WW threshold measurements precision & requirements

P. Azzurri (INFN Pisa)

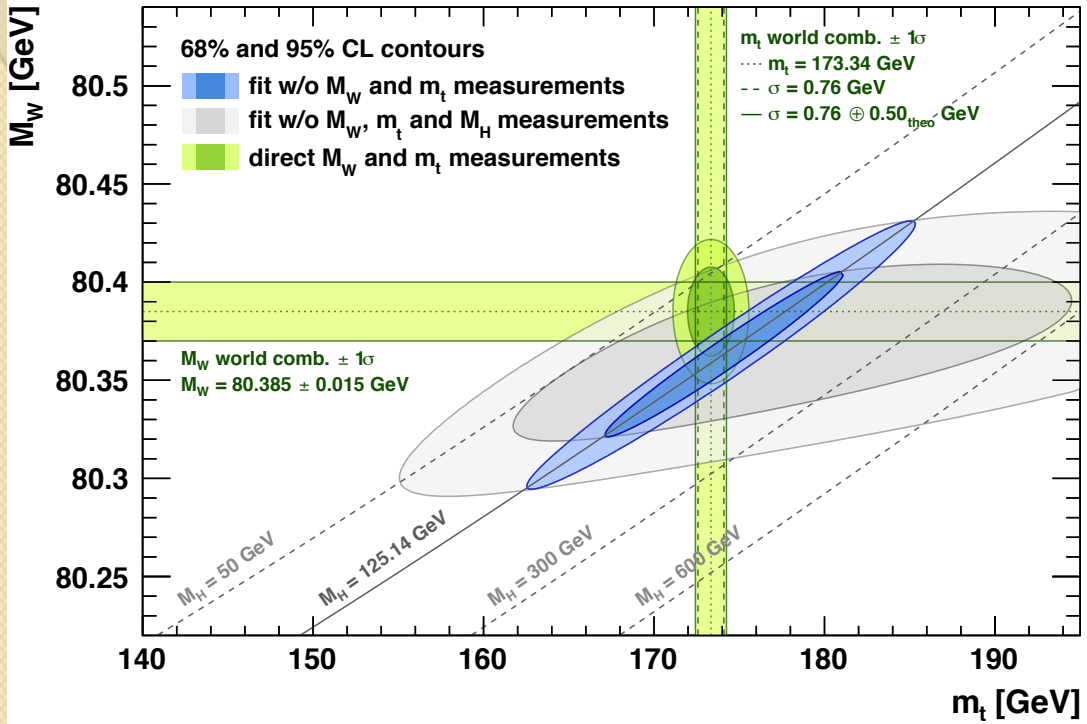
2nd mini-workshop on
FCC-ee detector requirements

Wednesday November 23, 2016

Outline

- recap of W measurements at threshold
- optimal data taking configurations
- limiting syst effects
- background
- acceptance
- a look at BRs and direct m_W

m_W & the SM



Indirect determinations

$M_t = 177.0^{+2.3}_{-2.5}$ GeV

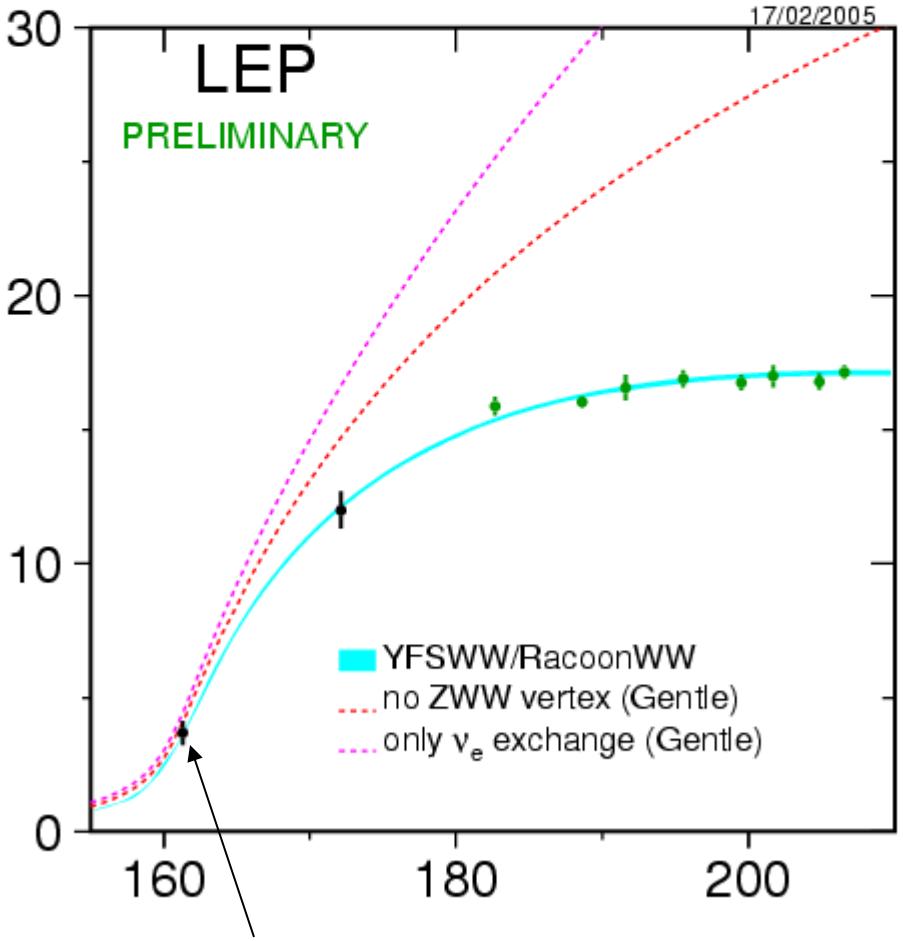
$M_H = 93^{+25}_{-21}$ GeV

M_W=80358±8 MeV

the ball is in the W court

Eur . Phys. J. C **74**, 3046 (2014)

Lep2 WW



$$\sigma\left(m_W, E\right)$$

$$m_W = \sigma^{-1}\left(E\right)$$

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

$$m_W = 80.40 \pm 0.21\,\mathrm{GeV}/c^2$$

Lep2 WW threshold

$$N = L\left(\varepsilon\sigma + \sigma_B\right) \qquad \sigma = \left(\frac{N}{L} - \sigma_B\right)\frac{1}{\varepsilon}$$

$$\Delta\sigma_{stat} = \frac{\sqrt{N}}{L\varepsilon} = \frac{\sqrt{\sigma}}{\sqrt{L\varepsilon}}\sqrt{1+\frac{\sigma_B}{\varepsilon\sigma}} = \frac{\sqrt{\sigma}}{\sqrt{L}}\frac{1}{\sqrt{\varepsilon p}}$$

At LEP2 $\sqrt{s}$=161 GeV σ=4pb ;
minimum stat $\Delta\sigma$ for max ε p
with overall ε =0.75, σ_B=300 fb
p=0.9 : ε p≈0.68 (@161)

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

WW threshold other $\Delta\sigma_{WW}$

$$\sigma = \left(\frac{N}{L} - \sigma_B\right)\frac{1}{\varepsilon}$$

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

$$\Delta\sigma_{WW} = \frac{\Delta\sigma_B}{\varepsilon}$$

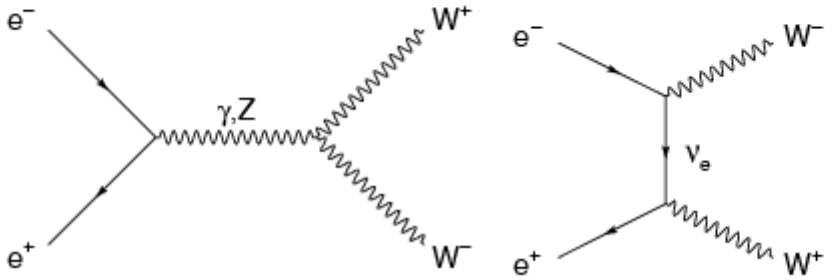
$$\Delta m_W(B) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\Delta\sigma_B}{\varepsilon}$$

$$\Delta\sigma_{WW} = \sigma\left(\frac{\Delta\varepsilon}{\varepsilon}\oplus\frac{\Delta L}{L}\right)$$

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

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

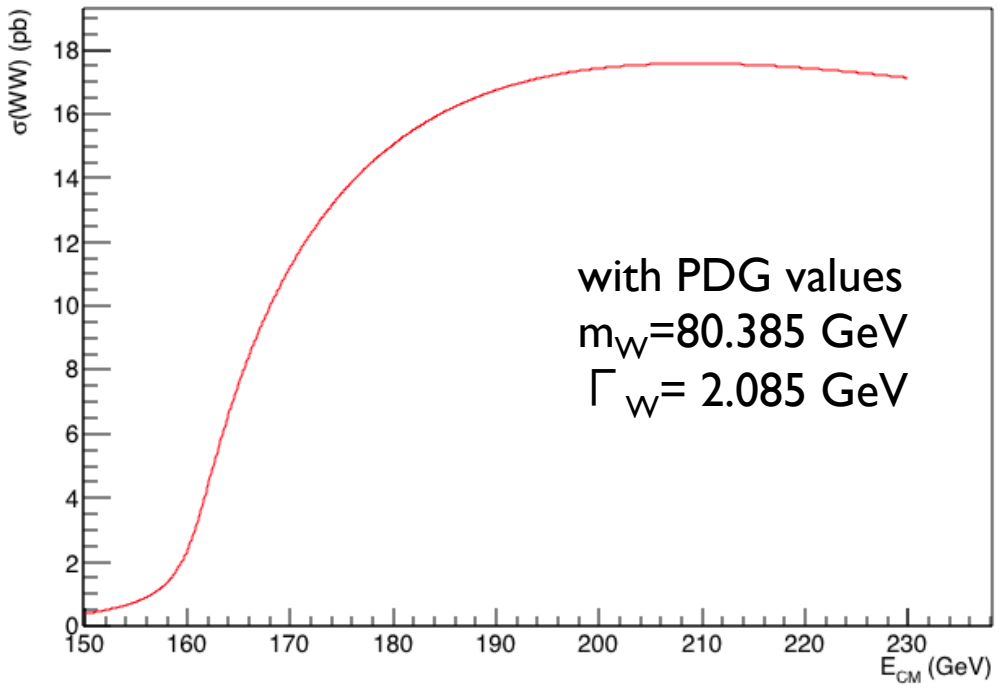
$e^+e^- \rightarrow W^+W^-$



$$\sigma(s) = B_{f_1\bar{f}_2} B_{f_3\bar{f}_4} \int_0^s ds_1 \rho(s_1) \int_0^{(\sqrt{s}-\sqrt{s_1})^2} ds_2 \rho(s_2) \sigma(s, s_1, s_2),$$

$$\rho(s) = \frac{1}{\pi} \frac{\sqrt{s}\Gamma(s)}{(s - M_W^2)^2 + M_W^2 \Gamma^2(s)}$$

m_W=80.385 GeV Γ_W=2.085 GeV

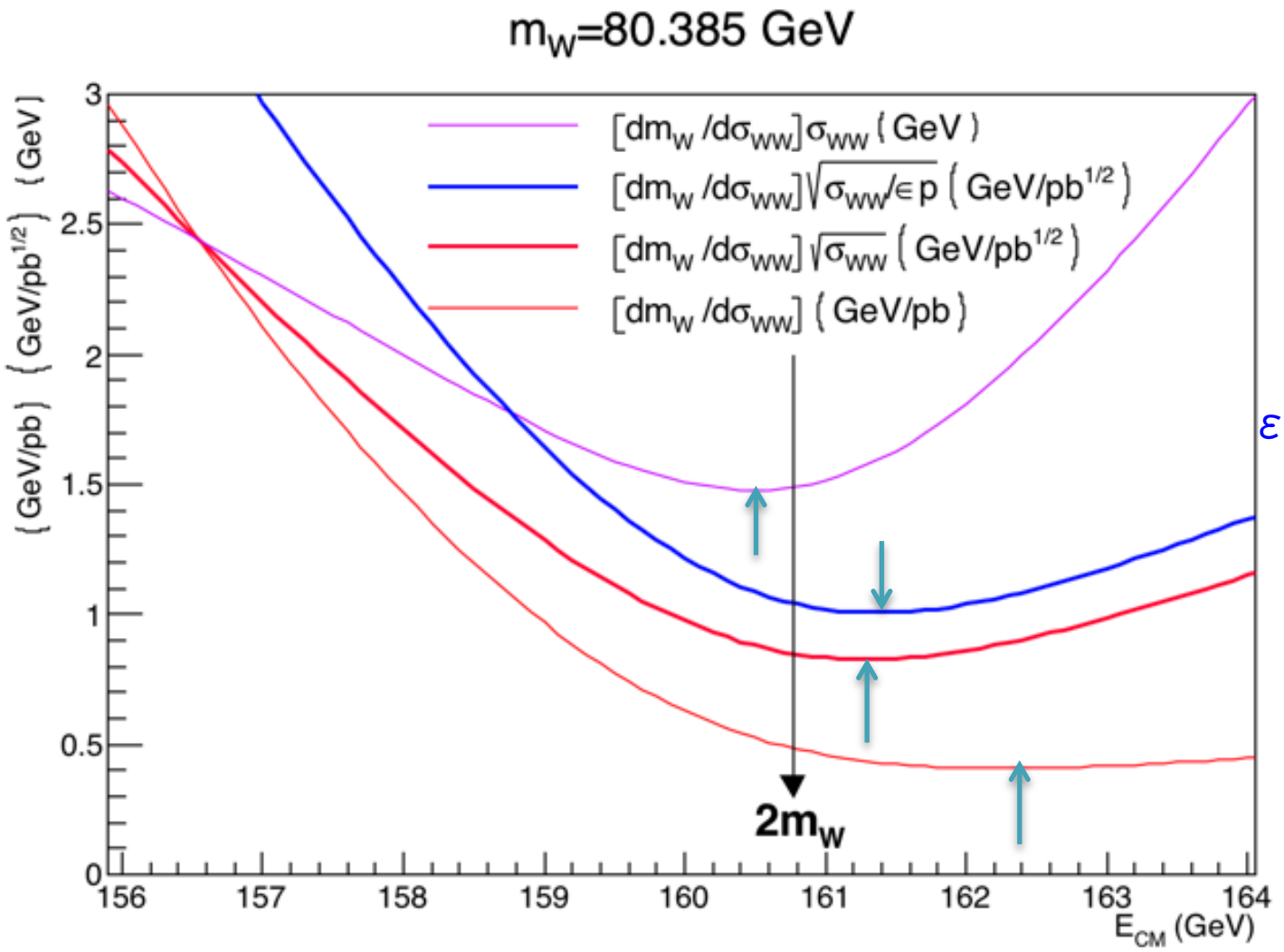


σ (E ,m_W, Γ_W) now evaluated with YFSWW3 <u>version 1.18</u>
<u>using best precision options and semi-analytical O(α^3) LL KorWan</u>

both calculations agree at 1% level in the threshold region

Many thanks to
Wiesław Płaczek for assistance

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



$\sqrt{\varepsilon}\, p$ 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 $\sqrt{s}\sim 2m_W+1.5$ GeV

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

at $\sqrt{s}\sim 2m_W$ -0.3 GeV

$$\left(\frac{d\sigma}{dm_W}\right)^{-1}\sqrt{\sigma}\Bigg|_{\min} \sim 0.83\frac{GeV}{pb^{1/2}}$$

at $\sqrt{s}\sim 2m_W+0.5$ GeV

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

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

Max stat sensitivity

m_W from σ_{WW} : precision

$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{\min} \approx 1.0\,\frac{GeV}{pb^{1/2}}$$

at $\sqrt{s}$~2m_W+600 MeV

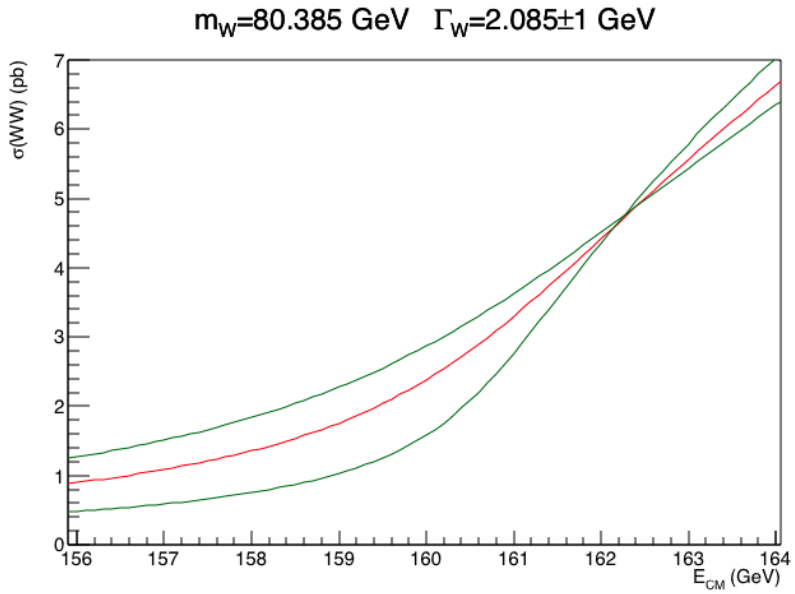
Max stat sensitivity

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)
- $\Delta\,\varepsilon/\varepsilon$, ΔL/L < 10-4
- $\Delta\,\sigma_B$<0.5 fb (10-3)

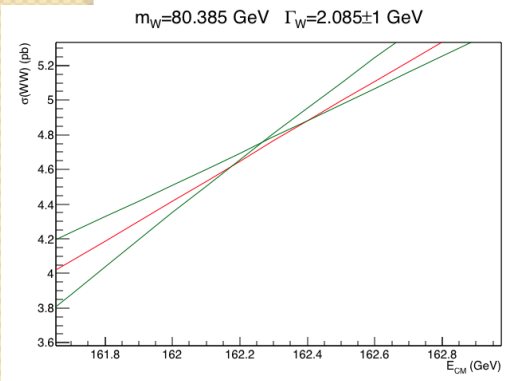
Γ_W from σ_{WW}



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

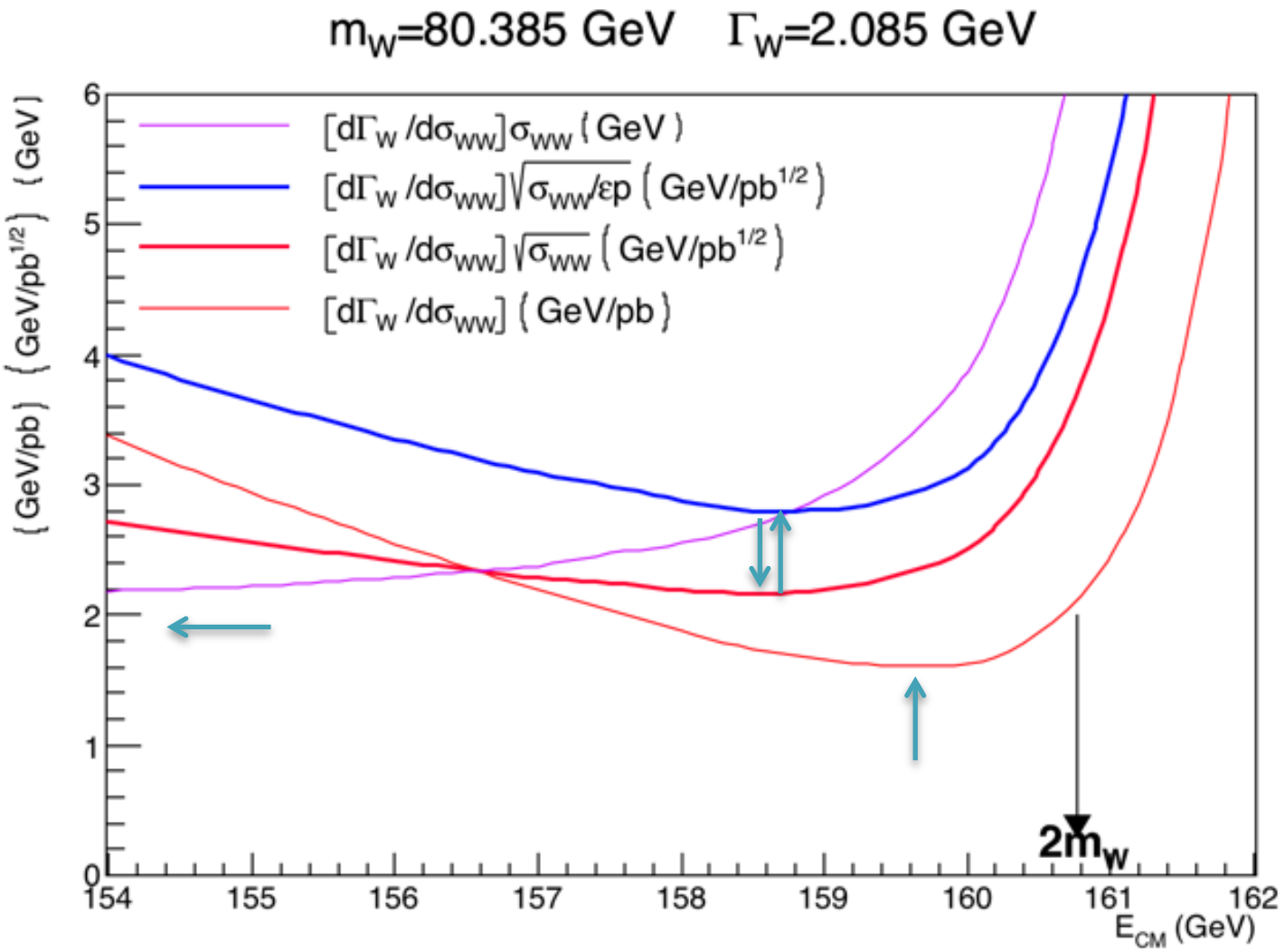
Determine f, E_1, E_2 such to mimimise ($\Delta\Gamma_W$, Δm_W) with some target

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}

Max sensitivity ECM points

$$\left(\frac{d\sigma}{d\Gamma_W}\right)^{-1}\Bigg|_{\min} \sim 1.6\,\frac{GeV}{pb}$$

at $\sqrt{s}\sim 2m_W$-1.1 GeV

$$\left(\frac{d\sigma}{d\Gamma_W}\right)^{-1}\sigma\Bigg|_{\min} \sim 2GeV$$

$$\left(\frac{d\sigma}{d\Gamma_W}\right)^{-1}\sqrt{\sigma}\Bigg|_{\min} \sim 2.2\,\frac{GeV}{pb^{1/2}}$$

at $\sqrt{s}\sim 2m_W$-2.2 GeV

$$\left[\left(\frac{d\sigma}{d\Gamma_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{\min} \approx 2.8\,\frac{GeV}{pb^{1/2}}$$

at $\sqrt{s}\sim 2m_W$-2.1 GeV

m_W & Γ_W from σ_{WW}

Uncertainty propagation

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

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

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

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

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

Δ m, $\Delta\ \Gamma$ 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}

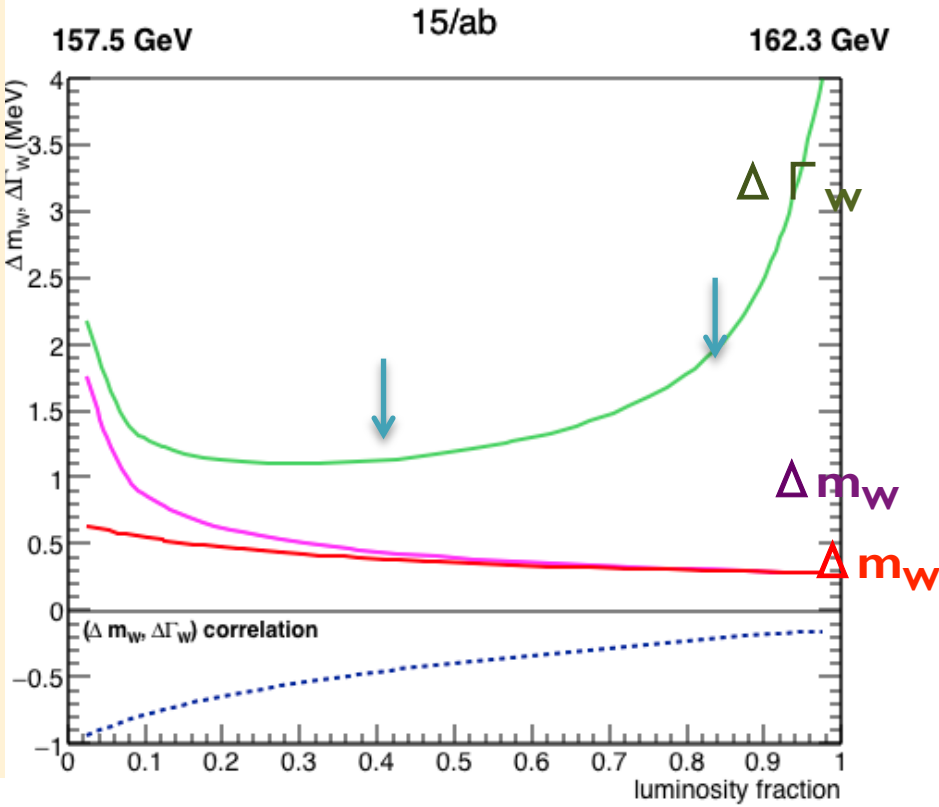
scan luminosity fractions

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 Δ Γw≈ 1.7 MeV
(r=-0.23)

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

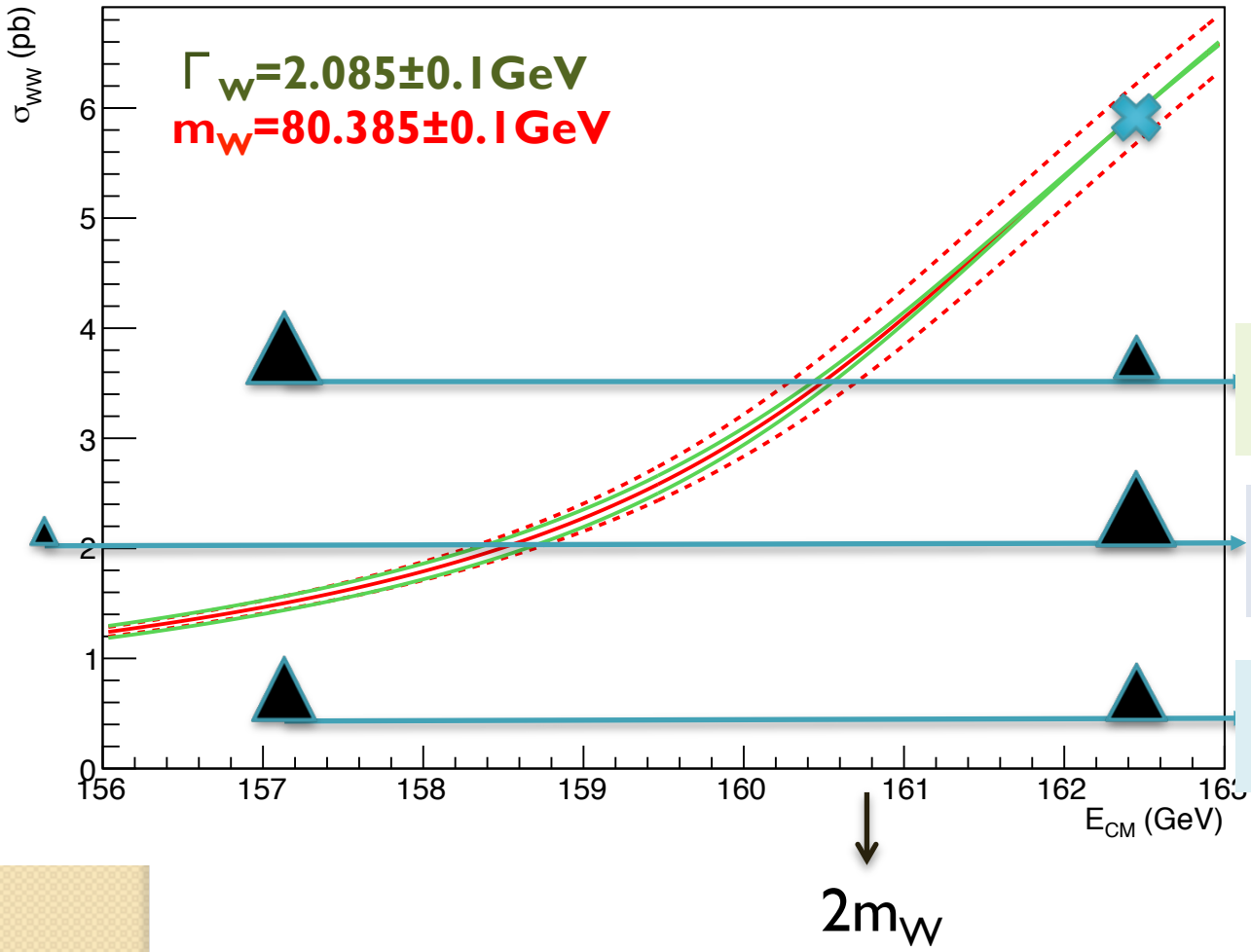


lumi fraction at higher energy

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}

Scan of possible energy point pairs and luminosity fractions



Δm_W=0.56 $\Delta \Gamma_W$=1.07
Δm_W=0.47 (MeV)

Δm_W=0.28 $\Delta \Gamma_W$=4.3
Δm_W=0.28 (MeV)

Δm_W=0.41 $\Delta \Gamma_W$=1.10
Δm_W=0.40 (MeV)

m_W & Γ_W from σ_{WW}

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

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

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

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

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

impact of limiting systematics

$$\Delta\sigma = k\sigma\left(k = 10^{-3}\right)$$

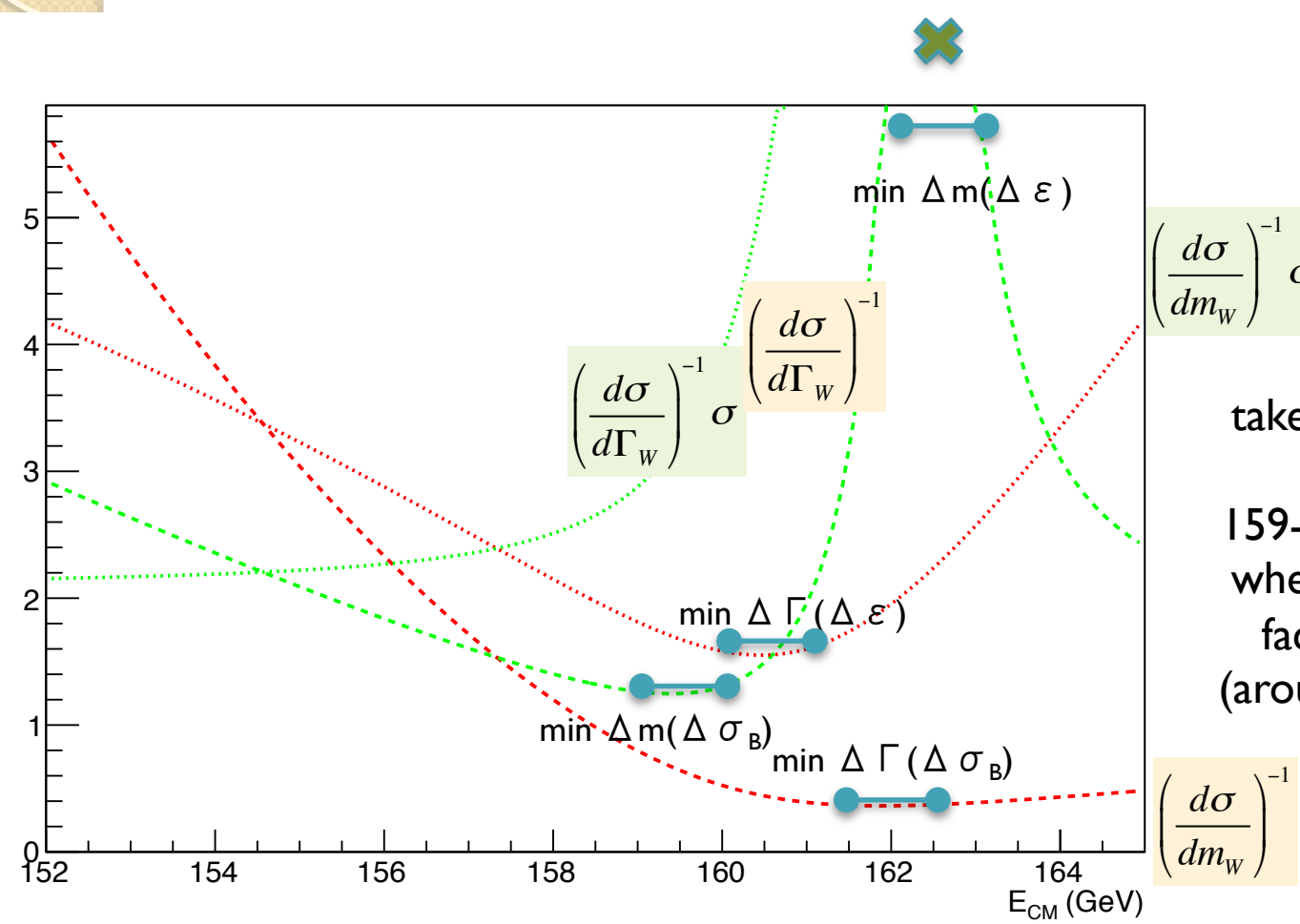
$\Delta\ \varepsilon$ limit

$$\Delta\sigma = c\left(c = 5\,fb\right)$$

$\Delta\ \sigma_B$ limit

m_W & Γ_W from σ_{WW}

optimal E points with limiting **correlated** systs

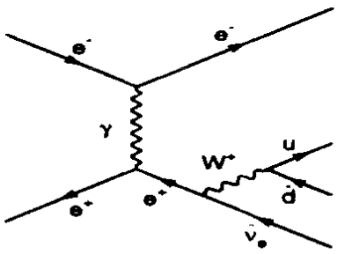


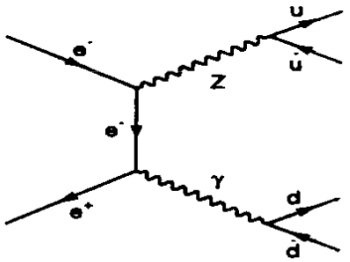
take data at different E_{CM} points 159-160-161-162-163 where the derivative factors are equal (around their minima)

background control

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

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





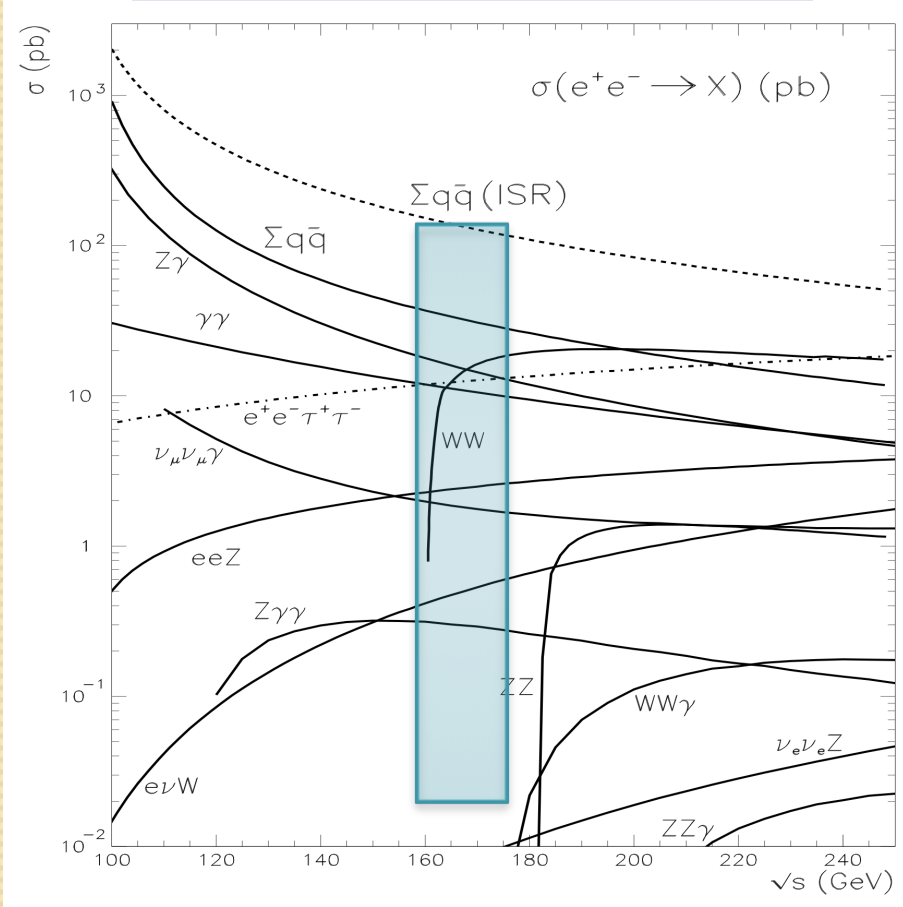
channel	efficiency	purity	bkg [ALEPH 1996]
lνlν	70-80%	80-90%	**50fb** (ττ,γγ→ττ,Zγ*→ννll)
eνqq	85%	~90%	**30fb** (qq, Zee, Zγ*) **-10fb** (Weν)
μνqq	90%	~95%	**10fb** (Zγ*,qq)
τνqq	50%	80-85%	**50fb** (qq, Zγ*)
qqqq	90%	~90%	**~200fb** (qq (qqqq,qqgg))

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

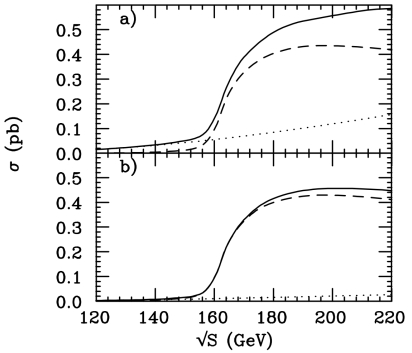
LEP2 "STANDARD MODEL PROCESSES"
hep-ph/9601224 (1996)



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

measure forward electrons ($\theta \leq 0.1$ rad)
for Zee Wev : determine forward pole
$d\sigma/d\theta$ and WW interference effects

σ (evud)
.. with $\theta_e > 8°$ cut



acceptance down to $\theta = 0.1$ **[cos θ = 0.995]** would also cover forward jets

what about beam (induced) bkg/noise ?

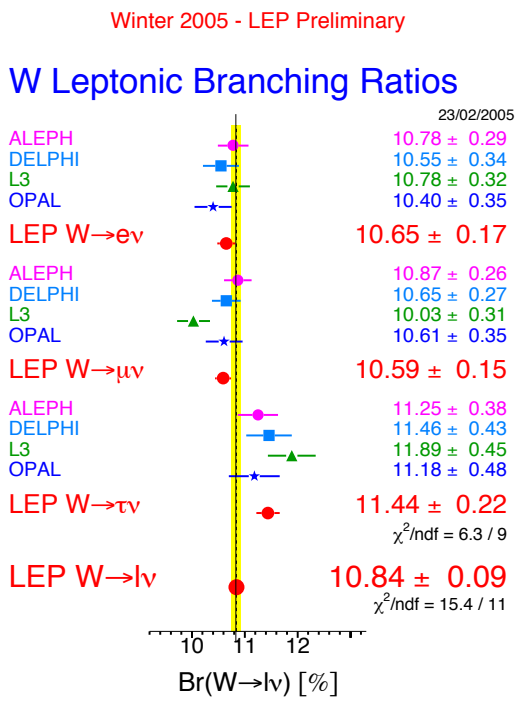
acceptance

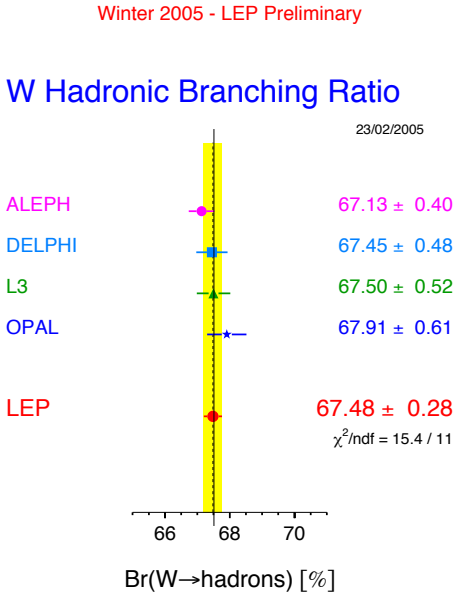
how do we control acceptance at the 10^{-4} level (0.01%) ?
➔ aim for the highest possible acceptance and efficiency WP

- 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 $\Delta\varepsilon \sim 2\ 10^{-3}$ 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 hopefully not limiting (arXiv:1310.6708)

W BR





q/ l universality at 0.6%

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

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

➔ Δ BR(lν)(stat)=[5-4]10^{-3} (rel)

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

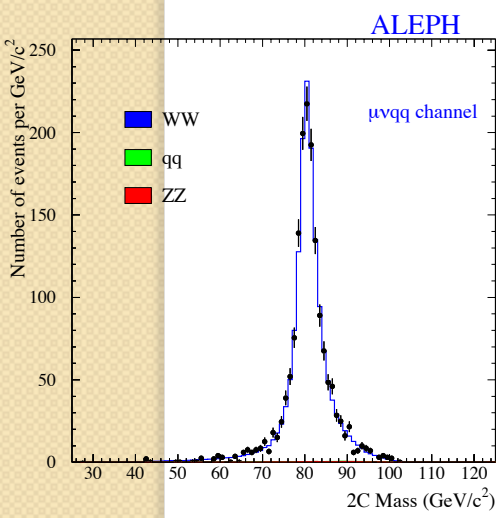
will need much better control of lepton id
i.e. cross contaminations in signal channels
(τ →e, μ in the e, μ channels and v.v.)

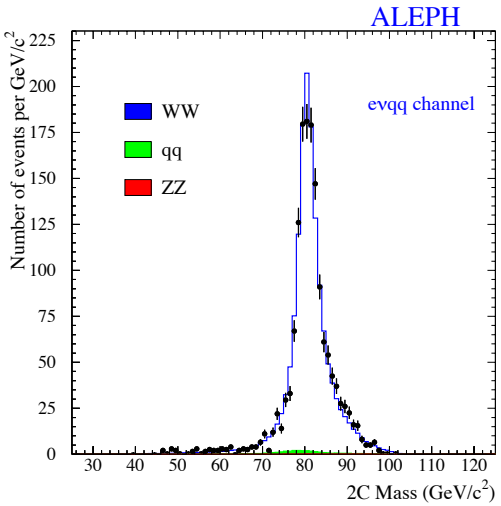
Flavor tagging would also allow to measure coupling to c & b-quarks (Vcs,Vcb,..)

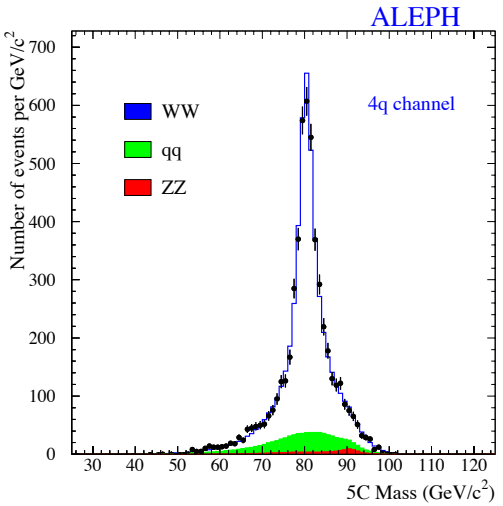
reco mass of the W boson

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

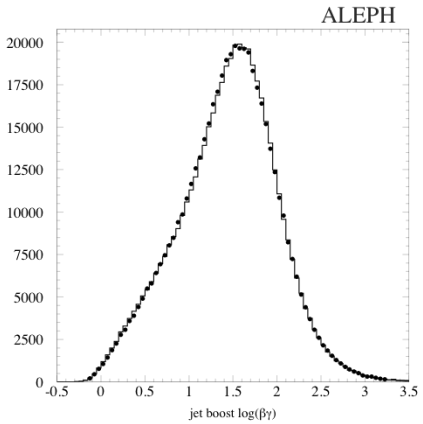
Γ_W = 2140 ±90(stat.) ±45(syst.) ±46(FSI) ± 7(LEP) MeV

reco mass of the W boson

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

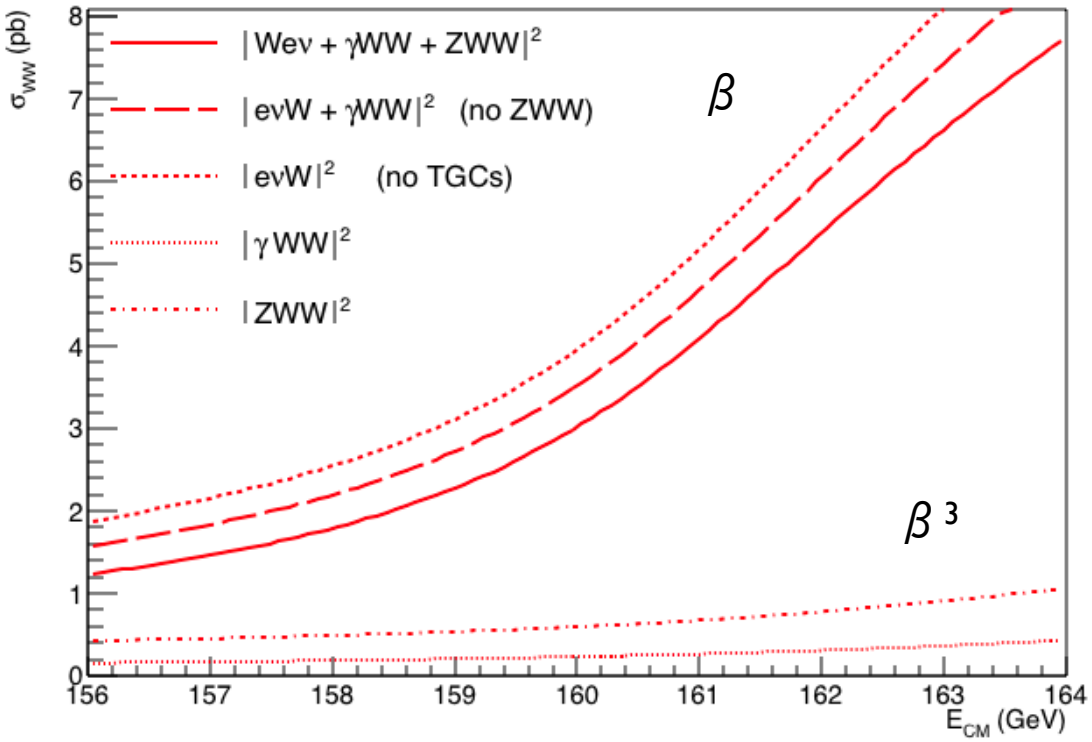
15/ab@160GeV + 10/ab@240GeV

➔ 60M+ 160M W-pairs

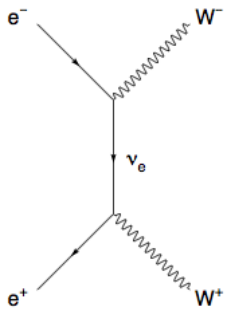
➔ Δm_W (stat)= 0.5-0.3 MeV

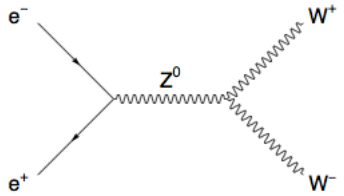
➔ Δm_W (syst) < 5 MeV ?

TGCs at threshold

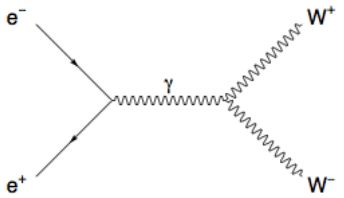


Wev





WWZ



WWγ

SU(2)⊗U(1) Gauge Cancellations

without TGCs

σ_{WW} +40% @157GeV +25%@162GeV

outlook

- The WW threshold lineshape is great to measure both m_W and Γ_W: Stat 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
- Challenge for knowledge of energy (<1 MeV), acceptance (10^{-4}), backgrounds (<1fb). Measurements at >2 E_{CM} points to tackle limiting syst uncertainties.
- Ideal to have **maximum acceptance** coverage for leptons and jets
  - also to measure backgrounds with forward electron poles (single-bosons , other 4f)
- high lepton-id eff, good jet energy resolution, and jet granularity
  - constrain the jet modeling uncertainties
- Interest in $\sigma_{WW}(E)$ lineshape goes beyond m_W and Γ_W: eg. the threshold raise β (ν), β^3 (TGCs)
- some thoughts on decay couplings and direct W reco
  - more challenging (detector) systematics out there