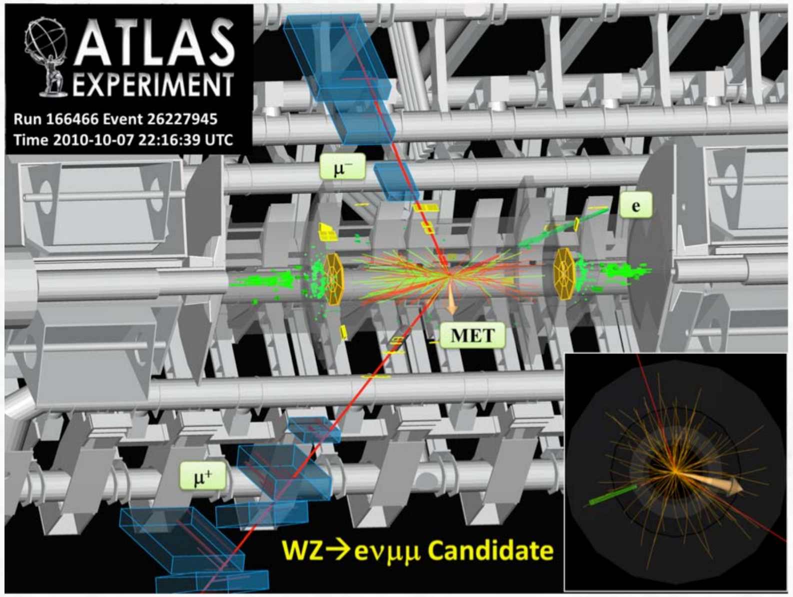
Physics at the LHC

Part 2



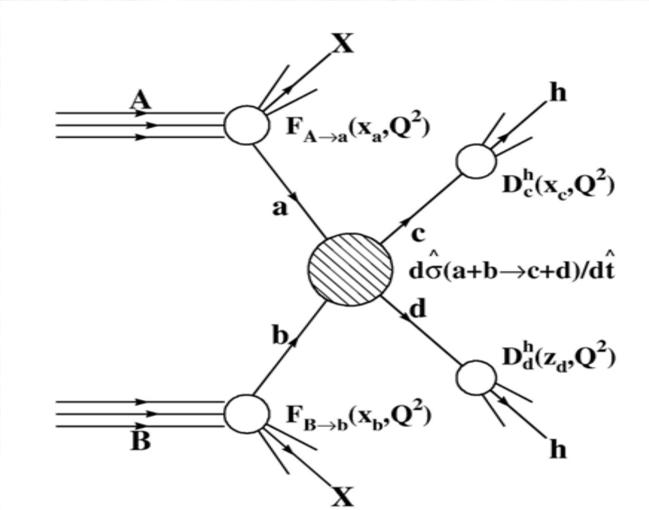
Standard Model Physics

Test of Quantum Chromodynamics

- **Jet production**
- **W/Z production**
- **Production of Top quarks**

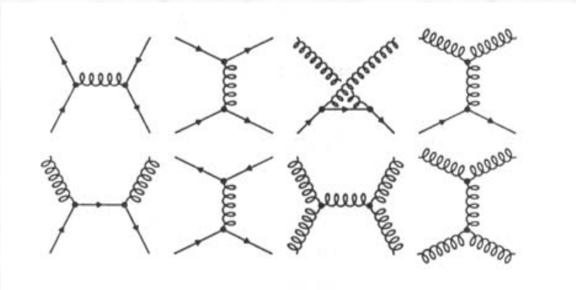
Brief comments on electroweak measurements

QCD processes at hadron colliders

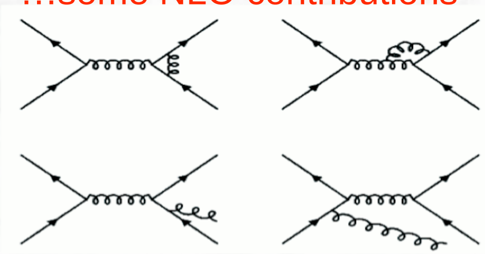


- Hard scattering processes are dominated by QCD jet production
- Originating from qq, qg and gg scattering
- Cross sections can be calculated in QCD (perturbation theory)

Leading order



…some NLO contributions



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

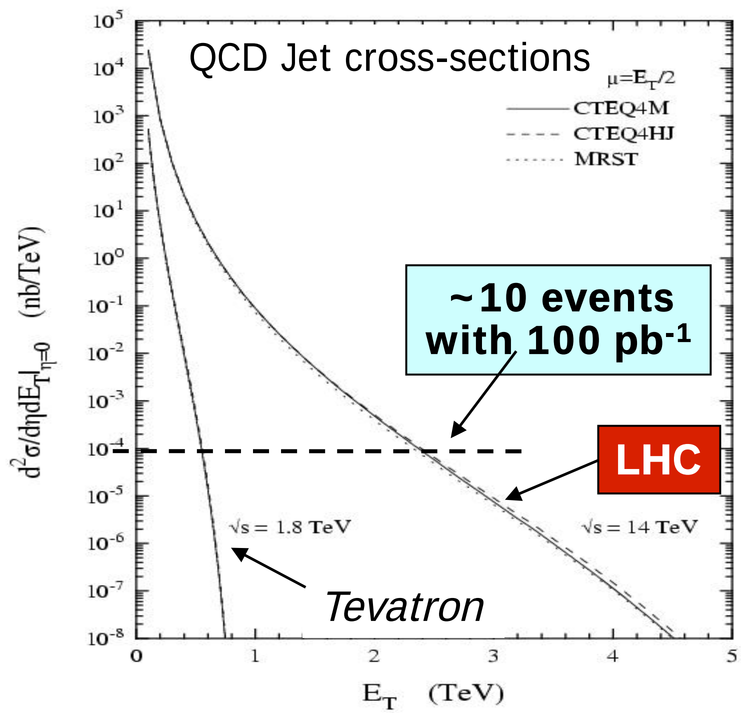
Deviations?
→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

Jets from QCD production: Tevatron vs LHC

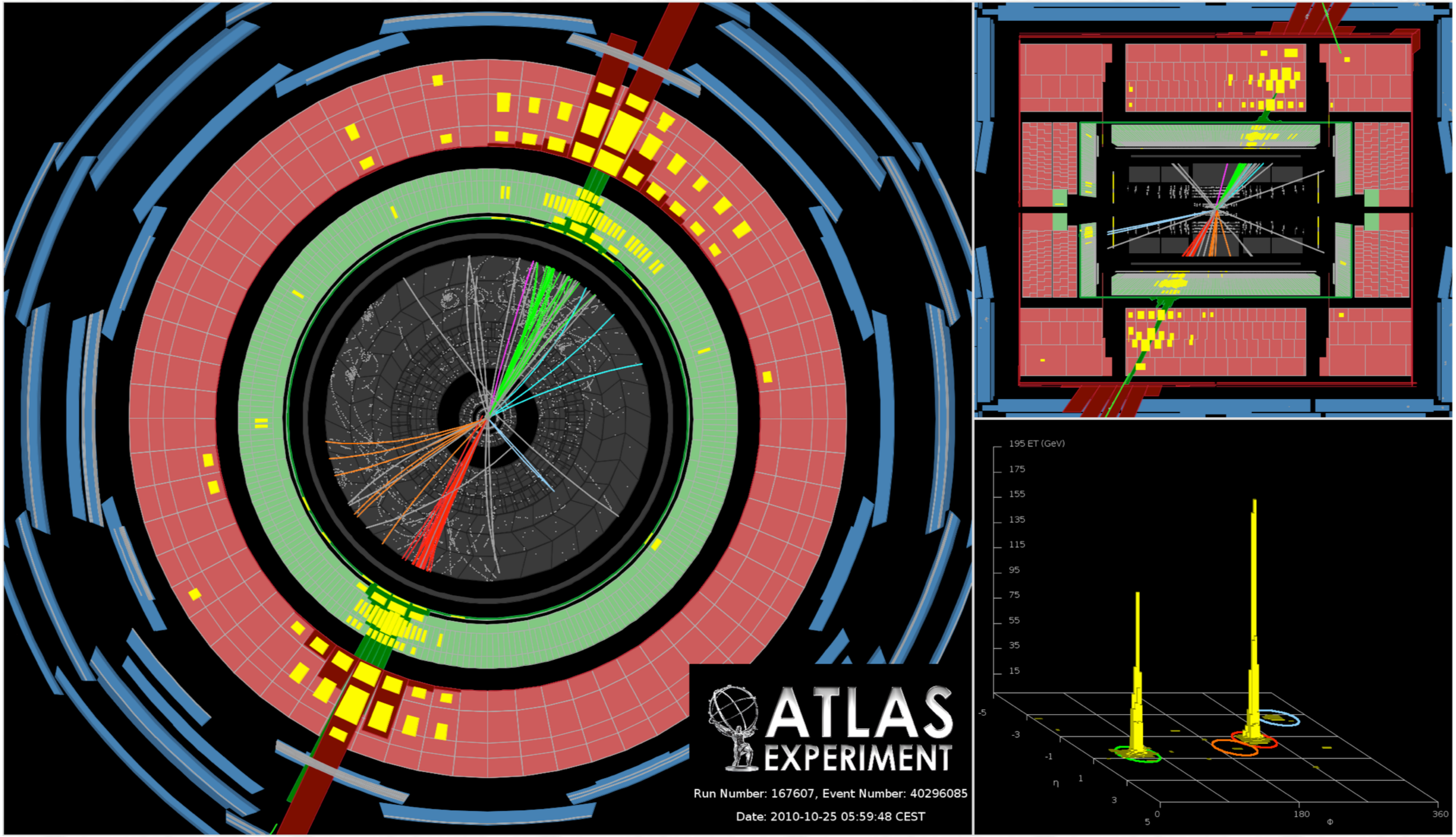
- Rapidly probe perturbative QCD in a new energy regime (at a scale above the Tevatron, large cross sections)

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

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

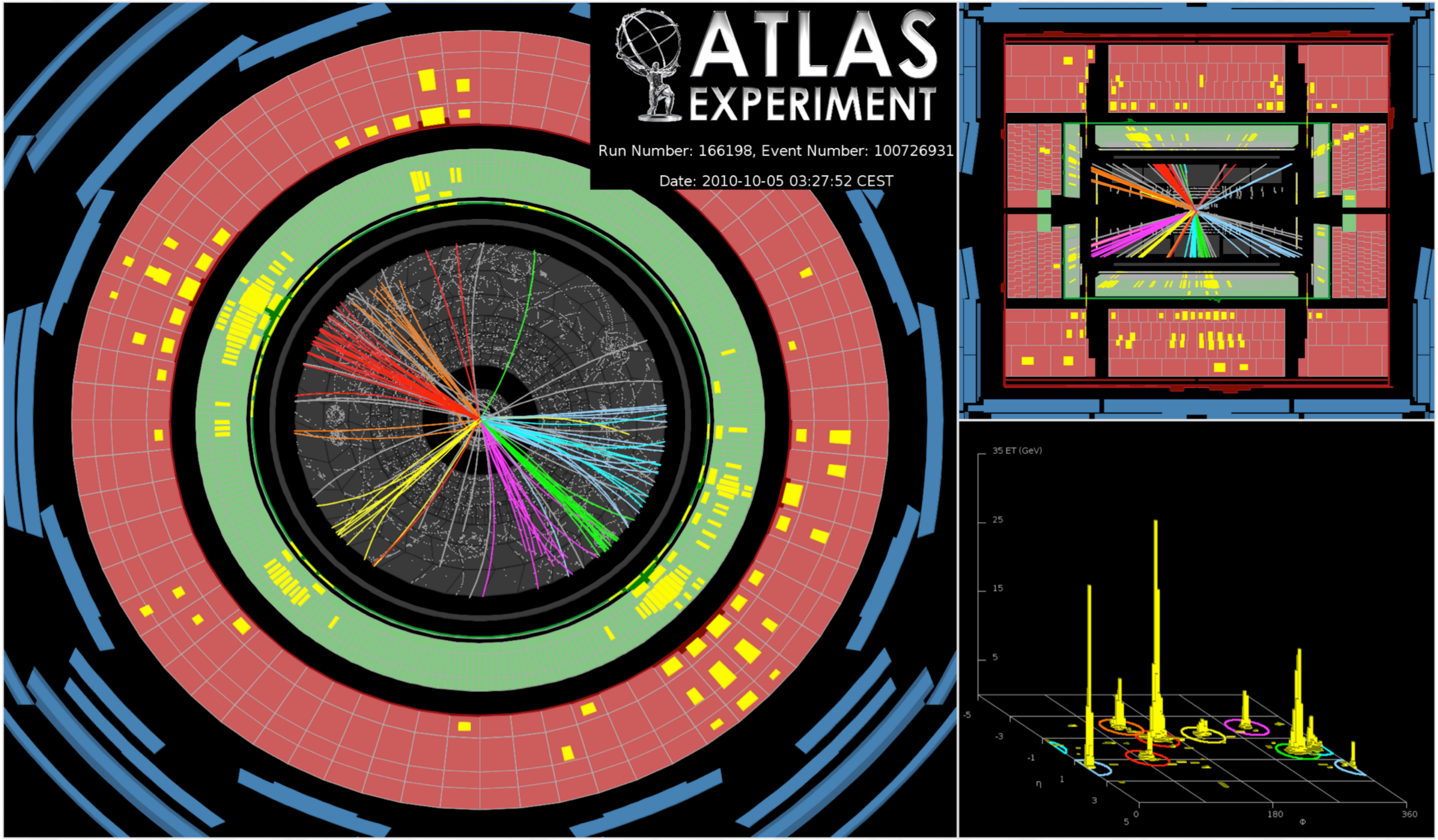


High p_T jet events at the LHC



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.

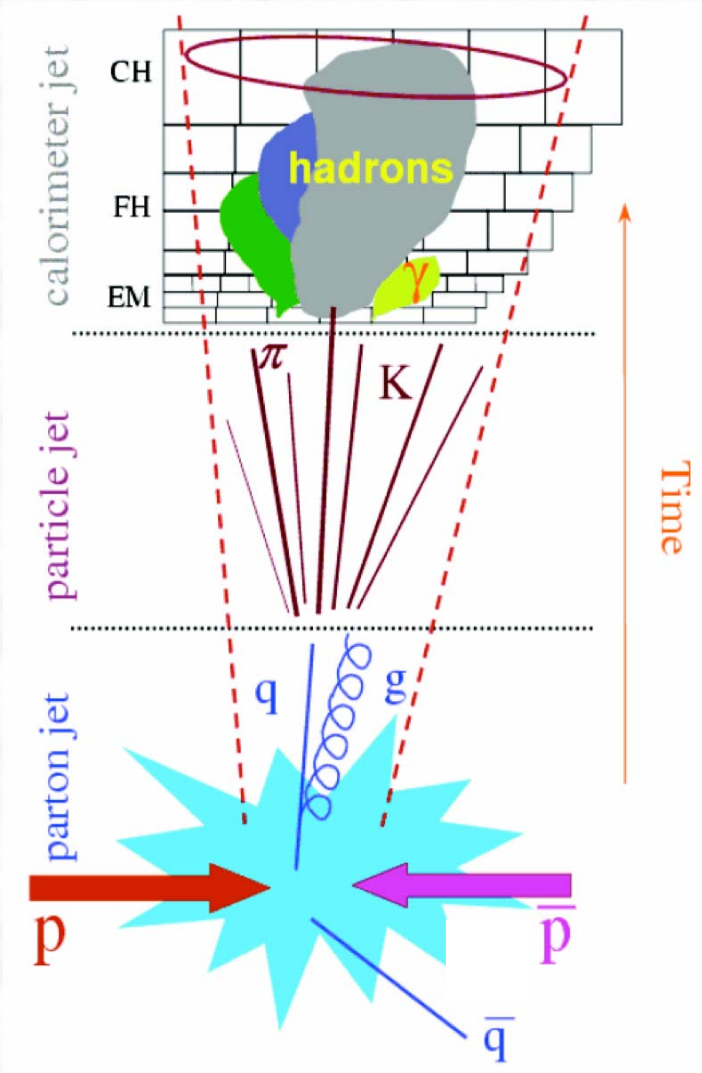
Jet reconstruction and energy measurement

- 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



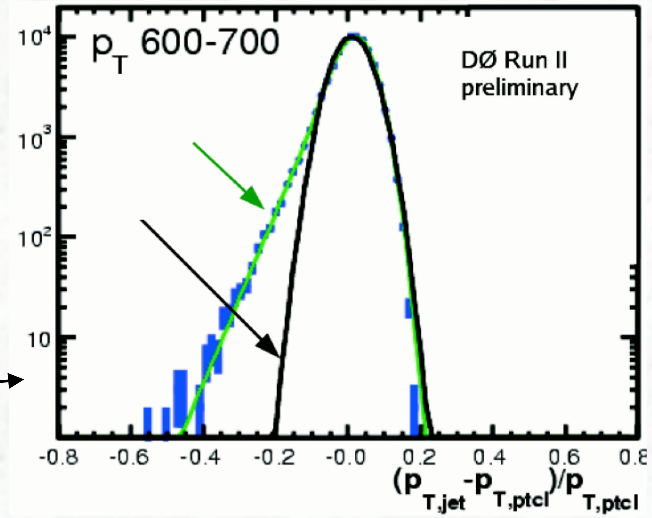
Jet measurements

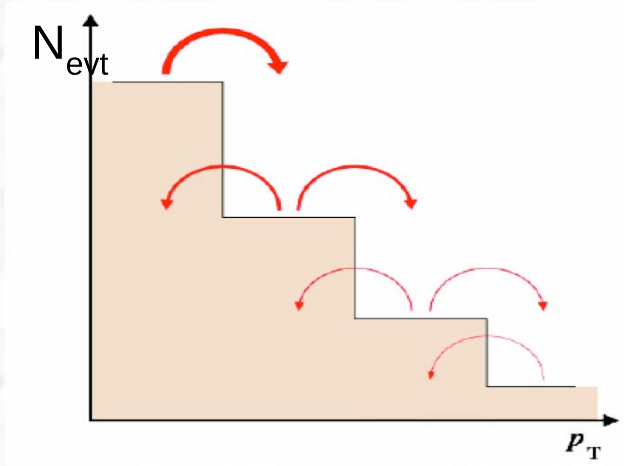
$$d^2\sigma / dp_T\, d\eta \;=\; N \,/\, (\varepsilon \cdot L \cdot \Delta p_T \cdot \Delta\eta)$$

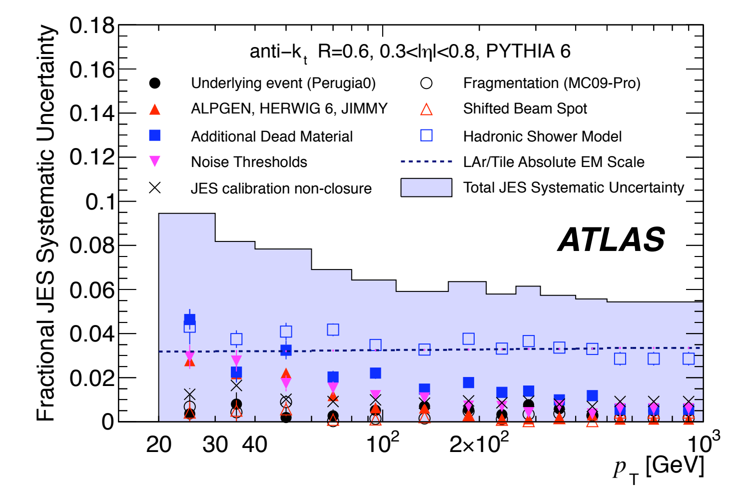
- In principle a simple counting experiment

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

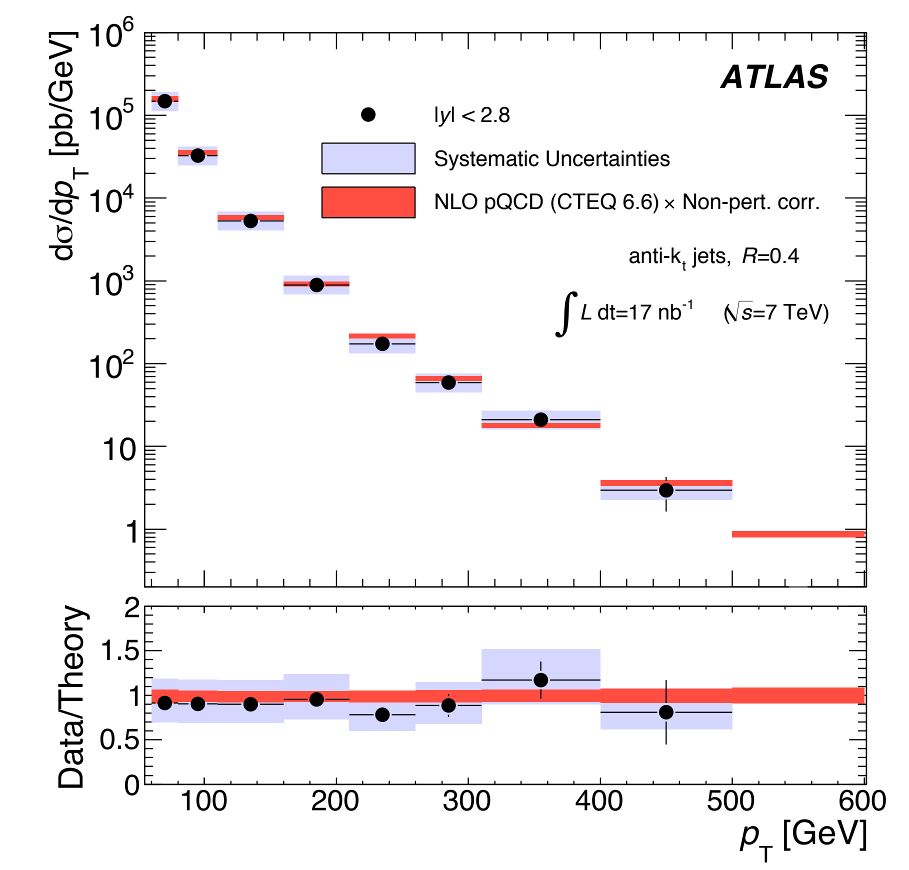
- Jet energy scale uncertainty:
  ATLAS: ~6% (after one year)
  (similar for CMS, impressive achievements)







Test of QCD Jet production



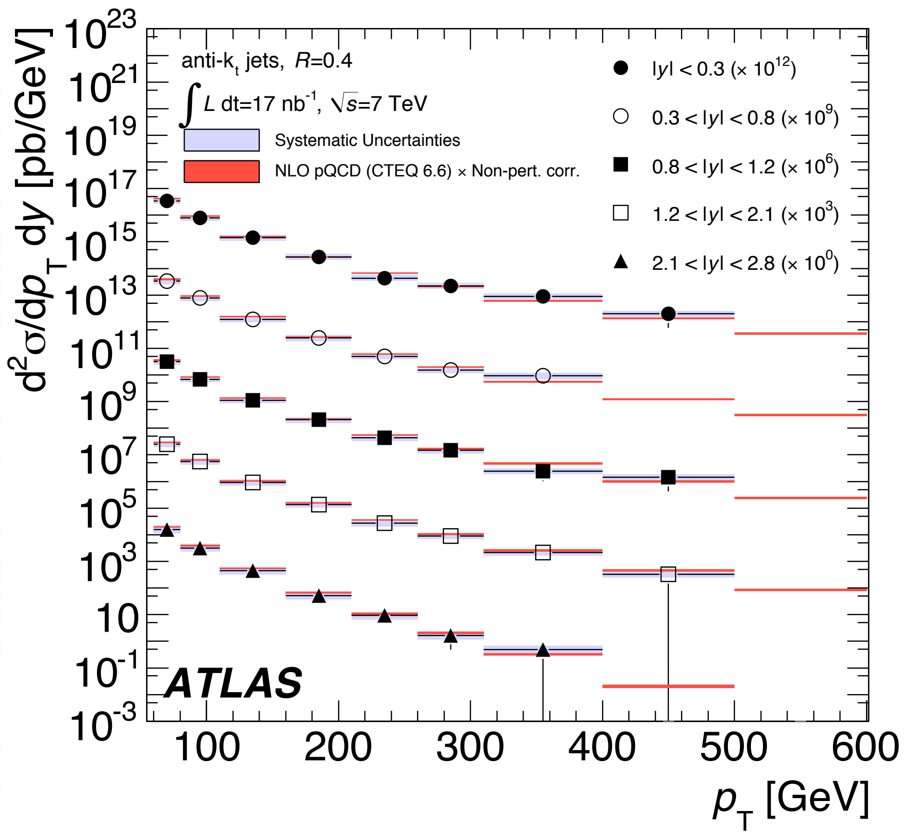
An **"early"** result from the ATLAS experiment (17 nb^{-1}, June 2010)

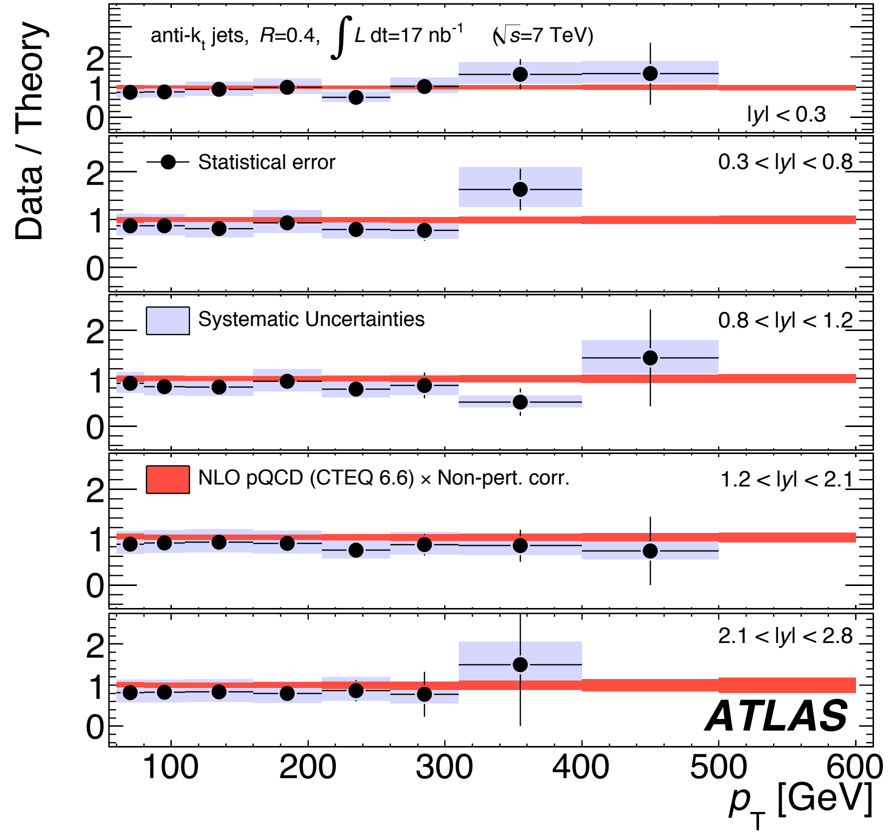
<u>Inclusive Jet spectrum as a function of Jet-P_T</u>

Very good agreement with NLO pQCD calculations over many orders of magnitude !

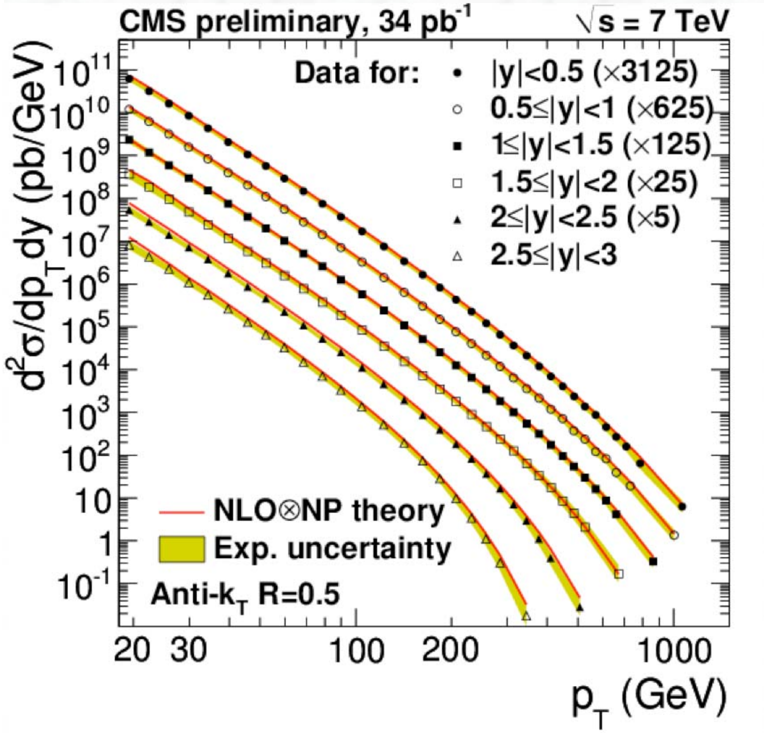
Within the large theoretical and experimental uncertainties

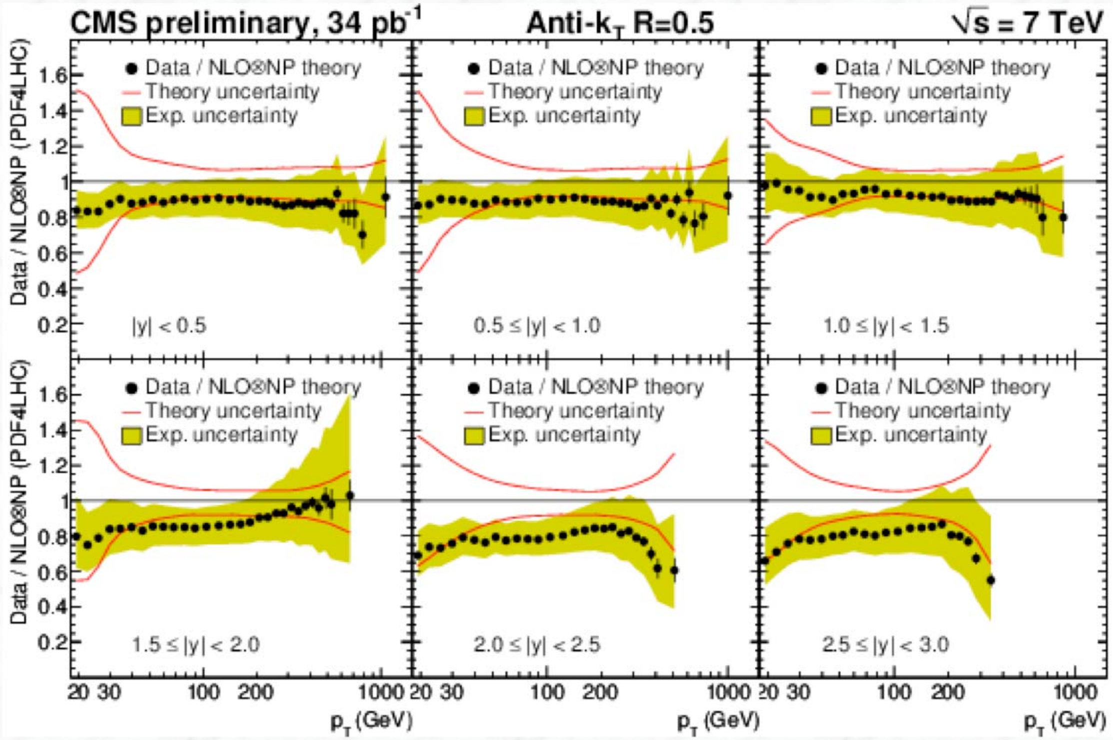
Double differential cross sections, as function of p_T and rapidity y:



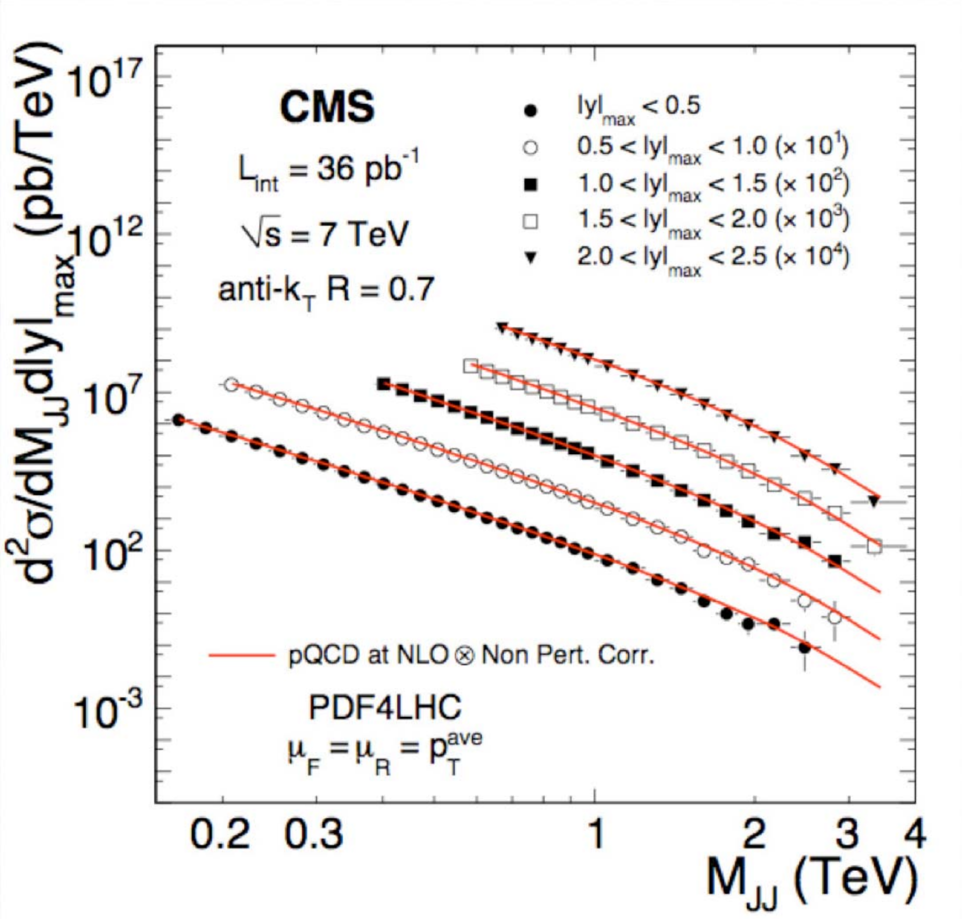


Similar results from CMS, full 2010 dataset:





Invariant di-jet mass spectra:



Dijet double-differential cross section as a function of dijet mass, binned in the maximum rapidity of the two leading jets, $|y|_{max}$. The data are compared to NLO pQCD calculations to which soft QCD corrections have been applied.

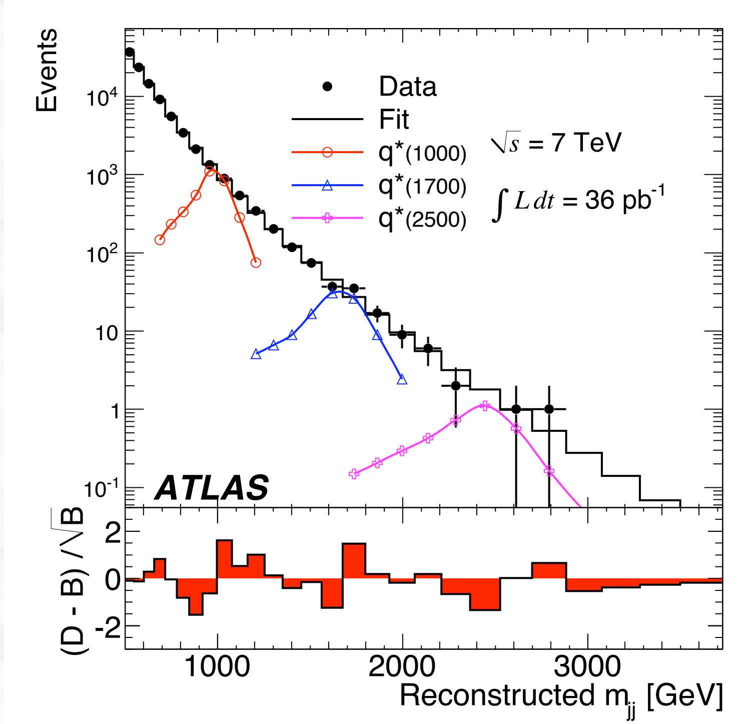
Important for: - Test of QCD
- Search for new resonances decaying into two jets (see later)

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

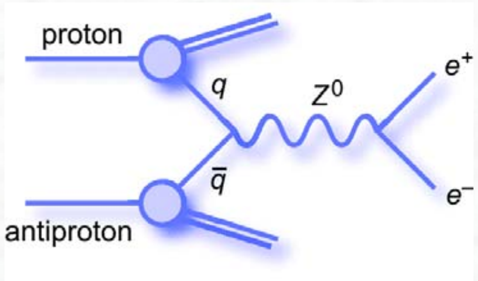


CDF (Tevatron), $L = 1.13\ fb^{-1}$: $0.26 < m_{q*} < 0.87$ TeV

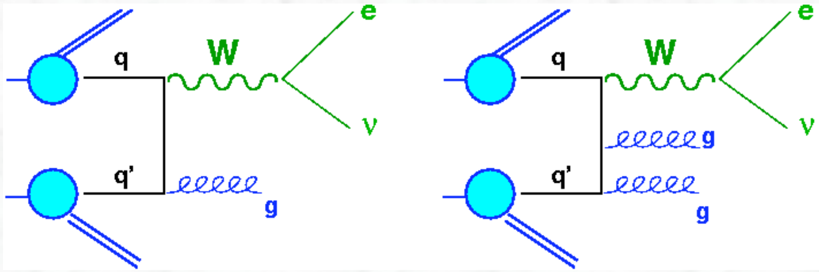
ATLAS (LHC), $L = 0.000315\ fb^{-1}$ exclude (95% C.L) q* mass interval $0.30 < m_{q*} < 1.26$ TeV

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

QCD aspects in W/Z (+ jet) production



QCD at work

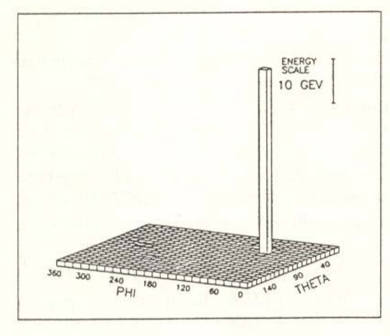


- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region
  (jet multiplicities, p_T spectra,….)
- Tuning and „calibration“ of Monte Carlos for background predictions in searches
  at the LHC

How do W and Z events look like ?

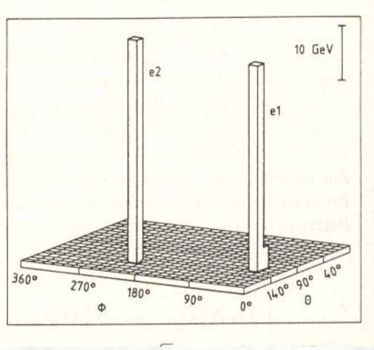
As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

→ Search for leptonic decays: **W → ℓ ν** (large P_T (ℓ), large P_T^{miss})
Z → ℓ ℓ

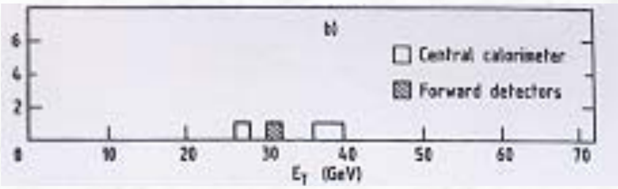


A bit of history: one of the first W events seen; UA2 experiment

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

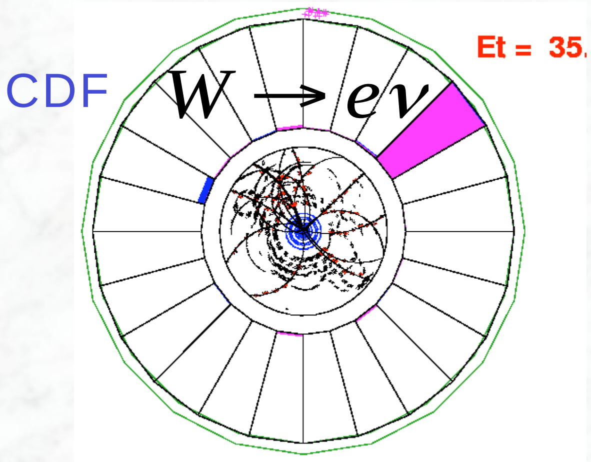


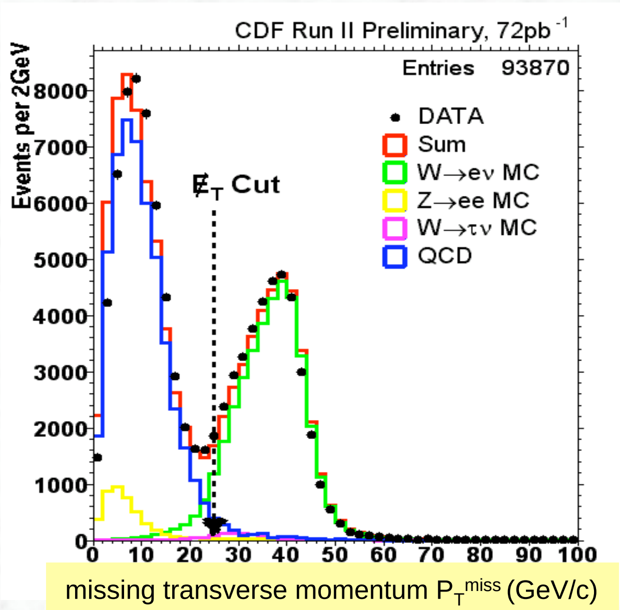
Transverse momentum of the electrons



Today's W / Z $\rightarrow$ eν / ee signals

CDF Experiment, Fermilab





Trigger:

- Electron candidate > 20 GeV/c

Electrons:

- Isolated el.magn. cluster in the calorimeter
- P_T> 25 GeV/c
- Shower shape consistent with expectation for electrons
- Matched with tracks

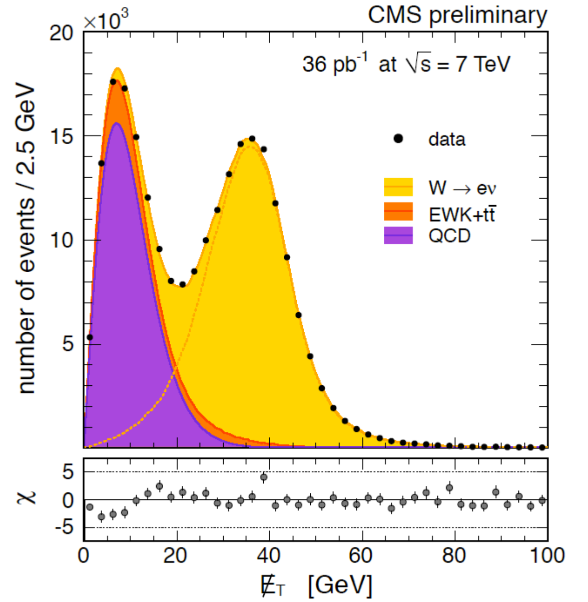
$Z \rightarrow ee$

- 70 GeV/c^2 < m_{ee} < 110 GeV/c^2

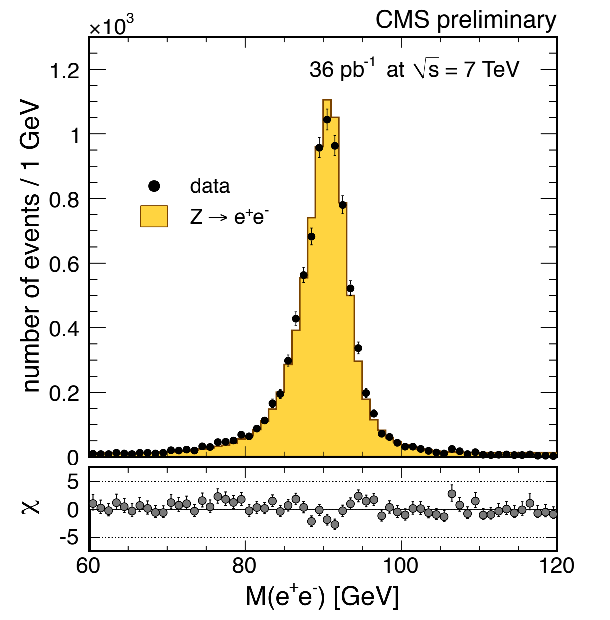
$W \rightarrow e\nu$

- Missing transverse momentum > 25 GeV/c

First measurements of W/Z production at the LHC
-CMS data from 2010: 36 pb^{-1} -



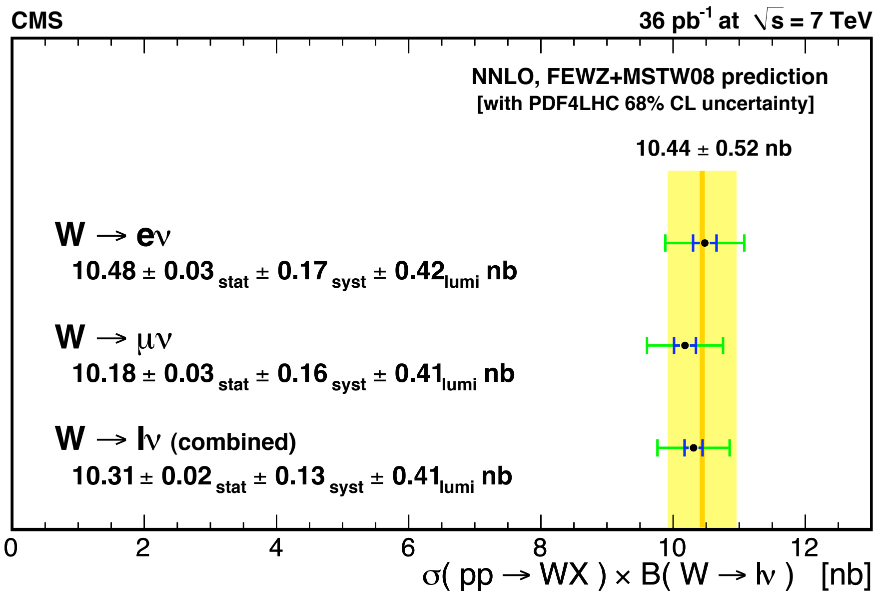
Distributions of the missing transverse energy, E_T^{miss}, of electron candidates for data and Monte-Carlo simulation, broken down into the signal and various background components.

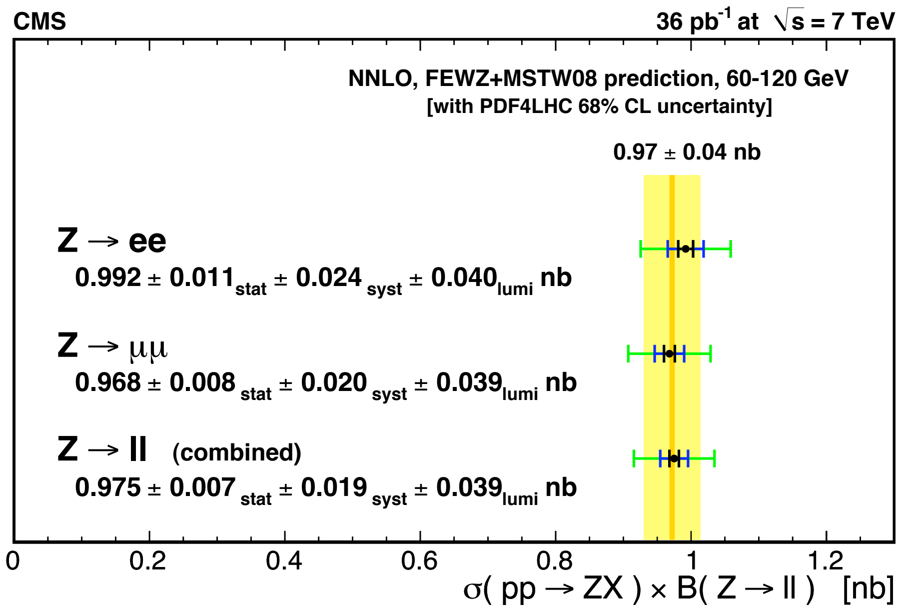


Distributions of the invariant di-electron mass, m_{ee}, for events passing the Z selection. The data are compared to Monte-Carlo simulation, the background is very small.

W and Z production cross sections at LHC

Measured cross section values in comparison to NNLO QCD predictions:





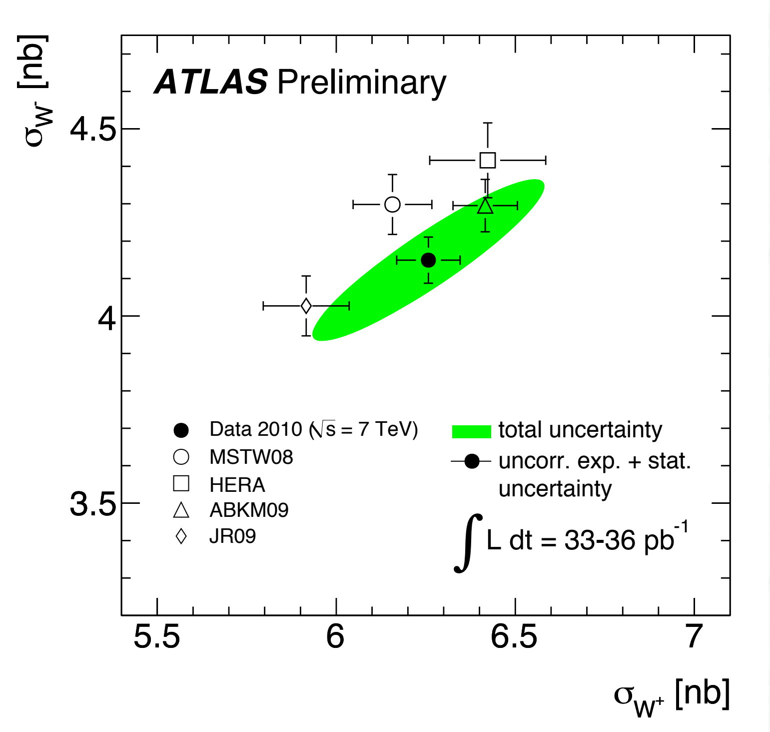
Good agreement with NNLO QCD calculations

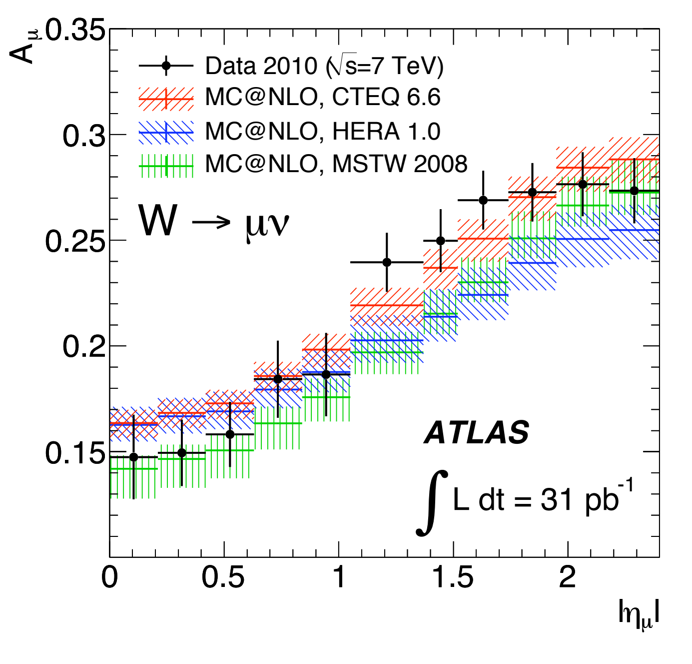
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

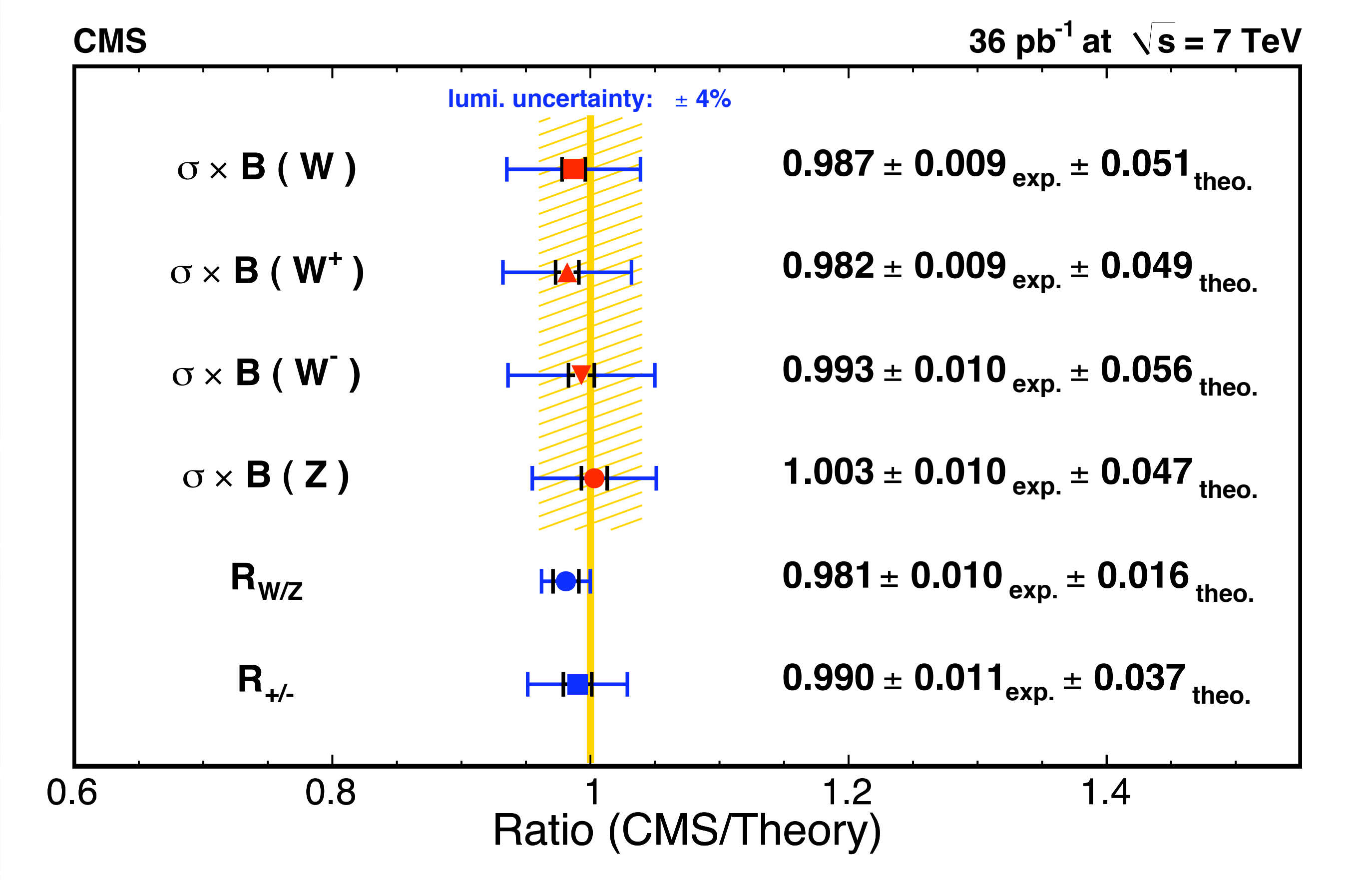




$$A_\mu = \frac{d\sigma_{W_{\mu^+}}/d\eta_\mu - d\sigma_{W_{\mu^-}}/d\eta_\mu}{d\sigma_{W_{\mu^+}}/d\eta_\mu + d\sigma_{W_{\mu^-}}/d\eta_\mu}$$

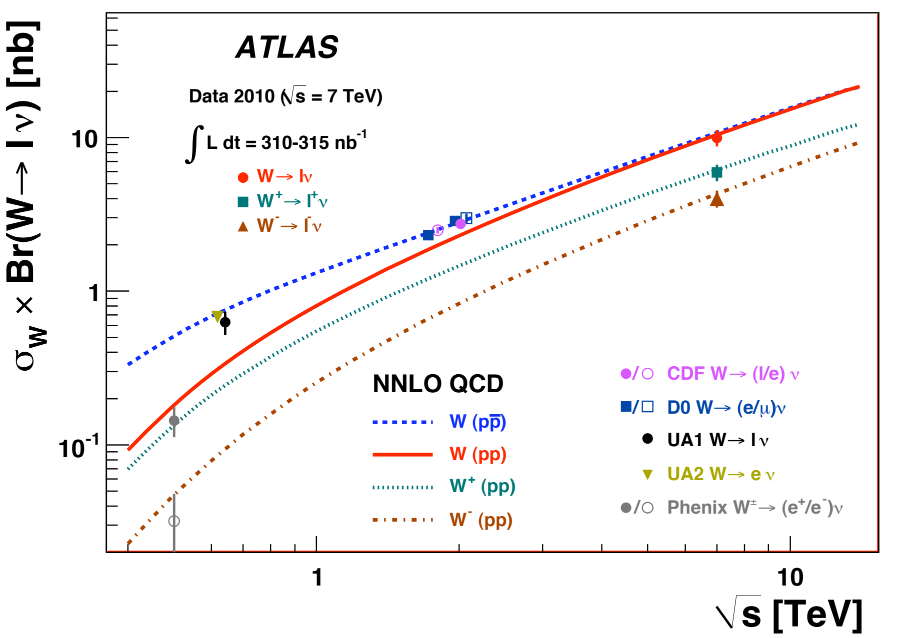
Provides important constraints on parton distributions (u, d-quark)

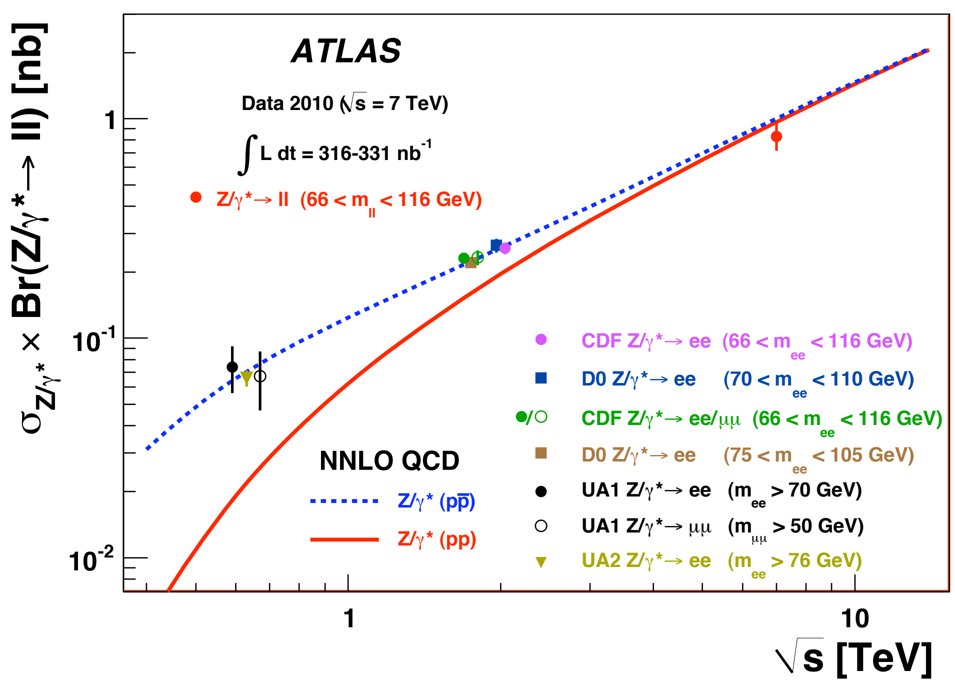
Summary of W/Z cross section results
-comparison between theory and CMS measurements-



Good agreement between data and NNLO QCD predictions for all measurements

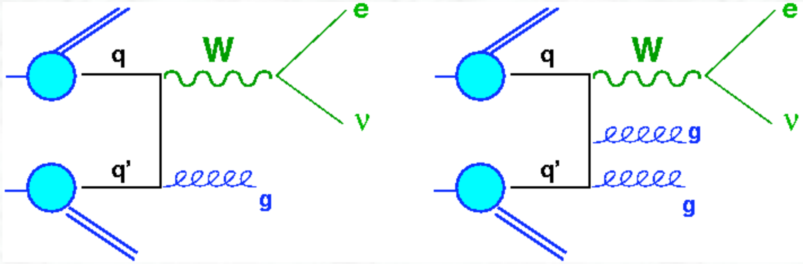
W and Z production cross sections at hadron colliders





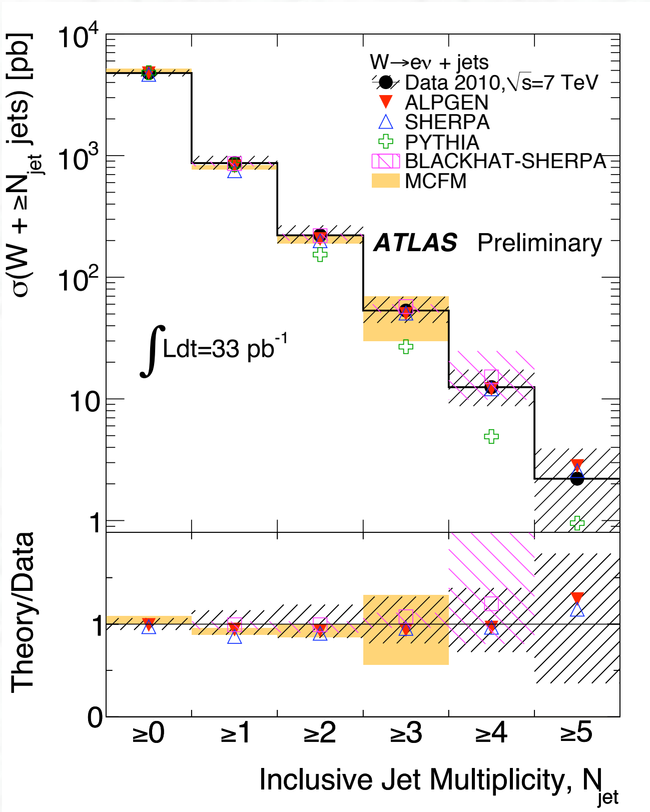
Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)

QCD Test in W/Z + jet production

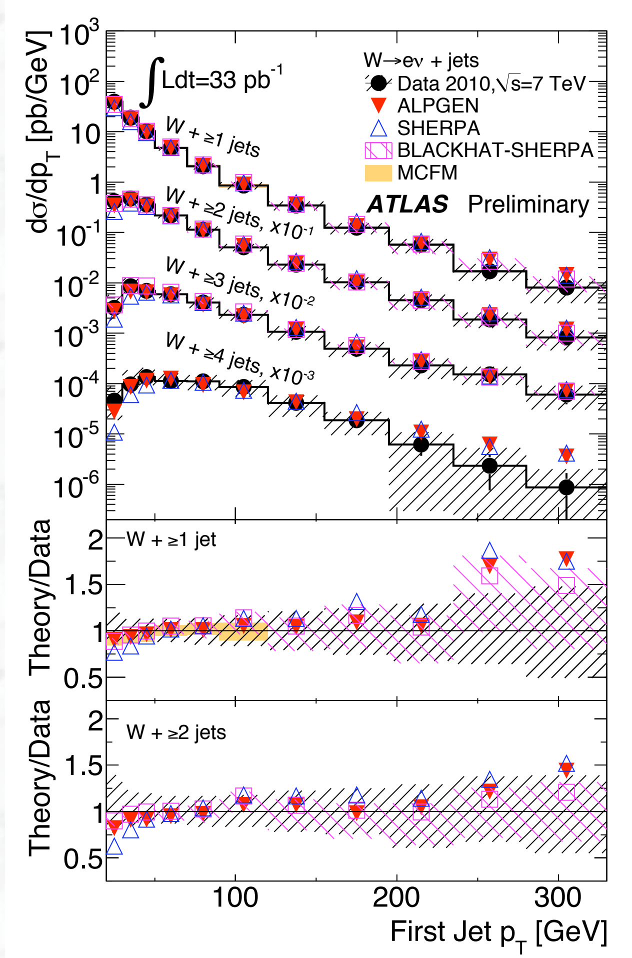


- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors; NLO central value ~10% low

Jet multiplicities in W+jet production



p_T spectrum of leading jet

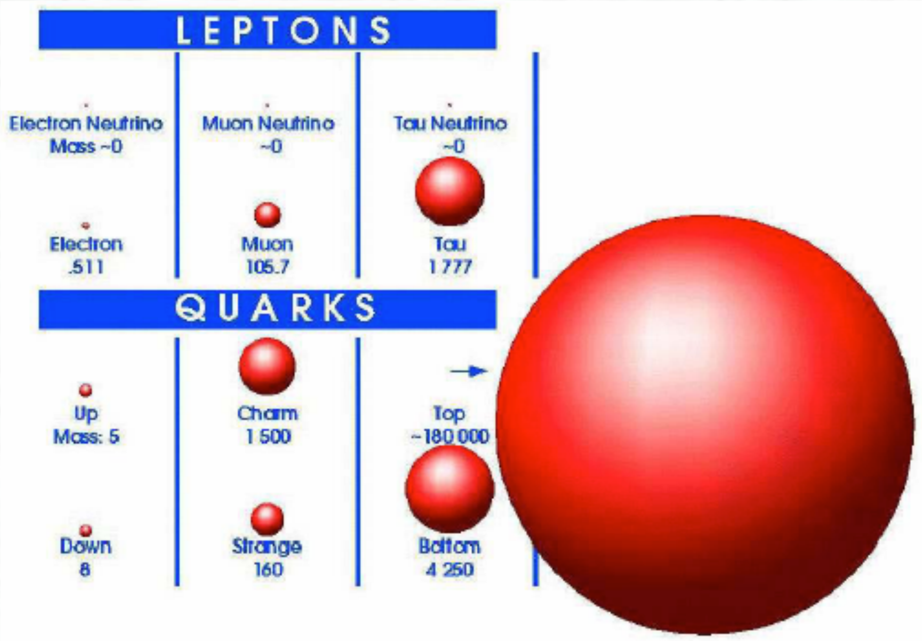


Top Quark Physics

- Discovered by the CDF and DØ collaborations at the Tevatron in 1995
- Tevatron top physics results are consistent with expectations from the Standard Model, however, often limited by statistics
- Tevatron achieved an impressive precision on the measurement of the top quark mass
- LHC: huge production rates (for $\sqrt{s}$ = 7 TeV: about a factor 25 larger cross sections than at the Tevatron)

  - Better precision
  - Search for deviations from Standard Model expectations

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 ??

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

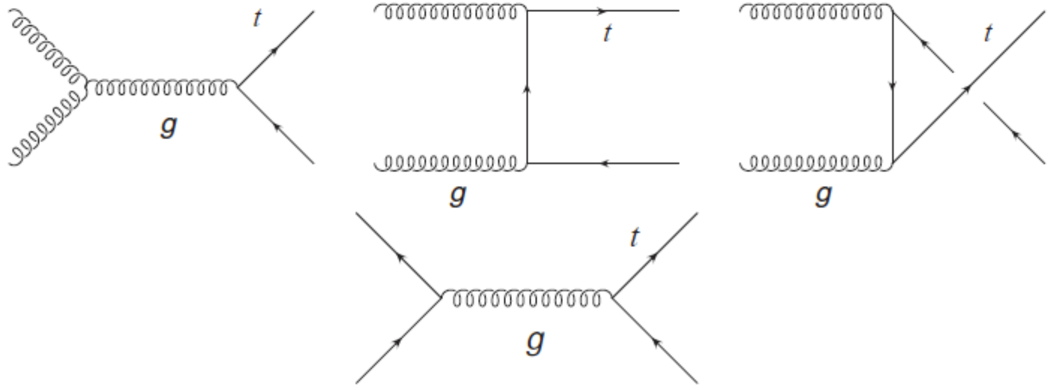
$$\Rightarrow \lambda_t = \frac{M_t}{173.9\ \mathrm{GeV}/c^2}$$

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

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

Top Quark Production

Pair production: qq and gg-fusion



Top-quark pair production in the Born approximation.

- NLO corrections completely known
- NNLO partly known

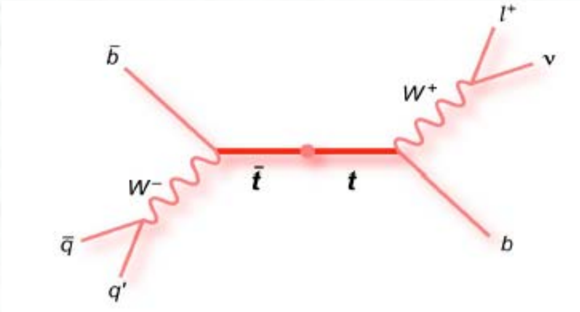
approximate NNLO results:

$$\sigma_{\rm LHC} = (887^{+9}_{-33}\,({\rm scale})^{+15}_{-15}\,({\rm PDF}))\ {\rm pb} \qquad (14\ {\rm TeV}),$$
$$\sigma_{\rm Tev} = (7.04^{+0.24}_{-0.36}\,({\rm scale})^{+0.14}_{-0.14}\,({\rm PDF}))\ {\rm pb} \qquad (1.96\ {\rm TeV}).$$

	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:

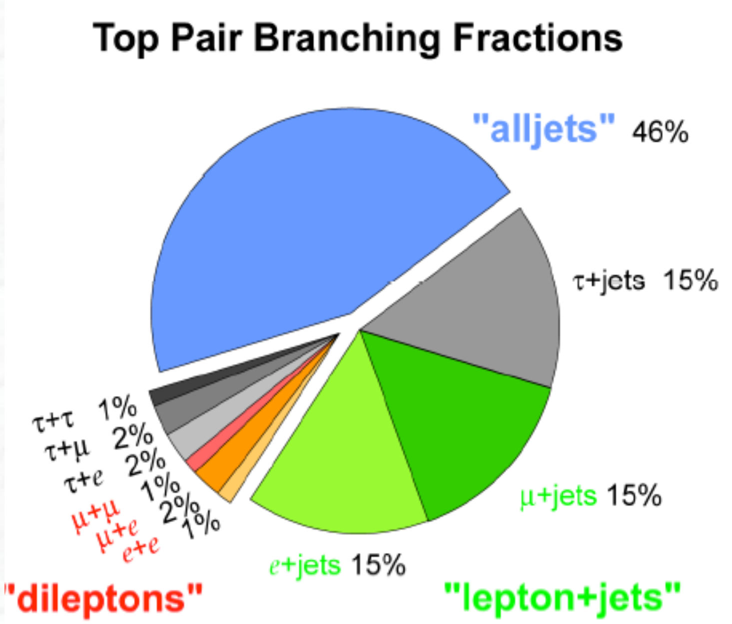
Both W's decay via $W \to \ell\nu$ (ℓ=e or μ; 4%)

Lepton + jet channel:

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

Full hadronic channel:

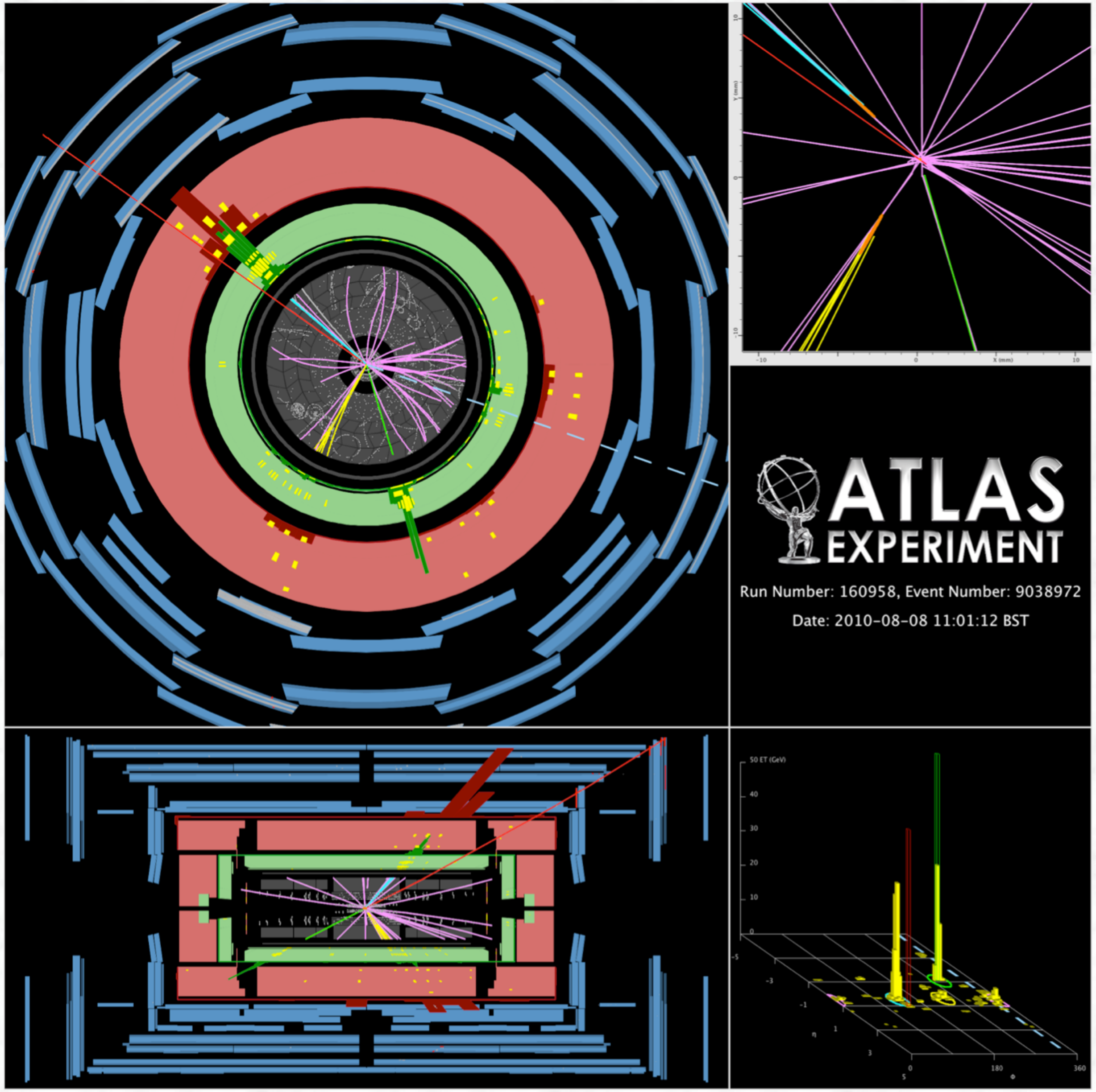
Both W's decay via $W \to qq$ (46%)



Important experimental signatures: : - Lepton(s)

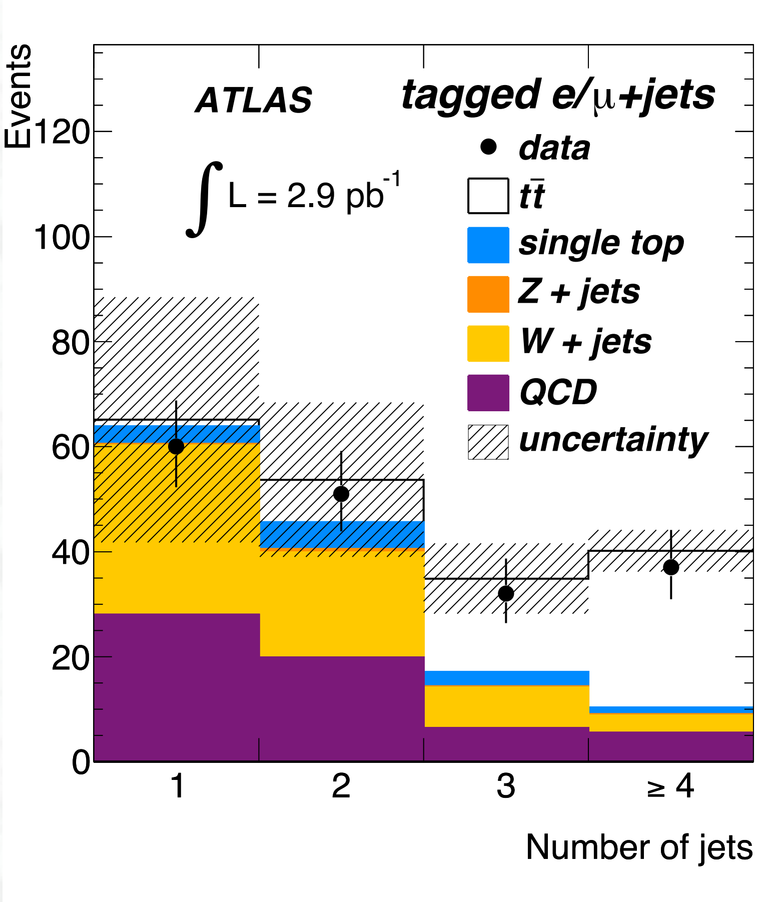
- Missing transverse momentum
- b-jet(s)

First measurements of Top Quark production at the LHC



Event display of a top pair e-μ dilepton candidate with two b-tagged jets. The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the missing E_T direction by the dotted line on the xy-view.
The secondary vertices of the two b-tagged jets are indicated by the orange ellipses on the zoomed vertex region view.

First results on top production from the LHC

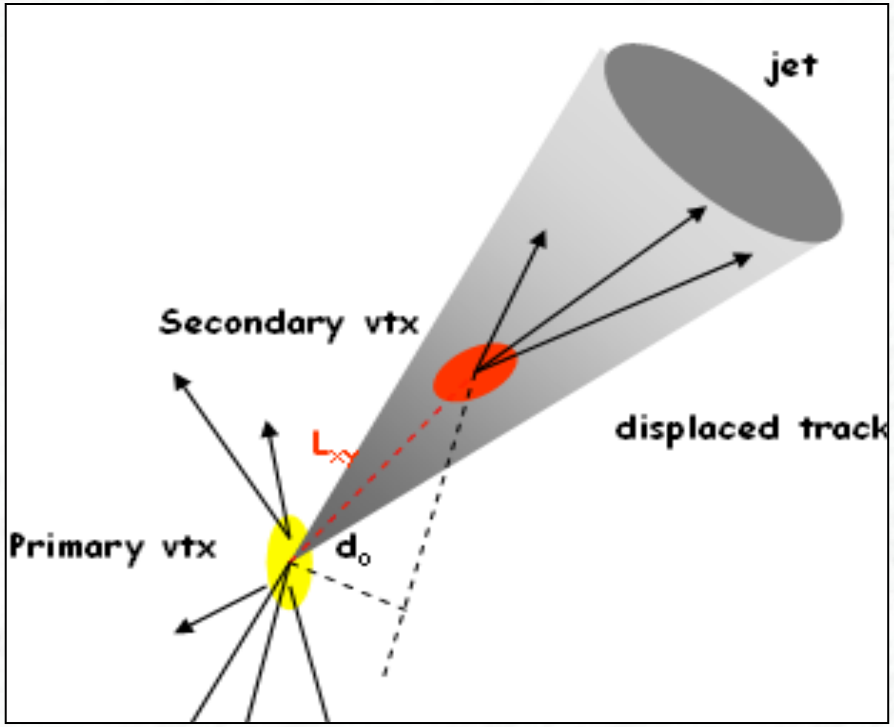


Event Selection:

- 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,ν) > 25 GeV (lepton from W decay in event)
- One or more jets with p_T > 25 GeV and η < 2.5

Tagging of b-quarks

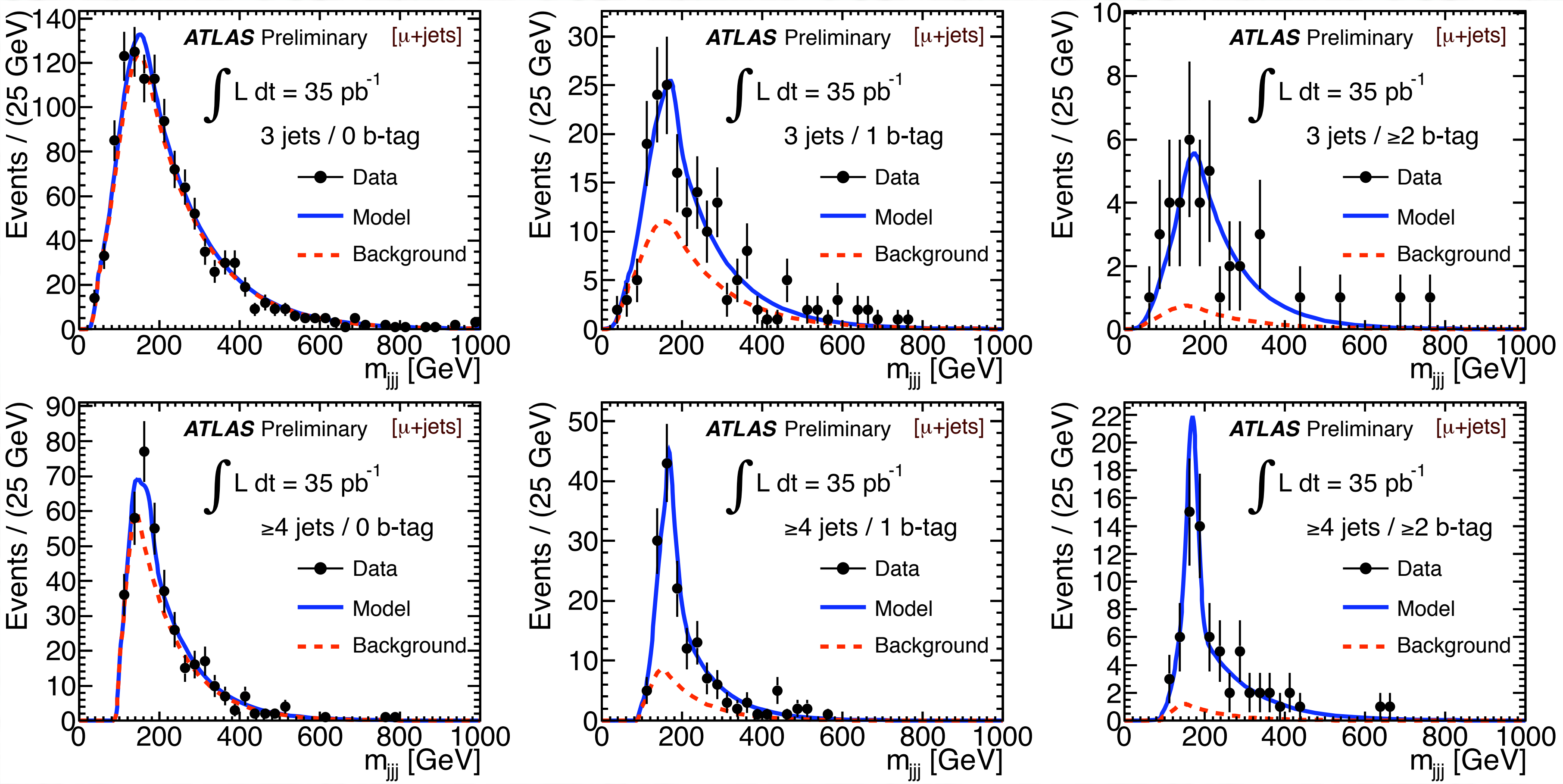
Silicon Vertex tag



B mesons travel ~ 3 mm before decaying:

– Search for secondary vertex

Description of the 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

CMS tt signals in the di-lepton channel

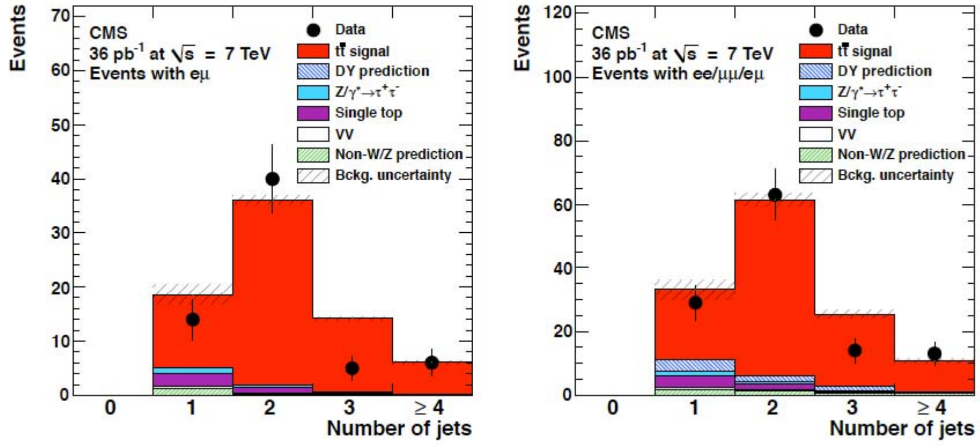


Figure 4: Jet multiplicity for events passing full dilepton selection criteria with at least one b-tagged jet, otherwise the same as in Fig. 3.

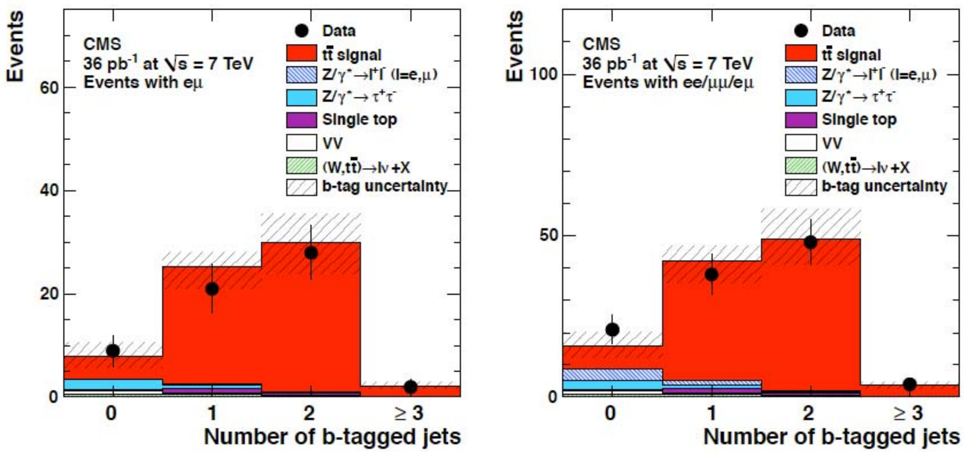
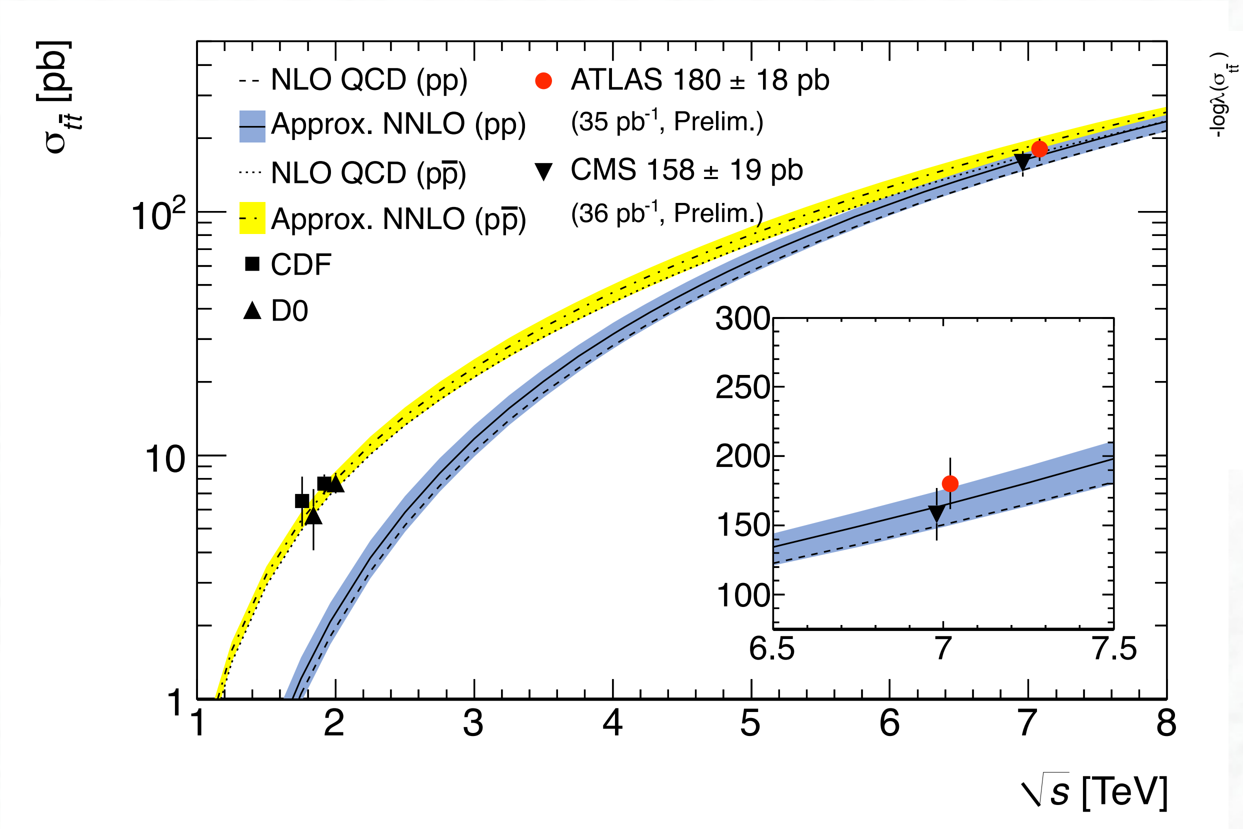
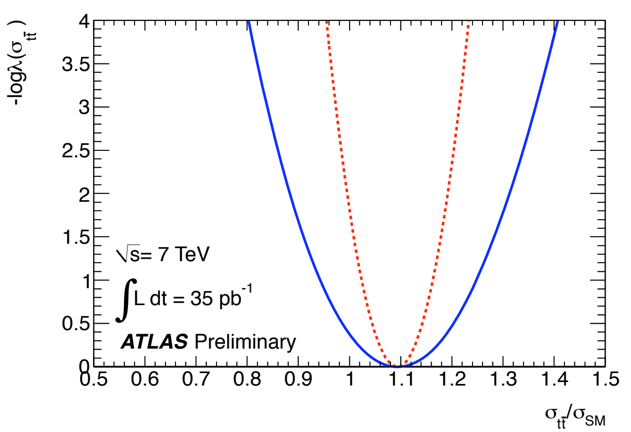


Figure 5: Multiplicity of b-tagged jets in events passing full dilepton selection criteria with at least two jets compared to signal and background expectations from simulation. The uncertainty on the number of signal events corresponding to the uncertainty in the selection of b-tagged jets is displayed by the shaded area. The distributions are for $e^{\pm}\mu^{\mp}$ (left) and all (right) final states combined.

Top cross section measurements based on 2010 data from ATLAS and CMS

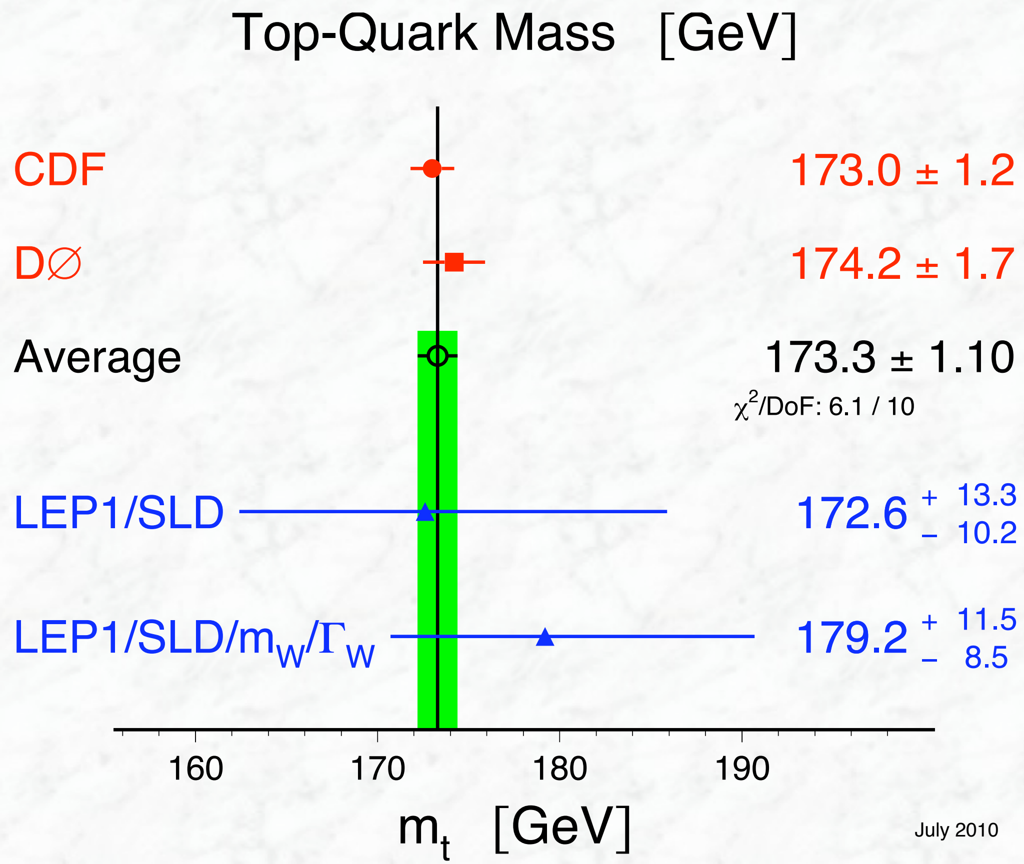




Best fit (ATLAS) gives
a slightly higher cross-section
than the expected approx.
NNLO QCD value,
but consistent within 1 σ
(red: likelihood, stat errors only;
blue: stat + syst. uncertainties)

- Results between the two experiments are consistent
- Perturbative QCD calculations are in agreement with the obtained results

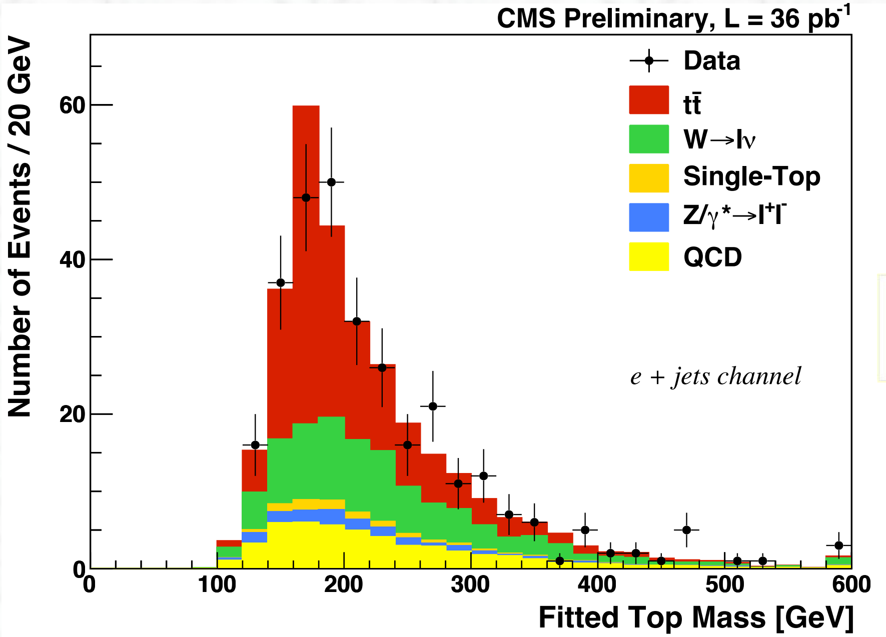
Top-quark mass measurement



First top quark mass measurements from CMS

CMS, 06.06.2011

- Use lepton + jet channel
- Full 2010 data set
- 637 candidate events selected

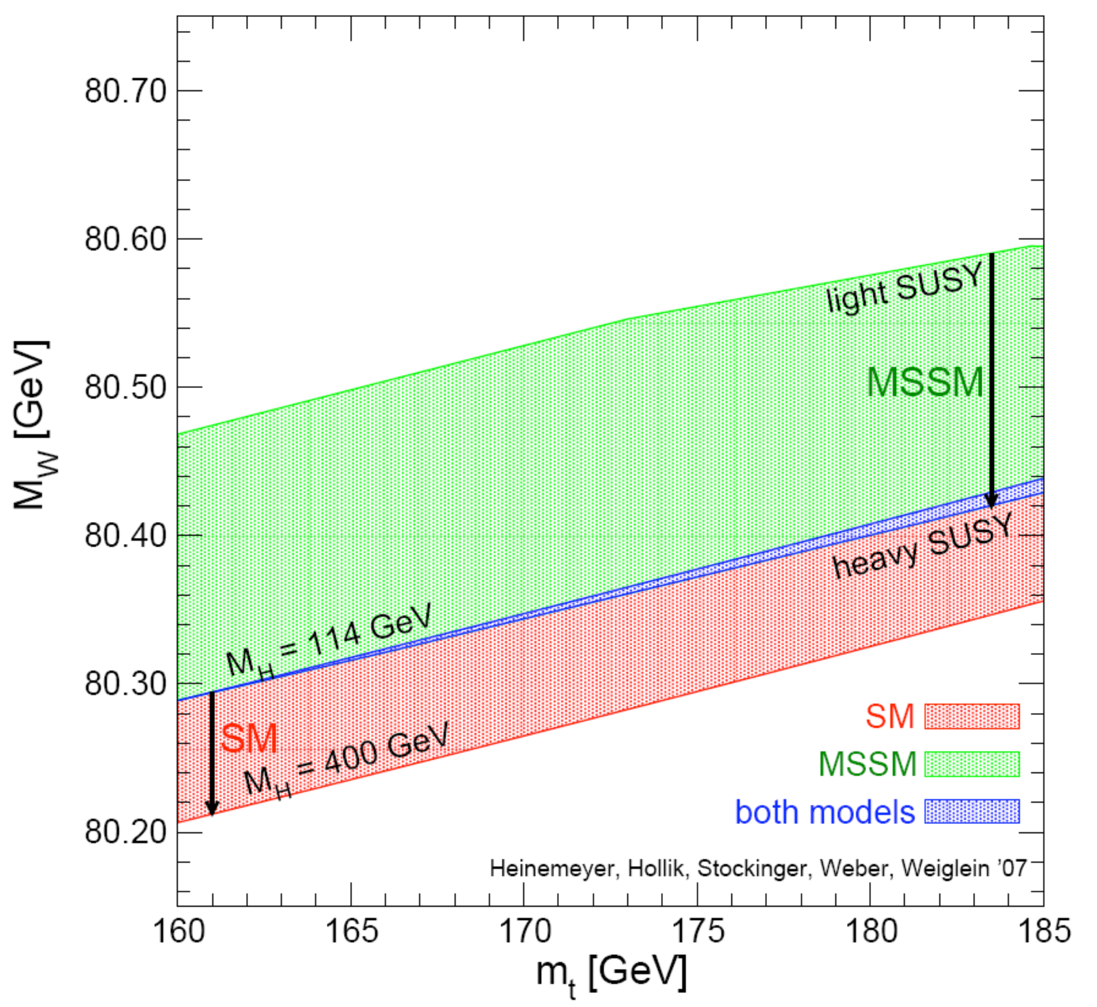


Top quark mass after the fit of the e+jets selected sample for an integrated luminosity of 36/pb after applying the event selection and requesting a good fit quality.

$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst})\ \text{GeV}.$$

Already impressive precision reached at that early stage of the experiment !

Relation between m_W, m_t, and m_H



The W-mass measurement

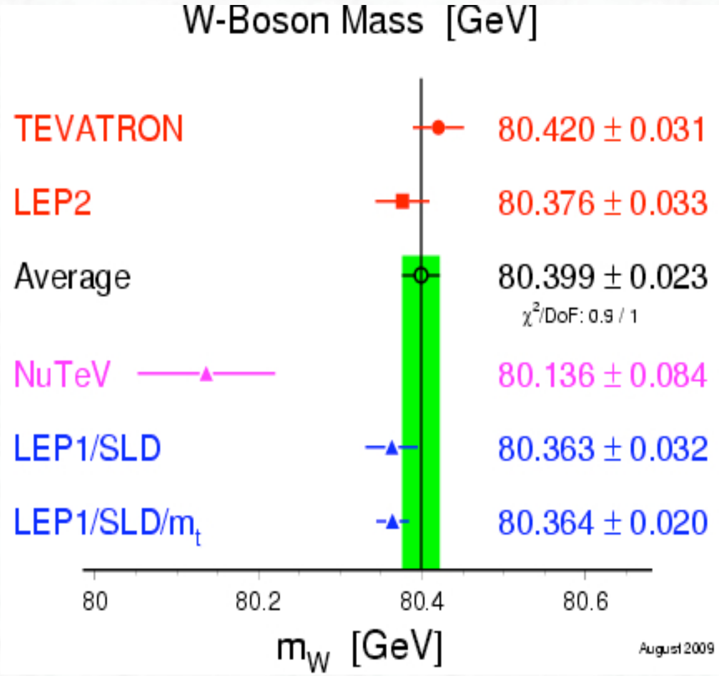
$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

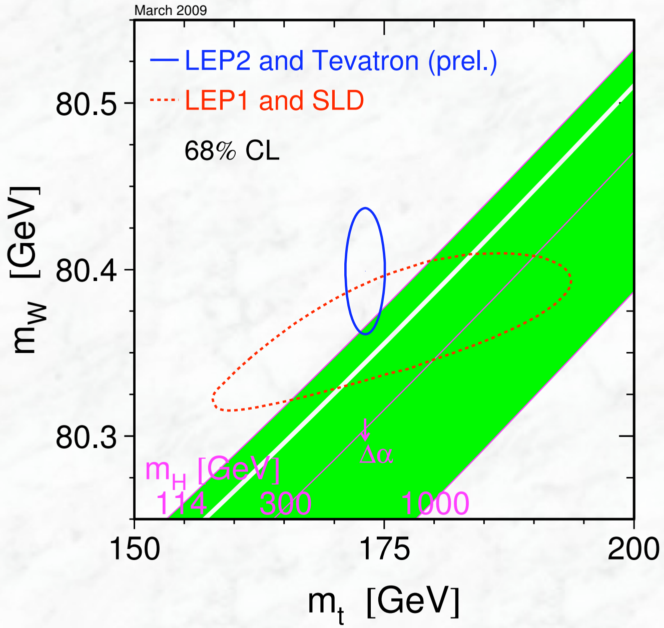
$3 \cdot 10^{-4}$

m_W (from LEP2 + Tevatron) = 80.399 ± 0.023 GeV

m_{top} (from Tevatron) = 173.3 ± 1.1 GeV

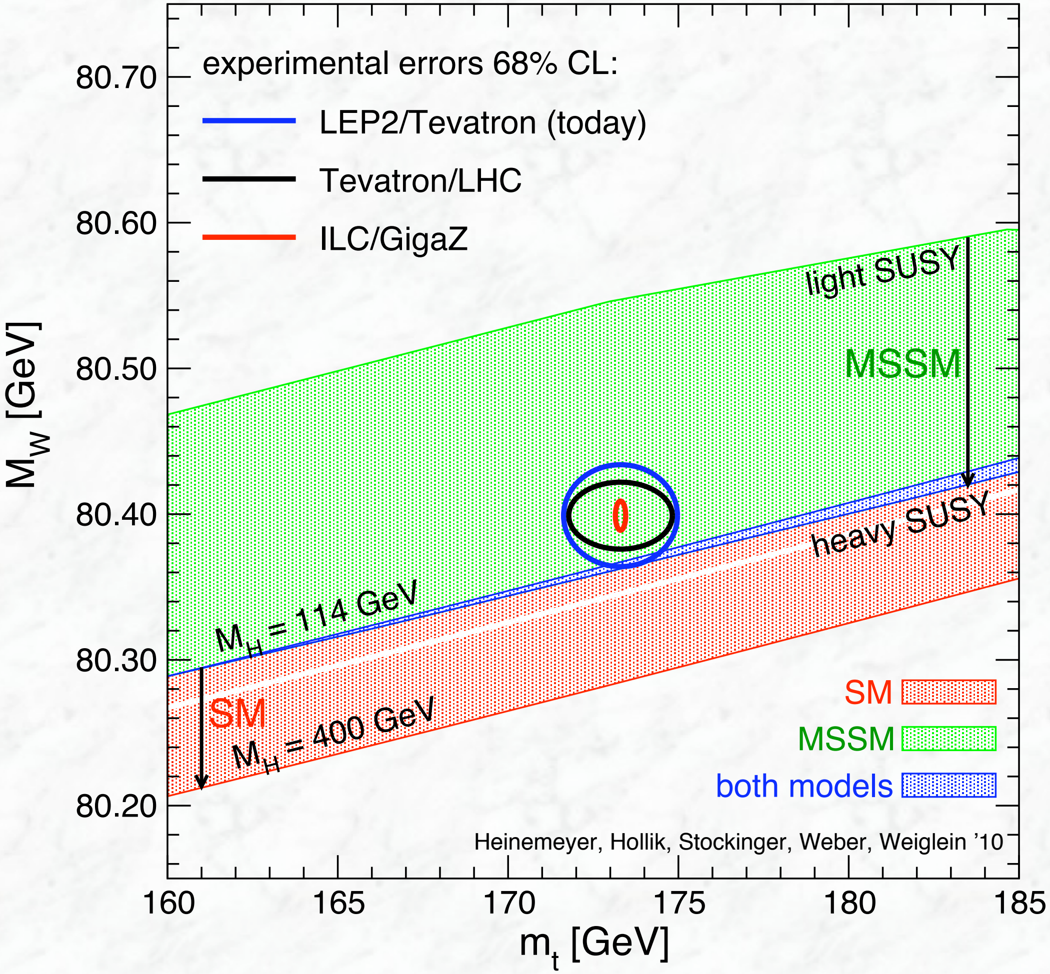
0.8%





A light Higgs boson is favoured by present measurements

Ultimate test of the Standard Model: comparison between the direct Higgs boson mass and predictions from radiative corrections….



Predictions for future precision (including LHC), compared to the Standard Model and its Minimal Supersymmetric Extension (MSSM)

Ultimate test of the Standard Model: compare direct prediction of Higgs mass with direct observation

Final cross section summary