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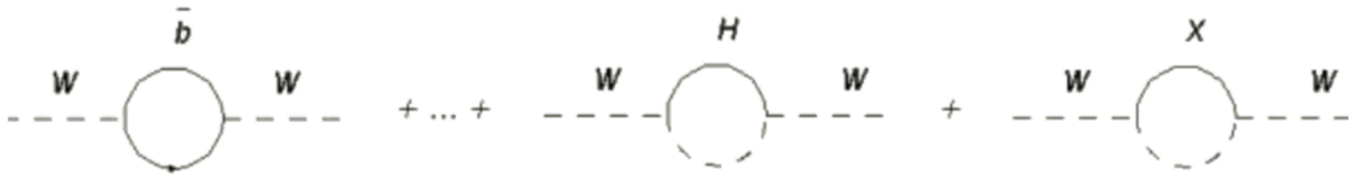
W mass & width measurement

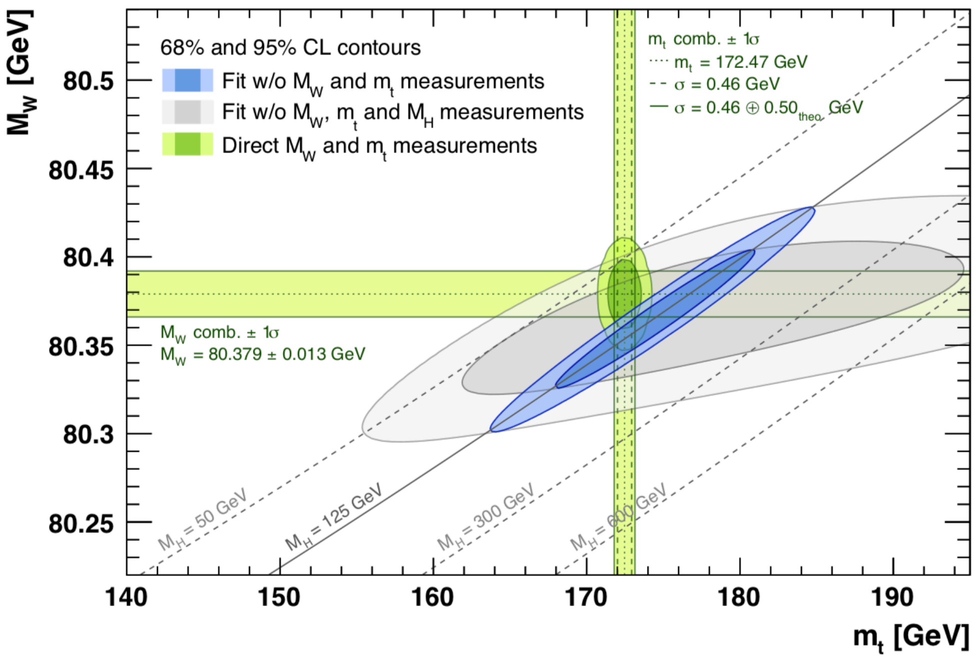
The W mass as a test of the self-consistency of the Standard Model



$$M_W^2 = \frac{\pi\, \alpha_{QED}(M_Z^2)}{\sqrt{2}\, G_F\, \sin^2\theta_W}\, \frac{1}{1-\Delta r}$$

$$\Delta r = -\frac{cos^2\theta_W}{sin^2\theta_W}\Delta\rho + \frac{\alpha}{3\pi}\left[\frac{1}{2} - \frac{1}{3}\,\frac{\sin^2\theta_W}{1-\tan^2\theta_W}\right]\log\frac{m_H^2}{m_Z^2} + \ldots \sim 1\%$$

$$\Delta\rho = \frac{\alpha m_t^2}{\pi m_Z^2} - \frac{\alpha}{4\pi}\log\frac{m_H^2}{m_Z^2} + \ldots \sim 1\%.$$



After the discovery of the Higgs boson at the LHC, all SM parameters are known and the global fit of electroweak observables is overconstrained

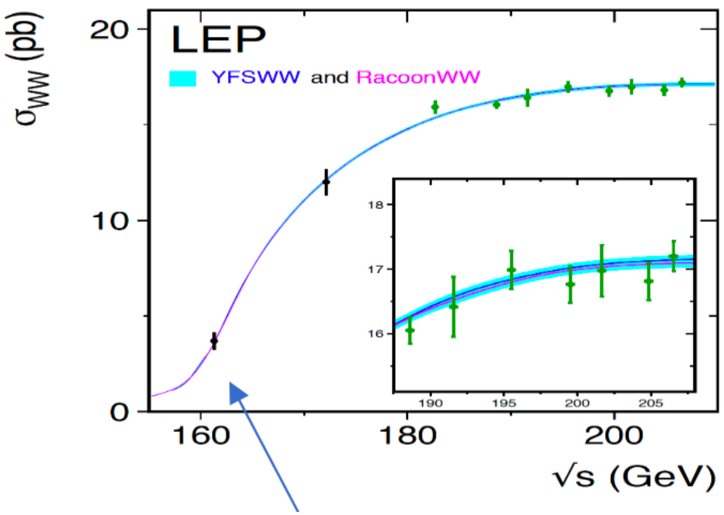
Predicted mass: 80.358 ± 4 MeV

Measured mass: 80.379 ± 12 MeV

With M_W (& other e.w. observables) precisely measured, the global fit will provide a stringent consistency test of the SM, which failure might reveal **new physics**

Mass measurement methods

From the W-pair production cross-section near its kinematic threshold



Involves selecting & counting events

Clean, uses all decay channels

$\sqrt{s}$ = 160 GeV, L = 12 ab^{-1} → 60. 10^6 WW

https://arxiv.org/pdf/1703.01626.pdf

From the full reconstruction of the WW decays

$$m_{inv} = \sqrt{(E_1 + E_2)^2 - (P_1 + P_2)^2}$$

Uses fully hadronic & semi-leptonic channels

Uses kinematic reconstruction techniques

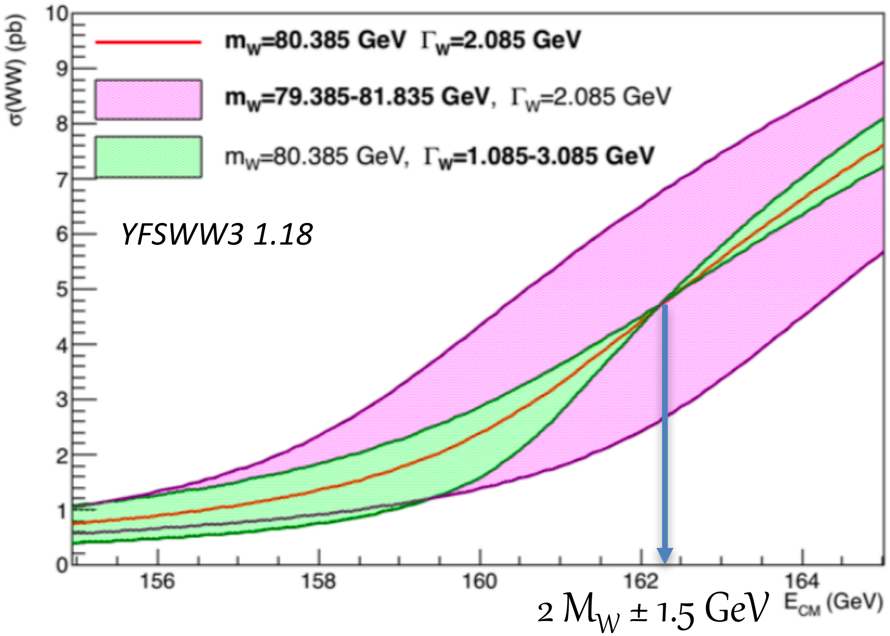
$\sqrt{s}$ = 160 GeV, L = 12 ab^{-1} → 60. 10^6 WW

$\sqrt{s}$ = 240 GeV, L = 5 ab^{-1} → 80. 10^6 WW

$\sqrt{s}$ = 350-365 GeV, L = 1.7 ab^{-1} → 20. 10^6 WW

http://www.theses.fr/2019SACLS393

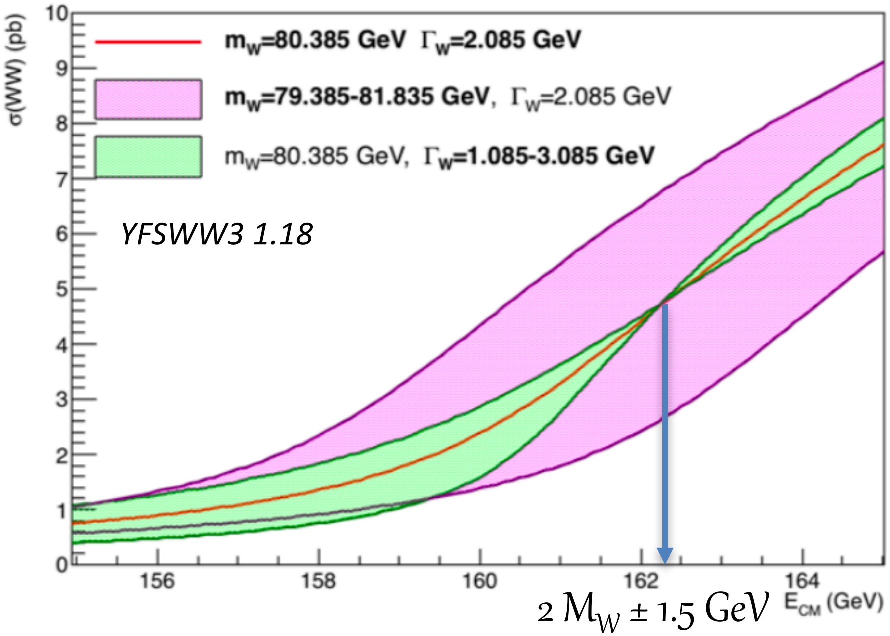
W mass from the W-pair production cross-section near threshold



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

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

W mass from the W-pair production cross-section near threshold



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

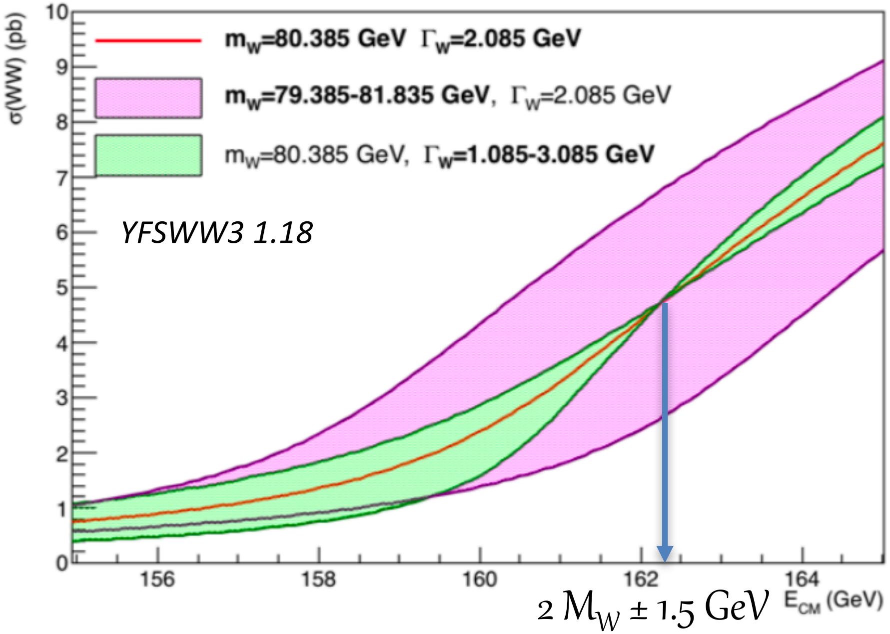
$$\Delta MW_{,sys} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\Delta\sigma_B}{\epsilon}$$ background

$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma \left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right)$$ efficiency luminosity

$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \Delta\sigma$$ WW cross-section

$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \left(\frac{d\sigma}{dE_{CM}}\right) \Delta E_{CM}$$ c.o.m. energy

W mass from the W-pair production cross-section near threshold



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

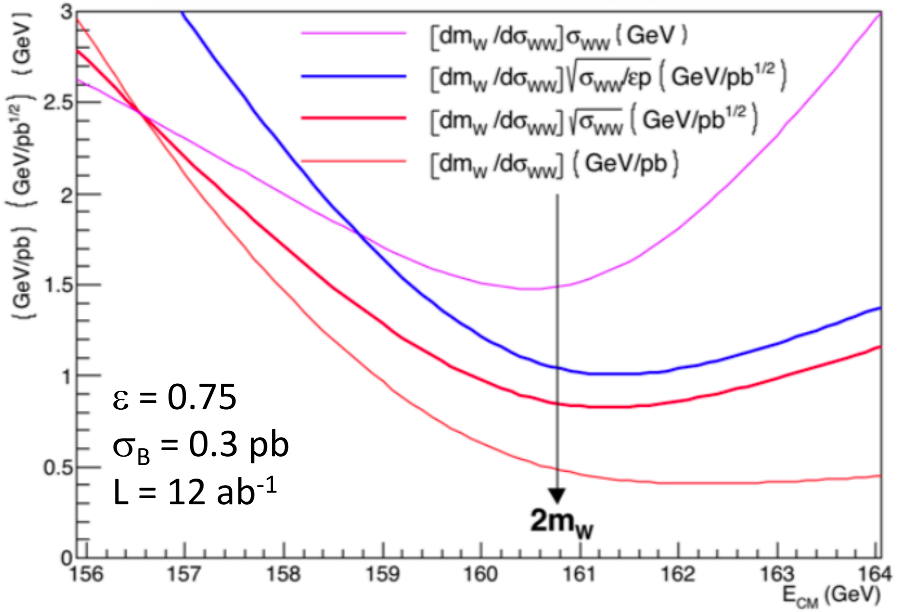
$$\Delta M_{W,\,sys} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\Delta\sigma_B}{\epsilon} \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma \left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right) \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \Delta\sigma \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \left(\frac{d\sigma}{dE_{CM}}\right) \Delta E_{CM}$$

Optimal energy: $E = 161.4$ GeV

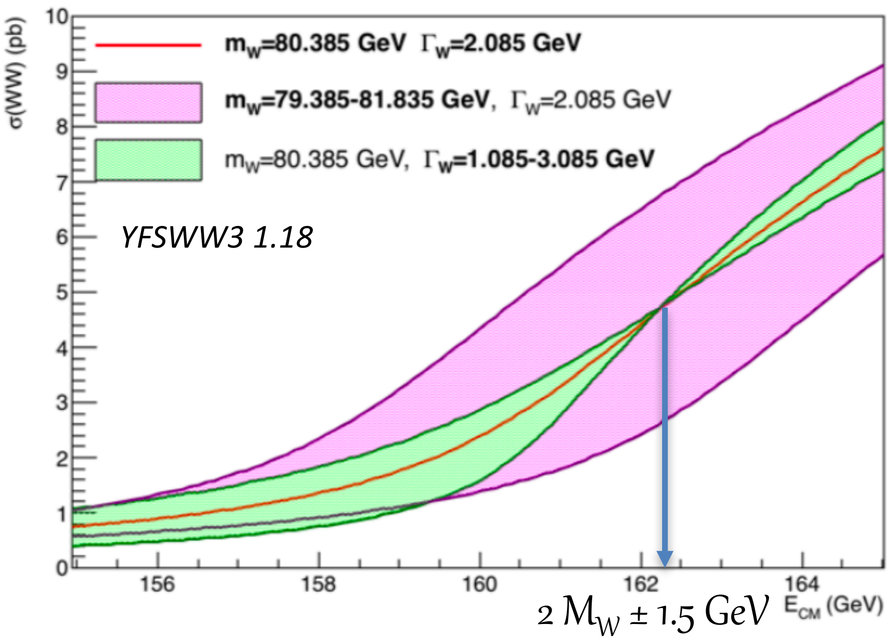
→ $\Delta M_W = 0.23$ MeV

@ LEP: $\Delta M_W = 210$ MeV

$L = 10\ pb^{-1}$



W mass from the W-pair production cross-section near threshold



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

$$\Delta M_{W,sys} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\Delta\sigma_B}{\epsilon} \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma\left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right) \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \Delta\sigma \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \left(\frac{d\sigma}{dE_{CM}}\right) \Delta E_{CM}$$

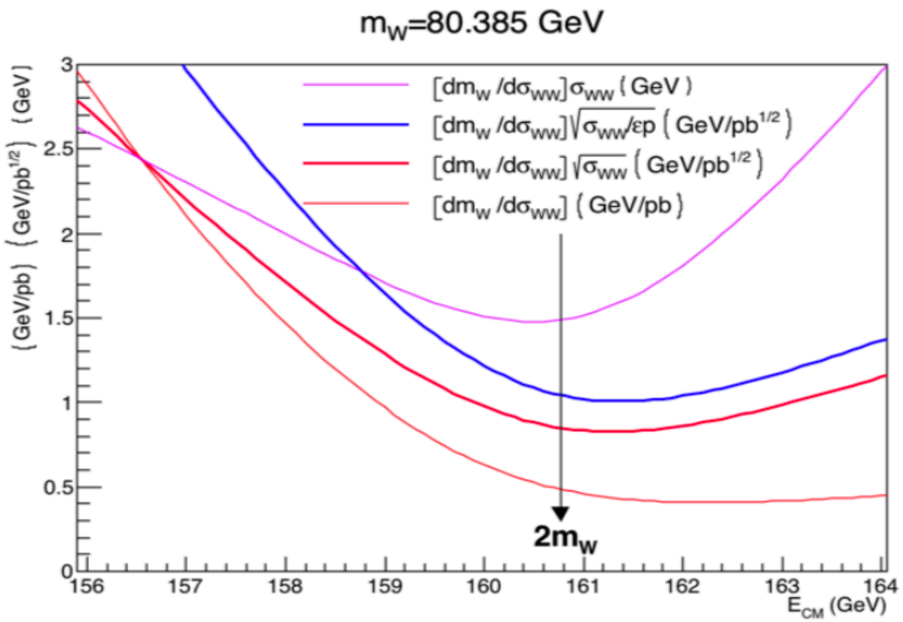
Optimal energy: E = 161.4 GeV

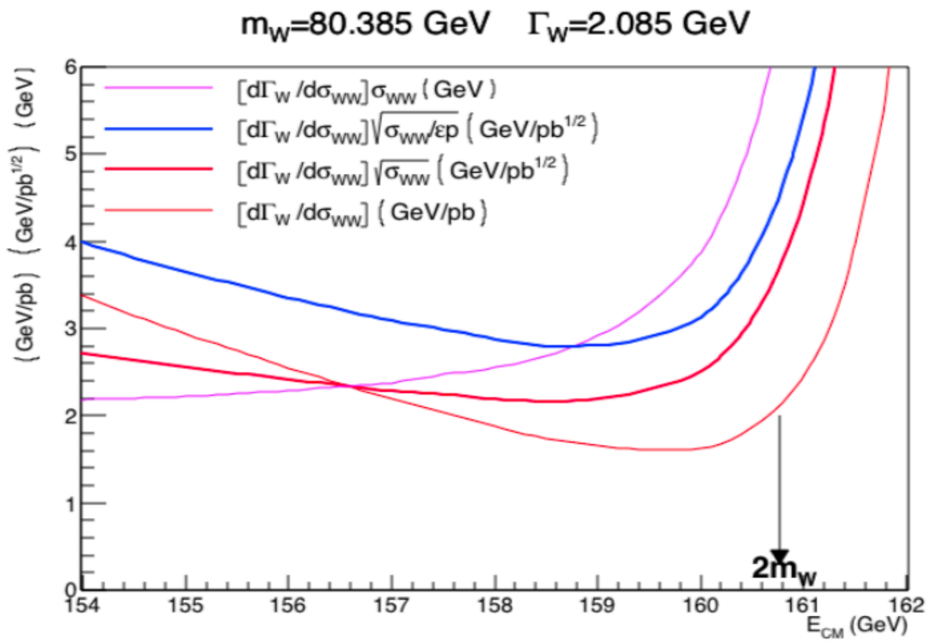
→ ΔM_W = 0.23 MeV

Systematics to be kept below:

- $\Delta\sigma_B < 0.6\ fb$ (2.10^{-3})
- $\left(\frac{\Delta\epsilon}{\varepsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right) < 2.10^{-4}$
- $\Delta\sigma_{theory} < 0.8\ fb$ (2.10^{-4})
- $\Delta E_{CM} < 0.2$ MeV (2.10^{-6})

W mass & width from the W-pair production cross-section near threshold





Optimal combination:

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

→ $\Delta M_W = 0.4$ MeV, $\Delta\Gamma_W = 1.2$ MeV

with resonant depolarisation: $E_b = 0.4406486\,(\nu + 0.5)$ MeV

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

→ $\Delta M_W = 0.45$ MeV, $\Delta\Gamma_W = 1.3$ MeV

W mass & width from the W-pair production cross-section near threshold

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

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

$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma \left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right)$$

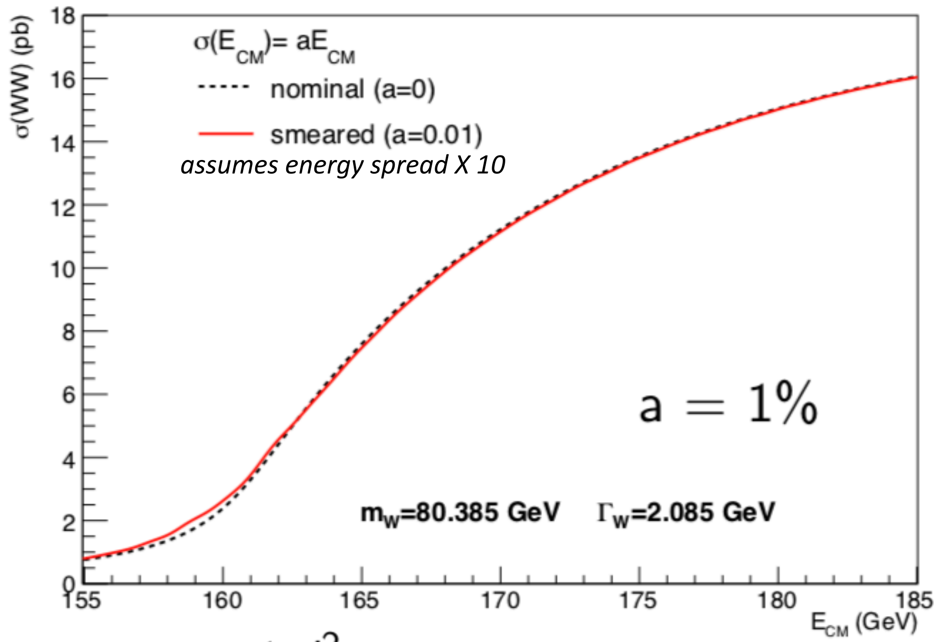
$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \Delta\sigma$$

$$\oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \left(\frac{d\sigma}{dE_{CM}}\right) \Delta E_{CM} \quad \lesssim \tfrac{1}{2}\,\Delta E_{CM}$$

→ ΔE_B < 0.2 MeV for a negligible impact on M_W

Effect of the beam energy spread σ_E

At WW energies the energy spread is estimated to be ~ 150 MeV.



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

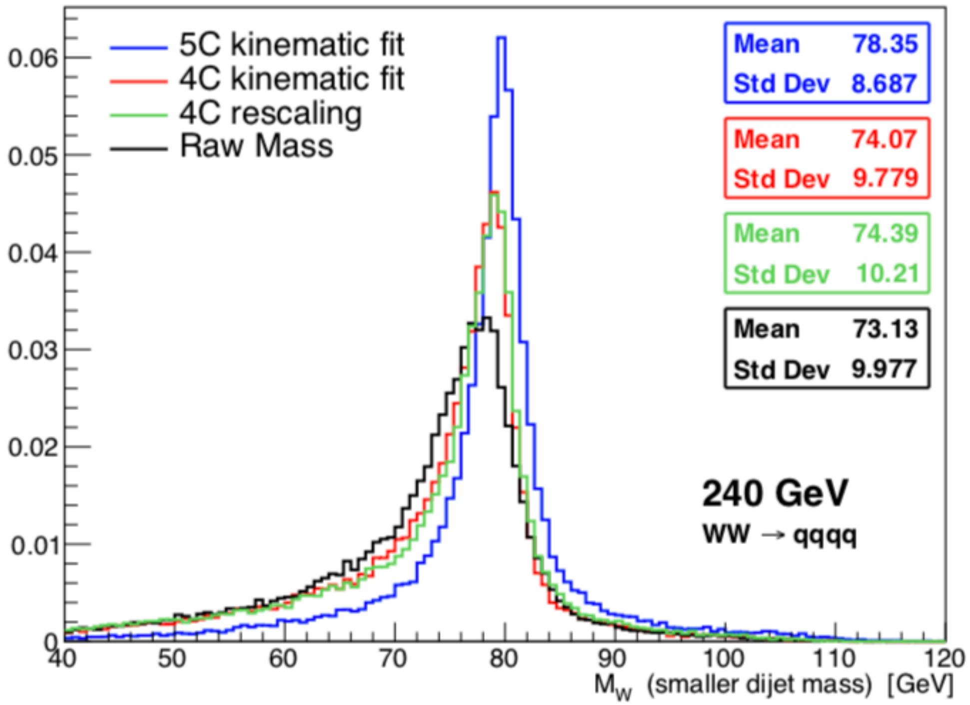
The energy spread will be measured with a relative precision better than 0.2%, using $e^+ e^- \to \mu^+ \mu^-$ events copiously produced at all energies

→ negligible contribution to ΔM_W & $\Delta\Gamma_W$

W mass & width from the full reconstruction of WW hadronic decays

@ 162.6 GeV, 240 GeV, 365 GeV

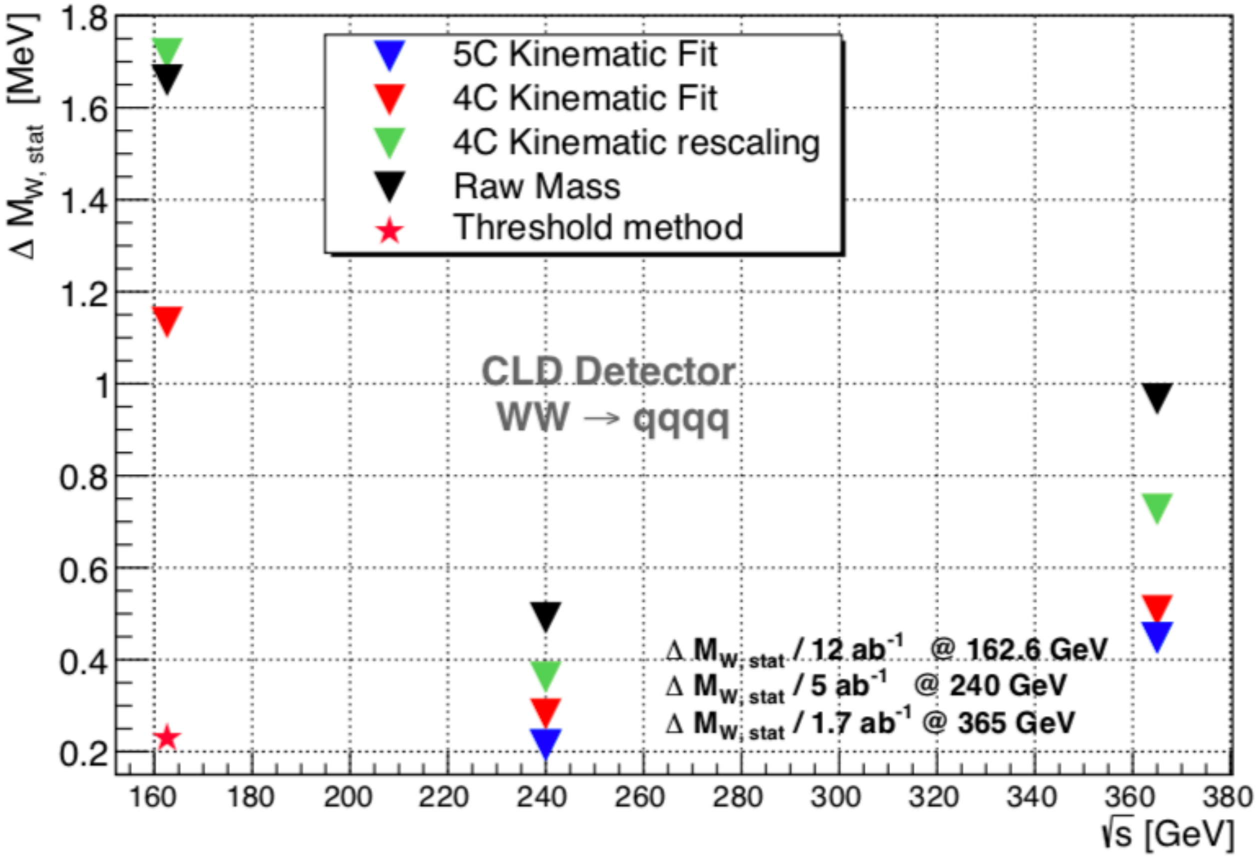
- PYTHIA v8.24 simulation
- Reconstruction with HEPPY (CLD detector, DURHAM algorithm)
- Jets paired by minimising the difference with m_{PDG}



W mass estimators:

- **Raw mass**
- **4C jets momenta rescaling**
- **Kinematic fit**

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) = 1.1 MeV

@ 240 GeV

$\Delta\Gamma_W$ (5C) = 0.47 MeV

@ 365 GeV

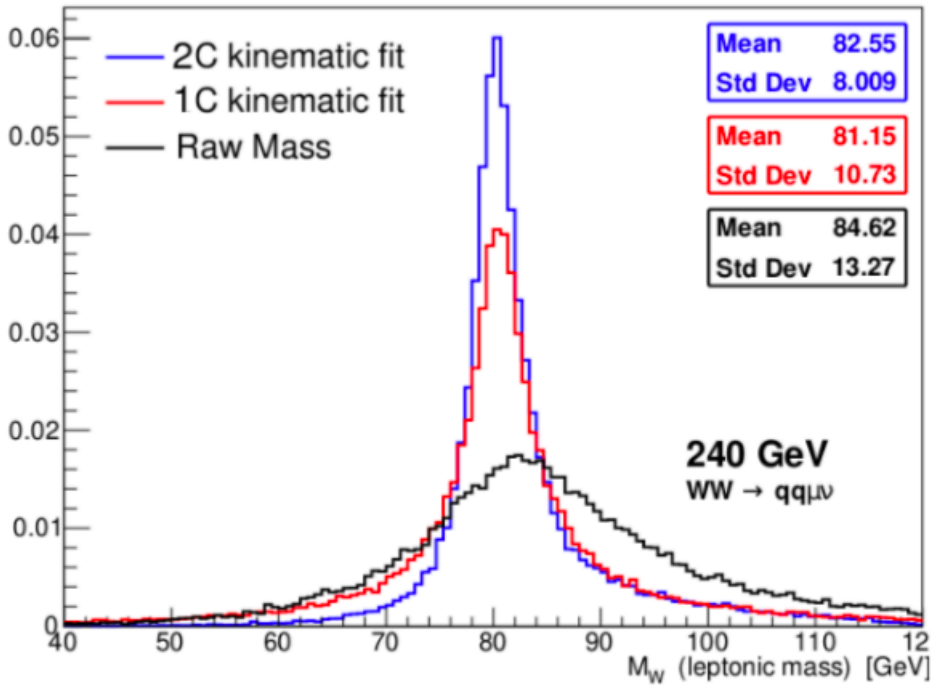
$\Delta\Gamma_W$ (5C) = 1 MeV

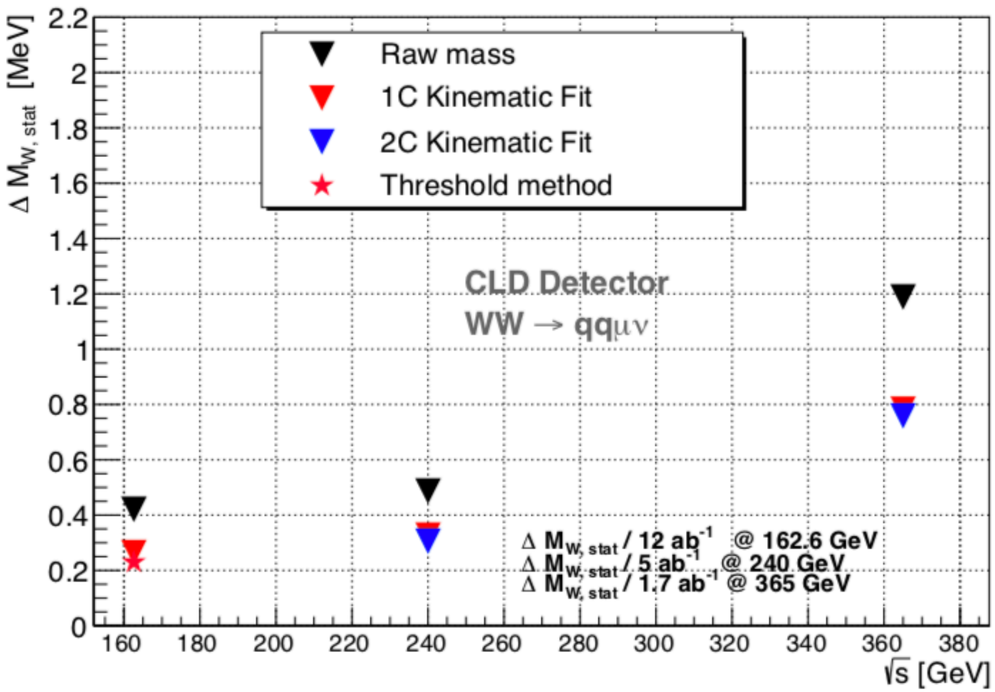
Mass & width uncertainties evaluated independently

Full FCC-ee luminosity

W mass & width from the full reconstruction of WW semi-leptonic decays

@ 162.6 GeV, 240 GeV, 365 GeV
Only leptonic muon decay





@ 162.6 GeV $\Delta\Gamma_W$ (1C) = 0.35 MeV

@ 240 GeV $\Delta\Gamma_W$ (2C) = 0.68 MeV

Full FCC-ee luminosity

@ 365 GeV $\Delta\Gamma_W$ (2C) = 1.56 MeV

W mass & width statistical uncertainties

Hadronic decays

	ΔM_W [MeV/c²]			$\Delta\Gamma_W$ [MeV/c²]		
$\sqrt{s}$ [GeV]	162.6	240	365	162.6	240	365
L [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	1.13	0.28	0.5	1.1	0.58	0.95
5C fit		**0.21**	0.44		0.47	1.0

Semi-leptonic decays

	ΔM_W [MeV/c²]			$\Delta\Gamma_W$ [MeV/c²]		
$\sqrt{s}$ [GeV]	162.6	240	365	162.6	240	365
L [ab⁻¹]	12	5	1.7	1.44	1.10	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

from σ_{WW}	0.23 **0.4**			1.2		

Full FCC-ee luminosity

W mass & width systematic uncertainties

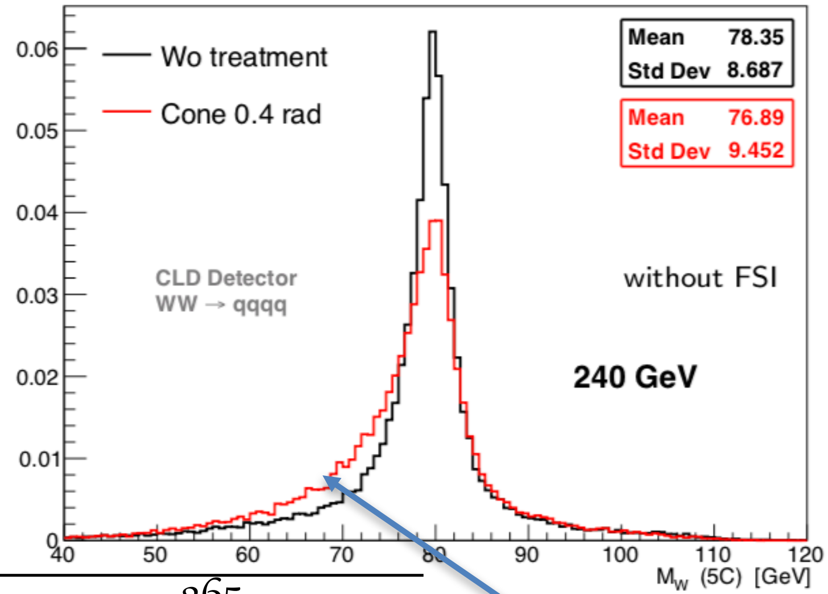
Main sources of systematic uncertainties @LEP2:

arXiv:hep-ex/0612034

Source	Systematic Uncertainty in MeV			
	on m_W			on Γ_W
	$q\bar{q}\ell\bar{\nu}_\ell$	$q\bar{q}q\bar{q}$	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: CR (SKI / SK2) & BEC

δM_{FSI} minimized by rejecting soft particles outside a cone (0.4 rad) at the level of jet clustering



$\sqrt{s}$ [GeV]	162.6		240		365	
δM_{FSI} [MeV]	standard	cone	standard	cone	standard	cone
SKI	14.6	7.5	23.9	11.5	32.2	17.5
SKII	7.9	3.8	12.1	6.0	14.7	8.3
BEC	3.1	1.8	5.9	2.1	9.9	5.5

loss of particle information

$\Delta M_{W,\,stat}$ is degraded with the cone by a few % @ threshold and 10-15% above, but compensated by a reduction of the systematic shift (~50%)

W mass & width : Conclusion and perspectives

The amount of W pairs @ planned FCC-ee energies presents a huge potential for many precision measurements: W mass & width, but also: aTGCs, BRs, α_s, CKM matrix....

- **M_W & Γ_W can be accurately derived. from σ_{WW} measurement @ threshold:**
  ΔM_W = 230 keV @ 161.4 GeV (ΔM_W = 450 keV, $\Delta\Gamma_W$ = 1.3 MeV @ 157.3 GeV & 162.6 GeV)

- **M_W & Γ_W measurements from WW decays reconstruction is statistically competitive:**
  ΔM_W = 210 keV @ 240 GeV in the hadronic channel
  ΔM_W = 260 keV @ 162.6 GeV in the semi-leptonic channel

- **Centre-of-mass energy precisely measured** from accurate M_W measurement above WW threshold where the resonant depolarisation cannot be used (2 MeV @ 365 GeV).

- **The systematic mass shift induced by FSI can be reduced** by using a cone in jet clustering (study to be refined?). Measure of FSI from W mass shift is possible.

- A very preliminary study shows that the expected **background level is not an issue.**

W mass & width : Conclusion and perspectives

Still some work to be done on systematic aspects and their consequences on detector requirements:

- **momentum & angular resolution, scale stability** (also Z, H)
- **lepton identification** (also for Z, τ decays)
- **angular acceptance definition & precision** (also Z)

Not an exhaustive list, many other studies common to W, H, t, heavy flavours

Lots of nice physics studies @ WW threshold & above !