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-Proton-Kollisionen

10.4 Bestimmung der starken Kopplungskonstanten α_s

1977: DESY macht die Gluonen sichtbar

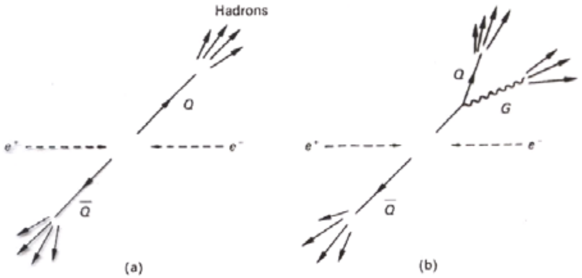
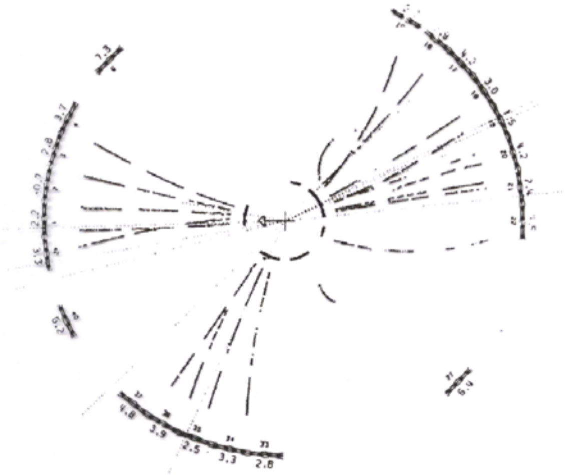


Fig. 8.27



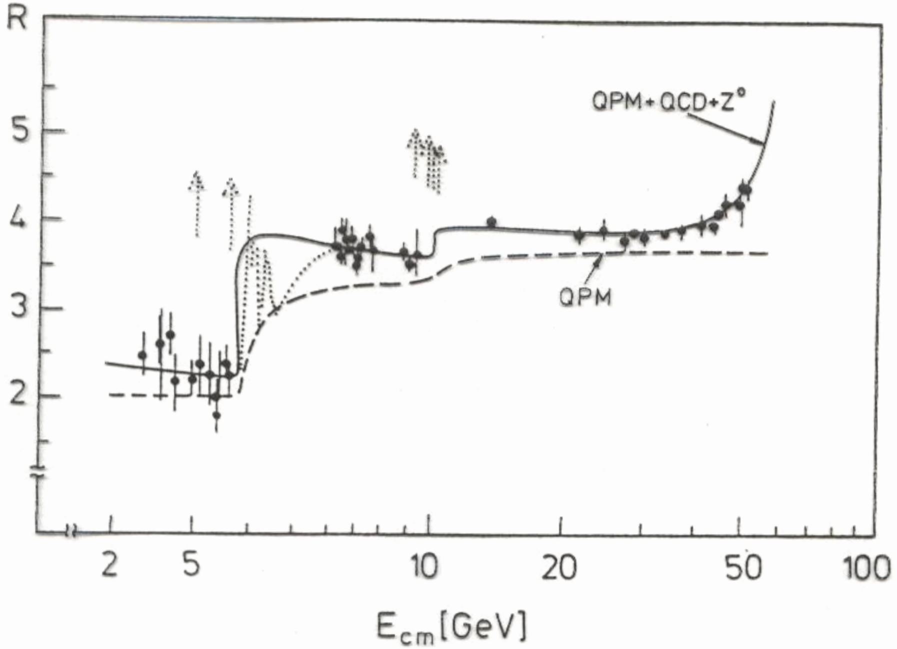
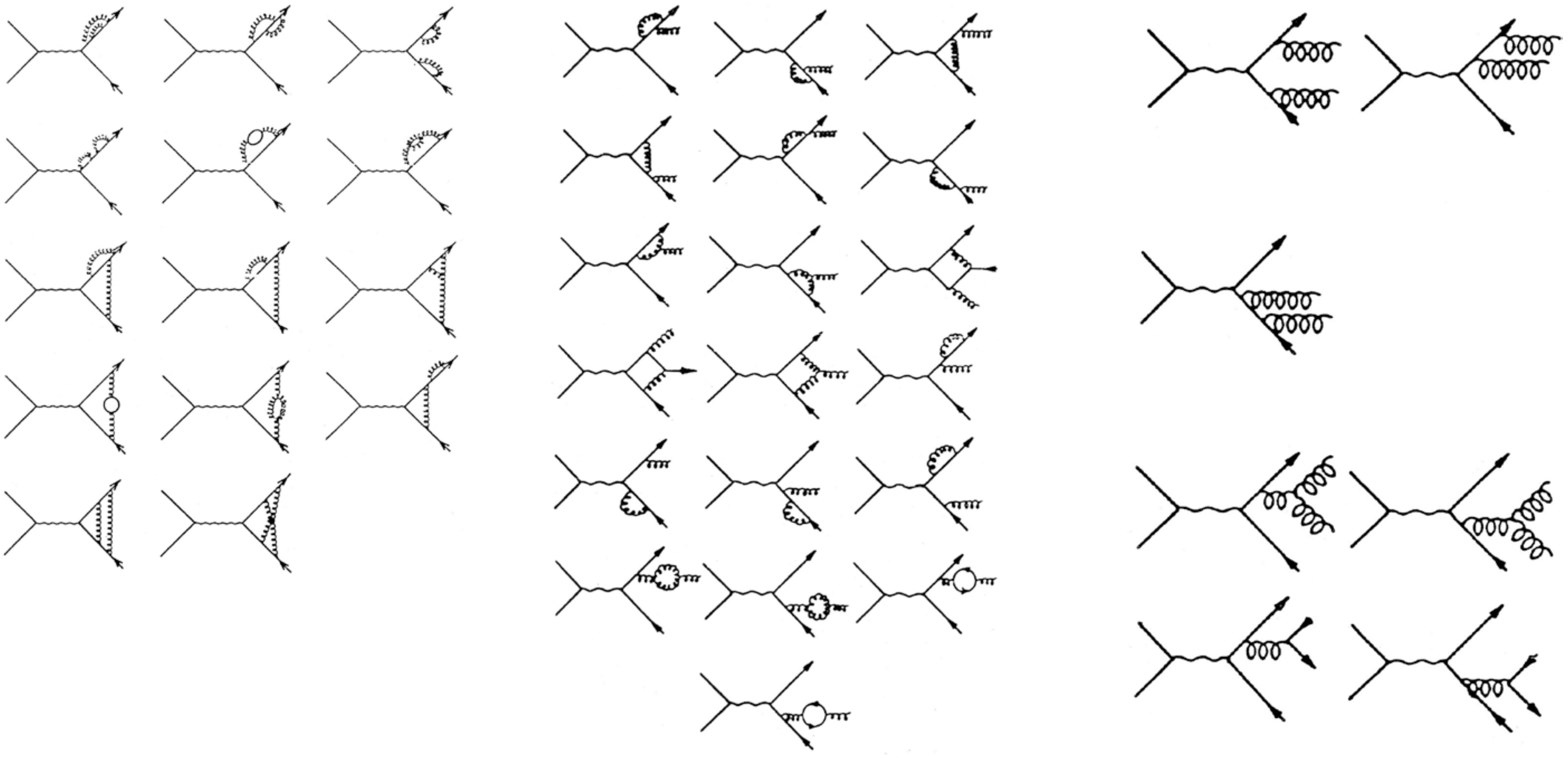


Abb. 12.20. Daten für das Verhältnis R und die Vorhersagen des Quark-Parton-Modell (QPM) und der QCD. Die ψ- und Υ-Resonanzen sind gestrichelt angedeutet. (Marshall 1989)



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

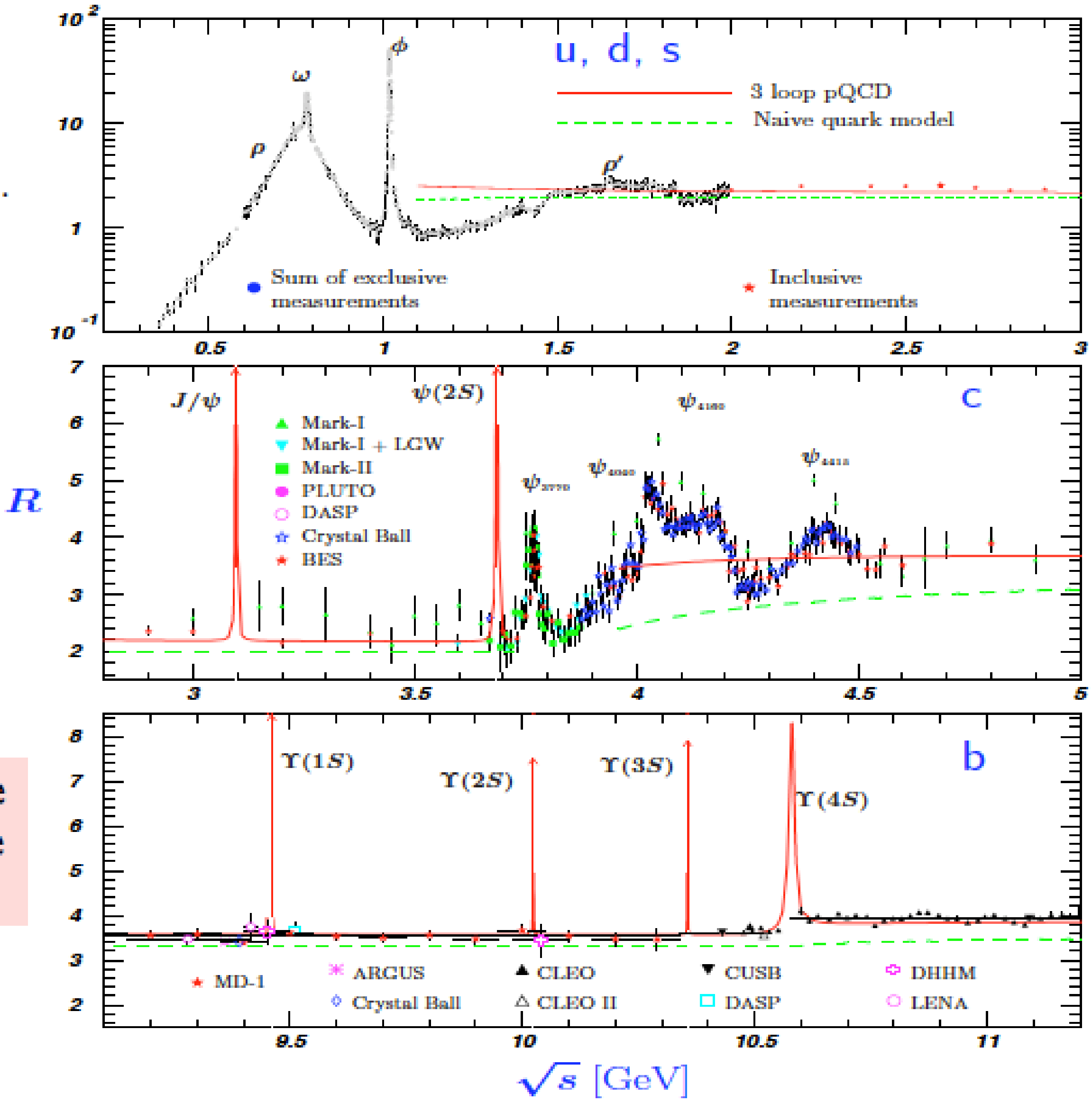
$$R = \frac{e^+e^- \to \text{Hadrons}}{e^+e^- \to \mu^+\mu^-}.$$

$$\sigma(e^+e^- \to \text{Hadrons}) \propto \sigma(e^+e^- \to \mu^+\mu^-).$$

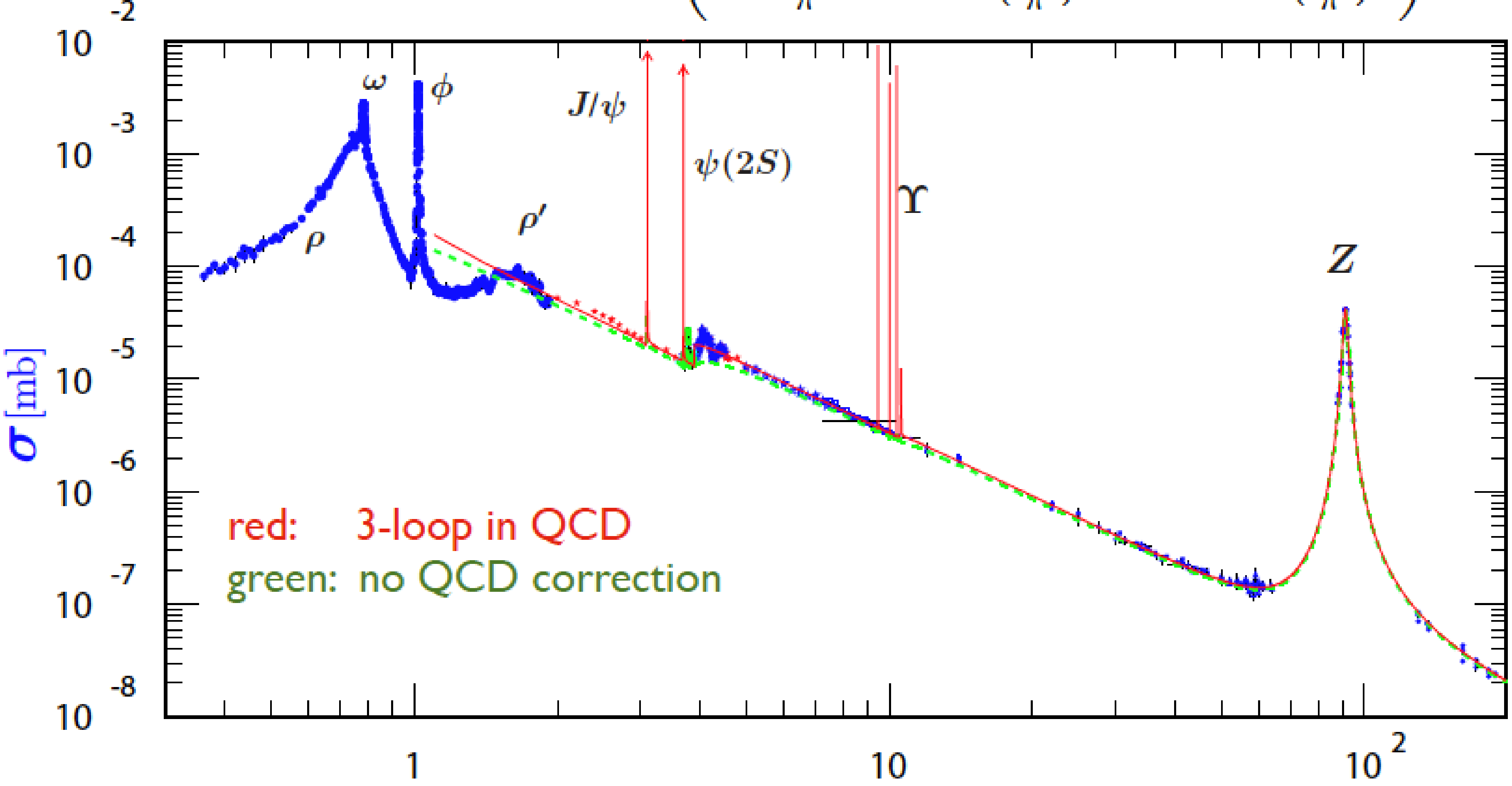
$$R = N_c \sum_{q=u,d,..} e_q^2,$$

$$R = \begin{cases} \frac{2}{3} N_c & (\text{u, d, s}), \\ \frac{10}{9} N_c & (\text{u, d, s, c}), \\ \frac{11}{9} N_c & (\text{u, d, s, c,b}), \end{cases}$$

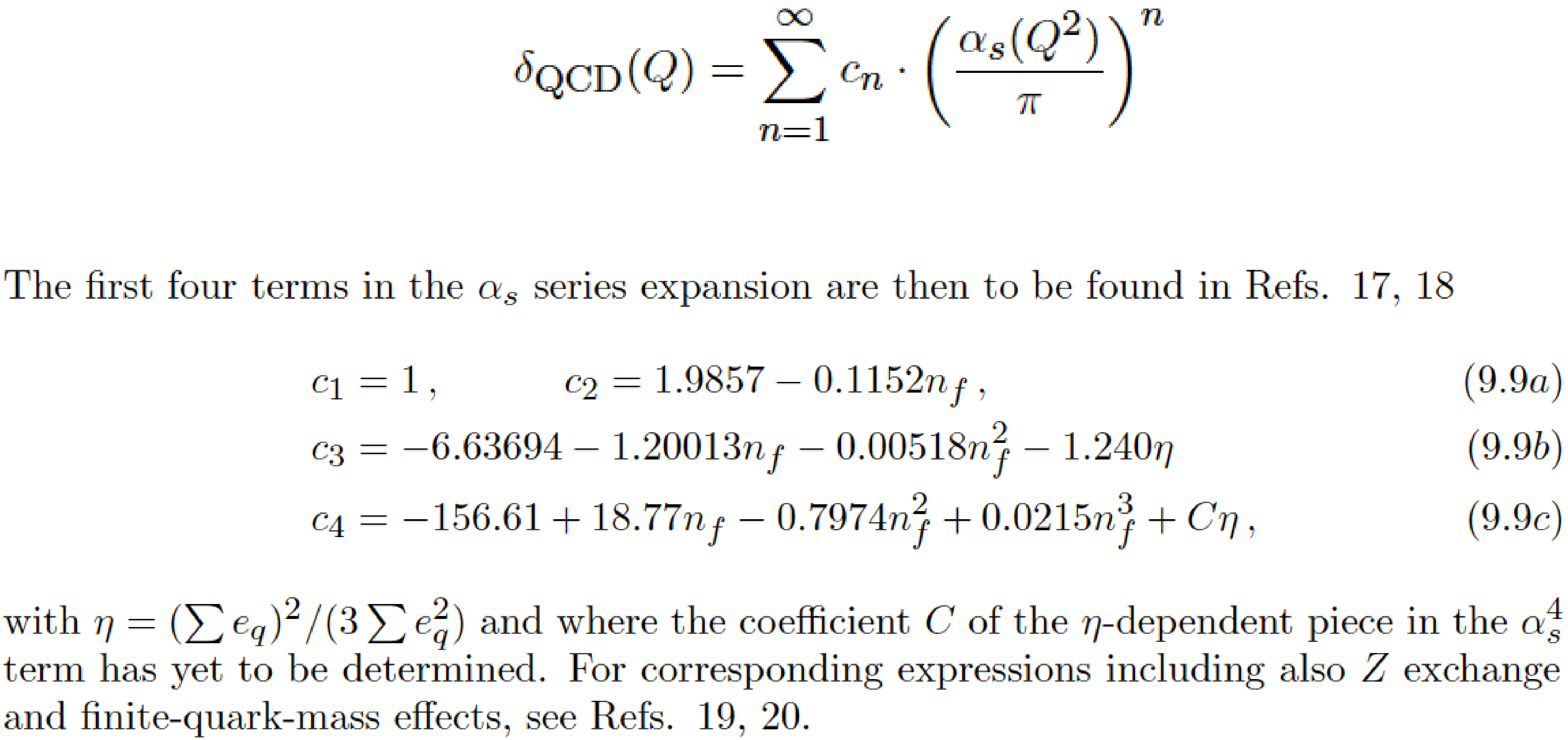
The R measurements are compatible with N_c=3 (outside of the resonance region).



$$\sigma(e^+e^- \to \text{hadrons}) = \sigma_0 \left(1 + \frac{\alpha_s}{\pi} + 1.409\left(\frac{\alpha_s}{\pi}\right)^2 - 12.805\left(\frac{\alpha_s}{\pi}\right)^3\right)$$



QCD – Korrekturen zum Prozess e^+e^- → Hadronen



$$\delta_{\mathrm{QCD}}(Q) = \sum_{n=1}^{\infty} c_n \cdot \left(\frac{\alpha_s(Q^2)}{\pi} \right)^n$$

The first four terms in the α_s series expansion are then to be found in Refs. 17, 18

$$c_1 = 1\,, \qquad c_2 = 1.9857 - 0.1152 n_f\,, \tag{9.9a}$$

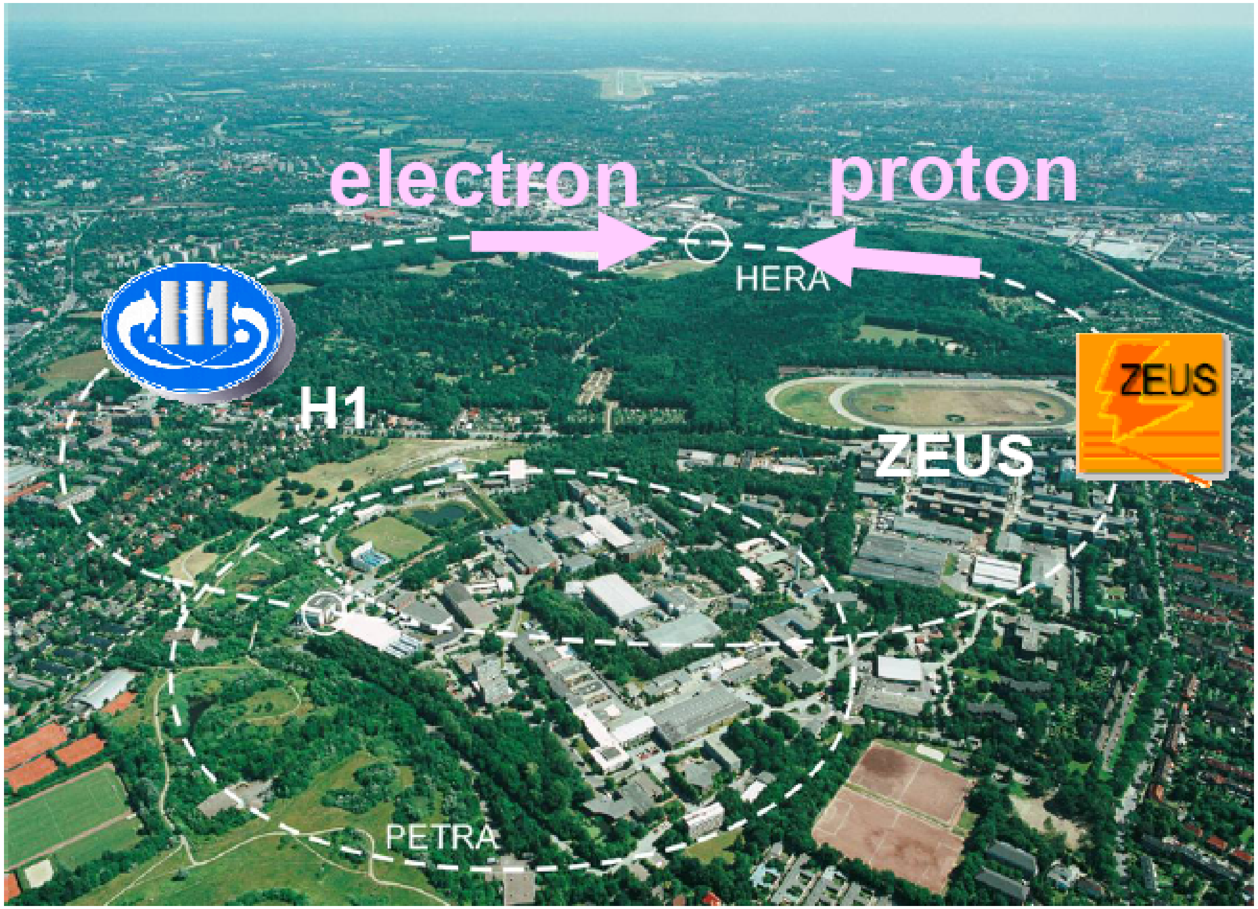
$$c_3 = -6.63694 - 1.20013 n_f - 0.00518 n_f^2 - 1.240\eta \tag{9.9b}$$

$$c_4 = -156.61 + 18.77 n_f - 0.7974 n_f^2 + 0.0215 n_f^3 + C\eta\,, \tag{9.9c}$$

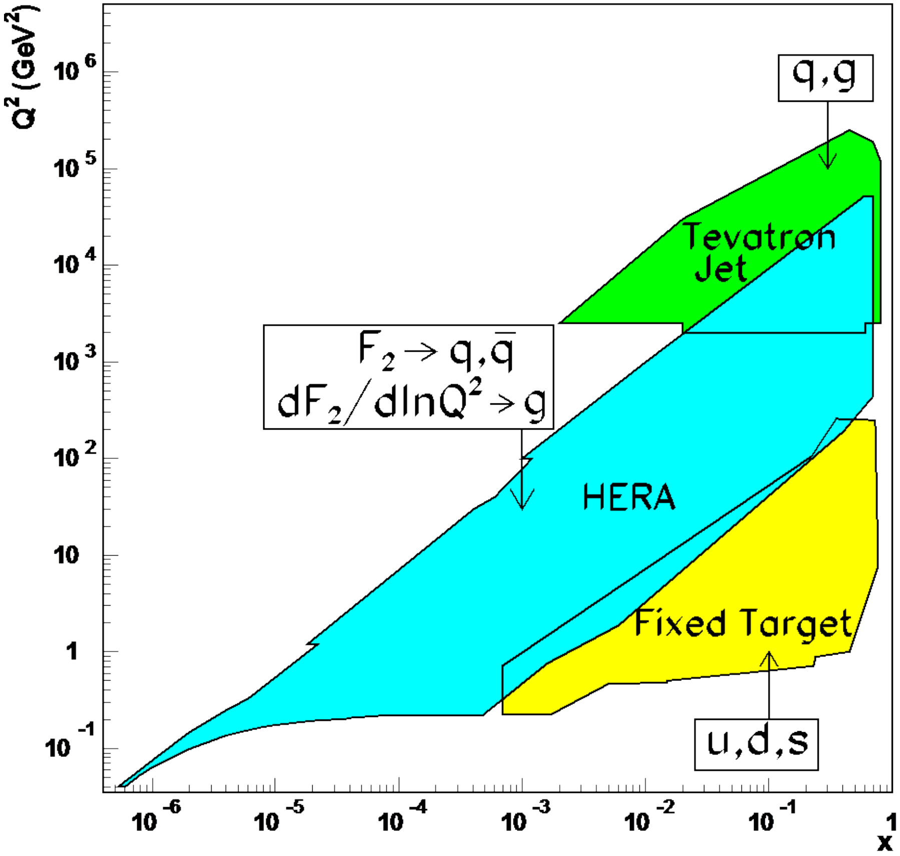
with $\eta = (\sum e_q)^2/(3\sum e_q^2)$ and where the coefficient C of the η-dependent piece in the α_s^4 term has yet to be determined. For corresponding expressions including also Z exchange and finite-quark-mass effects, see Refs. 19, 20.

(from Rev. Particle Properties, Particle Data Group, PDG (2012))

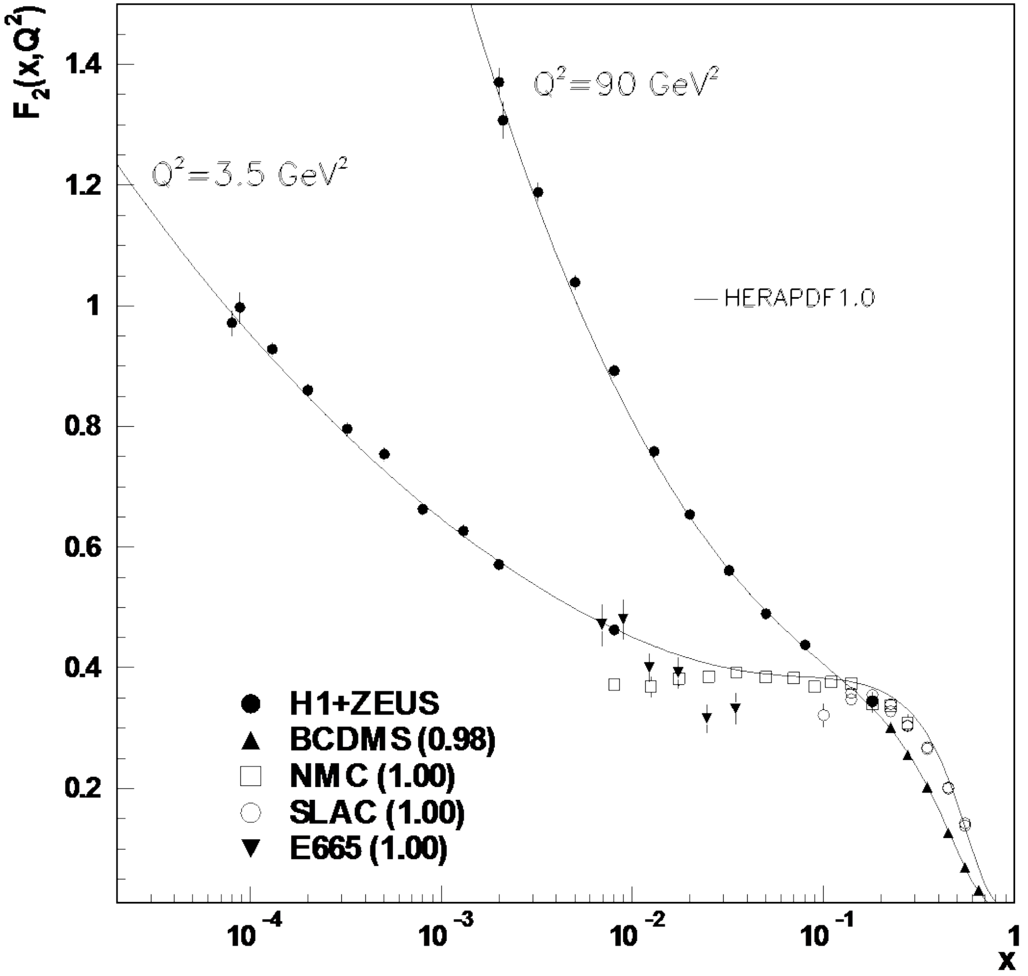
10.2 QCD-Effekte in der tief inelastischen Lepton-Nukleon-Streuung

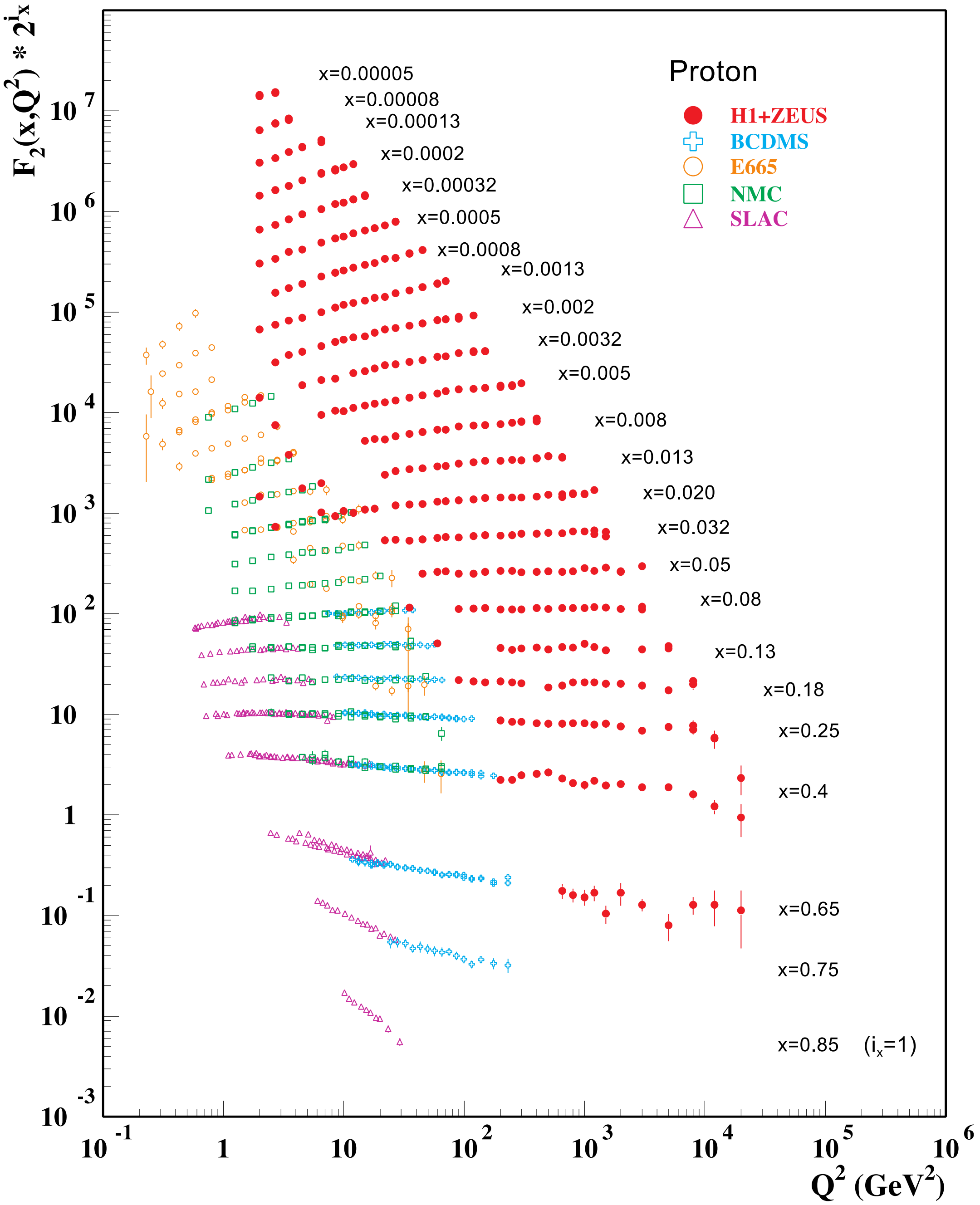


HERA-Beschleuniger am DESY in Hamburg (1990 – 2007:)
Elektron/Positron-Proton Kollisionen: 30 GeV $e^{\pm}$ auf 920 GeV p



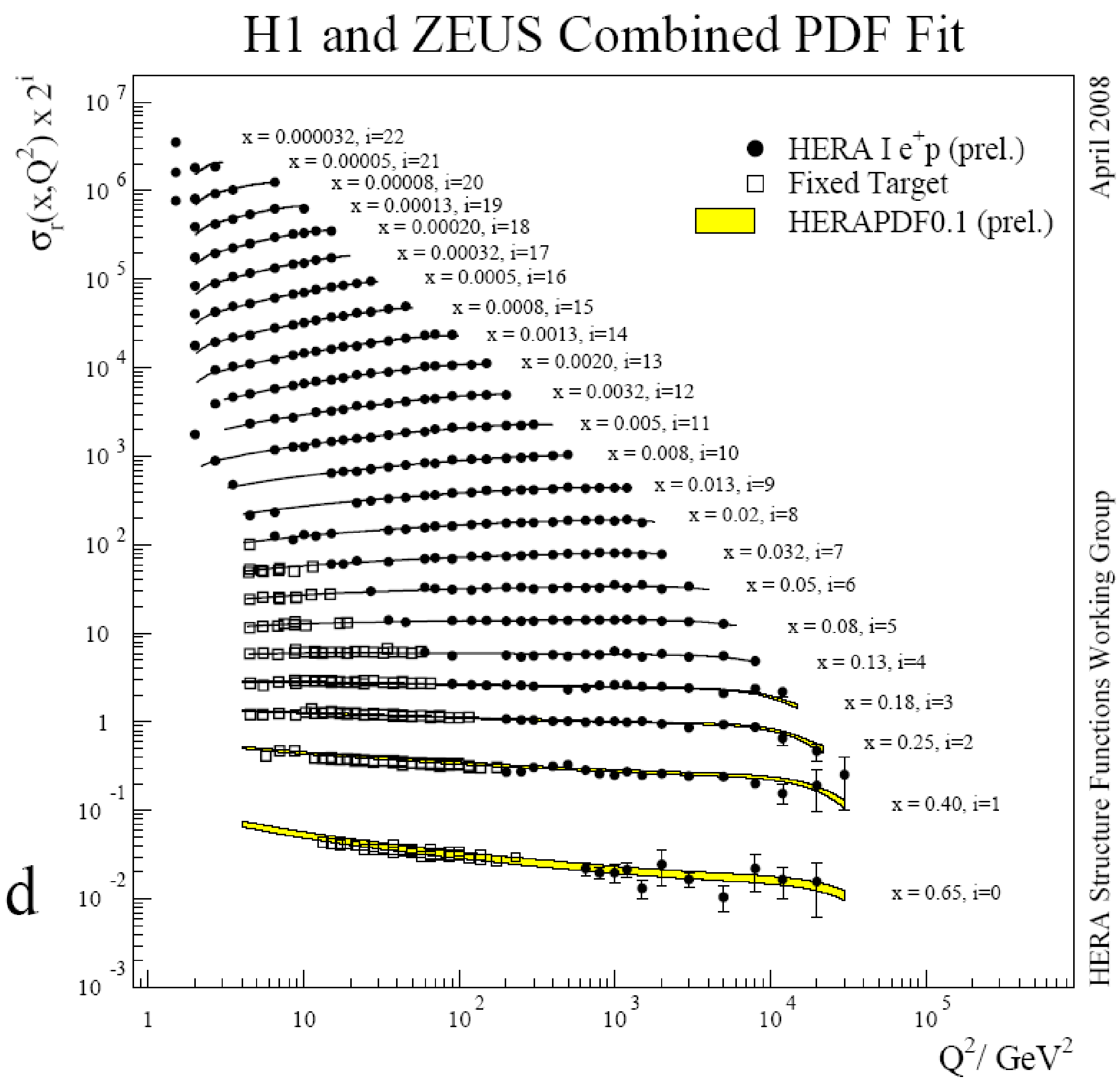
Q^2 (GeV^2)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
q,g
Tevatron Jet
$F_2 \to q,\bar{q}$
$dF_2/d\ln Q^2 \to g$
HERA
Fixed Target
u,d,s


$F_2(x,Q^2)$
1.4
1.2
1
0.8
0.6
0.4
0.2
$Q^2=90$ GeV^2
$Q^2=3.5$ GeV^2
— HERAPDF1.0
● H1+ZEUS
▲ BCDMS (0.98)
□ NMC (1.00)
○ SLAC (1.00)
▼ E665 (1.00)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

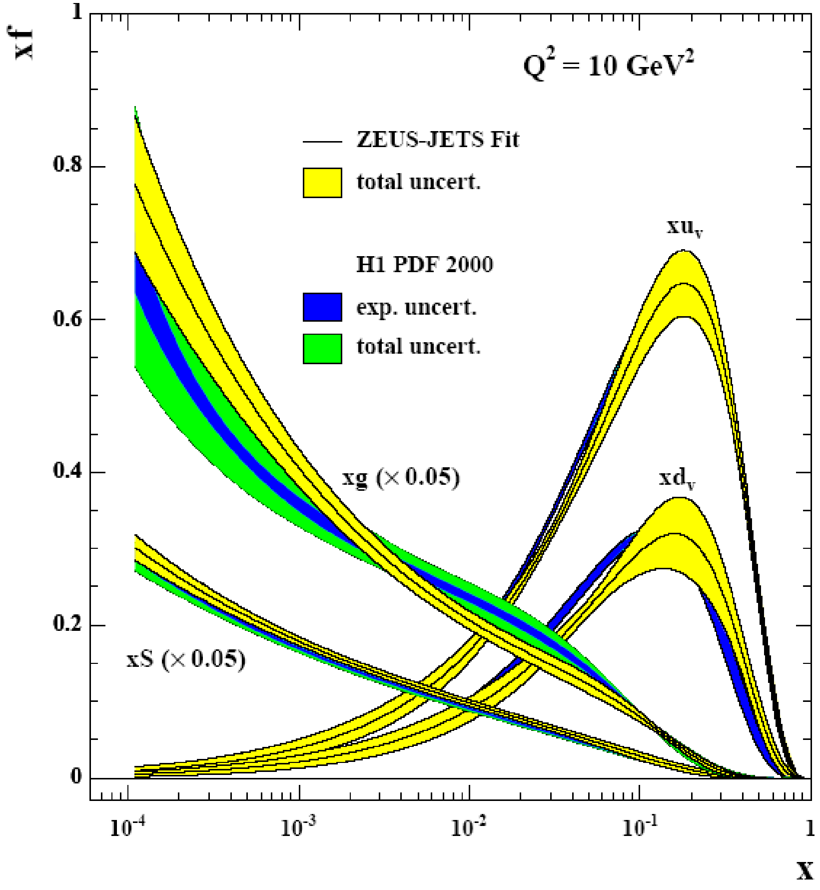


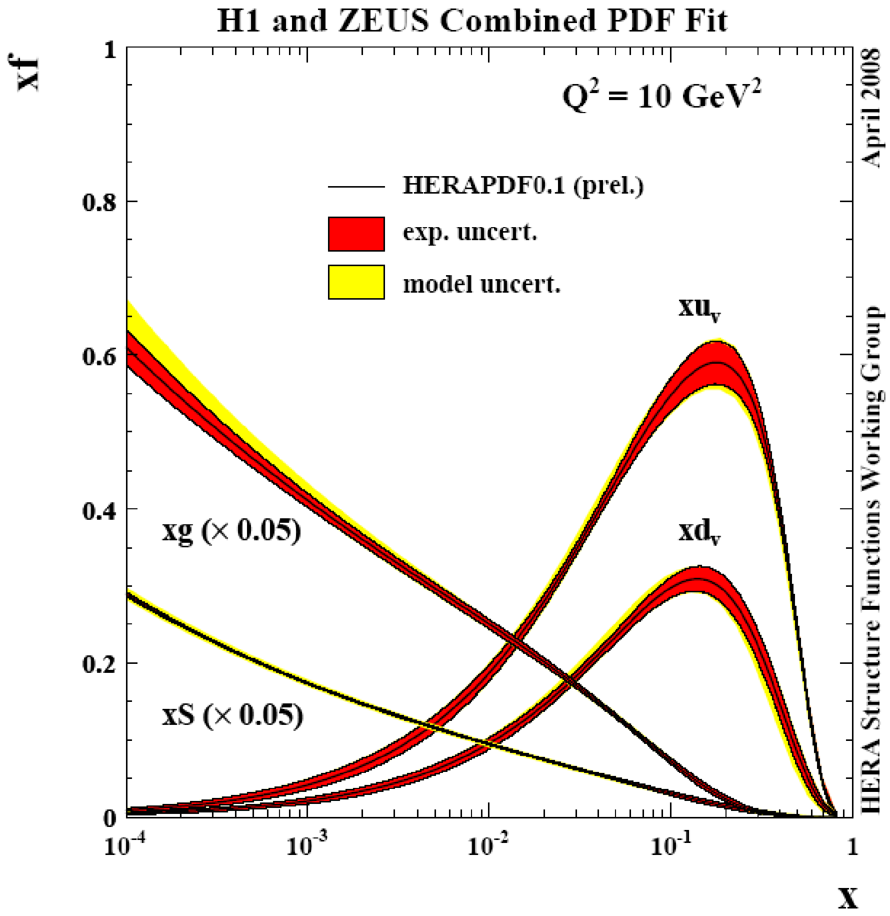
$F_2(x,Q^2) * 2^{i_x}$
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
Q^2 (GeV^2)
Proton
● H1+ZEUS
✚ BCDMS
○ E665
☐ NMC
△ SLAC
x=0.00005
x=0.00008
x=0.00013
x=0.0002
x=0.00032
x=0.0005
x=0.0008
x=0.0013
x=0.002
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.020
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
x=0.75
x=0.85
(i_x=1)

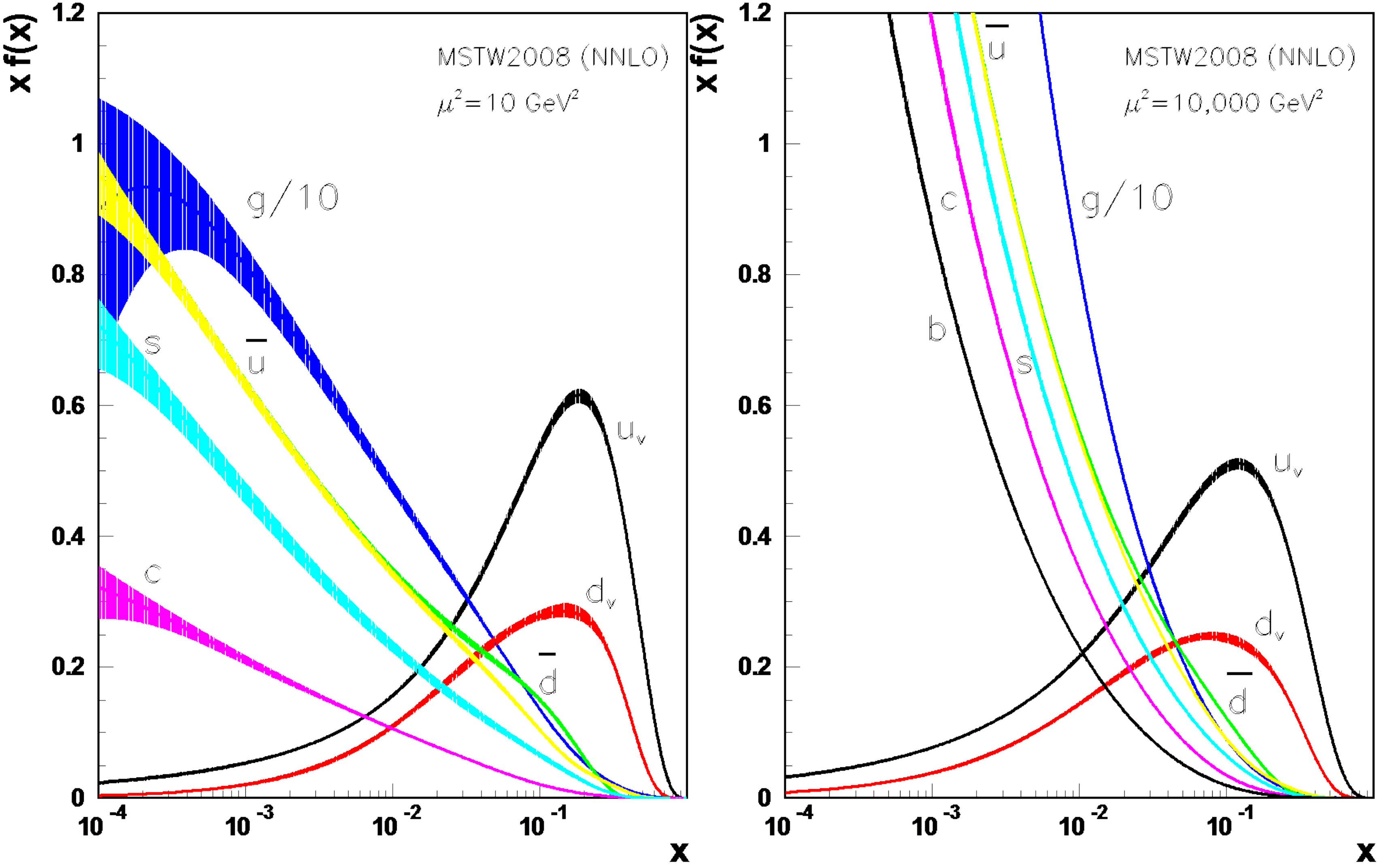
QCD at HERA


H1 and ZEUS Combined PDF Fit
$\sigma_r(x,Q^2) \times 2^i$
$Q^2/\ \mathrm{GeV}^2$
d
● HERA I e^+p (prel.)
☐ Fixed Target
HERAPDF0.1 (prel.)
April 2008
HERA Structure Functions Working Group
x = 0.000032, i=22
x = 0.00005, i=21
x = 0.00008, i=20
x = 0.00013, i=19
x = 0.00020, i=18
x = 0.00032, i=17
x = 0.0005, i=16
x = 0.0008, i=15
x = 0.0013, i=14
x = 0.0020, i=13
x = 0.0032, i=12
x = 0.005, i=11
x = 0.008, i=10
x = 0.013, i=9
x = 0.02, i=8
x = 0.032, i=7
x = 0.05, i=6
x = 0.08, i=5
x = 0.13, i=4
x = 0.18, i=3
x = 0.25, i=2
x = 0.40, i=1
x = 0.65, i=0
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1
10
10^2
10^3
10^4
10^5

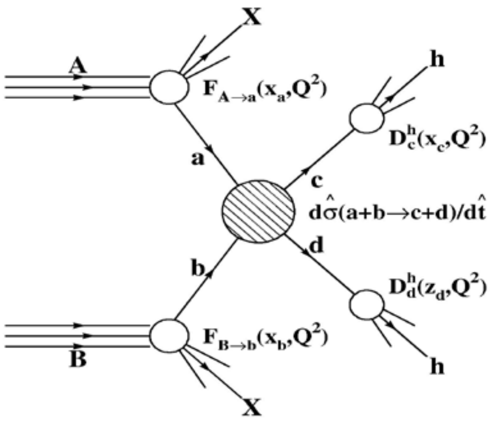
Parton Distribution functions (pdf)

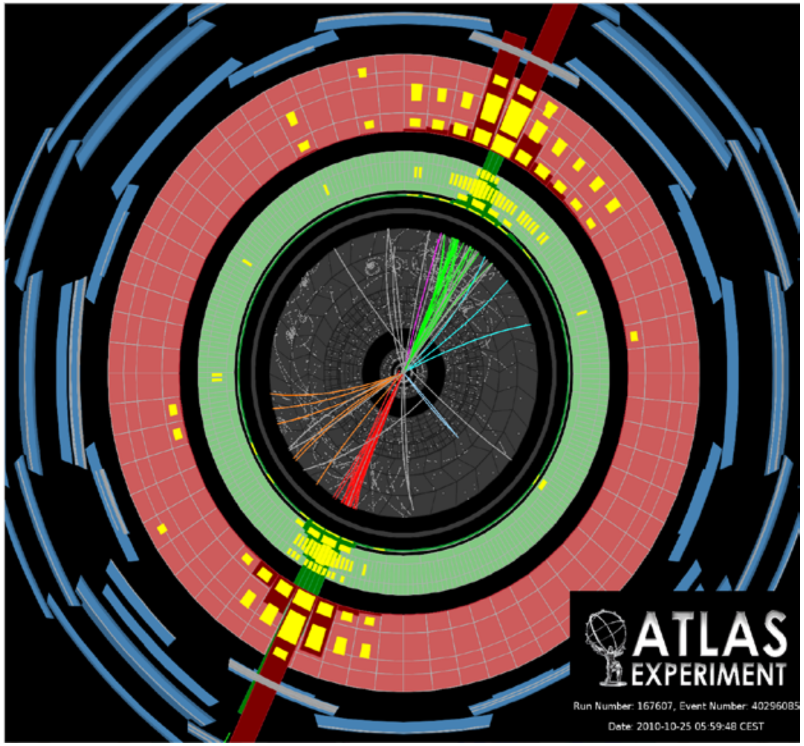




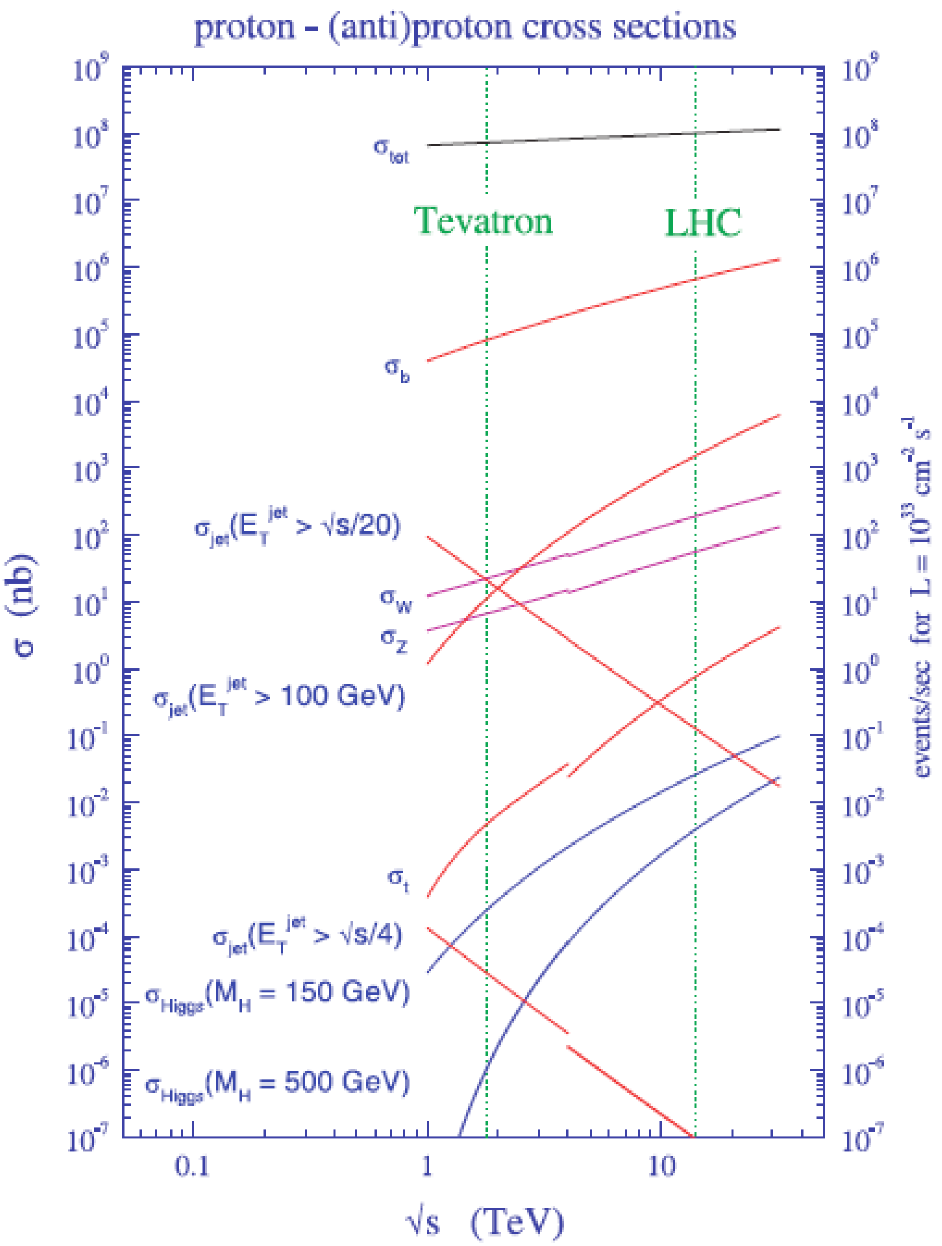

x f(x)
1.2
1
0.8
0.6
0.4
0.2
0
10 -4
10 -3
10 -2
10 -1
x
MSTW2008 (NNLO)
μ^2=10 GeV^2
g/10
s
$\bar{u}$
c
u_v
d_v
$\bar{d}$
x f(x)
MSTW2008 (NNLO)
μ^2=10,000 GeV^2
$\bar{u}$
c
g/10
b
s
u_v
d_v
$\bar{d}$

10.3 Test der QCD in Proton-Proton-Kollisionen



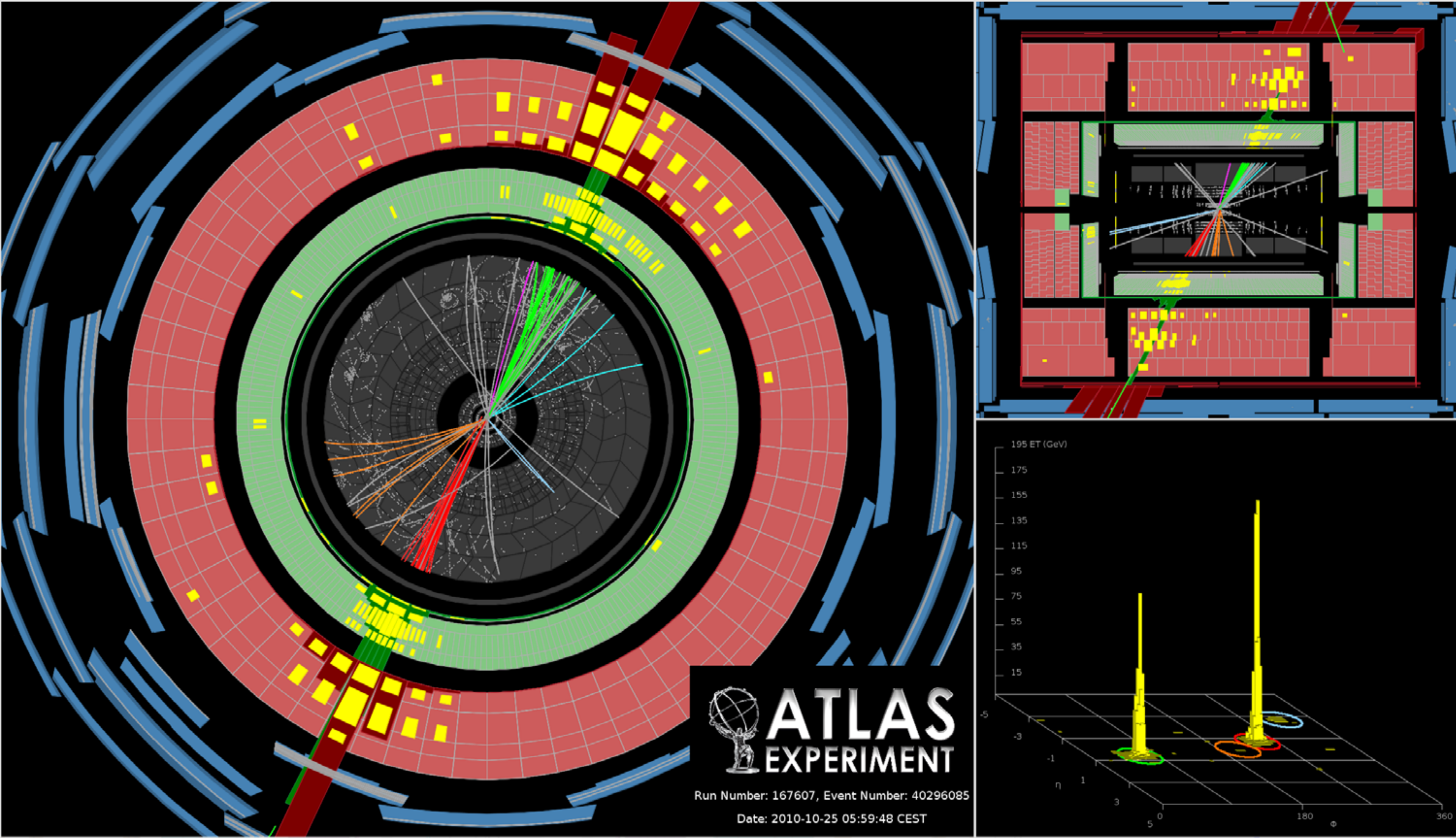


- Jet-Produktion
- Produktion von W- und Z-Bosonen
- Produktion von Top-Quarks



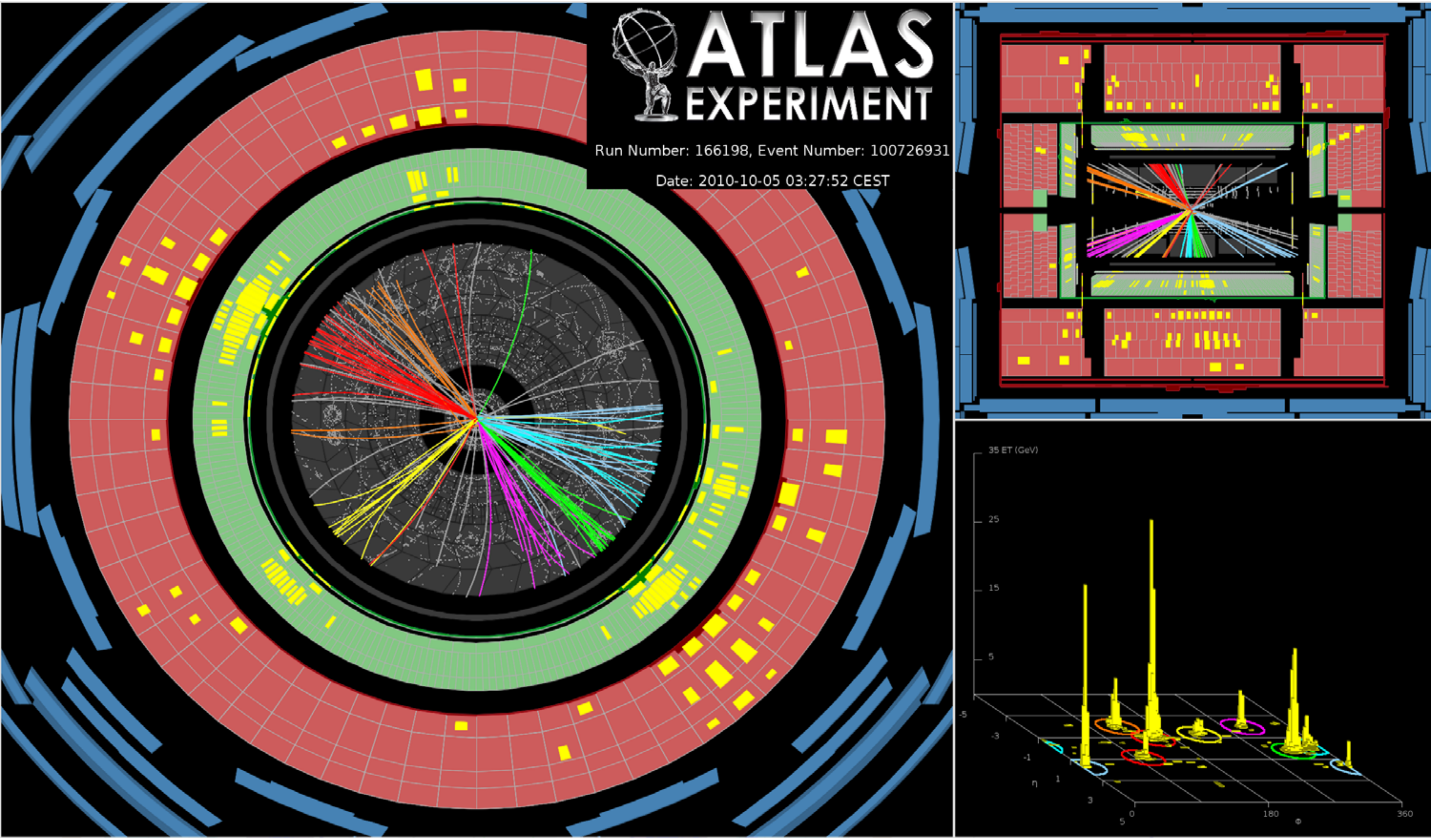
Cross sections for important hard scattering Standard Model processes at the Tevatron and the LHC colliders

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

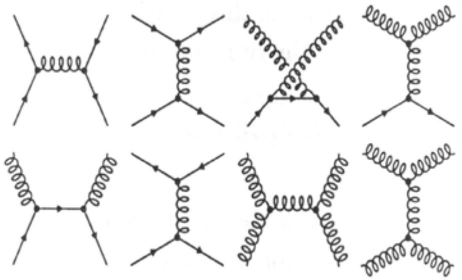


The highest jet multiplicity event collected by the end of October 2010, counting jets with p_T greater than 60 GeV: this event has eight. 1st jet (ordered by p_T): $p_T = 290$ GeV, $\eta = -0.9$, $\varphi = 2.7$; 2nd jet: $p_T = 220$ GeV, $\eta = 0.3$, $\varphi = -0.7$ Missing $E_T = 21$ GeV, $\varphi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

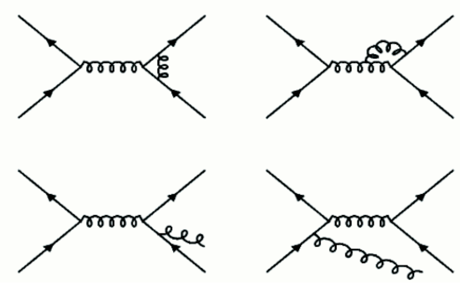
Theoretical calculations

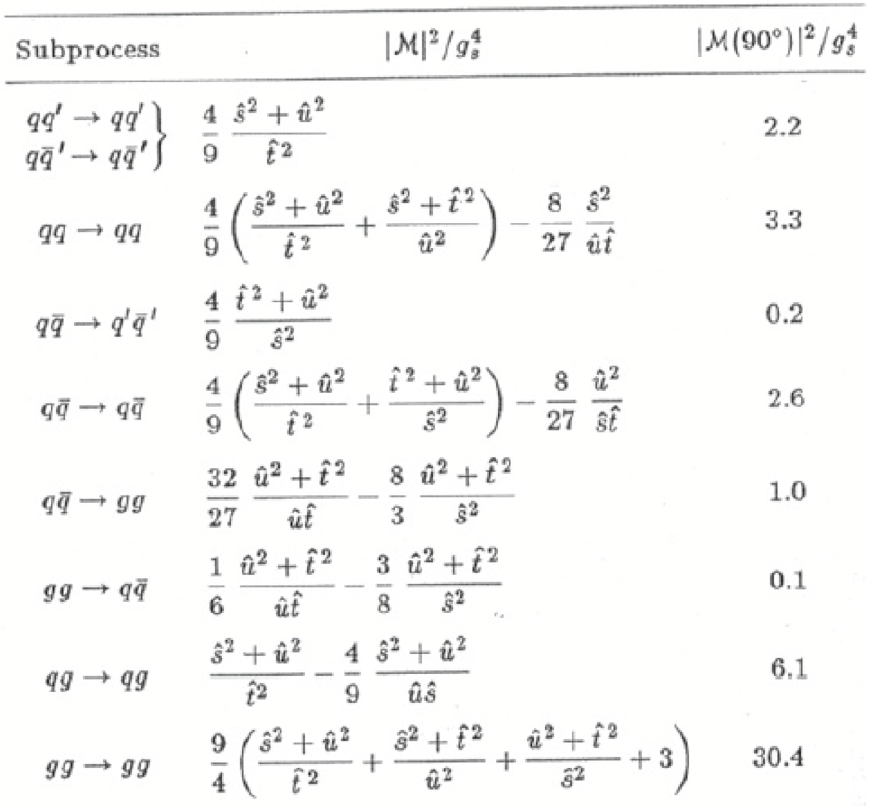
$$\frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) = \frac{|M|^2}{(16\pi\hat{s}^2)}$$

Leading order



…some NLO contributions

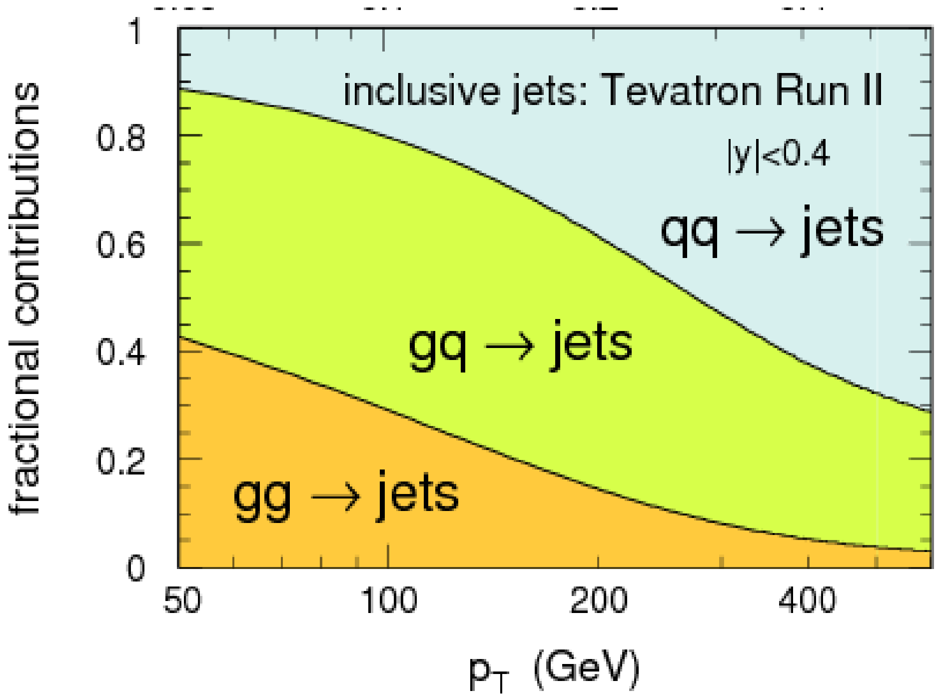




Subprocess	$\lvert\mathcal{M}\rvert^2/g_s^4$	$\lvert\mathcal{M}(90^\circ)\rvert^2/g_s^4$
$qq' \to qq'$ $q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.2
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.6
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{8}{3}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	1.0
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{3}{8}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	0.1
$gq \to gq$	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \to gg$	$\frac{9}{4}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}+\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}+3\right)$	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 90 degrees (η = 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

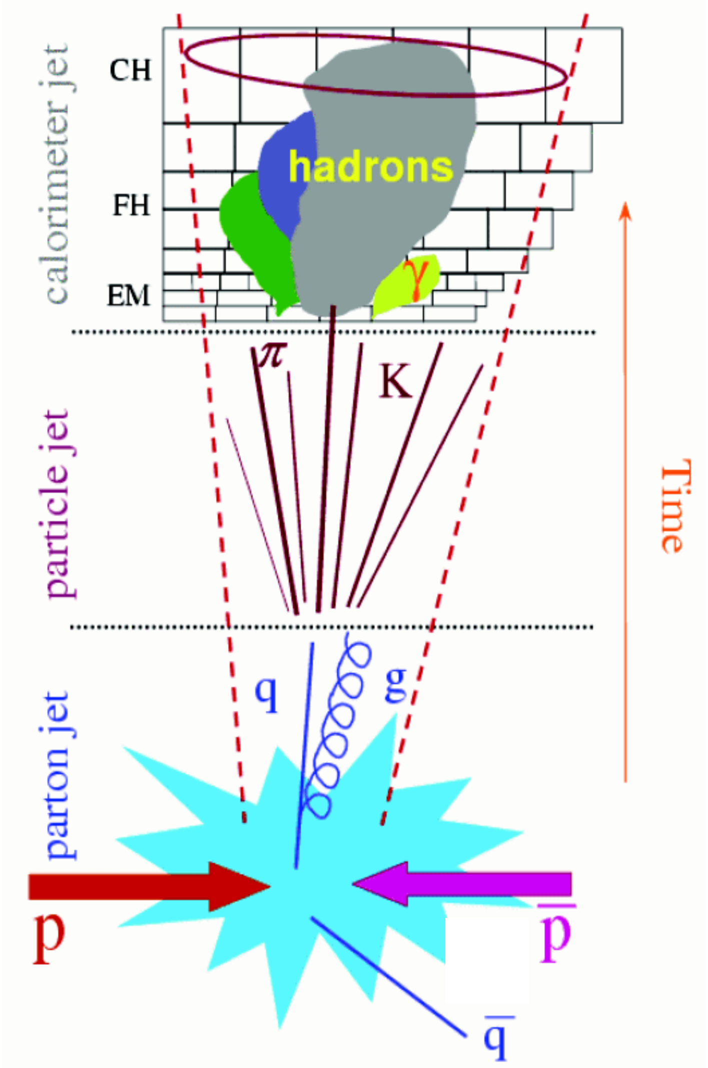
Jet reconstruction and energy measurement

- 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



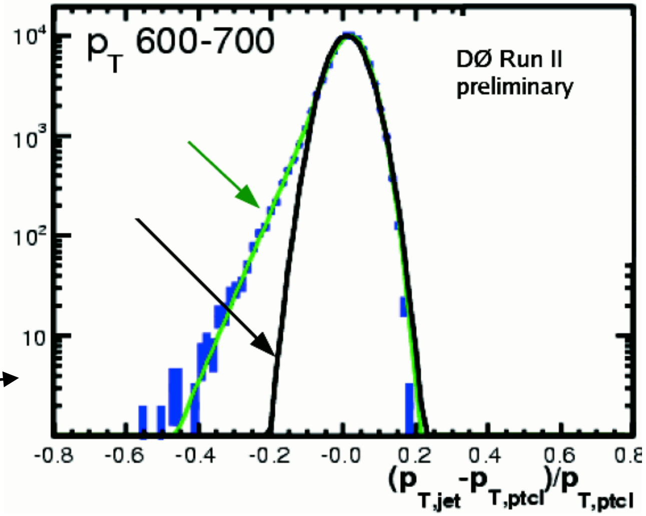
Experimental issues

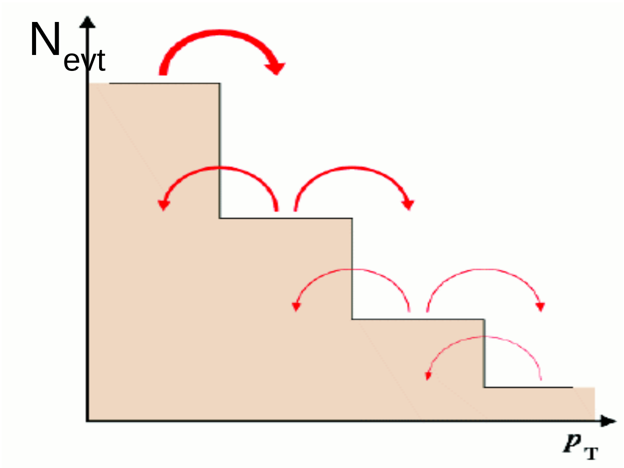
$$\mathbf{d^2\sigma / dp_T\, d\eta \;=\; N \;/\; (\varepsilon \cdot L \cdot \Delta\, p_T \cdot \Delta\eta)}$$

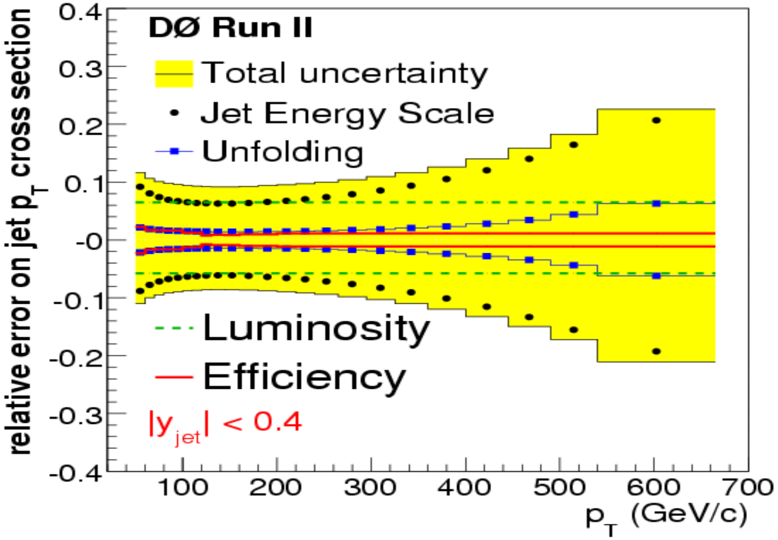
- In principle a simple counting experiment

- 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 $|\eta|<0.4$

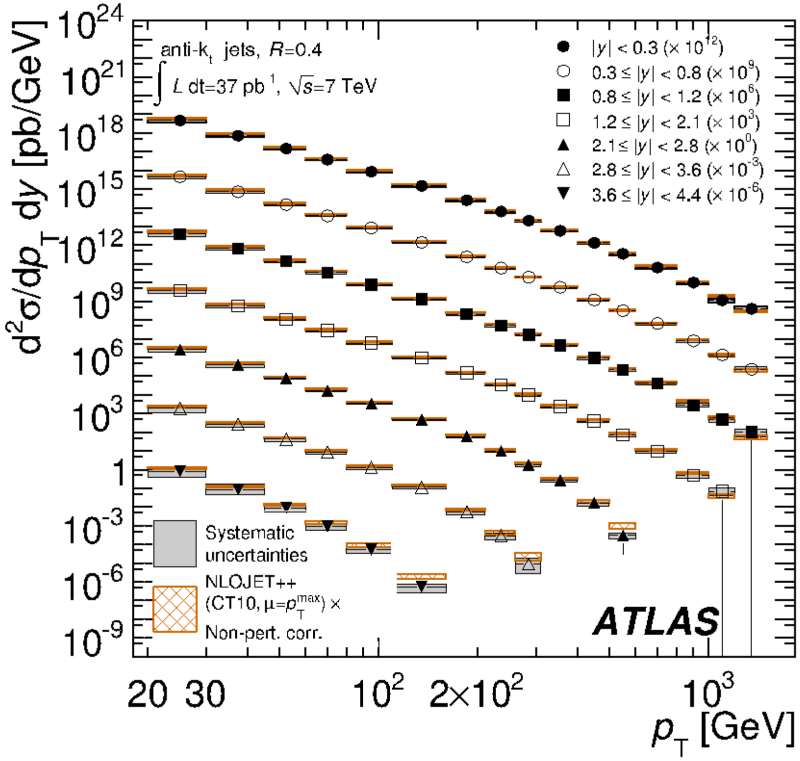


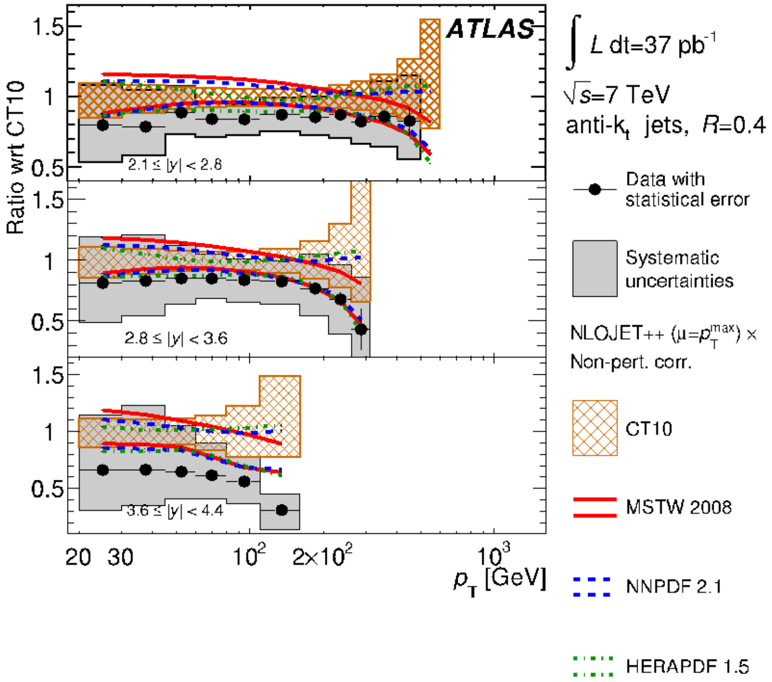




Major exp. errors:
energy scale, luminosity (6%),…

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

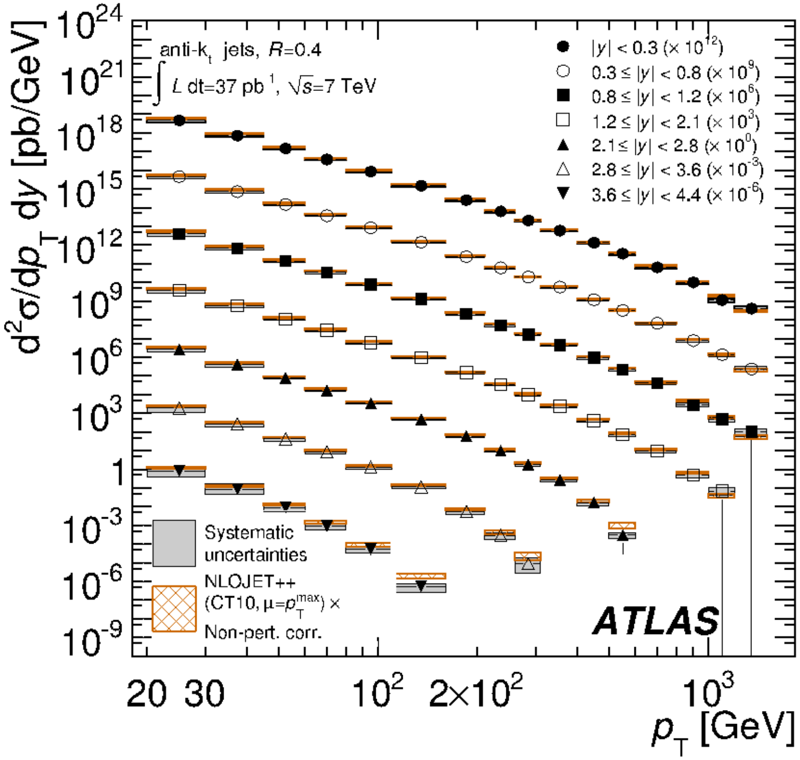


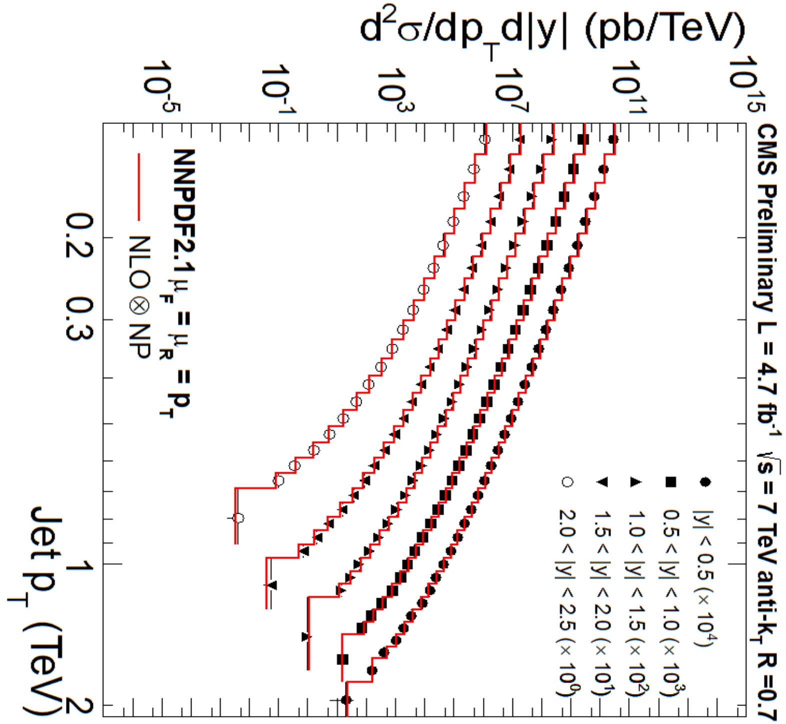


somewhat larger deviations in the forward region

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

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

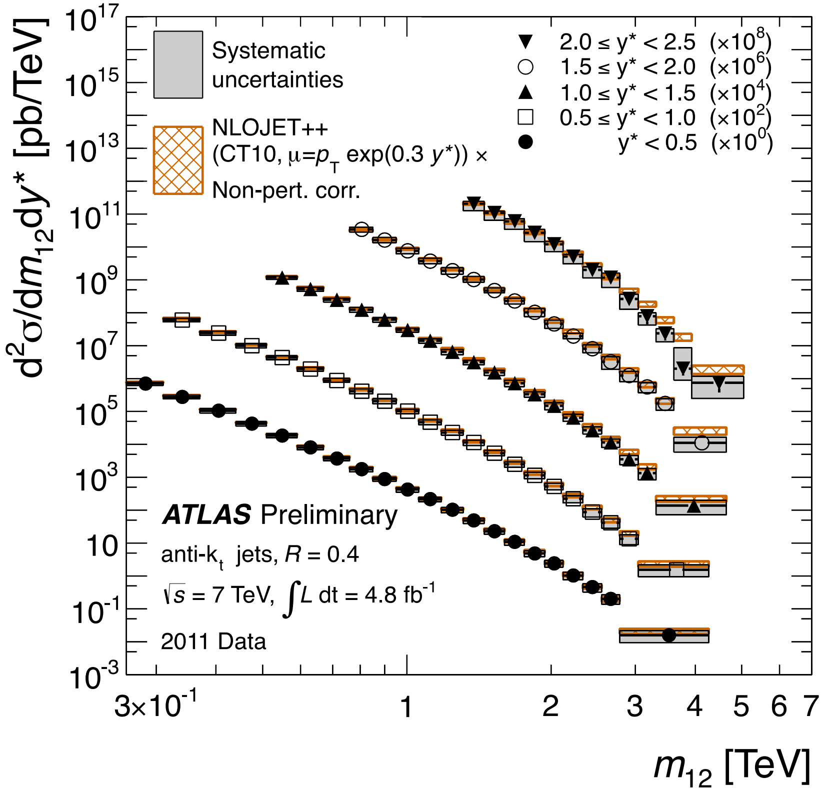


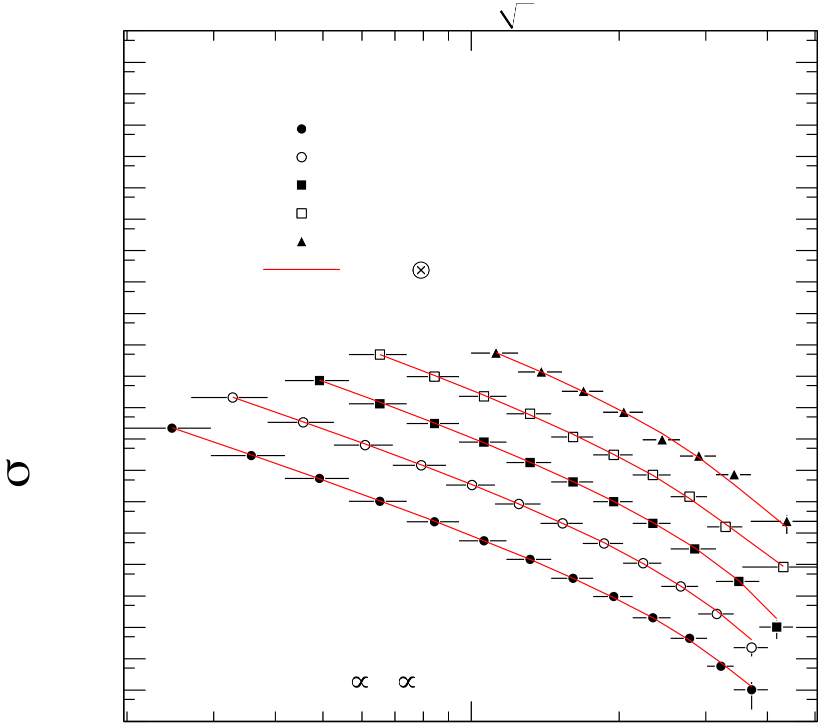


CMS: include full 2011 data set;
comparison up to 2 TeV (central rapidities)

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

Invariant di-jet mass spectra





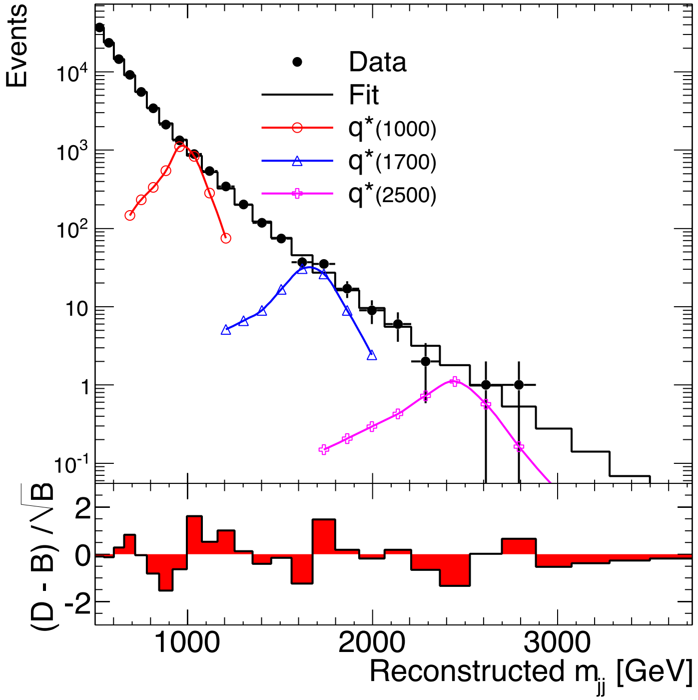
Important for: - Test of QCD
- Search for new resonances decaying into two jets (→ next slide)

In addition to QCD test: Sensitivity to New Physics

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

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

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



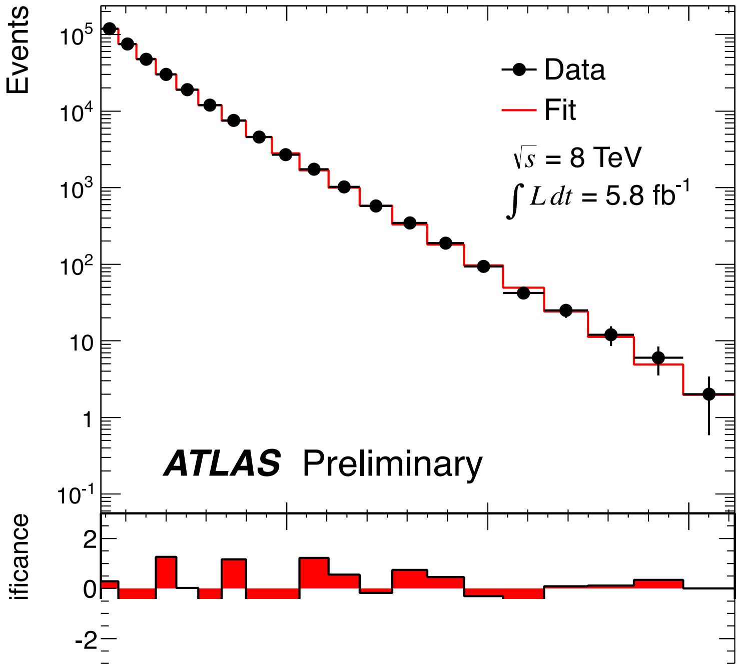
CDF (Tevatron), L =1.13 fb^{-1}: 0.26 < m_{q*} < 0.87 TeV

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

0.30 < m_{q*} < 1.26 TeV

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

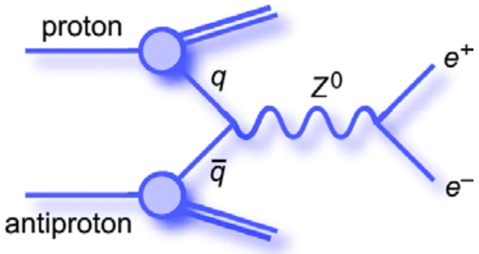
- Include new data at $\sqrt{s}$ = 8 TeV (2012)
- Invariant di-jet masses up to 4.1 TeV



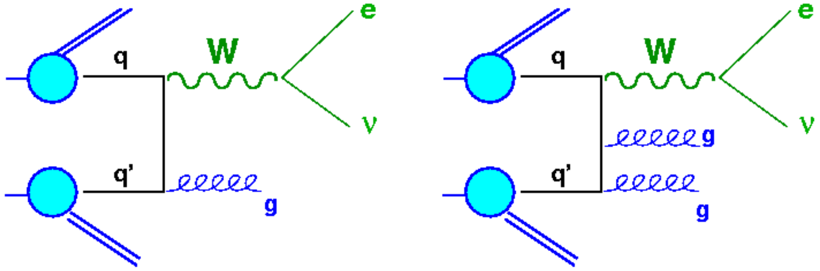
CDF (Tevatron), L =1.13 fb^{-1}: 0.26 < m_{q*} < 0.87 TeV

ATLAS (LHC), L = 0.000315 fb^{-1} exclude (95% C.L) q* mass interval
0.30 < m_{q*} < 1.26 TeV
L = 0.036 fb^{-1}: 0.60 < m_{q*} < 2.64 TeV
ATLAS (LHC), L = 5.8 fb^{-1}, 8 TeV: m_{q*} < 3.66 TeV

QCD aspects in W/Z (+ jet) production



QCD at work

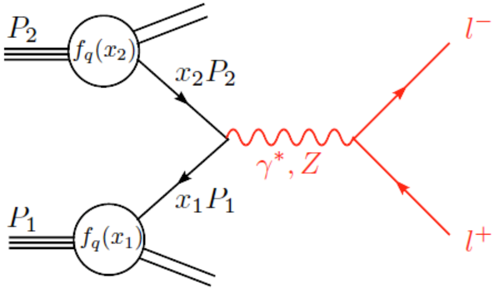


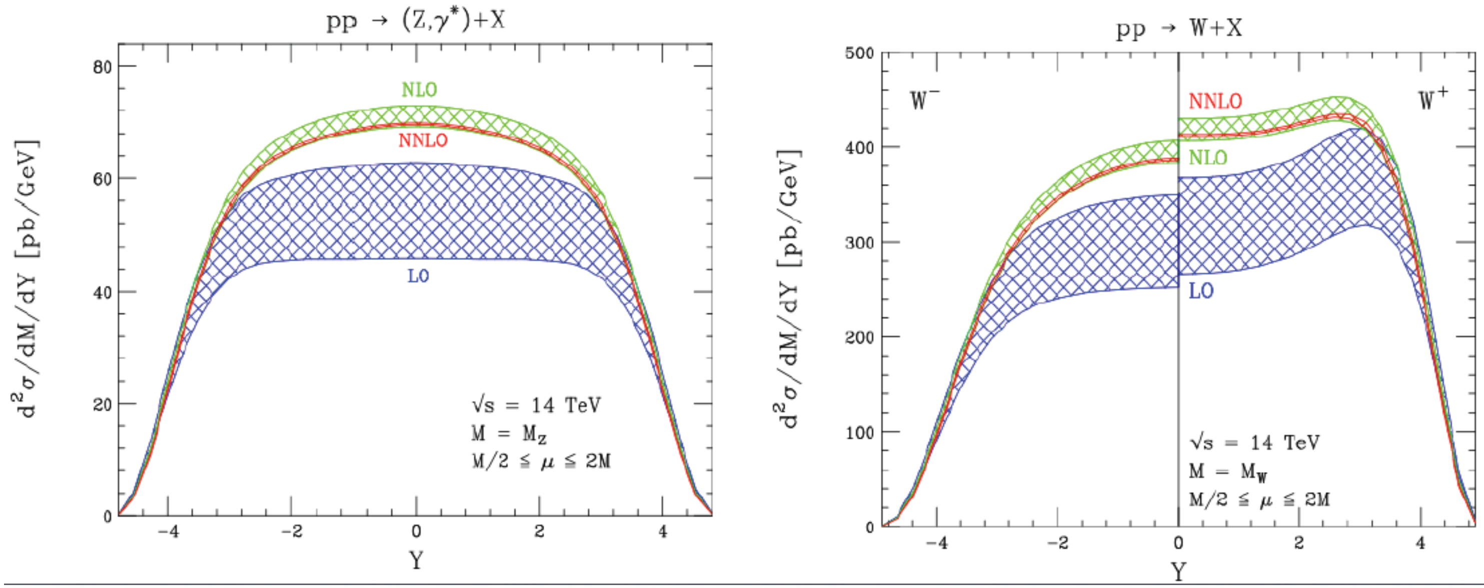
- Important test of NNLO Drell-Yan QCD prediction for the total cross section

- 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





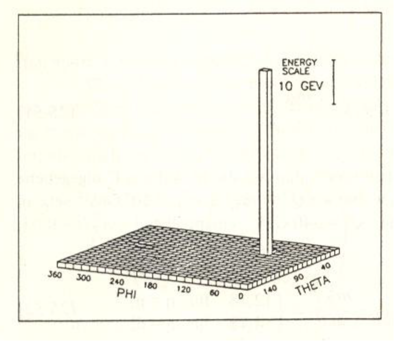
Rapidity distributions for Z and $W^{\pm}$ production at LO, NLO, and NNLO

How do W and Z events look like ?

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

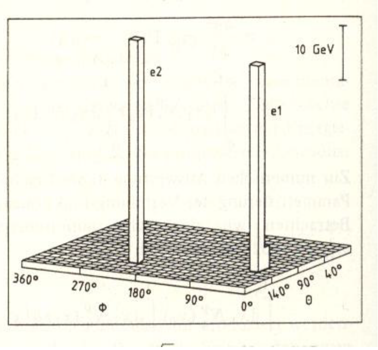
→ Search for leptonic decays: $W \to \ell \nu$ (large $P_T(\ell)$, large E_T^{miss})

$Z \to \ell \ell$

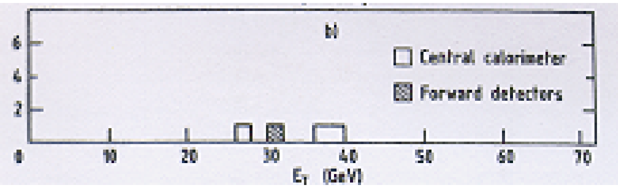


A bit of history: one of the first W events seen; UA2 experiment

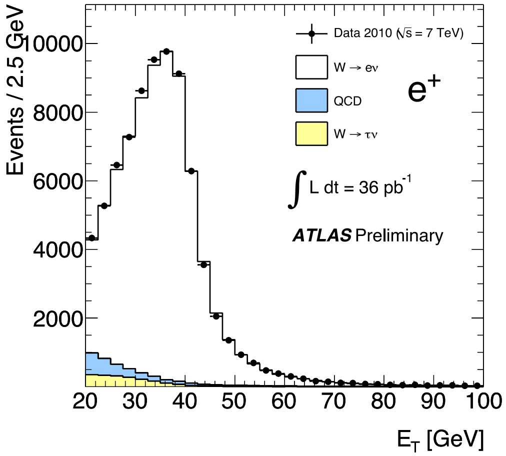
W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)

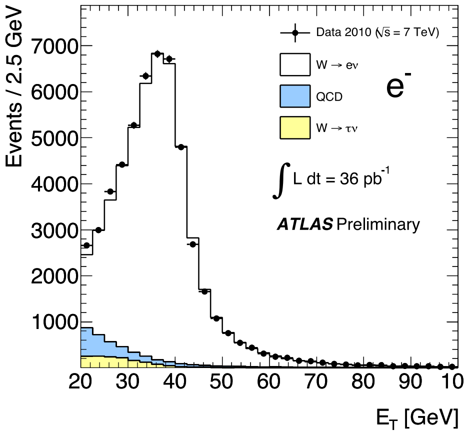


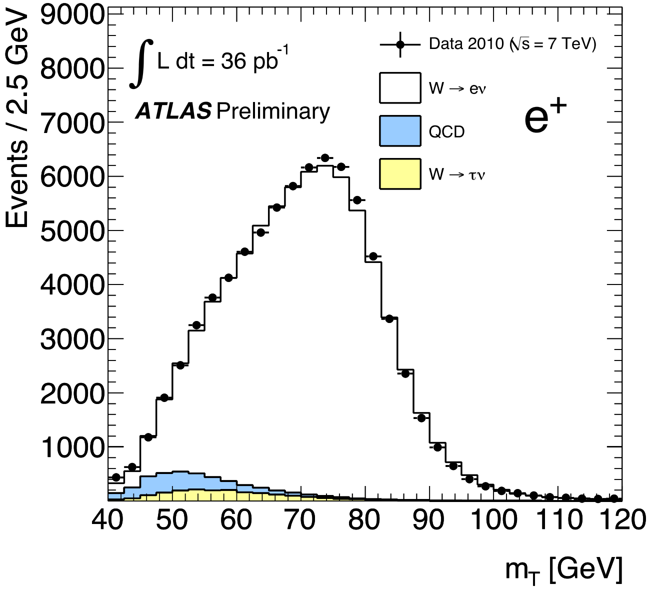
Transverse momentum of the electrons



W/Z selections in the ATLAS / CMS experiments







Electrons:

-Trigger: high p_T electron candidate in calorimeter

-Isolated el.magn. cluster in the calorimeter

-P_T> 25 GeV/c

-Shower shape consistent with expectation for electrons

- Matched with tracks

Z → ee

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

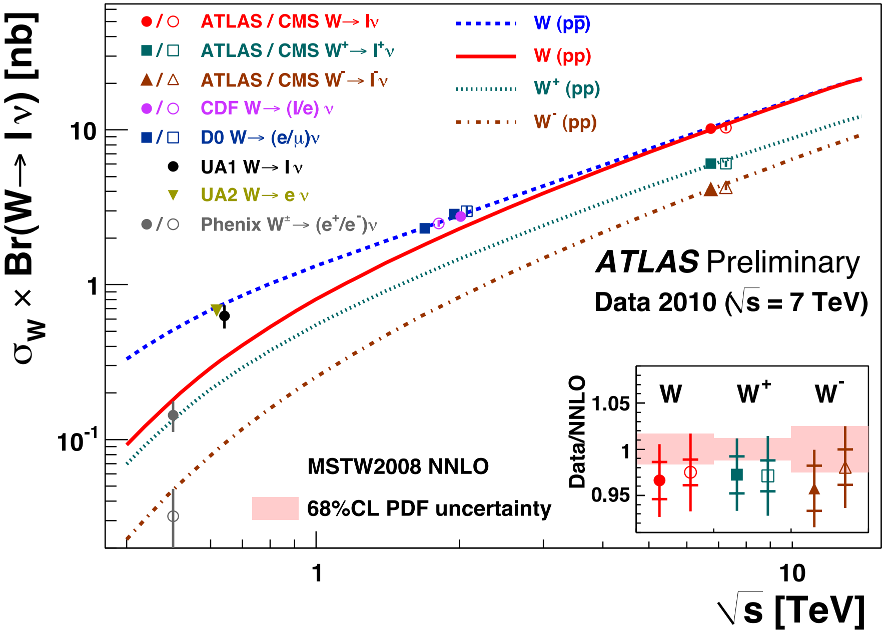
W → eν

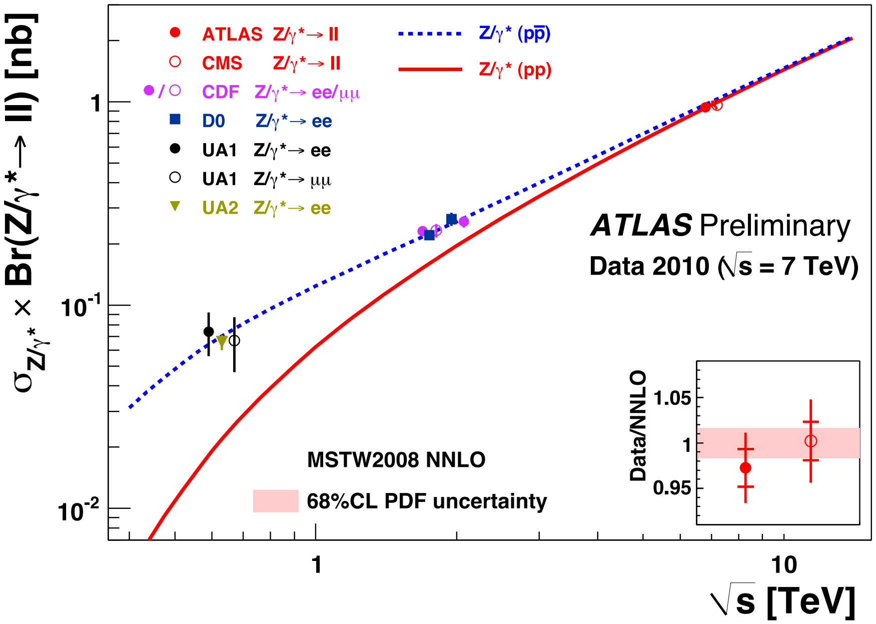
- Missing transverse momentum > 25 GeV/c
- Transverse mass M_T > 50 GeV

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

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

W and Z production cross sections at hadron colliders



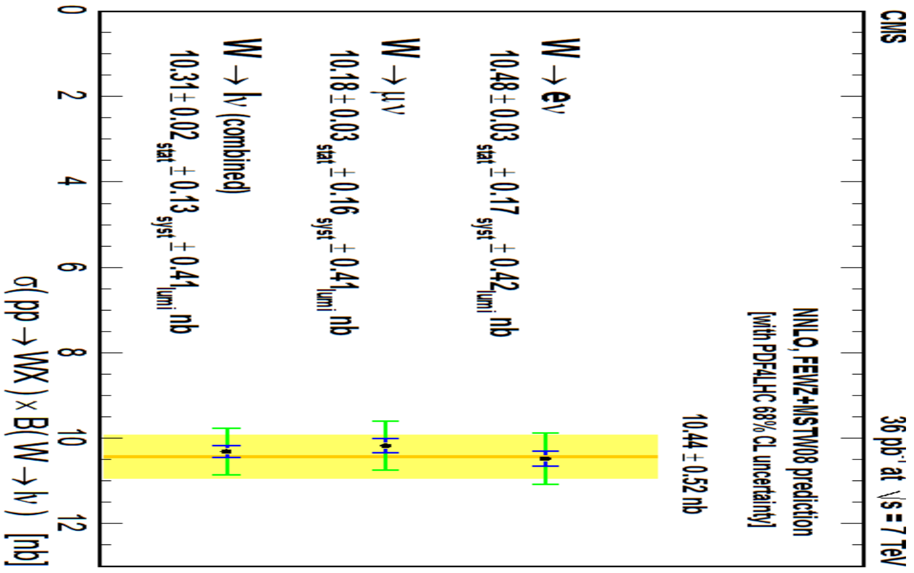


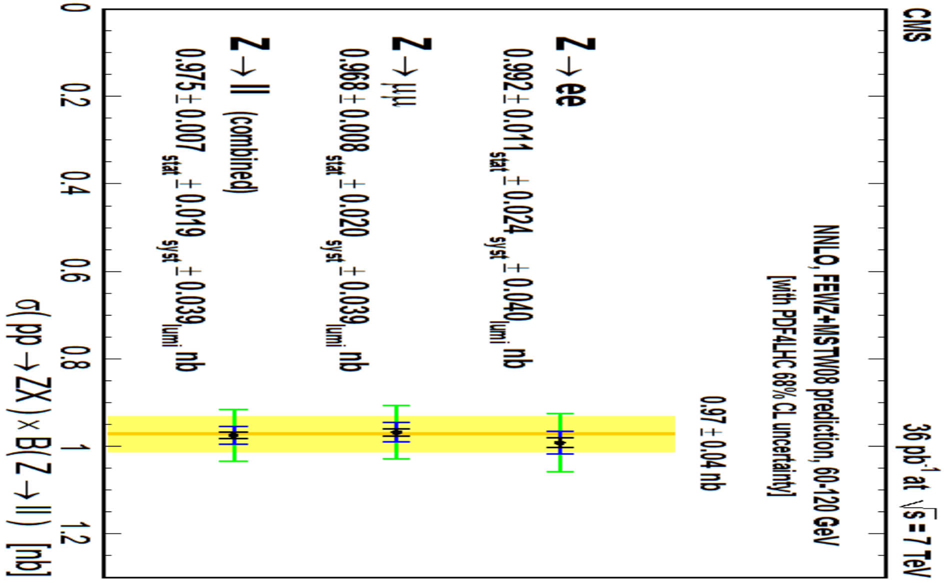
- Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)

- Good agreement as well between the ATLAS and CMS experiments

W and Z production cross sections at the LHC

Measured cross section values in comparison to NNLO QCD predictions:





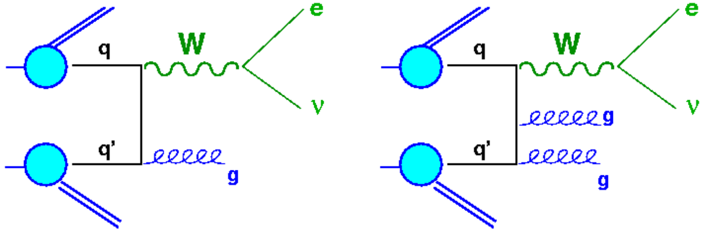
Data are well described by NNLO QCD calculations

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

Precision is already dominated by systematic uncertainties

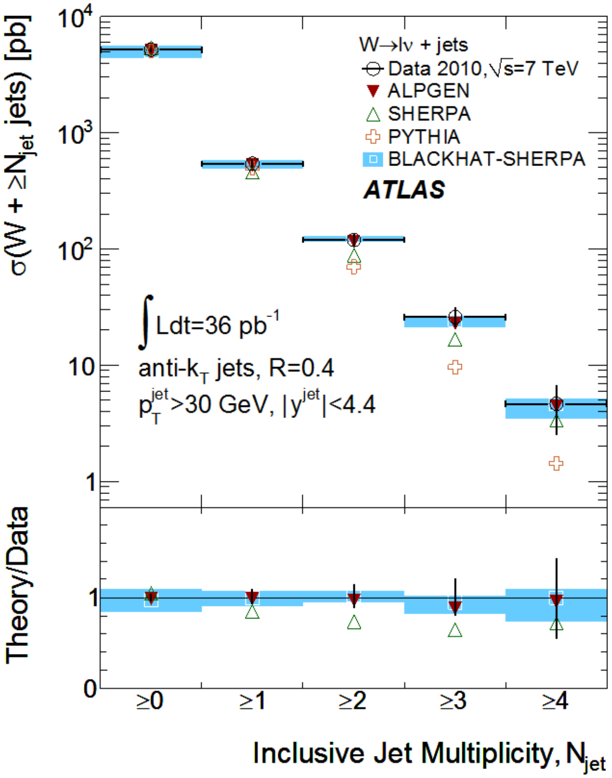
[The error bars represent successively the statistical, the statistical plus systematic and the total uncertainties (statistical, systematic and luminosity). All uncertainties are added in quadrature.]

W/Z + jet cross section measurements

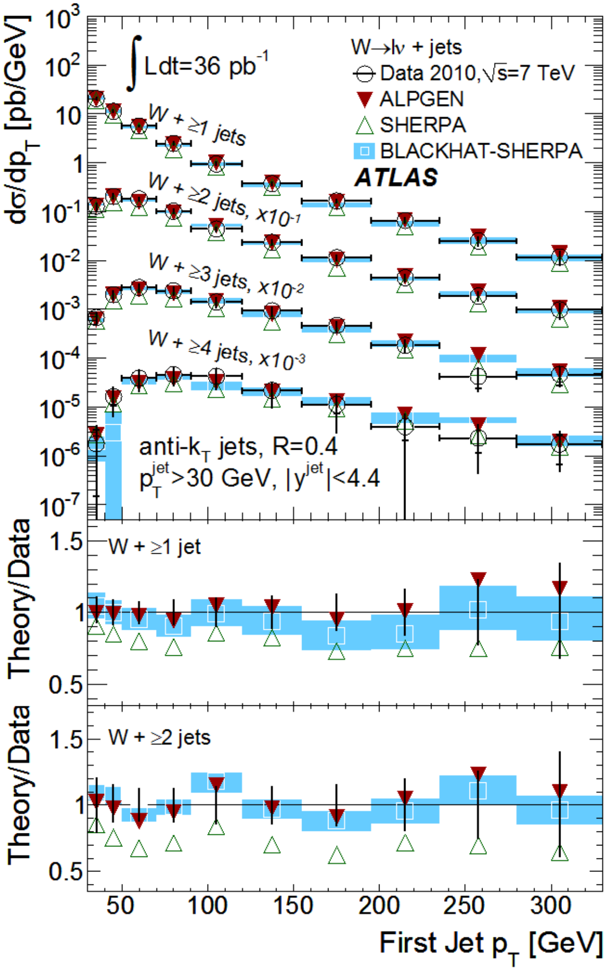


- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors;

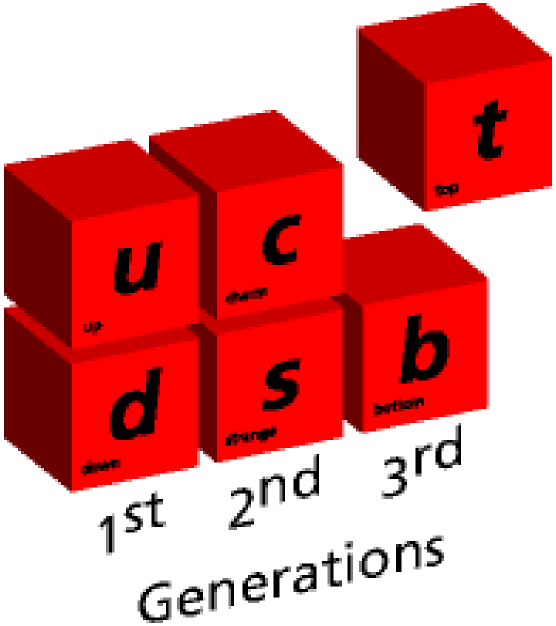
Jet multiplicities in W+jet production



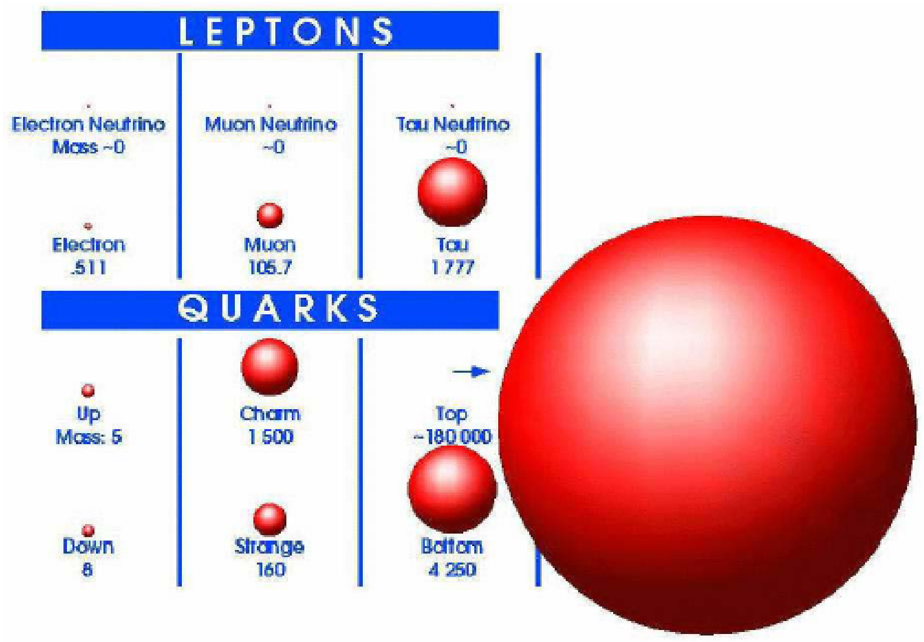
p_T spectrum of leading jet



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 ??

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

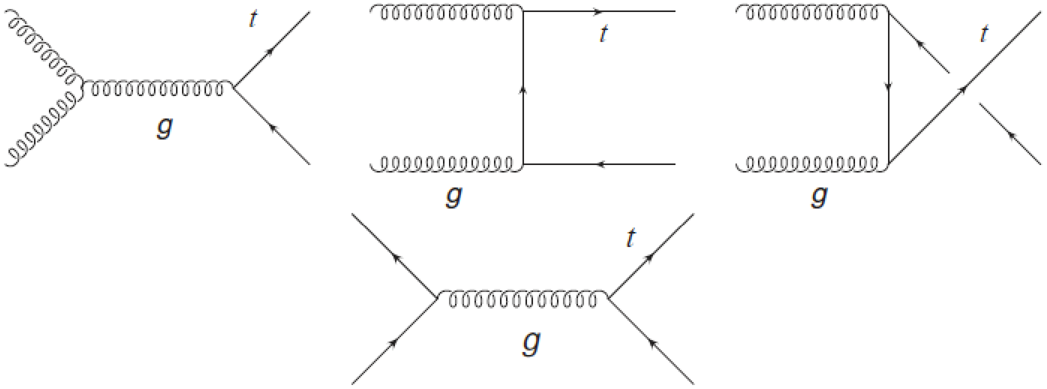
$$\Rightarrow \lambda_t = \frac{M_t}{173.9\ \mathrm{GeV}/c^2}$$

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

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

Top Quark Production

Pair production: qq and gg-fusion



Top-quark pair production in the Born approximation.

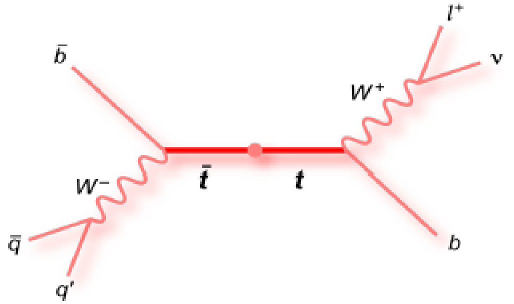
- NLO corrections completely known
- NNLO partly known

approximate NNLO results:

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

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

Top Quark Decays



BR (t→Wb) ~ 100%

Dilepton channel:

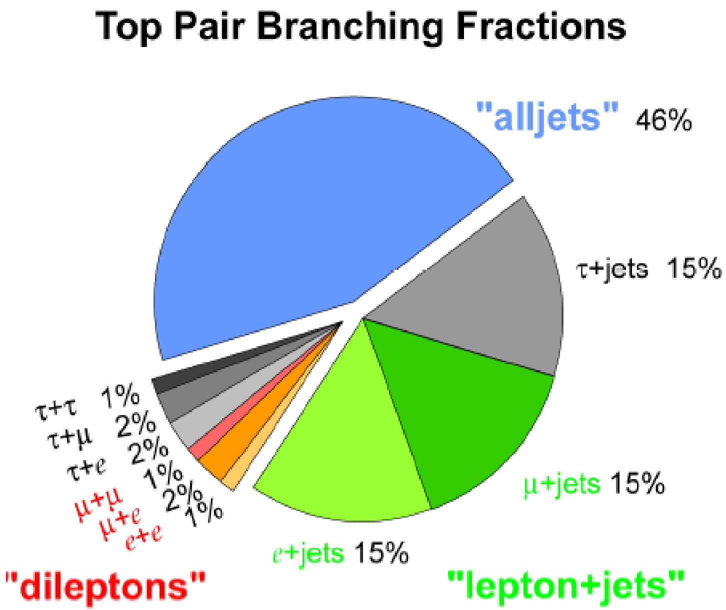
Both W's decay via W→ ℓν (ℓ=e or μ; 4%)

Lepton + jet channel:

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

Full hadronic channel:

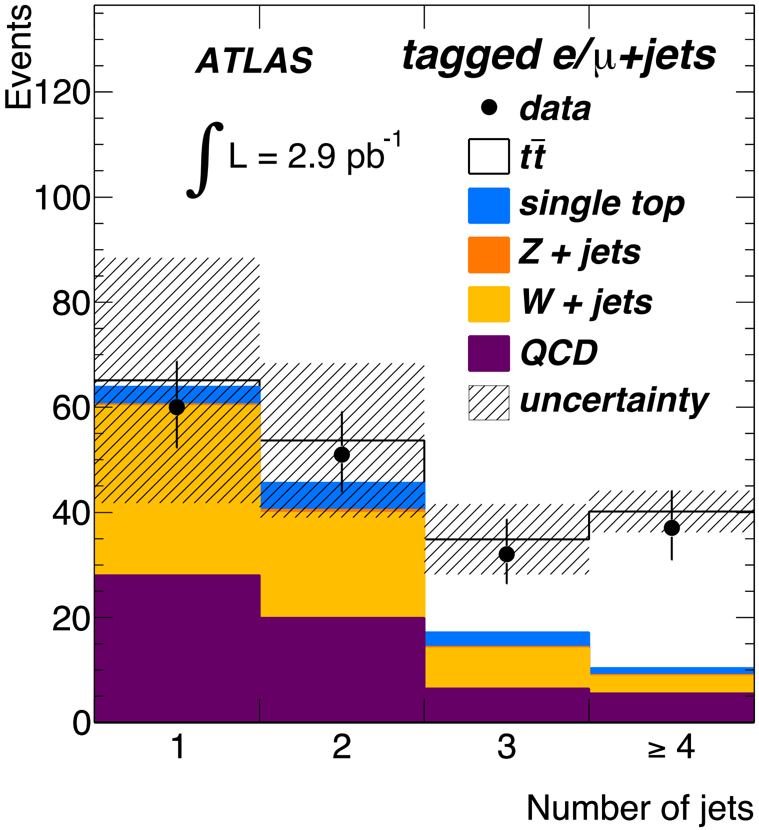
Both W's decay via W→qq (46%)



Important experimental signatures: : - Lepton(s)

- Missing transverse momentum
- b-jet(s)

First results on top production from the LHC



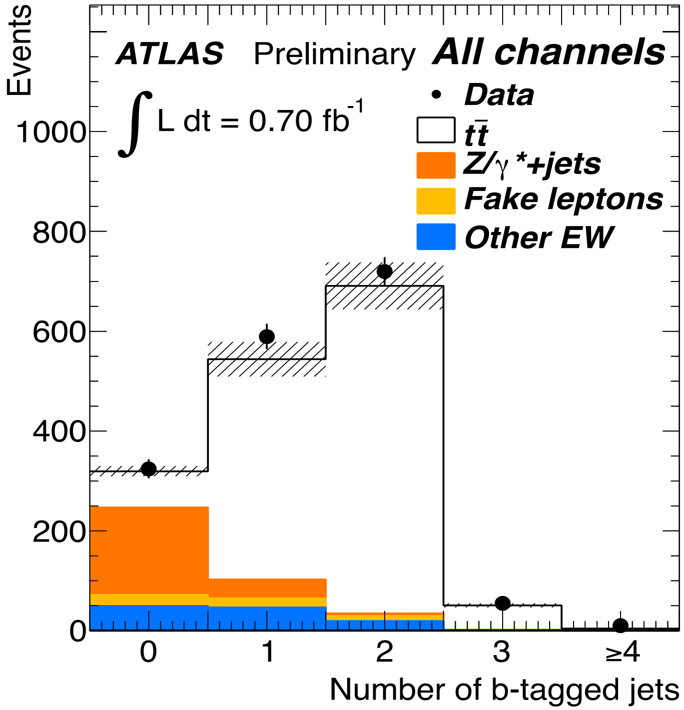
Event Selection:

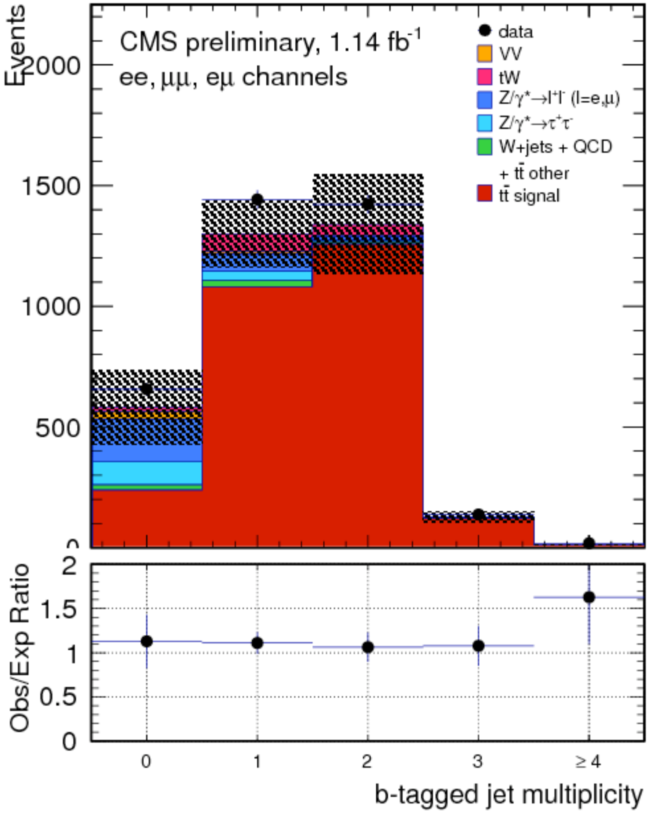
- Lepton trigger
- One identified lepton (e,μ) with $p_T > 20$ GeV
- Missing transverse energy: $E_T^{miss} > 35$ GeV (significant rejection against QCD events)
- Transverse mass: $M_T(l,\nu) > 25$ GeV (lepton from W decay in event)
- One or more jets with $p_T > 25$ GeV and $\eta < 2.5$

Top-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})

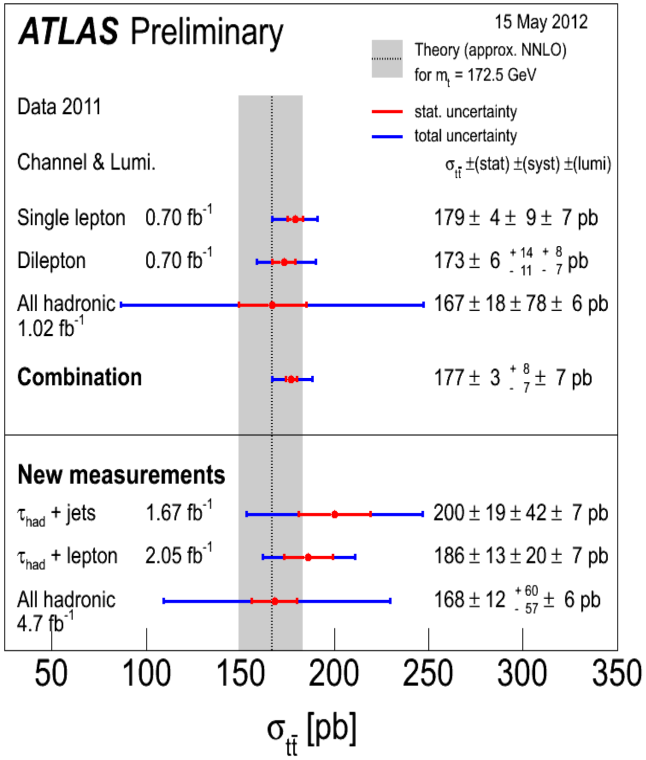
Multiplicity distributions of b-tagged jets
(small backgrounds, mainly from Z+jet production)

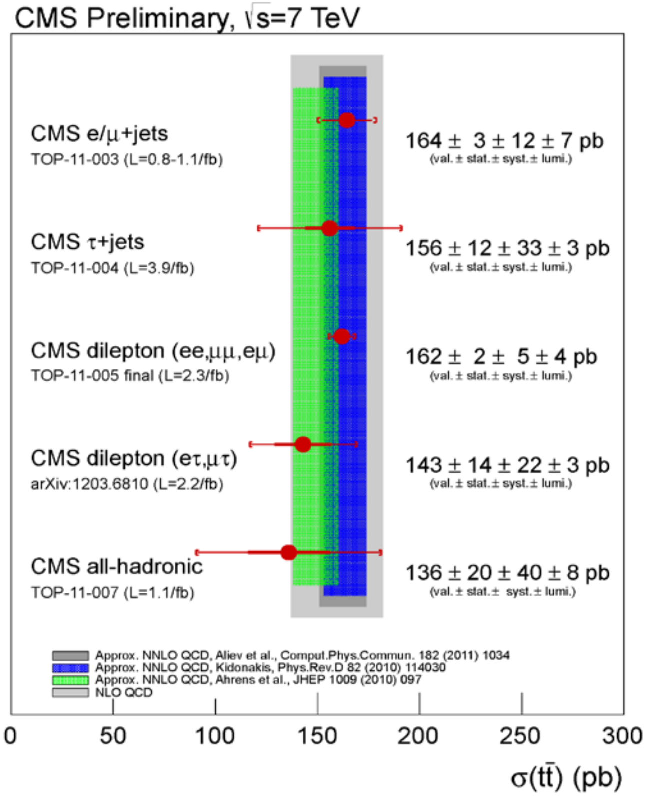




Top pair production cross section measurements

-likelihood combination of all channels-



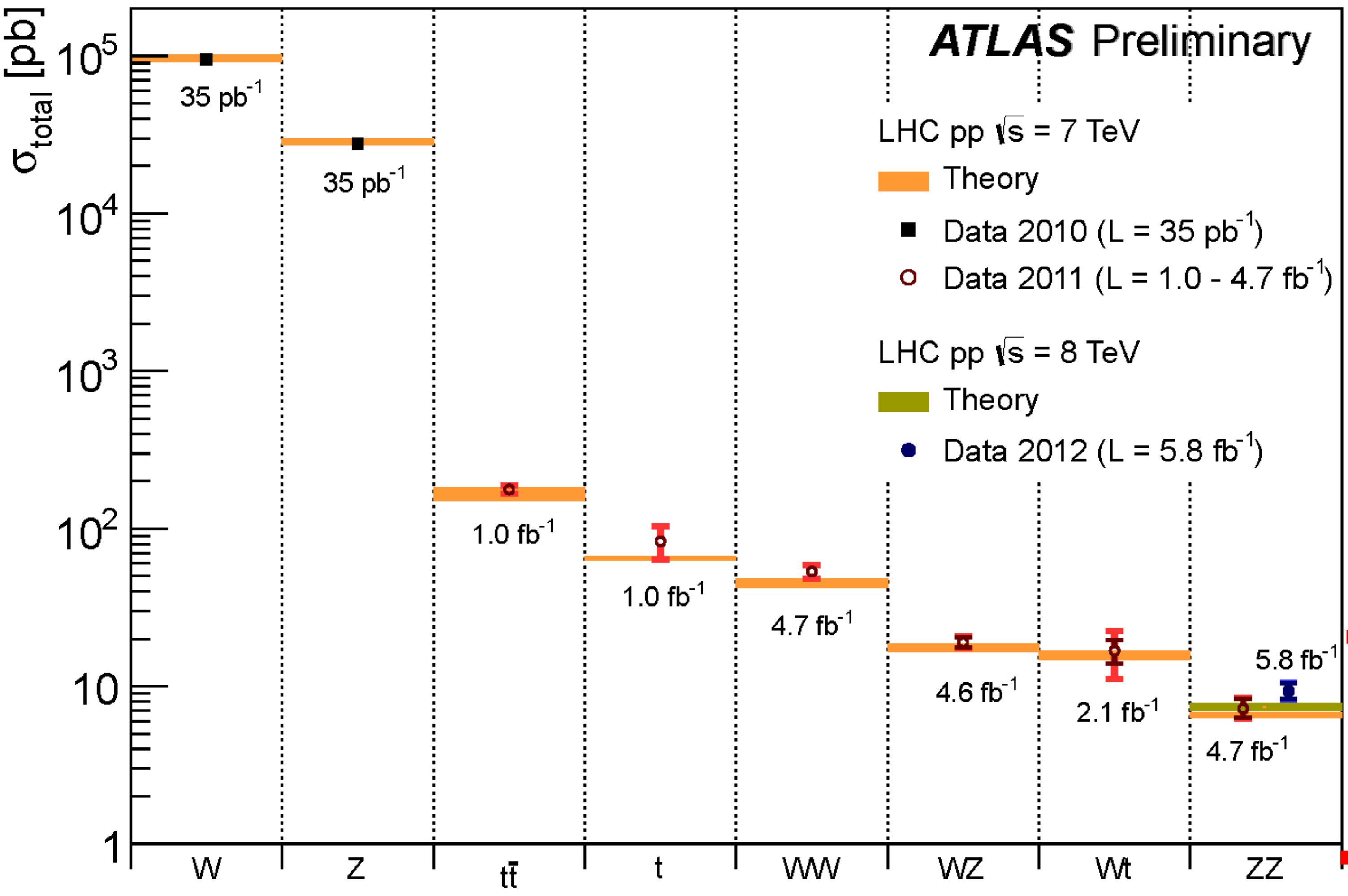


σ = 177 ± 3 (stat) ± 7 (syst) ± 7 (lum) pb

σ = 165.8 ± 2.2 (stat) ± 10.6 (syst) ± 7.8 (lum) p

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

The Standard Model at the LHC

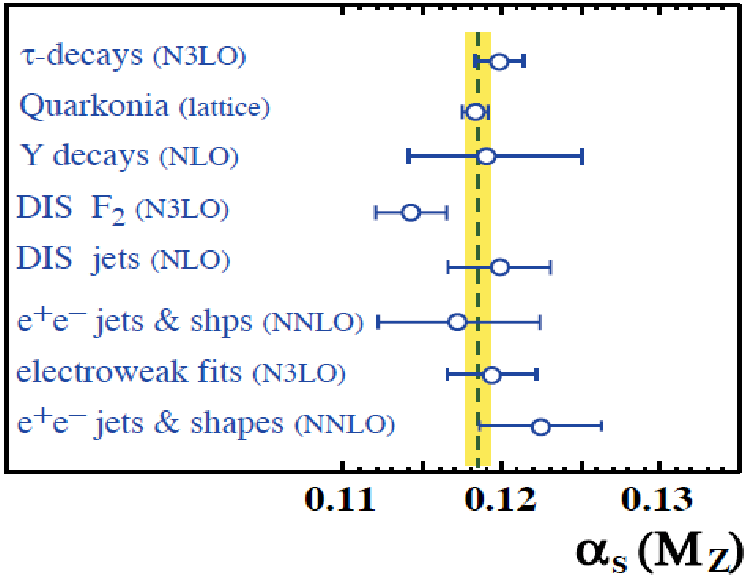


July 2012

H (20pb)

H → ZZ
(0.5 pb)

10.4 Bestimmung der starken Kopplungskonstanten 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 α_s (m_Z^2), used as input for the world average value (from Particle Data Group).