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 a substantial offer of 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
  - High-energy physics absolutely needs an e^+e^- collider at the EW scale
- **The scientific potential of circular colliders is unbeatable**
  - Four particles studied with unprecedented precision: Z, W, Higgs, and top
    - With unprecedented luminosity delivered to several interaction points
  - With a 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
- **A circular e^+e^- collider is great spring board for the 100 TeV collider**
  - Brings a large tunnel, infrastructure, cryogenics, time, physics, and performance goals
    - Circular ee+pp is a most powerful combination at the energy and 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 physics studies submitted to the European Strategy in 2012**
  - P. Azzi et al., "Prospective studies for LEP3 with the CMS detector", arXiV:1208.1662
- **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
    - 311 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	Higgs properties	Top quark physics
R. Tenchini, F. Piccinini	M. Klute, K. Peters	P. Azzi (F. Blekman)
S. Heinemeyer, A. Freitas	S. Heinemeyer, A. Freitas	S. Heinemeyer, A. Freitas

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

QCD and $\gamma\gamma$ physics	Flavours physics	New physics	Global Analysis Synergies
D. d'Enterria	S. Monteil	M. Pierini, C. Rogan	J. Ellis
P. Skands	J. Kamenik	M. McCullough	

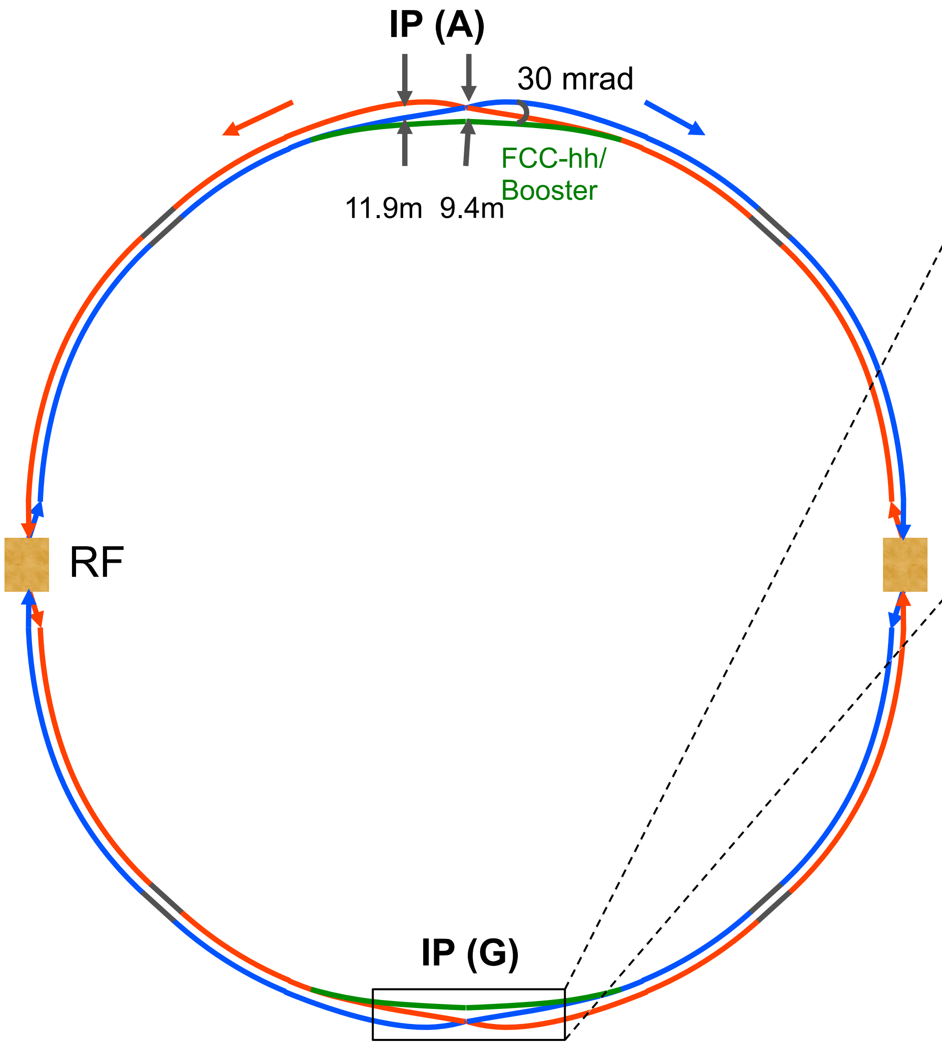
Physics software	Online selection & DAQ	Polarization, $\sqrt{s}$ meast	MDI, Exp'tal environment
C. Bernet, B. Hegner, C. Helsens	C. Leonidopoulos, E. Perez	A. Blondel, J. Wenninger	M. Boscolo, N. Bacchetta
Synergy with FCC-hh, LC, LHC		*Joint with FCC-ee Accelerator*	*Adapt (to) the interaction region* *Joint with FCC-ee Accelerator*

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

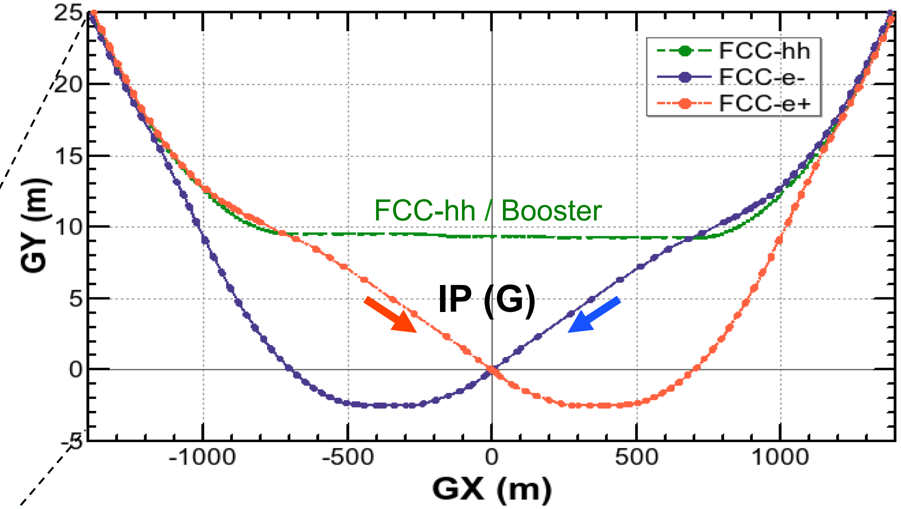
Synergy with LC and CEPC
Set constraints on designs
to match statistical precision
Propose detector designs

FCC-ee baseline layout

- Fits the FCC-hh tunnel and footprint



Asymmetric beam crossing at the IPs
Minimize synchrotron radiation

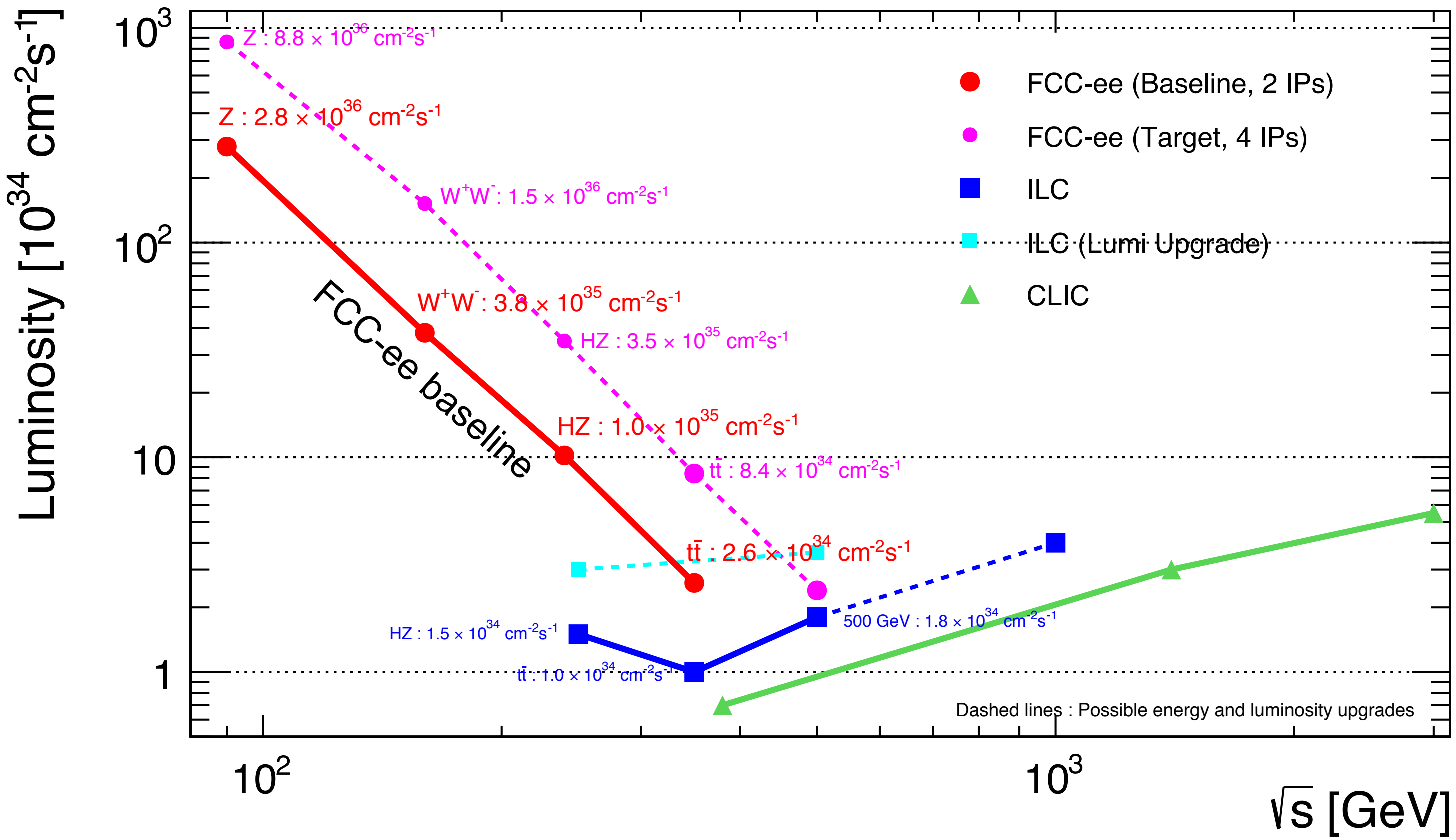


Conservative optics:
Two IPs – Relaxed $\beta*$
Number of IPs is to be decided
after a call for collaborations

Integrated time needed twice smaller with four detectors than with two

Luminosities and centre-of mass energies

- **"Study the properties of the Higgs boson and other particles … "**
  - **Run at $\sqrt{s}$ ~ 91.2 GeV (Z), ~161 GeV (W), ~240 GeV (Higgs), ~360 GeV (top and Higgs)**



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

Machine parameters

J. Wenninger et al.
FCC-ACC-SPC-003
and recent updates

parameter	FCC-ee				LEP2
physics working point	**Z**	**WW**	**ZH**	**tt_{bar}**	
energy/beam [GeV]	**~45.6**	**~80.5**	**~120**	**~180**	~105
bunches/beam	**91500**	**5260**	**780**	**81**	4
bunch spacing [ns]	**2.5**	**50**	**400**	**4000**	22000
bunch population [10^{11}]	**0.33**	**0.6**	**0.8**	**1.7**	4.2
beam current [mA]	**1450**	**152**	**30**	**6.6**	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	**140**	**19**	**5.1**	**1.3**	0.0012
energy loss/turn [GeV]	**0.03**	**0.33**	**1.67**	**7.55**	3.34
synchrotron power [MW]	**100**				22
RF voltage [GV]	**0.1**	**0.8**	**3.0**	**10**	3.5
√s spread SR [%]	**0.04**	**0.05**	**0.07**	**0.10**	0.11
√s spread SR+BS [%]	**0.06**	**0.07**	**0.08**	**0.12**	0.11

Operation model

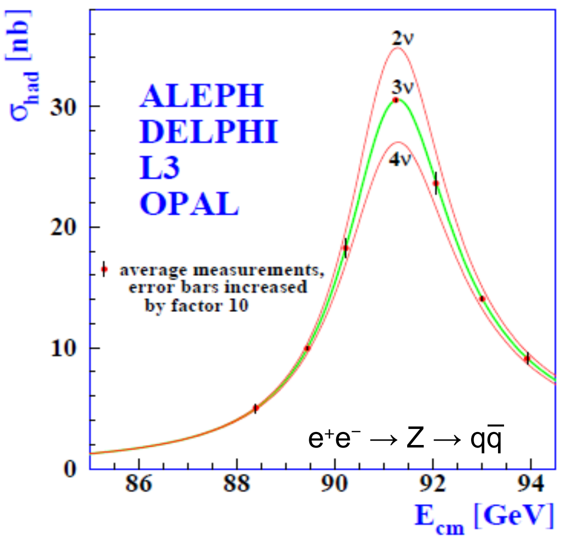
M. Benedikt
May 2017

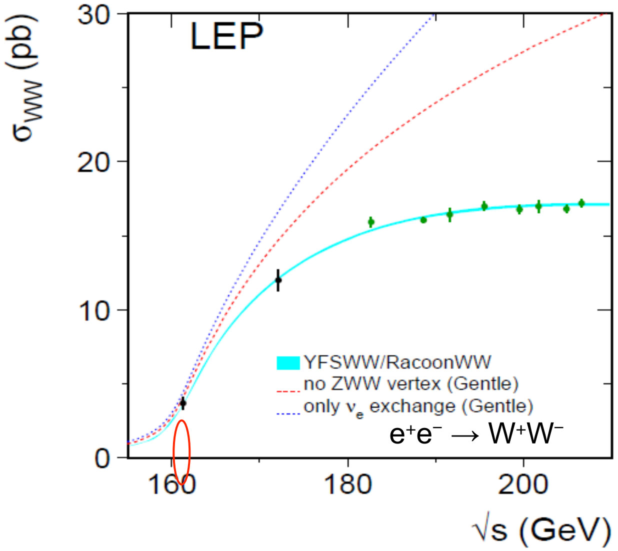
- **Physics goals (see next slides)**
  - 150 ab^{-1} around the Z pole (~ 25 ab^{-1} at 88 and 94 GeV, 100 ab^{-1} at 91 GeV)
  - 10 ab^{-1} around the WW threshold (161 GeV with ±few GeV scan)
  - 5 ab^{-1} at the HZ cross section maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the top threshold (0.2 ab^{-1} at threshold, 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 : total operation time of 18 years**
  - With two interaction points and the baseline optics

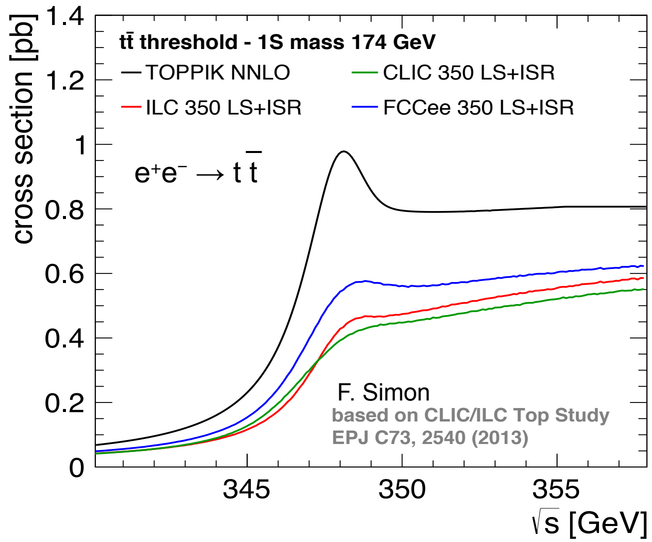
$\sqrt{s}$ (GeV)	Z	WW	HZ	top
Lumi (ab^{-1}/year)	30	4	1	0.3
Events/year	1.5×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}
Physics goal	150 ab^{-1}	10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}
Runtime (years)	6	2	5	5

Physics goals

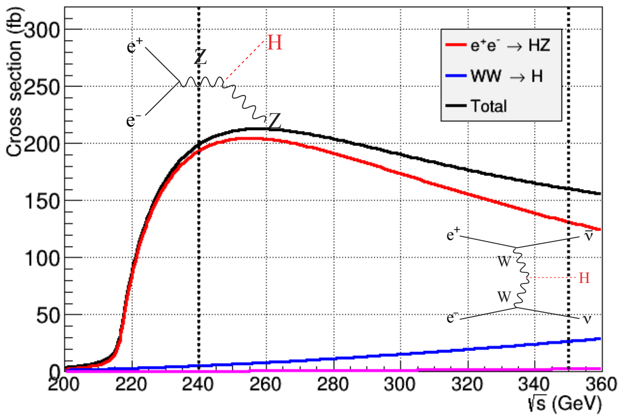
- Z pole scan — WW threshold scan — Top threshold and above

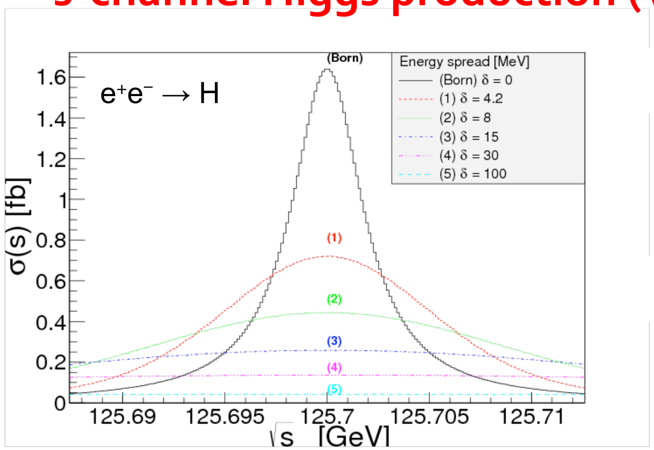


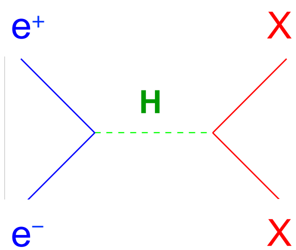




- Higgs production — s-channel Higgs production ($\sqrt{s}$ = 125 GeV) ?







Hee coupling !

Physics goals at the Z pole

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

- **Precision EW measurements with a Z resonance scan : 6 years, really ?**
  - Many (m_Z, Γ_Z, $\sin^2\theta_W^{eff}$, N_ν, α_S , …) are systematics limited after a year or less (< 10^{12} Z)
    - One to two orders of magnitude improvement with respect to LEP
    - Challenges in the control / improvement of the systematic uncertainties
      - $\sqrt{s}$ measurement with transverse polarization (< 100 keV) — Review talk from A. Blondel
      - Luminosity measurement (< 10^{-4}) — Review talk from M. Dam
      - Higher-order theory predictions (order of magnitude) — Review talk from F. Piccinini
    - The current knowledge of $\alpha_{QED}(m_Z)$ is a severe limiting factor
      - When it comes to discover (or set constraints on) weakly-coupled new physics
  - Direct improved measurement of $\alpha_{QED}(m_Z)$ is possible at the FCC-ee — JHEP 1602 (2016) 53
    - With a year at 87.9 GeV and a year at 94.3 GeV (large syst./th. cancellations)
      - From the measurement of asymmetries (e.g., $A_{FB}^{\mu\mu}$, maybe A_{pol}^{τ})
  - We discovered that a sample of 10^{13} Z opens a large variety of interesting possibilities
    - Discovery of new physics with rare Z (visible or invisible) decays — Review talks from A. Fischer and M. Pierini
      - e.g. dark Matter that couples very weakly to standard particles
    - Discovery of new physics with b, c, τ rare decays (from Z $\rightarrow$ bb, cc, $\tau\tau$)
      - e.g., Flavour conservation violation, CP violation, … — Review talk from S. Monteil
- **Six years at the Z make the link between the intensity and the energy frontiers**

Longitudinal polarization not required (compensated by statistics) !

Physics goals at the WW threshold

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

- **Within two years, measure m_W with < 500 keV statistical precision**
  - **Required to match that of the prediction from the Z pole standard-model fit**
    - **When it comes to set constraints on (or discover) the underlying new physics**

Today

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

Direct: 0.015

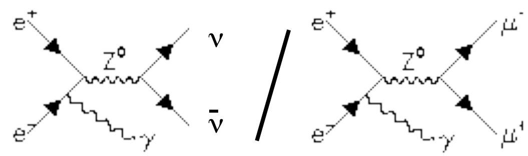
After FCC-ee

$$M_W = 80.3593 \pm 0.0001_{m_t} \pm 0.0001_{M_Z} \pm 0.0003_{\alpha_{QED}} \pm 0.0002_{\alpha_S} \pm 0.0000_{M_H} \pm 0.0004_{\text{theo}} = 80.359 \pm 0.0005_{\text{tot}} \text{ GeV}$$

Direct: 0.0005

  - **Again, challenging systematic uncertainty control on**
    - **$\sqrt{s}$ measurement with transverse polarization (< few 100 keV)** — Review talk from A. Blondel
    - **Selection efficiency, luminosity (< 10^{-4})**
    - **Background cross section (< 10^{-3})** — Review talk from P. Azzurri
    - **Higher-order theory predictions (order of magnitude)** — Review talk from F. Piccinini

- **Other possibilities**
  - **Measurement of N_ν with radiative returns $e^+e^- \to \gamma Z$**
  - **Measurement of $\alpha_S(m_Z)$ from W branching fractions**
    - **With a precision comparable (better) than at the Z pole**
  - **Rare W decays**

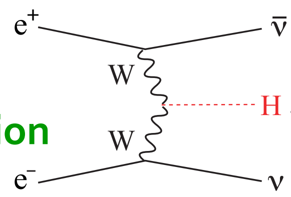


Physics goals at and above the top threshold

Review talk from P. Azzi

- **Primary goal : m_{top} measurement with ~20 MeV precision**
  - Can be achieved with moderate integrated luminosity (100 fb^{-1}) at $\sqrt{s}$ ~ 2 m_{top} (350 GeV)
    - Matches the precision of the prediction from the Z pole standard-model fit
    - Benefits from α_S measurement at the Z pole
  - Also measured with the scan: top decay width, top Yukawa coupling (indirect)
    - Requires good control of QCD corrections to the cross section
- **With more energy ($\sqrt{s}$ ~ 365-370 GeV) and luminosity (~1.5 ab^{-1})**
  - Allows the % precision measurement of the top EW couplings, $tt\gamma$ and ttZ
    - Indirect discovery of Higgs compositeness
      - ➨ In correlation with deviations at the Z pole and in Higgs couplings
    - Synergy with FCC-hh for a FCC-combined ttH coupling measurement
      - ➨ FCC-hh measures ttH/ttZ with % theory uncertainty
      - ➨ FCC-ee measures ttZ with % experimental accuracy
  - Allows the Higgs total width to be determined with % precision
    - Essential for model-independent Higgs coupling determination
  - Searches for rare top decays
    - e.g., FCNC decays $t \to cH, cZ$

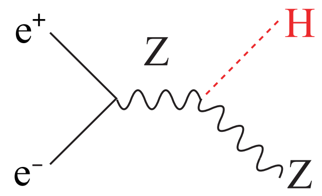
Review talk from C. Grojean



Review talk from M. Klute

Physics goals at 240 GeV

Review talk from M. Klute



- **Measure Higgs couplings in a model-independent manner**
  - With one million HZ events and $H \to XX$ decays
    - i.e., with precisions typically between 0.1 % and 1%
      - ➨ At least one order of magnitude better than HL-LHC / FCC-hh

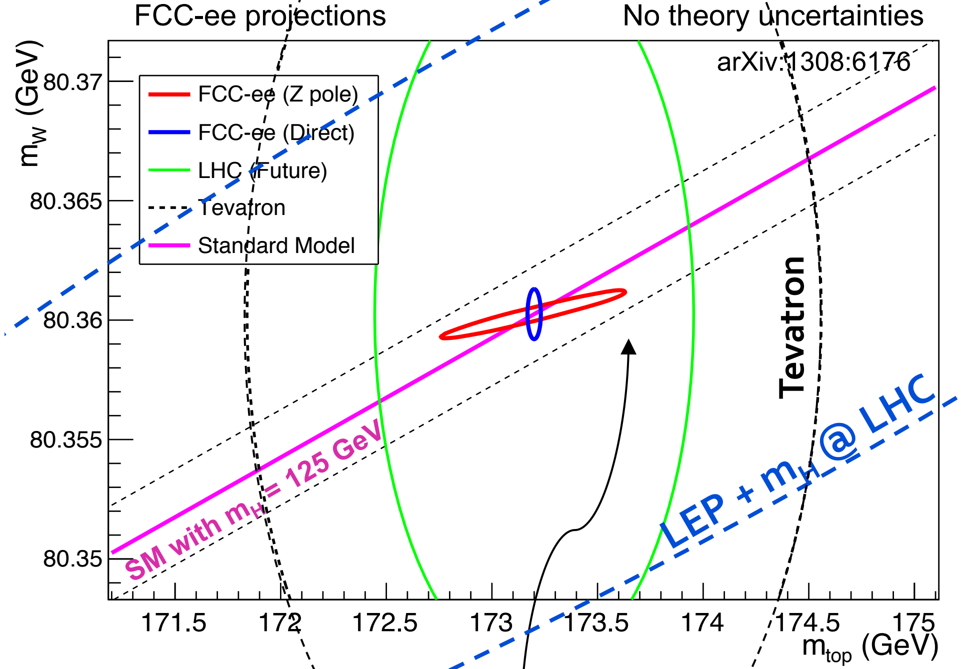
        (Systematics-limited and model-dependent measurements)
  - Principle: HZ events are tagged with a Z boson
    - Measure the HZ cross section (the HZZ coupling) independently of X
  - Model-independent couplings arises from the knowledge of the Higgs Γ_H (prev. slide)
    - And from the measurements of $\sigma(e^+e^- \to HZ) \times \Gamma(H \to XX) / \Gamma_H$
  - Higher-order EW / QCD corrections to be better controlled
    - Potentially set constraints on Higgs-coupled new physics scale up to 5-10 TeV
- **Discover / set constraints on new physics coupled to the Higgs sector**
  - Invisible or rare decays
  - Deviation of couplings with respect to standard model-predictions
  - CP violating decays with $H \to \tau\tau$
- **Possible addition: Set constraints on couplings to the lightest fermions**
  - s-channel Higgs production (Hee coupling): needs $\sqrt{s}$ monochromatization (Γ_H = 4.2 MeV)
  - Exclusive decays $H \to \rho\gamma$ or $\phi\gamma$, (Hdd, Huu, or Hss couplings)

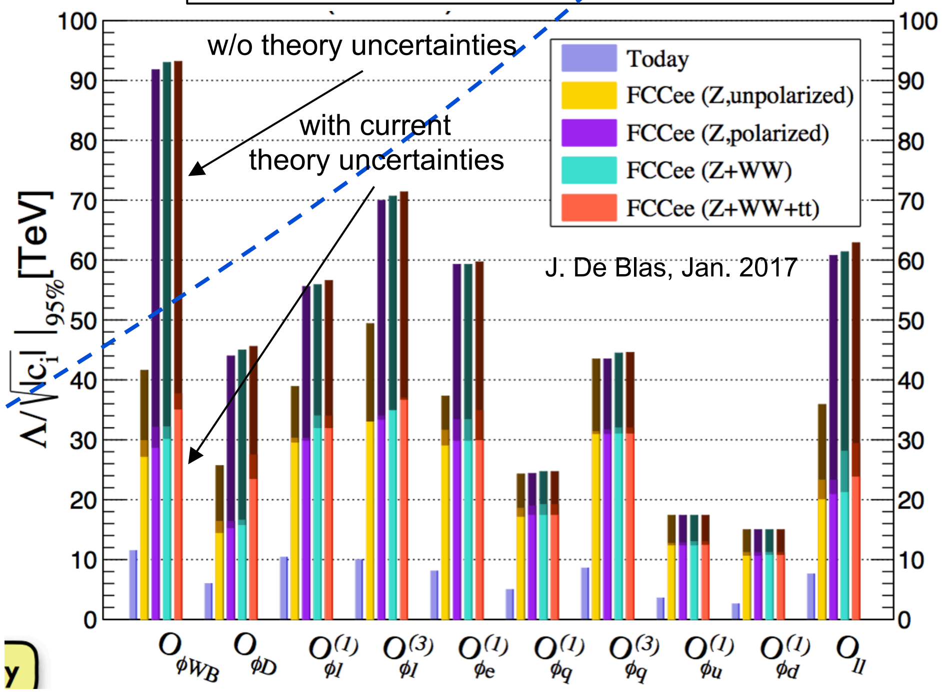
Global Fit and sensitivity to new physics

Review talk from J. Ellis

- **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**

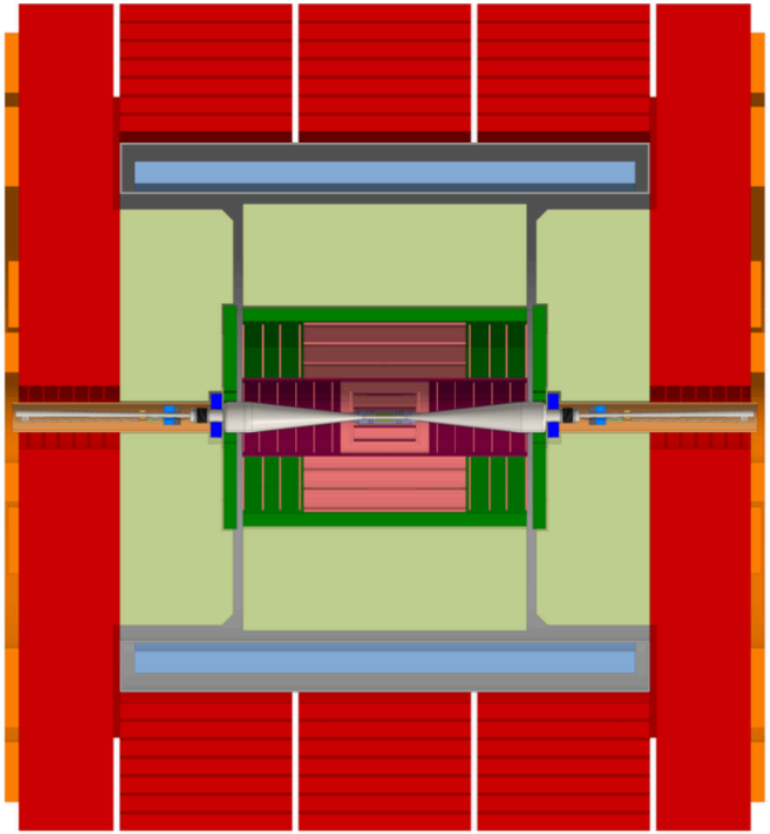
After FCC-ee: Λ > 50-100 TeV ?

Synergetic with FCC-hh

Detector design (1)

Review talk from E. Leogrande

- **Unprecedented precision**
  - Calls for a detector at least as accurate as developed for linear colliders
    - CLIC detector being revisited and adapted to FCC-ee interaction region
      - ➨ Si Tracker, Si/W ECAL, steel+scint. HCAL, solenoid and equipped return yoke
    - Preserve emmittance at IP
      - ➨ Smaller B field (2T)
    - Compensate for smaller B field
      - ➨ Larger tracker outer radius (2m)
    - Benefits from the smaller beam pipe
      - ➨ Vertex detector smaller inner radius
    - Benefits from smaller √s
      - ➨ Thinner HCAL
    - No readout electronics pulsing
      - ➨ More cooling, more material
    - etc.
  - Large experience from the CLIC group
    - Evaluate performance with LC software
    - Port simulation in the FCC software

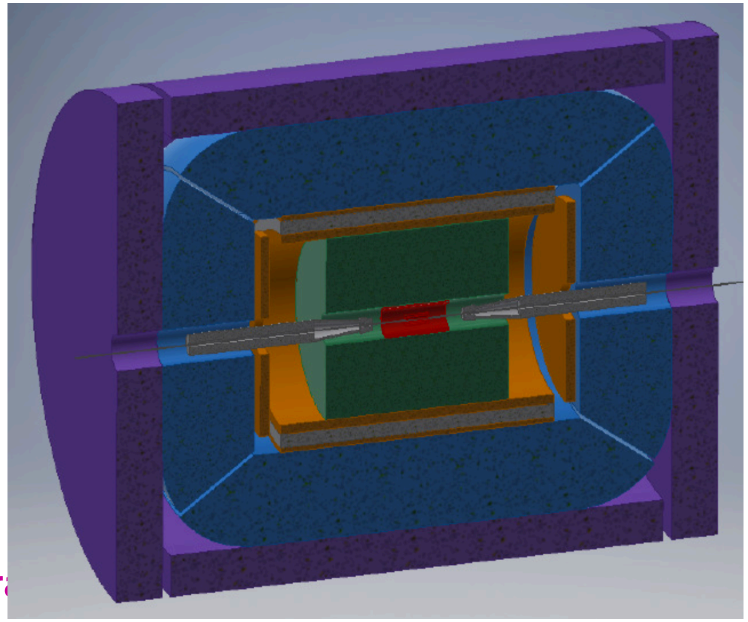


Detector design (2)

Review talk from M. Dam

- **Explore alternative designs**
  - With, possibly, even better accuracy – based on current R&D and simulations
    - VTX : 4-7 layers of 30x30 μm MAPS layers (~ALICE ITS upgrade)
      - 2m long, 40cm radius
      - 0.3 to 1% X_0 / layer
    - Wire drift chamber (~MEG)
      - 4m long, 2m radius, PID, 1.6% X_0
    - Two layers of Si Preshower\
      - Additional tracker layer

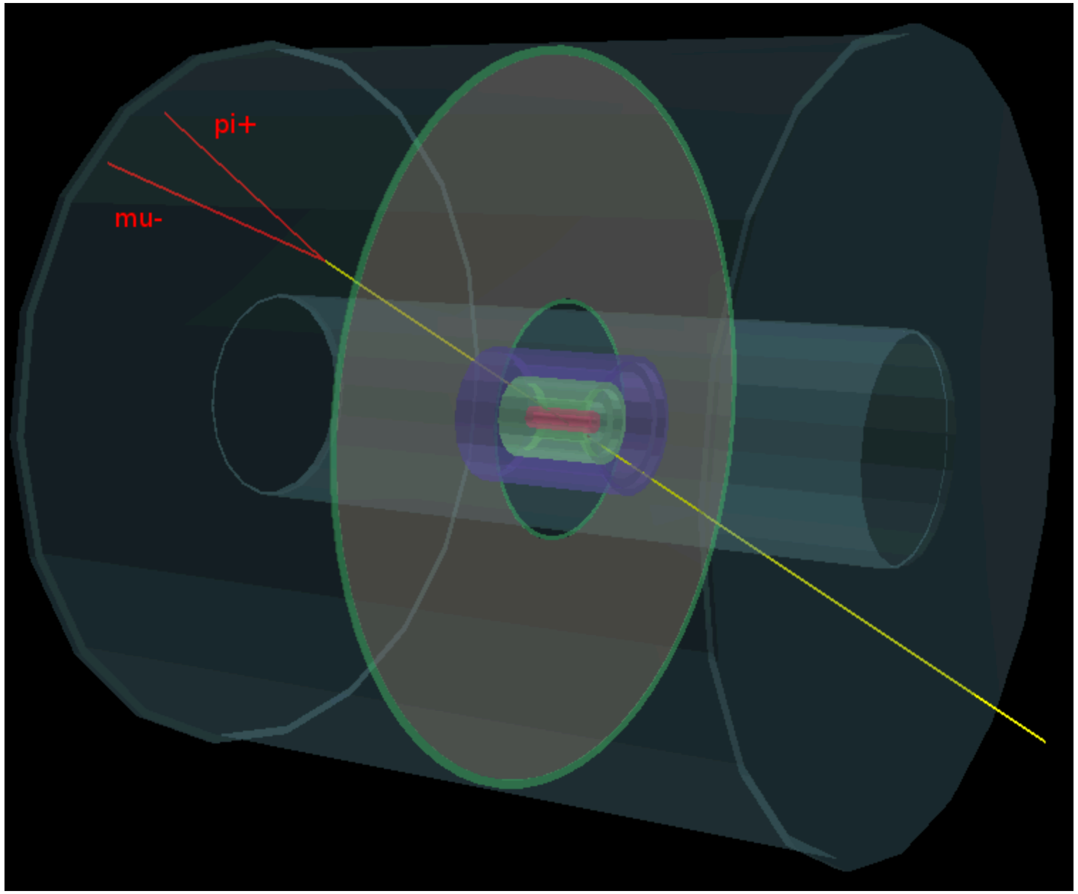
        (Acceptance definition)
      - Photon / Electron ID
    - Dual readout calorimeter (DREAM)
      - 2 m thickness, 2x2 cm transverse gr



    - Solenoid (2T) inside or outside the calorimeter
    - Equipped return yoke
- **All pieces to be assembled in a detector simulation (within FCCSW)**
  - Physics performance to be checked (PF reco, b/c tag, momentum resol., PID, ...)

Detector designs (3)

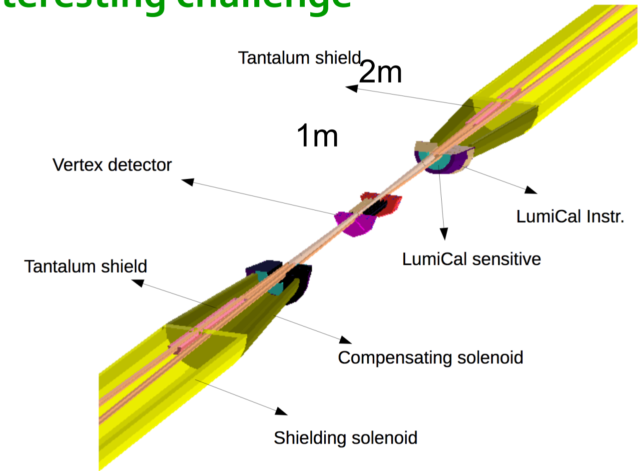
- **Possibility to add a very large tracking volume (R=8m) is studied**
  - **Useful to increase the discovery potential of long-lived (very weakly coupled) particles**
    - **No return yoke in that case**



Interaction region and beam backgrounds

Review talk from G. Voutsinas

- **Busy interaction region**
  - Quadrupole shieding and compensating solenoid inside the detector magnetic field
    - $L^* = 2.2$ m / compensating solenoid up to 1 m for the IP
    - Region below ~150 mrad (8 degrees) not usable for the main detector
    - Beam crossing angle of 30 mrad
    - Luminosity measurement (below 150 mrad) is an interesting challenge
      - ➨ In front of compensating solenoid



- **Important beam backgrounds in the detector**
  - Synchrotron radiation from last bend requires shielding
    - To reduce the number of hits in the tracker
  - Beamstrahlung at IP gives rise to $\gamma\gamma$ collisions
    - $\gamma\gamma \to e^+e^-$ and $\gamma\gamma \to q\bar{q}$
  - First investigations show that these backgrounds are under control
    - 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 2.5 ns at the Z ?

Physics software

No review talk
(this year)

- **Should I say anything more than what's said in slide 3 ?**
  - **Will ask Benedikt and Colin if you think I should.**

CDR Vol. 7 and Review Proceedings Outline

- Vol. 7 "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
    - 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)
- Plan participation to Vol. 1 (FCC overview)
  - Global fits, synergies, physics software (?), executive summary

Issues and help needed

- Physicists in Europe are quite busy with (HL-) LHC
  - Quickest return on investment by extrapolating (HL-) LHC work to HE-LHC & FCC-hh
    - As opposed to invest time in learning e^+e^- physics, experiments, and detectors
- A good fraction of European e^+e^- physicists joined ILC/CLIC long ago
  - There is a lot of potential synergies with FCC-ee , but …
    - Repeated calls for collaborative work could have been better responded …
      - ➨ … and more encouraged / politically promoted
- Groups in Europe are now joining the CEPC activity in China
  - Encouraged by the smart and proactive attitude of the leaders of the CEPC/SppC study
    - With a clear priority given to the e^+e^- first step of the project
- To complete the work needed for the CDR, we would benefit from
  - A stronger recognition of the synergetic scientific impact of circular e^+e^- colliders
  - A louder political support towards coherent participation of European institutes
  - A large-scale advertisement of the benefits of the FCC-ee within the FCC project
  - A larger commitment of young European physicists to the project
    - Be it only to learn e^+e^- physics from the (ageing) experts
  - (Request already made in 2015, and repeated to the FCC steering committee last March)

Summary

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