Physics at Future Colliders

- **Lecture 1 (Thursday 28 July, 10:20)**
  - 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 (Friday 29 July, 9:15)**
  - The quest for precision (2030-2050): Linear or Circular ?

- **Lecture 3 (Friday 29 July, 10:20)**
  - The energy frontier (2045-2080): Leptons or Hadrons ?
  - Thinking out of the box: Muon collider
  - Towards the next European Strategy update (2019-2020)

Mid-term perspectives (2030-2050)

The quest for precision: Linear or Circular ?

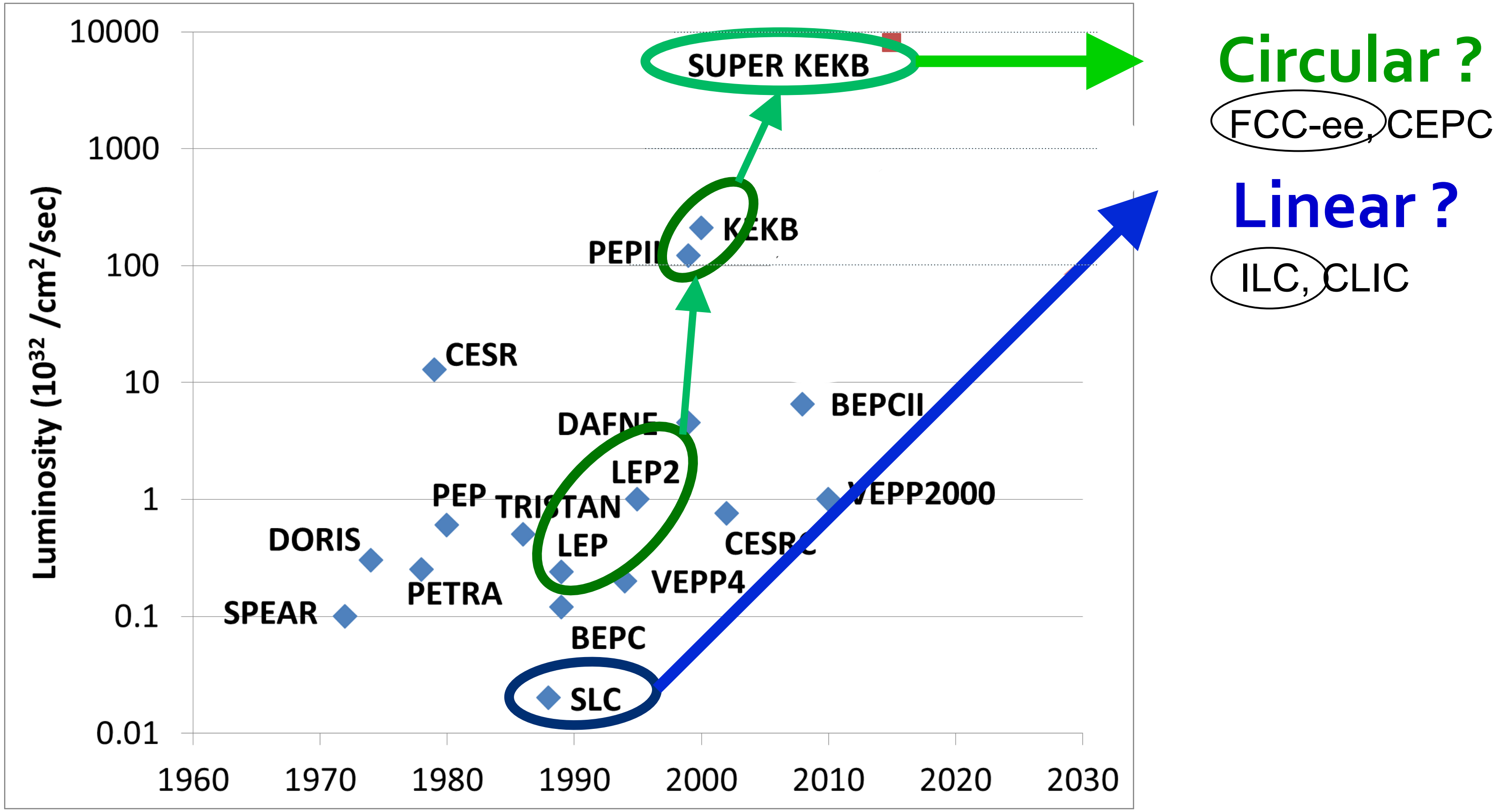
FCC (100 km)

First step: FCC-ee (88-370GeV)

[Use the tunnel ultimately aimed at FCC-hh]

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

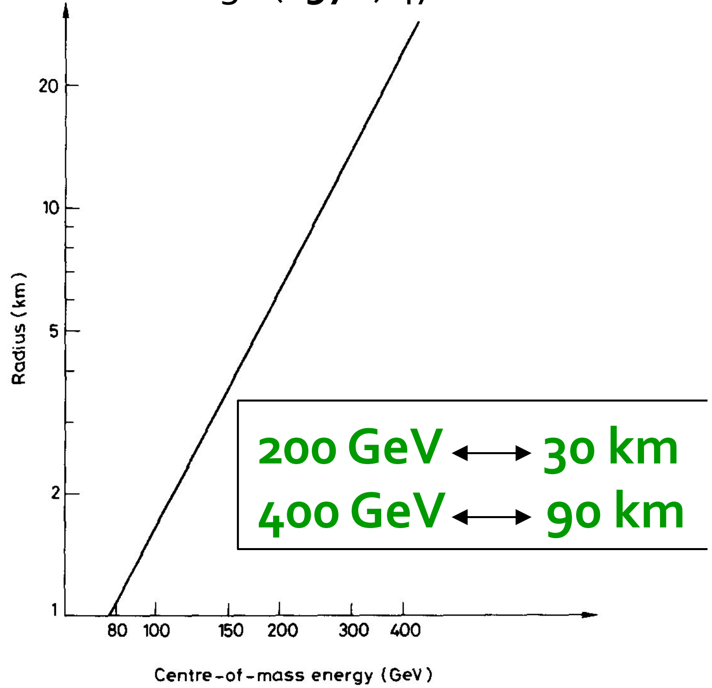
- Historically, e^+e^- colliders have been used for precision measurements
  - The accuracy of e^+e^- colliders led to predictions at higher scales (m_{top}, m_H, limits on NP)
    - And to [unexpected] discoveries (e.g., c, g, τ, ν_τ ...)



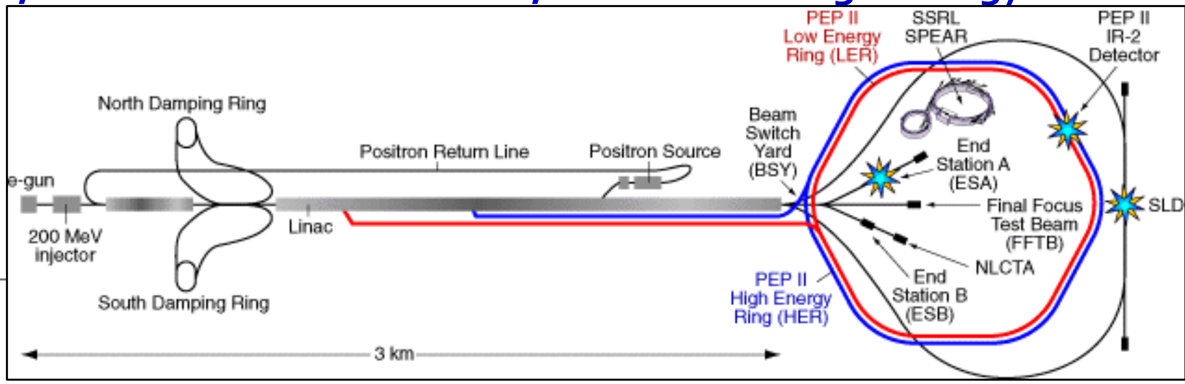
Precision with e^+e^- colliders (2)

- **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

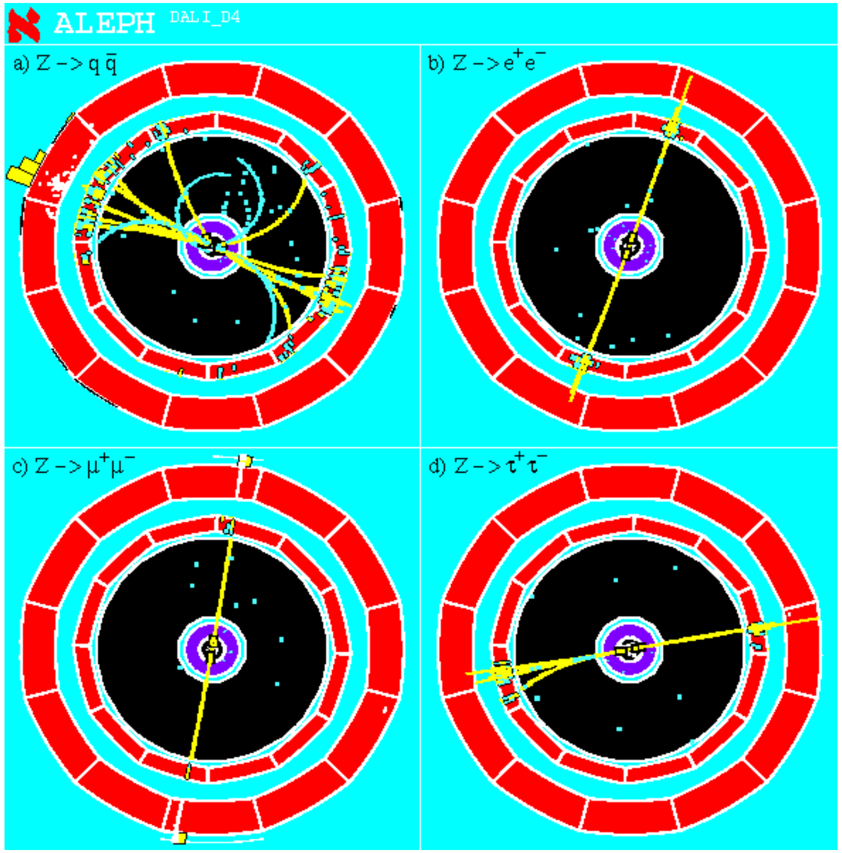


  - **B. Richter, "The SLAC Linear Collider", 11th Conf. on High-Energy Accelerators (1980)**

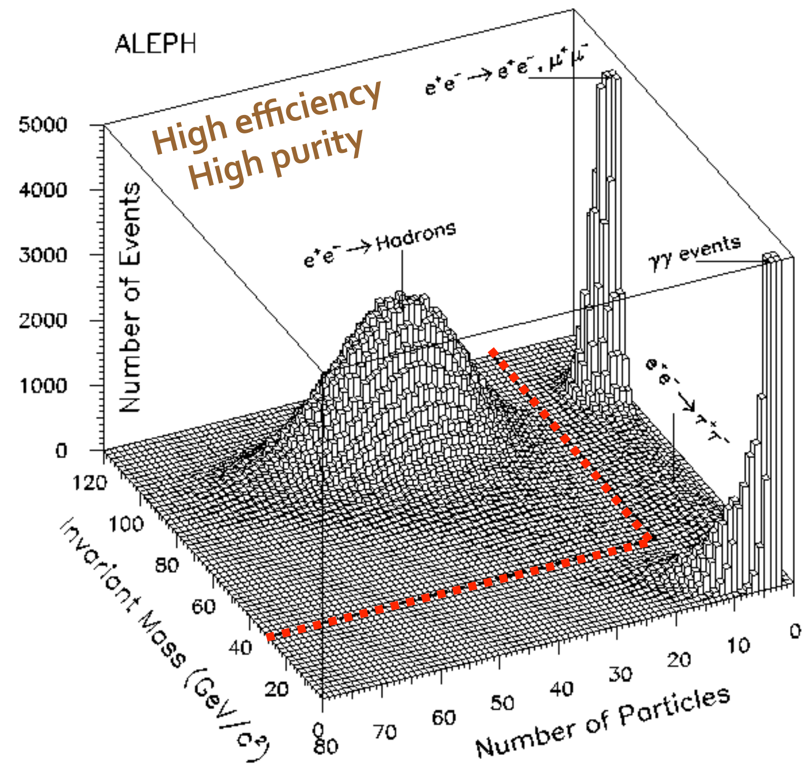


Precision with e^+e^- colliders (3)

- **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)**



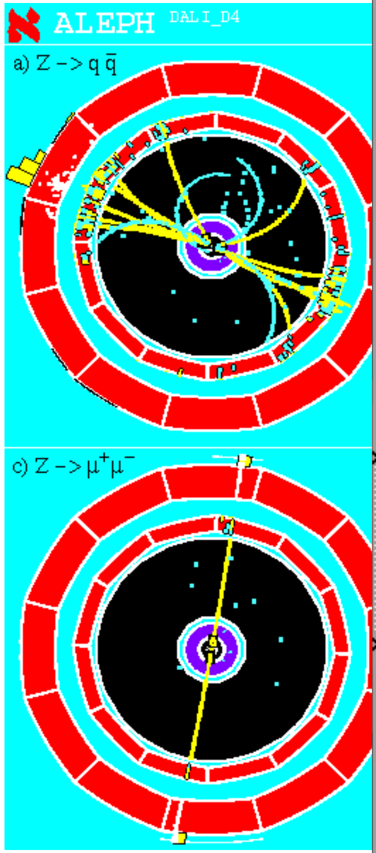
- **Analysis is a waking dream**

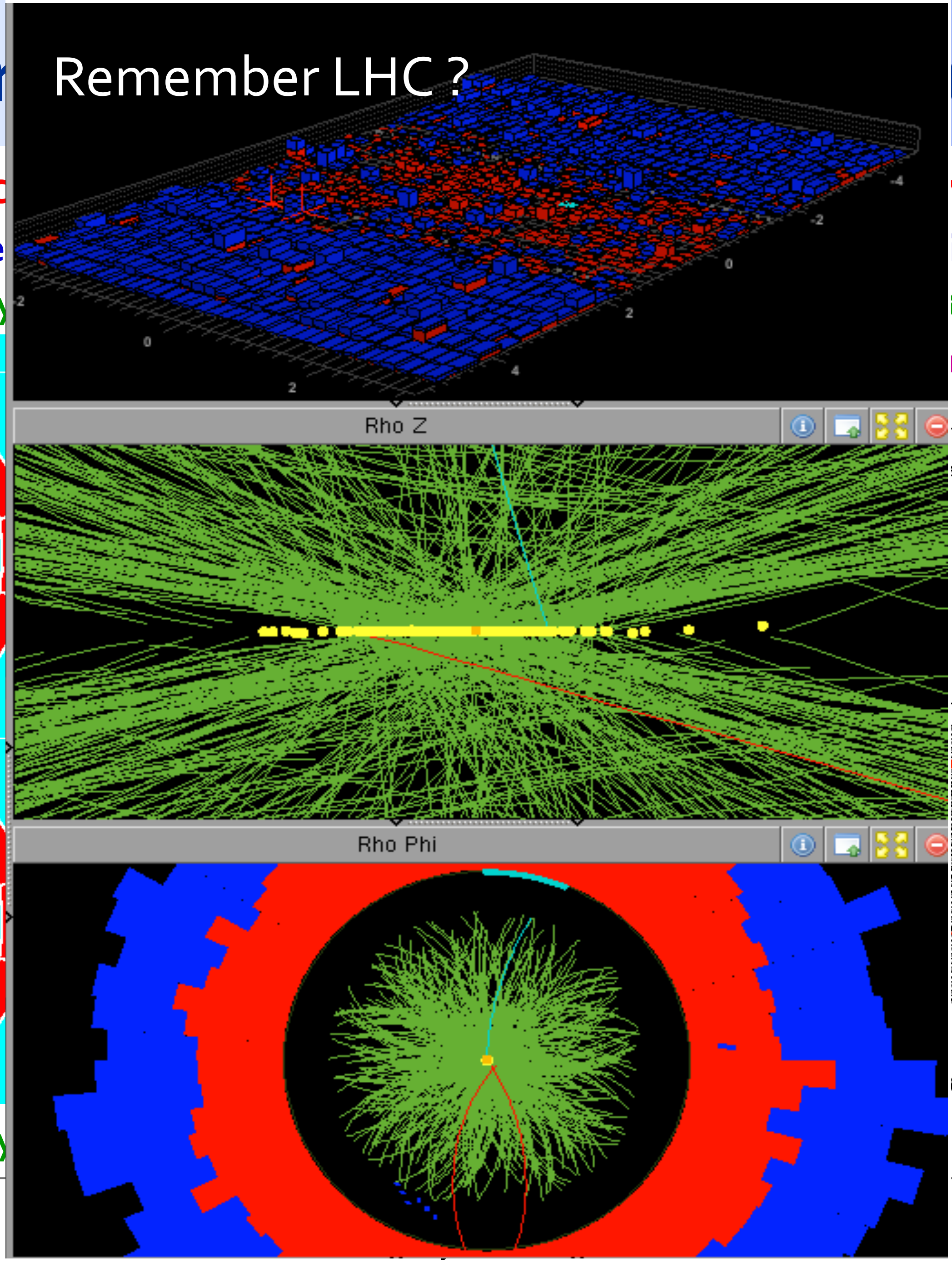


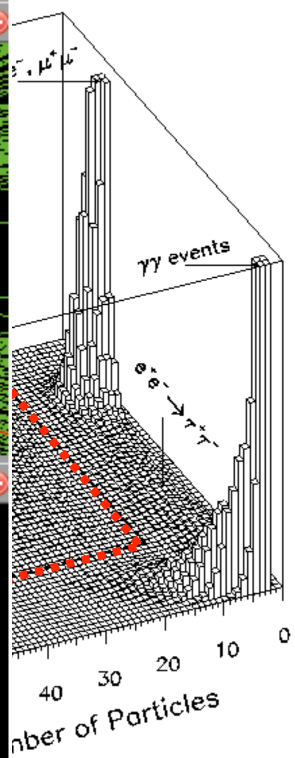
- **Corollary #2: No huge QCD cross section: All events are signal.**

Pr

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





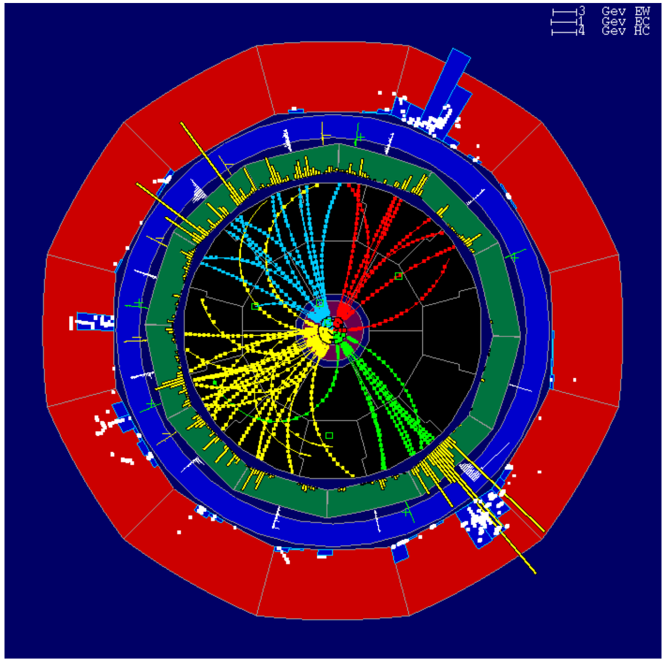


    - Corollary

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

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

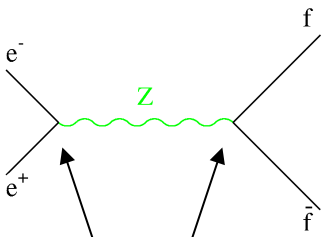


- Jet energies (or di-jet masses: m_W) determined analytically by inverting the matrix
  - ➨ No systematic uncertainty related to jet energy calibration

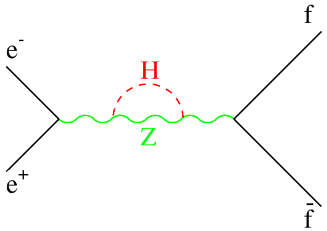
A lot of Z are available anyway to calibrate and align everything

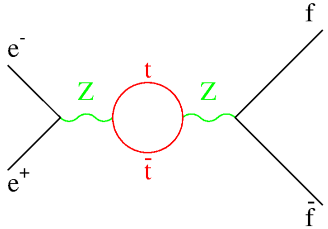
Precision with e^+e^- colliders (5)

- **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)



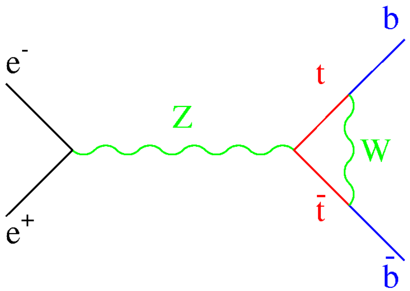


Tree-Level	Corrected
$a_0 = \pm 1/2$	$a = a_0(1+\Delta\rho)$
$v_0 = a_0(1-4\|Q\|\sin^2\theta_W)$	$v = a(1-4\|Q\|\sin^2\theta_W^{eff})$
$\sin^2\theta_W = 1 - m_W^2/m_Z^2$ ($m_W = m_Z \cos\theta_W$)	$\sin^2\theta_W = 1 - m_W^2/m_Z^2(1+\Delta\rho)$

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

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

      - **Specific correction for Rb**



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

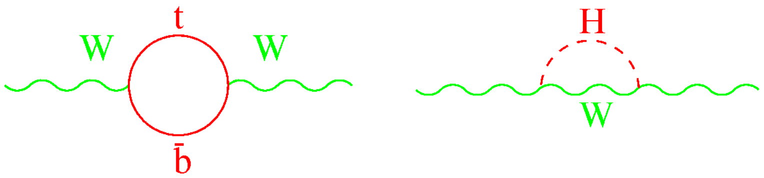
$$R_b \to R_b \times (1 + \delta_{vb})$$

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

No m_H !

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

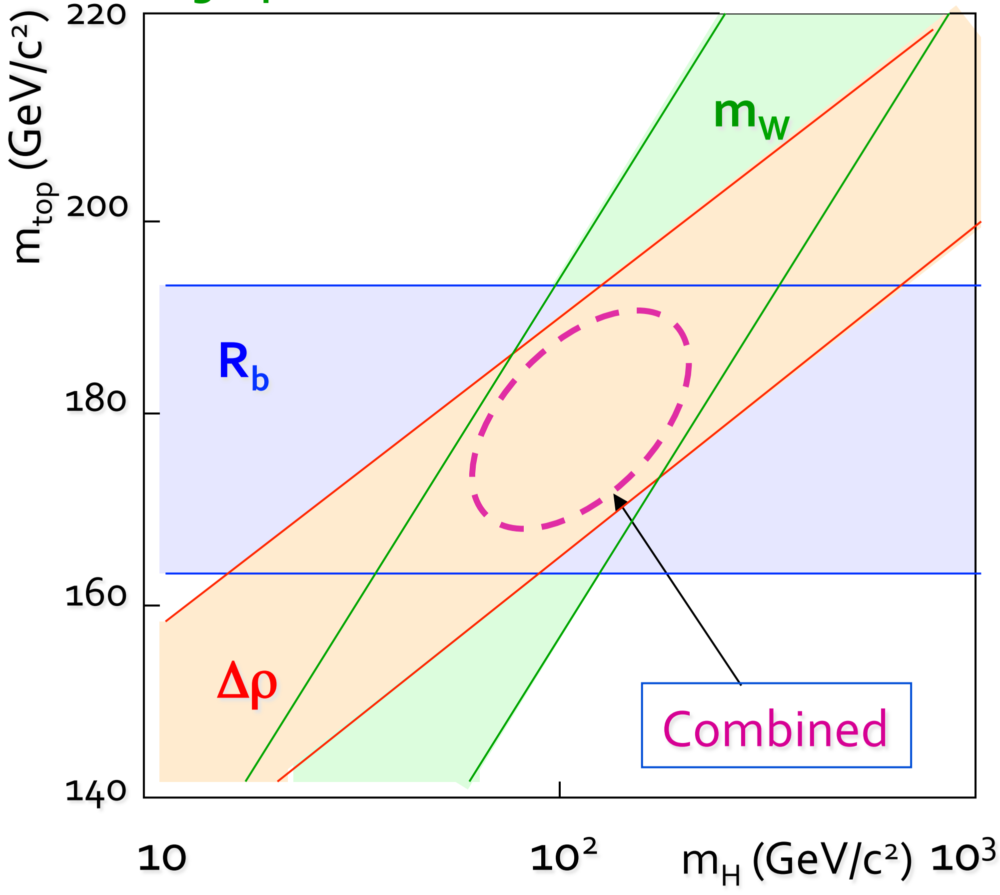
- **Why are e^+e^- colliders the tool of choice for precision anyway ? (cont'd)**
  - Electroweak observables can be calculated/predicted with precision
    - And are sensitive to heavier particles through quantum corrections
      - ➨ W mass



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

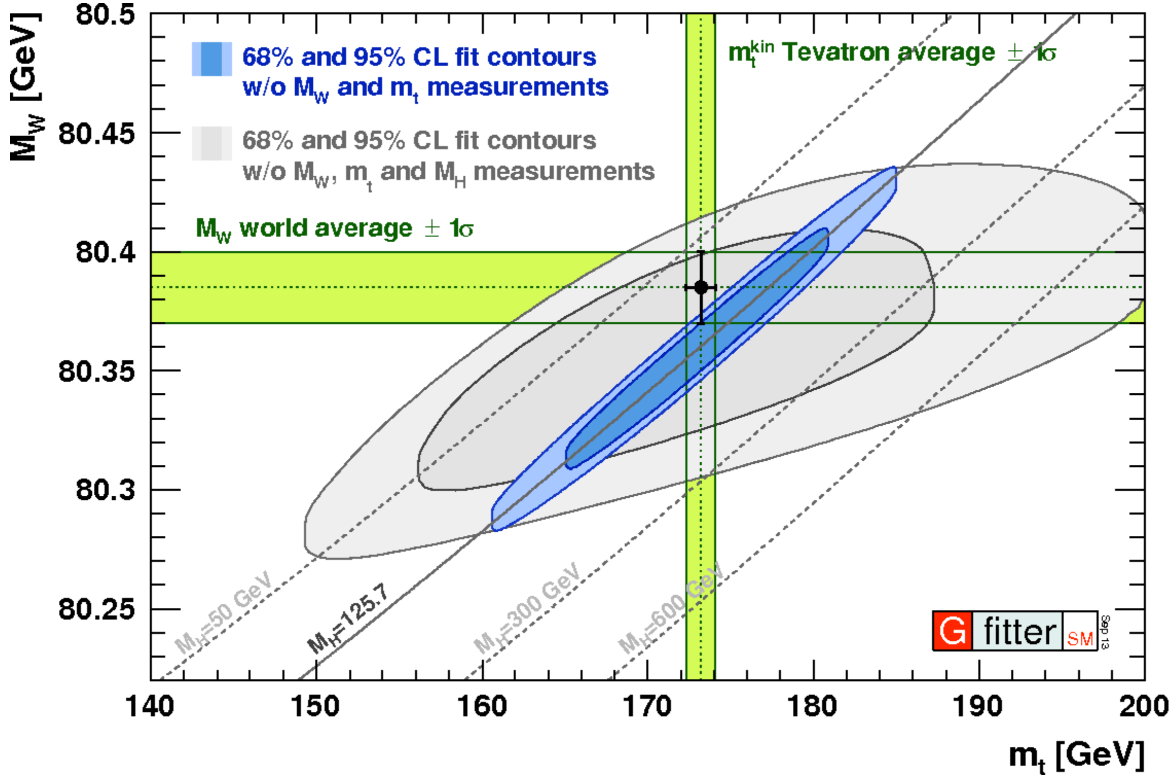
$$\Delta r = -\frac{\cos^2\vartheta_W}{\sin^2\vartheta_W}\Delta\rho \approx 1\%$$
$$+\frac{\alpha}{3\pi}\left[\frac{1}{2}-\frac{1}{3}\frac{\sin^2\vartheta_W}{1-\tan^2\vartheta_W}\right]\mathrm{Log}\frac{m_H^2}{m_Z^2}+\cdots$$

➨ 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

    And to understand the quantum structure of the underlying physics

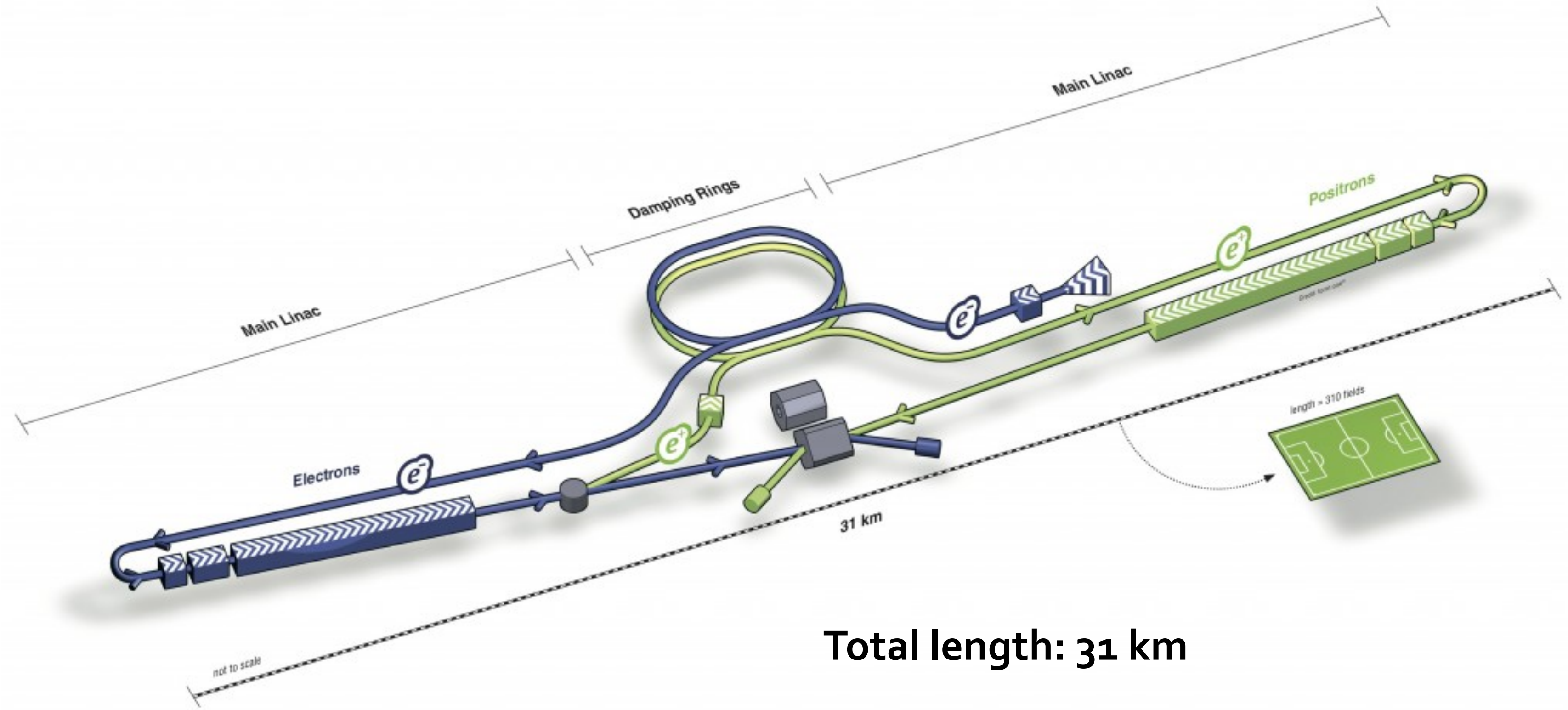
Precision with e^+e^- colliders (9)

- **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**

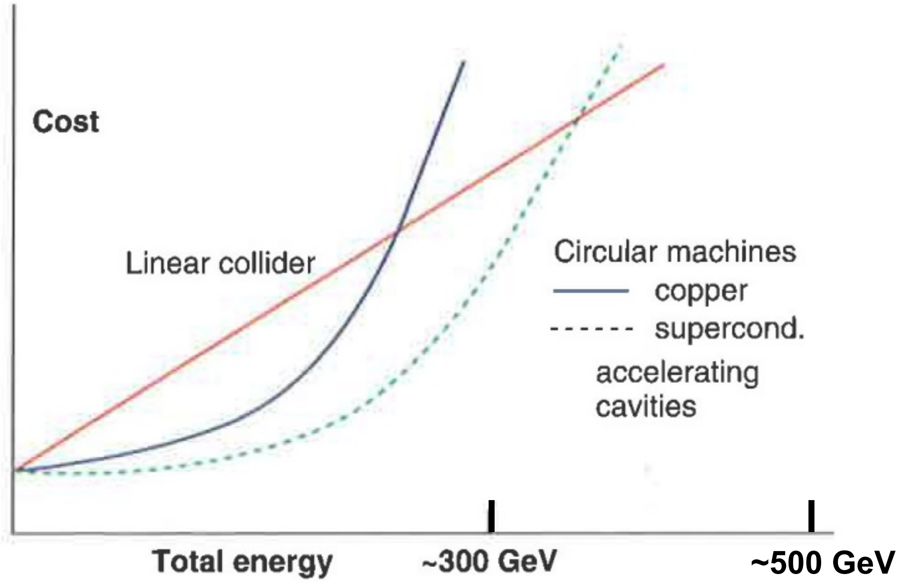


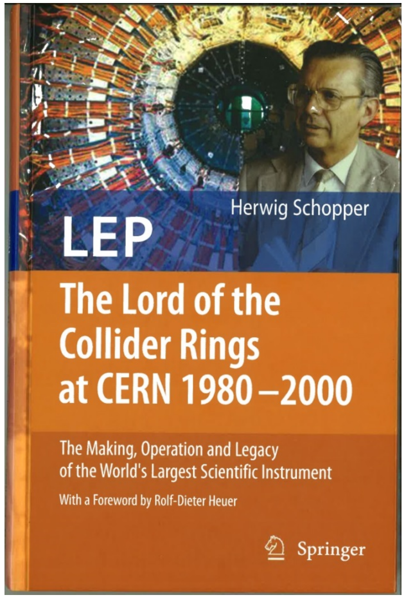
Total length: 31 km

- **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.





Author: Herwig Schopper
(Former CERN DG)

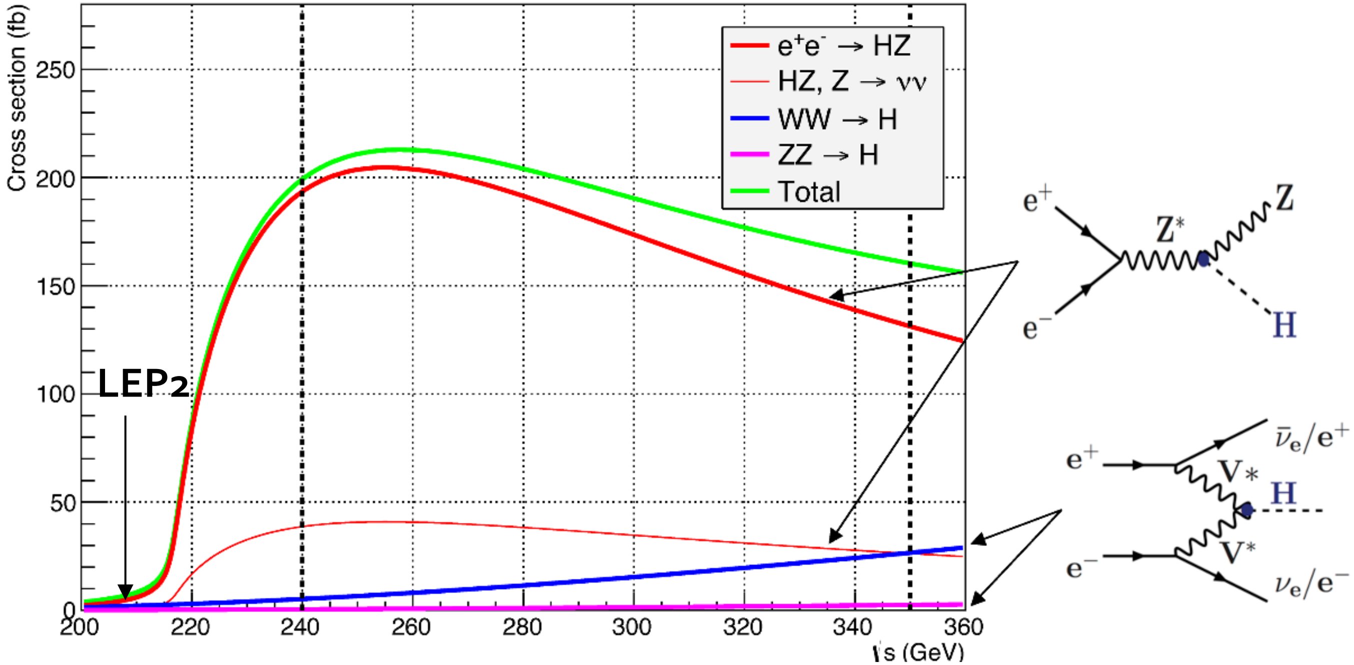
Foreword: Rolf Heuer
(Former CERN DG)

  - A e^+e^- collider with $\sqrt{s}$ > 500 GeV can only be linear. The circular cost 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 $\sqrt{s}$ = 500 GeV (works OK at $\sqrt{s}$ ~ 250 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
      - ➨ Not yet demonstrated to be achievable
    - 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 up to $\sqrt{s}$ = 1 TeV
    - And possibly more : CLIC or Plasma acceleration in the same tunnel (?)
      - ➨ But there is no design to run at the Z pole

Linear or Circular ? (5)

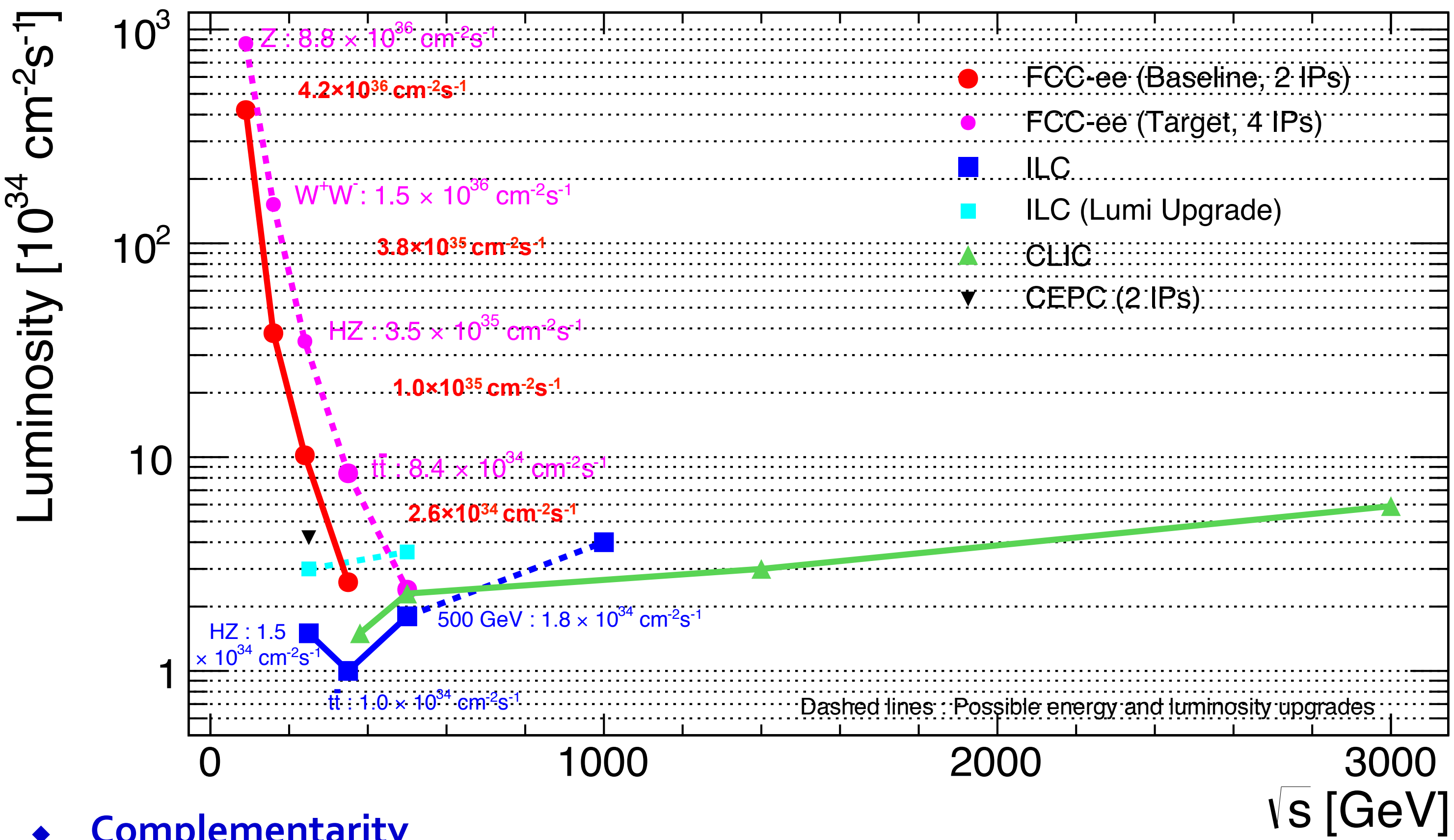
D. Schulte

- The FCC-ee is designed to be a Z, W, H, and top factory ($\sqrt{s}$ = 88-370 GeV)
  - It is a project in its infancy: less than three years old
    - Lots of progress were made in the past two years
      - ➨ Technology is ready – on paper
  - This machine has at least as many technological challenges
    - A high-power (200 MW), high-gradient (10 MV/m), 2 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
    - Transverse polarization for beam energy measurement
    - 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 are being addressed at SuperKEKB (starting 2015)
      - ➨ FCC-ee will have to build on this experience
  - It is a synergetic spring board 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)	40 – 80	4 – 15	1.0 – 3.5	0.25 – 1.0	0.25 – 1.0
Events/year	$2–4\times10^{12}$	$1.5–6\times10^{7}$	$2–7\times10^{5}$	$1.3–4.2\times10^{5}$	$0.6–2.5\times10^{4}$

- **Number of years needed to complete the core programme**

10 to 15 years
1 year = 10^7 s

# years	2 – 3	1 – 2	3 – 5	0.5	3 – 5

- **The ILC precision physics programme (first 10-15 years)**
  - with ±80% / ±30% longitudinal polarization for e^-/e^+ beams

~ 13 years
1 y = 1.6×10^7 s

# years	3 ? (*)	3 ? (*)	3	1	4
Total lumi (ab^{-1})	0.1	0.5	0.5	0.2	0.5
Events@ILC	3×10^{9} (*)	2×10^{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

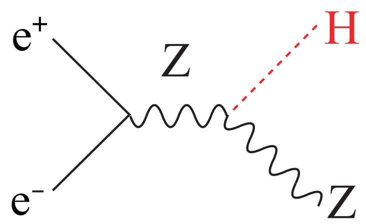
(*) No design available at the Z pole and the WW threshold: very difficult to achieve with a linear collider.

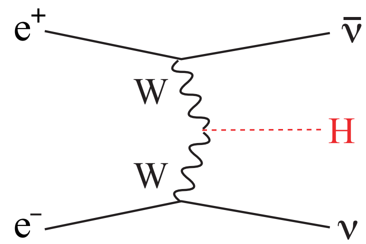
- **About one year is needed for the FCC-ee to complete the full ILC precision physics programme**

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

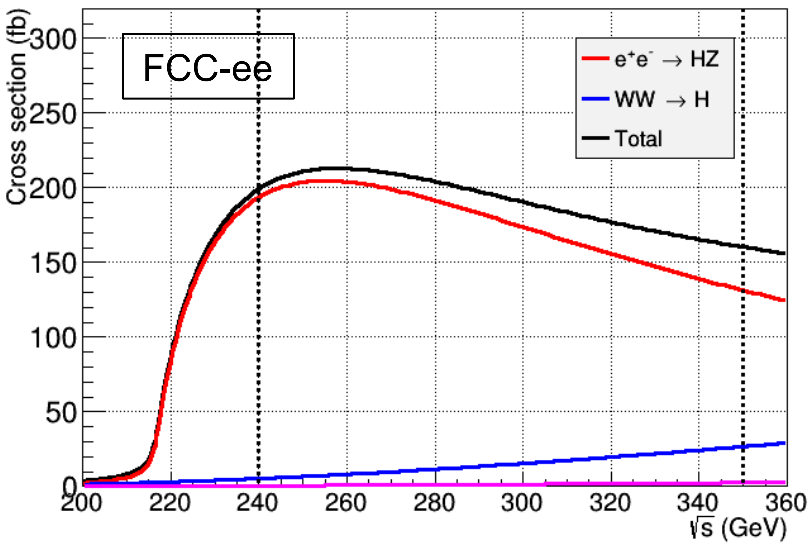
- Dominant production processes for $\sqrt{s} \le 500$ GeV

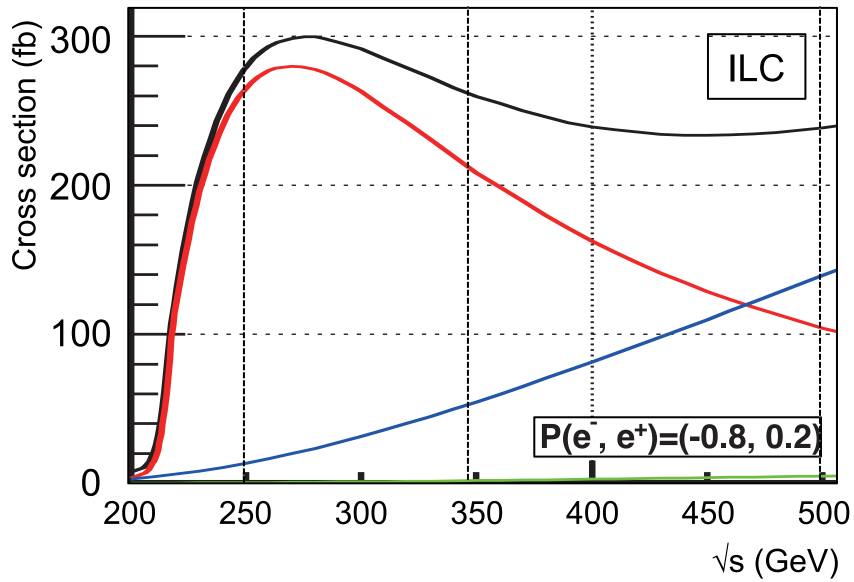
Higgs-strahlung





Boson fusion



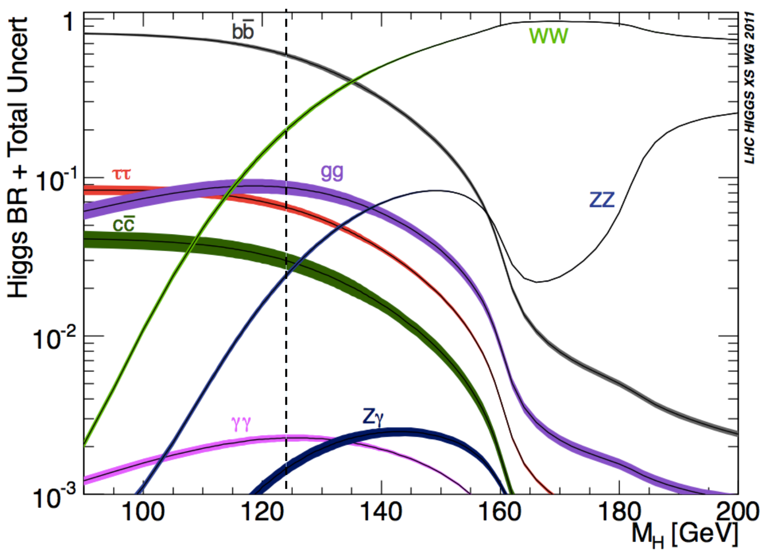


- Effect of beam polarization (exercise)
  - Higgs-strahlung cross section multiplied by $1 - P_-P_+ - A_e \times (P_- - P_+)$
  - Boson fusion cross section multiplied by $(1-P_-) \times (1+P_+)$

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

- The plan is to run at $\sqrt{s}$ = 240-250 GeV and 350-500 GeV in order to
  - Determine all Higgs couplings (κ_i) 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



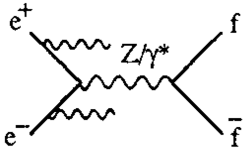
m_H = 125 GeV

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

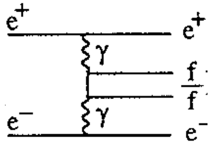
- m_H = 125 GeV is a very good place to be for precision measurements !
  - All decay channels open and measurable – can test new physics from many angles

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

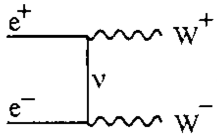
- **Physics backgrounds are "small"**
  - For example, at $\sqrt{s}$ = 240 GeV



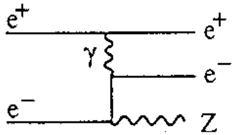
$e^+e^- \to q\bar{q}, l^+l^-$



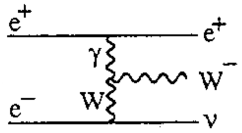
$\gamma\gamma \to qq, l^+l^-$
m > 30 GeV



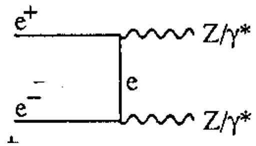
$e^+e^- \to W^+W^-$



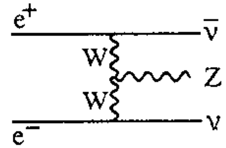
$e^+e^- \to Ze^+e^-$



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



$e^+e^- \to ZZ$



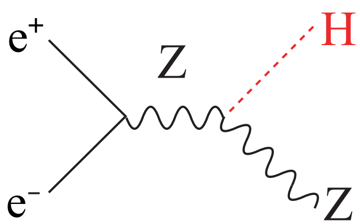
$e^+e^- \to Z\nu\bar{\nu}$

60 pb	30 pb	16 pb	3.8 pb	1.4 pb	1.3 pb	32 fb

- "Green" cross sections decrease like 1/s
  - "Purple" cross sections increase slowly with s

Add $e^+e^- \to t\bar{t}$ for $\sqrt{s}$ > 345 GeV — **0.6 pb**

- To be compared to

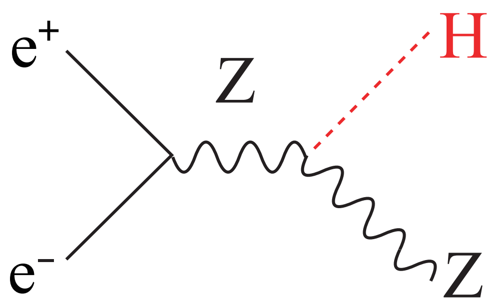


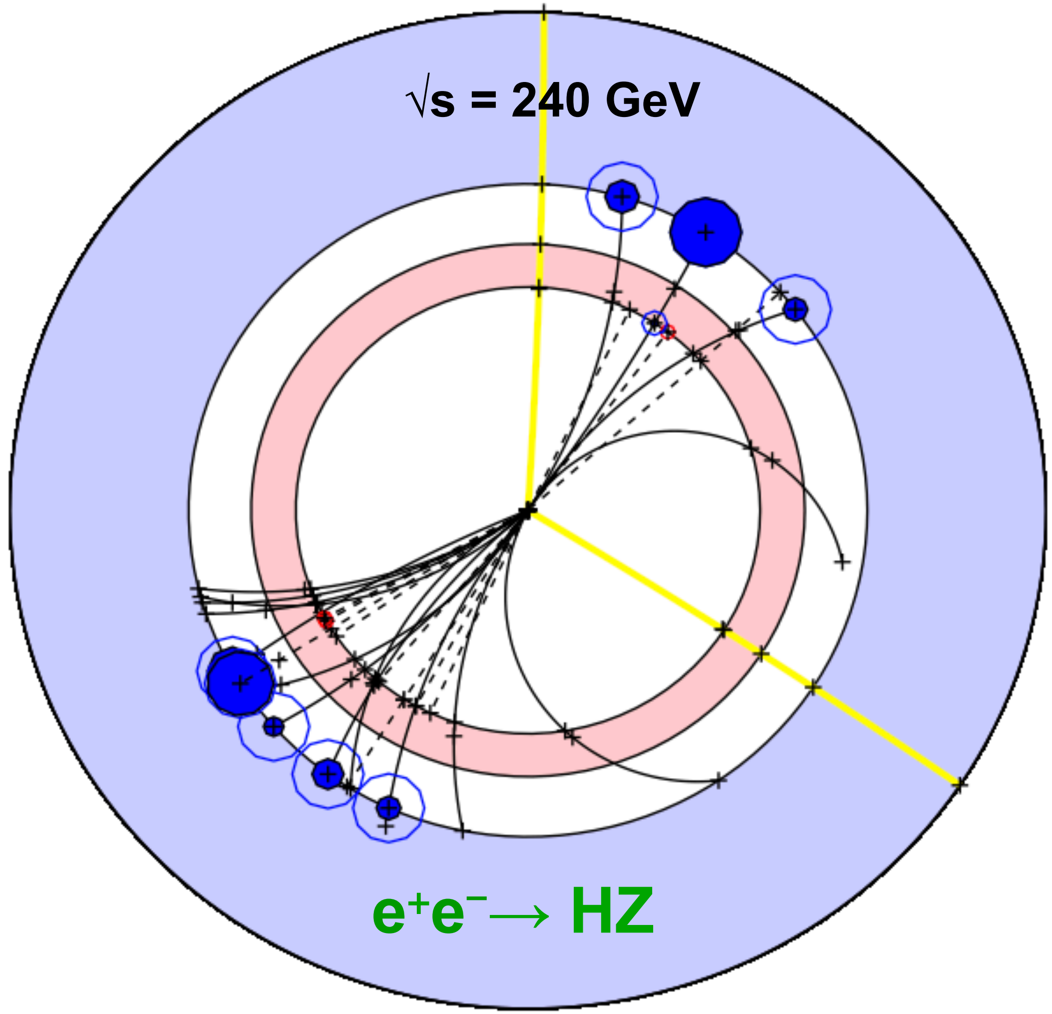
200 fb

- **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)

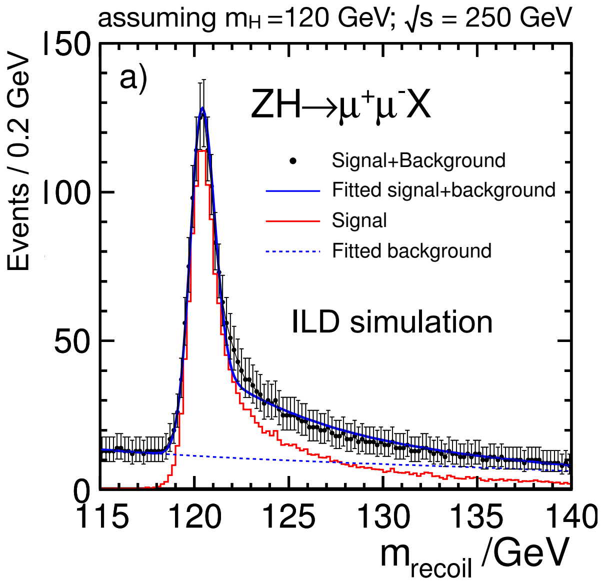
- **Example of a Higgs boson event**
  - Tagged with a Z boson
  - Very clean signature

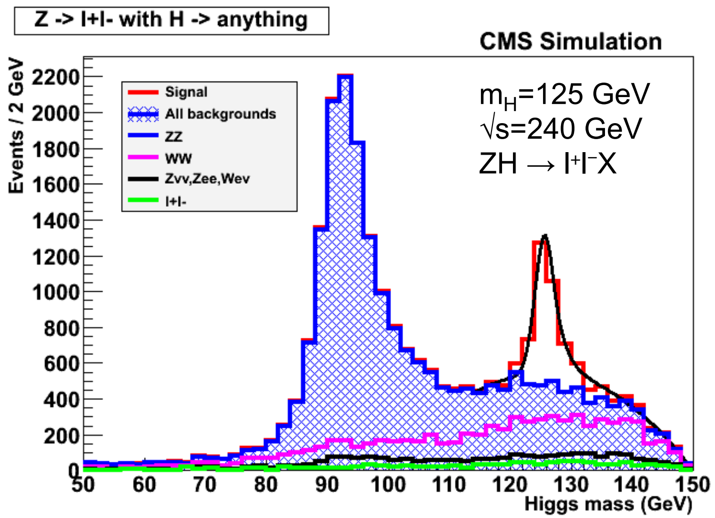




Precision Higgs physics at FCC-ee and ILC (5)

- **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 $\sigma_{HZ} \times BR(Z \to e^+e^-, \mu^+\mu^-)$
    - 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



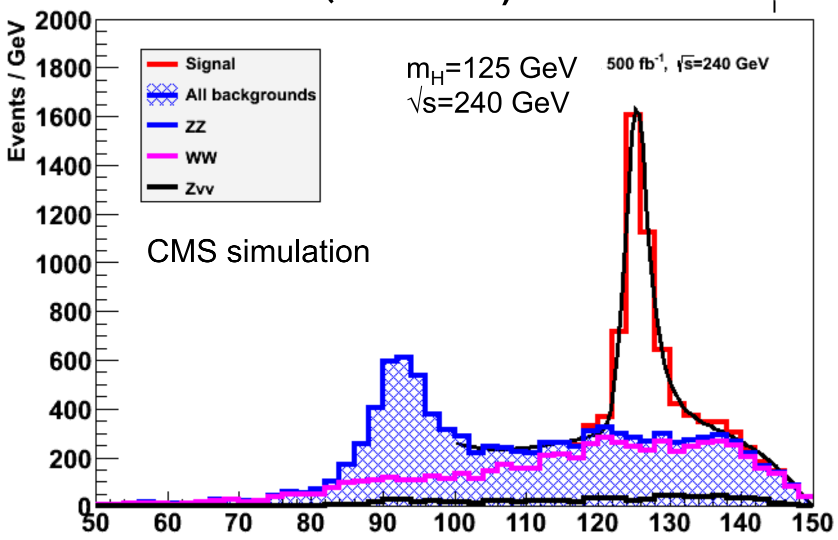


  - Provides an absolute measurement of κ_Z and set required detector performance

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

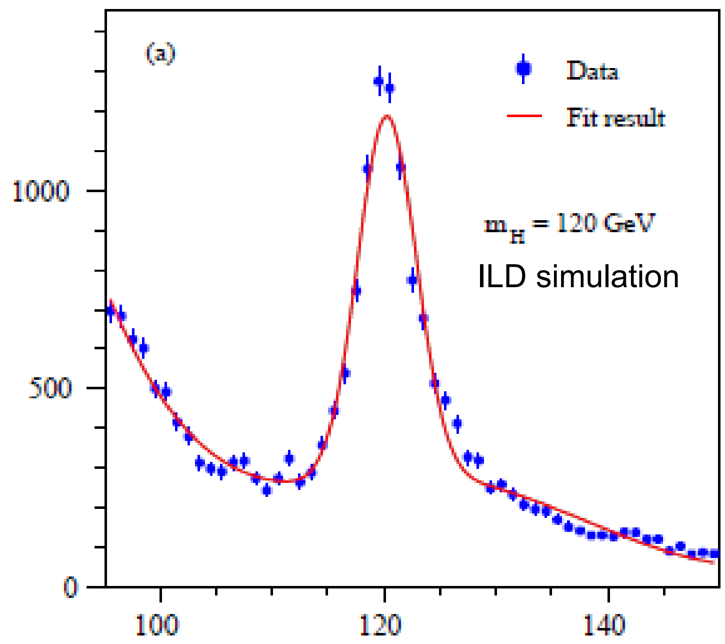
- **Repeat the search in all possible final states**
  - For all exclusive decays of the Higgs boson: measure $\sigma_{HZ} \times BR(H \to YY)$
    - Including invisible decays, just tagged by the presence of the lepton pair & m_{miss}
    - For all decays of the Z (hadrons, taus, neutrinos) to increase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

$ZH \to l^+l^-$ + nothing, 0.5 ab^{-1}
BR(H → invis) = 100%



M_{miss} (GeV)

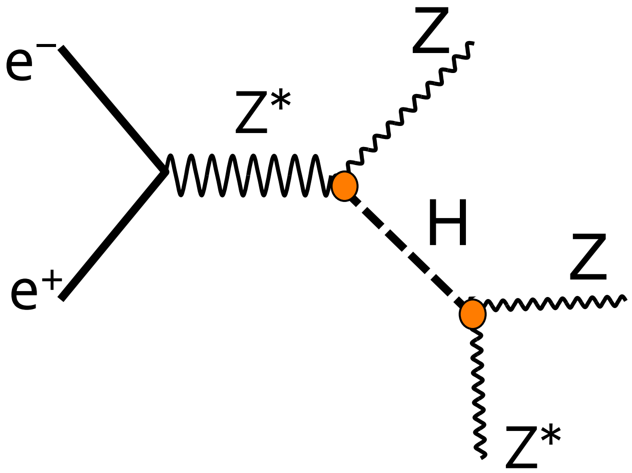
$ZH \to q\bar{q}\, b\bar{b}$, 0.25 ab^{-1}



M_{bb} (GeV)

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 $\sigma_{HZ} \times$ BR(H → ZZ)



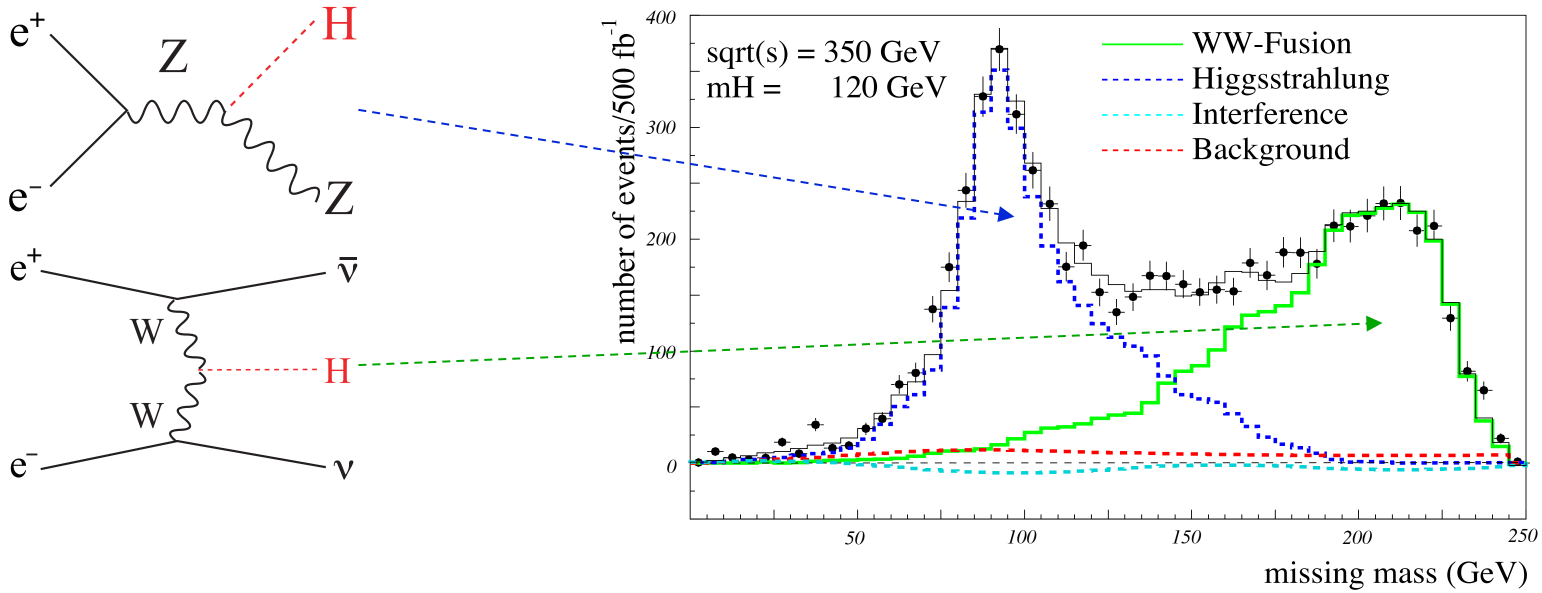
Final state with three Z's
Almost background free

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

- σ_{HZ} is proportional to κ_Z^2
- BR(H → ZZ) = Γ(H → ZZ) / Γ_H is proportional to κ_Z^2/Γ_H
  - ➨ $\sigma_{HZ} \times$ BR(H → 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 σ_{HZ}× BR(H → WW,bb)
- Infer the total width

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

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

- **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 (ILC (+) and FCC-ee columns)

κ_W to κ_μ: **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

κ_γ to $\kappa_{Z\gamma}$: **Sensitive to new physics in loops**

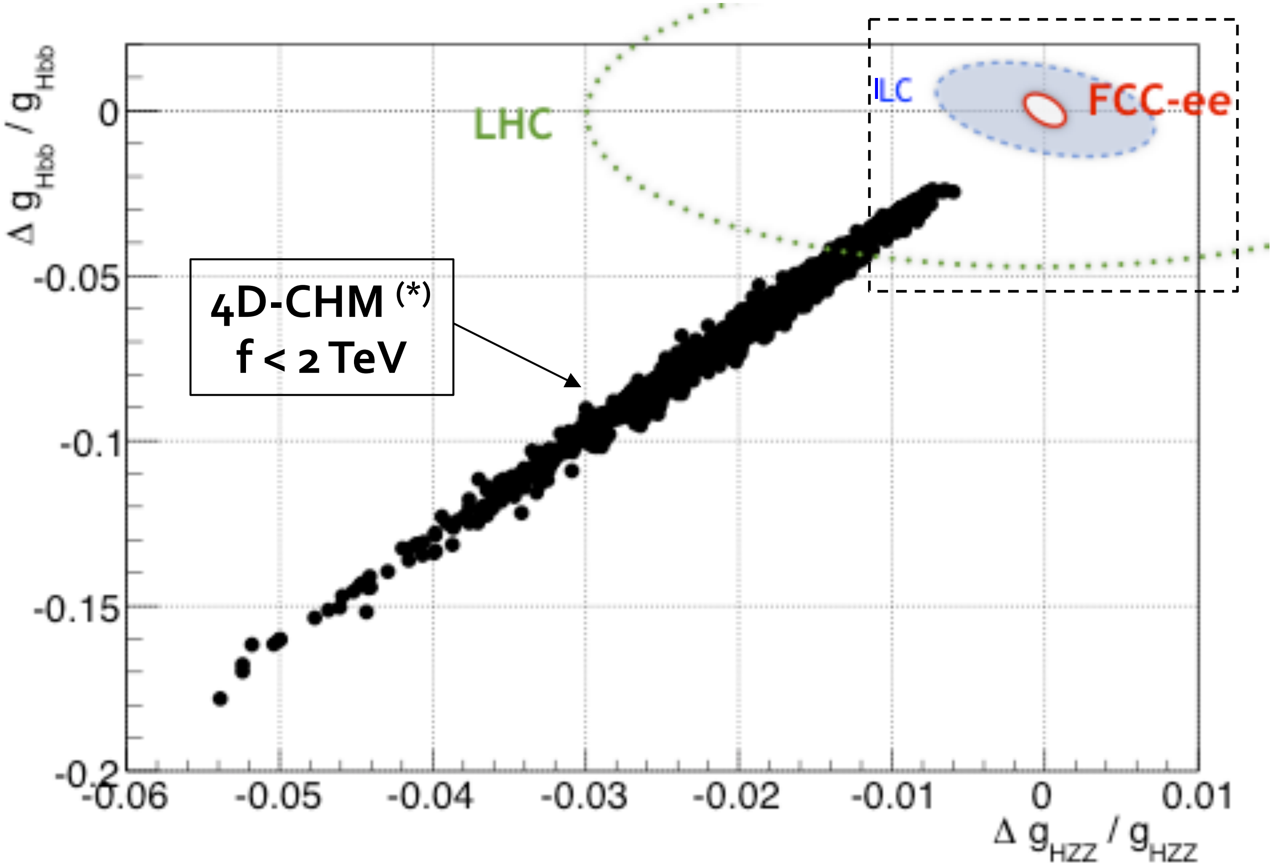
BR_{invis} and Γ_H: **Sensitive to light dark matter (sterile ν, χ, ...) and to other exotic decays**

κ_t and κ_H: **Need higher energy to improve on LHC**

(+) Factor 2 smaller errors if lumi upgrade and an additional 10-15 years of running.

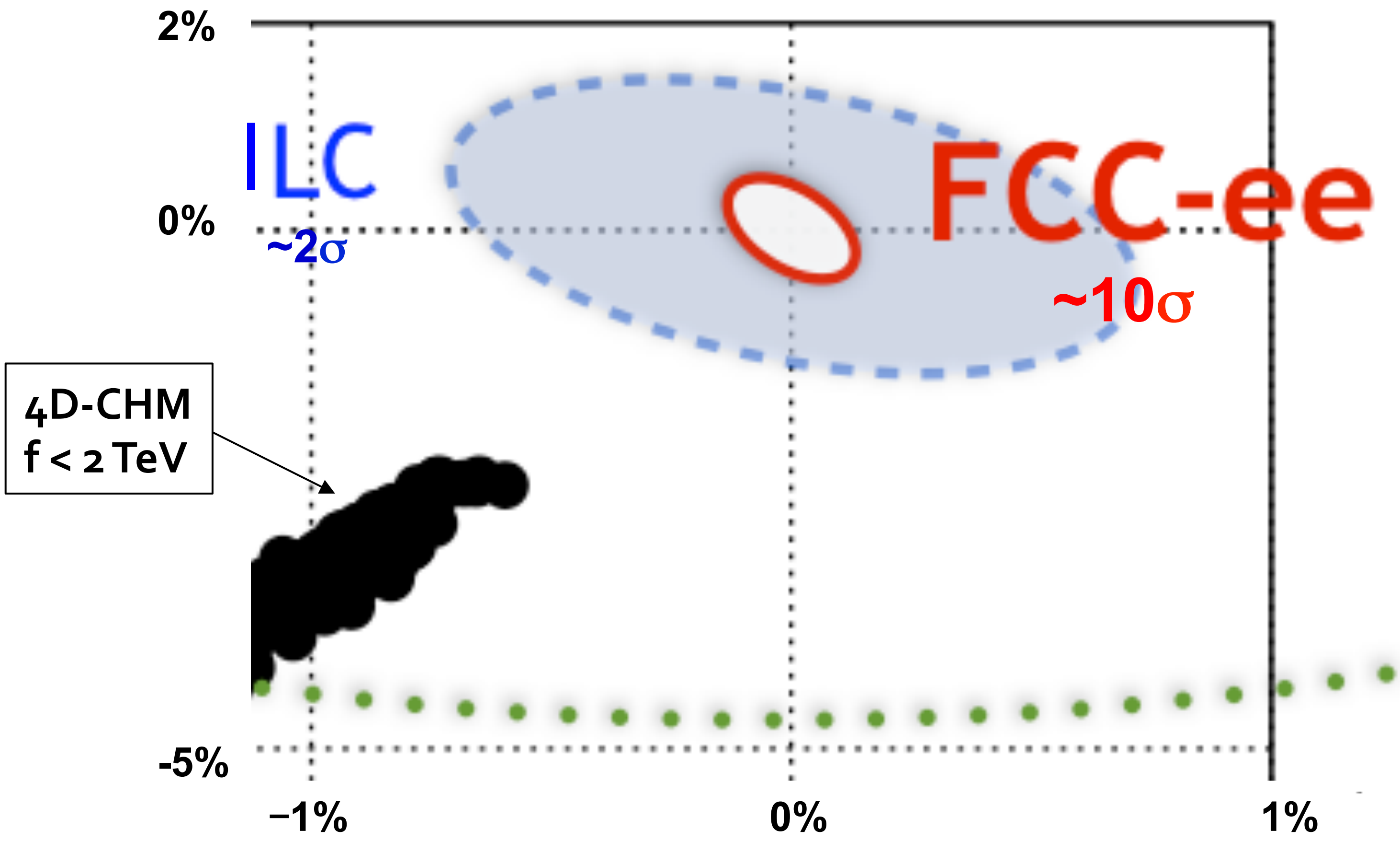
Precision Higgs physics at FCC-ee and ILC (10)

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



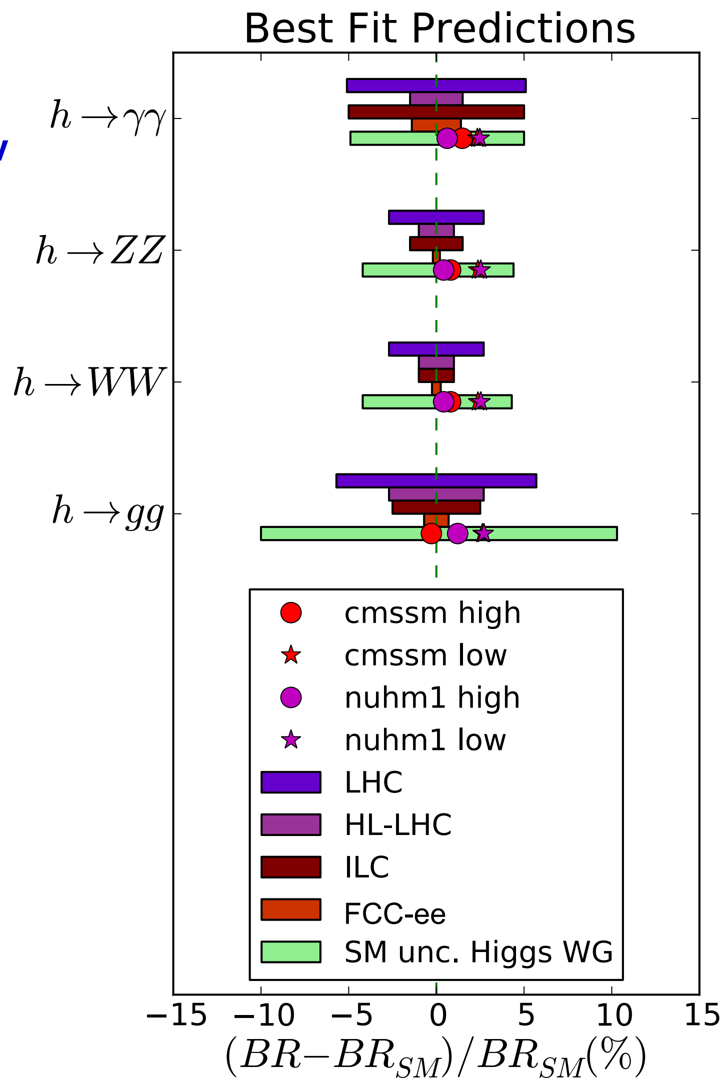
Precision Higgs physics at FCC-ee and ILC (10)

- **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	2-3 year	~10^{13} Z decays (Tera Z)	10^{9} (*)	2×10^{7}
161	1-2 year	~10^{8} WW pairs (Oku W)	10^{6} (*)	4×10^{4}
350	3-5 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 !

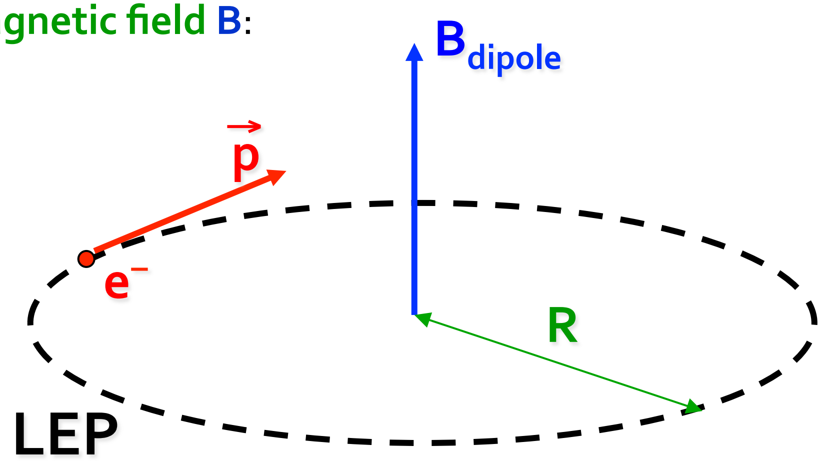
- Predicting accuracies with 300 times smaller statistical precision than at LEP is difficult
  - Conservatively used LEP experience for systematics. This is just the start.

- 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 (2)

- **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

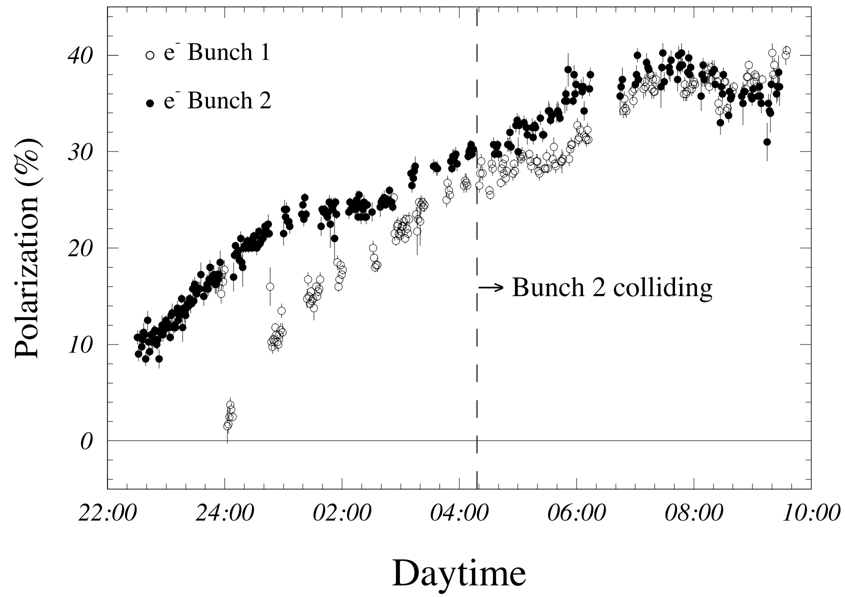
$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$

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

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

To be measured

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



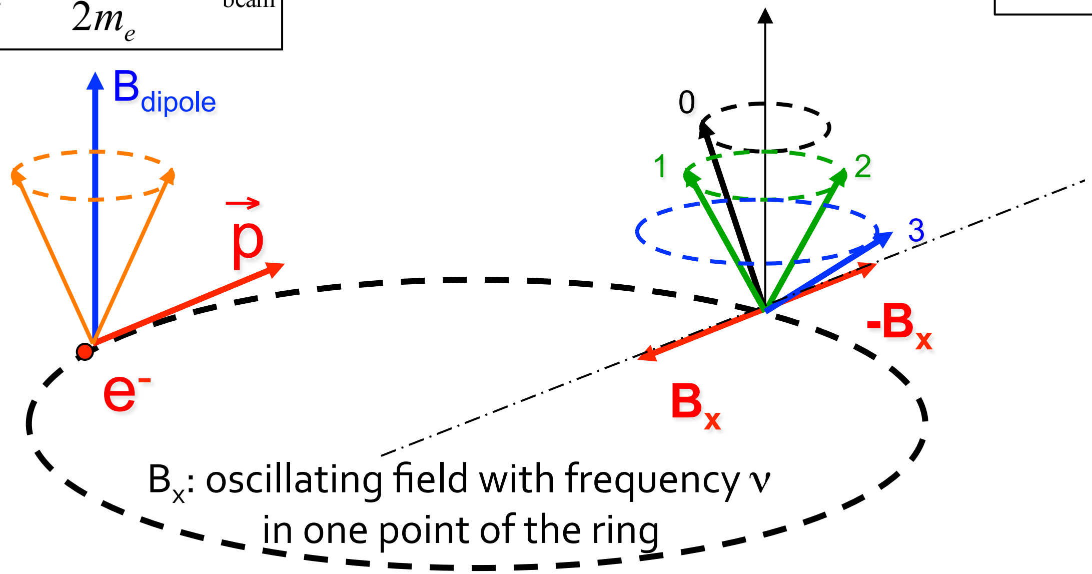
Slow process (~ 1 hour to get 10% polarization)

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

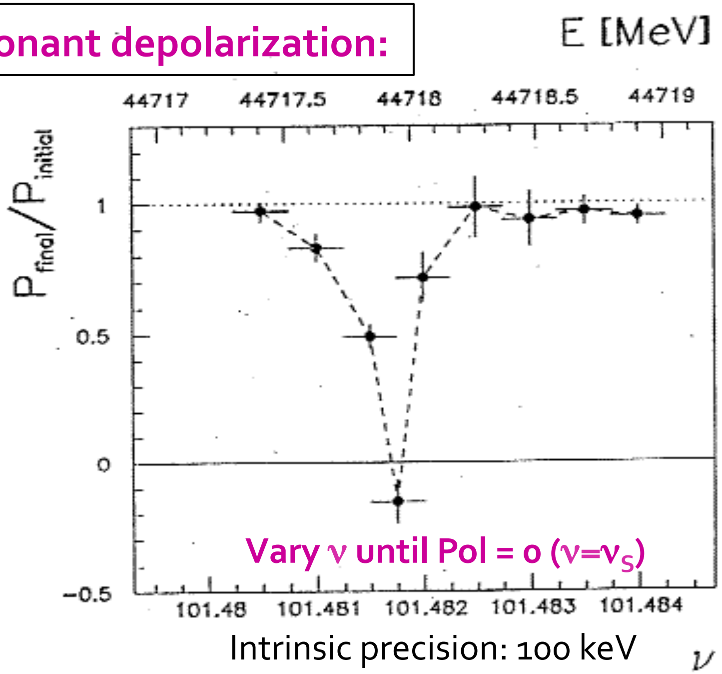
Precision electroweak physics at FCC-ee (3)

- **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 ∫Bdl)**

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



Resonant depolarization:

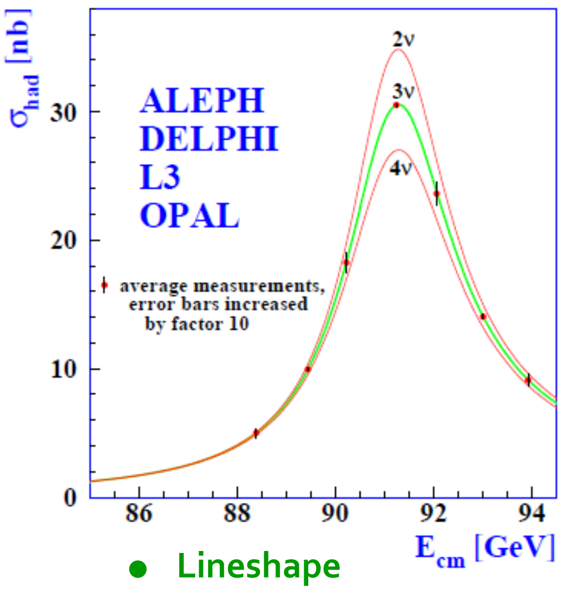


- **LEP was colliding 4 bunches of e⁺ and e⁻; FCC-ee will have 10,000's of bunches.**
  - **Use ~100 "single" bunches to measure E_{BEAM} with resonant depolarization**
    - ➠ **Each measurement gives 100 keV precision, with no extrapolation uncertainty**

Precision electroweak physics at FCC-ee (4)

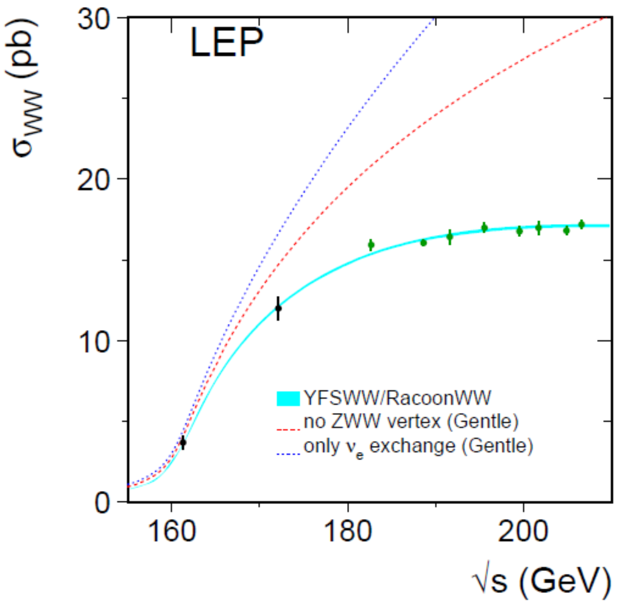
EW Precision measurements at FCC (see arXiv:1308.6176)

Z resonance: TeraZ

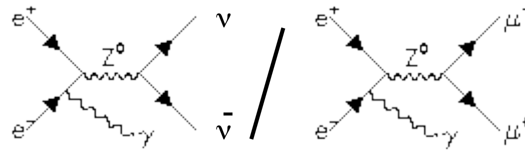


- Lineshape
  - ➨ Exquisite E_{beam} (unique!)
  - ➨ m_Z, Γ_Z to < 100 keV (2.2 MeV)
- Asymmetries
  - ➨ $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
  - ➨ $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})
- Branching ratios, R_l, R_b
  - ➨ $\alpha_S(m_Z)$ to 0.0002 (0.002)

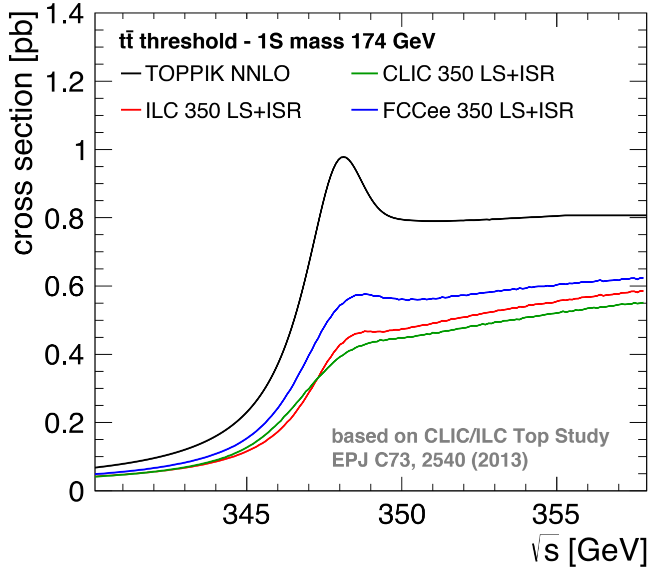
WW threshold scan: OkuW



- Threshold scan
  - ➨ m_W to 500 keV (15 MeV)
- Branching ratios R_l, R_{had}
  - ➨ $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^- \rightarrow \gamma Z$
  - ➨ N_ν to 0.0004 (0.008)



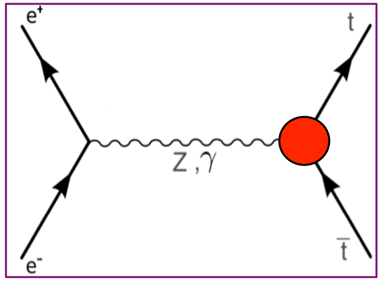
tt threshold scan: MegaTops

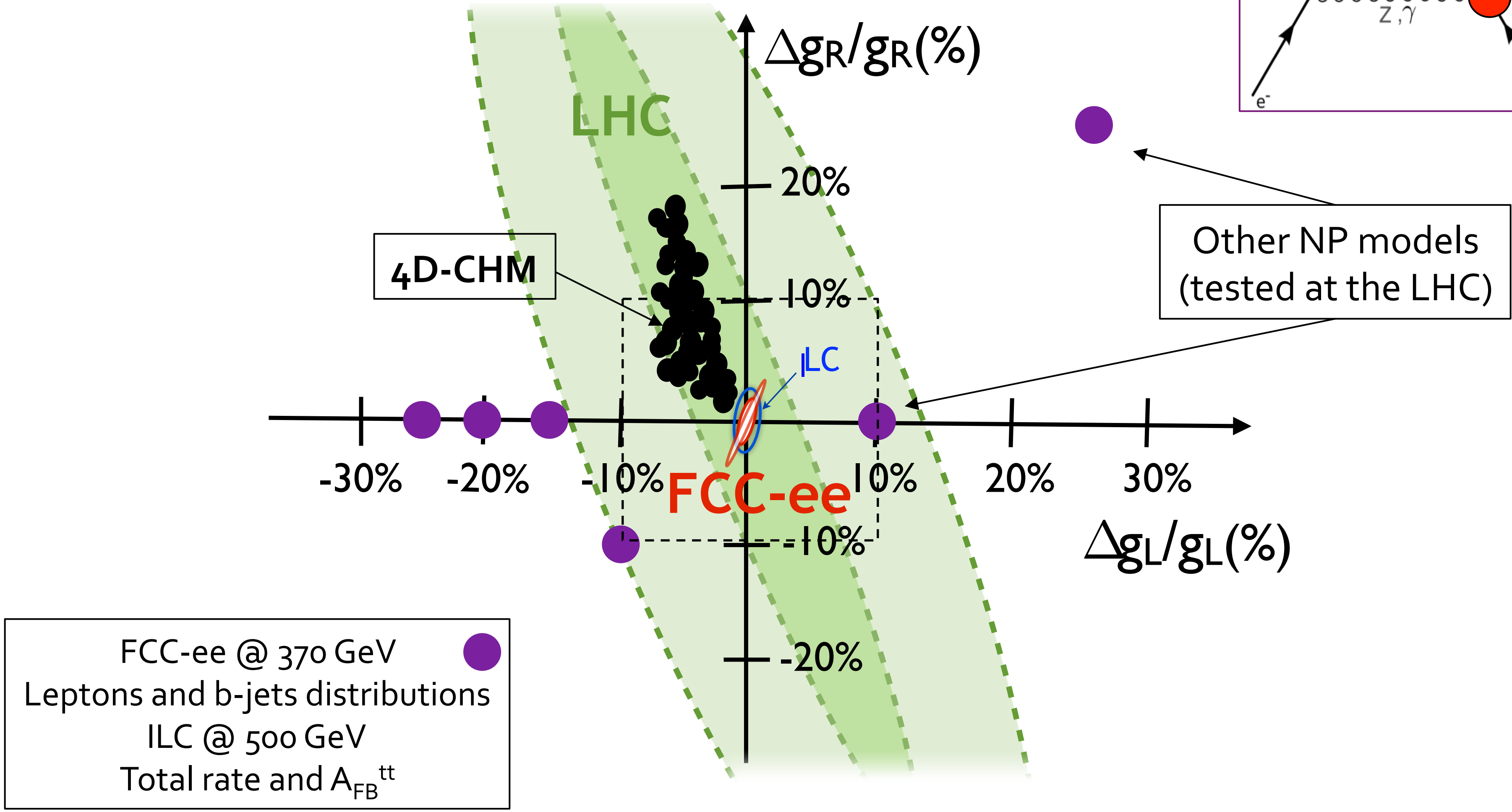


- Threshold scan
  - ➨ m_{top} to 10 MeV (500 MeV)
  - ➨ λ_{top} to 13%
  - ➨ EW couplings to 1%

Precision electroweak physics at FCC-ee (5)

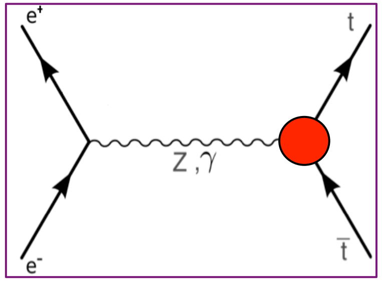
- **Measurements of $t_L t_L Z$ and $t_R t_R Z$ couplings, g_L and g_R**
  - **Couplings most sensitive to, e.g., composite Higgs models**





Precision electroweak physics at FCC-ee (5)

- **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

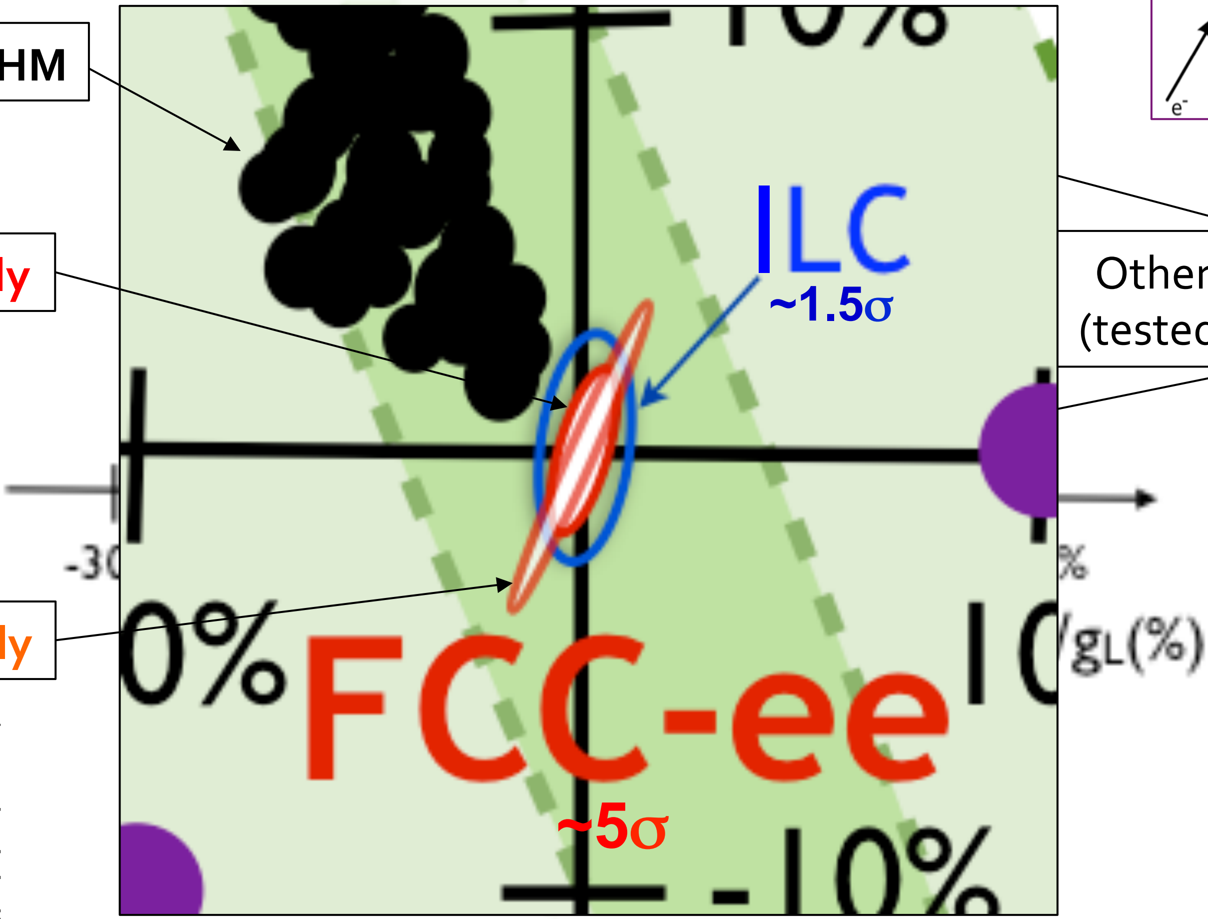


4D-CHM

b-jets only

Leptons only

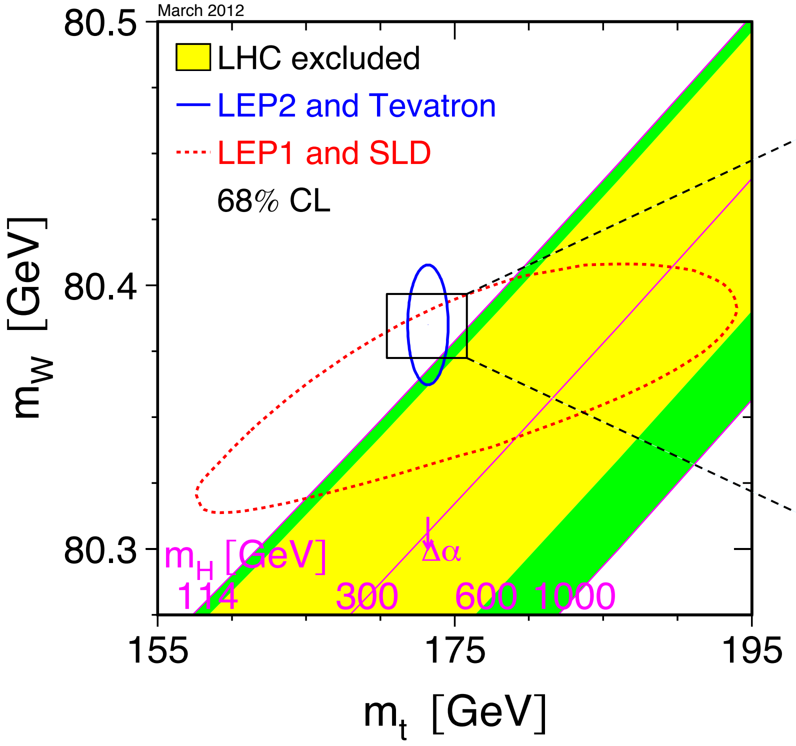
Other NP models (tested at the LHC)

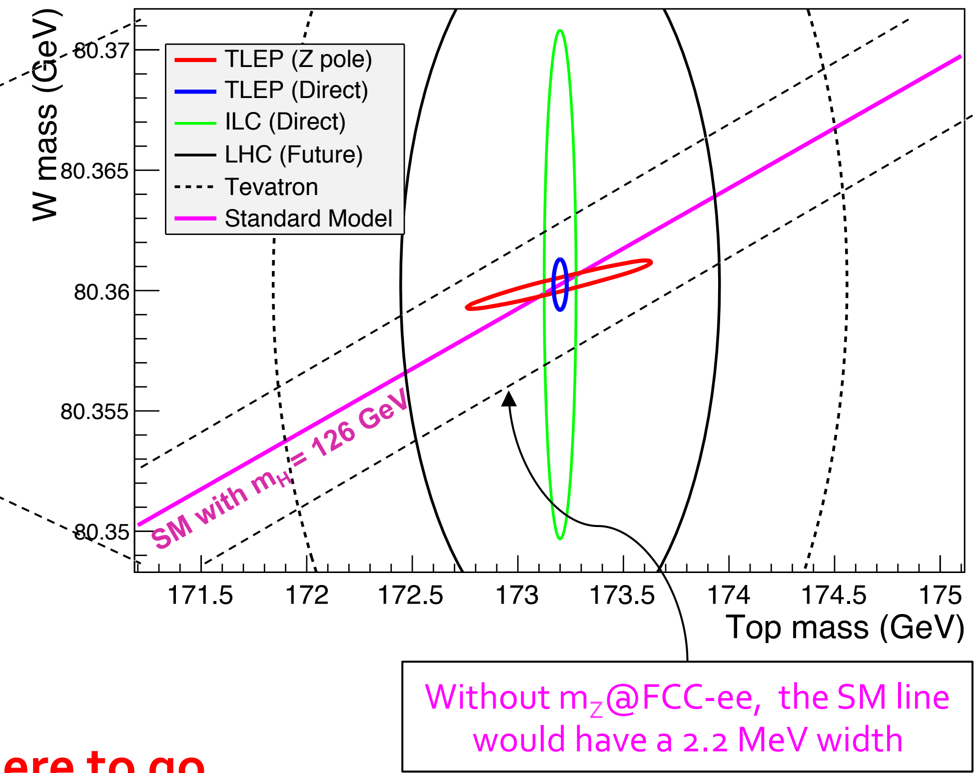


FCC-
Leptons and b-je
ILC
Total rate and A_{FB}

Precision electroweak physics at FCC-ee (6)

- **Combination of all precision electroweak measurements**
  - **FCC-ee precision allows m_{top}, m_{W}, m_H, $\sin^2\theta_W$ to be predicted in the SM**
    - **… and to be compared to the direct measurements**





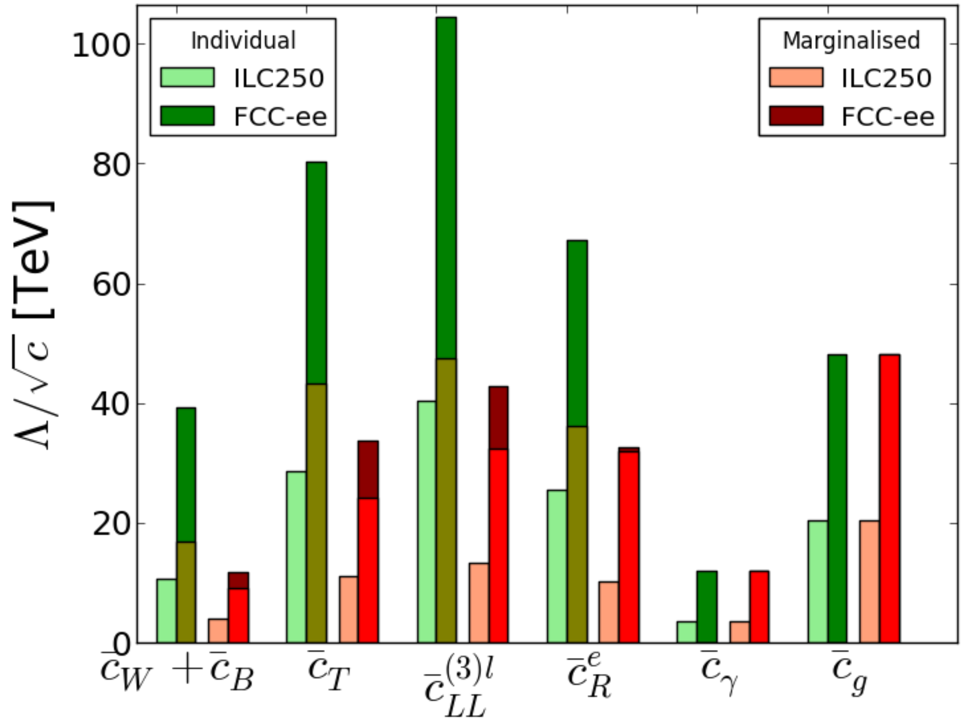
- **The Standard Model has nowhere to go**
  - **Constraints on new physics ?**

Precision electroweak physics at FCC-ee (7)

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

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

In green: one operator at a time
In red: all operators together
ILC250 sensitivity vanishes w/o Z and WW runs



After FCC-ee: Λ_{NP} > 100 TeV ?

Precision electroweak physics at FCC-ee (8)

- The predictions of m_{top}, m_W, m_H, $\sin^2\theta_W$ have theoretical uncertainties
  - Which may in turn cancel the sensitivity to new physics
- For m_W and $\sin^2\theta_W$ today, these uncertainties are as follows

$$\begin{aligned} M_W &= 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\ &\quad \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo} \\ &= 80.359 \pm 0.011_{\rm tot} \end{aligned}$$

Exp: 0.015

$$\begin{aligned} \sin^2\theta^\ell_{\rm eff} &= 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \\ &\quad \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo} \\ &= 0.23150 \pm 0.00010_{\rm tot} \end{aligned}$$

Exp: 0.00014

- Parametric uncertainties and missing higher orders in theoretical calculations:
  - Are of the same order
  - Smaller than experimental uncertainties

Precision electroweak physics at FCC-ee (8)

- **Most of the parametric uncertainties will reduce at FCC-ee**
  - **New generation of theoretical calculations is necessary to gain a factor 10 in precision**
    - **To match the precision of the direct FCC-ee measurements**

$$M_W = 80.3593 \pm 0.0001_{m_t} \pm 0.0001_{M_Z} \pm 0.0003_{\Delta\alpha_{\rm had}} \pm 0.0002_{\alpha_S} \pm 0.0000_{M_H} \pm 0.0040_{\rm theo} = 80.359 \pm 0.005_{\rm tot}$$

Exp: 0.0005

$$\sin^2\theta^\ell_{\rm eff} = 0.231496 \pm 0.000001_{m_t} \pm 0.000001_{M_Z} \pm 0.000008_{\Delta\alpha_{\rm had}} \pm 0.000001_{\alpha_S} \pm 0.000000_{M_H} \pm 0.000047_{\rm theo} = 0.23150 \pm 0.00006_{\rm tot}$$

Exp: 0.000006

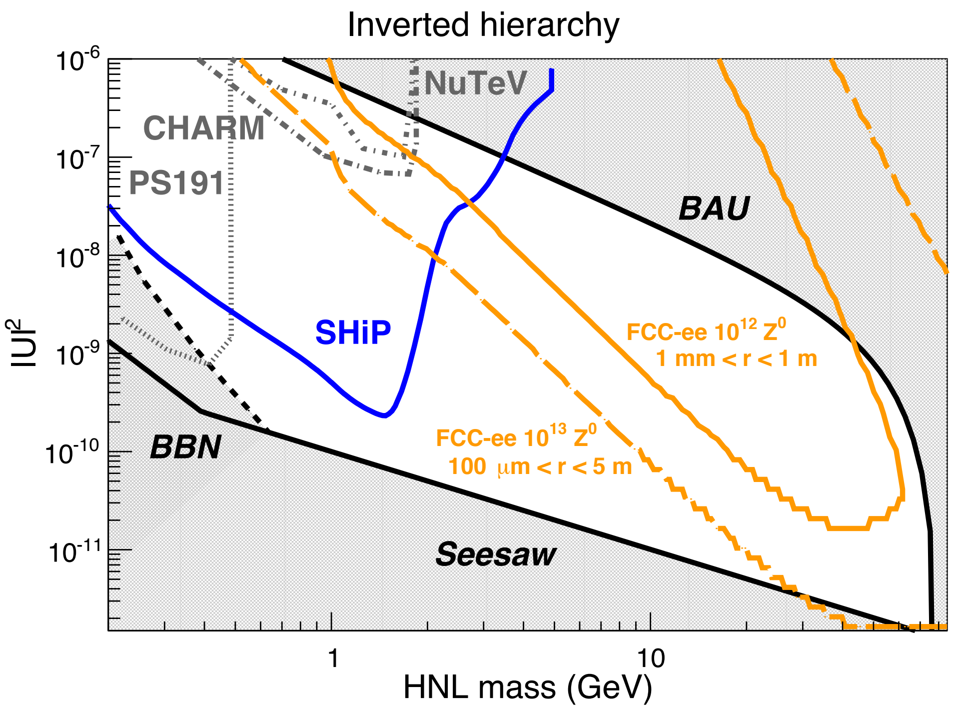
  - **Will require calculations up to three or four loops to gain an order of magnitude**
    - **Might need a new paradigm in the actual computing methods**
      - ➨ **Lot of interesting work for future generations of theorists**

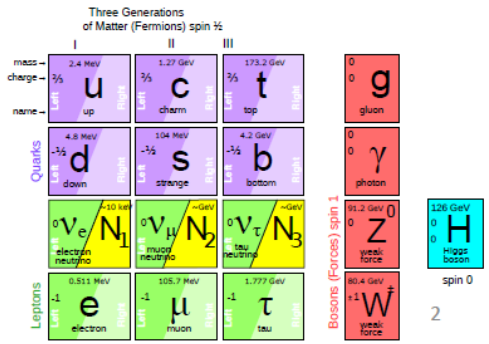
Opportunities for discoveries at FCC-ee

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

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

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





Precision 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 88-370 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

- **Understanding this physics <u>requires</u> an e^+e^- collider at the EW scale**
  - In an ideal world, this understanding can even profit from having two of them

- **Significant synergies (detectors) and real complementarities (physics)**
  - Between circular (FCC-ee, CEPC) and linear collider projects (ILC, CLIC)
    - FCC-ee offers the highest luminosities and discovery potential (Z, WW, ZH)
      - ➨ These features will remain unchallenged if a linear collider is built
    - Linear colliders can reach energies beyond 500 GeV
      - ➨ This advantage will remain unique if the FCC is built

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

- In practical terms
  - If a linear collider is built, the FCC-ee need not run at the top energy
    - Thus saving some RF cavities and running time
      - ➨ While remaining a real discovery machine
  - If FCC is built, a linear collider can concentrate on the highest energies
    - Where it is most effective and useful

- In a real world: both are technologically/politically/financially challenging
  - Both 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

- If a choice is to be made, high energy capabilities are essential to decide
  - 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 (soon!)

➨ High-energy frontier capabilities discussed in 3rd lecture

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

ARGUE & DEBATE !