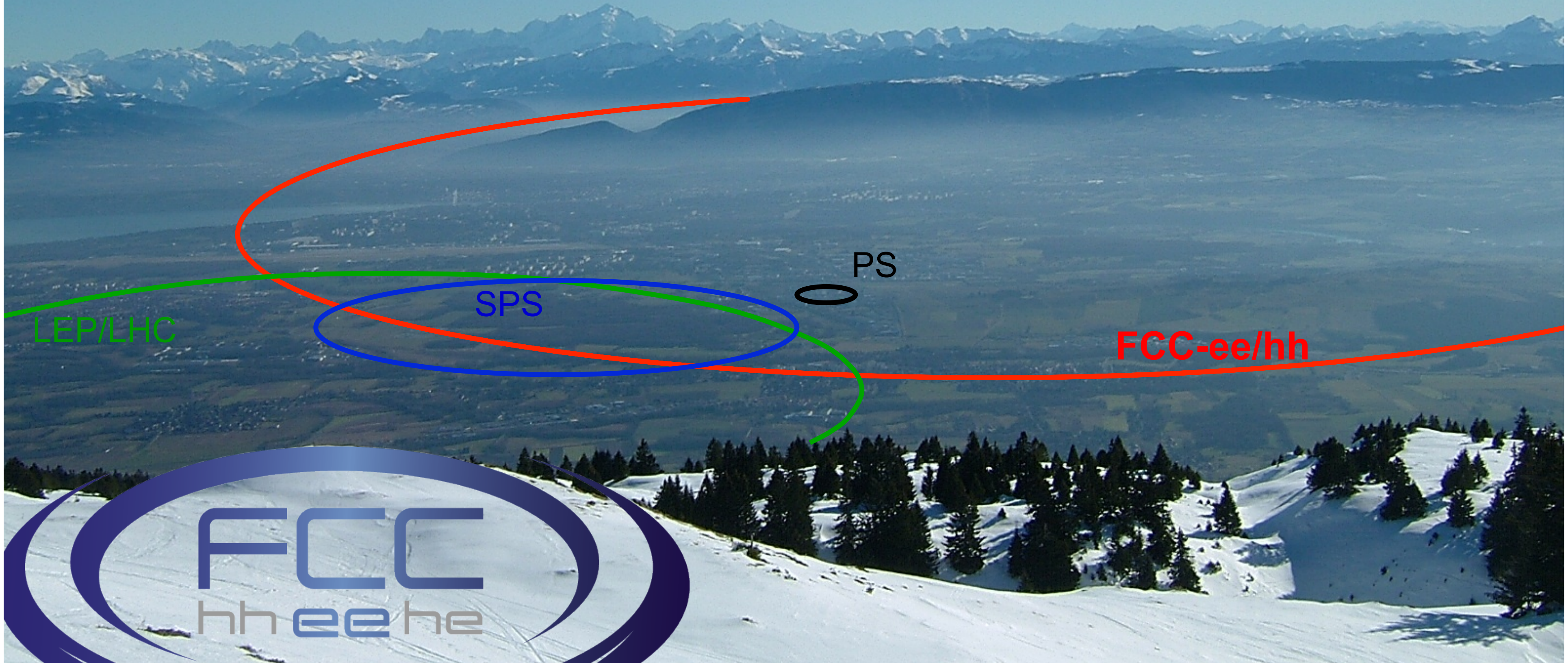
# Physics opportunities with the FCC

See Seminar of Frank Zimmermann, Future Colliders for Particle Physics  Jan 2018

See also three lectures on FCC at the CERN Academic Training, Oct. 2017




University of Geneva
28 March 2018

# Genesis of the FCC

- **Outcome of the European Strategy for Particle Physics in May 2013**
  - **From CERN Council official documents:**

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

To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

*CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.*

CLIC

*[...] coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, [...]*

https://cds.cern.ch/record/1567295

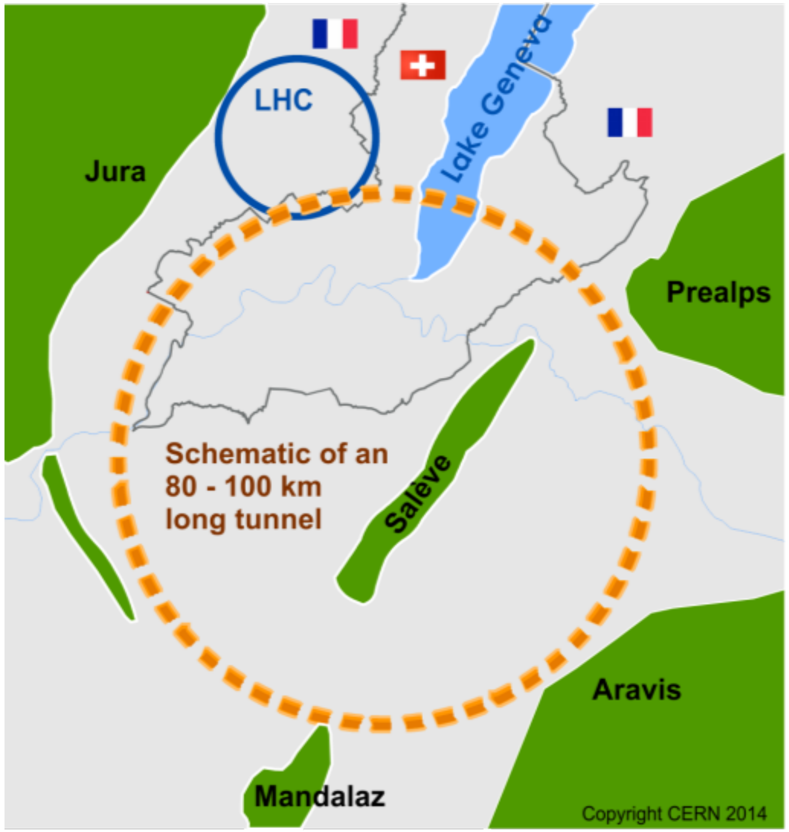
Possible proton-proton machines of higher energy than the LHC include HE-LHC, roughly doubling the centre-of-mass energy in the present tunnel, and V-LHC, aimed at reaching up to 100 TeV in a new circular 80km tunnel. A large tunnel such as this could also host a circular electron-positron machine (TLEP) reaching energies up to 350 GeV with high luminosity.

FCC !

- **Not based on a physics case. Mostly technological / strategical arguments.**

# The FCC Conceptual Design Study

- **Study kicked off in Geneva in Feb. 2014**
- **International collaboration (124 institutes)**
  - Study circular colliders fitting in a new ~100 km infrastructure, in the Geneva area
    - Baseline circumference: 97.75 km
- **Ultimate goal: 100TeV pp collider (FCC-hh)**
  - Requires R&D for 16T magnets
  - Defines the infrastructure
- **Possible first steps**
  - pp collider (HE-LHC) in the LEP/LHC tunnel
    - With FCC-hh technology (16T → 26-27 TeV)
  - $e^+e^-$ collider (FCC-ee) at the intensity frontier
    - High luminosity, $\sqrt{s}$ = 90-400 GeV
- **Possible add-on**
  - e-p option (FCC-eh)
    - With a new 60 GeV ERL for electrons




- **European Strategy update (2019)**
  - Conceptual design report (CDR)
  - Cost review for tunnel and each collider
  - Schedules and operation models

# Genesis of the FCC-ee

- **Seminal papers started in 2011**
  - **Original idea came with the first hints for the Higgs boson in LHC (Dec. 2011)**

    A High Luminosity $e^+e^-$ Collider in the LHC tunnel to study the Higgs Boson
    Alain Blondel (Geneva U.), Frank Zimmermann (CERN) https://arxiv.org/abs/1112.2518
  - **First physics studies followed immediately after (Aug. 2012)**

    Prospective Studies for LEP3 with the CMS Detector, Patrick Janot et al., https://arxiv.org/abs/1208.1662
  - **Extended to a larger tunnel in the wake of the HF2012 workshop (Nov. 2012)**

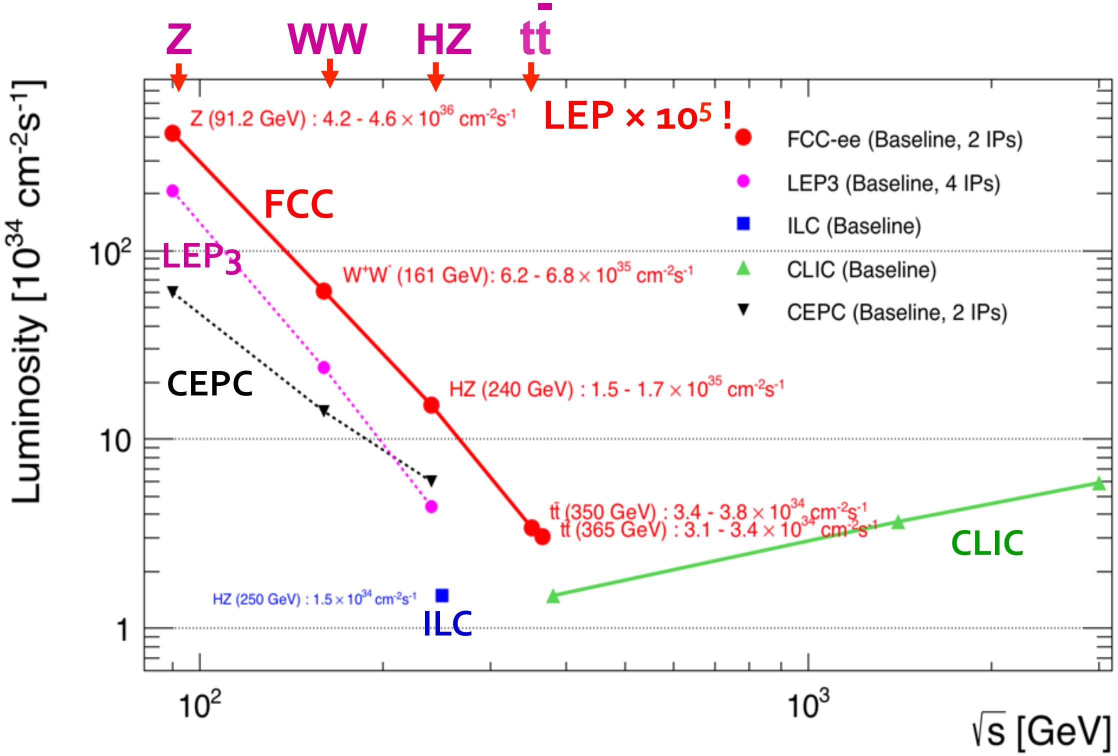
    Higgs Factory: Linear vs Circular (HF2012), Alain Blondel et al., https://indico.fnal.gov/event/5775/
    First look at the physics case of TLEP, Patrick Janot et al., https://arxiv.org/abs/1308.6176
- **Concluded with the ESPP'13 famous statement**

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

  > There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.
- **Unambiguously tailored to ILC at the time**
  - **The FCC-ee turns out to be ideally (and much better) suited to this physics case**
    - The synergetic combination of the FCC-ee and the FCC-hh is unique and unbeatable
    - Strategically kills two birds in one stone

# FCC-ee: Unprecedented precisions

- **Today: Not less than five projects for EW factories in the world**
  - To study the properties of the Higgs boson
    - And other particles: the Z (91.2 GeV) & W (80.4 GeV) bosons, the top quark (173.3 GeV)
  - Baseline luminosities and centre-of-mass energies:




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

**… in each detector**
  - In a clean exp'tal environment:
    - no pileup; beam backgrounds under control; E,p constraints

- **The FCC-ee unique discovery potential is multiplied by the presence of the four heavy particles of the standard model in its energy range**

# FCC-ee: Luminosity goals and operation model

- The FCC-ee physics goals require at least
  - 150 $ab^{-1}$ at and around the Z pole ($\sqrt{s}$~91.2 GeV)
  - 10 $ab^{-1}$ at the WW threshold ($\sqrt{s}$~161 GeV)
  - 5 $ab^{-1}$ at the HZ cross section maximum ($\sqrt{s}$~240 GeV)
  - 0.2 $ab^{-1}$ at the top threshold ($\sqrt{s}$~350 GeV) and 1.5 $ab^{-1}$ above ($\sqrt{s}$~365 GeV)

$5\times10^{12}$ Z
$10^8$ WW
$10^6$ HZ
$10^6$ $t\bar{t}$

- Operation model (with 10% safety margin) with two IPs
  - 200 scheduled physics days per year (7 months – 13 days of MD / stops)
  - Hübner factor ~ 0.75 (lower than achieved with KEKB top-up injection, ~0.8)
  - Half the design luminosity in the first years of Z and top operation (~LEP1)
  - Machine configuration between WPs changed during Winter shutdowns (3 months/year)

| Working point | Z, years 1-2 | Z, later | WW | HZ | $t\bar{t}$ threshold | 365 GeV |
|---|---|---|---|---|---|---|
| Lumi/IP ($10^{34}$ $cm^{-2}s^{-1}$) | 100 | 200 | 31 | 7.5 | 0.85 | 1.5 |
| Lumi/year (2 IP) | 26 $ab^{-1}$ | 52 $ab^{-1}$ | 8.1 $ab^{-1}$ | 1.95 $ab^{-1}$ | 0.22 $ab^{-1}$ | 0.39 $ab^{-1}$ |
| Physics goal | 150 | | 10 | 5 | 0.2 | 1.5 |
| Run time (year) | 2 | 2 | 1 | 3 | 1 | 4 |

- Total running time : 13 (+1) years (~ LEP)

Longer shutdowns: install 196 RF CMs
LEP Record: 32 in one shutdown !

# FCC-ee: Discovery potential in a nutshell

- **EXPLORE the 10-100 TeV energy scale**
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - 20-50 fold improved precision on ALL electroweak observables (EWPO)
      - ➨ $m_Z$, $\Gamma_Z$, $m_W$, $m_{top}$, $\sin^2\theta_W^{eff}$, $R_b$, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, top EW couplings …
    - 10 fold more precise and model-independent Higgs couplings measurements
- **DISCOVER that the Standard Model does not fit**
  - Then extra weakly-coupled and Higgs-coupled particles exist
  - Understand the underlying physics through effects via loops
- **DISCOVER a violation of flavour conservation / universality**
  - Examples: $Z \to \tau\mu$ in $5\times10^{12}$ Z decays; or $t \to cZ$, cH at $\sqrt{s}$ = 240 or 350 GeV
  - Also a lot of flavour physics in $10^{12}$ $b\bar{b}$ events, e.g., with $B^0 \to K^{*0}\tau^+\tau^-$ or $B_s \to \tau^+\tau^-$
- **DISCOVER dark matter as invisible decays of Higgs or Z**
- **DISCOVER very weakly coupled particles in the 5-100 GeV mass range**
  - Such as right-handed neutrinos, dark photons, …
    - May help understand dark matter, universe baryon asymmetry, neutrino masses

May help shape up FCC-hh detectors

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

# FCC-ee: Energy upgrade

- Requested by the European Strategy statement (2013)
  - In linear $e^+e^-$ colliders, an energy upgrade is mostly relevant for
    - The production and study of (a) putative new particle(s) at high mass
      - ➨ The ILC baseline design no longer plans an energy upgrade
      - ➨ The domain covered by CLIC (0.4 – 3 TeV) is being explored by the LHC

        CLIC becomes an interesting option to consider if a new particle produced in $e^+e^-$ collisions were discovered / hinted at in this range by the LHC
      - ➨ A much bigger energy step is needed to go beyond → hadron colliders

        With $\sqrt{s}$ = 100 TeV, the FCC-hh has access to a broader range

        The SppC is less ambitious with R&D for 12T dipoles
    - The measurement of the top Yukawa coupling (ttH) and Higgs self coupling (HHH)
      - ➨ In combination with FCC-ee, the FCC-hh does better than linear colliders
- The FCC-hh is the most ambitious scientifically
  - With numerous synergies and complementarities
    - Tunnel, infrastructure, cryogenics, time, long-term CERN future, and physics
  - And it paves the way to the FCC-$\mu\mu$, a lepton collider with potentially much higher $\sqrt{s}$

# FCC-hh: Luminosity goals and event rates

## Luminosity and pileup

- HL-LHC : 3 $ab^{-1}$ at 14 TeV in 15 years, up to 200 PU
- HE-LHC : 10 $ab^{-1}$ at 27 TeV in 15 years, up to 850 PU
- FCC-hh : 20 $ab^{-1}$ at 100 TeV in 25 years, up to 1000 PU
  - Baseline: 0.25 $ab^{-1}$ the first year, increasing for ~10 years towards…
  - Ultimate: 1.5 $ab^{-1}$ / year for 15 years

## Event rates (examples)

- $2 \times 10^{10}$ Higgs bosons (200 × HL-LHC)
  - $2 \times 10^{7}$ pairs of Higgs (400 × HL-LHC)
  - $10^{8}$ ttH events (600 × HL-LHC)
- $10^{12}$ top pairs (300 × HL-LHC)
- $10^{5}$ pairs of gluinos if $m_{gluino}$ ~ 8 TeV (none at HL-LHC)
- $5 \times 10^{13}$ W bosons, $10^{13}$ Z bosons (70 × HL-LHC)
- …

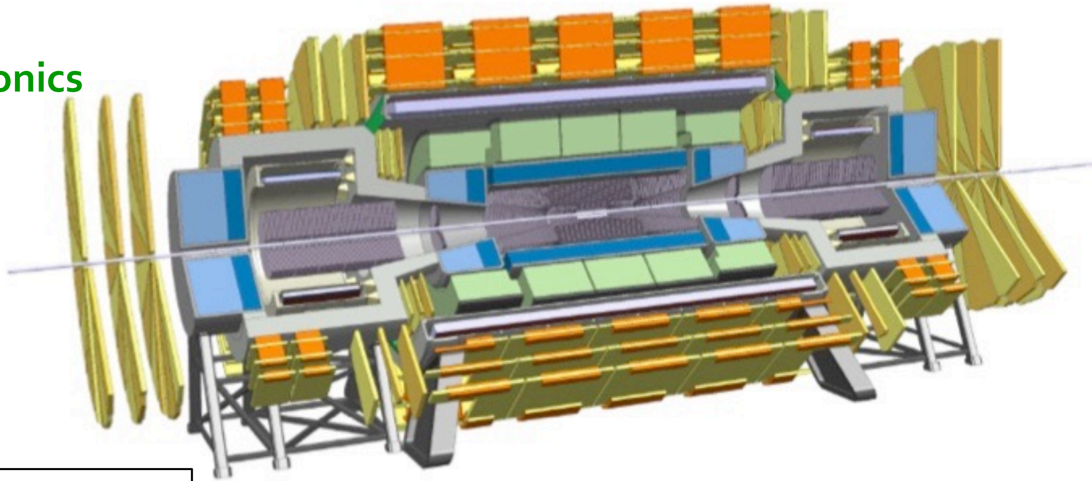
# FCC-hh: Discovery potential

Physics at the FCC-hh: https://cds.cern.ch/record/2270978

- **Two main features**
  - Mass reach of direct particle observation enhanced by a factor E/14 TeV ~ 7 @ 100 TeV
    - New gauge bosons up to 40 TeV
    - Strongly-interacting particles up to 15-20 TeV
    - Natural SUSY up to 5-20 TeV
    - Dark matter up to 1.5 – 5 TeV
      - ➨ Possibility to find or rule out thermal WIMP DM candidates
    - Increased sensitivity to high-energy phenomena (e.g. WW scattering, Drell-Yan )
  - Huge production rates
    - Precision study of Higgs and top quark properties
      - ➨ Exploration of EWSB phenomena with unmatchable sensitivity
        - Yes/No: Did baryogenesis take place during EW phase transition ?
      - ➨ Rare or BSM decays
    - Sensitivity to heavy new physics through indirect (precision) probes
      - ➨ E.g., with ratios of cross sections
      - ➨ E.g., with high-$p_T$ final states for channels systematics-limited at the LHC
        - Shift between statistics and systematics
        - Further improved by synergies with FCC-ee

# FCC-hh: Detectors

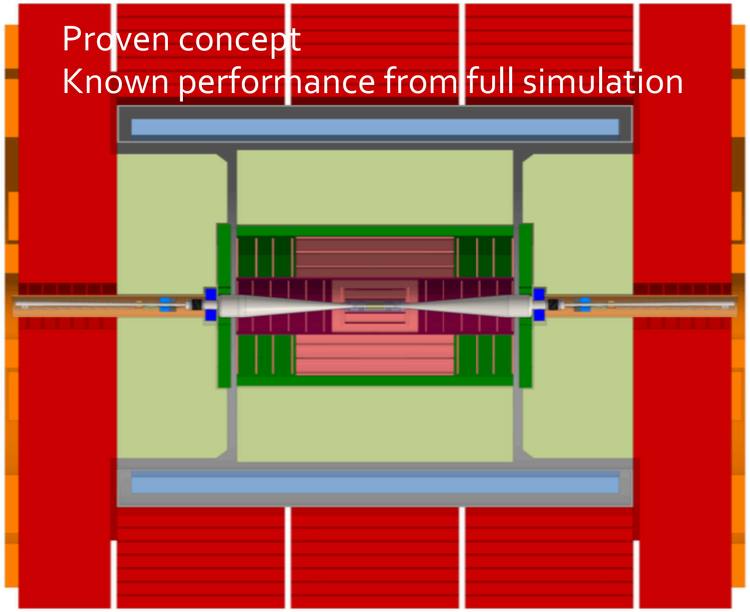
- A formidable challenge, well beyond HL-LHC
  - Much larger longitudinal event boost
    - Enhanced coverage at large rapidity (with tracking and calorimetry)
    - Forward solenoids or dipoles
    - Length ~ 46 m
  - Zs, Ws, Higgses, tops will be highly boosted (esp. in high $p_T$ final states)
    - High granularity tracking and calorimetry
    - 4T, 10 m bore main solenoid surrounding the calorimeters
  - Up to 1000 PU events over a bunch length of 5 cm
    - High resolution vertexing
    - Ultra fast detector / electronics
  - Energetic jets
    - 2m - thick HCAL
  - High $p_T$ muons
    - 20% resolution @ 10 TeV
  - Radiation hardness
  - …

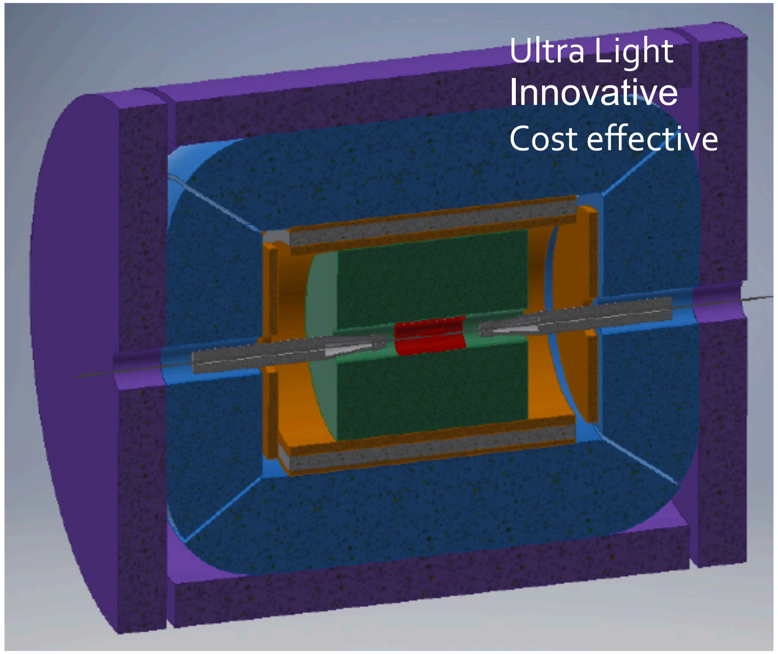


See Werner Riegler's Academic Training here

# FCC-ee: Detectors

- Two baseline designs aimed for high-precision measurements (~$10^{-5}$)
  - CLD: CLIC design adapted for FCC-ee
  - IDEA: FCC-ee specific, R&D ahead




CLD:
- Silicon tracker, thickness ~ 30%$X_0$
- High granularity (3D+timing) calorimetry
- 2T, 8m bore solenoid around calorimeters

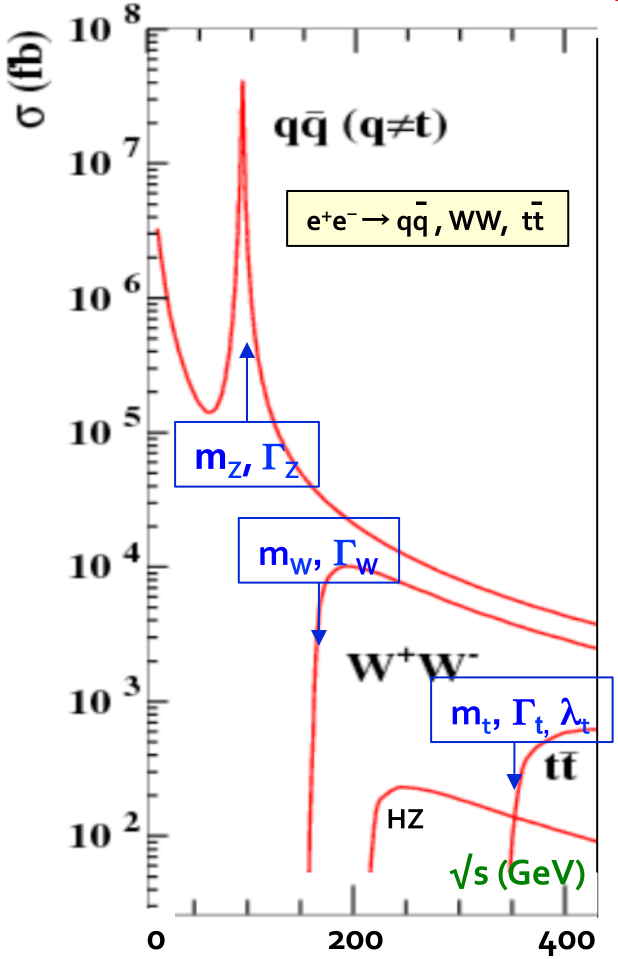
IDEA:
- Drift chamber (50K wires, L=4m, 0.4%$X_0$)
- 2T, 4m bore solenoid around tracker
- Dual readout lead/fibre calorimeter

- + maybe a large surrounding tracker to enhance long-lived particle searches ?

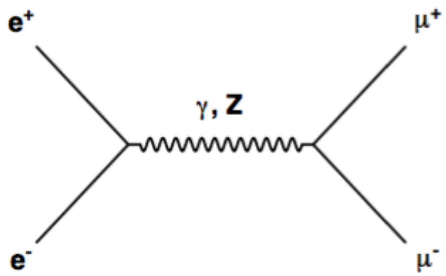
# Electroweak Precision Measurements

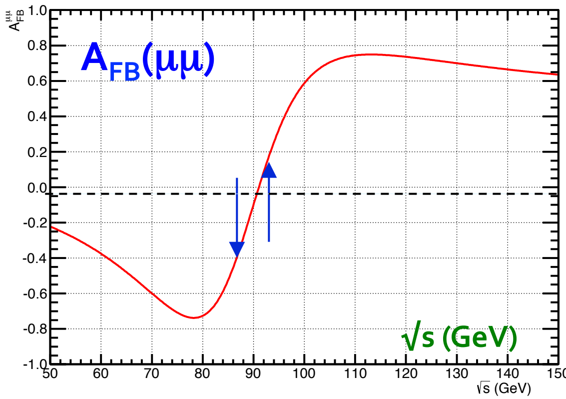
# EWPOs @ FCC-ee

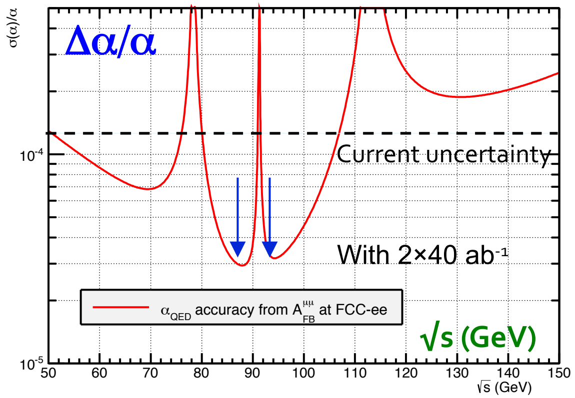
- **Boils down to measuring cross sections and asymmetries**




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




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

- 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
  - Measure $m_Z$, $\Gamma_Z$ from the three-point Z resonance scan

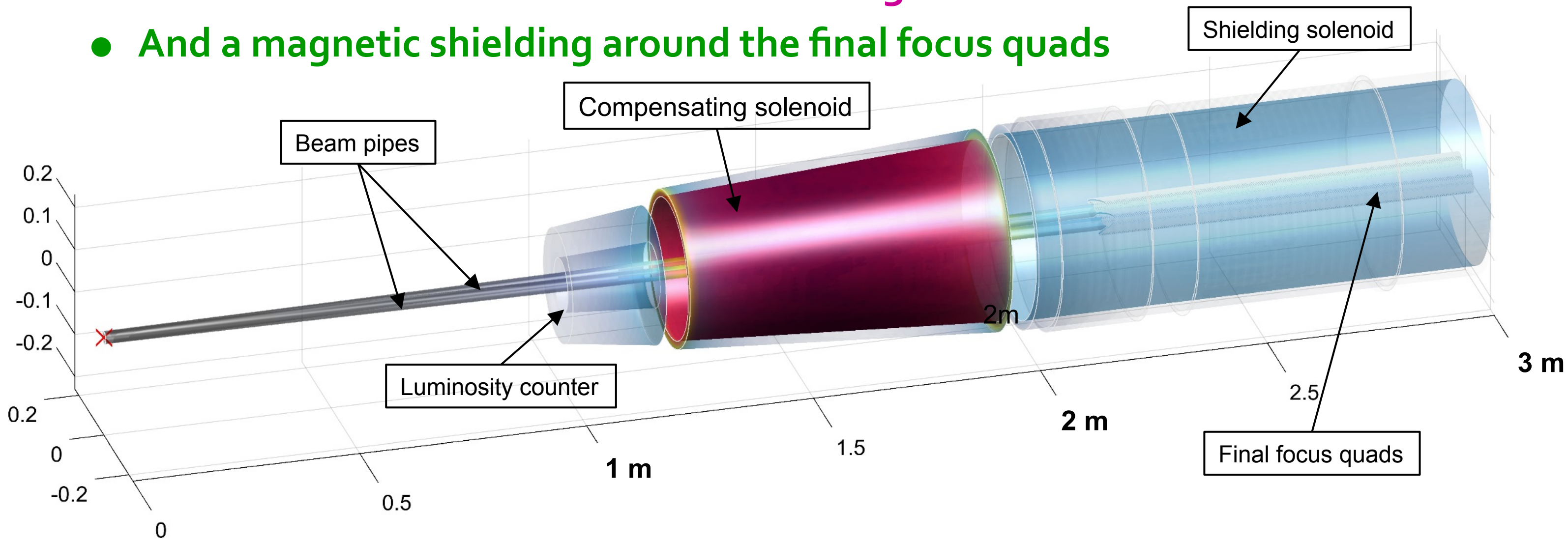
- **Dominant exp'tal uncertainties: beam energy knowledge, luminosity measurement**

# FCC-ee: Beam energy calibration

- **A unique feature circular $e^+e^-$ colliders**
  - Achieve transverse polarization of a few 10's of monitoring non-colliding bunches
    - Out of 16000 or 1300 bunches at the Z and W energies
    - Requires wigglers to have fast polarization at the beginning of physics run
    - Too much depolarizing effects (SR, energy spread) at higher energies
  - "Continous" beam energy calibration with resonant depolarization
    - One monitoring bunch at a time
    - Demonstrated (and used) at LEP, outside physics runs (extrapolation error 2 MeV)
  - Target precision on $\sqrt{s}$ is ± 100 keV at the Z pole ($m_Z$) and at the WW threshold ($m_W$)
    - Crucial for sensitivity to new physics of all electroweak measurements
    - Above WW threshold: Use WW,ZZ and Zγ events to determine $\sqrt{s}$ from $m_W$ and $m_Z$
  - Systematic studies ongoing with promising perspective
- **Note about longitudinal polarization (natural at linear collider)**
  - Much lower priority than transverse polarization
    - Brings no information that cannot be obtained otherwise (large FCC-ee statistics)
      - ➨ From unpolarized asymmetries or from final state polarization (tau, top)
    - Causes too much loss of luminosity to provide gain in precision

# FCC-ee : Luminosity measurement

- **Not much room for the luminosity counter** (with low angle Bhabha $e^+e^- \rightarrow e^+e^-$)
  - Emittance blow-up from detector magnetic field (beam crossing at angle)
    - Requires a compensating solenoid even closer to the IP
      - ➨ Which in turn limits the detector magnetic field to 2T
    - And a magnetic shielding around the final focus quads



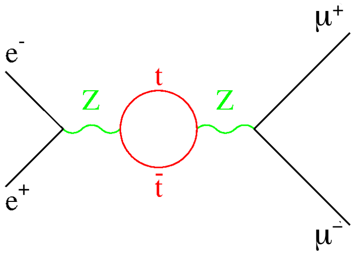

  - LumiCal Front face at 1.2 m from the IP (inside the tracker – was ~2.5m at LEP)
    - Strong magnetic forces, quenches : dangerous longitudinal movements
      - ➨ LumiCal supported by the calorimeter, fixed to the central beam pipe
  - Current challenge: Outgoing electrons deflected by charge density of the other bunch
    - Effect 10 times larger than the required luminosity accuracy ($10^{-4}$)

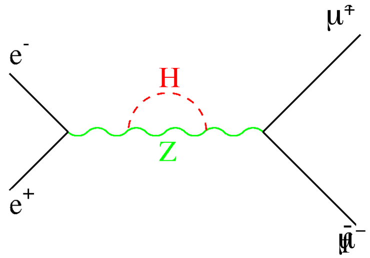
# FCC-ee: Summary of precisions achievable

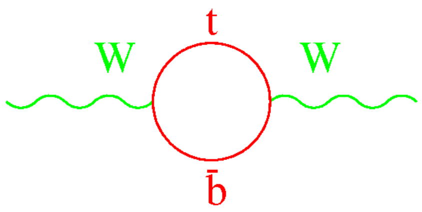
| Observable | Measurement | Current precision | FCC-ee stat. | Possible syst. | Challenge |
|---|---|---|---|---|---|
| **$m_Z$ (MeV)** | Lineshape | 91187.5 ± 2.1 | 0.005 | < 0.1 | QED corr. |
| **$\Gamma_Z$ (MeV)** | Lineshape | 2495.2 ± 2.3 | 0.008 | < 0.1 | QED / EW |
| **$R_l$** | Peak | 20.767 ± 0.025 | 0.001 | < 0.001 | Statistics |
| **$R_b$** | Peak | 0.21629 ± 0.00066 | 0.000003 | < 0.00006 | $g \rightarrow bb$ |
| **$N_\nu$** | 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 | <0.000005 | Beam energy |
| **$1/\alpha_{QED}(m_Z)$** | $A_{FB}^{\mu\mu}$ (off-peak) | 128.952 ± 0.014 | 0.004 | < 0.004 | QED / EW |
| **$\alpha_s(m_Z)$** | $R_l$ | 0.1196 ± 0.0030 | 0.00001 | <0.0002 | New Physics |
| **$m_W$ (MeV)** | Threshold scan | 80385 ± 15 | 0.6 | < 0.6 | EW Corr. |
| **$\Gamma_W$ (MeV)** | Threshold scan | 2085 ± 42 | 1.5 | <1.5 | EW Corr. |
| **$N_\nu$** | $e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$ | 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 | 20 | <40 | QCD corr. |
| **$\Gamma_{top}$ (MeV)** | Threshold scan | ? | 40 | <40 | QCD corr. |
| **$\lambda_{top}$** | Threshold scan | $\mu$ = 1.2 ± 0.3 | 0.08 | < 0.05 | QCD corr. |
| **ttZ couplings** | $\sqrt{s}$ = 365 GeV | ~30% | ~2% | <2% | QCD corr |

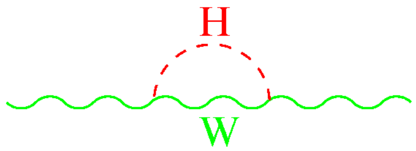
# Precision ⇔ Discovery

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




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

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

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

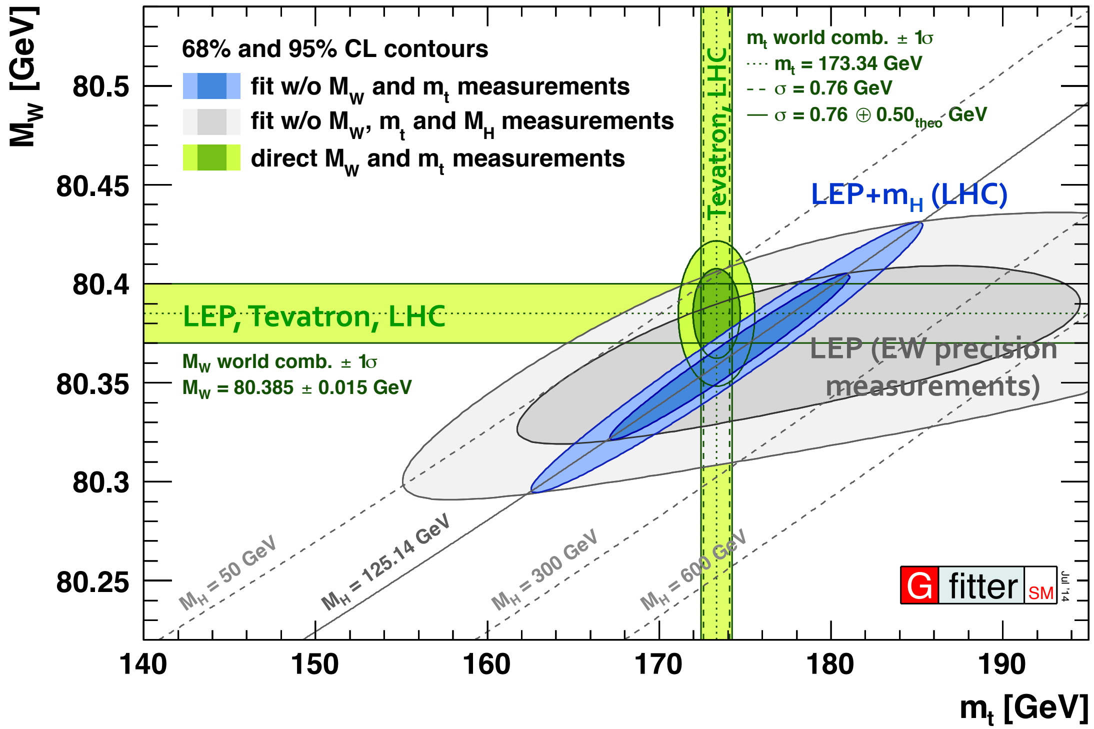
$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots \approx 1\%$$

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

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

# Precision ⟺ Discovery , cont'd

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




Fit of the SM and nothing else

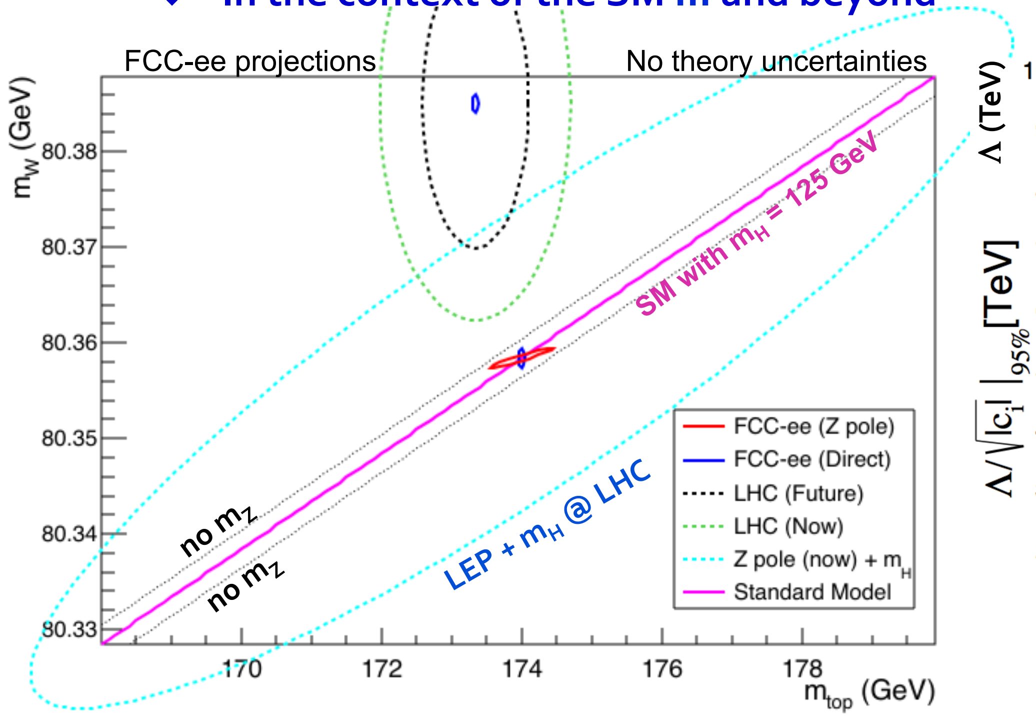
https://arxiv.org/pdf/1407.3792.pdf

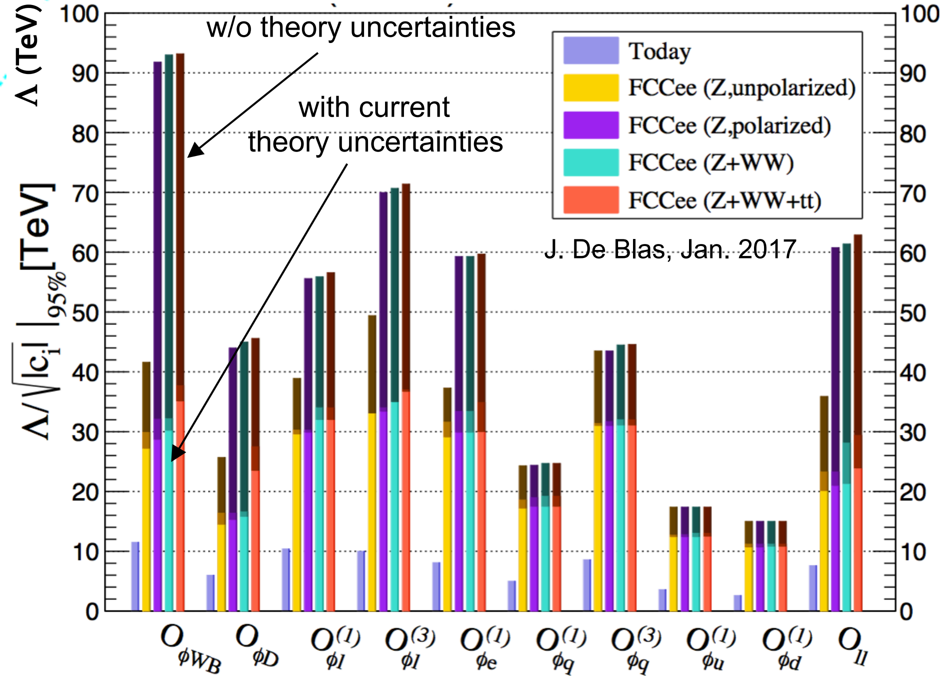
- The FCC-ee will significantly improve precision on all fronts
  - More precise measurements become sensitive to other (heavier) particles in the loops
    - If one ingredient is missing, the sensitivity to new physics drops / vanishes
      - ➨ Full programme (from the Z pole to above the top threshold)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

# Precision ⟺ Discovery , cont'd

- **Combining all FCC-ee EW measurements**
  - **In the context of the SM … and beyond**

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




**Requires 10-fold improved theory calculations**

Points to the physics to be looked for at FCC-hh

Today: $\Lambda/\sqrt{c}$ > **5-10 TeV**

  - **New physics: blue and red ellipses may not overlap**
    - **Or even better, data may not fit to the SM**

**After FCC-ee: $\Lambda/\sqrt{c}$ > 50-100 TeV ?**

# FCC-ee: Theory calculations

- **Today**

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

$$m_W^{direct} = 80.385 \pm 0.015 \text{ GeV},$$

- **With FCC-ee**

$$m_W = 80.3584 \pm 0.0002_{m_{top}} \pm 0.0001_{m_Z} \pm 0.0005_{\alpha_{QED}} \pm 0.0002_{\alpha_S} \pm 0.0000_{m_H} \pm 0.0040_{theory} \text{ GeV}$$
$$= 80.3584 \pm 0.0006_{exp} \pm 0.0040_{theory} \text{ GeV},$$

$$m_W^{direct} = 80.385 \pm 0.0006 \text{ GeV}$$

- **Theory R&D**

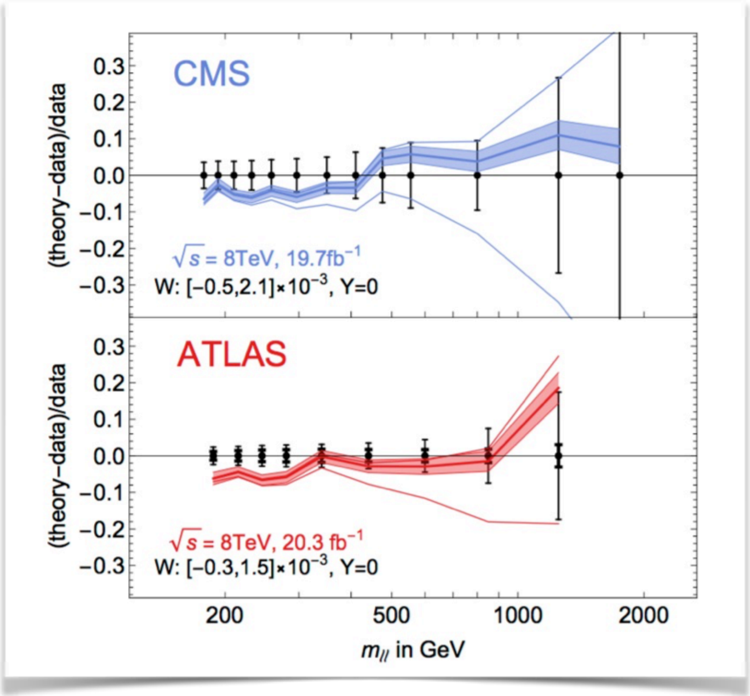
**Conclusion from Precision Calculations Mini-Workshop in January 2018:**
The necessary theoretical work is doable in 5-10 years perspective, due to steady progress in methods and tools, including the recent completion of NNLO SM corrections to EWPOS. This statement is conditional to a strong support by the funding agencies and the overall community. Appropriate financial support and training programs for these precision calculations are mandatory.

# FCC-hh: Probes dim 6 op's with high mass DY

- **Overall credo: Trade extreme precision for dynamical range @ 100 TeV**
  - In the same pursuit of high-scale sensitivity
    - Effect of Dim 6 operator in a process with momentum transfer Q on observable O

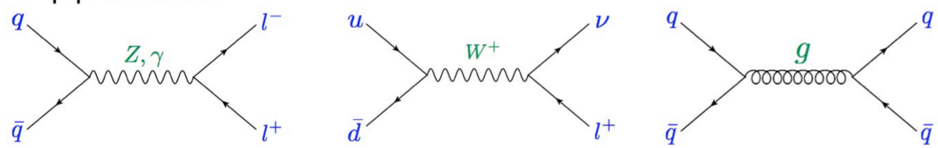
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

At Q~100 GeV, precision probes large $\Lambda$
e.g. $\delta O = 10^{-4} \Rightarrow \Lambda \sim 10$ TeV
Larger Q probe large $\Lambda$ even if precision is low
e.g. $\delta O$ = 15% at Q = 4 TeV $\Rightarrow \Lambda \sim 10$ TeV




$$\mathcal{L}_{\rm eff} \supset \frac{c_Y}{\Lambda_Y^2}(\partial_\rho B_{\mu\nu})^2 + \frac{c_W}{\Lambda_W^2}(D_\rho W^a_{\mu\nu})^2 + \frac{c_Z}{\Lambda_Z^2}(D_\rho G^a_{\mu\nu})^2$$

- FCC-pp reach:



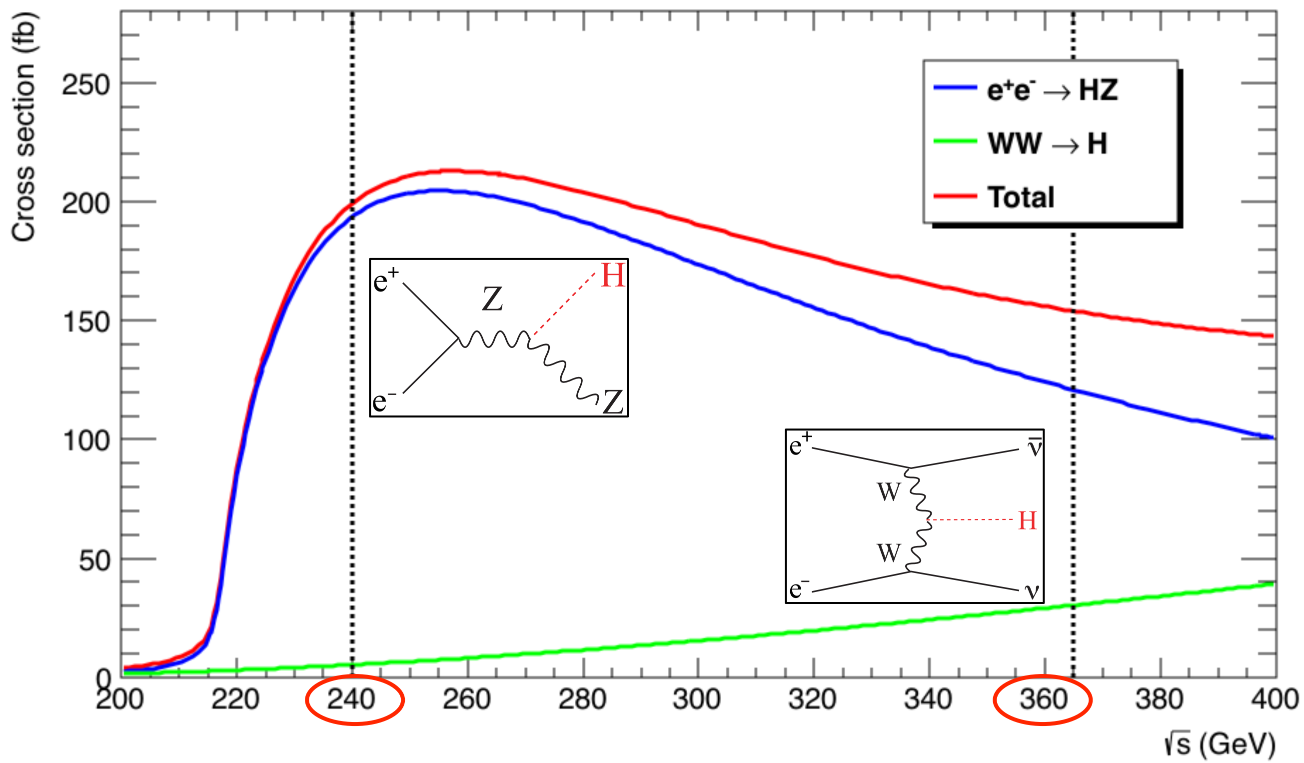

$\Lambda_Y/\sqrt{c_Y} \gtrsim 70$ TeV $\Lambda_W/\sqrt{c_W} \gtrsim 110$ TeV $\Lambda_Z/\sqrt{c_Z} \gtrsim 90$ TeV
(preliminary)

**Global fit with FCC-ee being performed**

# Electroweak Symmetry Breaking
# The Higgs boson as a BSM probe

# FCC-ee: Higgs boson production

- Largest rate at $\sqrt{s}$ ~ 240 GeV: $10^6$ $e^+e^- \rightarrow HZ$ events with 5 $ab^{-1}$




- Complemented with another 200k events at $\sqrt{s}$ = 350 – 365 GeV
  - Of which 30% in the WW fusion channel (useful for the $\Gamma_H$ precision)

# FCC-ee@240 : Model-independent couplings

- **H tagged by a Z and $m_{Recoil}$ (indep. of H decay)**

$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

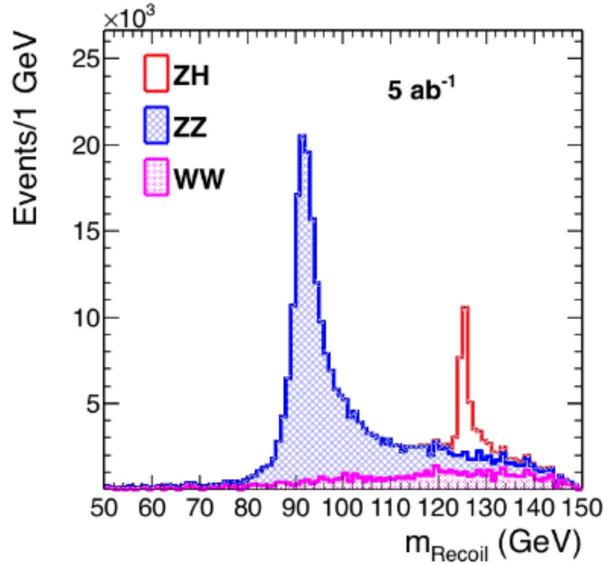
  - Measure $\sigma(e^+e^- \to HZ)$; deduce $g_Z$ coupling
    - Infer $\Gamma(H\to ZZ^*)$ proportional to $(g_Z)^2$
  - Measure $\sigma(e^+e^- \to HZ$, with $H\to ZZ^*)$

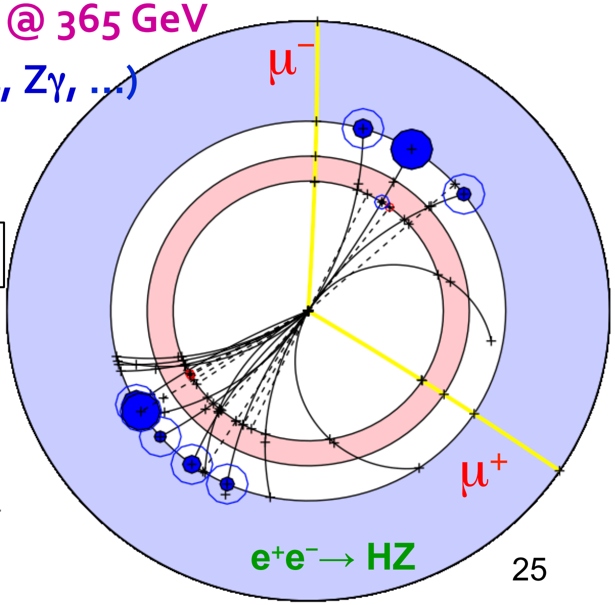
$$\sigma(e^+e^- \to HZ \to ZZZ) = \sigma(e^+e^- \to HZ) \times \frac{\Gamma(H\to ZZ)}{\Gamma_H}$$

    - Deduce the total Higgs boson width $\Gamma_H$
      - ➨ Significantly improved with $WW \to H \to WW$, bb @ 365 GeV
  - Measure $\sigma(e^+e^- \to HZ$, with $H \to$ bb, cc, gg, WW, ττ, γγ, μμ, Zγ, ...)
    - Deduce $g_b$, $g_c$, $g_g$, $g_W$, $g_\tau$, $g_\gamma$, $g_\mu$, $g_{Z\gamma}$, ...
  - Select events with H → "nothing"
    - Deduce BR(H→invisible)

$g_Z$, $g_W$

$g_\mu$, $g_{Z\gamma}$



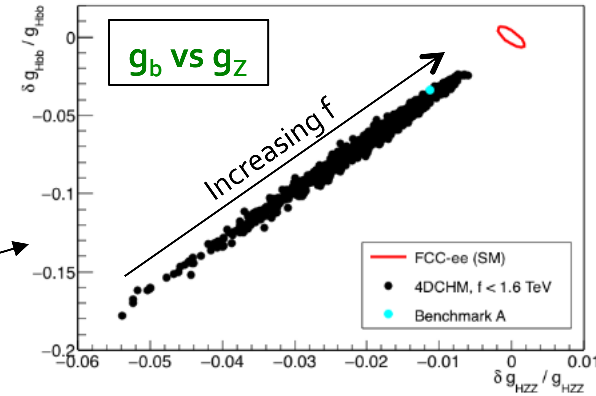



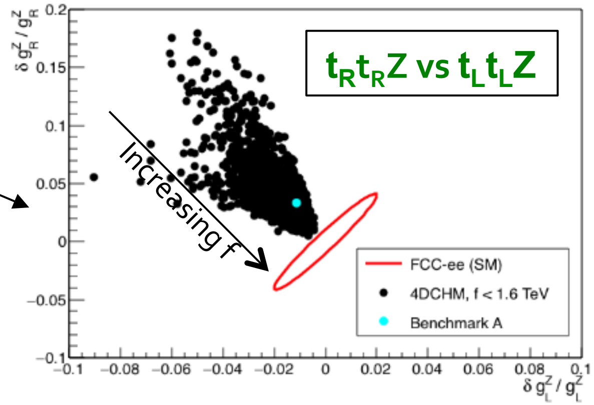

- **With $10^6$ HZ events, precisions range from 0.2% to 5%**
  - Sensitivity to $BR_{inv}$ ~ 0.5% ; Precision on $\Gamma_H$ ~ 1%
  - Note: 100K H →gg events for gluon fragmentation studies

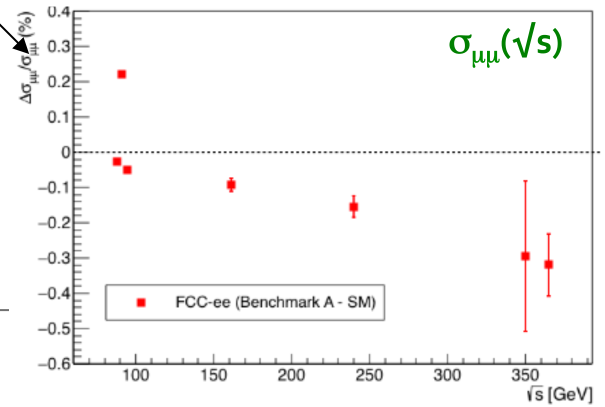
# FCC-ee: Sensitivity to new Physics

- **Higgs-coupled new physics in SMEFT**
  - Probes dim 6 operators for $\Lambda/\sqrt{c}$ up to 5 – 30 TeV

- **Specific models : pattern of deviations**
  - E.g, Composite Higgs Model to solve hierarchy problem
    - Deviations in Higgs couplings
    - Deviations in EW top couplings
    - Deviations in EW lepton couplings
  - Correlations between observations
    - Allow unique characterization of the model
  - For example, gauge sector parameters in benchmark A
    - $f = 1.6$ TeV, $g^*=1.78$, $m_{Z'} \sim 3$ TeV, $\Gamma_{Z'} \sim 600$ GeV
    - With the FCC-ee precision
      - ➨ Z′ mass predicted wth 2% precision
      - ➨ Scale f, coupling g* predicted with 8% precision

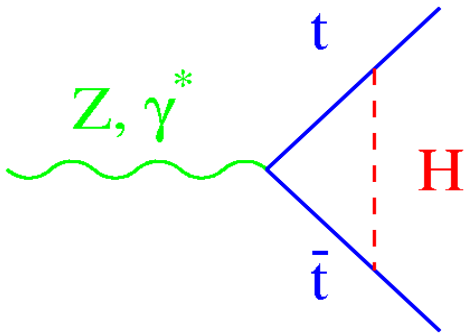


# FCC-ee: ttH and HHH couplings ?

- **Model-dependent measurements are possible**
  - Top pair cross section at threshold

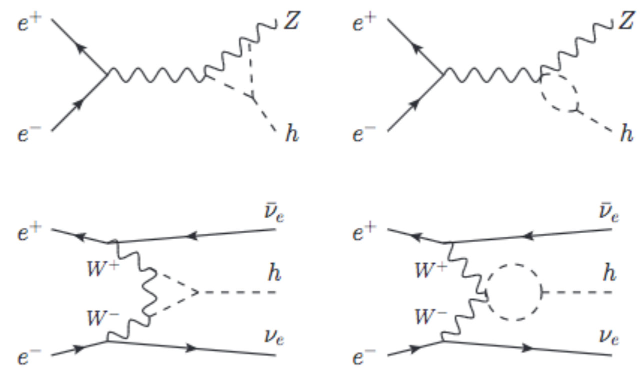



FCC-ee $\alpha_s$ precision measurement helps !
(Gluon and Higgs exchanges compete)

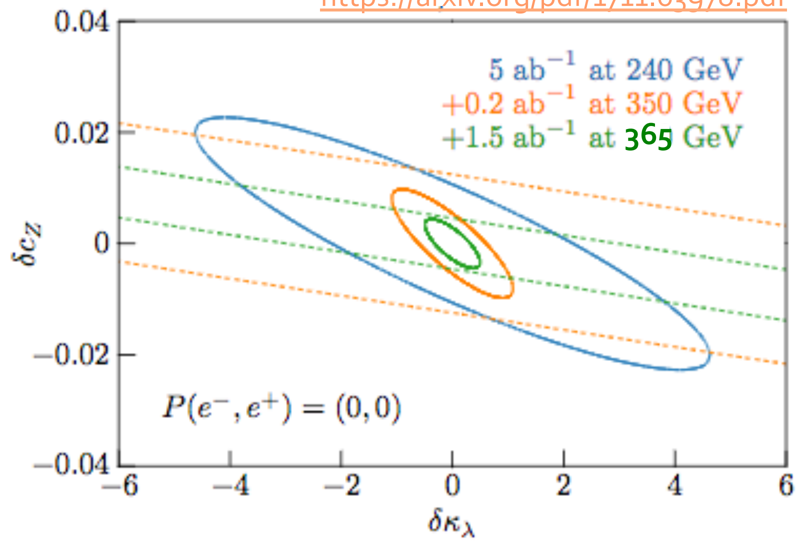
  - Top Yukawa coupling precision < 10%
  - Higgs self coupling precision ~30%
    - Reduced to ~20% with $g_{HZZ}$ from SM

Similar precisions are obtained with double Higgs production at CLIC ($\sqrt{s}$ = 1.4 and 3 TeV) or with the (no longer considered) 0.5 + 1 TeV upgrade of the ILC

Higgs cross section at 240, 350, and 365 GeV

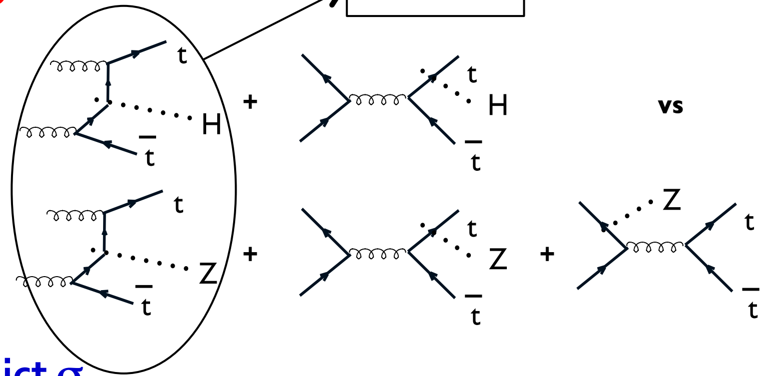



https://arxiv.org/pdf/1711.03978.pdf



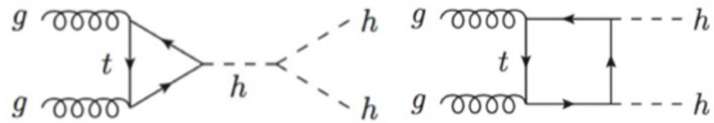
# FCC-hh: ttH and HHH couplings

- **ttH production evidence with 4.2σ in ATLAS**
  - Measurement of $\sigma_{ttH}/\sigma_{SM}$ systematics-limited
- **At FCC-hh, trade statistics for systematics**
  - Measure $\sigma_{ttH}/\sigma_{ttZ}$ at large $p_T(H,Z)$
    - Very similar production mechanism
    - Most theory uncertainties cancel
  - Use ttZ coupling measurements @ FCC-ee to predict $\sigma_{ttZ}$

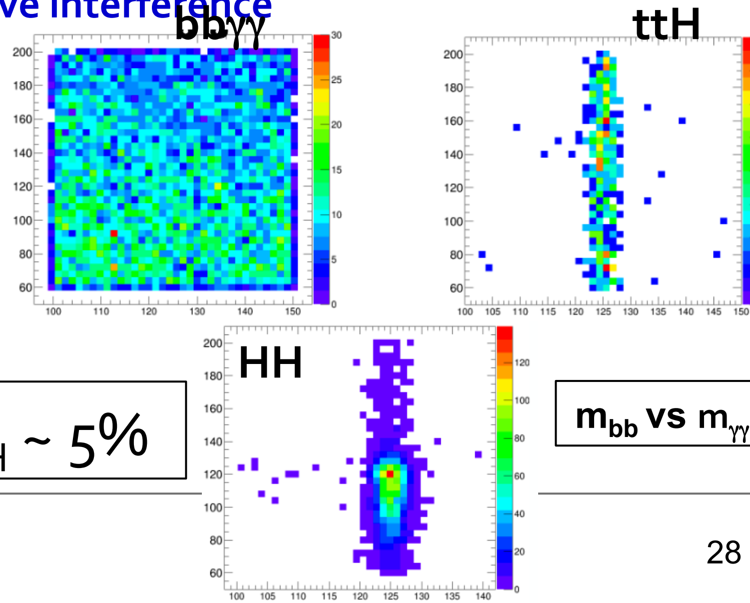



$\Delta\lambda_t/\lambda_t \sim 1\%$

- **Double Higgs production difficult at HL-LHC**
  - Sensitivity to self coupling reduced by destructive interference



- **At FCC-hh, go to large $p_T(H)$ again**
  - HH → bbγγ channel: $p_T(bb)$, $p_T(\gamma\gamma)$ > 100 GeV
  - Statistical target on $\lambda_H$: 3.4% with 20 $ab^{-1}$
    - Systematic studies ongoing, e.g.,
      - Signal & background SM rates
      - Luminosity measurement
      - Effect of pileup



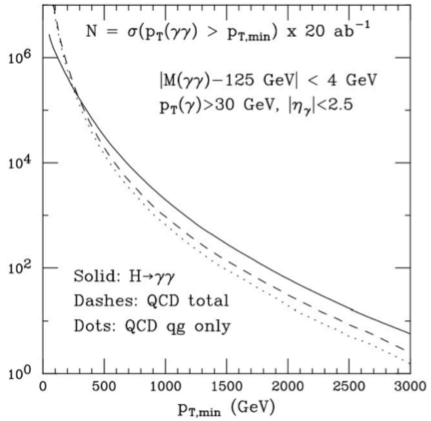

$m_{bb}$ vs $m_{\gamma\gamma}$

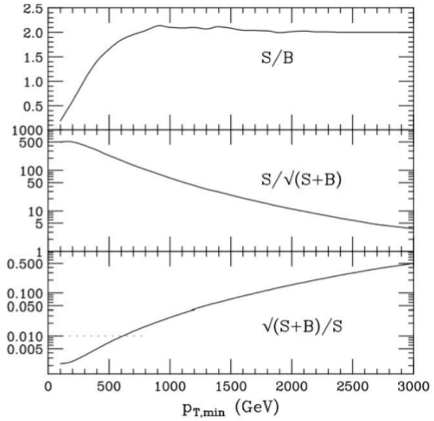
BR(H→ bb,ZZ) from FCC-ee

$\Delta\lambda_H/\lambda_H \sim 5\%$

# FCC-hh: Other Higgs couplings

- **Example: gg → H → γγ**
  - At LHC, S/B of the order of a few %
  - At FCC-hh, S/B ~ 1 for $p_T(H)$ > 300 GeV
    - Statistical uncertainty still < 0.5%
    - $p_T$ spectrum as BSM probe




- **Precise "ratios-of-BRs" measurements**
  - Many theory systematic uncertainties cancel
  - Absolute BR from feedback of precise $g_{HZZ}$ FCC-ee measurement
  - One should not underestimate the standalone value of these ratios as BSM probes
    - BSM effects typically influence BRs in different ways
      - ➨ BR(H→γγ)/BR(H→ZZ*) : loop-level vs tree-level
      - ➨ BR(H→μμ)/BR(H→ZZ*) : 2nd generation Yukawa vs gauge coupling
      - ➨ BR(H→γγ)/BR(H→Zγ) : different EW charges in the loops

# FCC-hh: Higgs measurement summary

- **Typical target precisions ~ %**

| Observable | Parameter | Precision (stat) | Precision (stat+syst) |
|---|---|---|---|
| $\mu = \sigma(H) \times B(H \to \mu\mu)$ | $\delta\mu/\mu$ | 0.5% | 0.9% |
| $\mu = \sigma(H) \times B(H \to \gamma\gamma)$ | $\delta\mu/\mu$ | 0.1% | 1% |
| $\mu = \sigma(H) \times B(H \to 4\mu)$ | $\delta\mu/\mu$ | 0.2% | 1.6% |
| $\mu = \sigma(t\bar{t}H) \times B(H \to b\bar{b})$ | $\delta\mu/\mu$ | 1% | tbd |
| $\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$ | $\delta\lambda/\lambda$ | 3.5% | 5.0% |
| $R = B(H \to \mu\mu)/B(H \to 4\mu)$ | $\delta R/R$ | 0.6% | 1.3% |
| $R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$ | $\delta R/R$ | 0.17% | 0.8% |
| $R = B(H \to \gamma\gamma)/B(H \to 2\mu)$ | $\delta R/R$ | 0.6% | 1.4% |
| $B(H \to \text{invisible})$ | $B$@95%CL | $1 \times 10^{-4}$ | $2.5 \times 10^{-4}$ |

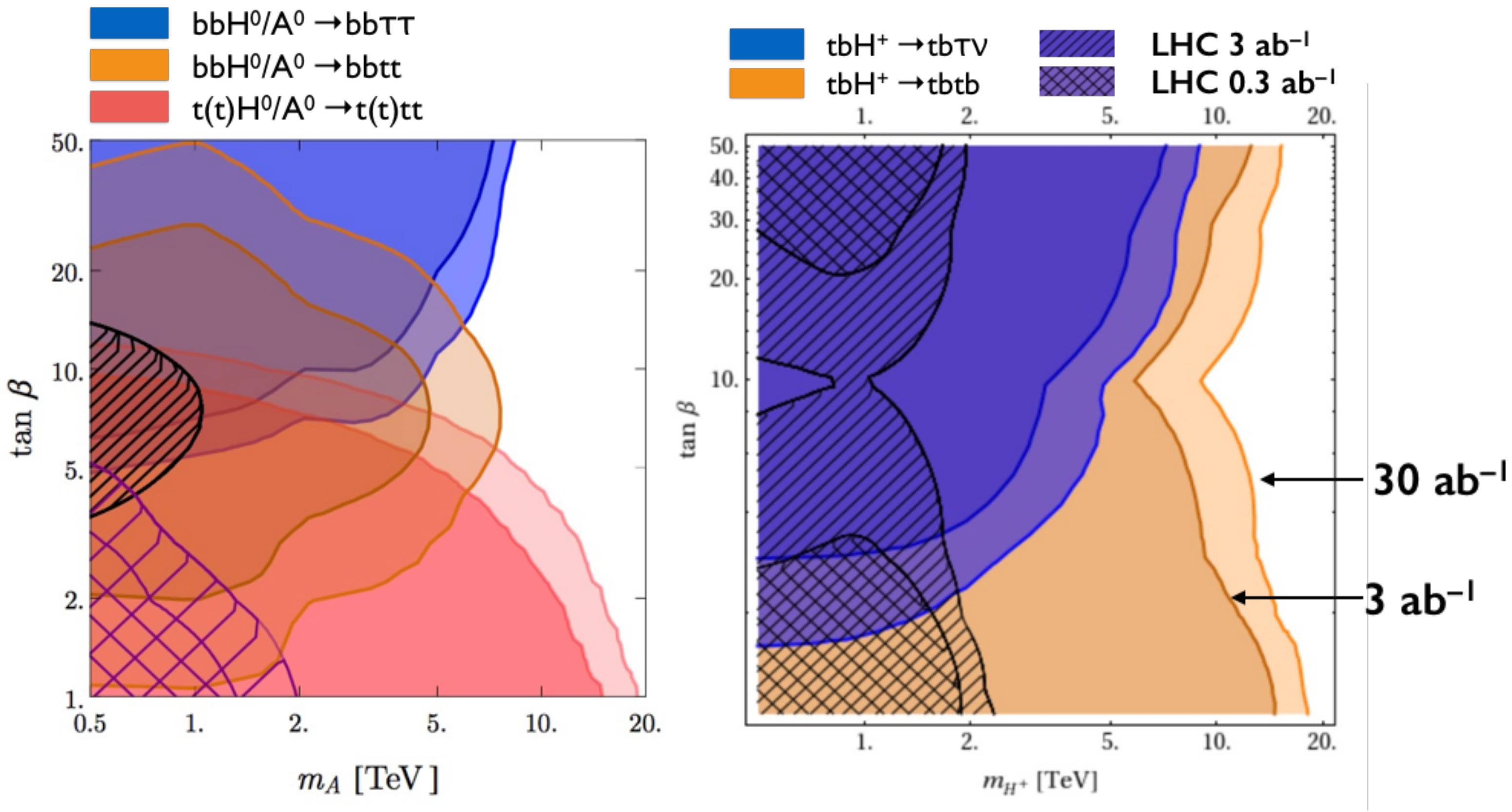
95% CL sensitivity ~ 4 times better than SM BR($H \to ZZ^* \to \nu\nu\nu\nu$)

- Constraints on BSM models under study

# Discovery potential via direct observation
# A few examples

# FCC-hh: Discovery potential at highest masses

- SUSY: Additional Higgs bosons (A, H, $H^{\pm}$) up to ~10 TeV




arXiv:1605.08744

arXiv:1504.07617

- Beyond any current lepton collider design

# FCC-hh: Discovery potential at highest masses

- **New gauge bosons**

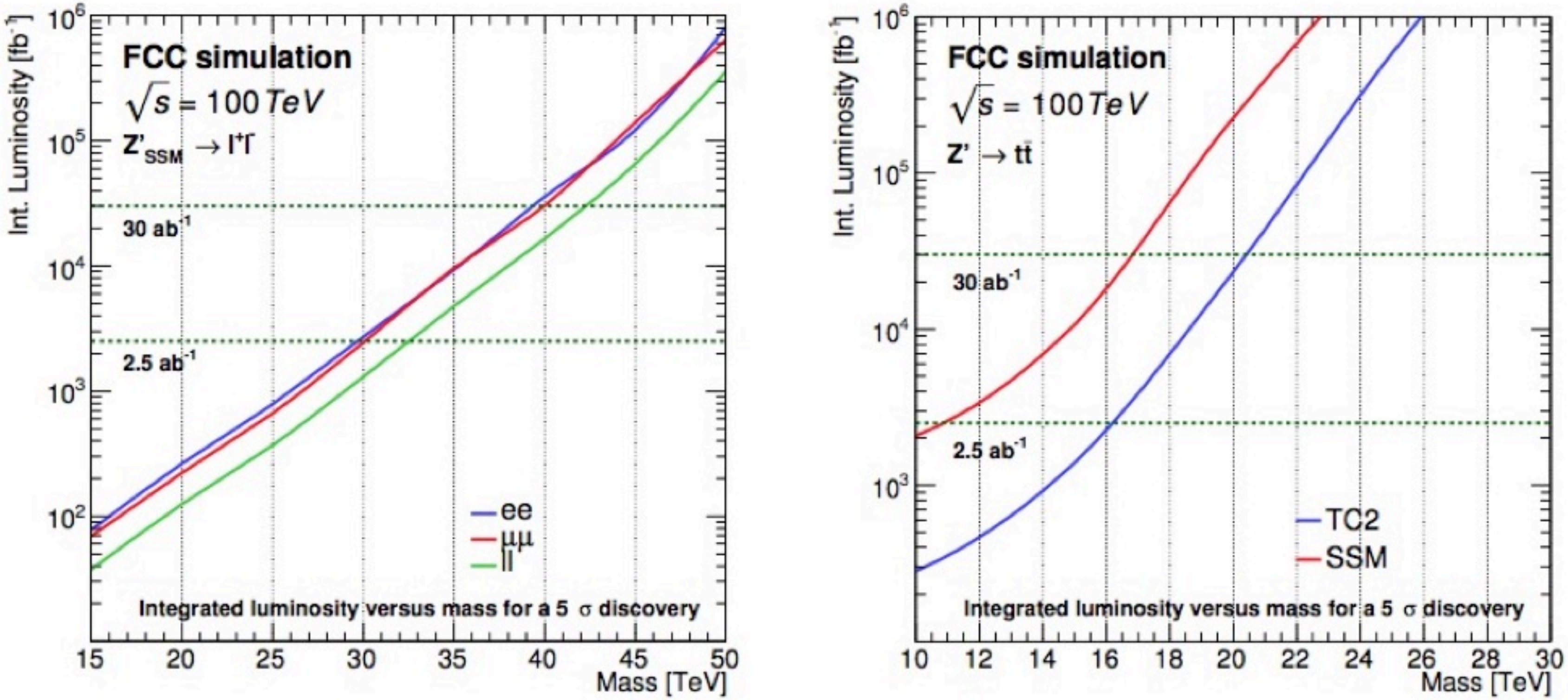
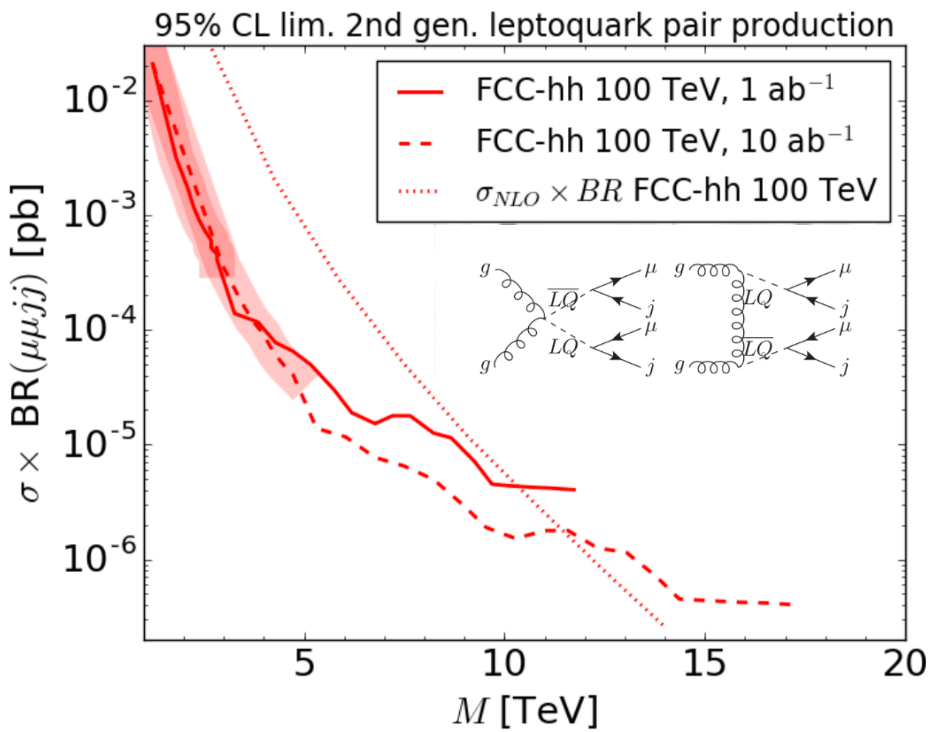



Figure 1.1: Integrated luminosity required for a 5-$\sigma$ discovery, as a function of the mass, for a $Z'$ gauge boson coupled with SM couplings and decaying to leptons (left) and to $t\bar{t}$ (right).

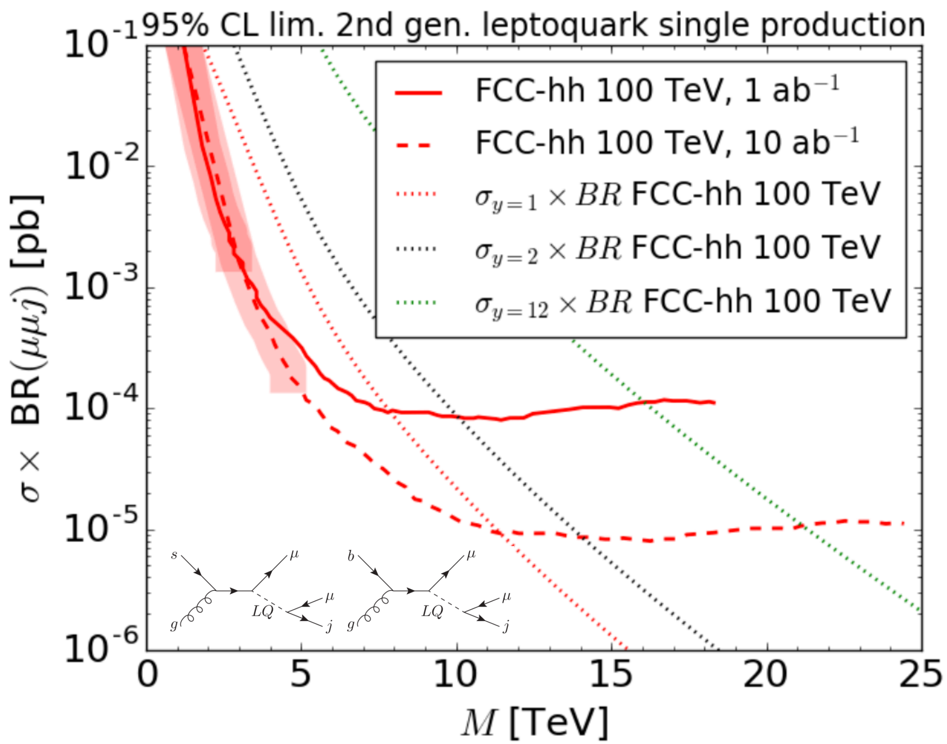
- **$Z' \to \mu\mu$ can cover all the parameter space where "LHCb anomalies" fit with Z' interpretation**

# FCC-hh: Discovery potential at highest masses

- $2^{nd}$ gen leptoquarks (as possible explanation for LHCb "anomalies")
  - Pair production




Single production

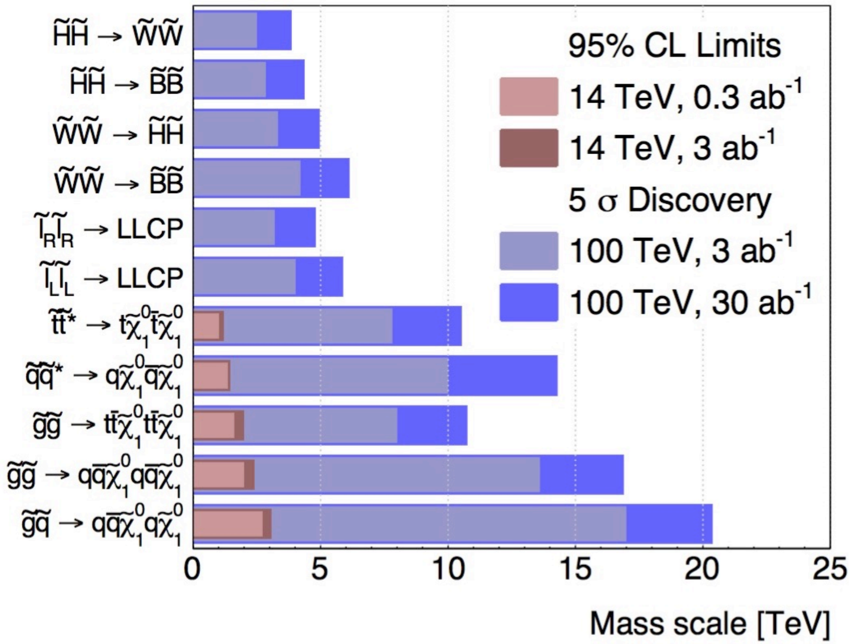


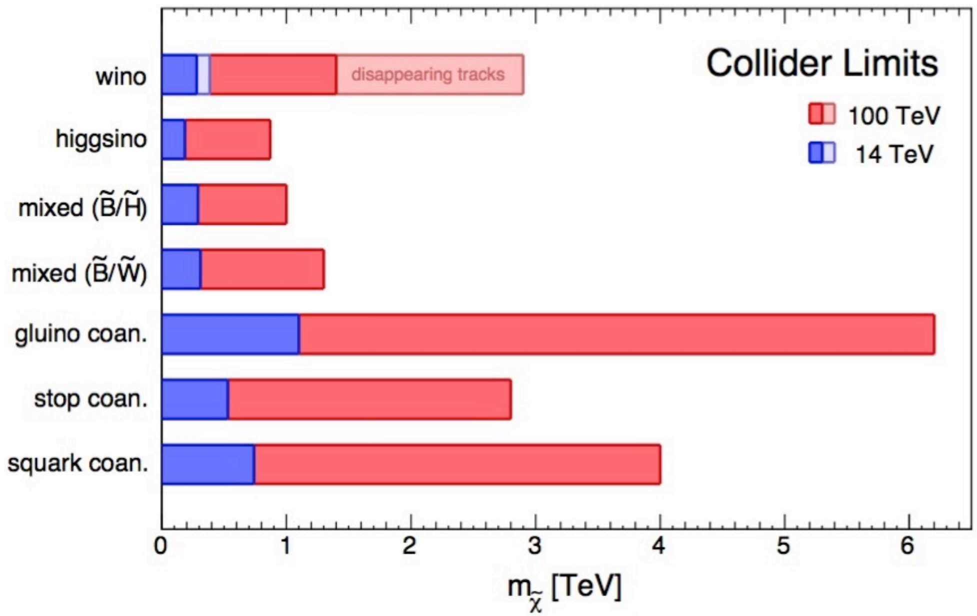

Ben Allanach, 2nd FCC Physics workshop

- Can cover large part of the "LHCb anomalies" parameter space which fit with the LQ interpretation

# FCC-hh: Discovery potential at highest masses

- **SUSY and WIMP Dark Matter : Far beyond the naturalness paradigm**
  - **Simplified models: same caveats as at LHC apply – direct discovery might be hidden**
    - **NLSP / LSP mass splitting; 100% BR; Heavy DM mediators; …**

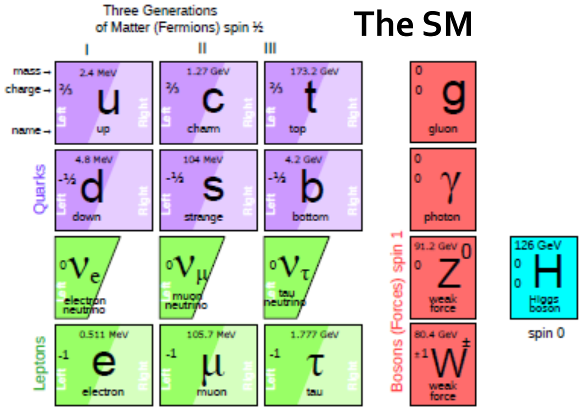


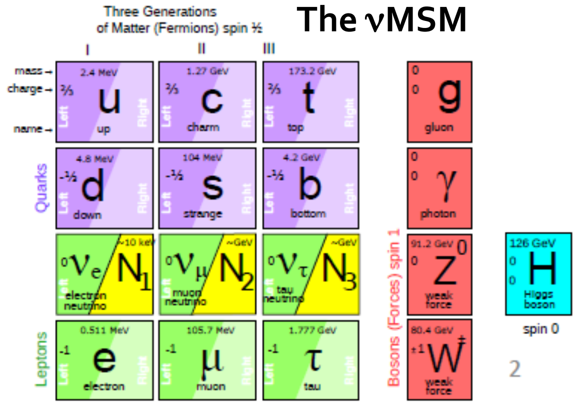




- **From DM relic abundance :** $M_{\rm WIMP} \leq 1.8~\mathrm{TeV} \left(\frac{g^2}{0.3}\right)$
    - **FCC-hh can dind (or rule out) lot's of weakly interacting massive DM candidates.**

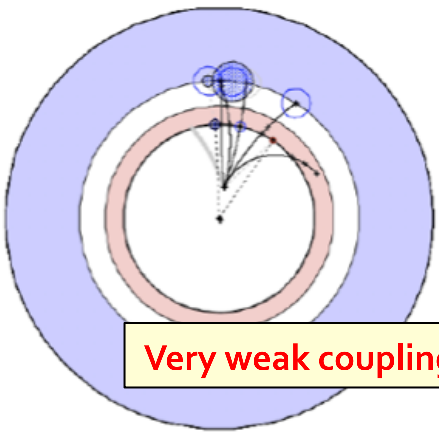
# FCC-ee: High mass or small couplings ?

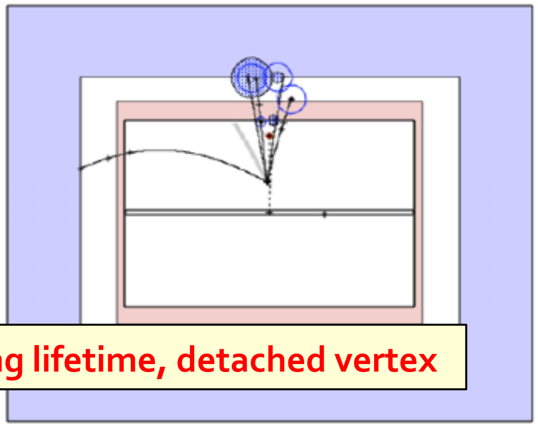
- (One of the) most natural extension of the standard model: the νMSM
  - Complete particle spectrum with the missing three right-handed neutrinos



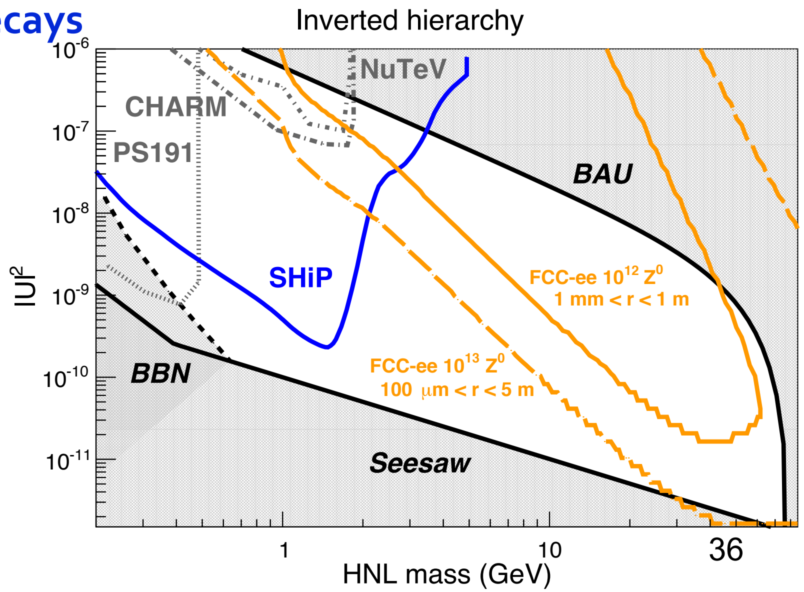




  - Could explain everything: Dark matter ($N_1$), Baryon asymmetry, Neutrino masses
- Searched for at FCC-ee in very rare $Z \to \nu N_{2,3}$ decays
  - Followed by $N_{2,3} \to W^*\ell$ or $Z^*\nu$



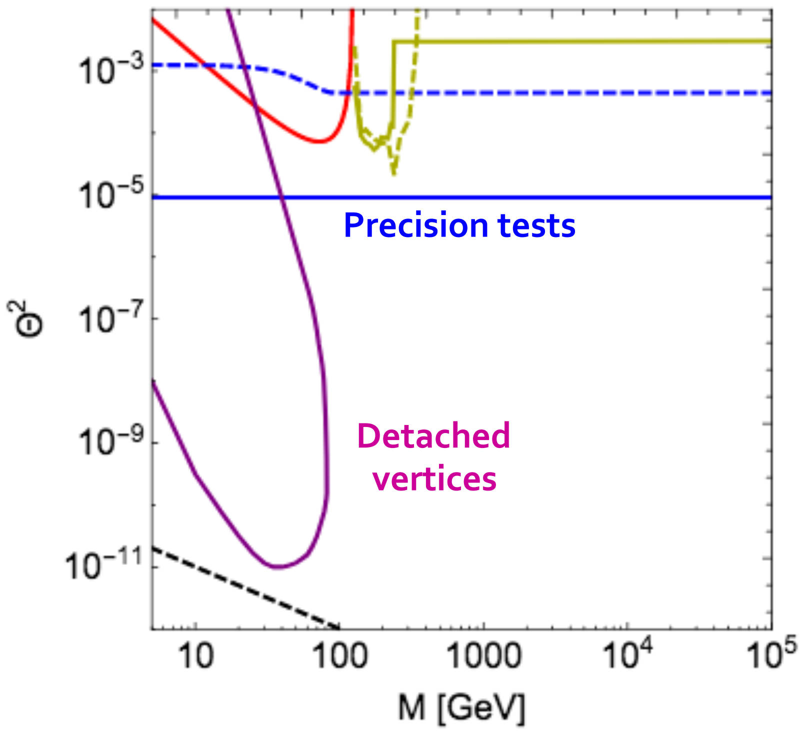


Very weak coupling : long lifetime, detached vertex



# FCC-ee: High mass or small couplings ?

- Mixing with $\nu_R$ reduce $\nu_L$ couplings
  - Affect many precision observables at FCC-ee
    - Leptonic $\tau$ branching ratios ($1.5\times10^{11}$ $\tau\tau$ at FCC-ee)
    - Rare lepton-flavour-conservation-violating decays
      - ➨ Irrespective of the mass of the right-handed neutrino (>> 100 TeV !)

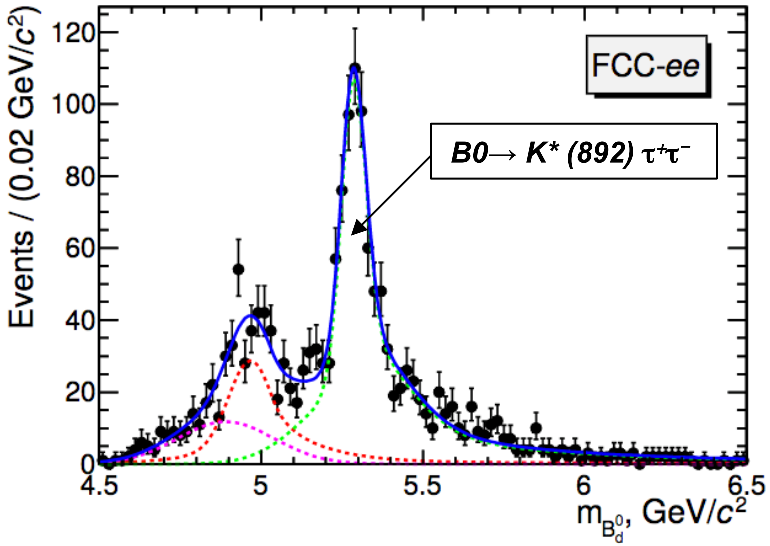



- Discovery would shape up FCC-hh detectors
  - For displaced vertex searches,
  - and lepton-flavour-violating signatures
    - Towards tests of the PMNS matrix
- Detailed FCC-hh study required
  - To understand feasibility

# Flavour physics

# FCC-ee : Flavour physics

- Current tensions (several 2-3$\sigma$ deviations) of LHCb data with SM predictions
  - In particular, lepton flavour universality is challenged in b $\rightarrow$ s $\ell^+\ell^-$ transitions
    - For example, the rates of $B^o$ $(B^+) \rightarrow K^{*o}$ $(K^+)$ $\ell^+\ell^-$ 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 $B \rightarrow K^{(*)} \tau^+\tau^-$
    - Extremely challenging in hadron colliders
    - With $10^{12}$ Z $\rightarrow$ b$\bar{\text{b}}$, FCC-ee is beyond any foreseeable competition
      - Decay can be fully reconstructed
      - Full angular analysis possible




- Also sensitive to new physics: $B_S \rightarrow \mu^+\mu^-$
  - None found yet at the LHC (~50 events)

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

    - Expect a few 1000's by the end of LHC
  - $B_S \rightarrow \tau^+\tau^-$ 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

# Synergies

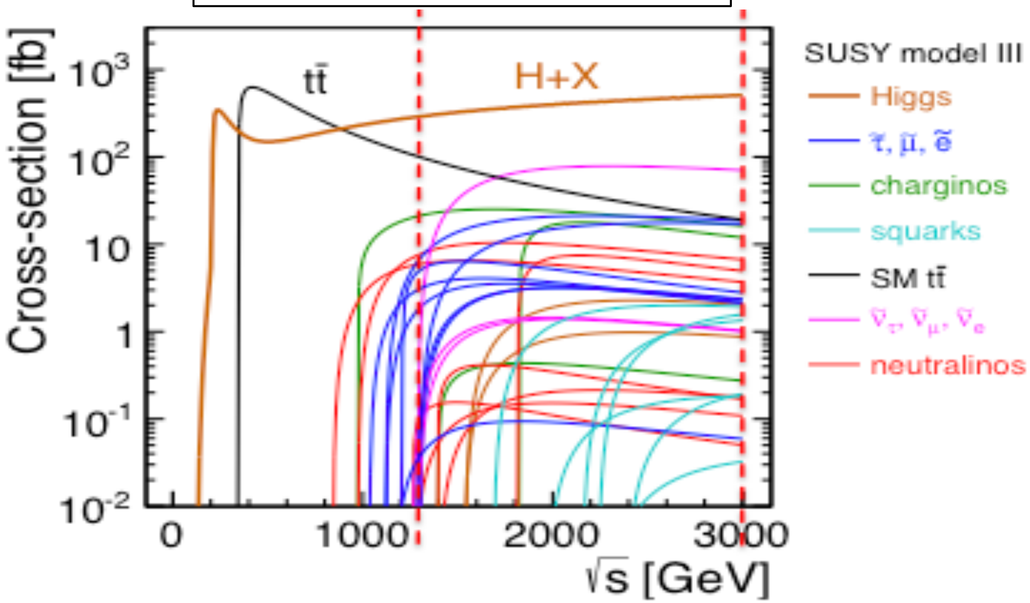
# Physics complementarity / synergy (examples)

- **Higgs physics**
  - FCC-ee fixes Higgs width, HZZ couplings, and ttZ couplings (and many others)
  - FCC-hh measures ratios-of-BR and gives huge statistics of ttZ, ttH, and HH events
    - For top Yukawa coupling and Higgs self coupling, in particular
  - Combination can find / rule out strong 1st order EWPT (candidate for baryogenesis)
- **Search for heavy physics**
  - FCC-ee gives precision measurements sensitive to heavy physics up to … 100 TeV
    - Patterns of deviations may points to specific BSM
  - FCC-hh gives access to direct observation at unprecedented masses and $p_T$'s
    - Also huge samples of Z, W, Higgs, top
- **Heavy neutrinos**
  - FCC-ee: powerful and clean, but flavour blind: $Z \to \nu N$, all $\nu$ flavours together — $5\times10^{12}$ Z
  - FCC-hh: more difficult, but potentially flavour sensitive: $W \to l_1 (Q_1) N$, $N \to l_2 (Q_2) W^*$ — $5\times10^{13}$ W
- **Flavour "anomalies" (if they persist – rich flavour physics programme otherwise)**
  - FCC-ee beyond any foreseeable competition with in $B \to K^{(*)} \tau^+\tau^-$ and $B_S \to \tau^+\tau^-$
  - FCC-hh gives direct access to Z' gauge bosons and leptoquarks
- **QCD**
  - FCC-ee gives $\alpha_S$ to ±0.0002 ($R_l$ for Z and W), but also 100k $H \to gg$ (gluon fragmentation)
  - FCC-eh provides structure functions and a similar precision on $\alpha_S$
  - Improves signal and background predictions for new physics discovery at FCC-hh

# Future synergy: Towards FCC-μμ ?

- **Why high-energy muon colliders ?**
  - Muons are leptons: Can a priori do all what electrons can do
  - Muons are heavy: Small circular colliders up to large √s (SPS/LHC/FCC: 6/28/100 TeV)
  - Muons decay: Ultra-precise beam energy measurement
  - Open the way to precision study of particles observed by the FCC-hh
    - Spectrum, masses, couplings, processes, … up to very large masses (√s/2)
    - Similar to CLIC, if new particles were observed by the LHC in the TeV range

(From CLIC study : SUSY spectrum)



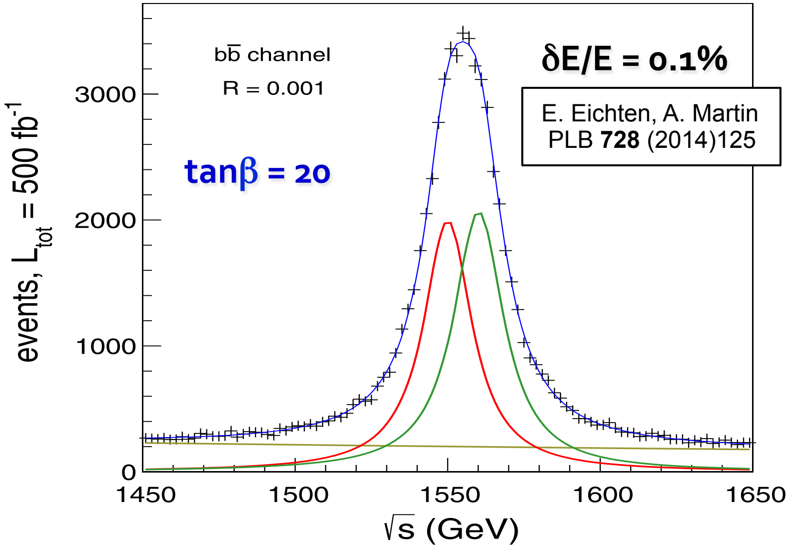
# Future synergy: Towards FCC-$\mu\mu$ ?

- **Recent intriguing approach to muon collider : LEMMA**
  - Produce low emittance muon beams with $e^+e^- \to \mu^+\mu^-$ at production threshold
  - The threshold $e^+$ energy for $\mu^+\mu^-$ production on a thin target ($e^-$) is … 43.7 GeV !
    - Can use the FCC-ee $e^+$ ring / booster as $\mu$ accumulation and internal target ring
      - (Or the FCC-ee RF installed in the LHC tunnel, or in the FCC-eh ERL)
      - Requires an $e^+$ source about 20 times more intense than FCC-ee / CLIC
    - All muons are produced with ~ the same energy, in the same direction
      - No muon cooling needed ($\Delta E/E$ ~ 0.07% at $\sqrt{s}$ = 6 TeV)
    - Transverse emittance 500 × smaller than with protons on target + cooling (MAP)
      - Two orders of magnitude less muons needed for same luminosity as MAP
        - Lower background from $e^\pm$ in the detector (from muon decays)
        - Lower radiation hazard from neutrino interactions at the surface
      - MAPs were limited to $\sqrt{s}$ = 4 TeV to cope with regulations on CERN site

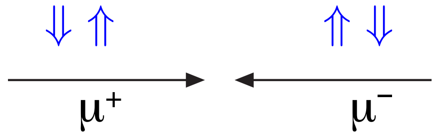
**LEMMA can go to $\sqrt{s}$ > 20 TeV (in the FCC tunnel) within the same regulations**

# Future synergy: Towards FCC-μμ ?

- **Example: FCC-hh discover MSSM Higgses with $m_{A,H} \sim 1.55$ TeV**
  - Scan the A and H poles




Produce either A or H with transverse polarization



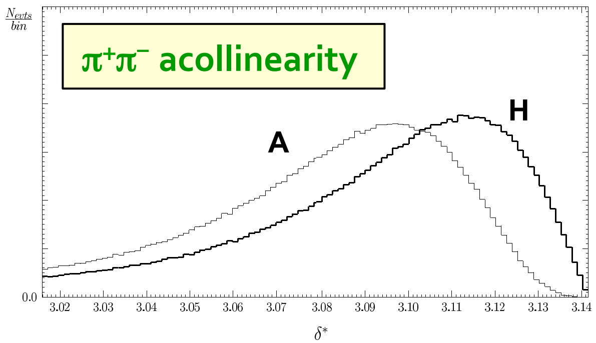

Parallel spins: produces H
Antiparallel spins: produces A

F. Palhen et al.
JHEP 0808:030
JHEP 0801:017

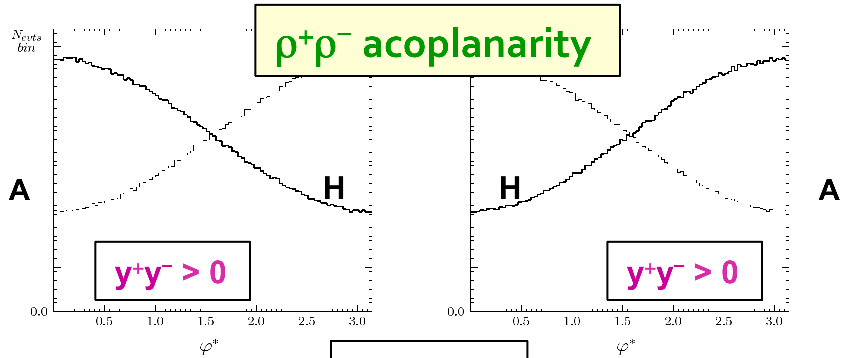
**Feasible ??**

**Unique CP (violation) and H/A mixing studies**

- From $H,A \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\nu_\tau$




From $H,A \to \tau^+\tau^- \to \rho^+\rho^-\nu_\tau\nu_\tau$ with $\rho^\pm \to \pi^\pm\pi^0$




$y^\pm = E_{\pi\pm} - E_{\pi0}$

# HE-LHC, CLIC, ILC, CEPC ?

# HE-LHC as a first step for the FCC-hh ?

- **Physics potential explored in the CERN workshop on HL/HE-LHC physics**
  - High-mass reach ~ 2 × $M_{LHC}$
  - Higgs self-couping $\delta\lambda_H$ ~ ±30%    https://arxiv.org/abs/1802.04319
  - Higgs properties, top and EW observables : under study

    Obvious theorem: Physics (HE-LHC ⊗ FCC-hh) ≡ Physics (FCC-hh)

  - Instead, with the complementarities and synergies shown today

    Physics (FCC-ee ⊗ FCC-hh) > Physics (FCC-ee + FCC-hh) > Physics (FCC-hh)

- **What does the HE-LHC practically entail ?**
  - Empty the LHC tunnel (more time and CHF than removing LEP)
  - Full replacement of the magnets (whose cost today > cost of LHC magnets)
  - Upgrade of RF cryogenics, collimation, beam dumps
  - Major upgrade of the SPS to inject at 1 TeV, possibly with SC magnets
  - Major overhaul of detectors

    Time without physics at CERN with HE-LHC > 7 years

    Time without physics at CERN with FCC-ee : NONE

# HE-LHC as a first step for the FCC-hh ?

- **Cost – not allowed to give numbers just as yet, but arithmetic's is easy**
  - Building HE-LHC is like building the LHC ex-novo – and more (SPS)
    - It's very unlikely to be cheaper
  - Today's estimates show that, for the collider, Cost (HE-LHC) ~ 2 to 3 × Cost (FCC-ee)
    - May argue that the FCC-ee needs a new tunnel in addition …
      - ➨ but so does the FCC-hh

Cost (HE-LHC + FCC tunnel + FCC-hh) > Cost (FCC tunnel + FCC-ee + FCC-hh)

- **Strategic value of HE-LHC on the way to 100 GeV**
  - The HE-LHC delays FCC by ~25 years, and weakens the case for FCC in two ways
    - It reduces the relative case for FCC-hh (smaller √s increment)
    - It reduces the absolute case for FCC (no FCC-ee)
  - It leaves CERN vulnerable to the possibility that a frontier collider is built elsewhere
    - With worse performance than FCC
    - But still sufficient to render the case for FCC much more difficult to make
  - It keeps physicists doing physics with the same techniques for many many years
    - After 30 years of LHC and HL-LHC, and before 30 years of FCC-hh
    - It might no be a very healthy plan to maintain CERN attractiveness

# So … FCC-ee as a first step ?

- **Physics absolutely need an $e^+e^-$ EW factory with 90 < $\sqrt{s}$ < 400 GeV**
  - Five $e^+e^-$ collider studies on the planet (ILC, CLIC, CEPC, LEP3, FCC) in this range !
    - FCC-ee covers the whole range: Z, W, H, and top.
      - with the highest luminosities (10×ILC at 250 GeV, $10^5$×LEP at 90 GeV)
      - with unique discovery potential to very high scale and very small couplings
      - technologically ready today – future R&D can only improve the case
      - well affordable within CERN constant budget once the tunnel is funded
  - Much harder to make a convincing physics case for $e^+e^-$ colliders with $\sqrt{s}$ > 400 GeV
    - Possibility that new physics be found by the end of LHC Run2/3 is getting thin
    - Exploration of the energy frontier best done with a hadron collider (e.g., FCC-hh)
  - Cannot continue indefinitely with R&D towards all possible future facilities
    - A choice will have to be made in 2019-2020
- **The FCC-ee is the best first step for FCC-hh**
  1. It gives a preview of the new physics to be searched for, up to a scale of 100 TeV
  2. It significantly reduces systematic uncertainties on many FCC-hh measurements
  3. It provides handles to understand the underlying theory upon particle discovery at the FCC-hh
  4. It provides the infrastructure (tunnel, experimental shafts, cryogenics, …) at reasonable cost
  5. It buys time to develop 16T (or – why not? – 20T) magnets for FCC-hh at lower cost
  6. It can even be a springboard for a FCC-μμ (circular $\mu^+\mu^-$ collider with $\sqrt{s}$ =6, 28, or 100 TeV?)

# A successful model !

- Back to the future …

PHYSICS WITH VERY HIGH ENERGY
$e^+e^-$ COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
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ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

CERN 76-18
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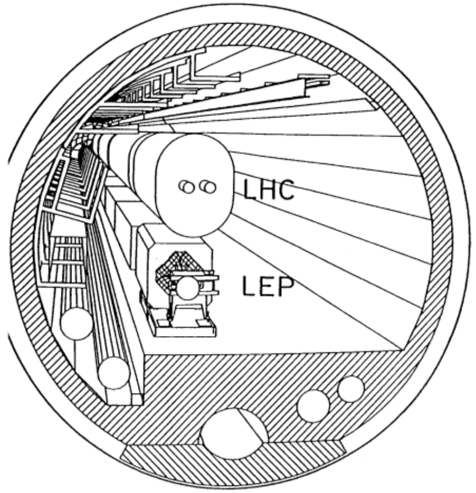


LARGE HADRON COLLIDER
IN THE LEP TUNNEL

- Did these people know that we would be running HL-LHC in the same tunnel more than 60 years later ?

**Let's not be shy !**
**The FCCs are shaping up as the most natural, complete, and powerful aspiration of HEP for its long-term future**