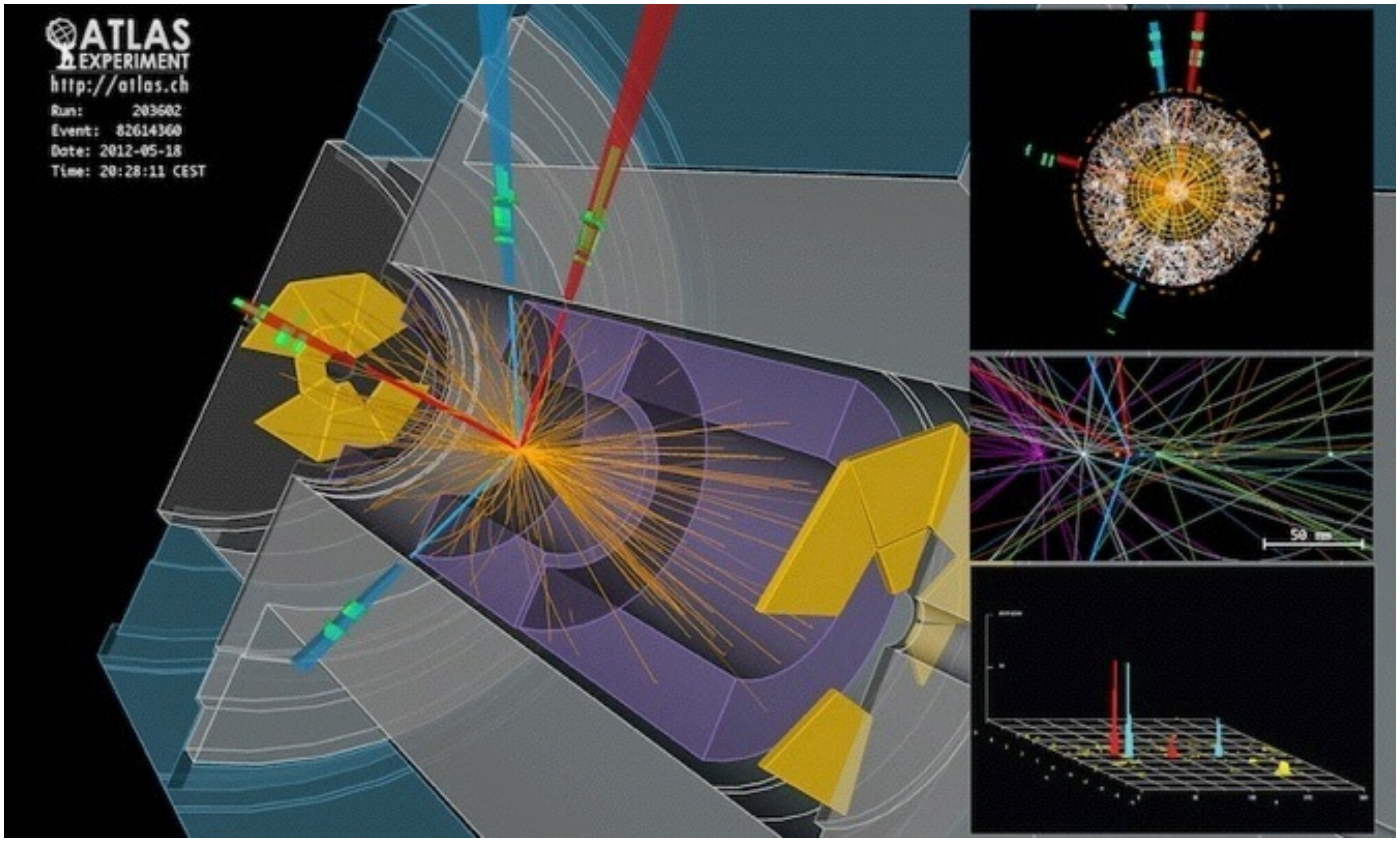
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



7. Precision Tests of the Standard Model

17.11.2014

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Overview

- The Standard Model - Structure, Motivation
- Vector boson properties
  - Z decay & width
  - W, Z production
  - W mass
  - W width
  - Triple Gauge couplings
- Topics of future lectures in the framework of the Standard Model:
  - QCD (Lecture 8)
  - Higgs (Lectures 9 & 10)
  - Top quark (Lecture 11)

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Quarks	**u** **d**	**c** **s**	**t** **b**	**Strong**	g	1
				el.-magn.	γ	1/137
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Underlying theories: QCD QED / weak interaction
➯ electroweak unification (GSW)

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- It:
  - describes the unified electroweak interactions and the strong force with gauge invariant quantum field theories
  - is extremely successful in consistently and precisely describing all particle reaction observed to date
  - provides a consistent (yet incomplete) picture of the evolution of the early universe -> particle cosmology

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- A complex scalar Higgs field is added for mass generation through spontaneous symmetry breaking to give mass to the gauge bosons and fermions -> Gives rise to one physical neutral scalar particle, the Higgs boson
- The electroweak SM describes in lowest order ("Born approximation) processes such as $f_1 f_2 \rightarrow f_3 f_4$ with only 3 free parameters: α, G_f, $\sin^2\theta_W$

Testing the Standard Model

- mainly physics with
  - electroweak gauge bosons (W, Z, γ)
  - top quarks (-> lecture 11)
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- measurements of
  - production cross sections
  - masses
  - decay rates / widths
  - decay asymmetries
  - gauge bosons couplings (WW, Wγ, WZ, ZZ, Zγ)

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- Since the establishment of the Standard Model, one main goal of particle physics has been (and still is) to test its predictions as a consistency check, and to look for cracks

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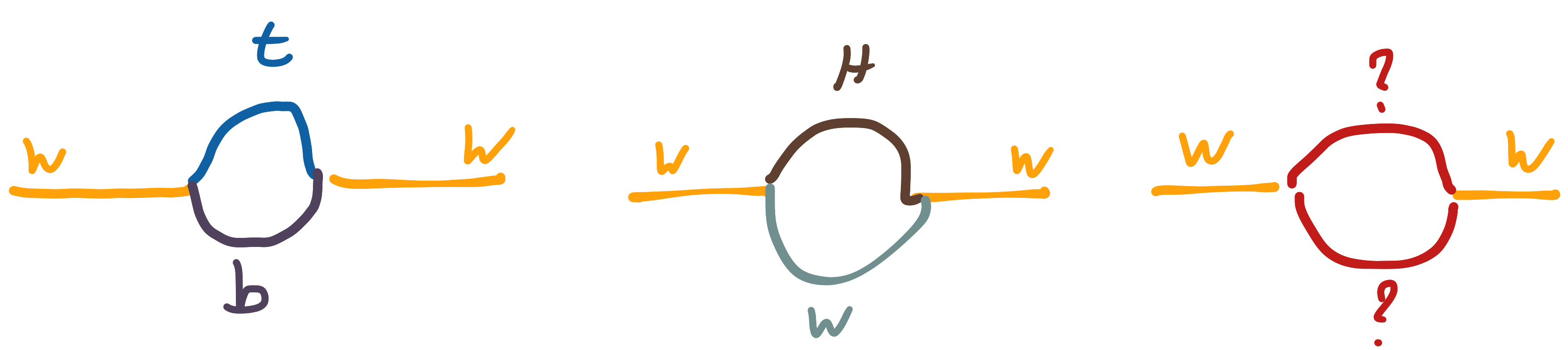
- Search for deviations from the SM:
    - properties, production and decay of gauge bosons are sensitive to the particle content and to various particle properties, and are modified by new physics



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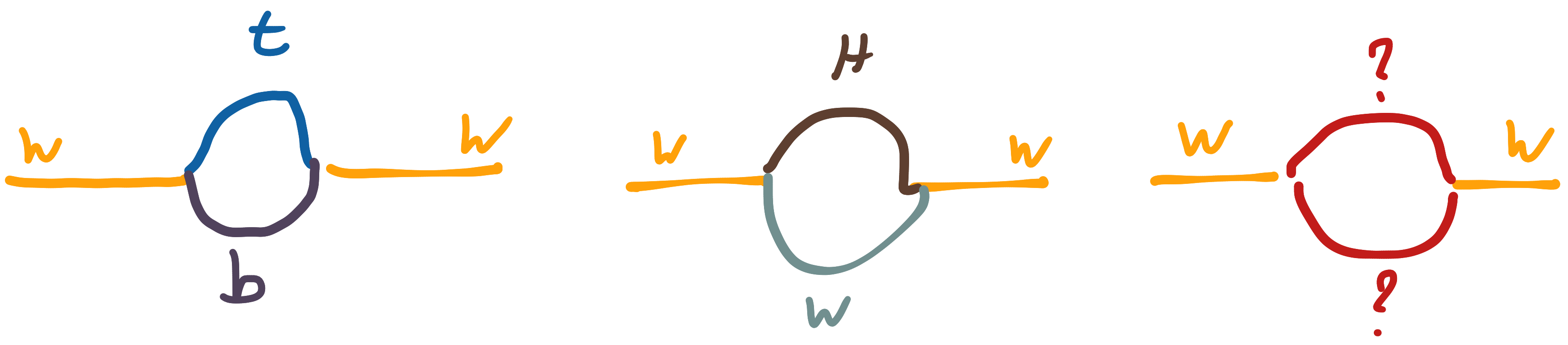
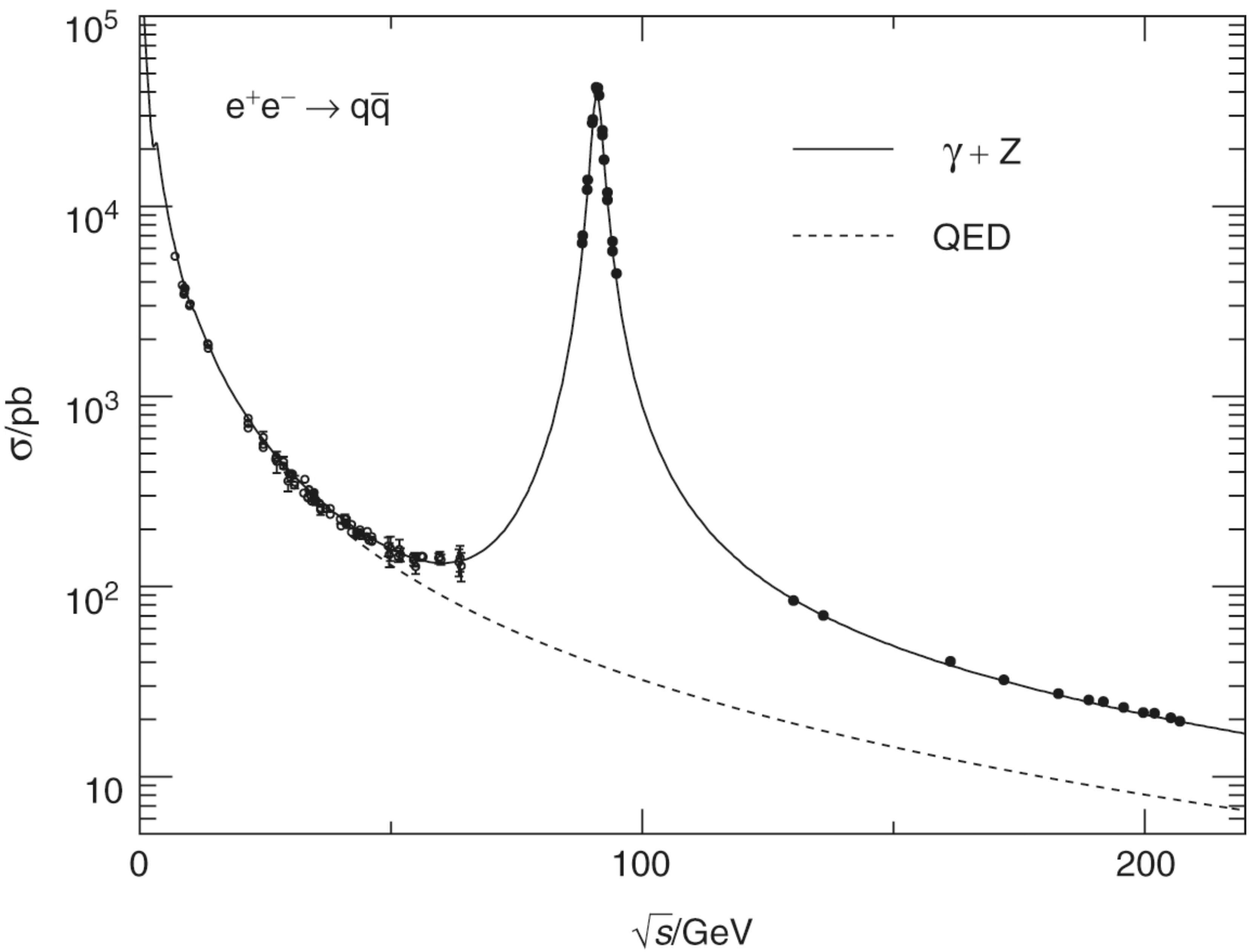


➩ used to place indirect limits on the Higgs mass based on M_{top} and M_W

- Use well-understood SM processes to measure luminosity at LHC
- Precisely define SM backgrounds in the search for new physics

The Z Boson in e^+e^- Annihilation

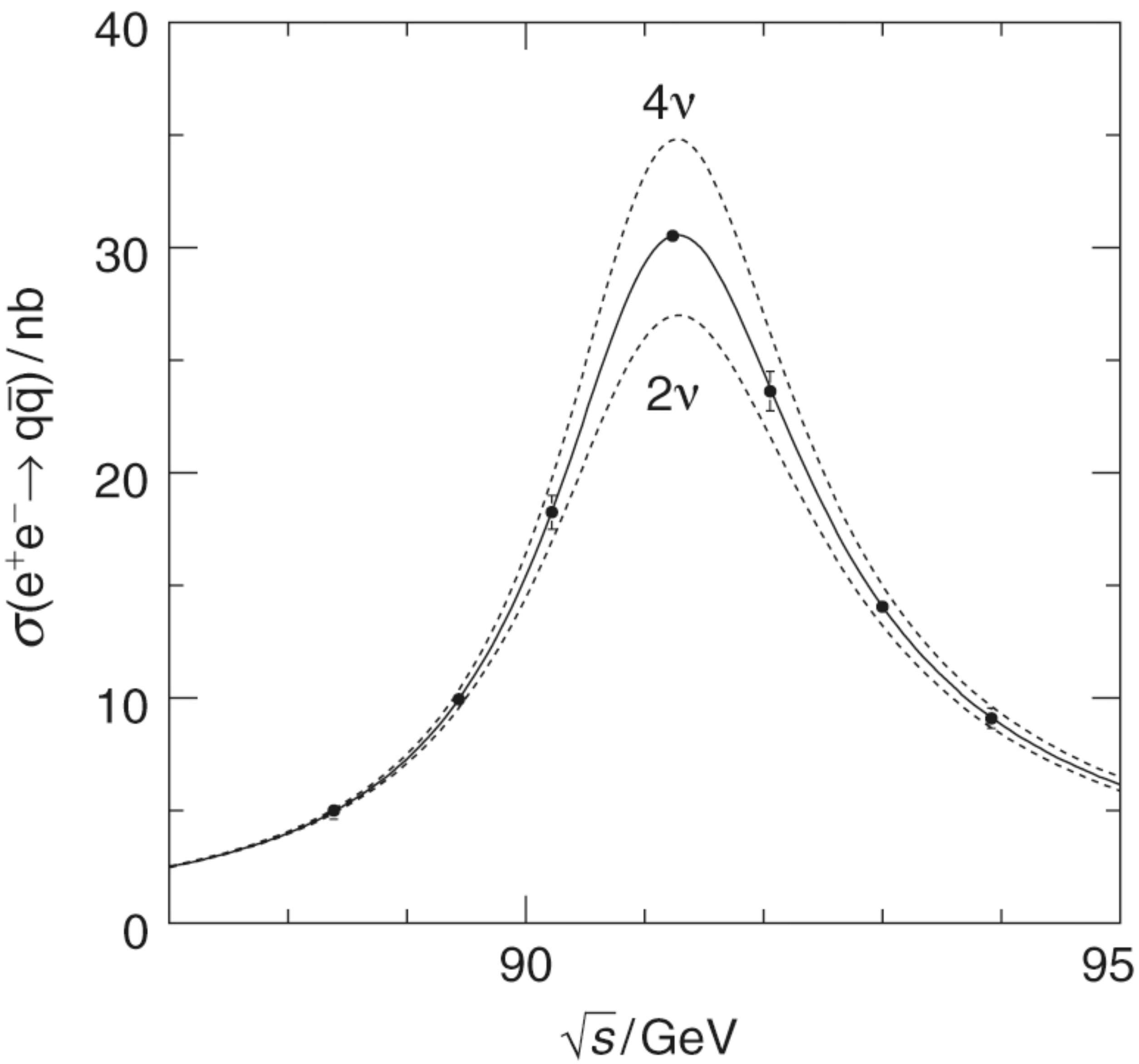
- A short excursion to e^+e^- Annihilation (covered in somewhat greater detail in the Summer)



Measurements at LEP (and lower-energy e^+e^- colliders):

Cross-section shows electroweak interactions: combination of γ and Z exchange - at high energy Z dominates

The Width of the Z Boson



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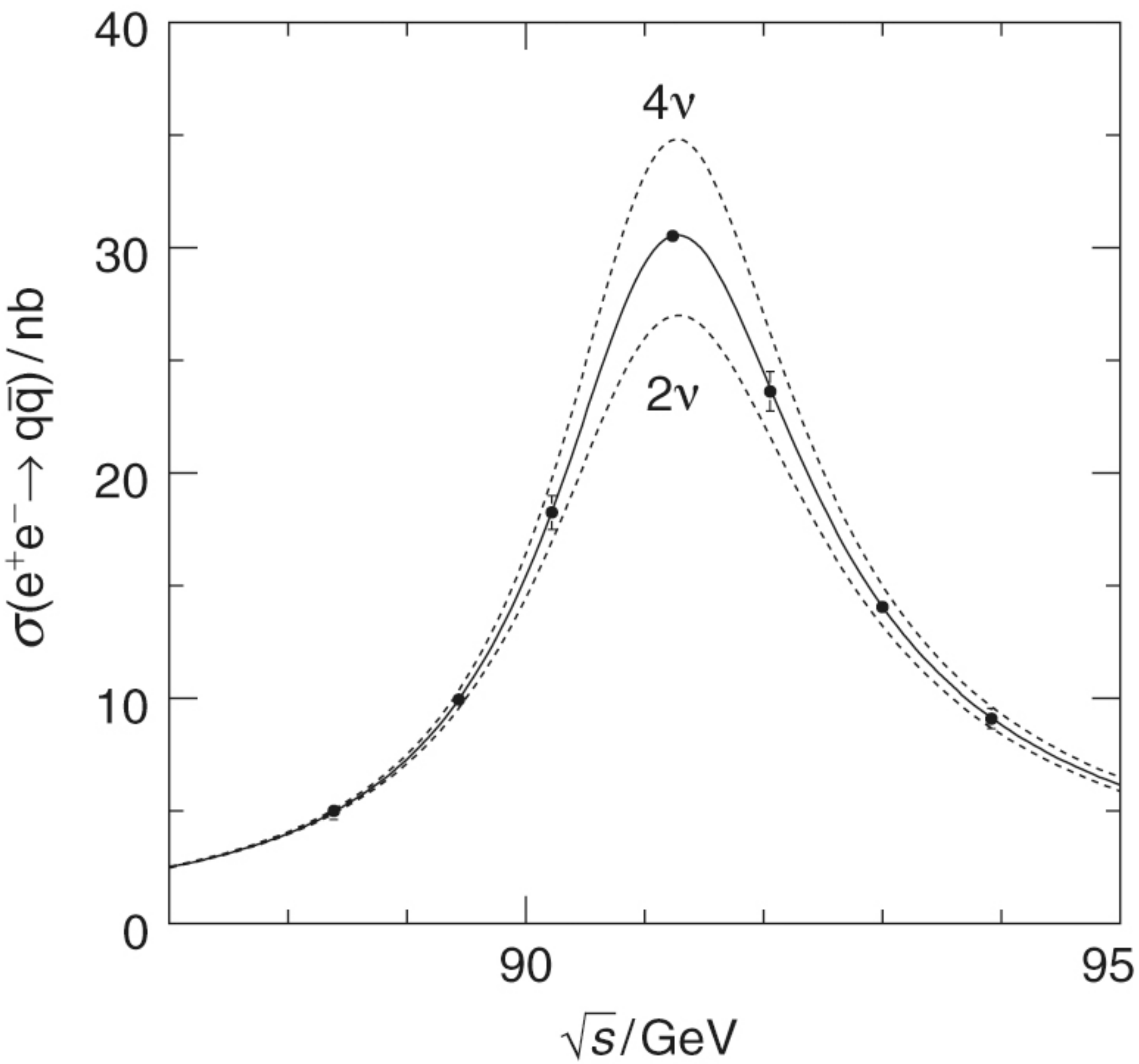

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Given by:

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had}$$
$$+ \Gamma_{\nu e \nu e} + \Gamma_{\nu\mu\nu\mu} + \Gamma_{\nu\tau\nu\tau}$$
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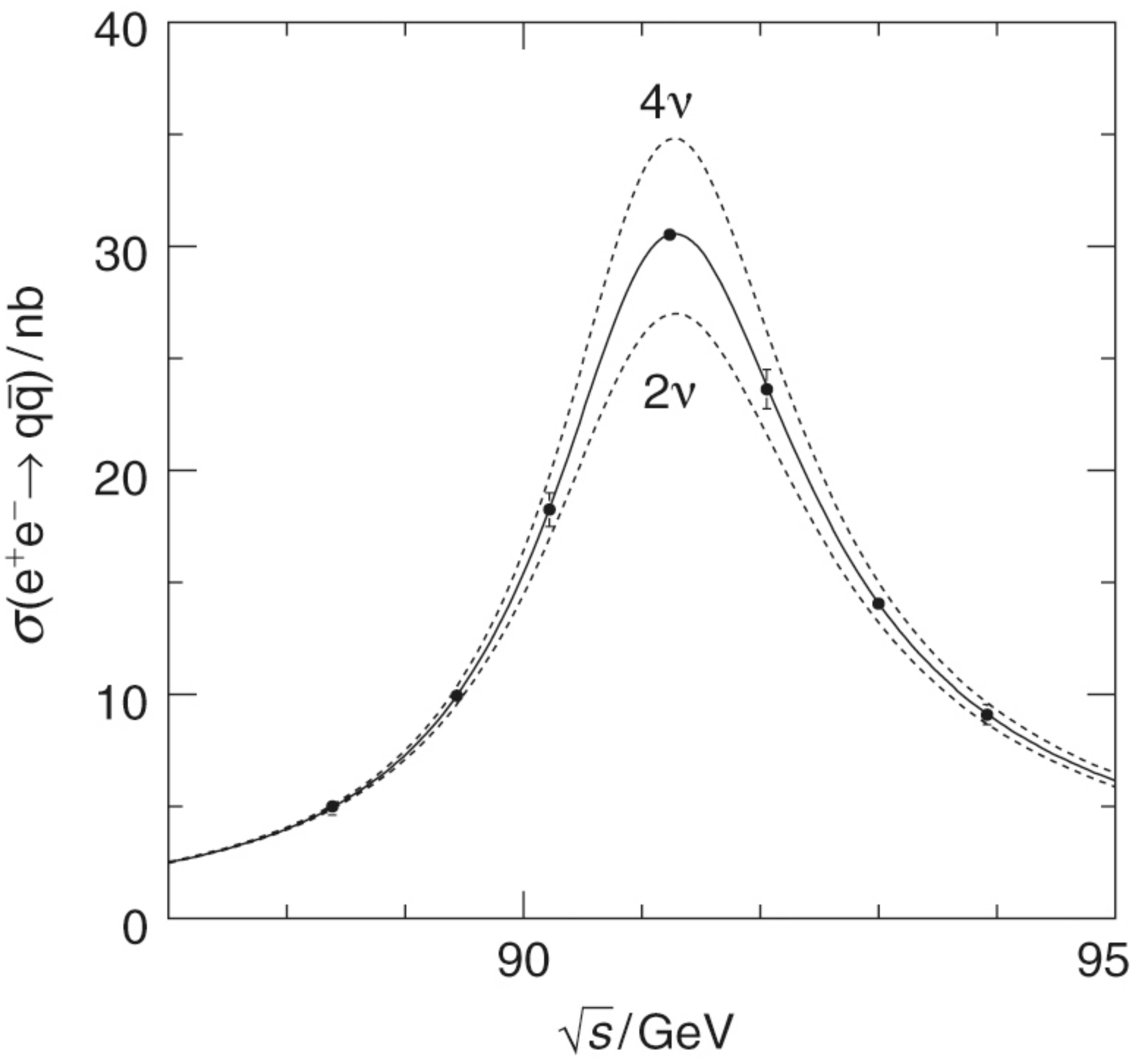

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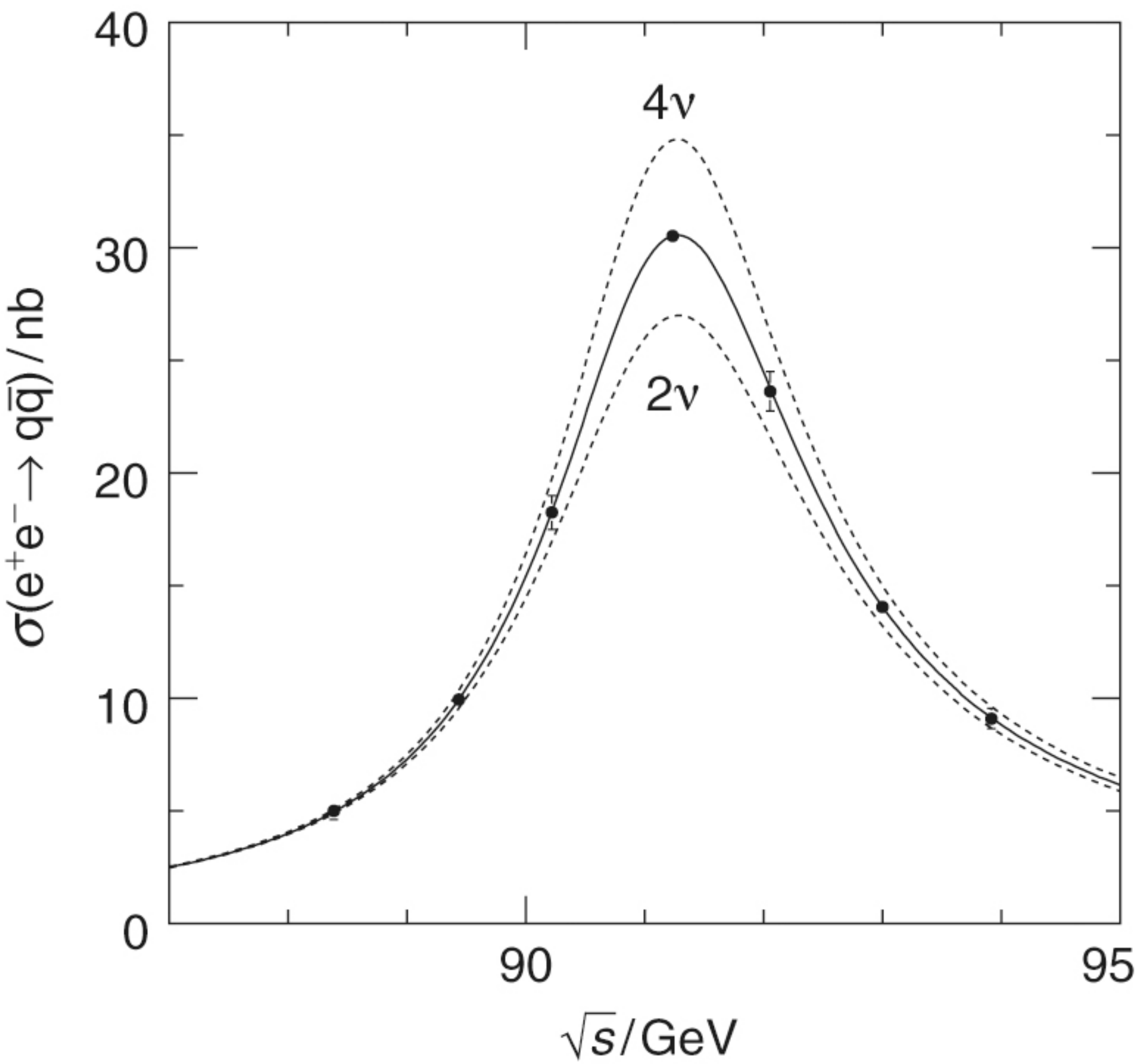

M_Z = 91.1875 ± 0.0021 GeV

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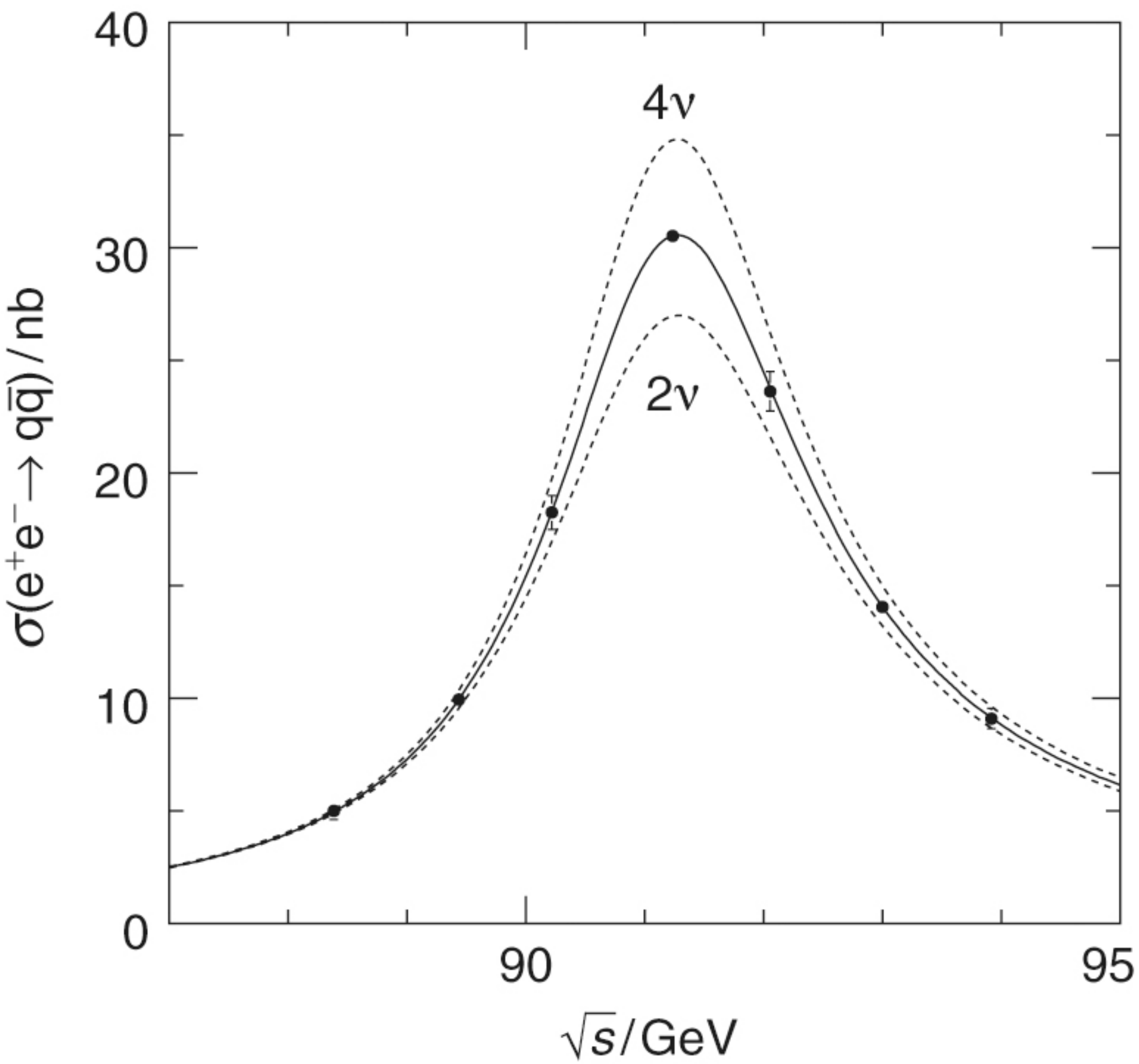

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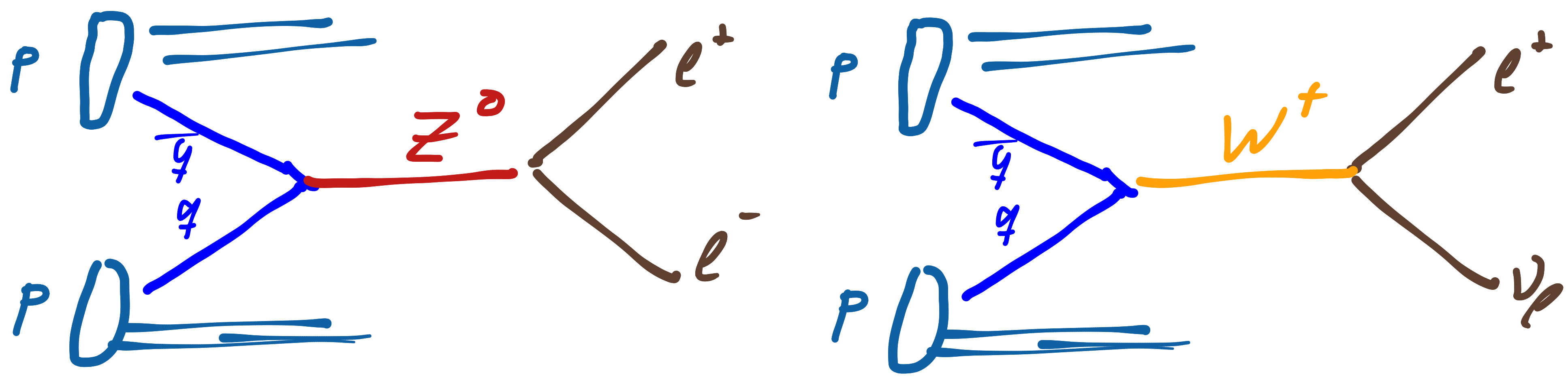
The SM makes a clean prediction for $\Gamma_{\nu\nu}$ - from the measured cross section and total width the number of (light) neutrinos can be determined

This precision can not be reached at hadron colliders - LEP input used for calibration at LHC

$N_\nu = 2.984 \pm 0.008$

Production (and Decay) of Gauge Bosons at LHC

- For precision measurements: hadronic final states can not be used due to dominating QCD background



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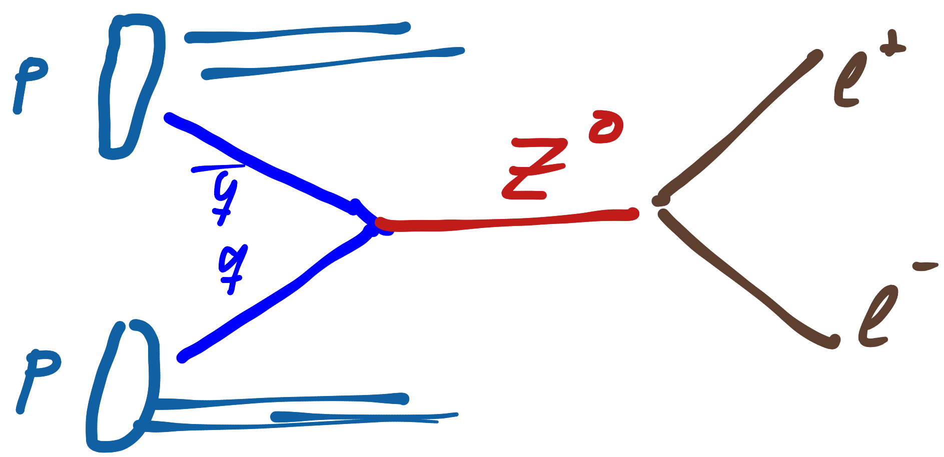
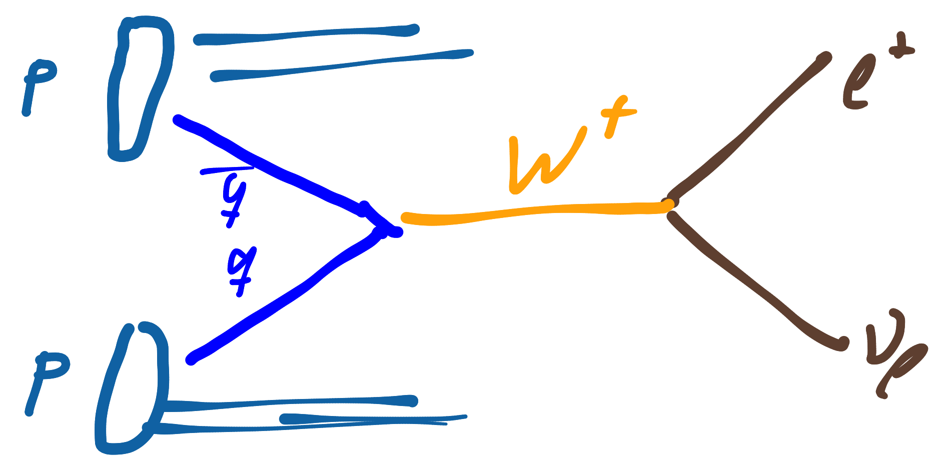
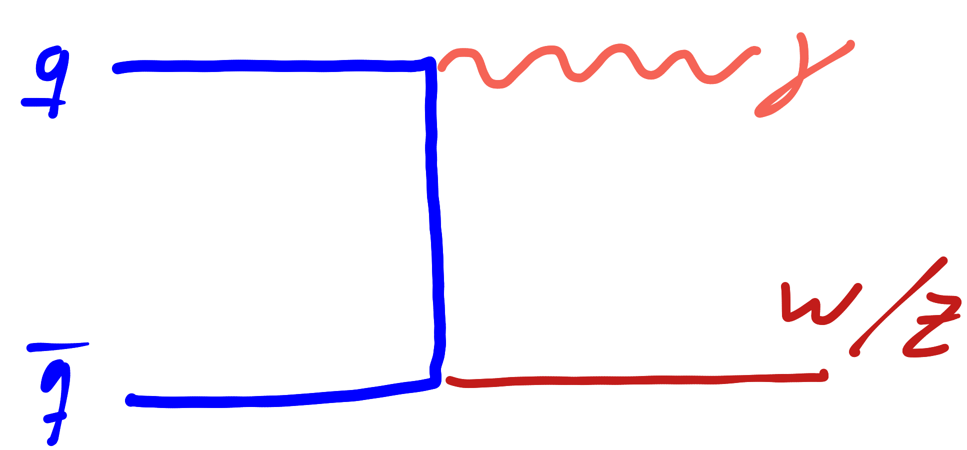




… but also t/u channel processes such as



Frank Simon (fsimon@mpp.mpg.de)

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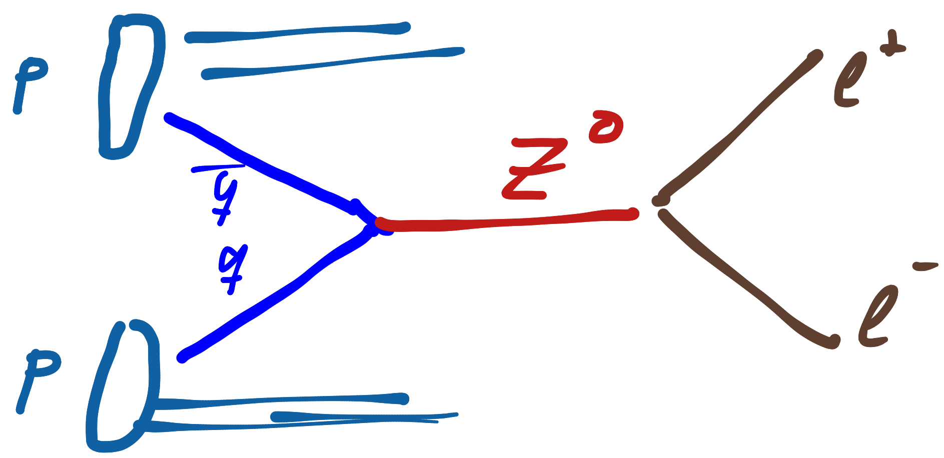

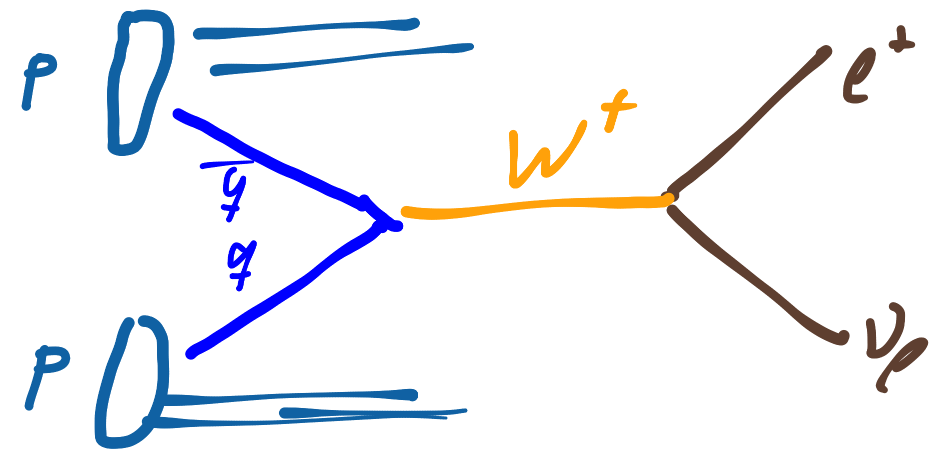

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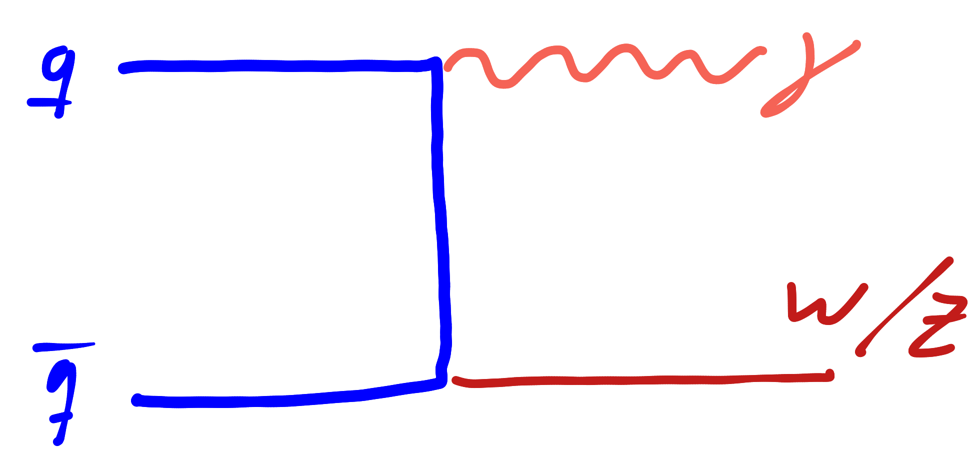
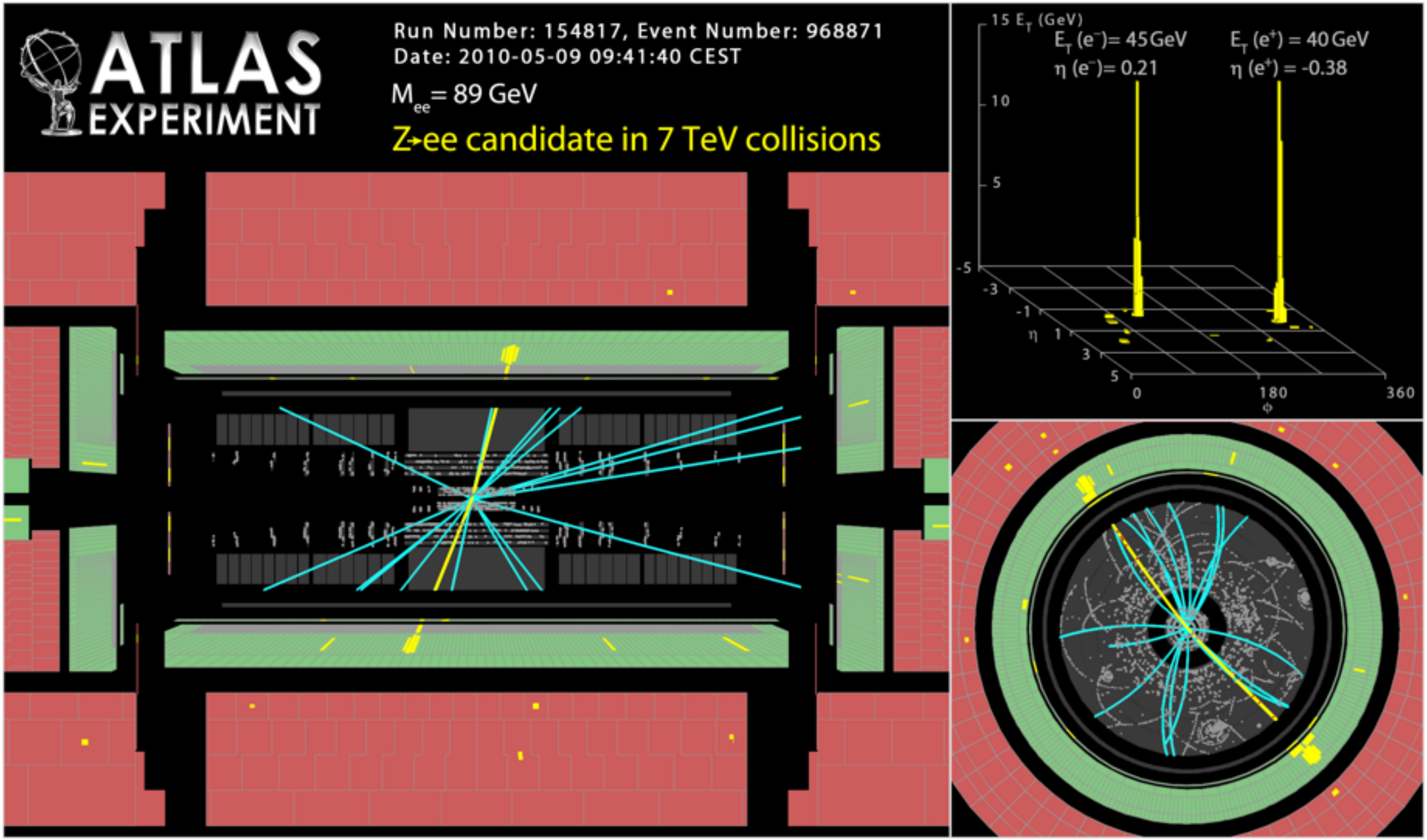


- theoretical uncertainties mainly due to quark structure of the proton: PDF uncertainties

Z Production at LHC

- Candidate $Z \to e^+e^-$



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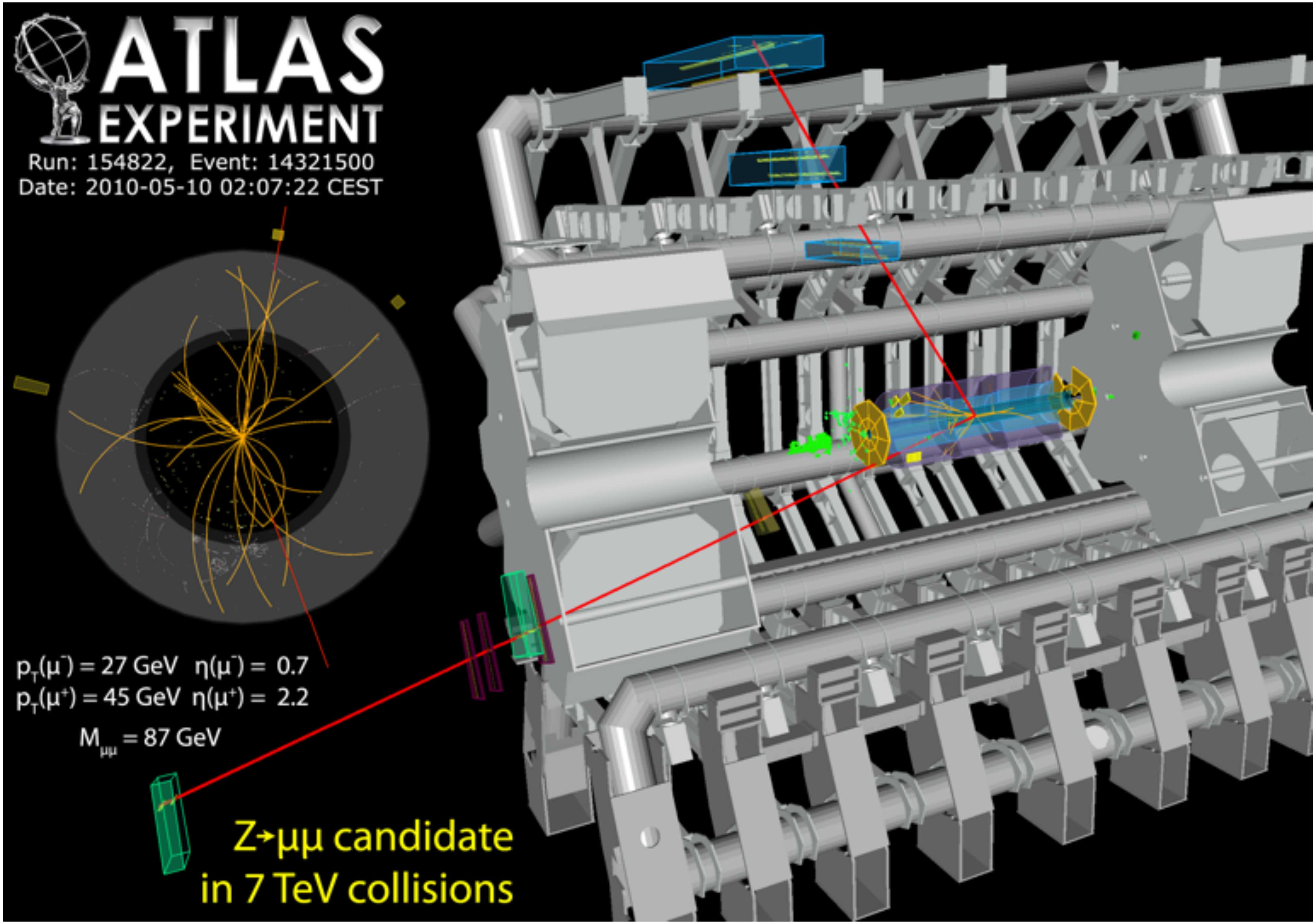
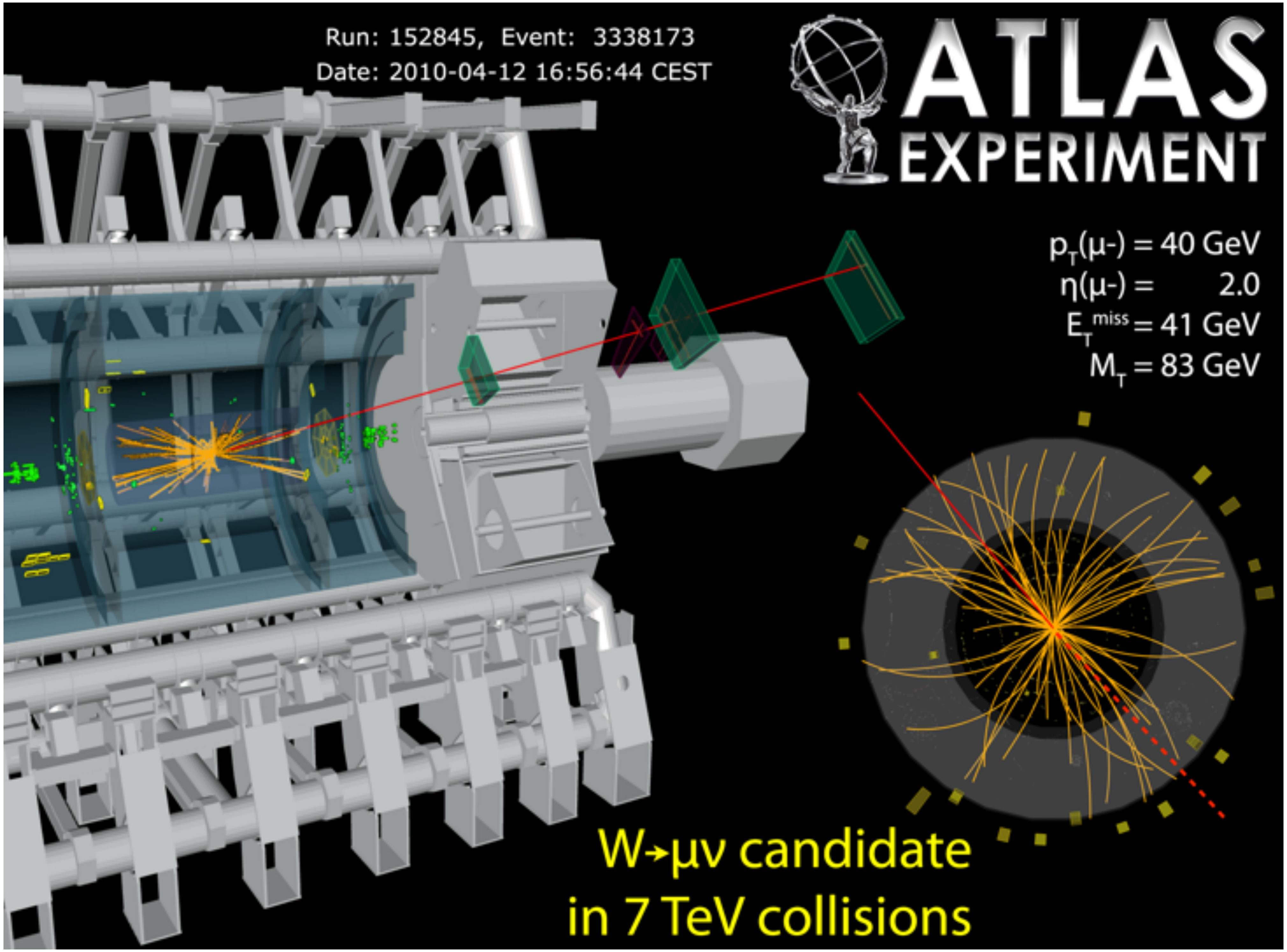


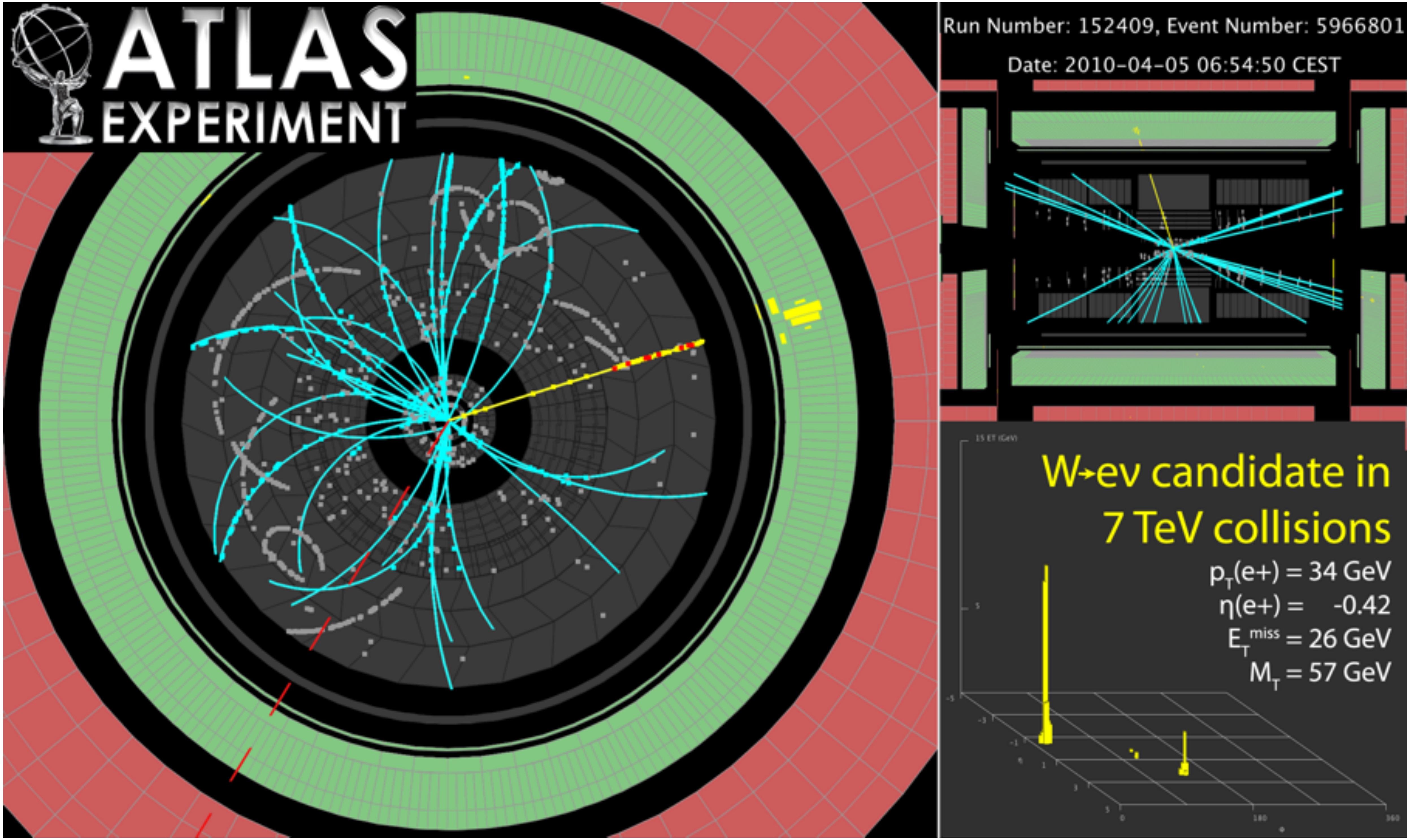
W Production at LHC

- W^- -> $\mu^-\nu$ candidate

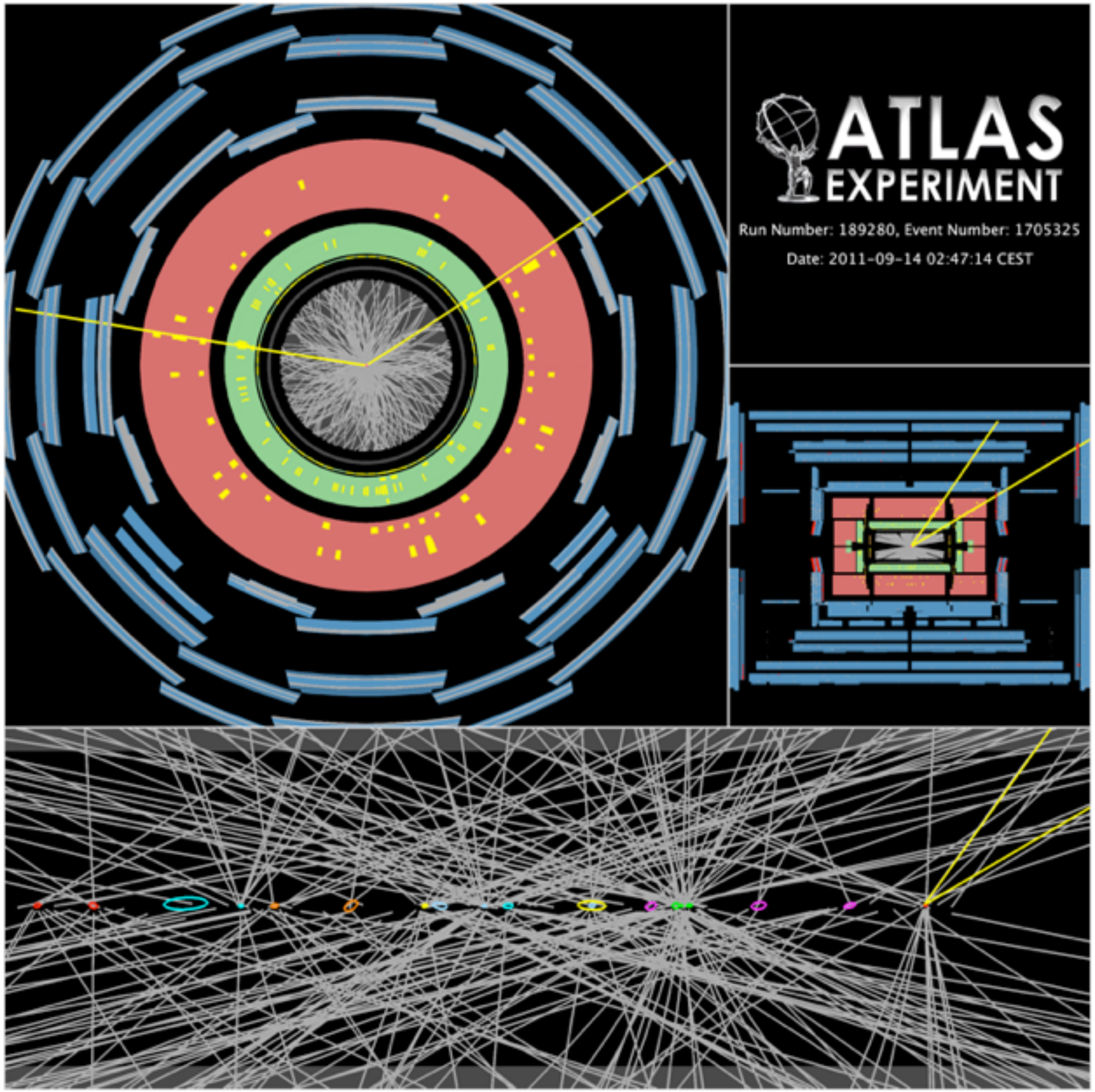


W Production at LHC

- $W^+ \to e^+\nu$ candidate

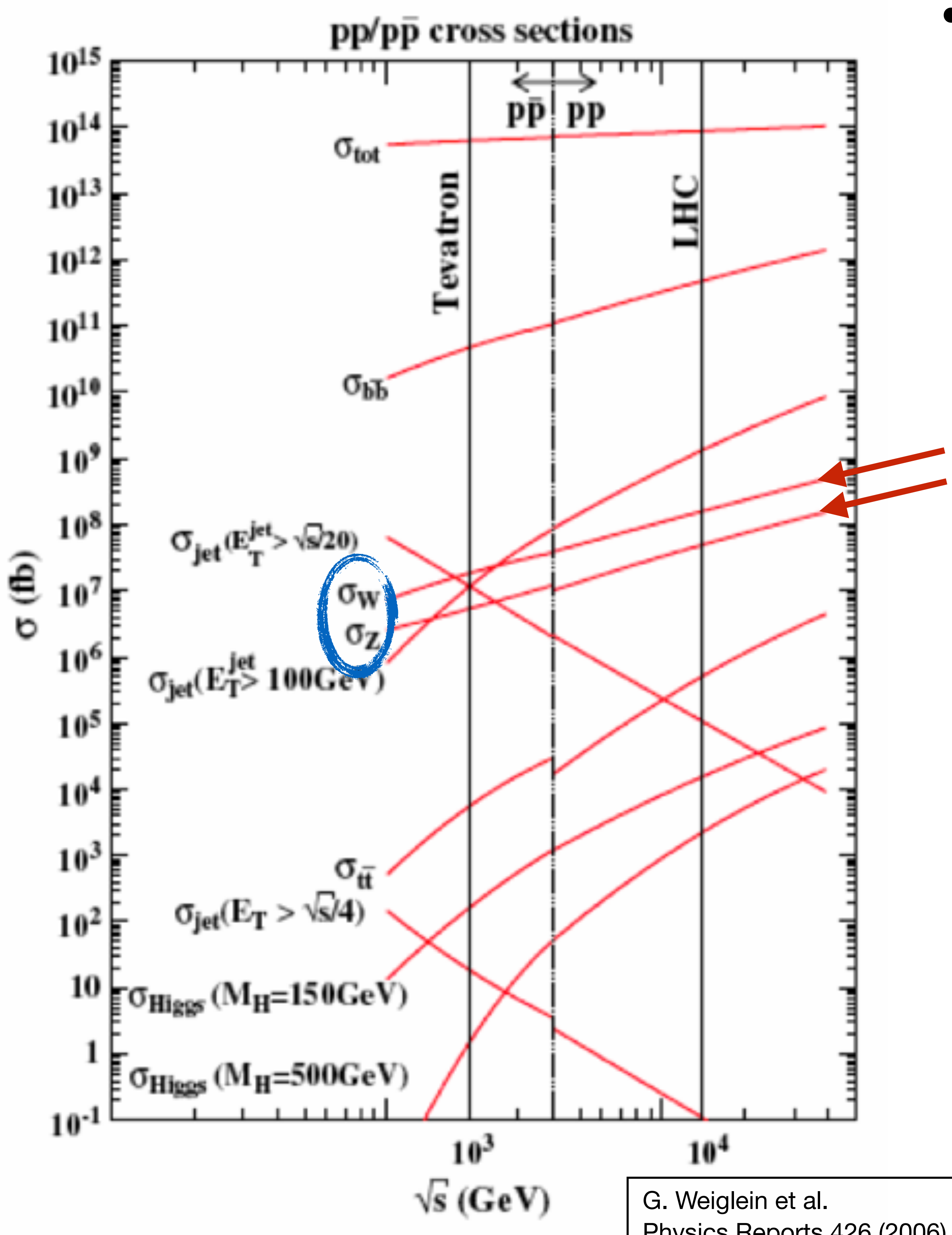


Z Production at LHC with high Pileup



- Z-> μμ
  … with 20 additional vertices

Gauge Boson Production: Cross Sections



G. Weiglein et al.
Physics Reports 426 (2006) 47–358

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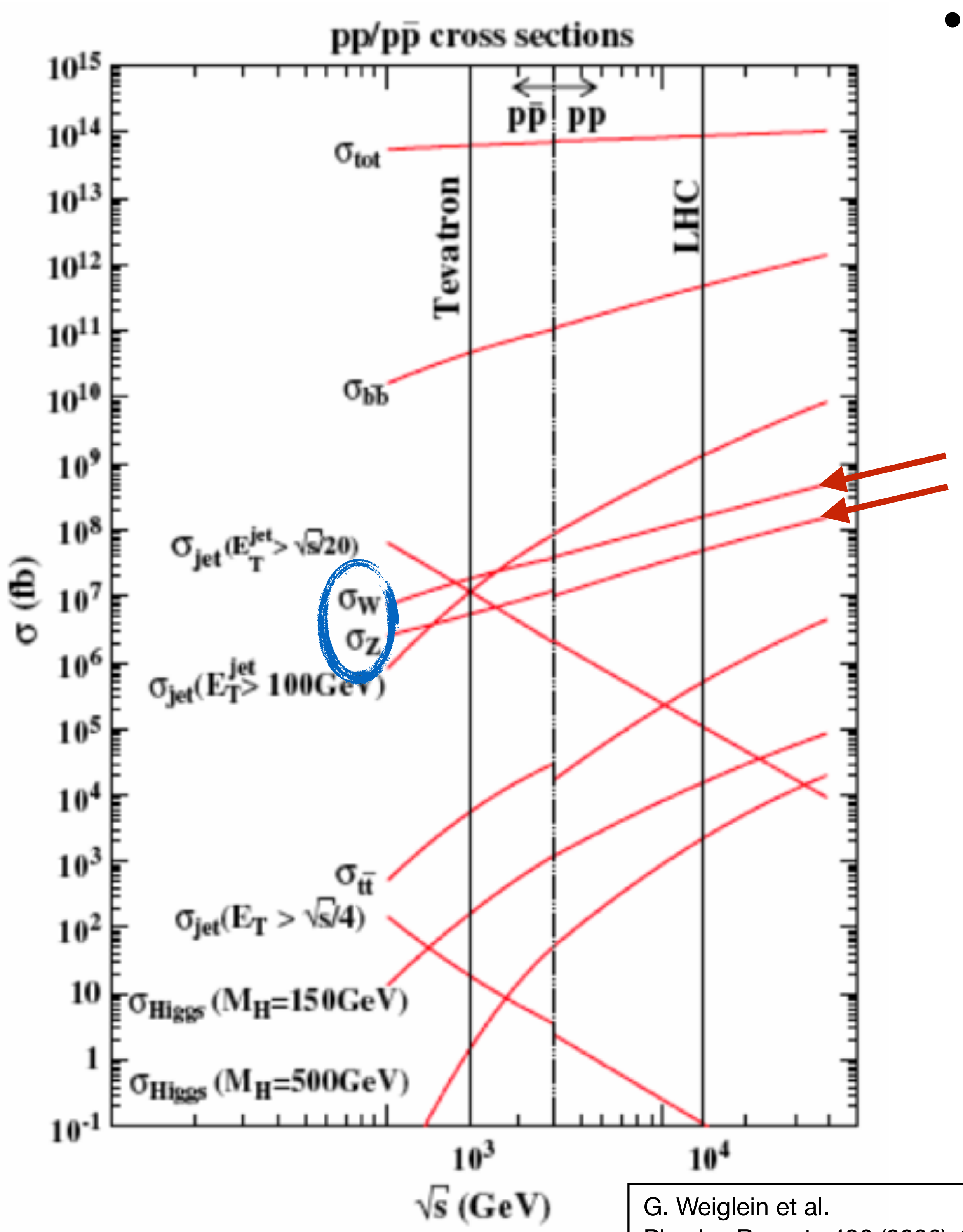

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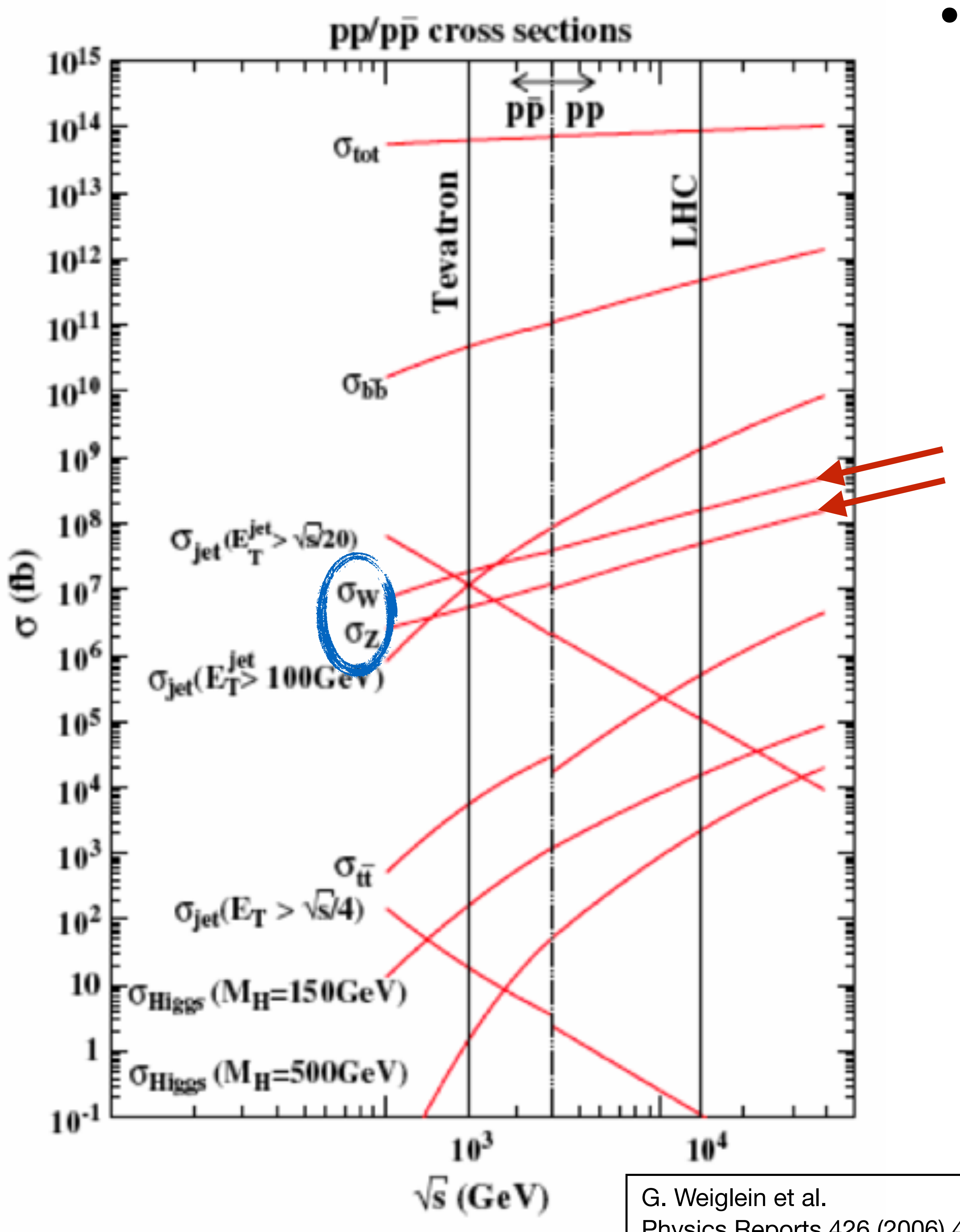

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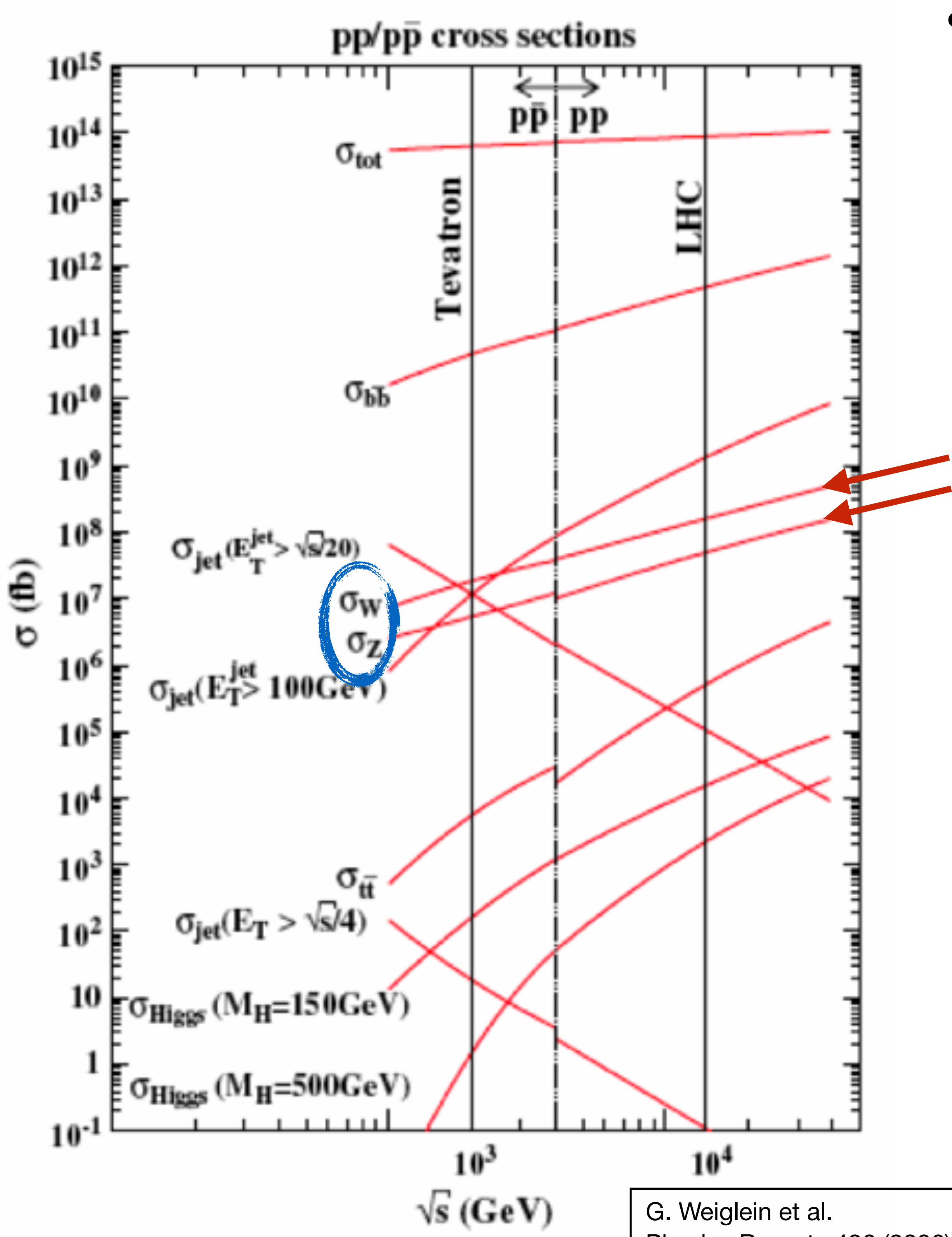

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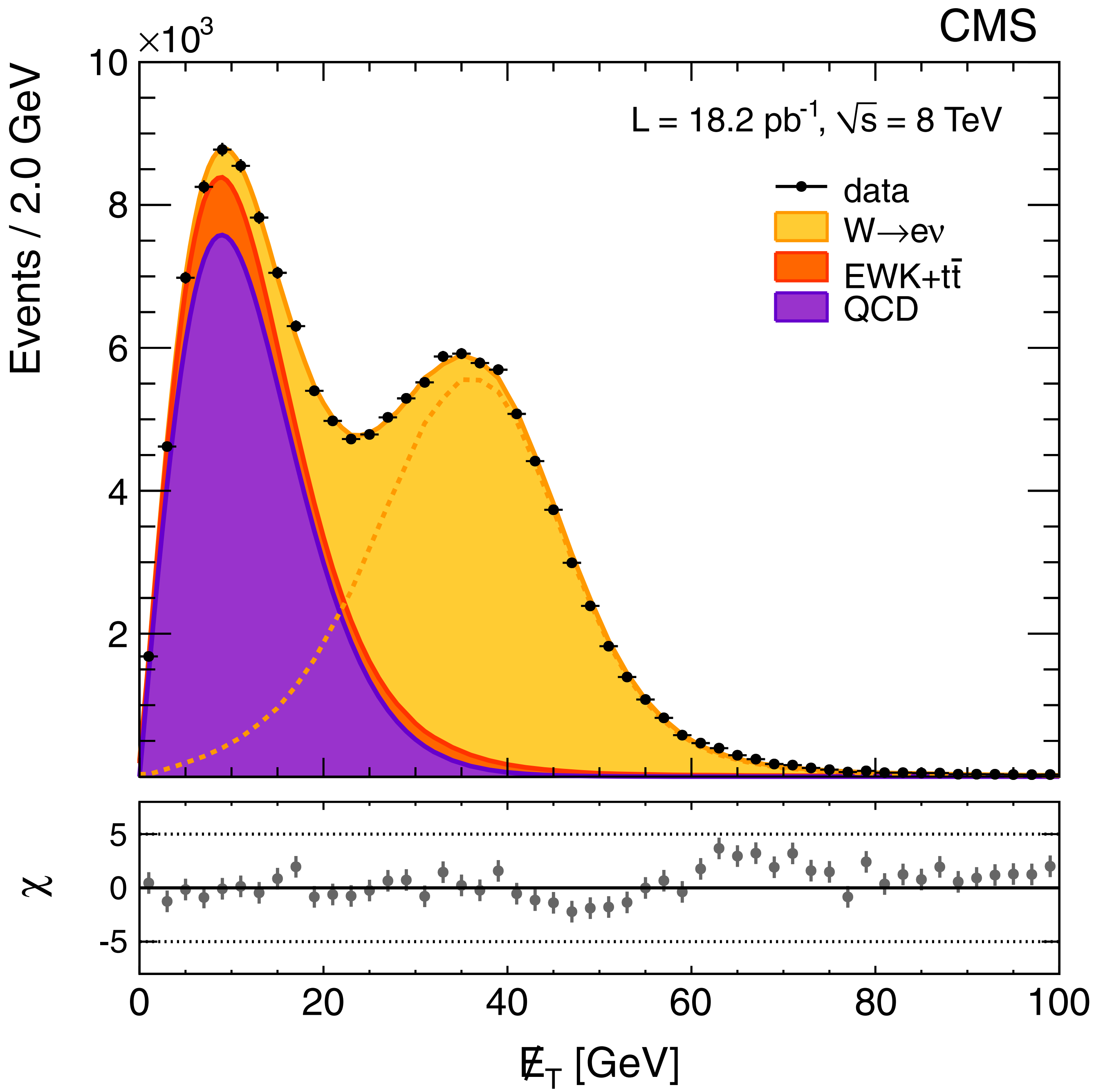
    - missing transverse energy / momentum
  - Determination of cross section - corrections to event numbers:
    - trigger efficiency (data)
    - reconstruction efficiency (MC, data)
    - luminosity

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

Vector Boson Reconstruction - LHC



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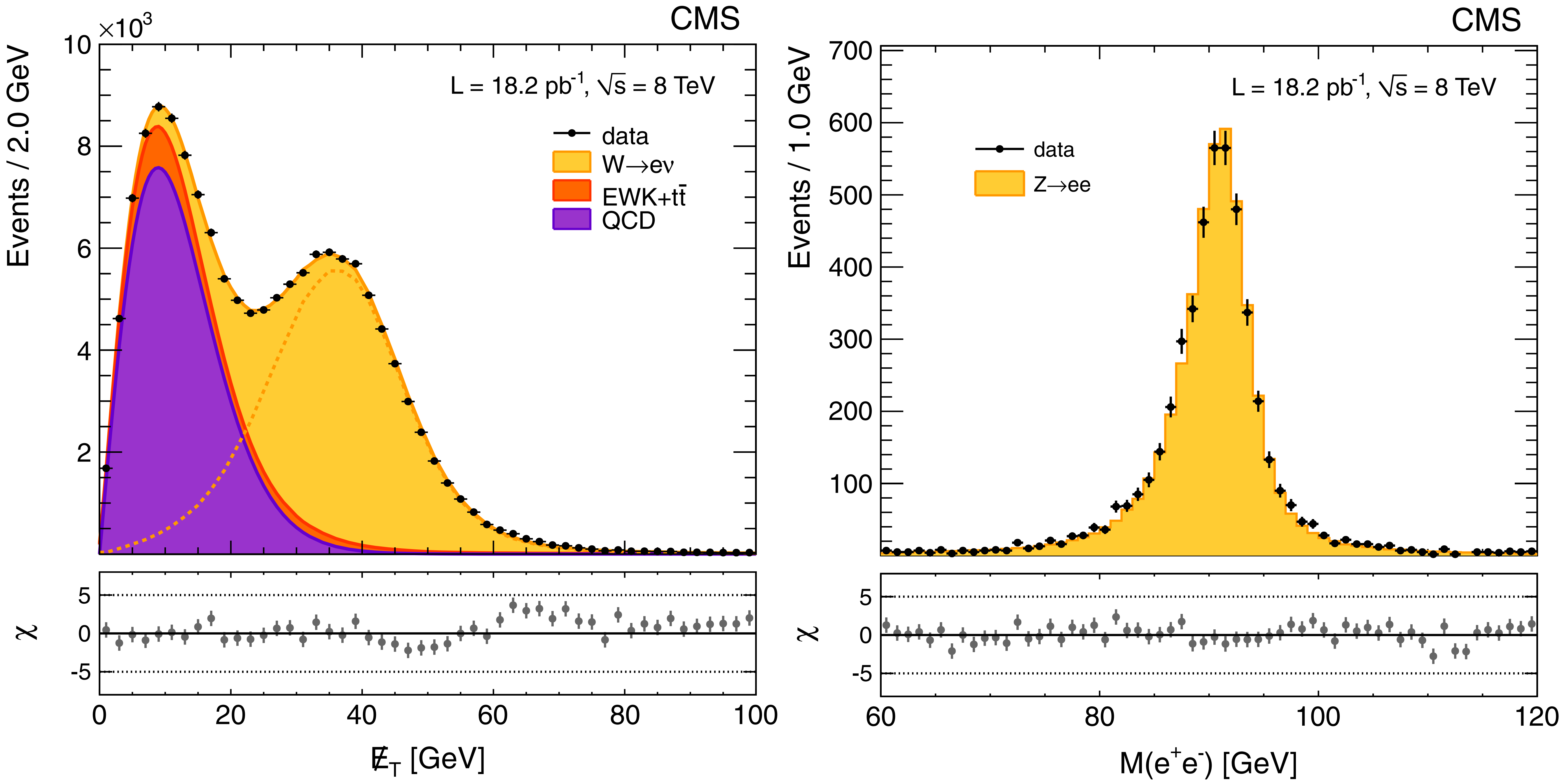

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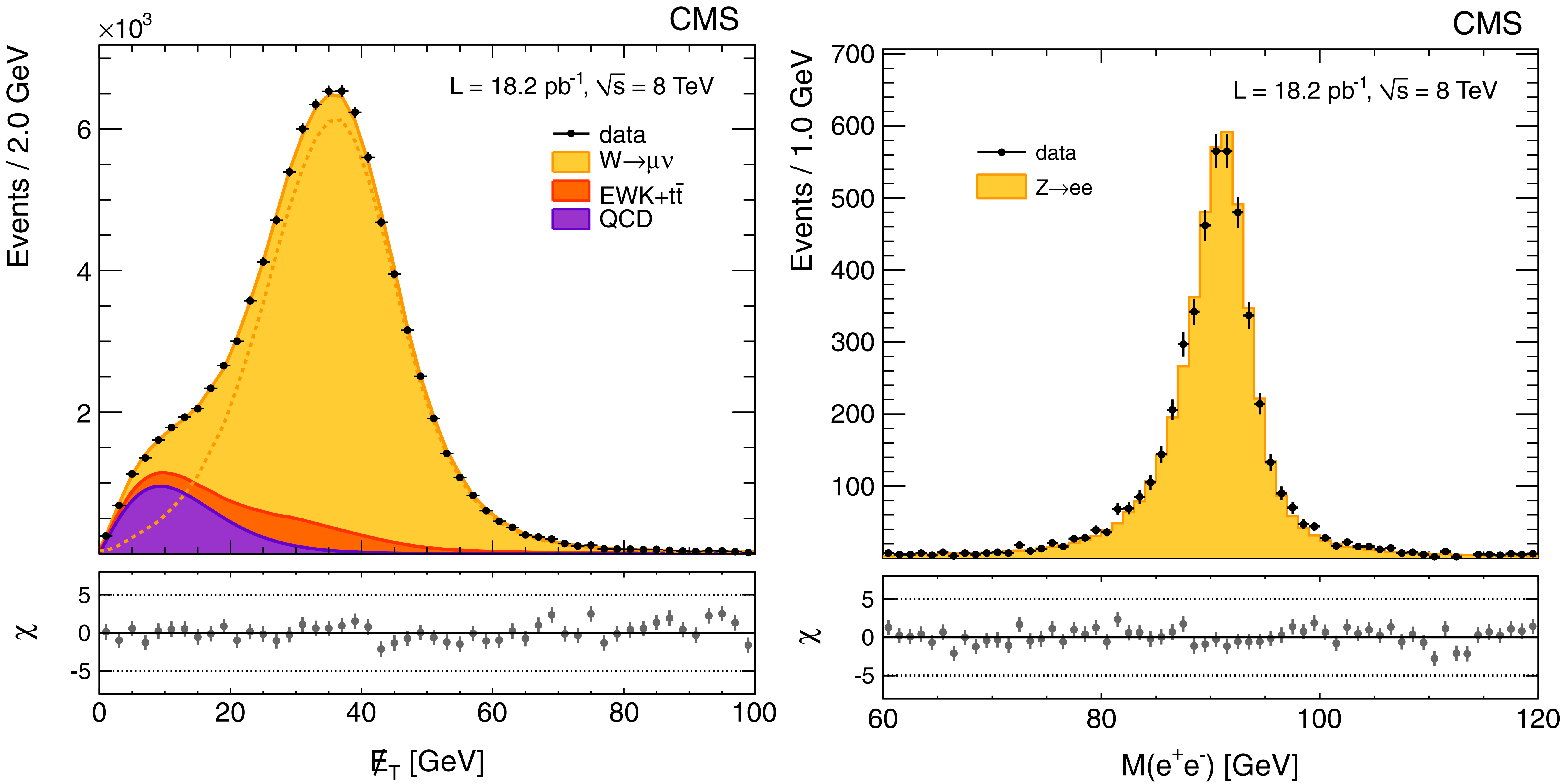

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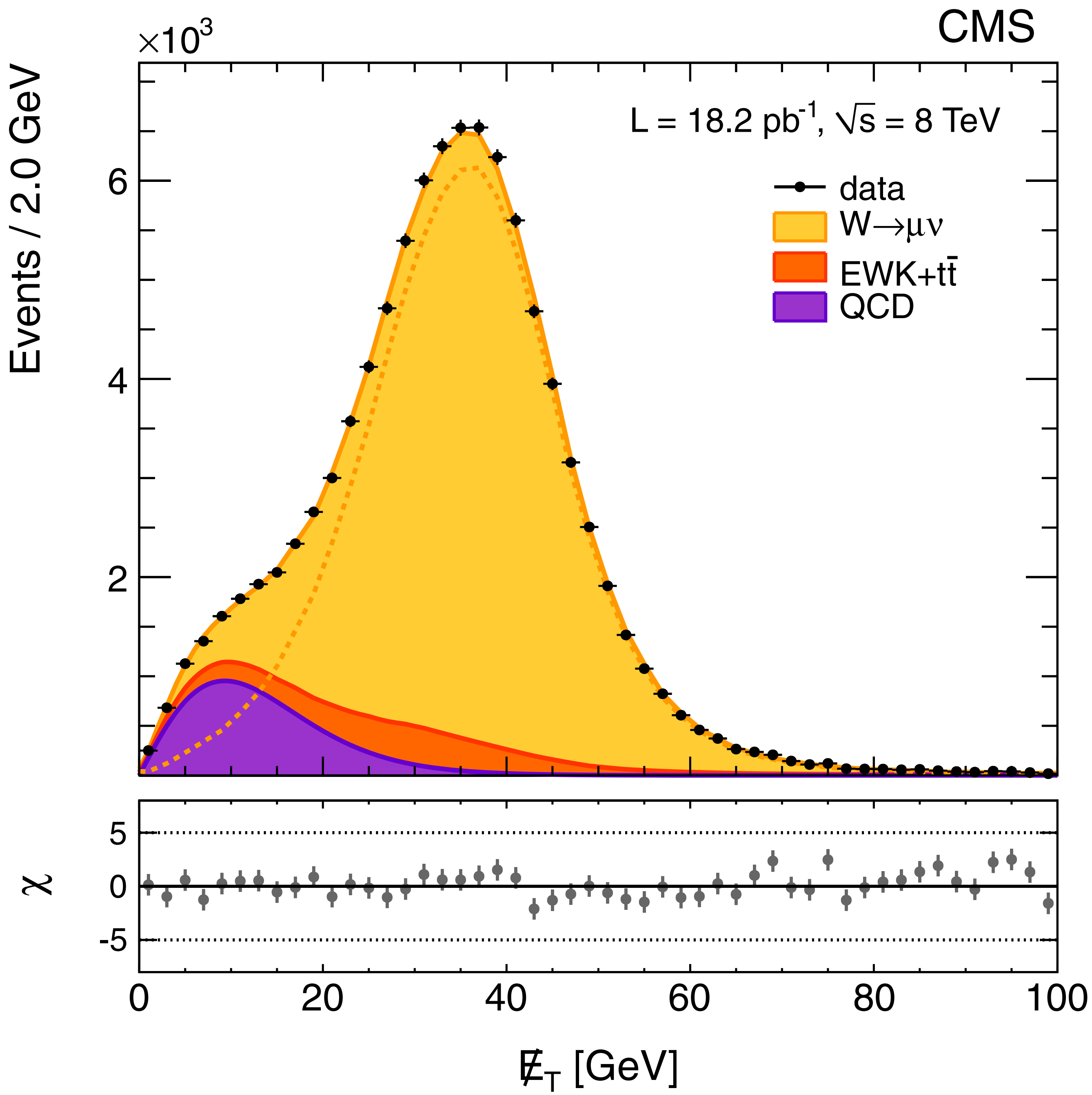

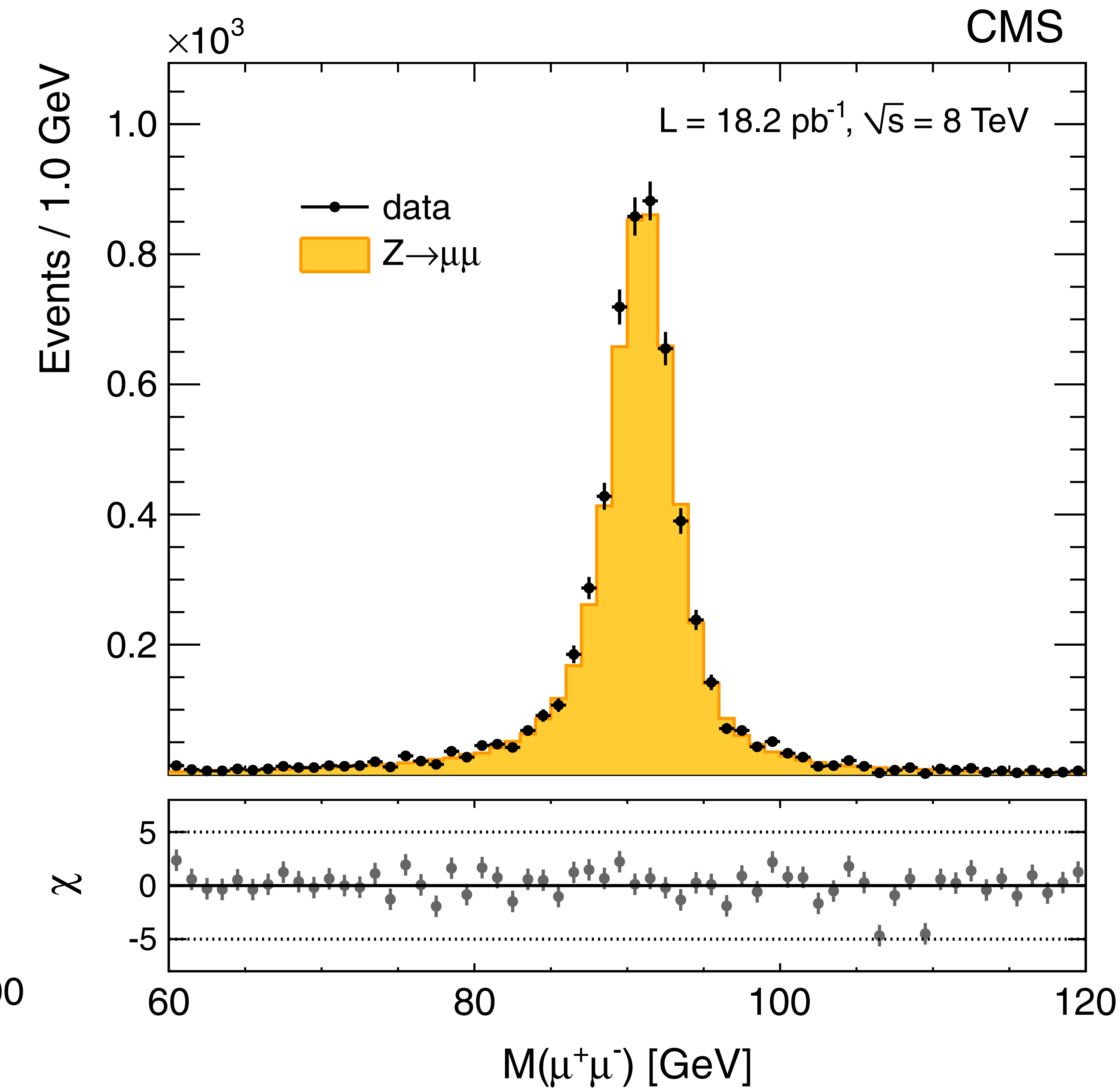

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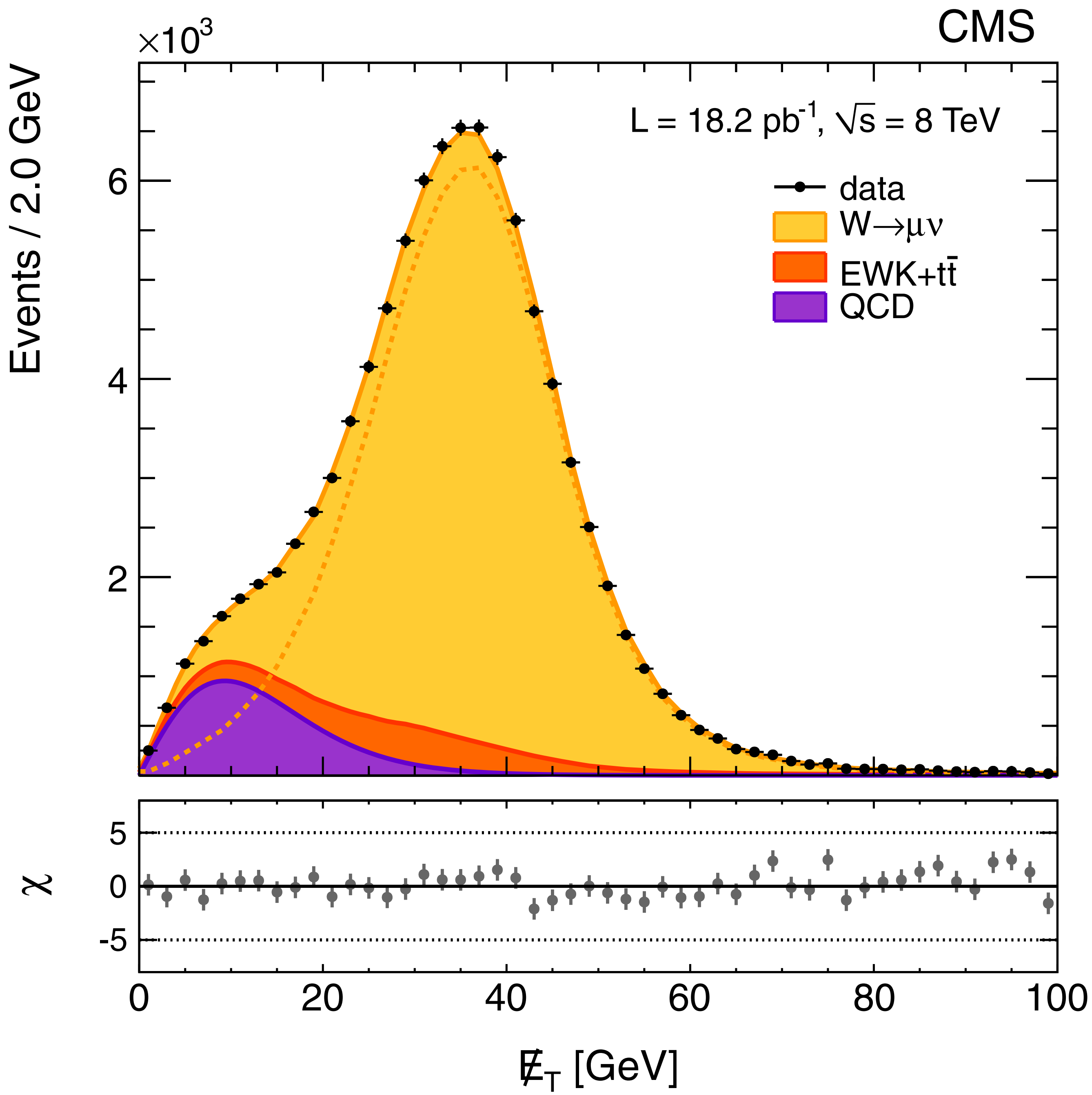
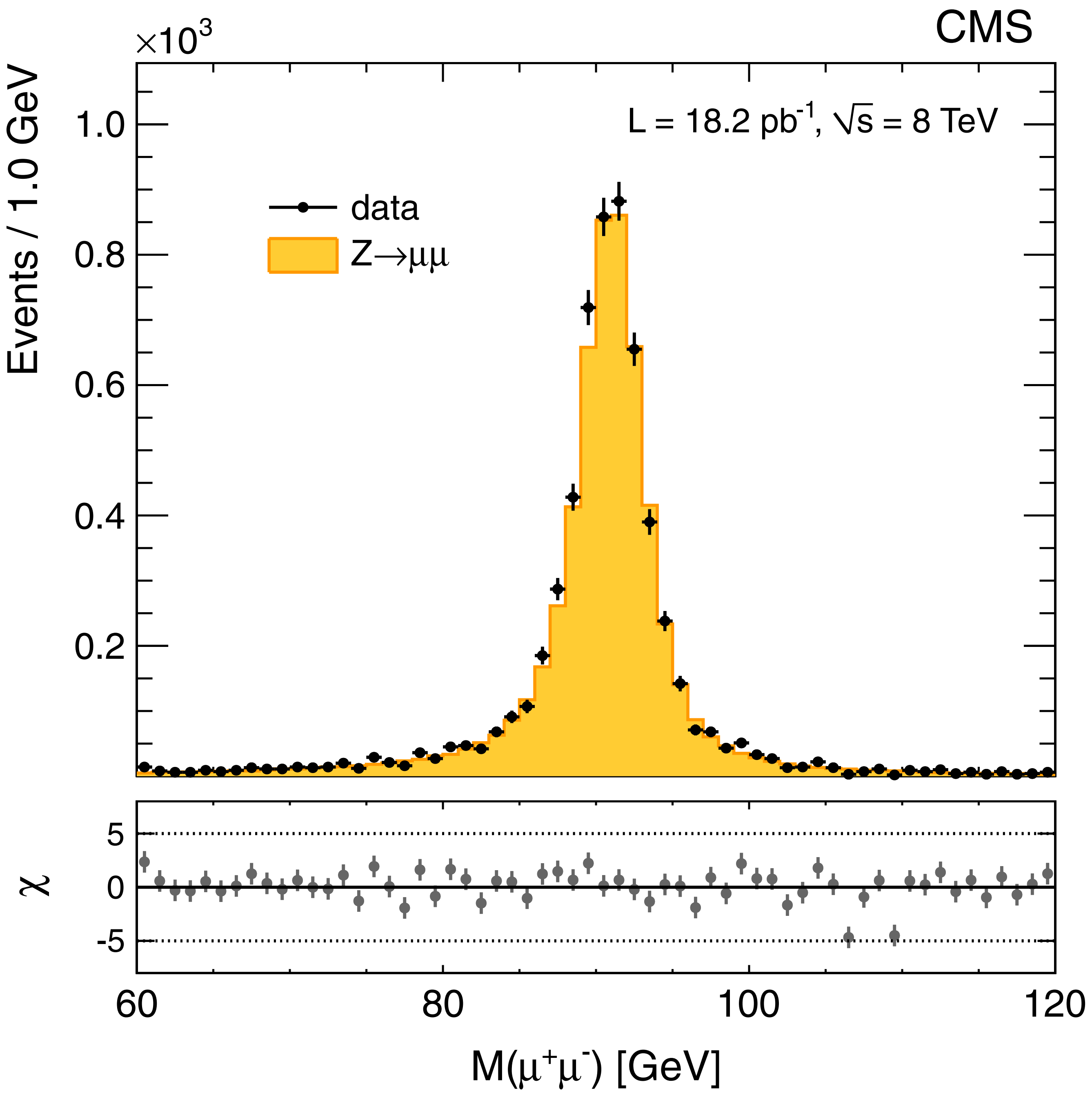
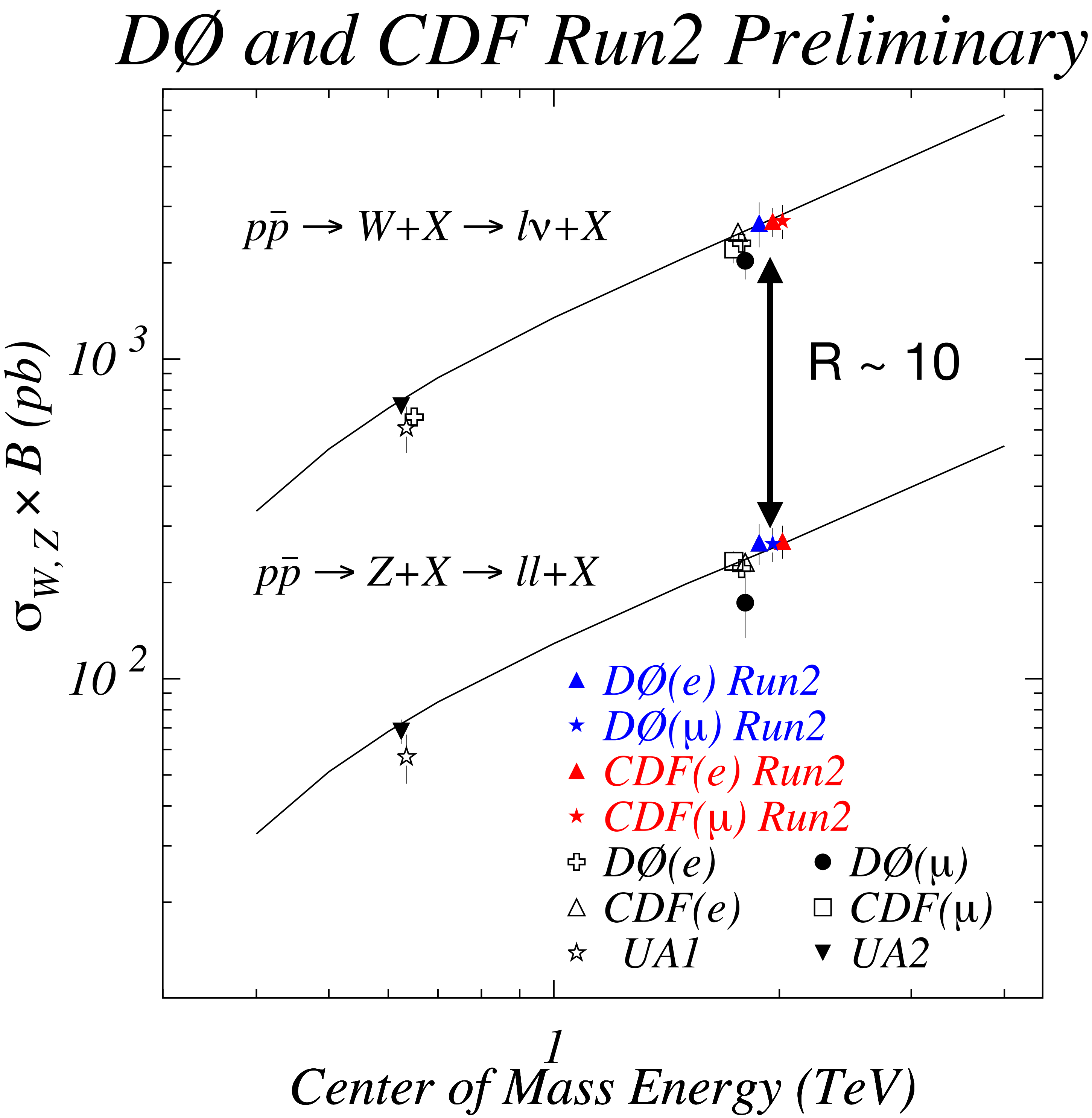




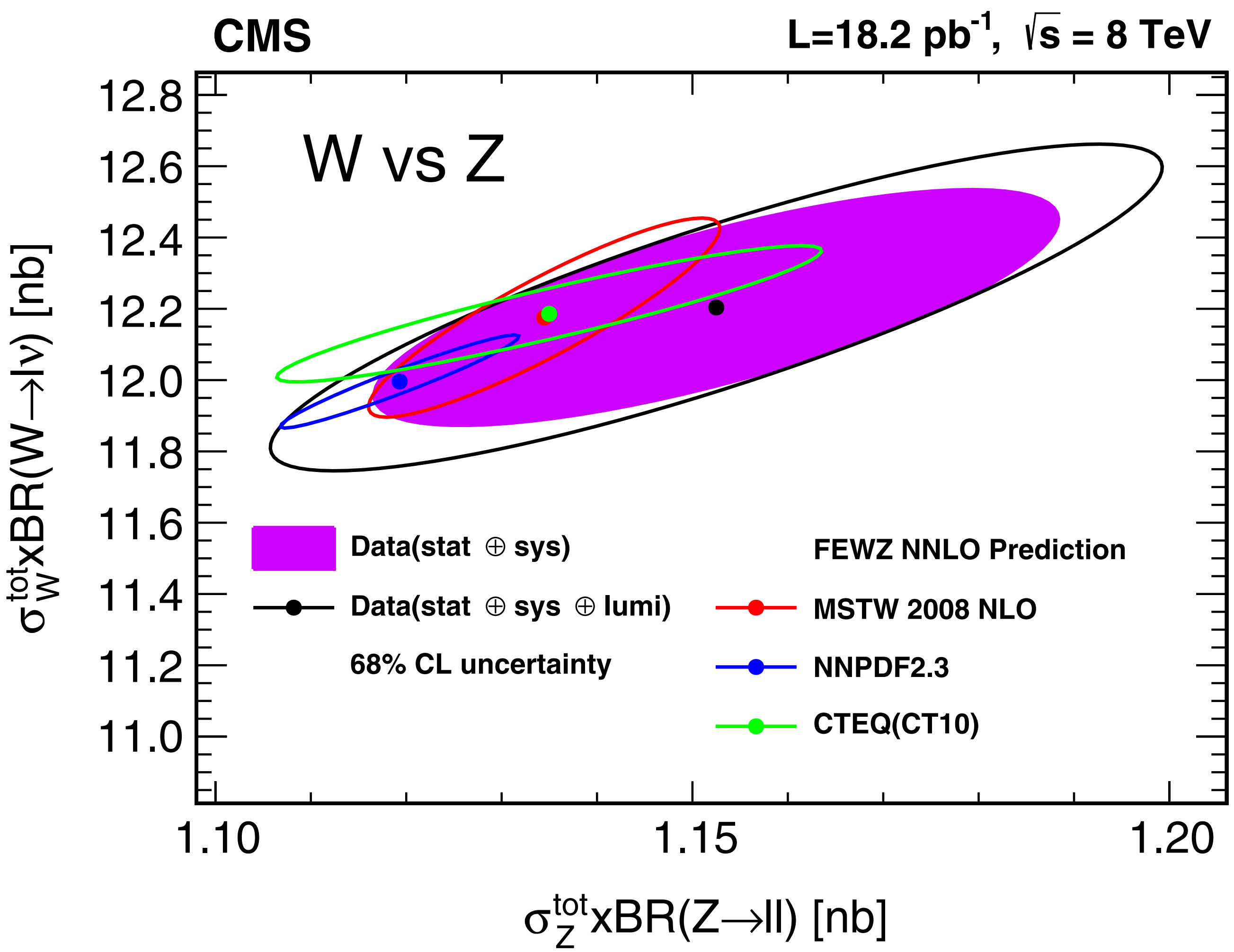
- "Best results" typically in the Muon channel

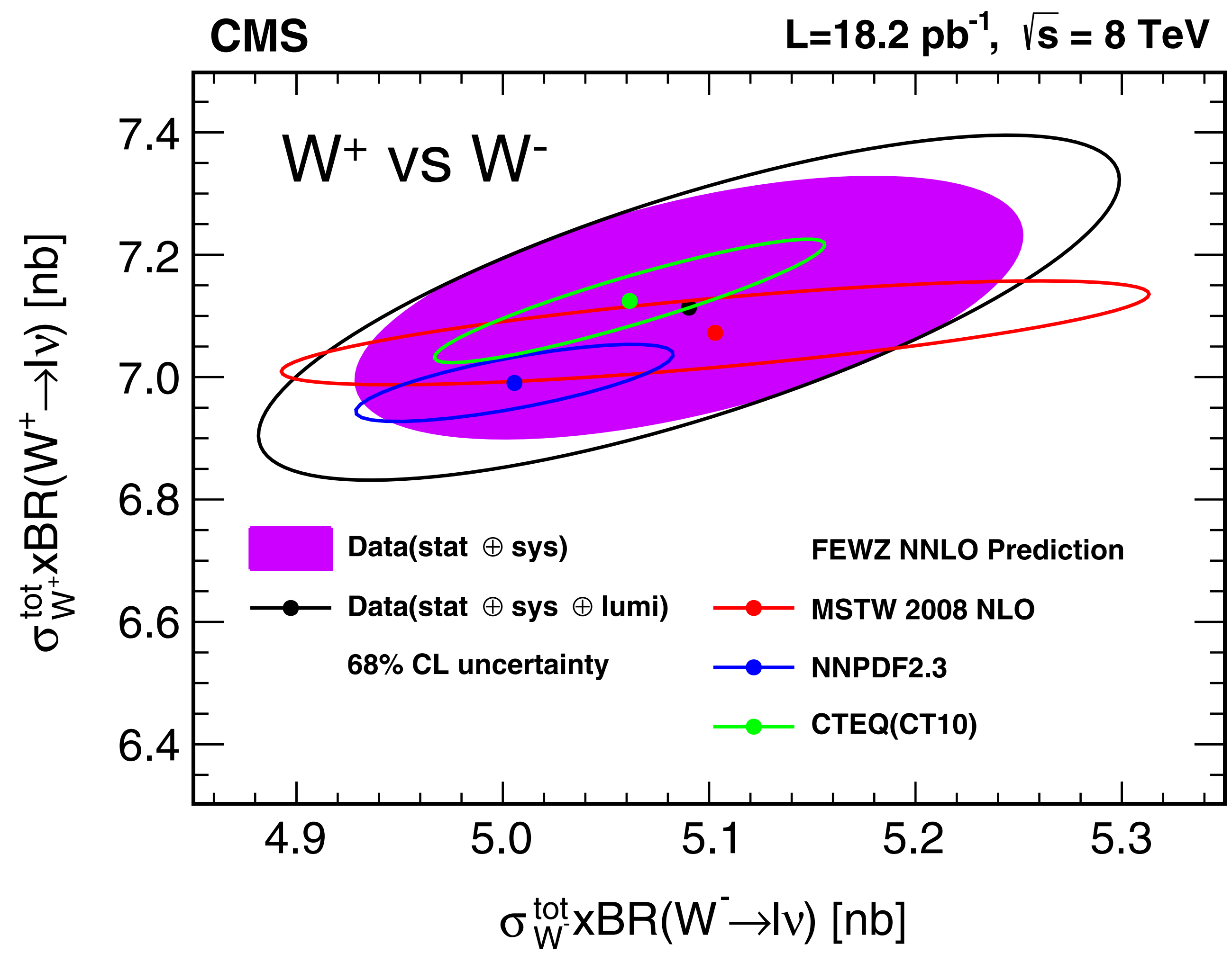
W and Z Production at the Tevatron



- Ratio of production of W and Z bosons R - very well predicted, since some of the PDF uncertainties cancel

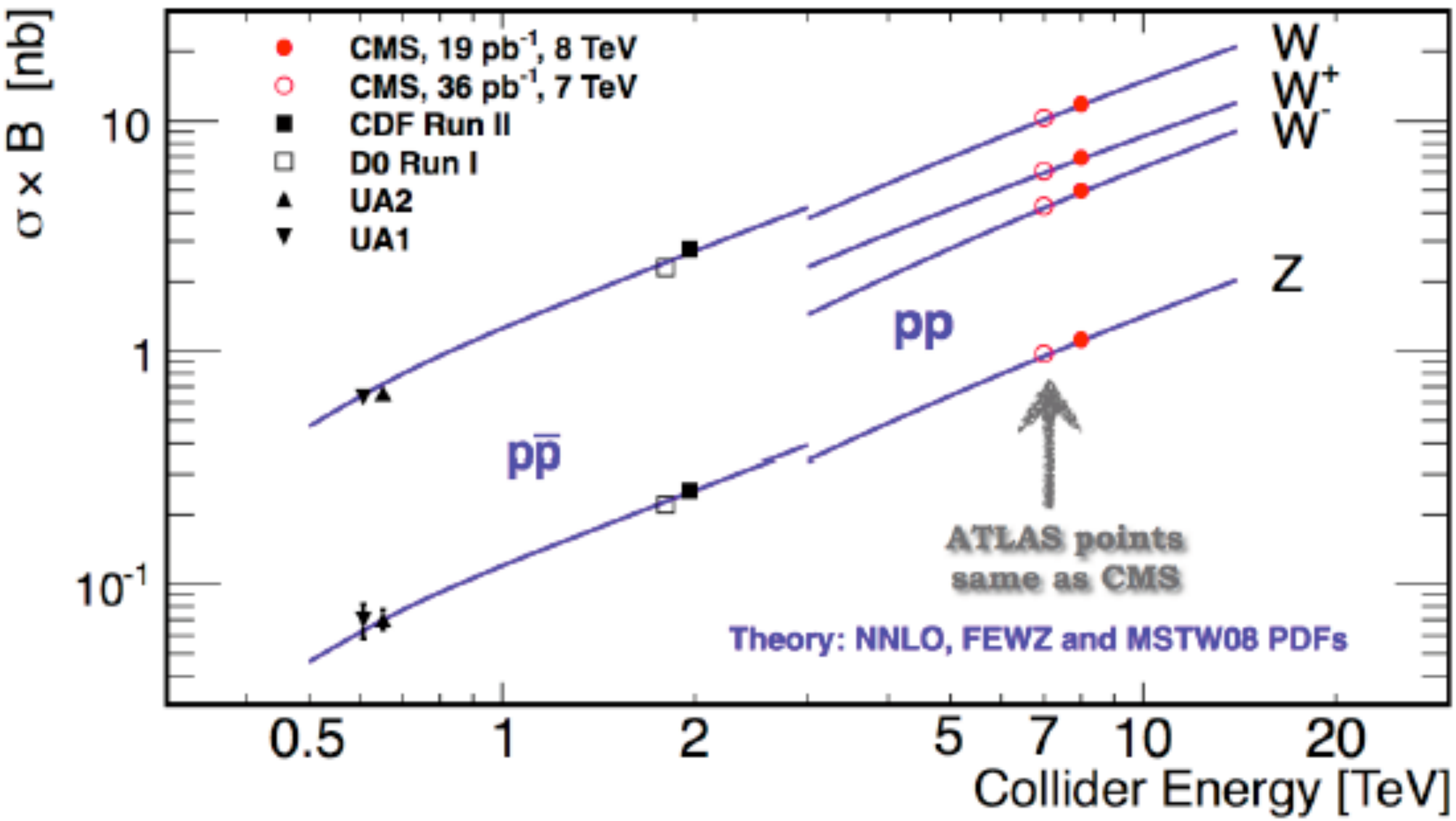
W and Z Measurements at the LHC





- Measured cross sections corrected for efficiency and acceptance
- Higher cross section for W^+ than for W^-: Due to valence quark content of protons: uud - higher probability to make a W^+

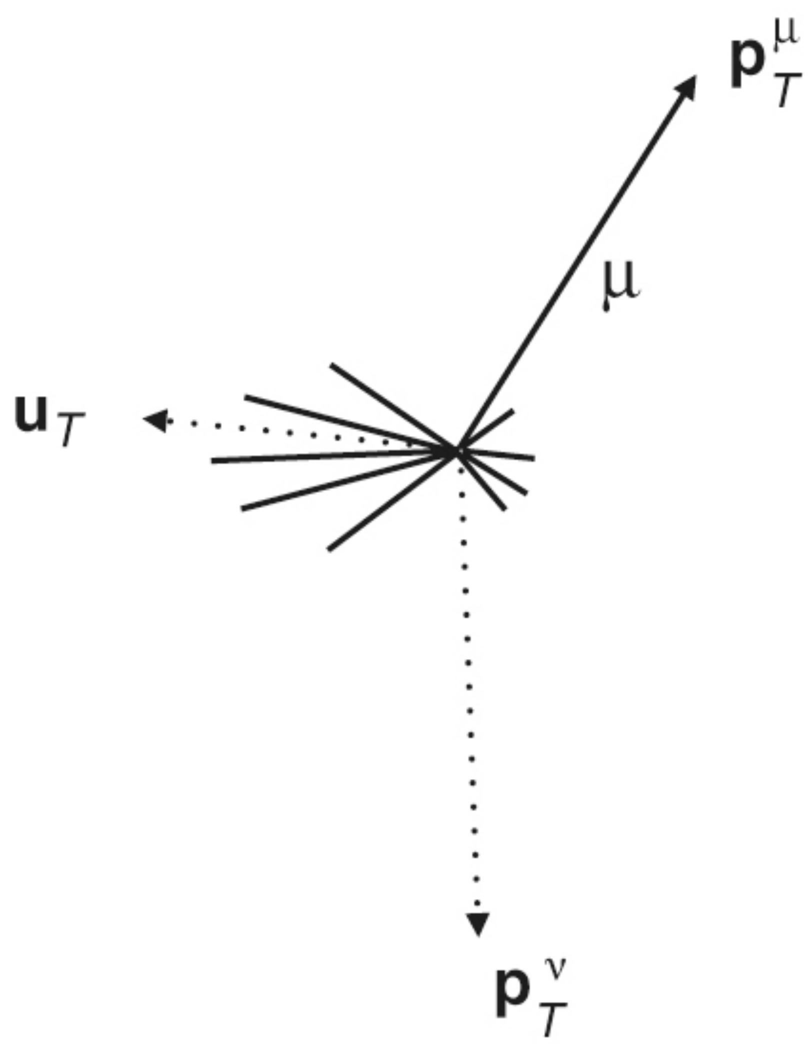
W and Z Production at the LHC



- Combined with Tevatron results to illustrate evolution with energy

Measuring the Mass of the W Boson

- Measurement of the mass from the transverse momentum distribution of the lepton and of the neutrino (inferred from lepton and hadronic system)



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

- Reconstruct transverse mass:

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

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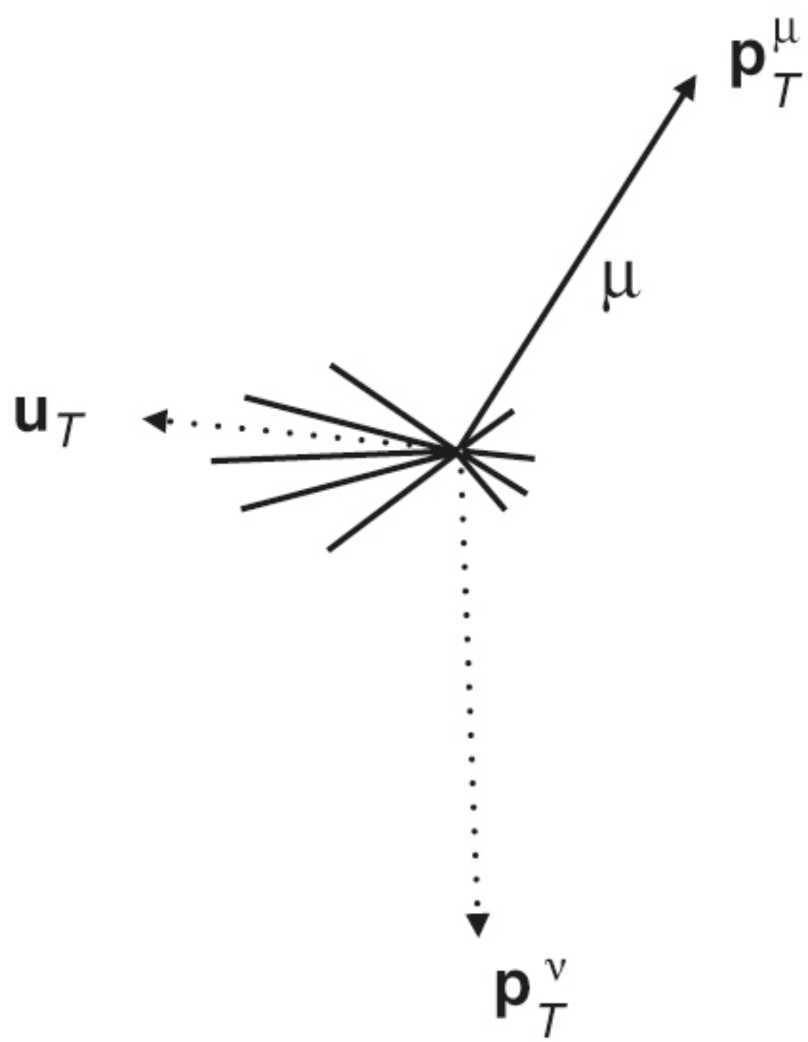

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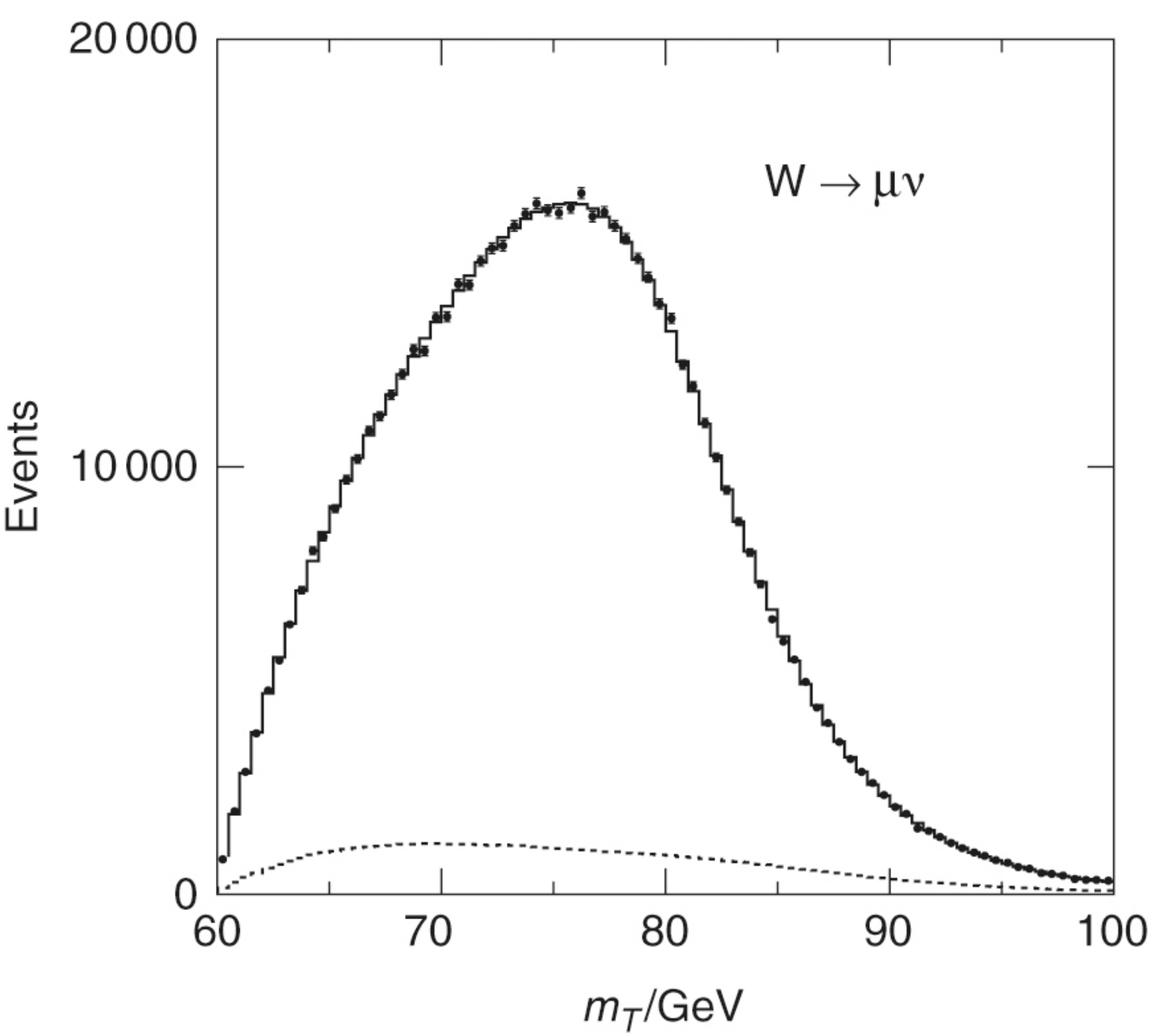
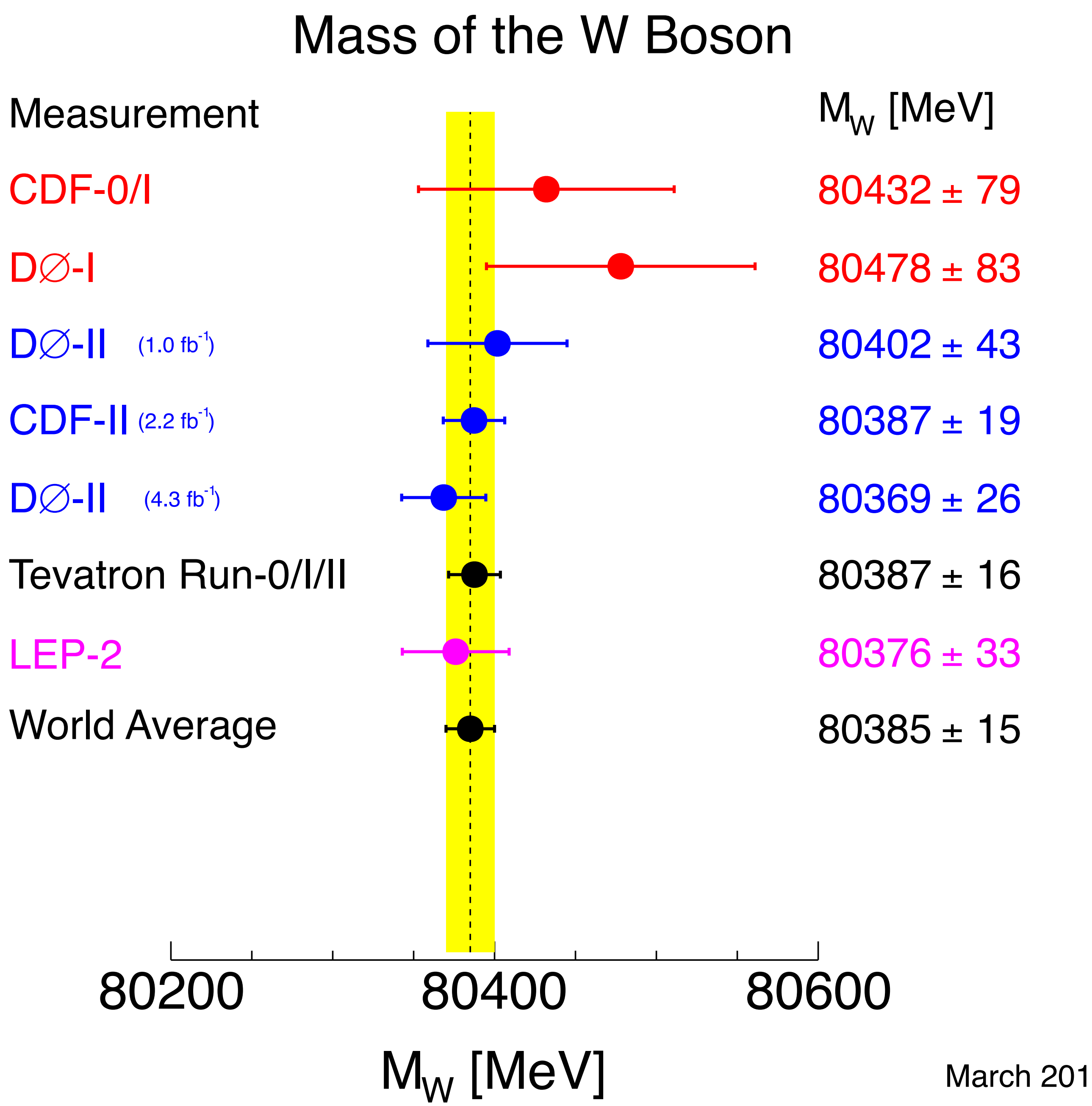
- Compare measured M_T distribution to simulated distributions with different W mass assumptions ("template fit")
- Requires excellent understanding of momentum and energy scale and resolution

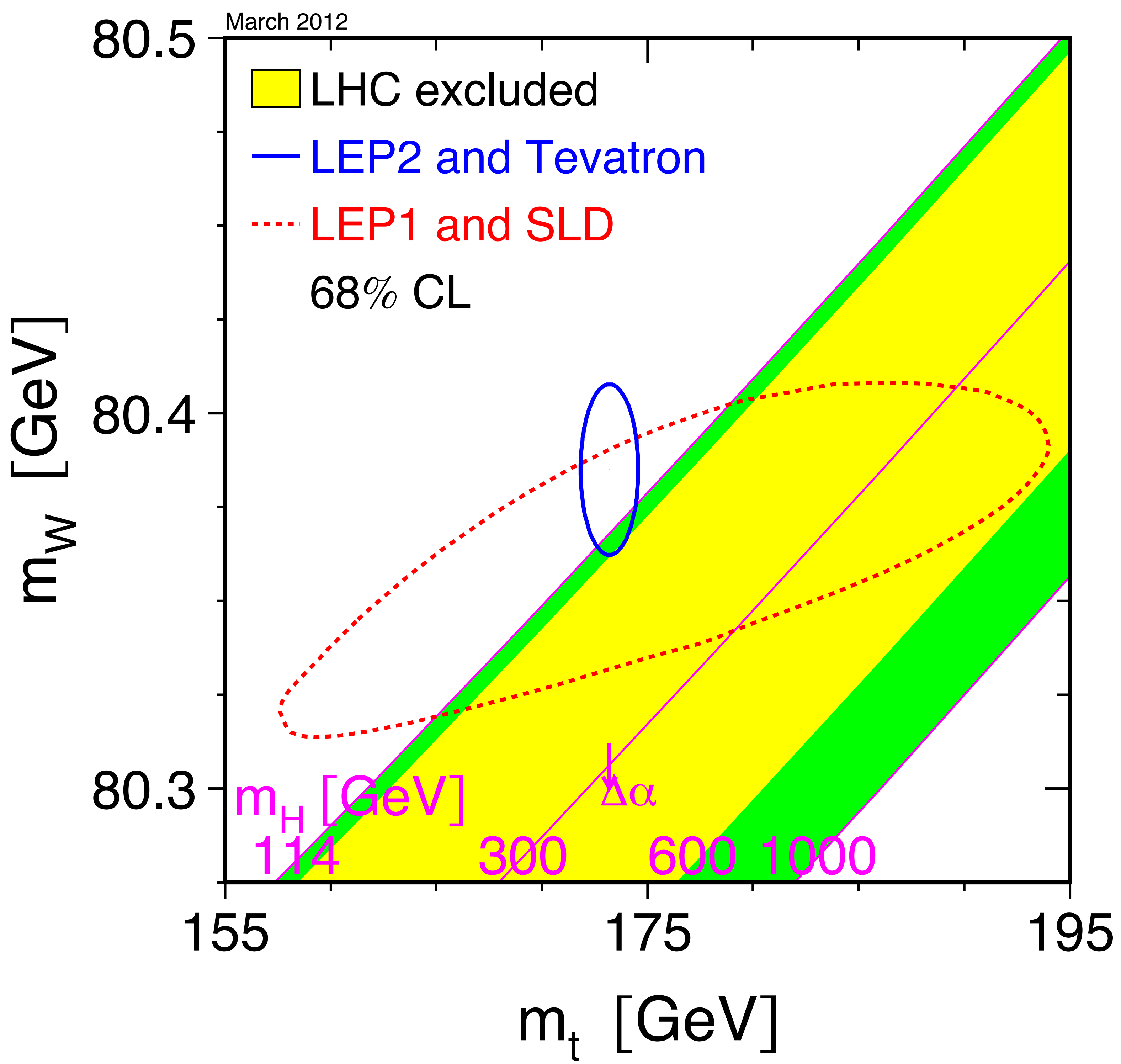
Measuring the Mass of the W Boson





- Best measurement from Tevatron
- Combination of CDF and D0: M_W = 80.387 ± 0.016 GeV
- World average with LEP: M_W = 80.385 ± 0.015 GeV

The Impact of the W Mass Measurement



- W mass measurement (together with top mass) provides indirect constraints on Higgs mass in the Standard Model

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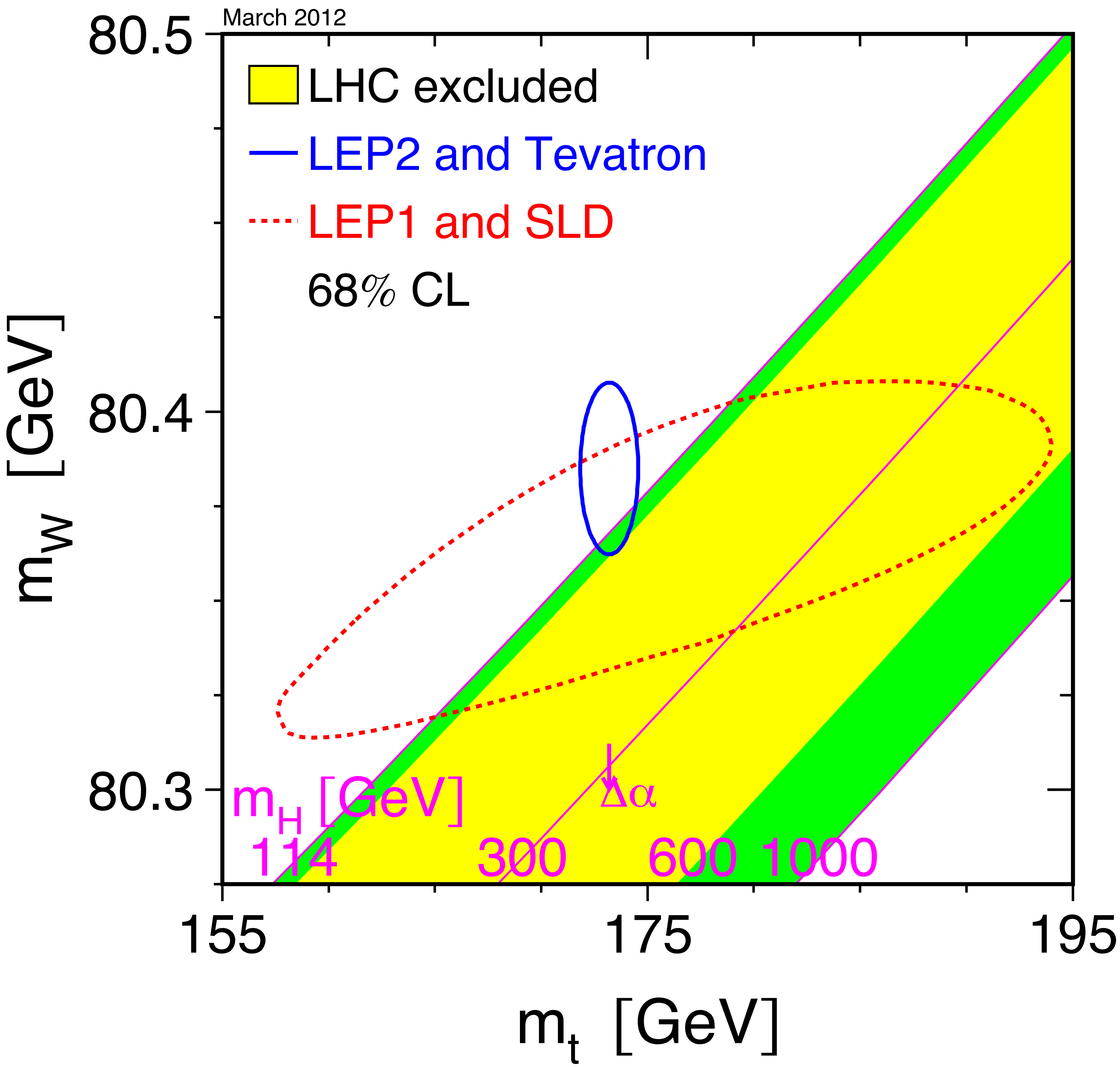

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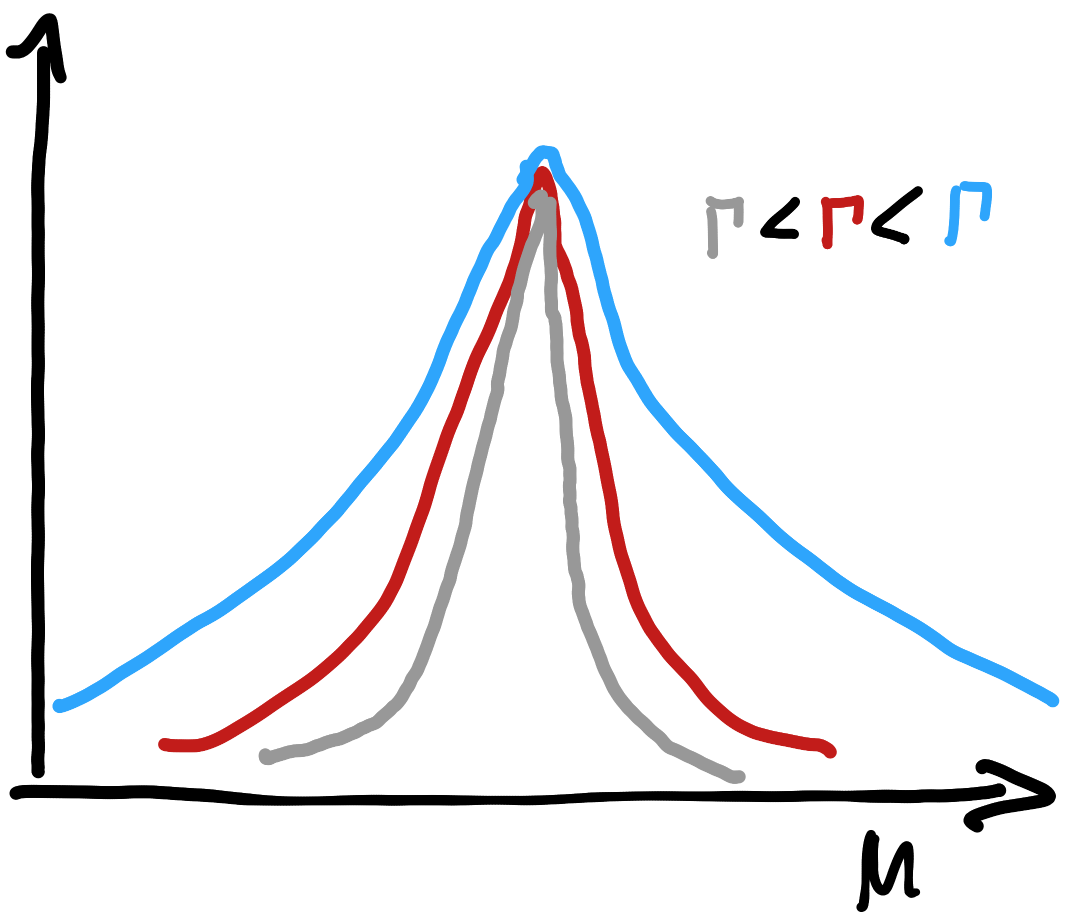
Targets for LHC

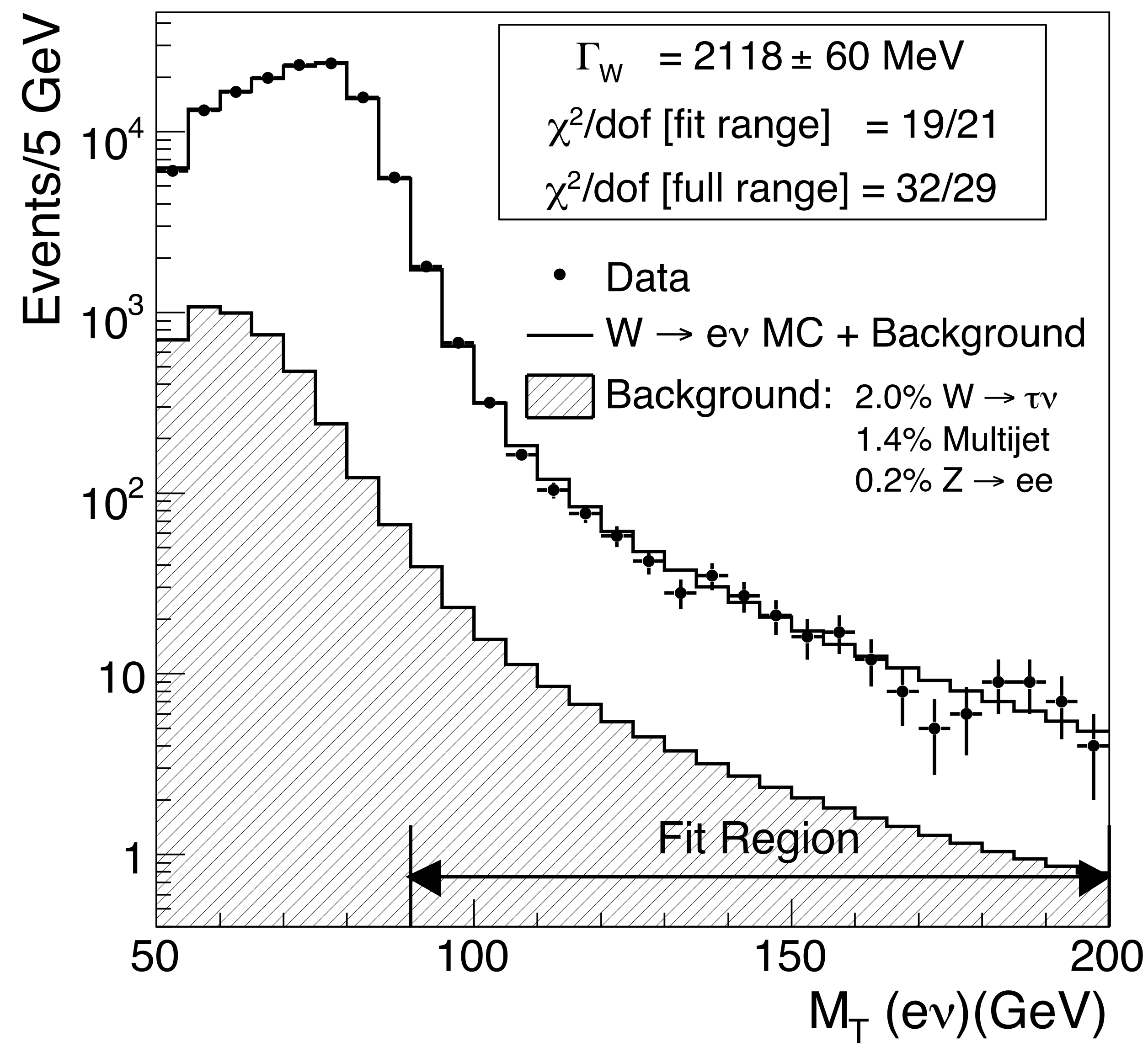
arXiv:1310.6708

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\text{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

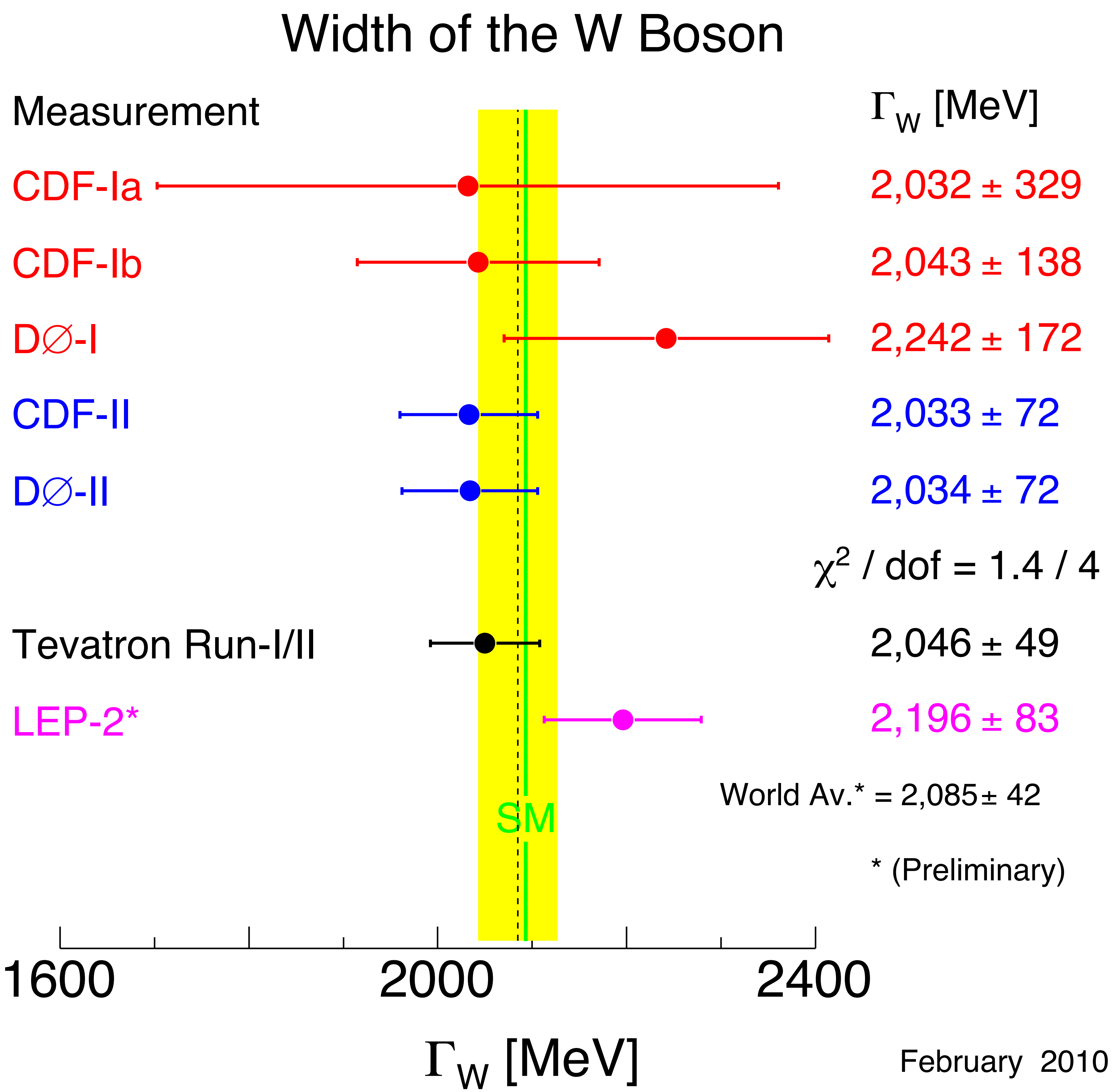
Measuring the Width of the W Boson

- The tail of the M_T distribution is sensitive to the total width of the W boson:
  - Events with $M_T > M_W$ are due to detector resolution effects and due to the finite width - the resolution contribution to this falls faster than the width contribution, allowing an accurate measurement of the width



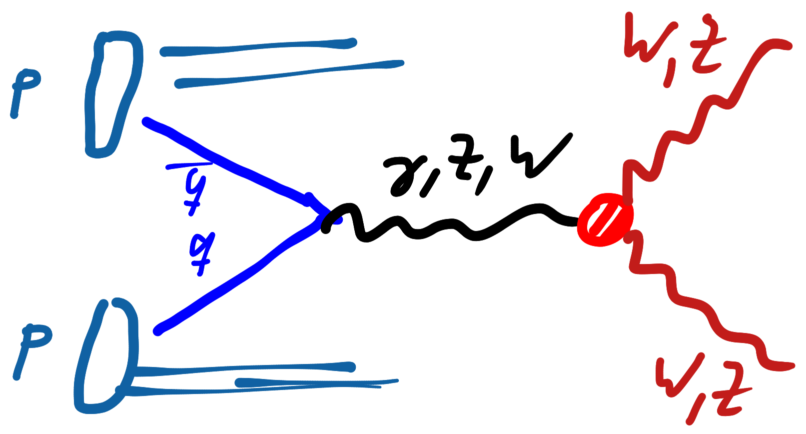


The Width of the W - Summary of Results



- Excellent agreement with the Standard Model

Triple Gauge Couplings



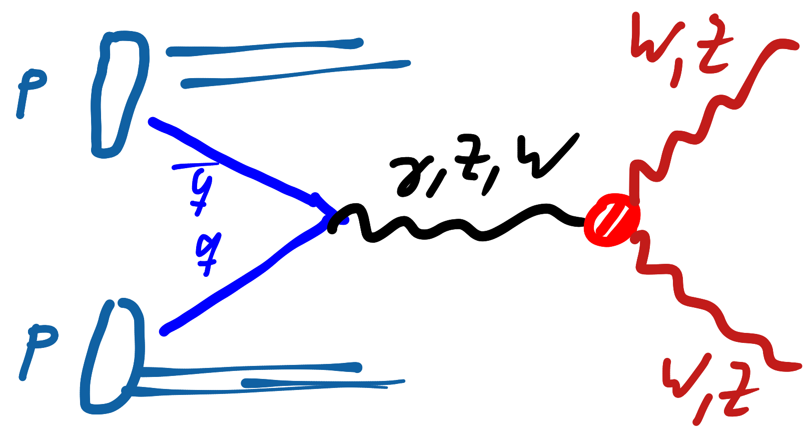
γ, Z -> W^+W^-

W -> WZ, Wγ

~~γ, Z -> ZZ~~

- In the SM: Space-like diagrams are = 0 if two of the three bosons are identical

Triple Gauge Couplings



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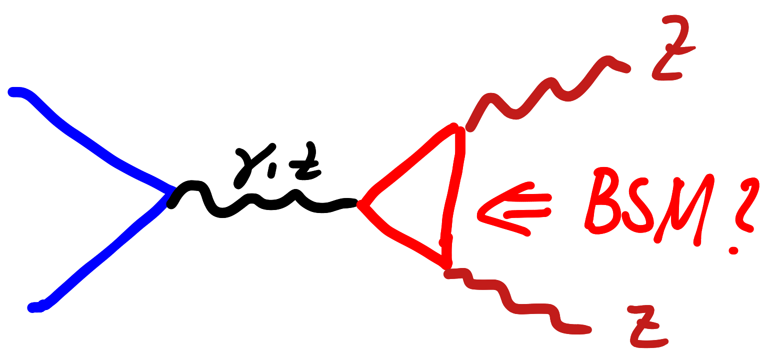

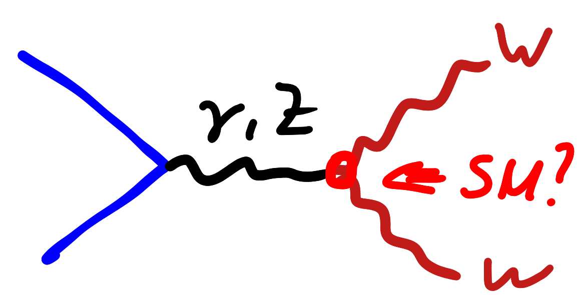

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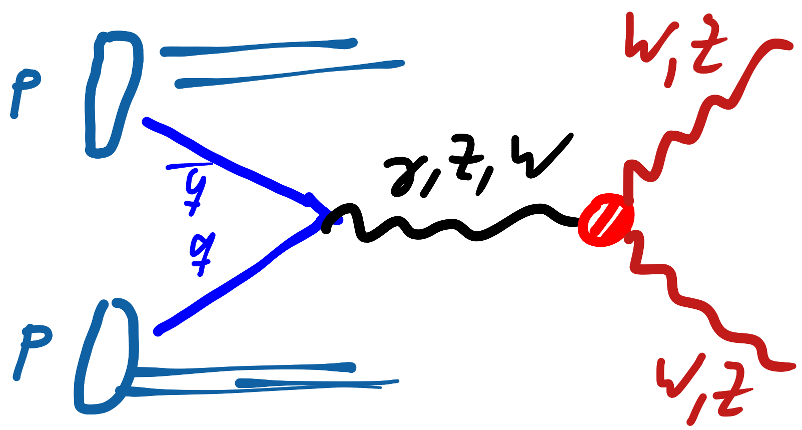

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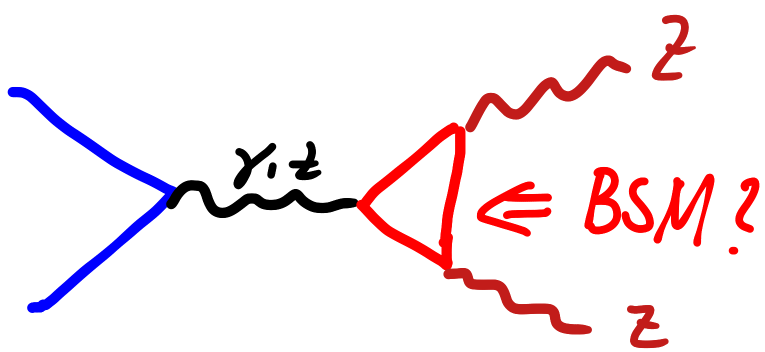
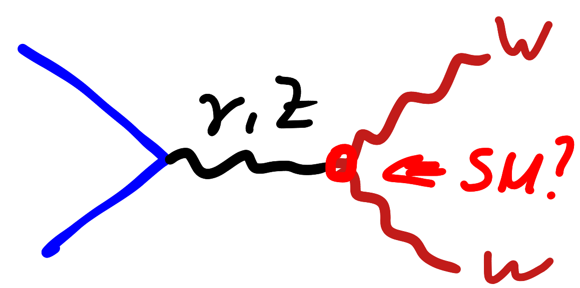
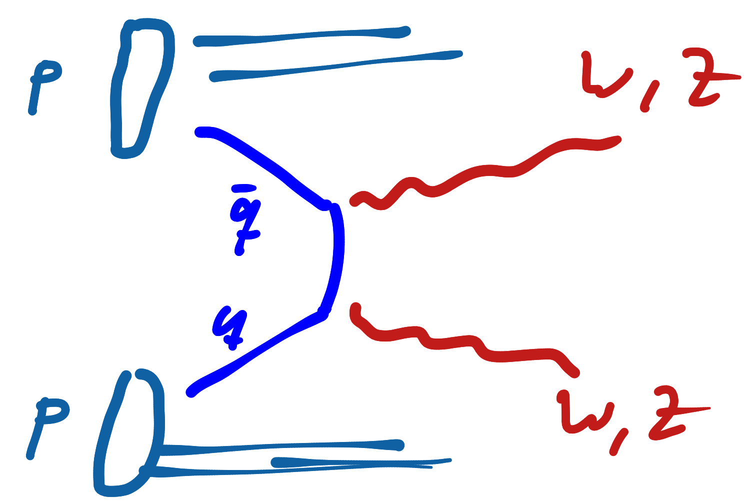
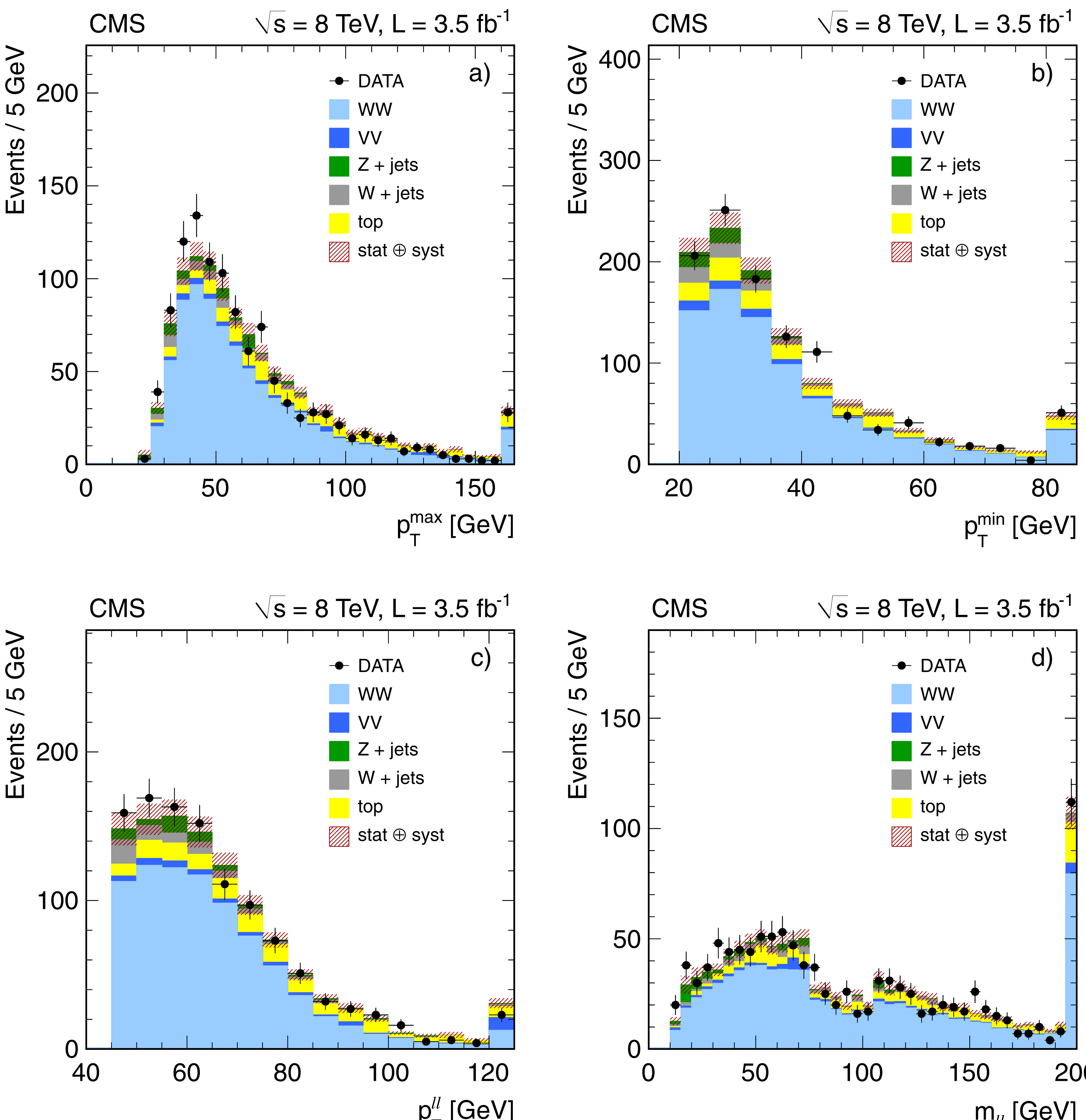




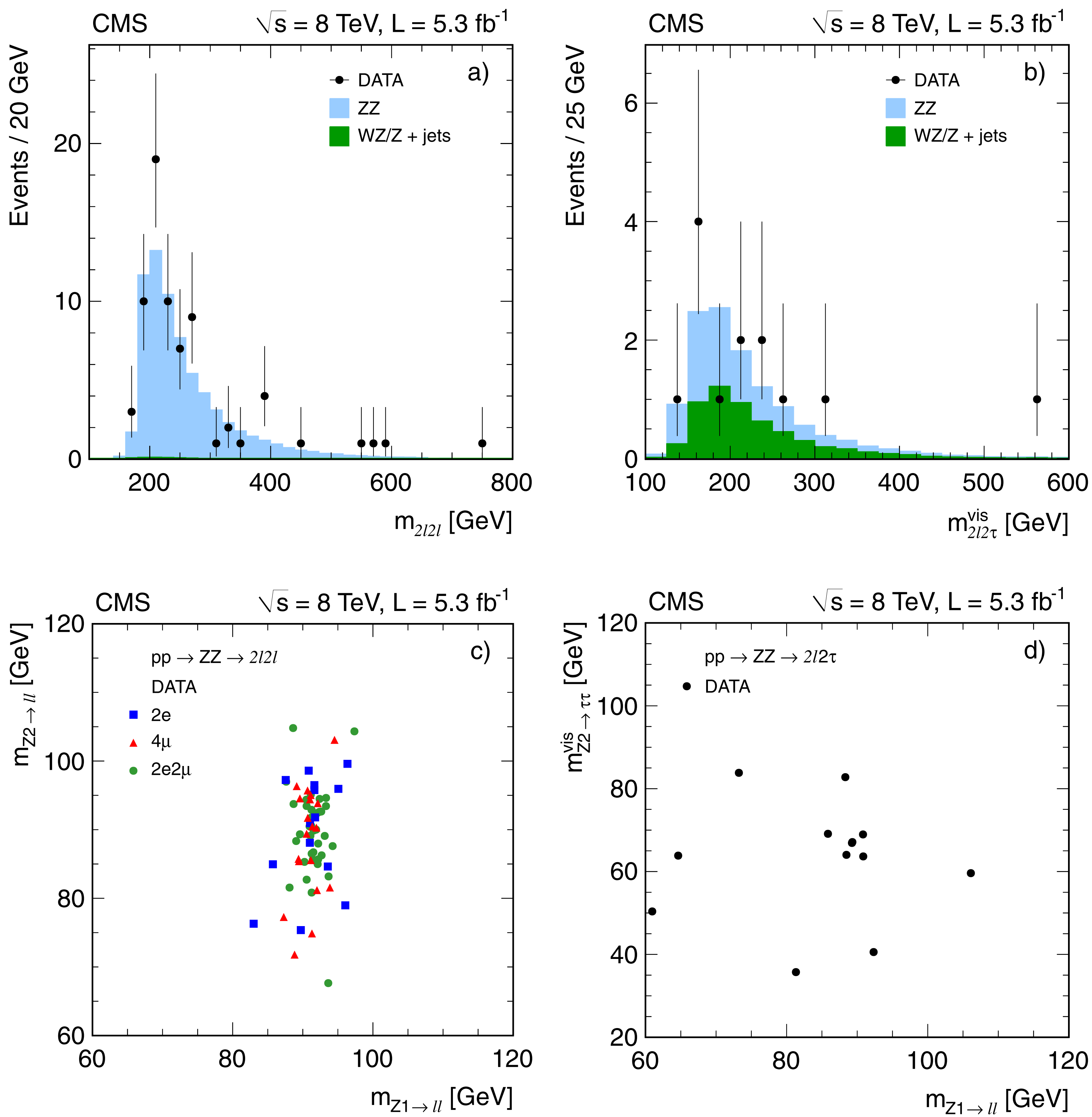


- SM: Time-like diagrams with two identical bosons in the final state are allowed
  - NB - No triple gauge coupling! SM background to TGC measurements

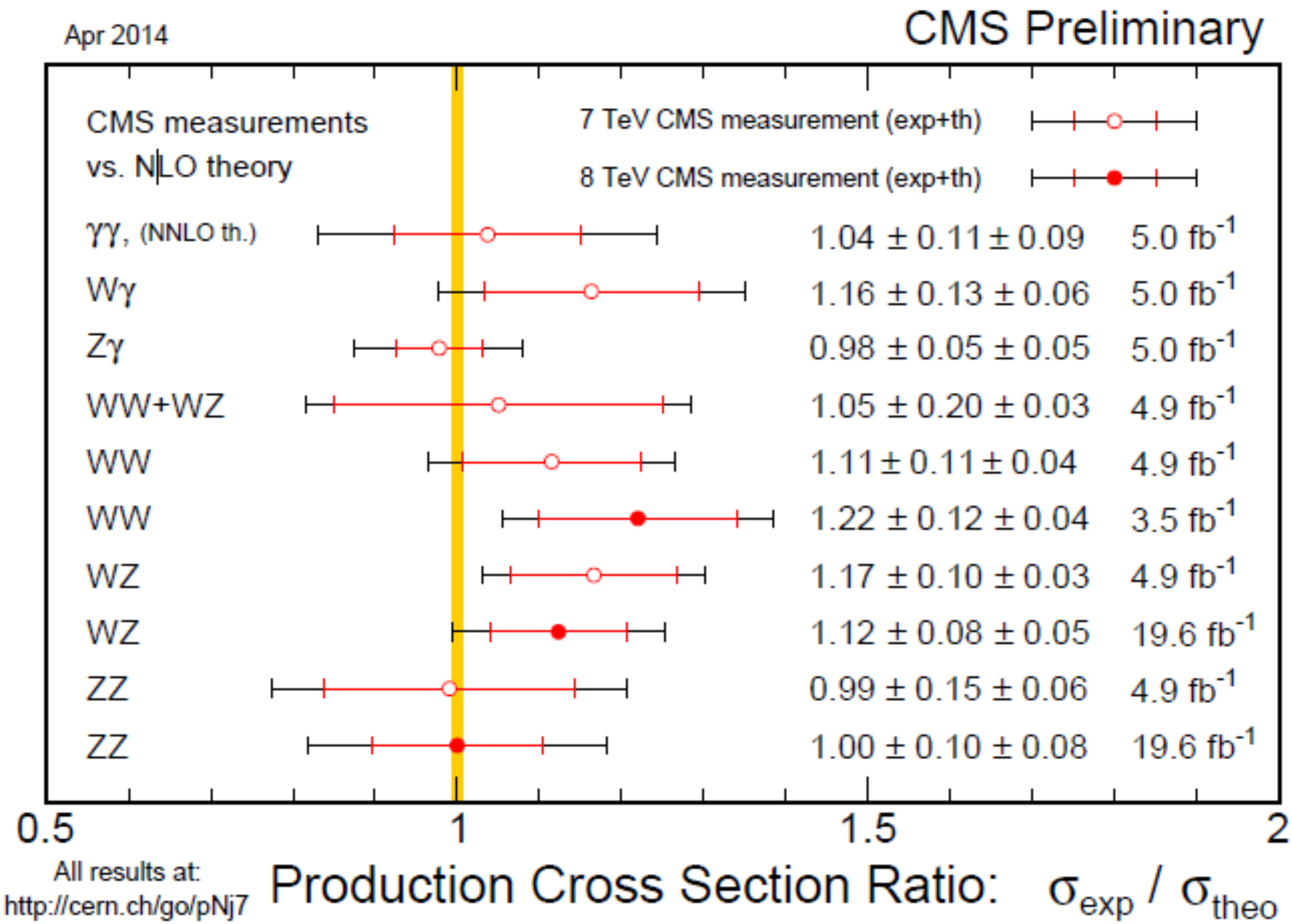
Measurement of WW Production



Measurement of ZZ Production



Double Vector Boson Production - CMS Summary



- Overall excellent agreement with SM expectations - Consistent for 7 and 8 TeV

Summary

- The (electroweak) Standard Model combines QED and the weak interaction theory to describe electromagnetic and weak interactions - based on the Gauge Group SU(2) x U(1)
- It has been extremely successful in describing all observations to date
- Its predictions are tested by measurements of
  - masses
  - cross-sections (and production asymmetries - not covered)
  - decay widths
  - triple gauge couplings - particularly sensitive to New Physics

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  - requires very precise understanding of detectors and excellent control of all systematics - will take a while!

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Next Lecture: QCD, S. Bethke 24.11.2014

Zeitplan

1.	Einführung; Stand der Teilchenphysik	06.10.
2.	Teilchendetektoren an Tevatron und LHC (I)	13.10.
3.	Teilchendetektoren an Tevatron und LHC (II)	20.10.
4.	Hadronenbeschleuniger: Tevatron und LHC	27.10.
5.	Monte Carlo Generatoren und Detektor Simulation	03.11.
6.	Trigger, Datennahme und Computing	10.11.
7.	Standard-Modell Tests	17.11.
8.	QCD, Jets, Strukturfunktionen	24.11.
9.	Higgs I	01.12.
10.	Higgs II	08.12.
11.	Top Physics	15.12.
	----------- No Lecture -------------	**22.12.**
	-----------Christmas — — — — — — — — — —	
12.	Supersymmetry	12.01.
13.	Exotica / LHC Pläne	19.01.
14.	Future Collider Projects	26.01.