Tests of the Standard Model of electroweak interactions

this lecture:

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

lecture 7:

- QCD, Jets, structure functions

lecture 8:

- Top Quark physics

lectures 9/10:

- Higgs Boson

The „Standard Model“ of Particle Physics

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

Elementary Particles

	Generation 1	Generation 2	Generation 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 $\sin^2\theta_w$.

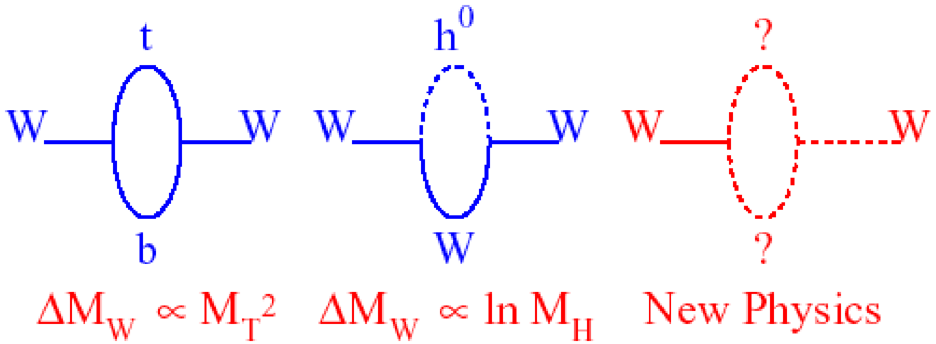
Tests of the elektroweak standard model at hadron colliders

- 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:

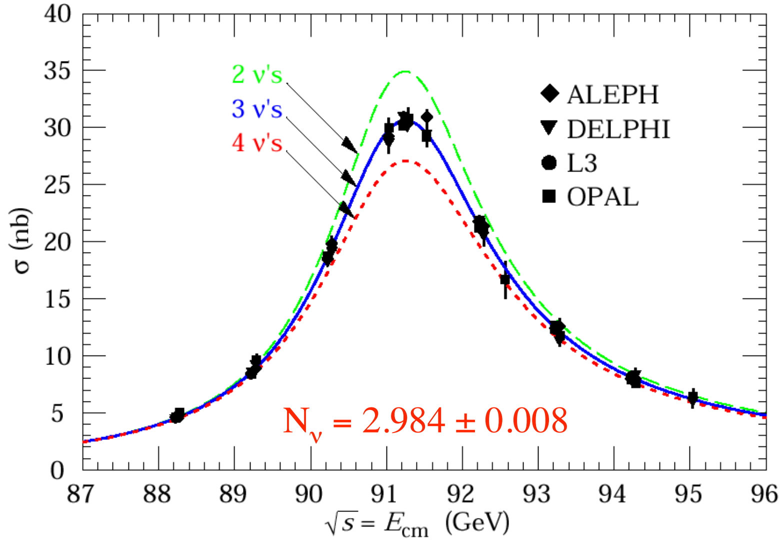
  production, decays and properties of gauge bosons are modified by "new physics":



- 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^- - annihilation):

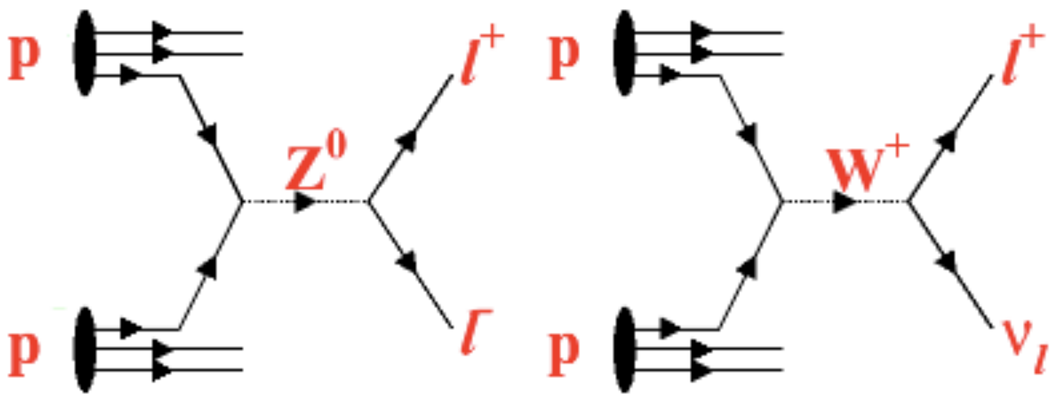


$M_Z = (91.1875 \pm 0.0021)$ GeV

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

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

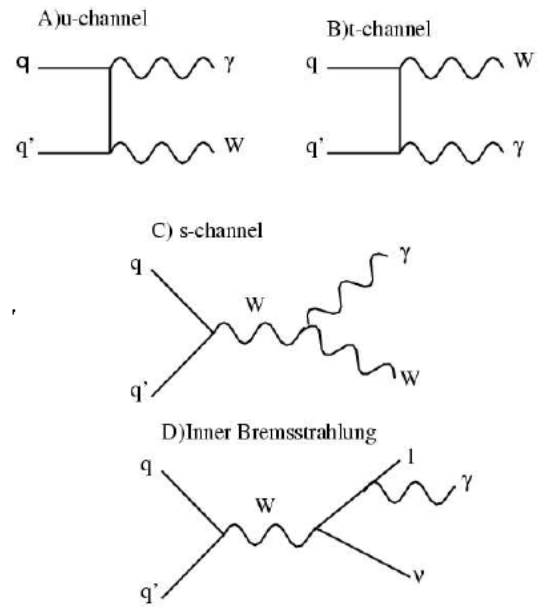
production and decay of gauge bosons



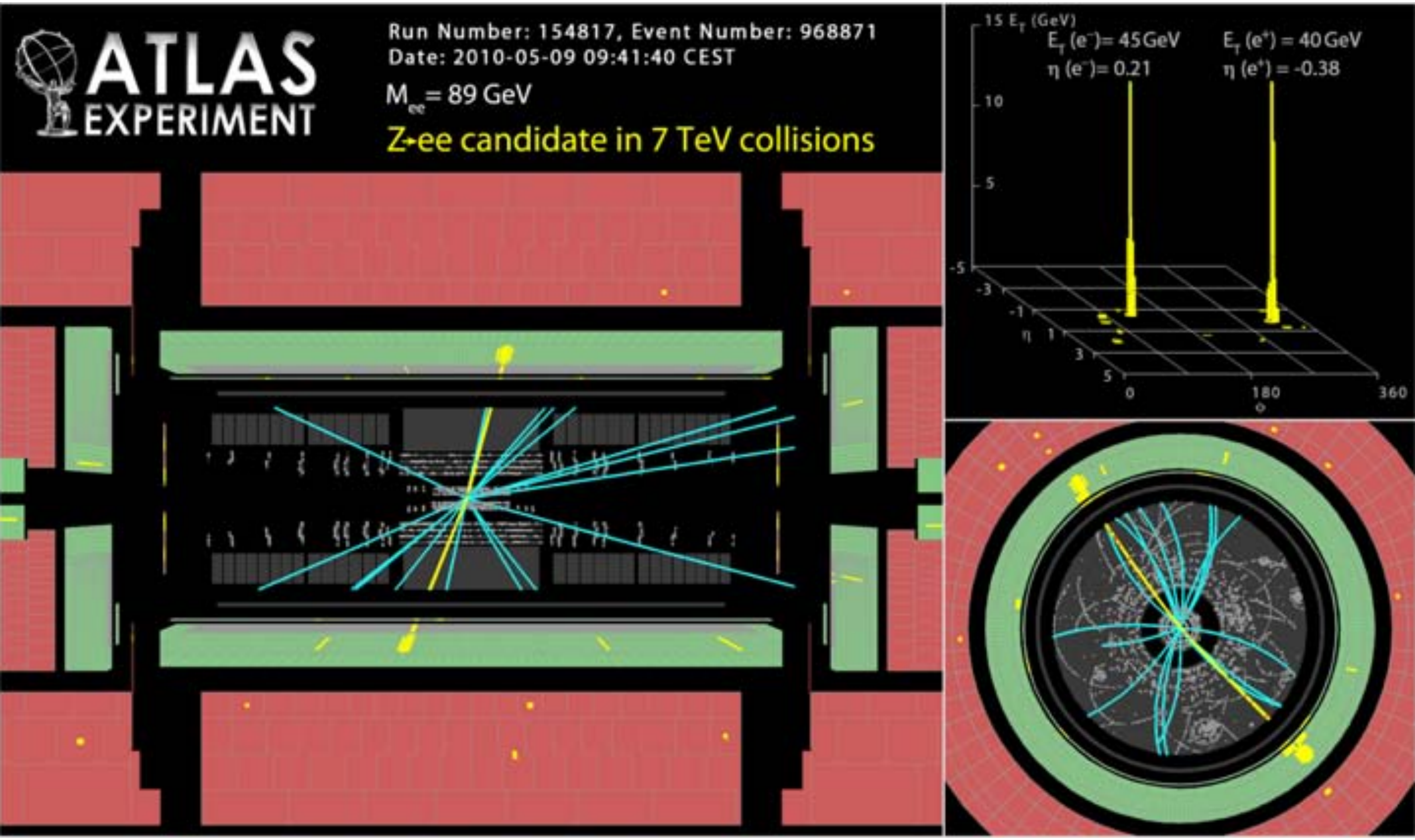
(missing energy)

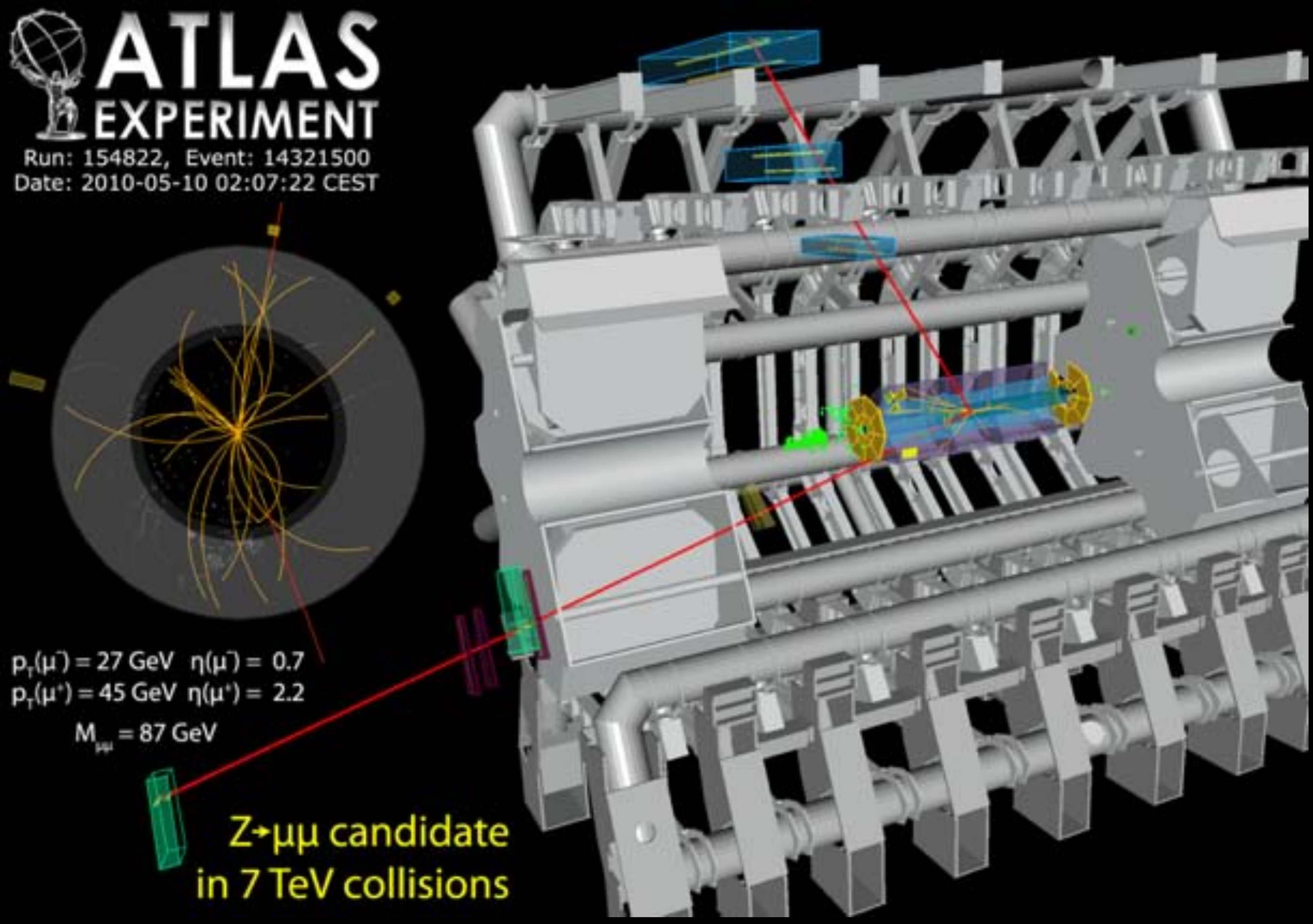
- hadronic final states cannot be used, due to dominating QCD background

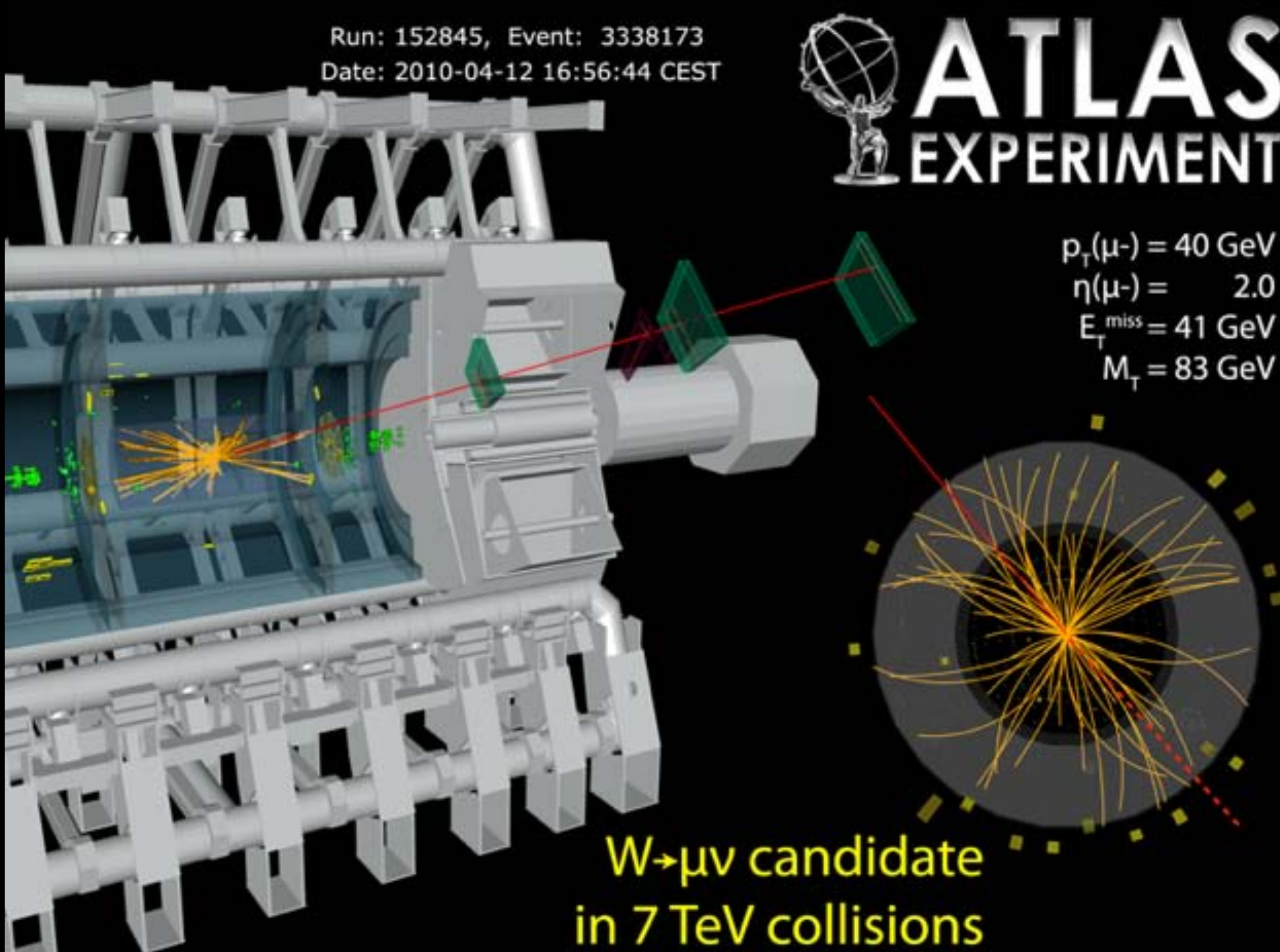
- theoretical uncertainties mainly due to quark-structure of protons

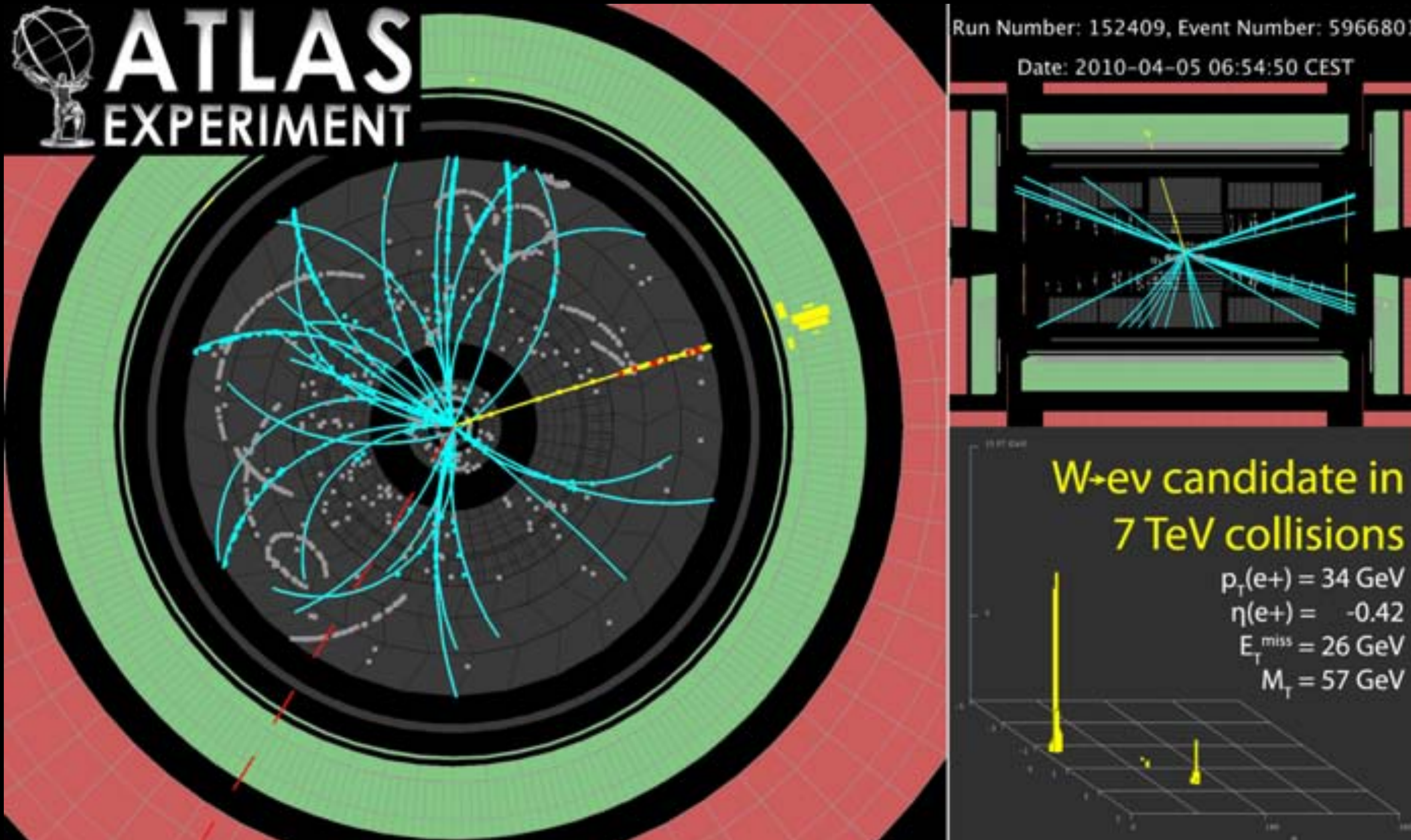


LHC: Beobachtung von Z/W (lept. Zerfall)



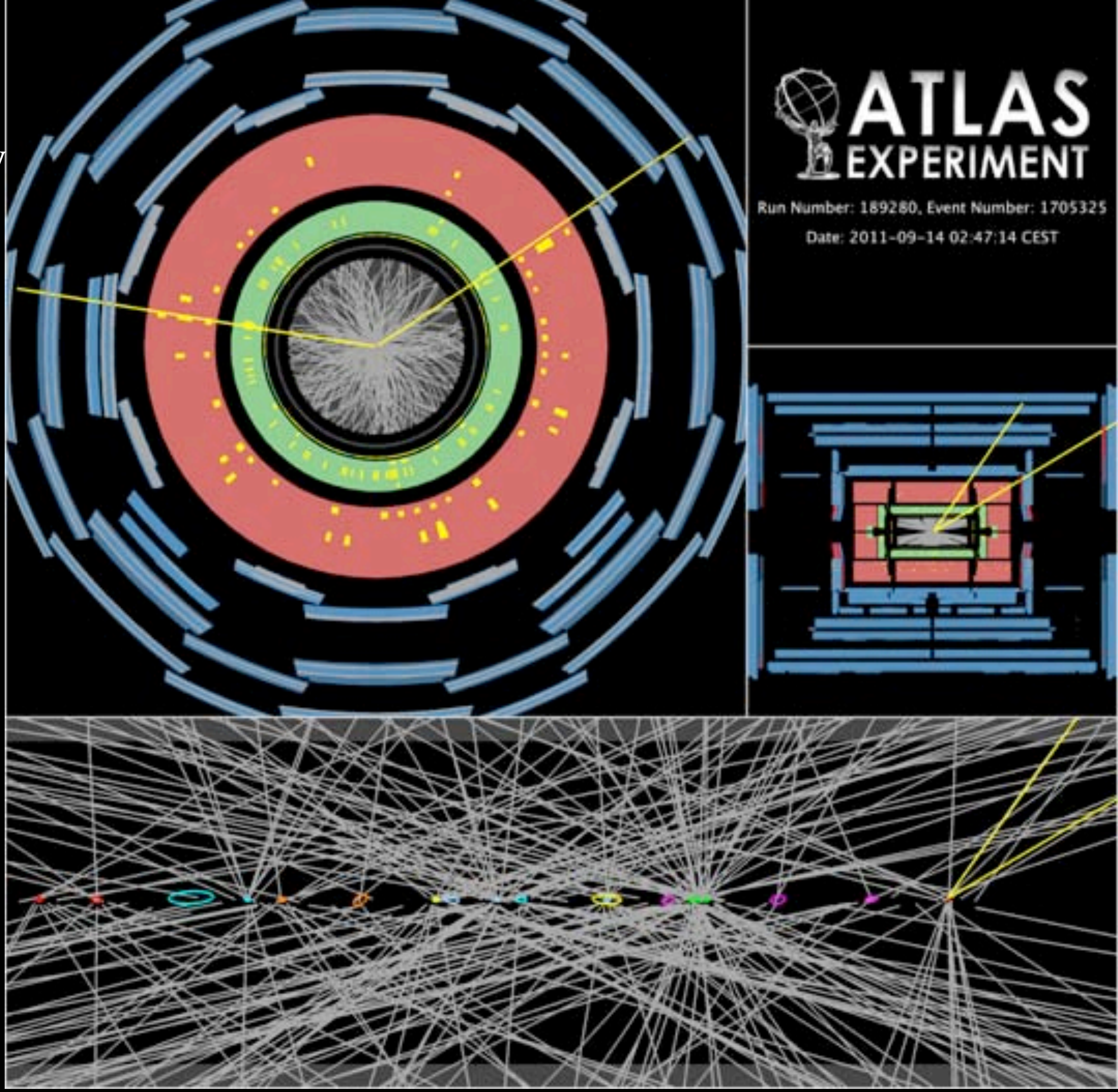

ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-)$ = 27 GeV $\eta(\mu^-)$ = 0.7
$p_T(\mu^+)$ = 45 GeV $\eta(\mu^+)$ = 2.2
$M_{\mu\mu}$ = 87 GeV
Z→μμ candidate
in 7 TeV collisions

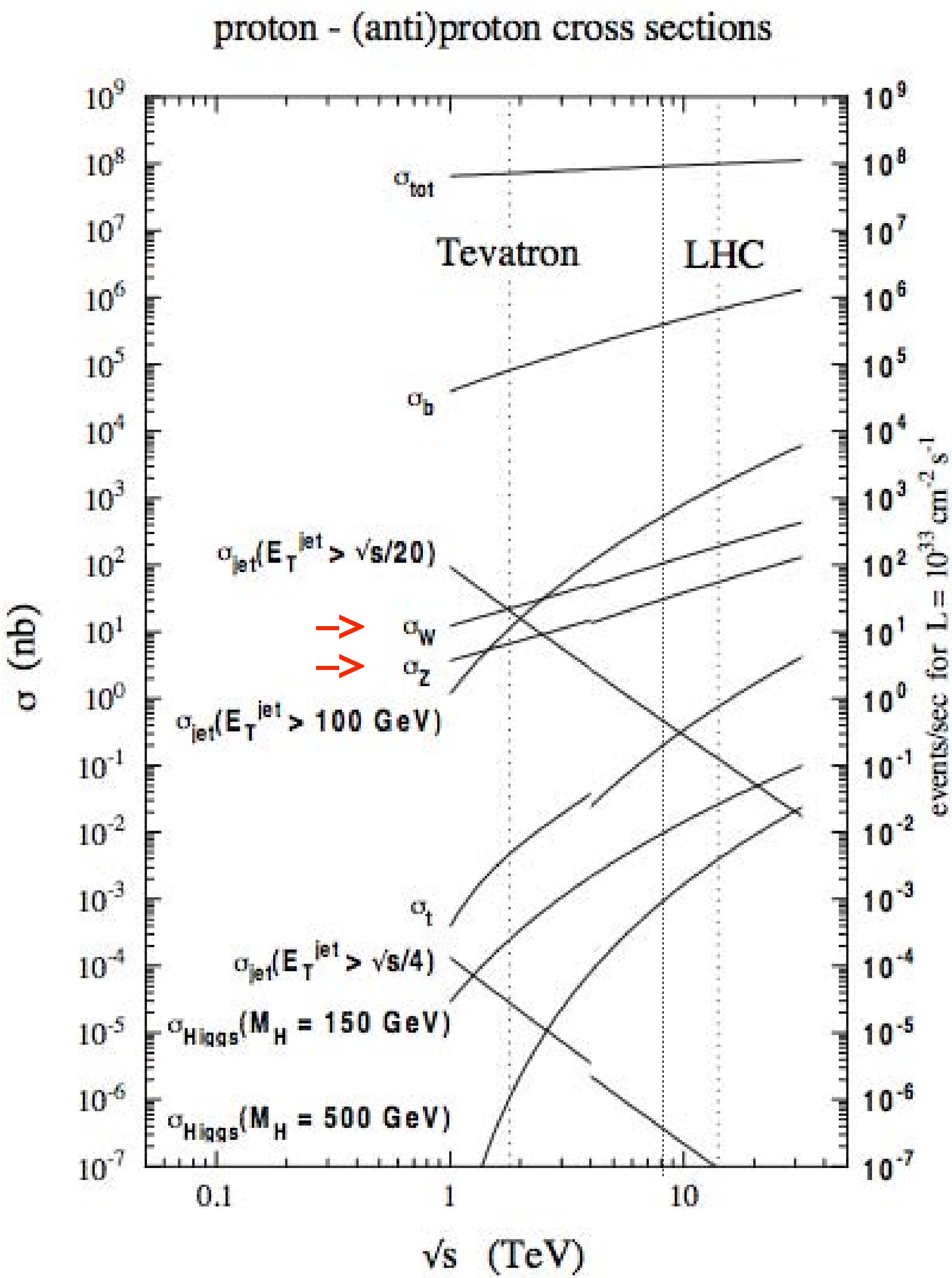

Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST
ATLAS
EXPERIMENT
$p_T(\mu -) = 40$ GeV
$\eta(\mu -) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV
W→μν candidate
in 7 TeV collisions


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
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

Z –> μμ

with 20 secondary vertices ...





proton - (anti)proton cross sections
Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV$)$
σ_t
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H = 150$ GeV$)$
$\sigma_{Higgs}(M_H = 500$ GeV$)$
σ (nb)
$\sqrt{s}$ (TeV)
events/sec for $L = 10^{33}$ cm^{-2} s^{-1}

Tevatron:

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

ATLAS / LHC:

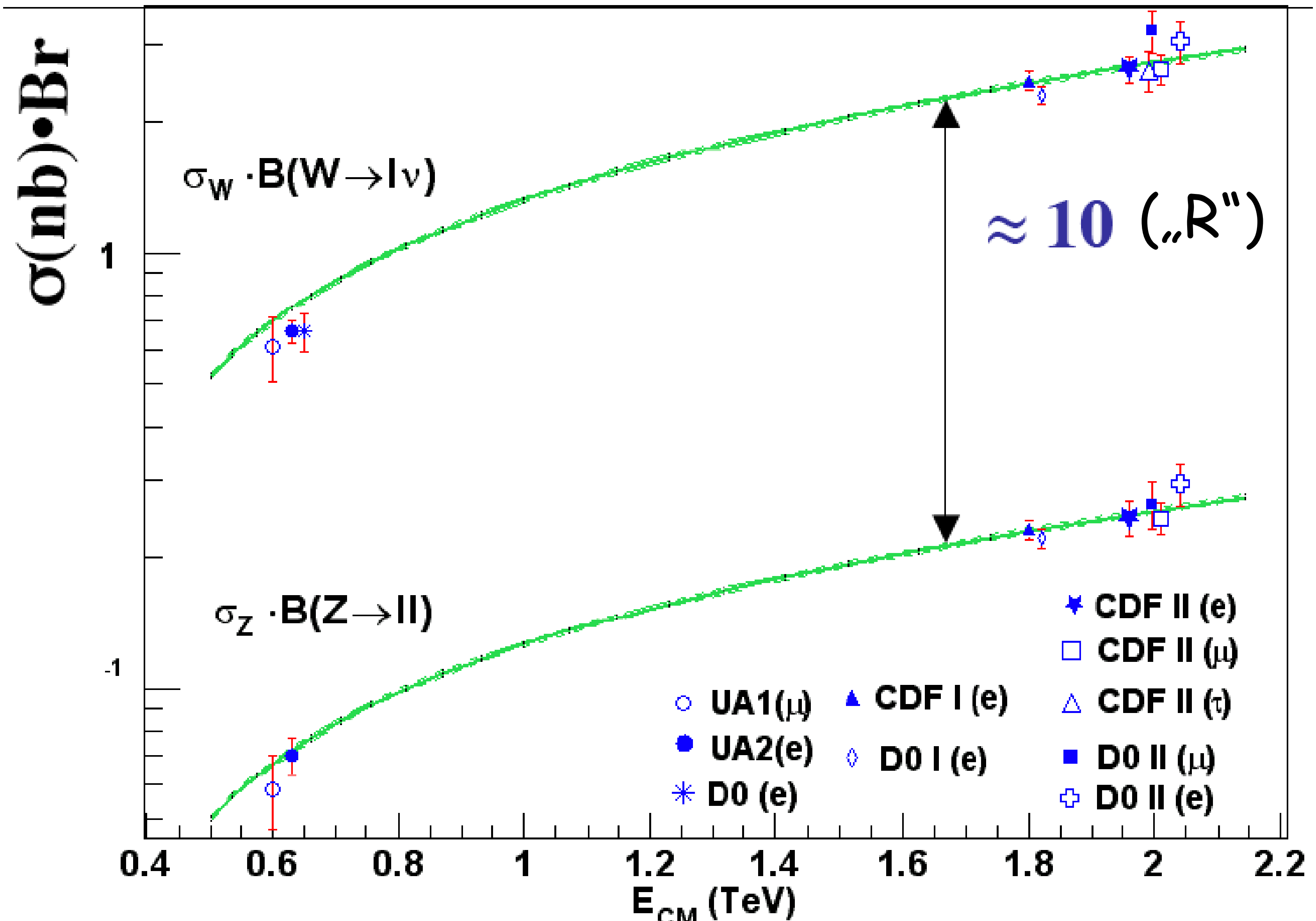
Process	**σ (nb)**	**Events/year ($\mathcal{L}$ = 5 fb^{-1})**
$W \to e\nu$	30	$\sim 10^8$
$Z \to e^+ e^-$	3.0	$\sim 10^7$
$t\bar{t}$	1.6	$\sim 10^7$
Inclusive jets **p_T > 200 GeV**	200	$\sim 10^9$

measurements of production cross sections

- 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

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

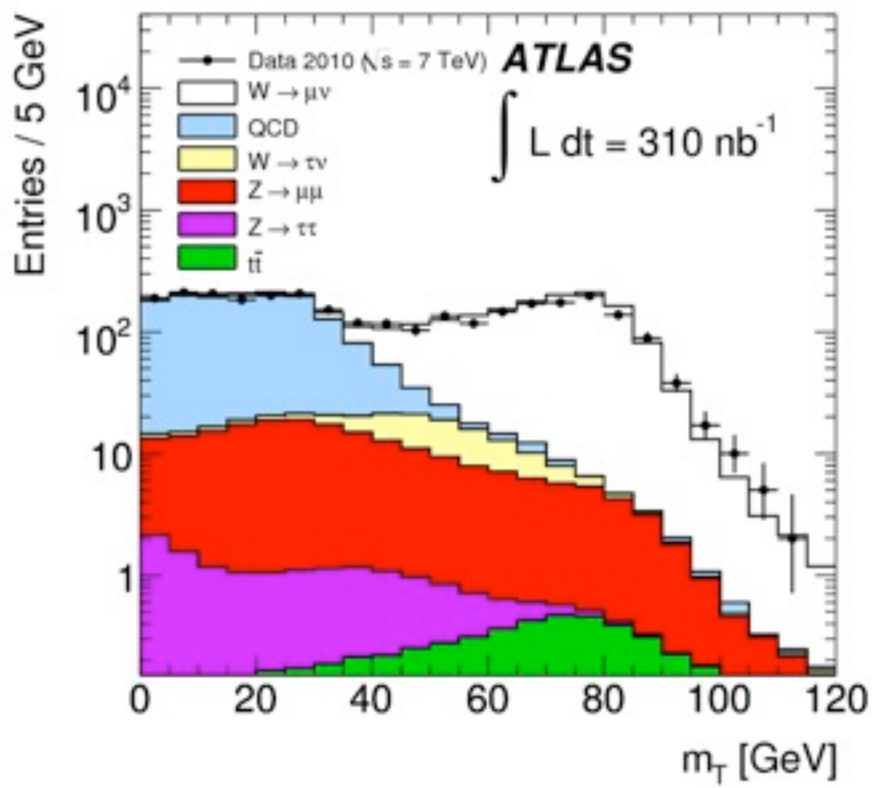
Messung der Produktionsquerschnitte (Tevatron)

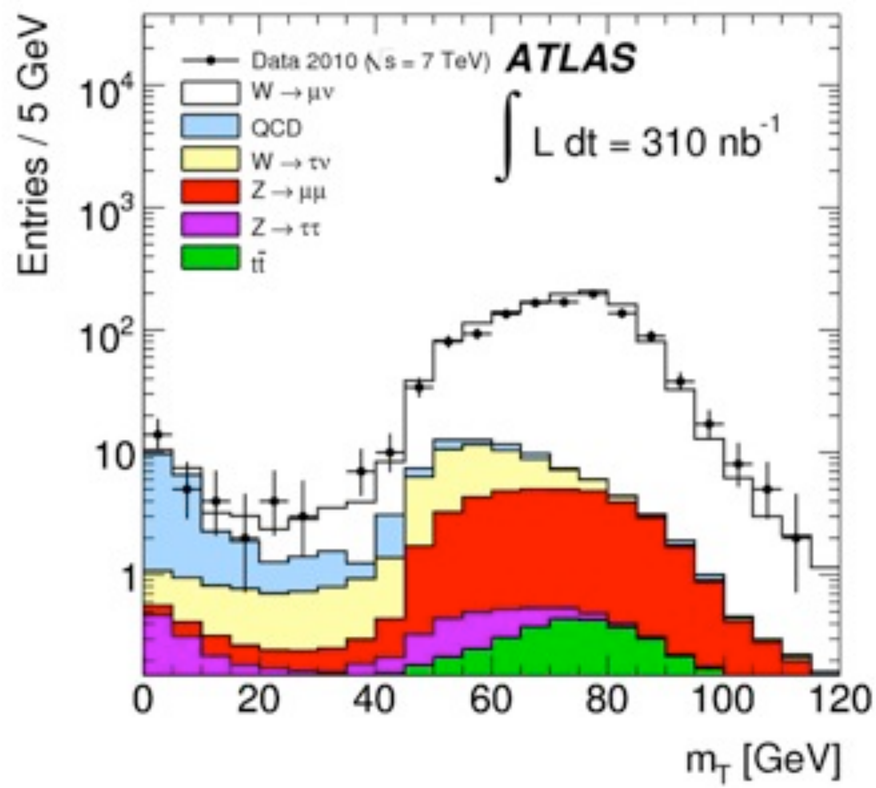


ATLAS Analyse der W/Z Produktionsquerschnitte

arXiv:1010.2130v1

arXiv:1109.5141



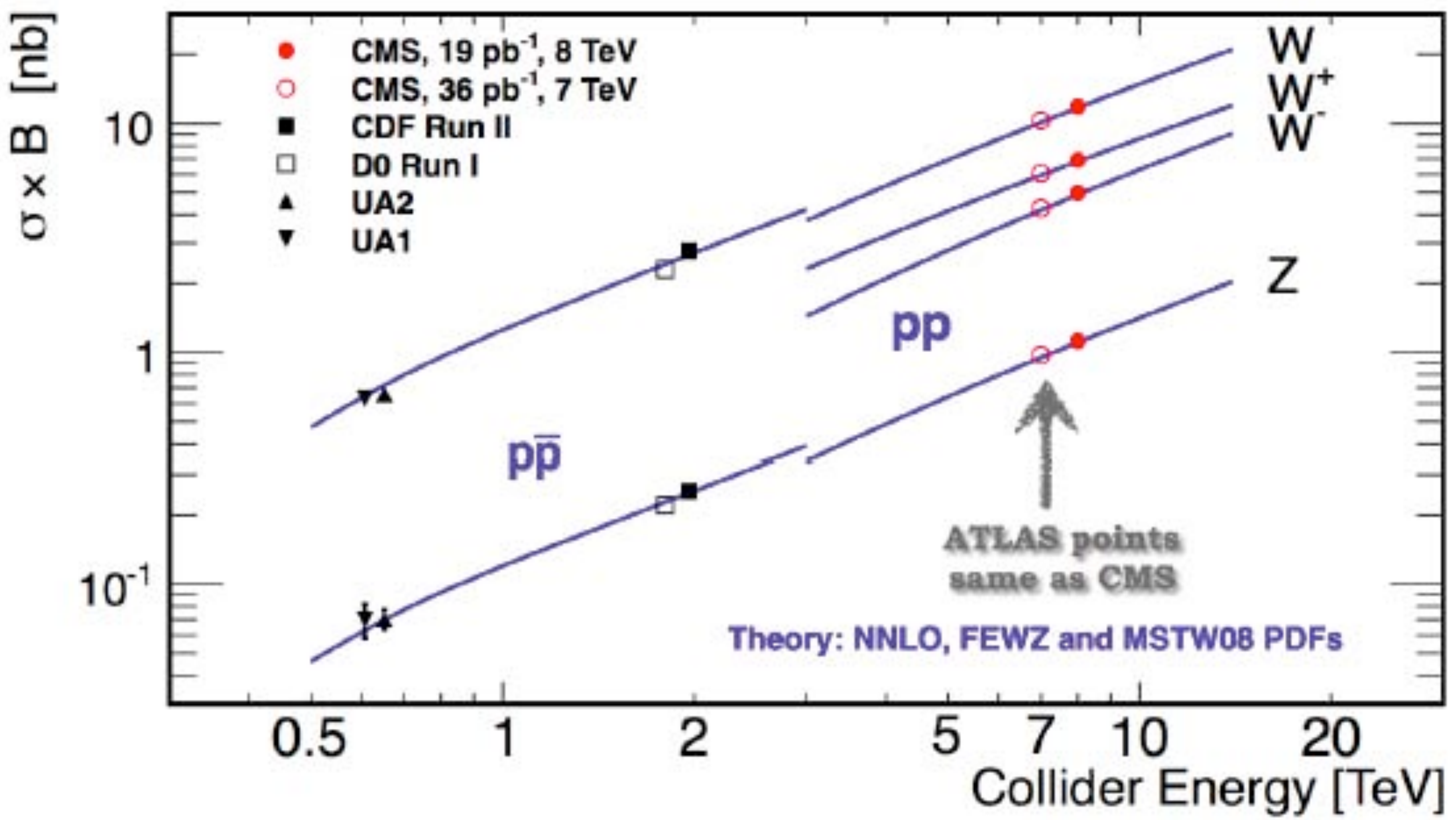


transverse mass distribution
ohne Schnitt in E_T^{miss}

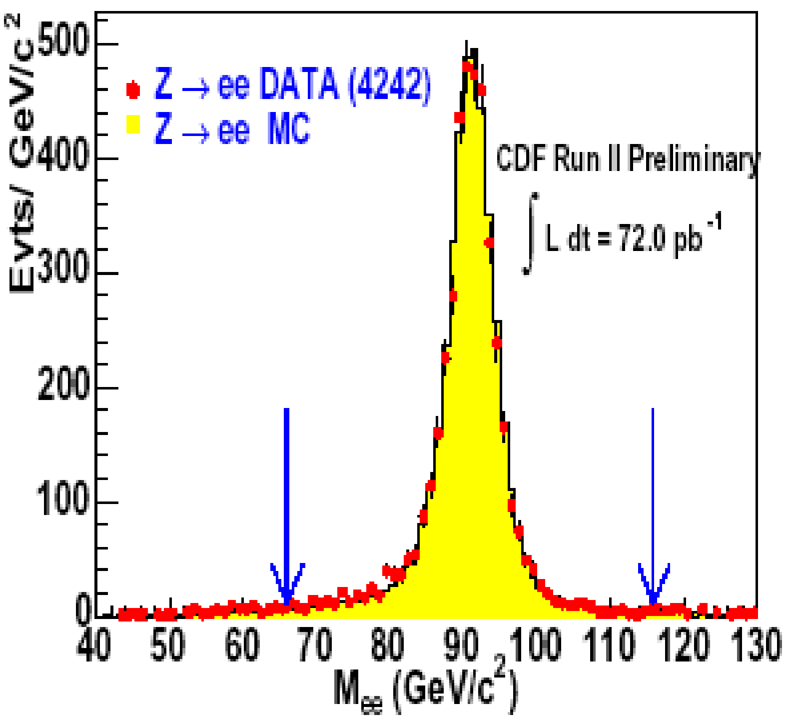
transverse mass distribution
mit Schnitt in $E_T^{miss} > 25$ GeV

W/Z Produktionsquerschnitte

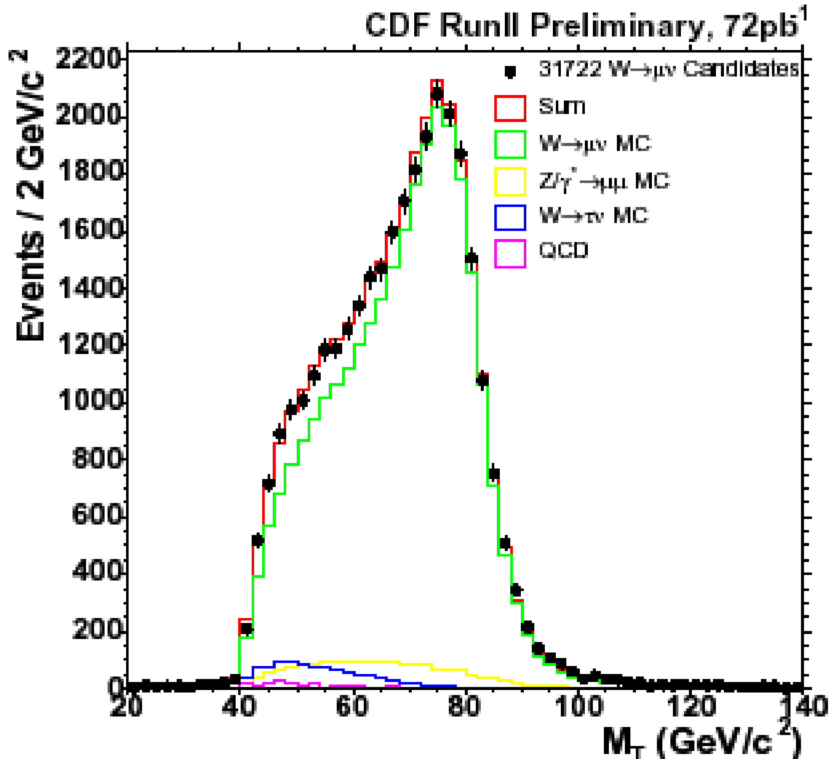
Nov. 2012



measurements of boson masses



invariant pair mass



„transverse mass“:

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

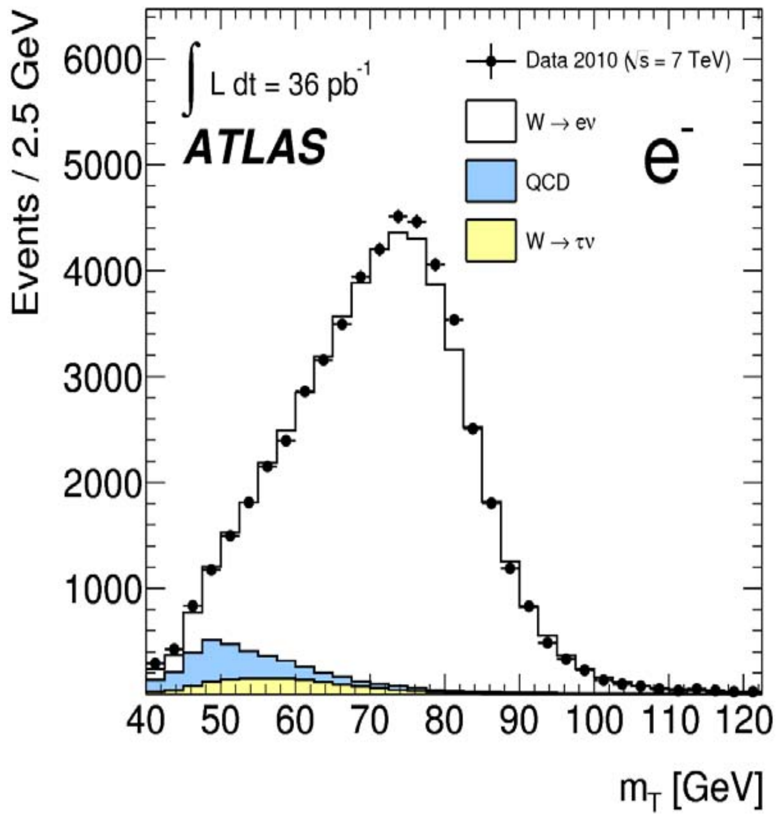
E_T^ν, P_T^ν werden aus Fehlender Energie bestimmt

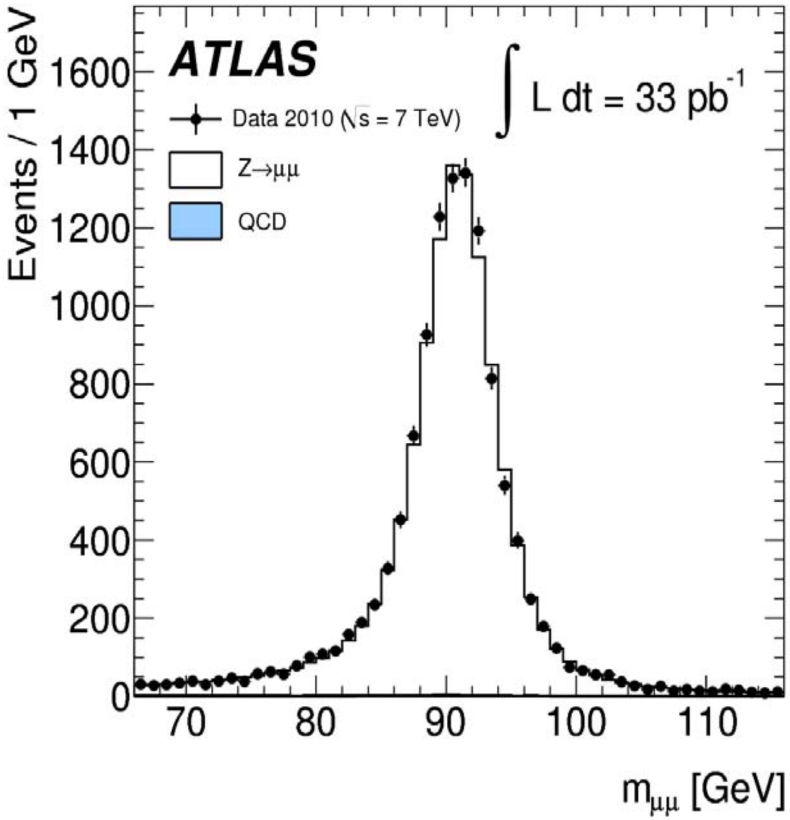
auch verwendet:

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

ATLAS Analyse der W/Z Produktionsquerschnitte

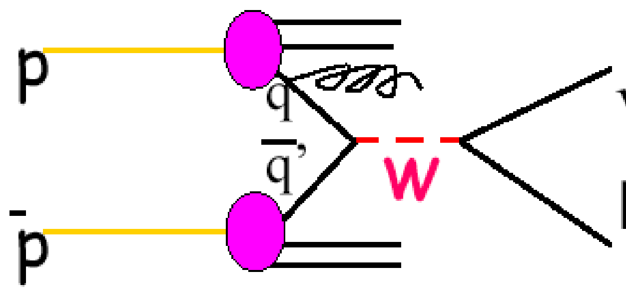
arXiv:1109.5141



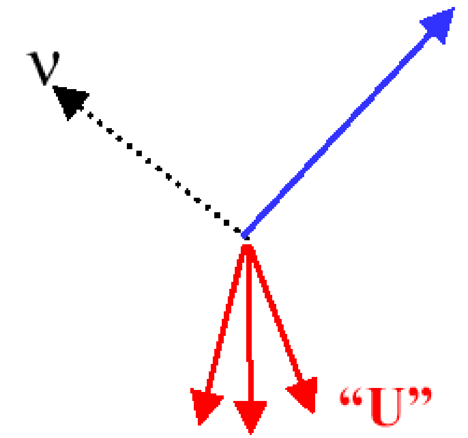


Bestimmung der W Masse

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

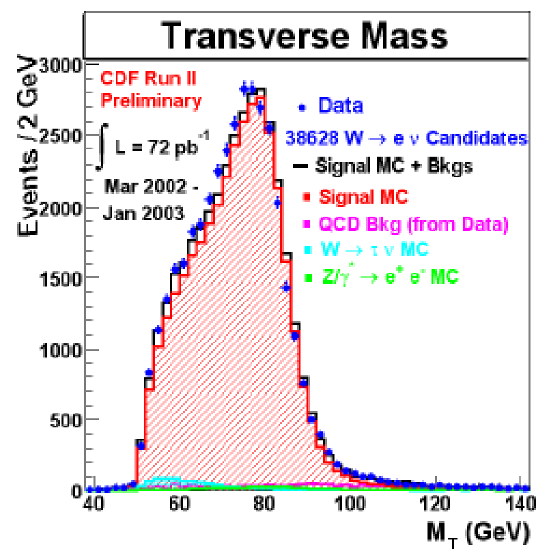
2. Bestimme fehlenden Transversalimpuls.

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

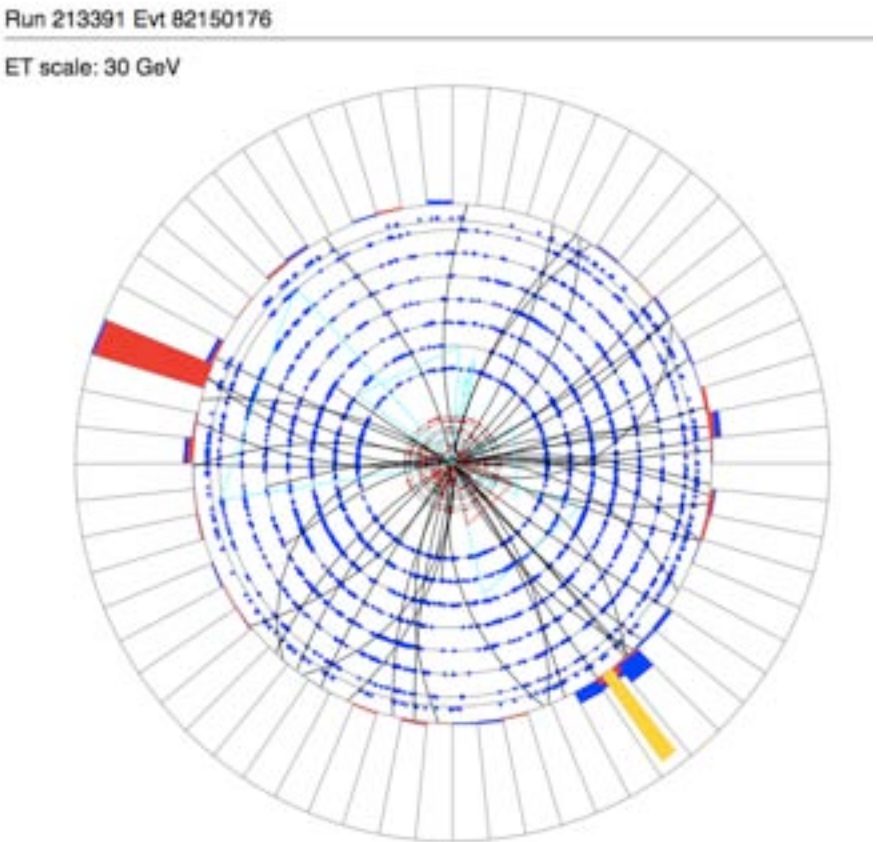
➔ modelliere ‚*U*nderlying event" und Rückstossverteilung , etc.

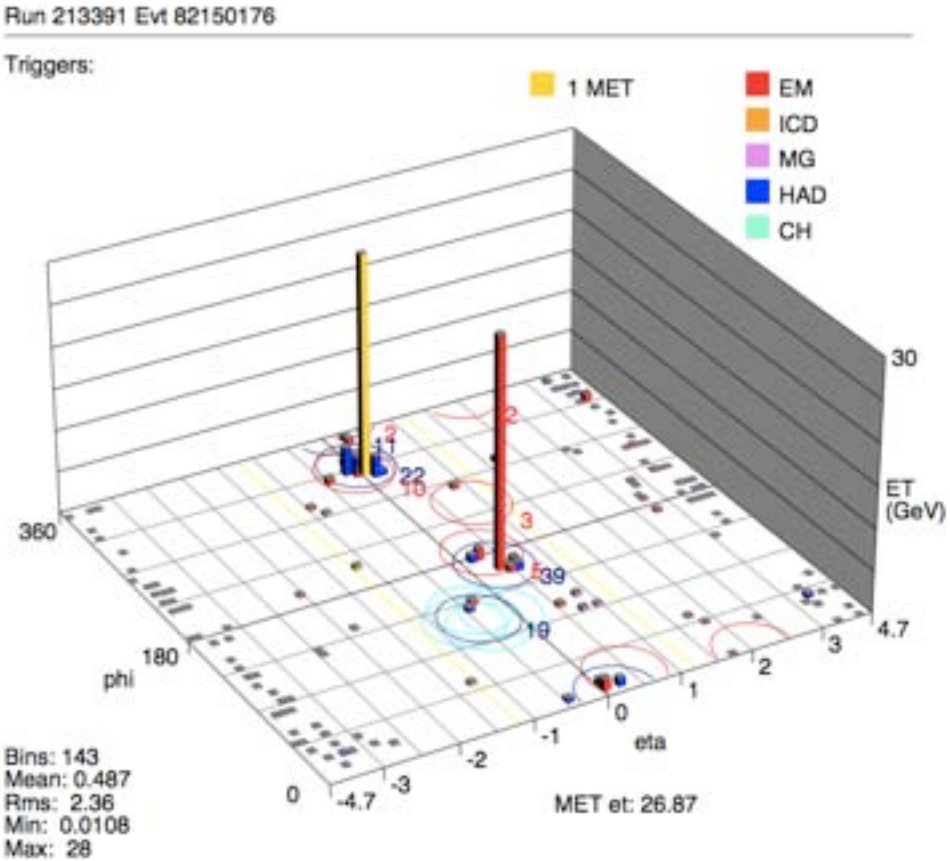
3. Messung von M_W aus M_T Verteilung

➔ Vergleich von Verteilung in den Daten mit Templates

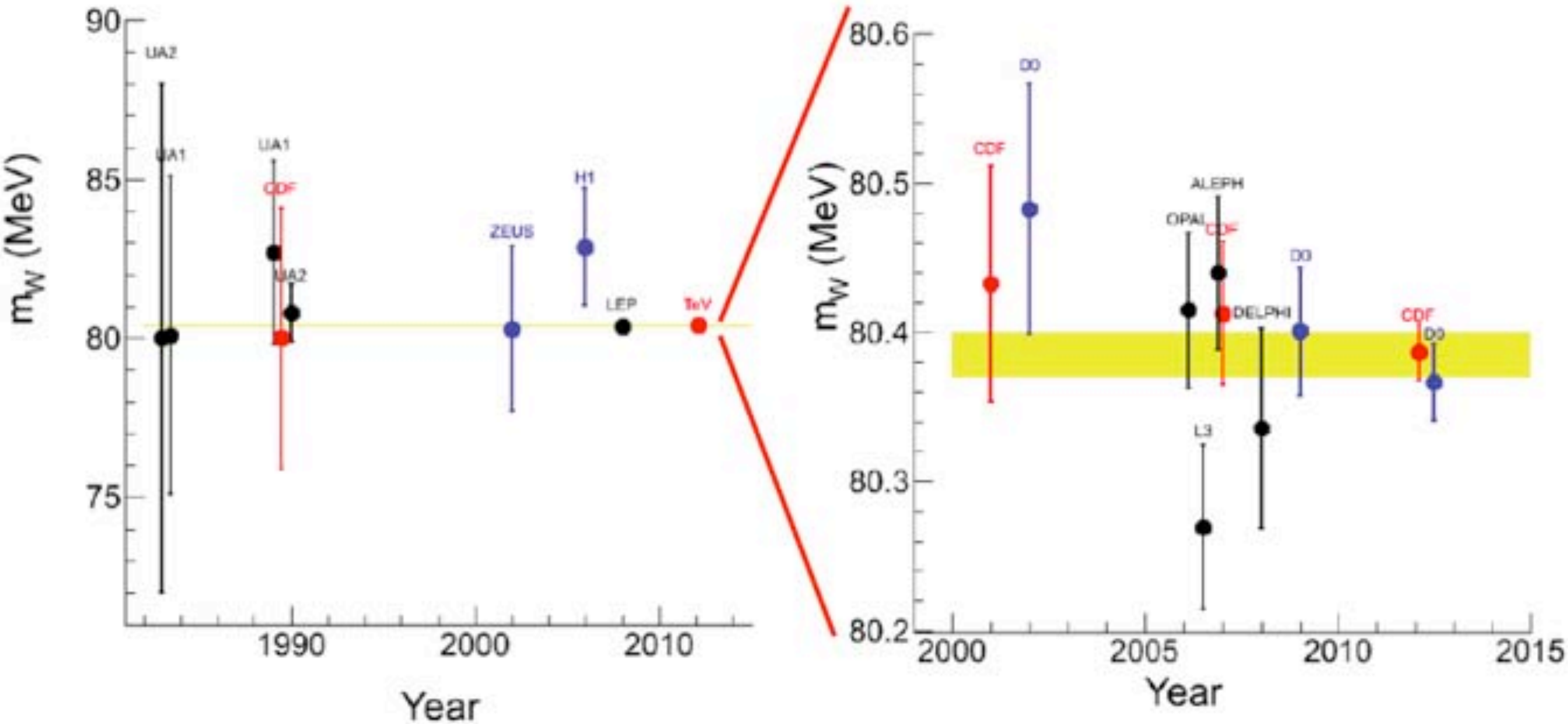


D0: W -> e ν

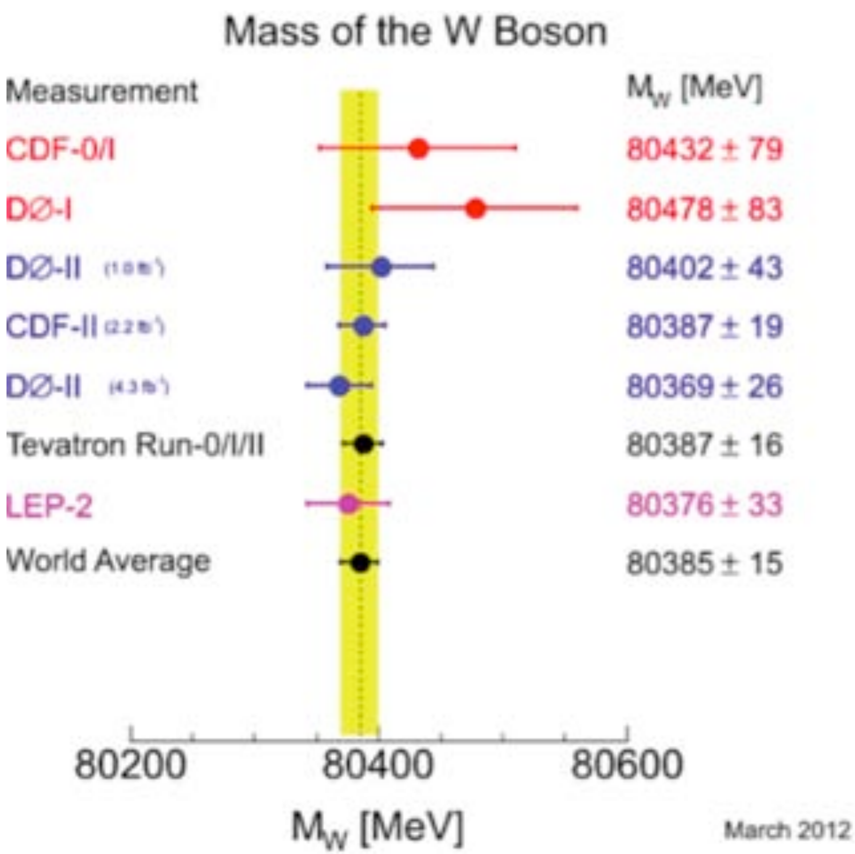

Run 213391 Evt 82150176
ET scale: 30 GeV

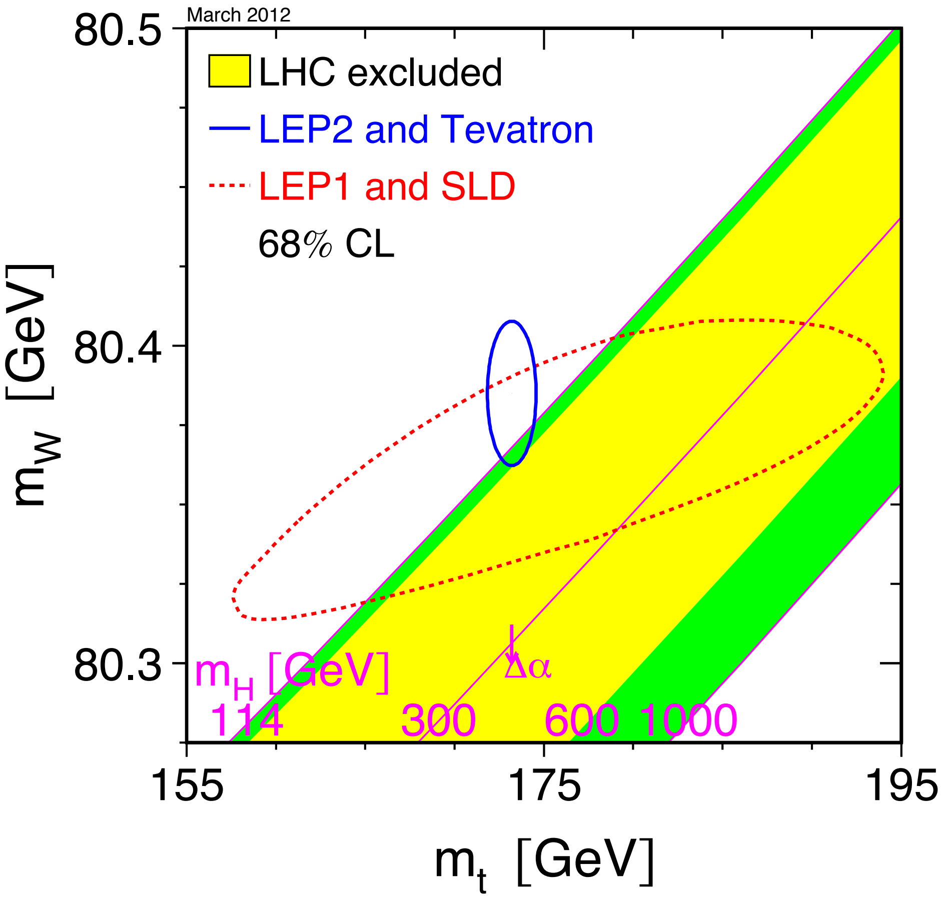

Run 213391 Evt 82150176
Triggers:
1 MET
EM
ICD
MG
HAD
CH
30
ET (GeV)
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
Bins: 143
Mean: 0.487
Rms: 2.36
Min: 0.0108
Max: 28
MET et: 26.87

Zusammenfassung M_W Messungen



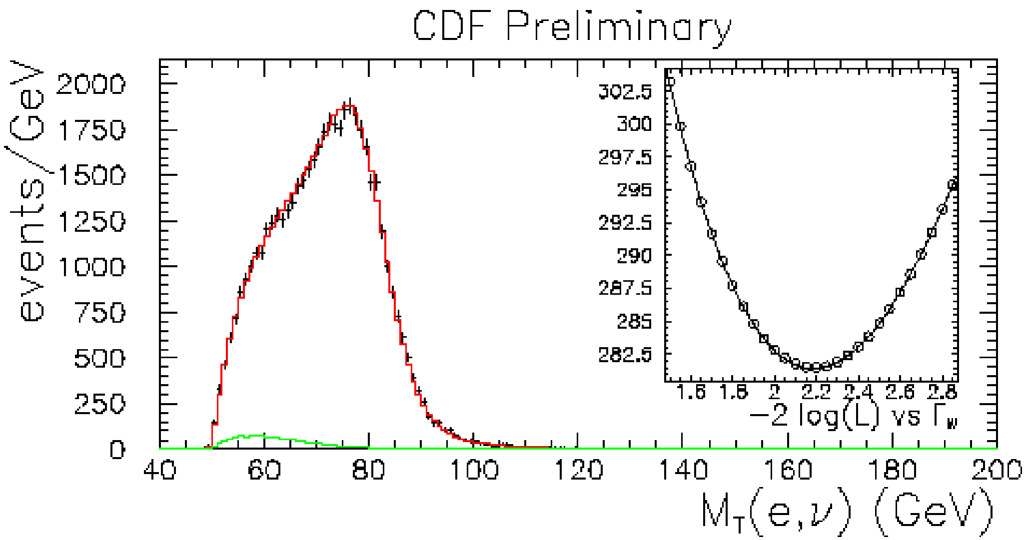
Aktuelle Ergebnisse und Kombination von M_w:

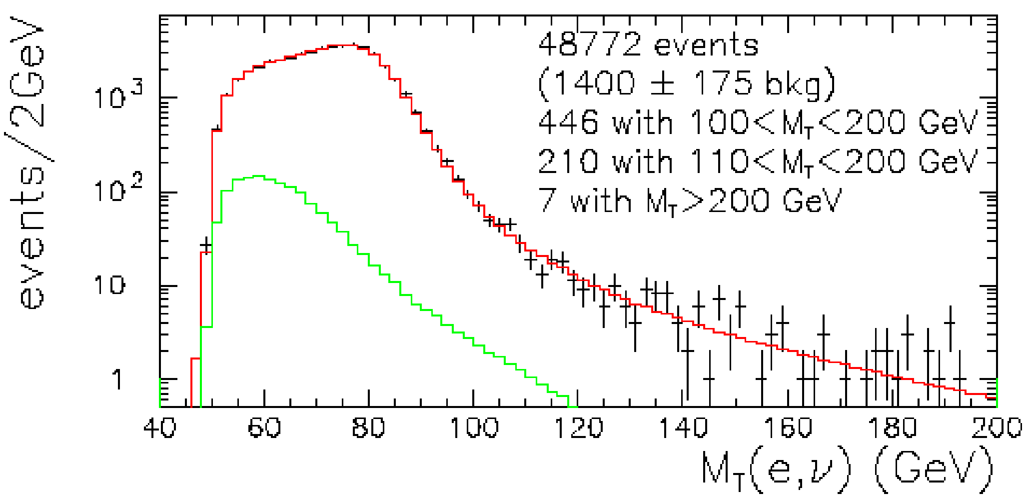


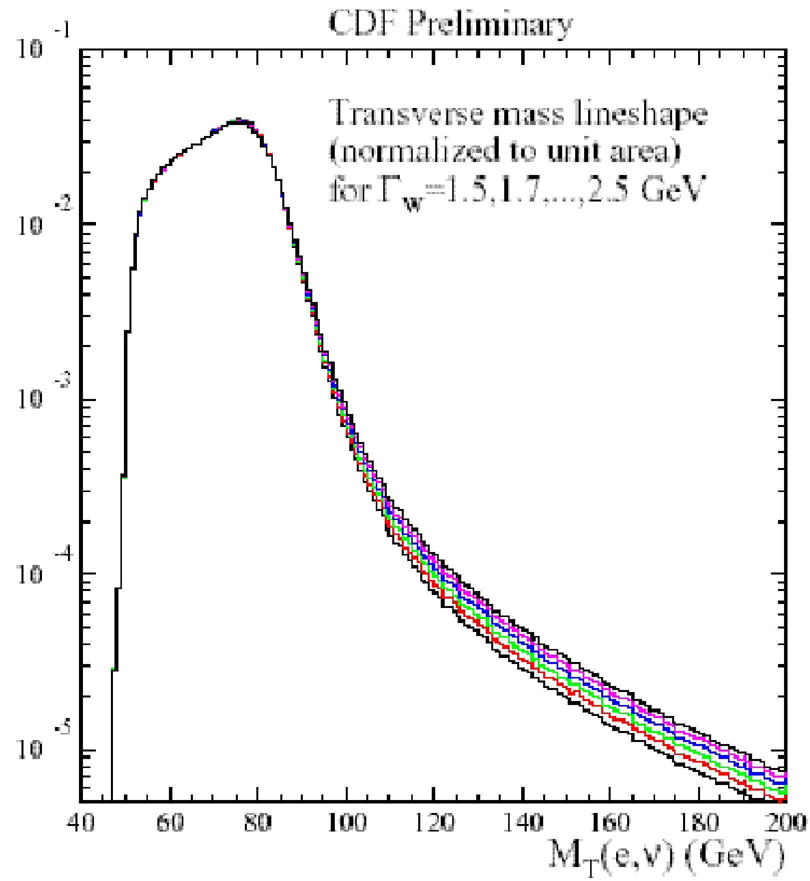


Direkte Messung der W Breite

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

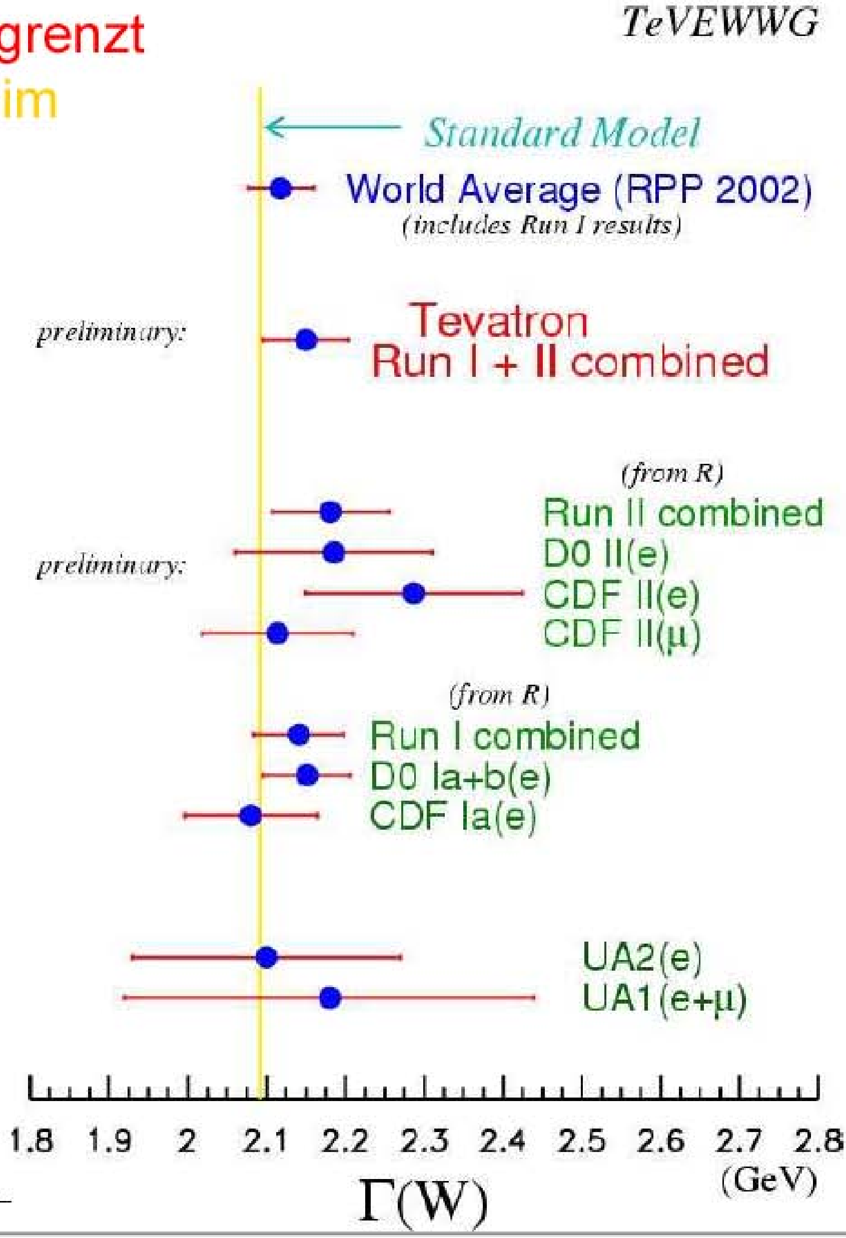
Γ(W) – PDG	2.118 ± 0.042 GeV
Run II	2.181 ± 0.074 GeV

Theorie

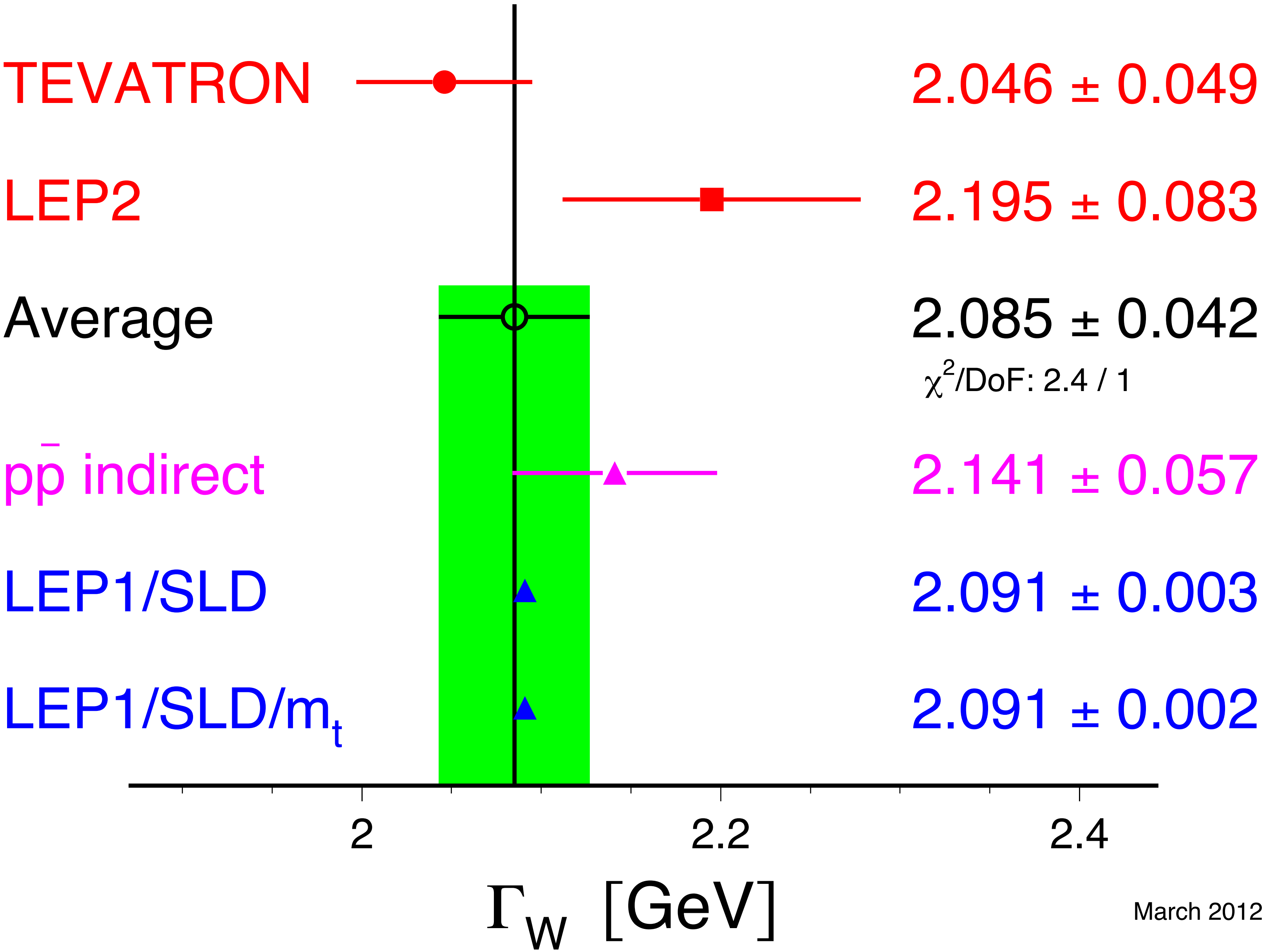
$$R = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)}$$

LEP

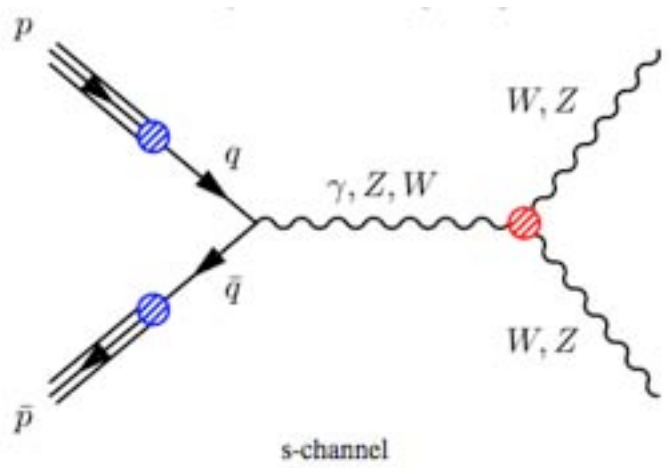
	R
CDF e	9.88 ± 0.24 ± 0.44
CDF μ	10.69 ± 0.28 ± 0.31
D0 e	10.34 ± 0.35 ± 0.49
Combined	10.36 ± 0.16 ± 0.27



W-Boson Width [GeV]



triple gauge couplings:



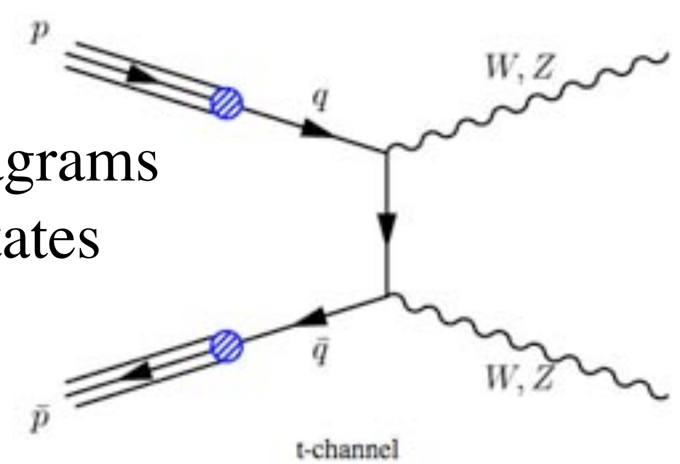
γ, Z –> W^+W^-

W –> WZ, W γ

~~γ, Z –> ZZ~~

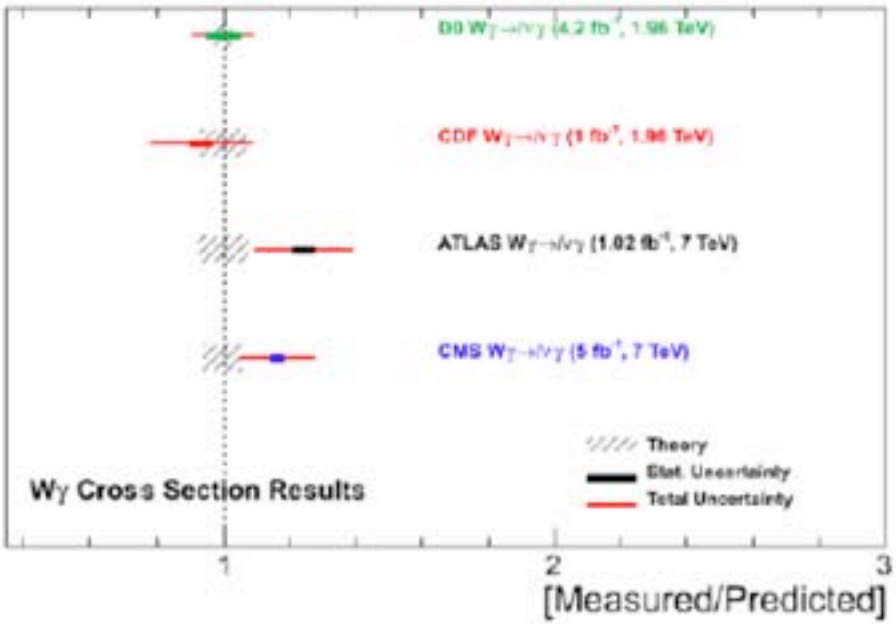
- SM: space-like diagrams are =0 if 2 of the 3 bosons are identical
- BSM: may contribute to triple gauge couplings in non-standard ways

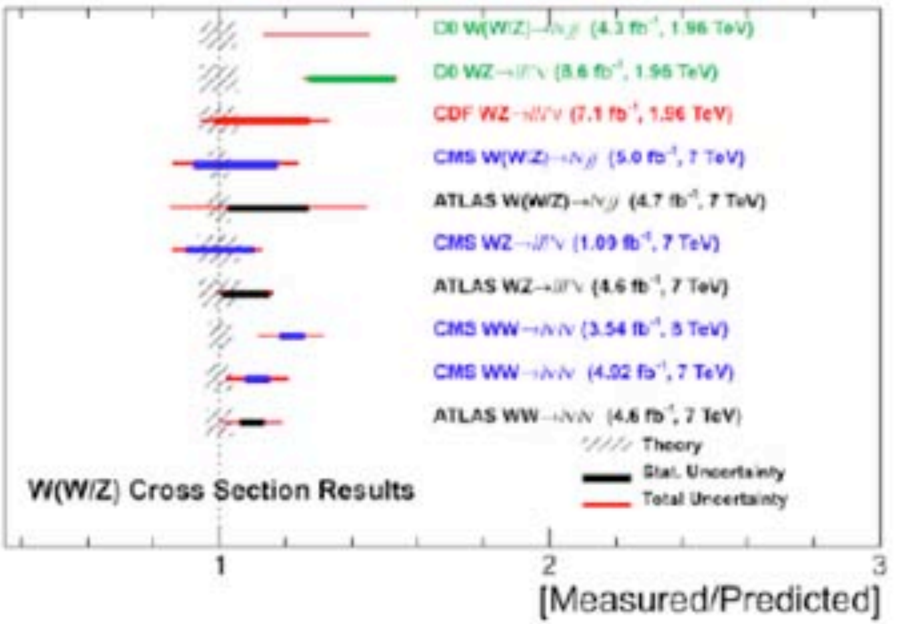
SM: time-like diagrams with same final states are allowed (n.b.: no triple-gauge!)

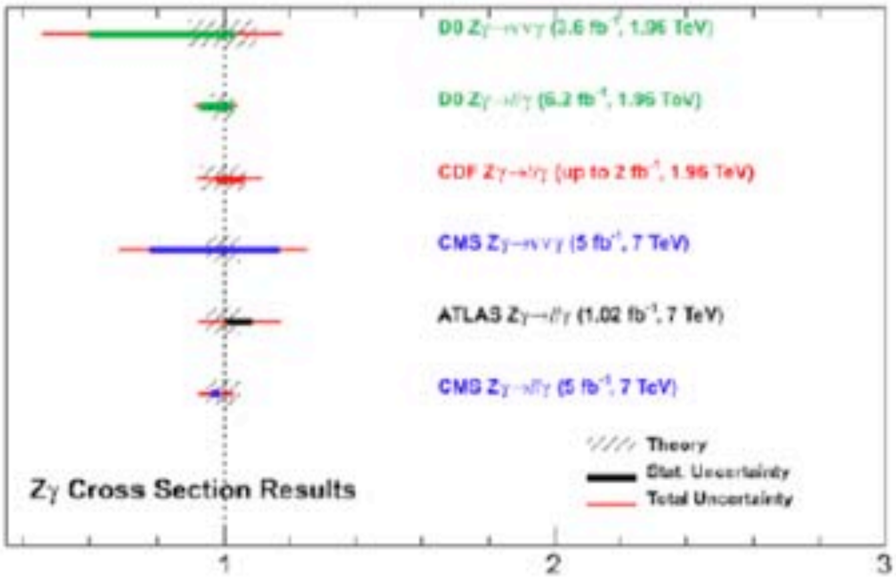


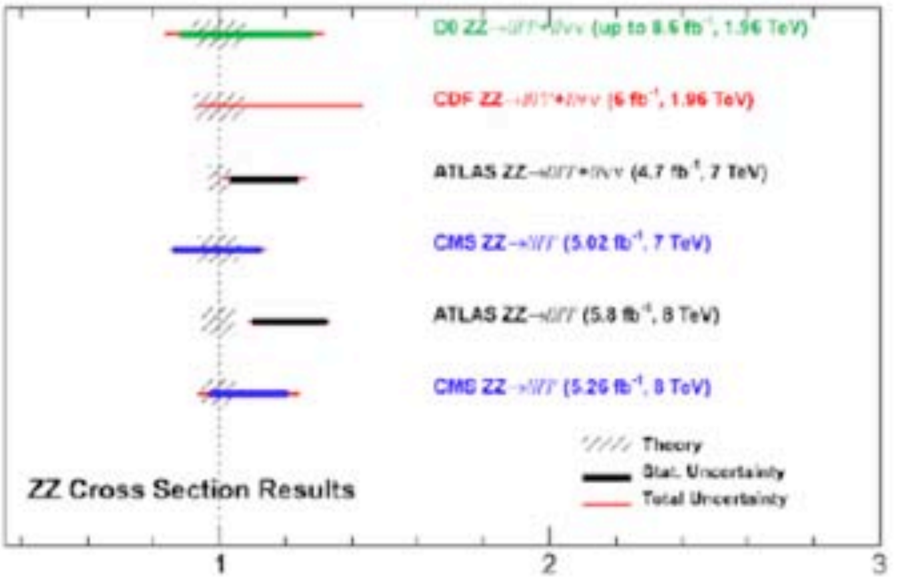
these are SM „background“ to signals of triple-gauge couplings!

Di-Boson production cross sections









Zusammenfassung:

- am LHC wurden detaillierte Messungen mit W und Z Bosonen durchgeführt: Produktionsquerschnitte in Übereinstimmung mit theor. Erwartungen.
- erwartet bei design-Luminositäten: 10^8 W/a, 10^7 Z/a
- wichtige Tests des SM: präzise Bestimmungen von
  - Massen
  - Zerfallsbreiten
  - Wirkungsquerschnitten
  - Produktionsasymmetrien
  - triple-gauge Kopplungen (grob)
- Ziel am LHC: **ΔM_w ~ 15 MeV** (ATLAS & CMS combined;benötigt extreme exp. Genauigkeit)
- Δm_{top} ~ 2 GeV und ΔM_W ~ 15 MeV werden im SM M_{Higgs} auf ca. 25% festlegen
- Z-Boson Parameter (M_Z, Γ_Z) als input von LEP; Z^0s als tool zur Kalibration
- erste Messungen der triple-gauge Kopplungen werden indikativ für Neue Physik

Literatur:

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