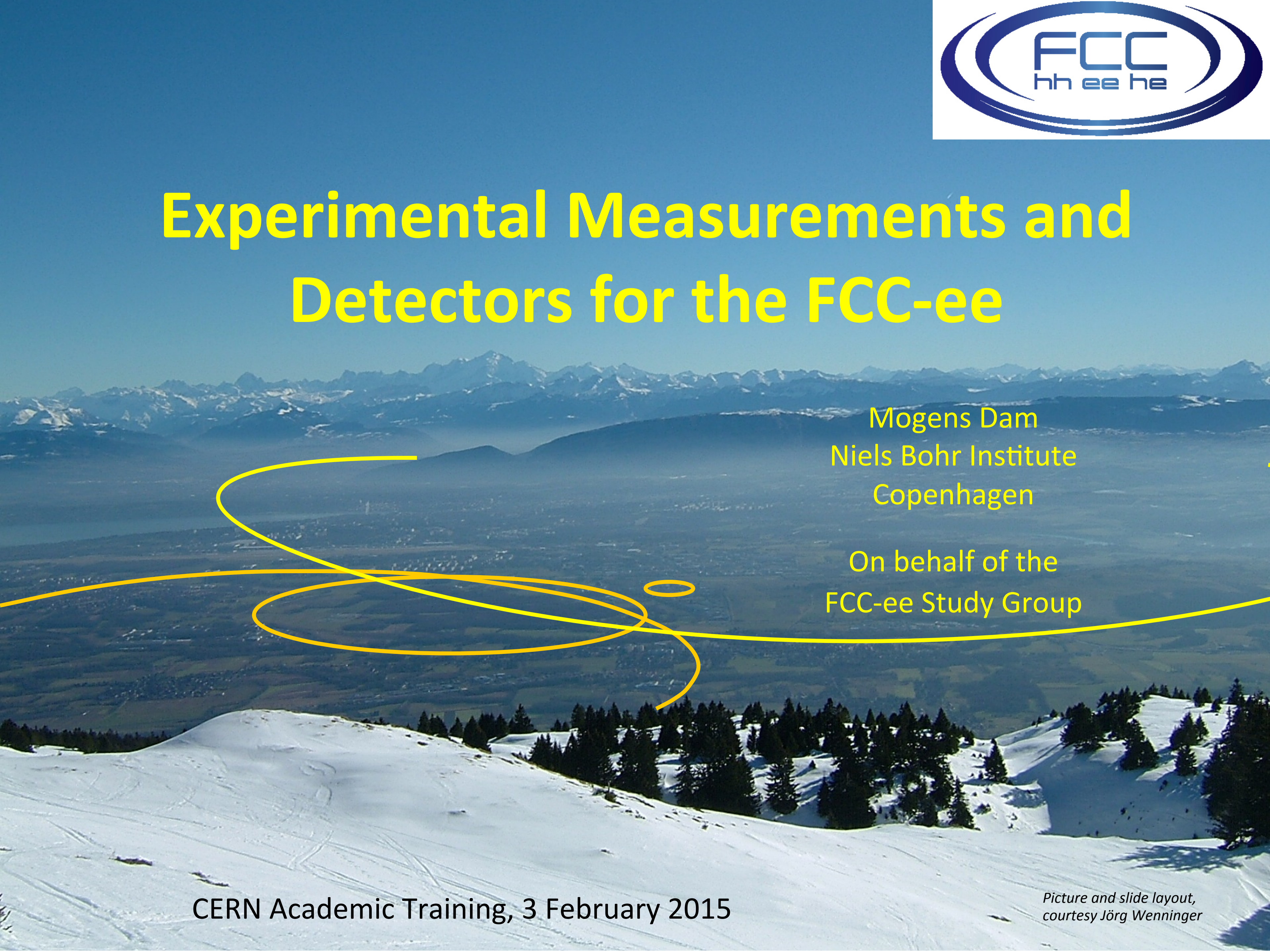


Experimental Measurements and Detectors for the FCC-ee

Mogens Dam
Niels Bohr Institute
Copenhagen

On behalf of the
FCC-ee Study Group

CERN Academic Training, 3 February 2015

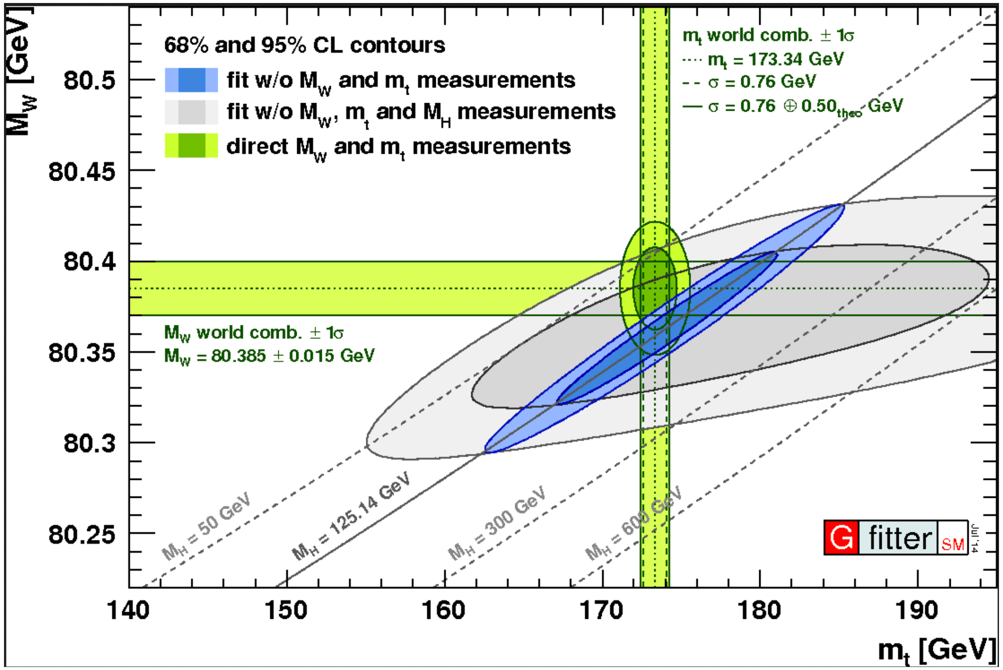
Picture and slide layout,
courtesy Jörg Wenninger

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

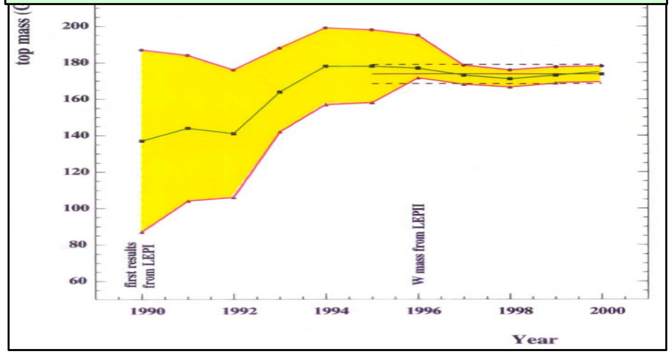
Historically, e^+e^- collisions have been used for precision measurements

- Precision measurements: τ mass, J/ψ mass, Z mass & width
- Predictions at higher scales: m_{top}, m_H, limits on NP
- Unexpected discoveries: c quark, gluon, τ lepton

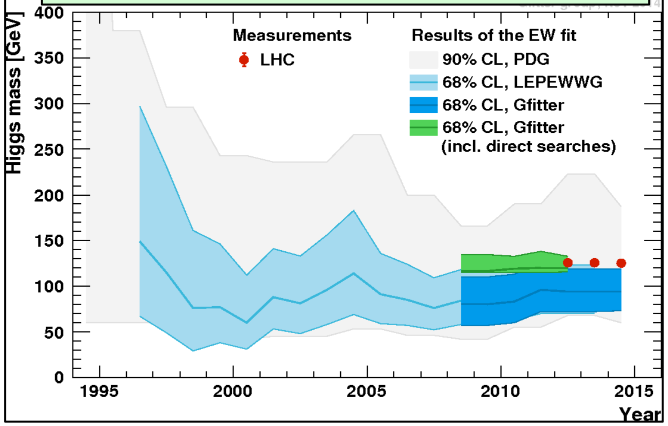
Electroweak precision measurements (largely from LEP) plays a crucial rôle in constraining "New Physics"



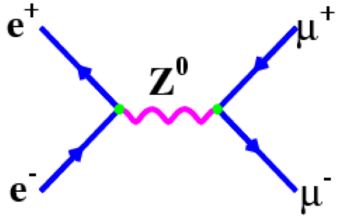
LEP: Prediction of top-quark mass prior to discovery



LEP: Prediction of Higgs mass prior to discovery



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

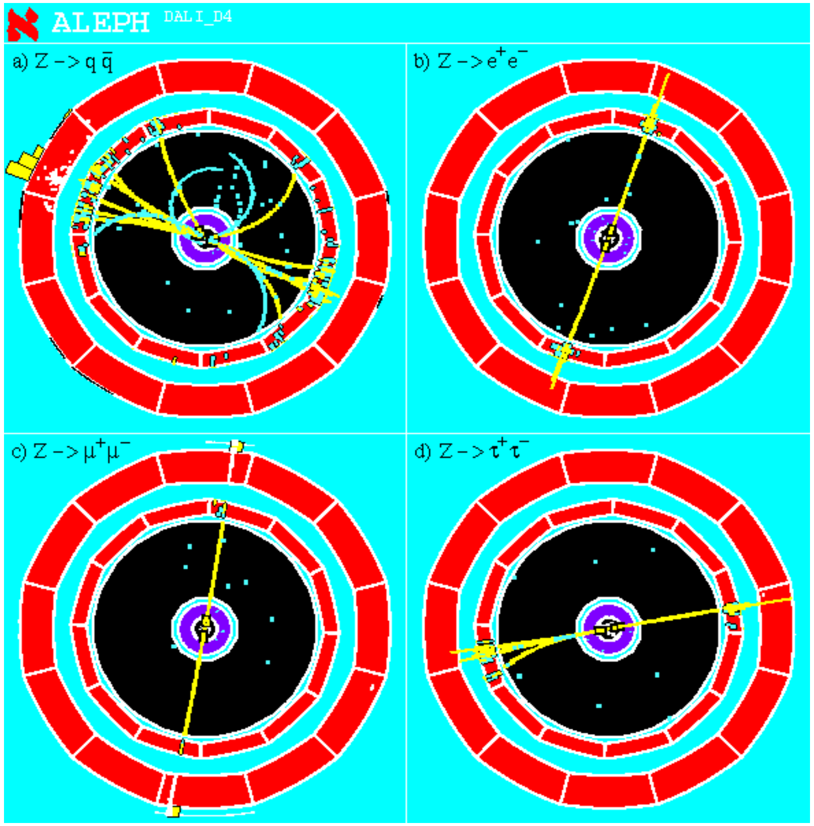


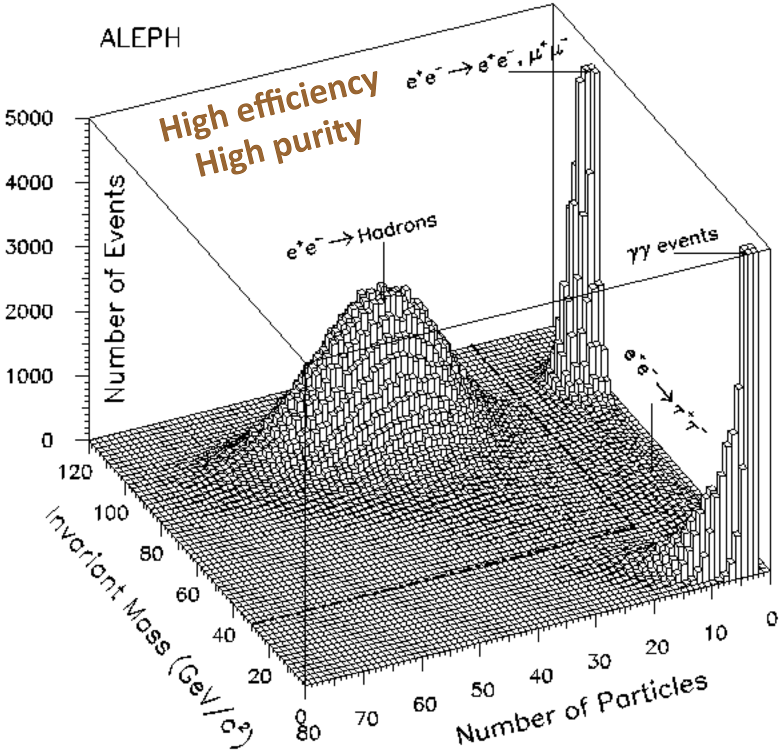
Annihilation of elementary point-like particles

- ✓ No underlying event
- ✓ No strong interactions between beam particles: No pile-up collisions
- ✓ "All events = signal events"

Final state is clean and cozy:

- ➢ triggering is easy (100% efficiency); analysis is a bliss

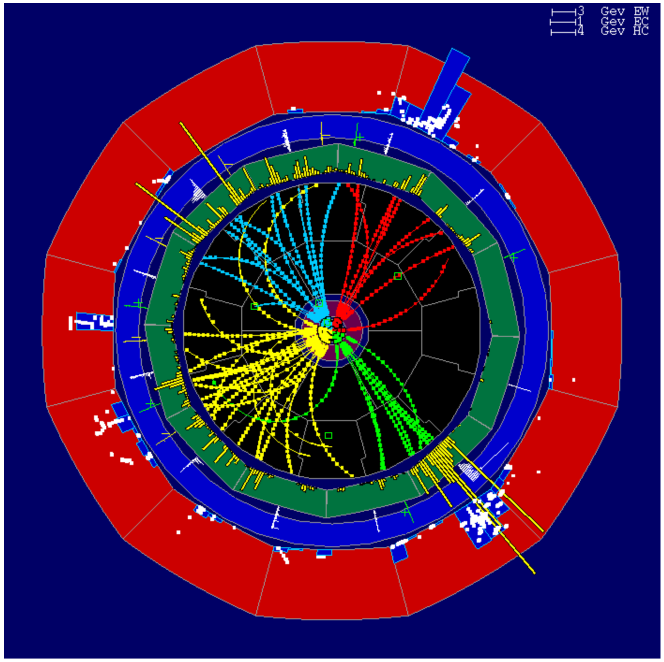




Precision physics with e^+e^- colliders (3)

Annihilation of elementary, point-line particles: no underlying event

- Initial state completely defined
- Final state has known energy and momentum: (√s, 0, 0, 0)



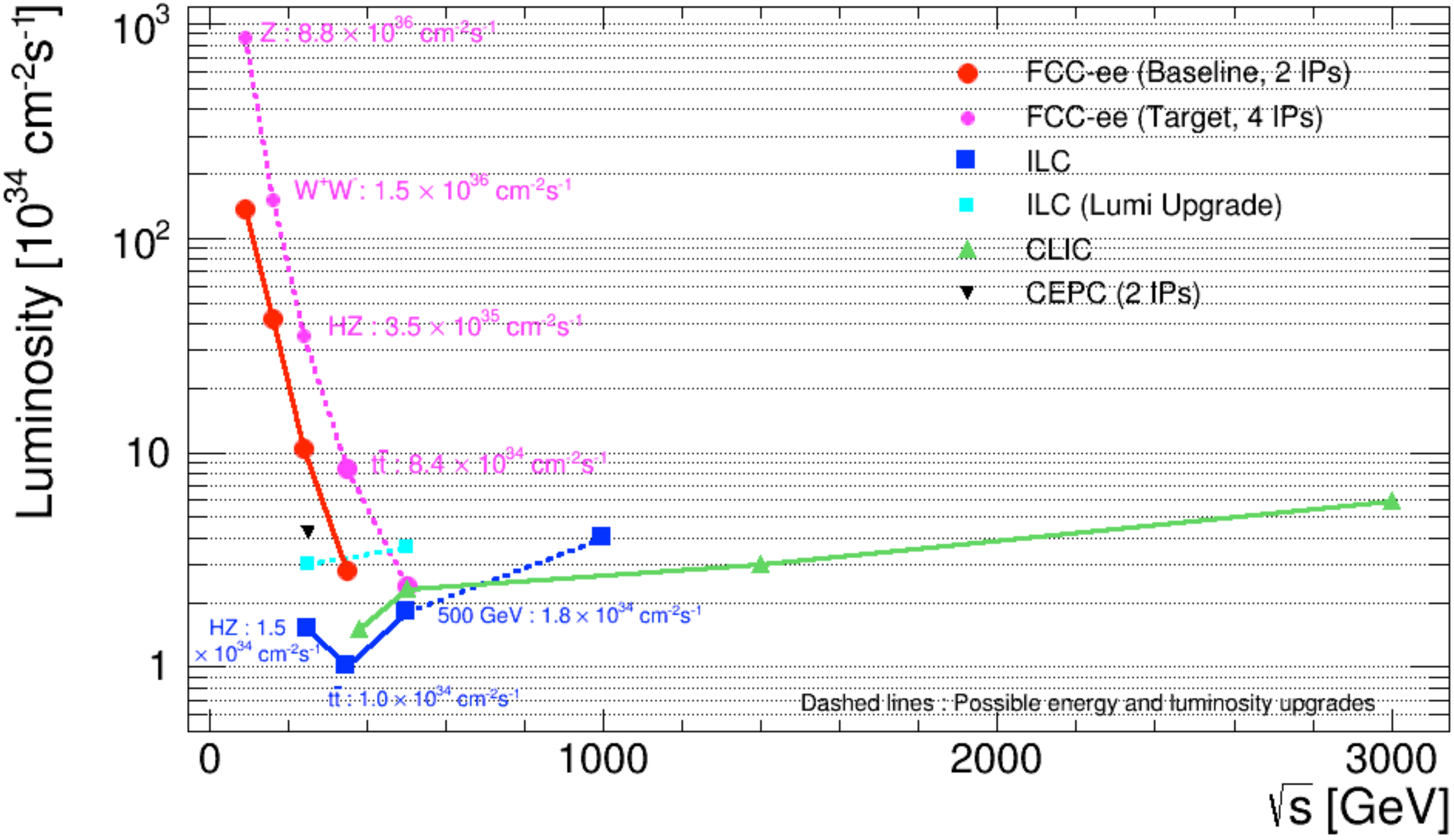
- Example: an $e^+e^- \to W^+W^- \to qq\bar{q}q$ c̄andidate
  - Four jets in the event and nothing else
  - Total energy and momentum are conserved
    - $E_1 + E_2 + E_3 + E_4 = \sqrt{s}$
    - $P_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} = 0$
  - Jet directions ($\beta_i^{x,y,z} = P_i^{x,y,z}/E_i$) are very well measured

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

  - Jet energies (or di-jet masses: m_W) determined analytically by inverting the matrix
    - No systematic uncertainty related to jet energy calibration

A lot of Zs are available anyway to calibrate and align everything

Performance targets for luminosity



Very rich FCC-ee physics programme

Appellation	***Tera-Z***	***Oku-W***	***Mega-Higgs***	***Mega-top***	
$\sqrt{s}$ (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350+ (WW→H)
Lumi [10^{34} cm^{-2}s^{-1}]	880	152	24	10	10
Lumi [ab^{-1}/yr]	88.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}
Target # events	**(10^{12}) 10^{13}**	**10^{8}**	**2×10^{6}**	**10^{6} $t\bar{t}$**	
# years	(0.3) 2.5	1	3	0.5	3

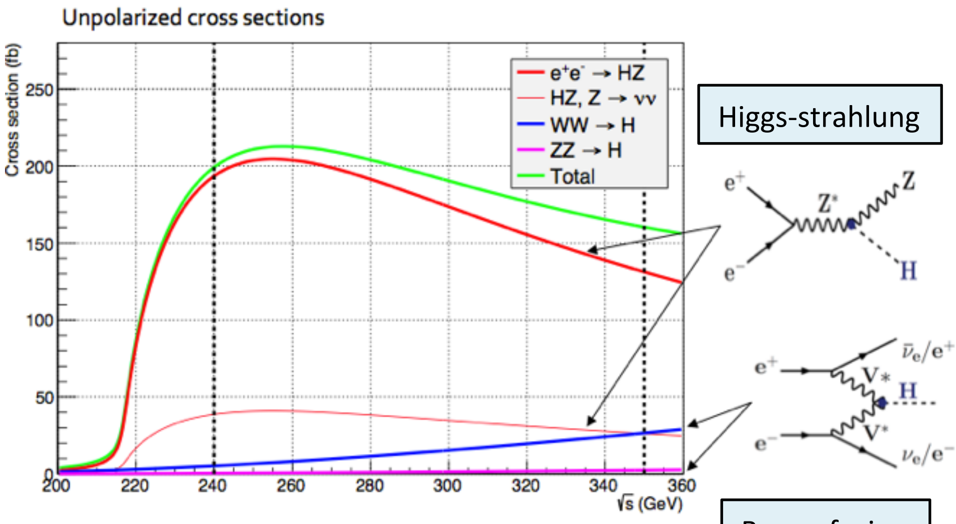
∴ FCC-ee is the ultimate Z, W, Higgs, and top factory!

See arXiv:1308.6176, “First Look at the Physics Case of TLEP”
FCC-ee physics meetings, https://indico.cern.ch/category/5259/

Logically, divide the programme into two main parts:

a. Precision Higgs physics at $\sqrt{s}$ = 240 GeV
b. Precision electroweak physics at $\sqrt{s}$ = 90, 160, and 350 GeV

Precision Higgs physics at FCC-ee (1)



Higgs-strahlung

Boson fusion

Luminosity optimised running point(s)

- Collect 2M HZ events at √s = 240 GeV
- Plus 100k VV → H events at √s ≈ 350 GeV

m_H = 125 GeV

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

Higgs decay modes

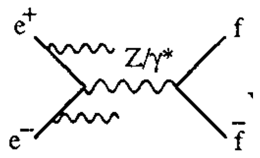
- Determine all Higgs couplings in a model-independent way
- Infer the Higgs total decay width
- Evaluate (or set limits on) Higgs invisible or exotic decays

Measurement of **$\sigma(e^+e^- \to H+X) \times BR(H \to YY)$** for **Y = b, c, g, W, Z, γ, τ, μ, invisible**

Precision Higgs physics at FCC-ee (2)

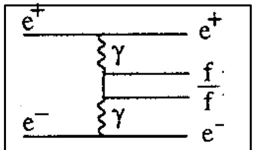
Physics backgrounds are "small"

- For example, at √s = 240 GeV



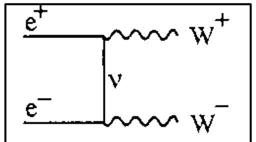
$e^+e^- \to q\bar{q}, l^+l^-$

60 pb



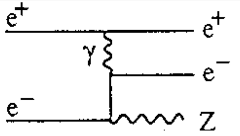
$\gamma\gamma \to qq, l^+l^-$
m > 30 GeV

30 pb



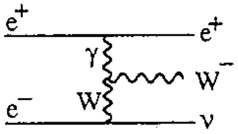
$e^+e^- \to W^+W^-$

16 pb



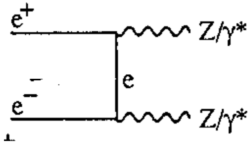
$e^+e^- \to Ze^+e^-$

3.8 pb



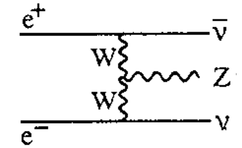
$e^+e^- \to We\nu$

1.4 pb



$e^+e^- \to ZZ$

1.3 pb



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

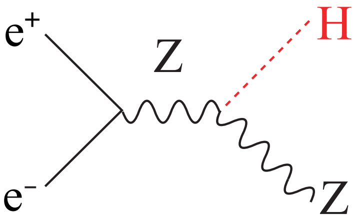
32 fb

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

Add $e^+e^- \to t\bar{t}$
for √s > 340 GeV

0.6 pb

- To be compared to



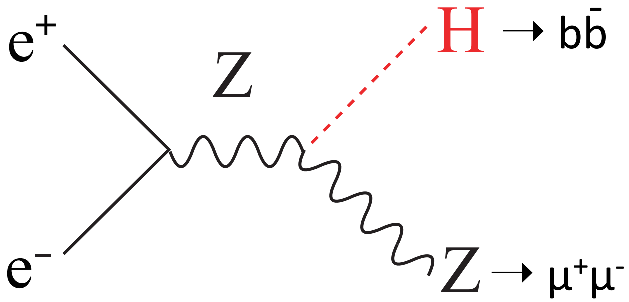
200 fb

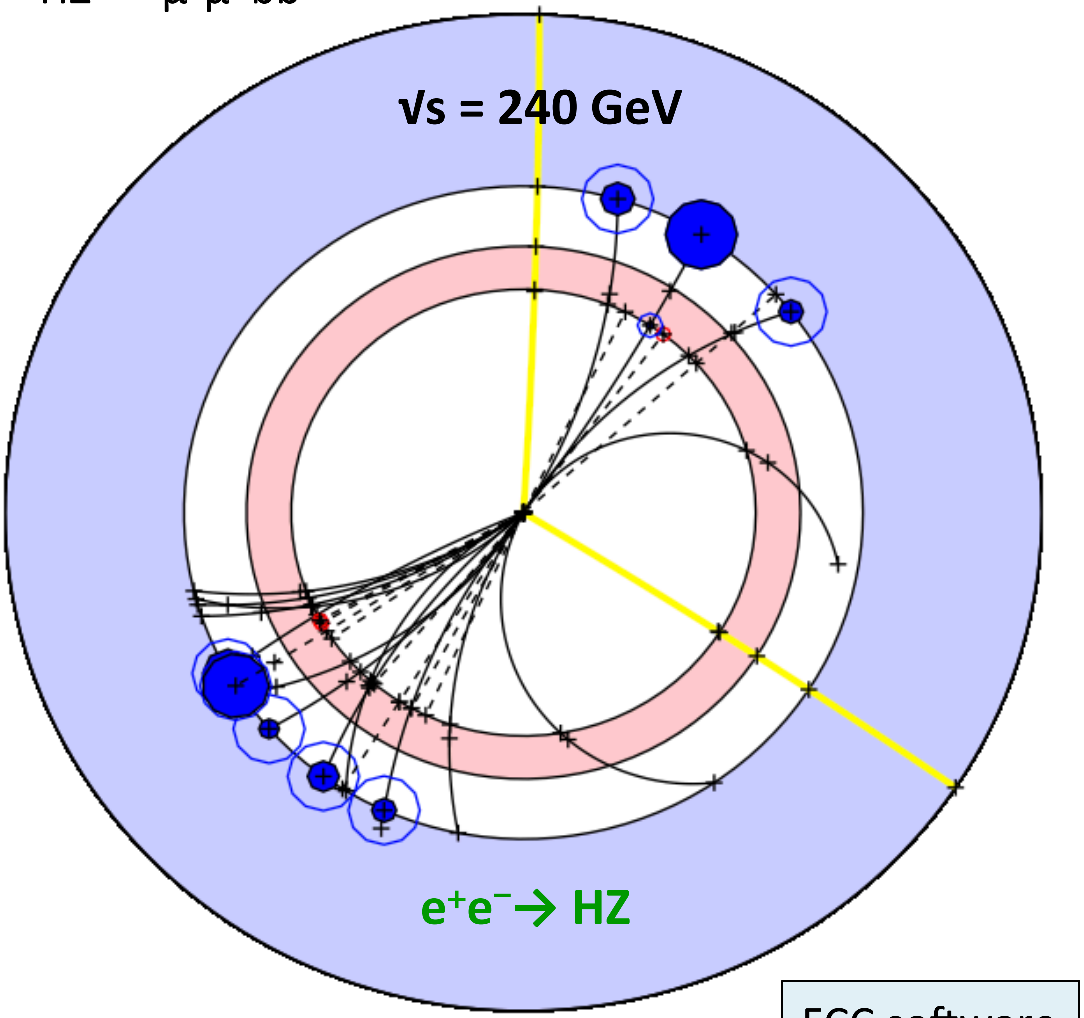
- **Only one to two orders of magnitude smaller**
  - **vs. 11 orders of magnitude in pp collisions**
- **Trigger is 100% efficient**
- **All Higgs events are useful and exploitable**
- **Signal purity is large**

Precision Higgs physics at FCC-ee (3)

Example of a Higgs boson event $e^+e^- \rightarrow HZ \rightarrow \mu^+\mu^- b\bar{b}$

- Tagged with $Z \rightarrow \mu^+\mu^-$
- Very clean signature





FCC software

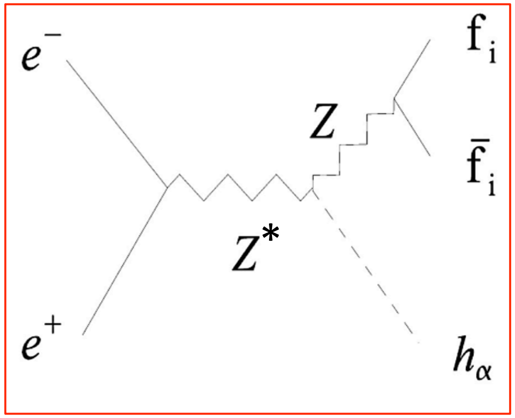
Precision Higgs physics at FCC-ee (4)

Recoil method unique to e^+e^- colliders

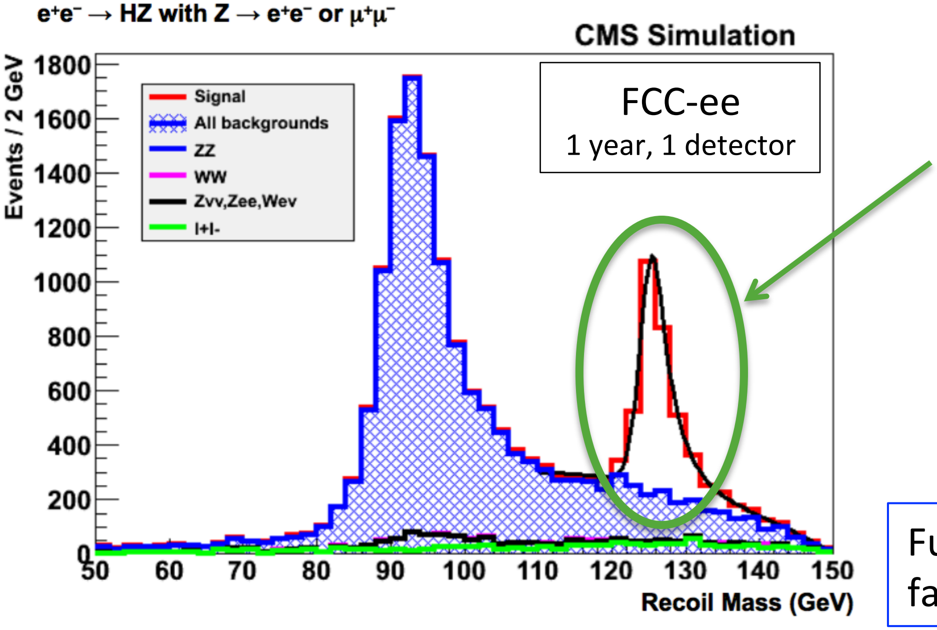
Tag Higgs boson in HZ event by the presence of a $Z \rightarrow e^+e^-, \mu^+\mu^-$

a. Select events with a lepton pair (e^+e^-, $\mu^+\mu^-$) with m_Z compatible mass
  - No requirement on Higgs decay
  - All Higgs decays also ***invisible*** will be selected

b. Apply energy-momentum conservation to determine ”recoil mass”



$$\boxed{m_{recoil}^2 = (\sqrt{s} - E_{ll})^2 - |p_{ll}|^2}$$



c. Plot recoil mass distribution - resolution proportional to momentum resolution

d. From fit, determine number of HZ events, i.e. determine σ_{HZ} x BR($Z \rightarrow e^+e^-, \mu^+\mu^-$)

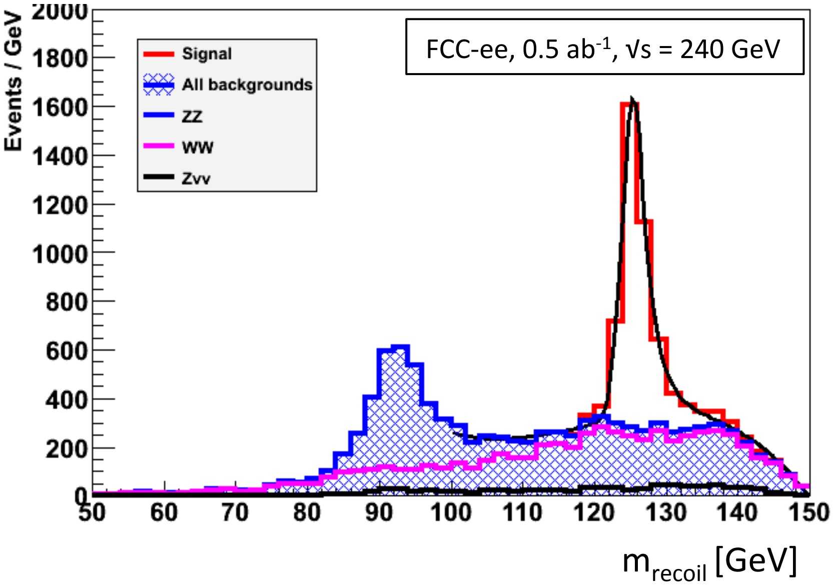
Full simulation studied, so far, using CMS detector

Precision Higgs physics at FCC-ee (5)

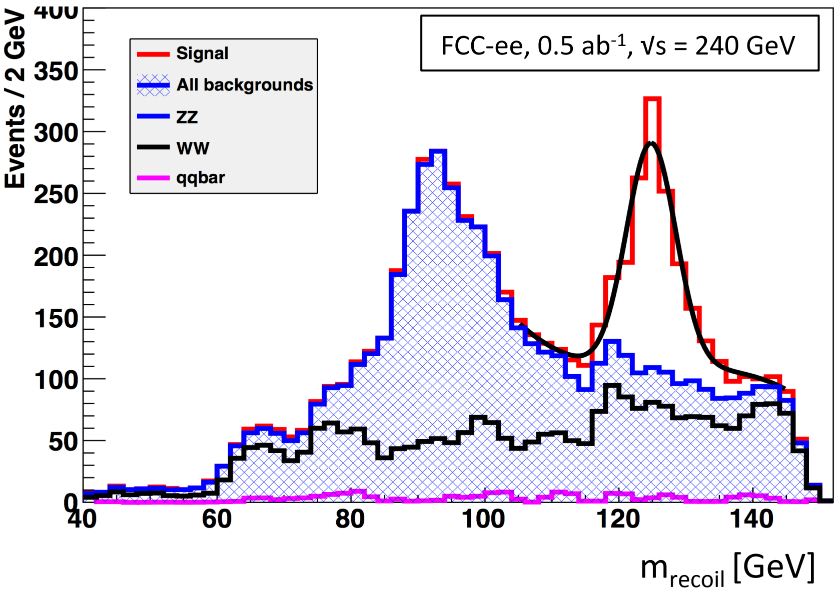
Repeat search in all possible final states

- For all exclusive decays of the Higgs boson: measure σ_{HZ} x BR(H→YY)
  - Including **invisible decays**, just tagged by the presence of the lepton pair & m_{recoil}
  - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics

ZH → l^+l^- + nothing
BR(H→invis) = 100%



H → $\tau^+\tau^-$ with Z → qq

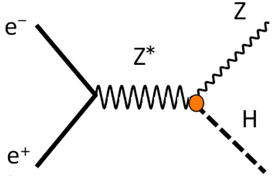


Precision Higgs physics at FCC-ee (6)

Indirect determination of the total Higgs decay width

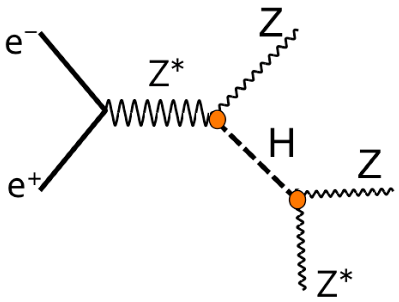
At √s=240 GeV

From the measurement of the total production cross section (slide 10)



$$\sigma_{HZ} \propto g_{HZ}^2$$

From a counting of HZ events with H → ZZ



Final state with three Zs.
Almost background free

- Measure σ_{HZ} x BR(H → ZZ)

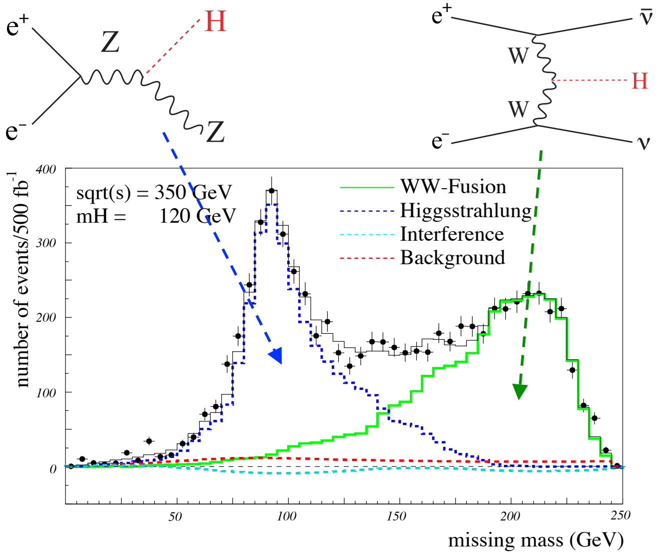
$$\sigma_{HZ} \times BR(H \to ZZ) \propto g_{HZ}^4/\Gamma_H$$

Infer Γ_H from combination of two measurements

$$\Gamma_H \propto \sigma_{HZ} / BR(H \to ZZ)$$

At √s ≥350 GeV

From counting of WW→H→bb events in bbνν final state



- Measure σ(WW →H→bb)
- Take BRs into WW and bb from 240 GeV run
- Infer the total width

$$\Gamma_H \propto \sigma_{W\to W\to bb} / BR(H \to WW) \times BR(H \to bb)$$

Precision Higgs physics at FCC-ee (7)

Summary of precisions

Coupling	HL-LHC	FCC-ee
κ_W	2-5%	0.19%
κ_Z	2-4%	0.15%
κ_b	4-7%	0.42%
κ_c	-	0.71%
κ_τ	2-5%	0.54%
κ_μ	~10%	6.2%
κ_γ	2-5%	1.5%
κ_g	3-5%	0.8%
$\kappa_{Z\gamma}$	~12%	?
BR_{inv}	~10-15%	0.25%
Γ_H	~50% ?	0.9%
κ_t	7-10%	13% (*)
κ_H	77%	80% (*)

(*) indirect

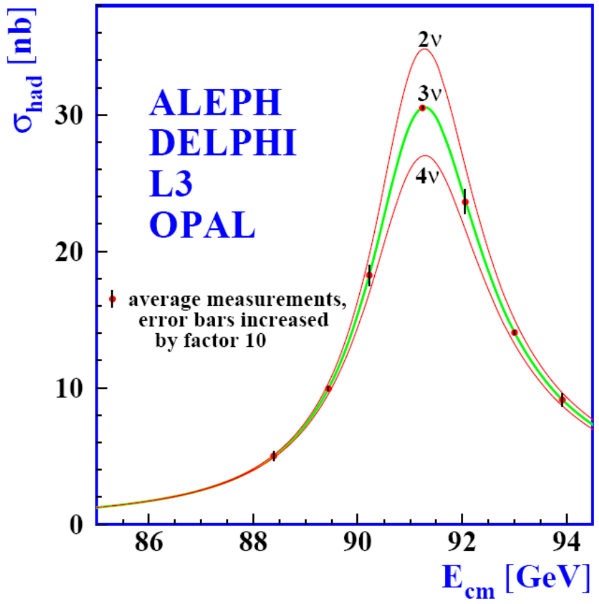
Precision electroweak physics at FCC-ee (1)

Z = atomic clock of HEP
Christophe Grojean

Tera-Z: The Z line-shape measurement

- Repeat the LEP1 programme every few minutes
  - Remember, after 5 years at LEP

$N_\nu = 2.984 \pm 0.008$
$\Gamma_Z = 2495.2 \pm 2.3$ MeV
$m_Z = 91187.5 \pm 2.1$ MeV
$R_l = 20.767 \pm 0.025$
$\alpha_s = 0.1190 \pm 0.0025$



- Predicting accuracies with 300 times smaller statistical precision than at LEP is difficult
  - Conservatively use LEP experience for systematics

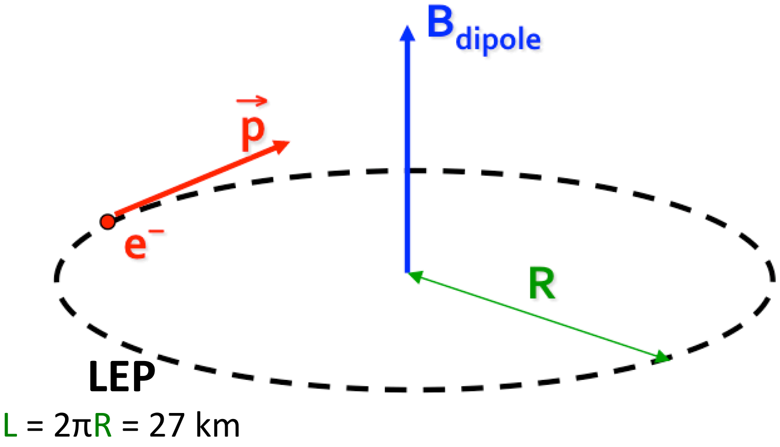
- Example: The uncertainty on E_{beam} (1.5 MeV) was the domnimant uncertainty on m_Z, Γ_Z
  - Can we do significantly better at FCC-ee ?

Precision electroweak physics at FCC-ee (2)

Measurement of the beam energy at LEP

- Ultra-precise measurement unique to circular colliders (crucial for m_Z, Γ_Z)

Electron with momentum **p** in uniform vertical magnetic fiend **B**



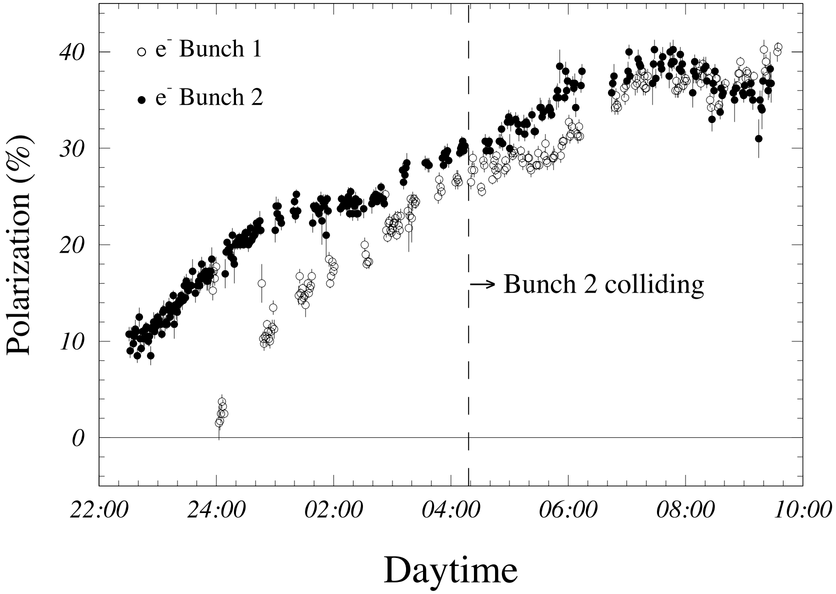
$$E \simeq p = eBR = (e/2\pi)\, BL$$

In real life, B non-uniform, LEP ring not circular

$$\boxed{E = \frac{e}{2\pi} \oint_{\mathrm{LEP}} B\,\mathrm{d}l}$$

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)

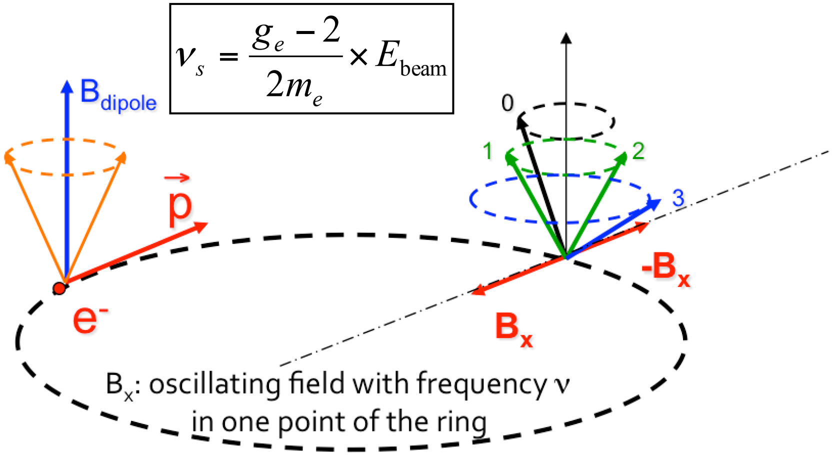
NB. Polarization can be maintained in collisions (was tried only once at LEP)

Precision electroweak physics at FCC-ee (3)

Measurement of the beam energy at LEP (cont'd)

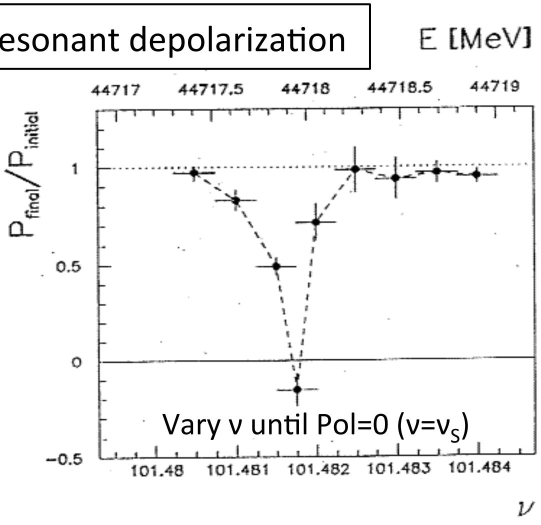
- The spin precesses around **B** with a frequency proportional to |**B**| (Larmor precession)
  - Hence, the number of revolutions ν_S for each LEP turn is proportional to BL (or $\oint$ BdL)

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



B_x: oscillating field with frequency ν in one point of the ring

Resonant depolarization



Vary ν until Pol=0 ($\nu=\nu_S$)

Intrinsic precision of the method: $\Delta E_{\text{beam}} < 100$ keV !

- However, m_Z and Γ_Z measured at LEP with a precision of 2.2 MeV
  - Extrapolation uncertainty from measurement performed w/o collisions

Measurement of the beam energy at FCC-ee

- LEP was colliding 4 bunches of e^+ and e^-; FCC-ee will have 10.000's of bunches.
- Use ~100 "single" bunches to measure E_{beam} with resonant depolarization
  - Measure E_{beam} directly in physics runs
  - Each measurement gives 100 keV precision; no extrapolation uncertainty

m_Z to < 100 keV

Precision electroweak physics at FCC-ee (4)

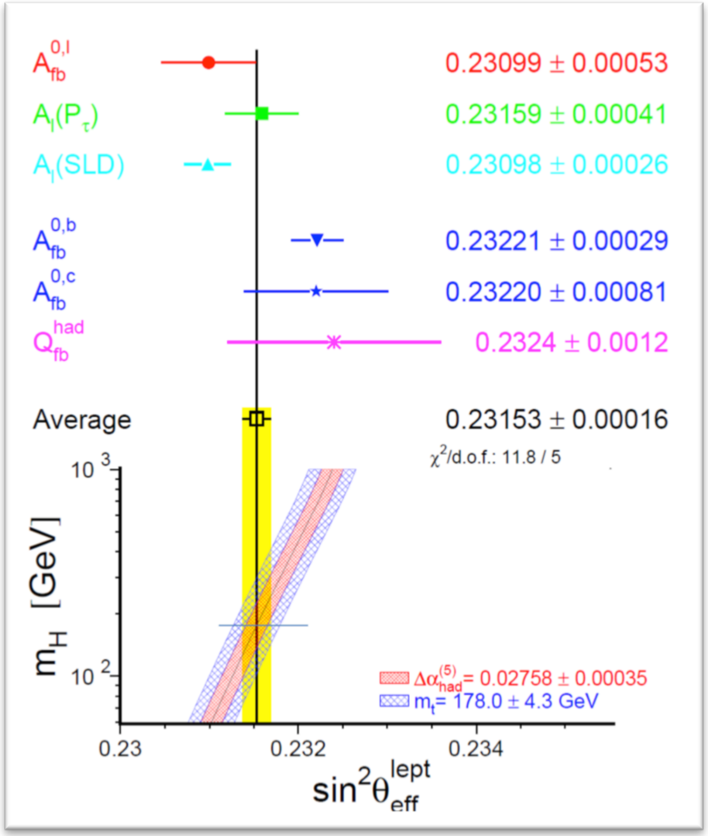
Asymmetries and $\sin^2\theta_W$

- LEP asymmetry measurements dominated by statistics
  - A_{FB}^{ll}, P_τ, A_{FB}^{bb}, A_{FB}^{cc}
- Large precision gain from $O(10^5)$ larger stats.

- Study of $A_{FB}^{\mu\mu}$ alone indicates factor 50 improvement compared to LEP
  - Matching uncertainties from stats. and beam energy syst. (assumed 100 keV)
- Study of $A_{FB}^{0,b}$ alone indicates gain of factor O(10)
- Potential of other asymmetries to be studied
  - e.g. P_τ

- Also, investigate A_{LR} with longitudinally polarized beam option
  - Beam energy calibration influenced by spin rotators?

- Still early days: much interesting work ahead …



Precision electroweak physics at FCC-ee (7)

Tera-Z: Examples of targeted accuracies

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	QED corr.
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g -> bb
N_ν	Peak	2.984 ± 0.008	0.00004	0.004	Lumi meast.
$A_{FB}^{\mu\mu}$	Peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meast.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.000001	0.00015	New Physics
$1/\alpha_{QED}(M_Z)$	$A_{FB}^{\mu\mu}$ around peak	128.952 ± 0.015	0.004	0.002	EW corr.

Experimental uncertainties mostly of systematic origin

- So far, mostly conservatively estimated based on LEP experience
- Work ahead to establish more solid numbers

Precison electroweak physics at FCC-ee (8)

Opportunities for direct searches for **new physics** through **rare decays**

- **10^{12} (10^{13}) Z, 10^{11} b, c or τ** : A fantastic potential that remains to be explored
- e.g, search for heavy “sterile” neutrino in Z decays

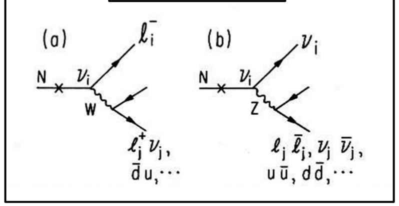
$$\nu_L = \nu \cos\theta + N \sin\theta$$

Light “normal” neutrino

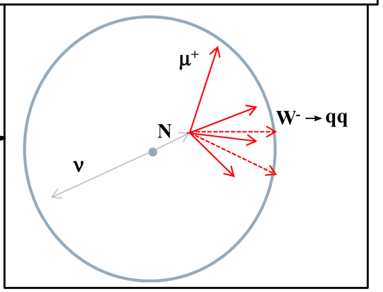
Heavy “sterile” neutrino

$Z \rightarrow N \nu_i$, with $N \rightarrow W^* l$ or $Z^* \nu_j$

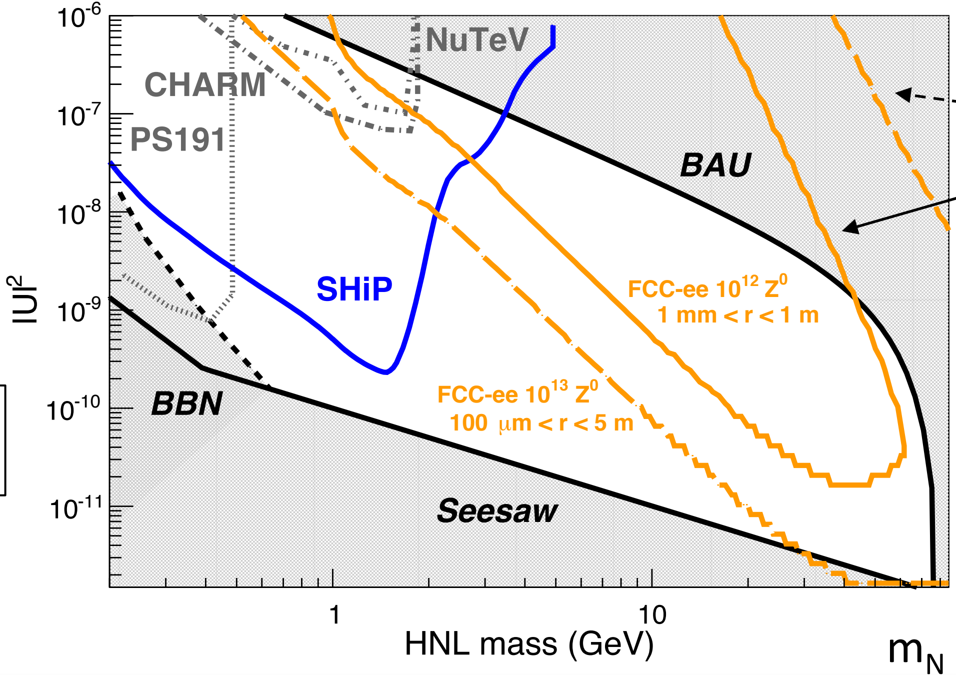
N decays



Signature: Detached vertex

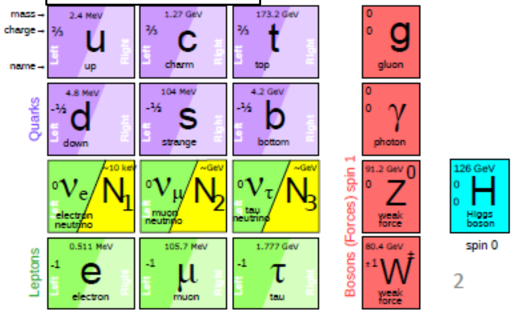


Inverted hierarchy



Mixing between N and ν

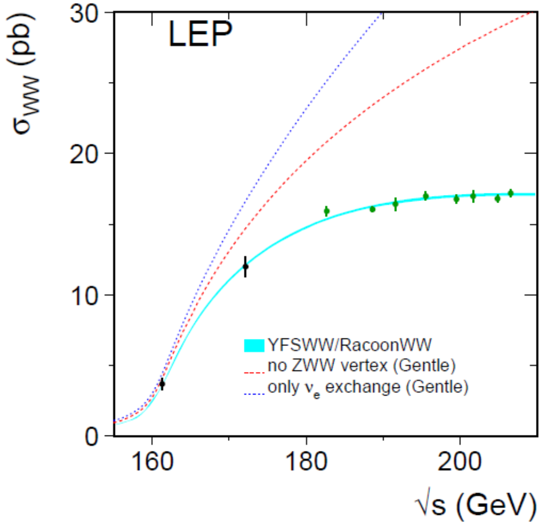
νMSM model



Precision electroweak physics at FCC-ee (9)

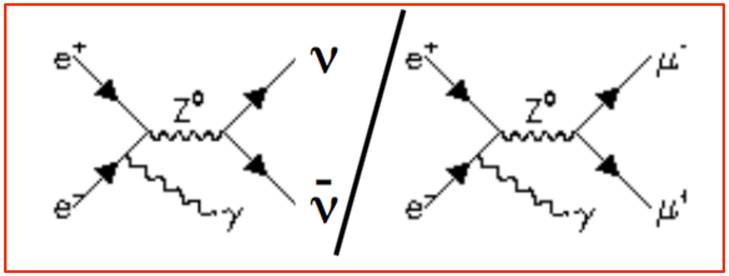
Oku-W: 10^8 WW events at production threshold

Measurement of the W mass
with cross section at threshold



Measurement of the number of neutrinos
(with single photon events)

$$N_\nu \sim \sigma(e^+e^- \to \nu\bar{\nu}\gamma) / 2\sigma(e^+e^- \to \mu^+\mu^-\gamma)$$



m_W to < 500 keV!

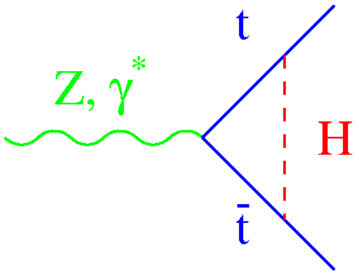
Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_W (MeV)	Threshold scan	80385 **± 15**	**0.3**	**< 0.5**	QED Corr.
N_ν	Radiative returns $e^+e^- \to \gamma Z, Z\nu\nu, ll$	2.92 **± 0.05** 2.984 **± 0.008**	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 **± 0.27**	**0.00018**	**< 0.00015**	CKM Matrix

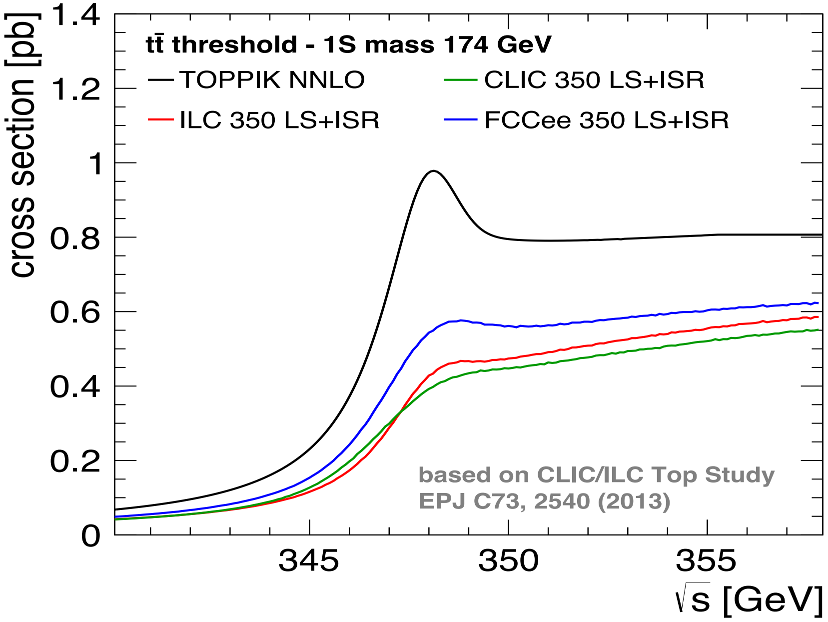
Precision electroweak physics at FCC-ee (10)

Mega-top: a million $t\bar{t}$ events at threshold

- Measure top quark mass and width
  - From cross section at threshold
    - No beamstrahlung systematics
- Measure the top Yukawa coupling
  - From top polarisation measurement

    (c.f. tau polarisation measurement at LEP)





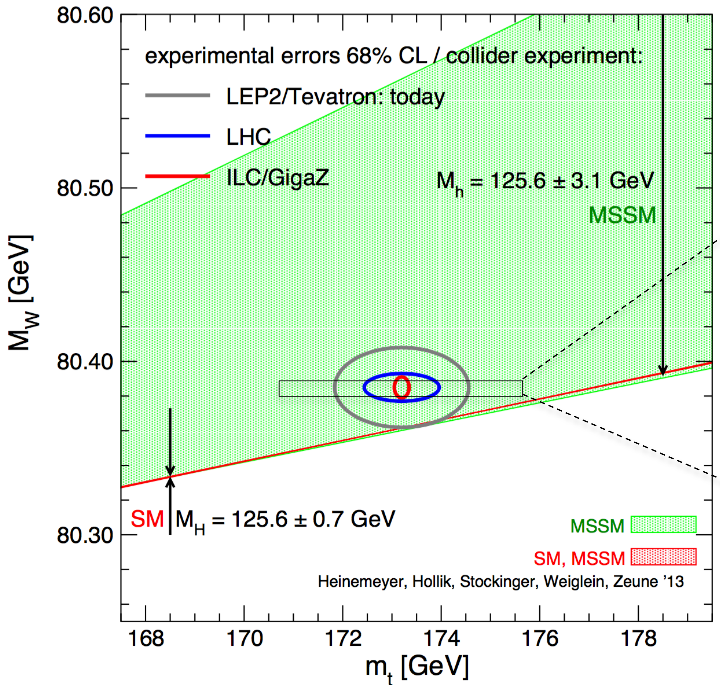
based on CLIC/ILC Top Study
EPJ C73, 2540 (2013)

m_{top} to 10 MeV!

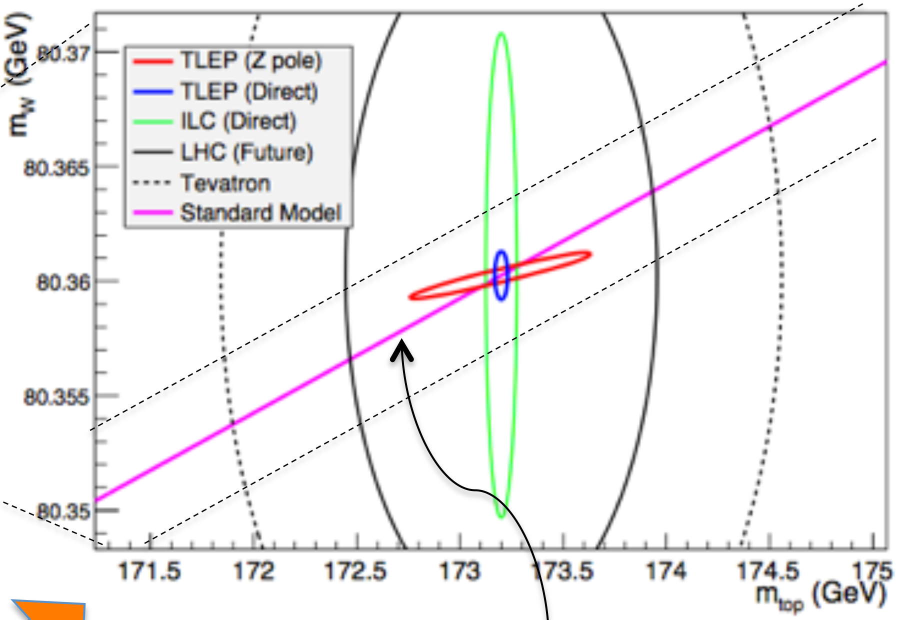
Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_{top} (MeV)	Threshold scan	173200 **± 900**	**10**	**10**	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	**?**	**12**	**?**	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	m = 2.5 **± 1.05**	**13%**	**?**	$\alpha_s(m_Z)$

Precision electroweak physics at FCC-ee (11)

Standard Model has no free knobs left to turn:
=> Any deviations between measurements would point to **New Physics**



If theory uncertainties match exp'tal uncertainties



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

Presence of New Physics could dramatically change this picture

Selected FCC-ee Beam Parameters

Baseline design	**LEP2**	**FCCee-Z**	**FCCee-W**	**FCCee-H**	**FCCee-t**
Beam energy E_b [GeV]	104.5	45.5	80	120	175
Circumference [km]	26.7	100	100	100	100
Beam current [mA]	4	1450	152	30	6.6
SR power total [MW]	22	100	100	100	100
No. bunches/beam	4	90300	5192	770	78
No. e^- per bunch [10^{11}]	6	0.33	0.6	0.8	1.7
Horizontal emittance [nm]	48	0.09	0.27	0.61	1.3
Vertical emittance [pm]	250	1.0	1.0	1.2	2.5
β^*_x [m]	1.5	1	1	1	1
β^*_y [mm]	50	2	2	2	2
σ^*_x [µm]	270	9.5	16	25	36
σ^*_y [nm]	3500	45	45	51	72
L/IP [10^{34} cm^{-2}s^{-1}] (2 IPs)	0.0125	68	19	4.9	1.3
Beam lifetime [min] (2 IPs)	360	247	109	78	63

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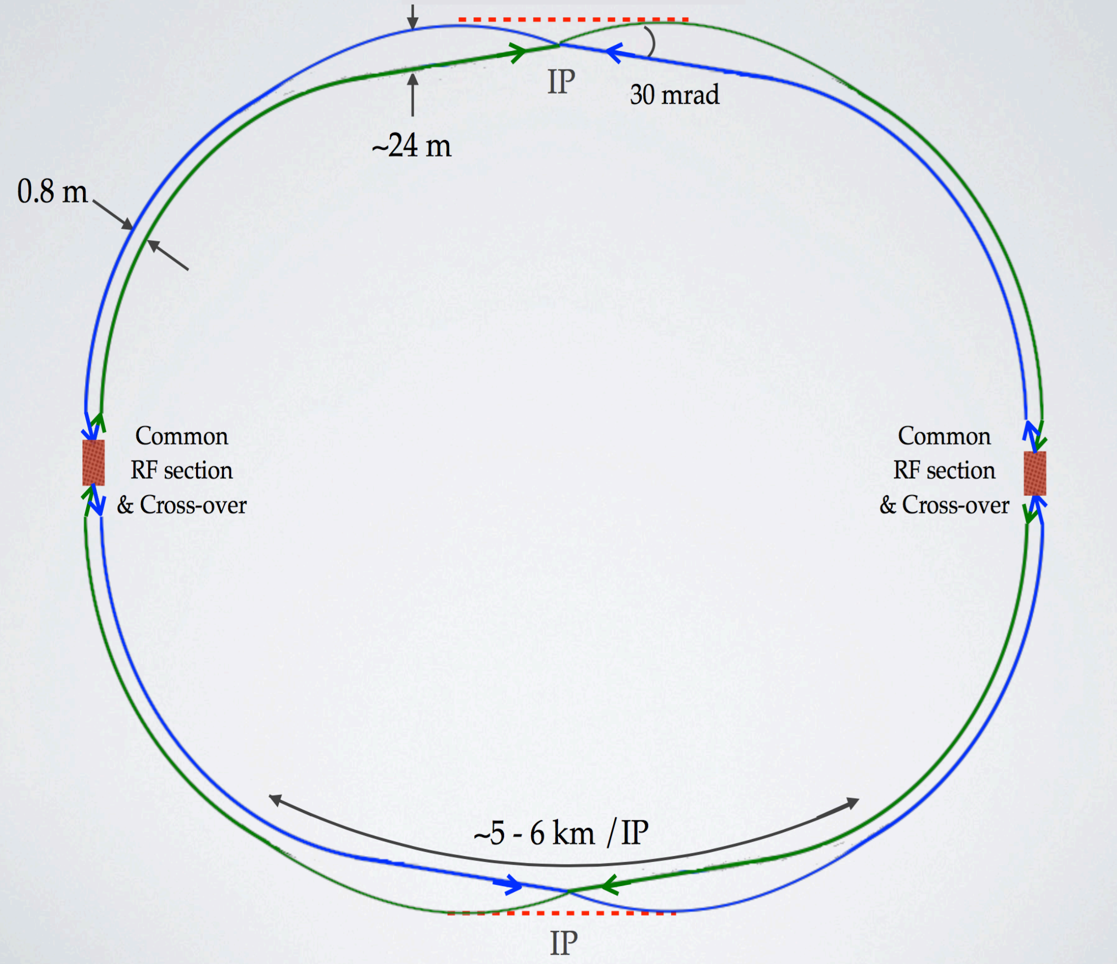
Bunch crossing time down to 3 ns

Very strong vertical focussing

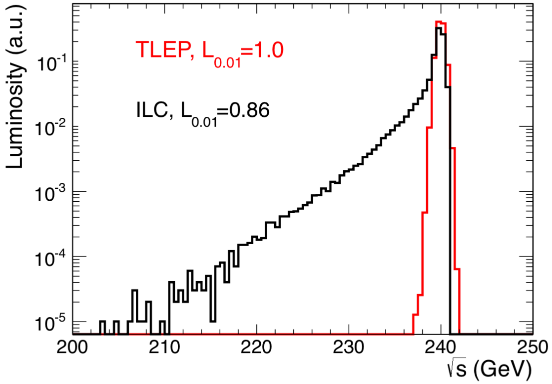
FCC-ee accelerator layout



Of particular importance for experiments

- 30 mrad beam crossing angle
  - Avoid parasitic crossings
- No bending of beams before crossing, only after
  - Minimize synchrotron radiation through interaction region
  - $P_{SR} < 1$ kW within 250 m from IP
  - $E^{\gamma}_{crit} < 100$ keV - minimize neutron production

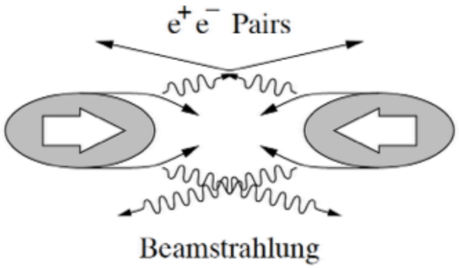
FCC-ee experimental conditions



Sharp beam-energy profile

- Beams are circulating, *i.e.* have to be reusable after collision
  - Non-destructive focusing and collision
  - Beam-beam interactions have to be kept at a minimum

Low beamstrahlung background (study for √s = 90 GeV)



- On average 4000 e^+e^- pairs created per BX
- Carry total energy of ~1 TeV (400 x less that at ILC500)
- Vertex detector layer at R = 10 mm would receive a tolerable 1.5 hit / BX / cm^2

No underlying events; No pile-up

- Running conditions most "extreme" at Z peak:
  - ~**100 kHz of Zs**
  - ~**200 kHz** of small angle elastic e^+e^- (Bhabha) scattering - normalisation
  - Compare to **300 MHz** beam-crossing rate

Only 1:1000 bunch-crossings will have an interaction: **μ = 0.001**

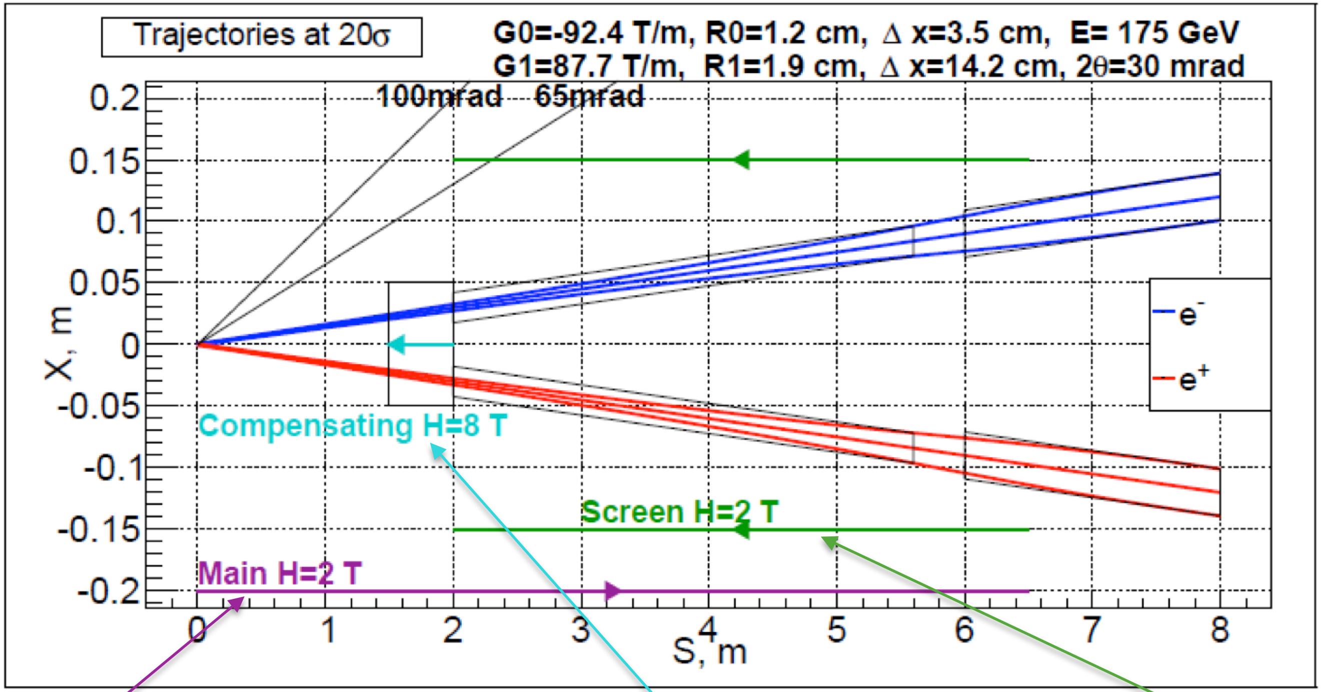
Interaction Region design (1)

The Interaction Region is complicated

- Very strong focussing; low β* (2 mm)
  - Small distance between IP and first quadupole: L* ≃ 2 m
    - Final-focus magnets will be located inside the detector volume
- Beams cross at an angle of 30 mrad
  - Beams traverse detector volume at 15 mrad w.r.t. experimental B-field
    - Beam particles receive vertical kick; emittance blow-up
- Shielding/compensation needed
  a. Final-focus magnets need to be shielded from the main experimental solenoid
  b. Compensating magnets are needed in order to "undo" the effect of experimental B-field
- Small angle region is very busy
  - Need to understand backscattering of beamstrahlung and synchrotron radiation from heavy machine elements close to IP
  - Need to find space for instrumentation at small angles
    - **Luminosity monitors,…**

Interaction Region design (2)

Interaction region magnet system layout principle



Assumed here:: +2 Tesla detector main field

Compensation for beam path through detector:
-8 Tesla over one quarter of path

Screening quadrupole: -2 Tesla

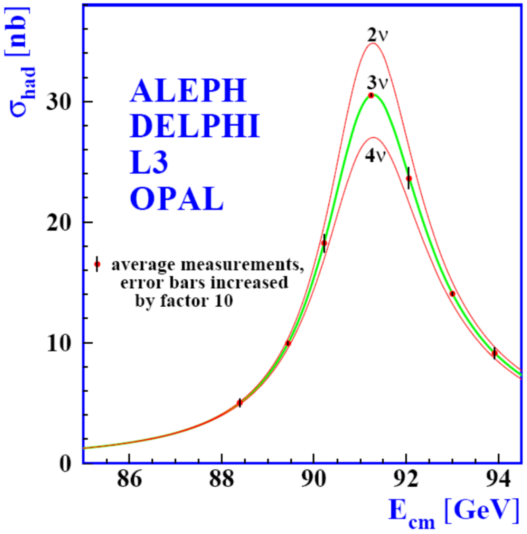
Very strong influence of solenoid edges on vertical emittance

- May in the end put an effective limit on the strength of the detector field

Luminosity measurement (1)

Luminosity measurement needed for normalization of all cross section measurements

- Most prominent example: Z line shape
  - Relative luminosity: energy-point to energy-point (m_Z)
  - Absolute luminosity: cross section measurement at Z pole
- LEP luminosity uncertainty (OPAL): **$\delta L/L = 6.4 \times 10^{-4}$**
  - Luminosity contribution important for e.g. N_ν measurement

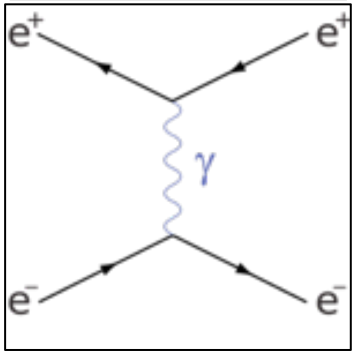


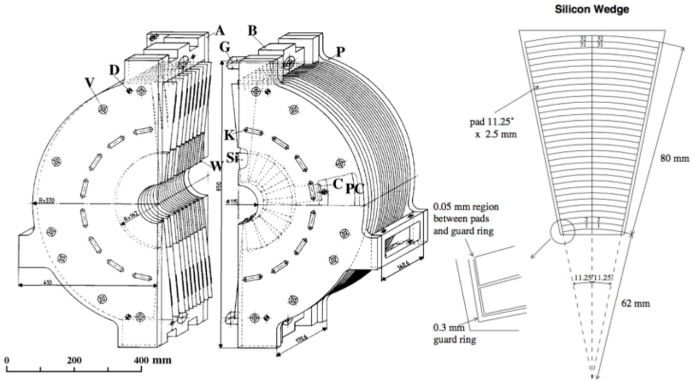
$$\boxed{N_\nu = 2.984 \pm 0.008} \quad \left\{ \begin{array}{l} \text{lumi theo: } \delta N_\nu = 0.004 \\ \text{lumi expt: } \delta N_\nu = 0.002 \end{array} \right.$$

Luminosity determined via small angle elastic $e^+e^- \longrightarrow e^+e^-$ scattering

- Bhabha scattering is very strongly forward peaked ($1/\theta^2$)
  - Requires a **small and very precisely known value of θ_{min}**
- Measured with a set of two detectors, one at each side of IP

Bhabha scattering





Example LEP (OPAL):

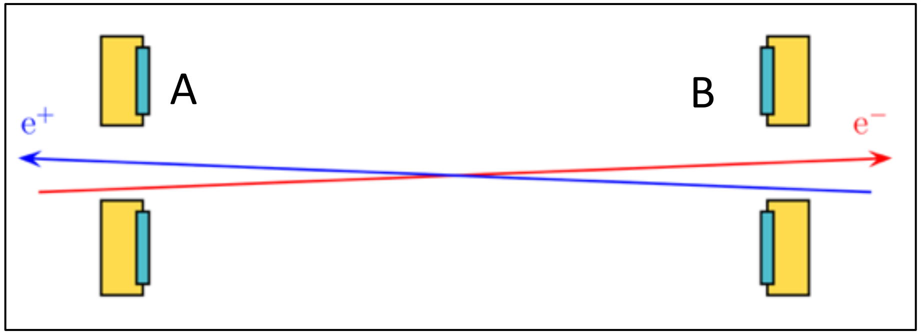
- Tungsten/silicon calorimeters
- Geometry controlled to better than 10 μm
- Systematic: **$\Delta L/L = 3.4 \times 10^{-4}$**

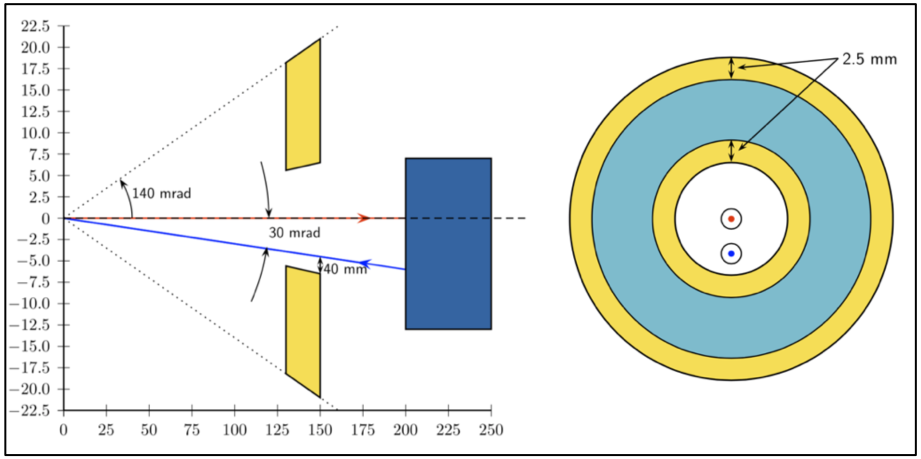
Luminosity measurement (2)

FCC-ee luminosity measurement

- **Beam crossing angle**: center monitors around the outgoing beams
- To eliminate first order dependence on beam parameters, need tight and looser fiducial volume:

Acceptance = tightA ∩ looseB + tightB ∩ looseA





FCC-ee (ambitious) target: **10^{-4} level**

Luminosity measurement – main differences w.r.t. LEP:

- Small angle area is very busy; monitors get pushed closer to IP (2500 mm ➞ 800 -1500 mm)
  - Need for mechanical precision approaching 1 μm (!)
- Beam crossing angle of 30 mrad
  - harder to get close to outgoing beam and match Bhabha rate to Z rate

Interaction region layout study

Recently formed: **Machine Detector Interface Working Group**

- Study the integration of beams, machine elements and detectors
- Come up with a plausible interaction region design

Topics

a. Synchrotron radiation and masking
b. Other accelerator backgrounds
c. Magnetic integration
d. Luminosity measurements and other desired particle detectors…

Detector Requirements

The FCC-ee physics programme is very broad.
With multiple IPs (up to 4) there is room for different design emphasis.
One could think of at least two major options:

- **Precision physics** & **new physics searches**

Higgs Precision Physics

Excellent energy/momentum resolution for e, μ, jet

- Z tagging via μμ, ee
- Possibility to use Z → qq tag for for several h final states (h→ invisible)
- Rare Higgs decay modes: μμ, γγ, ZZ, invisible

Excellent flavour tagging:

- Separation of Higgs to bb, cc, gg

EW Precision Physics

Extremely precise definition of **fiducial volumes** for signal and normalization.

This includes

- geometry: precise borders, no cracks
- momentum/energy: no bias

New Physics Searches

Detached vertices over a large lifetime range

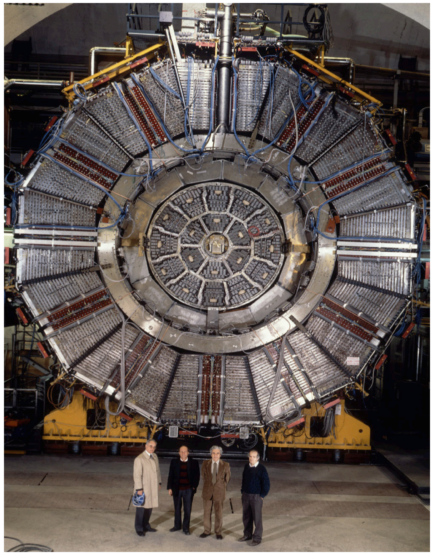
- Large radius tracking volume
- Excellent primary/secondary vertex resolution and flavour tagging

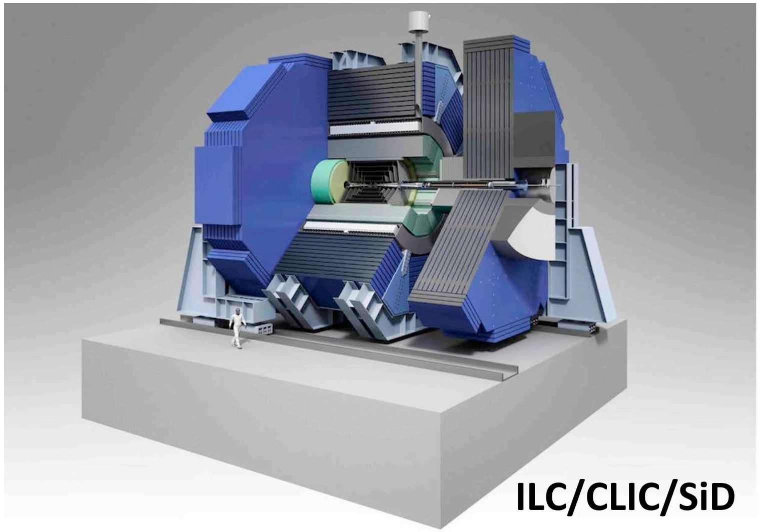
No escaping particles: Hermiticity

Detectors for FCC-ee (1)

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





ILC/CLIC/SiD

Detectors must have the ability to collect 100 kHz of Z decays, with 100% efficiency

… and be able to repeat the whole LEP1 programme in about two minutes.

Inspiration should come from LHC detector upgrades and DAQ systems.

Physics differences between linear collider and FCC-ee case

- Lower maximum energy – 400 vs. 1000 GeV
  - Momentum resolution, energy resolution, calorimeter depth
- Higher statistics: matching systematics – have to under acceptance to better than $1/\sqrt{N}$

Technical differences between linear collider and FCC-ee case

- Extremely high physics rate – 100 kHz Zs: DAQ
- Continuous running (no bunching of beams): cooling issues
- Machine Detector Interface

Detectors for FCC-ee (2)

Start design effort with a linear collider detector

B-field: Possibly weaker (~2 T)

- Accelerator constraint
  - Beam crossing angle
- Lower max momentum

Calorimetry

- Jet energy (1/3 x LEP)

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

Momentum: (1/10 x LEP)

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

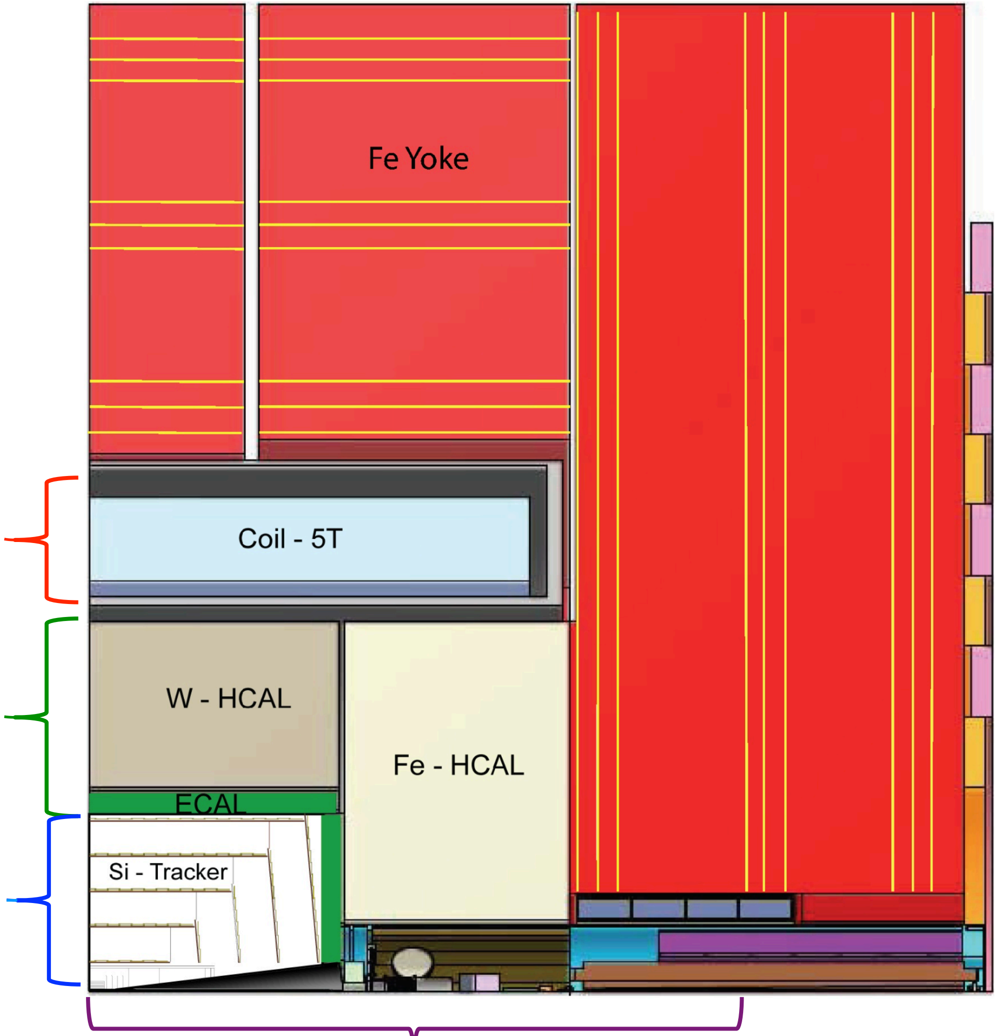
Impact parameter: (1/3 x SLD)

- e.g. b/c-tagging

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

Hermetic: down to θ = 5 mrad

CLIC - SiD

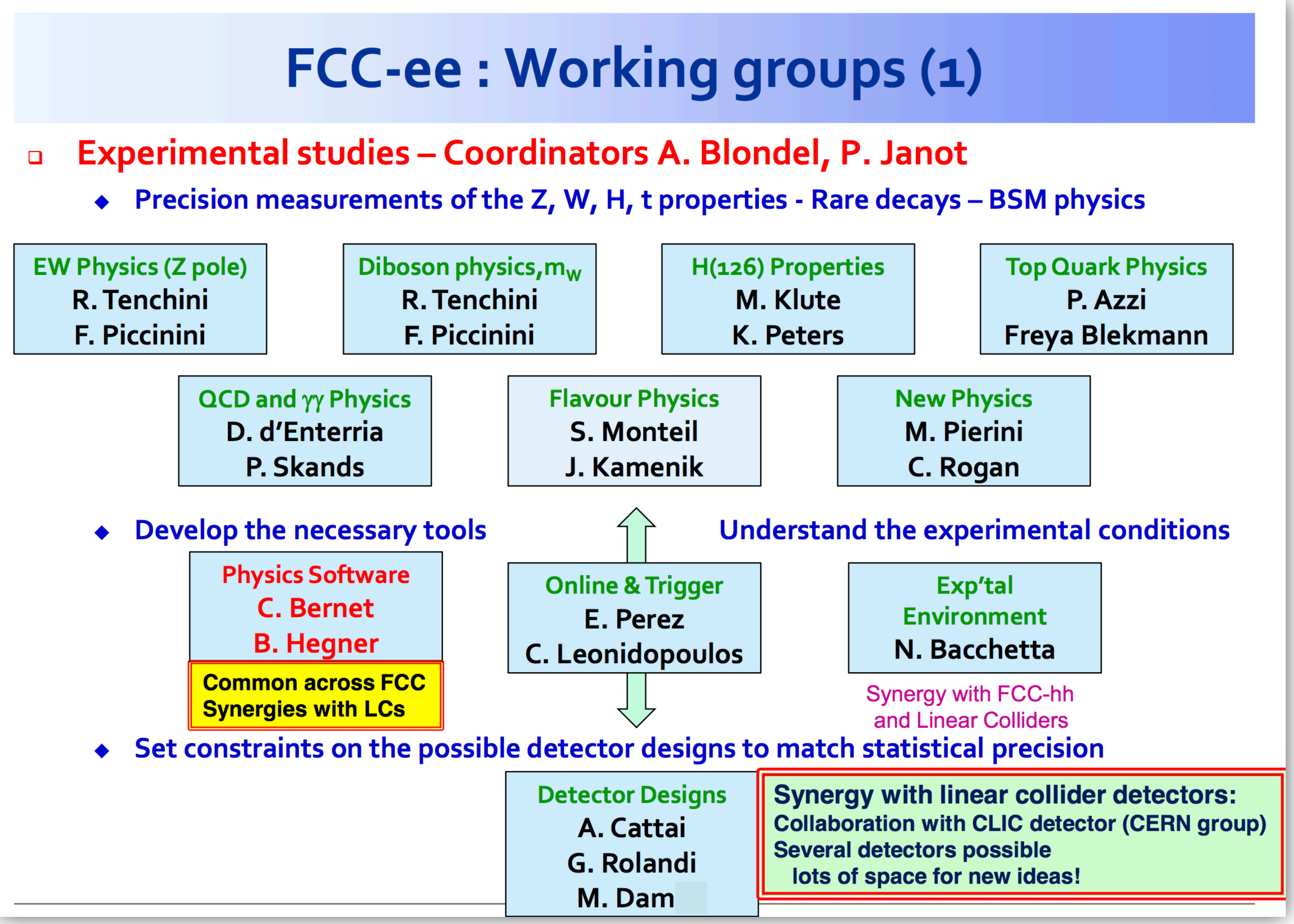


Summary

- FCC-ee has a very rich and diverse physics programme
  - Possibly several detector options with focus on different aspects
- Ambitious luminosity goal of especially FCC-Z dictates very high BX rates
  - Down to 3-5 ns; However, no pileup: $\mu \simeq 0.001$
- Optics exist with realistic synchrotron levels in detector regions
  - Masking work can begin
- Low beamstrahlung background
  - Small CM energy spread
  - Possible to place 1st VXD layer very close to beam line
- Very challenging Interaction Region design
  - 30 mrad beam X'ing angle; $L^* \simeq 2.0$ m
  - Beams cross detector B-field at an angle of 15 mrad: Need compensation
    - May eventually lead to a limit on the detector field(?)
  - Space for very forward instrumentation limited
    - Luminosity measurement, hermiticity
- Look to ILC (and LEP) for overall detector design. Differences wrt ILC
  - Continuous running / no pulsing: Power consumption / Cooling
  - Factor three lower energy reach
    - Relaxed requirements for momentum resolution(?), calorimeter depth and resolution(?)
- Much interesting and important work ahead
  - Many opportunities to contribute

Backup…

Organization of the experimental studies



FCC-ee : Working groups (1)

- Experimental studies – Coordinators A. Blondel, P. Janot
  - Precision measurements of the Z, W, H, t properties - Rare decays – BSM physics

EW Physics (Z pole)
R. Tenchini
F. Piccinini

Diboson physics, m_W
R. Tenchini
F. Piccinini

H(126) Properties
M. Klute
K. Peters

Top Quark Physics
P. Azzi
Freya Blekmann

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

Flavour Physics
S. Monteil
J. Kamenik

New Physics
M. Pierini
C. Rogan

- Develop the necessary tools

Understand the experimental conditions

Physics Software
C. Bernet
B. Hegner

Common across FCC
Synergies with LCs

Online & Trigger
E. Perez
C. Leonidopoulos

Exp'tal Environment
N. Bacchetta

Synergy with FCC-hh
and Linear Colliders

- Set constraints on the possible detector designs to match statistical precision

Detector Designs
A. Cattai
G. Rolandi
M. Dam

Synergy with linear collider detectors:
Collaboration with CLIC detector (CERN group)
Several detectors possible
lots of space for new ideas!

Precision electroweak physics at FCC-ee (5)

Direct $\alpha_{QED}(m_Z)$ measurement

For exploitation of precision EW measurements, need precise knowledge of $\alpha_{QED}(m_Z)$

- Standard method involves extrapolation from $\alpha_{QED}(0)$ to $\alpha_{QED}(m_Z)$
  - Dispersion integral over hadronic cross section – low energy resonances: **$\delta\alpha/\alpha = 1.1 \times 10^{-4}$**

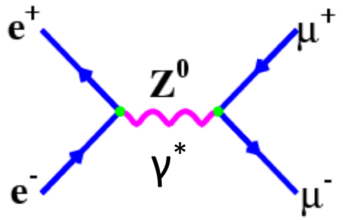
$$\boxed{\alpha^{-1}_{QED}(m_Z) = 128.952 \pm 0.014}$$

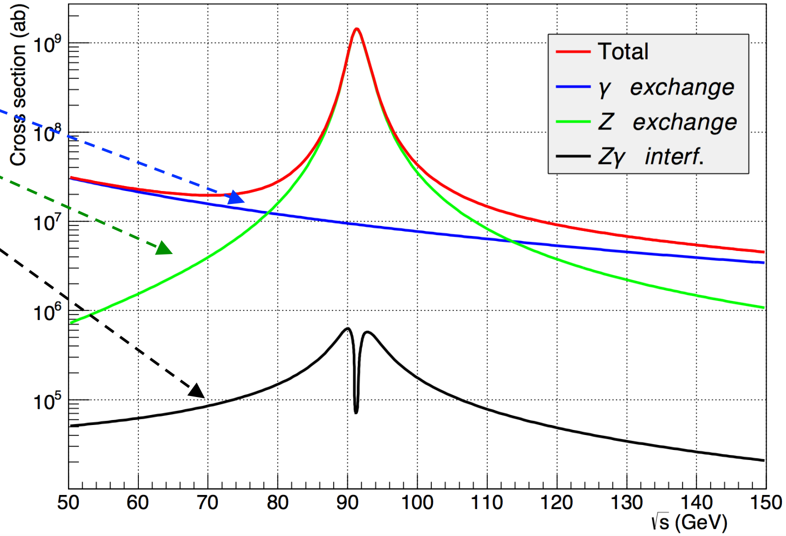
New idea: exploit large statistics of FCC-ee to **measure $\alpha_{QED}(m_Z)$ directly close to m_Z**

- Extrapolation error becomes negligible!

Two methods considered: Meast. of cross section, $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, and asymmetry, $A_{FB}^{\mu\mu}$

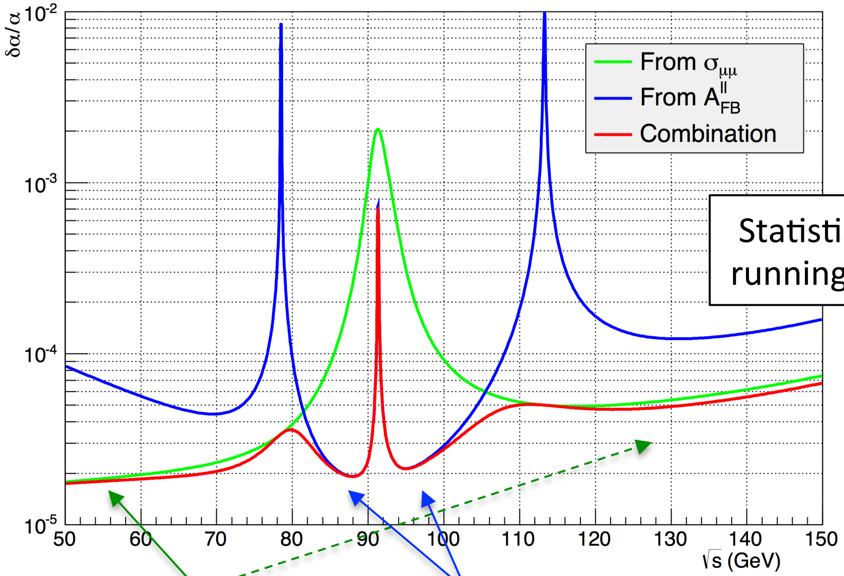
- γ exchange proportional to $\alpha^2_{QED}(\sqrt{s})$
- Z exchange independent of $\alpha_{QED}(\sqrt{s})$
- γZ interference proportional to $\alpha_{QED}(\sqrt{s})$





Precision electroweak physics at FCC-ee (6)

Direct $\alpha_{QED}(m_Z)$ measurement (cont'd)



Statistical uncertainty for one year of running at any centre-of-mass energy.

From $\sigma_{\mu\mu}$ measurement

- Sensitivity best "far" away from Z peak, particularly at the low side
- Systematics (normalisation) probably a killer

From $A_{FB}^{\mu\mu}$ measurement

- Sensitivity best at points $\sqrt{s}$ = 87.9 and 94.3 GeV
- Theoretical systs. largely cancel by "averaging" over 87.9 and 94.3 GeV points.
  - Higher order EW to be calculated (few x 10^{-4})
- Experimental systs. controlable; dominant contribution from knowledge of E_{BEAM}: **1 x 10^{-5}**

By running six months at each of 87.9 and 94.3 GeV points:

➢ Potential to reach a precision of : **$\delta\alpha/\alpha = 3 \times 10^{-5}$**

FCC-ee Physics Programme

See arXiv:1308.6176, “First Look at the Physics Case of TLEP”
FCC-ee physics meetings, https://indico.cern.ch/cetegory/5259/

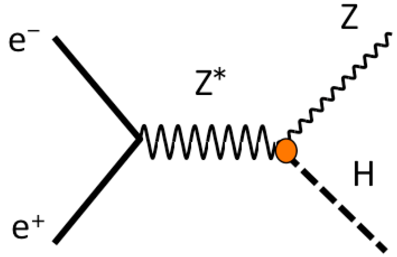
A very rich physics menu!

- Core physics programme
  - The Z pole scan, √s=88-95 GeV
    - m_Z, Γ_Z to < 100 keV, $\sin^2\theta_W$ to 5x10^{-6}, $\alpha_{QED}(m_Z)$ to 2x10^{-5}, $\alpha_s(m_Z)$ to 2x10^{-4}, …
    - Rare decays/process searches and flavour physics with up to 10^{13} Z decays
  - The WW threshold scan, √s=160-165 GeV
    - m_W to 300 keV, $\alpha_s(m_Z)$ to 2x10^{-4}, …
  - The Higgs factory, √s=240 GeV and above
    - Improve HL-LHC precision on Higgs couplings by an order of magnitude
    - Measure the Higgs width to better to 1%, and BR_{invis} to 0.1%
  - The top threshold scan, √s=340-350 GeV
    - m_{top} to 10-20 MeV
  - Set constraints on new physics scale to 100 (10) TeV if weakly (Higgs) coupled
    - Possibly discover very-weakly-coupled new physics through rare processes

Well matched to FCC-hh discovery range

- And also…
  - Top electroweak couplings at √s=365-370 GeV (as part of the top threshold scan)
  - The Hee coupling at √s=120 GeV
  - The highest centre-of-mass energy √s=500 GeV (physics case?)

Precision Higgs physics at FCC-ee (4)

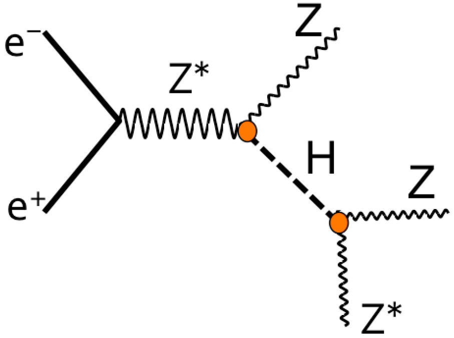


Indirect determination of the total Higgs decay width

a. From the measurement of the total production cross section (slide 10)

$$\sigma_{HZ} \propto g_{HZ}^2$$

b. From a counting of HZ events with H → ZZ
   - Measure σ_{HZ} x BR(H → ZZ)



Final state with three Zs
Almost background free

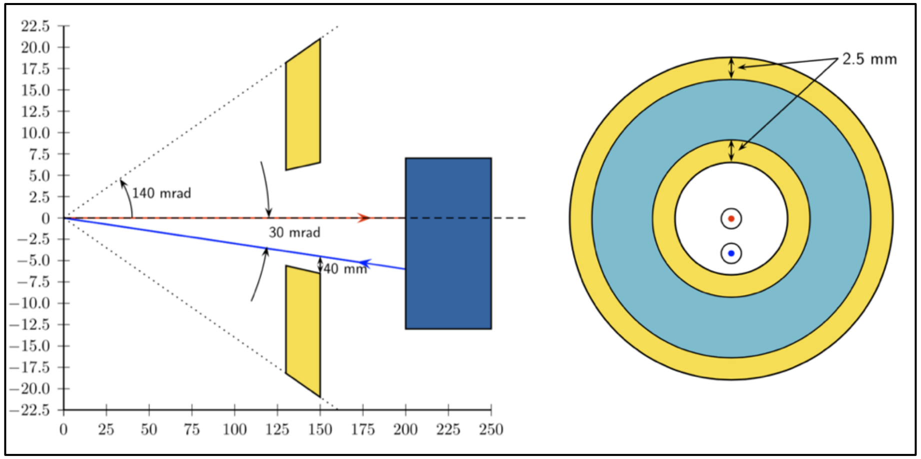
   - BR(H → ZZ) = Γ(H → ZZ) /Γ_H is proportional to g_{HZ}^2
     - ➢ σ_{HZ} x BR(H → ZZ) is proportional to g_{HZ}^4/Γ_H
   - Infer the total width Γ_H from the two measurements

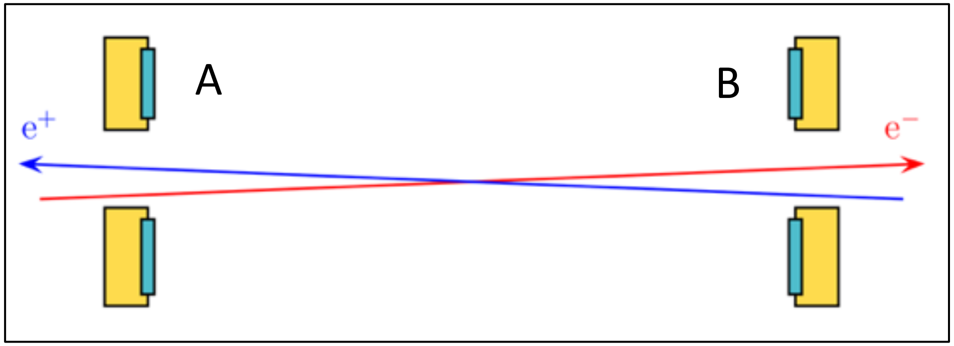
$$\boxed{\Gamma_H \propto \sigma_{HZ} / \mathrm{BR}(H \rightarrow ZZ)}$$

Luminosity measurement (2)

FCC-ee (ambitious) target: **10^{-4} level**

- **Beam crossing angle**: center monitors around the outgoing beams





- To eliminate first order dependence on beam parameters, need tight and looser fiducial volume:

Acceptance = tightA ∩ looseB + tightB ∩ looseA

LEP: 2500 mm

Shift in parameter for a shift of +10^{-4} in acceptance

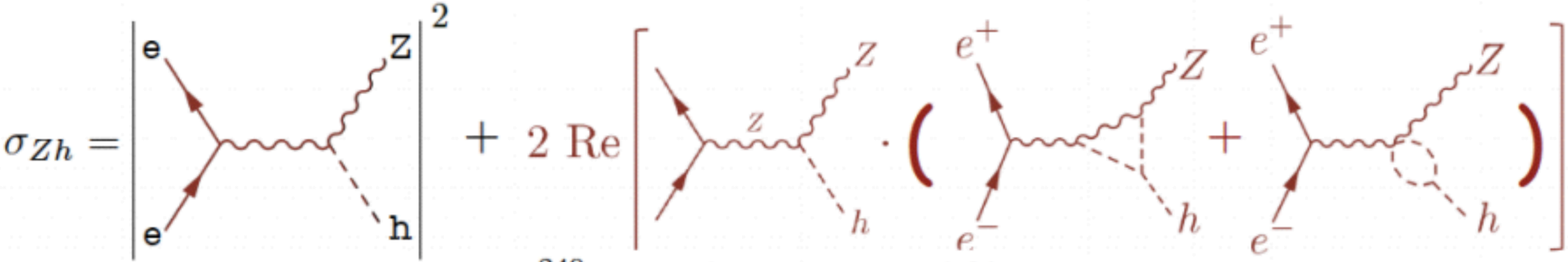
Need µm level of precision

A few geometries studies

z_{front} [mm]	r_{min} [mm]	r_{max} [mm]	θ_{min} [mrad]	θ_{max} [mrad]	σ [nb]	δz_{front} [μm]	δr_{min} [μm]	δr_{max} [μm]
1000	80	115	80	115	10	50	-2.1	6.1
1300	89	157	68	121	18	65	-3.0	17
1500	95	185	63	123	23	75	-3.5	26

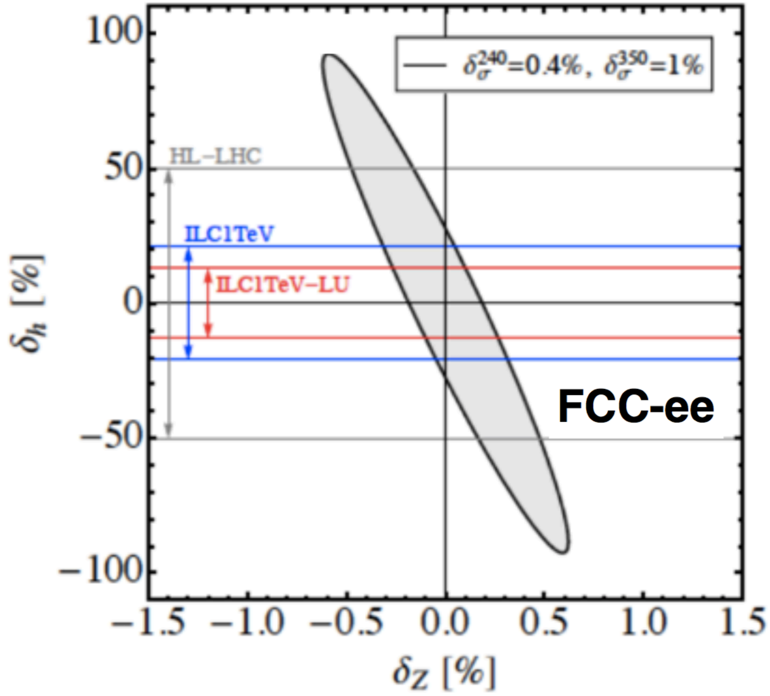
Hadronic peak cross section (Z⟶qq): 30 nb

Higgs self-coupling through loop corrections



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot



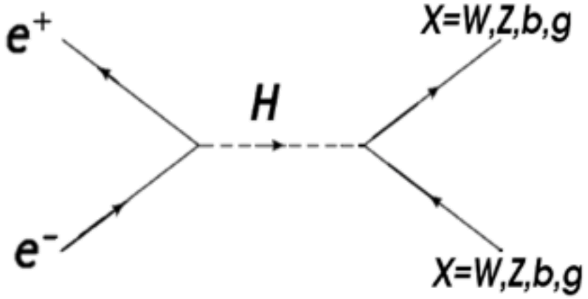
Matthew McCullough

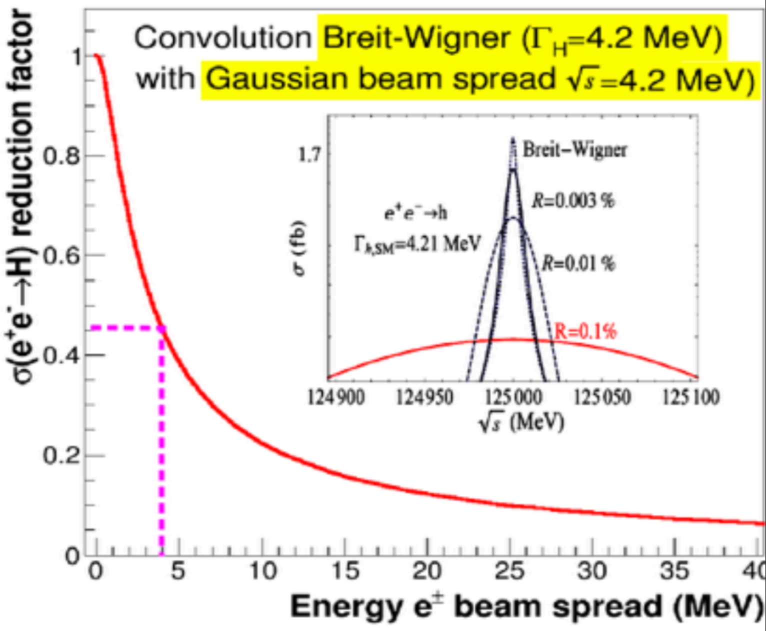
arxiv:1312.3322

First generation couplings

➡ **s-channel Higgs production**

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; σ(ee→H) = 1.6fb; various Higgs decay channels studied





➡ **Work in progress**

- Loop-induced production channels have cross section than pure s-channel. But, how large are BSM effects?
- Can monochromators yields energy spread of Higgs width or smaller? At what luminosity cost?
- Energy scan O(10MeV) around mH will be needed to locate exact sqrt(s)
- Polarization increases cross section (e.g. by x2 at P=70%). At what luminosity cost?

Preliminary Results

$L = 10\ ab^{-1}$

$\kappa_e < 2.2$ at 3σ

d'Enterria-Wojcik-Aleksan