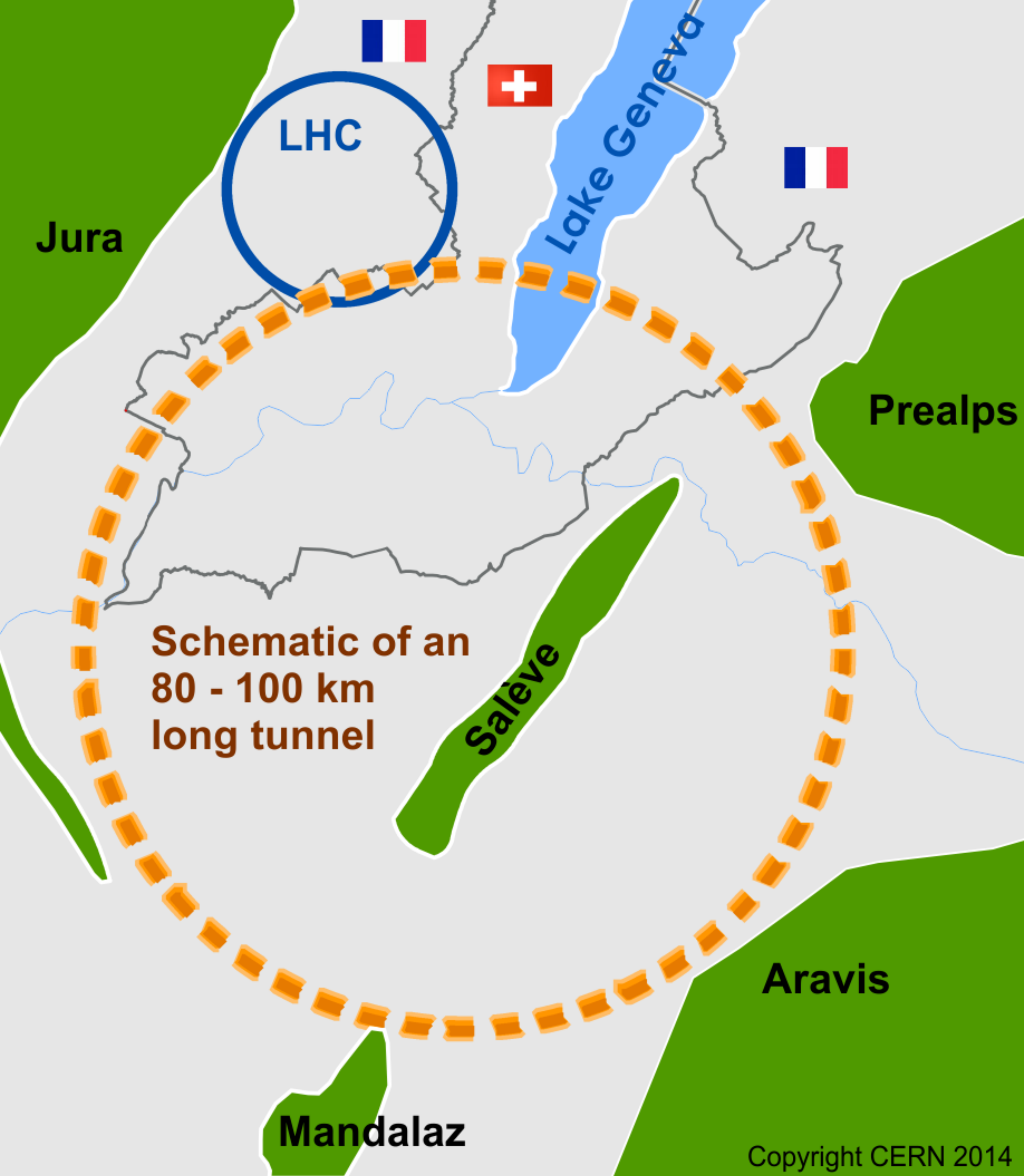
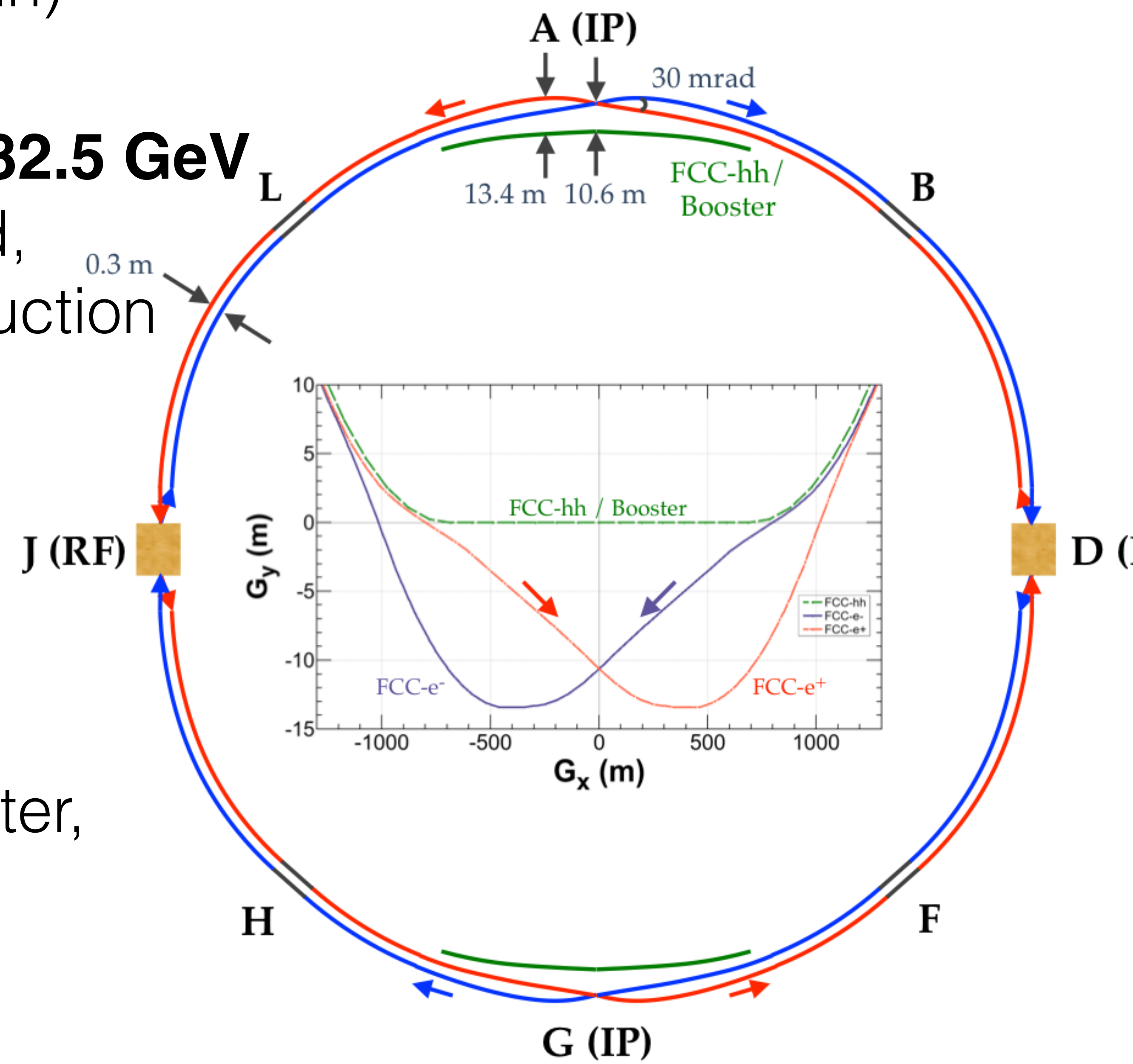


The Case for FCC-ee

Markus Klute (MIT)
August 25th, 2020
TOTW Fermilab

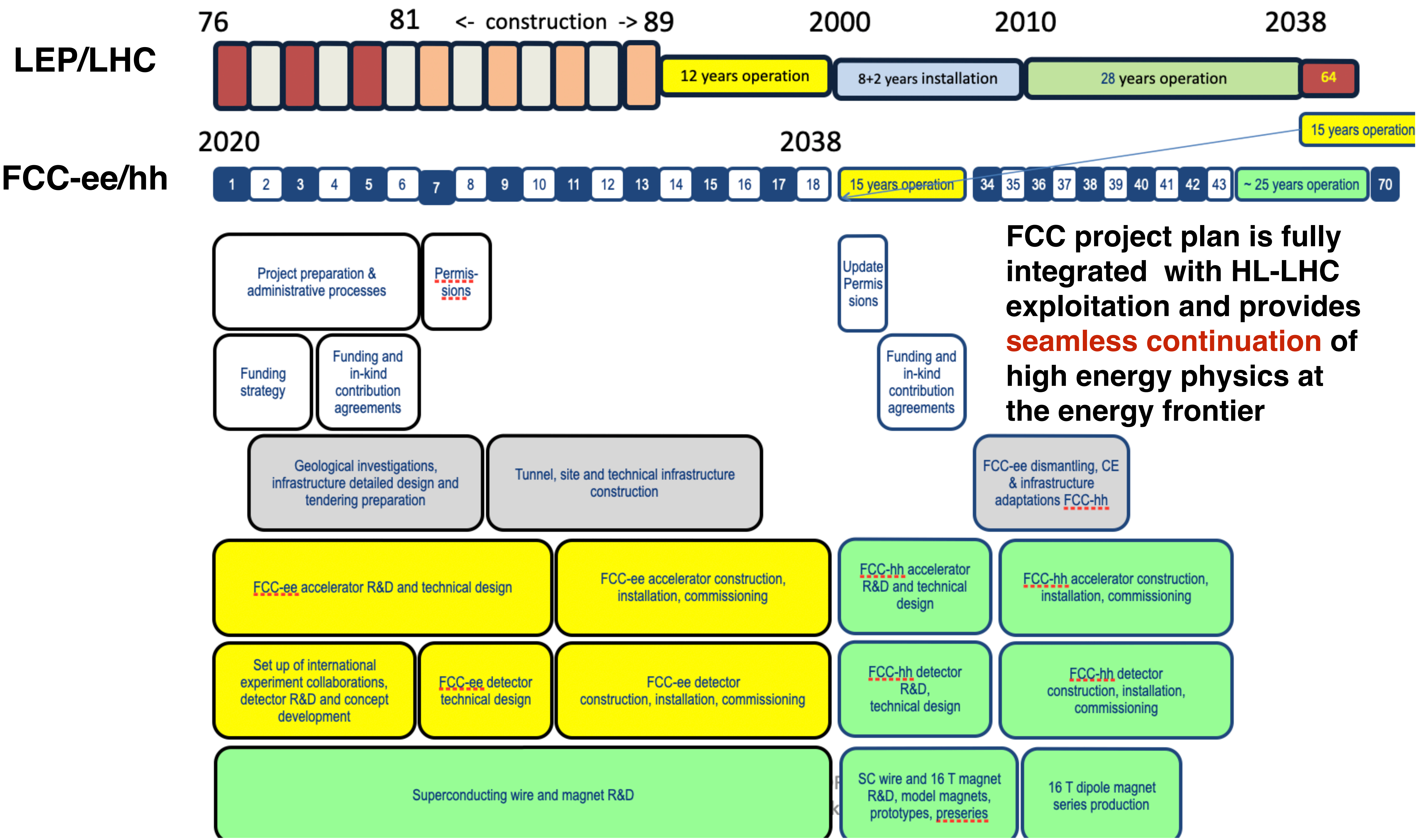
Introduction: the machine

- **FCC-ee** is an electron-positron collider sharing infrastructure with a subsequent hadron collider (FCC-hh)
- 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

Introduction: timeline



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

Introduction: goals

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.

Introduction: 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;

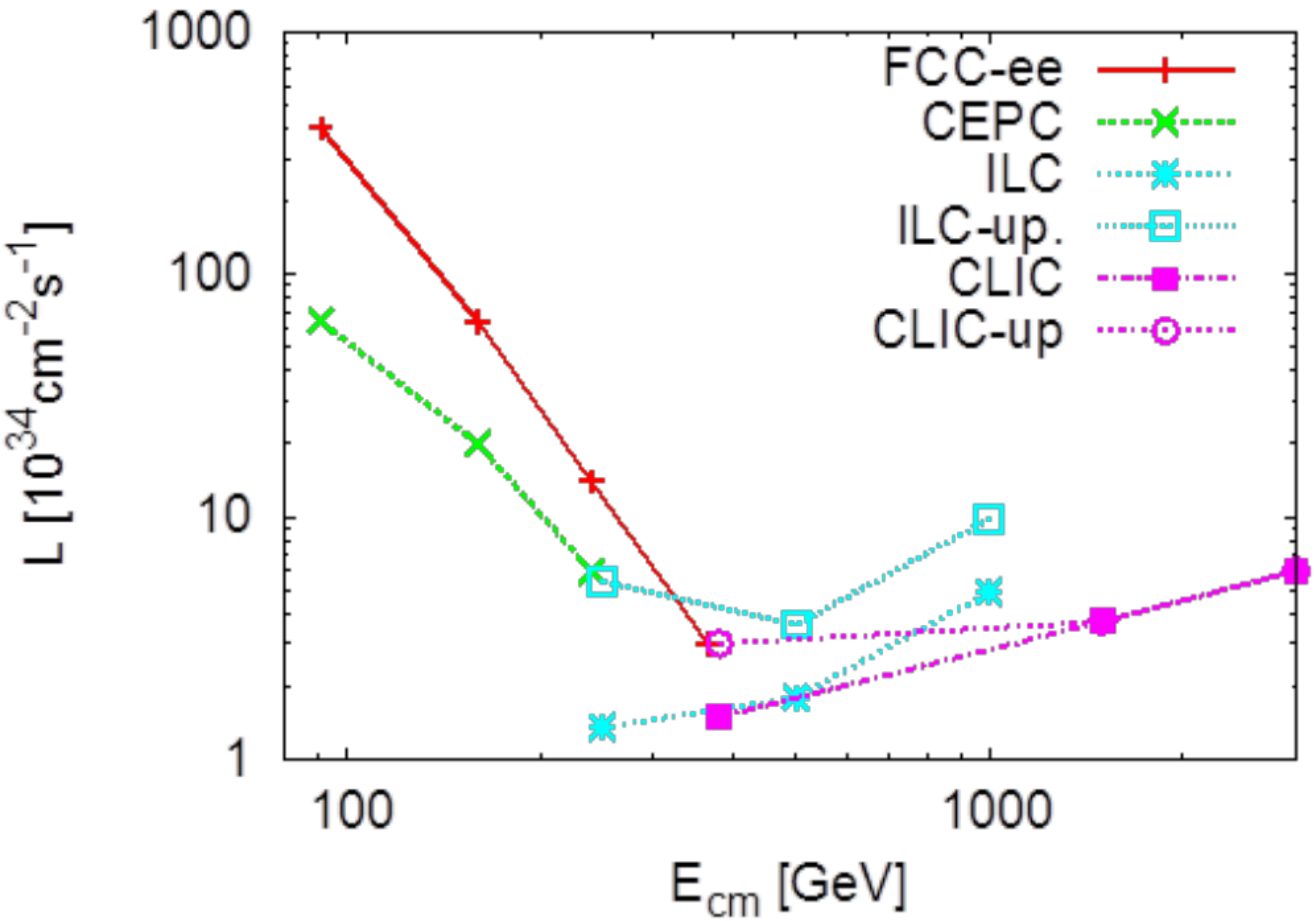
This is work for us in the US!

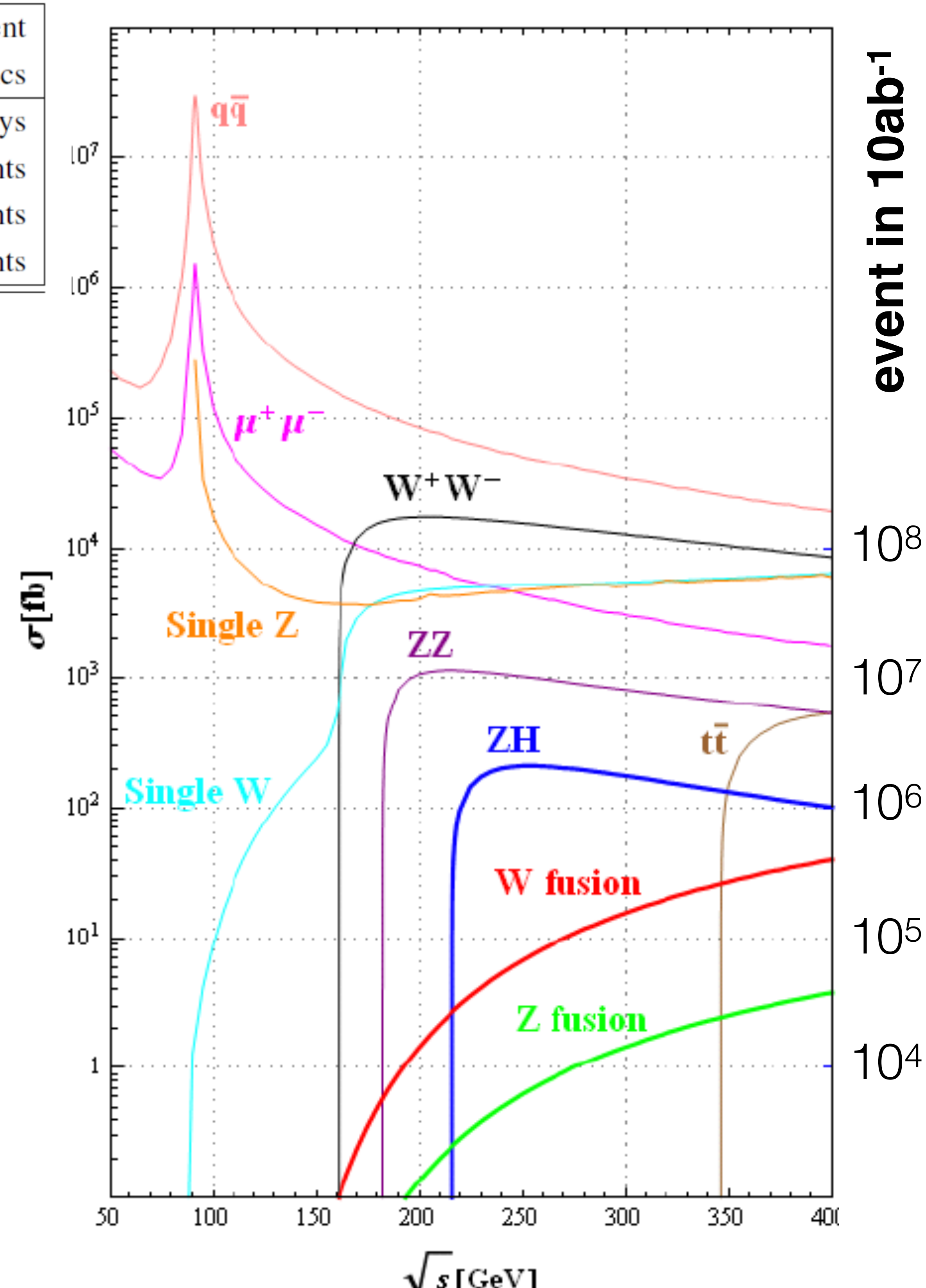
· Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility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

Introduction: event rates

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

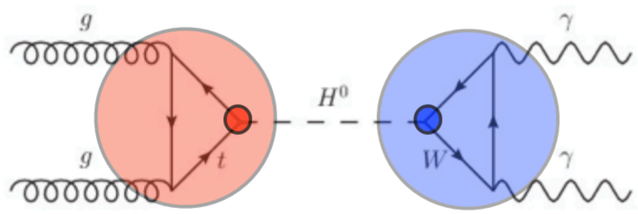




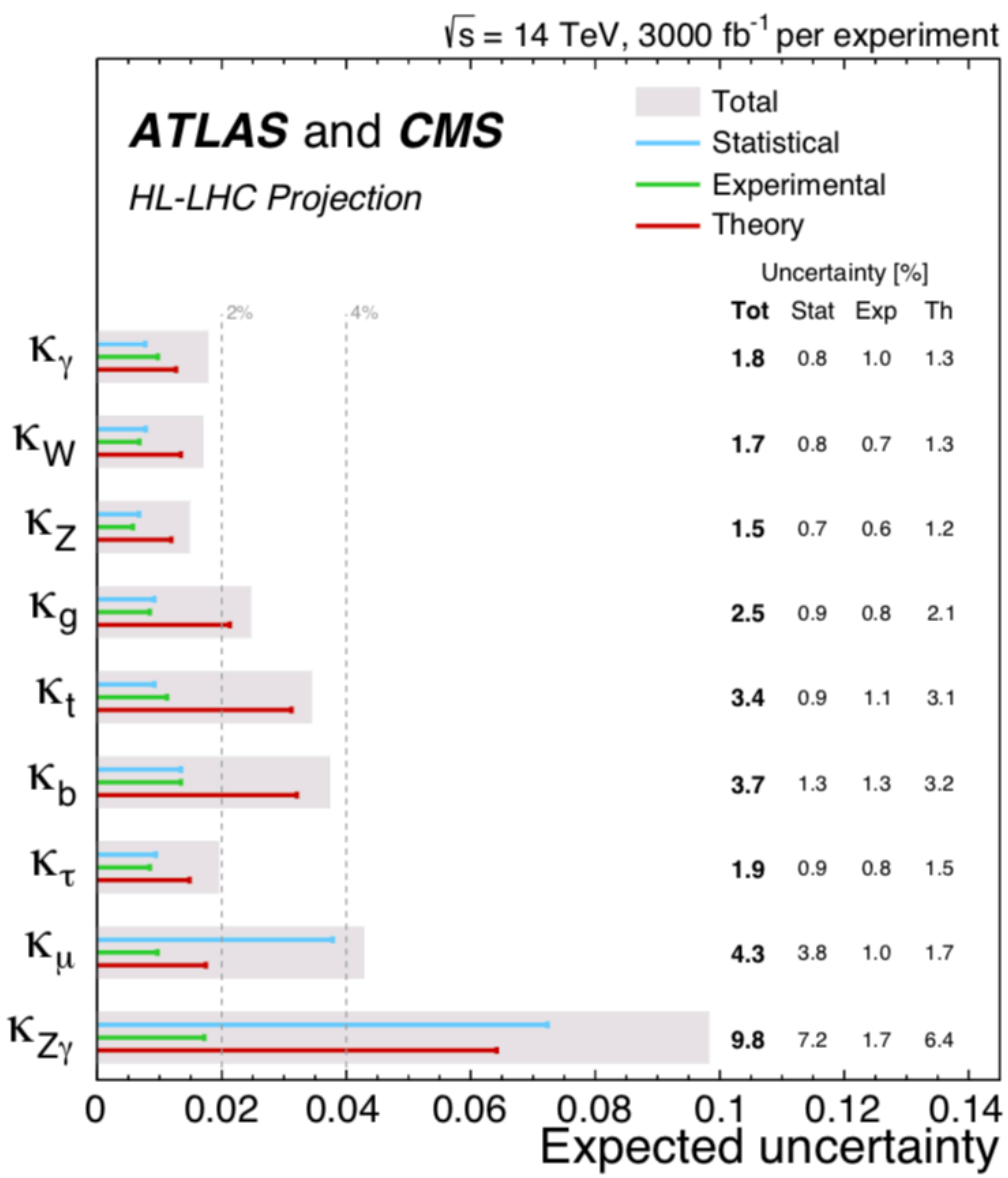
FCC-ee: The Higgs Factory

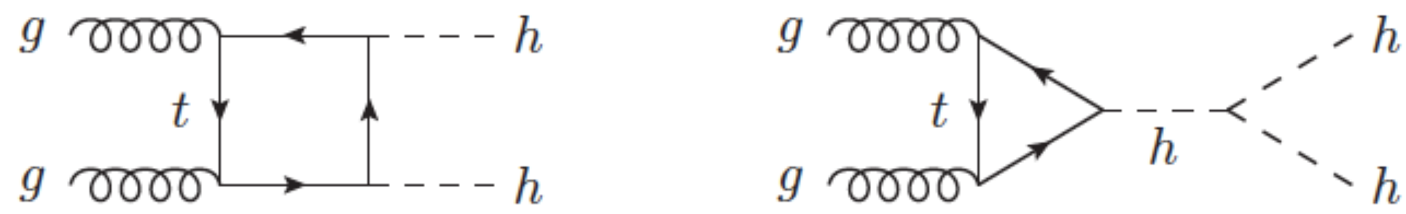
(4y)	Z peak	E_{cm} = 91 GeV	$5\ 10^{12}$	e+e- → Z
(2y)	WW threshold	E_{cm} = 161 GeV	10^{8}	e+e- → WW
(3y)	ZH threshold	E_{cm} = 240 GeV	10^{6}	e+e- → ZH
(4y)	$\bar{t}t$ threshold	E_{cm} = 350 GeV	10^{6}	e+e- → $t\bar{t}$
(ny)	H(optional)	E_{cm} = 125 GeV	10^{4}	e+e- → $\bar{H}$

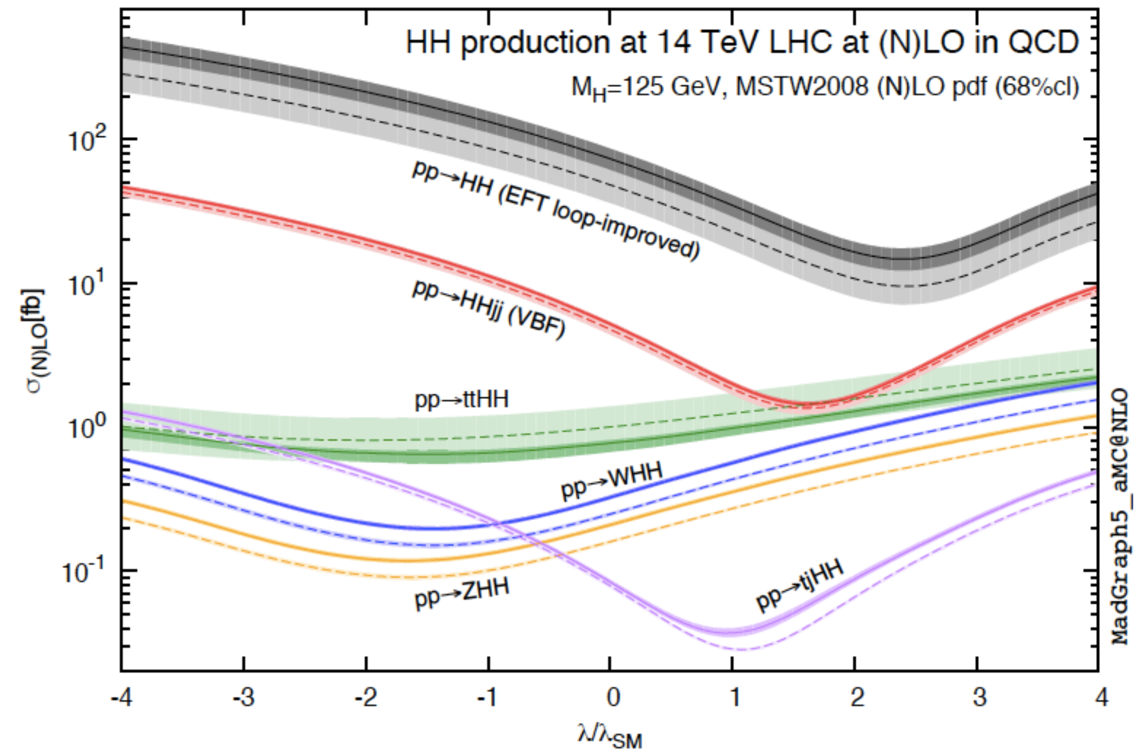
HL-LHC Higgs Legacy



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







	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	

Case for precision Higgs physics

➡ **How large are potential deviations from BSM physics?**

➡ **How well do we need to measure Higgs couplings?**

- To be sensitive to a deviation δ, the measurement needs a precision of at least δ/3, better δ/5
- Implications of new physics scale on couplings from heavy states or through mixing

$$g = g_{\rm SM}\left[1+\Delta\right] \quad : \quad \Delta = \mathcal{O}(v^2/\Lambda^2)$$

$\frac{\Gamma_{\rm 2HDM}[h^0\to X]}{\Gamma_{\rm SM}[h\to X]}$	type I	type II	lepton-spec.	flipped
VV^*	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$
$\bar{u}u$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$
$\bar{d}d$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$
$\ell^+\ell^-$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$

arXiv:1310.8361

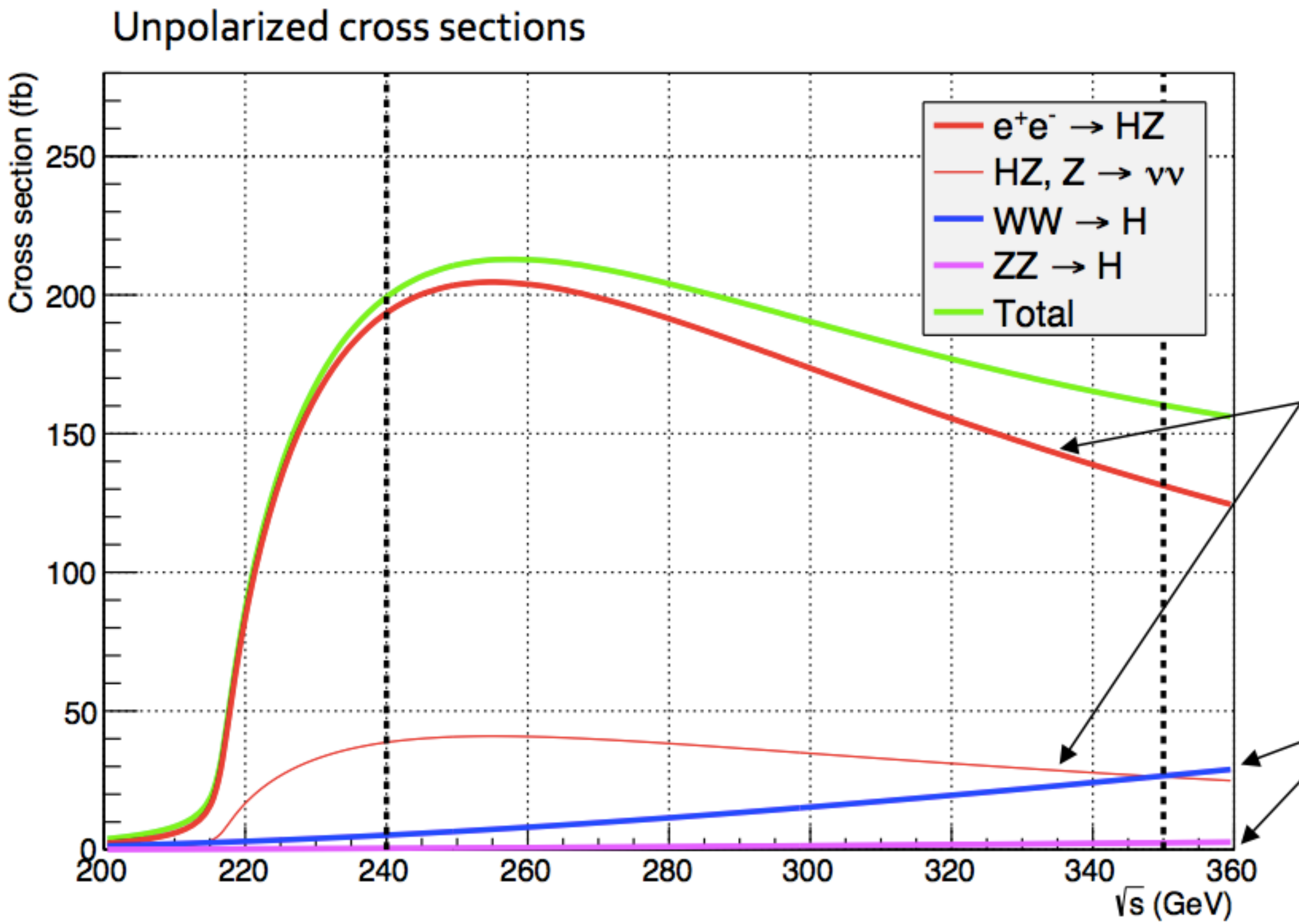
➡ **Percent-level precision test TeV scale**

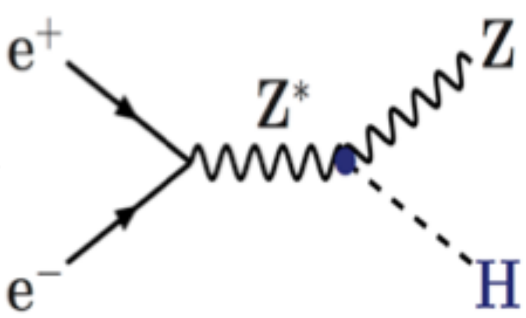
➡ **Requires 10^6 Higgs events**

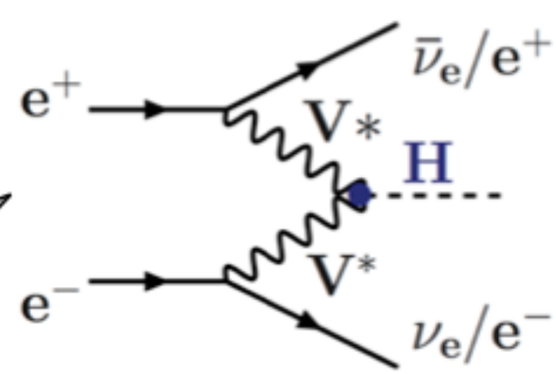
➡ **There is no strict limit to the precision needed!**

Higgs Production

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

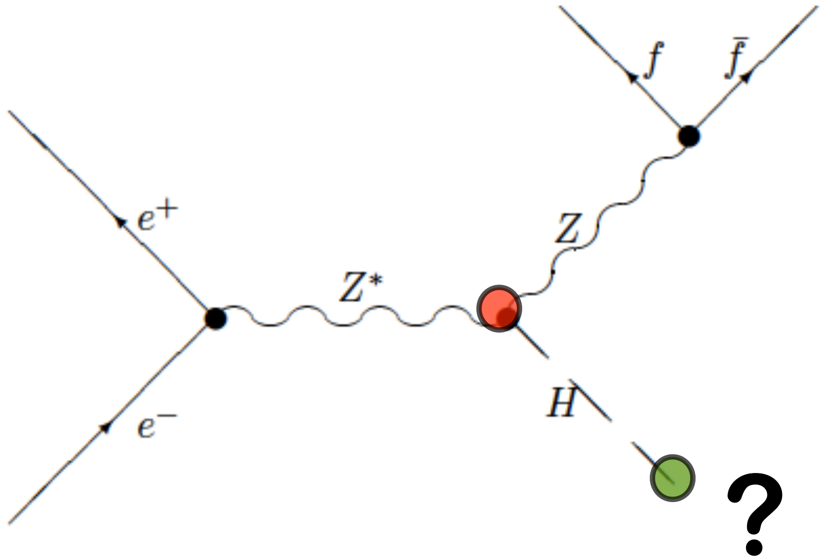




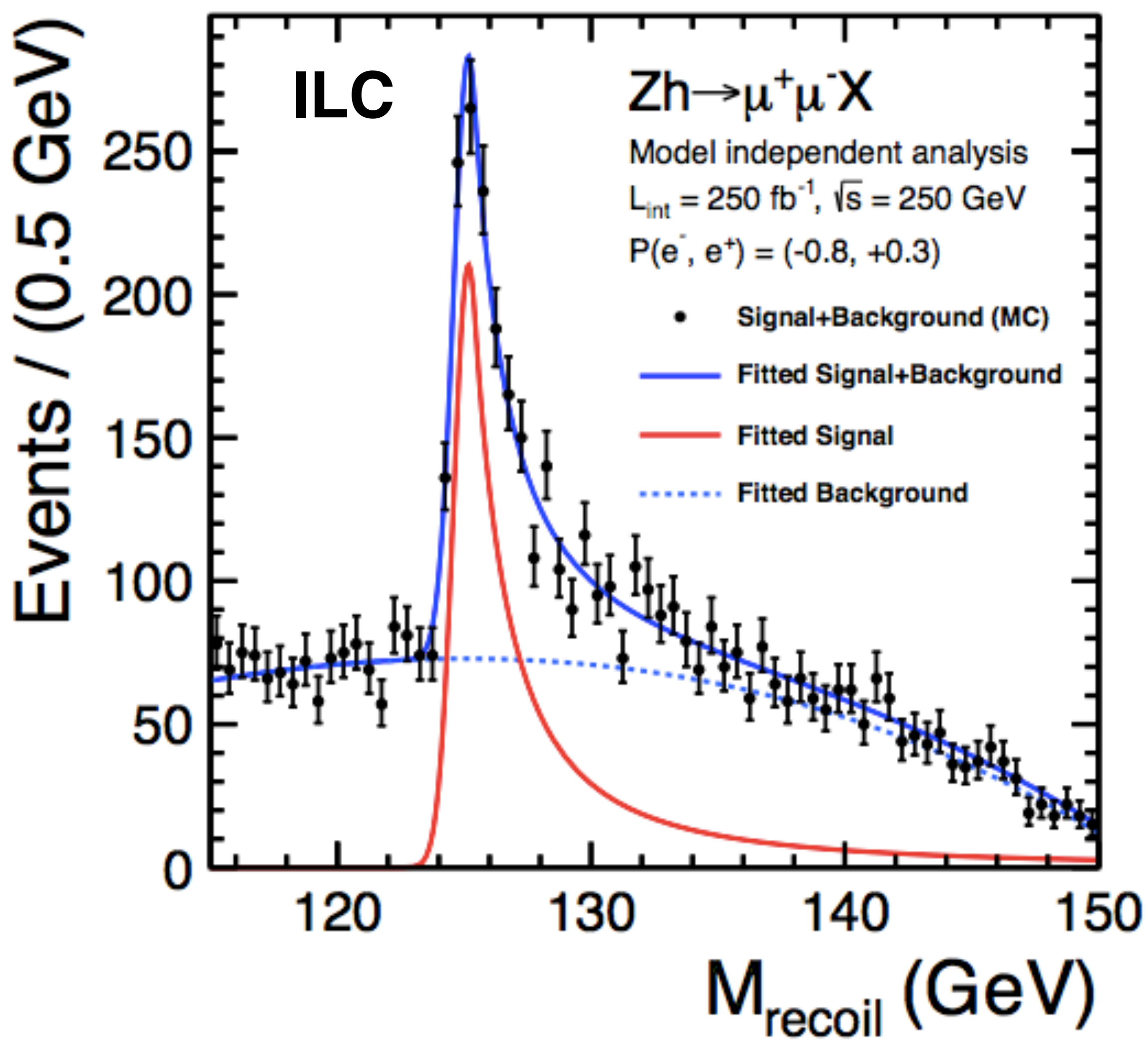


Higgs Precision Measurements

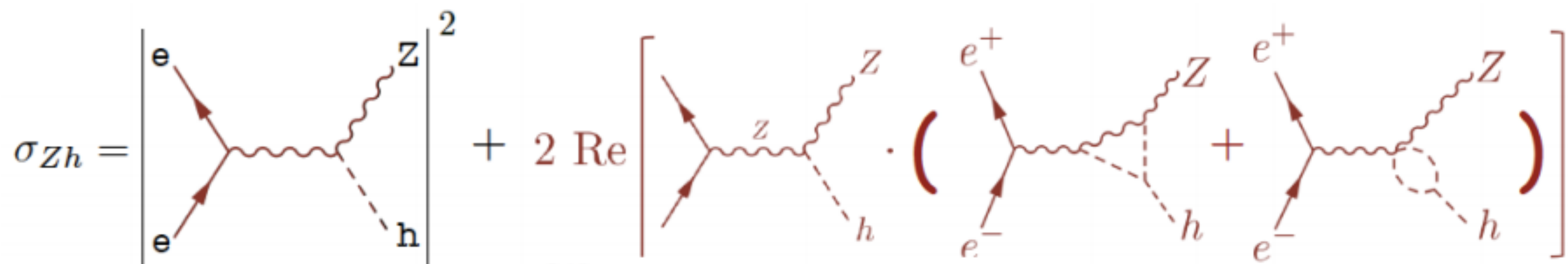
- ➡ Recoil method unique to lepton collider
- ➡ Tag Higgs event independent of decay mode
- ➡ Provides precision and model independent measurements of
  - ◉ $\sigma(ee \rightarrow ZH) \propto g_{HZZ}^2$
  - ◉ m_H
- ➡ Key input to Γ_H
- ➡ Sensitive channel for Higgs to invisible search



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



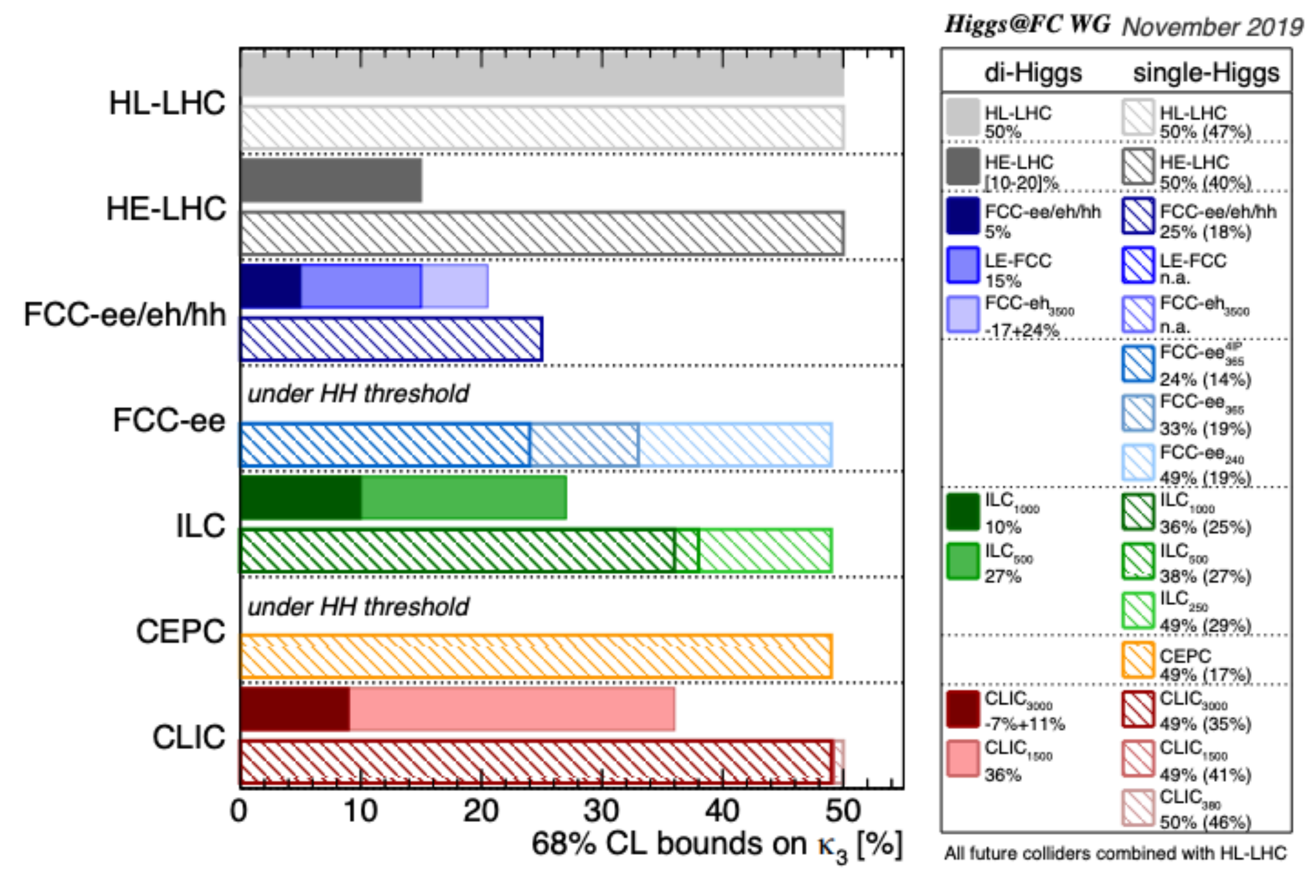
Higgs self-coupling through loop corrections



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

- ➡ 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

arxiv:1910.00012

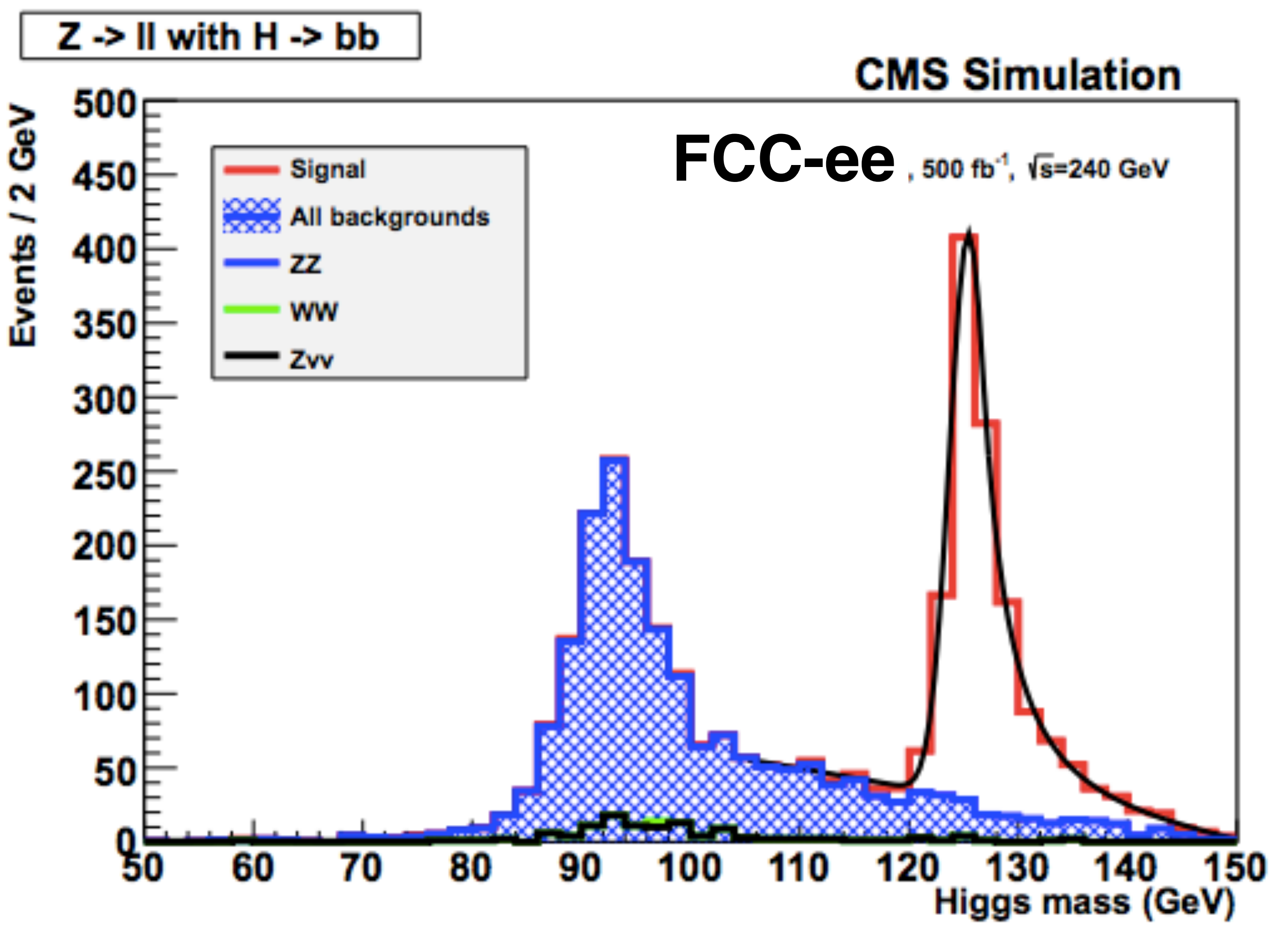
Precision Higgs Couplings

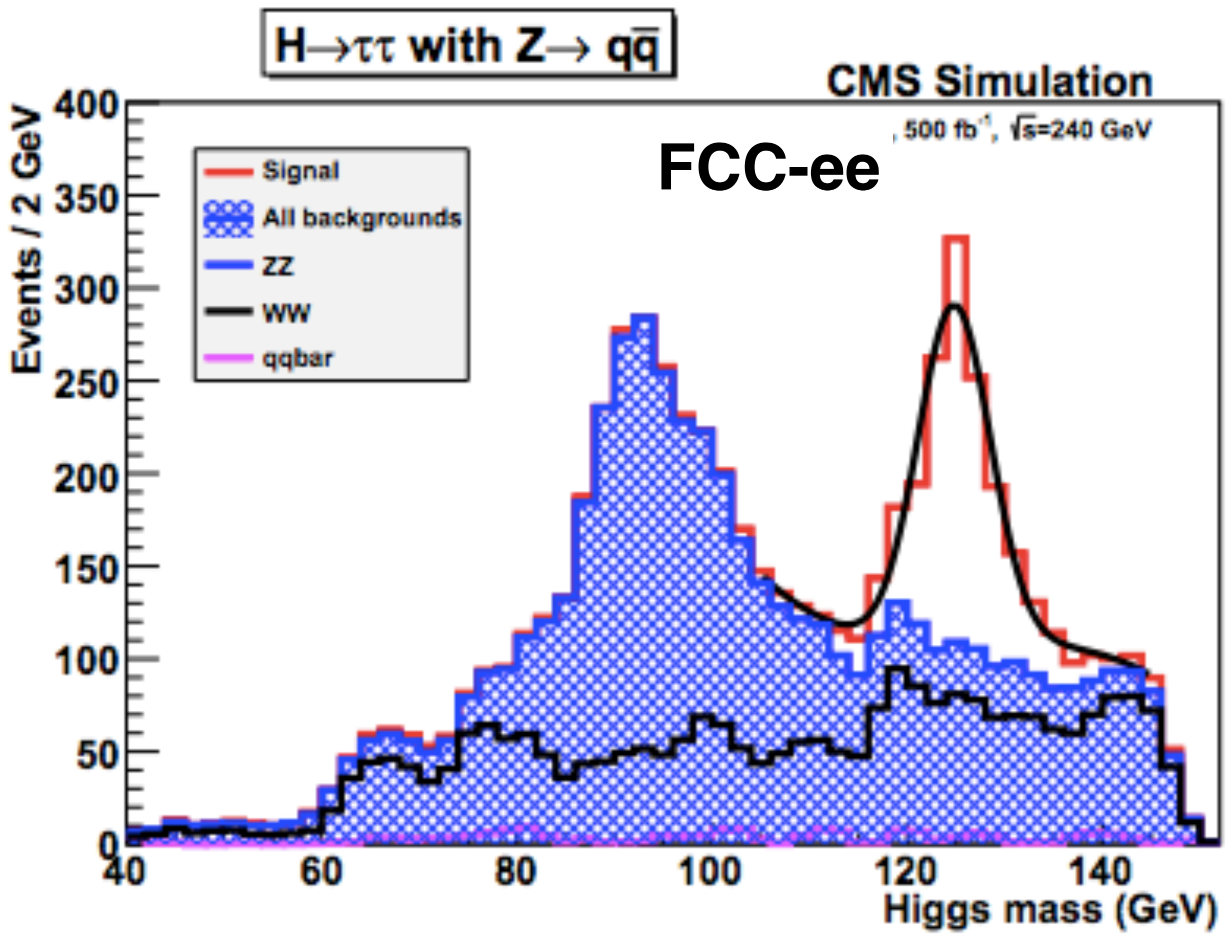
➡ Measure σ(ee→ZH) * BR (H→X) by identifying X

➡ Example: σ(ee→ZH) * BR (H→ZZ) $\propto g_{HZZ}^4/\Gamma_H$

➡ Total width from combination of measurements or fit

➡ Branching fraction to invisible tested directly



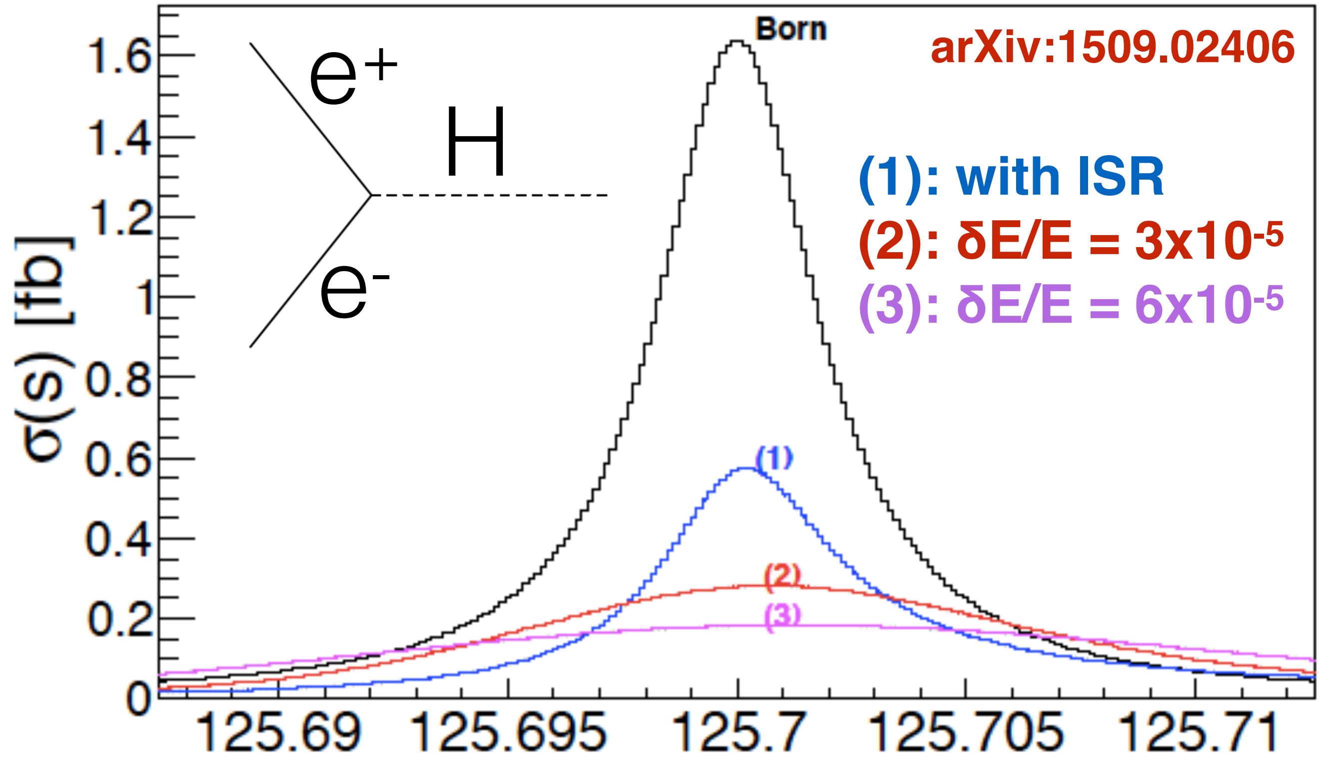


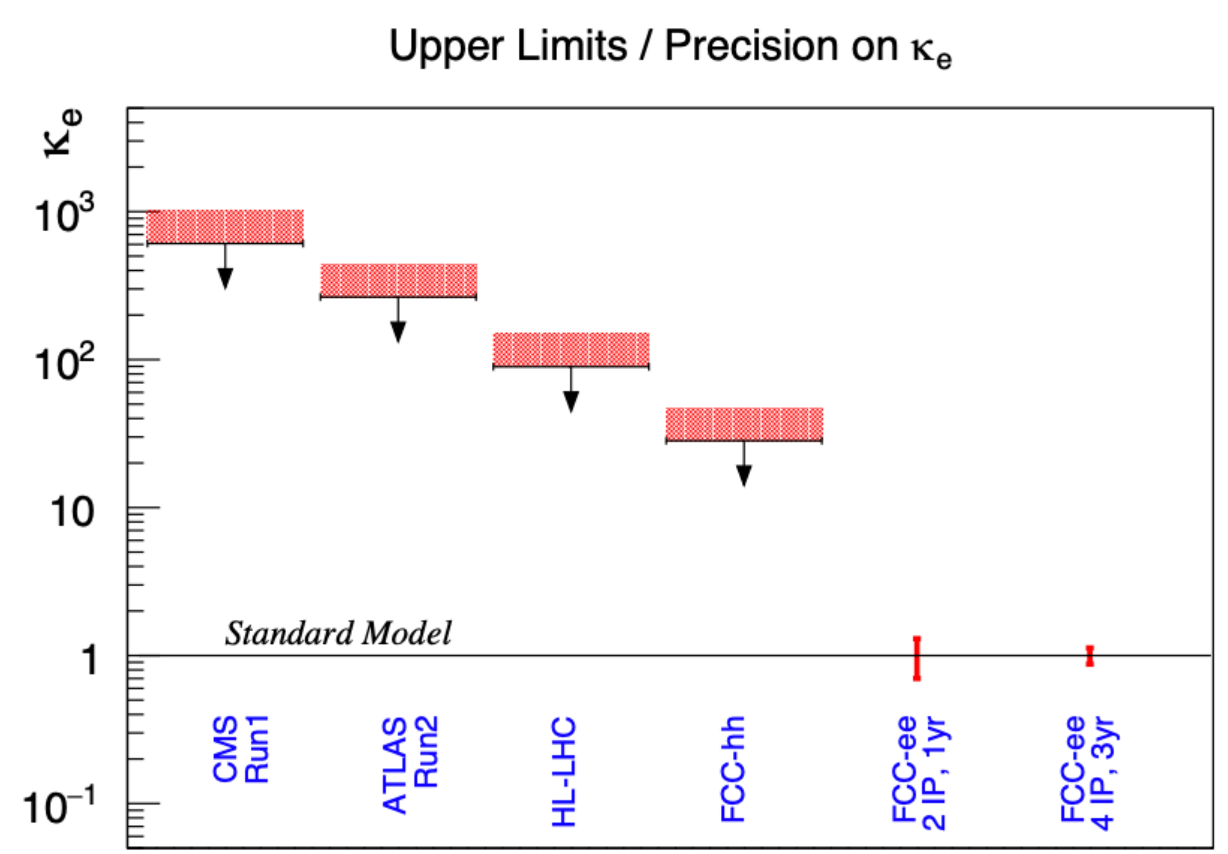
Precision Higgs Couplings

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	$< \mathbf{1.0}$	< 1.0	n.a.

S-channel Higgs Production

- **s-channel production**
  - very small cross section
  - reduced by ISR and beam spread
  - $\sigma^{born}(\mu^+\mu^- \rightarrow H) \approx 40.000\ \sigma^{born}(e^+e^- \rightarrow H)$
  - $\sigma(e^+e^- \rightarrow H)$ = 50ab (nominal $\delta E/E$)
  - $\sigma(\mu^+\mu^- \rightarrow H)$ = 15pb (nominal $\delta E/E$)
- **Beam-spread improvements**
  - FCC-ee via monochromators
  - Feasibility and impact on luminosity need study
- **Expected significance 0.7σ / 10ab-1**
  - Set an electron Yukawa coupling upper limit: k_e < 2.5 @95% CL

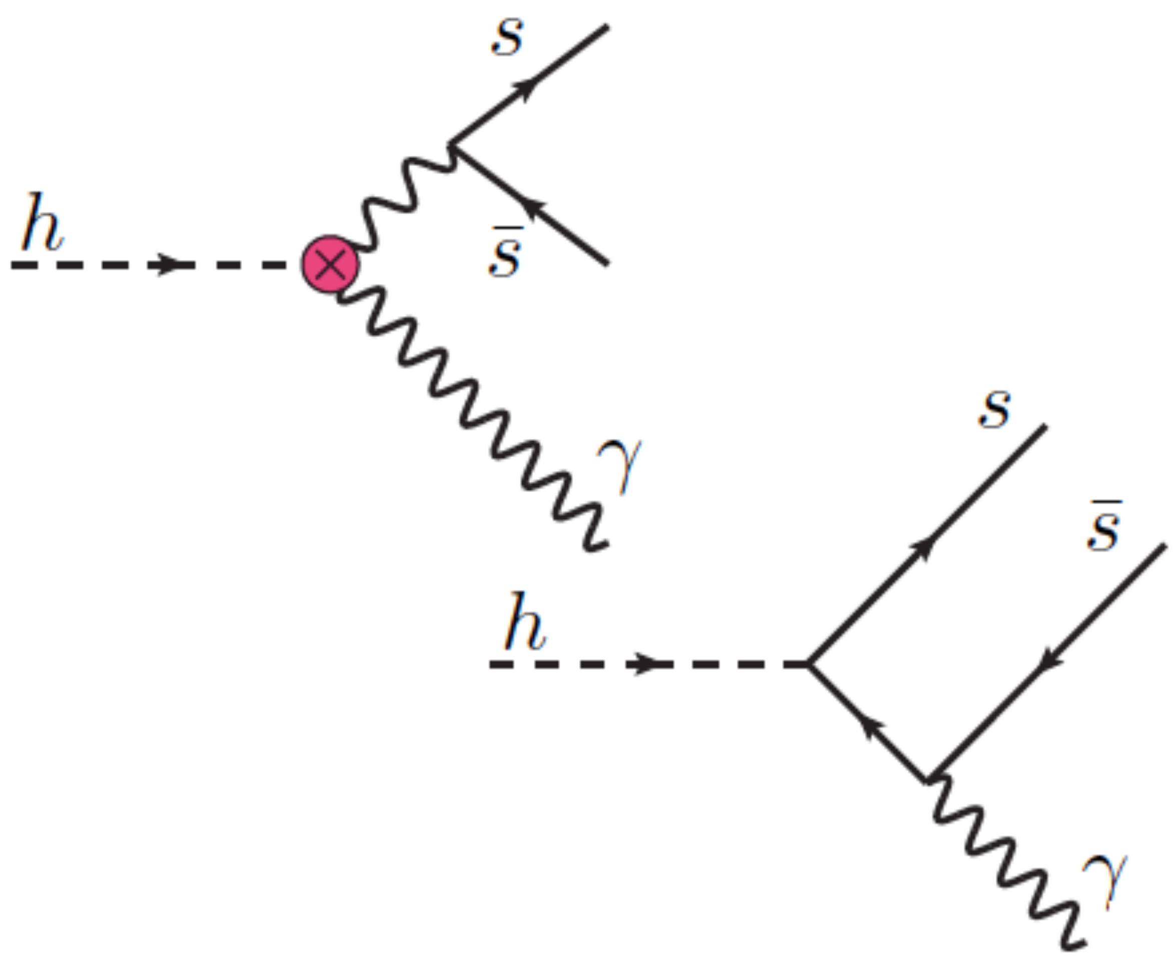




Exclusive Higgs boson decays

- First and second generation couplings accessible
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9 \pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$



- Also interesting to hadron collider program
- Alternative H→MV decays should be studied (V= γ, W, and Z)

H → J/Ψ γ → y_c

H → ϕ γ → y_s

H → ρ γ

H → ω γ → y_u, y_d

Rare and Exotics Higgs Bosons

- Largely unexplored!
- ZH events allow for detailed studies of rare and exotic decays
  - improved with hadronic and invisible Z decays
  - set requirements for lepton collider detector
- Coupling measurements have sensitivity to BSM decays
- Dedicated studies using specific final states improve sensitivity
- Example: Higgs to invisible, flavor violating Higgs, and many more
- Modes with of limited LHC sensitivity are of particular importance to lepton collider program
- Detailed discussion of exotic Higgs decays at [Phys. Rev. D 90, 075004 (2014)]

$h \to \not E_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau, 2\tau 2\mu$

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

$h \to ZZ_D, Za \to 4\ell$

$h \to Z_D Z_D \to 4\ell$

$h \to \gamma + \not E_T$

$h \to 2\gamma + \not E_T$

$h \to$ 4 ISOLATED LEPTONS $+ \not E_T$

$h \to 2\ell + \not E_T$

$h \to$ ONE LEPTON-JET $+ X$

$h \to$ TWO LEPTON-JETS $+ X$

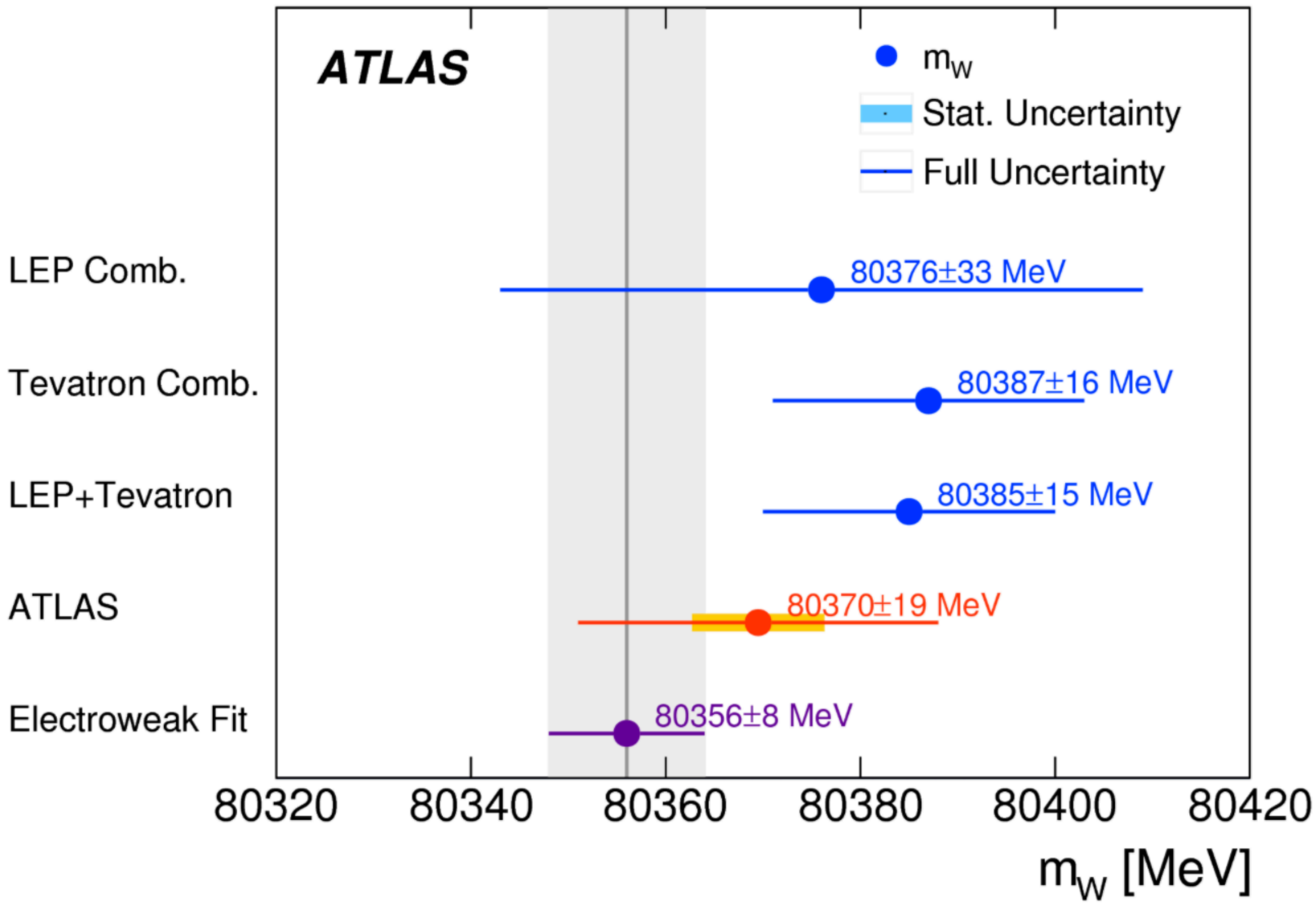
$h \to b\bar{b} + \not E_T$

$h \to \tau^+\tau^- + \not E_T$

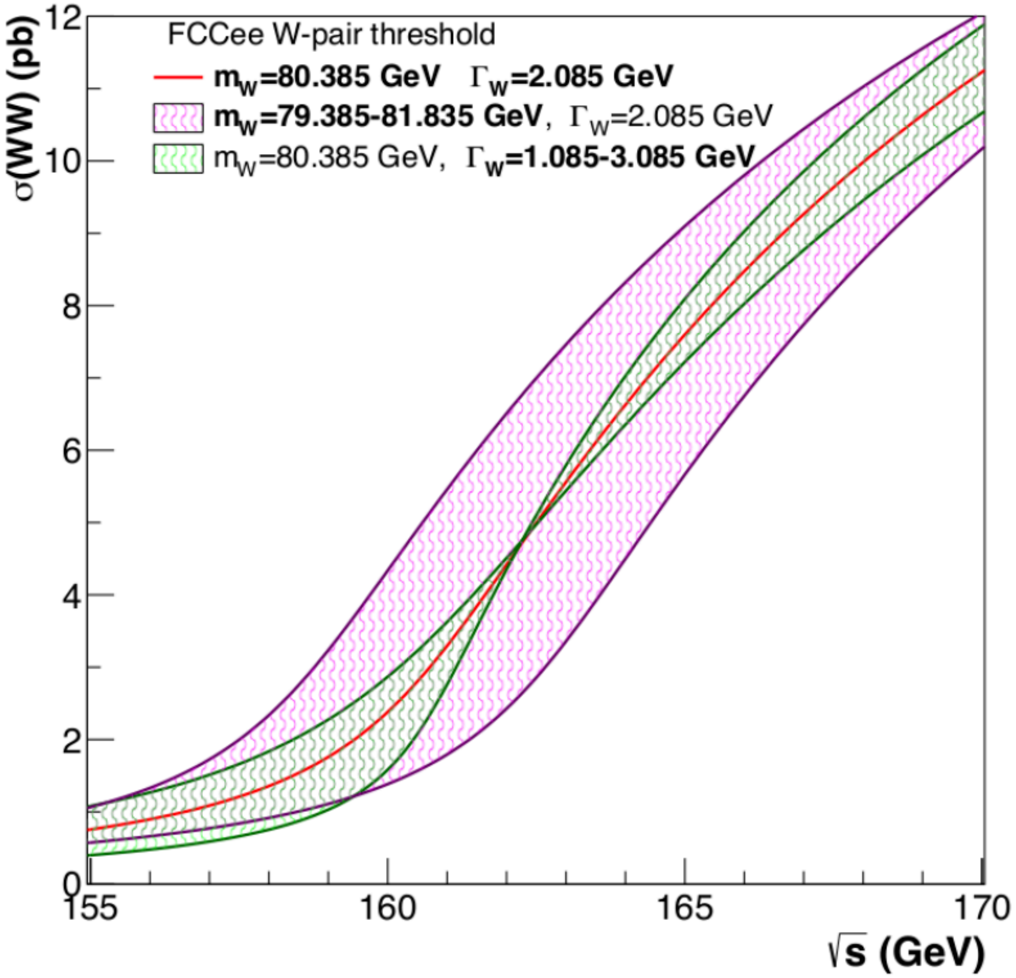
FCC-ee: The Electroweak Factory

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

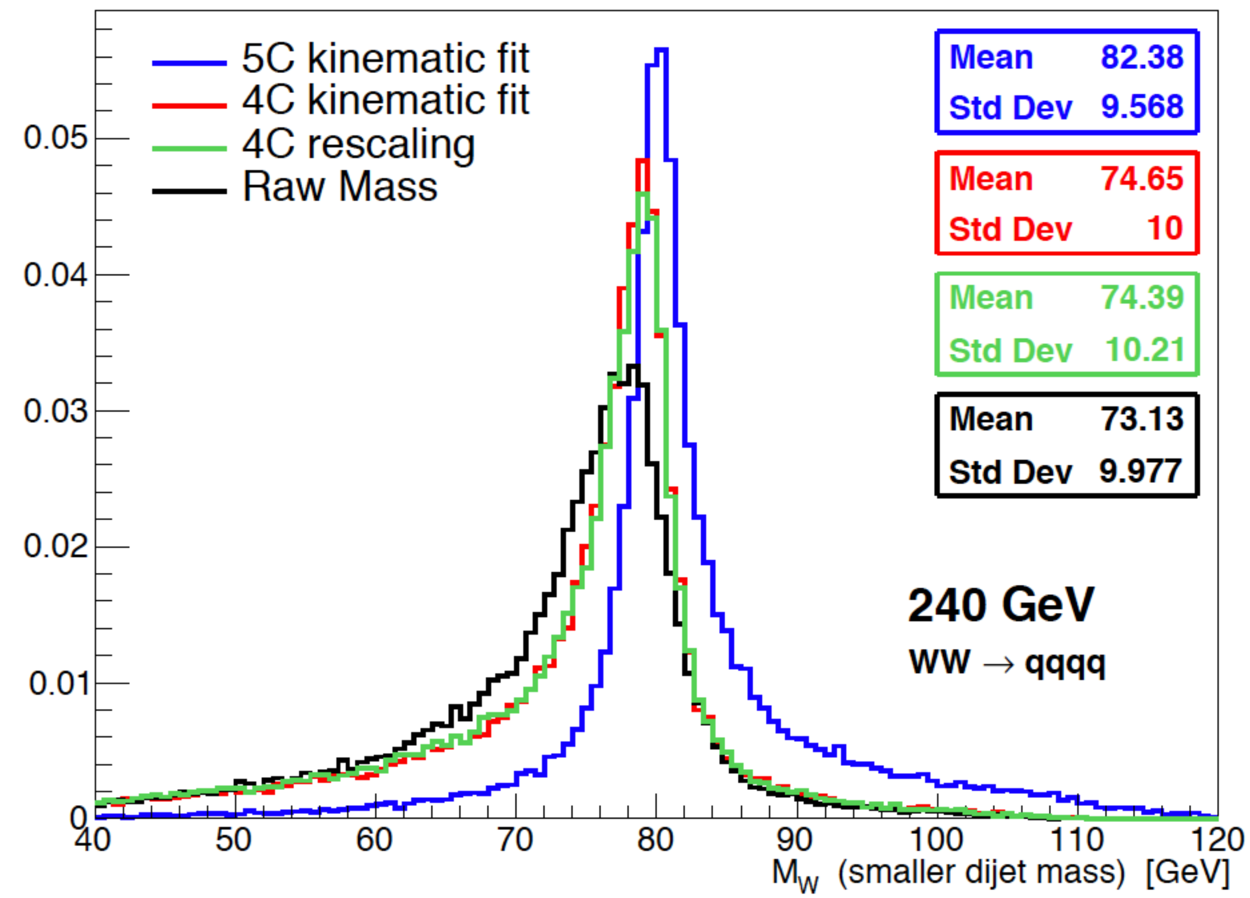
W Boson Mass


ATLAS
m_W
Stat. Uncertainty
Full Uncertainty
LEP Comb.
80376±33 MeV
Tevatron Comb.
80387±16 MeV
LEP+Tevatron
80385±15 MeV
ATLAS
80370±19 MeV
Electroweak Fit
80356±8 MeV
80320
80340
80360
80380
80400
80420
m_W [MeV]

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?

Electroweak Precision

TeraZ (5 X 10^{12} Z)

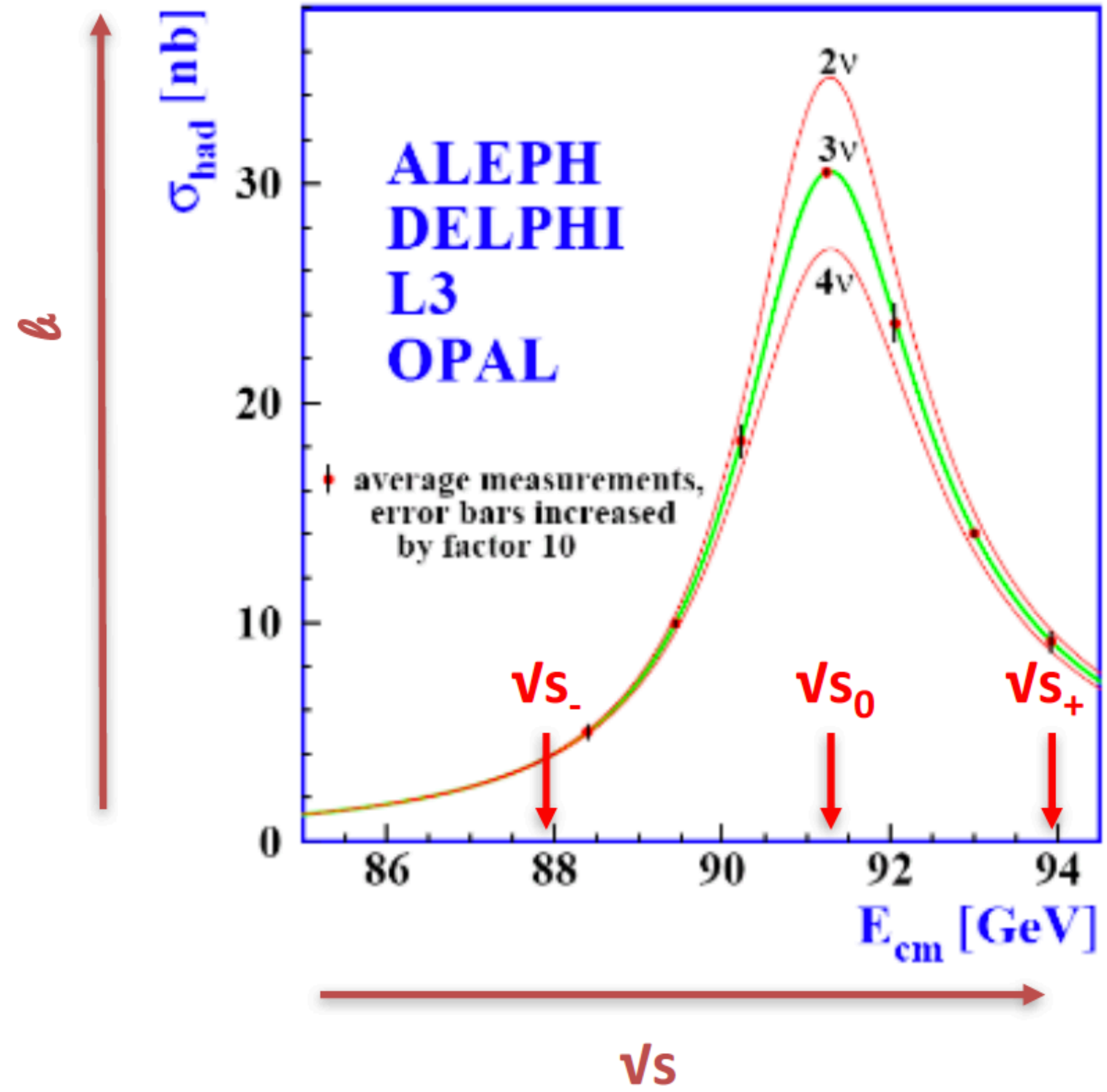
From data collected in a lineshape energy scan:

- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings, precise universality test)
- peak cross section (invisible width, N_ν)
- $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings)
- Tau polarization ($\sin^2\theta_{eff}$, lepton couplings)

- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)

Most critical systematic uncertainties:

- **Center-of-mass energy and energy spread**
- Luminosity

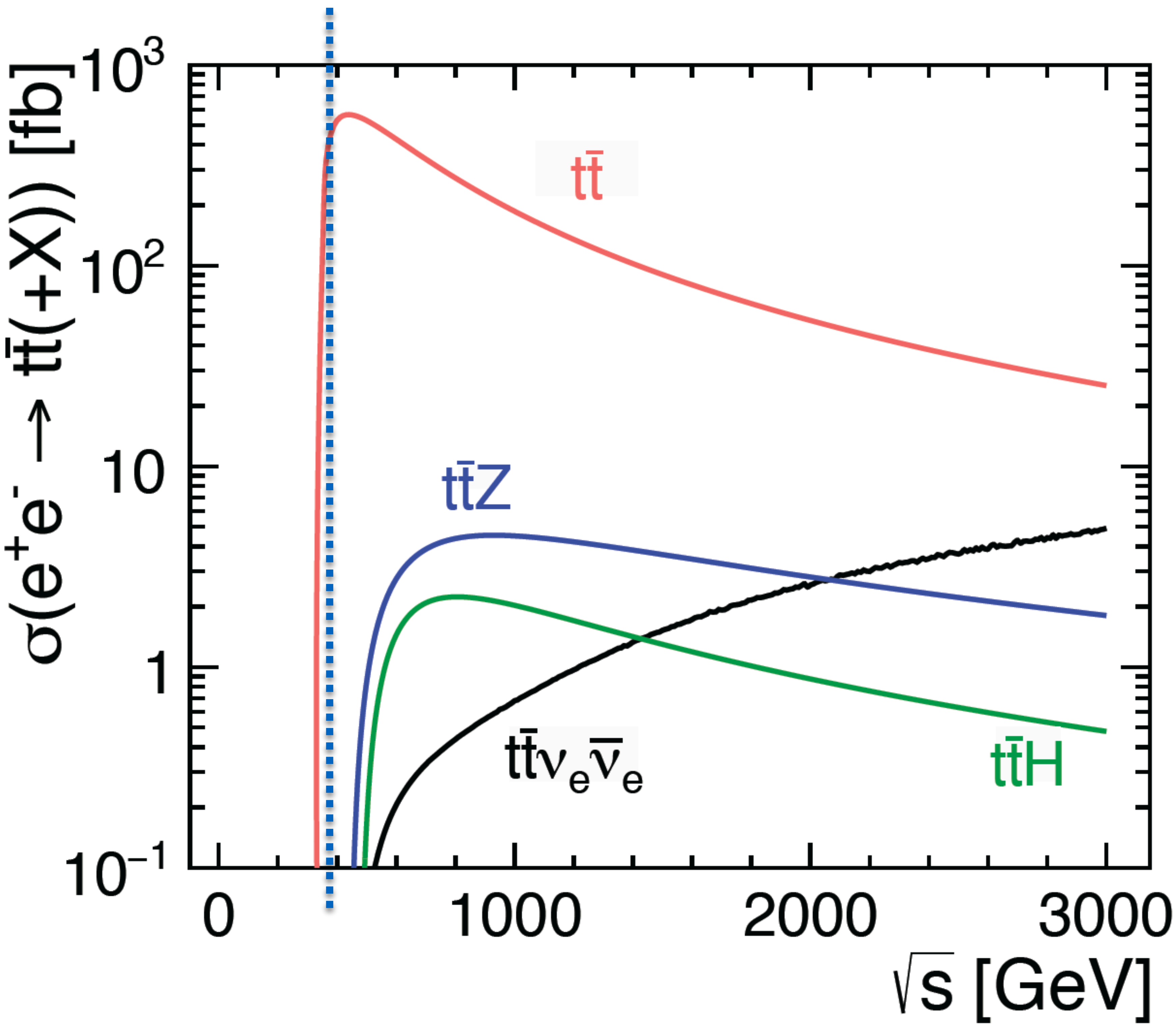


- ΔM_Z = 0.004 MeV (stat. only)

FCC-ee: The Top 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
(4y)	$\bar{t}t$ threshold	E_{cm} = 350 GeV	10^{6}	e+e- → $\bar{t}t$
(ny)	H(optional)	E_{cm} = 125 GeV	10^{4}	e+e- → $\bar{H}$

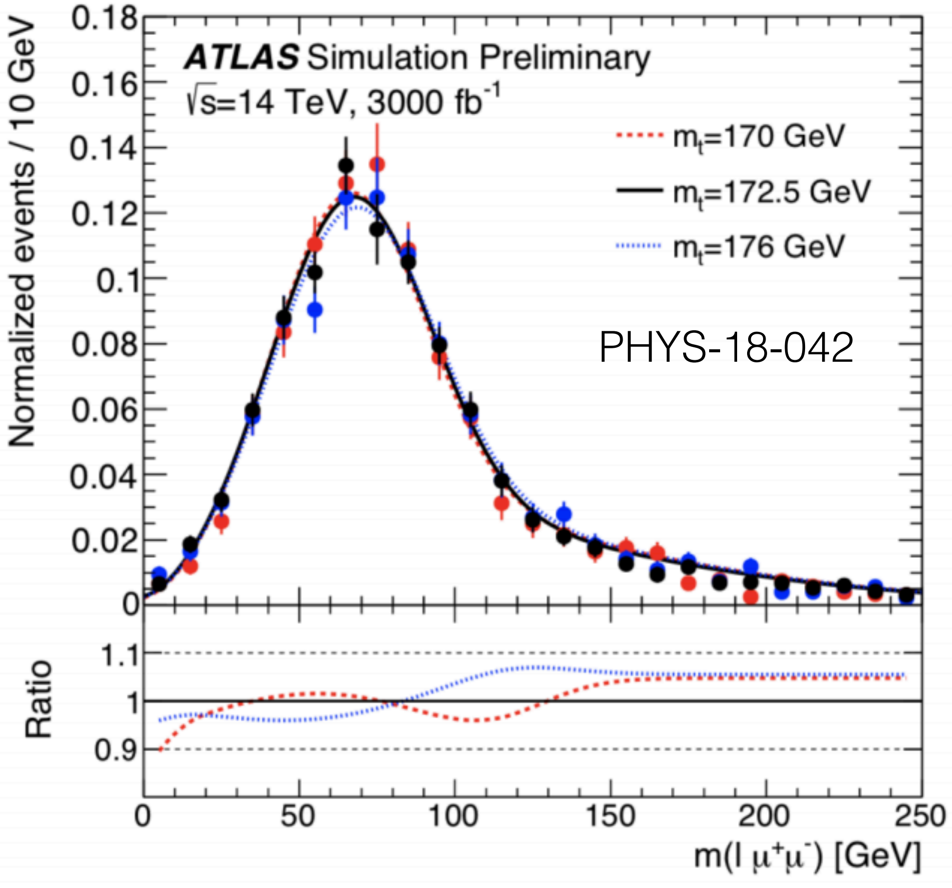
Top Physics

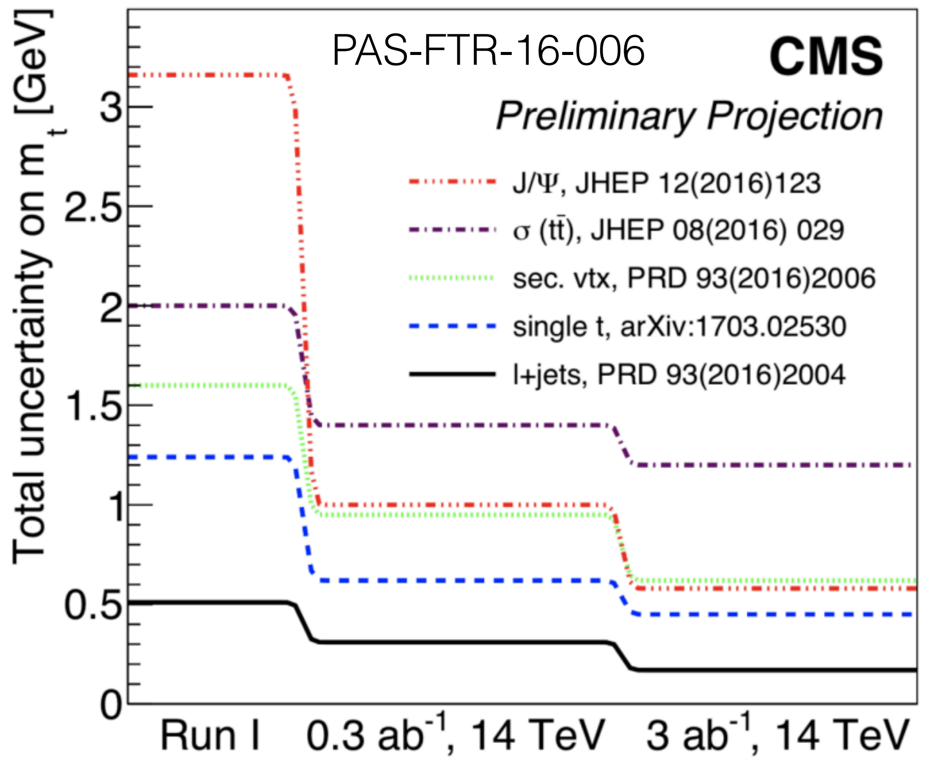


$\sigma(e^+e^- \to t\bar{t}(+X))$ [fb]
10^3
10^2
10
1
10^{-1}
0
1000
2000
3000
$\sqrt{s}$ [GeV]
$t\bar{t}$
$t\bar{t}Z$
$t\bar{t}\nu_e\bar{\nu}_e$
$t\bar{t}H$

Top Mass LHC Legacy

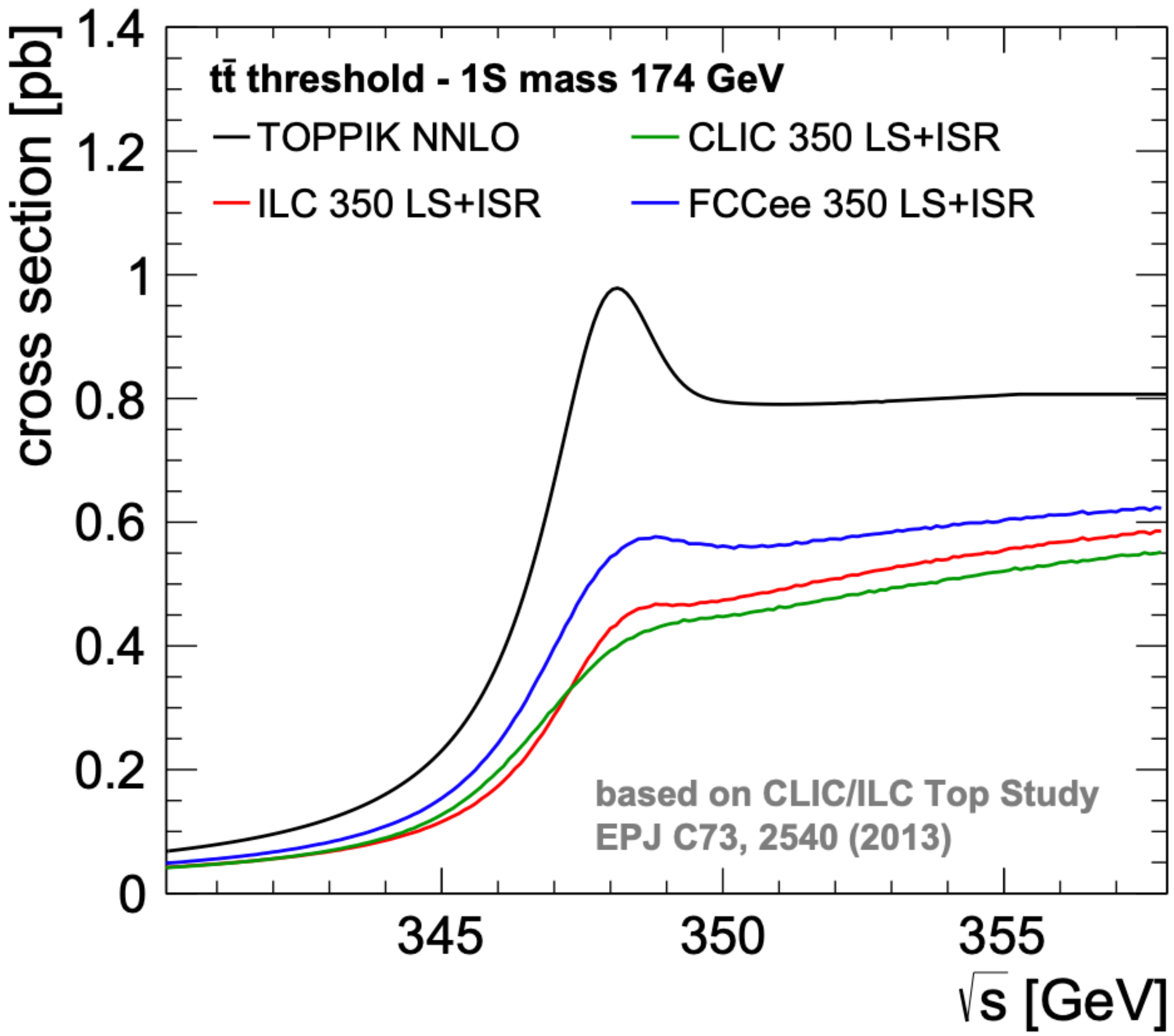
- **Projections for various techniques**
  - direct measurement in ttbar or single top
    - *jet systematics* dominate
  - indirect measurement from cross sections
    - *theory and luminosity* uncertainties dominate
  - using of l + (J/ψ→) μμ final state
    - uncert. on *modelling of b-fragmentation/-decay* dominate
    - clean signature, small BR, *limited by statistics*
  - Usually ambiguity of top mass definition not considered
- **ATLAS using only l + (J/ψ→) μμ final states**
  - Stat. 0.14 GeV, syst. 0.48 GeV (=0.28%, at the level of the current best mass value)
- **CMS**
  - Can reach between 0.1%-0.7% precision

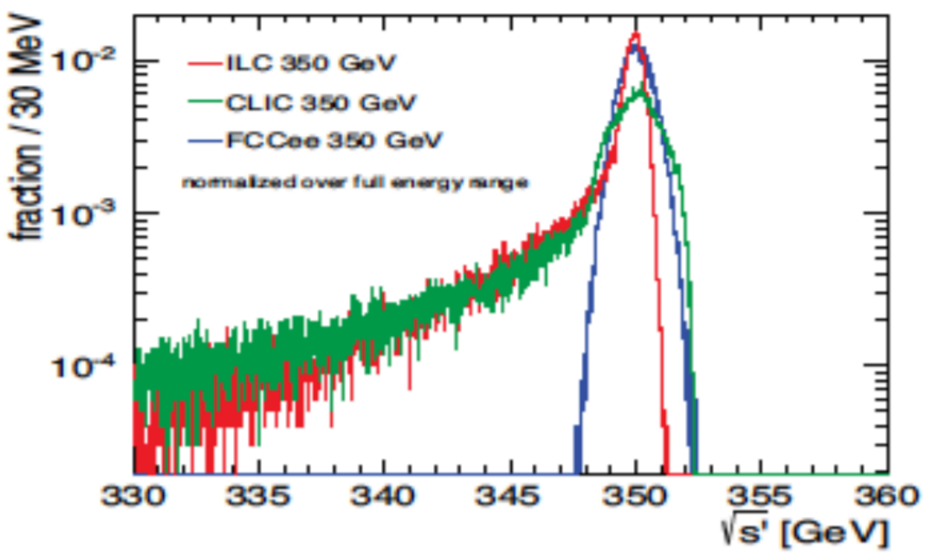


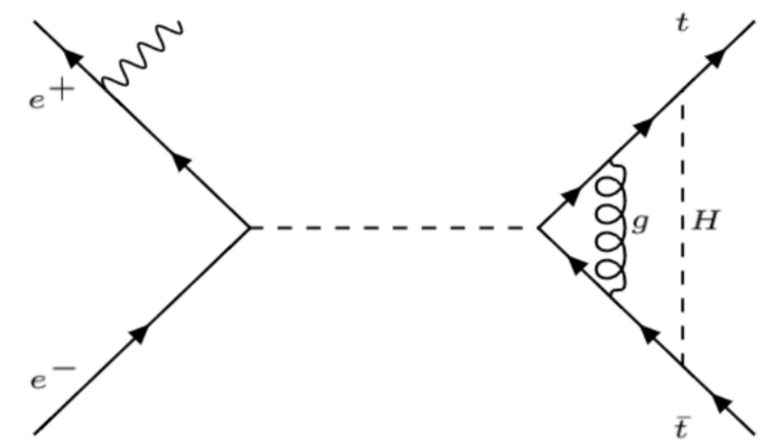


Top-pair threshold scan

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





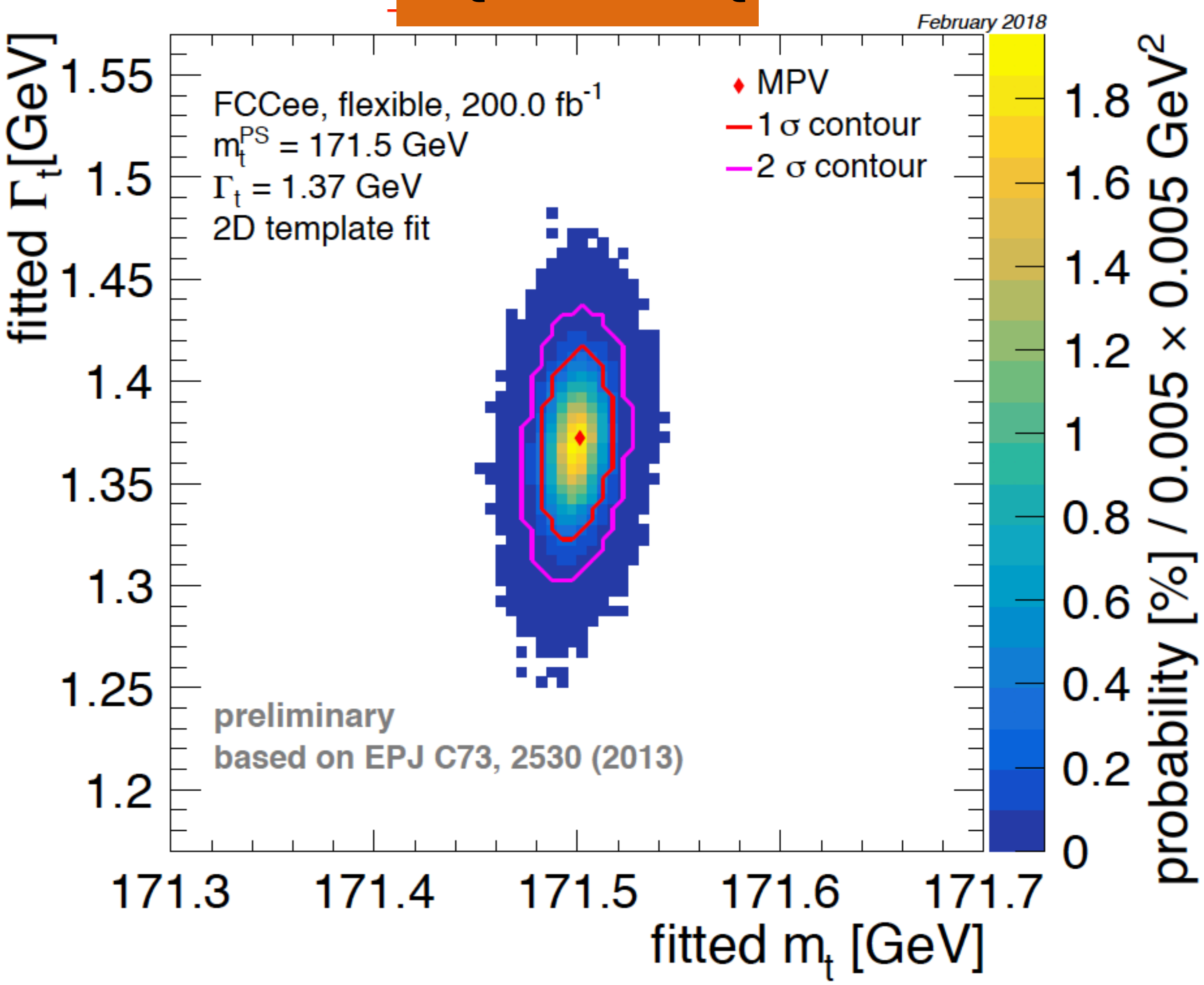


- Precise knowledge of α_s improved correlation of m_t, Γ_t, and Y_t drastically

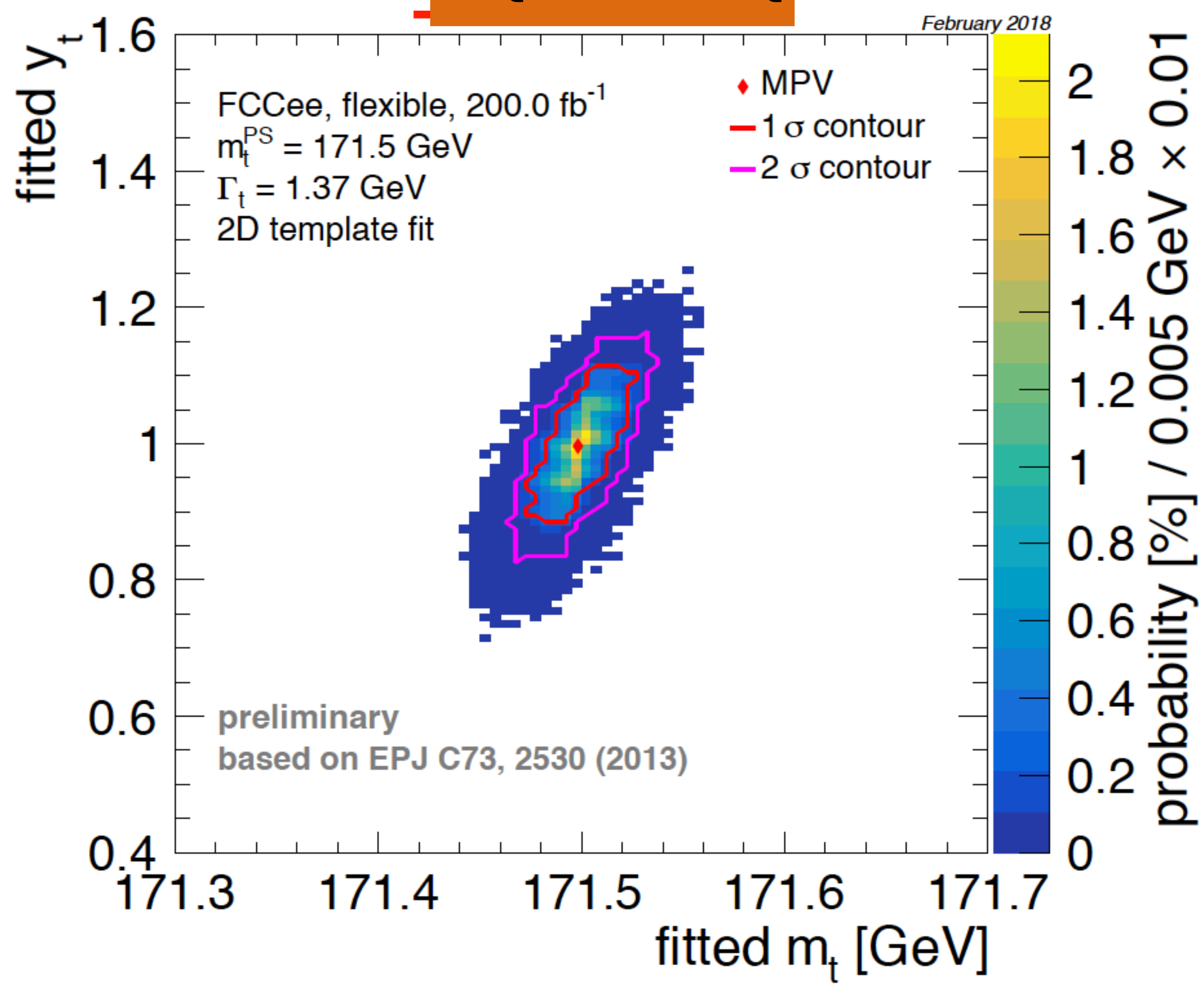
arxiv:1604.08122

Top-pair threshold scan

Γ_t vs m_t

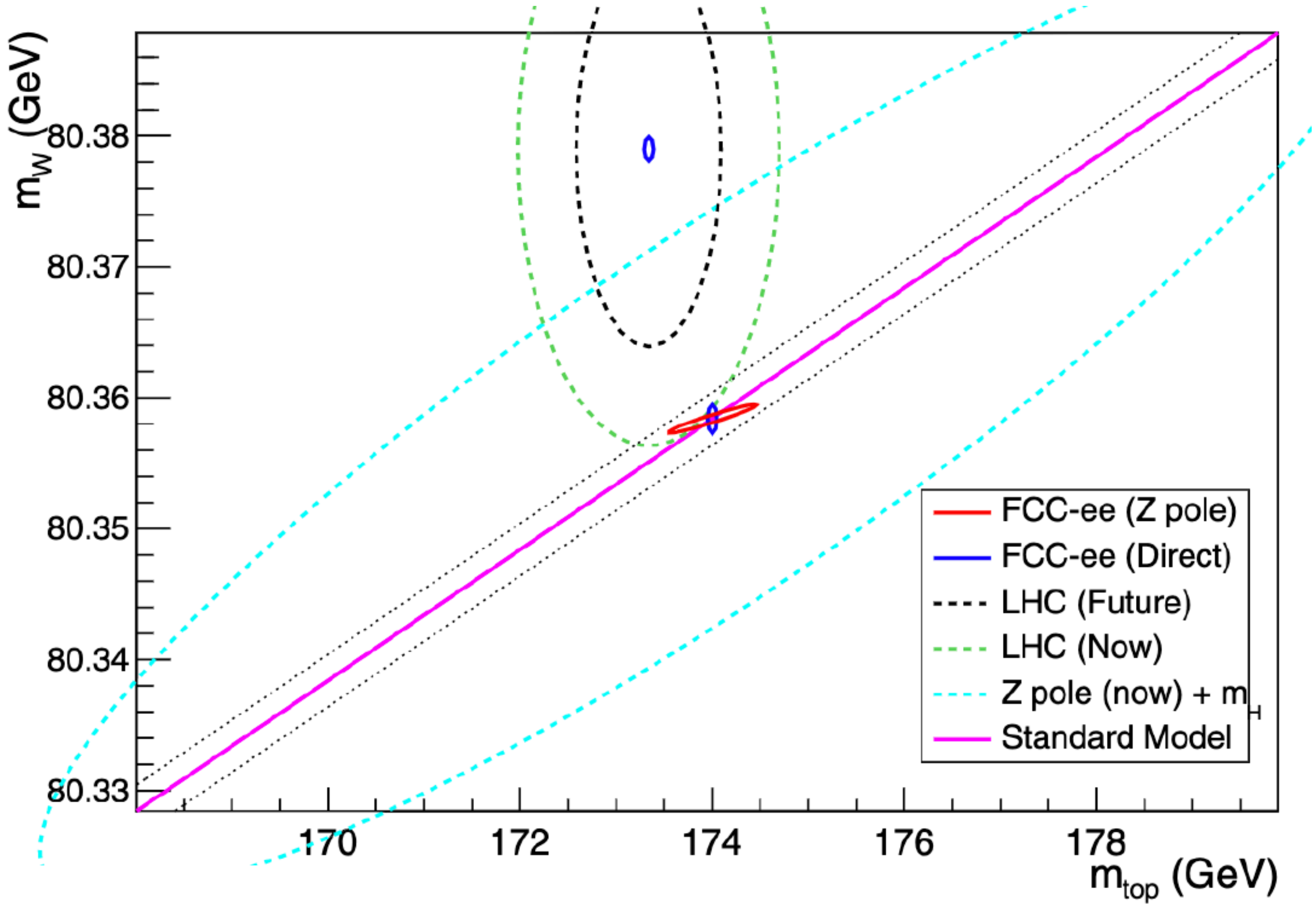


Y_t vs m_t



- Statistical accuracy on mt (Γ_t) is ~**17 (45) MeV** and **10%** on Y_t
- Systematic uncertainties
  - 3 MeV from center-of-mass energy
  - 5 MeV from α_s
  - ~40 MeV from theoretical uncertainties (NNLO)

Top-pair threshold scan



- Precision test of the Standard Model
- Improved understanding in top-W-H radiative corrections

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

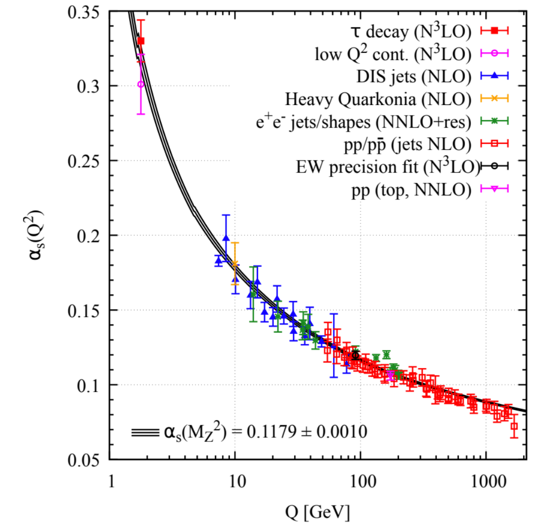
First set of main observables - needs to be improved

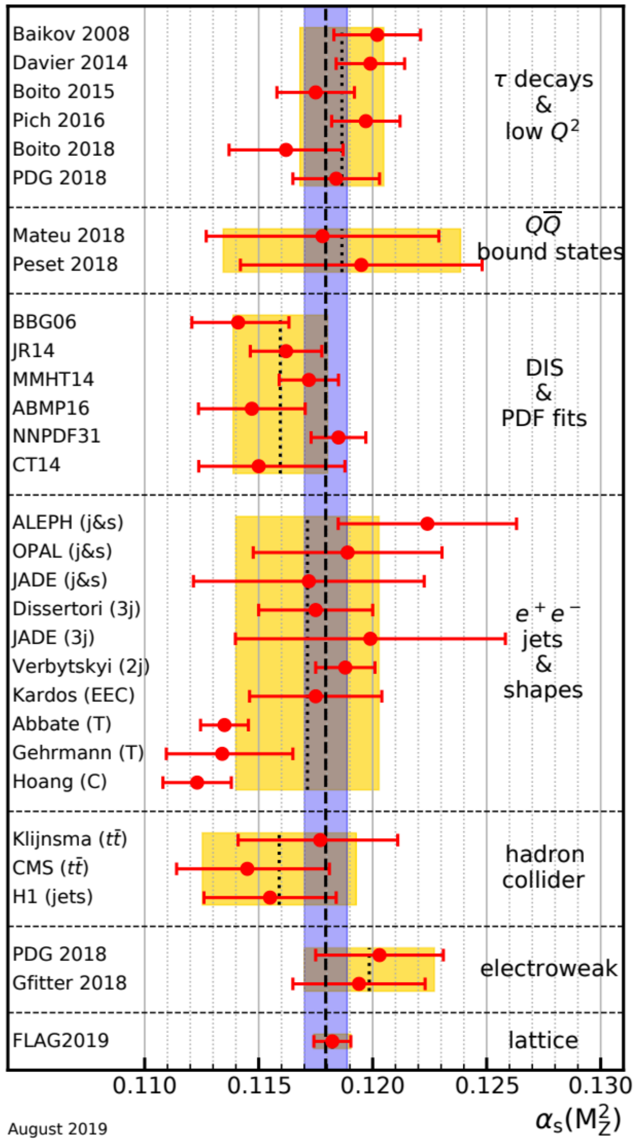
- **Focus was on statistical precision**
- **For Z and W boson mass, center-of-mass energy uncertainty will dominate**
- **For cross-section measurements the luminosity measurement will be limiting**
- **Possible experimental uncertainties are indicative**
- **Tau, b, and c observables to be added**
- **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**

FCC-ee: Taus, Flavor and QCD

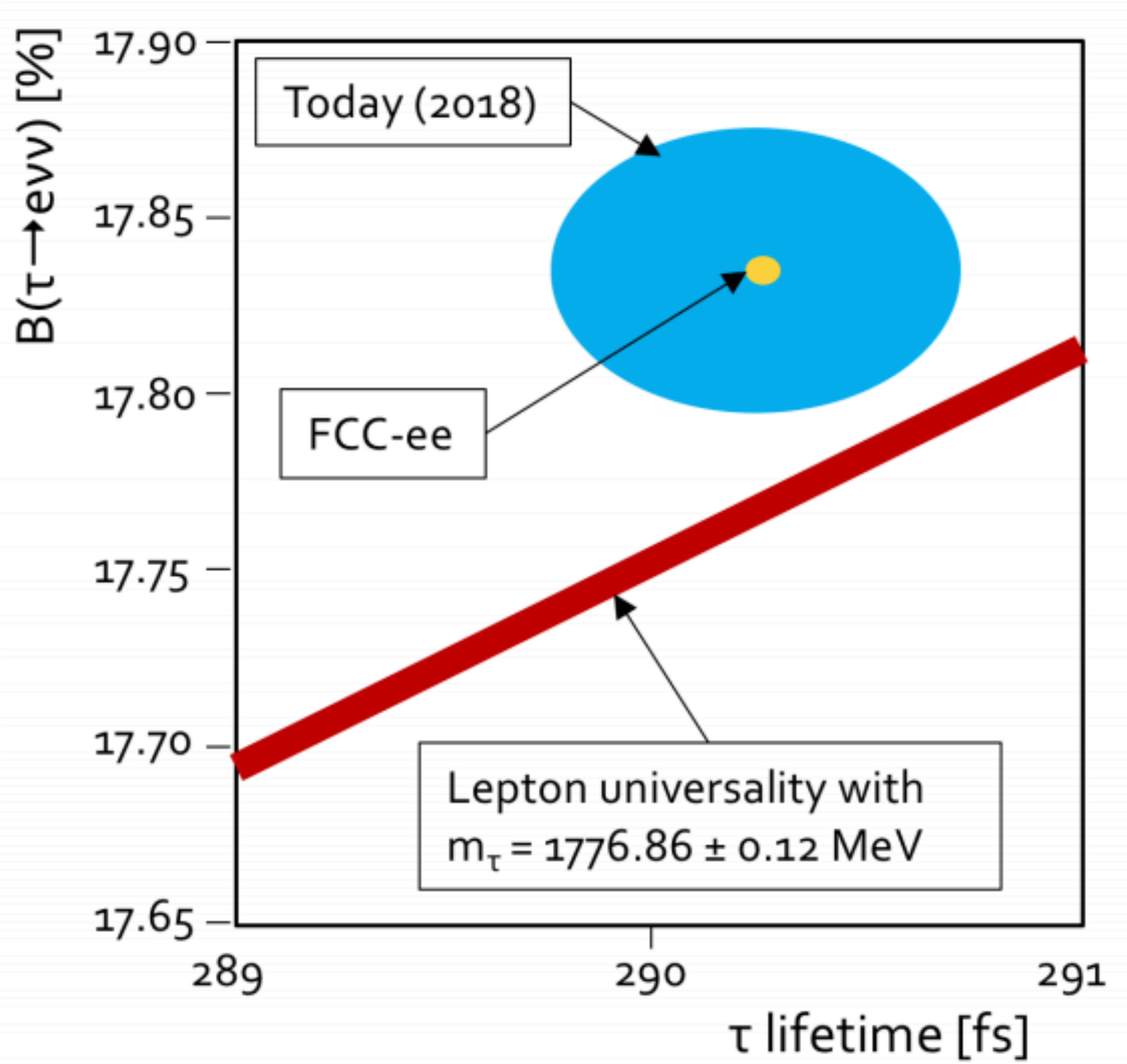
QCD Opportunities

- **High precision α_s (order of magnitude improvement) determination from**
  - Hadronic tau decays
  - Jet rates and event shapes
  - Hadronic Z decays
  - Hadronic W decays
- **High precision studies of perturbative parton radiation**
  - Jet rates and event shapes
  - Jet substructure
  - Quark/gluon/heavy-quark discrimination
  - q, g, b, c parton-to-hadron fragmentation functions
- **High precision non-perturbative QCD studies**
  - Color reconnection
  - Final-state multiparticle correlations
- **High precision hadronic studies**
  - Very rare hadron production and decays





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

FCC-ee: Discovery Machine

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.

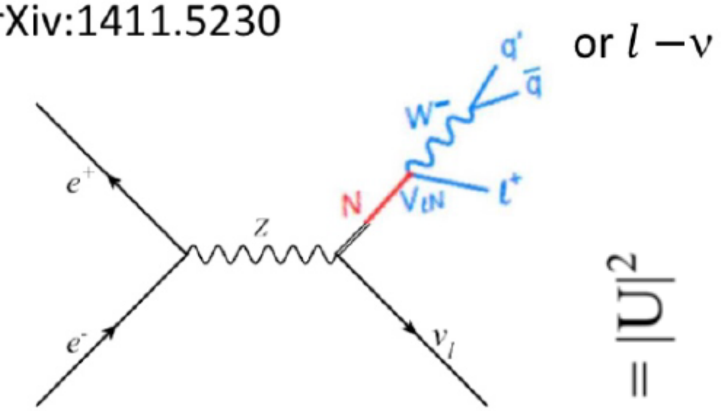
Two mass-differences ⇒ at least two sterile neutrinos.

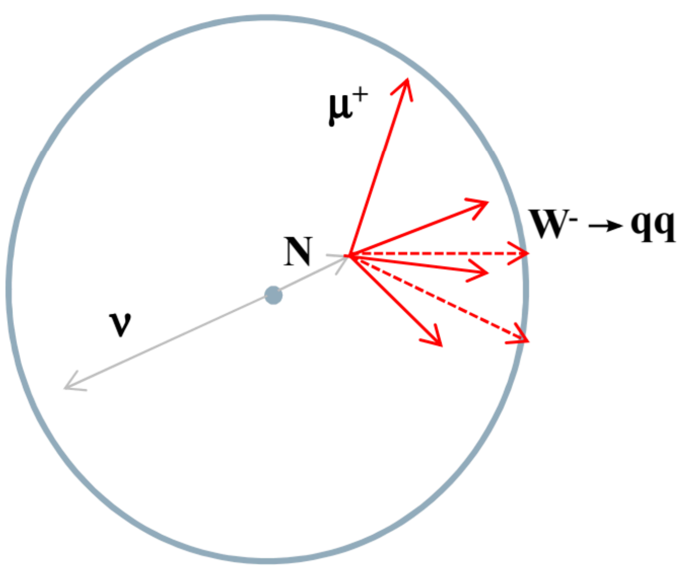
New mass scale, a priori unrelated to the known ones.

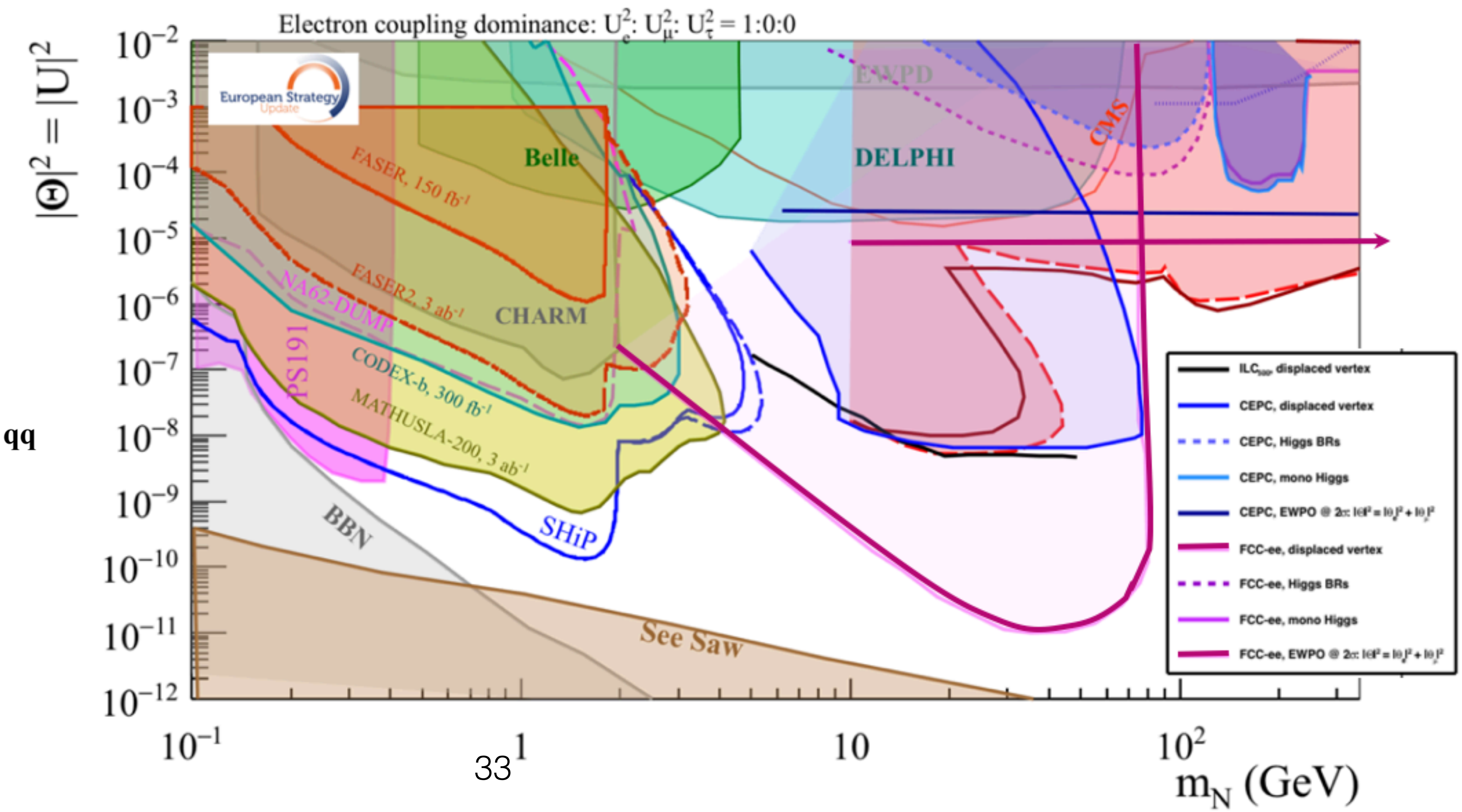
Many constraints from experiments on all energy scales.

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

arXiv:1411.5230

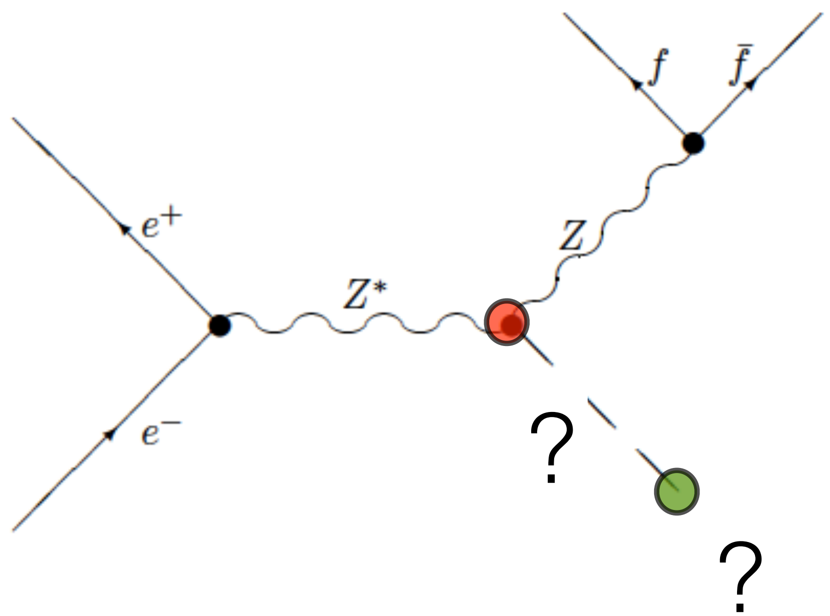






Search for New Scalars

➡ Measurement with OPAL at LEP



arXiv:hep-ex/0206022v1 10 Jun 2002

Decay-mode independent searches for new scalar bosons with the OPAL detector at LEP

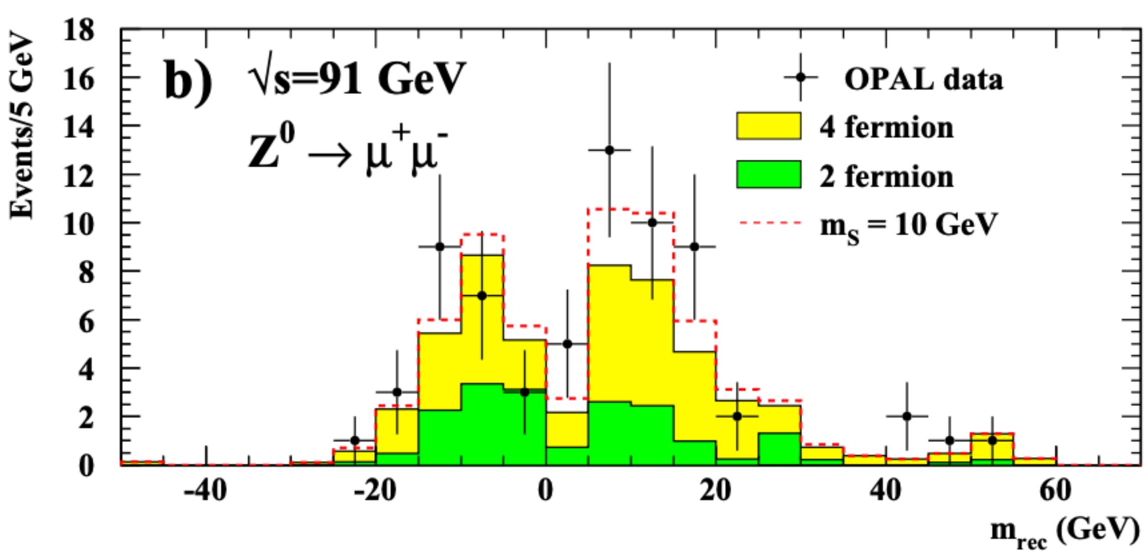
The OPAL Collaboration

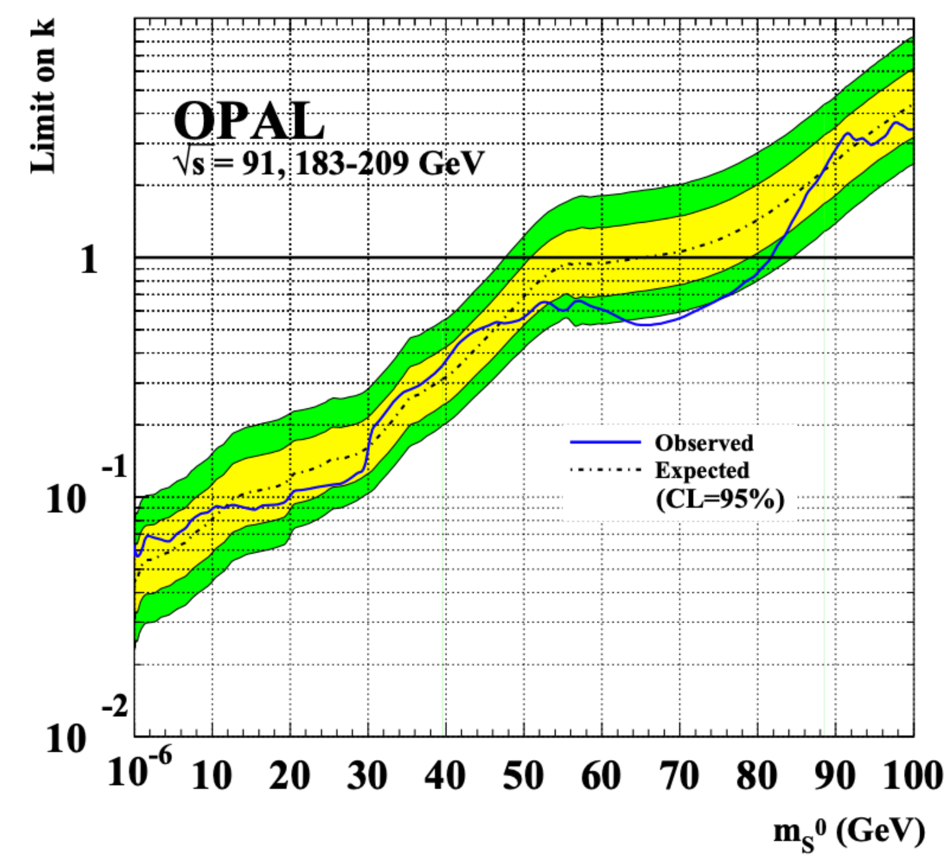
Abstract

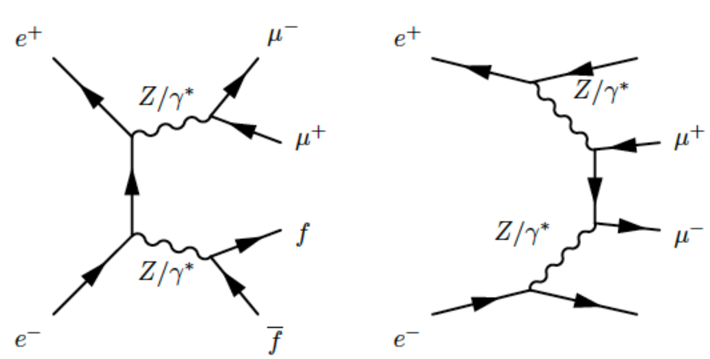
This paper describes topological searches for neutral scalar bosons S^0 produced in association with a Z^0 boson via the Bjorken process $e^+e^- \to S^0Z^0$ at centre-of-mass energies of 91 GeV and 183–209 GeV. These searches are based on studies of the recoil mass spectrum of $Z^0 \to e^+e^-$ and $\mu^+\mu^-$ events and on a search for S^0Z^0 with $Z^0 \to \nu\bar{\nu}$ and $S^0 \to e^+e^-$ or photons. They cover the decays of the S^0 into an arbitrary combination of hadrons, leptons, photons and invisible particles as well as the possibility that it might be stable.

No indication for a signal is found in the data and upper limits on the cross section of the Bjorken process are calculated. Cross-section limits are given in terms of a scale factor k with respect to the Standard Model cross section for the Higgs-strahlung process $e^+e^- \to H^0_{SM}Z^0$.

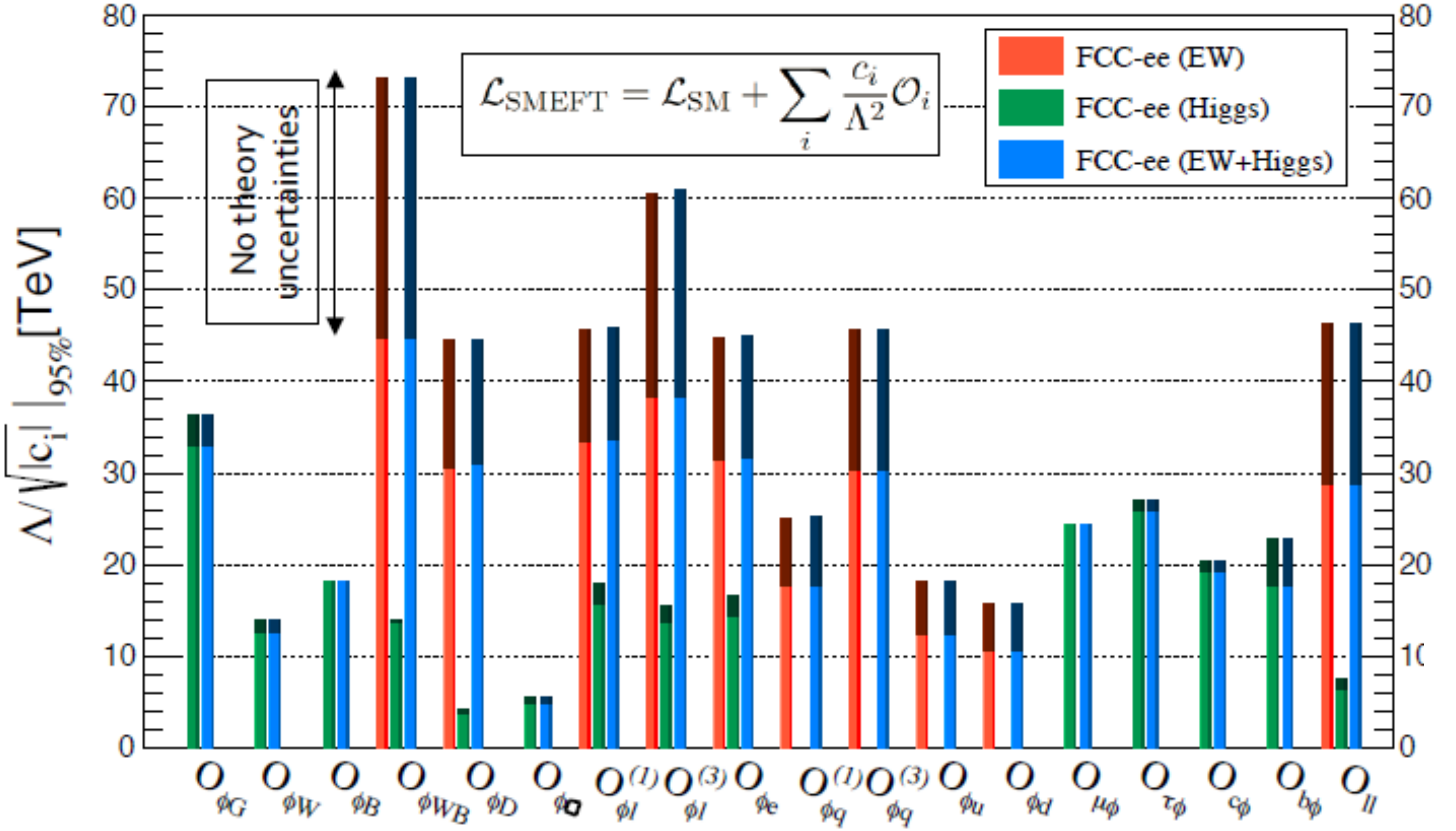
These results can be interpreted in general scenarios independently of the decay modes of the S^0. The examples considered here are the production of a single new scalar particle with a decay width smaller than the detector mass resolution, and for the first time, two scenarios with continuous mass distributions, due to a single very broad state or several states close in mass.







Discovery Physics



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

Your contributions

- ➡ **Can you (or your students)**
  - use studies to design or optimize detectors?
  - develop or optimize reconstruction, identification, and analysis using modern techniques?
  - come up with new or unexplored ideas?

- ➡ **For more details, see case studies for FCC-ee community**
- ➡ **Software tutorial mid September**

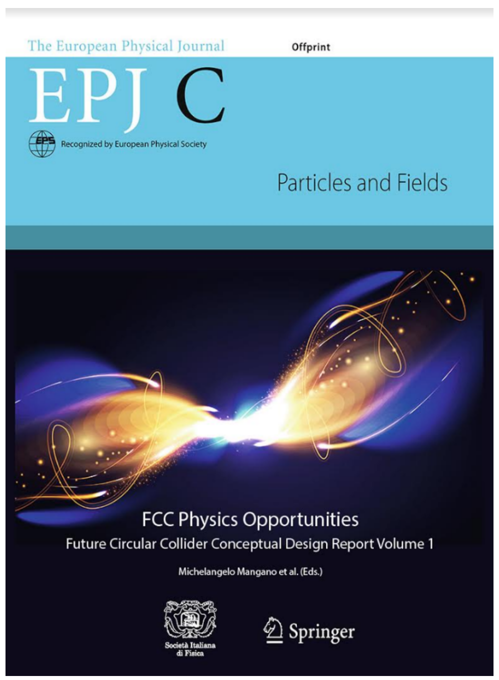
Conclusion

- **FCC-ee offers a huge physics program** with
  - ➡ Higgs and top measurements with > 10^6 events each 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
    - $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$, $\sin^2\theta_W^{eff}$ 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 (order(s) of magnitude) in understanding of nature
- Main 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

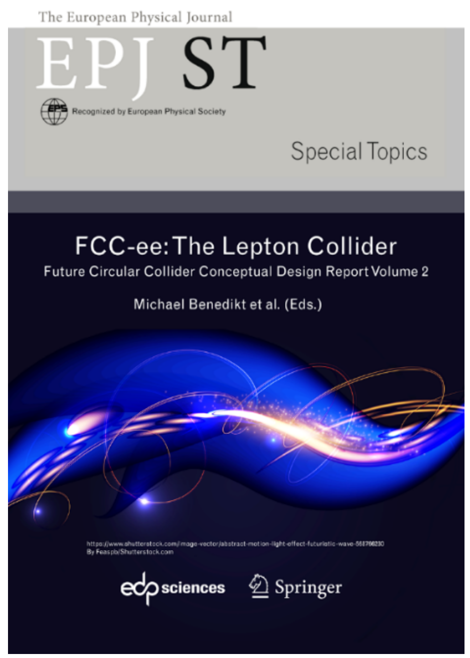
FCC documentation

Outcome of design studies recommended by the 2013 European Strategy

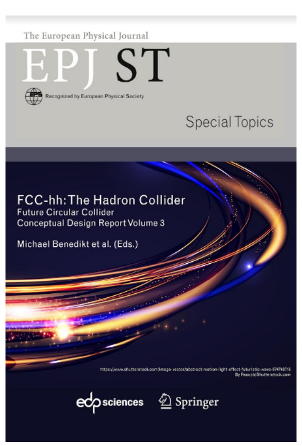
4 CDR volumes published in EPJ



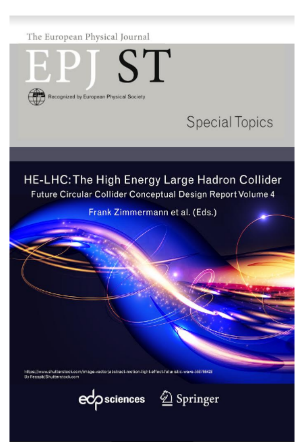
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider

Recent FCC publications

1) Future Circular Collider - European Strategy Update Documents

(FCC-ee), (FCC-hh), (FCC-int)

2) FCC-ee: Your Questions Answered - arXiv:1906.02693

3) Circular and Linear e+e- Colliders: Another Story of Complementarity

arXiv:1912.11871

4) Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders arXiv:1901.02648

5) Polarization and Centre-of-mass Energy Calibration at FCC-ee, arXiv:1909.12245

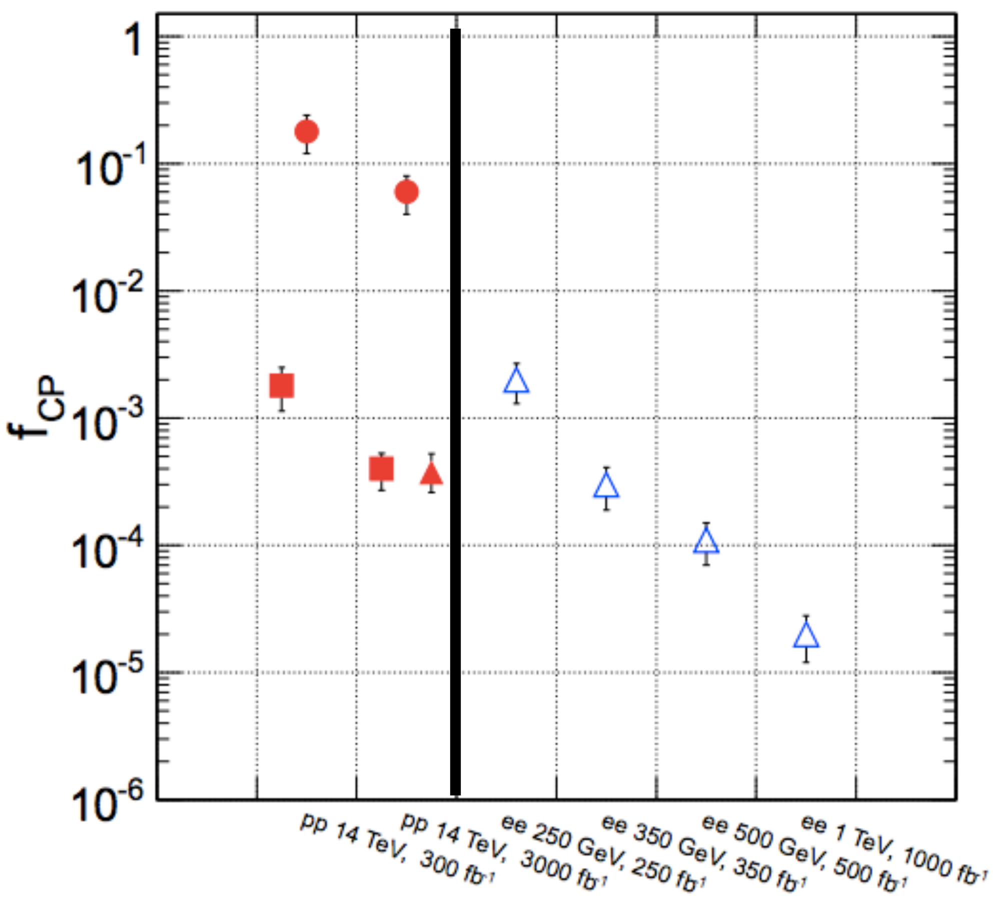
Higgs Related Physics at Lepton Colliders

$\sqrt{s}$ [GeV]	$\sqrt{s}$	Measurements (incomplete list)
90	$\mathbf{m_Z}$	m_Z, Γ_Z, α_s, α_{QED}, flavor, QCD
125	$\mathbf{m_H}$	s-channel Higgs production
160	$\mathbf{2m_W}$	m_W, α_s
240-250	$\mathbf{m_H+m_Z+\ldots}$	m_H, Γ_H, J^{PC}, g_{HXX}, BSM decays, indirect g_{HHH}
340-355	$\mathbf{2^*m_{top}}$	g_{HWW}, Γ_H, indirect g_{Htt}, m_{top}
500	$\mathbf{2^*m_{top}+m_H+\ldots}$	g_{HHH}, g_{Htt}
> 500	$\mathbf{m_{NP}}$	g_{Htt}, g_{HHH}, BSM Higgs

CP Measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Higgs to Tau decays of interest
- ➡ Studies consider intermediated resonances (ρ,a1)

for HVV couplings



$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$$

Colliders	LHC	HL-LHC	FCCee (1 ab^{-1})	FCCee (5 ab^{-1})	FCCee (10 ab^{-1})
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

http://arxiv.org/abs/1308.1094