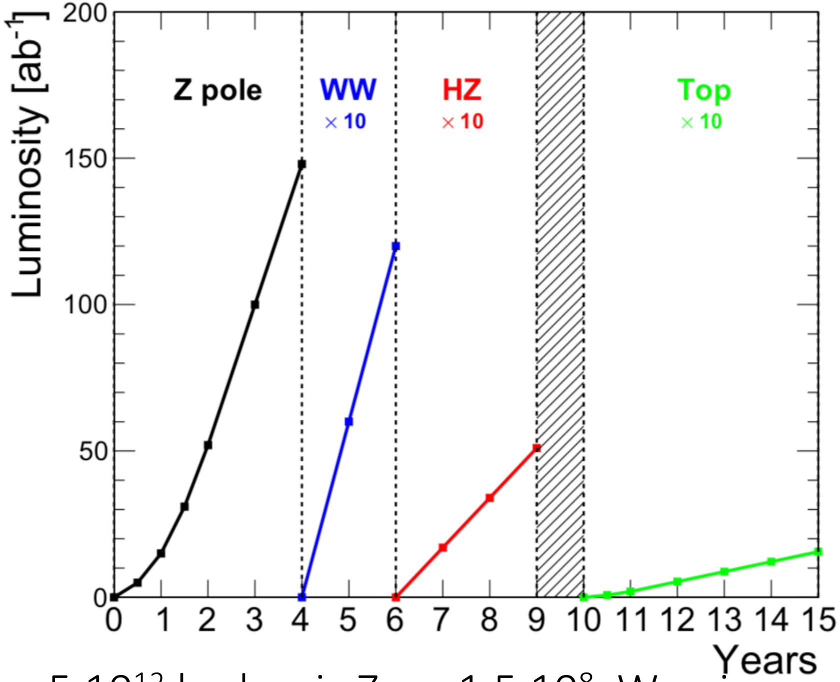
Electroweak Precision Physics at FCC-ee

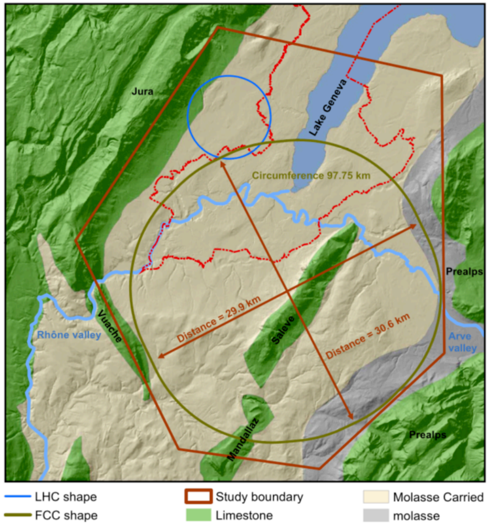
Paolo Azzurri – INFN Pisa

Weak Interactions and Neutrinos

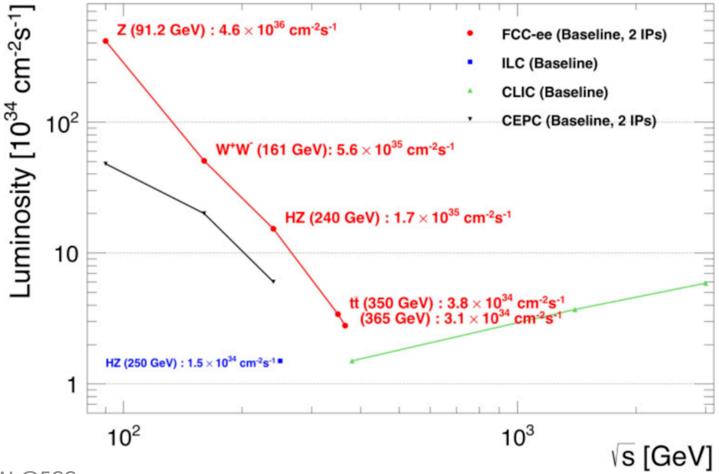
June 7-12, 2021

The FCC-ee





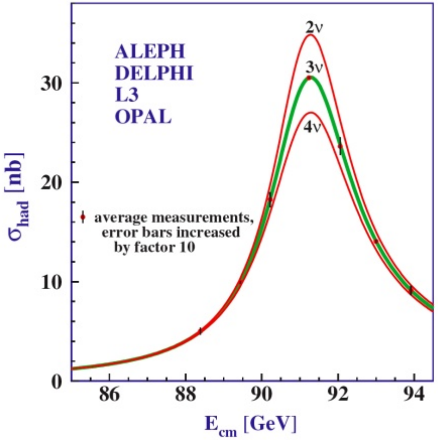
http://cern.ch/fcc



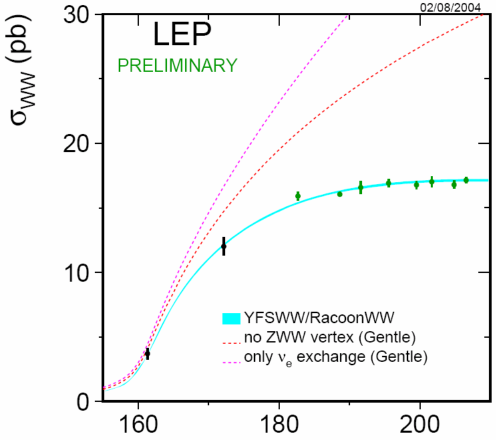
$5 \cdot 10^{12}$ hadronic Z
(10^5 LEP1)

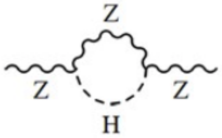
$1.5 \cdot 10^8$ W-pairs
(0.5 10^4 LEP2)

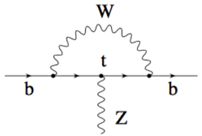
The LEP results and legacy

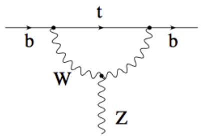


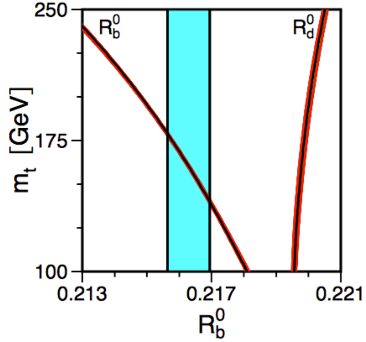
N=2.9840±0.0082



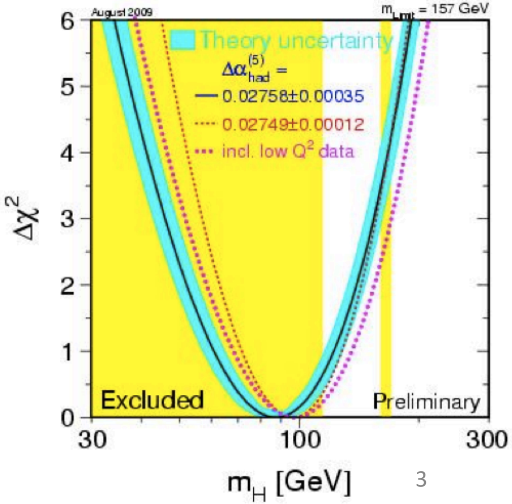








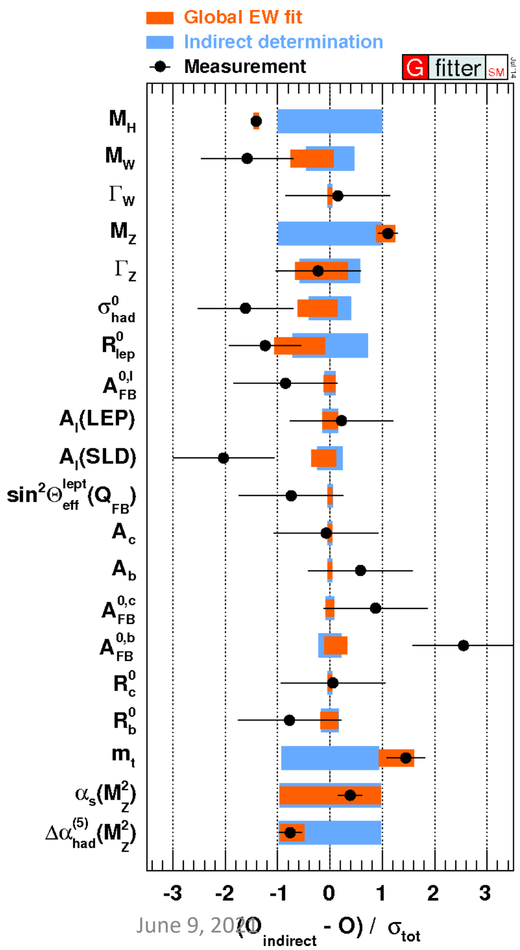
mt = 174.3 ± 5.1 GeV



$$m_W/(\mathrm{GeV}) = 80.409 - 0.507\left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1\right) + 0.542\left[\left(\frac{m_t}{178\mathrm{GeV}}\right)^2 - 1\right] - 0.05719\ell n(m_H/100\ \mathrm{GeV}) - 0.00898\ell n^2(m_H/100\ \mathrm{GeV})$$

$$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23101 + 0.00969\left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1\right) - 0.00277\left[\left(\frac{m_t}{178\ \mathrm{GeV}}\right)^2 - 1\right] + 0.0004908\ell n(m_H/100\ \mathrm{GeV}) + 0.0000343\ell n^2(m_H/100\ \mathrm{GeV})$$

http://gfitter.desy.de/Standard_Model



FCCee EW precision

Eur. Phys. J. C (2019) 79:474

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91,186,700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2,495,200 ± 2300	8	100	From Z line shape scan beam energy calibration
R^Z_ℓ ($\times 10^3$)	20,767 ± 25	0.06	0.2–1	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R^Z_ℓ above
R_b ($\times 10^6$)	216,290 ± 660	0.3	$<$ 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	41,541 ± 37	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta^{eff}_W$ ($\times 10^6$)	231,480 ± 160	3	2–5	From $A^{\mu\mu}_{FB}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	128,952 ± 14	4	Small	From $A^{\mu\mu}_{FB}$ off peak
$A^{b,0}_{FB}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A^{pol,\tau}_{FB}$ ($\times 10^4$)	1498 ± 49	0.15	$<$ 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV/c^2)	80,350 ± 15	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R^W_ℓ
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns

FCCee detector concepts

International Detector for Electron-positron Accelerators (IDEA)

- vertex detector
- drift chamber
- preshower detector
- dual-readout calorimeter
- muon system

CLIC-Like Detector (CLD)

Concept	CLICdet	CLD
Vertex inner radius (mm)	31	17
Tracker half length (m)	2.2	
Tracker outer radius (m)	1.5	2.1
ECAL absorber	W	
ECAL X_0	22	
HCAL absorber	Fe	
HCAL λ_I	7.5	5.5
Solenoid field (T)	4	2
Overall height (m)	12.9	12.0
Overall length (m)	11.4	10.6

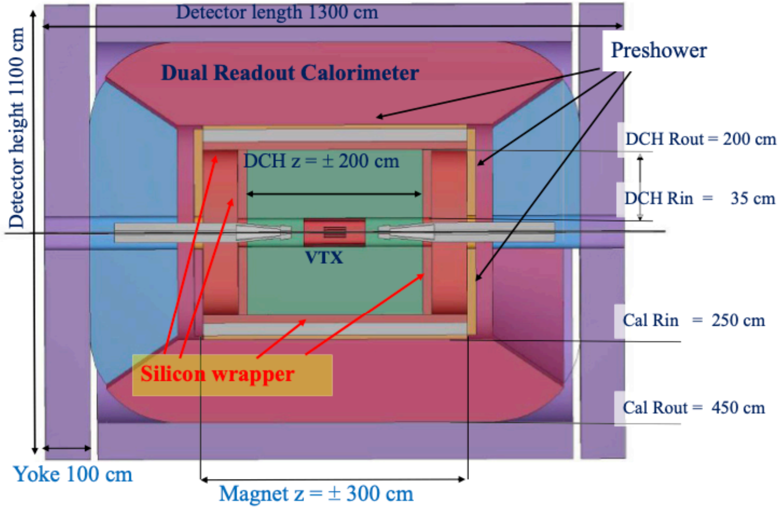


Fig. 7.9. Schematic layout of the IDEA detector.

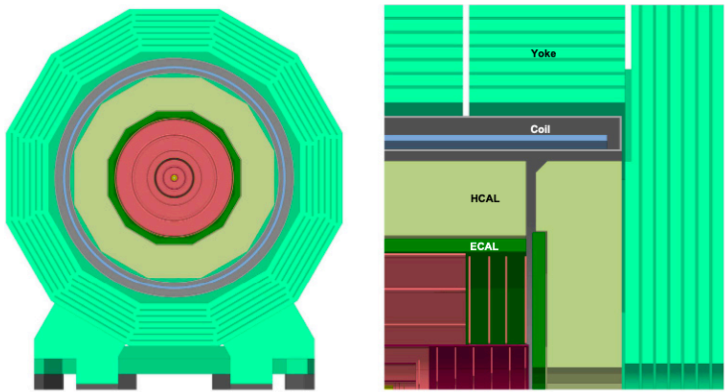
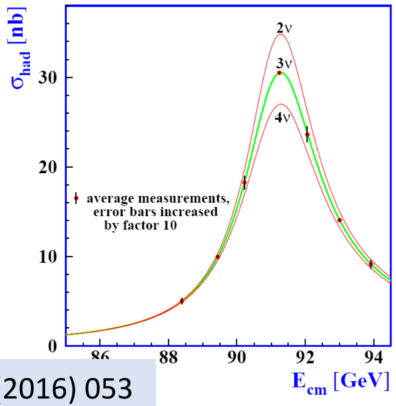
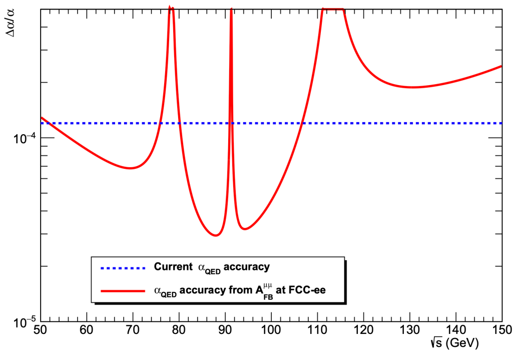


Fig. 7.4. The CLD concept detector: end view cut through (left), longitudinal cross section of the top right quadrant (right).

Z pole lineshape and decay rates



Data taken at 87.9 GeV (40/ab) + **91.2 GeV (80/ab)** + 93.9 GeV (40/ab)
resonant depolarisation on a continuous basis for both beams (**Δ**E=100 KeV=**Δ**m $_Z$ =**Δ*Γ***$_Z$)



Direct measurement of $\alpha_{QED}(m_Z^2)$

JHEP 1602 (2016) 053

High precision of FCCee will require higher order perturbative calculations : a **bottleneck** will be represented by the hadronic contributions to the vacuum polarization

Rely of a self-normalizing quantity, the forward-backward asymmetry

$\Delta\boldsymbol{\alpha}_{QED}(m_Z) \approx$ **3** 10^{-5} **(rel)**

$$A_{FB}^{\mu\mu} = A_{FB,0}^{\mu\mu} + \frac{3}{4}\frac{a^2}{v^2}\frac{\mathcal{I}}{\mathcal{G}+\mathcal{Z}}.$$

$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta A_{FB}^{\mu\mu}}{A_{FB}^{\mu\mu} - A_{FB,0}^{\mu\mu}} \times \frac{\mathcal{Z}+\mathcal{G}}{\mathcal{Z}-\mathcal{G}} \simeq \frac{\Delta A_{FB}^{\mu\mu}}{A_{FB}^{\mu\mu}} \times \frac{\mathcal{Z}+\mathcal{G}}{\mathcal{Z}-\mathcal{G}},$$

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma_{had}}$$

↓

$$\left(g_{Af}\right)^2 + \left(g_{Vf}\right)^2$$

- R_b Very sensitive to rad. vertex corrections due to new particles
- Important to sort out LEP b-couplings issue
- Measurement exploits the presence of two b hadrons and b-tagging.
- **Independent** from **b-tagging efficiency**, but **not** from **hemisphere correlations**
- b-tagging performance (vertex detectors) helps in reducing the correlation
- Correlations sources to be identified and studied with data

$\Delta R_b \approx$ **1** (**5-20**) 10^{-5} **stat** (**syst**)

$\Delta R_c \approx$ **3** (**20-50**) 10^{-5} **stat** (**syst**)

$\Delta R_\ell \approx$ **0.3** (**1-5**) 10^{-5} **stat** (**syst**) **(rel)**

⇒ $\Delta\boldsymbol{\alpha}_S(m_Z) \approx$ **1** (**4-20**) 10^{-5} **stat** (**syst**)

Z pole asymmetries

$$A_f = \frac{2 g_{Vf} g_{Af}}{(g_{Vf})^2 + (g_{Af})^2}$$

$$\sin^2\theta_{eff}^{\,l} \equiv \frac{1}{4}\left(1 - \frac{g_{Vl}}{g_{Al}}\right)$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_f$$

Can measure for e,**μ**,**τ**,c,b

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

Can measure with **τ**' s

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

tau polarization A

Polarization vs the production angle allows A_e to be separated from A_t : Universality test and $\sin^2\boldsymbol{\theta}_W$

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

➔ $\Delta A_\tau \approx$ **2** (**10-20**) 10^{-5} **stat** (**syst**)

sizably improve **b asymmetry**

- combine info of all particles in the hemisphere
- different systematic effects [QCD corrections to be improved]

➔ $\Delta A_b \approx$ **0.2** (**10-30**) 10^{-5} **stat** (**syst**) $\Delta A_c \approx$ **0.3** (**20-40**) 10^{-5} **stat** (**syst**)

Golden channel:

➔ $\Delta A_\mu \approx$ **0.3** (**0.9**) 10^{-5} **stat** (**syst**)

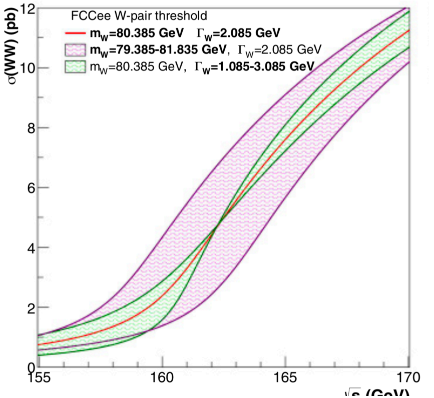
$A_{FB}(\mu^+\mu^-)$ and $A_{FB}(\tau^+\tau^-)$ can also be considerably improved.
$A_{FB}(e^+e^-)$ more difficult because of t-channel.

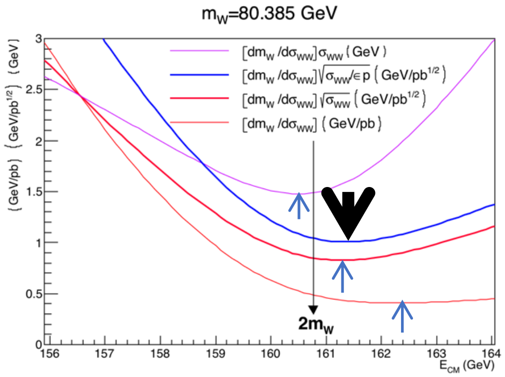
➔ **$\Delta\ \sin^2\theta_{eff} \approx$ 0.6 10^{-5} (syst)**

S-matrix approach : trade statistical power for reduced theoretical assumptions

WW threshold lineshape

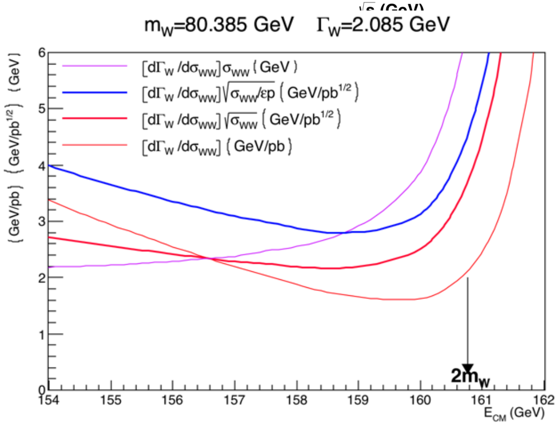
arXiv:1703.01626
arXiv:1909.12245
CDR(V2) Eur. Phys. J. ST 228 (2019) 261
Eur.Phys.J.C 80 (2020) 1 (with CEPC)





5/ab@**157.3** GeV
+7/ab@**162.6** GeV

Δm_W=0.5 MeV **$\Delta\Gamma_W$=1.2 MeV**



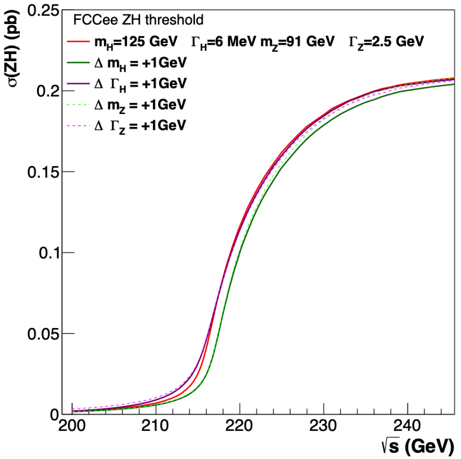
$(dm_W/d\sigma_{WW})_{min}$=0.5MeV/fb

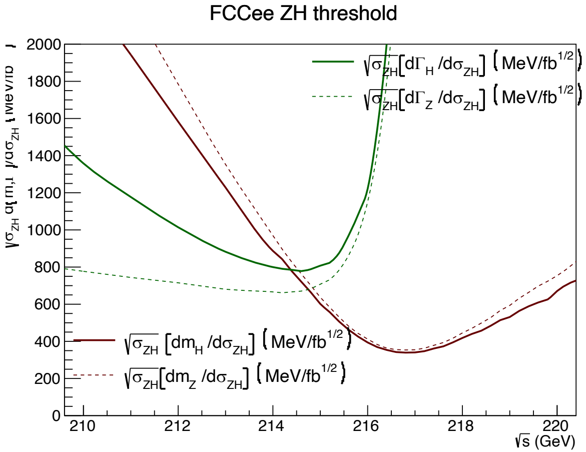
need syst control on :

- ΔE(beam)<0.5 MeV (**6x10^{-6}**)
- Δε/ε, ΔL/L < **2 10^{-4}**
- $\Delta\sigma_B$<1 fb (2 **10^{-3}**)

Need to improve TH uncertainty to <1fb (2 **10^{-4}**)

interlude : the ZH threshold



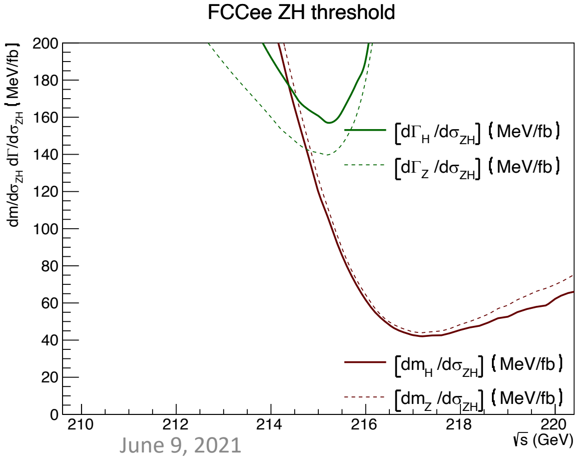


Optimal data-taking point for min Δm_H(stat)
Is $E_{CM} \simeq m_Z+m_H+0.6 \sim$ 217 GeV

$\sqrt{\sigma_{ZH}}(dm_H/d\sigma_{ZH})_{min}$=350 MeV/√fb

With 5/ab ⇒ **Δ**m_H(stat) = **5 MeV**
Not including $Q=\sqrt{\sum \varepsilon_i p_i}$ (over all channels)

$(dm_H/d\sigma_{ZH})$=40 MeV/fb



need syst control on :
- ΔE(beam)<5 MeV (**5×10^{-5}**)
- Δε/ε, ΔL/L < **10^{-3}**
- $\Delta\sigma_B$<0.1 fb (~**10^{-3}**)

On the way to the electron-Yukawa

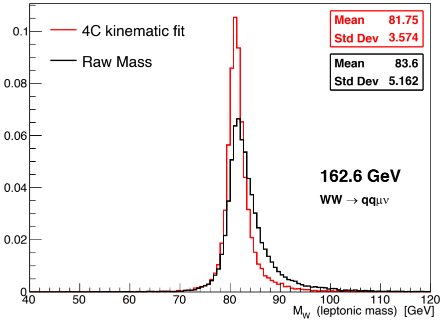
Taking some /ab at $E_{CM} \simeq$214-215GeV (off shell) should be sensitive to **$\Delta\Gamma_H$**≃40 MeV
⟹ *not very interesting*

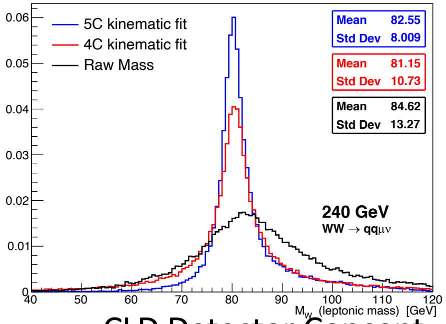
W kinematic reconstruction

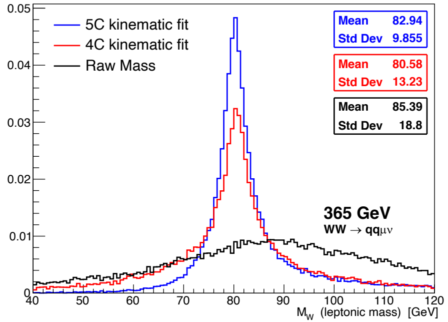
12/ab @157-162 GeV : **50 10^6 WW**
5/ab @240 GeV : **80 10^6 WW**
1.65/ab@365 GeV: **20 10^6 WW**
Total ~150M WW

$$M_Z^2 = s\frac{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 - \beta_1\beta_2|\sin(\theta_1+\theta_2)|}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 + \beta_1\beta_2|\sin(\theta_1+\theta_2)|}$$

θ, β: jet polar angles and velocities







CLD Detector Concept

M. Béguin, PhD thesis, 2019 https://cds.cern.ch/record/2710098
PA, M. Béguin, E.Locci *PoS* EPS-HEP2019 (2020) 653
https://doi.org/10.22323/1.364.0653

➔ Δm_W (stat) ~ 0.5 MeV
➔ $\Delta\Gamma_W$ (stat) ~ 1 MeV

W kinematic reconstruction

ΔE_{CM}=0.3 MeV at E_{CM}=162GeV with Resonant depolarization

$$M_Z^2 = s\frac{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 - \beta_1\beta_2|\sin(\theta_1+\theta_2)|}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 + \beta_1\beta_2|\sin(\theta_1+\theta_2)|}$$

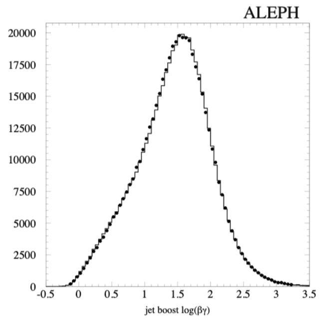
How to obtain ΔE_{beam}~1MeV at E_{CM}=240-365 GeV ?
Can make use of radiative Z-returns (Zγ) and ZZ events

What about other syst ?

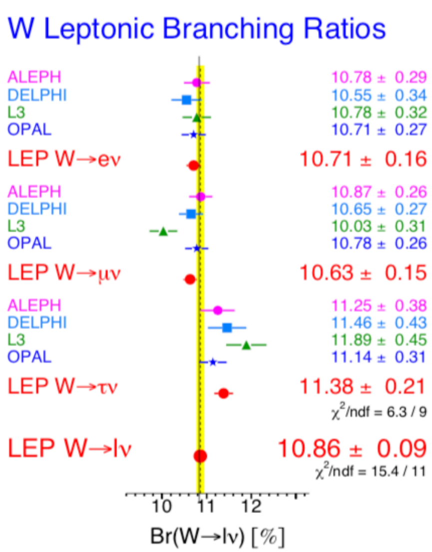
Table 9: Summary of the systematic errors on m_W and Γ_W in the standard analysis averaged ove 183-209 GeV for all semileptonic channels. The column labelled $\ell\nu q\bar{q}$ lists the uncertainties in m_W use in combining the semileptonic channels.

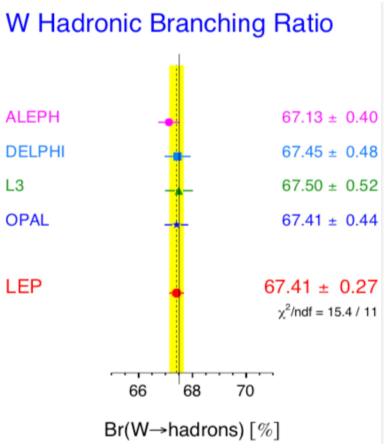
	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
Source	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	16	6
Jet energy resoln	4	2	8	4	20	18	36	22
Jet angle	5	5	4	5	2	2	3	2
Jet angle resoln	3	2	3	3	6	7	8	7
Jet boost	17	17	20	17	3	3	3	3
Fragmentation	10	10	15	11	22	23	37	25
Radiative corrections	3	2	3	3	3	2	2	2
LEP energy	9	9	10	9	7	7	10	8
Calibration ($e\nu q\bar{q}$ only)	10	-	-	4	20	-	-	9
Ref MC Statistics	3	3	5	2	7	7	10	5
Bkgnd contamination	3	1	6	2	5	4	19	7

lepton and jet uncertainties from (Z) calibration data



W decay BR





Lept universality test at 2% level
tau BR ~2.6 σ larger than e/mu
➔ *FCCee @ 3-4 10^{-4} level*

Scaling major syst uncertainties with data luminosity (as stat)

q/ l universality at 0.5%
➔ *FCCee @ 10^{-4} level*

$$R_W = \frac{B_q}{1-B_q} = \left(1 + \frac{\alpha_S(m_W^2)}{\pi}\right) \sum_{i=u,c;j=d,s,b} |V_{ij}|^2.$$

Table 3.1: Relative precision on the determination of the W decay branching ratios. Final combined results with LEP2 data are compared to the projected precision obtainable with FCC-ee.

Decay mode relative precision	$B(W \to e\nu)$	$B(W \to \mu\nu)$	$B(W \to \tau\nu)$	$B(W \to qq)$
LEP2	1.5%	1.4%	1.8%	0.4%
FCC-ee	$3 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$1 \cdot 10^{-4}$

stringent test of CKM unitarity for the five lightest quarks

➔ $\Delta\alpha_S(m_W) \approx (9\pi/2)\Delta B_q \approx 10^{-3}$

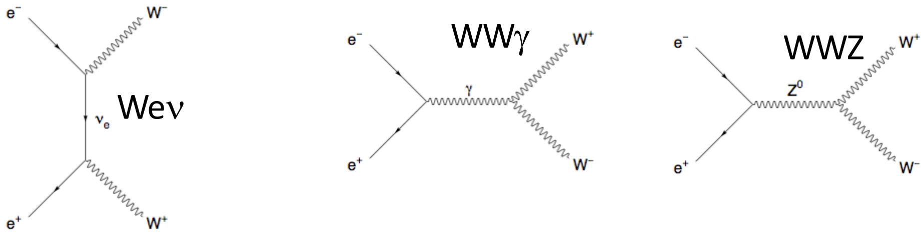
Flavor tagging can also allow to measure coupling to c & b-quarks (Vcs, Vcb,..) directly !

Δ $|V_{cs}|$ (rel) ≃ 3 10^{-4} **stat**
Δ $|V_{ub}|$ (rel) ≃ 3-5% **stat**
Δ $|V_{cb}|$ (rel) ≃ 0.2% **stat**

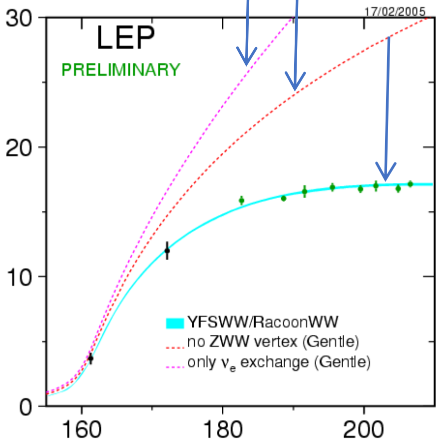
For lept BR will need excellent control of **lepton id** and cross contaminations in signal channels (τ➔e,μ and e,μ channels)

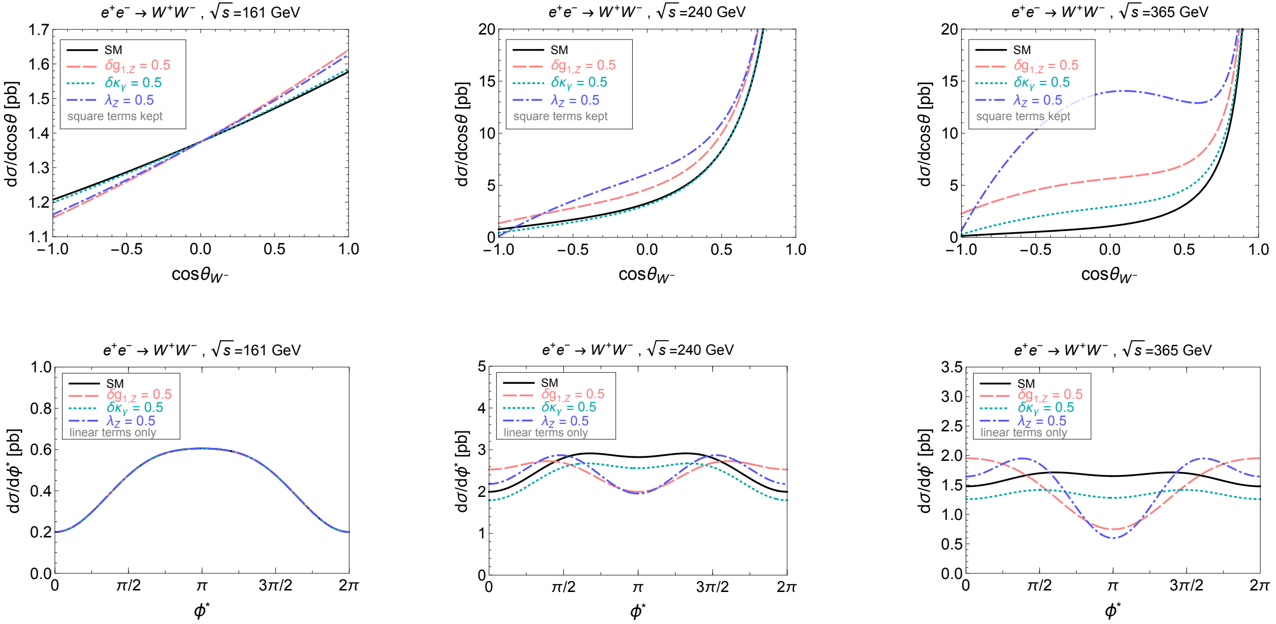
Less stringent requirements for syst uncertainty control for hadr BR

Gauge couplings



SU(2)⊗U(1) Gauge Cancellations



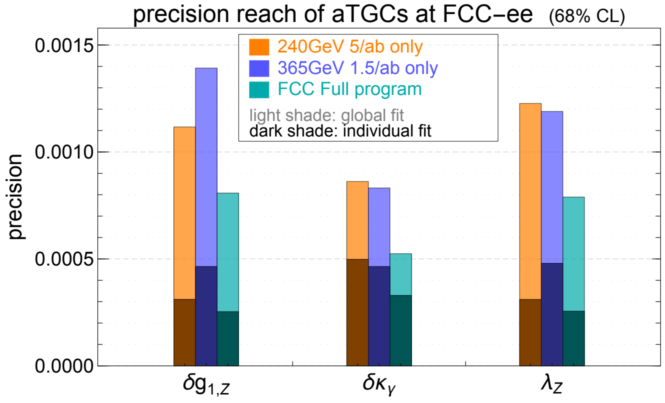


BSM can affect:
the **total rates** σ,
the **production angles** θ_W
the **decay angles** θ* ϕ*

Gauge couplings

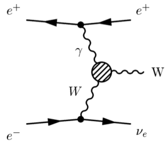
A binned chi-square fit is performed to estimate the precision reach of the three aTGCs at the FCCee.

Only the semileptonic channel, with one W decaying to e or μ is used. cThe chi-square is summed over all bins of the five angles, considering only statistical uncertainties.



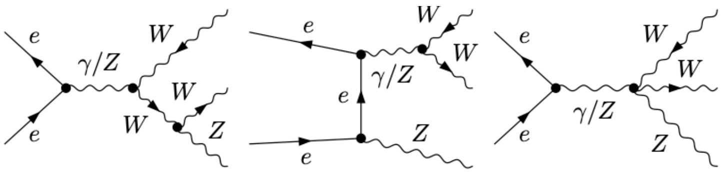
LEP2 precision : 2-4 10^{-2}

Other 4f processes



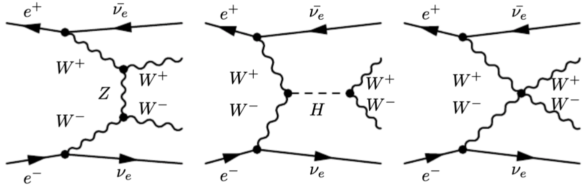
Channel relative precision	WW	ZZ	Weν	Zee
LEP2 183-209 GeV	0.8%	5%	8%	6%
FCCee 162 GeV	$2{\cdot}10^{-4}$		$5{\cdot}10^{-4}$	$5{\cdot}10^{-4}$
FCCee 240 GeV	$1{\cdot}10^{-4}$	$5{\cdot}10^{-4}$	$5{\cdot}10^{-4}$	$1{\cdot}10^{-3}$
FCCee 365 GeV	$3{\cdot}10^{-4}$	$1{\cdot}10^{-3}$	$5{\cdot}10^{-4}$	$1{\cdot}10^{-3}$

6f processes : tribosons



@356 GeV : Similar x-sections and luminosity wrt HL-LHC, but much better acceptance & purity

6f VBS

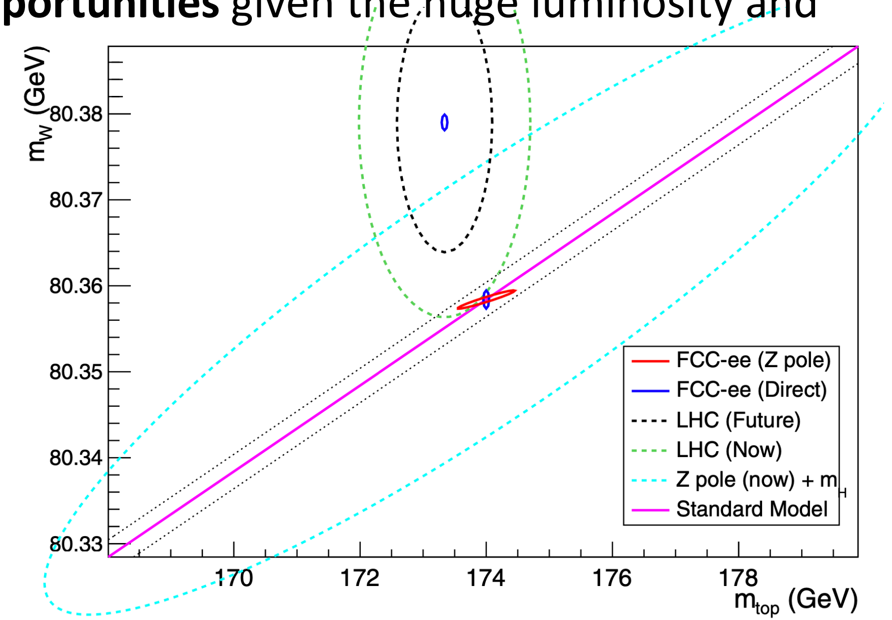


Kinematic threshold at VV mass very small cross sections

Potential of stringent TGC/QGC (EFT dim6 & dim8) explorations also with photons e+e- → WW**γ** ZZ**γ**

FCCee EW physics : rich program at and above the Z pole

- Core repetition of the LEP physics program with large **precision improvements (x20-500) capabilities, and a large number of additional opportunities** given the huge luminosity and higher collision energies
  - Z mass and width, $\alpha_{QED}(m_Z)$, N_ν
  - R_ℓ, $\alpha_S(m_Z)$, R_b, R_c, ..
  - A_{FB}, $\sin^2\theta_{eff}$
  - W mass and width (threshold and kinematic)
  - Direct W universality and CKM elements
  - Gauge couplings
  - Multiboson productions and scattering
  - Z radiative returns (Direct invisible Z width)
  - ....



- Work still ongoing to evaluate with more care all possibilities, design the measurements, estimate (limiting) systematics, study ways to overcome them, and reflect on the detector design requirements