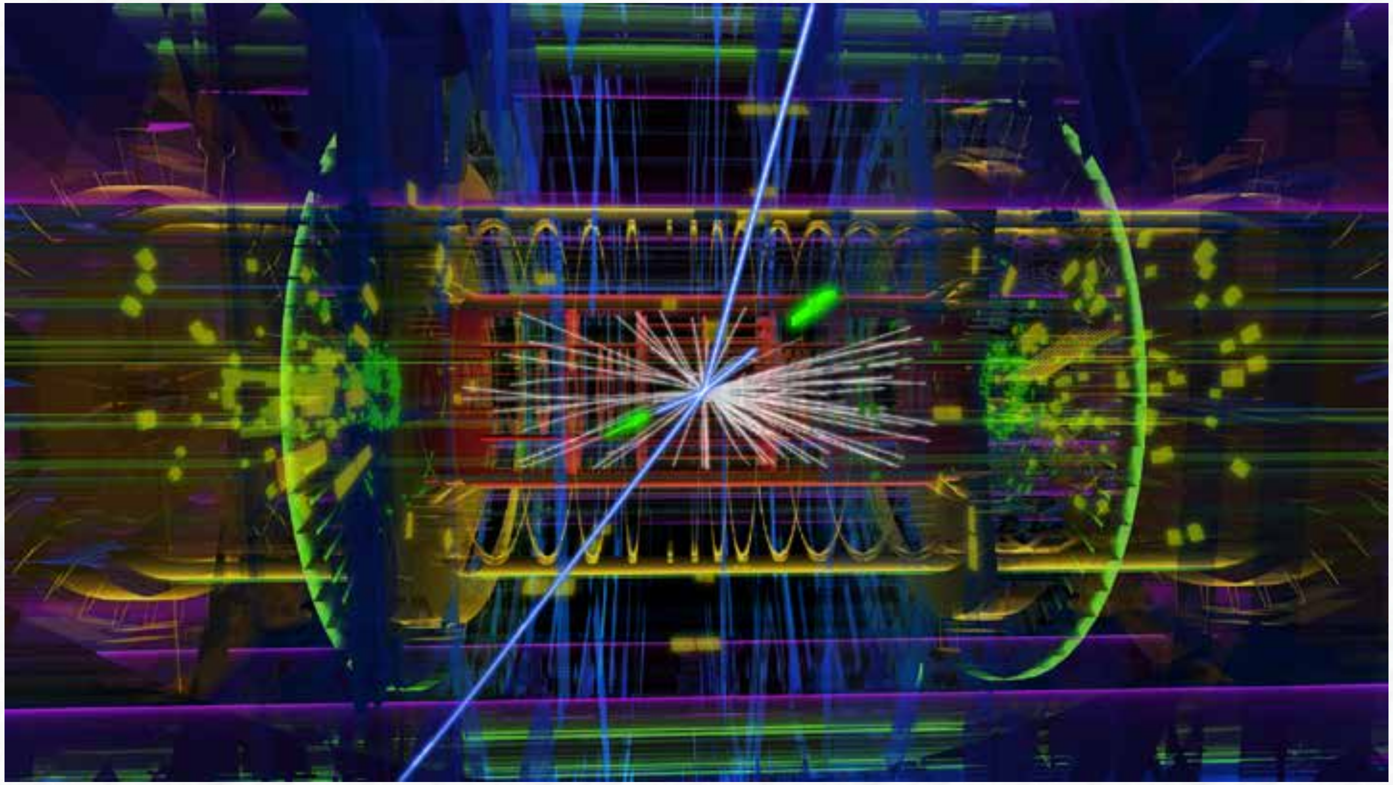
Physics at the LHC

- From the Standard Model to Searches for New Physics-



Karl Jakobs
Physikalisches Institut
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Outline of the talk

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

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

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

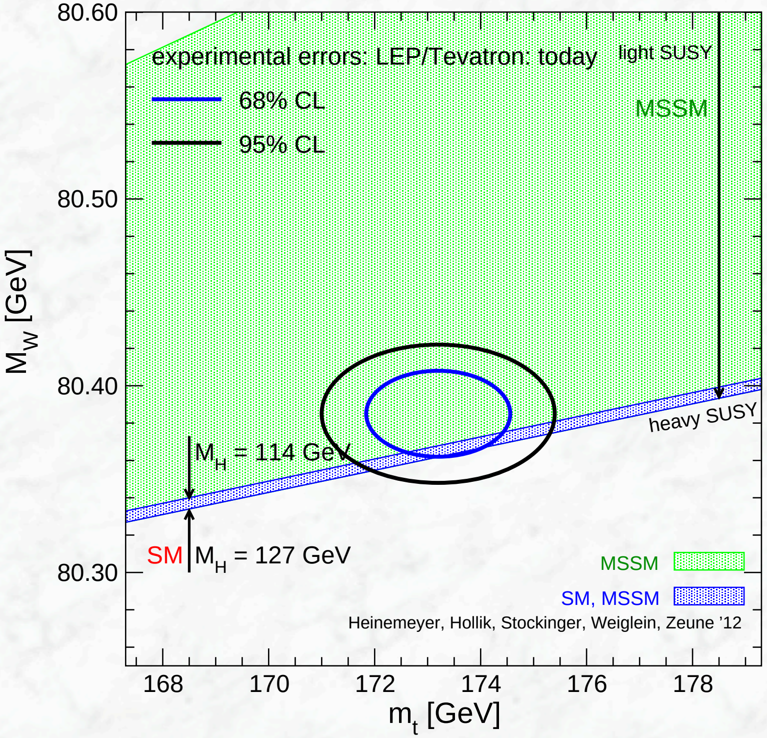
2. **Precise tests of the Standard Model**

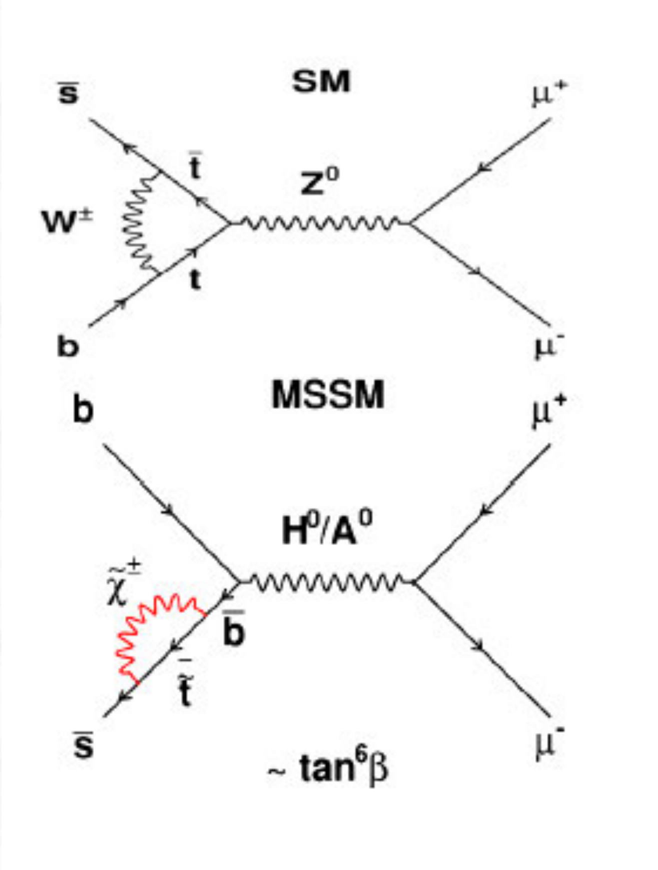
   - There is much sensitivity to physics beyond the Standard Model in the precision area (loop-induced effects, probe energy scales far beyond direct reach)
     → precise measurements, search for rare processes

→ Guidance to theory and Future Experiments

Two important examples:

2012

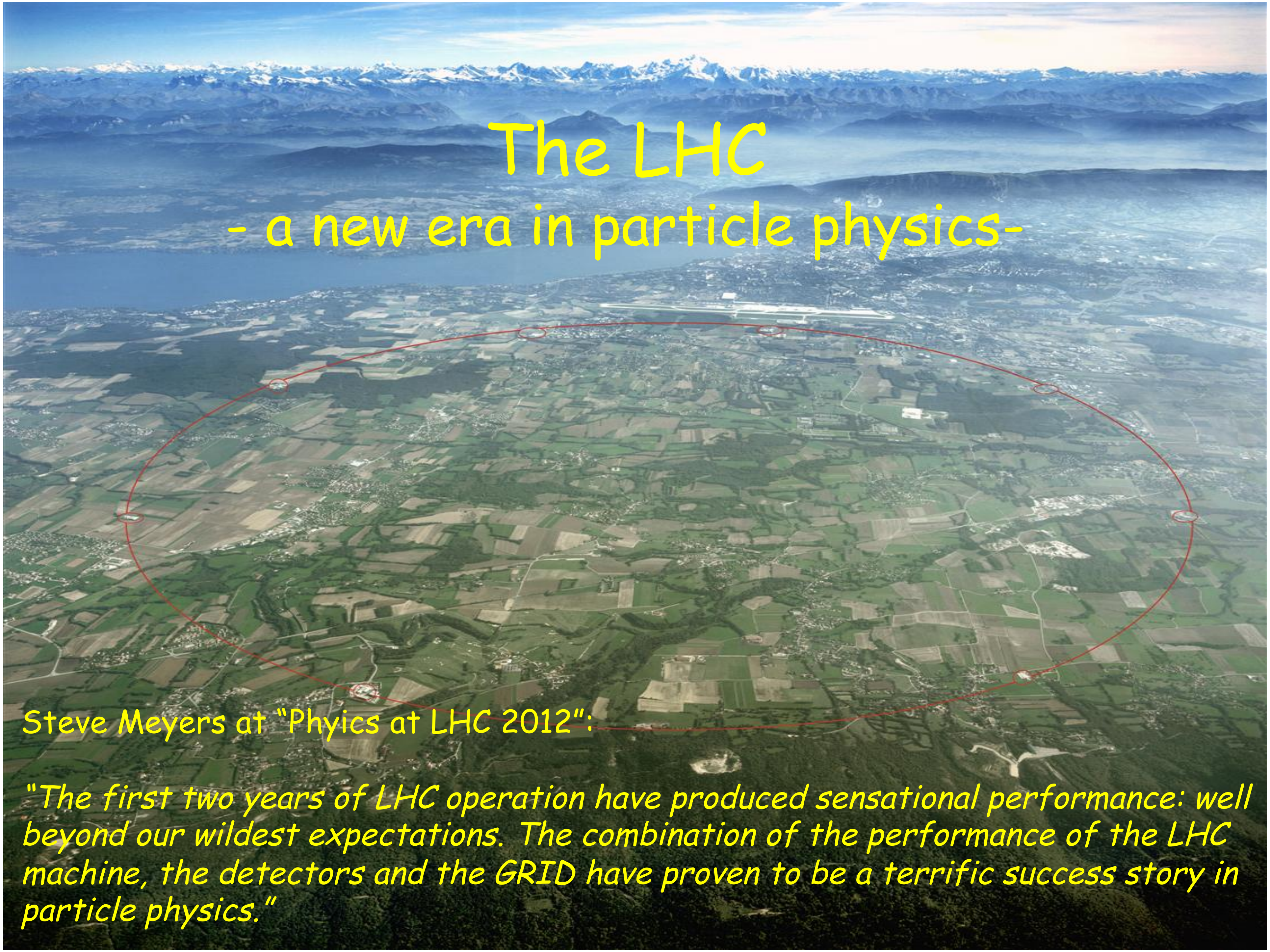




Ultimate test of the Standard Model:

Compare indirect prediction of the Higgs boson mass with the direct observation

Many theoretical models
for physics Beyond the
Standard Model

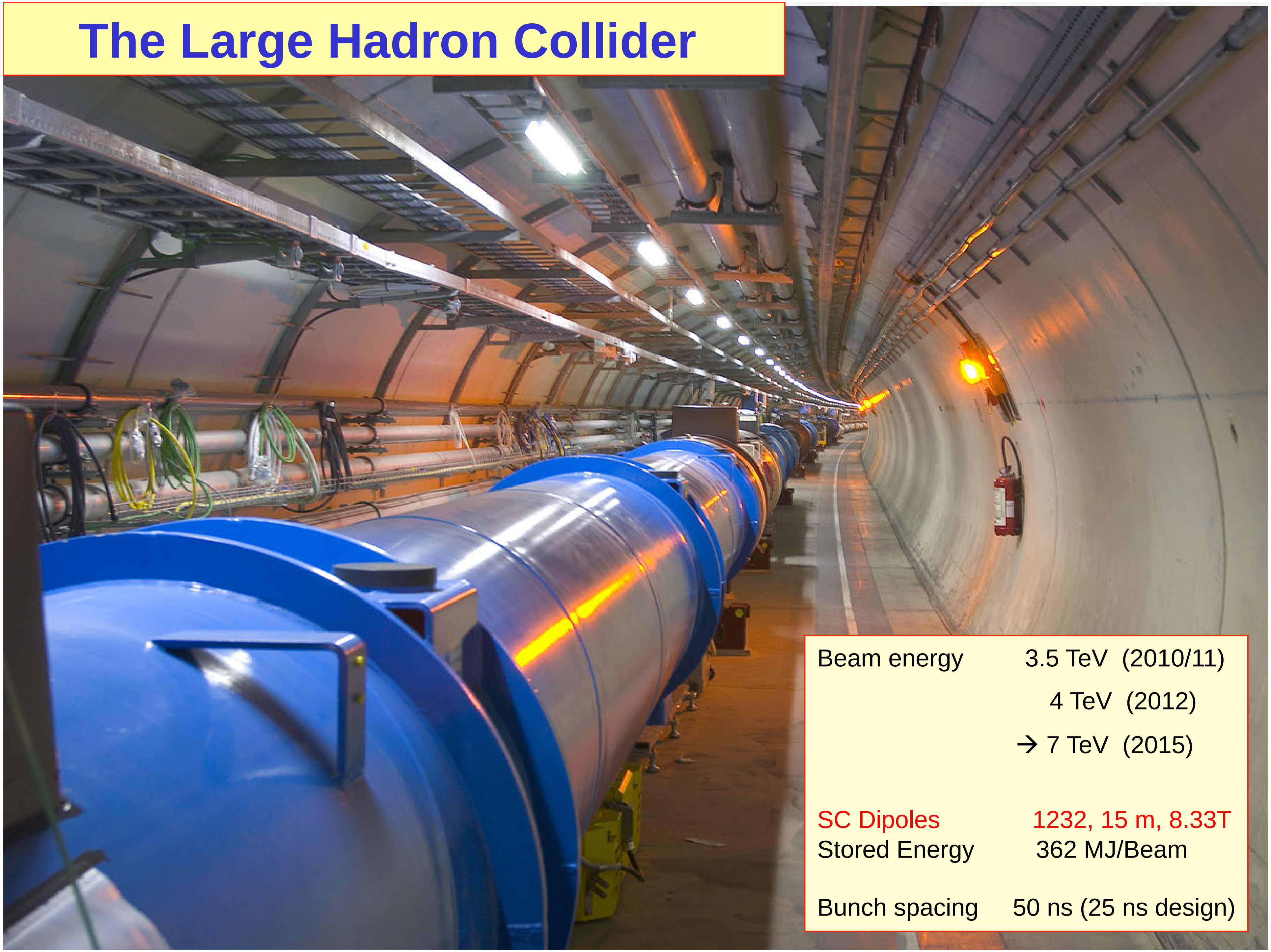


The LHC
- a new era in particle physics-

Steve Meyers at “Phyics at LHC 2012”:

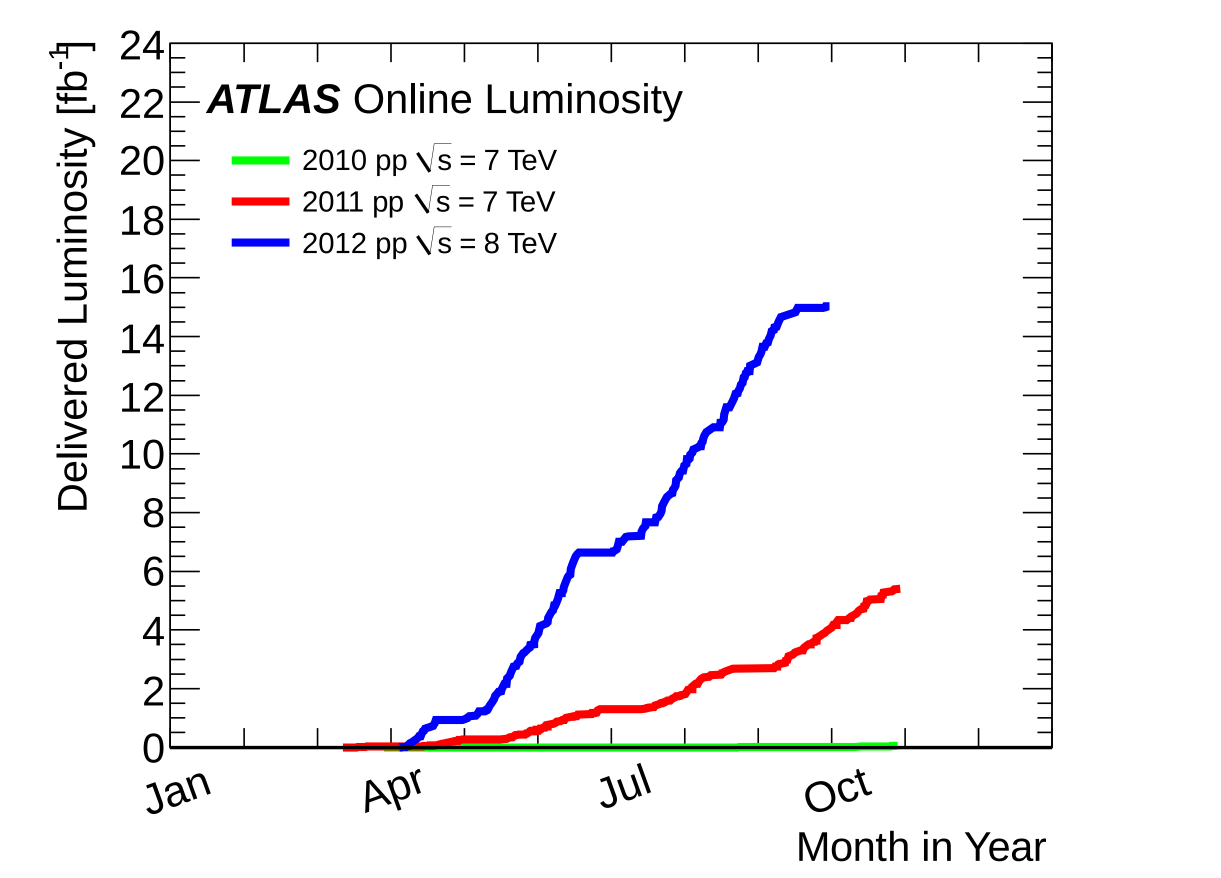
“The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics.”

The Large Hadron Collider



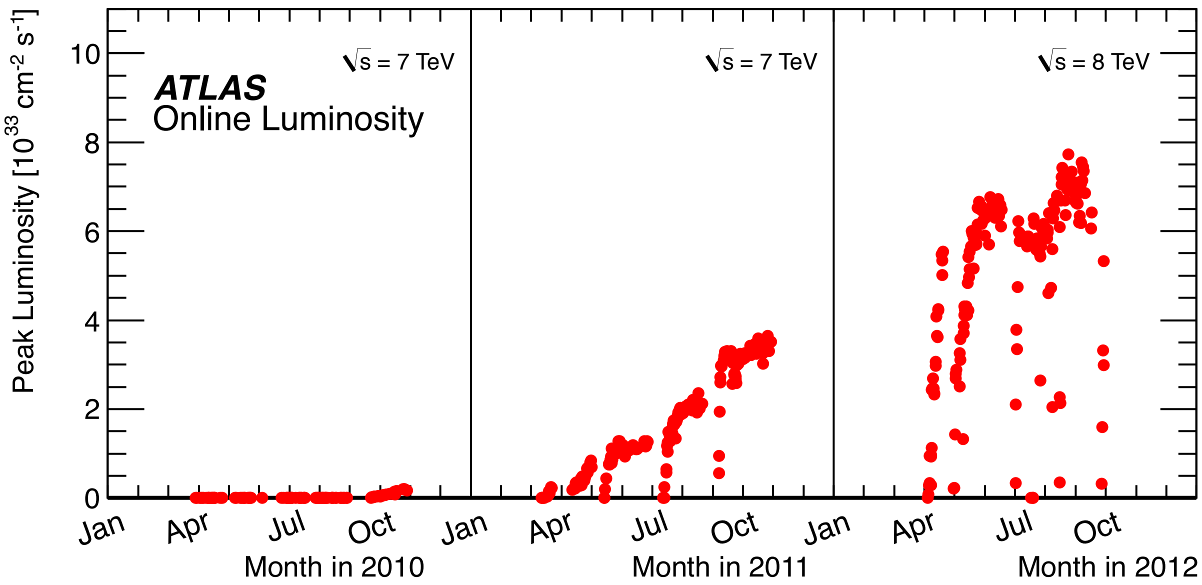
Beam energy	3.5 TeV (2010/11)
	4 TeV (2012)
	→ 7 TeV (2015)
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	50 ns (25 ns design)

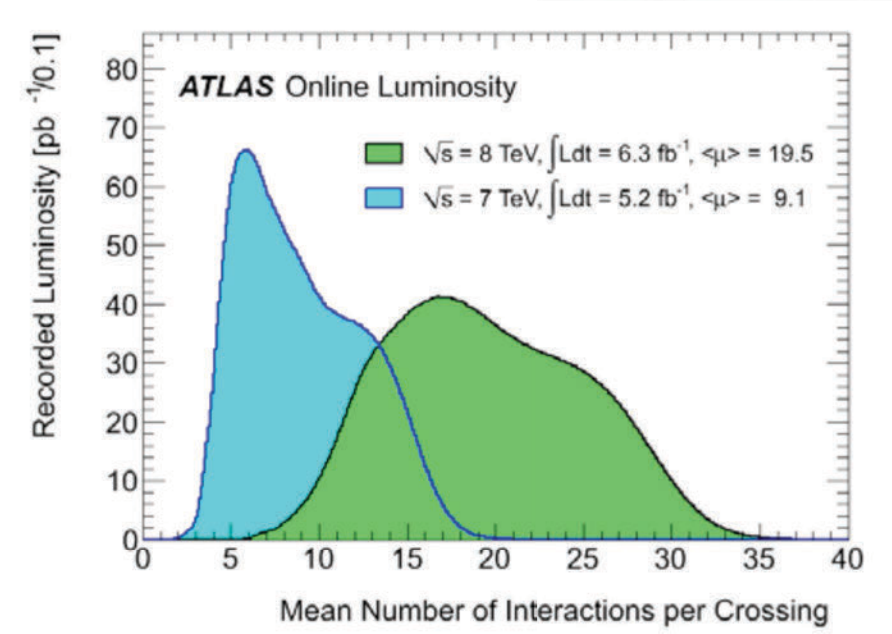
The LHC integrated luminosity



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

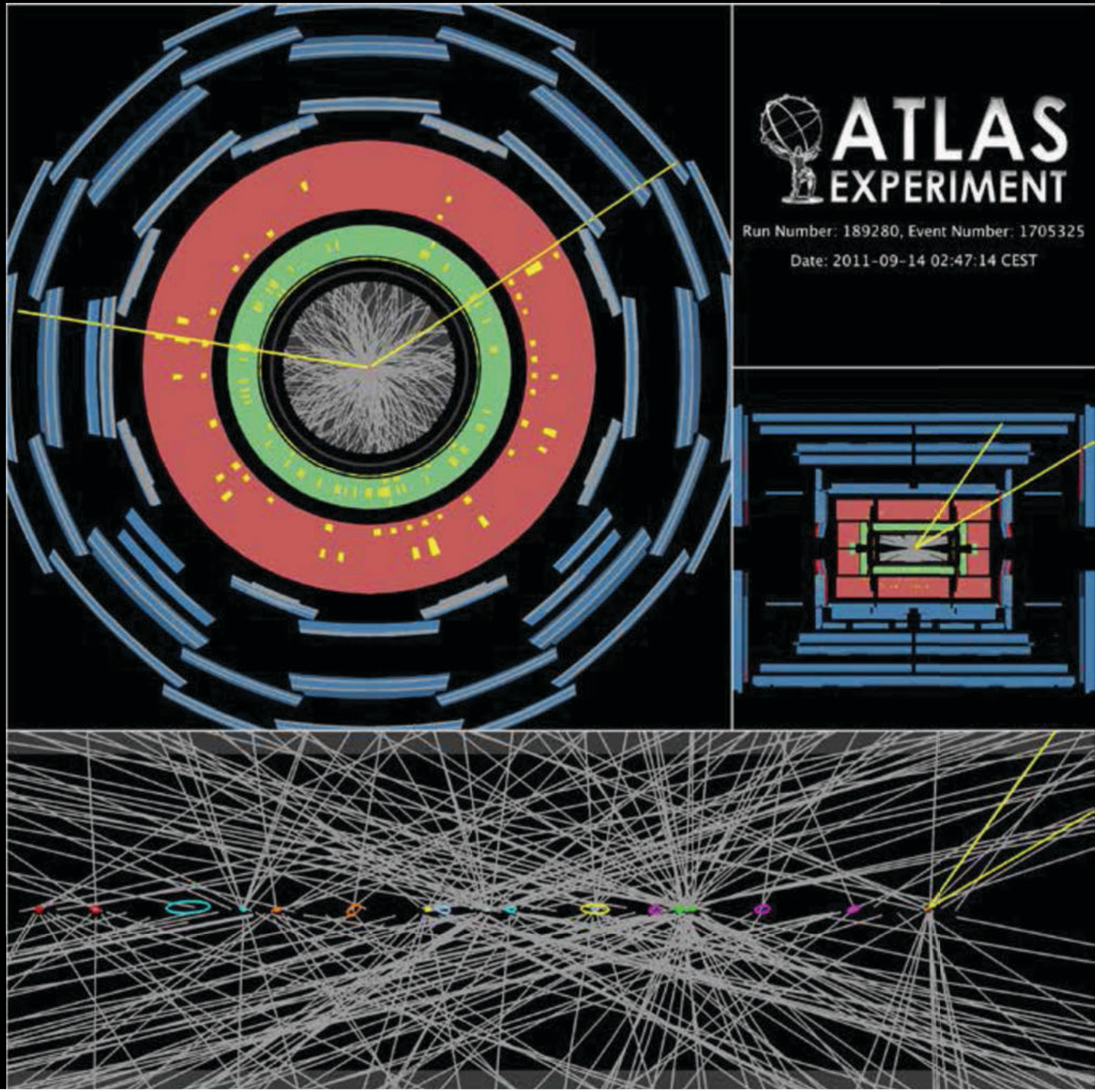
The LHC instantaneous luminosity





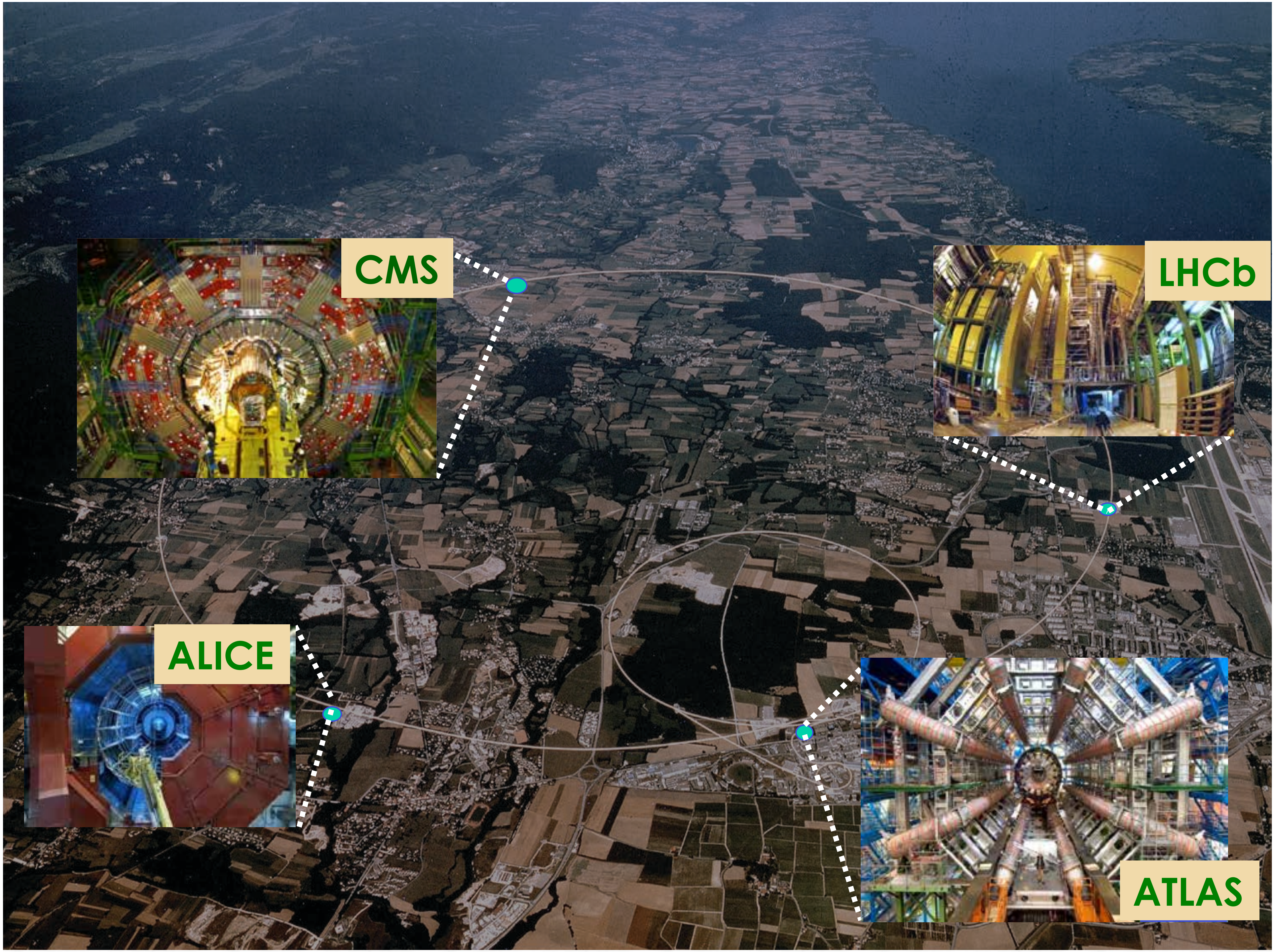
- World record on instantaneous luminosity on 22. April 2011: 4.67 10^{32} cm^{-2} s^{-1} (Tevatron record: 4.02 10^{32} cm^{-2} s^{-1})
- 2011: collect per day as much integrated luminosity as in 2010
- 2012: now regularly above 6 10^{33} cm^{-2}s^{-1}

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



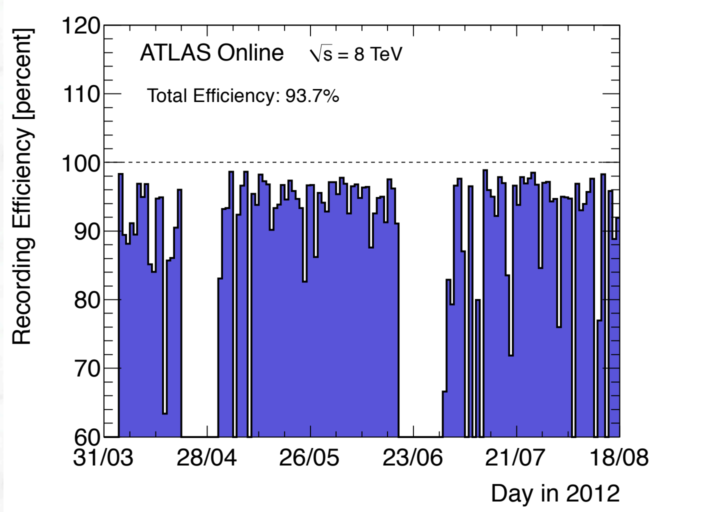
An event with 20 reconstructed vertices

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

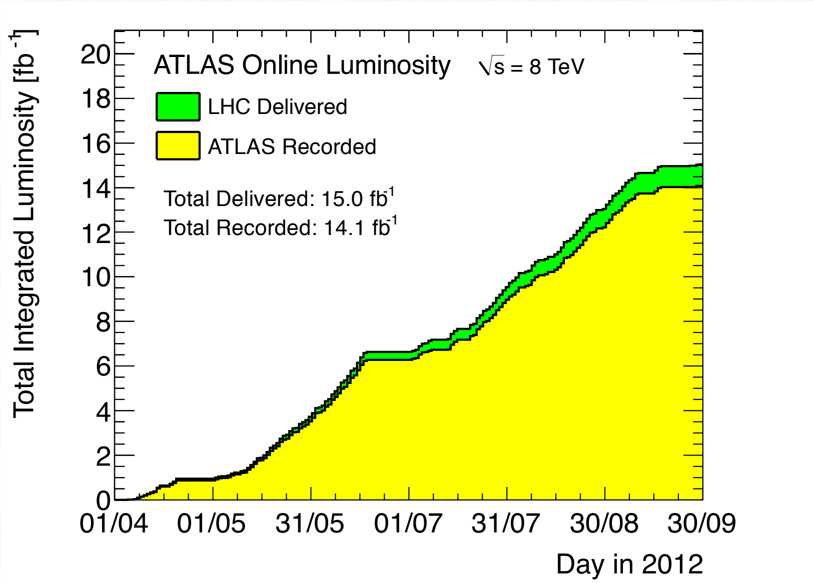

CMS
LHCb
ALICE
ATLAS

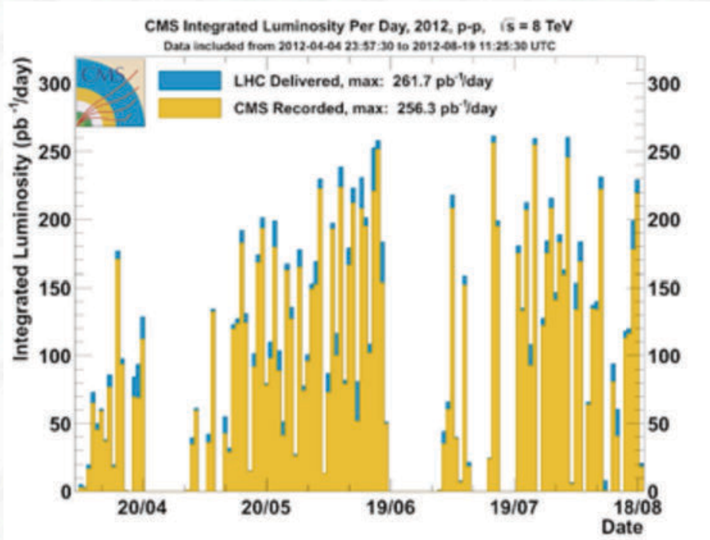
Detector performance is impressive:

- 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})

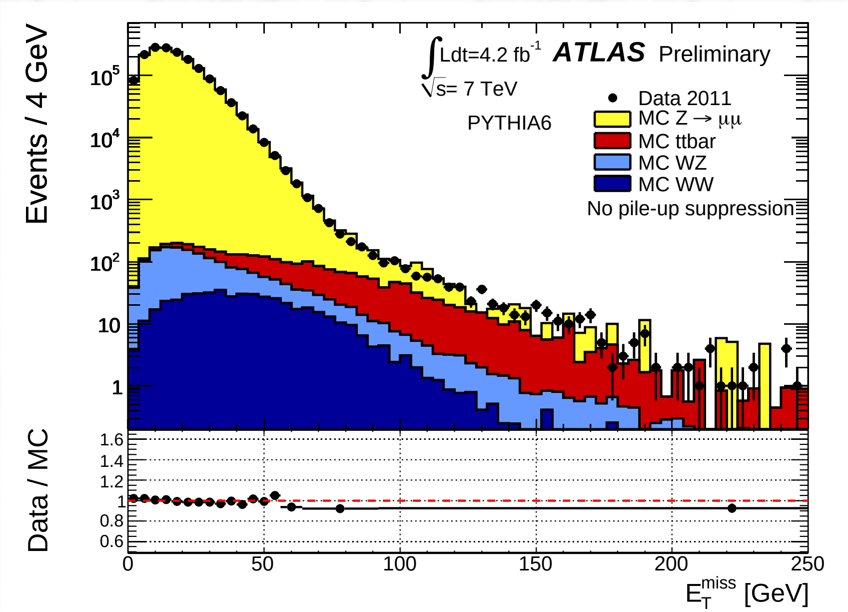


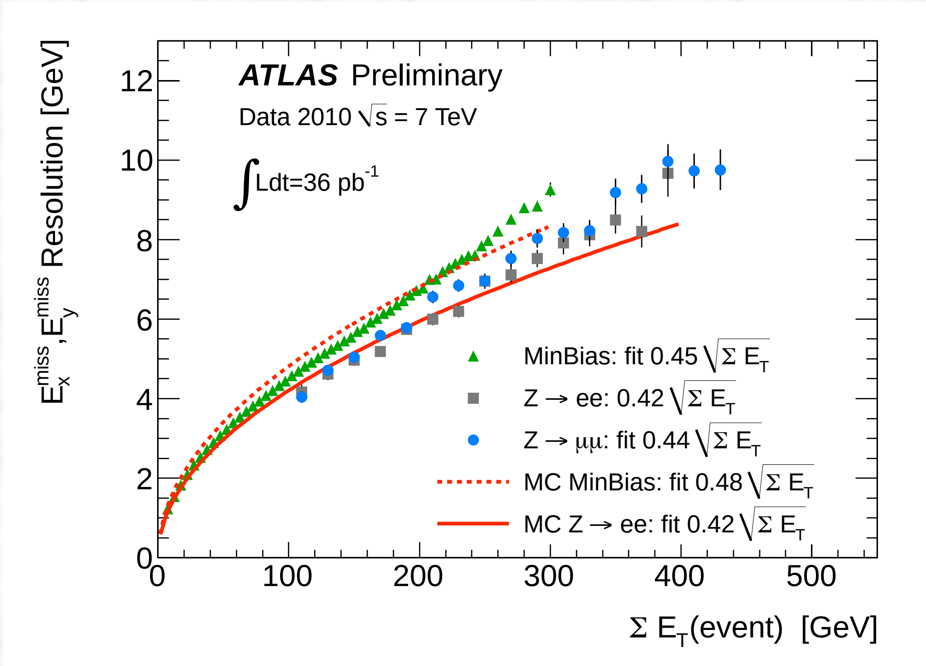
Have been optimized to cope with the ever increasing number of pile-up interactions





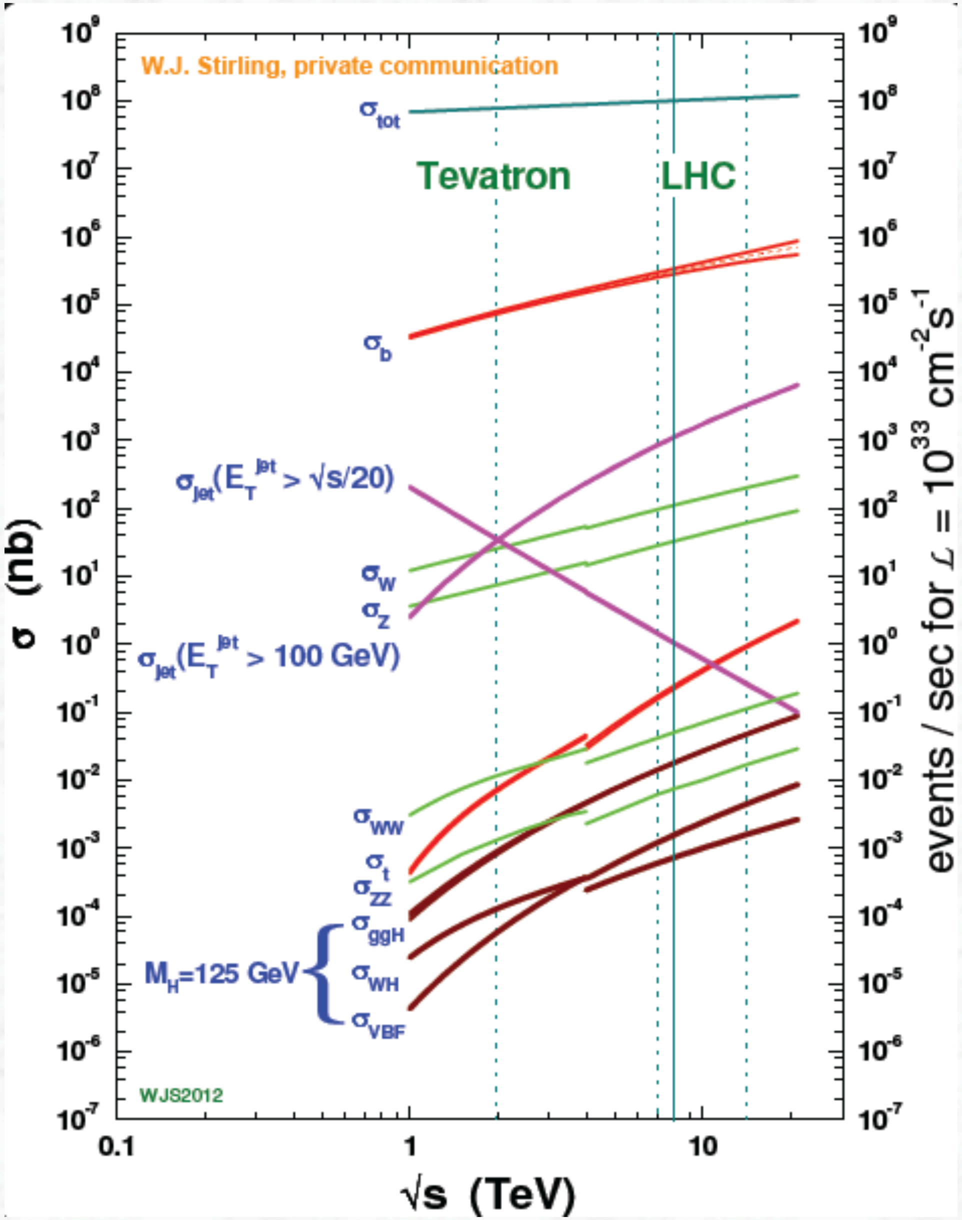
Measurement of the missing transverse energy E_T^{miss}





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.

Cross Sections and Production Rates



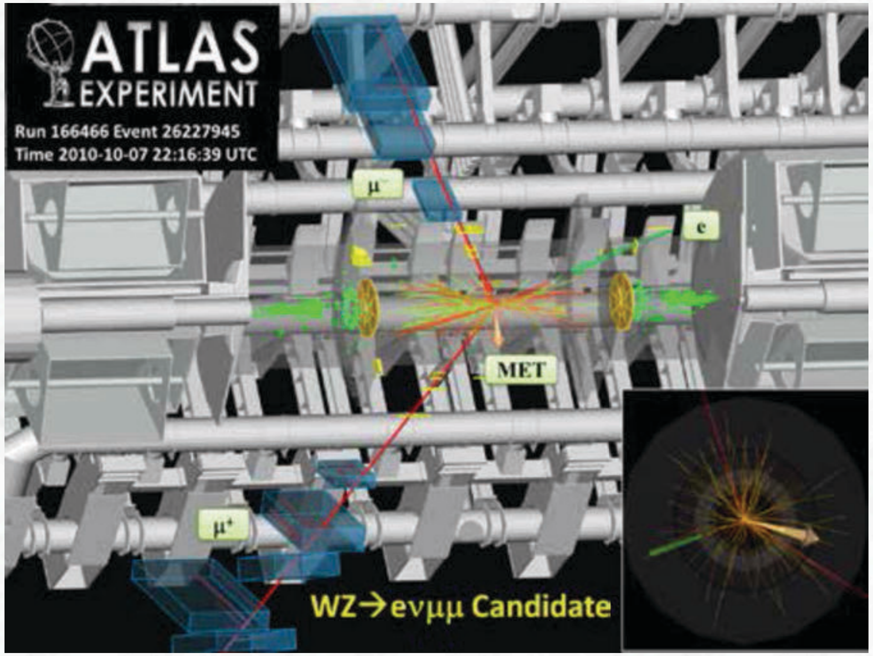
LHC is a factory for:
top-quarks, b-quarks, W, Z, …,Higgs, …

but other more prominent processes dominate the production rates:

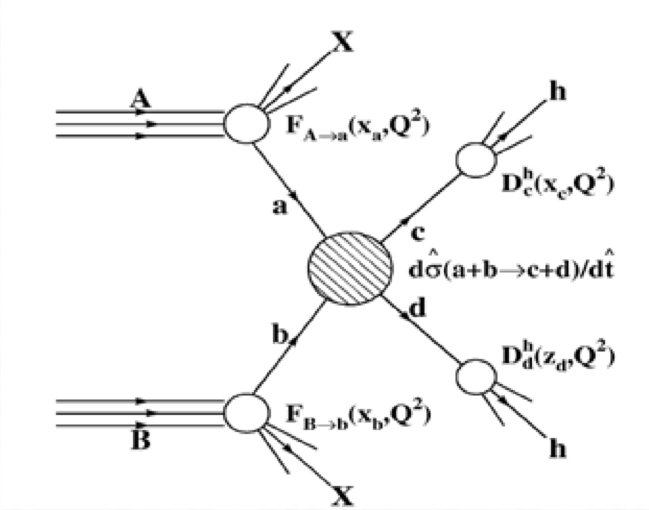
- Jet production via QCD scattering
- Soft pp collisions (σ ~ 100 mb)

Part 2: Test of perturbative QCD

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

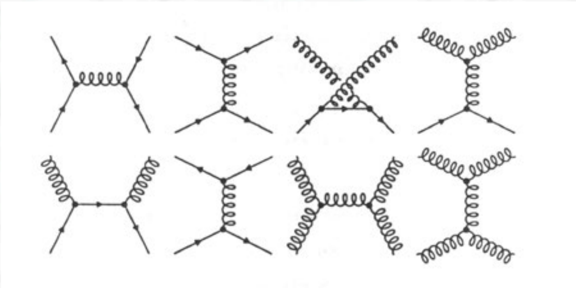


QCD processes at hadron colliders

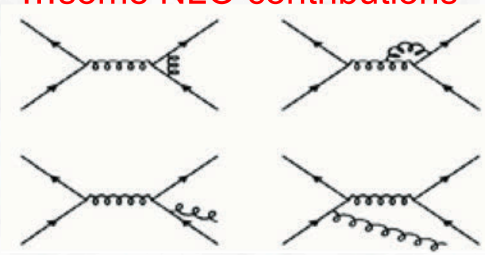


- Hard scattering processes are dominated by QCD jet production
- Originating from qq, qg and gg scattering
- Cross sections can be calculated in QCD (perturbation theory)

Leading order



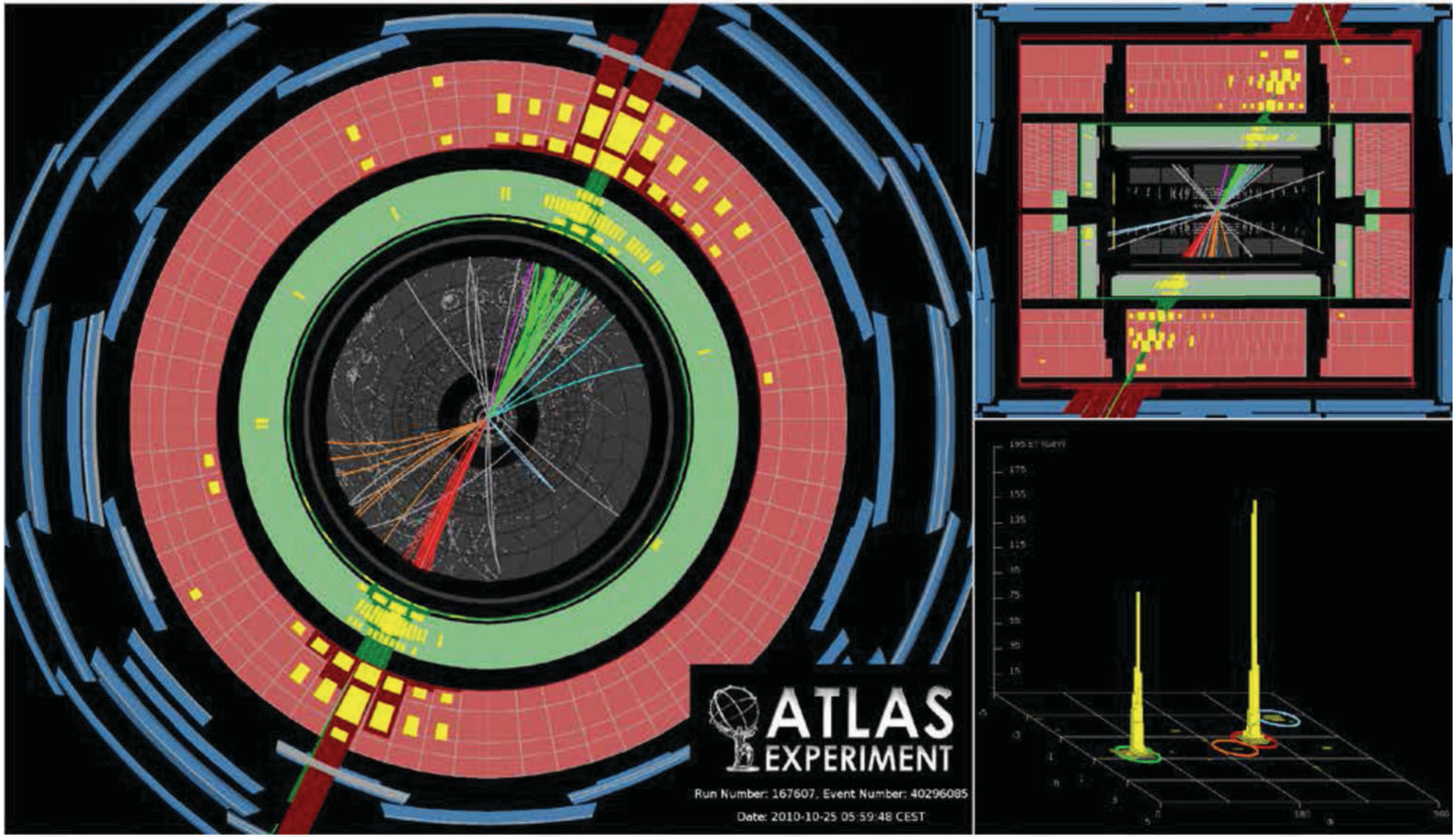
…some NLO contributions



Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

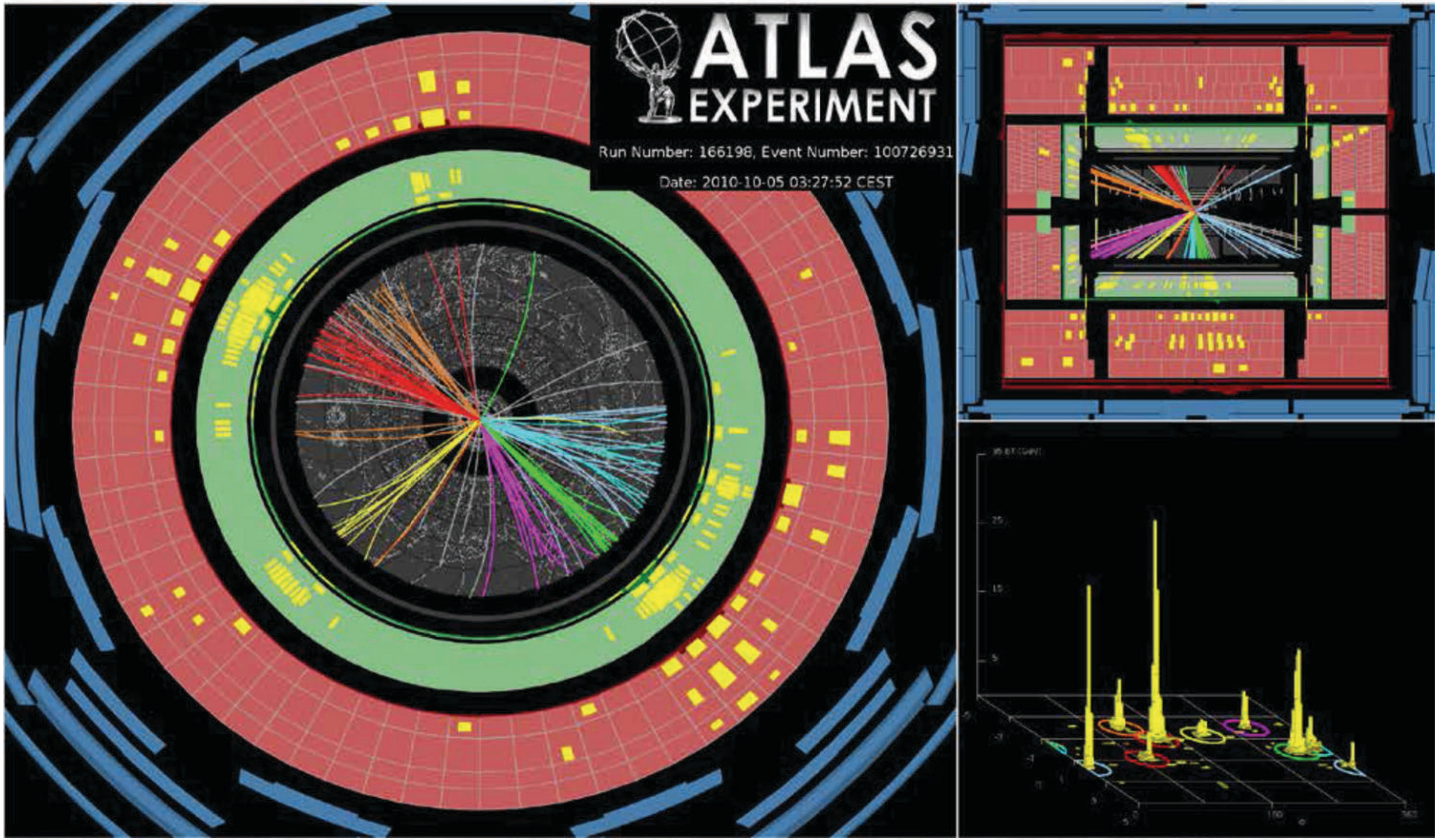
Deviations?
→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

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 in 2010, 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.

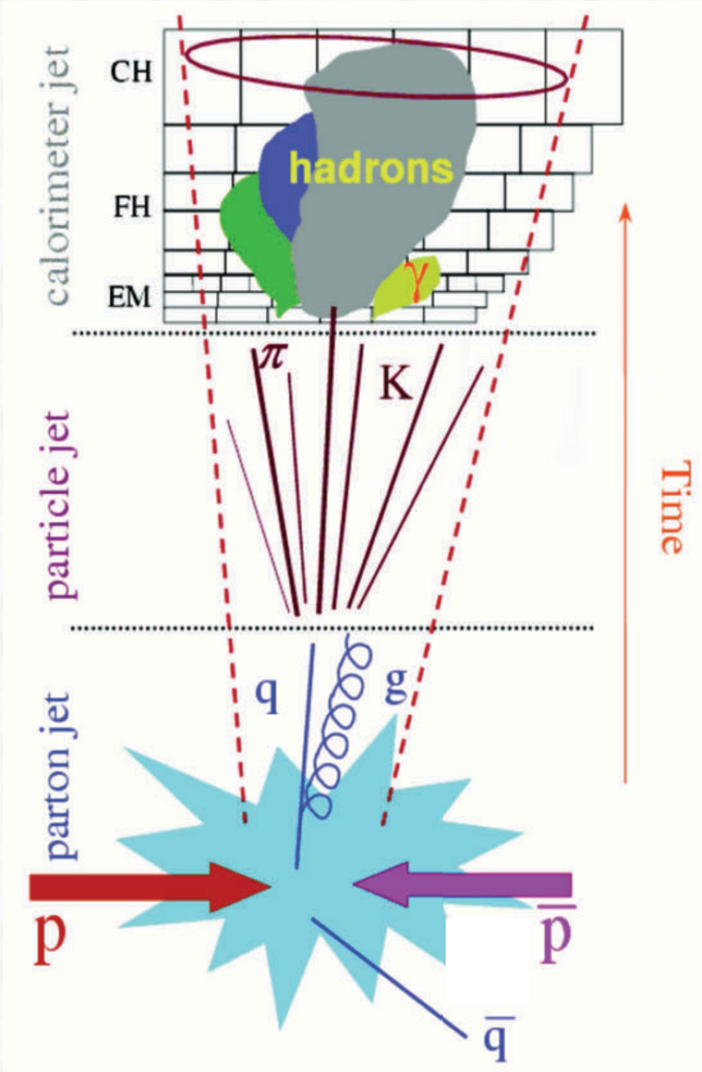
Jet reconstruction and energy measurement

- 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

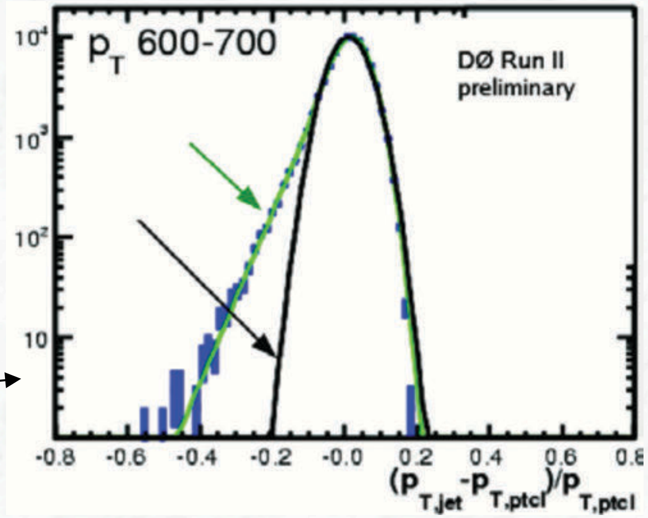


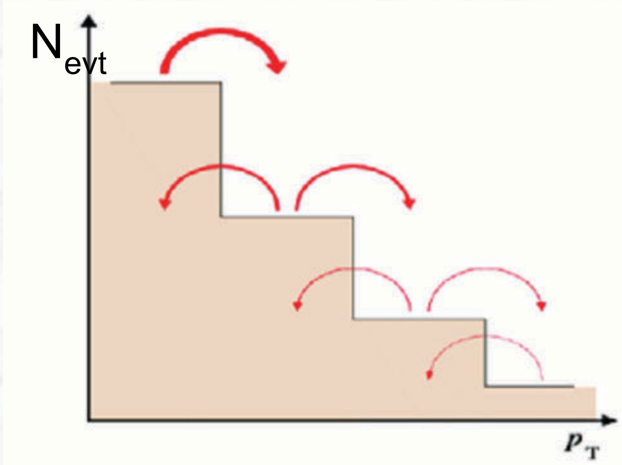
Jet measurements

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

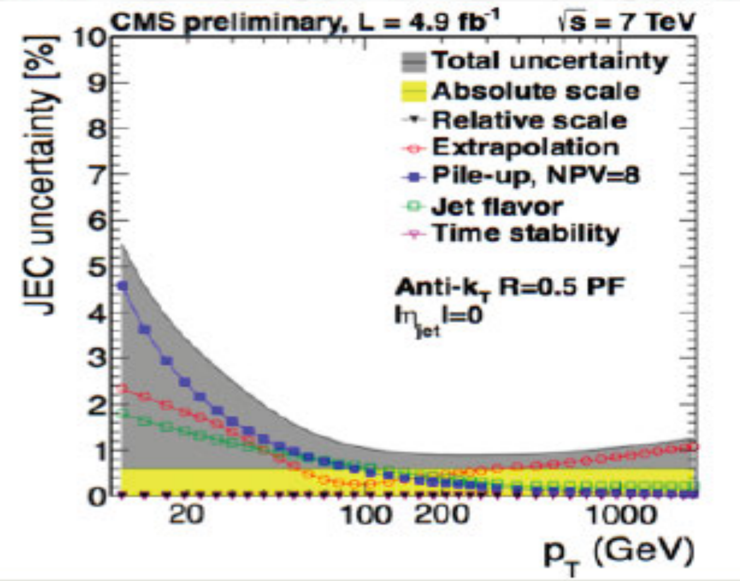
- In principle a simple counting experiment

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

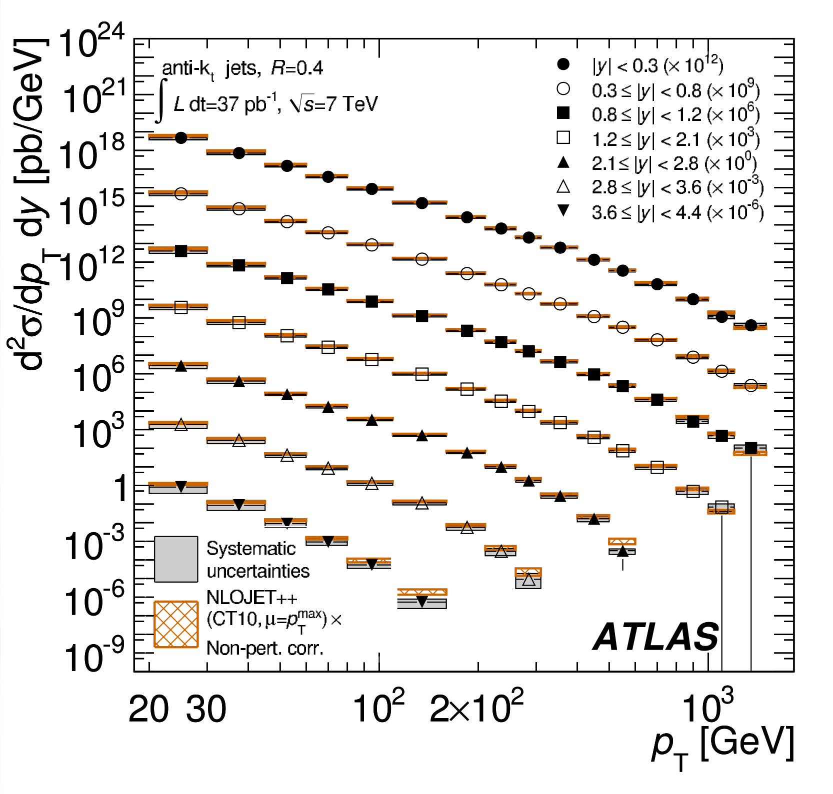


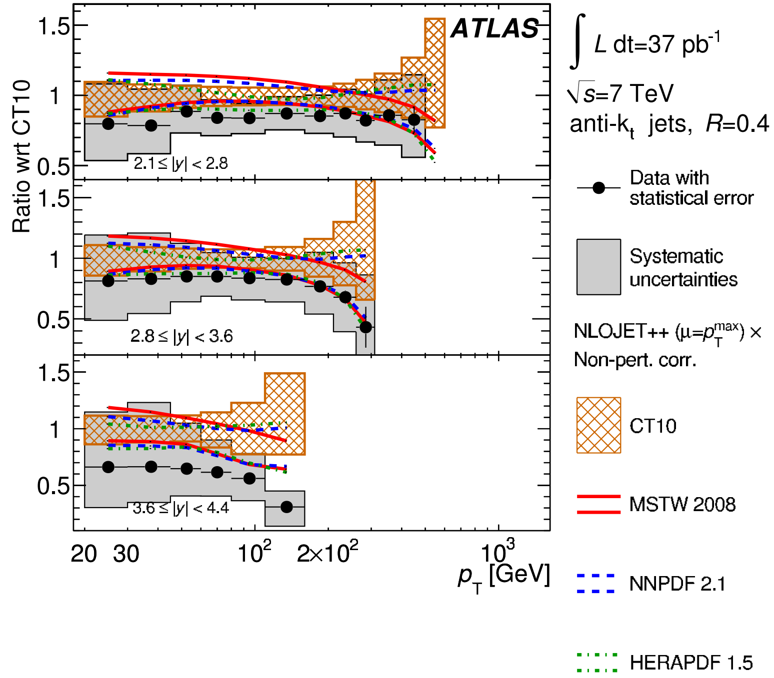


- Jet energy scale uncertainty:
  CMS: ~1.5 - 3% (after two years)
  (similar for ATLAS, impressive achievements)



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

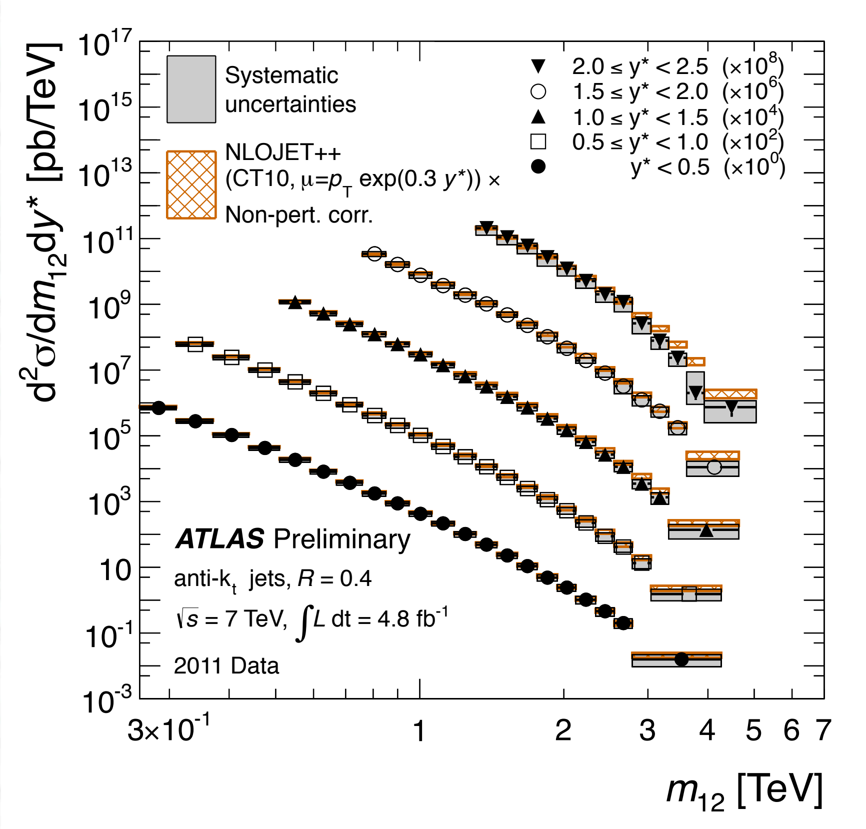


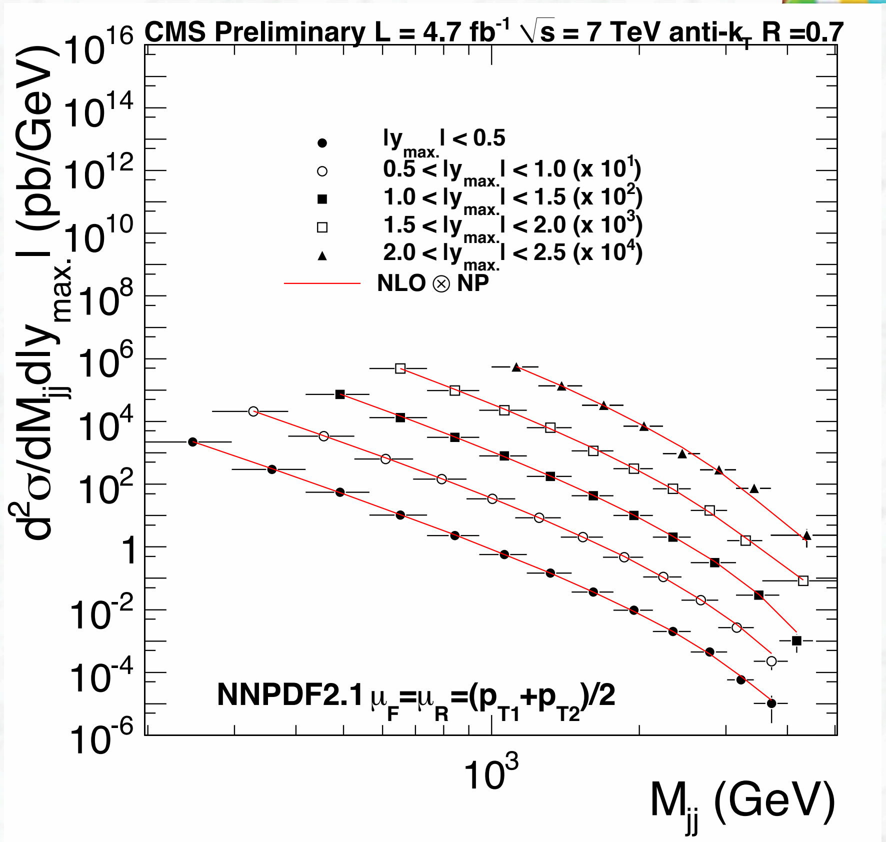


somewhat larger deviations in the forward region

- 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

Invariant di-jet mass spectra





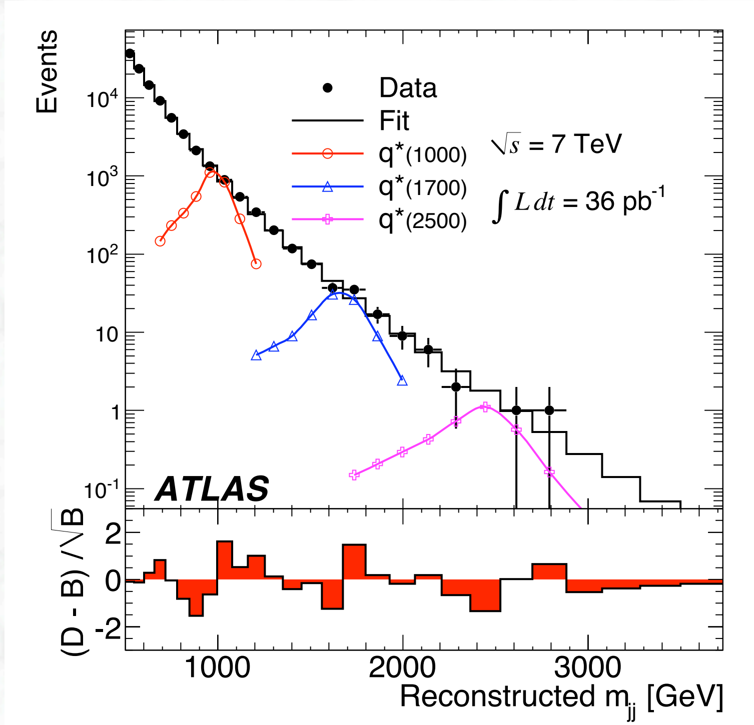
Important for:
- Test of QCD
- Search for new resonances decaying into two jets (→ next slide)

In addition to QCD test: Sensitivity to New Physics

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

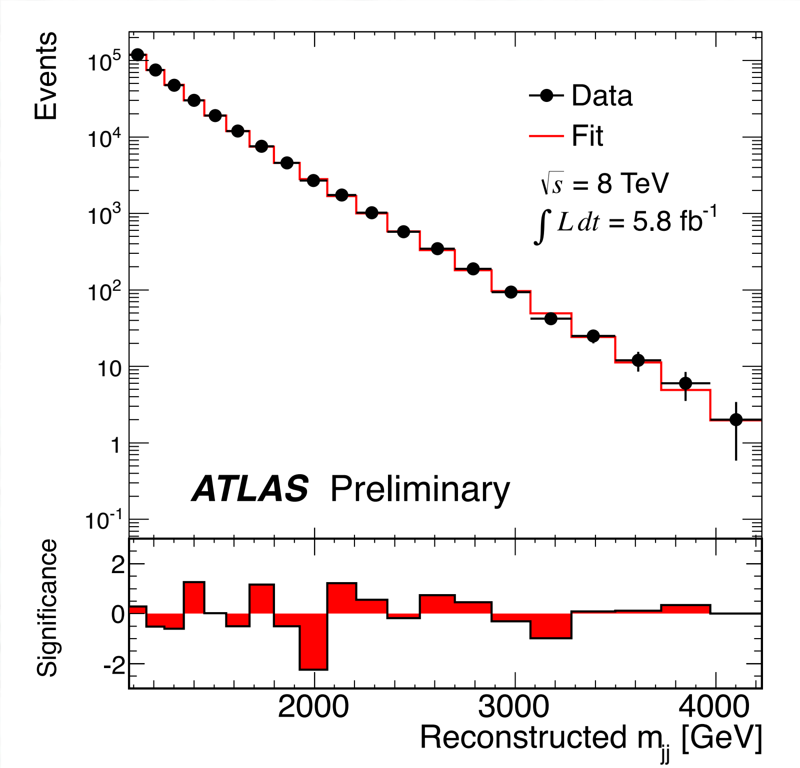
  e.g. Resonances decaying into qq, excited quarks q*, ….

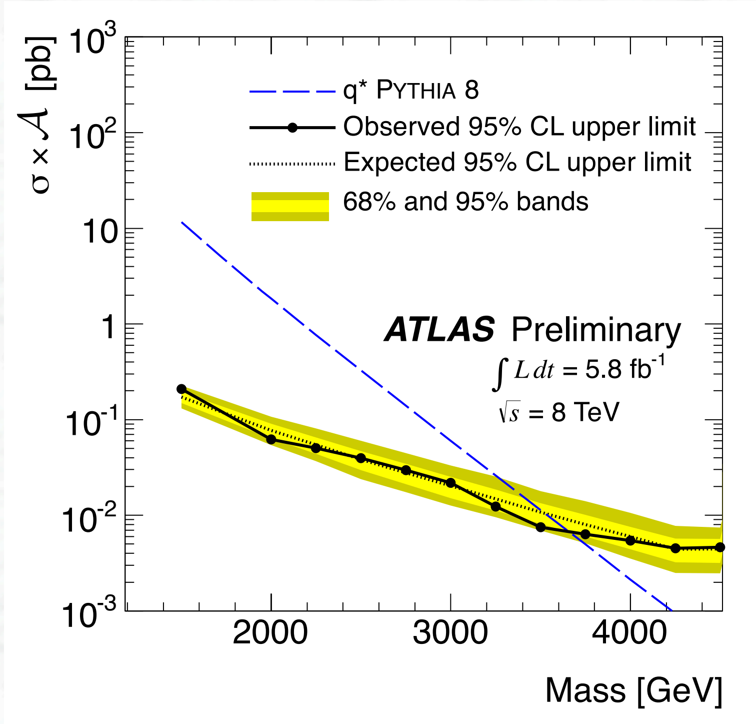
- Search for resonant structures in the di-jet invariant mass spectrum



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





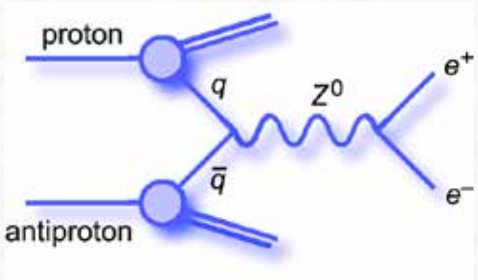
CDF (Tevatron), $L = 1.13\ fb^{-1}$: $0.26 < m_{q^*} < 0.87$ TeV

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

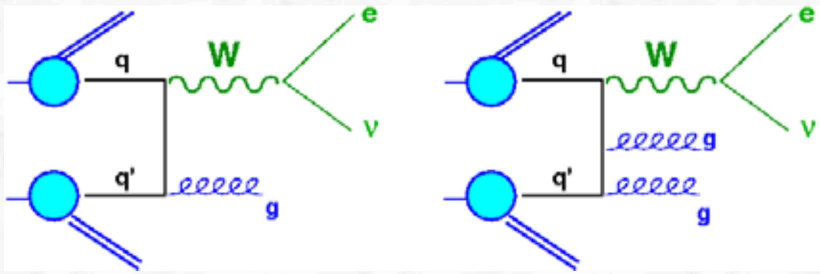
$L = 0.036\ fb^{-1}$: $0.60 < m_{q^*} < 2.64$ TeV

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

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

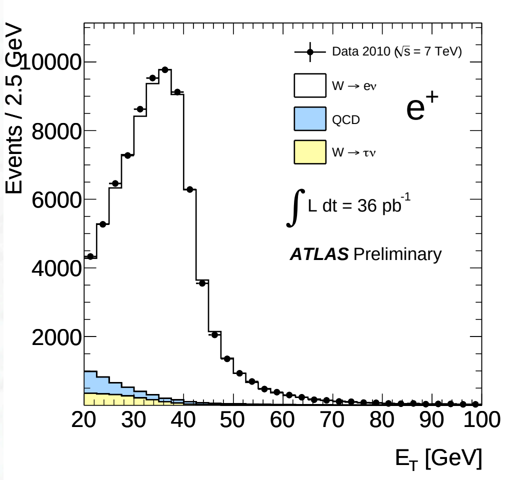


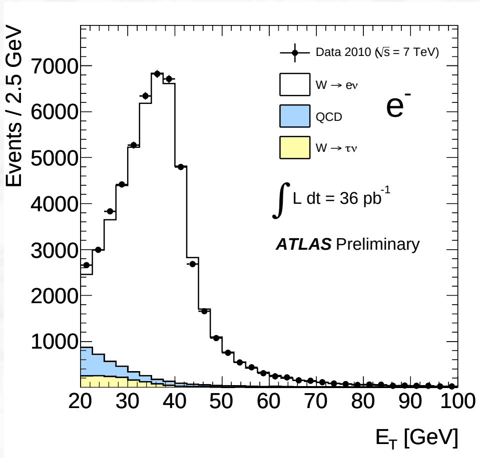
QCD at work

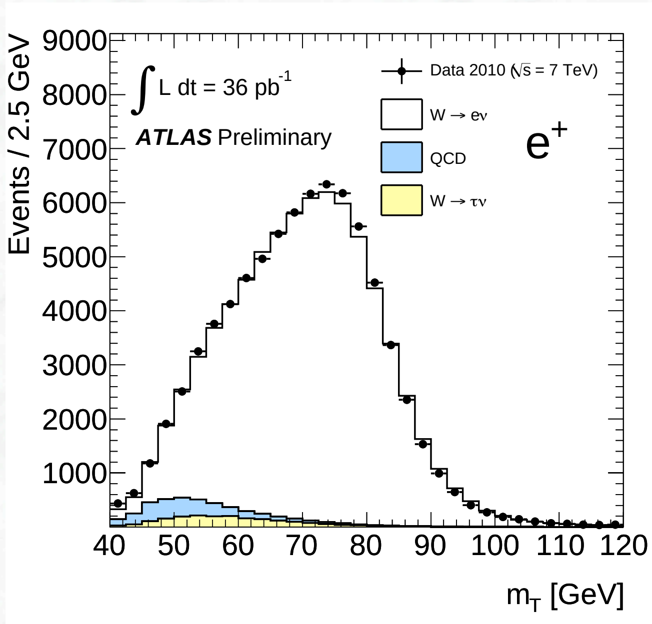


- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region
  (jet multiplicities, p_T spectra,….)
- Tuning and „calibration" of Monte Carlos for background predictions in searches
  at the LHC

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 → ee

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

W → eν

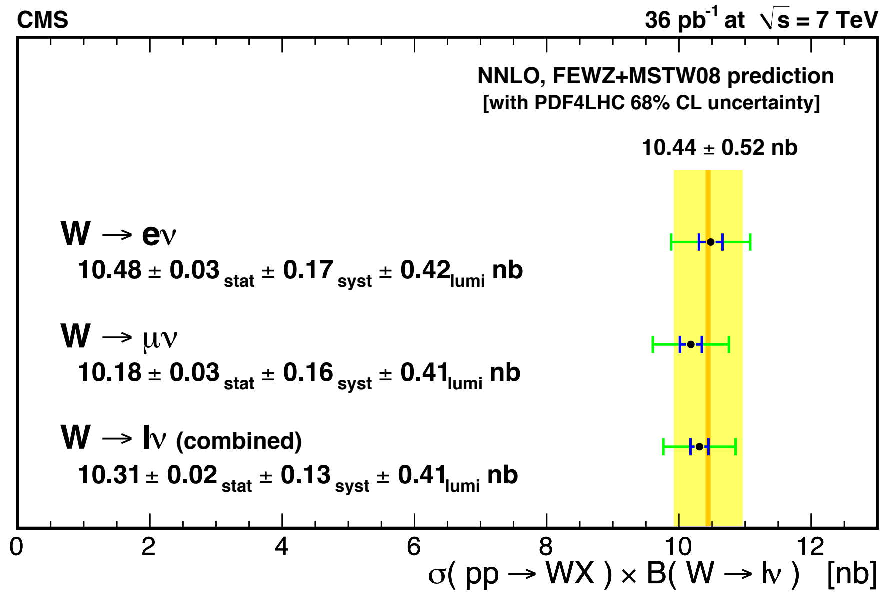
- Missing transverse momentum > 25 GeV/c
- Transverse mass cut M_T > 50 GeV

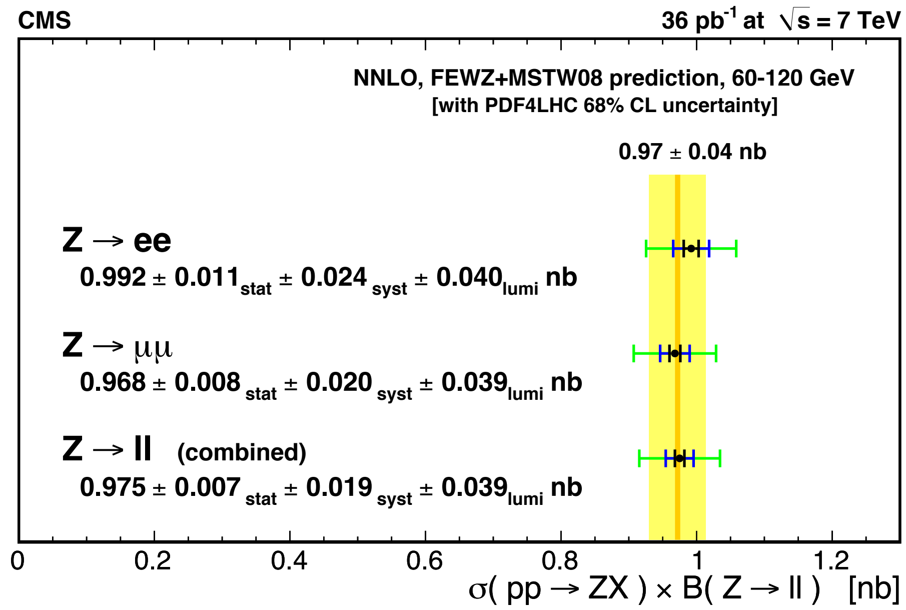
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

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

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

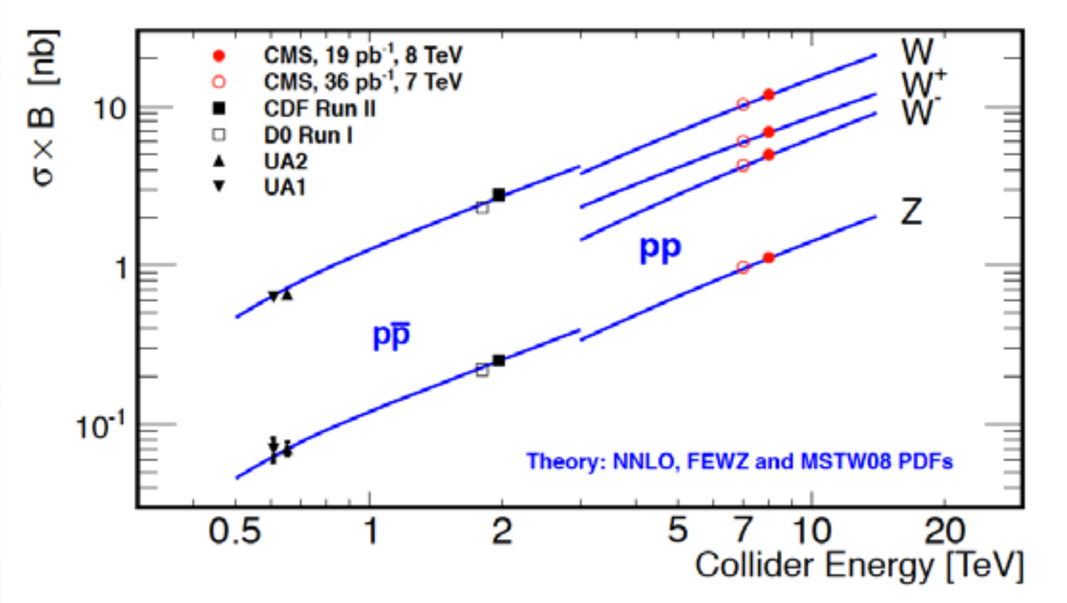
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

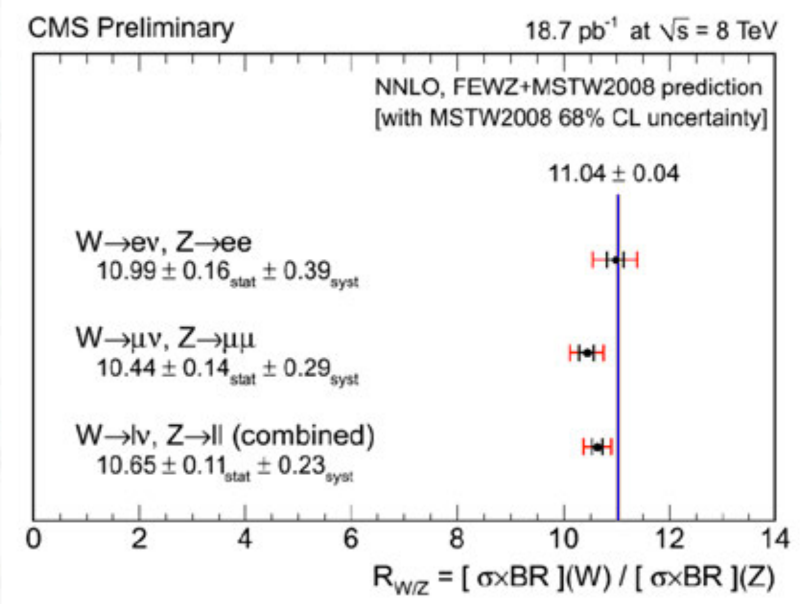
Precision is already dominated by systematic uncertainties

[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 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





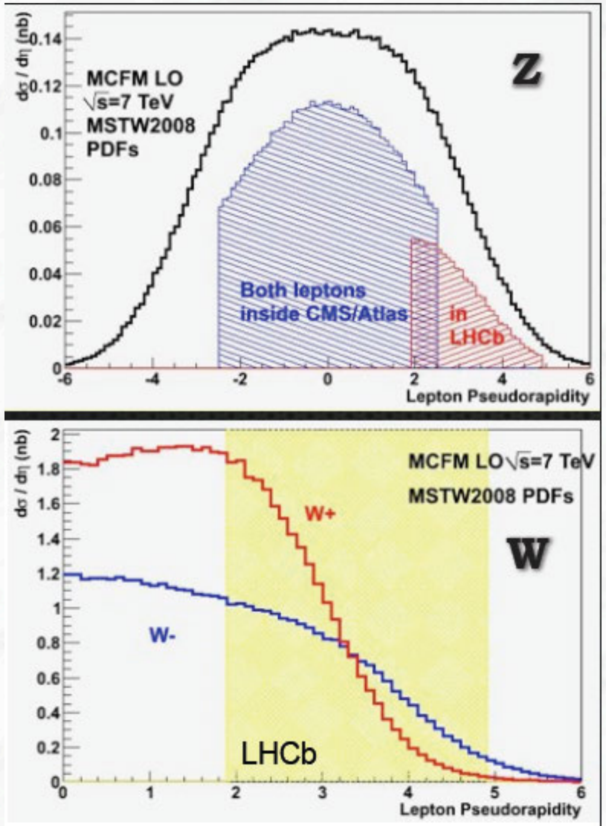
- No surprise at the new energy, theoretical predictions in good agreement with the measurements
- W/Z cross-section ratio remains a bit high, but consistent within uncertainties

Can the parton distribution functions be constrained?

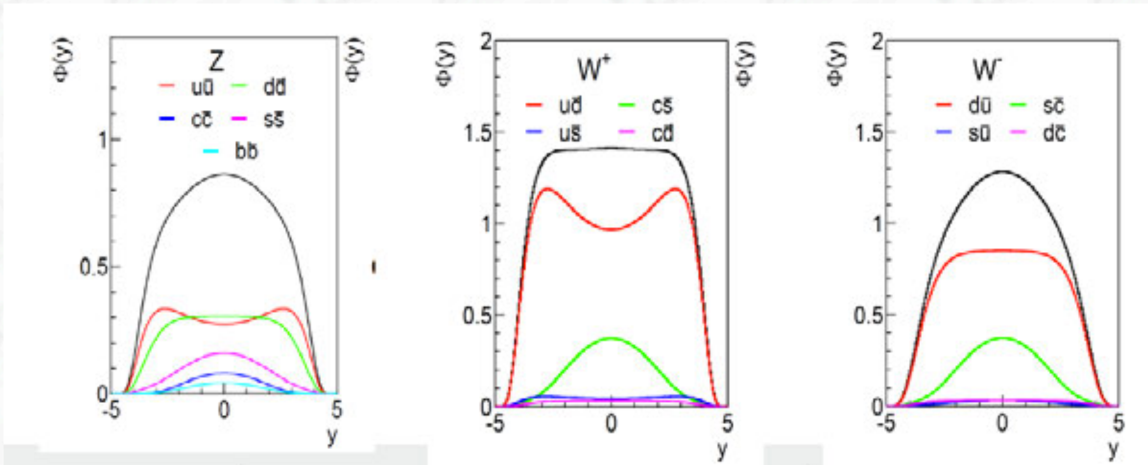
- Sensitive measurements: differential W and Z production cross sections as function of lepton or boson rapidity, charge separated for W^+ and W^-

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

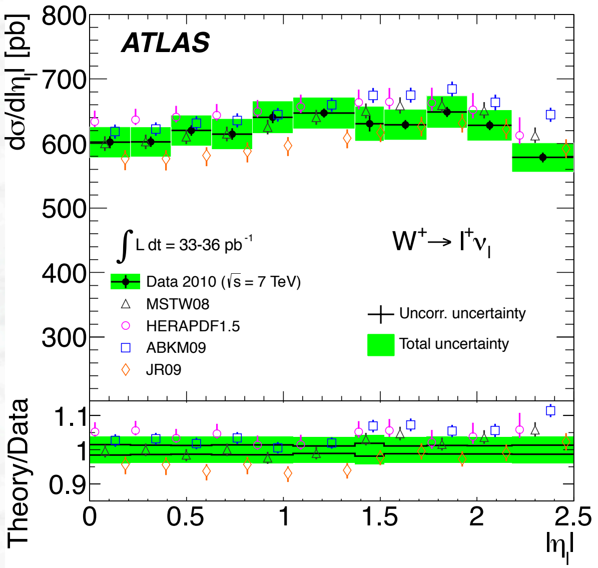
- Derived quantity: charge asymmetry: $\sigma(W^+) - \sigma(W^-)$ / $[\sigma(W^+) + \sigma(W^-)]$

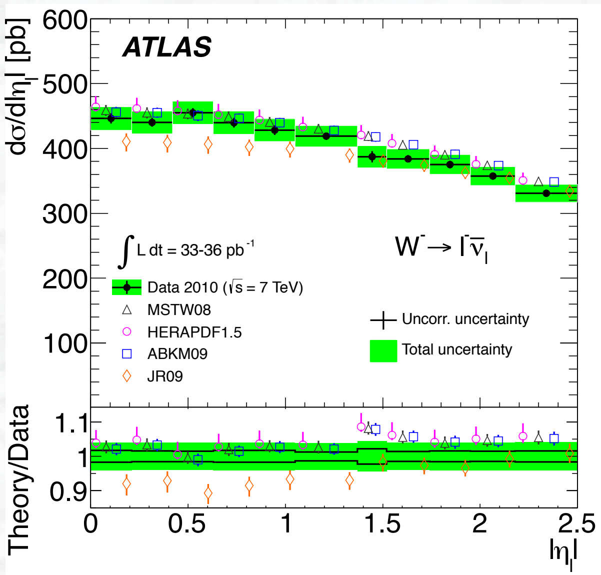


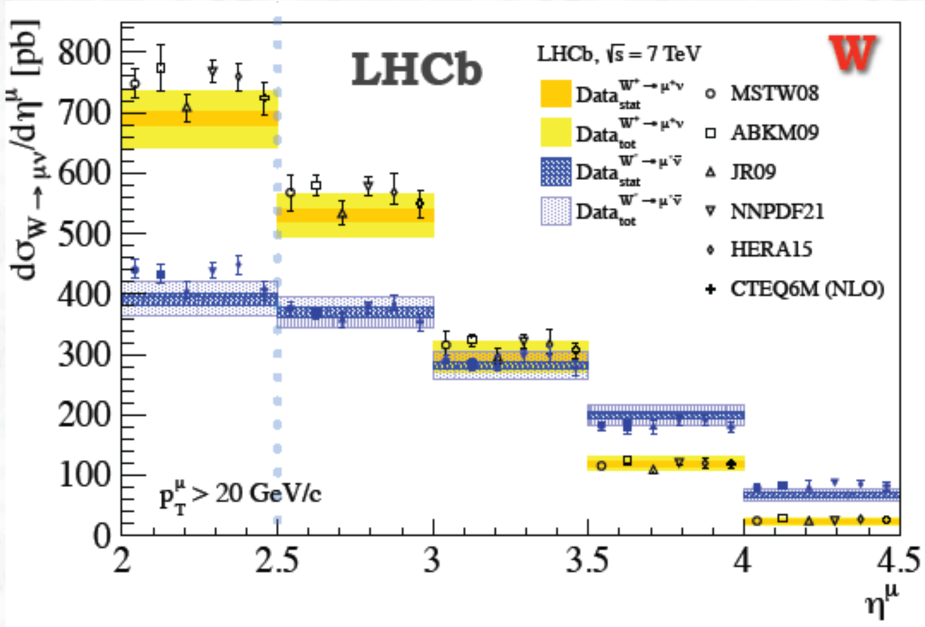
Leading order (tree level) contributions to W/Z production



Differential cross section measurements





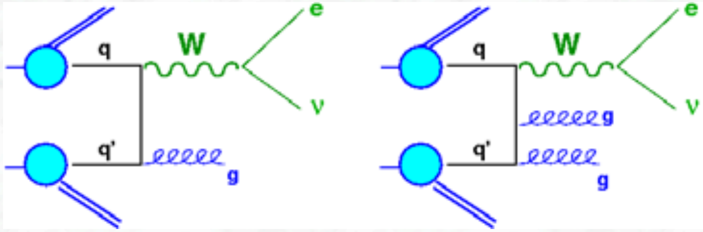


- Rough features of the measured differential cross sections are well described; (some tension at intermediate η region)

- Data start to be discriminating between pdf models;

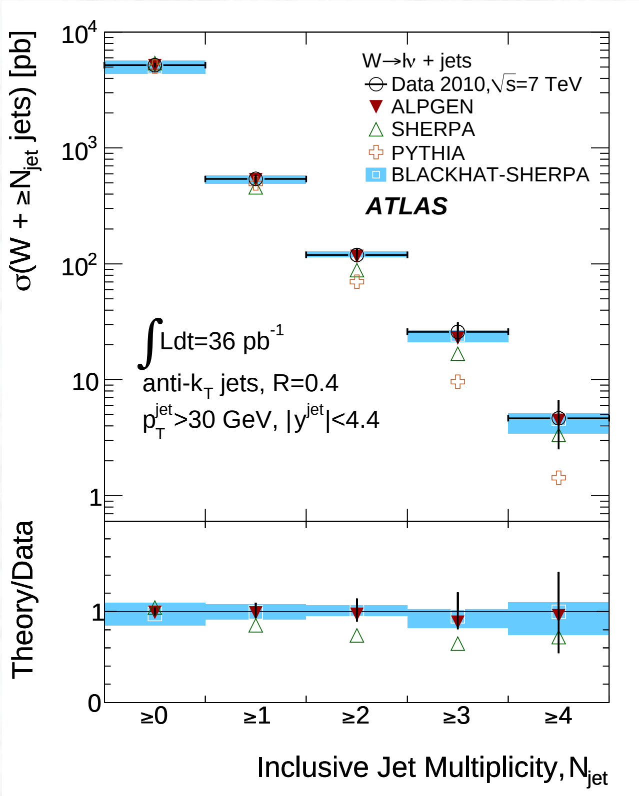
These data will have impact on pdf uncertainties

W/Z + jet cross section measurements

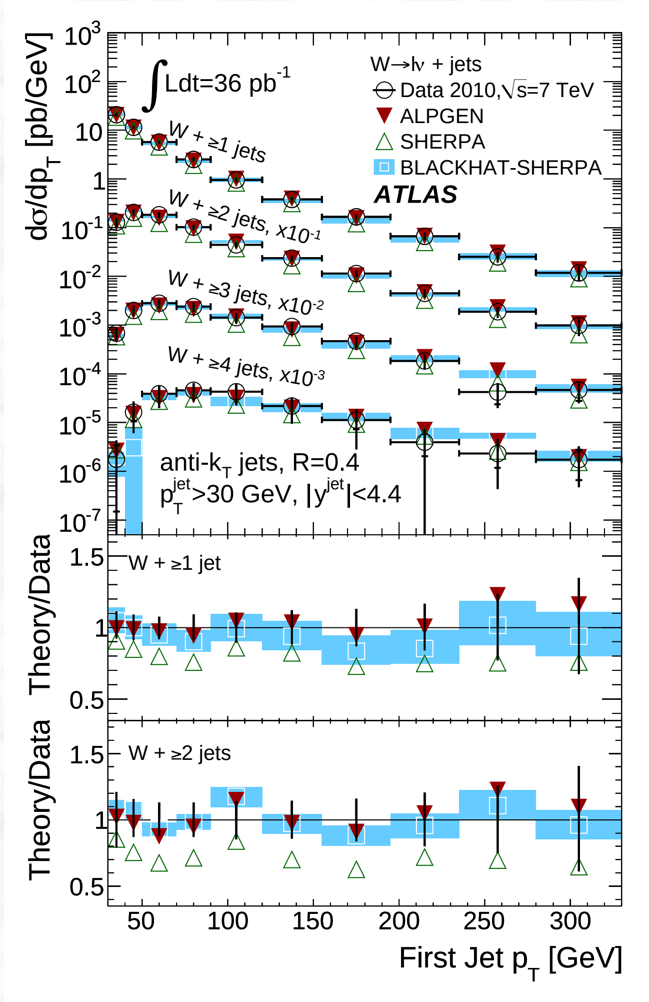


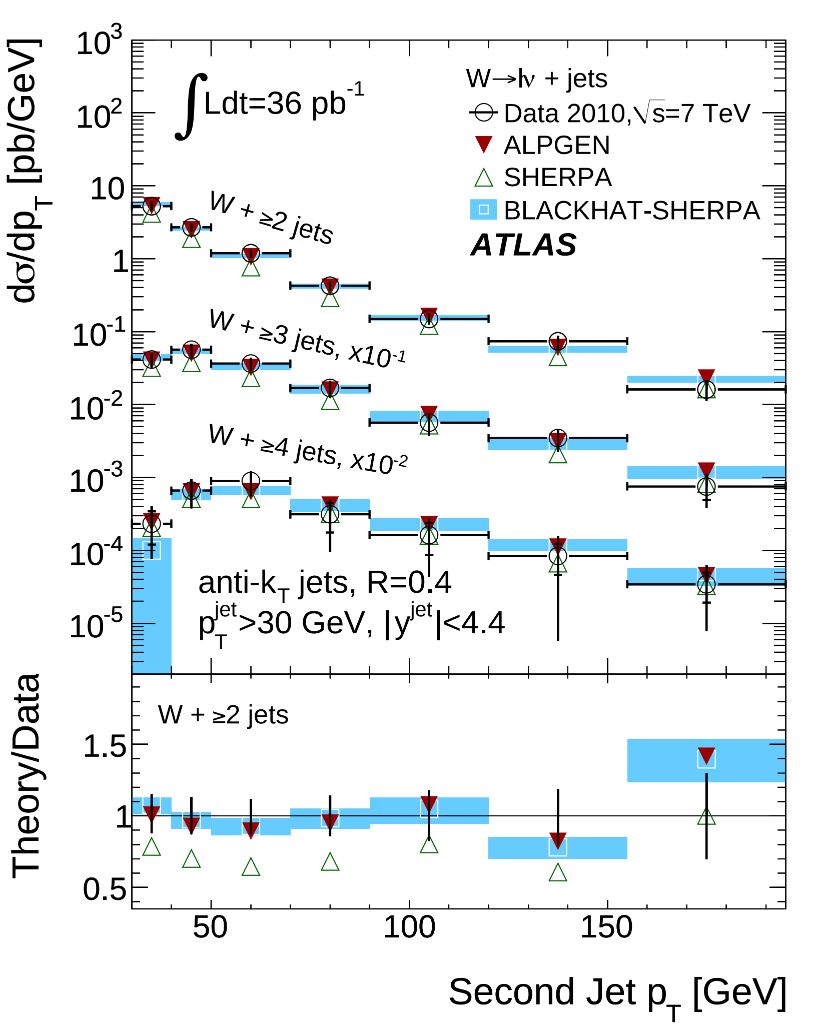
- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors;

Jet multiplicities in W+jet production

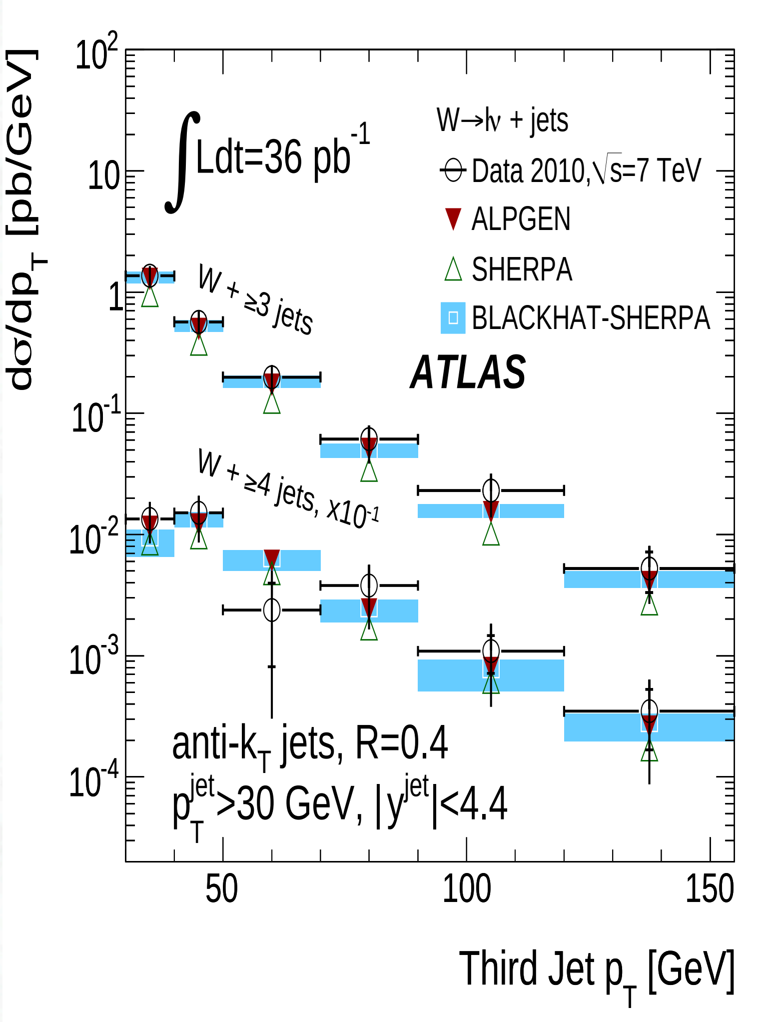


p_T spectrum of leading jet





$\int$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
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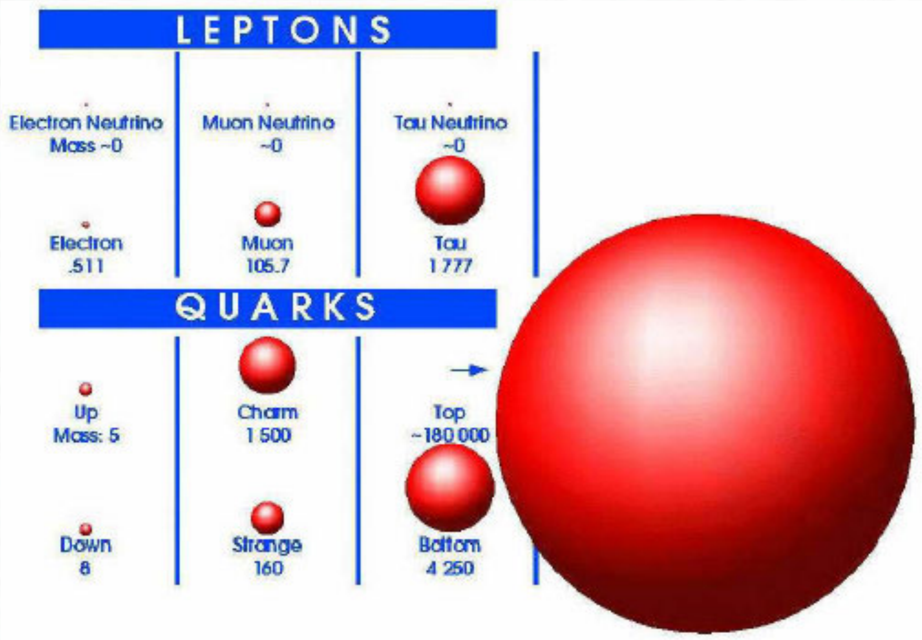
W + ≥3 jets
W + ≥4 jets, x10^{-1}
anti-k$_T$ jets, R=0.4
p$_T^{jet}$>30 GeV, |y^{jet}|<4.4
dσ/dp$_T$ [pb/GeV]
Third Jet p$_T$ [GeV]

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 ??

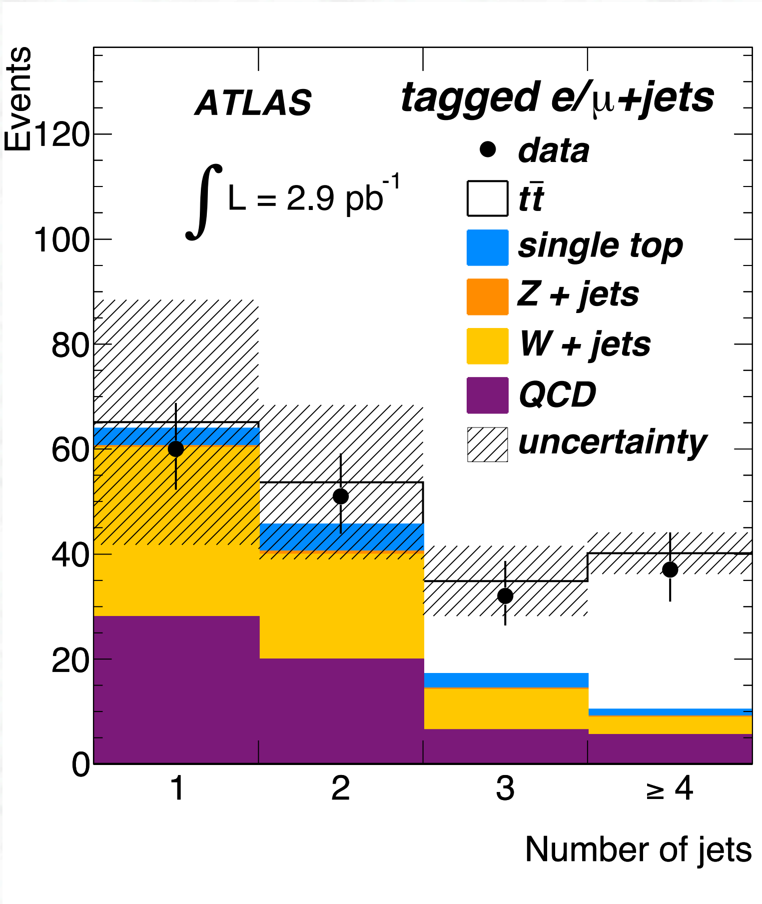
$$M_t = \frac{1}{\sqrt{2}} \lambda_t v$$

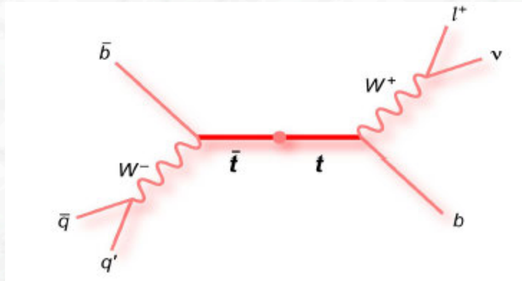
$$\Rightarrow \lambda_t = \frac{M_t}{173.9\ \mathrm{GeV}/c^2}$$

- 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,…

First results on top production from the LHC



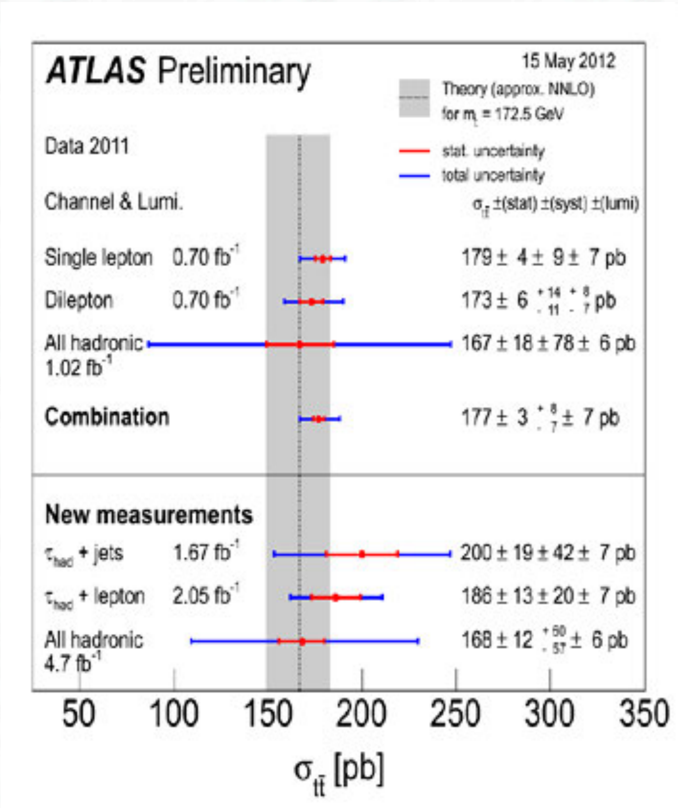


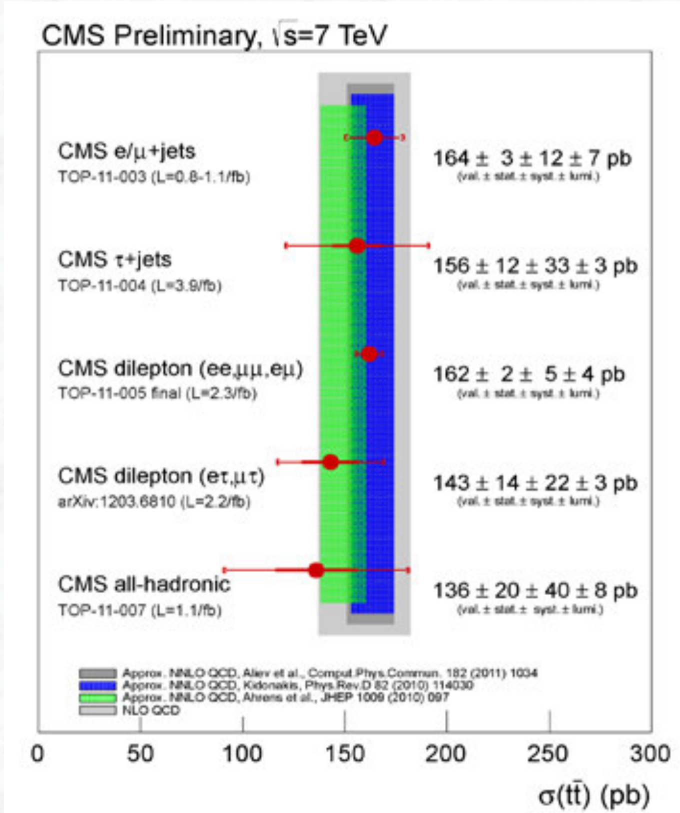
Event Selection:

- 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 $\eta < 2.5$

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%