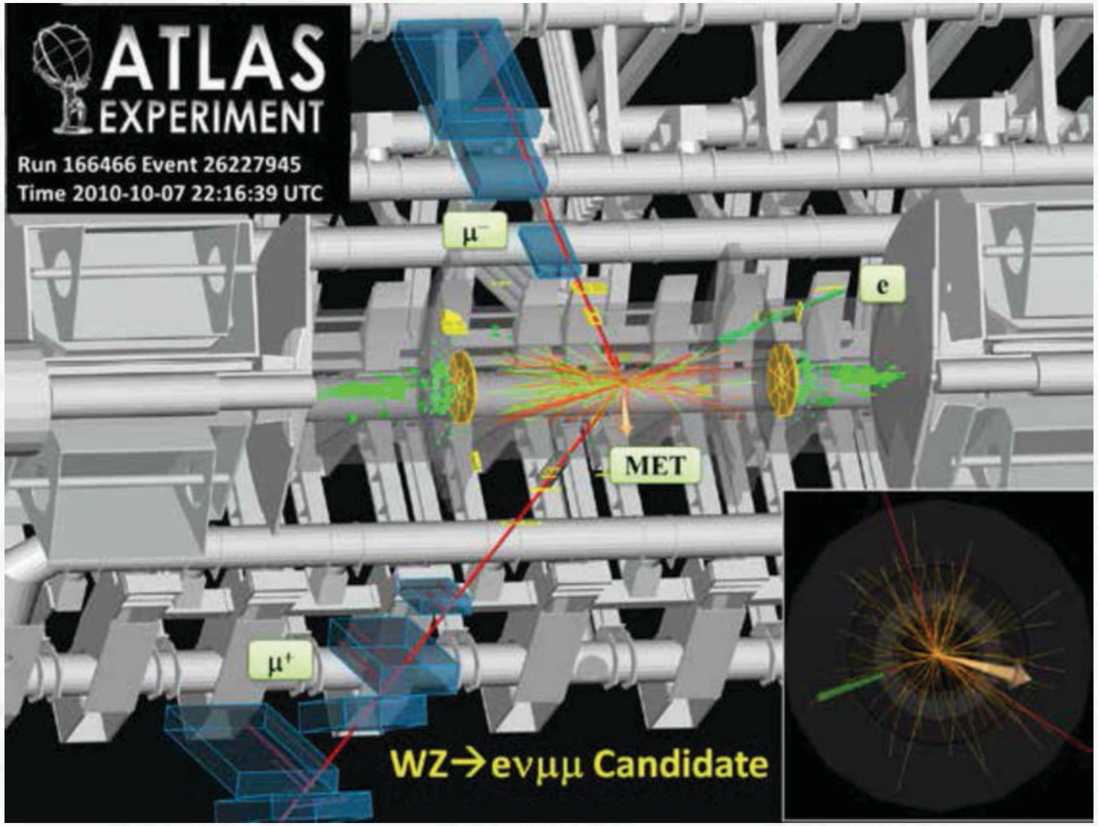
Physics at the LHC

- From the Standard Model to Searches for New Physics-



Karl Jakobs
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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

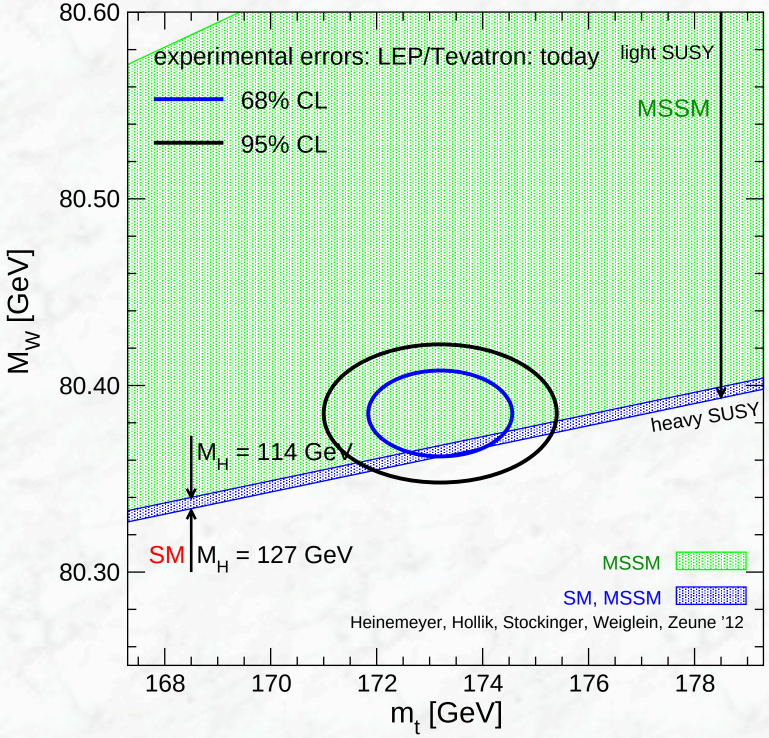
2. **Precise tests of the Standard Model**

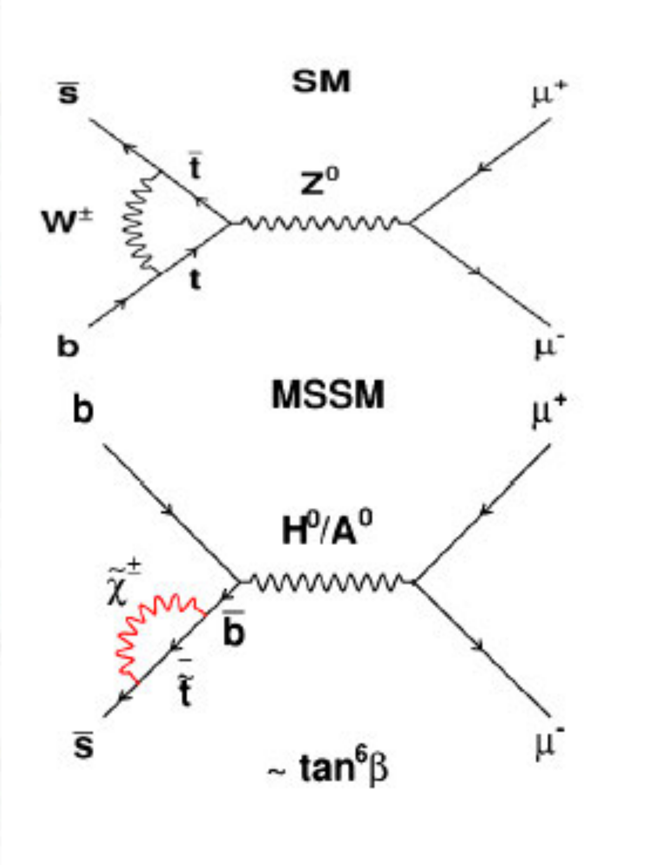
- There is much sensitivity to physics beyond the Standard Model in the precision area (loop-induced effects, probe energy scales far beyond direct reach)
  → precise measurements, search for rare processes

→ Guidance to theory and Future Experiments

Two important examples:

2012





Ultimate test of the Standard Model:

Compare indirect prediction of the Higgs boson mass with direct observation

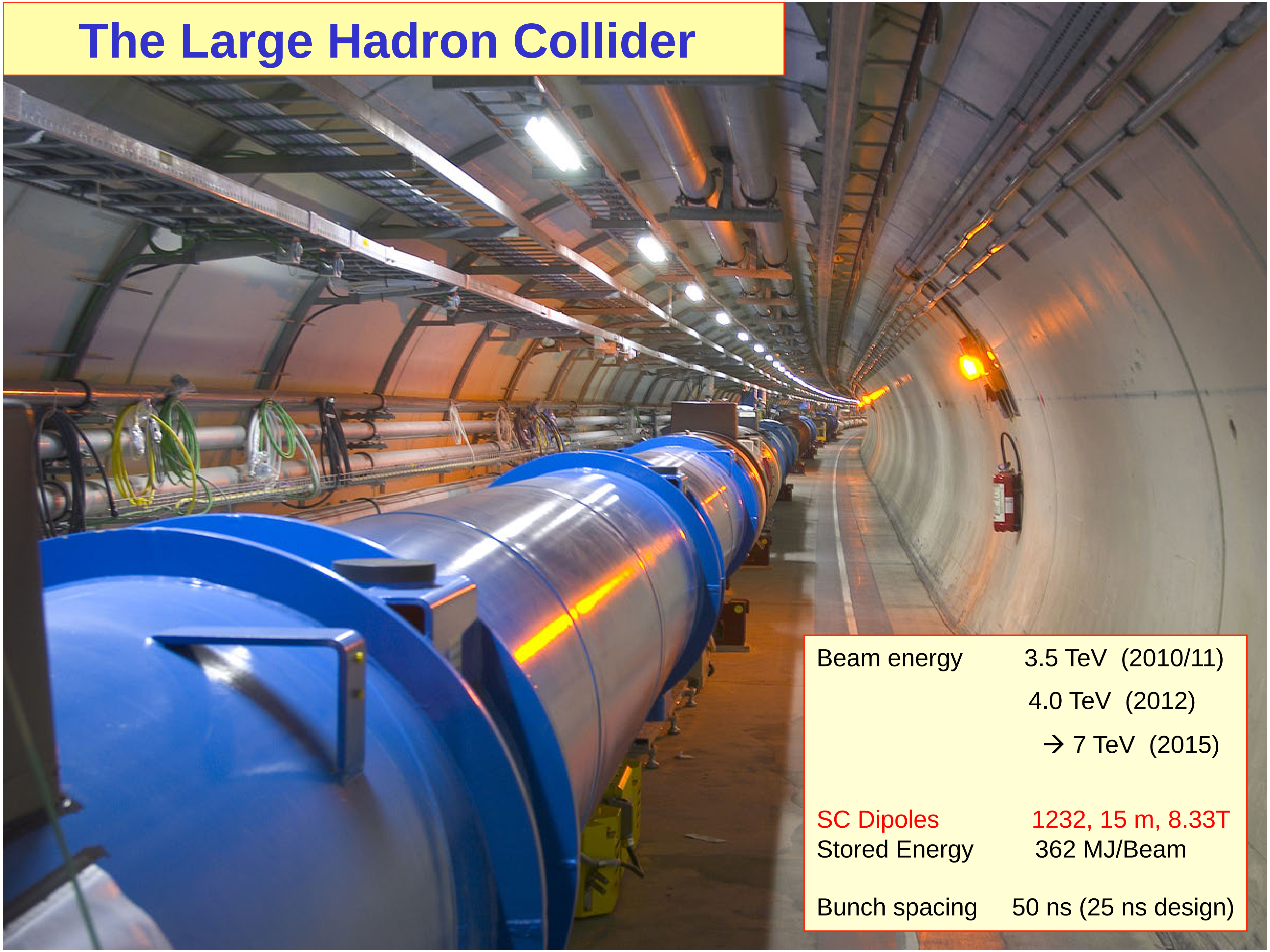
Many theoretical models
for physics Beyond the
Standard Model

The LHC
- a new era in particle physics-

Steve Meyers at “Phyics at LHC 2012”:

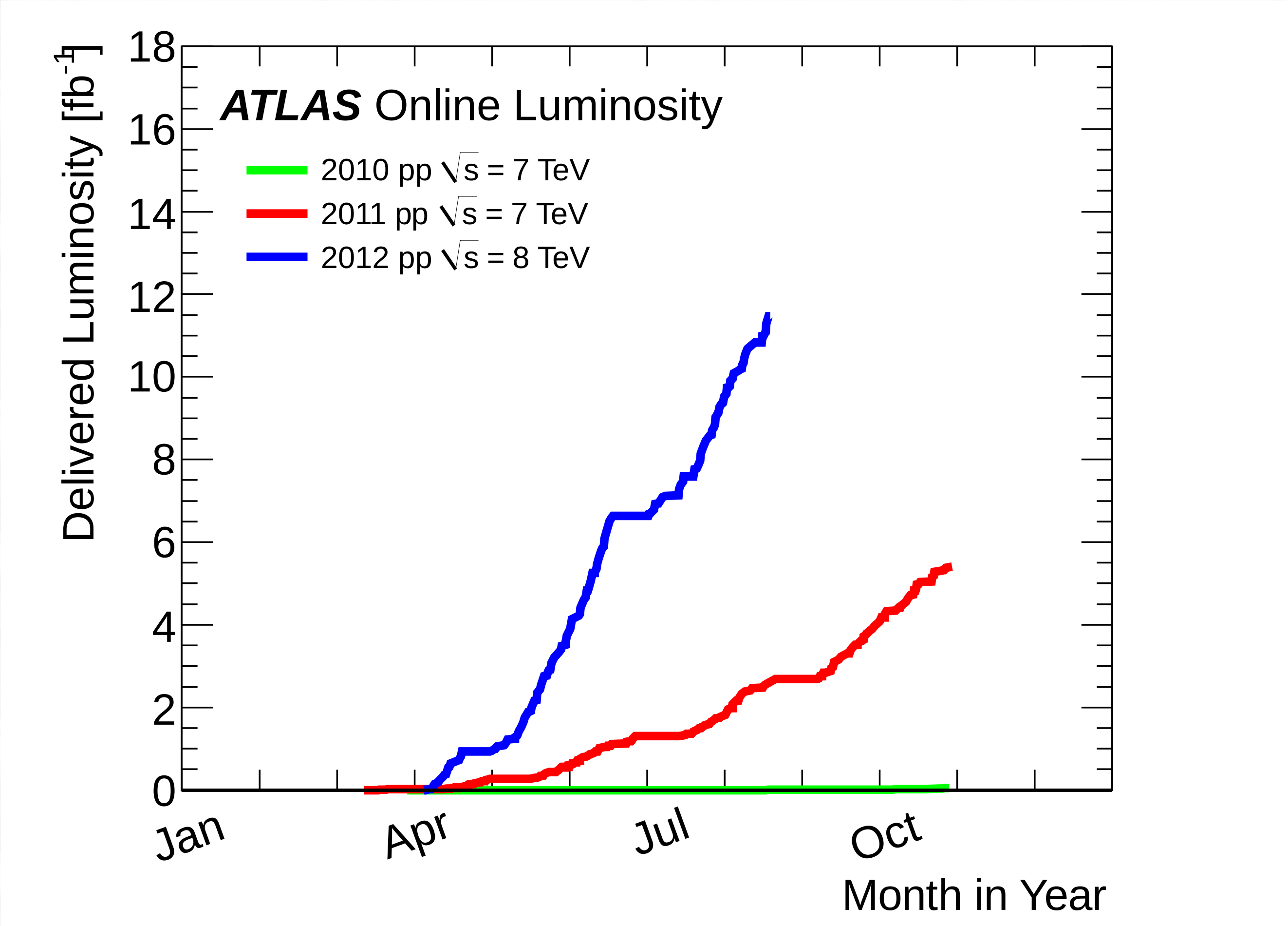
“The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics.”

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)

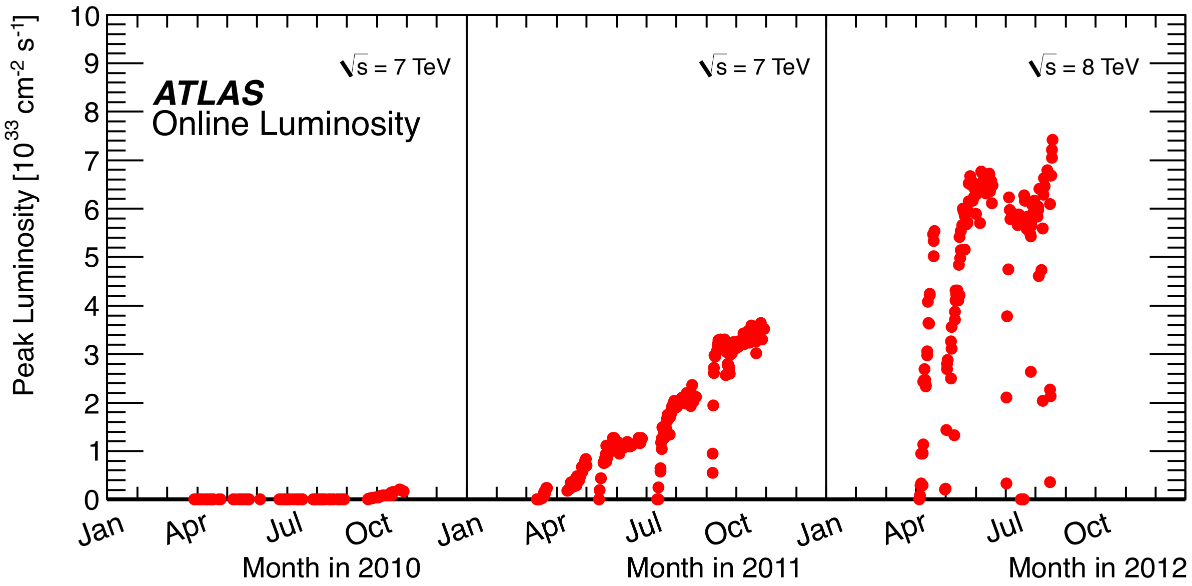
The LHC integrated luminosity

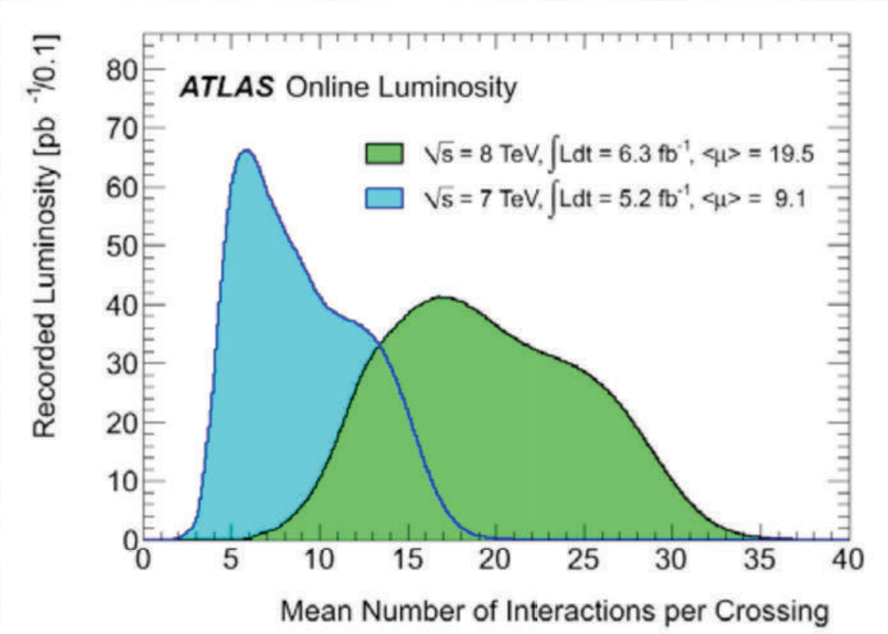


Very rapid rise in luminosity + good machine stability

→ high integrated luminosities

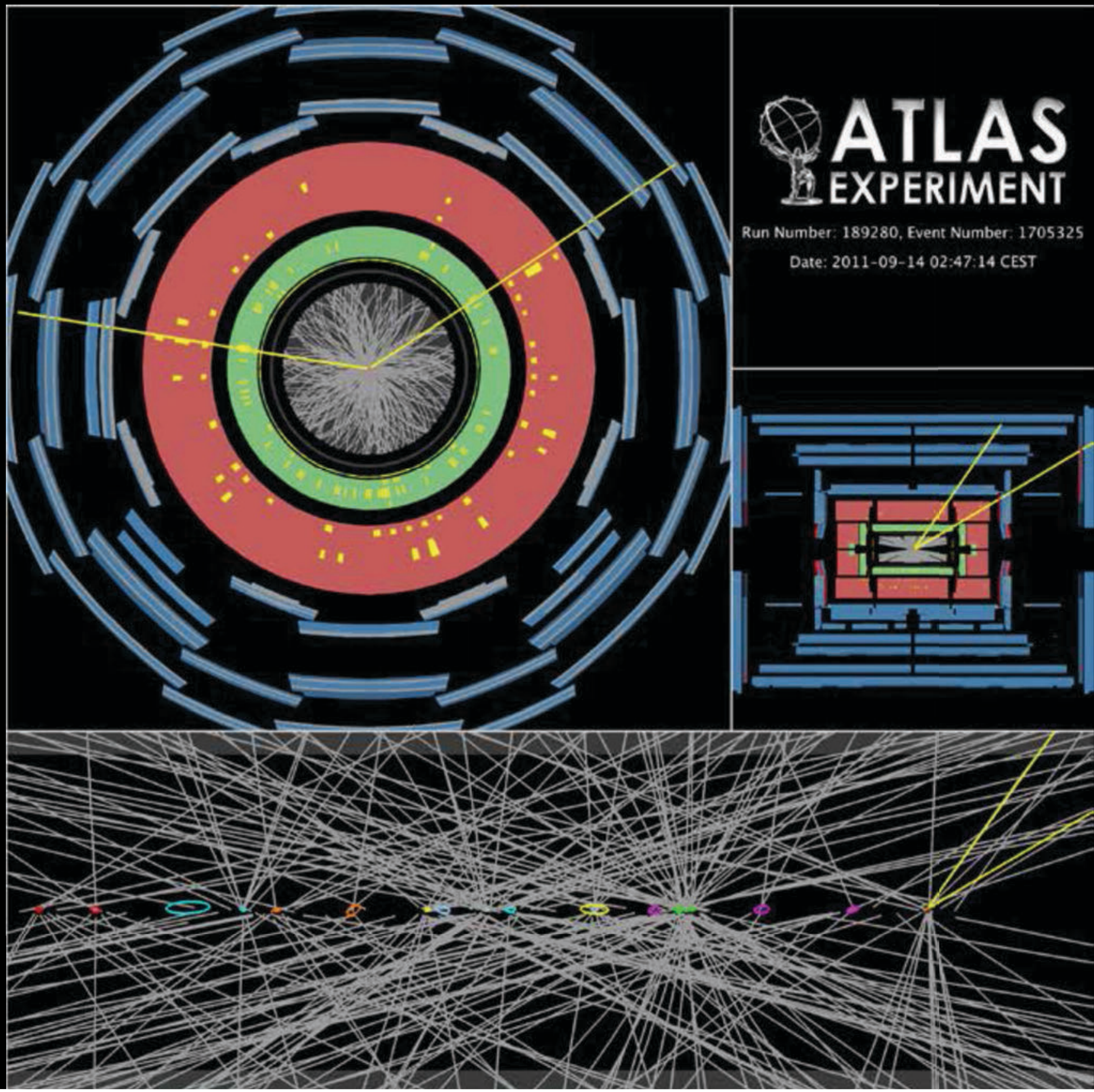
The LHC instantaneous luminosity





- 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

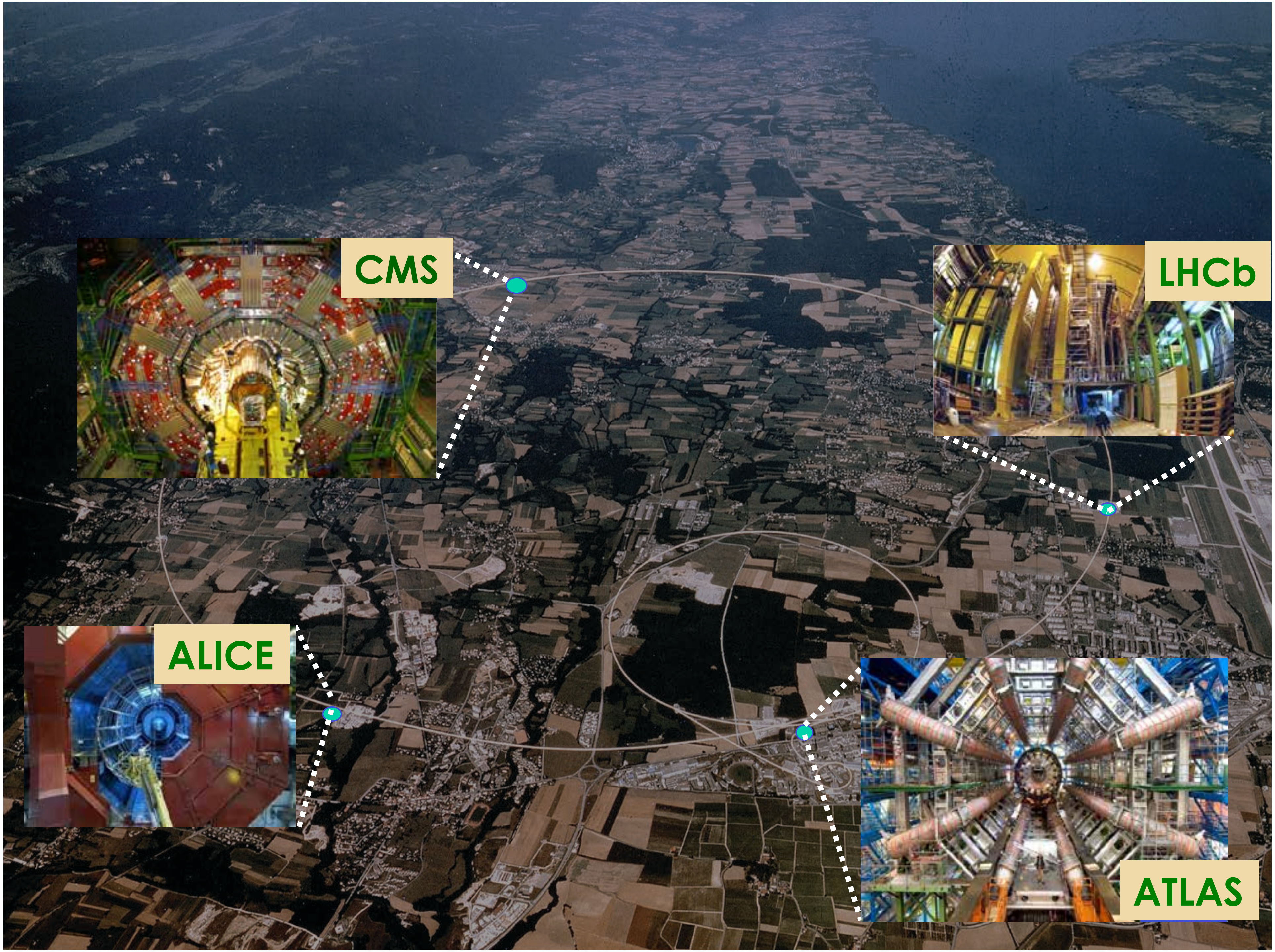
- GRID pioneers

Major discoveries

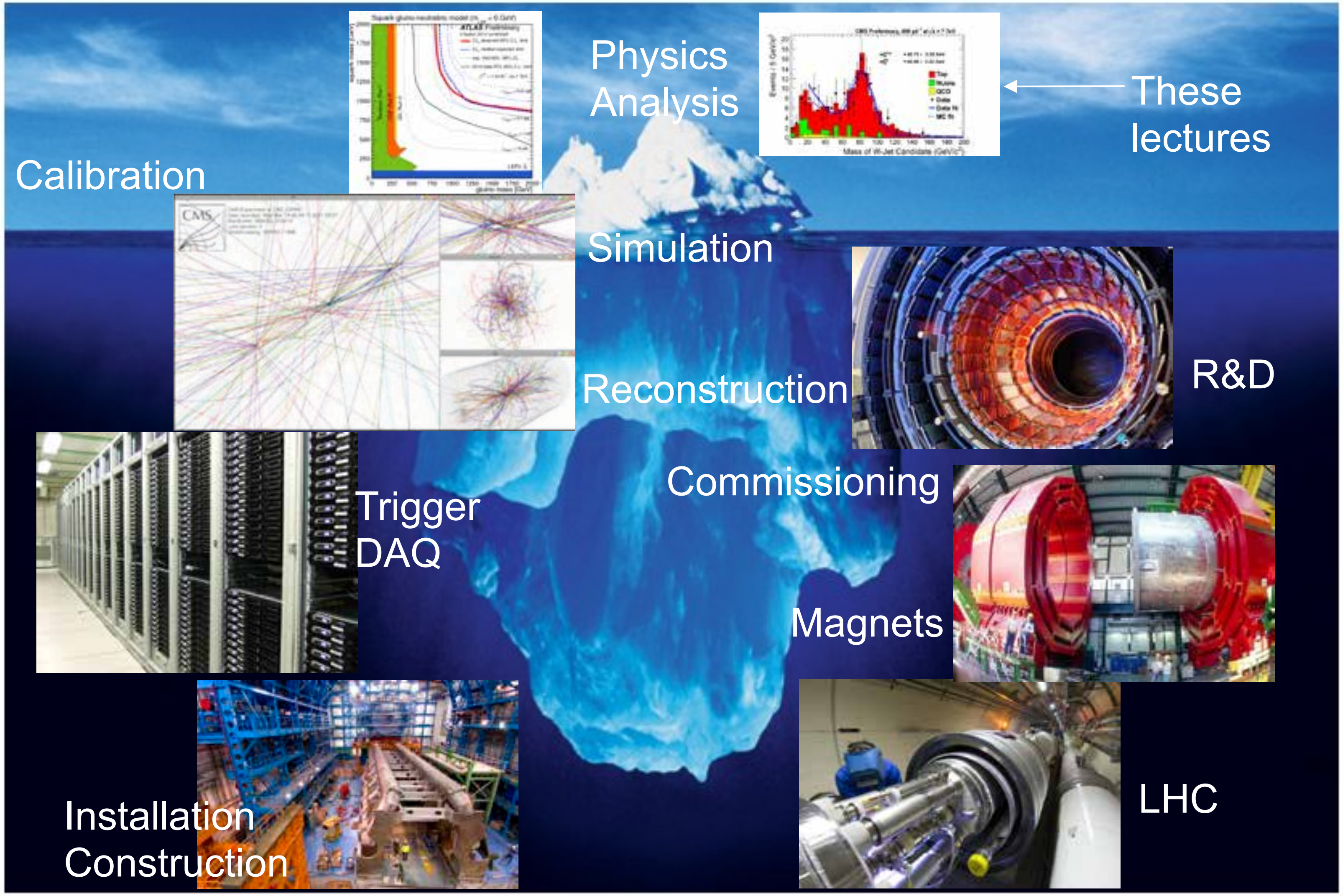
- Top quark
- B_s mixing
- Precision W and Top mass → Higgs mass prediction
- Direct Higgs searches
- Ruled out many exotica

The next generation

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

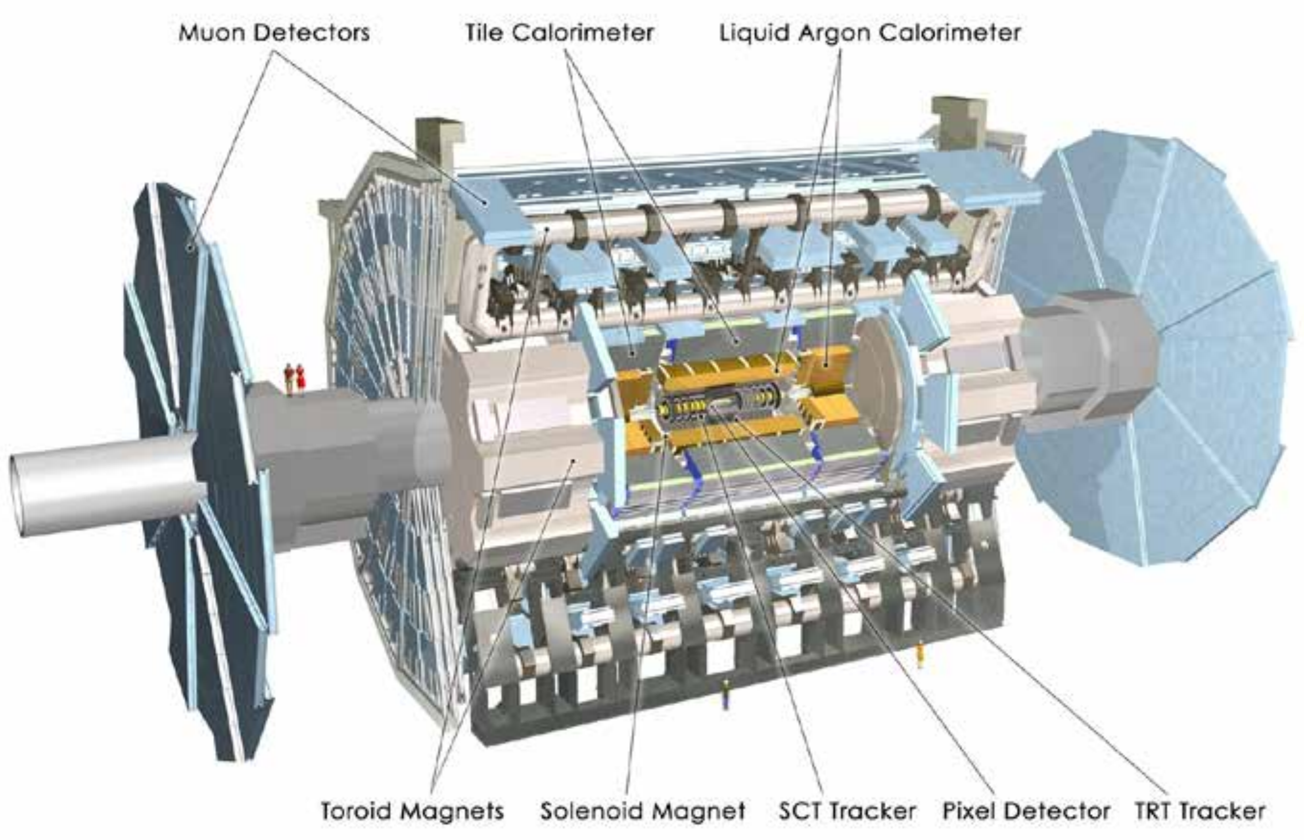

CMS
LHCb
ALICE
ATLAS

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)

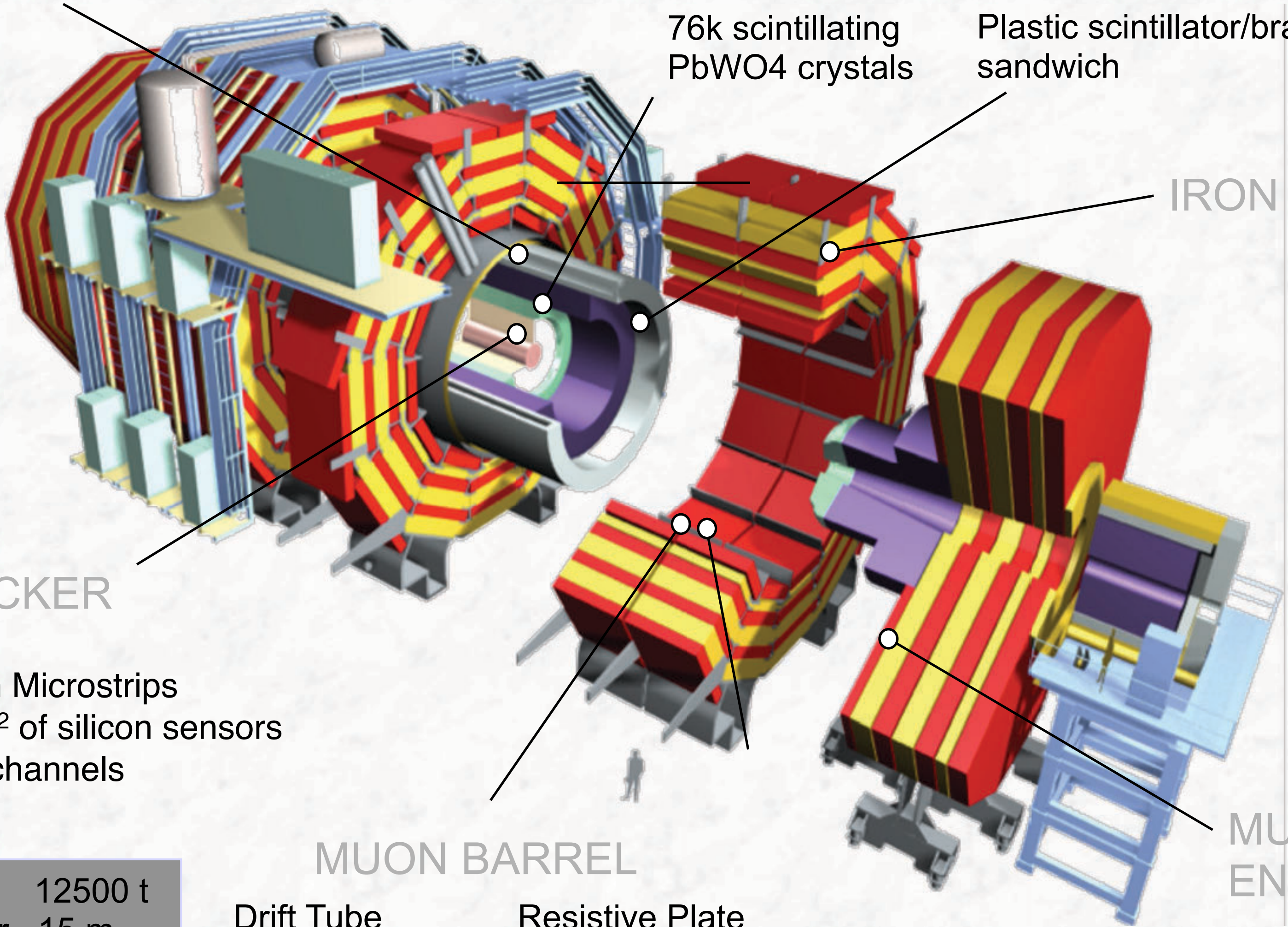
  space resolution: ~ 15 µm

- Energy measurement down to 1º to the beam line

- Independent muon spectrometer (supercond. toroid system)

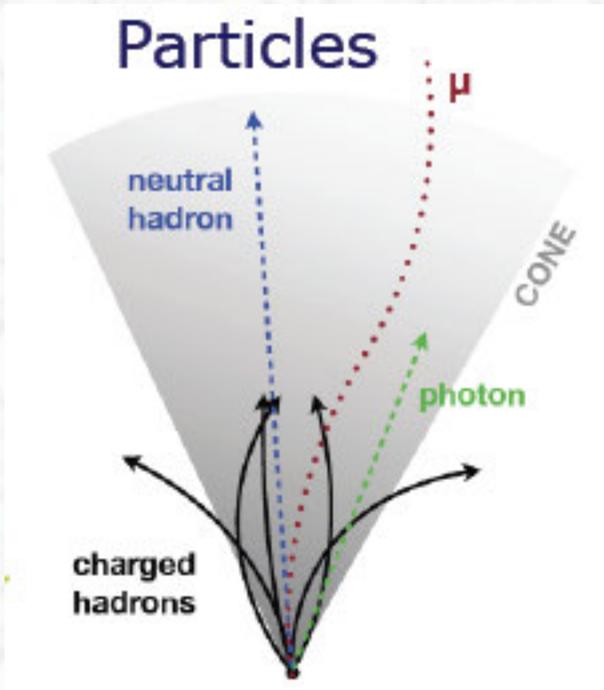
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

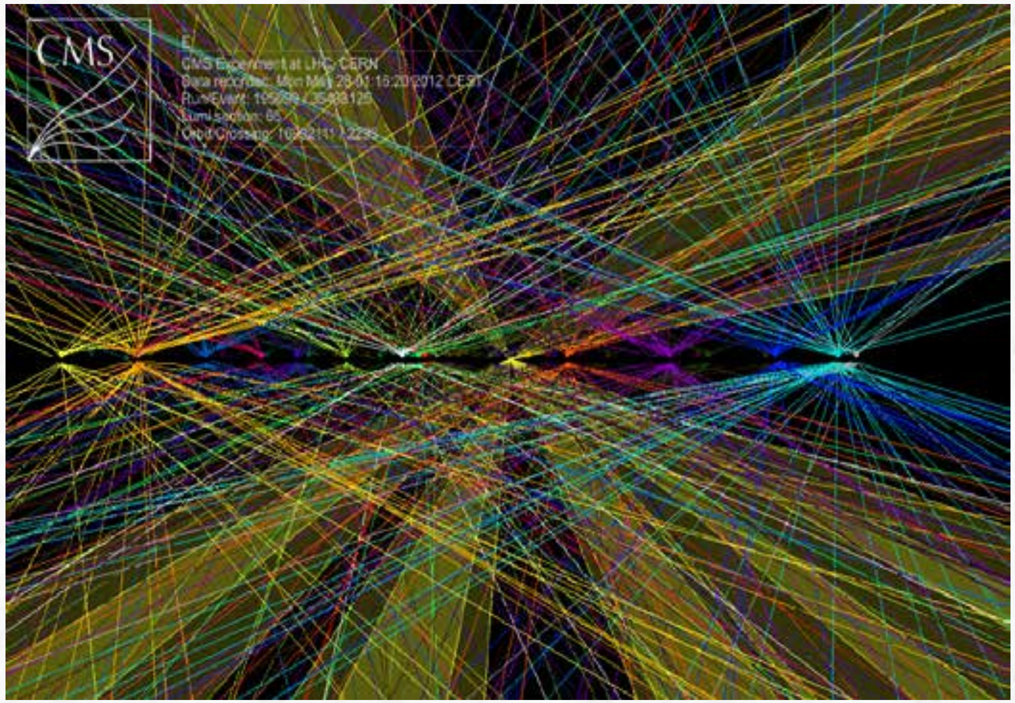
CMS



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

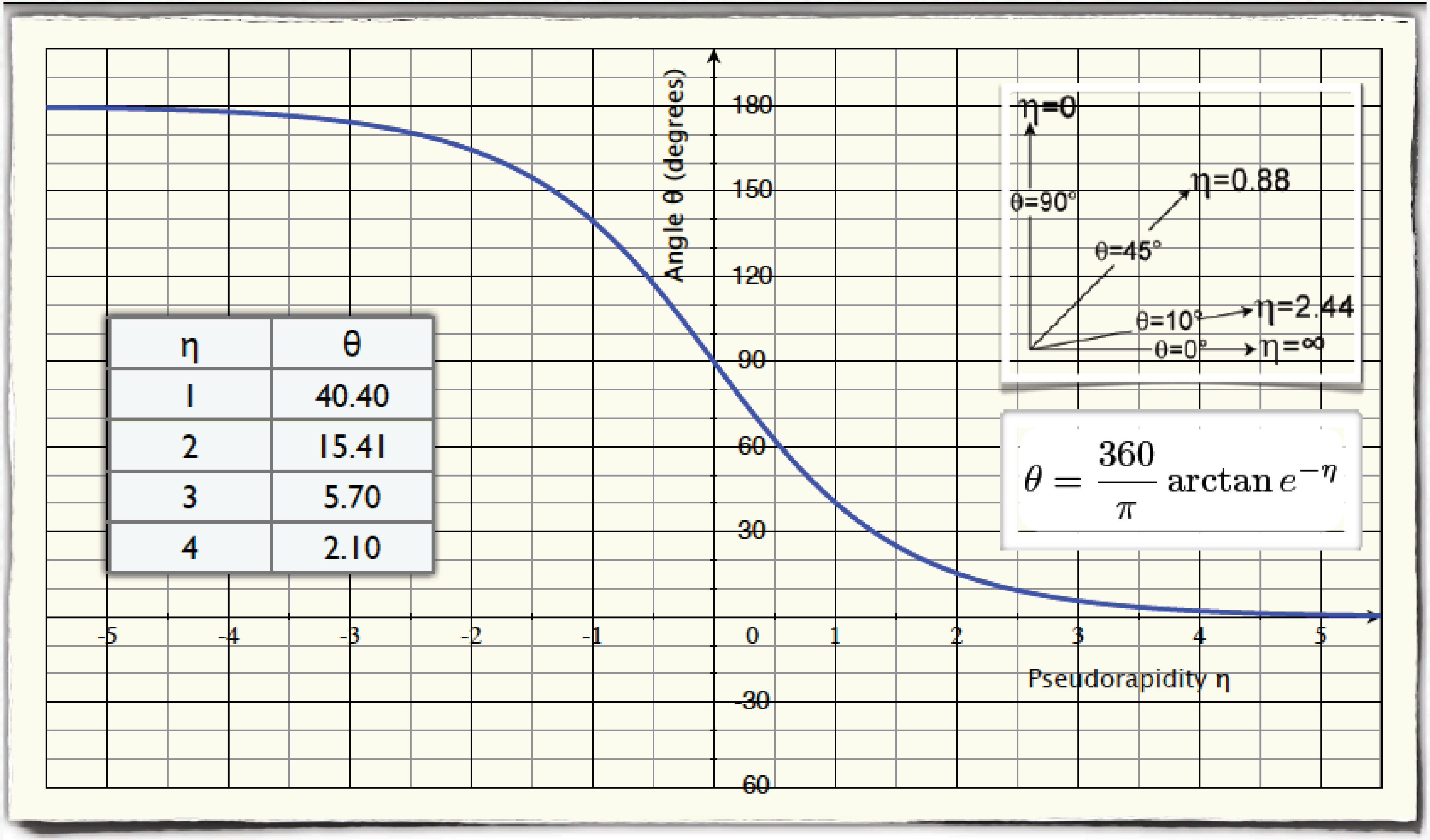
$$y = \frac{1}{2}\ln\frac{\cos^2(\theta/2) + m^2/4p^2 + \ldots}{\sin^2(\theta/2) + m^2/4p^2 + \ldots}$$

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

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

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

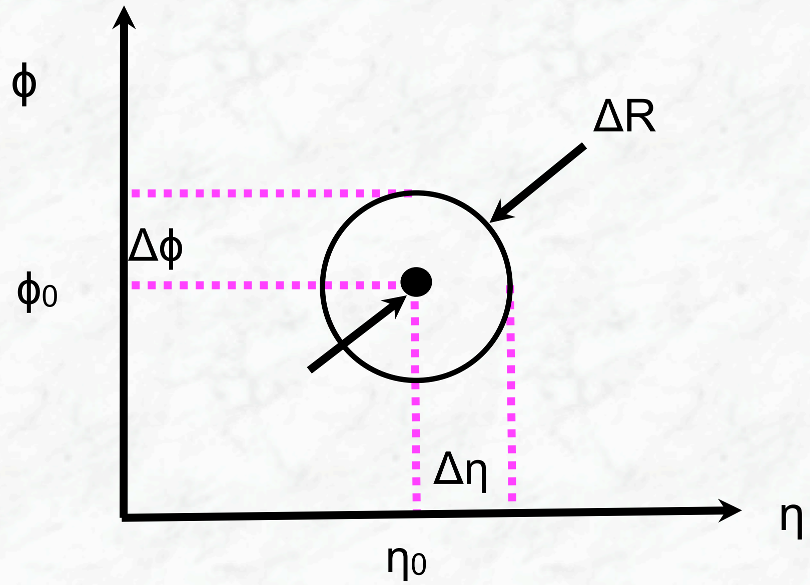
Relation between pseudorapidity η and polar angle θ



η	θ
1	40.40
2	15.41
3	5.70
4	2.10

$$\theta = \frac{360}{\pi} \arctan e^{-\eta}$$

(iii) Distance in $\eta - \phi$ 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

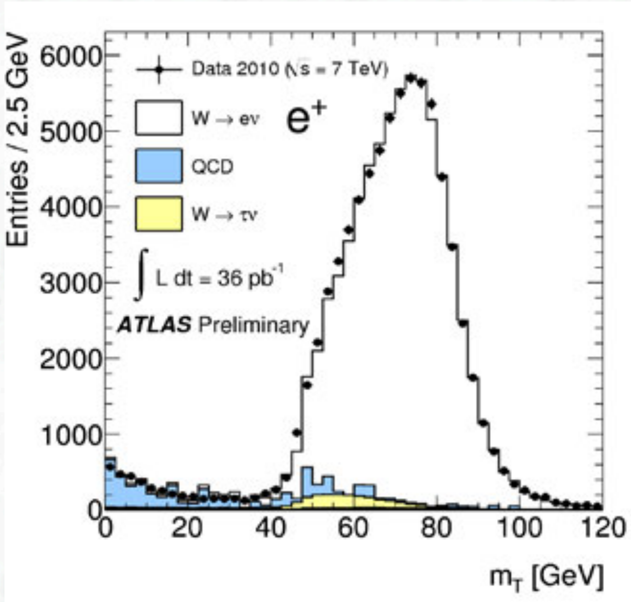
where $p_T(1) = - P_T^{miss}$

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

For $m_1 = m_2 = 0$ →

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

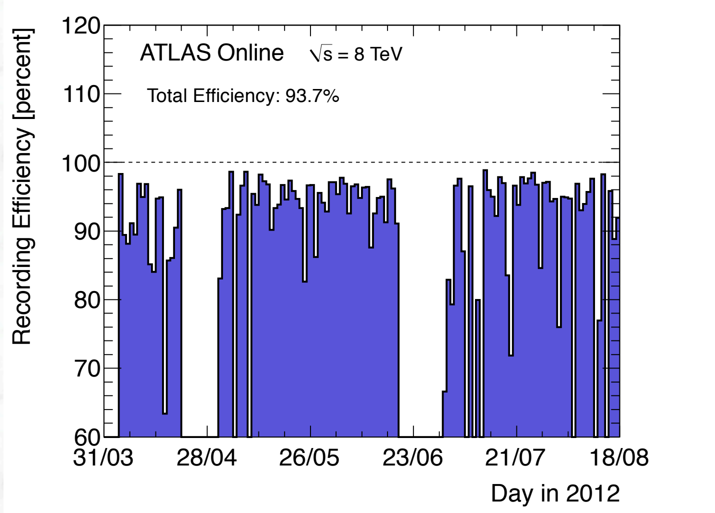
where ϕ_{ij} is defined as the angle between particles i and j in the transverse plane.



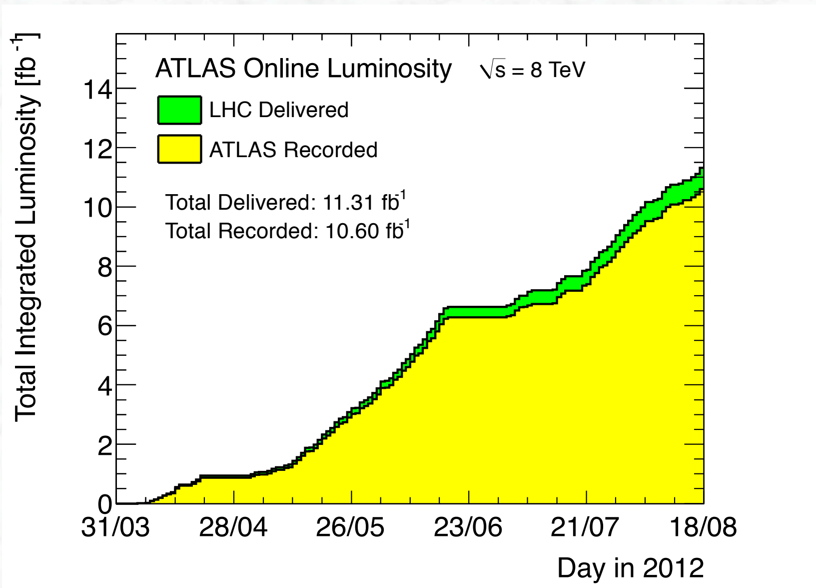
$$m_T = \sqrt{2P_T(e)E_T^{miss}(1 - \cos\Delta\phi)}$$

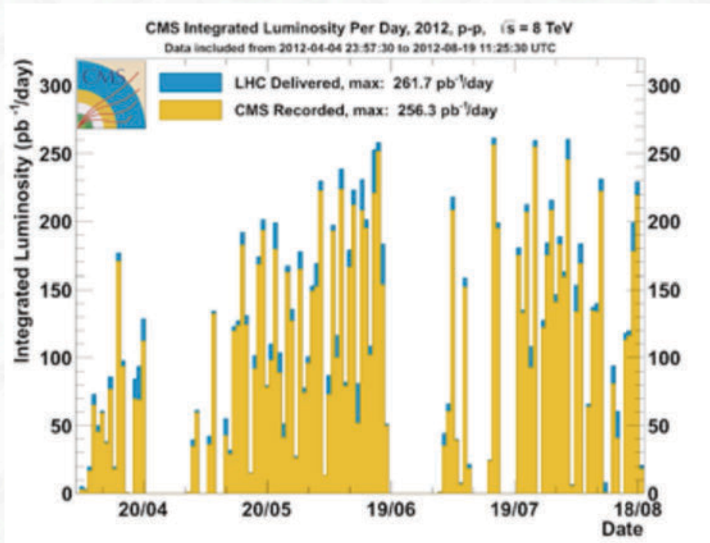
Detector performance is impressive:

- 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})

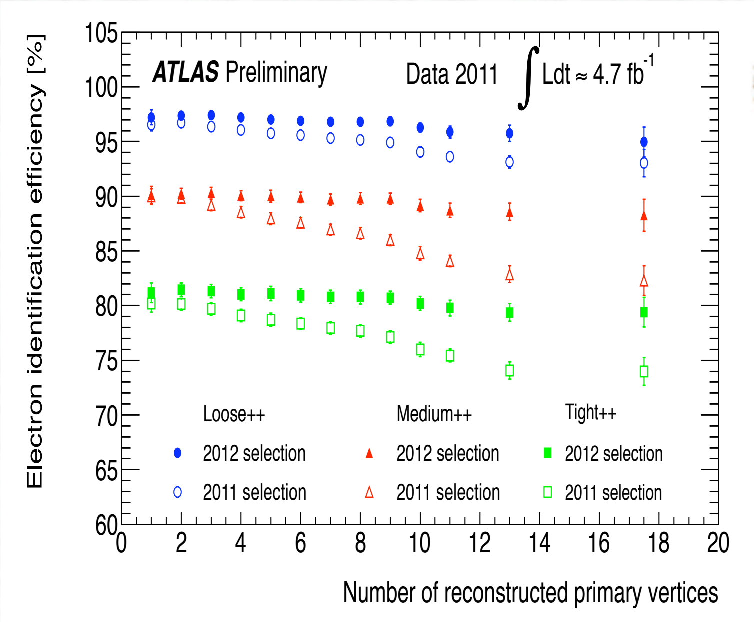


Have been optimized to cope with the ever increasing number of pile-up interactions

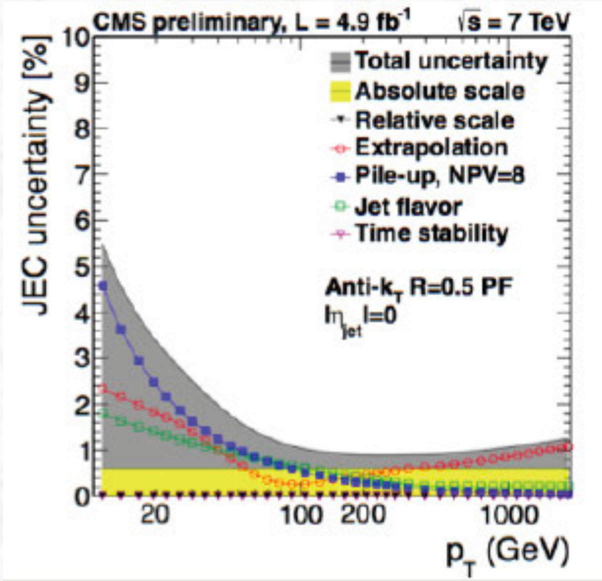




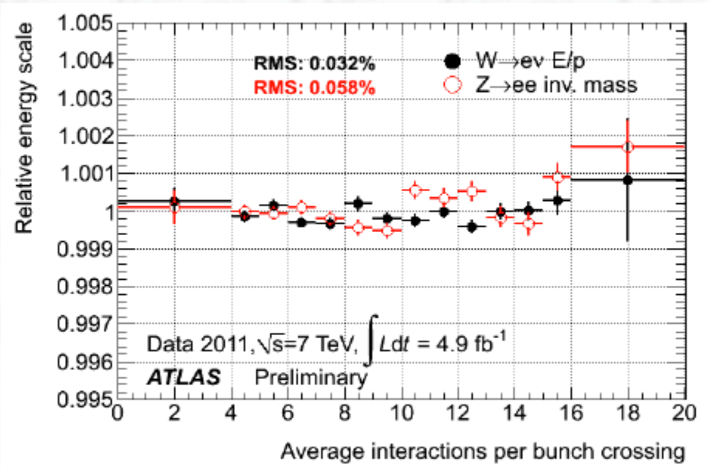
Some performance figures from 2011 data:

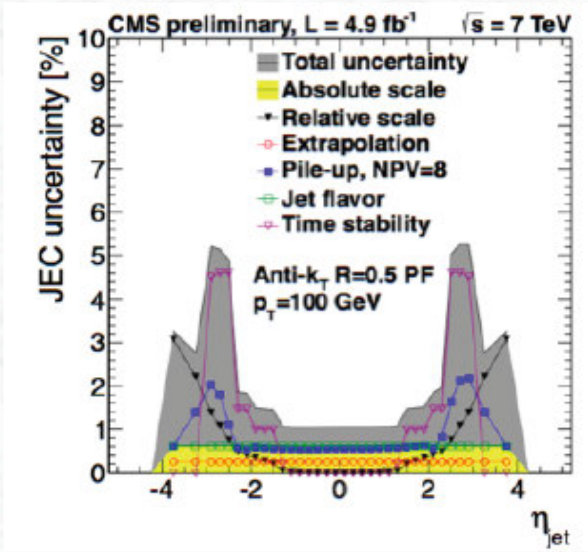


Electron ID efficiency in ATLAS



Jet energy scale, E-flow in CMS





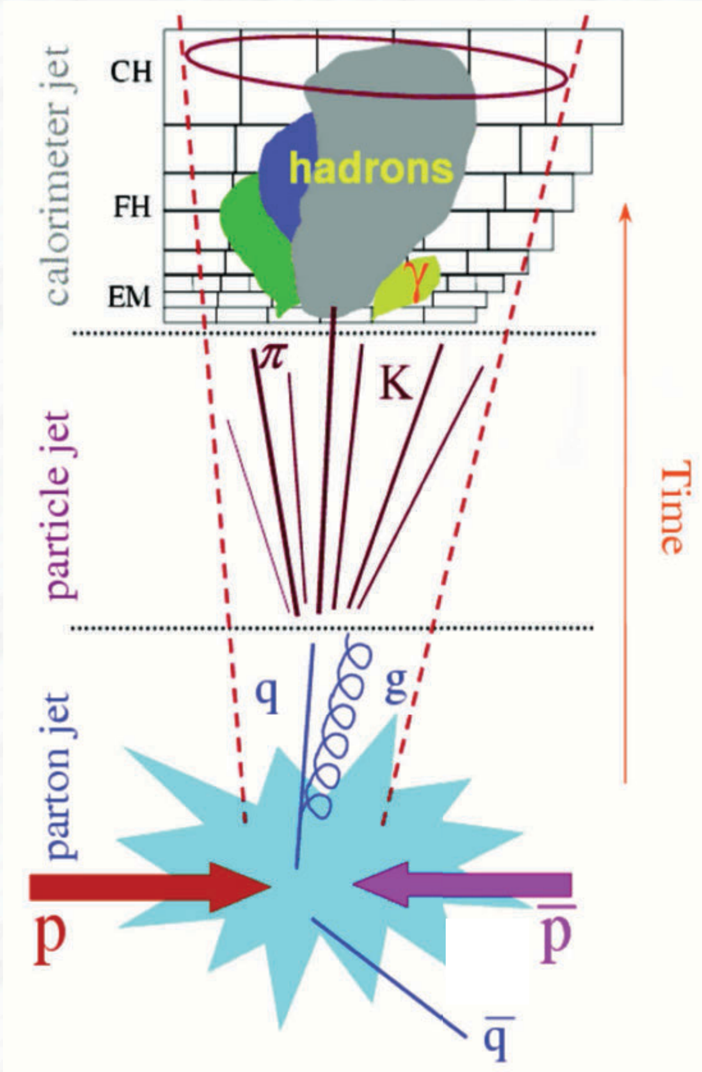
Jet reconstruction and energy measurement

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

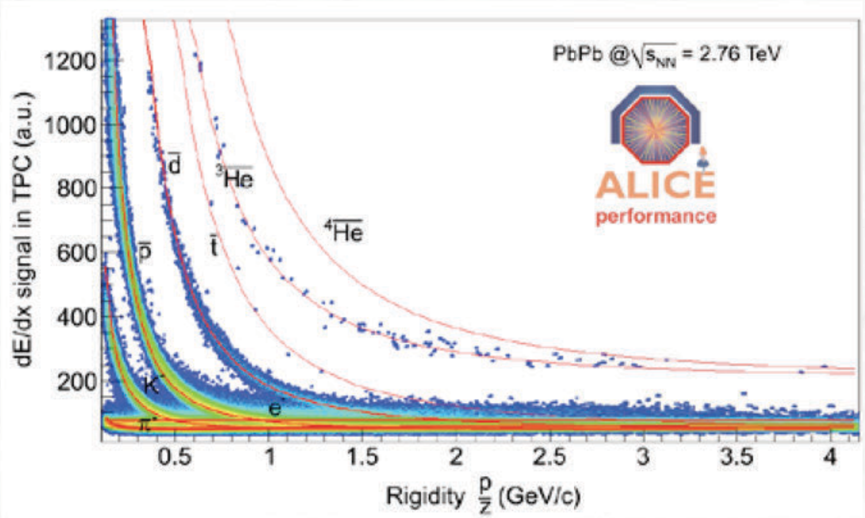
- The detector response is different for particles interacting electromagnetically (e,γ) and for hadrons
  → for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level“ (particle jet)
  Common ground between theory and experiment

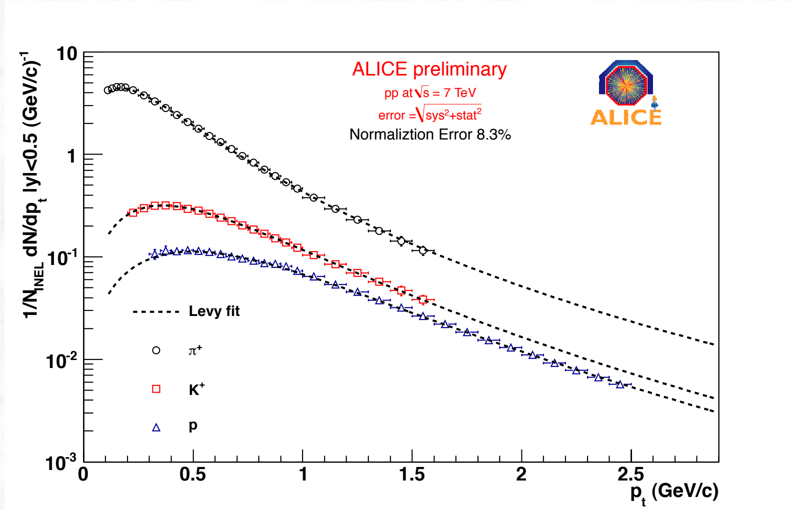
- One needs an algorithm to define a jet and to measure its energy
  conflicting requirements between experiment and theory (exp. simple, e.g. cone algorithm, vs. theoretically sound (no infrared divergencies))

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

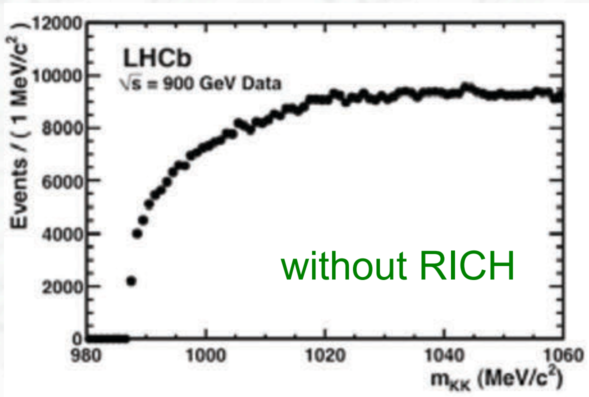


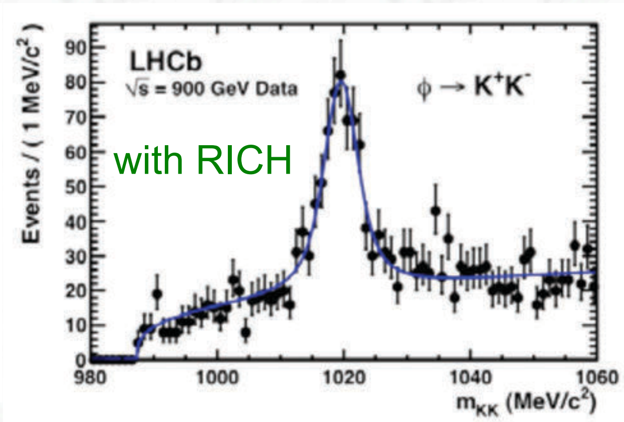
Particle Identification in ALICE and LHCb:

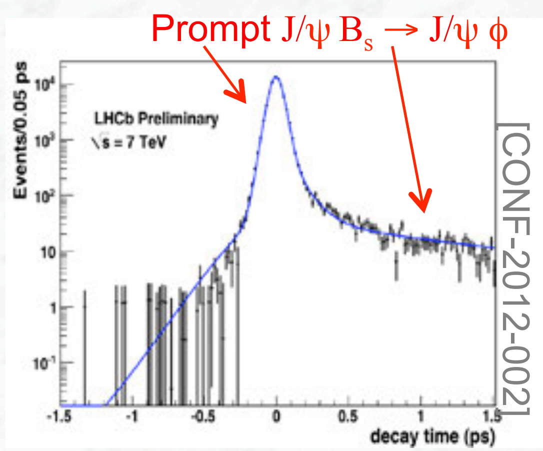




LHCb: Search for $\phi \rightarrow K^+K^-$

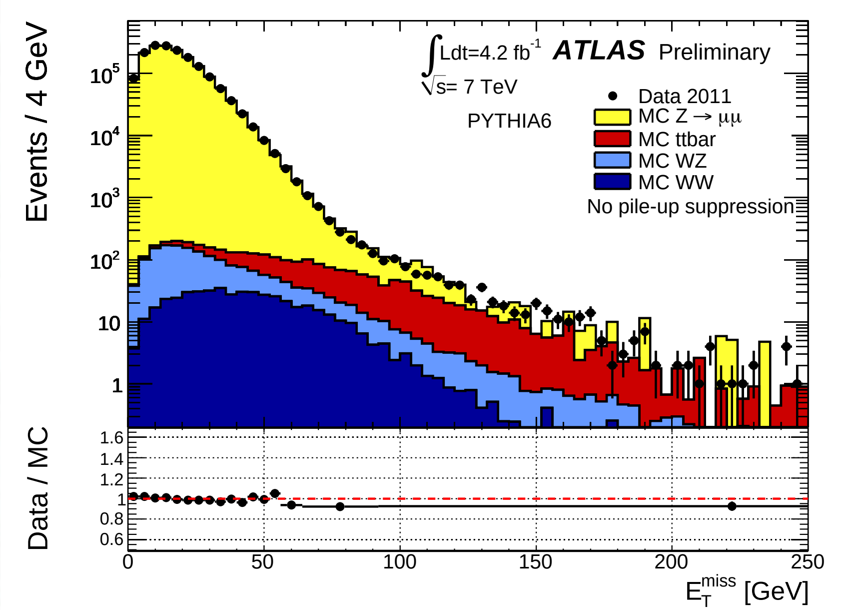


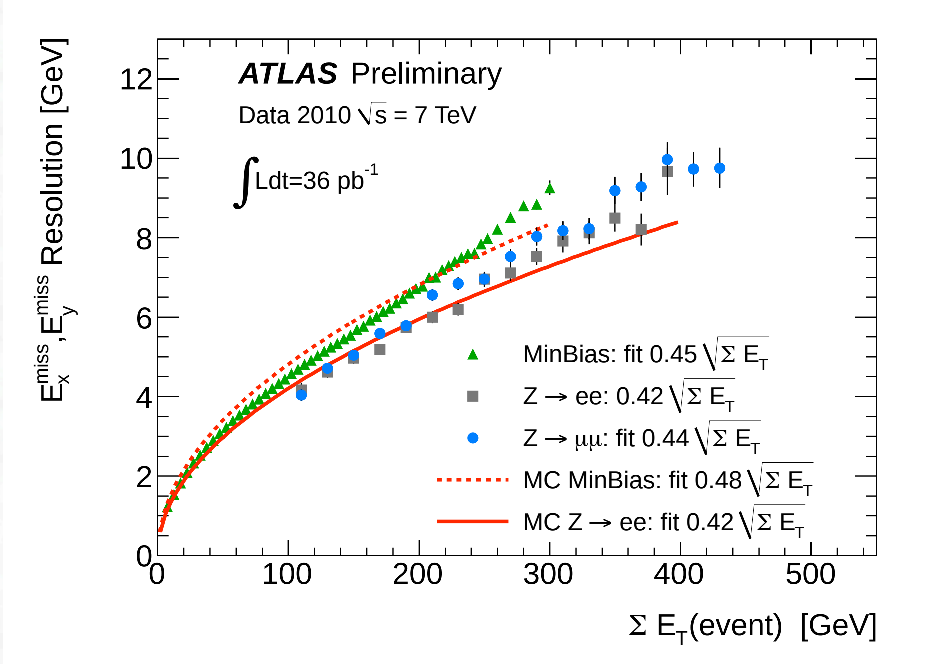




Proper time resolution: 45 fs

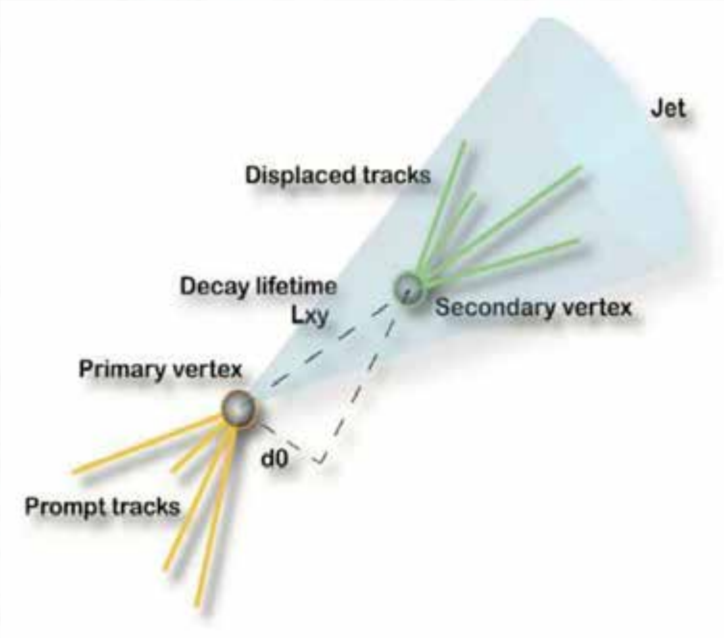
Measurement of the missing transverse energy E_T^{miss}





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 ?

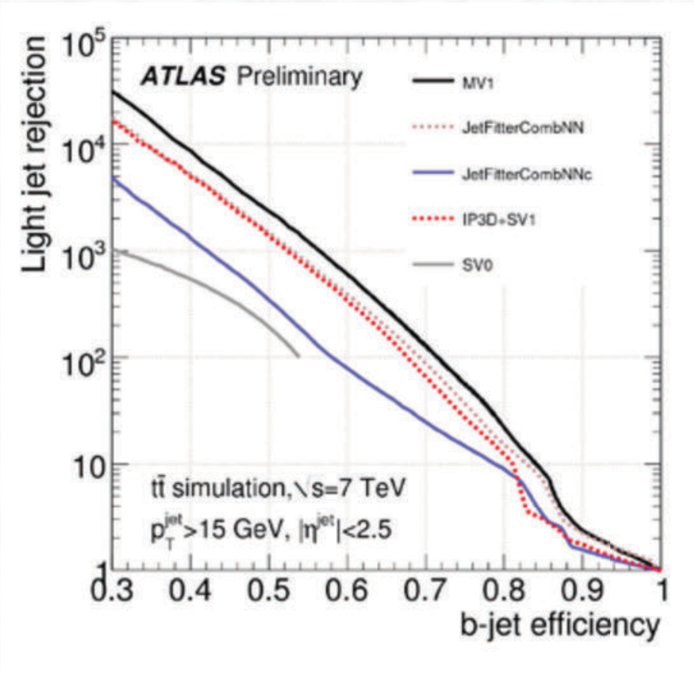


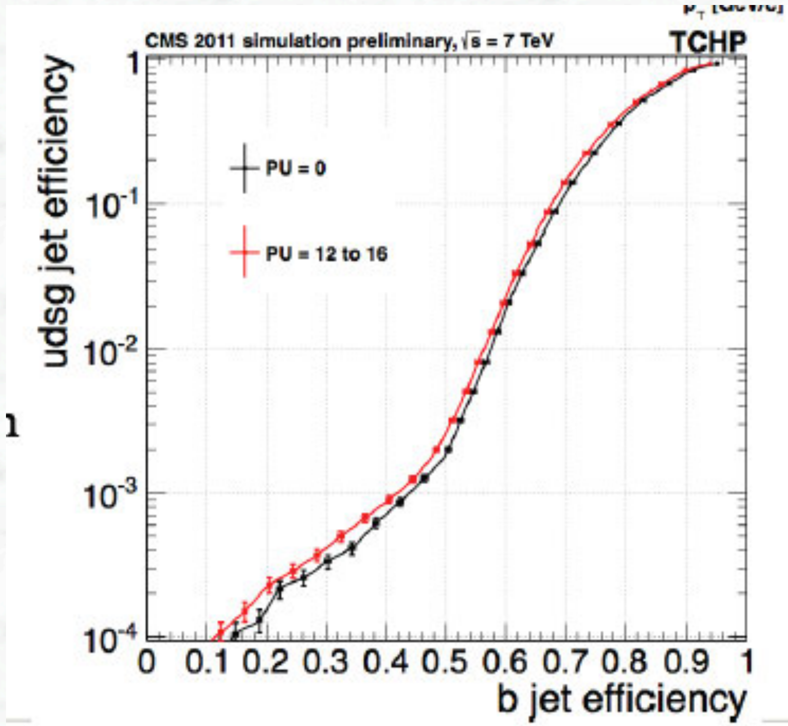
- b quarks fragment into B hadrons (mesons and baryons)
- B mesons have a lifetime of ~1.5 ps

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

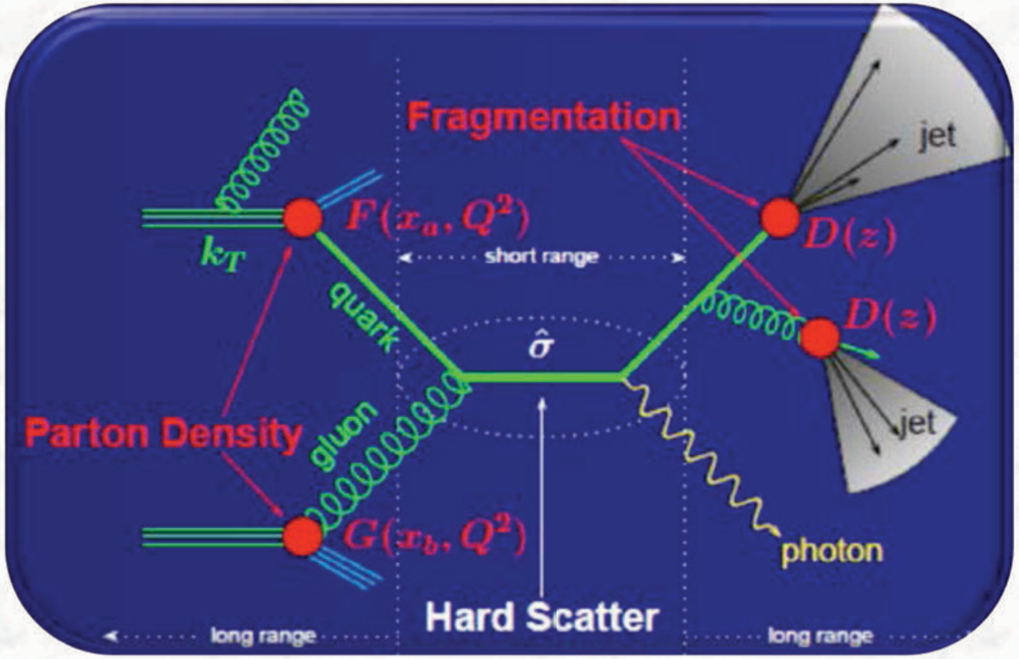
→ reconstruction of a secondary vertex possible
(requires high granularity silicon pixel and strip detectors close to the interaction point)
→ tracks from B meson decays have a large impact parameter w.r.t. the primary vertex

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



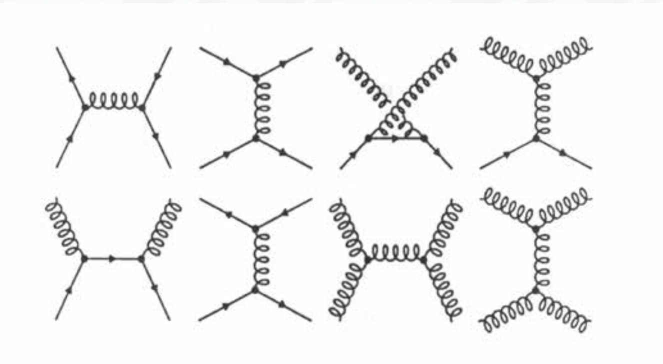


1.3 Scattering processes at a hadron collider

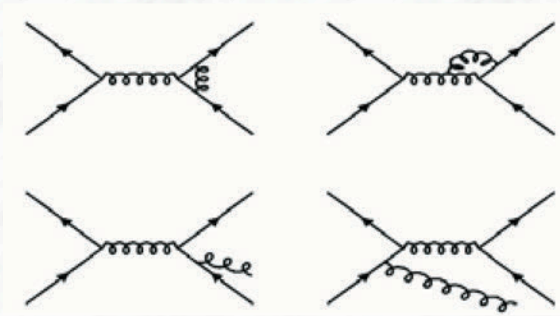


Dominant hard scattering processes: qq, qg and gg “scattering”

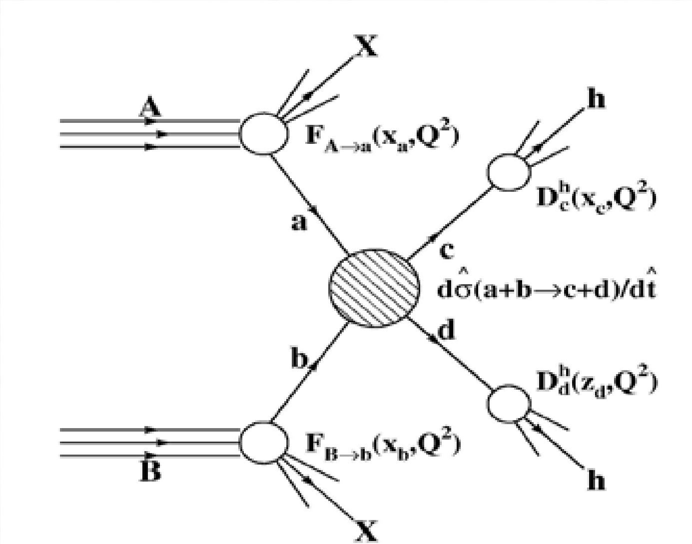
Leading order



…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

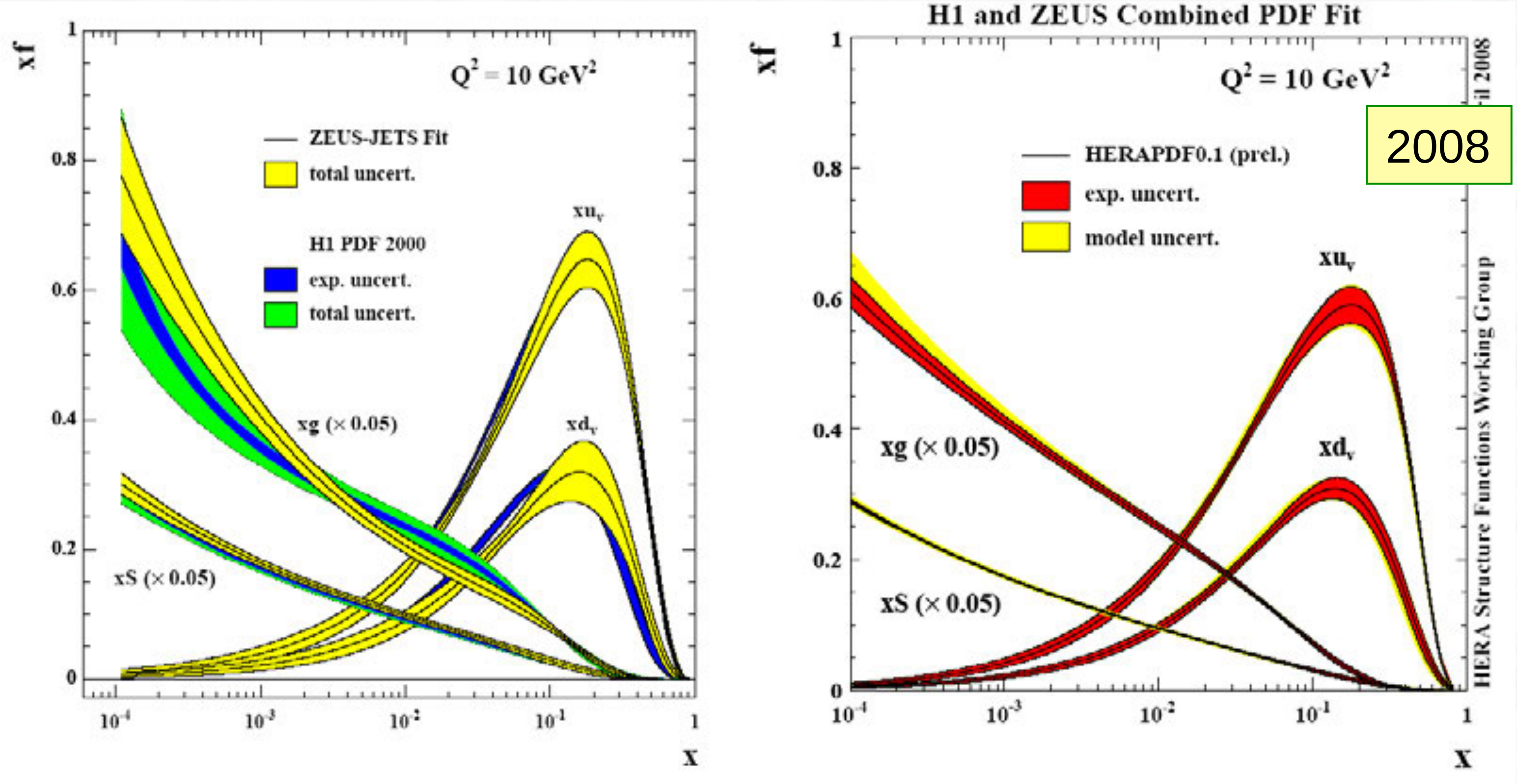
which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

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

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

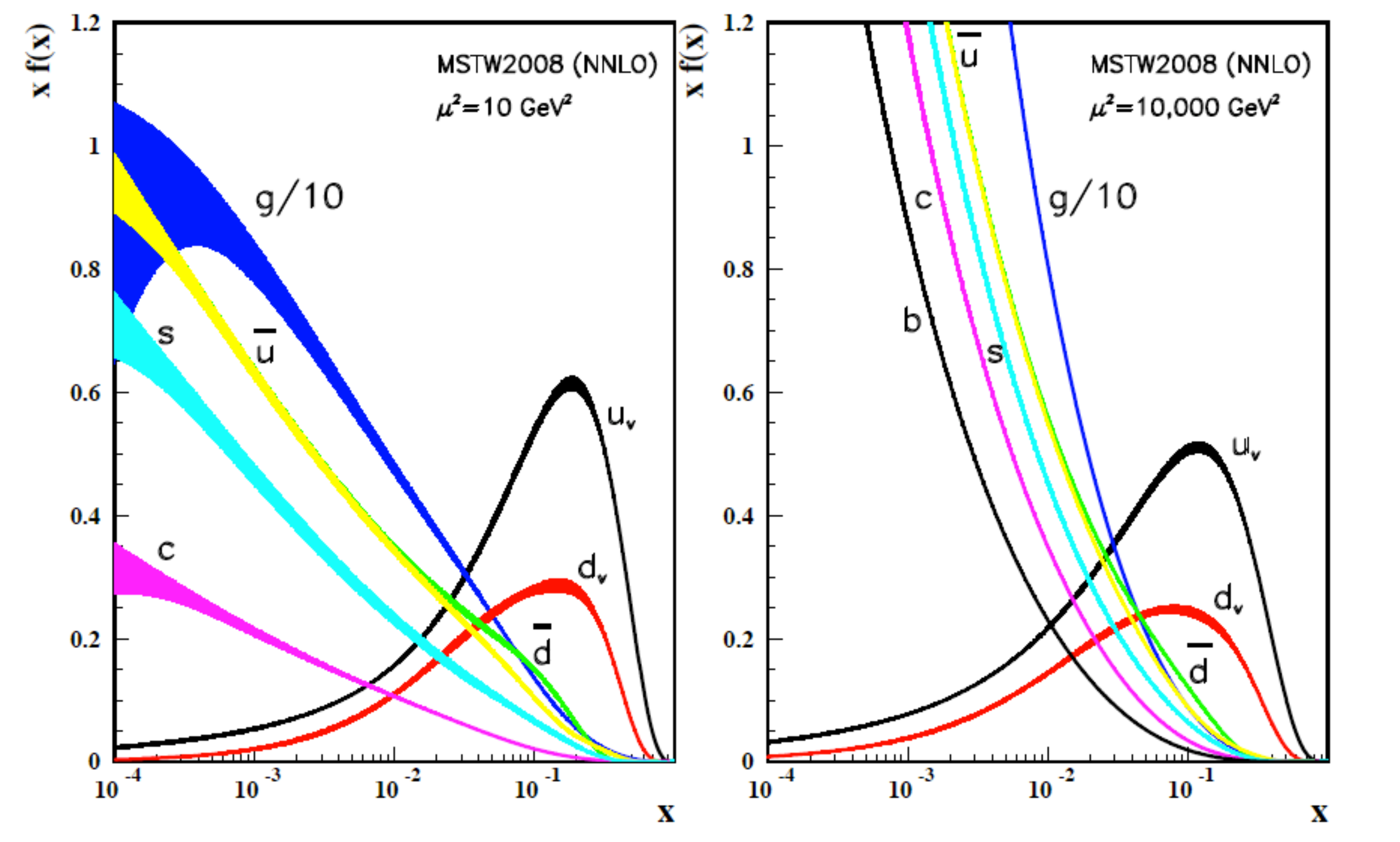
Results from HERA on the proton structure

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

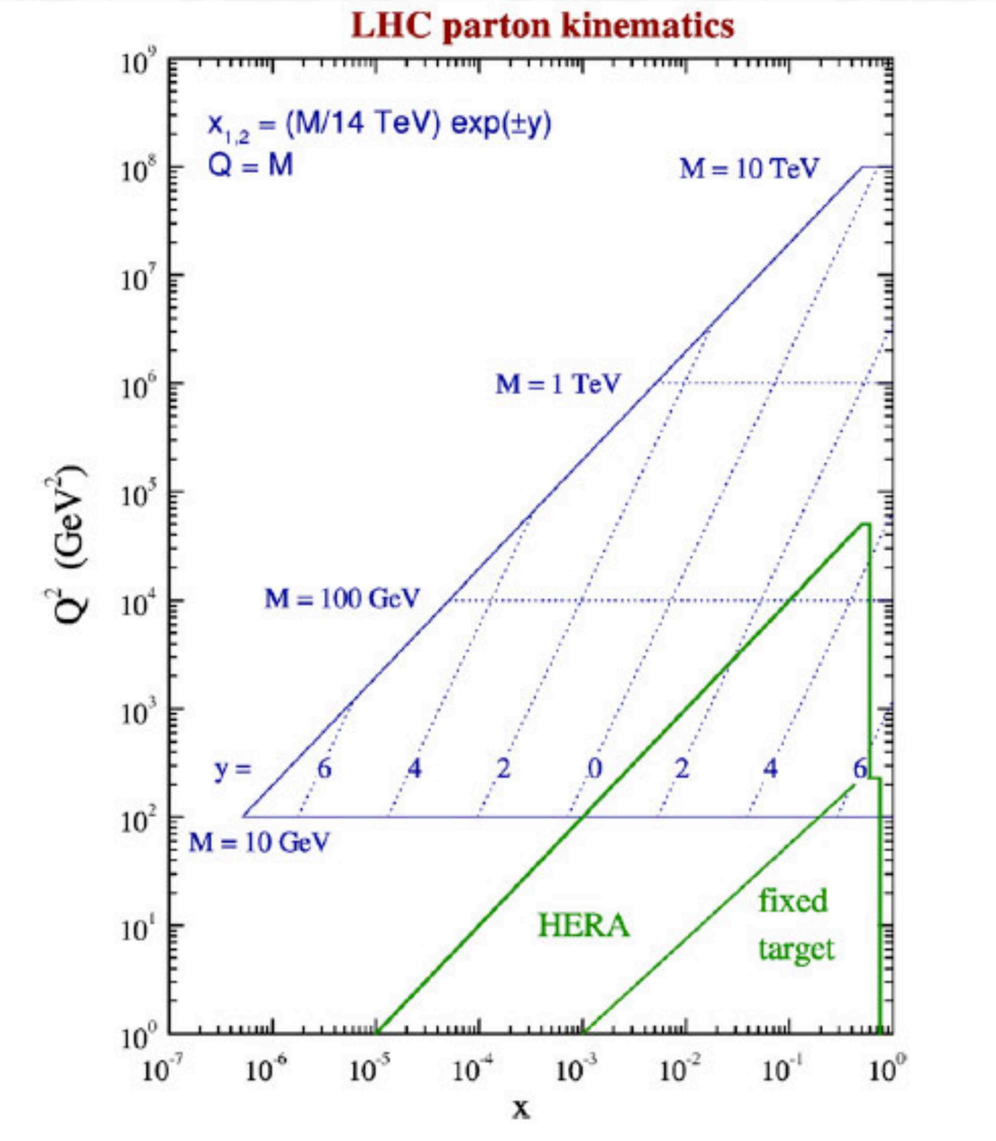


- Very important to reduce cross section uncertainties at hadron colliders; but still not good enough ….. (~ 10% errors for LHC cross sections)

Q^2 evolution following the DGLAP equation

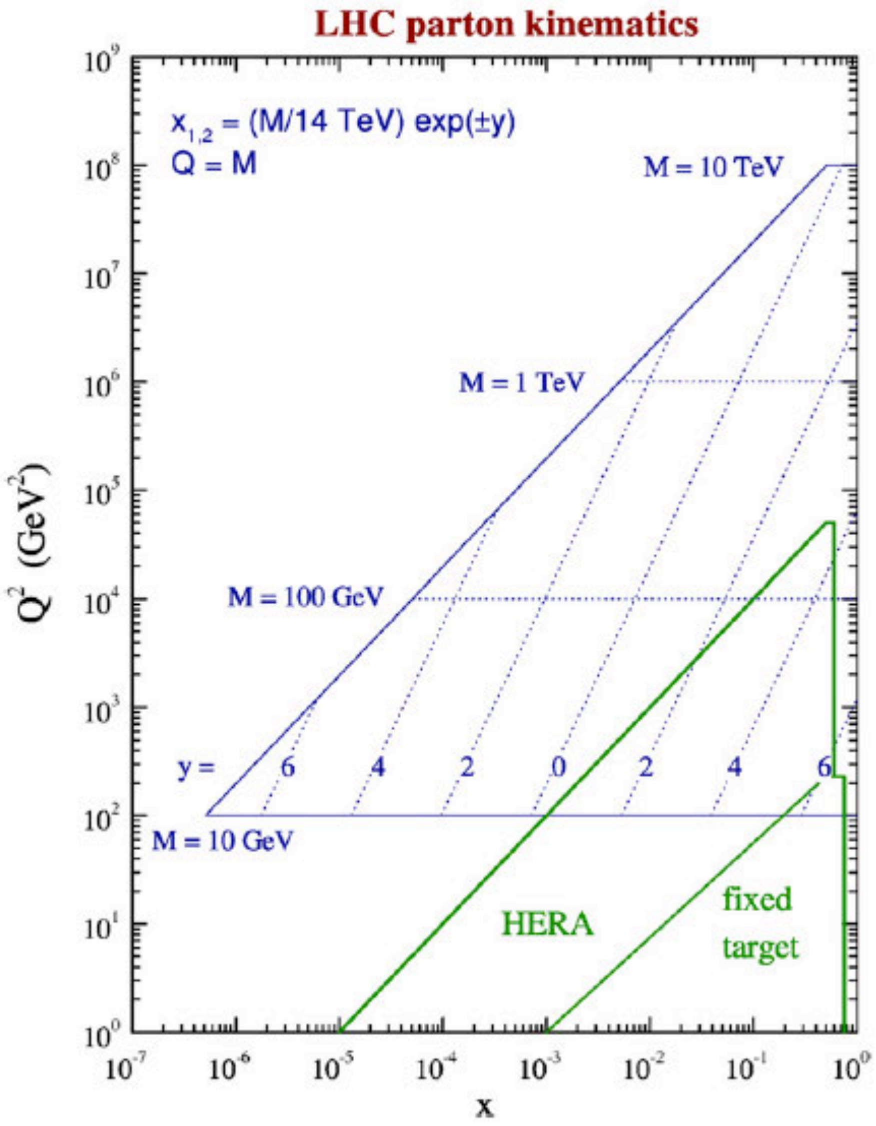


Distributions of x times the unpolarized parton distributions f(x), where f = u_v, d_v, ubar, dbar, s, b, g and their associated uncertainties using the NNLO MRST2008 parametrization at a scale μ^2 = 10 GeV^2 and μ^2 = 10.000 GeV^2.



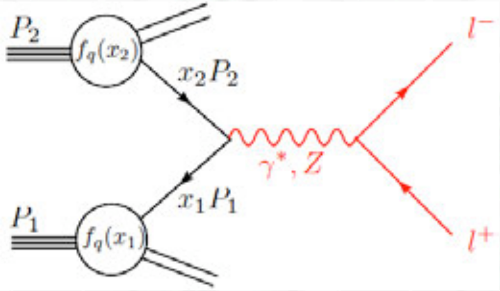
Graphical representation of the relationship between parton (x, Q^2) variables and the kinematic variables corresponding to a final state of mass M with rapidity y at the LHC with $\sqrt{s}$ = 14 TeV

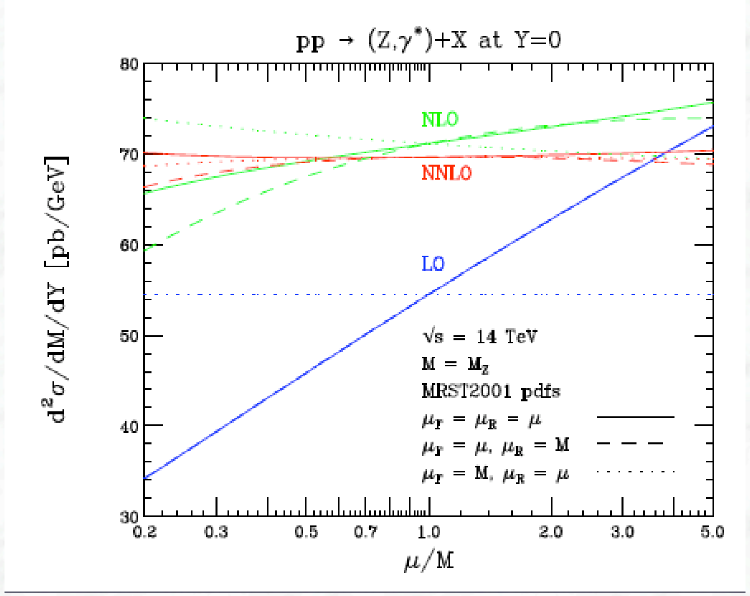
Comparison between the Tevatron and the LHC (14 TeV)

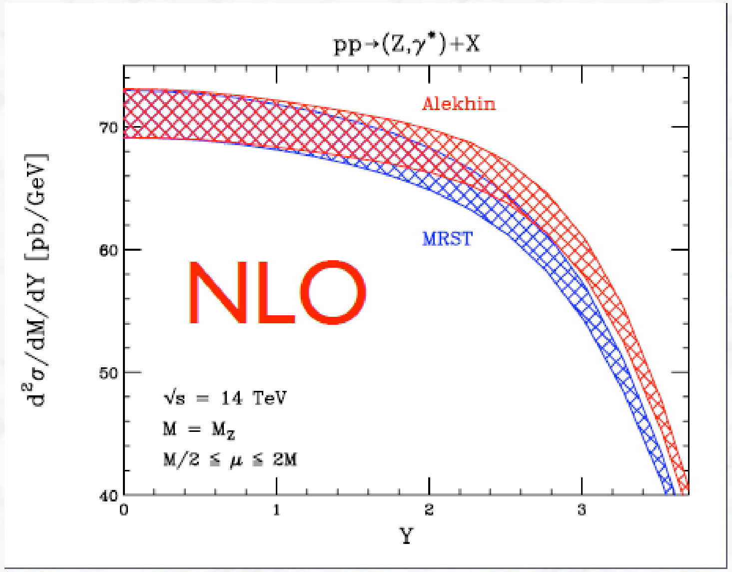


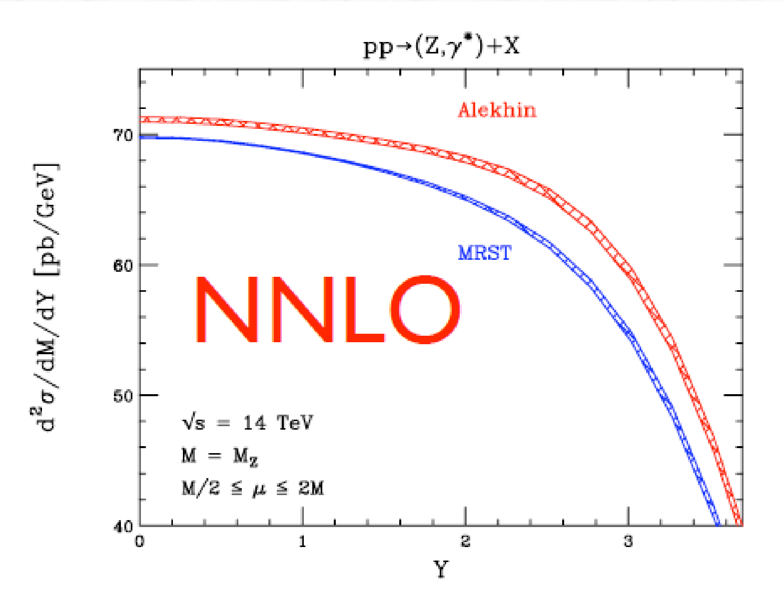
For the same masses (e.g. 100 GeV): x-values about 10 times lower at the LHC

Example: Drell-Yan production of W/Z bosons



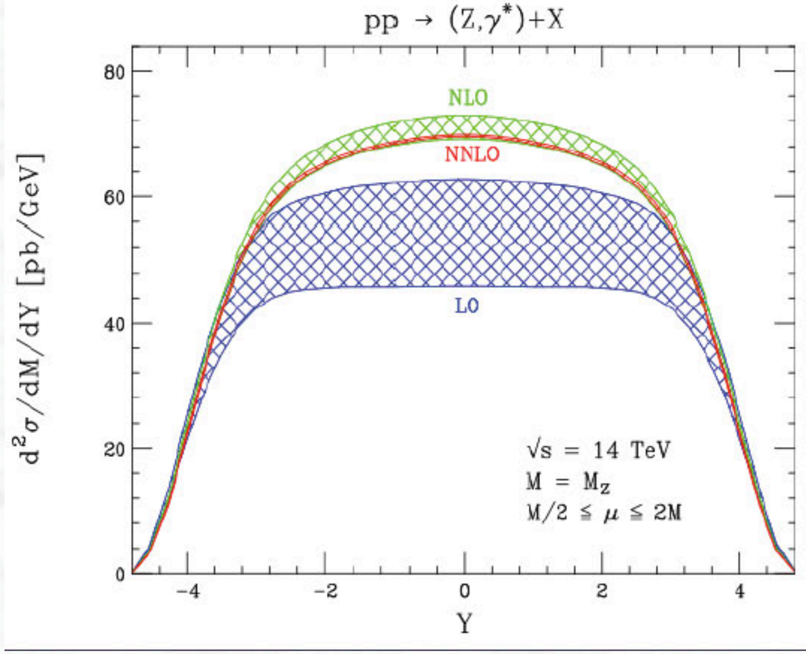


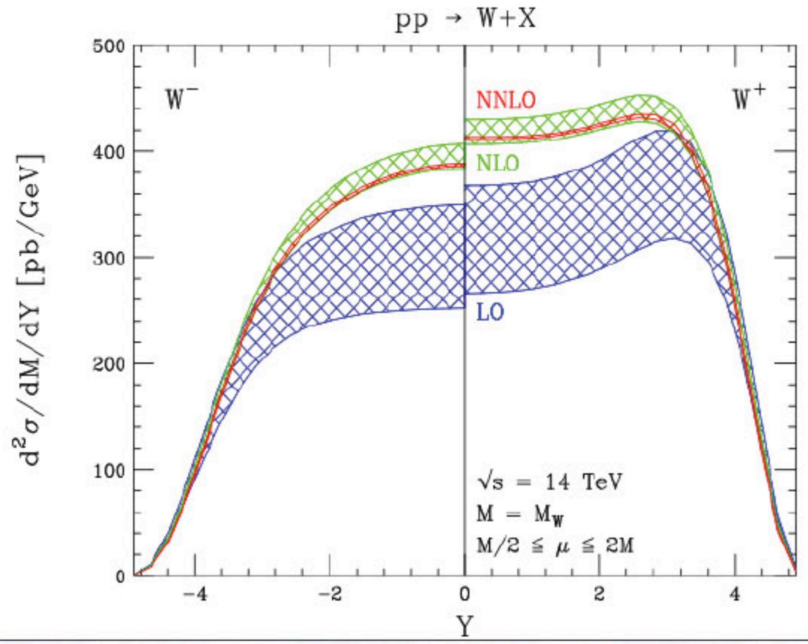




Example: Drell-Yan production of W/Z bosons (cont.)

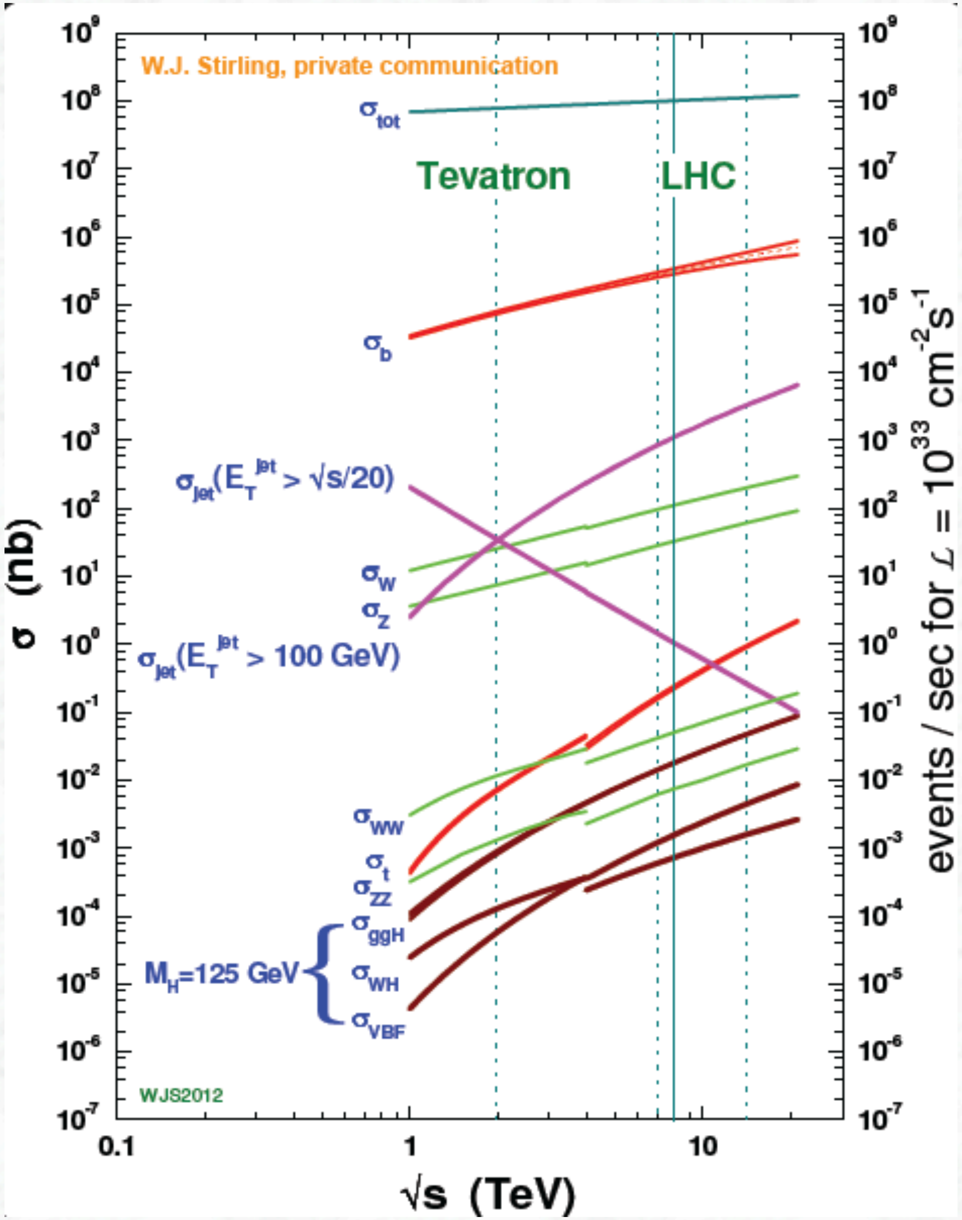
Rapidity distributions for Z and $W^{\pm}$ production at LO, NLO, and NNLO





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

Cross Sections and Production Rates

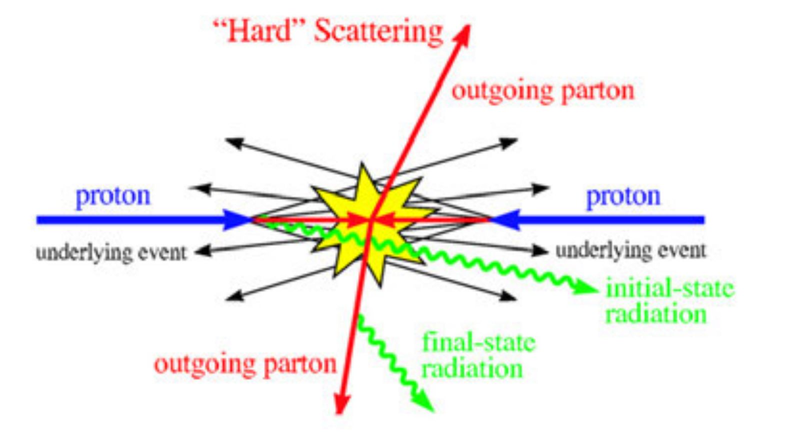


LHC is a factory for:
top-quarks, b-quarks, W, Z, …,Higgs, …

but other more prominent processes dominate the production rates:

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

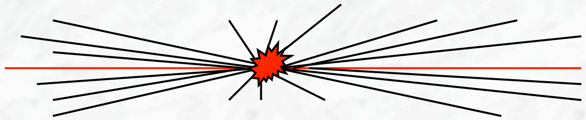
1.4 Soft proton-proton interactions



- 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, ….)

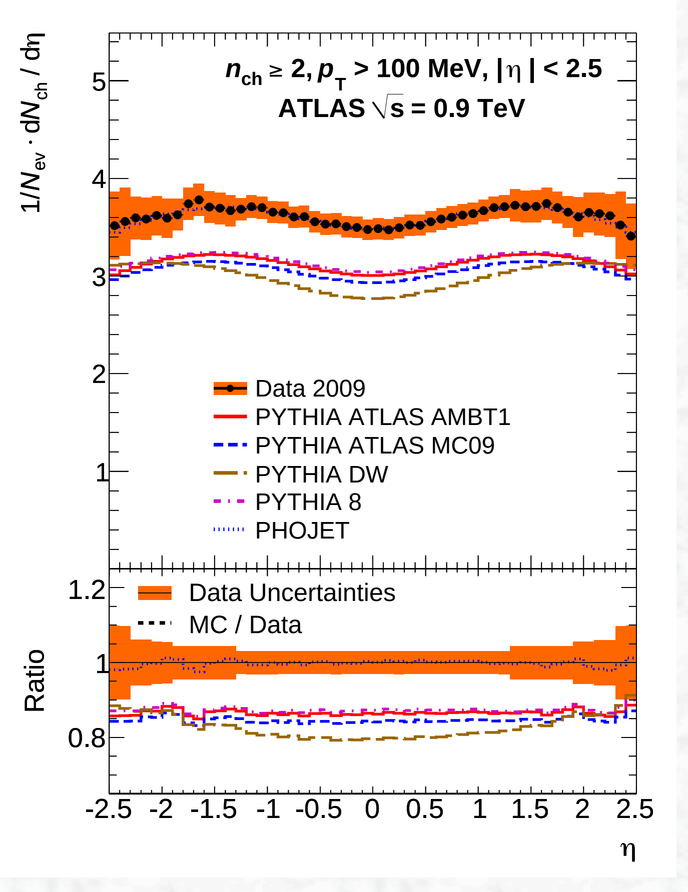
Charged particle density versus η

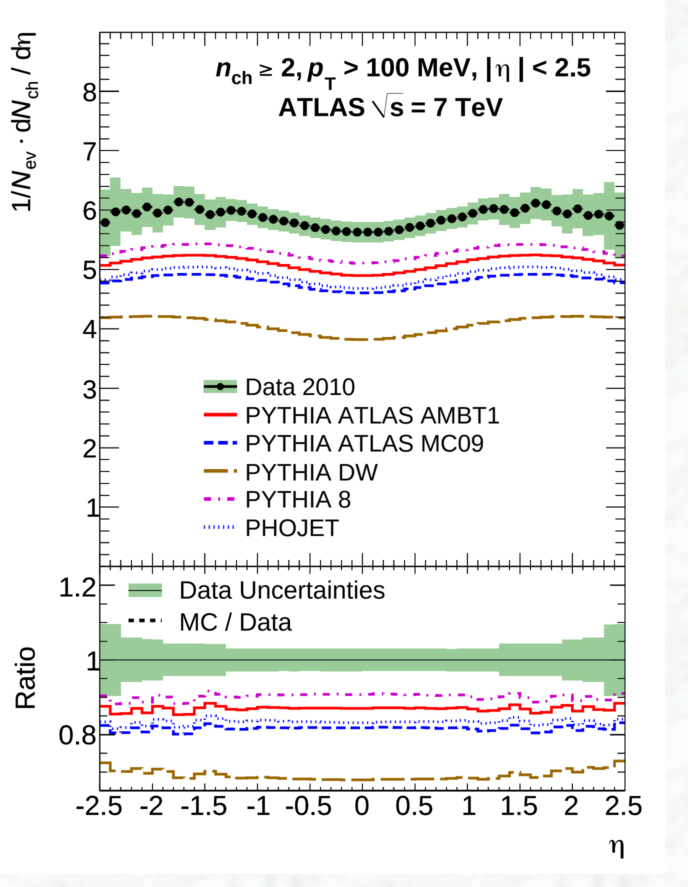
N_{ch}: number of primary charged particles corrected to particle level, normalized to the number of selected events N_{ev}

0.9 TeV

and

7 TeV data

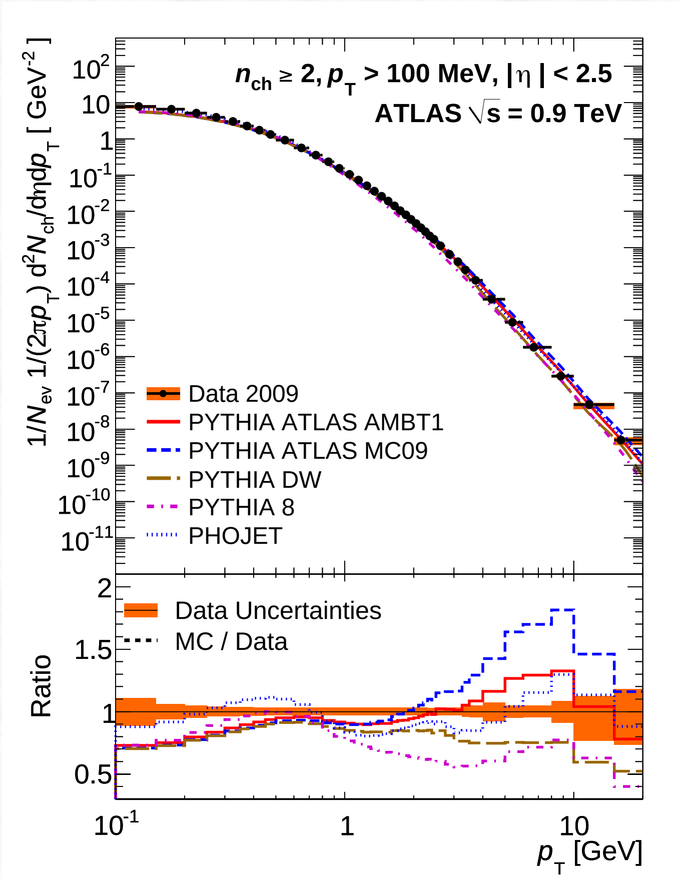


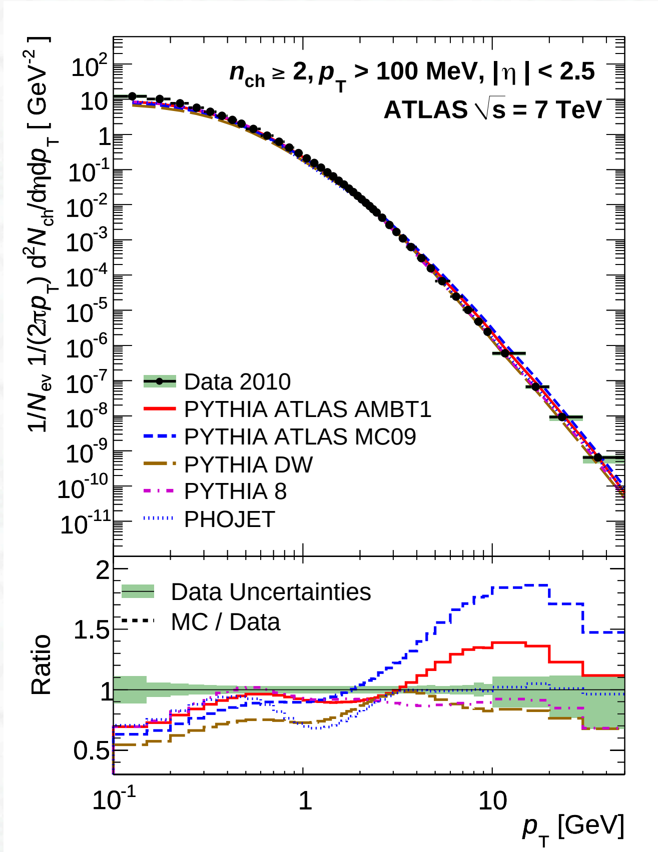


Various Monte Carlo models fail to describe the ATLAS data at both collider energies → tuning of Monte Carlo parameters needed

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}

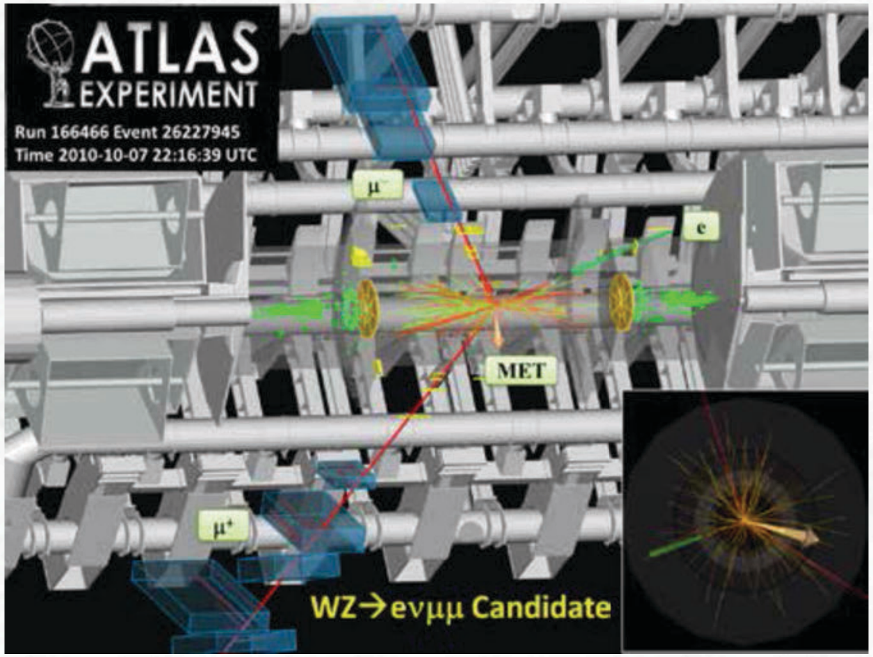




Monte Carlo models also fail to describe the p_T spectrum

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}

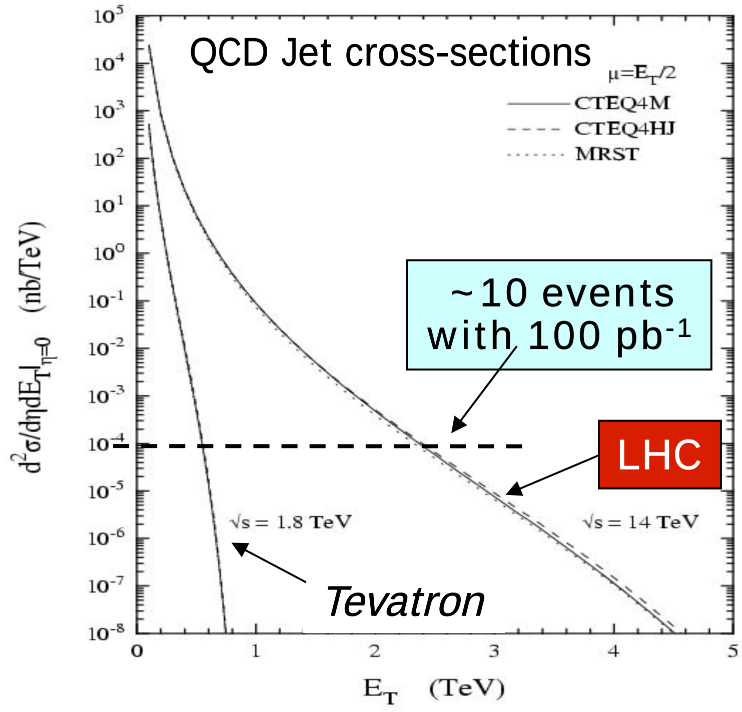
- Standard Model processes are important background processes for many searches for Physics Beyond the Standard Model
  "Physics Background"

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

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

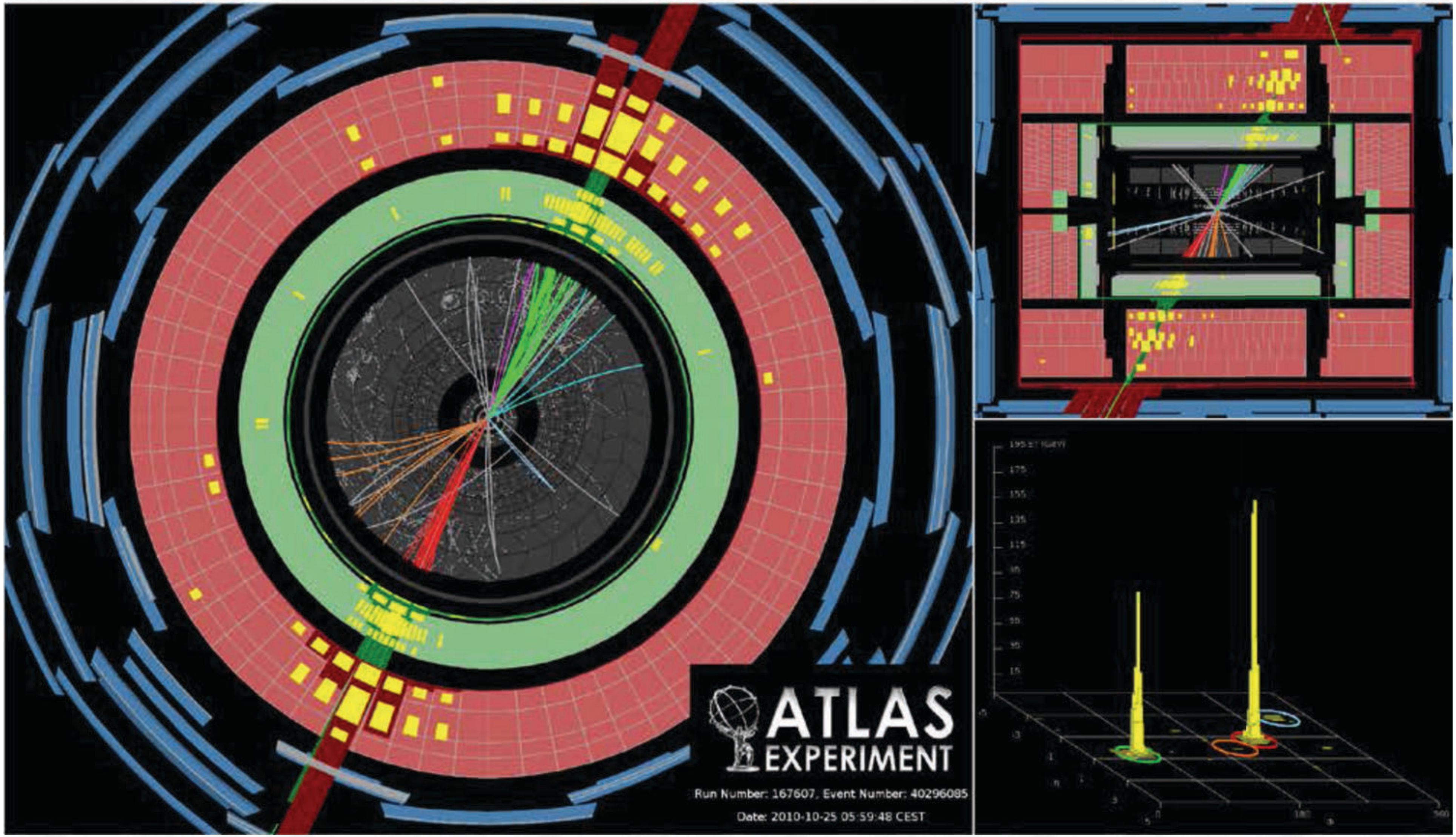
2.1 Jets from QCD production

- 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



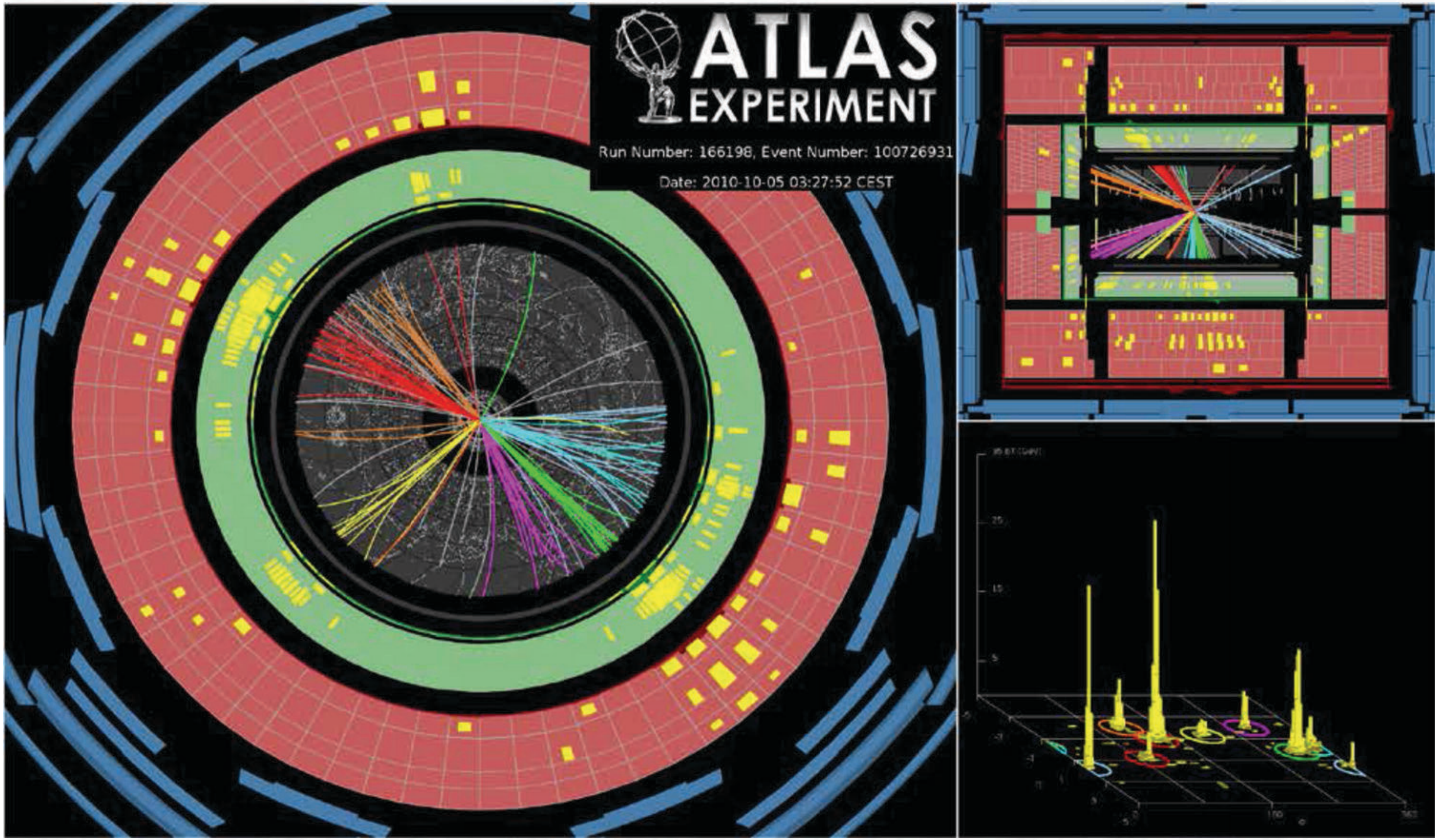
A comparison between the Tevatron and the LHC (14 TeV)

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



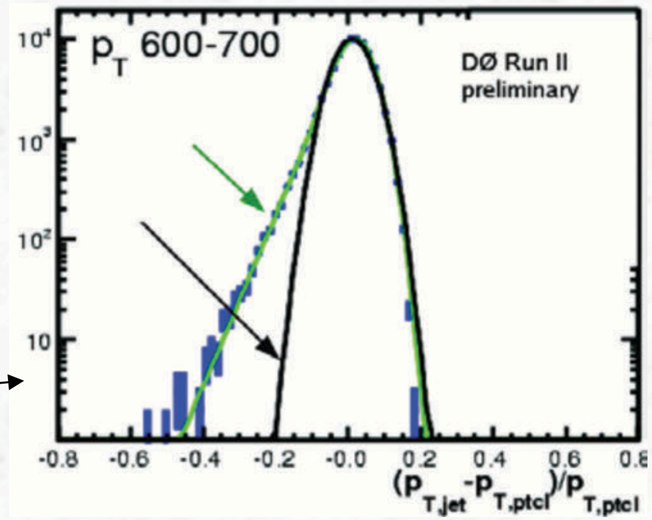
The highest jet multiplicity event collected, counting jets with p_T greater than 60 GeV: this event has eight. 1st jet (ordered by p_T): p_T = 290 GeV, η = -0.9, φ = 2.7; 2nd jet: p_T = 220 GeV, η = 0.3, φ = -0.7 Missing E_T = 21 GeV, φ = -1.9, Sum E_T = 890 GeV.

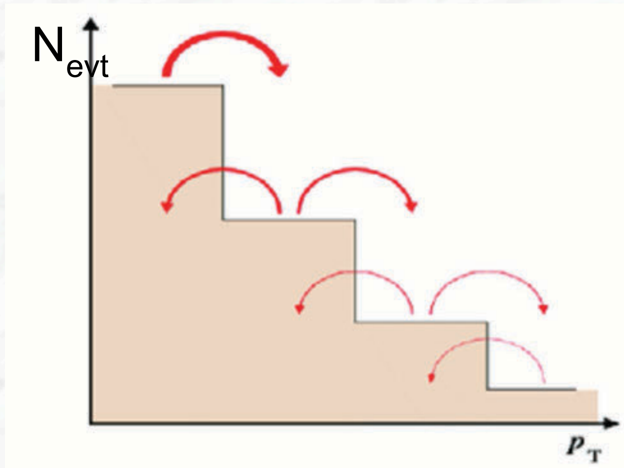
Jet measurements

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

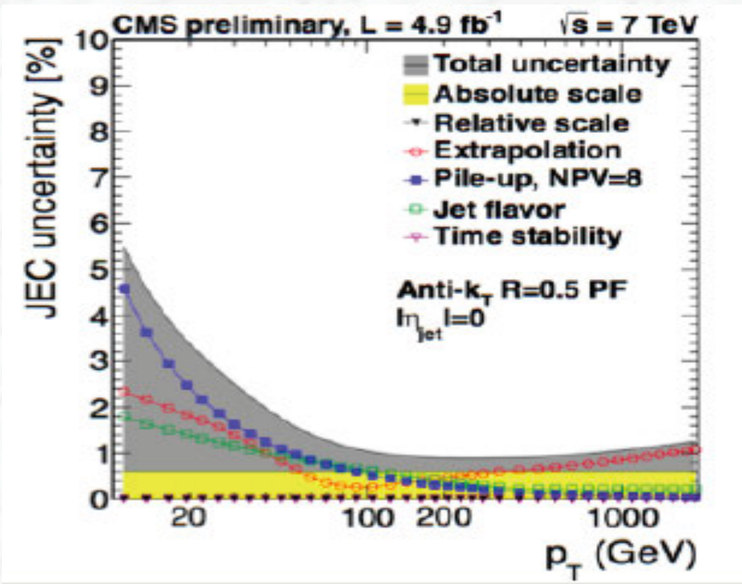
- In principle a simple counting experiment

- However, steeply falling p_T spectra are sensitive to jet energy scale uncertainties and resolution effects (migration between bins)
  → corrections (unfolding) to be applied

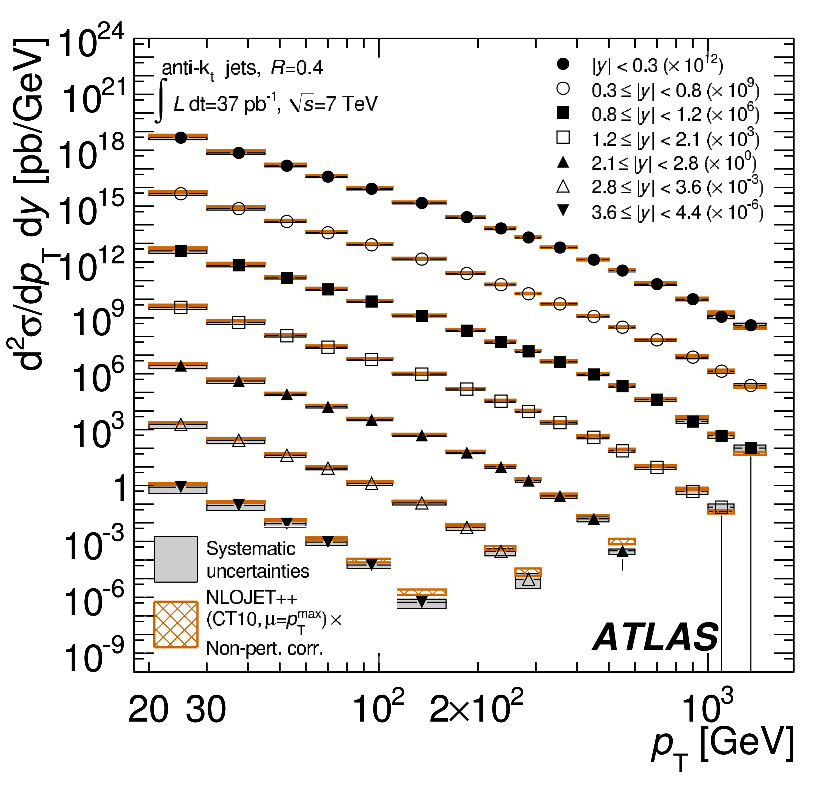


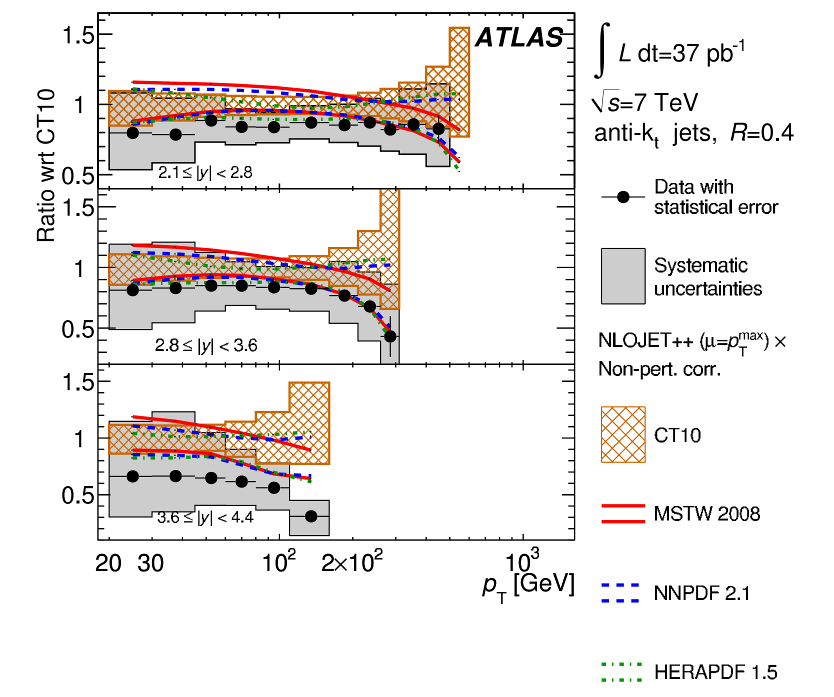


- Jet energy scale uncertainty:
  CMS: ~1.5 - 3% (after two years)
  (similar for ATLAS, impressive achievements)



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

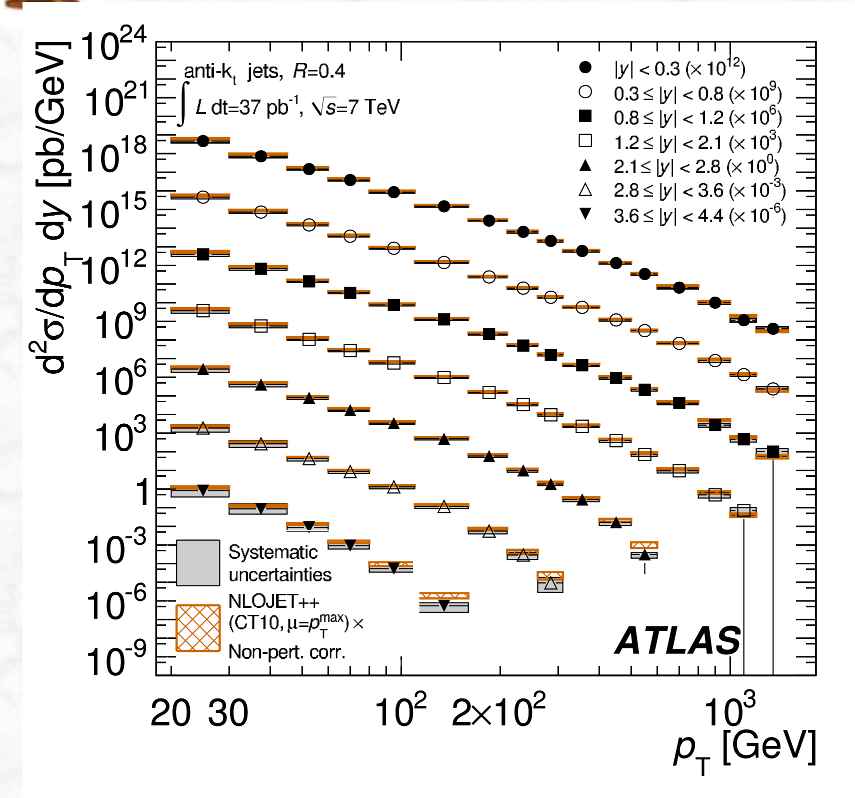


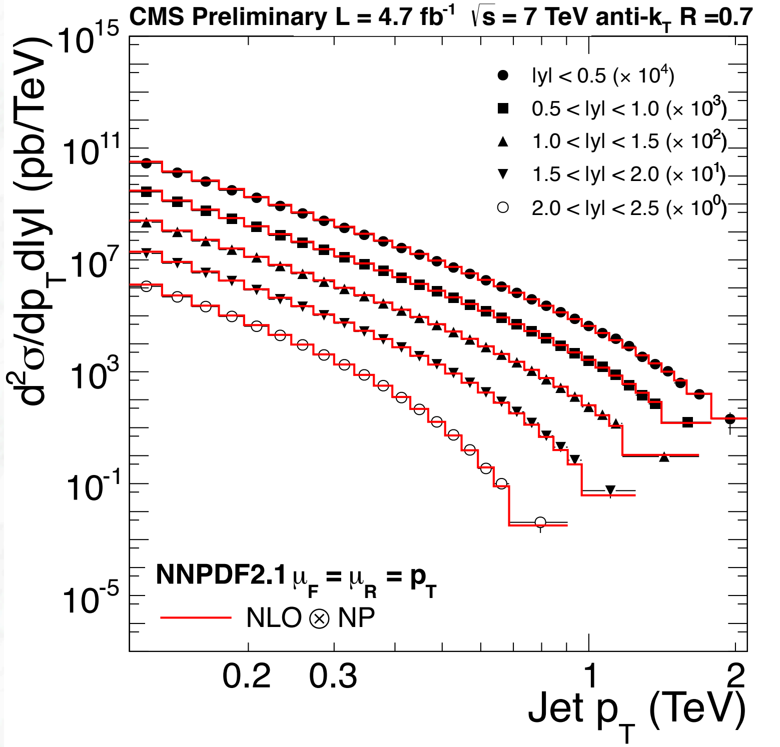


somewhat larger deviations in the forward region

- 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)

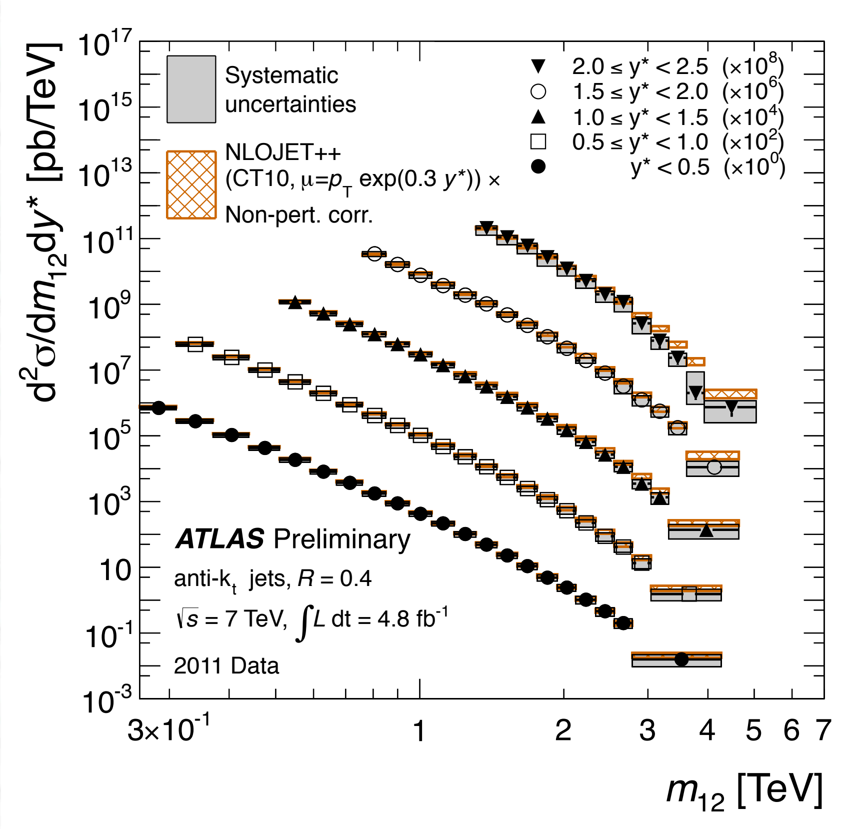


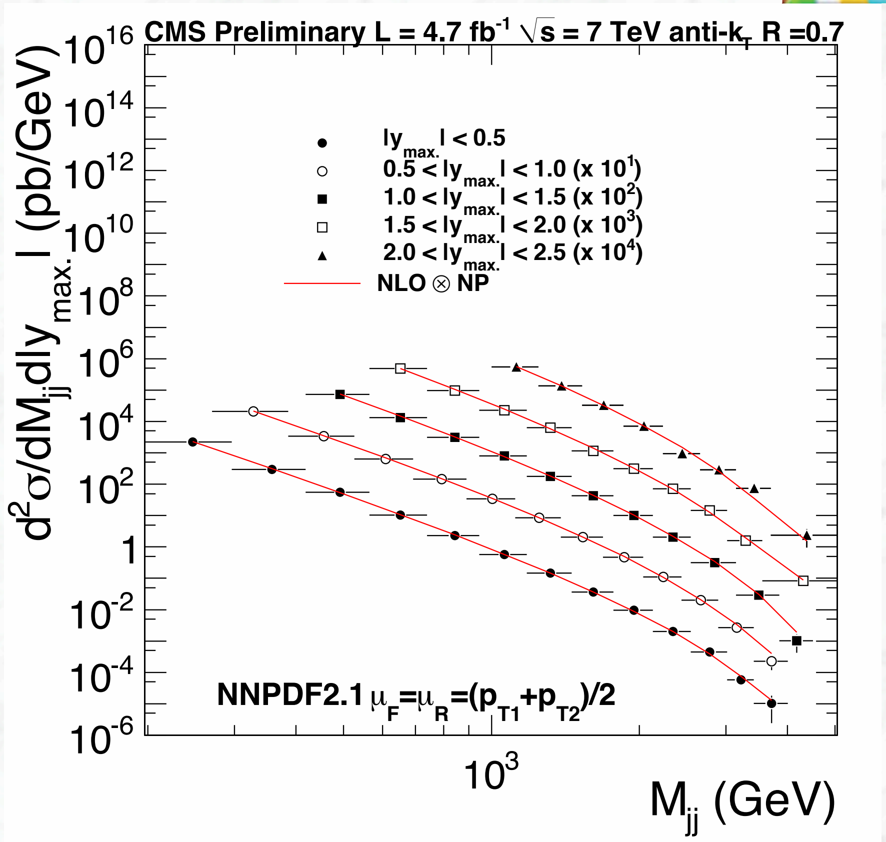


CMS: include full 2011 data set; comparison up to 2 TeV (central rapidities)

- 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

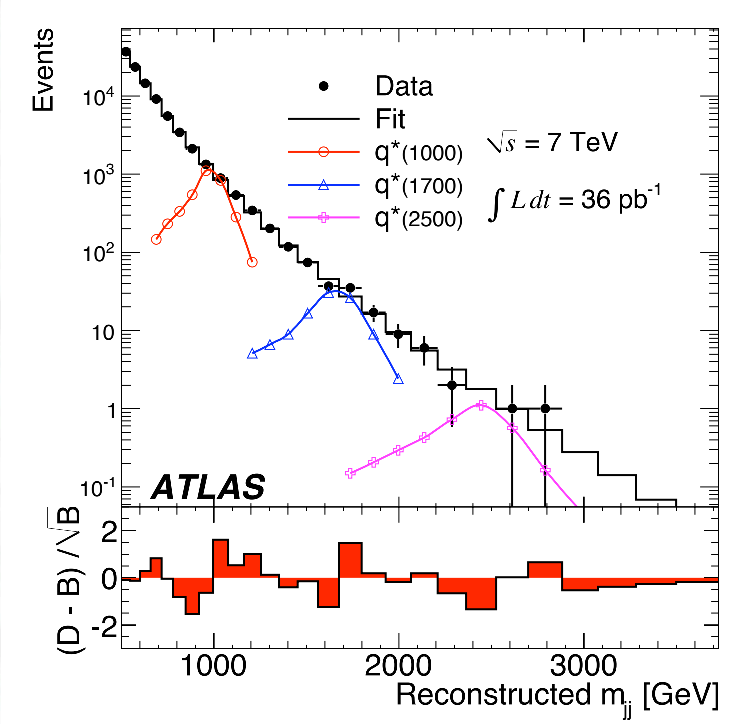
- Search for new resonances decaying into two jets (→ next slide)

In addition to QCD test: Sensitivity to New Physics

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

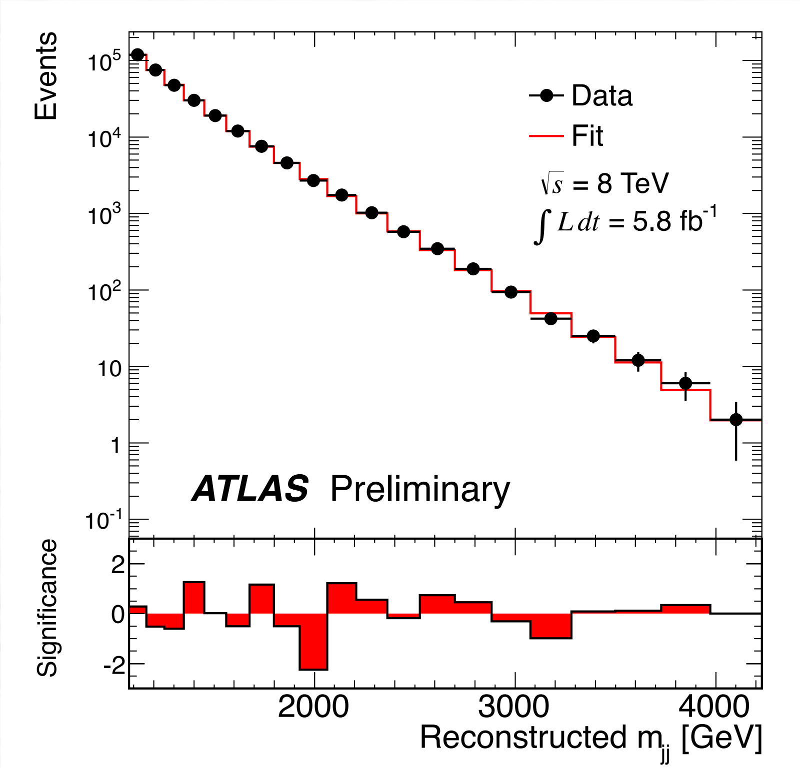
  e.g. Resonances decaying into qq, excited quarks q*, ….

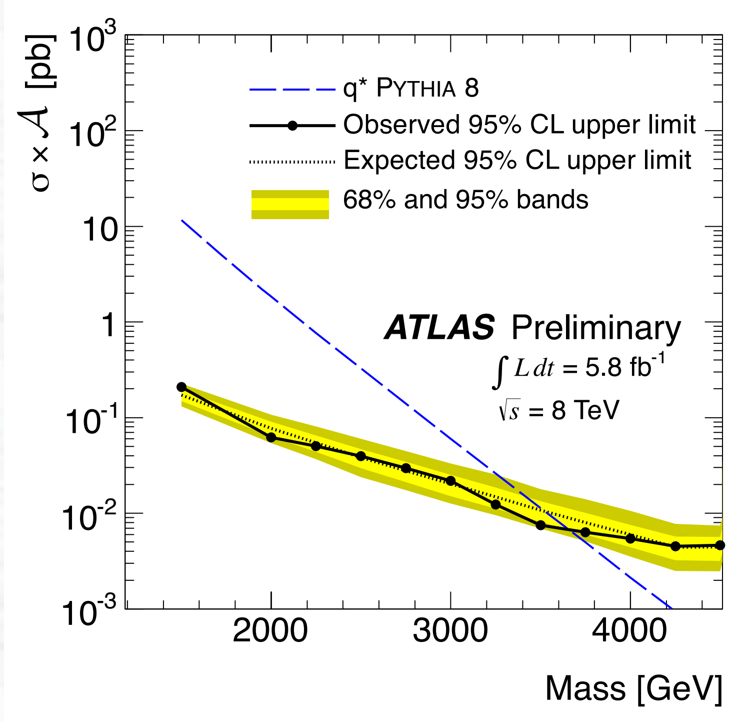
- Search for resonant structures in the di-jet invariant mass spectrum



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 $\sqrt{s}$ = 8 TeV (2012)
- Invariant di-jet masses up to 4.1 TeV





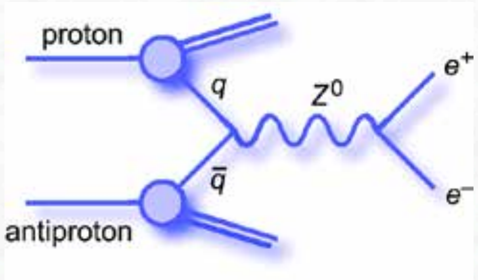
CDF (Tevatron), $L = 1.13\ fb^{-1}$: $0.26 < m_{q^*} < 0.87$ TeV

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

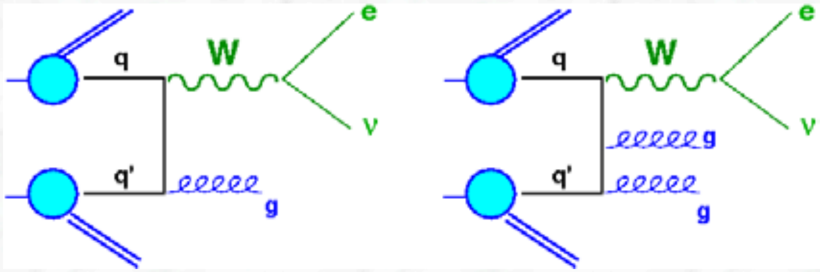
$L = 0.036\ fb^{-1}$: $0.60 < m_{q^*} < 2.64$ TeV

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

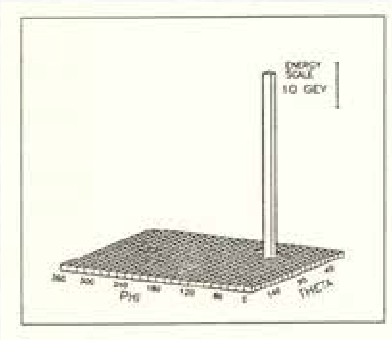


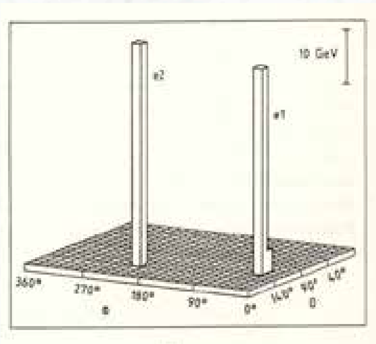
- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region (jet multiplicities, p_T spectra,….)
- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC

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})
$Z \rightarrow \ell \ell$

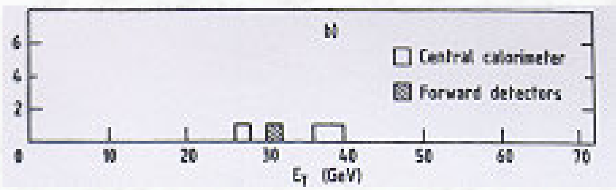




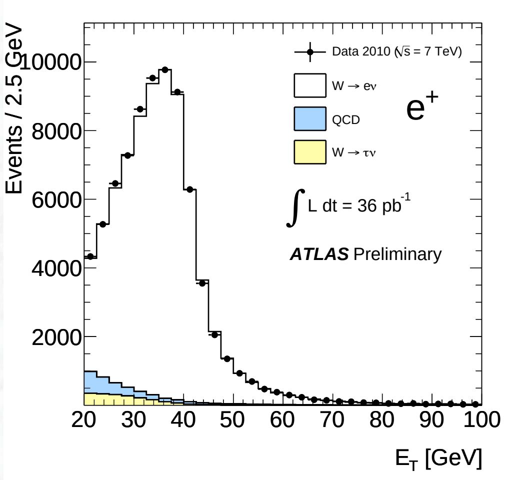
A bit of history: one of the first W events seen; UA2 experiment

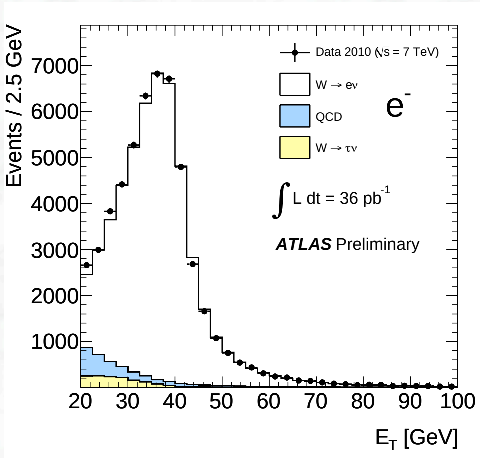
W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)

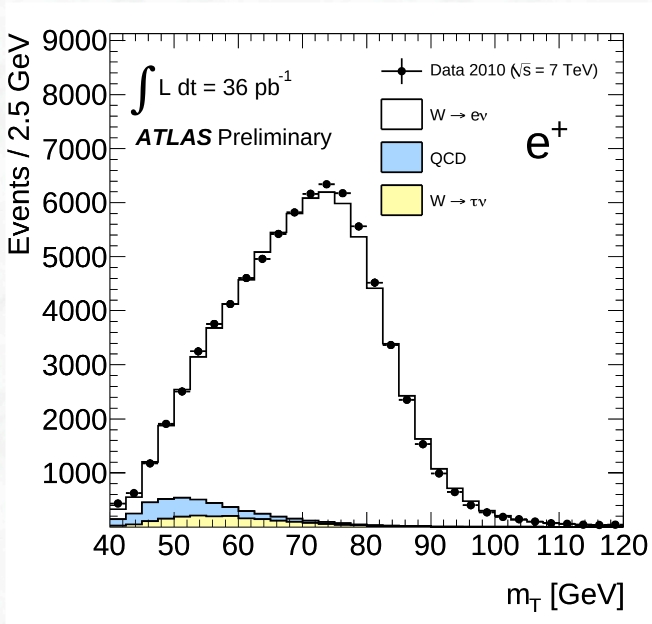
Transverse momentum of the electrons



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

$Z \rightarrow ee$

- 76 GeV/c² < m_{ee} < 106 GeV/c²

$W \rightarrow e\nu$

- 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

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

- 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, …

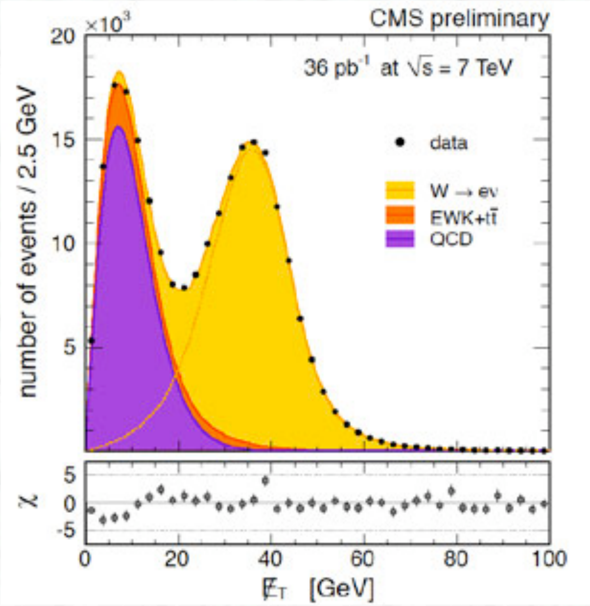
- $A_{W(Z)}$: acceptance (usually the final state products are measured in a so called fiducial region of the detector,
  e.g. η coverage of the muon detector, p_T threshold of the reconstruction)

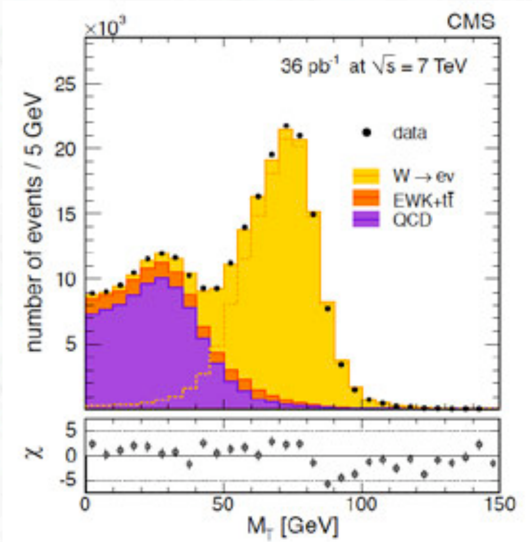
  This last quantity can only be calculated with Monte Carlo, using theoretical inputs !!
  (N)NLO calculations, parton density functions, ….

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

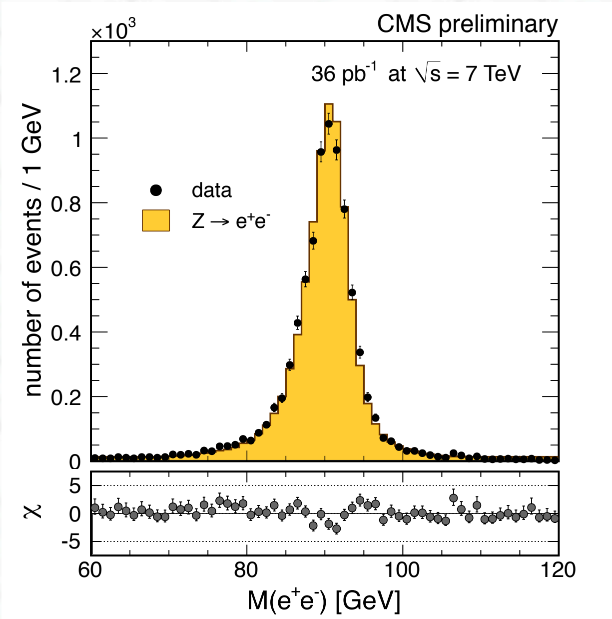
- $L_{W(Z)}$: integrated luminosity

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





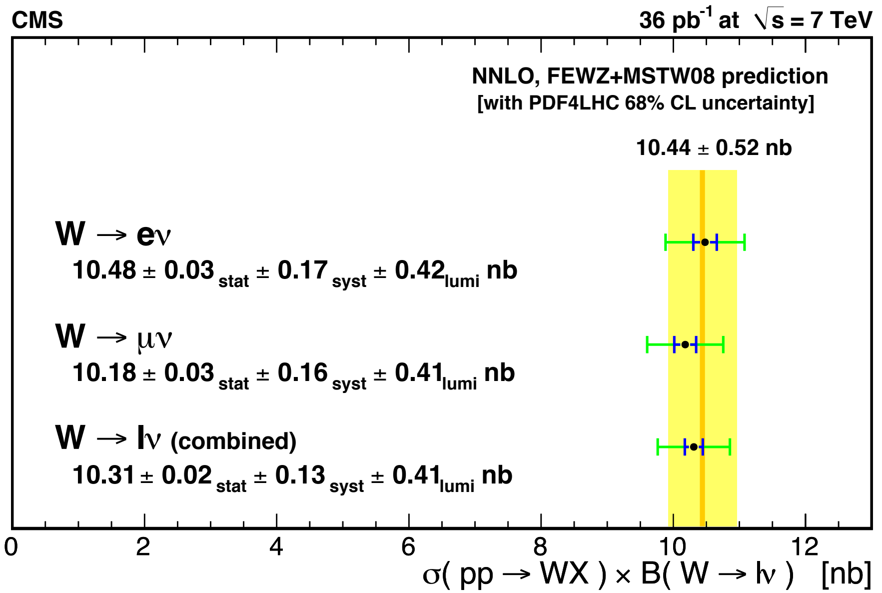
Distributions of the missing transverse energy, E_T^{miss}, (left) and transverse mass mT (right) of electron candidates for data and Monte Carlo simulation, broken down into the signal and various background components.

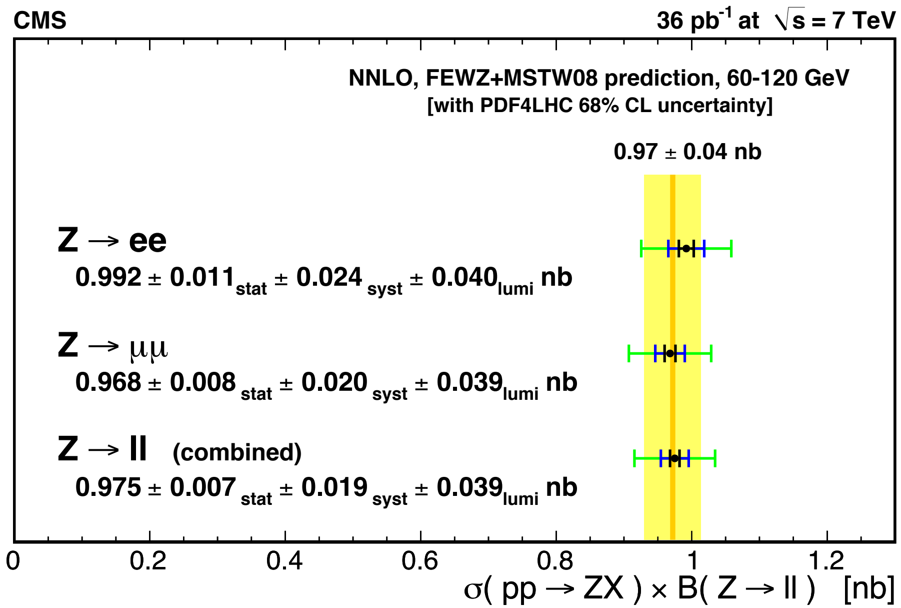


Distributions of the invariant di-electron mass, m_{ee}, for events passing the Z selection. The data are compared to Monte-Carlo simulation, the background is very small.

W and Z production cross sections at the LHC

Measured cross section values in comparison to NNLO QCD predictions:





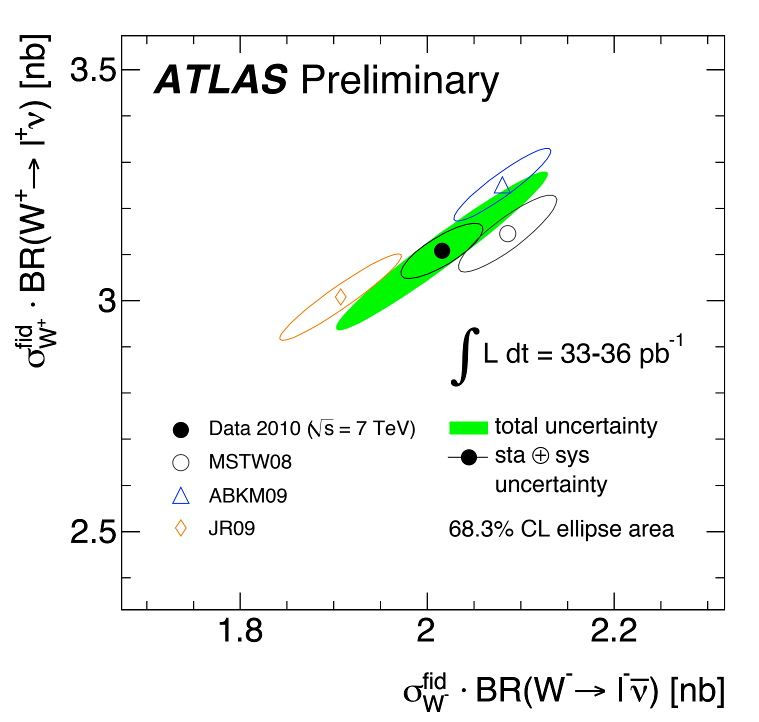
Data are well described by NNLO QCD calculations

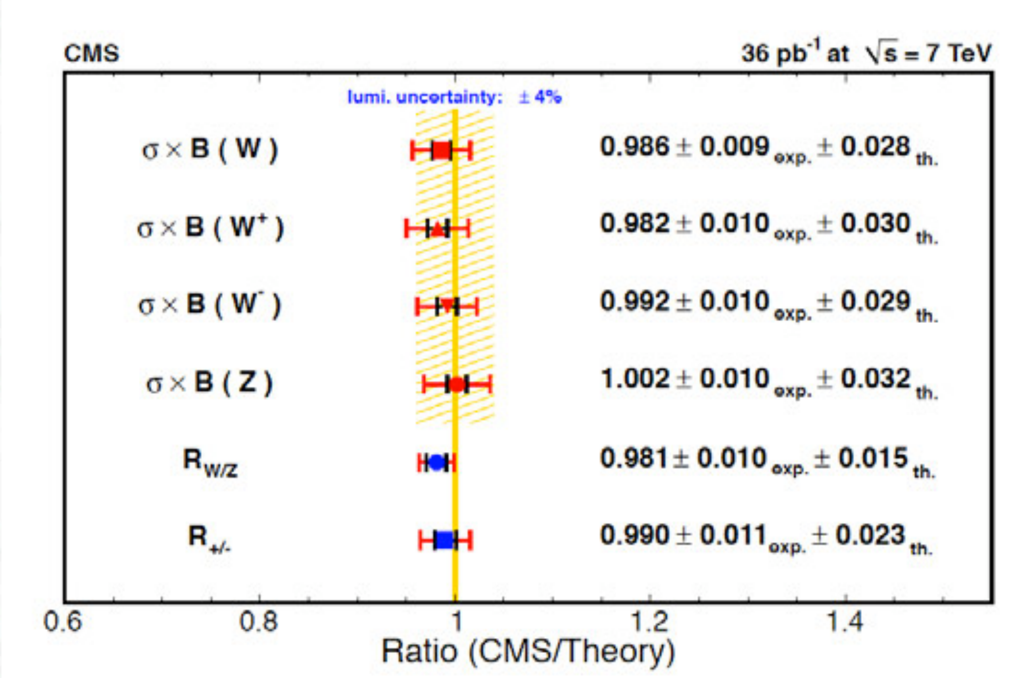
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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