

10. Experimentelle Tests der Quantenchromodynamik

10.1 Drei-Jet-Ereignisse in e^+e^- -Kollisionen

10.2 QCD-Effekte in der tief-inelastischen Lepton-Nukleon-Streuung

10.3 Test der QCD in Proton-Antiproton-Kollisionen

10.4 Bestimmung der starken Kopplungskonstanten α_s

1977: DESY macht die Gluonen sichtbar

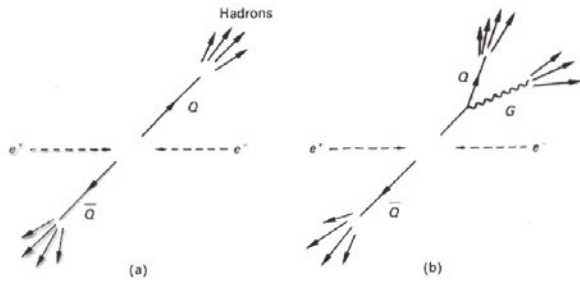


Fig. 8.27

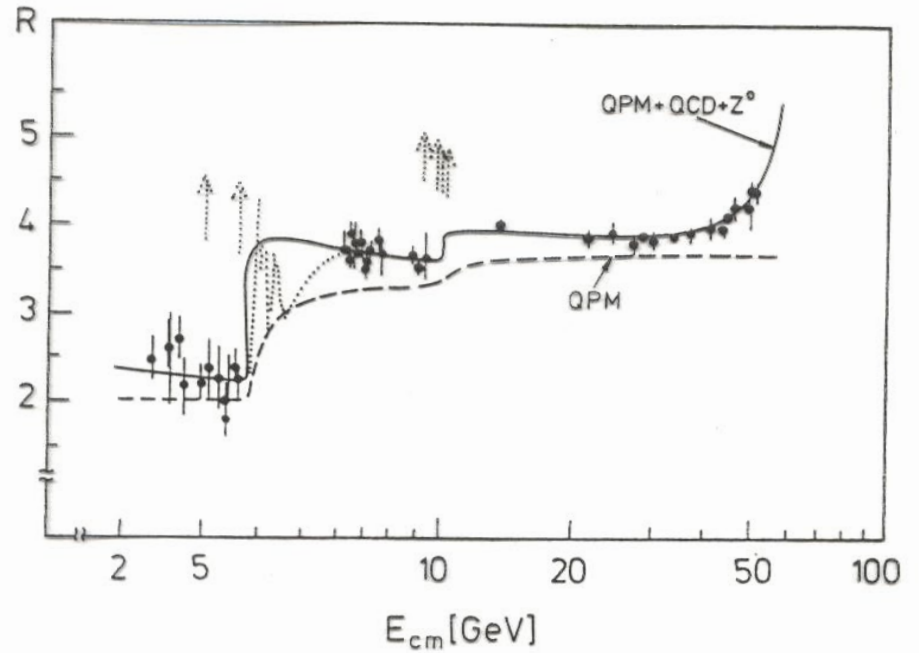
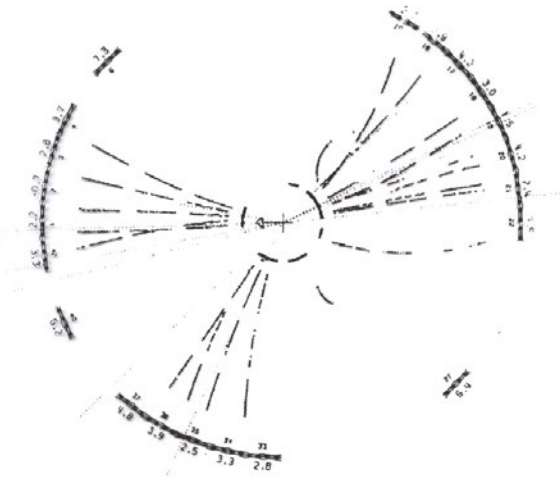
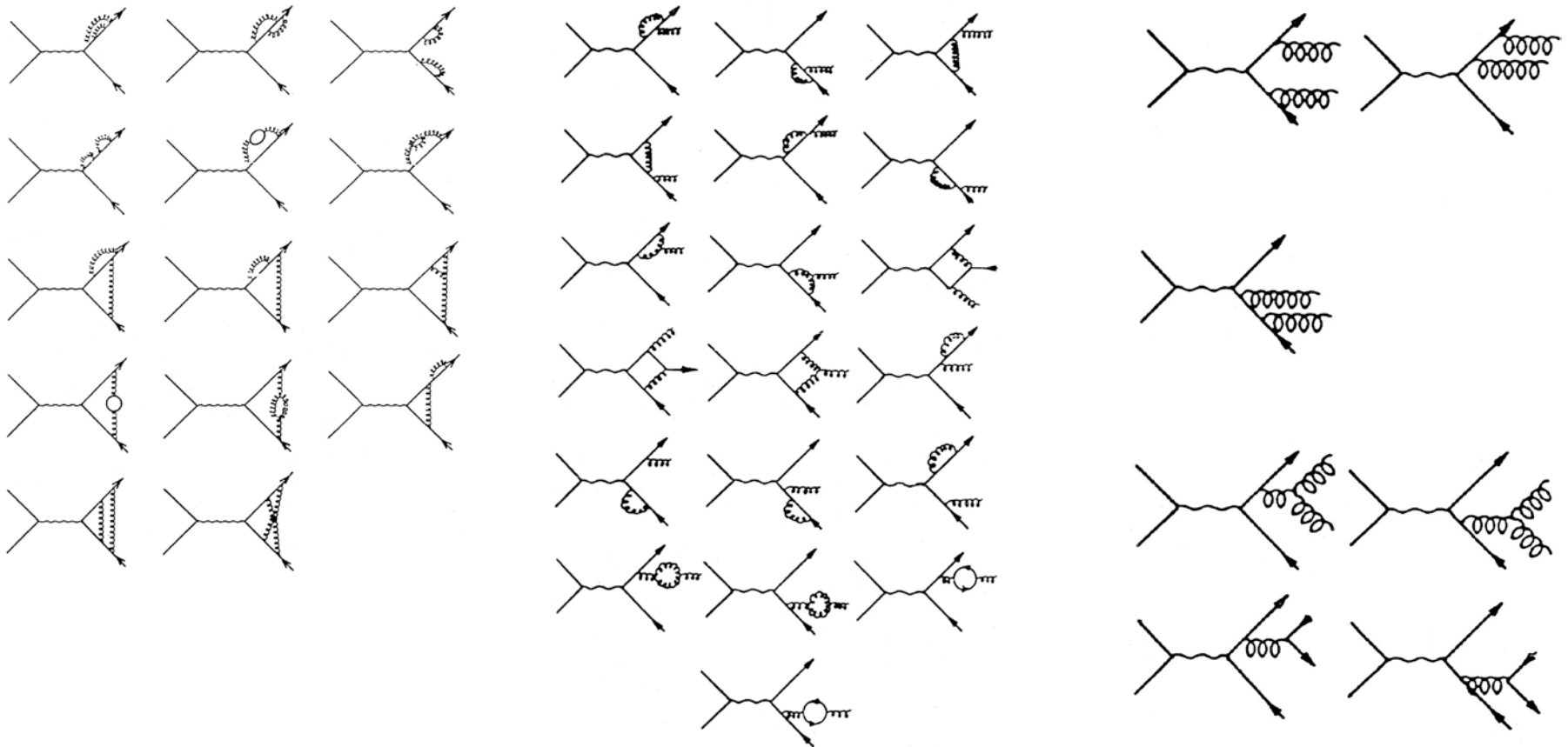
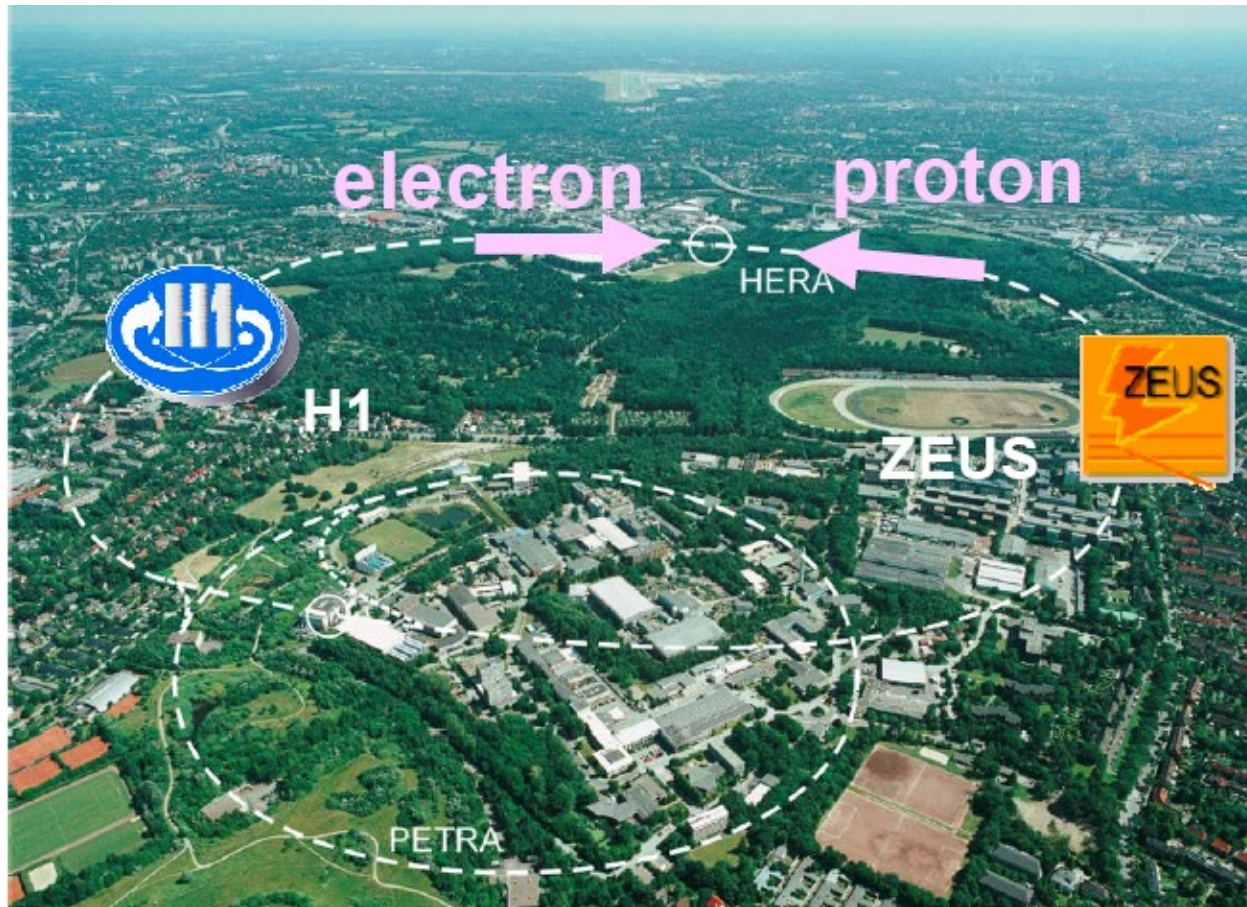


Abb. 12.20. Daten für das Verhältnis R und die Vorhersagen des Quark-Parton-Modells (QPM) und der QCD. Die ψ - und Υ -Resonanzen sind gestrichelt angedeutet. (Marshall 1989)

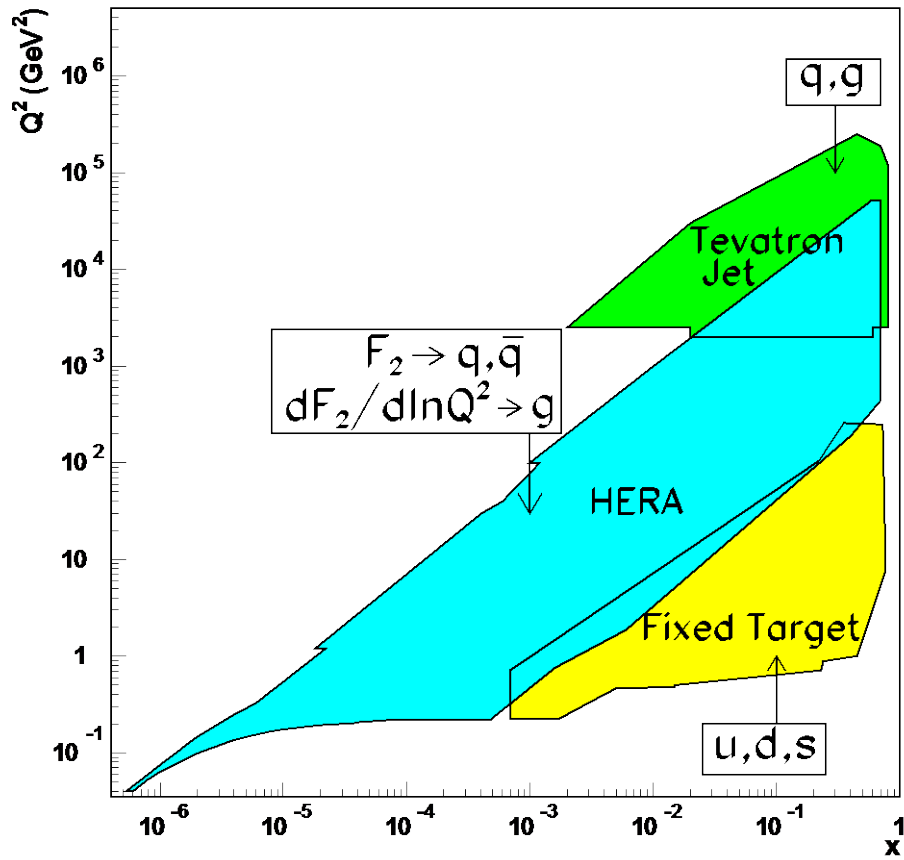


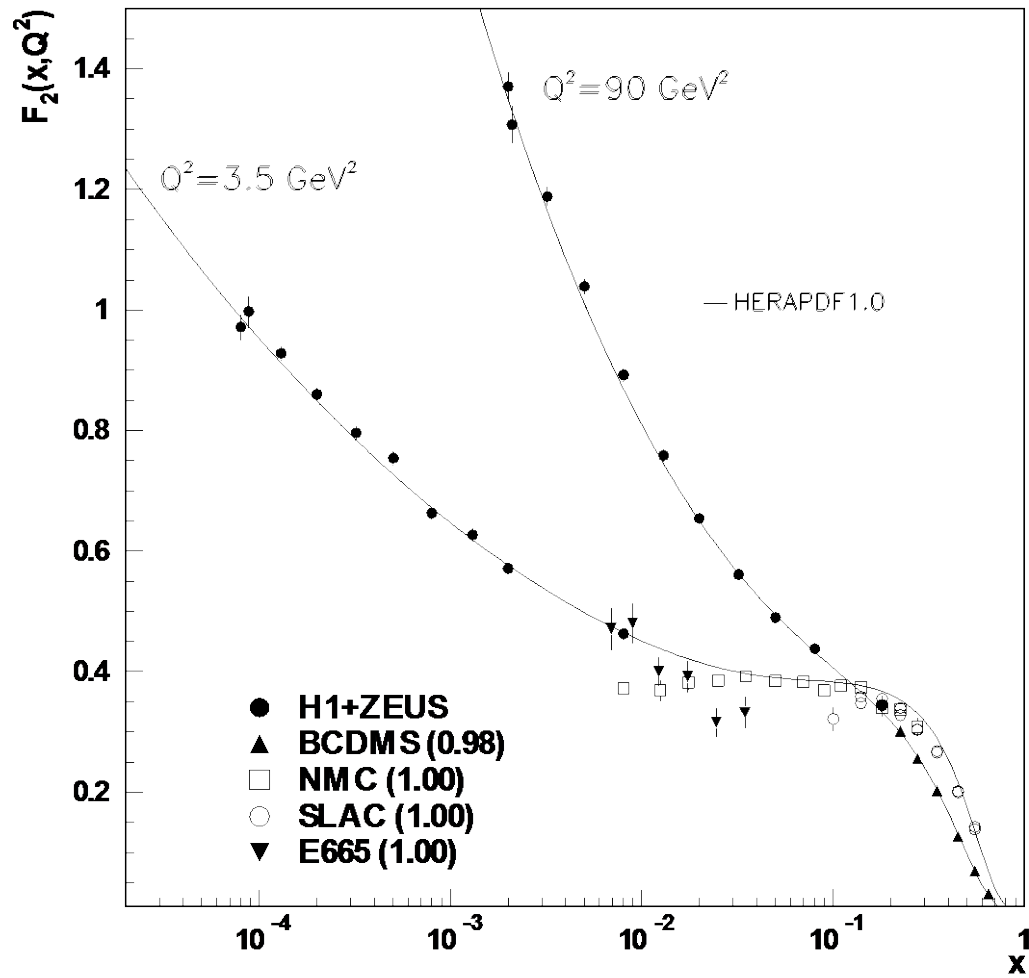
*Beiträge höherer Ordnung zur Jet-Produktion (2-, 3-, und 4-Jet-Ereignissen)
in e^+e^- Kollisionen*

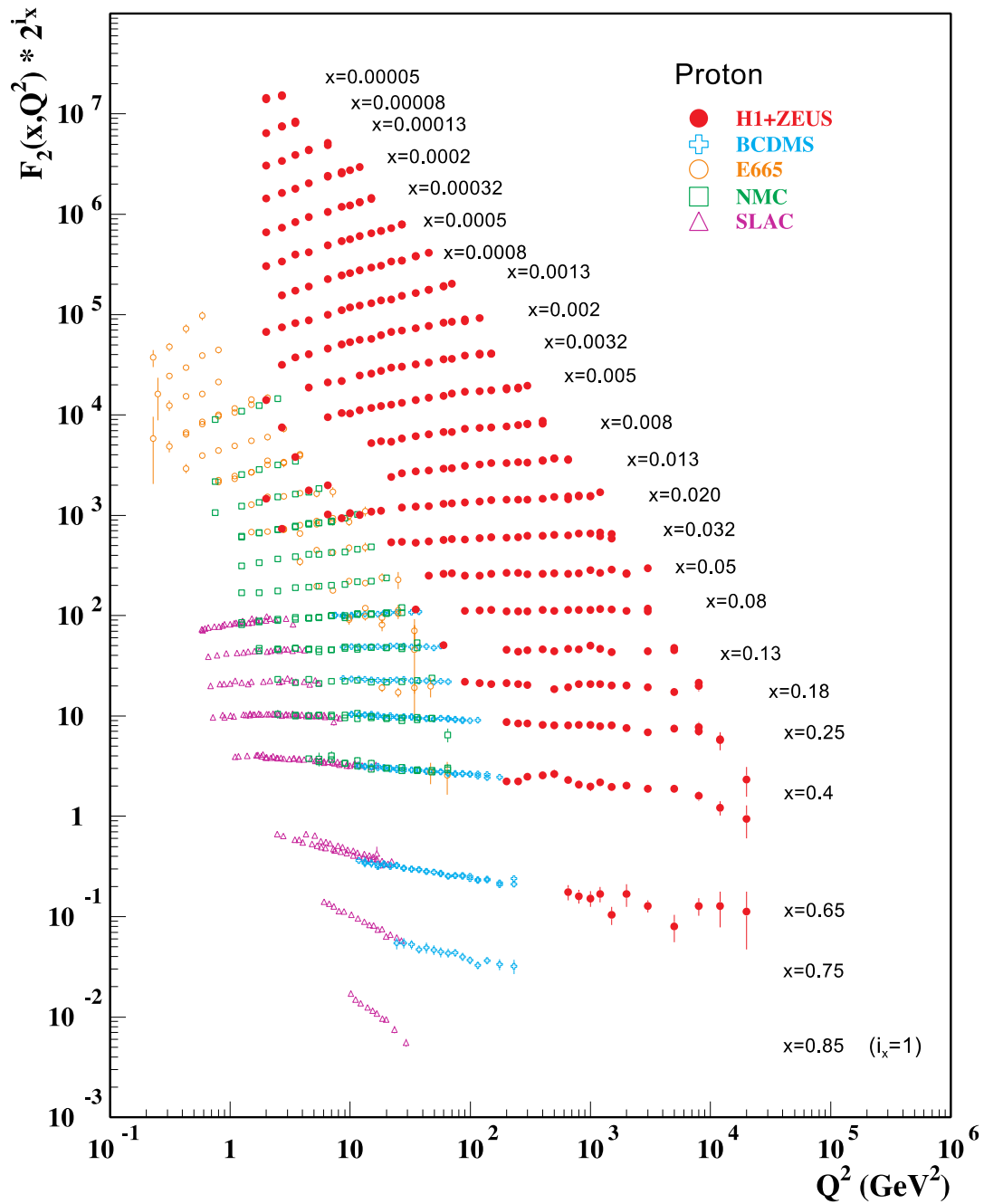
10.2 QCD-Effekte in der tief inelastischen Lepton-Nukleon-Streuung



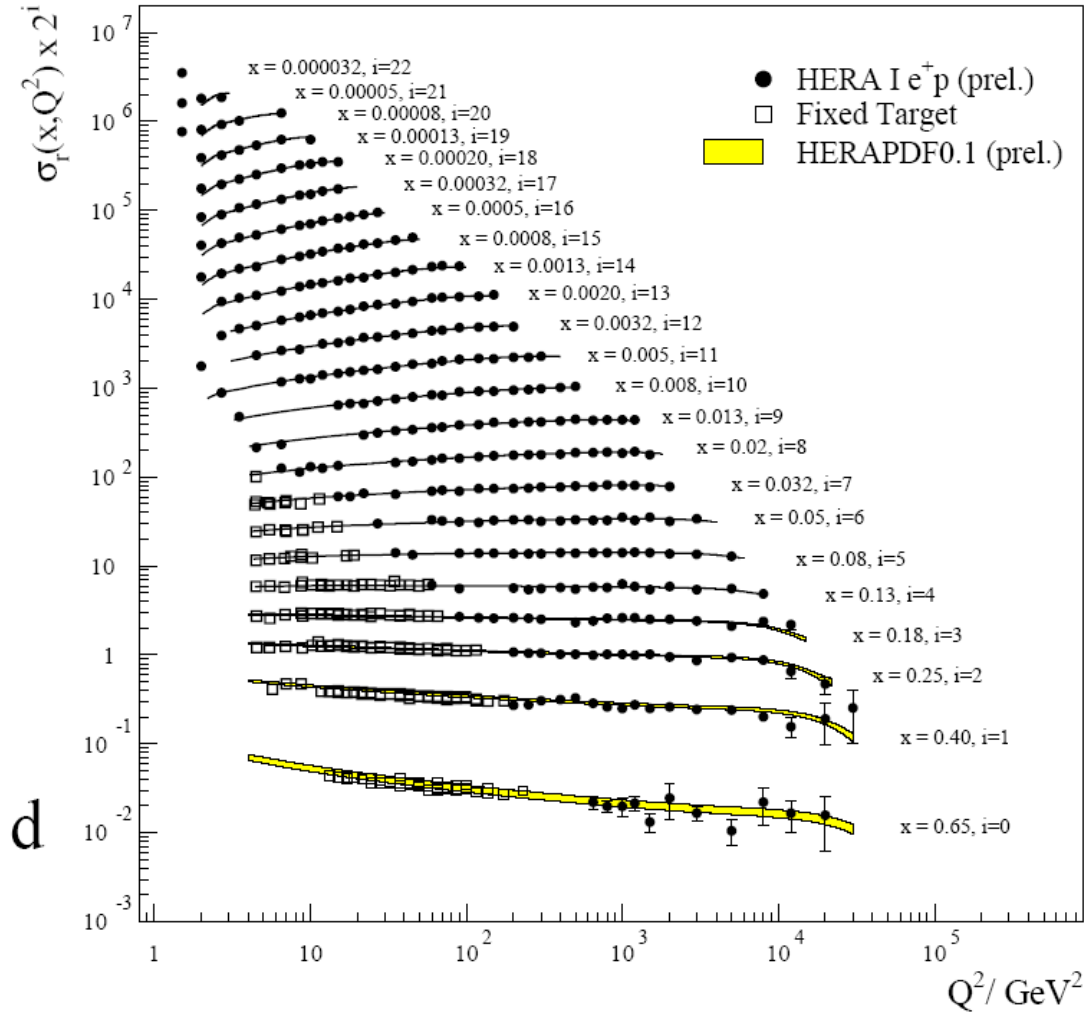
HERA-Beschleuniger am DESY in Hamburg (1990 – 2007:)
Elektron/Positron-Proton Kollisionen: 30 GeV e^\pm auf 920 GeV p







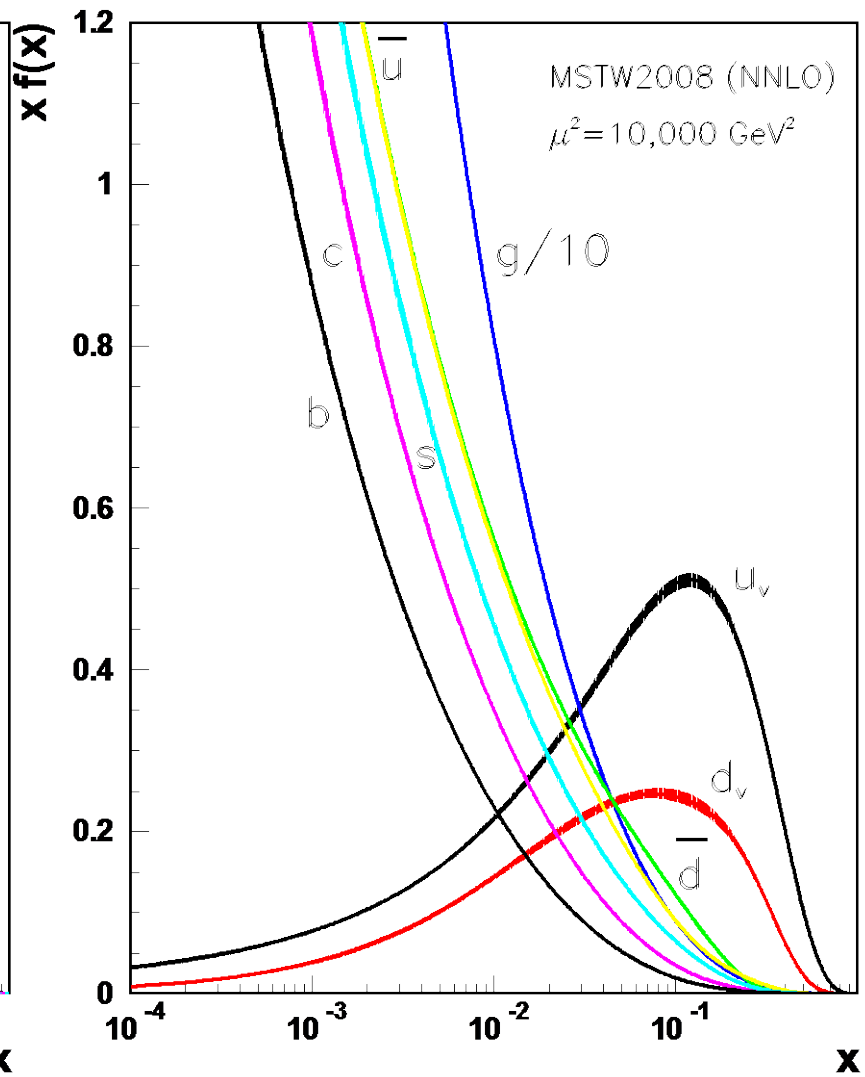
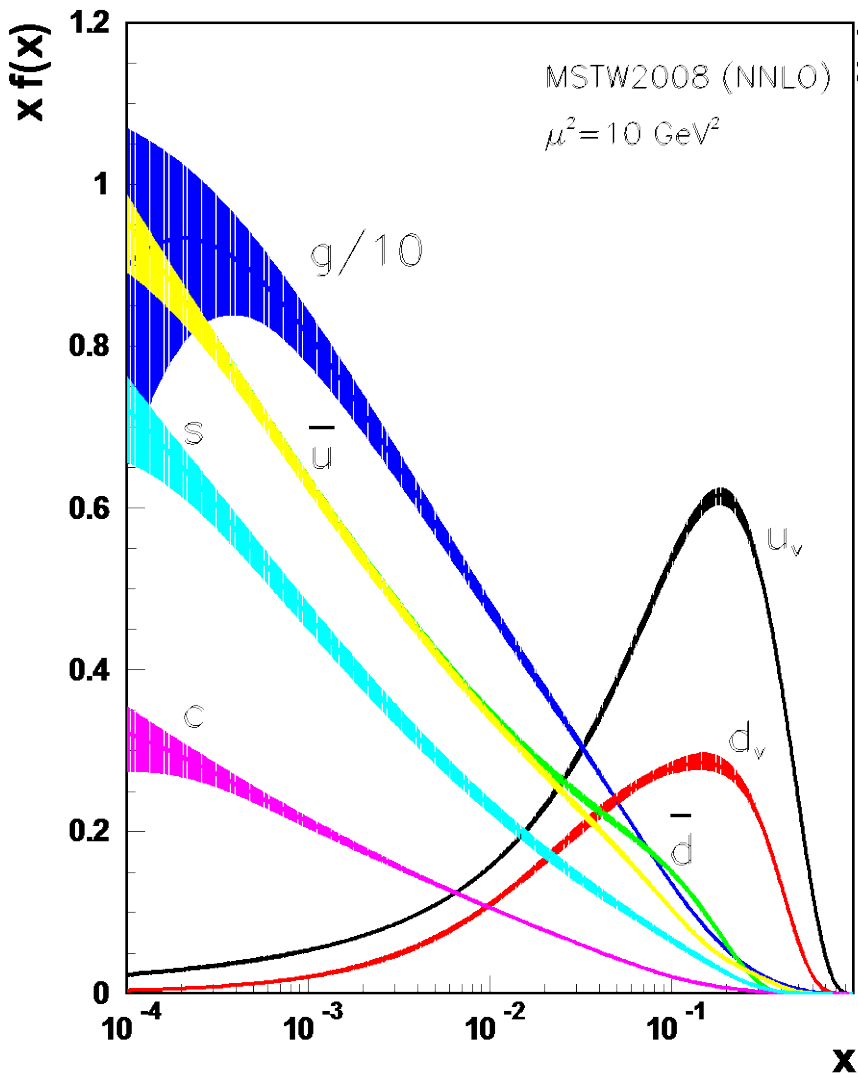
H1 and ZEUS Combined PDF Fit



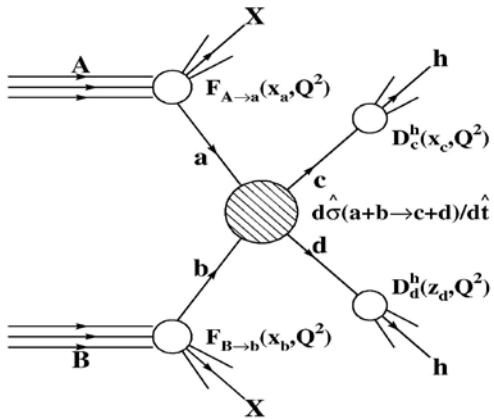
April 2008

HERA Structure Functions Working Group

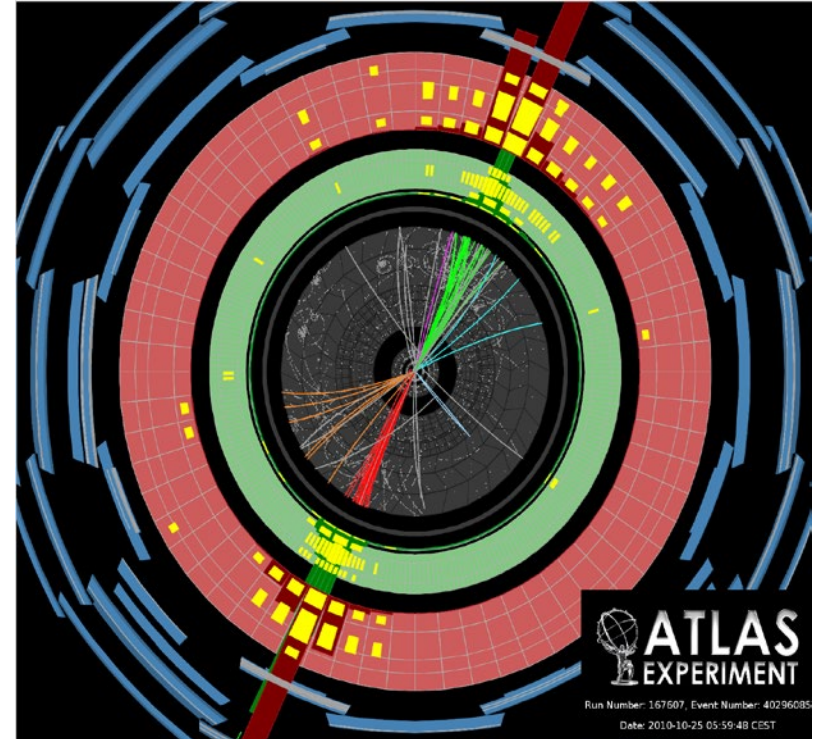
d



10.3 Test der QCD in Proton-Proton-Kollisionen



- Jet-Produktion
- Produktion von W- und Z-Bosonen
- Produktion von Top-Quarks



It is important to establish the Standard Model reference processes:

- Test of the theory itself

Deviations → evidence for Physics beyond the Standard Model

- Important to understand the detector performance

→ understand the so called “Fake” or “instrumental” background,
in particular for leptons (e,μ) and E_T^{miss}

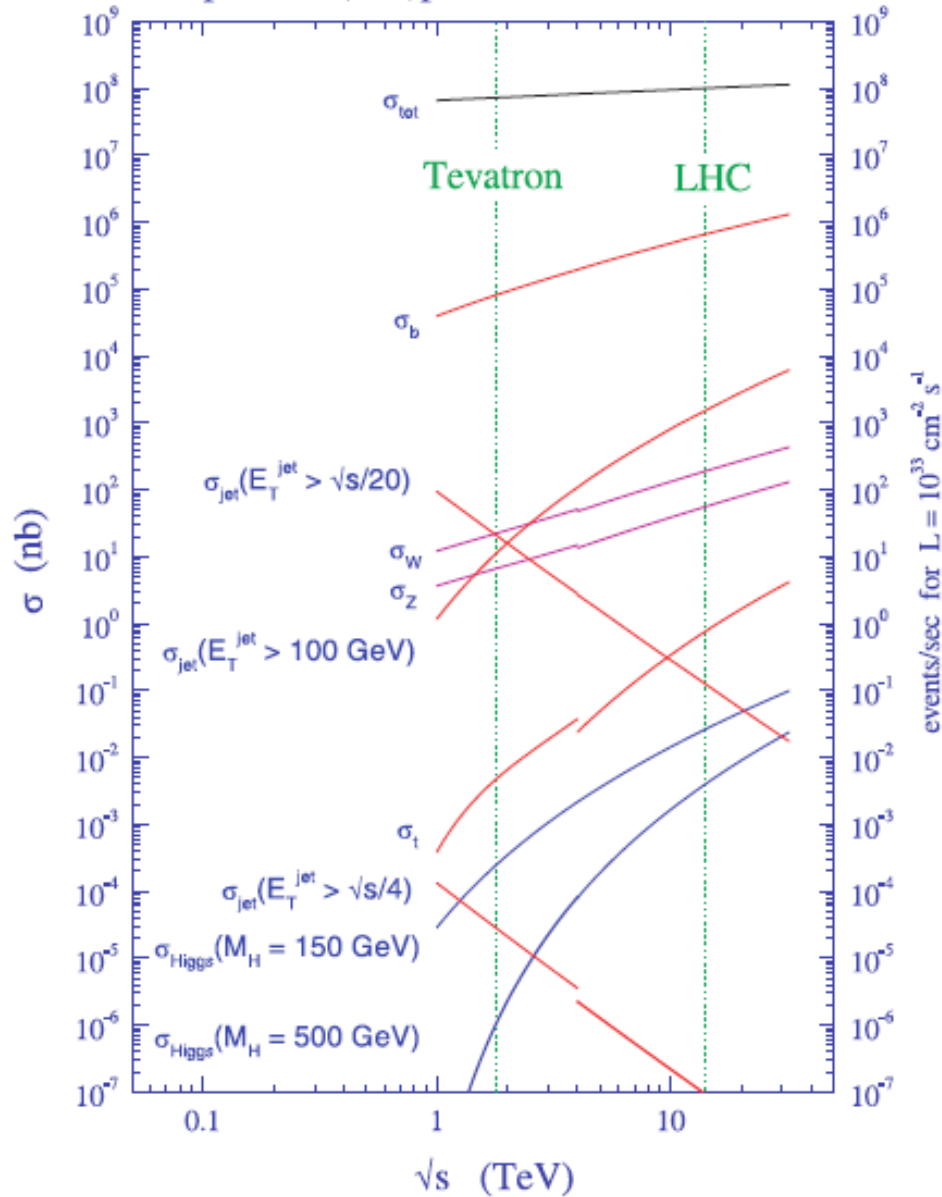
- Standard Model processes are important background processes for many searches for Physics Beyond the Standard Model

“Physics Background”

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

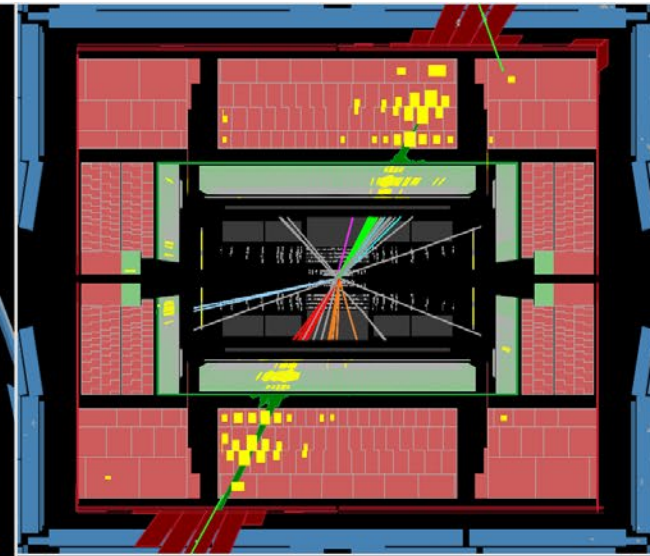
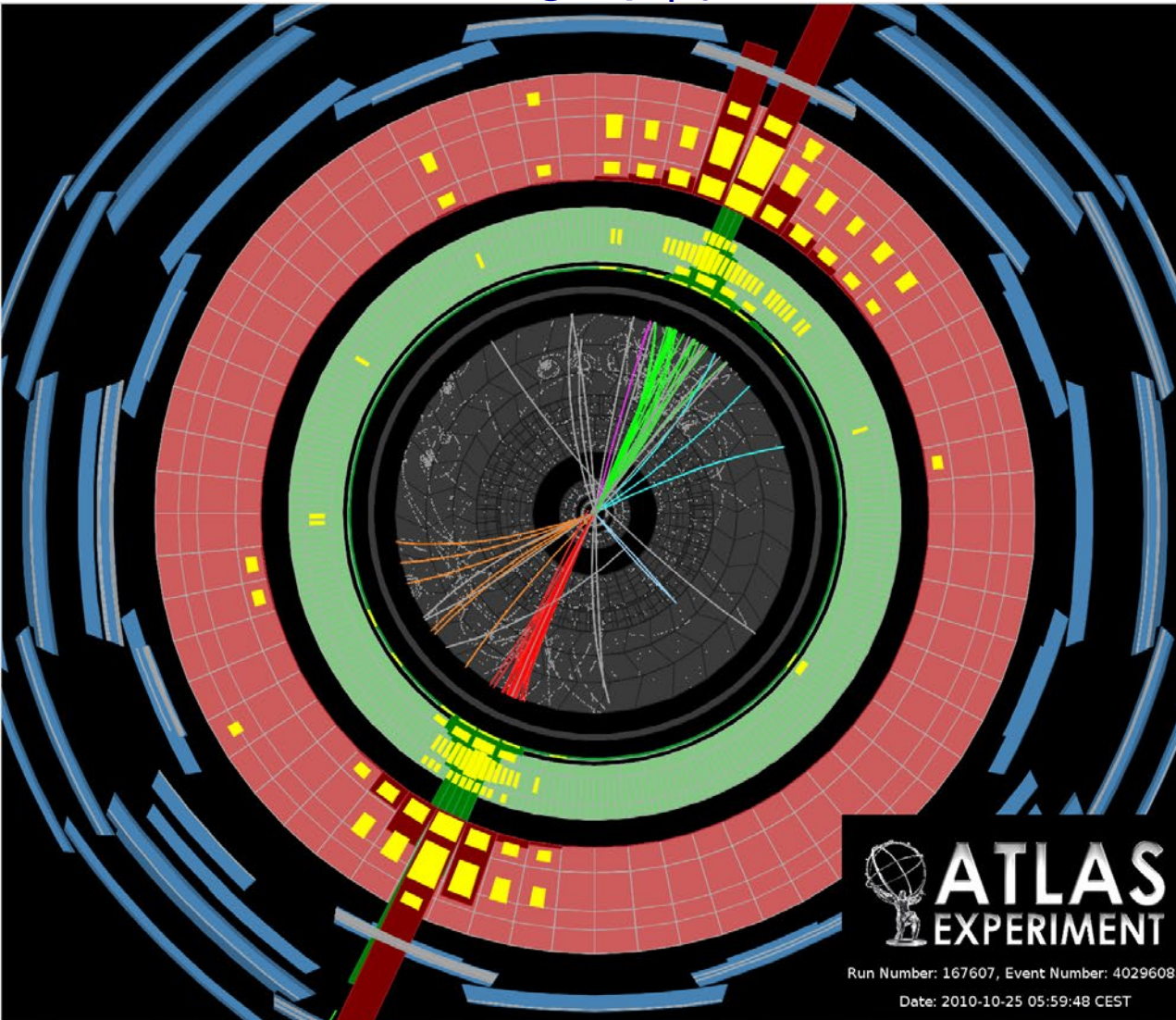
→ W/Z + jets and tt productions are omnipresent !

proton - (anti)proton cross sections

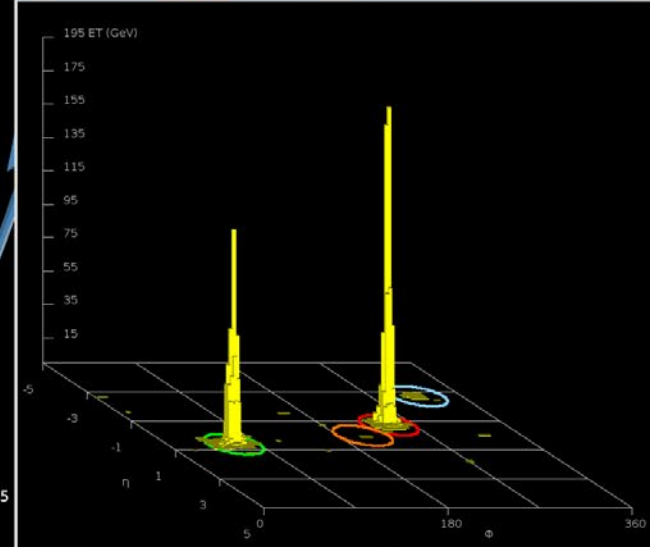


Cross sections for important hard scattering Standard Model processes at the Tevatron and the LHC colliders

High p_T jet events at the LHC

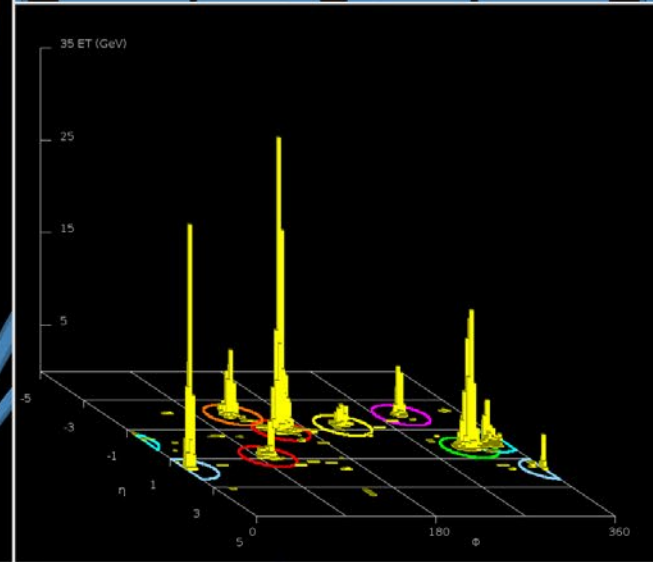
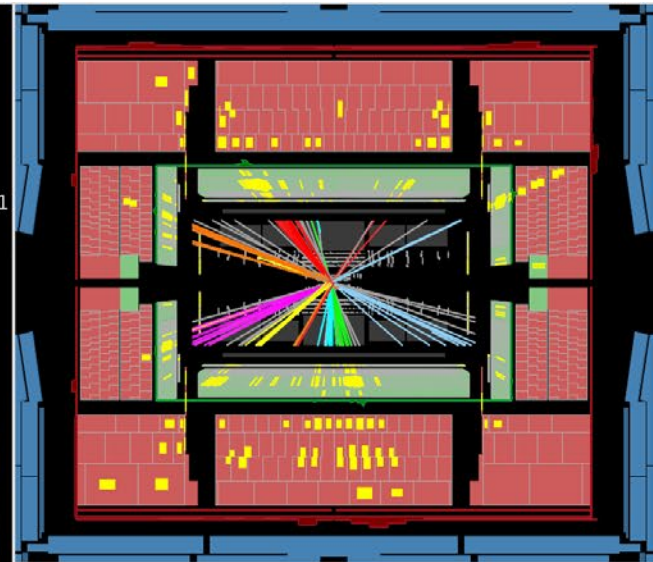
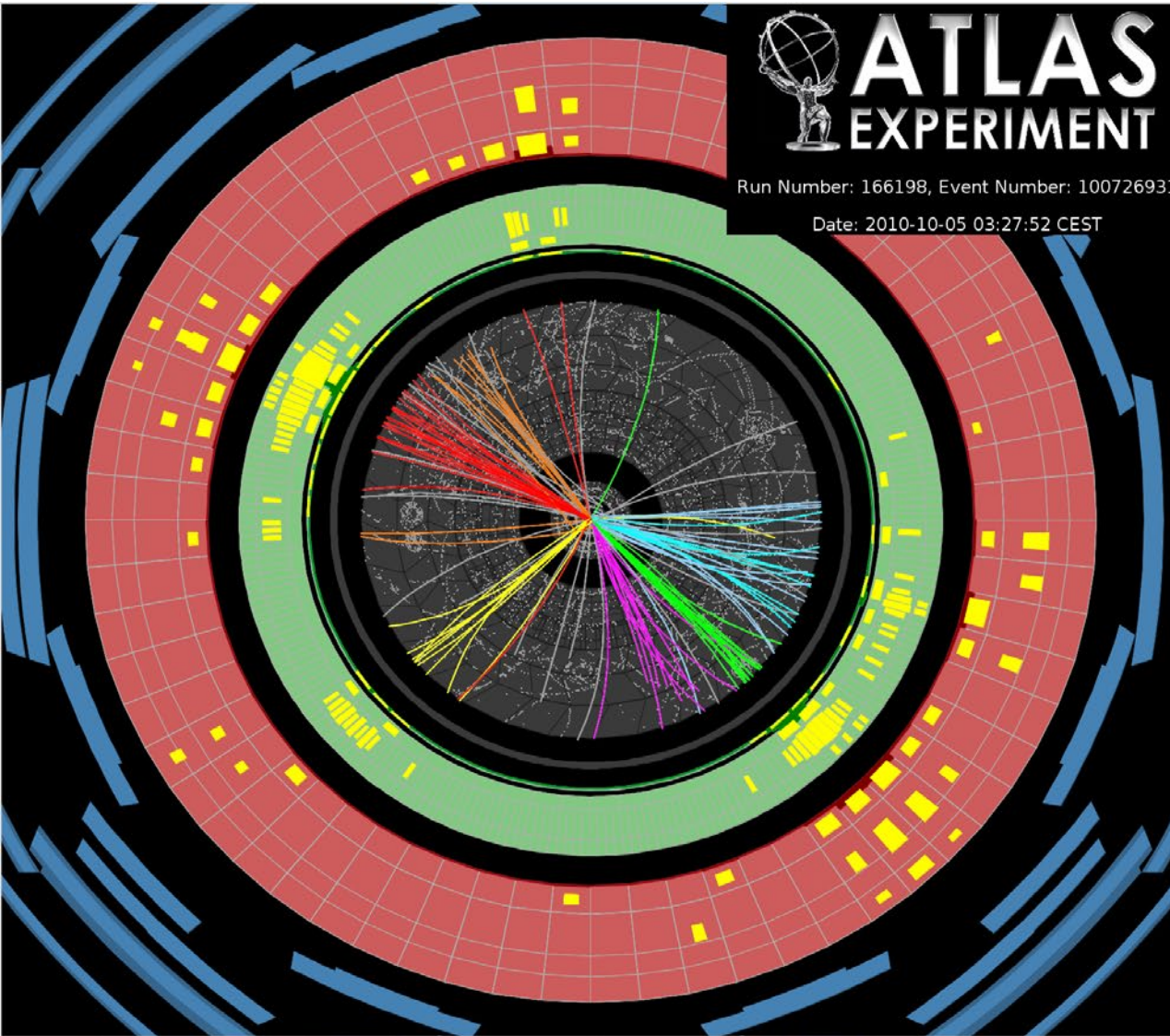


 **ATLAS**
EXPERIMENT
Run Number: 167607, Event Number: 40296085
Date: 2010-10-25 05:59:48 CEST



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](https://arxiv.org/abs/1101.047).

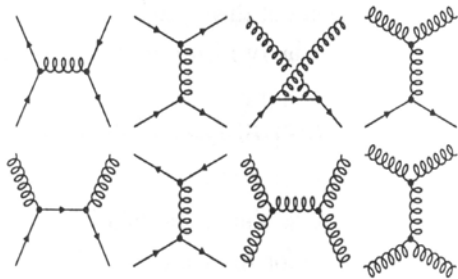
An event with a high jet multiplicity at the LHC



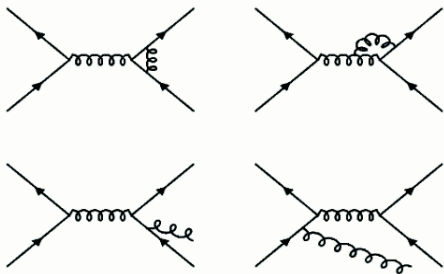
The highest jet multiplicity event collected by the end of October 2010, counting jets with p_T greater than 60 GeV: this event has eight. 1st jet (ordered by p_T): $p_T = 290$ GeV, $\eta = -0.9$, $\phi = 2.7$; 2nd jet: $p_T = 220$ GeV, $\eta = 0.3$, $\phi = -0.7$ Missing $E_T = 21$ GeV, $\phi = -1.9$, Sum $E_T = 890$ GeV. The event was collected on 5 October 2010.

Theoretical calculations

Leading order



...some NLO contributions

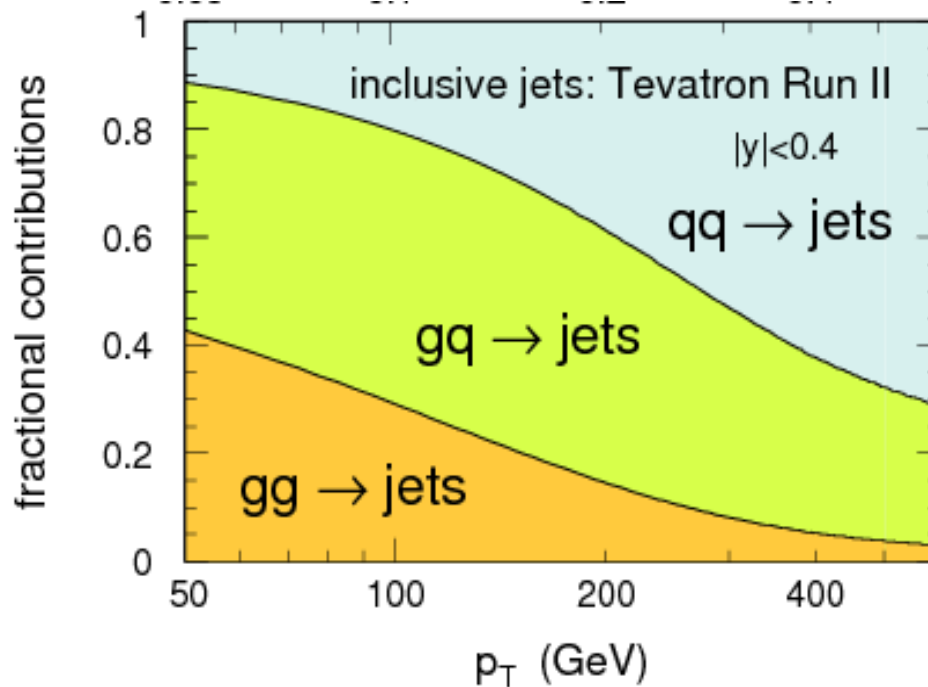


$$\frac{d\hat{\sigma}}{d\hat{t}}(ab \rightarrow cd) = \frac{|M|^2}{(16\pi\hat{s}^2)}$$

Subprocess	$ M ^2/g_s^4$	$ M(90^\circ) ^2/g_s^4$
$qq' \rightarrow qq'$ $q\bar{q}' \rightarrow q\bar{q}'$	$\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$	2.2
$qq \rightarrow qq$	$\frac{4}{9} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \right) - \frac{8}{27} \frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} \rightarrow q'\bar{q}'$	$\frac{4}{9} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \rightarrow q\bar{q}$	$\frac{4}{9} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} \right) - \frac{8}{27} \frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.6
$q\bar{q} \rightarrow gg$	$\frac{32}{27} \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} - \frac{8}{3} \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}$	1.0
$gg \rightarrow q\bar{q}$	$\frac{1}{6} \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} - \frac{3}{8} \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}$	0.1
$qg \rightarrow qg$	$\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} - \frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \rightarrow gg$	$\frac{9}{4} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} + \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2} + 3 \right)$	30.4

- Right: Results of the LO matrix elements for the various scattering processes, expressed in terms of the Mandelstam variables s , t and u . (Kripfganz et al, 1974);
- gg scattering is the dominant contribution under $\eta = 0$;
(sensitivity to gluons, sensitivity to gluon self-coupling, as predicted by QCD)
- NLO predictions have meanwhile been calculated (2002).

The composition of the partons involved as function of the p_T of the jet at the Tevatron:

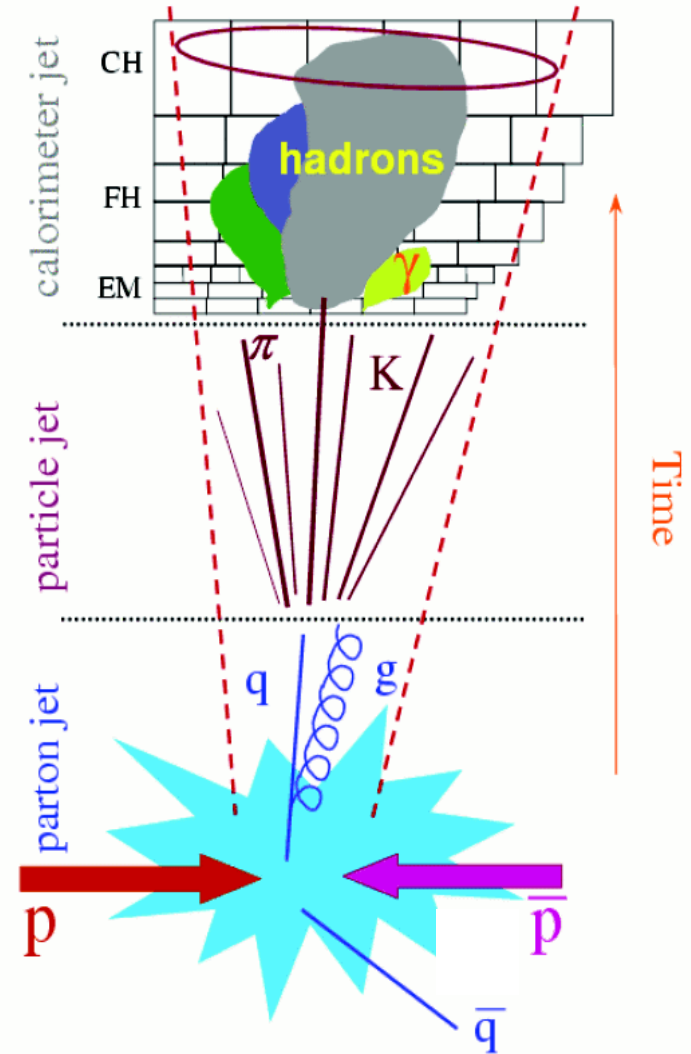


Tevatron,
ppbar, $\sqrt{s} = 1.96$ TeV,
central region $|\eta| < 0.4$

- qq scattering dominates at high p_T
- However, gluons contribute over the full range

Jet reconstruction and energy measurement

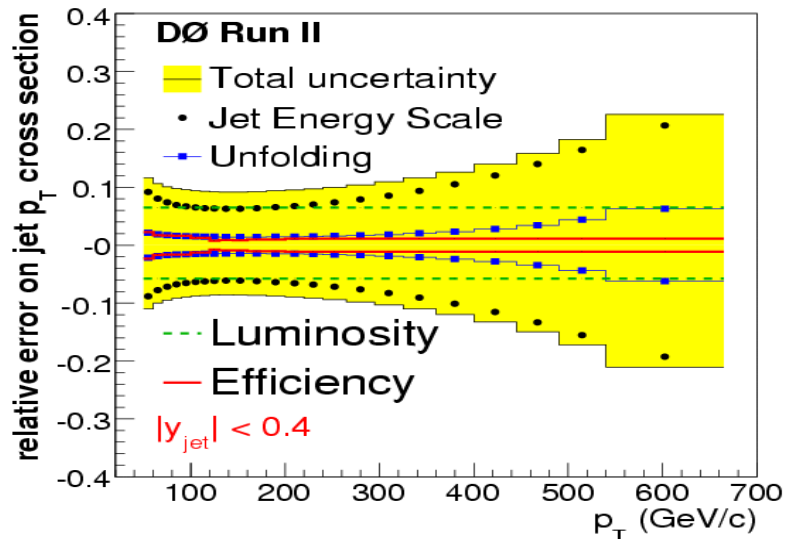
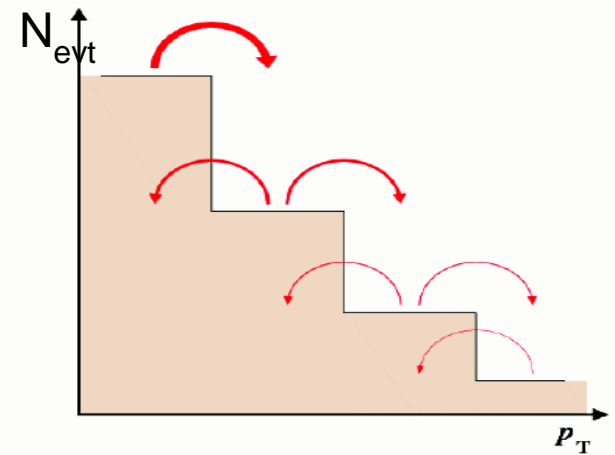
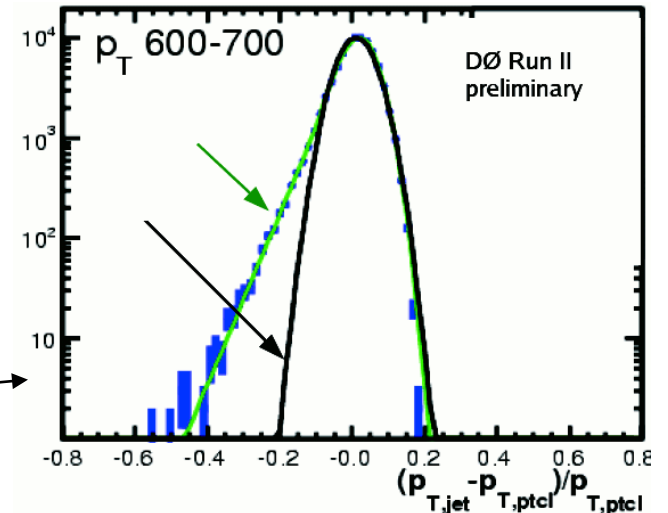
- A jet is NOT a well defined object
(fragmentation, gluon radiation, detector response)
- The detector response is different for particles interacting electromagnetically (e, γ) and for hadrons
→ for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level“ (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



Experimental issues

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

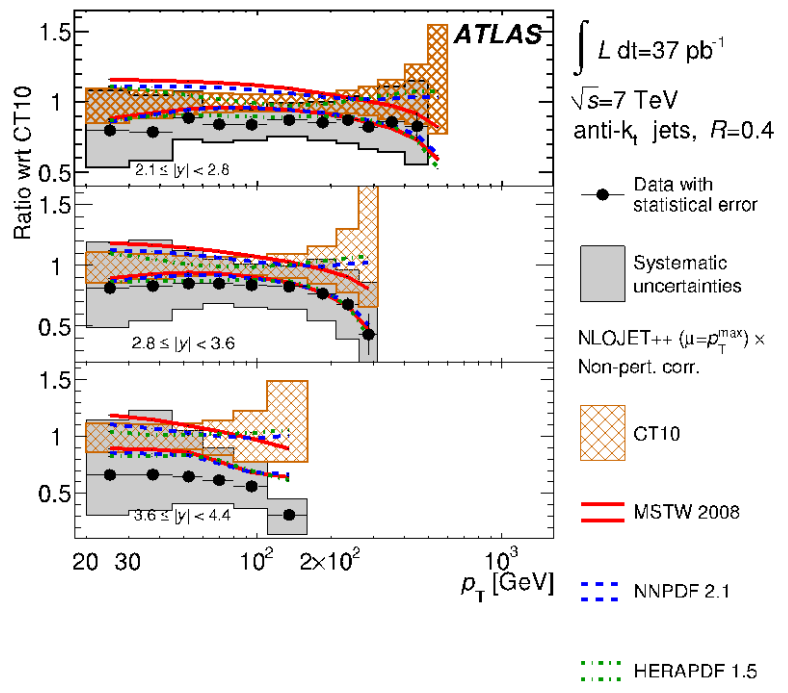
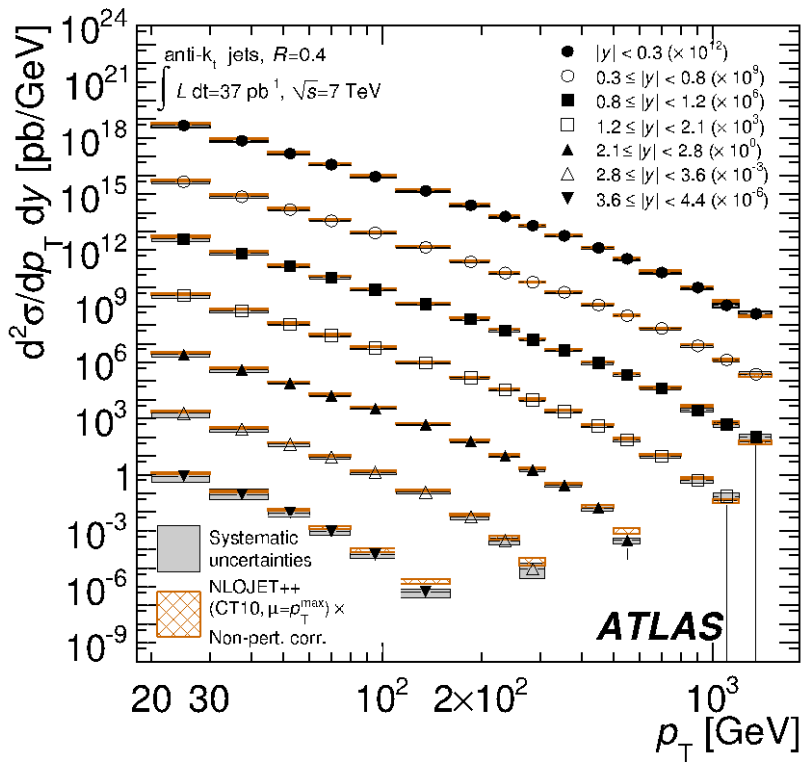
- In principle a simple counting experiment
- However, steeply falling p_T spectra are sensitive to jet energy scale uncertainties and resolution effects (migration between bins) → corrections (unfolding) to be applied
- Sensitivity to jet energy scale uncertainty:
 DØ: 1% energy scale error → 10% cross section uncert. at $|\eta| < 0.4$



Major exp. errors:
energy scale, luminosity (6%),...



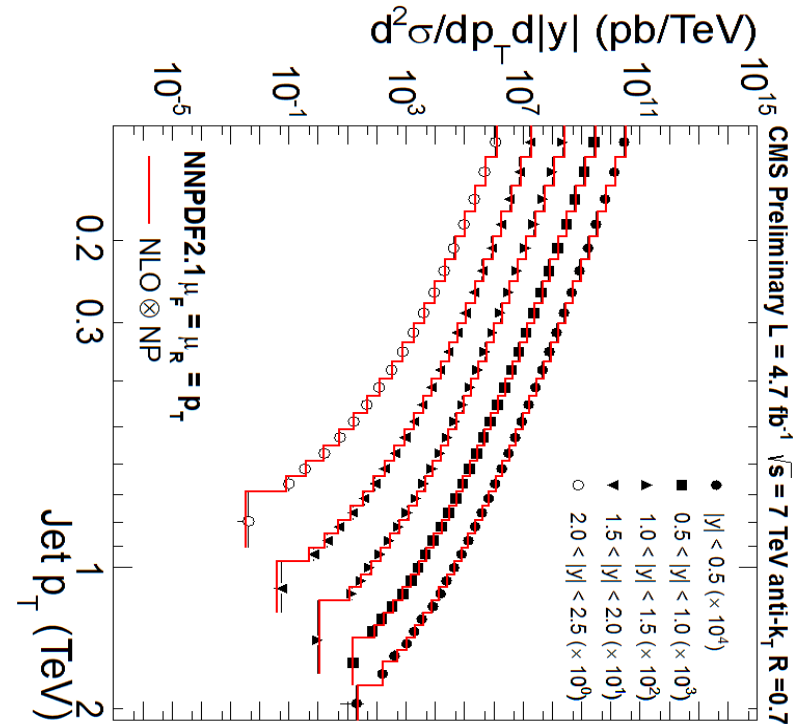
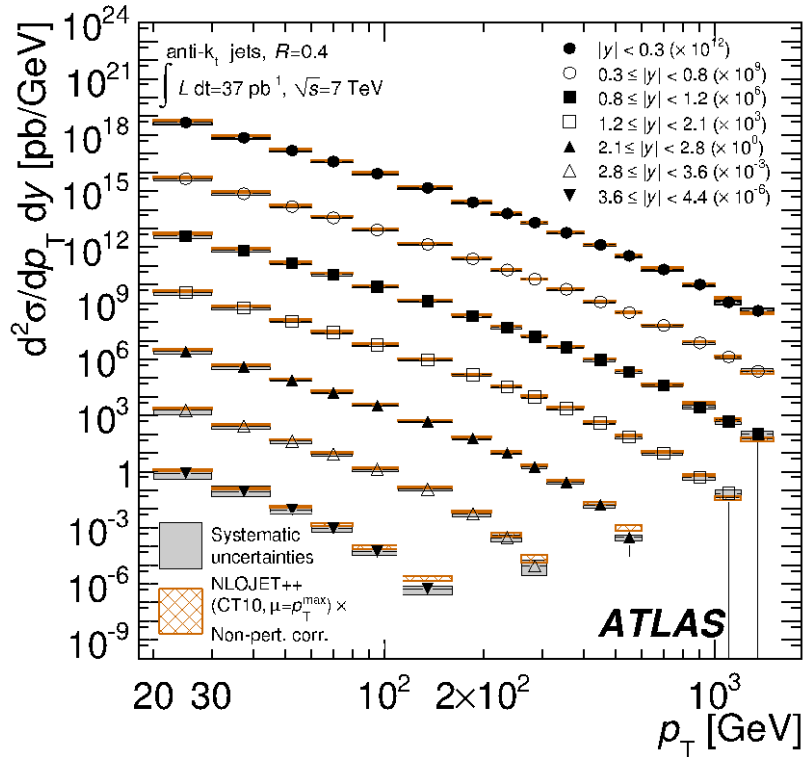
Double differential cross sections, as function of p_T and rapidity y (full 2010 data set)



somewhat larger deviations in the forward region

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

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

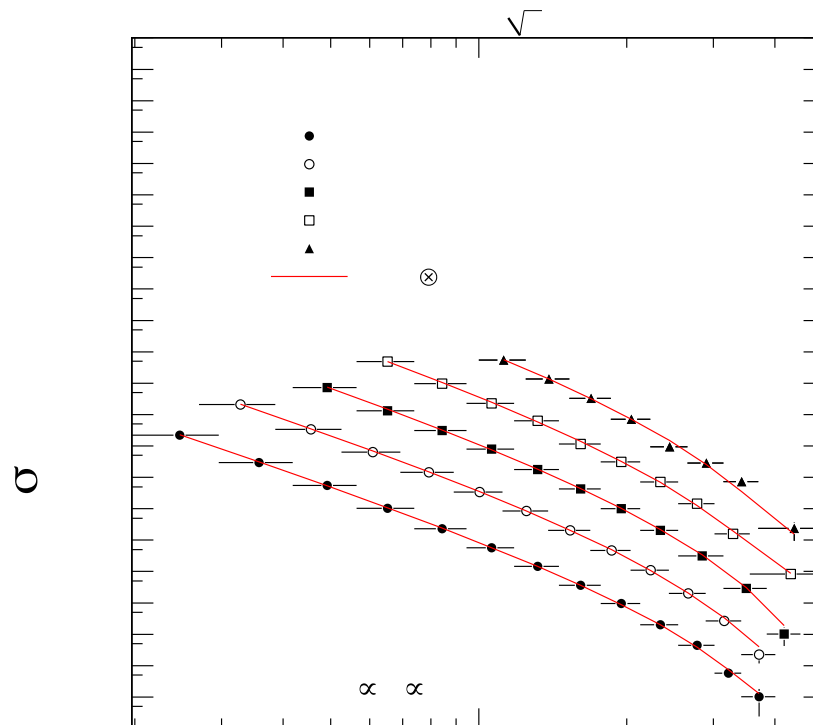
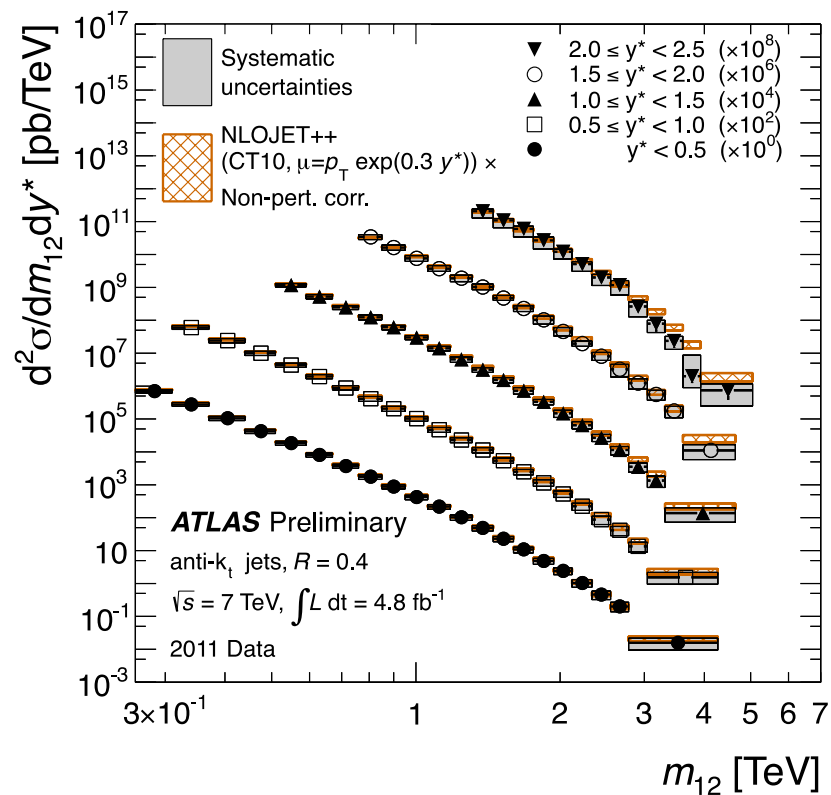


CMS: include full 2011 data set;
comparison up to 2 TeV (central rapidities)

- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: missing higher order corrections, parton density functions, α_s , ...



Invariant di-jet mass spectra

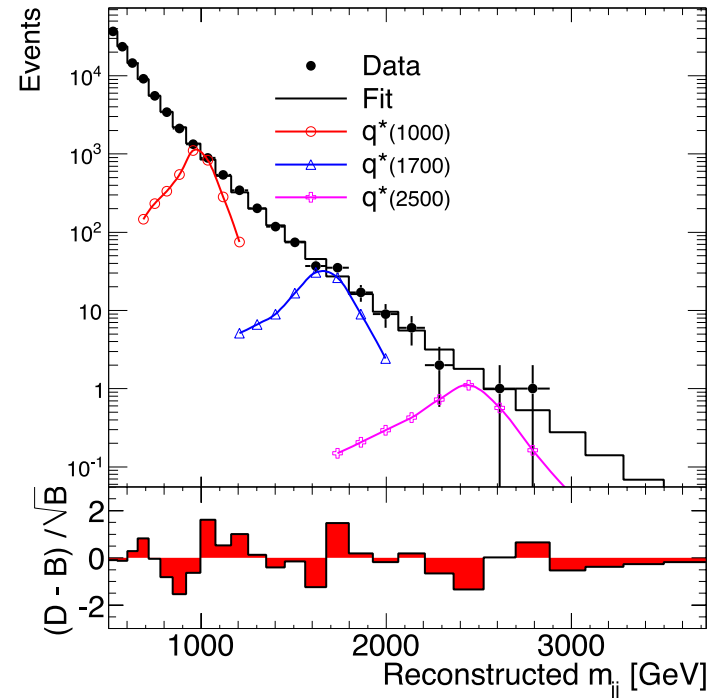


- Important for:
- Test of QCD
 - Search for new resonances decaying into two jets (\rightarrow next slide)



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

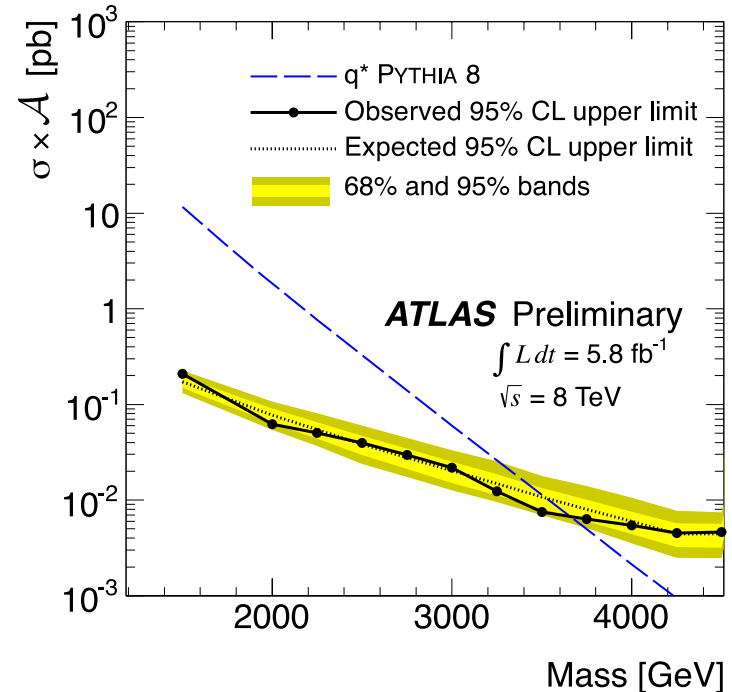
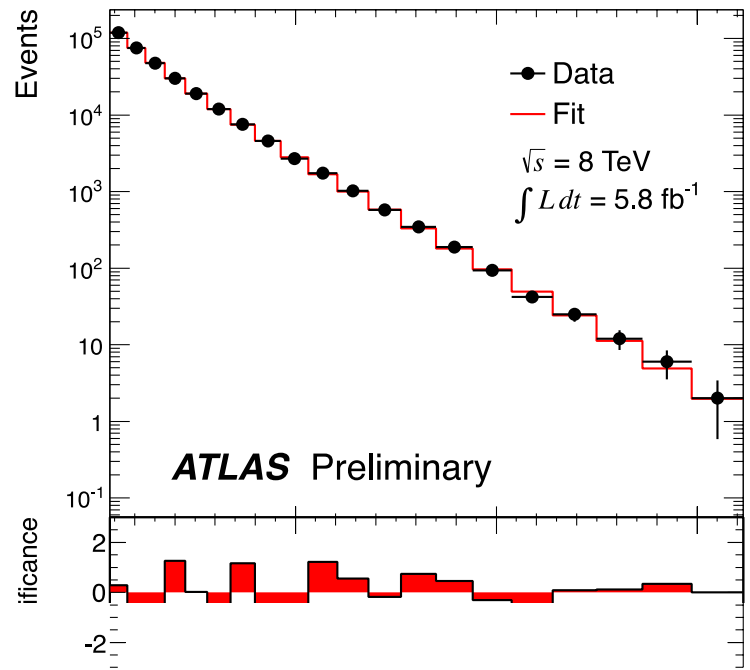


CDF (Tevatron), $L = 1.13 \text{ fb}^{-1}$: $0.26 < m_{q^*} < 0.87 \text{ TeV}$

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

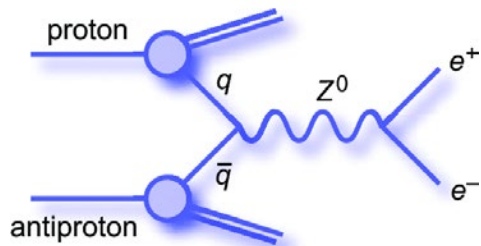


- Include new data at $\sqrt{s} = 8$ TeV (2012)
- Invariant di-jet masses up to 4.1 TeV

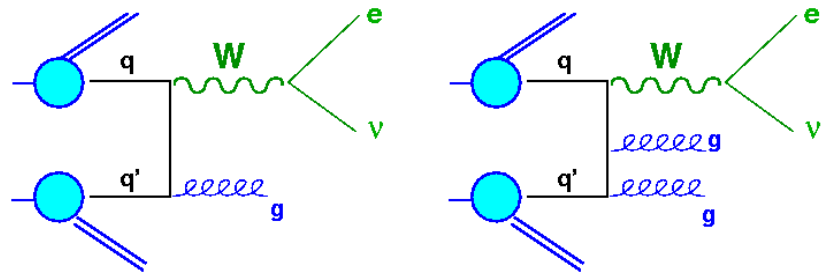


CDF (Tevatron), $L = 1.13 \text{ fb}^{-1}$:	$0.26 < m_{q^*} < 0.87 \text{ TeV}$
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ATLAS (LHC), $L = 5.8 \text{ fb}^{-1}$, 8 TeV:	$0.60 < m_{q^*} < 2.64 \text{ TeV}$
	$m_{q^*} < 3.66 \text{ TeV}$

QCD aspects in W/Z (+ jet) production

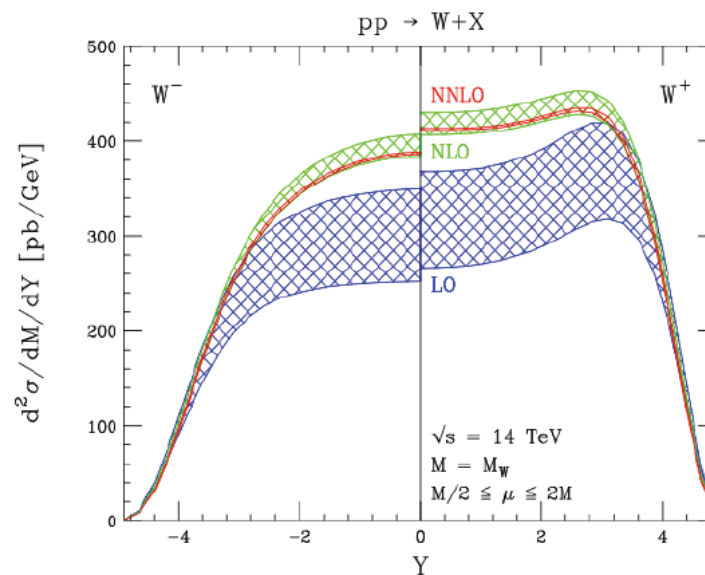
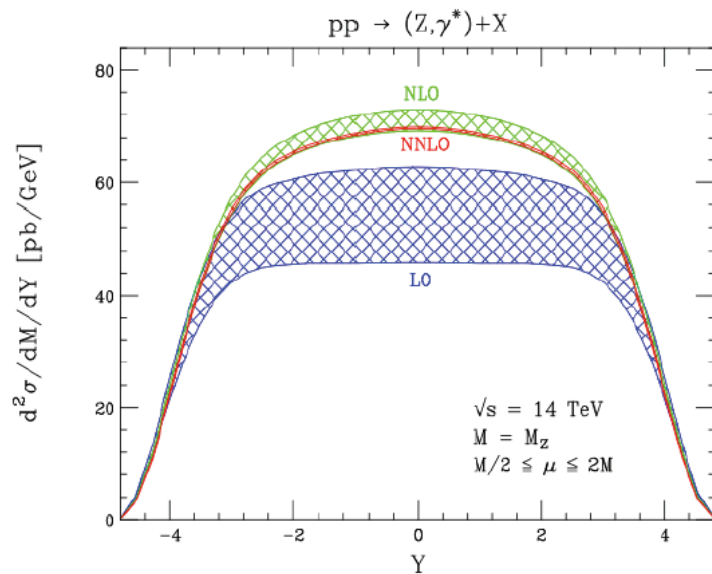
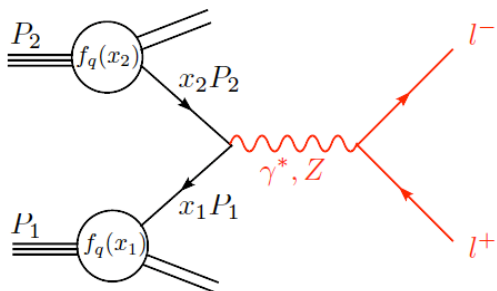


QCD at work



- 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

Example: Drell-Yan production of W/Z bosons



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

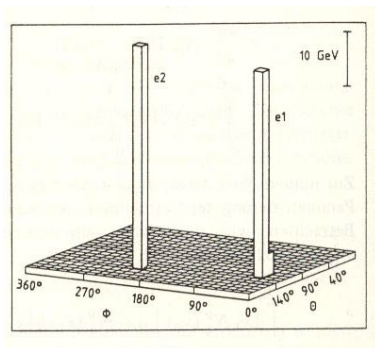
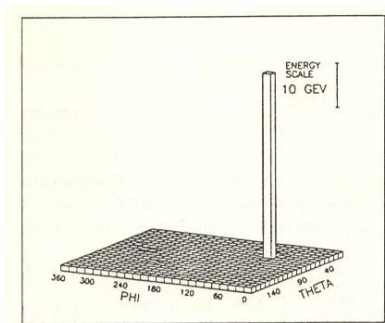
How do W and Z events look like ?

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

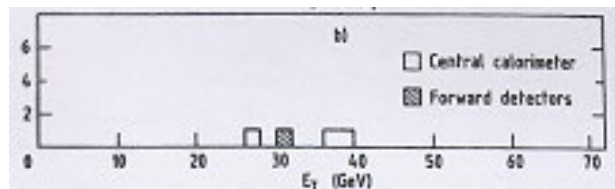
→ Search for leptonic decays: $W \rightarrow \ell \nu$ (large $P_T(\ell)$, large E_T^{miss})
 $Z \rightarrow \ell \ell$

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

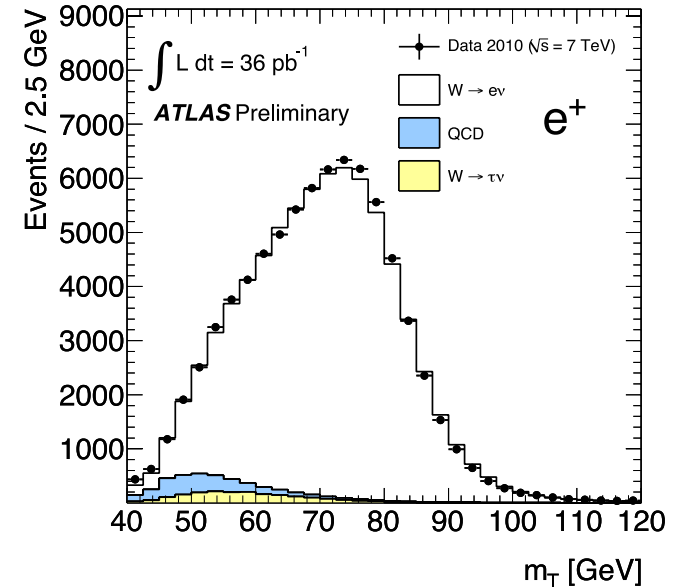
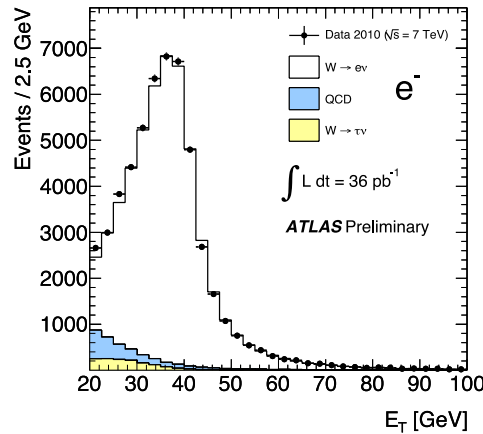
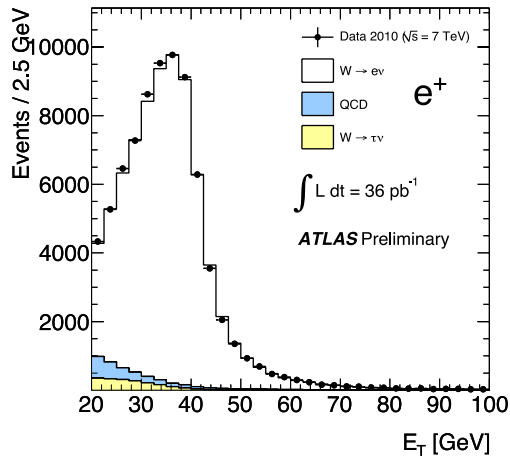
W/Z discovery by the UA1 and UA2 experiments at CERN
(1983/84)



Transverse momentum of
the electrons



W/Z selections in the ATLAS / CMS experiments



Electrons:

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

Z $\rightarrow ee$

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

W $\rightarrow e\nu$

- Missing transverse momentum $> 25 \text{ GeV}/c$
- Transverse mass cut $M_T > 50 \text{ GeV}$

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

Transverse mass

(longitudinal component of the neutrino cannot be measured)

Ingredients for cross-section measurements

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

- Number of W/Z signal candidates $N^{\text{sig}} = N^{\text{evt}} - N^{\text{back}}$
Estimated background (Physics background, “fake” background,...)
- $C_{W(Z)}$: reconstruction efficiencies, detector effects, ...
- $A_{W(Z)}$: acceptance (usually the final state products are measured in a so called fiducial region of the detector,
e.g. η coverage of the muon detector, p_T threshold of the reconstruction)

This last quantity can only be calculated with Monte Carlo, using theoretical inputs !!

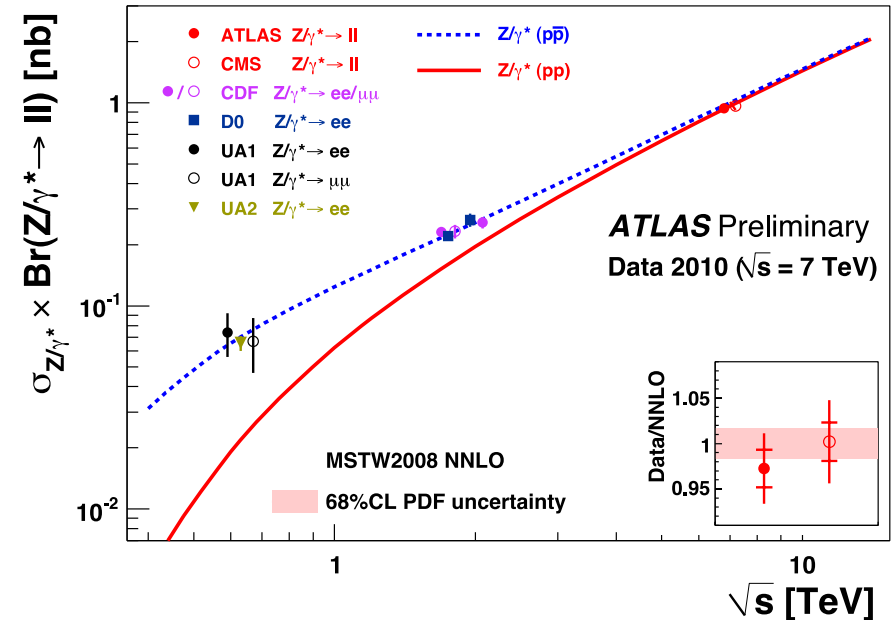
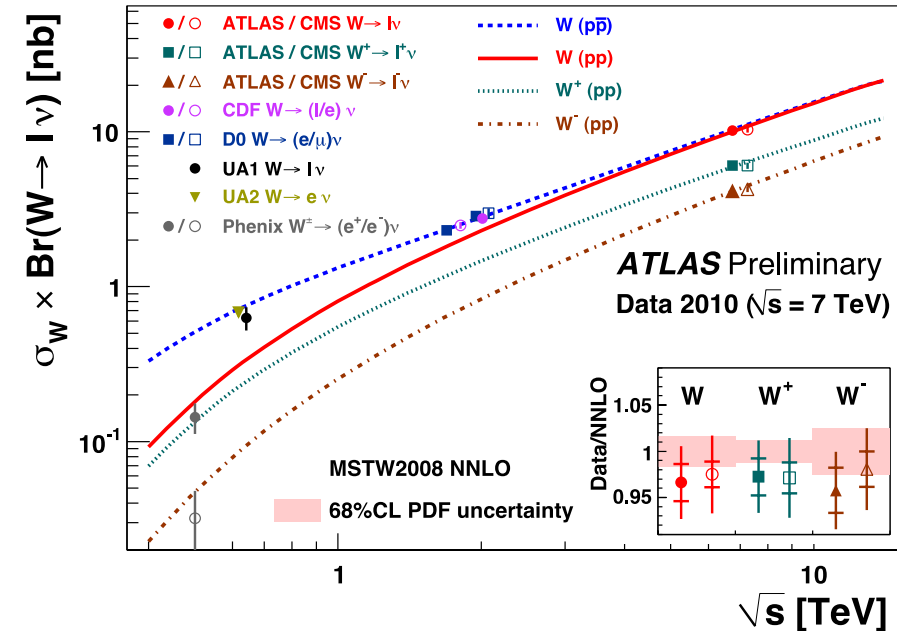
(N)NLO calculations, parton density functions,

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

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



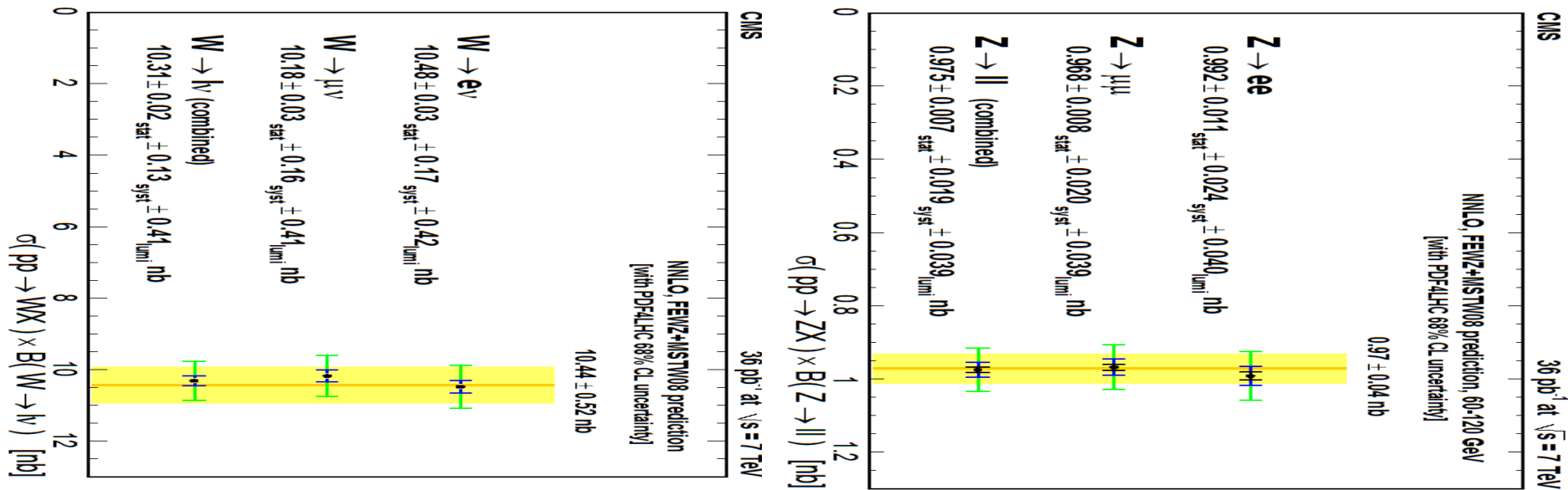
W and Z production cross sections at hadron colliders



- Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, p p-bar and as a function of energy)
- Good agreement as well between the ATLAS and CMS experiments

W and Z production cross sections at the LHC

Measured cross section values in comparison to NNLO QCD predictions:



Data are well described by NNLO QCD calculations

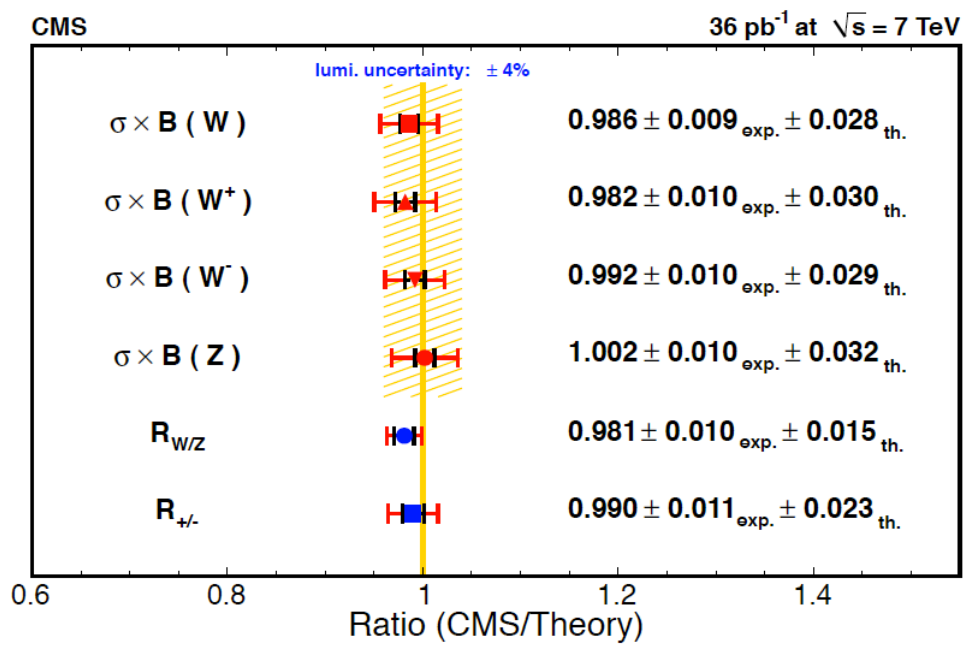
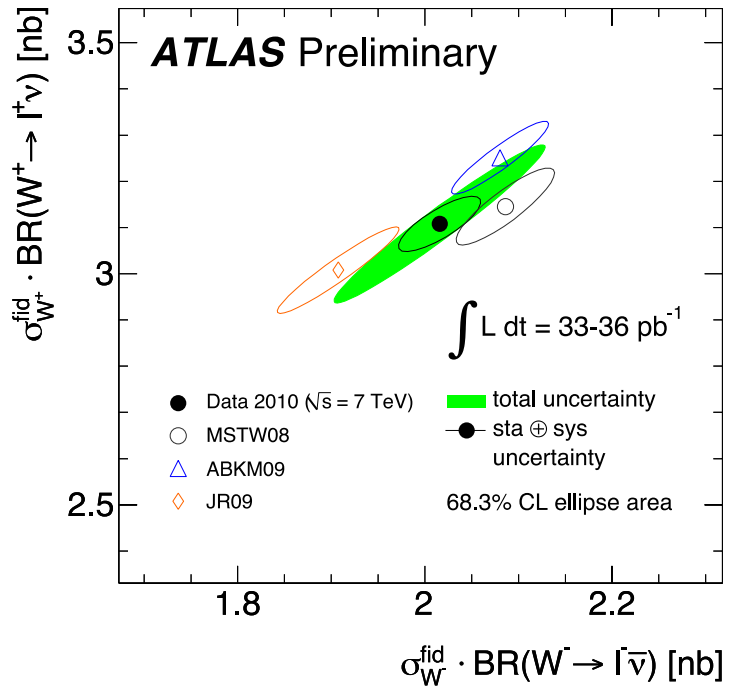
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

Precision is already dominated by systematic uncertainties

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

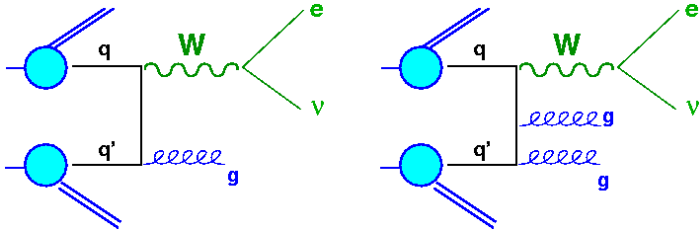


W cross sections at the LHC -charge separated, e/ μ universality



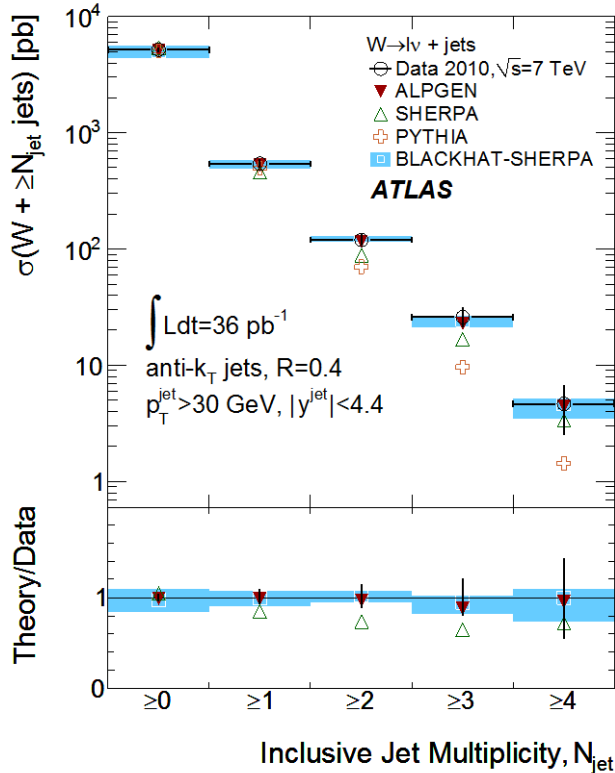
Good agreement between data and NNLO QCD predictions for all measurements

W/Z + jet cross section measurements

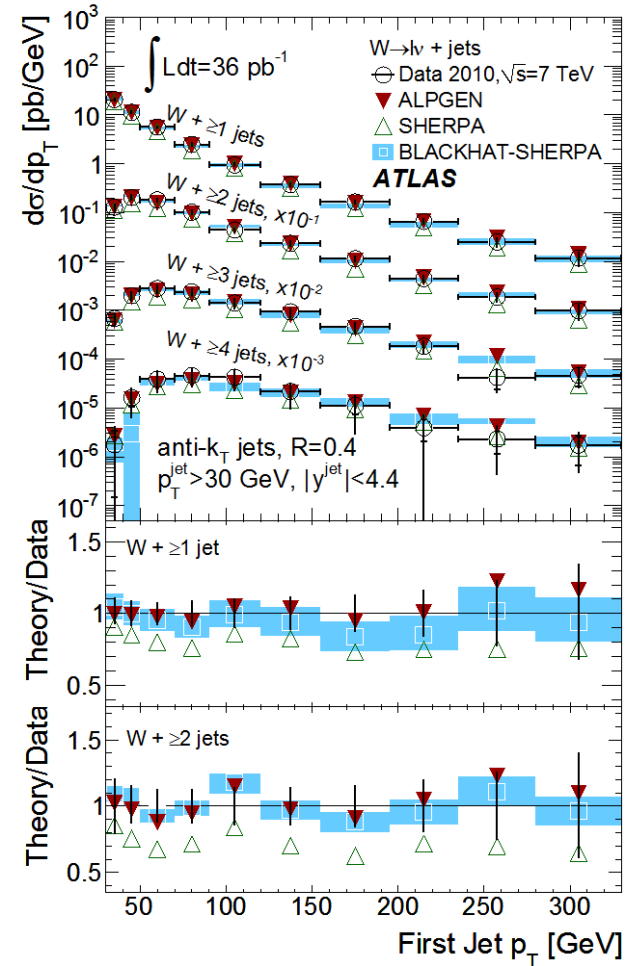


- LO predictions fail to describe the data;
 - Jet multiplicities and p_T spectra in agreement with NLO predictions within errors;

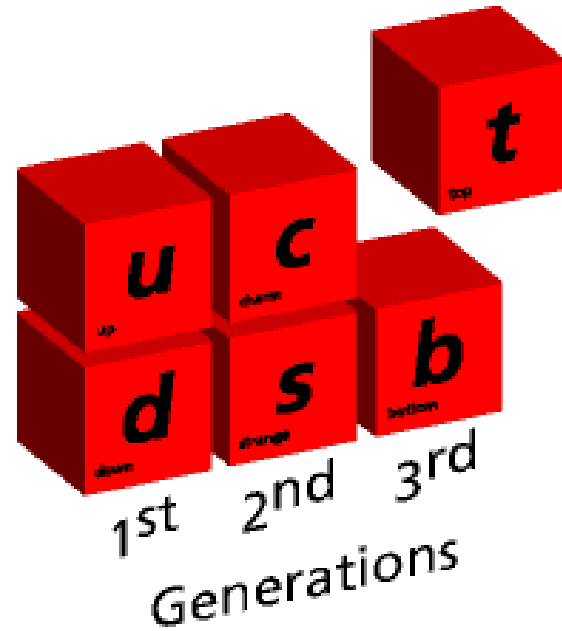
Jet multiplicities in W+jet production



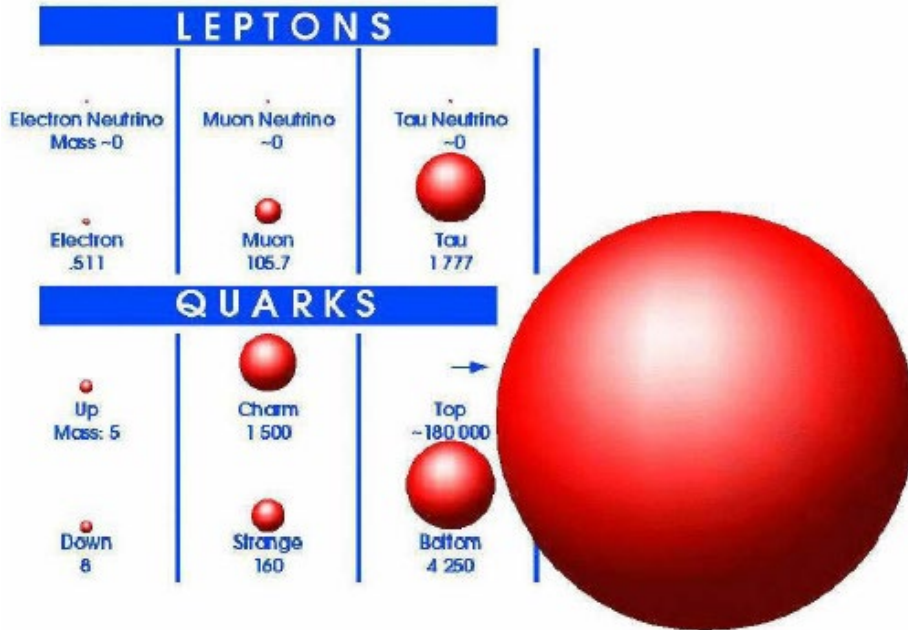
p_T spectrum of leading jet



Top Quark Physics



Why is Top-Quark so important ?



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

Why is its Yukawa coupling ~ 1 ??

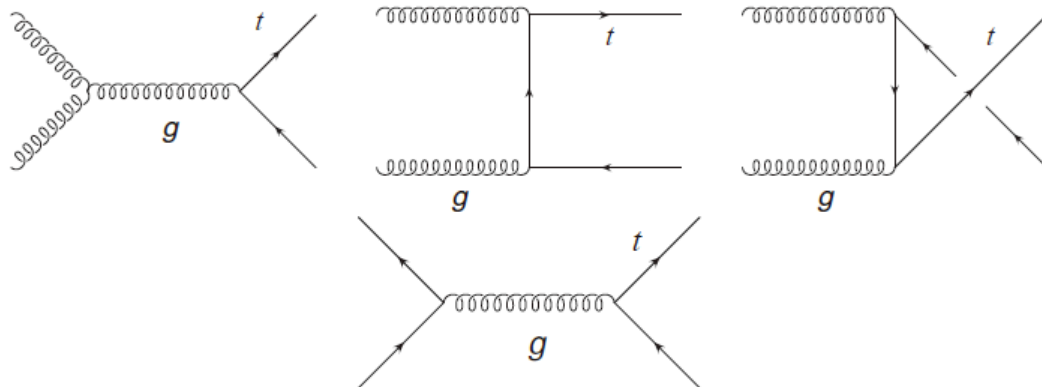
$$M_t = \frac{1}{\sqrt{2}} \lambda_t v$$

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

- A unique quark: decays before it hadronizes, lifetime $\sim 10^{-25}$ s
no “toponium states”
remember: bb, bd, bs..... cc, cs..... bound states (mesons)
- We still know little about the properties of the top quark:
mass, spin, charge, lifetime, decay properties (rare decays), gauge couplings, Yukawa coupling,...

Top Quark Production

Pair production: qq and gg-fusion



Top-quark pair production in the Born approximation.

- NLO corrections completely known
- NNLO partly known

approximate NNLO results:

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

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

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

For LHC running at $\sqrt{s} = 7 \text{ TeV}$, 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 ($t \rightarrow Wb$) $\sim 100\%$

Dilepton channel:

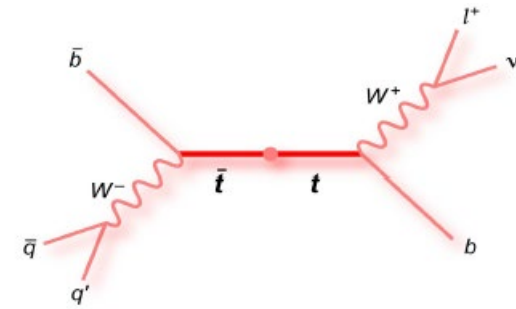
Both W 's decay via $W \rightarrow \ell\nu$ ($\ell=e$ or μ ; 4%)

Lepton + jet channel:

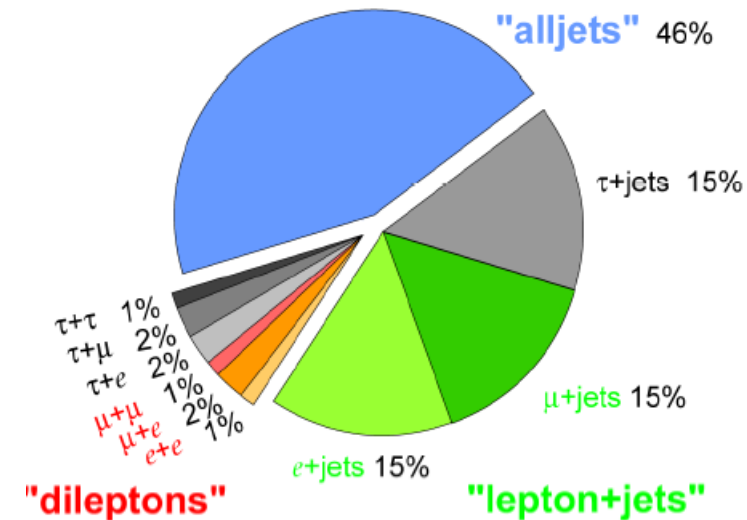
One W decays via $W \rightarrow \ell\nu$ ($\ell=e$ or μ ; 30%)

Full hadronic channel:

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



Top Pair Branching Fractions

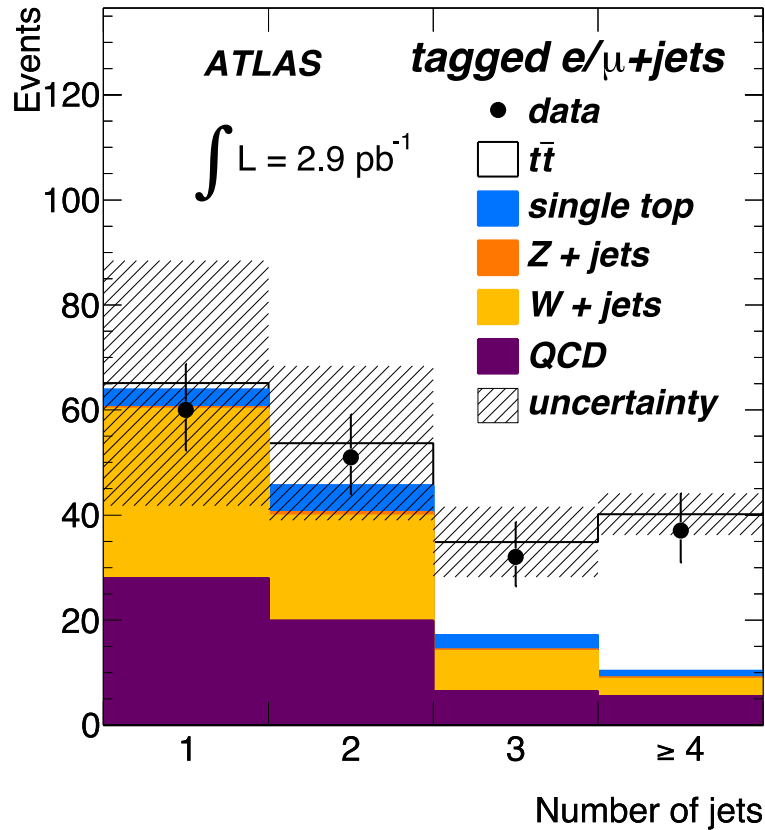


Important experimental signatures: - Lepton(s)

- Missing transverse momentum
- b-jet(s)



First results on top production from the LHC

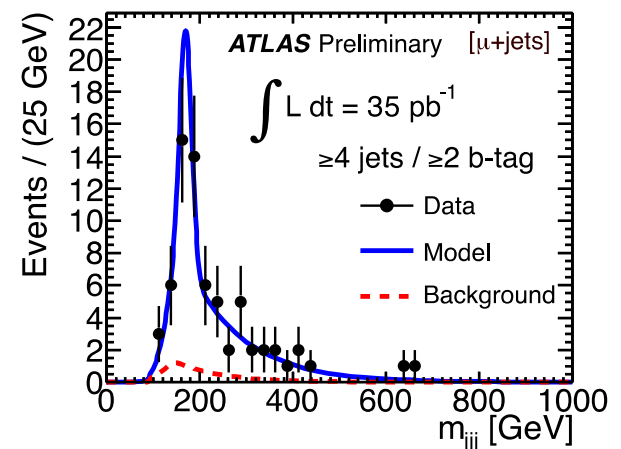
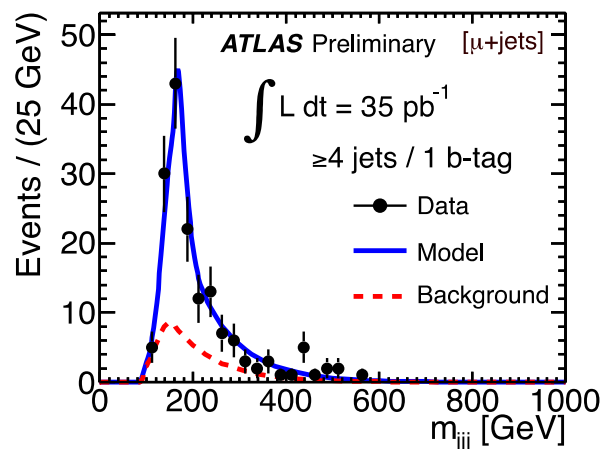
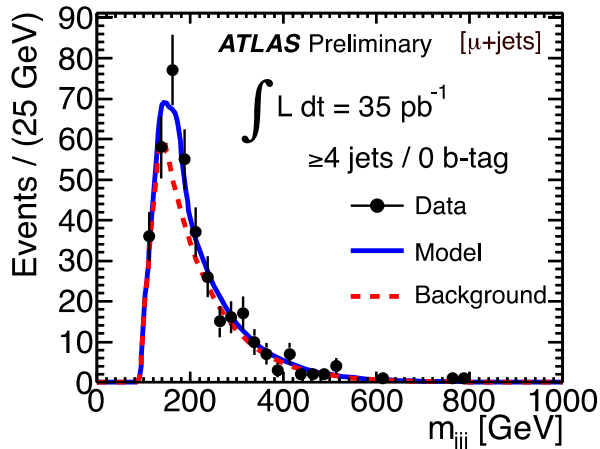
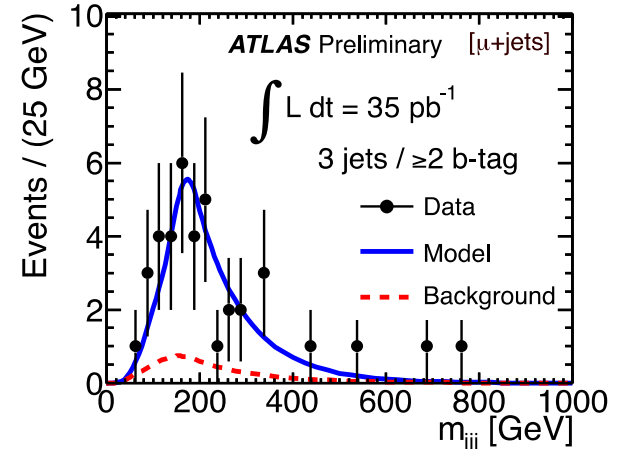
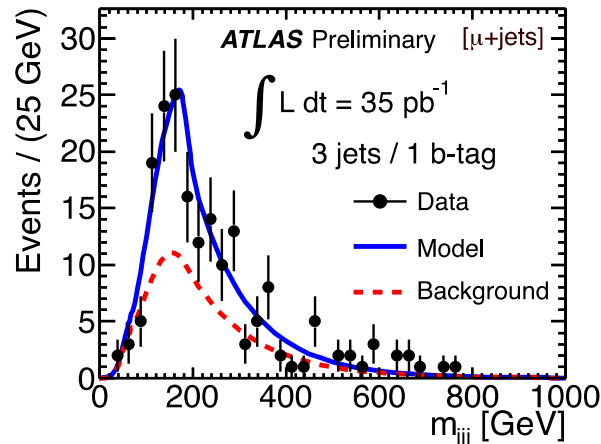
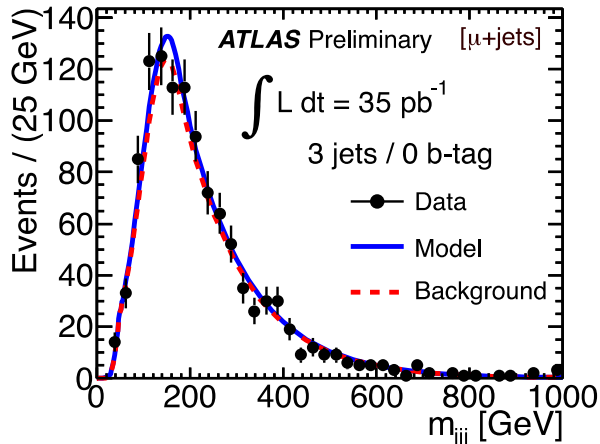
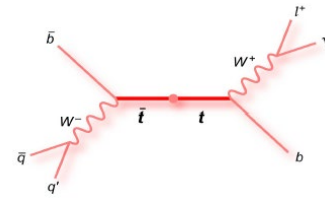


Event Selection:

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



Invariant mass distributions in the l-had channel

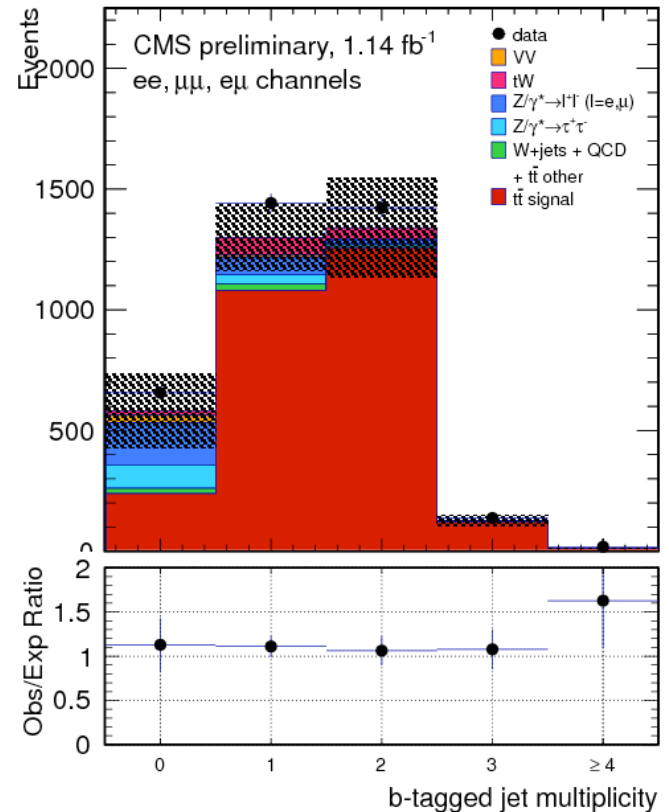
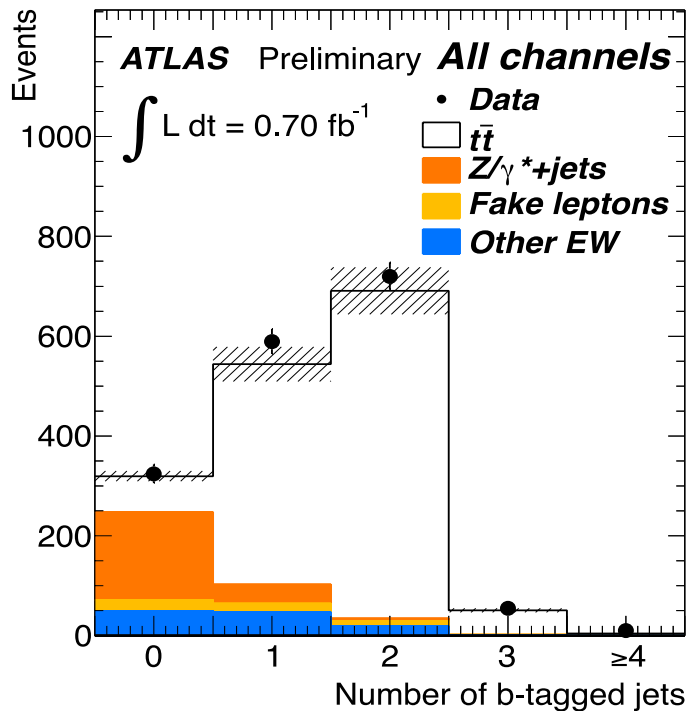


- Top fractions increase with number of b-tags
- Good description for all jet-multiplicity and b-tag combinations
- Data are consistent with top quark production with mass of 173 GeV

Top-quark production measured in many different decay modes

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

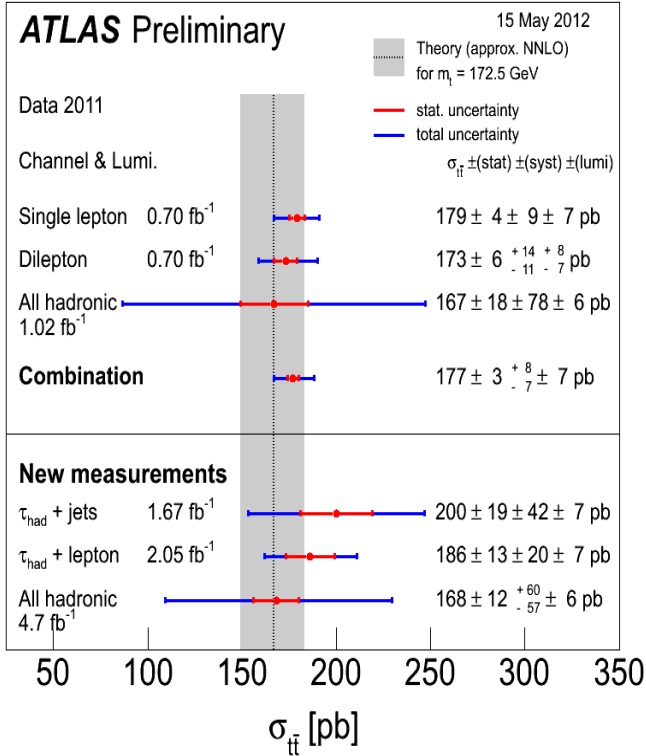
Multiplicity distributions of b-tagged jets
(small backgrounds, mainly from Z+jet production)



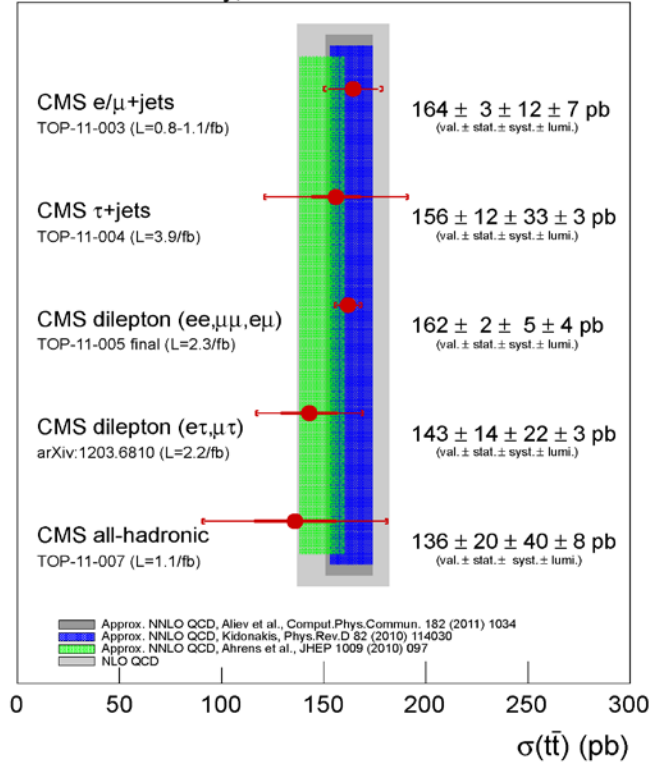


Top pair production cross section measurements

-likelihood combination of all channels-



CMS Preliminary, $\sqrt{s}=7$ TeV



$$\sigma = 177 \pm 3 \text{ (stat)} \pm 7 \text{ (syst)} \pm 7 \text{ (lum)} \text{ pb}$$

$$\sigma = 165.8 \pm 2.2 \text{ (stat)} \pm 10.6 \text{ (syst)} \pm 7.8 \text{ (lum)} \text{ pb}$$

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

10.4 Bestimmung der starken Kopplungskonstanten α_s

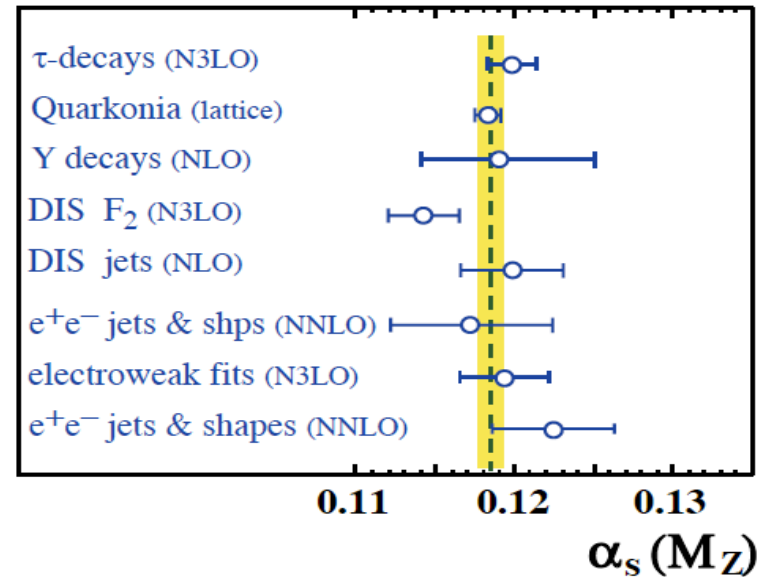
▼ τ decays (N³LO)

• fit (N³LO)

▼

-

α_s
 α_s
 α_s



Summary of measurements of α_s as a function of the respective energy scale Q (from Particle Data Group).

Summary of measurements of $\alpha_s(m_Z^2)$, used as input for the world average value (from Particle Data Group).