Physics at Future Colliders

- **Lecture 1 (Wednesday 29 July, 11:15)**
  - An historical perspective (1964-2014): The need for precision and energy
  - A strategy for the future: Towards the precision and energy frontier
  - The short-term perspectives (2020-2035): The HL-LHC

- **Lecture 2 (Thursday 30 July, 10:15)**
  - The quest for precision (2030-2050): Linear or Circular ?

- **Lecture 3 (Friday 31 July, 10:15)**
  - The energy frontier (2045-2080): Leptons or Hadrons ?
  - Thinking out of the box: Muon collider
  - Towards the next European Strategy update (2018-19)

Lecture 2

Mid-term perspectives (2030-2050)

The quest for precision: Linear or Circular ?

ILC (31 km)

e^+e^- : 250-500 GeV

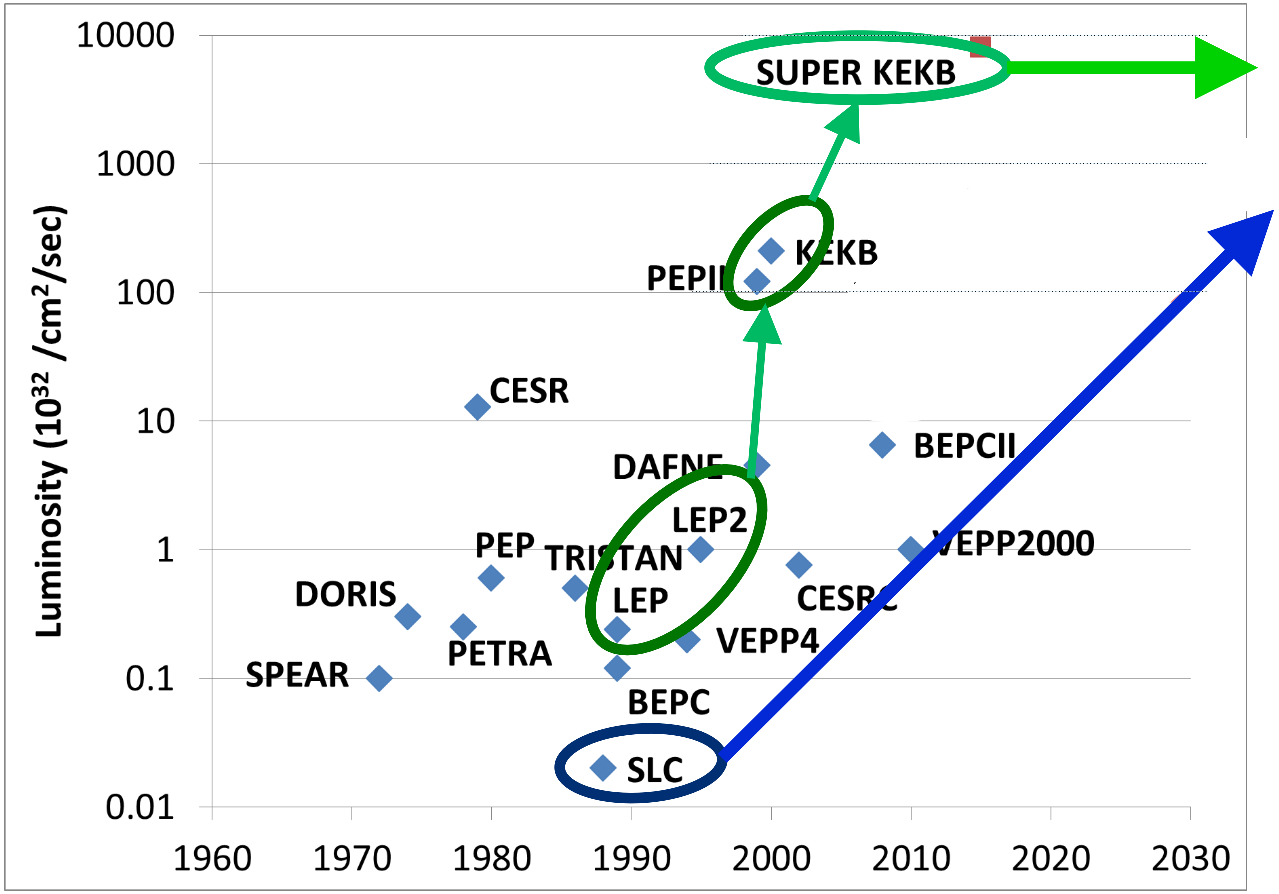
FCC (100 km)

First step: FCC-ee (91-400GeV)

[Use the tunnel ultimately aimed at FCC-hh]

Precision with e^+e^- colliders (1)

- **Historically, e^+e^- colliders have been used for precision measurements**
  - The accuracy of e^+e^- colliders led to predictions at higher scales (m_{top}, m_H, limits on NP)
    - And to [unexpected] discoveries (e.g., c quark, gluon, tau lepton, neutrino tau …)



Circular ?

FCC-ee, CEPC

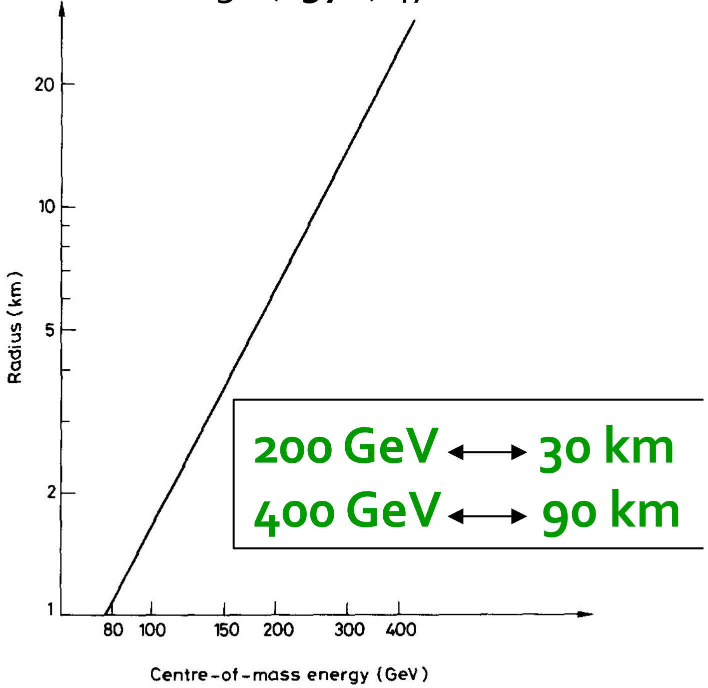
Linear ?

ILC, CLIC

Precision with e^+e^- colliders (2)

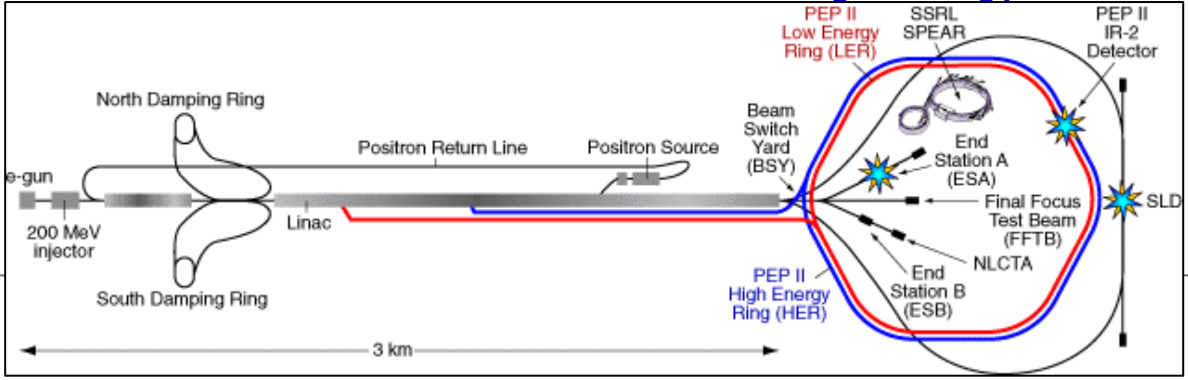
- **The dilemma is not really new**
  - **"An e^+e^- storage ring in the range of a few hundred GeV in the centre-of-mass can be built with present technologies [...] would seem to be [...] the most useful project on the horizon"**

Original LEP proposal, 1976
NIM 136 (**1976**) 47-60



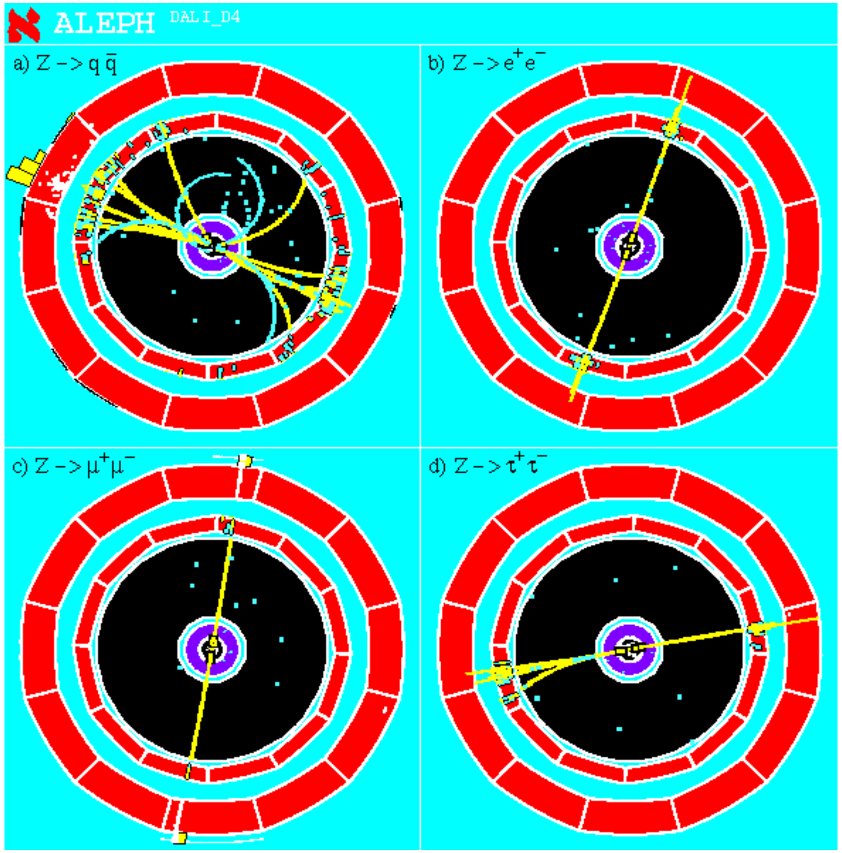
200 GeV ⟷ 30 km
400 GeV ⟷ 90 km

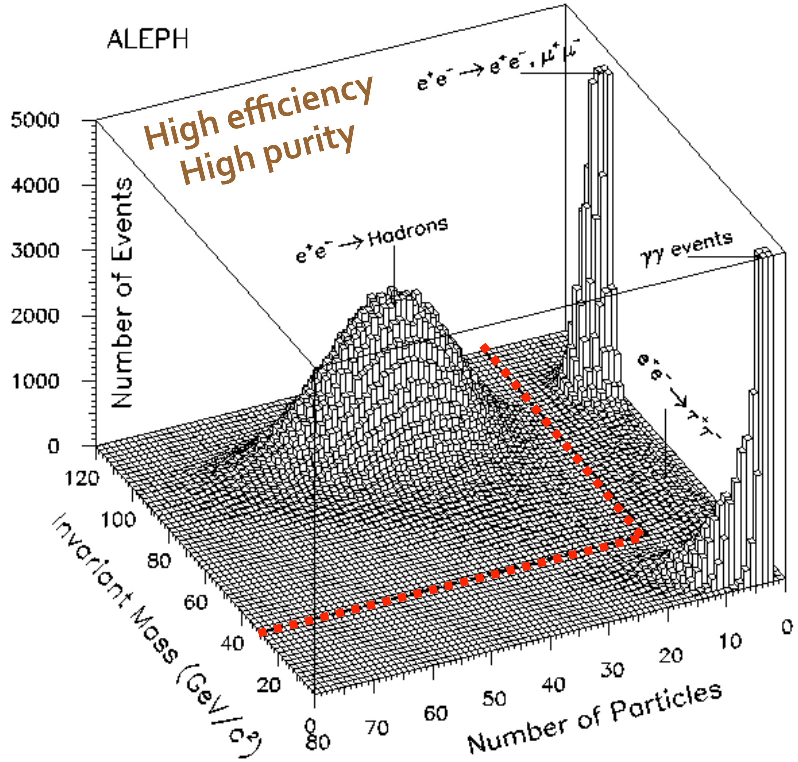
  - **B. Richter, "The SLAC Linear Collider", 11th Conf. on High-Energy Accelerators (1980)**



Precision with e^+e^- colliders (3)

- Why are e^+e^- colliders the tool of choice for precision anyway ?
  - Electrons are not protons, i.e., do not interact strongly: no pile-up collisions
    - Corollary #1: Final state is clean and cosy, triggering is easy (100% efficient)
      - Analysis is a waking dream



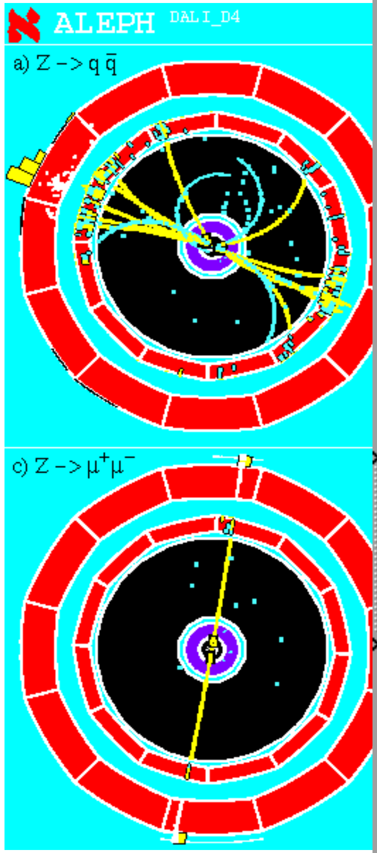


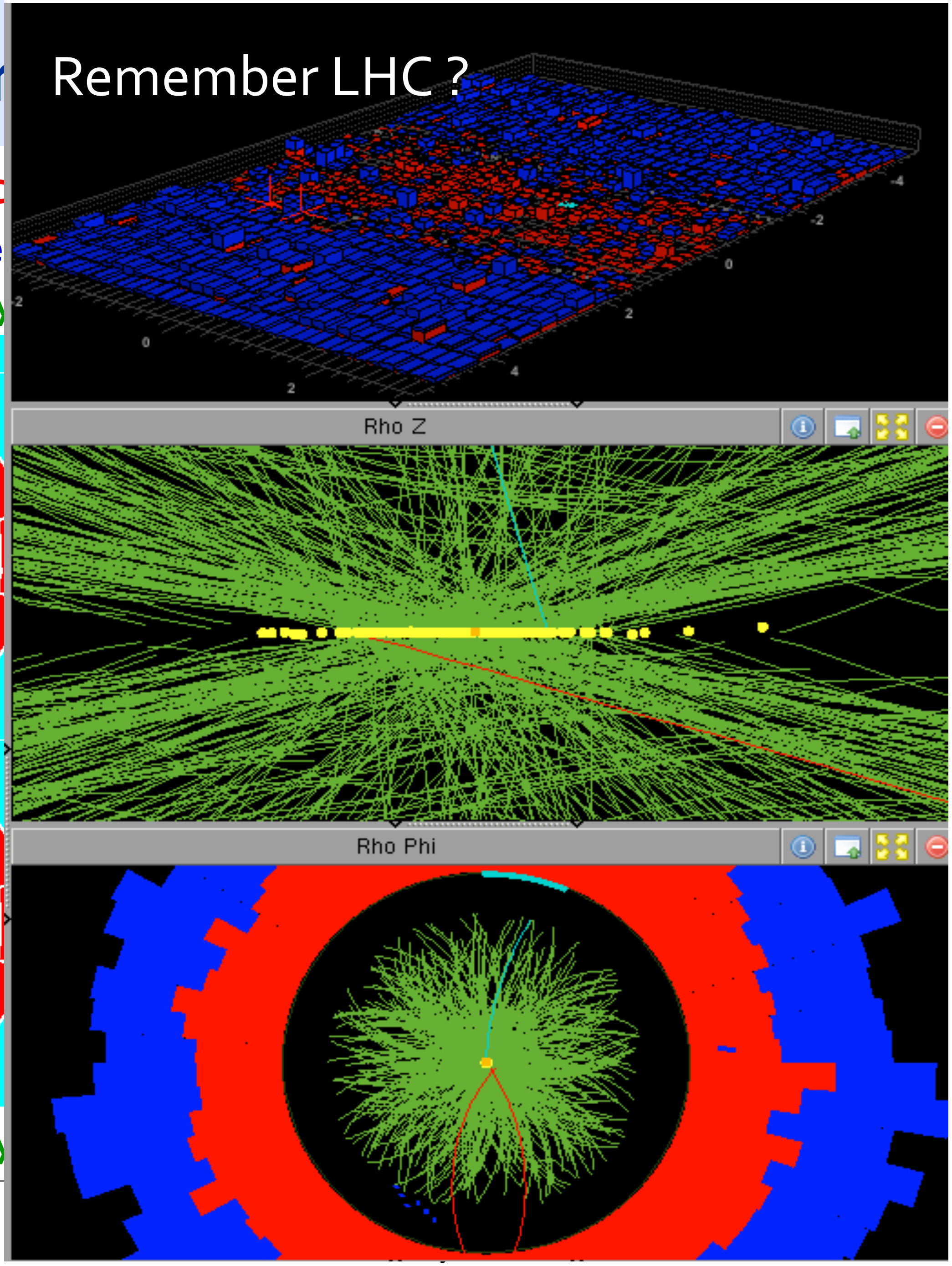
High efficiency
High purity

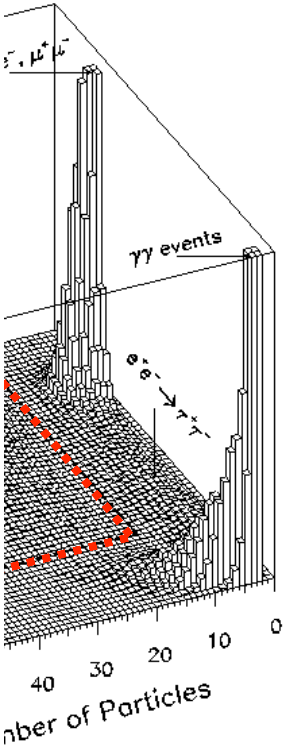
- Corollary #2: No huge QCD cross section: All events are signal.

Pr)

- Why are e^+e^- c y ?
  - Electrons are isions
    - Corollary % efficient)
    - g dream



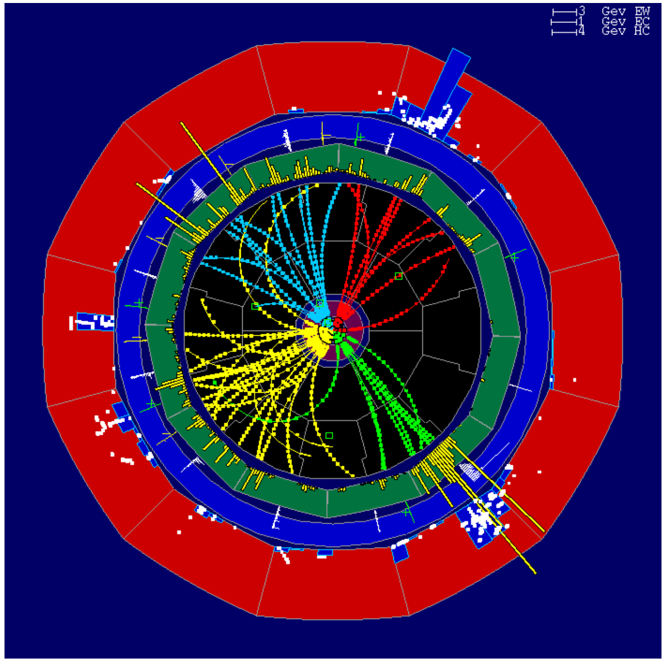

Remember LHC ?



    - Corollary

Precision with e^+e^- colliders (4)

- **Why are e^+e^- colliders the tool of choice for precision anyway ? (cont'd)**
  - Electrons are leptons, i.e., elementary particles: no underlying event
    - Corollary: Final state has known energy and momentum: ($\sqrt{s}$, 0, 0, 0)
  - Example: an $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$ candidate
    - Four jets in the event and nothing else
    - Total energy and momentum are conserved
      - ➨ $E_1 + E_2 + E_3 + E_4 = \sqrt{s}$
      - ➨ $P_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$
    - Jet directions ($\beta_i = p_i/E_i$) are very well measured



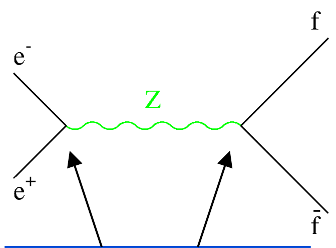
$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

  - Jet energies (or di-jet masses: m_W) determined analytically by inverting the matrix
    - ➨ No systematic uncertainty related to jet energy calibration

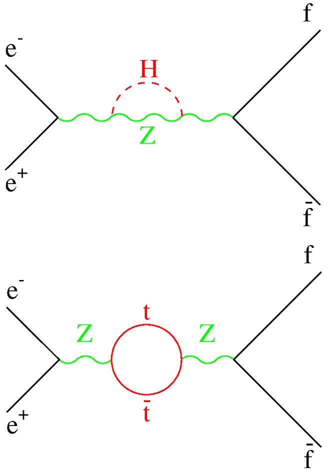
A lot of Z are available anyway to calibrate and align everything

Precision with e^+e^- colliders (5)

- **Why are e^+e^- colliders the tool of choice for precision anyway ? (cont'd)**
  - **Electroweak observables can be calculated/predicted with precision**
    - **And are sensitive to heavier particles through quantum corrections**
      - **At the Z pole**



L Couplings (v+a)
≠
R Couplings (v-a)

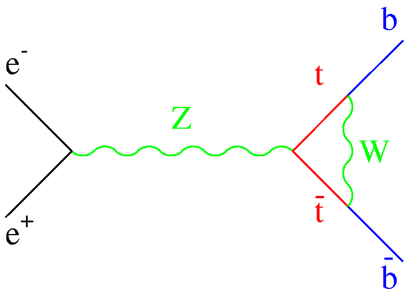


Tree-Level	Corrected
$a_0 = \pm 1/2$	$a = a_0(1+\Delta\rho)$
$v_0 = a_0(1-4\lvert Q\rvert \sin^2\theta_W)$	$v = a(1-4\lvert Q\rvert \sin^2\theta_W^{\text{eff}})$
$\sin^2\theta_W = 1 - m_W^2/m_Z^2$ $(m_W = m_Z \cos\theta_W)$	$\sin^2\theta_W = 1 - m_W^2/m_Z^2(1+\Delta\rho)$

$$\Gamma_Z \rightarrow \Gamma_Z \times (1+\Delta\rho)$$

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

- **Specific correction for Rb**



$R_b = \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$

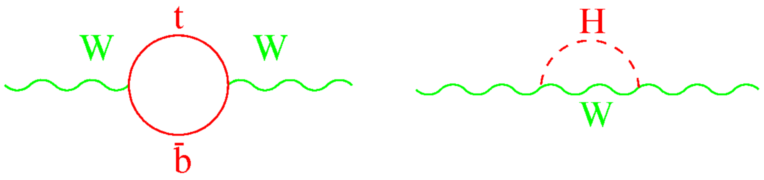
$$R_b \rightarrow R_b \times (1 + \delta_{vb})$$

$$\delta_{Vb} = -\frac{20}{13}\alpha\frac{m_t^2}{m_Z^2} \approx 5\%$$

No m_H !

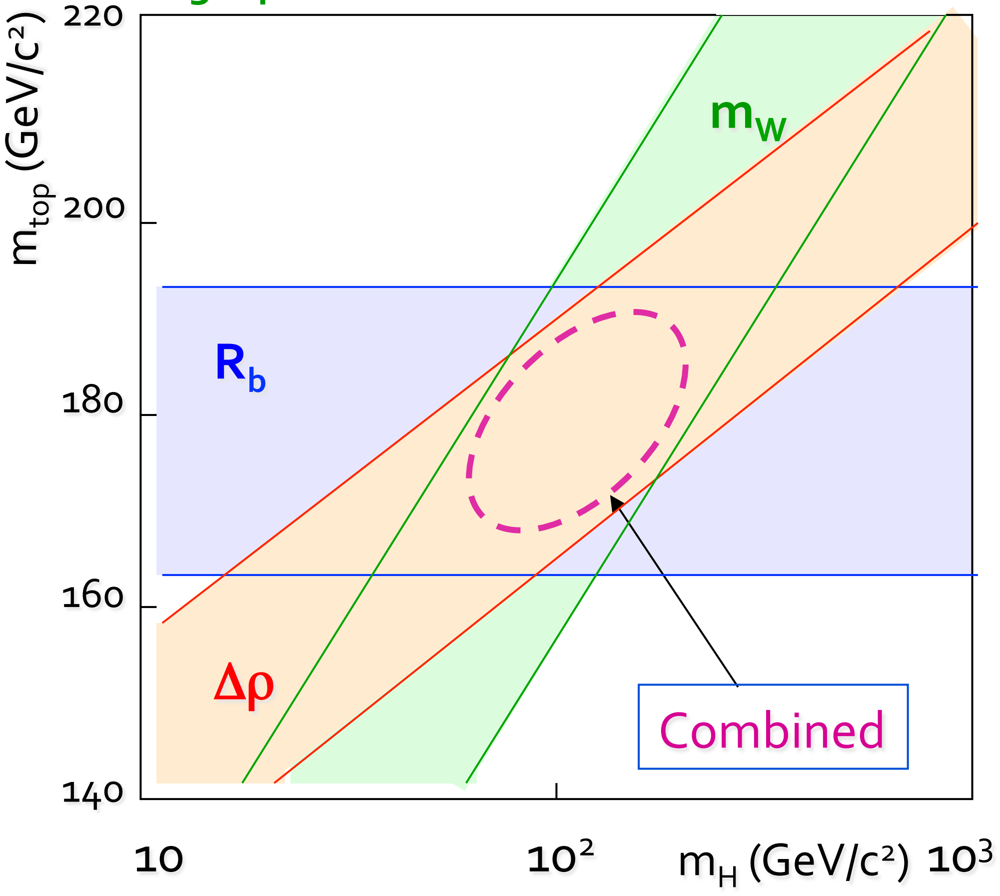
Precision with e^+e^- colliders (7)

- **Why are e^+e^- colliders the tool of choice for precision anyway ? (cont'd)**
  - **Electroweak observables can be calculated/predicted with precision**
    - **And are sensitive to heavier particles through quantum corrections**
      - **W mass**



$$\boxed{(m_W/m_Z)^2 \rightarrow (m_W/m_Z)^2 \times (1 + \Delta r)}$$

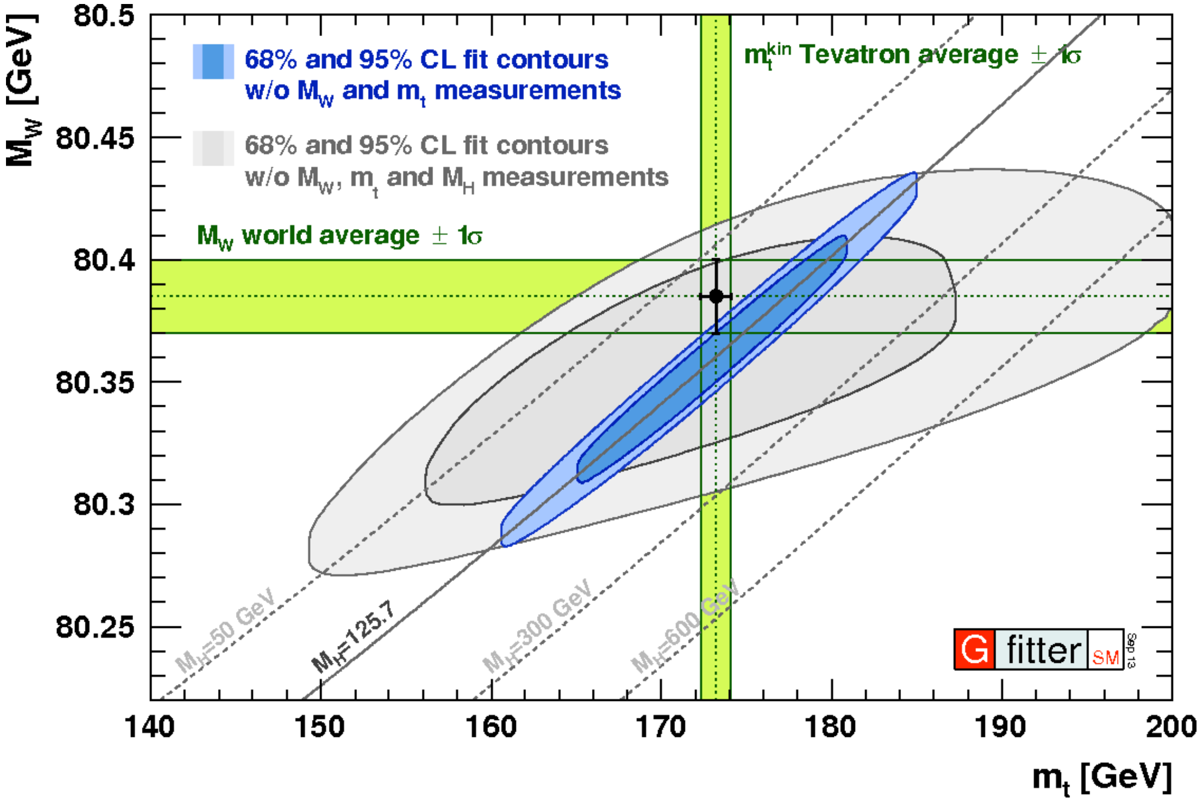
$$\Delta r = -\frac{\cos^2\vartheta_W}{\sin^2\vartheta_W}\Delta\rho \qquad \approx 1\%$$
$$+\frac{\alpha}{3\pi}\left[\frac{1}{2}-\frac{1}{3}\frac{\sin^2\vartheta_W}{1-\tan^2\vartheta_W}\right]\mathrm{Log}\frac{m_H^2}{m_Z^2}+\cdots$$



- **Prediction of m_{top} and m_H**

Precision with e^+e^- colliders (8)

- **Current status of precision measurements**
  - With m_{top}, m_W and m_H known, the standard model has nowhere to go



- Strong incentive to significantly improve the precision of all measurements
  - ➨ Towards being sensitive to 100 TeV new physics through quantum corrections

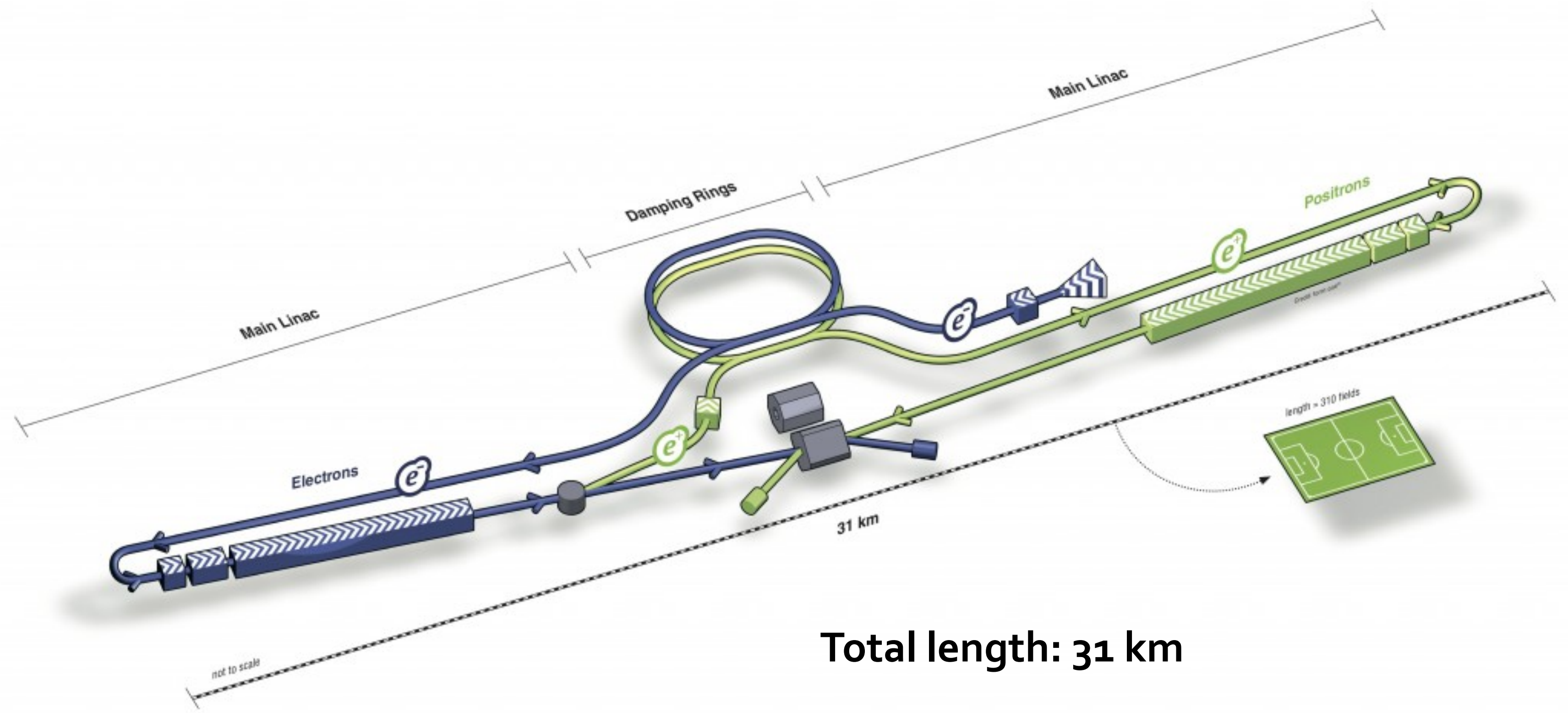
Precision with e^+e^- colliders (9)

- The European Strategy update in 2013 does not say otherwise

e) 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.

Linear or Circular ? (1)

- For 20 years, there was only one such project on the market
  - A 500 GeV e^+e^- linear collider, now called "ILC", proposed in the early 1990's

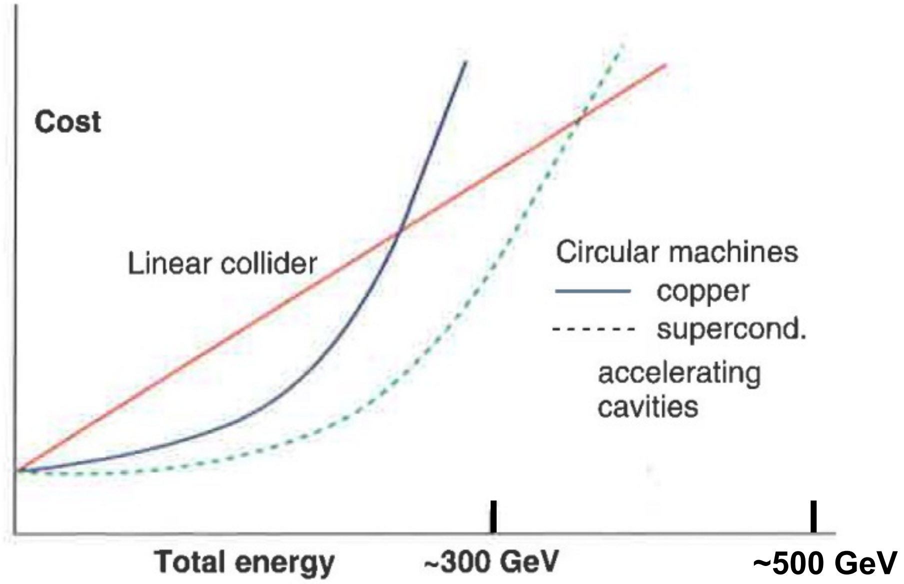


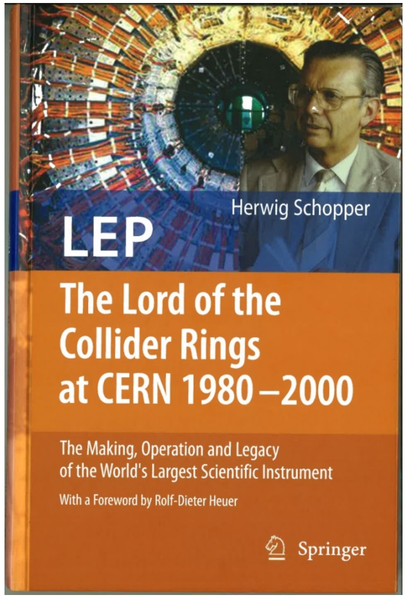
Total length: 31 km

- Why not a 500 GeV circular collider ?

Linear or Circular ? (2)

- **Why not a 500 GeV circular collider ?**
  - Synchrotron radiation in circular machines
    - Energy lost per turn grows like $\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$, e.g., 3.5 GeV/turn at LEP2
      - Must compensate with R and accelerating cavities ⟶ Cost grows like E^4 too.




Herwig Schopper

LEP

The Lord of the Collider Rings at CERN 1980–2000

The Making, Operation and Legacy of the World's Largest Scientific Instrument

With a Foreword by Rolf-Dieter Heuer

Springer

Author: Herwig Schopper
(Former CERN DG)

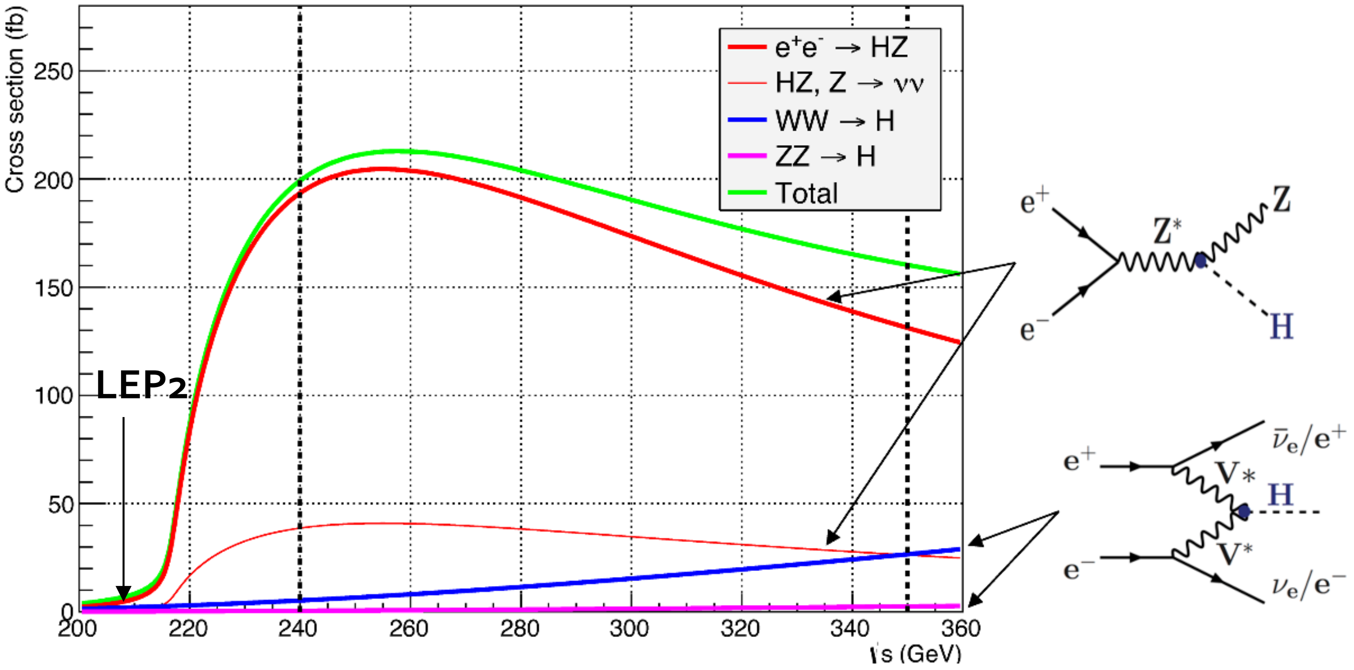
Foreword: Rolf Heuer
(Current CERN DG)

- A 500+ GeV e^+e^- collider can only be linear. Cost of a circular collider is prohibitive.
  - "Up to a centre of mass energy of 350 GeV at least, a circular collider with superconducting accelerating cavities is the cheapest option"

H. Schopper, private communication, 2014

Linear or Circular ? (3)

- ❑ Interest for circular collider projects grew up again after first LHC results
  - ◆ The Higgs boson is light – LEP2 almost made it: only moderate √s increase needed



- ● Need to go up to the top-pair threshold (~350 GeV) anyway to study the top quark
- ◆ There seems to be no heavy new physics below 500 GeV
  - ● The interest of √s = 500 GeV (and even 1 TeV) is now very much debated
- ◆ Way out: study with unprecedented precision the Z, W, H and top quark
  - ➨ Highest luminosities at 91, 160, 240 and 350 GeV are needed

Linear or Circular ? (4)

D. Schulte

- ❑ The ILC is designed for √s = 500 GeV
  - ◆ It is supported by 20 years of R&D and innovation
    - ● With a complete technical design report delivered in 2013
      - ➨ In principle, ready for construction as soon as decision is taken
  - ◆ This machine has many technological challenges
    - ● A 24 km-long, high-gradient (31 MV/m), RF system
    - ● A very low β^* optics delivering small beam spot sizes at high intensity
      - ➨ Never demonstrated to be achievable - ATF2 still struggling
    - ● A positron source with no precedent
      - ➨ Its performance cannot be verified before the construction is complete
    - ● A green-field project
  - ◆ It can deliver data to only one detector at a time
  - ◆ It is in principle upgradeable to √s = 1 TeV
    - ● And possibly more : CLIC or Plasma acceleration in the same tunnel (?)

Linear or Circular ? (5)

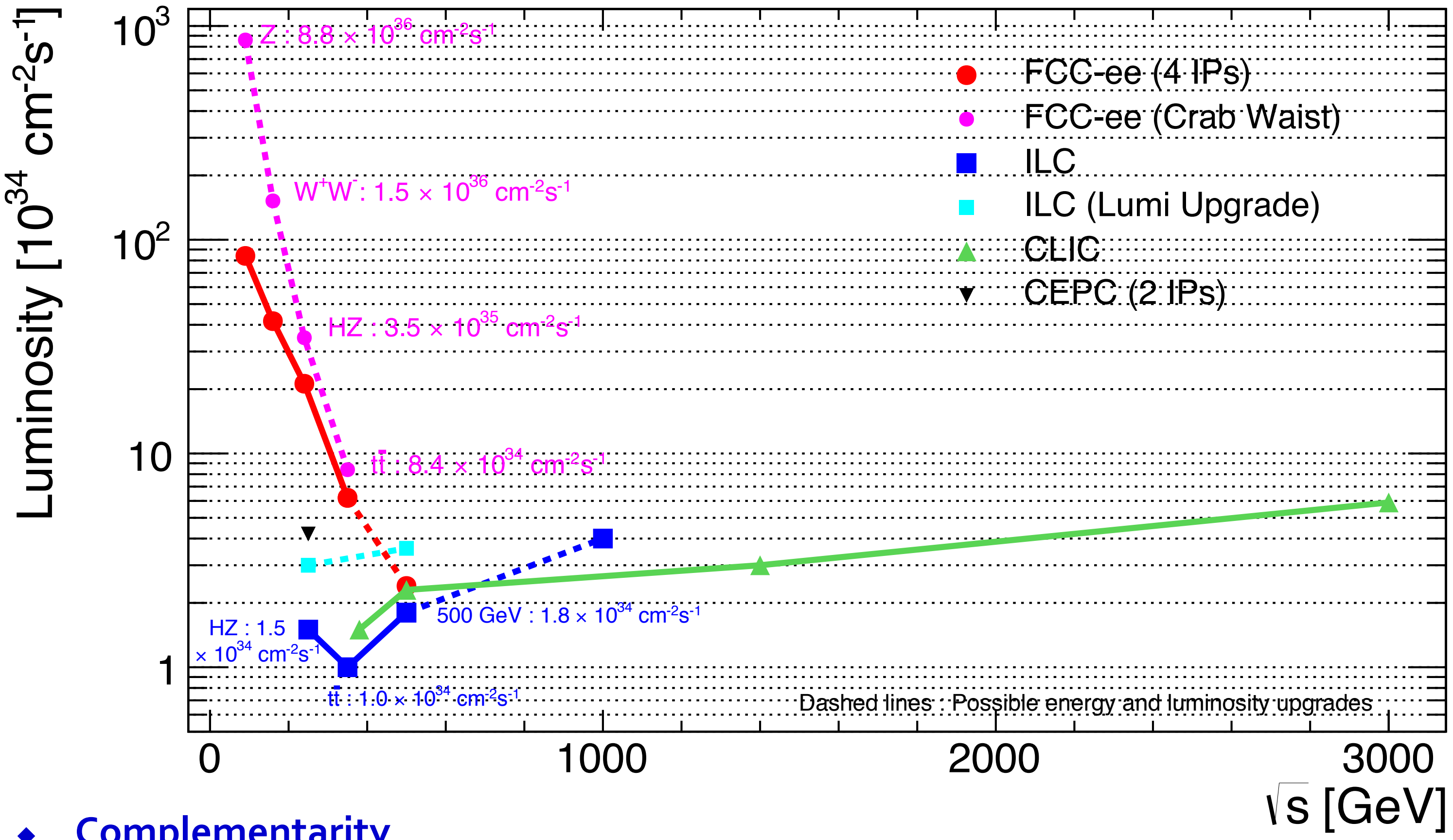
D. Schulte

- The FCC-ee is designed to be a Z, W, H, and top factory ($\sqrt{s}$ = 90-400 GeV)
  - It is a project in its infancy
    - Less than two years old
  - This machine has at least as many technological challenges
    - A high-power (200 MW), high-gradient (15-20 MV/m), 1 km-long, RF system
    - Loads of synchrotron radiation (100 MW) to deal with
    - A booster (for top up injection), and probably a double ring for e^+ and e^-
    - An optics with very low β^*, and large momentum acceptance
    - Polarization (at least transverse, maybe also longitudinal ?)
    - Up to four experiments to serve
    - … and much more
  - It is supported by 50 years of experience and progress with e^+e^- circular machines
    - Most of the above challenges will be addressed at SuperKEKB as of 2015
      - ➨ FCC-ee will have to build on this experience
  - It is the first step towards a 100 TeV proton-proton collider

Linear or Circular ? (6)

❑ Performance target for e^+e^- colliders

D. Schulte



- **Complementarity**
  - **Ultimate precision measurements with circular colliders (FCC-ee)**
  - **Ultimate e^+e^- energies with linear colliders (CLIC)**

Linear or Circular ? (7)

- **Performance target for e^+e^- colliders**
  - Number of events per year for the FCC-ee

√s (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	350 (WW→H)
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}

- The FCC-ee core programme can be completed in about 8 to 10 years

  - Number of years needed to complete the core programme $N_Z=10^{(12)13}$

1 year = 10^7 s

# years	(0.3) 2.5	1	3	0.5	3

  - The ILC precision physics programme
    - LC = 500 fb^{-1} @ 500 GeV (4y), 200 fb^{-1} @ 350 GeV (1y), 500 fb^{-1} @ 250 GeV (3y)
      - (*) Optional: 100 fb^{-1} @ 90 GeV (~3y?), 500 fb^{-1} @ 160 GeV (~3y?)

        with ±80% / ±30% polarization for e^-/e^+ beams

~ 13 years
1 y = 1.6×10^7 s

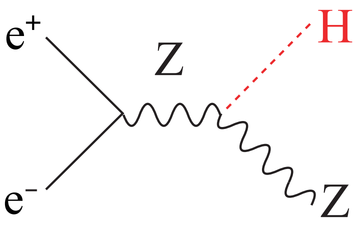
Events@ILC	$3\times10^{9\,(*)}$	$2\times10^{6\,(*)}$	1.4×10^{5}	10^{5}	3.5×10^{4}
ILC @ FCC-ee	1 day	1 week	2 months	3 months	1.5 year

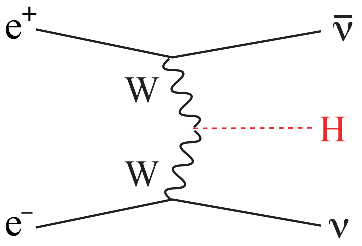
  - About one year is needed at the FCC-ee to complete the full ILC precision physics programme

Precision Higgs physics at FCC-ee and ILC (1)

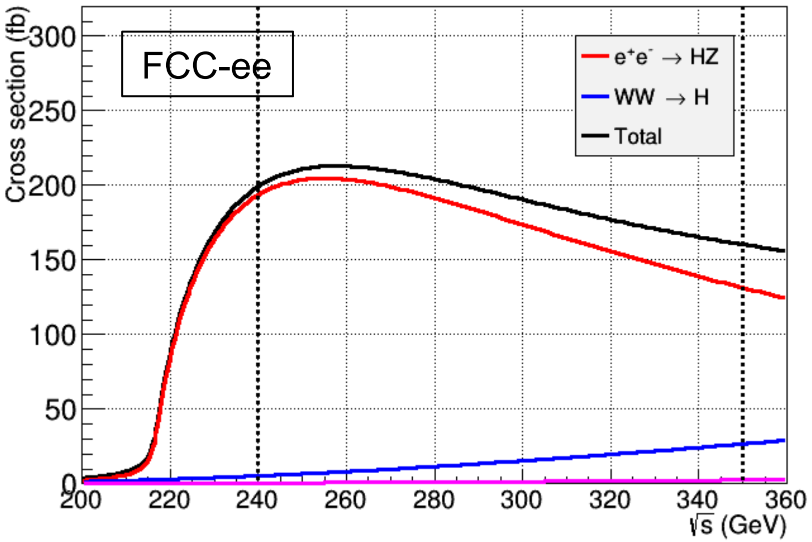
- **Dominant production processes for $\sqrt{s} \leq 500$ GeV**

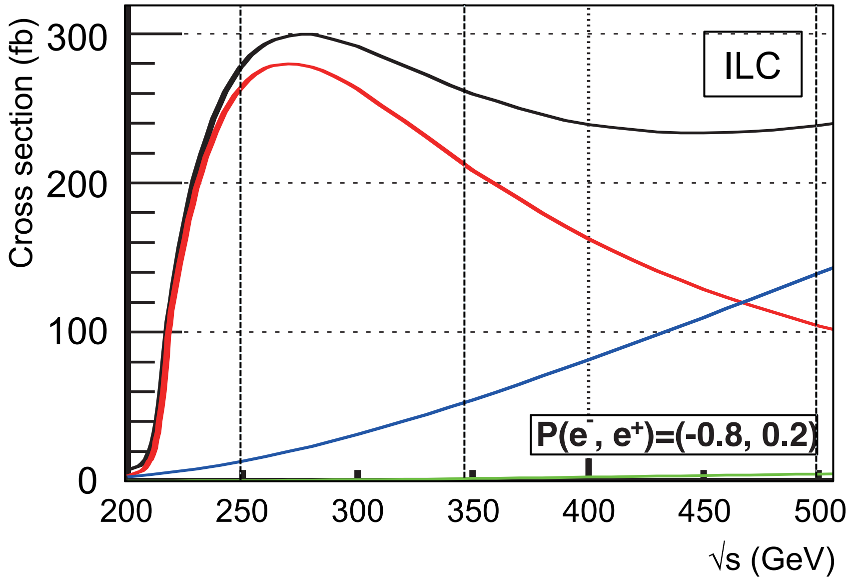
Higgs-strahlung





Boson fusion



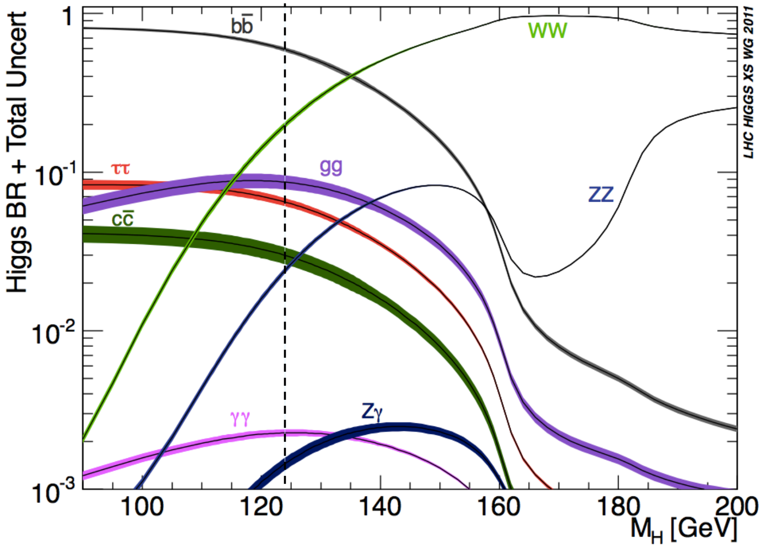


- **Effect of beam polarization (exercise)**
  - **Higgs-strahlung cross section multiplied by $1 - P_-P_+ - A_e \times (P_- - P_+)$**
  - **Boson fusion cross section multiplied by $(1-P_-) \times (1+P_+)$**

Precision Higgs physics at FCC-ee and ILC (2)

- The plan is to run at √s = 240-250 GeV and 350-500 GeV in order to
  - Determine all Higgs couplings in a model-independent way
  - Infer the Higgs total decay width
  - Evaluate (or set limits on) the Higgs invisible or exotic decays
    - Through the measurements of $\sigma(e^+e^- \to H+X) \times BR(H \to YY)$

with Y = b, c, g, W, Z, γ, τ, μ, invisible



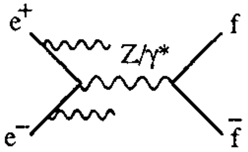
m_H = 125 GeV

Decay	BR [%]	Unc. [%]
bb	57.7	3.3
ττ	6.32	5.7
cc	2.91	12.2
μμ	0.022	6.0
WW	21.5	4.3
gg	8.57	10.2
ZZ	2.64	4.3
γγ	0.23	5.0
Zγ	0.15	9.0
ΓH [MeV]	4.07	4.0

- m_H = 125 GeV is a very good place to be for precision measurements !
  - All decay channels open and measurable – can test new physics from many angles

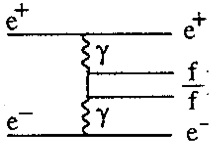
Precision Higgs physics at FCC-ee and ILC (3)

- Physics backgrounds are “small”
  - For example, at $\sqrt{s}$ = 240 GeV



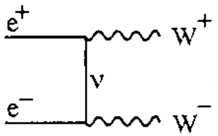
$e^+e^- \to q\bar{q}, l^+l^-$

60 pb



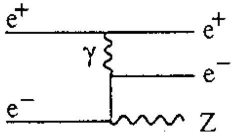
$\gamma\gamma \to qq, l^+l^-$
m > 30 GeV

30 pb



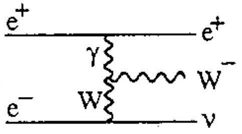
$e^+e^- \to W^+W^-$

16 pb



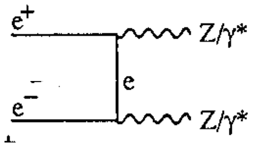
$e^+e^- \to Ze^+e^-$

3.8 pb



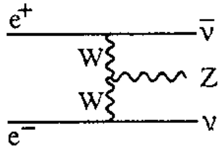
$e^+e^- \to We\nu$

1.4 pb



$e^+e^- \to ZZ$

1.3 pb



$e^+e^- \to Z\nu\bar{\nu}$

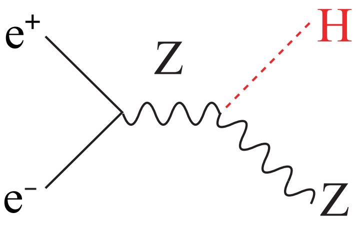
32 fb

- “Green” cross sections decrease like 1/s
  - ➨ “Purple” cross sections increase slowly with s

Add $e^+e^- \to t\bar{t}$
for $\sqrt{s}$ > 340 GeV

0.6 pb

- To be compared to

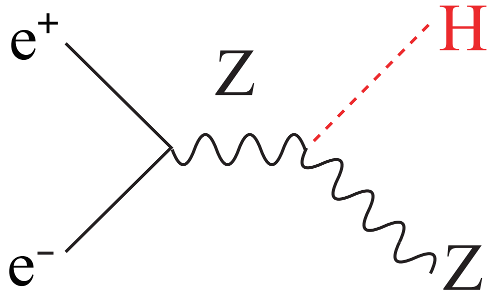


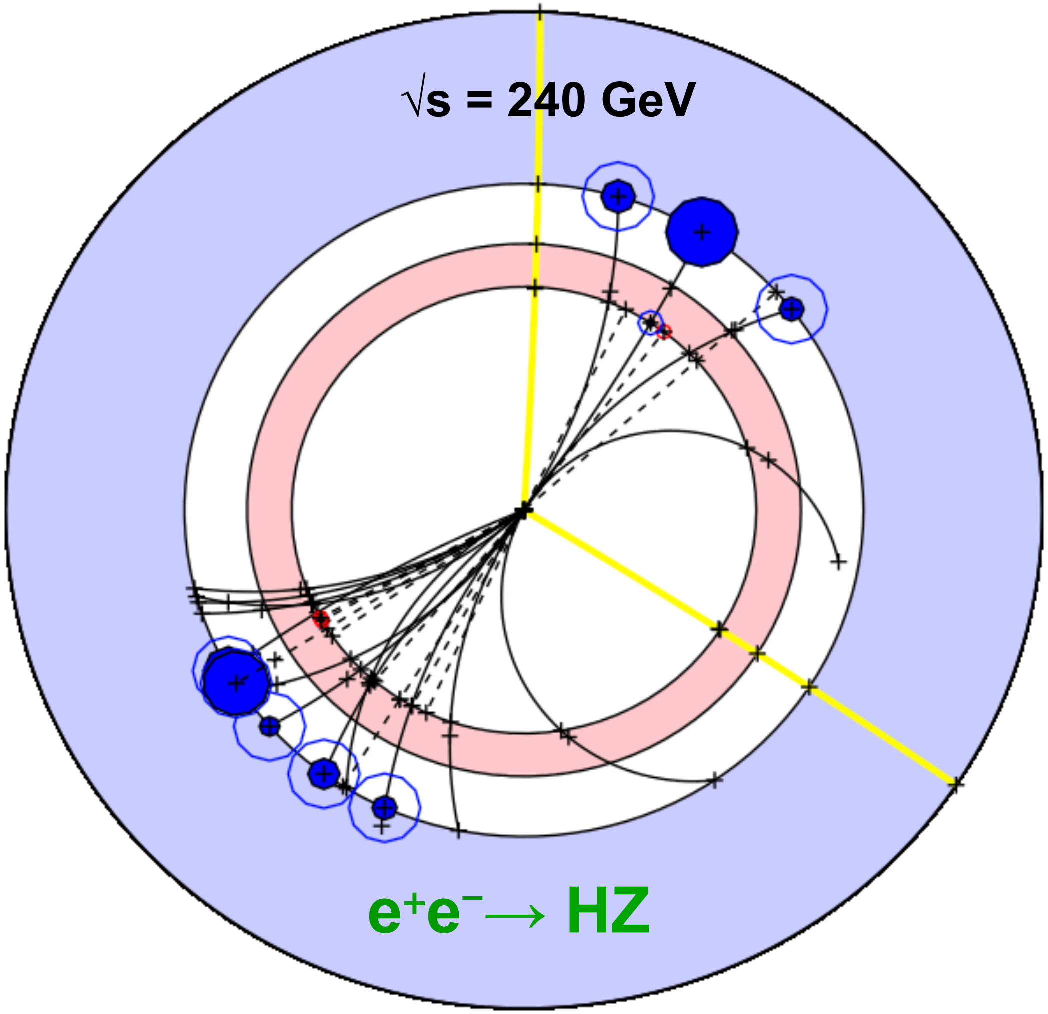
200 fb

- Only one to two orders of magnitude smaller
  - vs. 11 orders of magnitude in pp collisions
    - Trigger is 100% efficient (no need for trigger with ILC – all crossings are recorded)
    - All Higgs events are useful and exploitable
    - Signal purity is large

Precision Higgs physics at FCC-ee and ILC (4)

- **Example of a Higgs boson event**
  - Tagged with a Z boson
  - Very clean signature

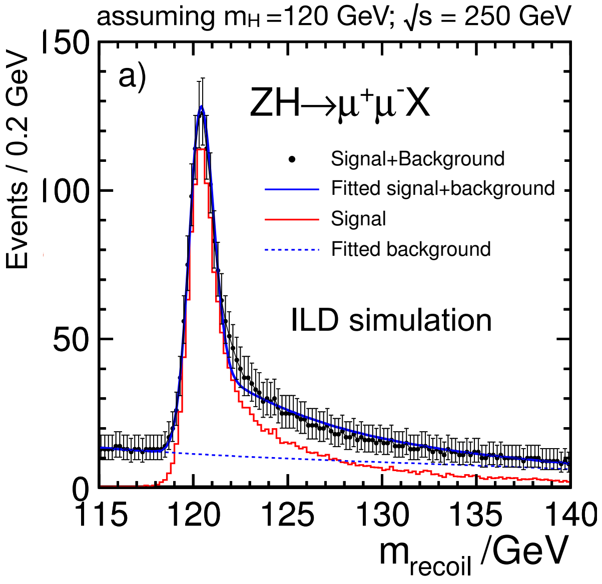




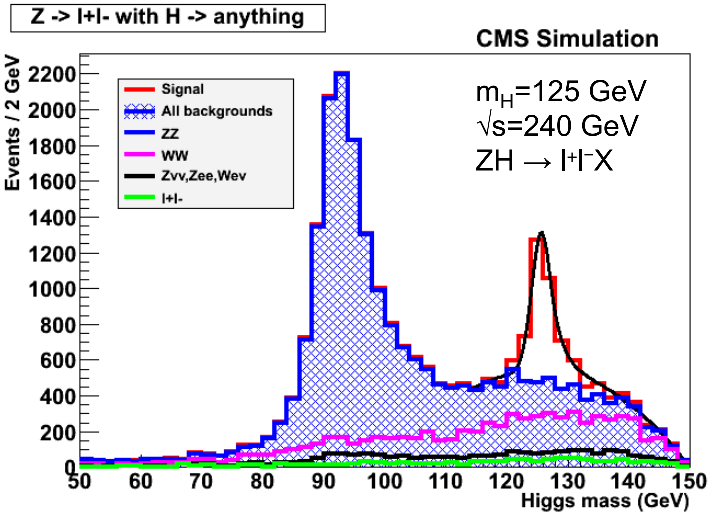
Precision Higgs physics at FCC-ee and ILC (5)

- **Example: Model-independent measurement of σ_{HZ} and κ_Z**
  - The Higgs boson in HZ events is tagged by the presence of the Z → e^+e^-, $\mu^+\mu^-$
    - Select events with a lepton pair (e^+e^-, $\mu^+\mu^-$) with mass compatible with m_Z
    - No requirement on the Higgs decays: measure $\sigma_{HZ} \times \mathrm{BR}(Z \to e^+e^-, \mu^+\mu^-)$
    - Apply total energy-momentum conservation to determine the "recoil mass"
      - $m_H^2 = s + m_Z^2 - 2\sqrt{s}\,(p_+ + p_-)$ Exercise !
    - Plot the recoil mass distribution – resolution proportional to momentum resolution

assuming m_H =120 GeV; $\sqrt{s}$ = 250 GeV



Z -> l+l- with H -> anything



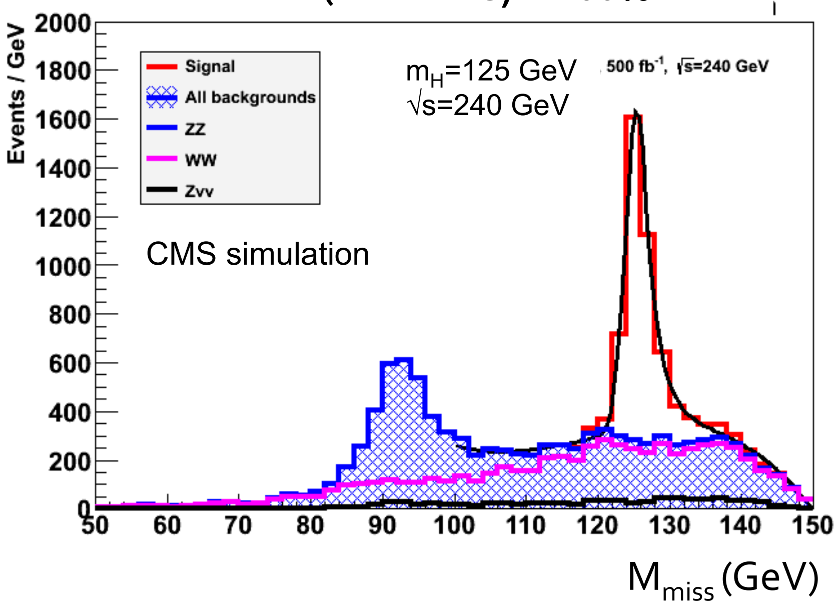
- Provides an absolute measurement of κ_Z and set required detector performance

Precision Higgs physics at FCC-ee and ILC (6)

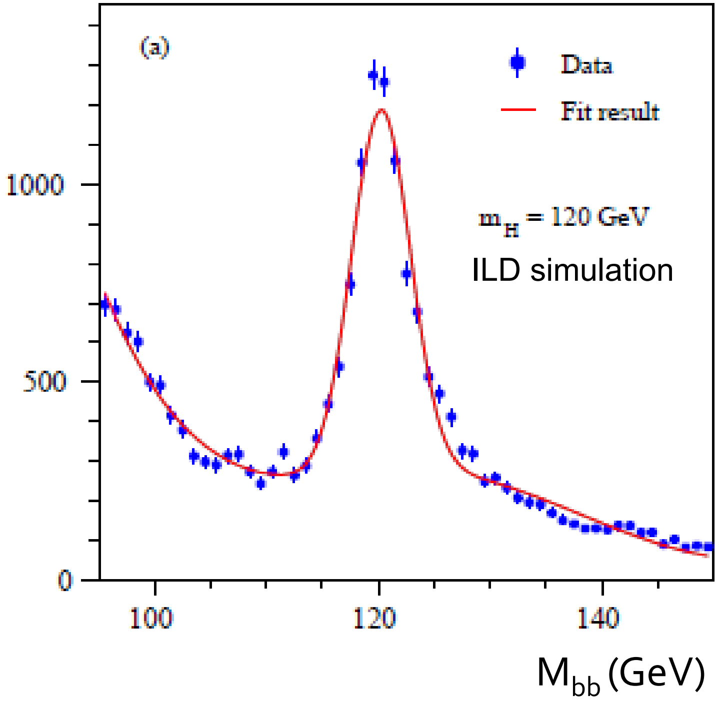
- Repeat the search in all possible final states
  - For all exclusive decays of the Higgs boson: measure σ_{HZ} × BR(H → YY)
    - Including invisible decays, just tagged by the presence of the lepton pair & m_{miss}
    - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics
  - For the WW fusion mode ($H\nu\bar{\nu}$ final state): measure $\sigma_{WW\to H}$ × BR(H → YY)

ZH → l^+l^- + nothing, 0.5 ab^{-1}

BR(H → invis) = 100%

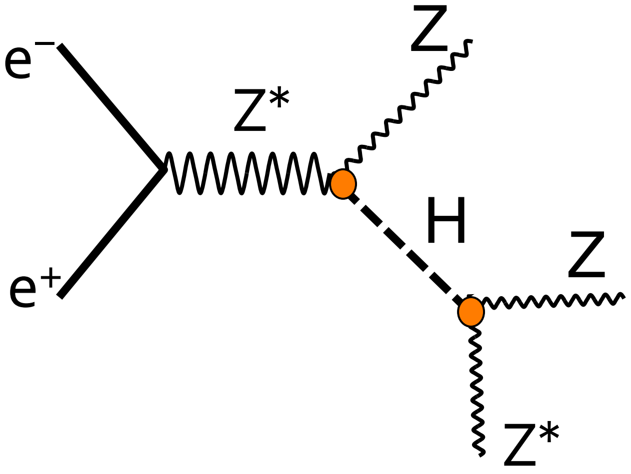


ZH → $q\bar{q}$ $b\bar{b}$, 0.25 ab^{-1}



Precision Higgs physics at FCC-ee and ILC (7)

- Indirect determination of the total Higgs decay width
  - From a counting of HZ events with H → ZZ at $\sqrt{s}$ = 240 GeV
    - Measure $\sigma_{HZ} \times \mathrm{BR}(H \rightarrow ZZ)$



Final state with three Z's
Almost background free

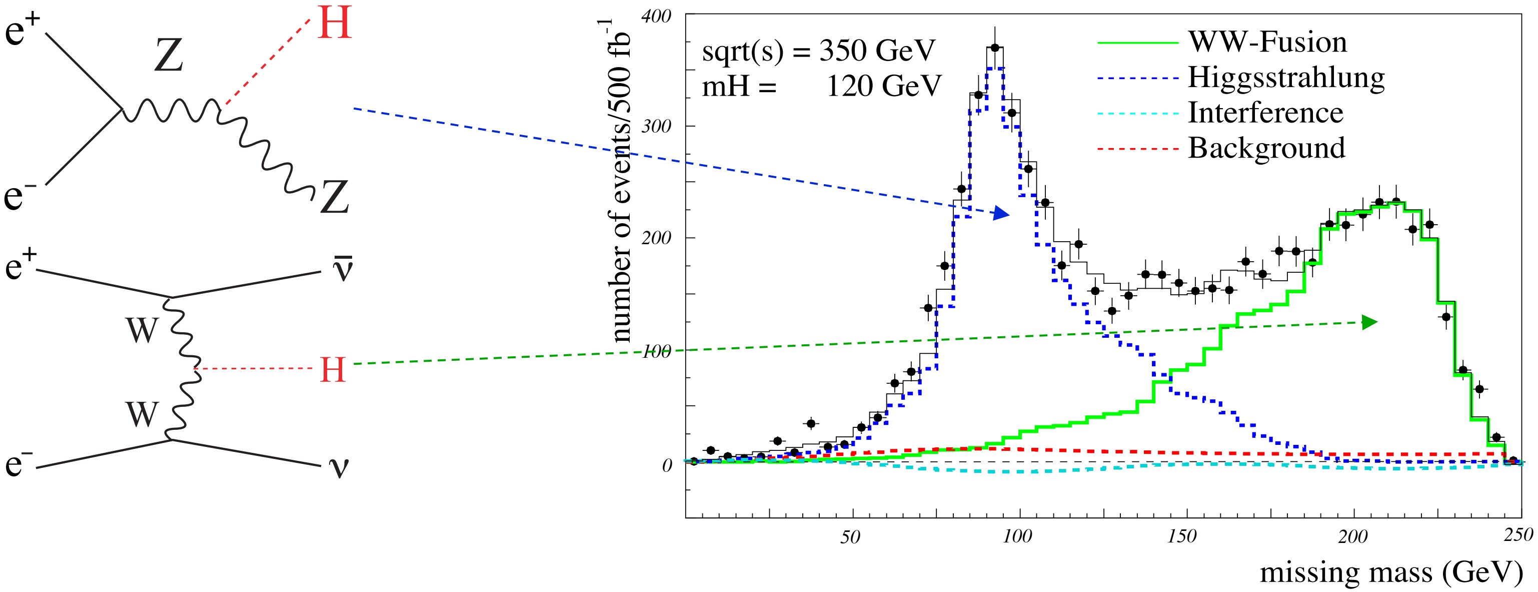
Measured with the Hl^+l^- final state
(see slide 23)

- σ_{HZ} is proportional to κ_Z^2
- $\mathrm{BR}(H \rightarrow ZZ) = \Gamma(H \rightarrow ZZ) / \Gamma_H$ is proportional to κ_Z^2/Γ_H
  - ➨ $\sigma_{HZ} \times \mathrm{BR}(H \rightarrow ZZ)$ is proportional to κ_Z^4 / Γ_H
- Infer the total width Γ_H

Precision Higgs physics at FCC-ee and ILC (8)

Indirect determination of the total Higgs decay width (cont'd)

- From a counting WW→ H→ $b\bar{b}$ events at 350-500 GeV in the $b\bar{b}\nu\bar{\nu}$ final state:



  - Measure σ(WW→ H→ bb)
  - Take the branching ratios into WW and bb from σ_{HZ} and $\sigma_{HZ}\times$ BR(H → WW,bb)
  - Infer the total width

$$\boxed{\Gamma_H \propto \sigma_{WW\to H} / \mathrm{BR}(H \to WW) = \sigma_{WW\to H\to bb} / \mathrm{BR}(H \to WW) \times \mathrm{BR}(H \to bb)}$$

Precision Higgs physics at FCC-ee and ILC (9)

- **Grand summary**
  - Results from a model-independent determination of the couplings
    - Mostly from measurements of σ_{HZ}, $\sigma_{HZ}\times BR(H \rightarrow YY)$, and Γ_H

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

The 10B$ ILC, 13 years
1-10% precision

FCC-ee, 6 years
0.1-1% precision

Precision Higgs physics at FCC-ee and ILC (10)

- **Comparison with LHC**

Coupling	HL-LHC	ILC	FCC-ee
κ_W	2-5%	0.8%	0.19%
κ_Z	2-4%	0.6%	0.15%
κ_b	4-7%	1.5%	0.42%
κ_c	–	2.7%	0.71%
κ_τ	2-5%	1.9%	0.54%
κ_μ	~10%	20%	6.2%
κ_γ	2-5%	7.8%	1.5%
κ_g	3-5%	2.3%	0.8%
$\kappa_{Z\gamma}$	~12%	?	?
BR_{invis}	~10-15%?	< 0.5%	< 0.1%
Γ_H	~50%?	3.8%	0.9%
κ_t	7-10%	18%	13% (*)
κ_H	30-50% ?	77%	80%(*)

(*) indirect

Model-independent results

Sensitive to new physics at tree level
Expected effects < 5% / Λ^2_{NP}
1% precision needed for Λ_{NP}~1TeV
Sub-percent needed for Λ_{NP}>1TeV

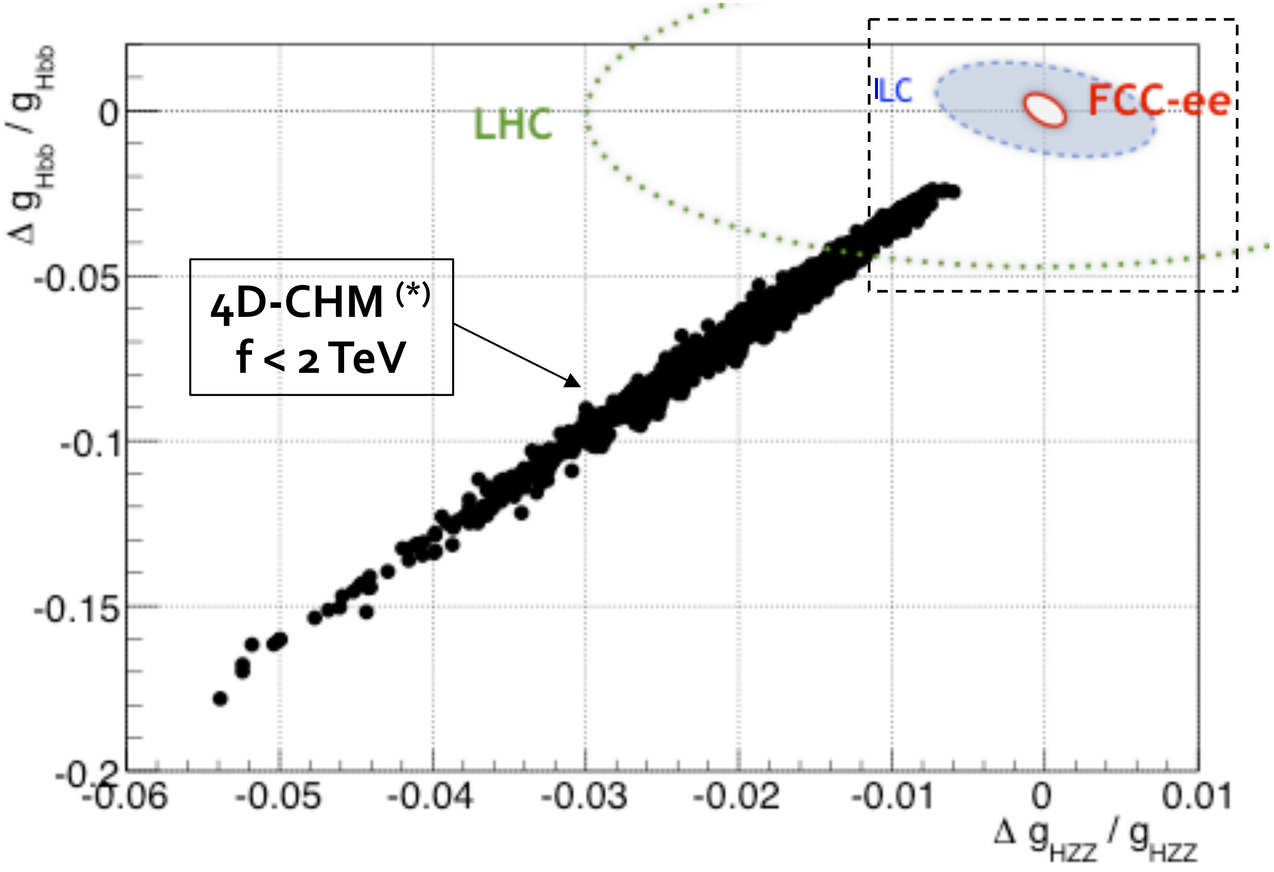
Sensitive to new physics in loops

Sensitive to light dark matter (sterile ν, χ, …)
and to other exotic decays

Need higher energy to improve on LHC

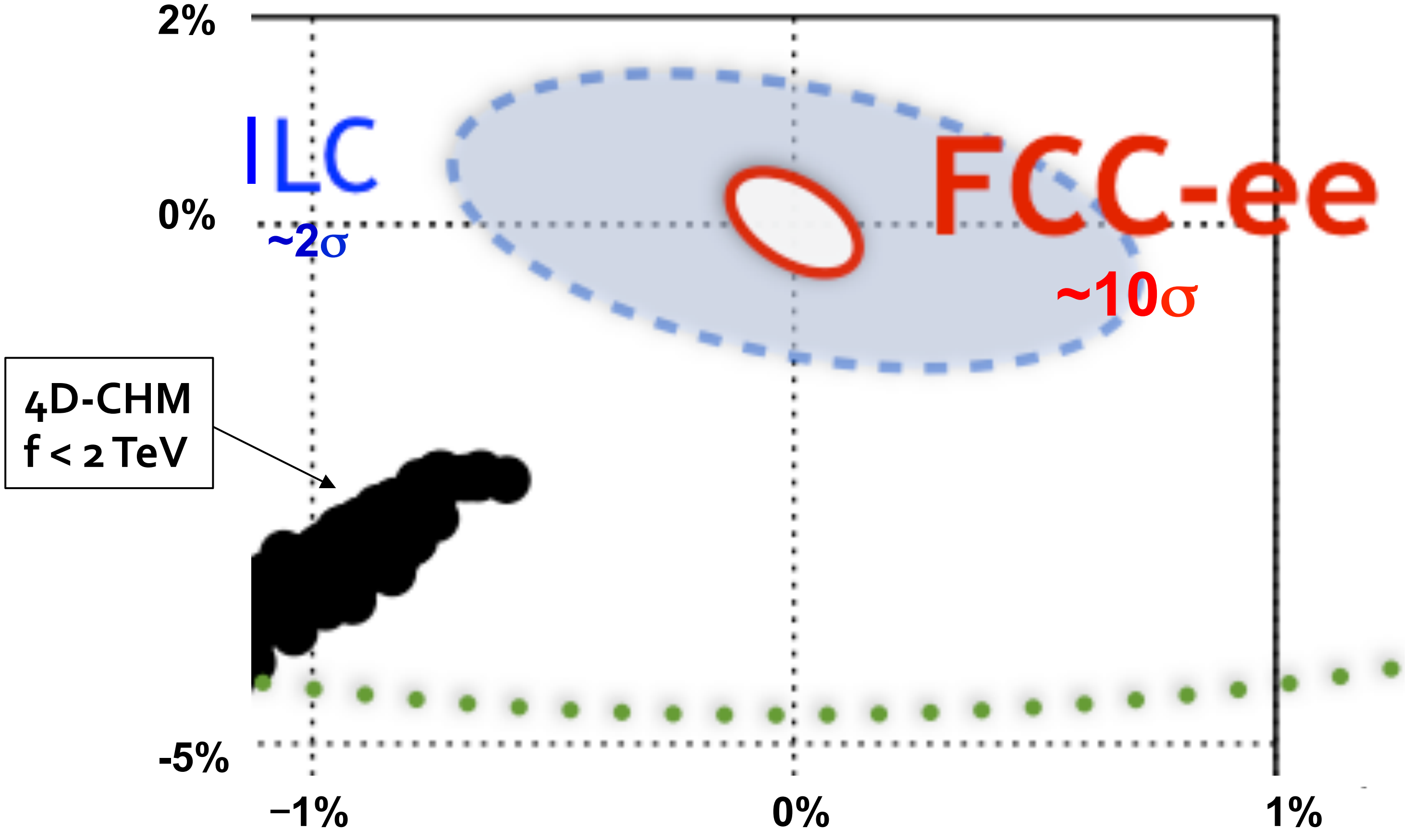
Precision Higgs physics at FCC-ee and ILC (11)

- **Higgs couplings are affected by new physics**
  - **Example: Effect on κ_Z and κ_b for 4D-Higgs Composite Models**



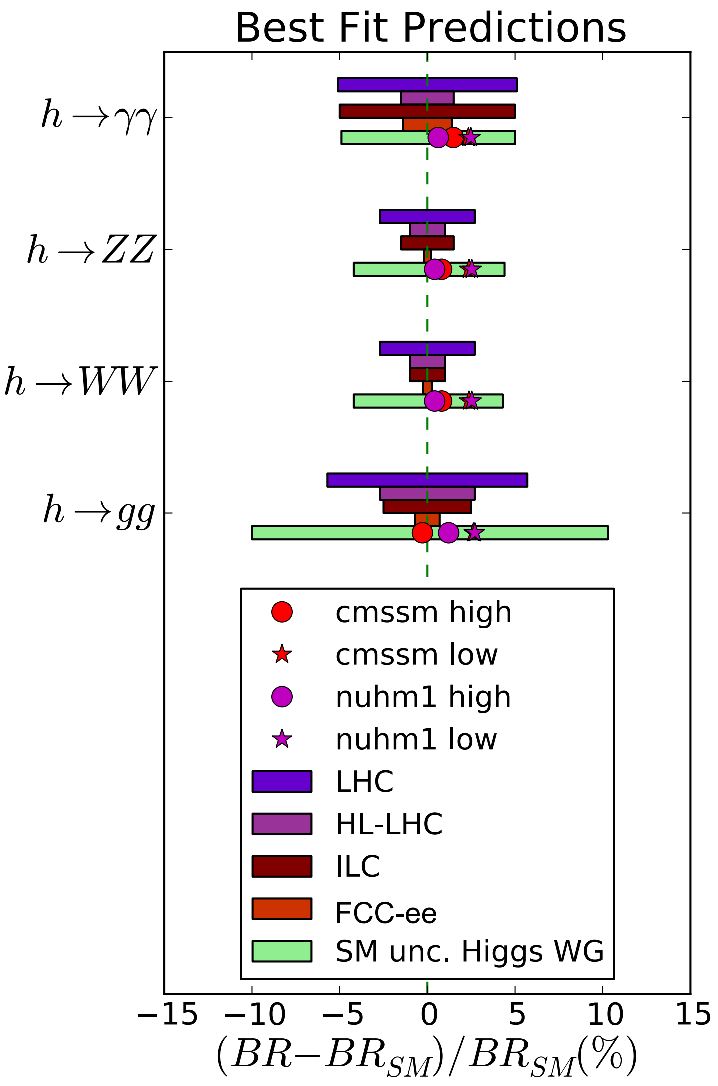
Precision Higgs physics at FCC-ee and ILC (11)

- Higgs couplings are affected by new physics
  - Example: Effect on κ_Z and κ_b for 4D-Higgs Composite Models



Precision Higgs physics at FCC-ee and ILC (12)

- **Sensitivity to new physics (example)**
  - Compare the difference between the predictions of a few simple SUSY models and the SM for a few Higgs branching fractions
    - With LHC, HL-LHC, ILC and FCC-ee expected precision
    - With the current SM prediction uncertainties
  - Basic messages
    - The statistics proposed by the FCC-ee are needed to distinguish these SUSY models from the Standard Model
    - The SM theoretical uncertainties (dominated by QCD) must be reduced to match the experimental potential
      - ➨ Feasible by FCC-ee / ILC timescales ?



Precision electroweak physics at FCC-ee (1)

Reminder: The FCC-ee goals in numbers (after commissioning)

√s (GeV)	Running time	FCC-ee Statistics	ILC	LEP
91	0.3 (2.5) year	10^{12} (10^{13}) Z decays (Tera Z)	10^{9} (*)	2×10^{7}
161	1 year	10^{8} WW pairs (Oku W)	10^{6} (*)	4×10^{4}
350	2 years	10^{6} top pairs (Mega Top)	10^{5}	–

(*) Estimate: not in the core programme

- FCC-ee is the ultimate Z, W, Higgs and top factory
  - 10 to 10,000 times the ILC targeted statistics at the same energies
  - 10^5 more Z's and 10^4 more W's than LEP1 and LEP2
    - ➨ Potential statistical accuracies are mind-boggling !

- It is the tool of choice for precision electroweak physics

Precision electroweak physics at FCC-ee (2)

- The Z line-shape measurement with TeraZ
  - Repeat the LEP1 programme every 15 minutes !
    - Remember, after 5 years at LEP:

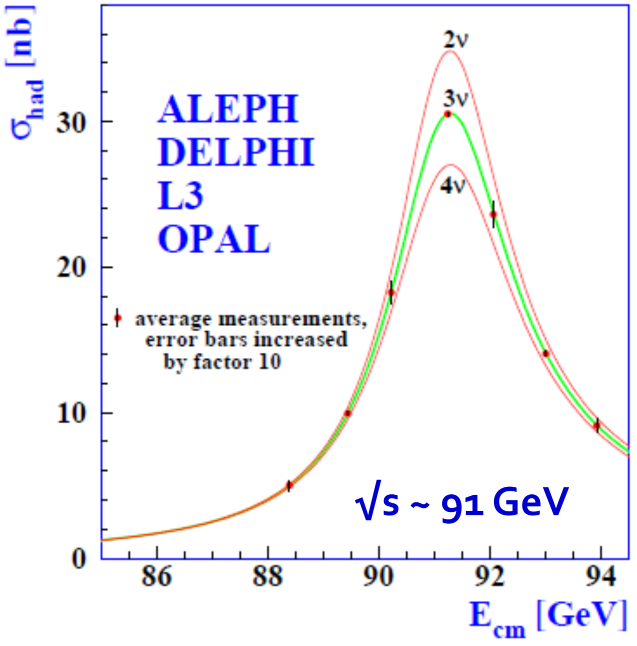
N_ν = 2.984 ± 0.008

Γ_Z = 2495.2 ± 2.3 MeV

m_Z = 91187.5 ± 2.1 MeV

R_l = 20.767 ± 0.025

α_S = 0.1190 ± 0.0025



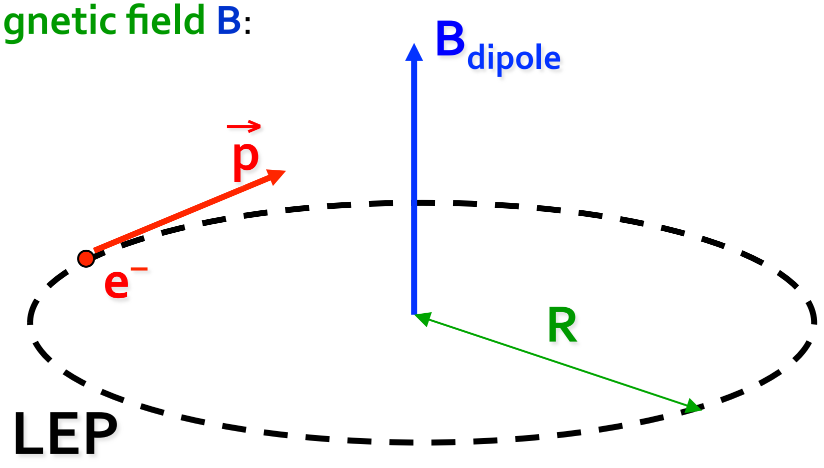
- Predicting accuracies with 300 times smaller statistical precision than at LEP is difficult
  - Conservatively used LEP experience for systematics. This is just the start.

- Example: The uncertainty on E_{BEAM} (2 MeV) was the dominant uncertainty on m_Z, Γ_Z
  - Can we do significantly better at FCC-ee ?

Precision electroweak physics at FCC-ee (3)

- **Measurement of the beam energy at LEP**
  - Ultra-precise measurement unique to circular colliders (crucial for m_Z, Γ_Z)

Electron with momentum **p** in a uniform vertical magnetic field **B**:



L = 2πR = 27km

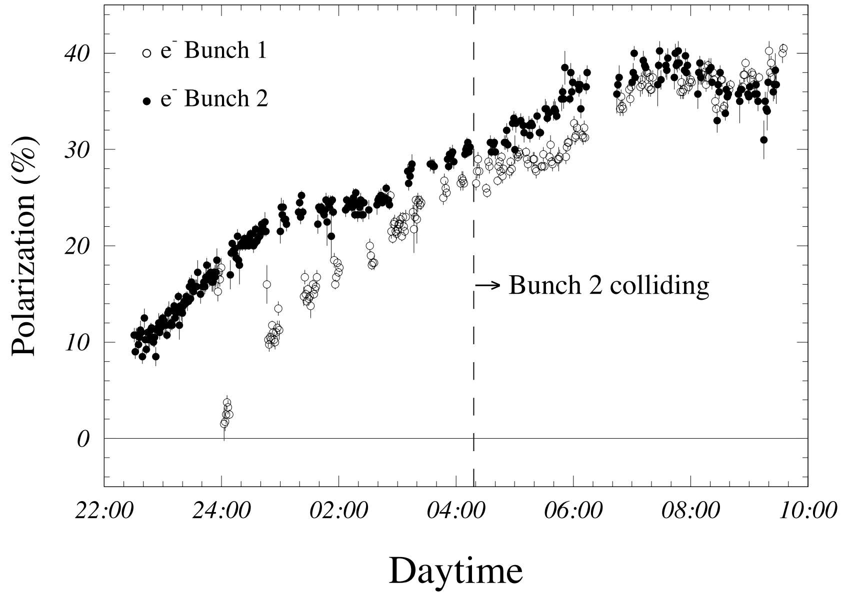
$$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$$

In real life, B non uniform, LEP ring not circular

$$\boxed{E = \frac{e}{2\pi}\oint_{\rm LEP} B\,\mathrm{d}l}$$

To be measured

The electrons get transversally polarized (i.e., their spin tends to align with **B**)



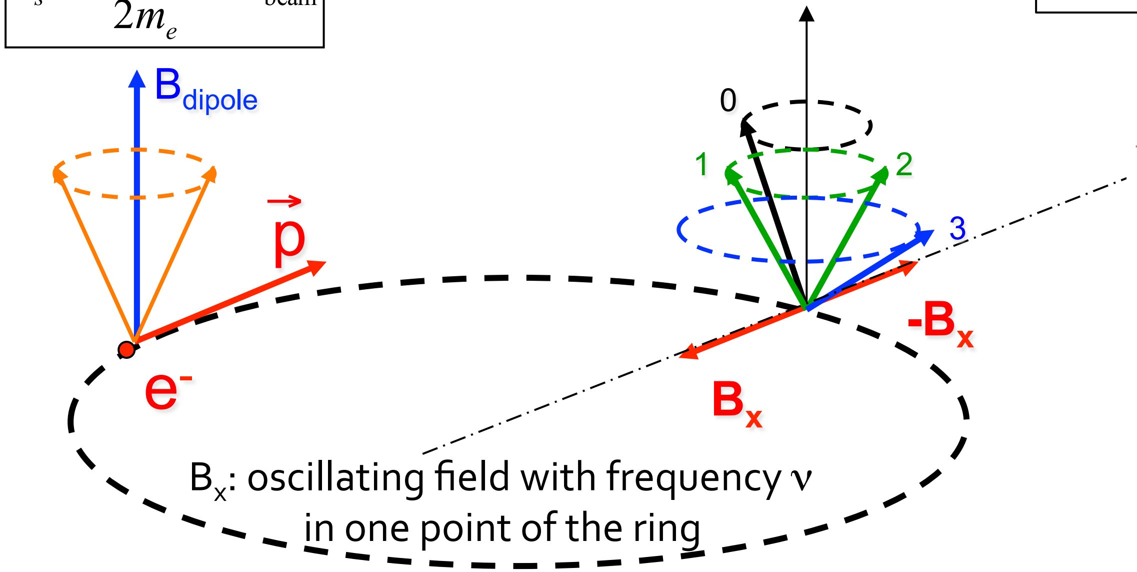
Slow process (~ 1 hour to get 10% polarization)

NB. Polarization can be kept in collision (was tried only once at LEP).

Precision electroweak physics at FCC-ee (4)

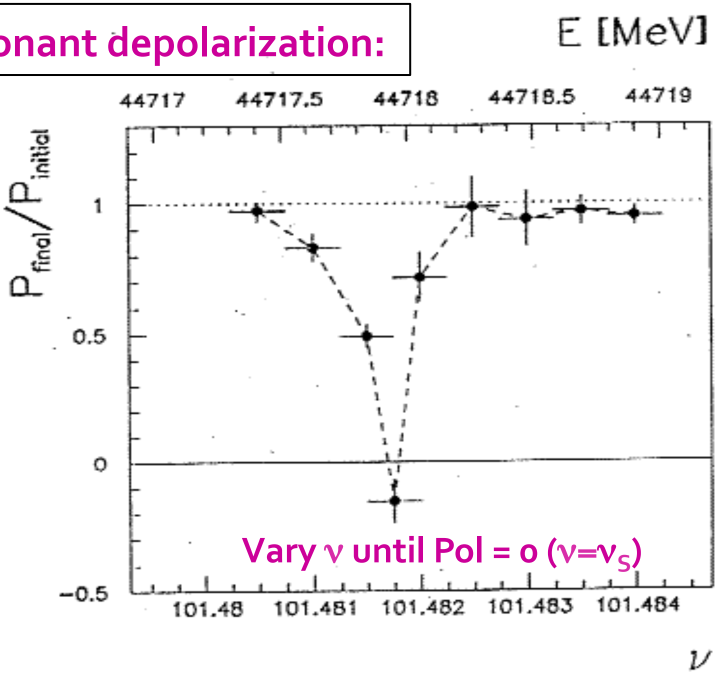
- **Measurement of the beam energy at LEP (cont'd)**
  - **The spin precesses around B with a frequency proportional to B (Larmor precession)**
    - **Hence, the number of revolutions ν_S for each LEP turn is proportional to BL (or $\int$Bdl)**

$$\nu_s = \frac{g_e - 2}{2m_e} \times E_{\text{beam}}$$



B_x: oscillating field with frequency ν in one point of the ring

Resonant depolarization:



Vary ν until Pol = 0 ($\nu=\nu_S$)

- **Resonant intrinsic precision of the method ΔE_{beam}<100 keV !**
  - **However, m_Z and Γ_Z measured at LEP with a precision of 2.2 MeV ...**
    - ➨ **Extrapolation uncertainty from measurements performed w/o collisions**

Precision electroweak physics at FCC-ee (5)

- **Measurement of the beam energy at the FCC-ee**
  - **LEP was colliding 4 bunches of e^+ and e^-; FCC-ee will have 10,000's of bunches.**
  - **Use ~100 "single" bunches to measure E_{BEAM} with resonant depolarization**
    - **Each measurement gives 100 keV precision, with no extrapolation uncertainty**
- **Examples of targeted accuracy**

m_Z to < 100 keV!

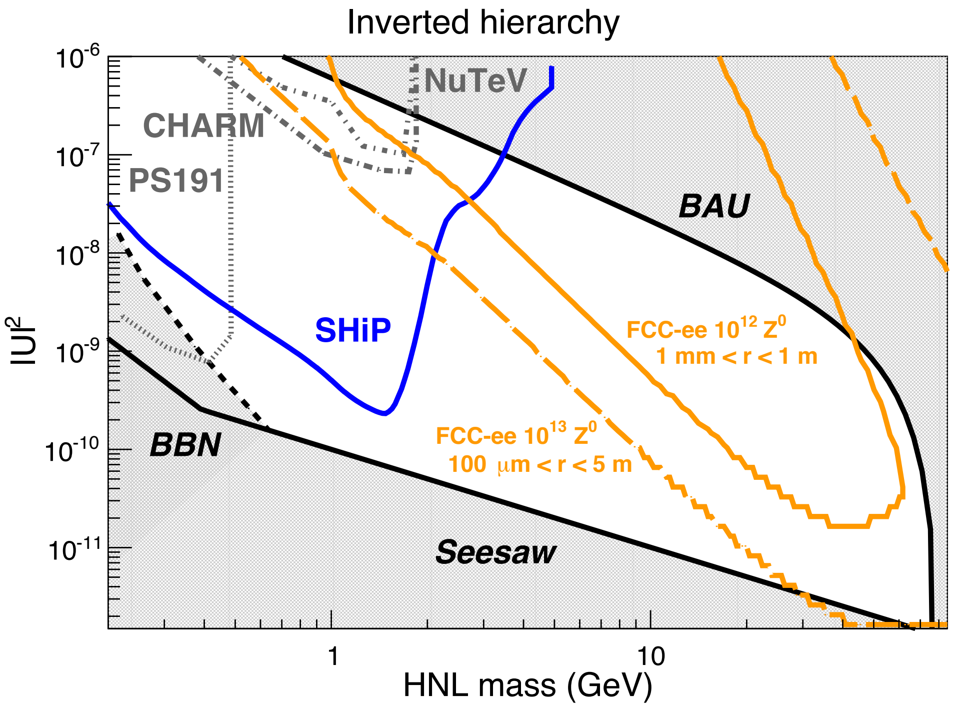
Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_Z (MeV)	Lineshape	91187.5 **± 2.1**	**0.005**	**< 0.1**	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 **± 2.3**	**0.008**	**< 0.1**	QED corr.
R_l	Peak	20.767 **± 0.025**	**0.0001**	**< 0.001**	Statistics
R_b	Peak	0.21629 **± 0.00066**	**0.000003**	**< 0.00006**	$g \rightarrow bb$
N_ν	Peak	2.984 **± 0.008**	**0.00004**	**< 0.004**	Lumi meast
$A_{FB}^{\mu\mu}$	Peak (Peak±3)	0.0171 **± 0.0010**	**0.000004**	**<0.00001**	E_{BEAM} meast
$\alpha_s(m_Z)$	R_l	0.1190 **± 0.0025**	**0.00001**	**0.0001**	New Physics

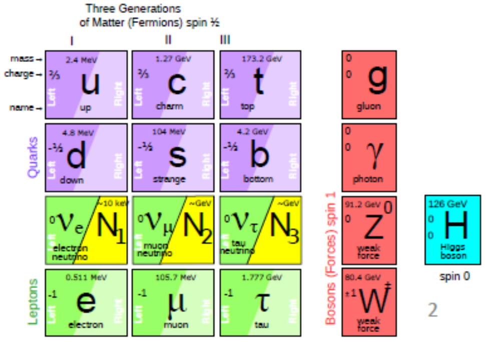
Precision electroweak physics at FCC-ee (6)

- Opportunities for direct searches for new physics through rare decays
  - 10^{12} (10^{13}) Z, 10^{11} b, c or τ : A fantastic potential that remains to be explored.
  - E.g, search for right-handed neutrino in Z decays

$$\boxed{Z \rightarrow N\nu_i, \text{ with } N \rightarrow W^{*}l \text{ or } Z^{*}\nu_j}$$

- Number of events depend on mixing between N and ν, and on m_N



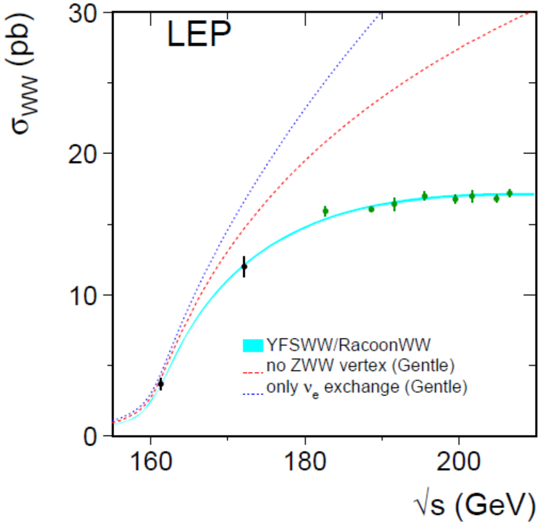


Precision electroweak physics at FCC-ee (7)

- **Oku-W: 10^8 WW events at production threshold**

Measurement of the W mass

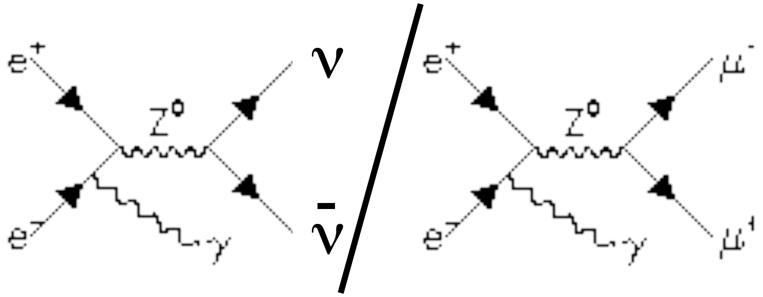
with cross section at threshold



Measurement of the number of neutrinos

(with single photon events)

$$N_\nu \sim \sigma(e^+e^- \to \nu\bar{\nu}\gamma) / 2\sigma(e^+e^- \to \mu^+\mu^-\gamma)$$



m_W to < 500 keV!

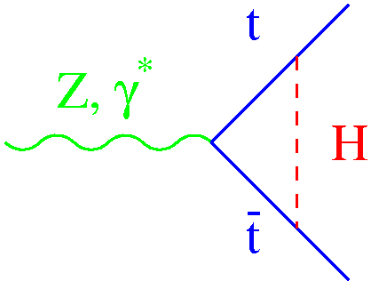
Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_W (MeV)	Threshold scan	80385 **± 15**	**0.3**	**< 0.5**	QED Corr.
N_ν	Radiative returns $e^+e^-\to\gamma Z$, $Z\to\nu\nu$, ll	2.92 **± 0.05** 2.984 **± 0.008**	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 **± 0.27**	**0.00018**	**< 0.0001**	CKM Matrix

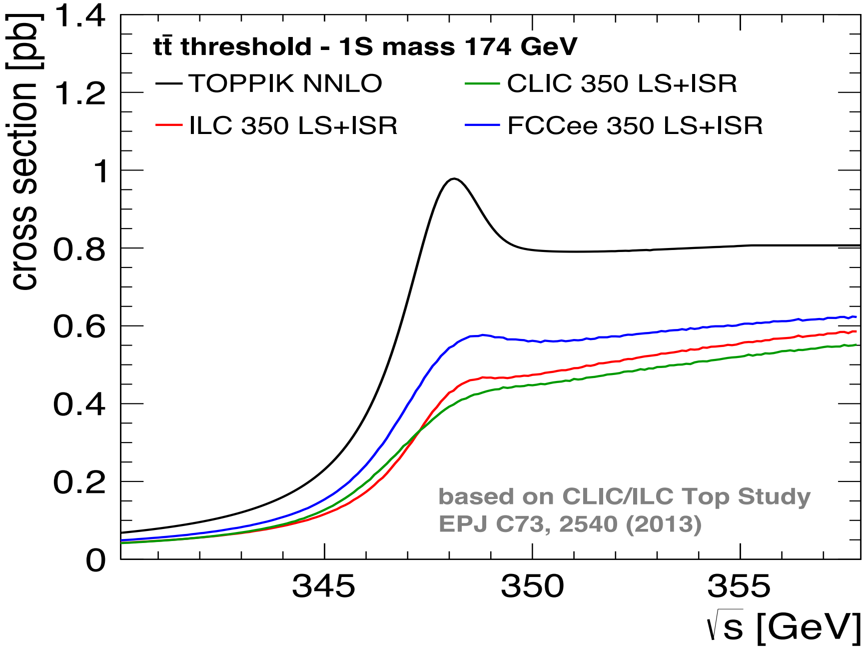
Precision electroweak physics at FCC-ee (8)

- **Mega-top: a million $t\bar{t}$ events at threshold**
  - **Measure top quark mass and width**
    - **From cross section at threshold**

      10 x the ILC statistics

      No beamstrahlung systematics
  - **Measure the top Yukawa coupling**





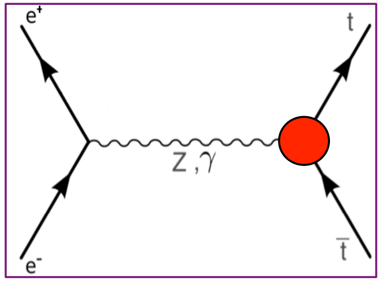
based on CLIC/ILC Top Study
EPJ C73, 2540 (2013)

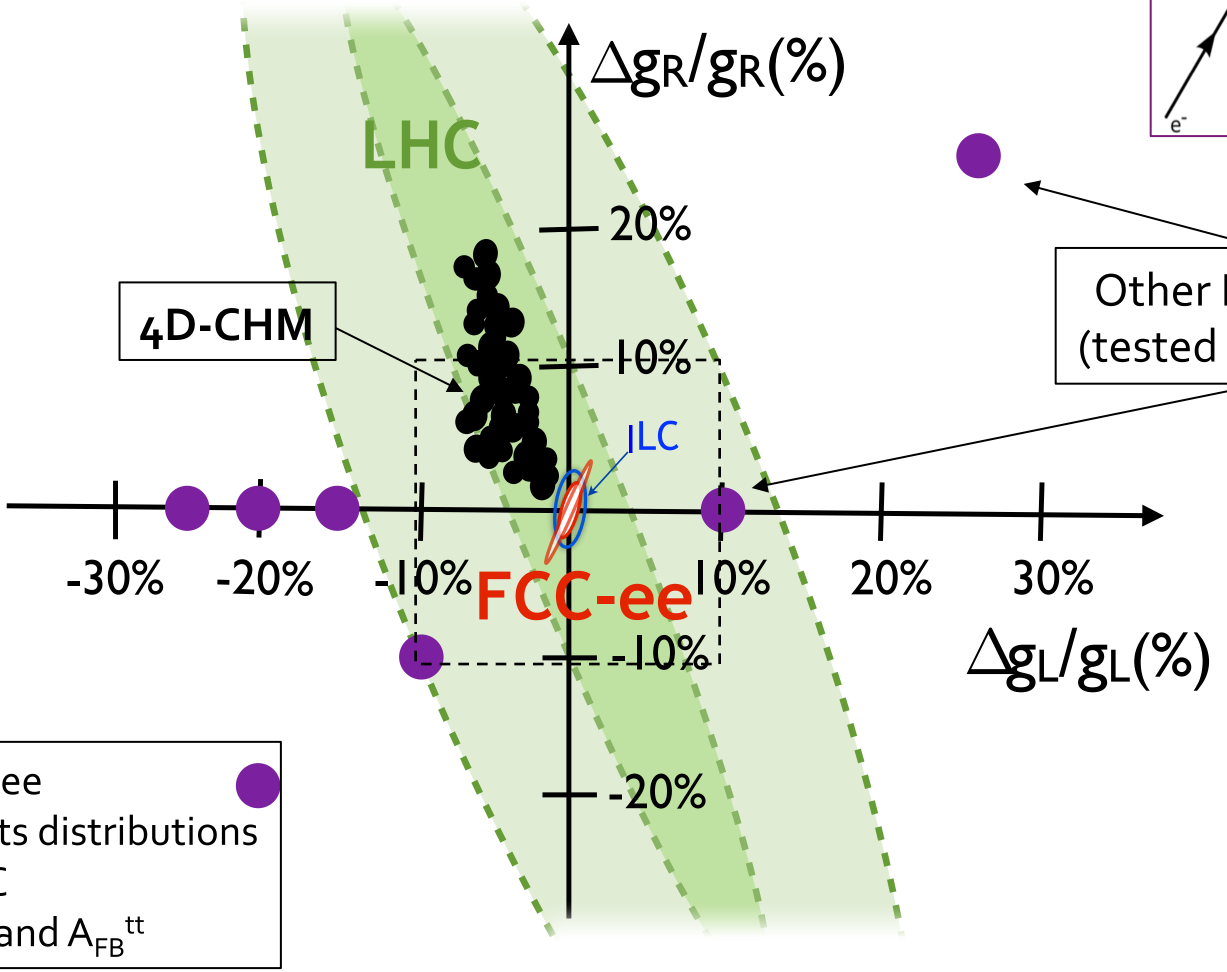
m_{top} to 10 MeV!

Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_{top} (MeV)	Threshold scan	173200 **± 900**	**10**	**10**	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	**?**	**12**	**?**	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 **± 1.05**	**13%**	**?**	$\alpha_s(m_Z)$

Precision electroweak physics at FCC-ee (9)

- **Measurements of $t_L t_L Z$ and $t_R t_R Z$ couplings, g_L and g_R**
  - **Couplings most sensitive to, e.g., composite Higgs models**



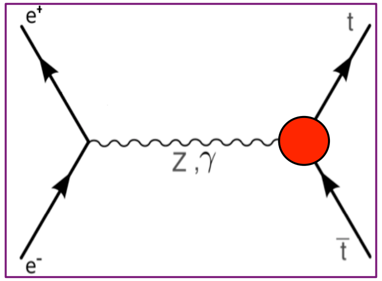


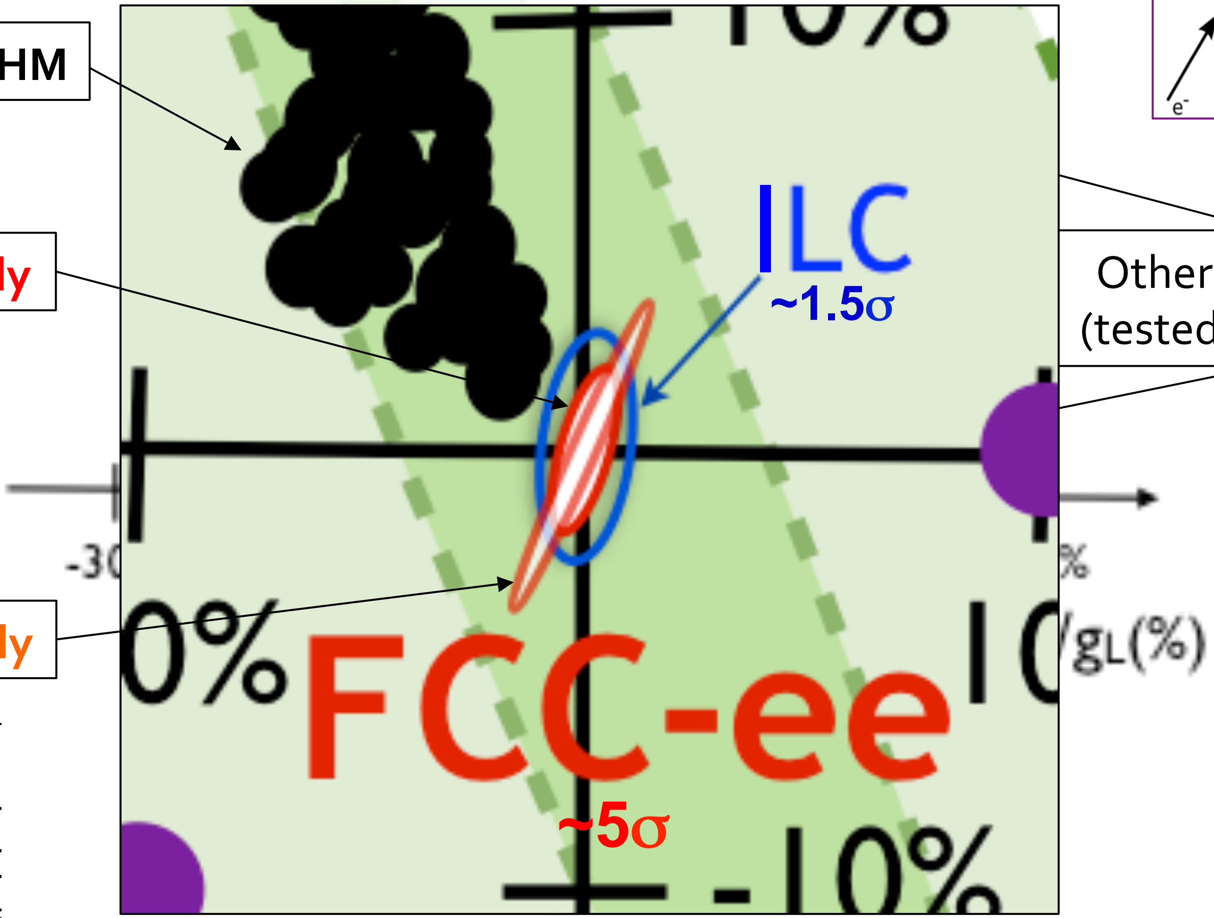
Other NP models
(tested at the LHC)

FCC-ee ●
Leptons and b-jets distributions
ILC
Total rate and A_{FB}^{tt}

Precision electroweak physics at FCC-ee (9)

- **Measurements of $t_L t_L Z$ and $t_R t_R Z$ couplings, g_L and g_R**
  - Couplings most sensitive to composite Higgs models





4D-CHM

b-jets only

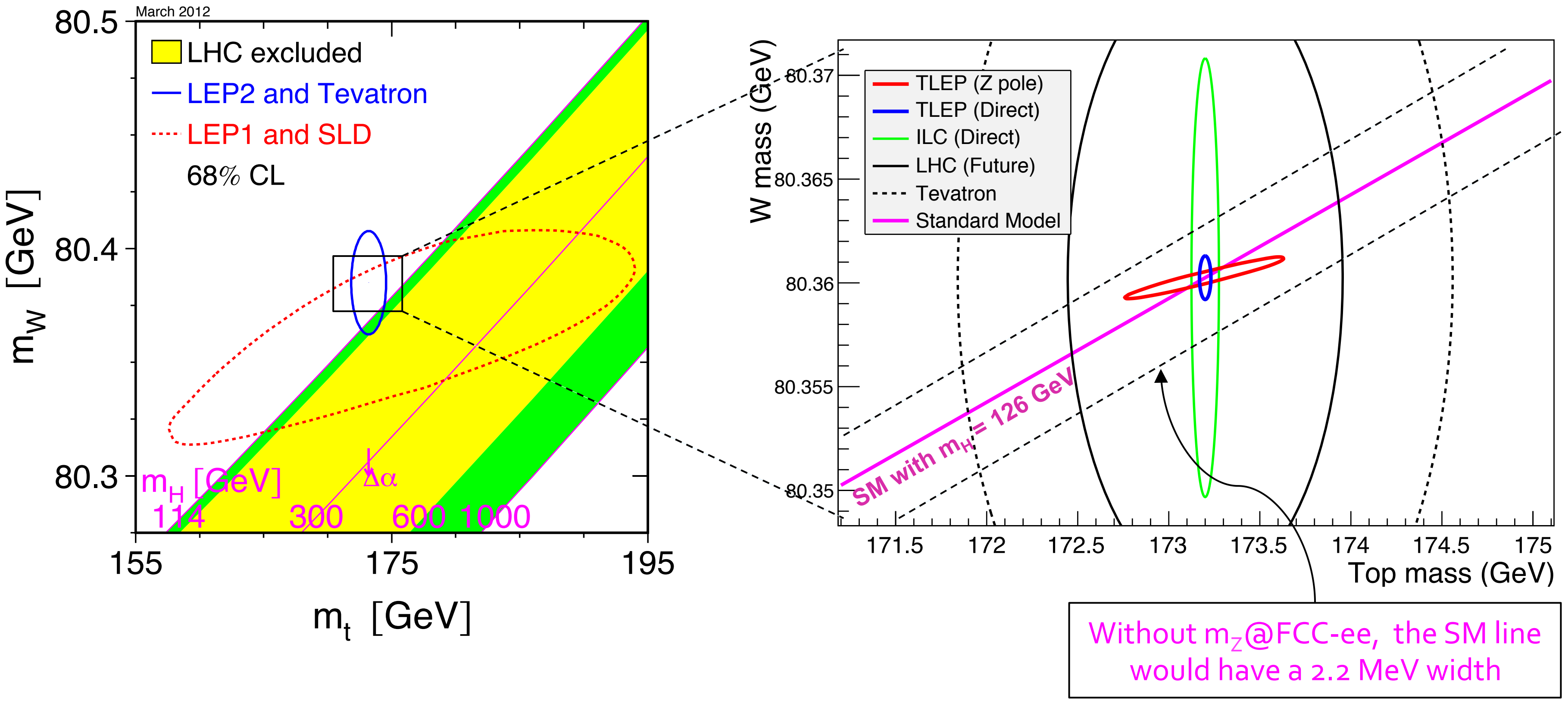
Leptons only

Other NP models (tested at the LHC)

FCC-
Leptons and b-je
ILC
Total rate and A_{FB}

Precision electroweak physics at FCC-ee (10)

- **Combination of all precision electroweak measurements**
  - **In absence of new physics, the (m_{top}, m_W) plot would look like this**



Without m_Z@FCC-ee, the SM line would have a 2.2 MeV width

  - **Constraints on new physics ?**

Precision electroweak physics at FCC-ee (11)

- **Higher-dimensional operators as relic of new physics ?**
  - **Possible corrections to the standard model**

$$L_{\mathrm{eff}} = \sum_n \frac{c_n \mathrm{v}^2}{\Lambda^2} O_n$$

$$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

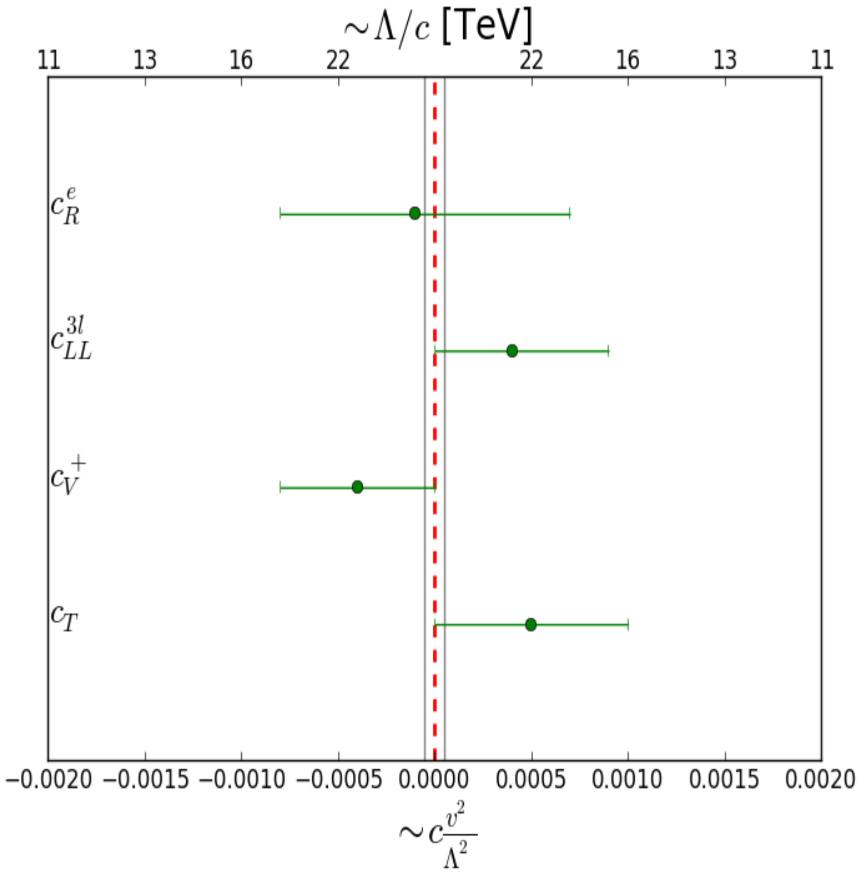
$$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

LEP constraints: $\Lambda_{\mathrm{NP}} > 10$ TeV



Precision electroweak physics at FCC-ee (11)

- **Higher-dimensional operators as relic of new physics ?**
  - **Possible corrections to the standard model**

$$L_{\text{eff}} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$

$$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

$$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

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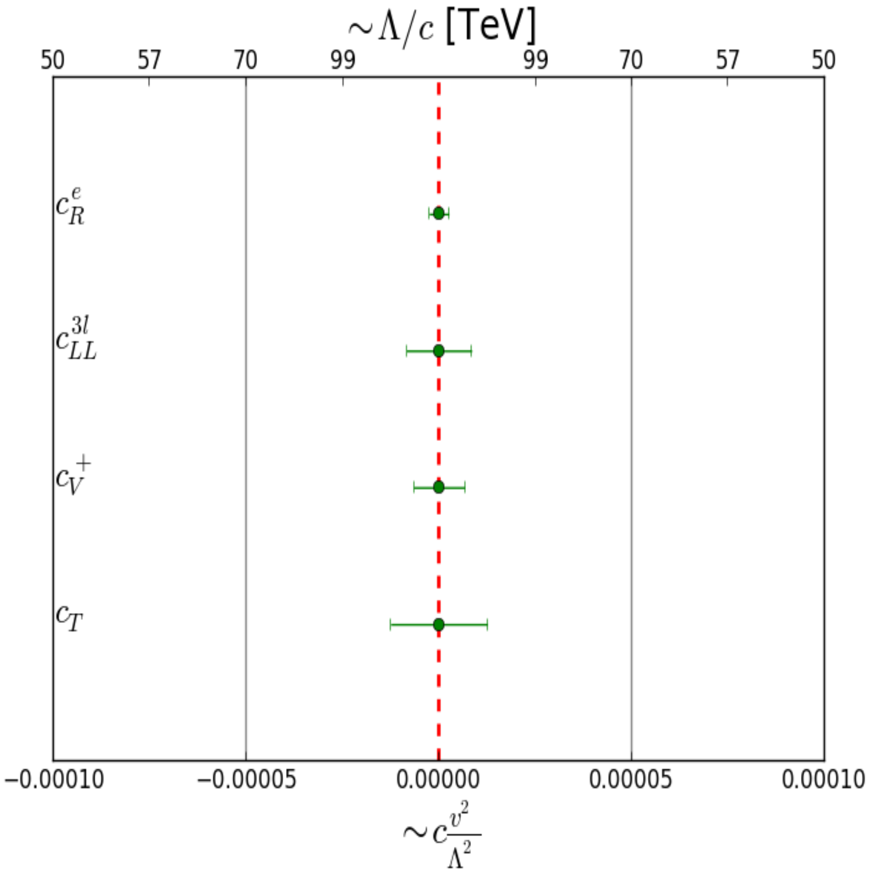
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

LEP constraints: $\Lambda_{\text{NP}} > 10$ TeV

After FCC-ee: $\Lambda_{\text{NP}} > 100$ TeV ?

Sensitivity to
Weakly-coupled NP



Matches well with the FCC-hh new physics reach

Precision electroweak physics at FCC-ee (12)

Theoretical uncertainties

- Today's measurements of m_Z, m_{top}, m_H, $\alpha_{QED}(m_Z)$ and $\alpha_S(m_Z)$ and lead to the predictions

$$\begin{aligned} m_{\mathrm{W}} &= 80.361 \pm 0.006 \pm 0.004\ \mathrm{GeV}, \\ \sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} &= 0.23152 \pm 0.00005 \pm 0.00005, \end{aligned}$$

OK for ILC, but …
5-10 × FCC-ee
exp'tal uncertainties

- First uncertainty is parametric, and arises from experimental uncertainties
  - ➨ Will need to reduce uncertainties on m_Z, m_{top}, α_{QED} and α_S by a factor 10

    m_Z, m_{top}, $\alpha_S(m_Z)$ and $\alpha_{QED}(m_Z)$ will be addressed by FCC-ee measurements

- Second uncertainty comes from the lack of higher-order electroweak corrections
  - ➨ Will need order of magnitude improvement here too
  - ➨ Requires a new generation of electroweak calculations to higher orders

    Beyond the state of the art today …

    May be within reach on the time scale required by FCC-ee
  - ➨ Until recently, theory efforts were motivated by the precision needed by ILC

    The FCC-ee brings an entirely renewed ambition towards better results

Precision with e^+e^- colliders: Summary (1)

- The small mass of the Higgs boson allows two options to be contemplated
  - A 250 – 500 GeV linear collider: ILC (also CLIC at $\sqrt{s}$ = 380 GeV)
  - A 90-400 GeV circular collider: FCC-ee (also CEPC at $\sqrt{s}$ = 240 GeV)

- Precision measurements at the EW scale are sensitive to new physics
  - To potentially very high scales (up to ~100 TeV with FCC-ee)
  - To potentially very small couplings (sterile neutrinos, dark matter, …)
    - Through a study of the Z, W, H, and top properties with unprecedented statistics

- Both options will be technologically / politically / financially challenging
  - But can potentially be ready for collisions in the 2030's
    - Go through the slides again to form a personal opinion – at this level – of the scientific capabilities of each option

- Access to the high-energy frontier is essential to evaluate these options
  - The likelihood of new physics below 1 TeV has reduced considerably with LHC Run1
    - An new evaluation will have to be made after LHC Run2
      - ➨ High-energy frontier capabilities discussed in 3rd lecture

Precision with e^+e^- colliders: Summary (2)

ARGUE & DEBATE !