Reconstruction of the W mass and width at and above WW threshold at FCC-ee

Marina Béguin

On behalf of the WG2 working group

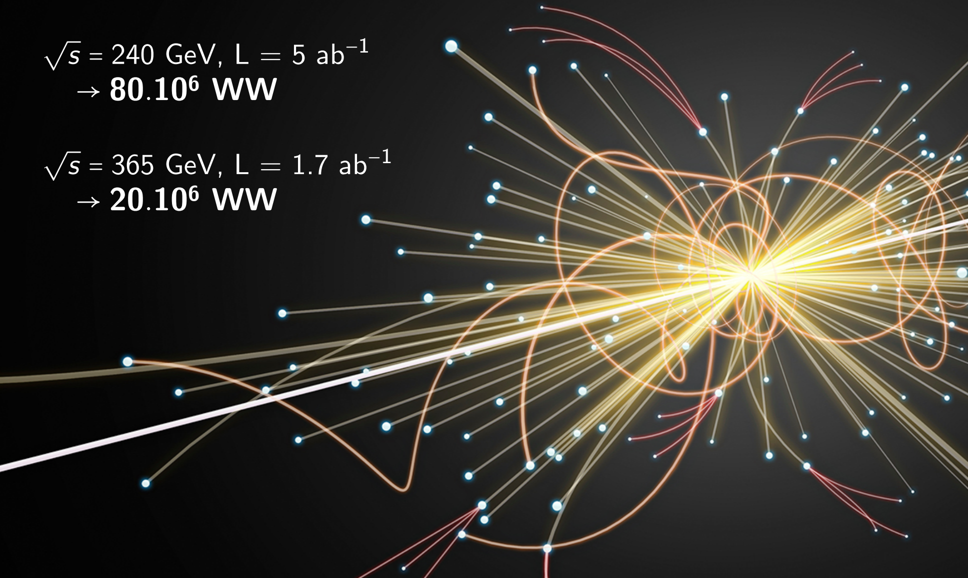
July 13, 2019

WW factory

$\sqrt{s} = 160$ GeV, L $= 12$ ab^{-1}
$\rightarrow$ **60.10^6 WW**

$\sqrt{s} = 240$ GeV, L $= 5$ ab^{-1}
$\rightarrow$ **80.10^6 WW**

$\sqrt{s} = 365$ GeV, L $= 1.7$ ab^{-1}
$\rightarrow$ **20.10^6 WW**

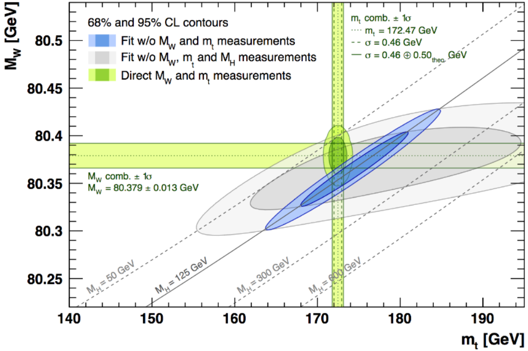


WW diboson physics at FCC-ee

- Measurements of the W mass and width directly and with threshold scan;
- W partial branching ratios;
- Strong coupling constant;
- CKM matrix;
- Gauge self-couplings ...

... **with unprecedented accuracy**

W mass measurement

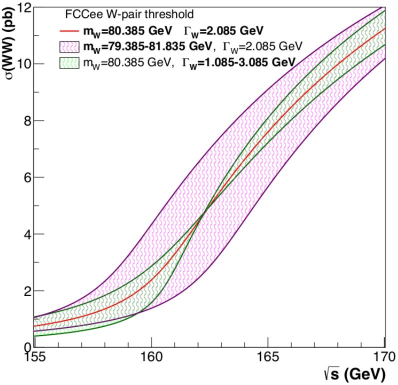


Precise relation between $\mathbf{M_W}$, M_H, M_t *is a* **crucial test** *of the internal consistency of SM and failure might reveal* **new physics**.

Methods

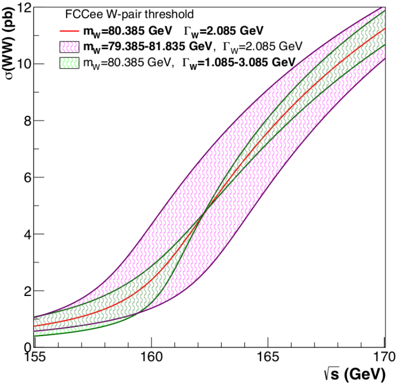
- At WW threshold;
- Direct determination

M_W at WW threshold



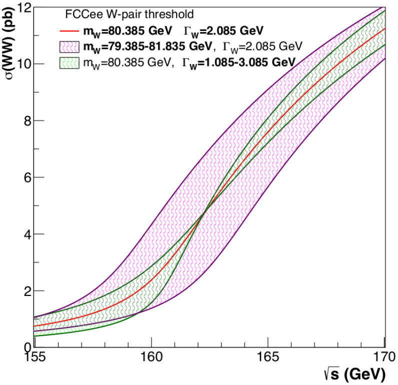
$$\Delta M_{W,stat} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \Delta\sigma$$

M_W at WW threshold



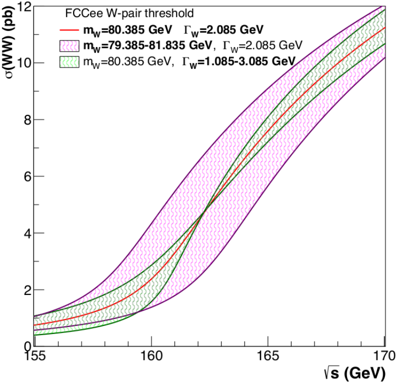
$$\Delta M_{W,stat} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\epsilon p}}$$

$$\text{with} \quad p = \frac{\epsilon\sigma}{\epsilon\sigma + \sigma_B}$$



$$\Delta M_{W,stat} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\epsilon p}}$$
$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\Delta\sigma_B}{\epsilon}$$
$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma \left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right)$$

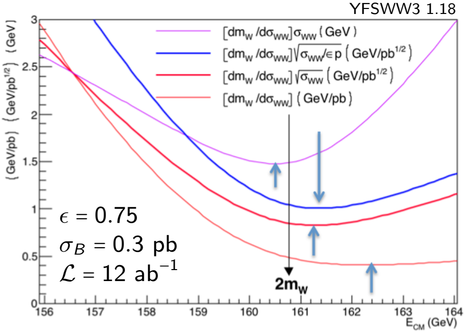
M_W at WW threshold



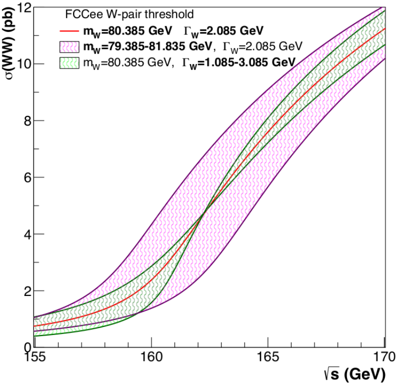
$$\Delta M_{W,stat} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\epsilon p}} \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\Delta\sigma_B}{\epsilon} \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma \left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right)$$

Optimal energy : E = 161.4 GeV
ΔM_W = 0.23 MeV

LEP : ΔM_W = 210 MeV
$\mathcal{L}$ = 10 pb^{-1}



M_W at WW threshold



$$\Delta M_{W,stat} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\epsilon p}}$$
$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\Delta\sigma_B}{\epsilon}$$
$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma \left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right)$$

Optimal energy : $E = 161.4$ GeV
$\Delta M_W = 0.23$ MeV

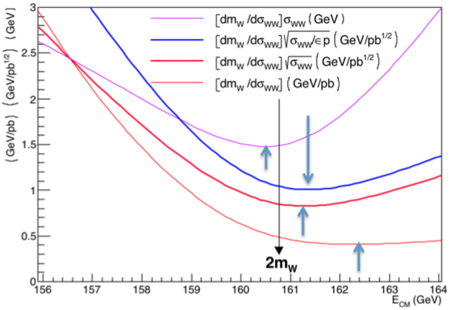
LEP : $\Delta M_W = 210$ MeV
$\mathcal{L} = 10\ \text{pb}^{-1}$

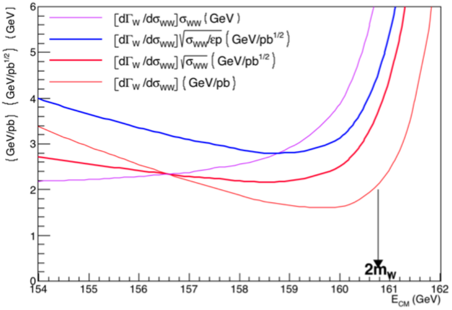
Need systematic controls on:

- $\Delta\sigma_B < 0.6$ fb $(2 \cdot 10^{-3})$
- $\left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right) < 2 \cdot 10^{-4}$
- $\Delta\sigma_{theory} < 0.8$ fb $(2 \cdot 10^{-4})$
- $\Delta E_{CM} < 0.2$ MeV $(2 \cdot 10^{-6})$

M_W and Γ_W at WW threshold

Paolo Azzurri





Optimal combination :

$E_1 = 157.1$ GeV, $E_2 = 162.3$ GeV, $f = 0.4$

ΔM_W = 0.4 MeV and **$\Delta\Gamma_W$ = 1.2 MeV**

With resonant depolarisation, $E_b = 0.4406486(\nu + 0.5)$ GeV

$E_1 = 157.3$ GeV, $E_2 = 162.6$ GeV, $f = 0.4$

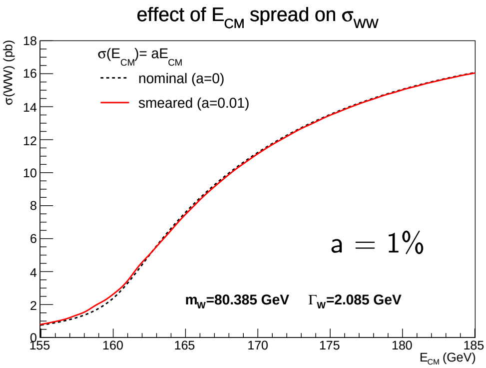
ΔM_W = 0.45 MeV and **$\Delta\Gamma_W$ = 1.3 MeV**

Effect of the energy spread (σ_E):

$$\delta\sigma_W \sim \frac{1}{2}\frac{d^2\sigma_W}{dE^2}\sigma_E^2$$

$$\frac{\sigma_E}{E} = a$$

σ_E measured/monitored with $e^+e^- \to \mu^+\mu^-$ events.

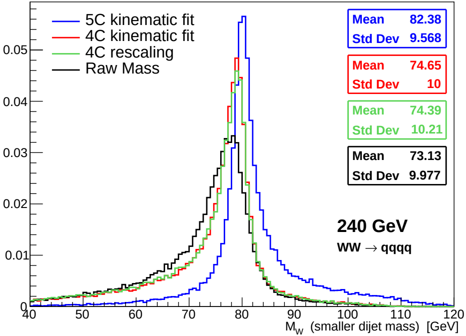


At FCCee the energy spread will be measured with a relative precision of better than 0.2%
→**Negligible** contribution on ΔM_W and $\Delta\Gamma_W$.

Direct reconstruction of M_W and Γ_W
Hadronic decay channel

Study at 162.6 GeV, 240 GeV and 365 GeV

- PYTHIA simulation
- Reconstruction with Heppy (CLD detector, Durham algorithm)

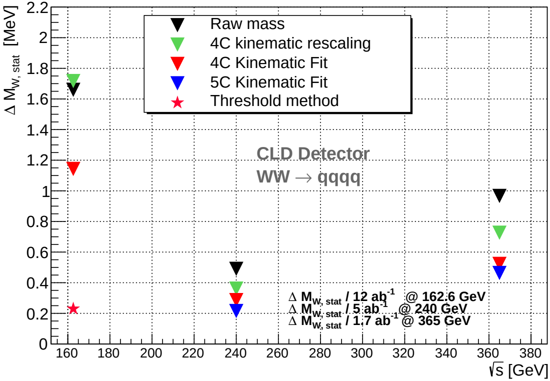


W mass estimators :

- **Raw mass**
- 4C **jets momenta rescaling**
- **Kinematic fit** with energy-momentum conservation (4C) and W masses equality (5C)

Direct reconstruction of M_W and Γ_W
Hadronic decay channel

Statistical uncertainty estimated with a **binned maximum likelihood fit** on the reconstructed M_W distributions, using **templates** with different nominal W mass(width) values.



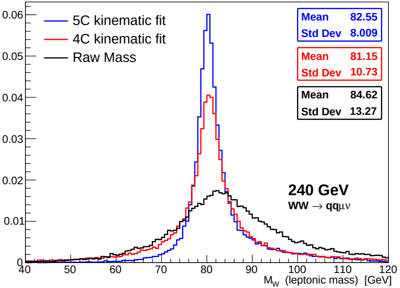
@162.6 GeV
$\Delta\Gamma_W(4C)$ = 1.11 MeV
@240 GeV
$\Delta\Gamma_W(5C)$ = 0.48 MeV
@365 GeV
$\Delta\Gamma_W(5C)$ = 1 MeV

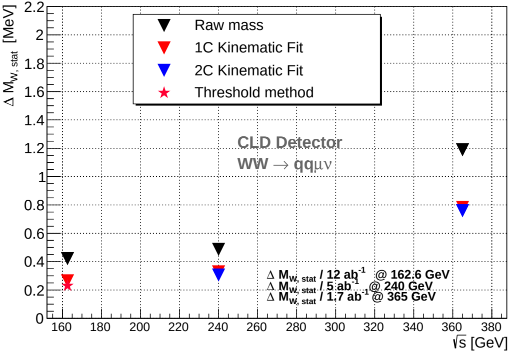
Full FCCee luminosity

Direct reconstruction of M_W and Γ_W
Semi-leptonic decay channel

Study at 162.6 GeV, 240 GeV and 365 GeV

Only the muon decay





@162.6 GeV $\Delta\Gamma_W(1C) = 0.35$ MeV
@240 GeV $\Delta\Gamma_W(2C) = 0.68$ MeV
@365 GeV $\Delta\Gamma_W(2C) = 1.56$ MeV

Full FCCee luminosity

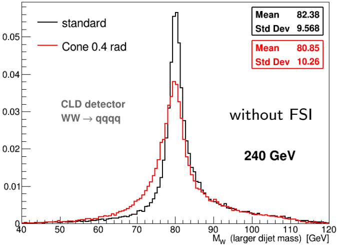
Systematic uncertainties

Main sources of systematic uncertainties at LEP2:
arXiv:1302.3415

Source	Systematic Uncertainty in MeV			
	on m_W			on Γ_W
	$q\bar{q}\ell\nu_\ell$	$q\bar{q}q\bar{q}$	Combined	
ISR/FSR	8	5	7	6
Hadronisation	13	19	14	40
Detector effects	10	8	9	23
LEP energy	9	9	9	5
Colour reconnection	$-$	35	8	27
Bose-Einstein Correlations	$-$	7	2	3
Other	3	10	3	12
Total systematic	21	44	22	55
Statistical	30	40	25	63
Statistical in absence of systematics	30	31	22	48
Total	36	59	34	83

FSI simulated with Pythia (SKI/SKII).

$\delta M_{W,FSI}$ reduced **using a cone (0.4 rad) on jets**



$\sqrt{s}$ [GeV]	162.6		240		365	
δM_{FSI} [MeV]	standard	cone	standard	cone	standard	cone
SKI	14.6	7.6	24.1	11.6	32.2	17.5
SKII	8	3.8	12.5	6.3	15.1	8.9
BEC	3.3	1.9	5.9	2.3	10.2	5.7

$\Delta M_{W,stat}$ is degraded with the cone by a few percents at threshold and 10-15% above.

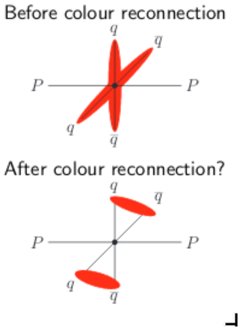
Conclusion

The amount of W-pairs at different centre-of-mass energies presents a huge potential for the W physics measurements.

- Measurement of M_W and Γ_W simultaneously at the W-pair production threshold with high precision ($\Delta M_W = 0.45$ MeV).
- Direct M_W and Γ_W measurements at threshold and above. Best statistical uncertainty expected at higher energies ($\Delta M_W = 0.28$ MeV at 240 GeV and $\Delta M_W = 0.46$ MeV at 365 GeV in the hadronic decay channel).
- Other W physics measurements: improvements of the gauge couplings sensitivity, W decay couplings at 10^{-4} level ($\alpha_s(M_W^2)$ and CKM matrix).

BACK-UP

Colour Reconnection - Models



Jesper Roy Christiansen, July 23, 2015,
EPS HEP, Vienna

Color Reconnection (CR) : interaction between partons of the two Ws

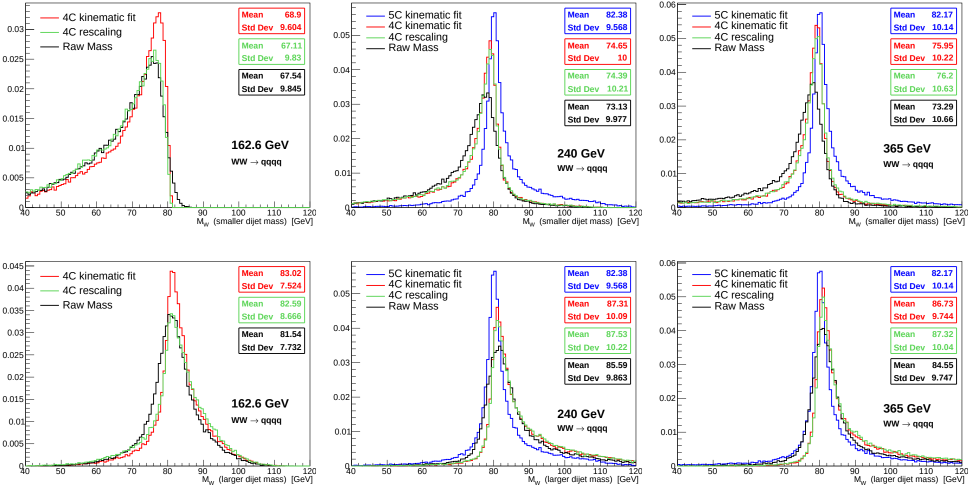
$$e^+e^- \rightarrow WW \rightarrow q_1\bar{q}_2q_3\bar{q}_4$$

Because WW separation in phase-space is smaller than the typical distance scale of hadronisation: $(q_1\bar{q}_4)$ and $(q_3\bar{q}_2)$

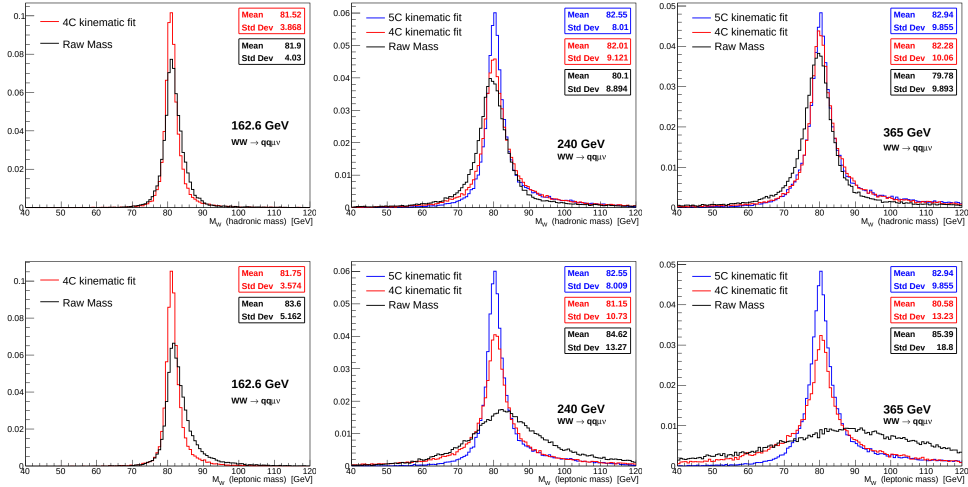
Models in PYTHIA for e^+e^- collisions are based on string hadronisation.

- SK1 : string = cylindrical bag. Colour reconnection probability proportional to the integrated overlap between cylinders.
- SK2 : string = vortex line. Colour reconnection if the cores are crossing.

W mass distributions - Hadronic channel



W mass distributions - Semi leptonic channel



W mass and width statistical uncertainties

Table: Hadronic decay

	σ_{M_W} $[MeV/c^2]$			σ_{Γ_W} $[MeV/c^2]$		
$\sqrt{s}$ $[GeV/c^2]$	162.6	240	365	162.6	240	365
Luminosity (ab^{-1})	12	5	1.7	12	5	1.7
Raw Mass	1.66	0.49	0.97	1.44	1.10	1.71
4C rescaling	1.72	0.36	0.73	1.53	0.77	1.48
4C fit	1.14	0.28	0.51	1.1	0.58	0.95
5C fit		0.22	0.45		0.47	1.02

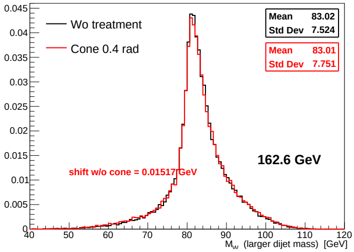
With threshold method $\sigma_{M_W} = 0.23$ GeV

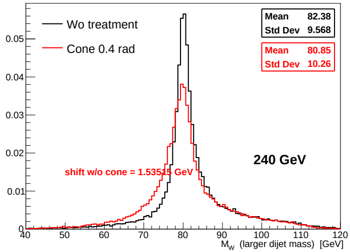
Full Luminosity

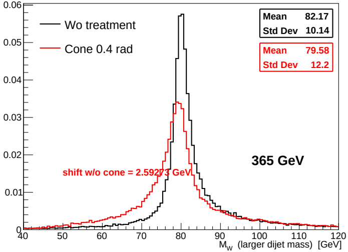
Table: Semi-leptonic decay

	σ_{M_W} $[MeV/c^2]$			σ_{Γ_W} $[MeV/c^2]$		
$\sqrt{s}$ $[GeV/c^2]$	162.6	240	365	162.6	240	365
Luminosity (ab^{-1})	12	5	1.7	12	5	1.7
Raw Mass	0.42	0.49	1.19	0.39	0.87	1.94
1C fit	0.26	0.33	0.78	0.35	0.59	1.36
2C fit		0.31	0.75		0.68	1.56

Cone reconstruction effect on W mass resolution







The loss of particle information degrades the resolution by 2.9% at 162.6 GeV, 6.7% at 240 GeV and 16.9% at 365 GeV

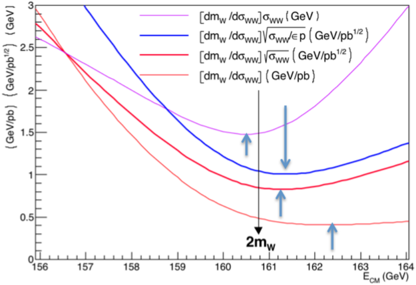
Cone effect on $\Delta M_{W,stat}$

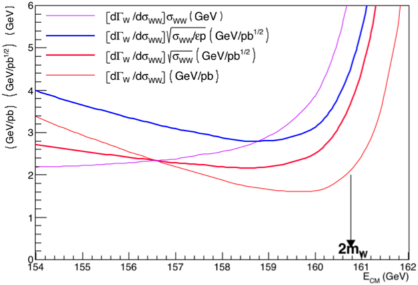
Full FCCee luminosity

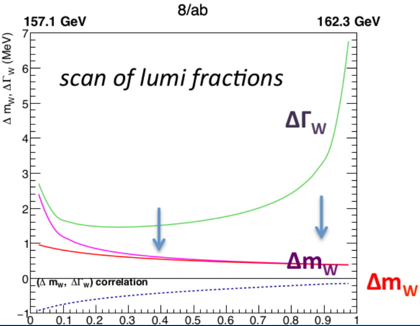
$\sqrt{s}$ [GeV]	162.6		240		365	
$\Delta M_{W,stat}$ [MeV]	standard	cone	standard	cone	standard	cone
woFSI	1.14	1.18	0.215	0.228	0.463	0.564
SKI	1.18	1.21	0.225	0.244	0.478	0.55
SKII	1.17	1.19	0.218	0.237	0.467	0.539
BEC	1.17	1.18	0.224	0.236	0.461	0.58

$\Delta M_{W,stat}$ is degraded with the cone by few percent at threshold and 10-15% above.

Fraction luminosity scan at threshold







f with 0.05 steps; E_1 and E_2 with 10 MeV

Data taking configuration that minimise arbitrary combination of the expected mass and width statistical uncertainties $F(\Delta M, \Delta\Gamma)$.

Here $F(\Delta M, \Delta\Gamma) = \Delta M_W + \Delta\Gamma_W$

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 0.2 10^{-3} precision level

background control

decay	efficiency	purity	bkg [LEP1996]
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)
μνqq	90%	~95%	**10fb** ($Z\gamma^*$,qq)
τνqq	50%	80-85%	**50fb** (qq, $Z\gamma^*$)
qqqq	90%	~90%	**~200fb** (qq (qqqq,qqgg))

2-fermion : ττ, qq
4-fermion : $\gamma\gamma\rightarrow\tau\tau$,llνν, Zee, Weν

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

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 Weν : 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

$$\left(\frac{d\sigma}{d\Gamma_W}\right)^{-1} \quad \left(\frac{d\sigma}{dm_W}\right)^{-1} \qquad \left(\frac{d\sigma}{dm_W}\right)^{-1}\sigma \quad \left(\frac{d\sigma}{d\Gamma_W}\right)^{-1}\sigma$$

differential factors are equal