Standard Model precision measurements
Misure di precisione del modello standard
Lesson 3: W mass measurement

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Outline

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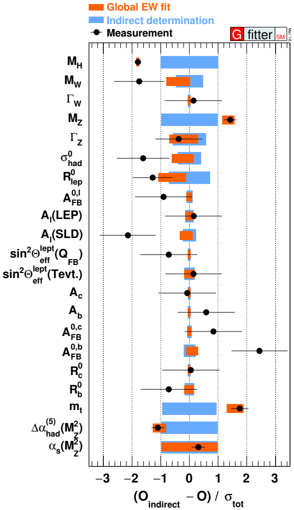
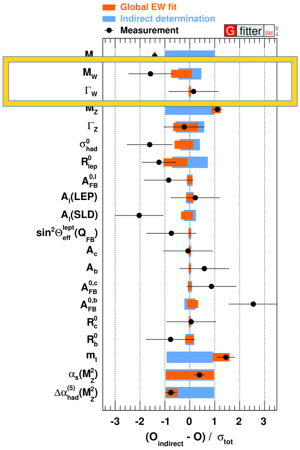
1. Introduction
2. Z-pole observables
3. Asymmetries
   - Forward-Backward Asymmetries
   - Left-Right Asymmetries
   - Tau polarization
4. W mass and width
5. Top mass
6. Higgs mass and features

Outline

Input to global EWK fit
(in parenthesis the order followed in these lessons)



- Higgs mass (4)
  - LHC
- W mass and width (3)
  - LEP2, Tevatron, LHC
- Z-pole observables (1)
  - LEP1, SLD
  - M_Z, Γ_Z
  - σ_0^{had}
  - $\sin^2\Theta_{eff}^{lept}$
  - Asymmetries
  - BR $R^0_{lep,b,c} = \Gamma_{had}/\Gamma_{\ell\ell,b\bar{b},c\bar{c}}$
- top mass (3)
  - Tevatron, LHC
- other:
  - $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}(M_Z^2)$



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Motivation:

W mass and top quark mass are fundamental parameters of the Standard Model;
The standard theory provides well defined relations between m_W, m_{top} and m_H

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2} G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Electromagnetic constant measured in atomic transitions, e^+e^- machines, etc.

Fermi constant measured in muon decay

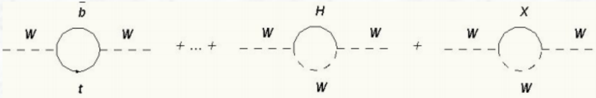
weak mixing angle measured at LEP/SLC

radiative corrections
$\Delta r \sim f(m_{top}^2, \log m_H)$
$\Delta r \approx 3\%$

G_F, α_{EM}, $\sin\theta_W$

are known with high precision

Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass
(and/or the theory, radiative corrections)

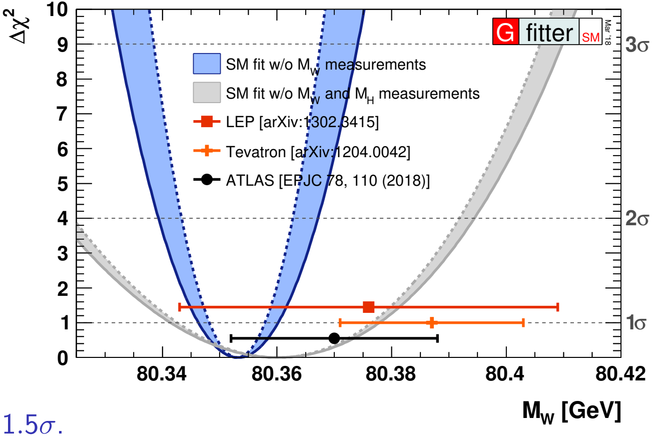


If we use the measured Higgs mass to constraint the W boson mass, assuming SM, we get:

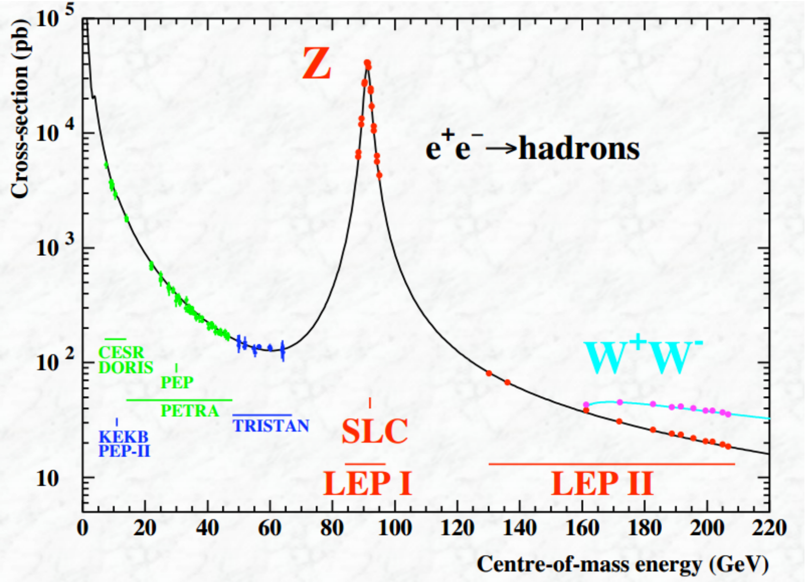
$$M_W = 80356 \pm 8\,\text{MeV}$$

The experimental results (LEPII + TeVatron + ATLAS)

$$M_W = 80379 \pm 12\,\text{MeV}$$

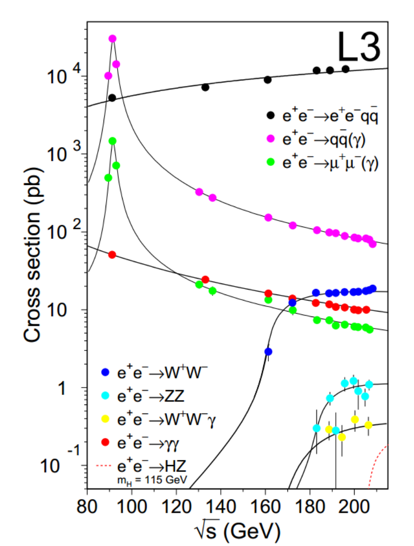


- Difference $\sim 23 \pm 15\,\text{MeV} \sim 1.5\sigma$.
  - was 80359 ± 11 vs 30585 ± 15 w/o ATLAS: $26 \pm 18\,\text{MeV}$ 1.3σ
- For a 2σ effect, we need M_W experimental precision of about $\pm 10\,\text{MeV}$

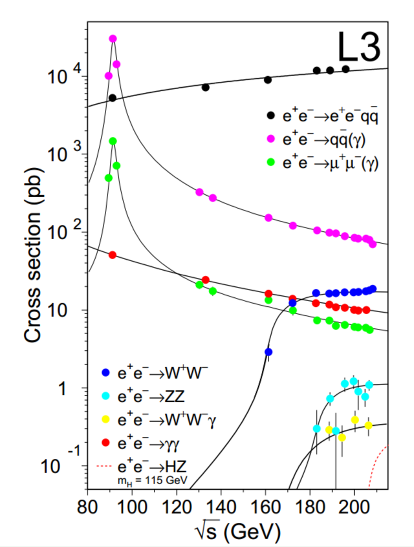

Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
$e^+e^- \to$ hadrons
W^+W^-
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

Year	Mean energy $\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
1995, 1997	130.3	6
	136.3	6
	140.2	1
1996	161.3	12
	172.1	12
1997	182.7	60
1998	188.6	180
1999	191.6	30
	195.5	90
	199.5	90
	201.8	40
2000	204.8	80
	206.5	130
	208.0	8
Total	130 – 209	745

- Most of luminosity taken around $ee \to WW$ production threshold ($\sqrt{s} = 2M_W$) for measurement of M_W;
- and at the highest possible $\sqrt{s}$ for discoveries.



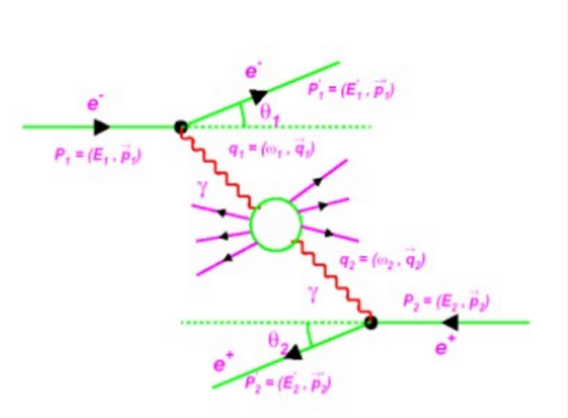
- Lines are theoretical expectation
- dots are LEP1/2 measurements.
- Will not discuss all measurement here, only the $ee \to WW$ as it is related to the measurement of M_W

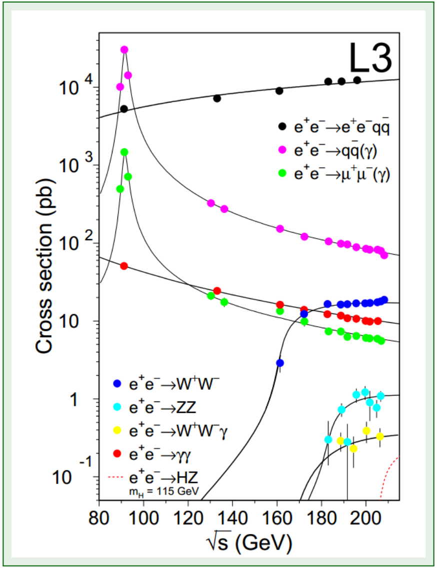


$ee \to 4f$

BLACK dots

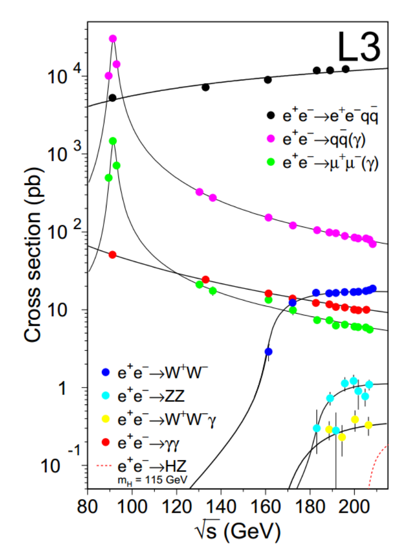
comes from the $\gamma\gamma$ interactions: dominant but reducible





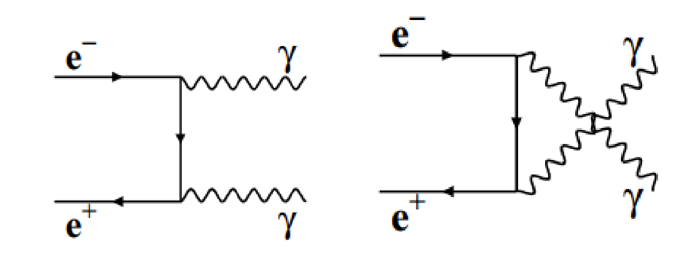
$ee \to f\bar{f}$

- green and magenta dots
- Z/γ $s(t)$-channel;
- very important ISR QED correction, up to 100% wrt born-level x-section due to radiative return to Z



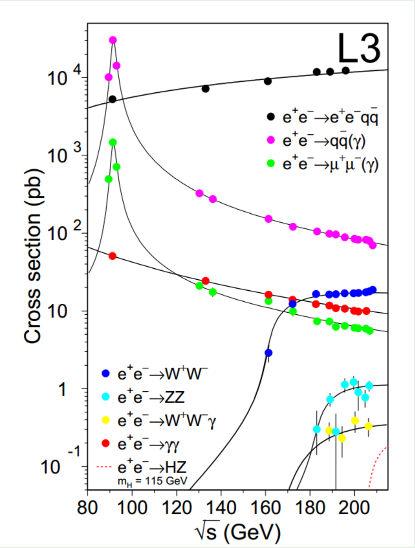
$ee \to \gamma\gamma$

RED dots

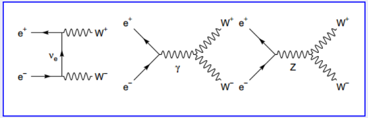


Negligible wrt to $ee \to Z$ at Z peak, but important elsewhere

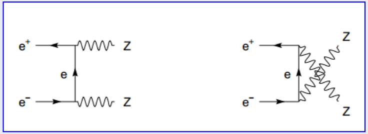
ee cross section at high energy ($\sim \sqrt{2M_W}$)



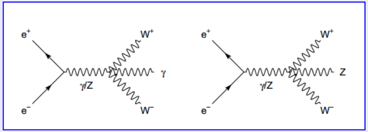
$ee \to WW/ZZ$ pairs



turn-on threshold at $\sqrt{s} = 2M_W$: at plateau $\sigma \approx 17pb$



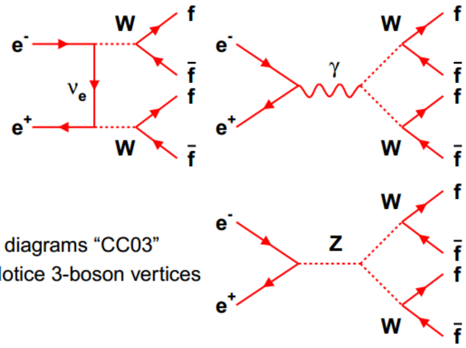
turn-on threshold at $\sqrt{s} = 2M_Z > 2M_W$: at plateau $\sigma \approx 1pb$



quadratic vector coupling in the SM

$e^-e^+ \to W^-W^+$ production

W pair production is achieved via three different Feynman diagrams

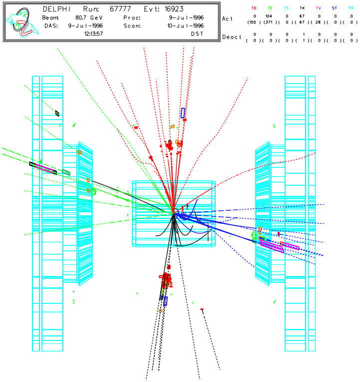


3 diagrams "CC03"
Notice 3-boson vertices

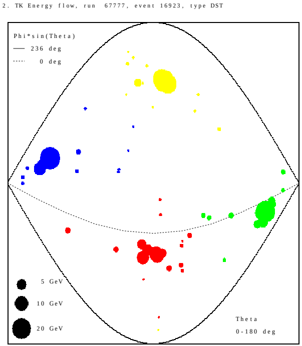
W pairs decays are:

- **fully hadronic: $q\bar{q}q\bar{q}$**
  - Seen as 4 jets
  - $BR = 45.6\%$
  - eff: 80-90%, purity: 80%
- **semi leptonic $q\bar{q}\ell\nu$**
  - Seen as 2 jets, isolated leptons, MET
  - $BR = 43.8\%$
  - eff: 70-90%, purity: 95%
- **full leptonic $\ell\nu\ell\nu$**
  - two isolated leptons, MET
  - $BR = 10.6\%$
  - eff: 70%, purity: 90%

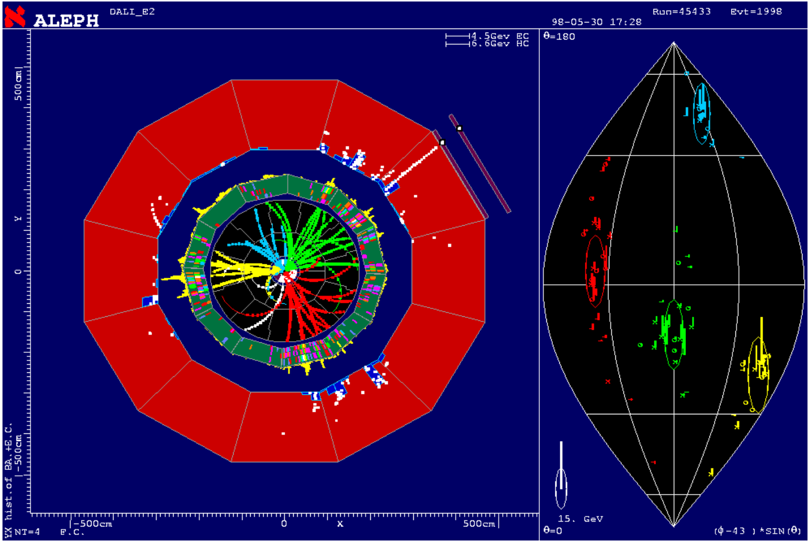
Total of $\approx$ 12 000 WW pairs produced/experiment ($17pb \times 700pb^{-1}$ above threshold)



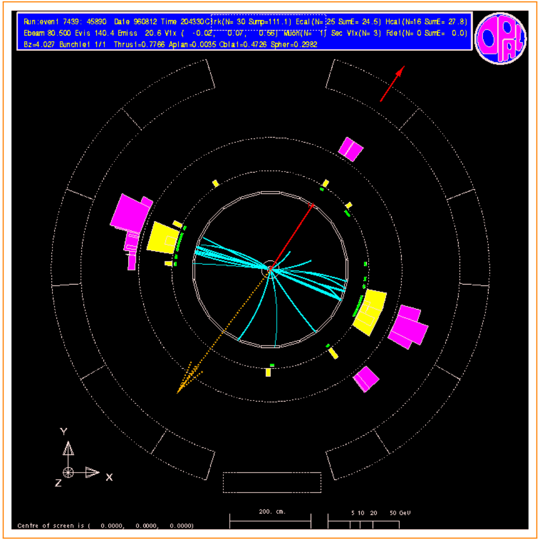
DELPHI Run: 67777 Evt: 16923
Beam: 80.7 GeV
DAS: 9-Jul-1996 12:13:57
Proc: 9-Jul-1996
Scan: 10-Jul-1996
DST
Act
Deact



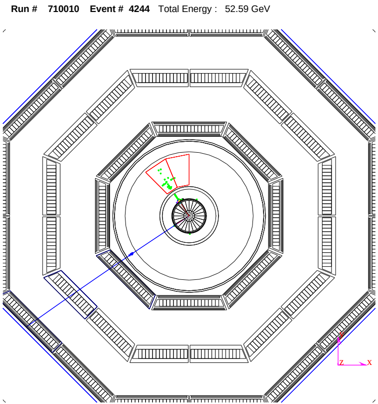
2. TK Energy flow, run 67777, event 16923, type DST
Phi*sin(Theta)
236 deg
0 deg
5 GeV
10 GeV
20 GeV
Theta
0-180 deg


ALEPH
DALI_E2
Run=45433 Evt=1998
98-05-30 17:28
4.5Gev EC
6.6Gev HC
θ=180
500cm
Y
0
hist.of BA.+E.C.
-500cm
YX NT=4
F.C.
-500cm
0
X
500cm
15. GeV
θ=0
(ϕ-43)*SIN(θ)

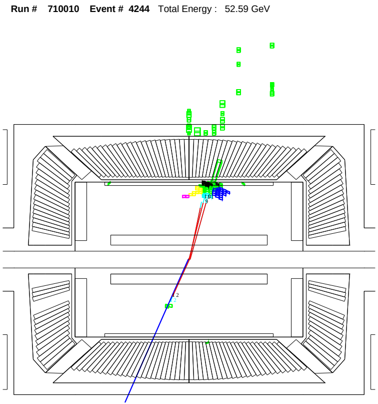
Semileptonic event: OPAL



Full leptonic event: L3



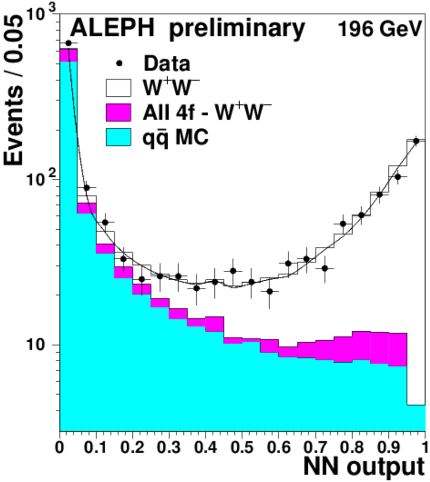
Transverse Imbalance :	.6909	Longitudinal Imbalance :	-.0187
Thrust : .7222	Major : .6816	Minor : .0224	
Event DAQ Time :	980728 104251		



Transverse Imbalance :	.6909	Longitudinal Imbalance :	-.0187
Thrust : .7222	Major : .6816	Minor : .0224	
Event DAQ Time :	980728 104251		

Hadronic decay

- 4 jets in the events;
- No missing energy;
- $\sqrt{s}$ is known! LEP is a $e^{\pm}$ collider!
- Event is central;
- Background from $ZZ \to 4q$, $ee \to qqg$ plus $g \to q\bar{q}$, etc;
- Use neural network to achieve high purity (75-85%) and efficiency (85-89%)
- Combinatorics problem with jet pairing



Event selection semi/full leptonic

Semi leptonic

- 2 jets, one high p_T, isolated lepton, MET;
- very clean, little background, high BR (44%);
- ID also τ from low multiplicity "jet" decay;
- cross contamination of τ to e and μ channel;
- 3-jet background for τ channel

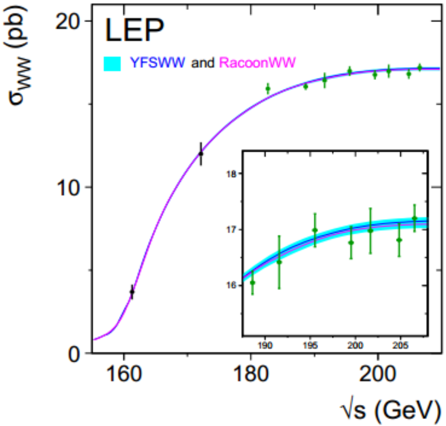
Full leptonic

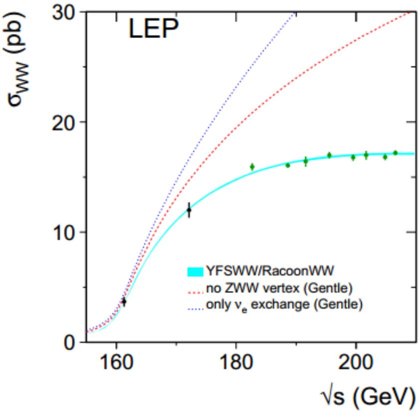
- 0 jets, two high p_T, isolated lepton, MET;
- very clean, little background, low BR (11%);
- background from $\gamma/Z* \to \ell\ell$ has no MET

M_W from σ_{WW} threshold

Threshold measurement

- **$\sigma_{ee\to WW}$ at threshold rises as the velocity of the W,** $\sigma \sim \beta = \sqrt{1 - 4M_W^2/s}$
- So, measurement of $\sigma_{WW}(s)$ is directly related to measurement of M_W.
- Precision comparable with the direct-reconstruction method;
  - Most sensitive measurement from $\sqrt{s}$ just above threshold;
  - At $\sqrt{s} = 161\ GeV$ collected only 12 pb^{-1} (out of 750 pb^{-1});
  - Moreover, at threshold σ is small $\approx 3pb$
  - Used also data at 172 GeV (not as sensitive);
  - Measure is statistically limited: expected $N = 12 \cdot 3 \cdot \epsilon \cdot \mathcal{A} \approx 30\ ev/exp$
  - Syst. error from LEP energy scale
    - resonant depolarization not possible at LEPII
    - $\sqrt{s}$ from extrapolation of magnets bending calibrated at LEPI
  - other from luminosity, final state interaction, radiative corrections, all negligible





Sensitivity to mass at threshold, very little $\int \mathcal{L} dt$ needed

Beautiful demonstration of the non-abelian nature of EWK theory: presence of ZWW vertex

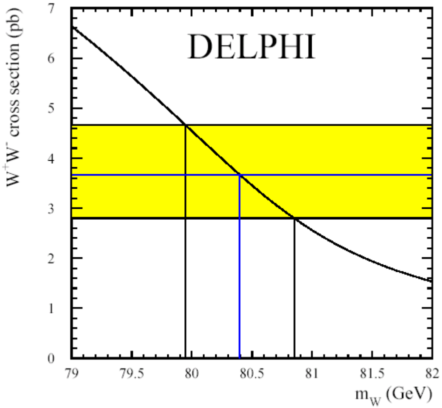
Threshold measurement (II)

- Measure σ at given $\sqrt{s}$
- DELPHI used **29 events** in total at $\sqrt{s} = 161\ GeV$
- $\sigma_{WW} = 3.67^{+0.97}_{-0.85} \pm 0.19\ pb$

Results

Experiment	M_W [GeV]
ALEPH	80.20 ± 0.34
DELPHI	$80.45^{+0.45}_{-0.41}$
L3	$80.78^{+0.48}_{-0.42}$
OPAL	$80.40^{+0.46}_{-0.43}$

Combined: $M_W = 80.42 \pm 0.20 \pm 0.03 (E_{LEP}) GeV$



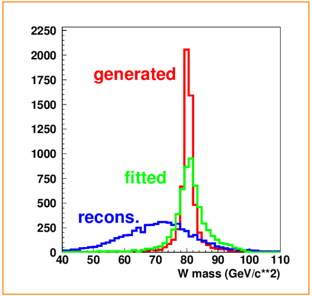
M_W: direct reconstruction, full hadronic

Pros and cons:

- Pros:
  - Large BR (45.6%)
  - fully reconstruct the two W;
  - all LEP energy visible;
- Cons:
  - large combinatorics
    - even larger if a 5^{th} jet is spawned from gluonsthralung;
  - jet resolution is poor
    - at best $\frac{\Delta E}{E} \approx \frac{60-80\%}{\sqrt{E/GeV}}$, leading to $\Delta M_W \approx 8-9\ GeV$;
    - Can be improved with kinematic fit
  - final state interaction
    - color reconnection
    - Bose-Einstein correlation;

Kinematical fit

- in full-hadronic WW decays, all LEP energy is visible;
- can use $(E, \vec{p})$ conservation as a constraint for the global reconstruction;
- perform a kinematic fit of the jets 4-momenta, within their known uncertainties (likelihood), to improve the jet resolution;
- known as 4C kin-fit (4 constraints)
  - also possible to constraint $M_{W^+} = M_{W^-}$ (5C fit)



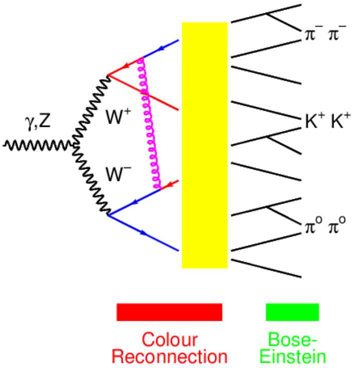
- Resolution improves from $8 - 9$ GeV to $1.5 - 1.7$ GeV
- Scale of M_W is directly linked to the scale of LEP $\sqrt{s}$
- Presence of ISR, if not detected by the apparatus, produces a bias.

Color Reconnection

- $W^{\pm}$ decay vertices separation $\approx 0.1\ fm$
- typical hadronization scale $\approx 1\ fm$
- so colored objects from different W decays can interact and modify the final hadronized state

Bose-Einstein Correlation

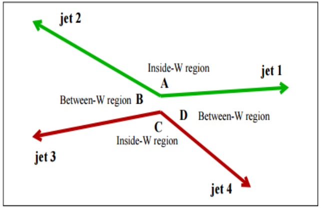
- quantum-mechanical effect:
- wave-functions of identical particles (boson π, K) obey to BE statistics, and this change thier dynamics
- Seen as an enhancement probability for identical boson with small relative momenta.

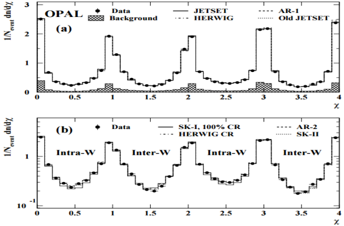


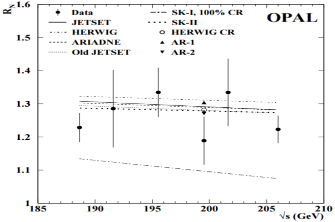
Both interaction shift the reconstructed M_W, introducing important systematic uncertainties $\mathcal{O}(30\ MeV)$

Can be studied by looking at the particles reconstruction as a function of the distance from the jet thrust axis.

- Two jets (1+2) from one W, other two jets (3+4) from the other.
  - Define inter-W region (A+C) and inter-W region (B+D).
- Sum inter/intra-W distribution (with rescaled $\phi = \phi \cdot \Delta\phi_{j_1 j_2}/\pi/2$).
  - R is ratio $(A+C)/(B+D)$ far from jet axis, normalized to MC w/ no-CR.
  - $R = 1$ correspond to no color reconnection
- Compare with MC prediction with various models.





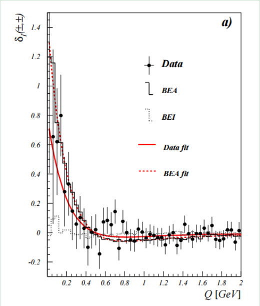


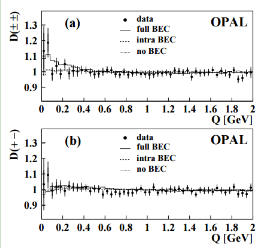
No-CR effect excluded at 99.5%, 51% of events are reconnected at 189 GeV

Look at identical bosons:

- pair of charged particles ($\pi^{\pm}$), with similar momenta;
- small $Q = \sqrt{-(p_1 - p_2)^2}$

$$R(Q) = \frac{dN/dQ}{dN/dQ_{ref}}.$$



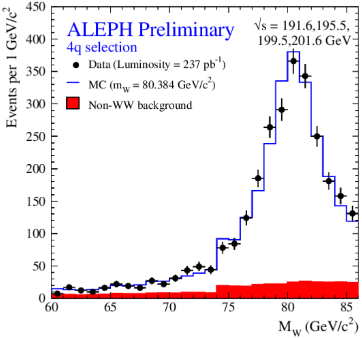


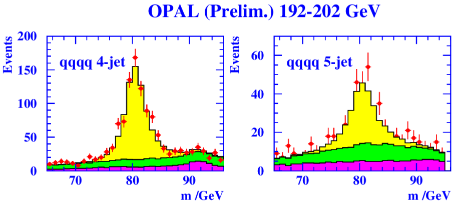
Need a reference sample (w/o BEC) to normalize the distribution *e.g.*:

- opposite charge pairs (resonances);
- pairs from opposite hemispheres;
- two π from different events;

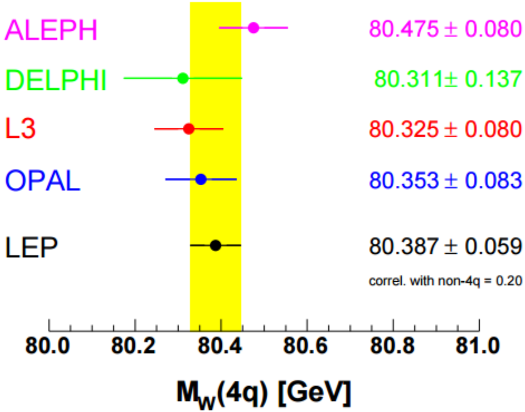
BEC clearly seen for intra-W jets, not for inter-W ones

Full hadronic



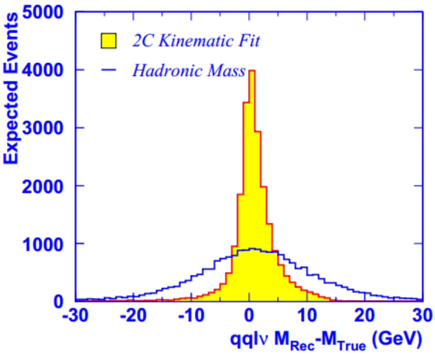


M_W from unbinned maximum likelihood fits to measured data



Pros and cons:

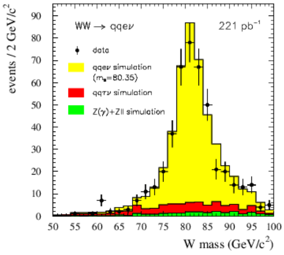
- Pros:
  - Large BR (43.8%)
  - no jet pairing combinatorics;
  - no FSI between W;
  - Low background;
  - Good lepton p_T resolution;
- Cons:
  - One neutrino not detected;
    - Use kinematic fit to reconstruct neutrino momentum;
    - 2C constraints (transverse momentum: p_x, p_y)

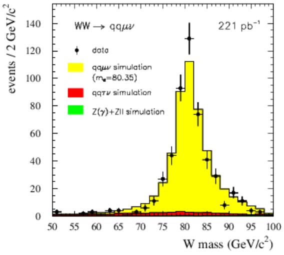


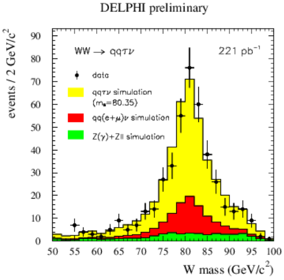
Selections:

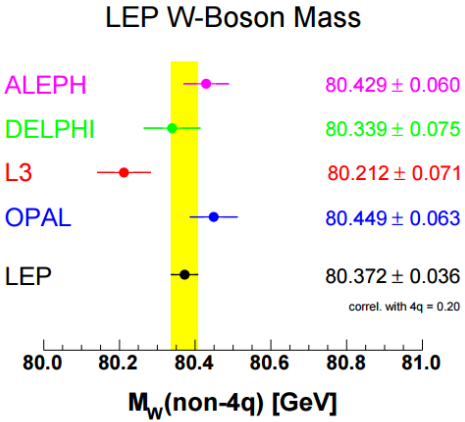
- Two jets, one isolated lepton, MET;
- Also τ from low multiplicity jet.

OPAL tried also a fully leptonic ($\ell\nu\ell\nu$): low BR, two ν's, not competitive for combination.


WW → qqeν
221 pb⁻¹
data
qqeν simulation (m_W=80.35)
qqτν simulation
Z(γ)+Zll simulation
events / 2 GeV/c²
W mass (GeV/c²)


WW → qqμν
221 pb⁻¹
data
qqμν simulation (m_W=80.35)
qqτν simulation
Z(γ)+Zll simulation
events / 2 GeV/c²
W mass (GeV/c²)


DELPHI preliminary
WW → qqτν
221 pb⁻¹
data
qqτν simulation (m_W=80.35)
qq(e+μ)ν simulation
Z(γ)+Zll simulation
events / 2 GeV/c²
W mass (GeV/c²)

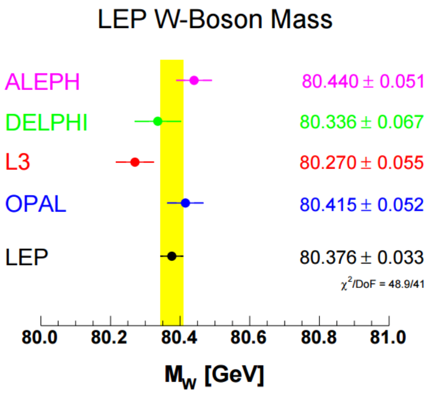

LEP W-Boson Mass
ALEPH 80.429 ± 0.060
DELPHI 80.339 ± 0.075
L3 80.212 ± 0.071
OPAL 80.449 ± 0.063
LEP 80.372 ± 0.036
correl. with 4q = 0.20
80.0
80.2
80.4
80.6
80.8
81.0
M_W(non-4q) [GeV]

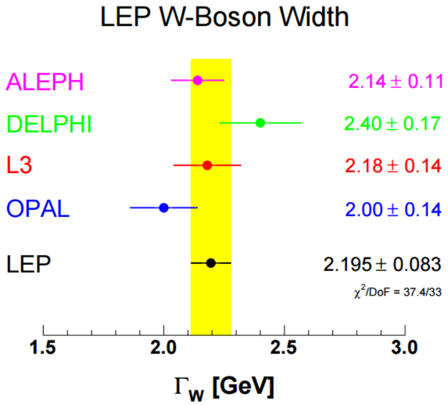
M_W extraction

- No direct fit to reconstructed mass
- Use invariant mass distribution as returned by the kinematic fit
- compared with MC templates for different M_W and Γ_W values.
- The best value are chosen via unbinned likelihood fit Template Method (more later)

Systematics

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

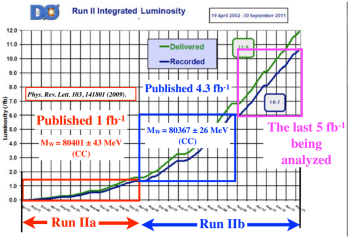


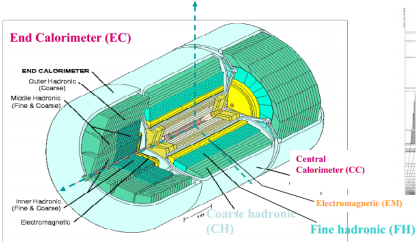


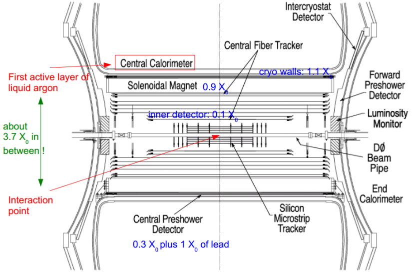
$$M_Z = 91.1875 \pm 0.0021 \ GeV$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \ GeV$$

- D0 was born as a quasi-calorimetry-only detector
- excellent E/HCAL (LAr + U absorber) with transverse and logitudinal segmentation
- for RunII, they added a magnet and a decent tracker
- M_W measurement: only $p\bar{p} \to XW \to e\nu$ considered.
- Not yet full lumi analyzed:
  - Statistics is not limiting factor

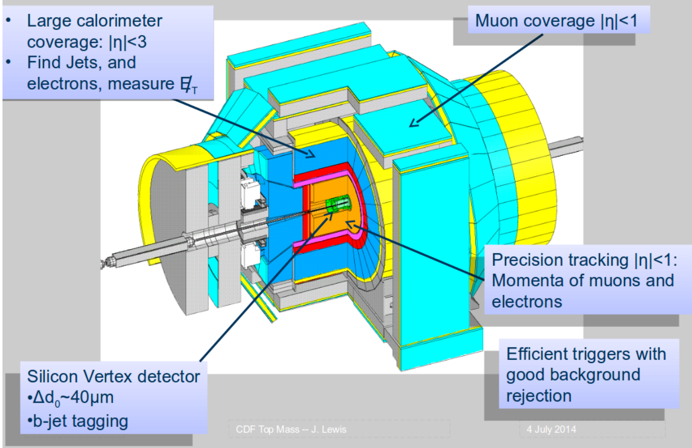


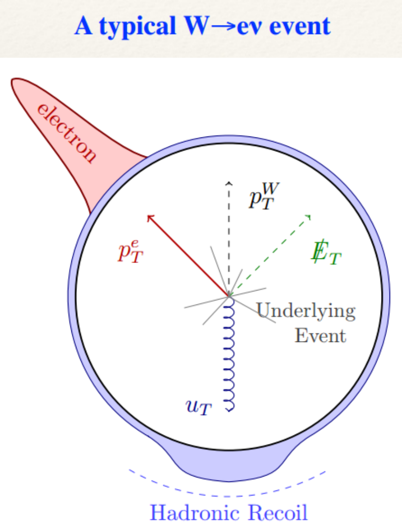




M_W with CDF at TeVatron[7]

- CDF had a good tracker system from the beginning
- good muon detector also (up to $|\eta| \sim 1$)
- consider both $e\nu$ and $\mu\nu$ dataset
- only 2.2/fb analyzed so far (out of 9/fb)





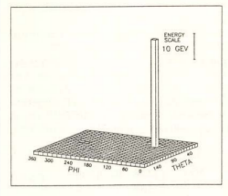
- At hadron collider, it is not possible to see a pure $W \to qq'$ signal: the QCD background is simply too overwhelming.
- $W + x$ production is large, so statistics is not the limiting factor.
- Consider only W leptonic decay $W \to \ell\nu$
- kinematic fit à la LEPII is not possible, because the initial state is not known!
  - *partially yes in the transverse plane*
  - *partially*, because the W typically recoils against some hadronic stuff

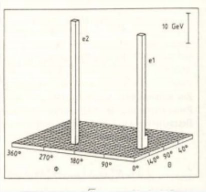
Uses three observables: p_T^ℓ, MET, and
$M_T^W = \sqrt{2p_T^\ell MET(1 - \cos\Delta\phi)}$ to extract M_W
Other possible (but not as sensitive)

Selection

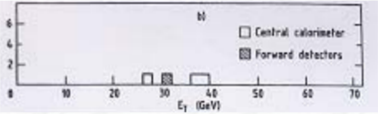
Like good old days: $p_T^\ell > 25GeV$, MET$> 25GeV$, $u_T < 15GeV$

W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)



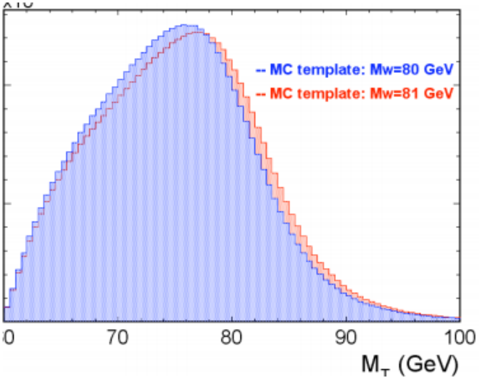


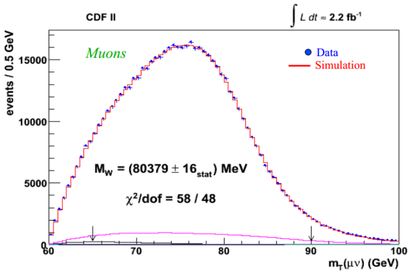
Transverse momentum of the electrons

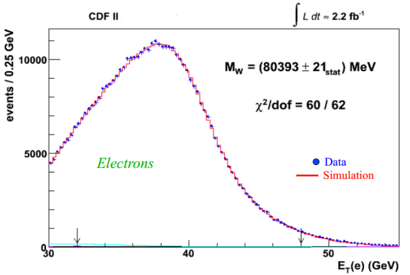


Carlo Rubbia (left, UA1) and Luigi Di Lella (right, UA2)

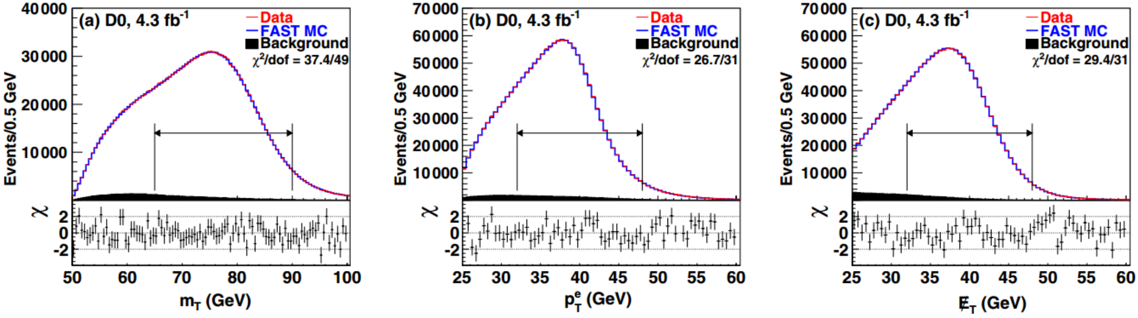
- p_T^ℓ, MET, and M_T^W are sensitive to M_W.
- Produce MC templates with different M_W,
- fit data to templates to select the best M_W





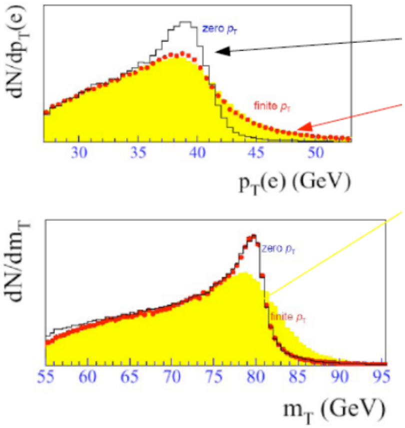


Mass extraction: Template Method (D0)



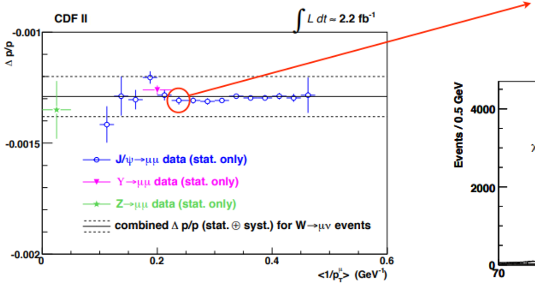
- Shown the range of the fit
- where the sensitivity to M_W is max
- typically fir all three variables at once

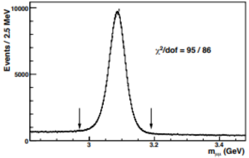
- Electron/muon energy response and resolution;
- MET modelling
- hadronic recoil energy response and smearing
  - Control sample with $Z \to \ell\ell$
  - extrapolation from M_Z to M_W
- Underlying event (PU + spectator parton interactions)
- parton density function (pdf)
  - In principle do not affect transverse observables
  - limited η coverage give sensitiveness
- detector description
- background (small)
- M_T less sensitive to recoil, but requires good MET modelling

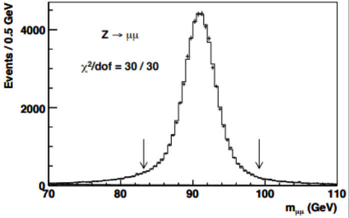


black: no recoil; red: recoil; yellow:+ det effect

- Foundation of CDF analysis is track p_T measurement with drift chamber (COT)
- Perform alignment using cosmic ray data: ~50μm→~5μm residual
- Calibrate scale using large sample of dimuon resonances (J/ψ, Υ, Z)
  - Span a large range of p_T
  - Flatness is a test of dE/dx modeling
  - Final scale error of 9×10^{-5}: ΔM_W = 7 MeV
- Confirm by **measuring M_Z**. Add as further constraint.

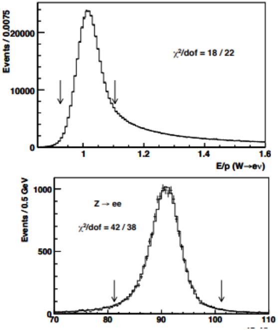






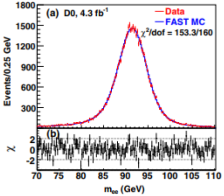
CDF

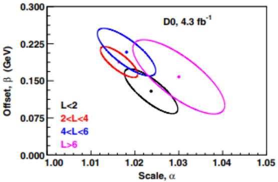
- Apply calibrated p-scale and set EM scale using E/p of W and Z events
  - Overall scale from peak
  - Radiative tail used to tune material model
- Confirm by measuring M_Z



DØ

- Use $Z \to ee$ events and LEP M_Z to calibrate scale
- Use subsamples to calibrate material model and response to pileup



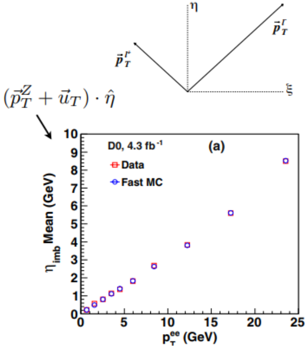


$E_{meas} = \alpha E_{true} + \beta$

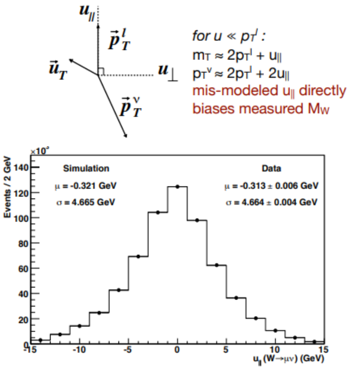
Z subsamples of inst. L [*36e30]

- Measured recoil: 1) hard recoil from hadronic activity in W/Z event, 2) underlying event/spectator interaction energy
- Tune using Z and minimum-bias data
- Validate using measured recoil in W events

Tuning with Z→ll



Validating with W→lν

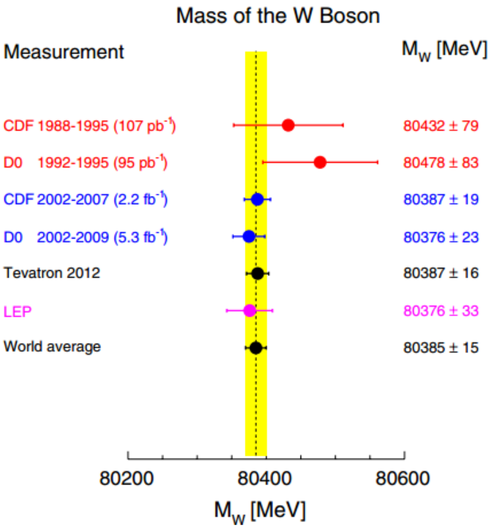


TeVatron results[8]

Major systematic uncertainties

Source	Uncert (MeV) D0	CDF
ℓ E scale & res	16	7
u_T	5	2
background	2	3
PDF	11	10
$p_T(W)$ model	2	5
QED rad	7	4
total	22	15
stat	13	12

syst error from calib, from QCD, and statistical



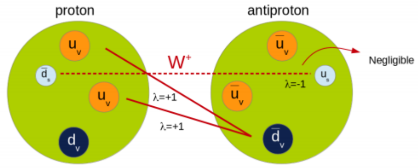
M_W at LHC

And what about LHC?

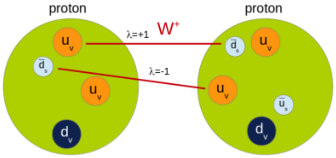
- Actual precision is already quite high, no rush to publish a non competitive measurement
  - Today $\delta(QCD) \sim \delta(calib) \sim \delta(stat)$
  - At LHC $\delta(QCD) > \delta(calib) > \delta(stat)$
- PDF knowledge play a critical role:
  - differences for $\sqrt{s}$ and $p\bar{p}$ vs pp
  - LHC: 25% of Z/W are produced from from s,c quarks (vs 5% at tevatron)
  - different pdf, less known for s,c, helicity, p_T^W
- modelling of p_T^W from p_T^Z
  - $\delta(M_W) \sim 5\,\text{MeV}$ plus extrapolation;
  - second gen. quarks are more important!
- 40% more W^+ than W^-: charge dependent analysis
- ATLAS did it [9], CMS not yet

M_W at LHC: helicity

A proton-proton collider is the most challenging enviroment to measure m_W, worse compared to e+e- and proton-antiproton



In $p\bar{p}$ collisions W bosons are mostly produced in the same helicity state



In pp collisions they are equally distributed between positive and negative helicity states

Large PDF-induced W-polarisation uncertainty affecting the p_T lepton distribution

Further QCD complications

- Heavy-flavour-initiated processes
- W+, W- and Z are produced by different light flavour fractions
- Larger gluon-induced W production

Larger Z samples, available for detector calibration given the precisely known Z mass → most of the measurement is then the transfer from Z to W

M_W measurement at ATLAS [9]

Dataset, Selection and method

Dataset: $L = 4.6 fb$ @ 7 TeV (2011)

- exactly one μ or e pt $p_T > 30$ GeV
- recoil $u_T < 30$ GeV
- $MET > 30$ GeV
- $M_T > 60$ GeV
- $5.8 \cdot 10^6$ $W \to e\nu$, $7.8 \cdot 10^6$ W $\to \mu\nu$
  - (10x TeVatron dataset)
  - statistics is not the limiting factor
  - Expected statistical uncertainties $\sigma_{M_W} \approx 10$ MeV

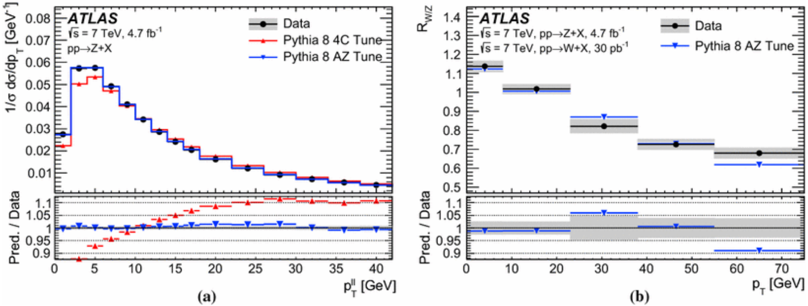
Analysis strategy

- Template fit based on p_T^ℓ and $M_t = \sqrt{2 p_T^\ell p_T^{miss}(1 - \cos\Delta\phi)}$
  - For W at rest, p_T^ℓ has a Jacobian edge at $M_W/2$
  - M_t has endpoint at M_W
- templates build by reweighting same full MC simulation according to BW(M_W).
- $\chi^2(M_W)$ interpolated, minimum found.
- several categories. In total 28 (12 e, 16 μ)
  - $\ell = \mathrm{e}, \mu$
  - $\mathrm{W}^+, \mathrm{W}^-$,
  - p_T^ℓ, p_T^{miss}
  - $|\eta_\ell|$ range (3e, 4μ)

Analysis strategy (II)

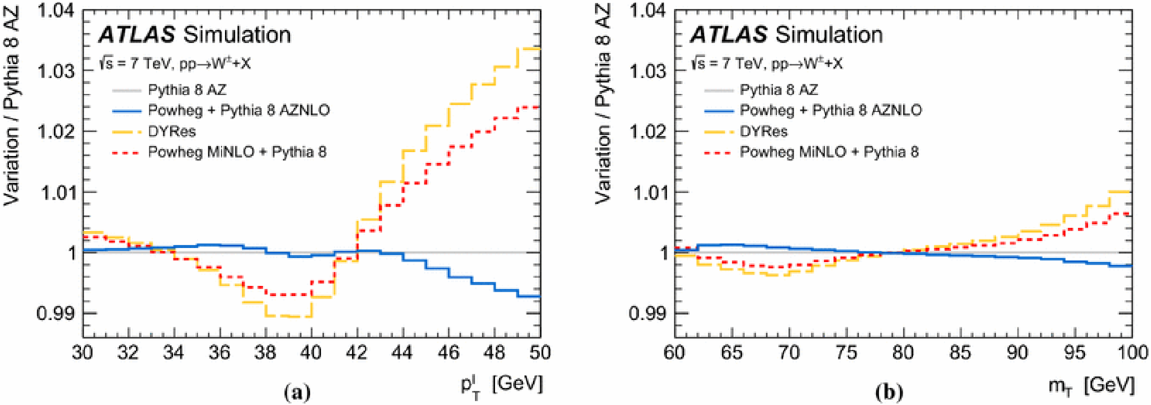
- p_T^ℓ and depend M_t on ℓ energy calibration
  - M_t also on recoil
  - p_T^ℓ and M_t are partially correlated
  - measurement based on p_T^{miss} done as consistency check but lower precision, not used for final combination.
- W are not at rest, and are affected by the W helicity, which depends on `pdf`
  - M_t is less sensitive than p_T^ℓ to physics effects, but more on recoil
- Z $\rightarrow \ell\ell$ to calibrate detector response, lepton calibration, and recoil
- cross check by measuring M_Z with same method used for M_Z, treating one ℓ as a ν
  - NB. dataset of $Z \rightarrow \ell\ell$ about 1/10 of $W \rightarrow \ell\nu$
- cross check among different independent categories
  - also as a function of pile-up, u_t, and different fit range
- Blind analysis: random value $\in [-100, +100]$ MeV added to M_W during analysis.

- EWK effects:
  - QED ISR and FSR, interference I/FSR, virtual loop, di-lepton radiation
- QCD corrections:
  - rapidity distribution at NNLO,
  - p_T^W distribution from fixed order PCD NNLO (includin nnlo pdf) plus MC tuning on Z data



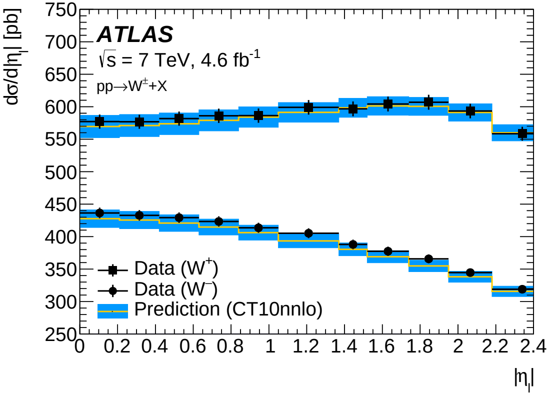
(a) $Z \to \ell\ell$, **(b)** $R(\sigma(W/Z))(p_T)$

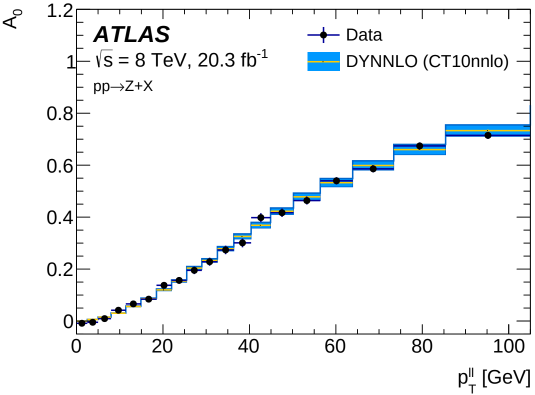
P_T^ℓ and M_T for differente generator



An example of the impact of MC generator/tuning on sensitive quantities.
Suggest fit range to reduce sistematics

Reweight distribution from POWHEG+PYTHIA 8 wrt NNLO prediction with complex multi step procedure, and tested on $p_T/\eta^{\ell\ell}$ $p_T\eta^{\ell}$ distrubution for Z and W.



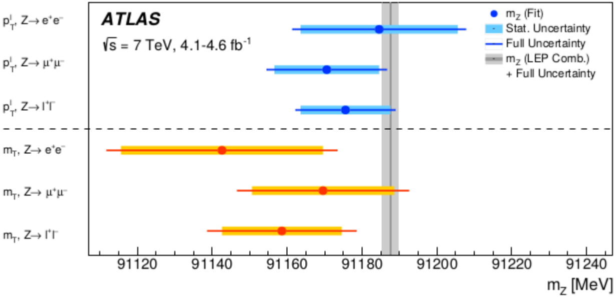


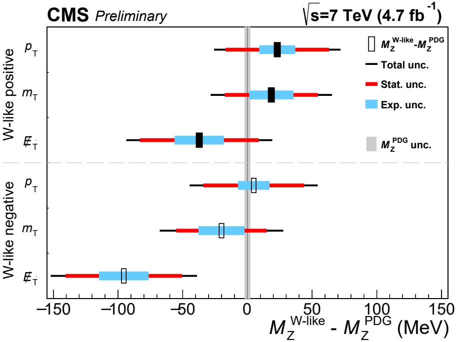
ATLAS: physics modelling summary

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

- PDFs are the dominant uncertainty, followed by p_T W uncertainty due to heavy-flavour-initiated production
- PDF uncertainties are partially anti-correlated between W+ and W-, and significantly reduced by the combination of these two categories.
- p_T W uncertainties are similar for m_W extracted from p_T lepton and from m_T

- ℓ calibration (scale and resolution) from $Z \to \ell\ell$
- Calibration with $Z \to \ell\ell$ where ℓ is considered as a a ν
- measure M_Z as M_W (template fit)
- CMS did this also [10], using also MET





ℓ calibration Systematics

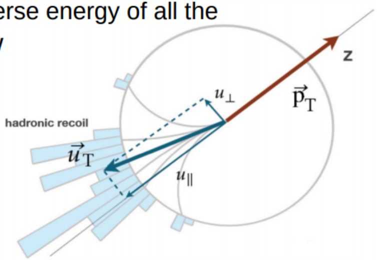
$\|\eta_\ell\|$ range	[0.0, 0.6]		[0.6, 1.2]		[1.8, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

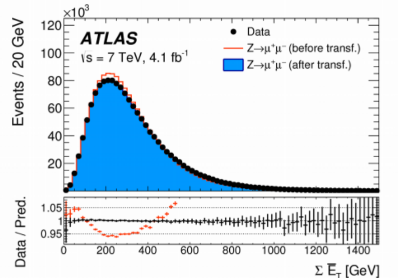
Recoil calibration

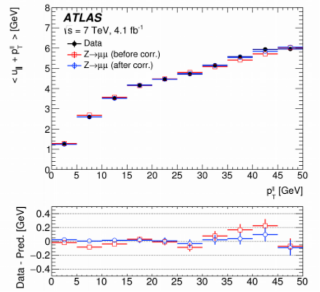
The recoil u_T is the vector sum of the transverse energy of all the calorimeter clusters: u_T is a measure of p_T W

Calibration steps:

- Correct pile-up multiplicity in MC to match the data
- Correct for residual differences in the ΣE_T distribution
- Derive scale and resolution corrections from the p_T balance in Z events







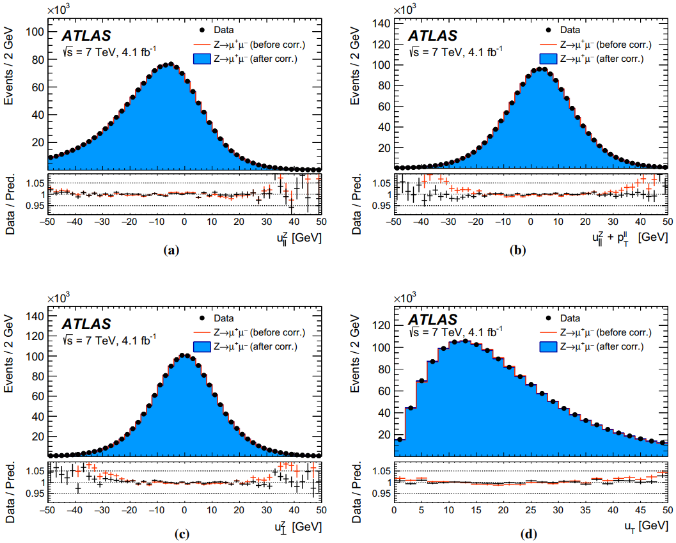
M_W recoil calibration

- recoil calibration from Z $\to \ell\ell$
- look at distribution of
  - $u_{\parallel}$ (to Z direction): scale
  - $u_{\perp}$ resolution
  - $u_{\parallel}^{\ell}$ (W events).
- apply correction on MC based on Z

$$\tilde{h}^{W}_{\text{data}}(\Sigma E^{*}_{\text{T}}, p^{W}_{\text{T}}) \equiv h^{Z}_{\text{data}}(\Sigma E^{*}_{\text{T}}, p^{\ell\ell}_{\text{T}}) \left(\frac{h^{W}_{\text{data}}(\Sigma E^{*}_{\text{T}})}{h^{W}_{\text{MC}}(\Sigma E^{*}_{\text{T}})} \Big/ \frac{h^{Z}_{\text{data}}(\Sigma E^{*}_{\text{T}})}{h^{Z}_{\text{MC}}(\Sigma E^{*}_{\text{T}})} \right),$$

$$u'_x = u_x + \left(\langle u_x \rangle_{\text{data}} - \langle u_x \rangle_{\text{MC}} \right) ,$$

$$u'_y = u_y + \left(\langle u_y \rangle_{\text{data}} - \langle u_y \rangle_{\text{MC}} \right) ,$$

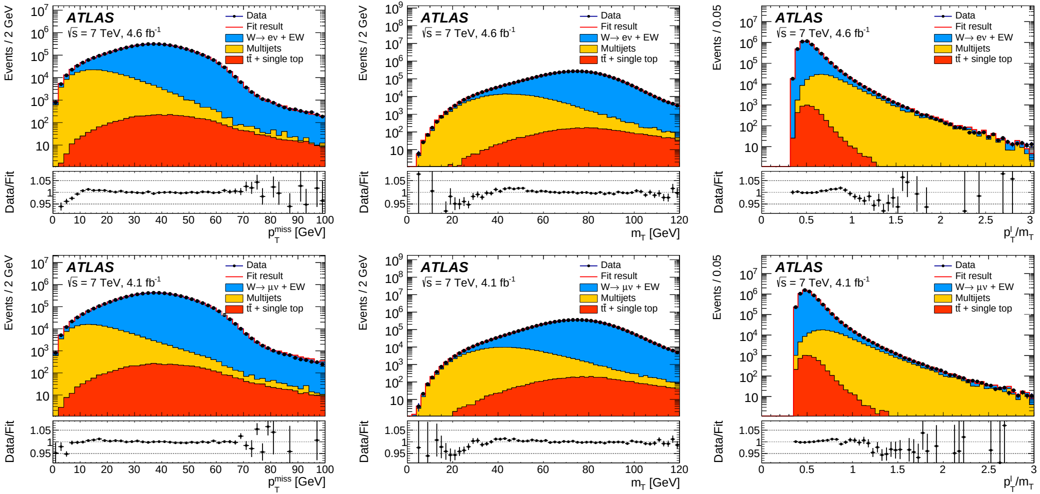


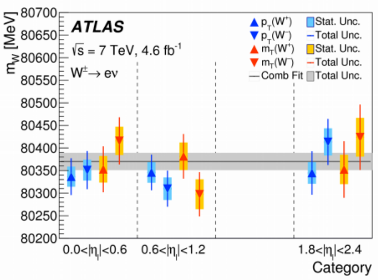
Recoil calibration Systematics

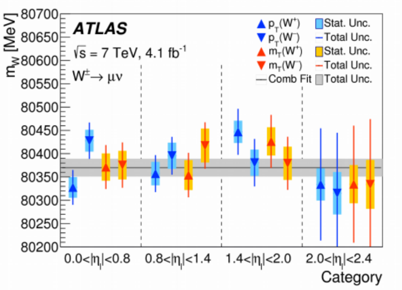
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
ΣE_T^* correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

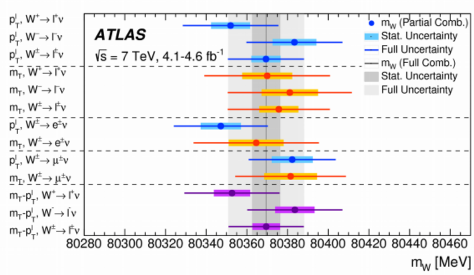
Larger for M_t than p_T^ℓ

Template fit to evaluate background p_T^{miss} M_t and p_T^{ℓ}/M_t



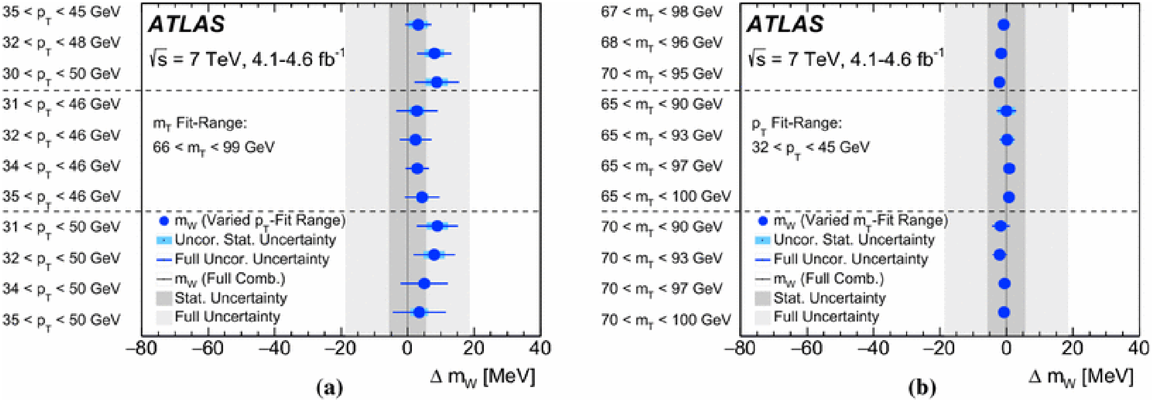






- All categories give consistent extractions of m_W

- Strong validation of physics modelling and detector calibration



(a) varying p_T fit range **(b)** variiying m_T fit range.

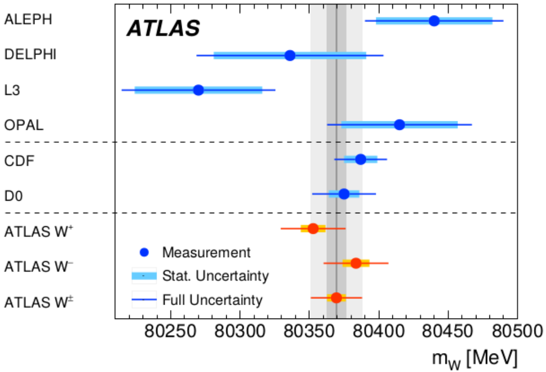
Demonstrate good understading of physics model

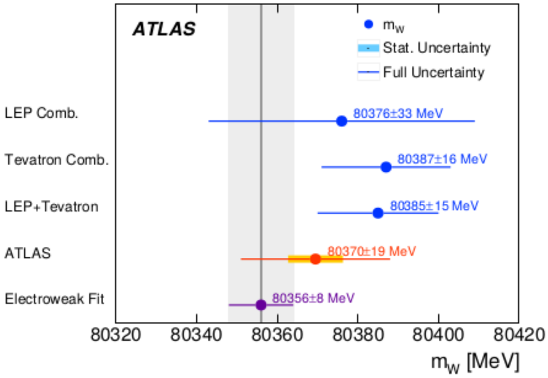
Systematics and results

$$M_W = 80370 \pm 7(\text{stat}) \pm 11(\text{exp syst}) \pm 14(\text{mod syst})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV}$$

source	MeV
stat	6.8
μ	6.6
e	6.4
recoil	2.9
Bkgn	4.5
QCD	8.3
EW	5.5
PDF	9.2
Total	18.5

- Combination of all categories.
- Competitive with CDF (± 19 MeV) and D0 (± 23 MeV)
- Additional masurement $\Delta M_{W^\pm} = -29 \pm 28$ MeV

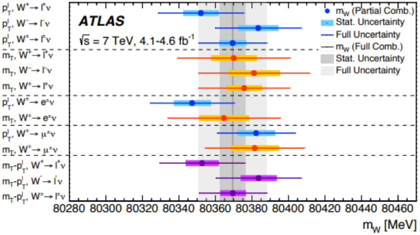




In some better agreement with SM global fit than TeVatron results

M_W combined

[ATLAS, EPJC 78 (2018) 110]

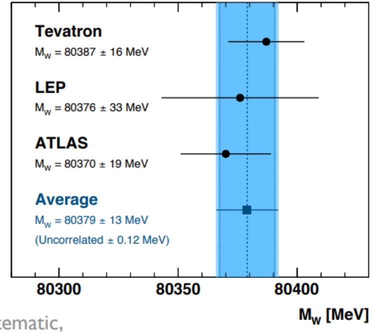


ATLAS

$M_W = 80370 \pm 7_{(stat)} \pm 11_{(exp.syst)}$
$\pm 14_{(mod.\,syst)}$ MeV

Tevatron [CDF, D0, 1204.0042]

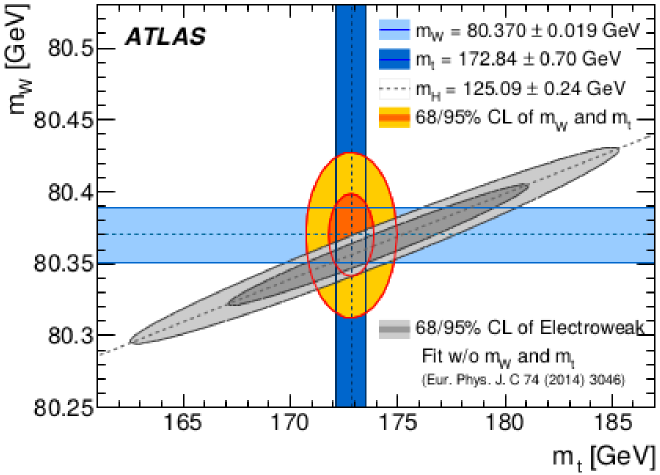
$M_W = 80387 \pm 8_{(stat)} \pm 8_{(exp.syst)}$
$\pm 12_{(mod.\,syst)}$ MeV



New average

smaller by 6 MeV, uncertainty of 13 MeV
(15 MeV previously)

Obtained by assuming 50% correlation of model systematic, very robust against changes


ATLAS
m_W = 80.370 ± 0.019 GeV
m_t = 172.84 ± 0.70 GeV
m_H = 125.09 ± 0.24 GeV
68/95% CL of m_W and m_t
68/95% CL of Electroweak
Fit w/o m_W and m_t
(Eur. Phys. J. C 74 (2014) 3046)
m_W [GeV]
80.25
80.3
80.35
80.4
80.45
80.5
165
170
175
180
185
m_t [GeV]

Outline

Outline

Outline

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