Niels Bohr Institute

# Physics at (Future) Lepton Colliders

## CERN Summer Student Lecture, 2018

## Lecture 2


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# Physics at (Future) Lepton Colliders

- Lecture 1 (Thursday 26 July, 11:35)
  - Introduction: Status and "near" future
  - A bit of history: Consolidation of Standard Model: Electroweak Precision Measurements
  - An experimental strategy: $e^+e^-$ colliders
  - Precision Higgs Physics: ILC and FCC-ee

- Lecture 2 (Friday 27 July, 10:25)
  - Electroweak Precision Physics: FCC-ee
  - High Energy $e^+e^-$ Physics: CLIC
  - Instrumentation: Detectors for $e^+e^-$ physics
  - Thinking out of the box: Muon colliders
  - Rounding off: Summary and Conclusions

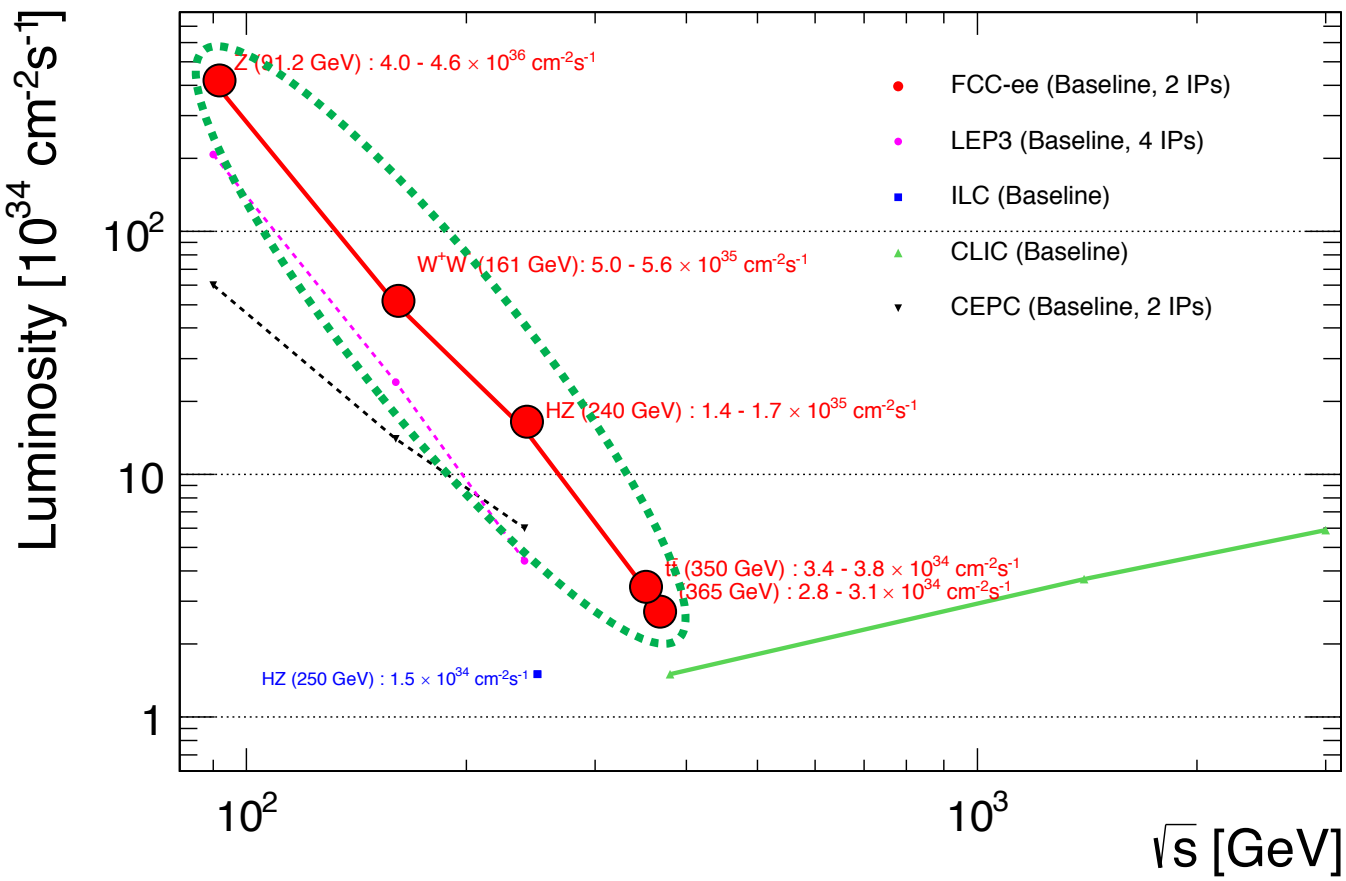
# Reminder from yesterday

- Things went a little fast yesterday, but I still hope I managed to convince you that $e^+e^-$ colliders promise very precise measurements of Higgs proporties

| Coupling | HL-LHC | $ILC_{250}$ | $CLIC_{380}$ | FCC-ee |
|---|---|---|---|---|
| $g_{HWW}$ | 3.5% | 1.7% | 1.3% | 0.47% |
| $g_{HZZ}$ | 3.5% | 0.35% | 0.80% | 0.22% |
| $g_{Hbb}$ | 8.2% | 1.8% | 2.8% | 0.68% |
| $g_{Hcc}$ | SM | 2.3% | 6.8% | 1.2% |
| $g_{H\tau\tau}$ | 6.5% | 1.9% | 4.2% | 0.80% |
| $g_{H\mu\mu}$ | 5.0% | 13% | n.a. | 8.6% |
| $g_{H\gamma\gamma}$ | 3.6% | 6.4% | n.a. | 3.8% |
| $g_{Hgg}$ | 3.9% | 2.2% | 3.8% | 1.0% |
| $g_{HZ\gamma}$ | ~12% | ? | ? | ? |
| $BR_{EXOT}$ | SM | < 1.8% | <3.0% | < 1.1% |
| $\Gamma_H$ | ~50% | 3.8% | 6.3% | 1.6% |
| $g_{Htt}$ | 4.2% | - | ? | 10% (*) |
| $g_{HHH}$ | 30-50% ? | - | ? | 40%(*) |

!!

# Electroweak Precision Physics
## FCC-ee



# Precision electroweak physics at FCC-ee (1)

- Reminder: The FCC-ee goals in numbers

| √s (GeV) | 90 (Z) | 160 (WW) | 240 (HZ) | 350 (tt) | 365 (WW→H) |
|---|---|---|---|---|---|
| Lumi ($ab^{-1}$/yr) | 40 | 6 | 1.7 | 0.4 | 0.3 |
| Events/year | $1.6 \times 10^{12}$ | $3 \times 10^{7}$ | $3.3 \times 10^{5}$ | $2.4 \times 10^{5}$ | 9,000 |
| # years | 4 | 2 | 3 | 5 | |
| Events@FCCee | $6 \times 10^{12}$ | $6 \times 10^{7}$ | $10^{6}$ | $10^{6}$ | 45,000 |
| Appellation | Tera-Z | Oku-W | Mega-Higgs | Mega-top | |

- FCC-ee is the ultimate Z, W, Higgs and top factory
  - $10^5$ times more Zs and $10^3$ times more Ws than LEP1 and LEP2
    - Potential statistical accuracies are mind-boggling !

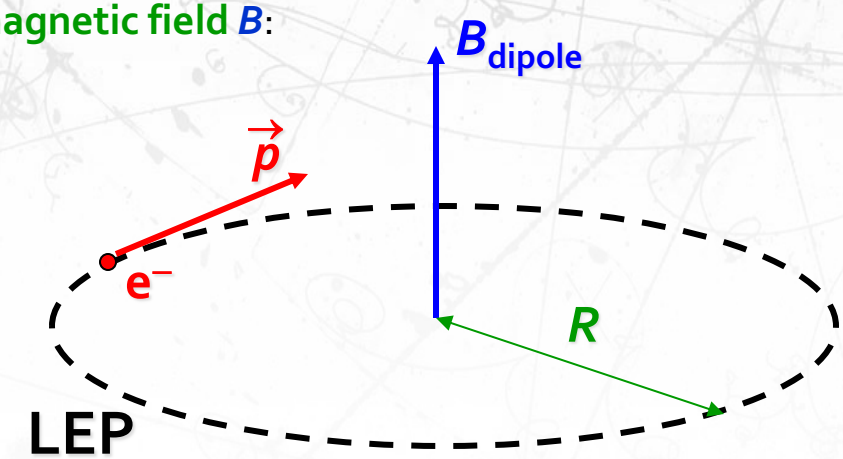
- Predicting accuracies with 200 times smaller statistical precision than at LEP is hard
  - Conservatively, use LEP experience for systematics. This is just the start…

- Example: The uncertainty on $E_{BEAM}$ (2 MeV) was the dominant uncertainty on $m_Z$, $\Gamma_Z$
  - 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 $m_Z$, $\Gamma_Z$)

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




L = 2πR = 27km

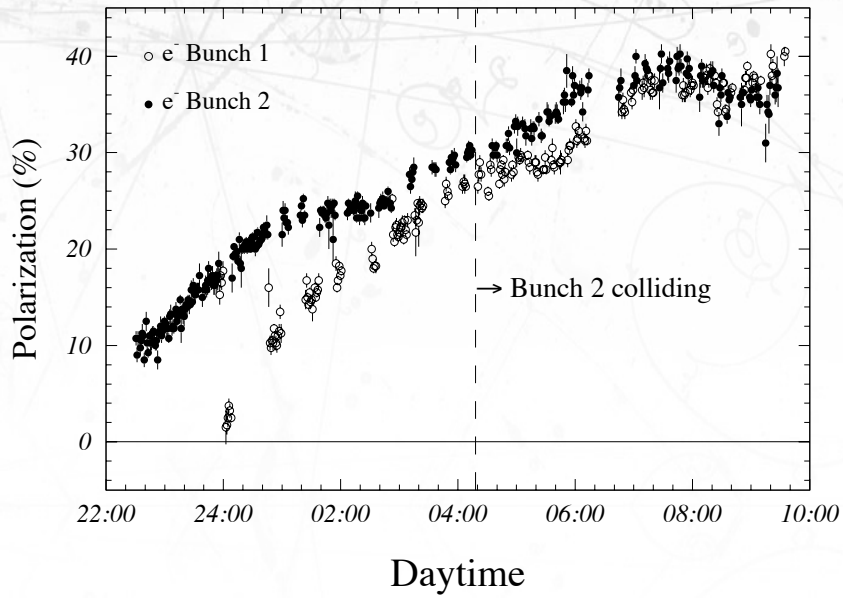
$$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$$

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*)



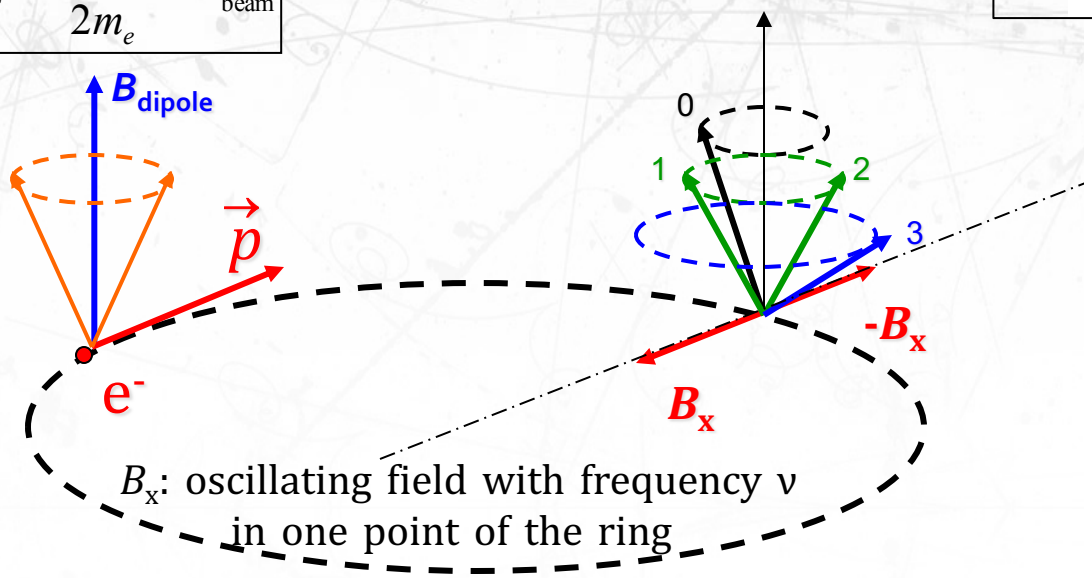

Slow process (~ 1 hour to get 10% polarization)

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

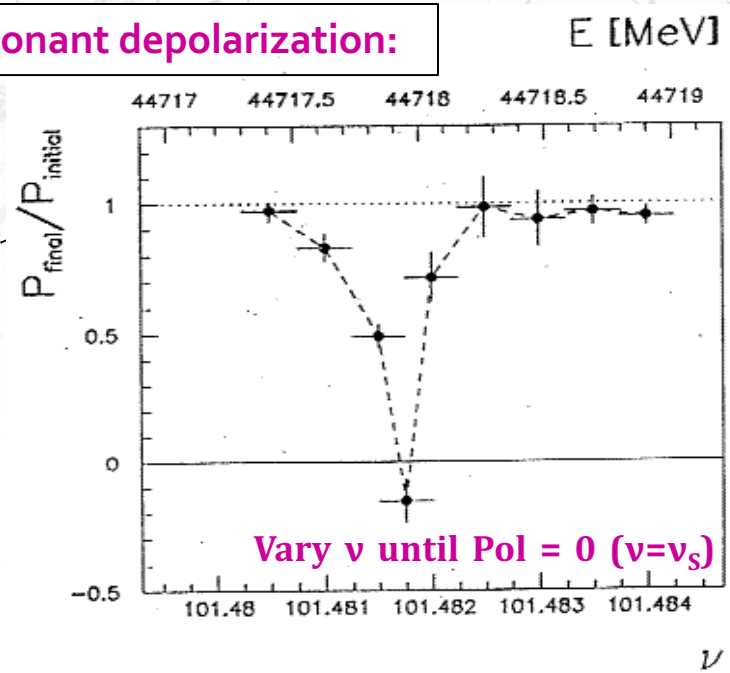
# Precision electroweak physics at FCC-ee (3)

- **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 $\nu_S$ for each LEP turn is proportional to $\int B dl$

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



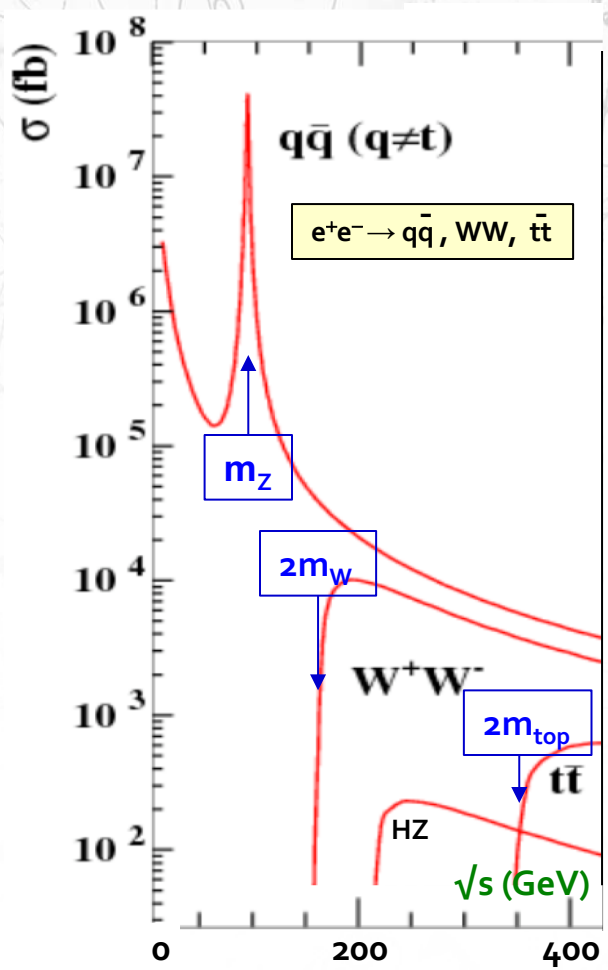

Resonant depolarization:



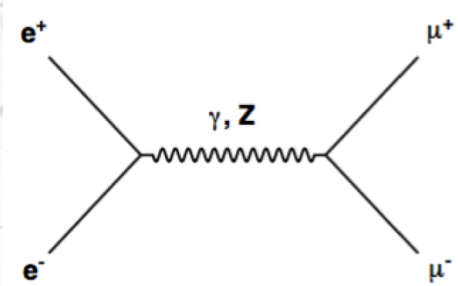

- LEP was colliding 4 bunches of $e^+$ and $e^-$; FCC-ee will have 1,000's of bunches
  - Use ~10 "single" bunches to measure $E_{\text{BEAM}}$ with resonant depolarization
    - Each measurement gives 100 keV precision, with no extrapolation uncertainty

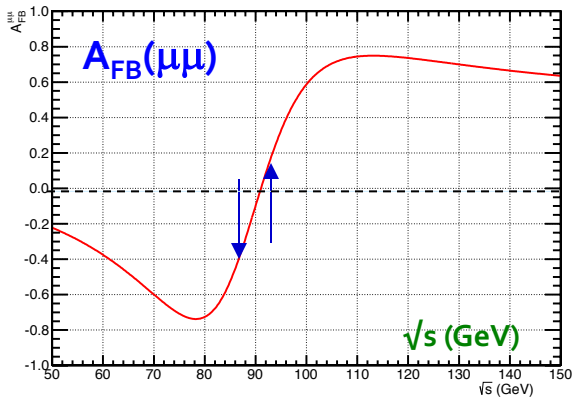
# Precision electroweak physics at FCC-ee (4)

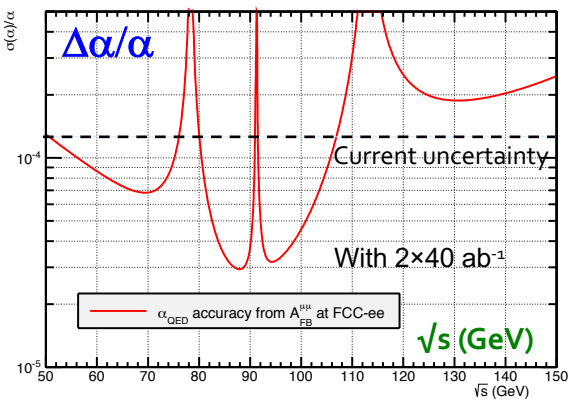
- Boils down to measuring cross sections and asymmetries




$e^+e^- \to \mu^+\mu^-$




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

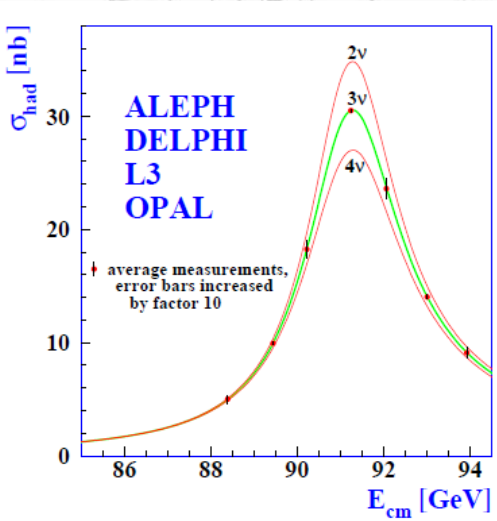
- Measure $\sin^2\theta_W$ with $A_{FB}$ at $\sqrt{s} = m_Z$
- Measure $\alpha_{QED}(m_Z)$ with $A_{FB}$ at $\sqrt{s}$ = 87.9 and 94.3 GeV
  - $\sqrt{s}$-points also for the Z resonance scan ($m_Z$, $\Gamma_Z$)

- The dominant experimental uncertainties (still!) come from the beam energy knowledge

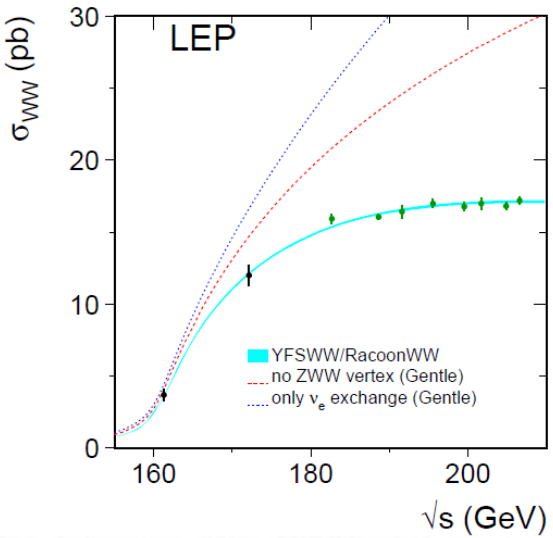
# Precision electroweak physics at FCC-ee (5)

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

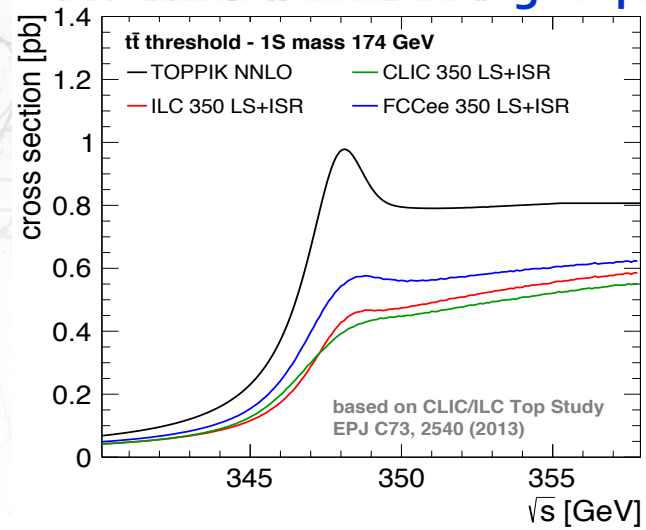
## Z reconance: TeraZ




## WW threshold scan: OkuW




## tt threshold scan: MegaTop




### Lineshape

- Exquisite $E_{beam}$ (unique!)
- $m_Z$, $\Gamma_Z$ to < 100 keV (2.2 MeV)

### Asymmetries

- $\sin^2\theta_W$ to $6\times10^{-6}$ ($1.6 \times 10^{-4}$)
- $\alpha_{QED}(m_Z)$ to $3\times10^{-5}$ ($1.5 \times 10^{-4}$)

### Branching ratios $R_l$, $R_b$

- $\alpha_S(m_Z)$ to 0.0002 (0.002)

### Threshold scan

- $m_W$ to 0.5 MeV (12 MeV)

### Branching ratios $R_l$, $R_b$

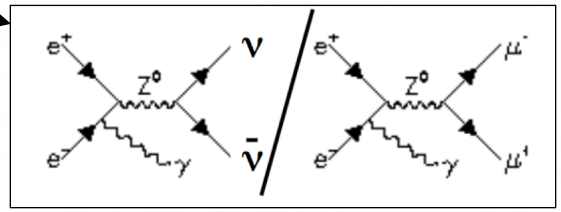
- $\alpha_S(m_Z)$ to 0.0002

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

- $N_\nu$ to 0.0004 (0.008)

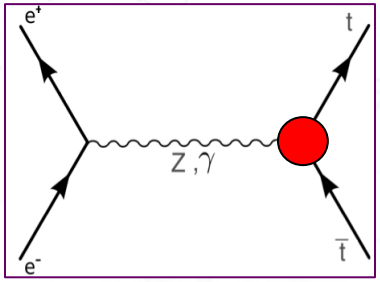
### Threshold scan

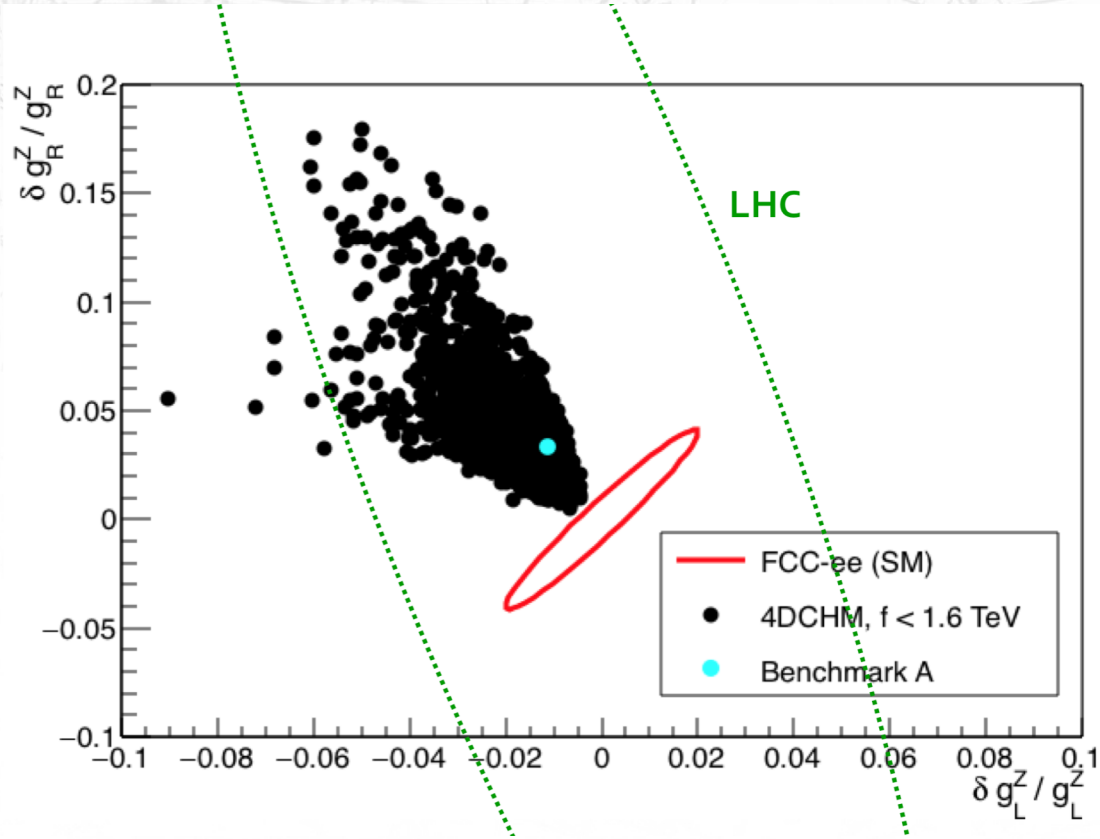
- $m_{top}$ to 10 MeV (500 MeV)
- $\lambda_{top}$ to 10%
- EW couplings to 1%



# Precision electroweak physics at FCC-ee (6)

- Measurements of $t_L t_L Z$ and $t_R t_R Z$ couplings, $g_L$ and $g_R$
  - At FCC-ee@360 GeV, couplings extracted from "top polarization measurement": Leptons and b-jet distributions
  - Couplings sensitive to, e.g., composite Higgs models



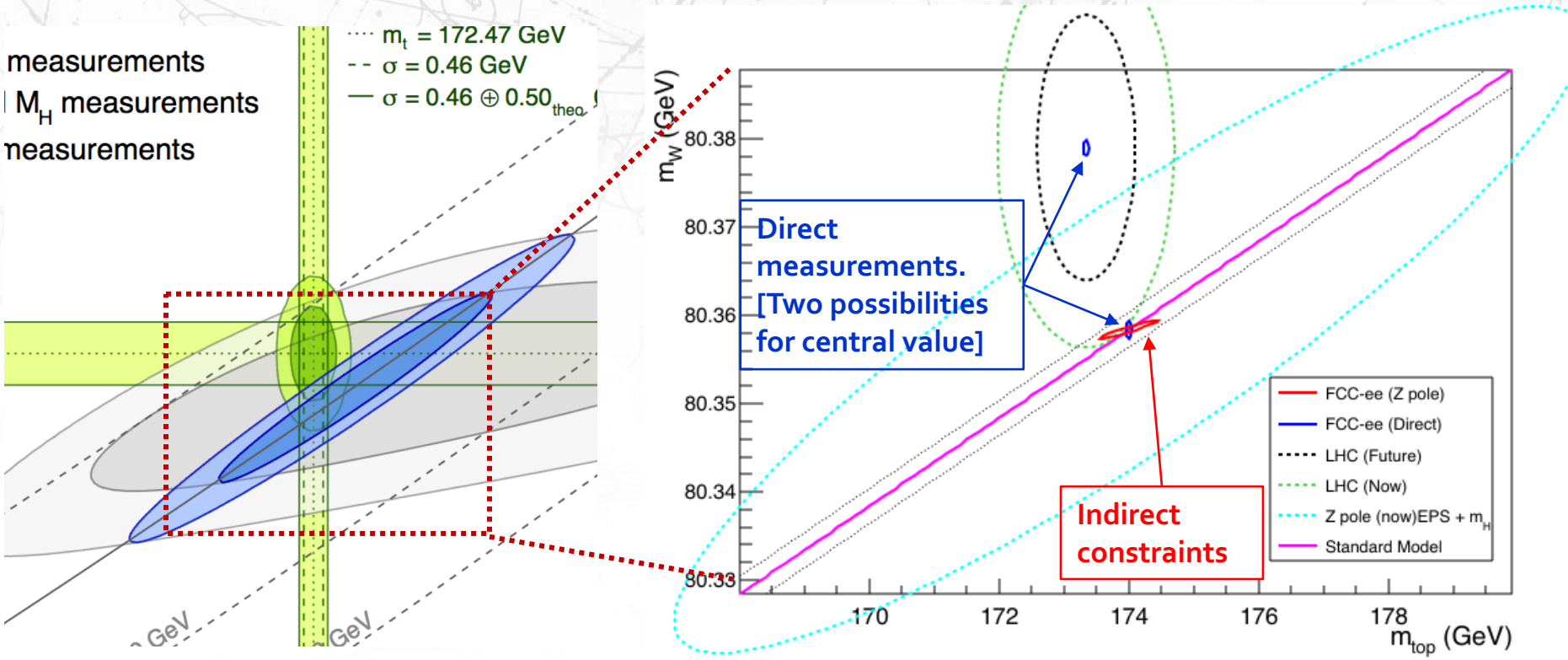
# Precision electroweak physics at FCC-ee (7)

- **Summary of achievable precisions**

| Observable | Measurement | Current precision | FCC-ee stat. | Possible syst. | Challenge |
|---|---|---|---|---|---|
| $m_Z$ (MeV) | Lineshape | 91187.5 ± 2.1 | 0.005 | < 0.1 | QED corr. |
| $\Gamma_Z$ (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 | $g \to bb$ |
| $N_\nu$ | Peak | 2.984 ± 0.008 | 0.00004 | < 0.004 | Lumi meast |
| $\sin^2\theta_W^{eff}$ | $A_{FB}^{\mu\mu}$ (peak) | 0.23148 ± 0.00016 | 0.000003 | 0.000006 | Beam energy |
| $1/\alpha_{QED}(m_Z)$ | $A_{FB}^{\mu\mu}$ (off-peak) | 128.952 ± 0.014 | 0.004 | < 0.004 | QED corr. |
| $\alpha_s(m_Z)$ | $R_l$ | 0.1190 ± 0.0025 | 0.00001 | 0.0001 | New Physics |
| $m_w$ (MeV) | Threshold scan | 80385 ± 15 | 0.3 | < 0.5 | EW Corr. |
| $N_\nu$ | $e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll | 2.92 ± 0.05 | 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 |
| $m_{top}$ (MeV) | Threshold scan | 173340 ± 760 ± 500 | 10 | 20 | QCD corr. |
| $\Gamma_{top}$ (MeV) | Threshold scan | ? | 25 | ? | $\alpha_s(m_Z)$ |
| $\lambda_{top}$ | Threshold scan | $\mu$ = 1.2 ± 0.4 | 15% | ? | $\alpha_s(m_Z)$ |

# Precision electroweak physics at FCC-ee (8)

- 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

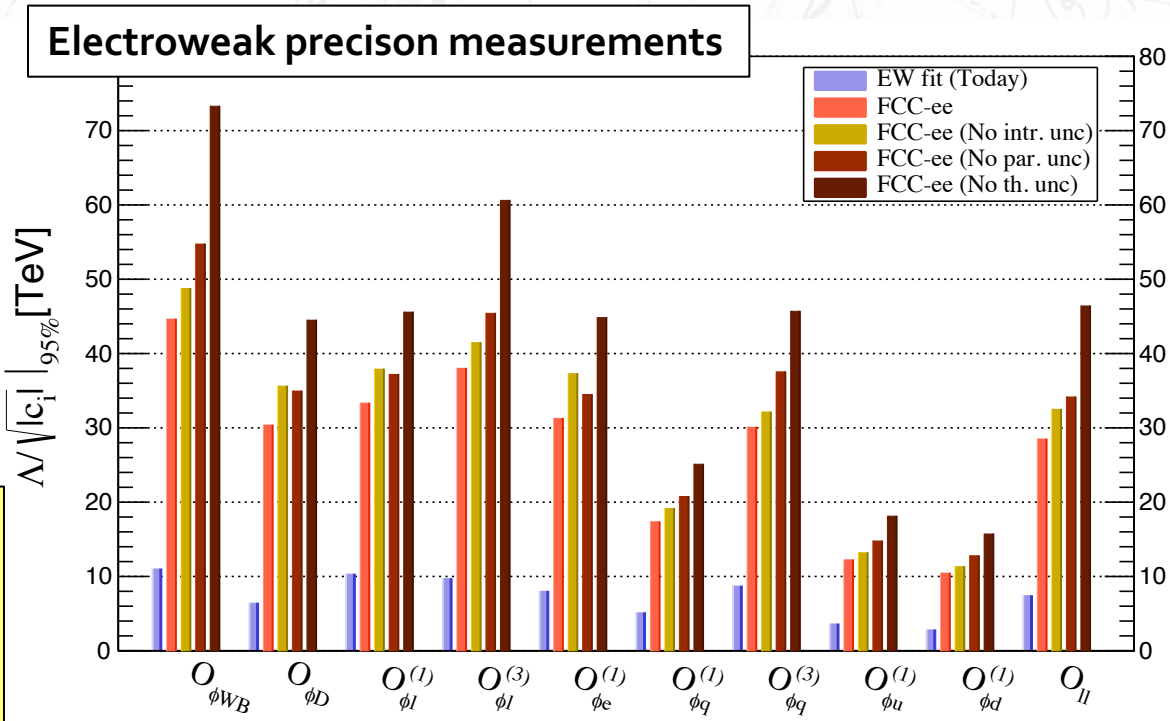



- New Physics ?
  - Direct measts (blue ellipse) and indirect constraints (red ellipse) may or may not overlap

# Precision electroweak physics at FCC-ee (9)

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

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




**Limits on new physics scale, $\Lambda$:**

**Today:**
**$\Lambda$ > 4-10TeV**

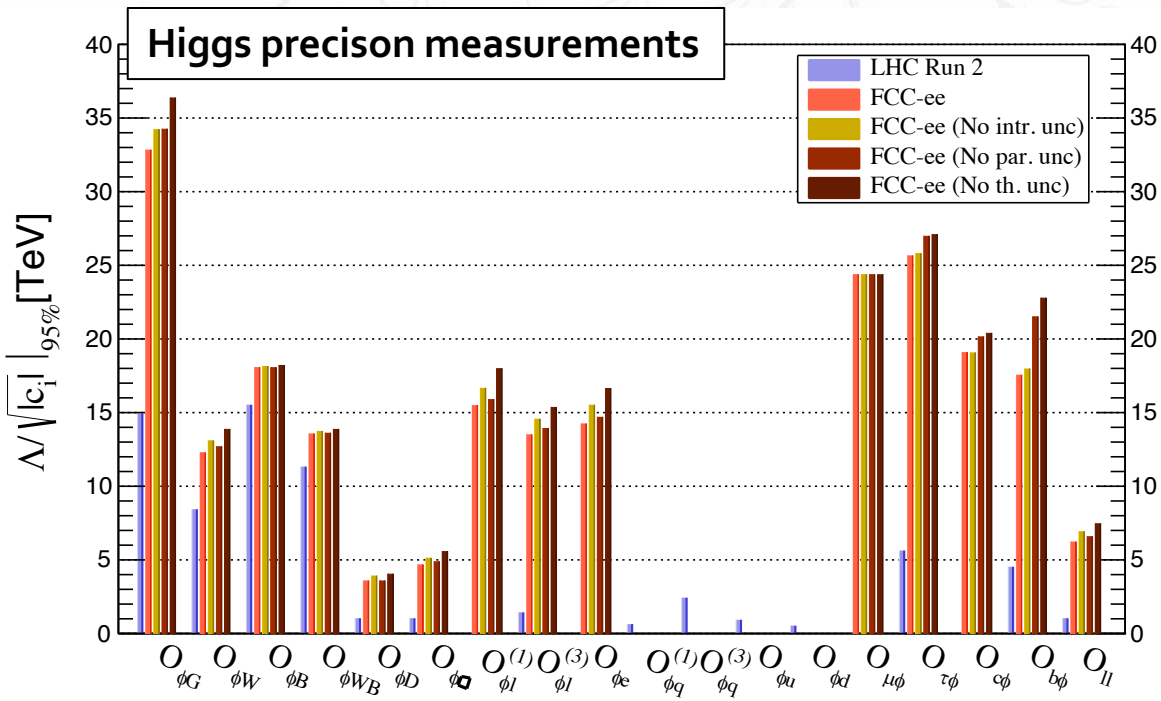
**Limits on new physics scale, $\Lambda$:**

**After FCC-ee:**
**$\Lambda$ > 20-70 TeV**

# Precision electroweak physics at FCC-ee (10)

- Interpret also precisely measured Higgs couplings (Lecture 1) in terms of higher-dimension operators

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




**Limits on new physics scale, $\Lambda$:**

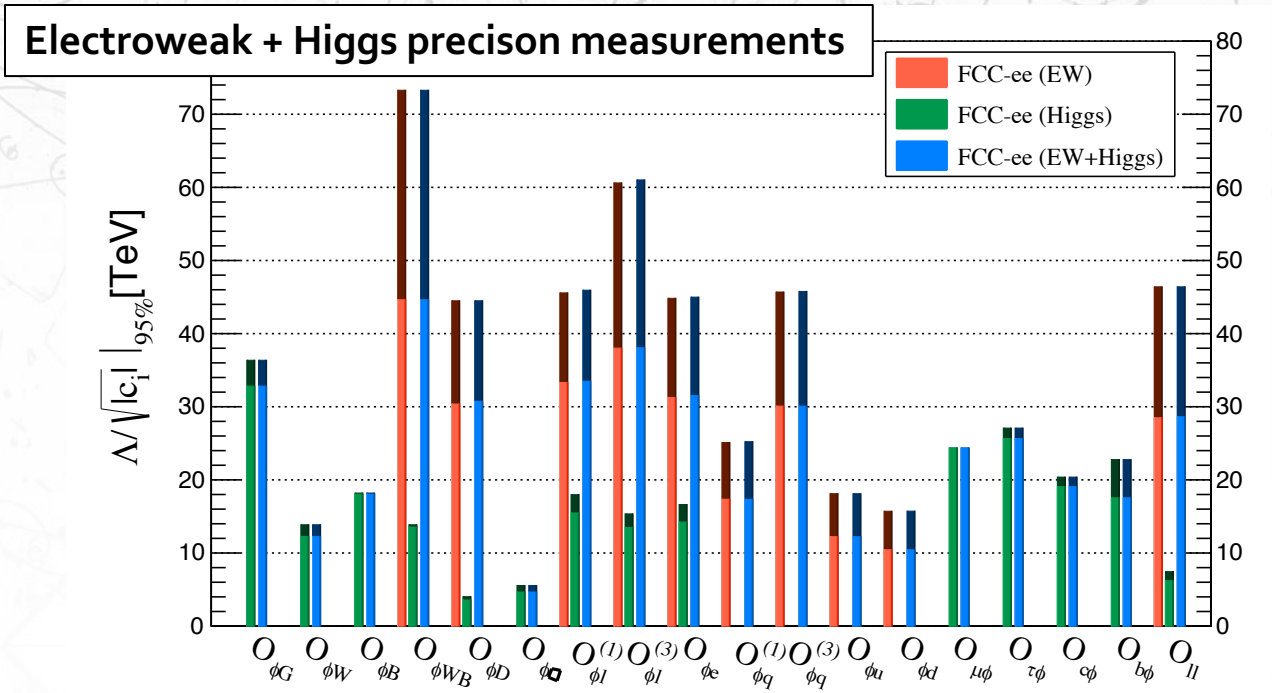
**Today:**
**$\Lambda$ > 1-15 TeV**

**Limits on new physics scale, $\Lambda$:**

**After FCC-ee:**
**$\Lambda$ > 1-35 TeV**

# Precision electroweak physics at FCC-ee (11)

- Combine EW precision observables with precise Higgs coupling measurements via higher-dimensional operators




- The EW and Higgs measurements are highly complementary
  - Together they provide precise constraints on a large number of operators
  - Different New Physics models give different pattern of deviations from SM
    - Pattern provides fingerprint to differentiate among models

# Precision electroweak physics at FCC-ee (12)

- 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

$$
\begin{aligned}
m_{\mathrm{W}} = \; & 80.3584 \; \pm 0.0055_{m_{\mathrm{top}}} \pm 0.0025_{m_{\mathrm{Z}}} \pm 0.0018_{\alpha_{\mathrm{QED}}} \\
& \pm 0.0020_{\alpha_{\mathrm{S}}} \pm 0.0001_{m_{\mathrm{H}}} \pm 0.0040_{\mathrm{theory}} \; \mathrm{GeV} \\
= \; & 80.358 \; \pm 0.008_{\mathrm{total}} \; \mathrm{GeV},
\end{aligned}
$$

Exp: 0.012 GeV

$$
\begin{aligned}
\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = \; & 0.231488 \; \pm 0.000029_{m_{\mathrm{top}}} \pm 0.000015_{m_{\mathrm{Z}}} \pm 0.000035_{\alpha_{\mathrm{QED}}} \\
& \pm 0.000010_{\alpha_{\mathrm{S}}} \pm 0.000001_{m_{\mathrm{H}}} \pm 0.000047_{\mathrm{theory}} \\
= \; & 0.23149 \; \pm 0.00007_{\mathrm{total}},
\end{aligned}
$$

Exp: 0.00016

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

# Precision electroweak physics at FCC-ee (13)

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

$$
\begin{aligned}
m_{\mathrm{W}} = \; & 80.3584 \; \pm 0.0001_{m_{\mathrm{top}}} \pm 0.0001_{m_{\mathrm{Z}}} \pm 0.0003_{\alpha_{\mathrm{QED}}} \\
& \pm 0.0002_{\alpha_{\mathrm{S}}} \pm 0.0000_{m_{\mathrm{H}}} \pm 0.0040_{\mathrm{theory}} \; \mathrm{GeV} \\
= \; & 80.358 \; \pm 0.005_{\mathrm{total}} \; \mathrm{GeV},
\end{aligned}
$$

Exp: 0.0005

$$
\begin{aligned}
\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = \; & 0.231488 \; \pm 0.000001_{m_{\mathrm{top}}} \pm 0.000001_{m_{\mathrm{Z}}} \pm 0.000008_{\alpha_{\mathrm{QED}}} \\
& \pm 0.000001_{\alpha_{\mathrm{S}}} \pm 0.000000_{m_{\mathrm{H}}} \pm 0.000047_{\mathrm{theory}} \\
= \; & 0.23149 \; \pm 0.00006_{\mathrm{total}},
\end{aligned}
$$

Exp: 0.000006

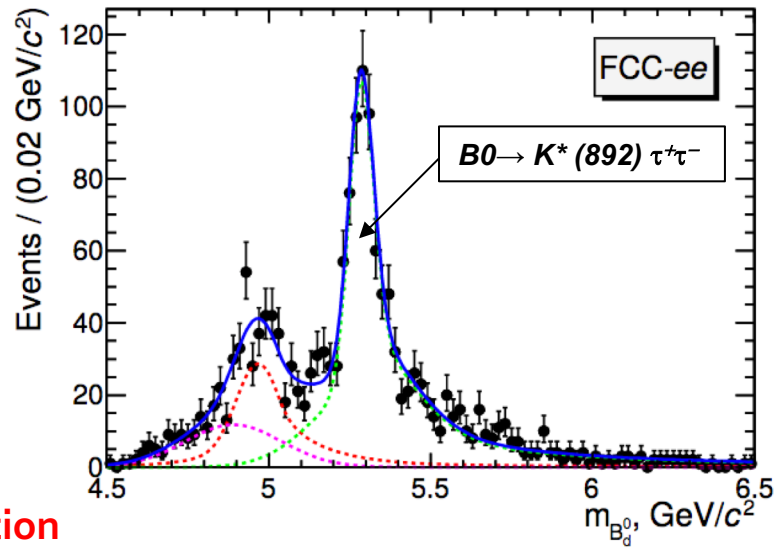
- Will require calculations up to three or four loops to gain an order of magnitude
  - Might need a new paradigm in the actual computing methods
    - Lots of interesting work for future generations of theorists (you?)

# FCC-ee: Flavour physics

- Current tensions (several 2-3 σ deviations) of LHCb data with SM predictions
  - In particular, lepton flavour universality is challenged in $b \to s\,\ell^+\ell^-$ transitions
    - For example, the rates of $B^0$ ($B^+$) $\to K^{*0}$ ($K^+$) $\ell^+\ell^-$ are different for $\ell$ = e and $\ell = \mu$
    - Differences are also observed in the lepton angular distributions
  - This effect, if real, could be enhanced for $\ell = \tau$, in $B \to K^{(*)}\tau^+\tau^-$
    - Extremely challenging in hadron colliders
    - With $10^{12}$ $Z \to b\bar{b}$, FCC-ee is beyond any foreseeable competition
      - Decay can be fully reconstructed
      - Full angular analysis possible
- Also sensitive to new physics in $B_S \to \mu^+\mu^-$
  - None found yet at the LHC (~50 events)

$$BR(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$ ~SM

    - Expect a few 1000's by the end of LHC
  - $B_S \to \tau^+\tau^-$ is 250 times more abundant
    - But almost hopeless at the LHC
  - Again, FCC-ee is beyond any foreseeable competition
    - Several 100,000 events expected – reconstruction efficiency under study

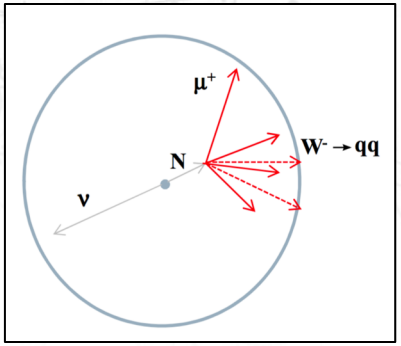


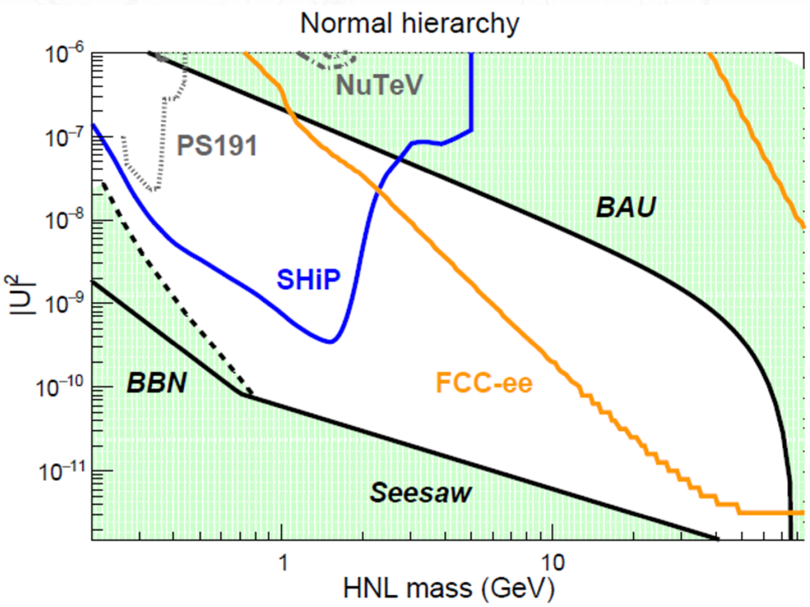
# FCC-ee: Opportunities for discoveries

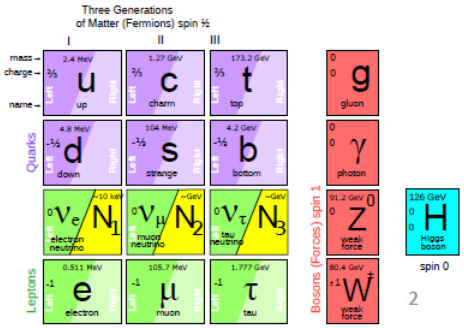
- Searches for new physics through rare decays
  - $5 \times 10^{12}$ Z, $10^{12}$ b, c and $10^{11}$ $\tau$ : A fantastic potential that remains to be explored
  - E.g., search for LVF Z decays: $Z \to e\mu$, $Z \to e\tau$, $Z \to \mu\tau$
    - Sensitivities down to $10^{-9}$ (four orders of magnitude better than todays ~$10^{-5}$ !)
  - E.g, search for right-handed neutrino in Z decays

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

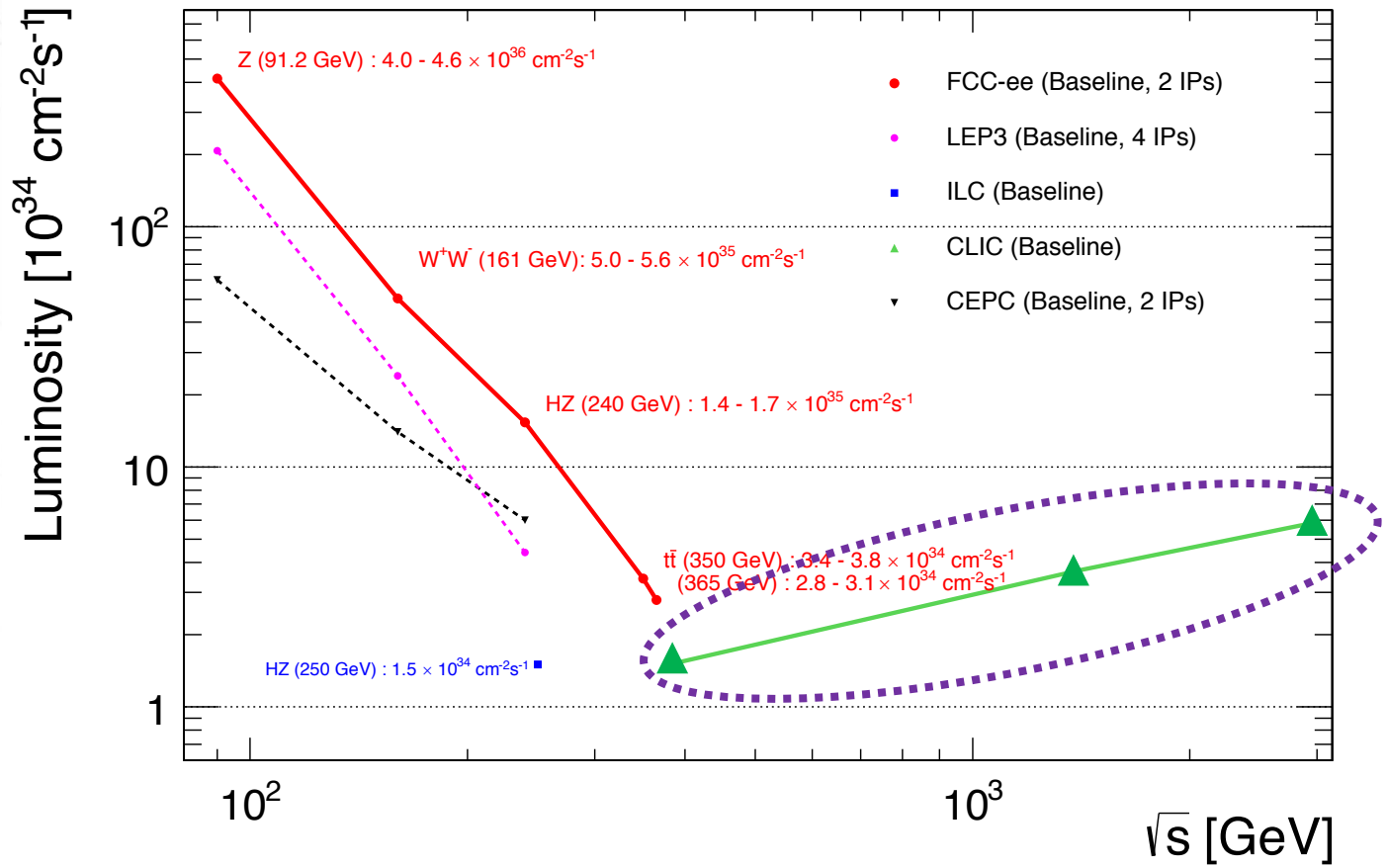
- Number of events depend on mixing between N and $\nu$, and on $m_N$



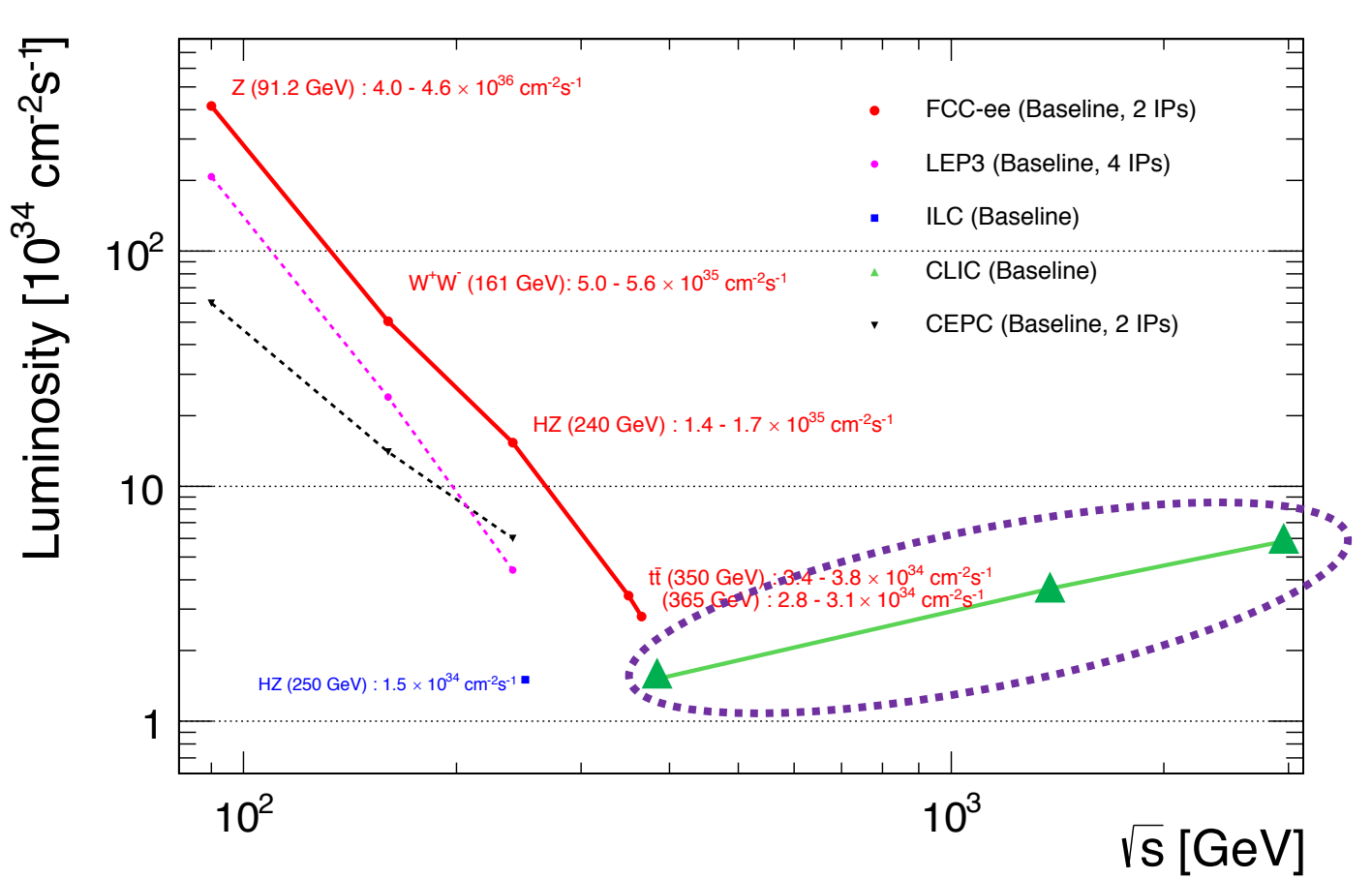



# High Energy $e^+e^-$ Physics
## CLIC



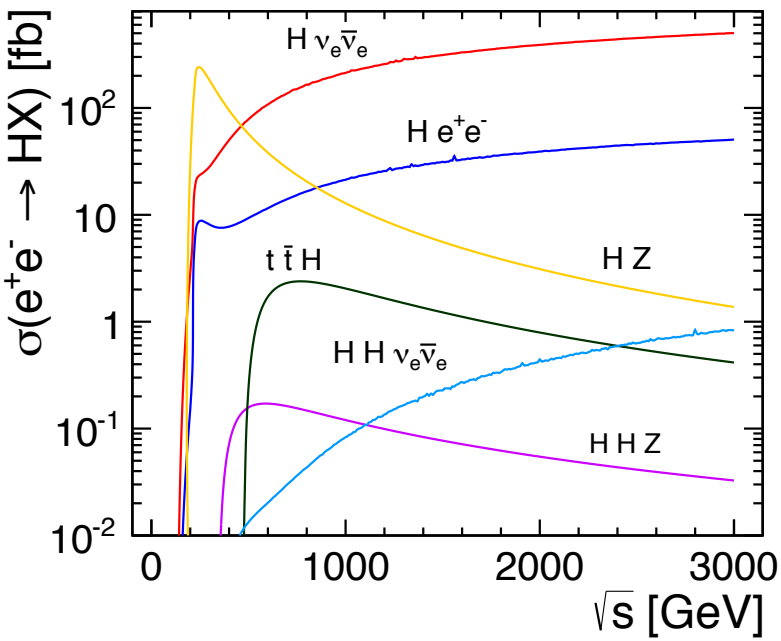
# High Energy $e^+e^-$ Physics




- **Luminosity targets for CLIC: 0.6 ab$^{-1}$ @ 380 TeV; 1.5 ab$^{-1}$ @ 1.5 TeV; 3 ab$^{-1}$ @ 3 TeV**
- **In original design, ILC kept compatible with a later energy upgrade to 1 TeV**
  - **Luminosity target for ILC at 1 TeV: ~2 ab$^{-1}$**

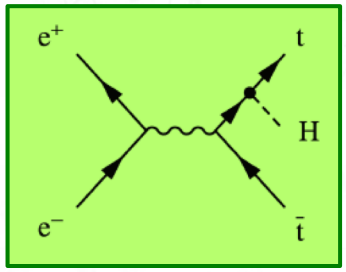
# Precision: Higgs properties at high energy (1)

- Why do precision Higgs physics at high √s ?
  - Precision achieved with $e^+e^-$ colliders at √s=240-350 GeV : 0.1% - 1%
    - Superior to what can be done at higher energy
      - $\sigma_{HZ}$ decreases, kinematics less favourable, backgrounds increase, …
- However …
  - Some production processes are not directly accessible at low-energy $e^+e^-$ colliders
    - Hence more couplings might become measurable at larger energy
      - Htt, HHH, HHHH, …



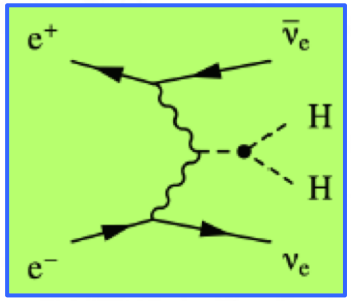

**Htt**

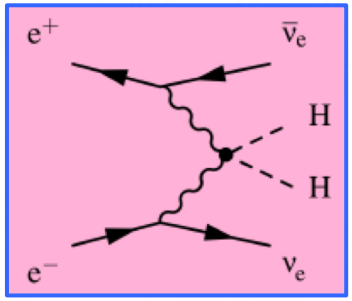
√s > 500 GeV




**HHH**

√s > 1 TeV




Background

# Precision: Higgs properties at high energy (2)

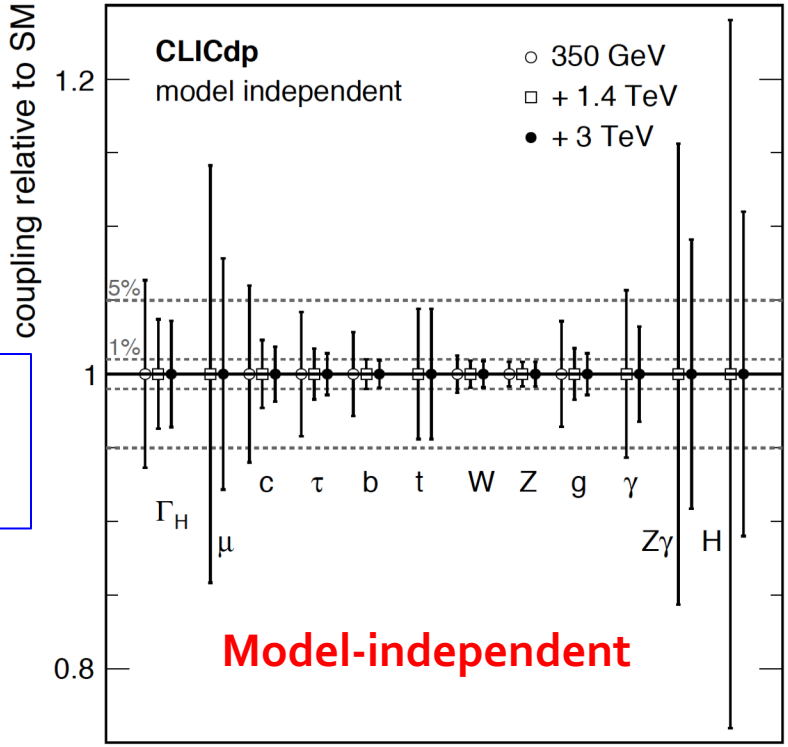
- Achievable precisions

(*) indirect

| Collider | HL-LHC | CLIC 1-3 TeV | FCC-ee (*) | FCC-ee+hh |
|---|---|---|---|---|
| $\Delta g_{Htt}/g_{Htt}$ | 4.2% | 2-4% | 10% | <1% |
| $\Delta g_{HHH}/g_{HHH}$ | 30-50% | 10-15% | 40% | 5-10% |

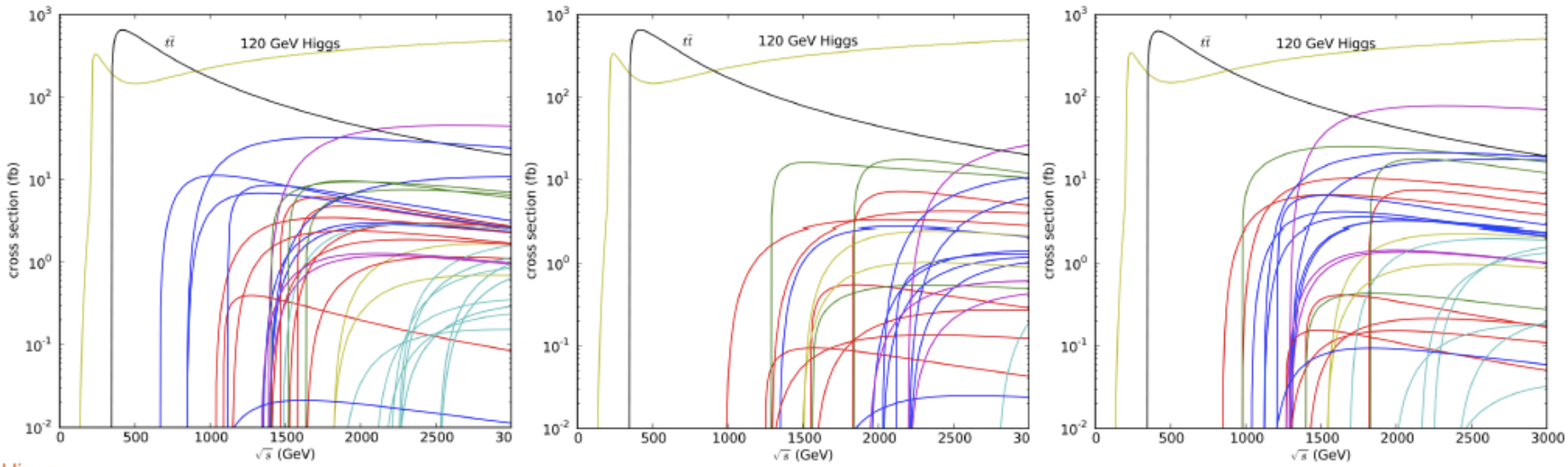
- Combined CLIC Higgs results
  - 380 GeV; 1.5 TeV, 3.0 TeV

Full CLIC program, ~5 yrs of running at each stage
- Precision down to ±1% for most couplings
- Accuracy on Higgs width: ±3.6%



# Direct BSM sensitivity – example SUSY

- **Unique opportunity to probe new particles with masses below 1.5 TeV**
  - ***If found*, very good mass resolution**




- Higgs
- $\tilde{\tau}, \tilde{\mu}, \tilde{e}$
- charginos
- squarks
- SM $t\bar{t}$
- $\tilde{\nu}_\tau, \tilde{\nu}_\mu, \tilde{\nu}_e$
- neutralinos

**"model I", 3 TeV:**
- Squarks
- Heavy Higgs

**"model II", 3 TeV:**
- Smuons, selectrons
- Gauginos

**"model III", 1.4 TeV:**
- Smuons, selectrons
- Staus, Gauginos

**Wider capability than only SUSY**: reconstructed particles can be interpreted as "states of given mass, spin and quantum numbers"

➔ In general, **O(1%)** precision on masses and production cross sections found

# BSM example: Z' via indirect measurement

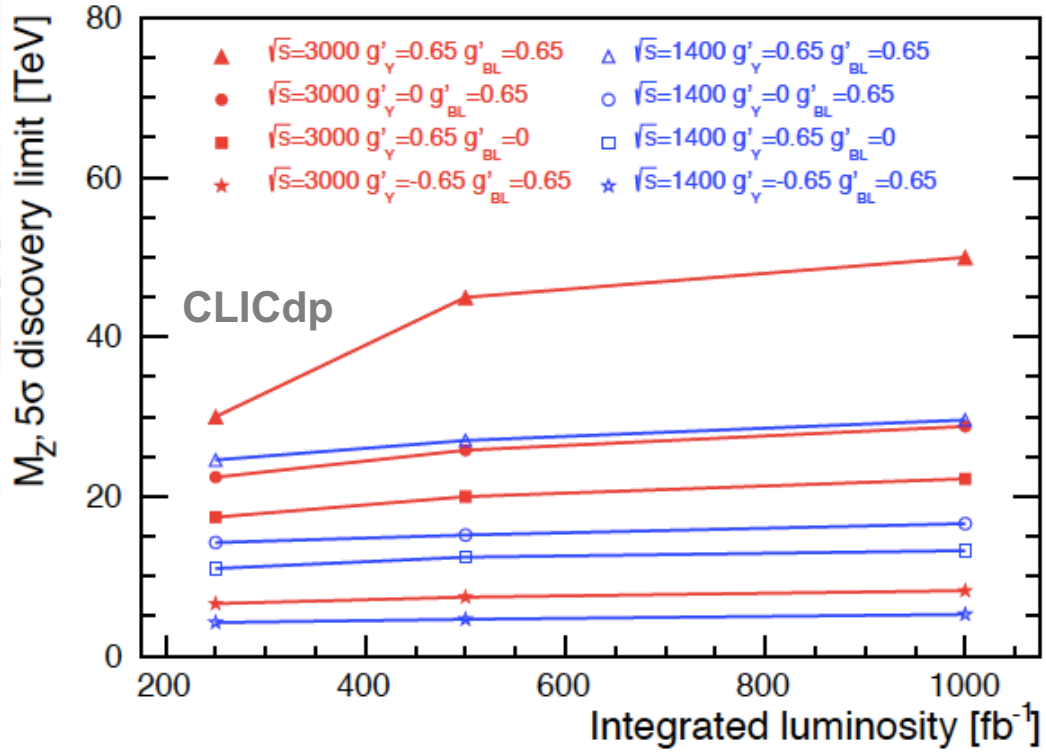
**Minimal anomaly-free Z' model**

$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$

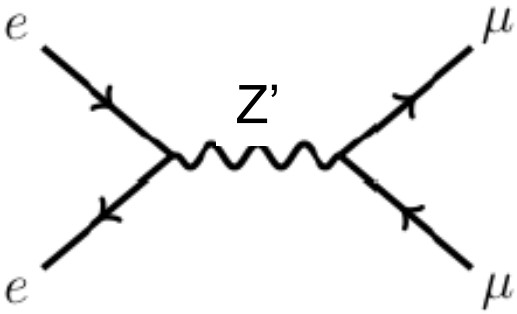
**Observables:**

- Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry

  (with ±80% $e^-$ polarisation)




- **If LHC discovers Z' (e.g. for $M_{Z'}$ = 5 TeV)**
  - **CLIC precision measurement of effective couplings**
- **Otherwise:**
  - **CLIC discovery reach up to tens of TeV (depending on the couplings)**



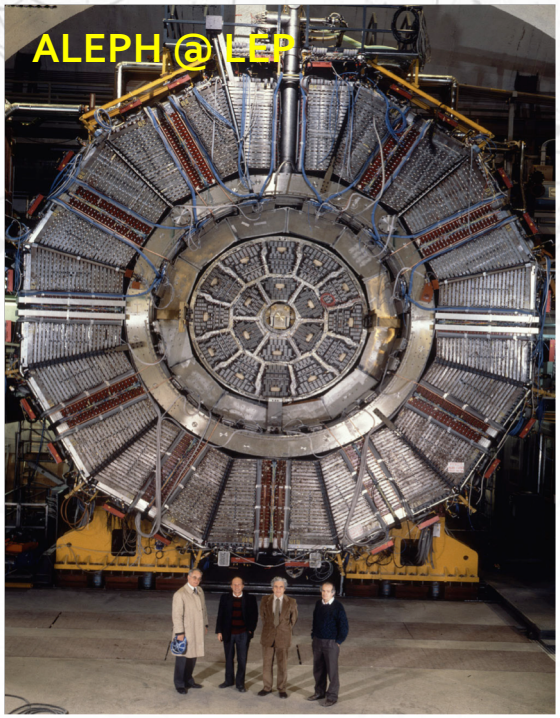
# Lecture 2

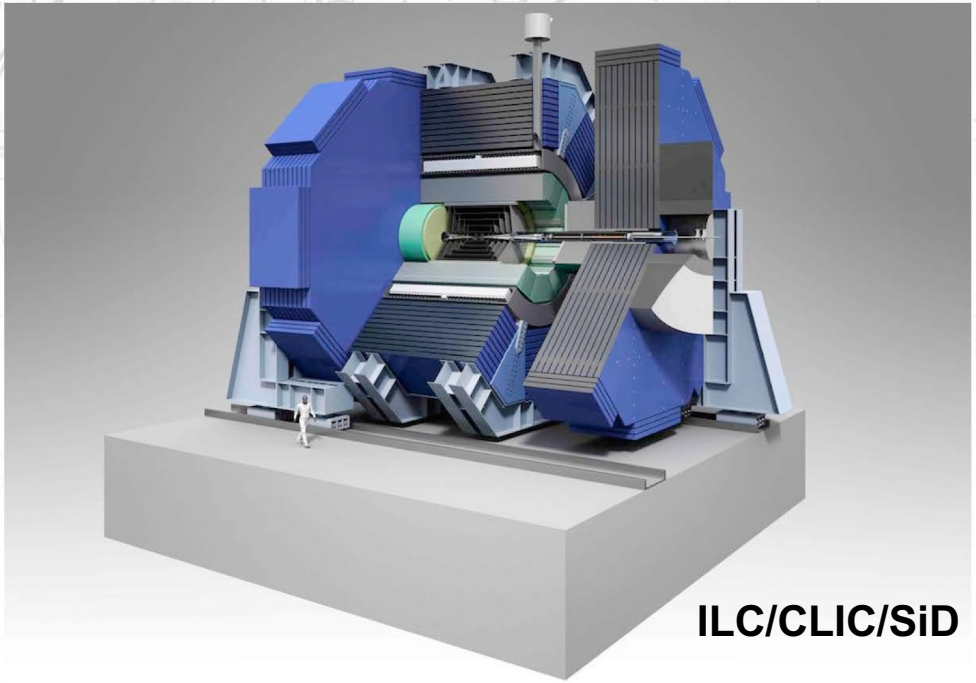
**Instrumentation**

**Detectors for $e^+e^-$ physics**

# Detectors $e^+e^-$ colliders

- We know today how to build a detector for $e^+e^-$ precision physics
  - Experience with LEP detectors and 20-years R&D with ILC/CLIC detectors




  - Compared to LHC, less challenging w.r.t. radiation damage, pile-up, etc.
  - However, need ultimate systematic precision to match the formidable statistical precision
    - Rememeber, up to $6 \times 10^{12}$ Z decays

# Typical Modern $e^+e^-$ Detector

**B-field: 2-5 Tesla**

- Limited to 2 Tesla at FCC-ee due to the 30 mrad crossing angle

**Calorimetry:**

- Jet energy (1/3 x LEP)

$$\frac{\sigma_E}{E} \approx 3-4\,\%$$

**Momentum:** (1/10 x LEP)

$$\sigma_{1/p} < 5 \times 10^{-5}\,\mathrm{GeV}^{-1}$$

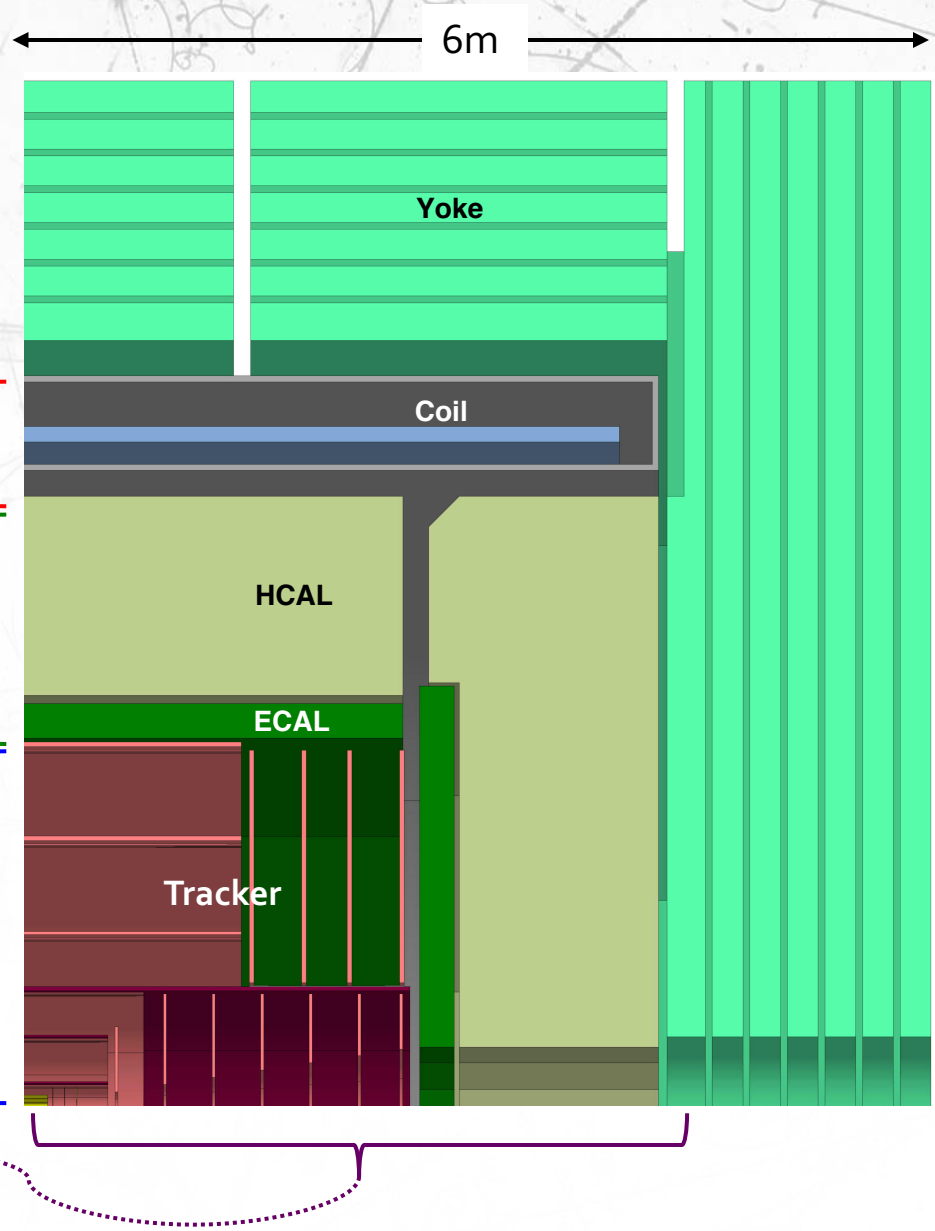
**Impact parameter:** (1/3 x SLD)

- e.g. b/c-tagging

$$\sigma_{r\phi} = 5 \oplus 10/(p \sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$

**Hermetic:** down to θ ≃ 5 mrad

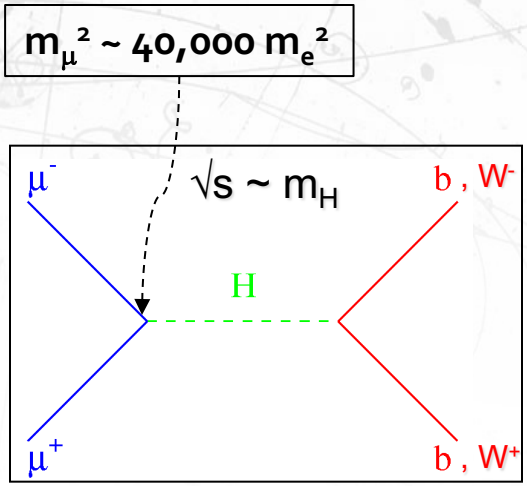
- Not possible with 30 mrad crossing angle, however



# Thinking out of the box
# Muon Colliders

# Why muon colliders ?

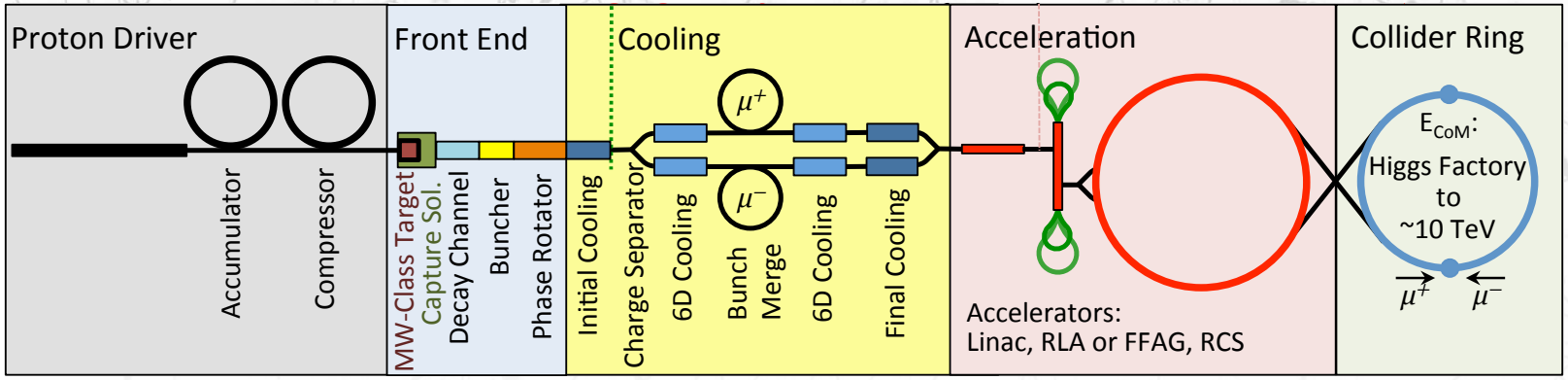
- Muons are leptons (like electrons)
  - Collisions at the full energy, small physics background, (E,p) conservation
    - Muons can *a priori* do all what electrons can do
- Muons are heavy (like protons)
  - Negligible synchrotron radiation, no beamstrahlung
    - Small circular colliders, up to large $\sqrt{s}$
    - Excellent energy definition (up to a few $10^{-5}$)
  - Large direct coupling to the Higgs boson
    - Unique *s*-channel Higgs factory at $\sqrt{s}$ = 125.093 GeV




- Muons are naturally longitudinally polarized (100%)
  - Because arising from $\pi^\pm$ decays to $\mu^\pm\nu_\mu$
    - Ultra-precise beam energy and beam energy spread measurement
- Muons eventually decay (in 2.2 μs) to $e\nu_\mu\bar{\nu}_e$
  - Outstanding neutrino physics programme
    - Muon colliders could be the natural successors of neutrino factories ?

# Muon colliders challenges

- **Muons decay: Produce, Collect, Cool, Accelerate and Collide them *fast* !**




- Intense proton driver to get the adequate number of muons
  - At least 4 MW for the desired muon luminosities
- Robust target to not evaporate at the first proton bunch
  - Re-circulating liquid metal
- Efficient muon collector from pion decays
  - Magnetic fields of 20T
- Unique 6D muon cooling
  - To reduce beam sizes and beam energy spread
- Fast acceleration and injection into circular ring(s)

**All these aspects are at the level of intense R&D. Will require decades to demonstrate feasibility**

# Muon collider challenges since 2014 ?

- Clever alternative muon source


- Intense $e^+$ beam with $E \simeq 45$ GeV
  - 100 kW for the desired muon intensity
- Non-destructive target for $e^+e^- \rightarrow \mu^+\mu^-$
  - Keep the $e^+$ beam in a ring
    - Possible synergy with FCC-ee
    - Energy Recovery Linac is also a possibility
- Production at $\mu^+\mu^-$ threshold ($\sqrt{s} \simeq 2\, m_\mu$)
  - Quasi-monocromatic muons, much less need for cooling
    - Except for a Higgs factory
  - Not obvious it is possible to cool at 23 GeV anyway ??
- Fast acceleration and injection into circular ring(s) remain as in the proton-driver option

**If feasible, this design would probably be faster, cheaper, and easier than the proton-driver option**

# Muon collider optimal circumference(s)

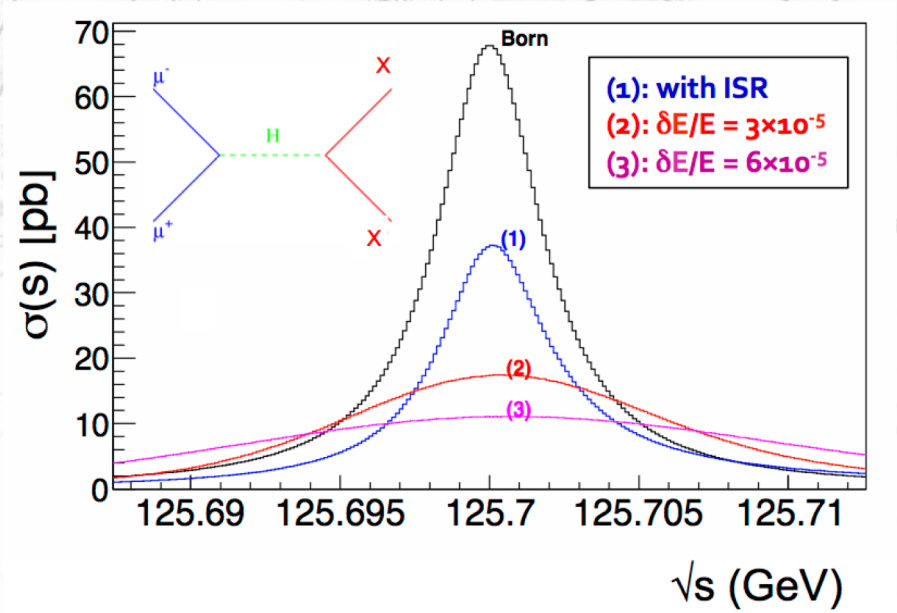
- Muon decay: Minimize the ring circumference
  - To allow the produced muons to collide as many times as possible before they decay
    - Optimal ring size is proportional to $E_\mu$. With 14 T state-of-the-art dipoles:

| $\sqrt{s}$ | 91 GeV | 125 GeV | 161 GeV | 350 GeV | 6 TeV | 24 TeV |
|---|---|---|---|---|---|---|
| $t = \gamma\tau_m$ | 0.94 ms | 1.30 ms | 1.67 ms | 3.64 ms | 62.3 ms | 249 ms |
| $L = \gamma\beta c\tau_m$ | 283 km | 389 km | 501 km | 1090 km | 18700 km | 74000 km |
| Ring | 100 m | 140 m | 180 m | 390 m | 6.6 km | 27 km |
| $N_{turns}$ | ~2800 turns | | | | | |

  - One ring per centre-of-mass energy
    - Two very small rings for precision studies
      - One for Z and H factories (140 m circumference)
      - One for W and top pair thresholds (390 m circumference)
    - Larger ring(s) for the energy frontier
      - $\sqrt{s}$ = 6 TeV can fit, for example, in the Tevatron tunnel (6.6 km circumference)
      - $\sqrt{s}$ = 24 TeV can fit in the LHC tunnel
    - Plus a number of rings for first stages of fast acceleration

# Muon collider as a Higgs factory (1)

- Challenges for the Higgs factory
  - $\Gamma_H$ is small (4.2 MeV in the SM)
    - Similar or smaller beam energy spread is required ($3 \times 10^{-5}$)
      - Fast longitudinal cooling to reduce energy spread
    - Beam energy reproducibility must be at the same level or better

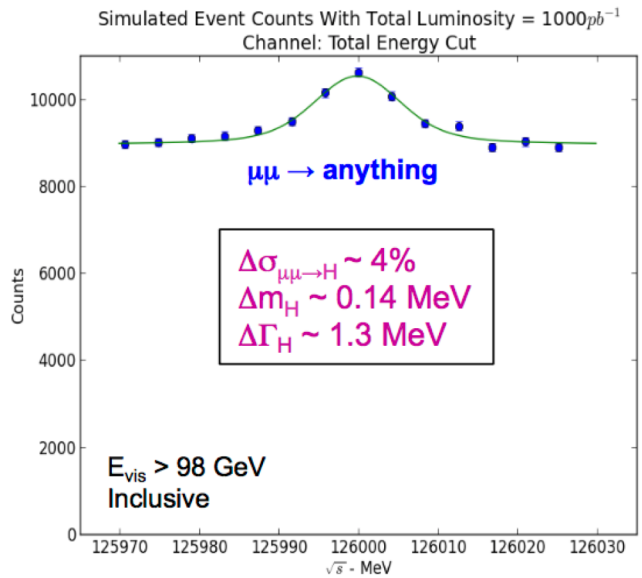


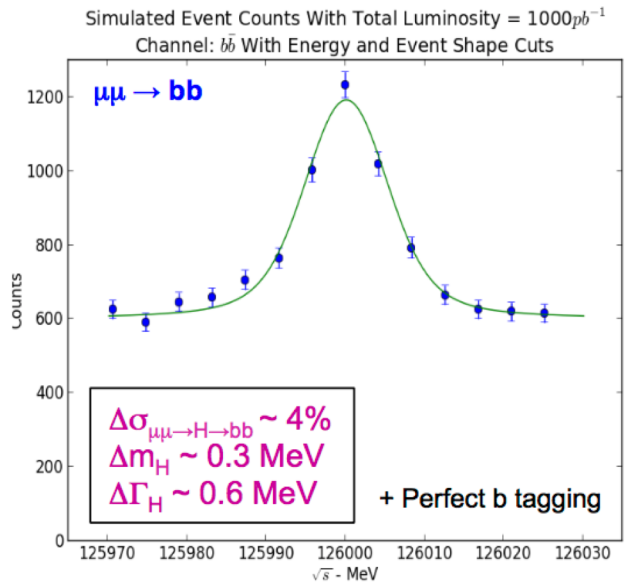

  - $\sigma(\mu^+\mu^- \rightarrow H)$ is about 20 pb
    - Luminosity must be at the level of $1.6 \times 10^{32}$ cm$^{-2}$s$^{-1}$ for the same number of Higgs bosons as ILC …
    - and at the level of $1.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$ for the same number of Higgs bosons as FCC-ee
      - Fast transverse cooling to reduce beam spot dimensions

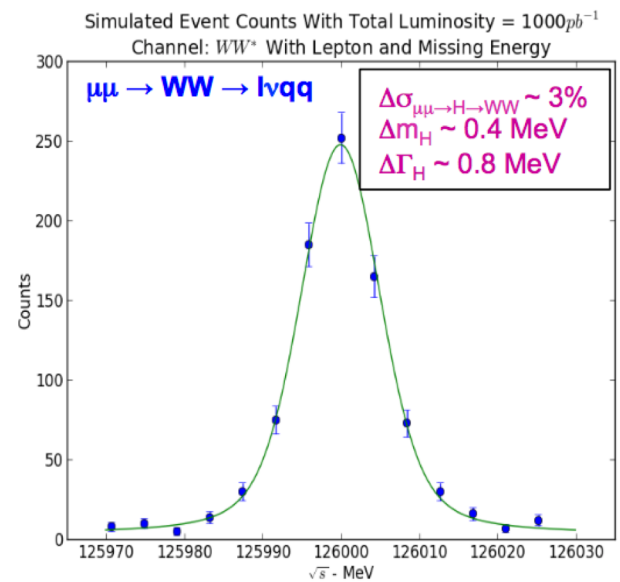
        And the Higgs bosons produced are not tagged with a Z anyway …
  - Problem
    - Longitudinal and transverse cooling are antagonistic
      - Luminosity is limited (as of today's knowledge) to a few $10^{31}$ cm$^{-2}$s$^{-1}$

# Muon collider as a Higgs factory (3)

- Physics performance of a Higgs factory
  - Scan of Higgs resonance in the inclusive $b\bar{b}$ and WW final states
    - Ten years of data taking at $10^{31}$ $cm^{-2}s^{-1}$, just count events




- Measure $\Gamma_H$ to 5% in 10 years (cf. 4% at ILC, <1% at FCC-ee)
  - Only way to see a structure in the resonance (several Higgs bosons?)
- Measure $\sigma_{peak}$ ~ $BR_{\mu\mu}$ to 2-3% in 10 years
- Other expected measurement on the figures

# Muon collider as a Higgs factory (4)

- Summary of precision measuremetns (after ~10 years of running)

| Error on | μμ collider | $ILC_{250}$ | FCC-ee |
|---|---|---|---|
| $m_H$ (MeV) | 0.06 | 14 | 8 |
| $\Gamma_H$ (MeV) | 0.17 | 0.11 | 0.07 |
| $g_{Hbb}$ | 2.3% | 1.8% | 0.68% |
| $g_{HWW}$ | 2.2% | 1.7% | 0.47% |
| $g_{H\tau\tau}$ | 5% | 1.9% | 0.80% |
| $g_{H\gamma\gamma}$ | 10% | 6.4% | 3.8% |
| $g_{H\mu\mu}$ | 2.1% | 13% | 8.6% |
| $g_{HZZ}$ | - | 0.35% | 0.22% |
| $g_{Hcc}$ | - | 2.3% | 1.2% |
| $g_{Hgg}$ | - | 2.2% | 1.0% |
| $BR_{invis}$ | - | <0.5% | <0.1% |

Not obvious what is the practical use of such high precision on $m_H$

The Higgs width is best measured at ee colliders

These Higgs couplings are best measured at ee colliders

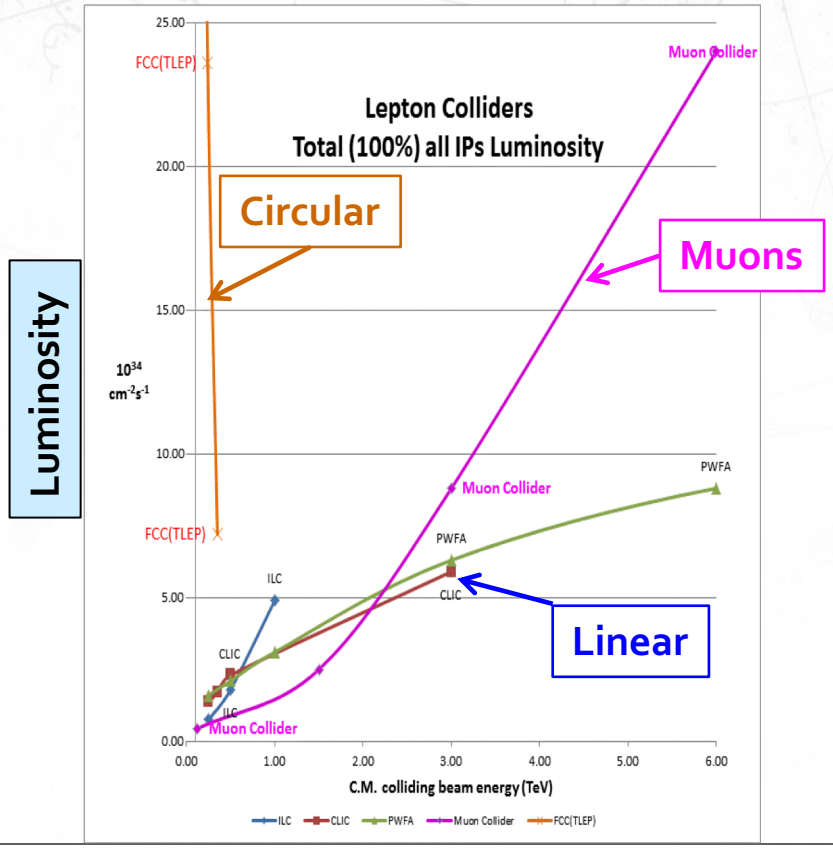
The Higgs coupling to muons is *the* added value of a μμ collider

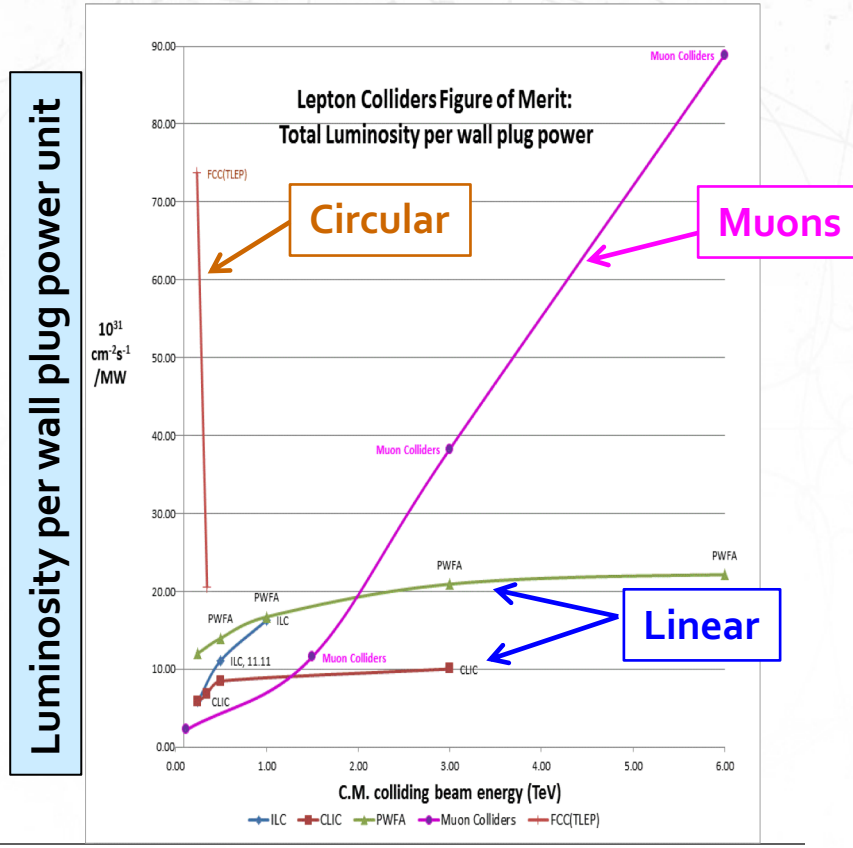
These Higgs couplings are *only* measured at ee colliders *)

- **Note: BR(H→μμ) can be also measured with % precision af FCC-hh (Will be already 10% after LHC)**

# Muon colliders at the energy frontier

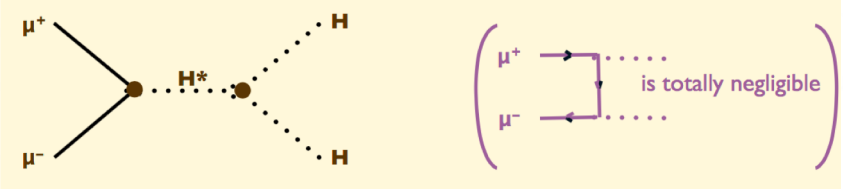
- Muon colliders might be a solution for high energy in the (far?) future
  - Many challenges to solve with sustained R&D and innovative thinking, as to
    - Increase luminosity for precision studies
    - Solve the radiation hazard at high energy (decay neutrino interactions in Earth)
  - Target luminosity competitive with CLIC above 2-3 TeV
    - With the possibility of several IPs



# Muon colliders: Summary

- A muon collider may be the best way to get lepton collisons at $\sqrt{s} \geq 3$ TeV
  - Much R&D remain in, e.g., muon cooling/acceleration
- A muon collider at $\sqrt{s} = 125$ GeV is a very pretty Higgs factory ($\mu^+\mu^- \to H$)
  - But not necessarily the one we need
    - If H(125) is a single particle, the process $e^+e^- \to HZ$ @ 240 GeV is better suited
      - In particular, the Higgs width can be measured very well in $e^+e^-$ collisions
    - A muon collider can also do that, but much higher luminosity would be necessary
      - At least two orders of magnitude – limited by the proton/positron source
- Several quasi-degenerate Higgs bosons is a strong case for μμ Higgs factory
  - If $\Delta m$ is between 4 MeV ($\Gamma_H$) and ~100 MeV (LHC resolution)
    - Such a situation may occur with two Higgs doublets, and quasi-degenerate H & A
      - Isolate the two peaks and perform nice CP studies !
- A muon collider at $\sqrt{s} > 2\ m_H$ provides the only way to *cleanly* probe HHH coupling




- A muon collider is the natural second step of neutrino factories
- Conclusion: don't write them off completely, but don't oversell them !

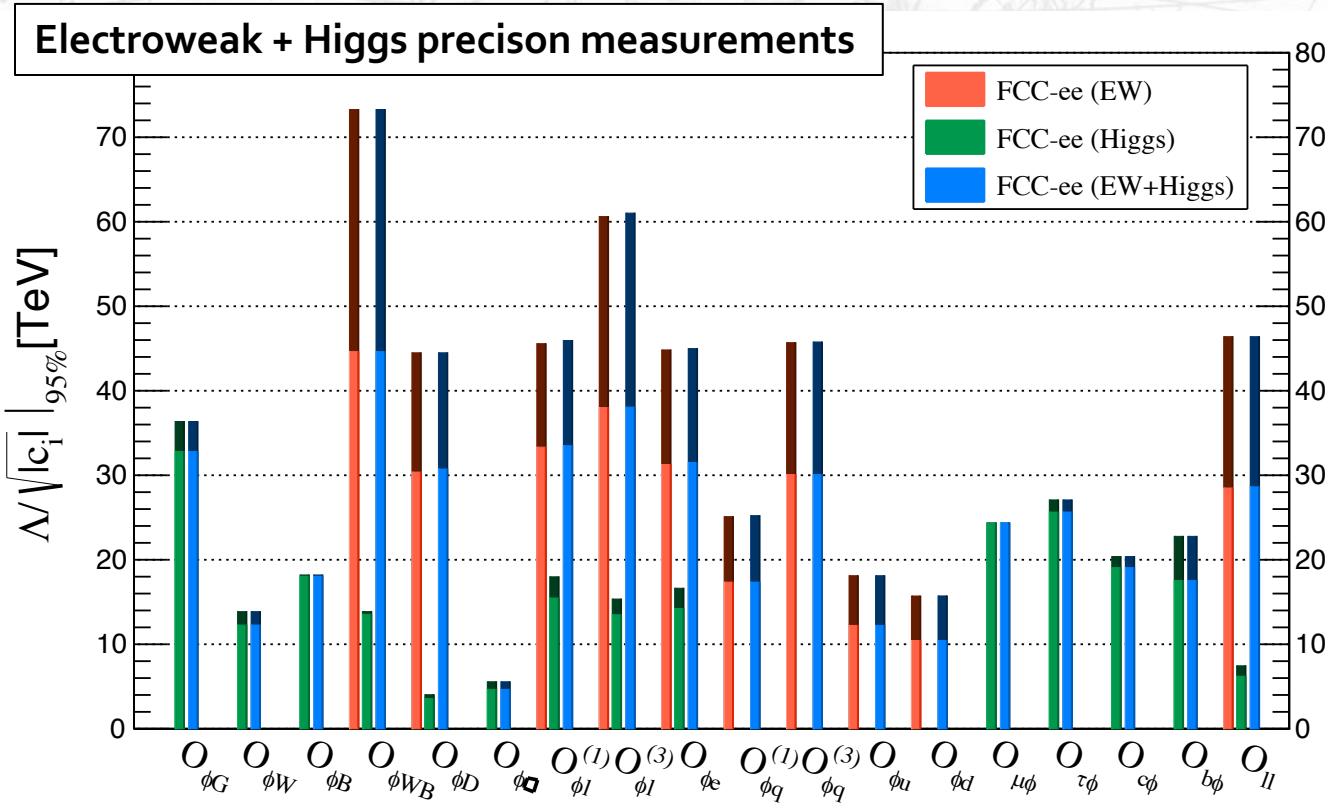
# Rounding off
# Summary and Conclusions

# Summary & Conclusions (1)

- Since LEP, there has been a dramatic development in $e^+e^-$ accelerator technology
  - Linear colliders: Energy reach up to $\sqrt{s}$ = 3 TeV
  - Circular colliders: Increase of instantaneous luminosity be 4-5 orders of magnitude
    - For $\sqrt{s}$ < 400 GeV, circular colliders provide competitive luminosity compared to linear
    - Repeat of LEP1 programme every ~5 min !
- With the discovery of the light Higgs boson and the non-discovery (so far) of new heavier states, $e^+e^-$ communities are now zooming in on the $\sqrt{s}$ < 400 GeV region
  - ILC: Higgs factory at $\sqrt{s}$ = 250 GeV as first stage (15 years)
    - Possibly later upgraded to $\sqrt{s}$ = 500 GeV (and $\sqrt{s}$ = 1 TeV)
  - CLIC: "Affordable" Higgs/top factory at $\sqrt{s}$ = 380 GeV as first stage
    - Possibly later upgraded to $\sqrt{s}$ = 1.5 TeV (and $\sqrt{s}$ = 3 TeV)
- A $e^+e^-$ Higgs factory with $\mathcal{O}(10^6)$ Higgs decays provided sub-% level measurement of (most) Higgs couplings
  - Strong New Physics reach !
- Electroweak precison measurements provide a strong test of SM
  - A $e^+e^-$ collider with 90 < $\sqrt{s}$ < 370-500 GeV could improve precision of all electroweak parameters by 1 – 2 orders of magnitude
    - Ultimate precision for Z, W, Higgs, and top
  - Strong New Physics reach !

# Summary & Conclusions (2)

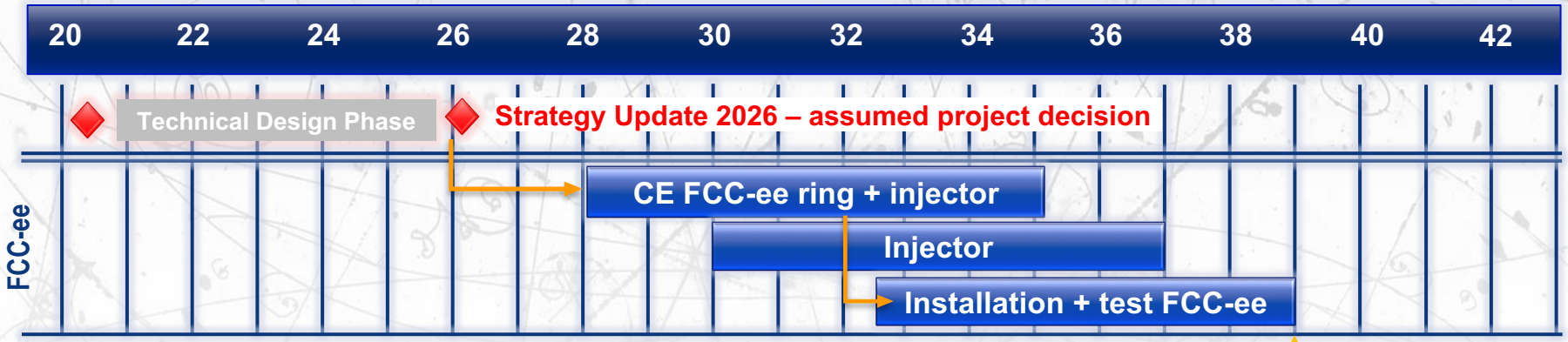
- Combined, the Higgs programme and the Electroweak Precision programme provides the ultimate precison test of the Standard model
  - The two programmes are largely complementary and test independent directions in theory space
    - Sensitivity to New Physics all the way up to ~75 TeV



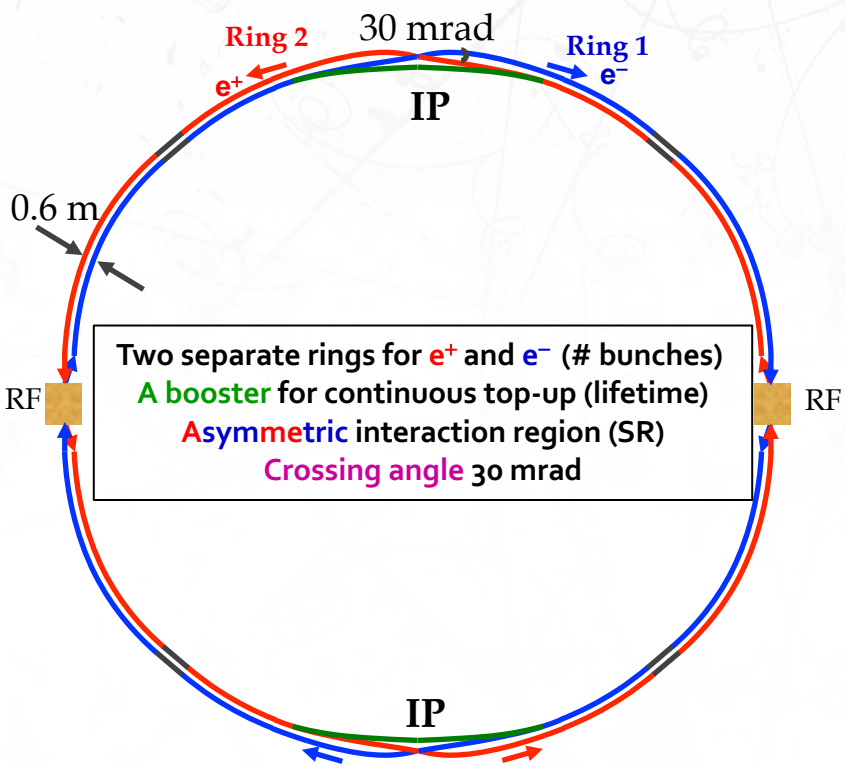
# Personal views

- Muon colliders provide a potential interesting option for *long-term* future high energy lepton colliders
  - Without major technological breakthroughs they unfortunately do not provide sufficient luminosity to be interesting as a Higgs factory
- Very clear physics case for an $e^+e^-$ collider with $90 < \sqrt{s} < 370\text{-}500$ GeV
  - Precision Higgs and electroweak physics
- Much harder to make physics case for $e^+e^-$ colliders with $\sqrt{s} > 370\text{-}500$ GeV
  - At least without clear evidence for accessible new particles
    - Produced copiously in $e^+e^-$ or $\gamma\gamma$ collisions
- Need serious assessment of relative merits of ILC and FCC-ee
  - As precision machines – as we have done in this series of lectures
    - Remember: Precise EW measurements of Z, W, and top provides tests of the SM *complementary* and *competitive in strength* to those of a Higgs factory;
    - In that respect, FCC-ee is a unique facility in providing both
      - And in paves the way for the FCC-hh (like LEP paved the way for the LHC)
- Exploration of energy frontier seems best done with a hadron collider
  - e.g., the 100 TeV FCC-hh proton-proton collider

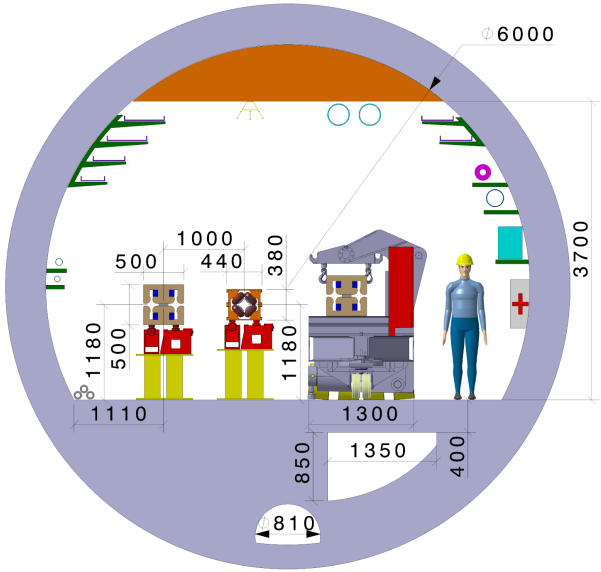
# Draft FCC-ee Schedule




**No time gap between HL-LHC and FCC-ee data taking !!**




Two separate rings for $e^+$ and $e^-$ (# bunches)
A booster for continuous top-up (lifetime)
Asymmetric interaction region (SR)
Crossing angle 30 mrad



# End of the second lecture

**Questions…**

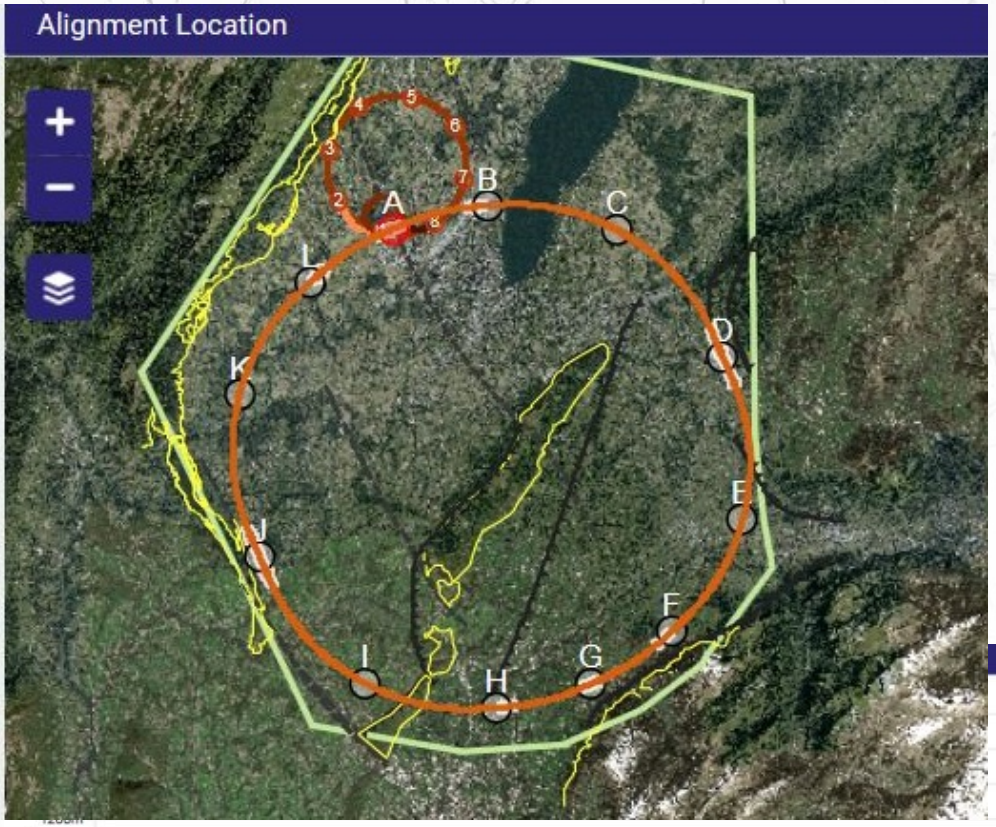
"*No doubt that future high energy colliders are extremely challenging projects.*

*However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable.*"

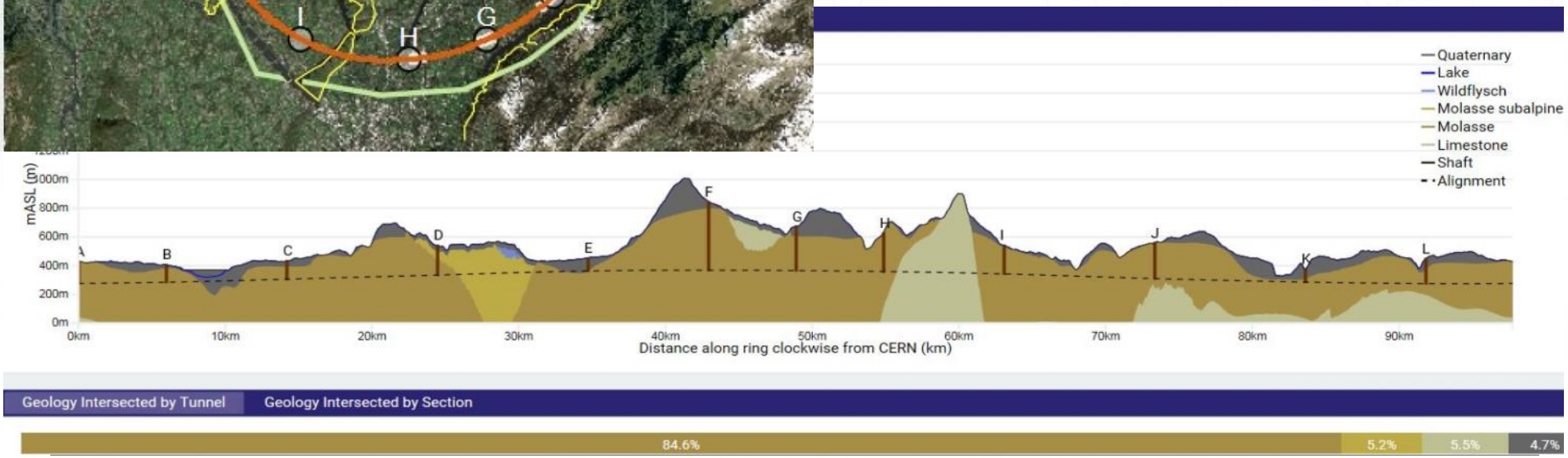
**Fabiola Gianotti, DG CERN**

# Extra Material

# The FCC Home




- Optimized length: 97.5 km
  - Accessibility, rock type, shaft depth, etc.
  - Tried different options from 80 to 100 km
- Tunneling
  - Molasse 90% (easy to dig)
  - Limestone 5%, Moraines 5% (tougher)
- Shallow implementation
  - 30m below Leman lakebed
  - Only one very deep shaft (F, 476m)
    - Alternatives studied (e.g. inclined access)



# FCC-ee Machine Parameters

| FCC-ee parameters | | Z | $W^+W^-$ | ZH | ttbar | |
|---|---|---|---|---|---|---|
| **Beam energy** | **GeV** | **45.6** | **80** | **120** | **175** | **182.5** |
| **Luminosity / IP** | **$10^{34}$ cm$^{-2}$ s$^{-1}$** | **230** | **28** | **8.5** | **1.8** | **1.55** |
| Beam current | mA | 1390 | 147 | 29 | 6.4 | 5.4 |
| Bunches per beam | # | 16640 | 2000 | 328 | 59 | 48 |
| Average bunch spacing | ns | 19.6 | 163 | 994 | 2763 | 3396 |
| Bunch population | $10^{11}$ | 1.7 | 1.5 | 1.8 | 2.2 | 2.3 |
| Horizontal emittance $\varepsilon_x$<br>Vertical emittance $\varepsilon_y$ | nm<br>pm | 0.27<br>1.0 | 0.84<br>1.7 | 0.63<br>1.3 | 1.34<br>2.7 | 1.46<br>2.9 |
| **$\beta_x^*$ / $\beta_y^*$** | **m / mm** | **0.15 / 0.8** | **0.2 / 1.0** | **0.3 / 1.0** | **1.0 / 1.6** | |
| beam size at IP: $\sigma_x^*$ / $\sigma_y^*$ | µm / nm | 6.4 / 28 | 13 / 41 | 13.7 / 36 | 36.7 / 66 | 38.2/68 |
| Energy spread: SR / total (w BS) | % | 0.038 / 0.132 | 0.066 / 0.131 | 0.099 / 0.165 | 0.144 / 0.196 | 0.15 / 0.192 |
| Bunch length: SR / total | mm | 3.5 / 12.1 | 3 / 6.0 | 3.15 / 5.3 | 2.75 / 3.82 | 1.97 / 2.54 |
| **Energy loss per turn** | **GeV** | **0.036** | **0.34** | **1.72** | **7.8** | **9.2** |
| RF Voltage /station | GV | 0.1 | 0.75 | 2.0 | 4/5.4 | 4/6.9 |
| Longitudinal damping time | turns | 1273 | 236 | 70.3 | 23.1 | 20.4 |
| Acceptance RF / energy (DA) | % | 1.9 / ±1.3 | 2.3 / ±1.3 | 2.3 / ±1.7 | 3.5/ (-2.8; +2.4) | 3.36 / (-2.8; +2.4) |
| Rad. Bhabha/ actual Beamstr. Lifetime | min | 68 / > 200 | 59 / >200 | 38 / 18 | 37/ 24 | 40 / 18 |
| Beam-beam parameter $\xi_x$/ $\xi_y$ | | 0.004 / 0.133 | 0.01 / 0.141 | 0.016 / 0.118 | 0.088 / 0.148 | 0.099 / 0.126 |
| Interaction region length | mm | 0.42 | 0.85 | 0.9 | 1.8 | 1.8 |

# FCC-ee Power consumption

- The RF system needs to compensate for 100 MW SR losses
  - Corresponds to 200 MW electric power with 50% RF power sources (klystrons)
    - Klystron efficiency was ~55% at LEP2
  - Recent (2015) breakthroughs in klystron design promise 90% efficiency
    - Assume 85% will be achieved and take 10 – 20% margins

| lepton collider | Z | | W | ZH | $t\bar{t}$ | LEP2 |
|---|---|---|---|---|---|---|
| luminosity / interaction point [$10^{34}$ cm$^{-2}$s$^{-1}$] | 207 | 90 | 19 | 5 | 1.3 | 0.012 |
| total RF power [MW] | 163 | | 163 | 145 | 145 | 42 |
| collider cryogenics [MW] | 3 | 2 | 5 | 23 | 39 | 18 |
| collider magnets [MW] | 3 | | 10 | 24 | 50 | 16 |
| booster RF & cryogenics [MW] | 4 | | 4 | 6 | 7 | N/A |
| booster magnets [MW] | 0 | | 1 | 2 | 5 | N/A |
| pre-injector complex [MW] | 10 | | 10 | 10 | 10 | 10 |
| physics detectors (2) [MW] | 10 | | 10 | 10 | 10 | 9 |
| cooling & ventilation [MW] | 47 | | 49 | 52 | 62 | 16 |
| general services [MW] | 36 | | 36 | 36 | 36 | 9 |
| total electrical power [MW] | 276 | ~275 | ~288 | ~308 | ~364 | ~120 |

  - For comparison
    - LHC Run1: 210 MW, HL-LHC: 260 MW, FCC-hh: ~500 MW
    - CLIC: 250 MW ( at 380 GeV) to 580 MW (at 3 TeV)