FCCee EW measurements at the Z pole and WW threshold

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1st FCC Physics Workshop
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Outline

- Z pole
  - lineshape asymmetries & couplings
    (R. Tenchini/ F.Piccinini)
  - Direct measurement of α_{QED} (P. Janot)

- W physics
  - threshold mW and ΓW
  - W couplings & direct mW

inputs to EW fits

EW fit based on *derived (pseudo-)*observables (easy combination among experiments and easy comparison data/theory within and beyond the SM)

- primary measured observables: cross section and asymmetries

FCC challenges for the EW (pseudo)-observables on the table

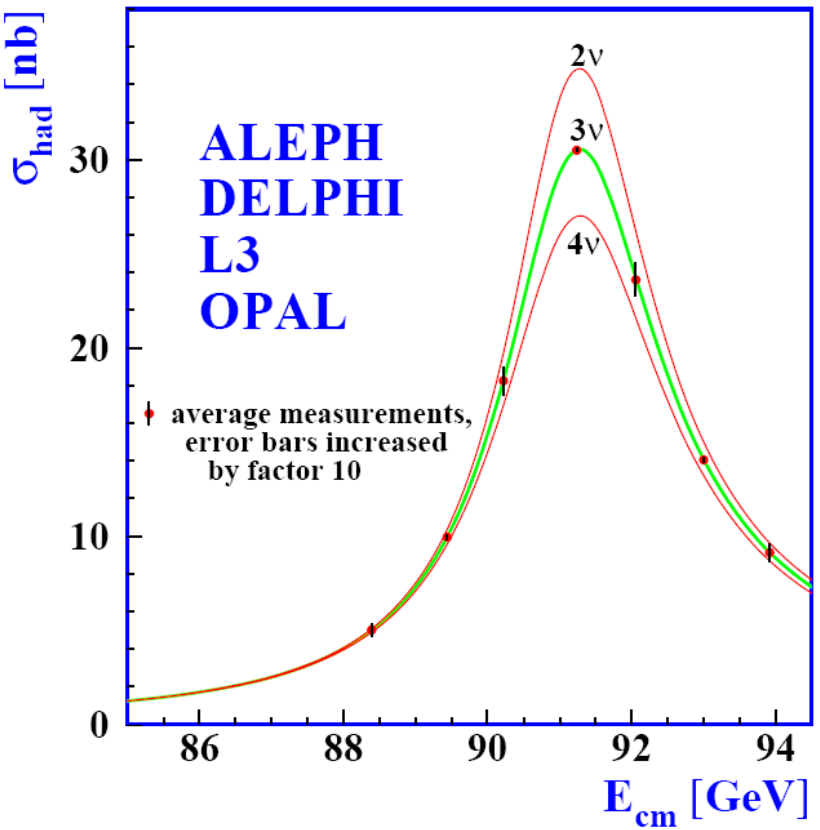
The goals in precision for FCC-ee are given in JHEP 01 (2014) 164

M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tev.
Γ_W [GeV]	2.085 ± 0.042	Tev.
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLD
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	SLD
A_c	0.670 ± 0.027	SLD
A_b	0.923 ± 0.020	SLD
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP
R^0_b	0.21629 ± 0.00066	LEP
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.34 ± 0.76	Tev.+LHC
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2757 ± 10	Tev.+LHC

Z lineshape for M_Z and Γ_Z

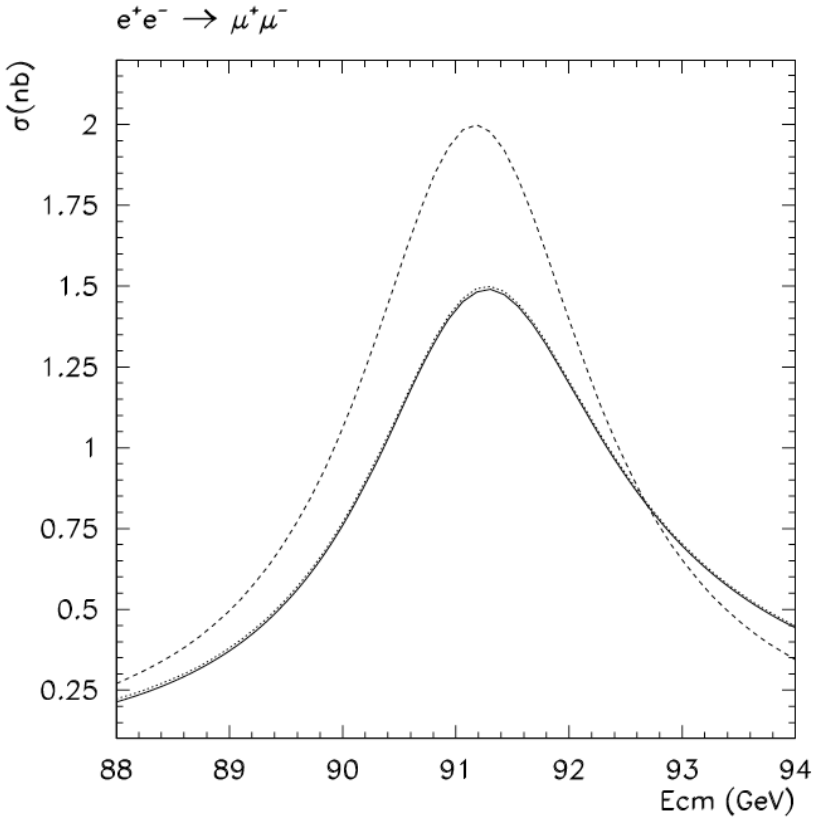
- Measure the Z lineshape by accumulating 10^{12} Z bosons in a energy scan
- At LEP reached 2 MeV level and gained a lot of experience on **centre-of-mass energy determination with resonant depolarization**
- Could potentially reach ~10^{-6} (100 keV on M_Z and Γ_Z)
- Continuous energy calibration at FCC with dedicated bunches

- Improve the knowledge of other observables, e.g. R_l and related $\alpha_s(M_Z)$ determination.



ISR deconvolution

- The lineshape is highly asymmetric because of radiative effects
- At LEP the cross section was convolved with a radiator function H(s',s)
- Current calculations gives a precision of 0.01% (TOPAZ0 and ZFITTER)
- higher precision requires improvements on the deconvolution process



Radiation function currently calculated up to $O(\alpha^3)$

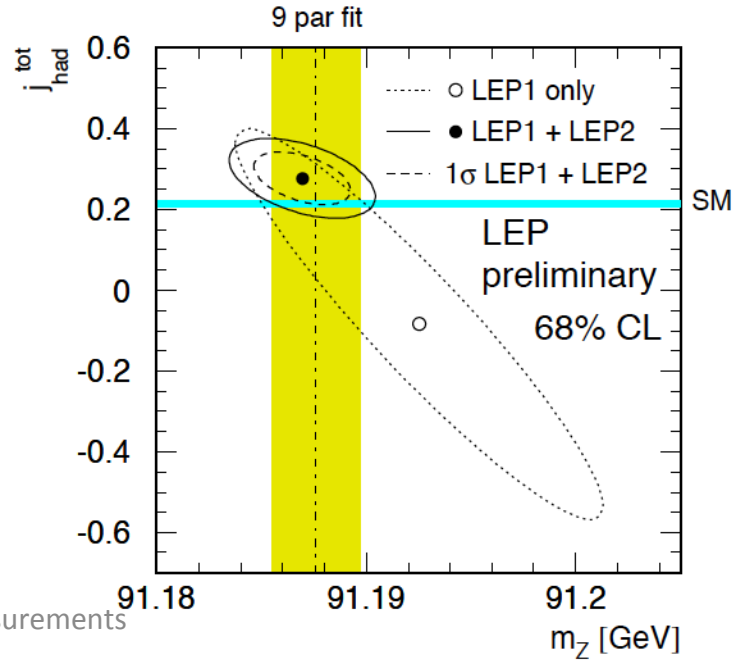
model independent lineshape

A. Leike, T. Riemann, J. Rose, PLB273 (1991) 513

- General parameterization in terms of exchange of a massless and a massive vector boson

$$\sigma_T(s) = \frac{4}{3}\pi\alpha^2 \int \frac{ds'}{s}\left[\frac{r^\gamma}{s} + \frac{sr + (s - M_Z^2)j}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2}\right]\rho_{ini}\left(\frac{s'}{s}\right)$$

- Leaves the contributions of Z exchange (r) and Z-γ interference (j) free
- Off-peak points greatly improve the measurement, adding LEP2 cross sections the M_Z precision obtained at LEP1 was recovered



Z pole acceptance

- @LEP acceptance effects at **10^{-4}** le 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 (the **relevant boundary**) was known at the level of **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 ?)

Z asymmetries

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

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

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

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

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

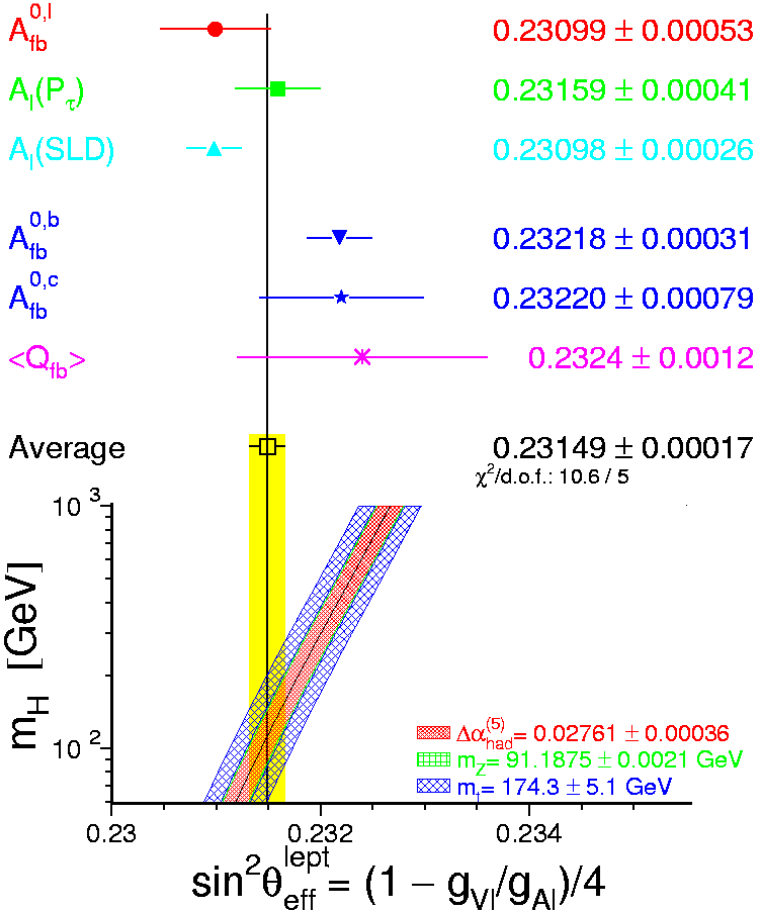
- Additional asymmetries with polarization of initial state :

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

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

Z asymmetries

- Long standing difference between AlR and $A_{FB}(b)$, **to be sorted out**
- measurement of AlR with **long. polarized beams**
- direct **measurement of the b couplings** (again need long. polarization)
- Could potentially reach ~10^{-6} on sin2theta
- What can be done without long polarization ?



FCCee can sizably improve b asymmetry (**LEP was statistically dominated)**

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

• Very different systematic effects [QCD corrections uncertainty to be improved]

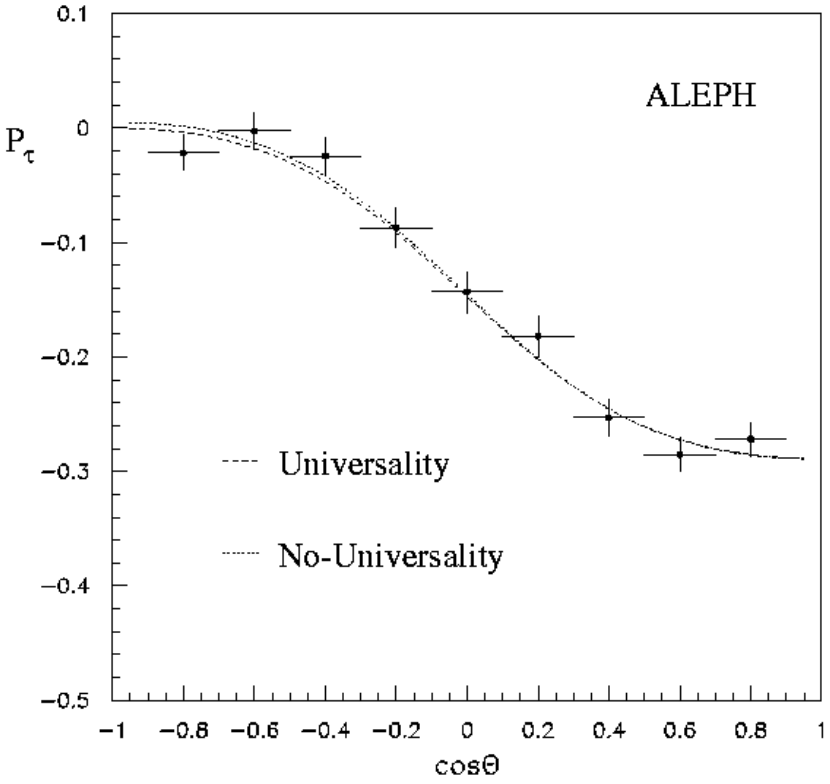
tau polarization A

•Polarization measurement as a function of the production angle allows A_e to be separated from A_τ

• Universality test and measurement of $\sin^2\theta_W$

• LEP combination statistically dominated

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



FB asymmetries : S-matrix model independent approach is desirable (not tried at LEP (trade statistical power for reduced theoretical assumptions)

$A_{FB}(\mu^+\mu^-)$ or $A_{FB}(\tau^+\tau^-)$ can also be considerably improved (currently largely dominated by statistics). $A_{FB}(e^+e^-)$ more difficult because of t-channel

couplings and Rb

couplings measurements require asymmetry and width ratios

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

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

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

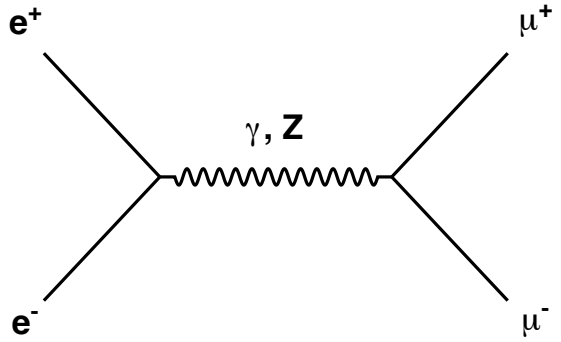
$$R_b = 0.21646 \pm 0.00065 \text{ (LEP + SLC)} \longrightarrow \left(g_{Af}\right)^2 + \left(g_{Vf}\right)^2$$

- Rb Very sensitive to rad. vertex corrections due to new particles (e.g. Susy)
- 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 (better vertex detectors) helps in reducing the correlation
- Correlations sources should be identified and studied with data (done at LEP)

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

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

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



- The $e^+e^- \rightarrow \mu^+\mu^-$ cross section
  - Photon exchange (G) proportional to $\alpha^2(s)$
  - Z exchange (Z) proportional to G_F^2
  - Interference term proportional to $\alpha(s)\, G_F$
    - Need to choose $\sqrt{s}$ judiciously to maximize sensitivity to $\alpha(s)$
    - If $\sqrt{s}$ is close to m_Z, the $\sqrt{s} \rightarrow m_Z$ extrapolation uncertainty is negligible

Sensitivity of $e^+e^- \to \mu^+\mu^-$ to $\alpha_{QED}(m_Z^2)$

- The $e^+e^- \to \mu^+\mu^-$ angular distribution
  - Absolute cross section measurement might be challenging to the required precision
    - Uncertainty of the integrated luminosity determination
  - Rely of a self-normalizing quantity, the forward-backward asymmetry

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

$$A_{\rm FB,0}^{\mu\mu} = (3/4) \times 4v^2a^2/(a^2+v^2)^2 \simeq 0.016.$$

$dZ/d\alpha = 0$ $\quad dI/d\alpha = I/\alpha$ $\quad dG/d\alpha = 2G/\alpha$

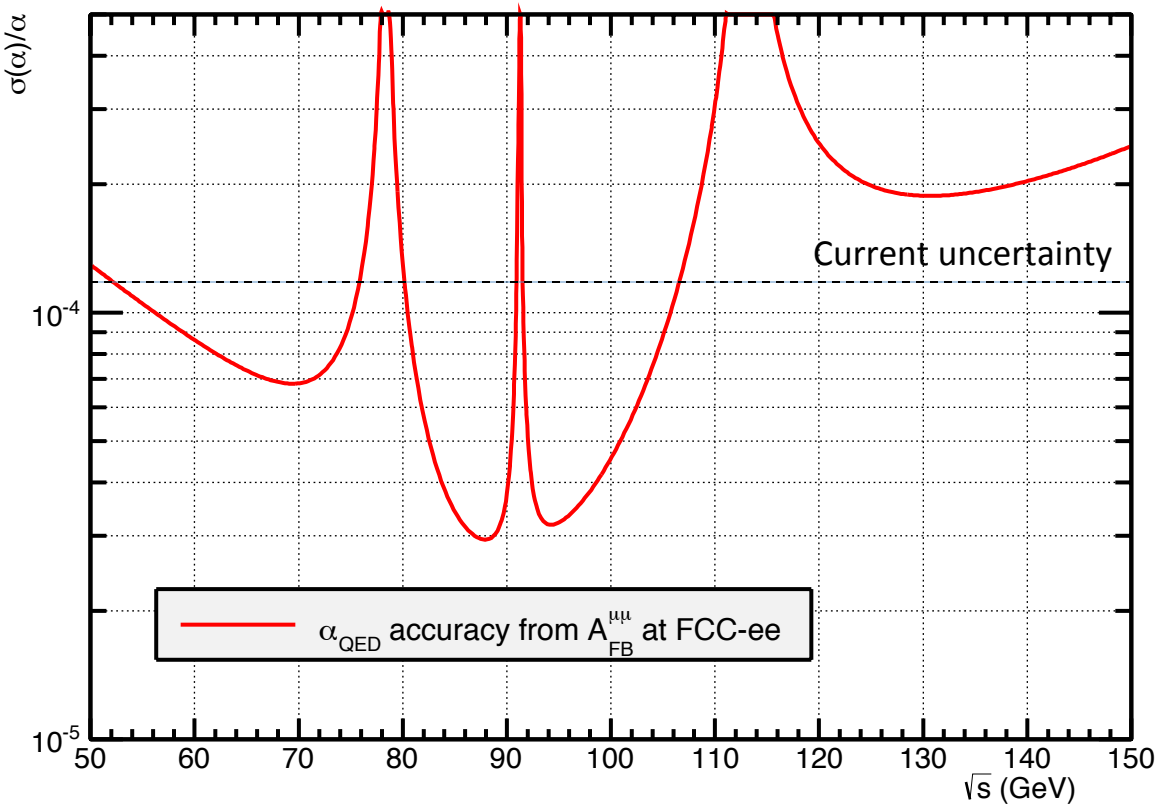
$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta A_{\rm FB}^{\mu\mu}}{A_{\rm FB}^{\mu\mu} - A_{\rm FB,0}^{\mu\mu}} \times \frac{\mathcal{Z}+\mathcal{G}}{\mathcal{Z}-\mathcal{G}} \simeq \frac{\Delta A_{\rm FB}^{\mu\mu}}{A_{\rm FB}^{\mu\mu}} \times \frac{\mathcal{Z}+\mathcal{G}}{\mathcal{Z}-\mathcal{G}},$$

Statistical uncertainty on A_{FB}

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

Sensitivity of $e^+e^- \rightarrow \mu^+\mu^-$ to $\alpha_{QED}(m_Z^2)$

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



  - Optimal centre-of-mass energies for a 3×10^{-5} uncertainty on α_{QED}
    - One year at $\sqrt{s}_- = 87.9$ GeV or one year at $\sqrt{s}_+ = 94.3$ GeV
    - Or maybe six months at $\sqrt{s}_-$ and six months at $\sqrt{s}_+$

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

- Two measurements
  - Two asymmetries at two √s: $A_{FB}(s_-)$ and $A_{FB}(s_+)$

$$\alpha_- \equiv \alpha_{\rm QED}(s_-) \text{ and } \alpha_+ \equiv \alpha_{\rm QED}(s_+),$$

- Running from $\sqrt{s_{-\pm}}$ to m_Z gives two determinations of α_0

$$\frac{1}{\alpha_0} = \frac{1}{\alpha_\pm} + \beta \log \frac{s_\pm}{m_{\rm Z}^2},$$

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

$$\frac{1}{\alpha_0} = \frac{1}{2}\left(\frac{1-\xi}{\alpha_-} + \frac{1+\xi}{\alpha_+}\right), \quad \text{where} \quad \xi = \frac{\log s_- s_+/m_{\rm Z}^4}{\log s_-/s_+} \simeq 0.045,$$

- With potential of almost exact cancellations for correlated effects at $s_\pm$

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

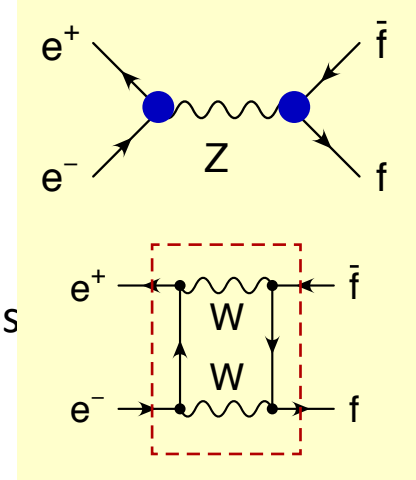
$\Delta A_{FB}/A_{FB}(s_-) > 0$
$\Delta A_{FB}/A_{FB}(s_+) < 0$

$\alpha_{QED}(m_Z^2)$ Systematic uncertainties

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, 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}

Missing EW higher orders: few 10^{-4}

- Current status: full one-loop calculation available
  - Box + Vertex EW correction : ~10^{-3}
  - Uncertainty : few 10^{-4}
- Higher-order corrections computable with current techniques
  - At the level of a few 10^{-4}
  - Uncertainty : few 10^{-5} - This is what we need.
- New techniques might be needed for 3-loop corrections
  - At the level of a few 10^{-5}
  - Uncertainty : < 10^{-5}



A. Freitas
FCC-ee Physics Meeting,
25 Januray 2016

- Significant precision improvement needed (as for all EWPO predictions)

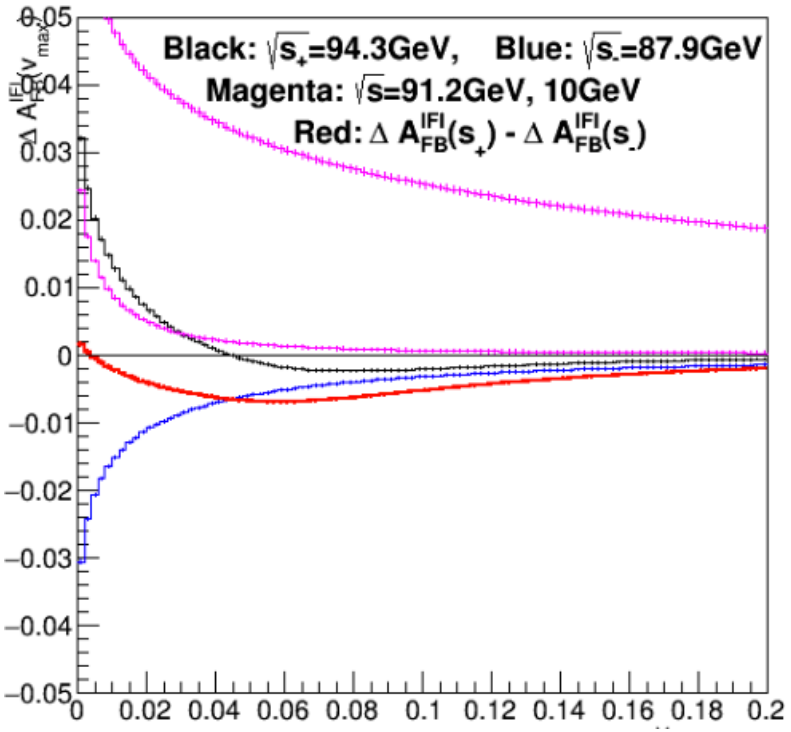
Initial-Final-state Interference (IFI)

- Angular distribution modified with another totally asymmetric function: creates yet another asymmetry
- Effect is more important then what inferred in arXiv:1512:05544
- Cancellation still occurs between s_ and s_+

Relative effect on $A_{FB}(s_{\pm})$ of the order of 10% for a tight cut on s'/s

Relative effect on the difference of the order of 0.2% [~used to determine $\alpha_{QED}(m_Z^2)$]

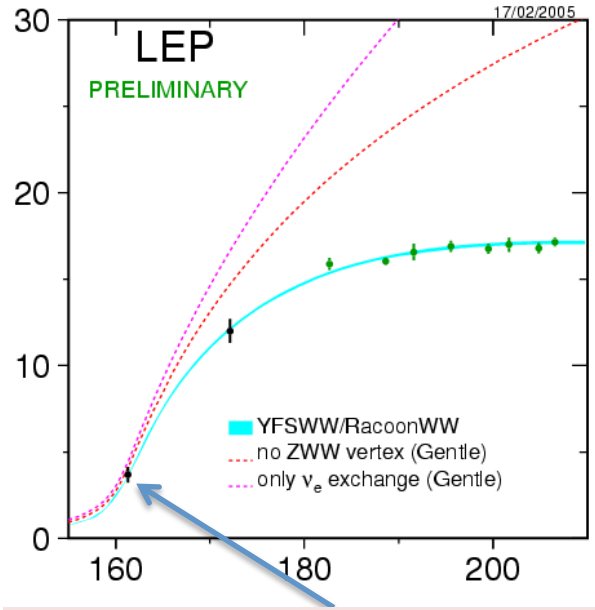
Requires IFI to be predicted to a precision better than 1% to reach the required precision on $\alpha_{QED}(m_Z^2)$: **work in progress**



can also try to fit IFI in the data at different √s

W physics

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

$$\Delta m_W(stat) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{L}} \frac{1}{\sqrt{\varepsilon p}}$$

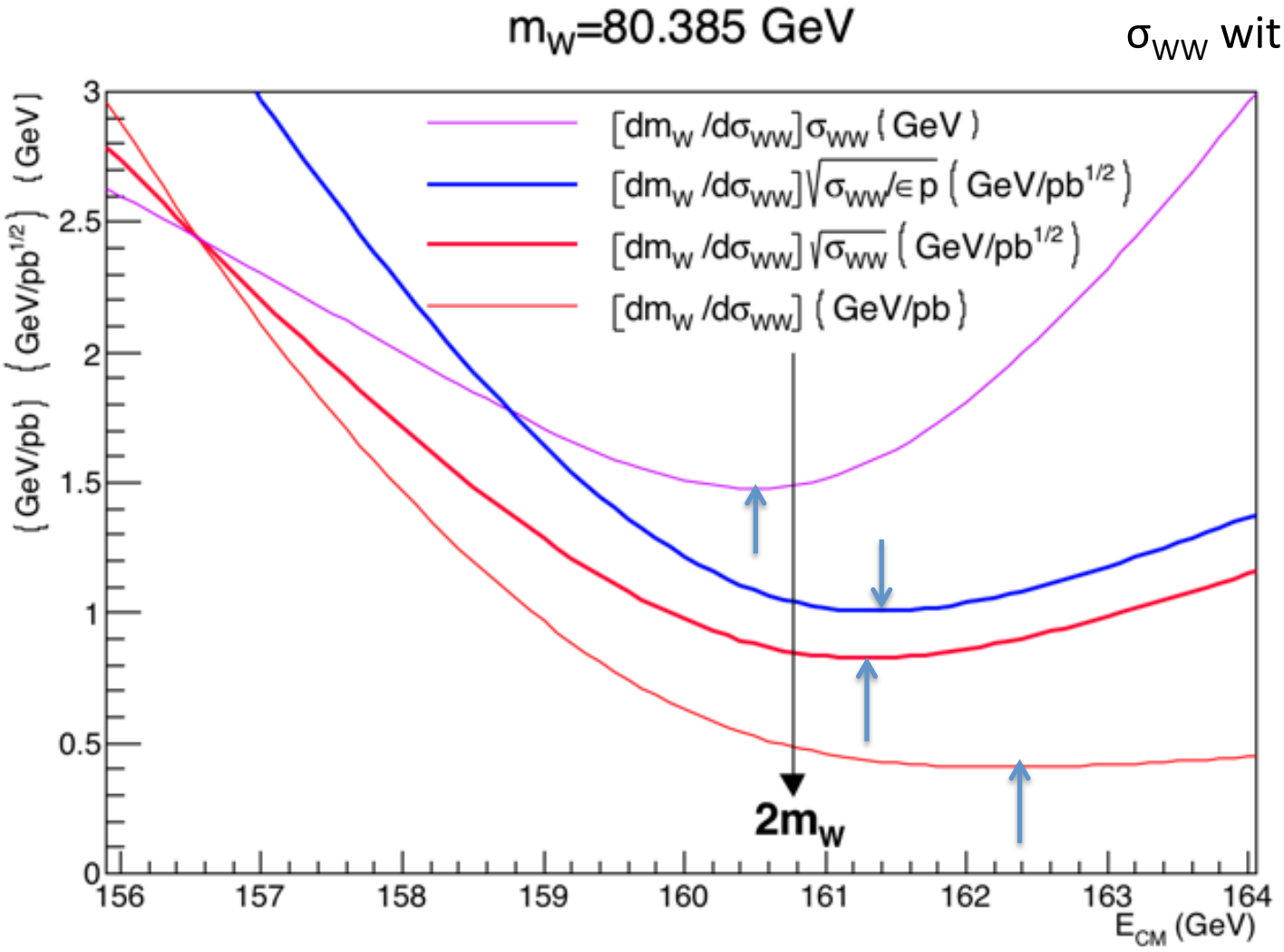
$$\Delta m_W(B) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\Delta\sigma_B}{\varepsilon}$$

$$\Delta m_W(\varepsilon) = \sigma \left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{\Delta\varepsilon}{\varepsilon} + \frac{\Delta L}{L}\right)$$

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

$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{d\sigma}{dE}\right) \Delta E \leq \frac{1}{2}\Delta E$$

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



σ_{WW} with YFSWW3 1.18

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

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

$$\left(\frac{d\sigma}{dm_W}\right)^{-1}\Bigg|_{\min} \sim 0.41\frac{GeV}{pb}$$

at √s~2m_W+1.5 GeV

$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{\min} \approx 1.01\frac{GeV}{pb^{1/2}}$$

Max stat sensitivity at √s~2m_W+600 MeV

$$\left(\frac{d\sigma}{dm_W}\right)^{-1}\sigma\Bigg|_{\min} \sim 1.5GeV$$

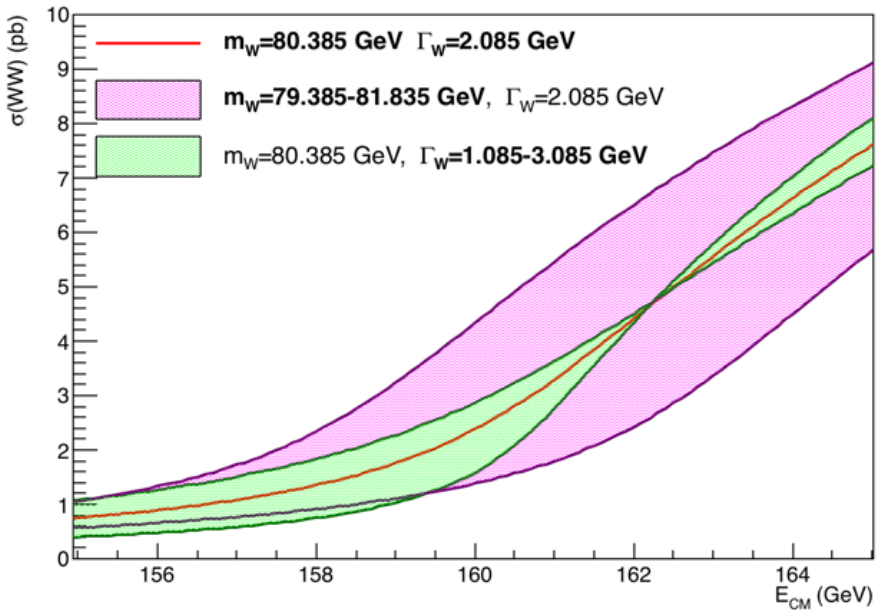
at √s~2m_W -0.3 GeV

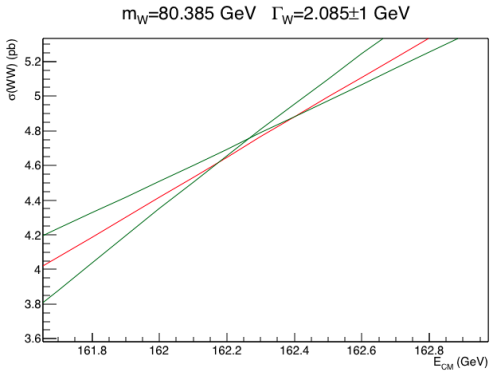
with L = 11/pb ➔ Δmw≈350MeV (ALEPH 96)
with L= 15/ab ➔ Δmw≈0.25 MeV

need syst control on :

- ΔE(beam)<0.25 MeV (3x10-6)
- Δε/ε, ΔL/L < 10-4
- $\Delta\sigma_B$<0.5 fb (10-3)

Γ_W from σ_{WW}





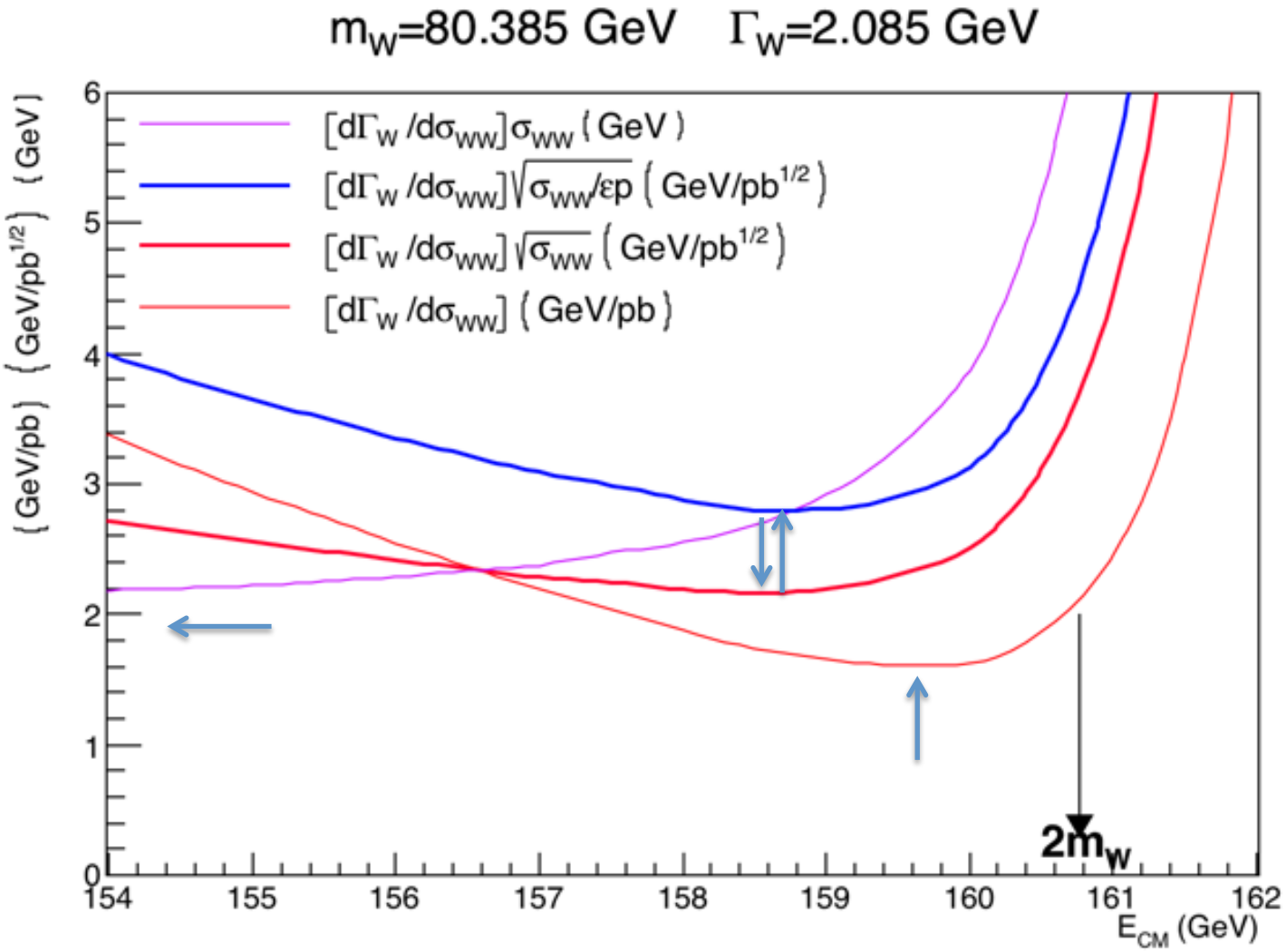
Measure σww in two energy points E_1, E_2 with a fraction f of lumi in E_1
➔ determine both m_W & Γ_W

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}



m_W & Γ_W from σ_{WW}

Uncertainty propagation

$$\begin{cases} \Delta\sigma_1 = a_1\Delta m + b_1\Delta\Gamma \\ \Delta\sigma_2 = a_2\Delta m + b_2\Delta\Gamma \end{cases}$$

$$a_1 = \frac{d\sigma_1}{dm} \qquad b_1 = \frac{d\sigma_1}{d\Gamma}$$

$$a_2 = \frac{d\sigma_2}{dm} \qquad b_2 = \frac{d\sigma_2}{d\Gamma}$$

$$\Delta m = -\frac{b_2\Delta\sigma_1 - b_1\Delta\sigma_2}{a_2 b_1 - a_1 b_2}$$

$$\Delta\Gamma = \frac{a_2\Delta\sigma_1 - a_1\Delta\sigma_2}{a_2 b_1 - a_1 b_2}$$

Δm,ΔΓ linear correlation with uncorrelated $\Delta\sigma_1$,$\Delta\sigma_2$

$$r = -\frac{1}{\Delta m\Delta\Gamma}\frac{a_2 b_2\Delta\sigma_1^2 + a_1 b_1\Delta\sigma_2^2}{\left(a_2 b_1 - a_1 b_2\right)^2}$$

m_W & Γ_W from σ_{WW}

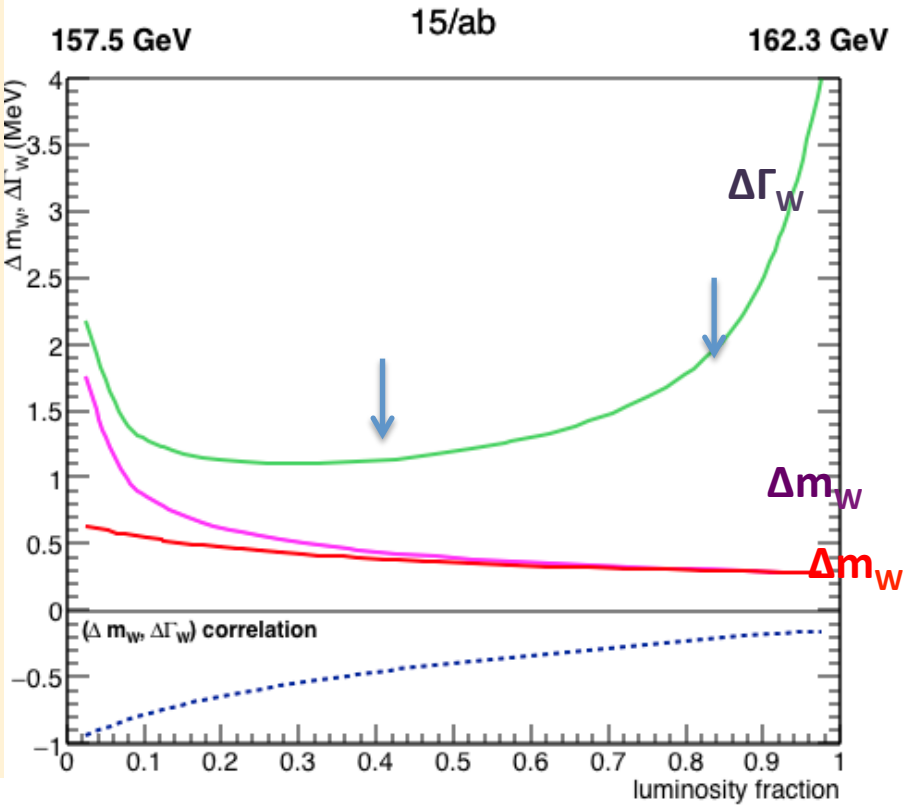
scan luminosity fractions

take an example
L = 12/ab @162.3 + 3/ab @157.5

Only stat uncertainty
measure only mw
➔ Δmw≈0.31 MeV [0.25 @161.2 only]

measure mw & Γw
➔ Δmw≈0.32 MeV ΔΓw≈ 1.7 MeV
(r=-0.23)

➔$\Delta\alpha_S \approx (3\pi/2)\Delta\Gamma/\Gamma \approx$ 0.004

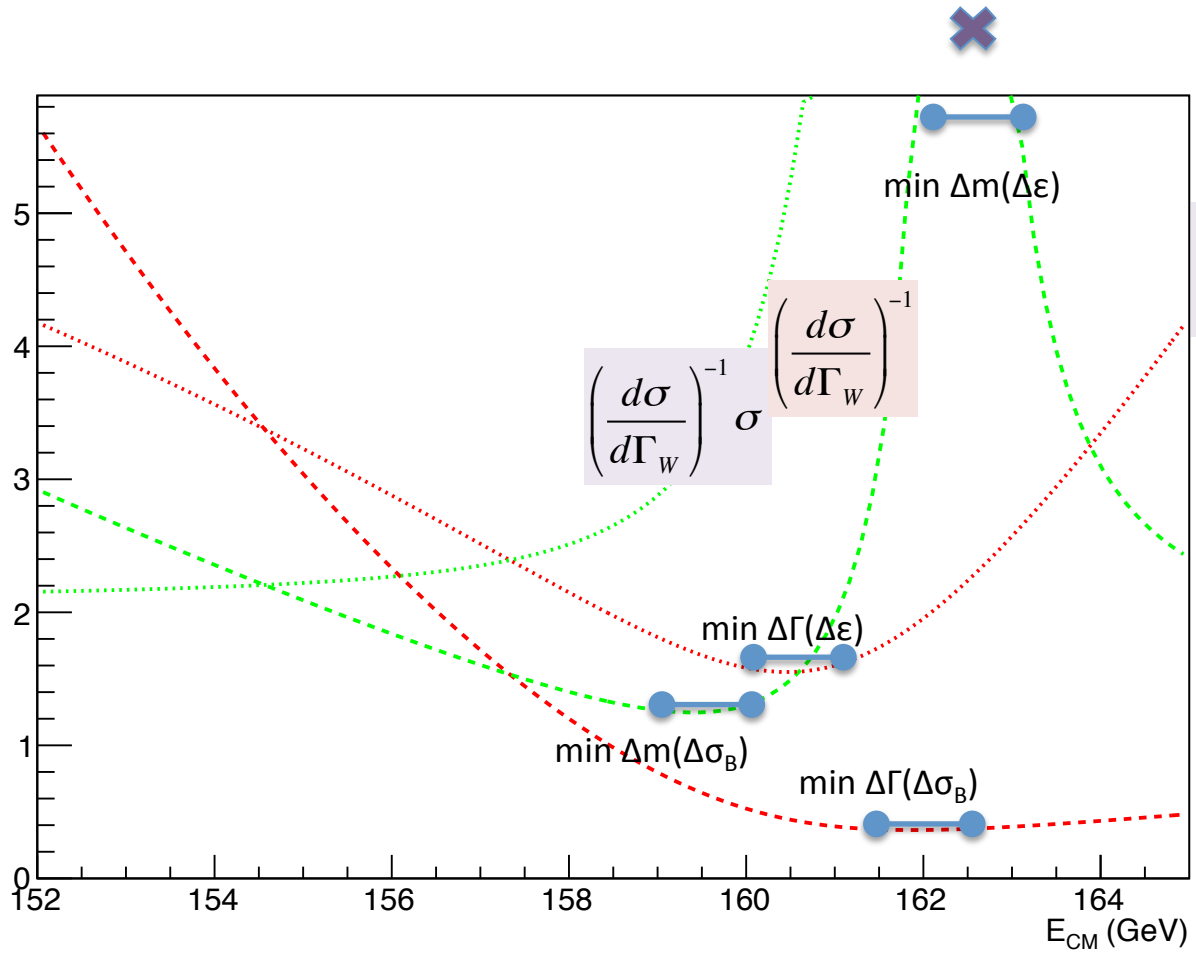


lumi fraction at higher energy

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

m_W & Γ_W from σ_{WW}

optimal E points with limiting **correlated** systs

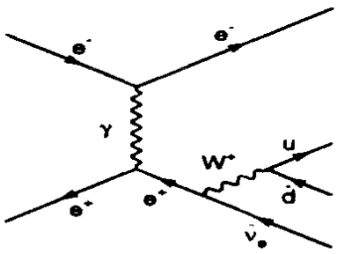


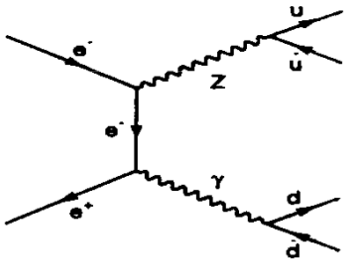
take data at different E_{CM} points 159-160-161-162-163 where the derivative factors are equal (around their minima)

background control

2-fermion : $\tau\tau$, qq
4-fermion : $\gamma\gamma \rightarrow \tau\tau$,ll$\nu\nu$, Zee, We$\nu$

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





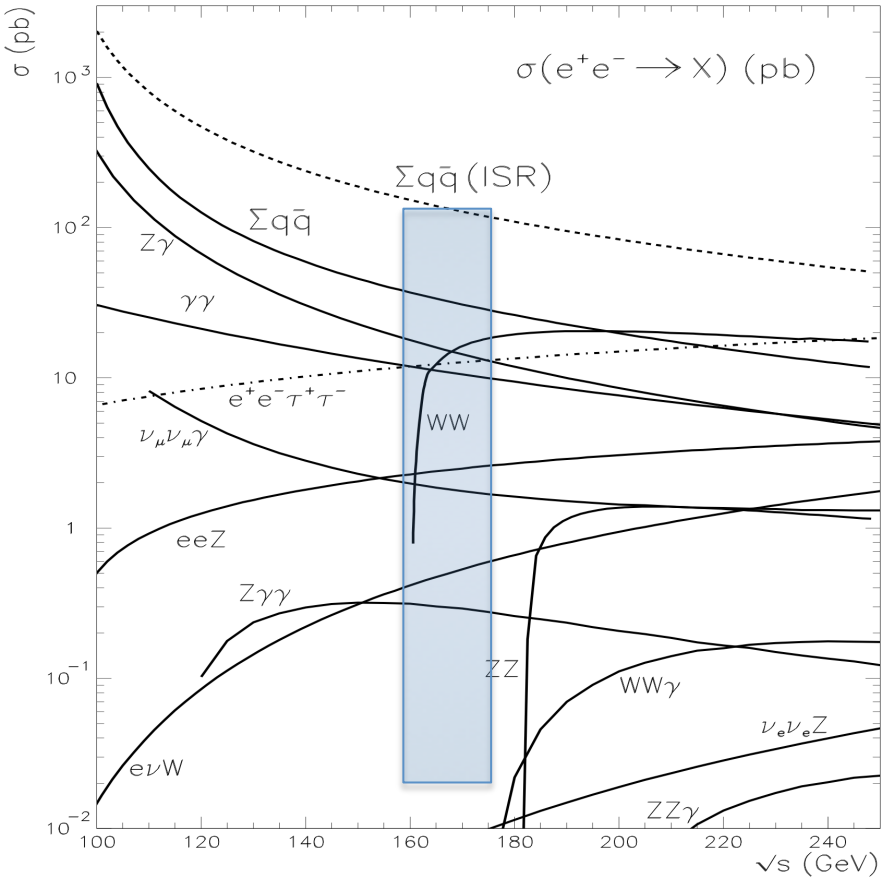
channel	efficiency	purity	bkg [ALEPH 1996]
lνlν	70-80%	80-90%	**50fb** ($\tau\tau$,$\gamma\gamma \rightarrow \tau\tau$,$Z\gamma^* \rightarrow \nu\nu$ll)
eνqq	85%	~90%	**30fb** (qq, Zee, $Z\gamma^*$) **-10fb** (Weν)
$\mu\nu$qq	90%	~95%	**10fb** ($Z\gamma^*$,qq)
$\tau\nu$qq	50%	80-85%	**50fb** (qq, $Z\gamma^*$)
qqqq	90%	~90%	~**200fb** (qq (qqqq,qqgg))

concern is mostly on the four-jet background

Polarization (ILC) can be used to change S/B rates and constrain bkgs at given E_{CM} points : Graham W. Wilson **arXiv:1603.06016**

background control

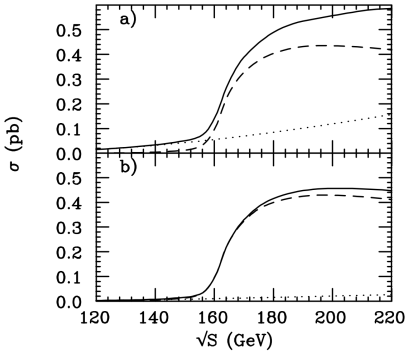
LEP2 "STANDARD MODEL PROCESSES"
hep-ph/9601224 (1996)



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

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

σ(evud)
.. with θ_e>8° cut



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

what about beam (induced) bkg/noise ?

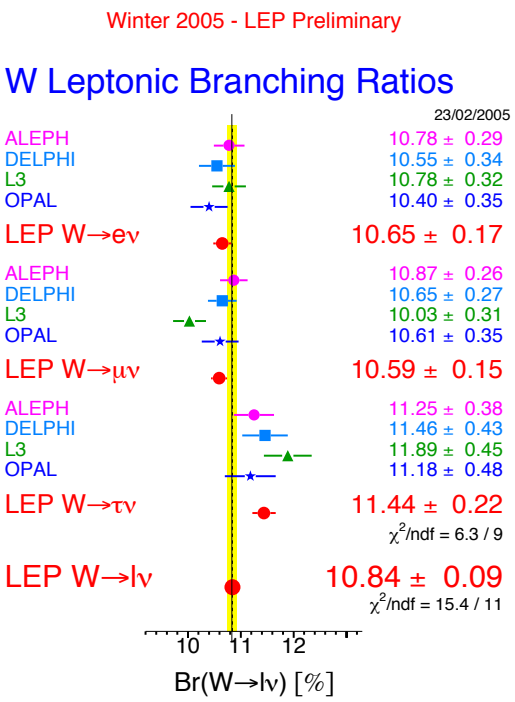
acceptance

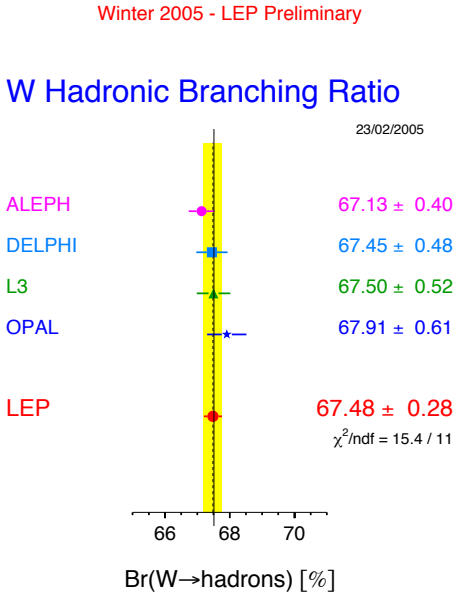
how do we control acceptance at the 10^{-4} level (0.01%) ?
➔ aim for the highest possible acceptance and efficiency WP

- 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 210^{-3} level)

impact of theoretical uncertainties will hopefully not be limiting
but work is needed to reach the required 10-4 -- 10-3 precision level

W BR





q/ l universality at 0.6%

15/ab@160GeV + 10/ab@240GeV
➔ 60M+ 160M W-pairs

➔ $\Delta BR(qq)\ (stat) = [1.4\text{-}0.9]\ 10^{-4}$ (rel)
➔ $\Delta\alpha_s \approx (9\ \pi/2)\Delta BR \approx 2\ 10^{-3}$

➔ $\Delta BR(l\nu)(stat) = [5\text{-}4]10^{-3}$ (rel)

Lept universality test at 1% level
tau BR ~2.7 σ larger than e/mu

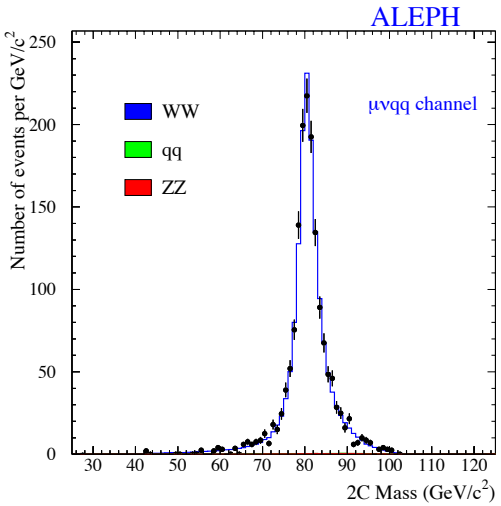
will need much better control of lepton id
i.e. cross contaminations in signal channels
(τ→e,μ in the e,μ channels and v.v.)

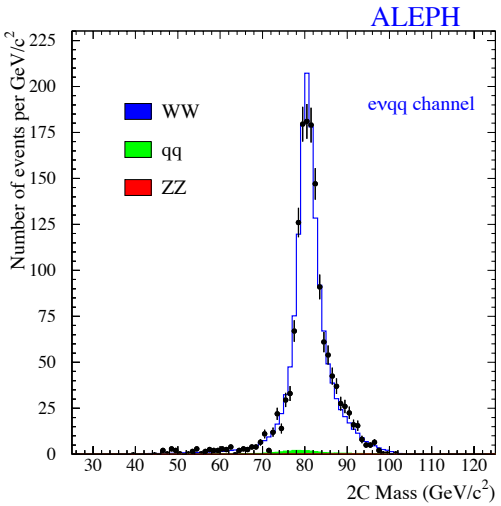
Flavor tagging would also allow to measure coupling to c & b-quarks (Vcs, Vcb,..)

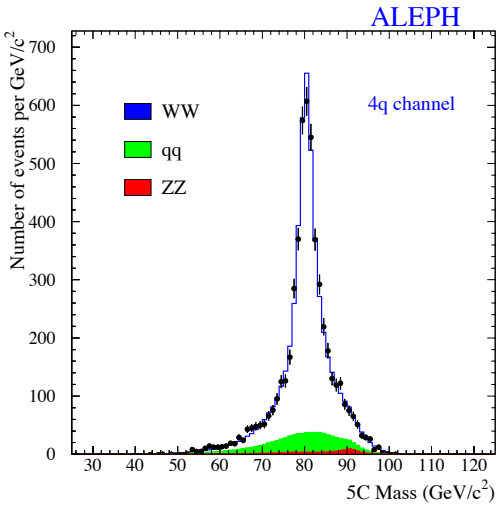
reco mass of the W boson

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

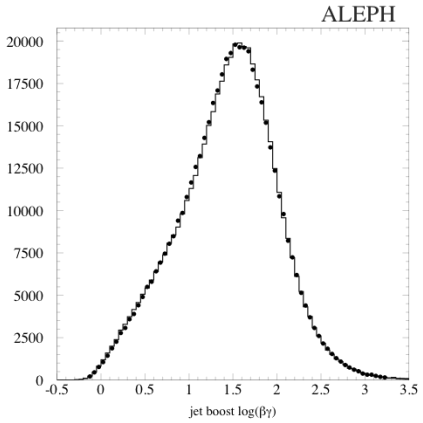
15/ab@160GeV + 10/ab@240GeV
➔ 60M+ 160M W-pairs
➔ Δm_W (stat)= 0.5-0.3 MeV

➔ Δm_W (syst) < 5 MeV ?

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.

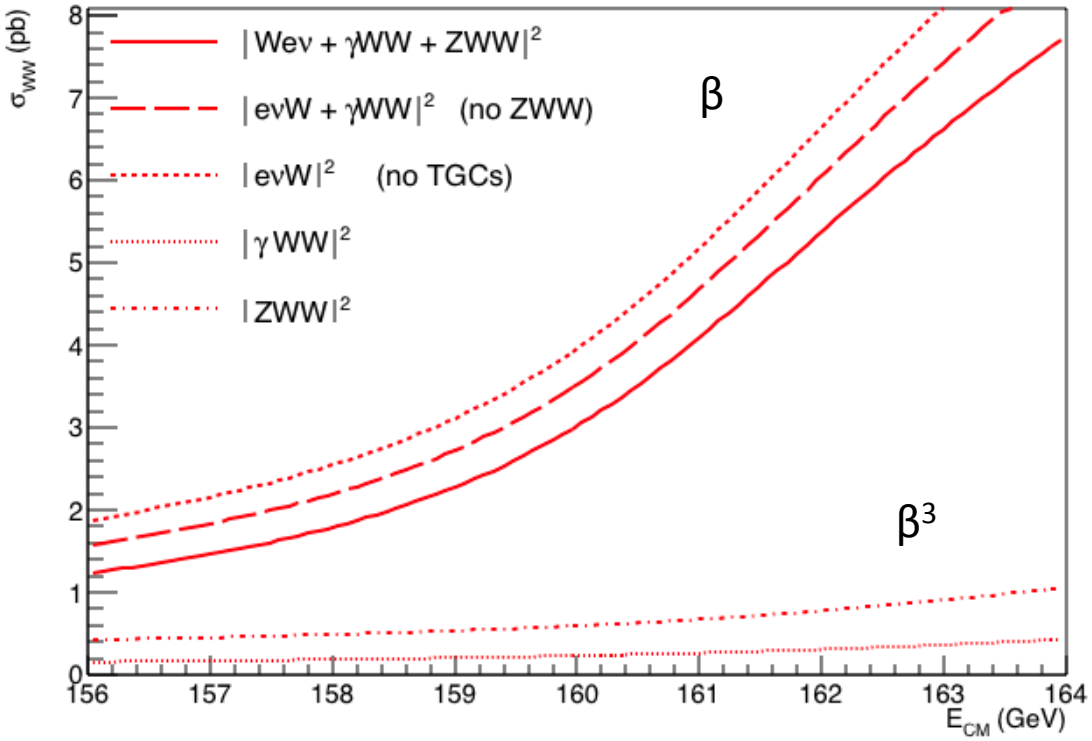
	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
Source	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	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

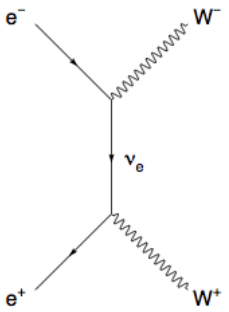


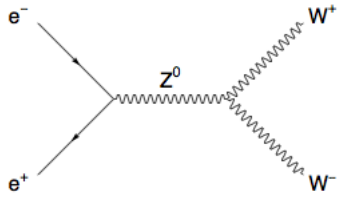
lepton and jet uncertainties from (Z) calibration data

TGCs at threshold

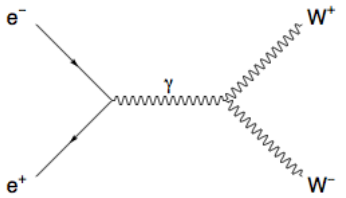


Weν





WWZ



WWγ

SU(2)⊗U(1) Gauge Cancellations

without TGCs

σ_{WW} +40% @157GeV +25%@162GeV

Conclusions

- 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: an opportunity to contribute
- 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**)
  - taking limited data "off-shell" will not ruin Δmw precision
- 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: also opportunities to contribute.

backup