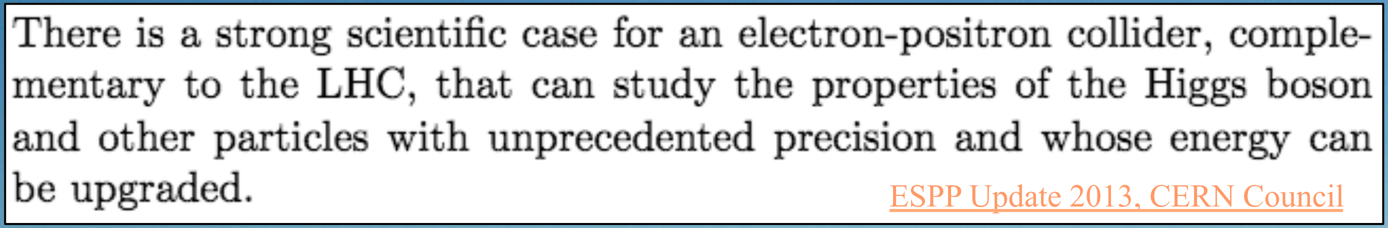
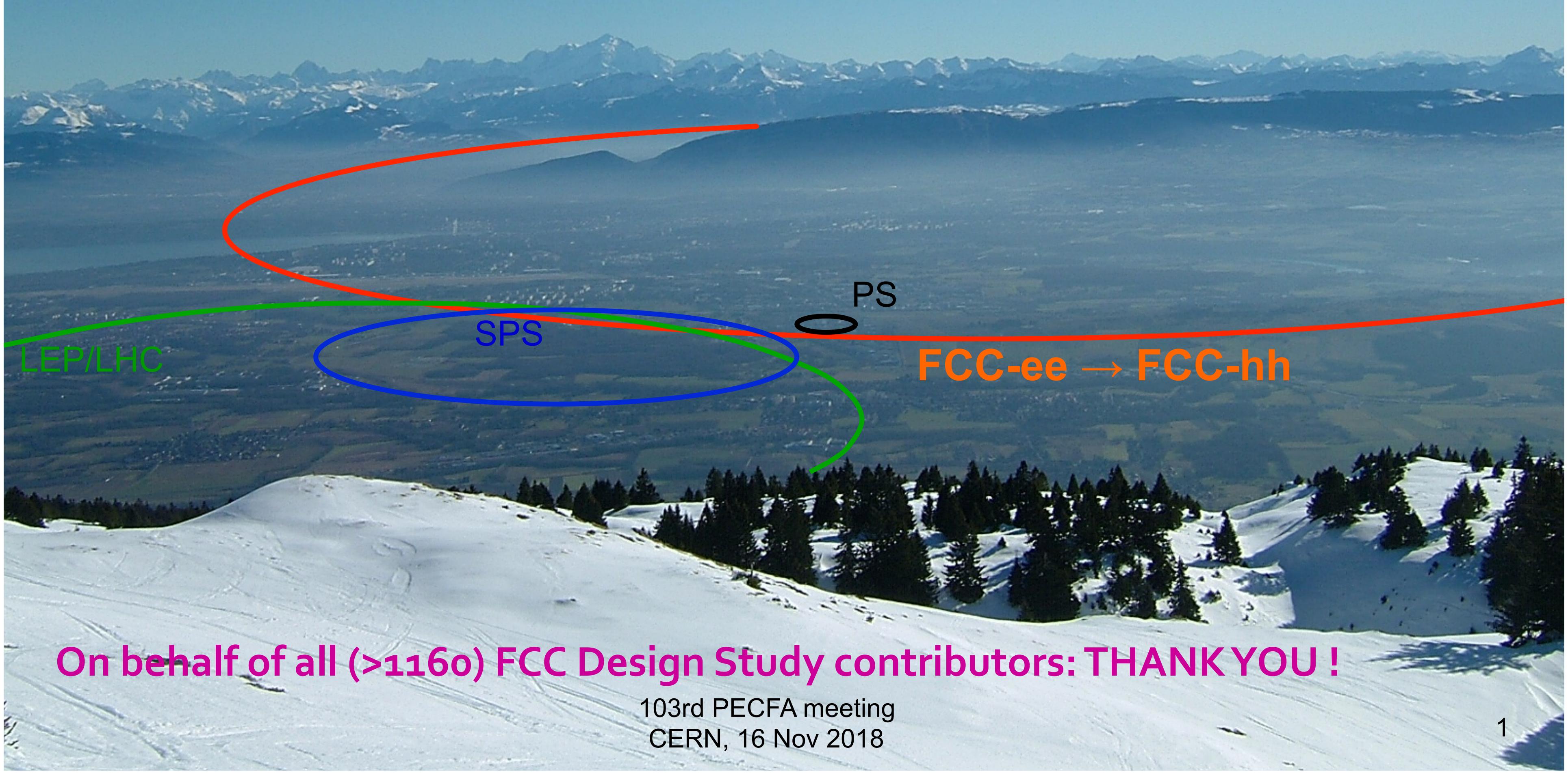
Future Circular Colliders, Phase 1: The FCC-ee



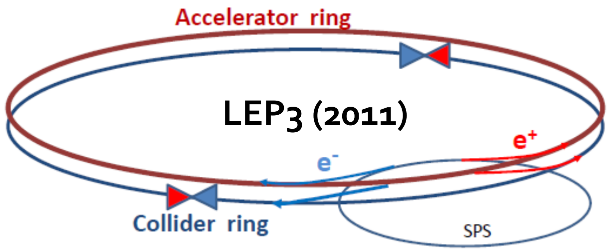
> There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.
>
> ESPP Update 2013, CERN Council



On behalf of all (>1160) FCC Design Study contributors: THANK YOU !

The FCC-ee: From genesis to ESU 2020

A. Blondel , F. Zimmermann https://arxiv.org/abs/1112.2518



A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

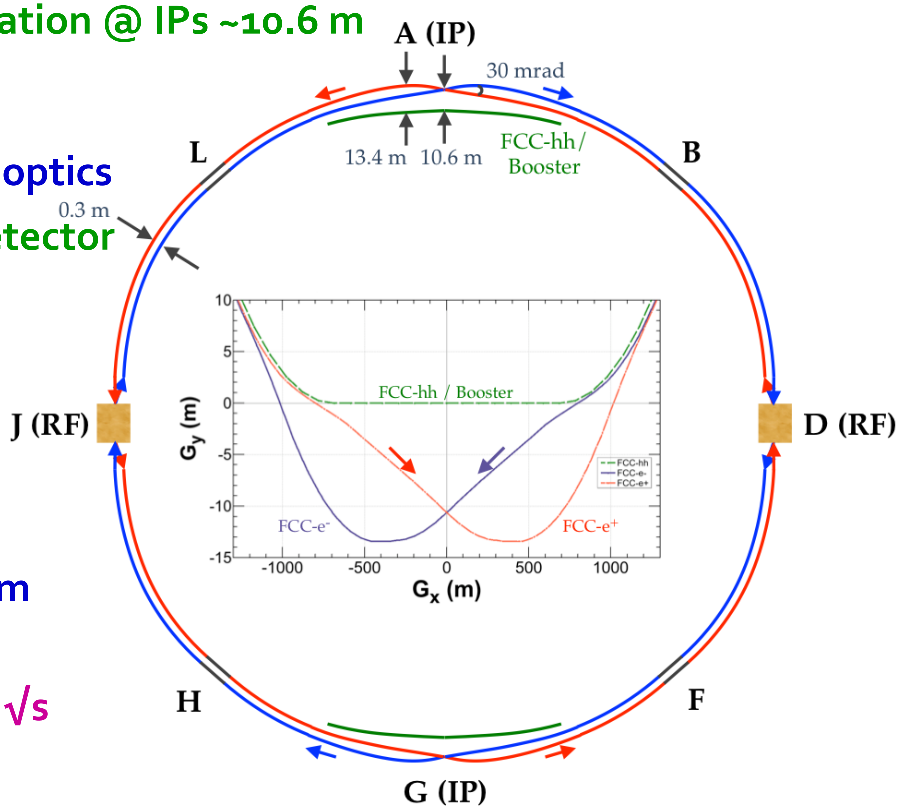
TLEP (2012)
in a 80-100 km tunnel

First look at the physics case of TLEP
M. Bicer et al. https://arxiv.org/abs/1308.6176

- **Future Circular Collider Design Study (FCC-ee + FCC-hh), 2014-2018**
  - FCC CDR and cost review to appear on 10 Dec 2018 for ESU
    - Vol.1 : Physics Opportunities
    - Vol.2 : The lepton collider (FCC-ee) "The Electroweak Factory"
    - Vol.3 : The hadron collider (FCC-hh) "The Energy Frontier" Talk from M. Aleksa
  - FCC-ee anticipated performance now backed-up by a robust and realistic design
    - Phase 1: 88 → 240 GeV (Z, W, Higgs) – Phase 2: 345 → 365 GeV (Higgs, top)
  - Most versatile & ambitious investment for "post-LHC accelerator" (ESU 13)
    - Same infrastructure, same tunnel, same experimental caverns for both FCC's
      - ➨ For at least 60 years of physics and several generations of physicists at CERN
      - ➨ Also a good start for a 20 TeV muon collider ? Talk from N. Pastrone

FCC-ee current basic design choices

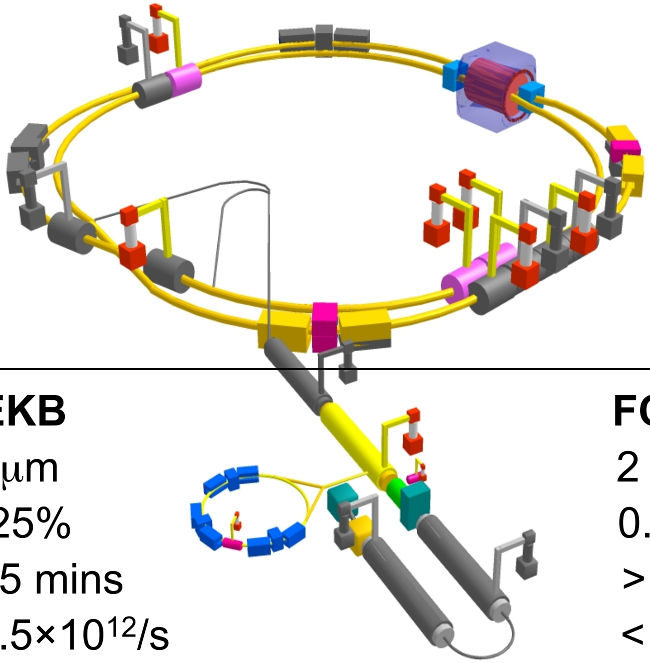
- Shares the same layout as for the FCC-hh
  - Top-up injection scheme for high luminosity
    - Requires booster in collider tunnel, following footprint of FCC-hh
  - Slight excursion of collider ring around IPs : wider tunnel for ±1.2 km
    - Maximum separation ~ 13.4 m; separation @ IPs ~10.6 m
  - Double ring (e^+, e^-) collider, ~100 km
  - Asymmetric interaction region layout and optics
    - Limits synchrotron radiation in the detector
  - Two interaction points (IP) in A and G
    - Configuration with 4 IPs to be studied
  - Crab-waist optics to maximize luminosity
    - Large crossing angle: 30 mrad
  - Synchrotron radiation power : 50 MW/beam
    - At all beam energies
      - ➨ Highest luminosities at smallest √s



A most mature technology

- The FCC-ee exploits 50 years of experience with circular e^+e^- colliders
  - LEP:
    - High energy
    - Nb/Cu RF cavities
    - SR effects
    - Energy calibration by spin resonance
  - B factories, KEKB and PEP-II:
    - High-beam currents
    - Top-up injection
  - DAΦNE:
    - Crab-waist optics
  - Super B factories
    - Low β_y^* , small L^*
  - SuperKEKB
    - Positron source

SuperKEKB : FCC-ee demonstrator



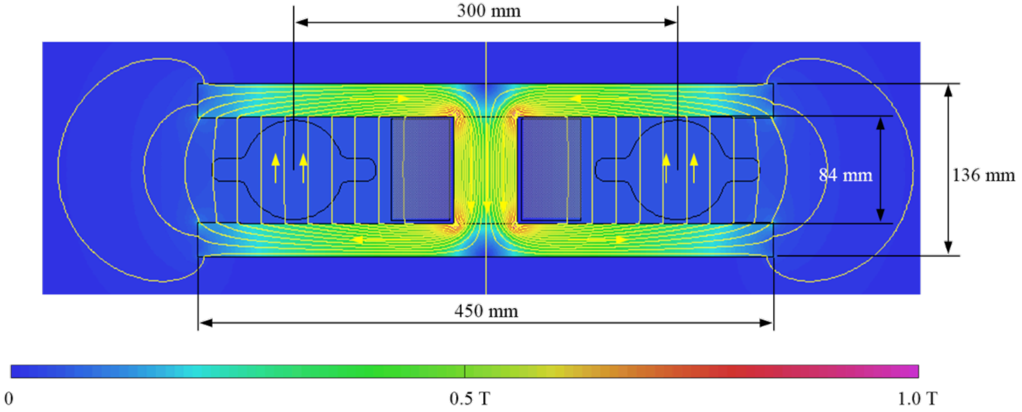
	SuperKEKB	**FCC-ee**
β_y^*	= 300μm	2 mm
$\varepsilon_y/\varepsilon_x$	= 0.25%	0.25%
Lifetime:	5 mins	> 1h
e^+ rate:	2.5×10^{12}/s	< 1.5×10^{12}/s
Off-momentum acceptance:	±1.5%	±1.5%

SuperKEKB goes beyond FCC-ee, and tests all concepts

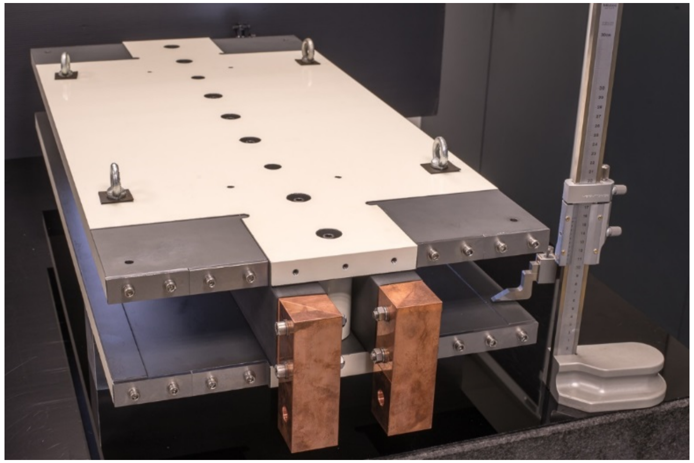
- The FCC-ee combines experience with recent, novel ingredients
  - Precision frontier – extremely high luminosities at high energy

Low-power / low-cost design for magnets

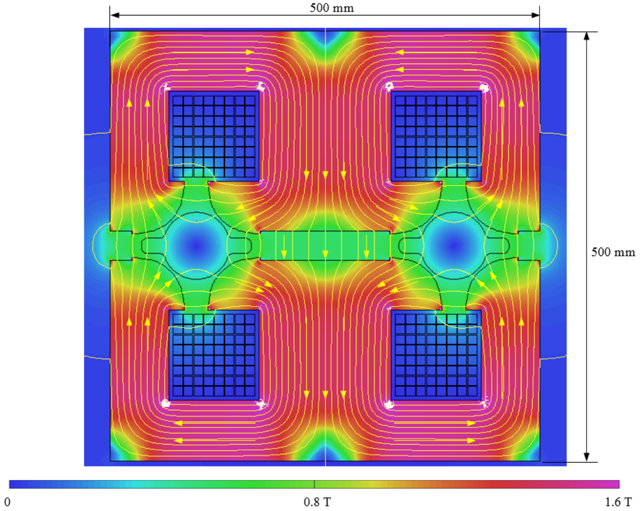
Twin-dipole design with 2× power saving
16 MW (at 175 GeV), with Al busbars



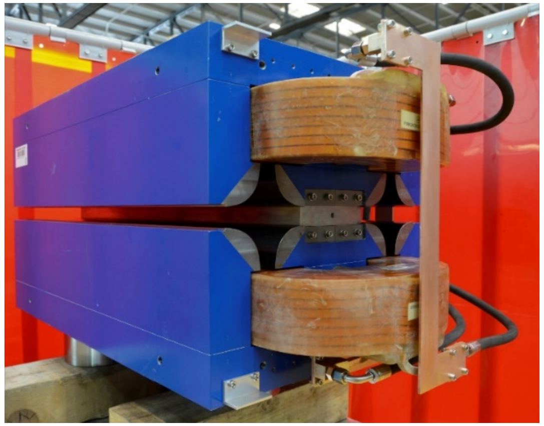
First 1 m prototype



Twin F/D quad design with 2× power saving;
25 MW (at 175 GeV), with Cu conductor

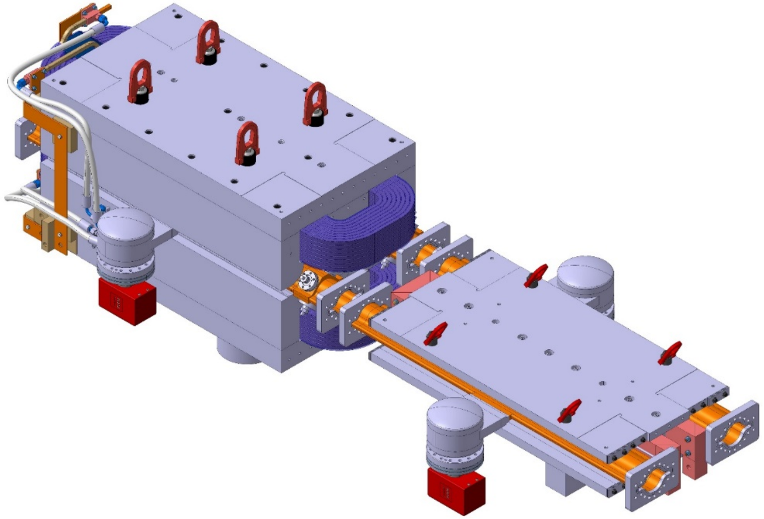


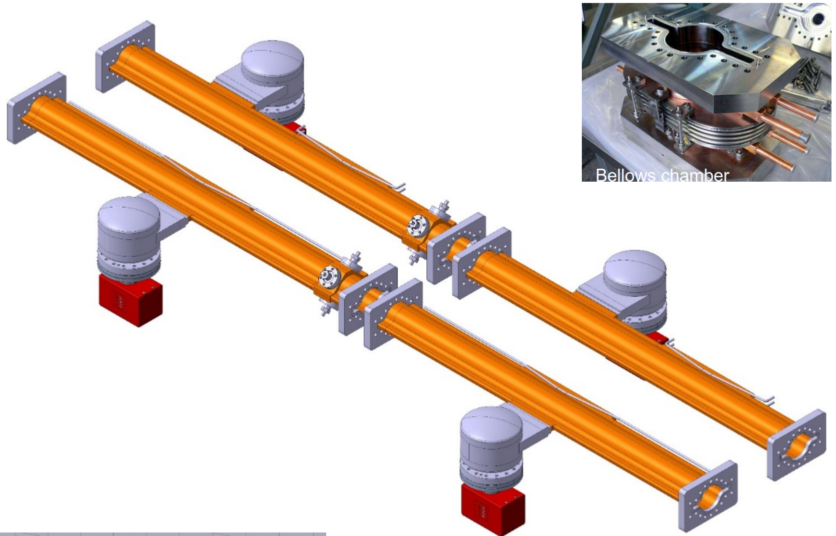
First 1 m prototype

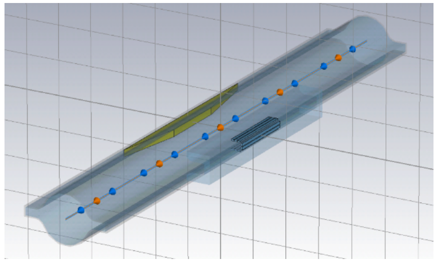


Arc vacuum chamber prototyping & integration

- **Vacuum system designed to control S.R. load of 50 MW / beam**







3D model of FCC-ee chamber with SR absorber and pumping slots used for CST impedance calculations

- **Strategically placed, water-cooled photon absorbers, with adjacent NEG pumps**
- **Construction of chamber prototypes and integration with twin magnets**

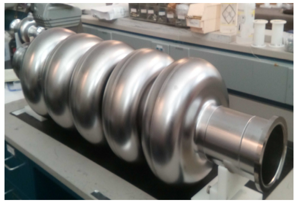
RF staging scenario

- **Three sets of cavities**
  - High intensity (Z, FCC-hh)
    - 400 MHz, mono-cell Nb/Cu cavities (4 / cryomodule)
  - Higher energy (WW, ZH, $t\bar{t}$)
    - 400 MHz, four-cell Nb/Cu cavities (4 / cryomodule)
  - $t\bar{t}$ complement
    - 800 MHz, five-cell, Nb cavities (4 / cryomodule)

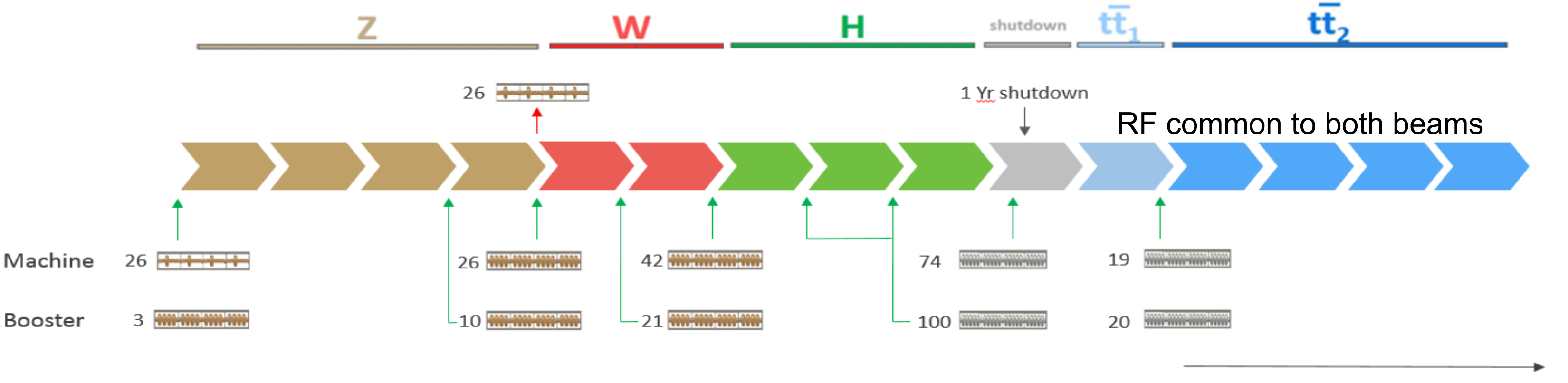
"Ampere-class" machine

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
WW	0.44	2000	147
ZH	2.0	393	29
$t\bar{t}$	10.9	48	5.4

"High-gradient" machine



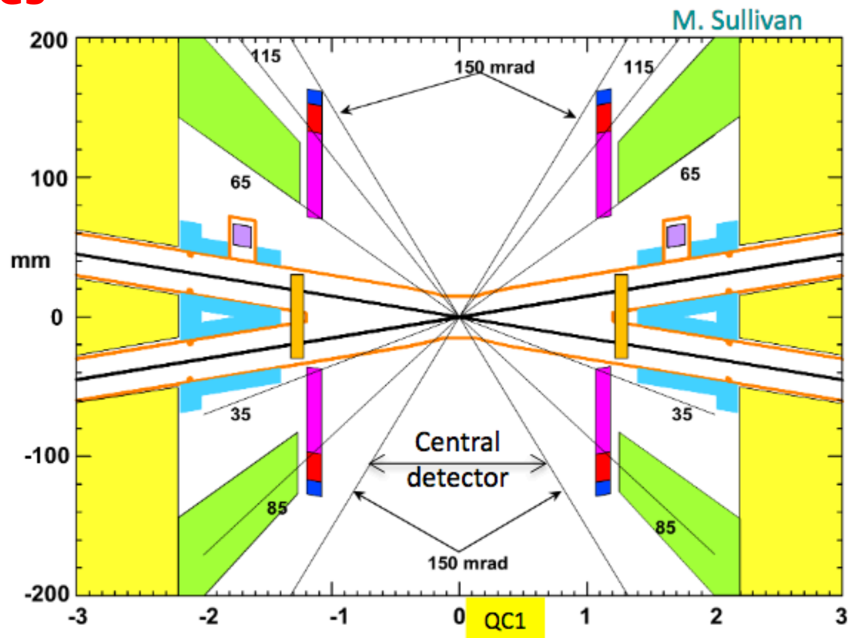
prototype FCC
5-cell 800-MHz
Nb cavity
(at JLAB, 2017)

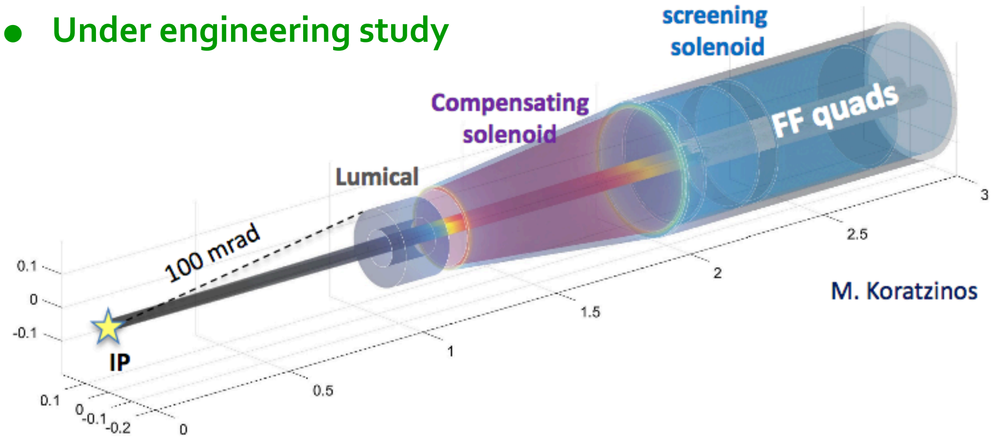


Installation sequence comparable to LEP: ~ 30 cryomodules / shutdown

Interaction Region Layout (MDI)

- **Unique and flexible design at all energies**
  - $L^* = 2.2$ m
    - Acceptance: 100 mrad
  - Solenoid compensation scheme
    - Reduce ε_y blow-up ⇒ $B_{Detector} \leq 2T$
  - Beam pipe
    - Warm, liquid cooled (~SuperKEKB)
    - Be in central region, then Cu
    - R = 15mm in central region
      - Vertex detector close to the IP
    - SR masks, W shielding
  - Mechanical design and assembly concept
    - Under engineering study

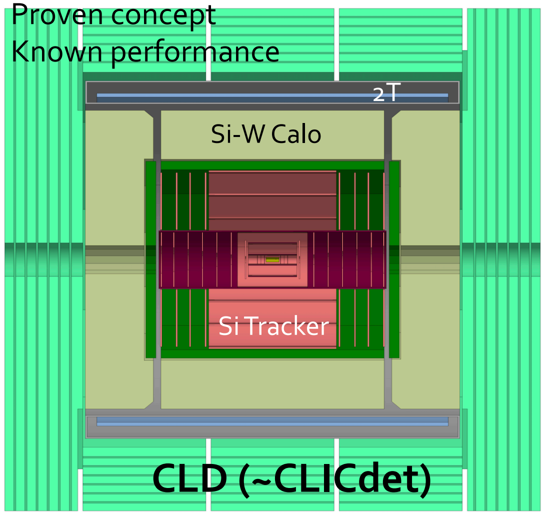


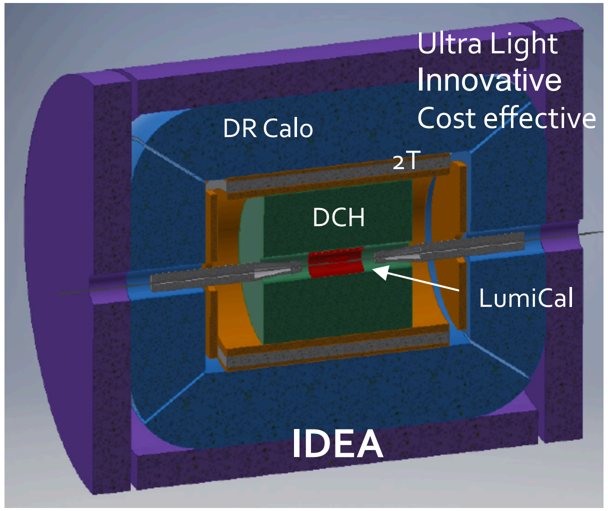


M. Koratzinos

Detector design concepts

- **Two designs studied so far**

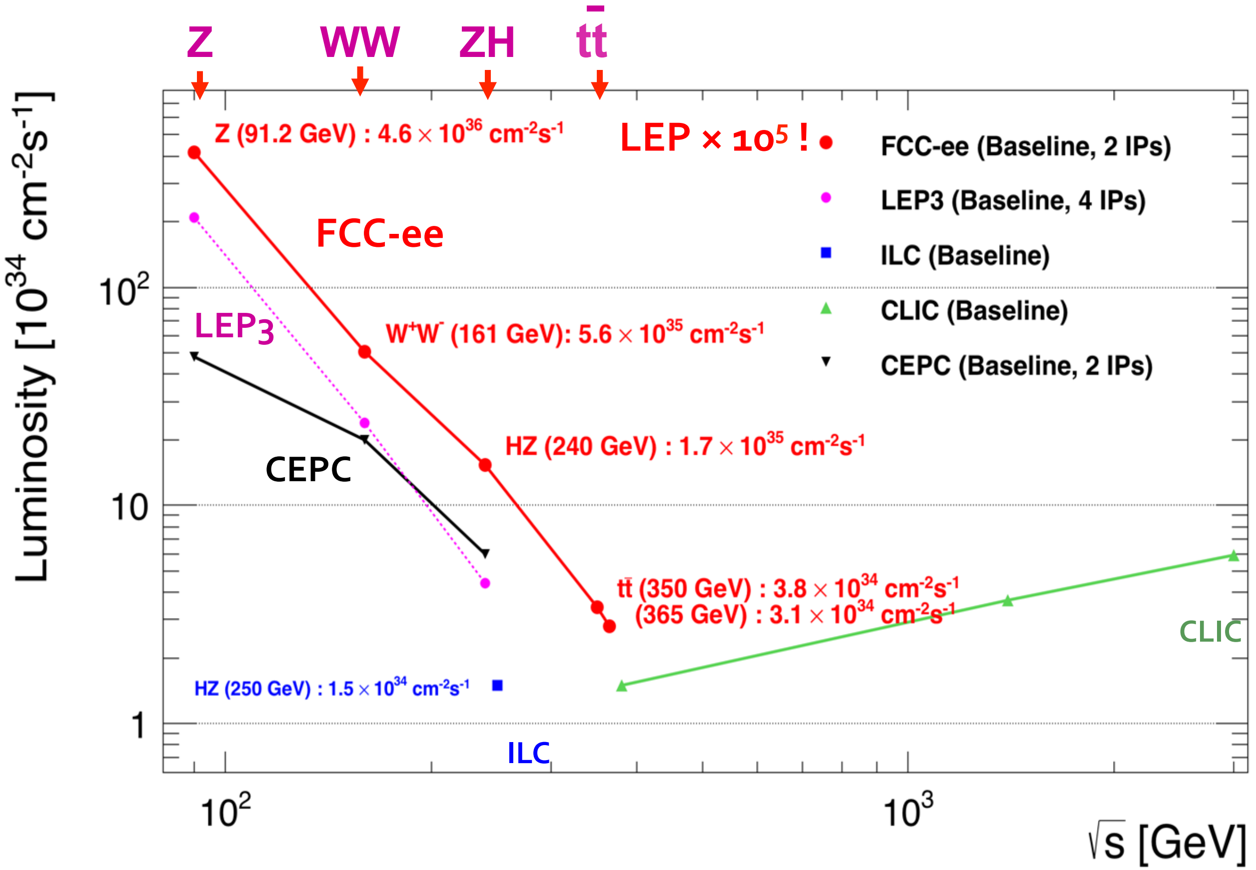




  - **It was demonstrated that detectors satisfying the requirements are feasible**
    - **Physics performance, invasive MDI, beam backgrounds**
- **Prompted by ESU, proto-collaborations should form soon**
  - **Towards two to four detector proposals to be made by ~2026**
    - **Light, granular, fast, b and c tagging, lepton ID and resolutions, hadron ID**
    - **Cost effective**
    - **Satisfy constraints from interaction region layout**

EW factories : Energies and luminosities

- The FCC-ee offers the largest luminosities in the 88 → 365 GeV √s range



- Ultimate precision:
  - 100 000 Z / second (!)
    - 1 Z / second at LEP
  - 10 000 W / hour
    - 20 000 W at LEP
  - 1 500 Higgs bosons / day
    - 10 times ILC
  - 1 500 top quarks / day

    in each detector

… in a clean environment:

- No pileup
- Beam backgrounds under control
- E,p constraints

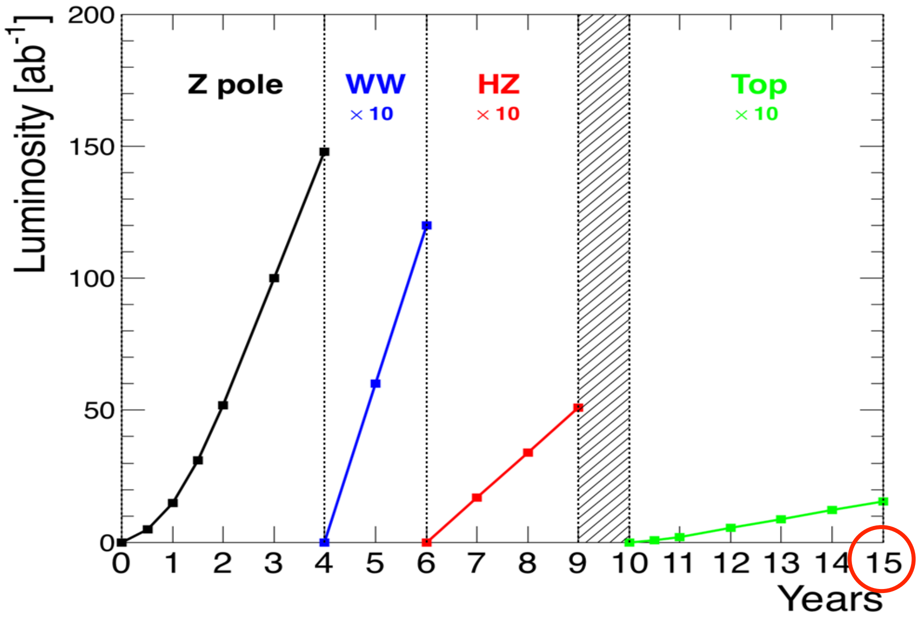
PRECISION and SENSITIVITY
to rare or elusive phenomena

- The FCC-ee discovery potential at the precision frontier is multiplied by the presence of the four heaviest SM particles (Z, W, H, and top) in its energy range

The FCC-ee operation model and statistics

- 185 physics days / year, 75% efficiency, 10% margin on luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold…	… and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

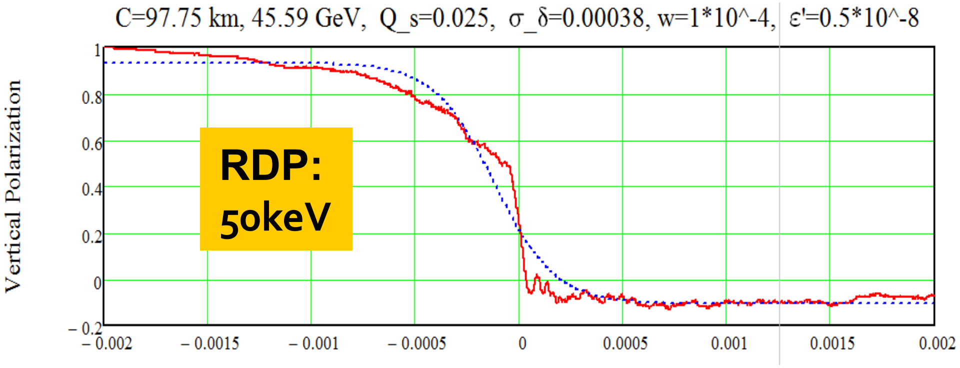


Total : 15 years

Event statistics	√s precision
5×10^{12} $e^+e^- \rightarrow Z$	100 keV
10^8 $e^+e^- \rightarrow W^+W^-$	300 keV
10^6 $e^+e^- \rightarrow HZ$	1 MeV
10^6 $e^+e^- \rightarrow t\bar{t}$	2 MeV

Beam Polarization and Energy Calibration

- **Simulation show transverse polarization at the Z and WW energies**
  - **Energy calibration by resonant depolarization every 10 mins on pilot bunches**
    - **UNIQUE TO CIRCULAR COLLIDERS**

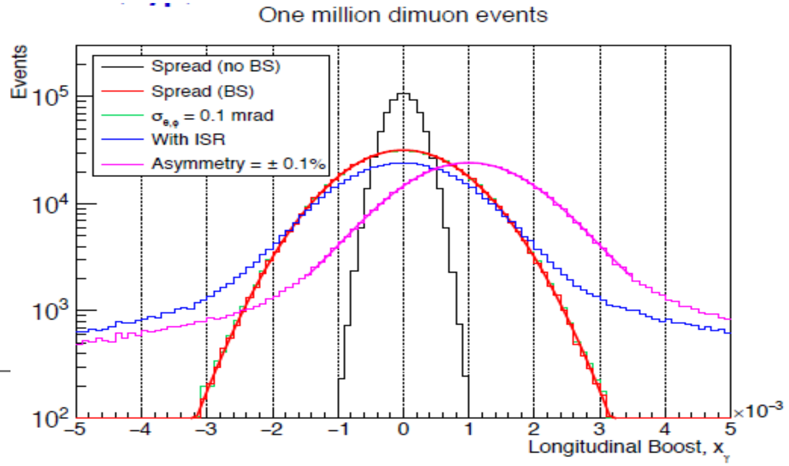


RDP: 50keV

260 seconds sweep of depolarizer frequency

- **Total √s uncertainty of 100 keV @ Z pole, and 300 keV at the WW threshold**

- **Energy spread (~100 MeV) will be measured**
  - **From $e^+e^- \rightarrow \mu^+\mu^-$ longitudinal boost**
    - **10^6 events every 4 mins @ Z pole**
      - **Continuous 35 keV precision on $\delta\sqrt{s}$**
    - **Also measures $\Delta E = E^+ - E^-$ to at both IPs**



The FCC-ee discovery potential (excerpt)

- EXPLORE the 10-100 TeV energy scale
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
      - ➨ m_Z , m_W , m_{top} , Γ_Z , $\sin^2 \theta_W^{eff}$, R_b , $\alpha_{QED}(m_z)$, $\alpha_s(m_z\ m_W\ m_\tau)$, top EW couplings …
    - Up to 10-fold more precise and model-independent Higgs couplings measurements

arXiv:1512.05544
arXiv:1603.06501
arXiv:1503.01325

- DISCOVER that the Standard Model does not fit
  - NEW PHYSICS ! Pattern of deviations may point to the source.
- DISCOVER a violation of flavour conservation / universality
  - Examples: $Z \rightarrow \tau\mu$ in 5×10^{12} Z decays; or $\tau \rightarrow \mu\nu$ / $\tau \rightarrow e\nu$ in 2×10^{11} τ decays; …
  - Also $B^0 \rightarrow K^{*0}\tau^+\tau^-$ or $B_S \rightarrow \tau^+\tau^-$ in 10^{12} bb events
- DISCOVER dark matter as invisible decays of Higgs or Z
- DIRECT DISCOVERY of very-weakly-coupled particles
  - in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, ALPs, …
    - Motivated by all measurements / searches at colliders (SM and "nothing else")

FCC-ee is not only a Higgs factory. Z, WW, and $t\bar{t}$ factories are important for discovery potential

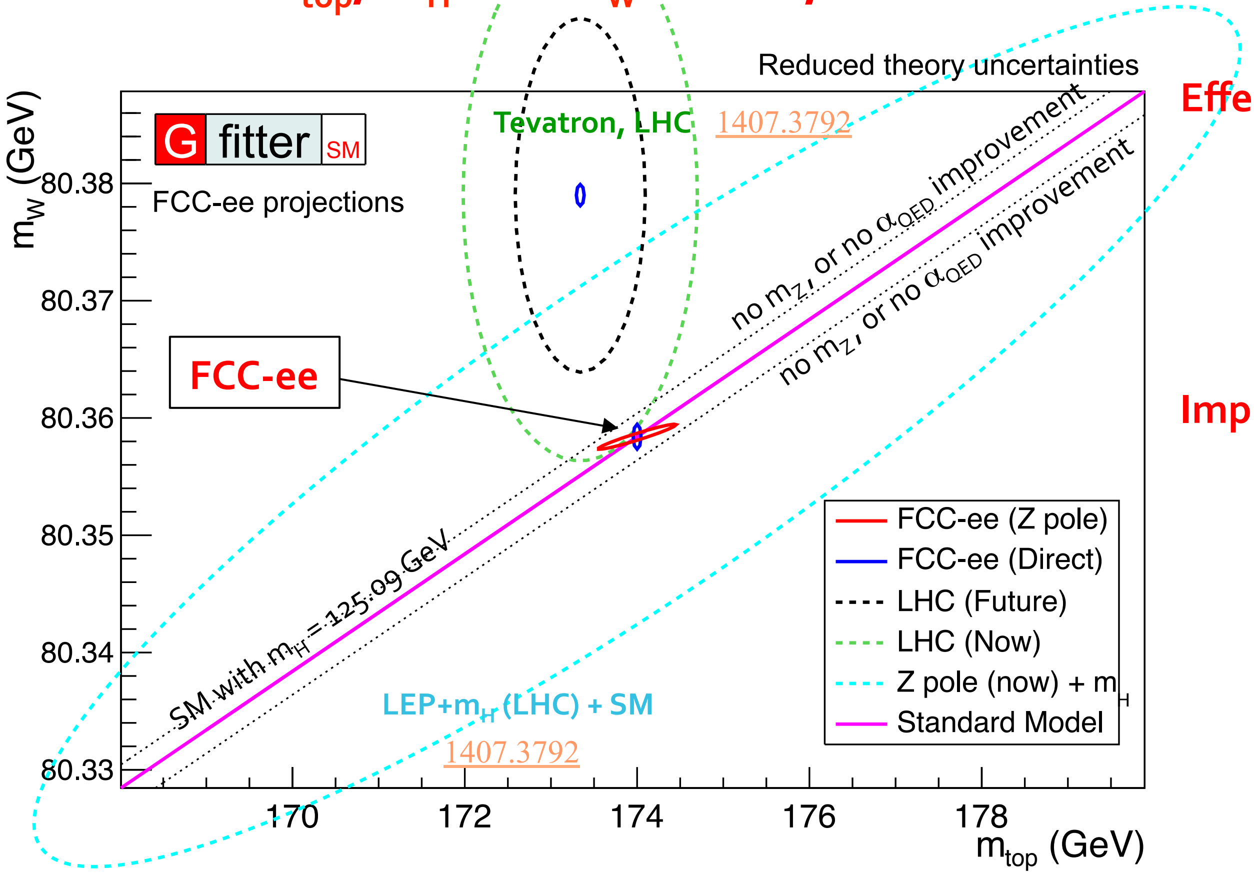
First look at the physics case of TLEP https://arxiv.org/abs/1308.6176 (Aug. 2013)

Sample of EW observables, exp'tal precisions

	Observable	Measurement	Current precision	FCC-ee **stat.**	FCC-ee **syst.**	Dominant exp. error
Z pole	**m_Z (keV)**	Z Lineshape	91187500 **± 2100**	**5**	**< 100**	Beam energy
	Γ_Z (MeV)	Z Lineshape	2495200 **± 2300**	**8**	**< 100**	Beam energy
	R_l ($\times 10^3$)	Z Peak ($\Gamma_{had}/\Gamma_{lep}$)	20767 **± 25**	**0.06**	**0.2 – 1**	Detector acceptance
	R_b ($\times 10^6$)	Z Peak (Γ_{bb}/Γ_{had})	216290 **± 660**	**0.3**	**< 60**	g → bb
	N_ν ($\times 10^3$)	Z Peak (σ_{had})	2984 **± 8**	**0.005**	**1**	Lumi measurement
	$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$A_{FB}^{\mu\mu}$ (peak)	231480 **± 160**	**3**	**2 – 5**	Beam energy
	$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	$A_{FB}^{\mu\mu}$ (off-peak)	128952 **± 14**	**4**	**< 1**	Beam energy
	$\alpha_s(m_Z)$ ($\times 10^4$)	R_l	1196 **± 30**	**0.1**	**0.4 – 1.6**	Same as R_l
WW thresh.	**m_W (MeV)**	WW Threshold scan	80385 **± 15**	**0.6**	**0.3**	Beam energy
	Γ_W (MeV)	WW Threshold scan	2085 **± 42**	**1.5**	**0.3**	Beam energy
	N_ν ($\times 10^3$)	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2920 **± 50**	**0.8**	**small**	?
	$\alpha_s(m_W)$ ($\times 10^4$)	$B_l = (\Gamma_{had}/\Gamma_{lep})_W$	1170 **± 420**	**2**	**small**	CKM Matrix
$t\bar{t}$ thresh.	**m_{top} (MeV)**	Top Threshold scan	173340 **± 760** ± 500	**17**	**< 40**	QCD corr.
	Γ_{top} (MeV)	Top Threshold scan	?	**45**	**< 40**	QCD corr.
	λ_{top}	Top Threshold scan	μ = 1.28 **± 0.25**	**0.10**	**< 0.05**	QCD corr.
	ttZ couplings	$\sqrt{s}$ = 365 GeV	**± 30%**	**0.5 – 1.5%**	**< 2%**	QCD corr

Combination of all EW measurements

- **With m_{top}, m_H and m_W known, the standard model has nowhere to go**



Effect of BSM physics

- Modify EW observables through quantum effects (*cf* top & H @ LEP)
  - Blue (direct) & red (Z pole) ellipses may not overlap
  - Standard Model may not fit

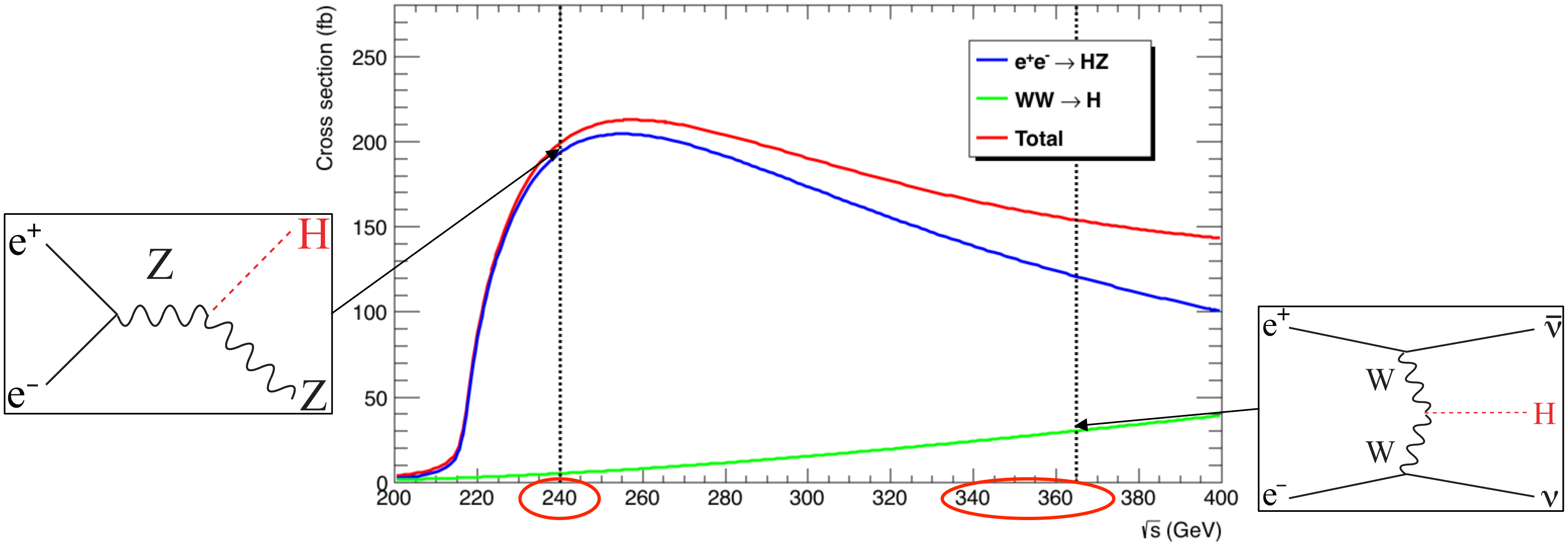
Improvement from all fronts

- Missing ingredients would spoil sensitivity to BSM physics
  - e.g. m_Z, α_{QED}, m_{top}, …
- FCC-ee experimental programme well justified and unique
  - From Z pole to top threshold
  - with the highest luminosities

- Precision of theory predictions may also spoil sensitivity to new physics
  - Theoretical calculations need to be brought to higher orders (more later)

The FCC-ee as a Higgs factory

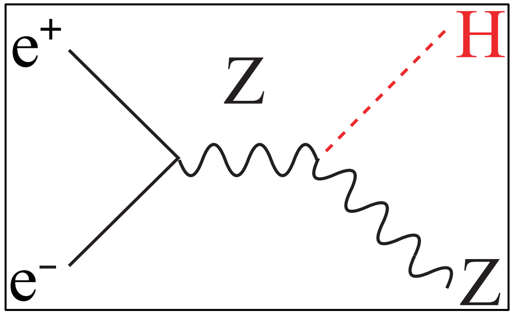
- Higgsstrahlung ($e^+e^- \rightarrow ZH$) event rate largest at $\sqrt{s}$ ~ 240 GeV : σ ~200 fb



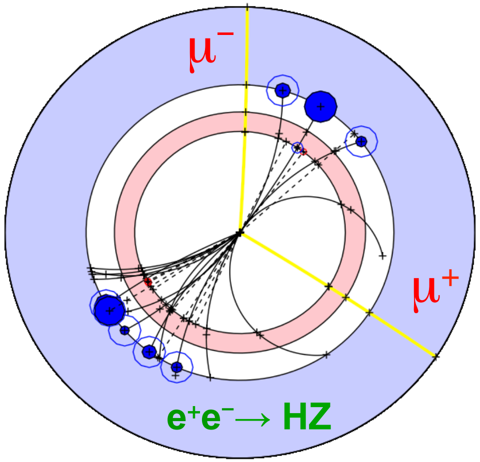
- 10^6 $e^+e^- \rightarrow ZH$ events with 5 ab^{-1} – cross section predicted with great accuracy
  - Target : (few) per-mil precision, statistics-limited.
  - Complemented with 200k events at $\sqrt{s}$ = 350 – 365 GeV
    - Of which 30% in the WW fusion channel (useful for the Γ_H precision)

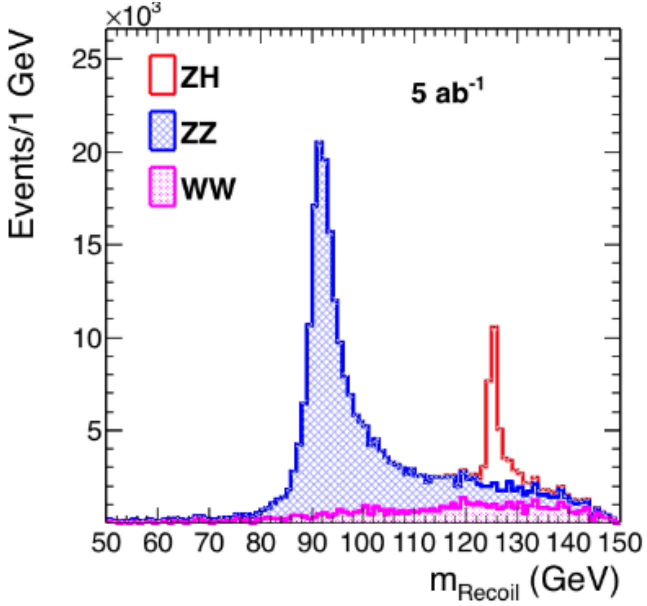
Absolute coupling and width measurement

- **Higgs tagged by a Z, Higgs mass from Z recoil**



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





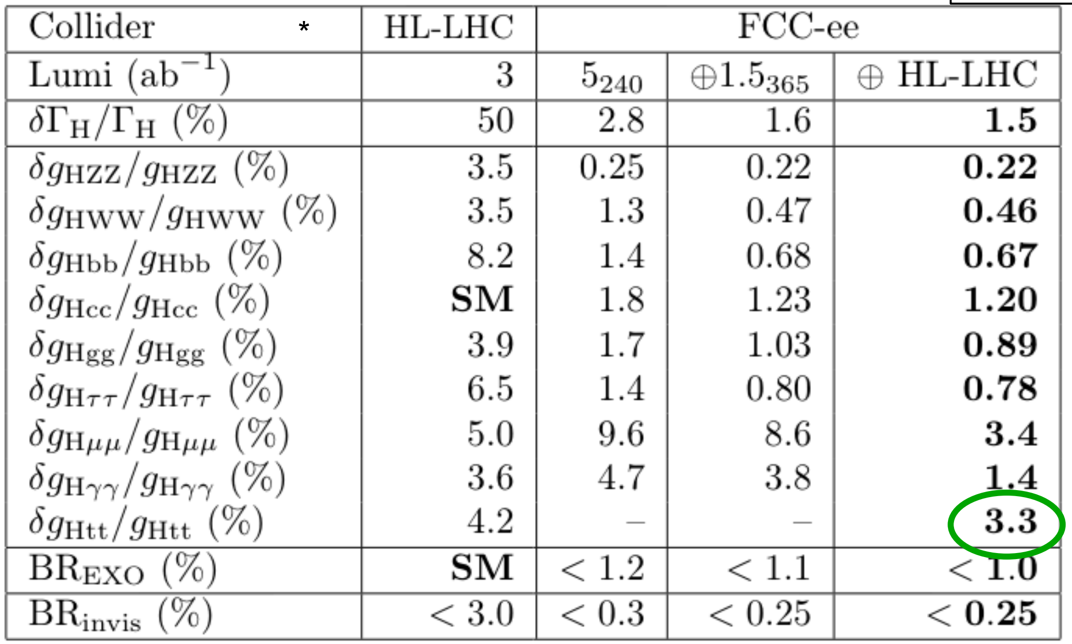
  - Total rate ∝ g_{HZZ}^2 → measure g_{HZZ} to 0.2%
  - ZH → ZZZ final state ∝ g_{HZZ}^4 / Γ_H → measure Γ_H to a couple %
  - ZH → ZXX final state ∝ $g_{HXX}^2\, g_{HZZ}^2 / \Gamma_H$ → measure g_{HXX} to a few per-mil / per-cent
  - Empty recoil = invisible Higgs width; Funny recoil = exotic Higgs decays

- **Note: The HL-LHC is a great Higgs factory (10^9 Higgs produced) but …**
  - $\sigma_{i\rightarrow f}^{(observed)} \propto \sigma_{prod}\, (g_{Hi})^2\, (g_{Hf})^2 / \Gamma_H$
    - Difficult to extract the couplings : σ_{prod} is uncertain and Γ_H is largely unknown
      - Must do physics with ratios or with additional assumptions.

Result of the “kappa” fit

- Relative precisions for HL-LHC [*] and the FCC-ee

* pre-PECFA HL-LHC projections
Updated in the talk from P. Azzi



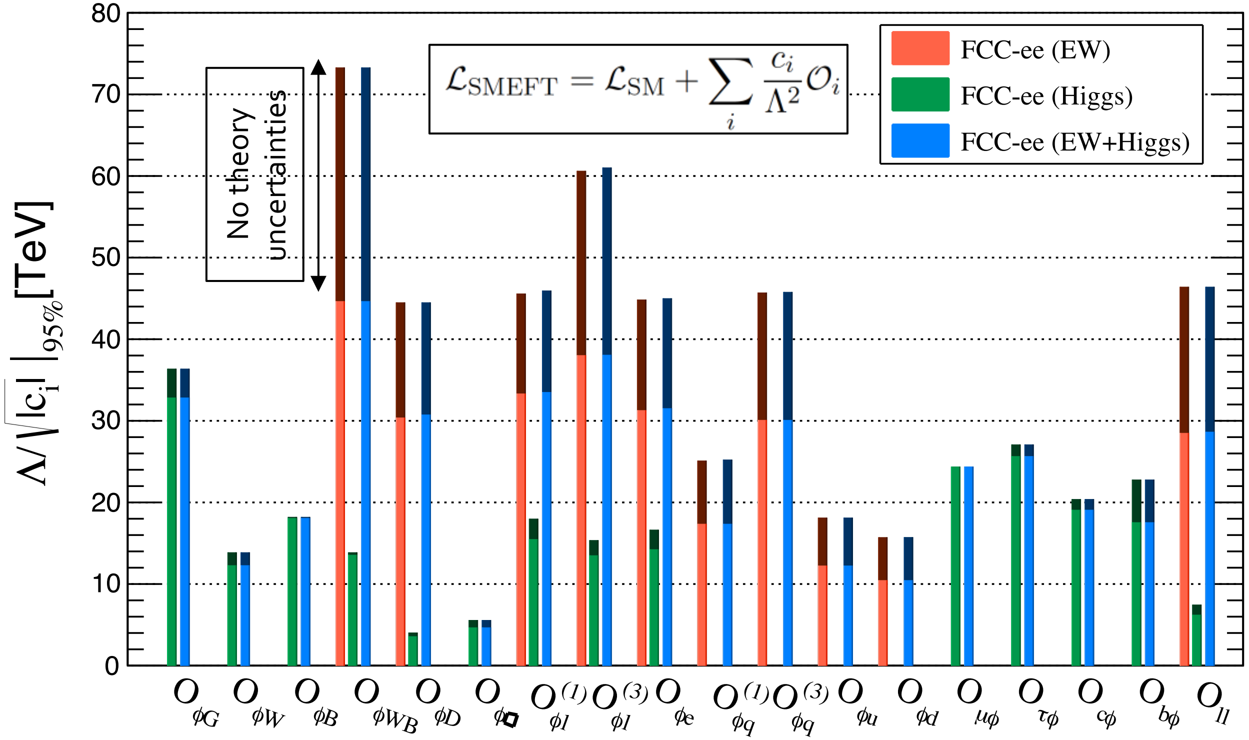
Collider *	HL-LHC	FCC-ee		
Lumi (ab^{-1})	3	5_{240}	$\oplus 1.5_{365}$	$\oplus$ HL-LHC
$\delta\Gamma_H/\Gamma_H$ (%)	50	2.8	1.6	**1.5**
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	0.25	0.22	**0.22**
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	1.3	0.47	**0.46**
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	1.4	0.68	**0.67**
$\delta g_{Hcc}/g_{Hcc}$ (%)	**SM**	1.8	1.23	**1.20**
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	1.7	1.03	**0.89**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	1.4	0.80	**0.78**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	9.6	8.6	**3.4**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	4.7	3.8	**1.4**
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	–	–	**3.3**
BR_{EXO} (%)	**SM**	< 1.2	< 1.1	$<$ **1.0**
BR_{invis} (%)	< 3.0	< 0.3	< 0.25	$<$ **0.25**

Model-independent

- The FCC-ee precision about an order of magnitude better than HL-LHC (copious modes)
  - With no need for additional assumptions – best on the e^+e^- collider market
- It is important to have two energy points (240 and 365 GeV), as at the FCC-ee
  - Combination better by a factor 2 (4) than 240 (365) GeV alone
- (HL-)LHC measures the σ_{ttH} , but requires assumptions for the g_{Htt}
  - Absolute g_{Htt} measurement in a combination with the FCC-ee (precision: 3.3%)

Precision ⇔ Discovery

- **Combining precision Higgs and EW measurements in SMEFT**



Deviating operators may point to the new physics to be looked for at the FCC-hh

- Higgs and EWPO measurements are well complementary
- EWPO are more sensitive to heavy new physics (up to 50-70 TeV, for c=1)
  - Sensitivity was at the level of up to ~5 TeV at LEP
- Larger statistics pays off for Higgs measurements (4 IPs ?)
- Further improvement in theory predictions pays off for EWPO measurements

Precision of theory predictions

- Improving the precision of EW and QCD calculations for the FCC
  - Is a great challenge (exponentially growing number of diagrams with # loops)
  - Has discovery potential (see previous slide)
  - Is therefore recognized as strategic
    - Included in the FCC-ee CDR volume as a target for "Strategic R&D"

- First workshop on "Methods and tools" in January 2018
  - 33 participants
  - Produced a 250+ pages proceedings !
  - Conclusion of the workshop
    - We cannot promise, but yes, we can do it !
    - Requires ~500 person-year (50 MCHF) over the next 20 years

Standard Model theory for the FCC-ee (2018)
J. Gluza et al., https://arxiv.org/abs/1809.01830

- Workshop series is being continued
  - Next workshop in January 2019: https://indico.cern.ch/event/766859/
  - Topics cover the whole FCC-ee programme
    - Z, W, Higgs, top, b, c, QED, Monte Carlo, software, and detector technologies

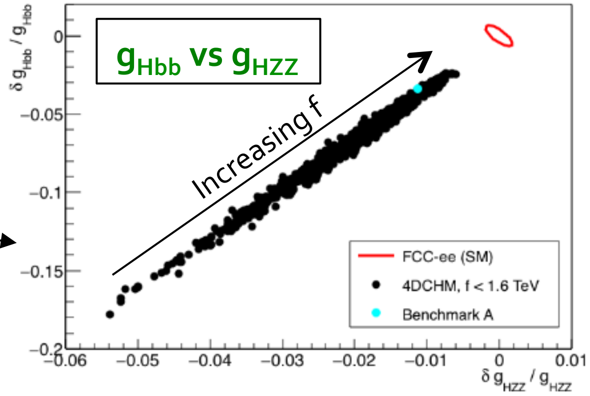
Pattern of deviations

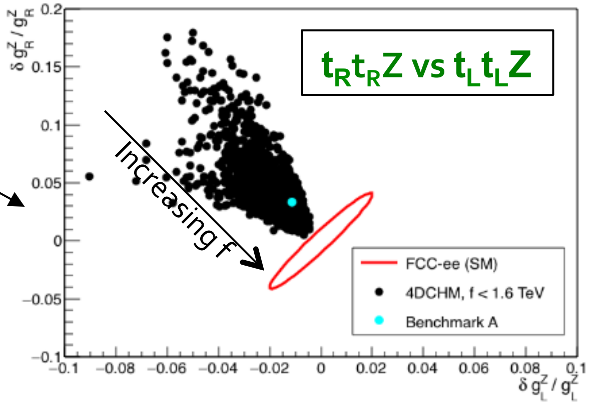
- May point to specific BSM physics
  - E.g, 4D Composite Higgs Model
    - Deviations in Higgs couplings
      - $\sqrt{s}$ = 240, 350, 365 GeV
    - Deviations in EW top couplings
      - $\sqrt{s}$ = 365 GeV optimal

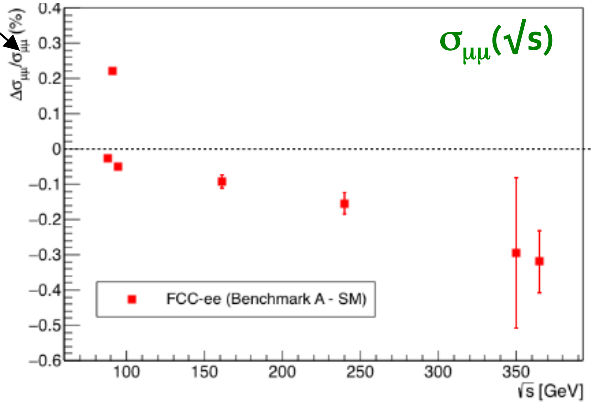
        No need for beam polarization
    - Deviations in EW lepton couplings
      - All energies
  - Correlations between observations
    - Allow first characterization of the model
  - For example, gauge sector parameters in benchmark A
    - $f = 1.6$ TeV, $g^* = 1.78$, $m_{Z'} \sim 3$ TeV, $\Gamma_{Z'} \sim 600$ GeV
    - With the FCC-ee precision
      - Z′ mass predicted wth 2% precision
      - Scale f, coupling g* predicted with 8% precision

S. de Curtis et al.
arXiv:1110.1613

P. J. arXiv:1503.01325

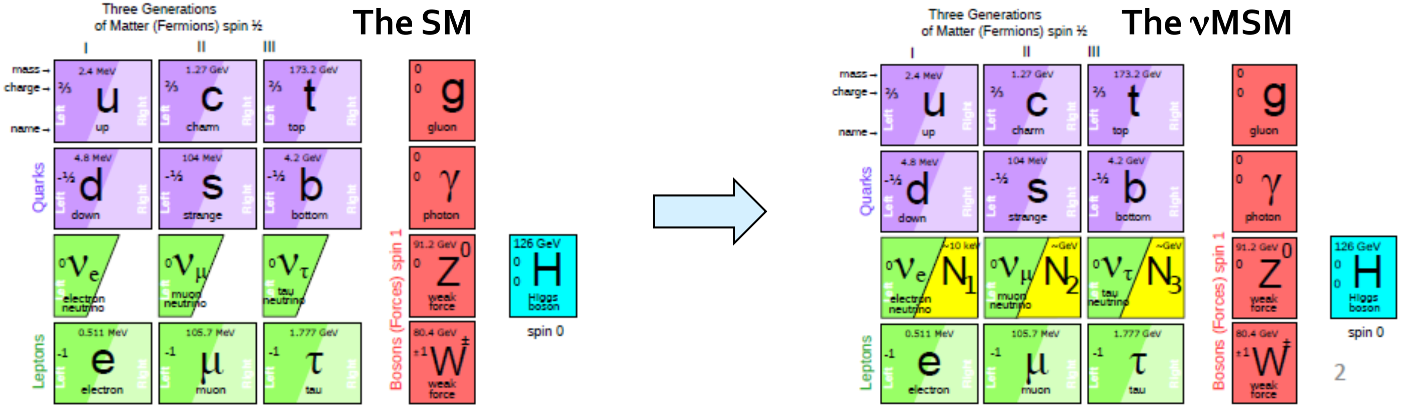






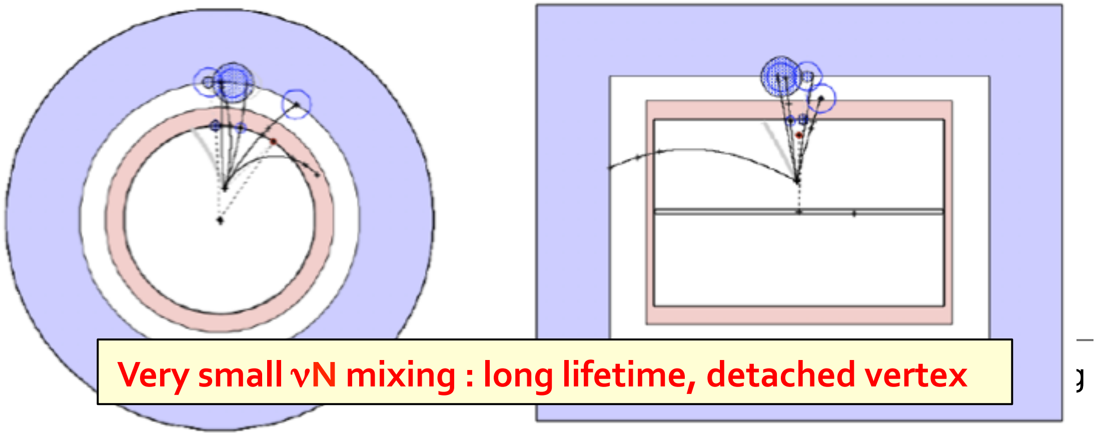
Direct discoveries

- **Discover right-handed neutrinos**
  - νMSM : Complete particle spectrum with the missing three right-handed neutrinos

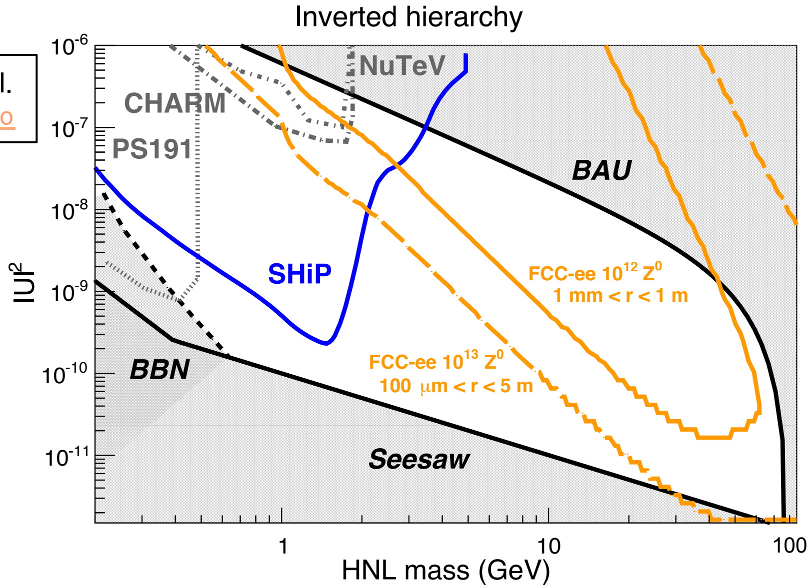


  - Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses
- Searched for in very rare $Z \to \nu N_{2,3}$ decays
  - Followed by $N_{2,3} \to W^{*}\ell$ or $Z^{*}\nu$

A. Blondel et al.
arXiv:1411.5230

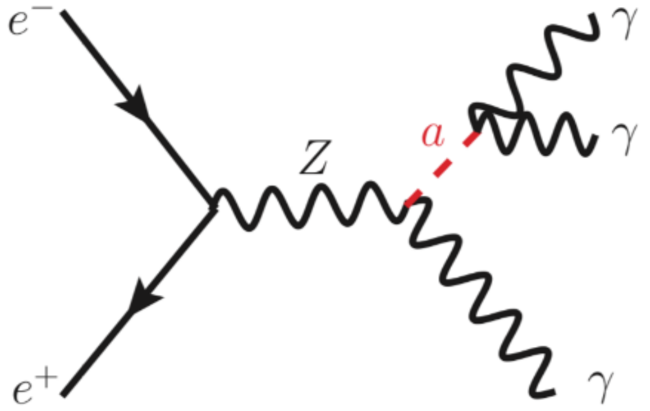


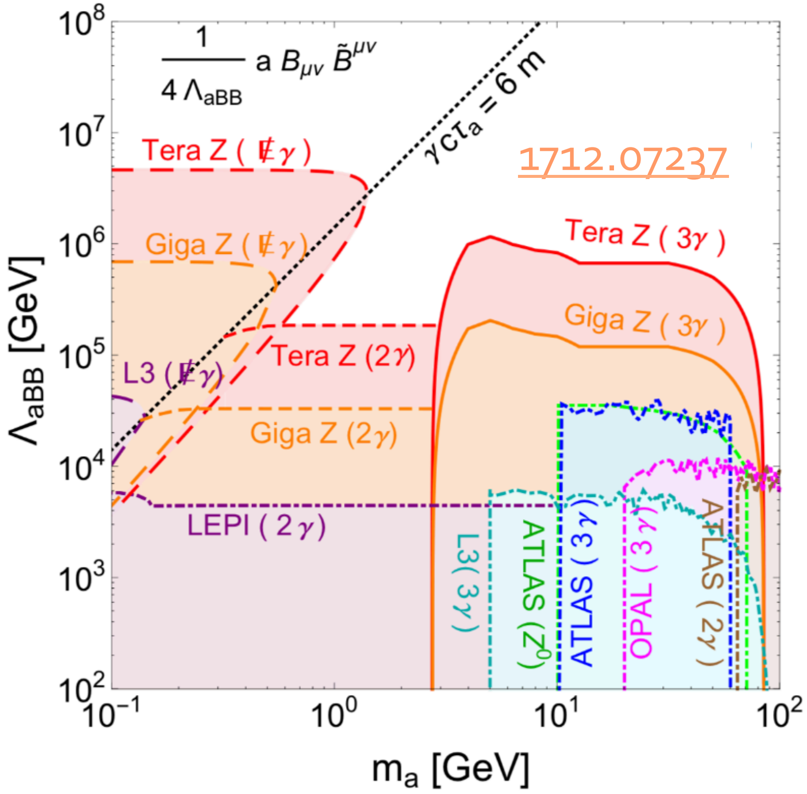
Very small νN mixing : long lifetime, detached vertex



Direct discoveries (cont'd)

- **Discover the dark sector**
  - A very-weakly-coupled window to the dark sector is through light "Axion-Like Particles" (ALPs)





1712.07237

- ➨ $\gamma + E_{\mathrm{MISS}}$ for very light a
- ➨ $\gamma\gamma$ for light a
- ➨ $\gamma\gamma\gamma$ for heavier a

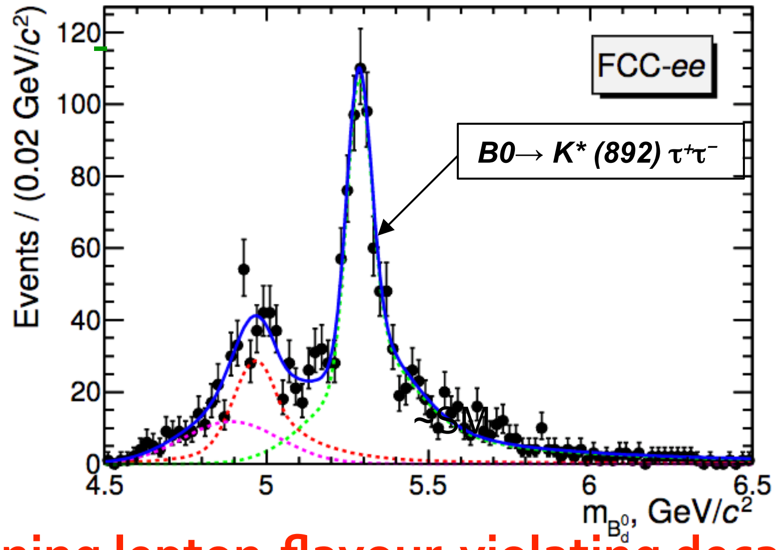
- Orders of magnitude of parameter space accessible at FCC-ee

Flavours : B anomalies, τ physics, …

- ❑ **Lepton flavour universality is challenged in $b \to s\, \ell^+\ell^-$ transitions @ LHCb**
  - ◆ This effect, if real, could be enhanced for $\ell = \tau$, in $B \to K^{(*)}\tau^+\tau^-$
    - ● Extremely challenging in hadron colliders
    - ● With 10^{12} Z → bb, FCC-ee is beyond any foreseeable competition
      - ➨ Decay can be fully reconstructed; full angular analysis possible

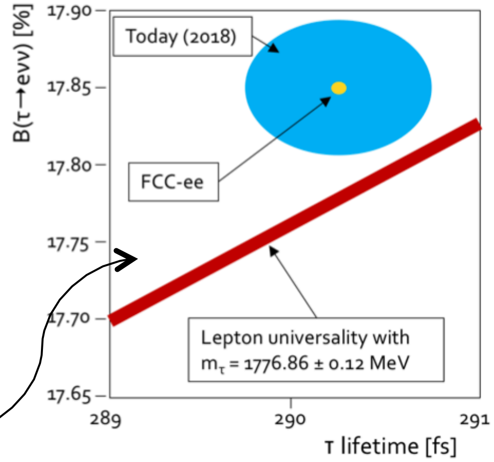
Talk from A. Bondar

J.F. Kamenik et al.
arXiv:1705.11106



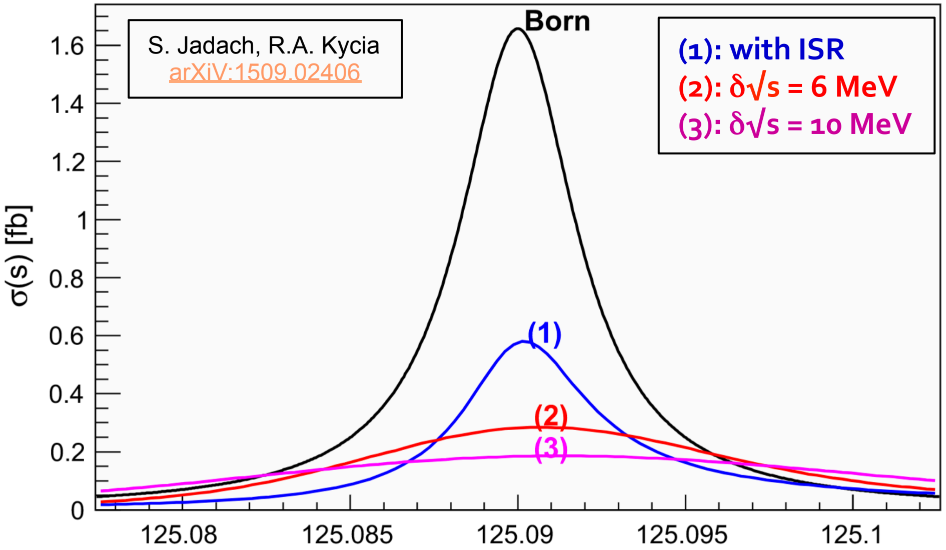
Also 100,000 $B_S \to \tau^+\tau^-$ @ FCC-ee
Reconstruction efficiency under study

- ❑ **Not mentioning lepton-flavour-violating decays**
  - ◆ BR(Z → eτ, μτ) down to 10^{-9} (improved by 10^4)
  - ◆ BR(τ → μγ, μμμ) down to a few 10^{-10}
  - ◆ τ lifetime vs BR($\tau \to e\nu_e\nu_\tau, \mu\nu_\mu\nu_\tau$) : lepton universality tests



And if there is time …

- ❑ **Spend few years at $\sqrt{s}$ = 125.09 GeV with high luminosity**
  - For s-channel production $e^+e^- \rightarrow H$ (a la muon collider, with 10^4 higher lumi)



- ❑ **FCC-ee monochromatization setups**
  - Default: $\delta\sqrt{s}$ = 100 MeV, 25 ab^{-1} / year
    - No visible resonance
  - Option 1: $\delta\sqrt{s}$ = 10 MeV, 7 ab^{-1} / year
    - $\sigma(e^+e^- \rightarrow H) \sim 100$ ab
  - Option 2: $\delta\sqrt{s}$ = 6 MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \rightarrow H) \sim 250$ ab
  - Backgrounds much larger than signal
    - $e^+e^- \rightarrow q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma$, …

- Expected signal significance of ~0.4σ / √year in both option 1 and option 2
  - Set a electron Yukawa coupling upper limit : $\kappa_e < 2.5$ @ 95% C.L.
  - Reaches SM sensitivity after five years (or 2.5 years with 4 IPs)

D. d'Enterria
arXiV:1701.02663

- Unique opportunity to constrain first generation Yukawa's

Is a $\sqrt{s}$ = 500 GeV upgrade required/useful ?

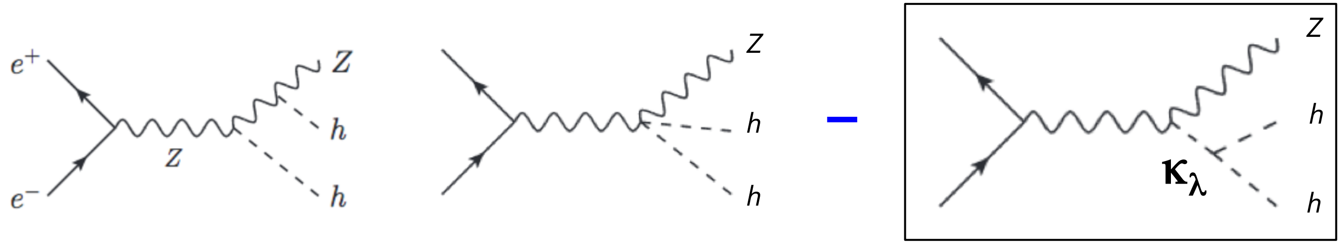
- **According to the white book of ESU 2013 :** https://cds.cern.ch/record/1567295/

At energies of 500 GeV or higher, such a machine could explore the Higgs properties further, for example **the coupling to the top quark, the self-coupling, and the total width.**

- **Responsible for the "… whose energy can be upgraded." in ESU update (CERN Council)**
  - **You will probably hear more of that during ESU 2020!**
- **So, should we foresee an upgrade of FCC-ee at $\sqrt{s}$ = 500 GeV ?**
  - **For the total width and the coupling to the top quark : the answer is NO (slide 18)**
  - **For the Higgs self-coupling (κ_λ):**

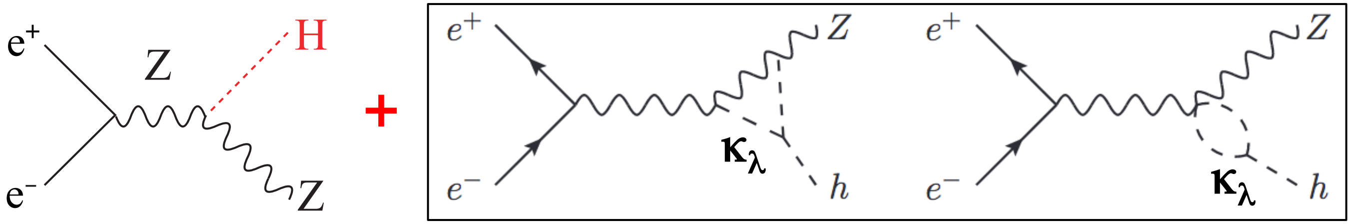
At $\sqrt{s}$ = 500 GeV

Di-Higgs production



At FCC-ee

σ_{HZ}

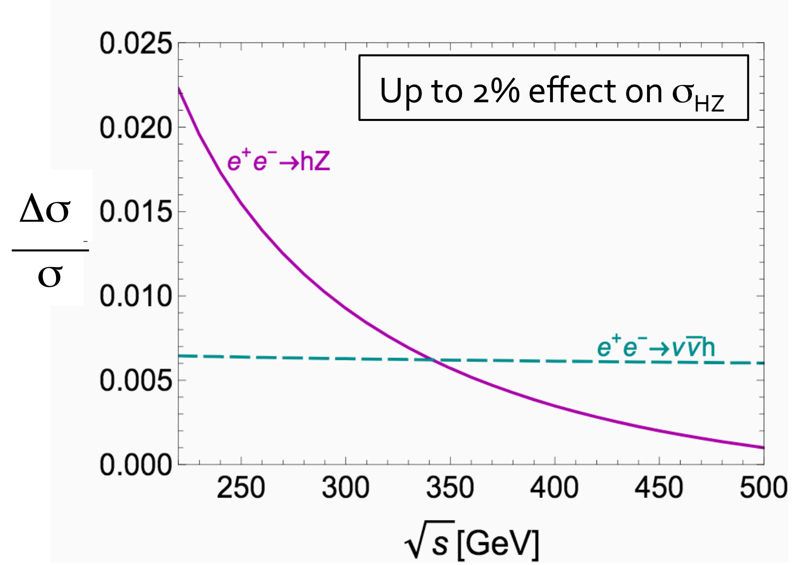


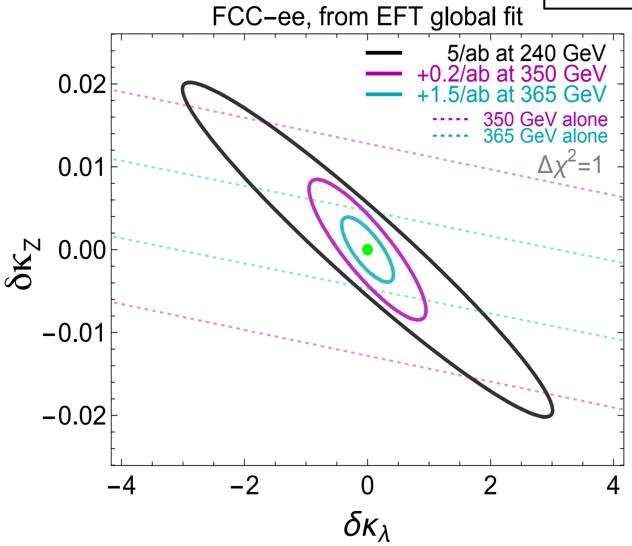
M. McCullough
arXiv:1312.3322

Higgs self-coupling at the FCC-ee

- **Effect of Higgs self coupling (κ_λ) on σ_{ZH} and $\sigma_{\nu\nu H}$ depends on √s**

C. Grojean et al. arXiv:1711.03978





- Two energy points lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_H$
  - Precision on κ_λ with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - Global EFT fit (model-independent) : ±35% ; in the SM : ±24% (3-4σ)
  - Precision on κ_λ with 4 IPs : ±23% (EFT fit) ; ±16% (SM fit)
    - 5σ discovery with 4 IPs instead of 2 – much less costly than 500 GeV upgrade (in time and funds, in view of FCC-hh)

A. Blondel, P. J. arXiv:1809.10041

- **And, most importantly**
  - Only FCC-hh, in combination with FCC-ee, can measure κ_{top} and κ_λ to 1% and 5%, resp.

See M. Aleksa's talk

Synergies and complementarities with 100 TeV pp collider

- Higgs physics
  - ee breaks model dependence (Γ_H, g_{HZZ}) – and measures precisely top EW couplings
    - Turns σ(ttH) measurement @ HL-LHC to an absolute ttH coupling precision of 3%
    - First 3-4σ observation or 5σ discovery of the Higgs self coupling, without a 500 GeV upgrade
  - pp measures ratios-of-BR and gives huge statistics of ttZ, ttH, and HH events
    - Bring top Yukawa and Higgs self coupling precisions to the per-cent level, in particular
- Search for heavy physics (with at least weak couplings)
  - ee gives precision measurements sensitive to heavy physics up to 50 TeV and more
    - Patterns of deviations may points to specific BSM
  - pp gives access to direct observation at unprecedented masses and p_T's
    - Also huge samples of Z, W, Higgs, top
- Right-handed neutrinos (and all very weakly-coupled particles)
  - ee: powerful and clean, but flavour blind: $Z \rightarrow \nu N$, all ν flavours together
  - hh: more difficult, but charge- and flavour-sensitive: $W \rightarrow l_1 (Q_1)\, N$, $N \rightarrow l_2 (Q_2)\, W^*$

5×10^{12} Z

5×10^{13} W

- Flavour "anomalies" (if they persist – rich flavour physics programme otherwise)
  - ee beyond any foreseeable competition with in $B \rightarrow K^{(*)} \tau^+\tau^-$ and $B_S \rightarrow \tau^+\tau^-$
  - hh gives direct access to Z' gauge bosons and leptoquarks
- QCD
  - ee gives α_S to ±0.0002 or better (R_l for Z and W), but also 100k $H \rightarrow gg$ (gluon fragmentation!)
  - Improves signal and background predictions for new physics discovery at pp

Conclusions

- The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology
  - The FCC CDR is on the verge of being publicly released

- Both FCC-ee and FCC-hh have outstanding physics cases
  - Each in their own right (Electroweak Factory and Energy Frontier)
  - The sequential implementation : FCC-ee → FCC-hh maximises the physics reach
    - Taking full advantage of multiple synergies and complementarities
  - Can serve High-Energy Physics in a cost effective manner throughout the 21st century

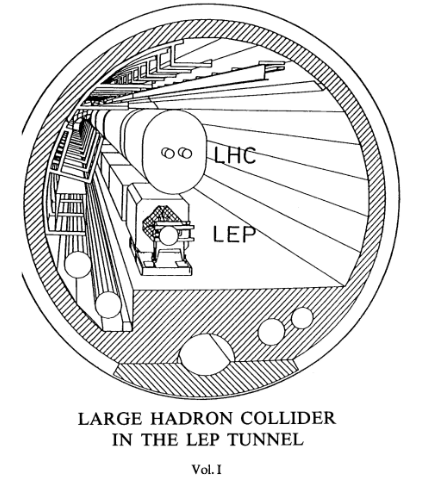
- The FCC-ee design is now robust and mature
  - We are ready to move to the next step, as soon as possible
    - Starting with the construction of the infrastructure
    - Followed by the implementation of the collider and the detectors
    - With a commissioning in parallel with the HL-LHC running

FCC-ee can start physics seamlessly at the end of HL-LHC

A successful model : Let’s not be shy !

CERN 76-18
8 November 1976

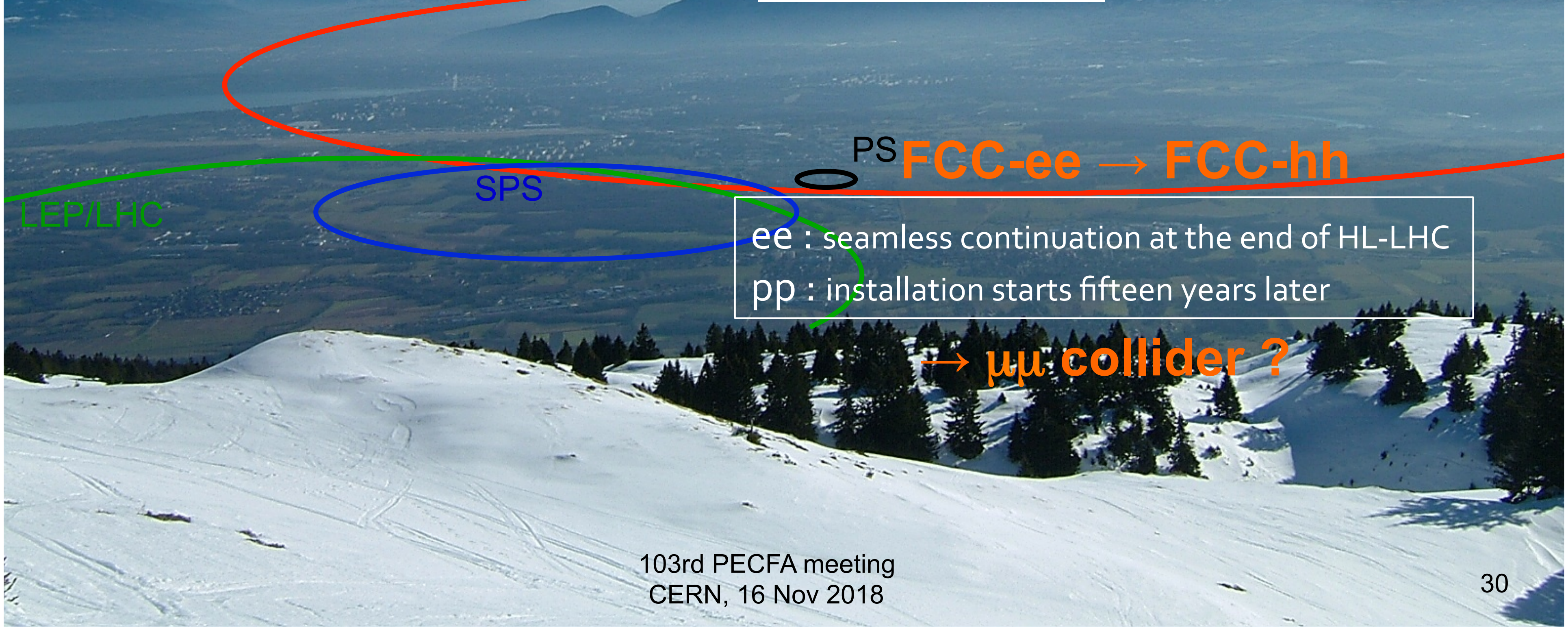
e^+e^- : 1989-2000



LARGE HADRON COLLIDER
IN THE LEP TUNNEL
Vol. I

ECFA 84/85
CERN 84-10
5 September 1984

pp : 2009-2035 (?)



FCC-ee → FCC-hh

ee : seamless continuation at the end of HL-LHC
pp : installation starts fifteen years later

→ μμ collider ?