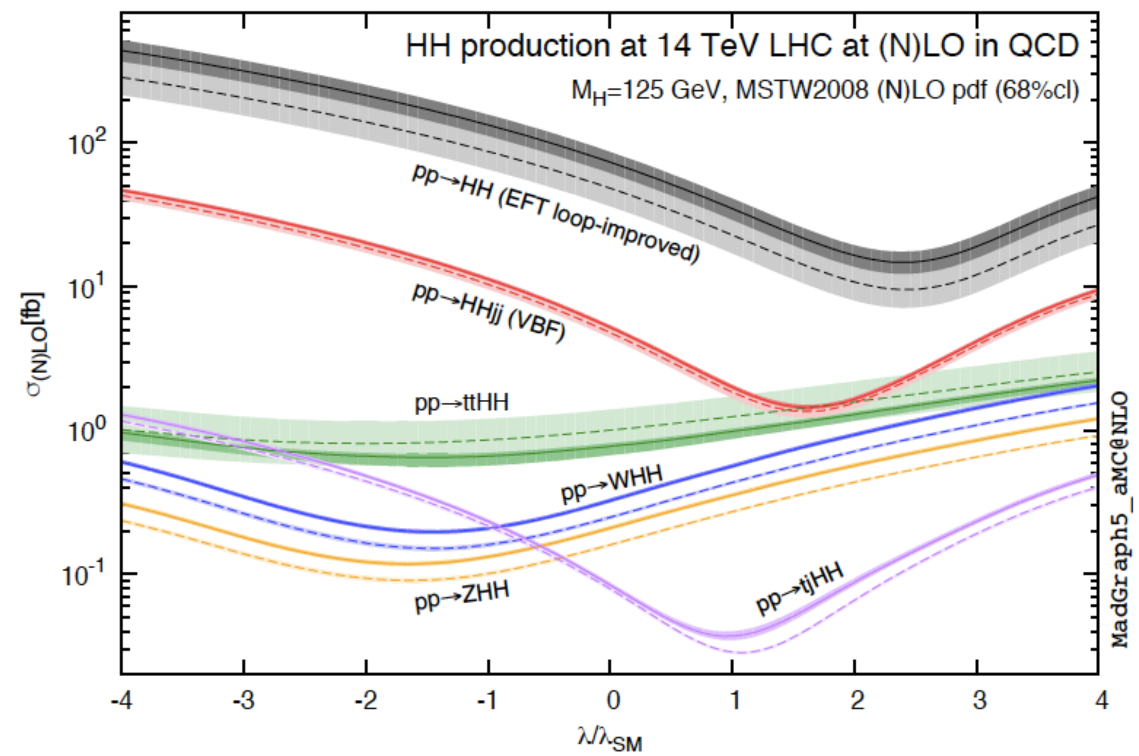


$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$





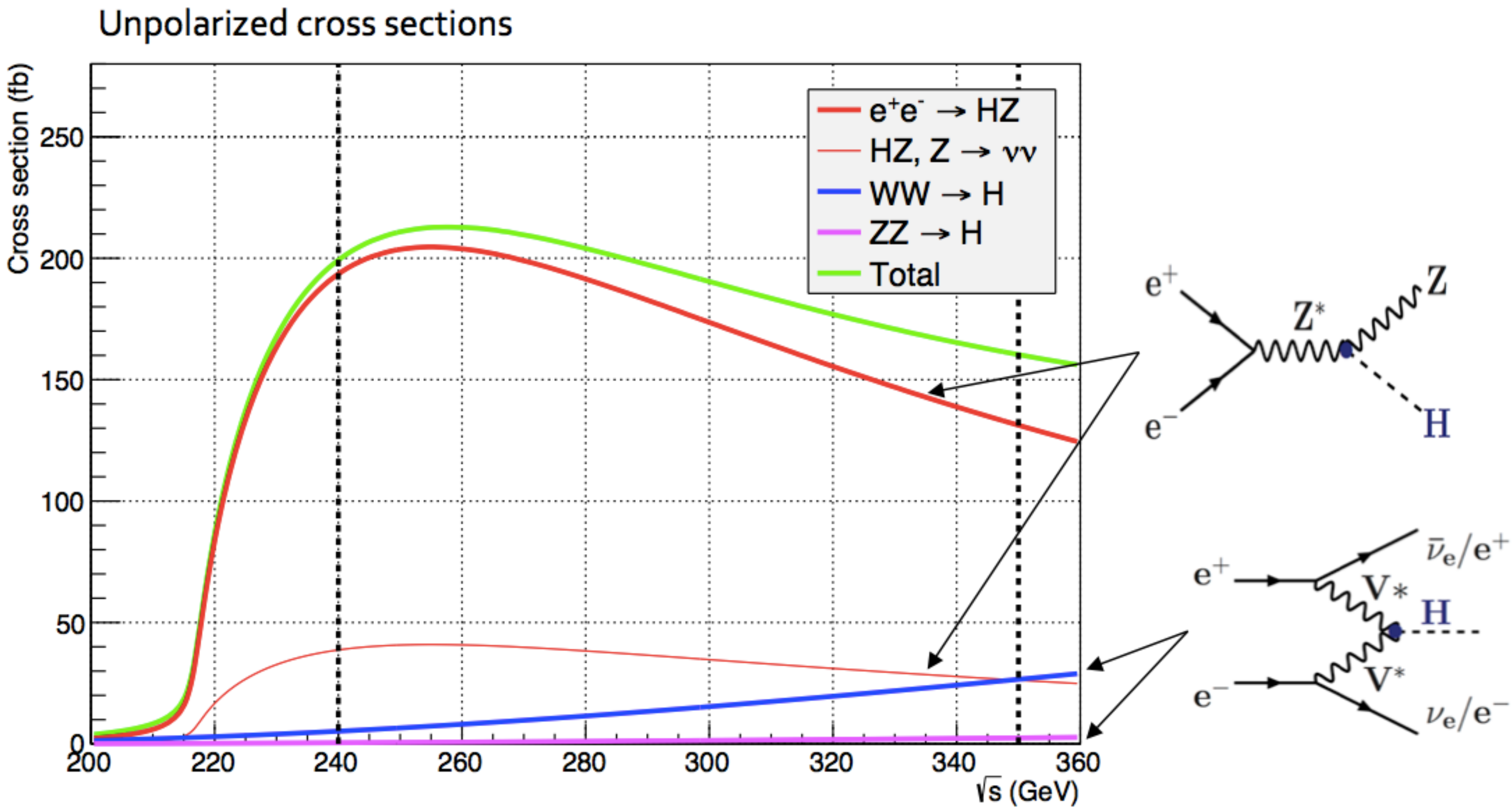




	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6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

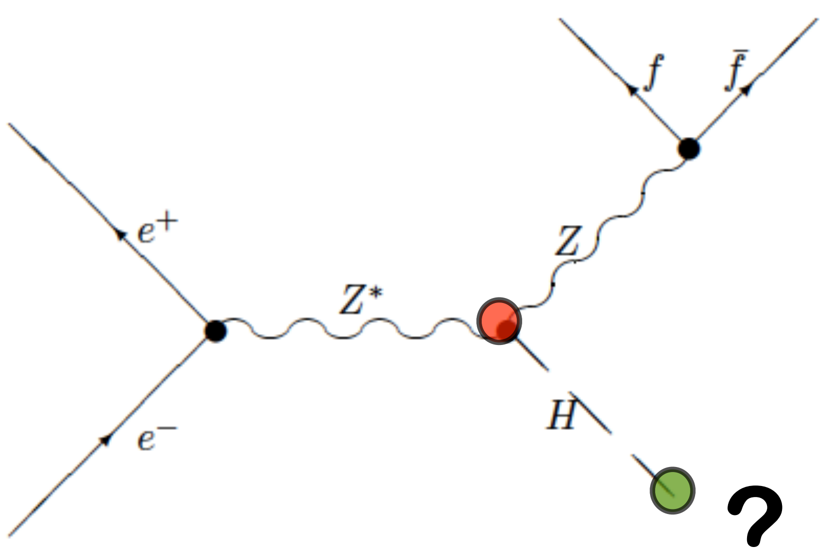
Higgs Production

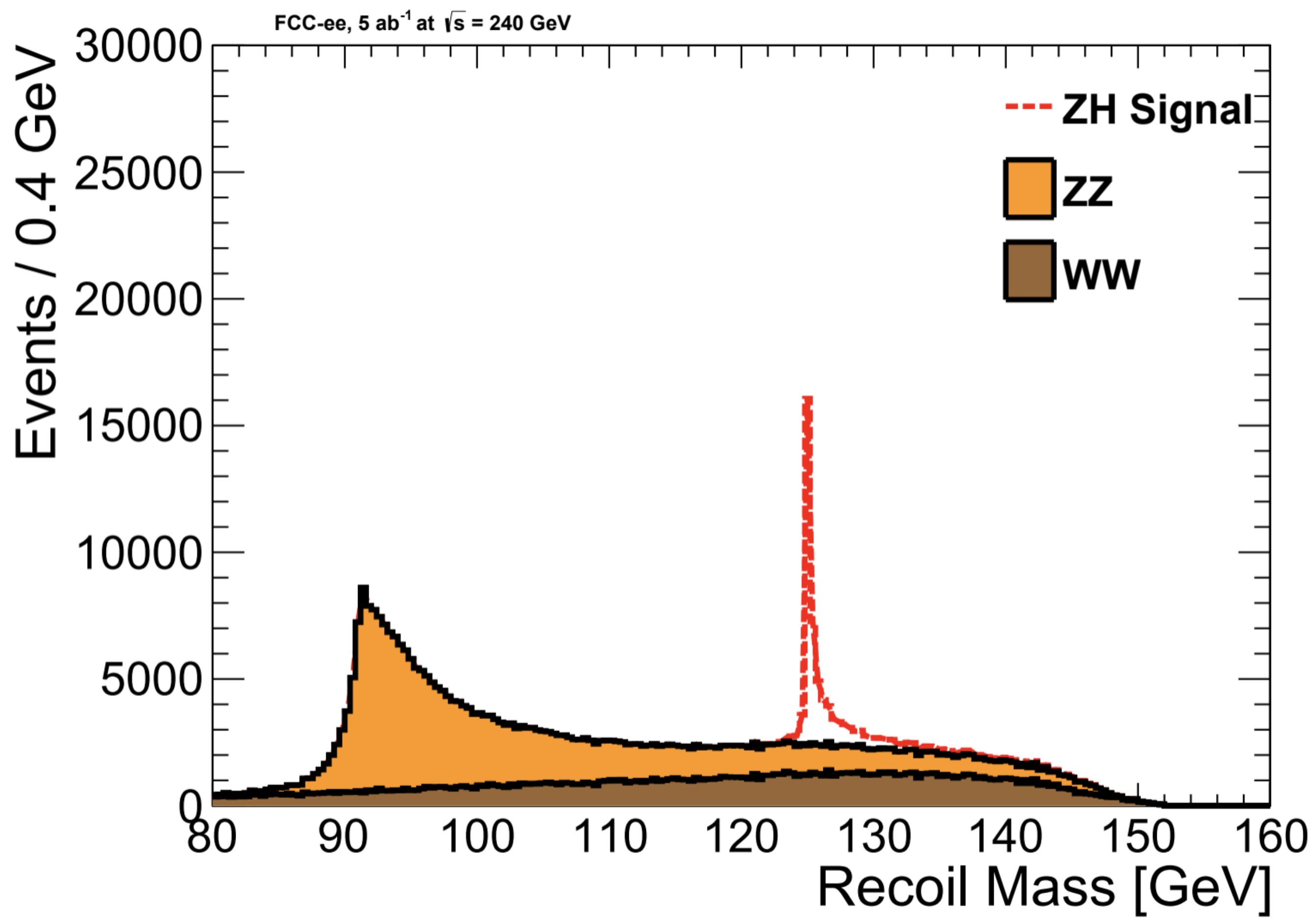
➡ $e^+e^- \rightarrow ZH$ production maximal at 240-260 GeV



Higgs Precision Measurements

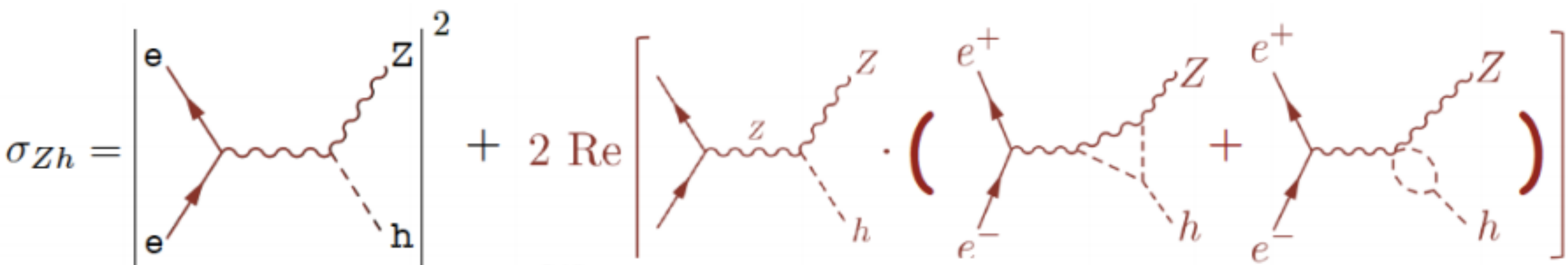
- ➡ Recoil method unique to lepton collider
- ➡ Tag Higgs event independent of decay mode
- ➡ Provides precision and model independent measurements of
  - $\sigma(ee \to ZH) \propto g_{HZZ}^2$
  - m_H
- ➡ Key input to Γ_H
- ➡ Sensitive channel for Higgs to invisible search





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

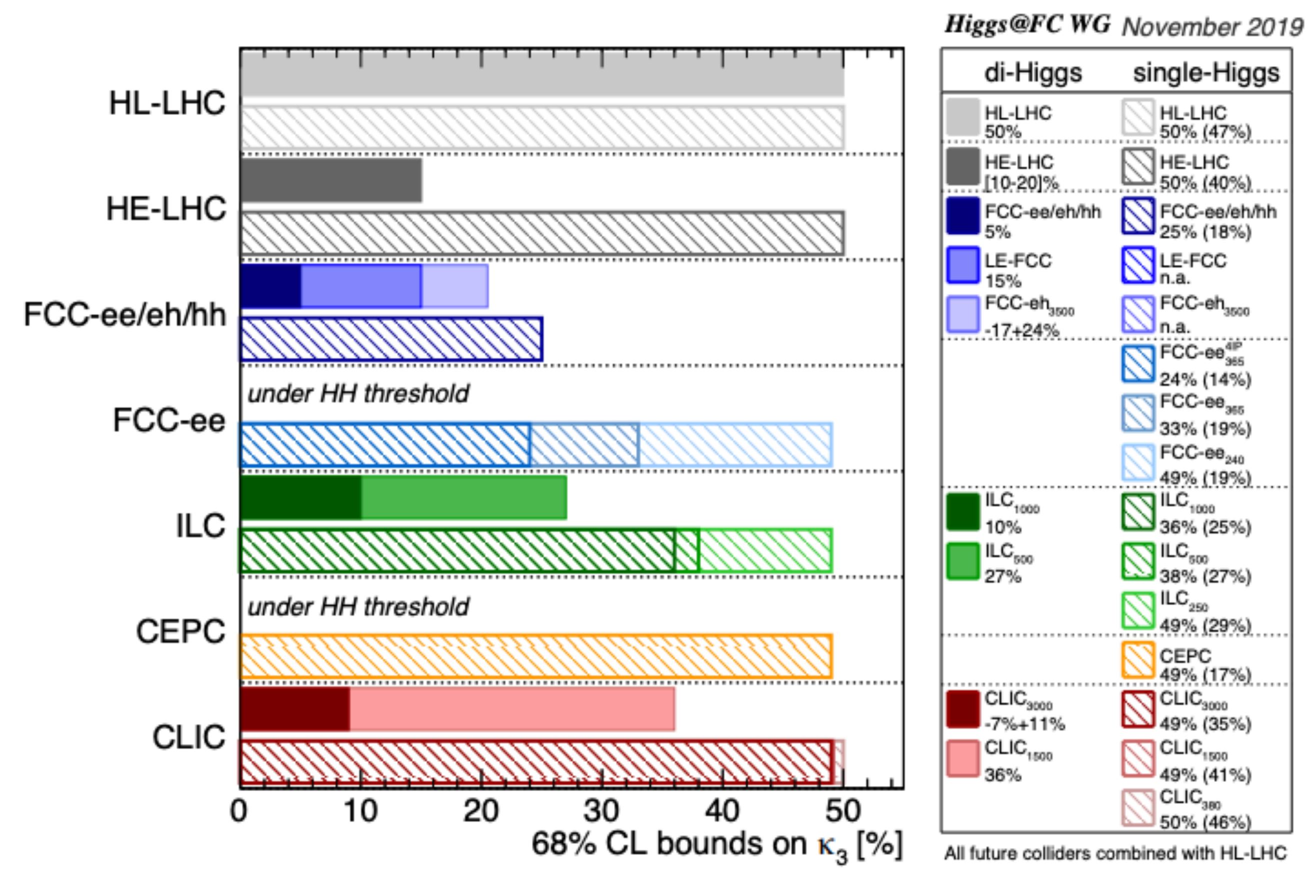
Higgs self-coupling through loop corrections



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling

collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-



[arxiv:1312.3322](https://arxiv.org/abs/1312.3322)

[arxiv:1910.00012](https://arxiv.org/abs/1910.00012)

Higgs Couplings

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+ 1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	8	3	+ 4	–	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.30	0.60	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.3	**0.61**	0.56	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	1.6	**1.01**	0.90	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.4	**0.74**	0.67	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	10.1	**9.0**	3.8	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	4.8	**3.9**	1.3	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	3.1	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	**< 1.0**	< 1.0	n.a.

➡ **With enough work, uncertainties not limited by experimental or theoretical uncertainties. Statistics sets the floor.**

➡ **3-5 standard derivation sensitivity to Higgs self-coupling via ZH cross section dependency**

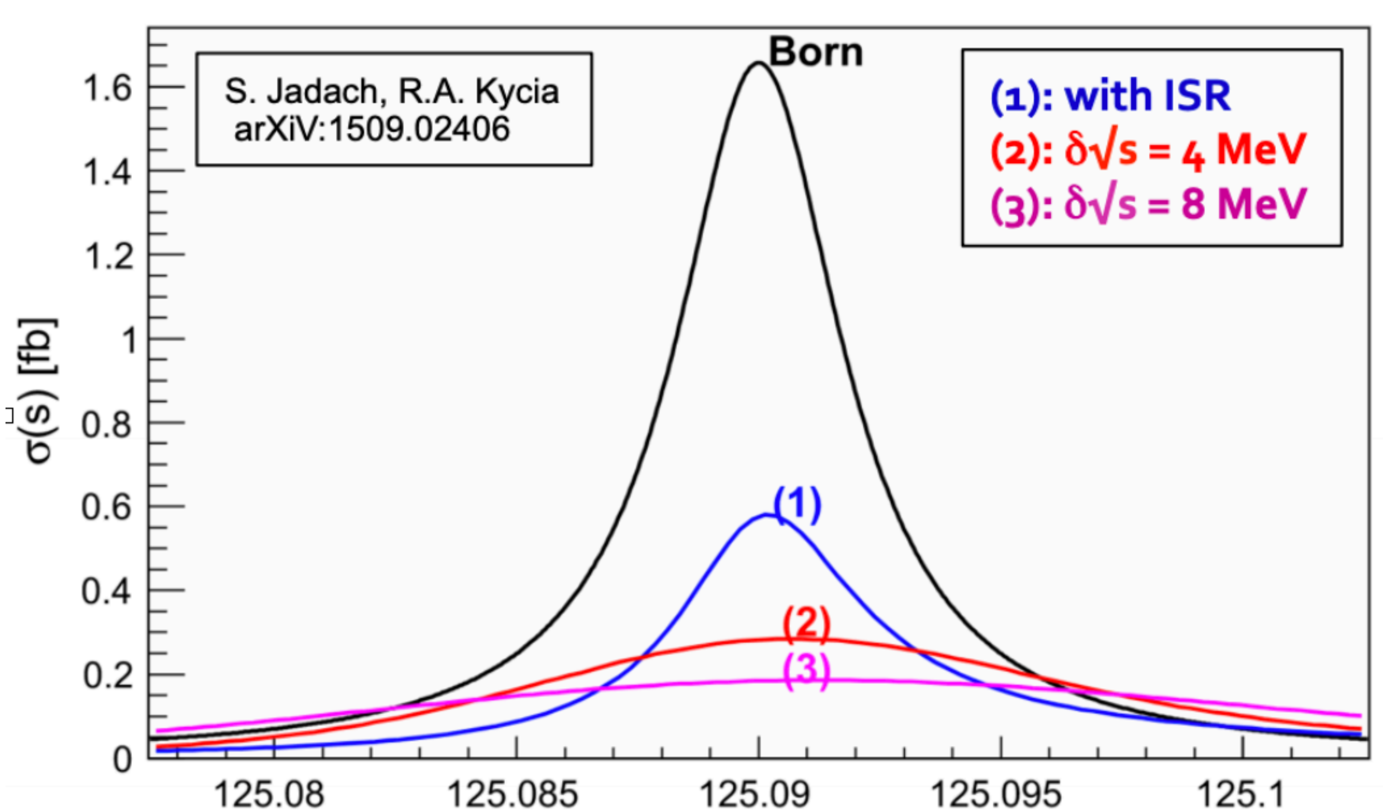
➡ **Complementarity with LHC and FCC-hh program**

Eur. Phys. J. C. (2019) 79:474

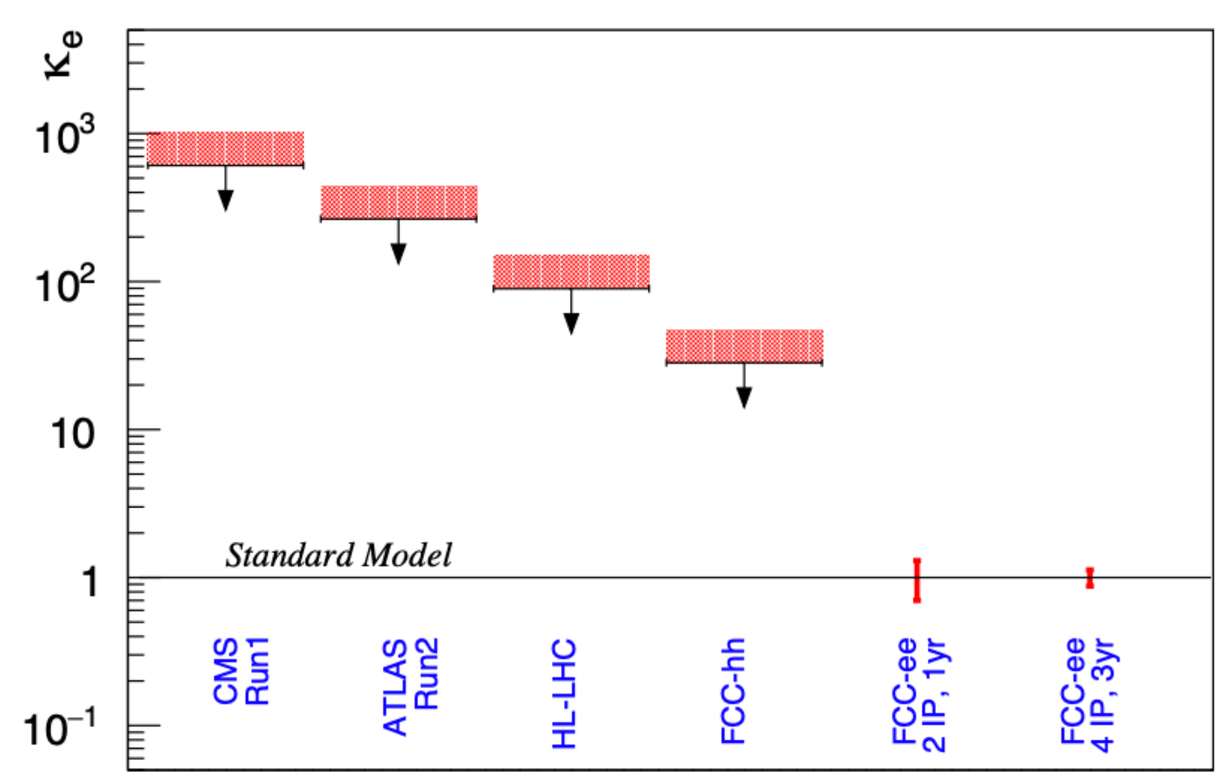
Unique measurement

➡ **First generation Higgs couplings**

- **Not part of baseline run plan but a few years at √s = mH with high luminosity and monochromatization is an interesting add-on**
- **Expected signal significance of 0.7σ / 10ab-1**
  - **Set a electron Yukawa coupling upper limit: $k_e < 2.5$ @95% CL**
  - **Reaches SM sensitivity after 5 years**



Upper Limits / Precision on κ_e



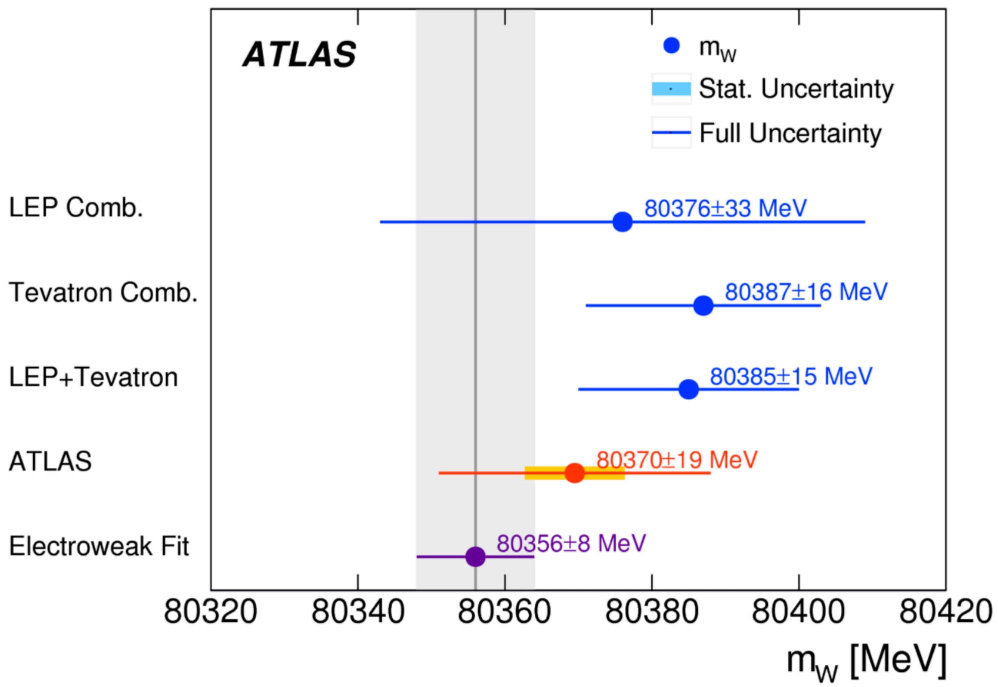
EW & Top Physics Program

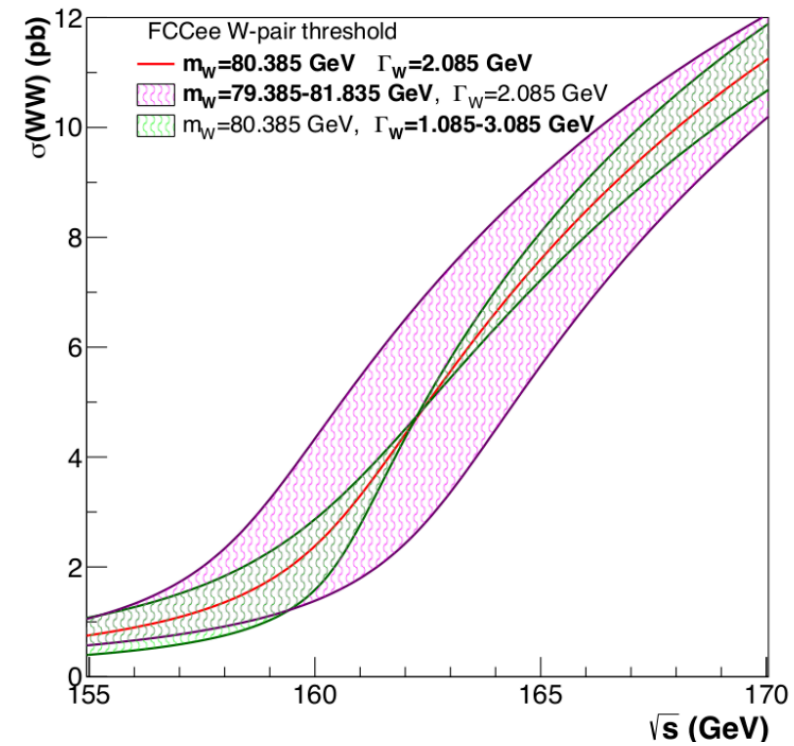
Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	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 above
R_b $(\times 10^6)$	216290 ± 660	**0.3**	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
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
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**3**	1	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
$A_{FB}^b, 0$ $(\times 10^4)$	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
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
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

First set of main observables - needs to be improved

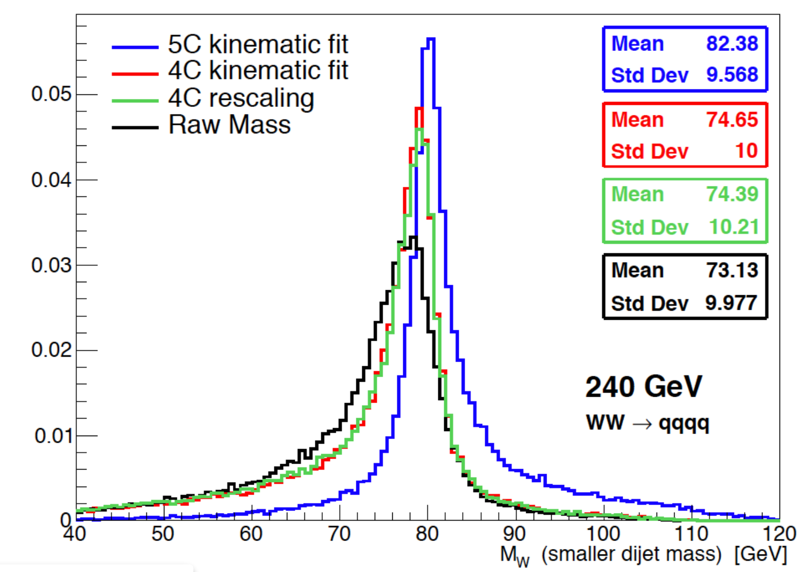
- **Focus on statistical precision**
- **For Z and W boson mass, center-of-mass energy uncertainty will dominate**
- **For cross-section measurements the luminosity measurement will be limiting**
- **Possible experimental uncertainties are indicative**
- **Tau, b, and c observables to be added**
- **Theory work is critical and has been initiated. A lot of work ahead.**
- **Aim for next study: detector design to match experimental systematic uncertainties to statistical precision**

W Mass Measurement





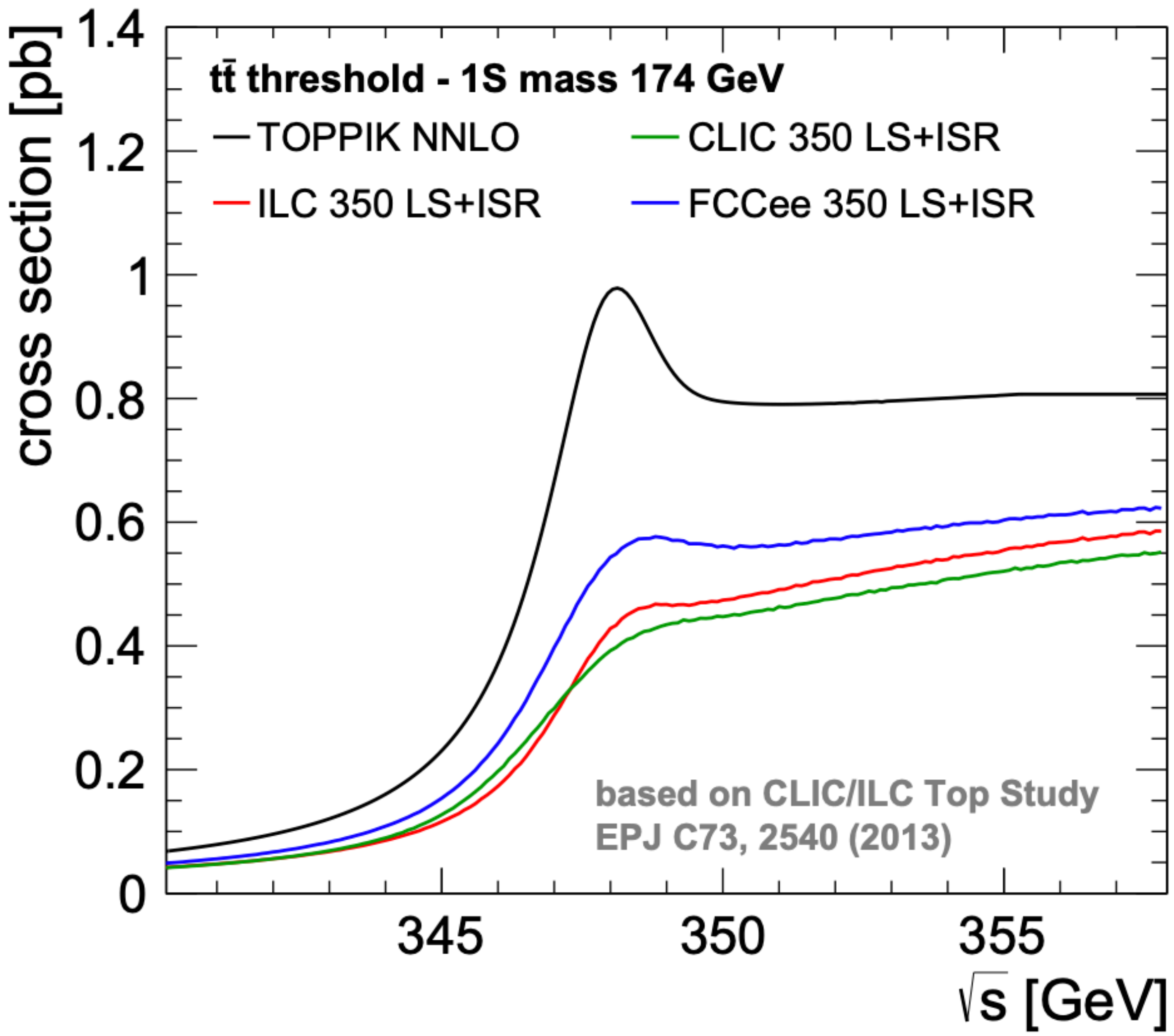
- W pair threshold scan with => ΔM_W = 0.45 MeV (stat. only)
    - Leading systematic: beam energy
- Direct W mass reconstruction => ΔM_W = 0.22 MeV (stat. only)
    - Leading systematic: theoretical

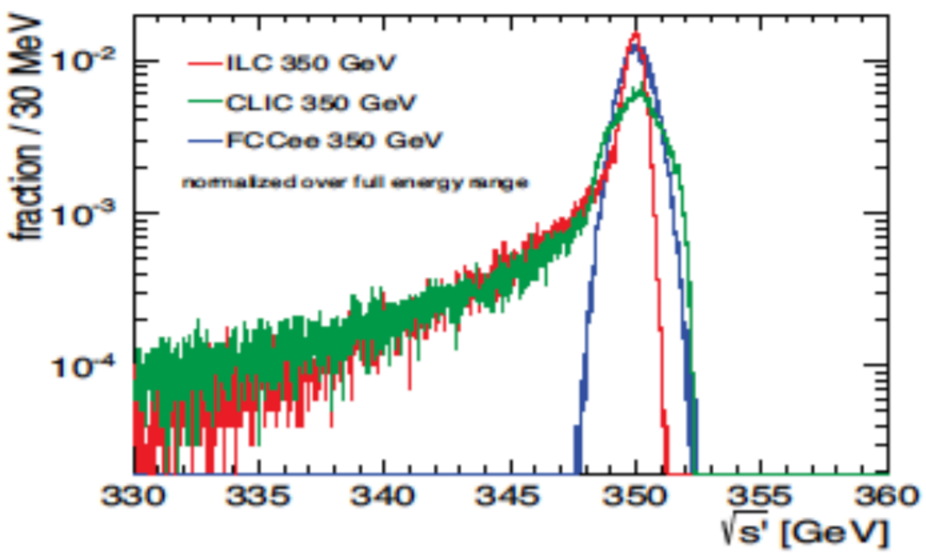


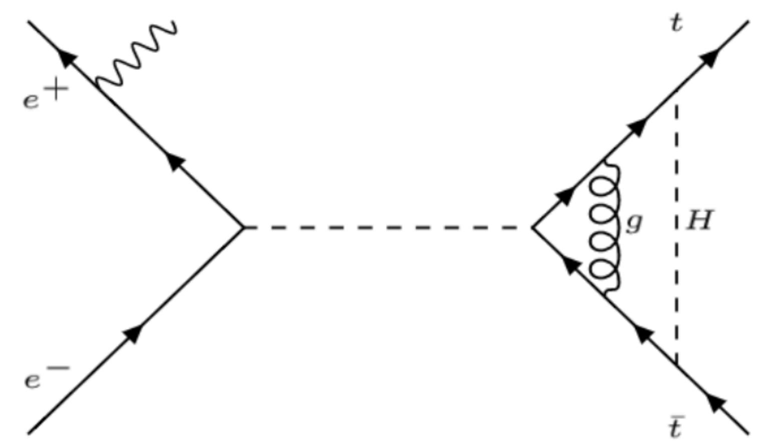
Can systematic uncertainties meet statistical precision?

Top-pair threshold scan

➡ Top mass and width can be measured directly with an accurate top cross section threshold scan



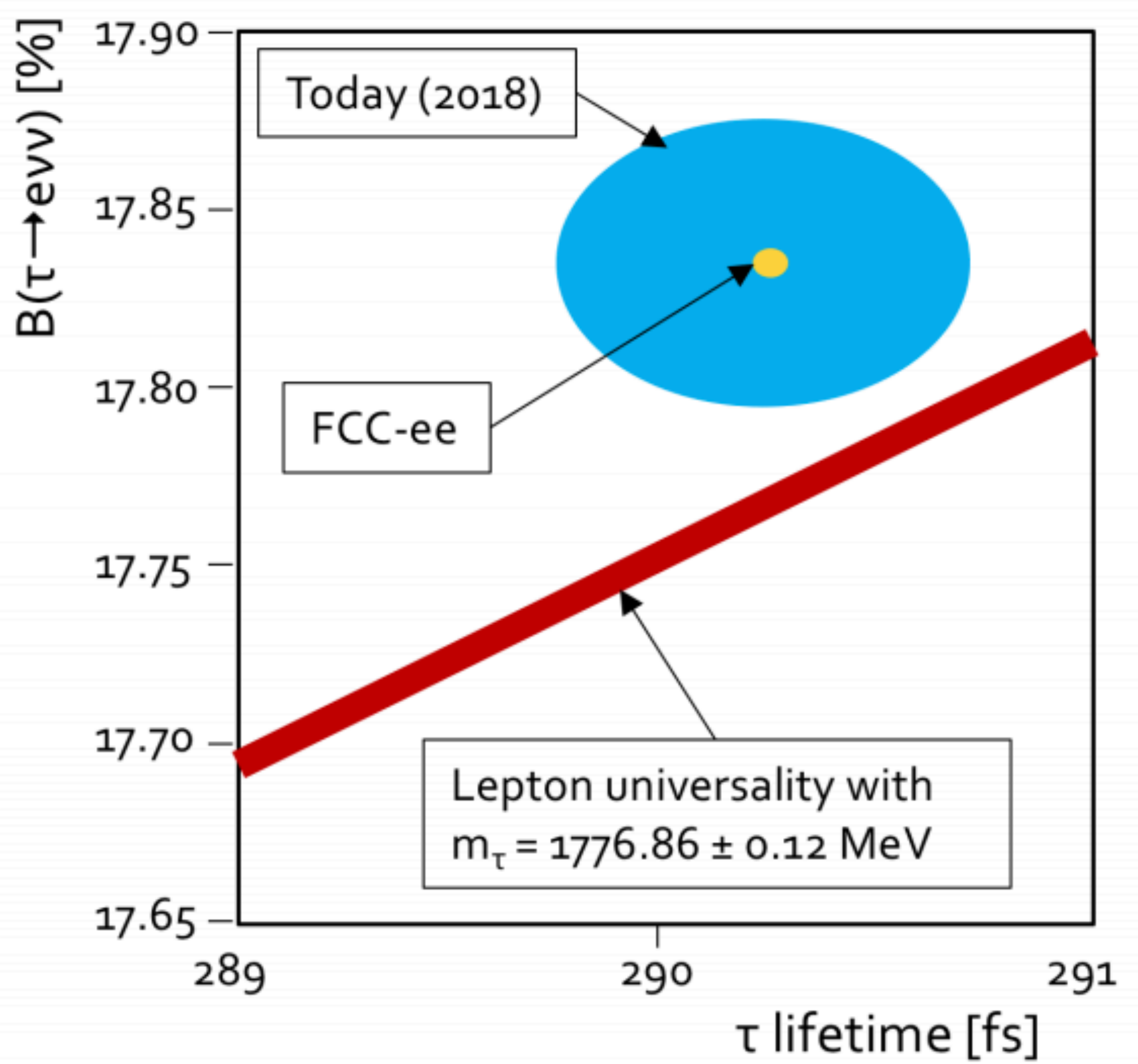




➡ Precise knowledge of α_s improved correlation of m_t, Γ_t, and Y_t drastically

arxiv:1604.08122

Tau and Flavor Physics



Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

Can systematic uncertainties meet statistical precision?

Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

arXiv:1811.09408

Discovery Physics

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0
I=1/2	I=0	

Economic extension by adding a number of Fermionic singlets

- "Right-handed" or "sterile" neutrinos.

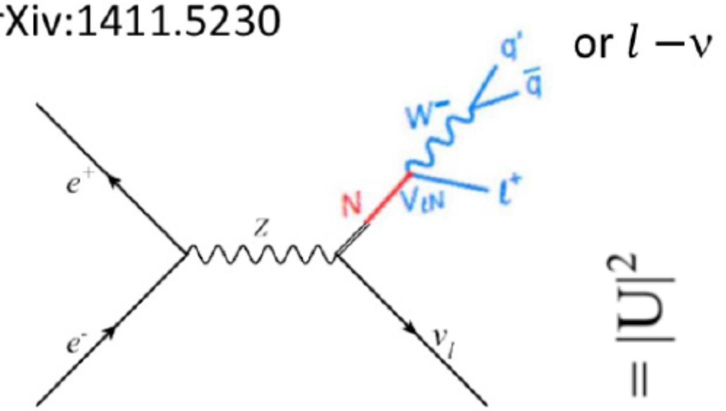
Two mass-differences ⇒ at least two sterile neutrinos.

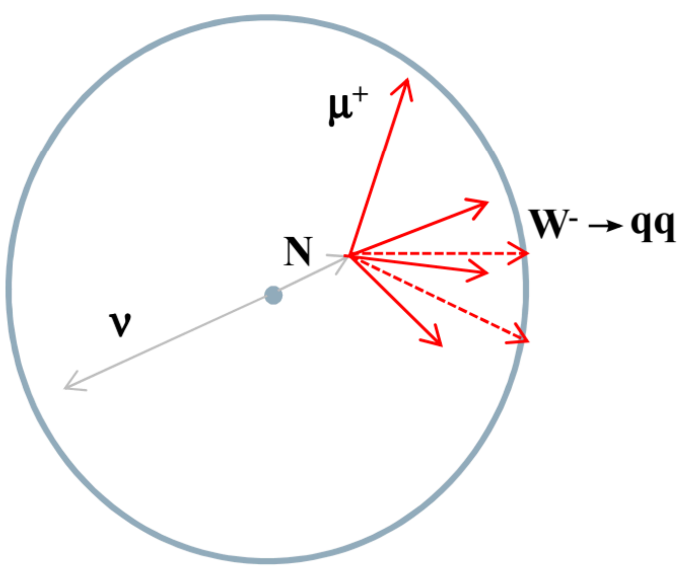
New mass scale, a priori unrelated to the known ones.

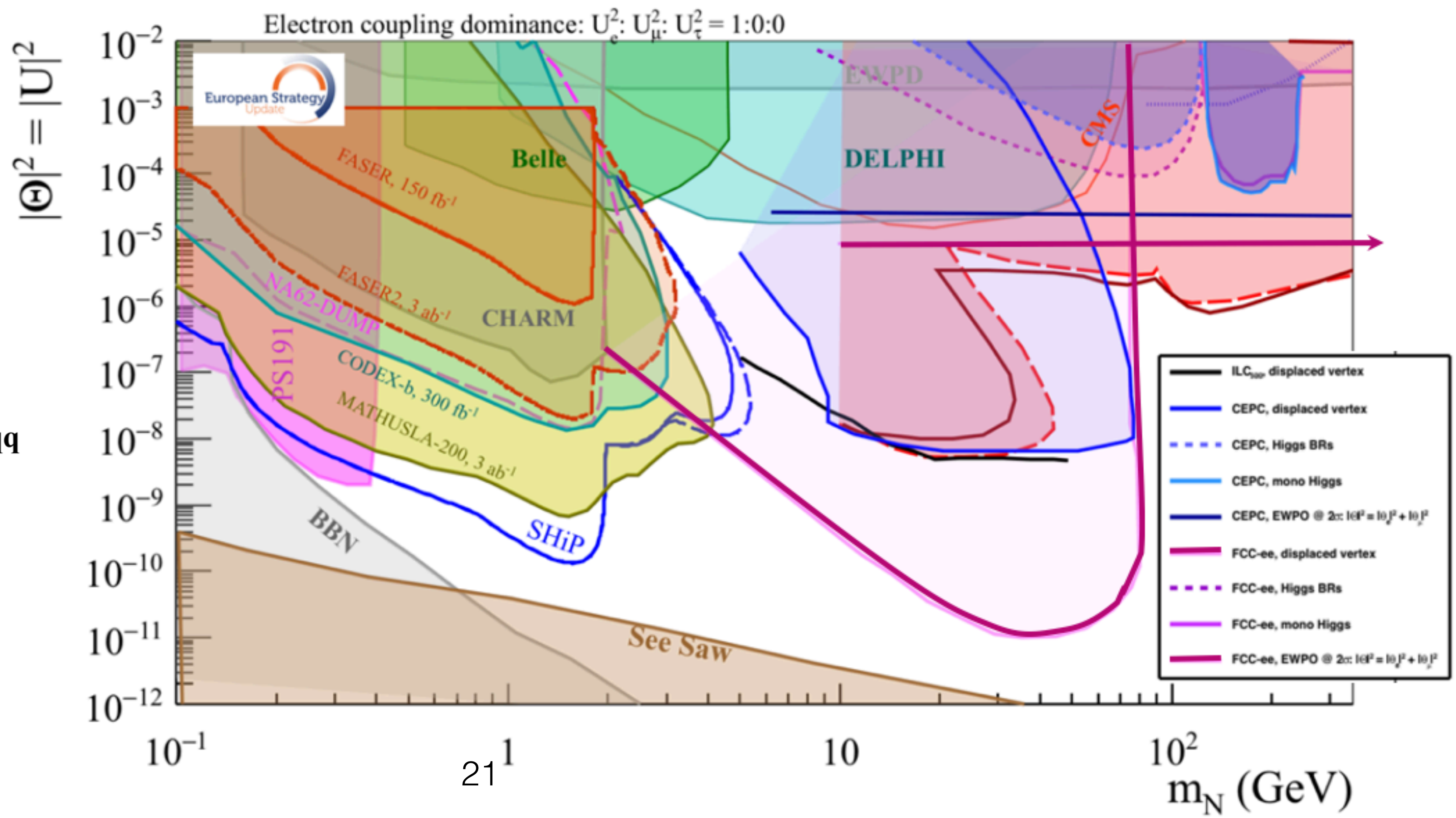
Many constraints from experiments on all energy scales.

May be connected to e.g. Dark Matter and Baryogenesis

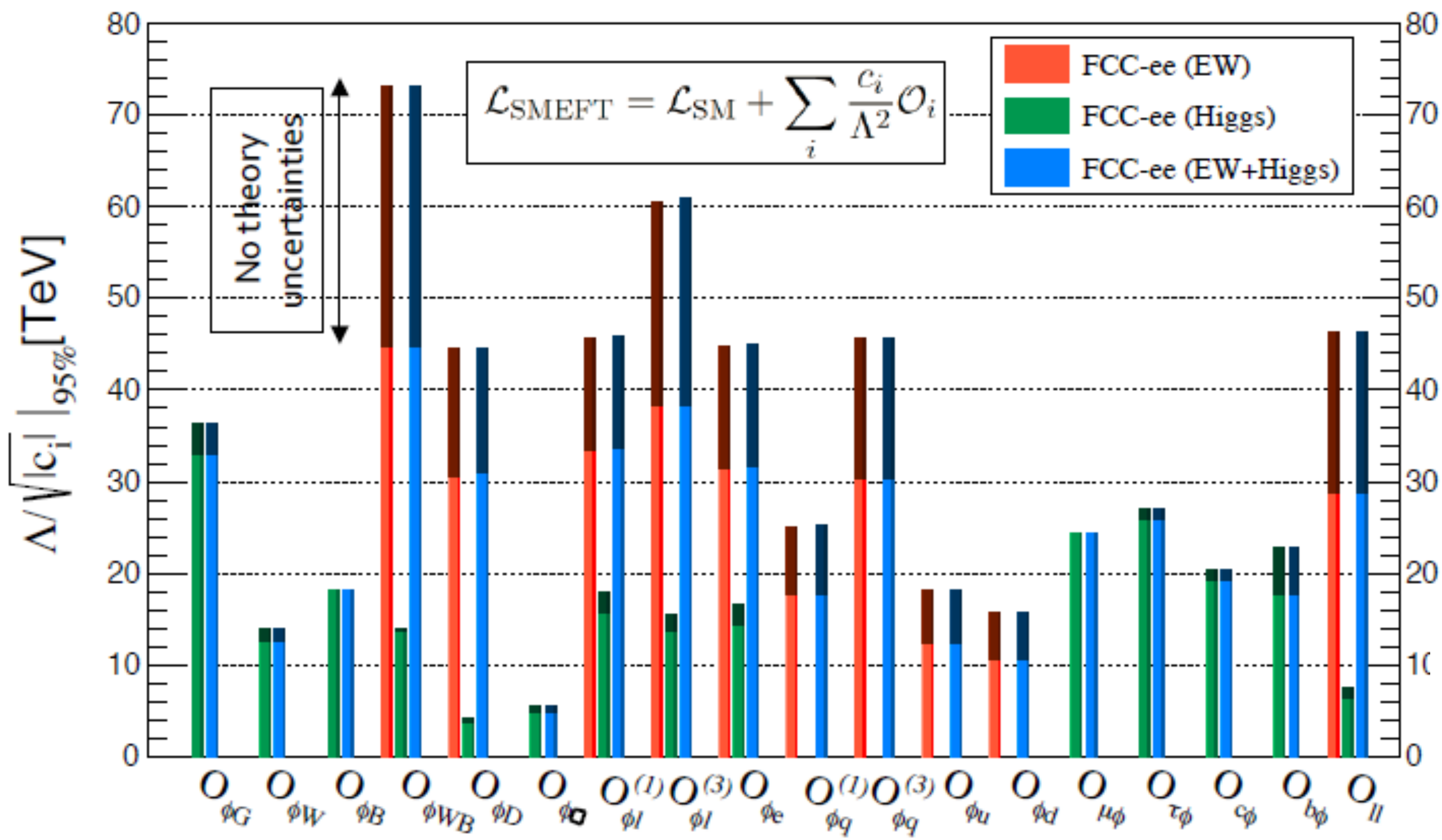
arXiv:1411.5230







Discovery Physics



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

CEPC: International workshop - October 26-28

➡ Excellent resource: https://indico.ihep.ac.cn/event/11444/

The 2020 International Workshop on the High Energy Circular Electron Positron Collider (Oct. 26-28, 2020)

26-28 October 2020
Shanghai
Asia/Shanghai timezone

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The 2020 international workshop on the high energy Circular Electron-Positron Collider (CEPC) will take place between October 26-28, 2020 at Shanghai Jiao Tong University and Tsung-Dao Lee Institute in Shanghai. As you would have expected, this workshop will be mostly online, with some local and domestic in-person participation.

The workshop intends to gather scientists around the world to study the physics potentials of the CEPC, pursue international collaborations for accelerator and detector optimization, deepen R&D work of critical technologies, and develop initial plans towards Technical Design Reports (TDR). The high energy Super proton-proton Collider (SppC), a possible upgrade of the CEPC, will also be discussed. Furthermore, industrial partnership for technology R&Ds and industrialization preparation of CEPC-SppC will be explored.

FCC Workshop - November 9-13

- ➡ https://indico.cern.ch/event/923801/
- ➡ https://indico.cern.ch/event/932973/

FUTURE CIRCULAR COLLIDER

FCC November Week 2020

9-13 November 2020
Europe/Zurich timezone

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The **Future Circular Collider Innovation Study** (FCCIS) will deliver a design and an implementation plan for a new research infrastructure, consisting of a 100 km long, circular tunnel and a dozen surface sites. It will initially host an electron-positron particle collider. With an energy frontier hadron collider as a second step, it can serve a world-wide community through the end of the 21st century. This project will validate the key performance enablers at particle accelerators.

Part of this event is the **4th FCC Physics and Experiments Workshop** (dedicated **agenda and registration**: click here)

This will be a **remote-only event using Zoom for webcast**.

Presentations for non physics or theory activities are on invitation only.

Conclusion

- **FCC-ee/CEPC offer a huge physics program** with
  - ➡ Higgs and top measurements with > 10^6 events in short (3-5y) runs
  - ➡ Unique possibilities
    - Electron Yukawa coupling
    - TeraZ + beam energy calibration
    - keV and ppm precision on EWPOs at Z resonance and WW threshold
    - α_{QED} (m_Z), α_S (m_Z), $\sin^2\theta_W^{eff}$ and $G\tau$
    - Searches for LLPs and rare phenomena (LFV, LNF, light scalars, ...)
    - Flavor physics program with 10^{12} Bs and 10^{11} τ's
    - Offering sensitivity to new physics at scales of 10 to 70 TeV
- Ambitious program aiming for significant progress in understanding of nature
- Many opportunities to participate
- Challenge is to imagine/optimize detector to match statistical power and to sharpen the theory calculations
- Last but not least: an essential springboard towards 100 TeV pp collisions