Tests of the Standard Model of electroweak interactions

- Standard Model and motivations
- W, Z production cross sections
- W mass
- W width
- triple-gauge couplings

The „Standard Model" of Particle Physics

... is rather simple (und „übersichtlich"):

Elementary Particles	Generation 1	2	3
Quarks	**u** **d**	**c** **s**	**t** **b**
Leptons	ν_e e	ν_μ μ	ν_τ τ

... as well as anti-particles

Elementary Forces	exchange boson	relative strength
Strong	g	1
el.-magn.	γ	1/137
Weak	$W^\pm, Z^0$	10^{-14}
Gravitation	*G*	10^{-40}

... describes the unified electro-weak interaction and the Strong force with gauge invariant quantum field theories;

... is extremely successful in consistently and precisely describing all particle reactions observed to date

... provides a consistent (yet incomplete) picture of the evolution of the very early universe –> particle cosmology

The elektroweak standard model at hadron colliders

- based on the gauge group SU(2)xU(1)
- with gauge bosons Z^0, W^+, W^- (SU(2)) and γ (U(1))

- left-handed fermion fields transforming as doublets under SU(2) ; there are 3 fermion families

- a complex scalar Higgs doublet, $\phi = (\phi+ , \phi-)$, is added for mass generation through sponateous symmetry breaking, with one neutral Higgs scalar H as physical particle

- e.w. SM describes, in lowest order perturbation theory ("Born Approximation"), processes like $f_1 f_2 \rightarrow f_3 f_4$ with only 3 free parameters: α, G_F und $\sin^2\theta_w$.

Tests of the elektroweak standard model at hadron colliders

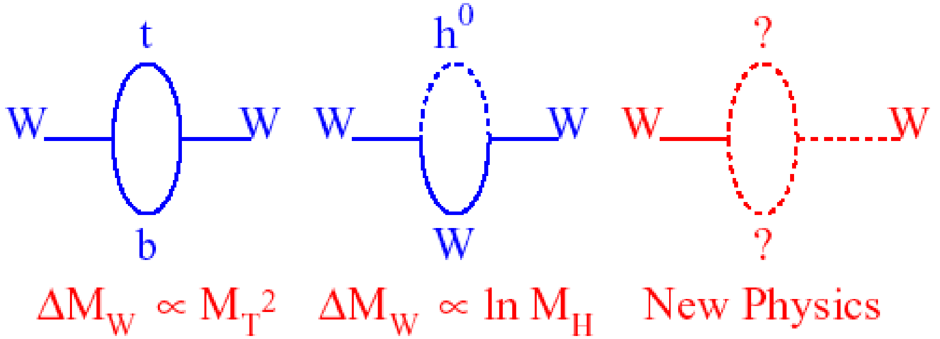
- mainly physics with
  - el.-w. gauge bosons (W, Z, γ)
  - with top-quarks -> V8
  - with hadron jets (QCD) -> V7
- measurements of:
  - production cross sections
  - masses
  - decay rates / widths
  - decay asymmetries
  - gauge boson couplings (WW, Wγ, WZ, ZZ, Zγ)

motivations for these measurements:

- in general: consistency checks with SM
- search for deviations from SM:

  production, decays and properties of gauge bosons

  are modified by "new physics":

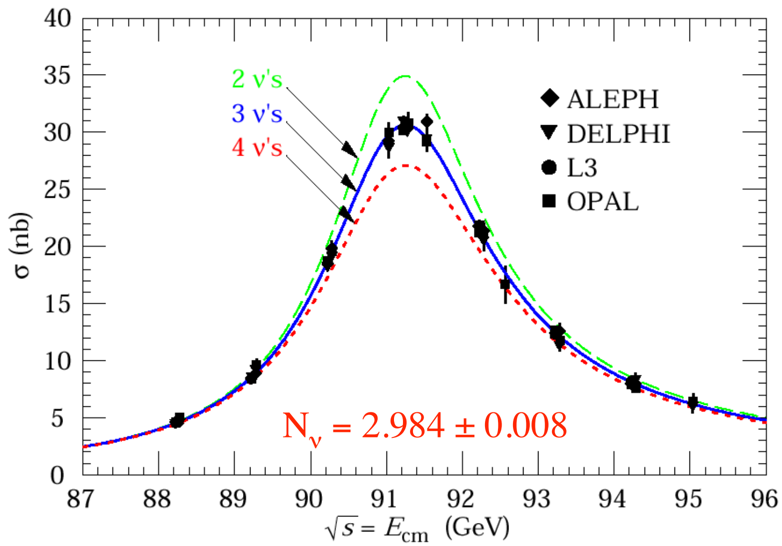


- indirect Higgs mass limits (from precision measurements

  of M_{top} and M_w)
- SM processes used to measure LHC luminosity
- precisely define SM background for signals of new physics

Z^0

precise determination of M_z und Γ_z from LEP data ($e^+e^- \rightarrow Z^0 \rightarrow$ hadrons):

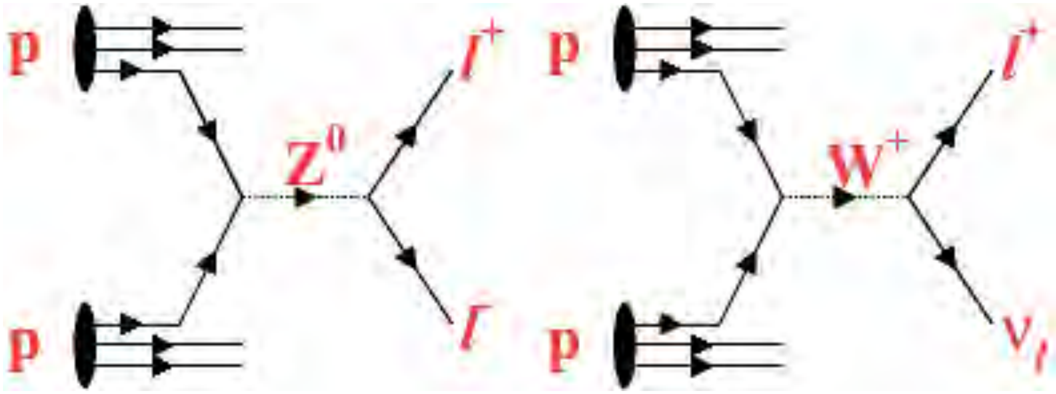


M_Z = (91.1875 ± 0.0021) GeV

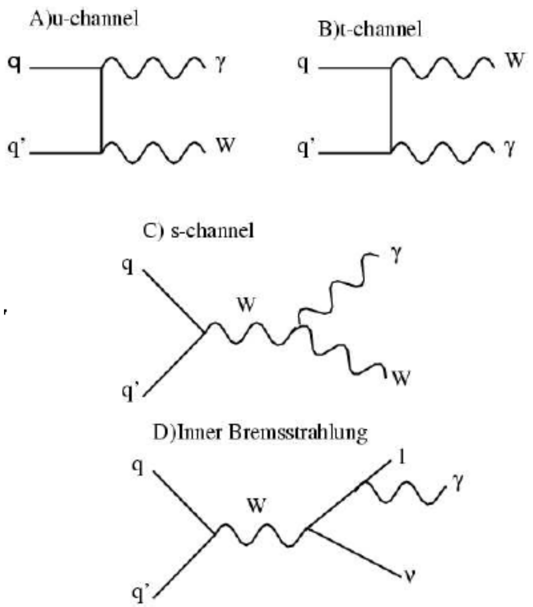
Γ_Z = (2.4952 ± 0.0023) GeV

- this precision cannot be achieved at hadron-colliders
- therefore at LHC: – LEP-results (M_Z, Γ_Z) used as input
  – Z^0-decays used e.g. for calibration

production and decay of gauge bosons

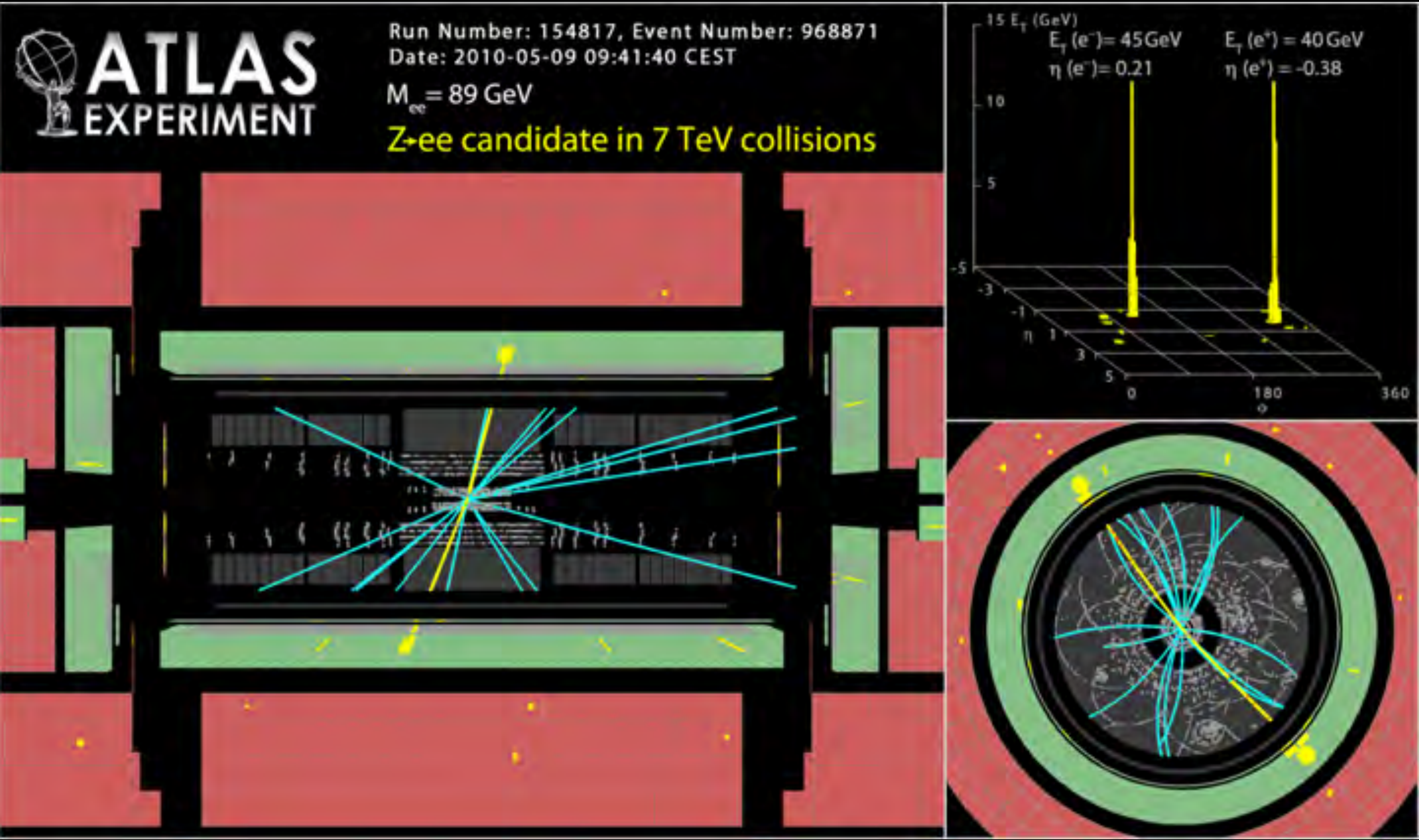


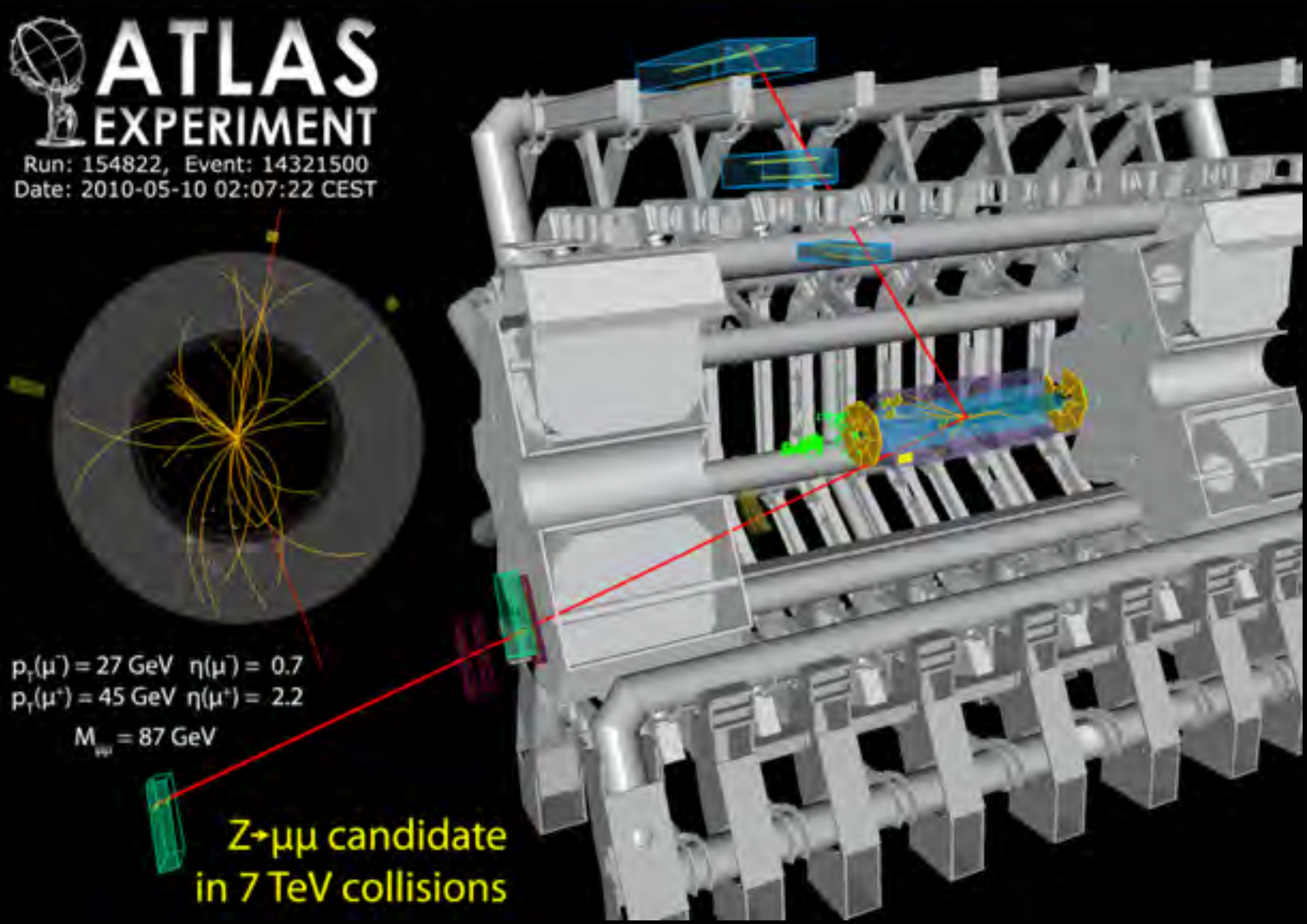
(missing energy)



- hadronic decays ($q\bar{q}$) cannot be used, due to dominating QCD background
- theoretical uncertainties mainly due to quark-structure of protons

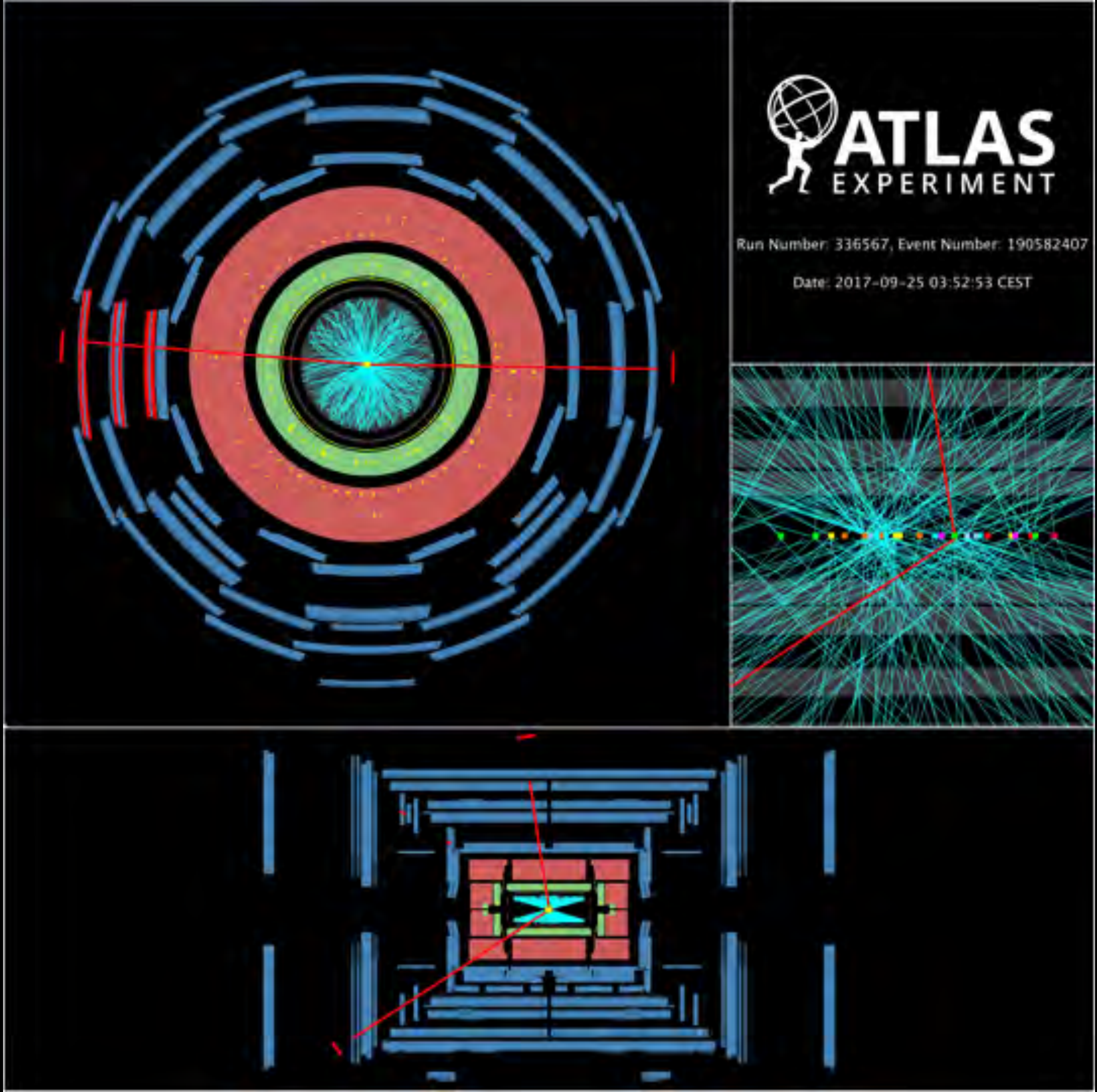
LHC: observation of Z/W (leptonic decay)

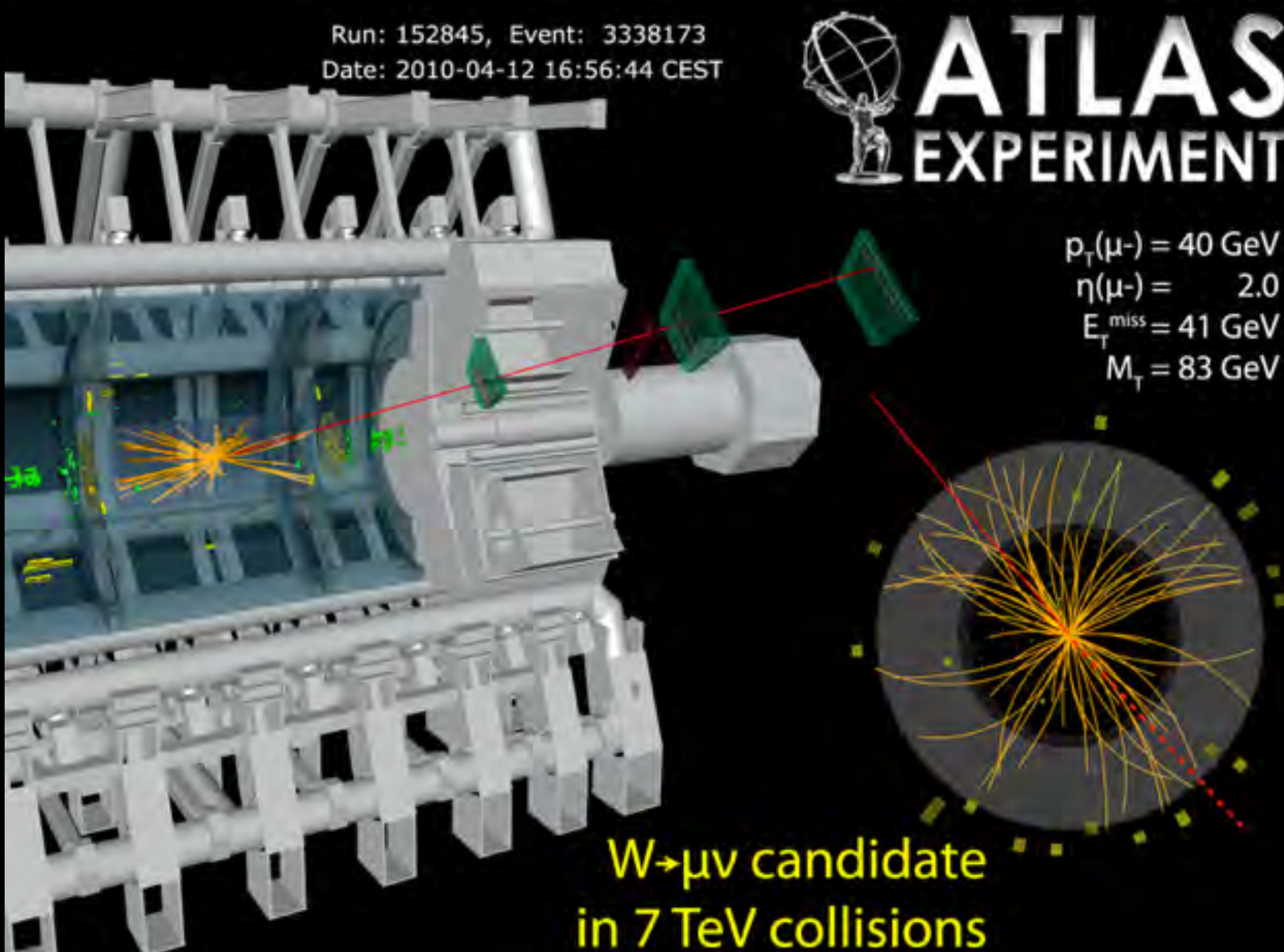


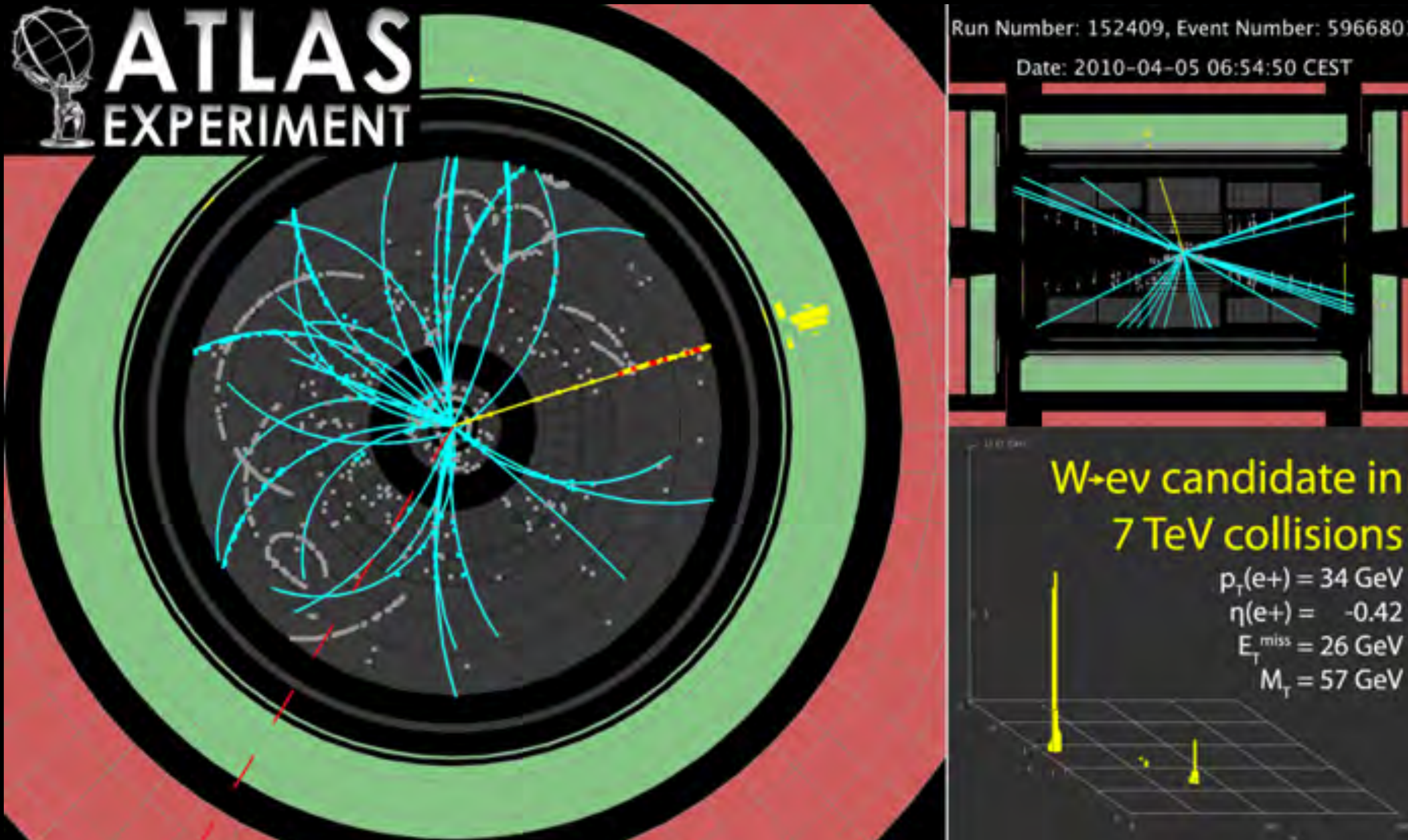

ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-)$ = 27 GeV $\eta(\mu^-)$ = 0.7
$p_T(\mu^+)$ = 45 GeV $\eta(\mu^+)$ = 2.2
$M_{\mu\mu}$ = 87 GeV
Z→μμ candidate
in 7 TeV collisions

Z –> μμ

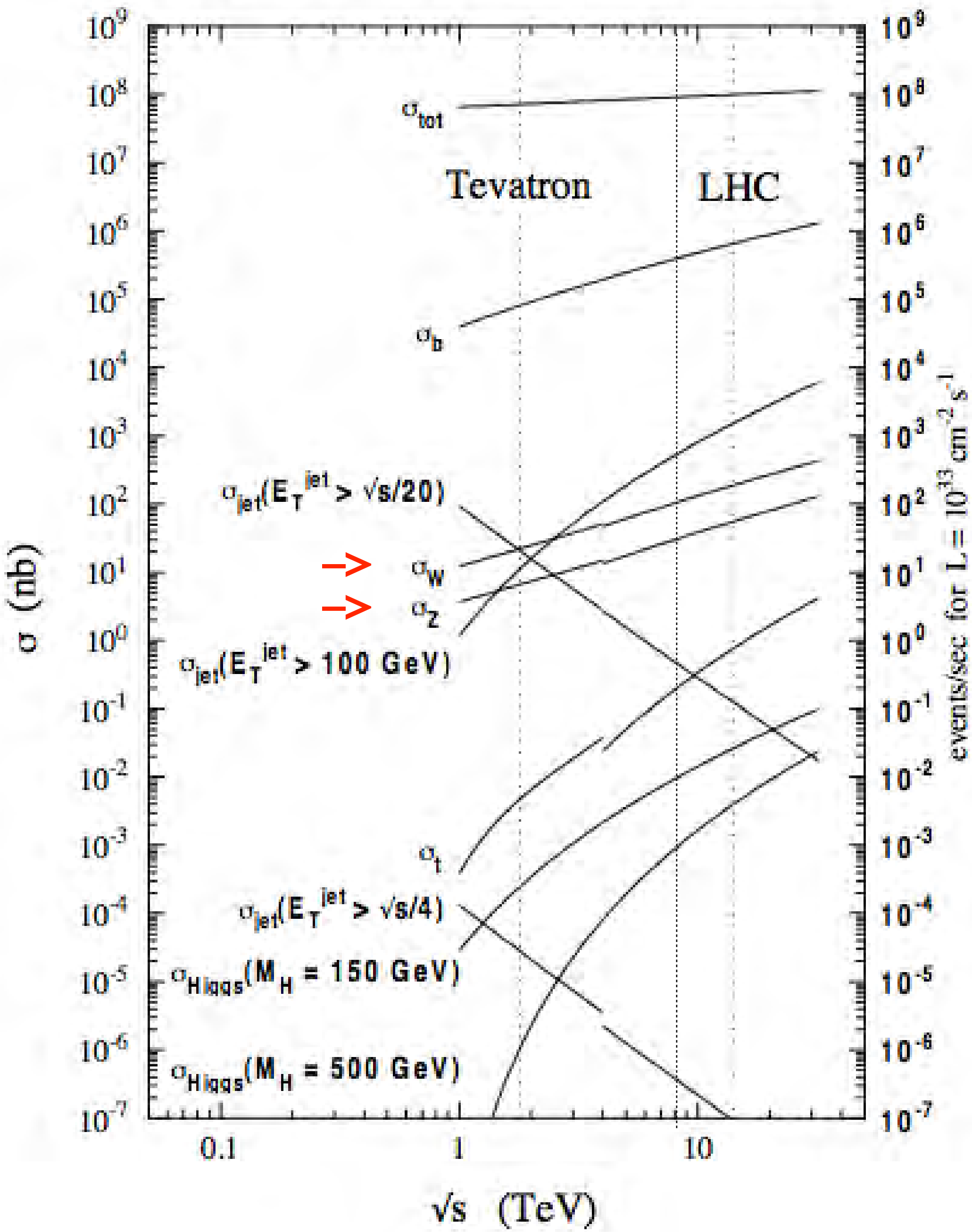
with 25 primary vertices ...




Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST
ATLAS
EXPERIMENT
$p_T(\mu-)$ = 40 GeV
$\eta(\mu-)$ = 2.0
E_T^{miss} = 41 GeV
M_T = 83 GeV
W→μν candidate
in 7 TeV collisions


ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
p_T(e+) = 34 GeV
η(e+) = -0.42
E_T^miss = 26 GeV
M_T = 57 GeV

proton - (anti)proton cross sections



W, Z data sets

Tevatron:

Datensatz	Run I	Run IIa
$W \to l\nu$	77k	2300k
$Z \to ll$	10k	202k
WV ($W \to l\nu$, V=W,γ,Z)	90	1800
ZV ($Z \to ll$, V=W,γ,Z)	30	500
tt (mass sample, ≥1 b-tag)	20	800

ATLAS / LHC:

Process	σ (nb)	Events/year ($\mathcal{L}$ = 5 fb^{-1})
$W \to e\nu$	30	~ 10^8
$Z \to e^+ e^-$	3.0	~ 10^7
$t\bar{t}$	1.6	~ 10^7
Inclusive jets $p_T > 200$ GeV	200	~ 10^9

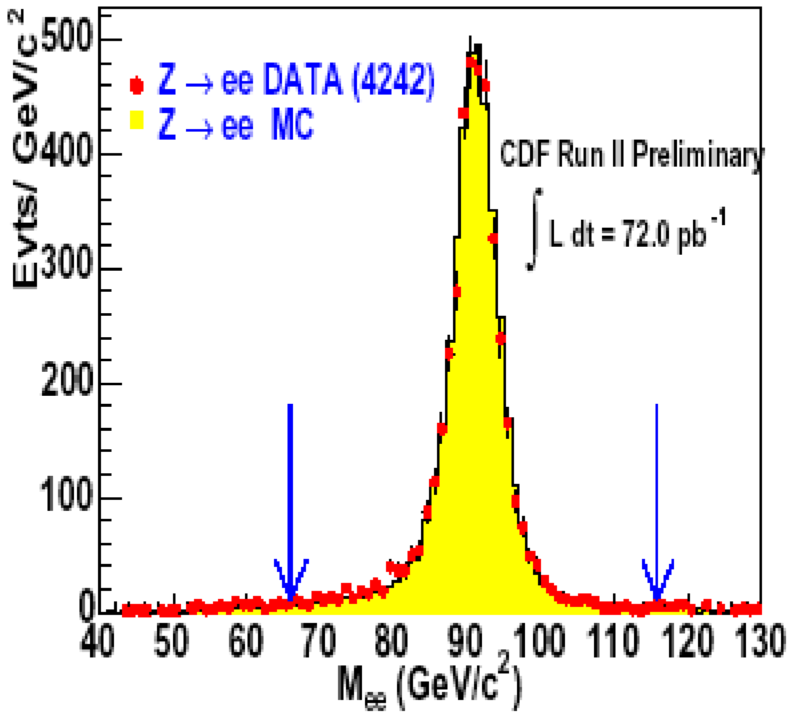
currently: ~100 fb^{-1}

reconstruction of Z, W

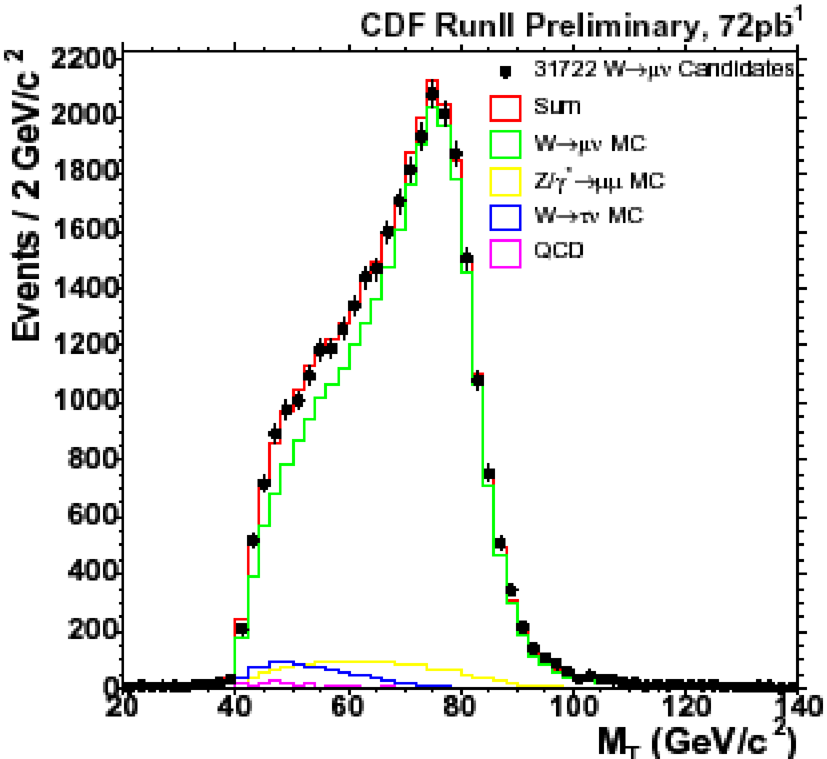
- Z selection: – one lepton with tight criteria
  (high energy, isolation, in central region,
  unambiguous detector signature)
  – a second lepton with relaxed criteria
- W selection: – one lepton with tight criteria
  – missing transverse energy / transv. momentum
- counting of events; corrections according to:
  – Trigger-efficiency (from data: redundant triggers,
  2-lepton-events etc)
  – reconstruction- and selection-efficiencies
  – luminosity

$$\sigma_Z = \frac{N}{\int L dt \cdot Br(Z^0 \to e^+ e^-) \cdot \varepsilon_{ee}}$$

reconstruction of Z, W



invariant pair mass



„transverse mass“:

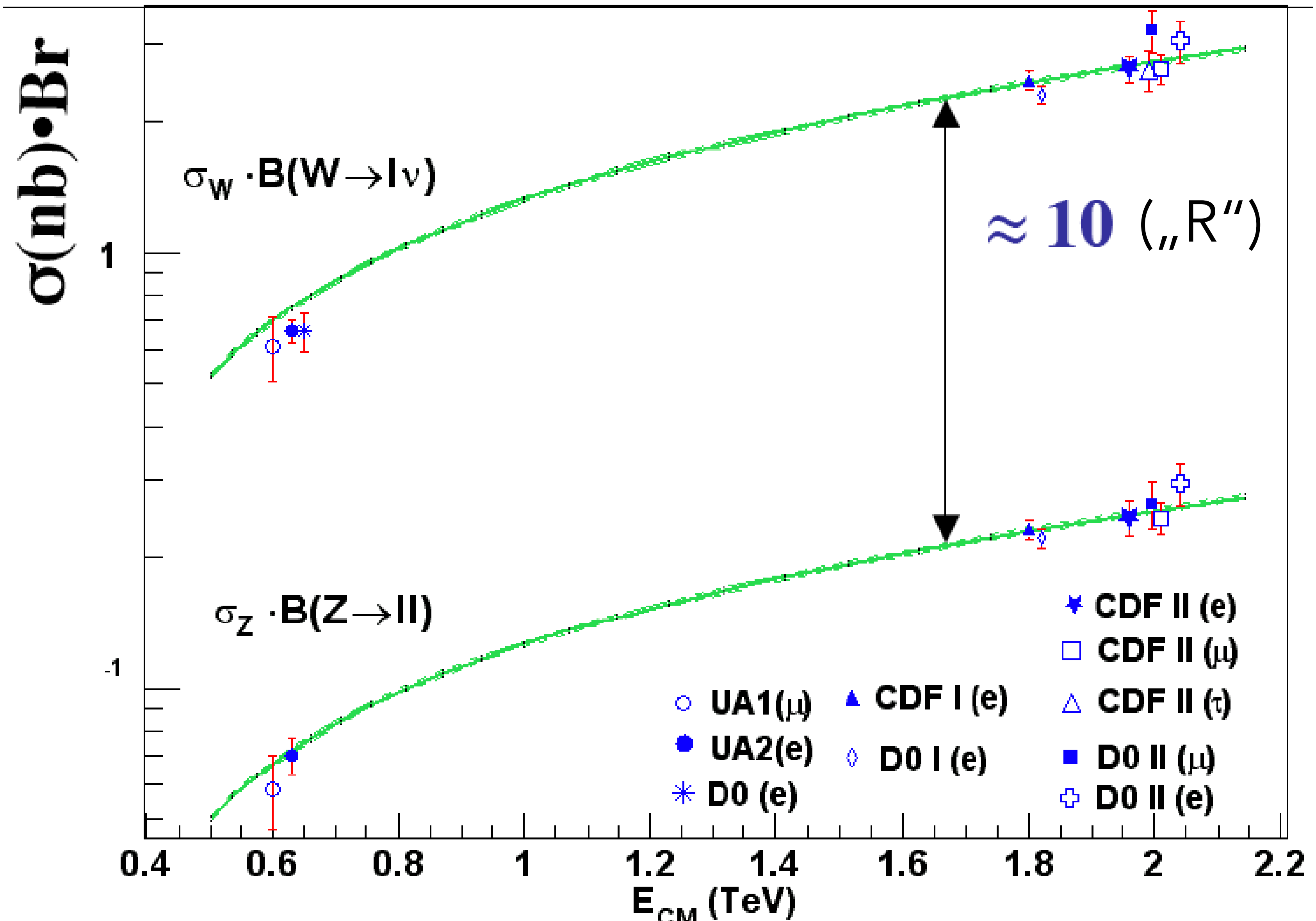
$$M_T = \sqrt{(E_T^\ell + E_T^\nu)^2 - (\vec{P}_T^\ell + \vec{P}_T^\nu)^2}$$

E_T^ν, P_T^ν werden aus Fehlender Energie bestimmt

auch verwendet:

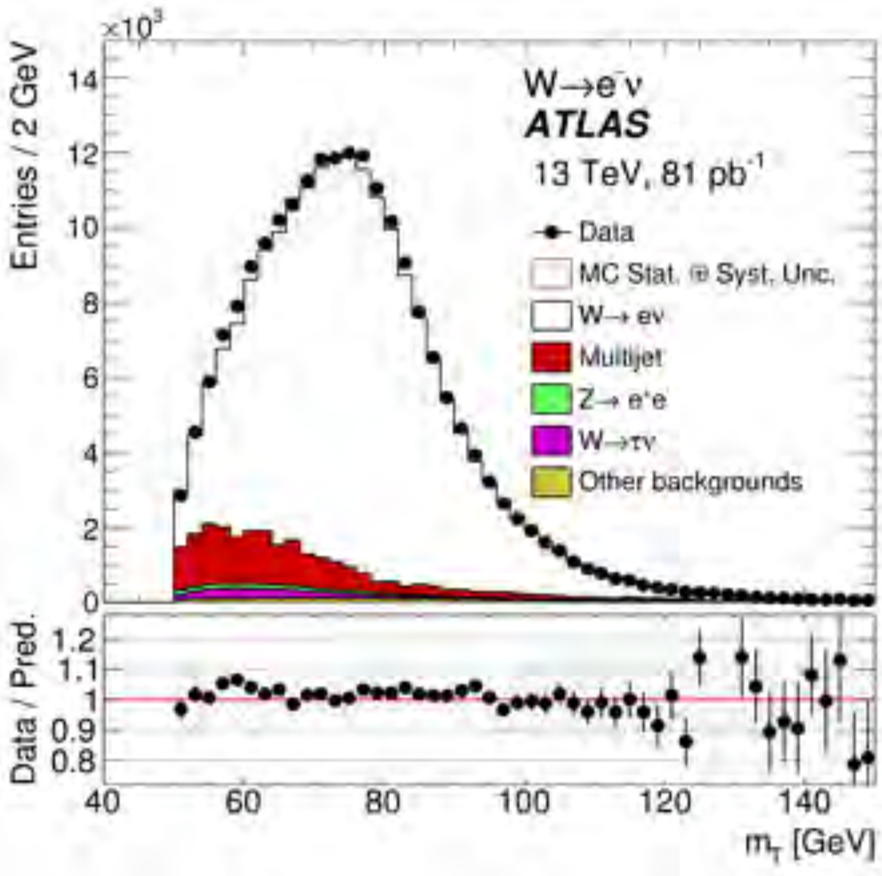
$$M_T = \sqrt{p_T^\ell p_T^\nu (1 - \cos \Delta\phi)}$$

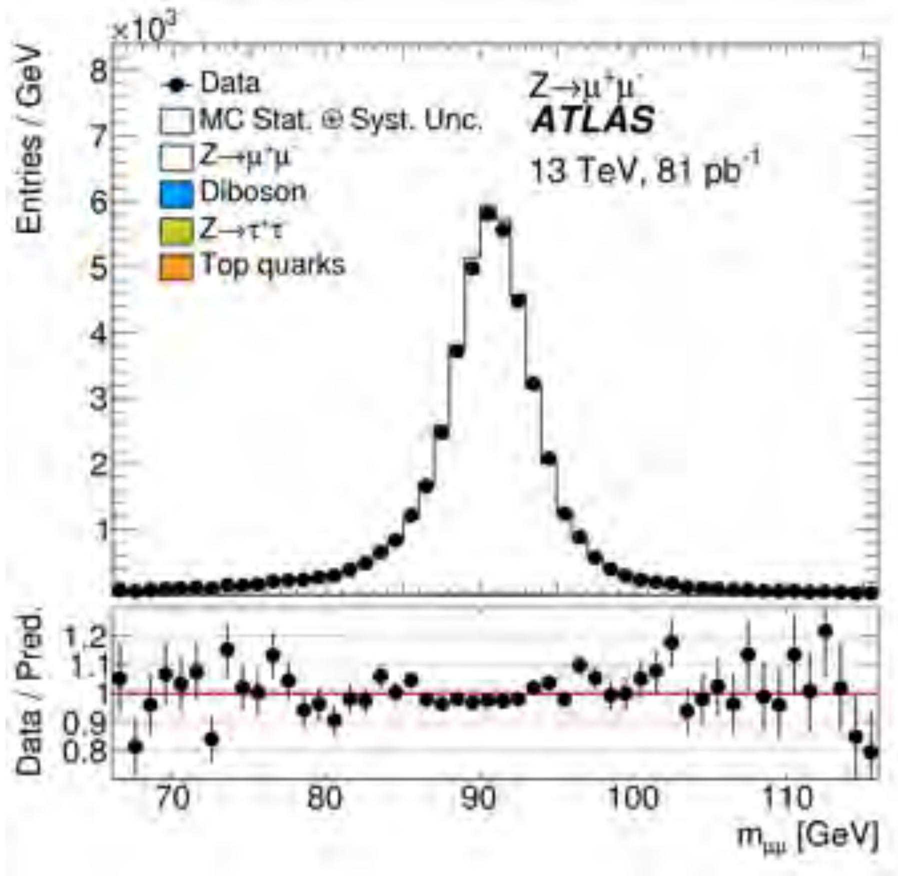
production cross sections (Tevatron)



W, Z boson production cross sections at $\sqrt{s}$ = 13 GeV

arXiv:1603.09222





W, Z boson production cross sections at $\sqrt{s}$ = 13 GeV

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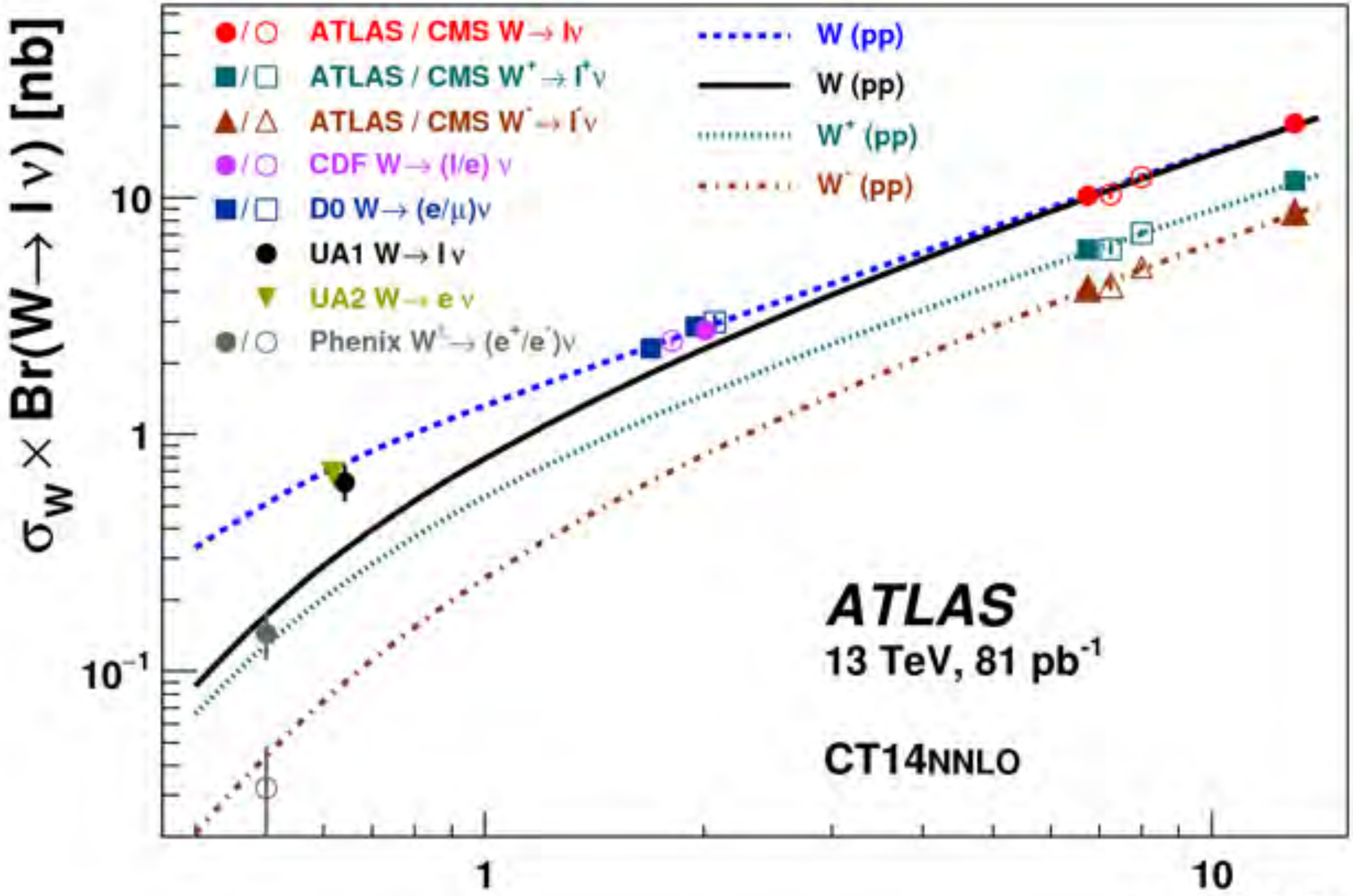
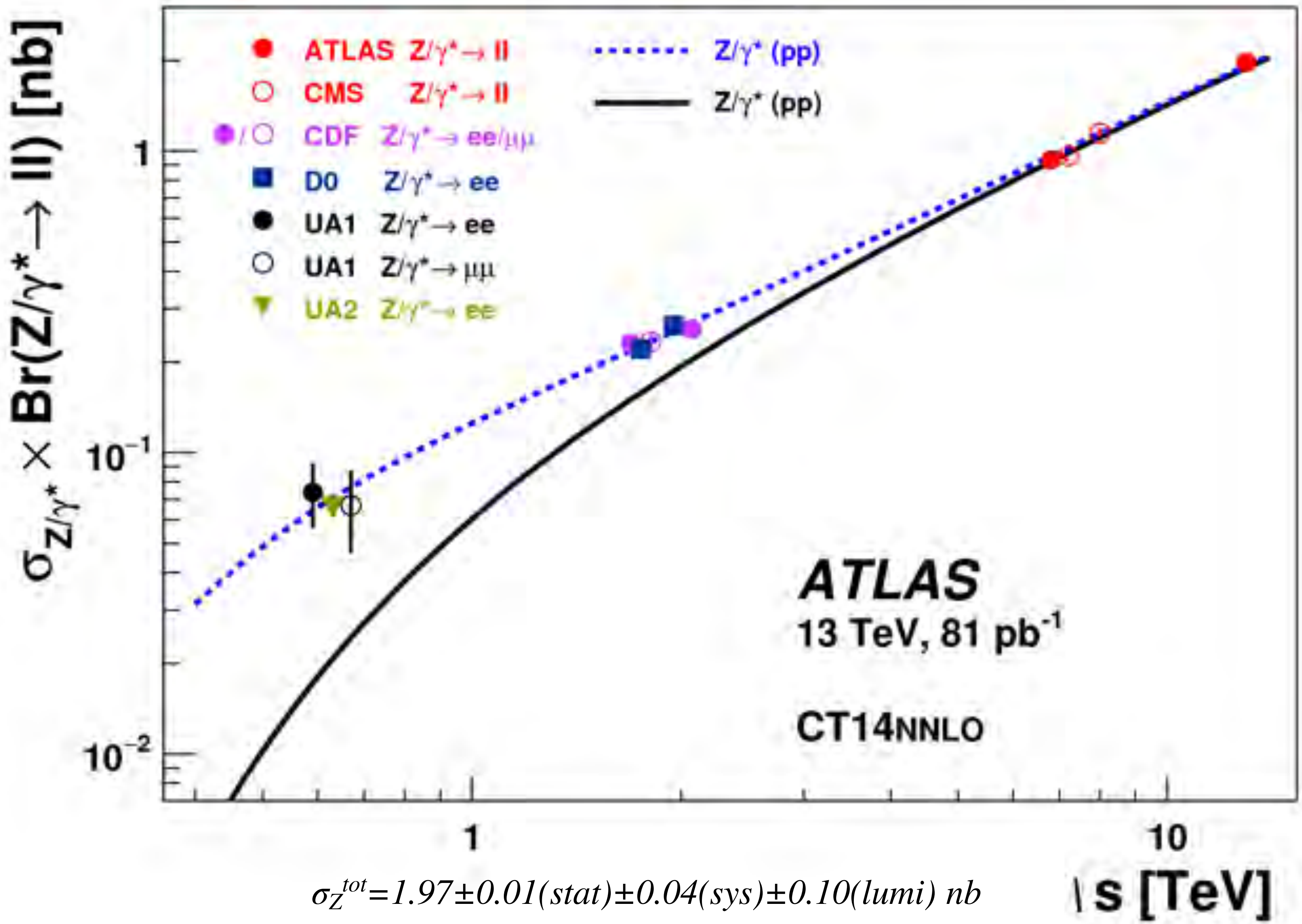


σ_{W+}^{tot} = *11.78±0.02(stat)±0.32(sys)±0.59(lumi)*

σ_{W-}^{tot} = *8.75±0.02(stat)±0.24(sys)±0.42(lumi)*

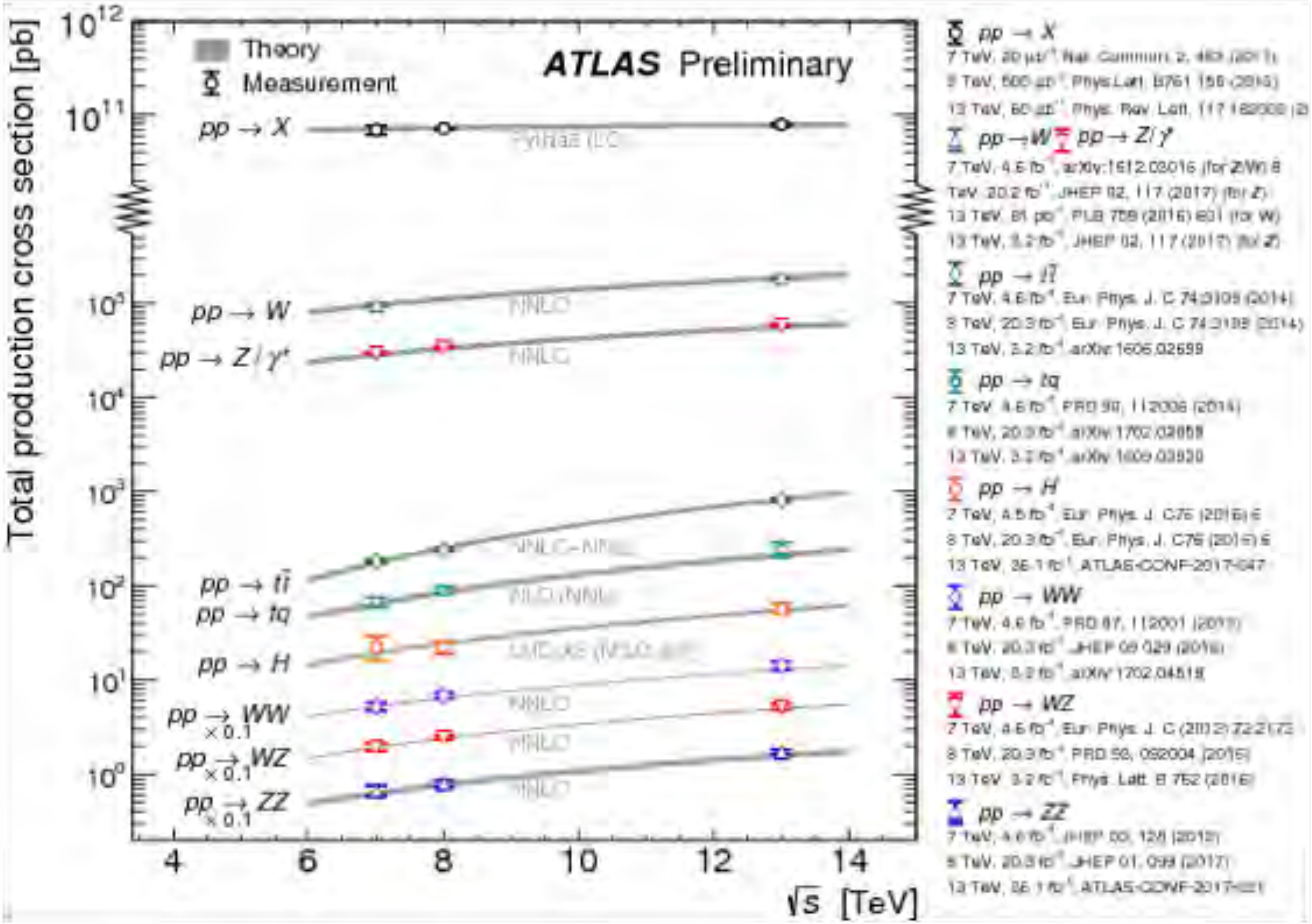
W, Z boson production cross sections at √s = 13 GeV

arXiv:1603.09222



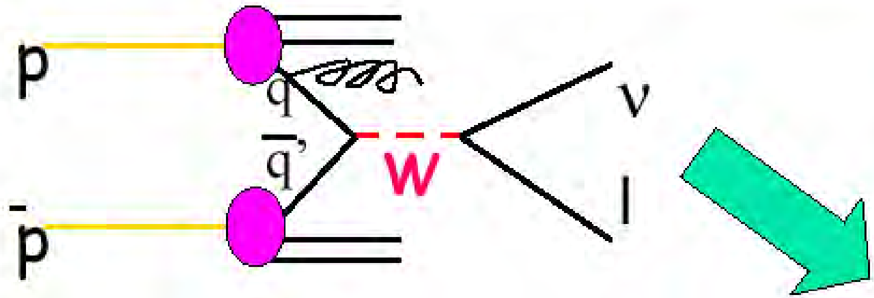
σ_Z^{tot}=1.97±0.01(stat)±0.04(sys)±0.10(lumi) nb

LHC production cross sections

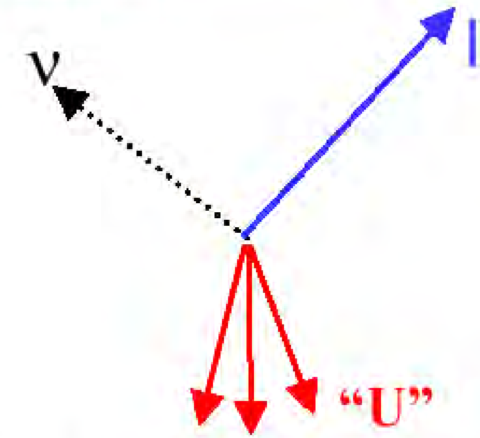


Bestimmung der W Masse

W Produktion am TeV:



Beobachtung im Detektor:



1. Berechne transversale Masse

$$M_T = \sqrt{(E_T^{\ell} + E_T^{\nu})^2 - (\vec{P}_T^{\ell} + \vec{P}_T^{\nu})^2}$$

➔ Verstehe E and **P** Skala und Auflösung

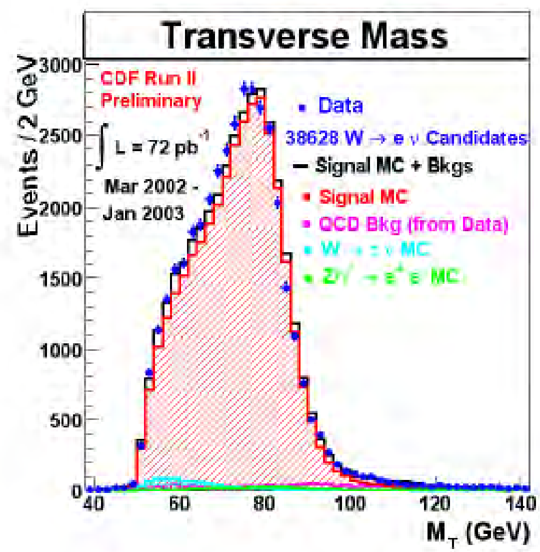
2. Bestimme fehlenden Transversalimpuls.

$$\vec{P}_T^{\nu} = -(\vec{P}_T^{\ell} + \vec{U})$$

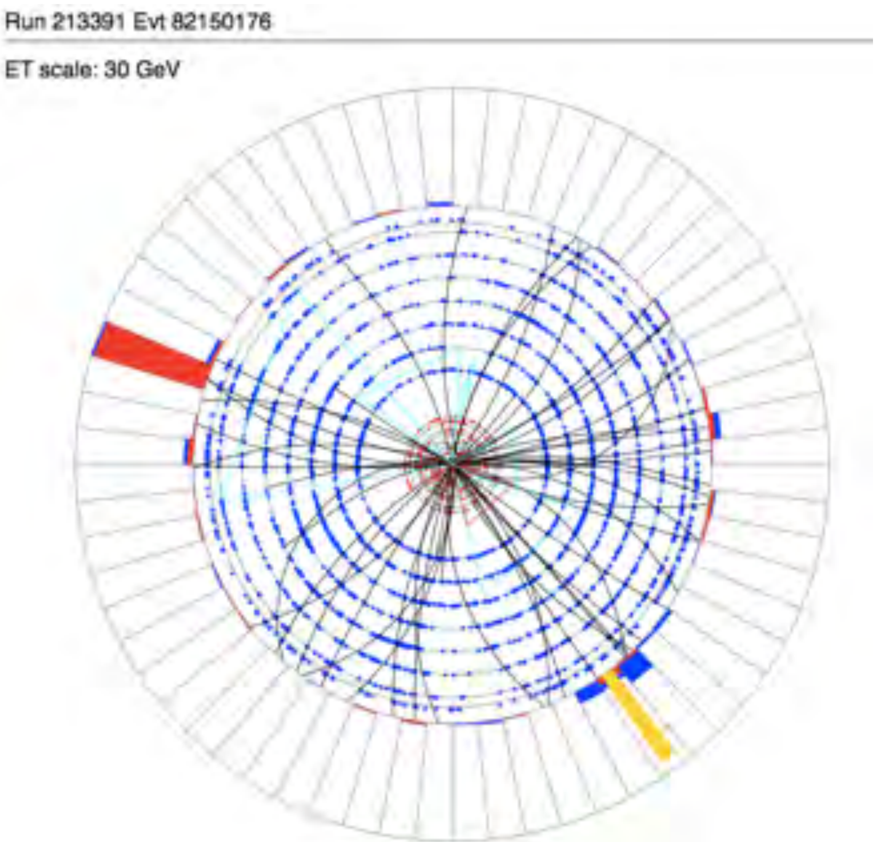
➔ modelliere ‚*U*nderlying event" und Rückstossverteilung , etc.

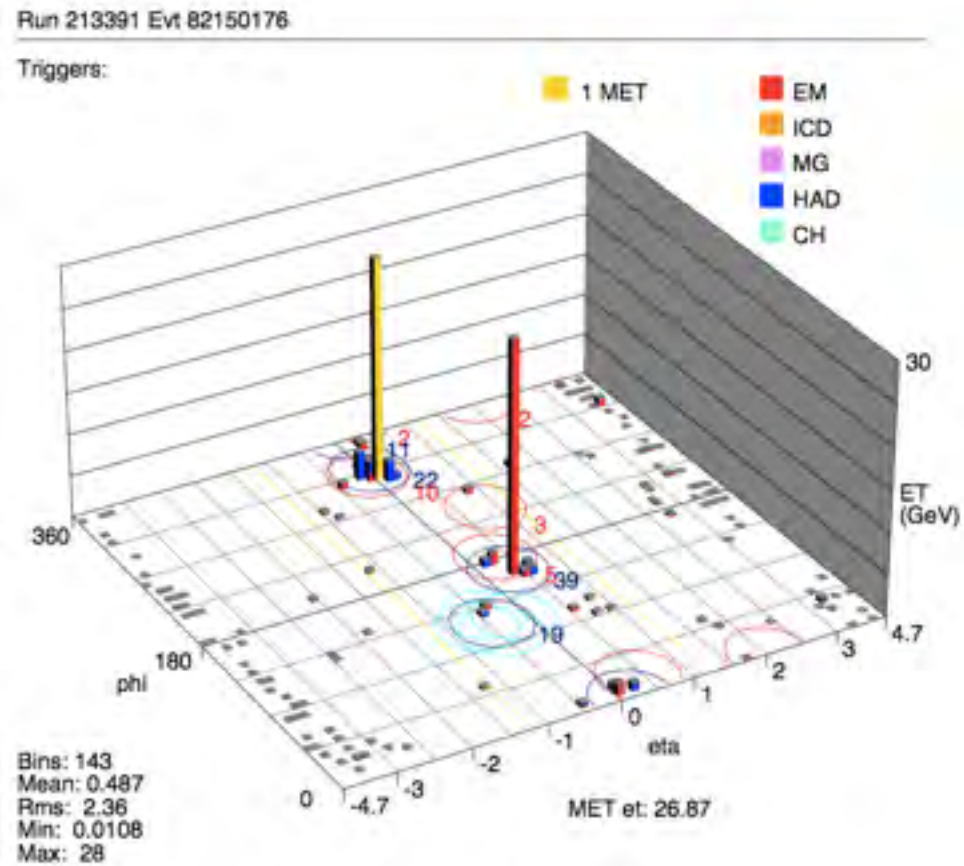
3. Messung von M_W aus M_T Verteilung

➔ Vergleich von Verteilung in den Daten mit Templates

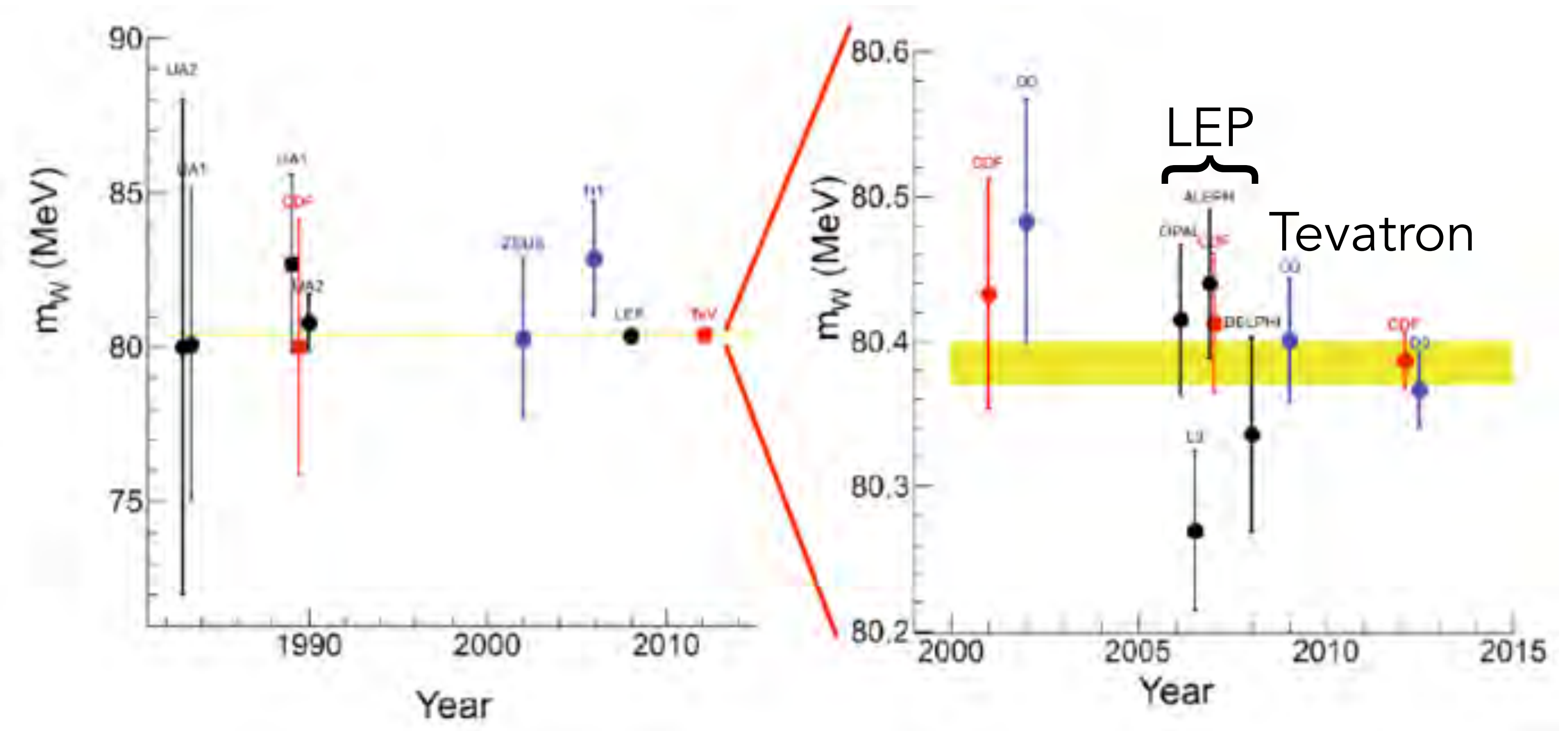


D0: W -> e ν


Run 213391 Evt 82150176
ET scale: 30 GeV


Run 213391 Evt 82150176
Triggers:
1 MET
EM
ICD
MG
HAD
CH
30
ET (GeV)
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
Bins: 143
Mean: 0.487
Rms: 2.36
Min: 0.0108
Max: 28
MET et: 26.87

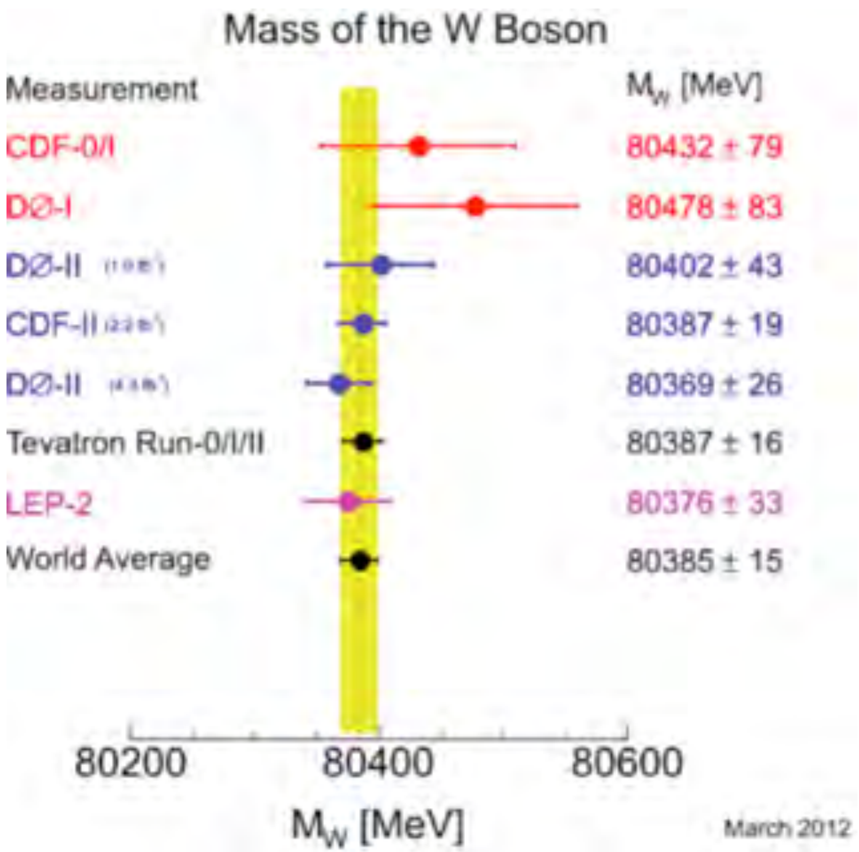
M_W from Tevatron and LEP

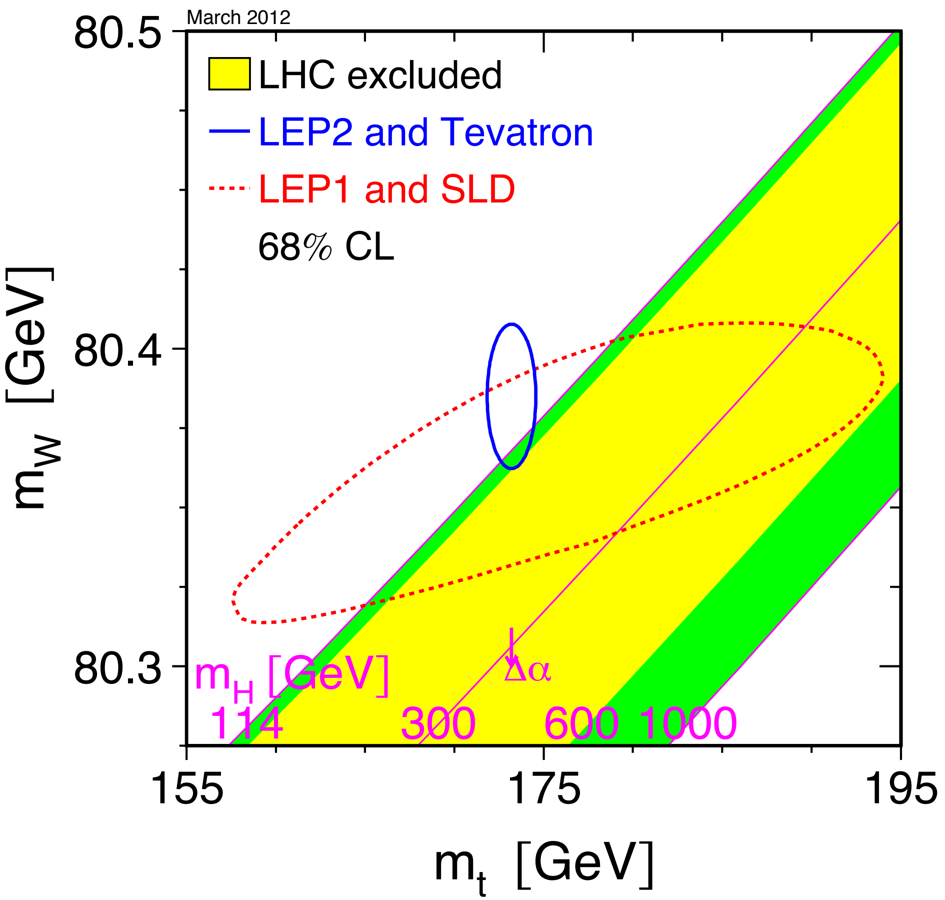


Tevatron: $M_W = 80387 \pm 16$ MeV

LEP: $M_W = 80376 \pm 33$ MeV

world average of M_w and its impact on precision SM predictions





Measurement of the W-boson mass in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

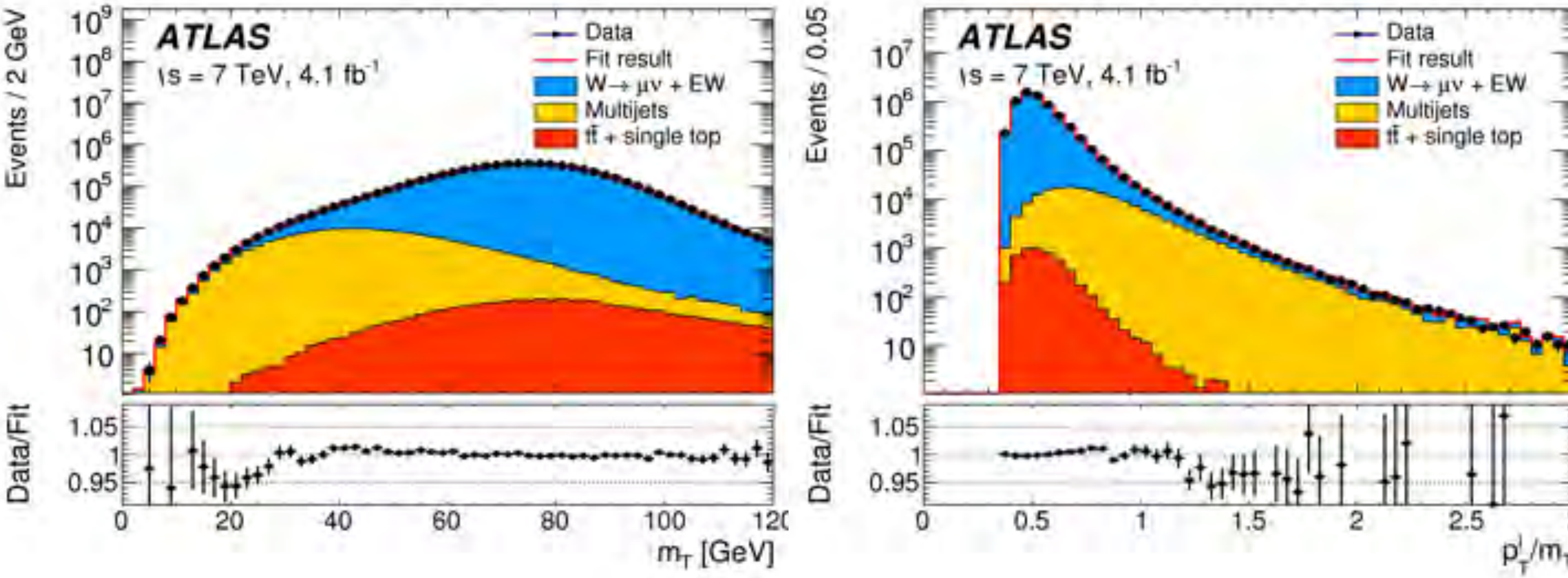
arXiv:1701.07240

A measurement of the mass of the W boson is presented based on proton-proton collision data recorded in 2011 at a centre-of-mass energy of 7 TeV with the ATLAS detector at the LHC, and corresponding to 4.6 fb−1 of integrated luminosity. The selected data sample consists of 7.8× 10^6 candidates in the $W \to \mu\nu$ channel and 5.9×10^6 candidates in the $W \to e\nu$ channel. The W-boson mass is obtained from template fits to the reconstructed distributions of the charged lepton transverse momentum and of the W boson transverse mass in the electron and muon decay channels, yielding

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

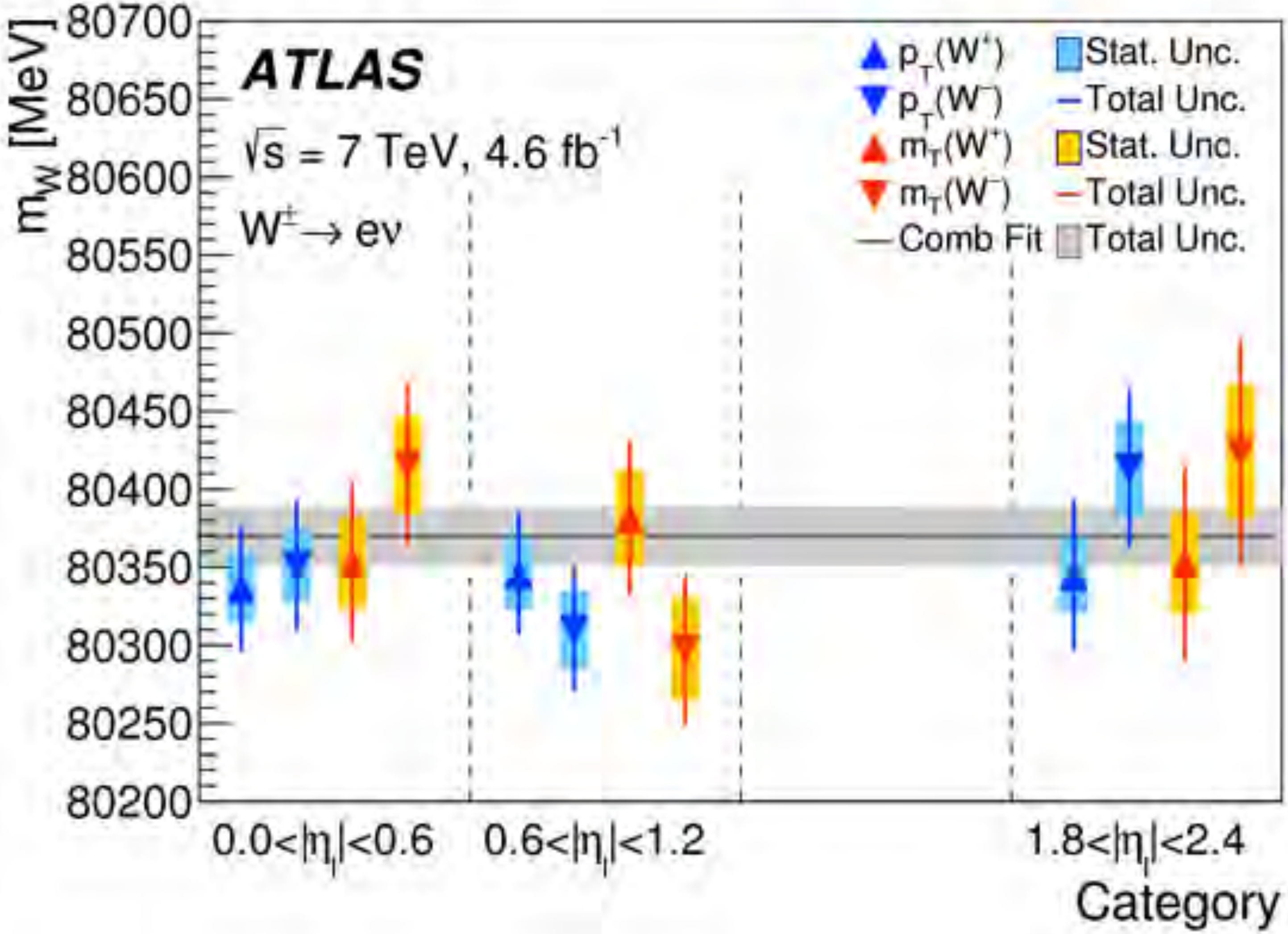
where the first uncertainty is statistical, the second corresponds to the experimental systematic uncertainty, and the third to the physics-modelling systematic uncertainty. A measurement of the mass difference between the W^+ and W^- bosons yields $m_{W+-} = -29 \pm 28$ MeV.

M_W at LHC



ATLAS
√s = 7 TeV, 4.1 fb⁻¹
Data
Fit result
W→ μν + EW
Multijets
tt̄ + single top
Events / 2 GeV
Data/Fit
m_T [GeV]
Events / 0.05
p_T^l/m_T

M_W at LHC



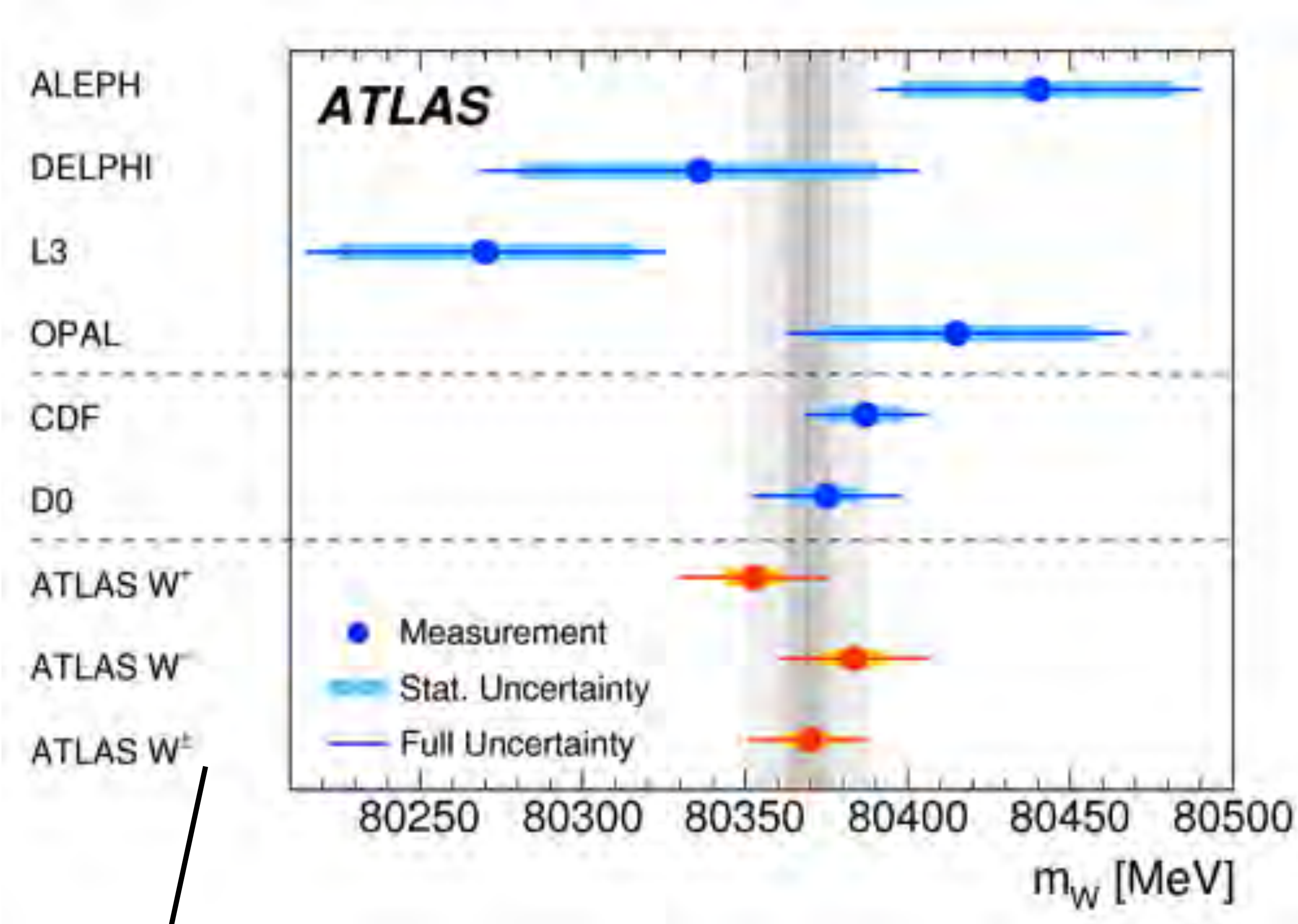
ATLAS
√s = 7 TeV, 4.6 fb-1
W± → eν
pT(W+)
pT(W-)
mT(W+)
mT(W-)
Comb Fit
Stat. Unc.
Total Unc.
Stat. Unc.
Total Unc.
Total Unc.
mW [MeV]
80700
80650
80600
80550
80500
80450
80400
80350
80300
80250
80200
0.0<|ηl|<0.6
0.6<|ηl|<1.2
1.8<|ηl|<2.4
Category

M_W at LHC

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

arXiv:1701.07240

M_W world summary

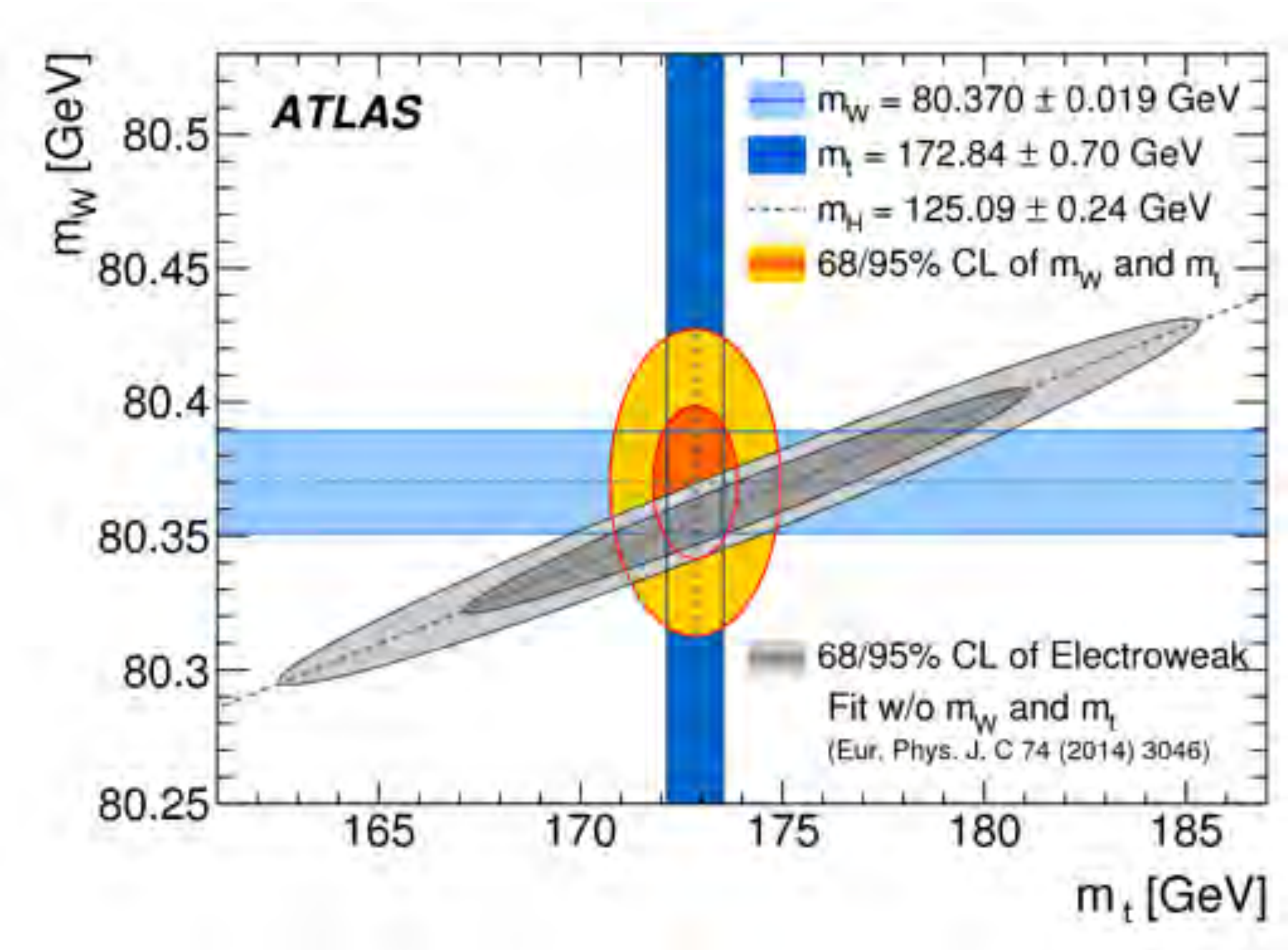


$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})\text{MeV}$$

$$= 80370 \pm 19\text{MeV}$$

arXiv:1701.07240

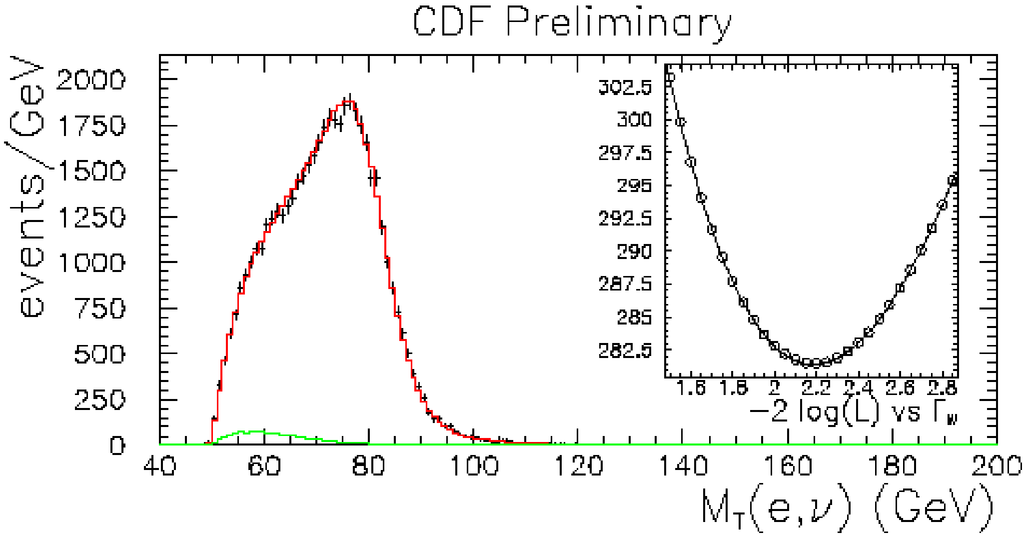
comparison: m_W, m_t, m_H and precision ew fits

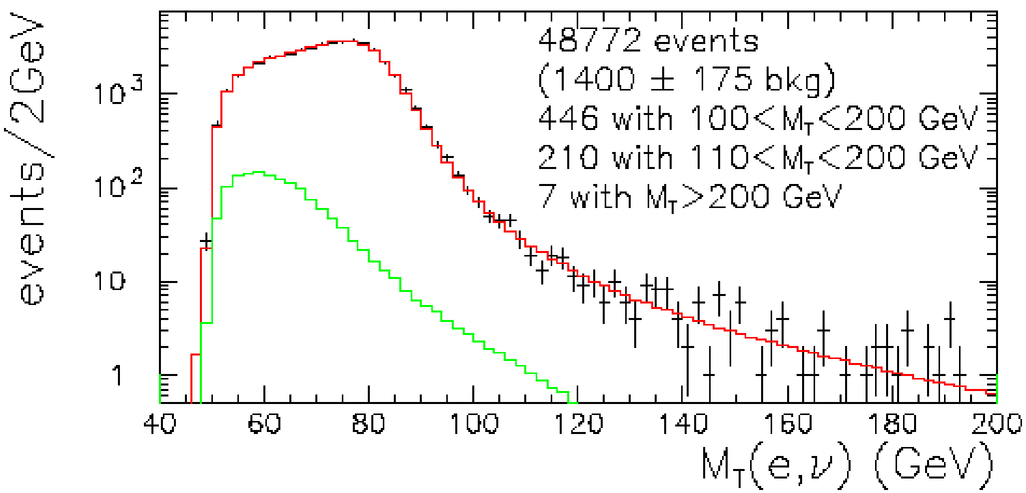


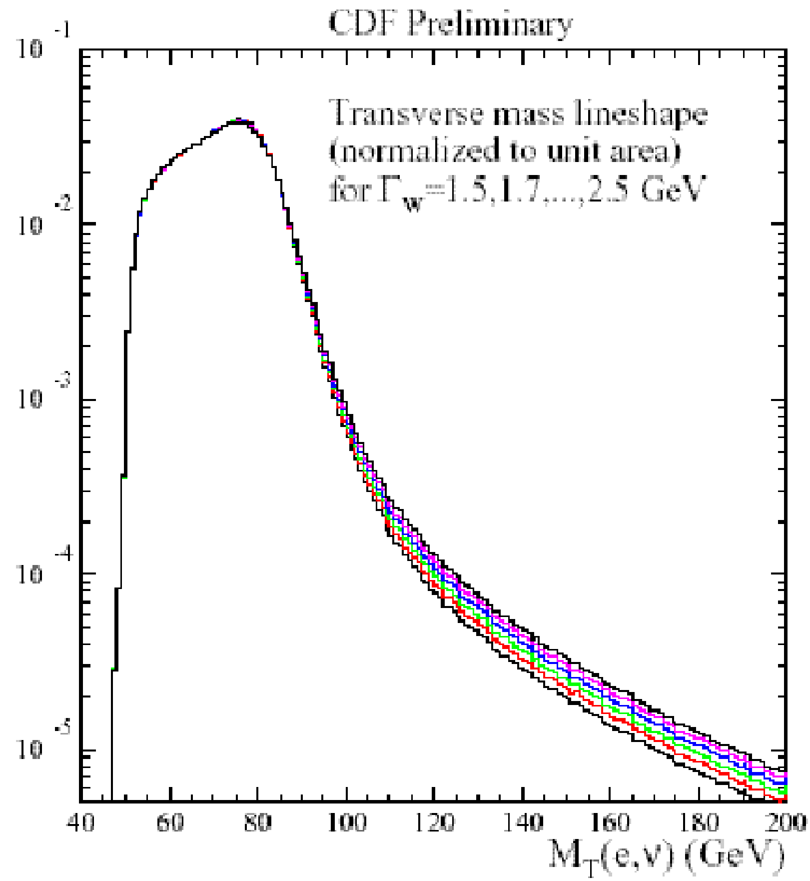
arXiv:1701.07240

Direkte Messung der W Breite

Anzahl der Ereignisse mit extrem hohen M_T hängt von der W Breite ab







$\Gamma_W = 2.19 \pm 0.17\ (stat) \pm 0.09\ (syst)$ GeV

(SM value $\Gamma_W = 2.077 \pm 0.014$ GeV)

Indirekte Messung der W Breite

W, Z Wirkungsquerschnitt Systematisch begrenzt

➢ Reduzierung der Systematischen Fehler im Verhältnis von Wirkungsquerschnitten

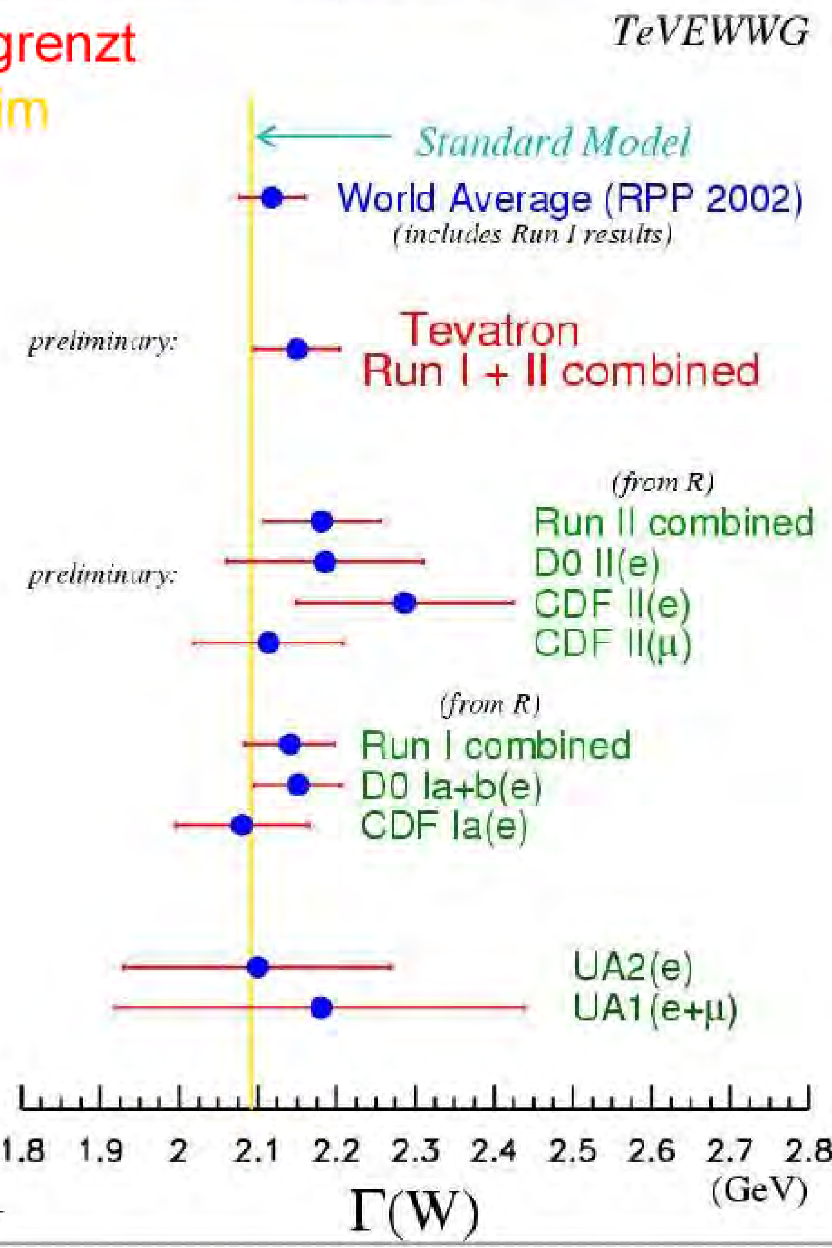
Γ(W) – PDG		2.118 ± 0.042 GeV
Run II		2.181 ± 0.074 GeV

Theorie

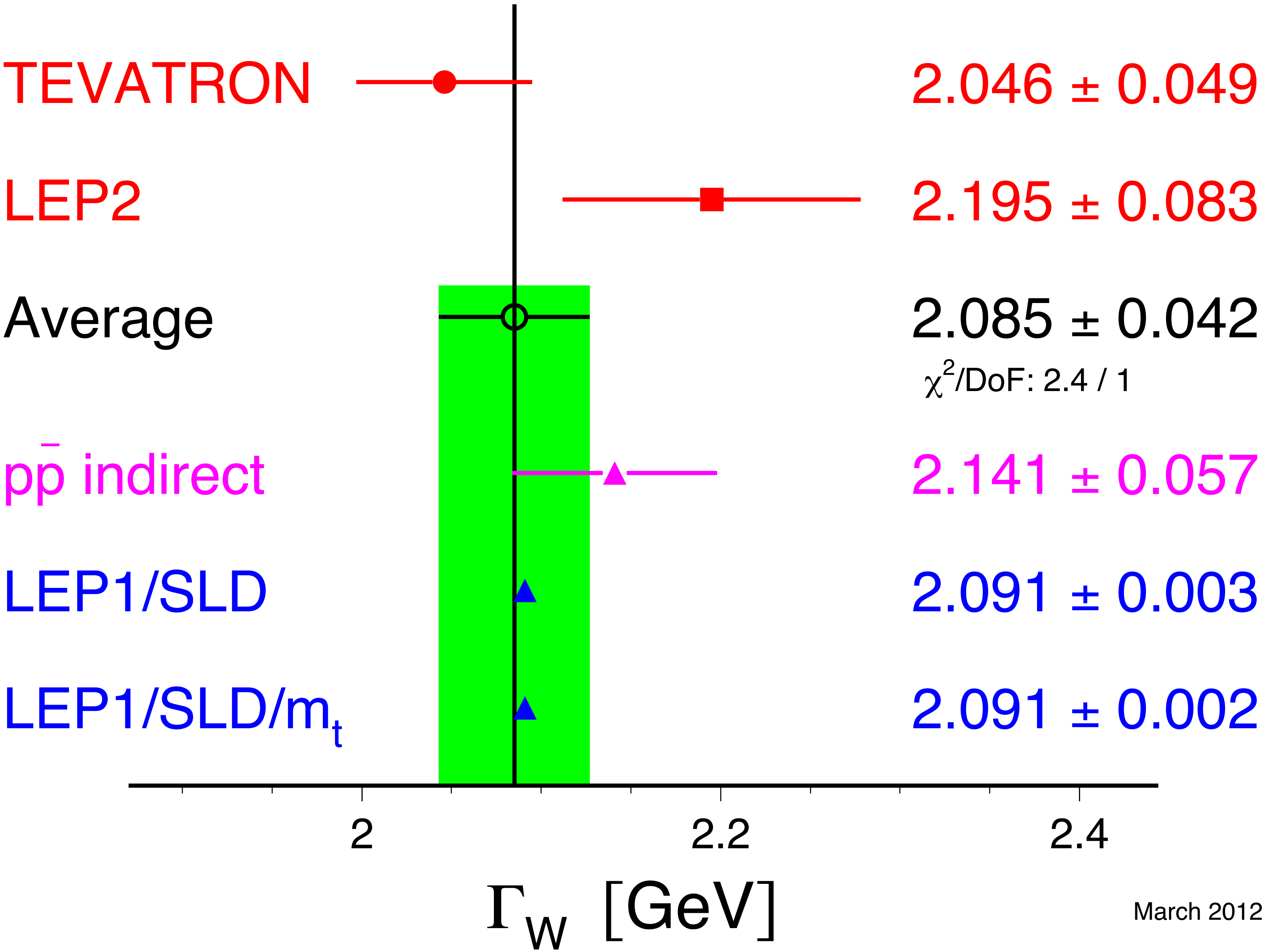
$$R = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)}$$

LEP

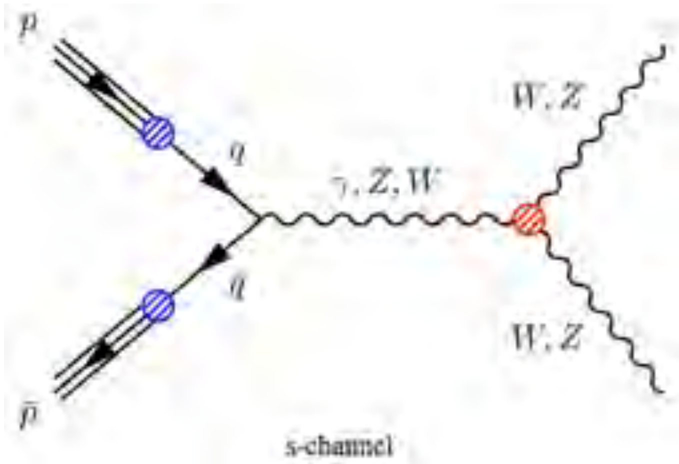
	R
CDF e	9.88 ± 0.24 ± 0.44
CDF μ	10.69 ± 0.28 ± 0.31
D0 e	10.34 ± 0.35 ± 0.49
Combined	10.36 ± 0.16 ± 0.27



W-Boson Width [GeV]



di-boson production and triple gauge couplings:



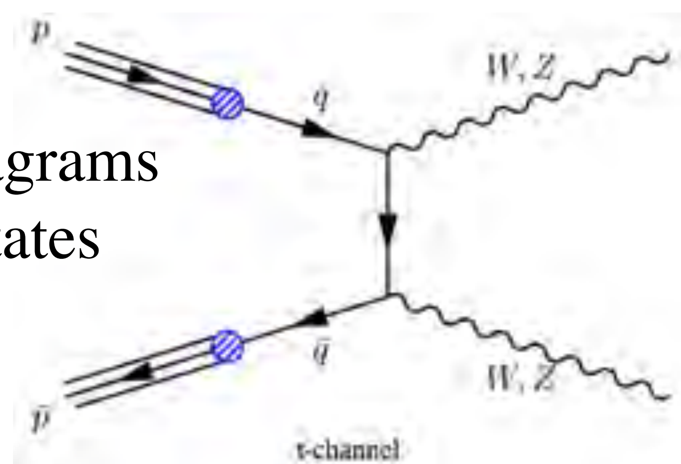
γ, Z –> W^+W^-

W –> WZ, W γ

~~γ, Z –> ZZ~~

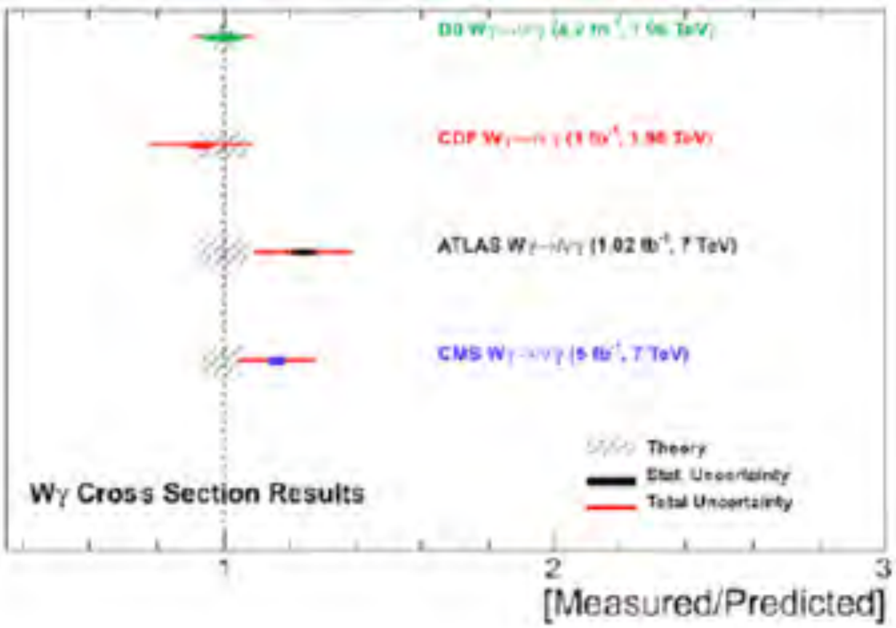
- SM: space-like diagrams are =0 if 2 of the 3 bosons are identical
- BSM: may contribute to triple gauge couplings in non-standard ways

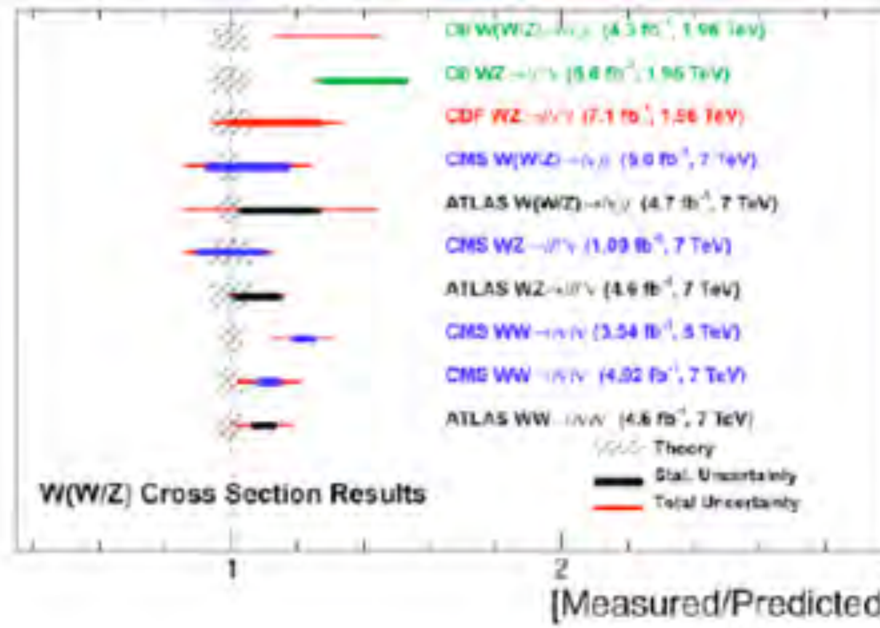
SM: time-like diagrams with same final states are allowed (n.b.: no triple-gauge!)

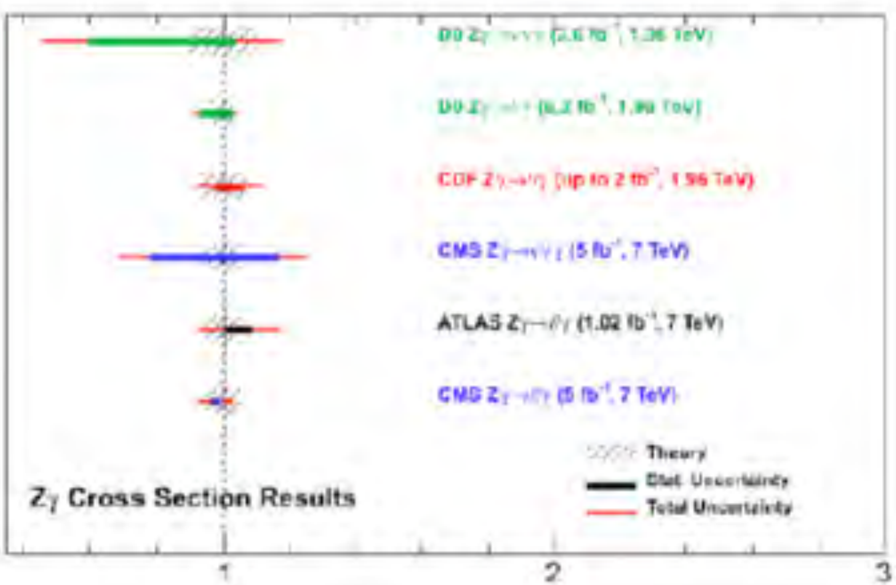


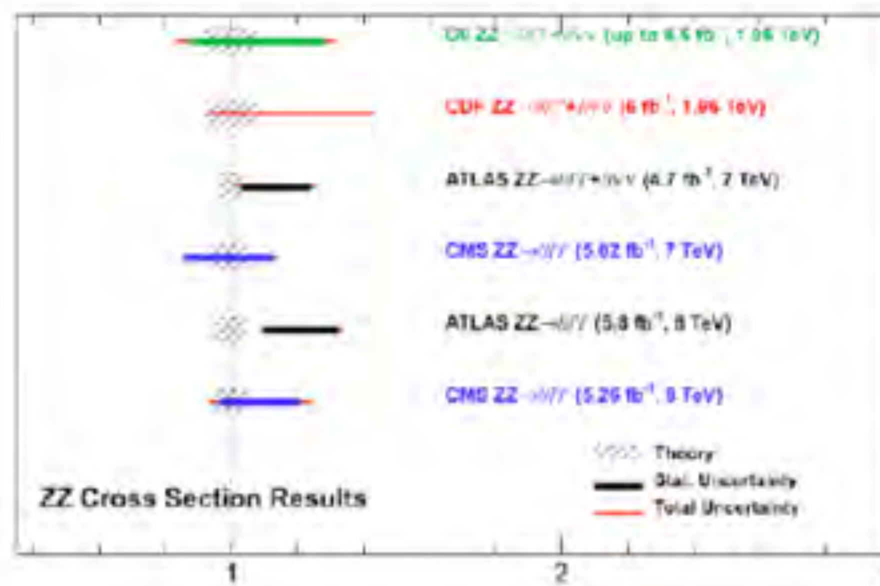
these are SM „background“ to signals of triple-gauge couplings!

Di-Boson production cross sections









Summary:

- detailed measurements with W und Z Bosonen at hadron colliders: production cross sections in good agreement with expectations of SM
- at design luminosities: 10^9 W/a, 10^8 Z/a
- Z-Boson Parameter (M_Z, Γ_Z) als input von LEP; Z^0s als tool zur Kalibration
- significant tests of SM: precise determinations of
  - masses
  - decay width
  - production cross sections
  - production asymmetries
  - triple-gauge couplings (approximate)
- so far, all measurements in excellent agreement with SM predictions
- LHC: $\Delta \mathbf{M_w}$ **~ 19 MeV** (ATLAS)
- first measurements of triple-gauge couplings from di-boson production: also in good agreement; may become indicative for BSM physics

Literature:

- Karl Jakobs: *Physics at the LHC -- From Standard Model measurements to Searches for New Physics*, arXiv:1206.7024 .

- ATLAS Collab: *Measurement of the W-boson am in pp collisions at √s= 7 TeV with the ATLAS detector, arXiv:1701.07240.*

- Particle Data Group: *Review of particle properties*, Chin.Phys. C40 (2016) no. 10, 100001 .
  http://pdg.lbl.gov/2017/reviews/rpp2017-rev-standard-model.pdf

next lectures:

- 8.1.2018: BSM
- 15.1.2018: Higgs (I)
- 22.1.2018: Higgs (II)
- 29.1.2018: Heavy Quarks
- 5.2.2018: Future…

Happy Holidays!