Physics at Future Colliders

- **Lecture 1 (Wednesday 2 August, 10:25)**
  - **An historical perspective (1964-2017): 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 3 August, 10:25)**
  - **The quest for precision (2030-2050): Linear or circular?**

- **Lecture 3 (Thursday 3 August, 11:35)**
  - **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

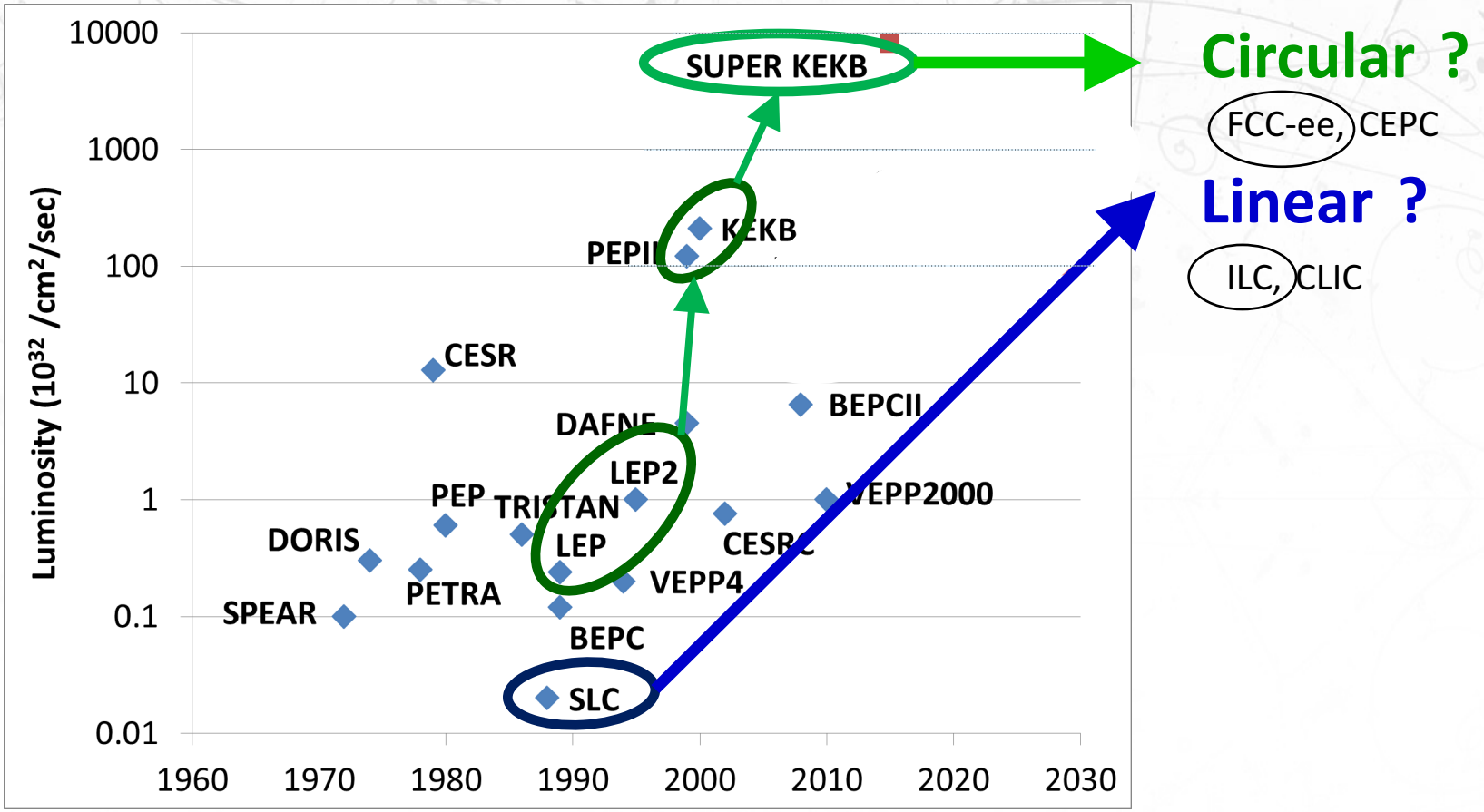
FCC (100 km)

First step: FCC-ee (88-400 GeV)

[Use the tunnel ultimately aimed at FCC-hh]

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

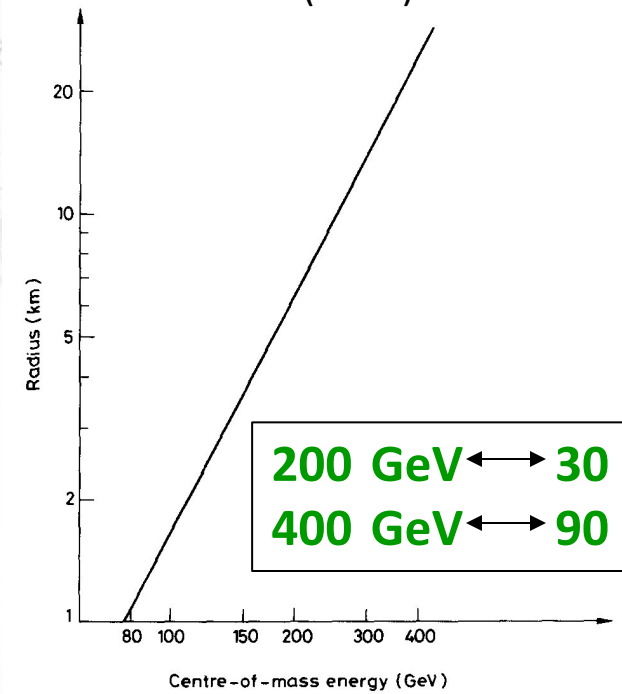
- Historically, e^+e^- colliders have been used for precision measurements
  - The accuracy of e^+e^- colliders led to predictions at higher scales (m_{top} , m_H , limits on NP)
    - And to [unexpected] discoveries (e.g., c quark, gluon, tau lepton, neutrino tau …)



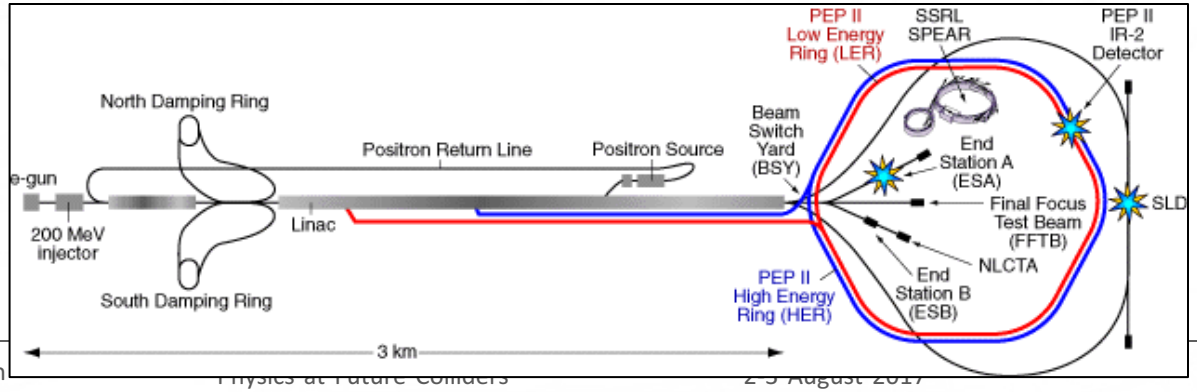
Precision with e^+e^- colliders (2)

- **The dilemma is not 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

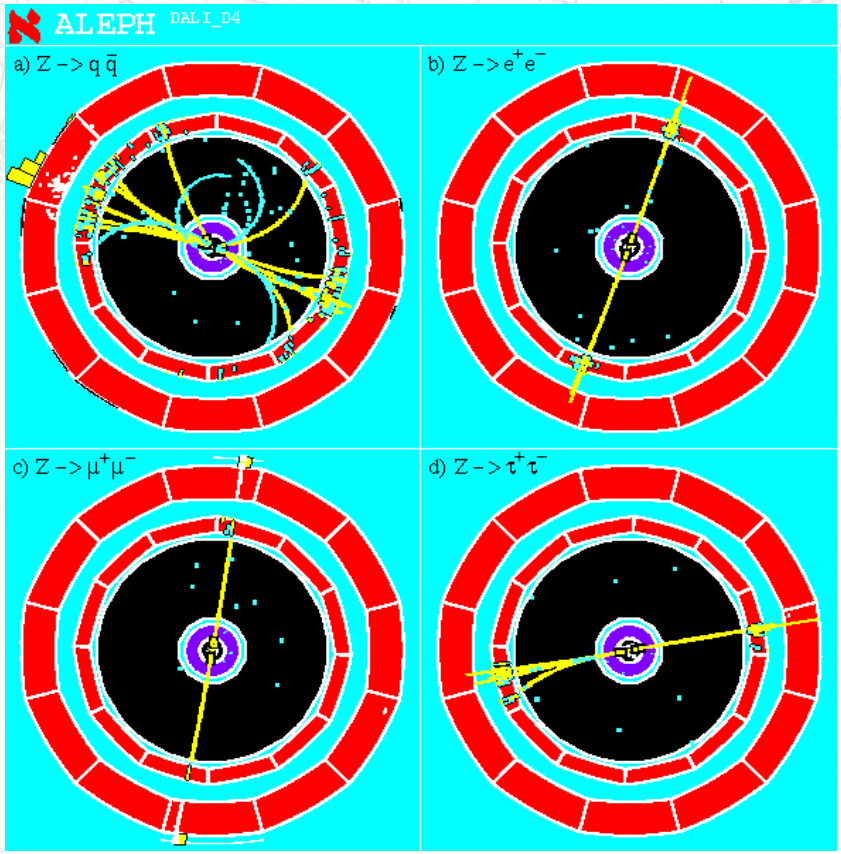


- **B. Richter, "The SLAC Linear Collider", 11th Conf. on High-Energy Accelerators (1980)**

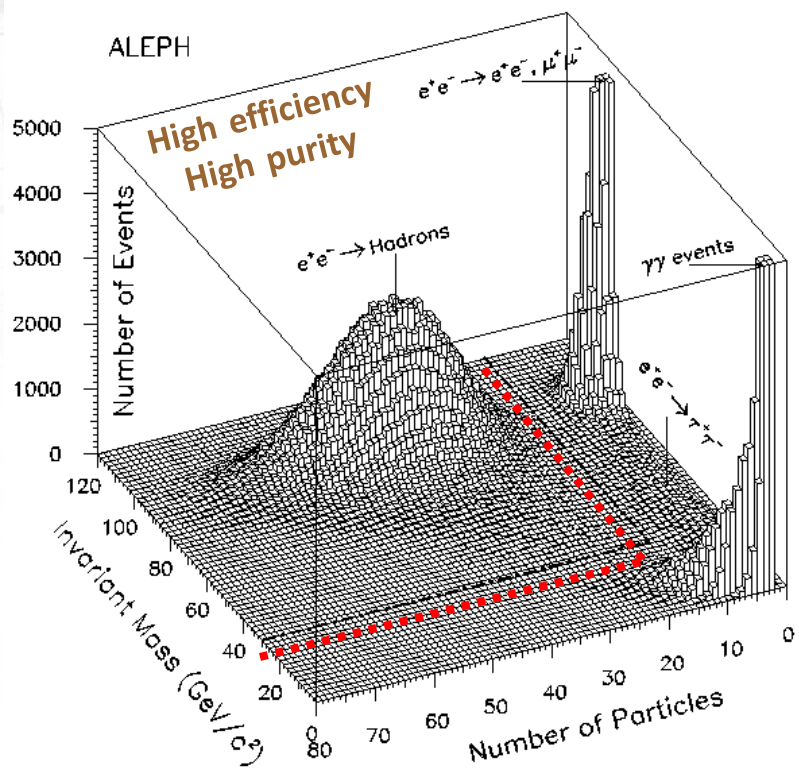


Precision with e^+e^- colliders (3)

- **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)**



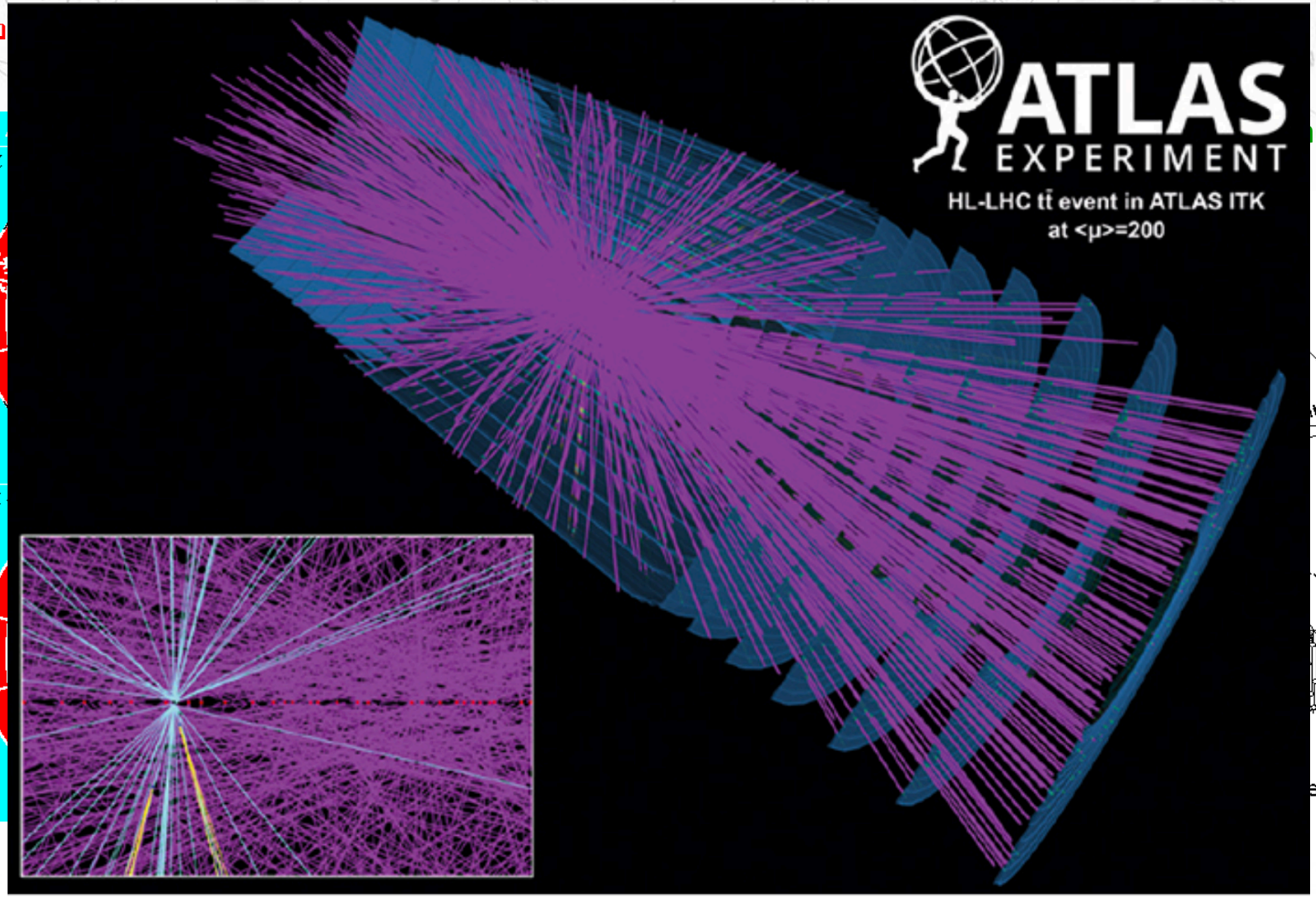
Analysis is a waking dream



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

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

- Why are e^+e^- colliders the tool of choice for precision anyway ?

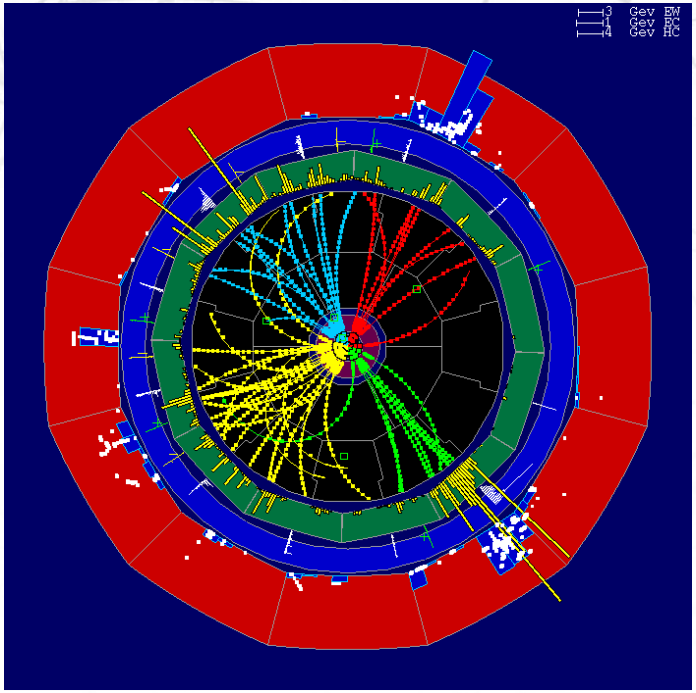


- Corollary #2: No huge QCD cross section: All events are signal.

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 #3: 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

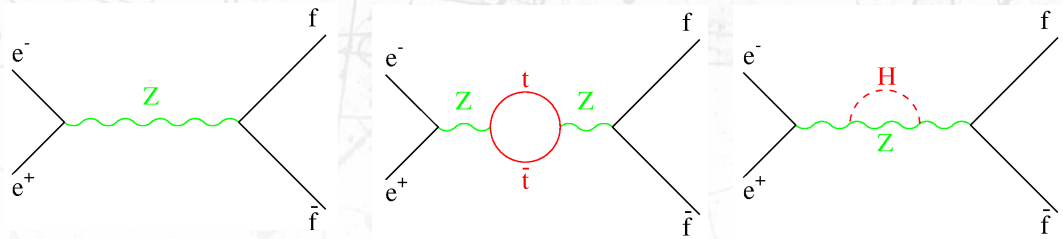
$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



    - Jet energies (and 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)

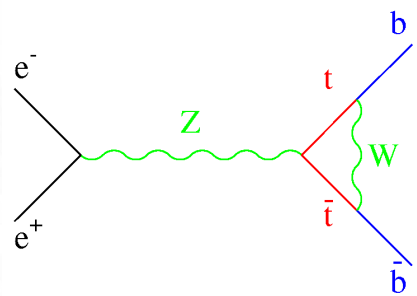
- **Why are e^+e^- colliders the tool of choice for precision anyway ? (cont'd)**
  - **Electroweak observables can be calculated/predicted with precision**
    - **And are sensitive to heavier particles through quantum corrections**
      - **At the Z pole**



m_{top} dependence
Weak m_H dependence

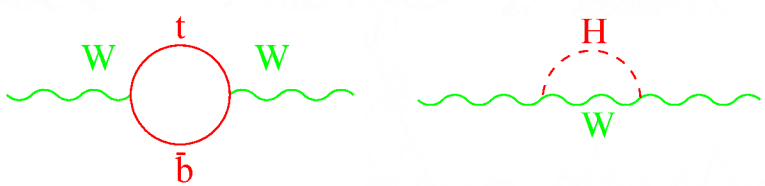
      - **Specific correction for Z decay to $b\bar{b}$**

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



No m_H dependence

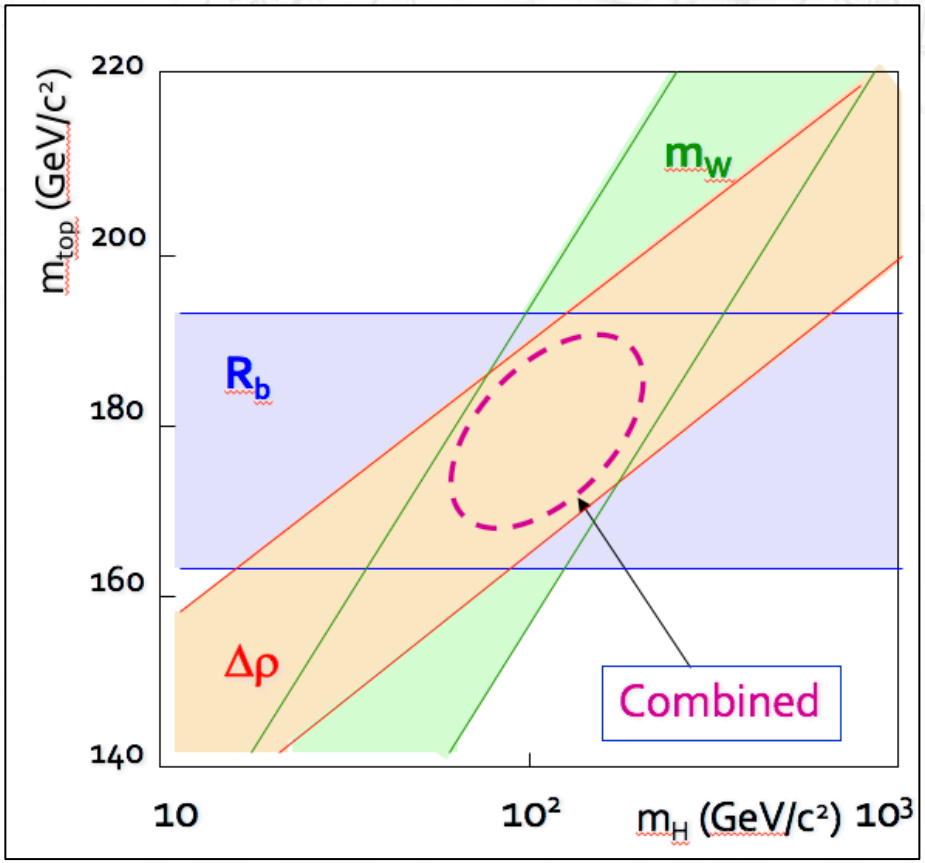
      - **W mass**



Different admixture of m_{top} and m_H dependence

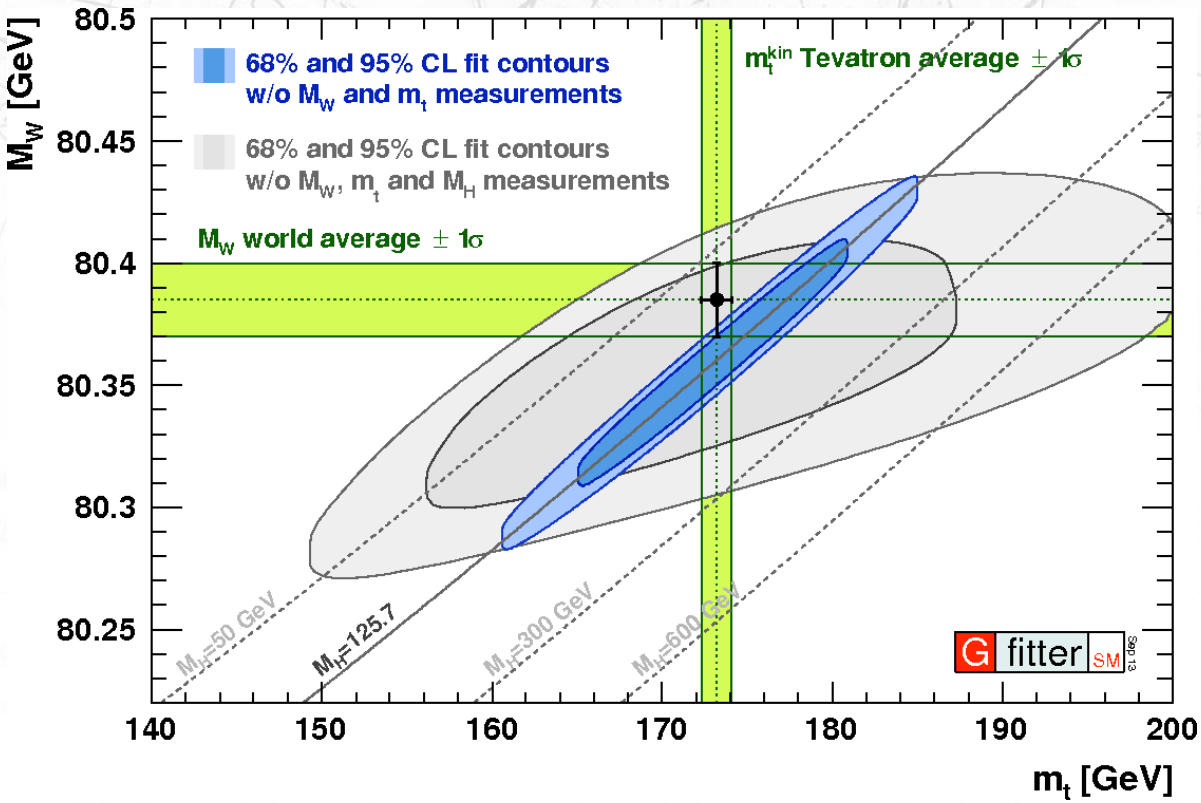
Precision with e^+e^- colliders (6)

- 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
      - Different observables – different dependence on m_{top} and m_H
        - Disentangle to get prediction for m_{top} and m_H



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

- **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**

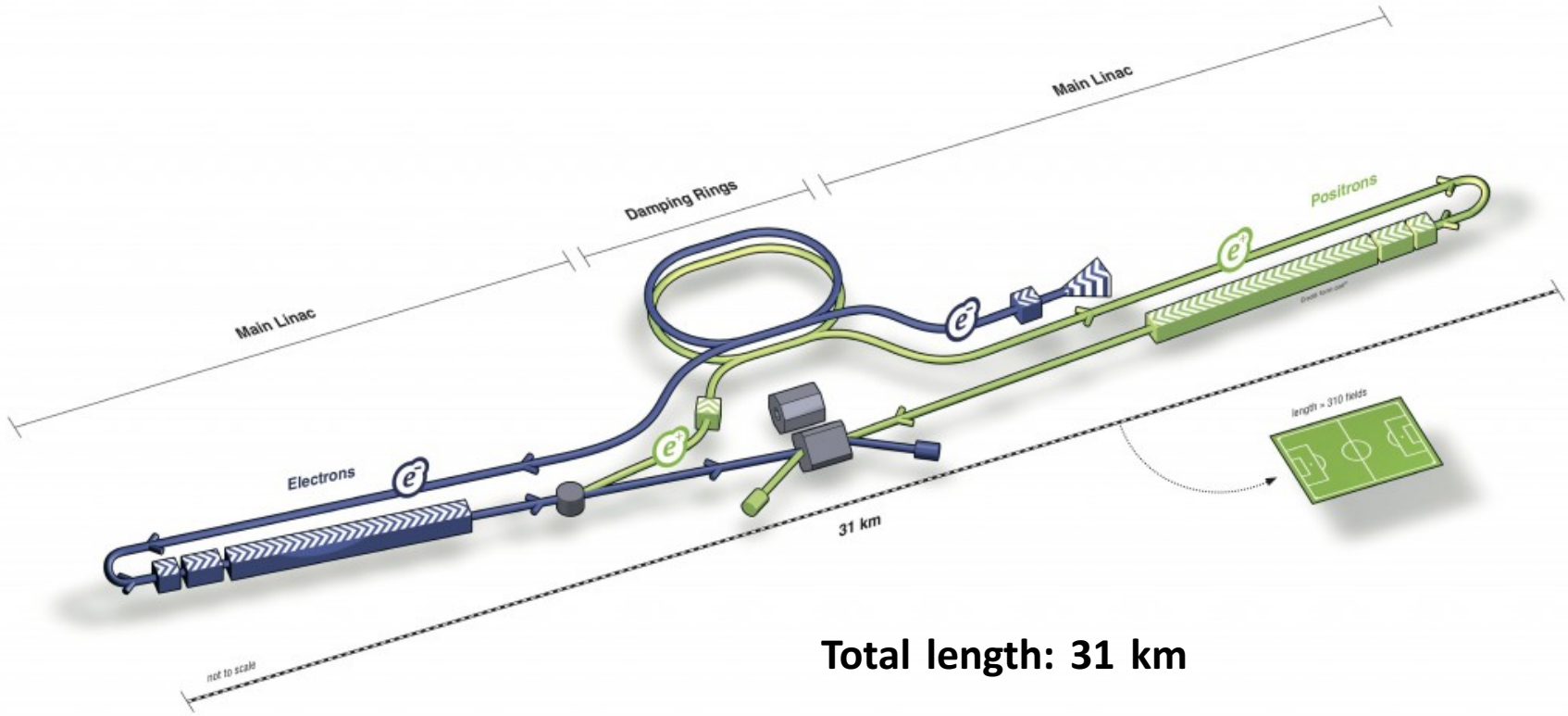
Precision with e^+e^- colliders (8)

- **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

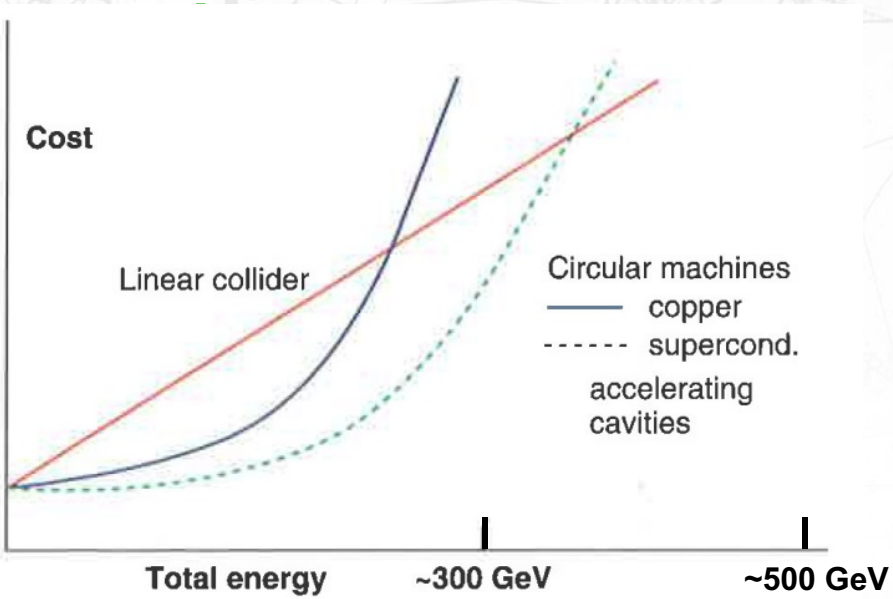


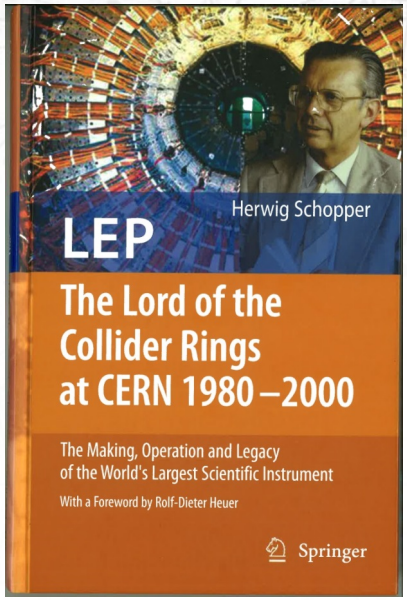
Total length: 31 km

- 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**





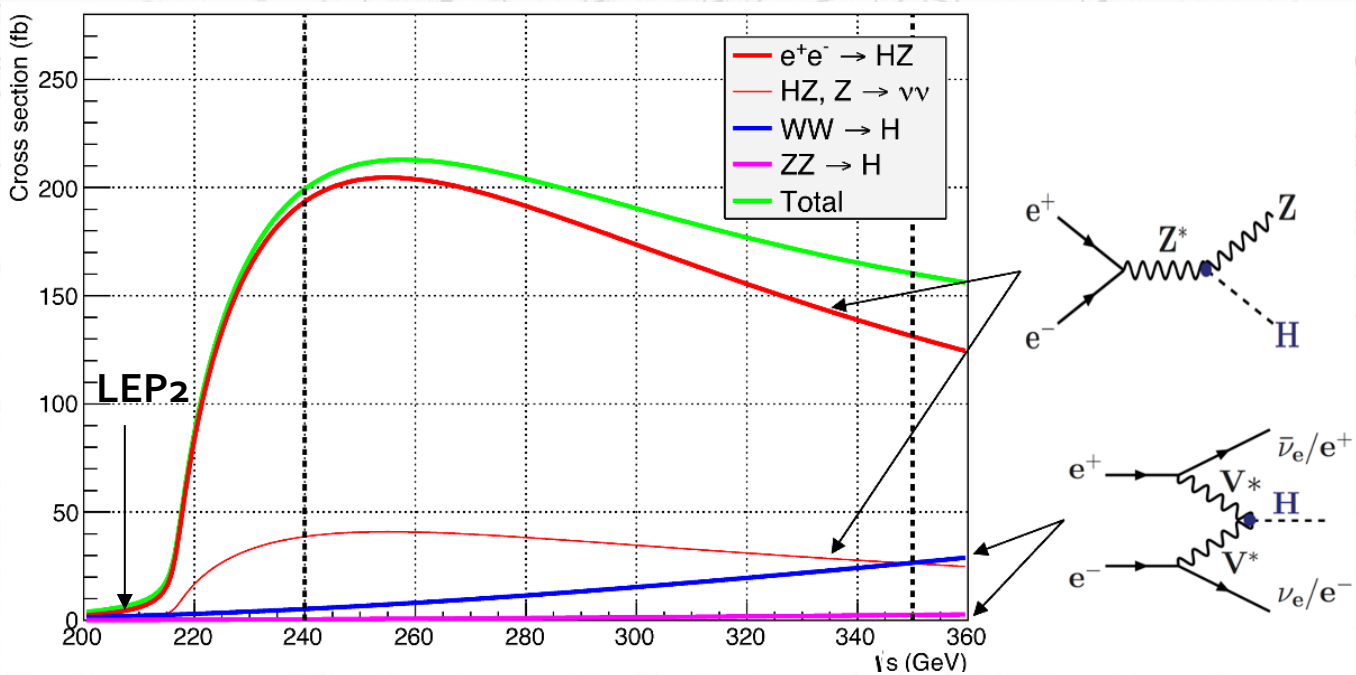
Author: Herwig Schopper (Former CERN DG)

- **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, 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 bosons and the top quark**
    - **Highest possible luminosities at 91, 160, 240 and 350 GeV are needed**

Linear or Circular ? (4)

- The ILC is designed for √s = 500 GeV (works OK at √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

D. Schulte

  - 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 to √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)

- 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 four years old
    - Lots of progress has been already made
      - Technology ready… on paper

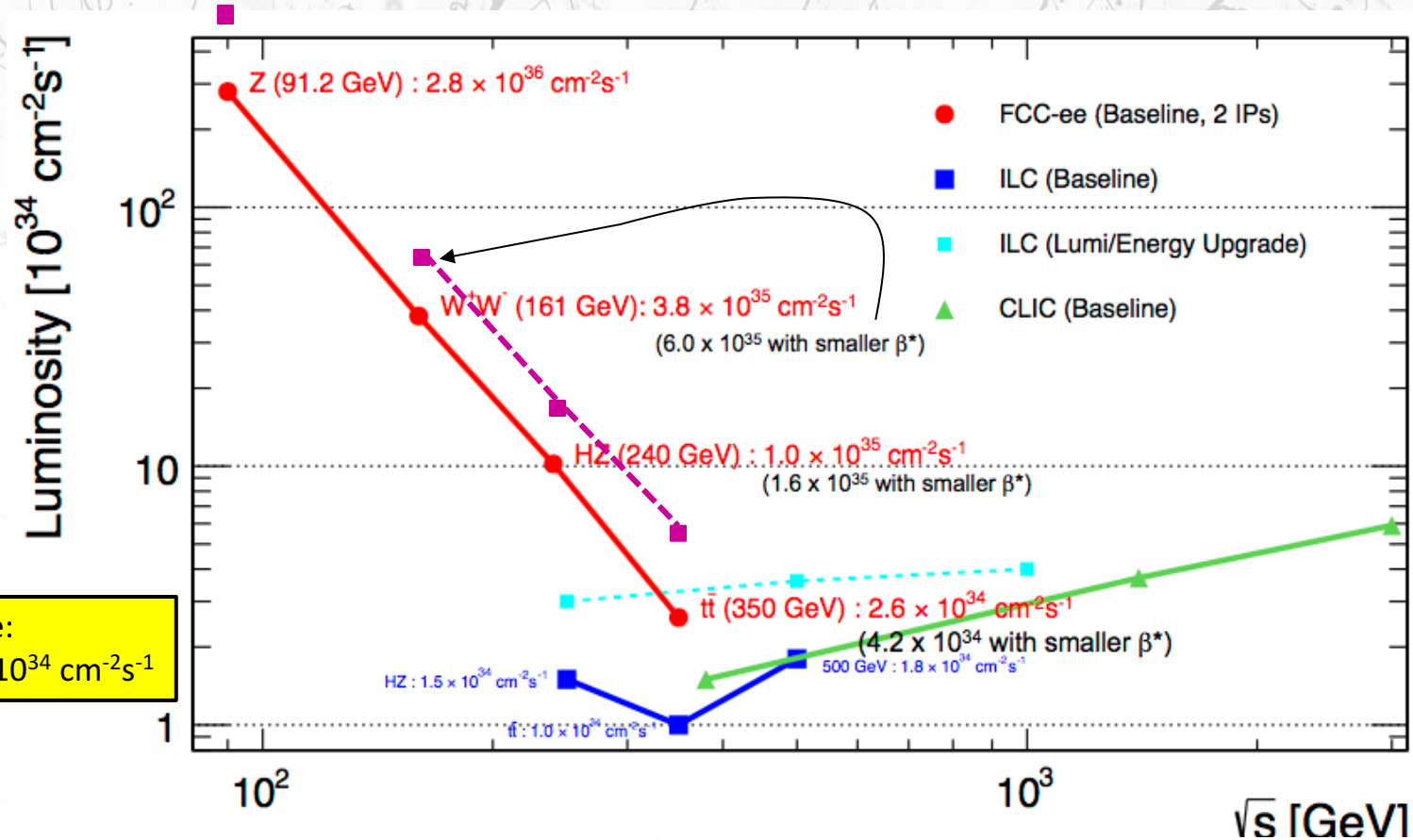
D. Schulte

  - 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 will be addressed at SuperKEKB
      - 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



LEP@Z-pole:
L = 0.01 x 10^{34} cm^{-2}s^{-1}

- **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)	30	4	1	0.3	0.3
Events/year	1.5×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}	2.0×10^{4}
# years	6	2	5	5	
Events@FCCee	10^{13}	3×10^{7}	10^{6}	10^{6}	10^{5}

    - **Total running time of ~18 years (~10 years with recent more optimistic lumi numbers)**

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

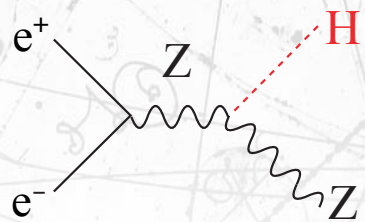
# years	3 ? (*)	3 ? (*)	3	1	4
Tot lumi (ab^{-1})	0.1	0.5	0.5	0.2	0.5
Events@ILC	3×10^{9} (*)	2×10^{6} (*)	1.4×10^{5}	10^{5}	3.5×10^{4}

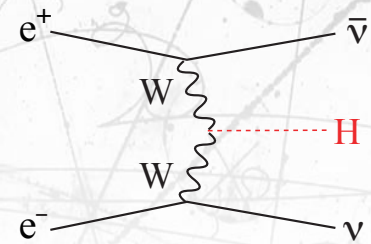
(*) No design available at the Z pole and the WW threshold: non-trivial to achieve with a linear collider

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

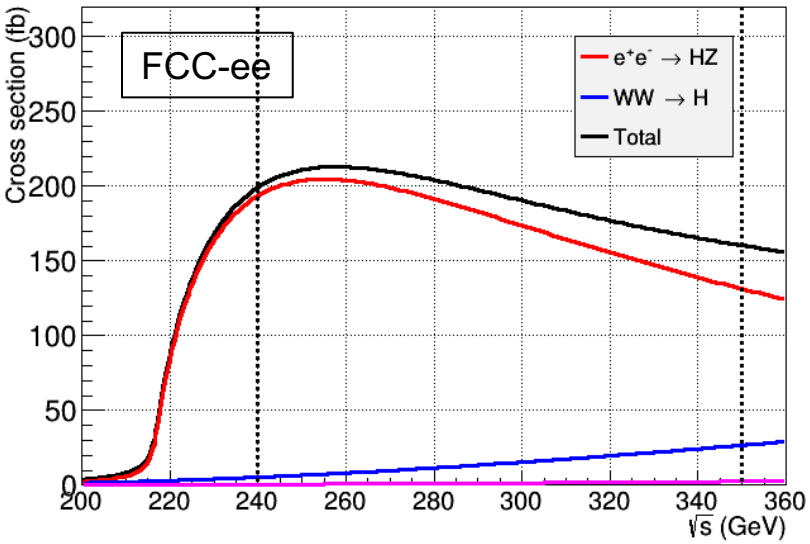
- **Dominant production processes for √s ≤ 500 GeV**

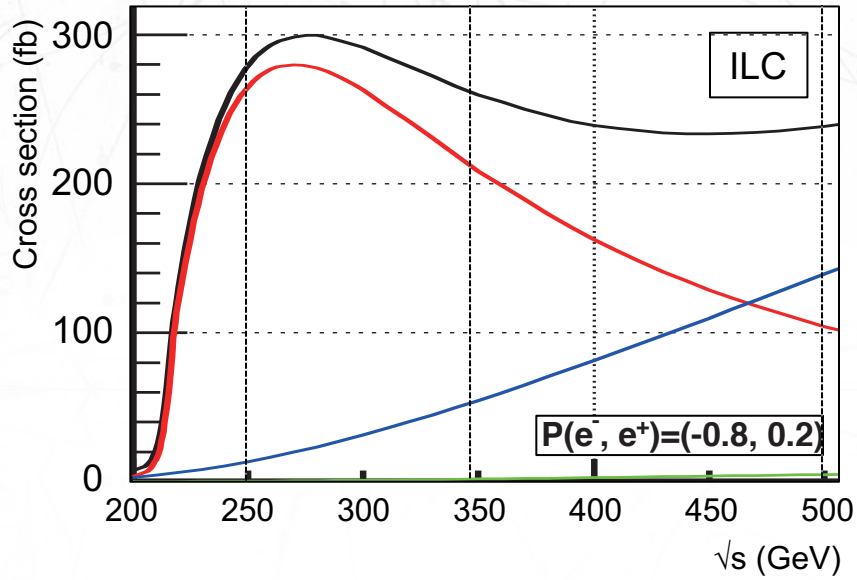
Higgs-strahlung





Boson fusion



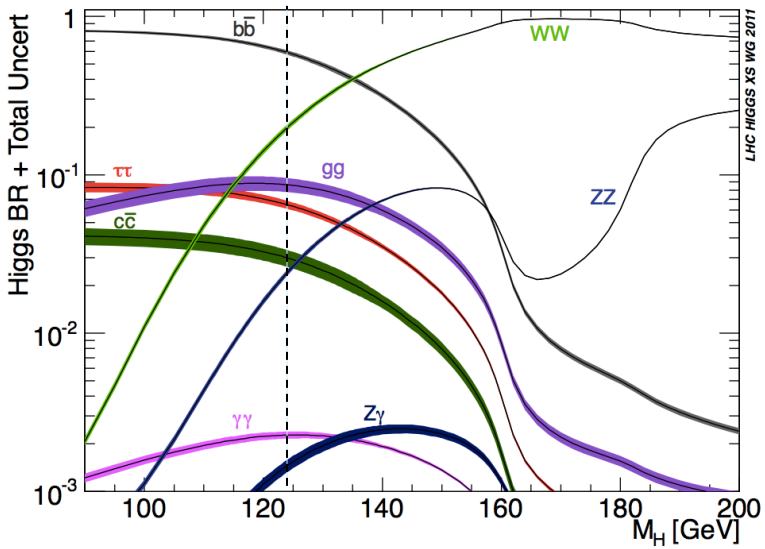


- **Effect of beam polarization (exercise)**
  - **Higgs-strahlung cross section multiplied by $1 - P_-P_+ - A_e \times (P_- - P_+)$**
  - **Boson fusion cross section multiplied by $(1-P_-) \times (1+P_+)$**

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 $\sigma(e^+e^- \rightarrow H + X) \times BR(H \rightarrow YY)$

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

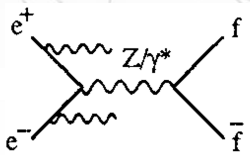


m_H = 125 GeV		
Decay	BR [%]	Unc. [%]
bb	57.7	3.3
ττ	6.32	5.7
cc	2.91	12.2
μμ	0.022	6.0
WW	21.5	4.3
gg	8.57	10.2
ZZ	2.64	4.3
γγ	0.23	5.0
Zγ	0.15	9.0
ΓH [MeV]	4.07	4.0

- 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

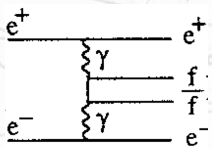
Precision Higgs physics at FCC-ee and ILC (3)

- **Physics backgrounds are "small"**
  - **For example, at √s = 240 GeV**



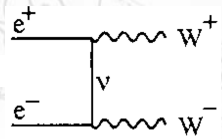
$e^+e^- \to q\bar{q}, l^+l^-$

60 pb



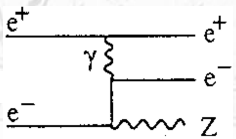
$\gamma\gamma \to q\bar{q}, l^+l^-$
m > 30 GeV

30 pb



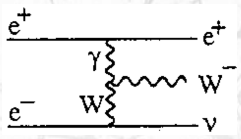
$e^+e^- \to W^+W^-$

16 pb



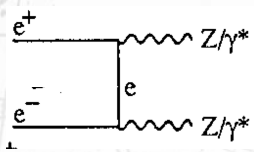
$e^+e^- \to Ze^+e^-$

3.8 pb



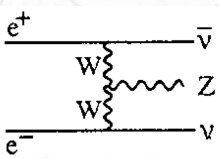
$e^+e^- \to We\nu$

1.4 pb



$e^+e^- \to ZZ$

1.3 pb



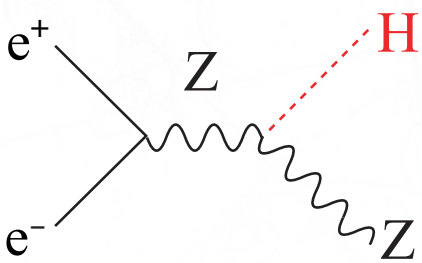
$e^+e^- \to Z\nu\bar{\nu}$

32 fb

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

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

- **To be compared to**

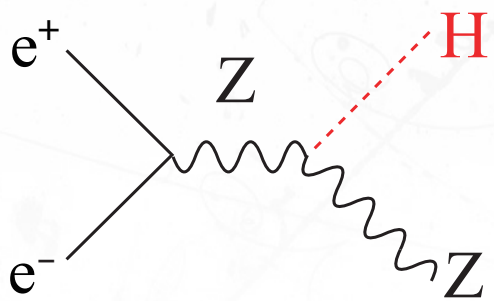


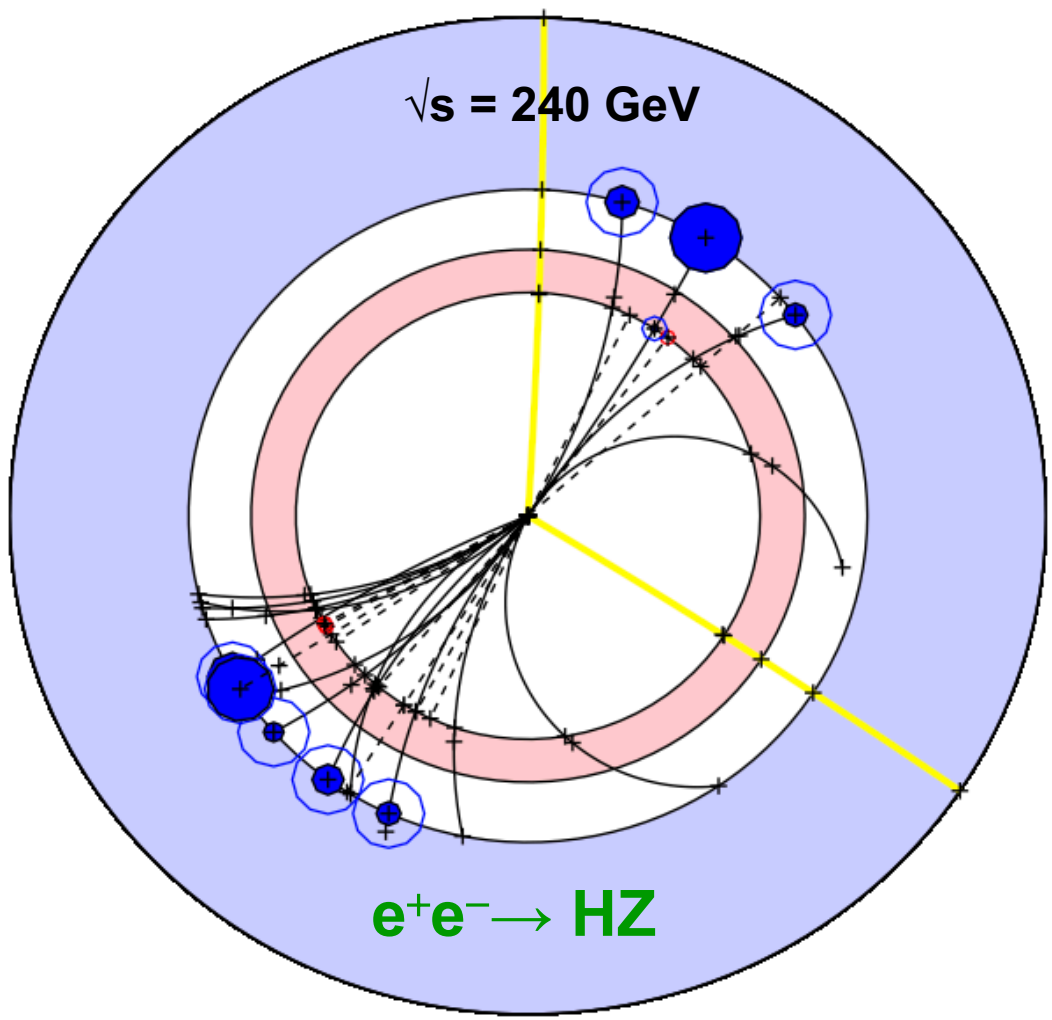
200 fb

- **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)

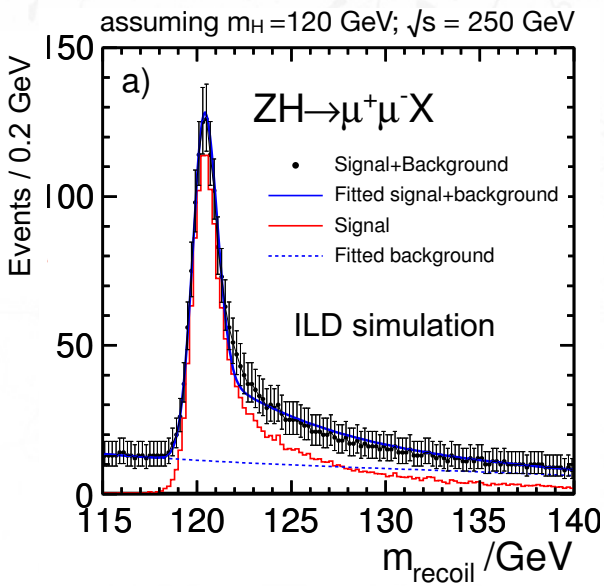
- **Example of a Higgs boson event**
  - **Tagged with a Z boson**
  - **Very clean signature**

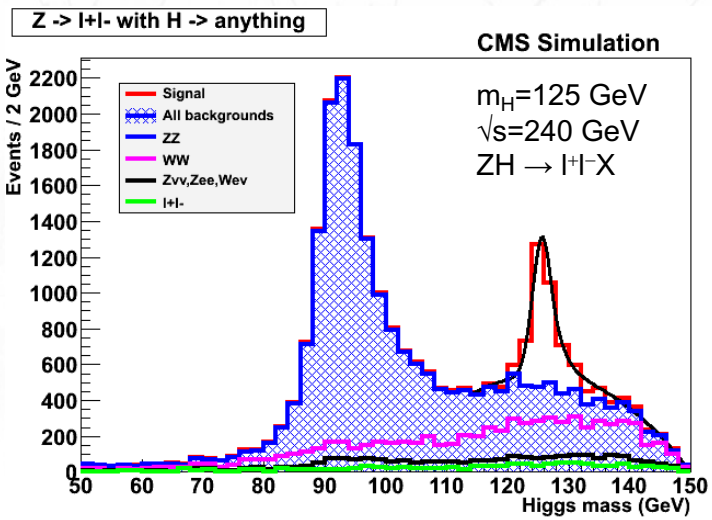




Precision Higgs physics at FCC-ee and ILC (5)

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





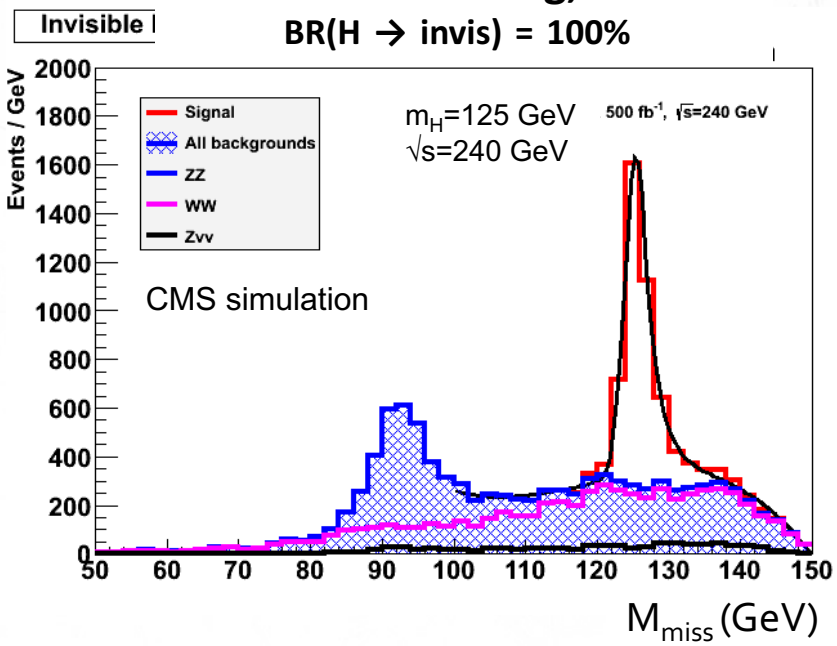
- **Provides an absolute measurement of κ_Z and set required detector performance**

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

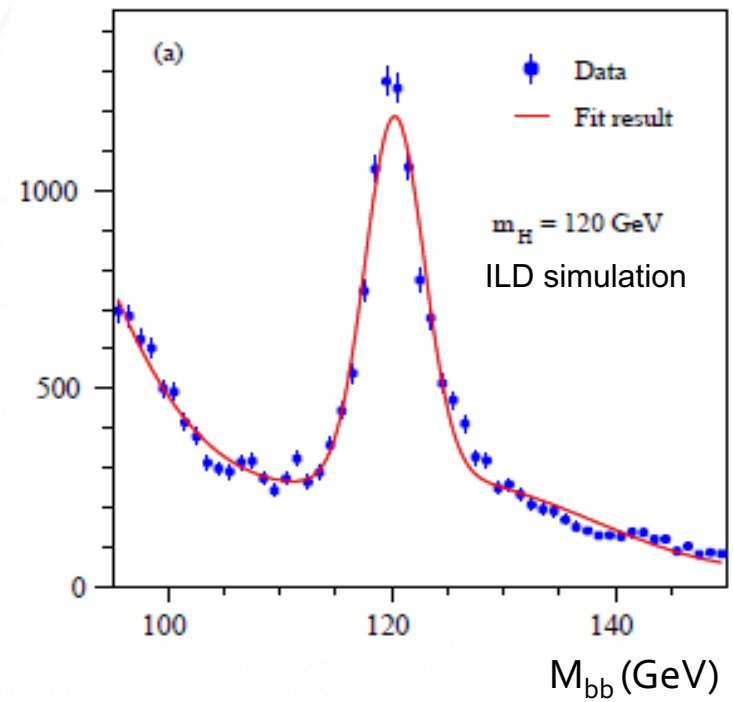
- Repeat the search in all possible final states
  - For all exclusive decays of the Higgs boson: measure $\sigma_{HZ} \times BR(H \rightarrow YY)$
    - Including invisible decays
      - event containing only the lepton pair with correct (m_{miss}, m_{recoil}), else empty
    - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics
  - For the WW fusion mode ($H\nu\bar{\nu}$ final state): measure $\sigma_{WW\rightarrow H} \times BR(H \rightarrow YY)$

$ZH \rightarrow l^+l^- +$ nothing, 0.5 ab^{-1}

BR(H → invis) = 100%

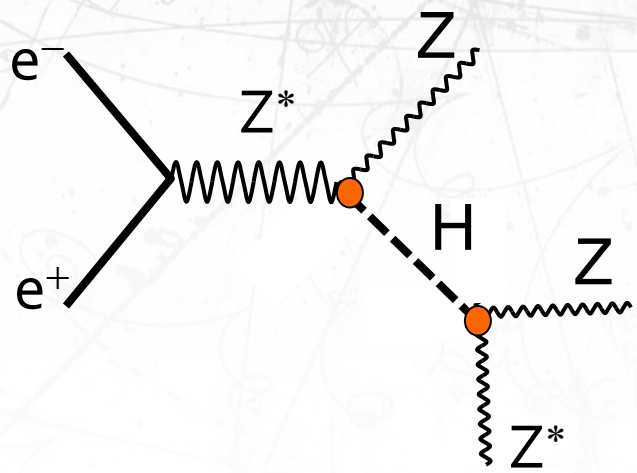


$ZH \rightarrow q\bar{q}\ b\bar{b}$, 0.25 ab^{-1}



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 √s = 240 GeV**
    - **Measure $\sigma_{HZ} \times BR(H \to ZZ)$**



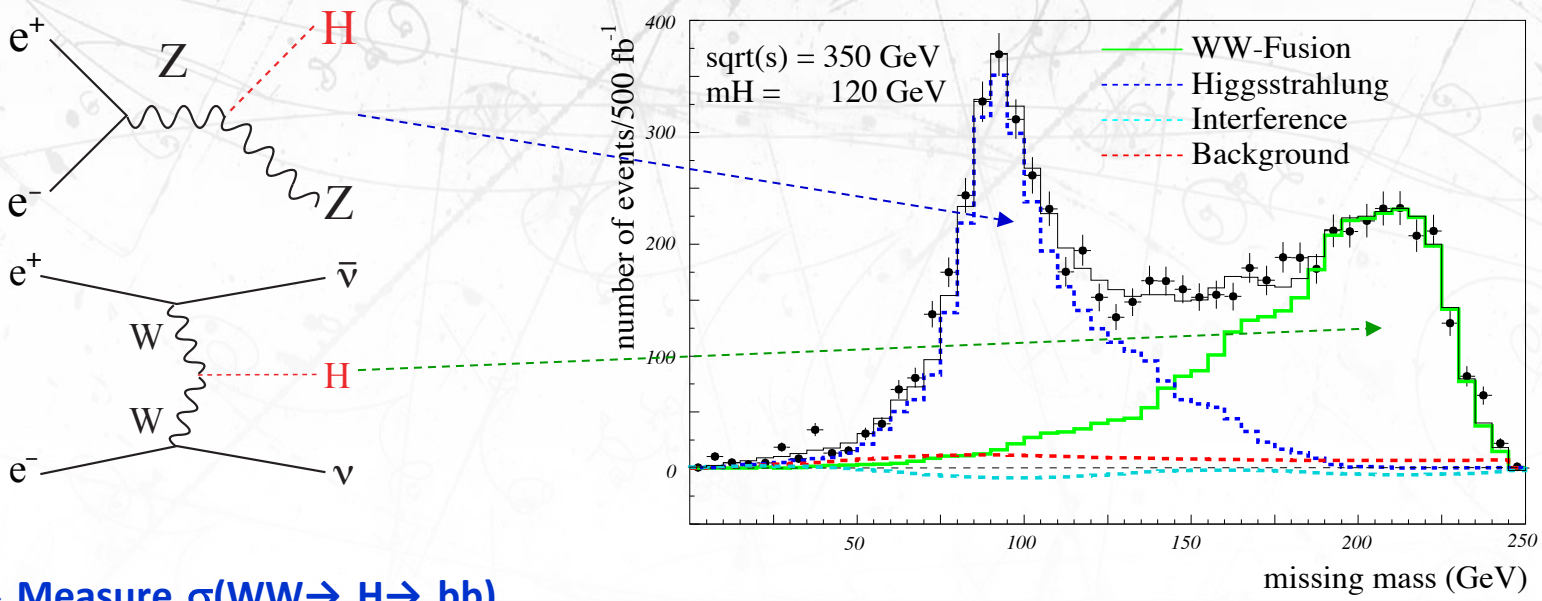
Final state with three Z's
Almost background free

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

- σ_{HZ} is proportional to κ_Z^2
- $BR(H \to ZZ) = \Gamma(H \to ZZ) / \Gamma_H$ is proportional to κ_Z^2/Γ_H
  - $\sigma_{HZ} \times BR(H \to ZZ)$ 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

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

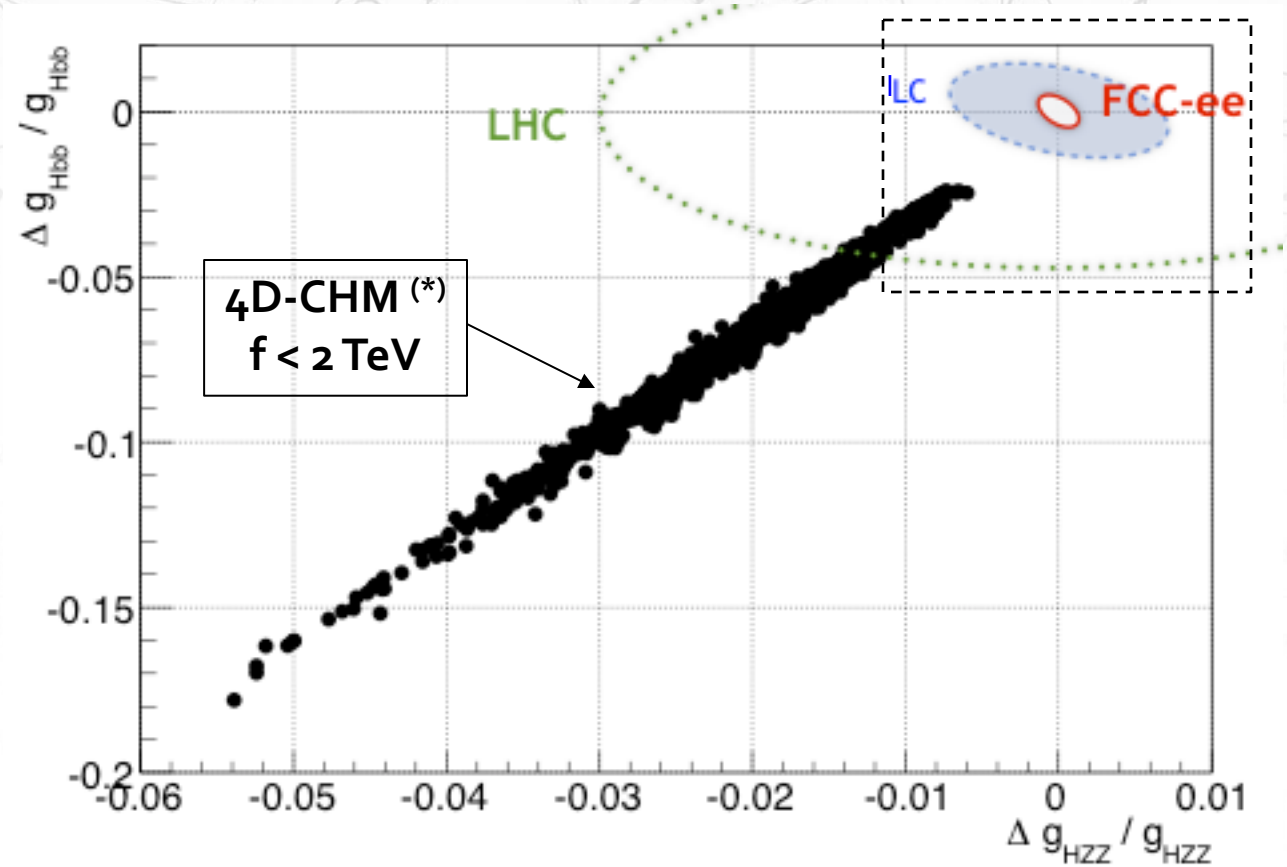
Sensitive to light dark matter particles (sterile ν, χ, …) and to other exotic decays

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)

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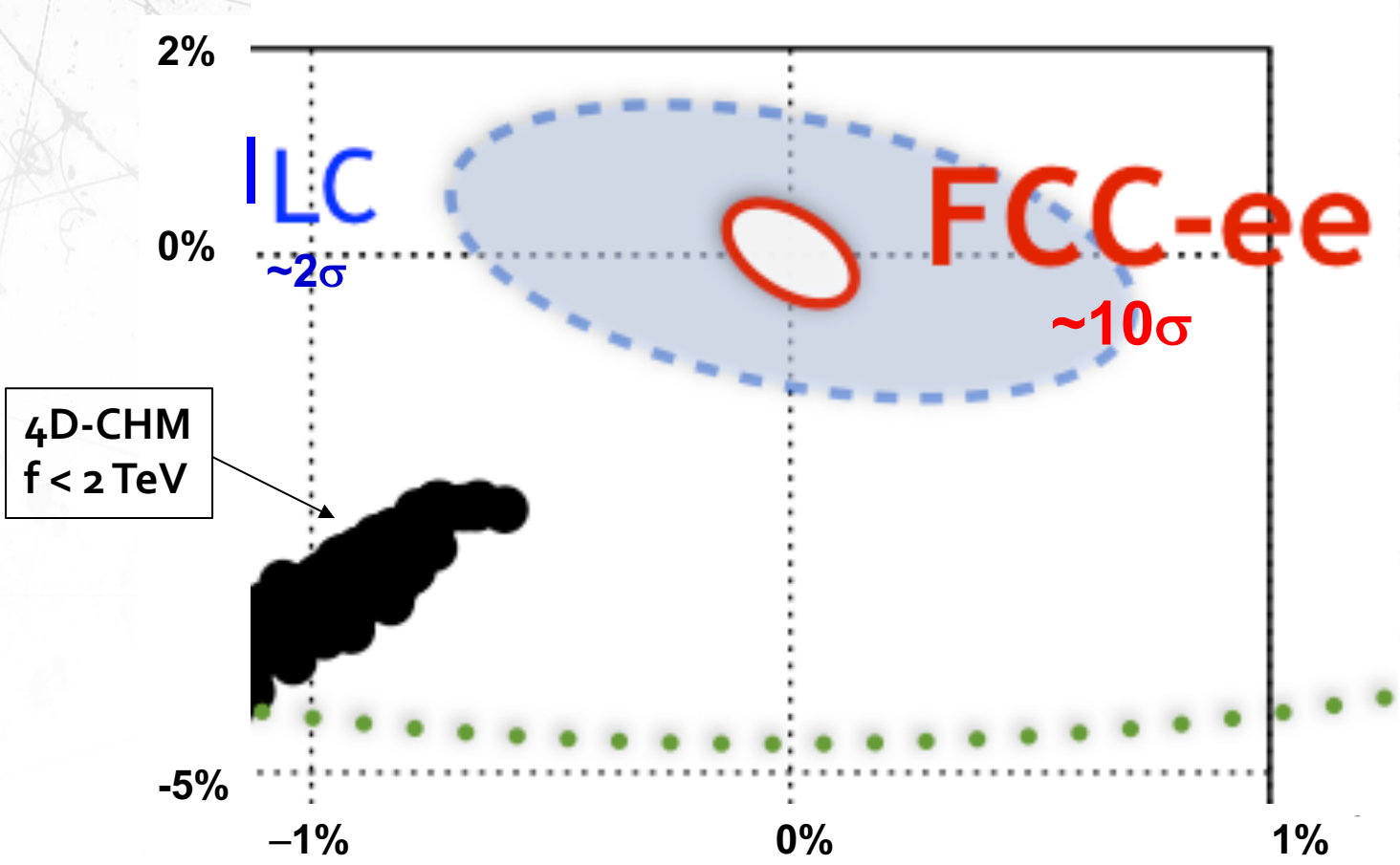
  - Example: Effect on κ_Z and κ_b for 4D-Higgs Composite Models



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	5-6 years	10^{12} (10^{13}) Z decays (Tera-Z)	3×10^{9} (*)	2×10^{7}
161	2 years	3×10^{7} WW pairs (Oku-W)	2×10^{6} (*)	4×10^{4}
350	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 3,000 times the ILC targeted statistics at the same energies**
  - **10^5 times more Zs and 10^3 times more Ws than LEP1 and LEP2**
    - **Potential statistical accuracies are mind-boggling !**

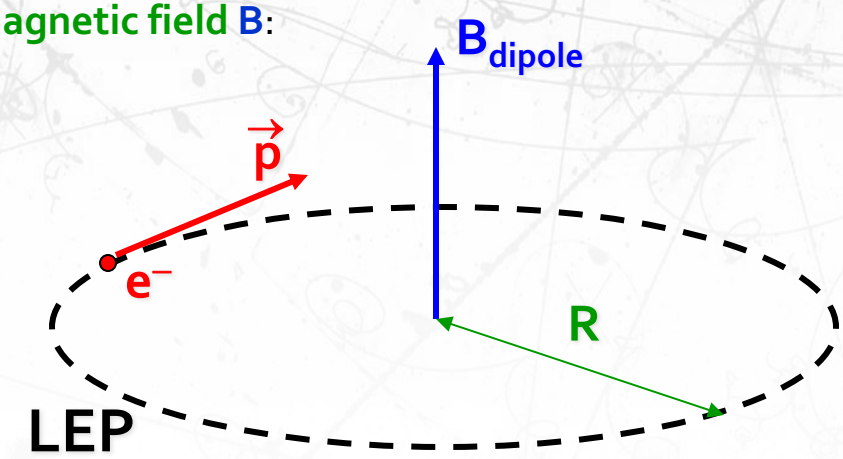
- **Predicting accuracies with 200 times smaller statistical precision than at LEP is difficult**
  - **Conservatively, use LEP experience for systematics. This is just the start**

- **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

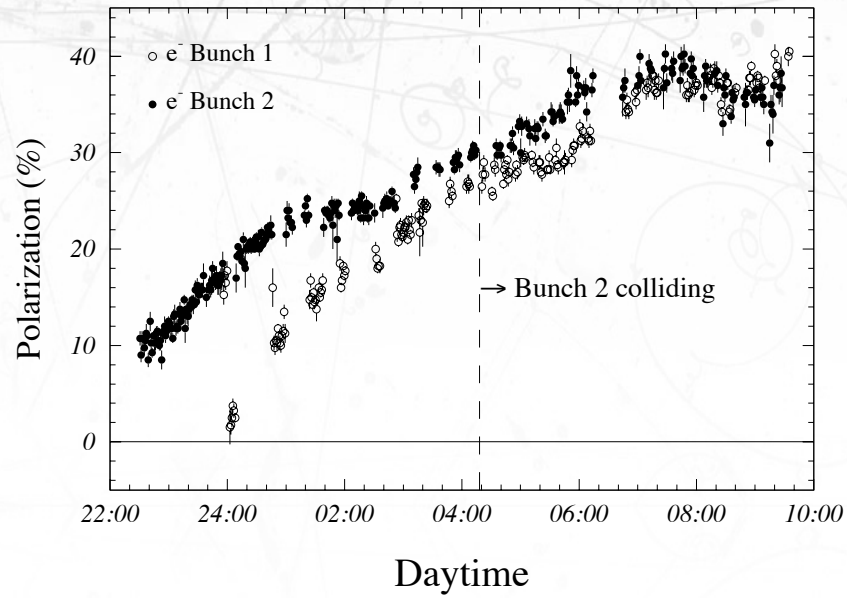
E ~ p = e B R = (e/2π) B L

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)



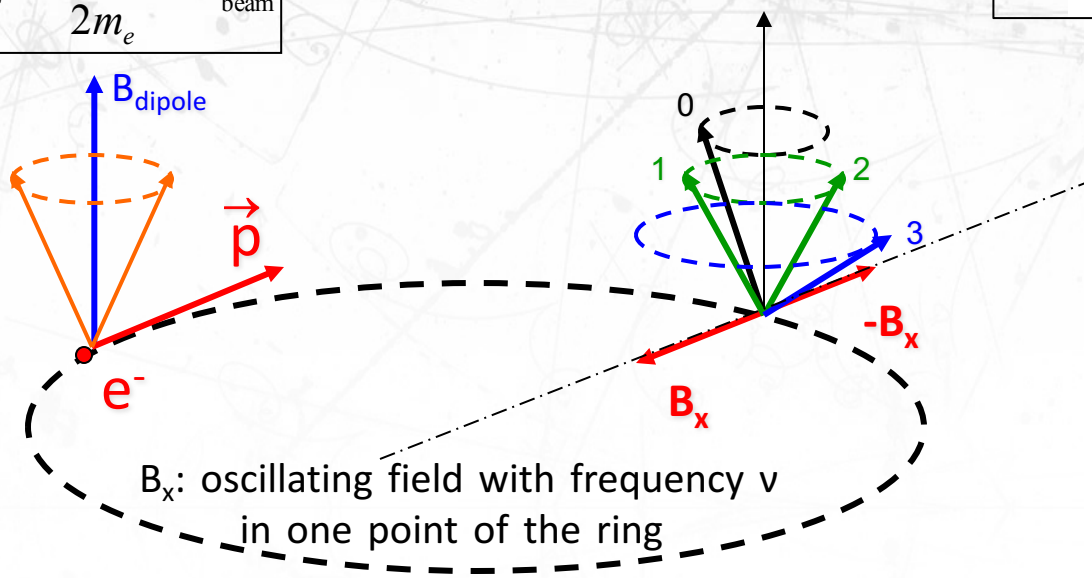
Slow process (~ 1 hour to get 10% polarization)

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

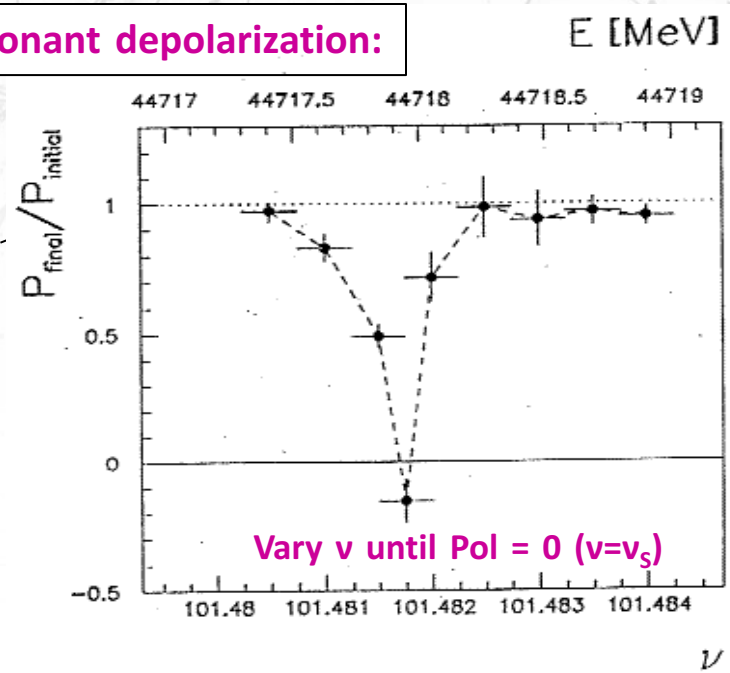
Precision electroweak physics at FCC-ee (3)

- **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)**

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



Resonant depolarization:

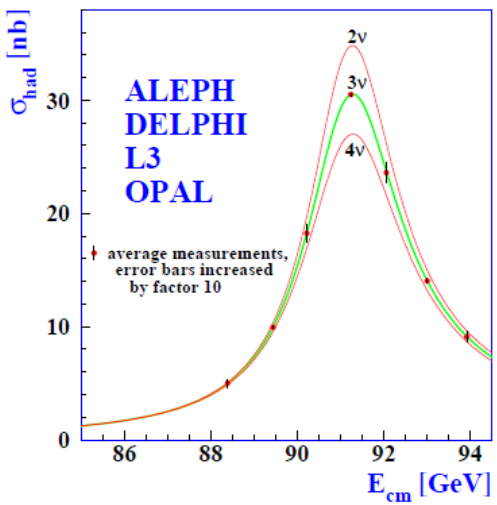


- **LEP was colliding 4 bunches of e^+ and e^-; FCC-ee will have 10,000's of bunches**
  - **Use ~100 "single" bunches to measure E_{BEAM} with resonant depolarization**
    - **Each measurement gives 100 keV precision, with no extrapolation uncertainty**

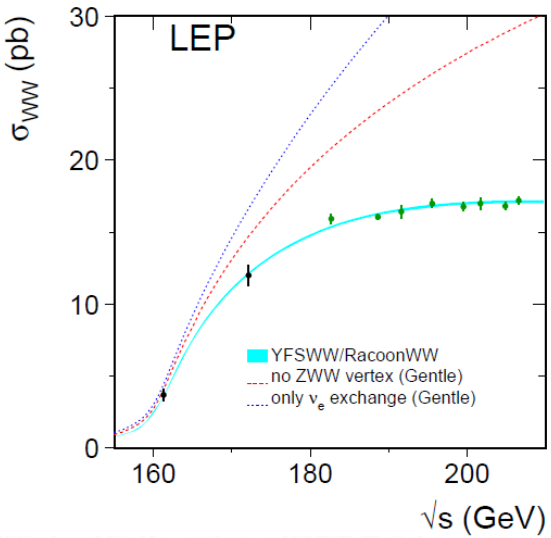
Precision electroweak physics at FCC-ee (4)

- EW precision measurements at FCC-ee (see arXiv:1308.6176)

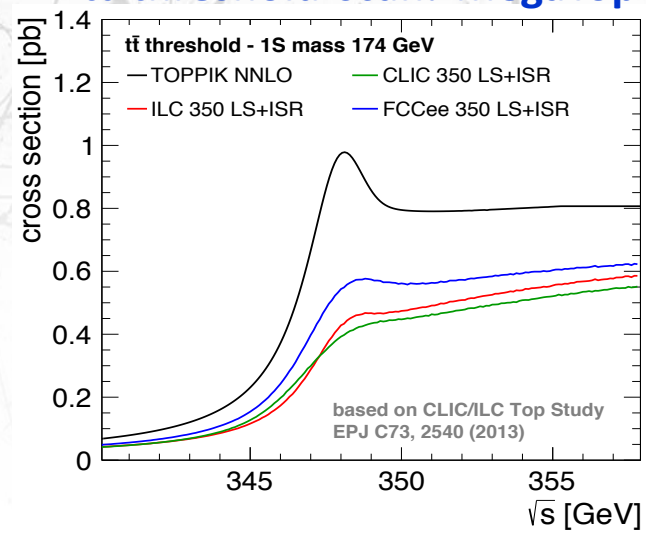
Z reconance: TeraZ



WW threshold scan: OkuW



$t\bar{t}$ threshold scan: MegaTop



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)

Threshold scan

- m_W to 0.5 MeV (15 MeV)

Branching ratios R_l, R_b

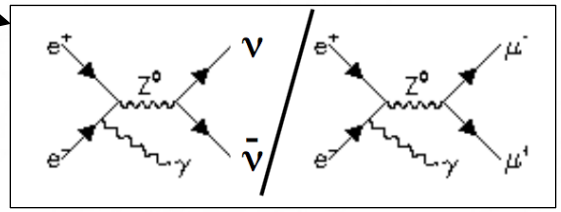
- $\alpha_S(m_Z)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

- N_ν to 0.0004 (0.008)

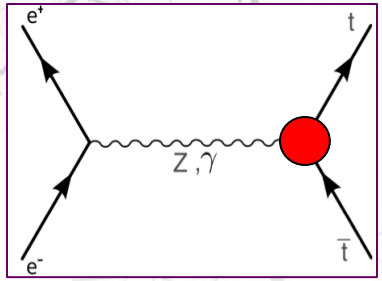
Threshold scan

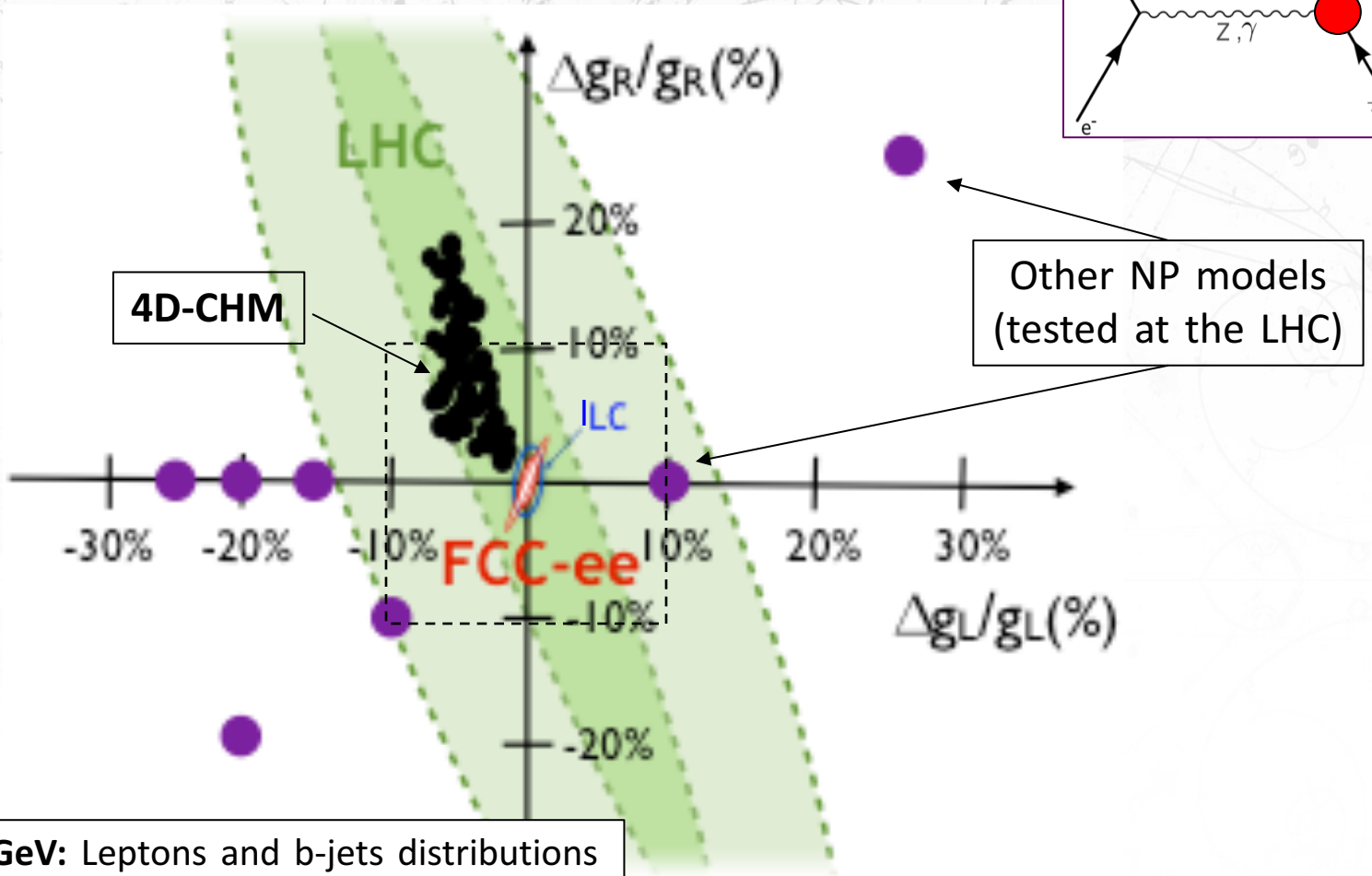
- m_{top} to 10 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 1%



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**





FCC-ee@370 GeV: Leptons and b-jets distributions
ILC@500 GeV: Total rate and A_{FB}^{tt}

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**
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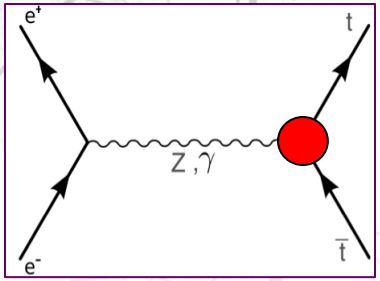
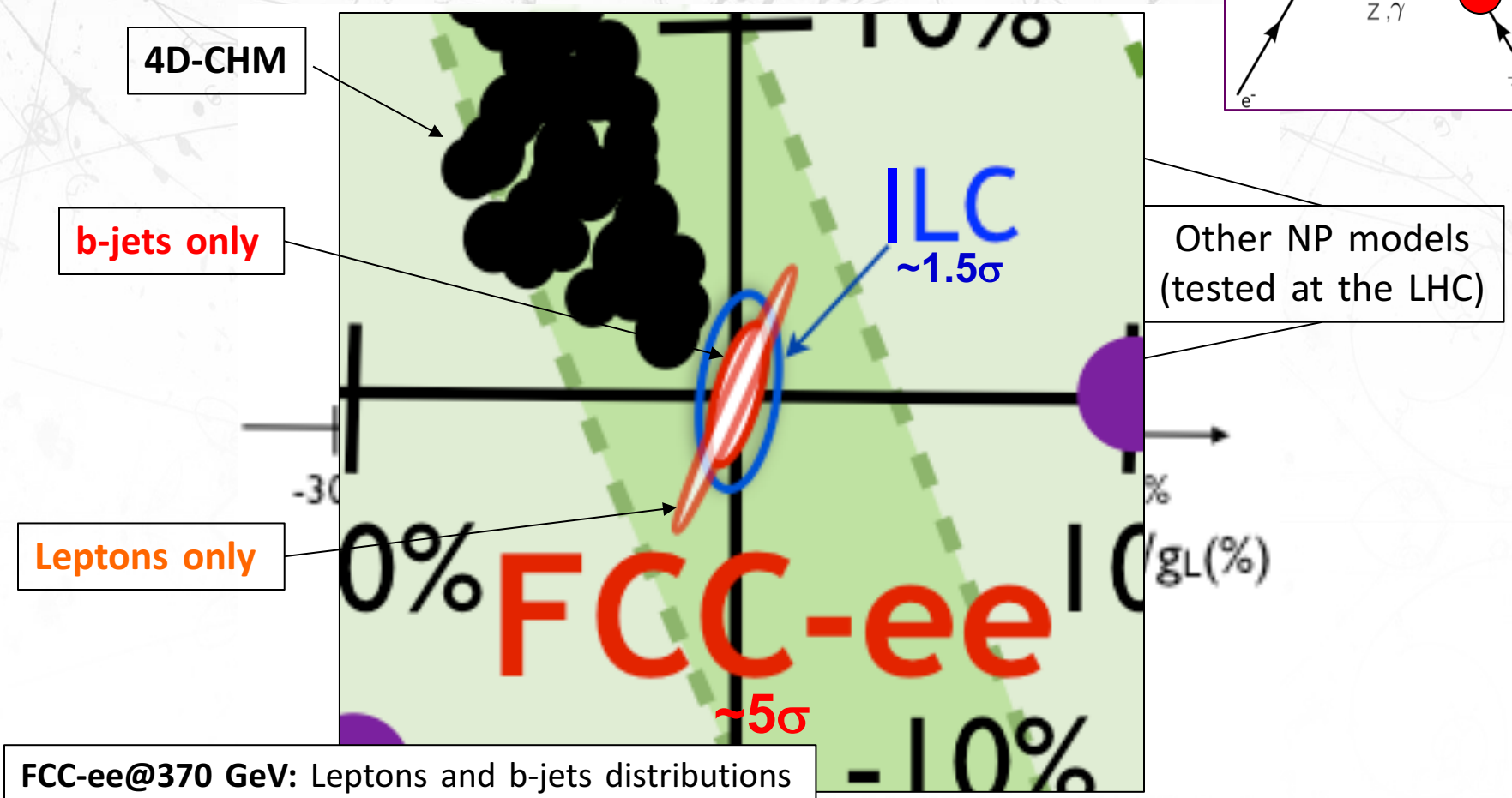
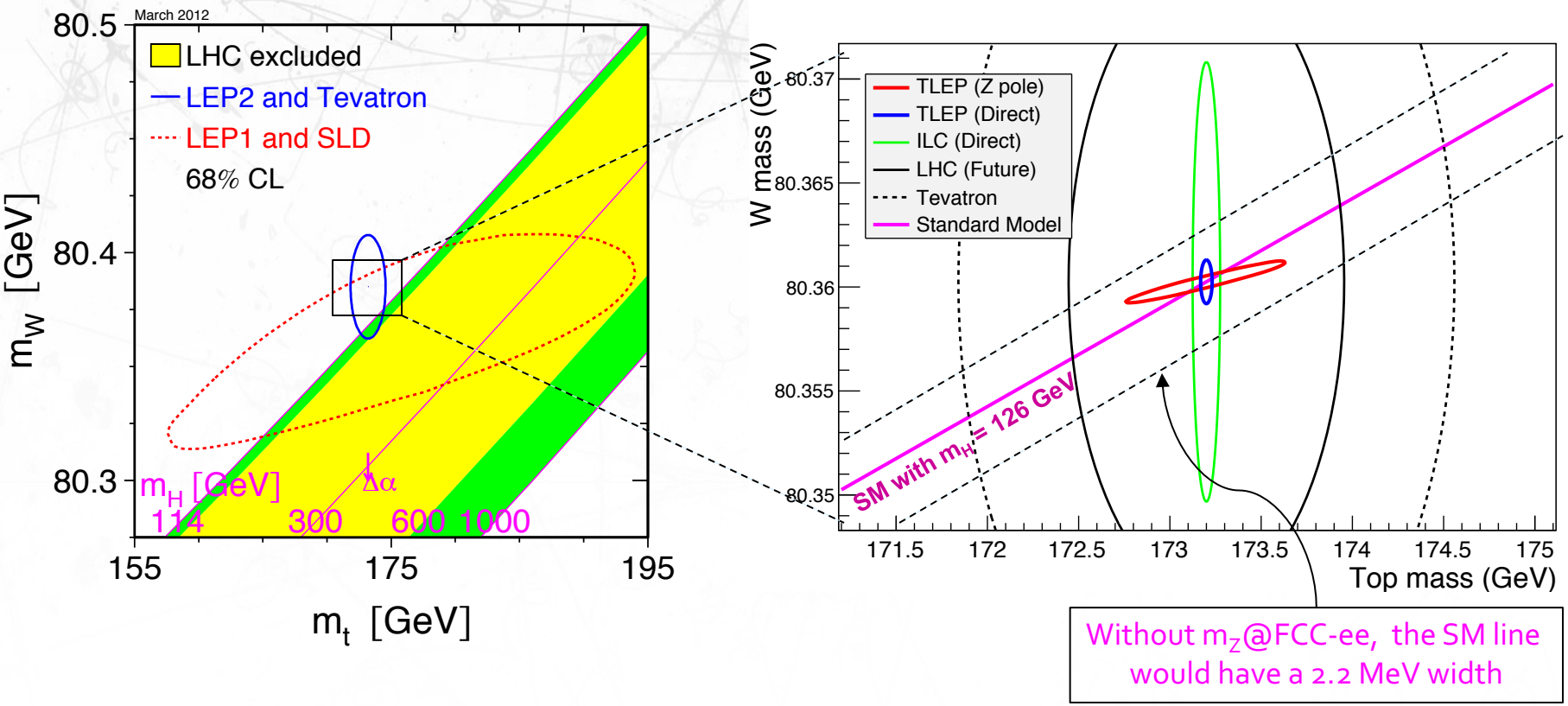




FCC-ee@370 GeV: Leptons and b-jets distributions
ILC@500 GeV: Total rate and A_{FB}^{tt}

Precision electroweak physics at FCC-ee (6)

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



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

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

Precision electroweak physics at FCC-ee (7)

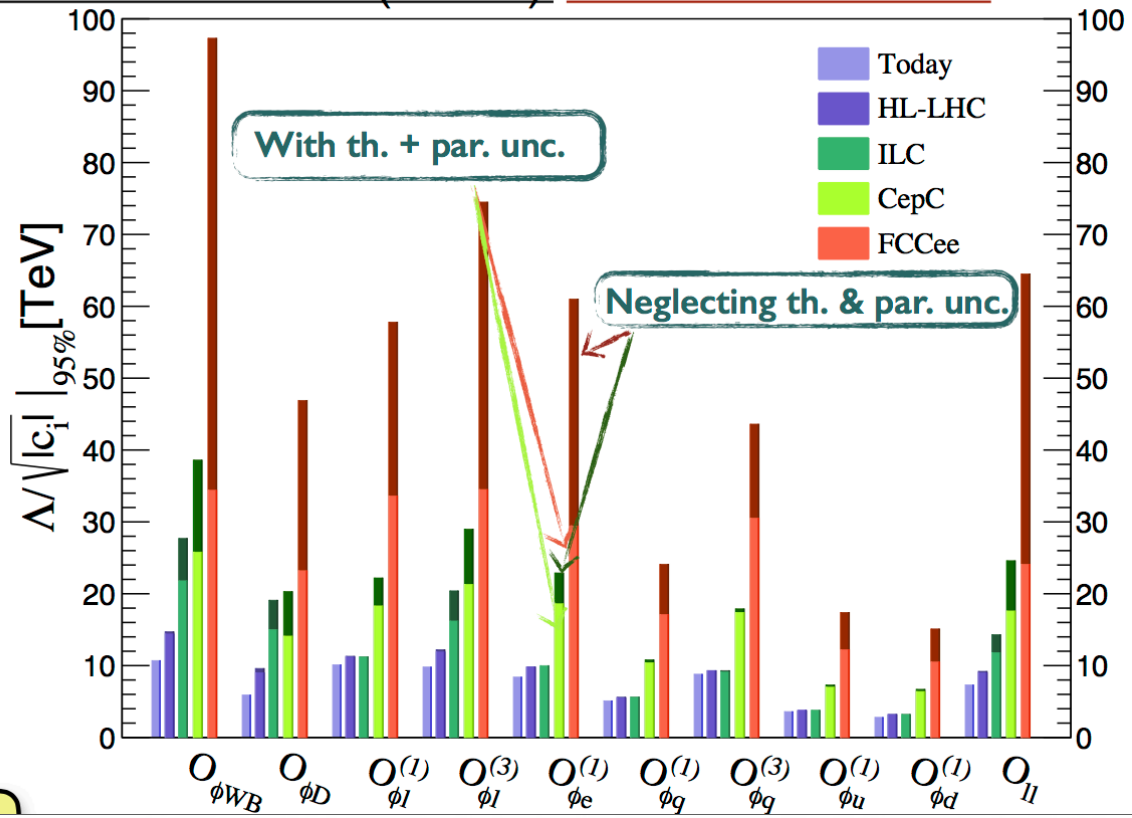
- **Higher-dimensional operators as a parametrization of new physics**
  - **Possible corrections to the Standard Model**
    - **Standard Model Effective Theories (SMEFT)**

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

Dimension six SMEFT (EWPD): **Present vs. Future**

Limits on new physics scale, Λ:

Today:
Λ > 5-10 TeV



Limits on new physics scale, Λ:

After FCC-ee:
Λ > 50-100 TeV

Precision electroweak physics at FCC-ee (9)

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

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

Exp: 0.015

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

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 the FCC-ee (8)

- **Most of the parametric uncertainties will reduce at the 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

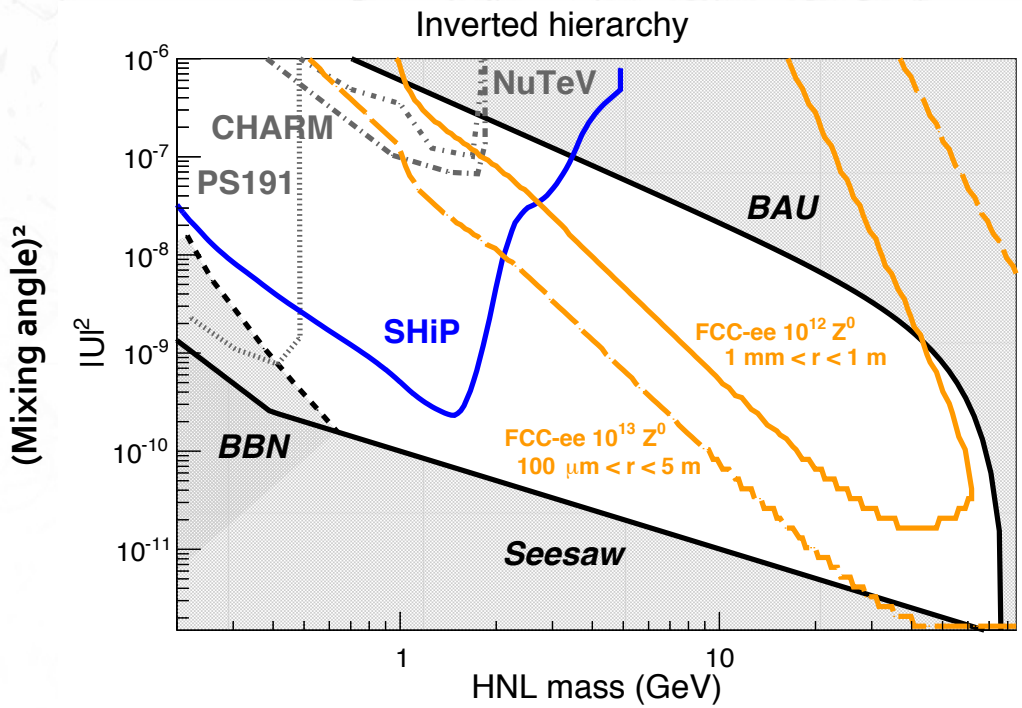
- **Will require calculations up to three or four loops to gain an order of magnitude**
  - **Might need a new paradigm in the actual computing methods**
    - **Lot of interesting work for future generations of theorists**

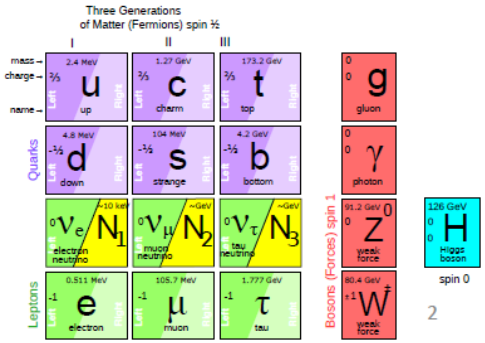
Opportunities for discoveries at FCC-ee

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

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

  - 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)
    - Through a study of the Z, W, H, and top properties with unprecedented statistics
  - To potentially very small couplings (sterile neutrinos, dark matter, …)

- Understanding this physics requires an e^+e^- collider at the EW scale
  - In an ideal world, this understanding could even benefit from having two of them

- Significant synergies (detectors) and complementarities (physics)
  - Beween 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 FC-ee 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 your personal opinion – at this level – of the scientific capabilities of each option

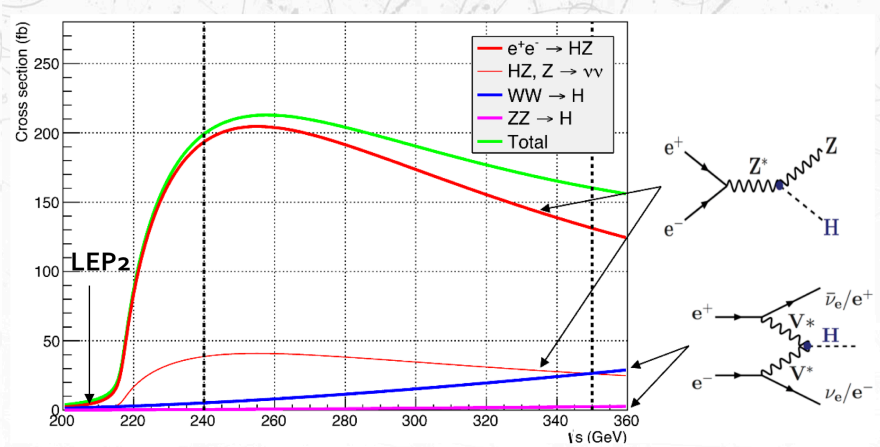
- If a choice is to be made, high energy capabilities are essential to decide
  - The likelihood of new physics below 1 TeV has reduced considerably with LHC Run1 (+ 2)
    - A new evaluation will have to be made after Run2 (soon!)

      - High-energy frontier capabilities discussed in 3rd lecture

Extra Slides

What if we are poor: LEP3

- If we do not have funding to construct a new tunnel, neither circular nor linear
  - After HL-LHC refurbish LEP/LHC tunnel with a state of the art modern e^+e^- collider
    - Will be comfortably able to work as a Higgs factory (remember LEP was close)



    - Will of course be able to cover Z and WW programmes
    - However, will not be able to operate at $t\bar{t}$ threshold
      - Synchrotron energy loss of 35 GeV per turn, i.e. 20%
      - Missing out on top mass and couplings and some of the Higgs programme (g_{HHH}, g_t)
    - Fast estimate says that luminosity could be ¼ of that of FCC-ee
      - However, we can operate with four detectors and regain a factor of ~2
  - Cost effective way to carry through Z, WW, and Higgs parts of FCC-ee programmme

Further studies needed