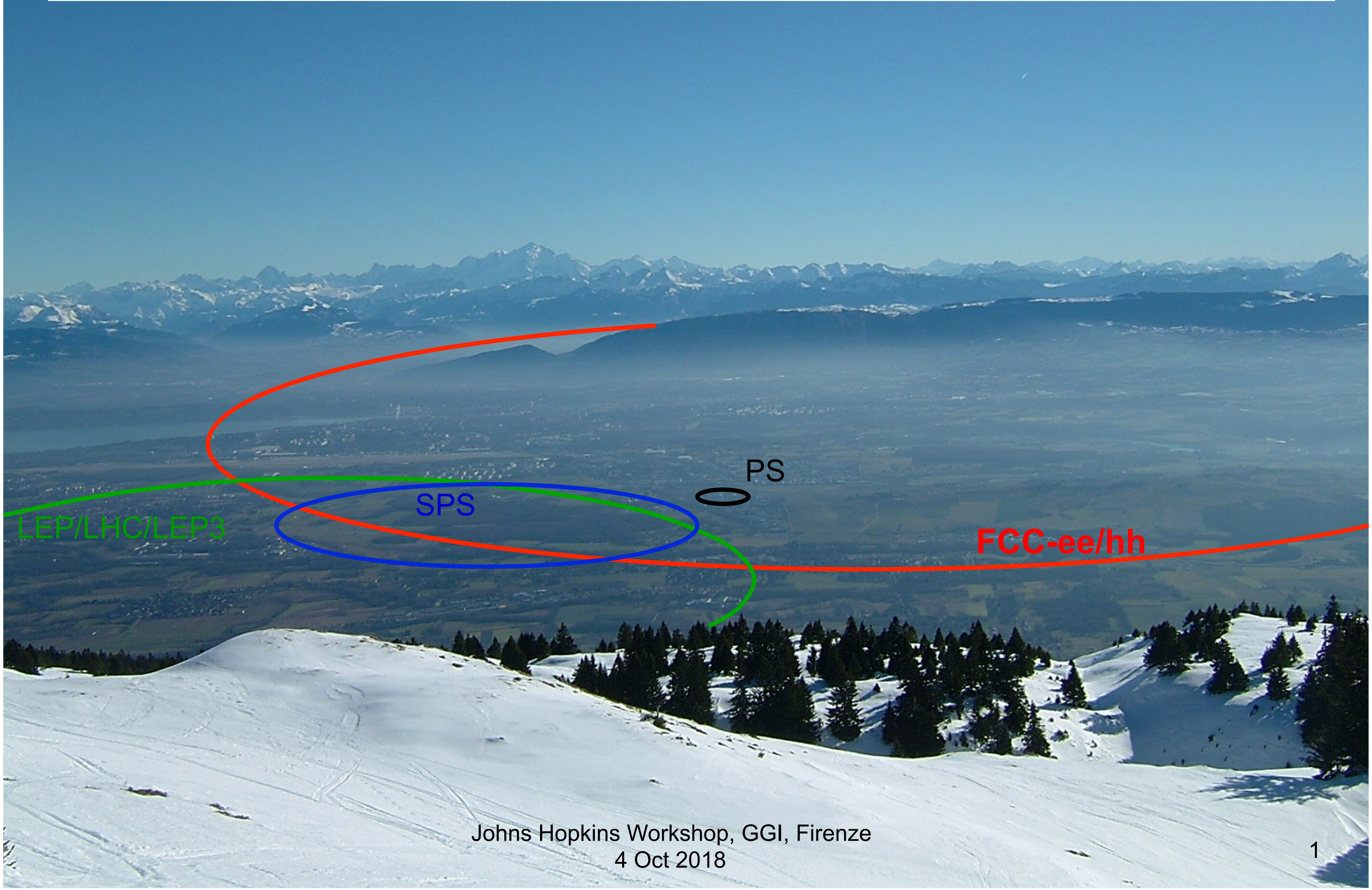
High-Luminosity Circular e^+e^- Colliders



Genesis of high-luminosity e^+e^- circular colliders

- **Started with the first hints of a light Higgs boson at LHC (Summer 2011)**
  - **LEP3, in the LHC tunnel. Also "DLEP" (double-LEP) in a new 50 km tunnel.**

    A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson
    A. Blondel and F. Zimmermann https://arxiv.org/abs/1112.2518 (Dec. 2011)

- **Extended with the first signals of a 125 GeV Higgs boson at LHC (Spring 2012)**
  - **IPAC12 conference, LEP3, DLEP, and TLEP (triple/tetra LEP) in a new 80-100 km tunnel.**

    A High Luminosity e^+e^- Collider to study the Higgs Boson
    A. Blondel et al. https://arxiv.org/abs/1208.0504 (Aug. 2012)

  - **First physics studies (LEP3, TLEP)**

    Prospective studies for LEP3 with the CMS detector
    P. Azzi et al. https://arxiv.org/abs/1208.1662 (Aug. 2012)

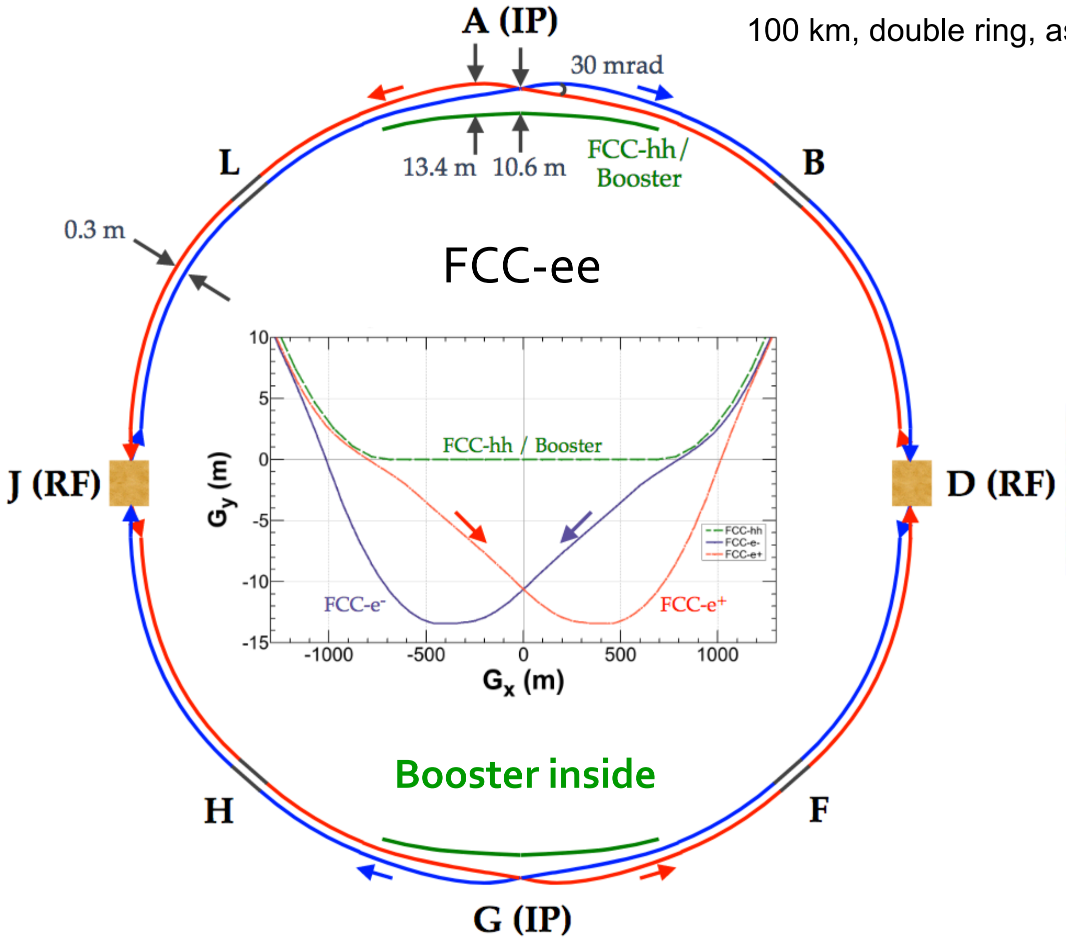
- **Presented to ICFA (HF2012, Fermilab, Fall 2012)**
  - **LEP3 (27 km) and TLEP (80-100 km) for CERN,**
    - **TLEP was renamed FCC-ee (double ring) in 2014 : Z, W, Higgs and top factory**

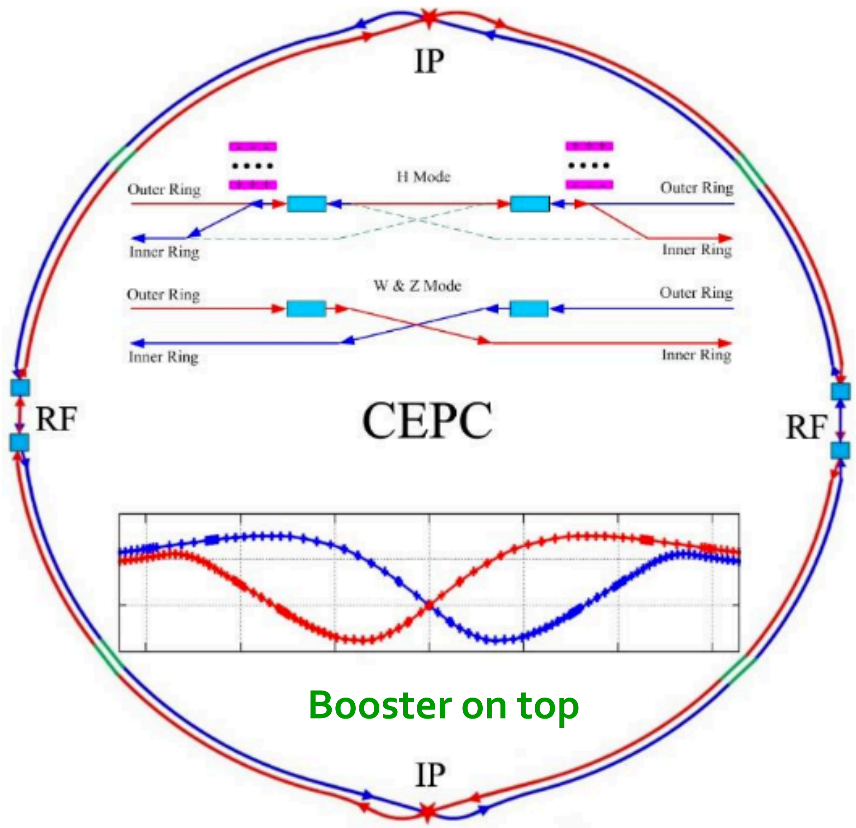
      First look at the physics case of TLEP
      M. Bicer et al. https://arxiv.org/abs/1308.6176 (Aug. 2013)
  - **CEPC (50 km) for IHEP, single ring, Higgs factory, pre-CDR in 2015**
    - **CEPC became double ring in 2016**
    - **CEPC length became 100 km in 2017 : Z, W, Higgs factory**
      - ➨ **2018-19 : top factory ?**

Today: Similar layouts for CEPC and FCC-ee

- CEPC has been (is) a moving target, but is converging towards FCC-ee

100 km, double ring, asymmetric IPs, two detectors, …

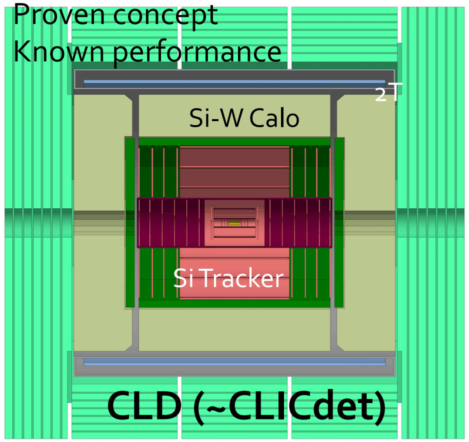


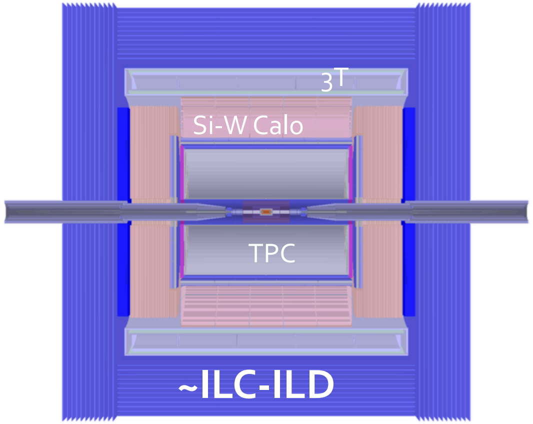


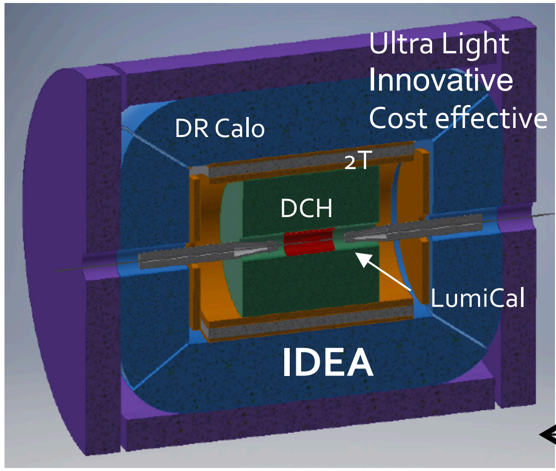
Note : Asymmetric IPs minimize synchrotron radiation in the detectors

Detectors

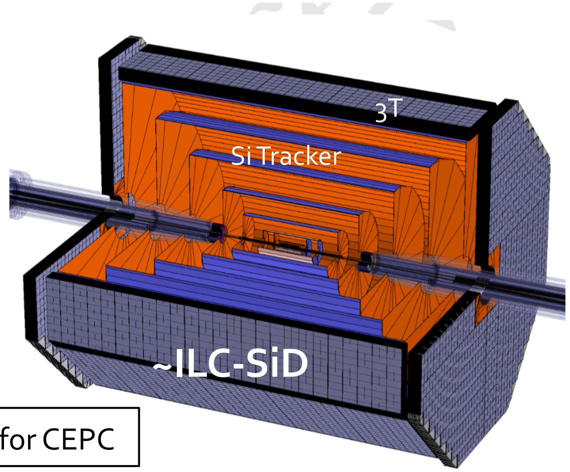
❑ **FCC-ee** **CEPC**







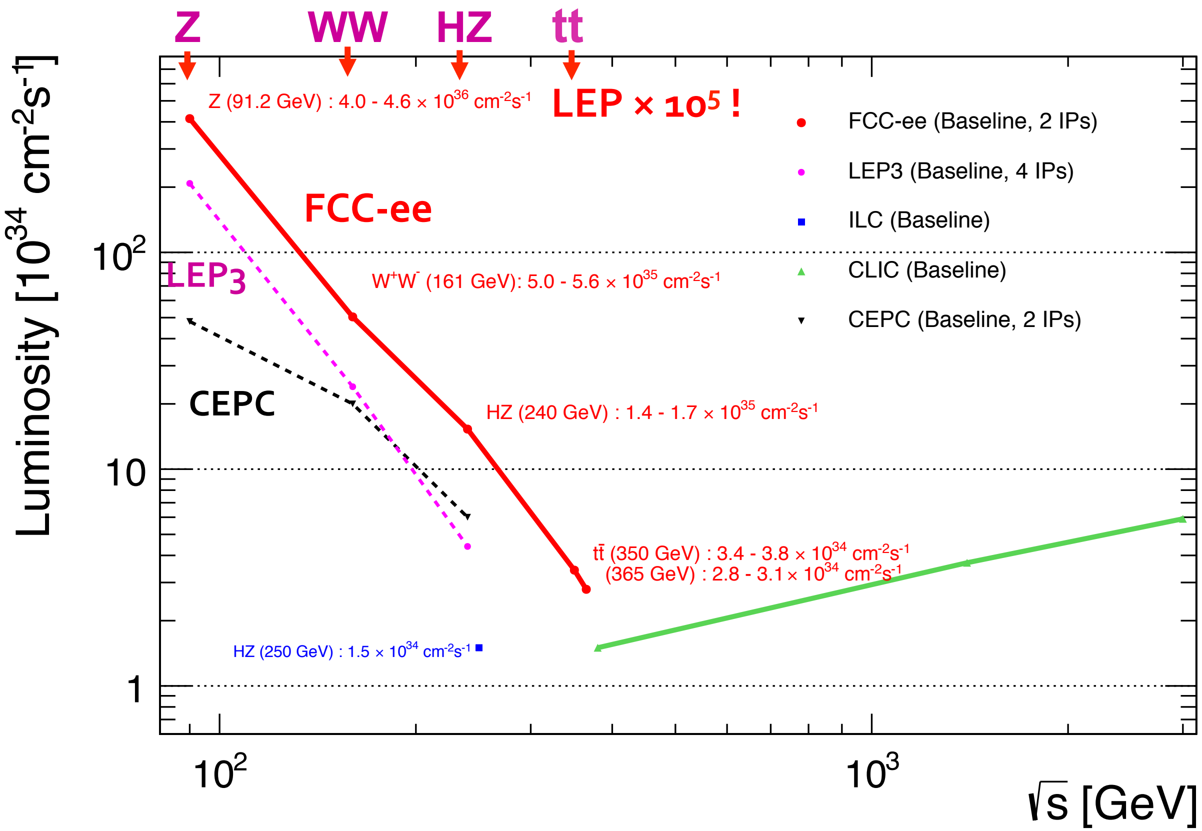
Also alternative detector for CEPC



- **All four detectors proven to cope with invasive MDI and experimental environment**

Projected luminosities

- Experience from b-factories (optics & top-up) injection for luminosity
  - Plus 50 years of experience and continuous progress in RF cavities and klystrons



- Ultimate precision @ FCC-ee :
  - 100 000 Z / second (!)
    - 1 Z / second at LEP
  - 10 000 W / hour
    - 20 000 W in 5 years at LEP
  - 1 500 Higgs bosons / day
    - 10 times more than ILC
  - 1 500 top quarks / day

… in each detector

  - In a clean exp'tal environment:
    - No pileup
    - Beam backgrounds under control
    - E,p constraints

  - CEPC luminosity/energy limited by (very) conservative machine parameters / politics
  - The FCC-ee is favoured over LEP3 for CERN's future

(One of the) Motivation(s)

- **From ESPP 2013**

https://cds.cern.ch/record/1567258/

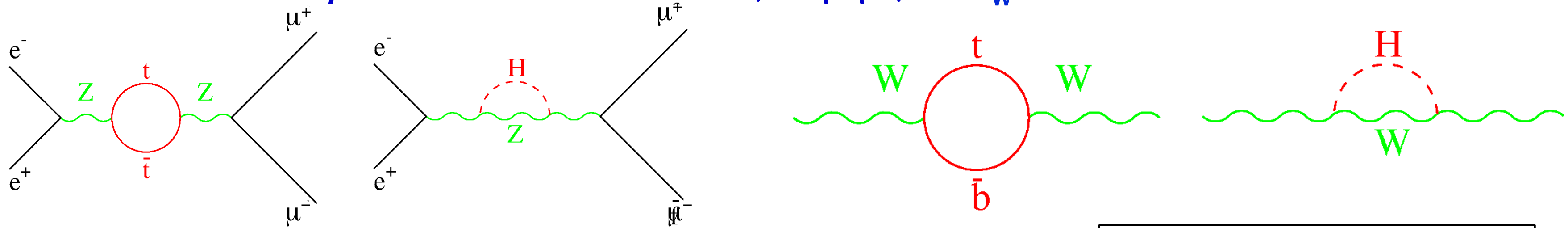
There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

- Now five EW factories projects in the world (ILC250, CLIC380, LEP3, CEPC, FCC-ee)
  - Circular colliders provide the largest luminosities
    - To study the properties of the Higgs boson, the Z, and the W

      … And the top-quark (at the FCC-ee, and potentially, CEPC)
    - "… with unprecedented precision"
  - The discovery potential of circular colliders is multiplied by the presence of the four heaviest particles of the standard model in their energy range
  - I'll come to the last part of the statement later in the talk
    - "… and whose energy can be upgraded"

Precision ⇔ Discovery

- **Electroweak observables are sensitive to heavy particles in "loops"**
  - For example, in the standard model: $\Gamma(Z\to\mu^+\mu^-)$ or m_W



$$\Gamma_{ll} = \frac{G_F}{\sqrt{2}}\frac{m_Z^3}{24\pi}\left(1+\left[\frac{1}{4}-\sin^2\theta_W^{eff}\right]^2\right)\times(1+\Delta\rho)$$

$$\sin^2\vartheta_W^{eff} = \left(1-\frac{m_W^2}{m_Z^2}\right)\times(1+\Delta\kappa)$$

$$m_W^2 = \frac{\pi\alpha_{QED}\left(m_Z^2\right)}{\sqrt{2}G_F\sin^2\theta_W}\times\frac{1}{1-\Delta r}$$

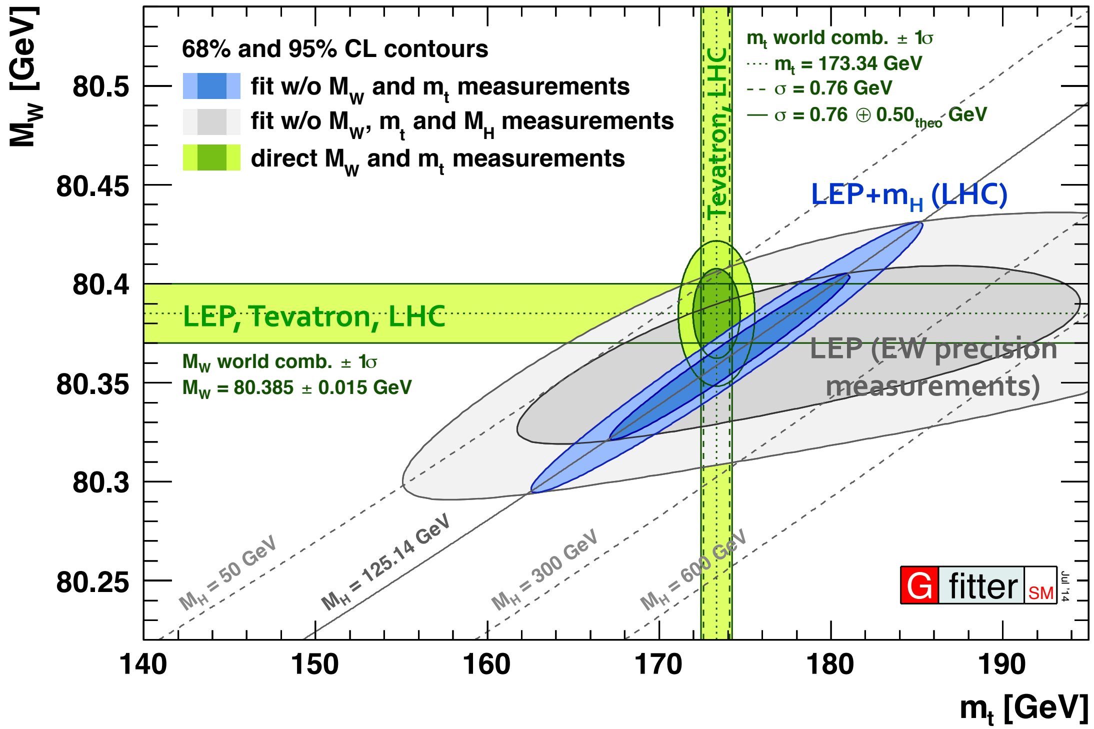
$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2}-\frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2}+\cdots\approx 1\%$$

$$\Delta r = -\frac{\cos^2\vartheta_W}{\sin^2\vartheta_W}\Delta\rho+\frac{\alpha}{3\pi}\left[\frac{1}{2}-\frac{1}{3}\frac{\sin^2\vartheta_W}{1-\tan^2\vartheta_W}\right]\mathrm{Log}\frac{m_H^2}{m_Z^2}+\cdots\approx 1\%$$

- With precise measurements of the Z mass, Z width, and Weinberg angle [+ $\alpha_{QED}(m_Z)$]
  - LEP confirmed the existence of the top quark and was able to predict m_{top} and m_W
- With the observation of the top (Tevatron) at the "right" mass (in the SM)
  - LEP confirmed the existence of the Higgs boson and was able predict m_H
- With the observation of the Higgs (LHC) at the "right" mass (in the SM)
  - LEP was able to improve the m_W prediction (and measured m_W as well)

Precision ⇔ Discovery , cont'd

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



Fit of the SM and nothing else

https://arxiv.org/pdf/1407.3792.pdf

- The FCC-ee (CEPC) will significantly improve precision on all (most) fronts
  - More precise measurements become sensitive to other (heavier) particles in the loops
    - If one ingredient is missing, the sensitivity to new physics drops
      - ➨ Full programme (from the Z pole to above the top threshold) well justified
    - Theoretical calculations need to be brought to higher orders (up to three loops)

Examples : m_W and $\sin^2\theta_W^{eff}$

- **Prediction in the Standard Model (with today's EWPO uncertainties)**

$$
\begin{aligned}
m_W = & \ 80.3584 \ \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \\
& \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{\text{theory}} \text{ GeV} \\
= & \ 80.358 \ \pm 0.008_{\text{total}} \text{ GeV},
\end{aligned}
$$

$$
\begin{aligned}
\sin^2\theta_W^{eff} = & \ 0.231488 \ \pm 0.000029_{m_{top}} \pm 0.000015_{m_Z} \pm 0.000035_{\alpha_{QED}} \\
& \pm 0.000010_{\alpha_S} \pm 0.000001_{m_H} \pm 0.000047_{\text{theory}} \\
= & \ 0.23149 \ \pm 0.00007_{\text{total}},
\end{aligned}
$$

  - **And their direct measurement**

$$m_W = 80.379 \pm 0.012 \text{ GeV}, \text{ and } \sin^2\theta_W^{eff} = 0.23153 \pm 0.00016.$$

- **Calls for much more precise measurements of**
  - **m_Z, $\alpha_{QED}(m_Z^2)$, $\alpha_S(m_Z^2)$, $\sin2\theta_W^{eff}$: run at and around the Z pole**
  - **m_W and m_{top}: run at the WW threshold and the top-pair threshold**
- **Also calls for order-of-magnitude improvement in theory precision**
  - **Work has started, will need ~ 500 person-year to reach the relevant precision**

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

Luminosity goals and operation models

FCC-ee, 15 years programme

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold…	… and above
√s (GeV)	88 – 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

CEPC, 10 years programme

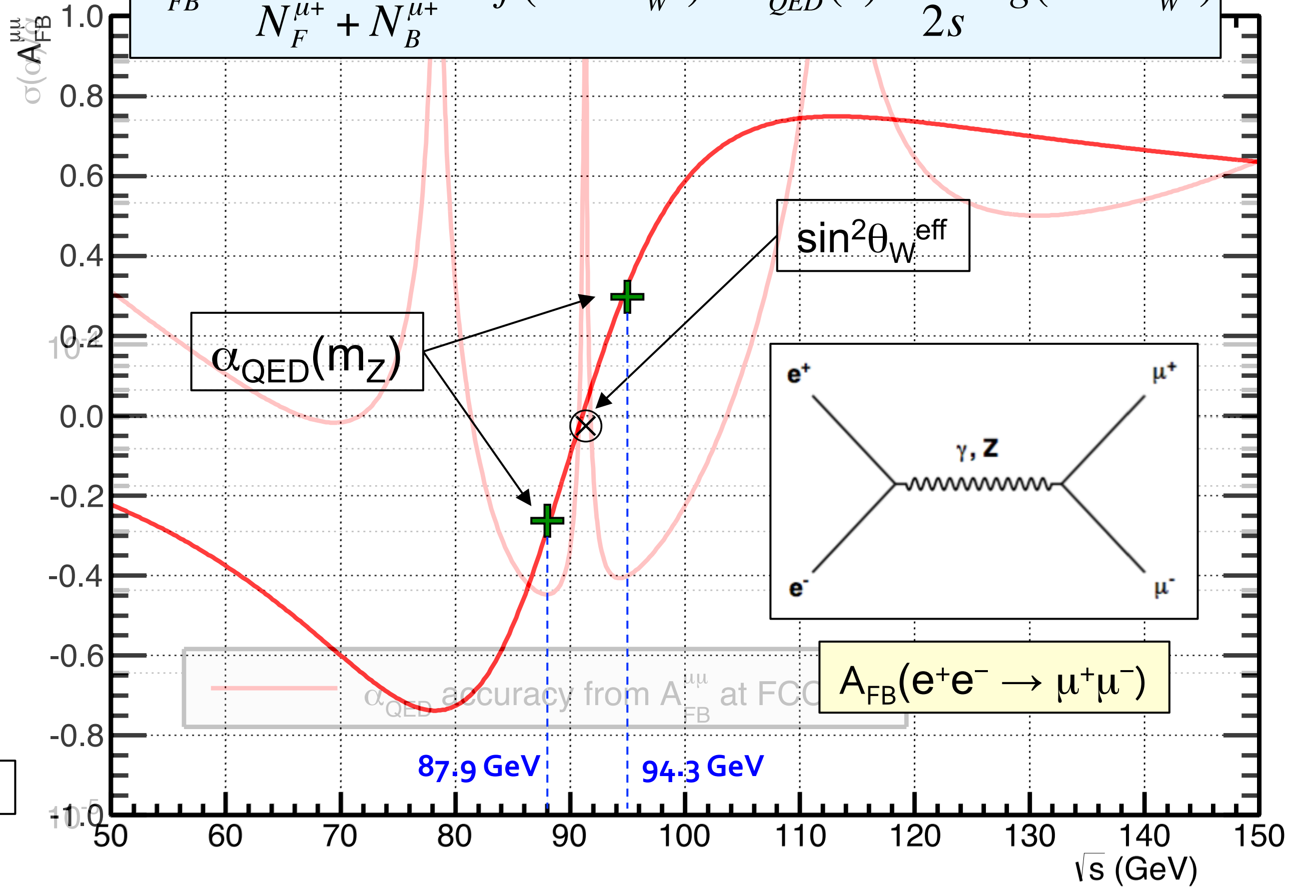
Working point	HZ	Z	WW
√s (GeV)	240	88 – 94	157 – 172
Lumi/IP (10^{34} cm^{-2}s^{-1})	3	16 - 32	10
Lumi/year (2 IP)	0.8 ab^{-1}	4 – 8 ab^{-1}	2.6 ab^{-1}
Total	5.6 ab^{-1}	8 – 16 ab^{-1}	2.6 ab^{-1}
Run time (year)	7	2	1

5×10^{11} to 5×10^{12} Z
10^8 WW
10^6 HZ
10^6 $t\bar{t}$

Unique feature at FCC-ee : $\alpha_{QED}(m_Z^2)$

- **Direct α_{QED} (m_Z^2) determination from $A_{FB}(\mu\mu)$: Requires ~70 ab^{-1} off peak**

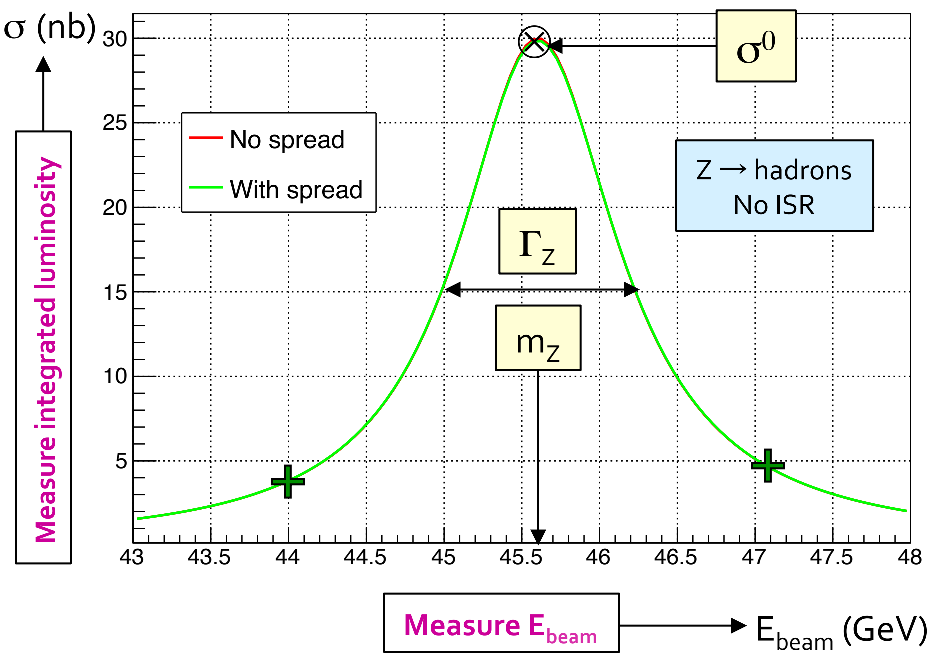
$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2\vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s}g(\sin^2\vartheta_W^{eff})$$

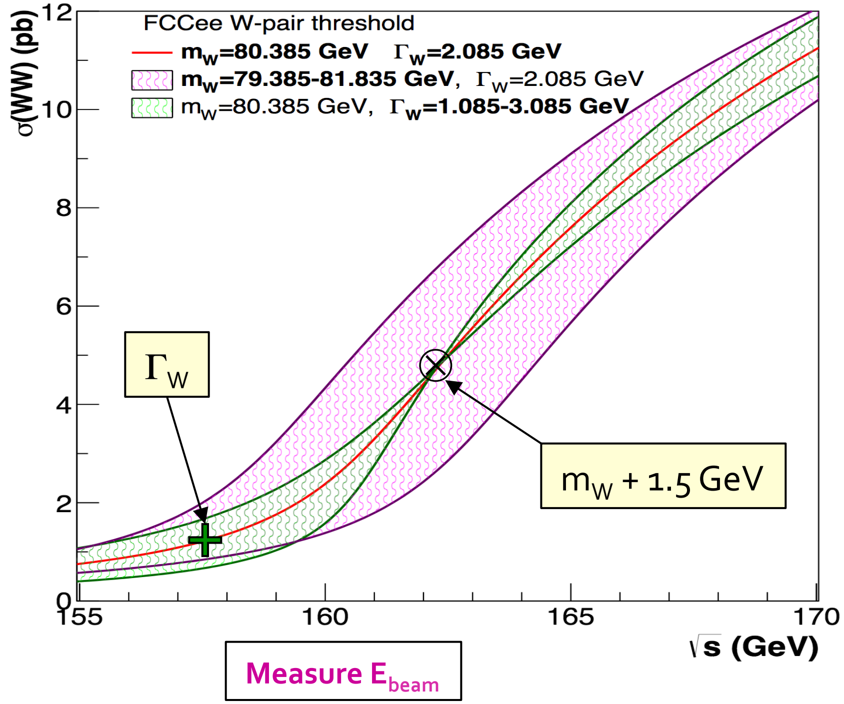


P. J. arXiv:1512.05544

Unique feature at circular colliders: E_{Beam}

- **Continuously measure √s (and spread) to ~100 keV precision**
  - **Resonant depolarization, $\mu^+\mu^-$ acollinearity, crossing angle**
    - **Centre-of-mass energy spread (~100 – 200 MeV) increases effective width**

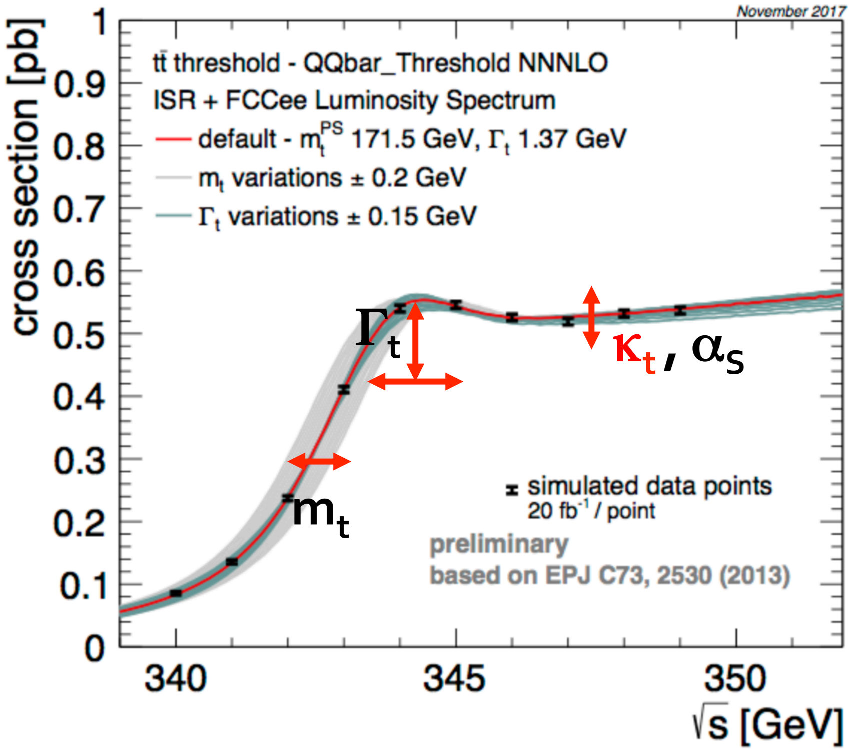




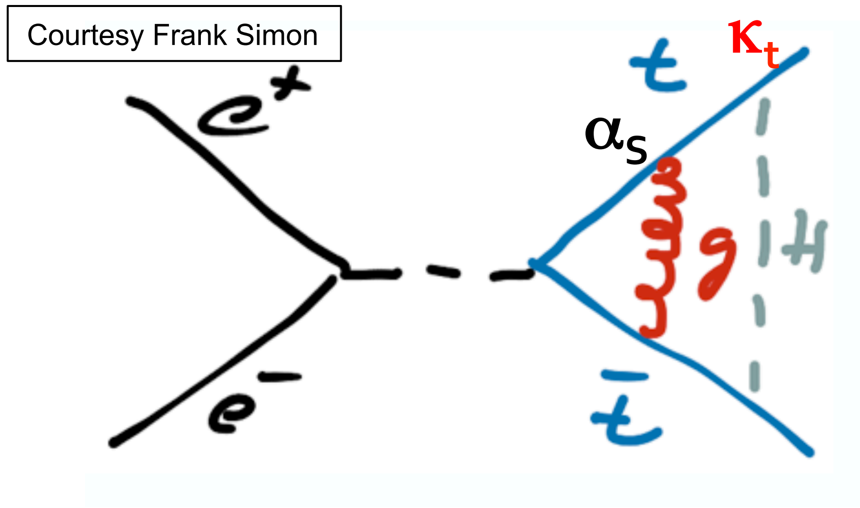
- **Potentially determine m_Z, Γ_Z to 100 keV, and m_W, Γ_W to 300 keV**

Data at and above the $t\bar{t}$ threshold

- **Measure the top mass and width in a short run at threshold**
  - **Eight-point scan between 340 and 350 GeV**



Small, correlated sensitivity to κ_t and α_S



α_S measured with precision with Z and WW runs

- **Precision of 17 MeV on m_t, 45 MeV on Γ_t, and 10% on κ_t**

- **Measure top EW couplings to the Z and the photon to ~1%**
  - **With a longer run @ 365 GeV, from angular distributions of top decay products**

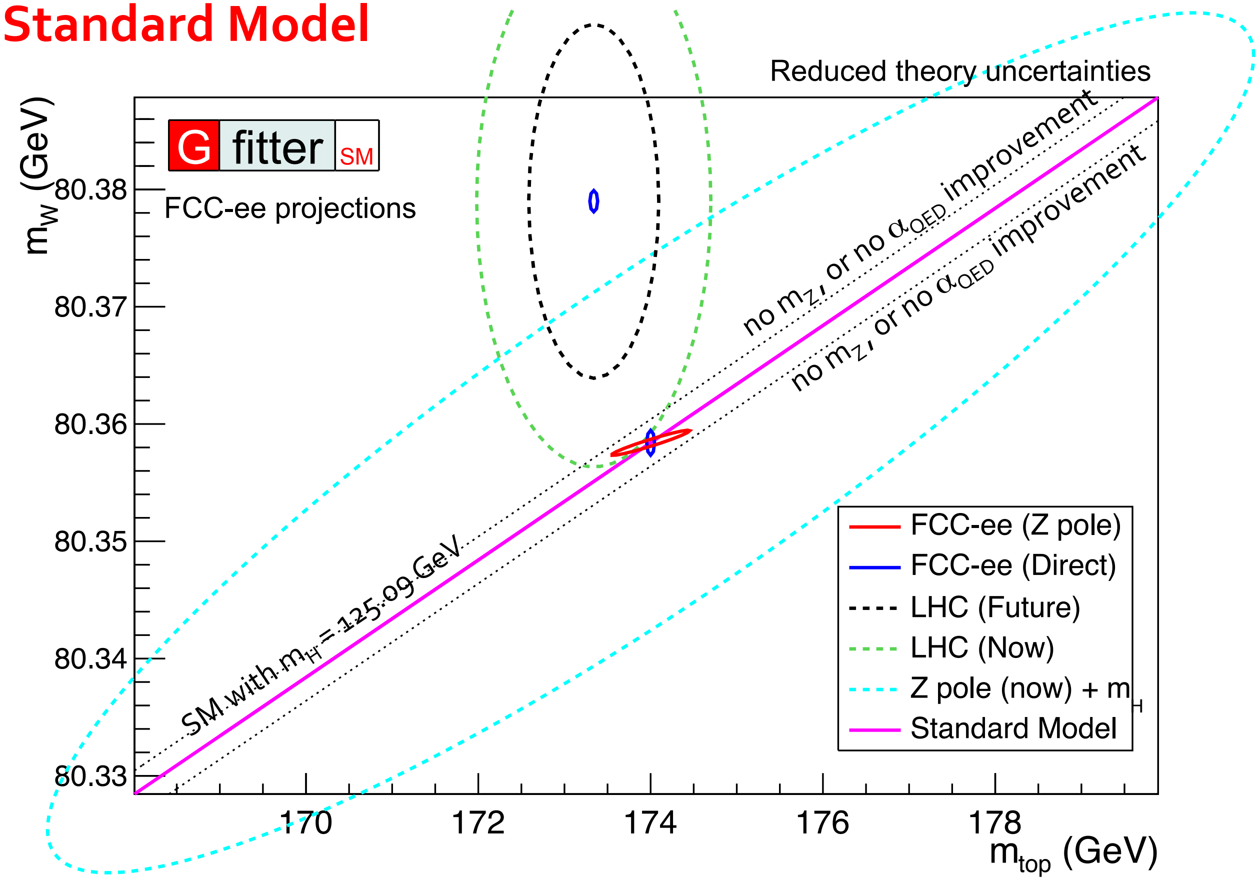
P. J. arXiv:1503.01325

Summary of precisions achievable

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED / EW
R_l	Peak	20.767 ± 0.025	0.00006	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.0000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.000005	0.001	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	<0.000005	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.001	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	0.00001	<0.00016	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.5	0.3	EW Corr.
Γ_W (MeV)	Threshold scan	2085 ± 42	1.2	0.3	EW Corr.
N_ν	$e^+e^- \rightarrow \gamma Z$, $Z \rightarrow \nu\nu$, ll	2.92 ± 0.05	0.0008	small	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 ± 760 ± 500	17	<40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	45	<40	QCD corr.
λ_{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

- **In the Standard Model**



- **Blue (direct) and red (Z pole) ellipses may not overlap**
- **Standard model may not fit**
  - **Then, new weakly-coupled particles exist [see mass scale sensitivity in three slides]**

Higgs precision measurements

- See Frank Simon's presentation for the basics at 250 and 380 GeV
  - Very similar at CEPC (240 GeV) and FCC-ee (240, 350, and 365 GeV)
    - Both can determine Higgs couplings and width in a model-independent way
      - Plus Higgs mass to better than 10 MeV

Collider	HL-LHC *	CEPC_{240}		$\mathrm{FCC\text{-}ee}_{240+365}$		
Lumi (ab^{-1})	3	5_{240}	$\oplus$ HL-LHC	5_{240}	$\oplus 1.5_{365}$	$\oplus$ HL-LHC
$\delta\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}$ (%)	50	3.1	**2.5**	2.8	1.6	**1.5**
$\delta g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}$ (%)	3.5	0.25	**0.25**	0.25	0.22	**0.22**
$\delta g_{\mathrm{HWW}}/g_{\mathrm{HWW}}$ (%)	3.5	1.4	**1.1**	1.3	0.47	**0.46**
$\delta g_{\mathrm{Hbb}}/g_{\mathrm{Hbb}}$ (%)	8.2	1.6	**1.2**	1.4	0.68	**0.67**
$\delta g_{\mathrm{Hcc}}/g_{\mathrm{Hcc}}$ (%)	**SM**	2.2	**1.9**	1.8	1.23	**1.20**
$\delta g_{\mathrm{Hgg}}/g_{\mathrm{Hgg}}$ (%)	3.9	1.6	**1.3**	1.7	1.03	**0.89**
$\delta g_{\mathrm{H}\tau\tau}/g_{\mathrm{H}\tau\tau}$ (%)	6.5	1.5	**1.2**	1.4	0.80	**0.78**
$\delta g_{\mathrm{H}\mu\mu}/g_{\mathrm{H}\mu\mu}$ (%)	5.0	8.7	**5.0**	9.6	8.6	**3.4**
$\delta g_{\mathrm{H}\gamma\gamma}/g_{\mathrm{H}\gamma\gamma}$ (%)	3.6	3.7	**1.6**	4.7	3.8	**1.4**
$\delta g_{\mathrm{Htt}}/g_{\mathrm{Htt}}$ (%)	4.2	–	$<$ **4.2**	–	–	**3.3**
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	**SM**	< 1.8	$<$ **1.8**	< 1.2	< 1.1	$<$ **1.0**
$\mathrm{BR}_{\mathrm{invis}}$ (%)	< 3.0	< 0.3	$<$ **0.3**	< 0.3	< 0.25	$<$ **0.25**

  - Combination of 240 and 365 GeV improves by almost a factor 2 wrt 240 GeV alone
    - And by almost a factor 4 wrt 365 GeV (or 380 GeV) alone
      - HZ maximal at 240 GeV (g_{HZZ}), but very little WW fusion there (Γ_Z)

* HL-LHC projections from A. Hoecker

"... and whose energy can be upgraded."

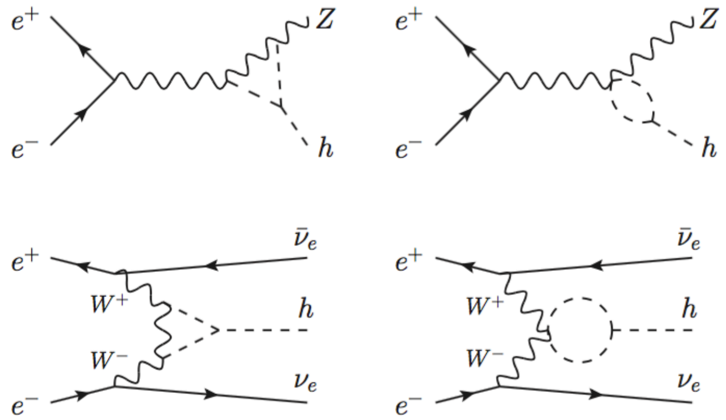
- **According to the white book of ESPP 2013 :** https://cds.cern.ch/record/1567295/

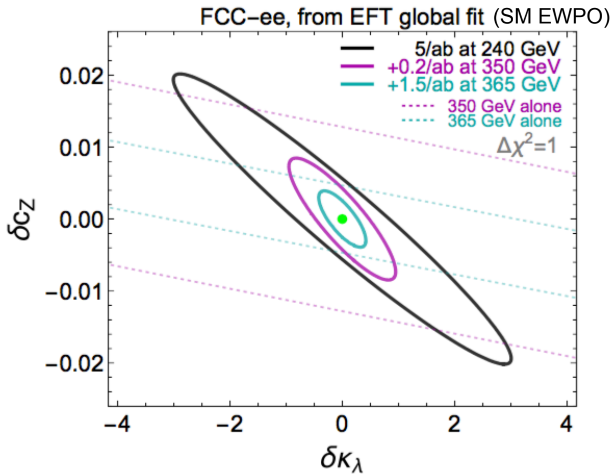
> At energies of 500 GeV or higher, such a machine could explore the Higgs properties further, for example **the coupling to the top quark, the self-coupling, and the total width.**

- **Should we foresee an upgrade of FCC-ee at √s = 500 GeV ?**
  - **For the total width, the coupling to the top quark : the answer is no (previous slide)**
  - **The Higgs self-coupling is also within reach at FCC-ee (240 + 365 GeV)**

M. McCullough
arXiv:1312.3322

C. Grojean et al.
arXiv:1711.03978





A. Blondel, P. J.
arXiv:1809.10041

- ➨ **~3σ observation in 15 years at FCC-ee (~ILC500 after three decades)**
- ➨ **~5σ discovery with four IPs instead of two – less costly than 500 GeV upgrade**

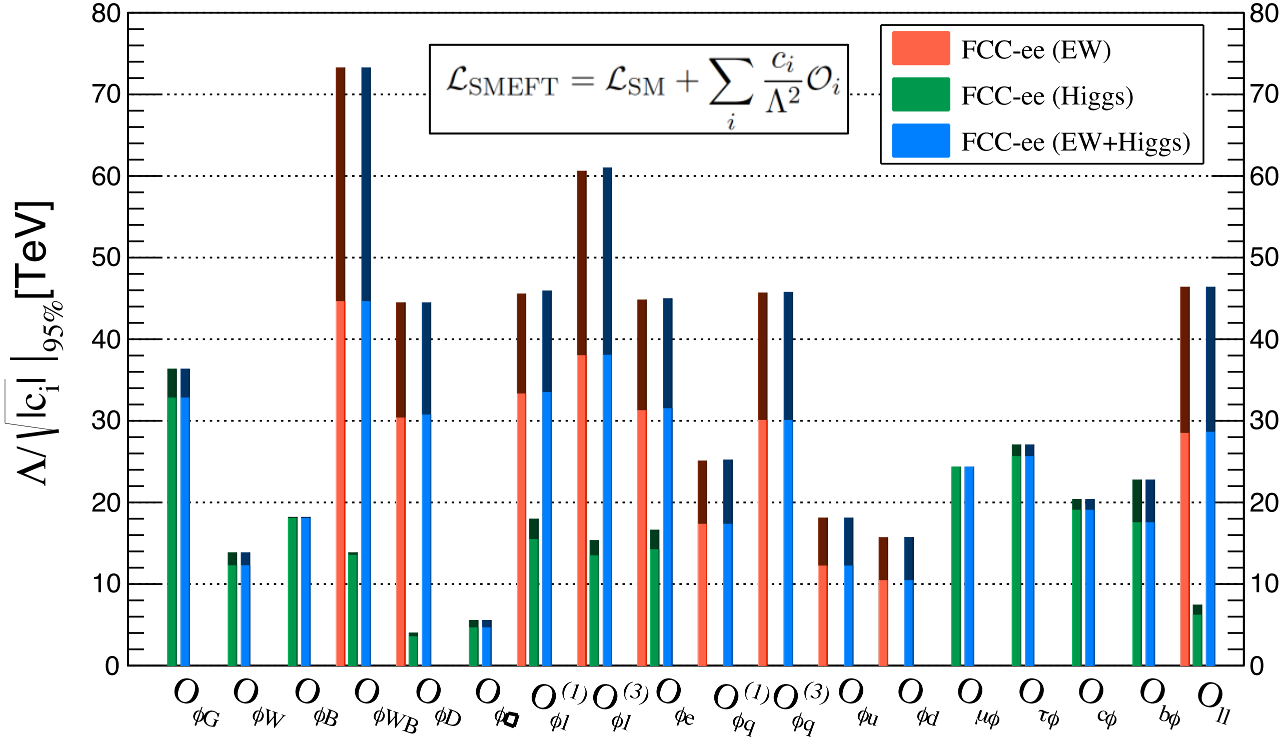
  Model-independent (global EFT fit).

- **Note: FCC-hh, in combination with FCC-ee, will measure κ_{top} and κ_λ to 1% and 5%, resp.**

See M. Mangano's talk

Precision ⇔ Discovery, again

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



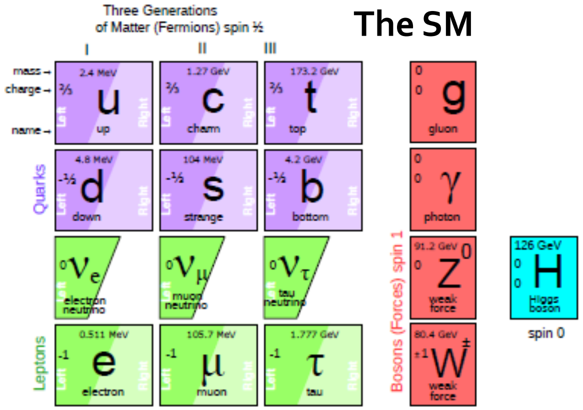
Courtesy J. de Blas

- 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
- Further improvement in theory predictions pays off for EWPO measurements
- Larger statistics pays off for Higgs measurements (4 IPs ?)

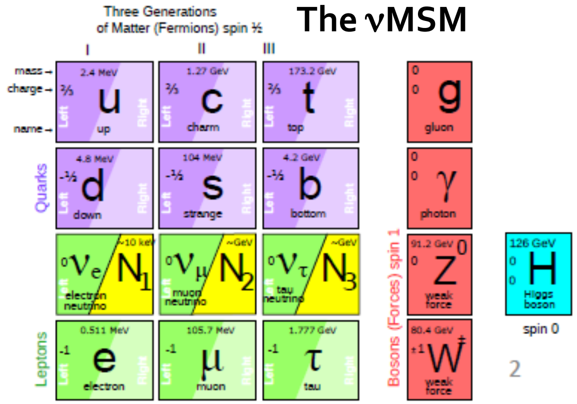
Right-handed neutrinos

- (One of the) most natural extension of the standard model: the νMSM
  - Complete particle spectrum with the missing three right-handed neutrinos

The SM



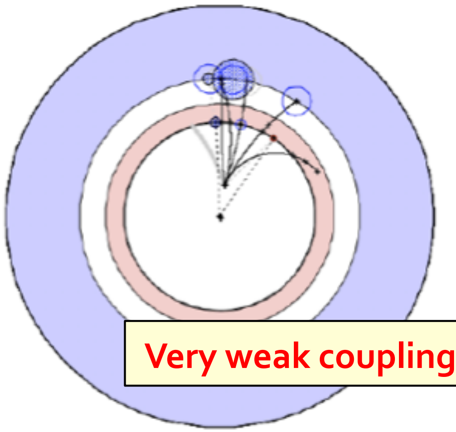
The νMSM

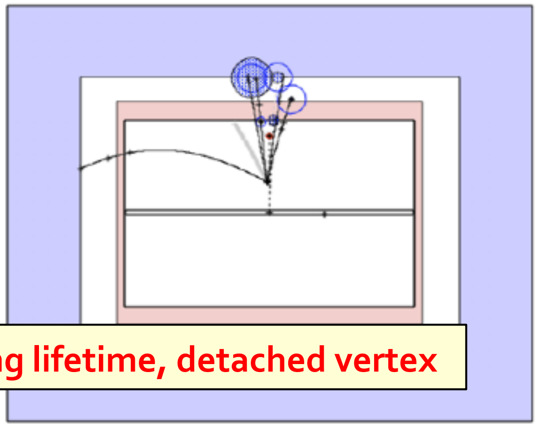


- Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses

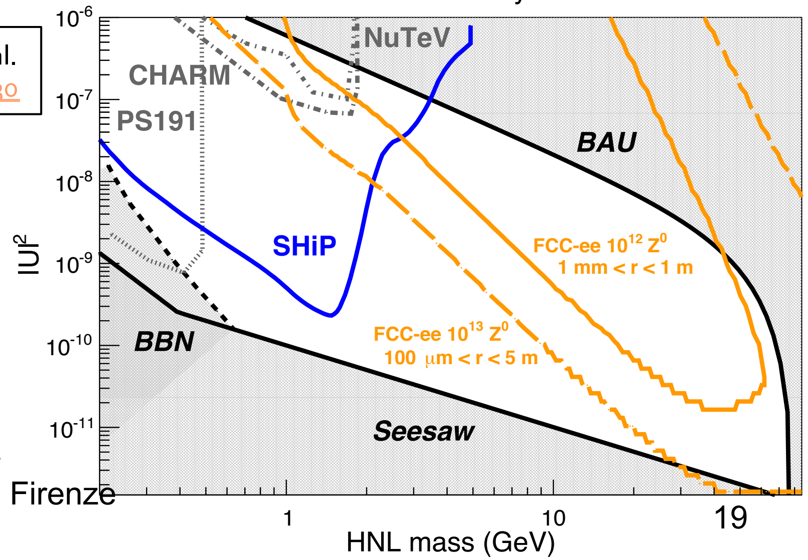
- Searched for in very rare $Z \to \nu N_{2,3}$ decays
  - Followed by $N_{2,3} \to W^* \ell$ or $Z^* \nu$

A. Blondel et al.
arXiv:1411.5230





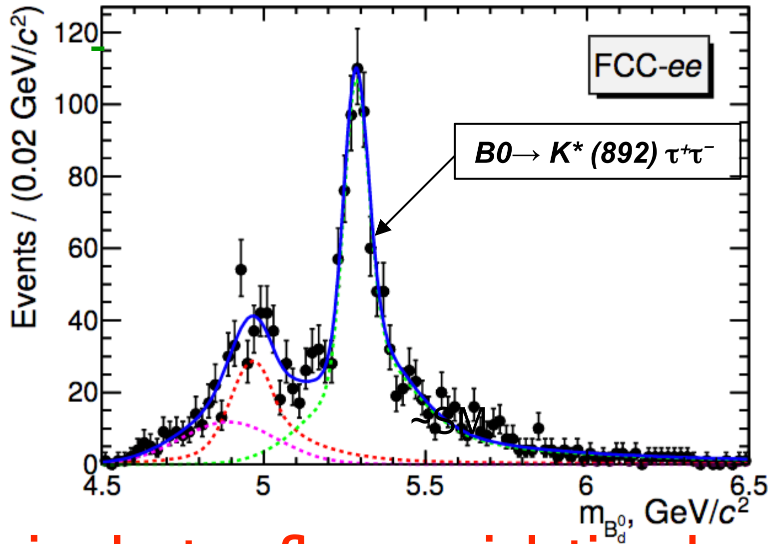
Very weak coupling : long lifetime, detached vertex



Flavours : B anomalies, etc.

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

J.F. Kamenik et al.
arXiv:1705.11106



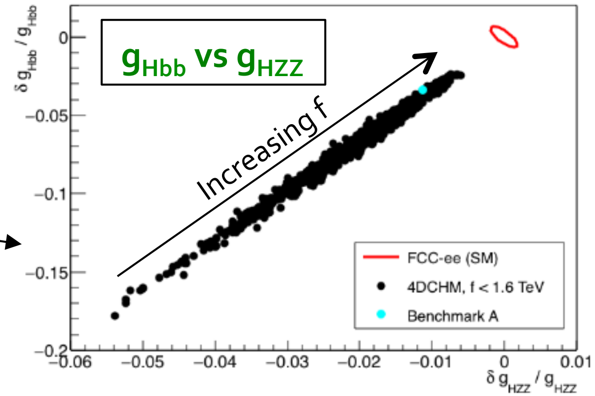
Also 100,000 $B_S \rightarrow \tau^+\tau^-$ @ FCC-ee
Reconstruction efficiency under study

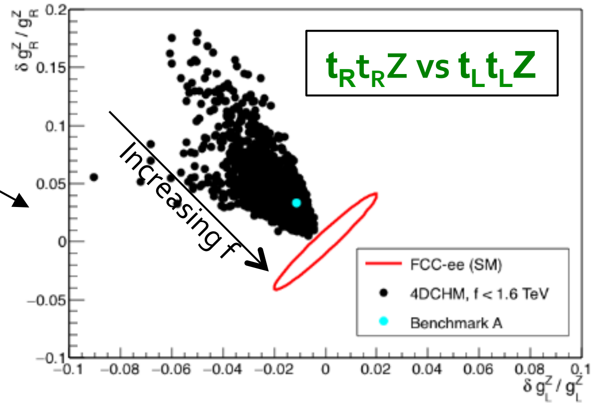
- **Not mentioning lepton-flavour-violating decays**
  - BR(Z $\rightarrow$ eτ, μτ) down to 10^{-9} (improved by 10^4)
  - BR(τ $\rightarrow$ μγ, μμμ) down to a few 10^{-10} (similar to Belle2 projections)
  - τ lifetime vs BR(τ $\rightarrow$ eνν) : lepton universality tests improved by O(10).

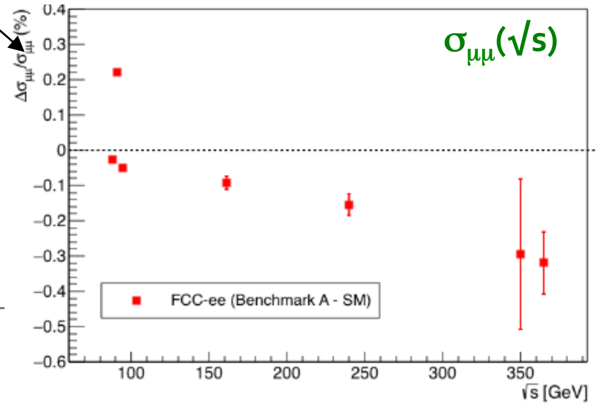
Composite Higgs

- **Expect pattern of deviations in all sectors**
  - E.g, 4D Composite Higgs Model
    - Deviations in Higgs couplings
    - Deviations in EW top couplings
    - Deviations in EW lepton couplings
  - 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

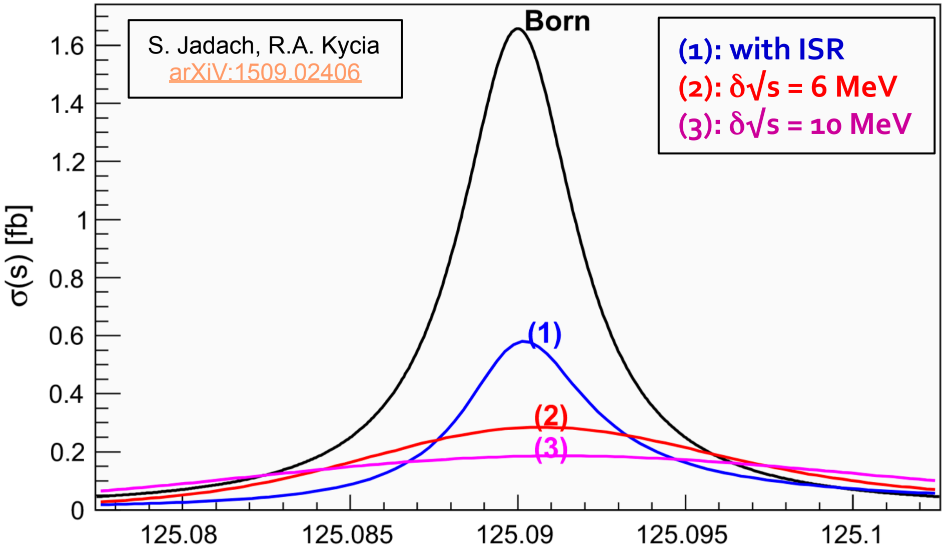






And if there is time …

- Spend few years at $\sqrt{s}$ = 125.09 GeV with high luminosity
  - For s-channel production $e^+e^- \to H$ (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
    - $\sigma(e^+e^- \to H) \sim 100$ ab
  - Option 2: $\delta\sqrt{s}$ = 6 MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \to H) \sim 250$ ab
  - Backgrounds much larger than signal
    - $e^+e^- \to q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots$

- 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

Summary of the discovery potential

- **EXPLORE the 10-50 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, Γ_Z, m_W, m_{top}, $\sin^2\theta_W^{eff}$, R_b, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, top EW couplings …**
    - **Up to 10-fold more precise and model-independent Higgs couplings measurements**
- **DISCOVER that the Standard Model does not fit**
  - **Then extra weakly-coupled and Higgs-coupled particles exist**
  - **Understand the underlying physics through effects via loops**
- **DISCOVER a violation of flavour conservation / universality**
  - **Examples: $Z \to \tau\mu$ in 5×10^{12} Z decays; or $\tau \to \mu\mu\mu$ in 3×10^{11} τ decays; …**
  - **Also $B^0 \to K^{*0}\tau^+\tau^-$ or $B_S \to \tau^+\tau^-$ in 10^{12} bb events**
- **DISCOVER dark matter as invisible decays of Higgs or Z**
- **DISCOVER very weakly coupled particles in the 5-100 GeV mass range**
  - **Such as right-handed neutrinos, dark photons, …**
    - **May help understand dark matter, universe baryon asymmetry, neutrino masses**

Today, we do not know how nature will surprise us: other things may come up with FCC-ee

Synergies with 100 TeV pp collider

- Higgs physics
  - ee fixes Higgs width, HZZ couplings, and ttZ couplings (and many others)
    - Turn HL-LHC ttH measurement to an absolute ttH coupling precision of 3%
    - Possibly first 5σ discovery of the Higgs self coupling
  - 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
  - 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
  - ee: powerful and clean, but flavour blind: $Z \rightarrow \nu N$, all ν flavours together — 5×10^{12} Z
  - hh: more difficult, but potentially flavour sensitive: $W \rightarrow l_1 (Q_1)\, N$, $N \rightarrow l_2 (Q_2)\, W^*$ — 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 (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