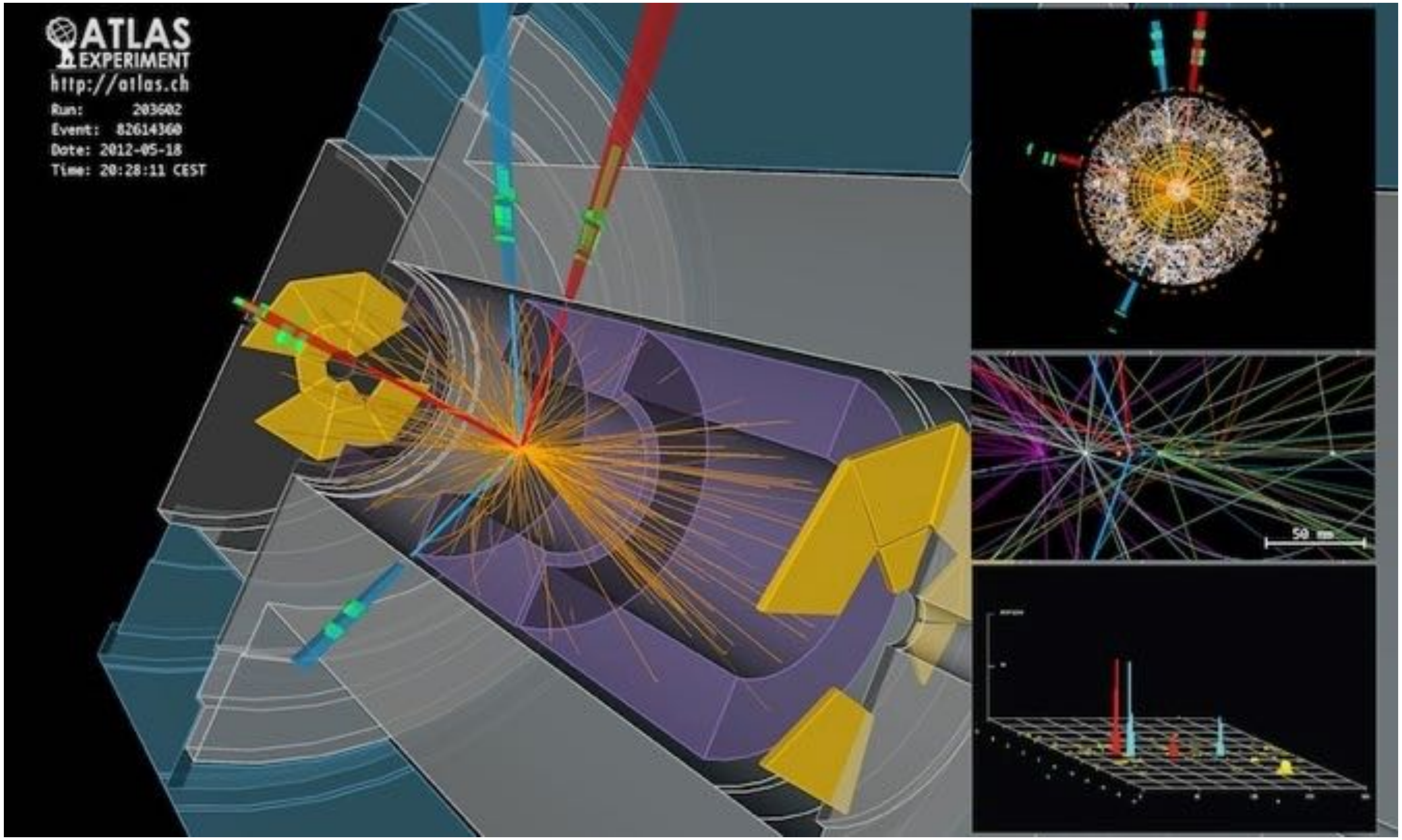
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



8. Precision Tests of the Standard Model

12.12.2016

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 12)

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Weak	$W^\pm$, Z^0	10^{-14}
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Underlying theories: QCD; QED / weak interaction ➾ electroweak unification (GSW)

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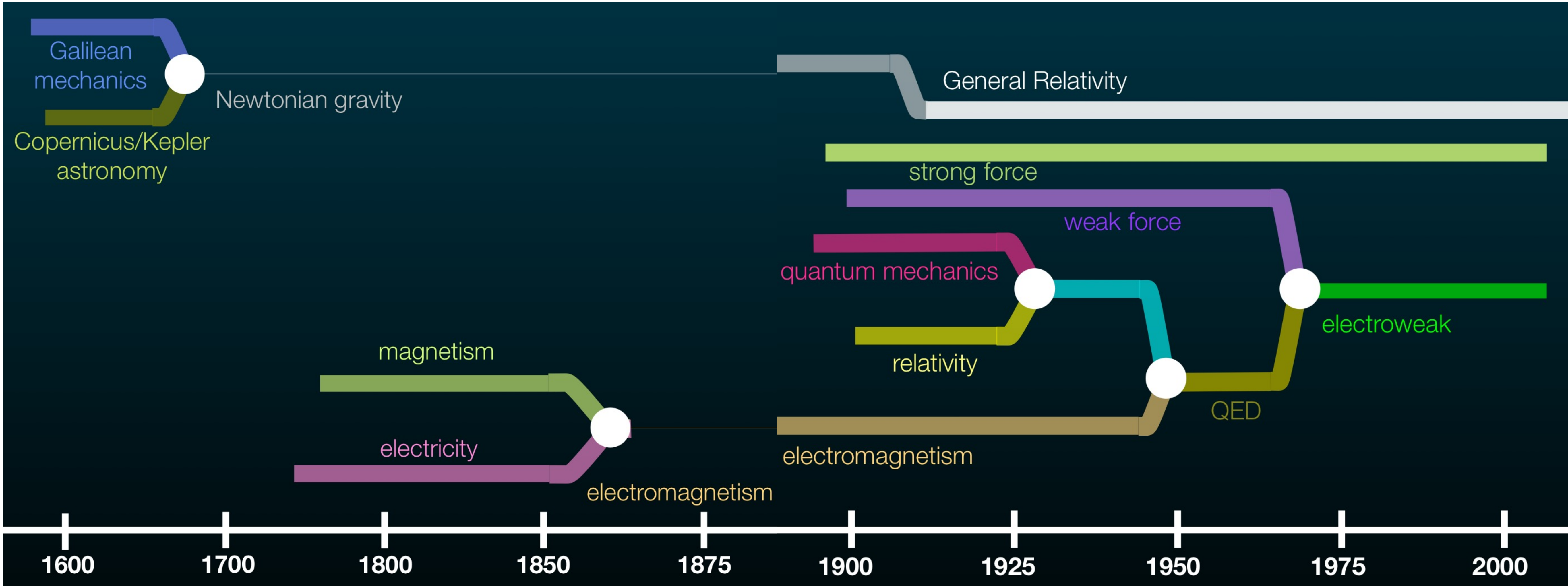
- It:
  - describes the unified electroweak interactions and the strong force with gauge invariant quantum field theories
  - is extremely successful in consistently and precisely describing all particle reaction observed to date
  - provides a consistent (yet incomplete) picture of the evolution of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

The Standard Model - Combining Theories



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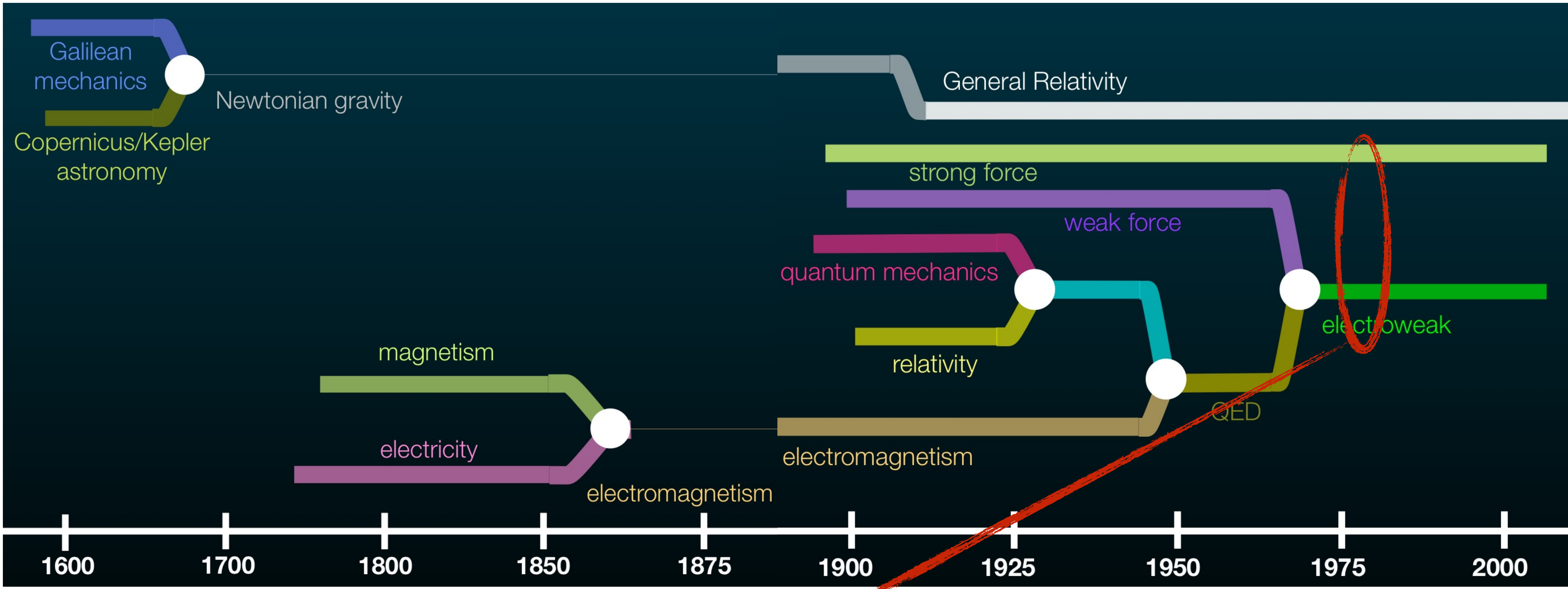
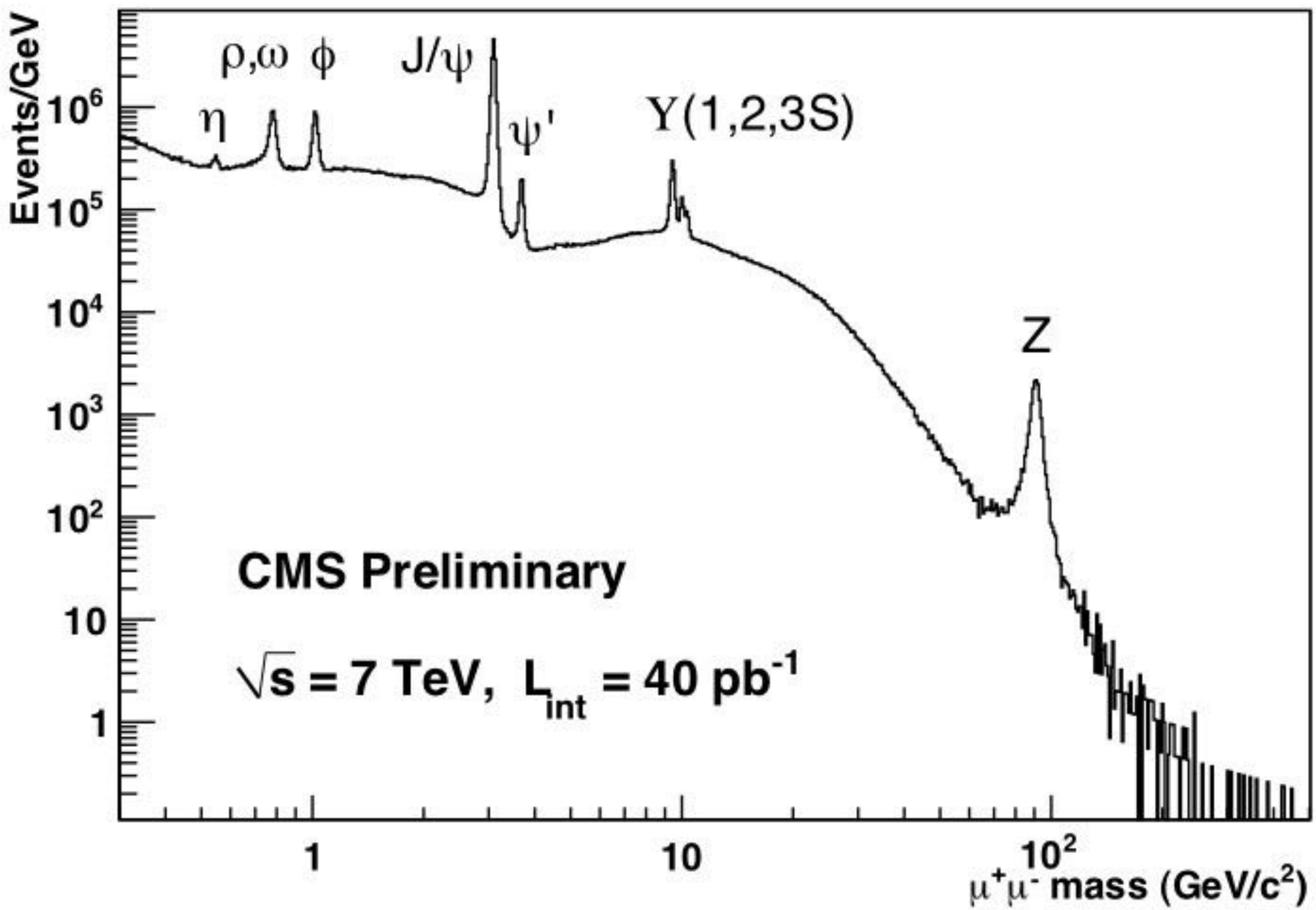


The Standard Model of Particle Physics

“Rediscovering” The Standard Model at LHC



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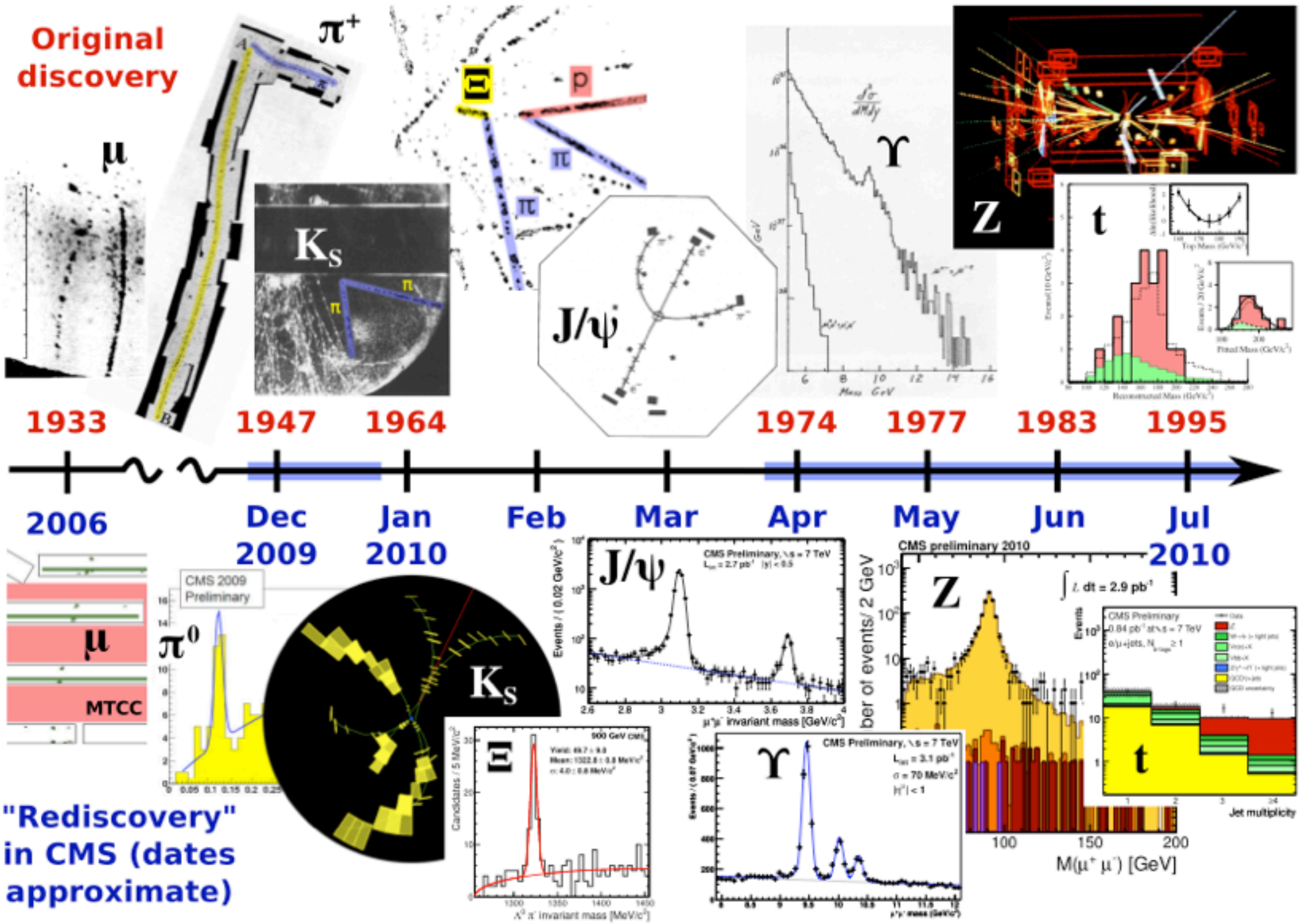

CMS

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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 $f_1 f_2$ -> $f_3 f_4$ 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 9)
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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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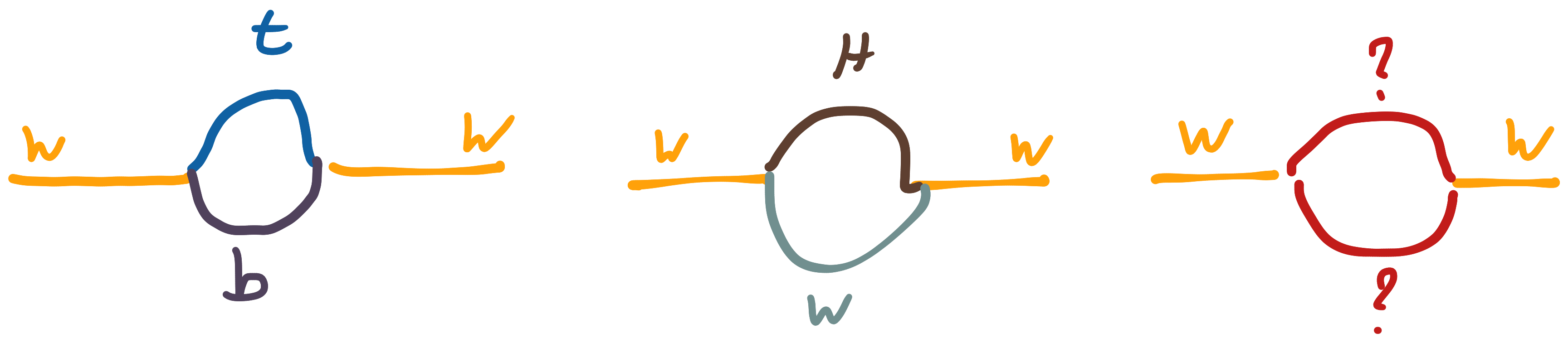

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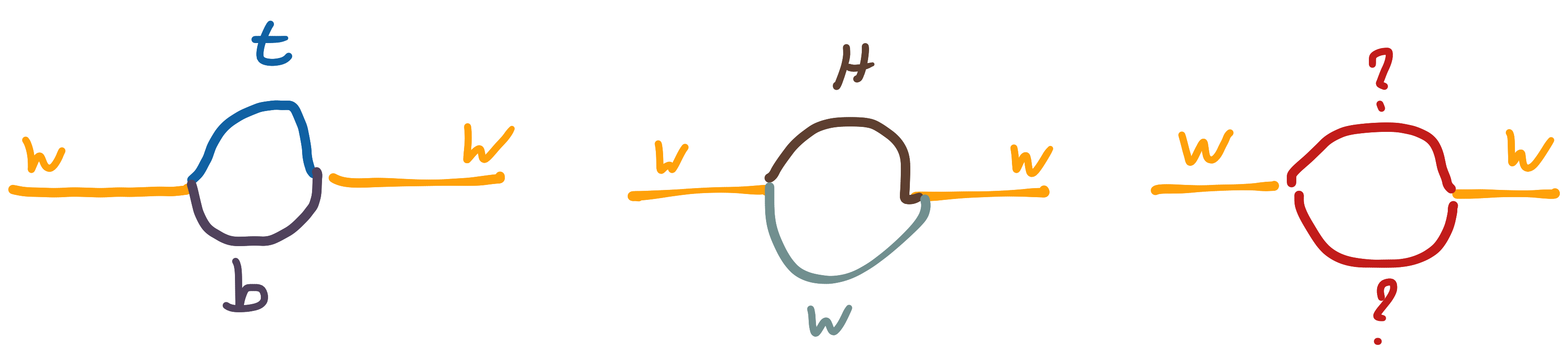
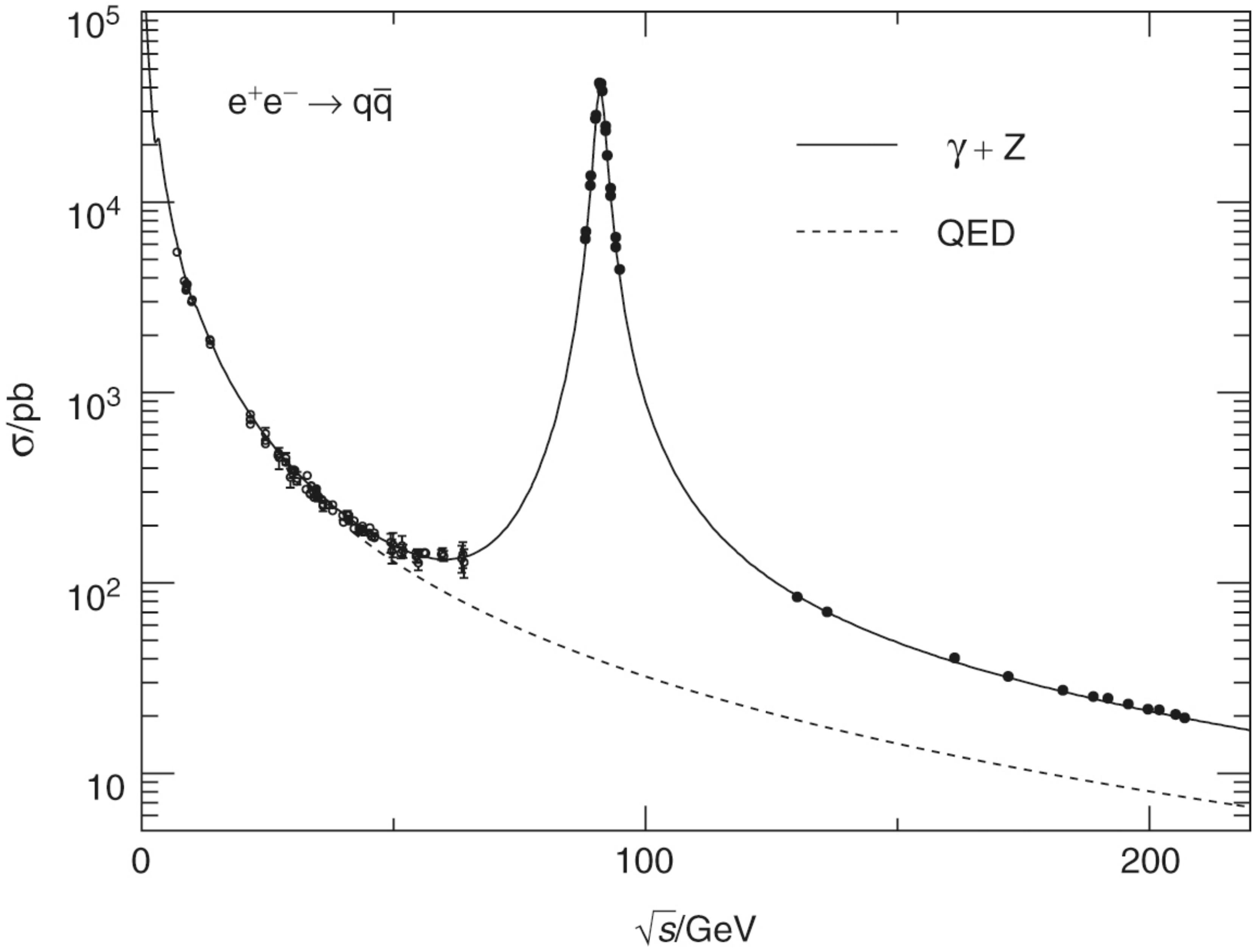


➩ used to place indirect limits on the Higgs mass based on M_{top} and M_W

- 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

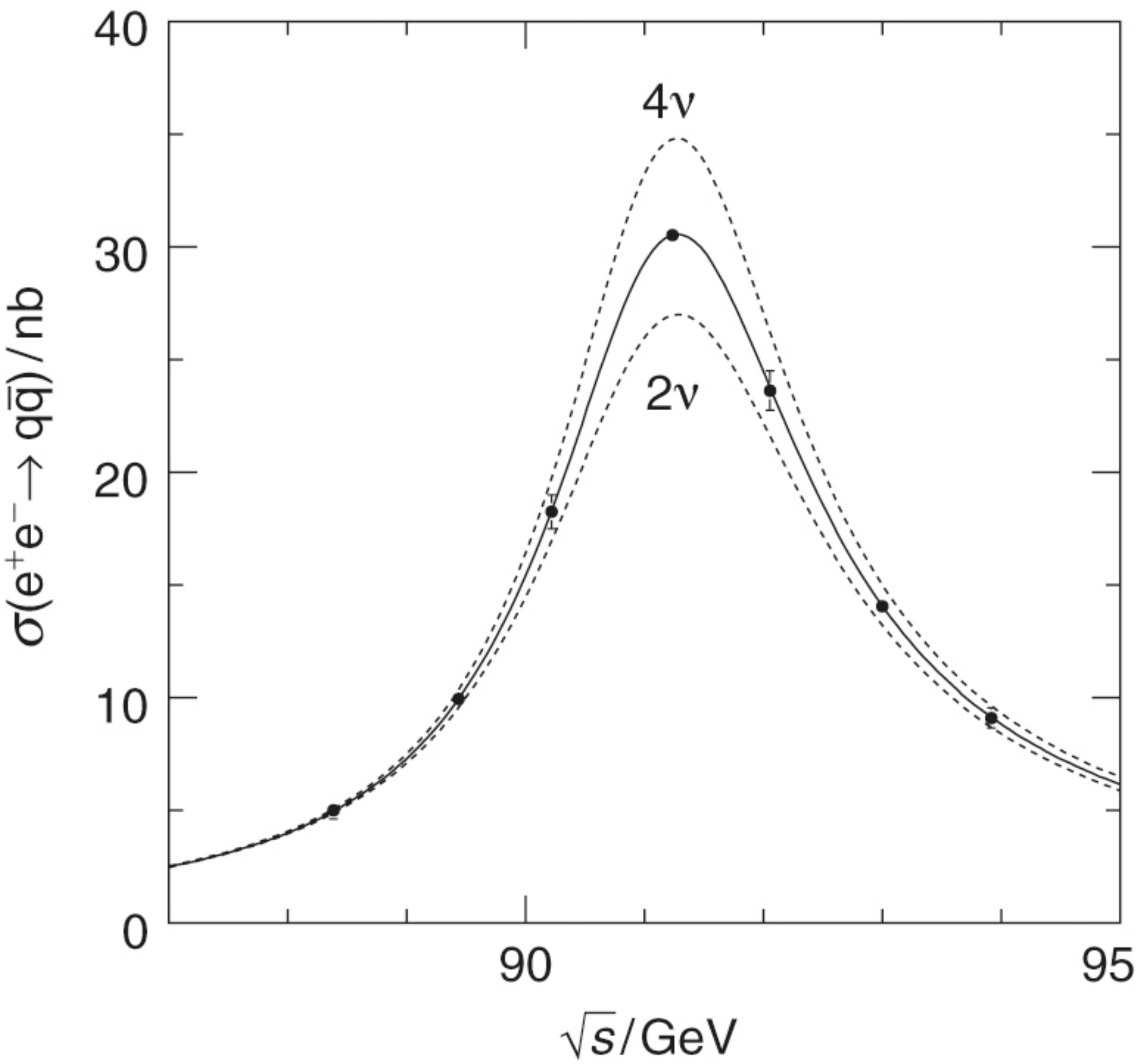
- A short excursion to e^+e^- Annihilation (covered in somewhat greater detail in the Summer)



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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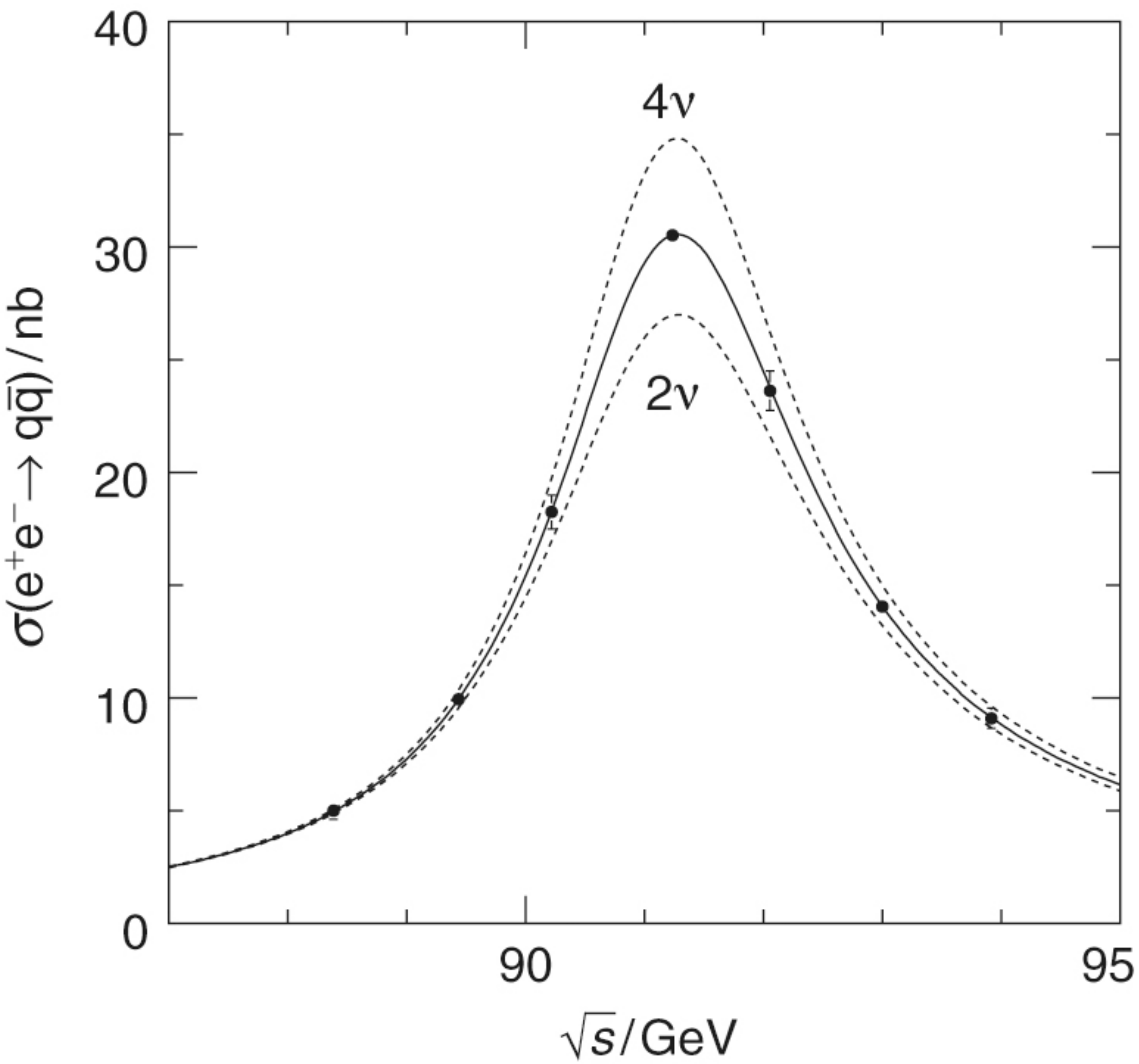

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Given by:

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{\nu e \nu e} + \Gamma_{\nu\mu\nu\mu} + \Gamma_{\nu\tau\nu\tau}$$
$$= 3\,\Gamma_{ll} + \Gamma_{had} + N_\nu\,\Gamma_{\nu\nu}$$

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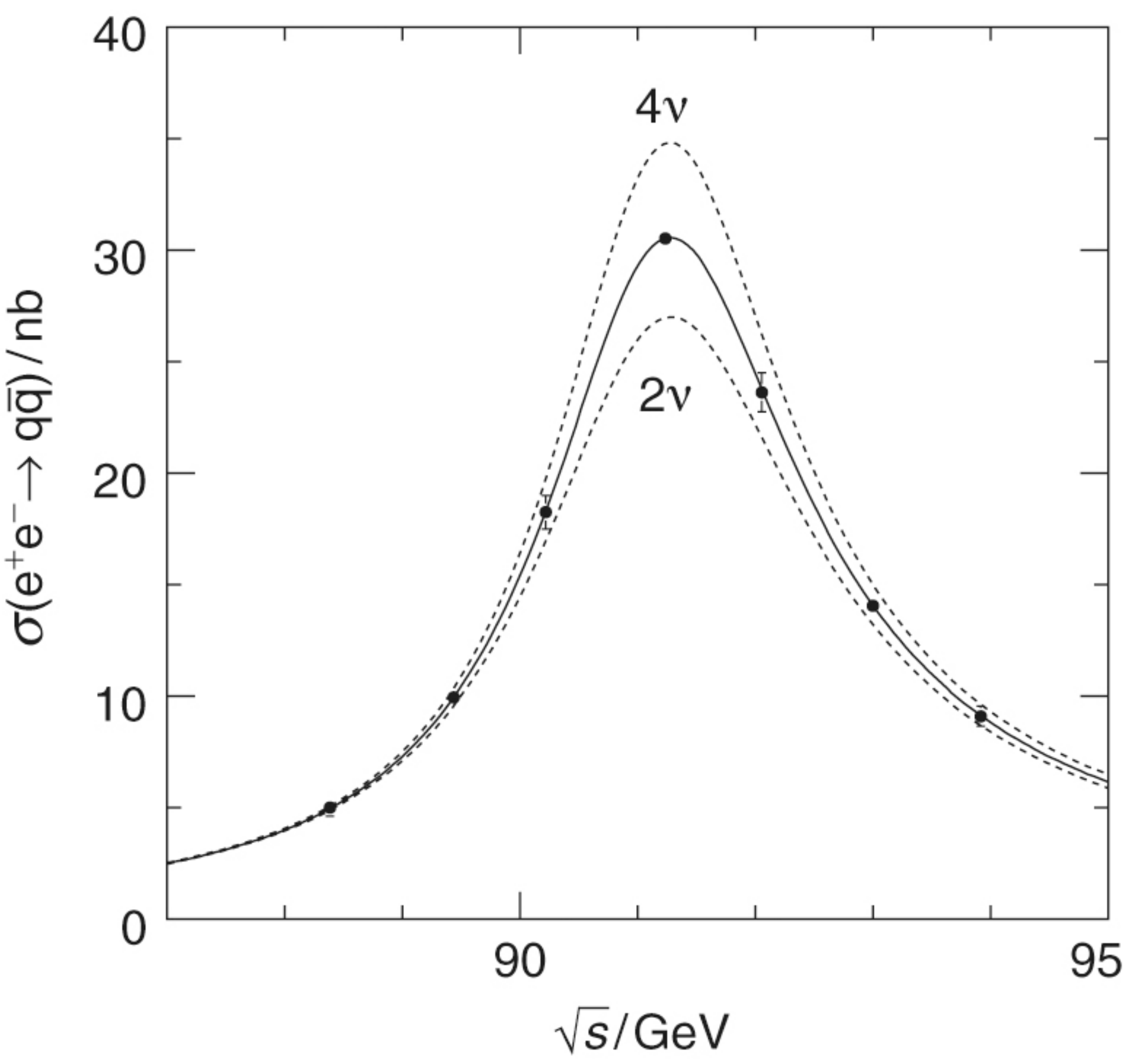

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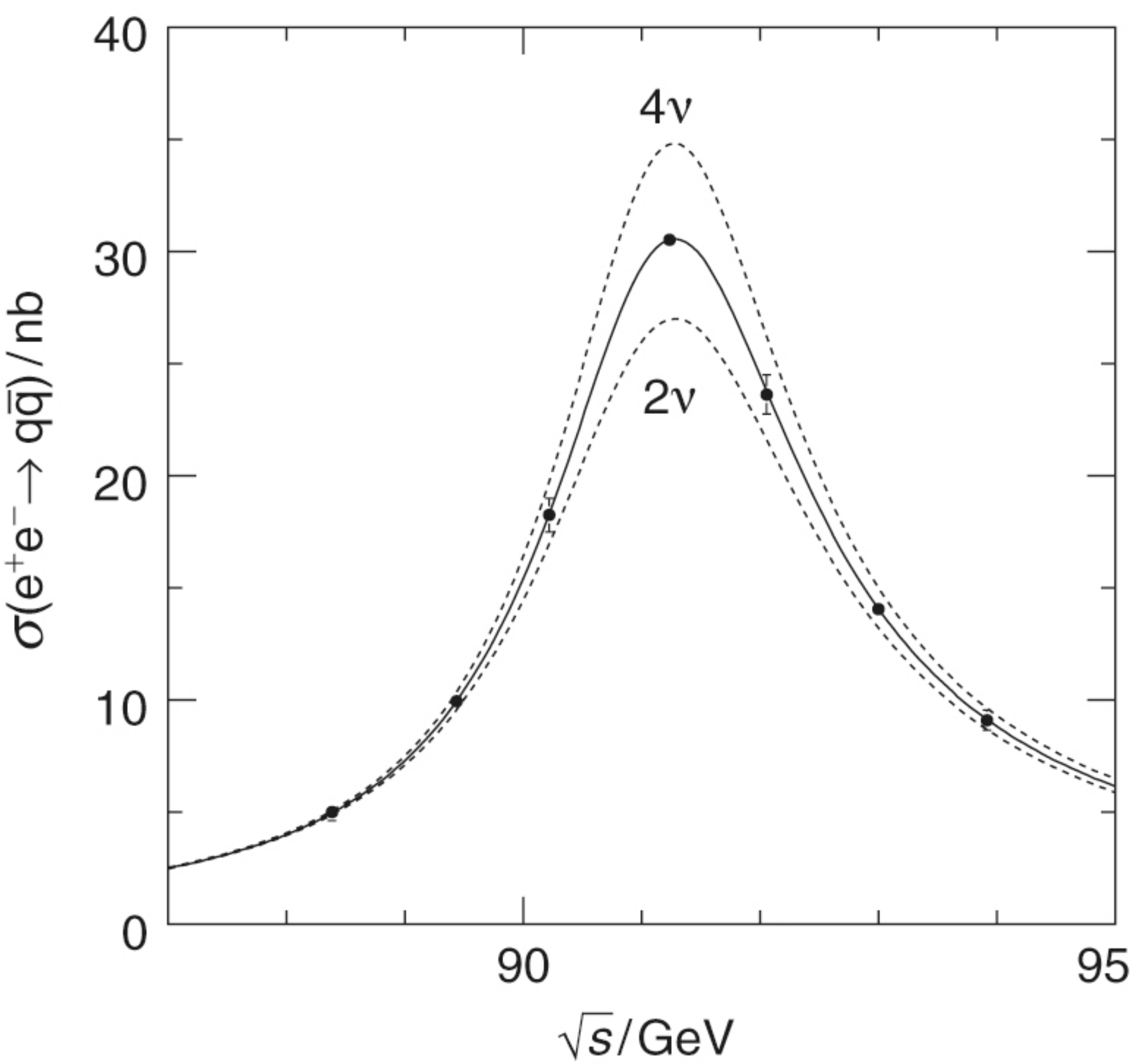

$M_Z = 91.1875 \pm 0.0021$ GeV

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

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

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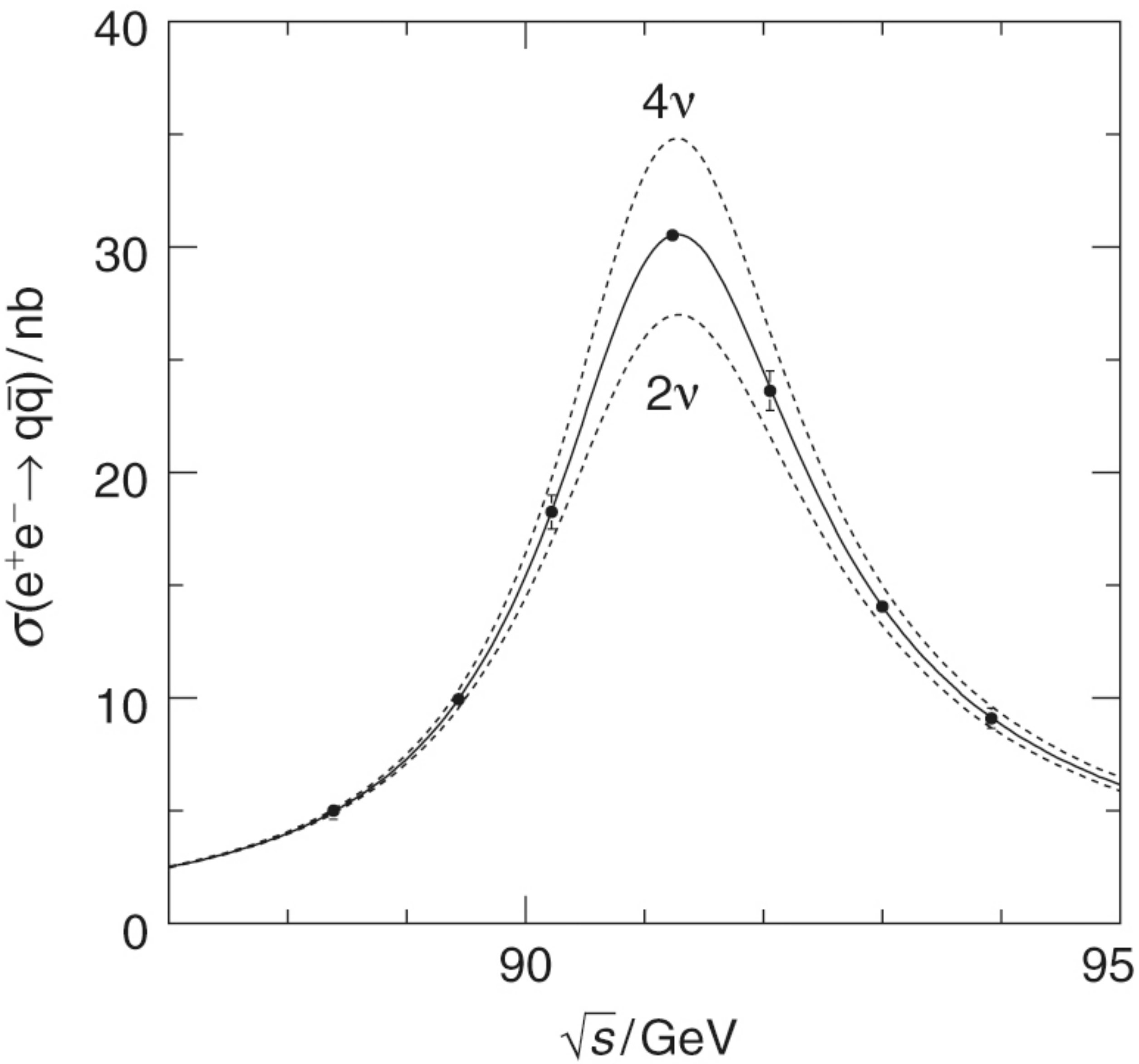

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The partial width into visible final states can be directly measured

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

$N_\nu = 2.984 \pm 0.008$

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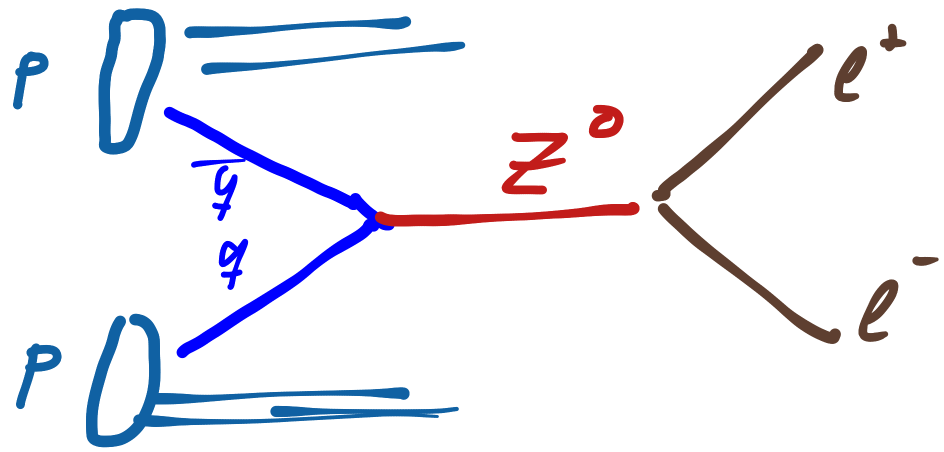
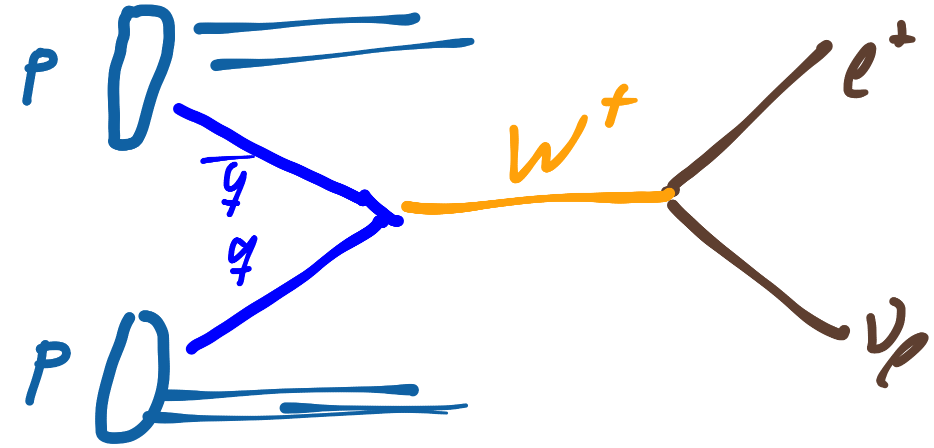
Production (and Decay) of Gauge Bosons at LHC

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





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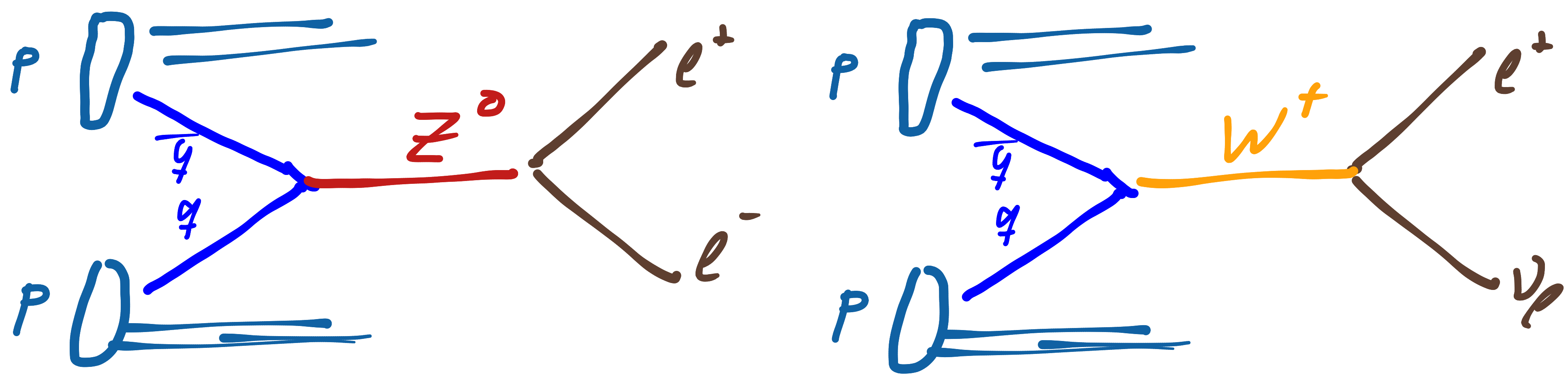
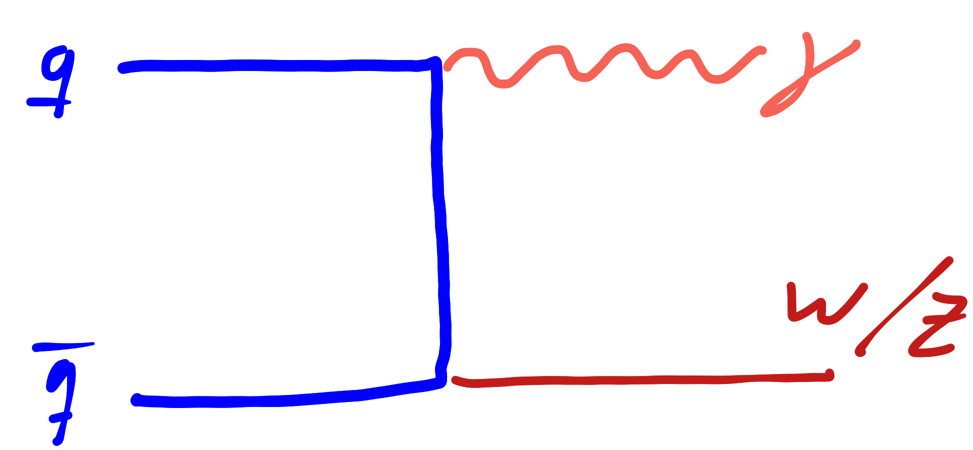


… but also t/u channel processes such as



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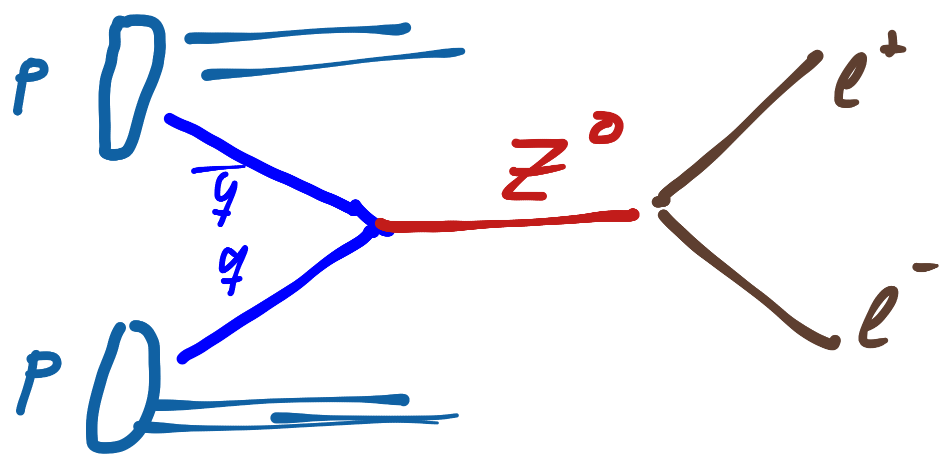

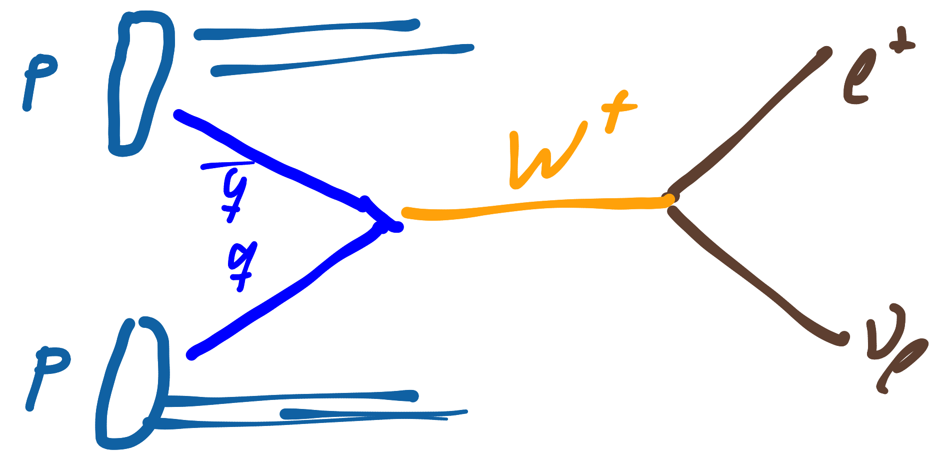

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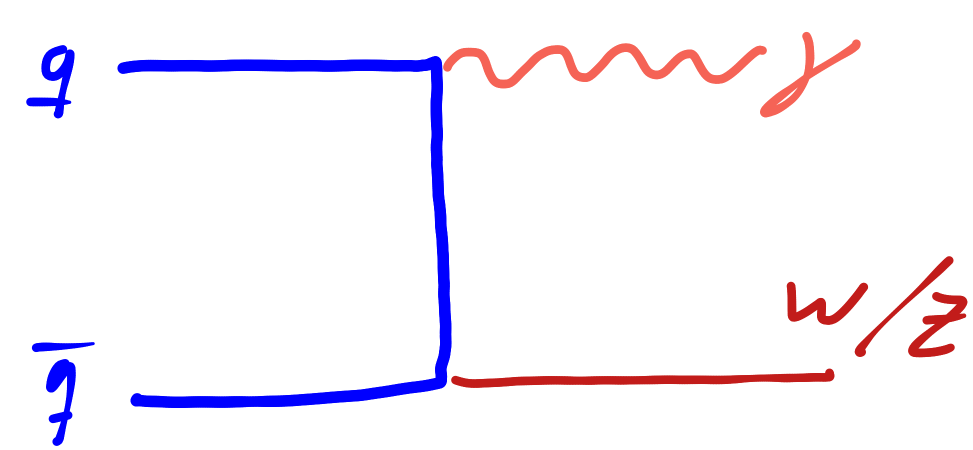
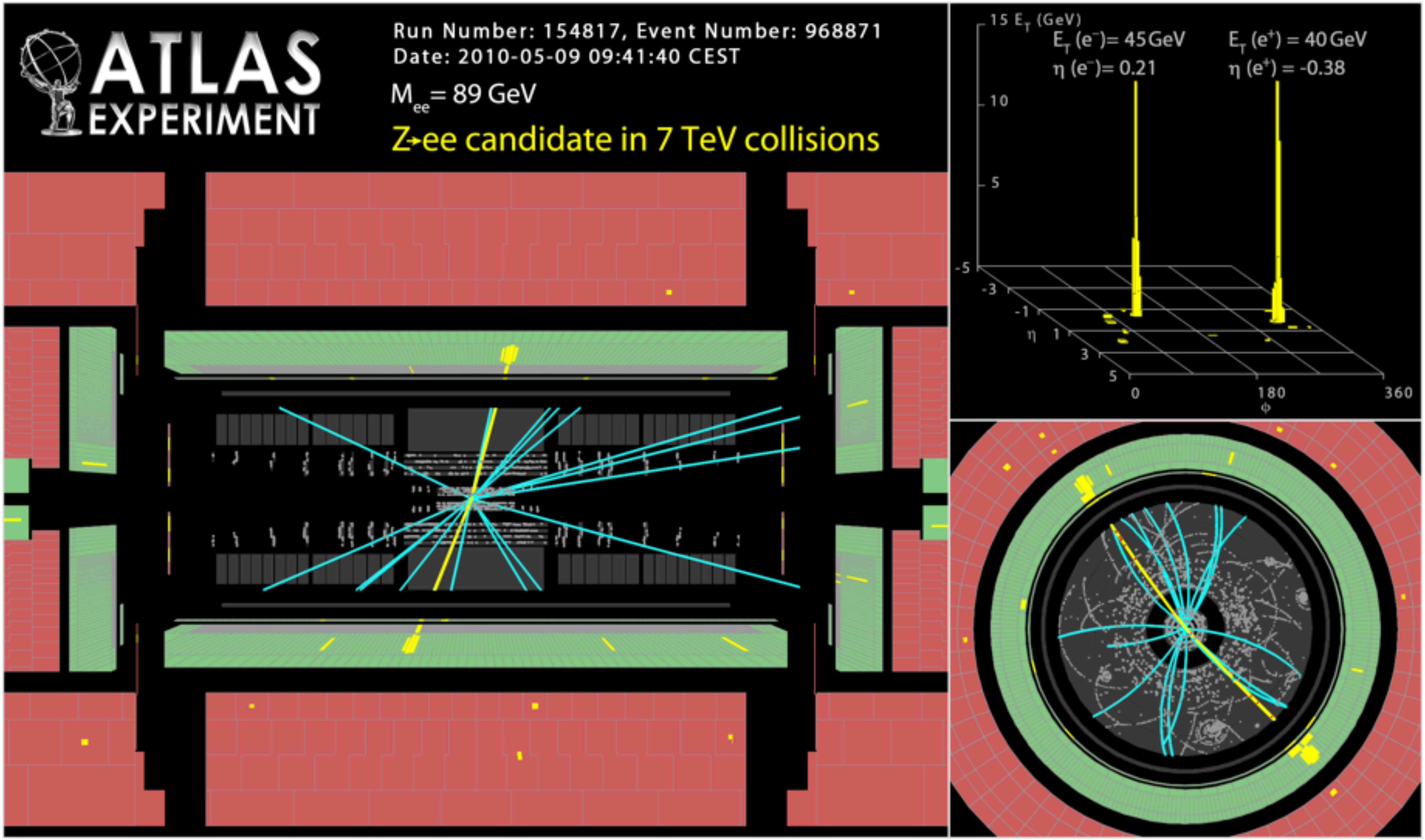


- theoretical uncertainties mainly due to quark structure of the proton: PDF uncertainties

Z Production at LHC

- Candidate Z->e^+e^-



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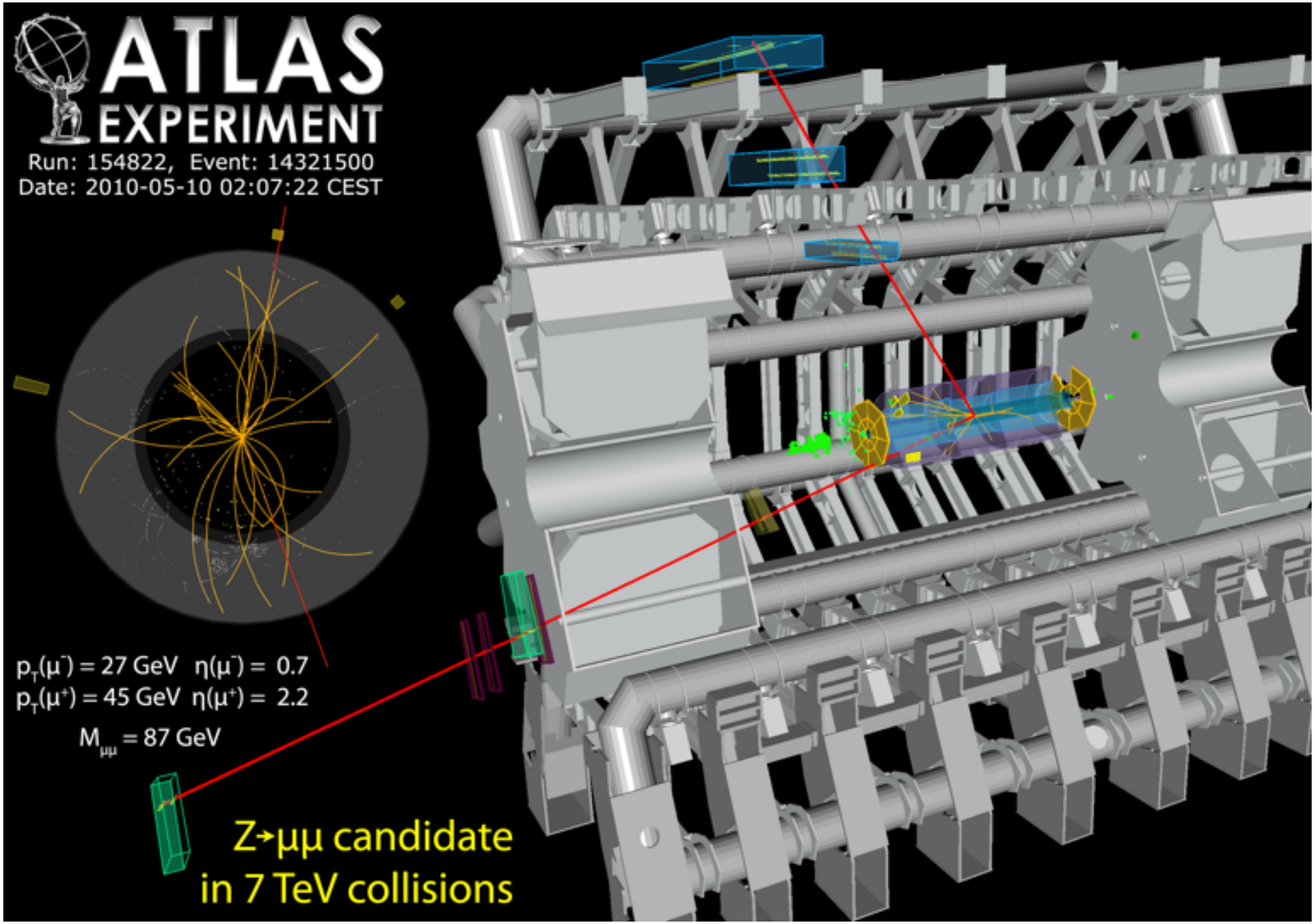
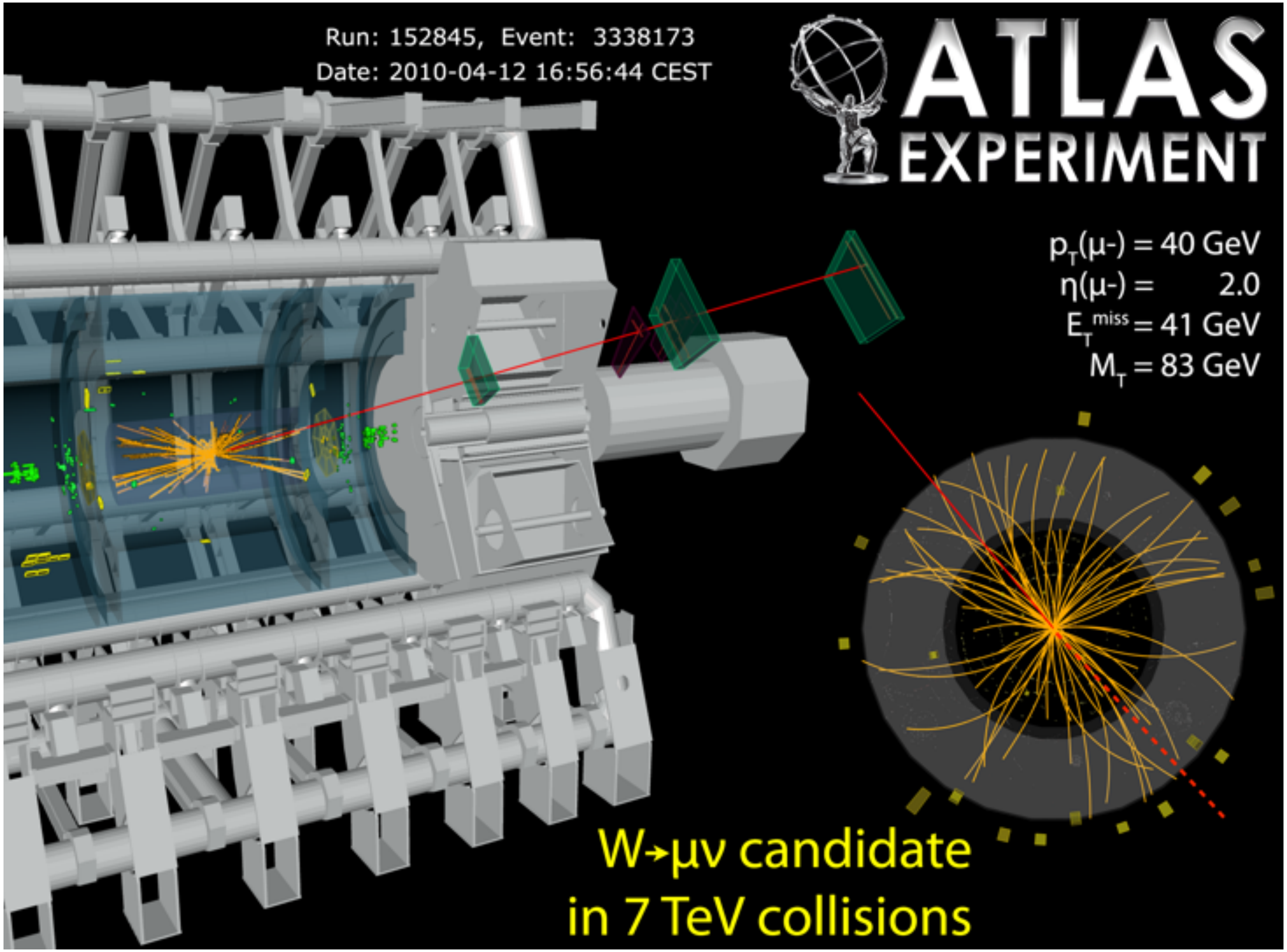


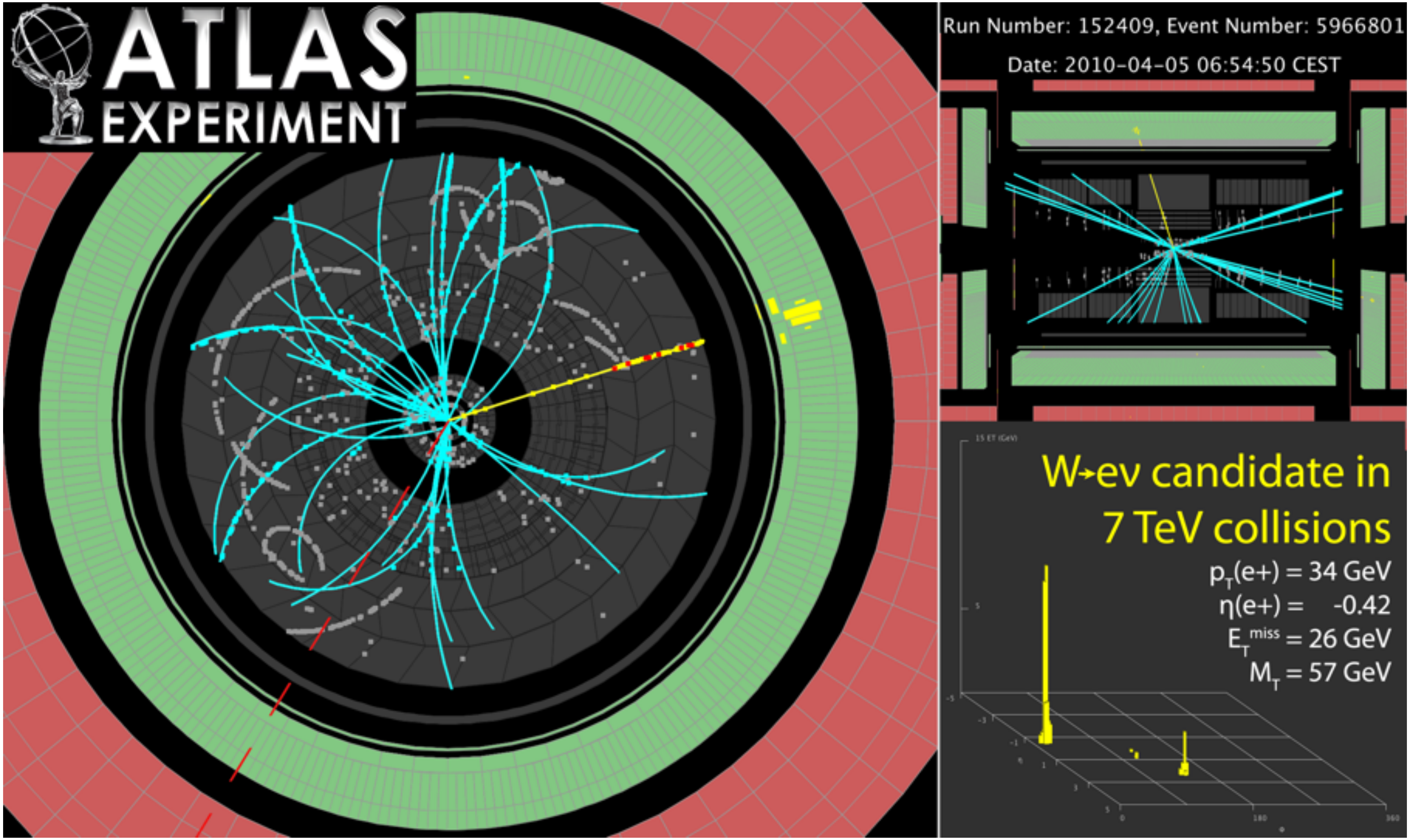
W Production at LHC

- $W^{-} \to \mu^{-}\nu$ candidate

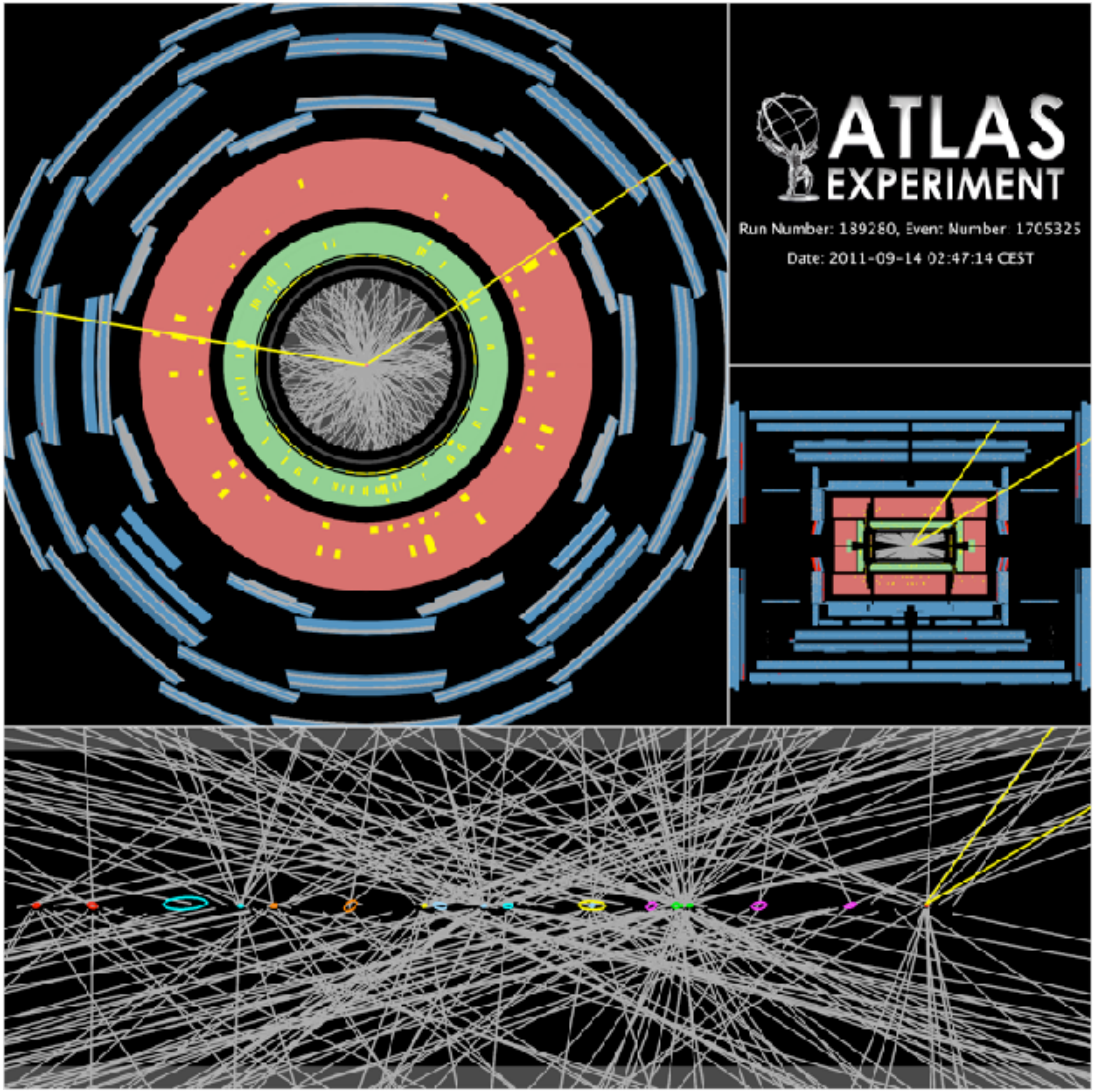


W Production at LHC

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

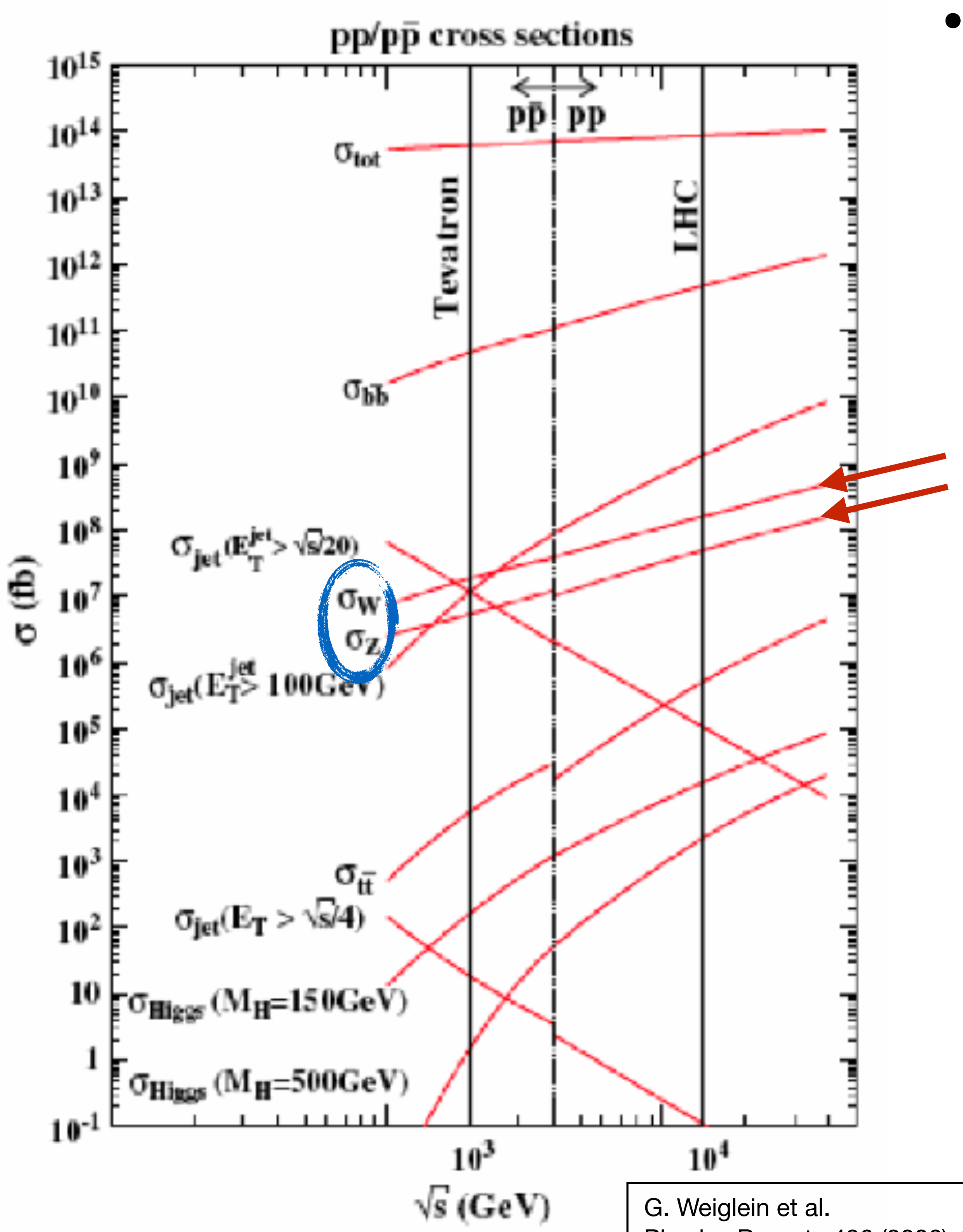


Z Production at LHC with high Pileup



- Z-> μμ
  … with 20 additional vertices

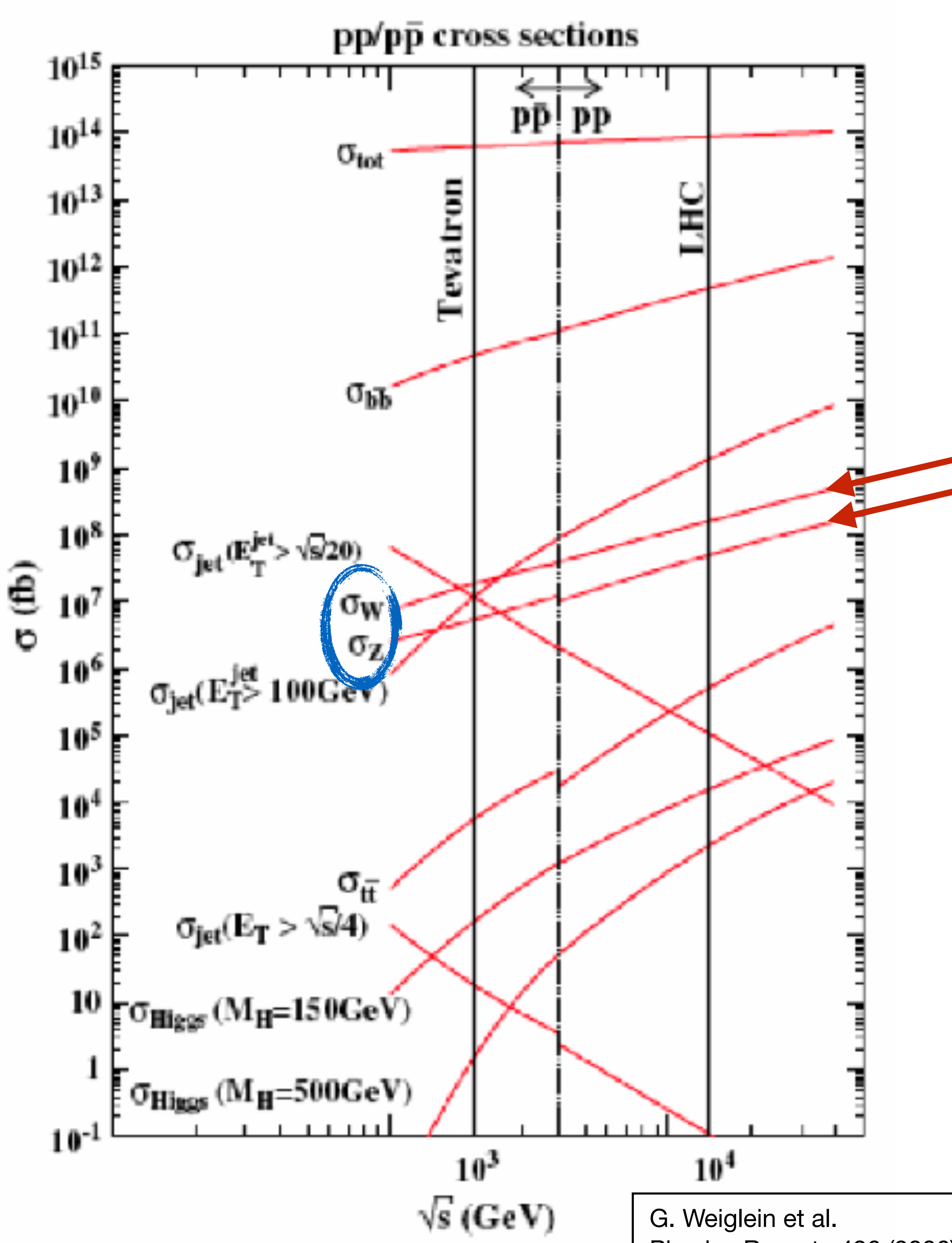
Gauge Boson Production: Cross Sections



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

- Measurement of Cross Sections:

Gauge Boson Production: Cross Sections



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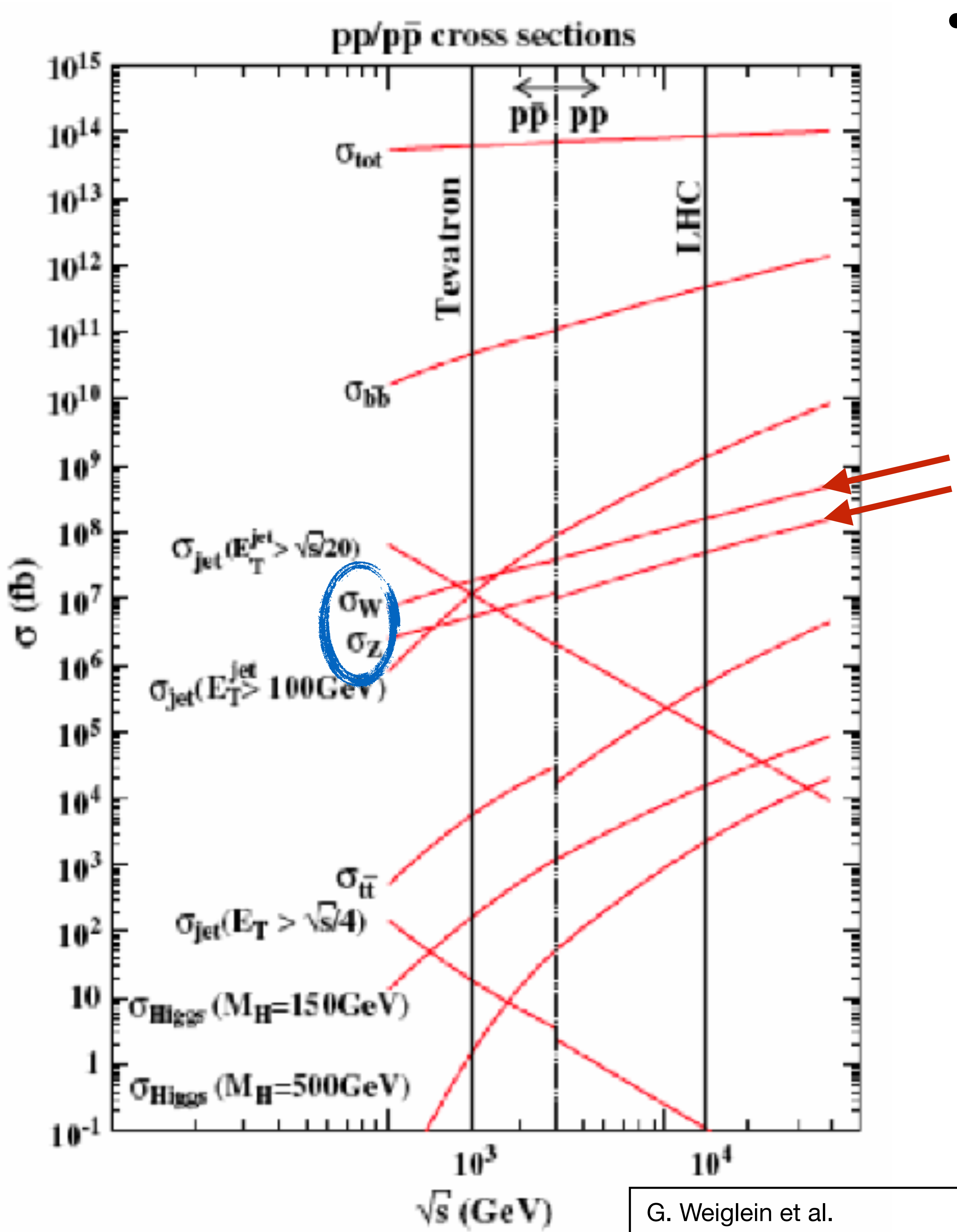

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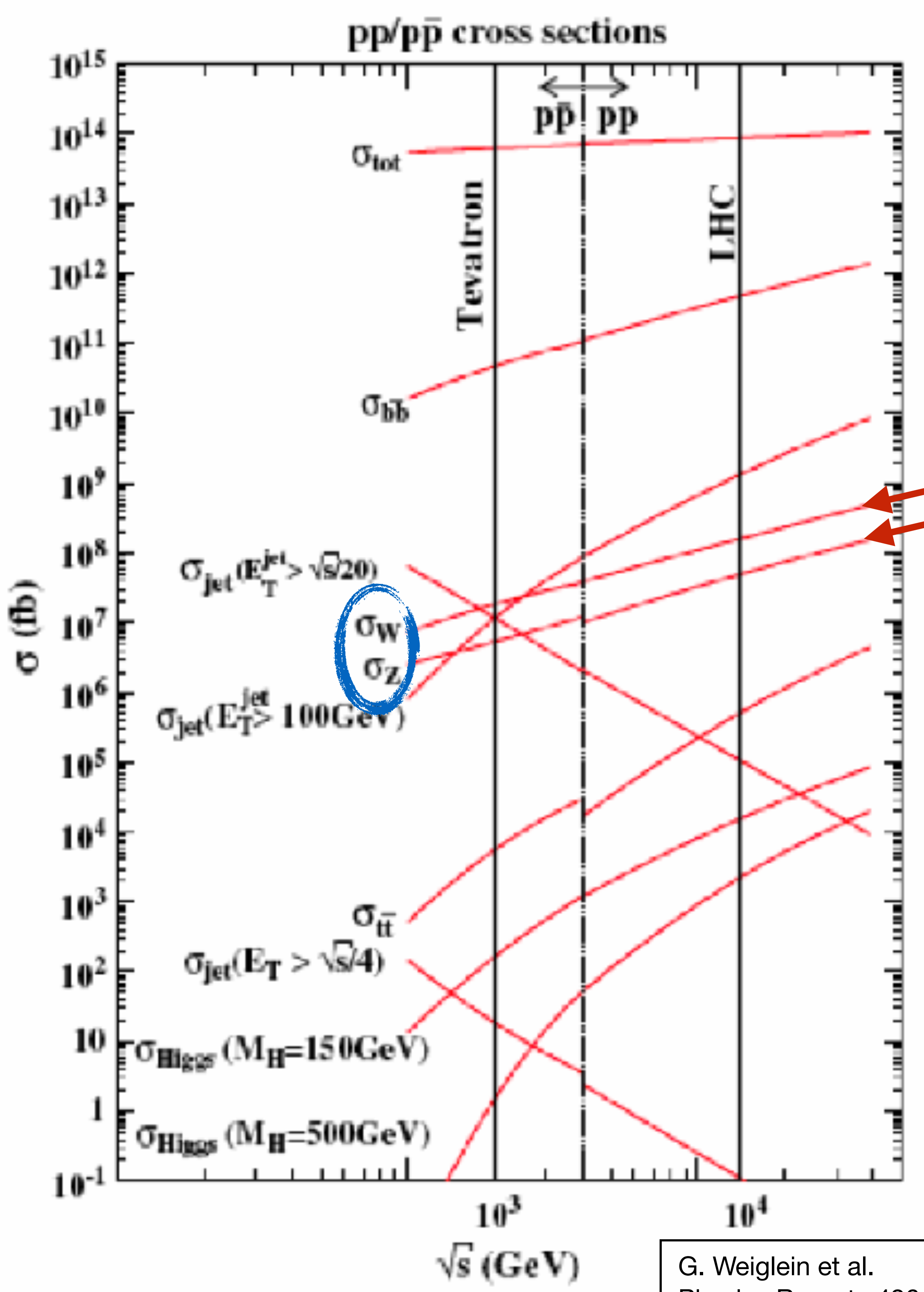

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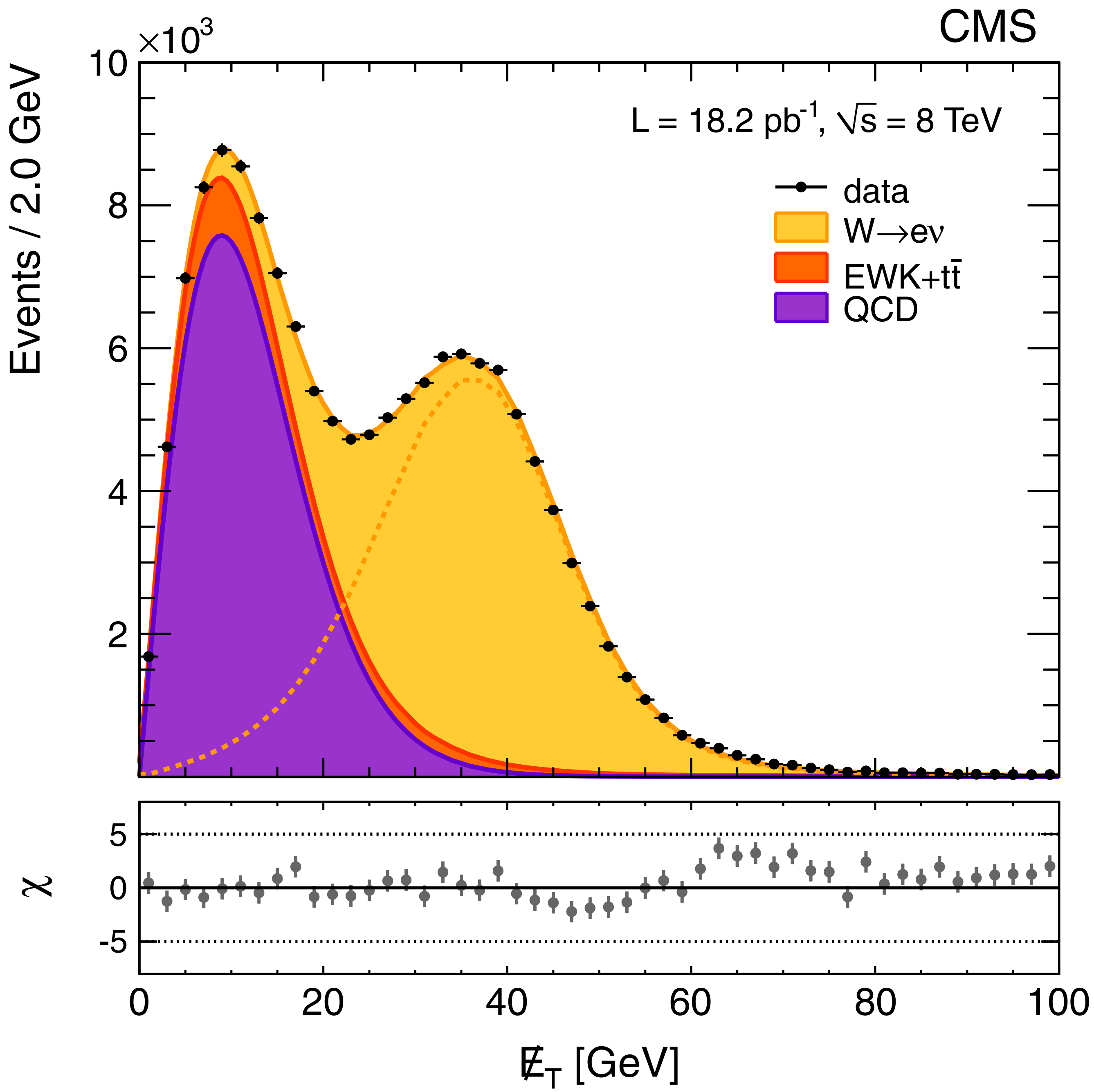
  - Determination of cross section - corrections to event numbers:
    - trigger efficiency (data)
    - reconstruction efficiency (MC, data)
    - luminosity

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

Vector Boson Reconstruction - LHC



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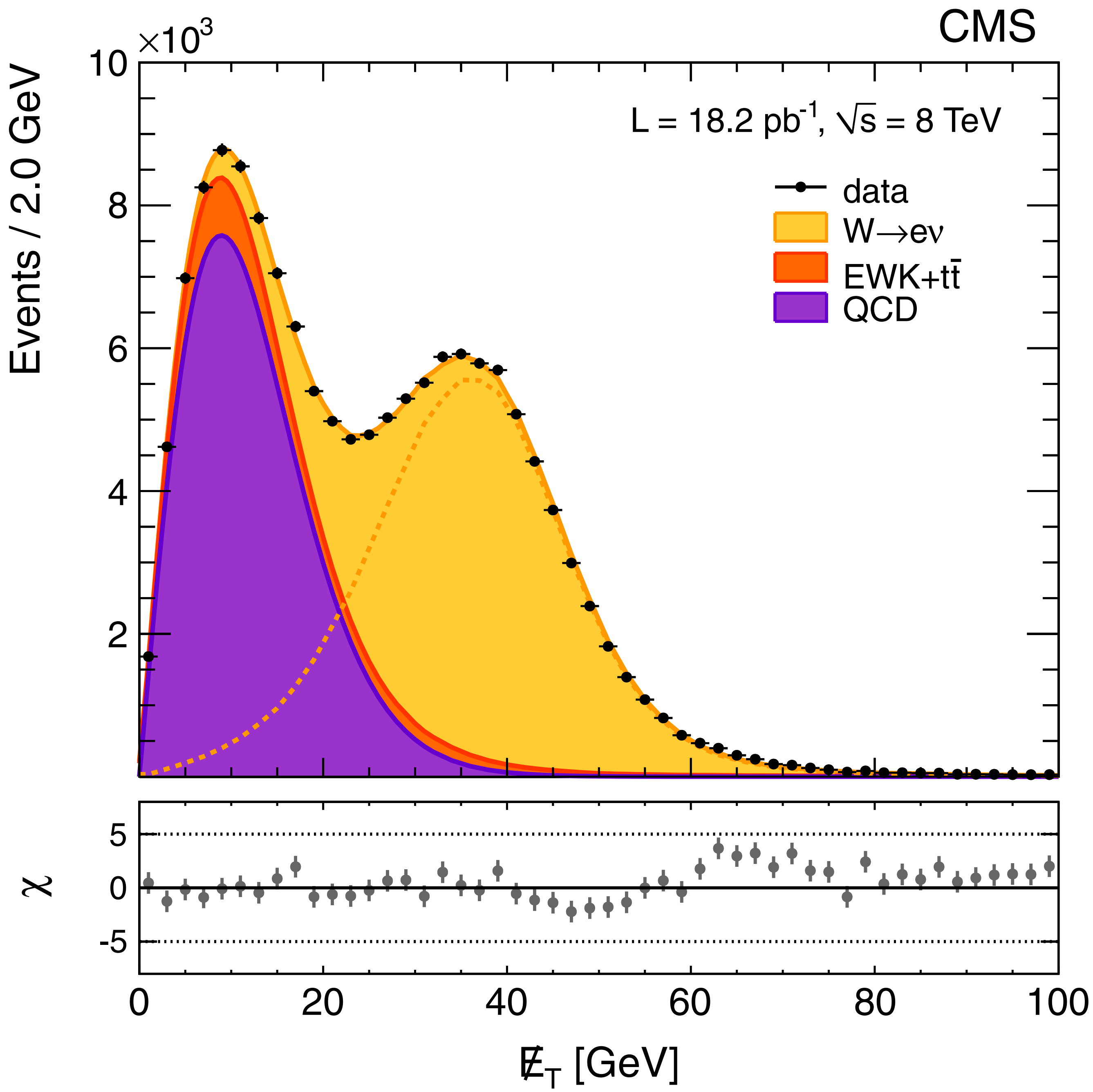

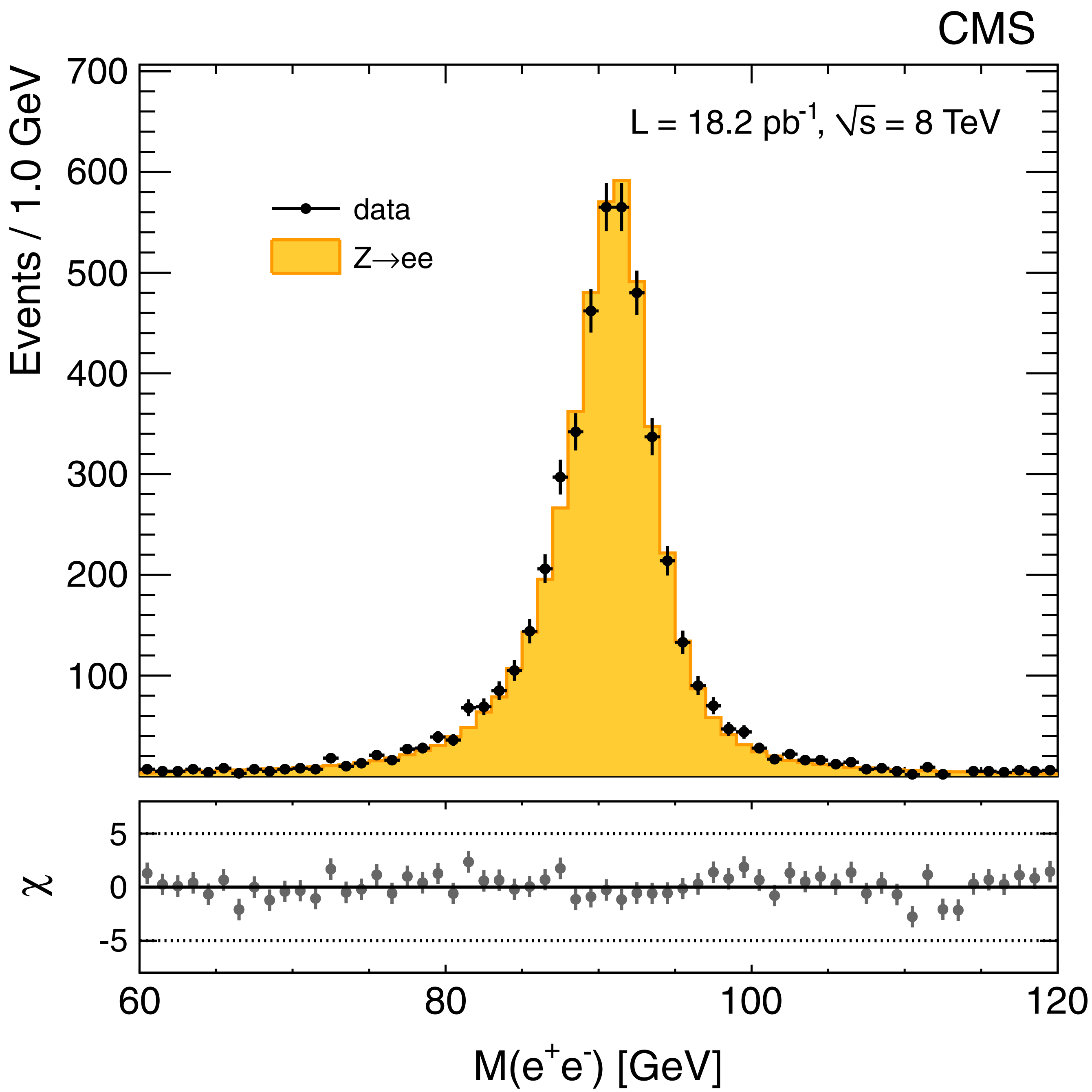

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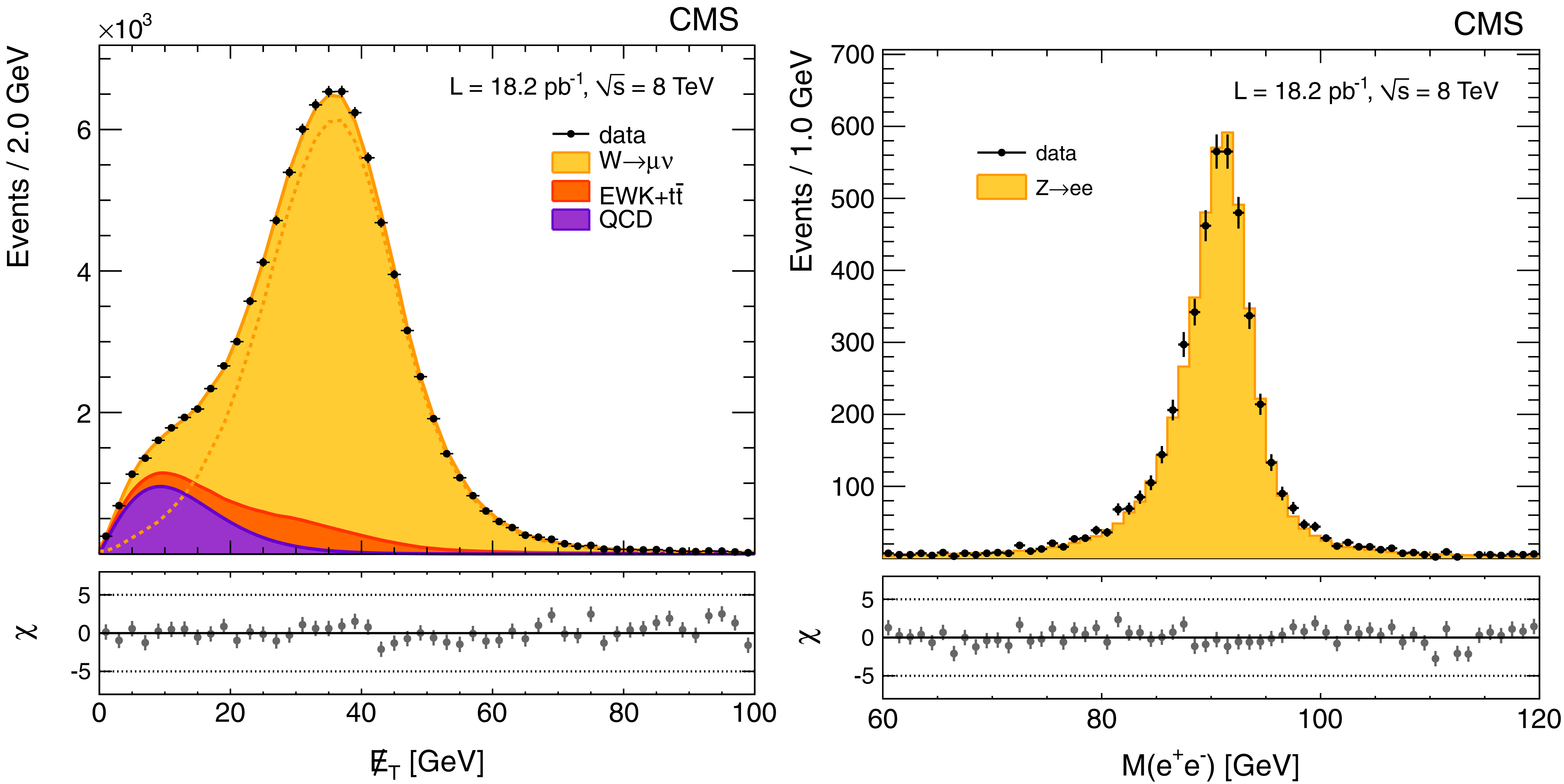

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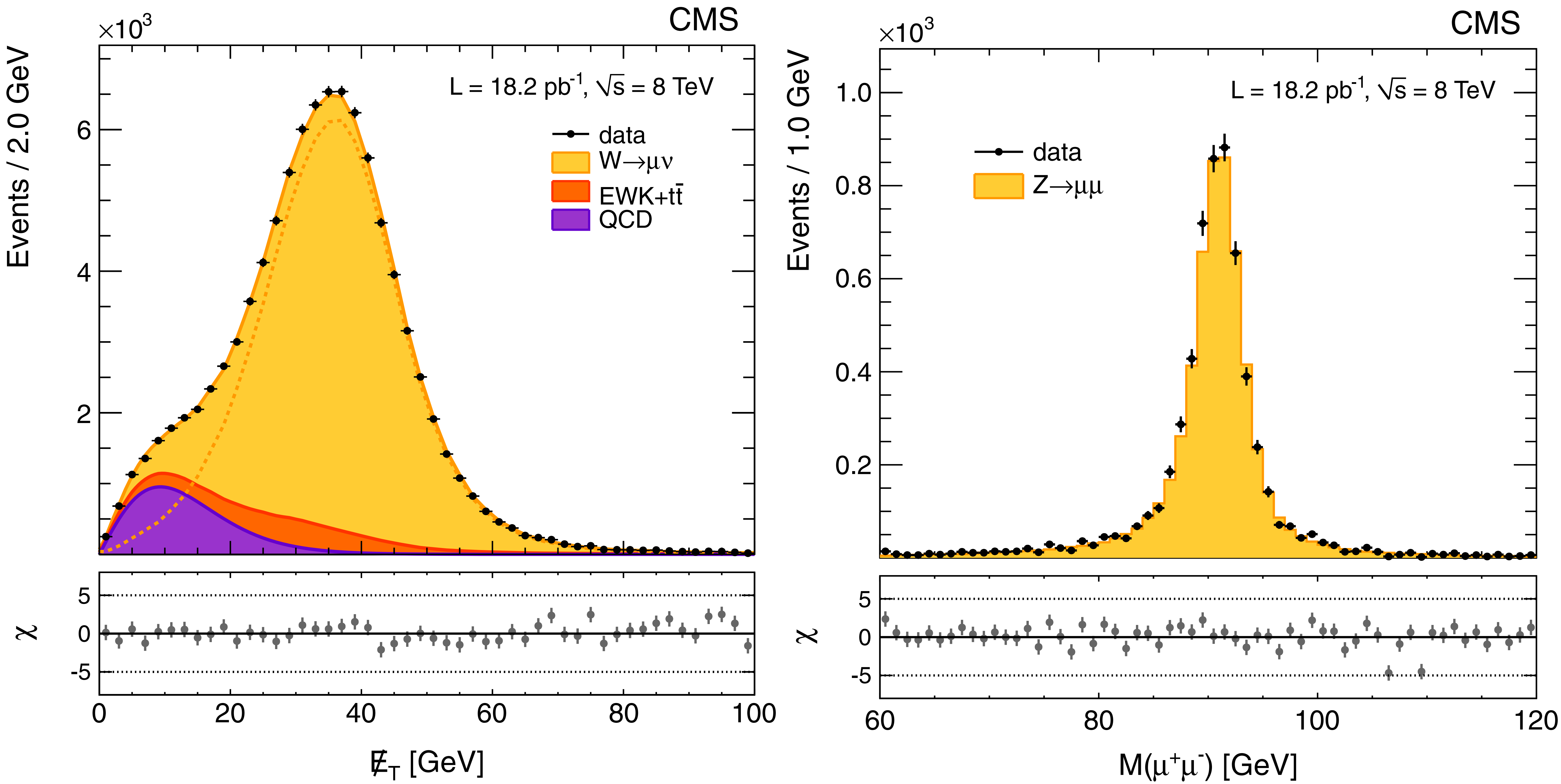

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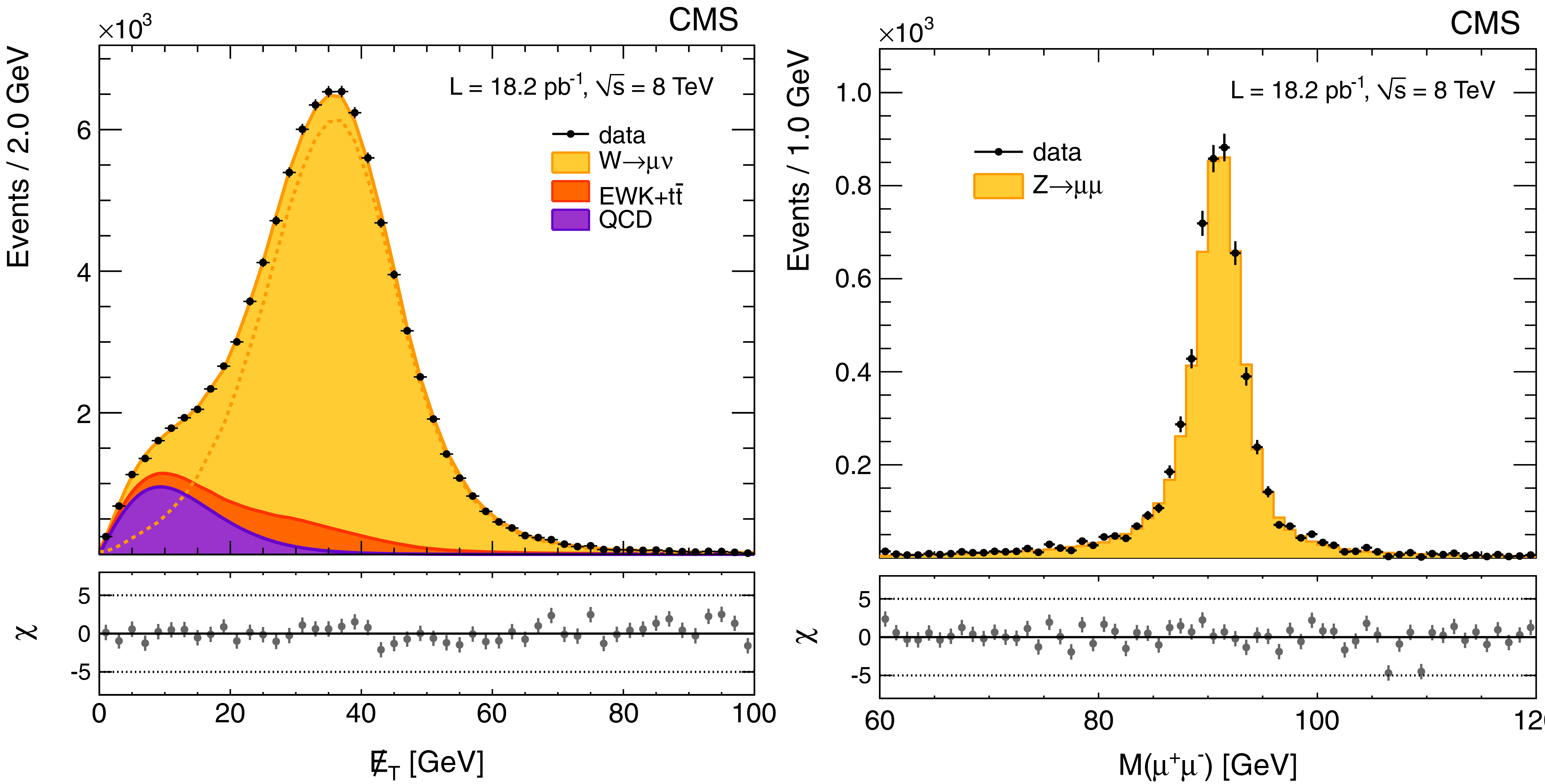
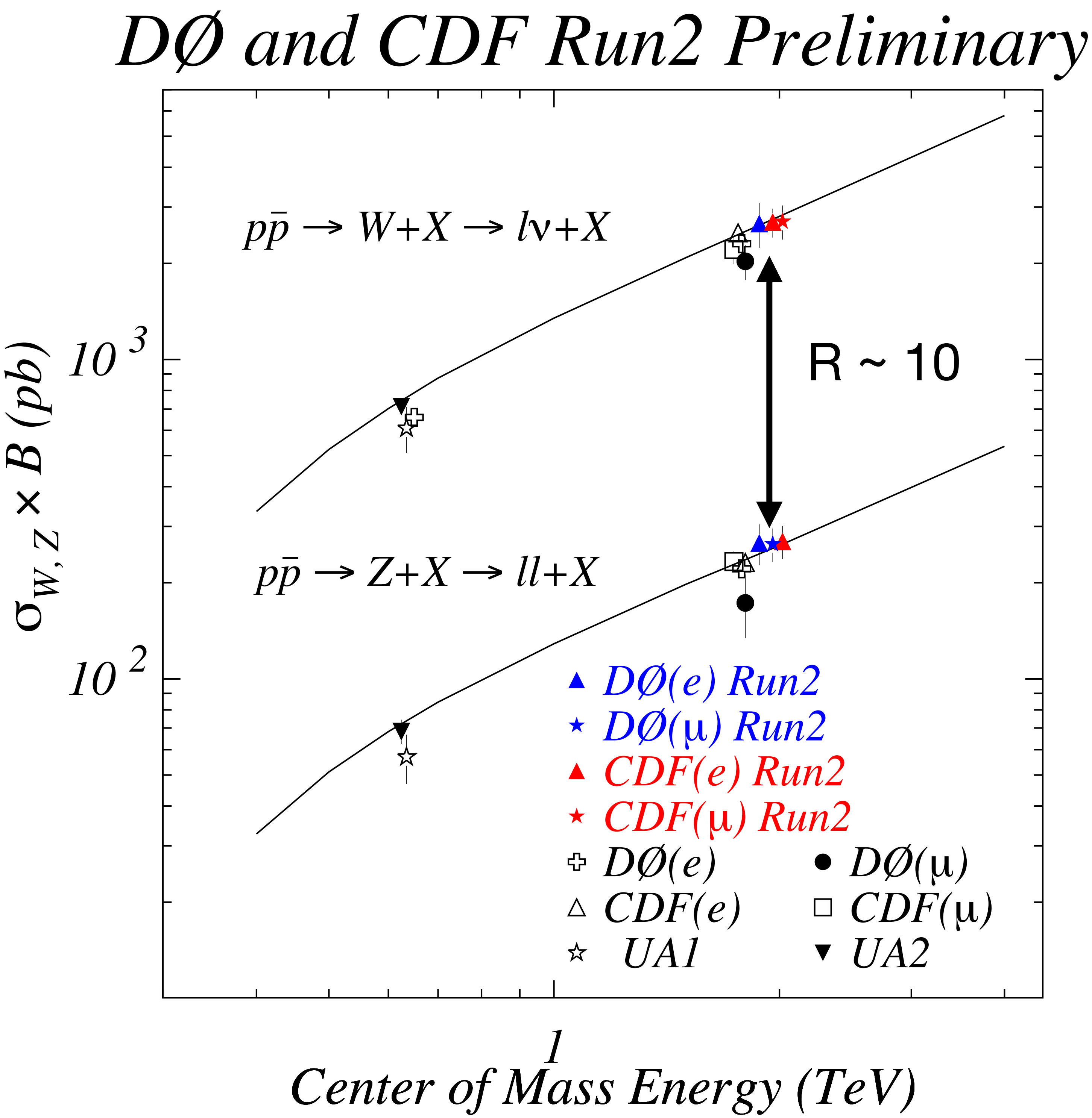


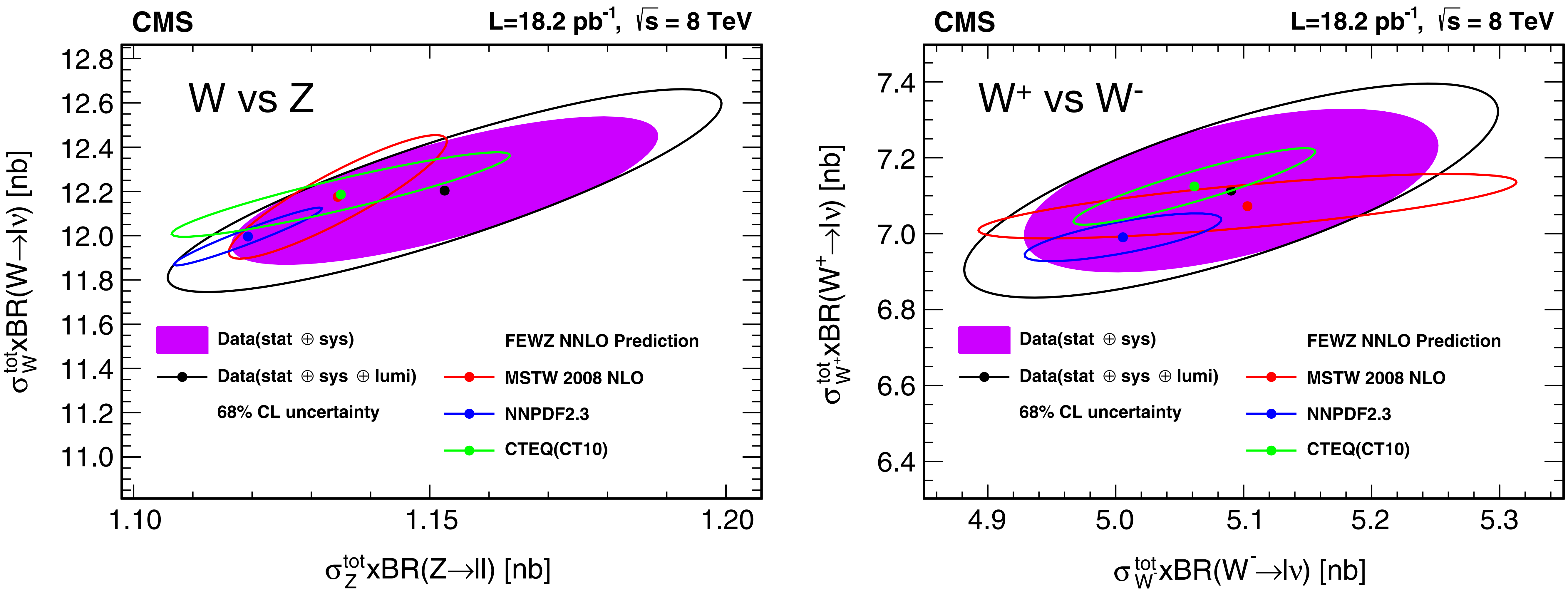
- “Best results” typically in the Muon channel

W and Z Production at the Tevatron



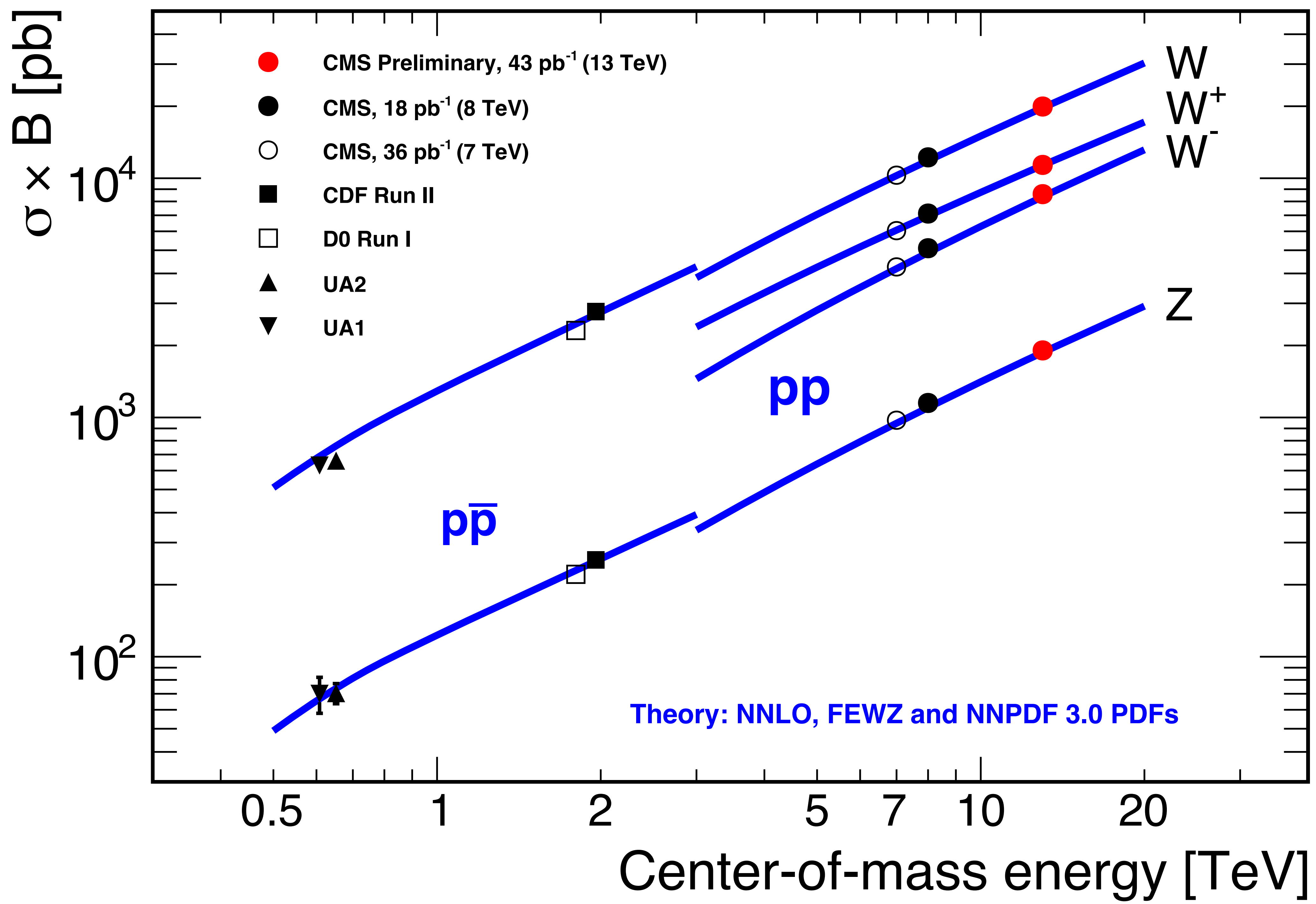
- Ratio of production of W and Z bosons R - very well predicted, since some of the PDF uncertainties cancel

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^+

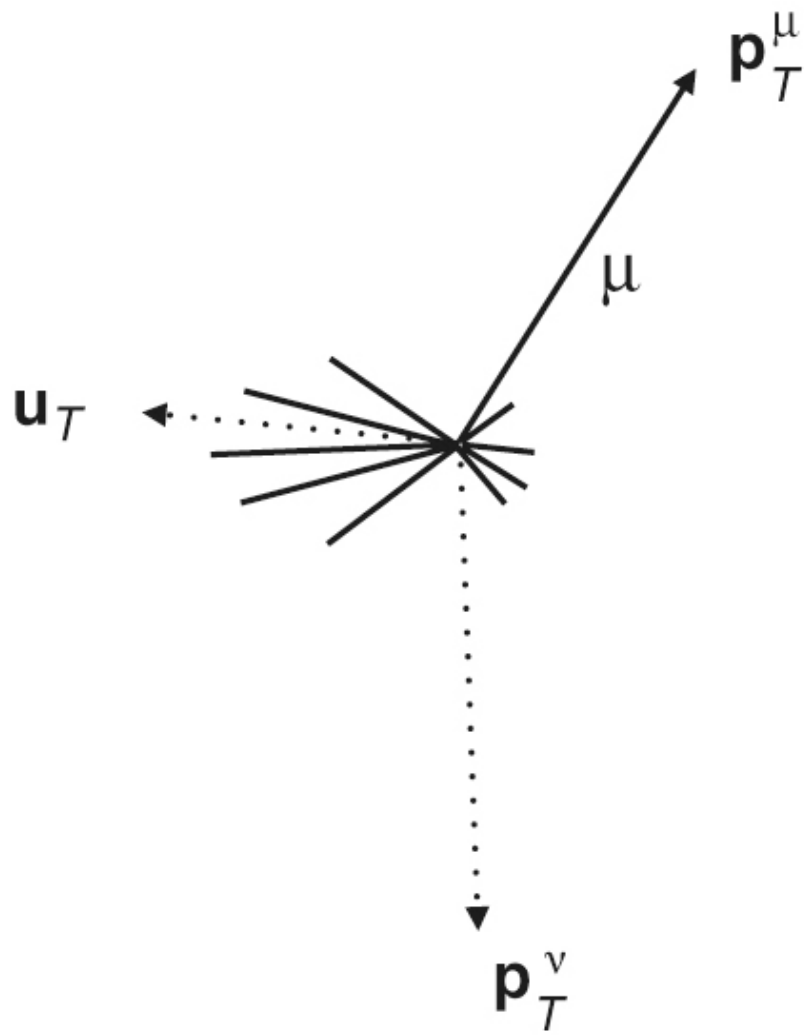
W and Z Production at the LHC



- 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)



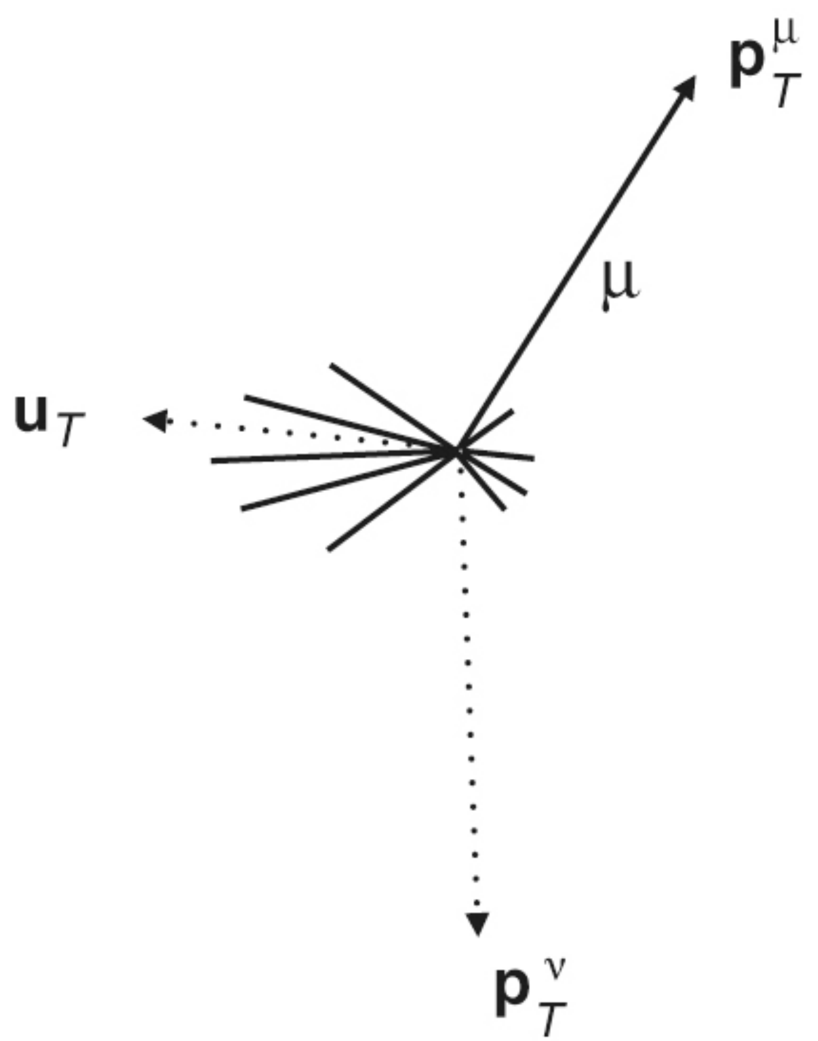
$$\vec{P}_T^\nu = -(\vec{P}_T^l + \vec{U})$$

- Reconstruct transverse mass:

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

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:

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

- 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

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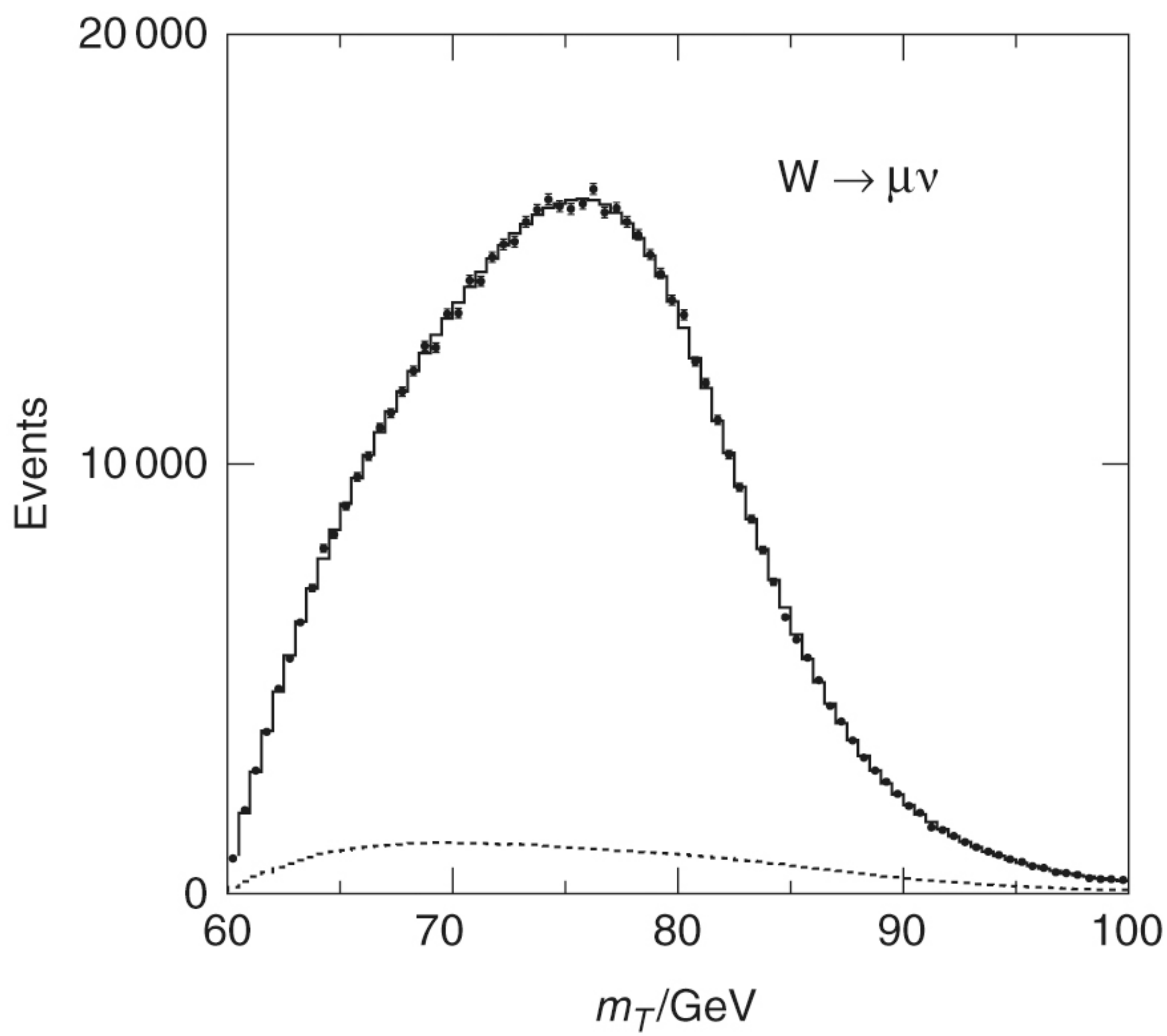
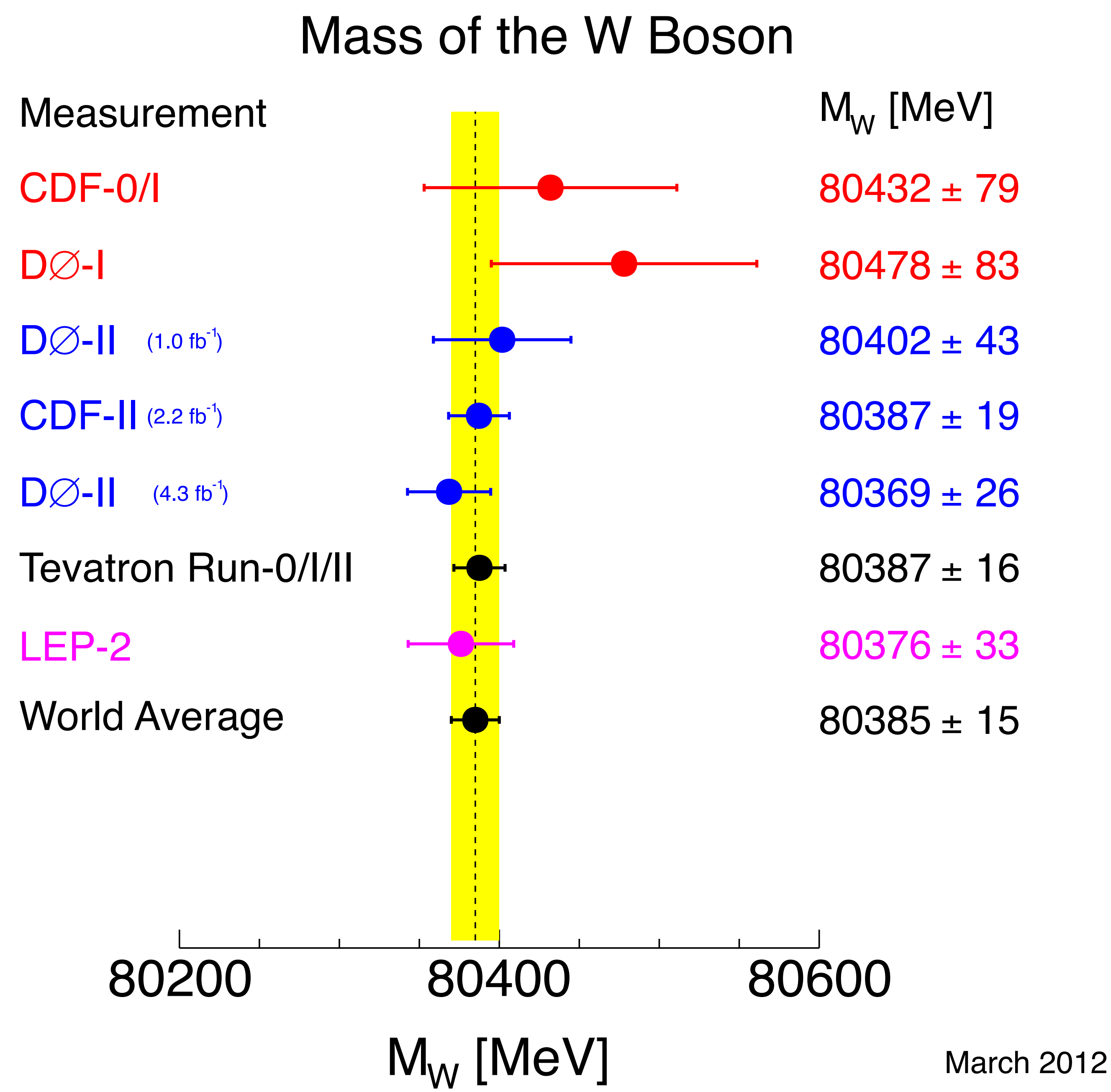
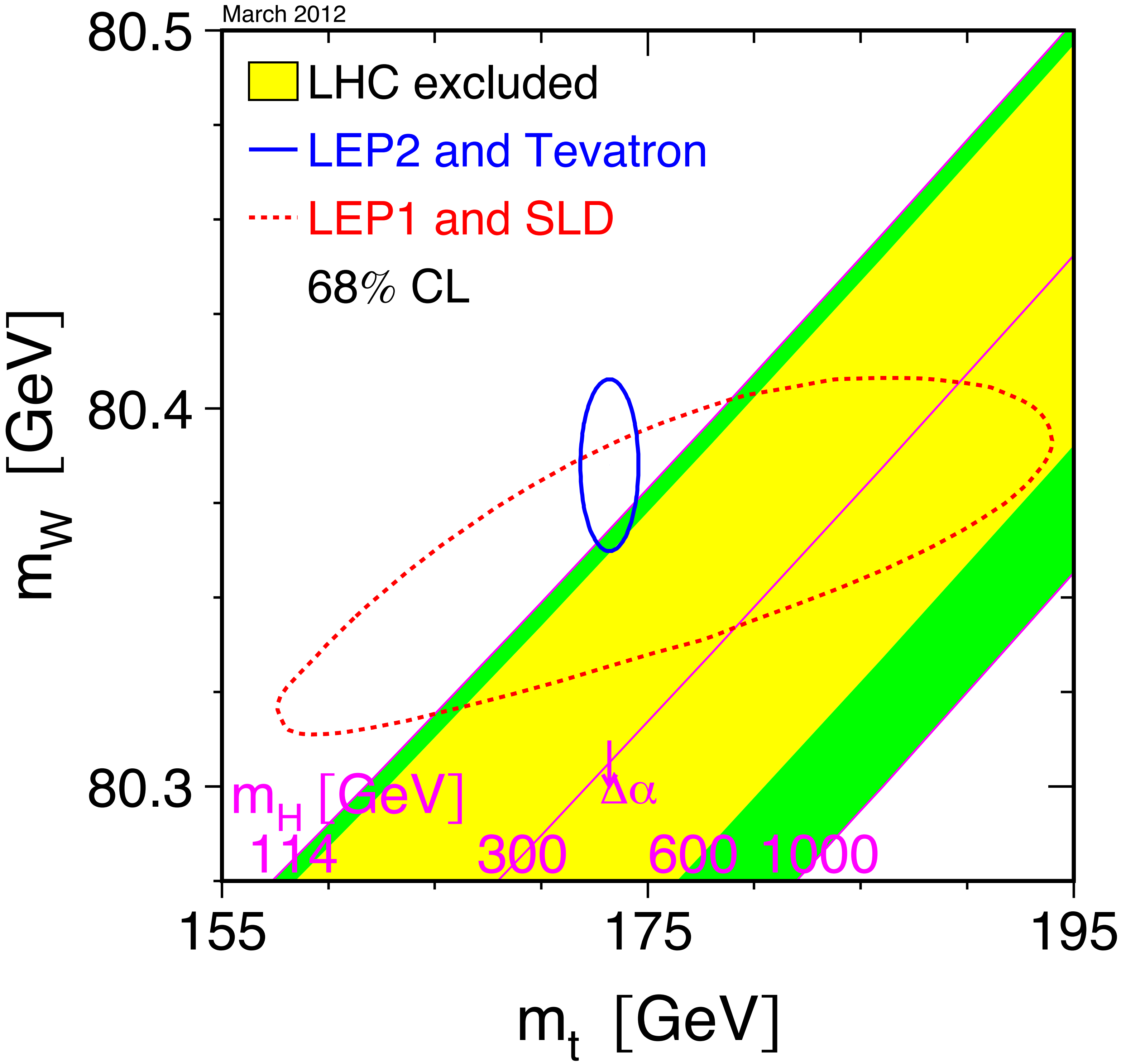




- Best measurement from Tevatron
- Combination of CDF and D0: M_W = 80.387 ± 0.016 GeV
- World average with LEP: M_W = 80.385 ± 0.015 GeV

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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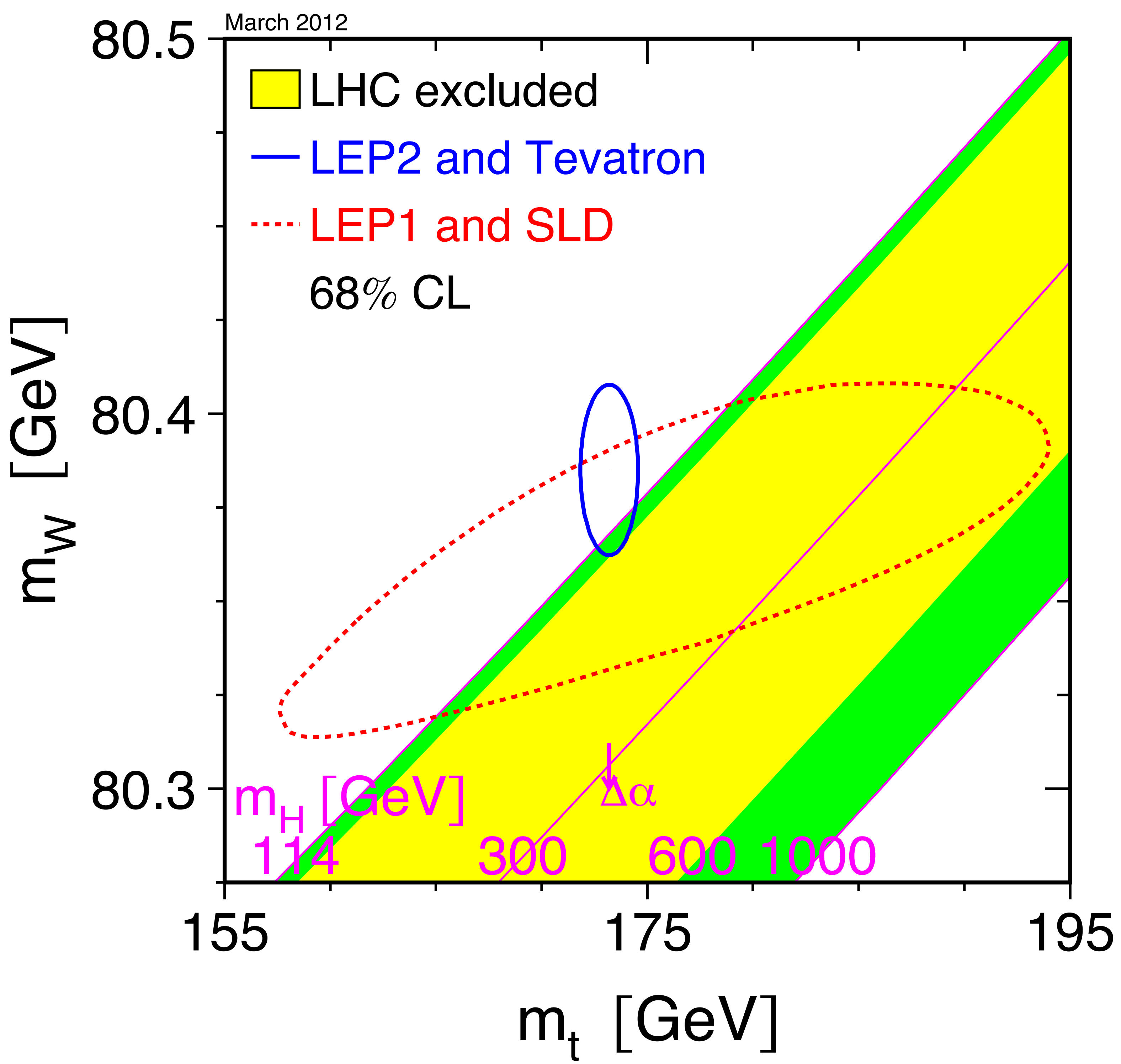

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Targets for LHC

arXiv:1310.6708

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\mathrm{fb}^{-1}]$	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

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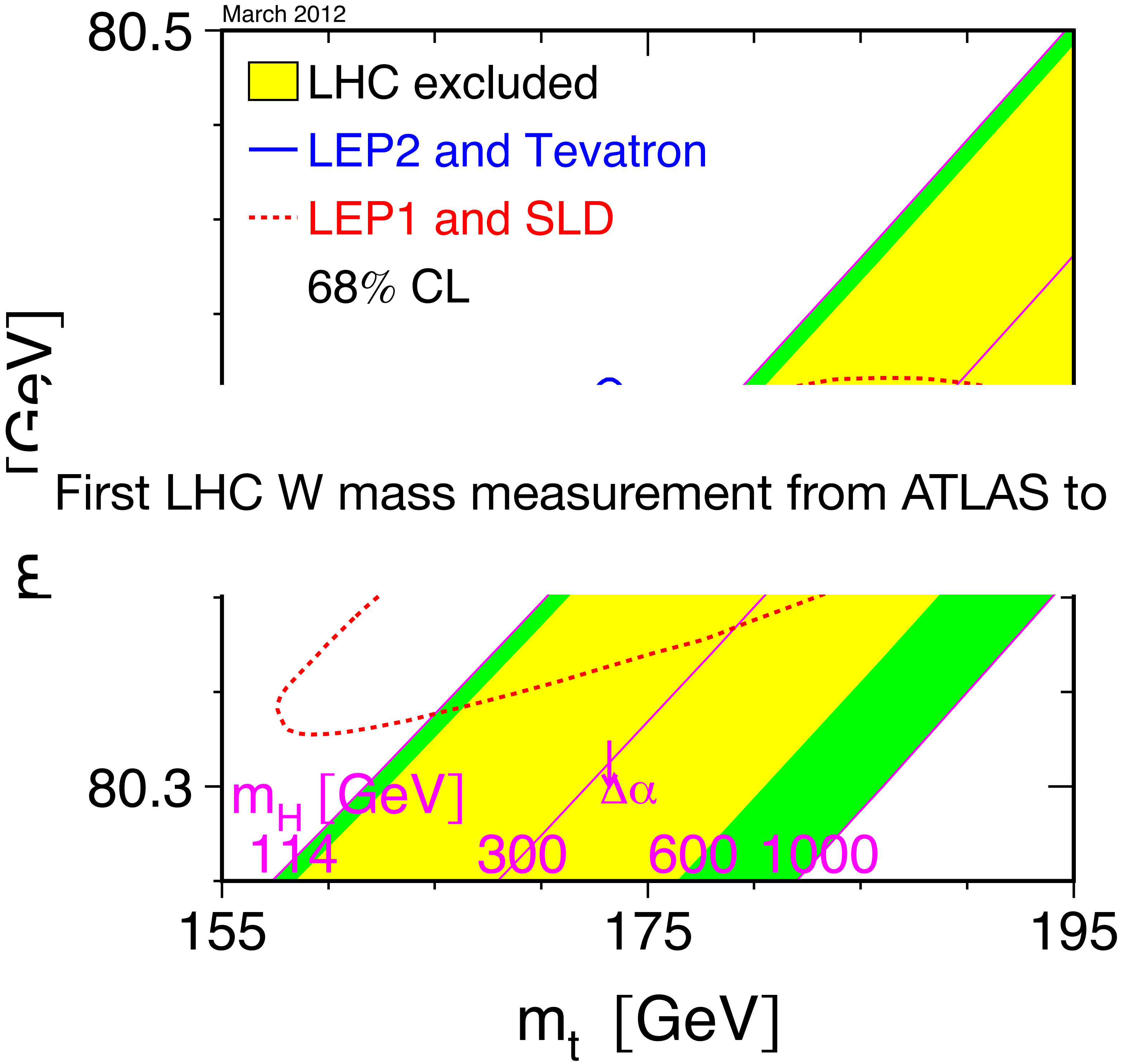

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First LHC W mass measurement from ATLAS to be announced tomorrow!

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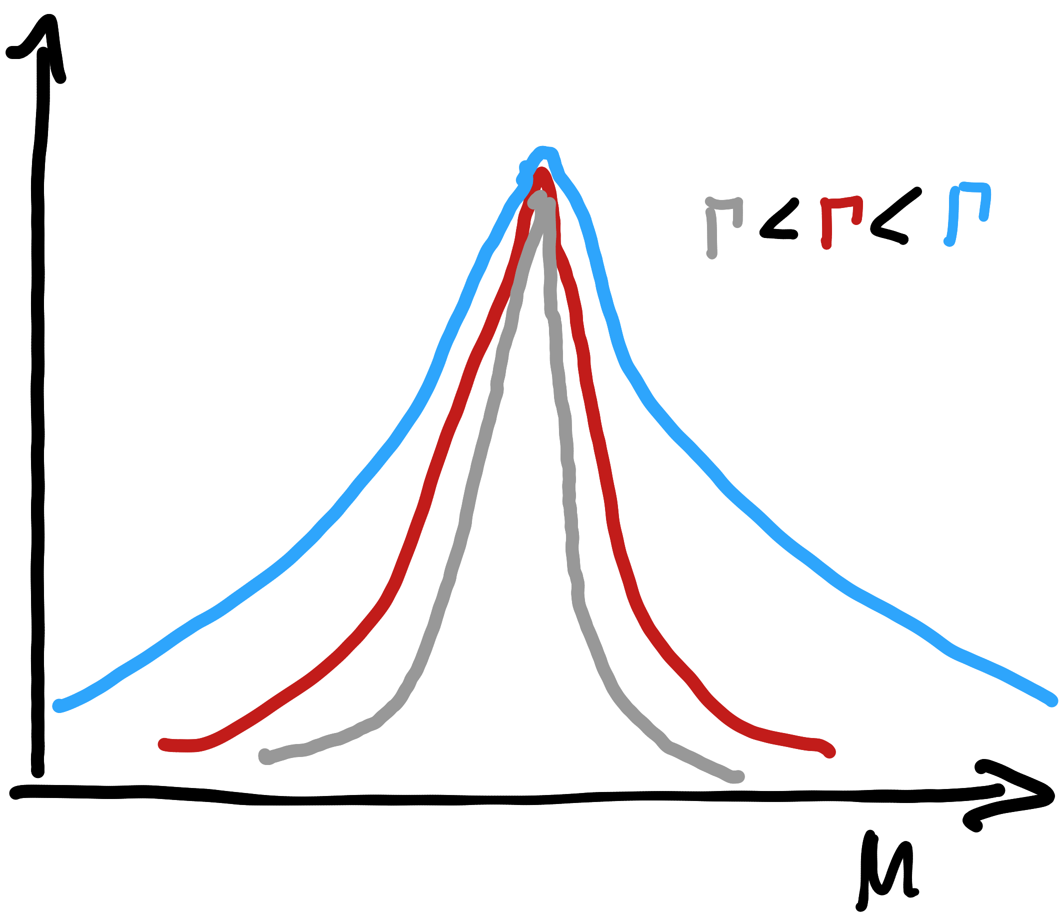
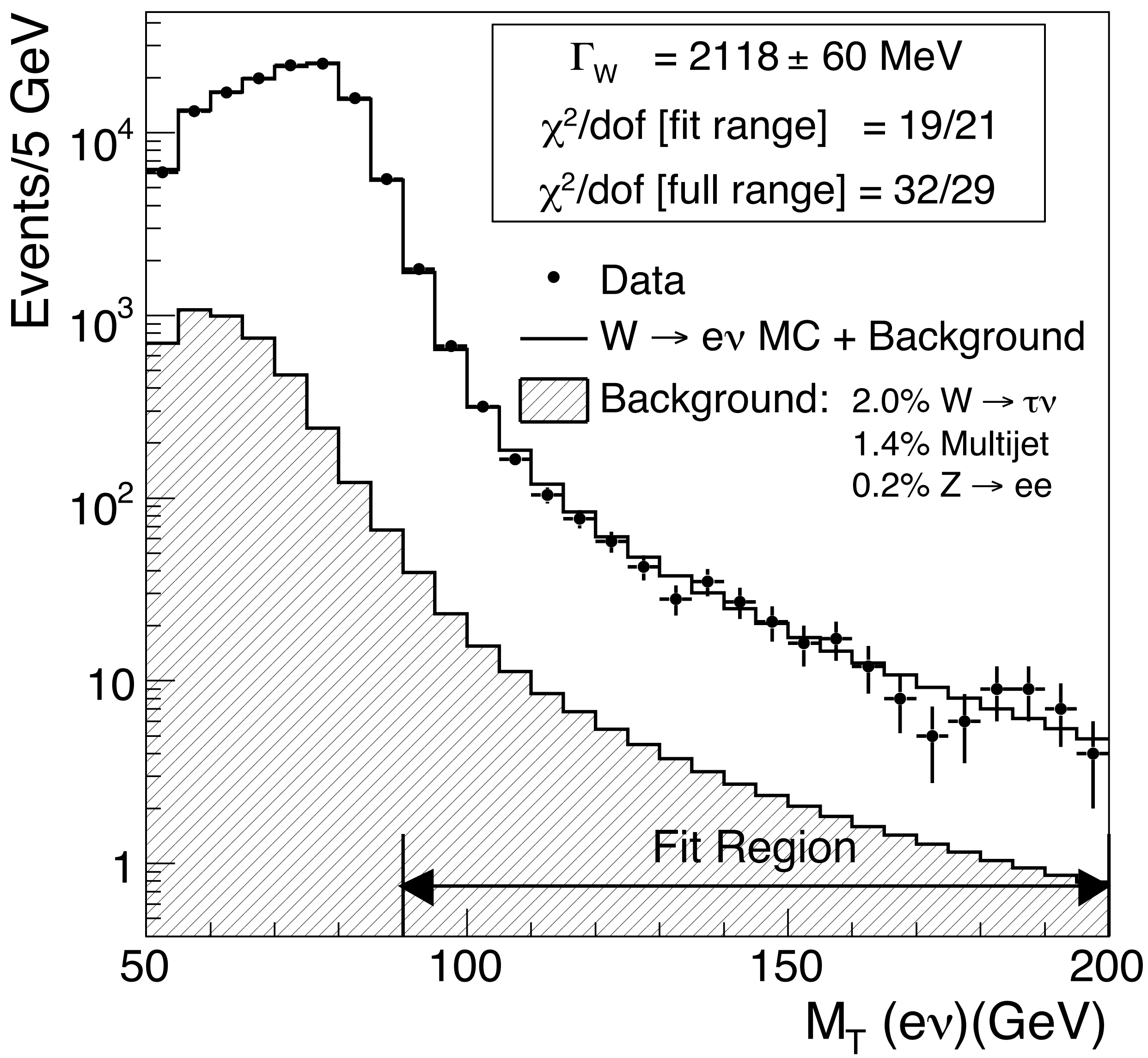
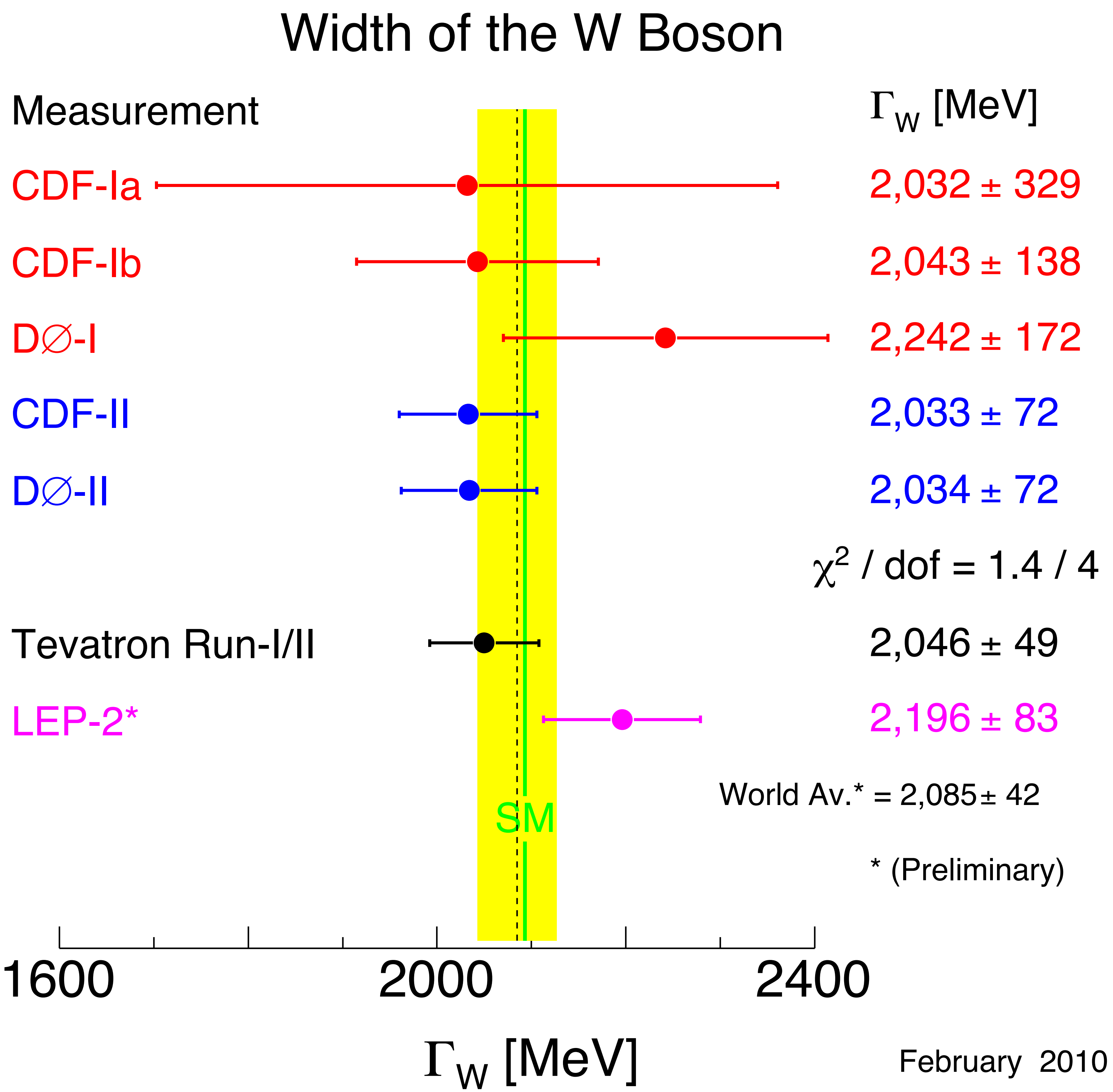
Measuring the Width of the W Boson

- 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



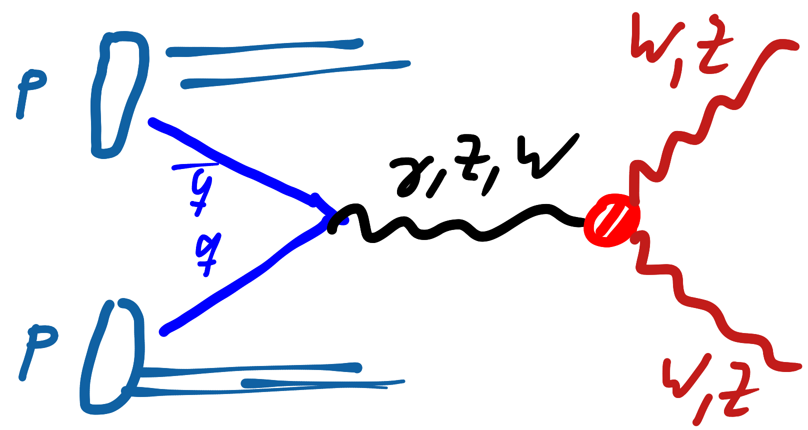


The Width of the W - Summary of Results



- Excellent agreement with the Standard Model

Triple Gauge Couplings



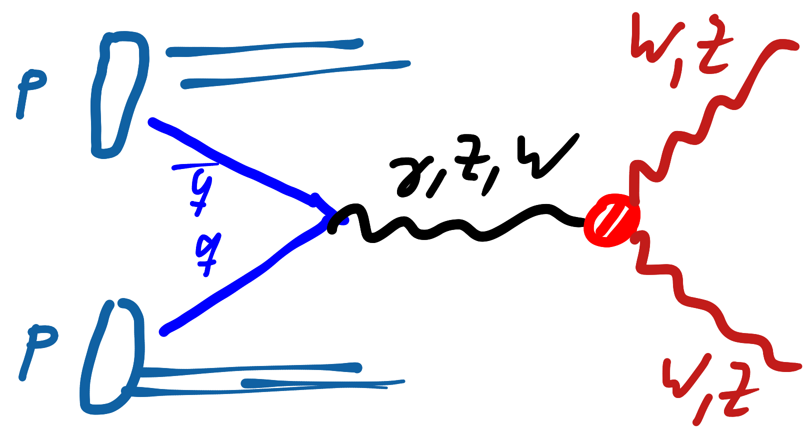
γ, Z -> W^+W^-

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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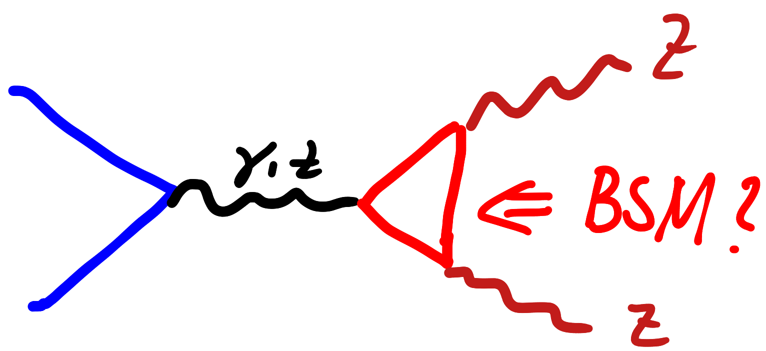

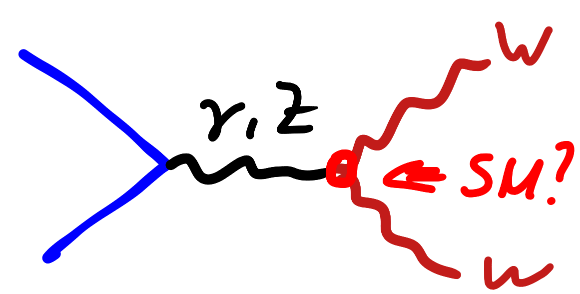

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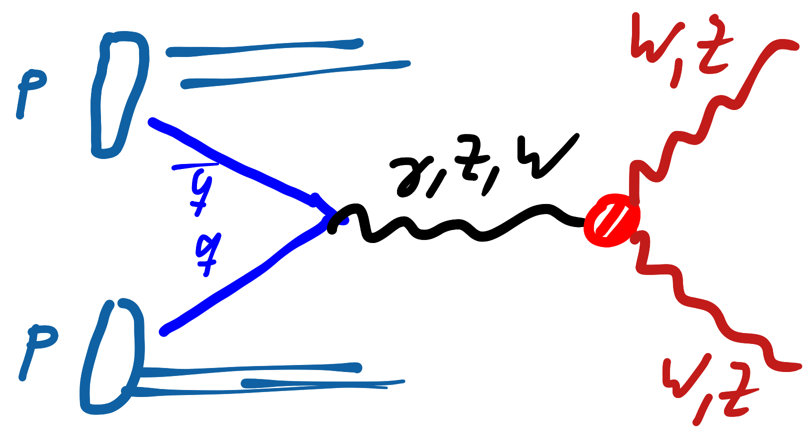

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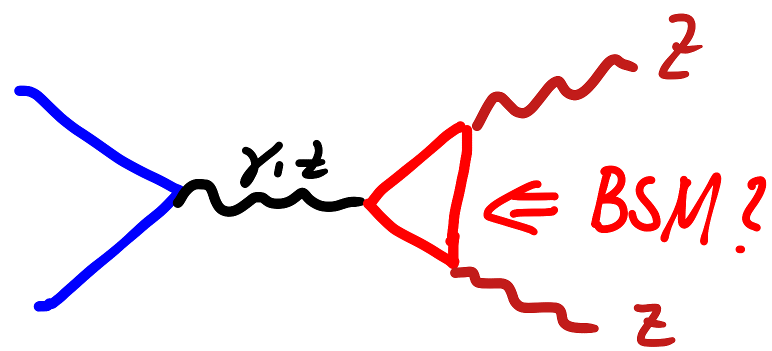
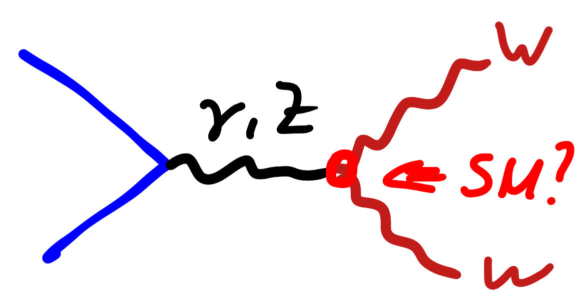
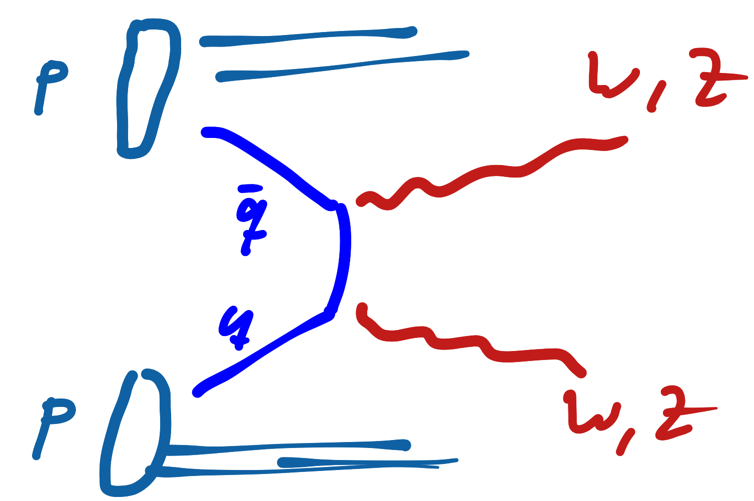
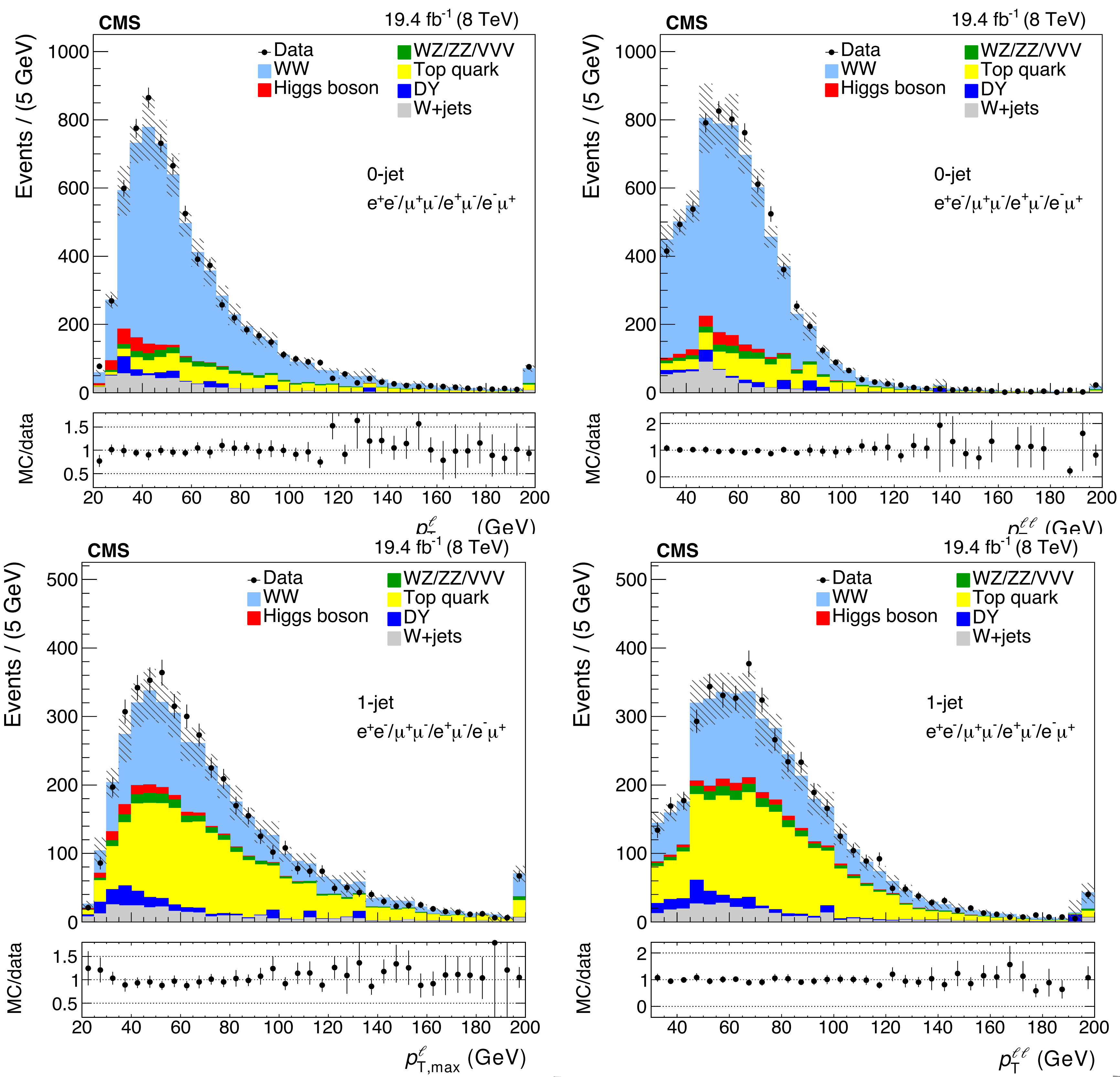




- SM: Time-like diagrams with two identical bosons in the final state are allowed
  - NB - No triple gauge coupling! SM background to TGC measurements

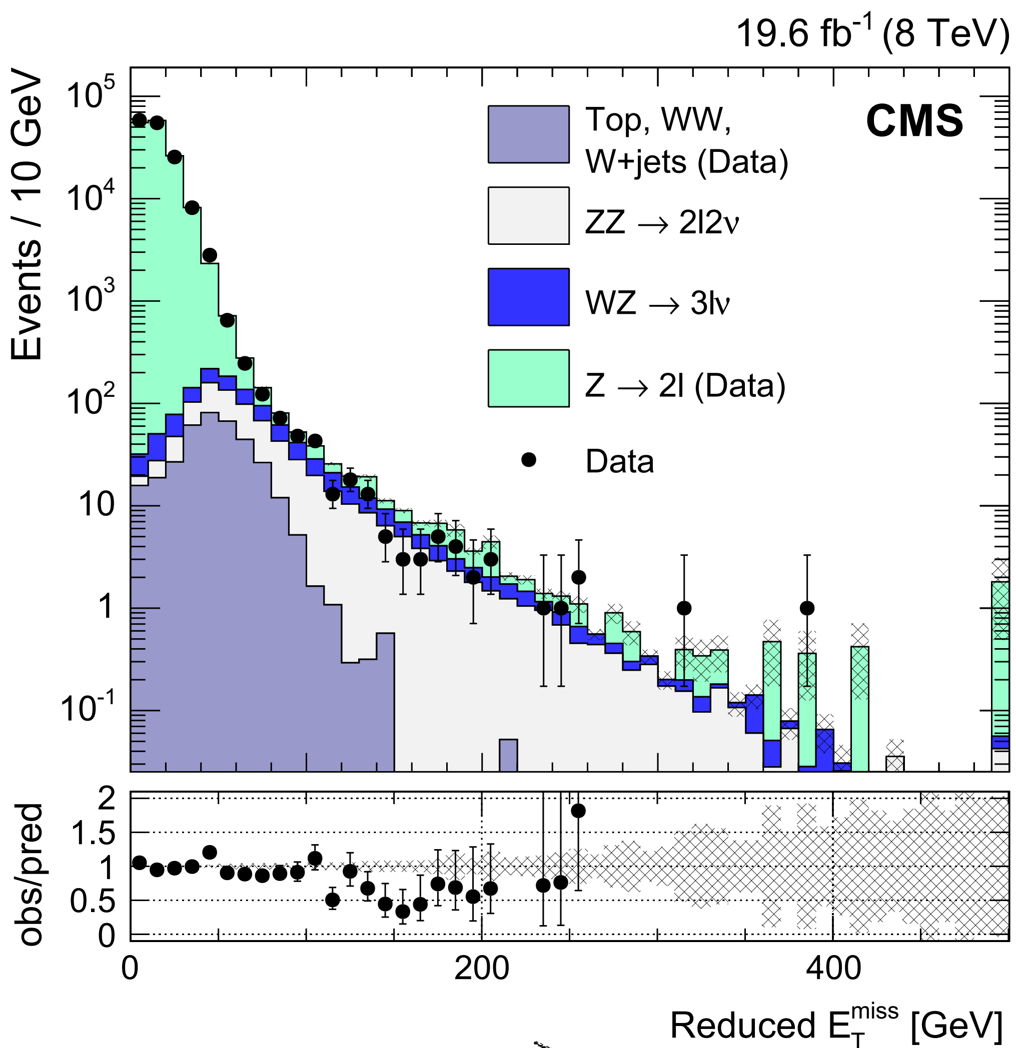


Measurement of WW Production



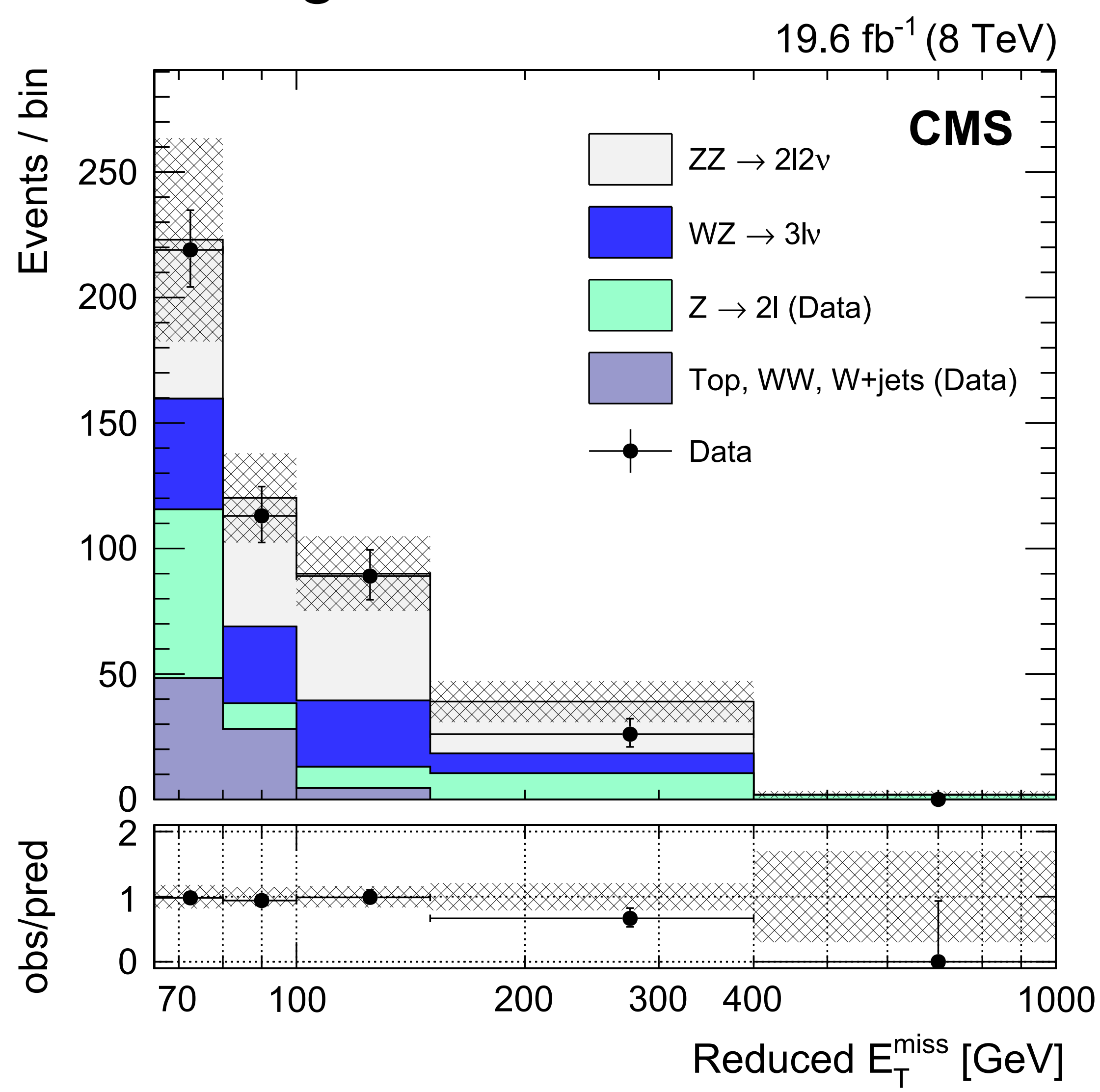
- Looking for W->lv: Best separation from background
- Cleanest signal: events w/o jets - one additional jet also considered

Measurement of ZZ Production

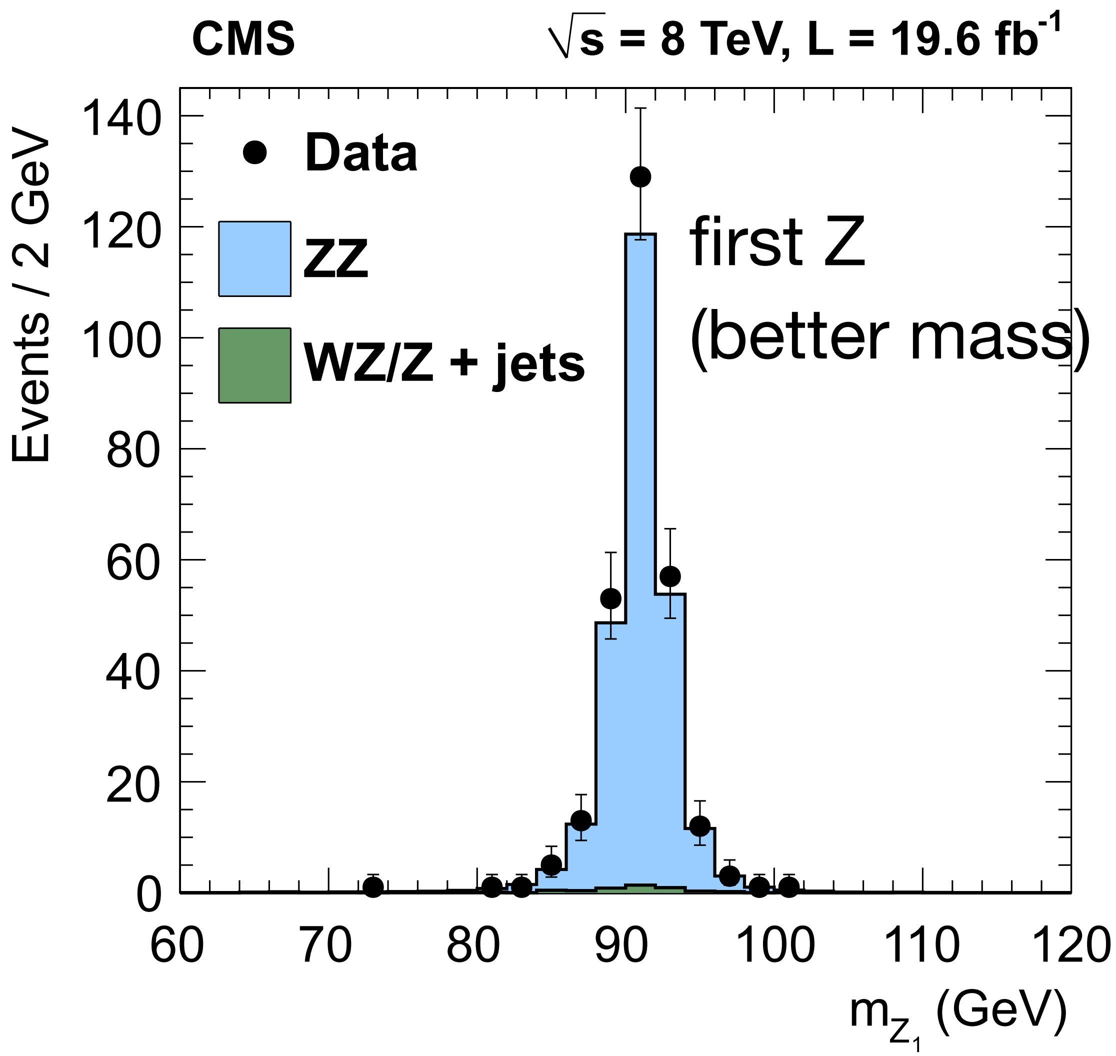


final selection

- One Z going into neutrinos: 20% of the total decays -> large missing energy
- One Z going to leptons (e, μ): 6.7%: Clean final state, can be identified above background

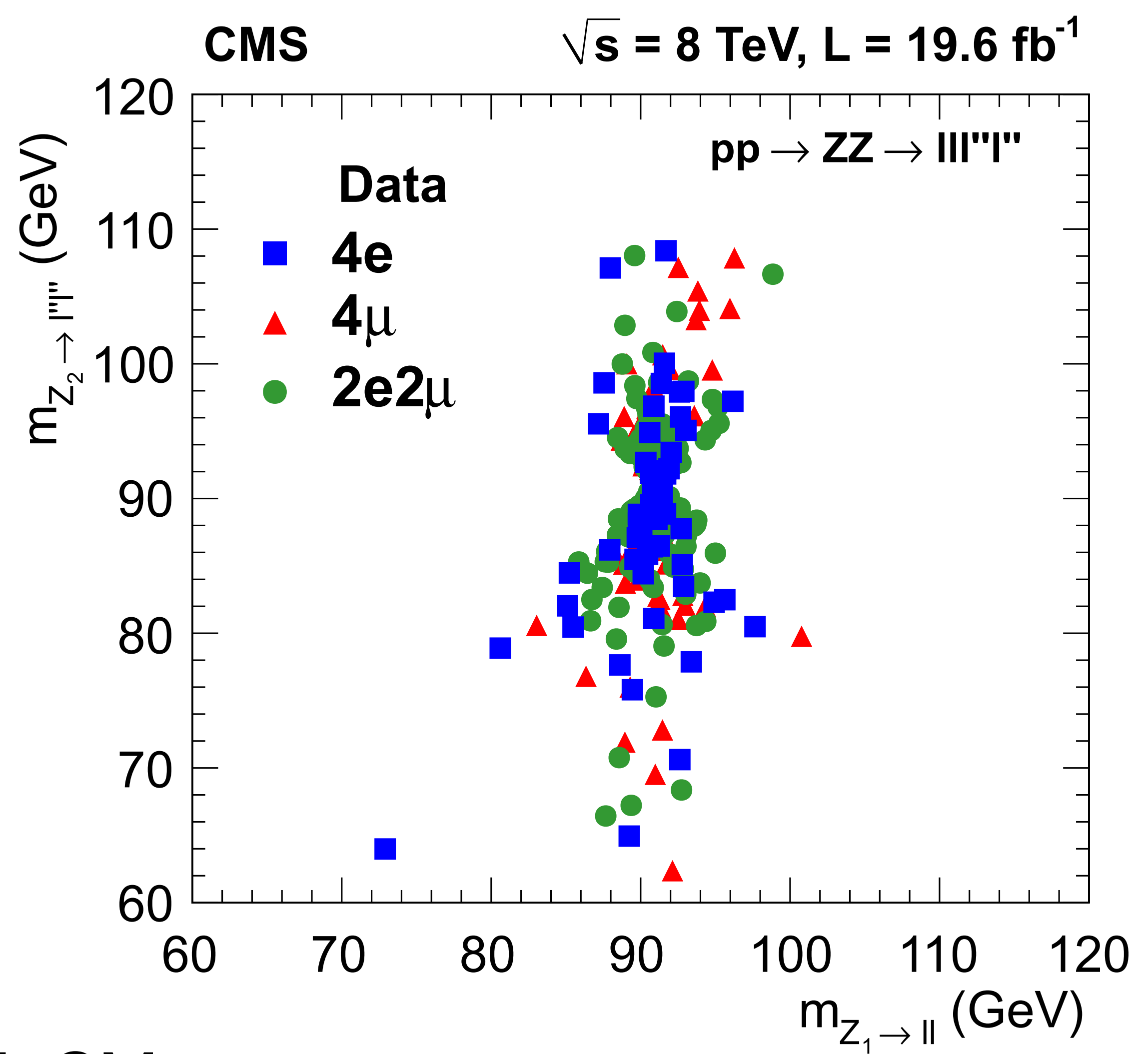


Measurement of ZZ Production



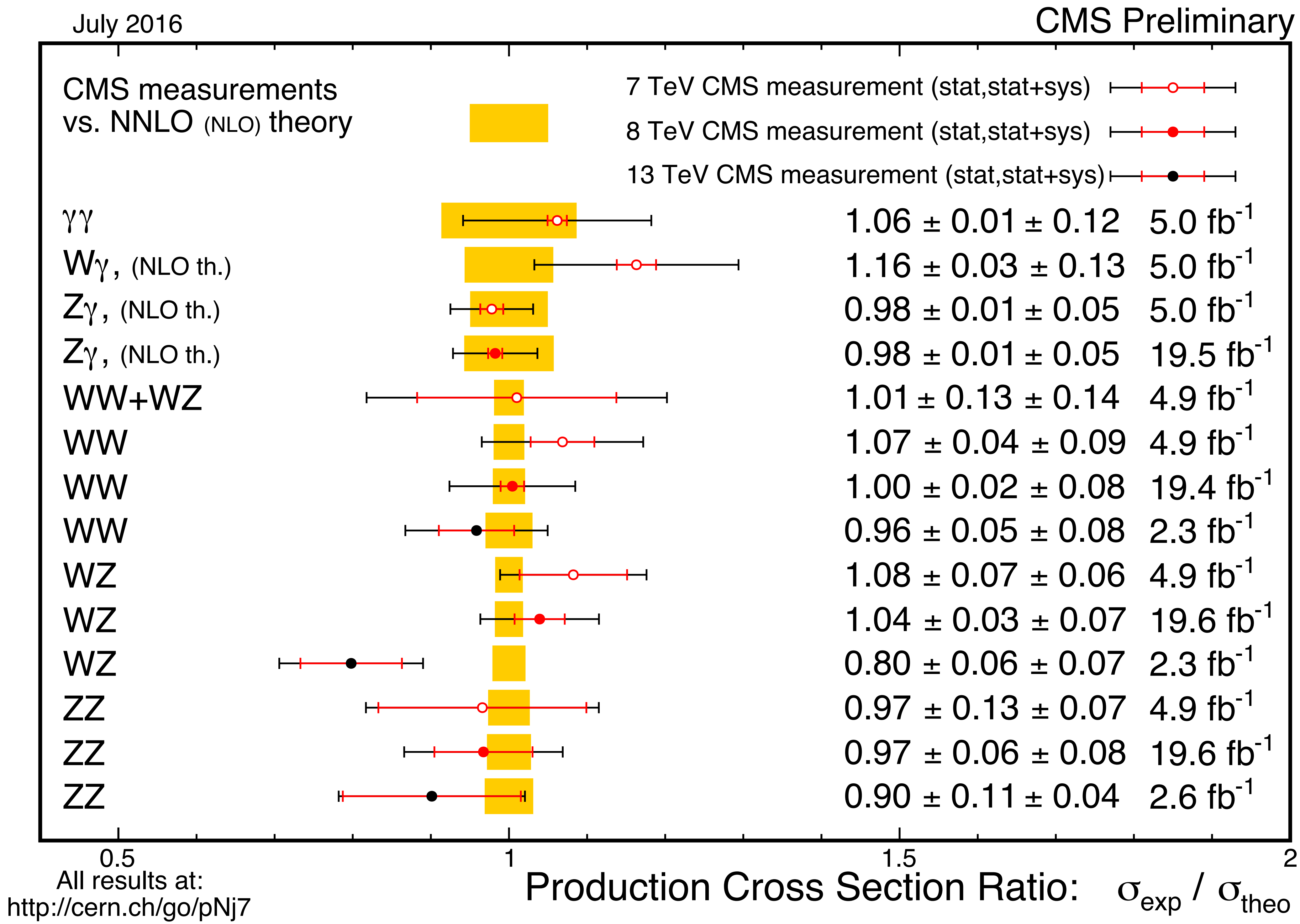
first Z
(better mass)

- Clean measurement when both Zs going to leptons - but small rate $(6.7\%)^2 = 0.45\%$



- So far all observations consistent with SM expectations

Double Vector Boson Production - CMS Summary



- Overall excellent agreement with SM expectations - Consistent for 7, 8 and 13TeV

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

- The Tevatron provides the most precise W mass measurement to date - global uncertainty 15 MeV - LHC might ultimately go to 5 MeV
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Next Lecture: Top Physics, F. Simon 19.12.2016

Schedule

1.	Introduction	17.10.
2.	Accelerators	24.10.
	----------- no lecture -------------	**31.10.**
3.	Particle Detectors I	07.11.
4.	Particle Detectors II	14.11.
5.	Trigger, Data Acquisition, Computing	21.11.
6.	Monte Carlo Generators and Detector Simulation	28.11.
7.	QCD, Jets, Proton Structure	05.12.
8.	Tests of the Standard Model	12.12
9.	Top Physics	19.12.
	----------- Christmas ---------------------	
10.	Higgs Physics I	09.01.
11.	Higgs Physics II	16.01.
12.	Physics beyond the SM	23.01.
13.	LHC Outlook & Future Collider Projects	30.01
	----------- no lecture -------------	**06.02**