6. Physics of W and Z bosons

6.1 The theory of electroweak interactions (a short repetition)

6.2 Summary of precision tests at LEP

6.3 W and Z boson production in hadron colliders

6.4 Test of QCD in W/Z (+jet) production

6.5 Di-boson measurements

6.6 W mass measurement

Weak Isospin and Hypercharge Quantum

Lepton	T	T^3	Q	Y
ν_e	$\frac{1}{2}$	$\frac{1}{2}$	0	-1
e_L^-	$\frac{1}{2}$	$-\frac{1}{2}$	-1	-1
e_R^-	0	0	-1	-2

Numbers of Leptons and Quarks

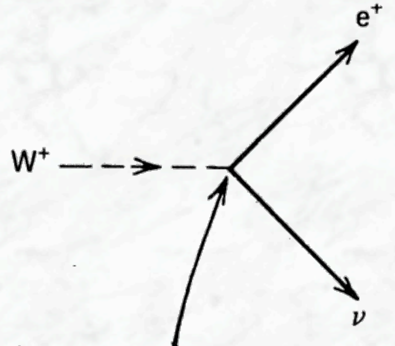
Quark	T	T^3	Q	Y
u_L	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$
d_L	$\frac{1}{2}$	-$\frac{1}{2}$	-$\frac{1}{3}$	$\frac{1}{3}$
u_R	0	0	$\frac{2}{3}$	$\frac{4}{3}$
d_R	0	0	-$\frac{1}{3}$	-$\frac{2}{3}$

Important Milestones towards Electroweak Unification

1961	S. Glashow proposes an electroweak gauge theory, Introduction of massive $W^{\pm}$ and Z^0 bosons, to explain the large difference in strength of electromagnetic and weak interactions. Key question: how acquire W and Z bosons mass?
1964	R. Brout, F. Englert and P. Higgs demonstrate that mass terms for gauge bosons can be introduced in local gauge invariant theories via spontaneous symmetry breaking
1967	S. Weinberg and A. Salam use Brout-Englert-Higgs mechanism to introduce mass terms for W and Z bosons in Glashow’s theory → GSW theory (Glashow, Salam, Weinberg) → mass terms for W, Z bosons, γ remains massless → Higgs particle (see chapter 7)
1973	G. t’Hooft and M. Veltman show that GSW theory is renormalizable
1979	Nobel price for S. Glashow, A. Salam and S. Weinberg
1983	Experimental discovery of the W and Z bosons by UA1 and UA2 experiments at the CERN SppbarS collider ($\sqrt{s}$ = 540 GeV)
1990-2000	Precise test of the electroweak theory at LEP
1999	Nobel price for G. t’Hooft and M. Veltman
2012	Discovery of a Higgs particle by the ATLAS and CMS experiments at the LHC

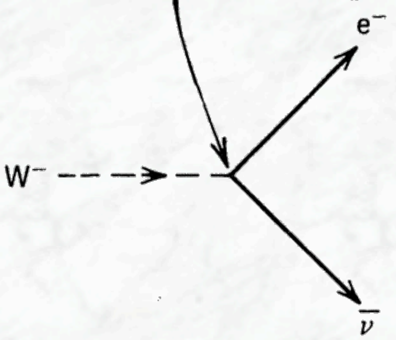
W and Z vertex factors

$$\left.\begin{aligned} &-i\frac{g}{\sqrt{2}}\left(\bar{\chi}_L\gamma^\mu\tau_+\chi_L\right)W^+_\mu \\ &= -i\frac{g}{\sqrt{2}}\left(\bar{\nu}_L\gamma^\mu e_L\right)W^+_\mu \end{aligned}\right\}$$



$$\boxed{-i\frac{g}{\sqrt{2}}\gamma^\mu\tfrac{1}{2}\left(1-\gamma^5\right)}$$

$$\left.\begin{aligned} &-i\frac{g}{\sqrt{2}}\left(\bar{\chi}_L\gamma^\mu\tau_-\chi_L\right)W^-_\mu \\ &= -i\frac{g}{\sqrt{2}}\left(\bar{e}_L\gamma^\mu\nu_L\right)W^-_\mu \end{aligned}\right\}$$



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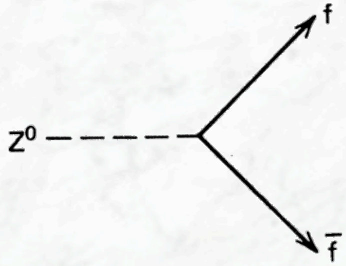
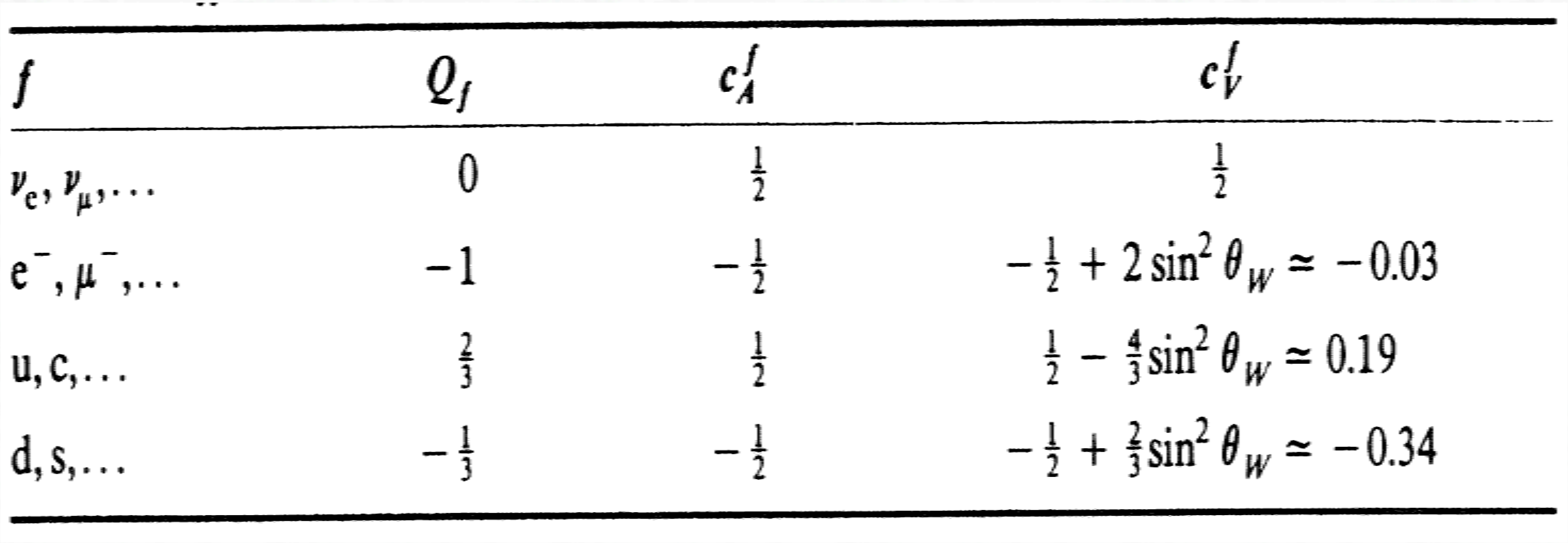


$$\boxed{-i\frac{g}{\cos\theta_W}\gamma^\mu\tfrac{1}{2}\left(c^f_V-c^f_A\gamma^5\right).}$$

The Z → ff vertex factors in the Standard Model

($\sin^2 \theta_W$ is assumed to be 0.234)

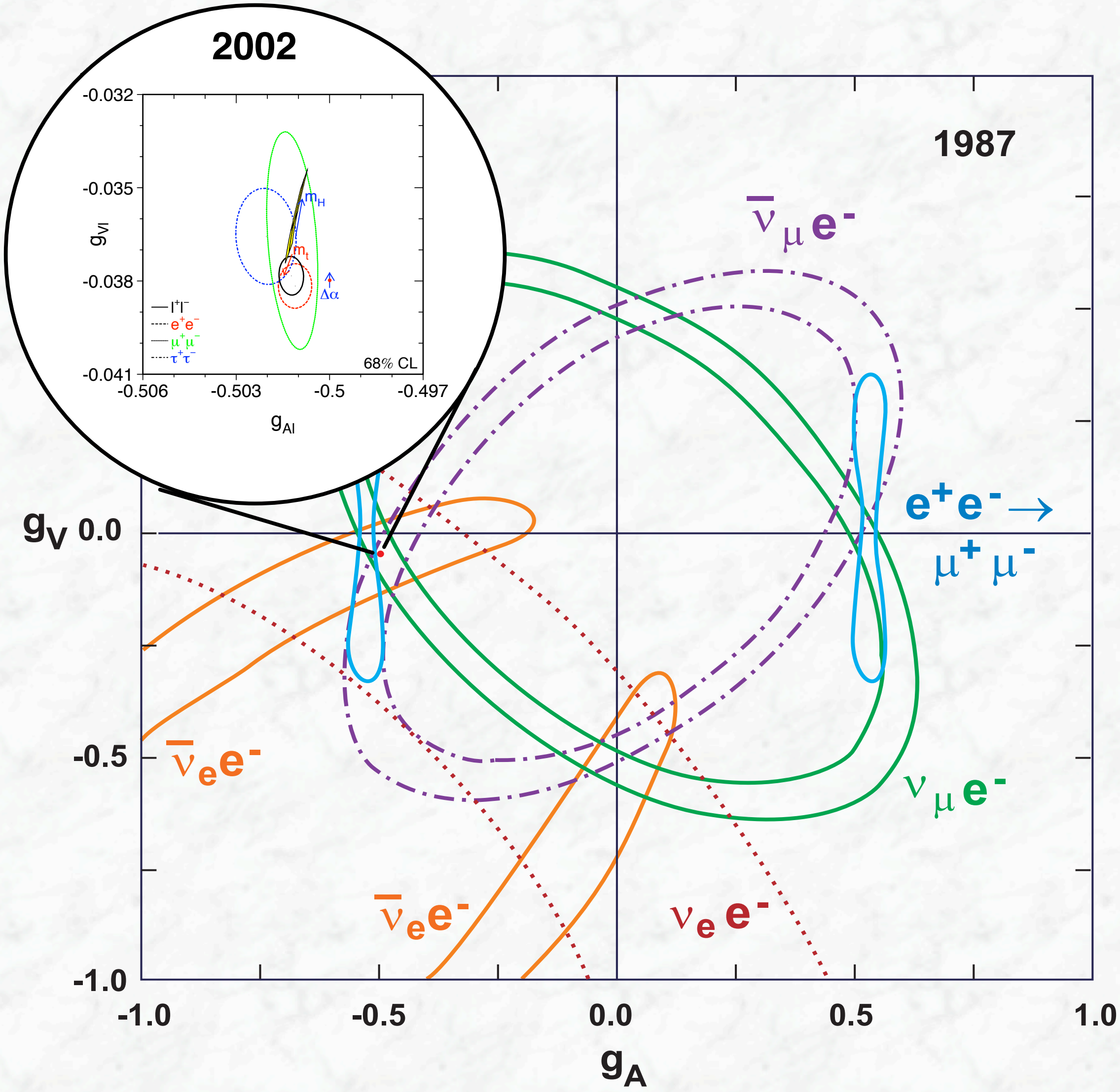


f	Q_f	c_A^f	c_V^f
$\nu_e, \nu_\mu, \ldots$	0	$\frac{1}{2}$	$\frac{1}{2}$
$e^-, \mu^-, \ldots$	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W \simeq -0.03$
$u, c, \ldots$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W \simeq 0.19$
$d, s, \ldots$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \simeq -0.34$

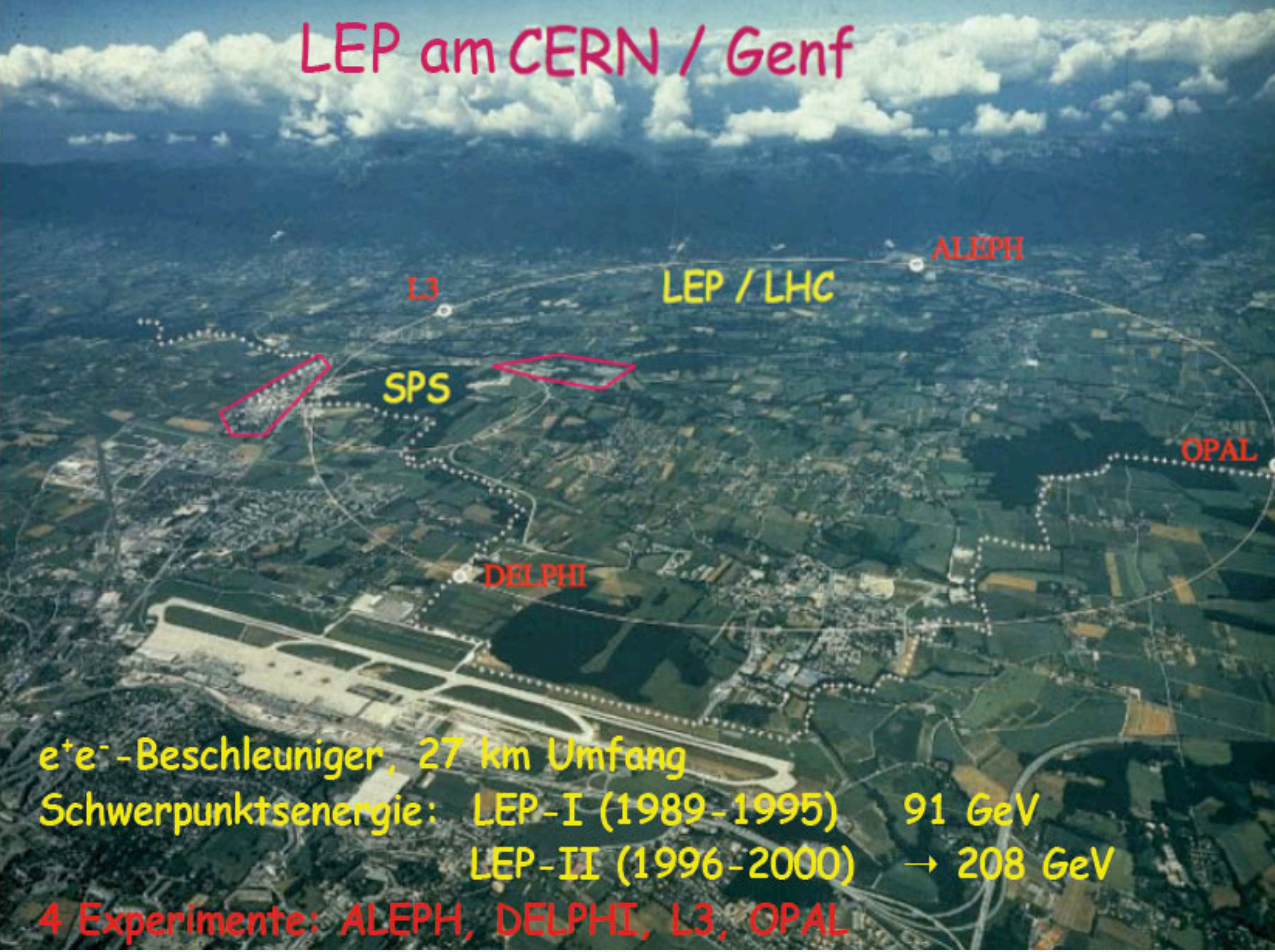
[Halzen&Martin]

6.2 Summary of electroweak precision tests at LEP

- Results of 30 years of experimental and theoretical progress
- The electroweak theory is tested at the level of 10^{-4}



LEP am CERN / Genf



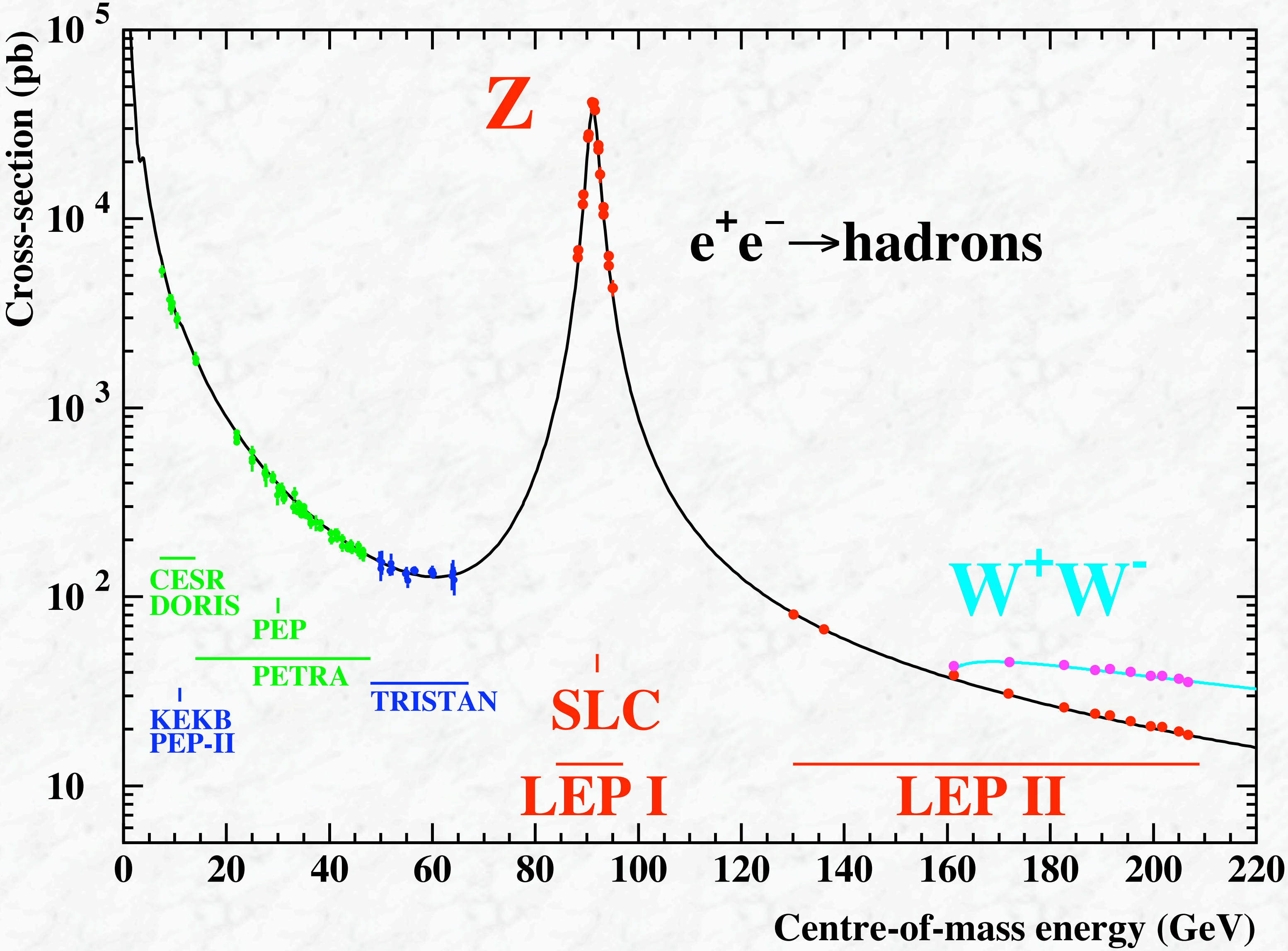
e^+e^--Beschleuniger, 27 km Umfang

Schwerpunktsenergie: LEP-I (1989-1995) 91 GeV

LEP-II (1996-2000) → 208 GeV

4 Experimente: ALEPH, DELPHI, L3, OPAL

Cross sections for W and Z boson production



Precision tests
of the Z sector

Tests of the
W sector

Cross section for e$^+$e$^-$ → $\mu^+\mu^-$ at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\Big[\underbrace{F_\gamma(\cos\theta)}_{\gamma} + \underbrace{\underbrace{F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}_{\gamma/Z\text{ interference}}}_{\text{vanishes at }\sqrt{s}\,\approx\, M_Z} + \underbrace{F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}_{Z}\Big]$$

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2(1+\cos^2\theta) = (1+\cos^2\theta)\\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}[2g_V^e g_V^\mu(1+\cos^2\theta)+4g_A^e g_A^\mu\cos\theta]\\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W\cos^4\theta_W}[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta)+8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta]
\end{aligned}$$

$\alpha=\alpha(m_Z)$: running el.magnetic coupling [$\alpha(M_Z) = \alpha/(1-\Delta\alpha)$ mit $\Delta\alpha\approx 0.06$]

$g_V, g_A = c_V, c_A$: effective coupling constants (vector and axial vector)

Cross section for e⁺e⁻ → ff at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ

γ/Z interference

Z

vanishes at $\sqrt{s} \approx M_Z$

x N_C^f
number of colour degrees of
freedom for fermion f

x $(1+\delta_{QCD})$
QCD correction term

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_f^2(1+\cos^2\theta) \\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_f}{4\sin^2\theta_W\cos^2\theta_W}\left[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^f\cos\theta\right] \\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[(g_V^{e^2}+g_A^{e^2})(g_V^{f^2}+g_A^{f^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^f g_A^f\cos\theta\right]
\end{aligned}$$

Cross section for $e^+e^- \rightarrow f\bar{f}$ on resonance ($\sqrt{s} = m_Z$)

- On resonance, $\sqrt{s} = m_Z$:
  - γ^*/Z interference terms vanishes
  - γ term contributes ~1%
  - Z contribution dominates !
- Contribution of the γ^*/Z interference term at $s = (M_Z - 3\text{ GeV})^2$: ~0.2%

Total cross section for $e^+e^- \rightarrow \mu^+\mu^-$ (integration over cos θ)

$$\sigma_{\text{tot}} \approx \sigma_Z = \frac{4\pi}{3s} \frac{\alpha^2}{16 \sin^4 \theta_W \cos^4 \theta_W} \cdot [(g_V^e)^2 + (g_A^e)^2][(g_V^\mu)^2 + (g_A^\mu)^2] \cdot \frac{s^2}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2}$$

$$\sigma_Z(\sqrt{s} = M_Z) = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$$

Peak cross section

$$\Gamma_f = \frac{\alpha M_Z}{12 \sin^2 \theta_W \cos^2 \theta_W} \cdot [(g_V^f)^2 + (g_A^f)^2]$$

Partial width

$$\Gamma_Z = \sum_i \Gamma_i$$

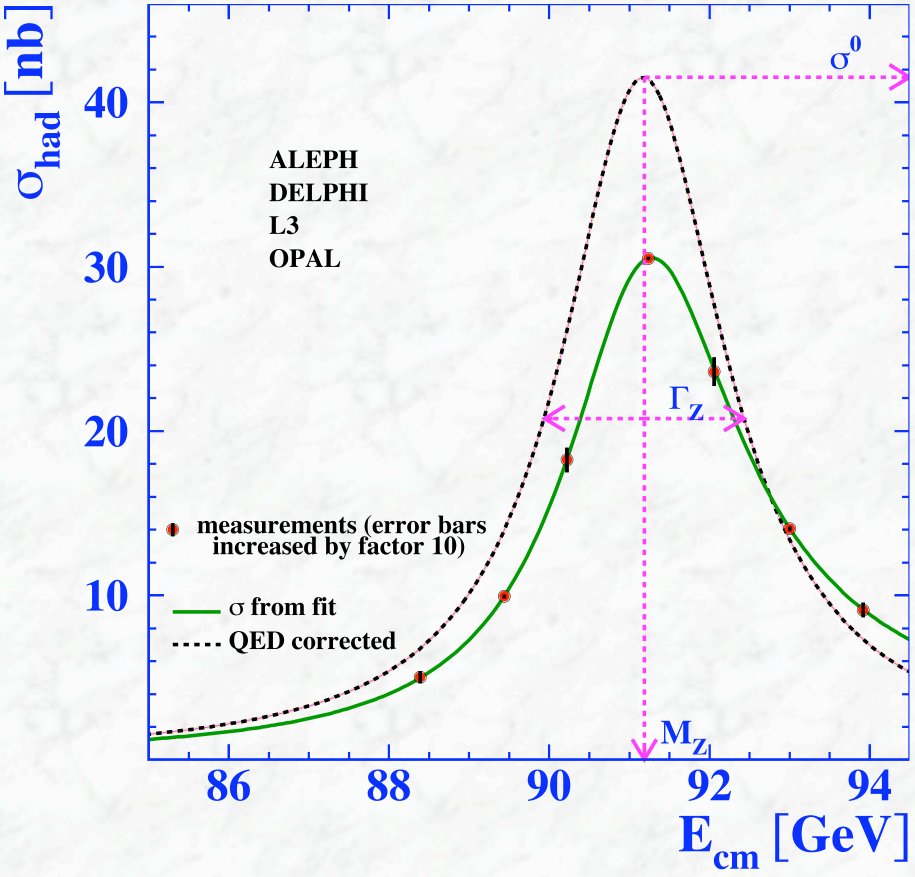
Total width

From the energy dependence of the total cross section (for various fermions f) the parameters

M_Z, Γ_Z, Γ_f

can be determined.

Measurement of the Z line-shape



Line shape (resonance curve):

$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

Peak: $\sigma_0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_\mu}{\Gamma_Z^2}$

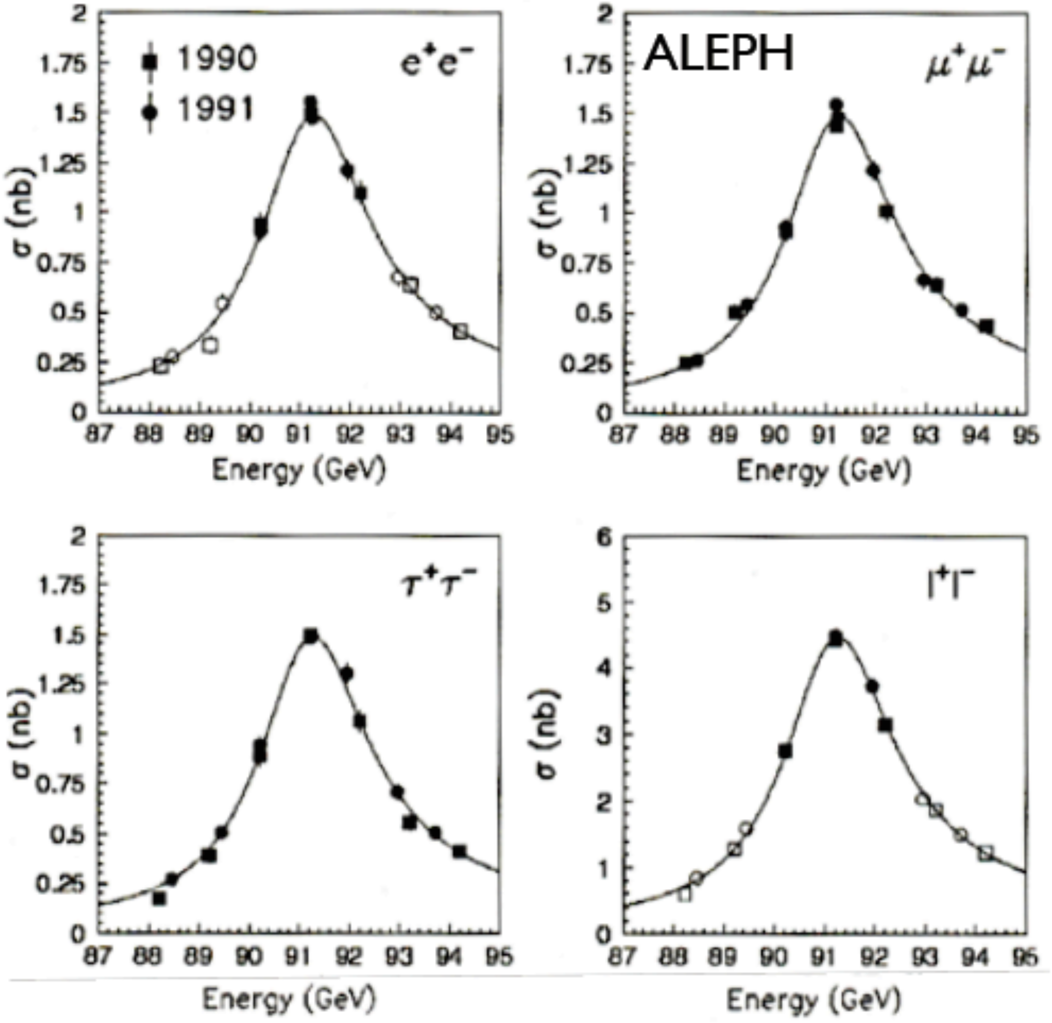
- Position of maximum → M_Z
- Full width at half maximum → Γ_Z
- Peak cross section σ_0 → $\Gamma_e\Gamma_\mu$

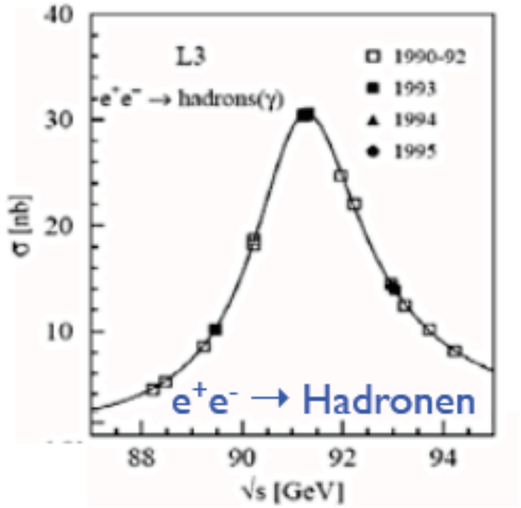
Radiative corrections (photon radiation) important

— with ISR (initial state radiation)

- - - without ISR

Measurement of the Z line-shape (cont.)





$e^+e^- \rightarrow$ Hadronen

Quark-Flavor i.a. nicht exp. trennbar
(Ausnahme: c,b → Lebendsdauer)
⇒ had. Breite: $\Gamma_{had} = \Gamma_u + \Gamma_d + \Gamma_s + \Gamma_c + \Gamma_b$

Messe Verhältnisse der Pol-WQ:

$$R_l^0 \equiv \frac{\Gamma_{had}}{\Gamma_{ll}} \qquad l = e, \mu, \tau$$

$$R_q^0 \equiv \frac{\Gamma_{qq}}{\Gamma_{had}} \qquad q = b, c$$

- Keine Unterschiede für verschiedene Leptonarten ⇒ Leptonuniversalität
- Form der Resonanzenkurve für alle Endzustände gleich (gleicher Propagator!)

Results on Z line-shape parameters

M_Z = 91.1876 ± 0.0021 GeV 23 ppm (*)

Γ_Z = 2.4952 ± 0.0023 GeV
Γ_{had} = 1.7458 ± 0.0027 GeV
Γ_e = 0.08392 ± 0.00012 GeV
Γ_μ = 0.08399 ± 0.00018 GeV
Γ_τ = 0.08408 ± 0.00022 GeV

3 lepton flavours treated independently

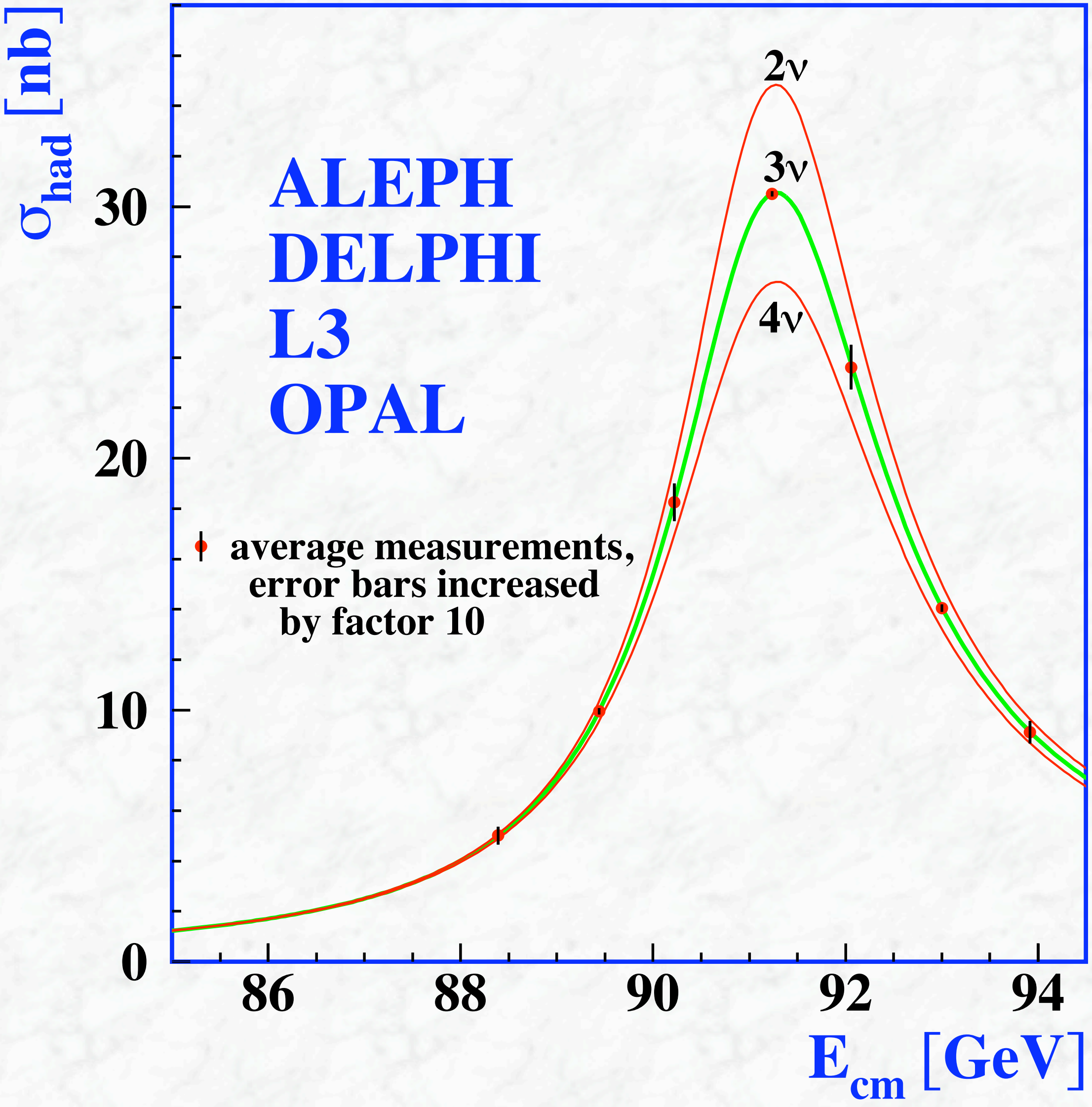
Test of lepton universality

Γ_Z = 2.4952 ± 0.0023 GeV
Γ_{had} = 1.7444 ± 0.0022 GeV
Γ_e = 0.083985 ± 0.000086 GeV

lepton universality assumed:
$\Gamma_e = \Gamma_\mu = \Gamma_\tau$

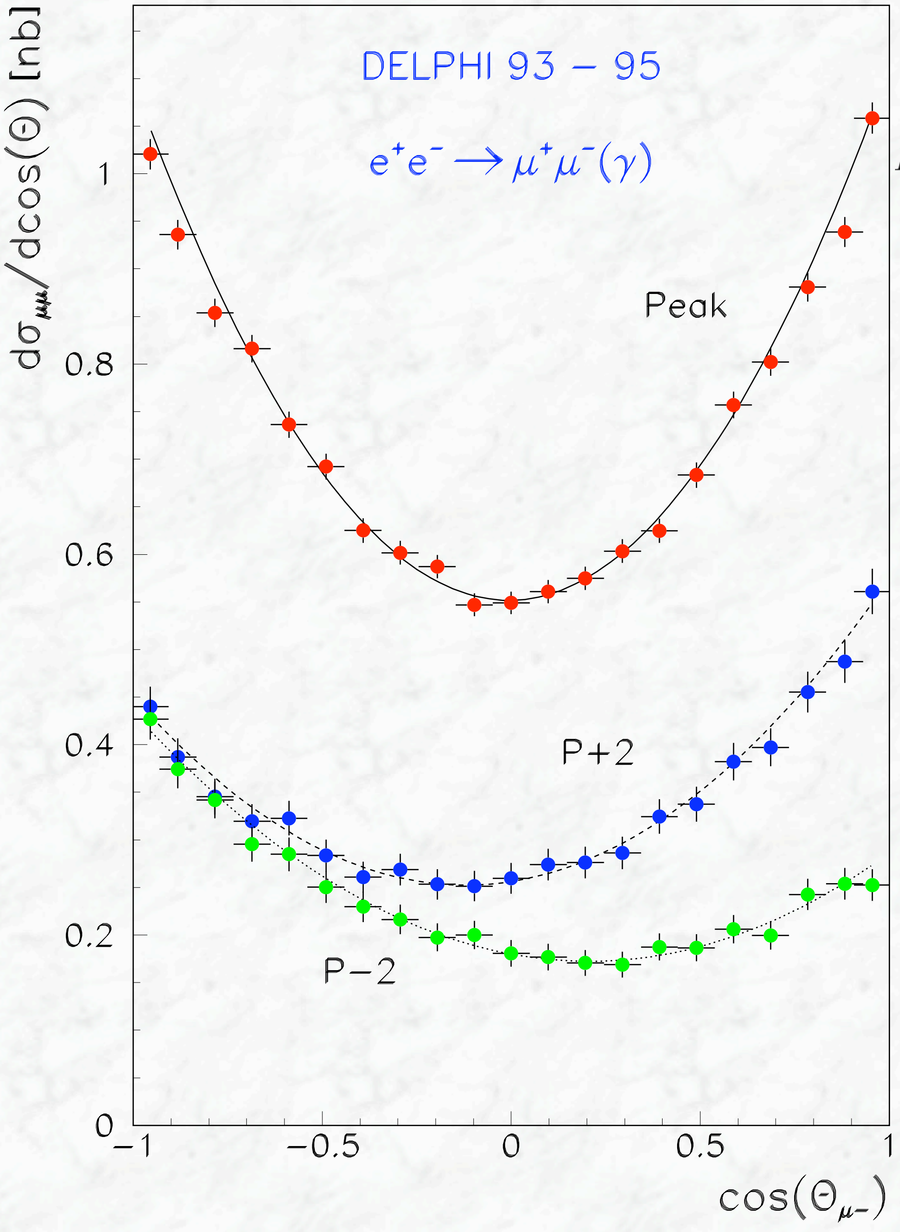
*) Uncertainty on LEP energy measurement: ± 1.7 MeV (19 ppm)

Number of neutrinos



$N_\nu = 2.9840 \pm 0.0082$

Forward-backward asymmetries



$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2 (1+\cos^2\theta) = (1+\cos^2\theta) \\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W \cos^2\theta_W}\left[2 g_V^e g_V^\mu (1+\cos^2\theta) + 4 g_A^e g_A^\mu \cos\theta\right] \\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W \cos^4\theta_W}\left[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) + 8 g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta\right]
\end{aligned}$$

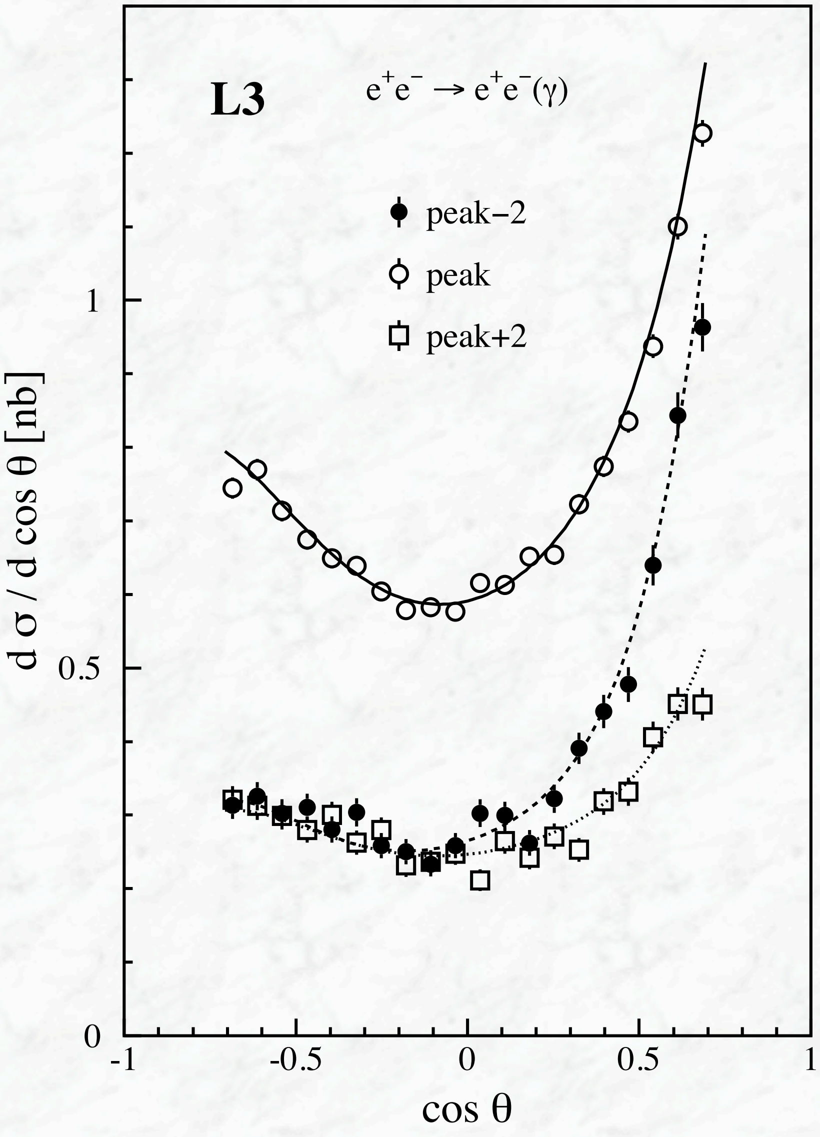
Terms ∝ cosθ in dσ/dcosθ
→ asymmetry

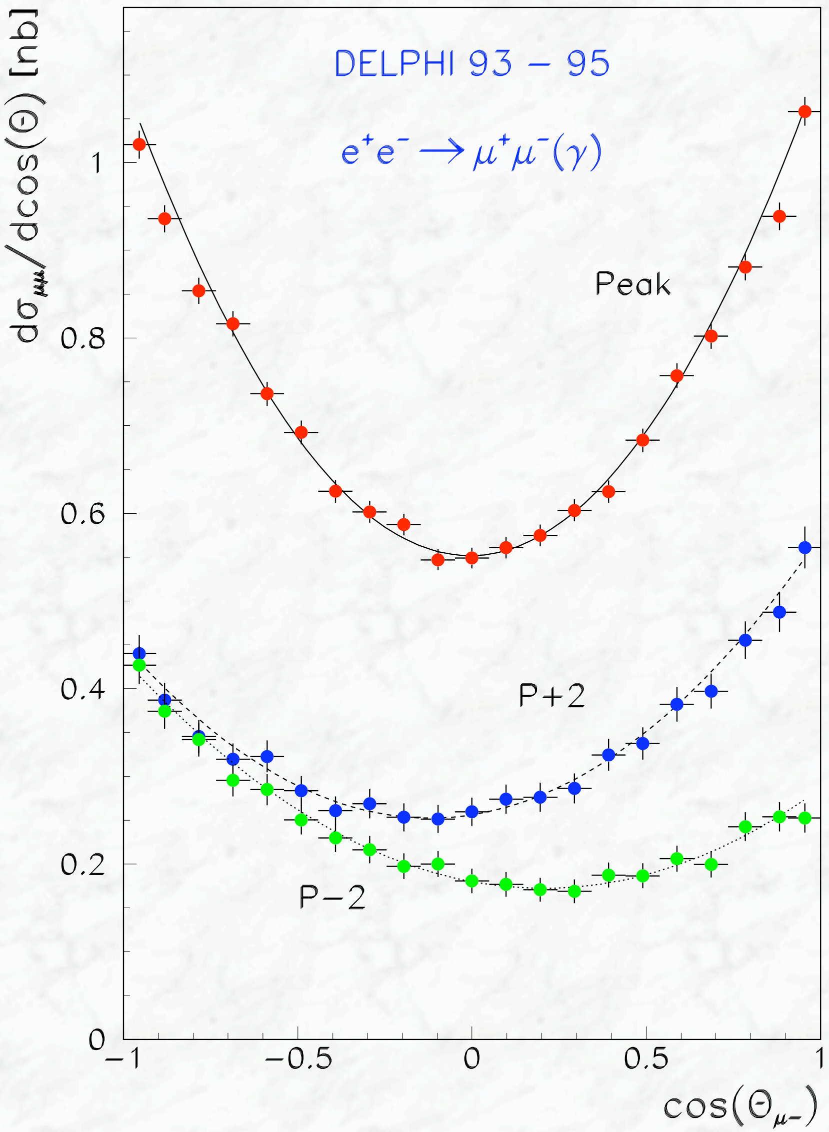
$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta}\, d\cos\theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Forward-backward asymmetries

-comparison between ee and μμ final states-





Forward-backward asymmetries and fermion couplings

- Asymmetry at the Z pole (no interference) is small

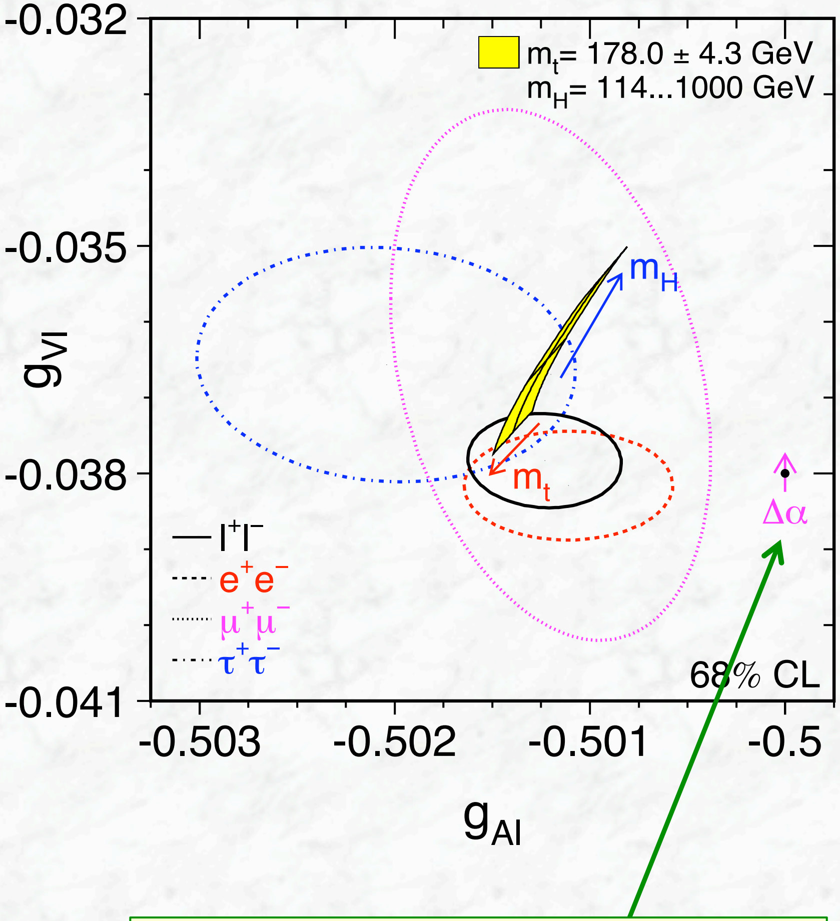
$$A_{\mathrm{FB}} \sim g_{\mathrm{A}}^{e} g_{\mathrm{V}}^{e} g_{\mathrm{A}}^{f} g_{\mathrm{V}}^{f}$$

since g_V^f is small (in particular for leptons)

- For off-resonance points, the interference term dominates and gives larger contributions

$$A_{\mathrm{FB}} \sim g_{\mathrm{A}}^{e} g_{\mathrm{A}}^{f} \cdot \frac{s(s-M_{\mathrm{Z}}^{2})}{(s-M_{\mathrm{Z}}^{2})^{2}+M_{\mathrm{Z}}^{2}\Gamma_{\mathrm{Z}}^{2}}$$

- A_{FB} can be used for the determination of the fermion couplings

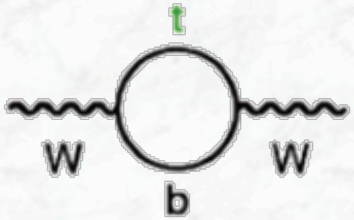


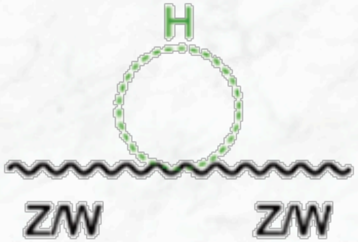
LO Standard Model prediction:

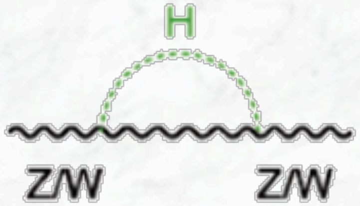
$g_A = T_3$

$g_V = T_3 - 2\,Q \sin^2 \theta_W$

Electroweak radiative corrections







Standard Model relations
(lowest order)

$$\rho = \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2 \cos^2\theta_{\mathrm{W}}} = 1$$

$$\sin^2\theta_{\mathrm{W}} = 1 - \frac{m_{\mathrm{W}}^2}{m^2\mathrm{Z}}$$

$$m_{\mathrm{W}}^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_{\mathrm{W}} G_{\mathrm{F}}}$$

$$\alpha(0)$$

Relations including
radiative corrections

$$\vec{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_{\mathrm{eff}} = (1 + \Delta\kappa)\sin^2\theta_{\mathrm{W}}$$

$$m_{\mathrm{W}}^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_{\mathrm{W}} G_{\mathrm{F}}} \cdot \frac{1}{(1-\Delta r)}$$

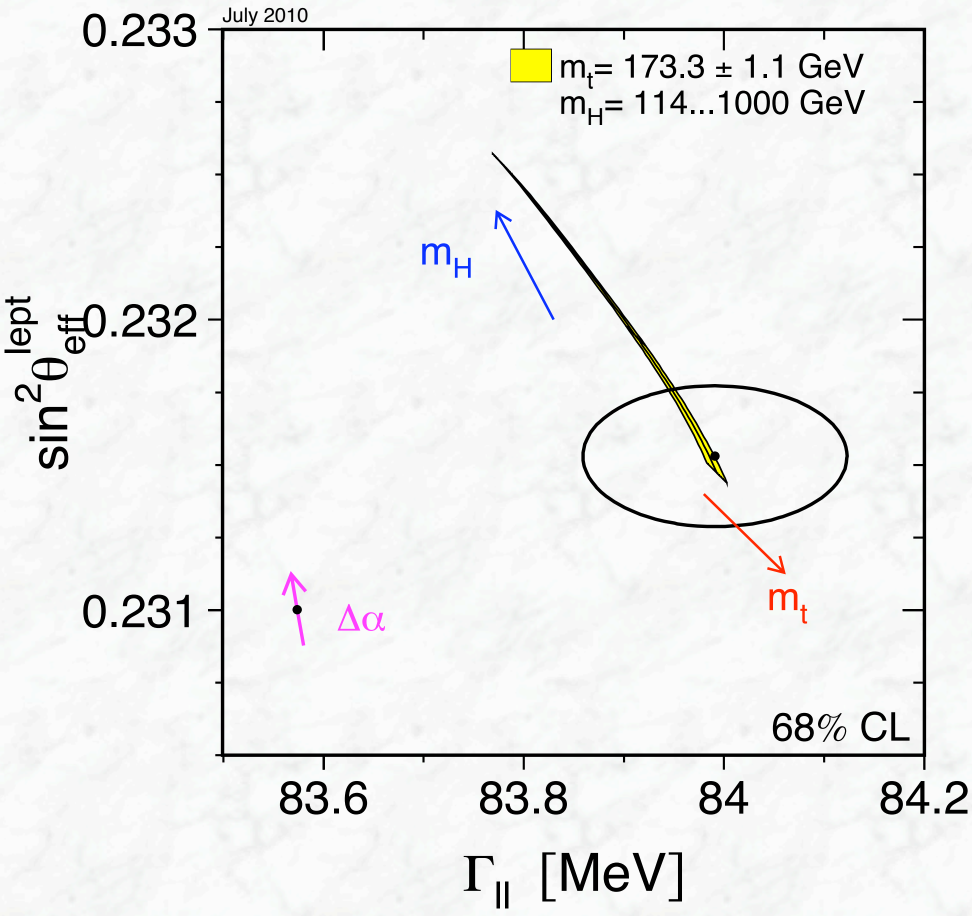
$$\alpha(m_{\mathrm{Z}}^2) = \frac{\alpha(0)}{1-\Delta\alpha}$$

$$\Delta\alpha = \Delta\alpha_{\mathrm{lepl}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{had}}^{(5)}$$

$$\Delta\rho, \Delta\kappa, \Delta r = f(m_t^2, \log(m_{\mathrm{H}}), \ldots)$$

Results of electroweak precision tests at LEP (cont.)

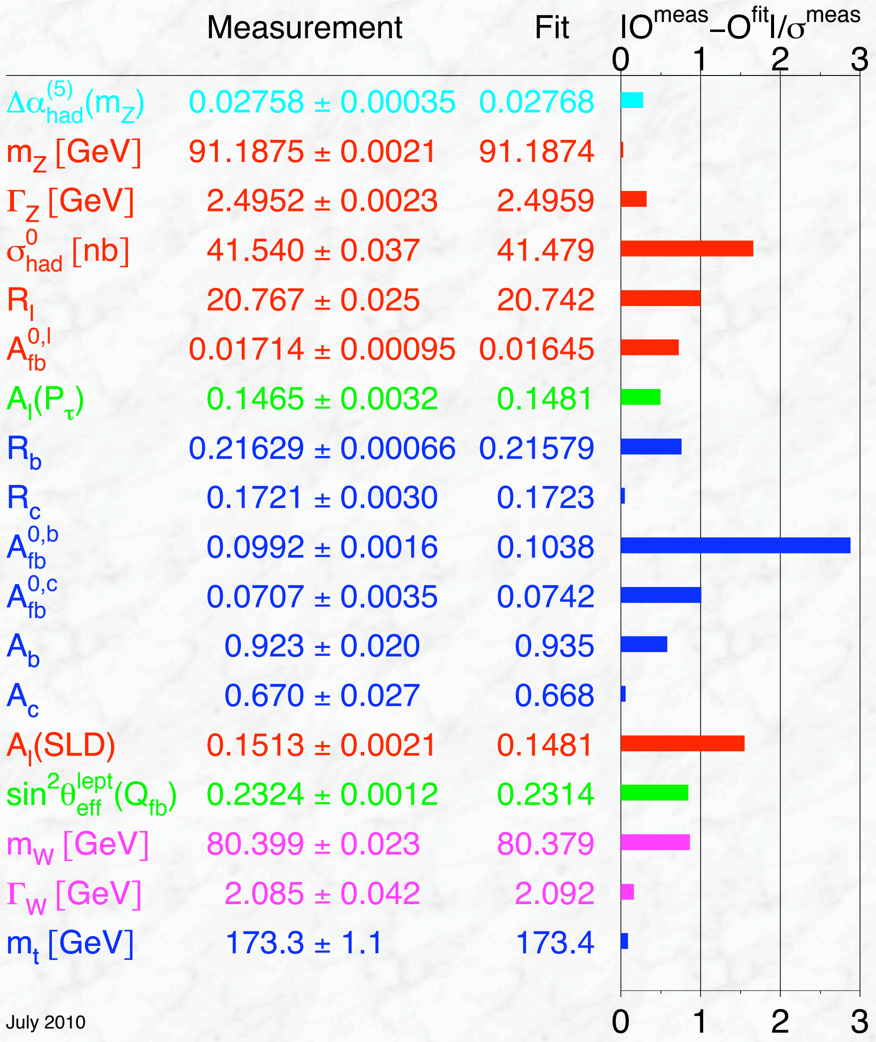
partial decay width versus $\sin^2 \theta_W$:



Results of electroweak precision tests at LEP (cont.)

Summary of results:

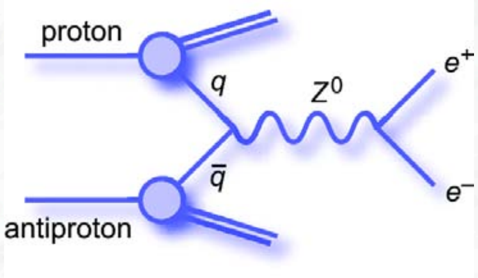
- All measurements in agreement with the Standard Model
- They can be described with a limited set of parameters



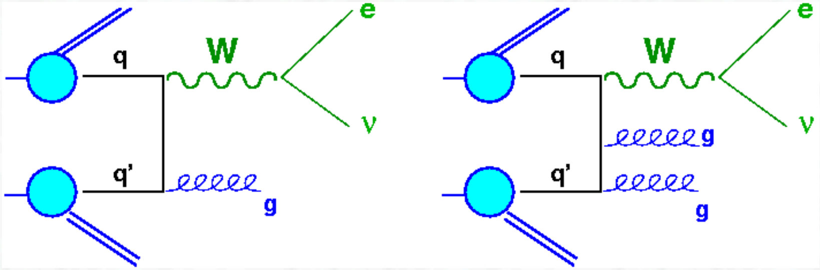
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

July 2010

6.3 W/Z production at hadron colliders



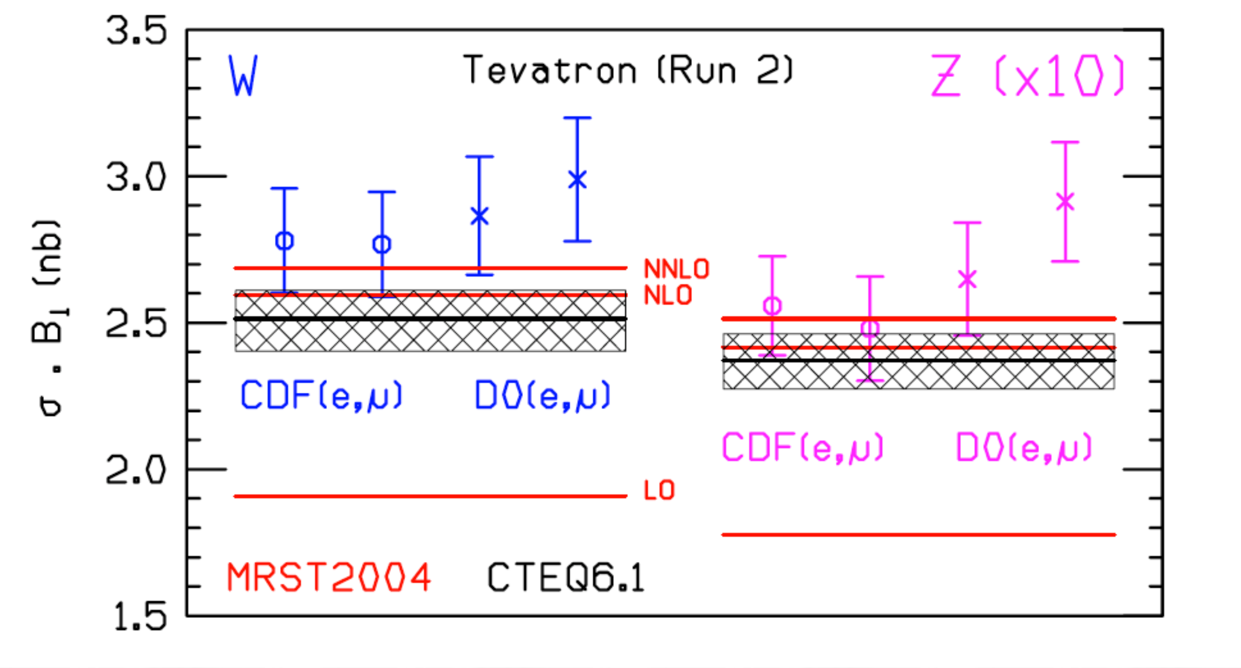
QCD at work



- Important test of NNLO Drell-Yan QCD prediction for the total cross section

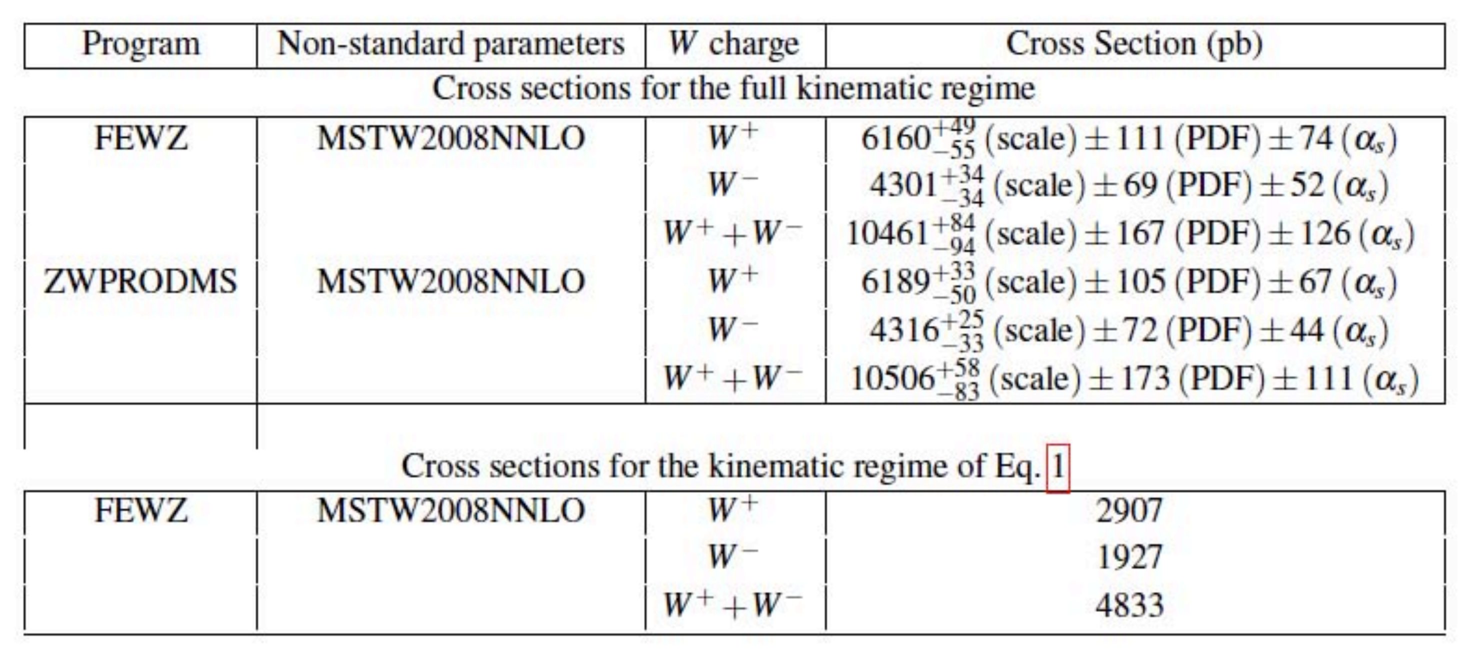
- Test of perturbative QCD in high p_T region (jet multiplicities, p_T spectra,….)

- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC



Predictions for the W and Z boson total cross sections at the Tevatron, using the MRST2004 and CTEQ pdfs, compared with measurements from the CDF and D0 collaborations. The predictions are shown at LO, NLO, and NNLO. For the NLO prediction the accompanying pdf uncertainties are shown as band.

W boson production cross sections at the LHC ($\sqrt{s}$ = 7 TeV)



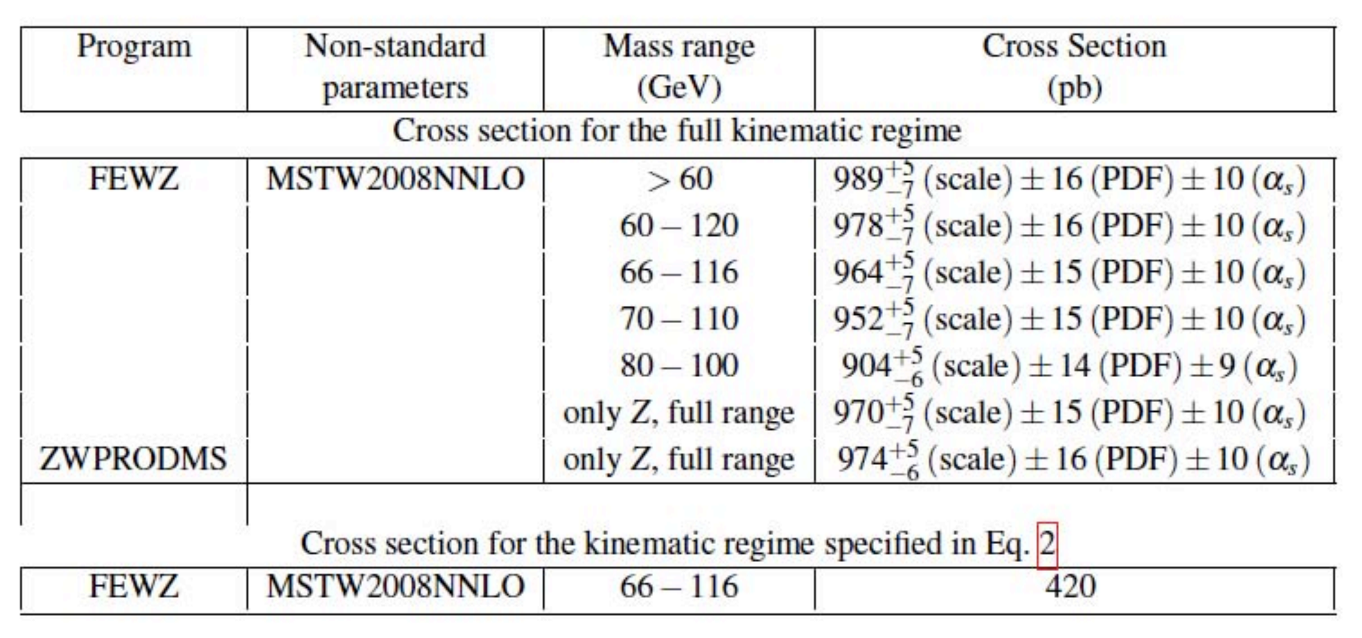
Program	Non-standard parameters	W charge	Cross Section (pb)
Cross sections for the full kinematic regime			
FEWZ	MSTW2008NNLO	W^+	6160^{+49}_{-55} (scale) ± 111 (PDF) ± 74 (α_s)
		W^-	4301^{+34}_{-34} (scale) ± 69 (PDF) ± 52 (α_s)
		$W^+ + W^-$	10461^{+84}_{-94} (scale) ± 167 (PDF) ± 126 (α_s)
ZWPRODMS	MSTW2008NNLO	W^+	6189^{+33}_{-50} (scale) ± 105 (PDF) ± 67 (α_s)
		W^-	4316^{+25}_{-33} (scale) ± 72 (PDF) ± 44 (α_s)
		$W^+ + W^-$	10506^{+58}_{-83} (scale) ± 173 (PDF) ± 111 (α_s)
Cross sections for the kinematic regime of Eq. 1			
FEWZ	MSTW2008NNLO	W^+	2907
		W^-	1927
		$W^+ + W^-$	4833

Predictions for the W → lν cross section at NNLO, calculated for the full kinematic range as well as in the fiducial region (see below).

Major uncertainties: renormalization and factorization scale (~ ±1%)
parton distribution functions (~ ±2)%
uncertainties of α_s (~ ±1%)

Fiducial region: PT(l) > 20 GeV, $\eta < 2.47$, excluding $1.37 < \eta < 1.52$
$E_T^{miss} > 25$ GeV
$m_T > 40$ GeV

Z boson production cross sections at the LHC ($\sqrt{s}$ = 7 TeV)



Program	Non-standard parameters	Mass range (GeV)	Cross Section (pb)
Cross section for the full kinematic regime			
FEWZ	MSTW2008NNLO	> 60	989^{+5}_{-7} (scale) ± 16 (PDF) ± 10 (α_s)
		$60 - 120$	978^{+5}_{-7} (scale) ± 16 (PDF) ± 10 (α_s)
		$66 - 116$	964^{+5}_{-7} (scale) ± 15 (PDF) ± 10 (α_s)
		$70 - 110$	952^{+5}_{-7} (scale) ± 15 (PDF) ± 10 (α_s)
		$80 - 100$	904^{+5}_{-6} (scale) ± 14 (PDF) ± 9 (α_s)
		only Z, full range	970^{+5}_{-7} (scale) ± 15 (PDF) ± 10 (α_s)
ZWPRODMS		only Z, full range	974^{+5}_{-6} (scale) ± 16 (PDF) ± 10 (α_s)
Cross section for the kinematic regime specified in Eq. 2			
FEWZ	MSTW2008NNLO	$66 - 116$	420

Predictions for the $Z / \gamma^* \rightarrow ll$ cross section at NNLO, calculated for the full kinematic range as well as in the fiducial region (see below).

Major uncertainties: renormalization and factorization scale (~ ±1%)
parton distribution functions (~ ±1.5)%
uncertainties of α_s (~ ±1%)

Fiducial region: PT(l) > 20 GeV, $\eta < 2.47$, excluding $1.37 < \eta < 1.52$
$66 < m_{ll} < 116$ GeV

6.4 Test of QCD in W/Z production at hadron colliders

As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

→ Search for leptonic decays: $W \to \ell \nu$ (large $P_T(\ell)$, large P_T^{miss})
$Z \to \ell \ell$

More difficult: $W \to \tau \nu \to$ had $\nu\nu$ $Z \to \tau \tau \to e(\mu)\, \nu\nu$ had ν

Ingredients for a cross-section measurement:

$$\sigma = \frac{N_{sel} - N_{back}}{L \cdot \varepsilon \cdot \eta}$$

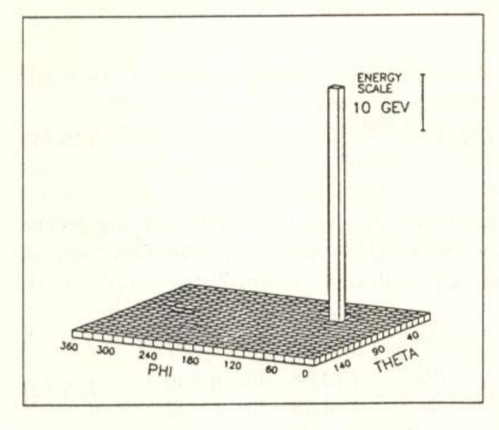
where: N_{sel} = number of selected events
N_{back} = number of background events in selected events

L = integrated luminosity (measured from machine, reference process)
ε = detection efficiency
η = acceptance of fiducial cuts ($P_T(l)$, E_T^{miss}, M_T, m_{ll},….)

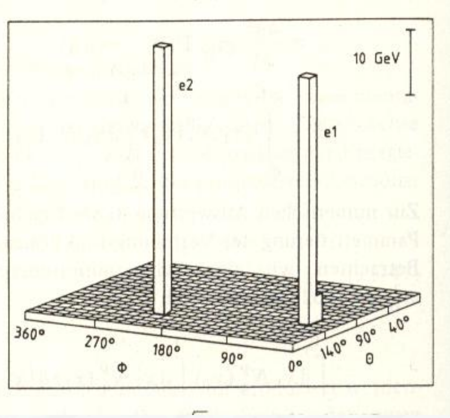
How do W and Z events look like ?

A bit of history: one of the first W and Z events seen (UA2 experiment)

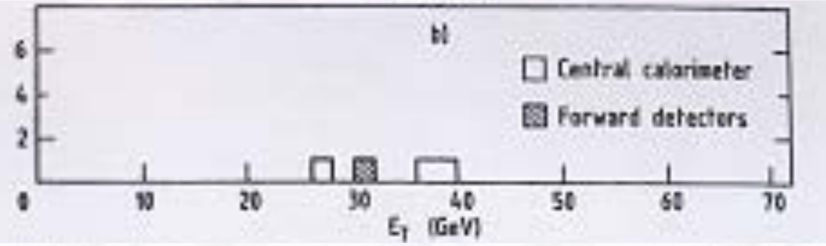
W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)



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



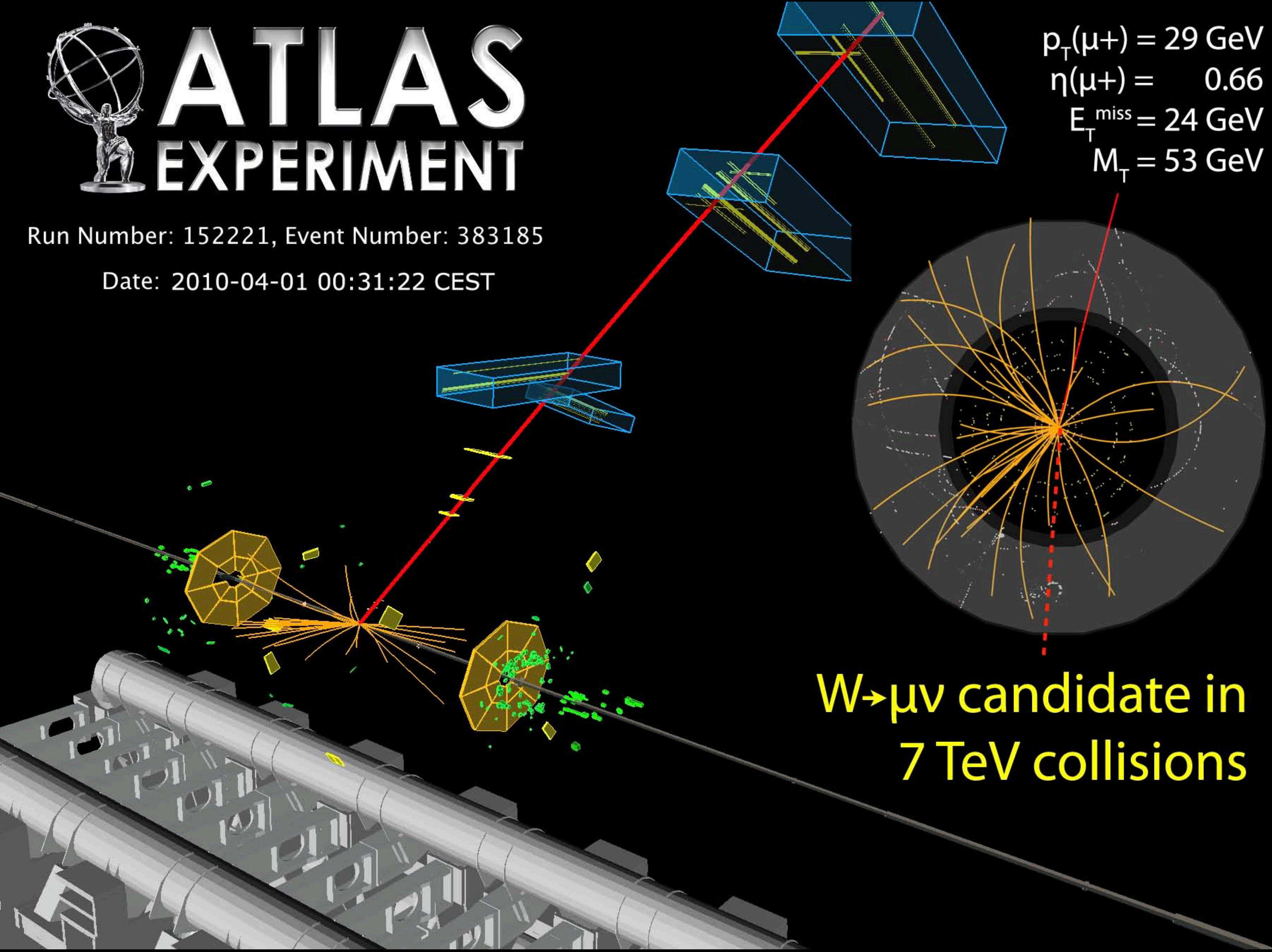
Transverse momentum of the electrons



ATLAS
EXPERIMENT

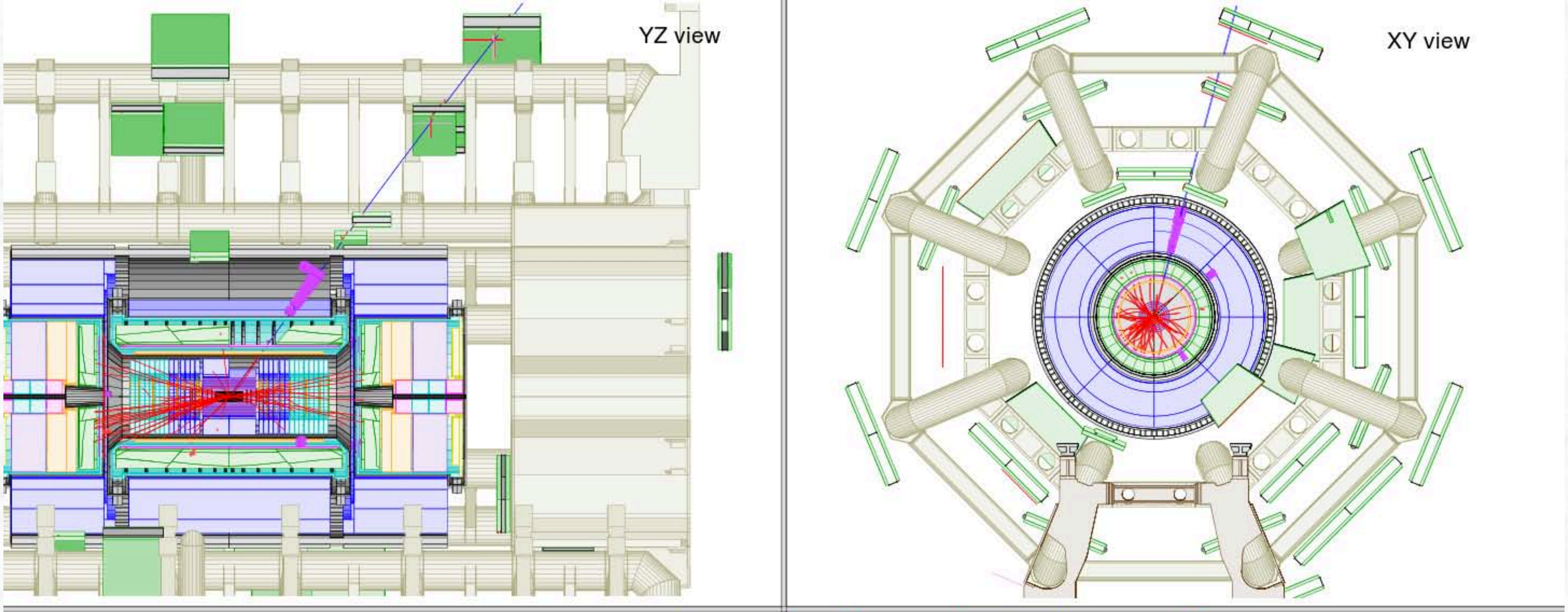
Run Number: 152221, Event Number: 383185

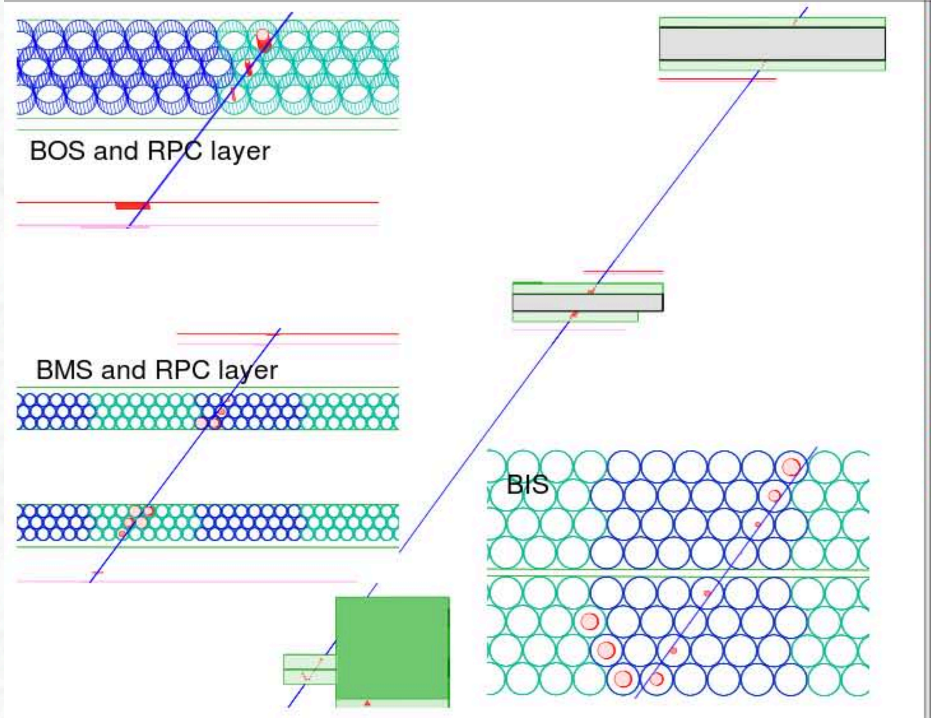
Date: 2010-04-01 00:31:22 CEST

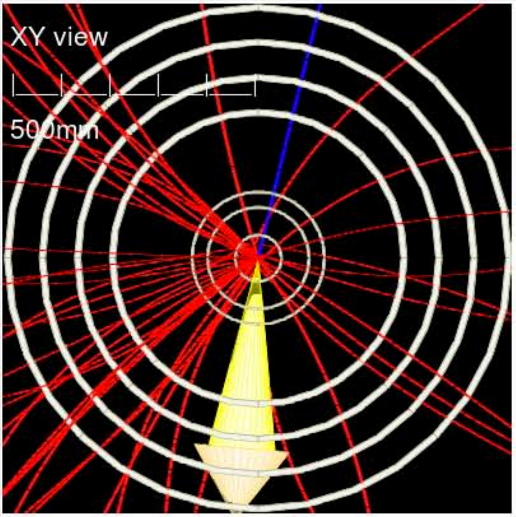


$p_T(\mu+) = 29$ GeV
$\eta(\mu+) = 0.66$
$E_T^{miss} = 24$ GeV
$M_T = 53$ GeV

W→μν candidate in
7 TeV collisions







W->μν candidate in 7 TeV collisions

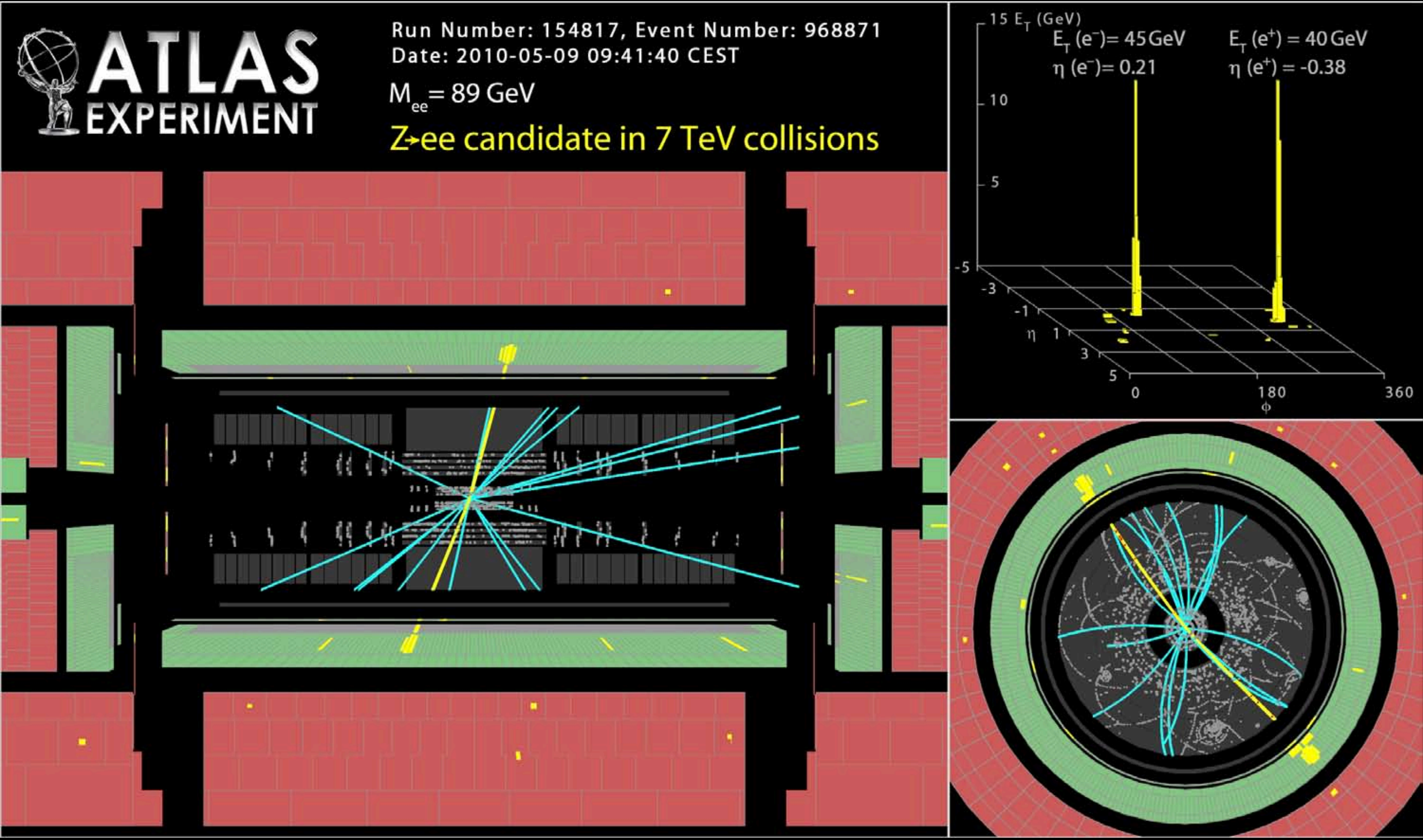
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
PT(μ+) = 29 GeV, η = 0.66
ETmis = 24 GeV
MT = 53 GeV

ATLAS EXPERIMENT
http://atlas.ch

Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST

M_{ee} = 89 GeV

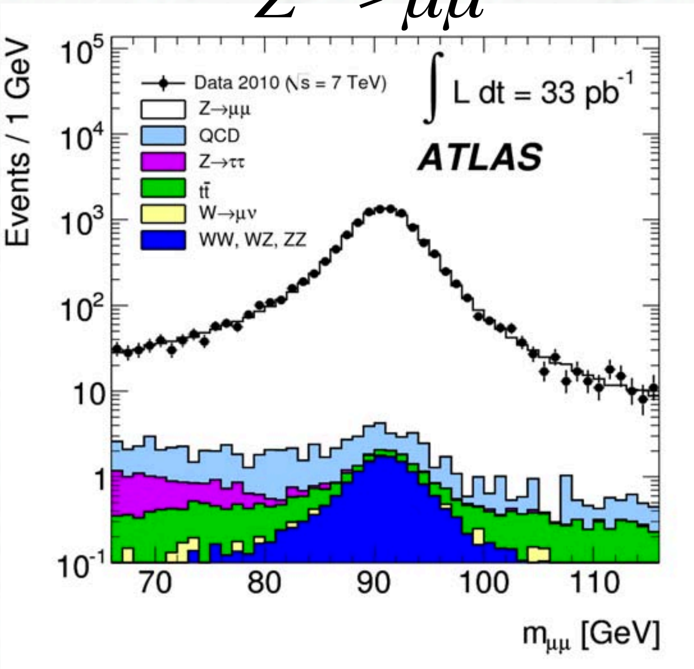
Z→ee candidate in 7 TeV collisions



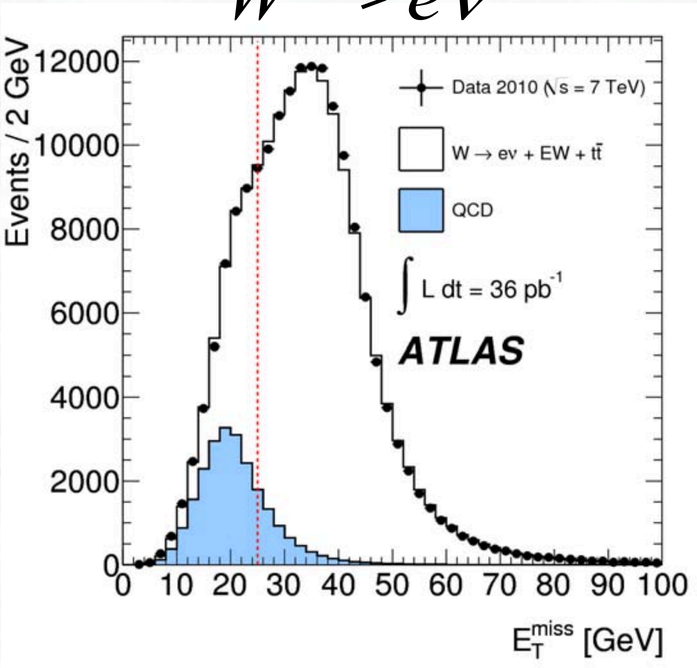
Today's W / Z → eν(μν) / ee(μμ) signals

ATLAS Experiment

$Z \rightarrow \mu\mu$



$W \rightarrow e\nu$



Trigger:

- Single-lepton candidate > 10-25 GeV/c (early 2010 data – Run 2)

Electrons:

- Isolated el.magn. cluster in the calorimeter
- Shower shape consistent with expectation for electrons
- Matched with tracks
- P_T> 25 GeV/c

Muons:

- Inner detector track matched with a muon spectormeter track (segment)

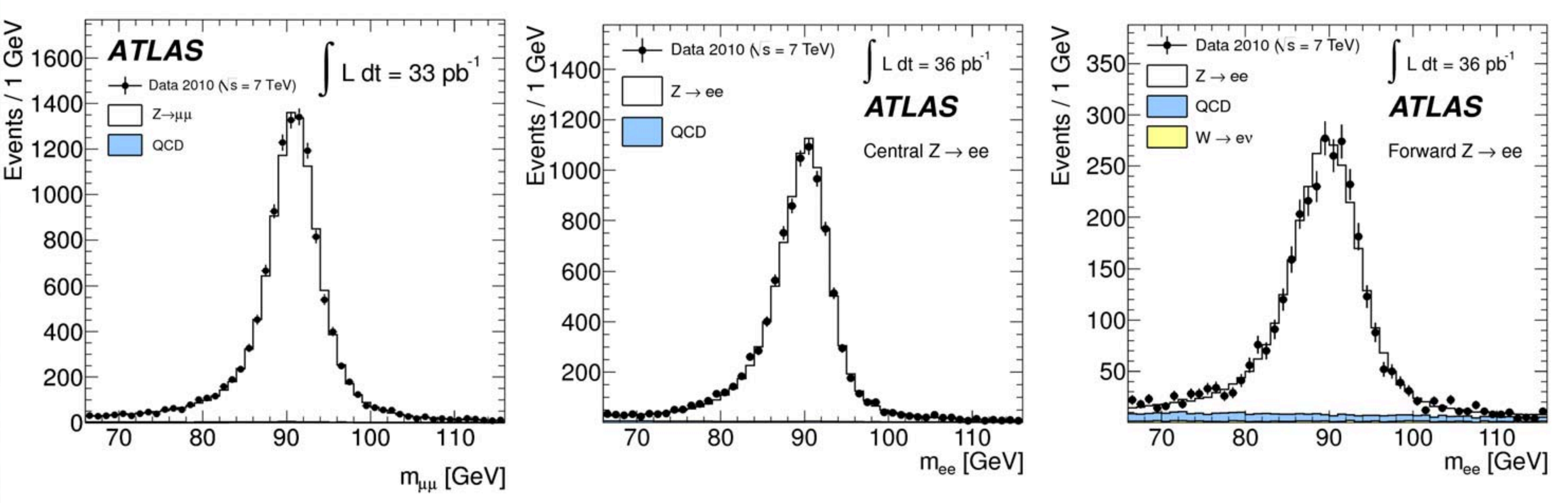
$Z \rightarrow ee$

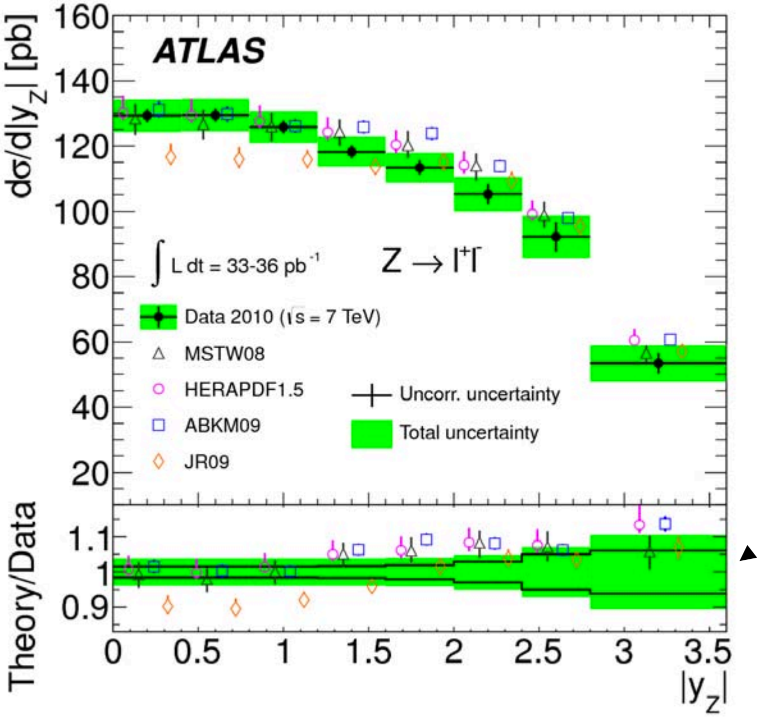
- $70\ \mathrm{GeV/c^2} < m_{ee} < 110\ \mathrm{GeV/c^2}$

$W \rightarrow e\nu$

- Missing transverse momentum > 25 GeV/c

Z→ ℓℓ cross sections



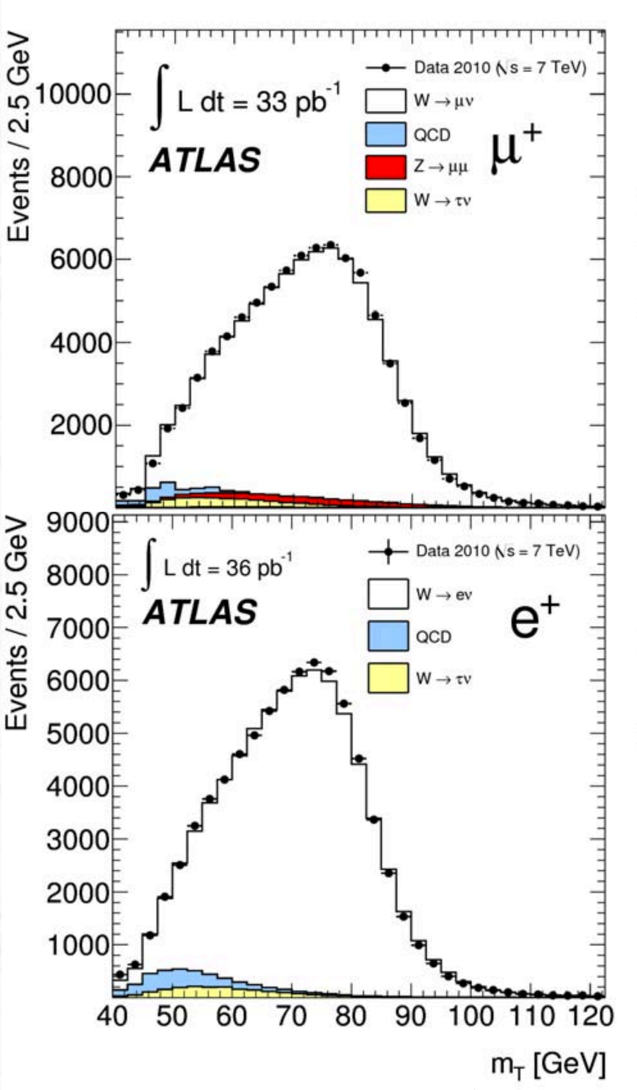


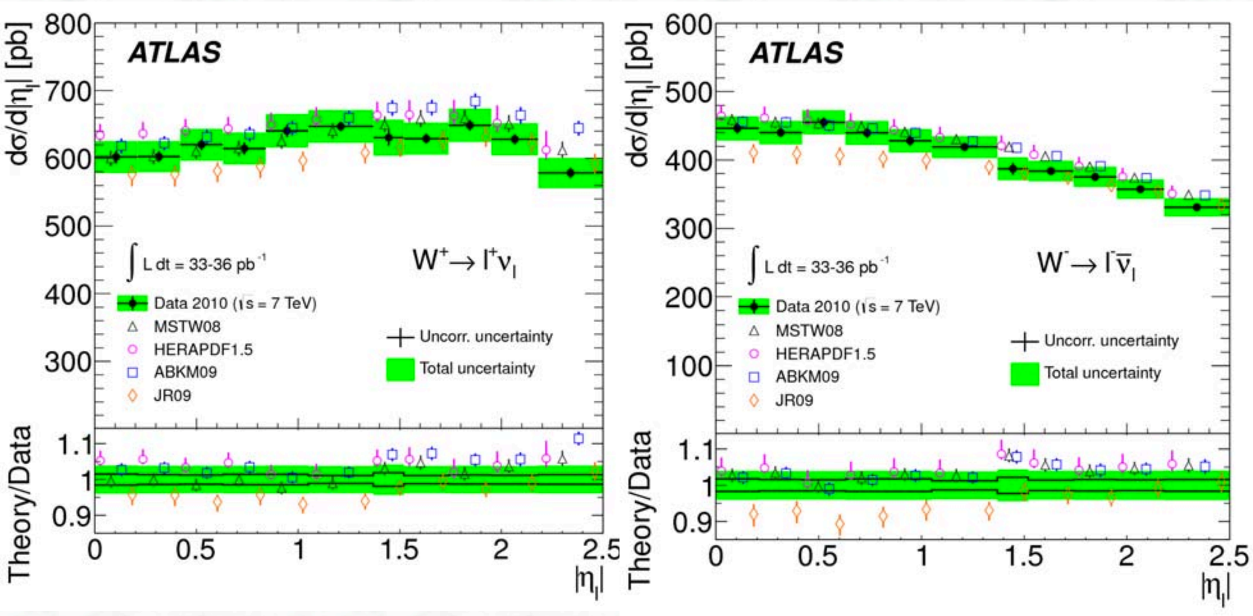
$$x_{1,2} = \frac{M_{\mathrm{W,Z}}}{\sqrt{s}} e^{\pm y_{\mathrm{W,Z}}}$$

Good agreement with
NNLO QCD calculations,
QCD corrections are large: factor ~ 1.25

Precision is limited by systematic effects
(uncertainties on luminosity, parton densities,...)

W → ℓν Cross Section





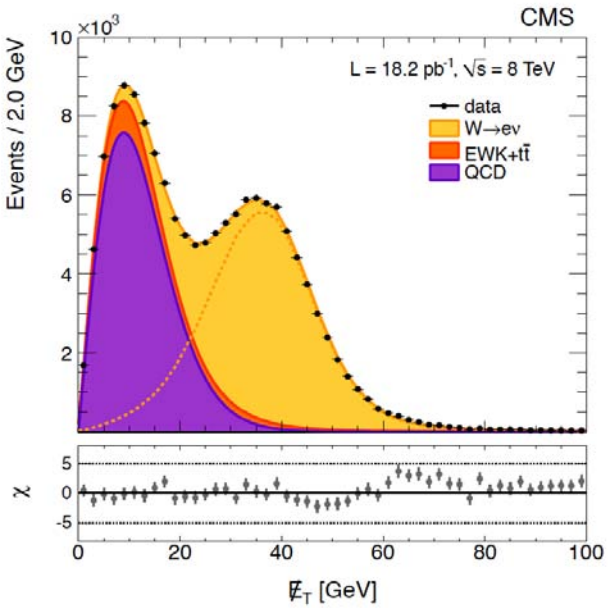
Good agreement with NNLO QCD calculations

$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos\Delta\phi^{l,\nu}\right)}$$

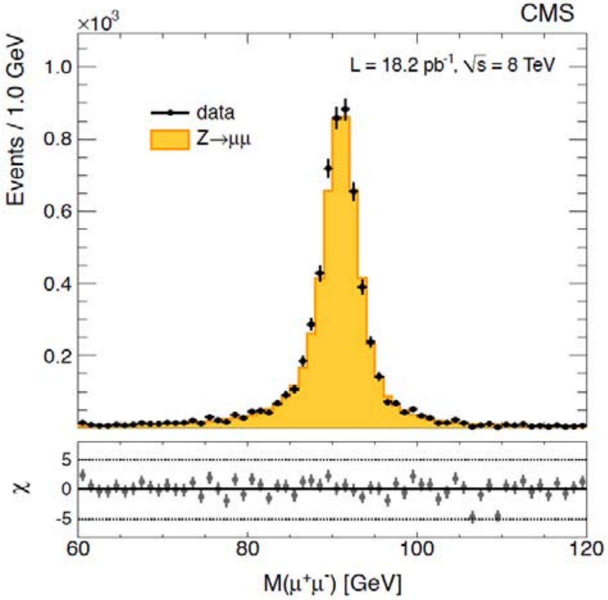
Note: the longitudinal component of the neutrino cannot be measured
→ only transverse mass can be reconstructed

Precision is limited by systematic effects (uncertainties on luminosity, parton densities,...)

First measurements of W/Z production at the LHC -CMS data from 2010: 36 pb^{-1} -

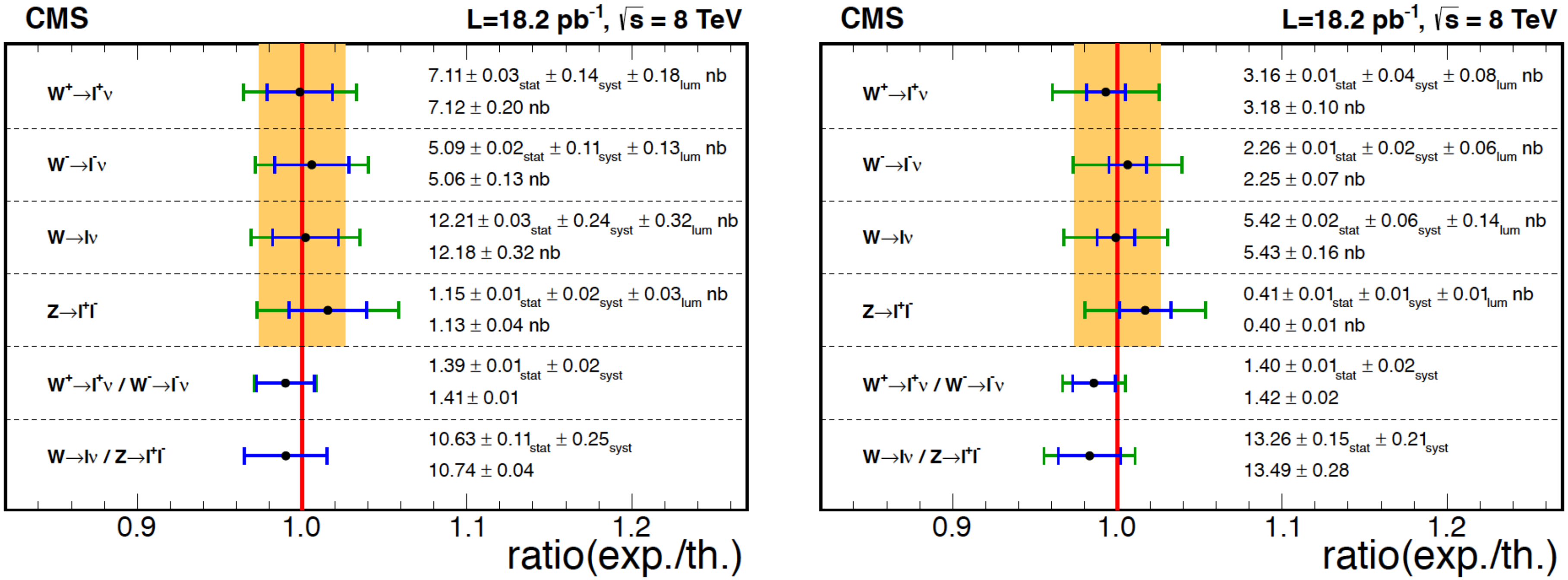


Distributions of the missing transverse energy, E_T^{miss}, of electron candidates for data and Monte-Carlo simulation, broken down into the signal and various background components.



Distributions of the invariant di-electron mass, m_{ee}, for events passing the Z selection. The data are compared to Monte-Carlo simulation, the background is very small.

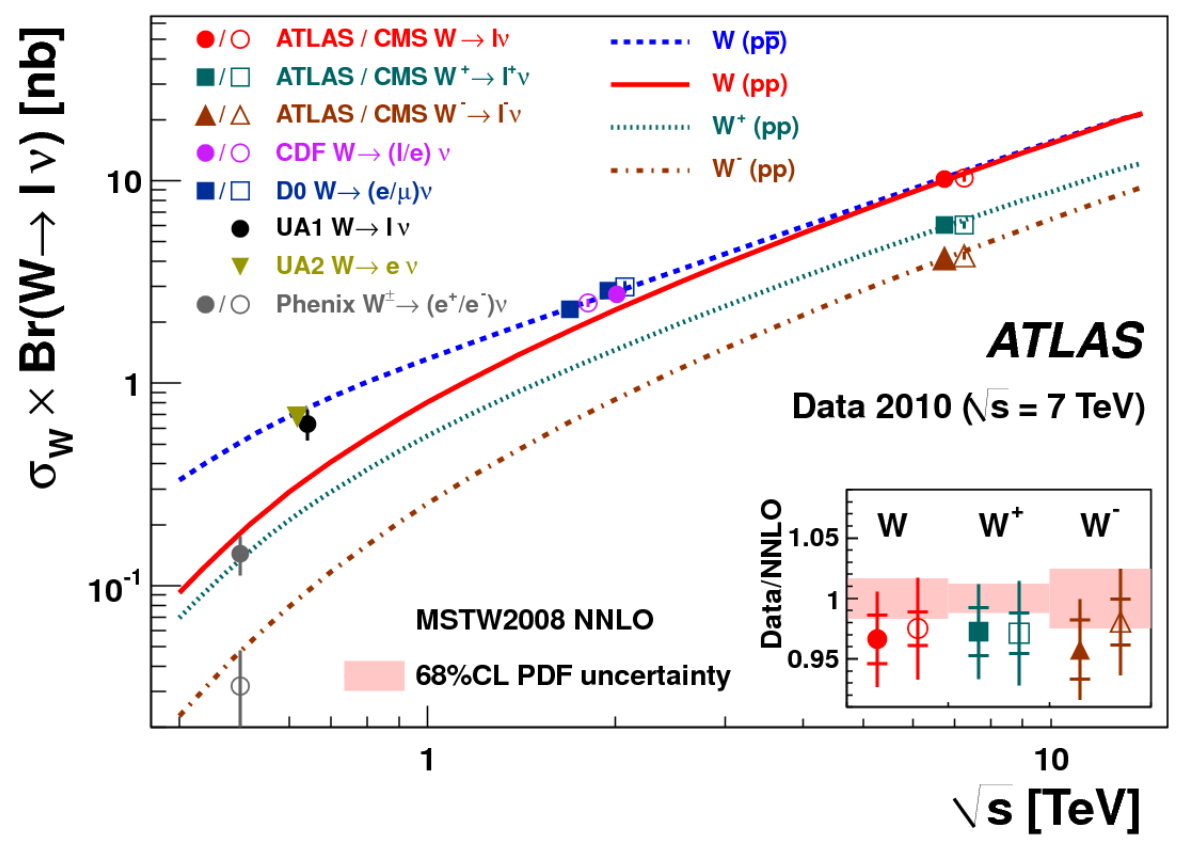
W and Z production cross sections at LHC



Summary of total (left) and fiducial (right) inclusive W^+, W^-, W, and Z production cross sections times branching fractions, W to Z and W^+ to W^- ratios, and their theoretical predictions. The shaded box indicates the uncertainties in the luminosity measurement. The inner error bars represent the experimental uncertainties, while outer error bars also include the uncertainties in the theoretical predictions. The individual measurements and theoretical predictions are given numerically on the right. The theoretical predictions of cross sections and cross section ratios are computed at NNLO with the program FEWZ and the MSTW2008 set of PDFs.

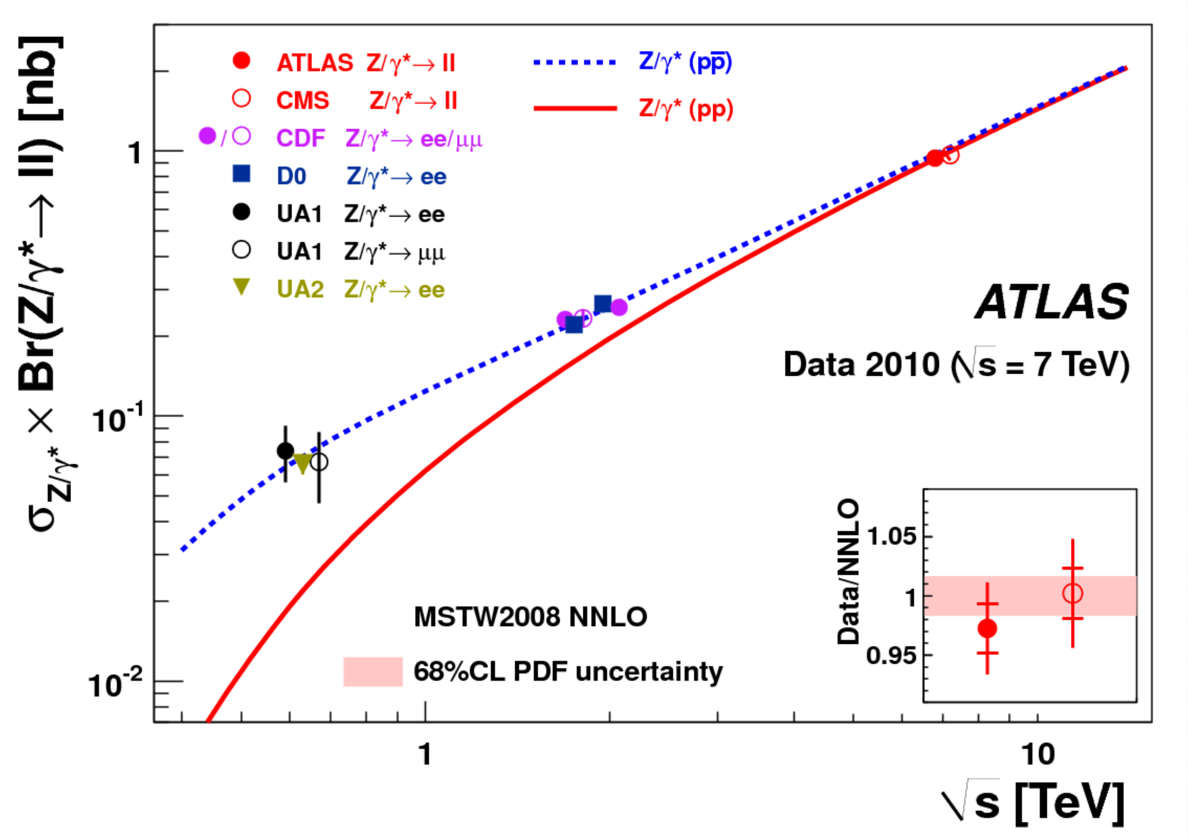
- Good agreement between data and NNLO QCD predictions for all measurements

W production cross sections at hadron colliders



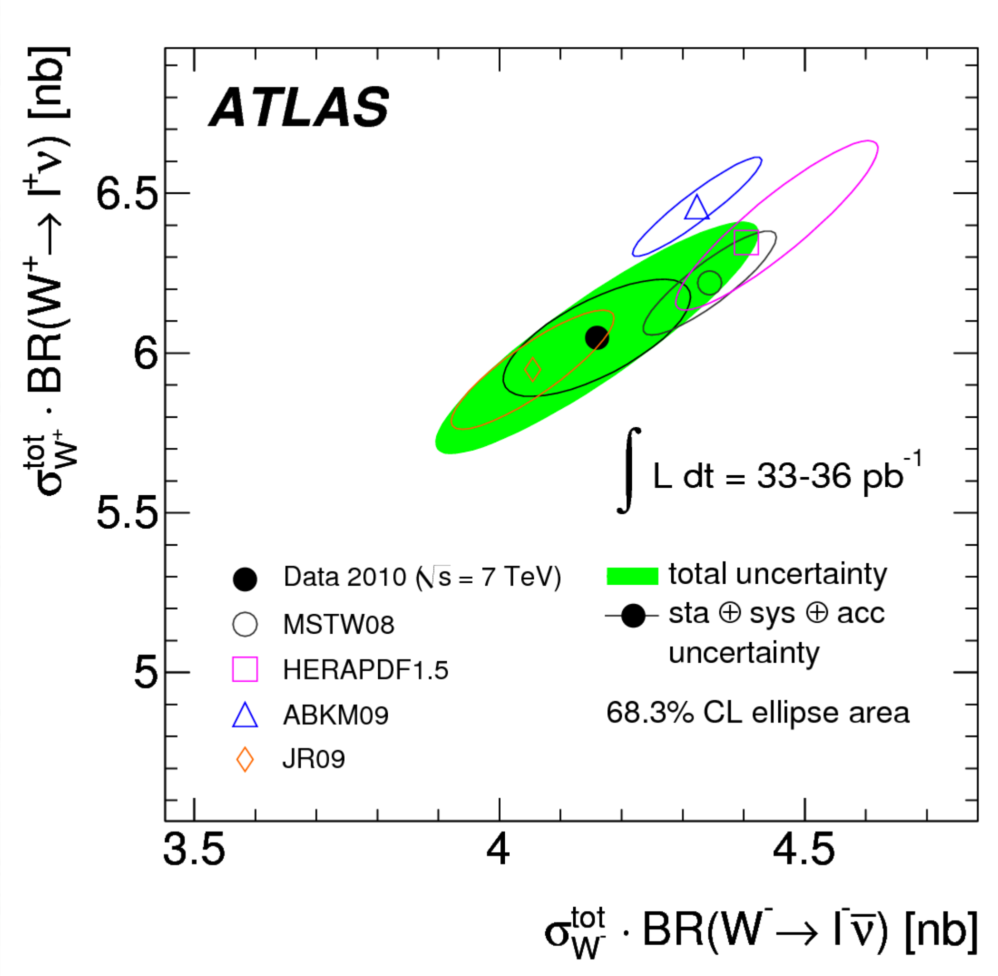
The measured values of σ(W) × BR(W -> lν) for W^+, W^- and for their sum compared to the theoretical predictions based on NNLO QCD calculations using the MSTW 2008 PDF set. Results are shown for the combined electron-muon results. The predictions are shown for both proton-proton (W^+, W^- and their sum) and proton-antiproton colliders (W) as a function of √s. In addition, previous measurements at proton-antiproton and proton-proton colliders are shown. The data points at the various energies are staggered to improve visibility. The CDF and D0 measurements are shown for both TeVatron collider energies, √s = 1.8 TeV and √s = 1.96 TeV. All data points in the main plot are displayed with their total uncertainty. The small inset shows the results at √s = 7 TeV for the ATLAS and CMS collaborations as ratio of measurement to NNLO prediction, where the inner error bars denote all but the luminosity uncertainty and the outer error bar the total uncertainty. Only in the insert the theoretical uncertainties are shown, where just the 68 per cent CL PDF errors of MSTW2008 are considered.

Z production cross sections at hadron colliders



The measured value of σ(Z/γ*) × BR(Z/γ* -> ll) where the electron and muon channels have been combined, compared to the theoretical predictions based on NNLO QCD calculations using the MSTW 2008 PDF set. The predictions are showns for both proton-proton and proton-antiproton colliders as a function of √s. In addition, previous measurements at proton-antiproton colliders are shown. The data points at the various energies are staggered to improve readability. The CDF and D0 measurements are shown for both Tevatron collider energies, √s = 1.8 TeV and √s = 1.96 TeV. All data points in the main plot are displayed with their total uncertainty. The small inset shows the results at √s = 7 TeV for the ATLAS and CMS collaborations as ratio of measurement to NNLO prediction, where the inner error bars denote all but the luminosity uncertainty and the outer error bar the total uncertainty. Only in the insert the theoretical uncertainties are shown, where just the 68 per cent CL PDF errors of MSTW2008 are considered. Note also, that various measurements were performed in slightly different invariant mass ranges, while the prediction is for 66 < m(ll) < 116 GeV. The difference are on the order of a few % and not visible on the double-log scale. For the small insert the CMS result is divided by the appropriate prediction for the invariant mass range of the measurement, which was 60 < m(ll) < 120 GeV.

W cross sections at the LHC, charge separated

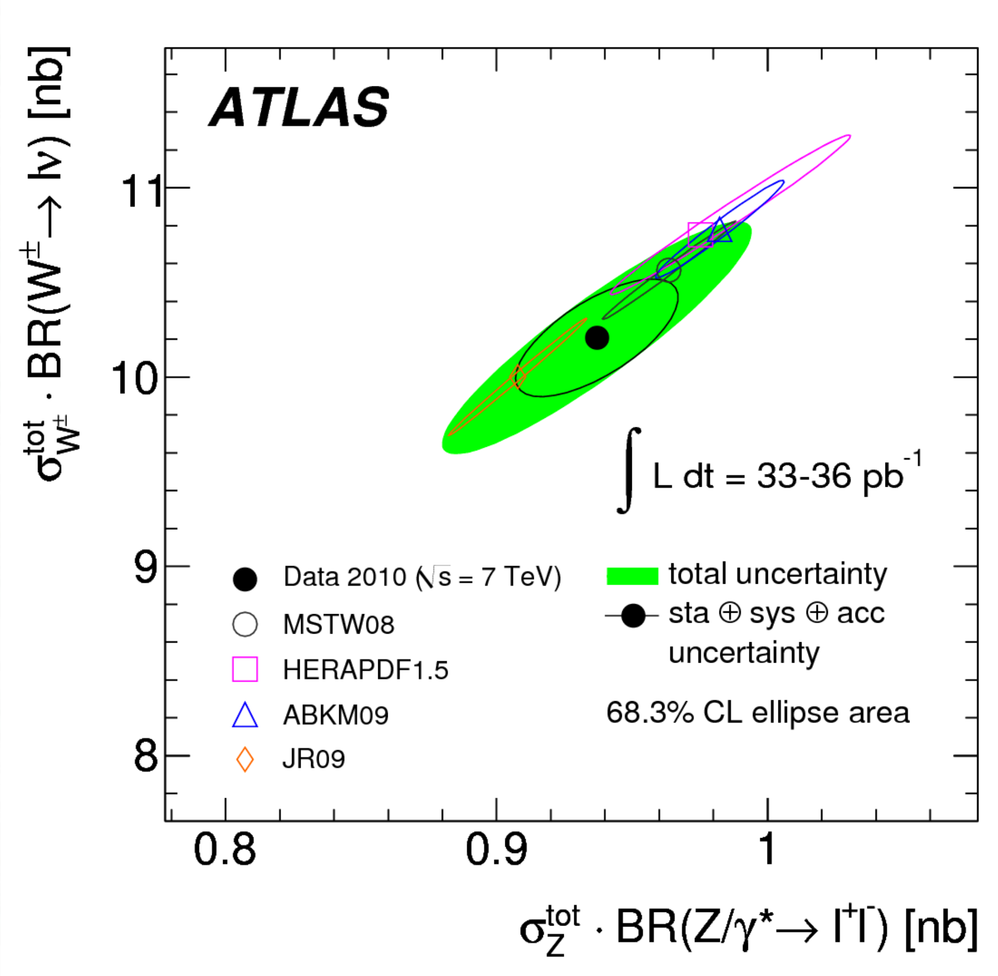


Full ATLAS data set from 2010

L = 36 pb^{-1}

Measured and predicted total cross sections times leptonic branching ratios, $\sigma(W^+)$ vs $\sigma(W^-)$. The ellipses illustrate the 68 per cent CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions correspond to the PDF uncertainties only.

W cross sections at the LHC, charge separated

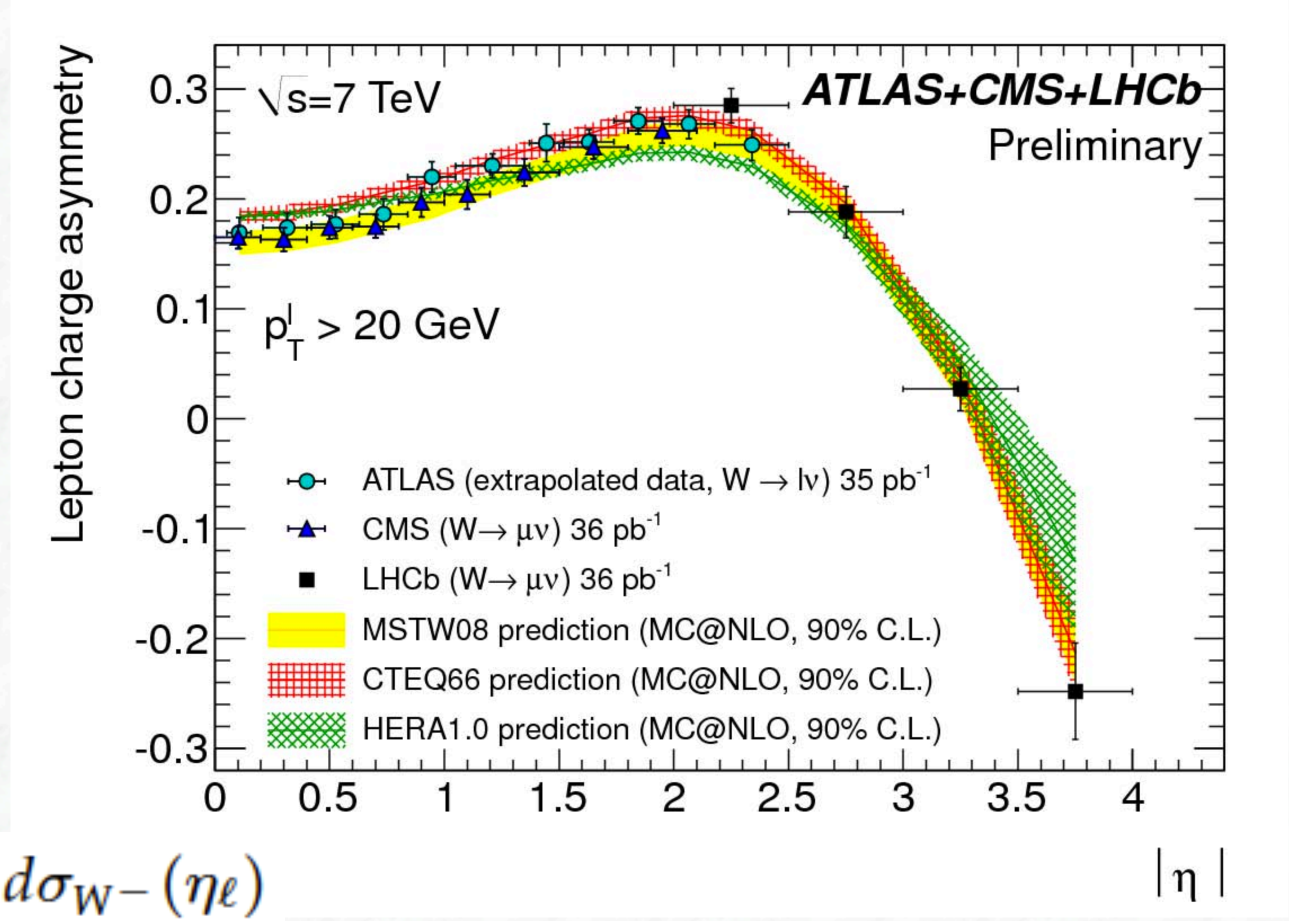


Full ATLAS data set from 2010

L = 36 pb^{-1}

Measured and predicted total cross sections times leptonic branching ratios, ($\sigma(W^+) + \sigma(W^-)$) vs. $\sigma(Z/\gamma^*)$. The ellipses illustrate the 68 per cent CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions correspond to the PDF uncertainties only.

W charge asymmetry as a function of pseudorapidity

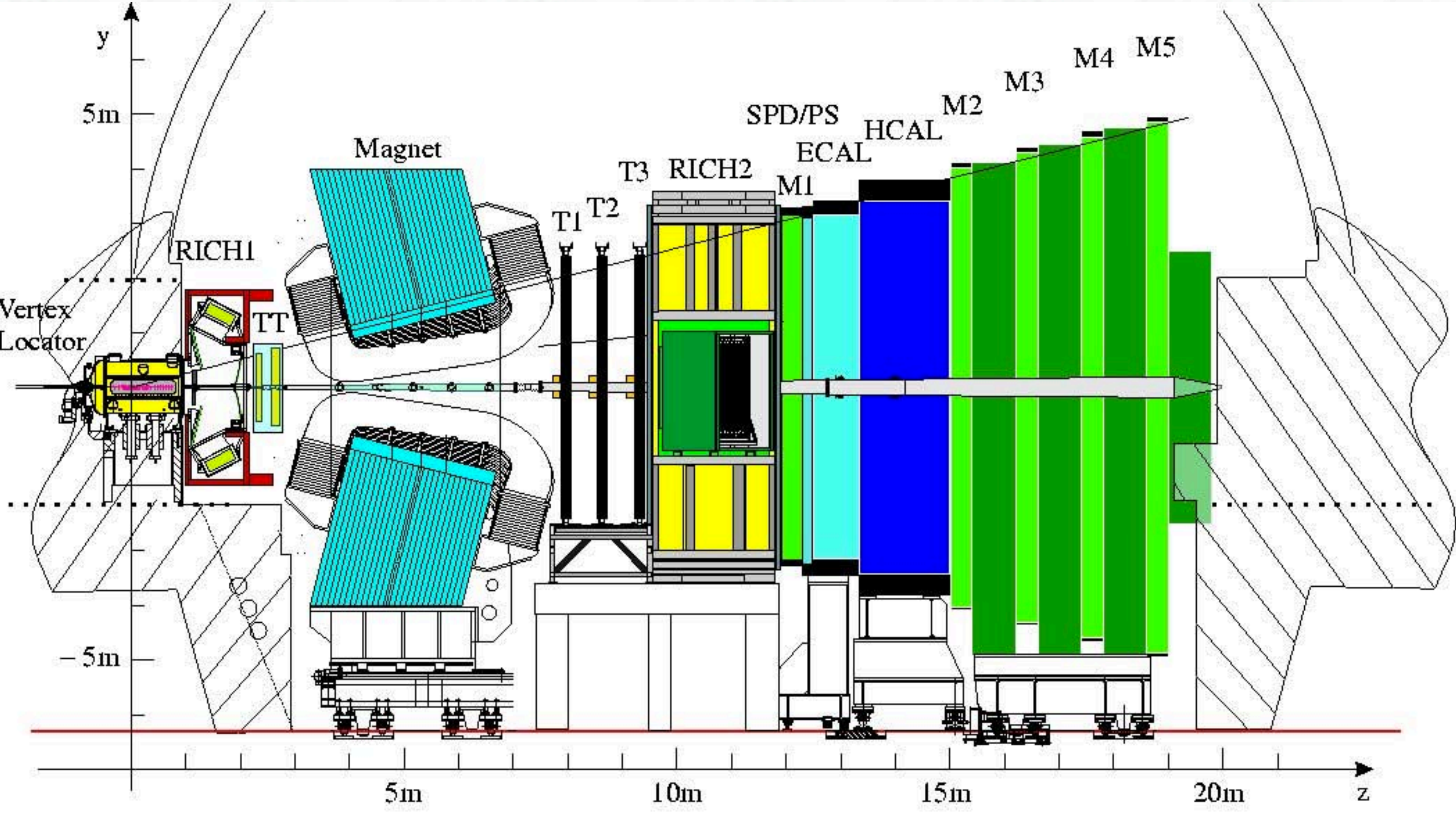


$$A(\eta_\ell) = \frac{d\sigma_{W+}(\eta_\ell) - d\sigma_{W-}(\eta_\ell)}{d\sigma_{W+}(\eta_\ell) + d\sigma_{W-}(\eta_\ell)}$$

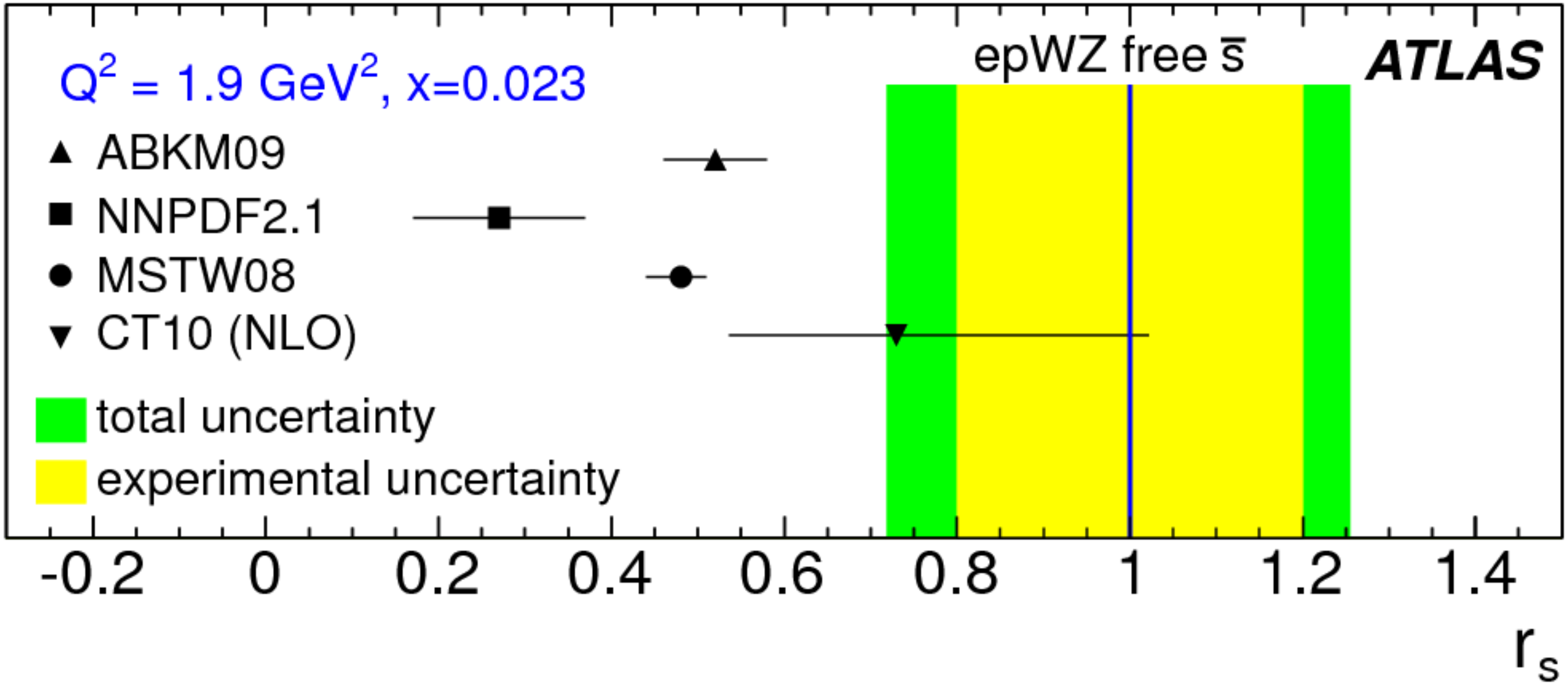
- Sensitive to valence quark $(u\bar{d} \to W^+ / d\bar{u} \to W^-)$
- Usable to constrain u_v/d_v at low x

The lepton charge asymmetry from W-boson decays in bins of absolute pseudorapidity for the three different experiments ATLAS, CMS and LHCb.

Reminder: The LHCb Detector



Extraction of strange-quark denisity

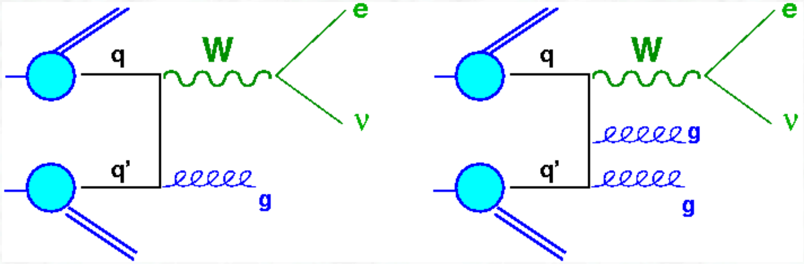


$$r_s = 0.5(s+\bar{s})/\bar{d}$$

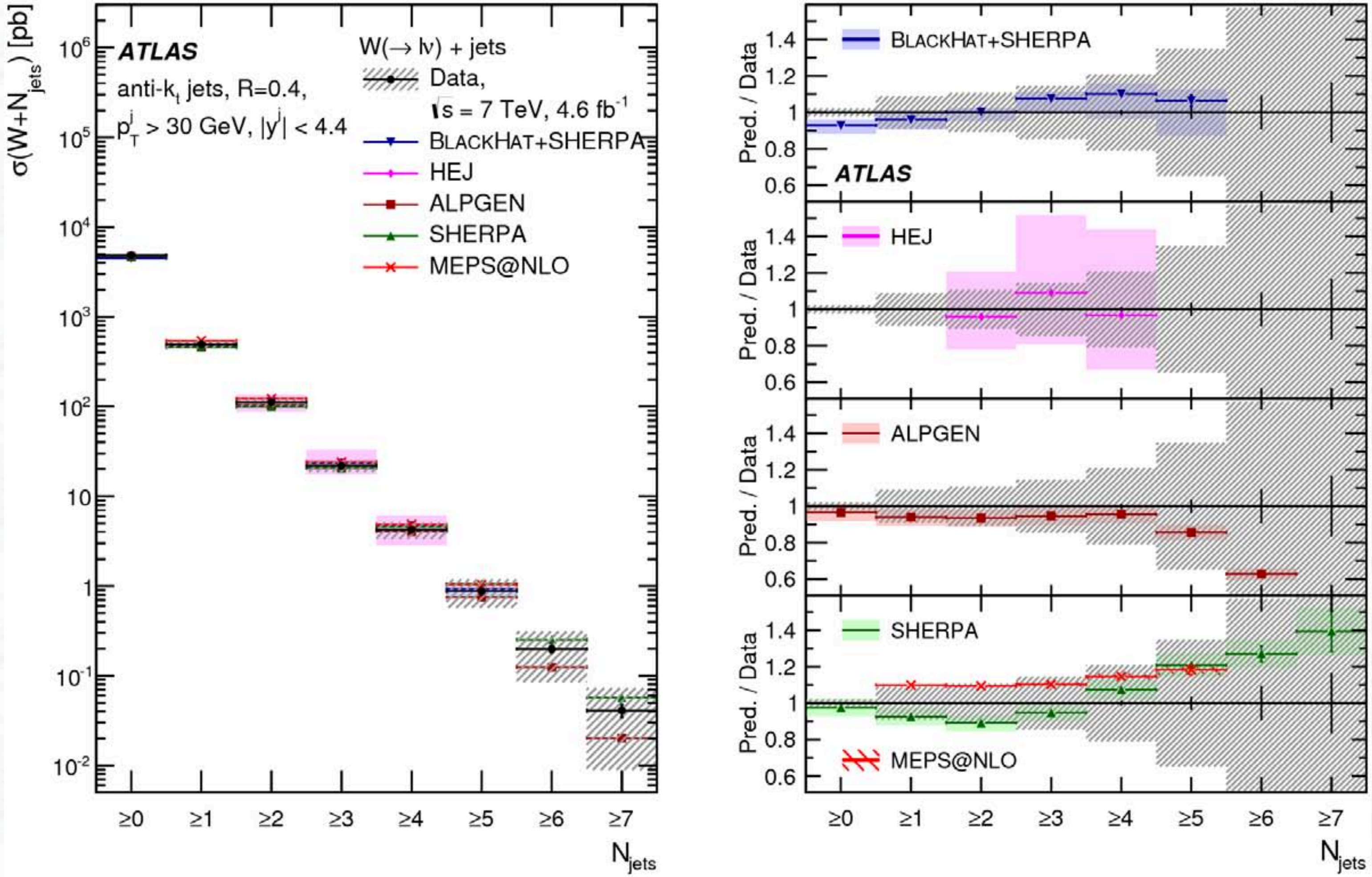
Little is known about strange quark density

- Flavor SU(3) suggests equal (*u*, *d*, *s*) in sea
- $m_s > m_{u,d}$; flavor SU(3) not exact symmetry
- *s* suppression assumed in many PDFs because of *s* mass (r_s ~ 0.5)

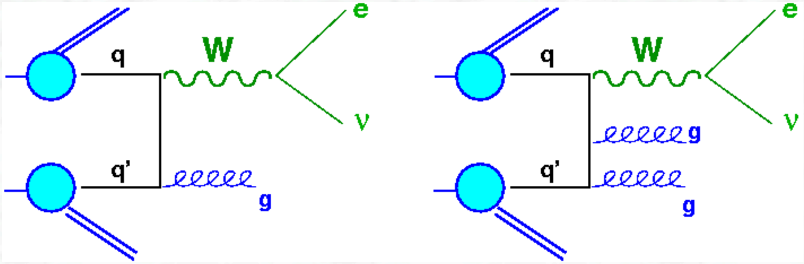
Test of QCD in W/Z + jet production



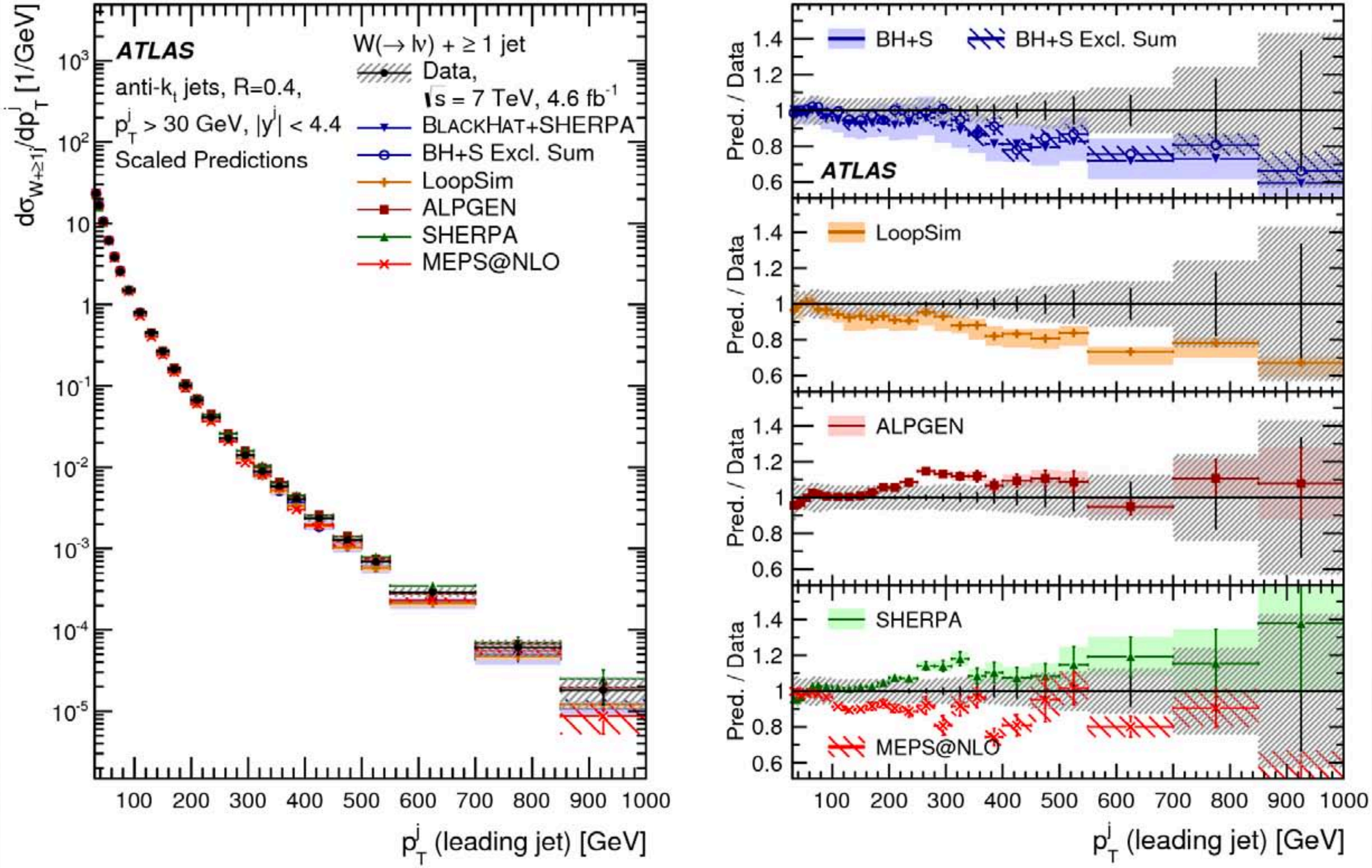
- Very large statistical power
- Agreement with several NLO and multi-lep predictions



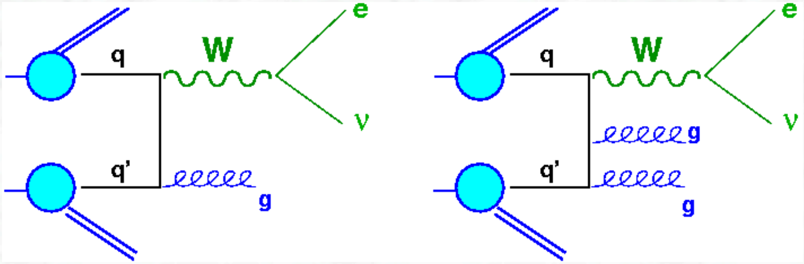
Test of QCD in W/Z + jet production



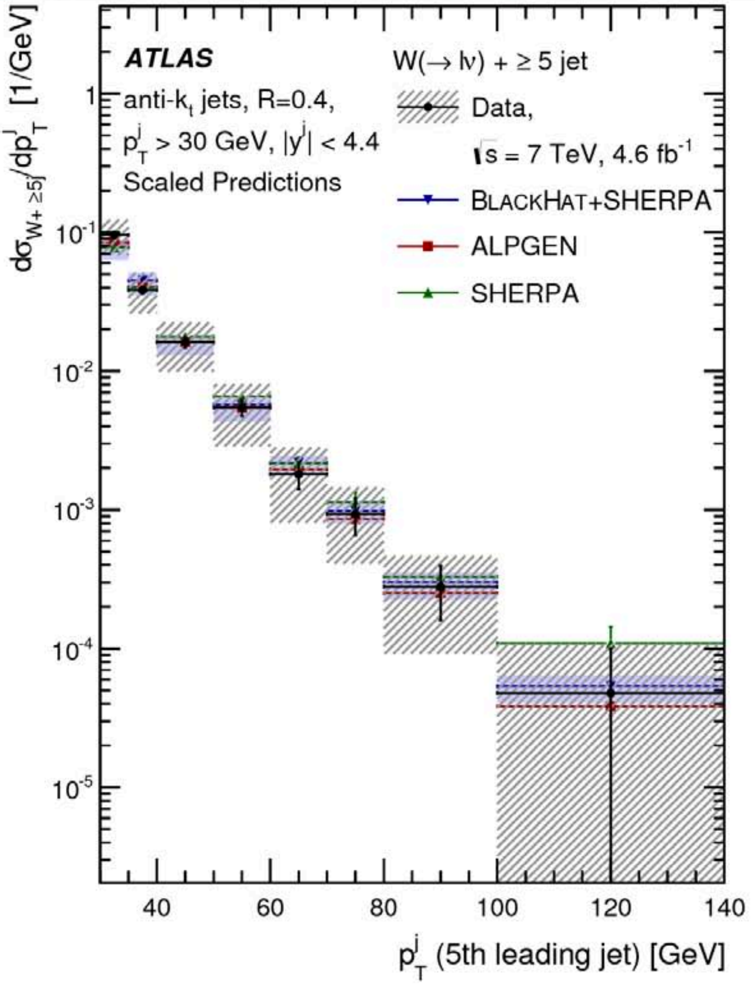
- Very large statistical power
- Agreement over many orders of magnitude

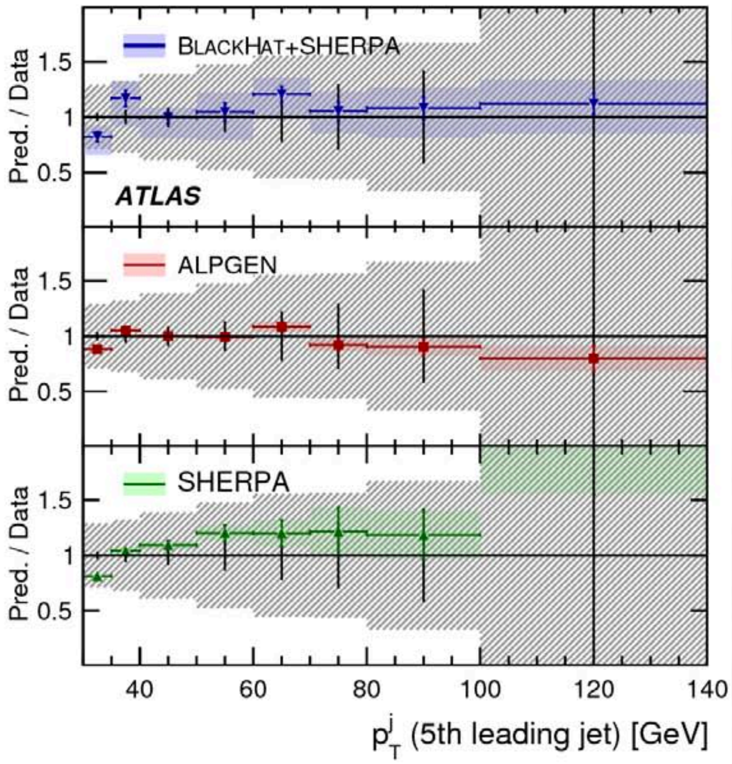


Test of QCD in W/Z + jet production



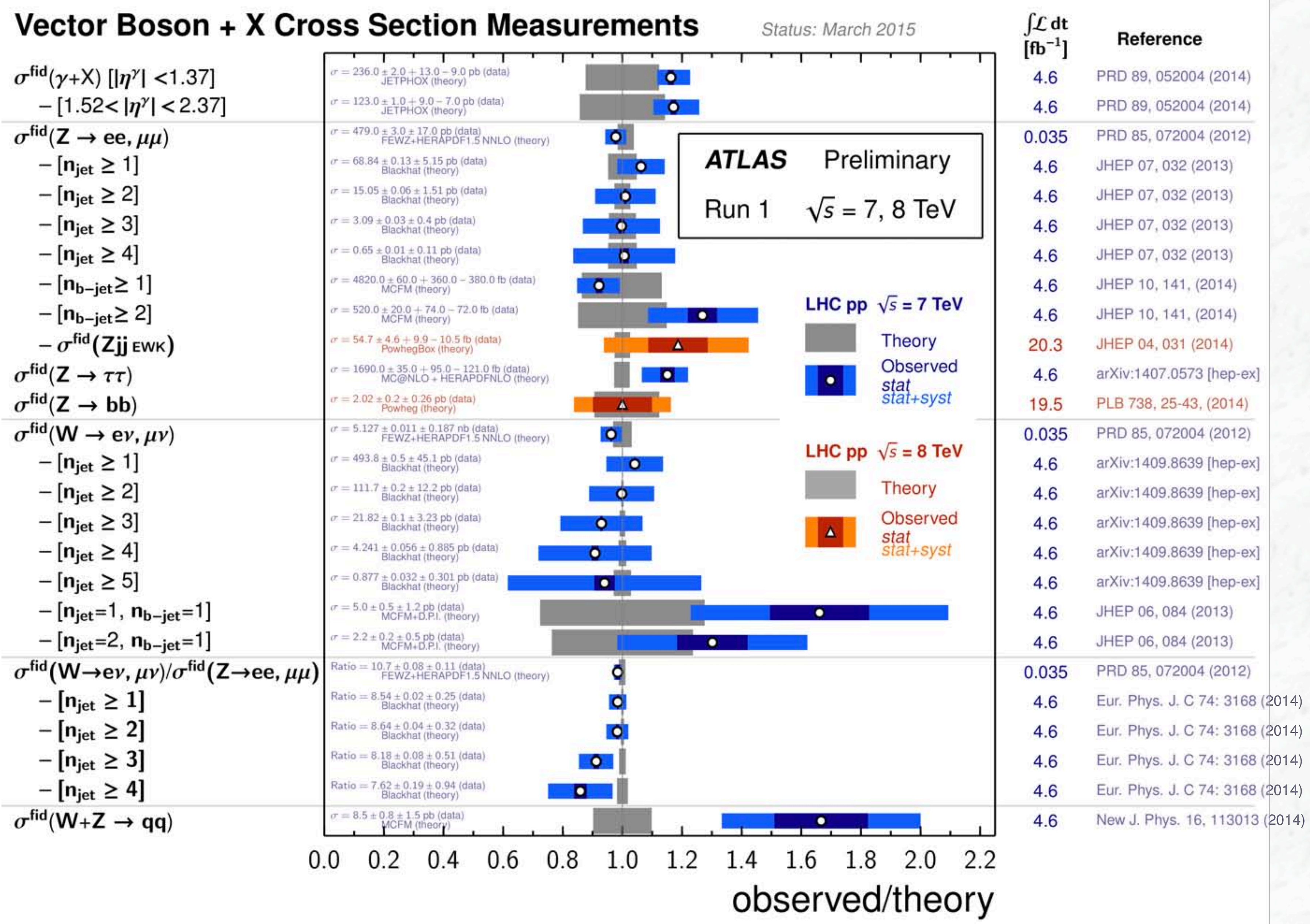
- Very large statistical power
- Agreement over many orders of magnitude



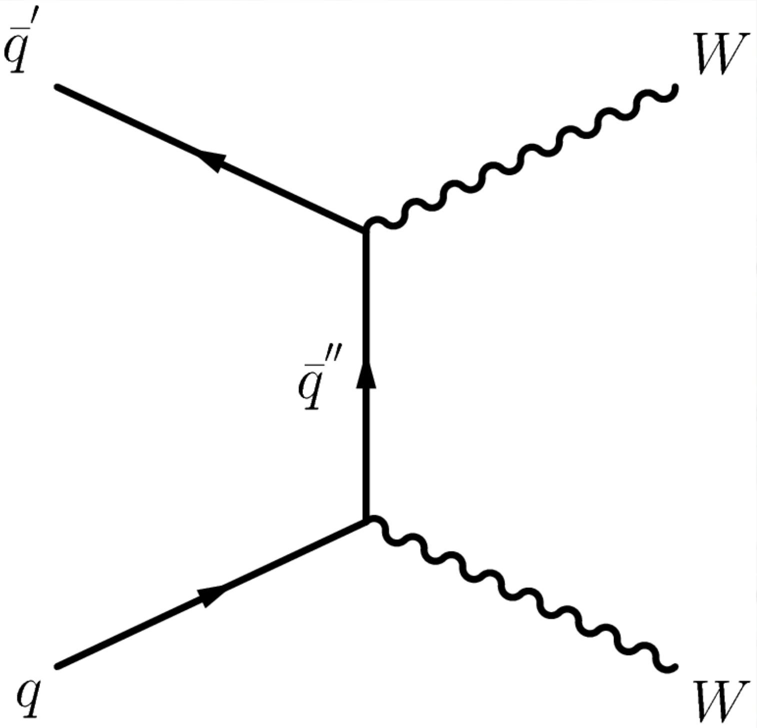


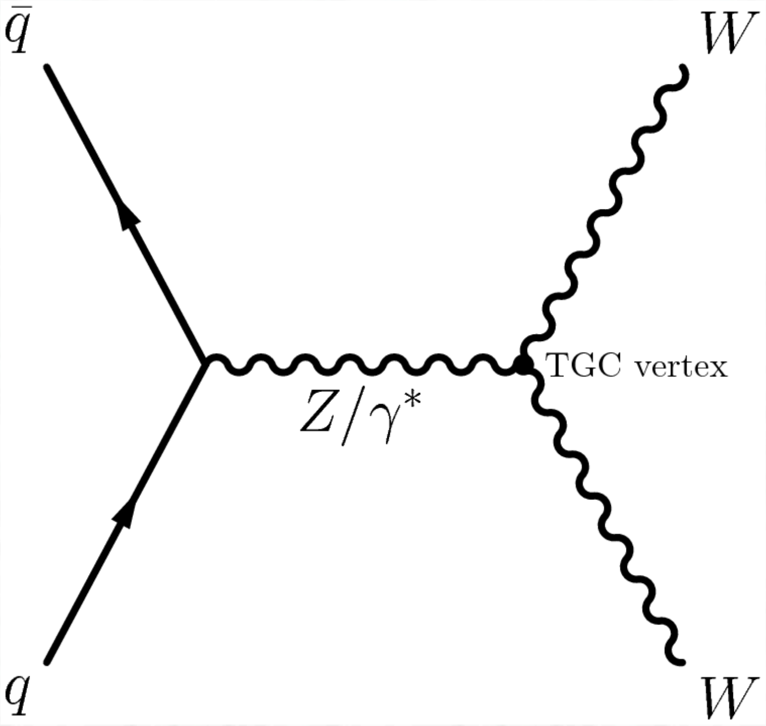
Both jet rates and p_T spectra are well described by perturbative QCD calculations

Summary of W/Z (+jets) measurements



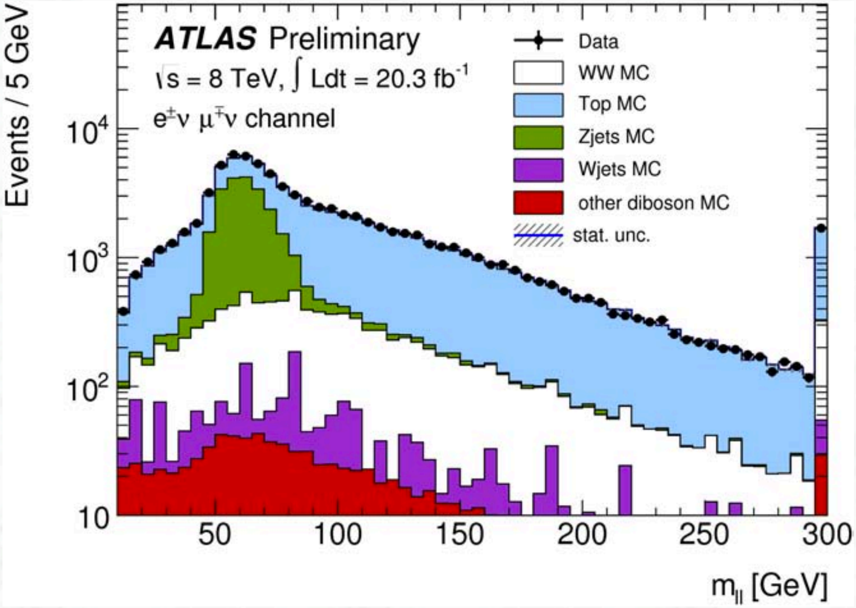
6.5 Di-boson measurements

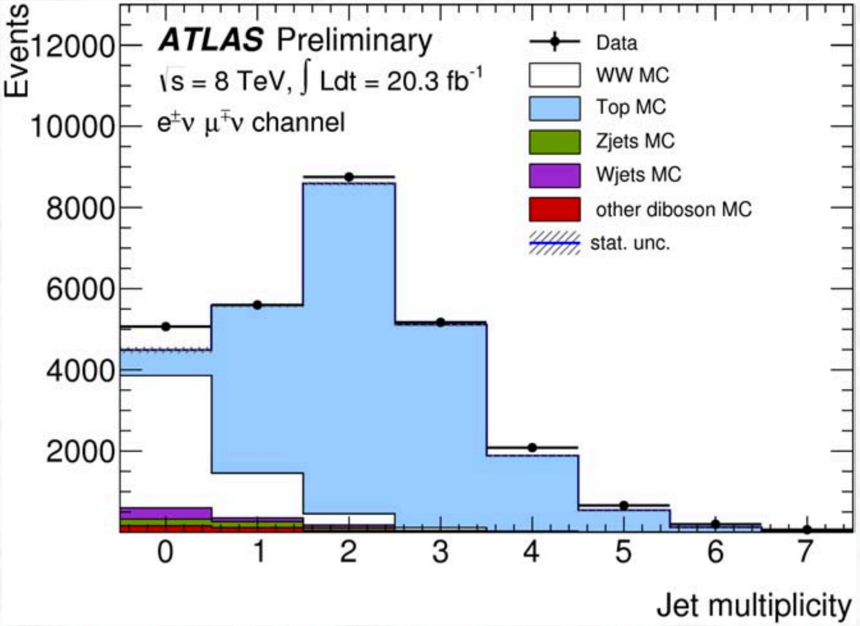


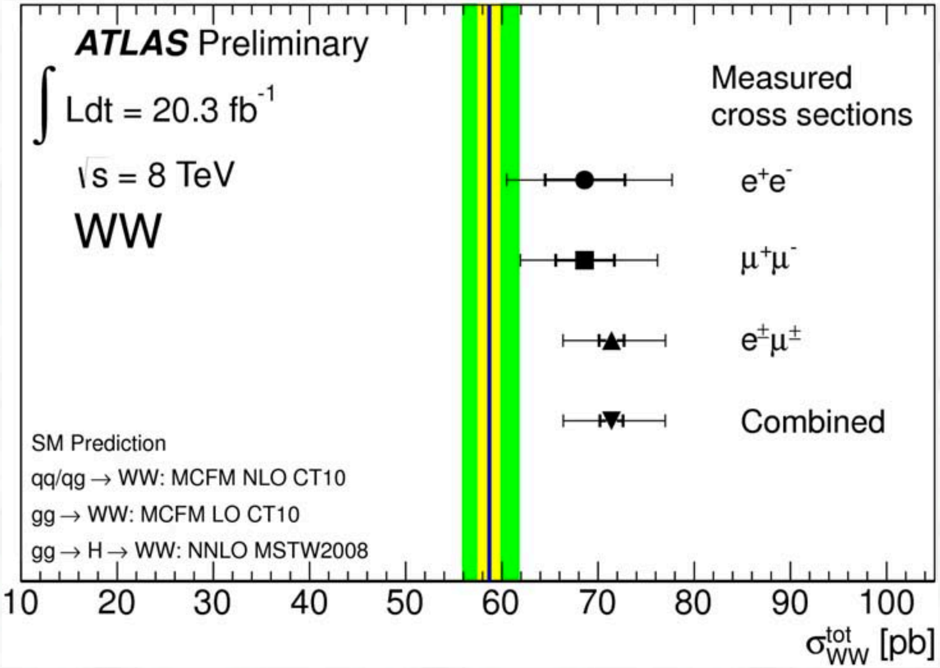


WW Production

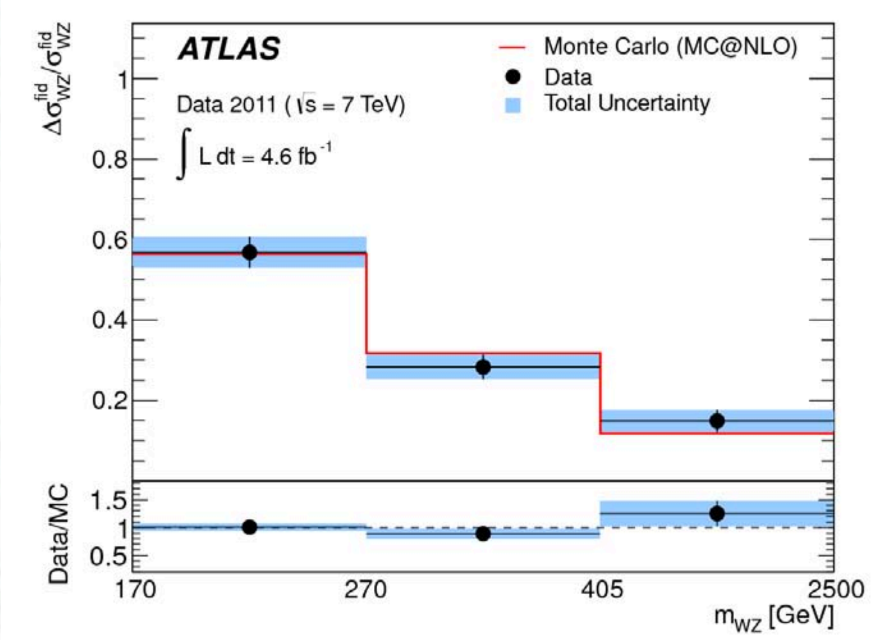
- **Cross section measurement only in 0-jet bin**
- **Result is factor 1.21 higher than NLO prediction; but not significant**
- **Newer calculations seem to (partially) reconcile this**
- **Measure also 1-jet bin in the future**

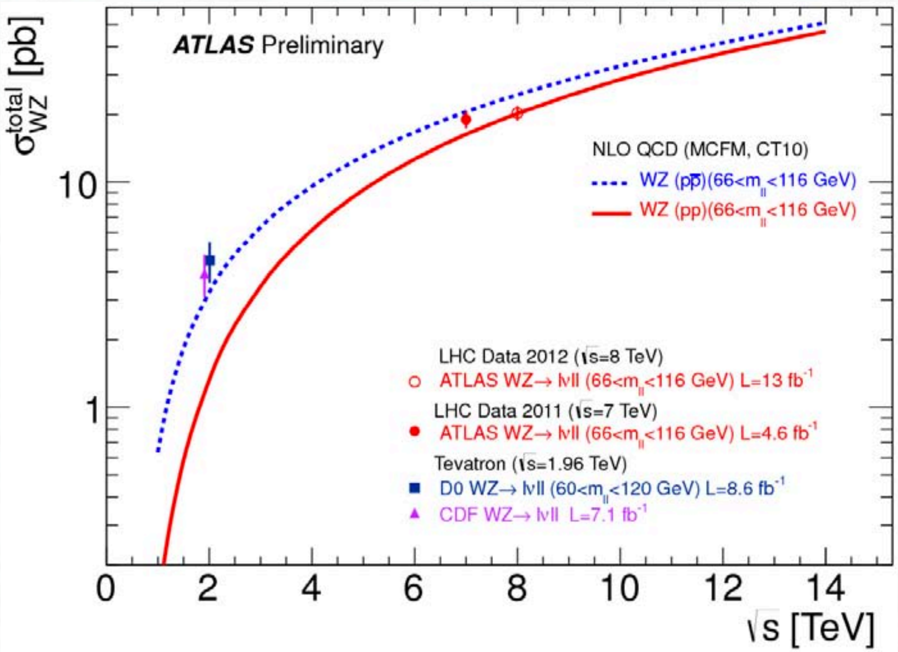


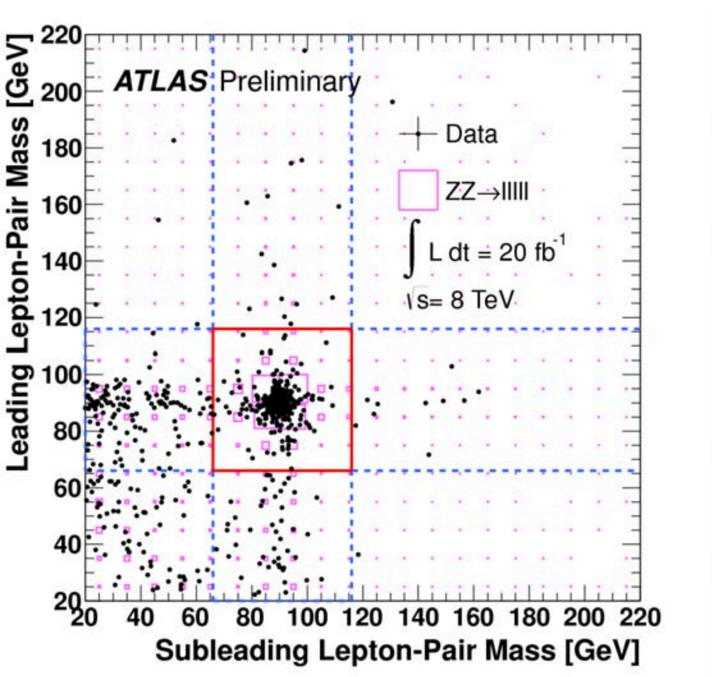


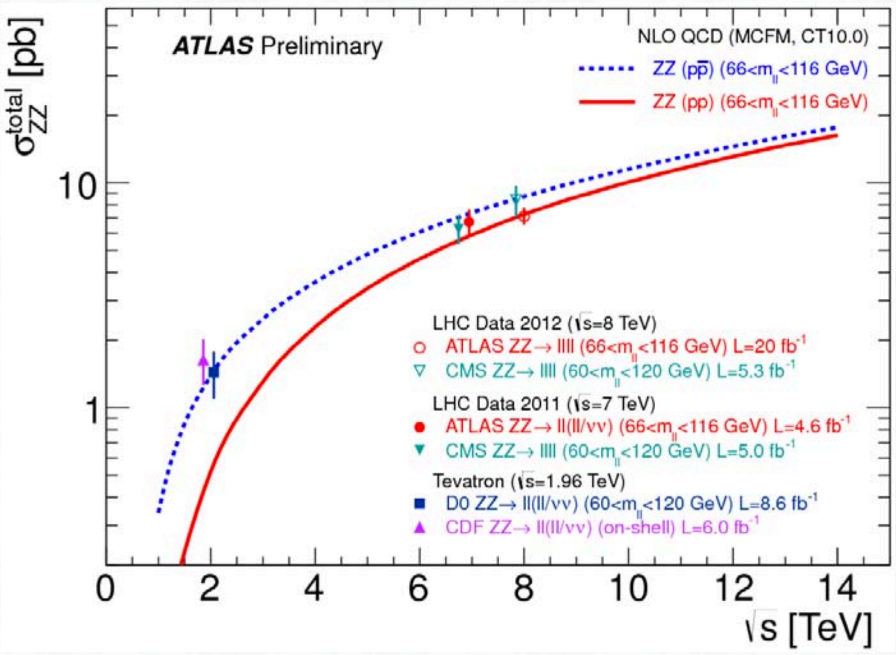


WZ and ZZ cross-sections

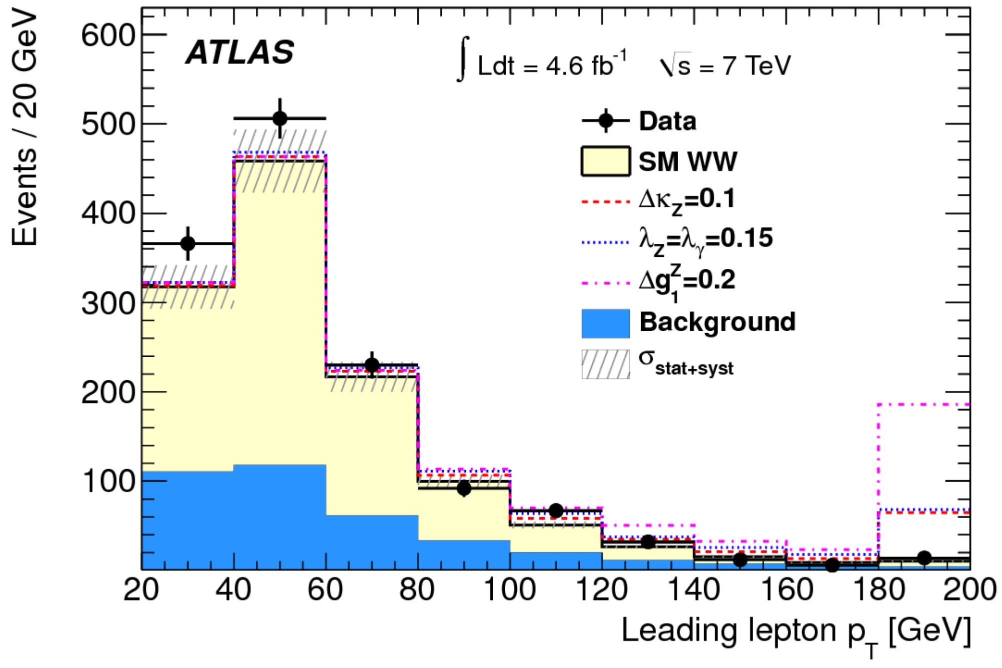


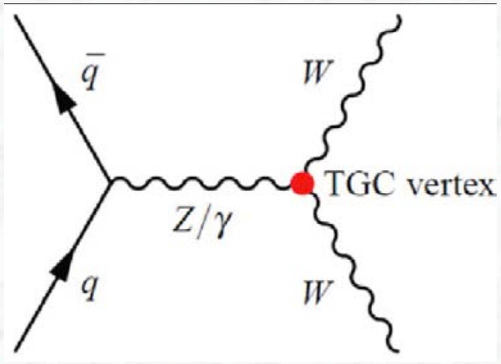


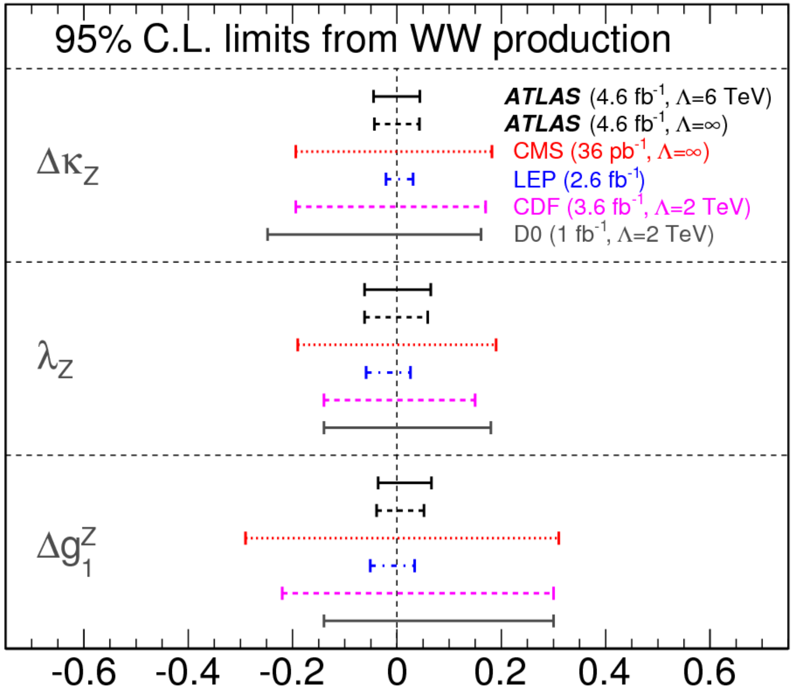




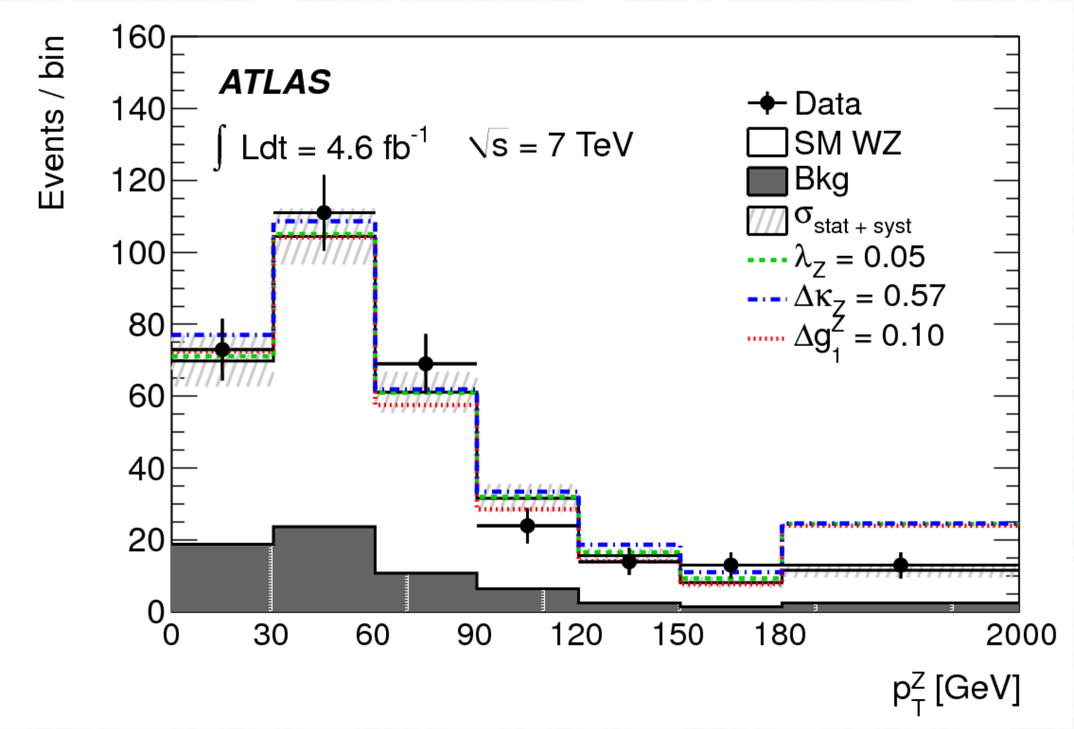
Limits on anomalous couplings: **WW**

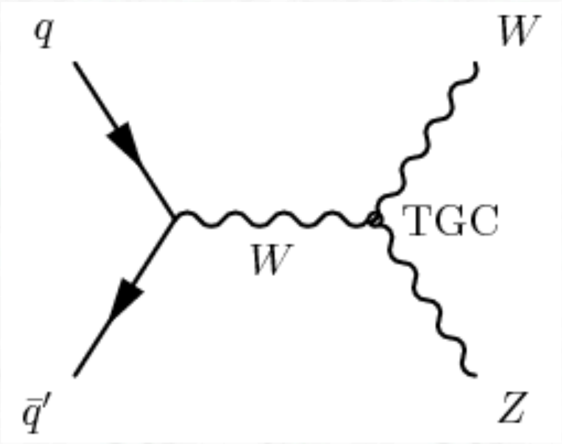


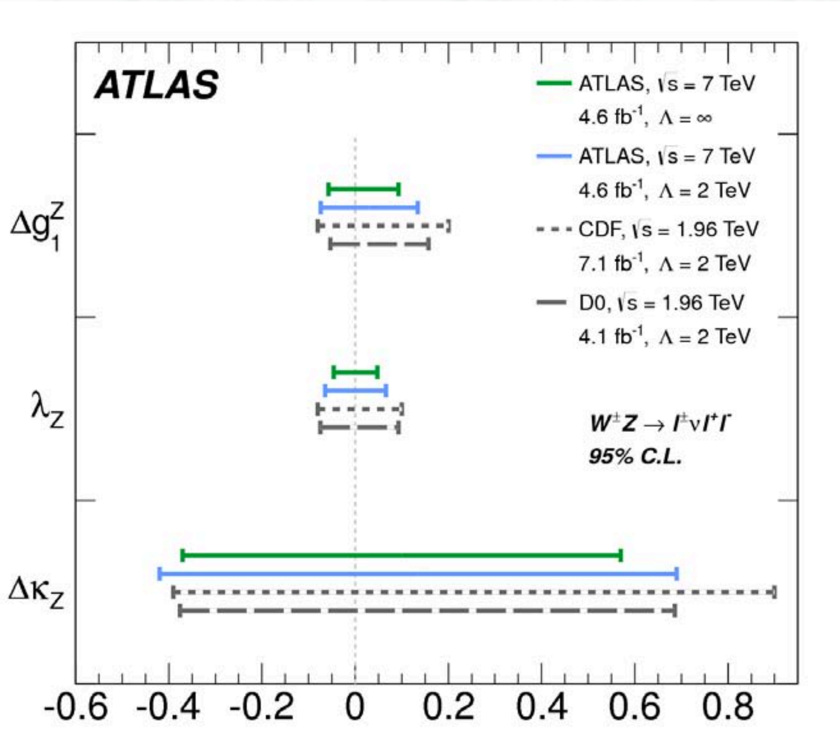




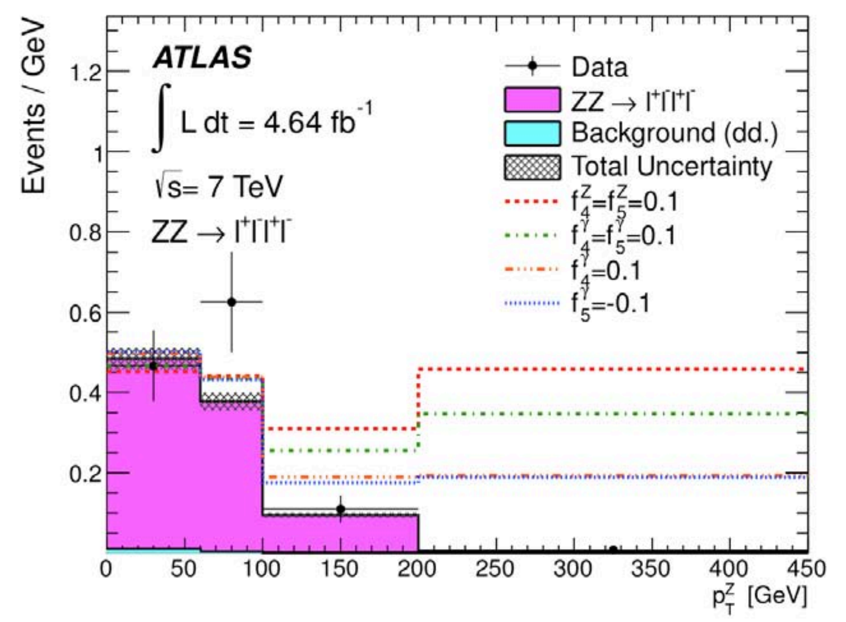
Limits on anomalous couplings: **WZ**

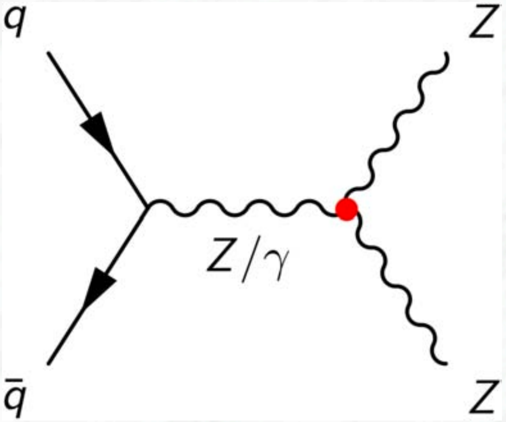


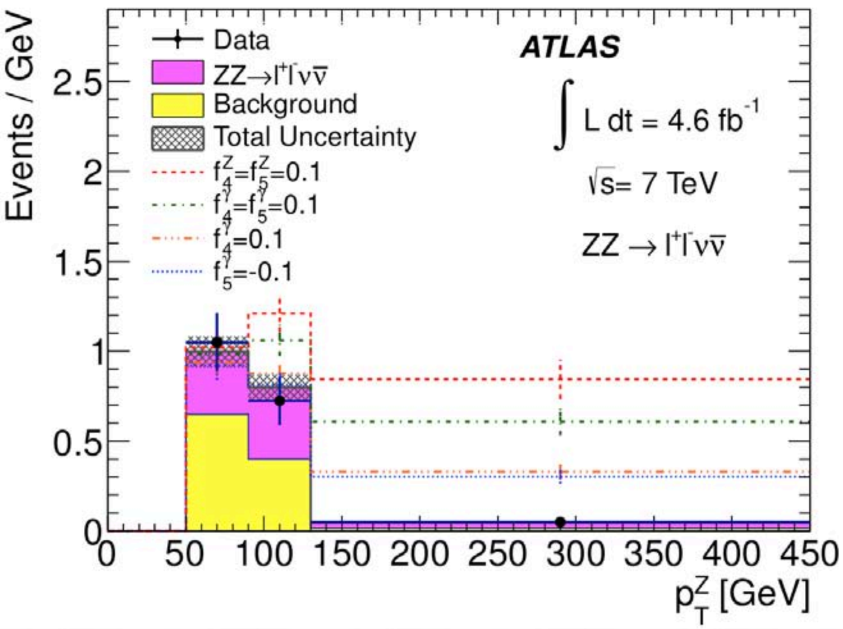


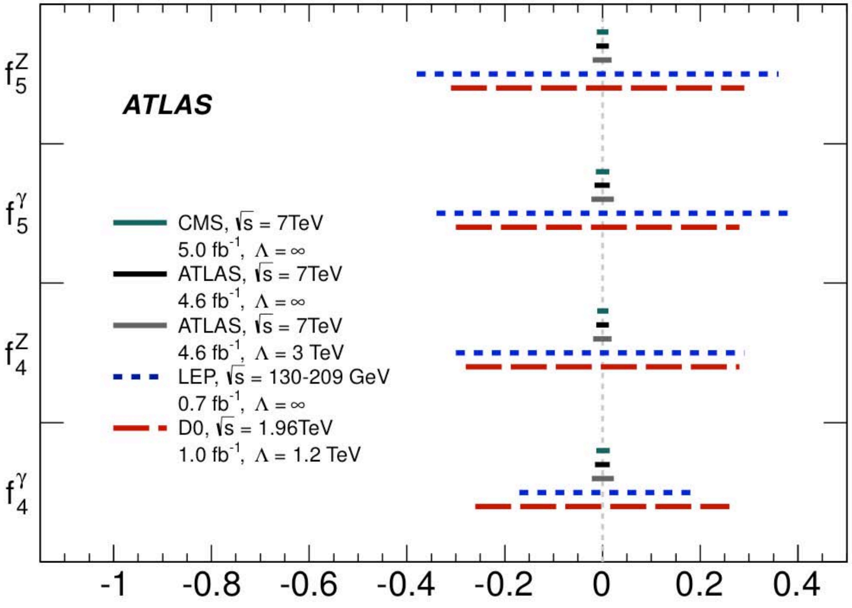


Limits on anomalous couplings: **ZZ**

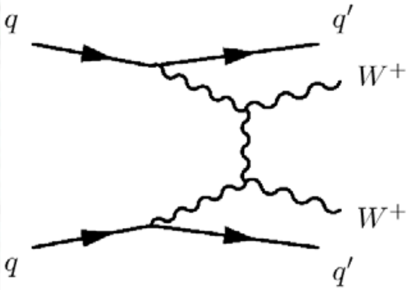


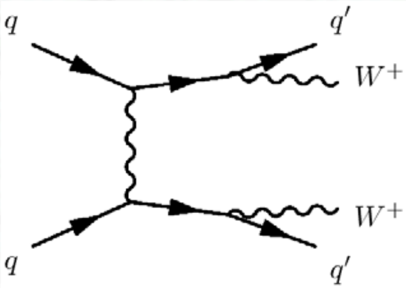


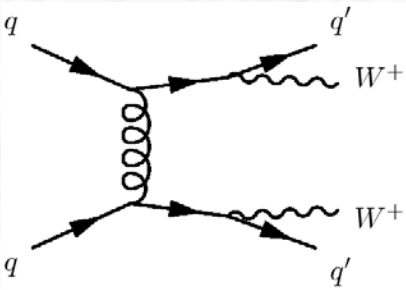


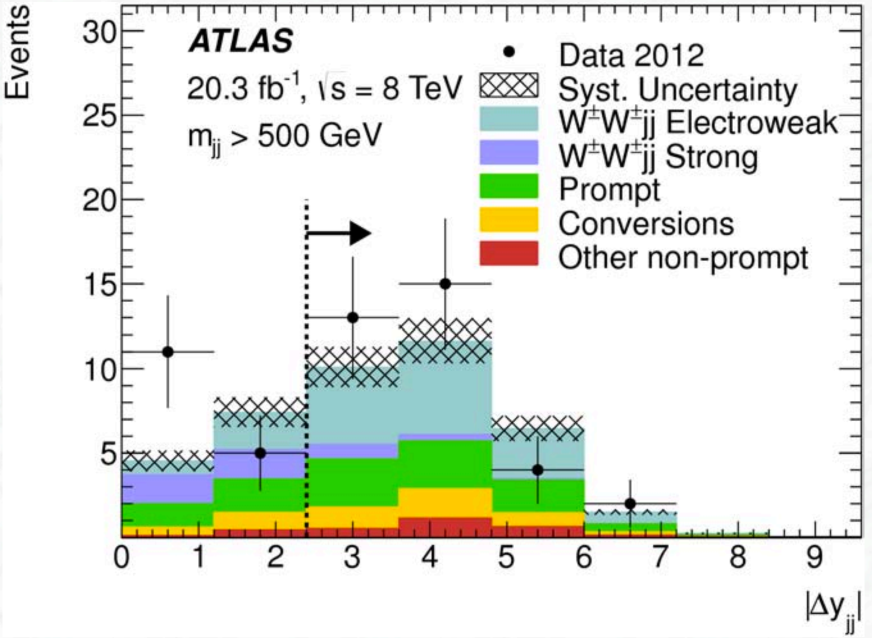


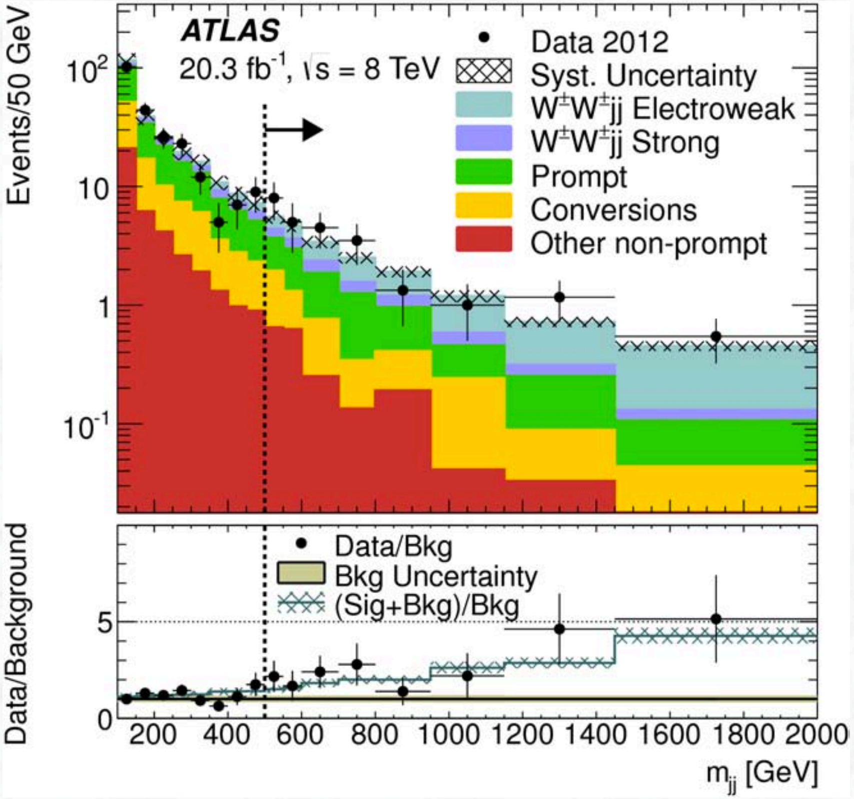
Electroweak production of W^+W^+jj

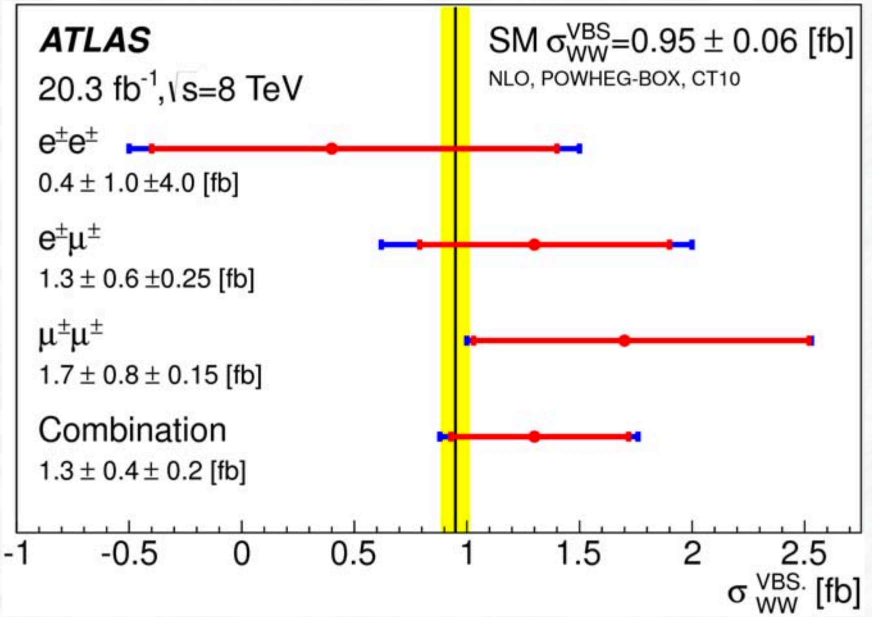






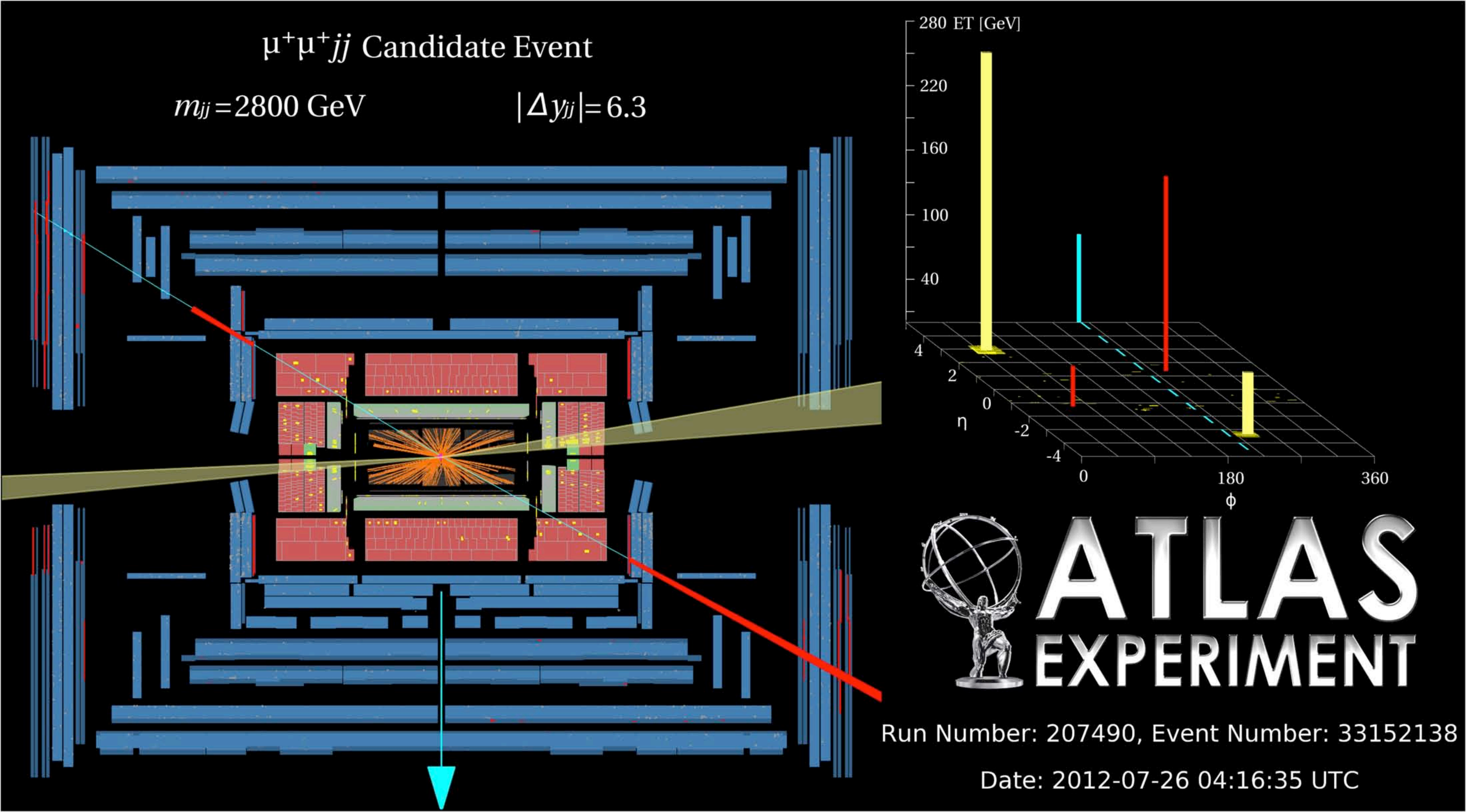






$\mu^+\mu^+jj$ Candidate Event

$m_{jj} = 2800$ GeV $\qquad |\Delta y_{jj}| = 6.3$

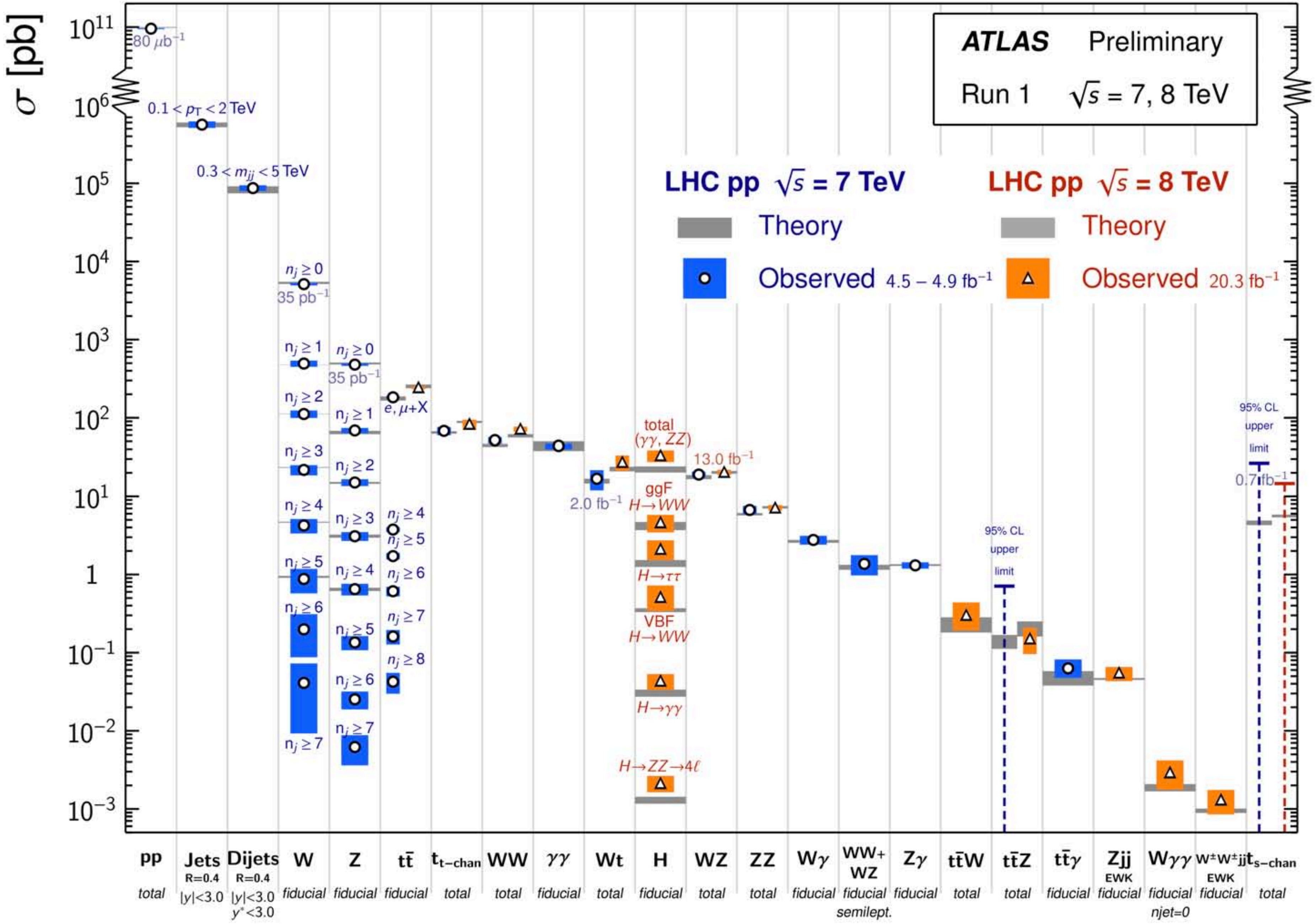


Run Number: 207490, Event Number: 33152138

Date: 2012-07-26 04:16:35 UTC

Standard Model Production Cross Section Measurements

Status: March 2015



6.6 W mass measurement

Major contributions: LEP-II, direct mass reconstruction

Hadron collider: Tevatron and LHC (in the future)

Precision measurements of m_W and m_{top}

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

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

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

Fermi constant
measured in muon
decay

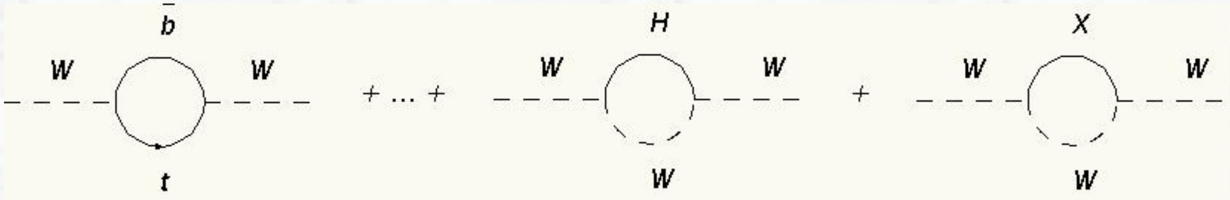
weak mixing angle
measured at
LEP/SLC

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

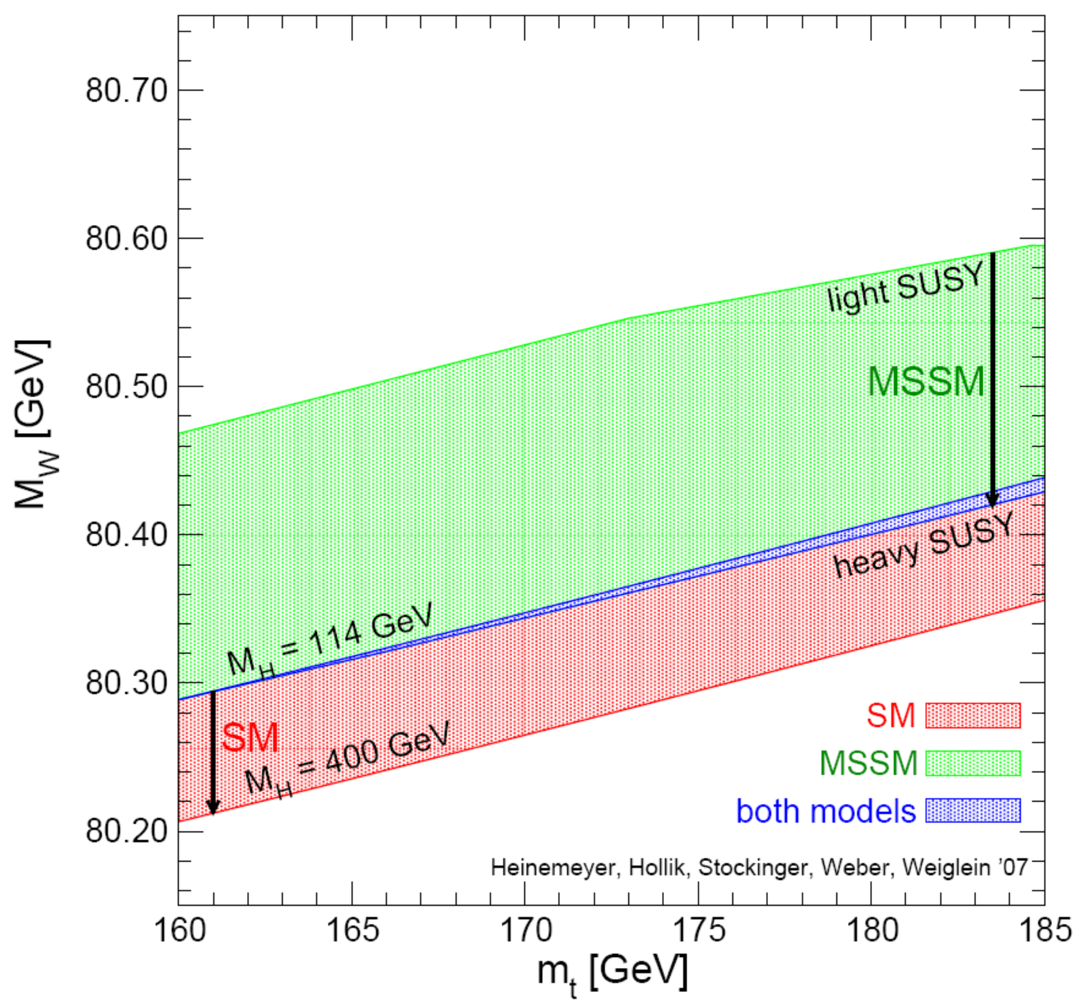
G_F, α_{EM}, $\sin\theta_W$

are known with high precision

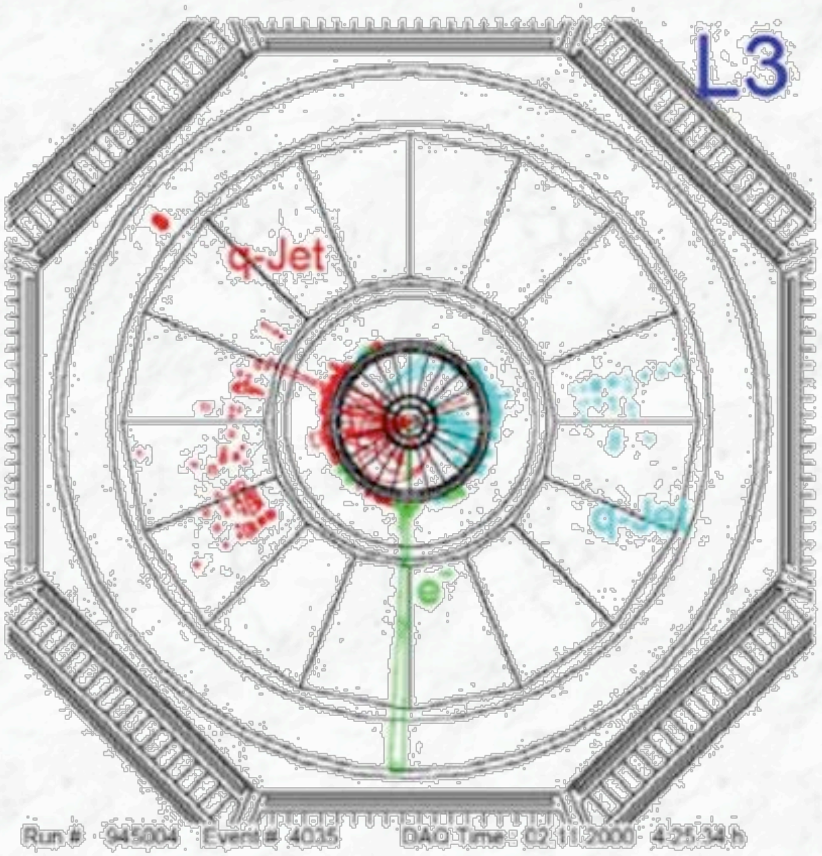
Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass
(and/or the theory,
radiative corrections)



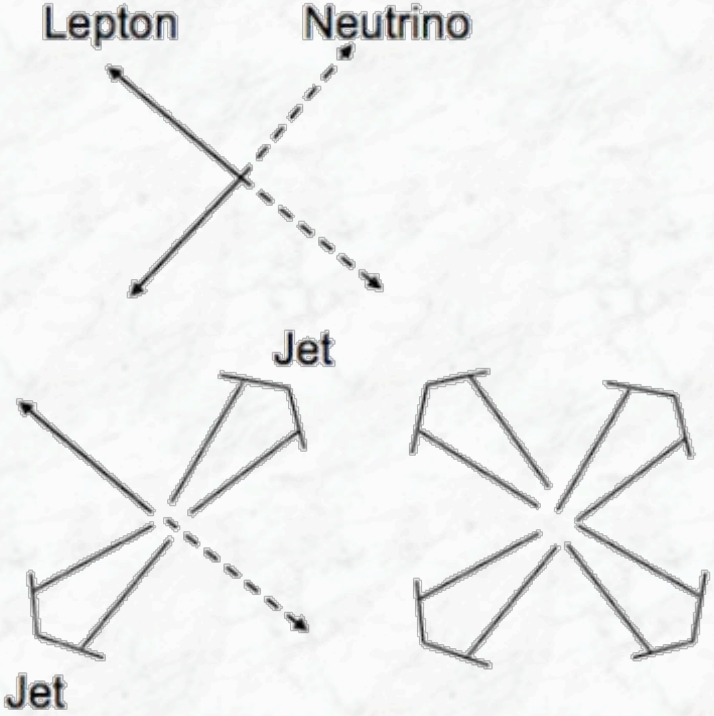
Relation between m_W, m_t, and m_H



W bosons at LEP – II

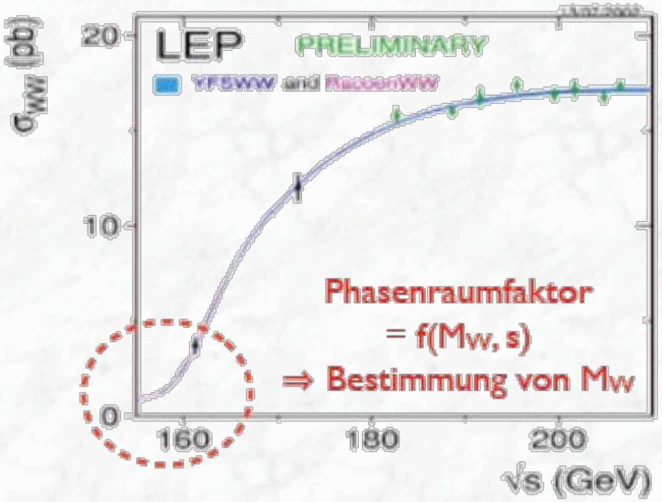


$$WW \rightarrow \begin{cases} qq\ell\nu & 44\% \\ qqqq & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$



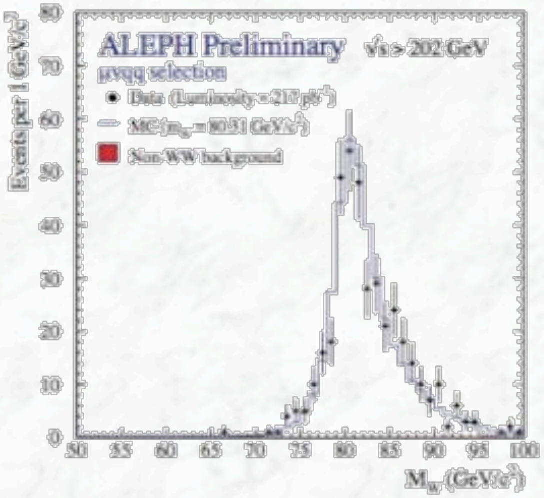
W mass measurement

(1) Messung des WQs an der WW-Produktionsschwelle

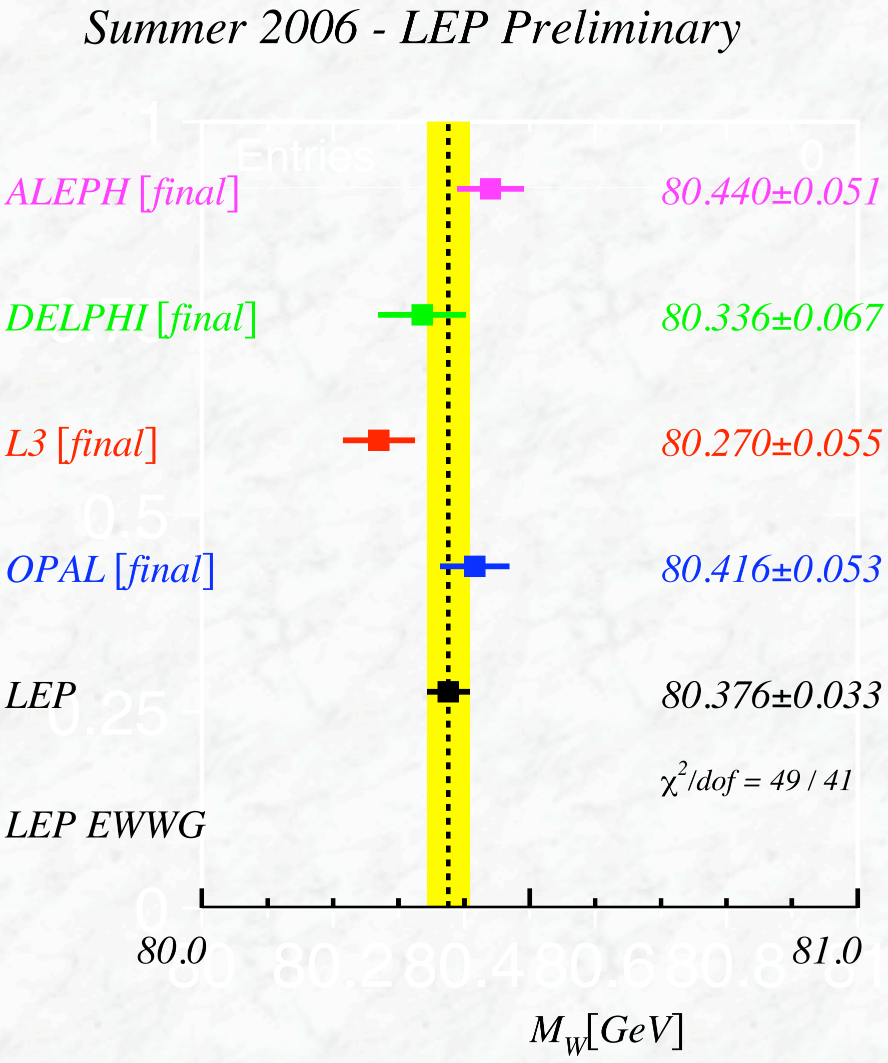


Phasenraumfaktor
= f(M$_W$, s)
⇒ Bestimmung von M$_W$

(2) LEP-II: Direkte Rekonstruktion der invarianten Masse des W-Bosons:



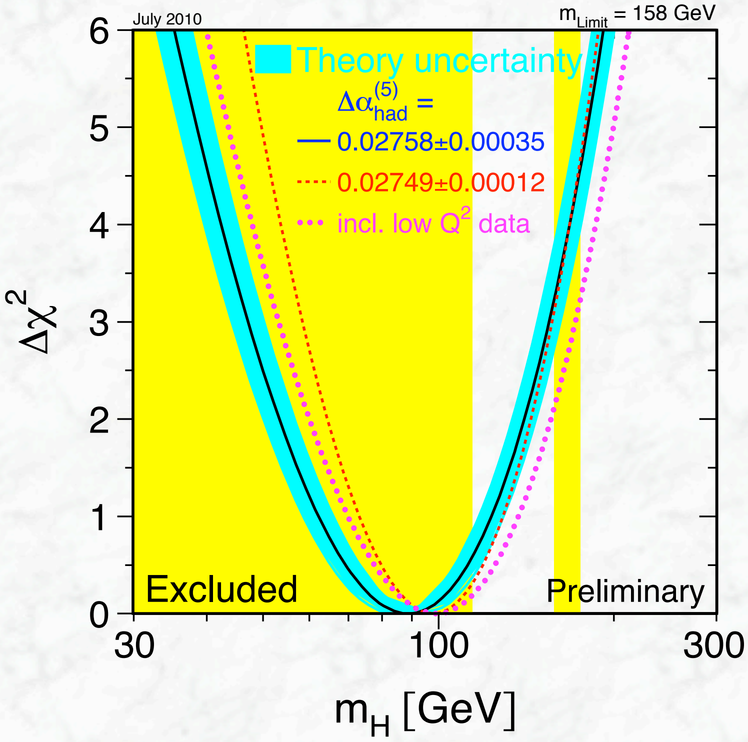
Results from W mass measurements at LEP-II

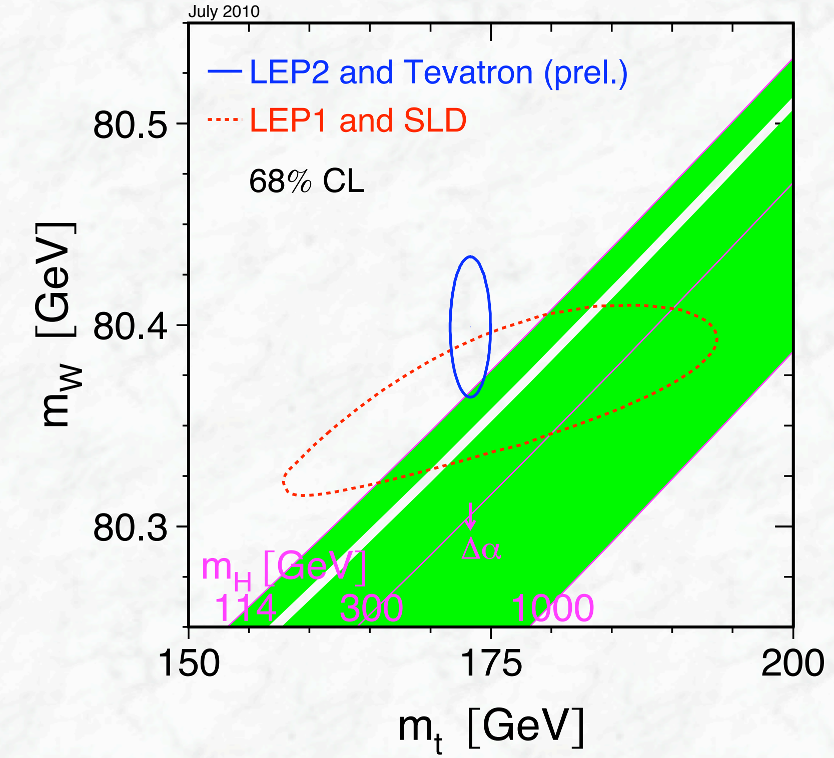


- Results from all four LEP experiments are consistent
- Statistical error is dominant
- Total precision from LEP-II

  $\Delta m_W = \pm 33$ MeV

Results of electroweak precision tests at LEP (cont.)





- Radiative corrections (loop, quantum corrections) can be used to constrain yet unobserved particles (however, sensitivity to m_H only through log terms)

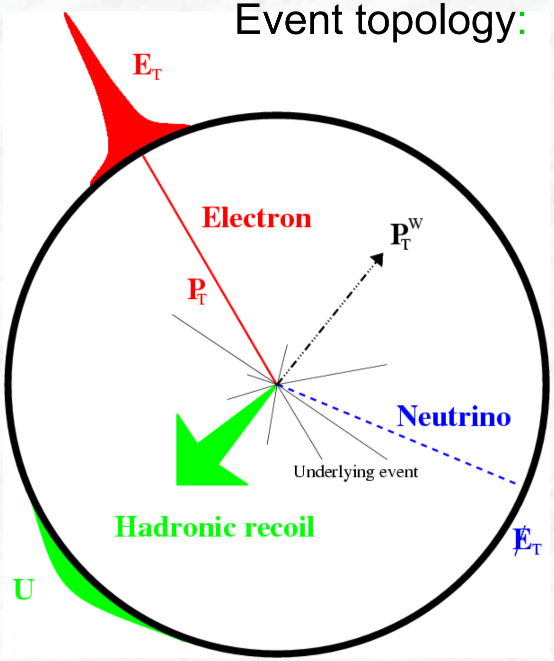
- Main reason for continued precision improvements in m_t , m_W

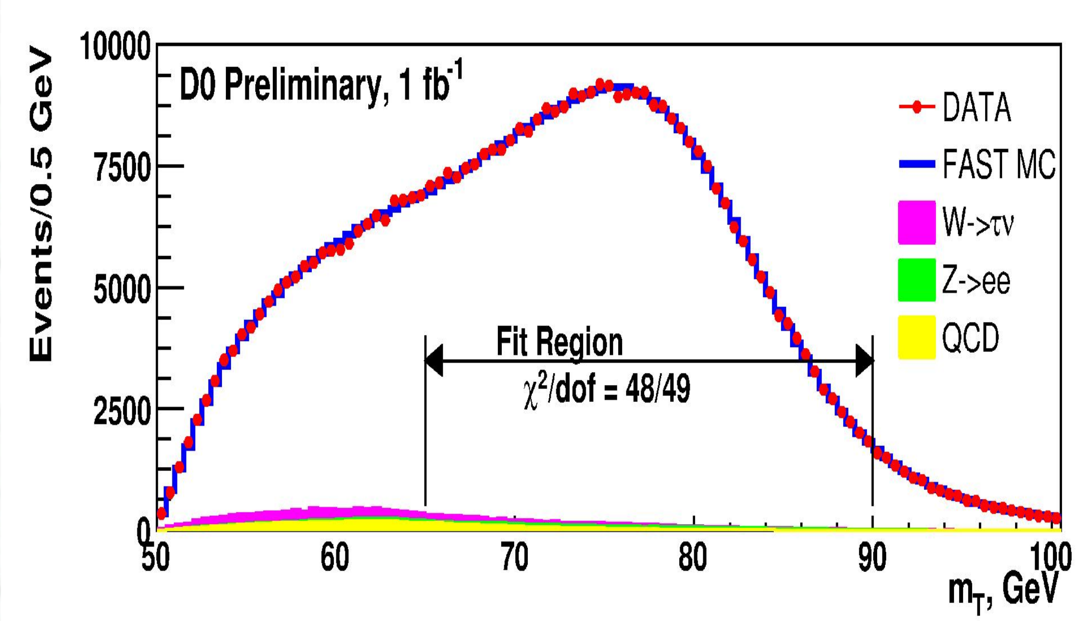
What can hadron collider contribute ?

How can W mass be measured at a hadron collider ?

Technique used for W mass measurement at hadron colliders:

Event topology:





Observables: $P_T(e)$, $P_T(had)$

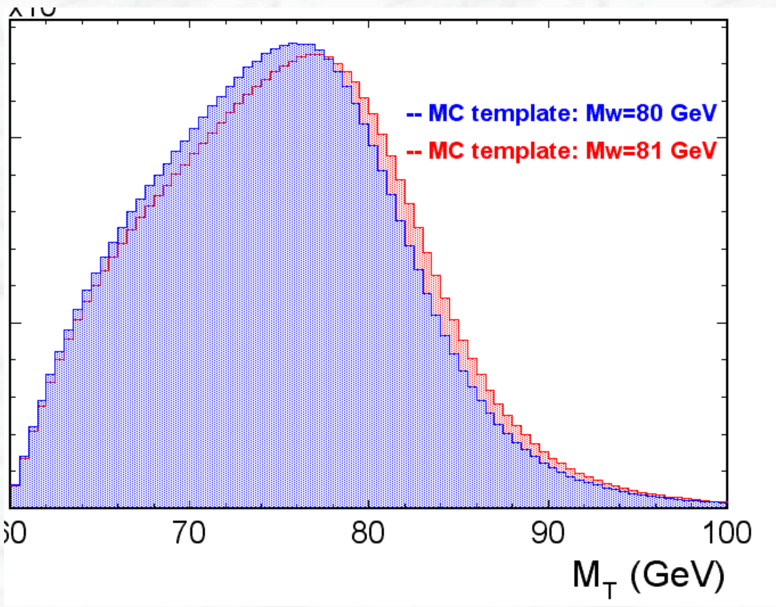
⇒ $P_T(\nu) = -(P_T(e) + P_T(had))$

long. component cannot be measured

⇒ $$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

In general the transverse mass M_T is used for the determination of the W mass (smallest systematic uncertainty).

Shape of the transverse mass distribution is sensitive to m_W, the measured distribution is fitted with Monte Carlo predictions, where m_W is a parameter



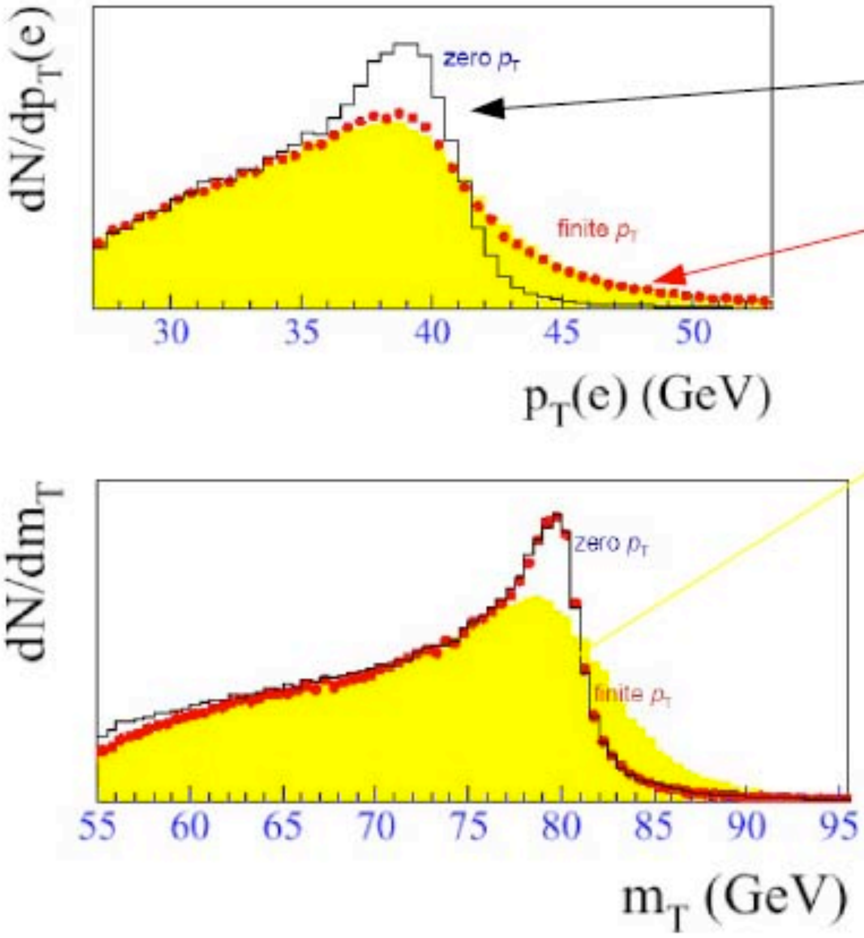
Main uncertainties:

Ability of the Monte Carlo to reproduce real life:

- Detector performance
  (energy resolution, energy scale, ….)
- Physics: production model
  $p_T(W)$, Γ_W, ...
- Backgrounds

In principle any distribution that is sensitive to m_W can be used for the measurement;

Systematic uncertainties are different for the various observables.



True distribution

Including p_T(W) effects

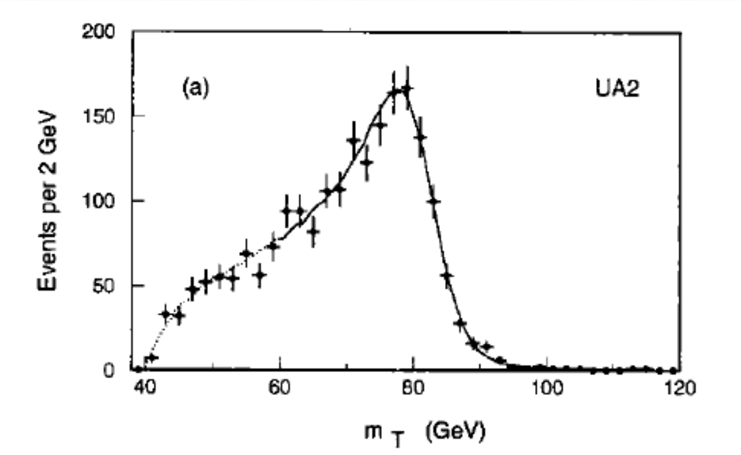
Including detector effects

p_T(e) not sensitive to detector effects, requires p_T(W) knowledge

Transverse mass less sensitive to p_T(W), requires good modeling of missing E_T

W mass measurements

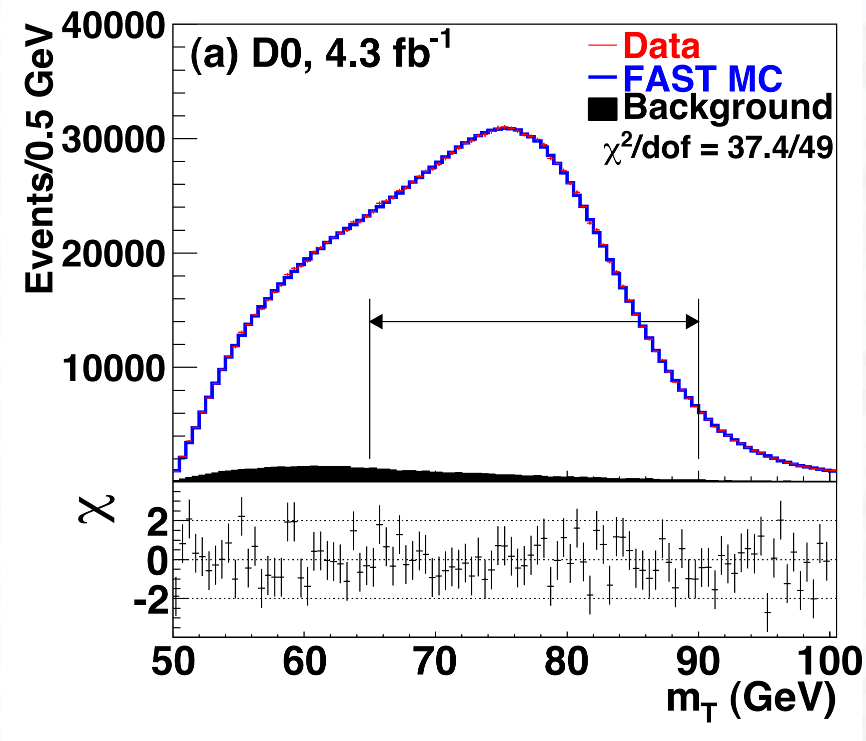
The beginning



$$m_W = 80.35 \pm 0.33 \pm 0.17\ \text{GeV}$$

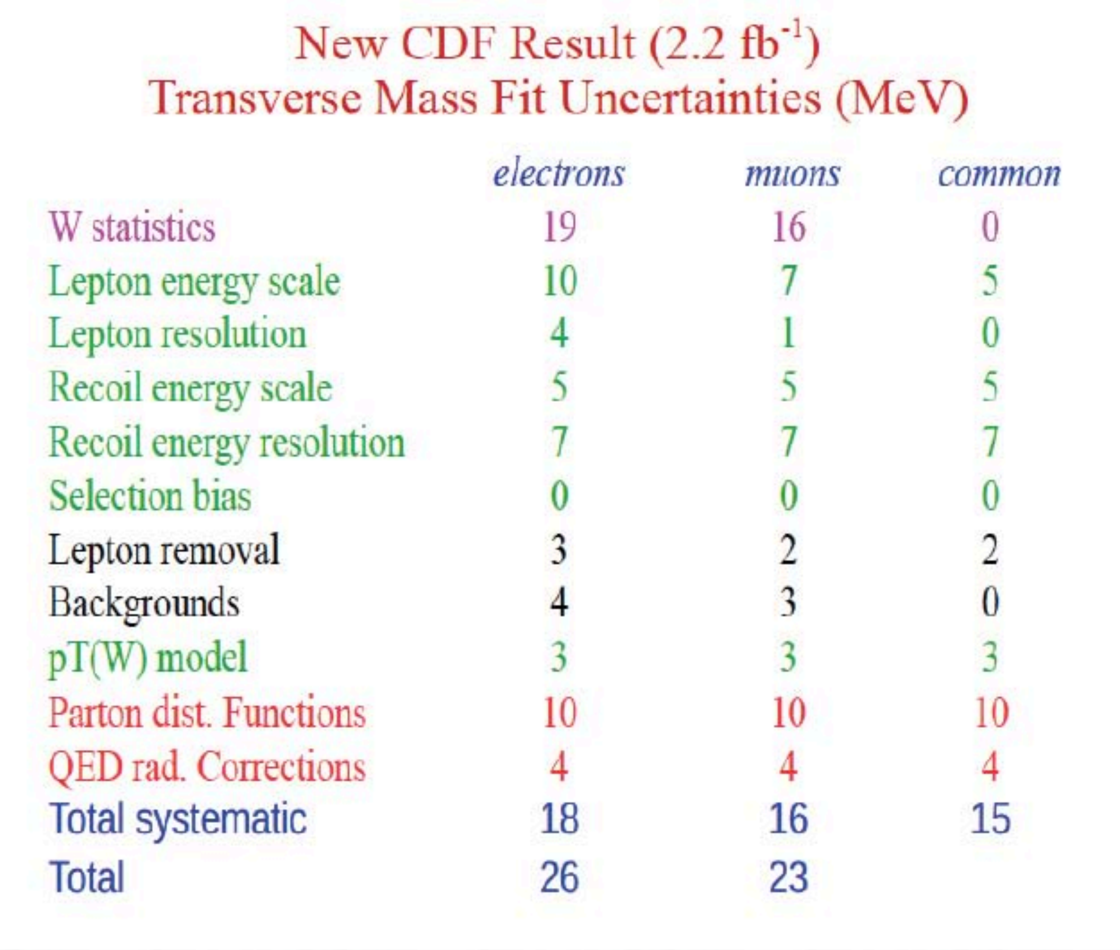
State of the art, today

1.68 M events, electrons $|\eta| < 1.05$



m_W = 80.371 ± 0.013 (stat.) GeV

Systematic uncertainties:



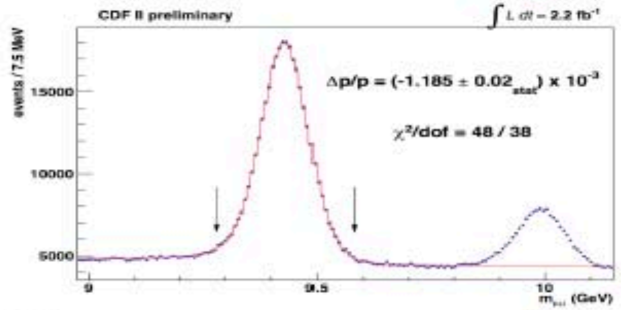
New CDF Result (2.2 fb^{-1})

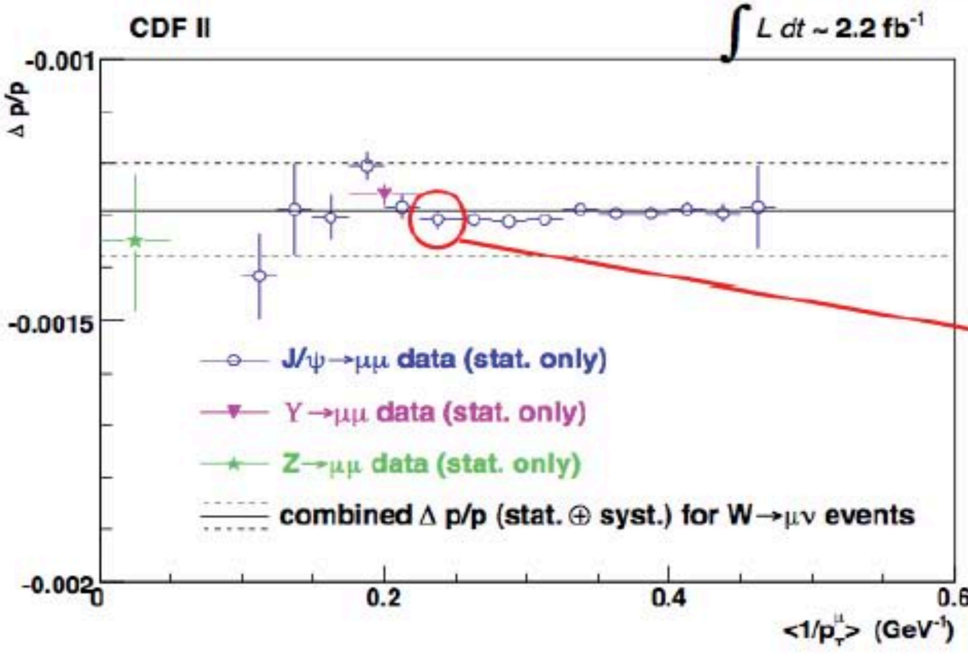
Transverse Mass Fit Uncertainties (MeV)

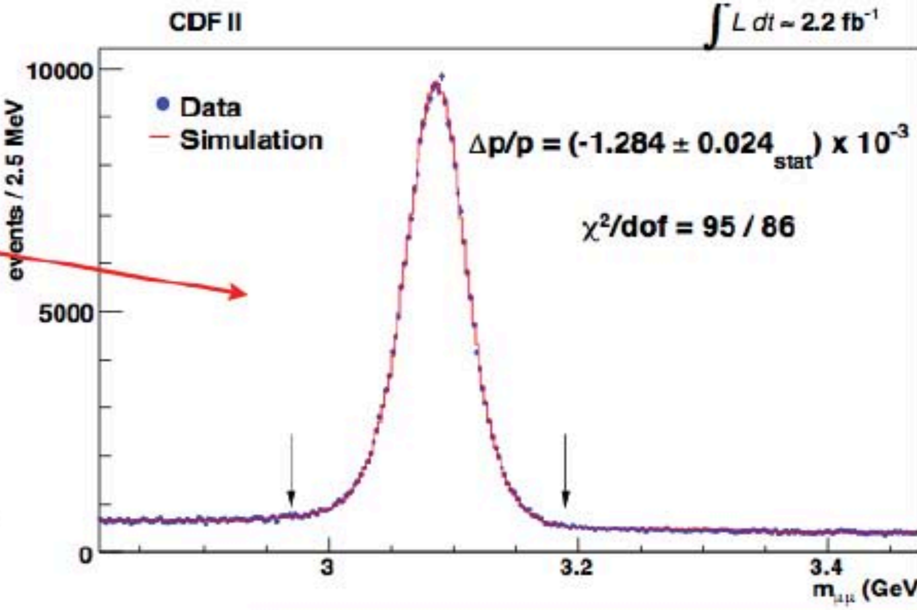
	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic	18	16	15
Total	26	23	

Momentum Scale Calibration

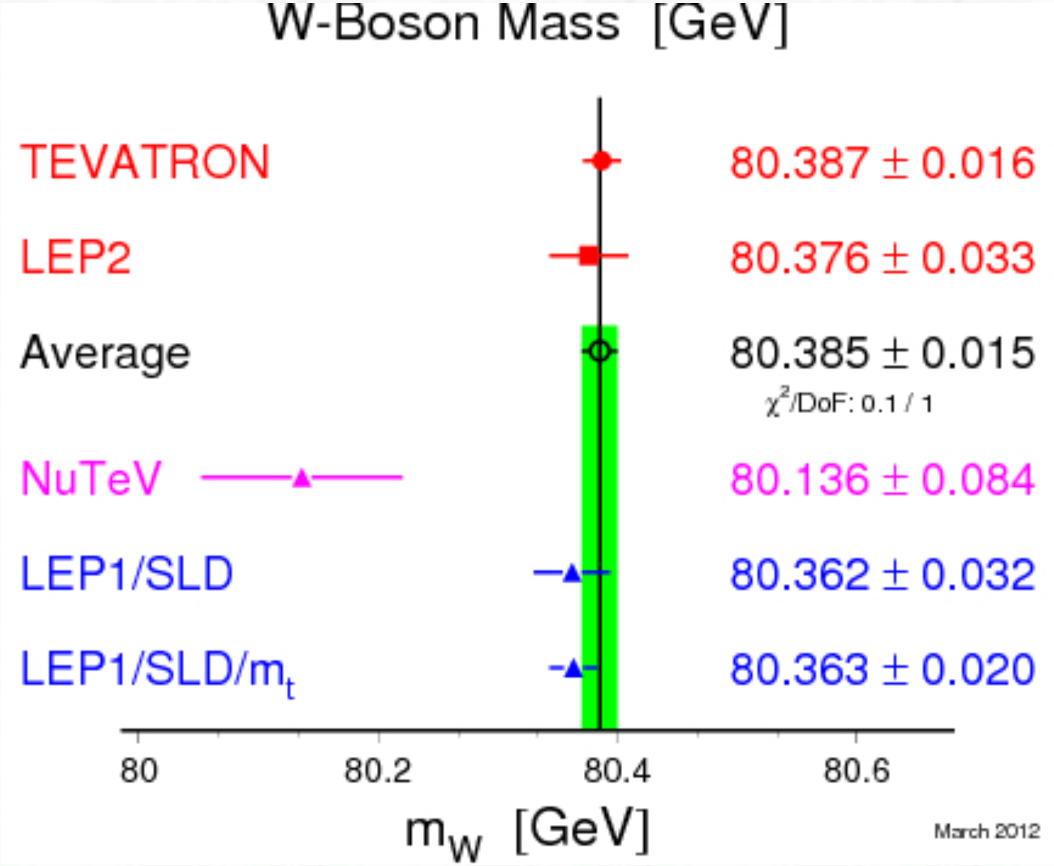
- "Back bone" of CDF analysis is track p_T measurement in drift chamber (COT)
- Perform alignment using cosmic ray data: ~50μm→~5μm residual
- Calibrate momentum scale using samples of dimuon resonances (J/ψ, Υ, Z)
  - Span a large range of p_T
  - Flatness is a test of dE/dx modeling
- Final scale error of 9×10^{-5}: $\Delta m_W = 7$ MeV







Summary of W-mass measurements

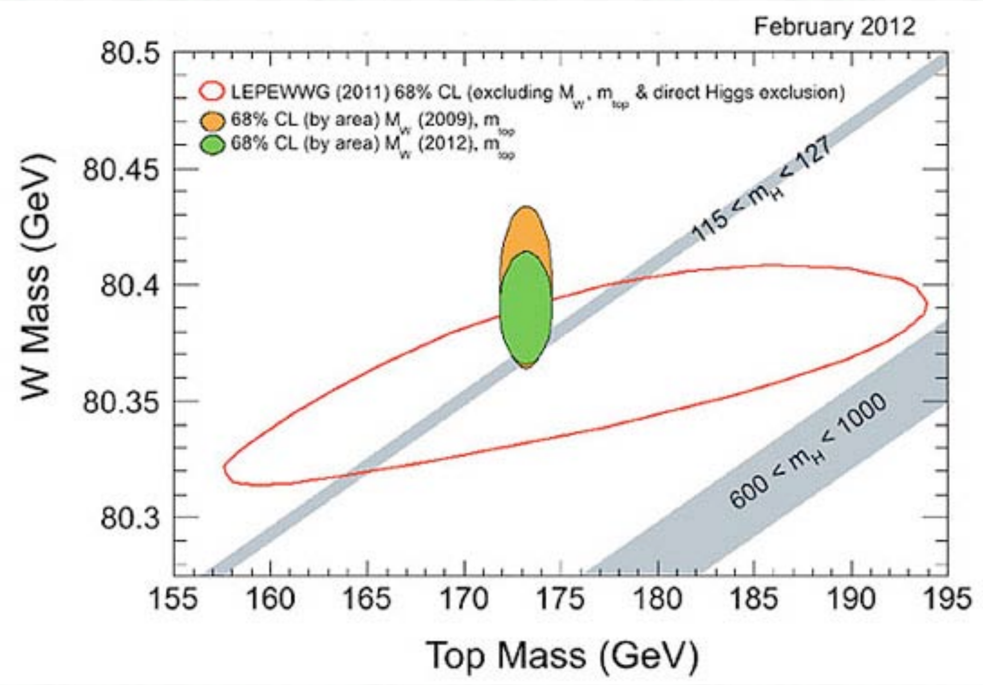


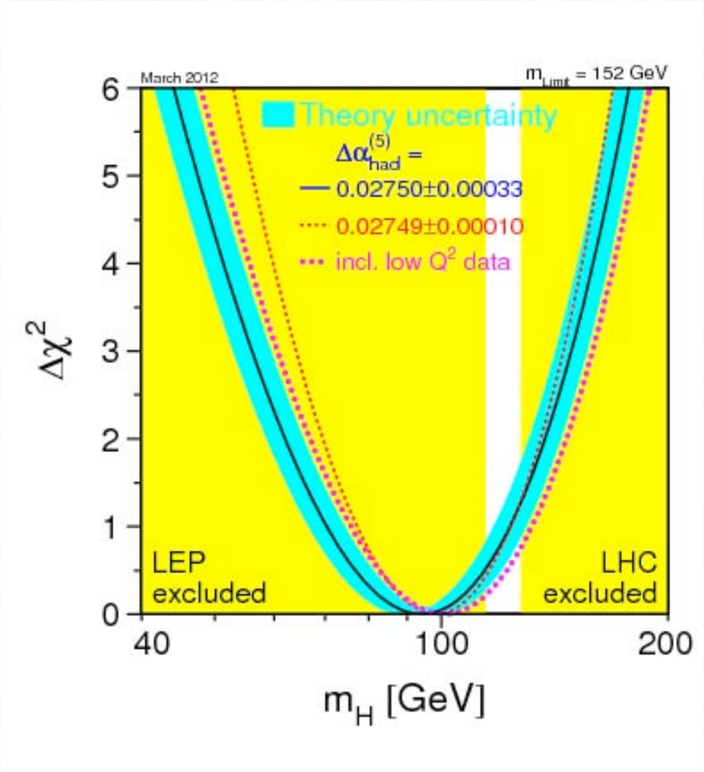
Precision obtained at the Tevatron is superior to the LEP-II precision

m_W (from LEP2 + Tevatron) = 80.385 ± 0.015 GeV

$2\cdot10^{-4}$

Indirect limits from electroweak precision measurements

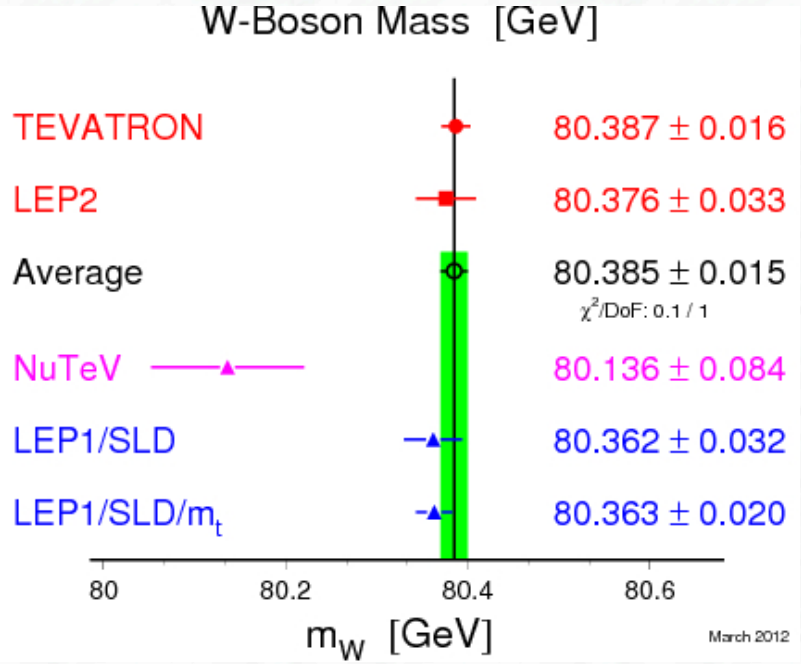




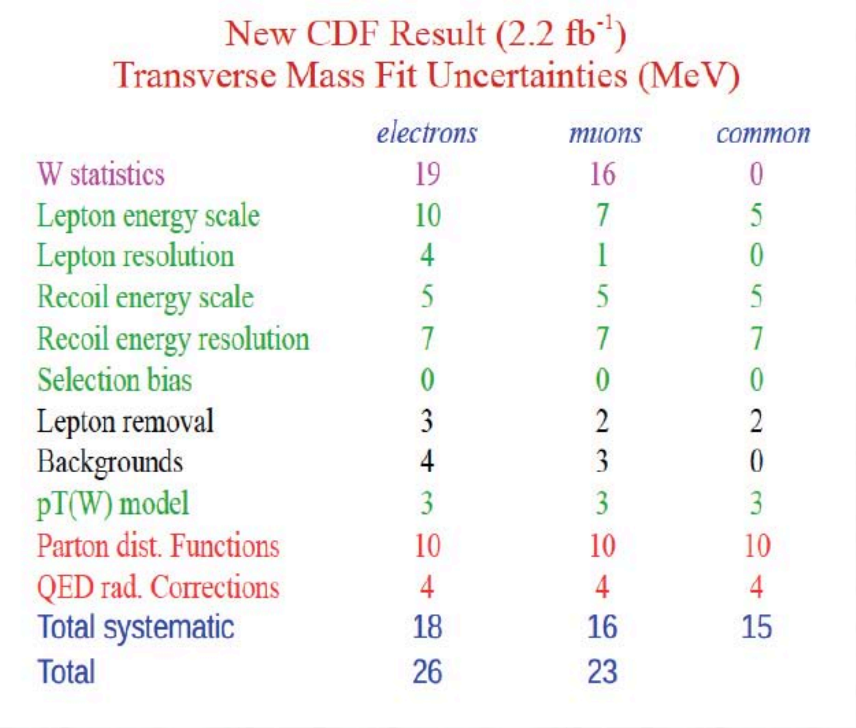
Impressive precision in W mass from the Tevatron (February 2012)

$m_H = 94^{+29}_{-24}$ GeV/c^2
$m_H < 152$ GeV/c^2 (95 % C.L.)

The main story of 2011: eliminate 470 GeV of Higgs boson mass range



Systematic uncertainties:



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Parton dist. Functions	10	10	10
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Total systematic	18	16	15
Total	26	23	

Can the LHC improve on this?

In principle yes, but probably not soon .and. not with 30 pileup events

- Very challenging (e-scale, hadronic recoil, p_T (W),..)

- However there is potential for reduction of uncertainties
  - statistics
  - statistically limited systematic uncertainties (marked in green above)
  - pdfs, energy scale, …., recoil(?)

What precision can be reached in Run II and at the LHC ?

Numbers for a single decay channel

$W \rightarrow e\nu$

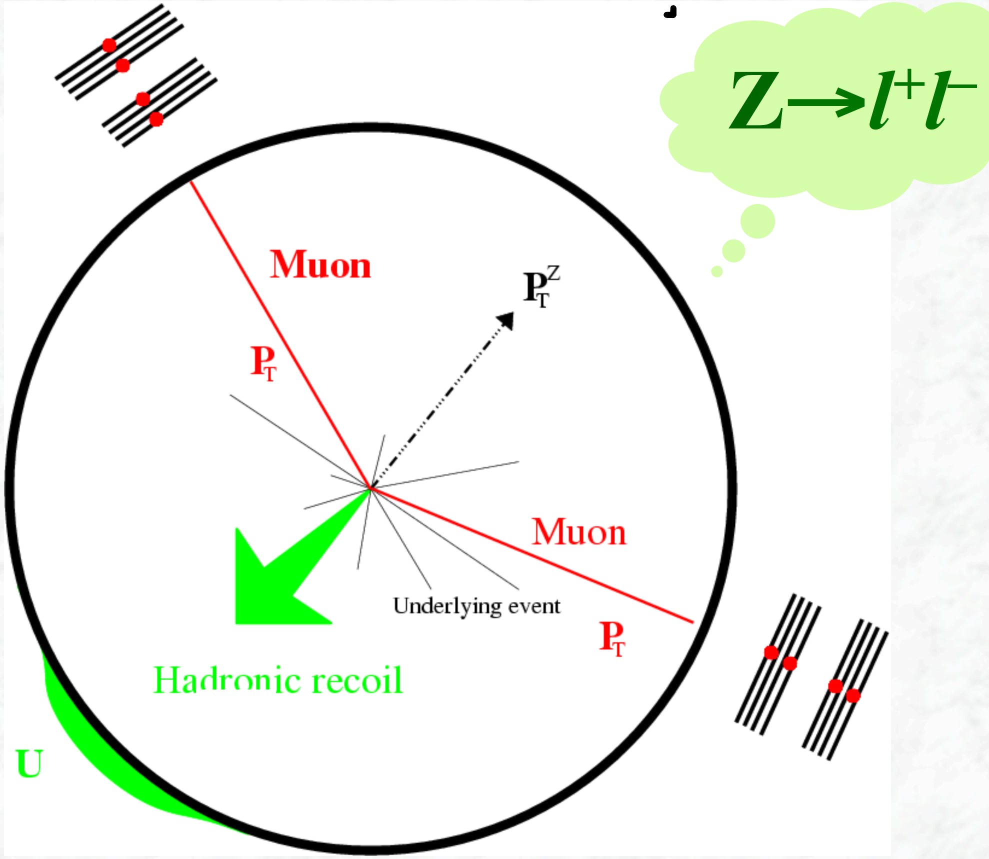
Int. Luminosity	CDF	DØ	LHC
	$0.2\ fb^{-1}$	**$1\ fb^{-1}$**	**$10\ fb^{-1}$**
Stat. error	**48 MeV**	**23 MeV**	**2 MeV**
Energy scale, lepton res.	30 MeV	34 MeV	4 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	16 MeV	12 MeV	7 MeV
Background	8 MeV	2 MeV	2 MeV
Tot. Syst. error	**39 MeV**	**37 MeV**	**8 MeV**
Total error	**62 MeV**	**44 MeV**	**~10 MeV**

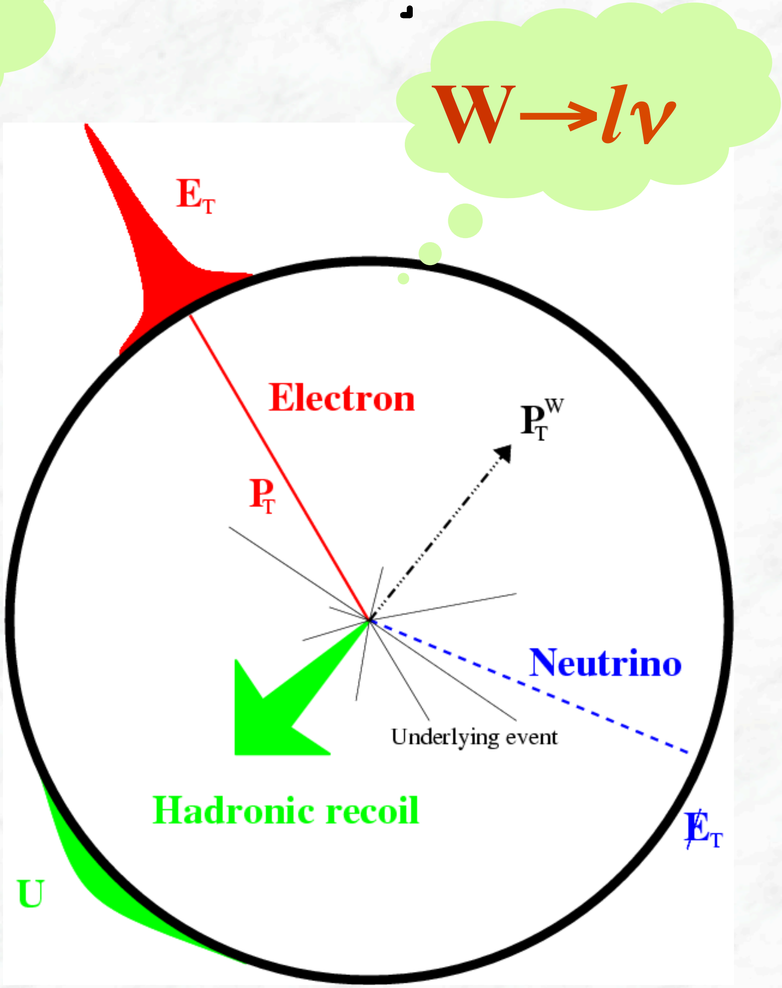
- Tevatron numbers are based on real data analyses
- LHC numbers should be considered as „ambitious goal“
  - Many systematic uncertainties can be controlled in situ, using the large $Z \rightarrow \ell\ell$ sample ($p_T(W)$, recoil model, resolution)
  - Lepton energy scale of ± 0.02% has to be achieved to reach the quoted numbers

Combining both experiments (ATLAS + CMS, $10\ fb^{-1}$), both lepton species and assuming a scale uncertainty of ± 0.02% a total error in the order of

$\Rightarrow \Delta m_W \sim \pm 10$ MeV might be reached.

Signature of Z and W decays





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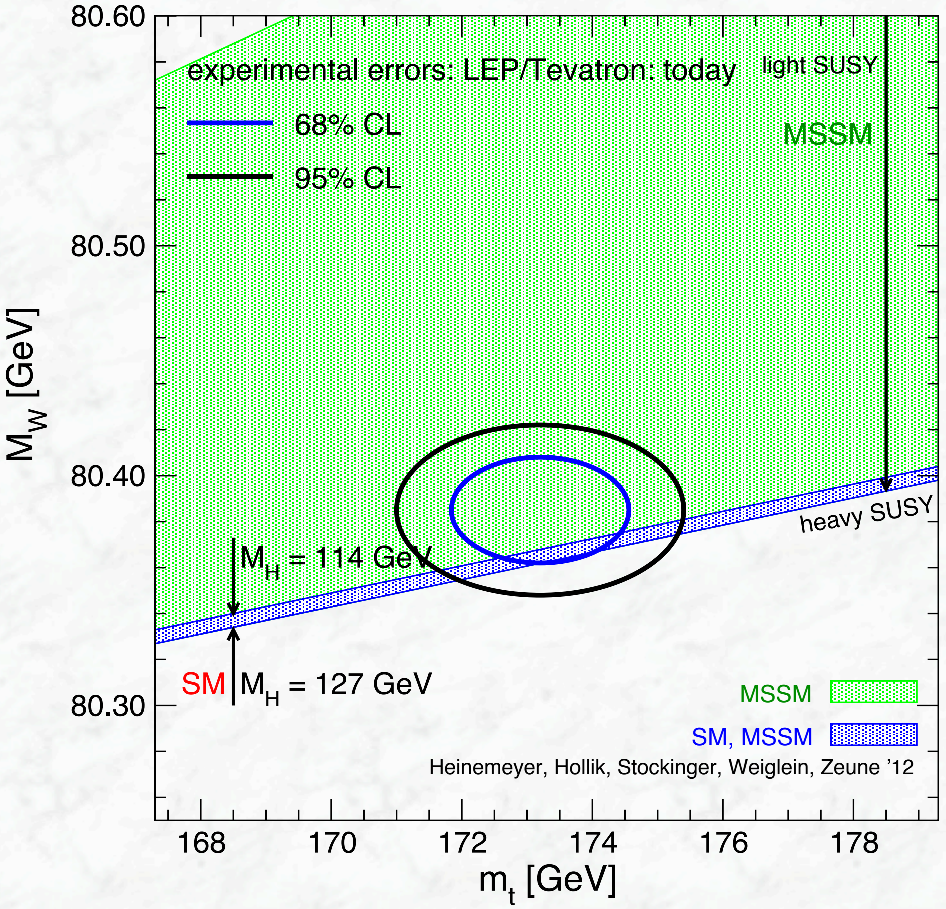

2012

Ultimate test of the Standard Model:

Compare direct prediction of the Higgs boson mass with direct observation