Hadron Collider Physics I:
PPP-II Lecture 11 (FS 2012)

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15.5.2012

15.5.2012 Introduction: Why we want(ed) the LHC.

15.5.2012 From "low" Q^2 pp physics to W, Z and other medium Q^2
LHC questions and answers.

22.5.2012 QCD, TOP and "known"(?) SM physics at the LHC,
status and perspectives.

29.5.2012 Higgs@LHC and searches for new phenomena, status and perspectives.

29.5.2012 "Some kind of PPP2 "Summary": The next few years at the LHC.

Hadron Collider Physics:
PPP-II Lecture 11 (15.5.2012)

- Introduction: Why we need/want(ed) the LHC.
- Experimental LHC requirements and achievements.
- pp collisions: The total cross section and its components and physics from low Q^2 reactions.
- W and Z production: A LHC tool(!) to “calibrate” experiment and theory!

Possibilities and limitations of the LHC (I)

- *"The LHC is a discovery machine. We don't know what we'll find,"* said Abraham Seiden, professor of physics and director of the Santa Cruz Institute for Particle Physics (SCIPP) at the University of California, Santa Cruz (talk at the American Physical Society 2008)

- Technically, the Higgs boson was postulated to explain a feature of particle interactions known as the breaking of electroweak symmetry, and *"the LHC is virtually guaranteed to explain that phenomenon"*, according to theoretical physicist Howard Haber (in 2008) professor of physics at UCSC. He continues: *"We've been debating this for 30 years, and one way or another, the LHC will definitively tell us how electroweak symmetry breaking occurs."*

- See `http://atlas.ch/etours_physics/etours_physics08.html`
  But the Standard Model leaves many other questions unanswered..
  and click on forward:
  "One of the main goals of the ATLAS program is to discover and study the Higgs particle."

Possibilities and limitations of the LHC (II)

The LHC (and the SSC) pp collider was "designed" after the W and Z discovery, but before the SM (LEP) precision measurements to:

- Discover the mechanism of electroweak-symmetry breaking, the Higgs boson, and its mass between ≈ 100 GeV to about 1000 GeV.
- Discover new physics into the 1-2 TeV mass range (Supersymmetry, extra Z and W like bosons).
- Perform a large number of QCD and electroweak measurements up to a jet p_t (or mass) of a few TeV ("search for deviations and substructures").

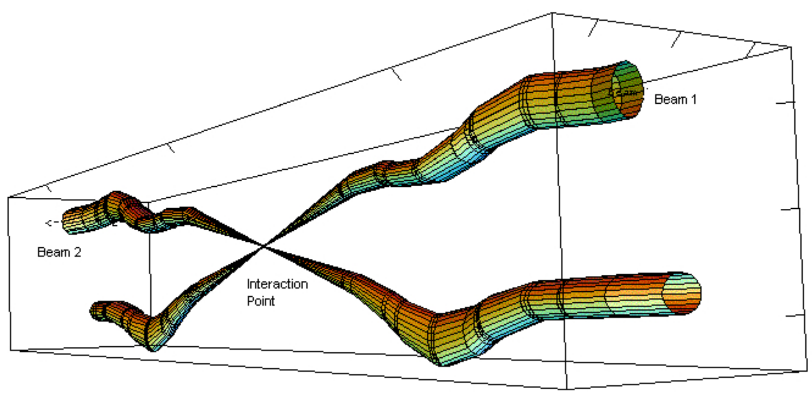
One could also say: The LHC design ideas were "mirroring" the SSC (USA)
http://en.wikipedia.org/wiki/Superconducting_Super_Collider
(SSC was a 40 TeV pp collider project with a luminosity of $10^{33}/cm^2sec^1 = 10\ fb^{-1}$/year)
The LHC in the LEP tunnel was considered to do "competitive" and forefront physics and provide a long term future for CERN.
(the cancelation of the SSC in 1993 helped somehow)

Possibilities and limitations of the LHC (III)

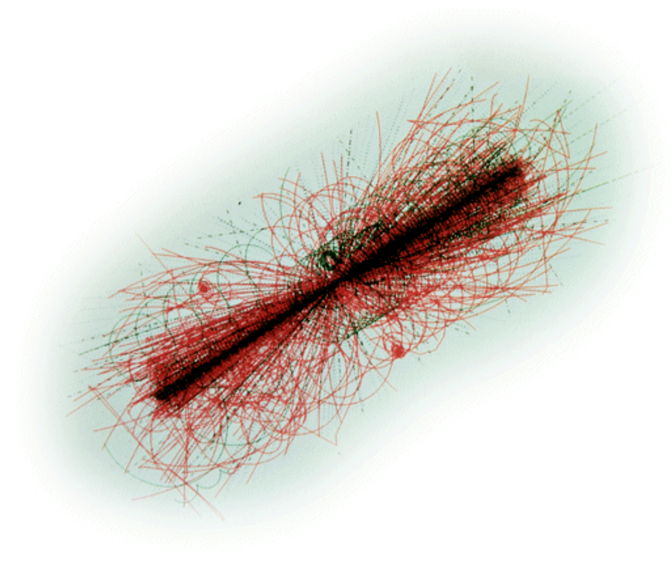
- Existing LEP tunnel (27km) allowed to reach with the most optimistic magnet design: $\sqrt{s}$ = 18 TeV (1986). Final design (2000) = 14 TeV and 8 TeV achieved so far (2012).

- Simulation results of various theoretical signal and background reactions require luminosities of a few ten to hundred fb^{-1} to reach the full physics potential!

- Tough experimental conditions: (1) high particle density in each pp collisions collision frequency about 25 nsec (45 Mhz) multi pp collisions per crossing at higher luminosities.

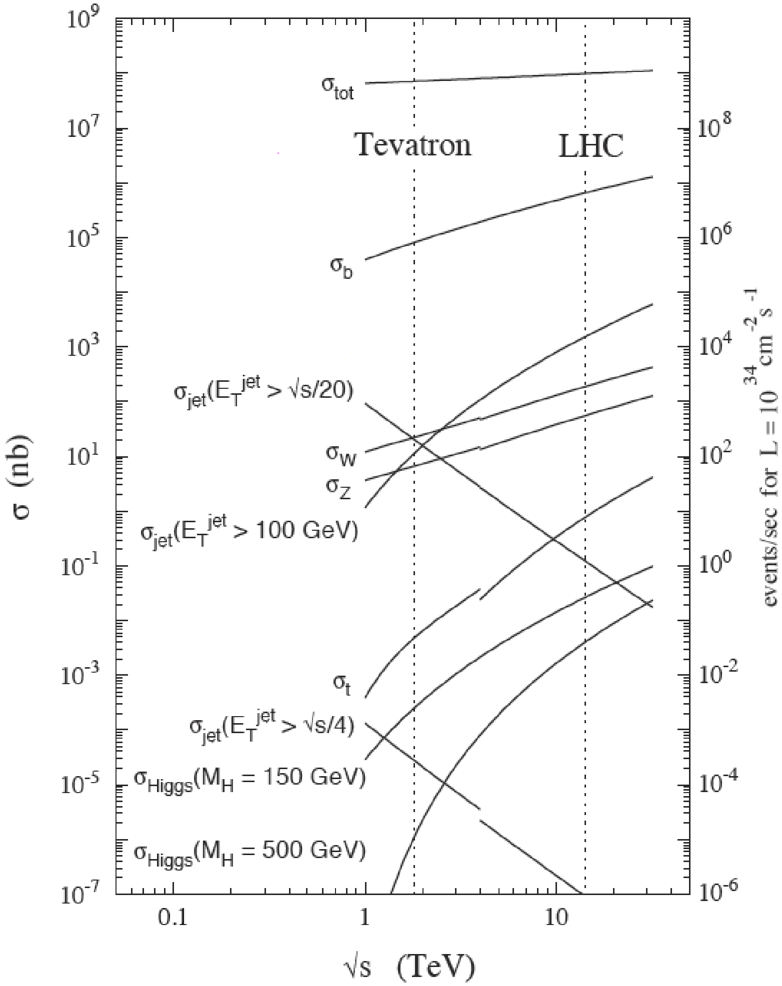


Relative beam sizes around IP1 (Atlas) in collision



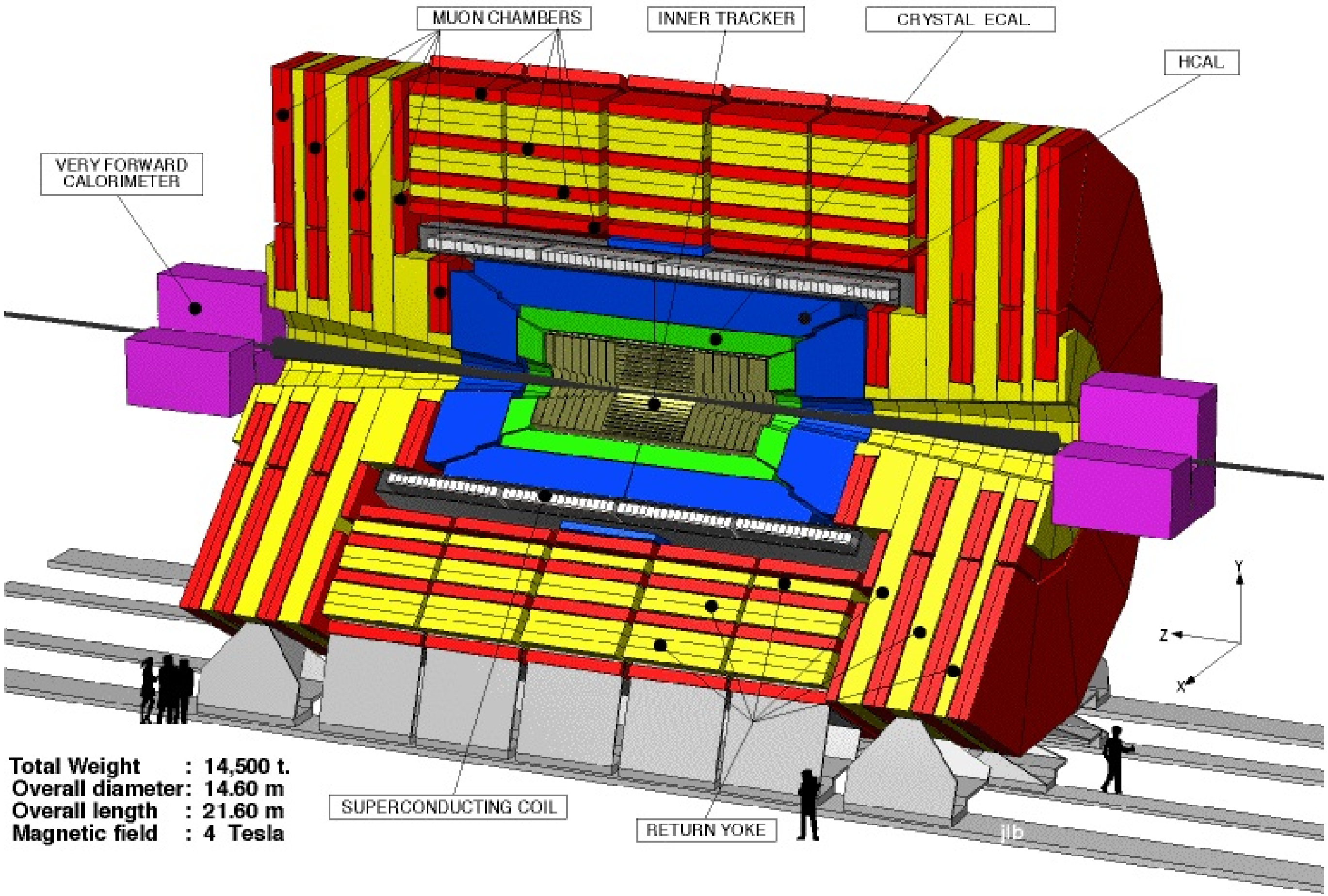
Possibilities and limitations of the LHC (IV)

Large cross sections for soft and hard QCD physics, medium cross section for W, Z and top production low cross section for the Higgs and new types of physics with TeV masses.
Lots of "new" physics even at 7 TeV center of mass energies and low luminosities!



Possibilities and limitations of the LHC (V)

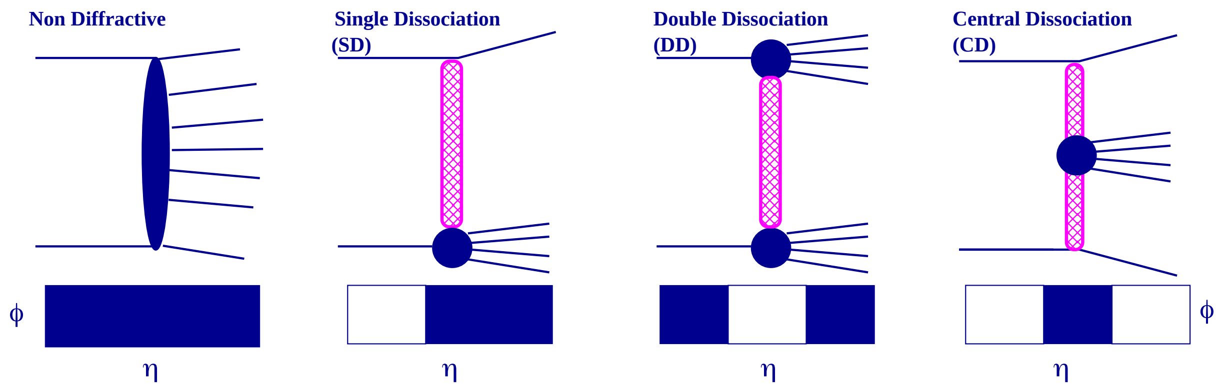
The CMS detector: A multi purpose high precision experiment for the LHC



Total pp cross section (I): elastic and inelastic pp scattering

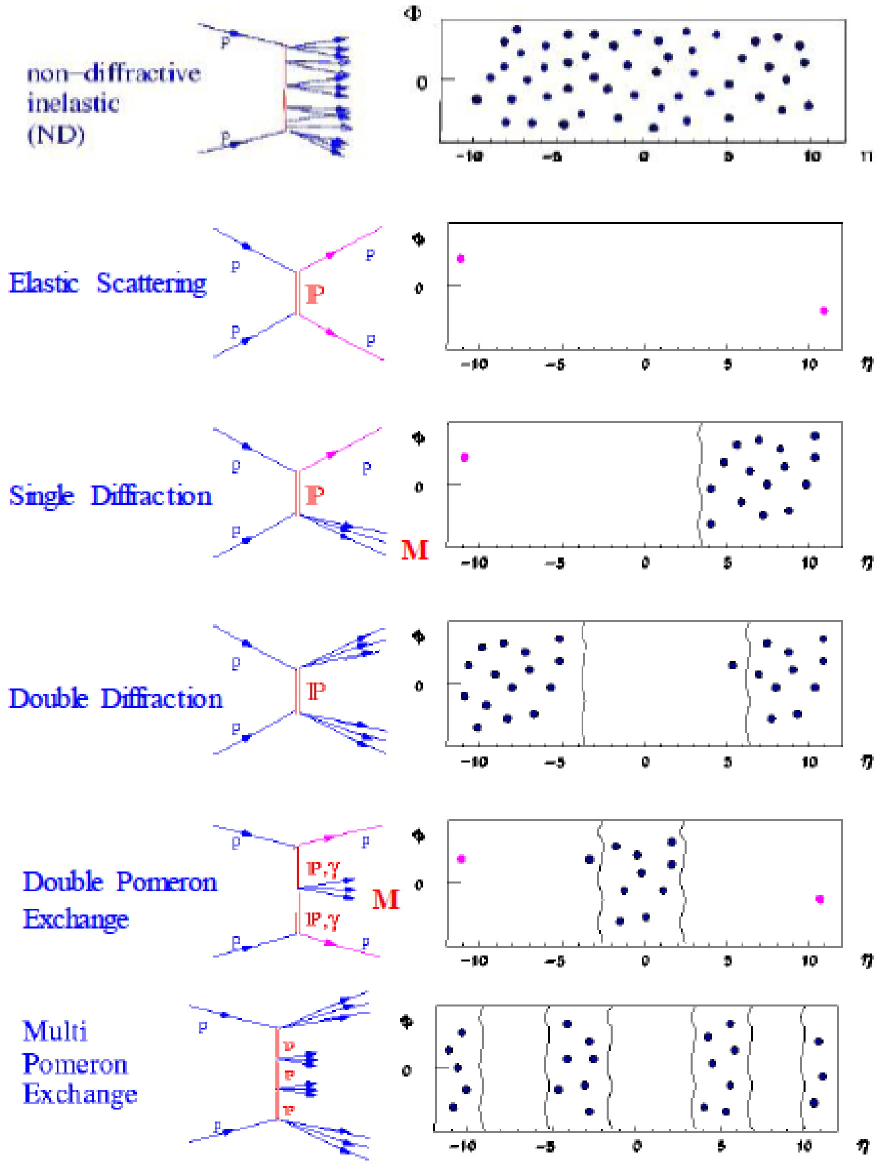
$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic}$$

- Elastic scattering: low Q^2 $pp \to pp$ (very small angle) scattering
- The different components of inelastic pp scattering



Total pp cross section (II): elastic and inelastic pp scattering

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic}$$



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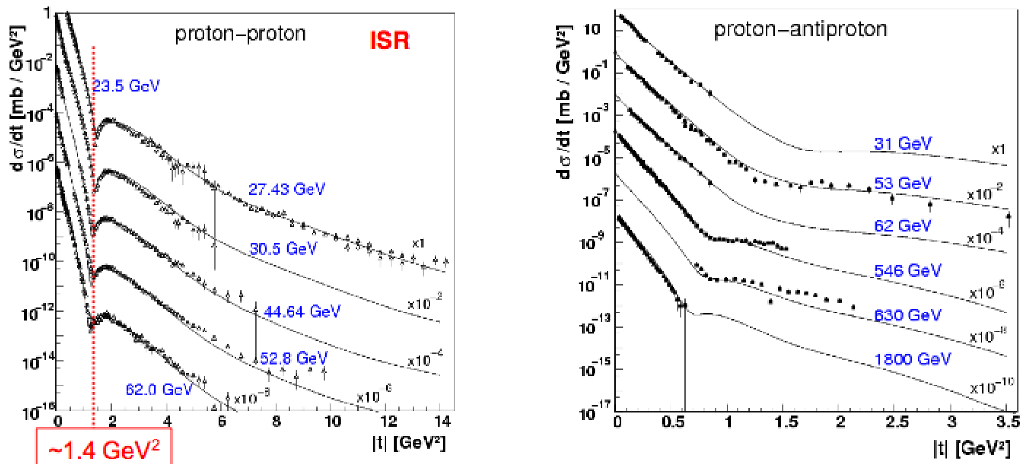
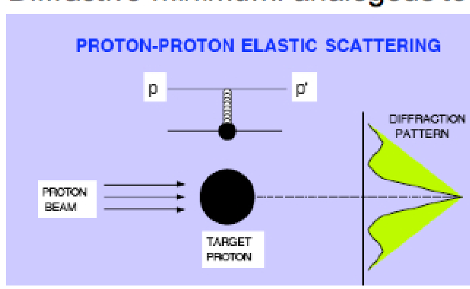
Total pp cross section (III):
elastic pp scattering

- Elastic scattering: low Q^2 $pp \to pp$ (very small angle) scattering

Elastic scattering – from ISR to Tevatron



Diffractive minimum: analogous to Fraunhofer diffraction: $|t| \sim p^2\theta^2$

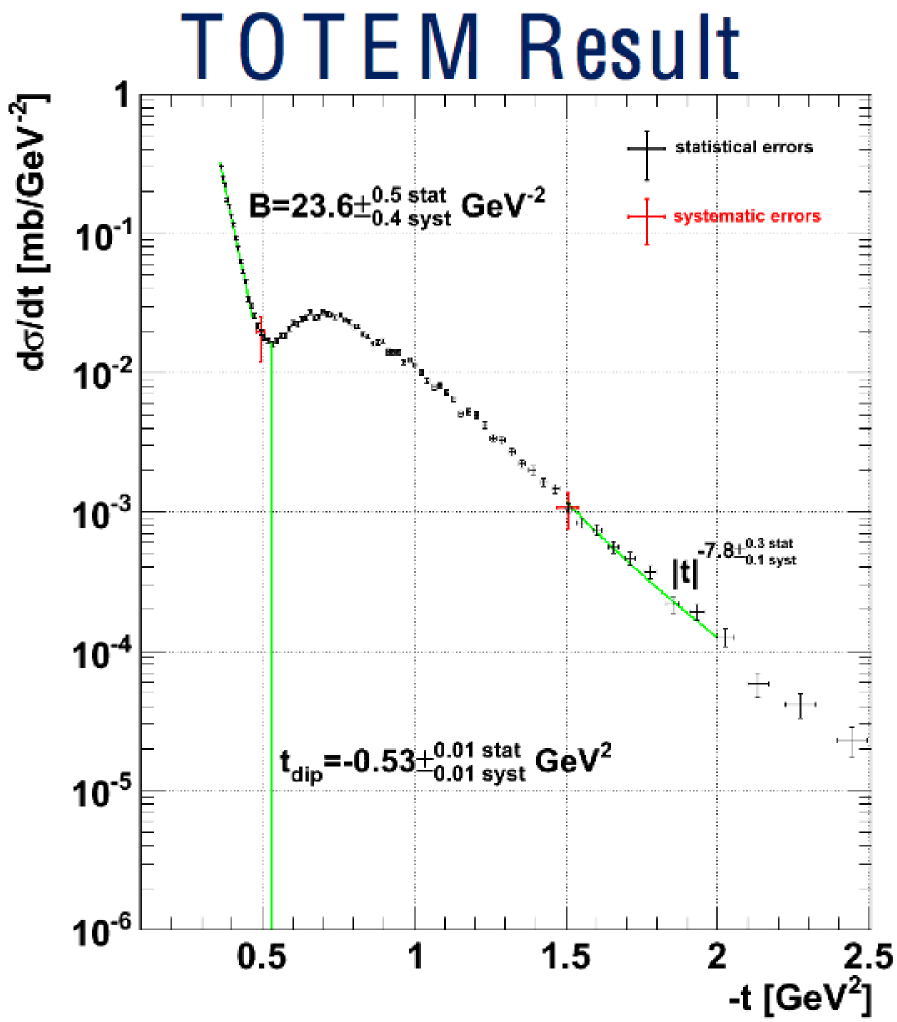


- exponential slope B at low |t| increases
- minimum moves to lower |t| with increasing s
  → interaction region grows (as also seen from σ_{tot})
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, $\bar{p}p$
  → different mix of processes

For many fine details see: Totem Seminar 22.11.11,
https://indico.cern.ch/getFile.py/access?resId=1&materialId=slides&confId=162623

Total pp cross section (IV): elastic pp scattering with TOTEM at 7 TeV

- Elastic scattering: low Q^2 $pp \to pp$ (very small angle) scattering



For many fine details see: Totem Seminar 22.11.11,
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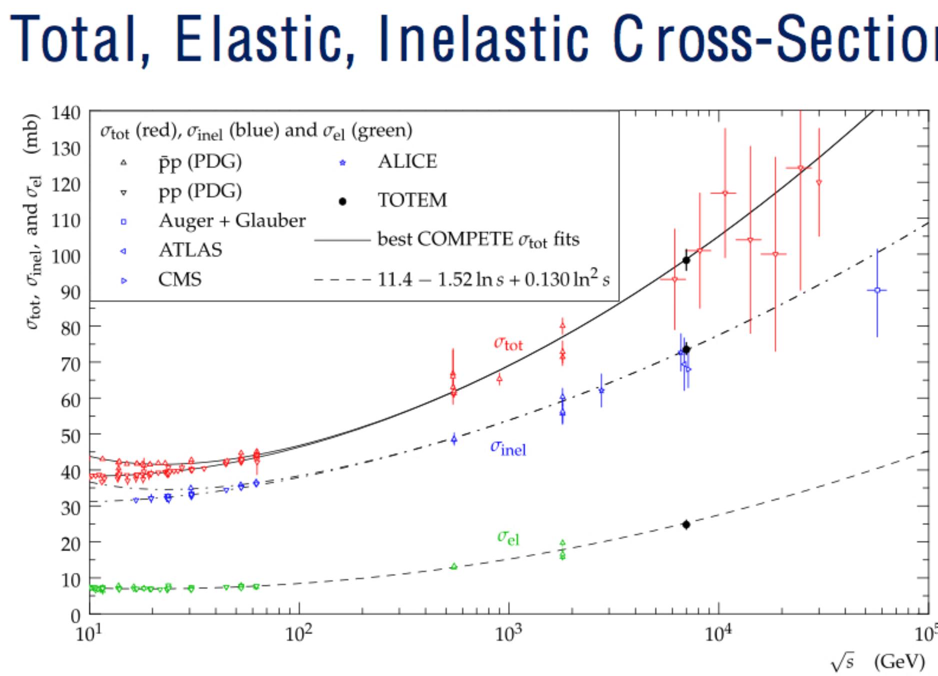
Total pp cross section (V):
elastic and inelastic pp scattering at 7 TeV

- **Next Steps: measure different "inelastic" cross sections and understand at what $\sqrt{s}$ the pp cross section will stop growing!**



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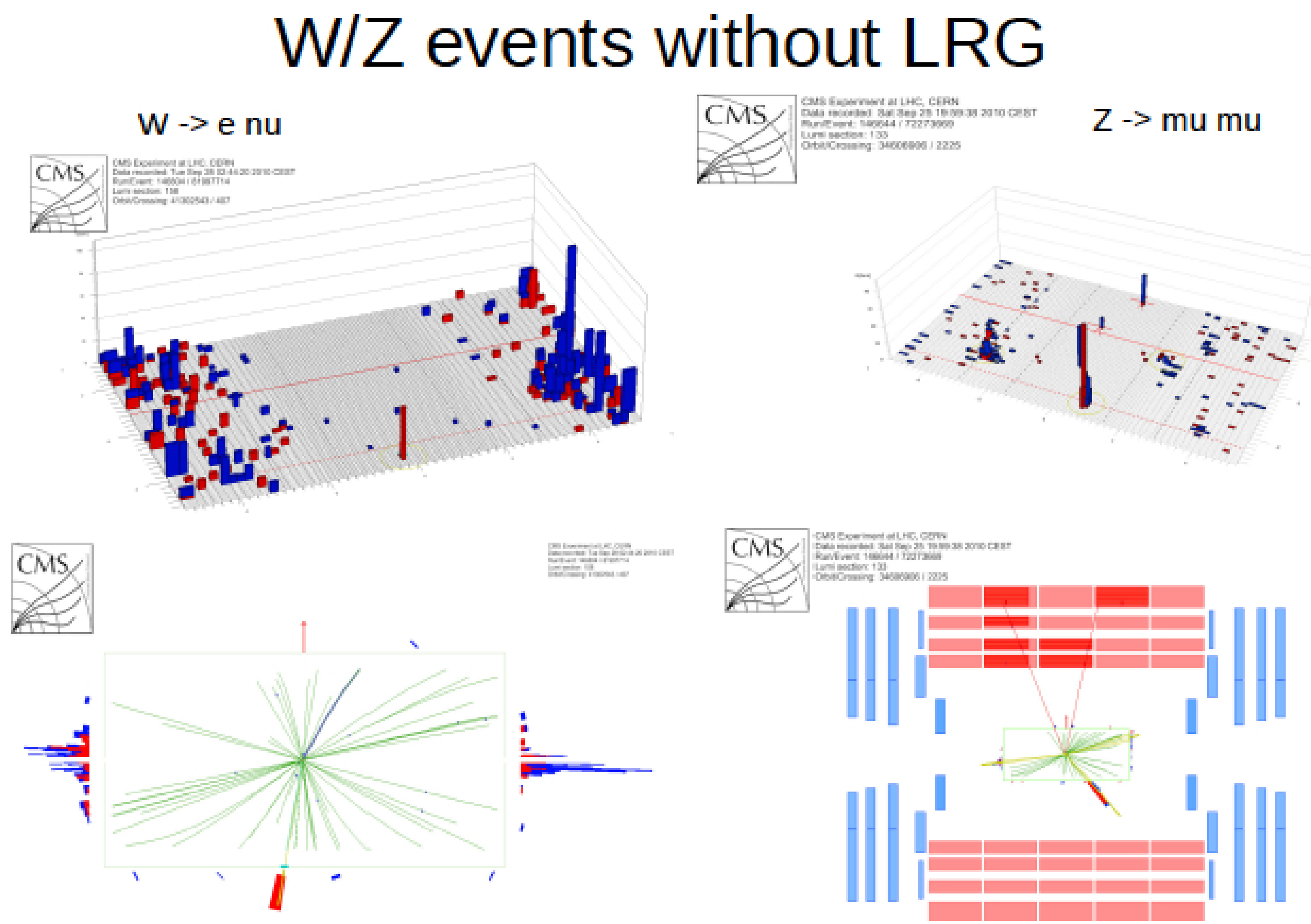
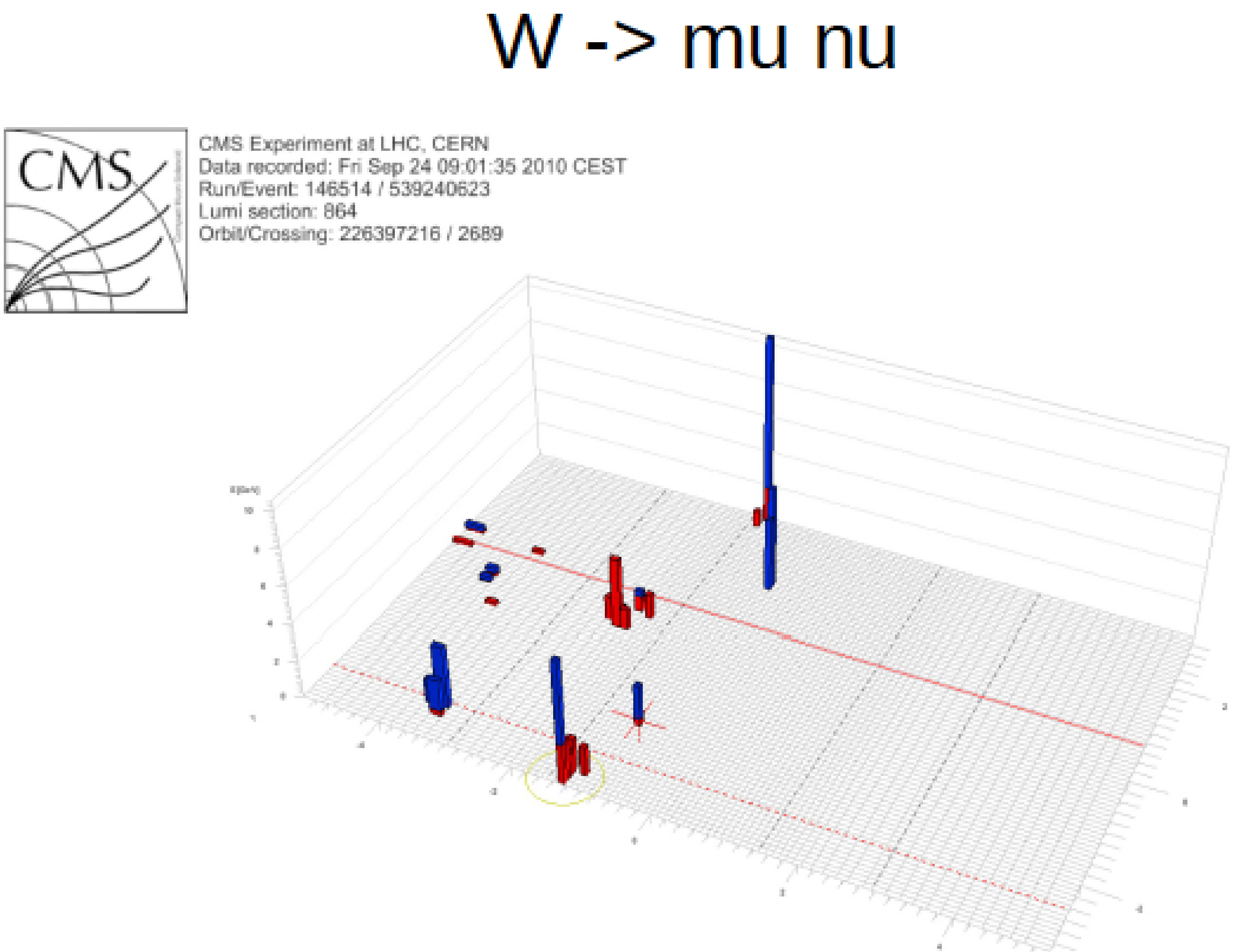
Some “typical” LHC collision events (I)

Some “normal” $pp \to W(Z) \to$ lepton events



Some "typical" LHC collision events (II)

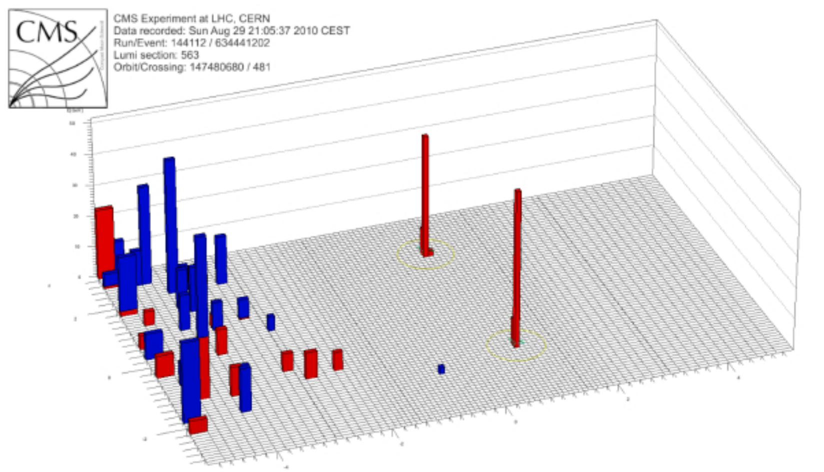
A less "normal" $pp \to W \to \mu\nu$ **event ("half empty" detector)**



Some “typical” LHC collision events (III)

A less “normal” $pp \to Z \to e^+e^-$ event (“half empty” detector)

Z -> e e



W and Z production: A LHC tool(!) to calibrate experiment and theory! (I)

LHC (pp collider) dynamics:

$q\bar{q} \to W(Z) \to$ leptons:

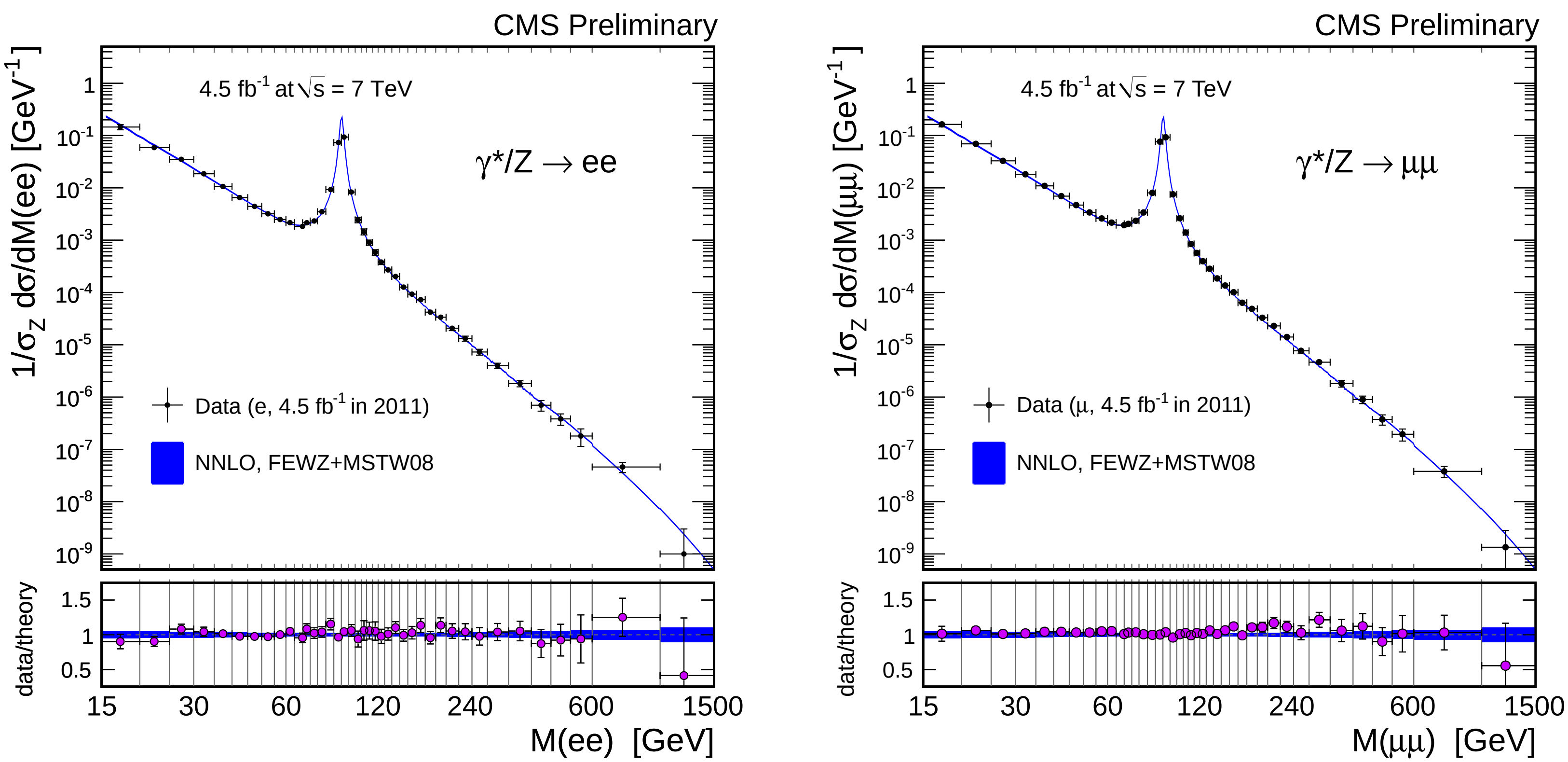
- Huge production cross sections
  (about 10 nb for $W \to \ell\nu$ and 1 nb for $Z \to \ell\ell$).

- Isolated high p_t leptons provide almost background free signature with high efficiency.
  Understand signature and precision "measurement" of leptons in the detector. Use it to "calibrate " the experiment!

- Theoretically best understood final state at the LHC!
  Use it to "calibrate " the theory!

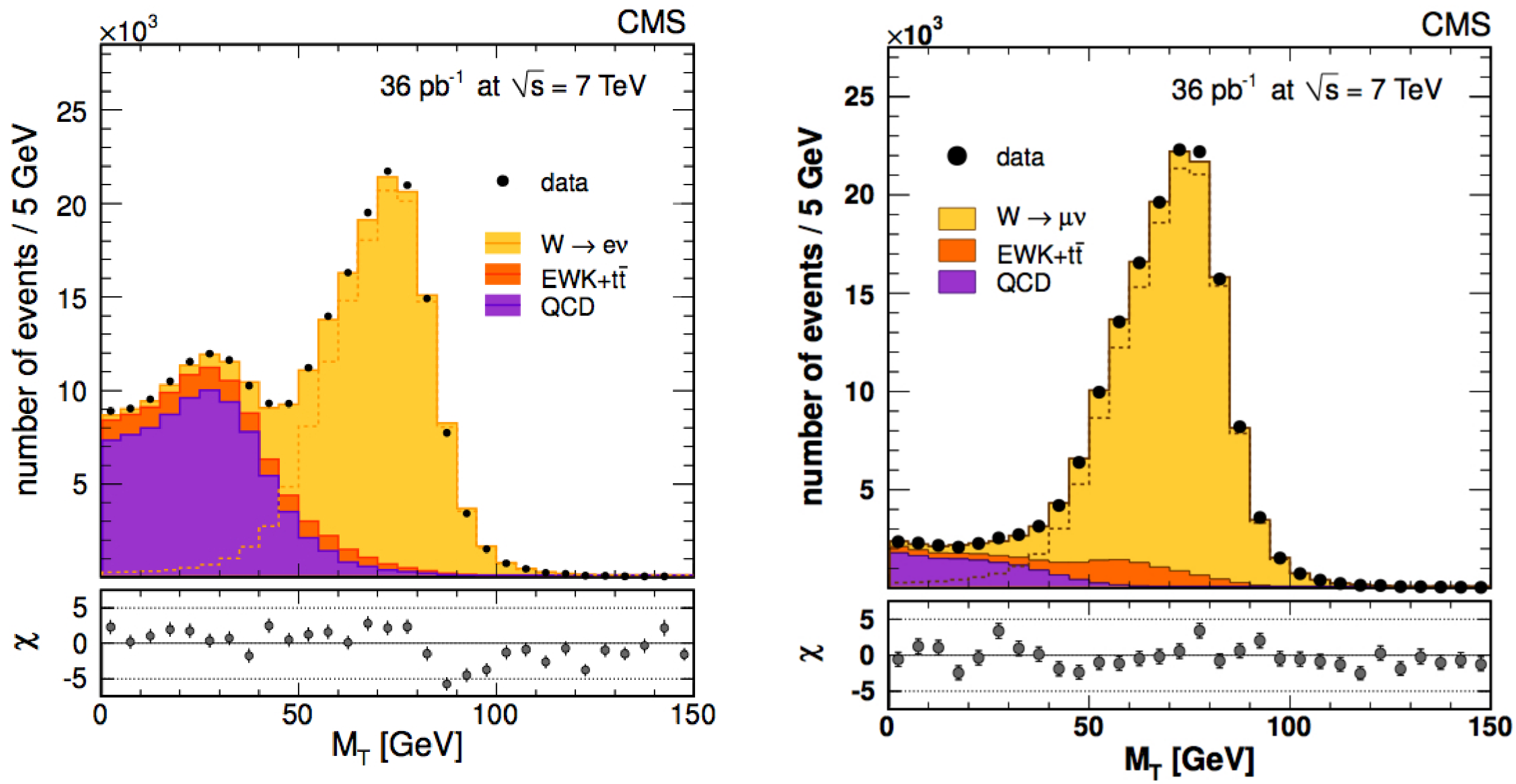
W and Z production: A LHC tool(!) to calibrate experiment and theory! (II)

Z (γ^*) signals in CMS: (up to large masses) essentially background free!



W and Z production: A LHC tool(!) to calibrate experiment and theory! (III)

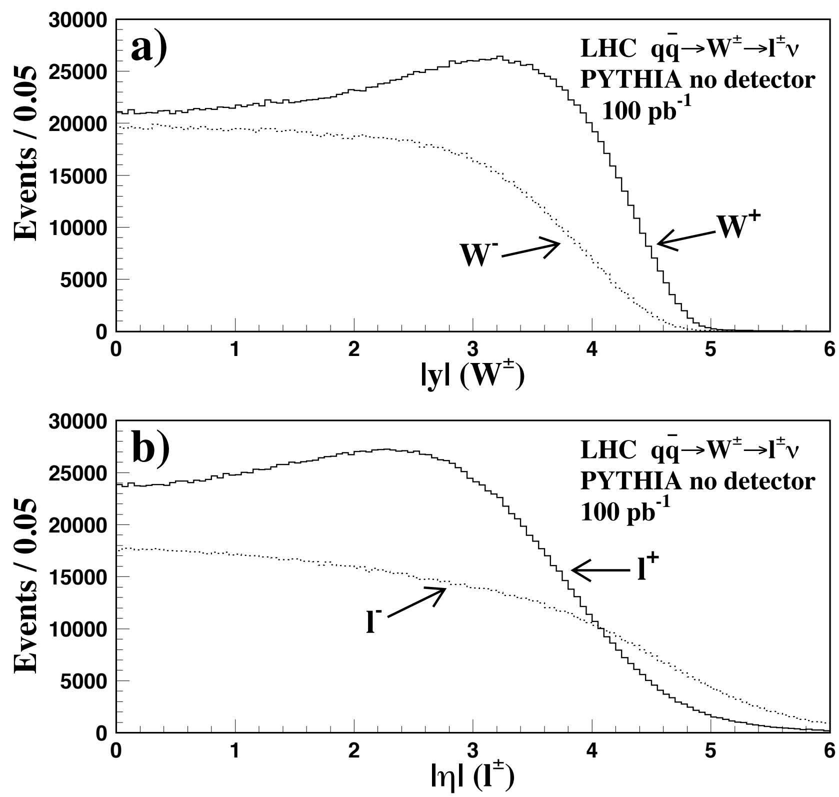
W signals in CMS: very little background for $M_T > 60$ GeV



W and Z production: A LHC tool(!) to calibrate experiment and theory! (IV)

LHC production kinematics: $\mathsf{N}_{pp\to Z} = \mathsf{L}_{pp} \times \mathsf{PDF}(x_1, x_2, Q^2) \times \sigma_{q,\bar{q}\to Z}(+\mathrm{ho})$

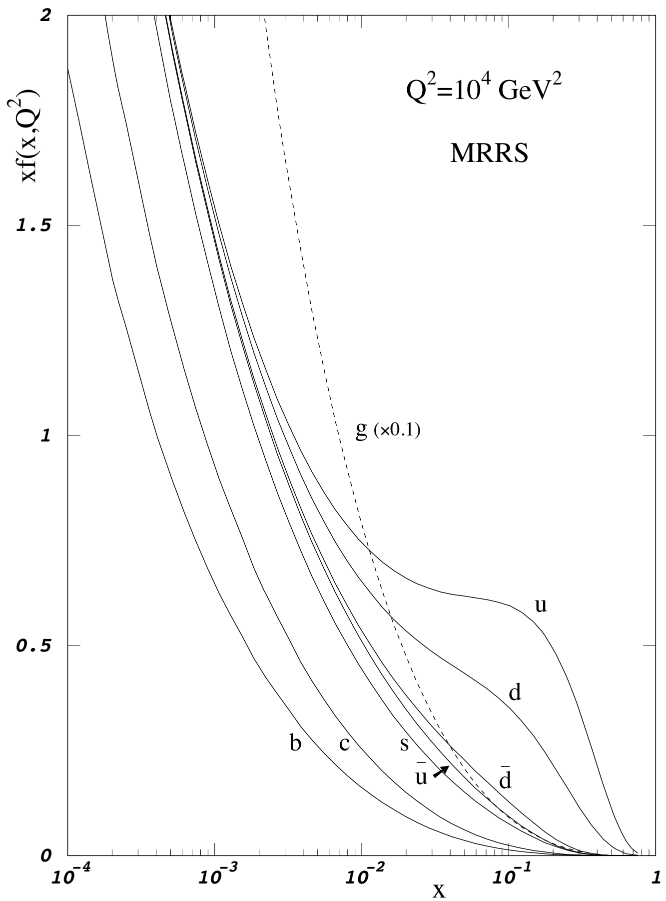
$$M^2 = s\ x_1 \times x_2 \qquad\qquad Y = 1/2\ ln(x_1/x_2)$$

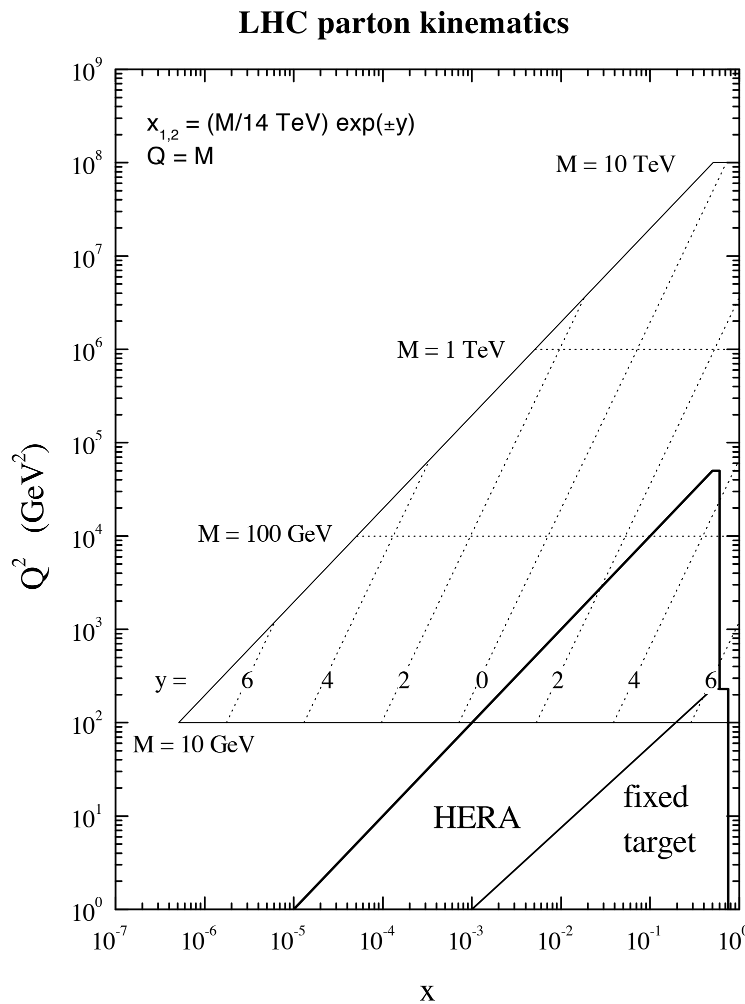


For more details see `http://arxiv.org/abs/hepex/9705004`

W and Z production: A LHC tool(!) to calibrate experiment and theory! (V)

Measure differential W and Z cross sections as a function of rapidity!





W and Z production: A LHC tool(!) to calibrate experiment and theory! (VI)

Precision measurements of PDF's and quarks and gluons, a lot remains to be done, we need you!

- Minimize uncertainties with ratio measurements e.g. $\sigma(pp \to WW)/\sigma(pp \to Z)$.
- Find the best signatures to constrain the different quarks and the gluon parton luminosities.
- Include the parton luminosity measurements into the PDF fits.
- With better known SM backgrounds $\to$ improve search sensitivity for new phenomena at the LHC!