FCC-ee review: Physics and Experiments

- **Introduction to the review**
  - **Motivation, history, design study overview, operation model, issues, …**

Motivation

- There is a political vision: European Strategy statement (2013)

  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.

- The interest of the scientific community is (world)wide
  - With several collider projects in Europe, Japan, China
    - Two e^+e^- linear colliders: ILC & CLIC, with potential energy upgrades to 1 and 3 TeV
    - Two e^+e^- circular colliders: CEPC & FCC-ee, with 100 TeV pp collision upgrades
  - With a consensus that HEP needs an e^+e^- collider at the EW scale (Z, W, Higgs, top)
- Circular colliders have indeed much to offer
  - All four particles studied – and needed in a sound precision measurement program
    - With very high luminosity delivered to several interaction points
    - With high precision on the centre-of-mass energy
  - Large discovery potential through precise measurements and rare decays
    - Up to very high scales (up to 100 TeV) and to very small couplings
  - With synergetic access to the highest centre-of-mass energies in pp collisions
    - Brings tunnel, infrastructure, cryogenics, time, physics, performance goals …
      - ➠ Circular ee+pp is a powerful combination at the energy & intensity frontiers

Brief history

- Seminal paper #1 in December 2011
  - A. Blondel and F. Zimmermann, "A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson", arXiV:1112.2518
- First Higgs studies at $\sqrt{s}$=240 GeV for the European Strategy in 2012
  - P. Azzi et al., "Prospective studies for LEP3 with the CMS detector", arXiV:1208.1662
- First ICFA Beam Dynamics worskhop in 2012
  - A. Blondel et al., "Accelerators for a Higgs factory: Linear vs. Circular", arXiV:1302.3318
- Seminal paper #2: Physics potential with a 100 km ring in 2013
  - M. Bicer et al., "First look at the physics case of TLEP", arXiV:1308.6176, JHEP 01 (2014) 164
    - 312 citations
- Merge in the FCC project in 2014: "FCC-ee, potential first step of FCC"
  - Creation of a coordination group for "Physics and Experiments" (next slide)
    - 2014-2016 emphasis: Physics opportunities (experiment and theory)
    - 2016-2017 emphasis: FCC synergies, detector designs, MDI, $\sqrt{s}$ measurement
    - 2017-2018 emphasis: Full sim (?), Online selection (?), CDR editing and delivery
  - Creation of a software group common to all FCC's
    - Prepare the software of the future, with the best from past experience
    - Deliver physics software for future FCC studies (physics, detectors, MDI)

Physics and Experiments Studies Coordination

Physics Studies coordination
A. Blondel, P. Janot (EXP), C. Grojean, M. McCullough, J. Ellis (TH)

EW Physics with Z's and W's
R. Tenchini, F. Piccinini
S. Heinemeyer, A. Freitas

Higgs properties
M. Klute, K. Peters
S. Heinemeyer, A. Freitas

Top quark physics
P. Azzi (F. Blekman)
S. Heinemeyer, A. Freitas

Synergies with FCC-hh physics, LC studies, LEP legacy

QCD and $\gamma\gamma$ physics
D. d'Enterria
P. Skands

Flavours physics
S. Monteil
J. Kamenik

New physics
M. Pierini, C. Rogan
M. McCullough

Global Analysis Synergies
J. Ellis

Physics software
C. Bernet, B. Hegner,
C. Helsens

Synergy with FCC-hh, LC, LHC

Online selection & DAQ
C. Leonidopoulos
E. Perez

Polarization, $\sqrt{s}$ meast
A. Blondel
J. Wenninger

Joint with FCC-ee Accelerator

MDI, Exp'tal environment
M. Boscolo
N. Bacchetta

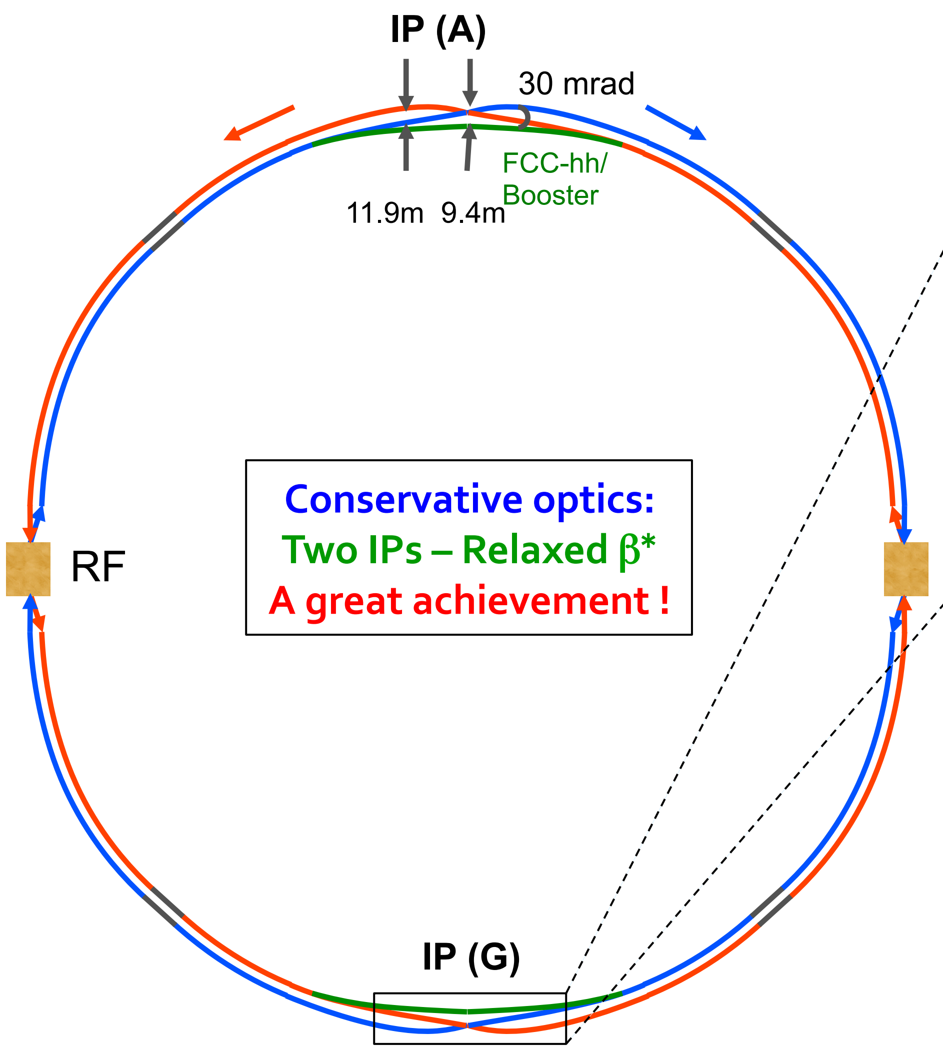
Adapt (to) the interaction region
Joint with FCC-ee Accelerator

Detector designs
A. Cattai, G. Rolandi,
M. Dam

Synergy with LC and CEPC
Set constraints on designs
to match statistical precision
Propose detector designs

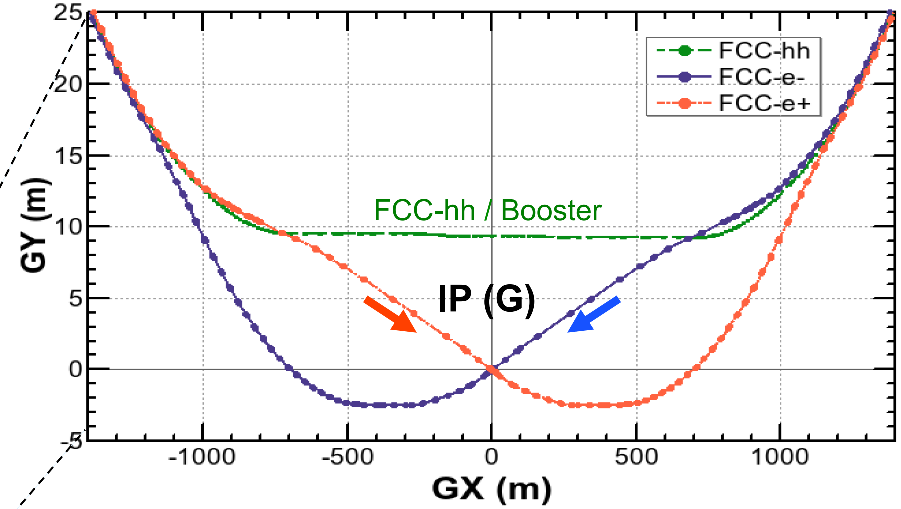
FCC-ee baseline layout

- Fits the FCC-hh tunnel and footprint



Conservative optics:
Two IPs – Relaxed β^*
A great achievement !

Asymmetric beam crossing at the IPs
Minimize synchrotron radiation

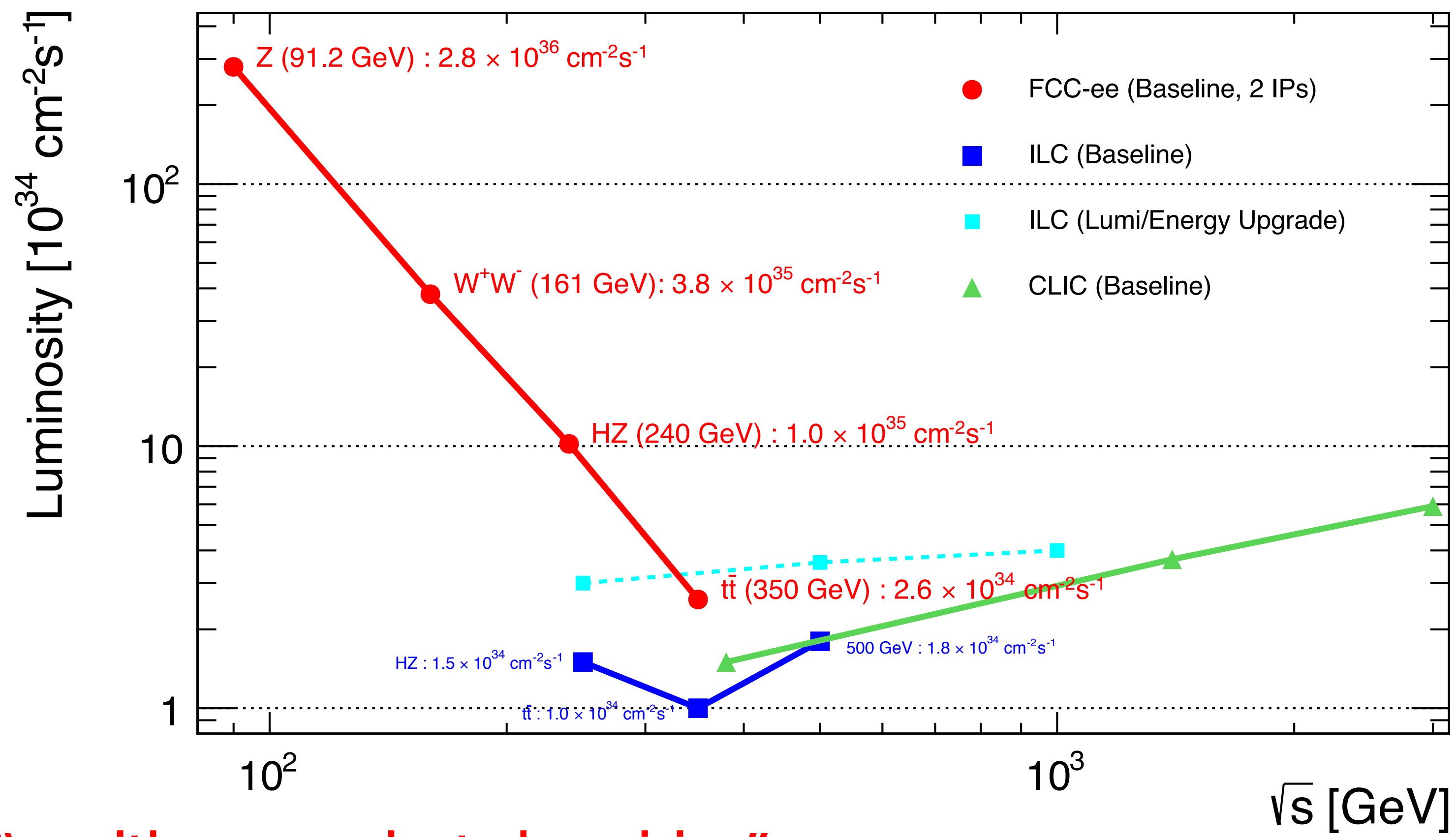


Integrated time needed twice smaller with four detectors than with two

How much work would it be to switch to a 3 or 4 detector lattice if FCC physics programme required ?

Luminosities and centre-of mass energies

- "Study the properties of the Higgs boson and other particles … "
  - Run at √s ~ 91.2 GeV (Z), ~161 GeV (W), ~240 GeV (Higgs), ~350 GeV (top and Higgs)



- "… with unprecedented precision"
  - Largest luminosities at all these energies

Machine parameters

J. Wenninger et al.
FCC-ACC-SPC-003
Revision 4.0

parameter	FCC-ee				LEP2
physics working point	**Z**	**WW**	**ZH**	**$t\bar{t}$** (tt$_{bar}$)	
energy/beam [GeV]	**~45.6**	**~80.5**	**~120**	**~175**	~105
bunches/beam	**71200**	**6000**	**740**	**62**	4
bunch spacing [ns]	**3.0**	**50**	**400**	**4000**	22000
bunch population [10^{11}]	**0.4**	**0.5**	**0.8**	**2.1**	4.2
beam current [mA]	**1400**	**152**	**30**	**6.6**	3
luminosity/IP x 10^{34}cm^{-2}s^{-1}	**158**	**19.5**	**5.1**	**1.4**	0.0012
energy loss/turn [GeV]	**0.036**	**0.34**	**1.71**	**7.72**	3.34
synchrotron power [MW]	**100**				22
RF voltage [GV]	**0.25**	**0.8**	**3.0**	**9.5**	3.5
√s spread SR [%]	**0.04**	**0.07**	**0.10**	**0.15**	0.11
√s spread SR+BS [%]	**0.06**	**0.08**	**0.11**	**0.17**	0.11

Operation model

M. Benedikt
May 2017

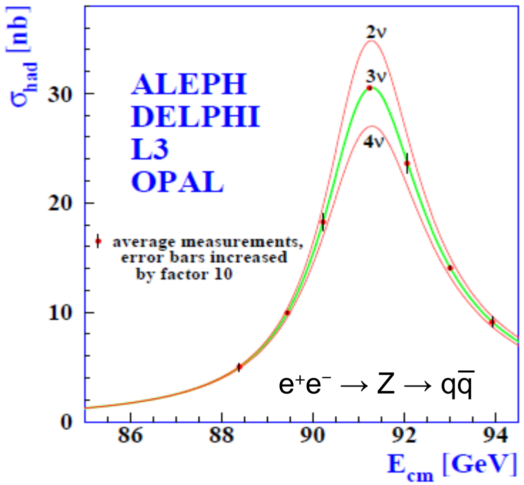
- **Physics goals (see next slides)**
  - 150 ab^{-1} around the Z pole (~ 25 ab^{-1} at 88 and 94 GeV, 100 ab^{-1} at 91 GeV)
  - 10 ab^{-1} around the WW threshold (161 GeV with ±few GeV scan)
  - 5 ab^{-1} at the HZ cross section maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the top threshold (a fraction at ~350 GeV, the rest at ~370 GeV)
- **Assumptions**
  - 200 scheduled physics days per years
  - Hübner factor ~ 0.6 (lower than PEPII, 0.63, and KEKB, 0.8)
  - Winter shutdowns used to change machine configuration between working points
- **Run plan with 2 IP and the baseline optics**

$\sqrt{s}$ (GeV)	Z	WW	HZ	top
Lumi (ab^{-1}/year)	15, then 30	4	1	0.3
Events/year	1.5×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}
Physics goal	150 ab^{-1}	10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}
Runtime (years)	6	2	5	5

  - Numbers of years are soft numbers that can be revised and negotiated

Physics goals at the Z pole

- **Precision EW measurements with a Z resonance scan : 6 years, really ?**



- **Lineshape** (Current)
  - 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)

Review talks from P. Azzuri, D. d'Enterria

- **Most measurements are systematic-limited after the first (couple) year(s) (~10^{12} Z)**
  - √s precision, luminosity accuracy, higher-order theory predictions

Review talk from A. Blondel | Review talk from G. Voutsinas | Review talk from F. Piccinini

- **Severe limitation comes from the knowledge of $\alpha_{QED}(m_Z)$**
  - Direct measurement possible with two more years at √s = 87.9 and 94.3 GeV
- **A sample of 10^{13} Z (two more years) opens a large variety of interesting possibilities**
  - Discovery new physics with rare Z (visible or invisible) decays
  - Discovery new physics with b, c, τ rare decays ($Z \to bb, cc, \tau\tau$)

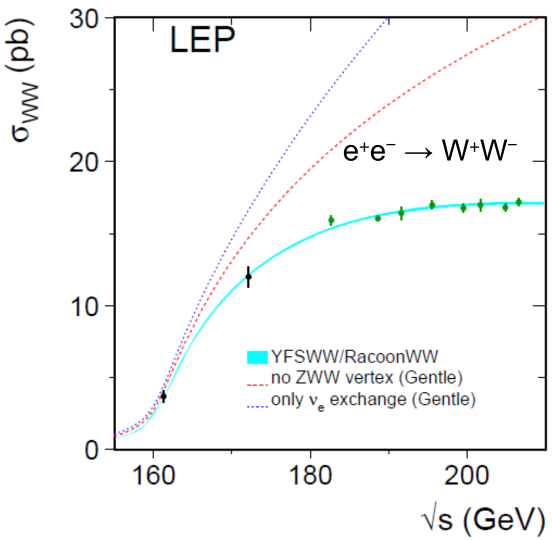
Review talks from A. Fischer and M. Pierini

Review talk from S. Monteil

- **Six years at the Z make the link between the intensity and the energy frontiers**

Physics goals at the WW threshold

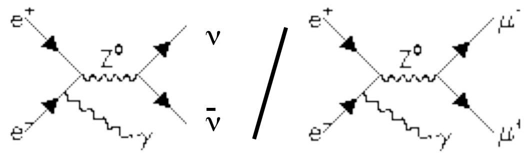
- **Within two years at the WW threshold**



(Current)

- **Threshold scan**
  - **m_W to < 500 keV** (15 MeV)
- **Branching ratios R_l, R_{had}**
  - **$\alpha_S(m_W)$ to 0.0002** (0.002)
- **Radiative returns $e^+e^- \to \gamma Z$**
  - **N_ν to 0.0004** (0.008)

α_{QED}



Review talks from
P. Azzuri,
D. d'Enterria

And also :
- **TGC / QCG**
- **Rare W decays**

- **This m_W precision is essential for the full exploitation of the Z precision measurements**

Prediction from Z measurements

$$m_W = 80.3593 \pm 0.0001\ (m_{top})\ \pm 0.0001\ (m_Z)\ \pm 0.0003\ (\alpha_{QED})$$
$$\pm 0.0002\ (\alpha_S)\ \pm 0.0000\ (m_H)\ \pm 0.0004\ (\text{theo.})$$
$$= 80.3593 \pm 0.0005\ \text{GeV}$$
(~precision of direct measurement)

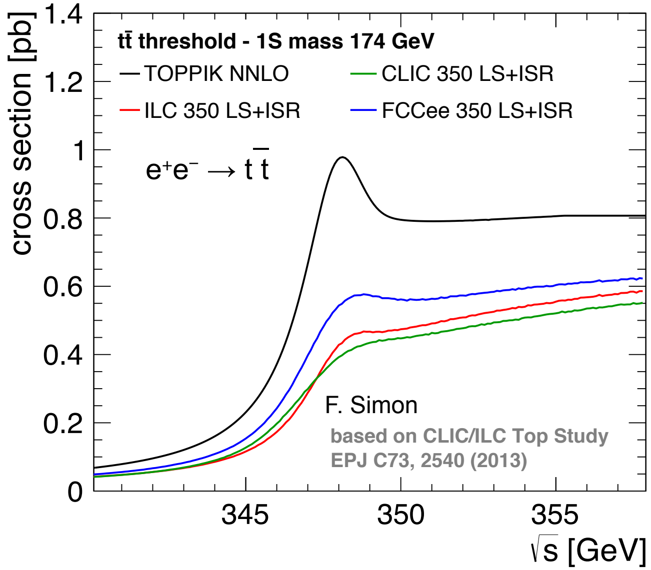
- **With similar systematic limitations as at the Z pole**
  - ➨ **E.g., higher-order theory predictions (order of magnitude improvement)**

Review talk from F. Piccinini
Talks from J. Gluza & S. Heinemeyer

Physics goals at and above the top threshold

- **Primary goal : precise m_{top} measurement at threshold**

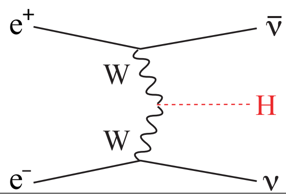
Review talk from P. Azzi



- Essential for full harnessing of Z & W precision data
  - 10 MeV precision (stat.) reached with 0.2 ab^{-1}
- Benefits from α_S measurement at lower $\sqrt{s}$
  - QCD higher orders : dominant syst. (30 MeV)
- Also from threshold scan:
  - Top decay width, top Yukawa coupling

- **Many interesting opportunities slightly above threshold (370 GeV)**
  - Top EW couplings, ttγ and ttZ, to 1%
    - Sensitive to new physics
    - Synergetic with FCC-hh for ttH Yukawa coupling measurement
  - Anomalous top production and decay
  - Higgs decay width to 1%
  - …

Review talk from C. Grojean

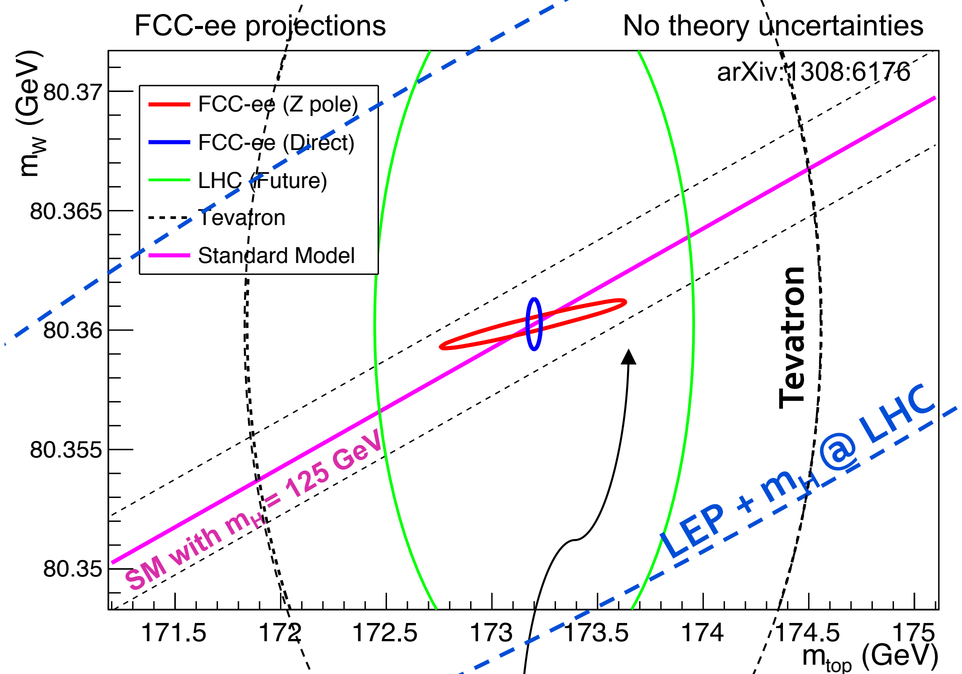


Review talk from M. Klute

Global Fit and sensitivity to new physics

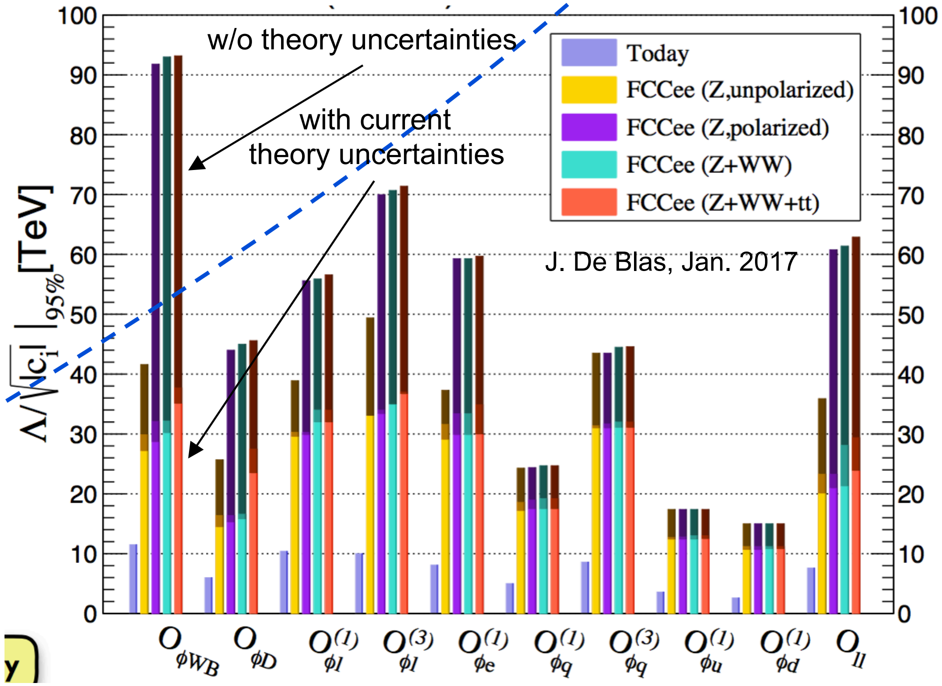
- **Combining all EW measurements**
  - **In the context of the SM … and beyond**

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



Without m_Z (α_{QED})@FCC-ee, the SM line would have a 2.6 (1.8) MeV width

FCC-ee sensitivity severely drops without POLARIZATION + STATISTICS (and improved theory calculations)



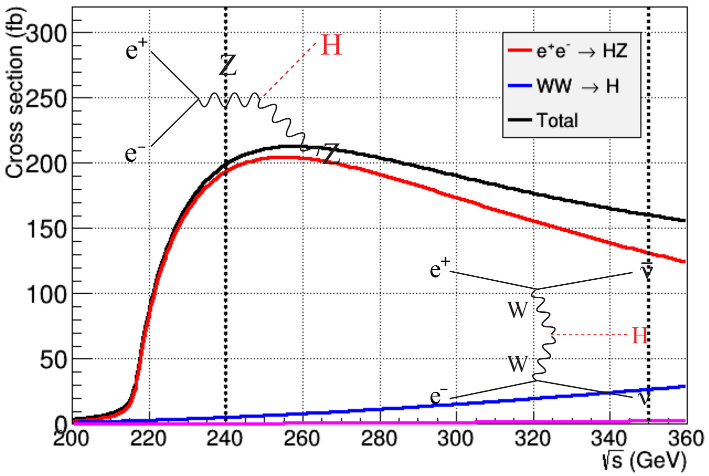
Today: **Λ > 5-10 TeV**

After FCC-ee: Λ > 50-100 TeV ?

Synergetic with FCC-hh

Physics goals at 240 GeV

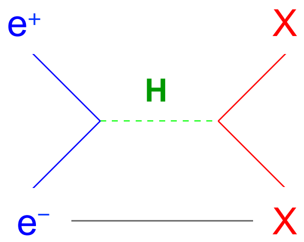
- **Measure Higgs couplings in a model-independent manner**



- **With one million HZ events and $H \to XX$ decays**
  - **Precisions typically between 0.1 % and 1% (stat.)**
  - **At least a factor 10 better than HL-LHC / FCC-hh**
- **Model-independence from**
  - **Absolute measurement of $\sigma(e^+e^- \to HZ)$**
  - **Indirect measurement of Higgs decay width**

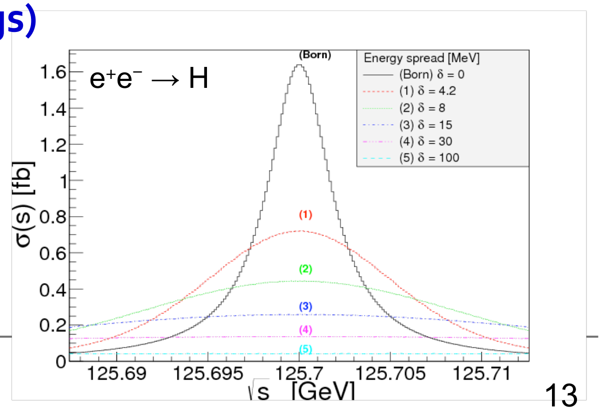
Review talk from M. Klute

- **Discover / set constraints on new physics coupled to the Higgs sector**
  - **Deviation of couplings with respect to standard model-predictions**
  - **Invisible or rare decays; CP violating decays with $H \to \tau\tau$**
  - **Exclusive decays $H \to \rho\gamma$ or $\phi\gamma$ (Hdd, Huu, or Hss couplings)**
- **Possible addition : s-channel production**



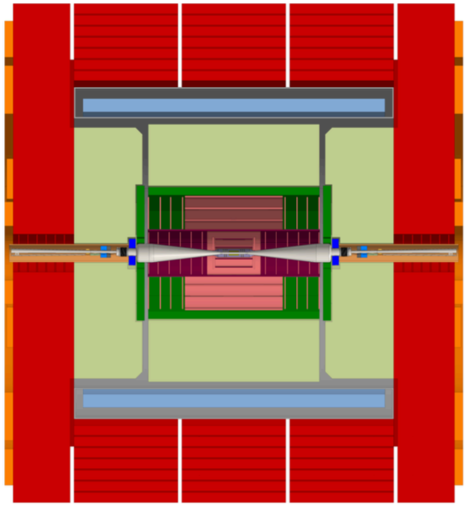
Hee coupling @ $\sqrt{s}$ = 125 GeV

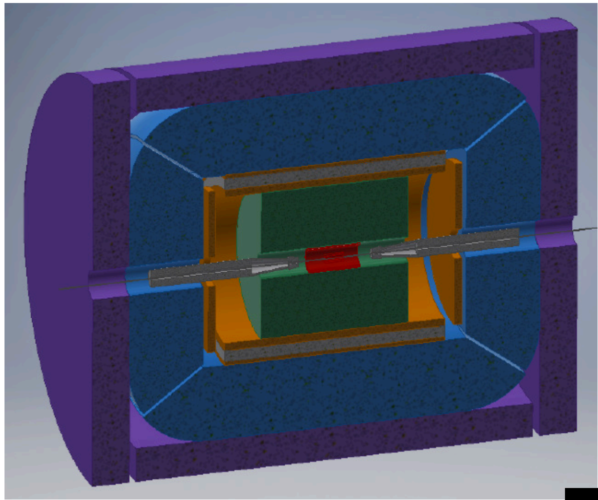
Requires $\sqrt{s}$ monochromatization
(Γ_H = 4.2 MeV)



Detector designs

- Designs driven by the unprecedented precision of the measurements
  - "CLIC-detector revisited" "IDEA"

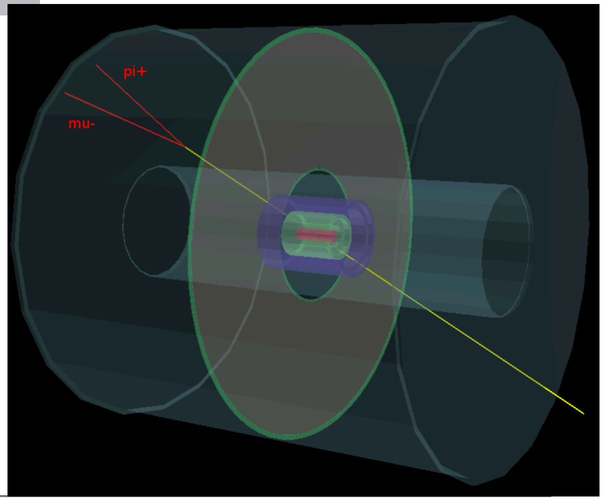




- Vertex detector: ALICE
- Tracking: MEG
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

Review talk from E. Leogrande

Review talk from M. Dam

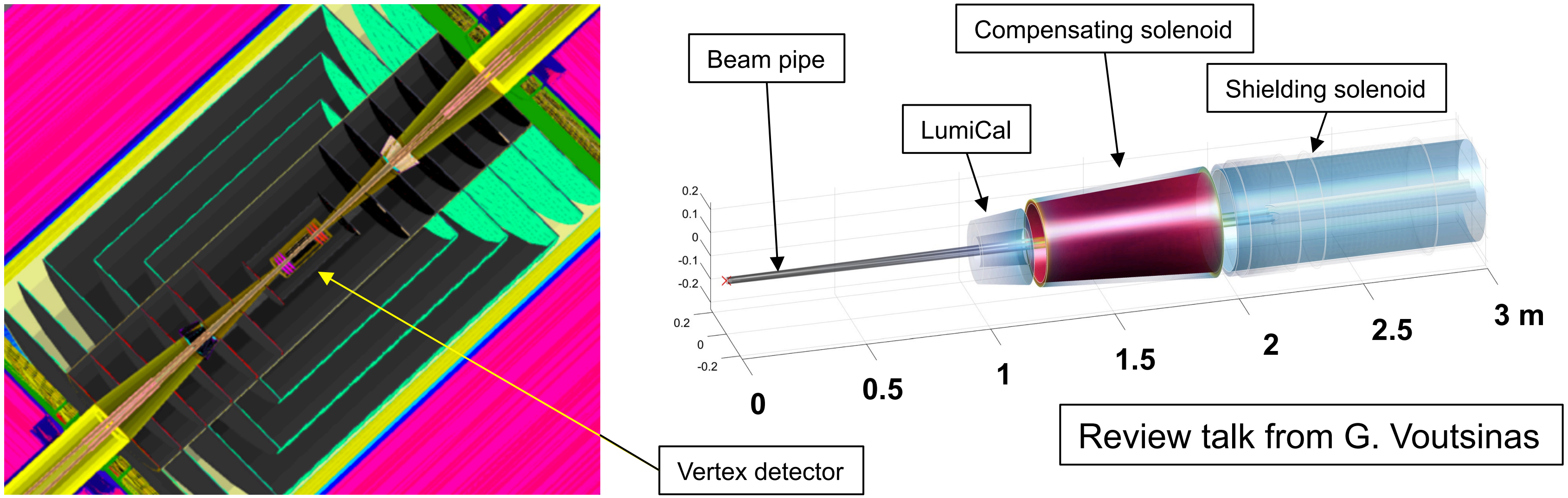


- Possibly surrounded by large tracking volume (R = 8m)
  - Very weakly coupled (long-lived) particles
    - ➨ E.g., RH neutrinos as DM candidates

Review talk from A. Fischer

MDI and experimental environment

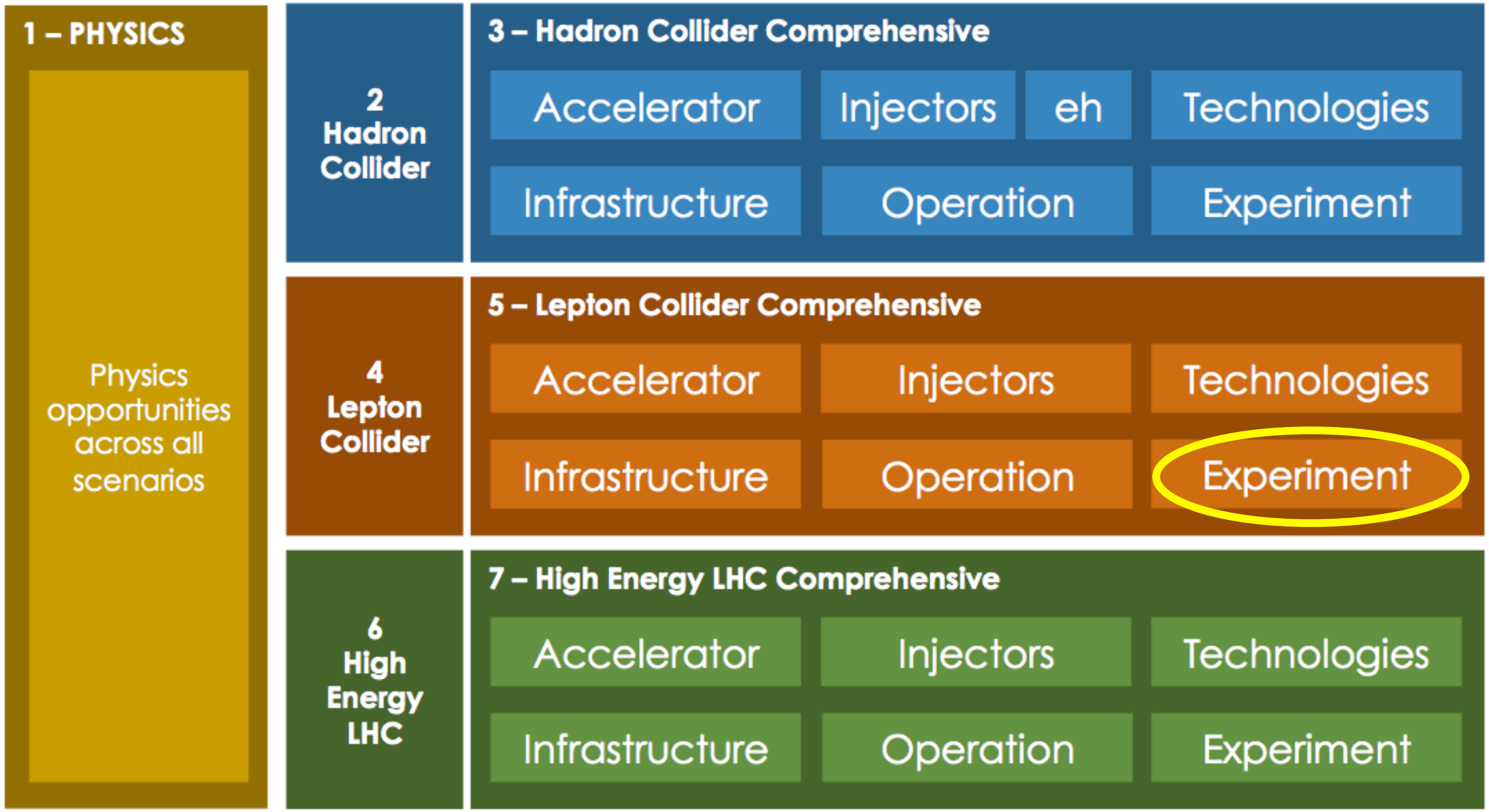
- **Busy interaction region with 30 mrad crossing angle**
  - **Quadrupole, shieding and compensating solenoids, lumiCal, are inside the detector**



- **Important beam backgrounds in the detector**
  - **Synchrotron radiation requires Tantalum beam-pipe shielding**
  - **Beamstrahlung at IP gives rise to $\gamma\gamma$ collisions ($\gamma\gamma \to e^+e^-$ and $\gamma\gamma \to qq$)**
  - **First investigations show detector occupancies at the 10^{-5} level or smaller**
    - **Up to the highest centre-of-mass energies (top threshold)**
- **Next: understand online selection and readout requirements**
  - **In particular : readout speed with one bunch crossing every 3-10 ns at the Z**

Contributions to the CDR

- "FCC-ee Physics, Experiments, and Detectors" within Vol. 5



- Summarized in Volumes 4 (Lepton collider) and 1 (Physics opportunities)

CDR Vol. 5 Outline

- Vol. 5 "FCC-ee: Physics & Experiments"
  - Introduction (running plan, history, motivation, …)
  - Electroweak physics with Z's and W's
  - Higgs physics
  - Top quark physics
  - QCD and $\gamma\gamma$ physics
  - Flavours
  - BSM (Physics behind precision, global fits, direct searches)
  - MDI and experimental environment
  - Polarization and beam energy measurement
  - Detector designs
  - Summary and outlook

5 – Lepton Collider Comprehensive

Experiment

- Each of the "physics" sections will contain
  - ➨ The theory counterpart (e.g., the quest for precision calculations)
  - ➨ The requirements on detectors (geometry, acceptance, resolution, tolerances)
  - ➨ The requirements on accelerator (luminosity, polarization, E_{beam} knowledge)

Issues and help needed

- **Main issue: the study is vastly understaffed**
  - Main consequences are in the details with which the study is carried out
    - Physics potential evaluated mostly with paper studies
      - ➨ Few fast simulation studies, and even fewer full simulation studies
    - We are not yet in a position of closing the loop
      - ➨ Detector design → Simulation → Analysis → Design optimization
  - No major issue identified so far with the detector design
    - The help brought by our colleagues from CLIC has been precious
    - We look forward to a similar collaboration with the IDEA experts
  - In this context, priority is given to detailed studies of essential MDI aspects
    - Beam backgrounds, luminosity measurement, interaction region geometry
- **Critical analysis of the situation, and points where help is welcome**
  - Competition and lack of coordination between e^+e^- projects (in spite of our efforts)
  - Confusing political and outreach profile given to e^+e^- option in FCC/CERN statements
    - Makes it hard to get funding for students, postdocs, ….
    - Makes it hard to motivate outside institutes to join our FCC-ee studies
  - Confusions on time scales
    - Many conflicting opinions/prejudices among the senior physicists in the community

Statement from the FCC ISC

- **We have sought help from the FCC ISC to circumvent these issues**

The FCC-ee study is fully supported by the CERN management, by the FCC ISC and the FCC community until the CDR and the European Strategy update. The ES will then recommend how to proceed further (linear/circular, electrons/hadrons, etc.)

The remarkable progress on the FCC-ee machine design during the past 3 years (also compared with the CEPC activities) testifies to the seriousness of the FCC-ee efforts.

As a scientific, organizational and administrative framework, the FCC mandate, the FCC collaboration (with MoU and addenda), and the FCC Governance Structures offer all the prerequisites and means for globally coordinated efforts with a clear definition of goals and parameters, deriving from the mandate, which underlines CERN's support.

For all the above reasons, we don't see the need, at this stage, to create additional structures, and **the ISC encourages the continuation and, if possible, intensification of the successful FCC-ee physics and detector efforts** within the existing framework. The ISC is convinced that this present set up guarantees the best scientific and technical success.

Informal collaboration and exchanges on physics studies with our CEPC colleagues are obviously possible and welcome.

Summary

- **To be thought of**
  - **after receiving your comments and suggestions**