Workshop on the Circular Electron-Positron Collider - EU edition

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Europe/Rome timezone

FCCee Physics/Detectors

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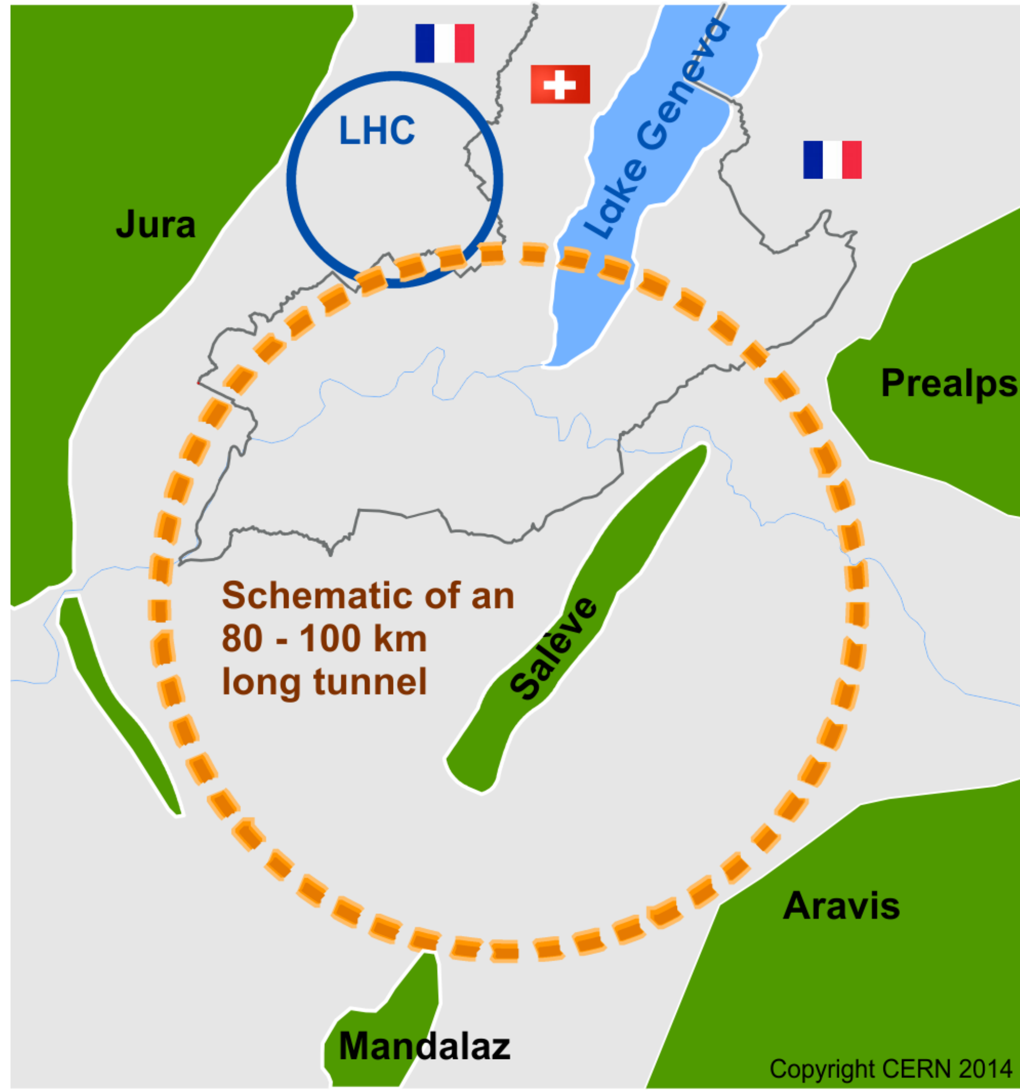
SEZIONE DI PISA

The Future Circular Collider (FCC)

International FCC collaboration (CERN as host lab) to study:

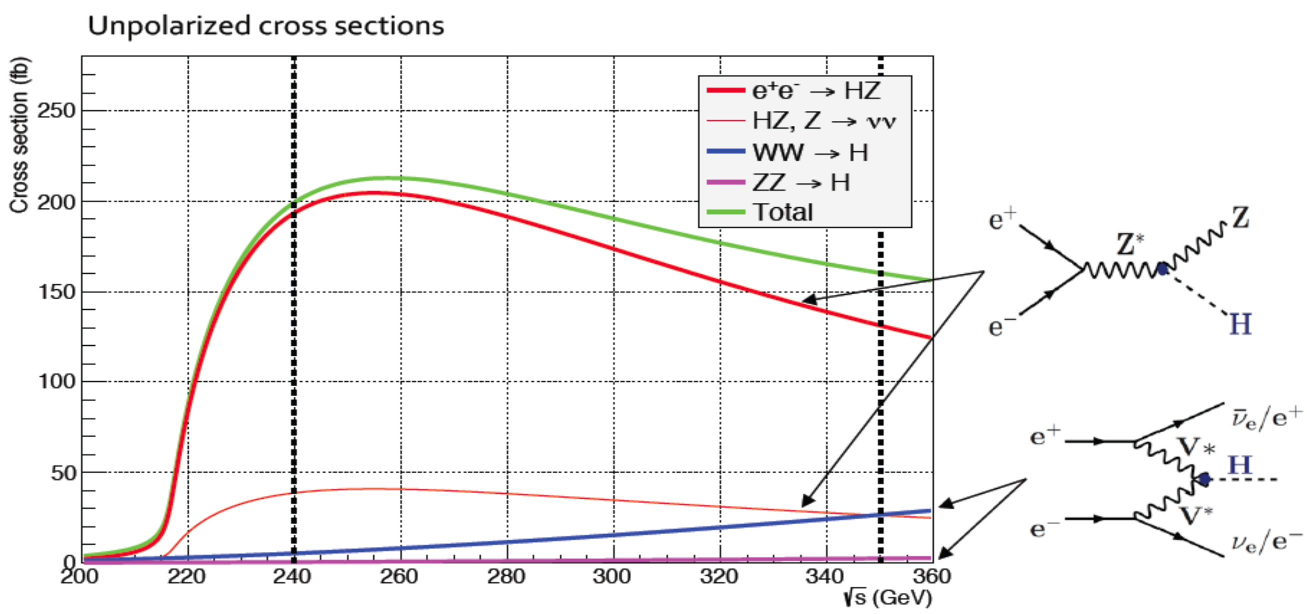
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,**

e^- from ERL



e+e- circular colliders revitalized by Higgs discovery

- The Higgs mass is low: at LEP we were close … sensitive up to 115 GeV, (125/115=1.09)
- Synchrotron energy loss per turn goes as E^4/ρ , increasing the radius by a factor 3 you have $(1.09)^4/3=0.47$, RF cavities "a la LEP" in principle would be enough !



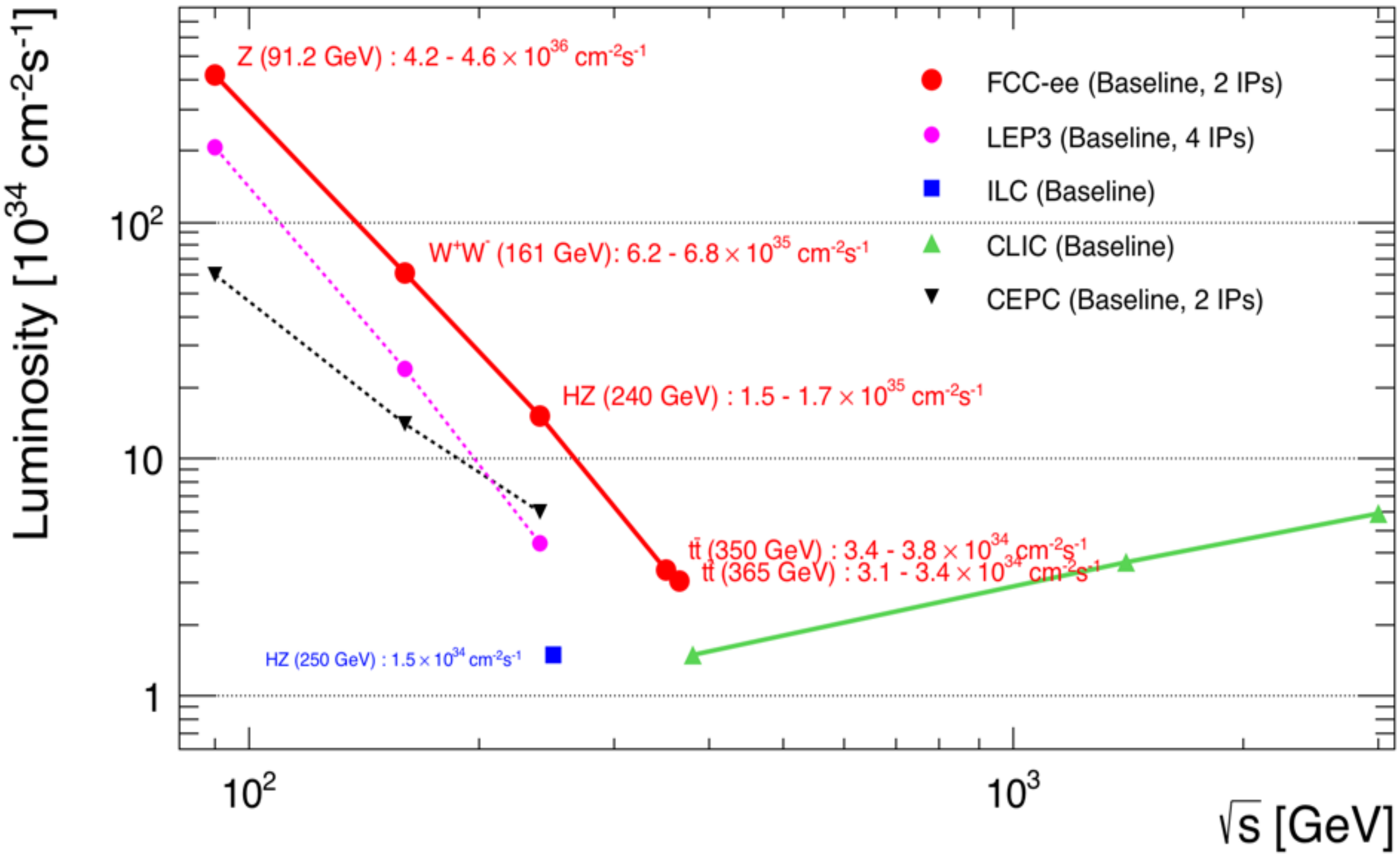
Excellent opportunity to make a significant jump in precision for the two nearby EW vector bosons (W,Z) and the heaviest quark (top):

- change the landscape of electroweak precision measurements !

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5

Lepton Colliders luminosities



FCC-ee operation model

working point	**luminosity /IP [10^{34} $cm^{-2}s^{-1}$]**	**total luminosity (2 IPs)/ yr**	**physics goal**	**run time [years]**
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	25	7 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	0.36 ab^{-1}/year	**1.5 ab^{-1}**	**4**

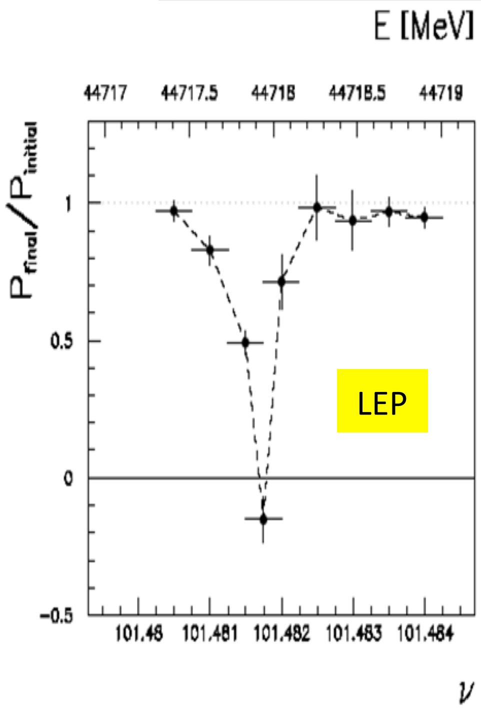
total program duration: 14 years - ***including machine modifications***

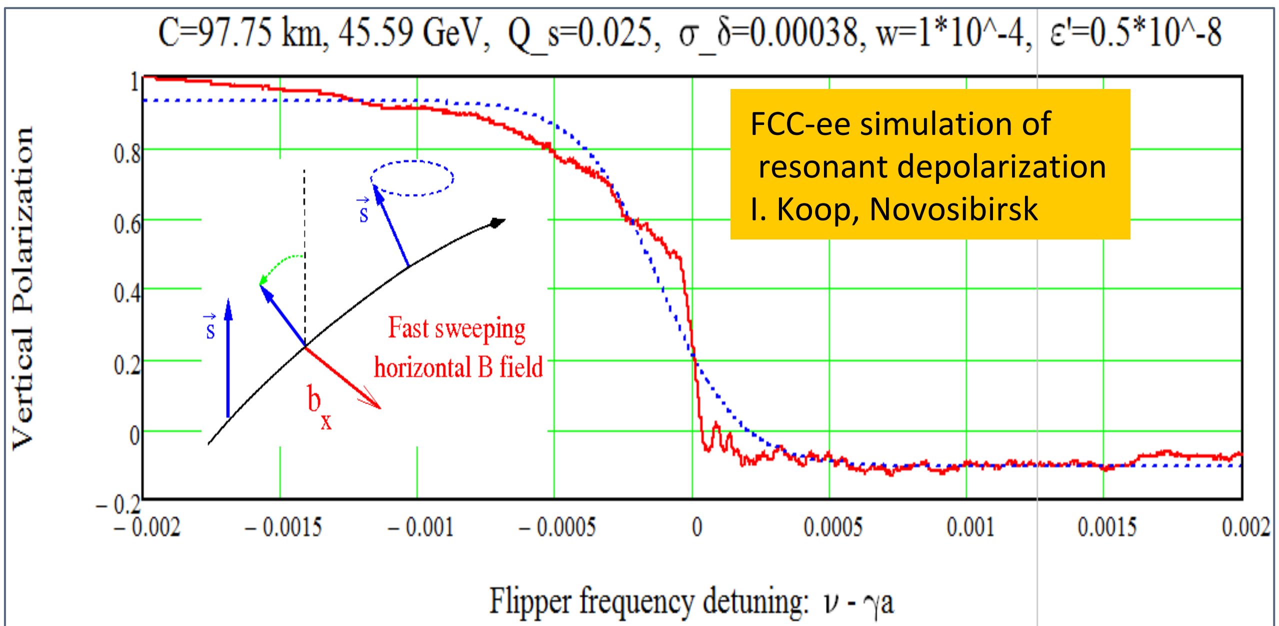
phase 1 (*Z*, *W*, *H*): 8 years, **phase 2 (top): 6 years**

FCC-ee Beam Polarization and Energy Calibration

1. **Priority from Physics** : ΔE/E ~O(10^{-6}) around Z pole and WW threshold → **Z,W mass&width**
2. Exploit natural transverse beam polarization <u>present at Z and W</u>
   2.1 This is a unique capability of e+e- circular colliders
   2.2 Sufficient level is obtained if machine alignment is good enough for luminosity
   2.2 Resonant depolarization has intrinsic stat. precision of ~10^{-6} on spin tune
   2.3 Required hardware (polarimeter, wigglers depolarizer) is defined & integrated
   2.4 Running mode with 1% non-colliding bunches and wigglers defined

Corresponding uncertainty on Z mass 100 keV and W mass 500 keV





260 seconds sweep of depolarizer frequency

Detector and MDI general requirements at FCC-ee

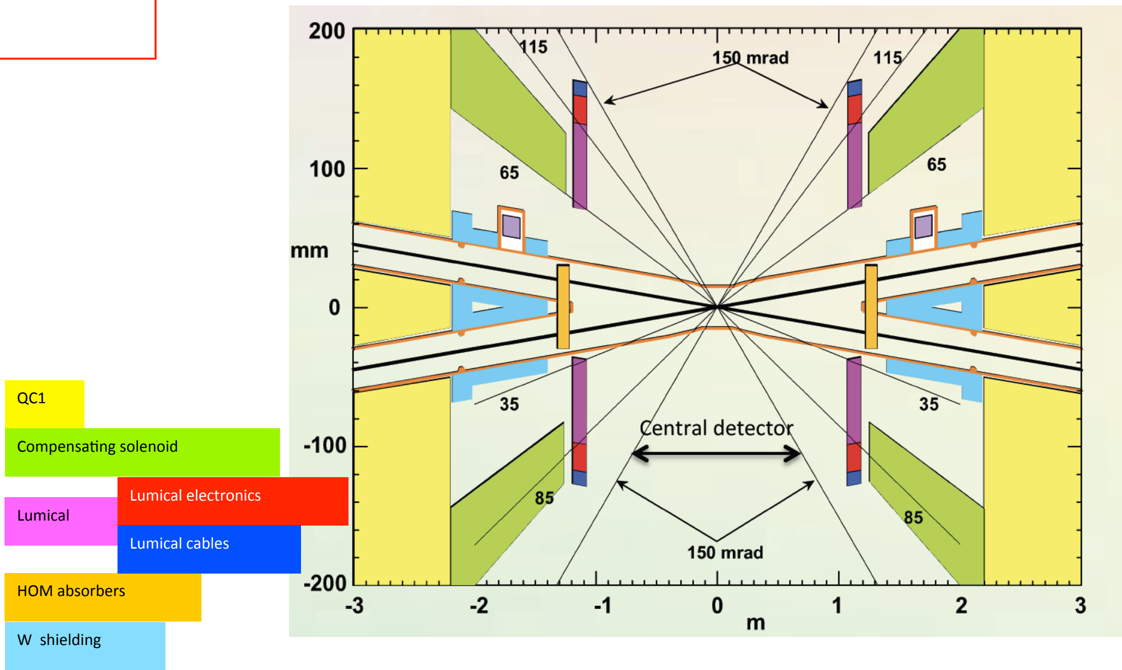
- Be suitable for high precision measurements
  →precise tracking in a low X0 tracker
- Excellent lepton id and momentum resolution
- Excellent photon id and energy/direction res.
- Precise angular (and energy) jet measurement
- Particle flow friendly
  → adequate calorimeter granularity
- High granularity vertex detector with b and c tagging capabilities

→ in a low occupancy environment maximum event rate 20 kHz @ Z peak

Two benchmarks for CDR

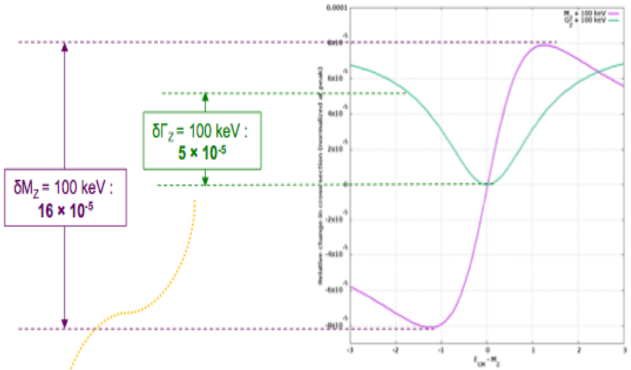
- **IDEA**: circular collider detector from present state-of-the-art technology
- **CLD**: CLIC detector revisited for FCC-ee

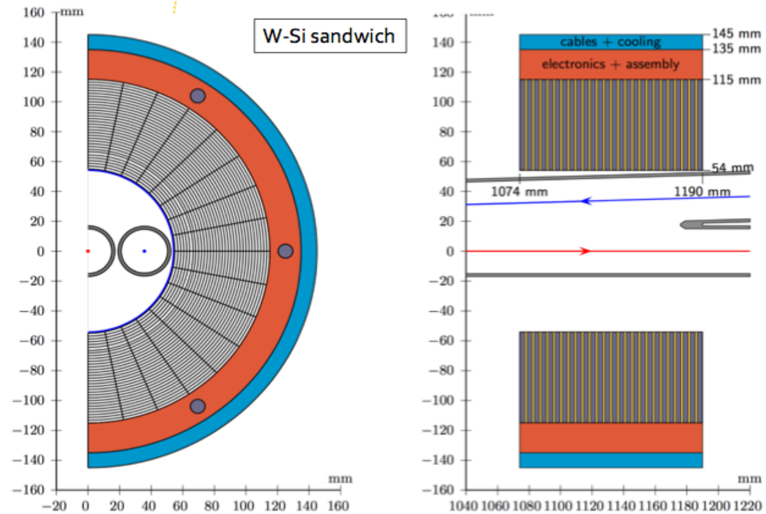
- Asymmetric optics with beam crossing angle of 30 mrad
- IP displaced by about 9.4 m wrt proton beam line
- Maximum magnetic field 2T (compensation)
- Beam pipe radius 15 mm
- Last quadrupole L* =2.2 m
- Detector has to "stay above" the 100 mrad line

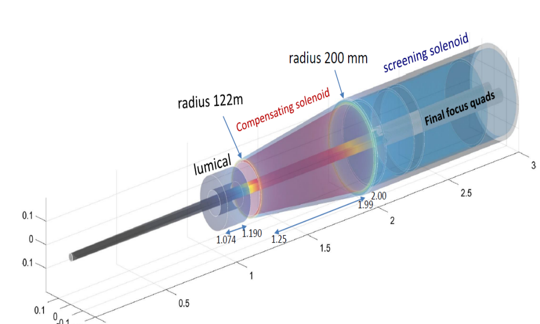


Luminometer

- **Using small angle Babha scattering, Very precise normalization needed: absolute normalization at 10^{-4} and relative to $5x10^{-5}$**
- Basic design: Cylindrical detectors of W+Si sandwich centered around, and perpendicular to the outgoing beam line (asymmetric)
- Studied effect of:
  - synchrotron radiation: negligible with shielding
  - beam background: ee pairs soft and and close to detector boundaries. √s dependence
  - beam-gas background: negligible
- Focusing effect of opposite beam to be studied
- To match the goal an accuracy on detector construction and boundaries of ≈ 2 μm is required
  - clever acceptance algorithms, a la LEP, with independence on beam spot position should be extended to beam with crossing angle
  - luminometer fixed to central beam pipe



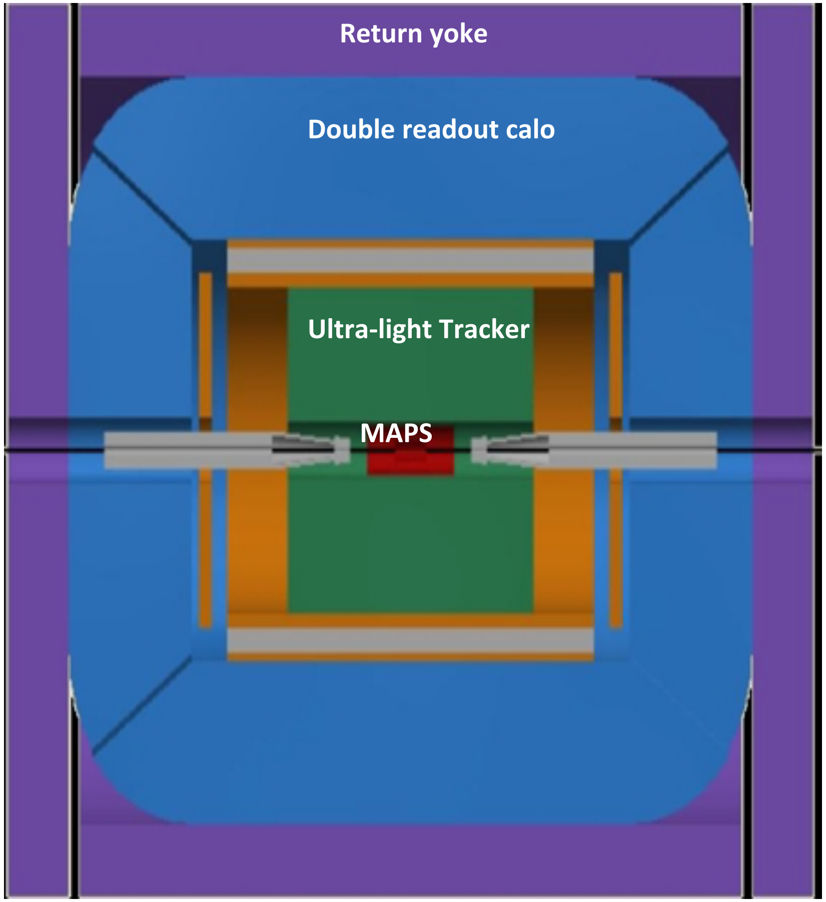




FCC-ee detector: the IDEA concept

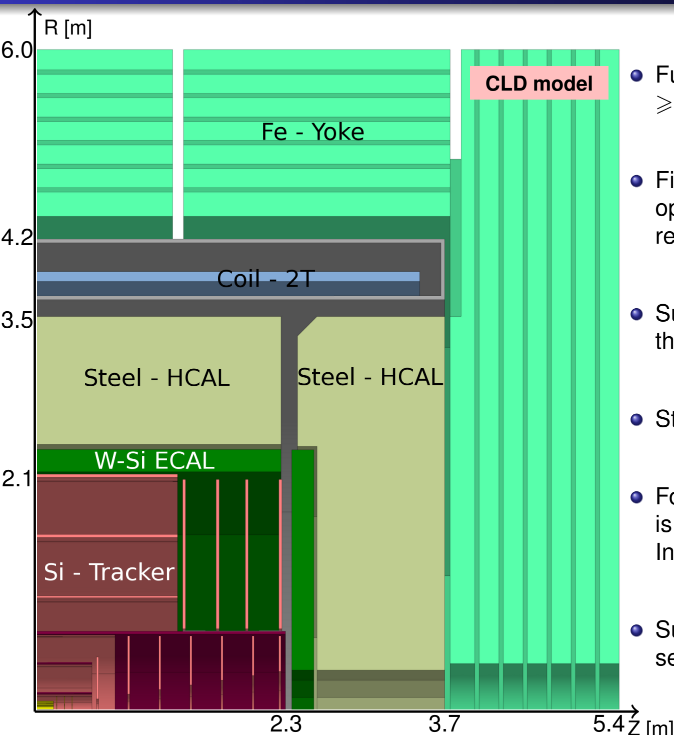
- Vertex detector, MAPS (a la ALICE)
- Ultra-light drift chamber with PID (a la MEG2)
  - **≈ 0.04 X0 up to the preshower face**
- Pre-shower counter
  - **defines acceptance ≈ 10-20 μm precision**
- Double read-out calorimetry (RD52 - DREAM)
- 2 T solenoidal magnetic field
- Possibly instrumented return yoke
- Possibly surrounded by large tracking volume (R = 8m) for very weakly coupled (long-lived) particles

Two Options: Calorimetry inside or outside coil

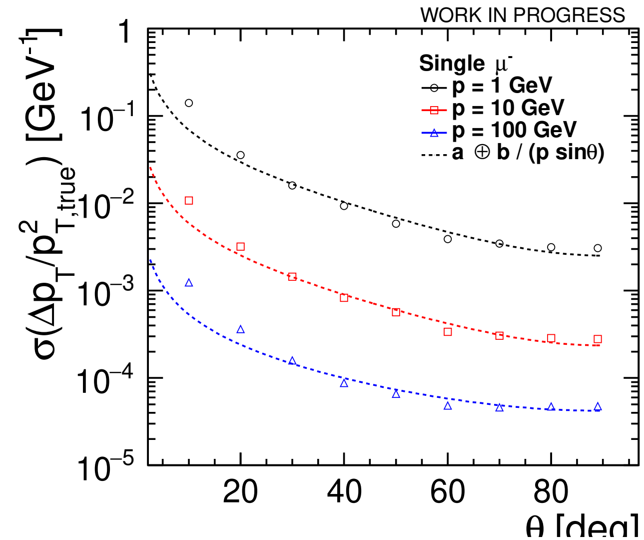


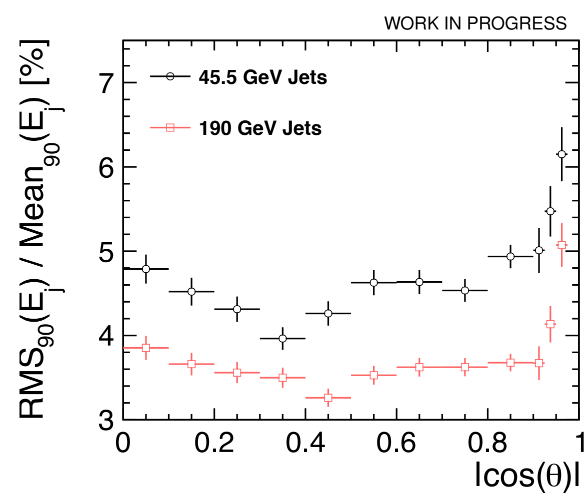
FCC-ee detector: CLD (CLIC inspired)

CLD detector layout



- Full silicon tracking system - provides ⩾12 hits per track
- Fine-grained ECAL and HCAL optimised for particle flow reconstruction
- Superconducting solenoid is outside of the calorimeter
- Steel return yoke with muon chambers
- Forward detector region (< 150 mrad) is reserved for Machine-Detector Interface (accommodates LumiCal)
- Support structures, cables and services are included in the model





- Jet energy resolution in barrel region:
  - 45.5 GeV jets: 4-5 %
  - 190 GeV jets: 3-4 %

- Tracking fully efficient from 700 MeV
  - Pt Resolution of $4\times10^{-5}\,GeV^{-1}$ for 100 GeV muons
- >95% Photon and electron efficiency
  - Energy resolution in barrel region 3-5%

Very similar to original CLIC detector

Z & W Physics observables at FCC-ee

Integrated luminosity goals for Z and W physics

- 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)

LEP (4 IPs)
0.6 fb^{-1}
2.4 fb^{-1}

TeraZ (5 X 10^{12} Z)

From data collected in a lineshape energy scan:

- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings)
- peak cross section (invisible width, N_ν)
- $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings)
- Tau polarization ($\sin^2\theta_{eff}$, lepton couplings, $\alpha_{QED}(m_Z^2)$)
- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)

OkuWW (10^8 WW)

From data collected around and above the WW threshold:

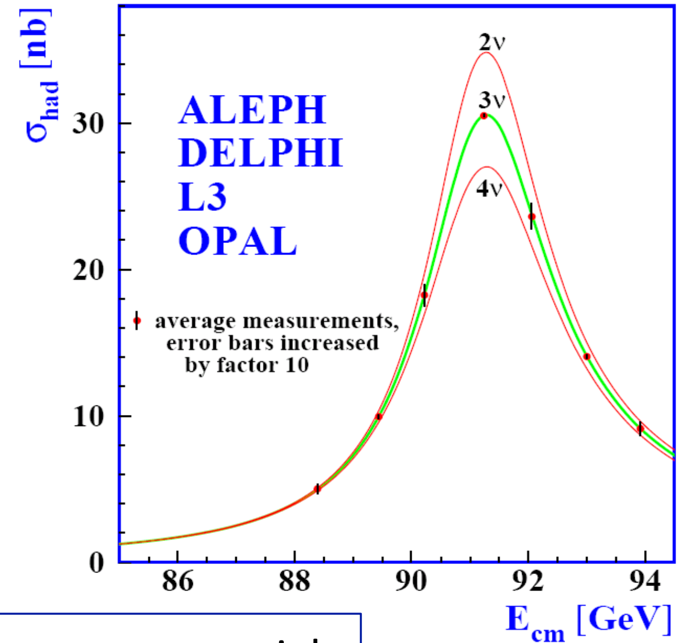
- W mass (key for jump in precision for ewk fits)
- W width (first precise direct meas)
- $R^W = \Gamma_{had}/\Gamma_{lept}$ ($\alpha_s(m^2_Z)$)
- Γ_e , Γ_μ , Γ_τ (precise universality test)
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

Determination of Z mass and width

- uncertainty on m_Z (≈ 100 KeV) is dominated by the correlated uncertainty on the centre-of-mass energy at the two off peak points

at FCC-ee continuous E_{CM} calibration (resonant depolarization) gives $\Delta E_{CM} \approx$ 10 KeV (stat) + 100 KeV (syst)

- the off peak point-to-point anti-correlated uncertainty has a similar impact (≈ 100 KeV) on Γ_Z



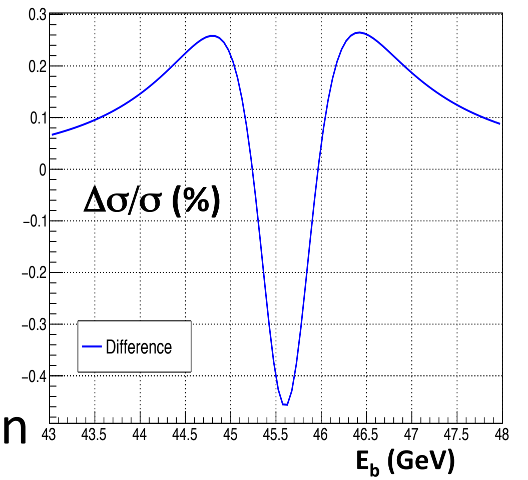
The exact choice of the off peak energies for m_Z , Γ_Z is not very crucial at FCC-ee (differently from LEP) because of the high statistics. Instead the exact choice is crucial for $\alpha_{QED}(m_Z^2)$ which is driving the choice of $\sqrt{s_-} \approx$ **88 GeV** and $\sqrt{s_+} \approx$ **94 GeV**

FCC-ee **precision calls for a model independent fit of the lineshape (S-matrix) where γ-Z interference is measured independently,** A measurement of the γ-Z interference term for 100 keV precision for m_Z, Γ_Z requires 100 fb^{-1} collected at CM energy of ≈ 60-70 GeV ... or use the 160 GeV run !

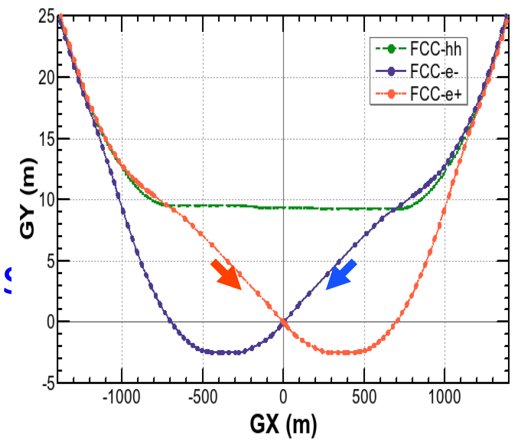
Γ_Z and beam energy spread

- The beam energy spread affects the lineshape changing the cross section by

$$\delta\sigma \simeq 0.5 \frac{d^2\sigma}{dE^2}\epsilon_{CMS}^2$$



- The size of the energy spread (≈ 60 MeV) and its impact on Γ_Z (≈4 MeV) is similar to LEP, but the approach to tackle the corresponding systematic uncertainty different because of FCC-ee beam crossing angle
- At LEP it was controlled at 1% level by measuring the longitudinal size of the beam spot, at FCC-ee can be measured with similar precision from the scattering angles of $\mu^+\mu^-$ events



Control of energy spread with $\mu^+\mu^-$

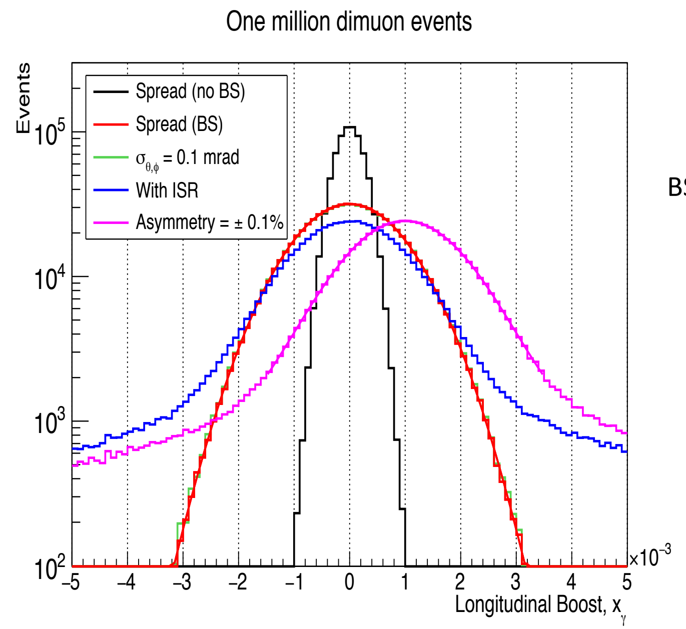
- FCC-ee: Asymmetric optics with beam crossing angle α of 30 mrad
- α is measured in e+e-→$\mu^+\mu^-(\gamma)$

$$\alpha = 2\arcsin\left[\frac{\sin(\varphi^- - \varphi^+)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]$$

together with γ (ISR) energy, both distributions sensitive to energy spread.

- Energy spread measured at 0.1% with 10^6 muons (4 min at FCC-ee)
- Current calculations of ISR emission spectrum sufficient
- Detector requirement on muon angular resolution 0.1 mrad

Patrick Janot, FCC Week Amsterdam



BS=beamstrahlung

$$x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|}$$

Can keep related systematic uncertainty on Γ_Z at less than 30 keV

σ_{had}, Z invisible width, number of neutrino families

- Goal on theoretical uncertainty from higher order for low angle Bhabha is 0.01%, corresponding to a **reduction of a factor 8 in uncertainty on number of light neutrino families** (we are already not far ≈ 0.02%)
  - Another goal is a point to point relative normalization of 5 10^{-5} for Γ_Z

$$\frac{\Gamma_{inv}}{\Gamma_l} = \frac{\Gamma_Z}{\Gamma_l} - R_l - 3 = (\frac{12\pi R_l}{\sigma^0_{had} M_Z^2})^{1/2} - R_l - 3 = N_\nu \cdot \frac{\Gamma_\nu}{\Gamma_l}$$

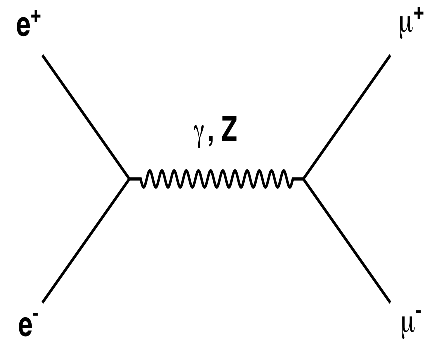
- Can potentially reach an uncertainty of 0.01% also with $e^+e^- \rightarrow \gamma\gamma$, statistically 1.4 ab^{-1} are required (theory uncertainty already at this level, requires control of large angle Bhabha)
- A precise measurement of the the invisible width is also obtained from single photon events at higher centre-of-mass energy from $Z \rightarrow \nu\nu\gamma$

$$E_\gamma = \frac{s - M_Z^2}{2\sqrt{(s)}}$$

e.m. coupling: direct measurement of $\alpha_{QED}(m_Z^2)$

At LEP hadronic contributions to the vacuum polarization as external input (dispersion relations+ lower energy experiments) $\Delta_{rel} \approx 10^{-4}$

FCC-ee: direct measurement with better precision



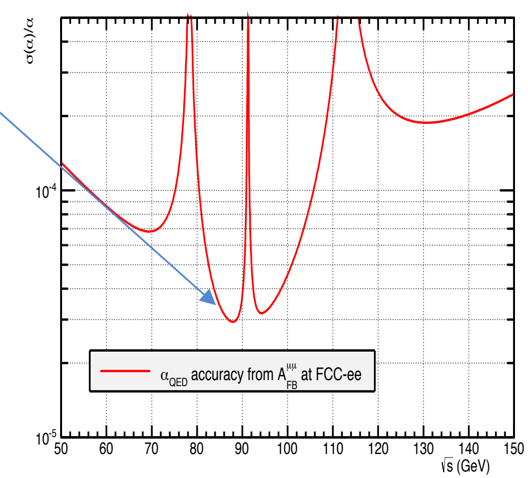
Patrick Janot: JHEP 02 (2016) 53

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

Optimal centre-of-mass energies for a 3×10^{-5} uncertainty on α_{QED} : $\sqrt{s}_- =$ **87.9 GeV** and $\sqrt{s}_+ =$ **94.3 GeV**

Type	Source	Uncertainty
Experimental	E_{beam} calibration	1×10^{-5}
	E_{beam} spread	$< 10^{-7}$
	Acceptance and efficiency	negl.
	Charge inversion	negl.
	Backgrounds	negl.
Parametric	m_Z and Γ_Z	1×10^{-6}
	$\sin^2\theta_W$	5×10^{-6}
	G_F	5×10^{-7}
Theoretical	QED (ISR, FSR)	$< 10^{-6}$
	Missing EW higher orders, QED(IFI)	few 10^{-4}
	New physics in the running	0.0
Total	Systematics	1.2×10^{-5}
(except missing EW higher orders)	Statistics	3×10^{-5}

Work on EWK theoretical corrections required to reach $\approx 3\ 10^{-5}$



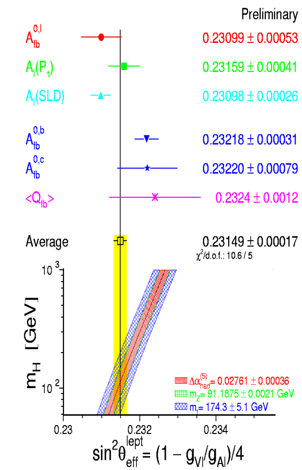
$\sigma(\alpha)/\alpha$ plot, for a year of running at any $\sqrt{s}$

FCC-ee strategy for neutral couplings and $\sin^2\theta_{eff}$

$$\mathcal{A}_e = \frac{2 g_{Ve} g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2 g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

- Muon forward backward asymmetry at pole, $A_{FB}^{\mu\mu}$ (m_Z) gives $\sin^2\theta_{eff}$ with 5 10^{-6} precision
  - **uncertainty driven by knowledge on CM energy**
  - **assumes muon-electron universality**
- **Tau polarization can reach similar precision without universality assumption**
  - tau pol measures A_e and A_τ, can input to **$A_{FB}^{\mu\mu} = 3/4\ A_e\ A_\mu$** to measure separately electron, muon and tau couplings, (together with Γ_e, Γ_μ, Γ_τ)
- Asymmetries A_{FB}^{bb}, A_{FB}^{cc} provide input to quark couplings together with Γ_b, Γ_c

NOTE that LEP approach was different: all asymmetries were limited by statistics and primarily used to measure $\sin^2\theta_{eff}$



tau polarization plays a central role at FCC-ee

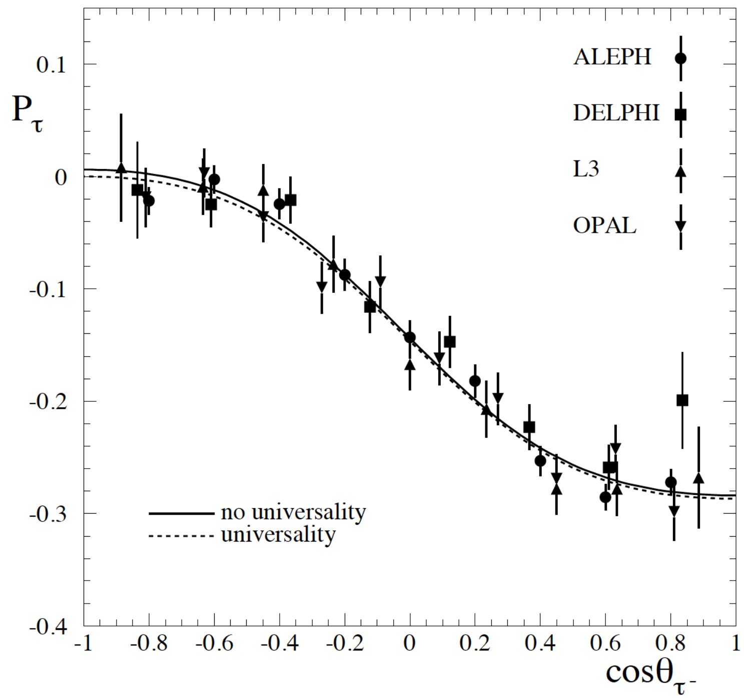
- Separate measurements of A_e and A_τ from

$$P_\tau(\cos\theta) = \frac{A_{pol}(1+\cos^2\theta) + \frac{8}{3}A_{pol}^{FB}\cos\theta}{(1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta}$$

$$A_{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -A_f$$

$$A_{pol}^{FB} = \frac{\sigma_{F,R} - \sigma_{B,R} - \sigma_{F,L} + \sigma_{B,L}}{\sigma_{tot}} = -\frac{3}{4}A_e$$

Measured P_τ vs $\cos\theta_{\tau^-}$



At FCC-ee

- very high statistics: improved knowledge of tau parameters (e.g. branching fraction, tau decay modeling) with FCC-ee data
- use best decay channels (e.g. $\tau \rightarrow \rho\nu_\tau$ decay very clean), note that detector performance for photons / π^0 very relevant

→ **measure $\sin^2\theta_{eff}$ with 6.6 10^{-6} precision**

Precisions on vector and axial neutral couplings

From Asymmetries (gv/ga)

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
A_e	$5. \times 10^{-5}$	$1. \times 10^{-4}$	50
A_μ	2.5×10^{-5}	1.5×10^{-4}	30
A_τ	$4. \times 10^{-5}$	$3. \times 10^{-4}$	15
A_b	2×10^{-4}	30×10^{-4}	5
A_c	3×10^{-4}	80×10^{-4}	4
$\sin^2\theta_{W,eff}$ (from muon FB)	10^{-7}	$5. \times 10^{-6}$	100
$\sin^2\theta_{W,eff}$ (from tau pol)	10^{-7}	6.6×10^{-6}	75

+

From partial widhts (gv^2+ga^2)

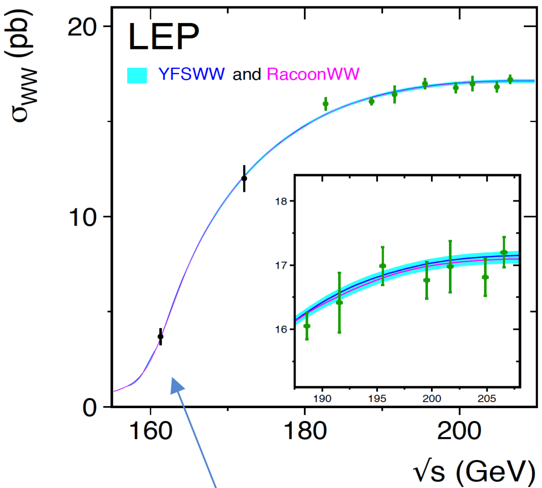
	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
R_μ (R_ℓ)	10^{-6}	5×10^{-5}	20
R_τ	1.5×10^{-6}	10^{-4}	20
R_e	1.5×10^{-6}	3×10^{-4}	20
R_b	5×10^{-5}	3×10^{-4}	10
R_c	1.5×10^{-4}	15×10^{-4}	10

Relative precisions

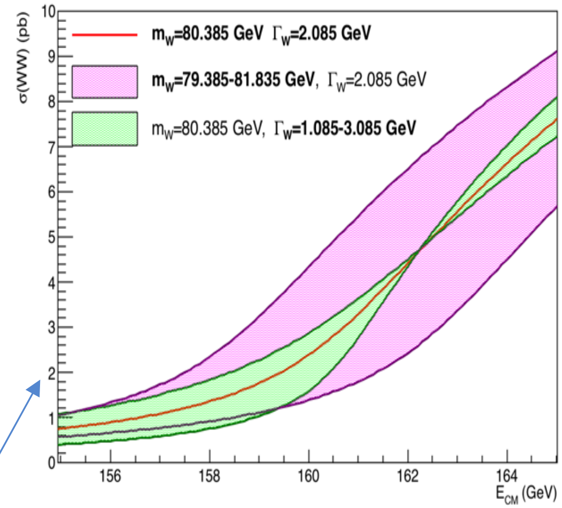
fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10^{-2}
c	2×10^{-3}	1×10^{-2}

Improvements 1 – 2 orders of magnitudes with respect to LEP, depending on the fermion (Still need to explore the potential for a measurement of the s quark coupling)

W mass and width from WW cross section

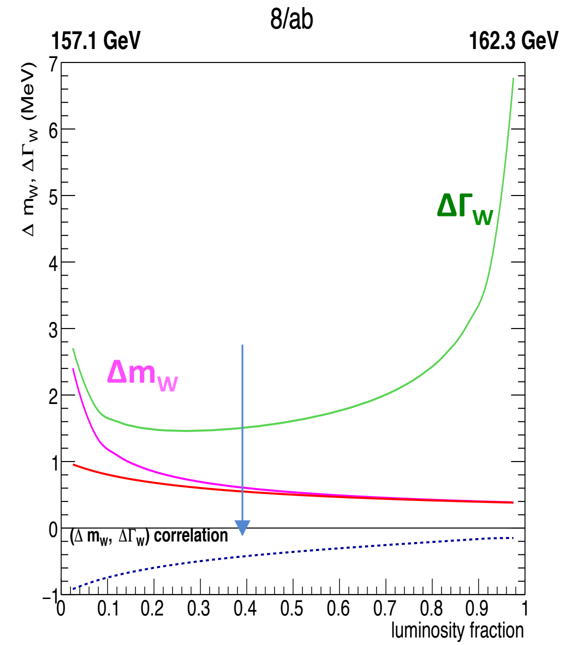


At LEP2 √s=161 GeV with 11/pb
➔ m_W=80.40±0.21 GeV



Sensitivity to mass and width is different at different E_{CM}: can optimize mass AND width by choosing carefully two energy points.

- Same concept can be used to minimize systematics (e.g. due to backgrounds)
- Centre-of-mass known by resonant depolarization (available at ≈ 160 GeV)
- Luminosity from Bhabha, requirements similar to Z pole case



with E_1=**157.1** GeV E_2=**162.3** GeV f=**0.4**
Δm_W=0.62 $\Delta\Gamma_W$=1.5 (MeV)

need syst control on :

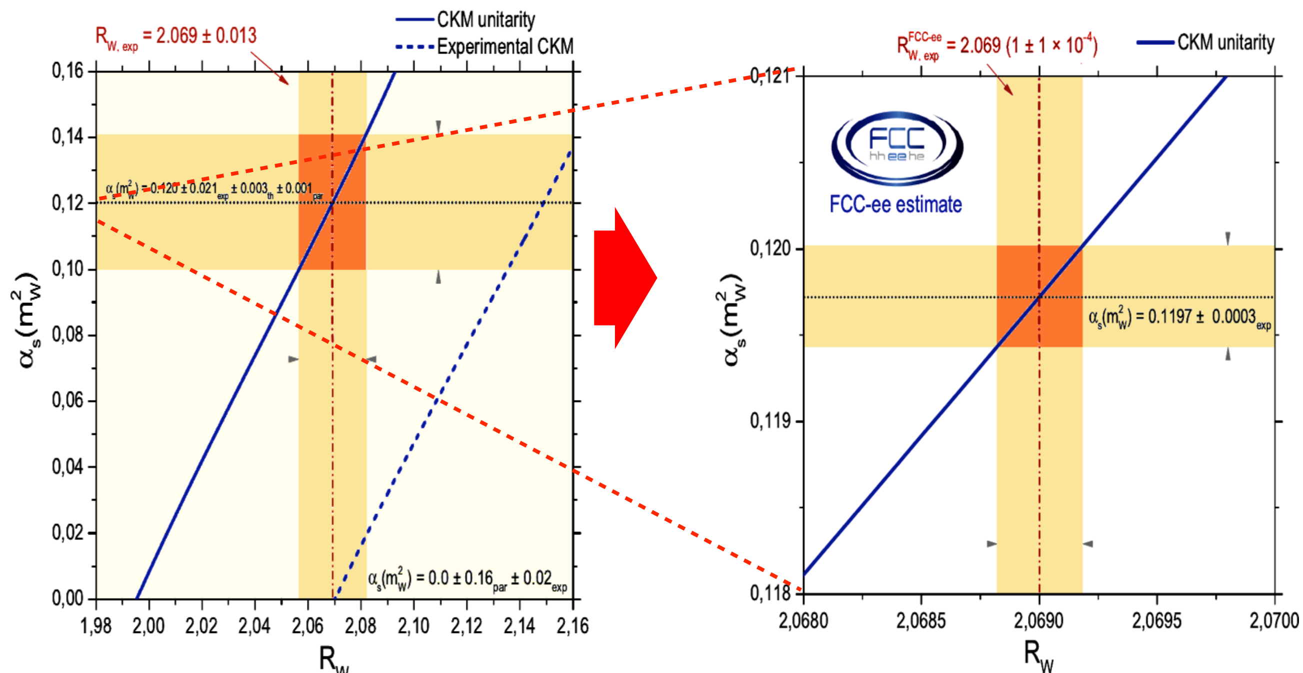
- **ΔE(beam)<0.35 MeV (4×10^{-6})**
- **Δε/ε, ΔL/L < 2 10^{-4}**
- **$\Delta\sigma_B$<0.7 fb (2 10^{-3})**

α_s via hadronic W decays

- Computed at N[2,3]LO:

$$\Gamma_{W,had} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks i,j}} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha\alpha_s) \right]$$

- LEP: Γ_W = 1405±29 MeV (±2%), BR_W = 0.6741±0.0027 (±0.4%)
  Extraction with large exp. & parametric (CKM V_{cs}) uncertainties today: **$\alpha_s(M_z)$ = 0.117 ± 0.040** **(±35%)**



[D.d'Enterria, M.Srebre, PLB763(2016)465]

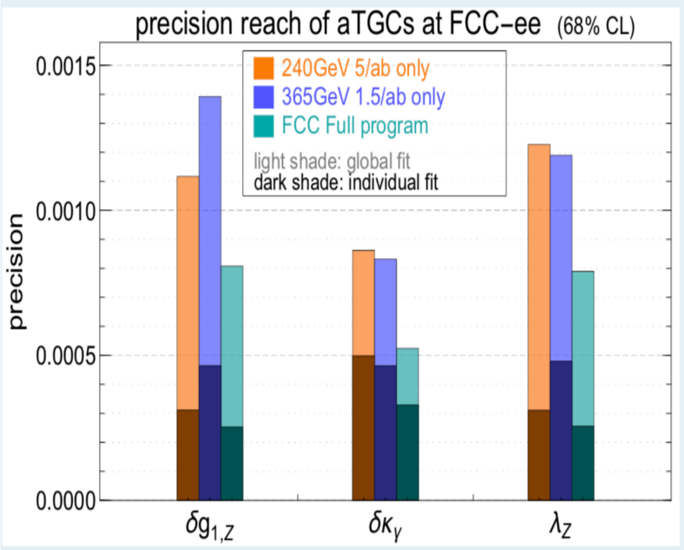
- FCC-ee: – Huge W stats (×10[4] LEP) will lead to: : Δ_{rel} **α_s < 0.3%**
  – TH uncertainty: $\Delta|V_{cs}|$ to be significantly improved (10^{-4})

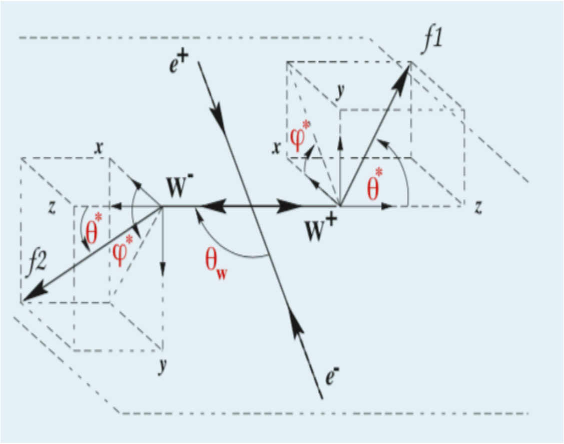
Can measure α_s at **< 0.1%** uncertainty combining Z, W, tau hadronic decays and jets rates & shapes

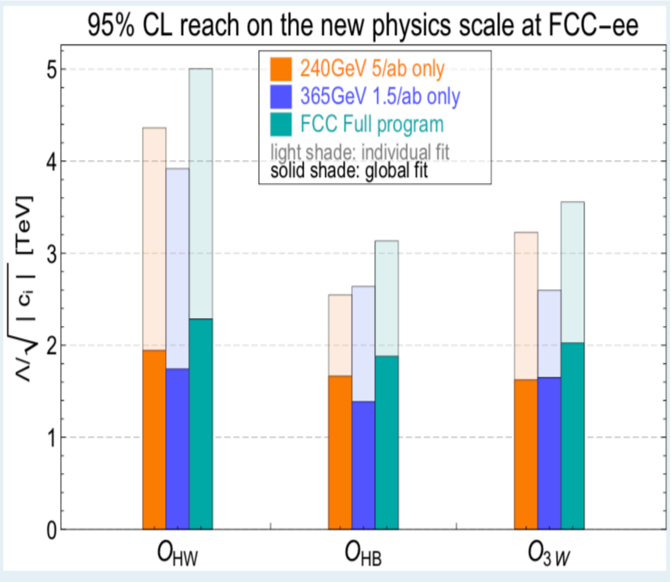
FCC-ee : probing the TGCs at high precision

Jiayin Gu

- Based on expected luminosity at 161, 240, 350 and 365 GeV
- Consider CP-even dimension 6 operators, SU(2)XU(1) symmetry leaves three independent anomalous couplings
- Include both total cross section and angles
- For the moment only statistical uncertainties
- **One order of magnitude improvement with respect to LEP**



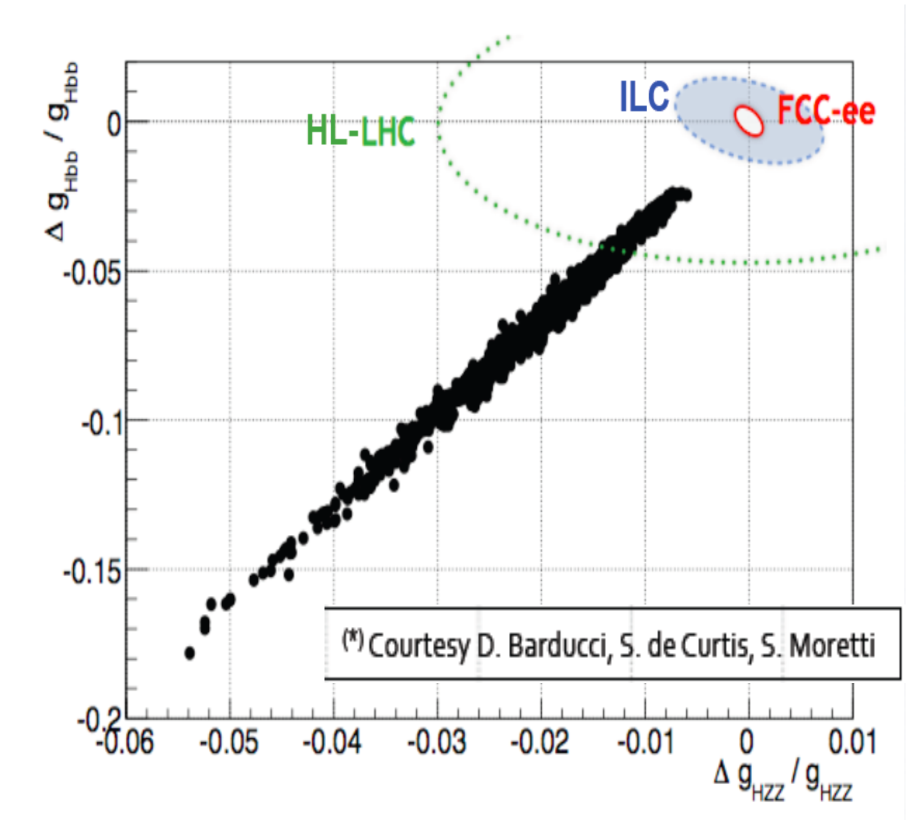




Higgs couplings precision and sensitivity to new physics

(HL- LHC measurements are model dependent)

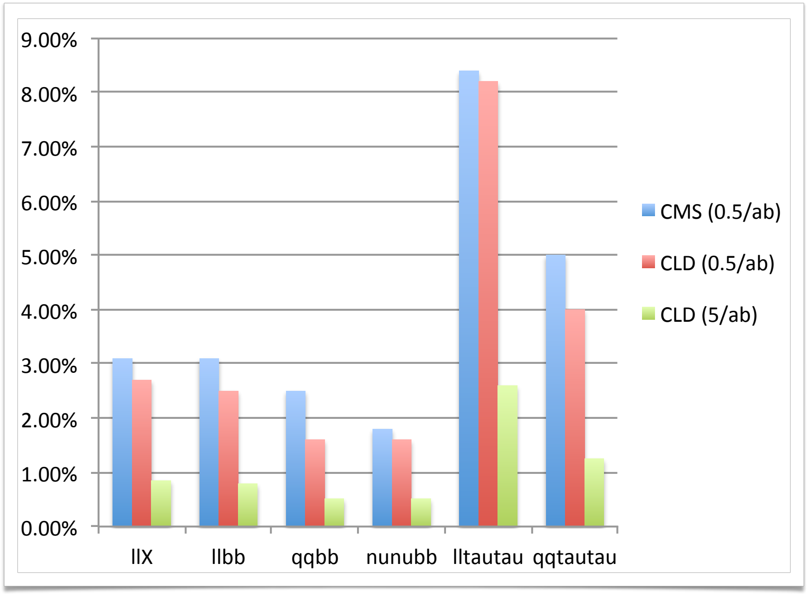
Example from Composite Higgs Models (4HDM)



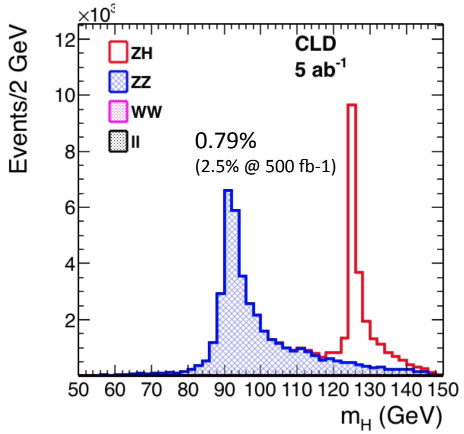
in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.0
g_{Hg}	3-5	1.2
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.8
$g_{H\gamma}$	2-5	2.1
Γ_H	5-8%	1.5

Higgs couplings studies with realistic simulations and detectors

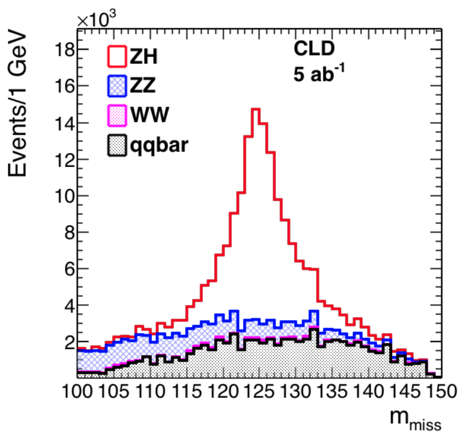
- **Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.**
- **Model independent determination of the total Higgs decay width**
- New estimates of Higgs coupling precision made with custom simulation (PAPAS)



$$\mathrm{ZH} \rightarrow \ell\ell bb$$



$$\mathrm{ZH} \rightarrow qqbb$$

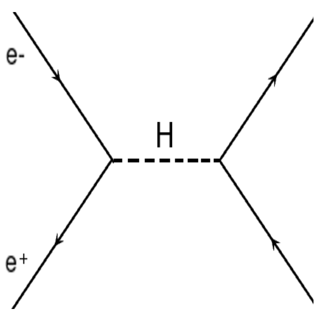


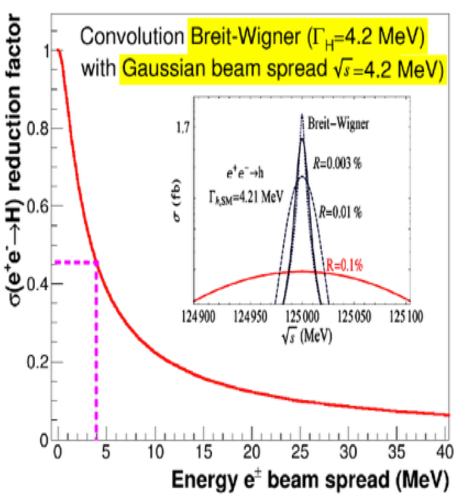
- CLD performs 10-35% better compared to results with CMS simulation
- now ready to study variation in detector design cost/performance

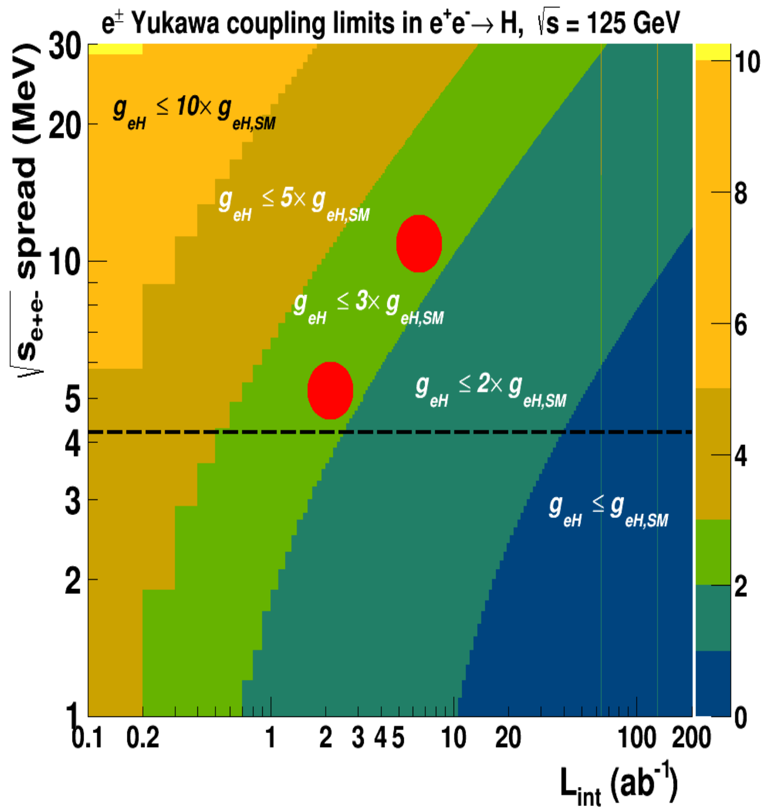
Higgs boson and first generation: s-channel production

Unique opportunity to measure the electron Yukawa coupling, highly challenging: σ(ee→H) = 1.6 fb, further reduced to ≈ 0.3 fb accounting for the finite energy spread and ISR of the e± beams.

Requires beam "monochromatization" at 62.5 GeV





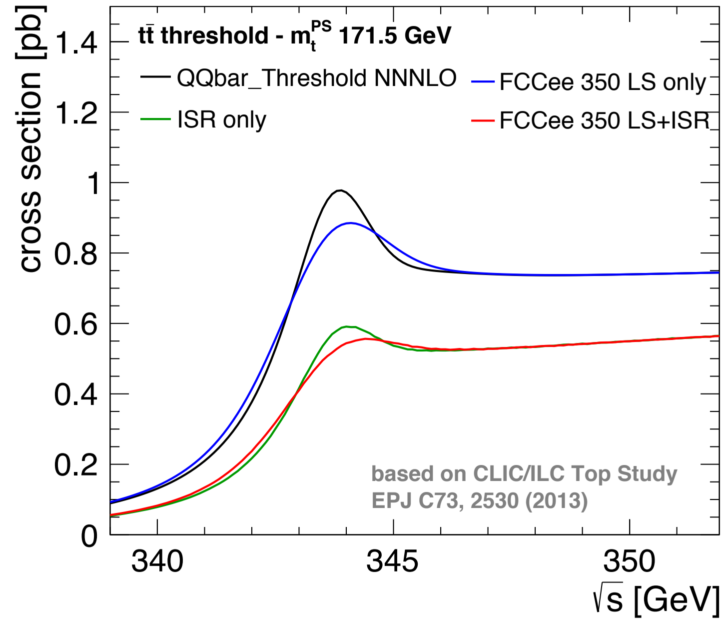


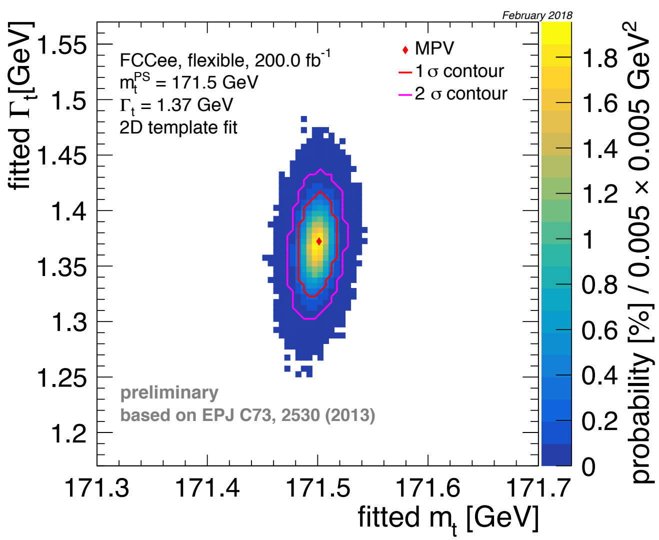
Two monochromatization options studied for FCC-ee

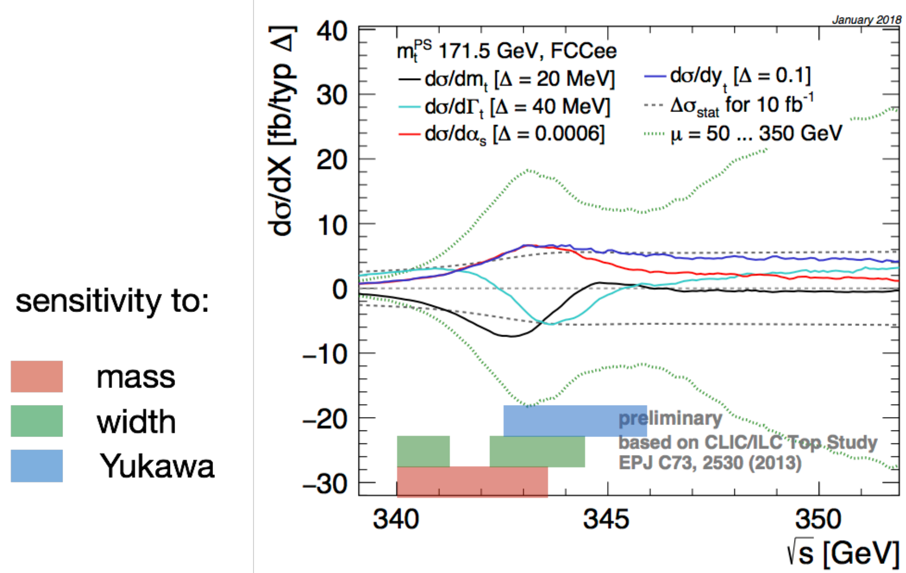
http://jacow.org/ipac2016/papers/wepmw009.pdf

The TOP quark

- **Precise measurements of top quark properties at the FCC-ee, coupled with precise theoretical calculation provide excellent discovery potential**
- Threshold region allows most precise measurements of mass, width, and estimate of Yukawa coupling. NEW Study of optimizing the scan strategy.
- Running at 365 GeV to be used for other measurements such as top couplings, FCNC etc.



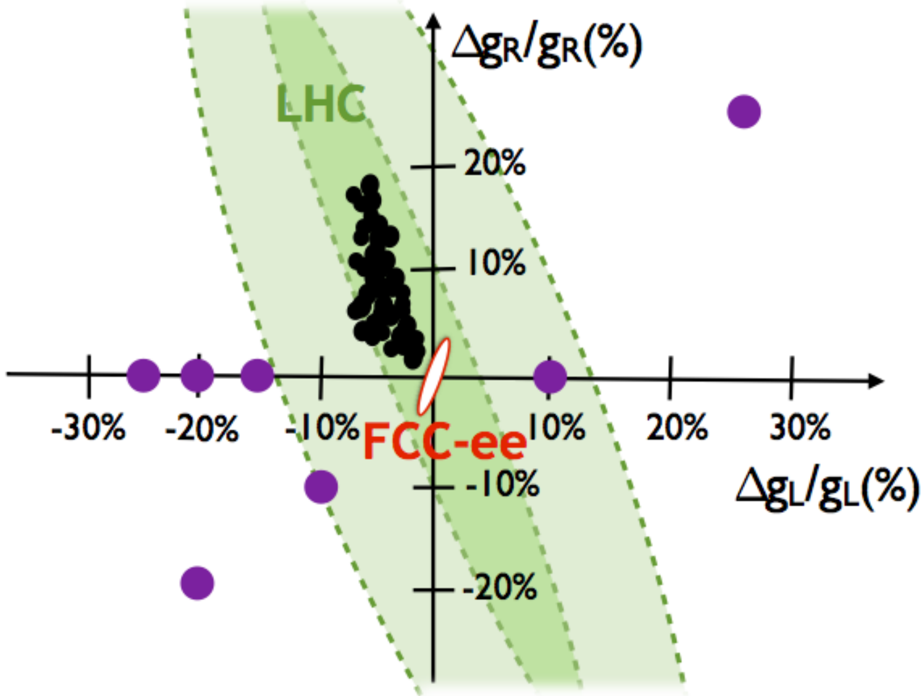


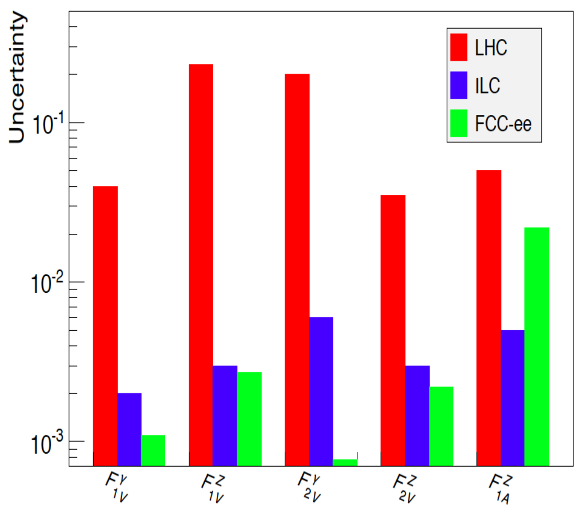


Mass only: **8.8 MeV** (stat), **5.4 MeV (α_s [2 x 10-4])**, **44 MeV (theo)**

Electroweak couplings of the top quark

- Large statistics and final state polarization allow a full separation of the ttZ/γ couplings with **NO need for polarization in the initial state.**
- **Optimal √s= 365-370 GeV**

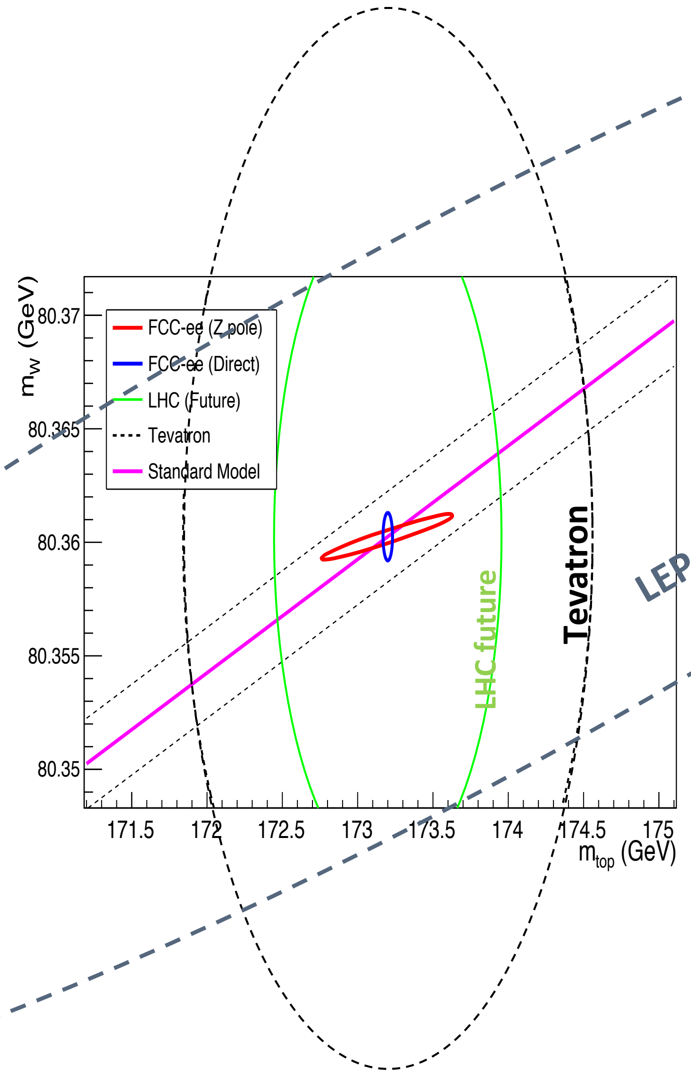




- ➤ Fit includes conservative assumptions detector performance
- ➤ Theory uncertainty on production mechanism dominates

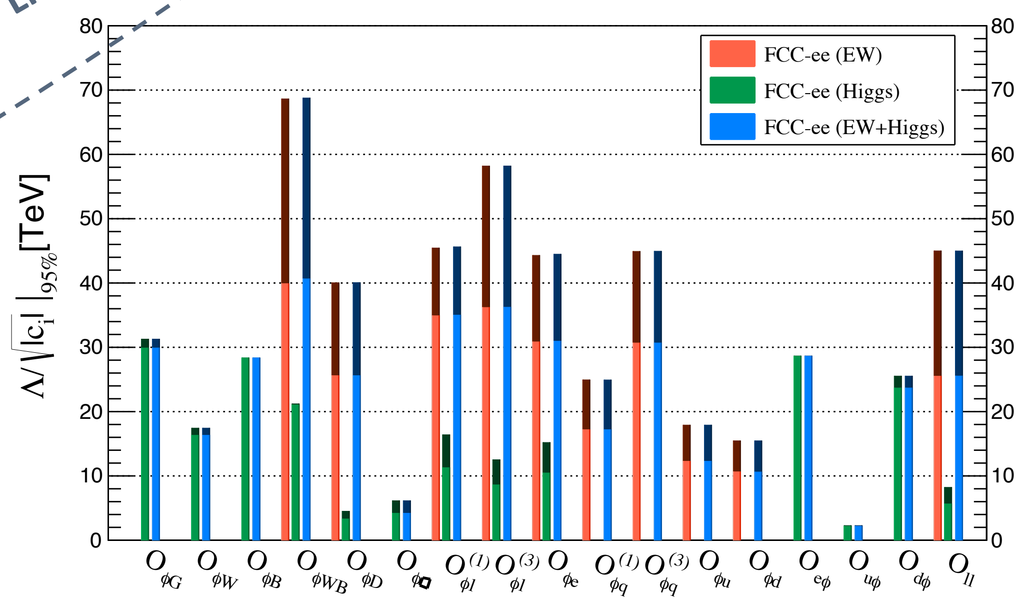
FCC-ee expected precision of order 10^{-2} to 10^{-3}

Global ewk fit and sensitivity to new physics



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

Jorge de Blas



poster by Dubovyk, Freitas, Gluza, Grzanka, Jadach, Riemann, Usovitsch

Precision calculations for the FCC-ee

- From Workshop on EW precision calculations held in January.
- Next decade: complete 3 loop calculation, will provide the needed precision
- Need to invest adequate resources

Matches the demand in precision by the experiment !

Bottom line: YES we will be able to use EWPO with the precision provided by the experiments !

Three-loop corrections needed: theory estimations [3]

	δ_1 :	δ_2 :	δ_3 :	δ_4 :	δ_5 :	$\delta\Gamma_Z$ [MeV]
	$\mathcal{O}(\alpha^3)$	$\mathcal{O}(\alpha^2\alpha_s)$	$\mathcal{O}(\alpha\alpha_s^2)$	$\mathcal{O}(\alpha\alpha_s^3)$	$\mathcal{O}(\alpha_{bos}^2)$	$\sqrt{\sum_{i=1}^{5}\delta_i^2}$
TH1	0.26	0.3	0.23	0.035	0.1	0.5
TH2	0.13	0.15	0.11	0.017	$\mathbf{10^{-4}}$	$\sqrt{\sum_{i=1}^{5}(\delta_i/2)^2} \sim \mathbf{0.2}$
TH3	0.026	0.03	0.023	0.0035	$\mathbf{10^{-4}}$	$\sqrt{\sum_{i=1}^{5}(\delta_i/10)^2} \sim \mathbf{0.05}$

Table 2: At FCC-ee: $\mathbf{\Delta\Gamma_Z \sim 0.1}$ **MeV**.

TH1 = 0.5 MeV (2016): Estimate of residual uncertainty of theoretical errors for Γ_Z [4]. Does not match the FCC-ee demand.

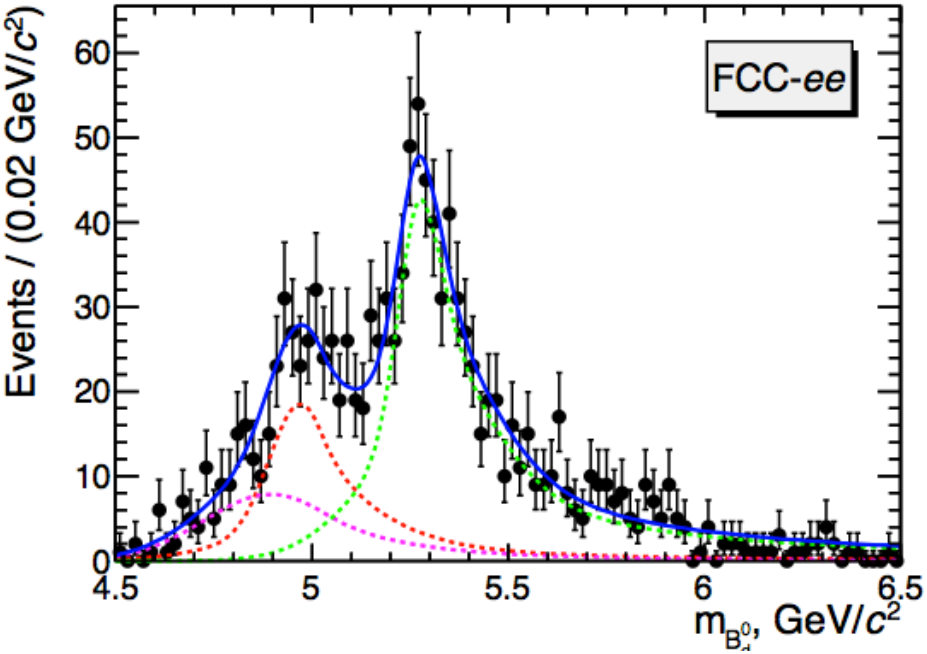
TH2 = 0.2 MeV: Value derives from TH1 by assuming the uncertainty ("no-go") to be solved ("how-to") by calculating the unknowns at an accuracy of 50% (1 digit). Would be not sufficent.

TH3 = 0.05 MeV: Like TH2, but assuming an accuracy of 10% (corresponding to a knowledge of 2 relevant digits) for the so far unknown weak 3-loops and QCD 4-loops. Matches the demand.

Term δ_5 was unknown in TH1 and was determined in [3] with 4 relevant digits. The δ_5 is 5 times bigger than its assumed uncertainty in TH1!

Example of B physics at FCC-ee - $B^0 \rightarrow K^{*0} \tau^+\tau^-$

- Persistent tensions seen in FCNC decays $b \rightarrow s\ \ell^+\ell^-$ w.r.t. SM / QCD, e.g. $B^0 \rightarrow K^{*0}\ \mu^+\mu^-$, $B^0 \rightarrow K^{*0}\ e^+e^-$
- A challenging channel: $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$
- At baseline **Tera Z** luminosity, 10^3 events of reconstructed signal. Angular analysis possible.
- Makes use of partial reconstruction technique to solve the kinematics of the decay. Sensitivity relies on vertexing performance (crucial)
- *Another interesting and more challenging mode is* $B_s \rightarrow \tau^+\tau^-$
- *Also FCNC in Z decays:* $Z \rightarrow \mu e, \mu\tau, e\tau$

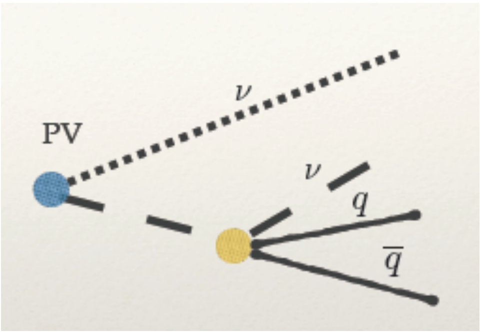


Backgrounds (pink) and (red), signal in green.
Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector.

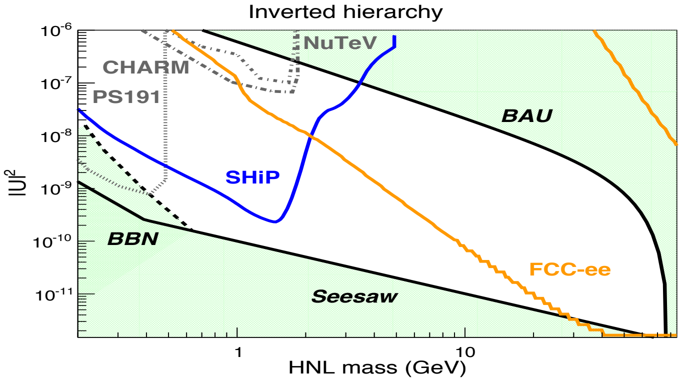
BSM Physics with TeraZ

- **Search for sterile neutrinos in Z decays:** Number of events depends on mixing between N and ν, and m_N

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



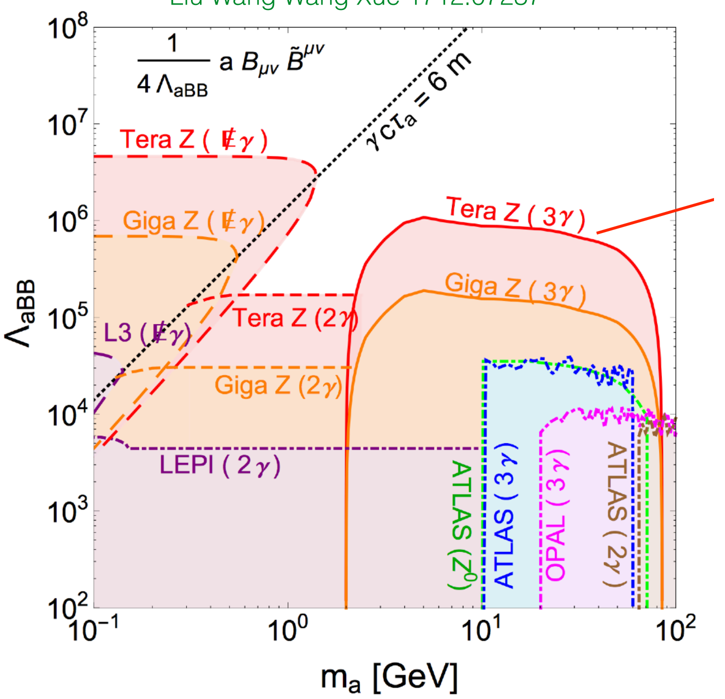
(Very) Displaced SV



- **Search for axions in Z decays:** Axion Like Particles (ALPS) appear in several extensions of the SM

For Tera Z $\mathrm{BR}[Z \to \gamma a(\gamma\gamma)] \lesssim 3 \times 10^{-9}$
[current LEP limit $\lesssim 5 \times 10^{-6}$]

Liu Wang Wang Xue 1712.07237

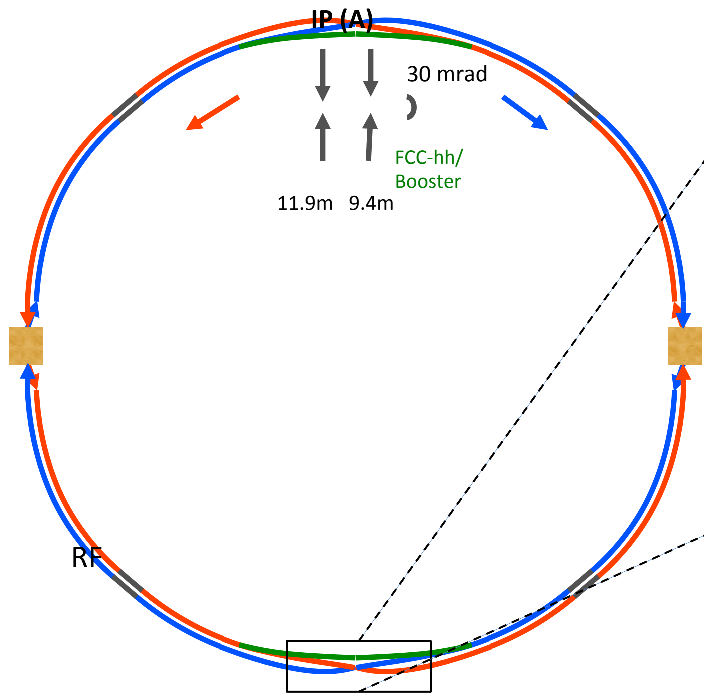


Conclusions

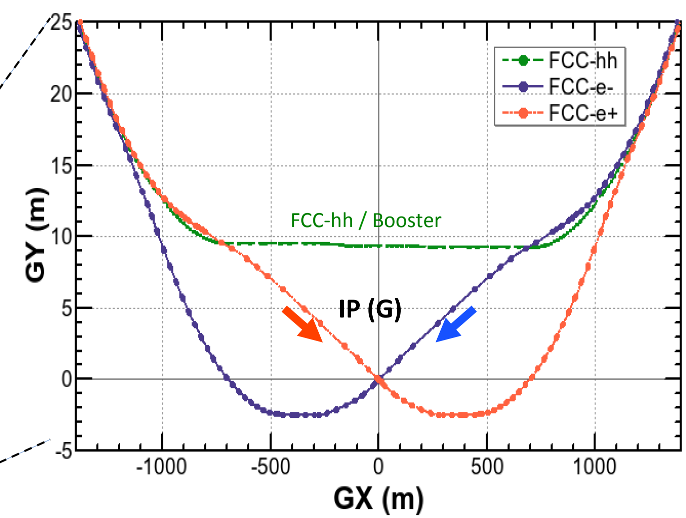
- The efforts of the past 2-3 years have shown that FCC is not just a repetition of LEP with huge statistics: **the considerable physics potential** has required, and will **require new strategies, new solutions and a lot of interesting work for experiment and theory**.
- The prize is a **gain of 1 – 2 orders of magnitude in precision for observables in the Z, W, Higgs, top sector: a change of scenario for eletroweak physics**
- **Extend considerably the explored territory for new physics (direct and indirect)**

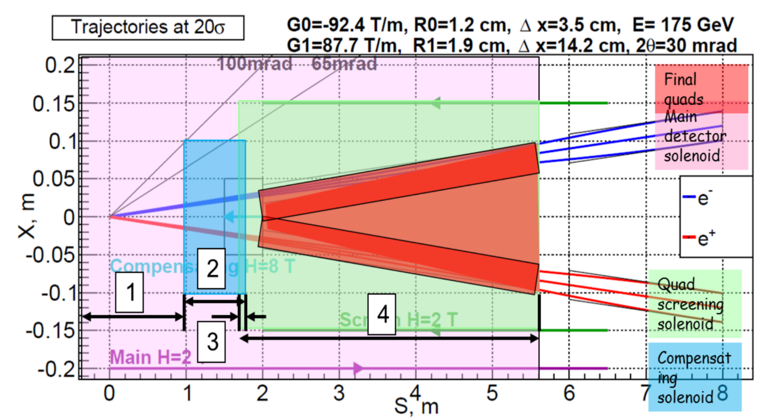
Backup slides

FCC-ee baseline layout



Asymmetric beam crossing at the IPs
Minimize synchrotron radiation





- Asymmetric optics with beam crossing angle of 30 mrad
- IP displaced by about 9.4 m wrt proton beam line
- Maximum magnetic field 2T (compensation)
- Beam pipe radius 15 mm
- Last quadrupole L* =2.2 m
- Detector has to "stay above" the 100 mrad line

A_{FB}^{bb} : from LEP to FCC-ee

LEP combination dominated by statistics, projection for FCC-ee considers conservative reduction of various uncertainty components

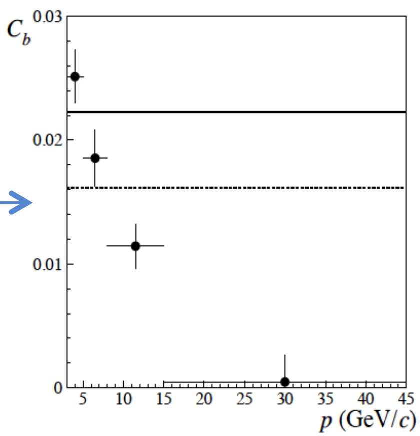
	ΔAFB(b)
STATISTICS	0.00156
UNCORRELATED SYSTEMATIC	0.00061
QCD CORRECTION	0.00030
LIGHT QUARK FRAGMENTATION	0.00013
SEMILEPTONIC DECAYS MODELLING	0.00013
CHARM FRAGMENTATION	0.00006
BOTTOM FRAGMENTATION	0.00003
TOTAL SYSTEMATIC ERROR	0.00073

→ 0.00002 (statistics)

→ Most of this depends on stat. (uncorrelated systematic)

→ Can be reduced with improved calculations and proper choices of analysis methods (e.g. measure the asymmetry as a function of jet parameters, etc.) (QCD correction)

Simple method to reduce QCD corrections for lepton analysis: raise cut un lepton momentum, as statistics is no longer dominant



Improved measurements also for the charm sector: A_{FB}^{cc}

Precisions on coupling ratio factors, A_f

$$\mathcal{A}_e = \frac{2 g_{Ve} g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2 g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
$\mathcal{A}_e$	$5. \times 10^{-5}$	$1. \times 10^{-4}$	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	$4. \times 10^{-5}$	$3. \times 10^{-4}$	15
$\mathcal{A}_b$	2×10^{-4}	30×10^{-4}	5
$\mathcal{A}_c$	3×10^{-4}	80×10^{-4}	4
$\sin^2\theta_{W,eff}$ (from muon FB)	10^{-7}	$5. \times 10^{-6}$	100
$\sin^2\theta_{W,eff}$ (from tau pol)	10^{-7}	6.6×10^{-6}	75

Relative precisions, but for $\sin^2\theta_{eff}$

Partial widths ratio (R_l)

- $R_l = \Gamma_l/\Gamma_{had} = \sigma_l/\sigma_{had}$ is a robust measurement, necessary input for a precise measurement of lepton couplings (and $\alpha_s(m^2_Z)$)
- Exploiting FCC-ee potential requires an accurate control of acceptance, particularly for the leptons
  - acceptance uncertainties were sub-dominant at LEP, but need to be reduced by a factor ≈ 5 to match precision goal on R_l of 5 10^{-5}
  - knowledge of boundaries, mechanical precisions: need to exploit 40 years of improvements in technology, need to use clever selections (at LEP was necessary only for luminosity)
  - fiducial acceptance is asymmetric in azimuth at FCC-ee because of 30 mrad cross angle→ boost in trasverse direction $\beta_x = tg(\alpha/2) \approx 0.015$, however can measure ϕ^* and $\cos(\theta^*)$ event by event for dileptons !

Measurement of R_b : double tagging

Divide event in two hemispheres according to thrust direction

- F_1 fraction of single tag
- F_2 fraction of double tag

$$F_1 = R_b(\varepsilon_b - \varepsilon_{uds}) + R_c(\varepsilon_c - \varepsilon_{uds}) + \varepsilon_{uds}$$

$$F_2 = R_b(C_b\varepsilon_b^2 - \varepsilon_{uds}^2) + R_c(\varepsilon_c^2 - \varepsilon_{uds}^2) + \varepsilon_{uds}^2$$

$$R_b \approx \frac{C_b F_1^2}{F_2}$$

$$\varepsilon_b \approx \frac{F_2}{C_b F_1}$$

LHC detectors and current taggers can reach three times b tagging efficiency at same suppression of charm and uds, in a more harsh environment → sizeable improvement possible at FCC-ee

- statistical uncertainty coming from double tag sample
- **systematic uncertainty from hemisphere correlations becomes dominating**

Efficient and pure secondary vertex finding will be important to study gluon splitting and nasty sources of correlations (e.g. momentum correlations) → **keep b-tag efficiency flat in momentum**

FCC-ee projections conservatively consider reduction of uncertainty on hemisphere correlations from ≈0.1% (LEP) to ≈0.03%

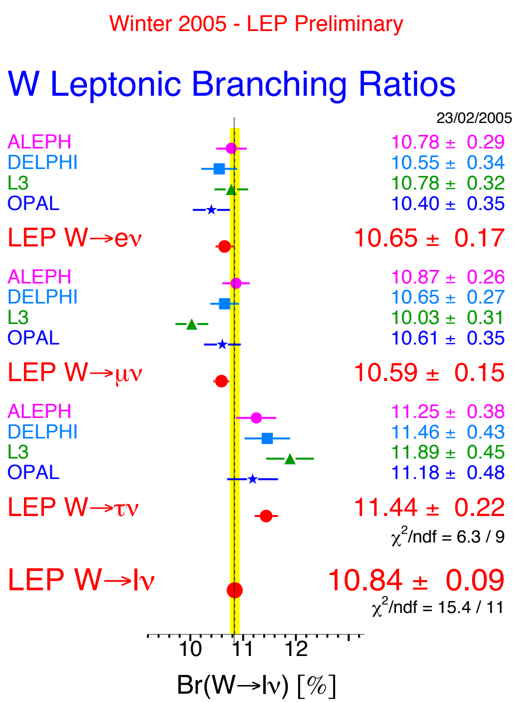
Improved measurements also for the charm sector: R_c

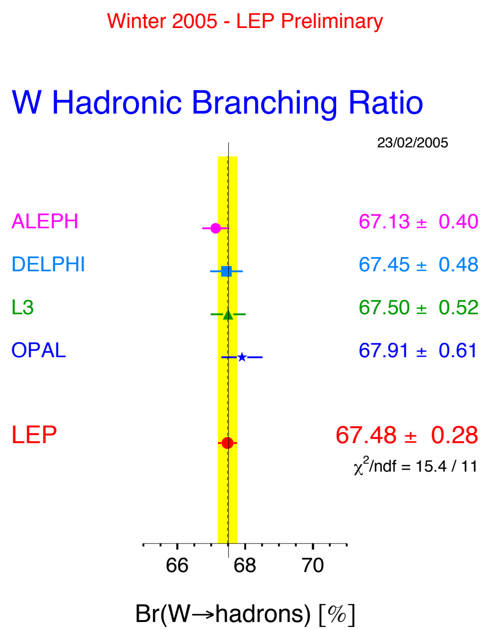
Precisions on normalized partial widths $R_f = \sigma_f / \sigma_{had}$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
R_μ (R_ℓ)	10^{-6}	5×10^{-5}	20
R_τ	1.5×10^{-6}	10^{-4}	20
R_e	1.5×10^{-6}	3×10^{-4}	20
R_b	5×10^{-5}	3×10^{-4}	10
R_c	1.5×10^{-4}	15×10^{-4}	10

Relative precisions

W decay Branching Fractions





8/ab@160GeV + 5/ab@240GeV
➔ 30M+ 80M W-pairs

➔ ΔBR(qq) (stat) =[1] 10^{-4} (rel)
➔ $\Delta\alpha_S \approx (9\ \pi/2)\Delta BR \approx 2\ 10^{-4}$

➔ ΔBR(e/μ/τν)(stat)=[4]10^{-4} (rel)

requires excellent control of lepton id
i.e. cross contaminations in signal channels
(e.g., τ➔e,μ versus e,μ channels)

lepton universality test at 2% level
tau BR 2.8 σ larger than e/μ
➔ **FCCee @ 4 10^{-4} level**

quark/lepton universality at 0.6%
➔ **FCCee @ 10^{-4} level**

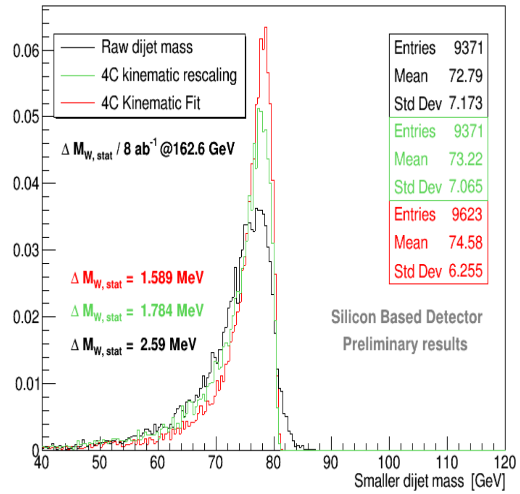
Flavor tagging ➔W coupling to c & b-quarks (V_{cs}, V_{cb} CKM elements)

W mass from di-jet invariant mass (standard at LEP)

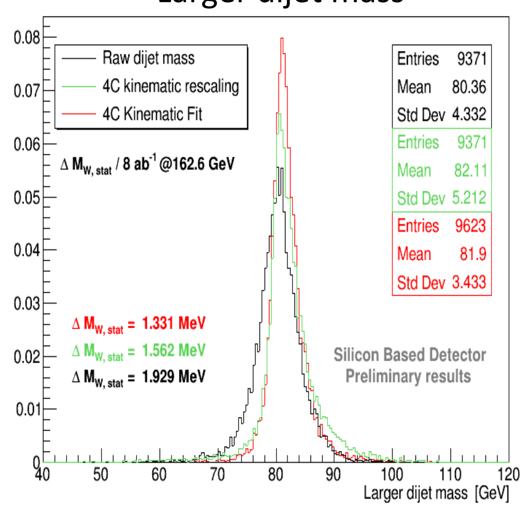
Marina Béguin

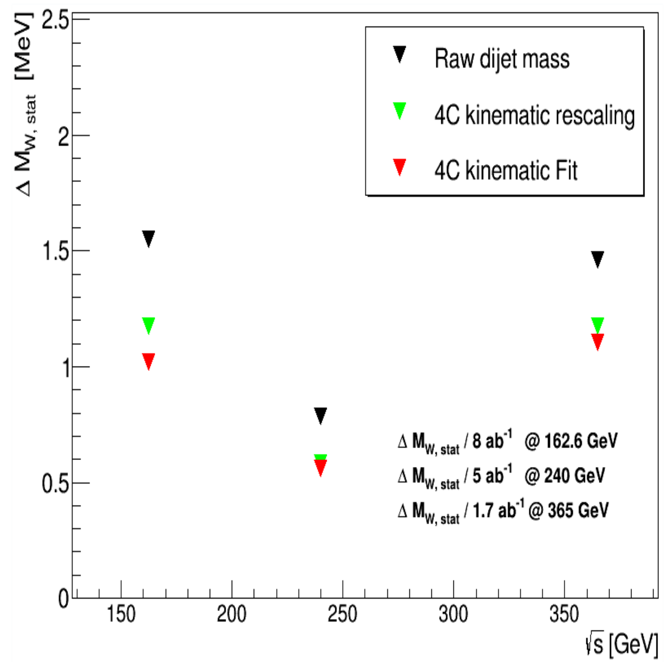
- Work in progress, started with the 4-quark channel, exploring resolution and kinematic fits (knowledge of beam energy crucial here, too !)
- Statistical uncertainty at the ≈ 1 MeV level
- Need to investigate how statistics can help in reducing LEP systematics (e.g. fragmentation, jet mass)
- Best result will be provided by the lvqq channel (no color reconnection)

Smaller dijet mass



Larger dijet mass





Statistical uncertainties with various kinematic fit option, as a function of the centre-of-mass