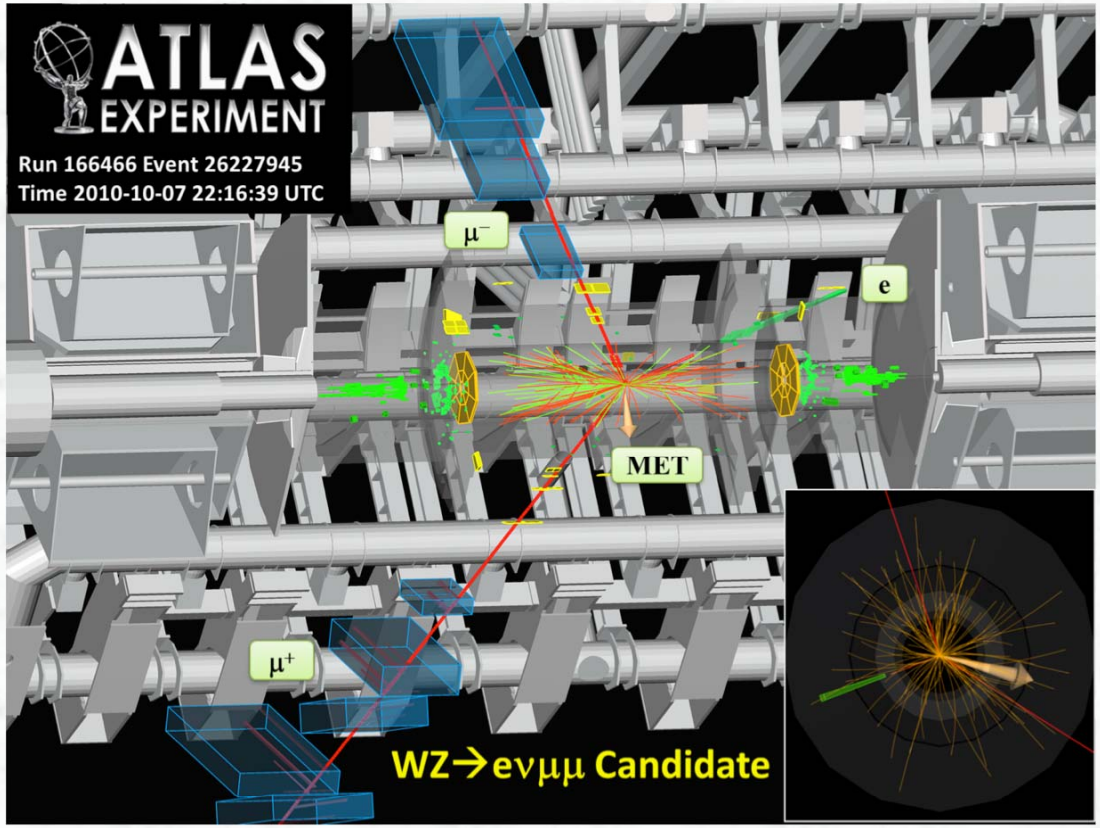
Physics at the LHC

- From the Standard Model to Searches for New Physics-



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Outline of the lectures:

1. Introduction

2. Test of the Standard Model
   (QCD, Electroweak parameters)

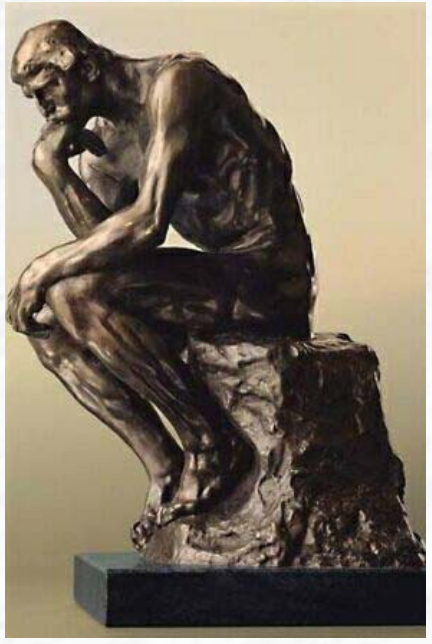
3. Search for the Higgs Boson

4. Search for Supersymmetry

5. Search for Other New Phenomena
   (New particles, Extra dimensions,…)

Disclaimer: I will try to highlight important first physics measurements and results on searches for new physics. The coverage is not complete, i.e. not all results available will be presented; Results from both general purpose experiments, ATLAS and CMS, 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 open questions



Key Questions of Particle Physics

1. Mass: What is the origin of mass?

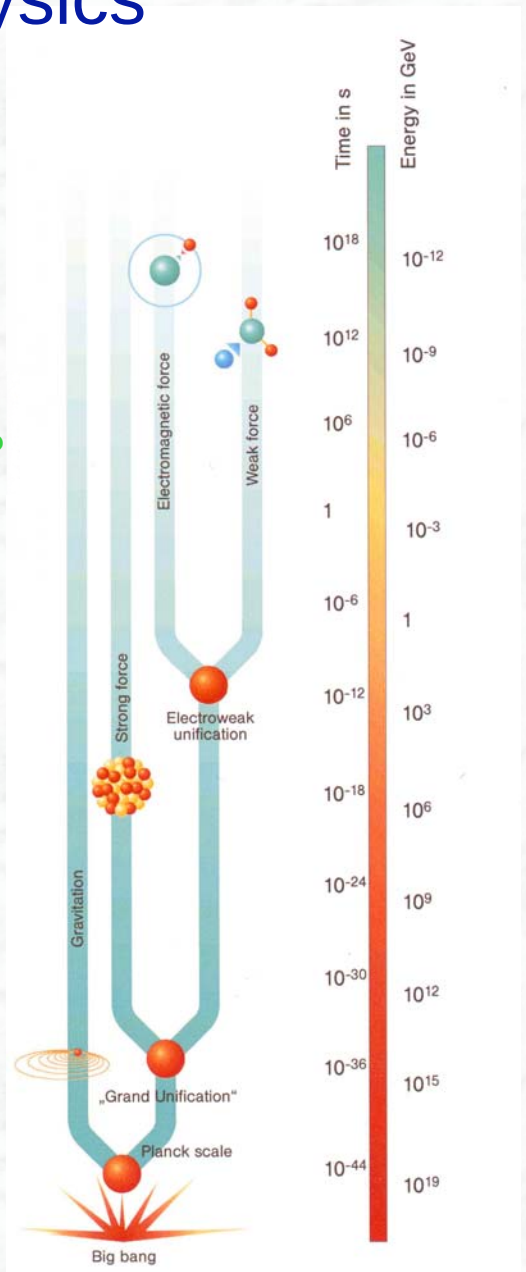
- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

2. Unification: What is the underlying fundamental theory ?

- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world supersymmetric ?
- What is the Dark Matter in the universe made off?
- ….

3. Flavour: or the generation problem

- Why are there three families of matter?
- Neutrino masses and mixing?
- What is the origin of CP violation?



Many theoretical models for physics Beyond the Standard Model

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?

- The search for “low energy” supersymmetry
  Can a link between SUSY and dark matter be established?

- Other scenarios beyond the Standard Model
- …….

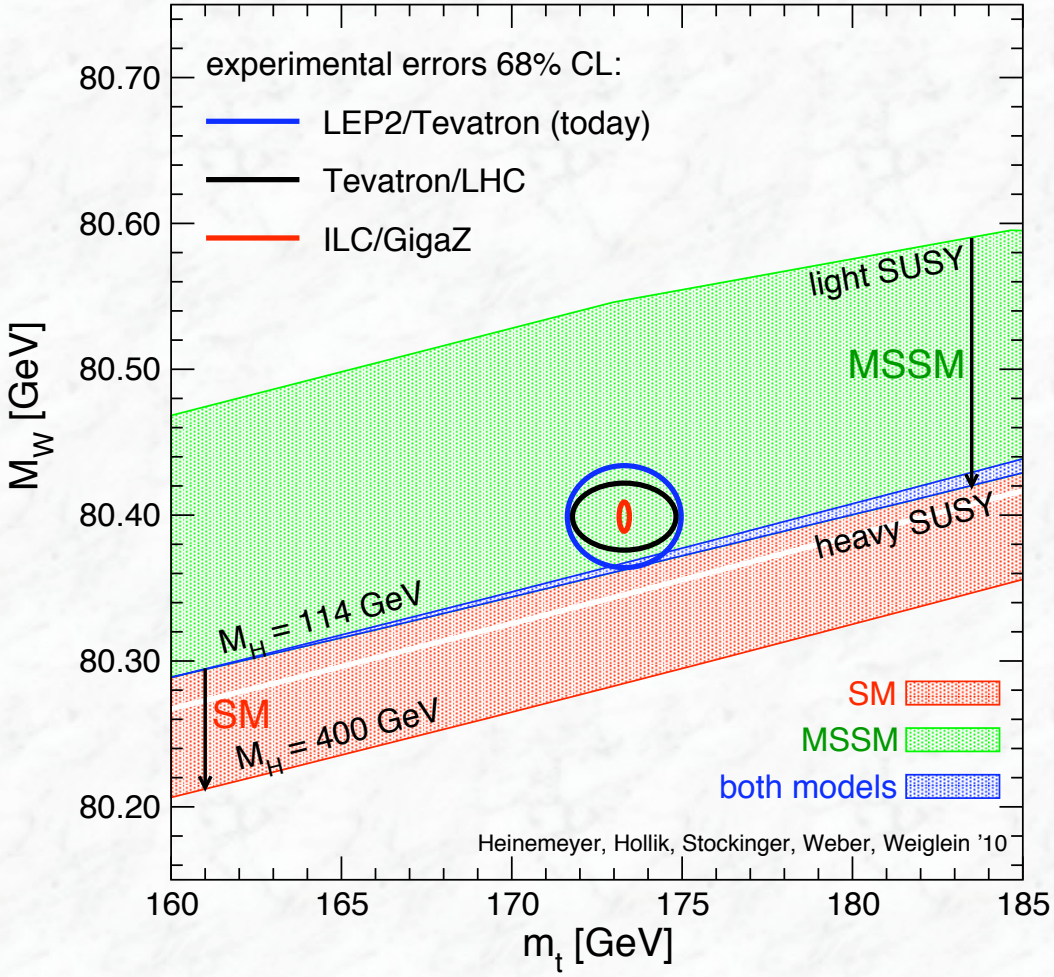
Look for the “expected”, but we need to be open for surprises

→ 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

- Many Standard Model measurements can be used to test and to tune the detector performance

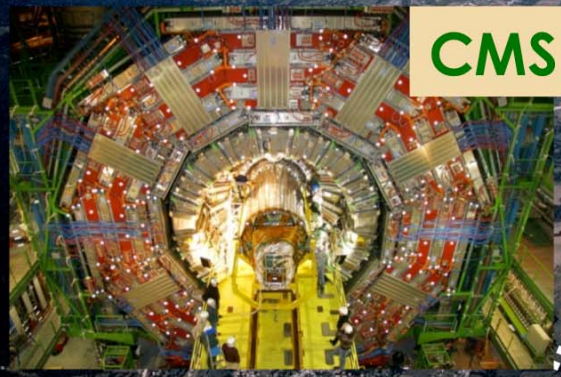


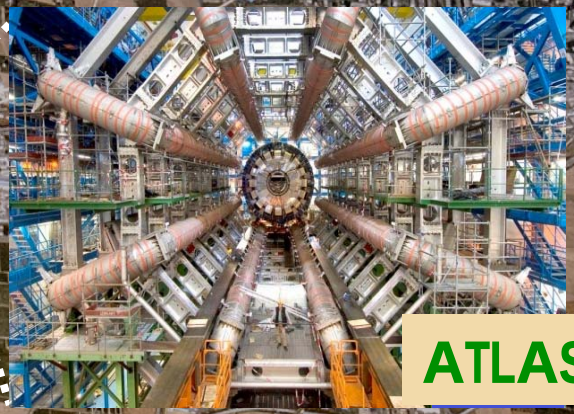
Predictions for future precision (including LHC), compared to the Standard Model and its Minimal Supersymmetric Extension (MSSM)

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

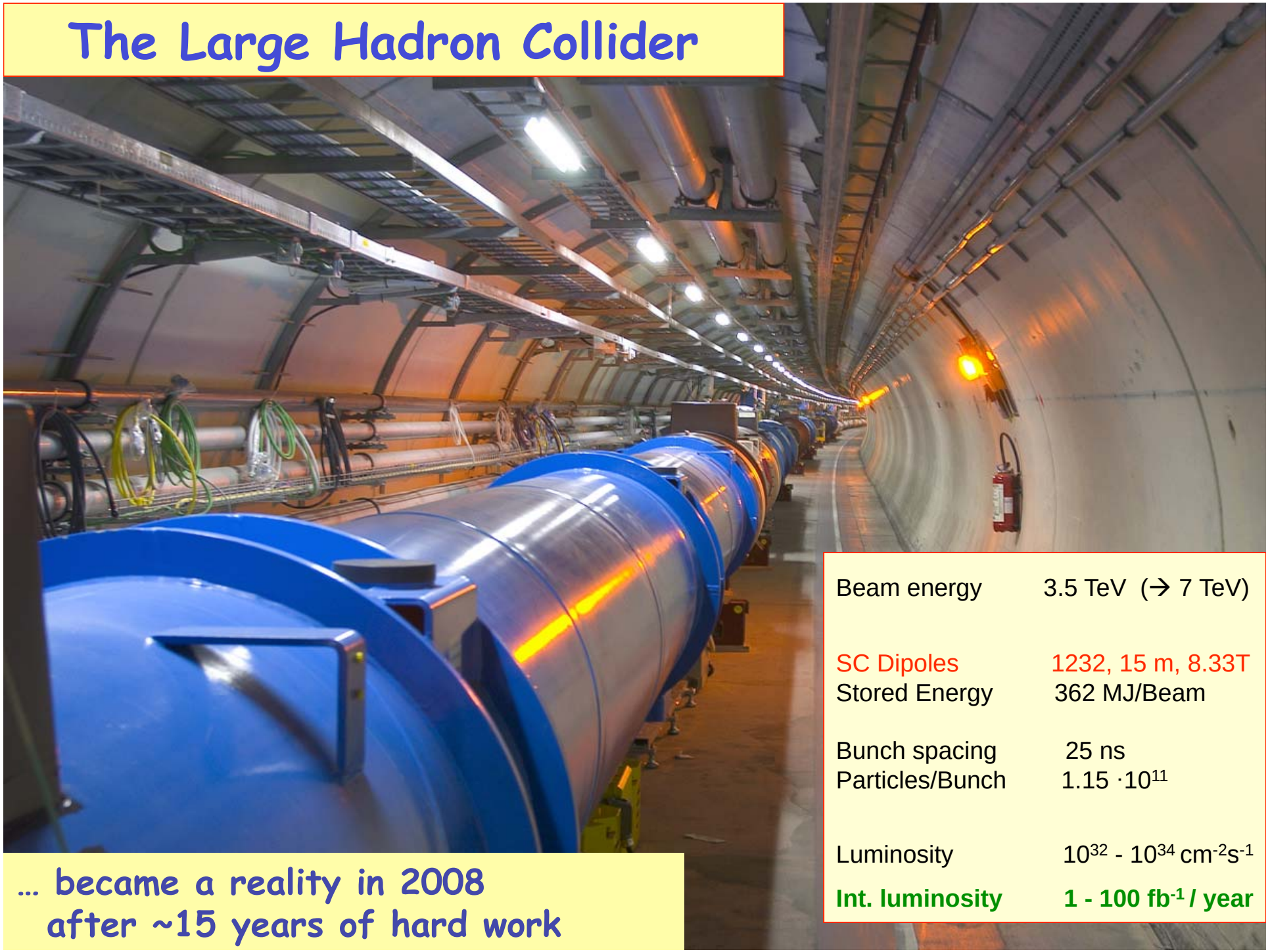
The Large Hadron Collider (LHC)

Begin of a new era in particle physics





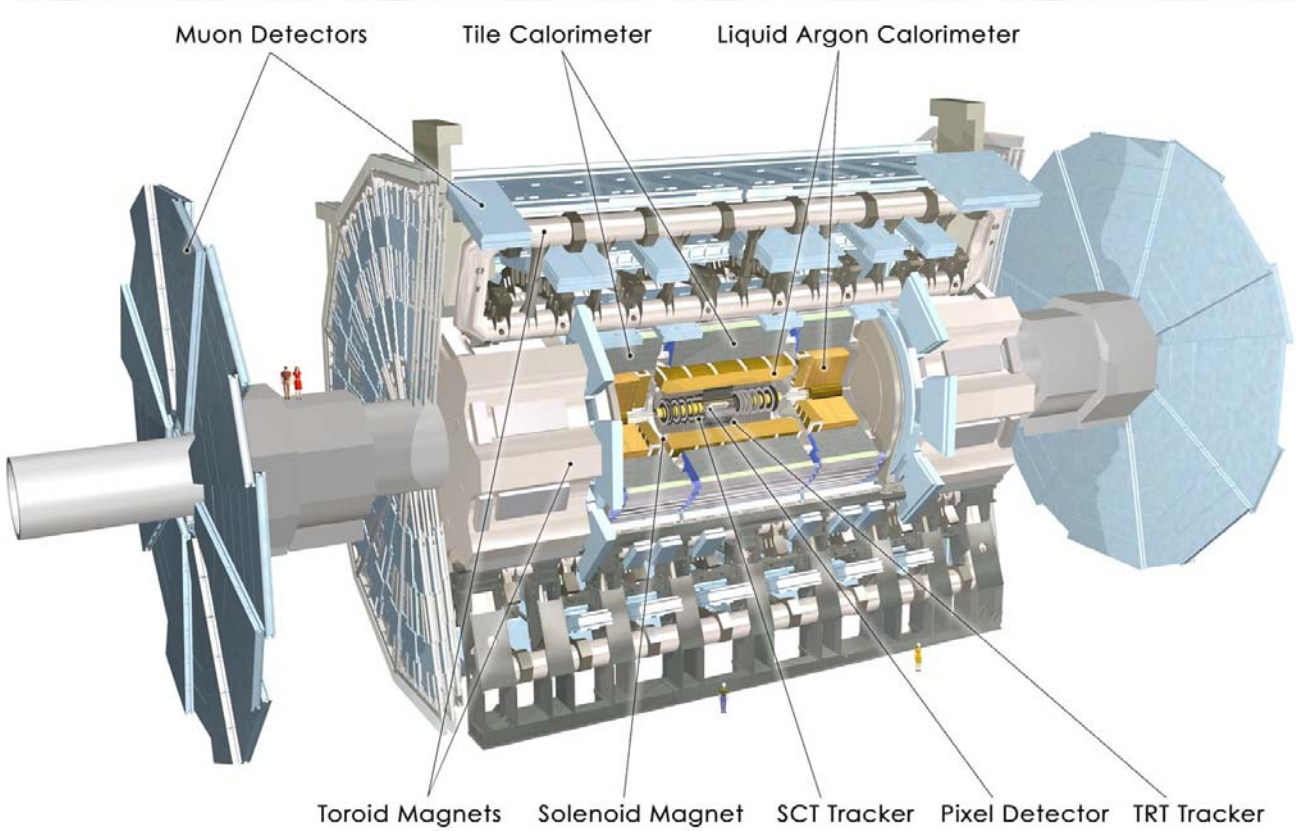
The Large Hadron Collider



Beam energy	3.5 TeV (→ 7 TeV)
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
Luminosity	10^{32} - 10^{34} $cm^{-2}s^{-1}$
Int. luminosity	**1 - 100 fb^{-1} / year**

… became a reality in 2008
after ~15 years of hard work

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

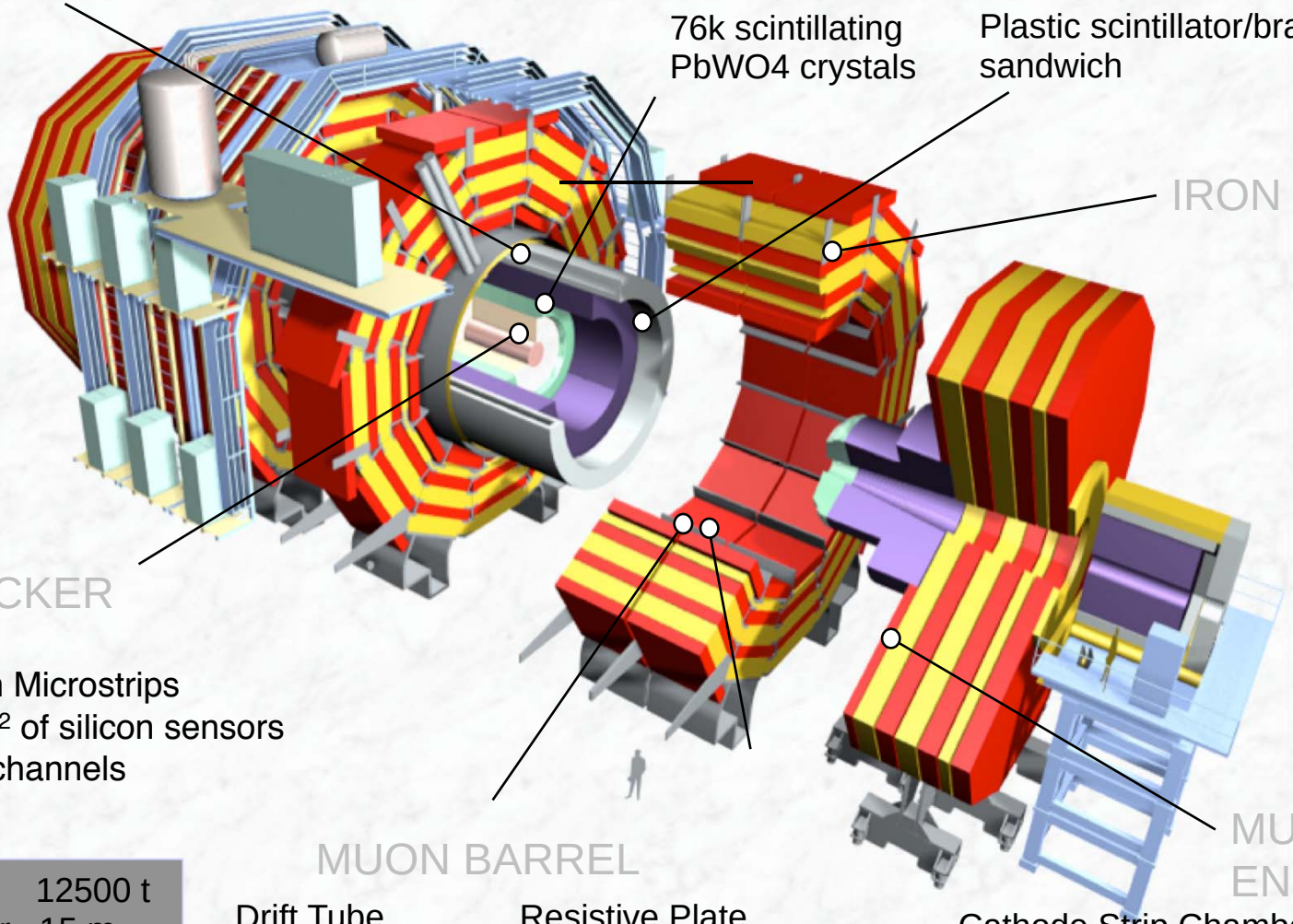
Superconducting Coil, 4 Tesla

CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

IRON YOKE



TRACKER

Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M channels

MUON BARREL

Drift Tube Chambers (**DT**)

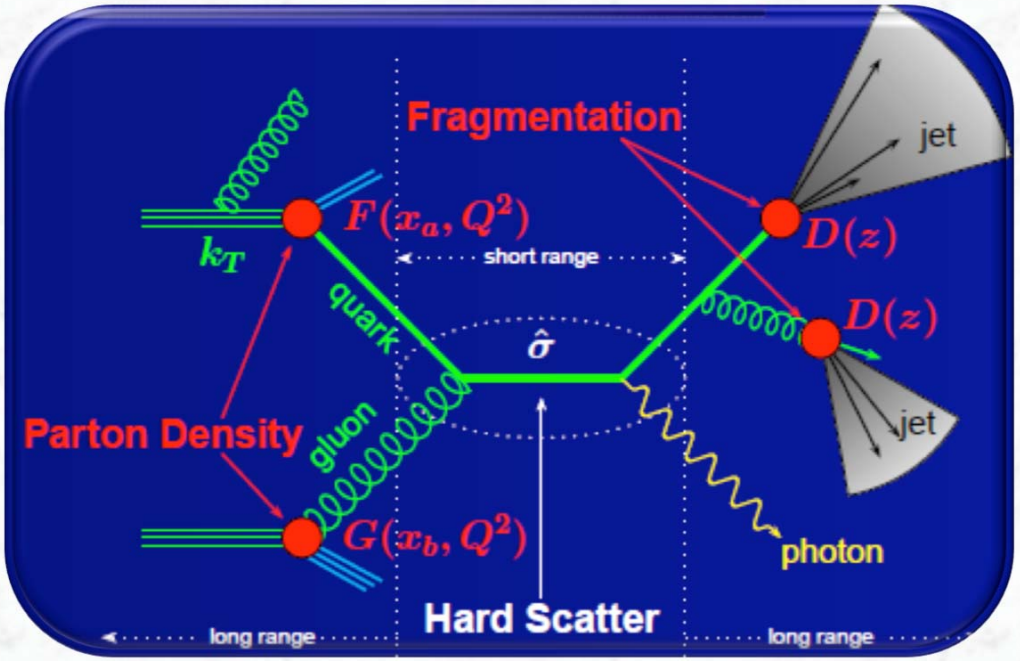
Resistive Plate Chambers (**RPC**)

MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

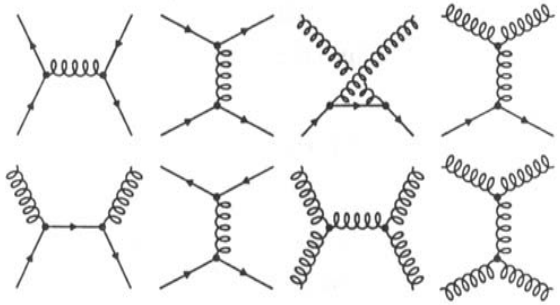
Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

Scattering processes at a hadron collider

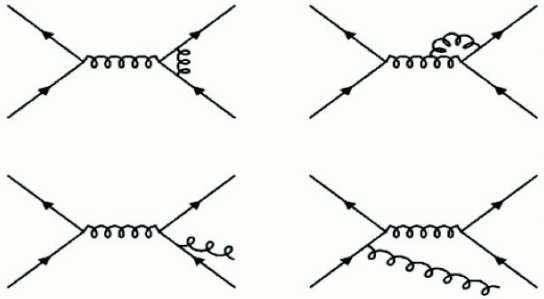


Dominant hard scattering processes: qq, qg and gg “scattering”

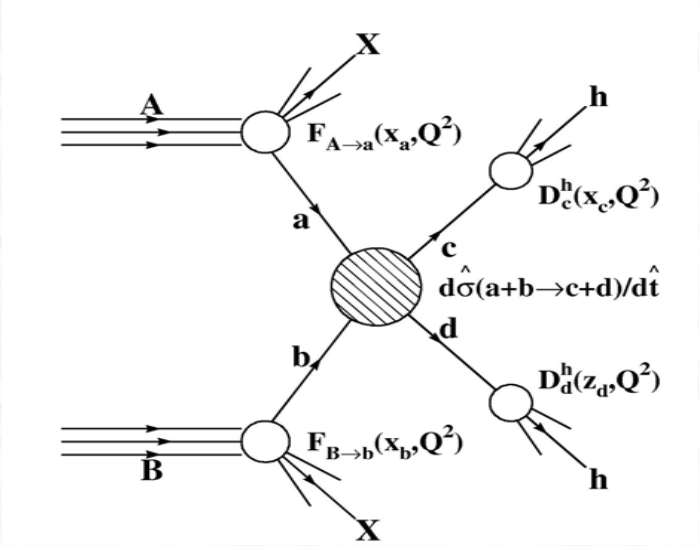
Leading order



…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 !

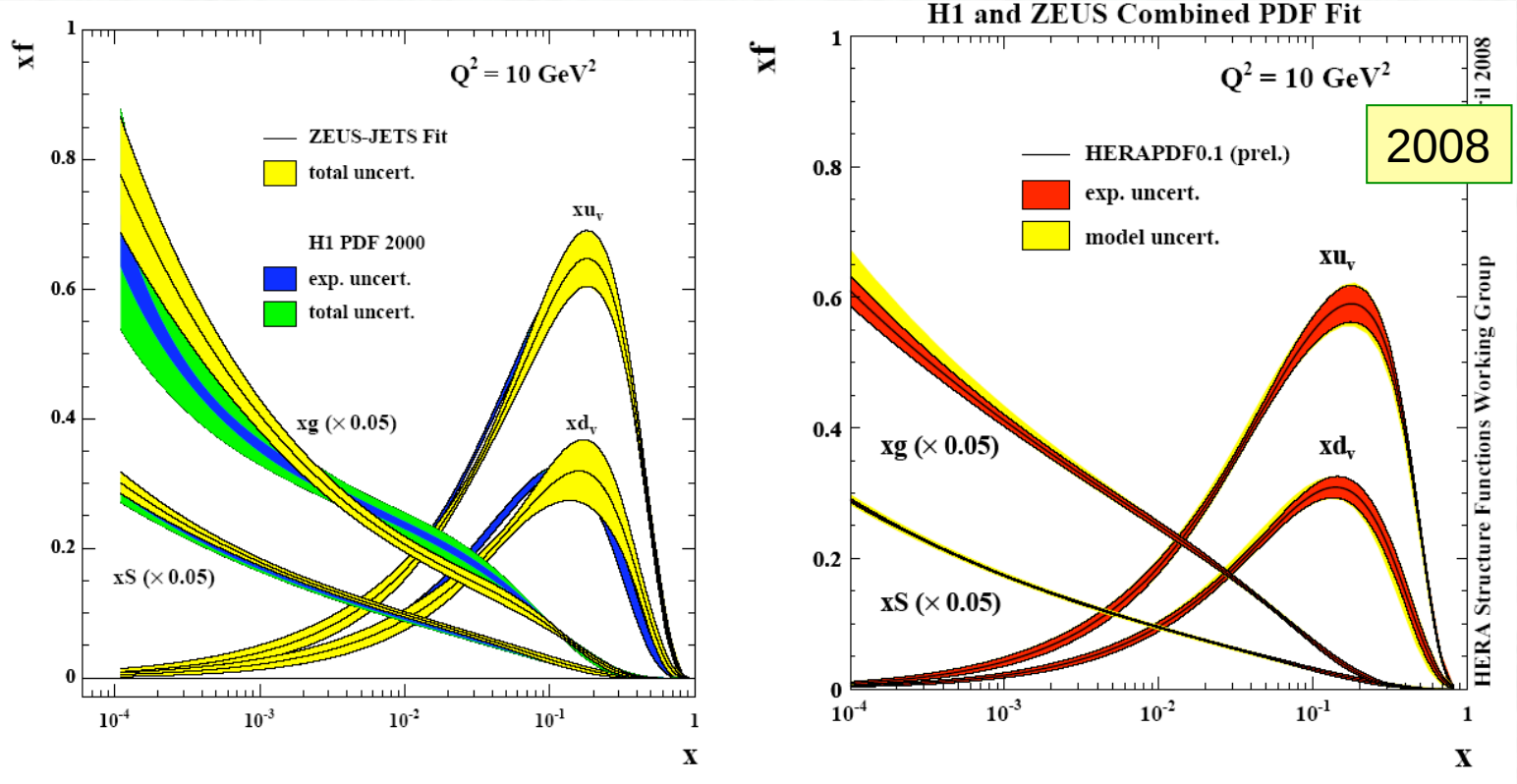
which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

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

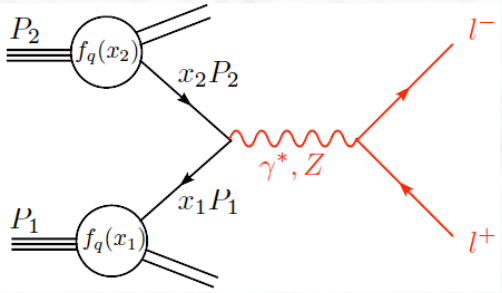
Results from HERA on the proton structure

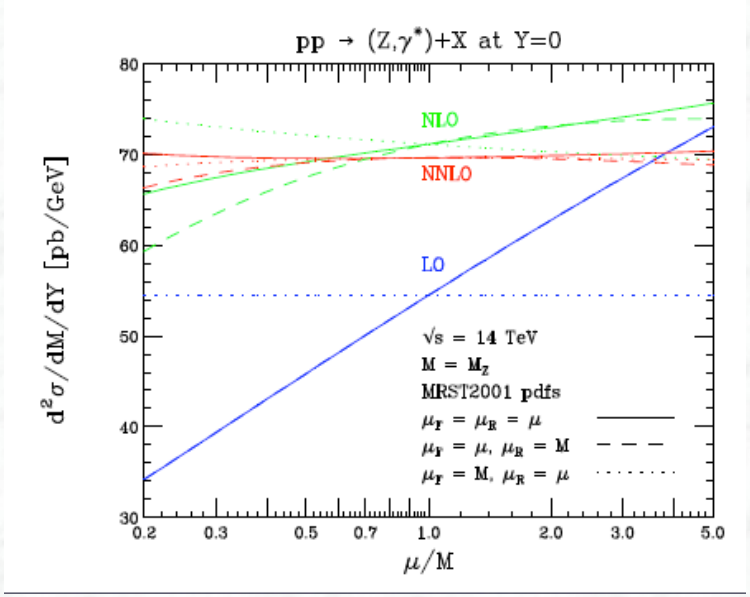
- Large data sets and combination of the two HERA experiments (H1 and ZEUS) improve the precision on the parton distribution functions

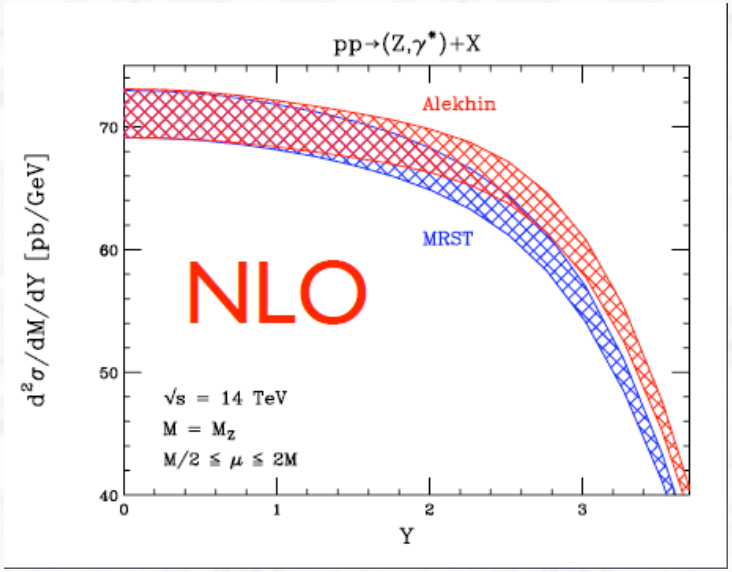


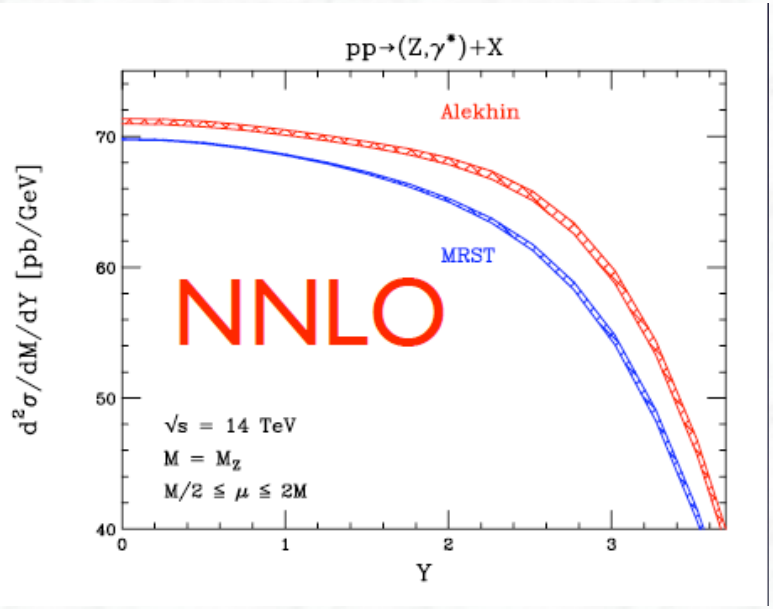
- Very important to reduce cross section uncertainties at hadron colliders; but still not good enough ….. (~ 10% errors for LHC cross sections)

Example: Drell-Yan production of W/Z bosons



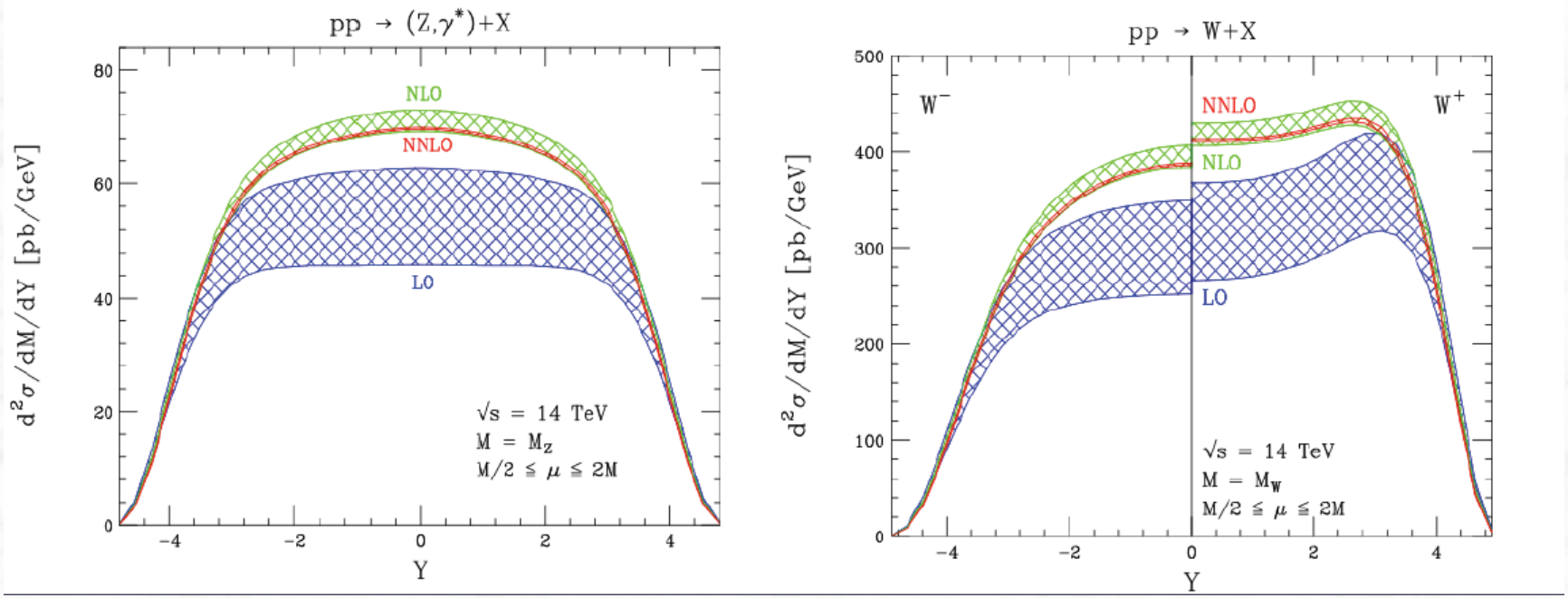






Example: Drell-Yan production of W/Z bosons (cont.)

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

Luminosity

The rate of events produced for a given physics process is given by:

$$N = L \cdot \sigma$$

L = Luminosity
σ = cross section

dimensions: $s^{-1} = cm^{-2}\, s^{-1} \cdot cm^2$

Luminosity depends on the machine:
important parameters: number of protons stored, beam focus at interaction region,….

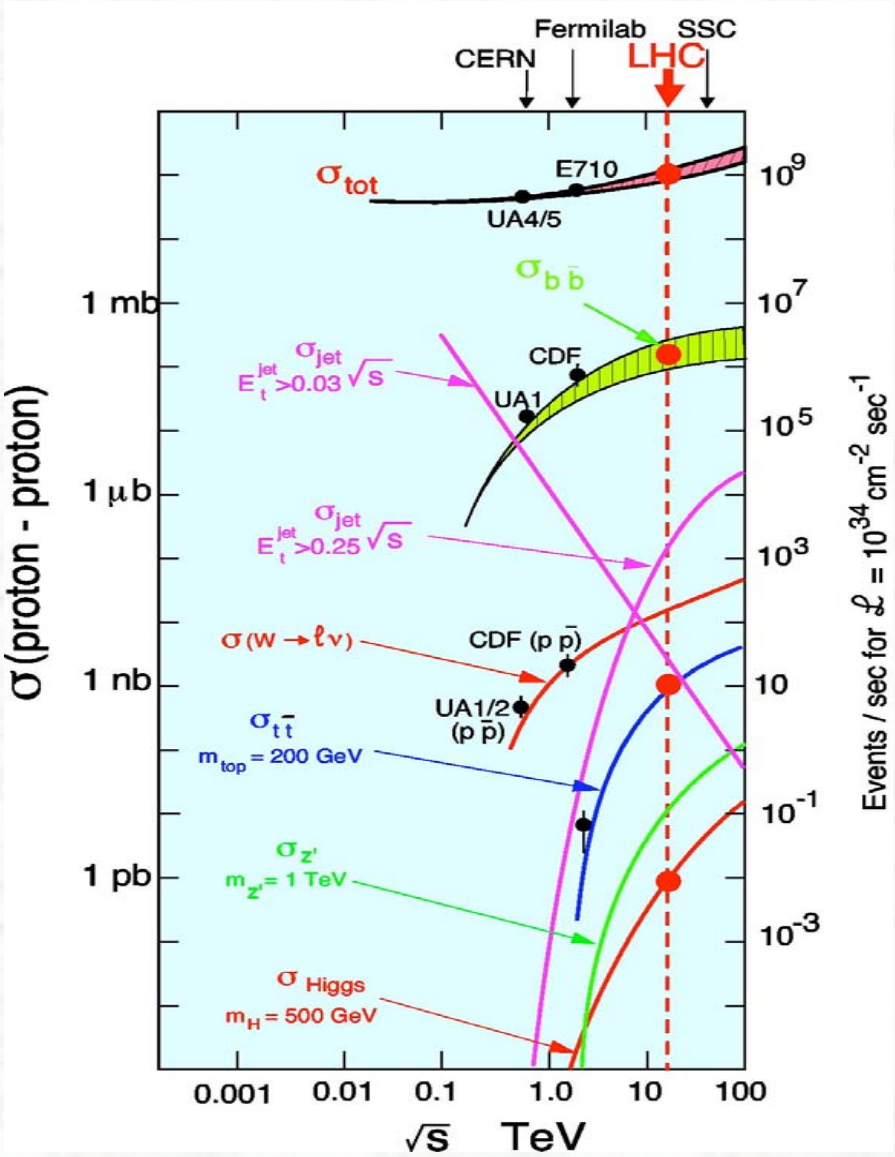
In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high !

$L = 2 \cdot 10^{32}\ cm^{-2}\, s^{-1}$ design value for Tevatron Run II
$L = 10^{33}\ cm^{-2}\, s^{-1}$ planned for the initial phase of the LHC
$L = 10^{34}\ cm^{-2}\, s^{-1}$ LHC design luminosity, very large !!
(1000 x larger than LEP-2, 50 x Tevatron Run II design)

One experimental year has ~ 10^7 s →

Integrated luminosity at the LHC: 10 fb^{-1} per year for $L = 10^{33}\ cm^{-2}\, s^{-1}$
100 fb^{-1} per year for $L = 10^{34}\ cm^{-2}\, s^{-1}$

Cross Sections and Production Rates



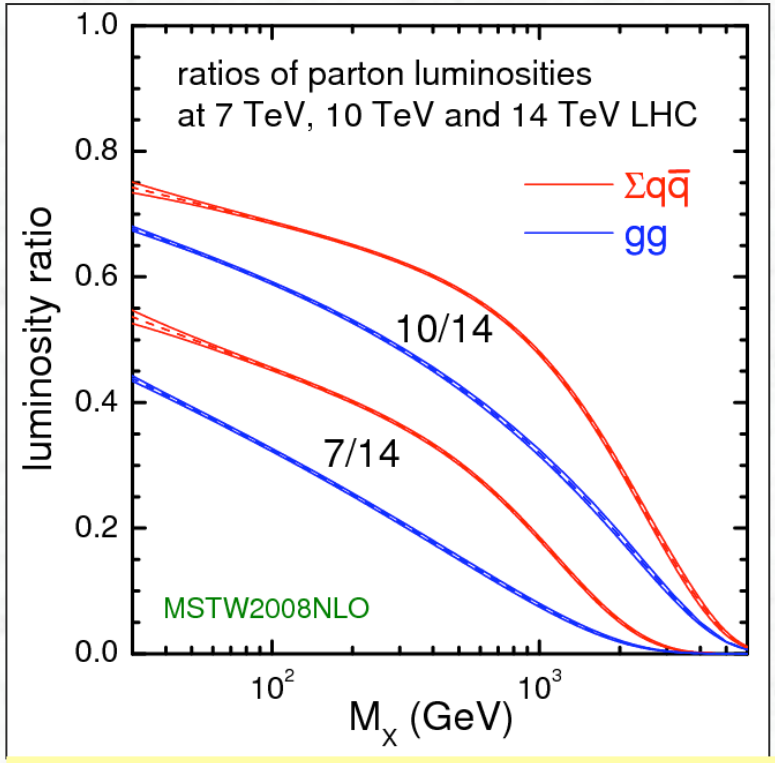
Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^9 / s
• bb pairs	5 10^6 / s
• tt pairs	8 / s
• W → e ν	150 / s
• Z → e e	15 / s
• **Higgs (150 GeV)**	**0.2 / s**
• **Gluino, Squarks (1 TeV)**	**0.03 / s**

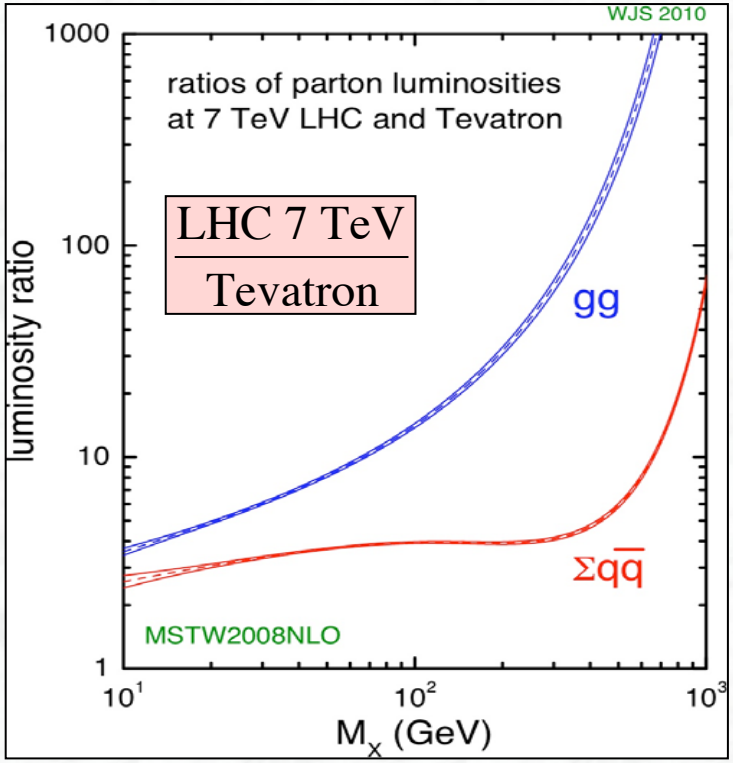
LHC is a factory for:
top-quarks, b-quarks, W, Z, …,Higgs, …

Impact of reduced beam energy

- Ratio of parton luminosities for 7/14 and 10/14 TeV …



J.Stirling
http://projects.hepforge.org/mstwpdf/plots/plots.html



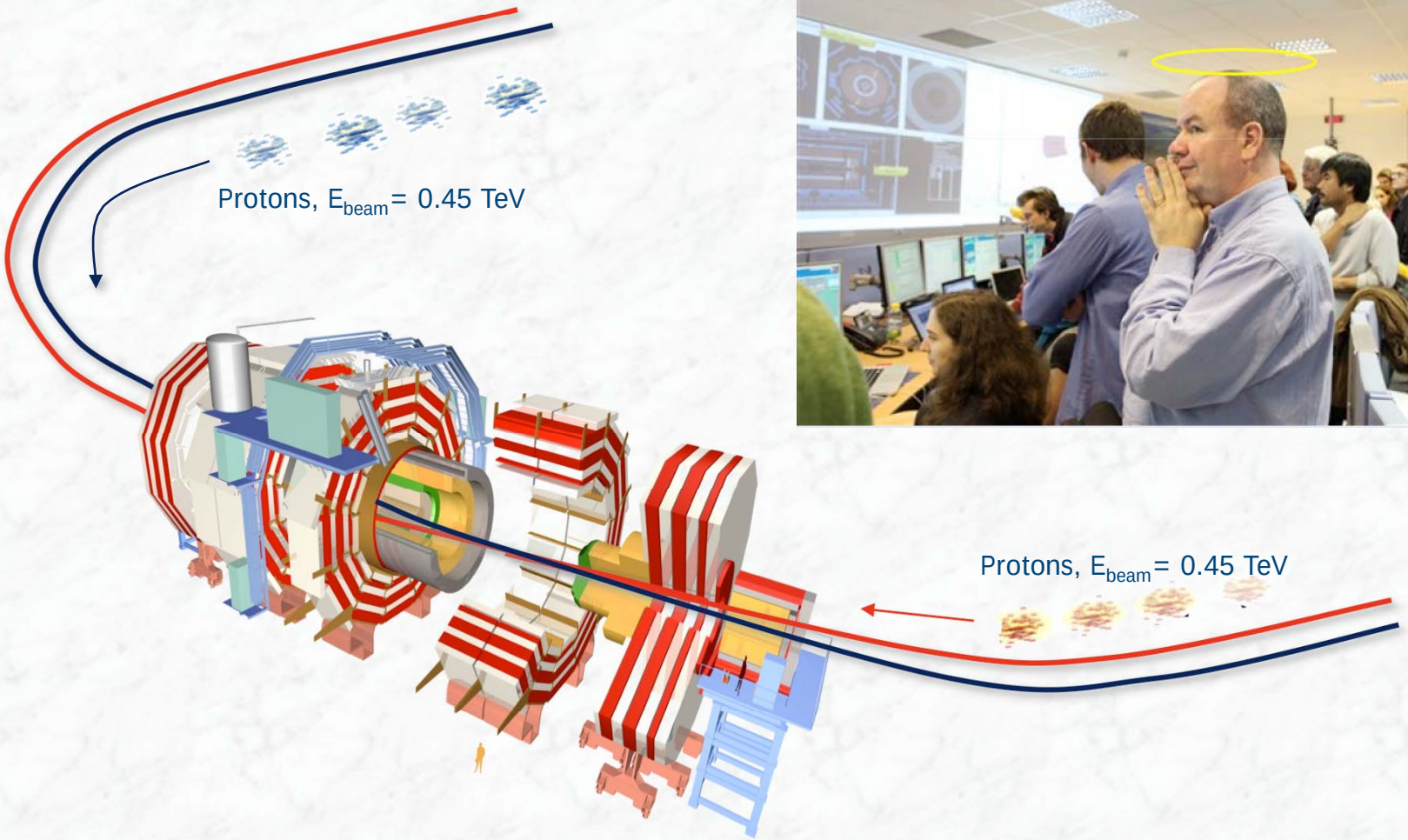
ttbar:
7/14 = 0.2

W' (1.5 TeV):
7/14 = 0.1

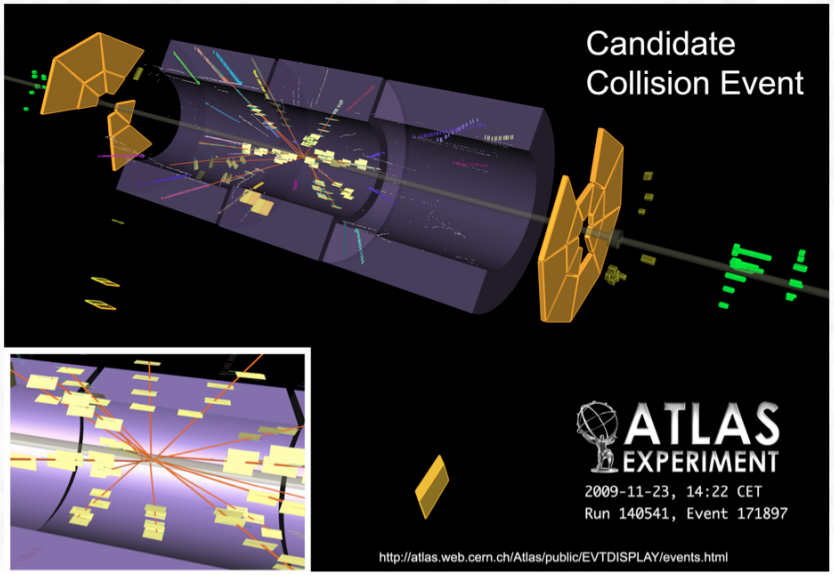
W' (1 TeV):
7(pp) / 2(ppbar) ~ 60

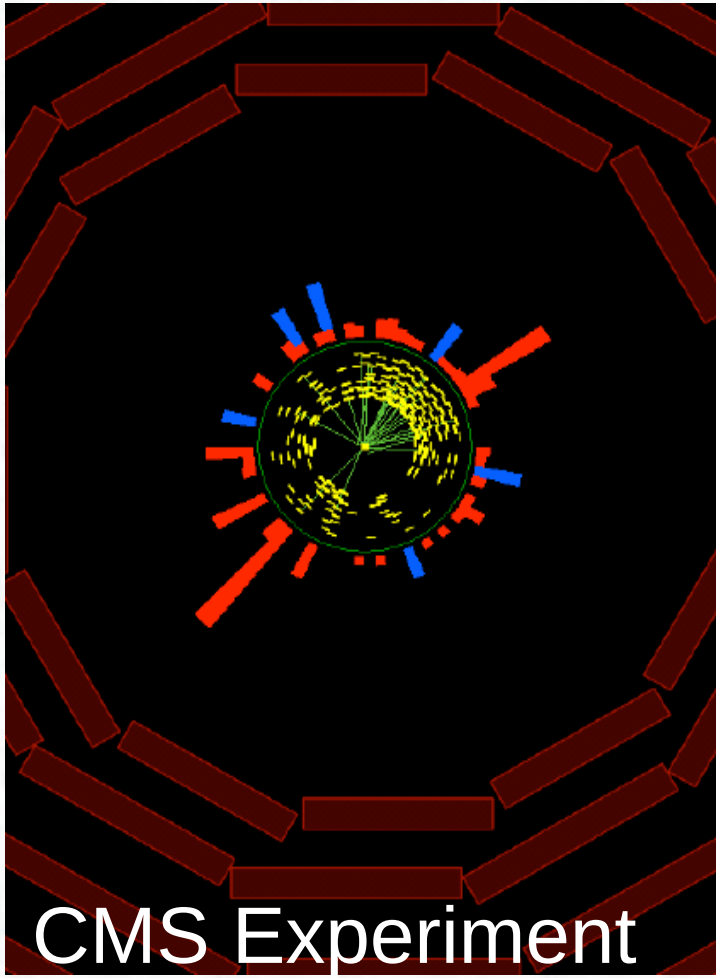
...but still large factor compared to the Tevatron ($\sqrt{s}$ =1.96 TeV)

LHC re-start in Nov. 2009



The collisions in the ATLAS and CMS



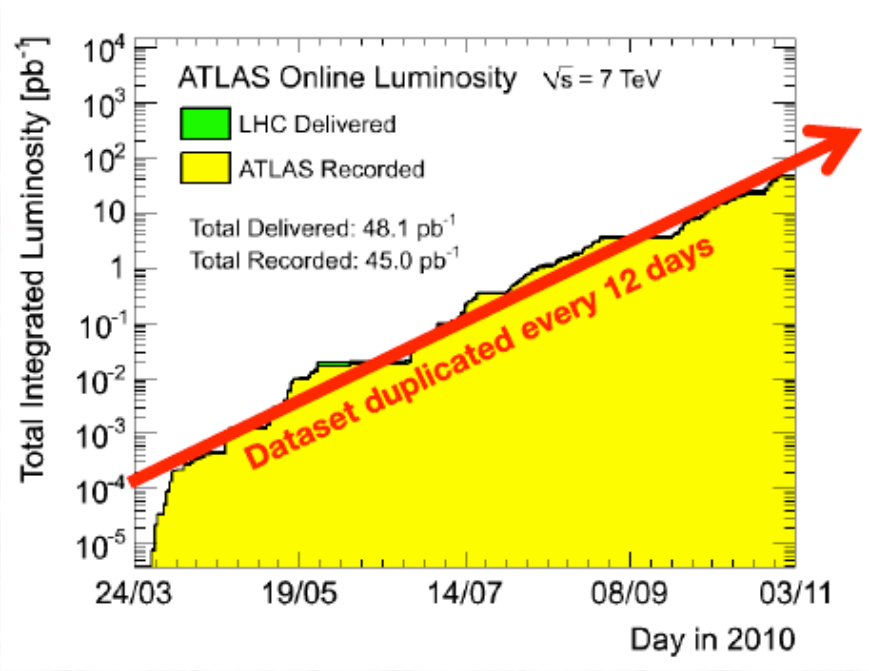


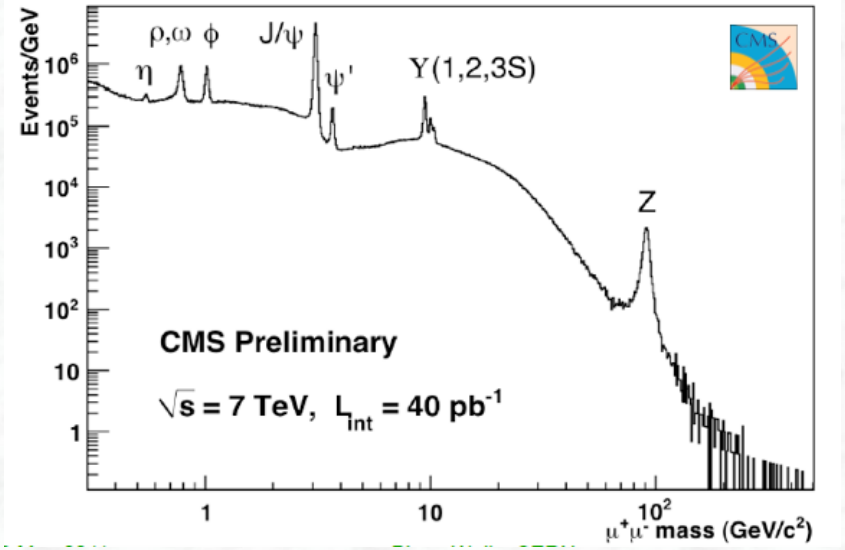
Collected data in 2010:

~40 pb^{-1} recorded
~36 pb^{-1} used in analysis
(good quality)

Both experiments have a very high data taking efficiency !

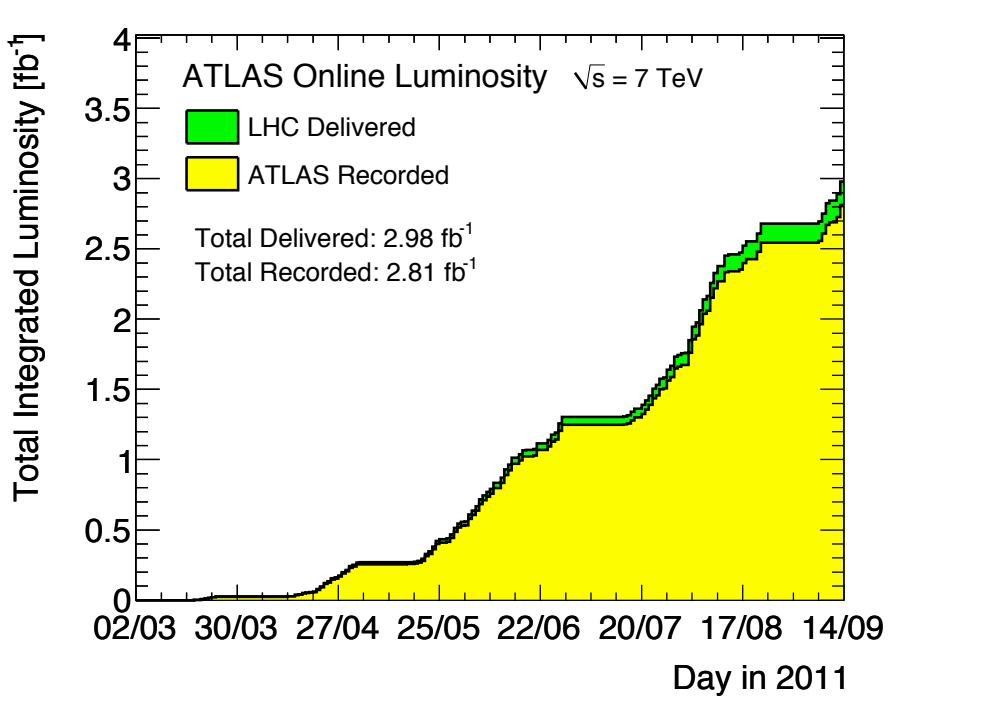
Well known resonances appeared "online"



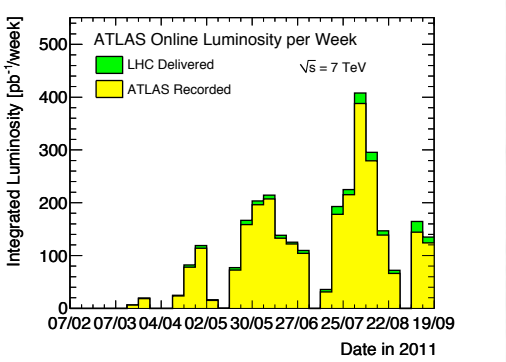


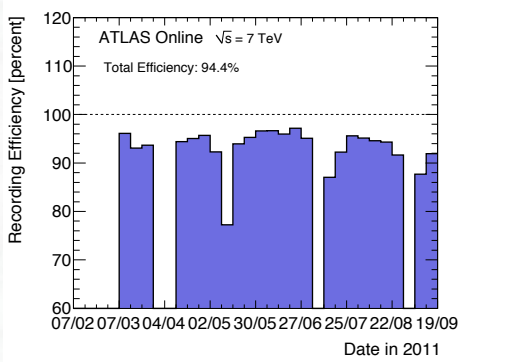
Data taking in 2011

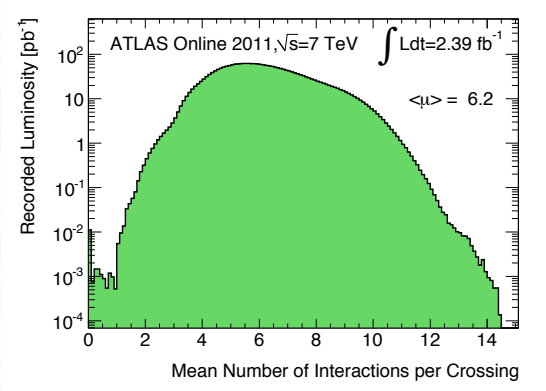
Original goal to collect 1 fb^{-1} already surpassed in June 2011



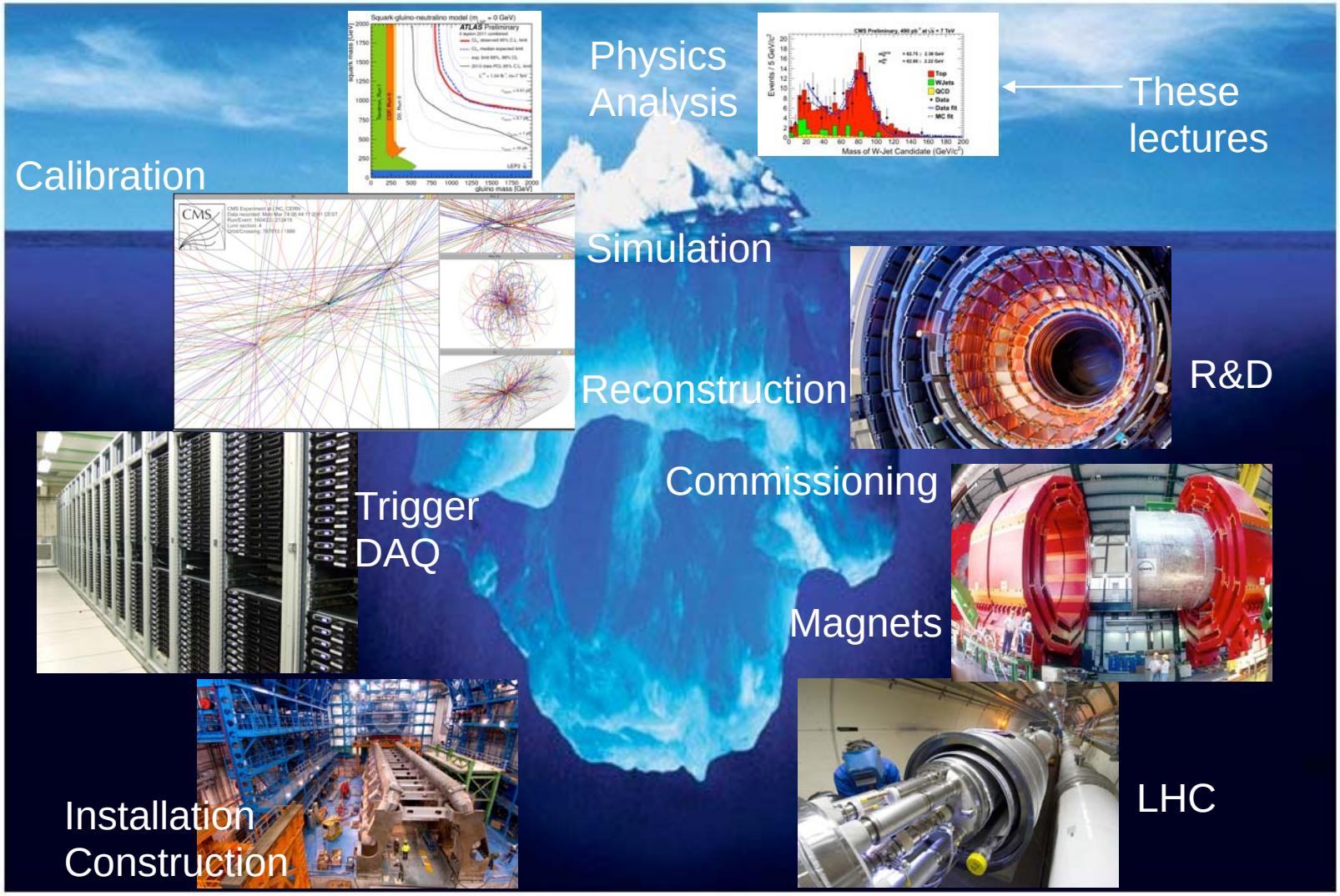
- World record on instantaneous luminosity on 22. April 2011:
  $4.67\ 10^{32}\ cm^{-2}\ s^{-1}$
  (Tevatron record: $4.02\ 10^{32}\ cm^{-2}\ s^{-1}$)
- 1 fb^{-1} line passed in June 2011
- Collect per day as much luminosity as in 2010
- Data taking efficiency is high
- Pile-up is high
  (high intensity bunches)





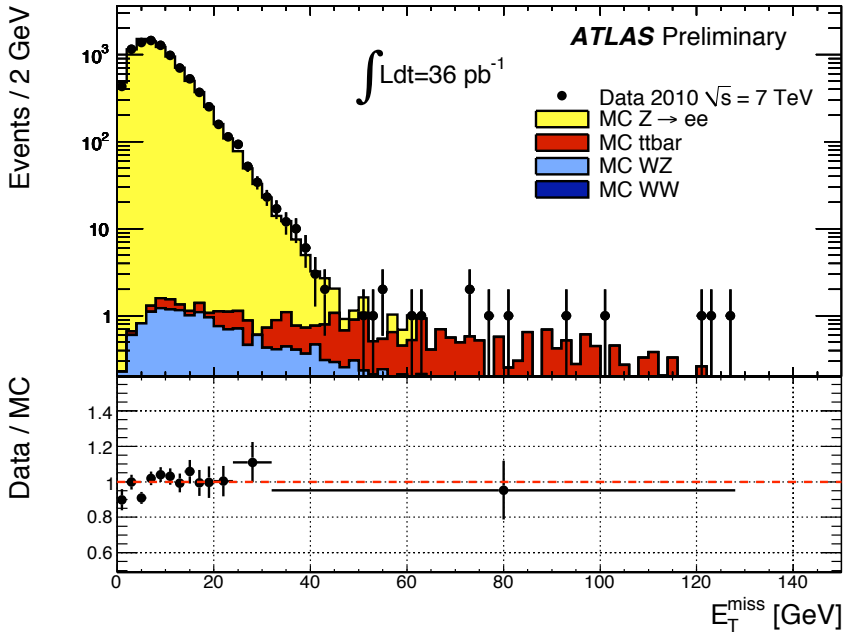


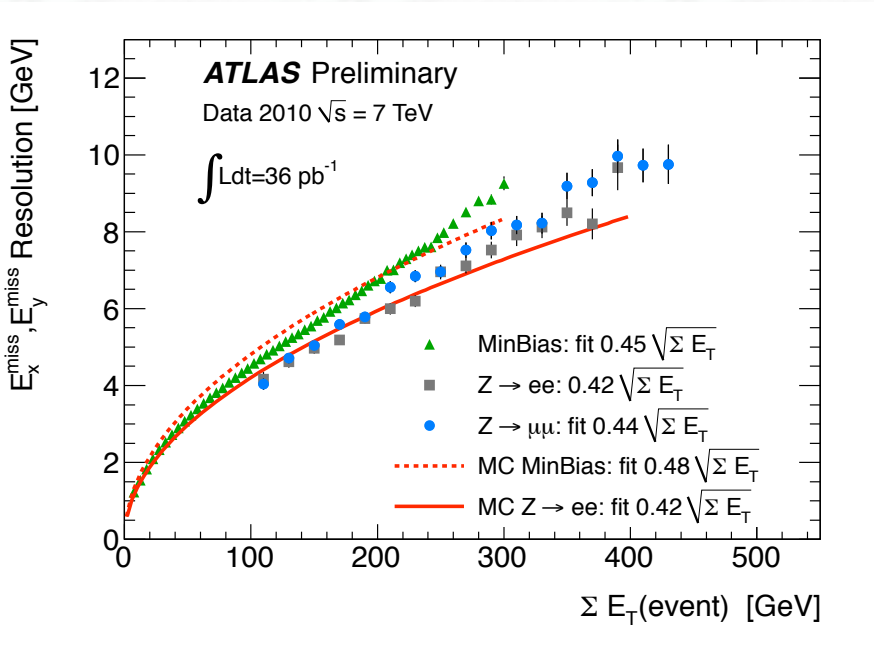
After a huge effort from many people over a long time, we arrived at physics analysis



H. Bachacou

How well can the missing transverse energy be measured ?

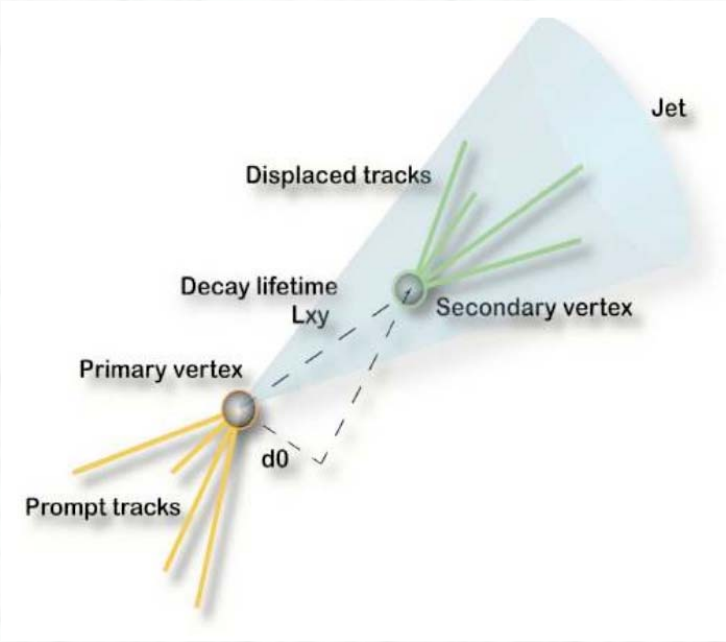




Distribution of E_T^{miss} as measured in a data sample of Z → ee events. The expectation from Monte Carlo simulation is superimposed (histogram) and normalized to data, after each Monte Carlo sample is weighted with its corresponding cross-section. The ratio of the data distribution and the Monte Carlo distribution is shown below the plot.

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.

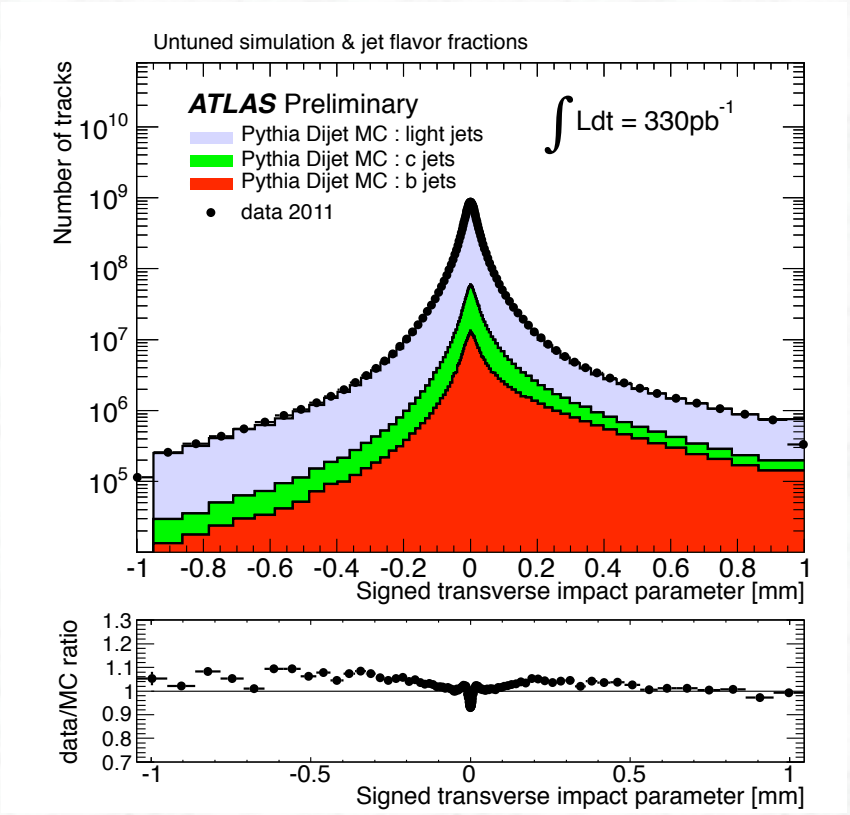
How well can b-quarks be tagged ?



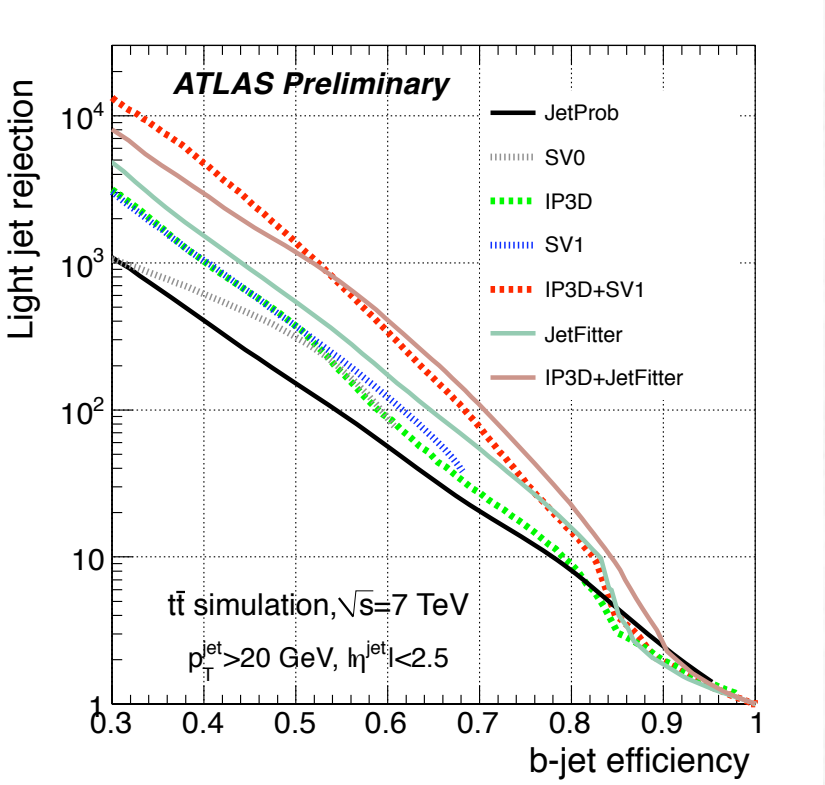
- b quarks fragment into B hadrons (mesons and baryons)
- B mesons have a lifetime of ~1.5 ps
  They fly in the detector about 2-3 mm before they decay

  → 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

ATLAS results on b-tagging performance:



Distribution of the signed transverse impact parameter with respect to primary vertex for tracks of b-tagging quality associated to jets, for experimental data (solid black points) and for simulated data (filled histograms for the various flavors). The ratio data/simulation is shown at the bottom of the plot.



Light-jet rejection as a function of the b-jet tagging efficiency for the early tagging algorithms (JetProb and SV0) and for the high performance algorithms, based on simulated top-antitop events.

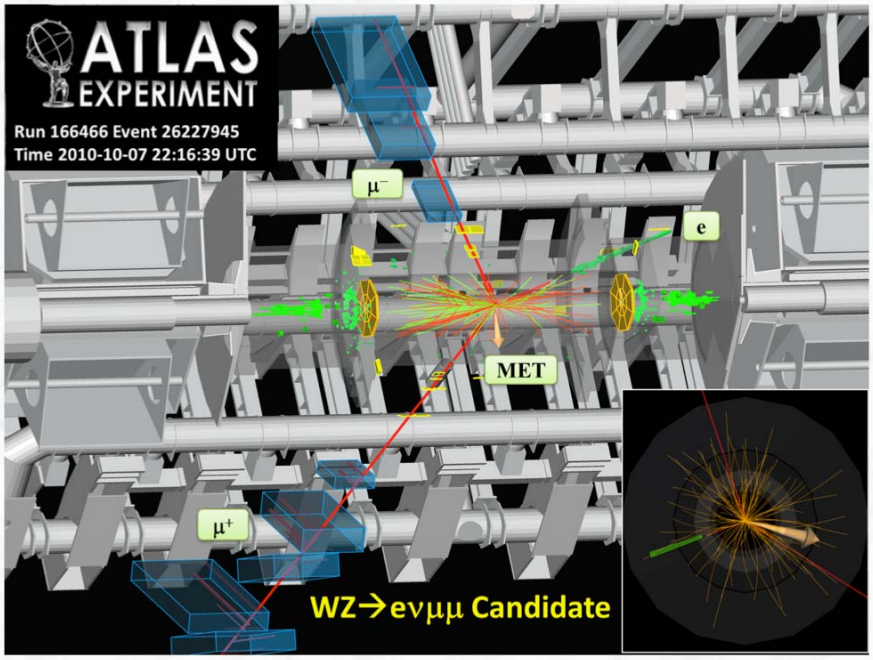
Part 2: Test of the Standard Model

1. Test of Quantum Chromodynamics

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

2. Measurement of electroweak processes and parameters

   - W and top quark masses
   - Gauge boson pair production



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} , ….

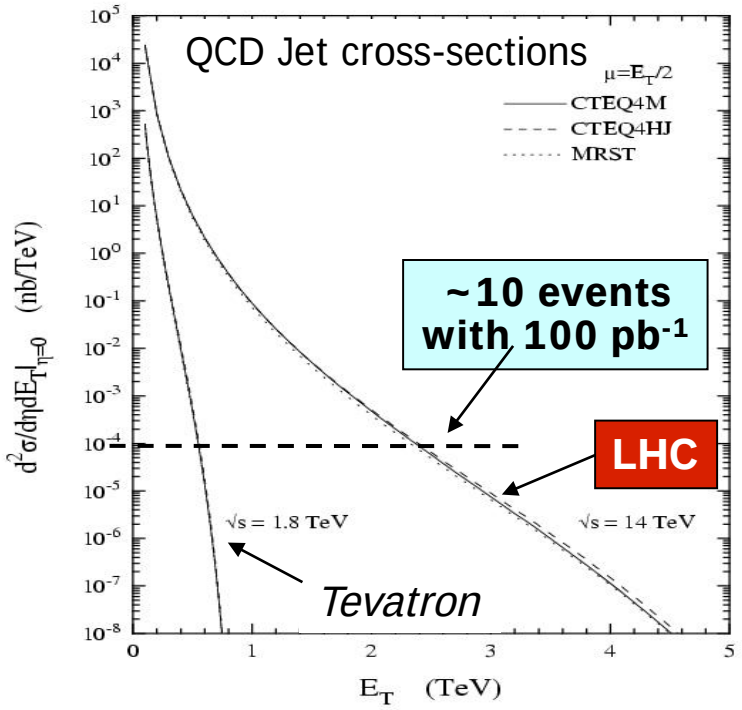
  → W/Z + jets and tt productions are omnipresent !

2.1 Jets from QCD production

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

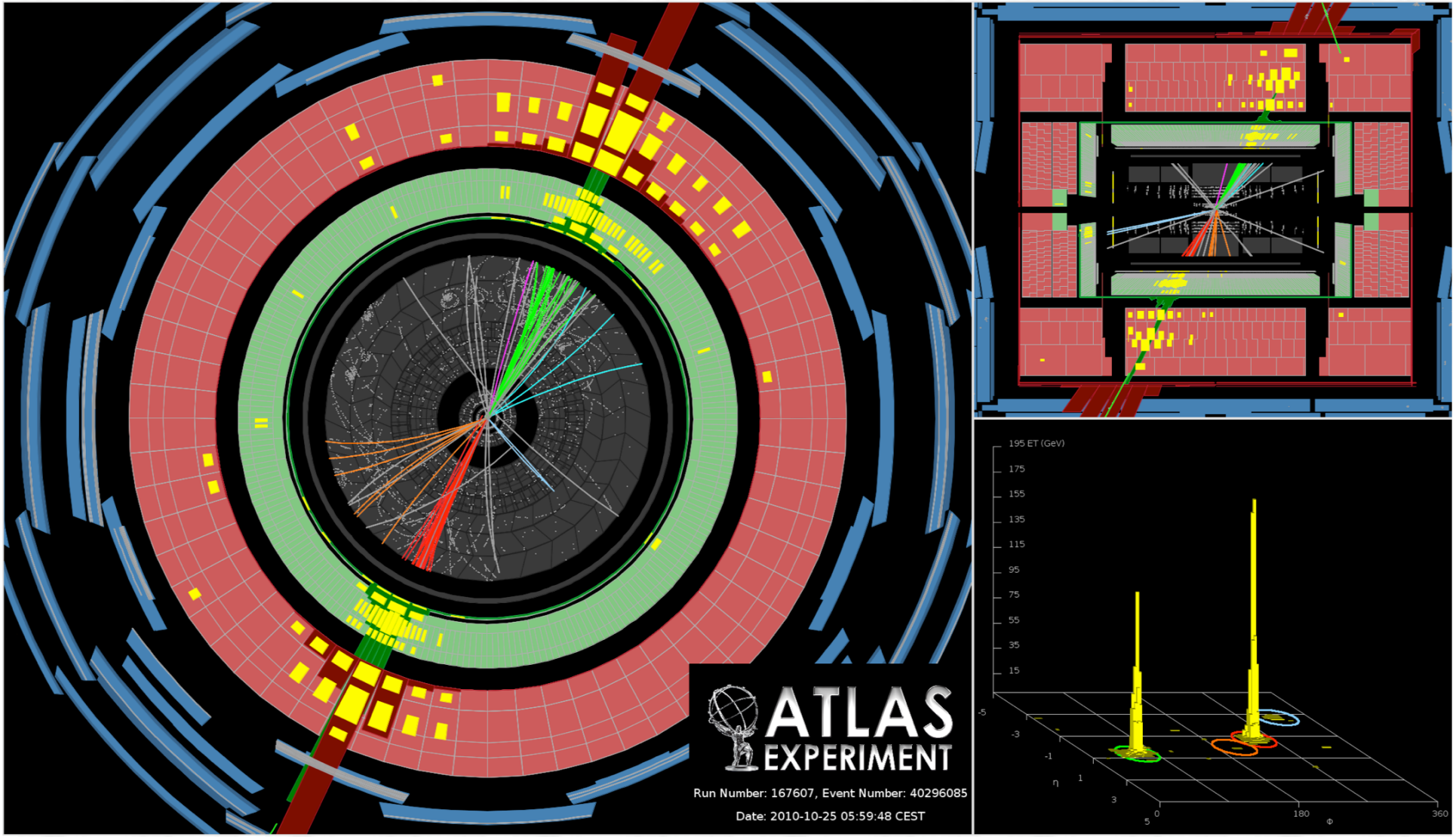
- Experimental challenge: understanding of the detector
  - main focus on jet energy scale
  - resolution

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



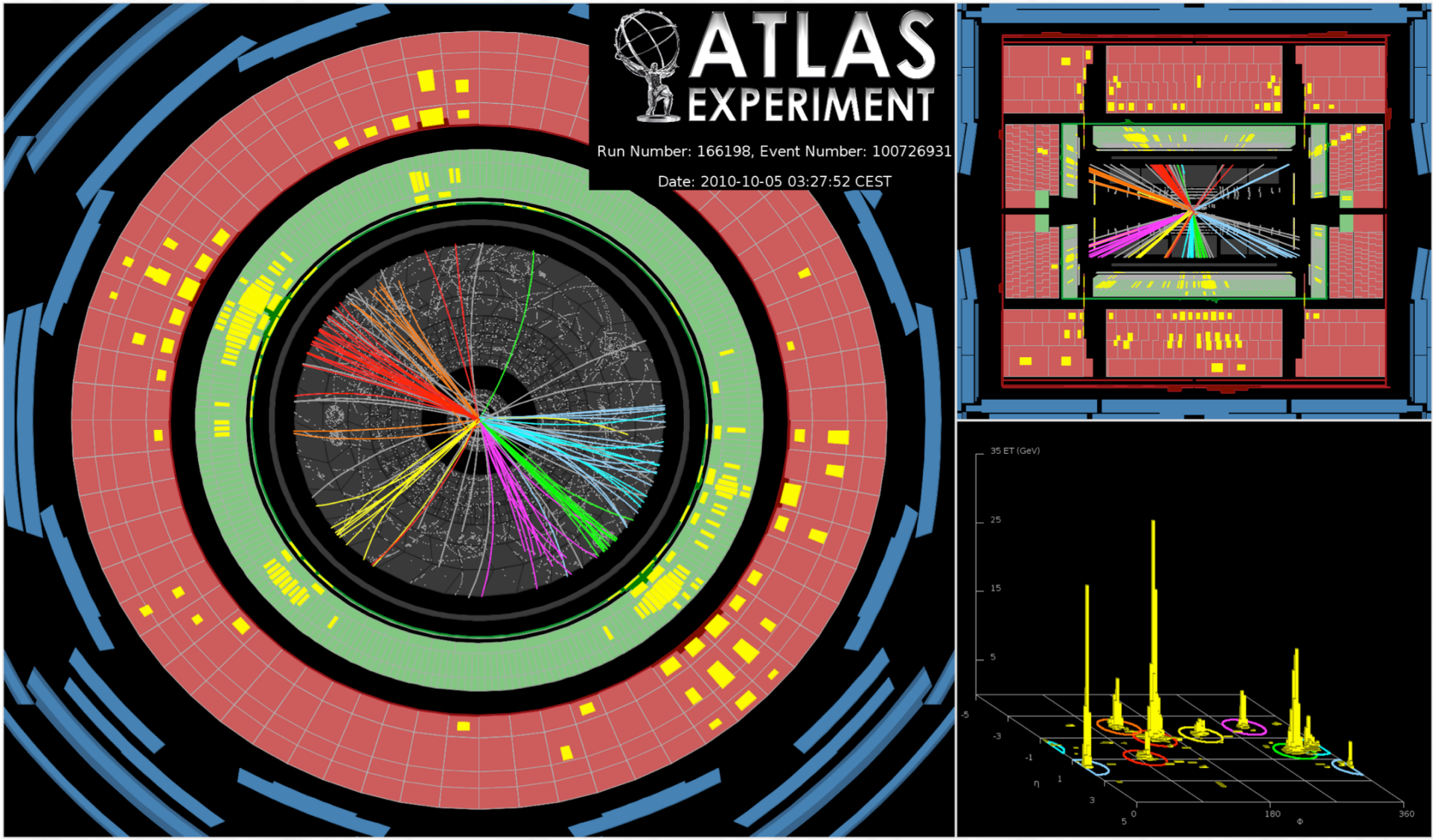
A comparison between the Tevatron and the LHC (14 TeV)

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.

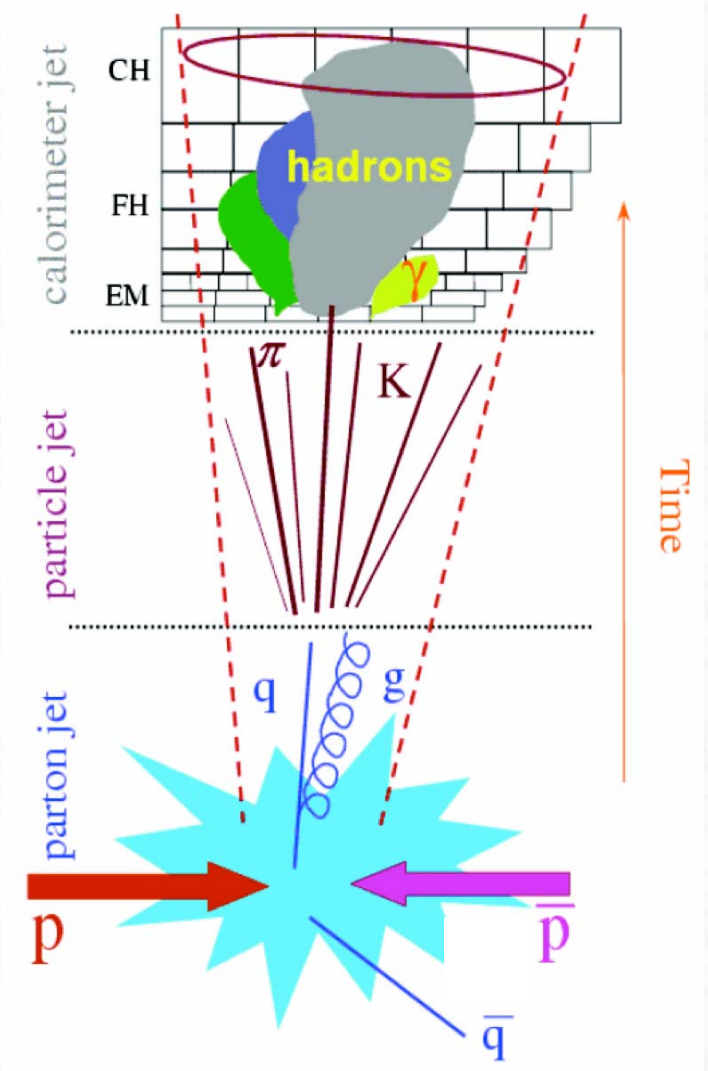
Jet reconstruction and energy measurement

- 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))

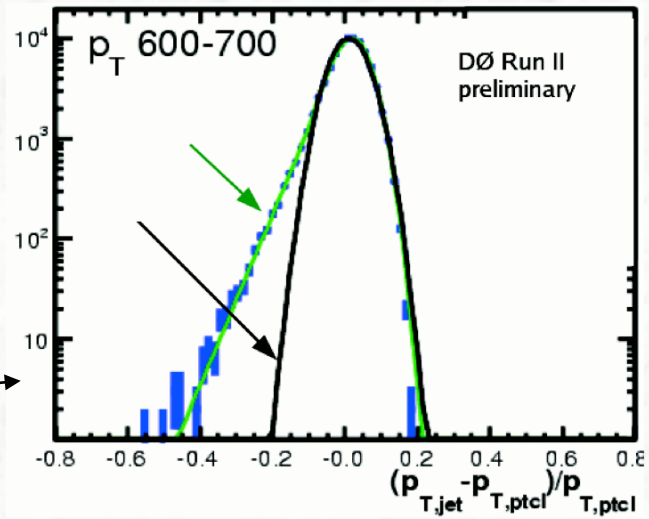
- Energy corrections for losses of fragmentation products outside jet definition and underlying event or pileup energy inside

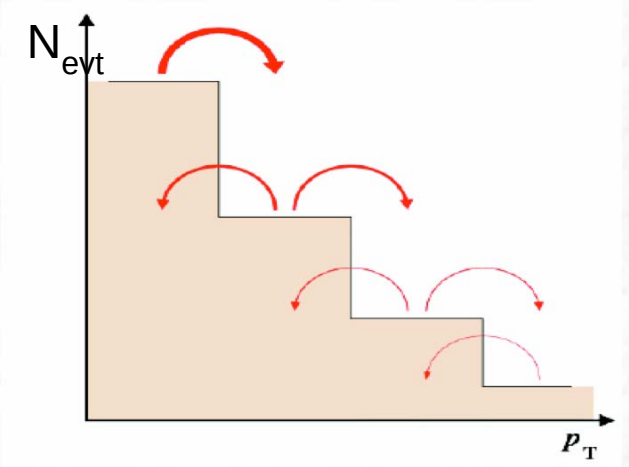


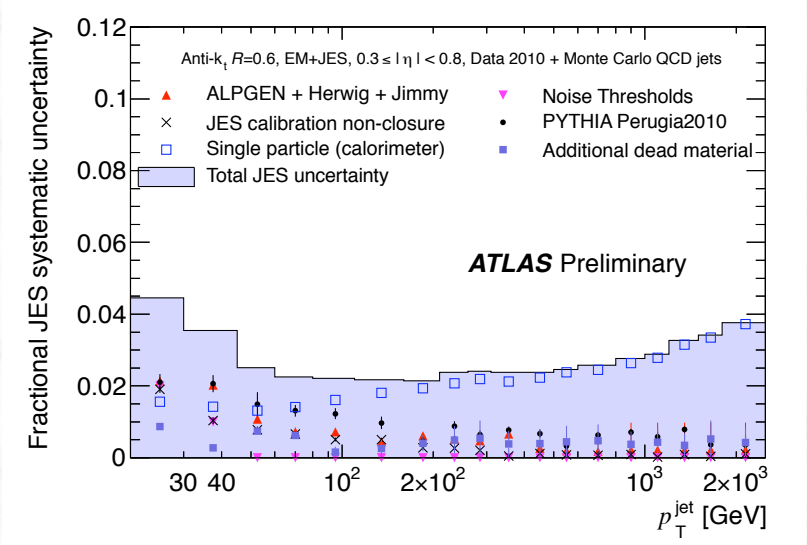
Jet measurements

$$\frac{d^2\sigma}{dp_T\, d\eta} = \frac{N}{\varepsilon \cdot L \cdot \Delta p_T \cdot \Delta\eta}$$

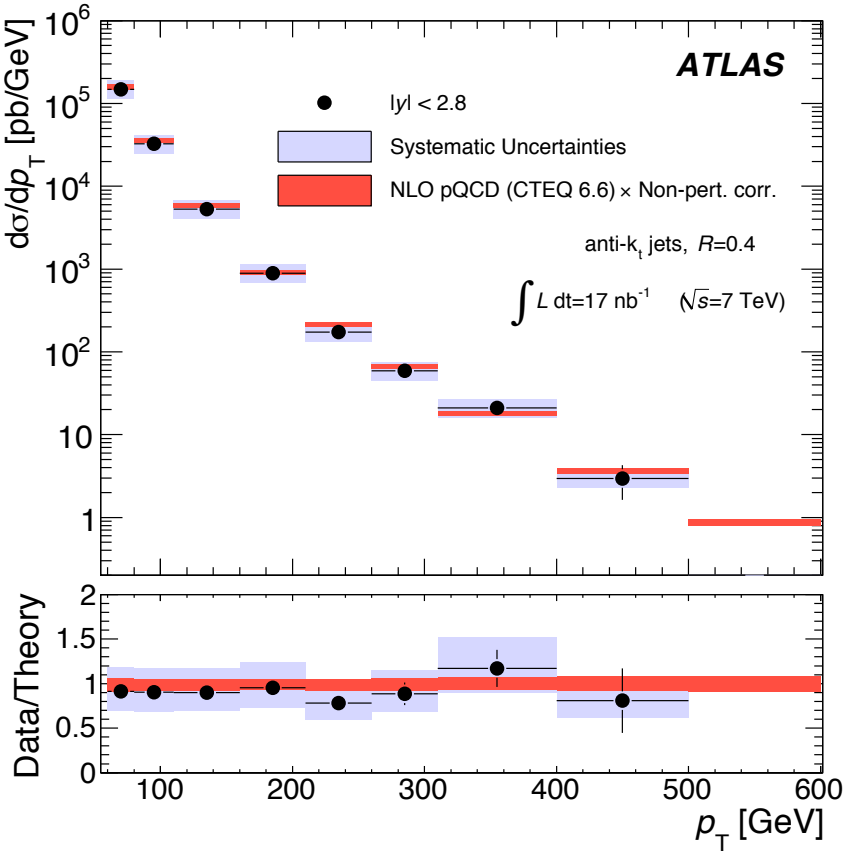
- In principle a simple counting experiment
- However, steeply falling p_T spectra are sensitive to jet energy scale uncertainties and resolution effects (migration between bins)
  → corrections (unfolding) to be applied
- Jet energy scale uncertainty:
  ATLAS: ~2.5 - 4% (after one year)
  (similar for CMS, impressive achievements)







Test of QCD Jet production



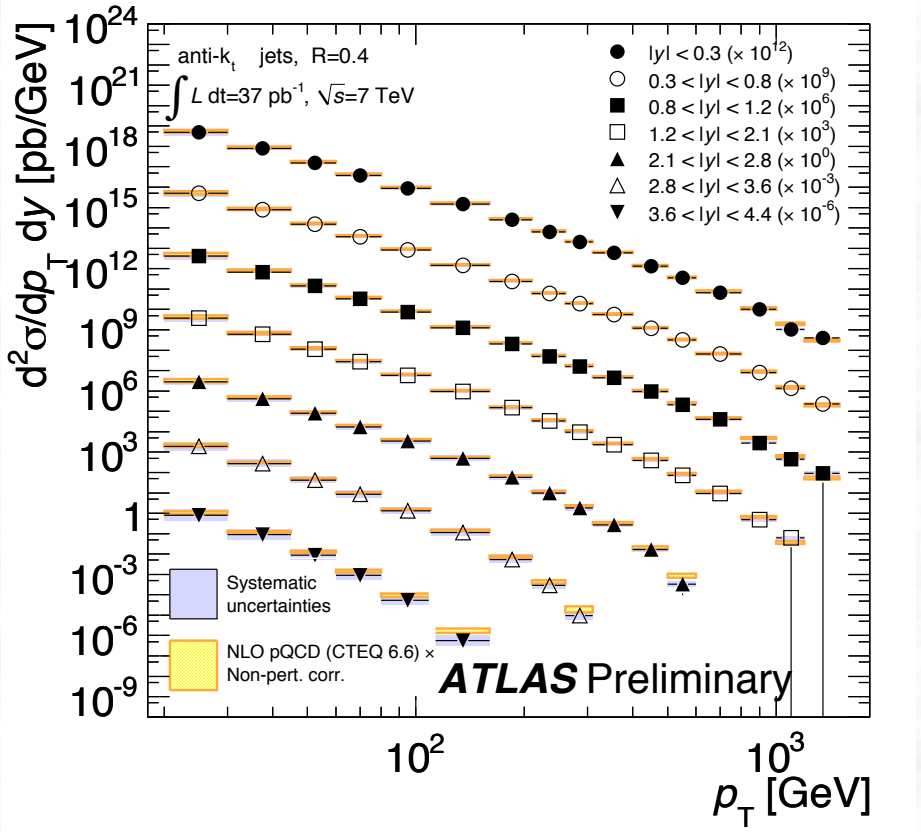
An **"early"** result from the ATLAS experiment (17 nb^{-1}, June 2010)

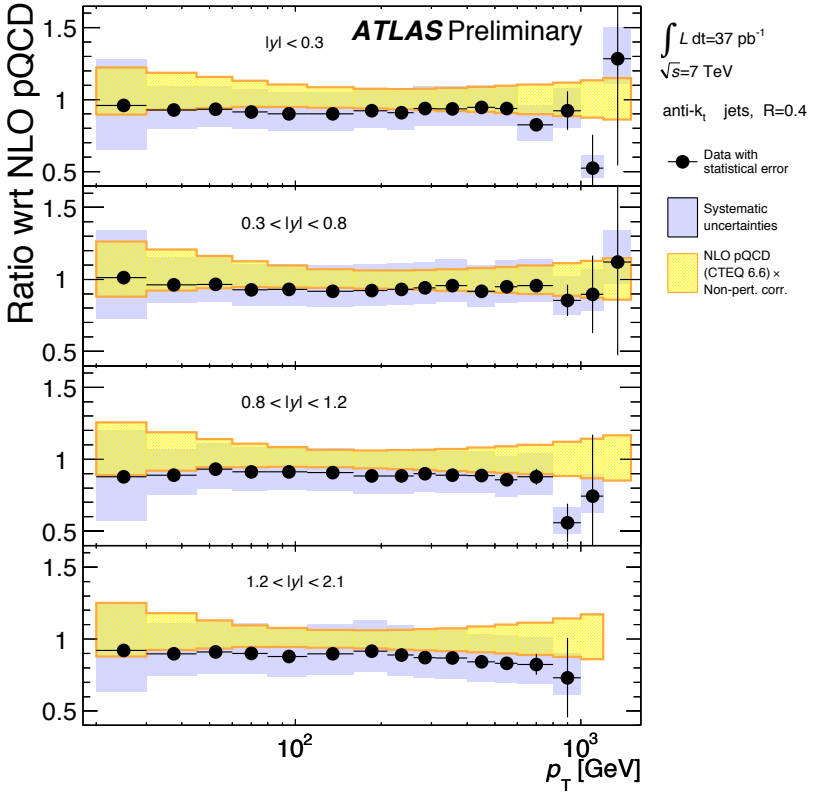
Inclusive Jet spectrum as a function of Jet-P_T

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

Within the large theoretical and experimental uncertainties

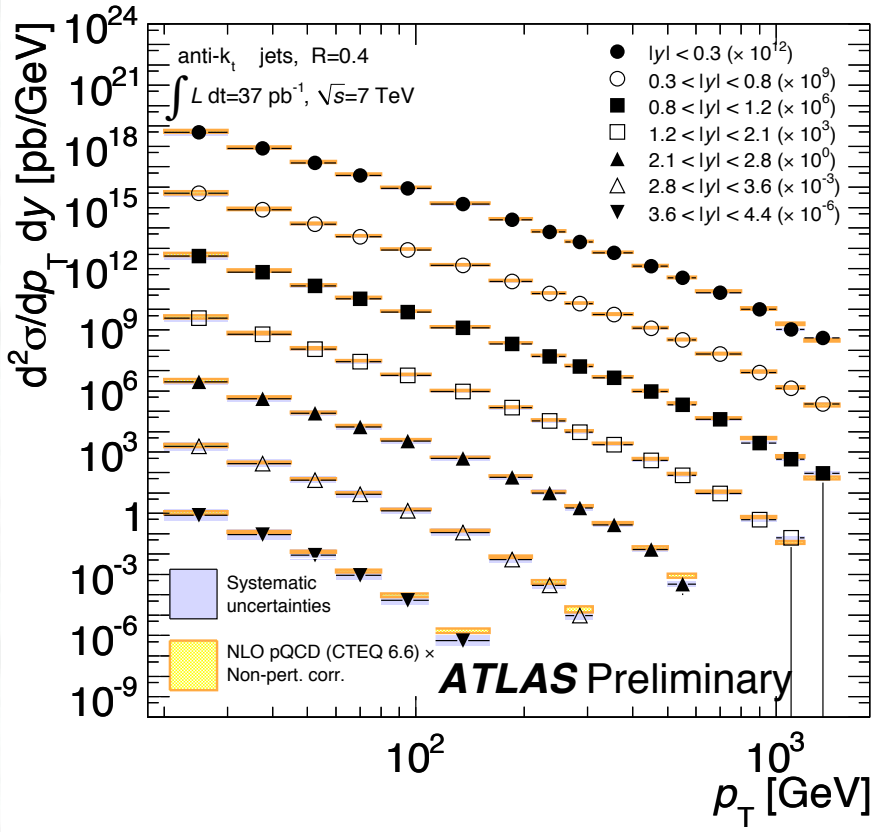
Double differential cross sections, as function of p_T and rapidity y: (full 2010 data set)

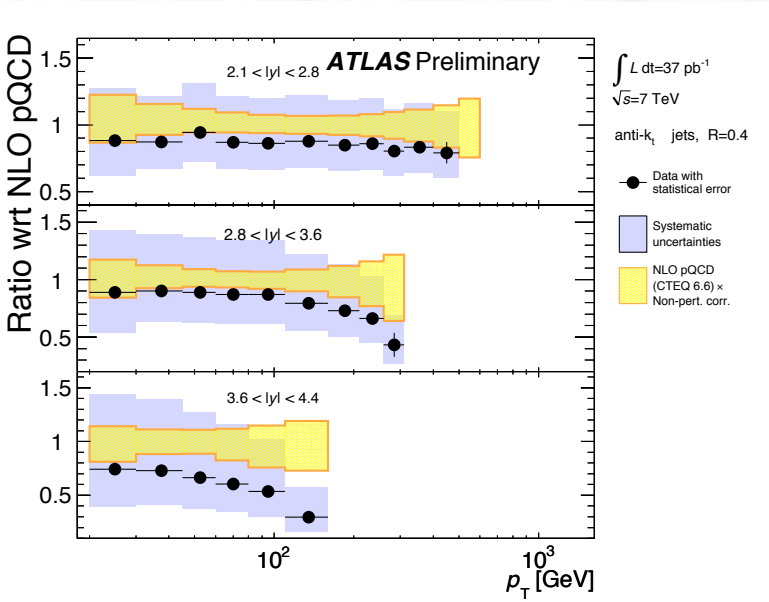




- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: renormalization/ factorization scale, pdfs, α_S, …, uncertainties from non-perturbative effects

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





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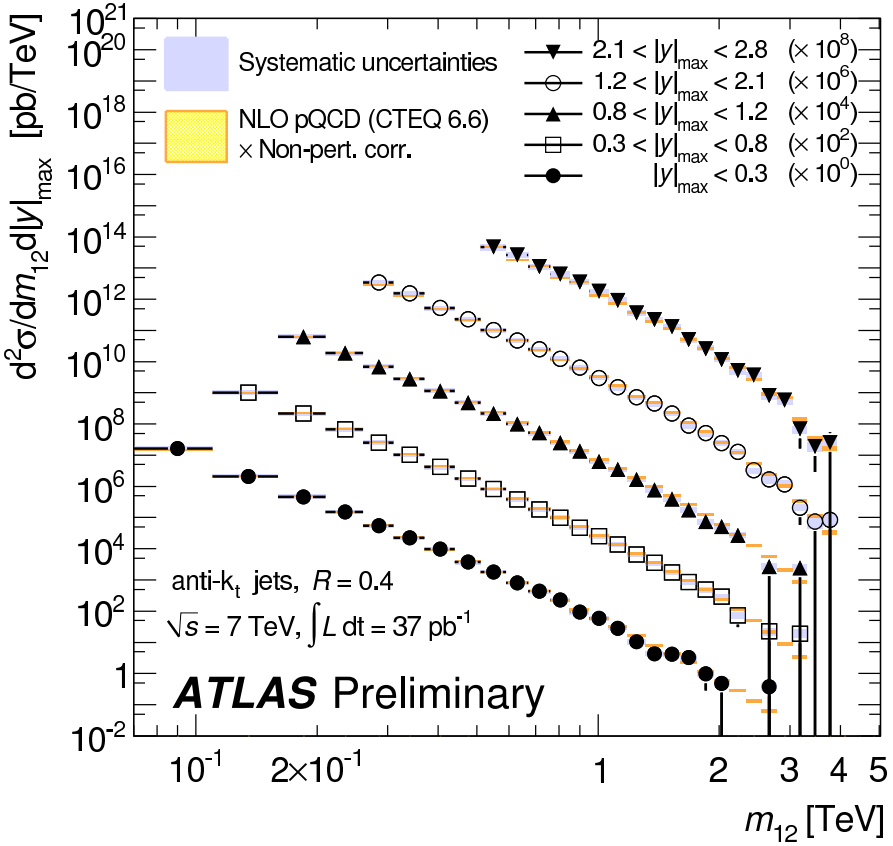
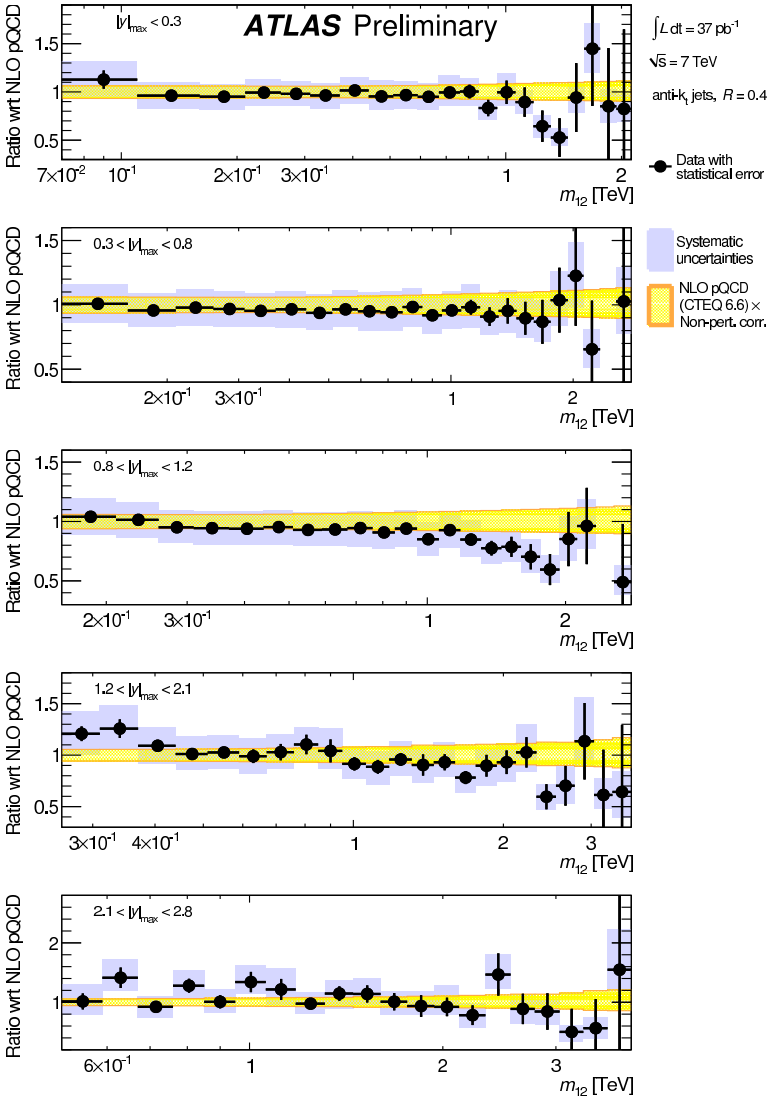
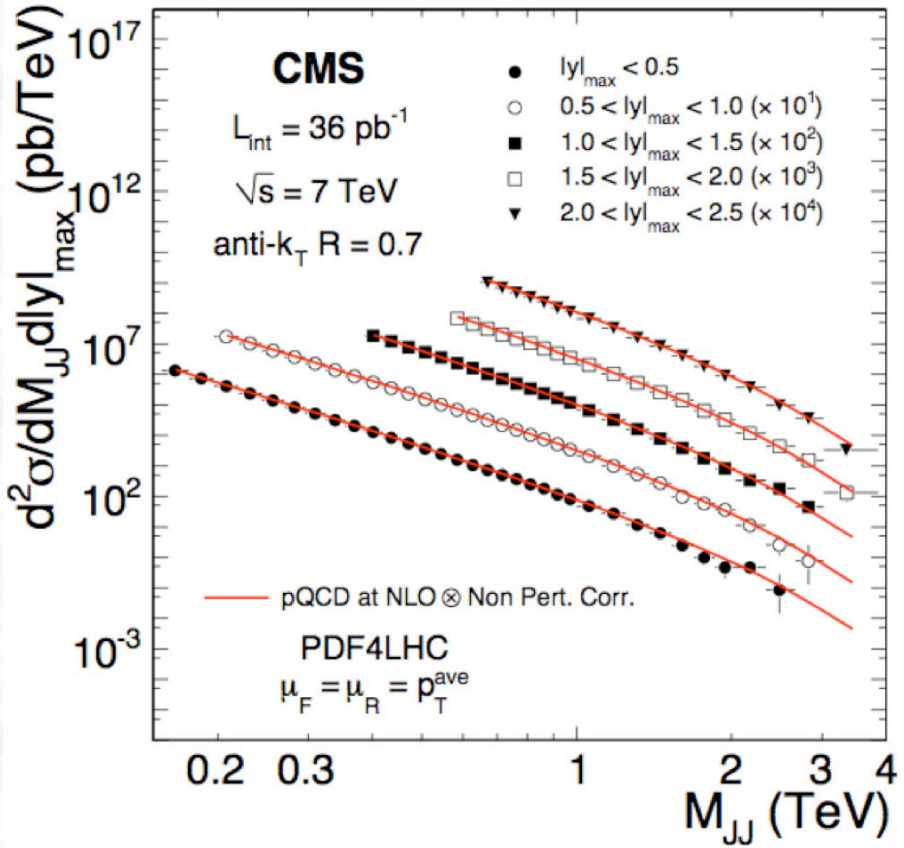
Invariant di-jet mass spectra, ratio data/theory:

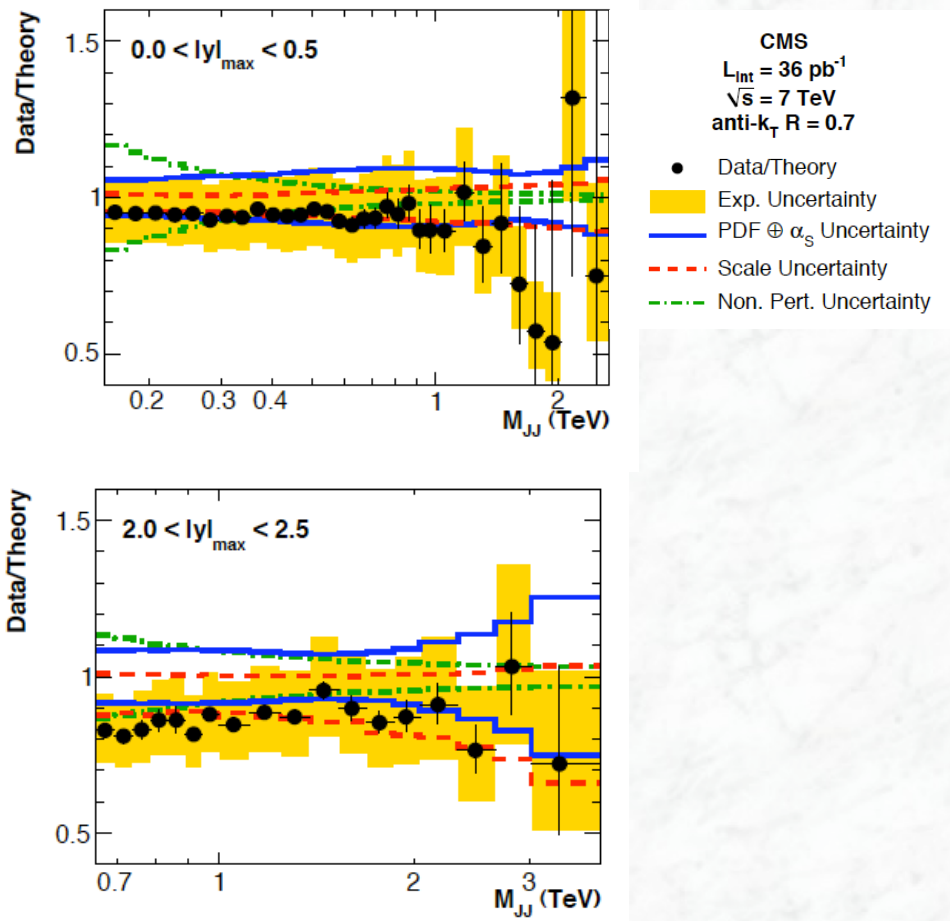




Important for: - Test of QCD
- Search for new resonances decaying into two jets (see later)

Invariant di-jet mass spectra, ratio data/theory:





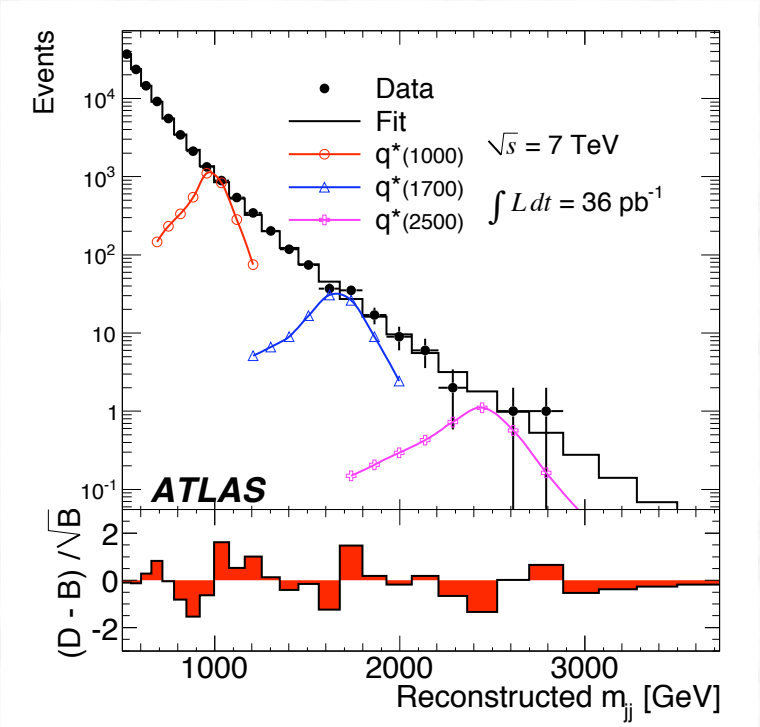
Important for: - Test of QCD
- Search for new resonances decaying into two jets (→ next slide)

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

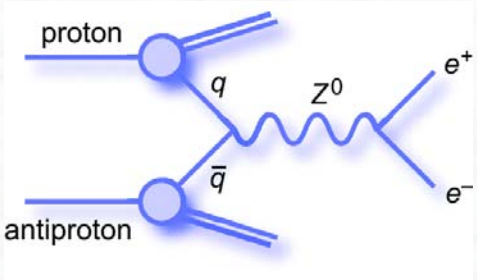


CDF (Tevatron), L =1.13 fb^{-1}: 0.26 < m_{q^*} < 0.87 TeV

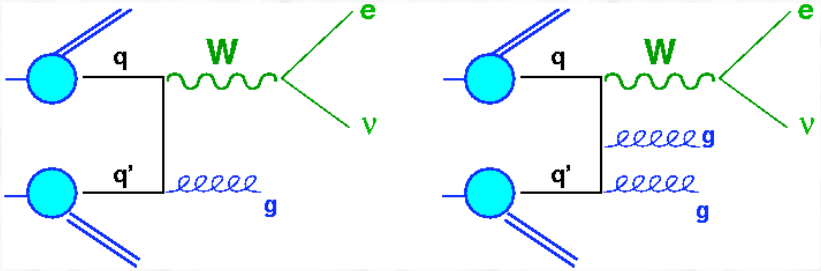
ATLAS (LHC), L = 0.000315 fb^{-1} exclude (95% C.L) q* mass interval
0.30 < m_{q^*} < 1.26 TeV

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

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



QCD at work

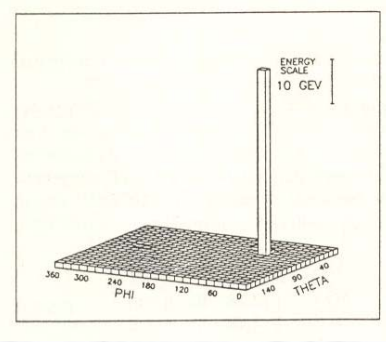


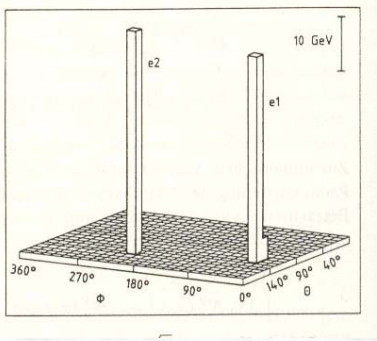
- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region (jet multiplicities, p_T spectra,….)
- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC

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})
$Z \rightarrow \ell\,\ell$

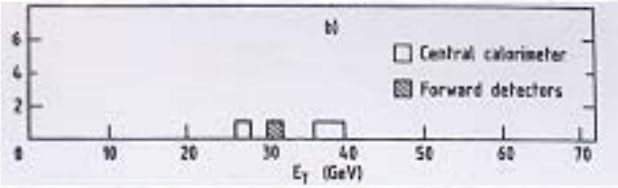




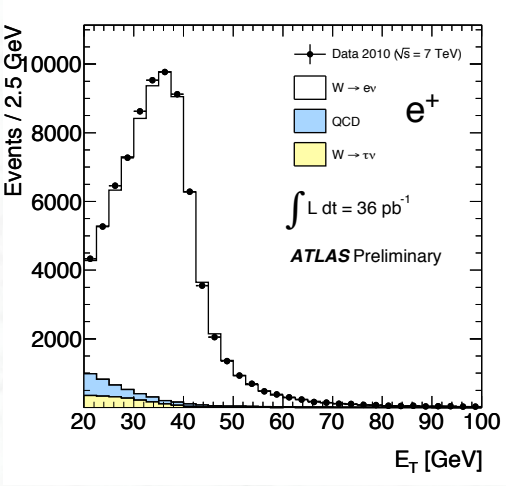
A bit of history: one of the first W events seen; UA2 experiment

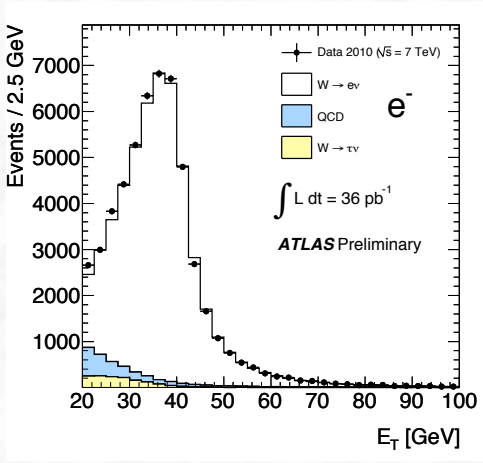
W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)

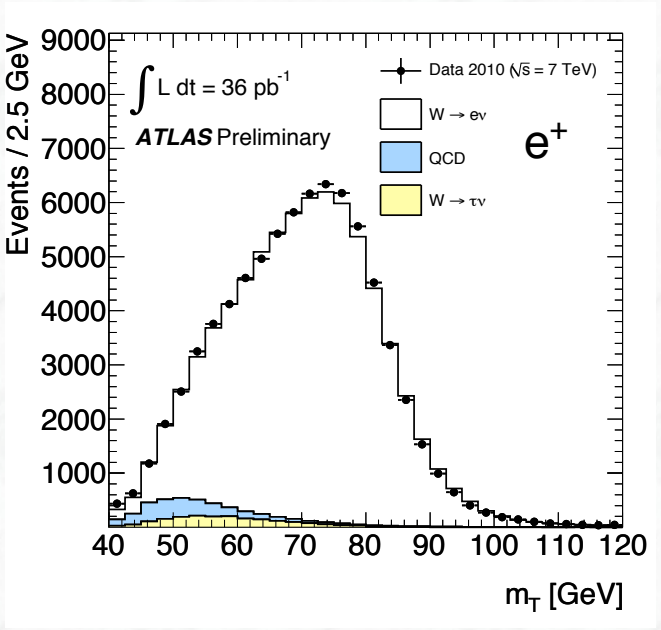
Transverse momentum of the electrons



W/Z selections in the ATLAS / CMS experiments







Electrons:

- Trigger: high pT 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/c^2 < m_{ee} < 106 GeV/c^2

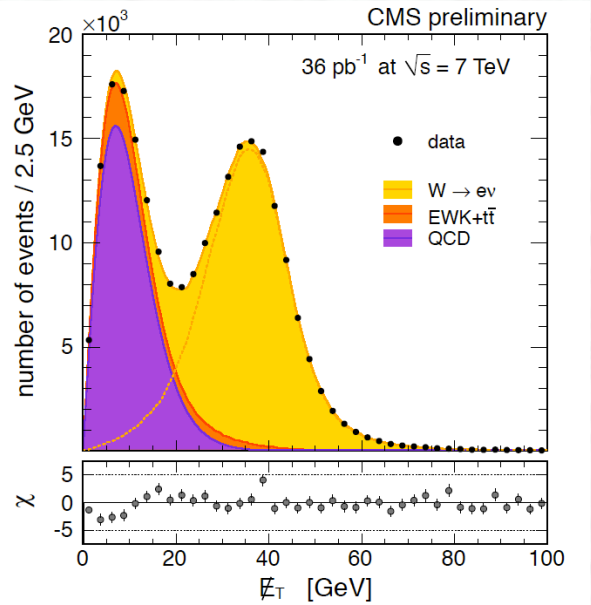
$W \rightarrow e\nu$

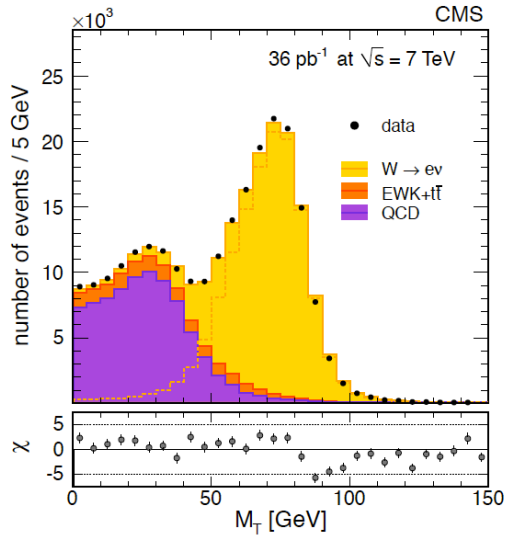
- Missing transverse momentum > 25 GeV/c
- Transverse mass cut M_T > 50 GeV

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

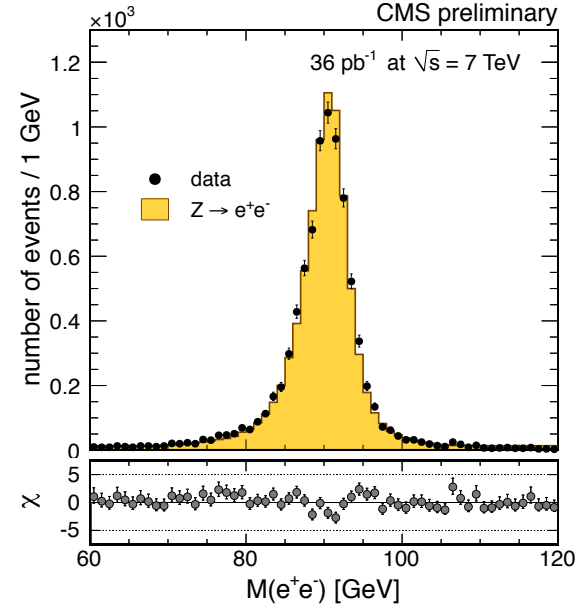
Transverse mass (longitudinal component of the neutrino cannot be measured)

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





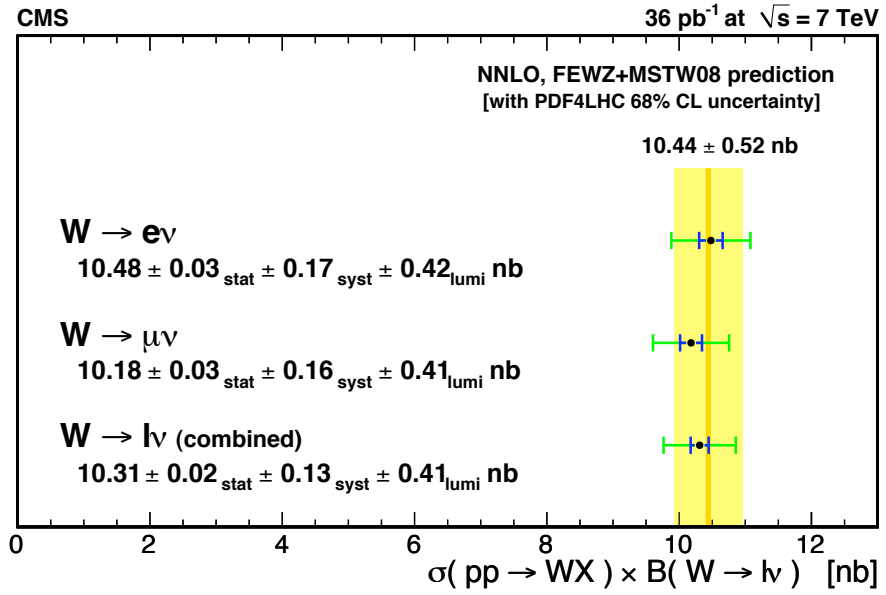
Distributions of the missing transverse energy, E_T^{miss}, (left) and transverse mass mT (right) of electron candidates for data and Monte Carlo simulation, broken down into the signal and various background components.

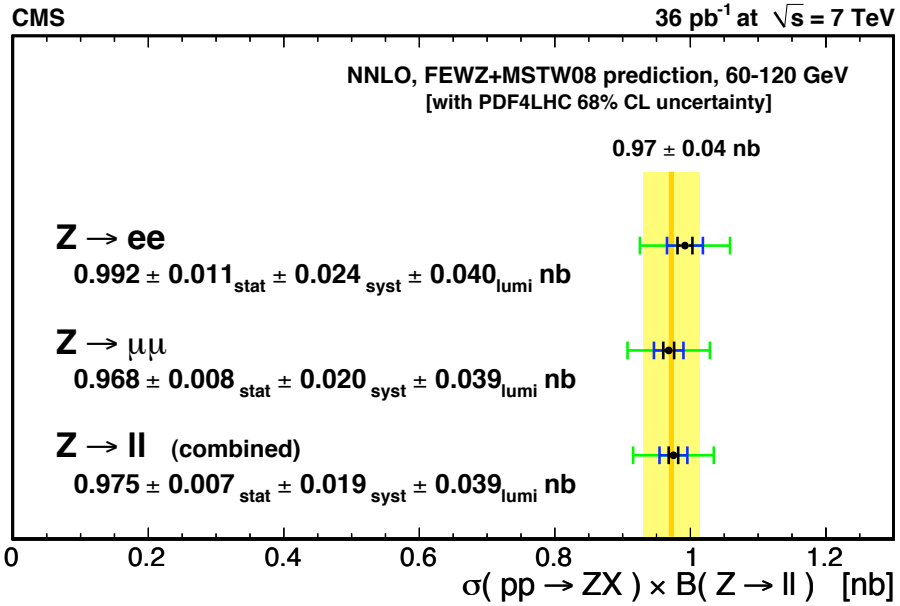


Distributions of the invariant di-electron mass, m_{ee}, for events passing the Z selection. The data are compared to Monte-Carlo simulation, the background is very small.

W and Z production cross sections at LHC

Measured cross section values in comparison to NNLO QCD predictions:





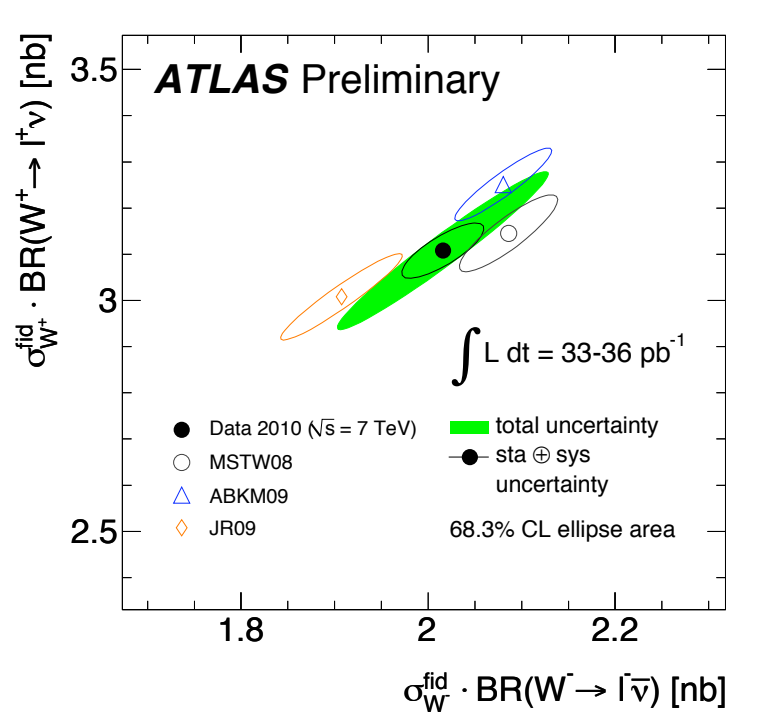
Data are well described by NNLO QCD calculations

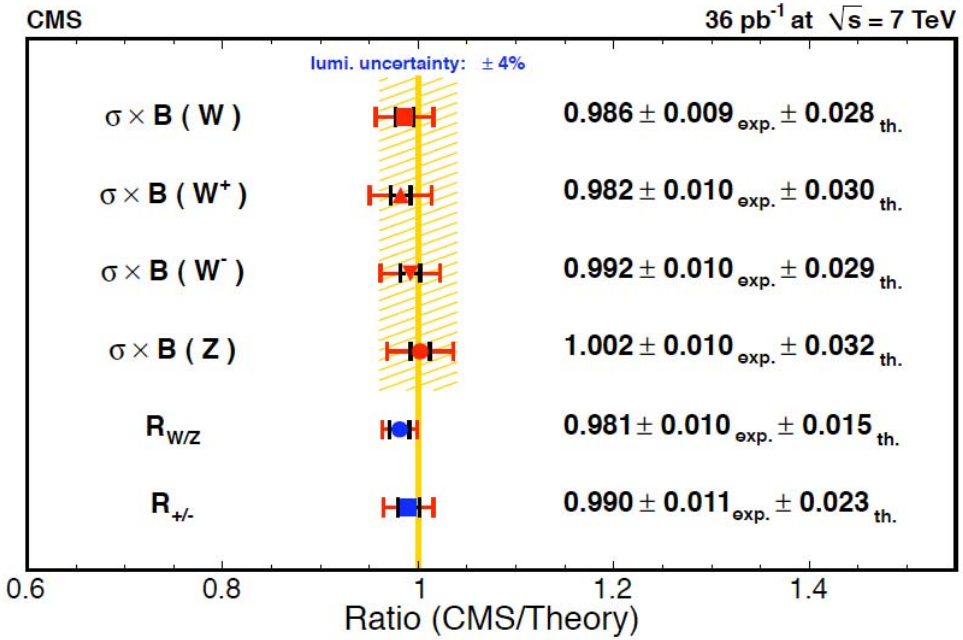
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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.]

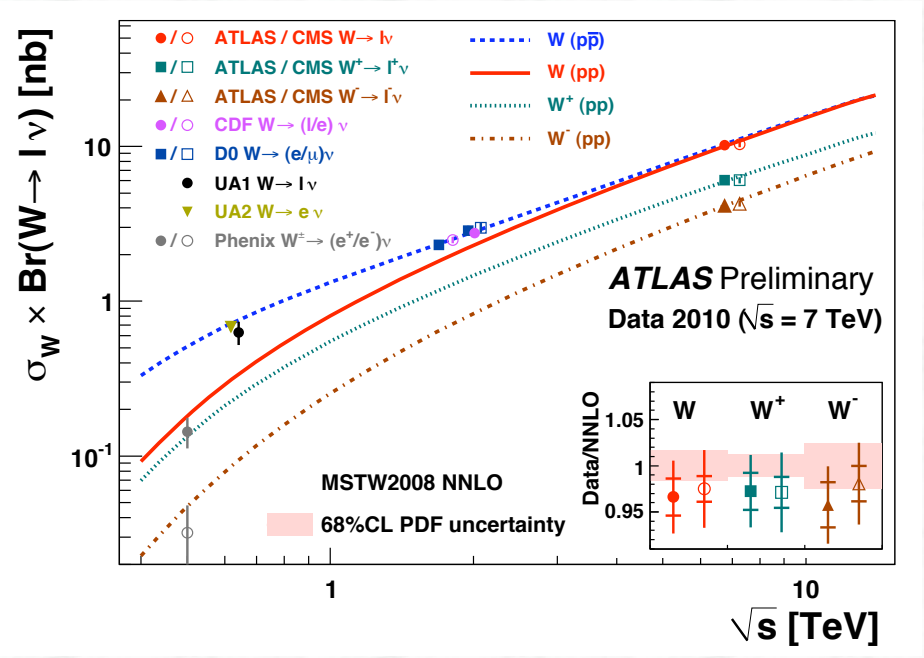
W cross sections at the LHC
-charge separated, e/μ universality

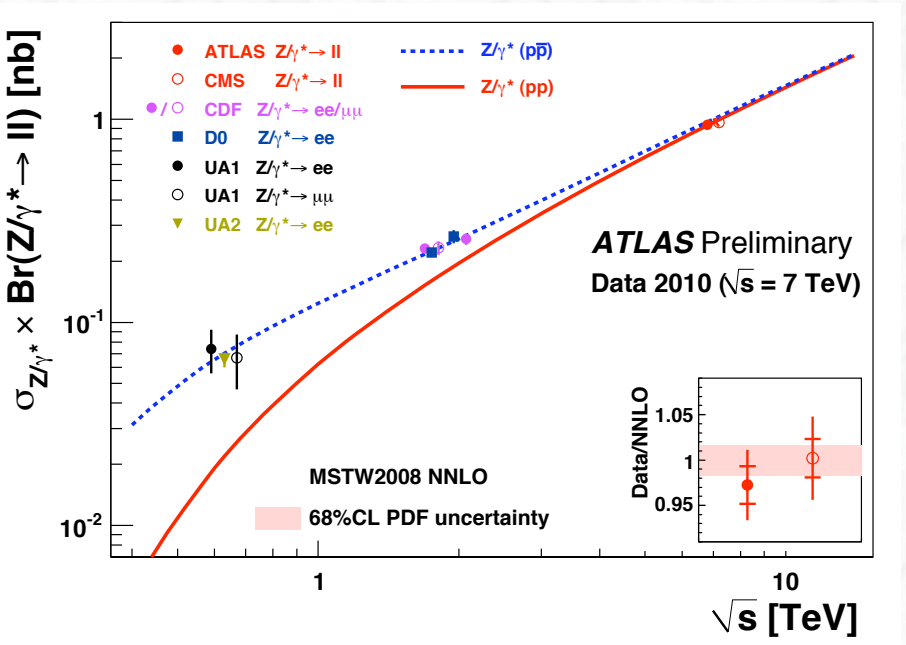




Good agreement between data and NNLO QCD predictions for all measurements

W and Z production cross sections at hadron colliders



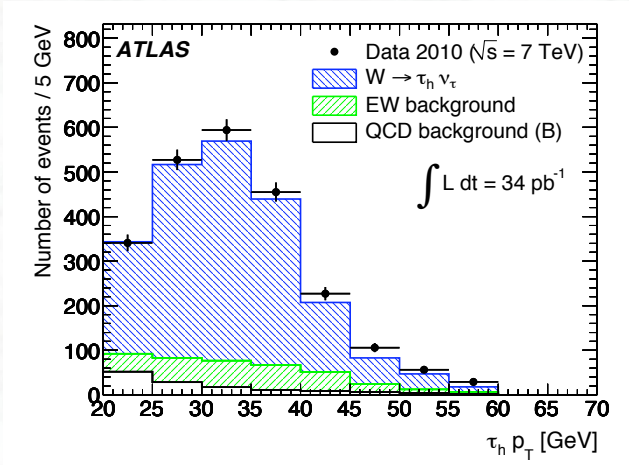


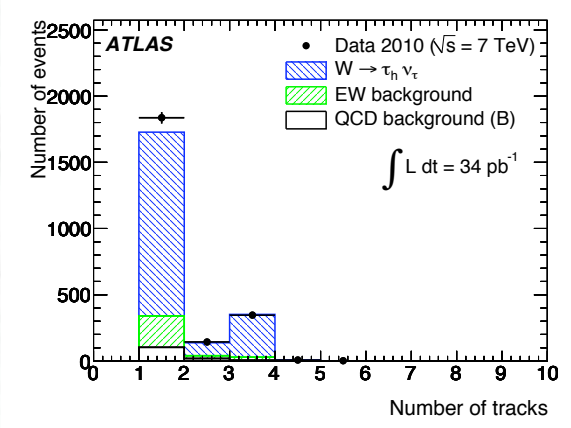
- Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)

- Good agreement as well between the ATLAS and CMS experiments

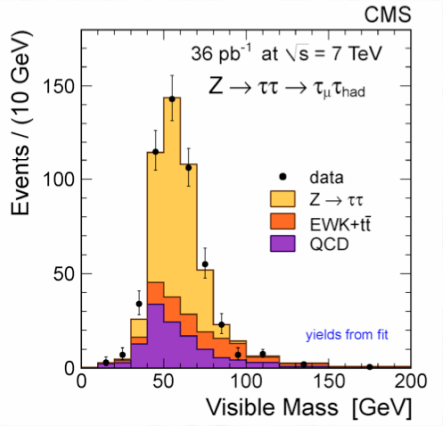
First physics signals with hadronic tau final states

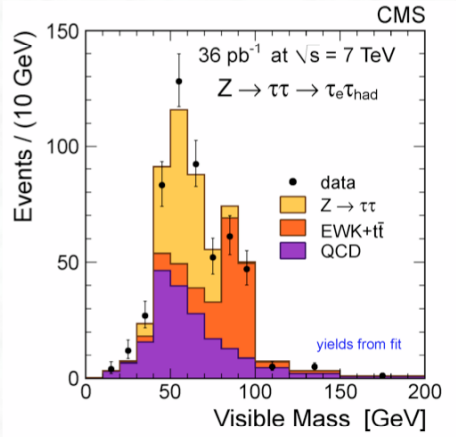
- Taus are more difficult to detect
- They decay with a short lifetime (0.3 ps) into 1 or 3 charged hadrons (65%) and a neutrino
- Taus have to be separated from hadronic jets





W → τ ν



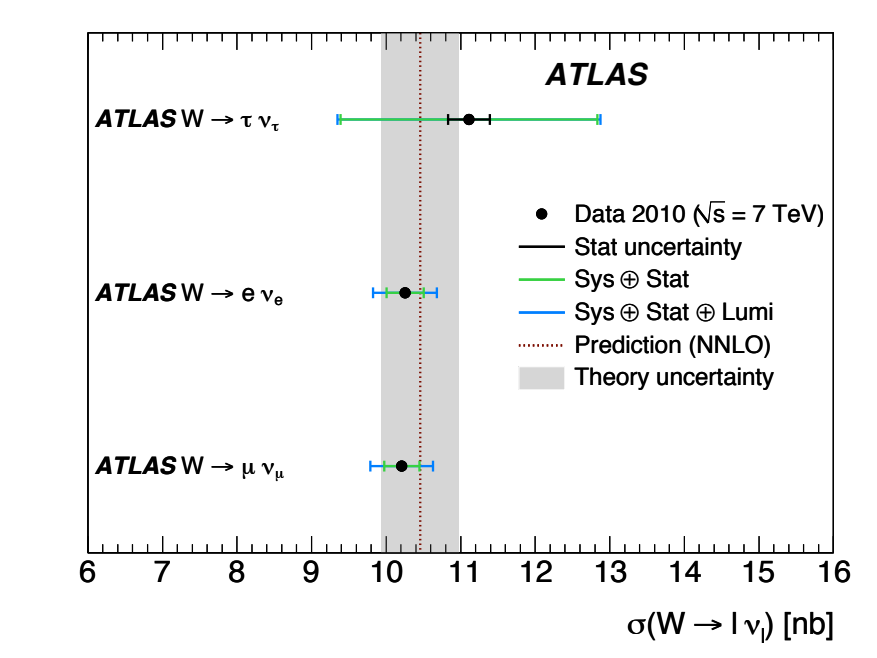


Z → τ τ

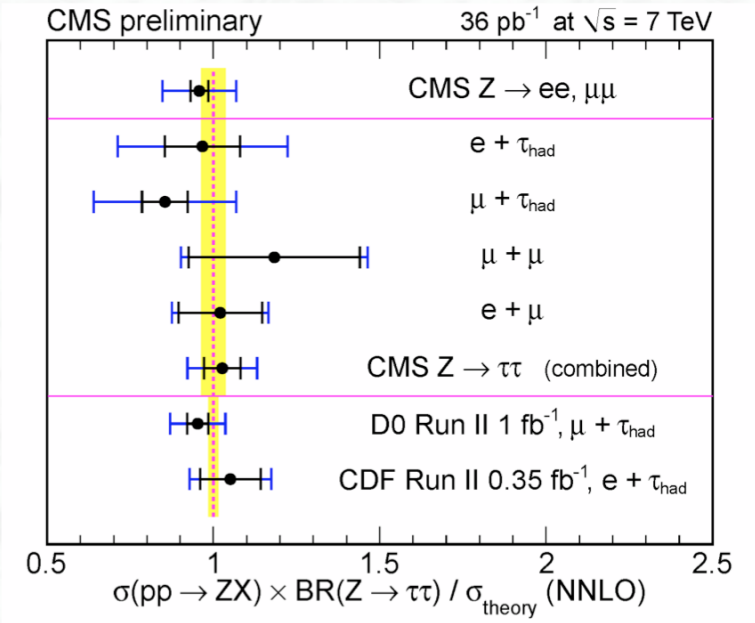
- First tau signals established in both ATLAS and CMS
- Important reference signals for searches with taus in Higgs and SUSY areas

First physics signals with hadronic tau final states

$W \rightarrow \tau \nu$



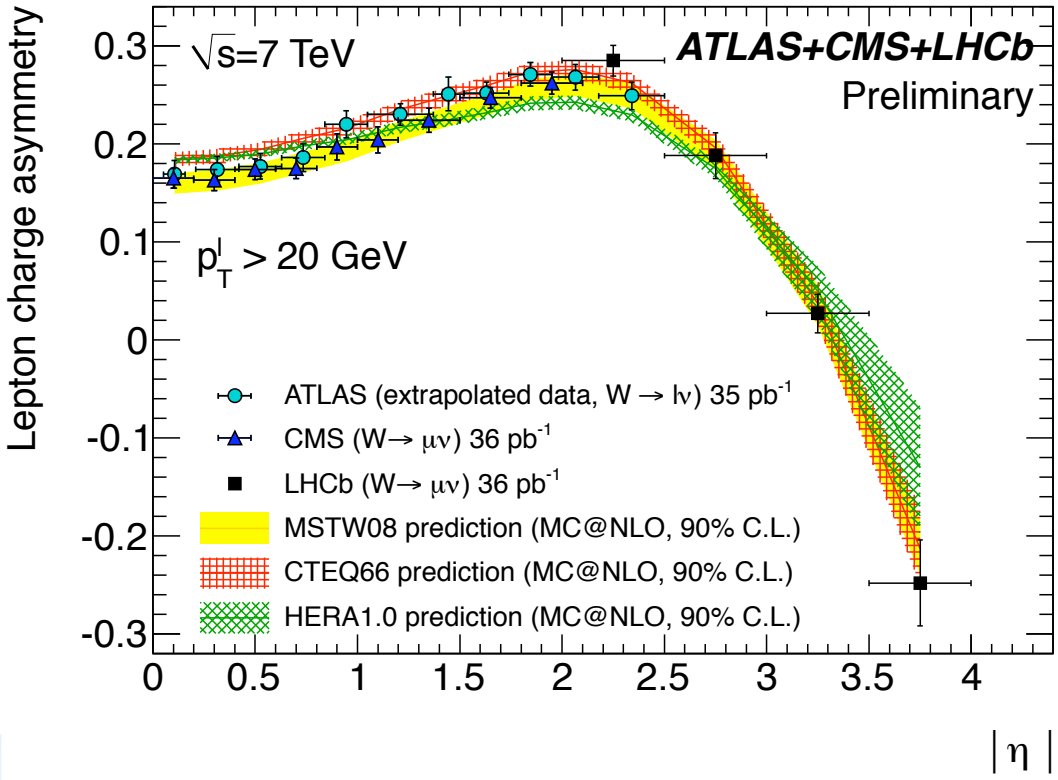
$Z \rightarrow \tau \tau$



- Good agreement between the measured cross sections in the three lepton flavours
- Experimental uncertainites ($Z \rightarrow tt$) already comparable to Tevatron measurements

Can the parton distribution functions be constrained?

- Sensitive measurement: charge asymmetry as function of rapidity
- LHCb contributes significantly, since W production can be measured at forward rapidities



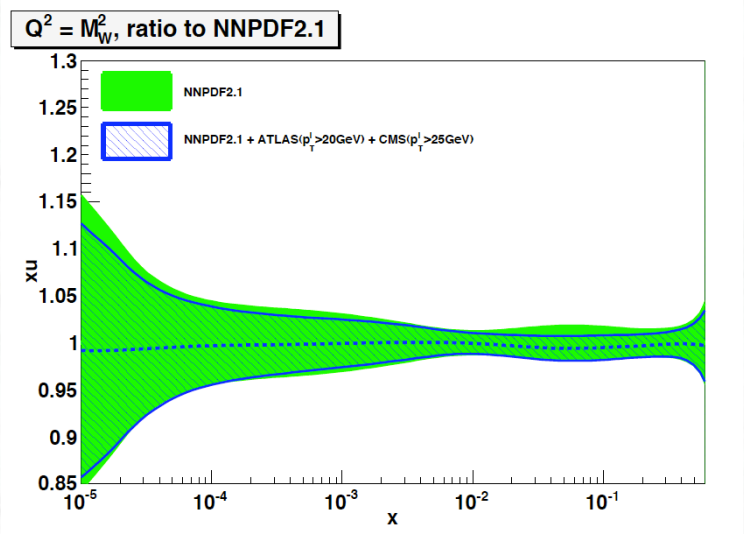
All data are unfolded,

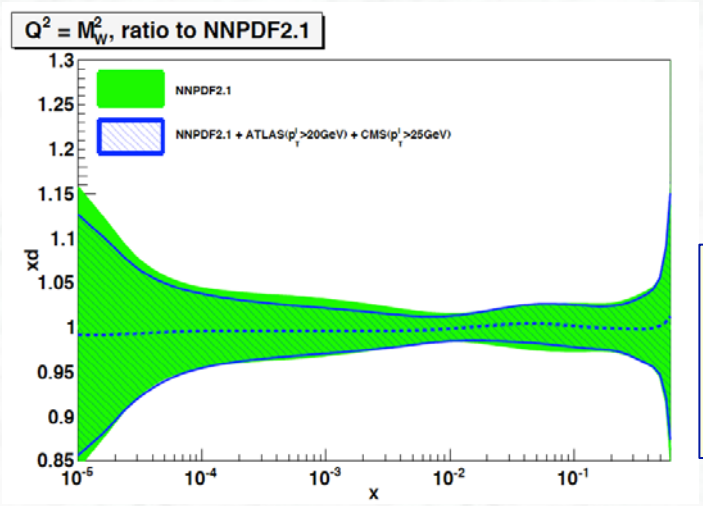
$P_T(l) > 20$ GeV

Can be used in pdf fits

Can the parton distribution functions be constrained?

- First studies of the impact of the ATLAS and CMS data have been performed, e.g. NNPDF collaboration, arXiv:1108.1758





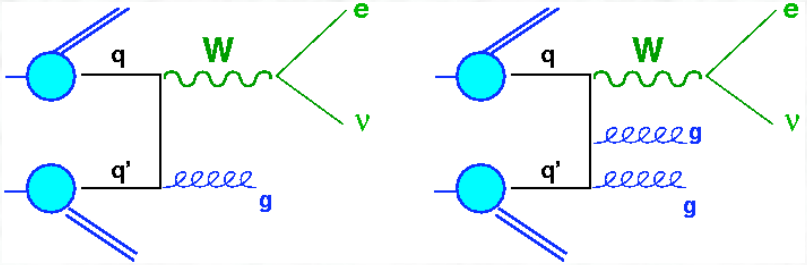
bands of relative uncertainties

of u and d quark distributions

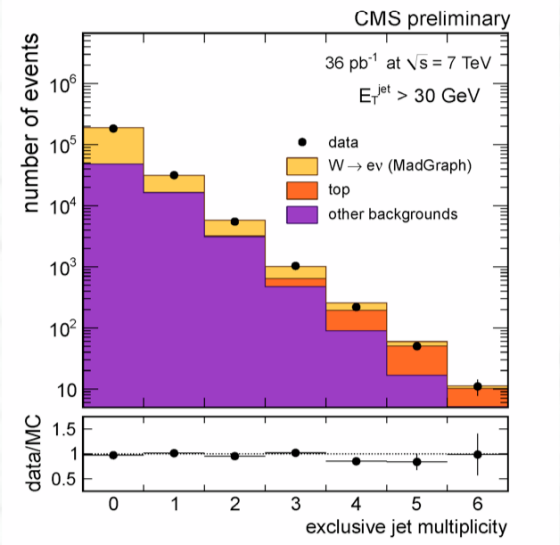
- Reduction of the relative uncertainty of the u- and d- valence quark distribution at low x values by ~10-20%

- LHCb data probe smaller and larger values of x, that are less constraint

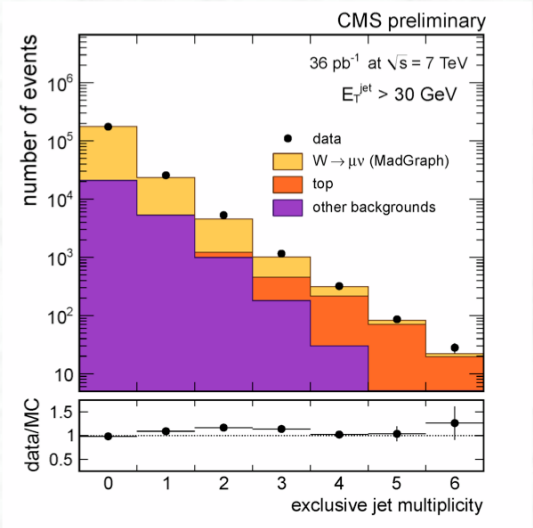
QCD Test in W/Z + jet production



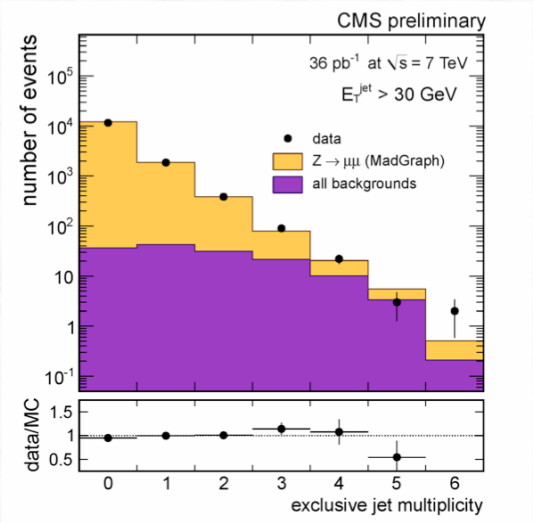
- CMS inclusive spectra of jets associated to W/Z production (36 pb^{-1});
- At detector level, compared to Monte Carlo Simulation (Madgraph + PYTHIA) (normalized to (N)NLO calculations)



W → eν



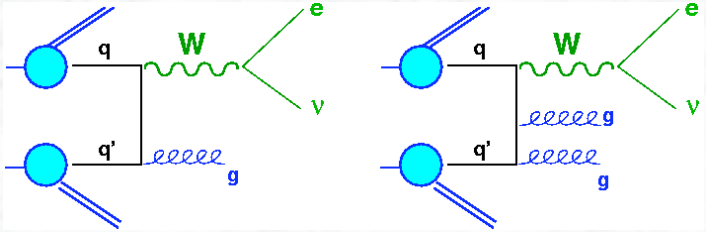
W → μν



Z → μμ

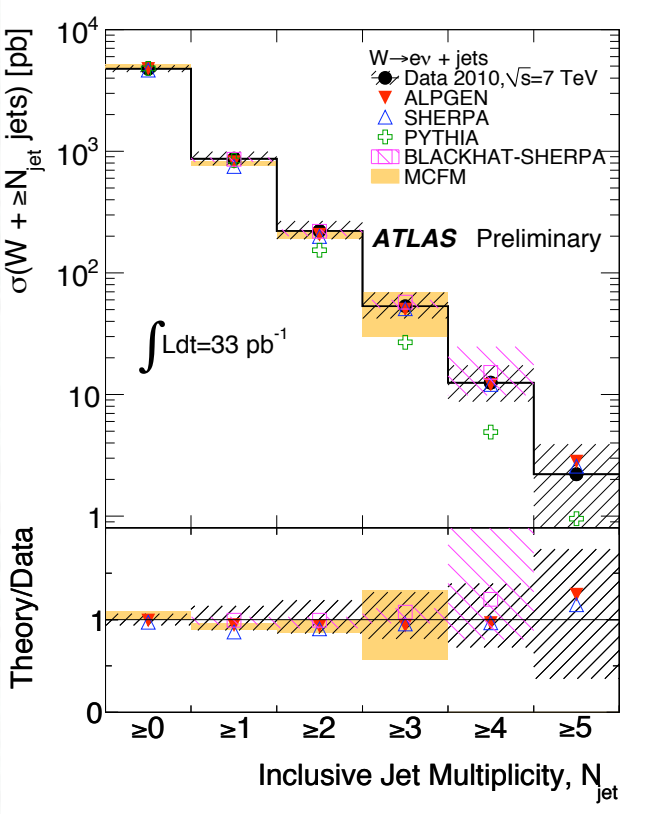
- Good agreement at that stage (jets with pT > 30 GeV),
- Top contribution clearly visible in high multiplicity bins of W + jet production

W/Z + jet cross section measurements

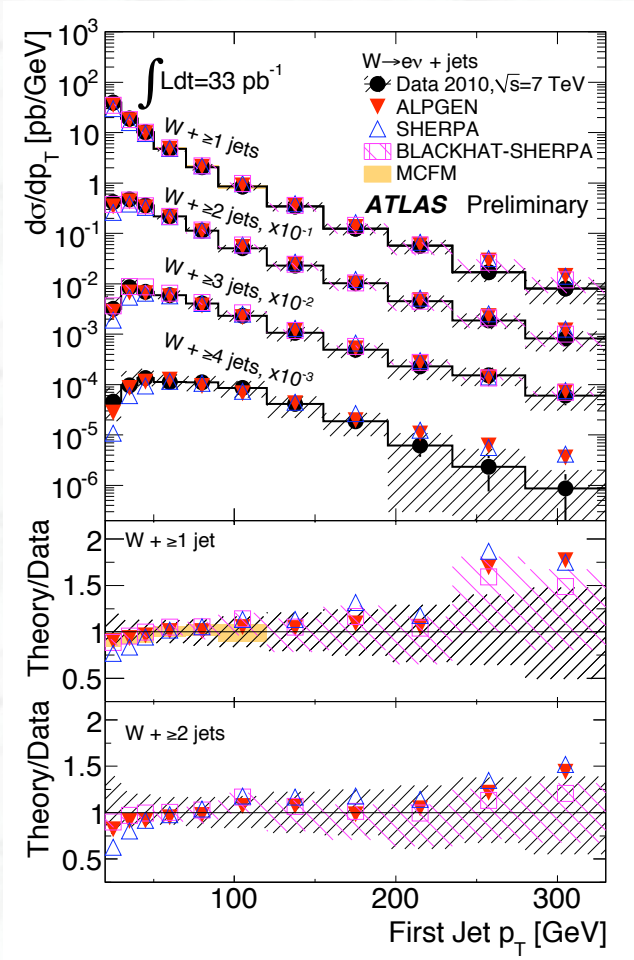


- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors; NLO central value ~10% low

Jet multiplicities in W+jet production



p_T spectrum of leading jet

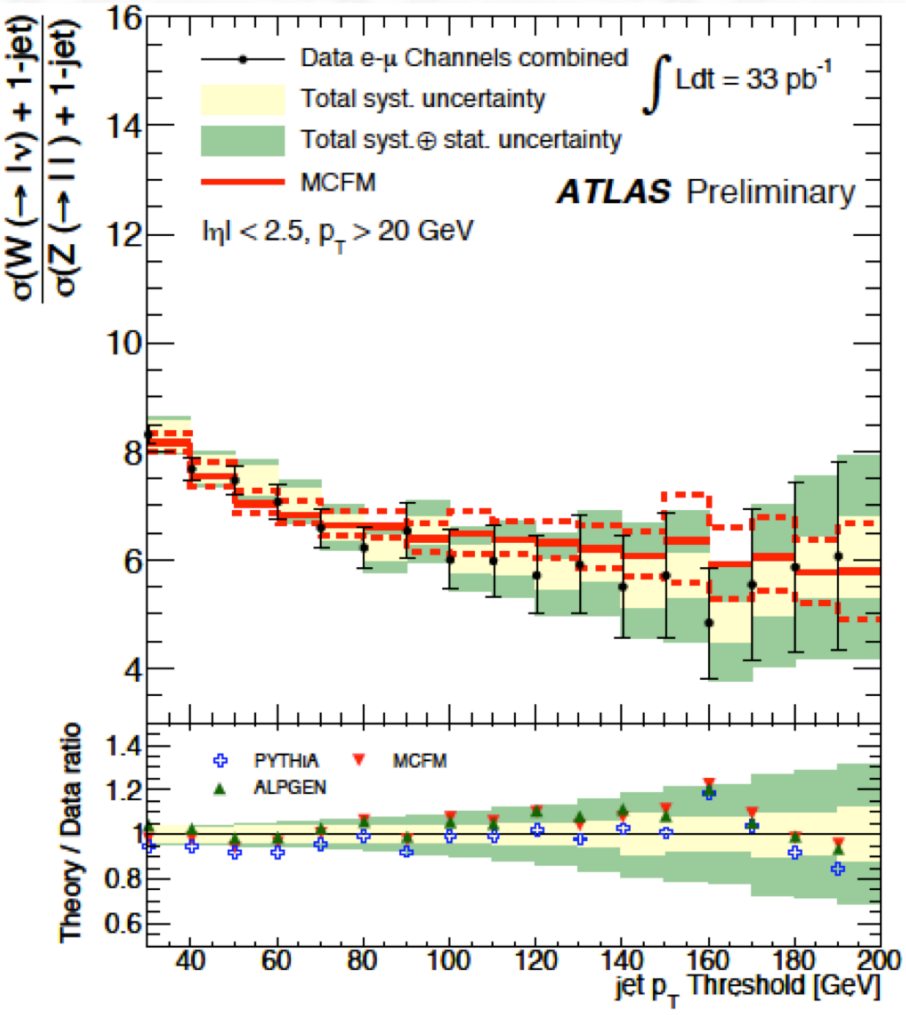


Ratio of cross sections

- Ratio $\sigma(W + n\text{-jet}) / \sigma(Z + n\text{-jet})$
  less sensitive to syst. uncertainties
  - pdfs and energy scales
  - experimental jet energy scale and resolution
  - new physics might upset ratio

- Measured by ATLAS for n = 1 vs p_T threshold for counting jets

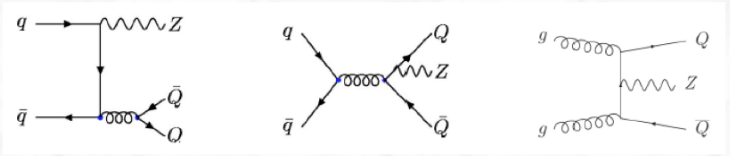
- Good agreement with NLO predictions
  - overall uncertainty is 4% for p_T > 30 GeV
  - will gain from higher statistics
  - largest systematic is boson reconstruction
  - can also extend to higher n

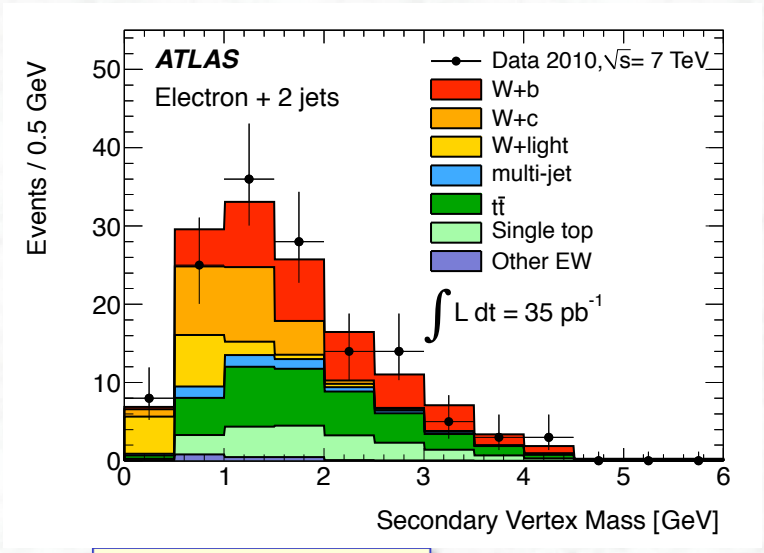


W + b jets

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

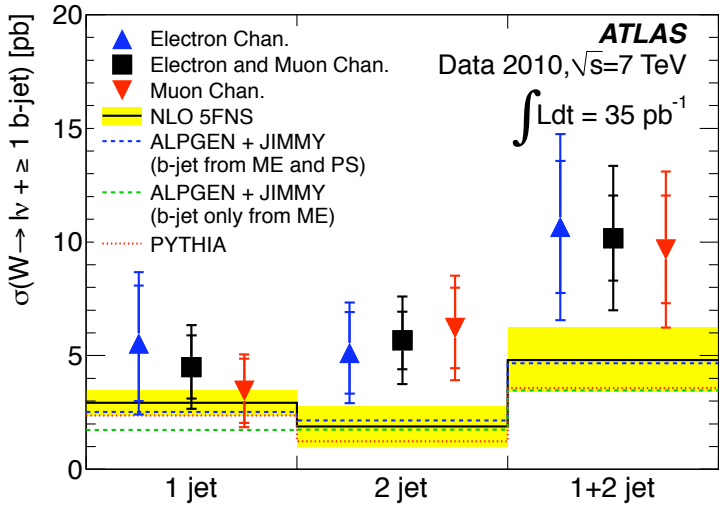
- Measured by ATLAS using 2010 data sample
  - studied W + 1 jet and W + 2 jets
  - require at least one b-tagged jet





W→ e ν + 2 jets

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



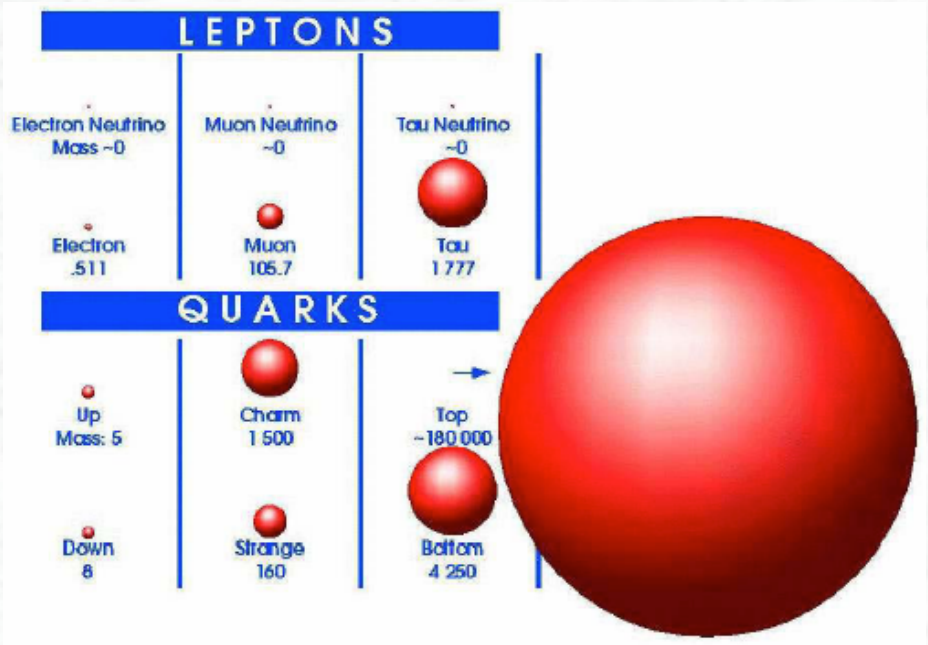
Results from e and μ combined. Measurements ~1.5σ above NLO prediction, but still consistent within uncertainties

2.3 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 ??

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

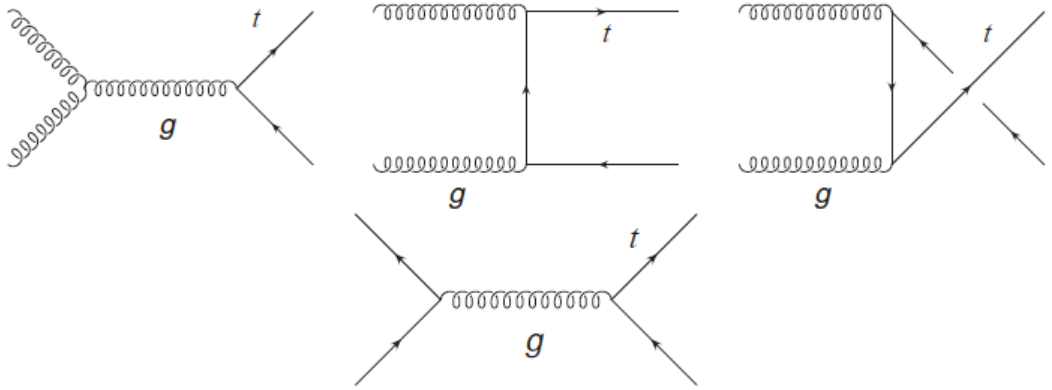
$$\Rightarrow \lambda_t = \frac{M_t}{173.9\ \mathrm{GeV}/c^2}$$

- 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:

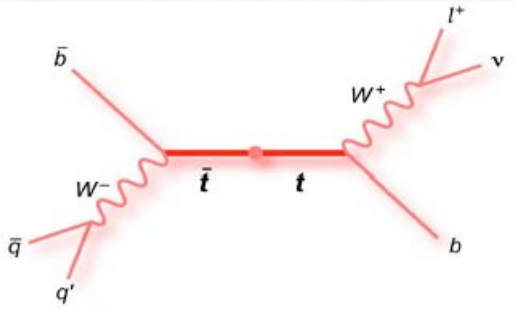
$$\sigma_{\rm LHC} = (887^{+9}_{-33}\,({\rm scale})^{+15}_{-15}\,({\rm PDF}))\ {\rm pb} \qquad (14\ {\rm TeV})\,,$$

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

	Tevatron 1.96 TeV	LHC 14 TeV
qq	85%	5%
gg	15%	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→Wb) ~ 100%

Dilepton channel:

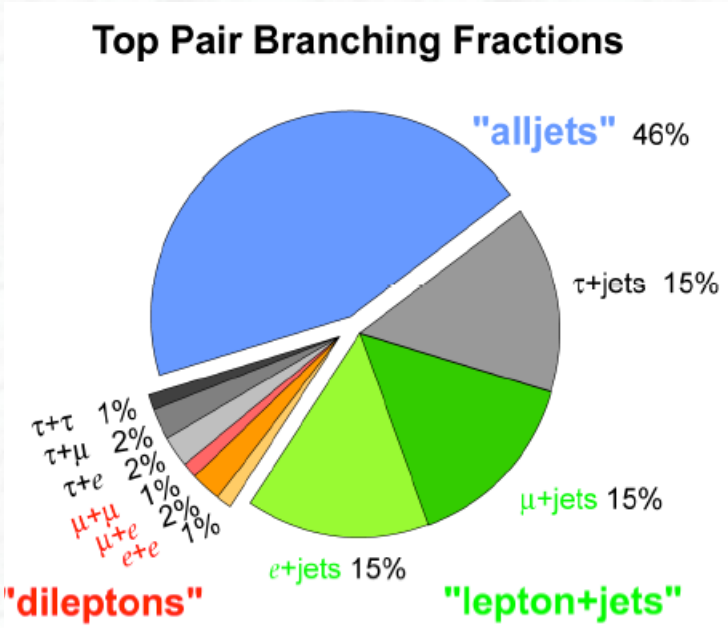
Both W's decay via W→ ℓν (ℓ=e or μ; 4%)

Lepton + jet channel:

One W decays via W → ℓν (ℓ=e or μ; 30%)

Full hadronic channel:

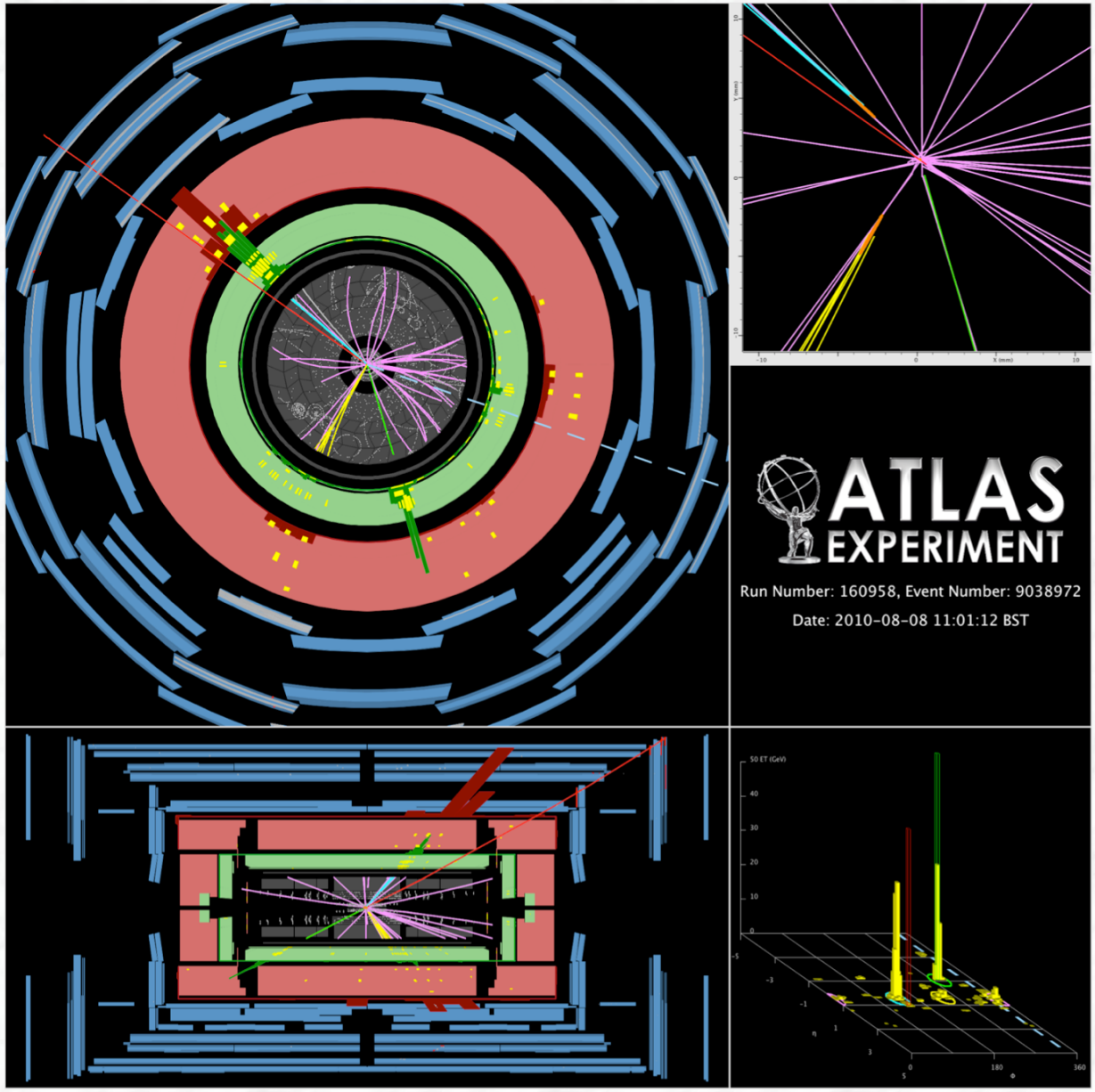
Both W's decay via W→qq (46%)



Important experimental signatures: : - Lepton(s)

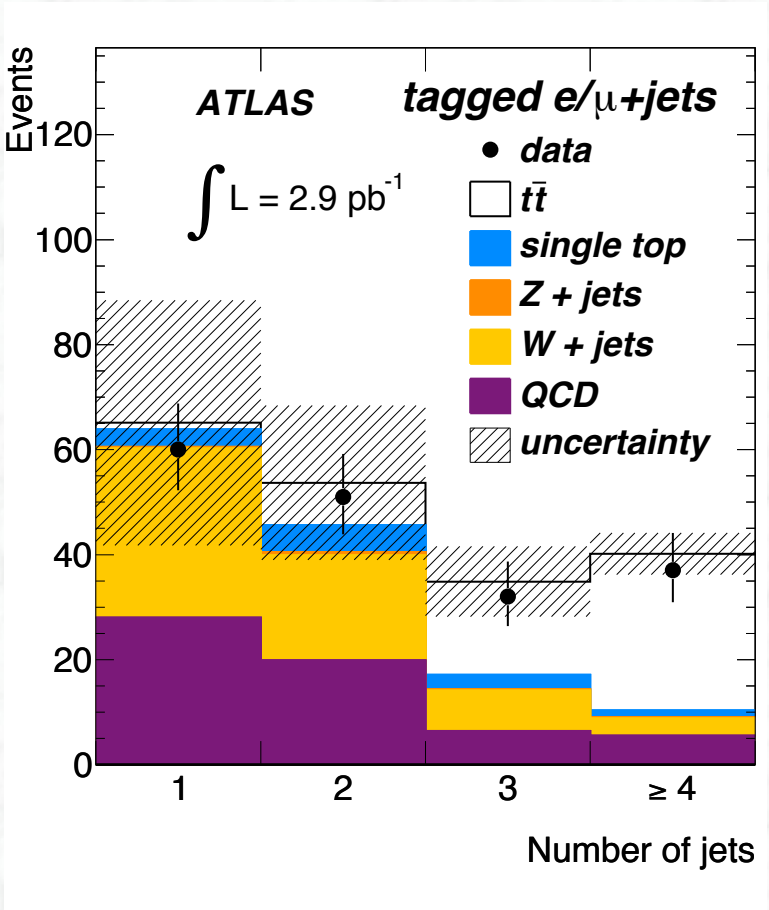
- Missing transverse momentum
- b-jet(s)

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.

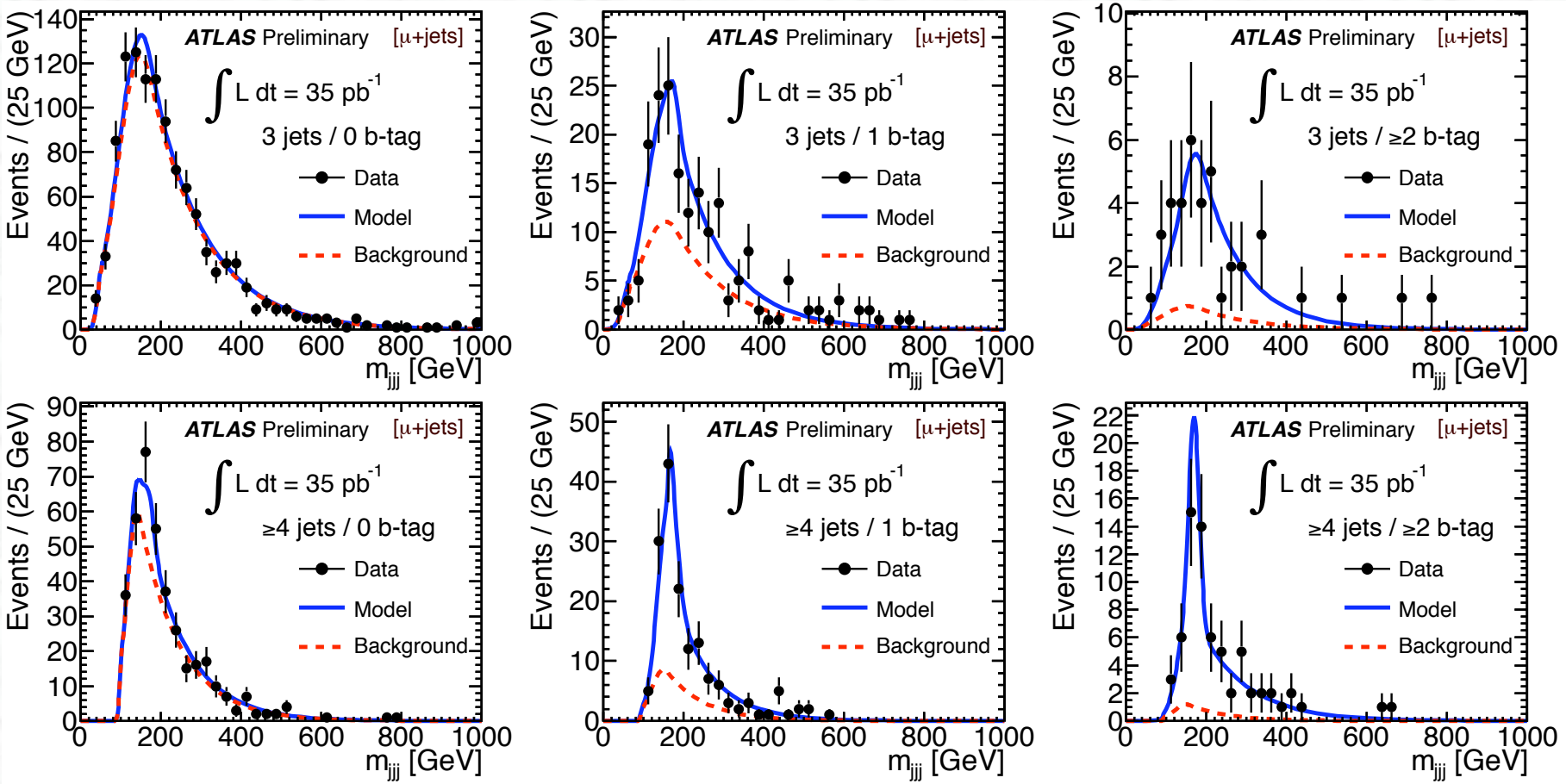
First results on top production from the LHC



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

Description of the invariant mass distributions in the l-had channel

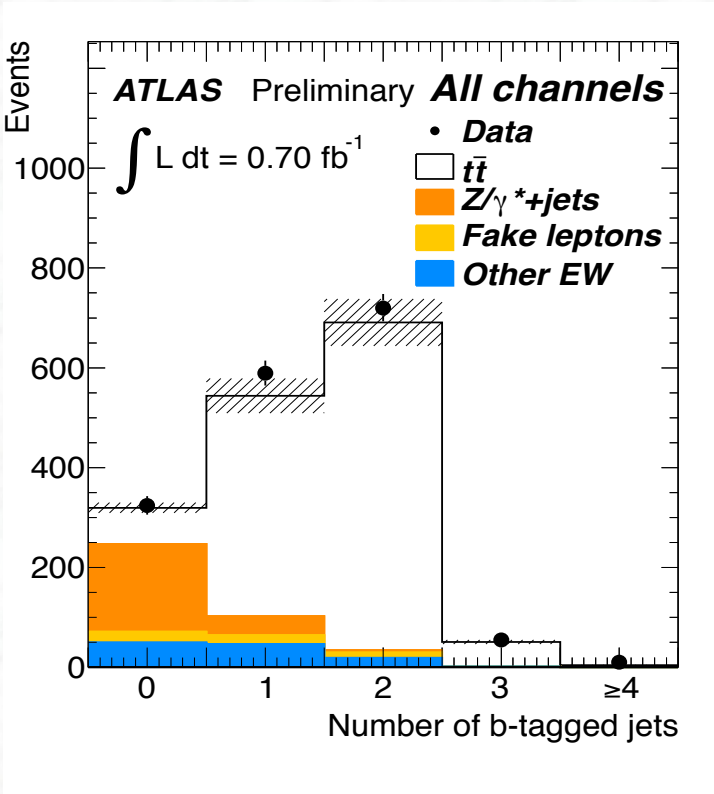


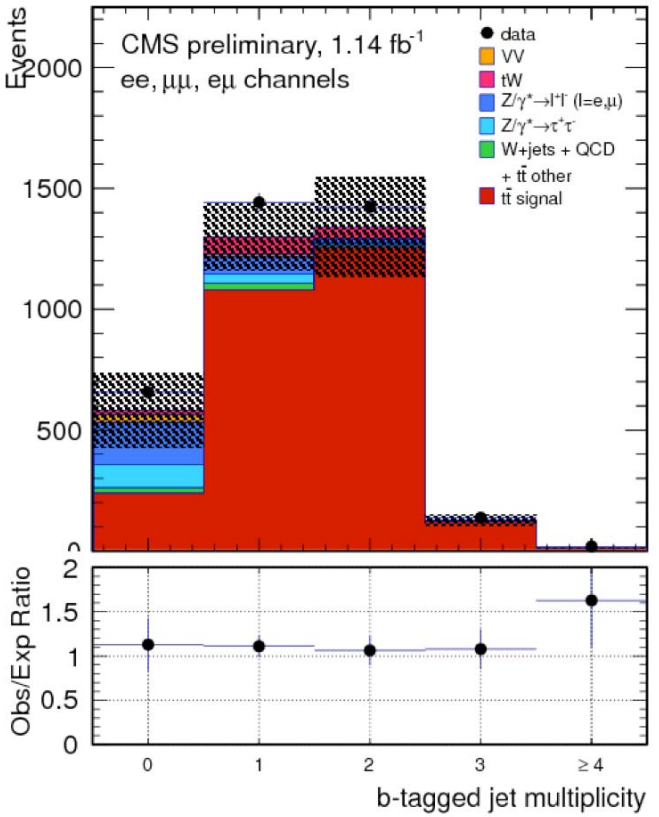
- Top fractions increase with number of b-tags
- Good description for all jet-multiplicity and b-tag combinations
- Data are consistent with top quark production with mass of 173 GeV

Evidence for top quark in many different decay modes

(i) Dilepton 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)

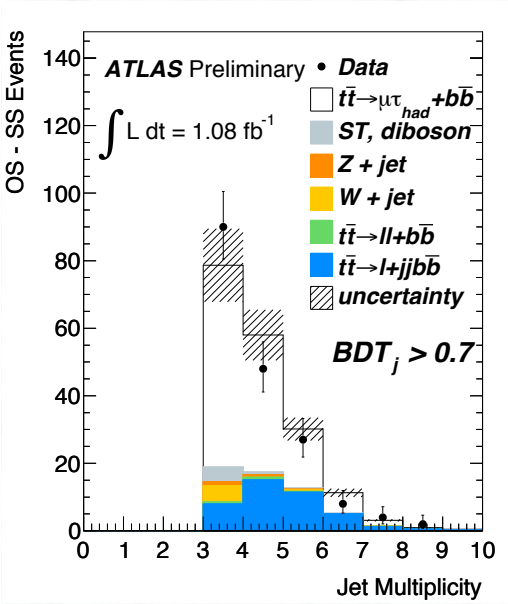


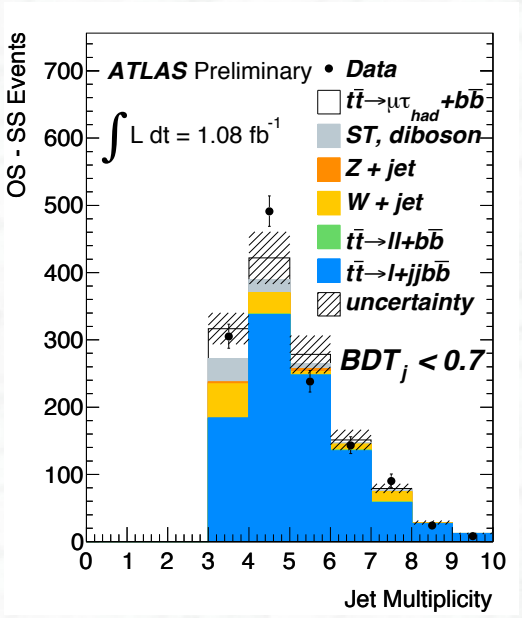


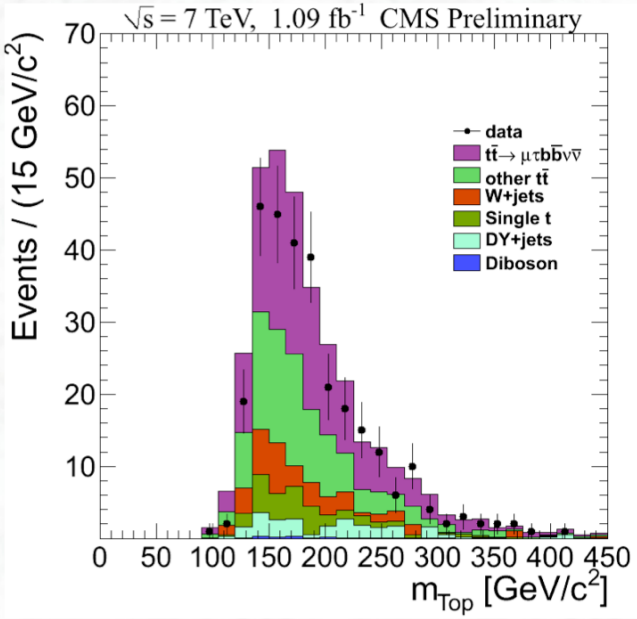
Evidence for top quark in many different decay modes

(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)



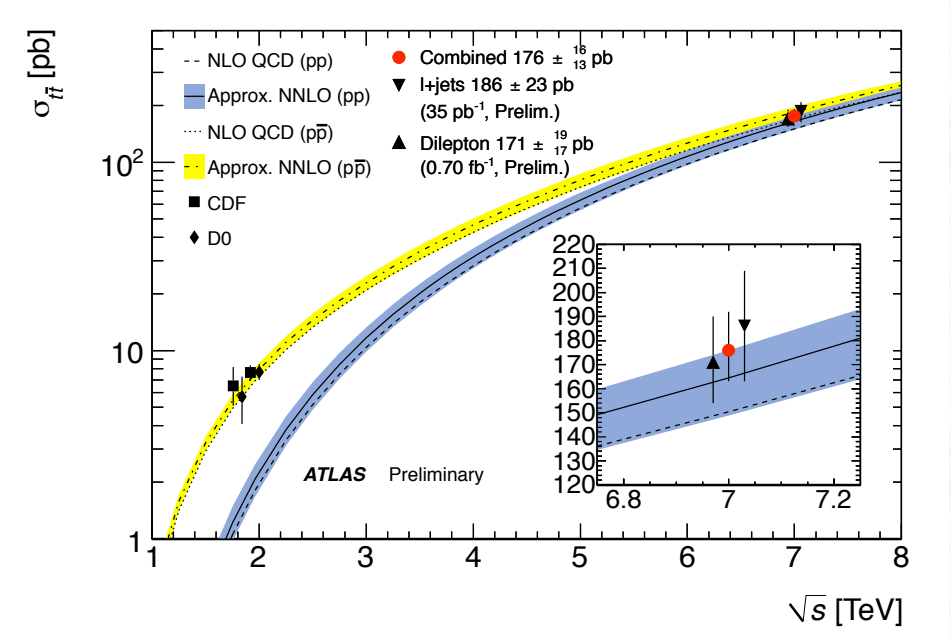


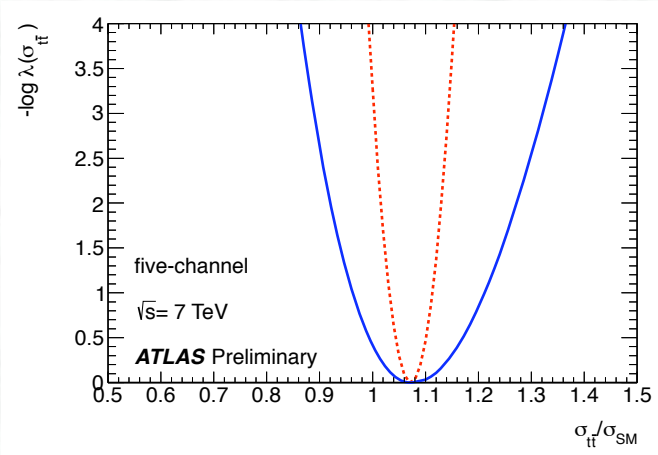


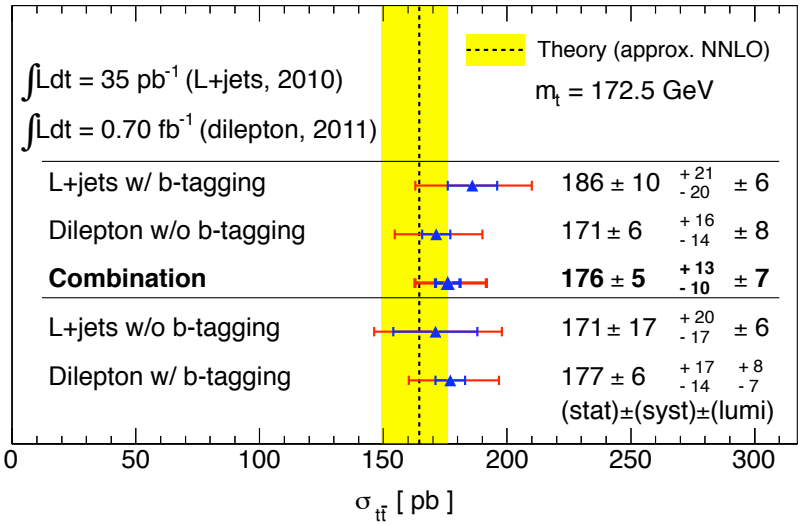
ATLAS: Multivariate analysis
Jet multiplicity distribution in signal (left)
and background (right) regions

reconstructed mass in CMS

Top cross section measurements based on 2010 data from ATLAS

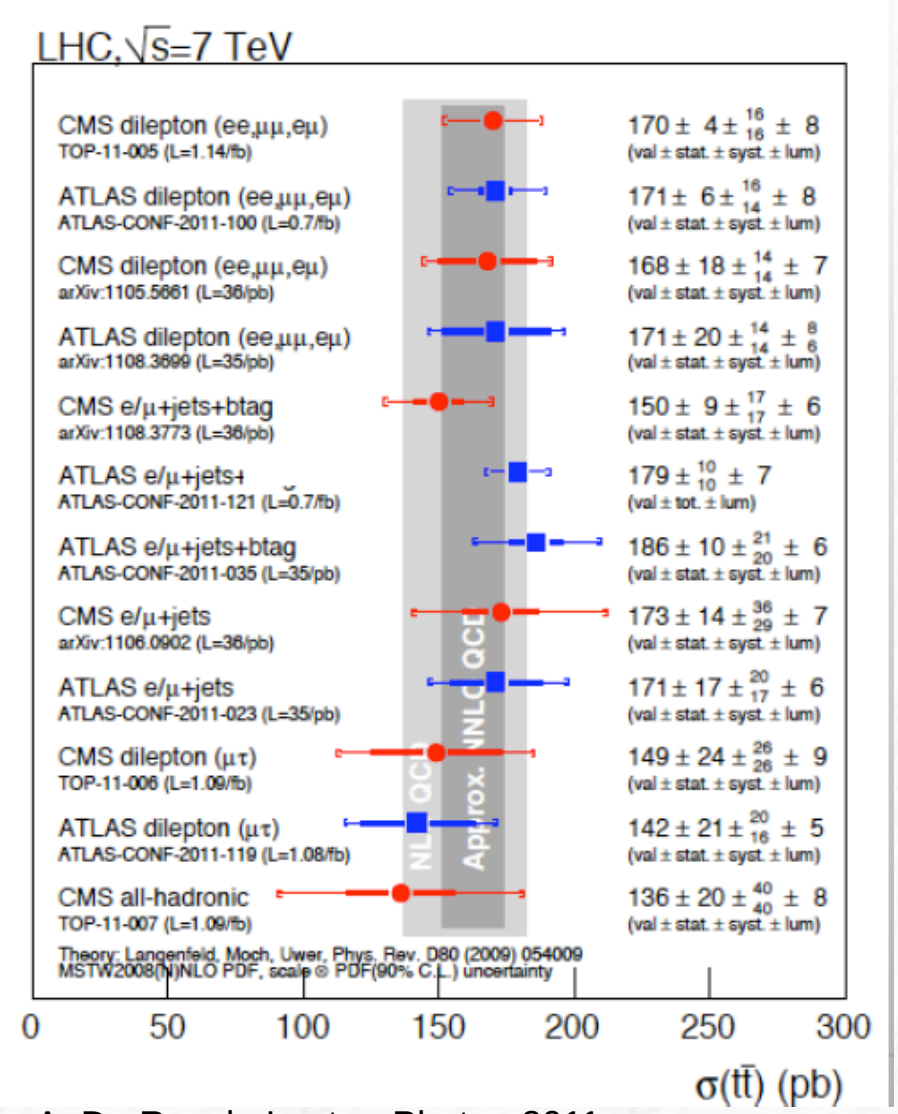






Best fit (ATLAS) gives
a slightly higher cross-section
than the expected approx.
NNLO QCD value,
but consistent within 1 σ
(red: likelihood, stat errors only;
blue: stat + syst. uncertainties)

Summary of ATLAS and CMS measurement on the tt cross section in pp collisions at $\sqrt{s}$ = 7 TeV



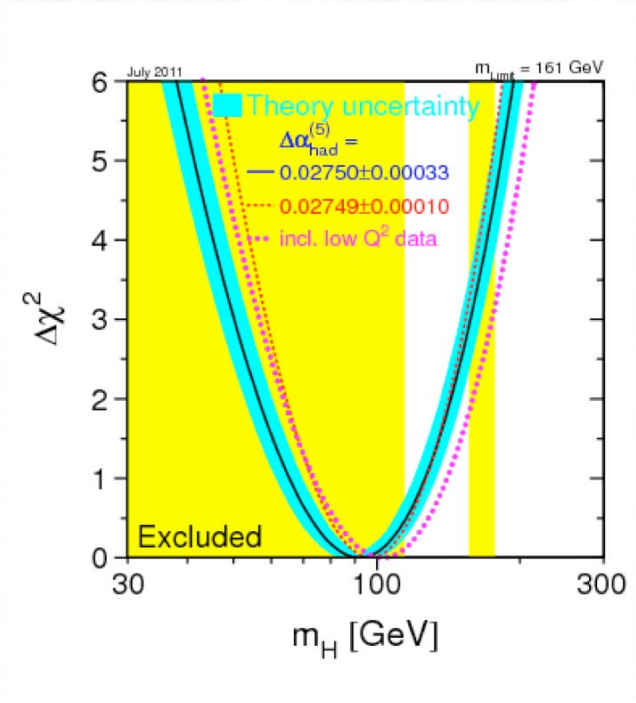
A. De Roeck, Lepton-Photon 2011

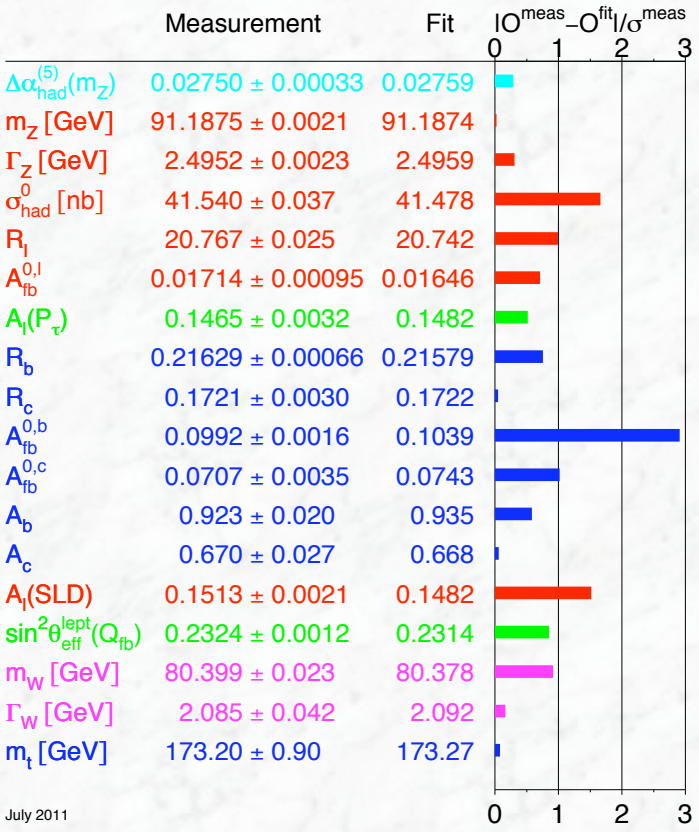
Summary:

- Perturbative QCD calculations (approx. NNLO) describe the data well
- Total uncertainty now at the level of ±7% (most precise measurement)

2.4 Electroweak parameters

- W mass
- Top Quark Mass & Properties
- Gauge Boson pair production





Precision measurements of m_W and m_{top}

Motivation:

W mass and top quark mass are fundamental parameters of the Standard Model;
The standard theory provides well defined relations between m_W, m_{top} and m_H

Electromagnetic constant
measured in atomic transitions,
e^+e^- machines, etc.

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

Fermi constant
measured in muon decay

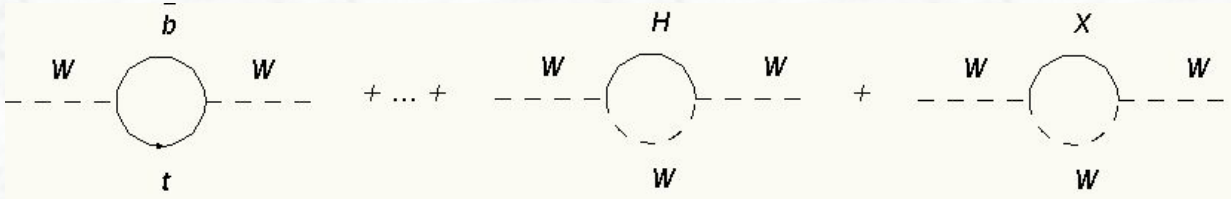
weak mixing angle
measured at LEP/SLC

radiative corrections
$\Delta r \sim f(m_{top}^2, \log m_H)$
$\Delta r \approx 3\%$

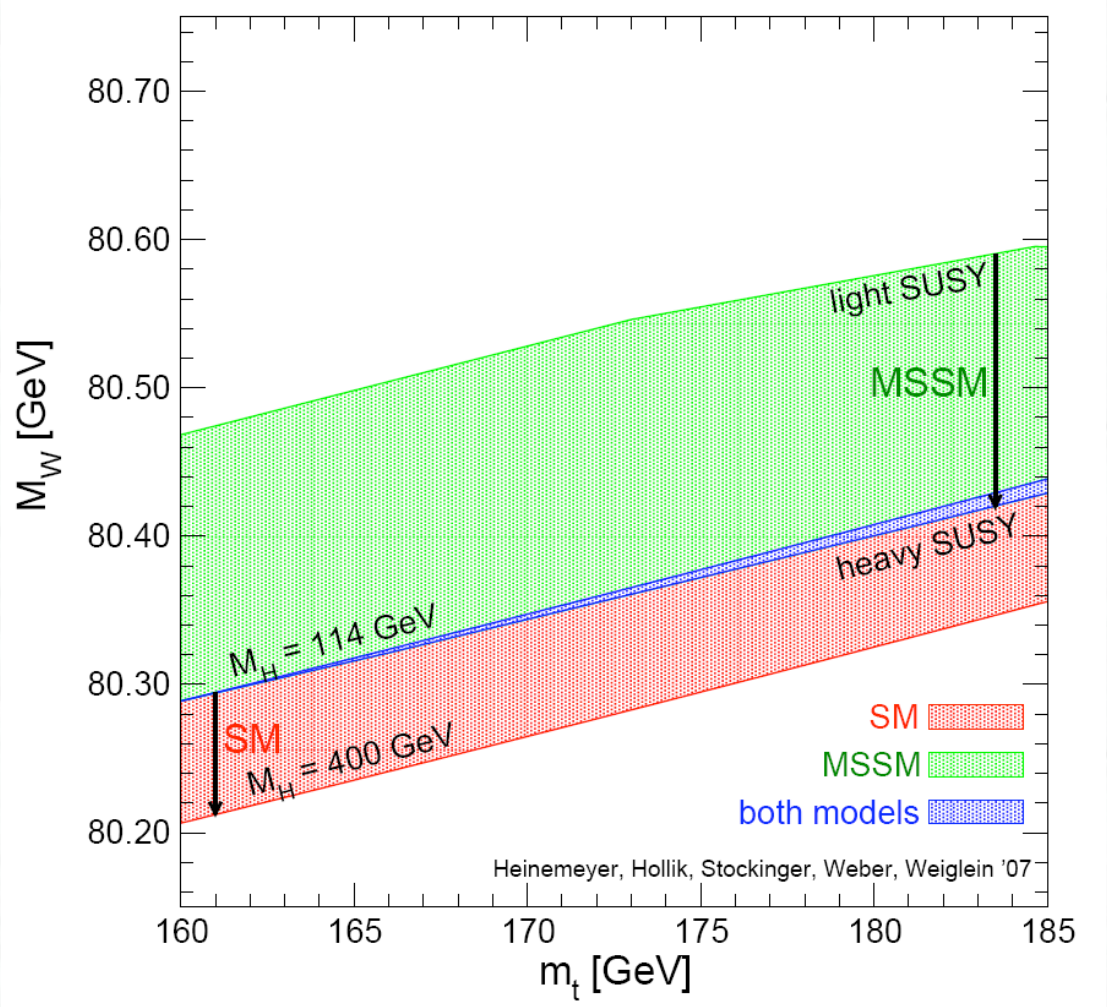
G_F, α_{EM}, $\sin\theta_W$

are known with high precision

Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass
(and/or the theory, radiative corrections)



Relation between m_W, m_t, and m_H



The W-mass measurement

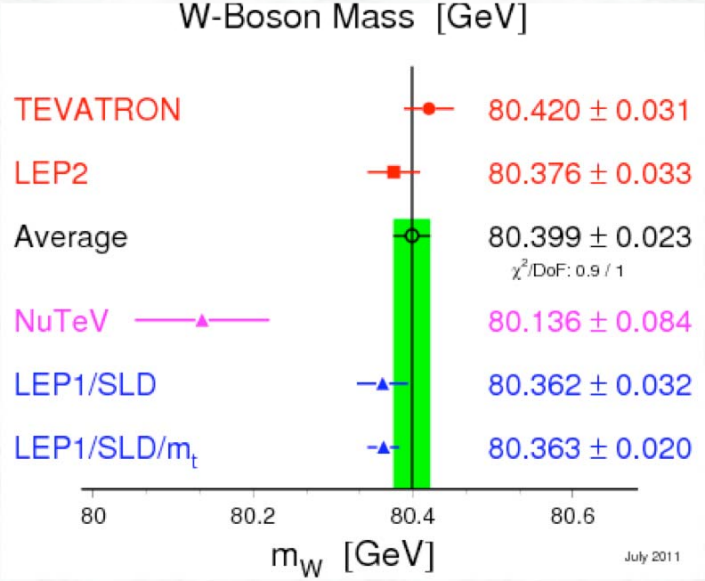
$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

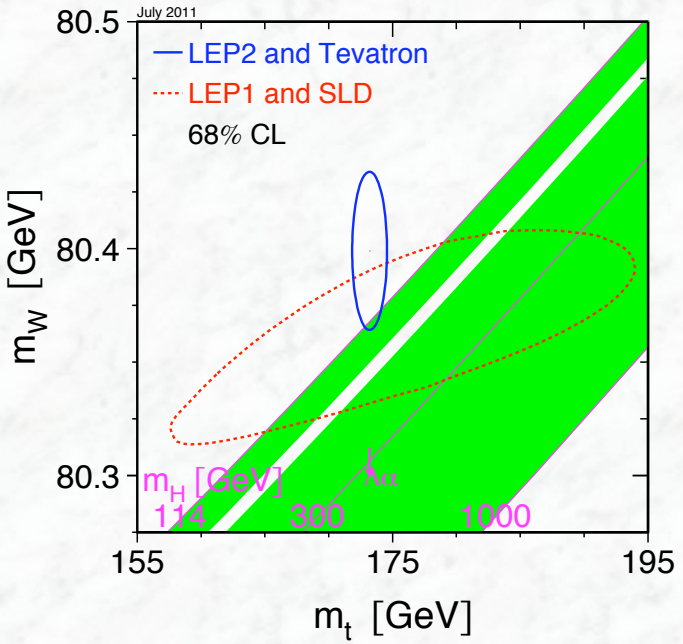
3·10^{-4}

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

m_{top} (from Tevatron) = 173.2 ± 0.9 GeV

0.8%

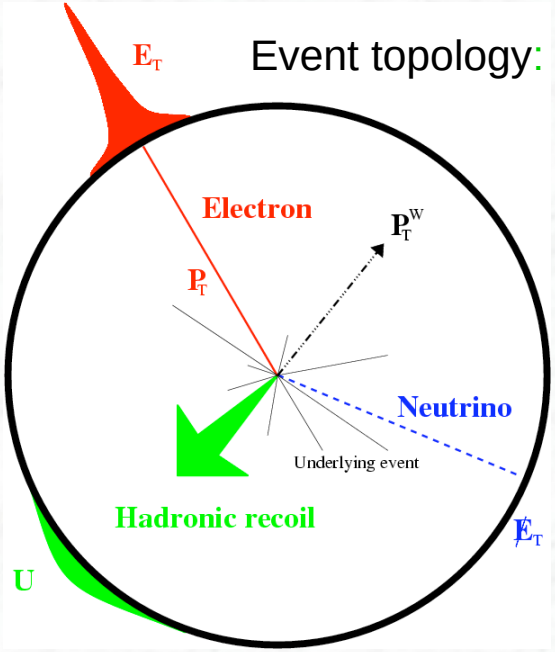


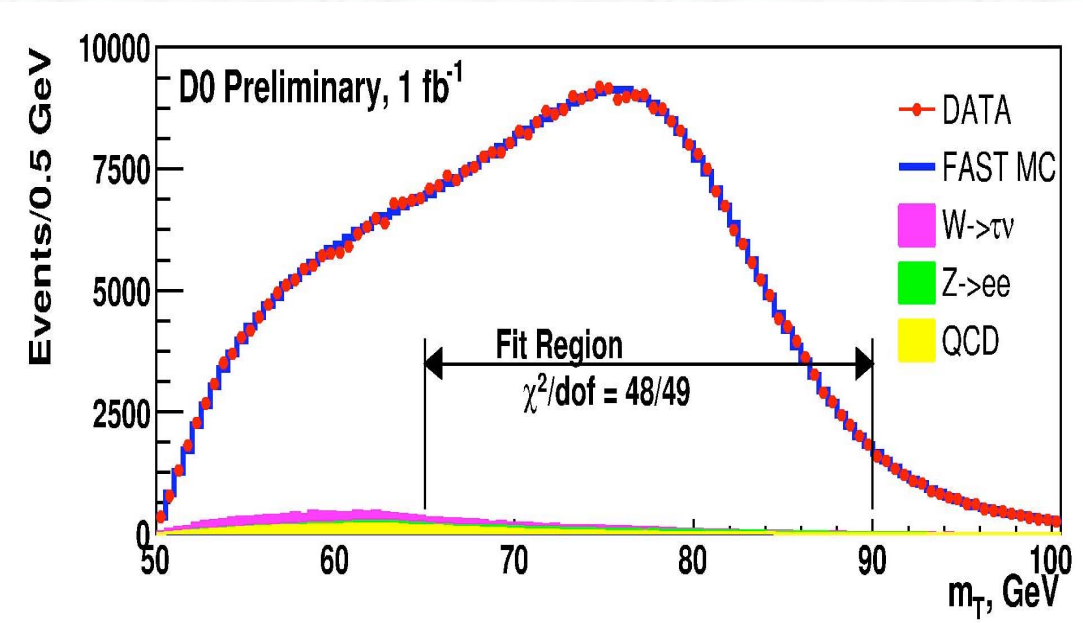


A light Higgs boson is favoured by present measurements

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

Technique used for W mass measurement at hadron colliders:





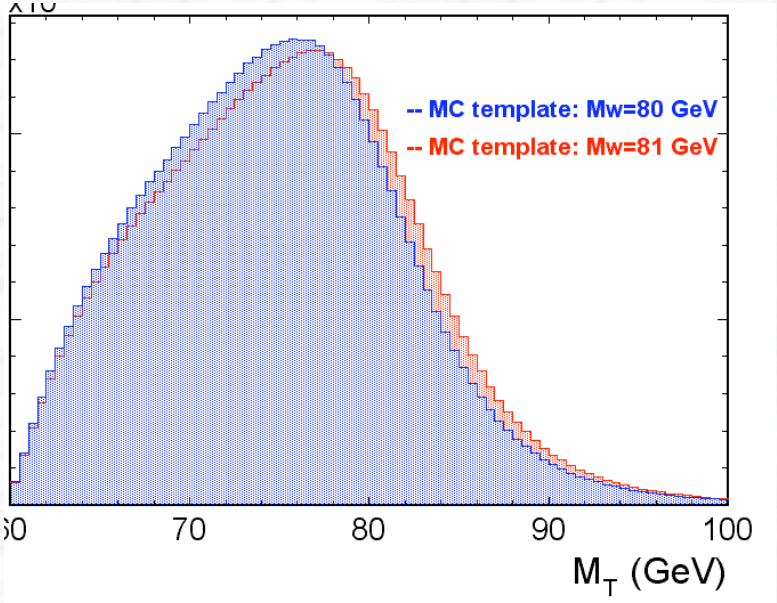
Observables: $P_T(e)$, $P_T(had)$

$\Rightarrow$ $P_T(\nu) = -(P_T(e) + P_T(had))$ long. component cannot be measured

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

In general the transverse mass M_T is used for the determination of the W mass (smallest systematic uncertainty).

Shape of the transverse mass distribution is sensitive to m_W, the measured distribution is fitted with Monte Carlo predictions, where m_W is a parameter



Main uncertainties:

Ability of the Monte Carlo to reproduce real life:

- Detector performance
  (energy resolution, energy scale, ….)
- Physics: production model
  $p_T(W)$, Γ_W, ...
- Backgrounds

What precision can be reached in Run II and at the LHC ?

Numbers for a single decay channel

$W \rightarrow e\nu$

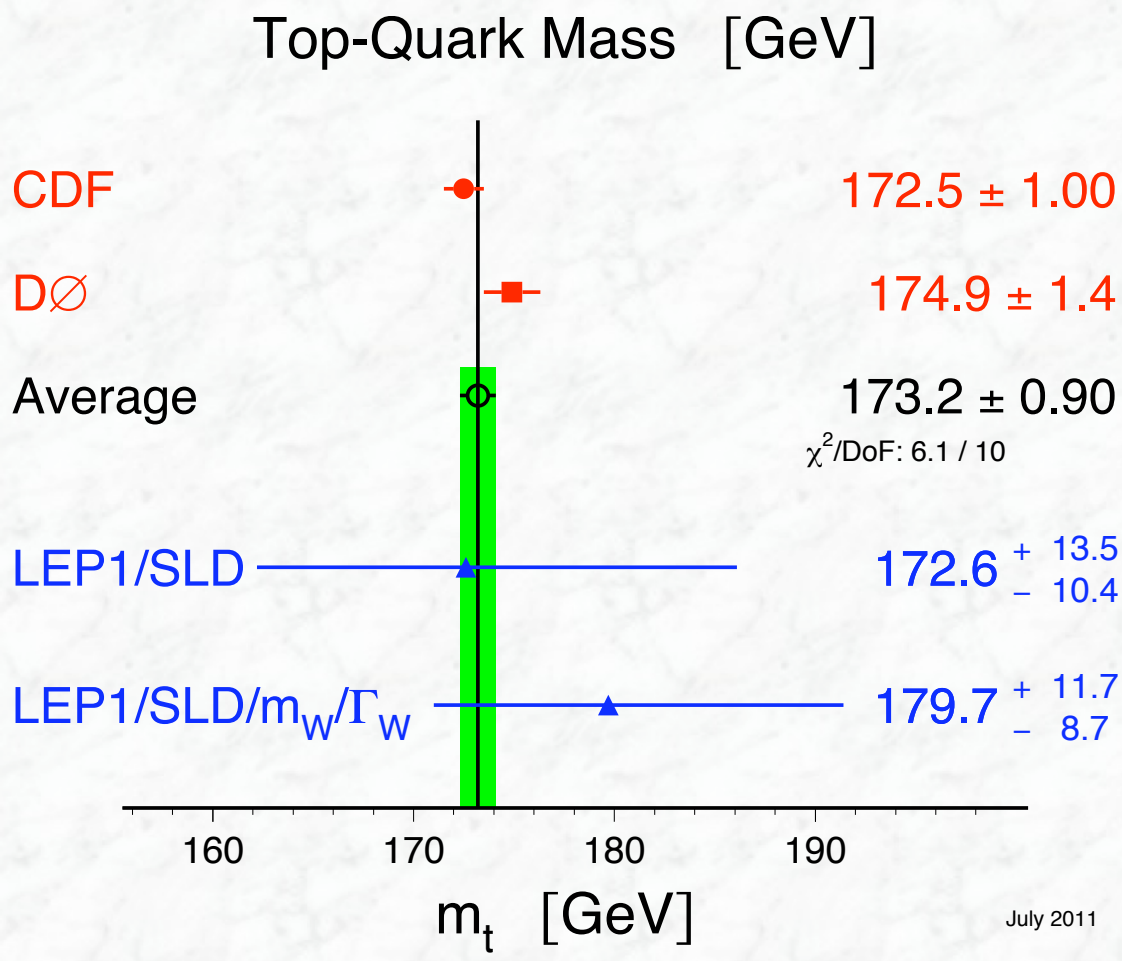
Int. Luminosity	CDF 0.2 fb^{-1}	DØ 1 fb^{-1}	LHC 10 fb^{-1}
Stat. error	**48 MeV**	**23 MeV**	**2 MeV**
Energy scale, lepton res.	30 MeV	34 MeV	4 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	16 MeV	12 MeV	7 MeV
Background	8 MeV	2 MeV	2 MeV
Tot. Syst. error	**39 MeV**	**37 MeV**	**8 MeV**
Total error	**62 MeV**	**44 MeV**	**~10 MeV**

- Tevatron numbers are based on real data analyses
- LHC numbers should be considered as „ambitious goal“
  - Many systematic uncertainties can be controlled in situ, using the large $Z \rightarrow \ell\ell$ sample ($p_T(W)$, recoil model, resolution)
  - Lepton energy scale of ± 0.02% has to be achieved to reach the quoted numbers

Combining both experiments (ATLAS + CMS, 10 fb^{-1}), both lepton species and assuming a scale uncertainty of ± 0.02% a total error in the order of

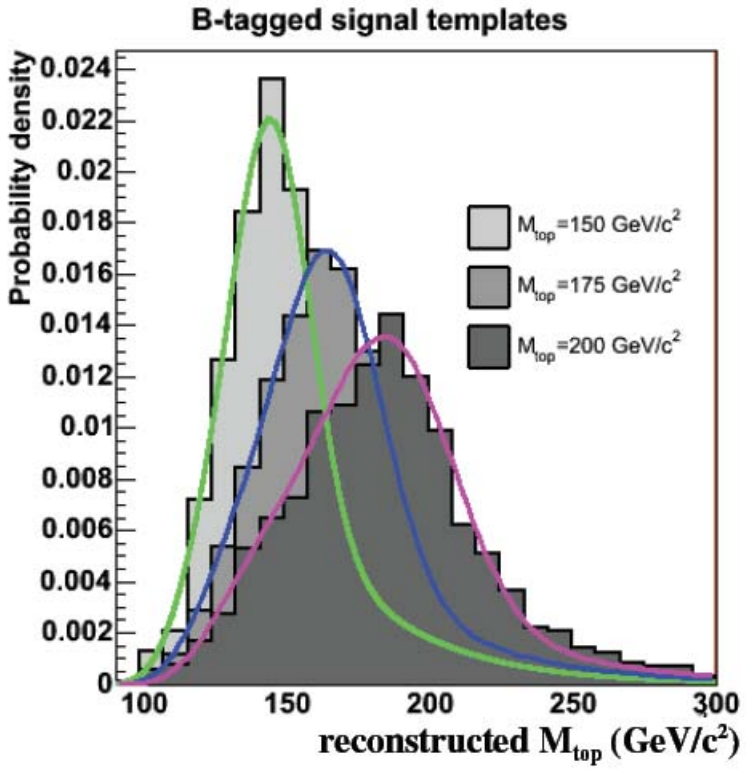
$\Rightarrow \Delta m_W \sim \pm 10 - 15$ MeV might be reached.

Top-quark mass measurement



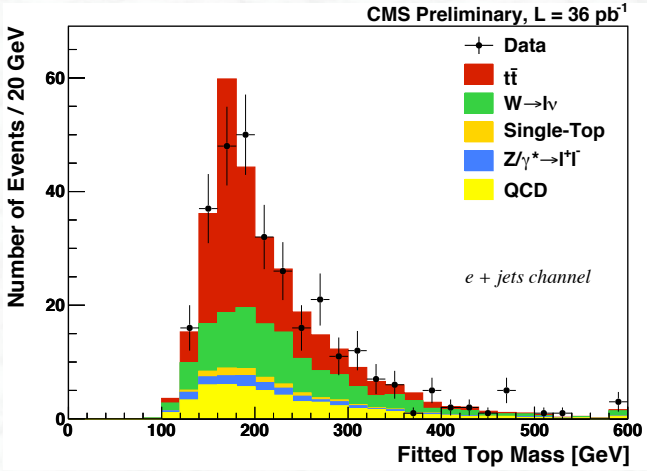
Example: template method

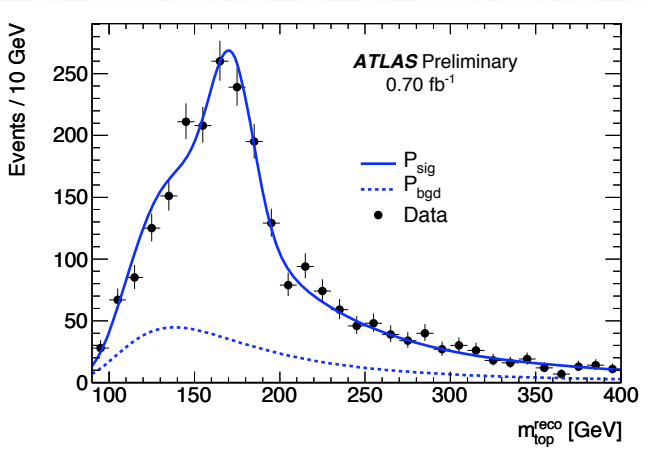
- Calculate a per-event observable that is sensitive to m_t
- Make templates from signal and background events
- Use pseudo-experiments (Monte Carlo) to check that method works
- Fit data to templates using maximum likelihood method

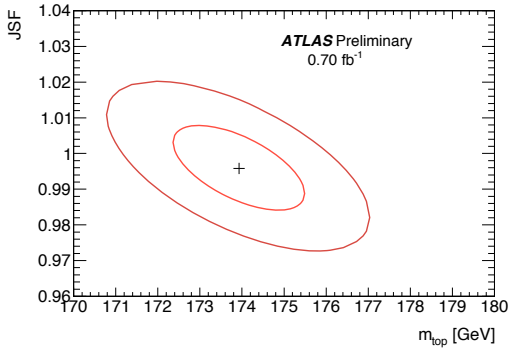


First top quark mass measurements at the LHC

- Use lepton + jet channel (e,μ + 4 jets, at least 1 b-tagged jet)
- Include part of the 2011 data (0.7 fb^{-1})
- Combined fit of top mass and jet energy scale (in situ) à la Tevatron







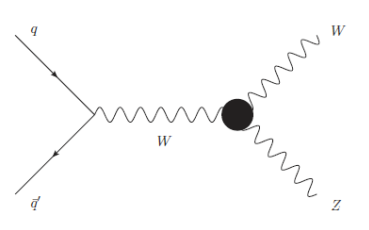
CMS: m_t = 173.4 ± 1.9 (stat) ± 2.7 (syst) GeV (incl. di-lepton channel)

ATLAS: m_t = 175.9 ± 0.9 (stat) ± 2.7 (syst) GeV

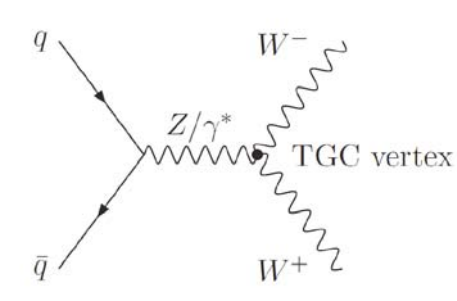
Already impressive precision reached at that early stage of the experiment !

Di-boson production: Wγ, WW, WZ, ZZ

- Motivation: - test of the Standard Model gauge structure
  - search for deviations,
    anomalous triple gauge couplings (TGC)



- Allowed Standard Model vertices
  - γ/Z → WW
  - W → Wγ
  - W → WZ

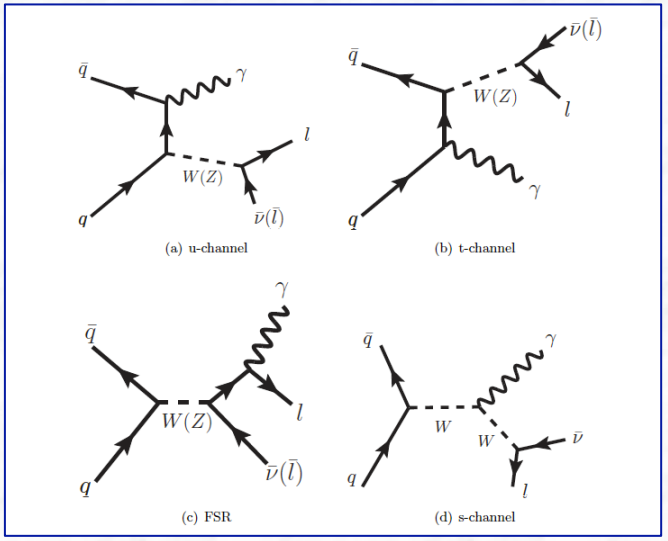


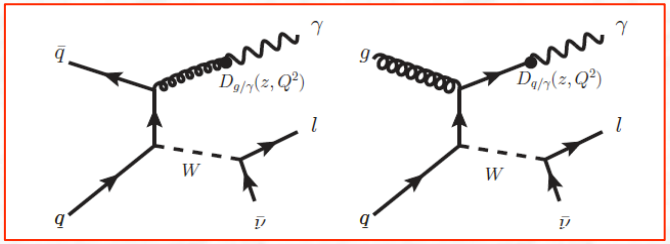
- Forbidden Standard Model vertices: γ → ZZ or Zγ
  Z → ZZ or Zγ

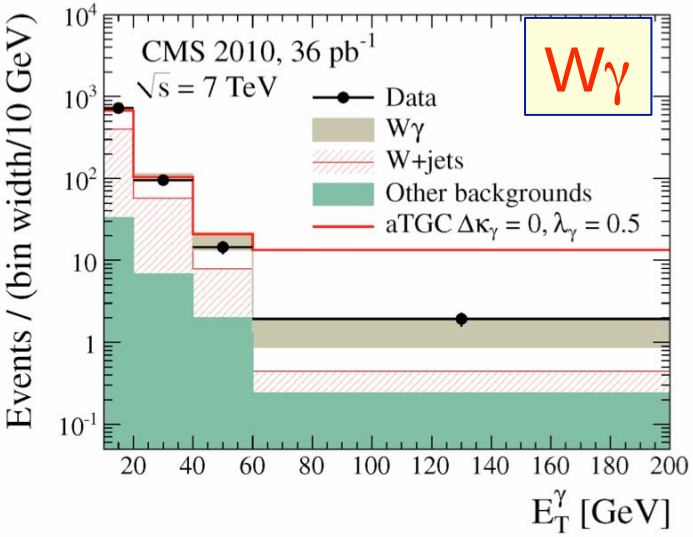
- Start from most general ansatz for TGCs in Lagrangian
  → 14 couplings
  CP invariance and gauge invariance
  → 5 parameters $\lambda_\gamma = \lambda_Z = 0$
  $g_1 = K_\gamma = K_Z = 1$

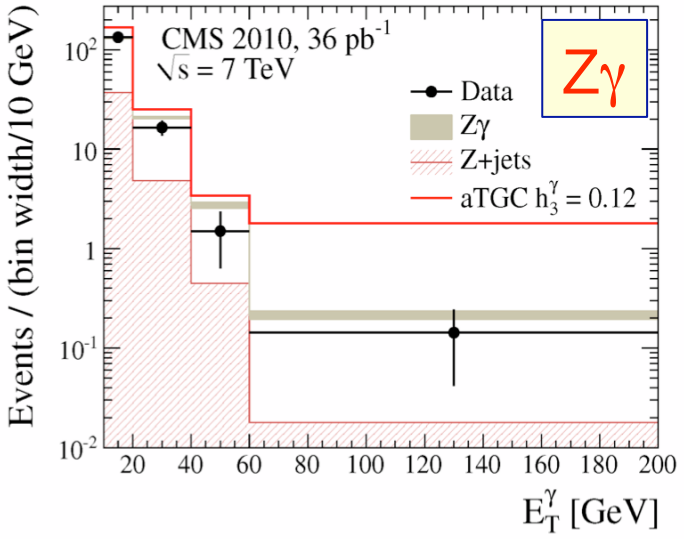
Wγ and Zγ production

- Expected contributions within the Standard Model (including initial and final state radiation)
- Additional contribution from quark and gluon fragmentation (W/Z + jet production)
- Search for an additional isolated photon in W and Z events
- E_T spectra of photons are in agreement with the expectations from the Standard Model



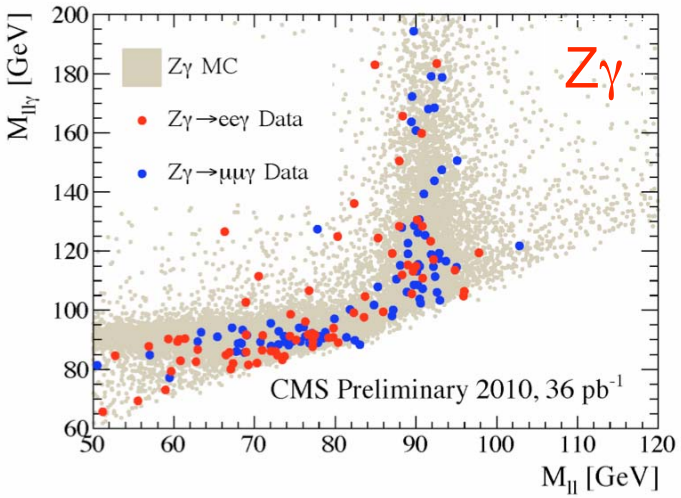


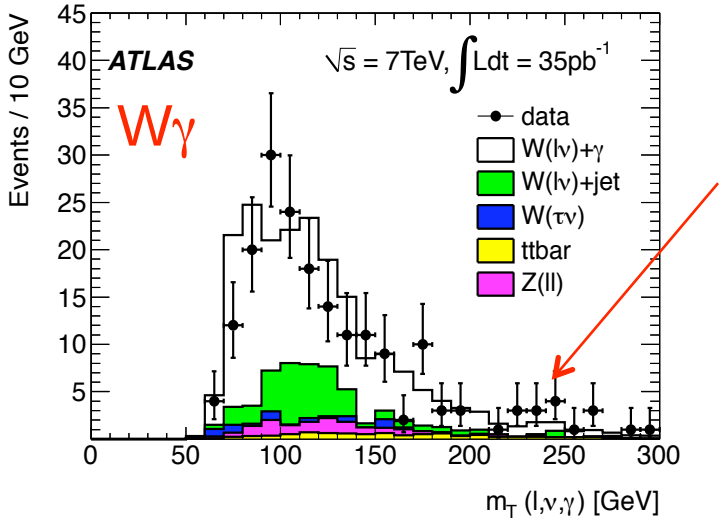




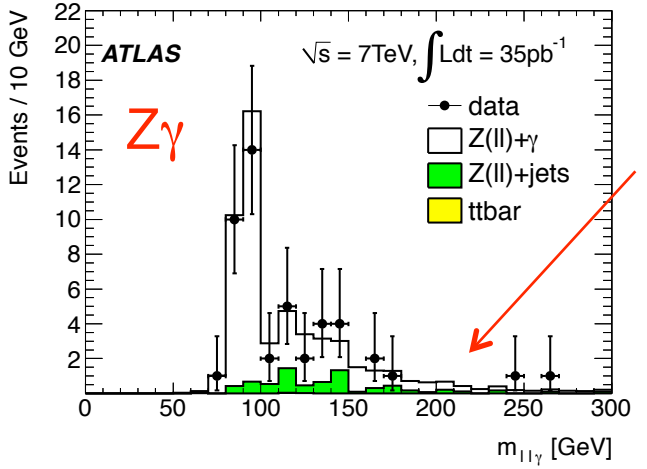
Wγ and Zγ production (cont.)

- Also kinematic distributions are well described by Standard Model processes
- No evidence for anomalous couplings / anomalous Wγ / Zγ production





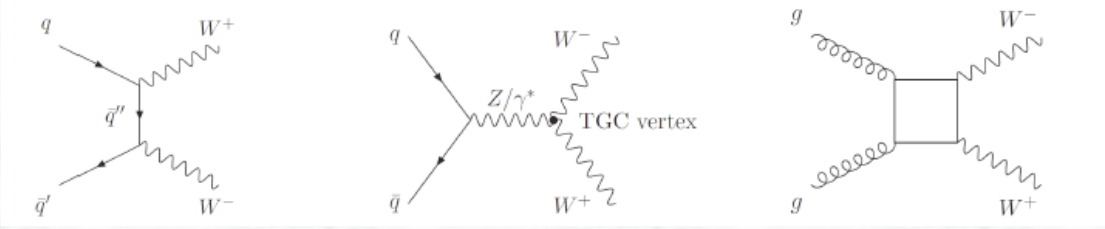
expect signal here

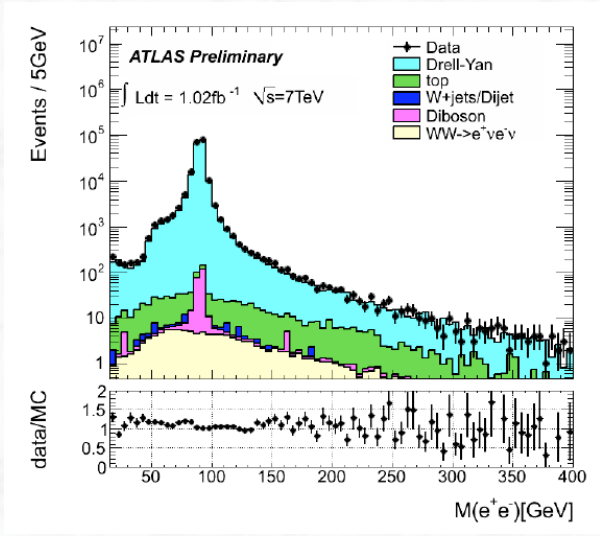


expect signal here

WW production

- Expected contributions within the Standard Model
  (TGC contribution, gg-box is higher order)

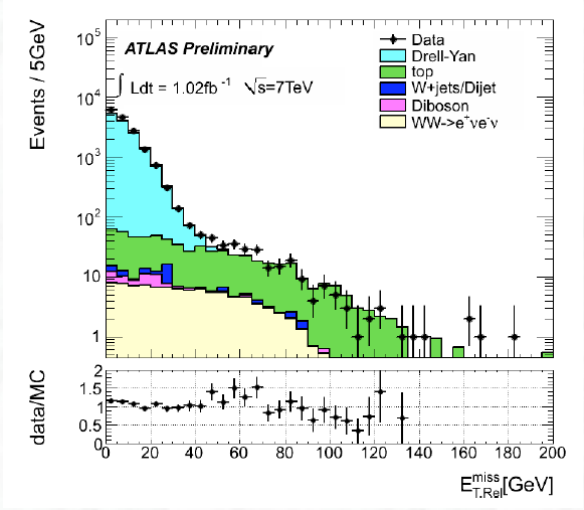




- Search for WW production in di-leptonic decays
  (WW→ lν lν)

- Major backgrounds:
  - Drell-Yan production pp → Z/γ* → ll
  - W → lν + jet production, one jet fakes a lepton,
    E_T^{miss} from mis-measurement
  - tt production, with di-leptonic decays: tt → lν b lν b

- This is an important background process for Higgs boson searches in the H → WW → lν lν channel

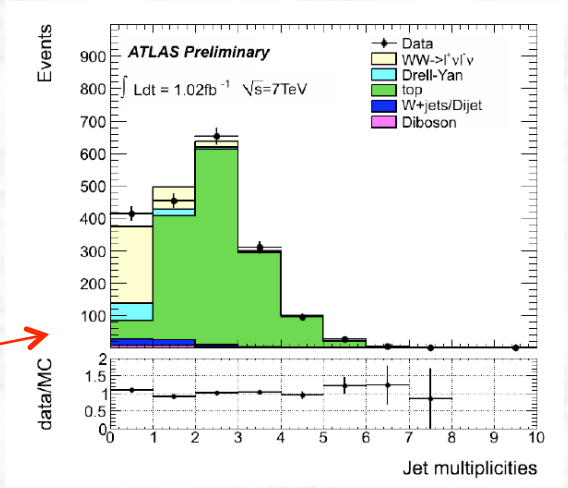


Di-lepton mass and E_T^{miss} after basic selection of two high p_T leptons (25 / 20 GeV)

WW production (cont.)

- Accepted number of events after various cuts:

Cuts	$ee + E_T^{miss}$	$\mu\mu + E_T^{miss}$	$e\mu + E_T^{miss}$
2 leptons (SS+OS)	205199	391374	3969
2 leptons (OS)	204023	391238	3739
leading electron $p_T > 25$GeV	200285	-	2990
trigger matching	199913	391050	2989
$M_{\ell\ell} > 15$ GeV, $M_{e\mu} > 10$ GeV	199585	388701	2984
Z mass veto	16463	40632	-
$E_{T,\,Rel}^{miss}$ cut	308	425	1227
Njet(0,1,2,3,4,>=5)	(74,78,94,45,14,3)	(97,93,147,62,20,6)	(243,283,412,203,62,24)
Jet veto (No. of jet=0)	74	97	243



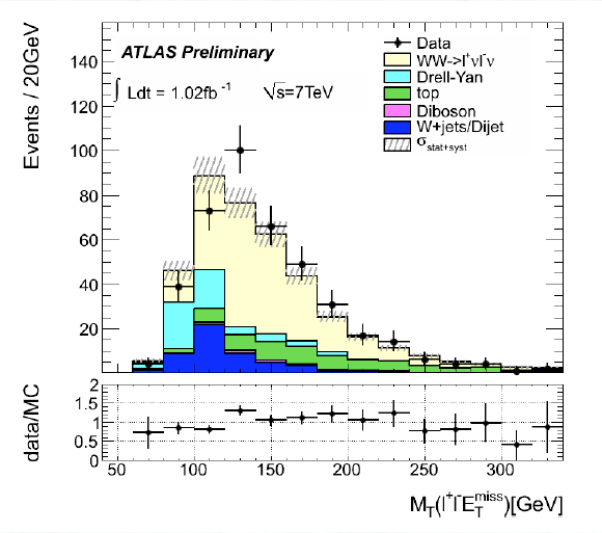
Jet multiplicity distribution after all cuts

- Jet veto applied to suppress large remaining top contribution i.e. require no jet with $p_T > 30$ GeV within $|\eta| < 4.5$

WW production (cont.)

- After jet-veto cuts:

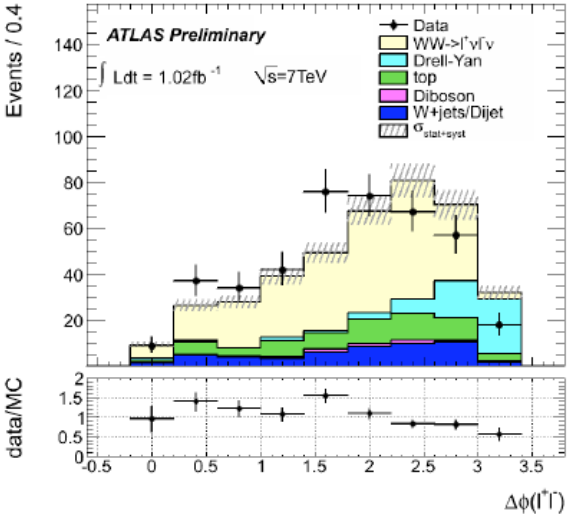
Final State	$e^+e^-E_T^{miss}$	$\mu^+\mu^-E_T^{miss}$	$e^\pm\mu^\mp E_T^{miss}$	Combined
Observed Events	74	97	243	414
Background estimations				
Top(data-driven)	9.5±0.3±3.6	12.3 ±0.4±4.7	36.8±1.3±14.0	58.6±2.1±22.3
W+jets (data-driven)	5.3±0.4±1.7	12.4±2.9±5.2	32.9±3.8±9.2	50.5±4.8±14.7
Drell-Yan (MC/data-driven)	18.7±1.9±1.9	19.2±1.7±2.1	16.0±2.8±1.7	54.0±3.7± 4.5
Other dibosons (MC)	0.9±0.1±0.1	2.4±0.2±0.3	3.4±0.3±0.4	6.8±0.4±0.8
Total Background	34.4±2.0±4.4	46.3±3.4±7.3	89.1±4.9±16.8	169.8±6.4±27.1
Expected WW Signal	29.5±0.3±3.0	52.5±0.4±4.9	150.5±0.7±13.4	232.4±0.9±21.5
Significance ($S/\sqrt{B}$)	5.0	7.7	15.9	17.8



- Signal-to-background ratio between 1:1 and 2:1

- Backgrounds largely estimated using data
  (define control regions that are dominated by one background source, normalize there, use Monte Carlo for extrapolation in signal region)

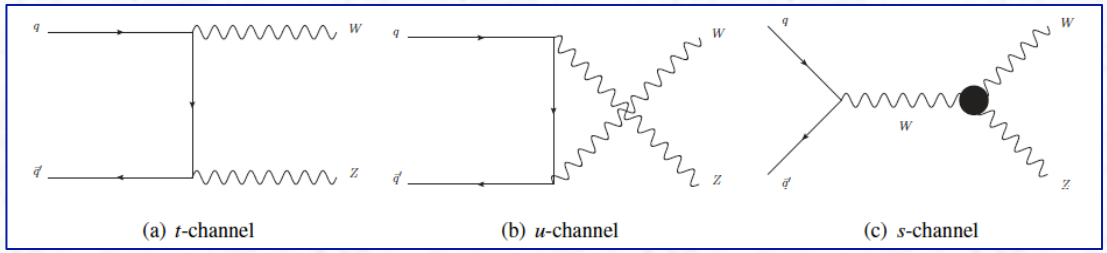
  tt: require b-tagging in control sample
  W+jets: "invert" electron ID (fake letpons from jets)



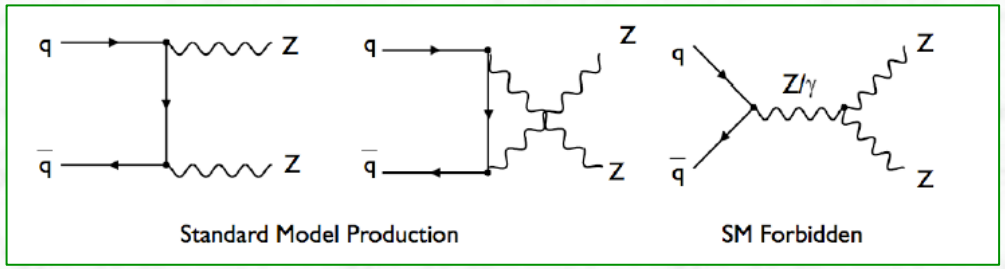
These are important distributions for the H → WW search

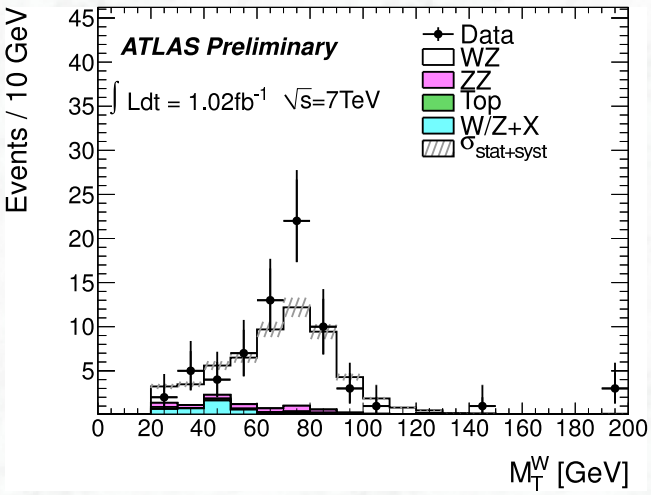
WZ and ZZ production

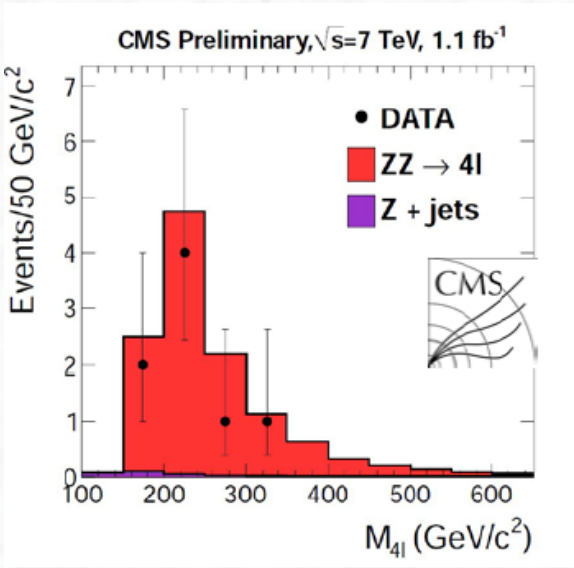
- Expected contributions within the Standard Model
  (t-, u, s-channel contributions for WZ)



(t- and u- channel contributions for ZZ)





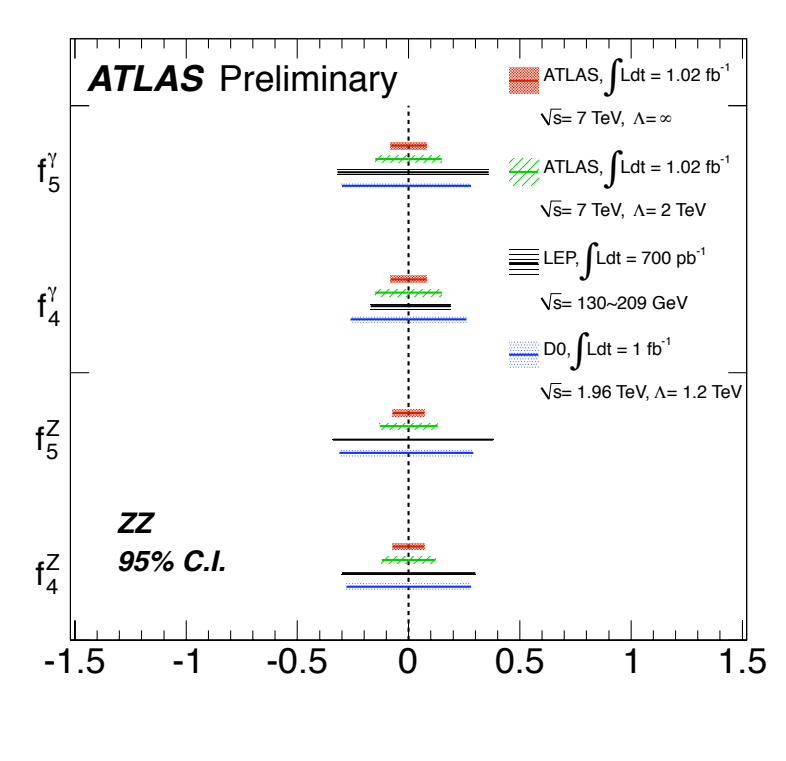


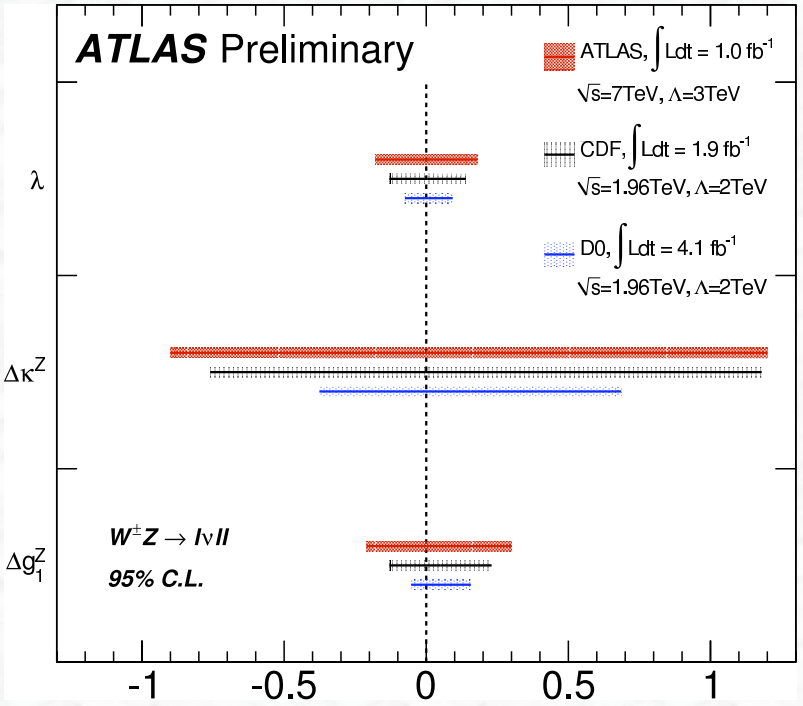
- Search for di-boson production in three (WZ→ lν ll) and four (ZZ→ ll ll) lepton final states

- These are important background processes for Higgs boson searches, e.g. H → 4 l

Limits on anomalous gauge couplings

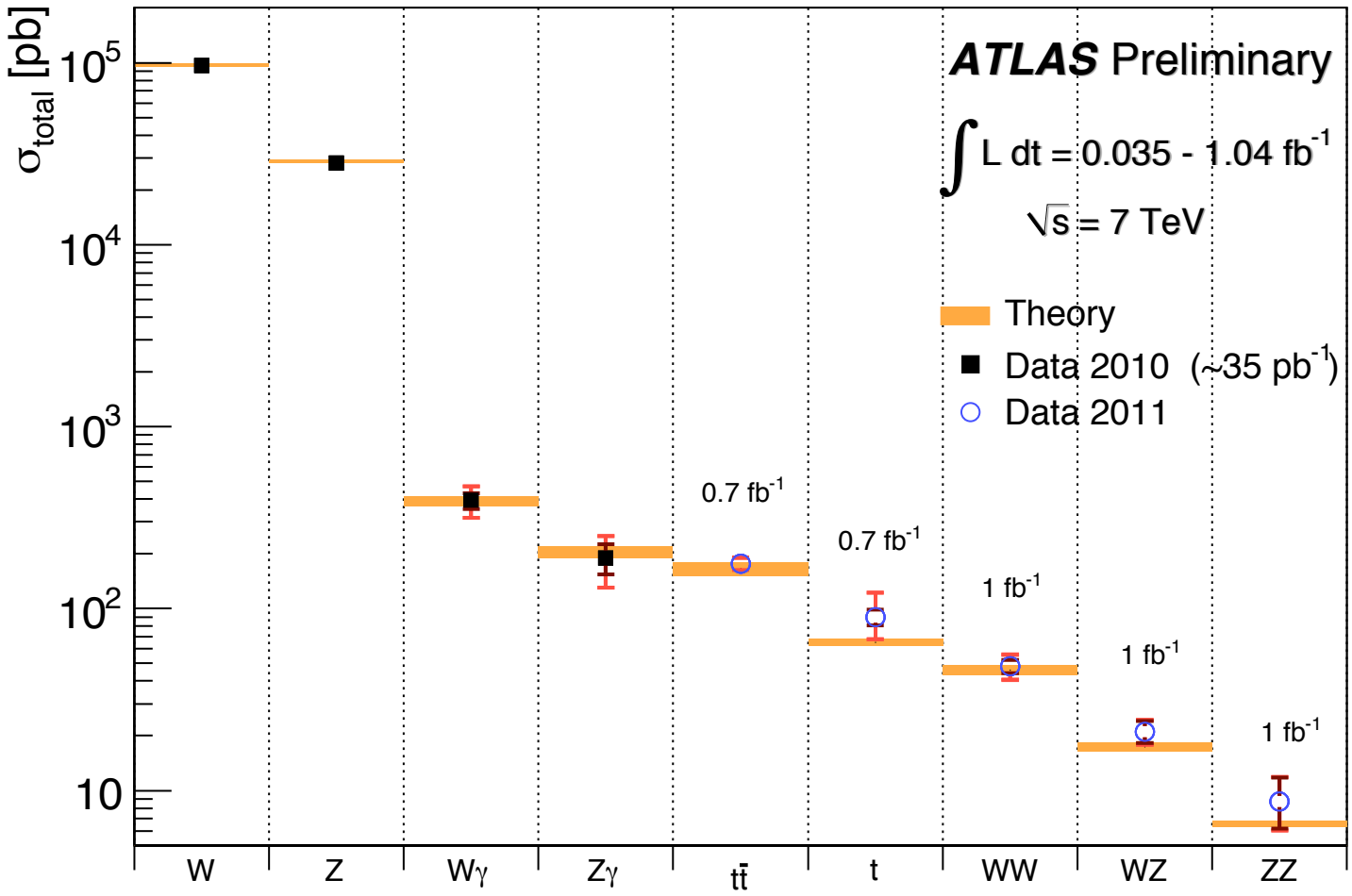
- Observed rates and differential distributions do not allow for significant contributions from anomalous gauge couplings
  → 95% C.L. limits on anomalous couplings are extracted





- LHC limits are becoming competitive with limits from the Tevatron (significant gain with more data expected)

Final cross section summary



Summary of the 1st lecture

- After a long way of design, construction, installation, commissioning of both machine and experiments the LHC had an excellent start in 2010
- The running in 2011 is superb; the integrated luminosity > 2 fb^{-1} already
- Physics analyses are done with incredible speed
- The Standard Model has been established, all relevant processes measured down to cross sections of 10 fb…
  In many areas measurements have reached the precision phase
- So far: no deviations from the Standard Model seen
- Ready for direct searches of low cross section processes