Electroweak physics at the Z and W experimental capabilities

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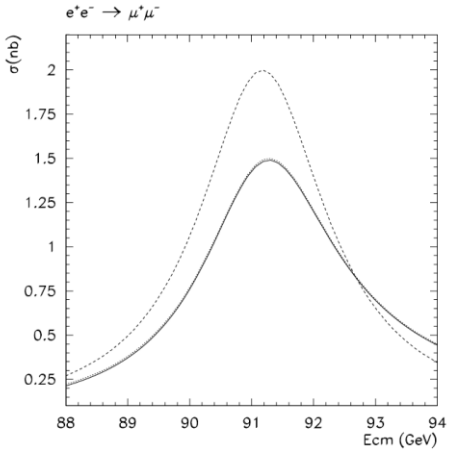
EWK CDR content

R.Tenchini, F.Piccinini *work in progress*

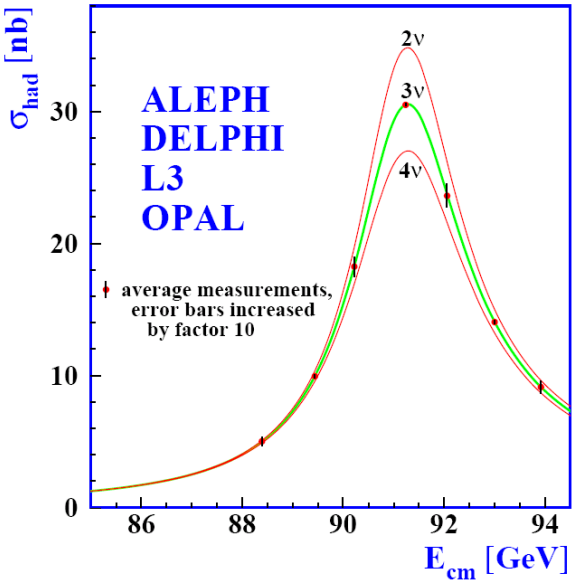
- 1. Electroweak physics at the Z pole
  - 1.a Experimental categorisation of Z decays
  - 1.b The Z lineshape
  - 1.c Measurement of the number of neutrino species
  - 1.d Measurement of Rb and Rc
  - 1.e Measurement of forward-backward asymmetries
- 2. Electroweak physics at the WW production threshold and above
  - 2.a Measurement of the W mass and width at threshold
  - 2.b Measurement of W decay branching fractions
  - 2.c Direct measurement of W mass and width
  - 2.d Single and double boson cross sections
  - 2.e Constraints on gauge couplings
  - 2.f Radiative Z events

the Tera Z pole precision

L~2 10^{36} ➔ ~4 10^{12} Z decays



continuous E_{CM} calibration (resonant depolarization)
Z **mass** and **width** : 10 KeV (stat) + 100 KeV (syst)



Radiation function calculated up to O(α^3) : 10^{-4} precision

relative precisions JHEP01(2014)164
R_l hadronic/leptonic width : 5 10^{-5}
R_b Zbb partial width : 5 10^{-5}
Invisible width : 10^{-3} N_ν ($Z\gamma$)

$\alpha_s(m^2_Z)$: 2 10^{-3}

$\alpha_{QED}(m_Z^2)$: 3 10^{-5}

Z pole acceptance

- @LEP acceptance effects at **10^{-4}**
  OK for cross sections at **10^{-3}** level.
  Main effects were due to track losses, angle mis-measurements and knowledge of boundaries.
- @FCCee exploit a statistical uncertainty at **10^{-5}** !

Example from ALEPH, EPJC 14 (2000) 1

Table 13. Exclusive $\mu^+\mu^-$ selection: examples of relative systematic uncertainties (in %) for the 1994 (1995) peak points

Source	$\Delta\sigma/\sigma$ (%)
Acceptance	0.05
Momentum calibration	0.006 (0.009)
Momentum resolution	0.005
Photon energy	0.05
Radiative events	0.05
Muon identification	$\simeq$ 0.001 (0.02)
Monte Carlo statistics	0.06
Total	0.10 (0.11)

@LEP detectors inner edge (**relevant boundary**) was known at the level of up to **20 µm**
The beam displacement (**vertical** and **horizontal**) becomes ineffective by choosing two fiducial regions (**loose and tight**) and **alternating them** in the two sides

@FCCee can **use similar methods for cross sections** measurements (e.g. different and alternating forward and backward fiducial regions), but still need to identify and know well the relevant boundaries (~1µm level)

couplings and Rb

couplings measurements require asymmetry and width ratios

$$A_{FB}(b) = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_b \text{ (LEP)} \longrightarrow \frac{g_{Vf}}{g_{Af}}$$

$$A_b = A_{FB}^{pol}(b) = 0.921 \pm 0.021 \text{ (SLC)}$$

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

$$R_b = 0.21646 \pm 0.00065 \text{ (LEP + SLC)} \longrightarrow \left(g_{Af}\right)^2 + \left(g_{Vf}\right)^2$$

- 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**
- Higher b-tagging performance (vertex detectors) helps in reducing the correlation
- Correlations sources should be identified and studied with data (done at LEP)

$\Delta R_b = \approx$ **1** (**5-20**) 10^{-5} **stat** (**syst**) $\Delta R_c = \approx$ **3** (**50**) 10^{-5} **stat** (**syst**)

Z asymmetries

- Z boson decay to ff : 3 observables from the direction and decay of the outgoing fermion

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

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

$$A_{FB} = \frac{s_F - s_B}{s_{tot}} = \frac{3}{4} A_e A_f$$ Can measure for e,μ,τ,c,b

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

Can measure with τ's

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

- Additional asymmetries with polarization of initial state :

$$A_{LR} = \frac{\sigma_l - \sigma_r}{\sigma_{tot}} = A_e$$

$$A_{FB}^{pol} = \frac{\sigma_{F,l} - \sigma_{B,l} - \sigma_{F,r} + \sigma_{B,r}}{\sigma_{tot}} = \frac{3}{4} A_f$$

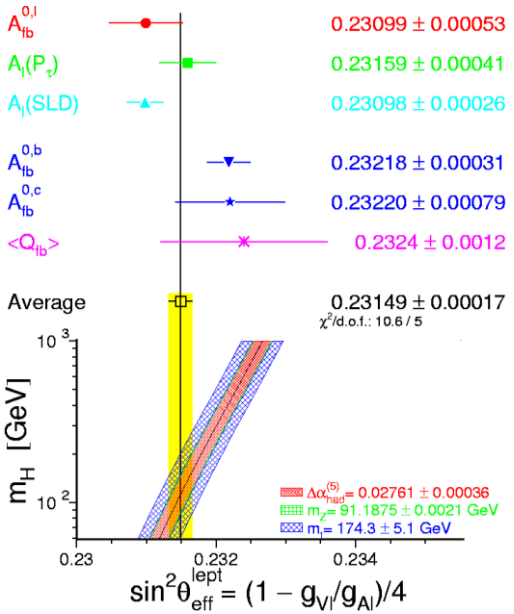
Z asymmetries

FCCee will sizably improve **b asymmetry**

- use semileptonic b decays
- use weighted charge of particles in the hemisphere

•different systematic effects [QCD corrections to be improved]

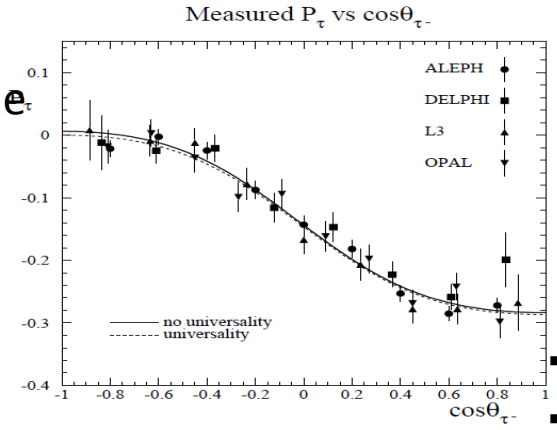
➔ $\Delta A_b \approx$**2** (**40**) 10^{-5} **stat** (**syst**) $\Delta A_c \approx$**3** (**40**) 10^{-5} **stat** (**syst**)



tau polarization A

Polarization vs the production angle allows A_e to be separated from A_τ : Universality test and $\sin^2\theta_W$

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



➔ $\Delta A_\tau \approx$**4** (**30**) 10^{-5} **stat** (**syst**)

➔ $\Delta A_e \approx$**5** (**10**) 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.

➔ $\Delta A_{FB}(e) \approx$**?** (**??**) 10^{-5} **stat** (**syst**)

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

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

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

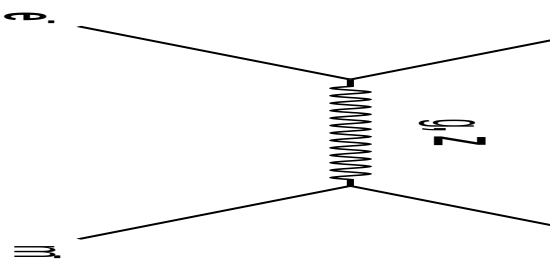
Z pole summary

Stolen from A. Blondel

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_{CM}	QED corrections
Γ_Z MeV	**Δρ (T)** **(no Δα!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_{CM}	QED corrections
R_ℓ	**α_s , δ_b**	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(161 GeV)	**0.00008** **±0.004** **0.001**	->lumi Statistics	**QED Bhabha corrections**
R_b	**δ_b**	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{FB}	**Δρ, ε_3 ,Δα (T, S)**	0.0171 ±0.0010	Z peak	**0.000003** **±0.00001**		

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

Patrick Janot: arXiv:1512:05544, JHEP 2016(2) 1



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

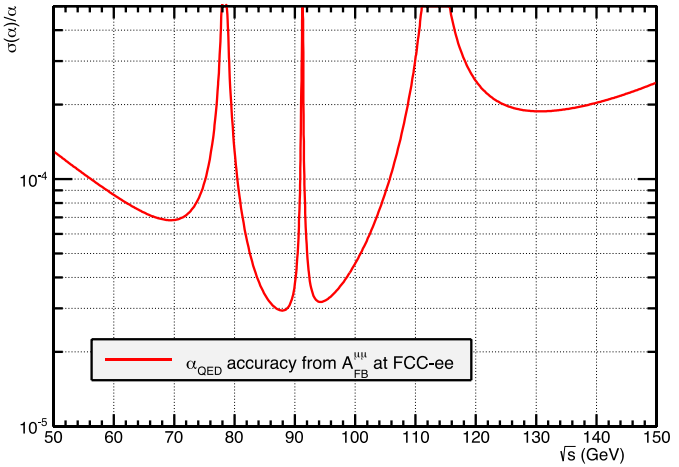
Rely of a self-normalizing quantity, the forward-backward asymmetry

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

$$\sigma\left(A_{\rm FB}^{\mu\mu}\right) = \sqrt{\frac{1-A_{\rm FB}^{\mu\mu\,2}}{\mathcal{L}\sigma_{\mu\mu}}}.$$

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

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



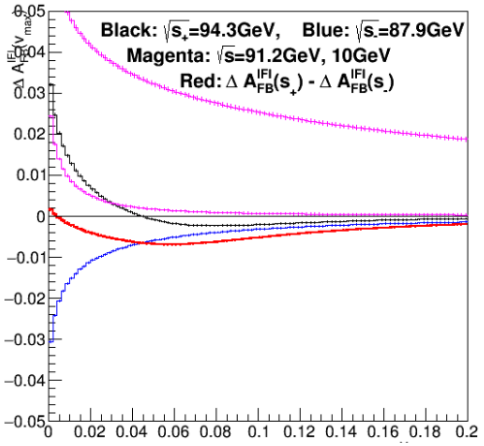
Optimal centre-of-mass energies for a 3×10^{-5} uncertainty on α_{QED} :
$\sqrt{s}_- =$ **87.9 GeV** and $\sqrt{s}_+ =$ **94.3 GeV**

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

Two measurements : $\alpha_- \equiv \alpha_{\rm QED}(s_-)$ and $\alpha_+ \equiv \alpha_{\rm QED}(s_+)$,

Solve for $\alpha_0 = \alpha_{QED}(m_Z^2)$

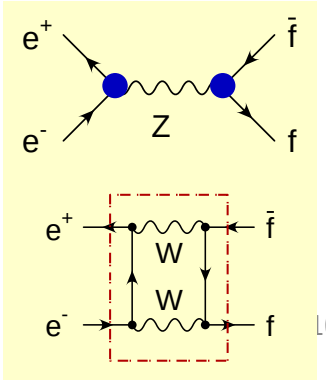
$$\frac{1}{\alpha_0} = \frac{1}{\alpha_\pm} + \beta \log \frac{s_\pm}{m_Z^2}$$



$$\frac{\Delta\alpha_0}{\alpha_0} \simeq 0.528\frac{\Delta A_{\rm FB}}{A_{\rm FB}}(s_-) + 0.563\frac{\Delta A_{\rm FB}}{A_{\rm FB}}(s_+)$$

Type	Source	Uncertainty
Experimental	$E_{\rm beam}$ calibration	1×10^{-5}
	$E_{\rm beam}$ 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, IFI)	$< 10^{-6}$
	Missing EW higher orders	few 10^{-4}
	New physics in the running	0.0
Total (except missing EW higher orders)	Systematics	1.2×10^{-5}
	Statistics	3×10^{-5}

IFI at better than 1% to reach the required precision on $\alpha_{QED}(m_Z^2)$: **work in progress**



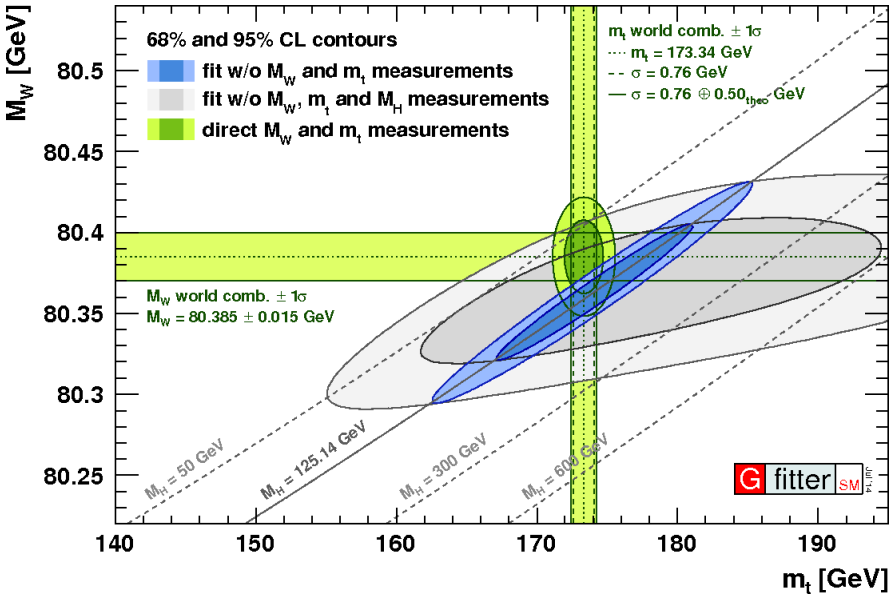
Box + Vertex EW correction

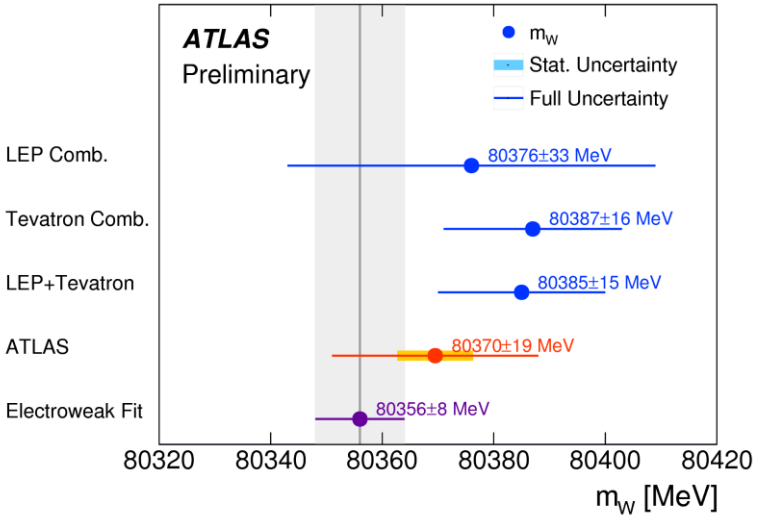
the OkuW

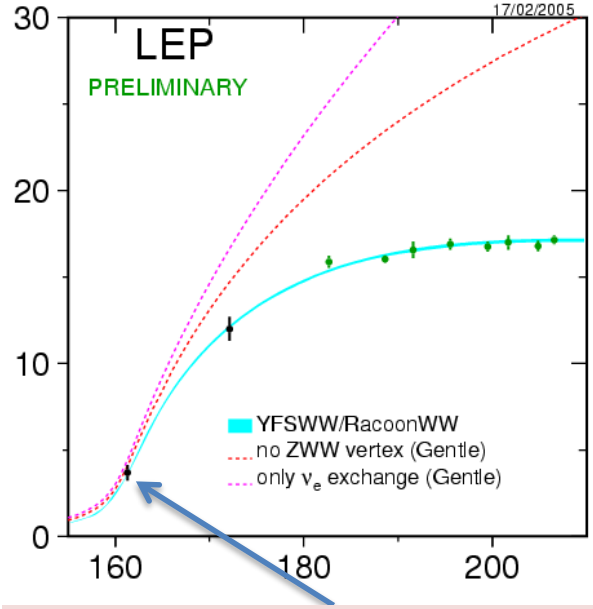
$\sqrt{s}$=161 : L~4 10^{35} collect 8/ab ~30 10^{6} WW decays

$\sqrt{s}$=240 : L~0.9 10^{35} collect 5/ab ~80 10^{6} WW decays

WW threshold





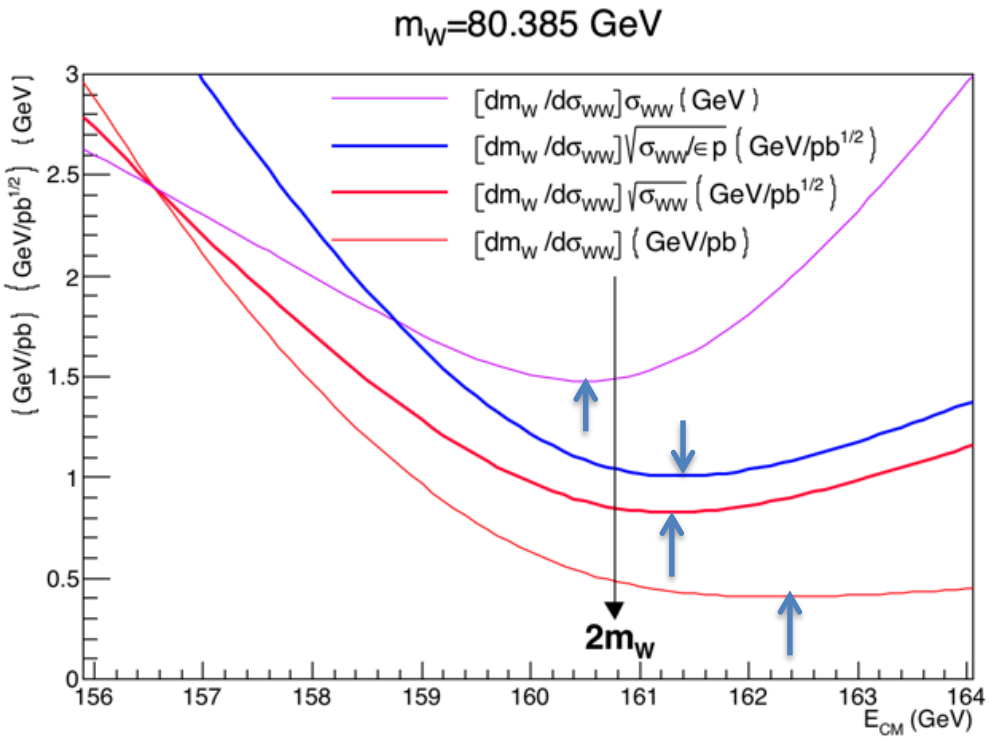


At LEP2 √s=161 GeV σ=4pb
ε=0.75, σ_B=300 fb
p=0.9 : εp≈0.68 (@161)
➔ m_W=80.40±0.21 GeV
with 11/pb @E_{CM}=161 GeV

$$\Delta m_W = \left(\frac{ds}{dm_W}\right)^{-1} \Delta s$$

m_W from σ_{WW}: sensitivity vs E_{CM}

σ_{WW} with YFSWW3 1.18



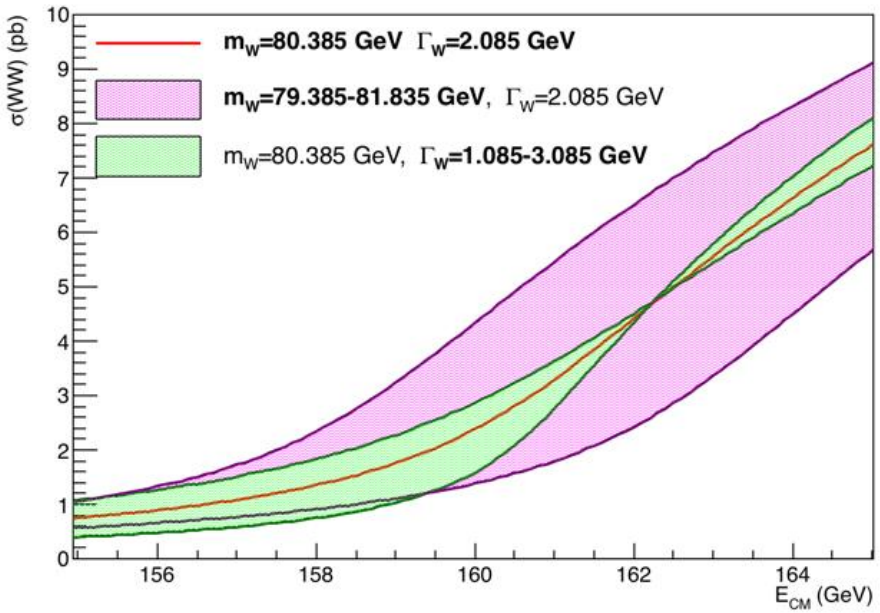
Max stat sensitivity at $\sqrt{s}\sim 2m_W$+600 MeV

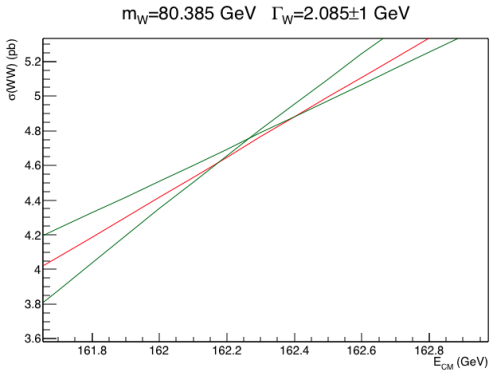
$\sqrt{\epsilon}p$ with fixed : ϵ=0.75 and σ_B=0.3pb

statistical precision
with L = 11/pb ➔ Δmw≈350MeV
with L= 8/ab ➔ Δmw≈0.40 MeV

need syst control on :
- ΔE(beam)<0.40 MeV (**5x10^{-6}**)
- Δε/ε, ΔL/L < **10^{-4}**
- $\Delta\sigma_B$<0.7 fb (2 **10^{-3}**)

Γ_W from σ_{WW}





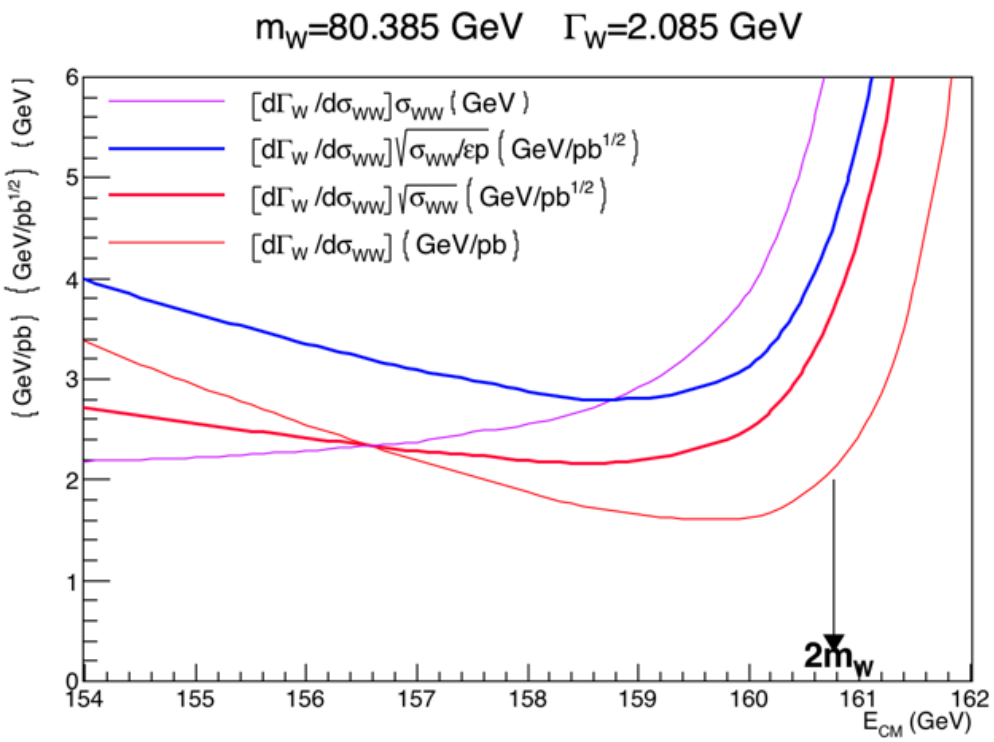
Measure σww in two energy points E_1, E_2 with a fraction f of lumi in E_1
➔ determine both m_W & Γ_W

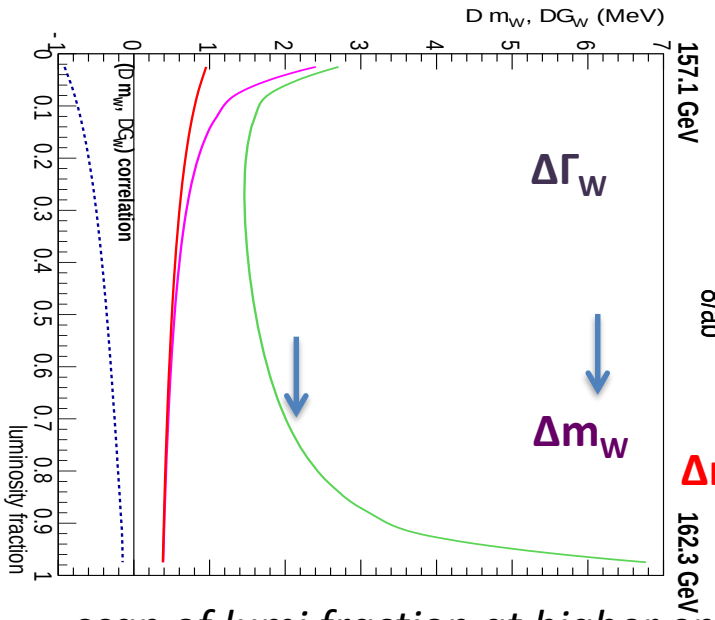
Determine f, E_1, E_2 such to mimimise ($\Delta\Gamma_W$, Δm_W) with some target

Evaluate loss of Δm_W precision in the single parameter (m_W) determination
wrt scenario of running only at an optimal E_0=161 point

$d\sigma_{WW}/d\Gamma_W = 0$
at E_{CM}~**162.3 GeV**
~$2m_W$ + 1.5 GeV

m_W &Γ_W from σ_{WW}





scan of lumi fraction at higher energy

Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both

Δm_W : error on W mass from fitting only m_W

with E_1=157.1 GeV E_2=162.3 GeV f=0.4

Δm_W=0.62 $\Delta\Gamma_W$=1.5 Δm_W=0.56 (MeV)

➔$\Delta\alpha_S \approx (3\,\pi/2)\Delta\Gamma/\Gamma \approx$ 0.003

acceptance

how do we control acceptance at the 10^{-4} level (0.01%) ?
➔ aim for the highest possible acceptance and efficiency WP

- lepton **tracking** reco efficiency (was controlled at the 10^{-3} level at LEP2)
- lepton **identification** performances
  - @LEP2 10^{-3} level: (T&P with Z): effects on total $\Delta\sigma$ mitigated down to the 2-3 10^{-4} level thanks to $\tau \rightarrow$e,u channel migrations recoveries
  - would need lepton-id at 10^{-4} level for max BR precision
- jet reconstruction and **energy calibration**
  - @LEP2 1-2% level ➔ 0.1% on $\Delta\varepsilon$:
  - FCCee would need calibration at 0.1% level (10x better) with control data ; best possible jet energy resolution helps
- **missing momentum** scale/resolution : similar to jet energy for qqlv
- lepton **isolation**
  - @LEP2 control at the $\Delta\varepsilon$~2 10^{-3} level: need to do 10x better
- jet **modeling** (signal & bkg)
  - was important syst on σ_{WW}@LEP2 (at the 2 10^{-3} level)

impact of theoretical uncertainties will hopefully not be limiting but work is needed to reach the target 0.5 10^{-3} precision level

background control

2-fermion : ττ, qq
4-fermion : γγ→ττ,llνν, Zee, Weν

some 4f bkg is identical to the signal final state ➔ CC03-4f interferences

decay	efficiency	purity	bkg [LEP1996]
lνlν	70-80%	80-90%	**50fb** (ττ,γγ→ττ,Zγ*→ννll)
eνqq	85%	~90%	**30fb** (qq, Zee, Zγ*) **-10fb** (Weν)
μνqq	90%	~95%	**10fb** (Zγ*,qq)
τνqq	50%	80-85%	**50fb** (qq, Zγ*)
qqqq	90%	~90%	**~200fb** (qq (qqqq,qqgg))

measure directly the **backgrounds** with very different S/B levels **at different E_{CM} points**

concern is mostly on the four-jet background

measure forward electrons (θ≤0.1 rad) for Zee Wev : determine forward pole dσ/d**θ** and WW interference effects

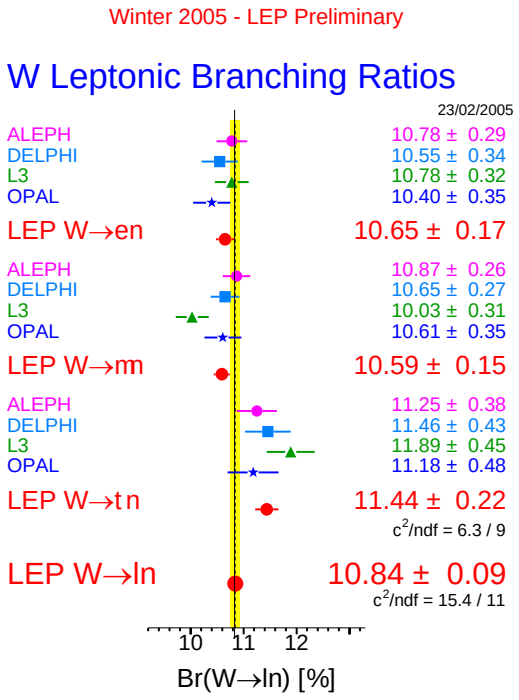
acceptance down to **θ=0.1 [cosθ= 0.995]** would also cover forward jets

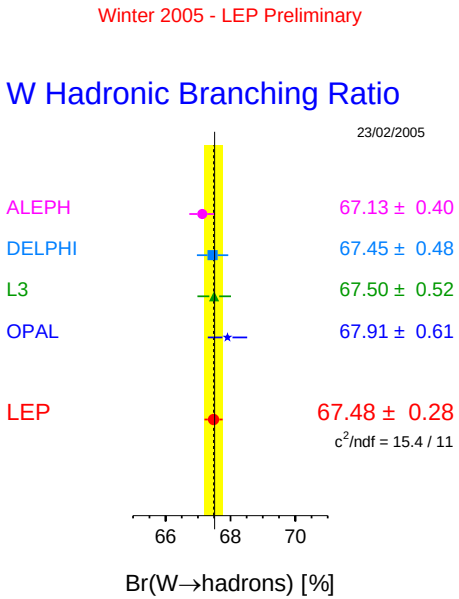
limiting **correlated** systs can cancel out taking data at more E_{CM} points where

$$\left(\frac{ds}{dG_W}\right)^{-1} \left(\frac{ds}{dm_W}\right)^{-1} \left(\frac{ds}{dm_W}\right)^{-1} s \left(\frac{ds}{dG_W}\right)^{-1} s$$

differential factors are equal

W BR





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

➔ $\Delta BR(qq)\ (stat) = [1.5]\ 10^{-4}$ (rel)
➔ $\Delta\alpha_s \approx (9\ \pi/2)\Delta BR \approx 2\ 10^{-3}$

➔ $\Delta BR(lv)(stat) = [3]10^{-3}$ (rel)

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

Lept universality test at 1% level
tau BR ~2.7 σ larger than e/mu
➔ *FCCee @ 2 10^{-4} level*

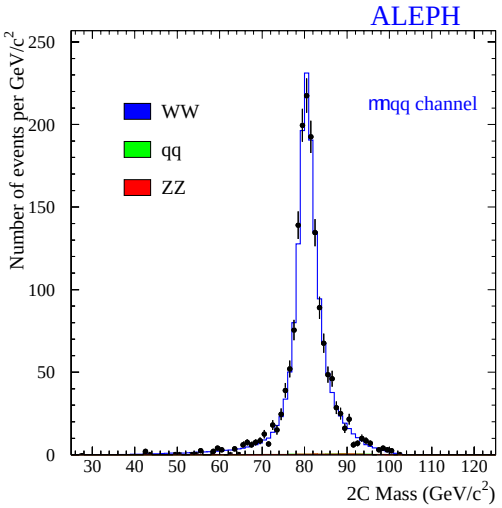
will need much better control of lepton id
i.e. cross contaminations in signal channels
(τ→e,μ in the e,μ channels and v.v.)

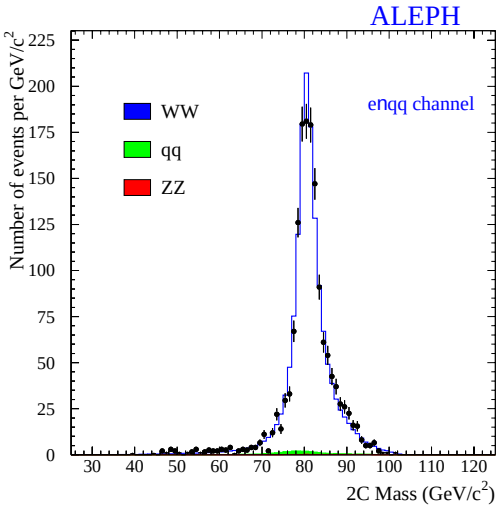
Flavor tagging would also allow to measure coupling to c & b-quarks (Vcs, Vcb,..)

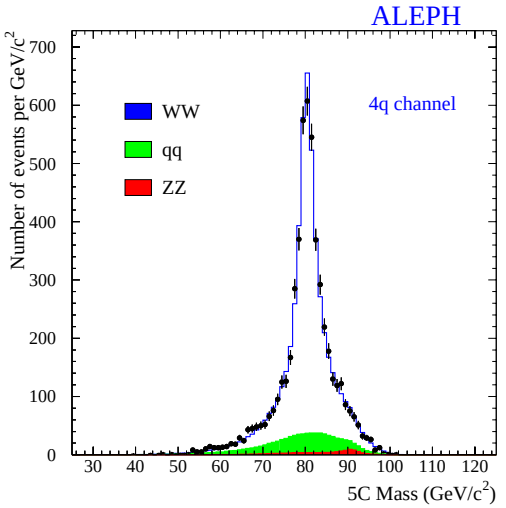
reco mass of the W boson

full m_W reco with kinematic fit. main ingredients :
E_{CM} – jet/lepton angles – (jet boost)

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







ALEPH Eur.Phys.J.C47:309 (2006) : 683 /pb ~10k WW events

ignoring low energy particles in the qqqq channel

m_W = 80440±**43**(**stat**.)±24(syst.)±9(FSI)±9(LEP) MeV

Γ_W = 2140 ±**90**(**stat**.) ±45(syst.) ±46(FSI) ± 7(LEP) MeV

reco mass of the W boson

8/ab@160GeV + 5/ab@240GeV
➔ 30M+ 80M W-pairs
➔ Δm_W (stat)= 0.5 MeV

➔ Δm_W (syst) ≤ 1 MeV ?

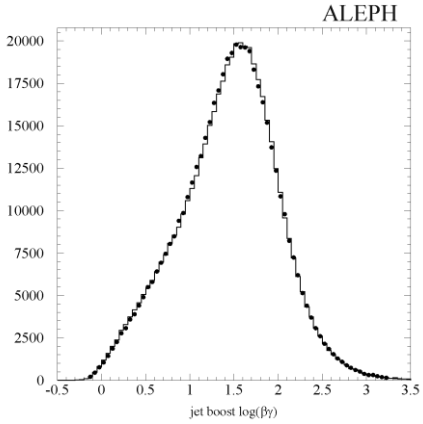
Is ΔE_{beam}<1MeV at E_{CM}=240 GeV possible ?
With Zγ events ?

Do WW events produced near threshold carry kin information on m_W ?

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

jet boost

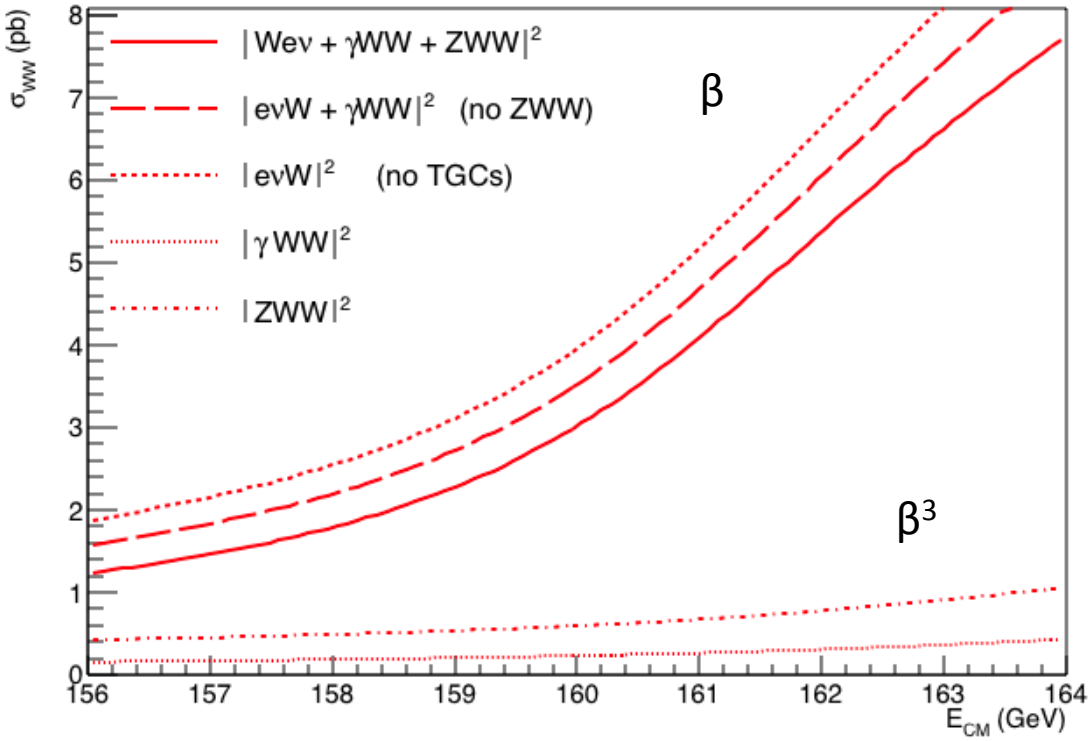


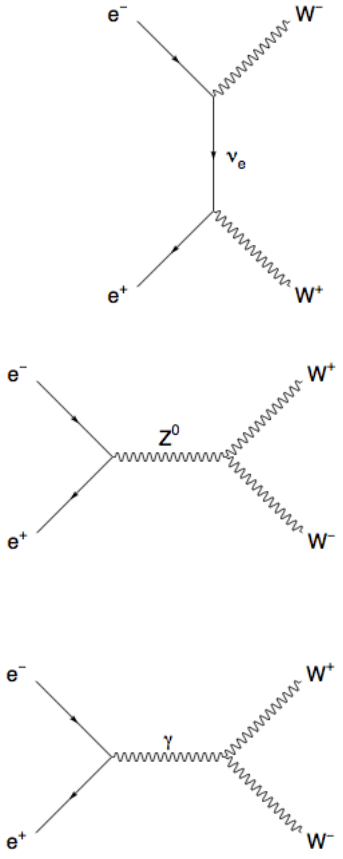
lepton and jet uncertainties from (Z) calibration data

TGCs at threshold

Weν

SU(2)⊗U(1) Gauge Cancellations





without TGCs

σ_{WW} +40% @157GeV +25%@162GeV

while $\Delta\sigma/\sigma \approx 0.5\ 10^{-3}$

add here some rough extrapolations from LEP2 limts ?

Conclusions

- FCC ee is a total game-changer for EW W/Z physics measurements
- No "a priori" walls on the road map to achieve the FCC goals for EW precision measurements but a lot of work, firstly on the theoretical calculations side
- At the Z, off peak data will play an important role (more than at LEP times)
  - can deliver $a_{QED}(m_Z^2)$ to 3×10^{-5}
- The WW threshold lineshape is a great opportunity to measure both m_W and Γ_W:
  - optimal points to take data are $\sqrt{s}=2m_w+1.5$ GeV (**Γ-insensitive**) and $\sqrt{s}=2mw-2-3$ GeV (-Γ**off shell**)
- Huge potential for other W physics measurements including higher energy data still need to be explored with attention
  - direct mW , W BRs, TGCs
- Work from experimentalist needed to evaluate with care limiting systematics, study ways to overcome them, and reflect on the detector design consequences: opportunities to contribute
- The potential of FCCee data for EW Z/W measurements needs to be fully unraveled