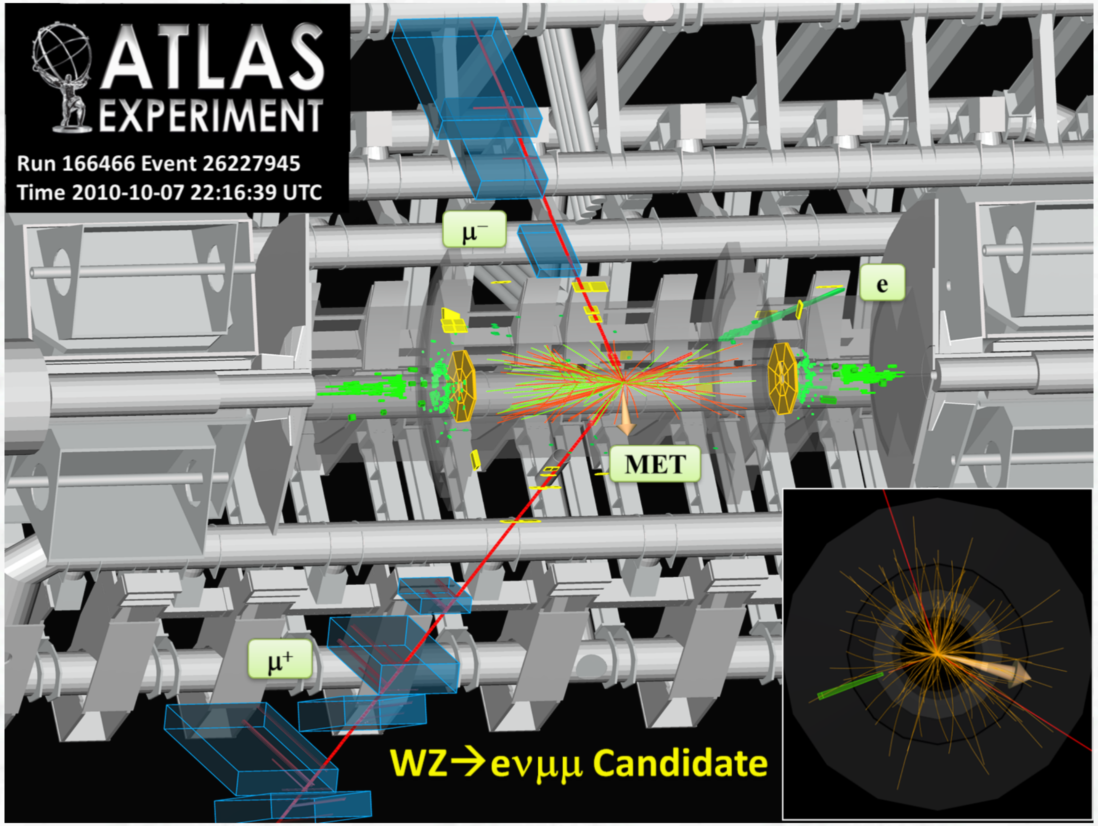
Physics at the LHC

- From the Standard Model to Searches for New Physics-



Karl Jakobs
Physikalisches Institut
Universität Freiburg

Outline of the lectures

1. Introduction
   (LHC, detector performance)

2. Test of perturbative QCD
   (Jet production, W/Z production, tt production)

3. Electroweak parameters
   (m_W, m_t, gauge couplings, ..)

4. Summary of the search for the Higgs Boson (short → C. Mariotti)

5. Search for Physics Beyond the Standard Model
   (Supersymmetry, a few other selected examples (short → M. Narain))

Disclaimer: I will try to highlight important physics measurements and results on searches for new physics. The coverage is not complete, i.e. not all results available are presented; Results from both general purpose experiments, ATLAS and CMS, plus a few from LHCb, are shown, but there might still be a bias towards the experiment I am working on. This bias is not linked to the scientific quality of the results.

The role of the LHC

1. **Explore the TeV mass scale**

   - What is the origin of the electroweak symmetry breaking ?
     Does the Higgs boson exist?

   - Search for physics Beyond the Standard Model
     (Low energy supersymmetry, other scenarios…,)

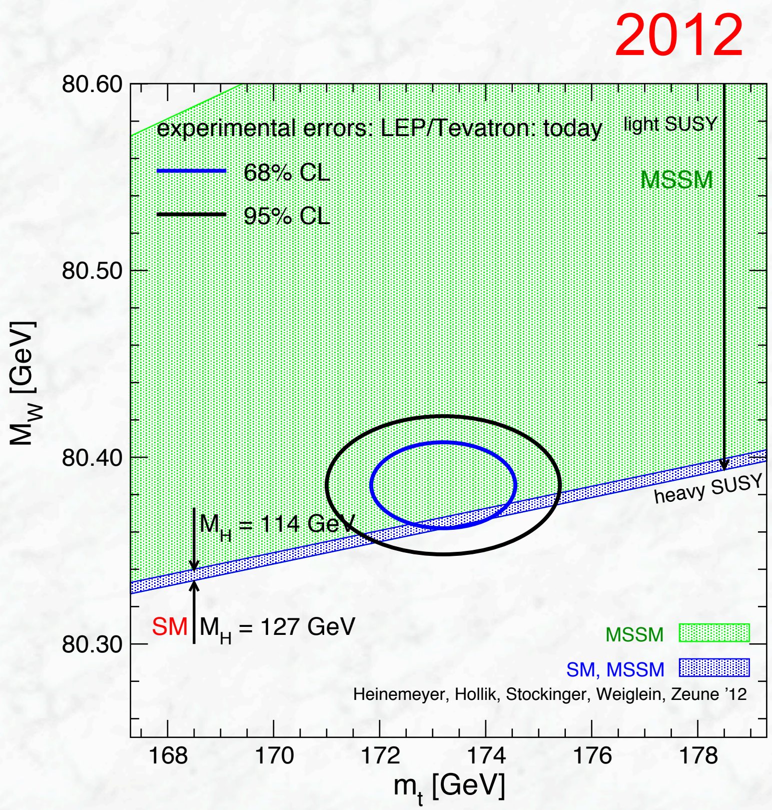
   Look for the "expected", but we need to be open for surprises
   → perform as many searches (inclusive, exclusive…) for as many final states as possible

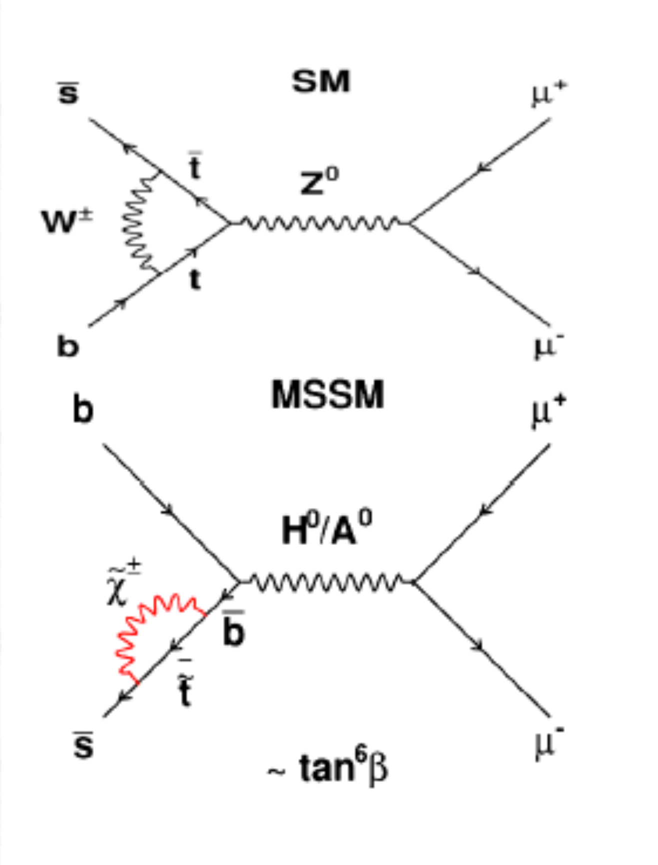
2. **Precise tests of the Standard Model**

   - There is much sensitivity to physics beyond the Standard Model in the precision area (loop-induced effects, probe energy scales far beyond direct reach)
     → precise measurements, search for rare processes

   → Guidance to theory and Future Experiments

Two important examples:





Ultimate test of the Standard Model:

Compare indirect prediction of the Higgs boson mass with direct observation

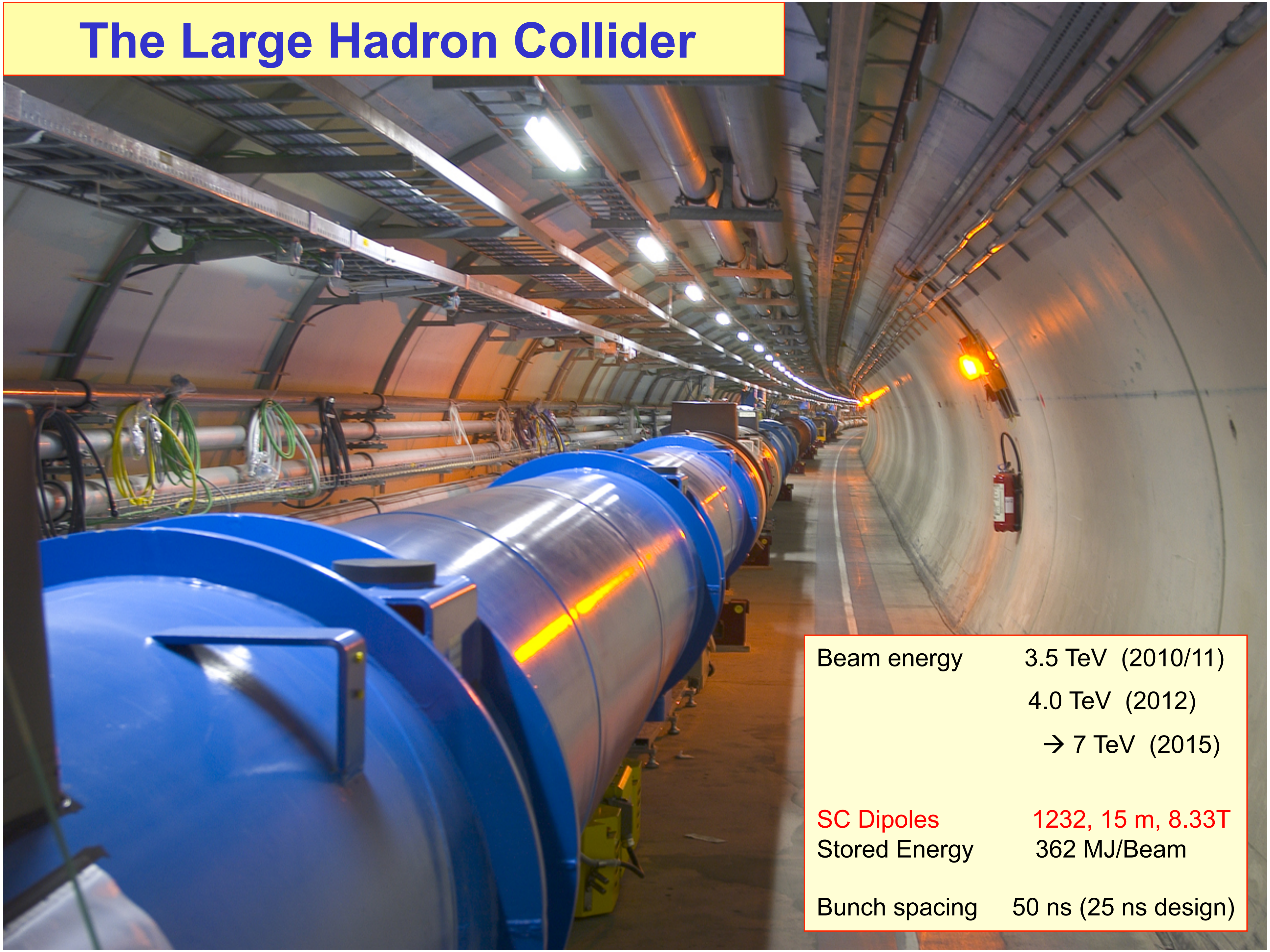
Many theoretical models for physics Beyond the Standard Model

The LHC
- a new era in particle physics-

Steve Meyers at "Phyics at LHC 2012":

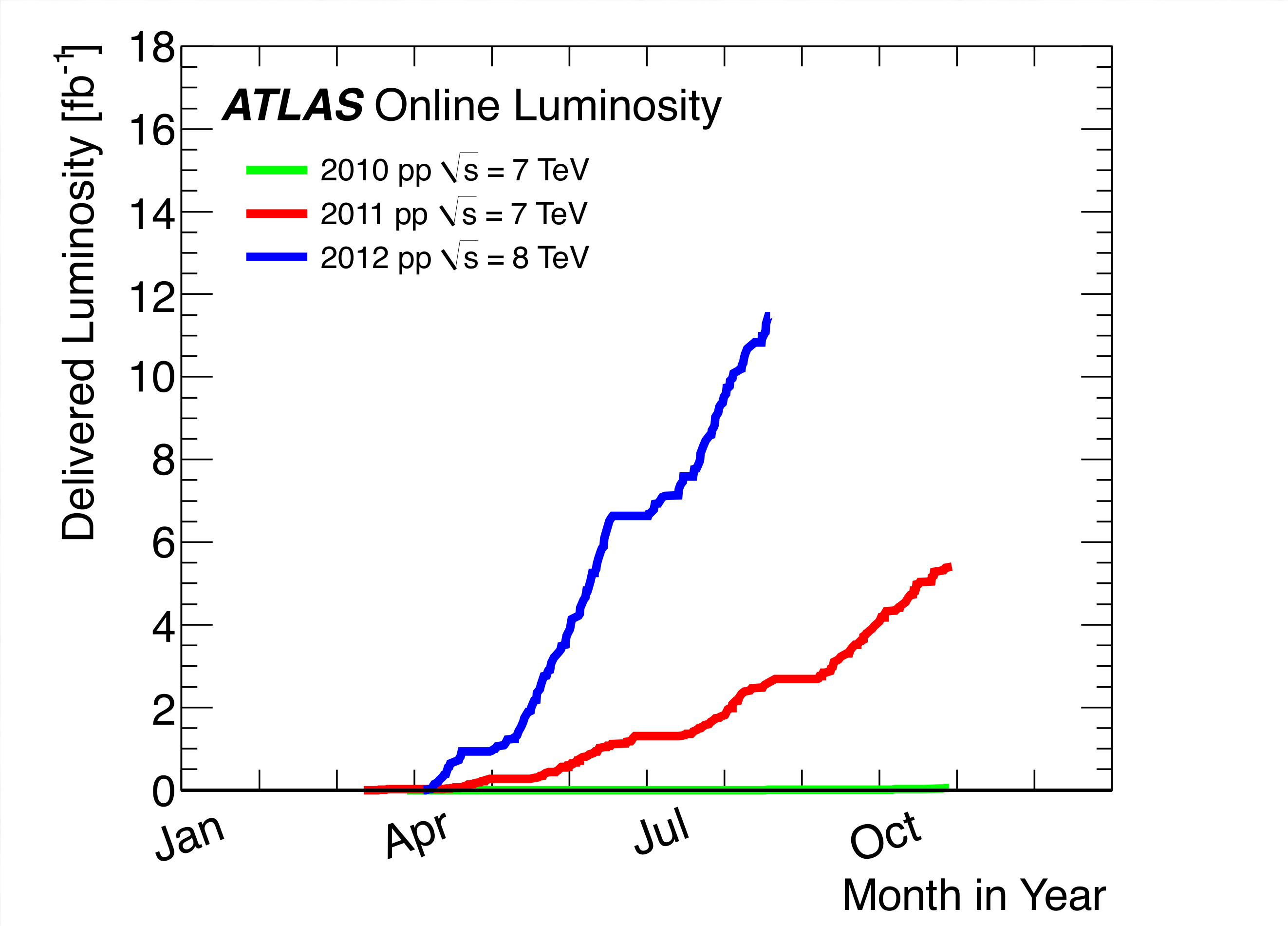
"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."

The Large Hadron Collider



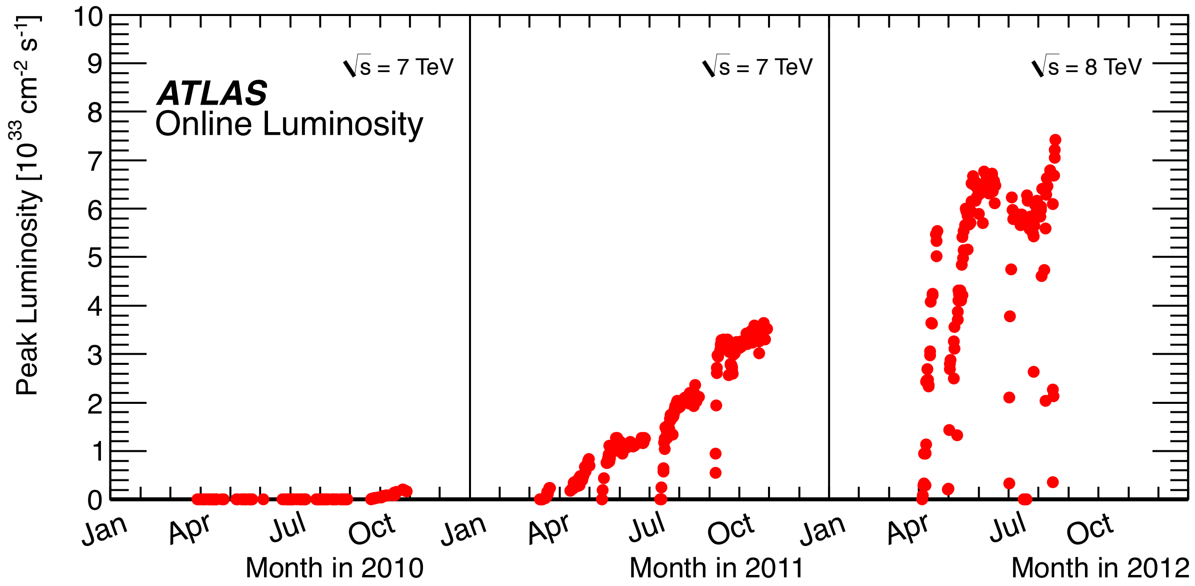
Beam energy	3.5 TeV (2010/11)
	4.0 TeV (2012)
	→ 7 TeV (2015)
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	50 ns (25 ns design)

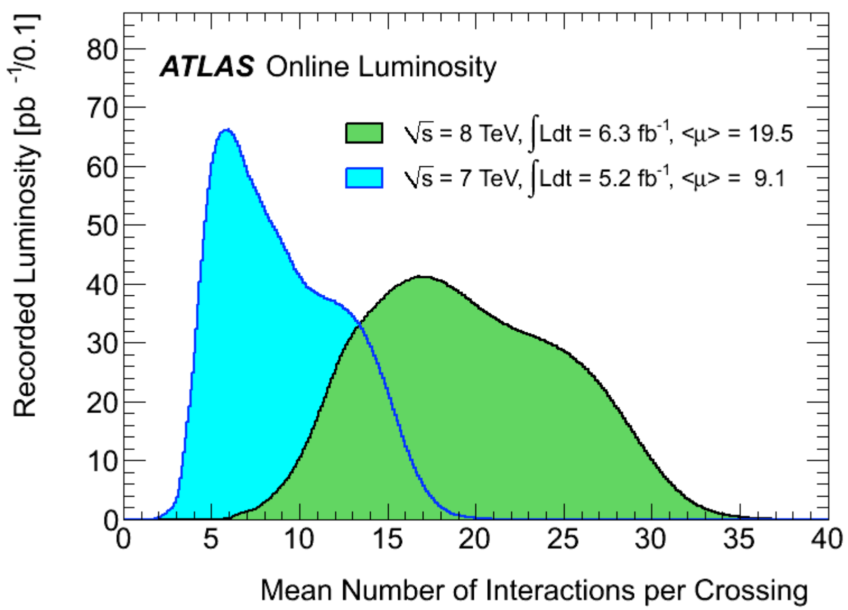
The LHC integrated luminosity



Very rapid rise in luminosity + good machine stability
→ high integrated luminosities

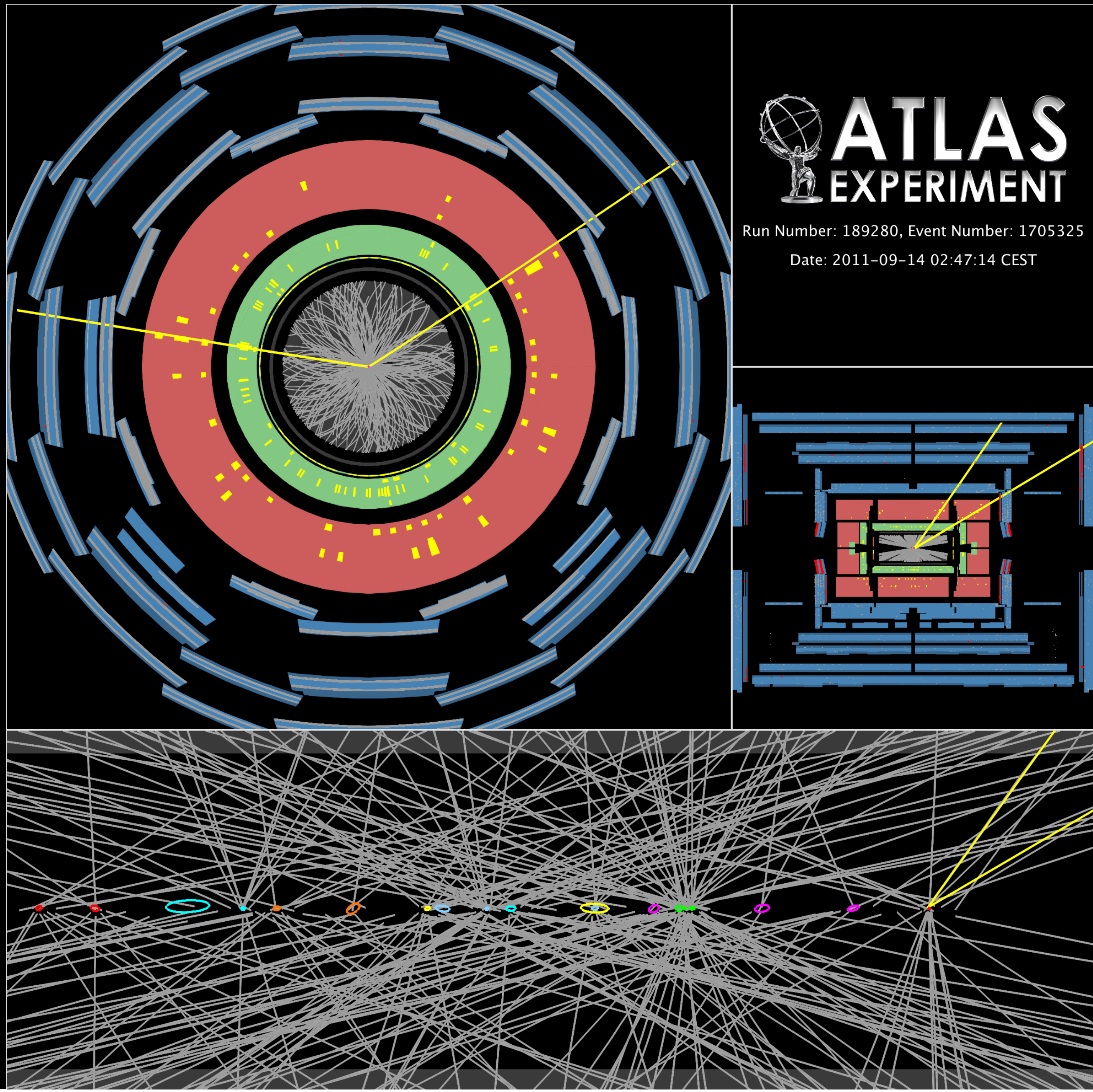
The LHC instantaneous luminosity





- World record on instantaneous luminosity on 22. April 2011: $4.67\ 10^{32}\ cm^{-2}\ s^{-1}$ (Tevatron record: $4.02\ 10^{32}\ cm^{-2}\ s^{-1}$)
- 2011: collect per day as much integrated luminosity as in 2010
- 2012: now regularly above $6\ 10^{33}\ cm^{-2}s^{-1}$

$Z \rightarrow \mu^+ \mu^-$ with 20 superimposed events



An event with 20 reconstructed vertices

(error ellipses are scaled up by a factor of 20 for visibility reasons)

Completion of an era: Tevatron

Accelerator Innovations

- First major SC synchrotron
- Industrial production of SC cable (MRI)
- Electron cooling
- New RF manipulation techniques

But Tevatron is still in the game:

- W mass
- H → bb
- B physics
- …

and developing

- GRID pioneers

ajor iscoveries

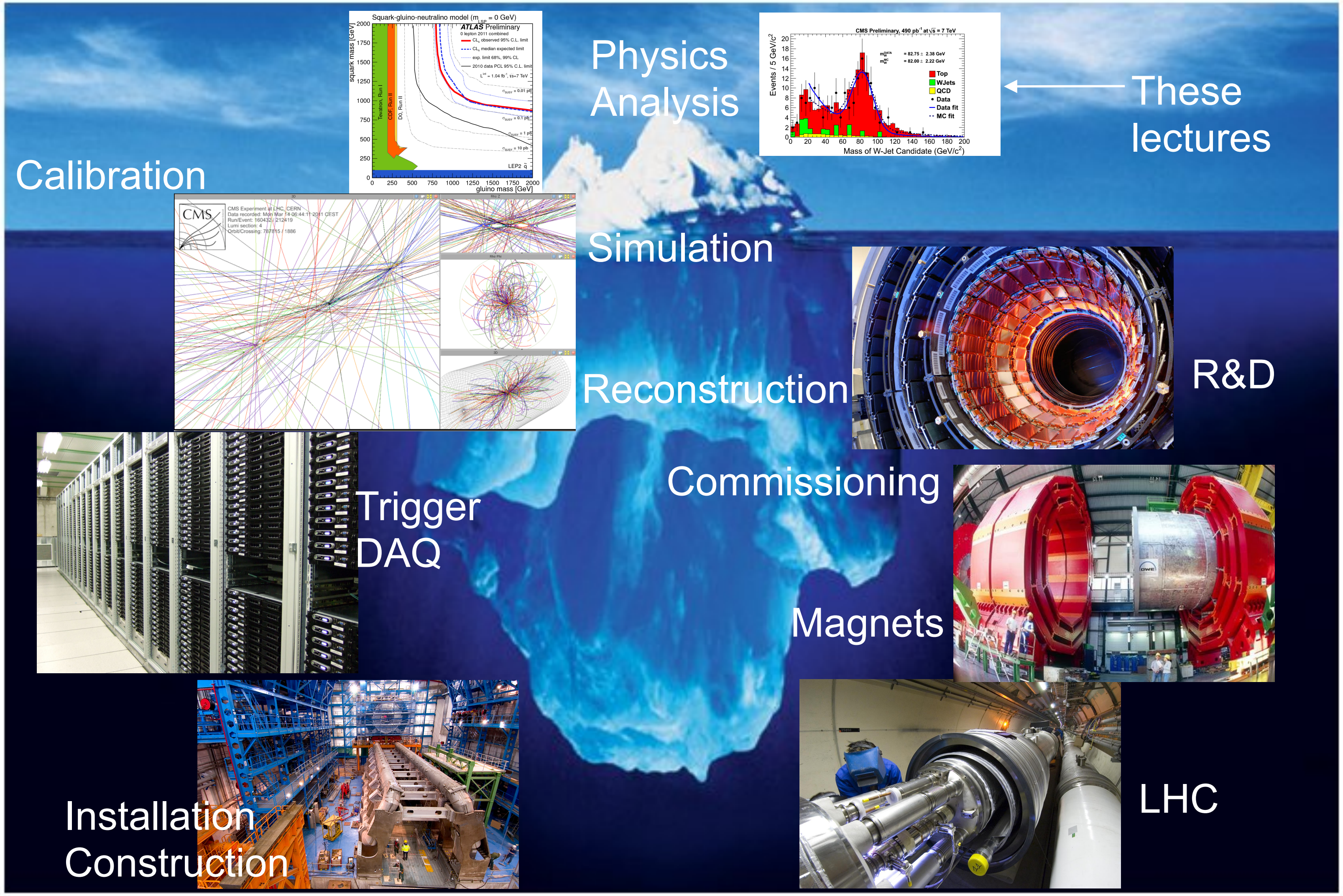
- Top quark
- B_s mixing
- Precision W and Top mass → Higgs mass prediction
- Direct Higgs searches
- Ruled out many exotica

The next generation

- Fantastic training ground for next generation
- More than 500 Ph.D.s
- Produced critical personnel for the next steps, especially LHC

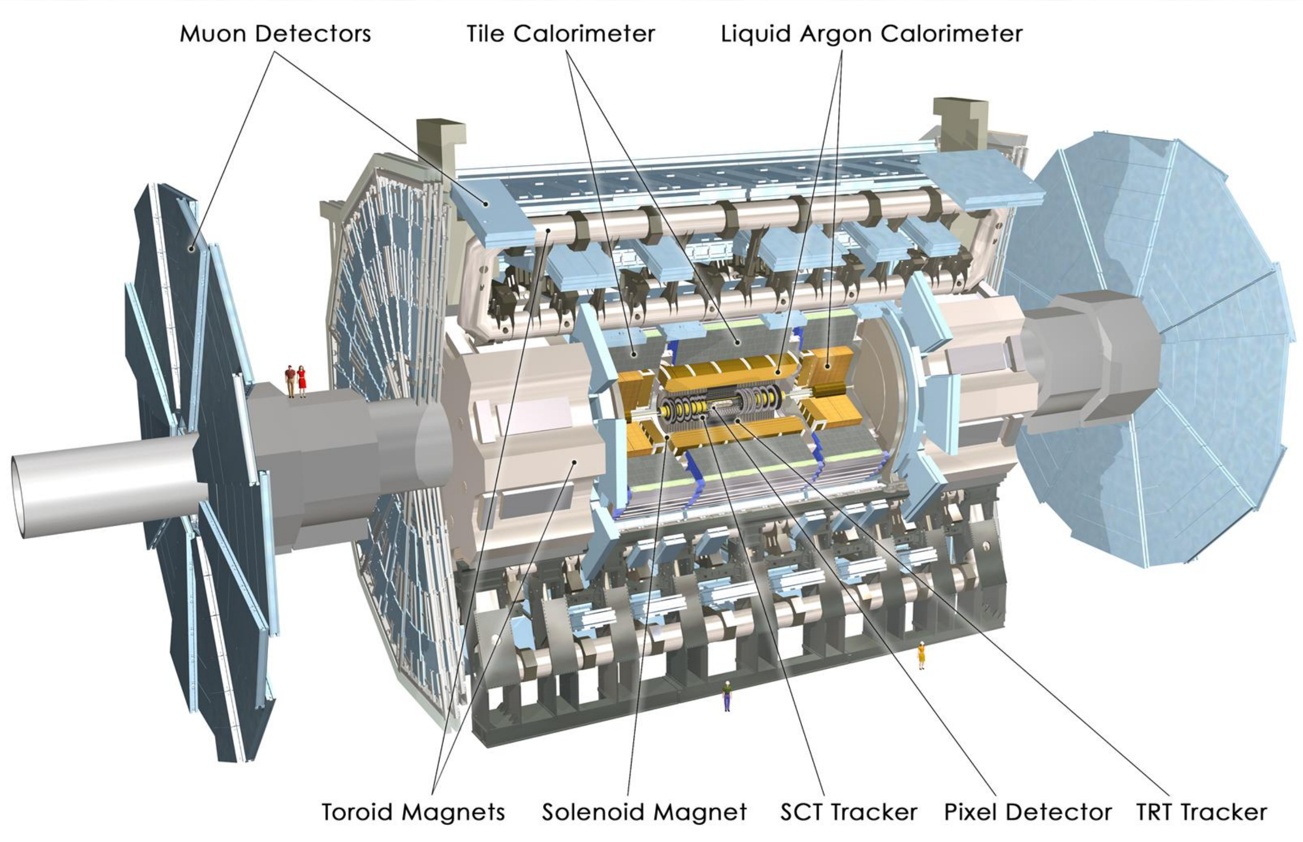
CMS
LHCb
ALICE
ATLAS

After a huge effort from many people over a long time, we arrived at physics analysis



H. Bachacou

The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)

  High resolution silicon detectors:
  - 6 Mio. channels (80 µm x 12 cm)
  - 100 Mio. channels (50 µm x 400 µm)

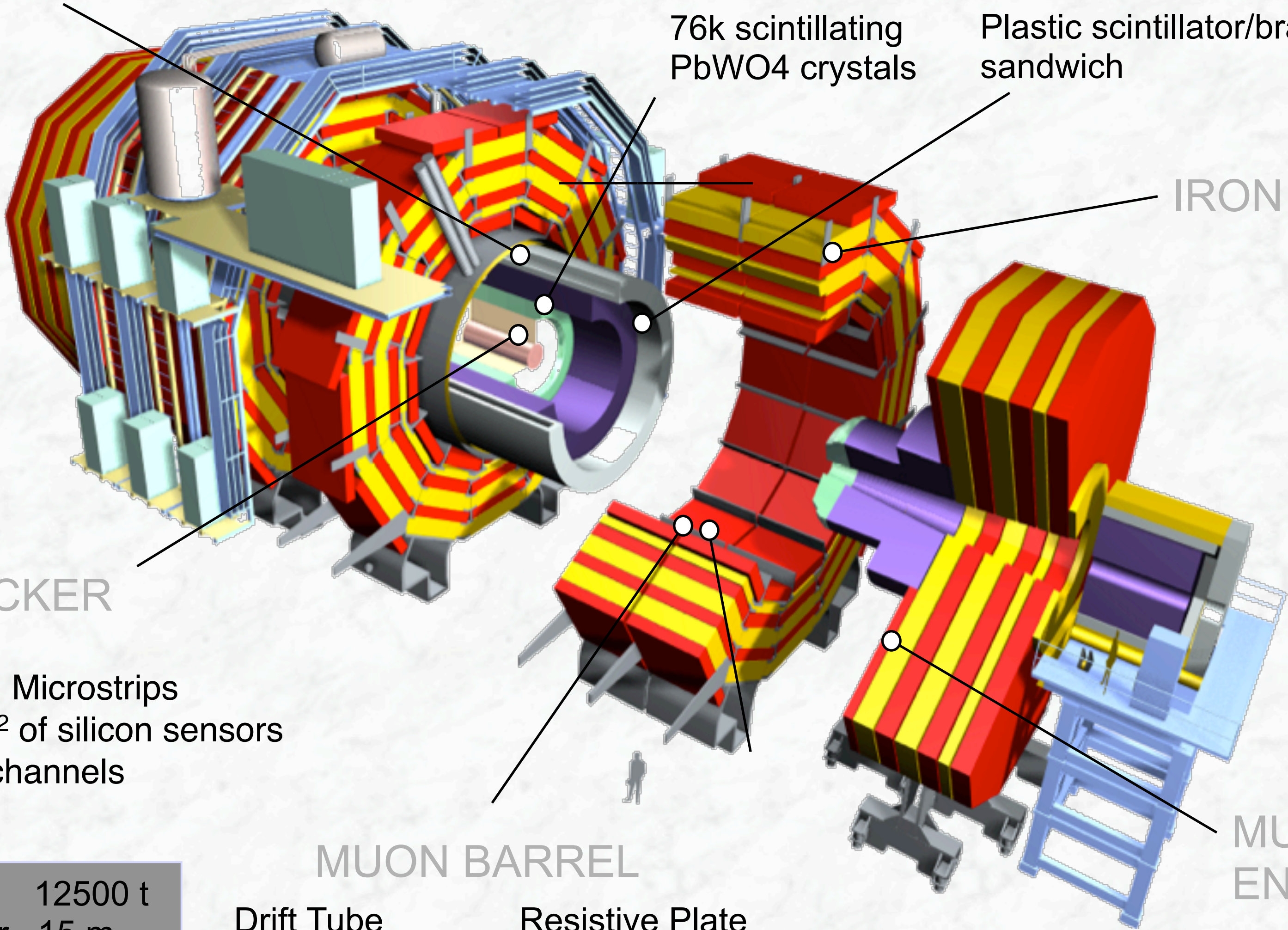
  space resolution: ~ 15 µm

- Energy measurement down to 1° to the beam line

- Independent muon spectrometer (supercond. toroid system)

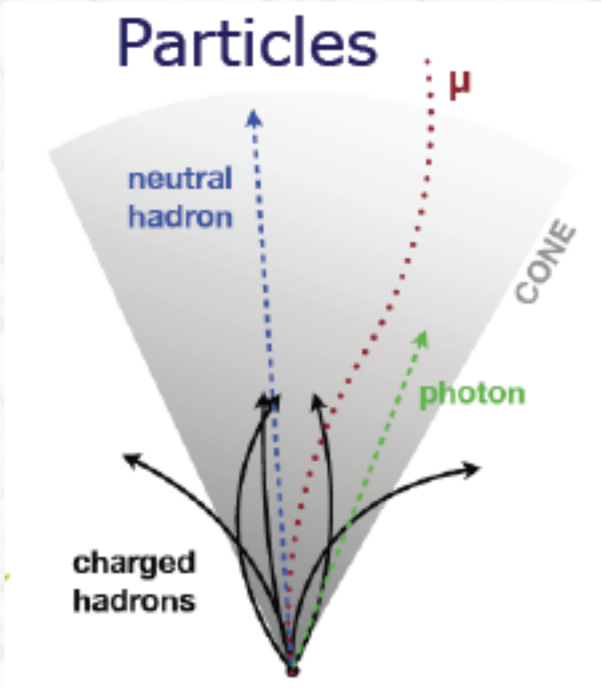
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

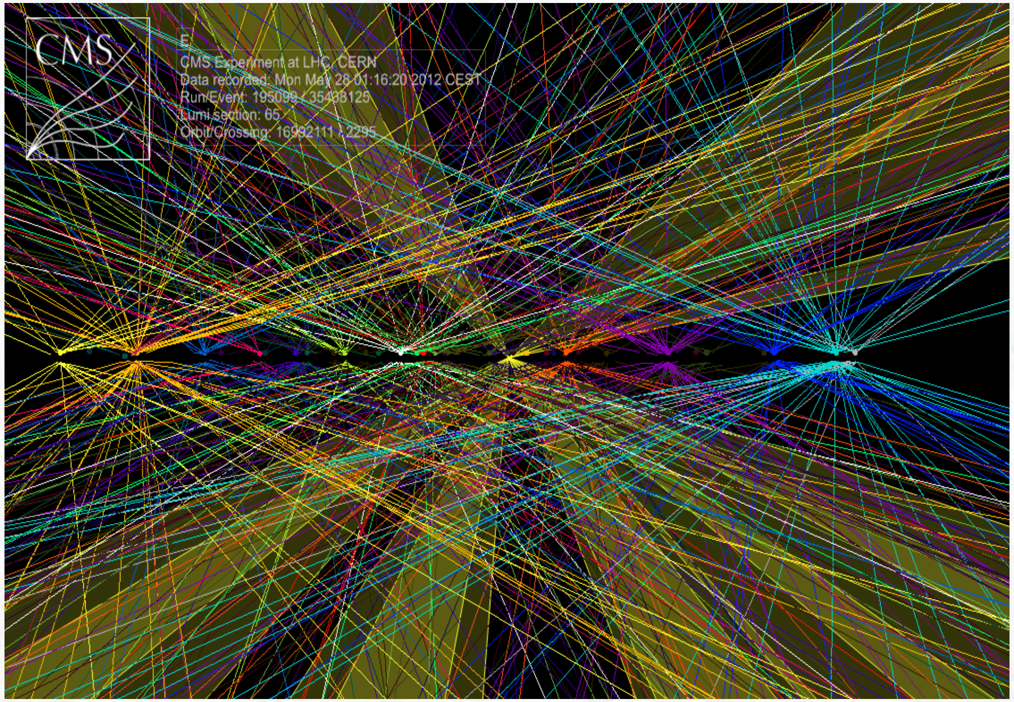
CMS



Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

1.2 Detector Performance





Some bonus slides on

"Important kinematic variables

in pp collisions"

(i) Rapidity y

Usually the beam direction is defined as the z axis (Transverse plane: x-y plane).

The rapidity y is defined as:

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

Under a Lorentz boost in the z-direction to a frame with velocity β

the rapidity y transforms as: $$y \rightarrow y - \tanh^{-1}\beta$$

Hence the shape of the rapidity distribution dN/dy is invariant, as are differences in rapidity.

(ii) Pseudorapidity η

Rapidity: $$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

For $p \gg m$, the rapidity may be expanded to obtain

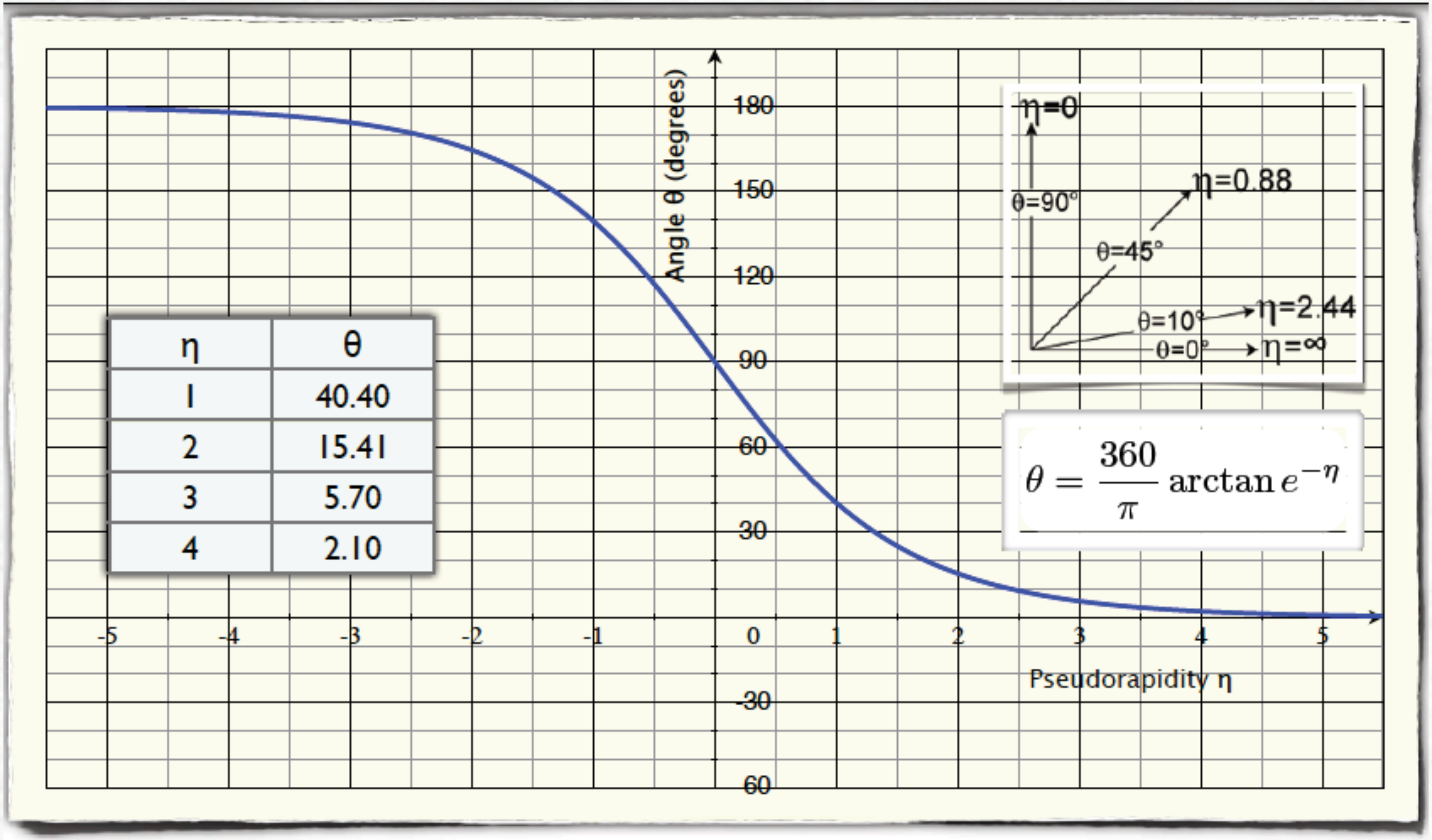
$$y = \frac{1}{2}\ln\frac{\cos^2(\theta/2) + m^2/4p^2 + \ldots}{\sin^2(\theta/2) + m^2/4p^2 + \ldots}$$

$$\approx -\ln\tan(\theta/2) \equiv \eta$$

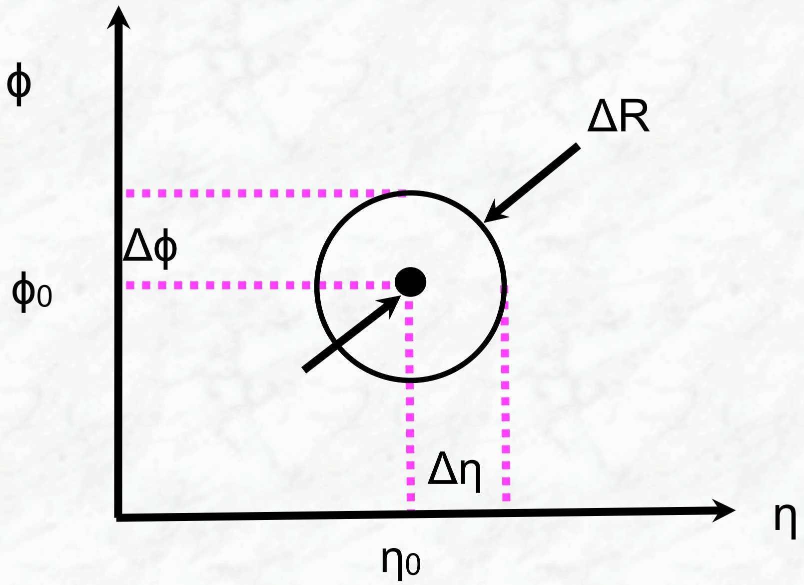
where $\cos\theta = p_z/p$.

Identities: $\sinh\eta = \cot\theta$, $\cosh\eta = 1/\sin\theta$, $\tanh\eta = \cos\theta$

Relation between pseudorapidity η and polar angle θ



(iii) Distance in η − ϕ space:



Rapidity y: $y = 1/2\ln[(E+p_z)/(E-p_z)]$

Pseudorapidity η: $\eta = -\ln\tan(\theta/2)$

Distance in η-ϕ: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

(iv) Transverse Energy

At hadron colliders, a significant and unknown proportion of the energy of the incoming hadrons in each event escapes down the beam-pipe. Consequently if invisible particles are created in the final state, their net momentum can only be constrained in the plane transverse to the beam direction . Defining the z-axis as the beam direction, this net momentum is equal to the missing transverse energy vector

missing transverse energy

$$\boldsymbol{E}_T^{\text{miss}} = -\sum_i \boldsymbol{p}_T(i)$$

where the sum runs over the transverse momenta of all visible final state particles.

(v) Transverse mass (invisible particles)

Consider a single heavy particle of mass M which decays to two particles, of which one (labelled particle 1) is invisible. The mass of the parent particle can be constrained with the quantity M_T defined by

$$M_T^2 \equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2$$
$$= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)]$$

Transverse mass

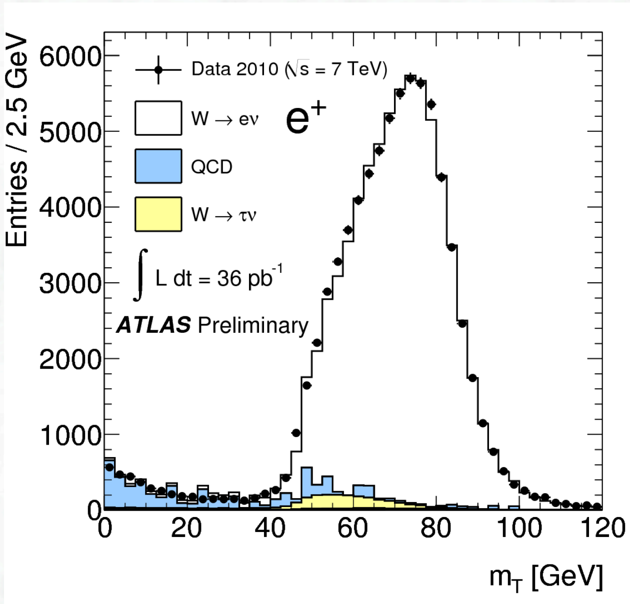
where $p_T(1) = - P_T^{\ miss}$

This quantity is called the transverse mass. Its distribution possesses an endpoint at $M_T^{max} = M$.

For $m_1 = m_2 = 0$ →

$$M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$$

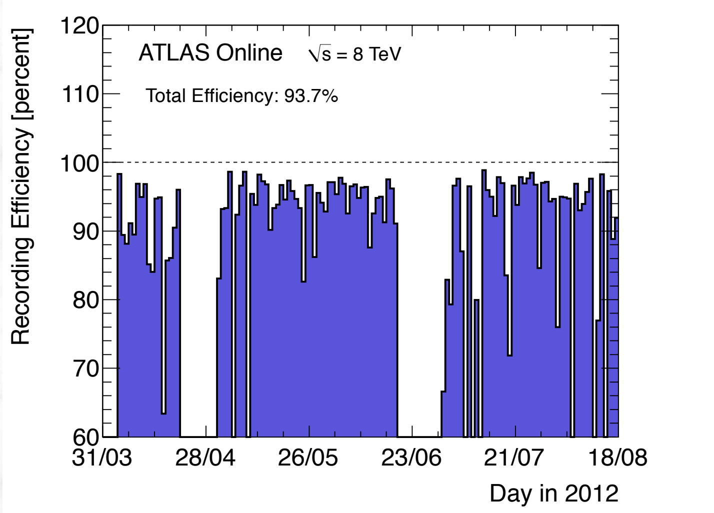
where ϕ_{ij} is defined as the angle between particles i and j in the transverse plane.



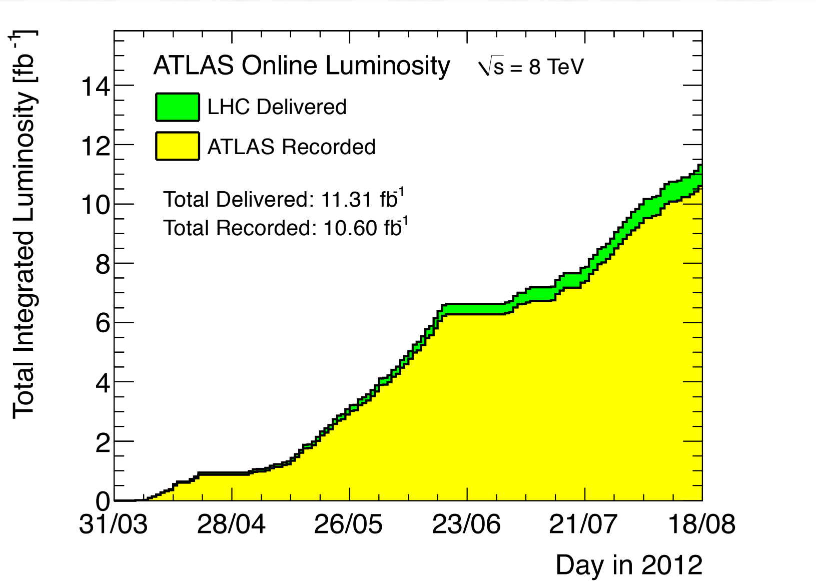
$$m_T = \sqrt{2P_T(e)E_T^{miss}(1 - \cos\Delta\phi)}$$

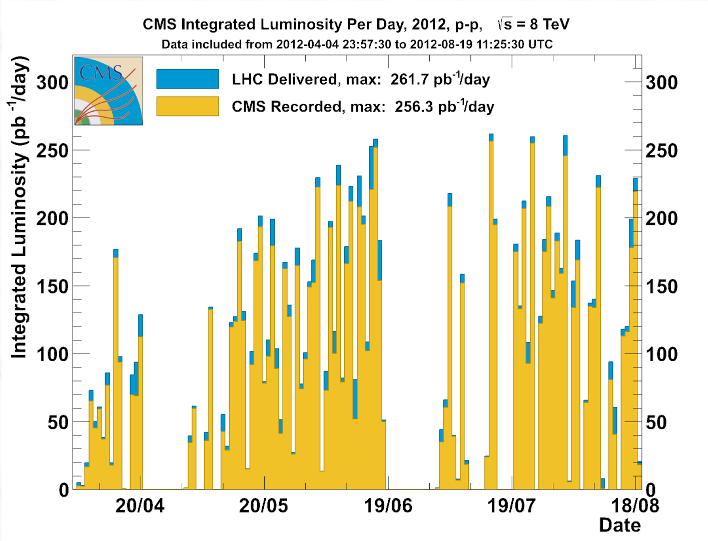
Detector performance is impressive:

- Very high number of working channels (> 99% for many sub-systems) in all experiments;
- Data taking efficiency is high (> 94%)
- Impressive reconstruction capabilities for physics objects (e, γ, μ, τ, jets, b-tagging, E_T^{miss})

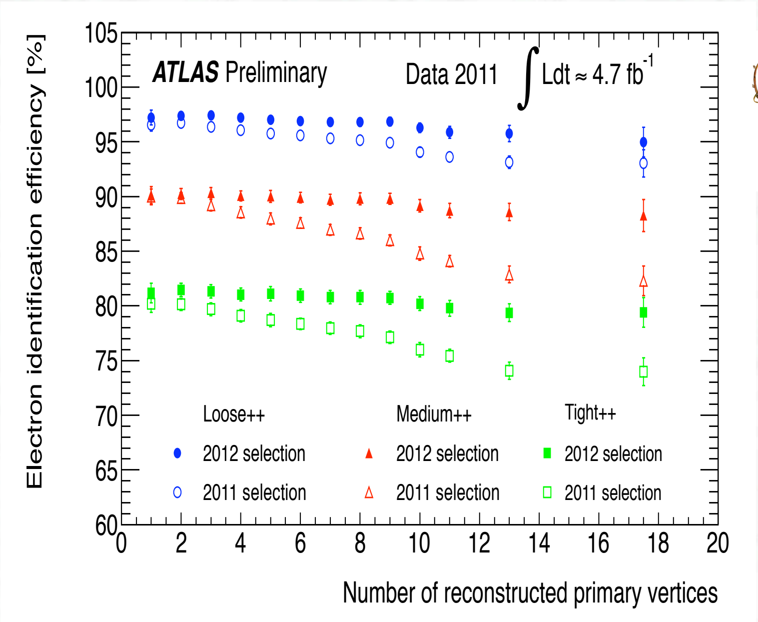


Have been optimized to cope with the ever increasing number of pile-up interactions

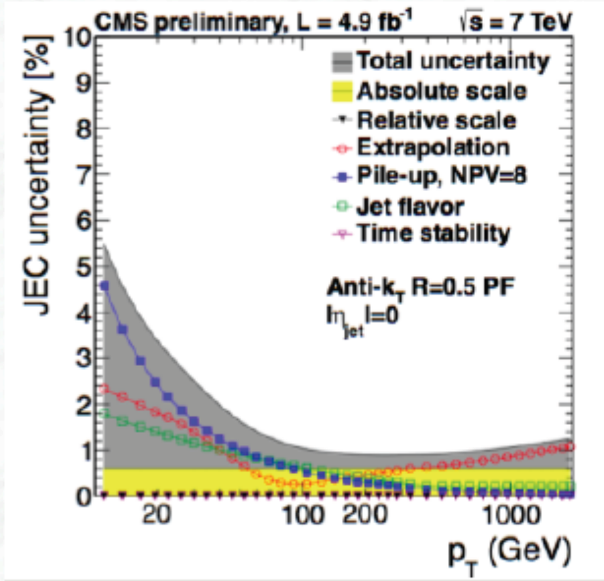




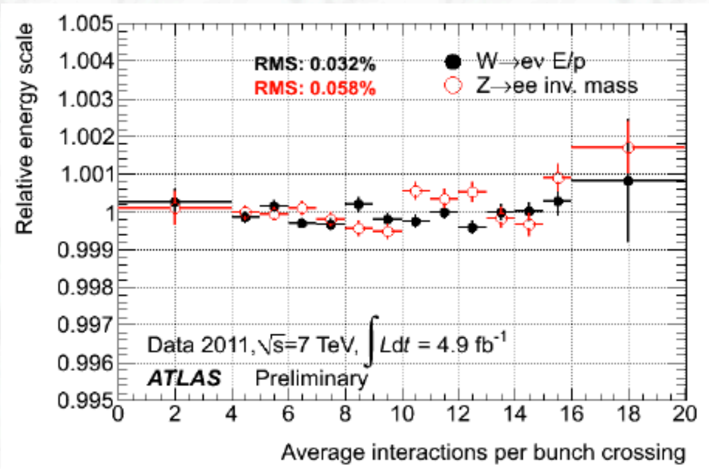
Some performance figures from 2011 data:

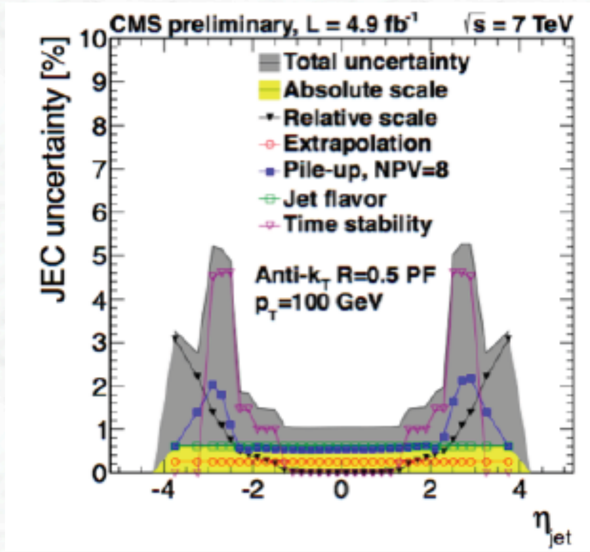


Electron ID efficiency in ATLAS



Jet energy scale, E-flow in CMS





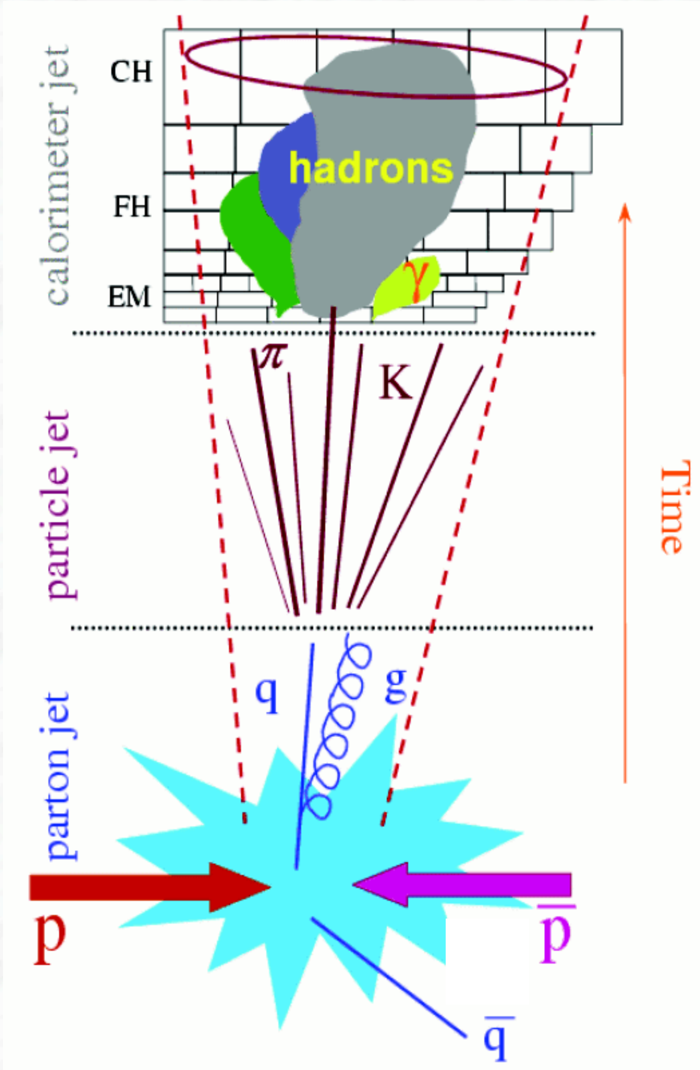
Jet reconstruction and energy measurement

- A jet is NOT a well defined object
  (fragmentation, gluon radiation, detector response)

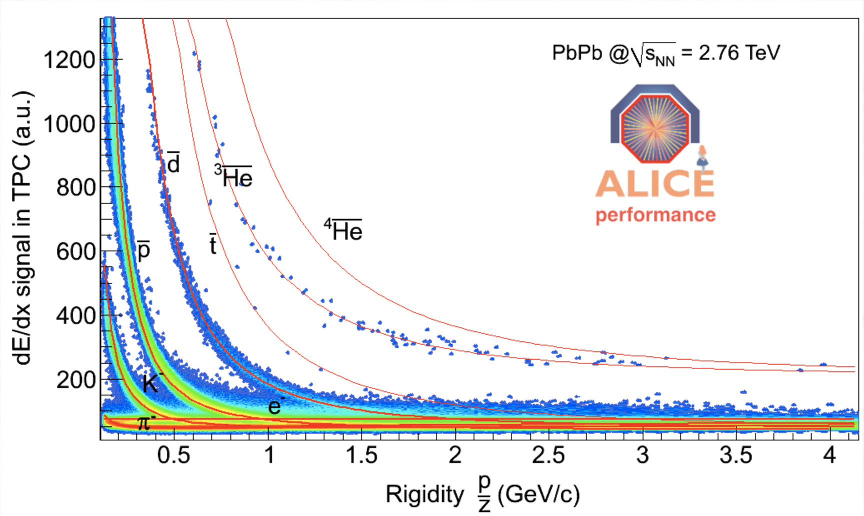
- The detector response is different for particles interacting electromagnetically (e,γ) and for hadrons
  → for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level“ (particle jet)
  Common ground between theory and experiment

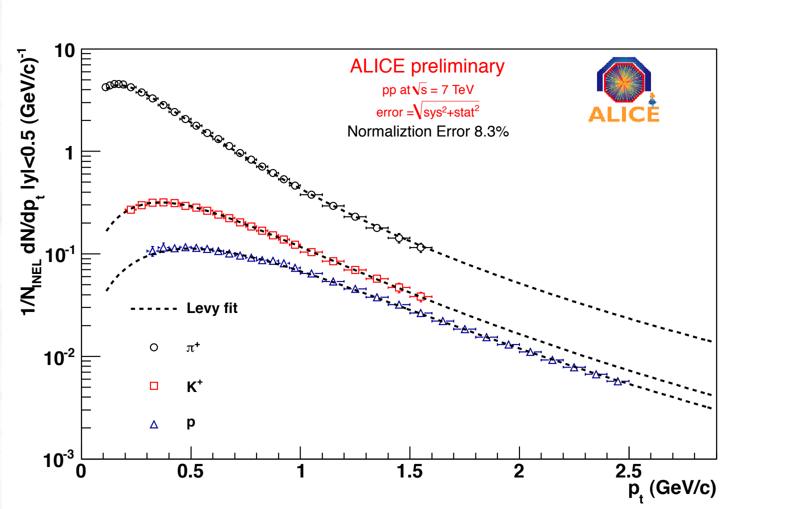
- One needs an algorithm to define a jet and to measure its energy
  conflicting requirements between experiment and theory (exp. simple, e.g. cone algorithm, vs. theoretically sound (no infrared divergencies))

- Energy corrections for losses of fragmentation products outside jet definition and underlying event or pileup energy inside

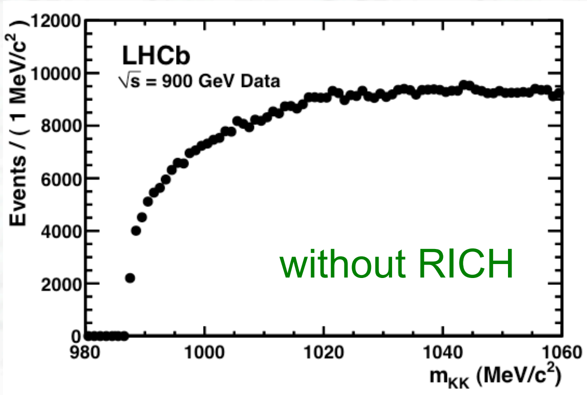


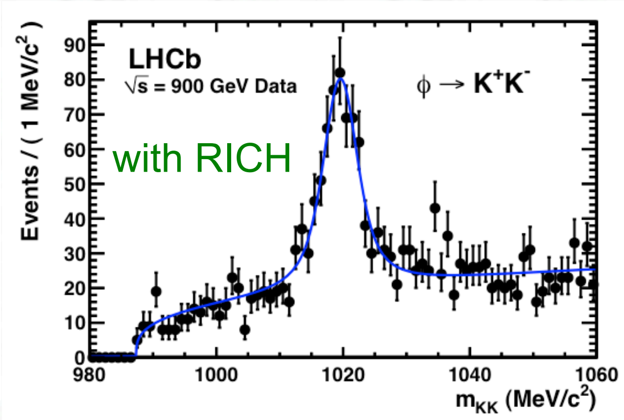
Particle Identification in ALICE and LHCb:

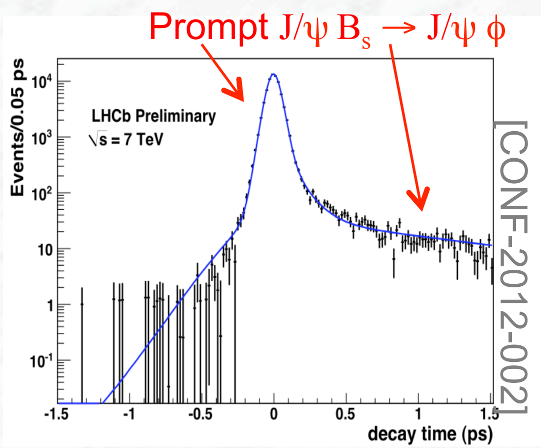




LHCb: Search for $\phi \rightarrow K^+K^-$

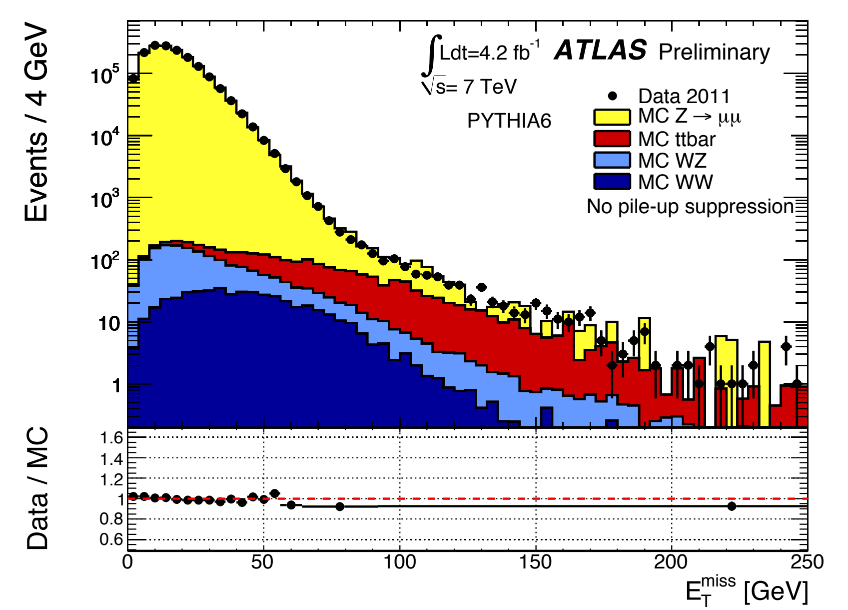


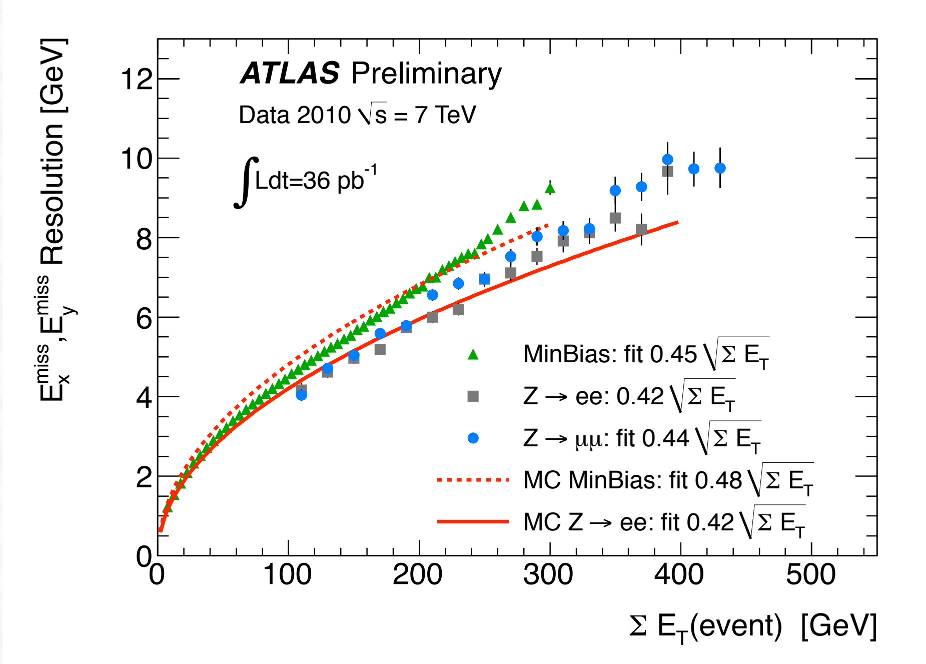




Proper time resolution: 45 fs

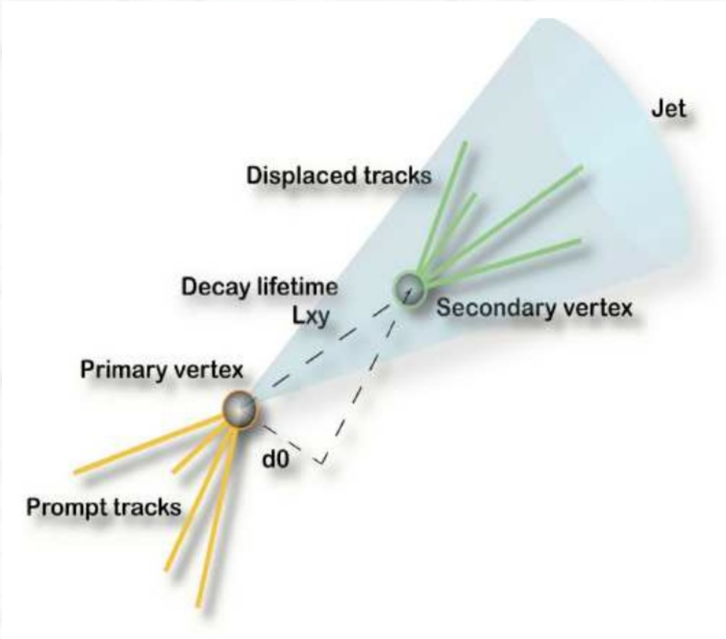
Measurement of the missing transverse energy E_T^{miss}





Resolution of E_x^{miss} and E_y^{miss} as a function of the total transverse energy in the event calculated by summing the p_T of muons and the total calorimeter energy. The resolution in Z→ee and Z→μμ events is compared with the resolution in minimum bias for data taken at √s = 7 TeV. The fit to the resolution in Monte Carlo minimum bias and Z→ee events are superposed.

How well can b-quarks be tagged ?



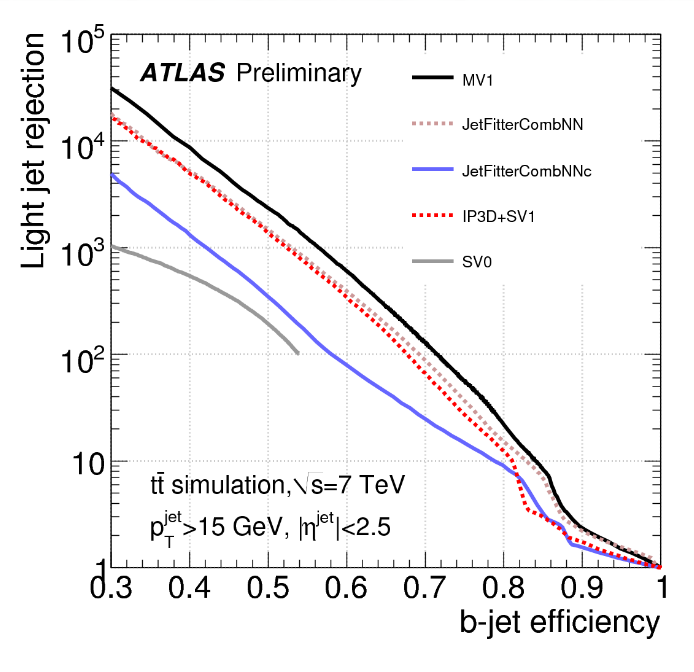
- b quarks fragment into B hadrons (mesons and baryons)
- B mesons have a lifetime of ~1.5 ps

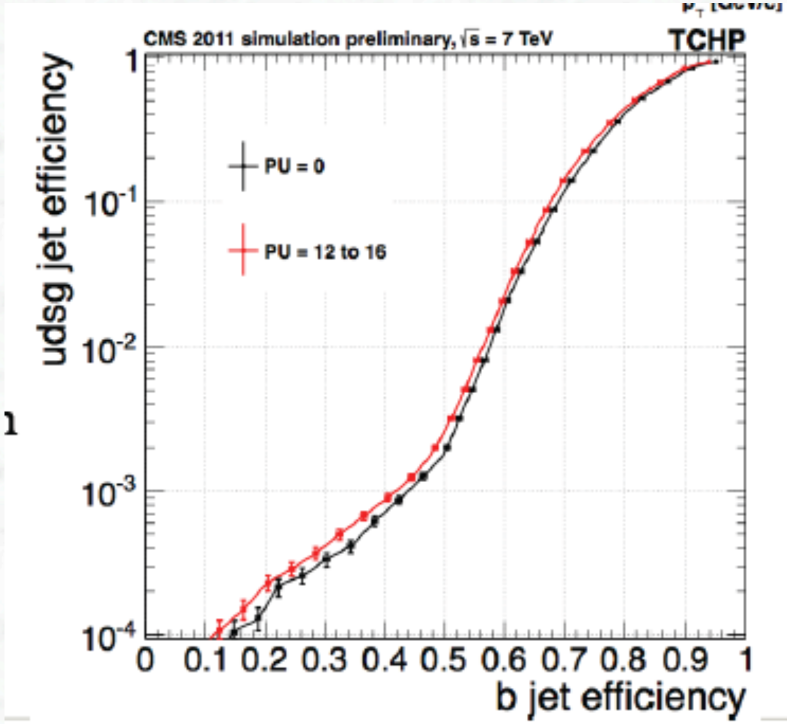
  They fly in the detector about 2-3 mm before they decay

  → reconstruction of a secondary vertex possible
  (requires high granularity silicon pixel and strip detectors close to the interaction point)

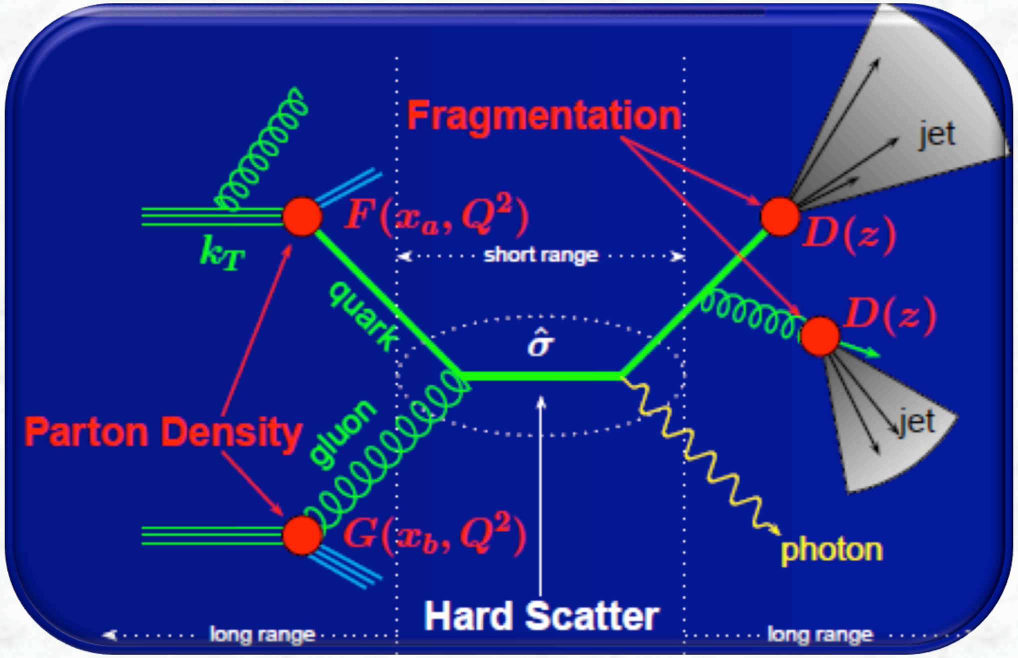
  → tracks from B meson decays have a large impact parameter w.r.t. the primary vertex

b-tagging performances in ATLAS and CMS:
extremely important for many physics analyses (Higgs, SUSY, SM, ….)



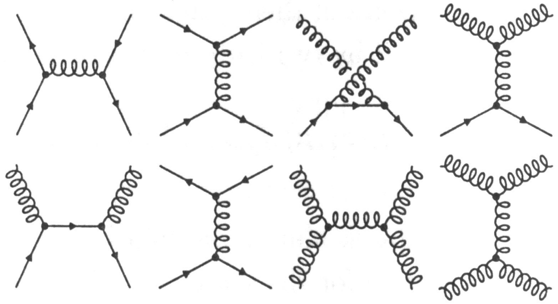


1.3 Scattering processes at a hadron collider

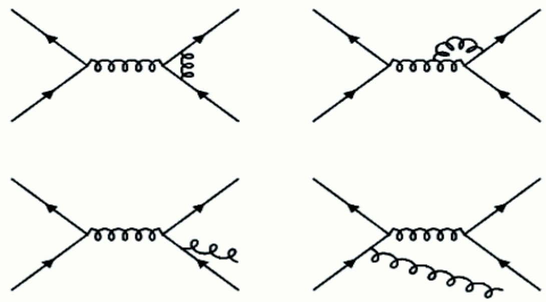


Dominant hard scattering processes: qq, qg and gg “scattering”

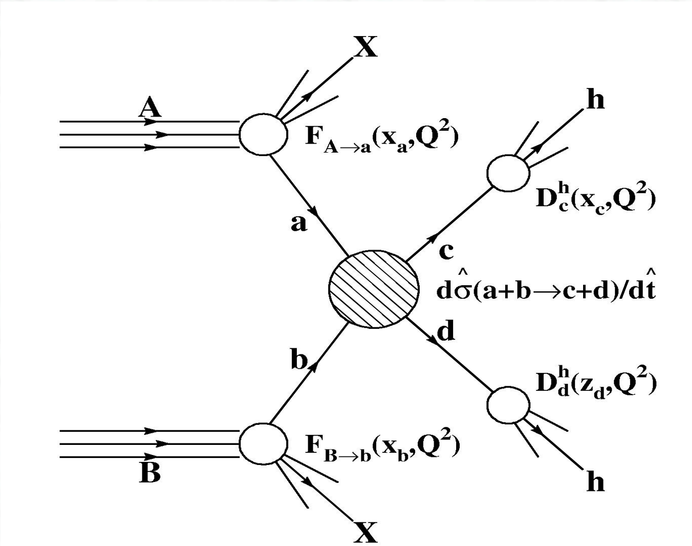
Leading order



…some NLO contributions



Calculation of cross sections



$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b, \alpha_s)$$

Sum over initial partonic states a,b

$\hat{\sigma}_{ab}$ ≡ hard scattering cross section

$f_i(x, Q^2)$ ≡ parton density function

… + higher order QCD corrections (perturbation theory)
meanwhile available for many signal and background processes !
Huge theoretical effort

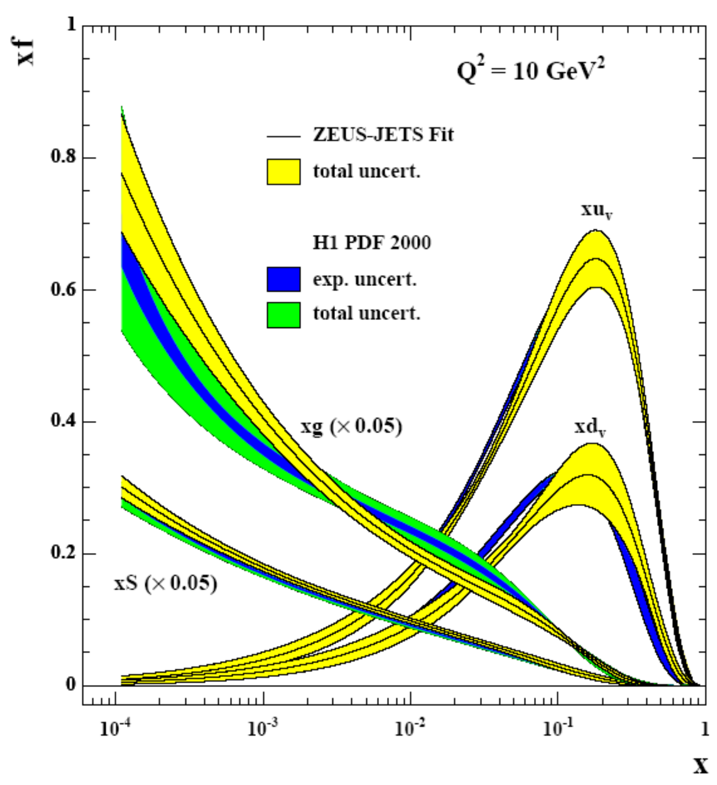
which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

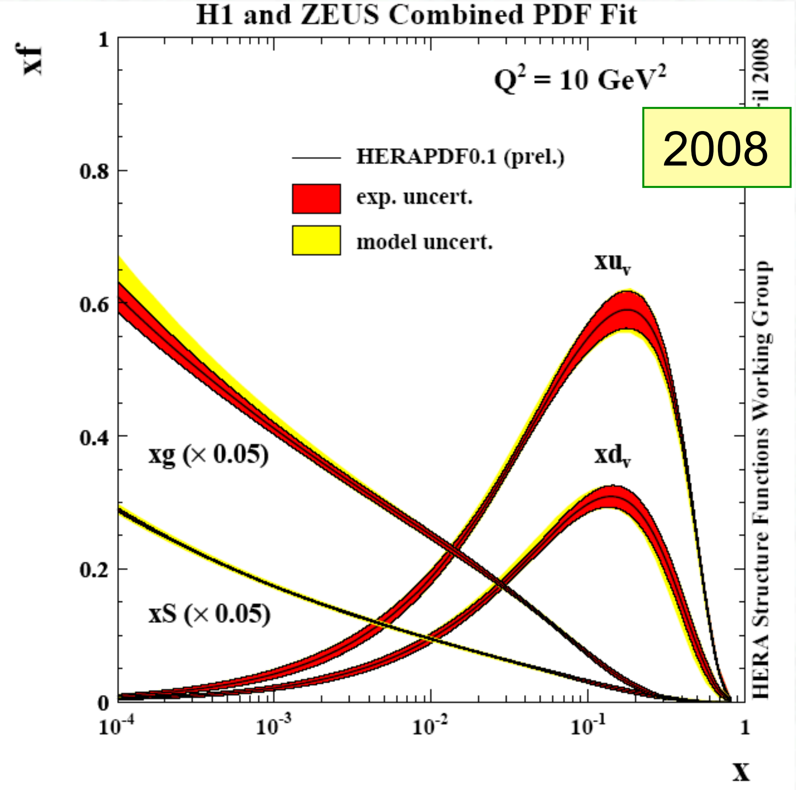
usually introduced as K-factors: $K_{[n]} = \sigma_{[n]} / \sigma_{[LO]}$

a few examples: Drell-Yan production of W/Z: $K_{NLO} \sim 1.2$
Higgs production via gg fusion: $K_{NLO} \sim 1.8$

Results from HERA on the proton structure

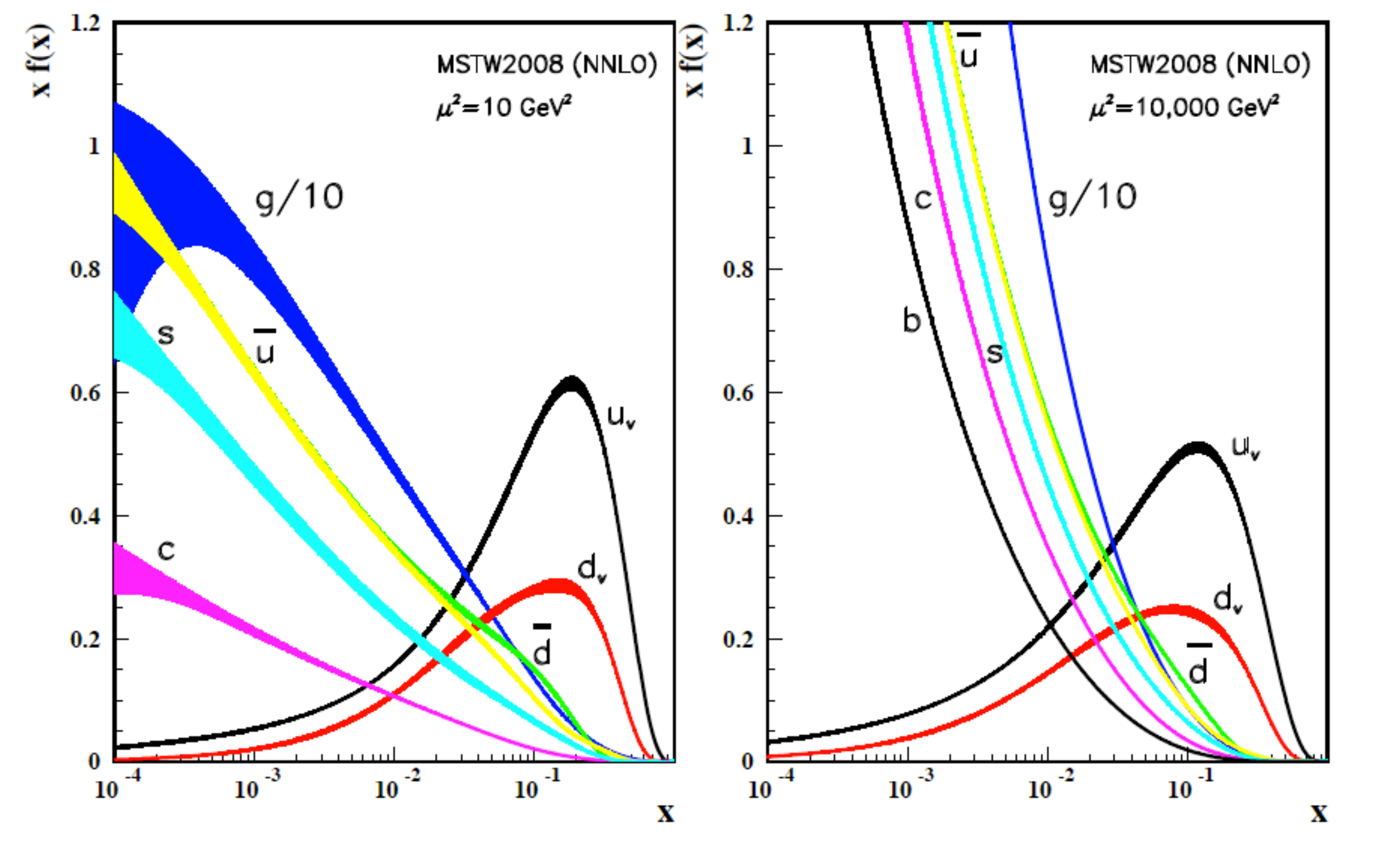
- Large data sets and combination of the two HERA experiments (H1 and ZEUS) improve the precision on the parton distribution functions



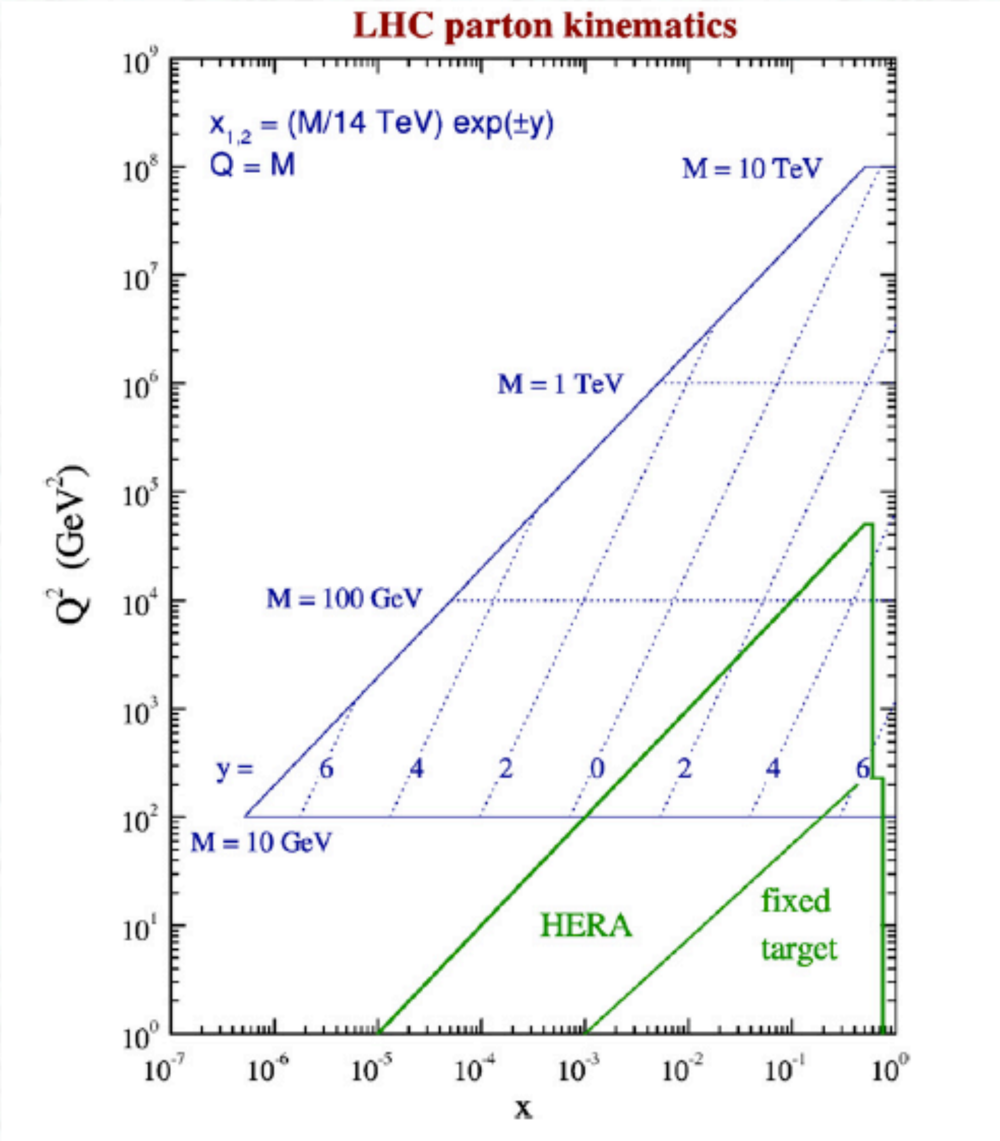


- Very important to reduce cross section uncertainties at hadron colliders; but still not good enough ….. (~ 10% errors for LHC cross sections)

Q^2 evolution following the DGLAP equation

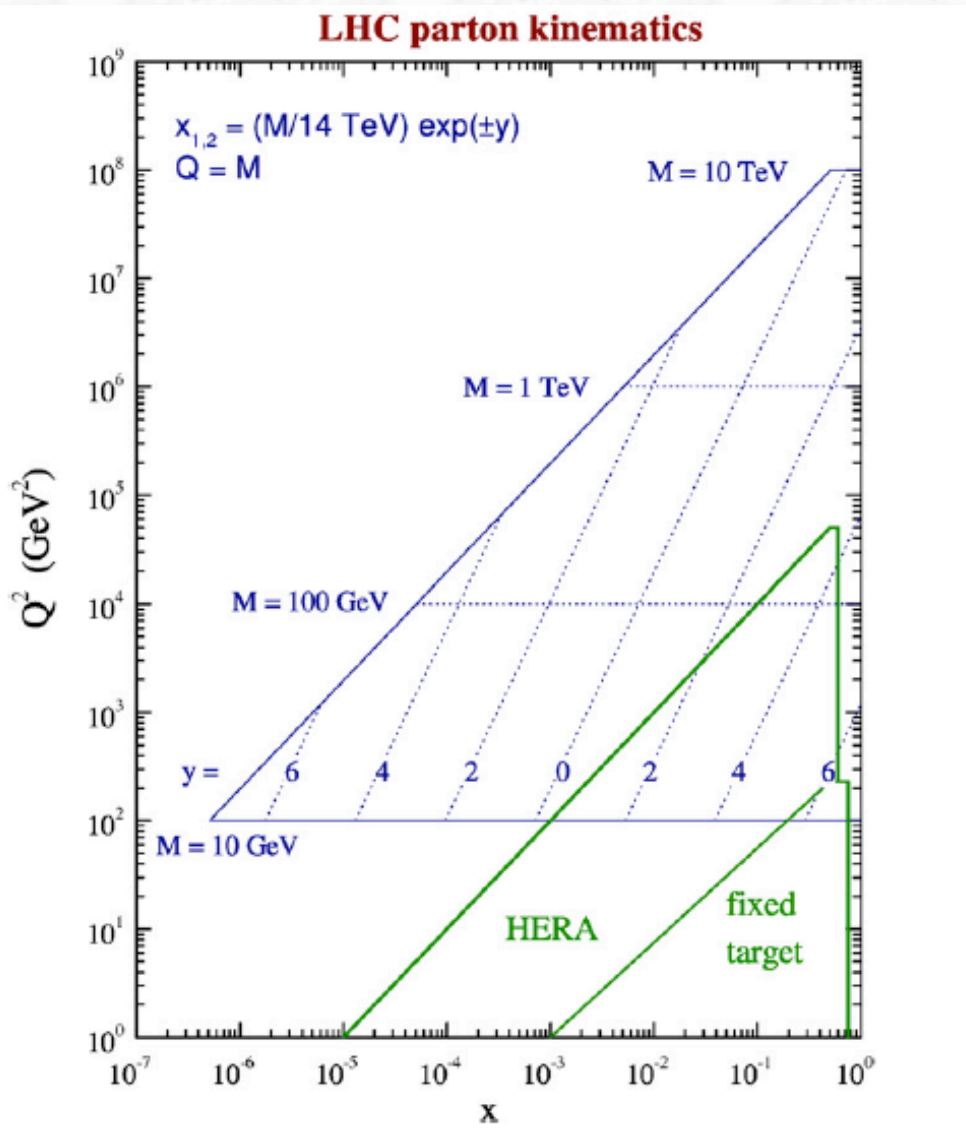


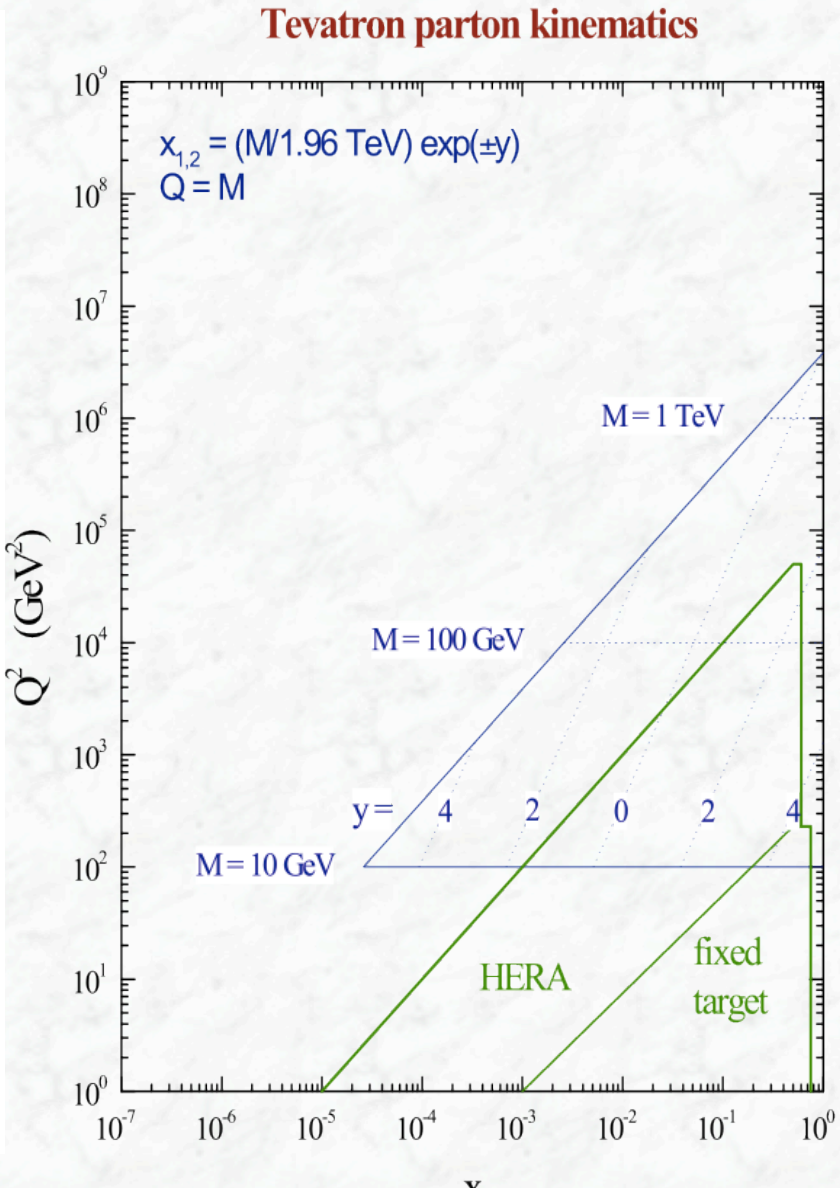
Distributions of x times the unpolarized parton distributions f(x), where f = u_v, d_v, ubar, dbar, s, b, g and their associated uncertainties using the NNLO MRST2008 parametrization at a scale μ^2 = 10 GeV^2 and μ^2 = 10.000 GeV^2.



Graphical representation of the relationship between parton (x, Q^2) variables and the kinematic variables corresponding to a final state of mass M with rapidity y at the LHC with $\sqrt{s}$ = 14 TeV

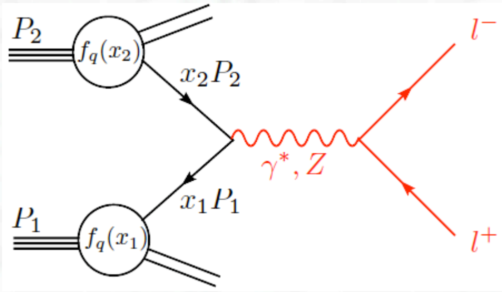
Comparison between the Tevatron and the LHC (14 TeV)

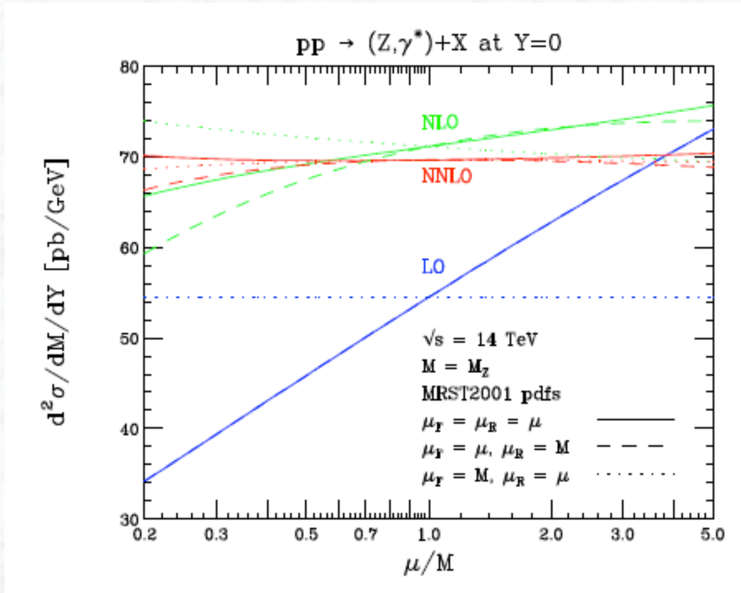


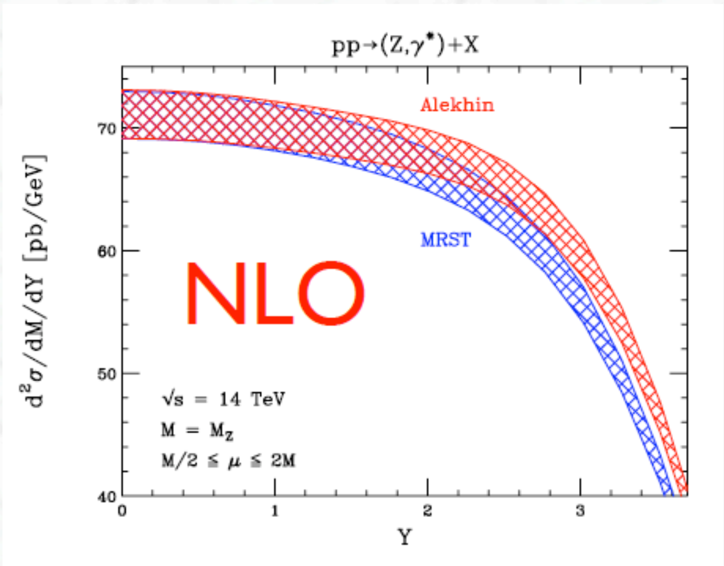


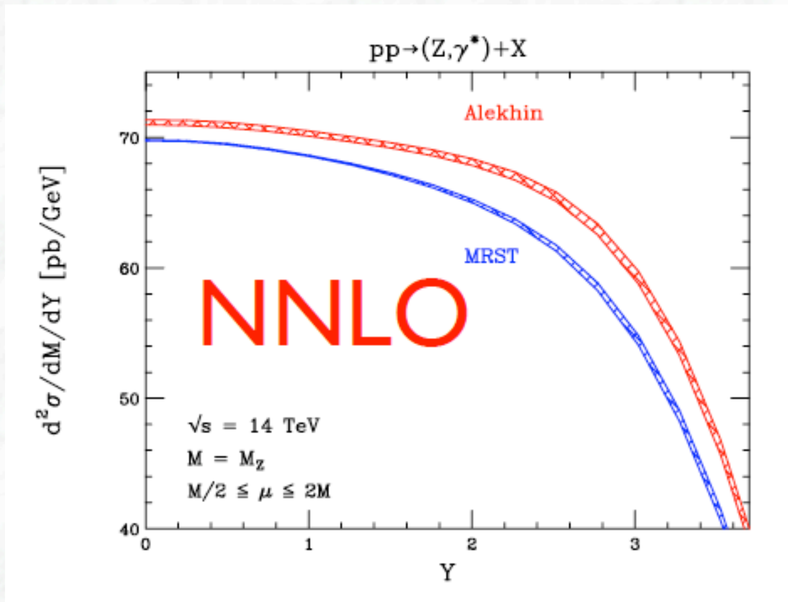
For the same masses (e.g. 100 GeV): x-values about 10 times lower at the LHC

Example: Drell-Yan production of W/Z bosons



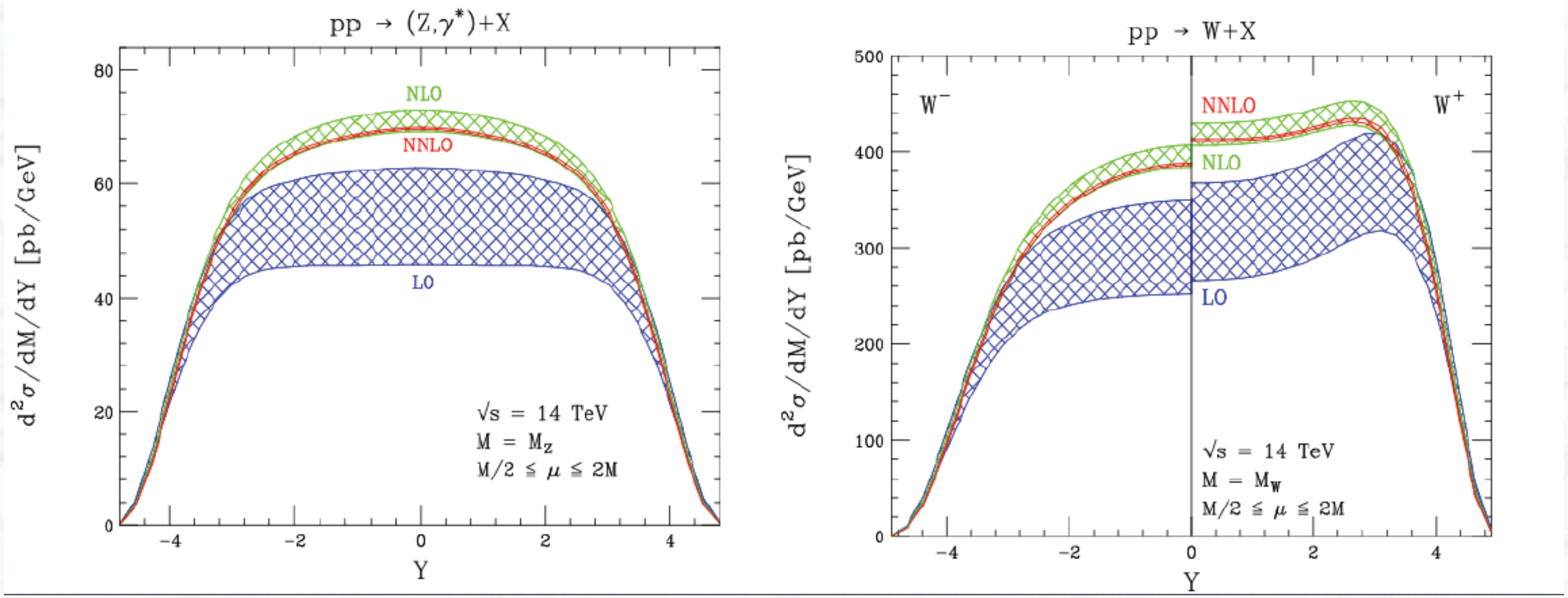






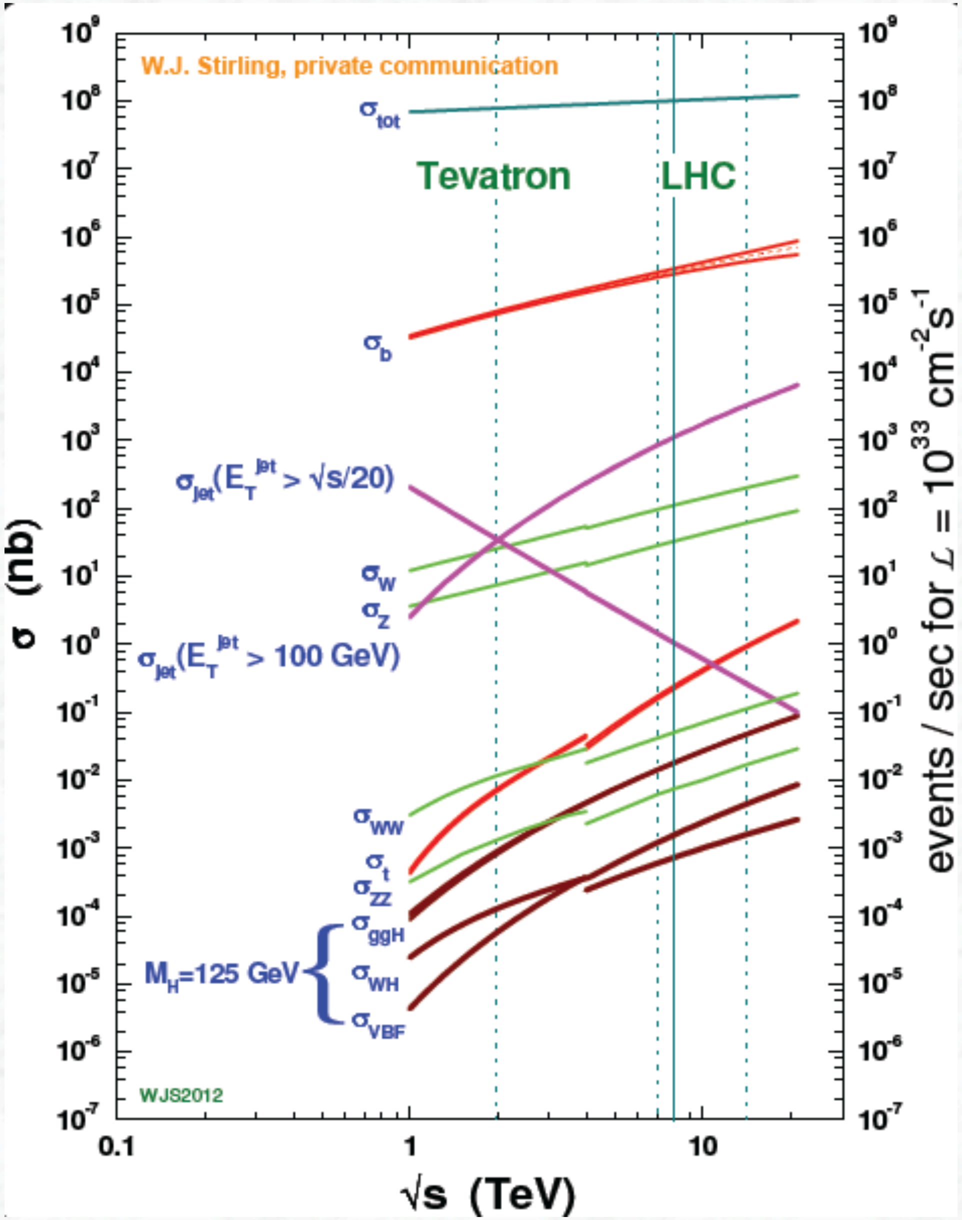
Example: Drell-Yan production of W/Z bosons (cont.)

Rapidity distributions for Z and $W^{\pm}$ production at LO, NLO, and NNLO



Note: LHC data will be used in the future to further constrain the parton densities

Cross Sections and Production Rates

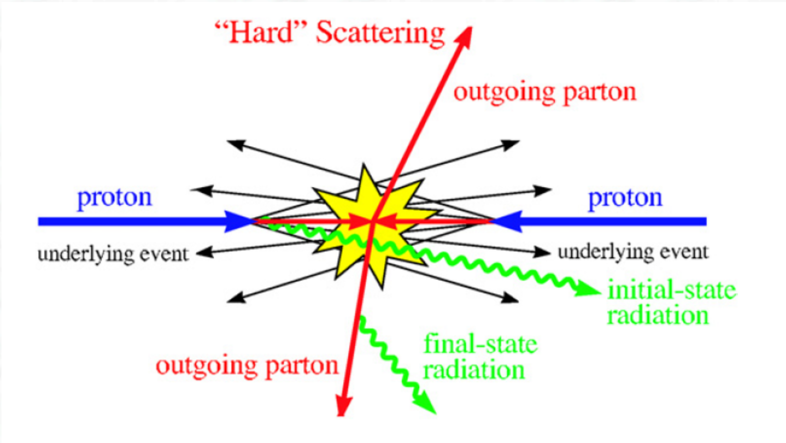


LHC is a factory for:
top-quarks, b-quarks, W, Z, …,Higgs, …

but other more prominent processes dominate the production rates:

- Jet production via QCD scattering
- Soft pp collisions
  (σ ~ 100 mb)

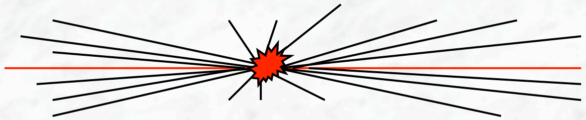
1.4 Soft proton-proton interactions



- First physics at the LHC was dominated by large cross section of inelastic hadronic interactions

- Most interactions are due to interactions at large distance between incoming protons → small momentum transfer, particles in the final state have large longitudinal, but small transverse momentum

  $< p_T > \approx 600$ MeV (of charged particles in the final state)



- Measurements necessary to constrain phenomenological models of soft-hadronic interactions and to predict properties at higher centre-of-mass energies (underlying event, pile-up of minimum bias events at high luminosity, ….)

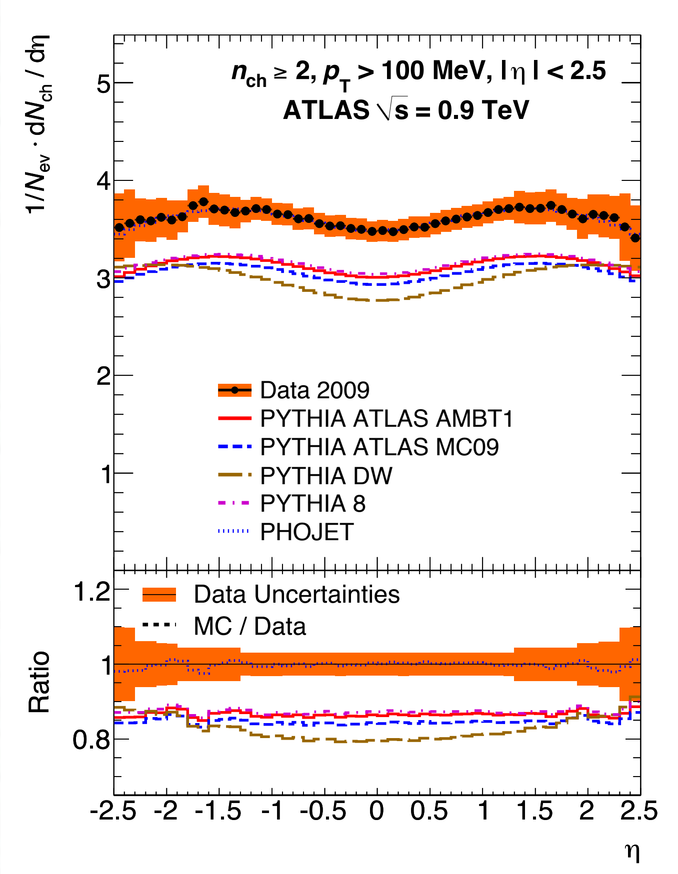
Charged particle density versus η

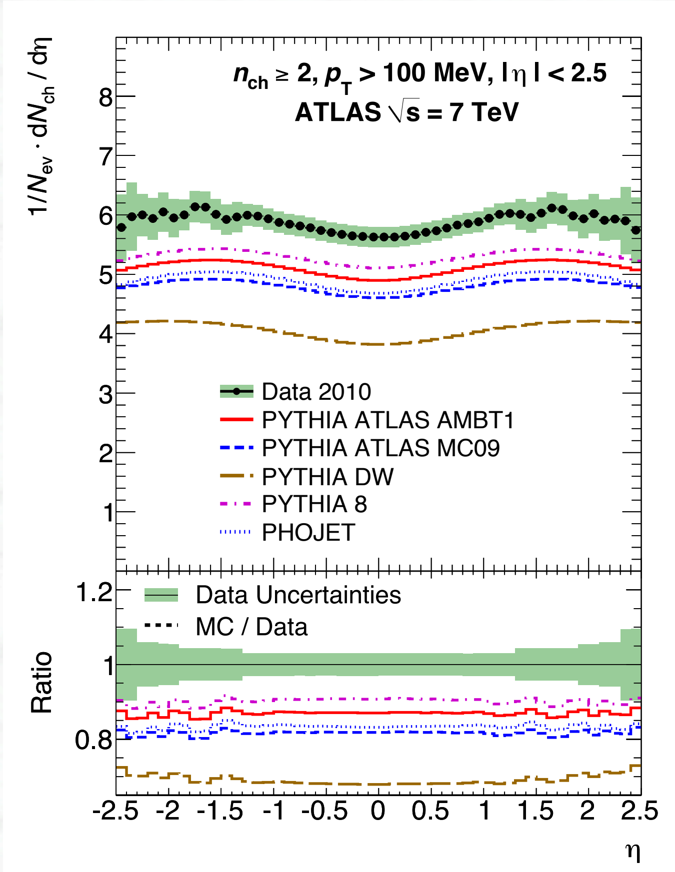
N_{ch}: number of primary charged particles corrected to particle level, normalized to the number of selected events N_{ev}

0.9 TeV

and

7 TeV data

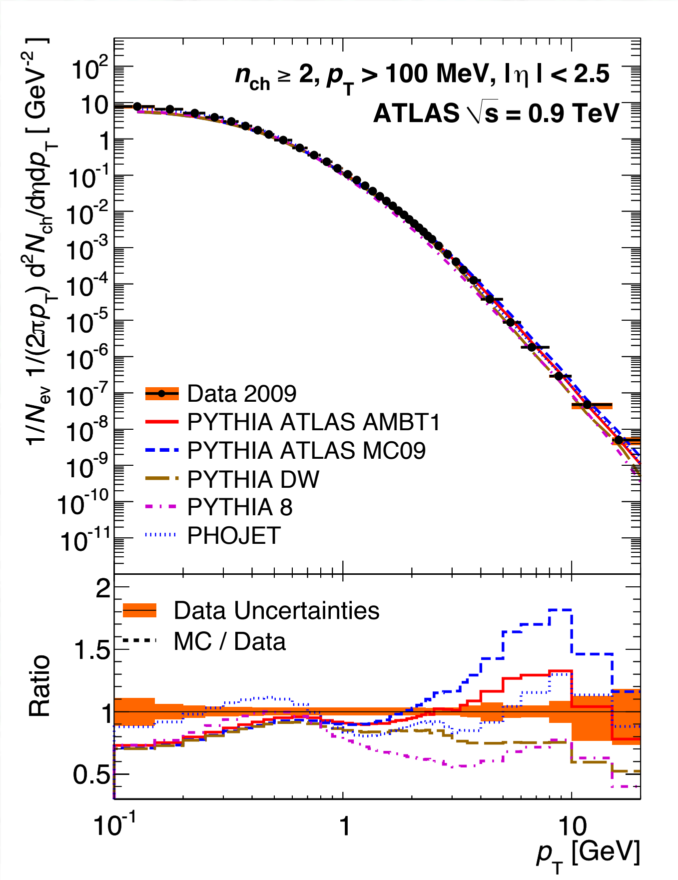


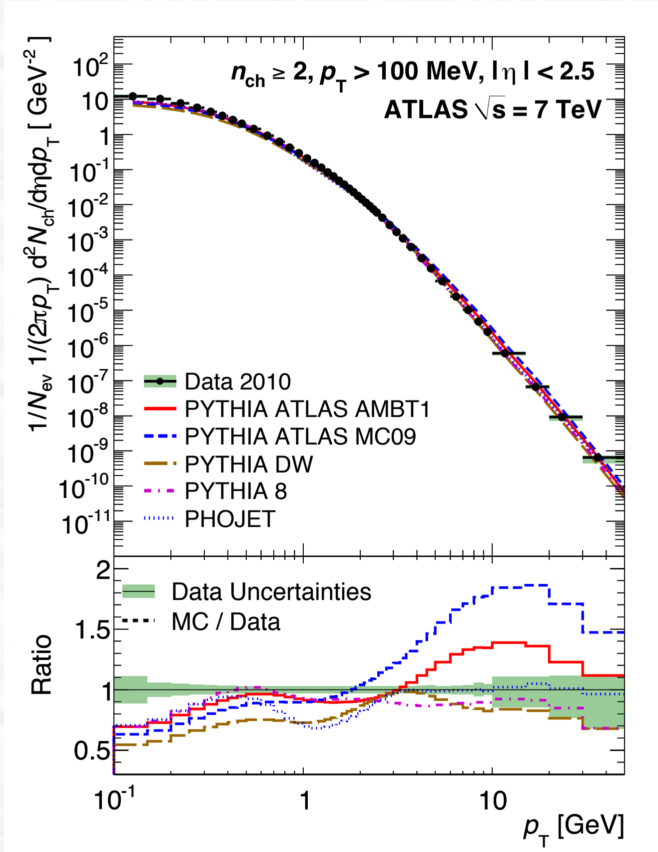


Various Monte Carlo models fail to describe the ATLAS data at both collider energies → tuning of Monte Carlo parameters needed

Charged particle multiplicities as function of p_T

N_{ch}: number of primary charged particles corrected to particle level, normalized to the number of selected events N_{ev}

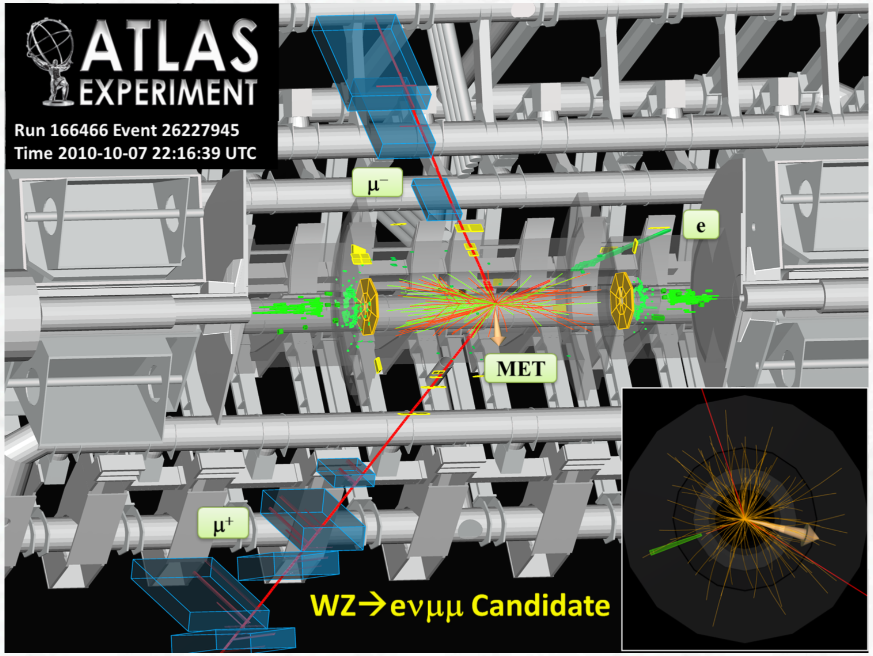




Monte Carlo models also fail to describe the p_T spectrum

Part 2: Test of perturbative QCD

- Jet production
- W/Z production
- Production of top quarks



It is important to establish the Standard Model reference processes:

- Test of the theory itself
  Deviations → evidence for Physics beyond the Standard Model

- Important to understand the detector performance
  → understand the so called "Fake" or "instrumental" background,
  in particular for leptons (e,μ) and E_T^{miss}

- Standard Model processes are important background processes for many searches for Physics Beyond the Standard Model
  "Physics Background"

  Typical selections require: leptons, jets, E_T^{miss} , ….

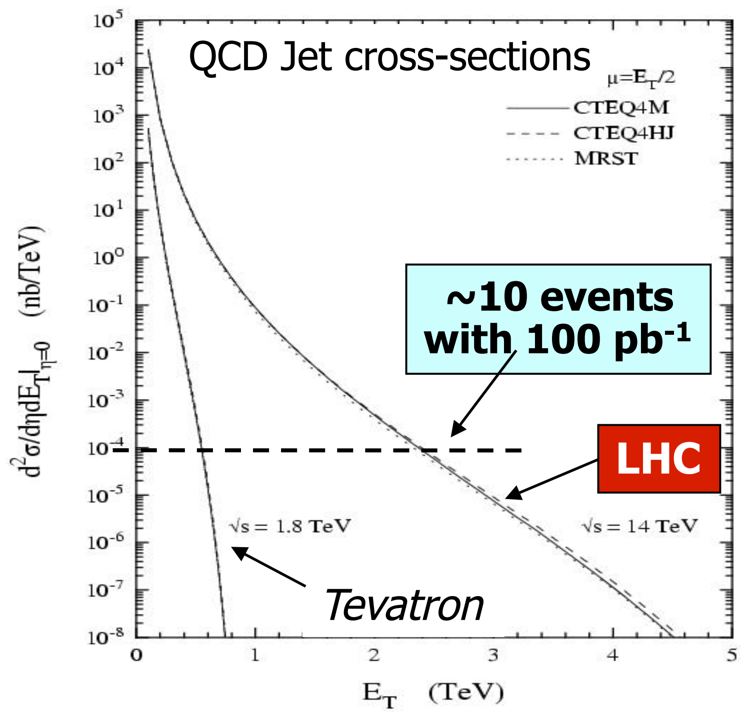
  → W/Z + jets and tt productions are omnipresent !

2.1 Jets from QCD production

- Rapidly probe perturbative QCD in a new energy regime (at a scale above the Tevatron, large cross sections)

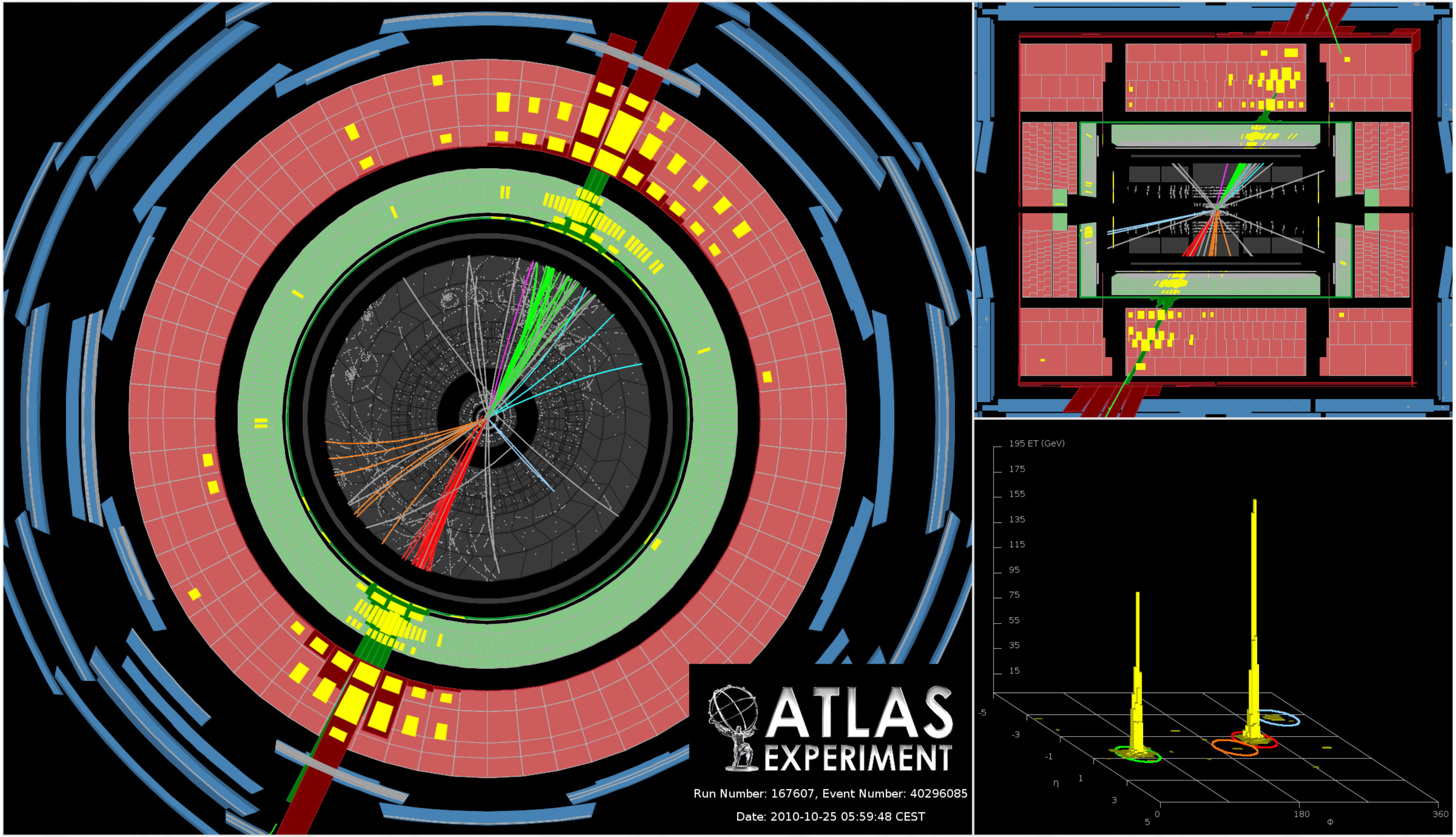
- Experimental challenge:
  understanding of the detector
  - main focus on jet energy scale
  - resolution

- Theory challenge:
  - improved calculations…
    (renormalization and factorization scale uncertainties)
  - pdf uncertainties



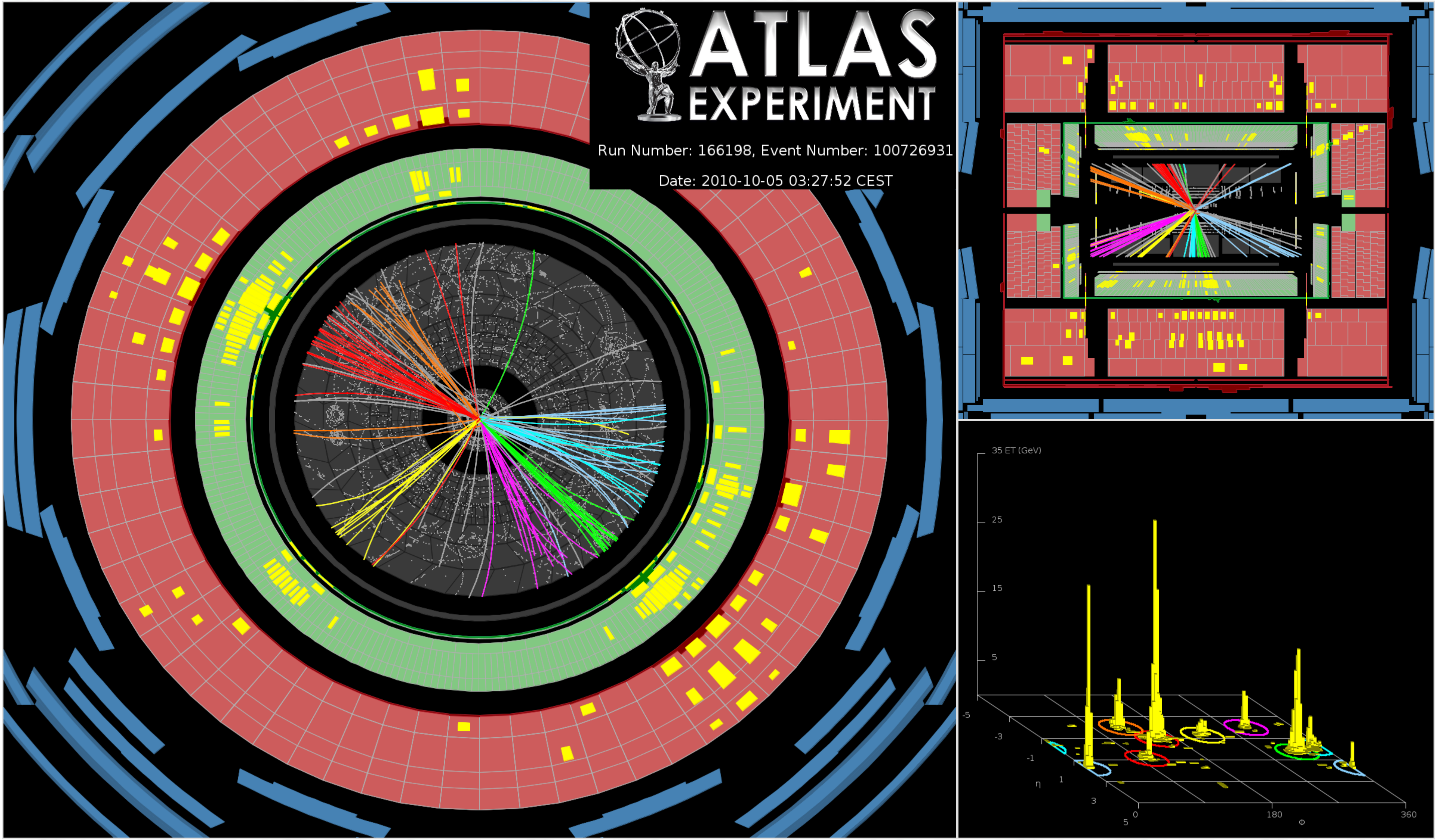
A comparison between the Tevatron and the LHC (14 TeV)

High p_T jet events at the LHC



Event display that shows the highest-mass central dijet event collected during 2010, where the two leading jets have an invariant mass of 3.1 TeV. The two leading jets have (p_T, y) of (1.3 TeV, -0.68) and (1.2 TeV, 0.64), respectively. The missing E_T in the event is 46 GeV. From ATLAS-CONF-2011-047.

An event with a high jet multiplicity at the LHC

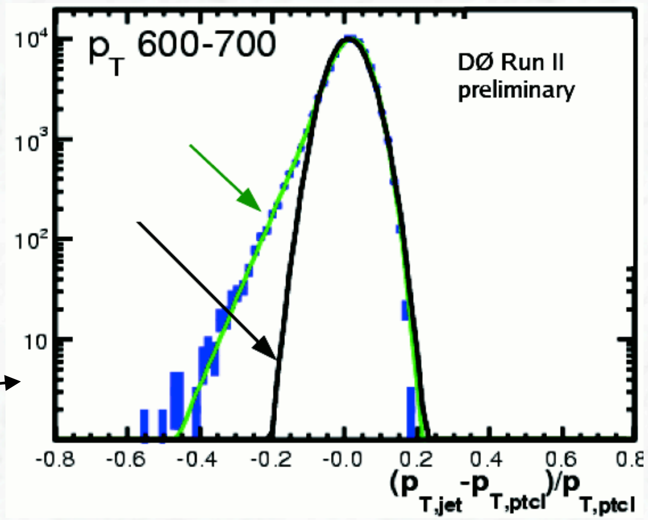


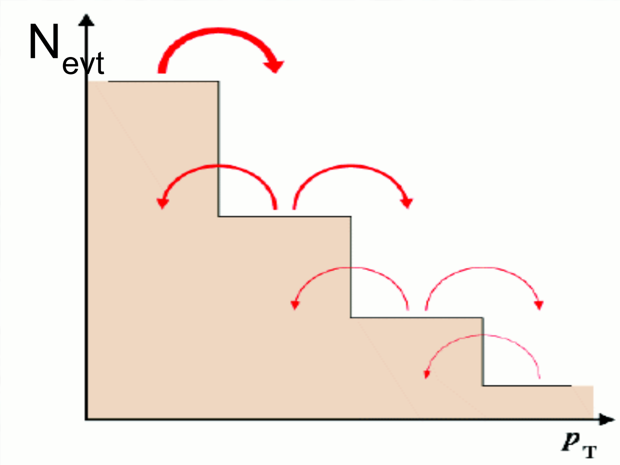
The highest jet multiplicity event collected, counting jets with p_T greater than 60 GeV: this event has eight. 1st jet (ordered by p_T): p_T = 290 GeV, η = -0.9, φ = 2.7; 2nd jet: p_T = 220 GeV, η = 0.3, φ = -0.7 Missing E_T = 21 GeV, φ = -1.9, Sum E_T = 890 GeV.

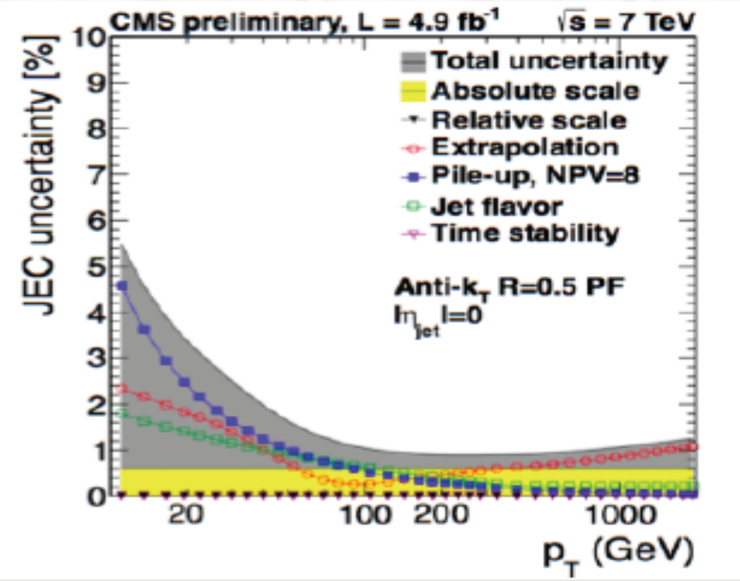
Jet measurements

$$d^2\sigma / dp_T\, d\eta \;=\; N \,/\, (\varepsilon \cdot L \cdot \Delta p_T \cdot \Delta\eta)$$

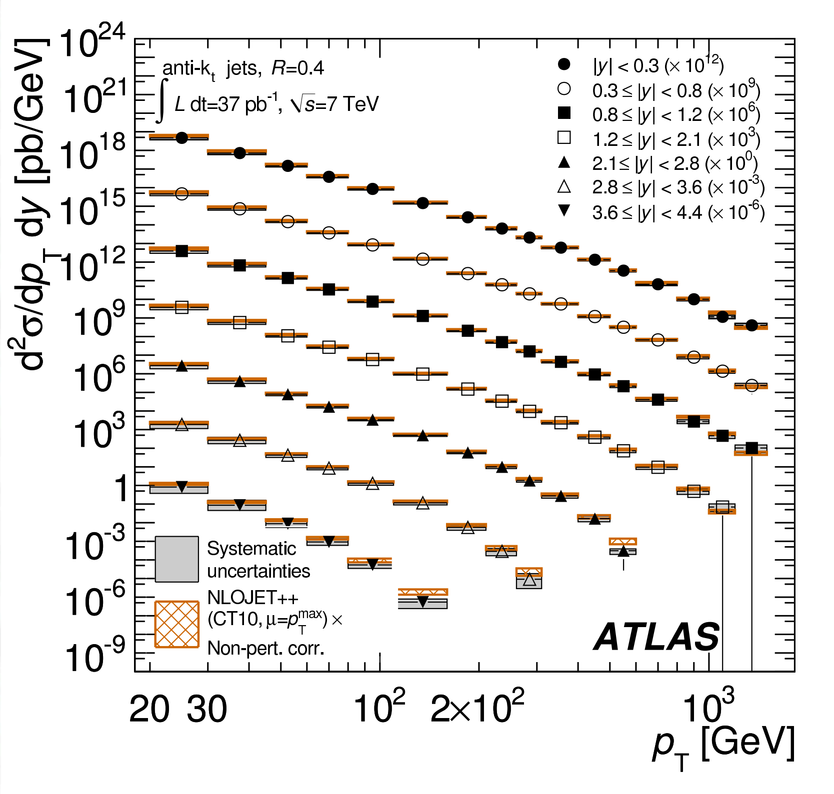
- In principle a simple counting experiment
- However, steeply falling p_T spectra are sensitive to jet energy scale uncertainties and resolution effects (migration between bins) → corrections (unfolding) to be applied
- Jet energy scale uncertainty:
  CMS: ~1.5 - 3% (after two years)
  (similar for ATLAS, impressive achievements)

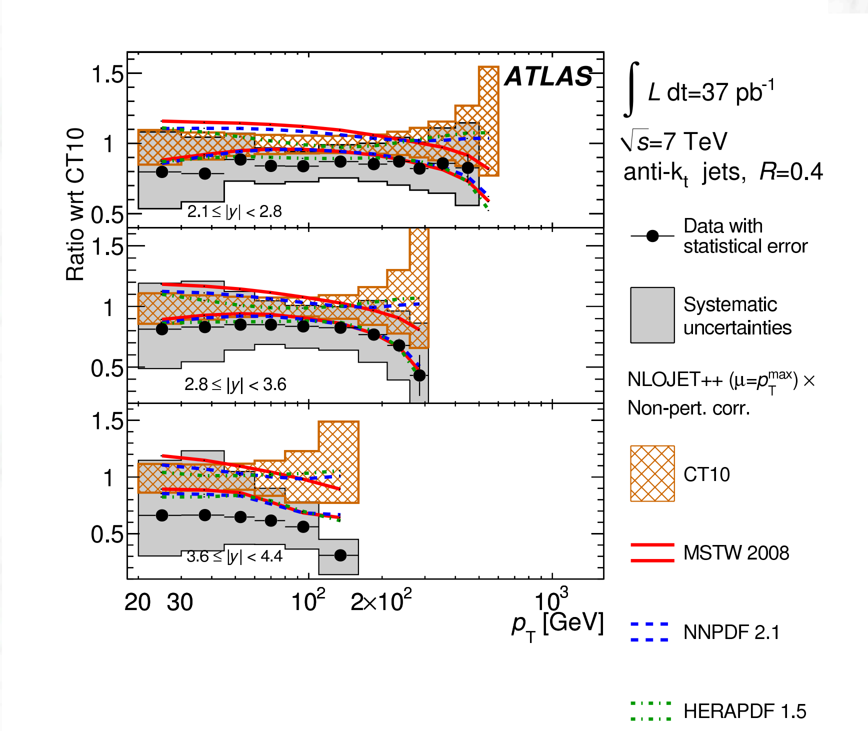






Double differential cross sections, as function of p_T and rapidity y (full 2010 data set)

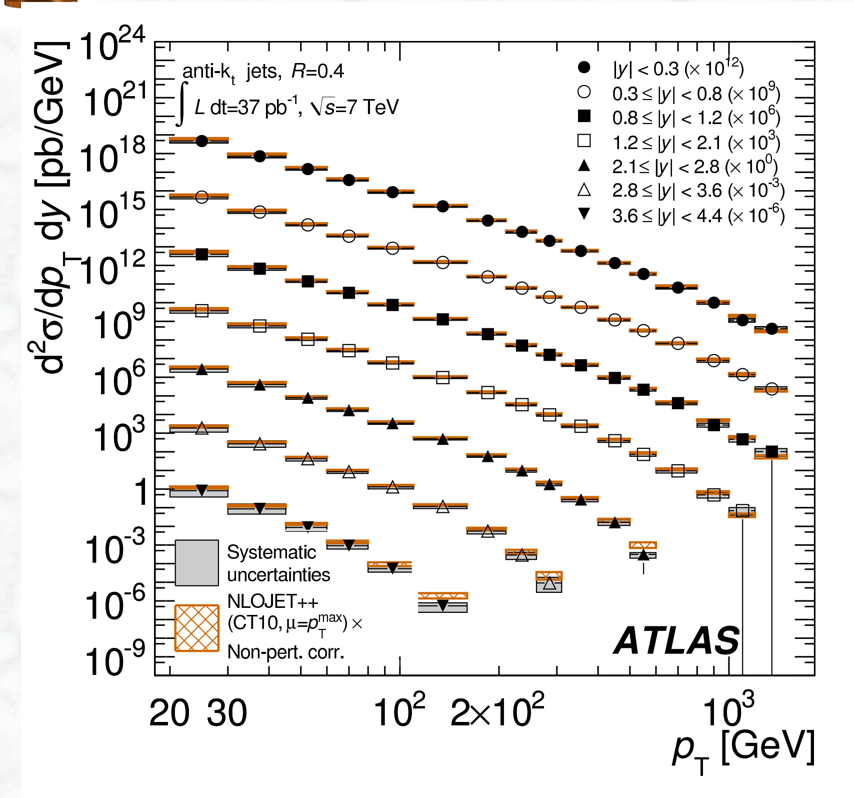


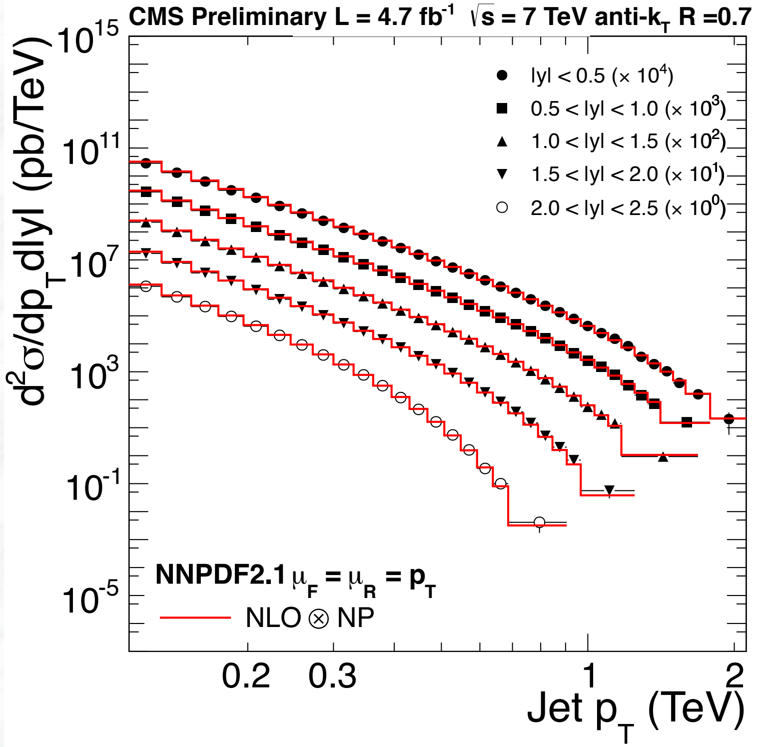


somewhat larger deviations in the forward region

- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: renormalization/ factorization scale, pdfs, α_s, …, uncertainties from non-perturbative effects

Double differential cross sections, as function of p_T and rapidity y: (full 2010 data set)

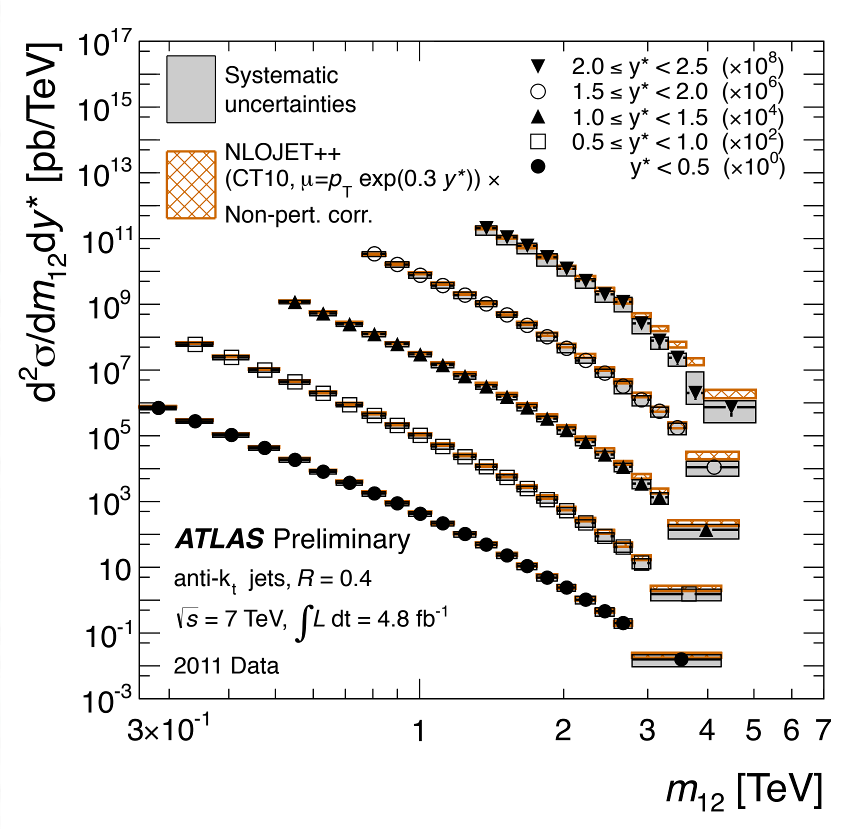


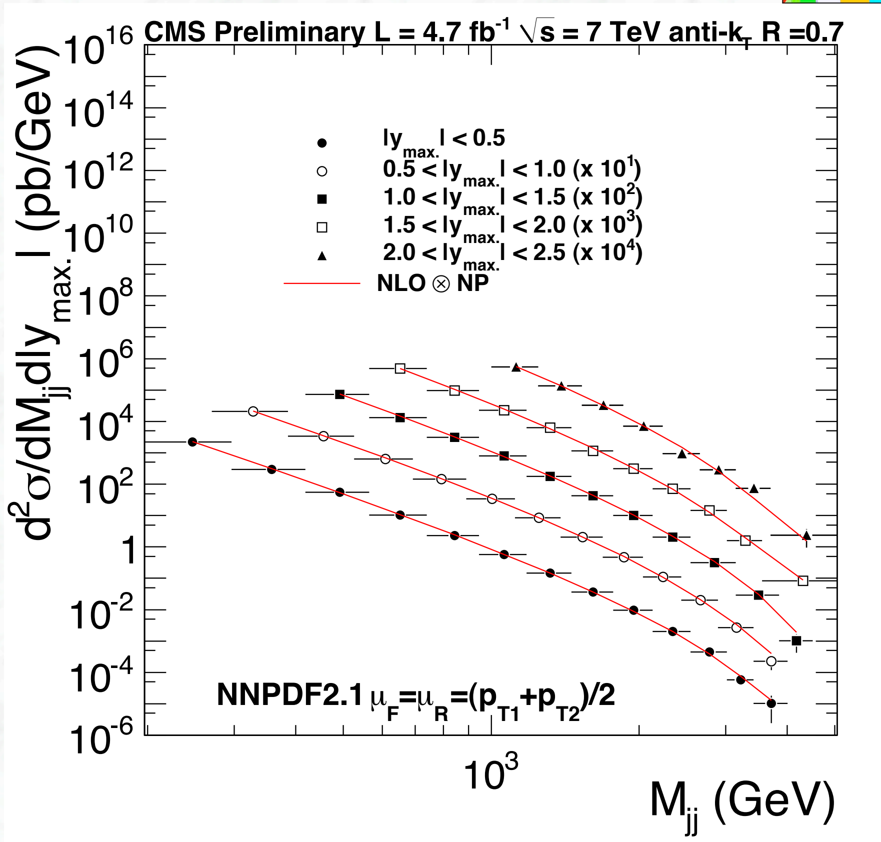


CMS: include full 2011 data set; comparison up to 2 TeV (central rapidities)

- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: renormalization/ factorization scale, pdfs, α_s, …, uncertainties from non-perturbative effects

Invariant di-jet mass spectra





Important for: - Test of QCD

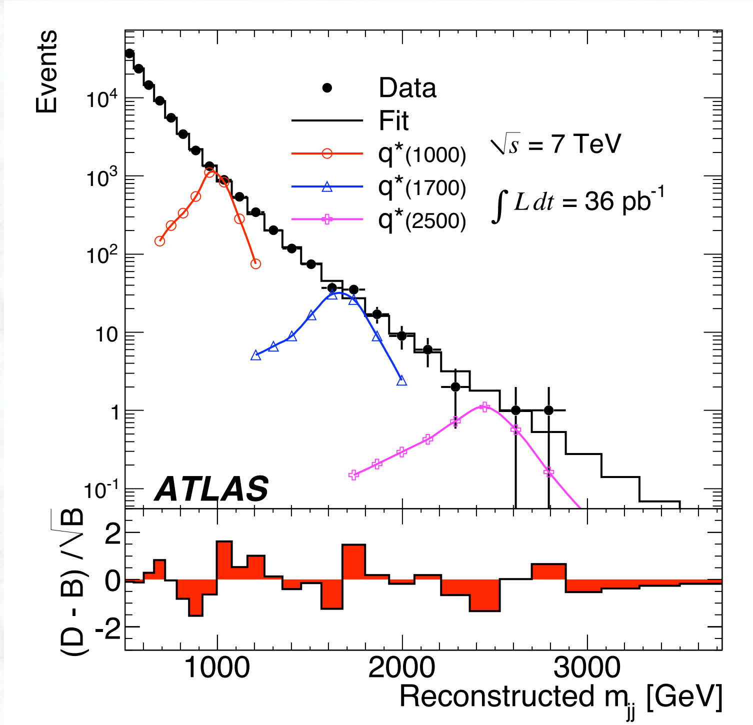
- Search for new resonances decaying into two jets (→ next slide)

In addition to QCD test: Sensitivity to New Physics

- Di-jet mass spectrum provides large sensitivity to new physics

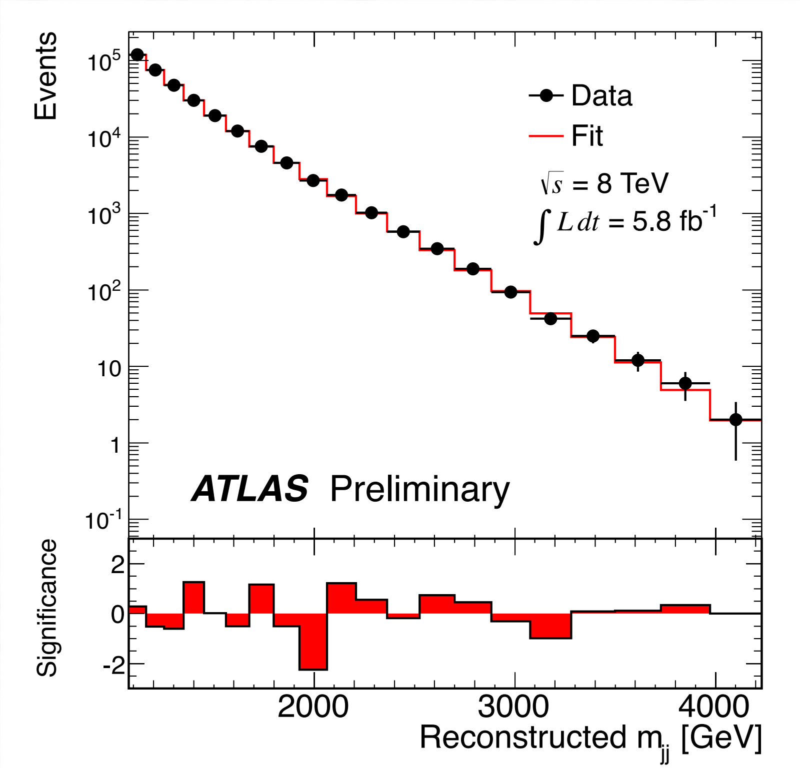
  e.g. Resonances decaying into qq, excited quarks q*, ….

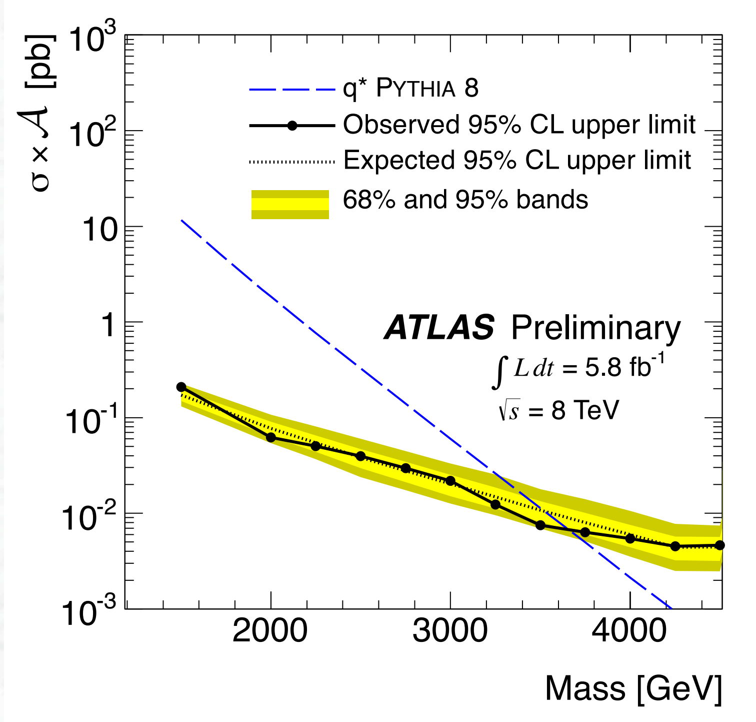
- Search for resonant structures in the di-jet invariant mass spectrum



CDF (Tevatron),	$L = 1.13\ fb^{-1}$:	$0.26 < m_{q^*} < 0.87$ TeV
ATLAS (LHC),	$L = 0.000315\ fb^{-1}$	exclude (95% C.L) q* mass interval $0.30 < m_{q^*} < 1.26$ TeV
	$L = 0.036\ fb^{-1}$:	$0.60 < m_{q^*} < 2.64$ TeV

- Include new data at √s = 8 TeV (2012)
- Invariant di-jet masses up to 4.1 TeV





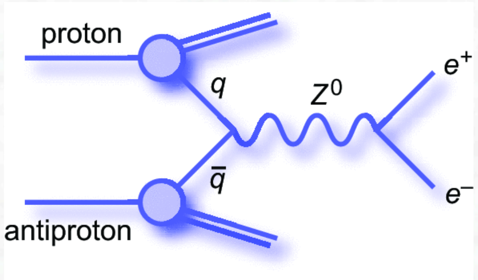
CDF (Tevatron), L = 1.13 fb^{-1}: 0.26 < m_{q^*} < 0.87 TeV

ATLAS (LHC), L = 0.000315 fb^{-1} exclude (95% C.L) q* mass interval
0.30 < m_{q^*} < 1.26 TeV

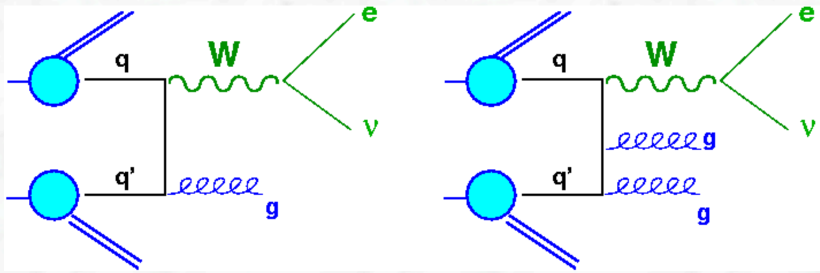
L = 0.036 fb^{-1}: 0.60 < m_{q^*} < 2.64 TeV

ATLAS (LHC), L = 5.8 fb^{-1}, 8 TeV: m_{q^*} < 3.66 TeV

2.2 QCD aspects in W/Z (+ jet) production



QCD at work

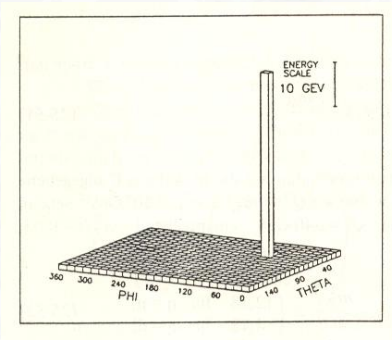


- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region
  (jet multiplicities, p_T spectra,….)
- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC

How do W and Z events look like ?

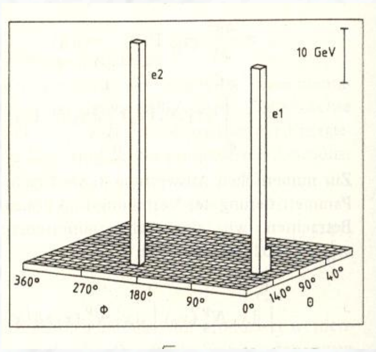
As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

→ Search for leptonic decays: $W \rightarrow \ell \nu$ (large $P_T(\ell)$, large E_T^{miss})
$Z \rightarrow \ell \ell$

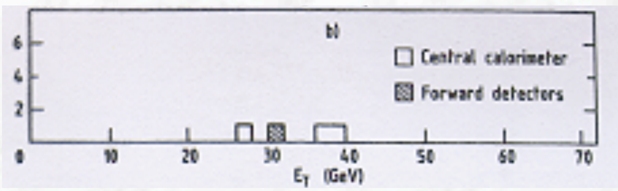


A bit of history: one of the first W events seen; UA2 experiment

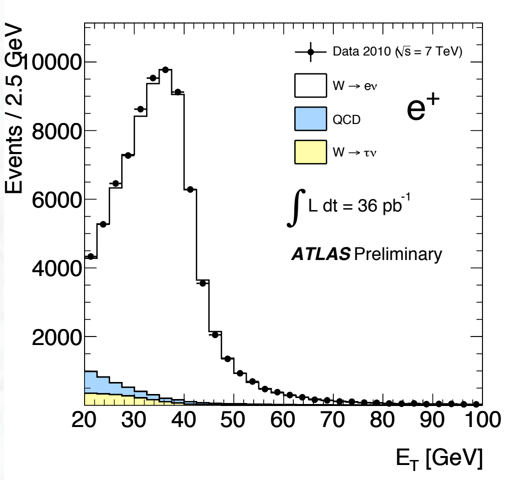
W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)

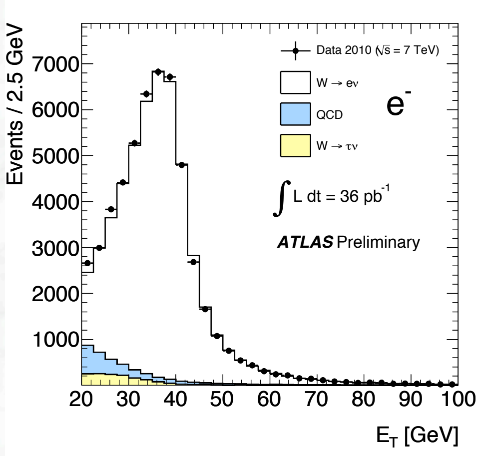


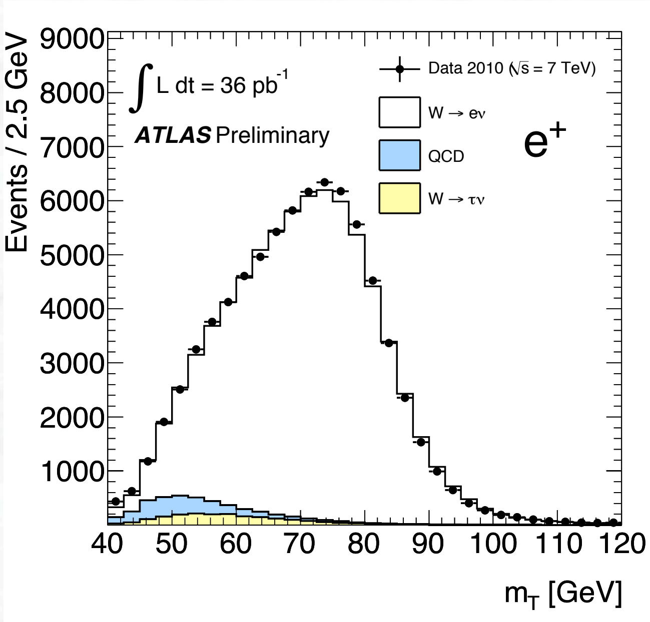
Transverse momentum of the electrons



W/Z selections in the ATLAS / CMS experiments







Electrons:

- Trigger: high p_T electron candidate in calorimeter
- Isolated el.magn. cluster in the calorimeter
- $P_T > 25$ GeV/c
- Shower shape consistent with expectation for electrons
- Matched with tracks

$Z \to ee$

- $76\ \mathrm{GeV}/c^2 < m_{ee} < 106\ \mathrm{GeV}/c^2$

$W \to e\nu$

- Missing transverse momentum > 25 GeV/c
- Transverse mass cut $M_T > 50$ GeV

$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos\Delta\phi^{l,\nu}\right)}$$

Transverse mass
(longitudinal component of the neutrino cannot be measured)

Ingredients for cross-section measurements

$$\sigma_{W(Z)}^{\text{tot}} \cdot BR(W(Z) \to \ell\nu\ (\ell\ell)) = \frac{N_{W(Z)}^{\text{sig}}}{A_{W(Z)} \cdot C_{W(Z)} \cdot L_{W(Z)}}$$

- Number of W/Z signal candidates $N^{sig} = N^{evt} - N^{back}$
  Estimated background (Physics background, "fake" background,…)

- $C_{W(Z)}$: reconstruction efficiencies, detector effects, …

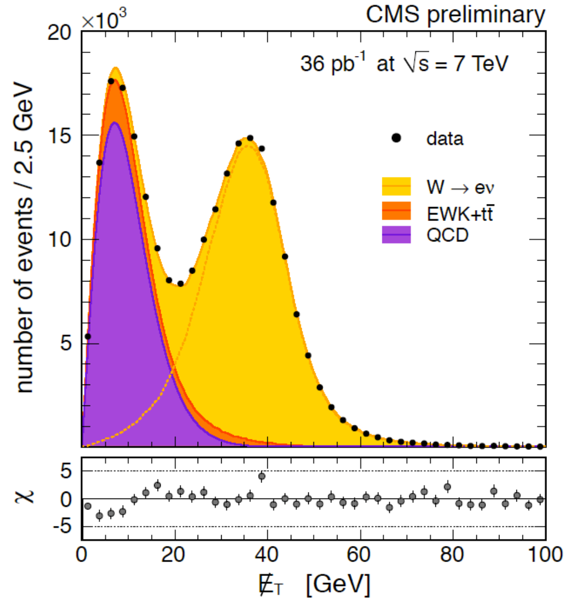
- $A_{W(Z)}$: acceptance (usually the final state products are measured in a so called fiducial region of the detector,
  e.g. η coverage of the muon detector, p_T threshold of the reconstruction)

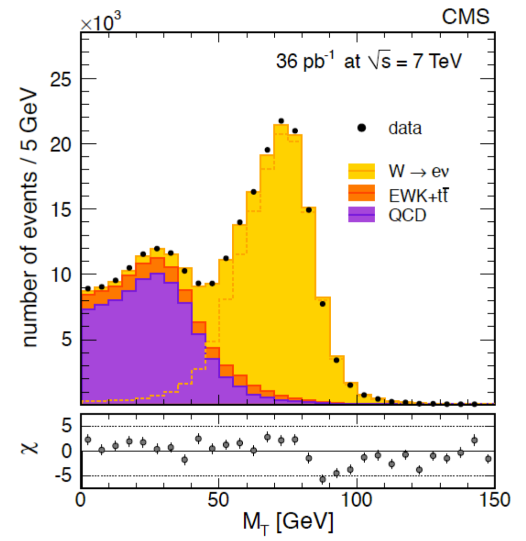
  This last quantity can only be calculated with Monte Carlo, using theoretical inputs !!
  (N)NLO calculations, parton density functions, ….

  - Cross sections for $A_{W(Z)}$ = 1 are called "fiducial cross sections"
  - Less affected by theoretical / pdf uncertainties…

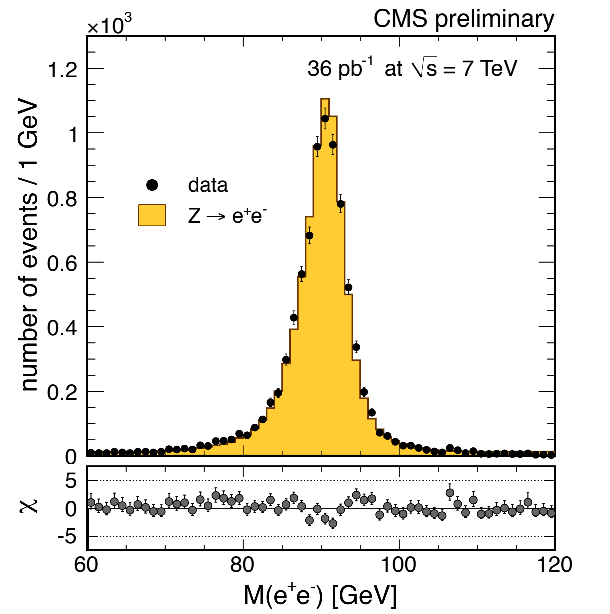
- $L_{W(Z)}$: integrated luminosity

An example: CMS data from 2010: 36 pb^{-1}





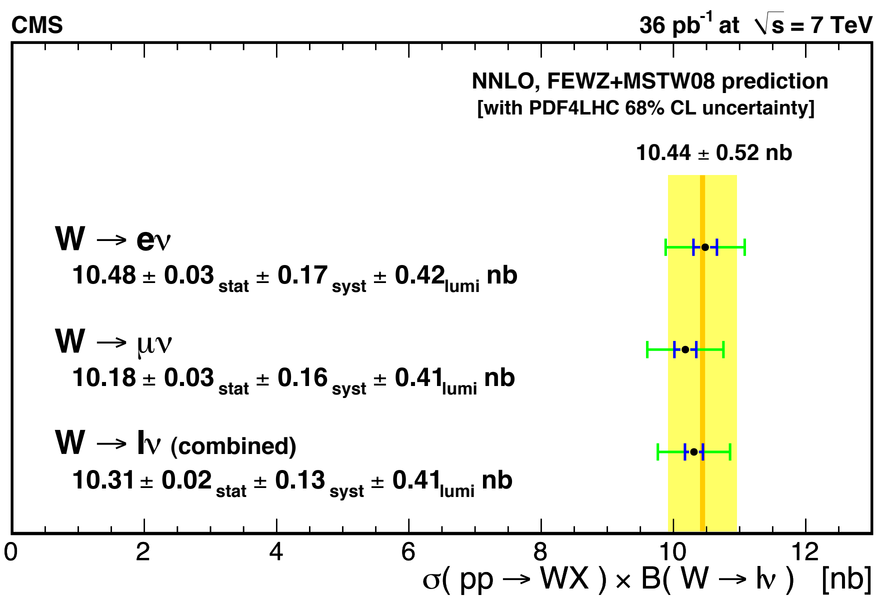
Distributions of the missing transverse energy, E_T^{miss}, (left) and transverse mass mT (right) of electron candidates for data and Monte Carlo simulation, broken down into the signal and various background components.

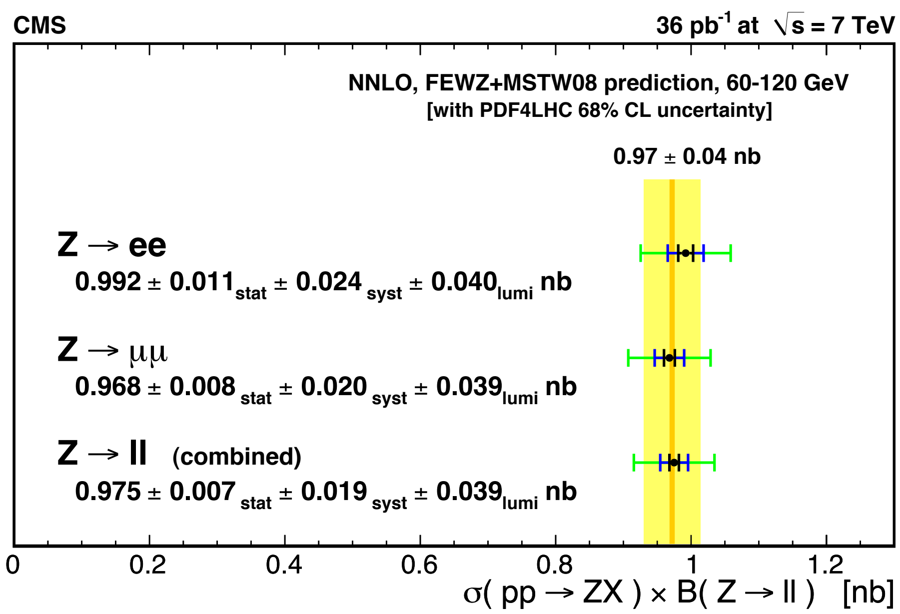


Distributions of the invariant di-electron mass, m_{ee}, for events passing the Z selection. The data are compared to Monte-Carlo simulation, the background is very small.

W and Z production cross sections at the LHC

Measured cross section values in comparison to NNLO QCD predictions:





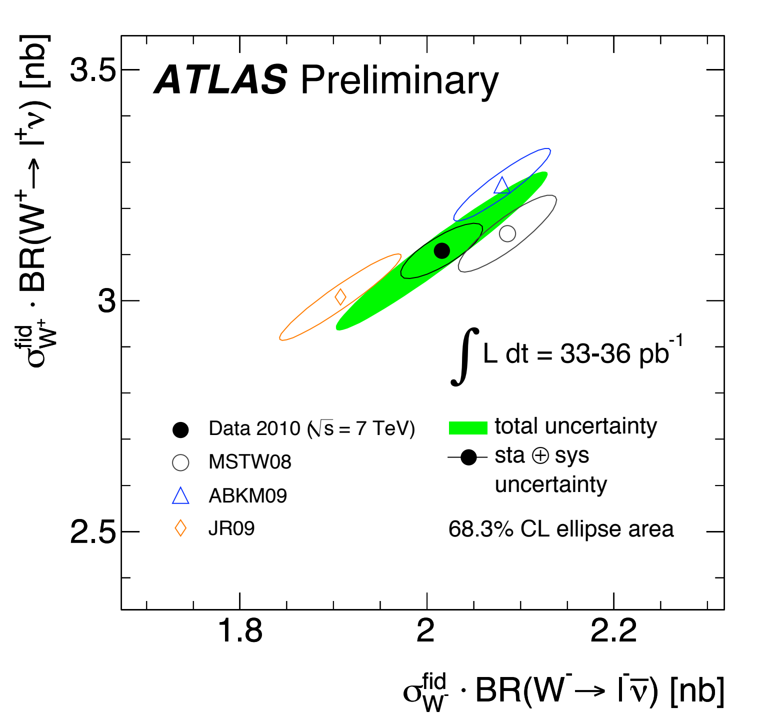
Data are well described by NNLO QCD calculations

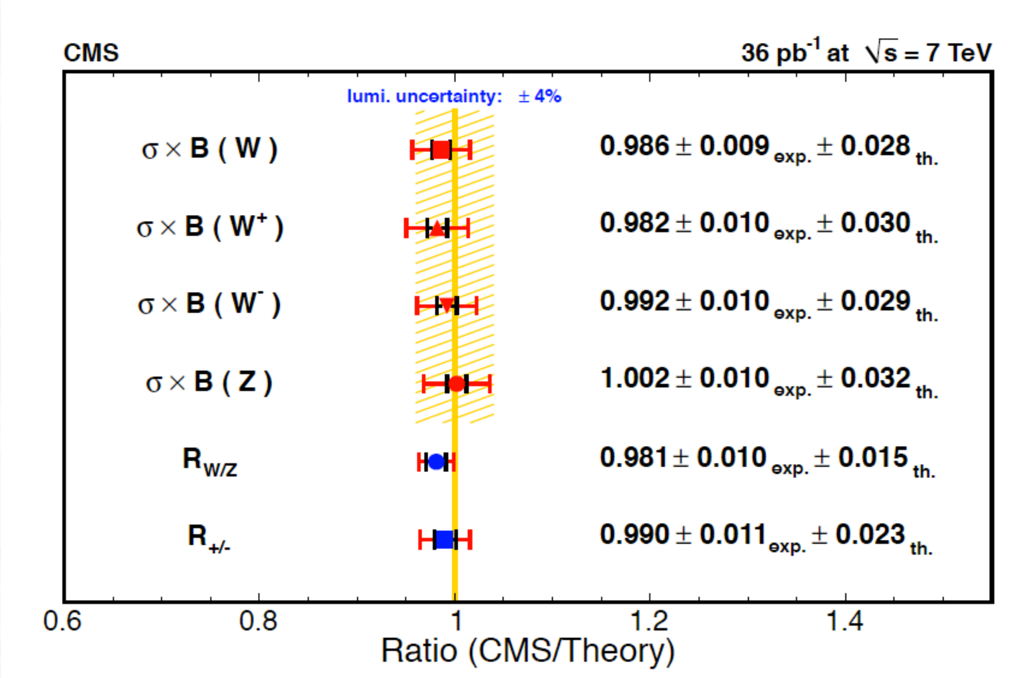
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

Precision is already dominated by systematic uncertainties

[The error bars represent successively the statistical, the statistical plus systematic and the total uncertainties (statistical, systematic and luminosity). All uncertainties are added in quadrature.]

W cross sections at the LHC
-charge separated, e/μ universality

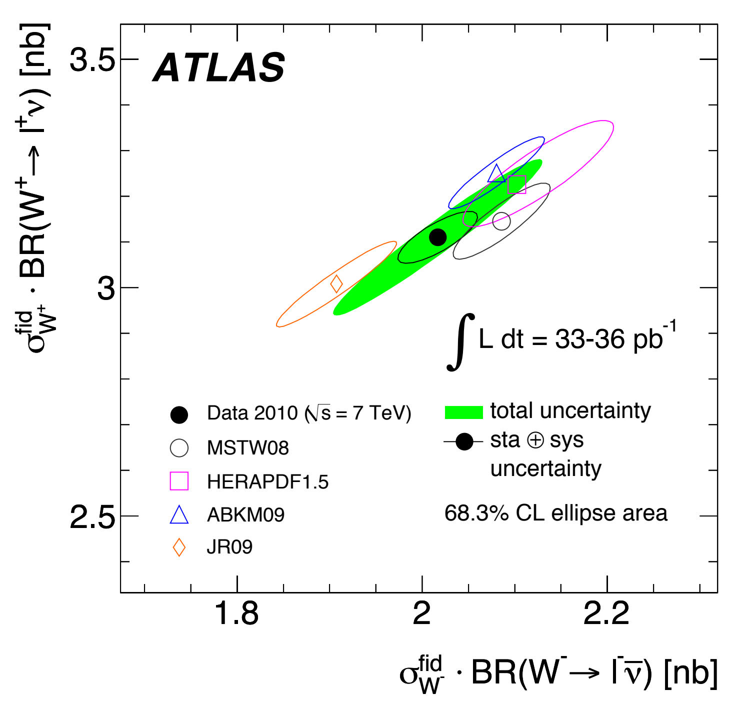




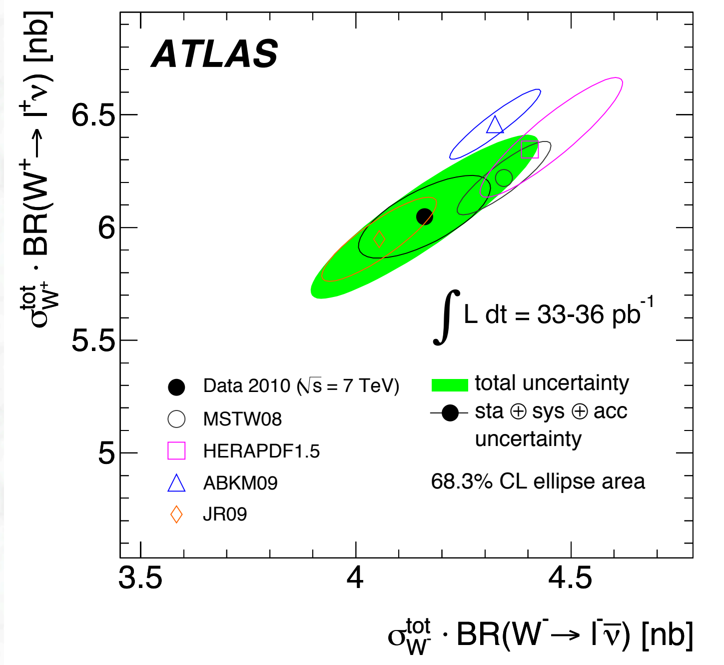
Good agreement between data and NNLO QCD predictions for all measurements

From fiducial cross sections to total cross sections

Fiducial cross sections



Total cross sections



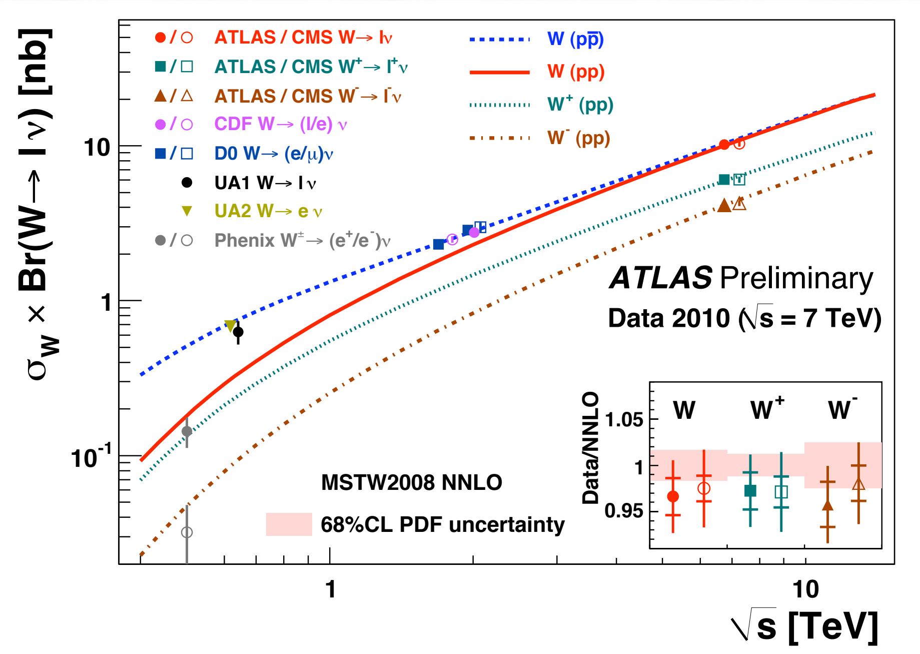
$P_T(e) > 20$ GeV, $\eta < 2.5$
$P_T(\nu) > 25$ GeV
$m_T(e\,\nu) > 40$ GeV

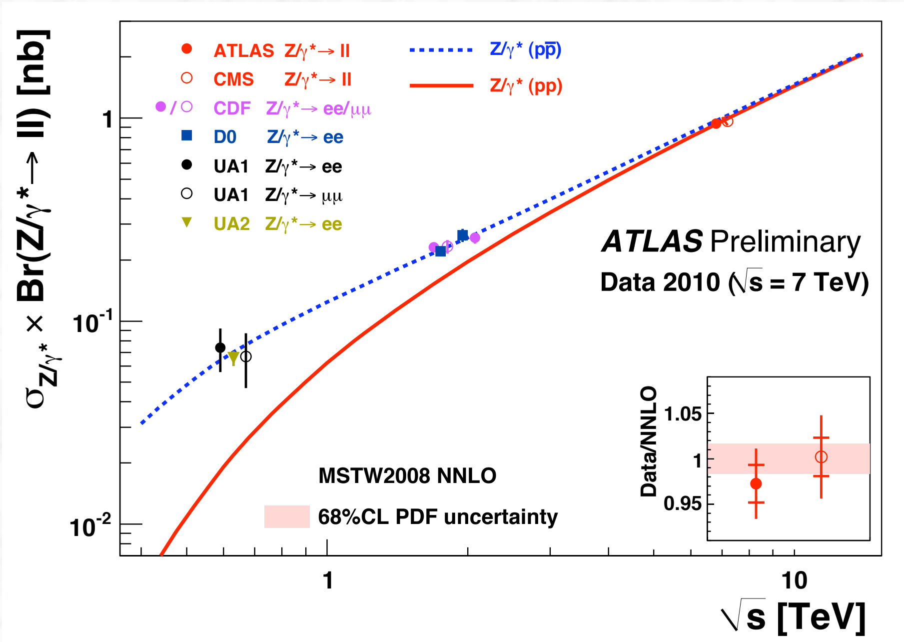
Uncertainties in W/Z cross section measurements

Electron channels (%)	$W^\pm$	W^+	W^-	Z
Trigger	0.4	0.4	0.4	<0.1
Reconstruction	0.8	0.8	0.8	1.6
Identification	0.9	0.8	1.1	1.8
Isolation	0.3	0.3	0.3	—
Energy scale and resolution	0.5	0.5	0.5	0.2
Defective LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	<0.1	0.1	0.1	0.6
E_T^{miss}	0.8	0.7	1.0	—
Pile-up	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
QCD Background	0.4	0.4	0.4	0.7
EWK+$t\bar{t}$ Background	0.2	0.2	0.2	<0.1
$C_{W/Z}$ Theor. uncertainty	0.6	0.6	0.6	0.3
Total Exp. uncertainty	**1.8**	**1.8**	**2.0**	**2.7**
$A_{W/Z}$ Theor. uncertainty	1.4	1.6	1.9	1.9
Total excluding Luminosity	2.3	2.4	2.8	3.3

In addition: luminosity uncertainty ±3.4%
(now better known in both experiments, better than ±2%

W and Z production cross sections at hadron colliders



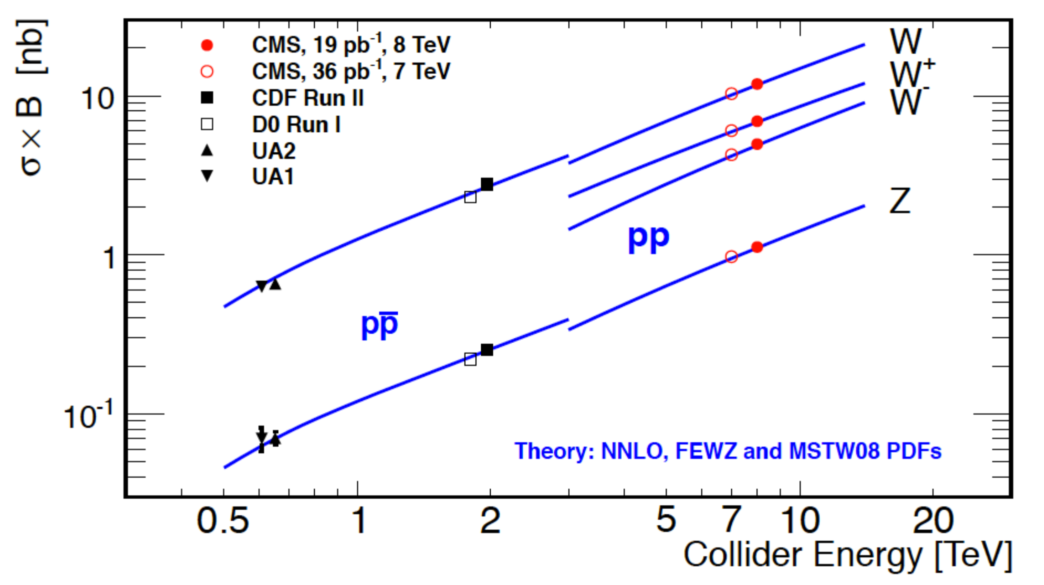


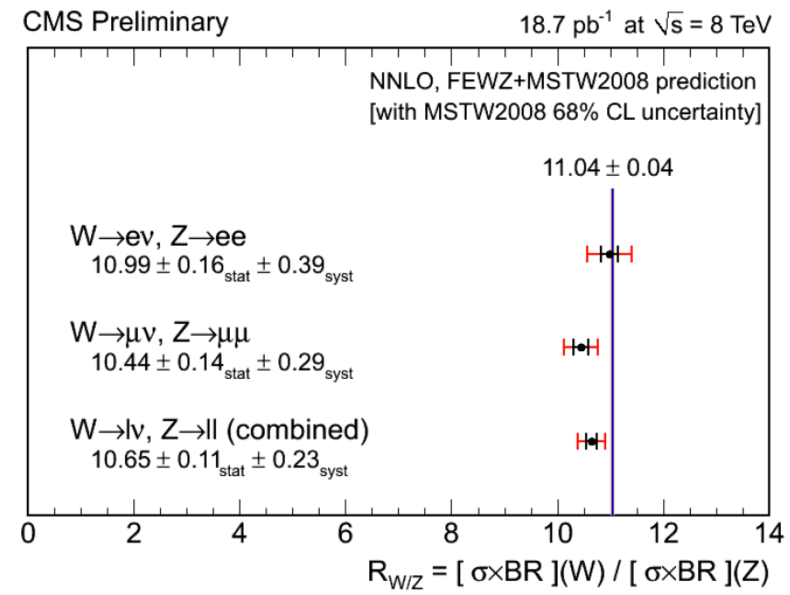
- Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)

- Good agreement as well between the ATLAS and CMS experiments

W and Z production cross sections at √s = 8 TeV

- CMS has already presented first results at 8 TeV (the first 18.7 pb^{-1})
  About 75.000 W → eν and 4.800 Z → ee candidates

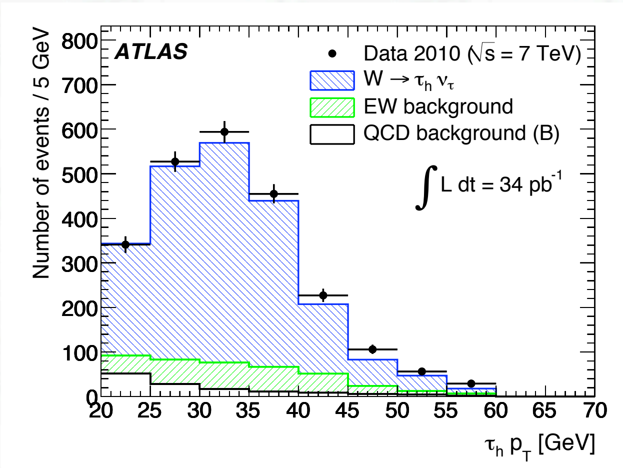


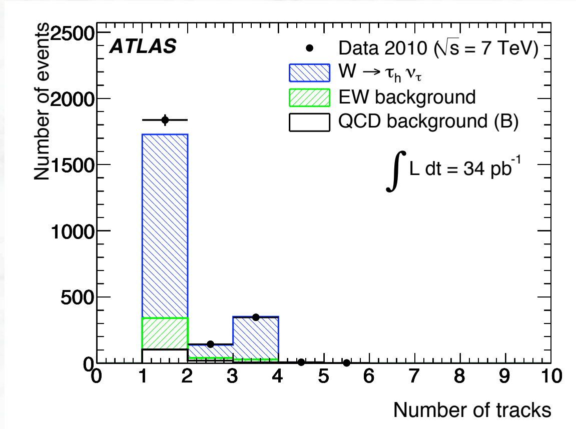


- No surprise at the new energy, theoretical predictions in good agreement with the measurements
- W/Z cross-section ratio remains a bit high, but consistent within uncertainties

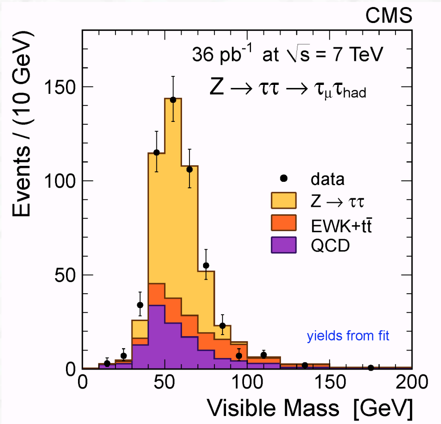
First physics signals with hadronic tau final states

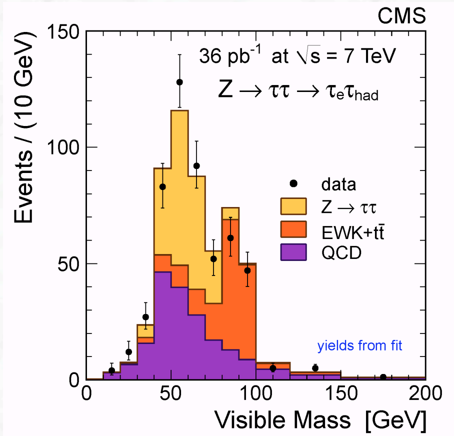
- Taus are more difficult to detect
- They decay with a short lifetime (0.3 ps) into 1 or 3 charged hadrons (65%) and a neutrino
- Taus have to be separated from hadronic jets





$W \to \tau \nu$



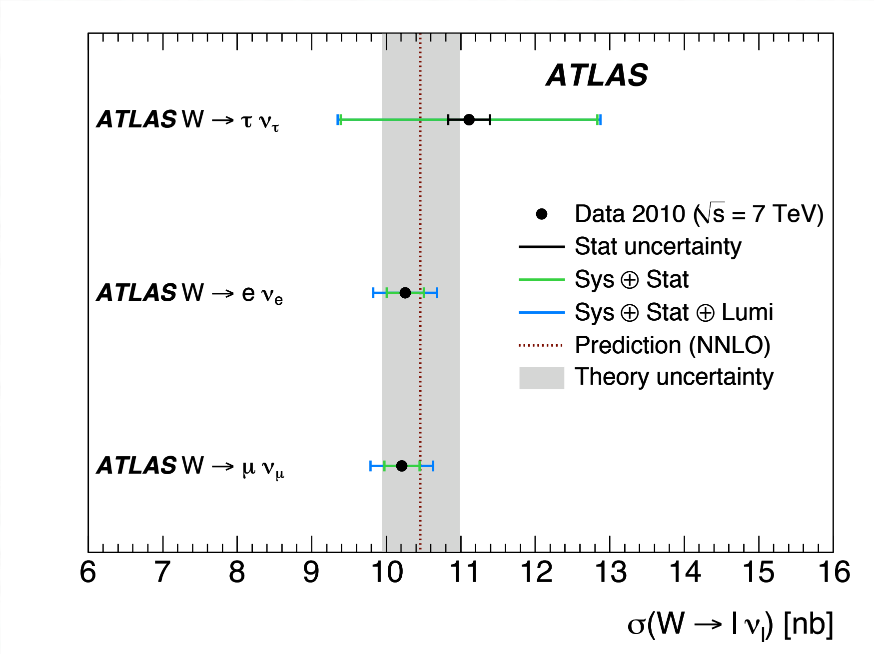


$Z \to \tau \tau$

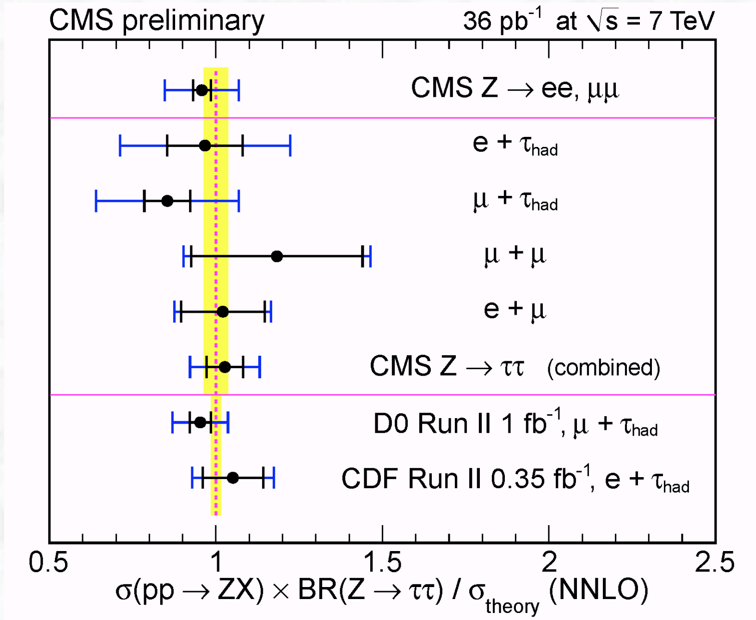
- First tau signals established in both ATLAS and CMS
- Important reference signals for searches with taus in Higgs and SUSY areas

First physics signals with hadronic tau final states

W → τ ν



Z → τ τ



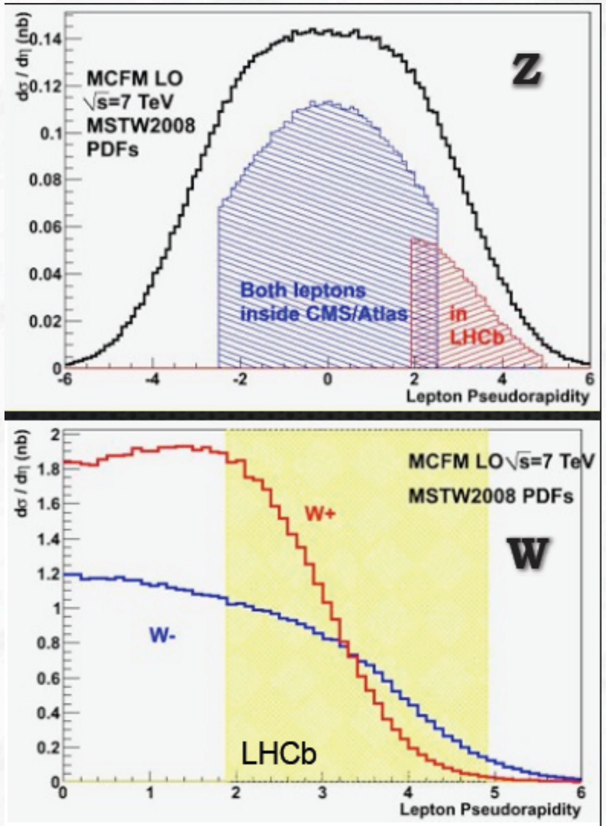
- Good agreement between the measured cross sections in the three lepton flavours
- Experimental uncertainites (Z → ττ) already comparable to Tevatron measurements

Can the parton distribution functions be constrained?

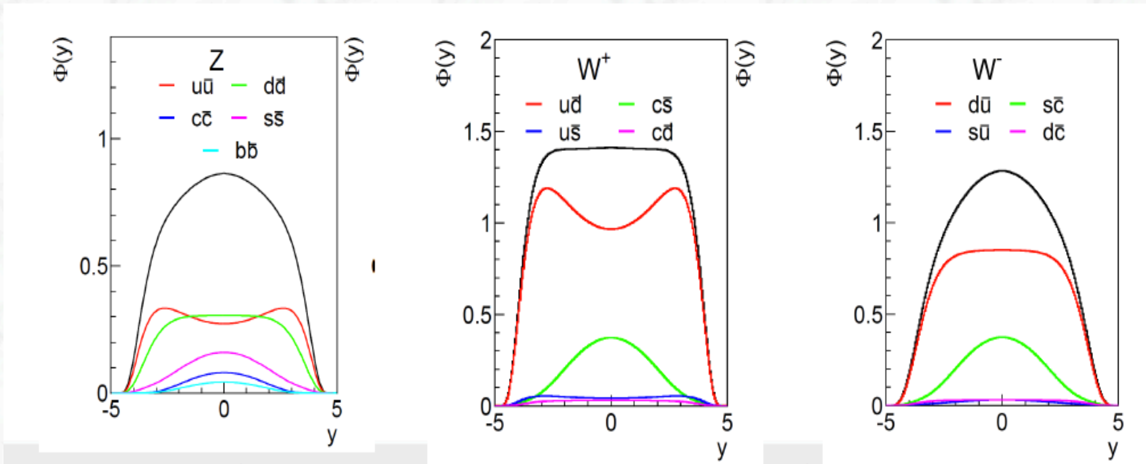
- Sensitive measurements: differential W and Z production cross sections as function of lepton or boson rapidity, charge separated for W^+ and W^-

  LHCb experiment can contribute significantly in the forward region: η coverage from 1.9 – 4.9

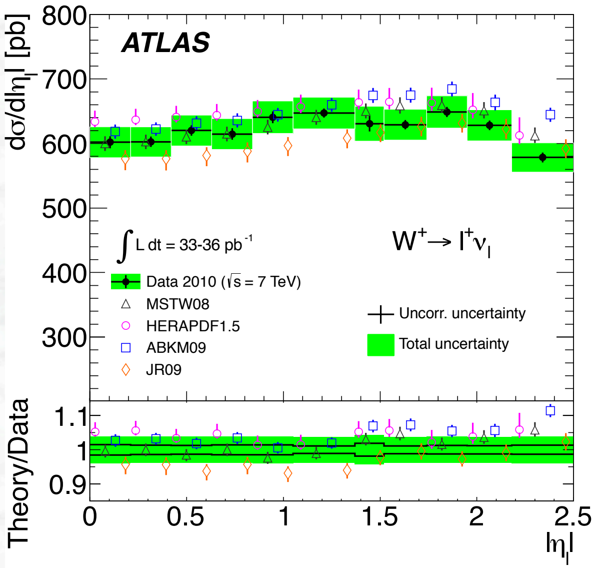
- Derived quantity: charge asymmetry: $\sigma(W^+) - \sigma(W^-) \;/\; [\sigma(W^+) + \sigma(W^-)]$

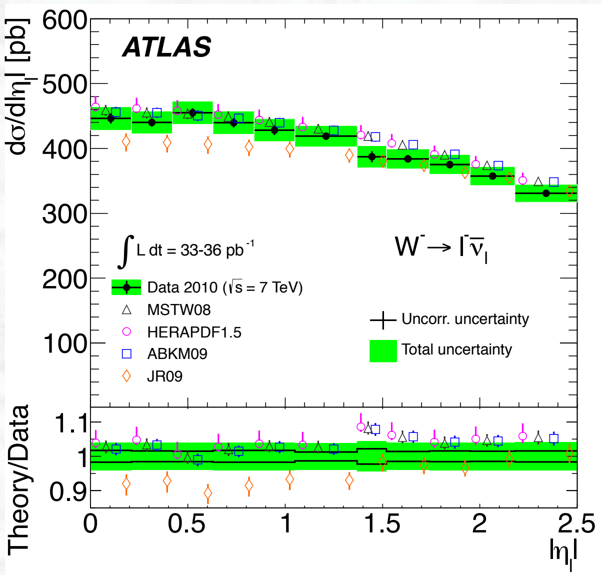


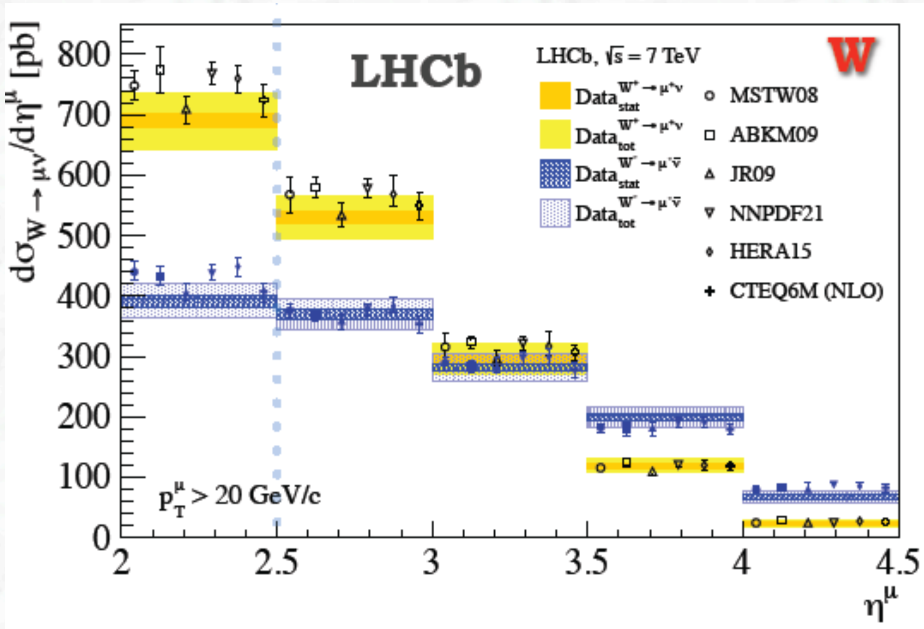
Leading order (tree level) contributions to W/Z production



Differential cross section measurements



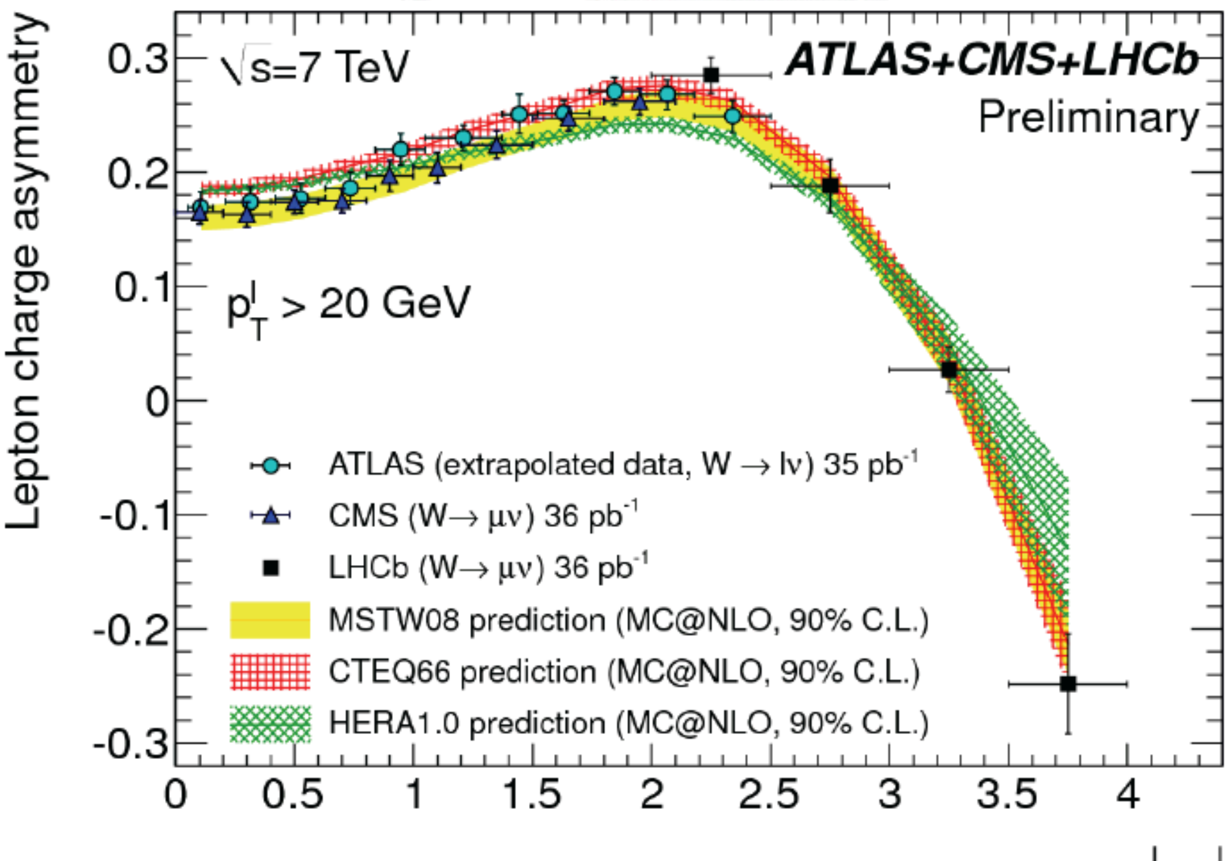




- Rough features of the measured differential cross sections are well described; (some tension at intermediate η region)
- Data start to be discriminating between pdf models;

These data will have impact on pdf uncertainties

W charge asymmetries



First LHC combined plot (LHC EWK WG)

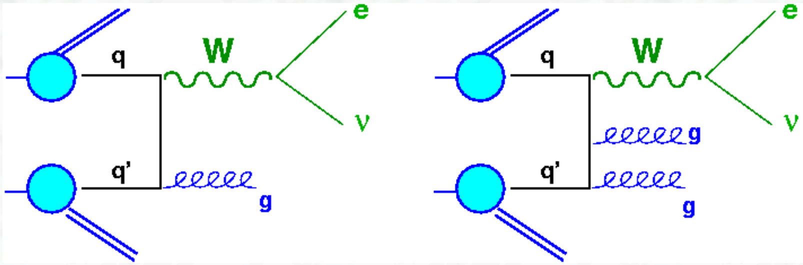
$$A(\eta_\ell) = \frac{d\sigma_{W+}(\eta_\ell) - d\sigma_{W-}(\eta_\ell)}{d\sigma_{W+}(\eta_\ell) + d\sigma_{W-}(\eta_\ell)}$$

All data are unfolded,

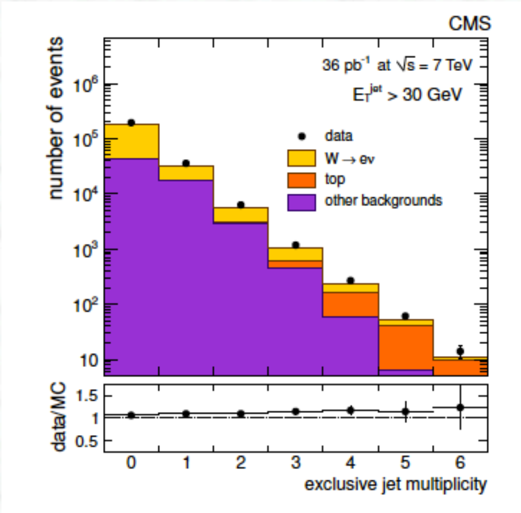
$P_T(l) > 20$ GeV

- Combination of the LHC experiments leads to large η coverage interesting constraints already today

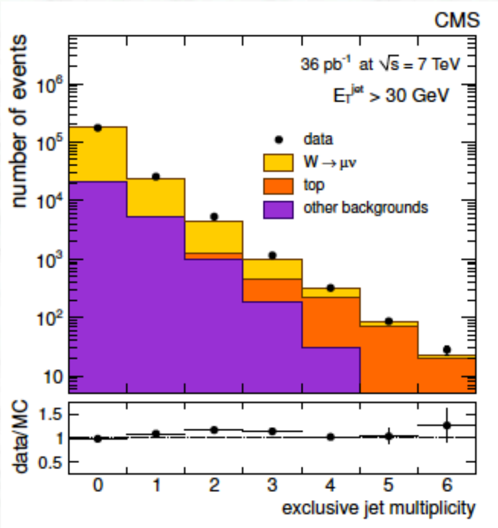
QCD Test in W/Z + jet production



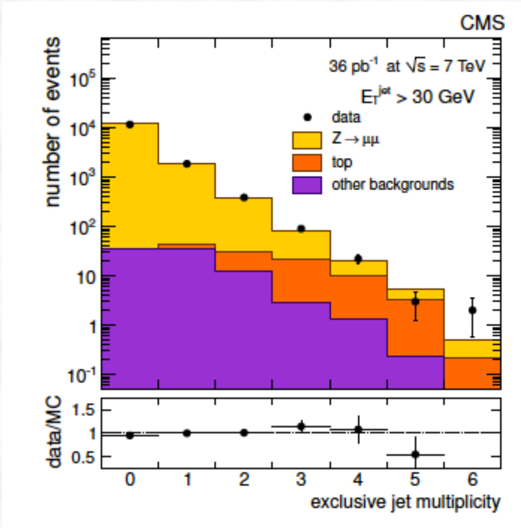
- CMS inclusive spectra of jets associated to W/Z production (36 pb^{-1});
- At detector level, compared to Monte Carlo Simulation (Madgraph + PYTHIA) (normalized to (N)NLO calculations)



W → eν



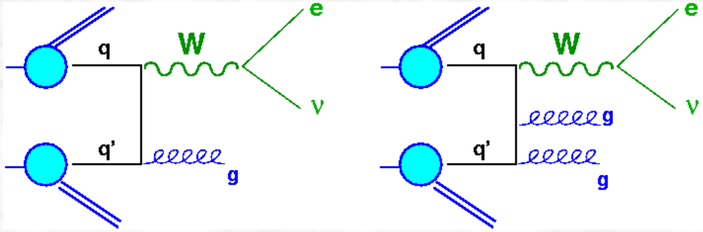
W → μν



Z → μμ

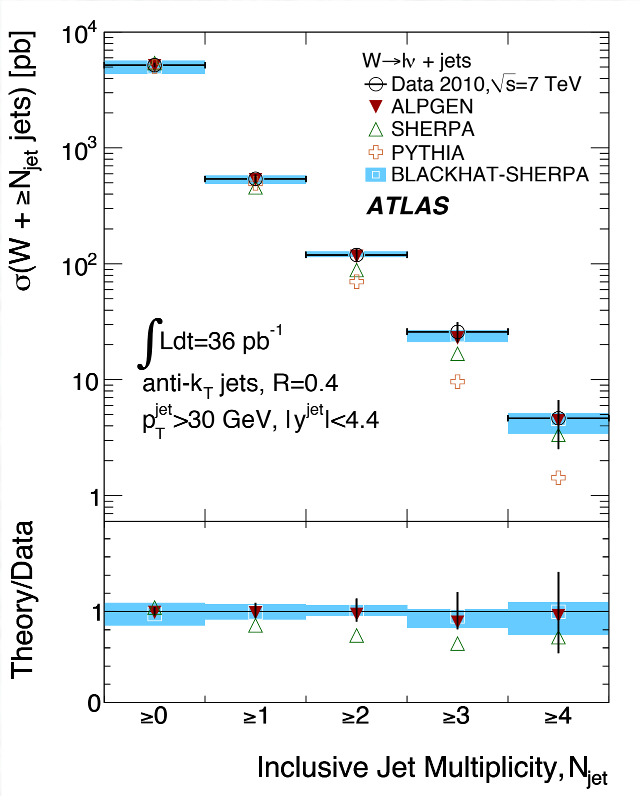
- Good agreement at that stage (jets with p_T > 30 GeV),
- Top contribution clearly visible in high multiplicity bins of W + jet production

W/Z + jet cross section measurements

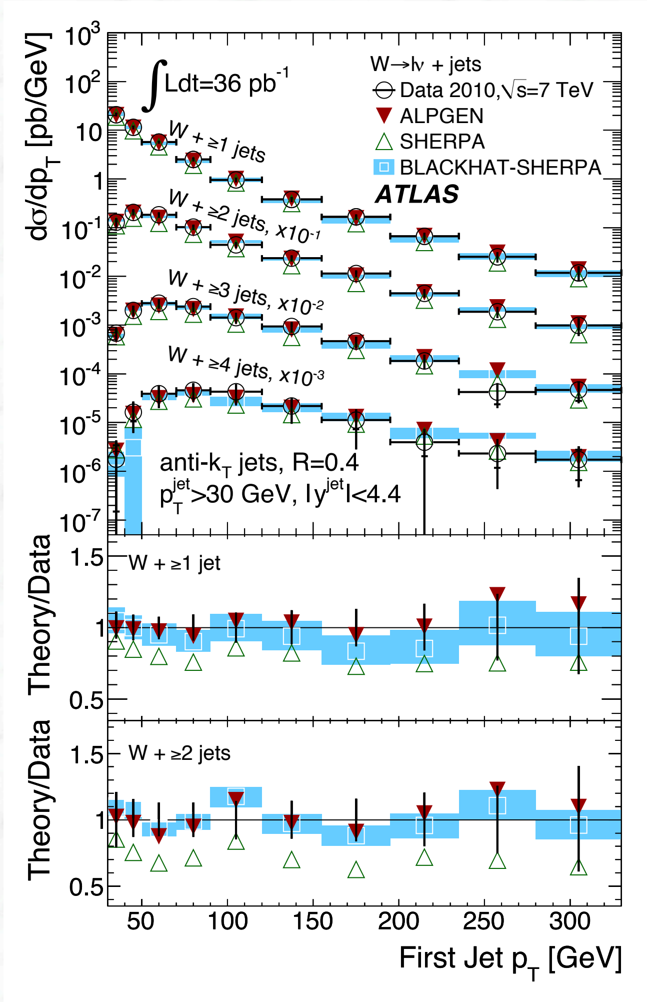


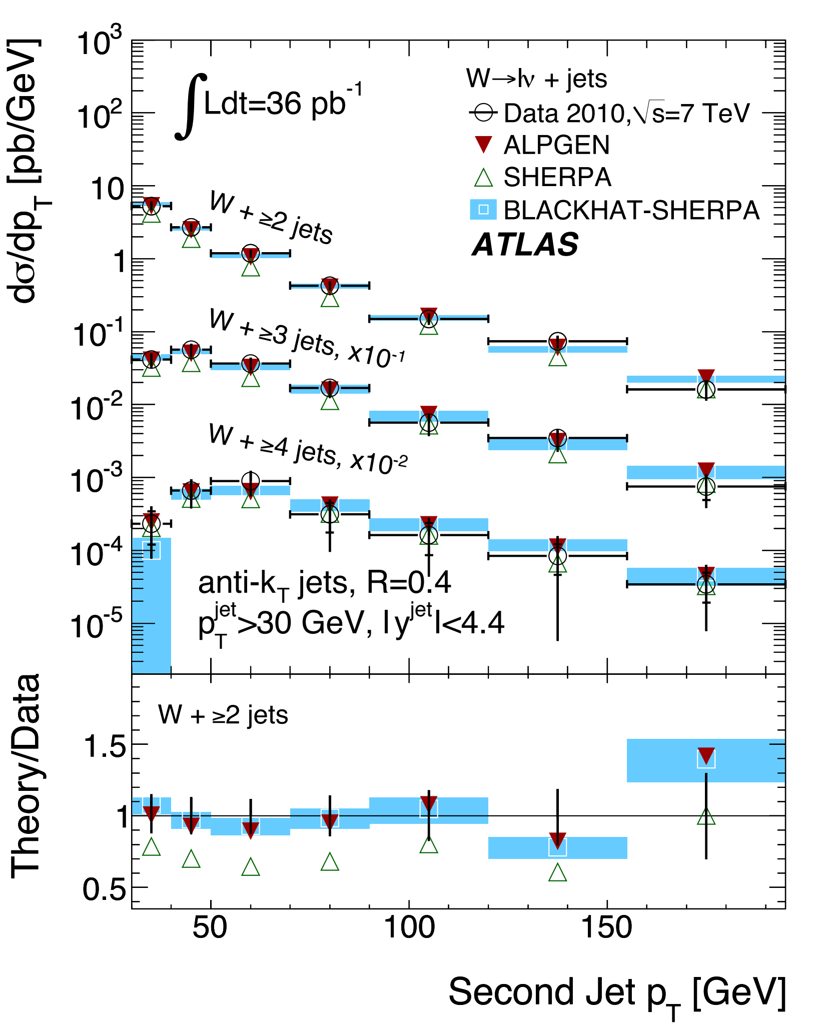
- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors;

Jet multiplicities in W+jet production

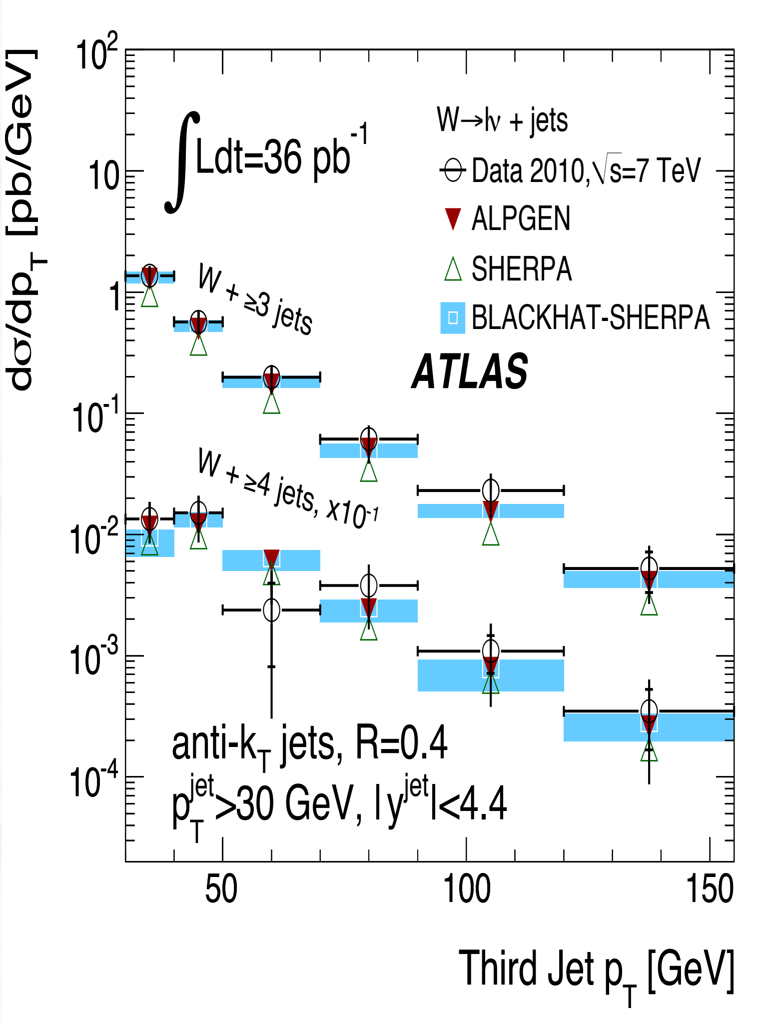


p_T spectrum of leading jet





$\int$Ldt=36 pb^{-1}
W→lν + jets
Data 2010,√s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
ATLAS
W + ≥2 jets
W + ≥3 jets, x10^{-1}
W + ≥4 jets, x10^{-2}
anti-k$_T$ jets, R=0.4
p$_T^{jet}$>30 GeV, |y^{jet}|<4.4
dσ/dp$_T$ [pb/GeV]
Theory/Data
W + ≥2 jets
Second Jet p$_T$ [GeV]

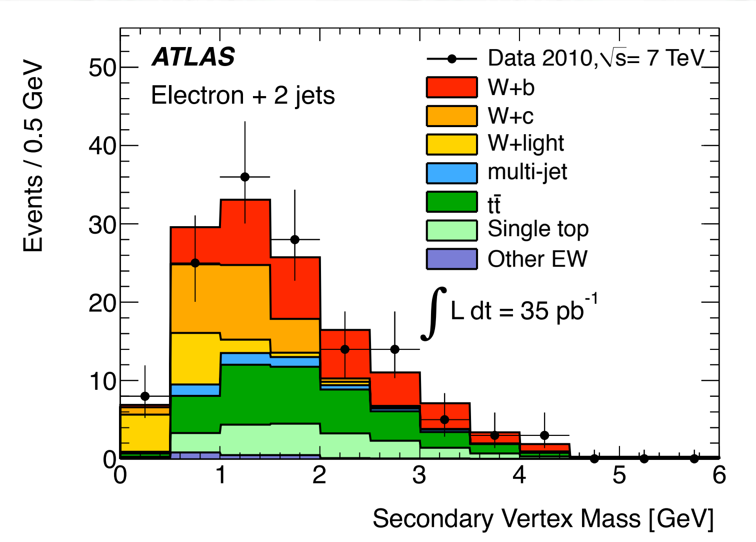


$\int$Ldt=36 pb^{-1}
W→lν + jets
Data 2010,√s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
ATLAS
W + ≥3 jets
W + ≥4 jets, x10^{-1}
anti-k$_T$ jets, R=0.4
p$_T^{jet}$>30 GeV, |y^{jet}|<4.4
dσ/dp$_T$ [pb/GeV]
Third Jet p$_T$ [GeV]

W + b jets

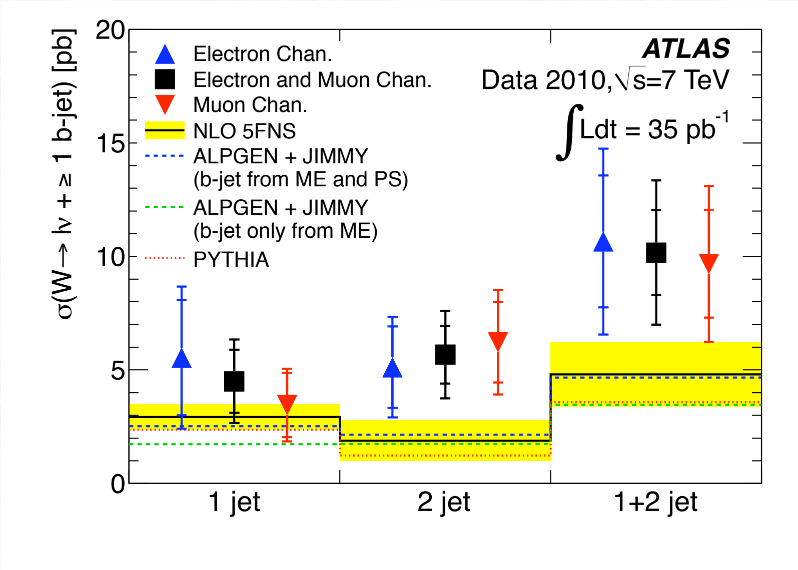
- Important background for many studies (Higgs, SUSY, top)
- Measurements at the Tevatron exceed NLO prediction

- Measured by ATLAS using 2010 data sample
  - studied W + 1 jet and W + 2 jets
  - require at least one b-tagged jet



W→ e ν + 2 jets

Distribution of the mass of the particles associated to the secondary vertex for b-tagged jets

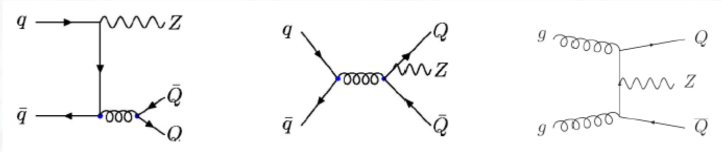


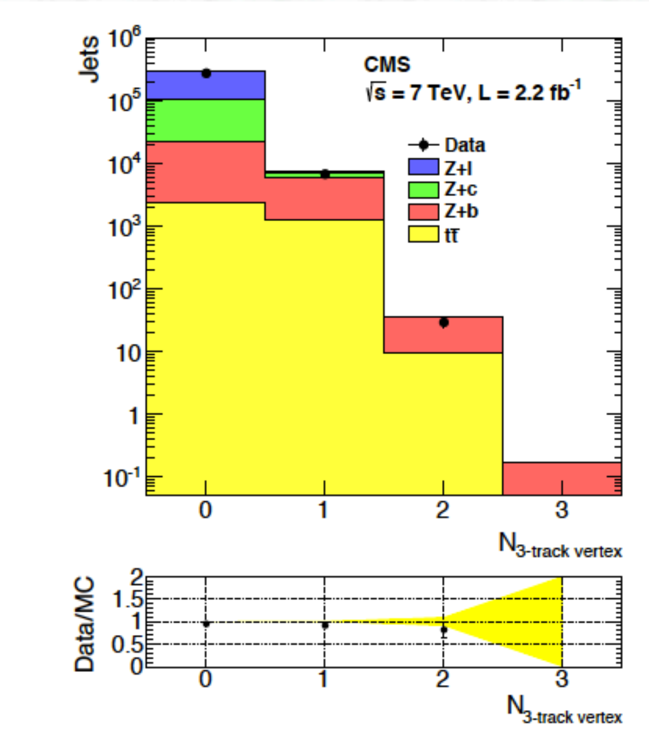
Results from e and μ combined. Measurements ~1.5σ above NLO prediction, but still consistent within uncertainties

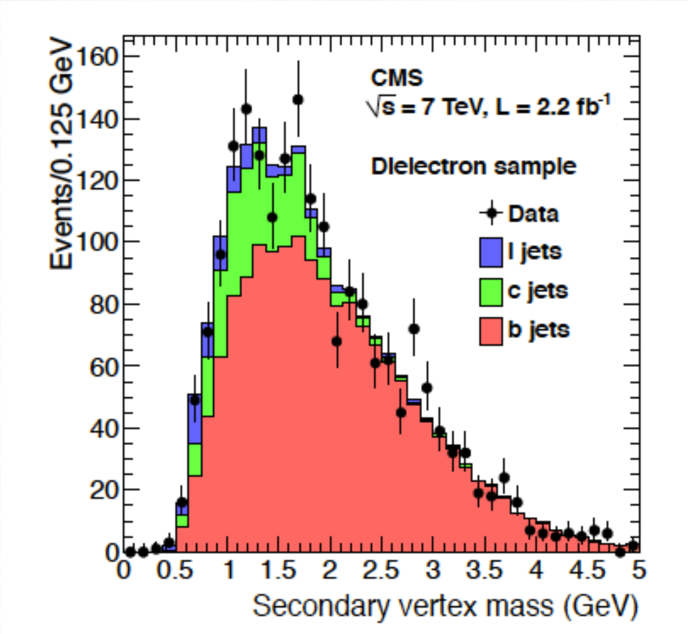
Z + b jets

- Important background for many studies (Higgs, SUSY, top)

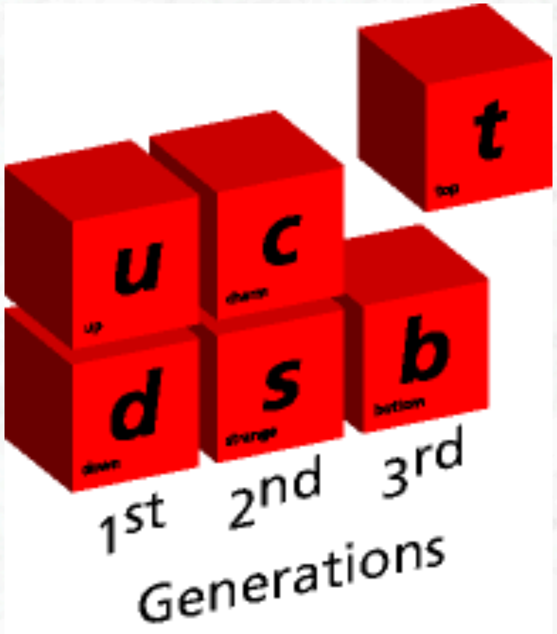
- Measured by CMS using 2011 data sample



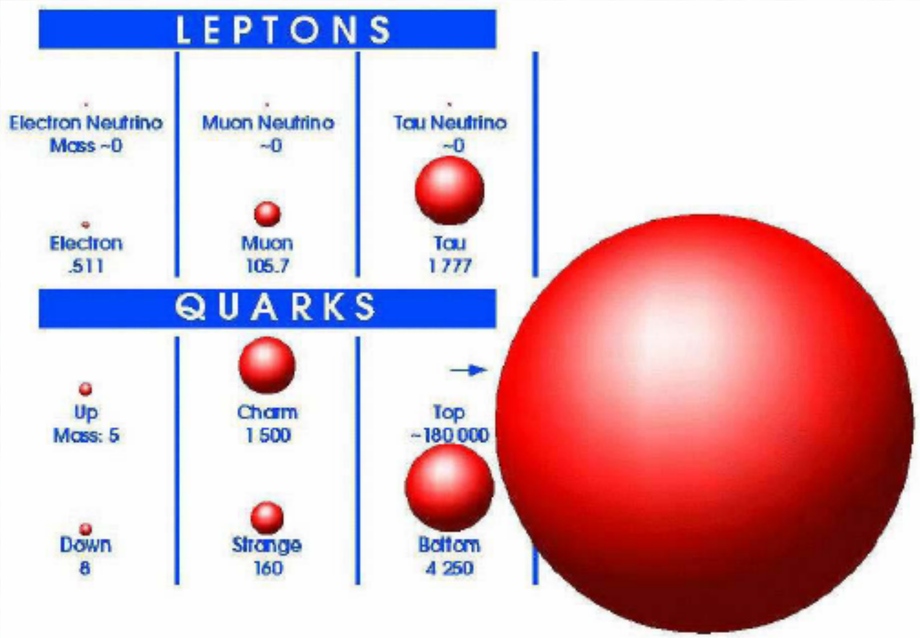




Top Quark Physics



Why is Top-Quark so important ?



The top quark may serve as a window to **New Physics** related to the electroweak symmetry breaking;

Why is its Yukawa coupling ~ 1 ??

$$M_t = \frac{1}{\sqrt{2}} \lambda_t v$$

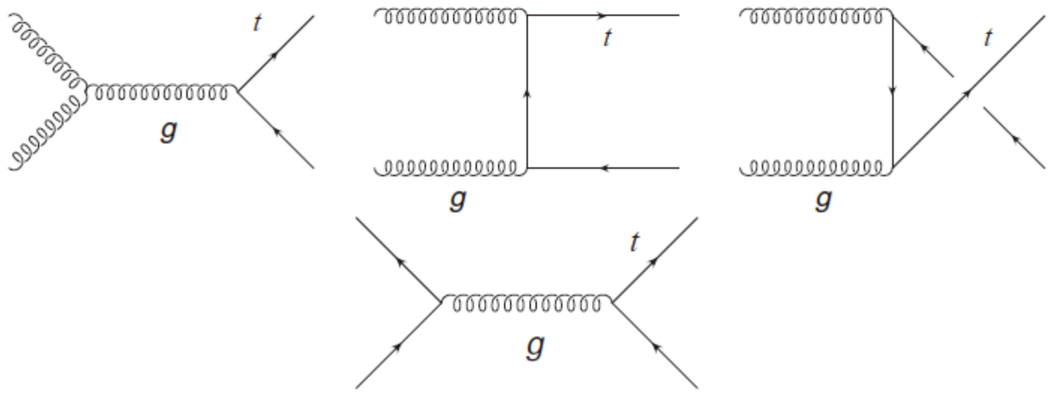
$$\Rightarrow \lambda_t = \frac{M_t}{173.9 \text{ GeV}/c^2}$$

- A unique quark: decays before it hadronizes, lifetime ~10^{-25} s
  no "toponium states"
  remember: bb, bd, bs….. cc, cs….. bound states (mesons)

- We still know little about the properties of the top quark:
  mass, spin, charge, lifetime, decay properties (rare decays), gauge couplings, Yukawa coupling,…

Top Quark Production

Pair production: qq and gg-fusion



Top-quark pair production in the Born approximation.

- NLO corrections completely known
- NNLO partly known

approximate NNLO results:

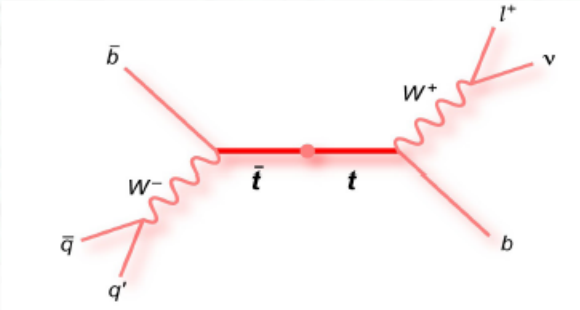
$$\sigma_{\mathrm{LHC}} = (887^{+9}_{-33}\,(\mathrm{scale})^{+15}_{-15}\,(\mathrm{PDF}))\ \mathrm{pb} \qquad (14\ \mathrm{TeV}),$$

$$\sigma_{\mathrm{Tev}} = (7.04^{+0.24}_{-0.36}\,(\mathrm{scale})^{+0.14}_{-0.14}\,(\mathrm{PDF}))\ \mathrm{pb} \qquad (1.96\ \mathrm{TeV}).$$

	Tevatron 1.96 TeV	LHC 14 TeV
qq gg	85% 15%	5% 95%
σ (pb)	7.0 pb	887 pb

For LHC running at √s = 7 TeV, the cross section is reduced by a factor of ~5, but it is still a factor 25 larger than the cross section at the Tevatron

Top Quark Decays



BR ($t \to Wb$) ~ 100%

Dilepton channel:

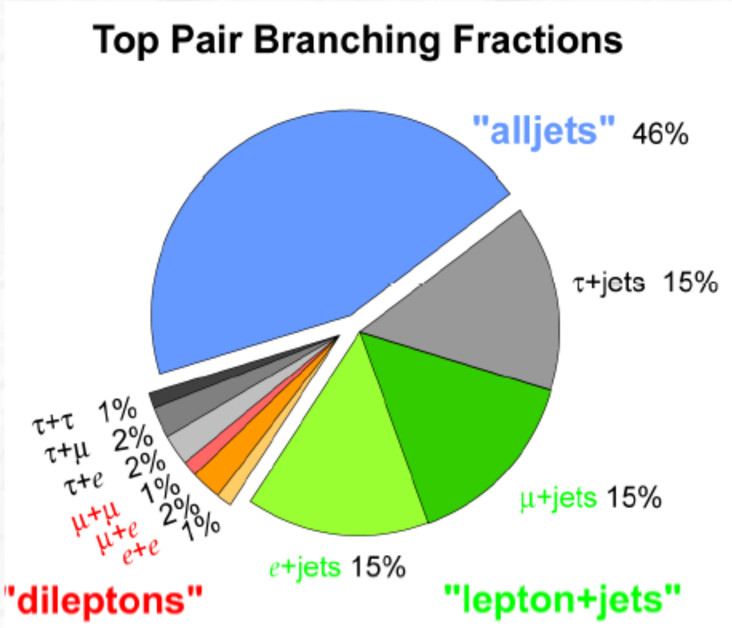
Both W's decay via $W \to \ell\nu$ (ℓ=e or μ; 4%)

Lepton + jet channel:

One W decays via $W \to \ell\nu$ (ℓ=e or μ; 30%)

Full hadronic channel:

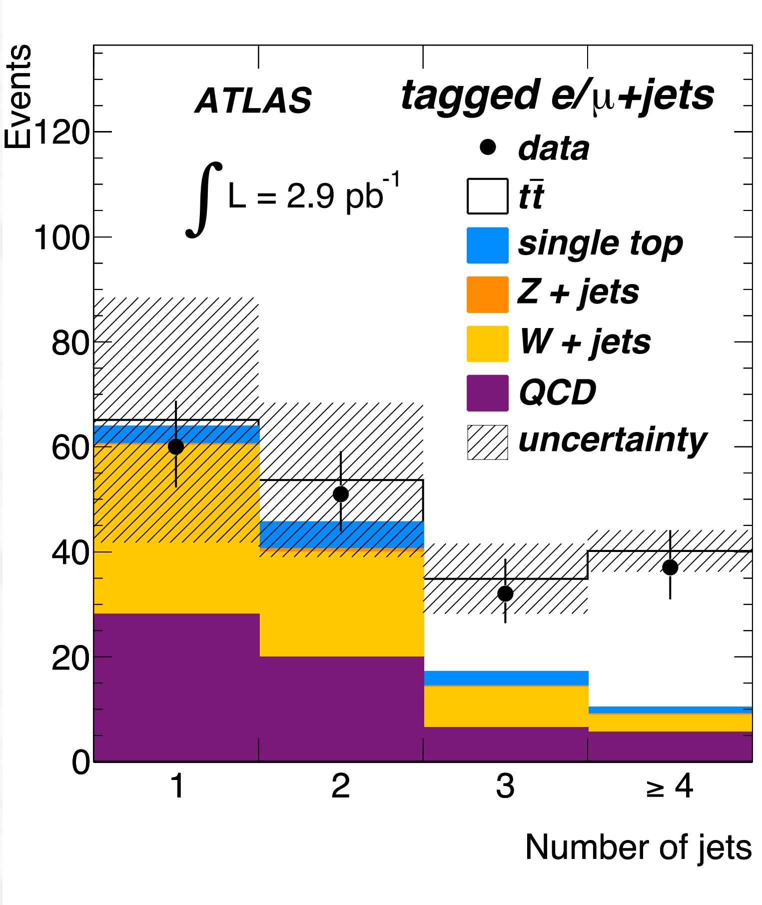
Both W's decay via $W \to qq$ (46%)



Important experimental signatures: : - Lepton(s)

- Missing transverse momentum
- b-jet(s)

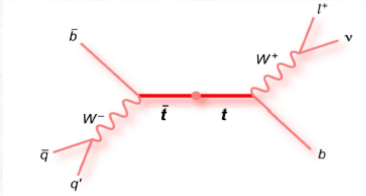
First results on top production from the LHC

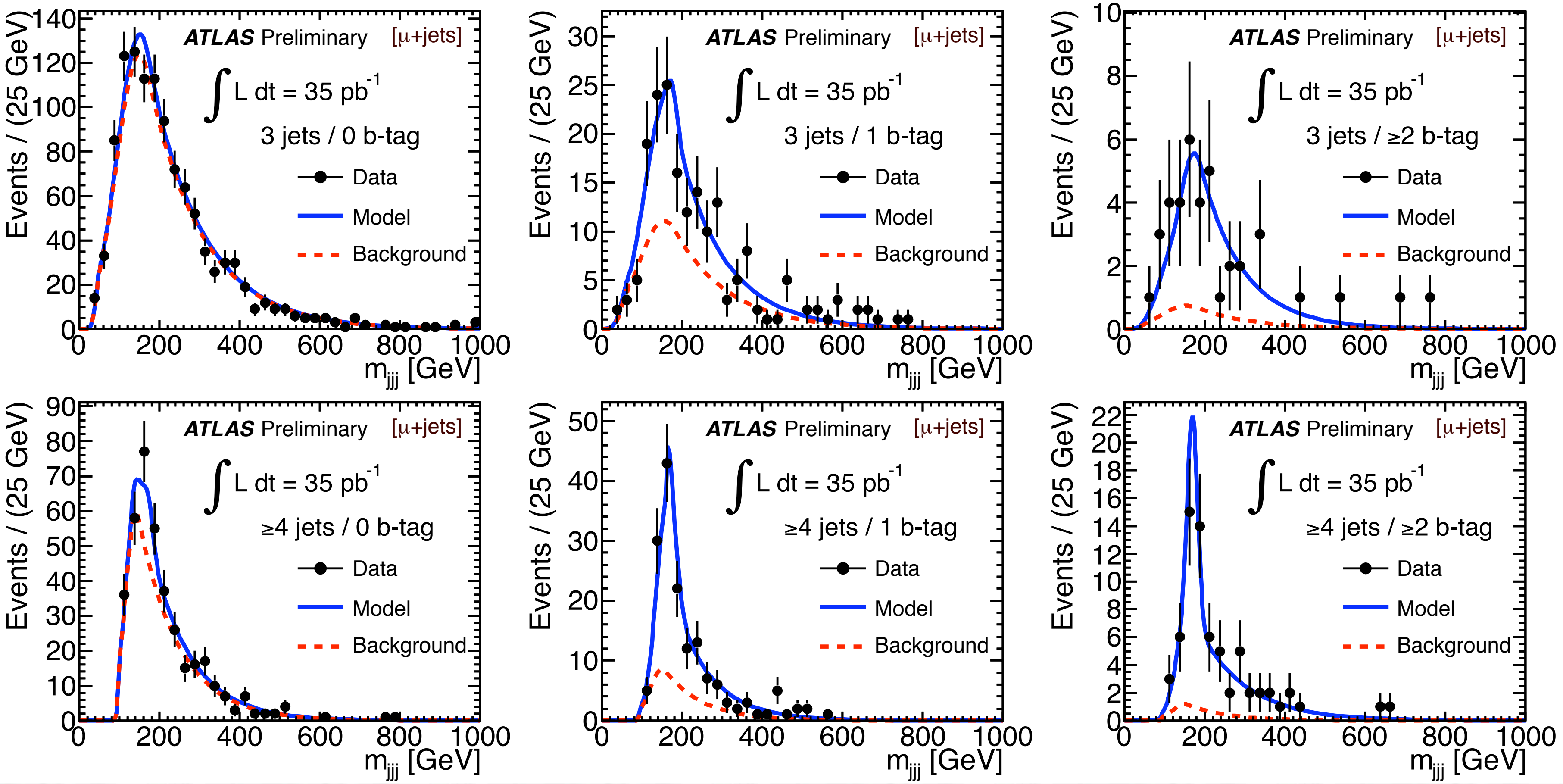


Event Selection:

- Lepton trigger
- One identified lepton (e,μ) with $p_T > 20$ GeV
- Missing transverse energy: $E_T^{miss} > 35$ GeV (significant rejection against QCD events)
- Transverse mass: $M_T(l,\nu) > 25$ GeV (lepton from W decay in event)
- One or more jets with $p_T > 25$ GeV and $\eta < 2.5$

Invariant mass distributions in the l-had channel



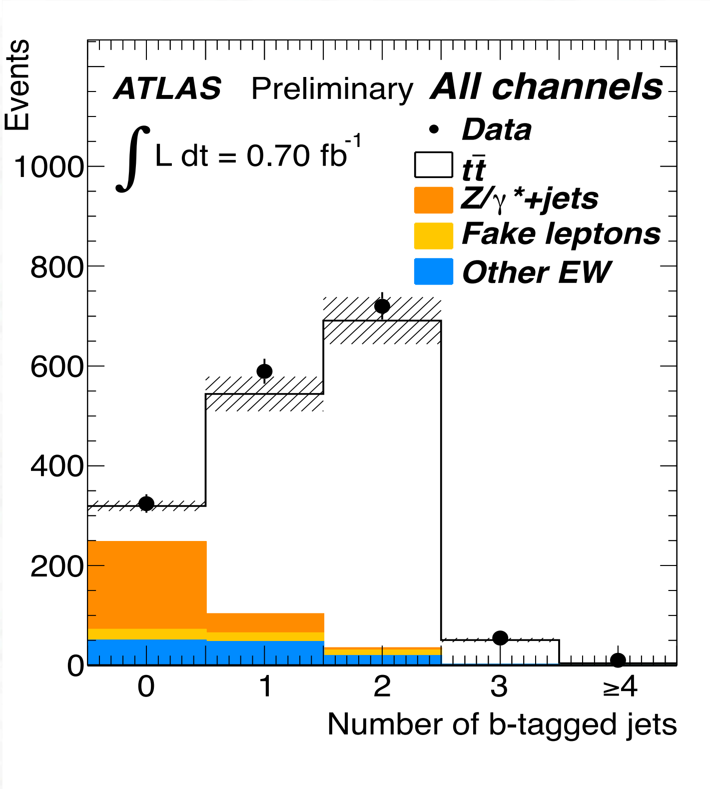


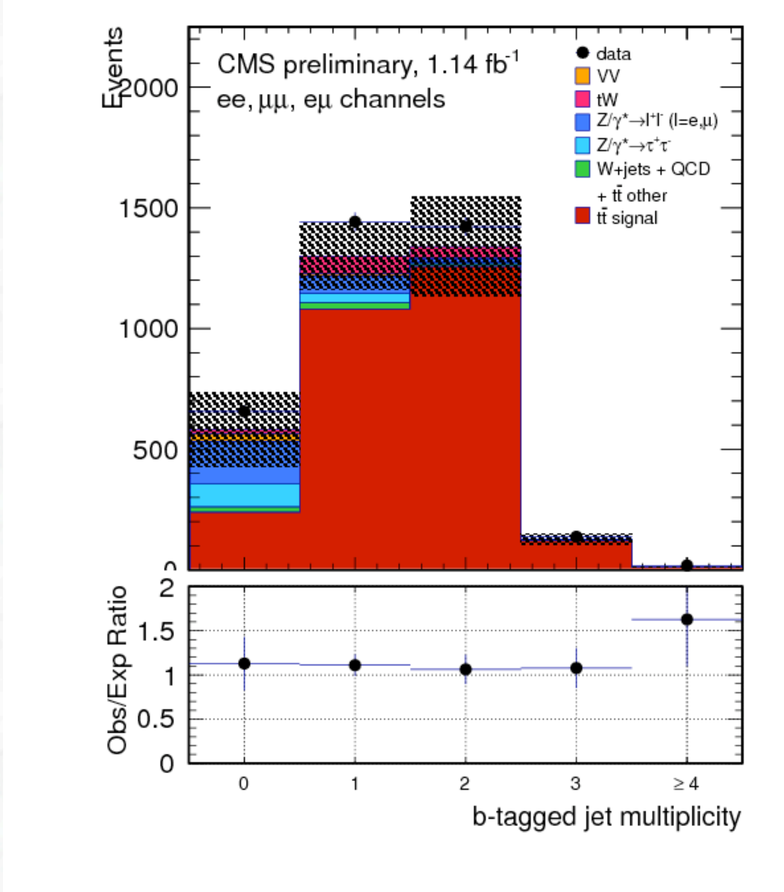
- Top fractions increase with number of b-tags
- Good description for all jet-multiplicity and b-tag combinations
- Data are consistent with top quark production with mass of 173 GeV

Top-quark production measured in many different decay modes

(i) Di-lepton selection in both ATLAS and CMS (0.7 fb^{-1} – 1.14 fb^{-1})

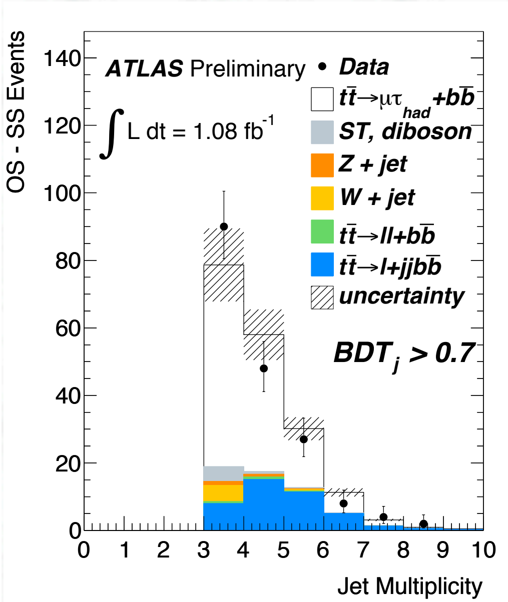
Multiplicity distributions of b-tagged jets
(small backgrounds, mainly from Z+jet production)

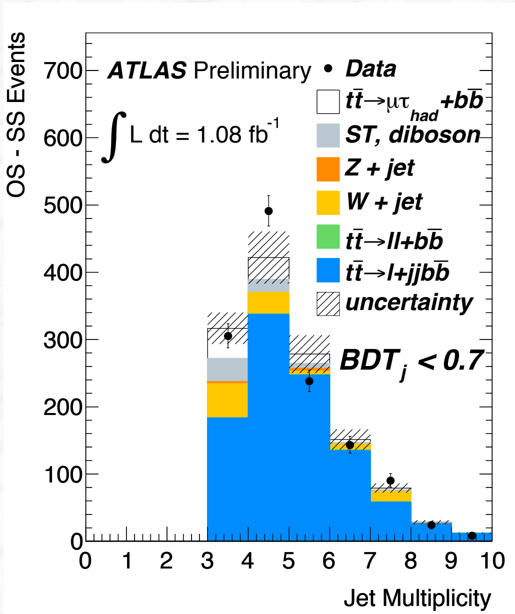


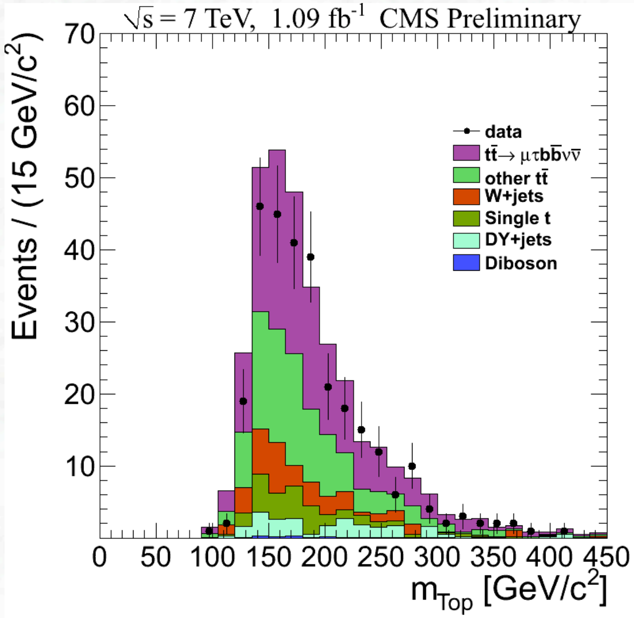


(ii) $\mu + \tau$ final states in both ATLAS and CMS (0.7 fb^{-1} – 1.14 fb^{-1})

Require: μ + hadronically decaying τ, E_T^{miss} + b-jets
(significant backgrounds, but signal contribution needed)





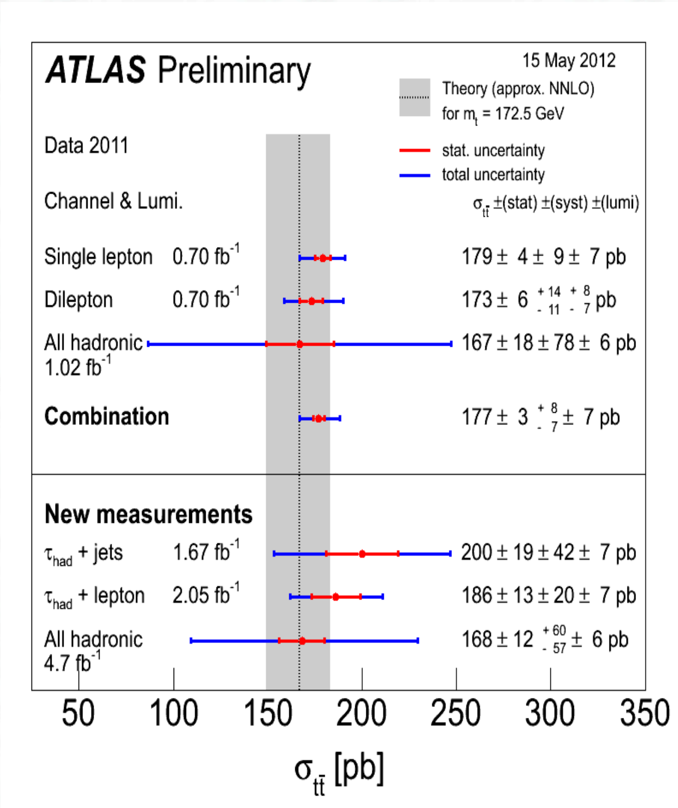


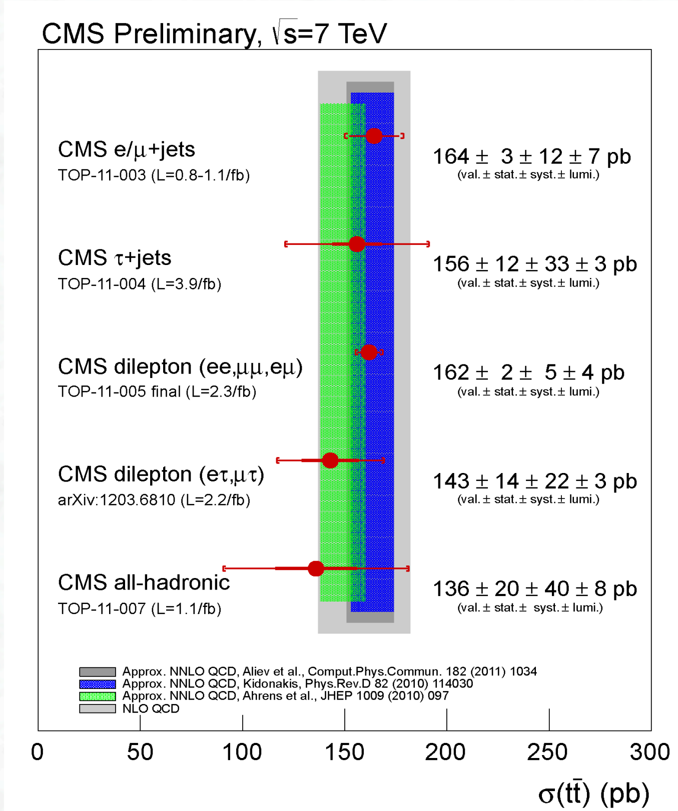
ATLAS: Multivariate analysis
Jet multiplicity distribution in signal (left)
and background (right) regions

reconstructed mass in CMS

Top pair production cross section measurements

-likelihood combination of all channels-





σ = 177 ± 3 (stat) ± 7 (syst) ± 7 (lum) pb

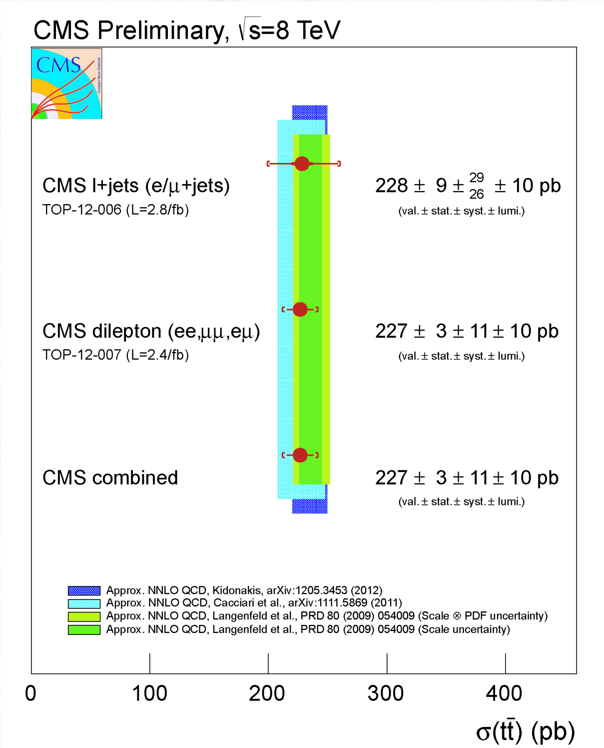
σ = 165.8 ± 2.2 (stat) ± 10.6 (syst) ± 7.8 (lum) pb

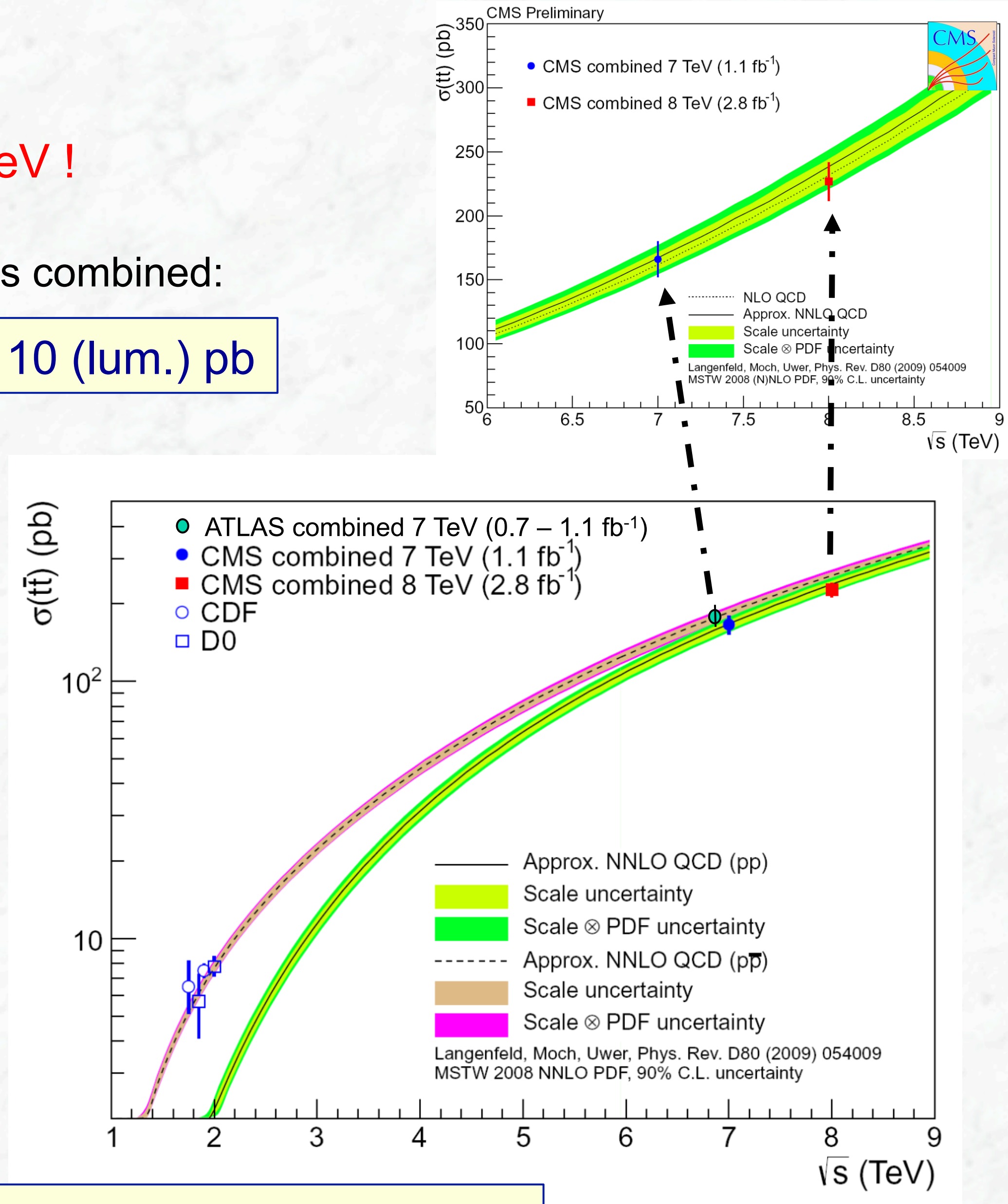
- Perturbative QCD calculations (approx. NNLO) describe the data well;
- The two LHC experiments agree within the systematic uncertainties
- Total uncertainty already at the level of ±6%

- CMS: new measurement at 8 TeV !

- Lepton + jets and di-lepton channels combined:

σ = 227 ± 3 (stat) ± 11 (syst.) ± 10 (lum.) pb



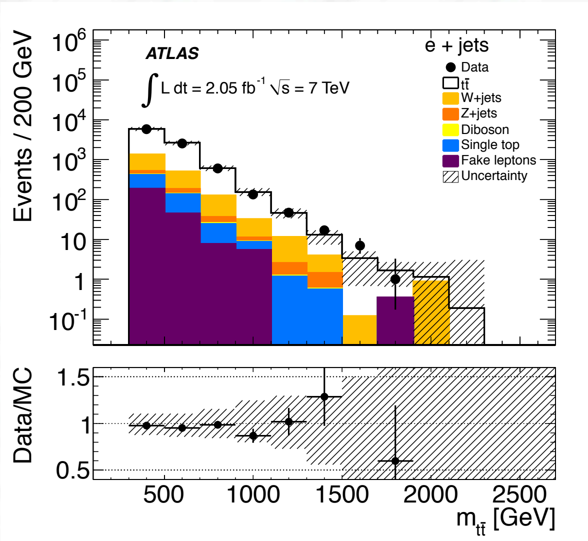


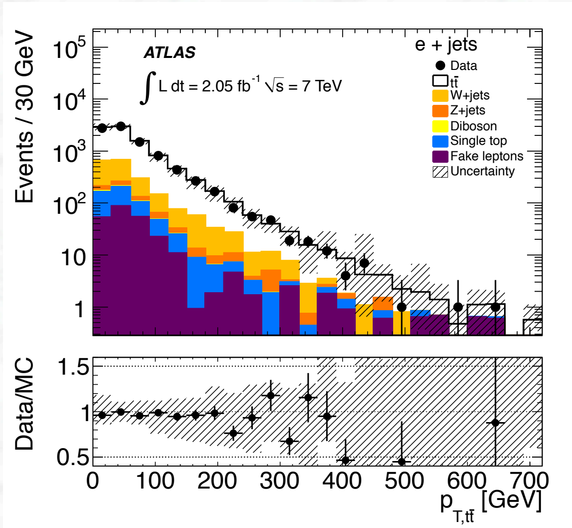
σ(8TeV)/σ(7TeV) = 1.41 ± 0.11; no correlation assumed

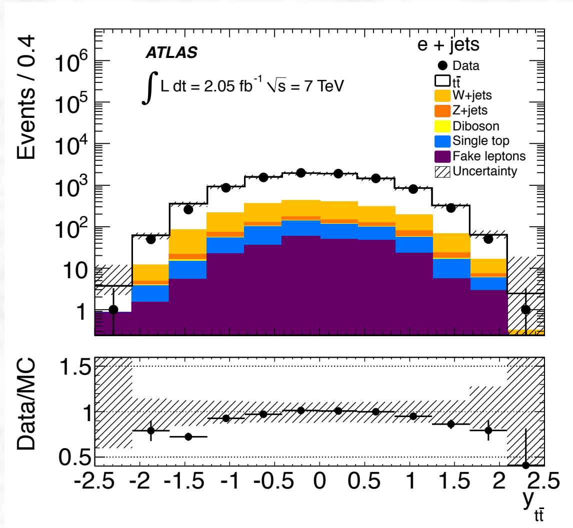
Top-antitop differential cross sections

- Important test of the Standard Model (perturbative QCD), deviations may indicate new physics
  e.g. new particles (resonances) decaying into tt, or other new/unexpected effects (→ Tevatron charge asymmetry)

- Important variables studied: - tt mass distribution
  - Rapidity y and p_T of the tt system



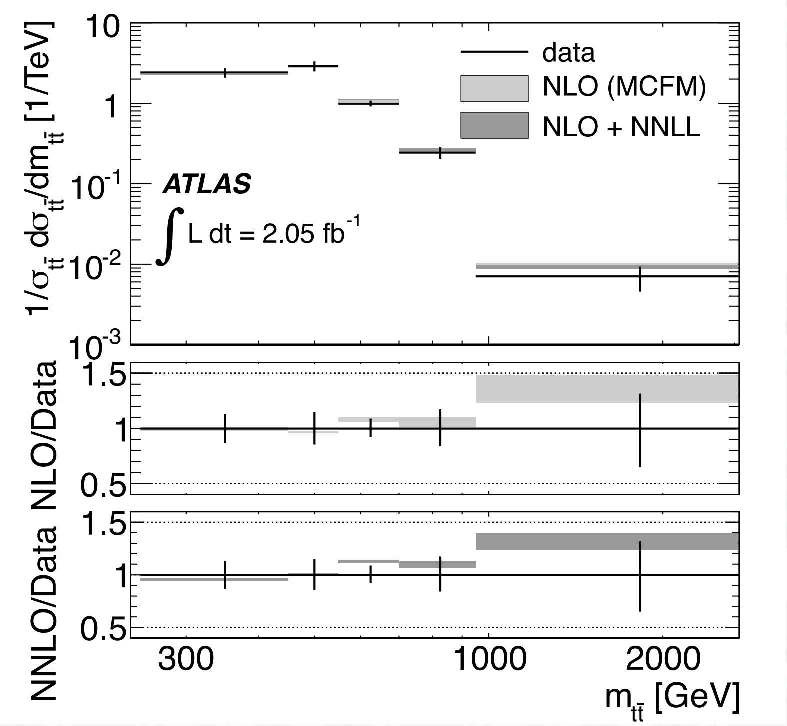


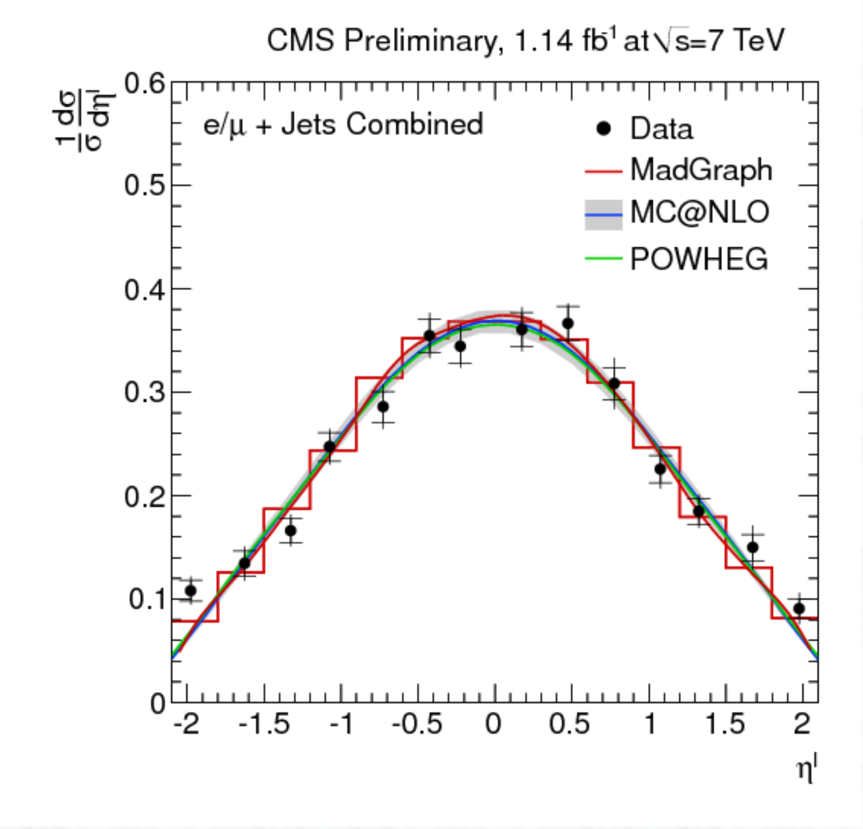


ATLAS comparison on detector level shows good agreement in all variables (background partially extracted from data)

→ not much room left / no signs yet of Physics beyond the Standard Model (more in the lecture of M. Narain)

- Both collaborations have unfolded the detector effects and have extracted differential cross-section measurements (normalized to the tt cross section → sensitivity in shapes of distributions)





new