PIC2010 – QCD 2

Precision QCD tests and α_s measurements
(at HERA)

Ian C. Brock
University of Bonn

Karlsruhe
02/09/2010

Why test QCD?

- Everyone knows QCD is the theory of the strong interaction

Why test QCD?

- Everyone knows QCD is the theory of the strong interaction
- Everyone knows that a particle and an antiparticle have the same mass

Why test QCD?

- Everyone knows QCD is the theory of the strong interaction
- Everyone knows that a particle and an antiparticle have the same mass
- Everyone knows that (after the big bang) there is the same amount of matter and antimatter in the universe

Why test QCD?

- Everyone knows QCD is the theory of the strong interaction
- Everyone knows that a particle and an antiparticle have the same mass
- Everyone knows that (after the big bang) there is the same amount of matter and antimatter in the universe
  - or not?
- It is important not to take such things for granted and continue to test even established theories

Why test QCD and measure α_s?

- With the start of the LHC we hope to discover life beyond the Standard Model
- The pp cross section is many orders of magnitude larger than the interesting new physics cross sections
- QCD backgrounds are dominant in many processes
- α_s is the parameter (apart from masses) that fixes QCD!
- Calculations and precise tests are hard as α_s is large

Outline

- Measurements of α_s
  - How can one measure α_s?
  - Low-energy (τ, Υ) + LEP measurements
  - HERA measurements
  - Averages
- Other precision QCD tests
  - What one has to worry about
  - Selected results
- Summary

How to measure α_s?

- Measure the leptonic branching fraction of the τ lepton!
  - Obvious?
  - 3 colours lead to leptonic BR of 20%
  - QCD corrections lead to:
    e: (17.85 ± 0.05)%, μ: (17.36 ± 0.05)%
  - From this extract α_s

$$R_\tau = \frac{\Gamma(\tau \rightarrow \text{hadrons})}{\Gamma(\tau \rightarrow l \, \nu_l \nu_\tau)}$$

  - Using properties of hadronic system leads to further improvement:

$$\alpha_S(m_\tau) = 0.330 \pm 0.014$$

Refs in S. Bethke
EPJ C64:(2009) 689,
arXiv:0908.1135

Running of α_s

- Running coupling satisfies renormalisation group equation(RGE):

$$\mu^2 \frac{d\alpha_S}{d\mu^2} = \beta(\alpha_S) = -(\beta_0 \alpha_S^2 + \beta_1 \alpha_S^3 + \beta_2 \alpha_S^4 + \cdots)$$

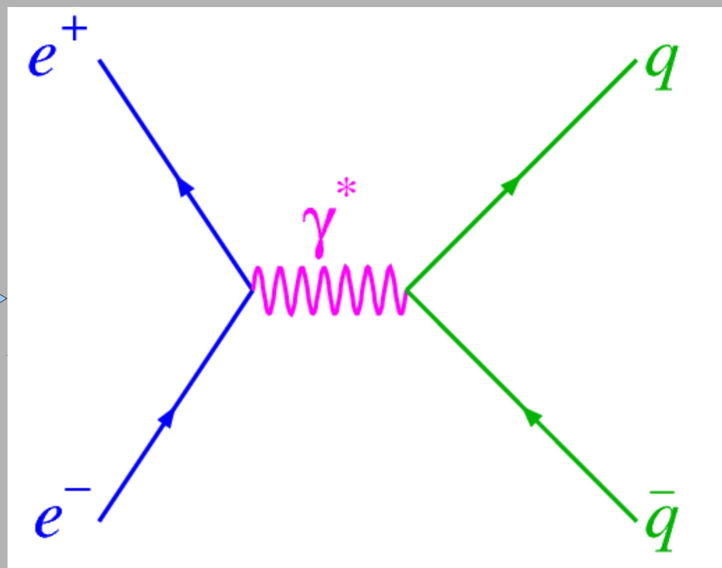
- 1-loop approximation ($\beta_1 = 0$)

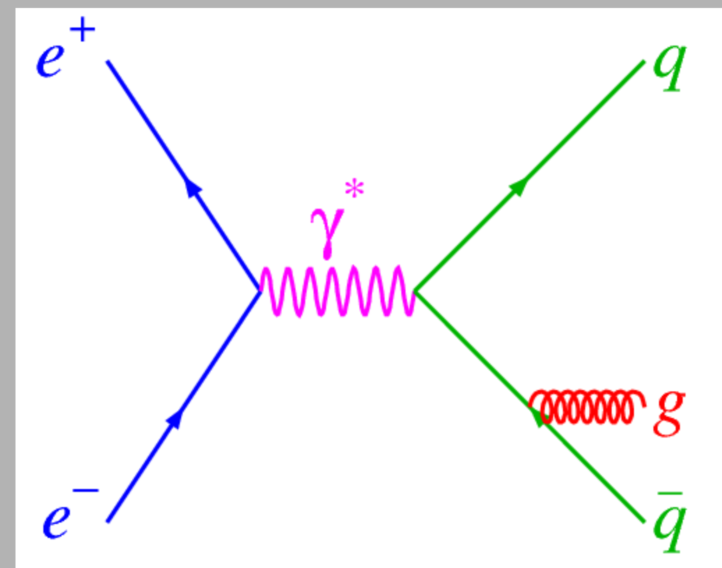
$$\alpha_S(Q^2) = \frac{\alpha_S(\mu^2)}{1 + \alpha_S(\mu^2)\beta_0 \ln(Q^2/\mu^2)} \quad \text{or} \quad \alpha_S(Q^2) = \frac{1}{\beta_0 \ln(Q^2/\Lambda^2)}$$

LO, NLO, NNLO and all that

- What is leading order (LO)?

QED LO





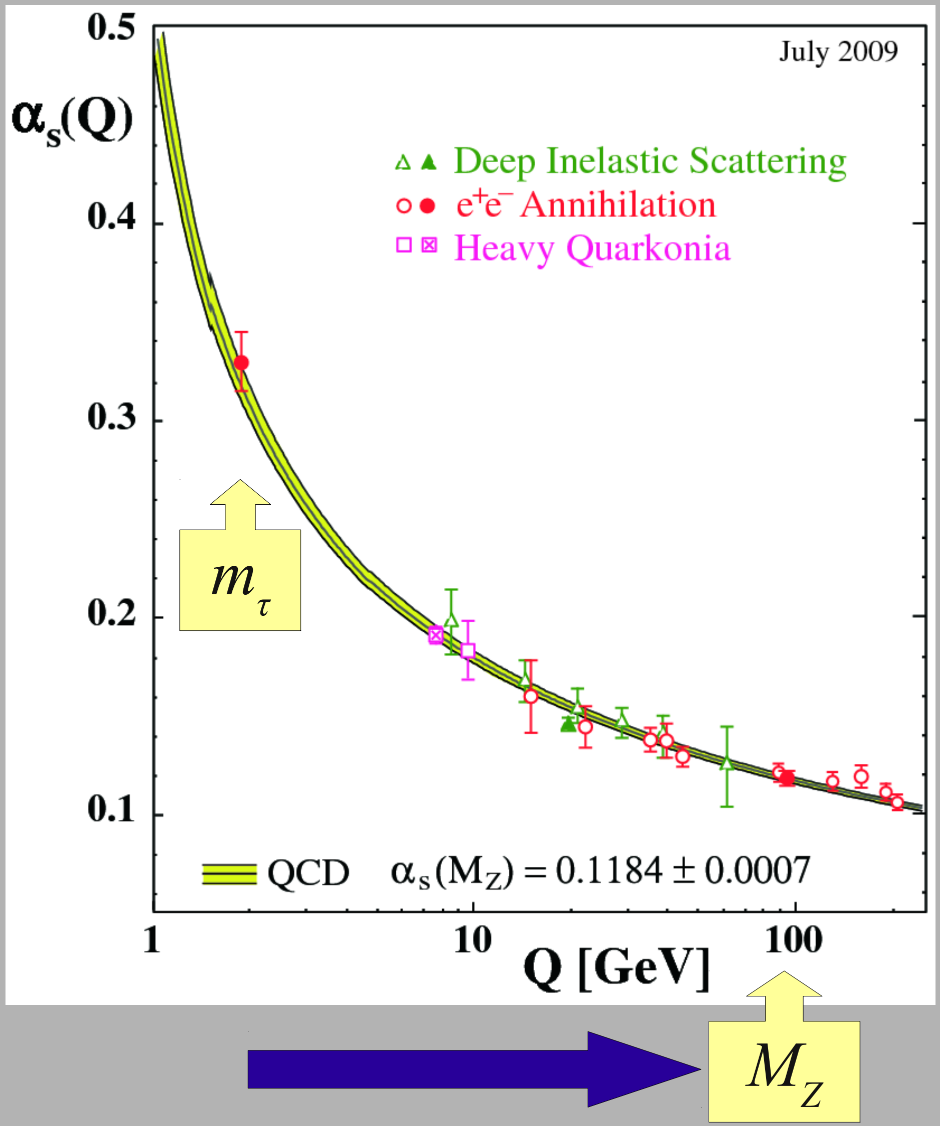
QCD LO

- Usually defined as lowest relevant order in α_S
- In this talk NLO means calculations to α_S^2
- NNLO = next-to-next-to-leading order: N^2LO
- NNNLO = next-to-next-to-next-to...: N^3LO

LO, NLO, NNLO and all that

- LO: calculations exist (by definition) for all processes
- NLO: exist for many processes
  - but not always in the form of a MC
- NNLO: few results mostly for inclusive kinematics
- N^3LO: very few, e.g. 4-loop running coupling
- Summing/including leading logs helps precision:
  - NLL etc.

Running of α_s



- Is a precision of 4% at m_τ competitive?
  - α_s runs and error goes down!
  - Error goes as

$$\Delta\alpha_s(Q^2)/\alpha_s(Q^2) \sim \alpha_s(Q^2)$$

- Swim to M_Z:

$$\alpha_s(M_Z) = 0.1197 \pm 0.0016$$

N³LO

How to measure α_s?

- $\Upsilon(1S) \rightarrow ggg$ is proportional to α_s^3
  - but significant theoretical uncertainties
- Look at ratio:
  BR($\Upsilon(1S) \rightarrow \gamma gg$) / BR($\Upsilon(1S) \rightarrow ggg$)
  - Slightly more obvious?
  - Many systematics cancel:

$$\alpha_S(M_Z) = 0.119^{+0.006}_{-0.005}$$

NLO

N. Brambilla et al.
Phys. Rev.D75 (2007) 074014
arXiv:hep-ph/0702079
CLEO Collab.
Phys. Rev. D74 (2006) 012003
arXivhep-ex/:0512061

How to measure α_s?

- Take $m(\Upsilon(2S)) - m(\Upsilon(1S))$
- Adjust u,d,s masses to give correct light mesons masses
- Let lattice gauge theory do the work for you!

$$\alpha_s(M_Z) = 0.1183 \pm 0.0008$$

Lattice

C.T.H. Davies et al., HPQCD Collab., Phys.Rev. D78 (2008) 114507; arXiv:0807.1687 [hep-lat]

Refs in S. Bethke EPJ C64:(2009) 689, arXiv:0908.1135

How to measure α_s?

- Take lots of data with an e^+e^- collider, i.e. LEP (c.m. energy 90 GeV)
- Measure event shapes in hadronic events

$$\alpha_S(M_Z)=0.1224\pm0.0039$$

NNLO

- Include α_S in the electroweak fits

$$R_Z=\frac{\Gamma(Z\rightarrow \text{hadrons})}{\Gamma(Z\rightarrow l^+l^-)}$$

$$\alpha_S(M_Z)=0.1193^{+0.0028}_{-0.0027}\pm0.0005$$

N^3LO

- Go back and re-analyse JADE (PETRA) data including latest theory

$$\alpha_S(M_Z)=0.1172\pm0.0051$$

NNLO

How to measure α_s?

- Take lots of data with an *ep* collider, i.e. HERA
- Use PDF data and its development as a function of Q^2
  - See also earlier talk (K. Lipka)

$$\alpha_S(M_Z) = 0.1142 \pm 0.0023$$

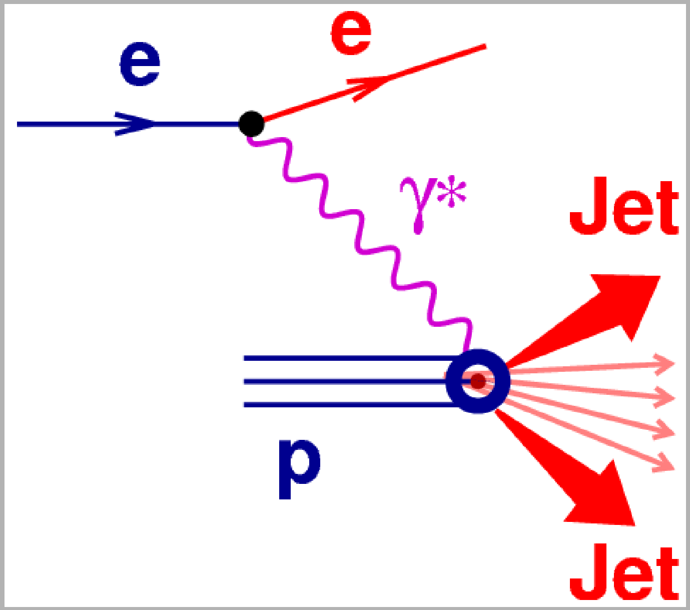
N^{3}LO

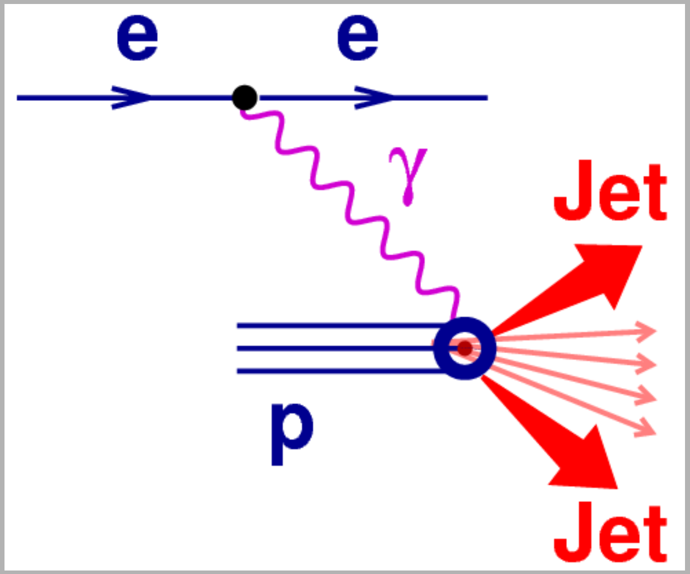
- Look at jet cross sections and ratios of cross sections

J. Blümlein, H. Böttcher and A. Guffanti
Nucl. Phys. B774 (2007) 182; hep-ph/0607200

Jets and Kinematics at HERA

- Measurements in both DIS and photoproduction (PhP) are used to determine α_S



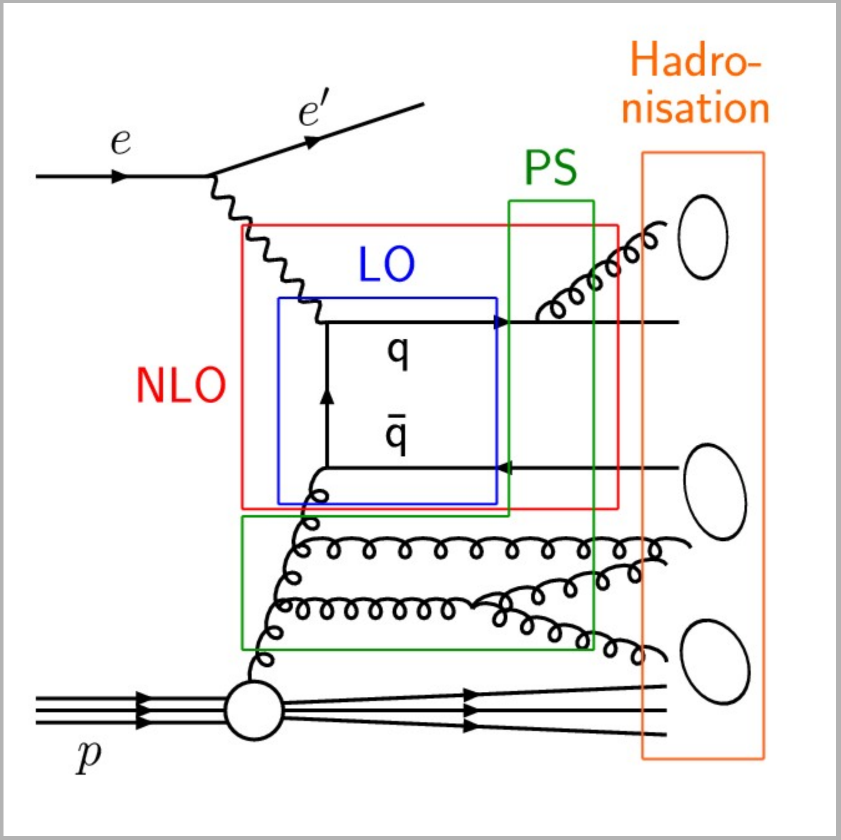


- Cross-section ratios are a good way to reduce systematics

From jets to α_s

- QCD factorisation theorem allows perturbative from non-perturbative contributions to cross-sections to be separated:

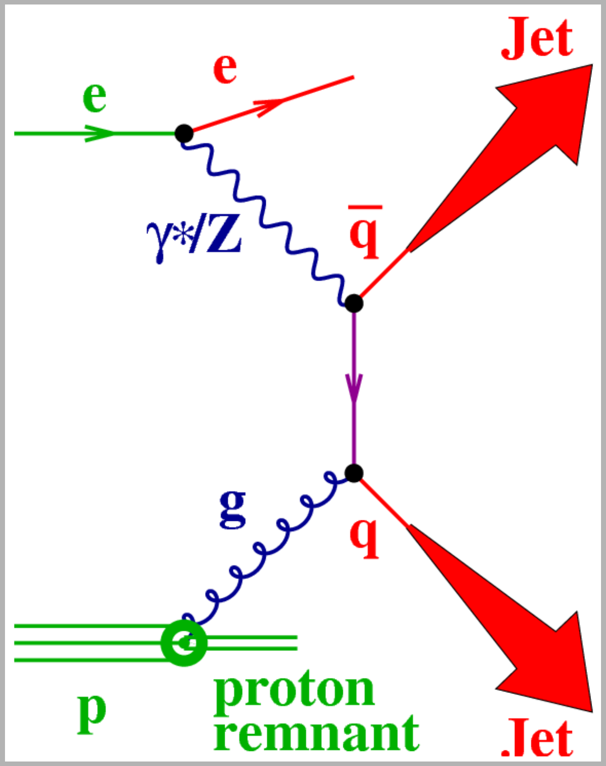
$$d\sigma_{\text{jet}} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x,\mu_F) \cdot d\hat{\sigma}_a(x, \alpha_S(\mu_R), \mu_R, \mu_F)$$



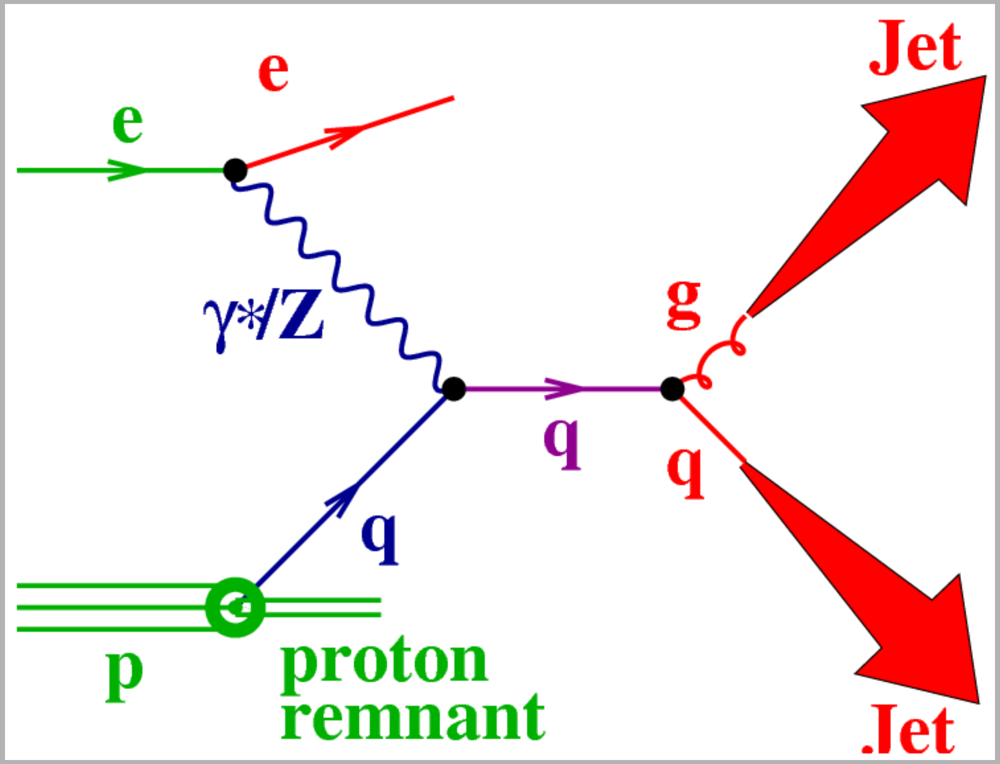
  - f_a: parton density
  - $d\hat{\sigma}_a$: subprocess cross-section

Jets in DIS

- Sources of (di)jet production:



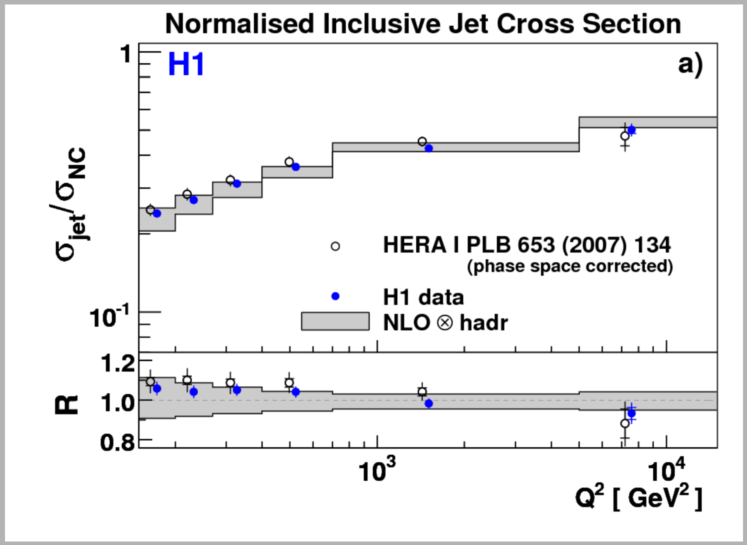
Boson-gluon fusion

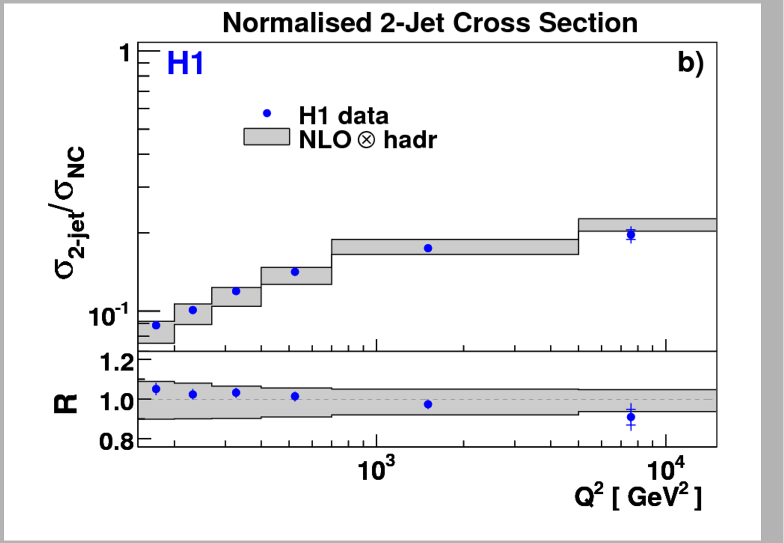


QCD Compton

Jets at high Q^2

- DIS events with 1,2 and 3 jets and their ratios
- Compare cross-sections as a function of Q^2, P_T^{jet} and ξ with NLO predictions $\xi = x_{\text{Bj}}(1 + M_{jj}/Q^2)$
- Normalise to NC cross-section





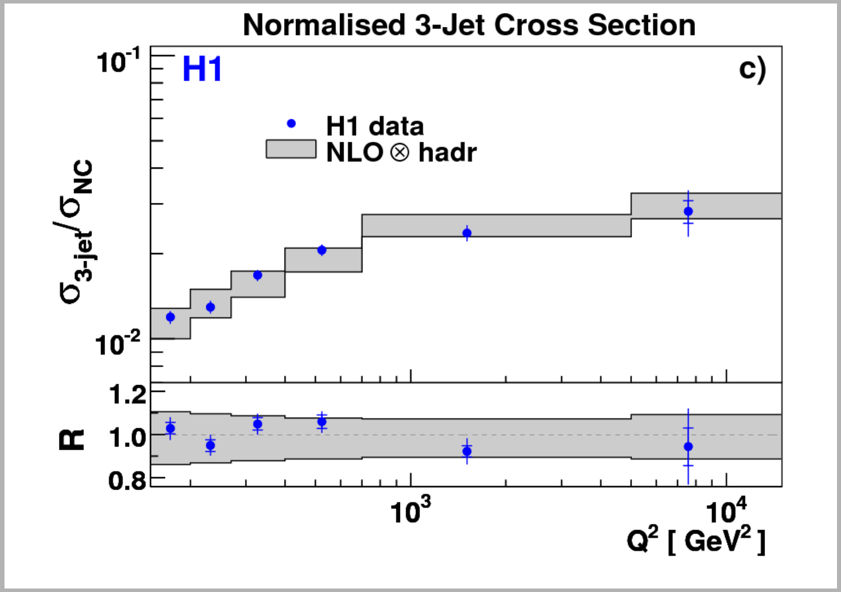
395 pb^{-1}, Event:
  150 < Q^2 < 15000 GeV^2
  0.2 < y < 0.7
Jet:
  P_T > 7(5) GeV
  -0.8 < η_{lab} < 2.0
  k_T algorithm in BF

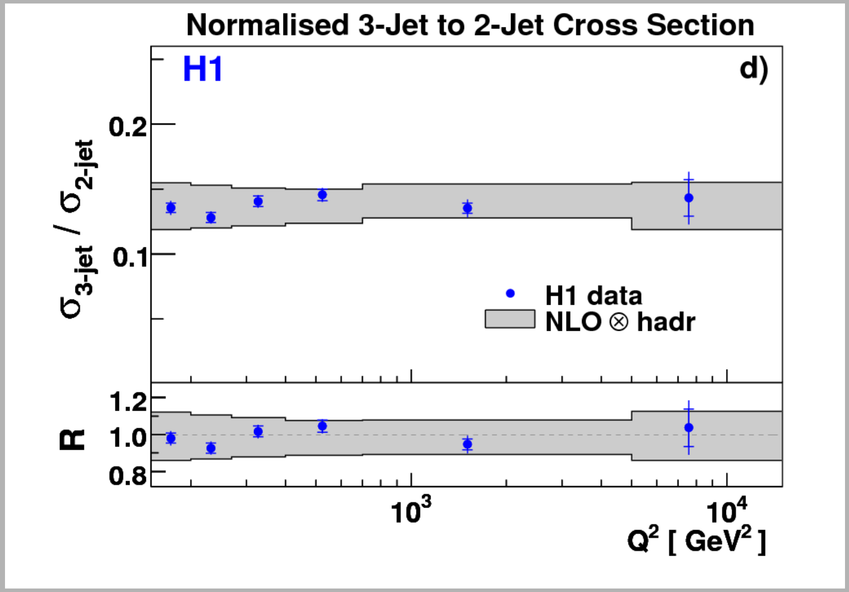
H1 Collab, Eur Phys J. C 65 (2010) 363

universitätbonn

Jets at high Q^2

- Plenty of statistics even in 3-jet channel
- NLO uncertainties at 10% level
- Good agreement with predictions over whole Q^2 range

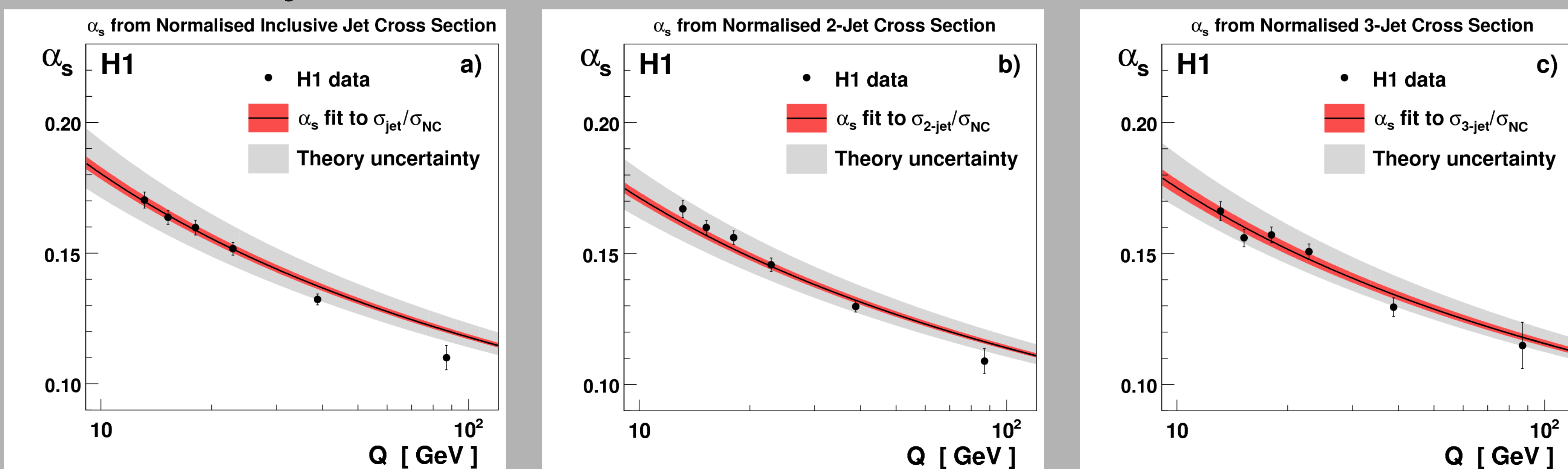




H1 Collab, Eur Phys J. C 65 (2010) 363

Jets at high Q^2

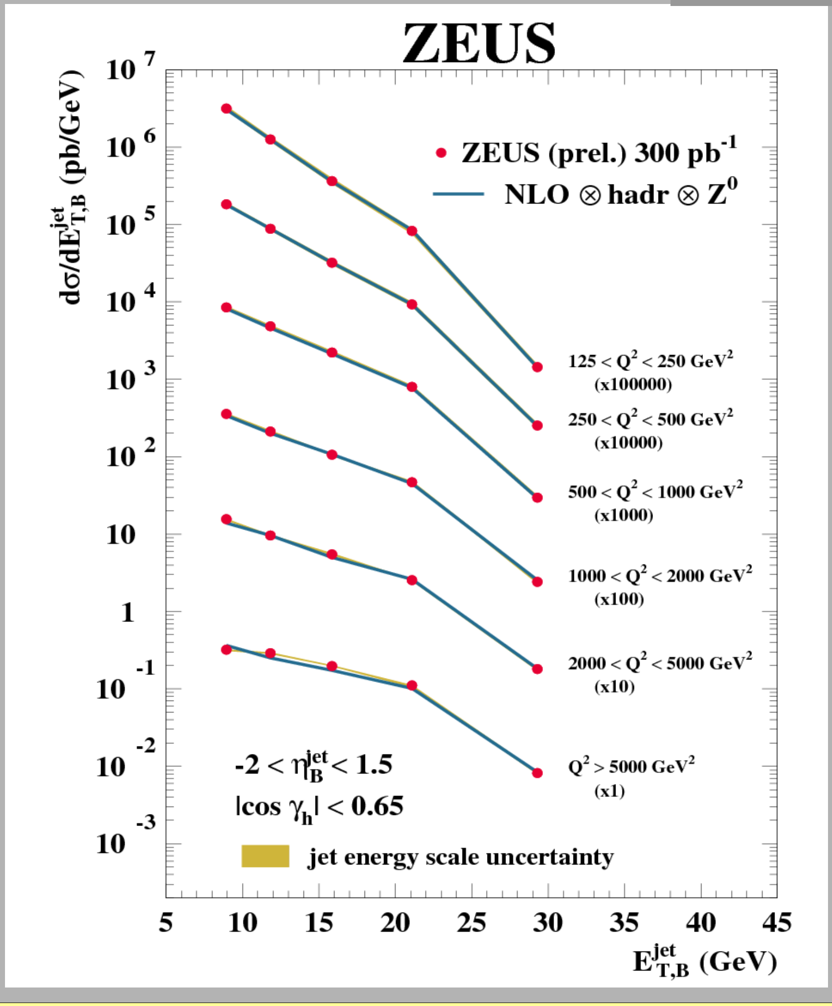
- Each cross-section and cross-section ratio can be used to derive α_s as a function of the scale
- Running of α_s (within a single experiment) clearly seen



H1 Collab, Eur Phys J. C 65 (2010) 363

Jets at high Q^2

- Inclusive jet cross-sections: Q^2, E_T (BF)
- Compare with NLO predictions
- Good agreement over whole measured range



300 pb^{-1}, Event:

$Q^2 > 125$ GeV^2

$|\cos\gamma_h| < 0.65$

Jet:

$E_T > 8$ GeV

$-2 < \eta_{BF} < 1.5$

k_T algorithm in BF

NLO

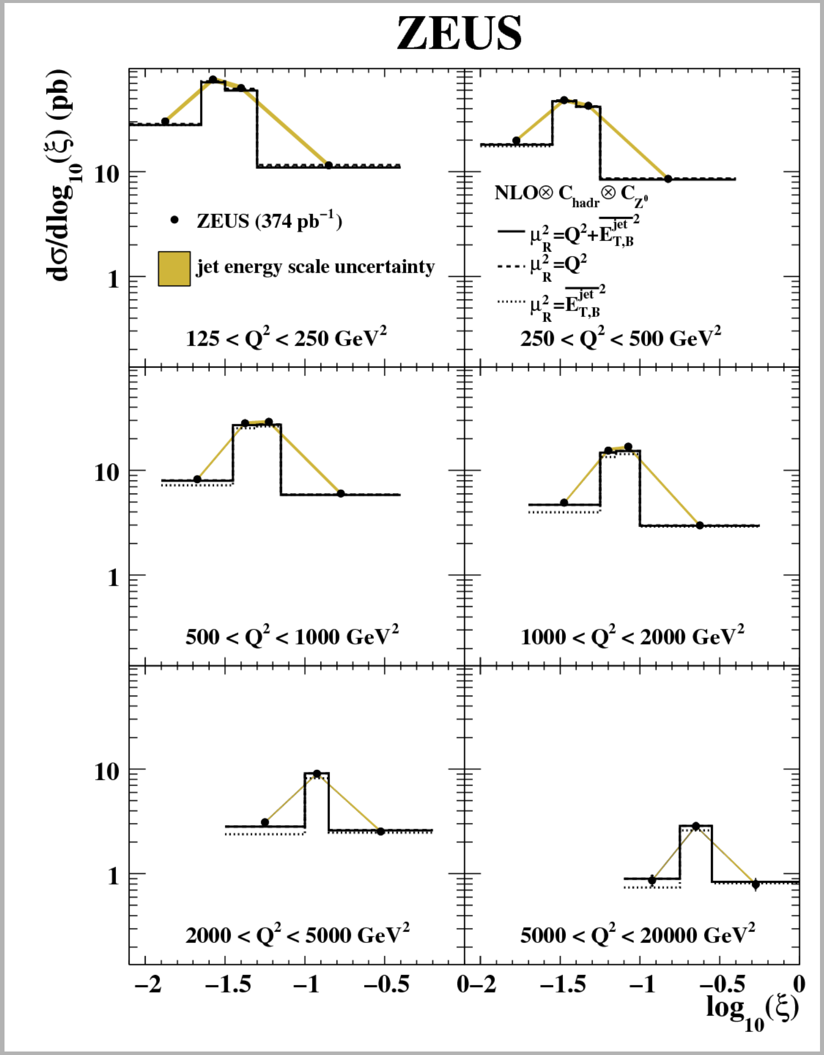
$$\alpha_S(M_Z) = 0.1208 \pm 0.0007(\text{stat.})^{+0.0036}_{-0.0031}(\text{exp.}) \pm 0.0022(\text{th.})$$

ZEUS Collab, ZEUS-prel-10-002

Dijets in NC DIS

- NLO predictions using NLOJET++
- Gluon fraction substantial up to $Q^2 \sim 500$ GeV^2
- Theory uncertainty ~ 5-10%

→ PDF sensitivity



374 pb^{-1}, Event:
$125 < Q^2 < 20000$ GeV^2
$0.2 < y < 0.6$
Jet:
$E_T > 8$ GeV (BF)
$-1 < \eta_{lab} < 2.5$
k_T algorithm in BF

ZEUS Collab, ZEUS-pub-10-005

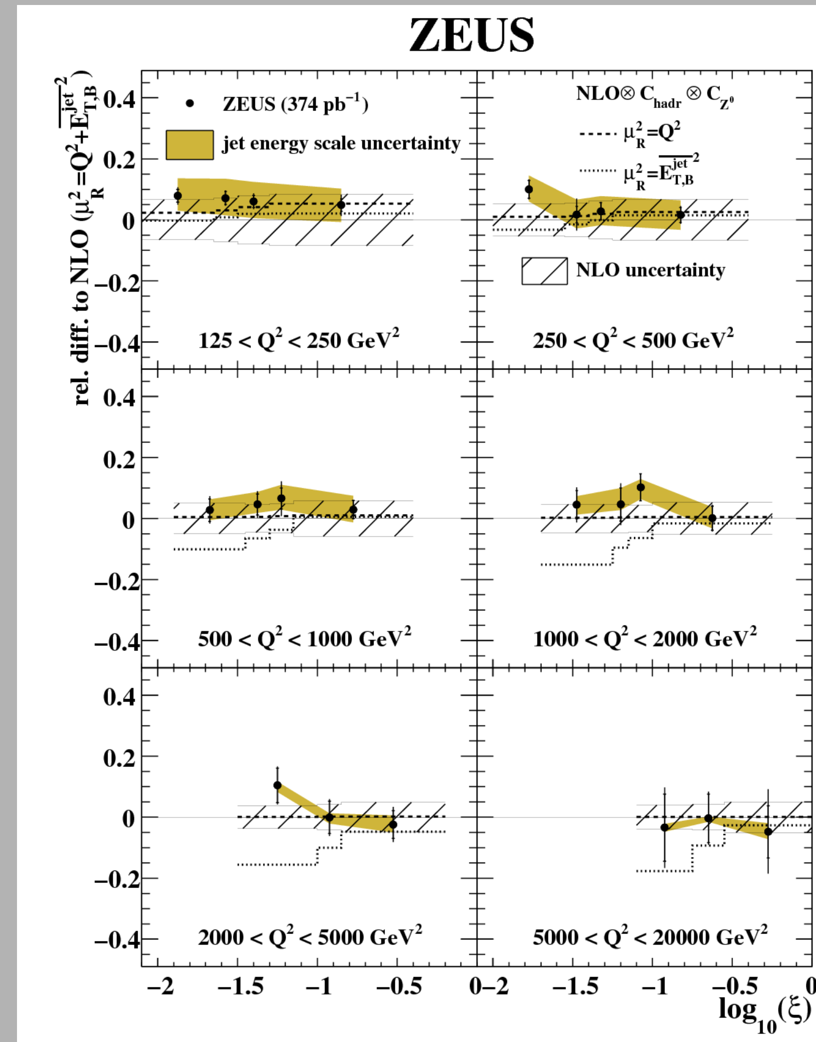
Dijets in NC DIS

- NLO predictions using NLOJET++
- Gluon fraction substantial up to $Q^2 \sim 500$ GeV^2
- Theory uncertainty ~ 5-10%

→ PDF sensitivity

374 pb^{-1}, Event:
: $125 < Q^2 < 20000$ GeV^2
: $0.2 < y < 0.6$

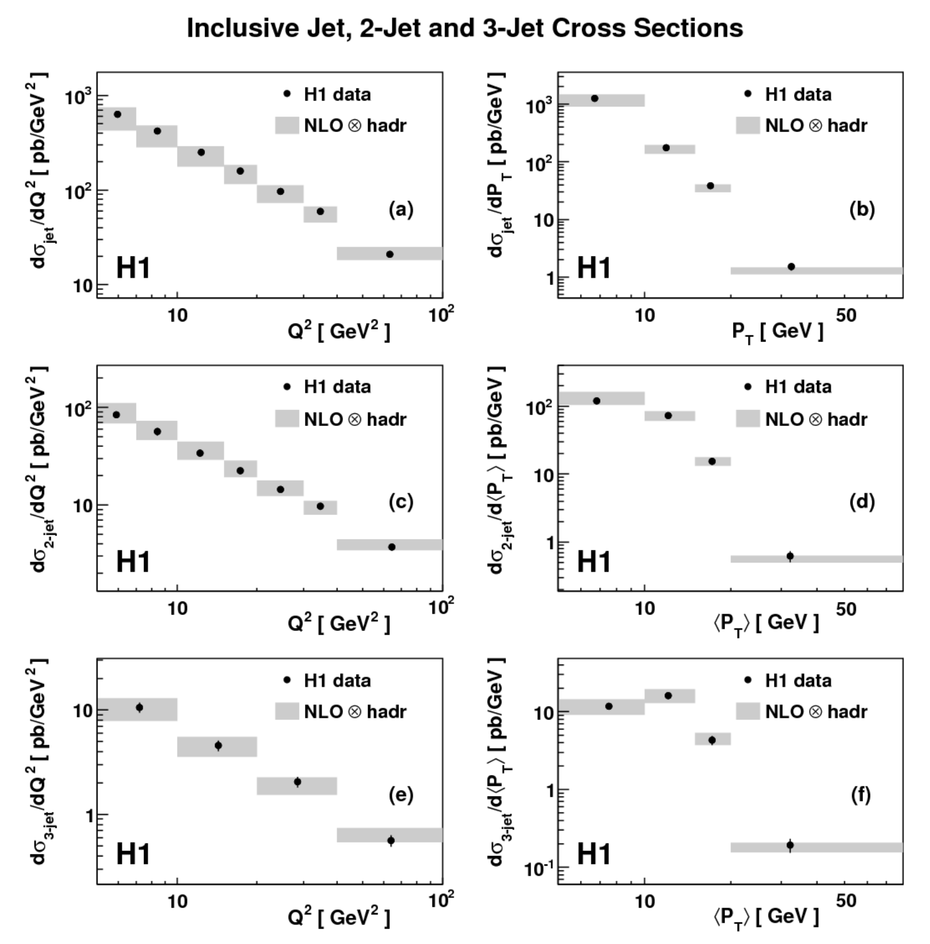
Jet:
: $E_T > 8$ GeV (BF)
: $-1 < \eta_{lab} < 2.5$
: k_T algorithm in BF



ZEUS Collab, ZEUS-pub-10-005

Jets at low Q^2

- Look at distributions as a function of Q^2, P_T^{jet} and ξ
- Good description of data by NLO predictions



43.5 pb^{-1}, Event:

$5 < Q^2 < 100$ GeV^2

$0.2 < y < 0.7$

Jet:

$P_T > 5$ GeV

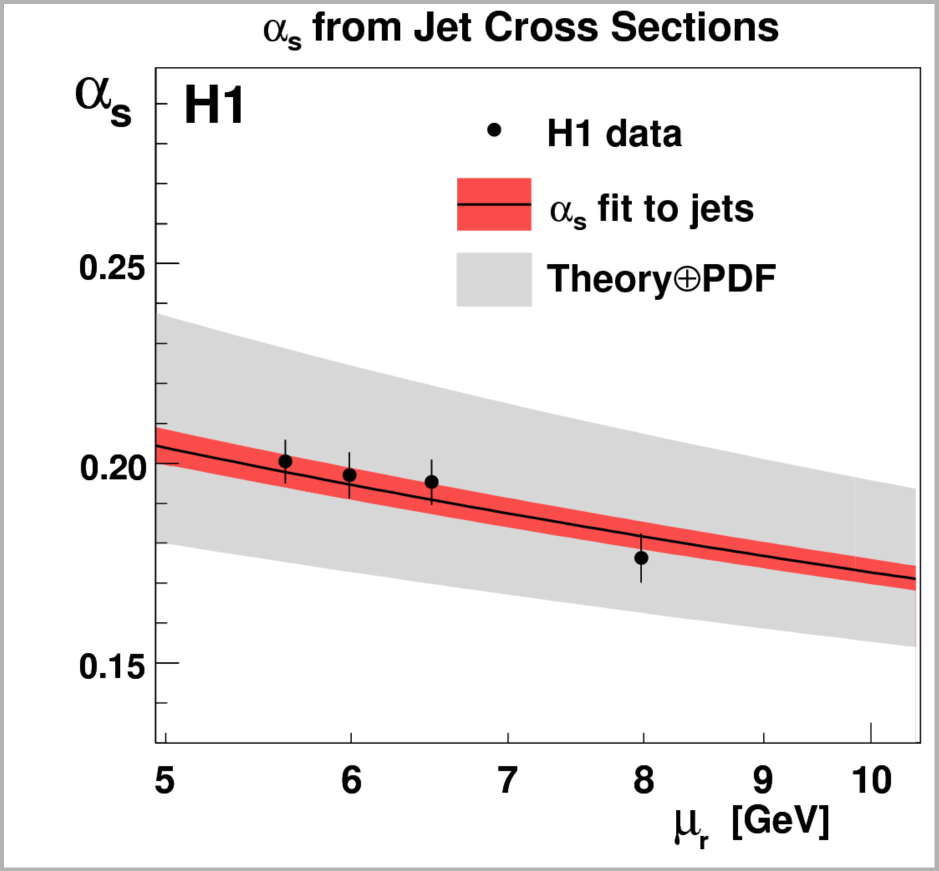
$-1 < \eta_{lab} < 2.5$

k_T algorithm in BF

H1 Collab, Eur Phys J. C67 (2010) 1

Jets at low Q^2

- Use measured jet cross-sections to extract α_s
- Simultaneous fit of inclusive, dijet and trijet measurements

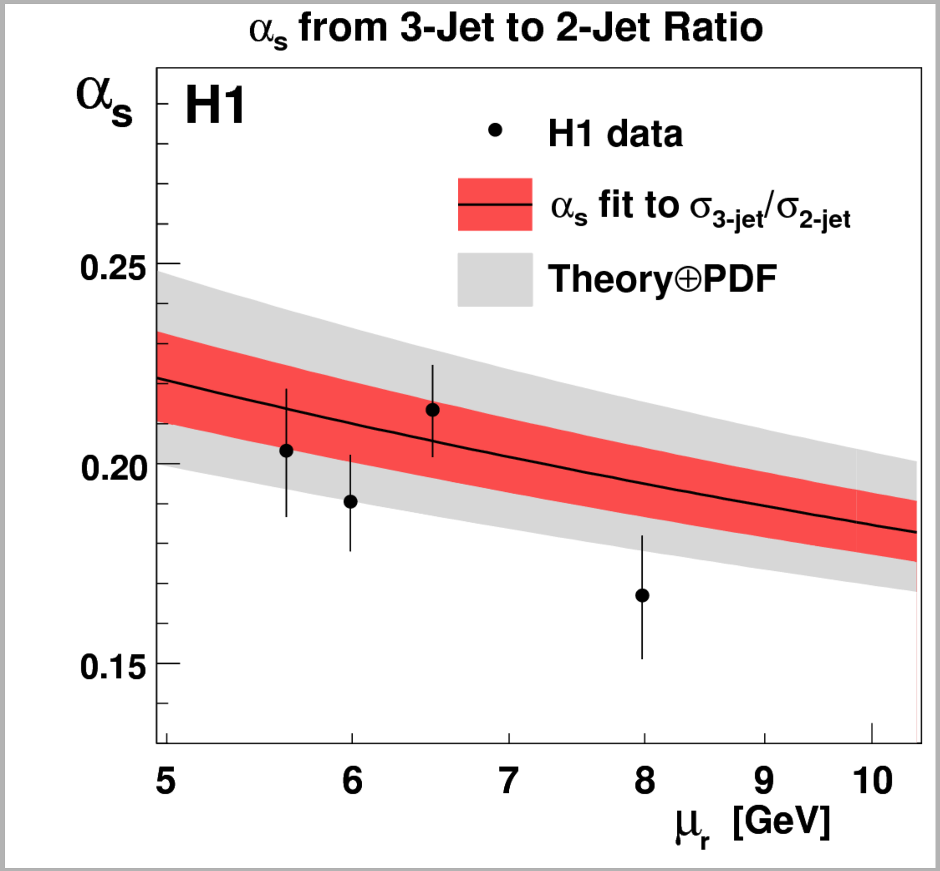


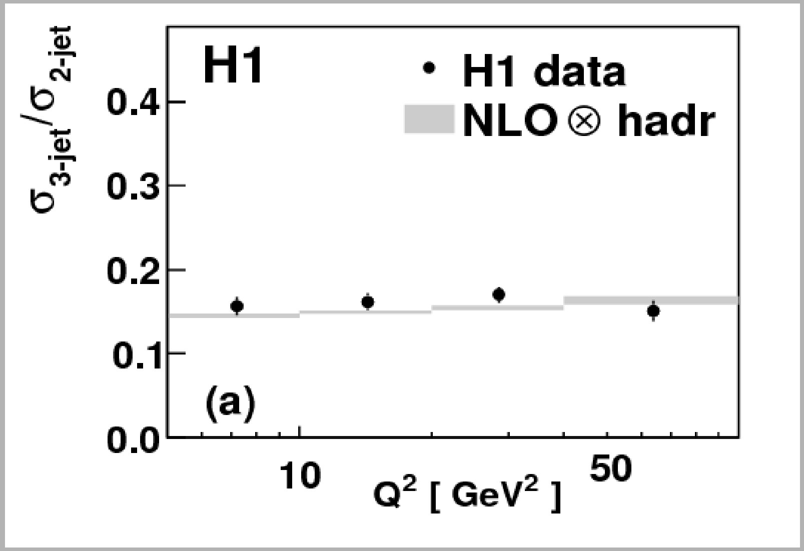
$$\alpha_S(M_Z)=0.1160\pm0.0014(\text{exp.})^{+0.0094}_{-0.0079}(\text{th.})$$

NLO

Jets at low Q^2

- Shame that precise exp. measurement has large theory error
- Using 3-jet/2-jet ratio reduces theory error



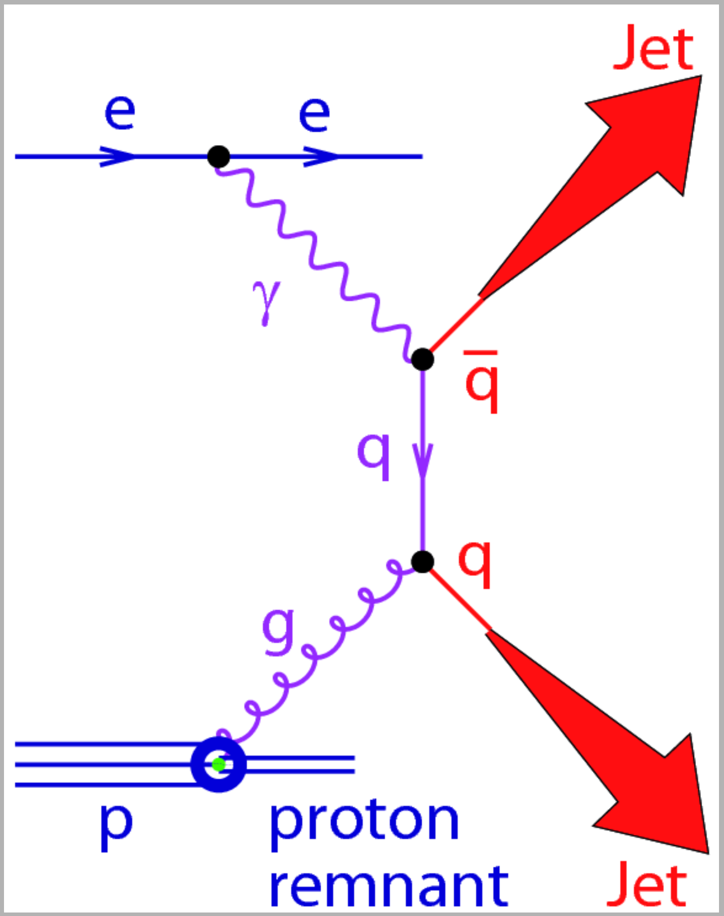


NLO

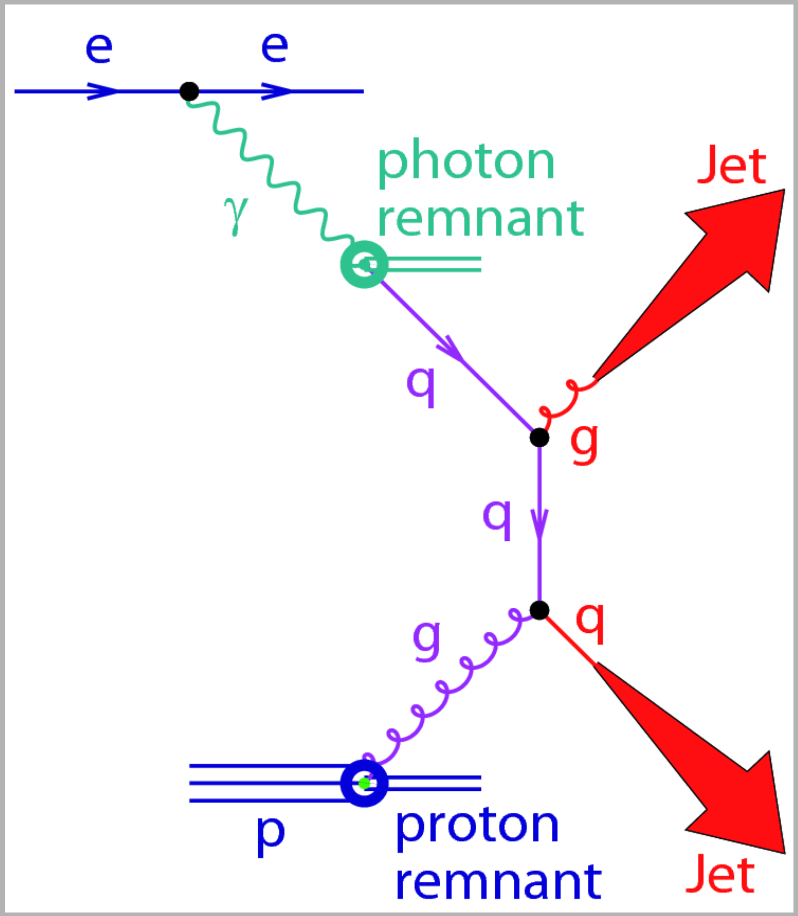
$$\alpha_S(M_Z) = 0.1215 \pm 0.0032(\mathrm{exp.})^{+0.0067}_{-0.0059}(\mathrm{th.})$$

universitätbonn

Jets in Photoproduction



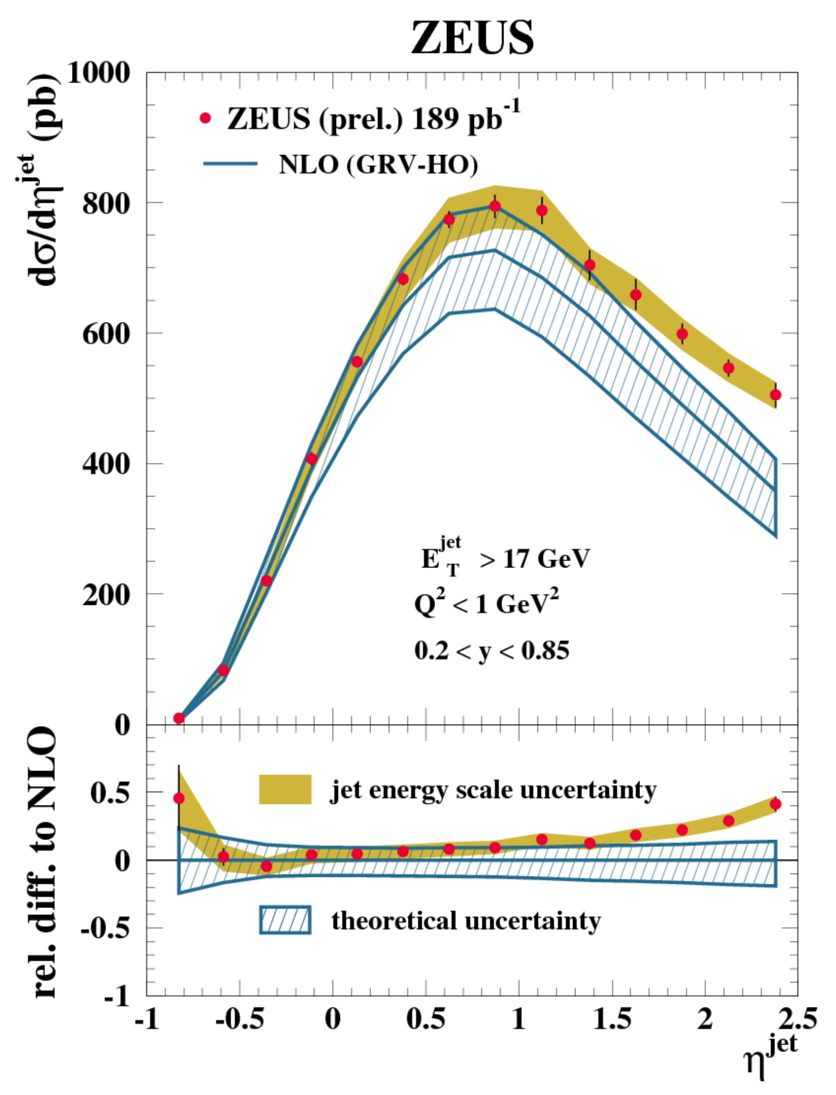
Direct photoproduction



Resolved photoproduction

Jets in Photoproduction

- High E_T inclusive jet cross sections used to extract α_S
- Proton and photon PDFs play a role
- Non-perturbative effects (underlying event) are also relevant

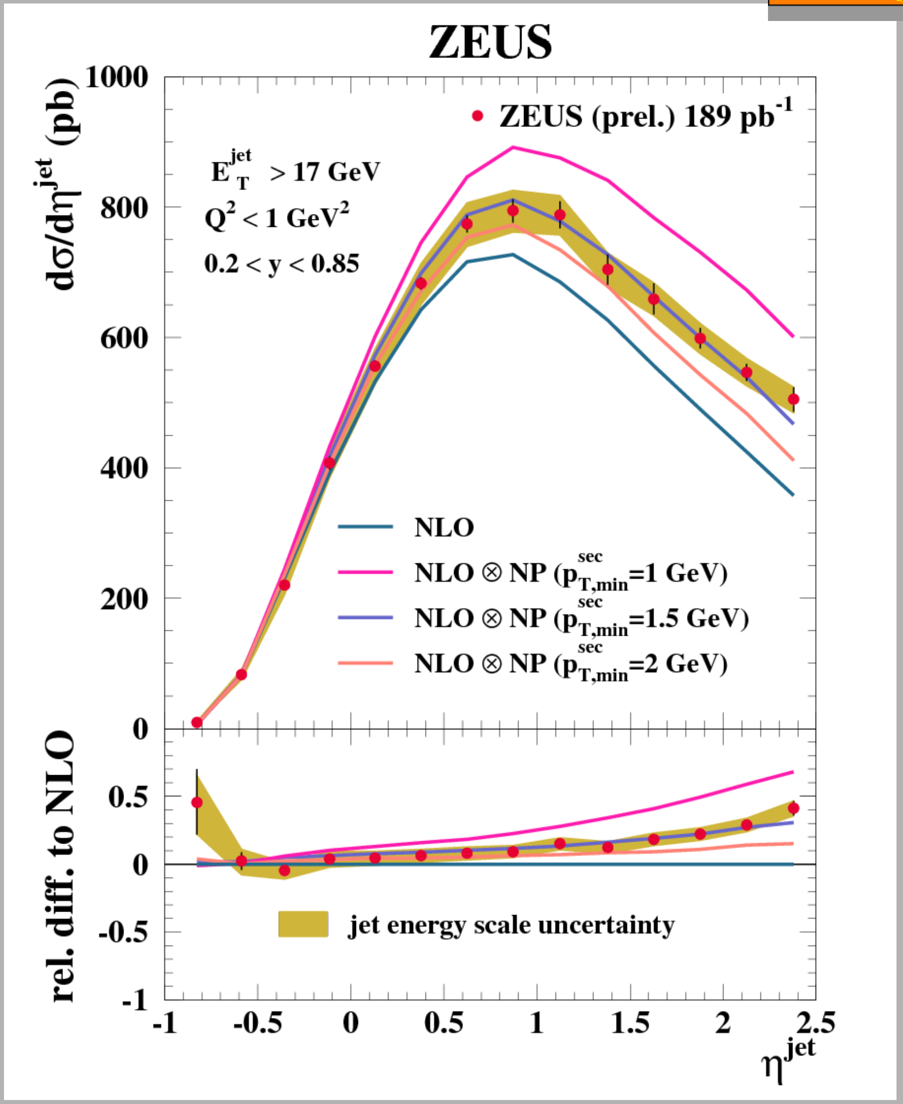


$$\eta = -\ln \tan \theta/2$$

ZEUS Collab, ZEUS-prel-10-003

Jets in Photoproduction

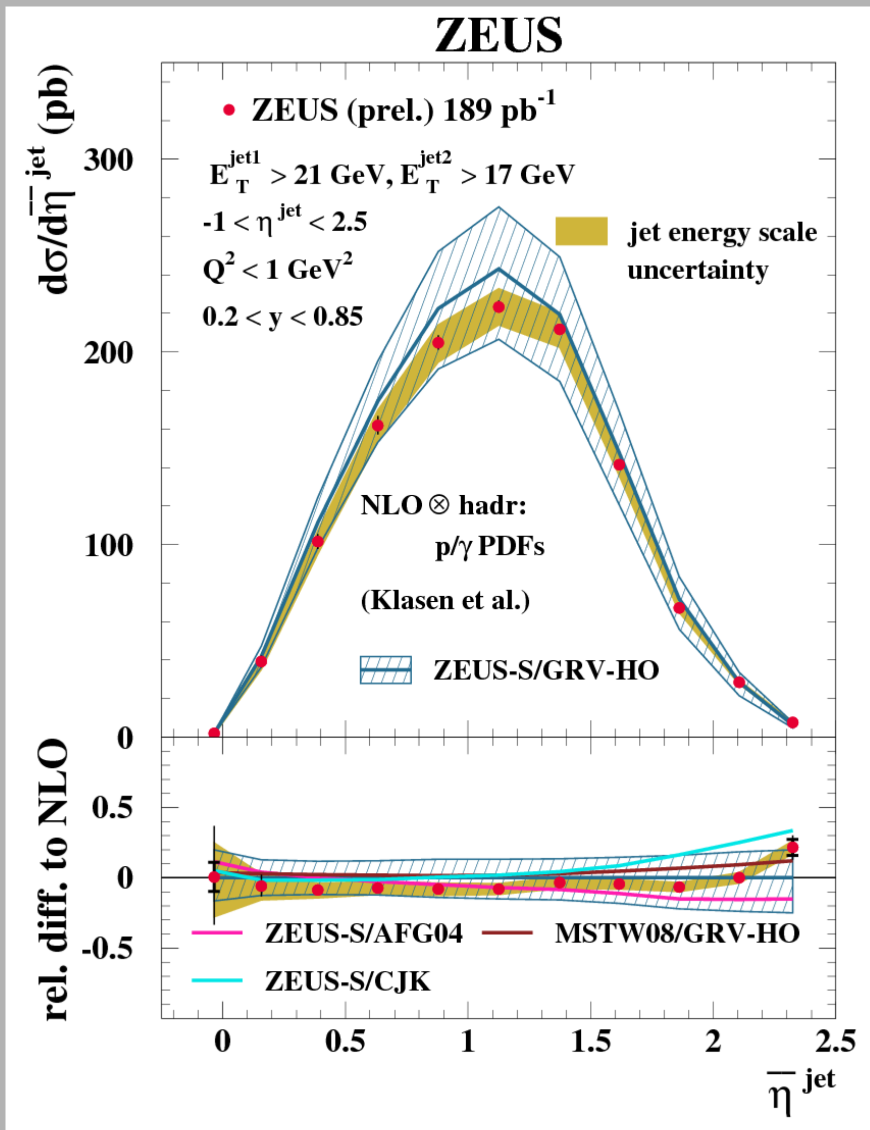
- Include non-perturbative effects using PYTHIA-MI
  - much better agreement at large η
- Size of effect also much reduced for higher E_T^{jet}

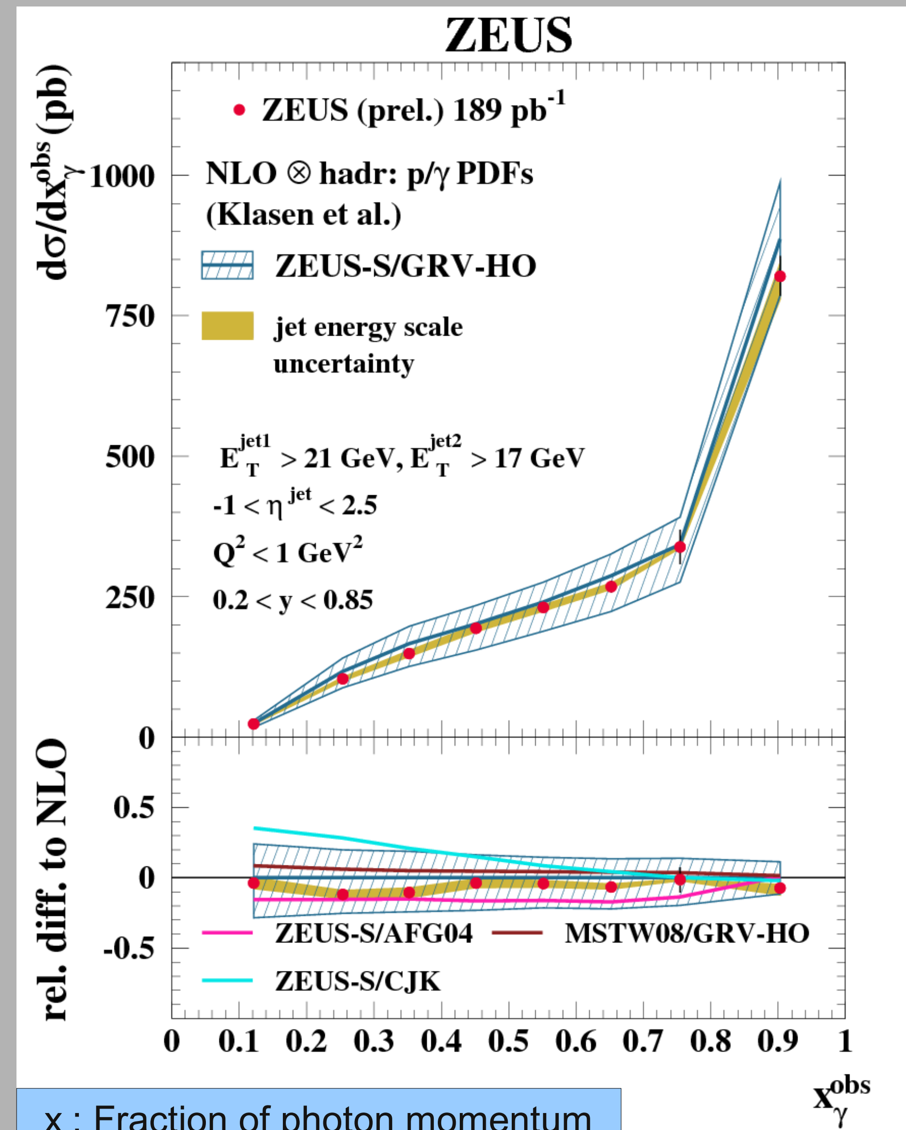


$$\alpha_S(M_Z) = 0.1160^{+0.0024}_{-0.0023}(\exp)^{+0.0044}_{-0.0033}(\text{th})$$

NLO

Dijets in Photoproduction

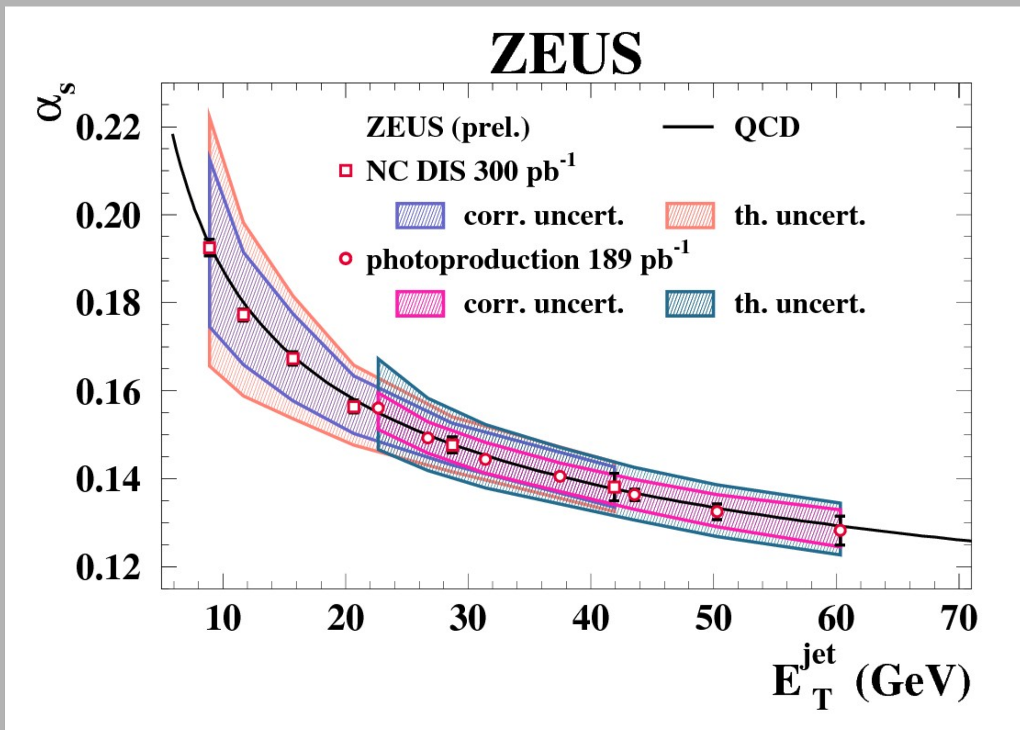


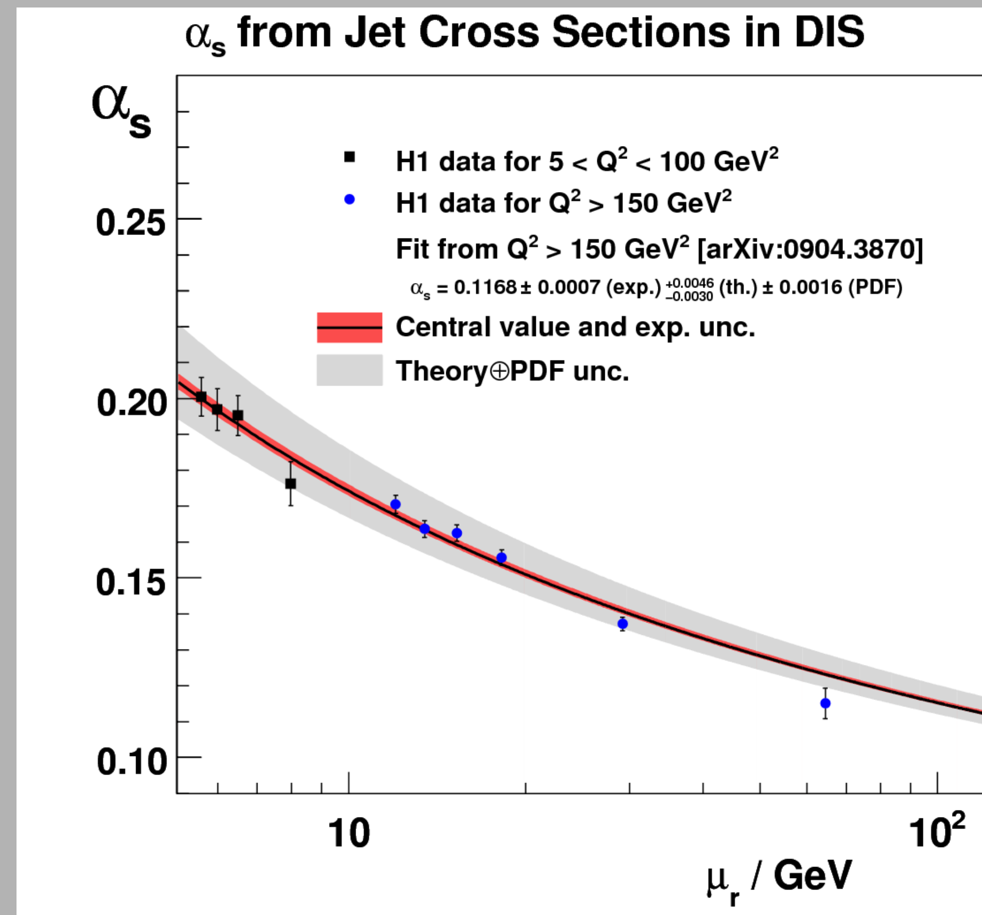


x_γ: Fraction of photon momentum carried by interacting parton

universitätbonn

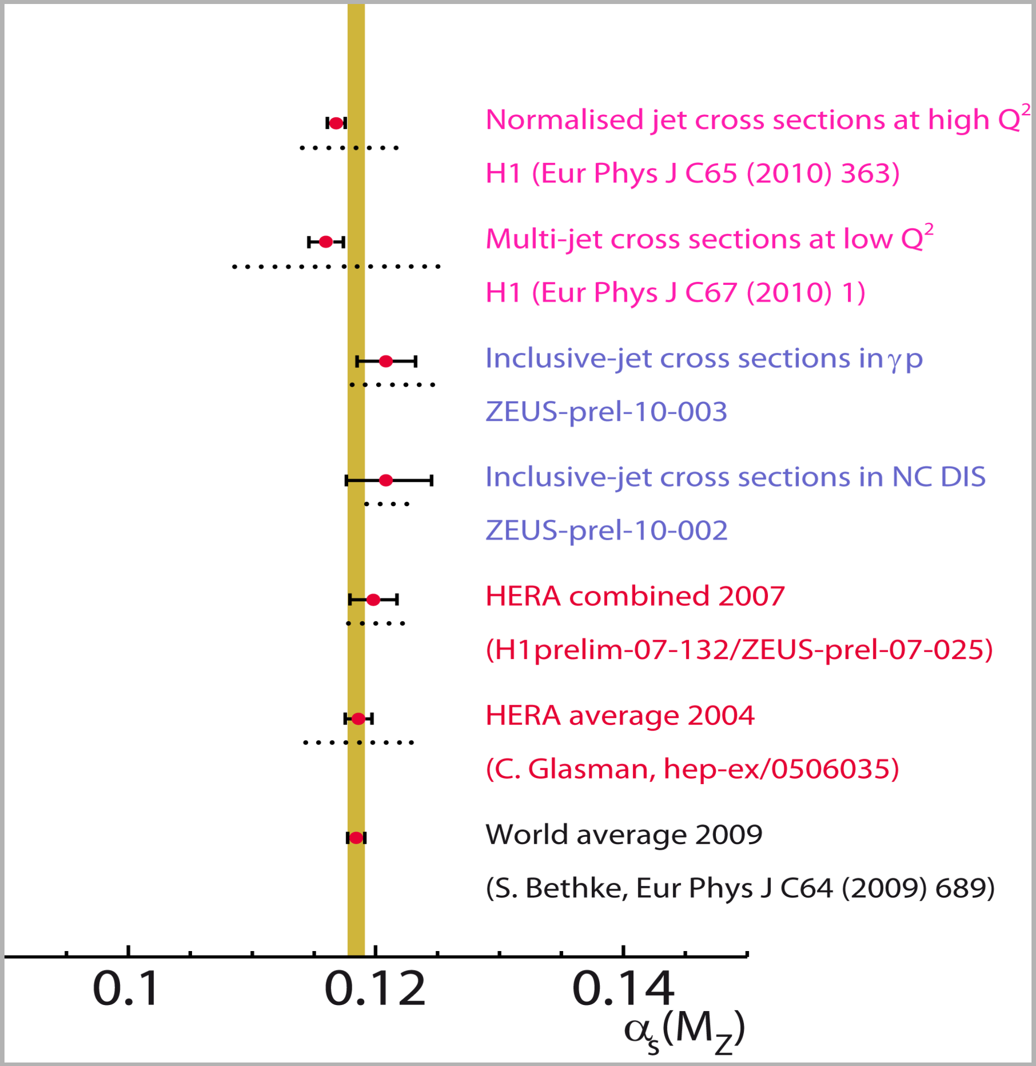
HERA α_s measurements





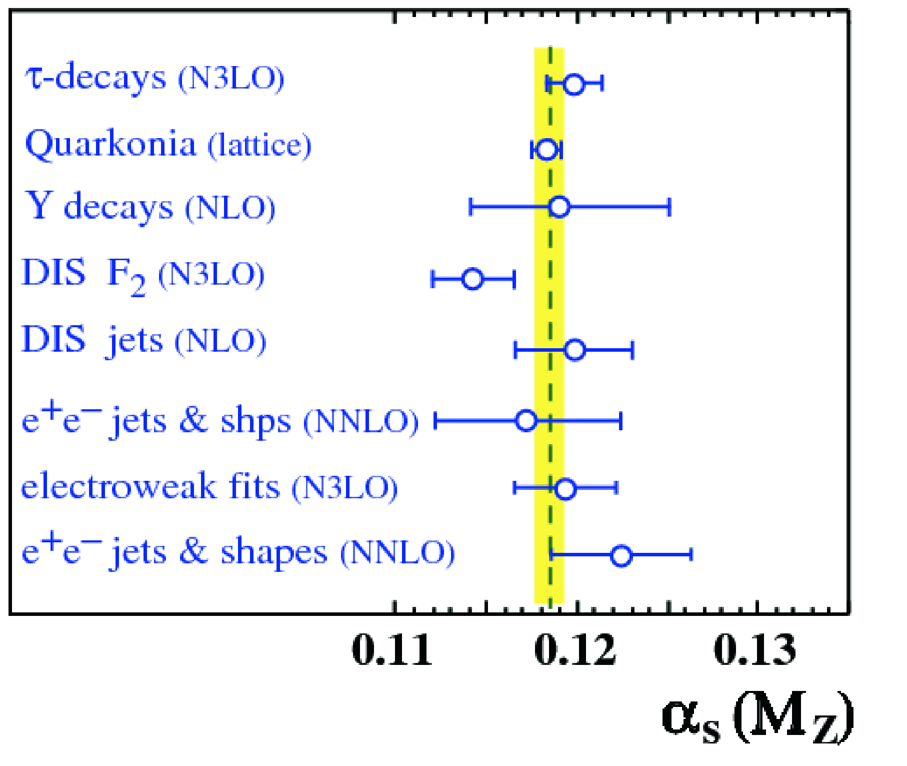
- DIS and photoproduction measurements in good agreement with each other

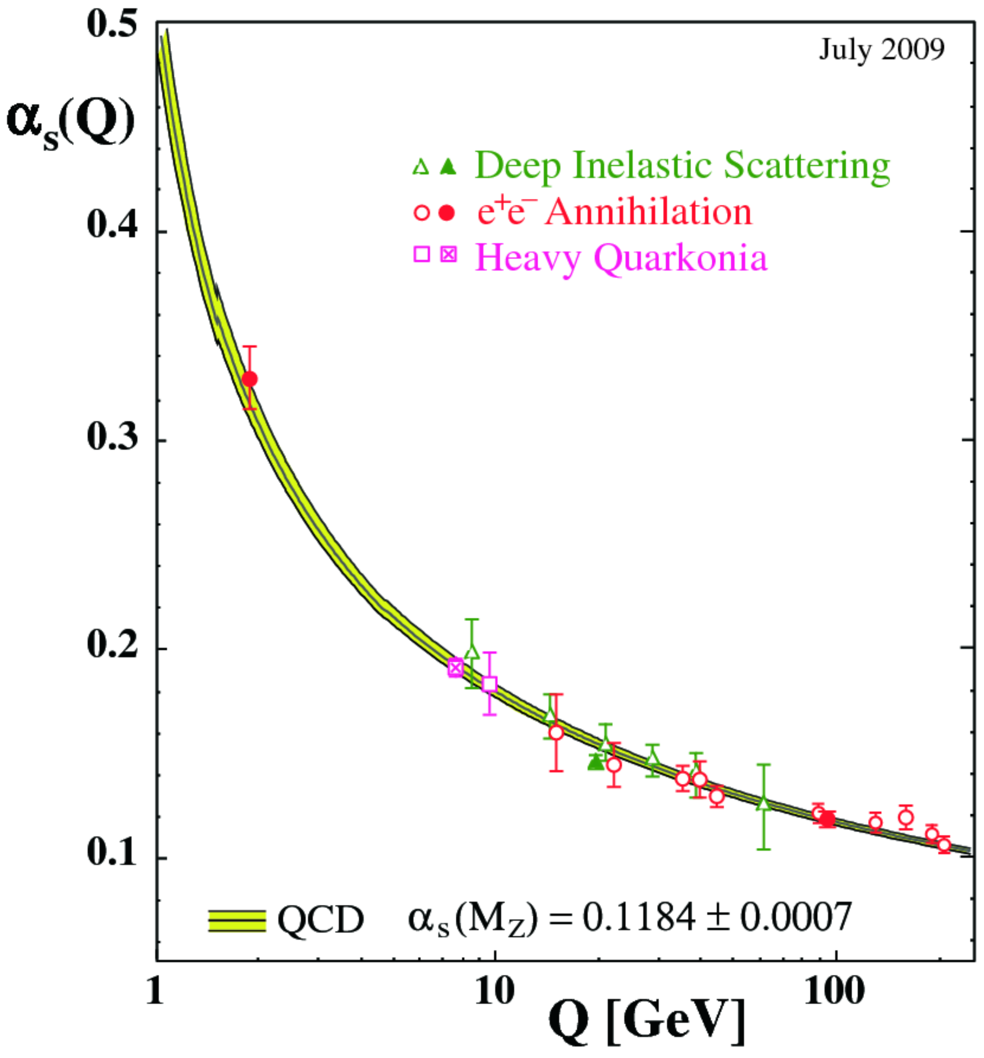
HERA α_s measurements summary



- Compare several precise determinations of α_s
- Trade off between statistics and theoretical uncertainties clearly visible

α_s measurements summary

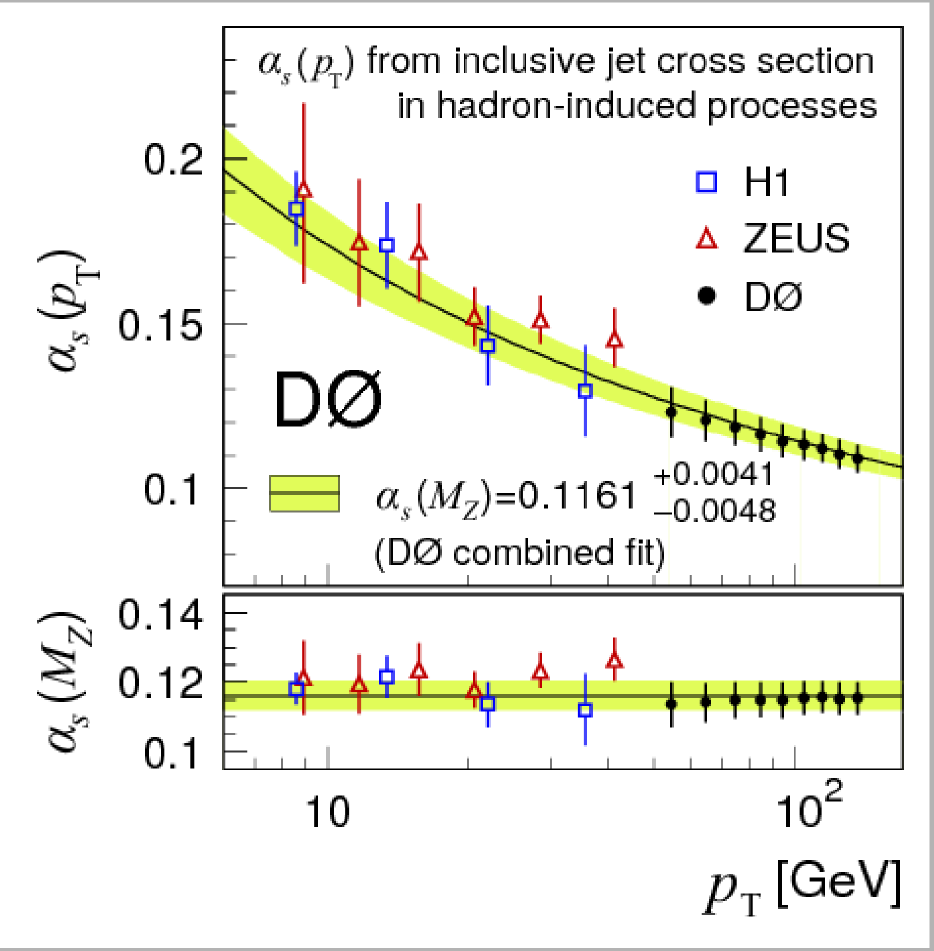




- Most effort on NLO MC generators expended for LHC; similar effort for HERA would be very welcome!

$$\alpha_S(M_Z)=0.1184\pm0.0007$$

Running at the Tevatron



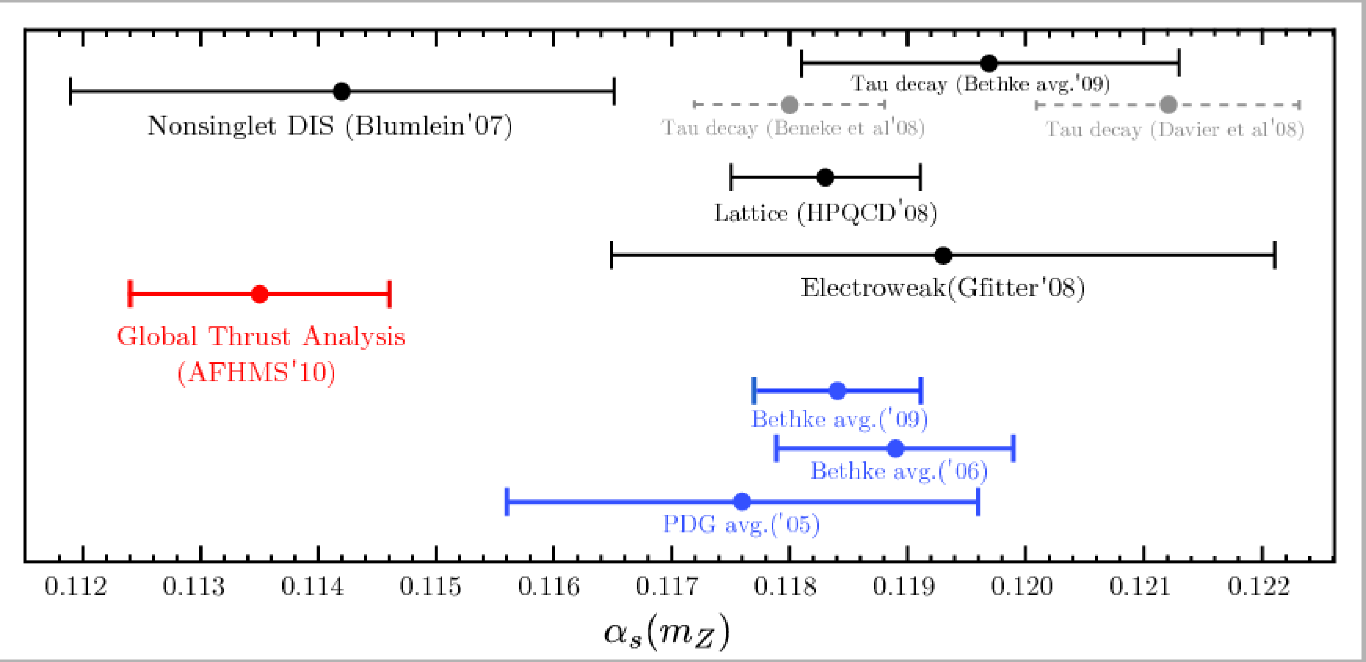
- Careful attention paid to avoid circular reasoning!
  - $g(x)$ and α_S are often correlated
- DØ errors are dominated by correlated experimental uncertainties
- Complementarity of HERA and Tevatron kinematic ranges

DØ Collab.
Phys.Rev.D80 (2009) 111107
arXiv:0911.2710

α_s measurements summary

- Recent determination using soft collinear effective theory and only thrust:

N^{3}LL'

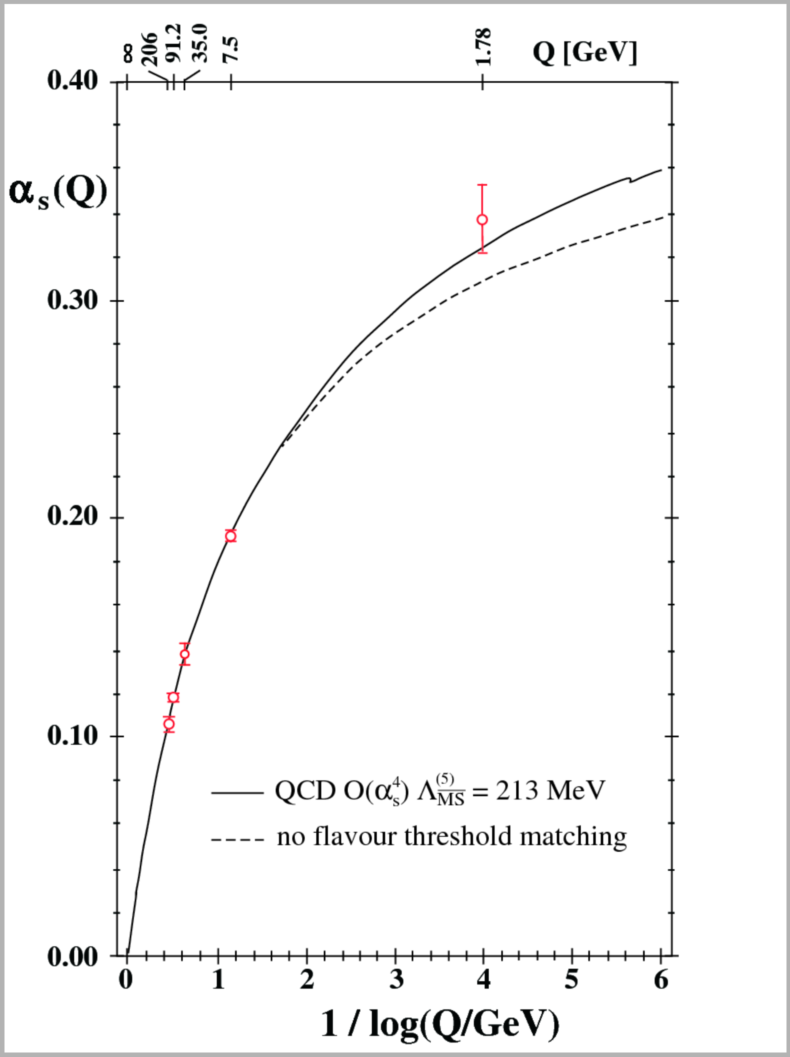


- Not included in current world average (data is already in LEP event shape)

R. Abbate et al., arXiv:1006.3080

Does α_s run as expected?

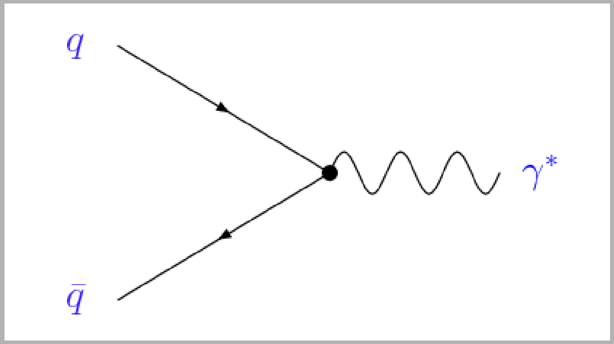
- For selected measurements look at α_S as a function of 1 / log Q
- $\alpha_S(Q) \to 0$ as $Q \to \infty$
- Demonstrate the validity of the concept of asymptotic freedom
- "Threshold matching" also necessary

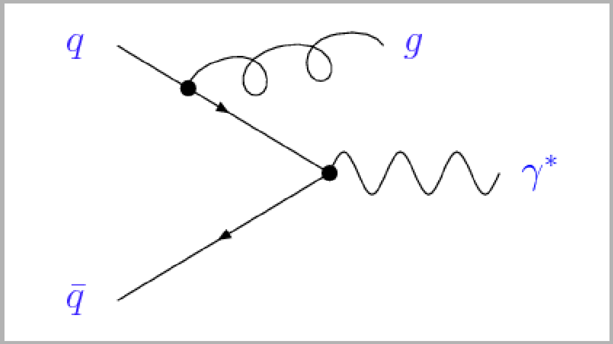


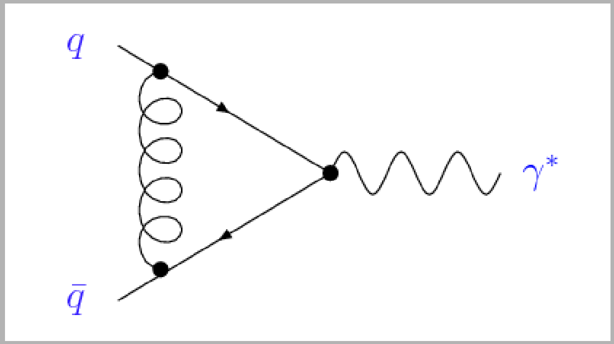
universitätbonn

Precision QCD tests

- What do we have to worry about?
  - α_S is not small
  - Leading order calculations are often/usually not sufficient
  - Divergences!







  - Improve if summed over all orders, but...
  - Absorb most of remaining infinities in renormalisation
- Buzzwords: soft and collinear divergences

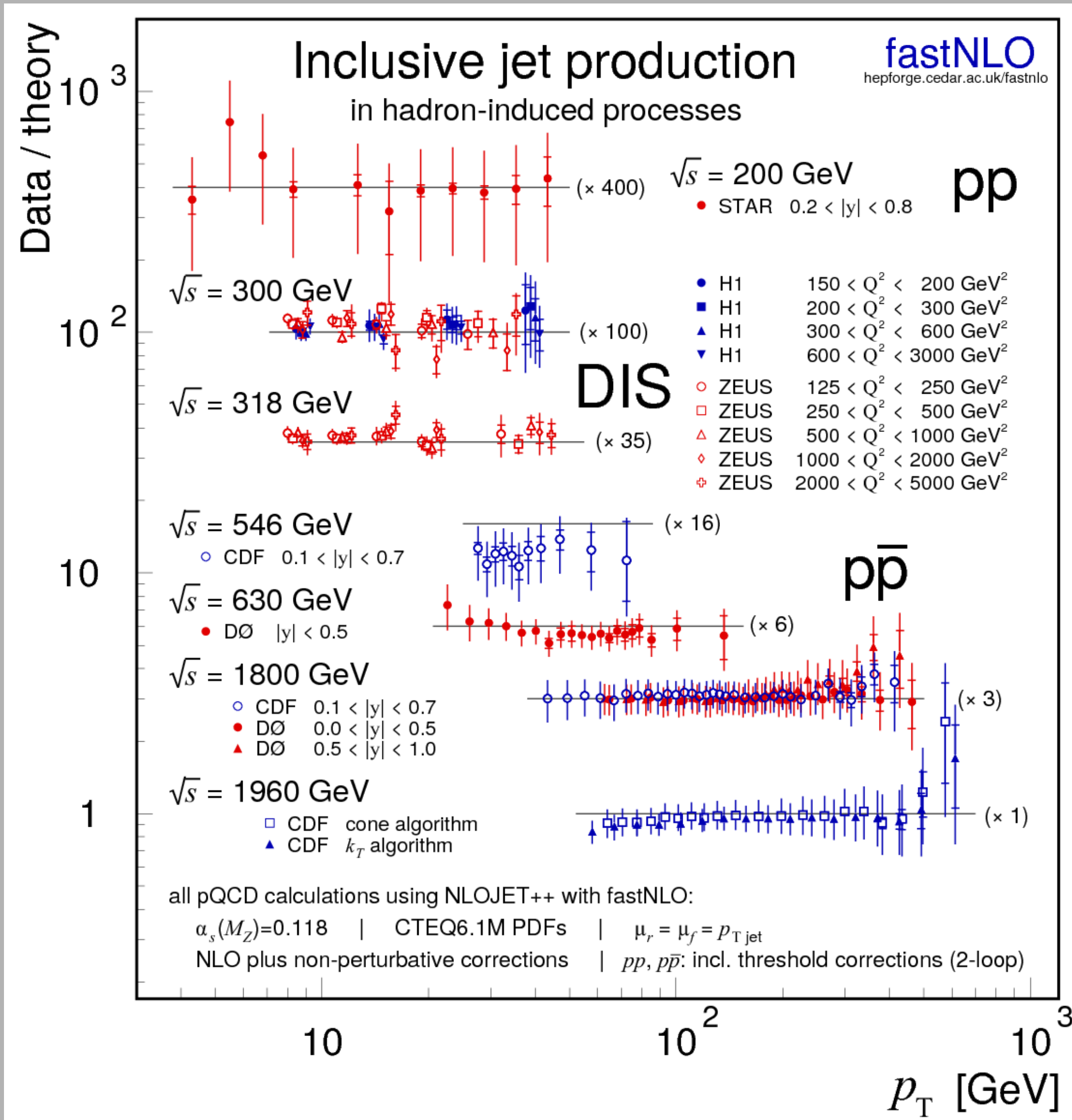
Precision QCD tests

- Inclusive quantities without initial-state hadrons best suited for precision tests (can be calculated to higher order):
  - τ decay rates
  - Z width

Even here convergence not as fast as expected!

- Infrared safe quantities:
  - Event shape distributions
  - Jet cross-sections
- Unsafe quantities:
  - Hardest QCD particle
  - Require absence of radiation (rapidity gaps etc.)
  - Particle multiplicity

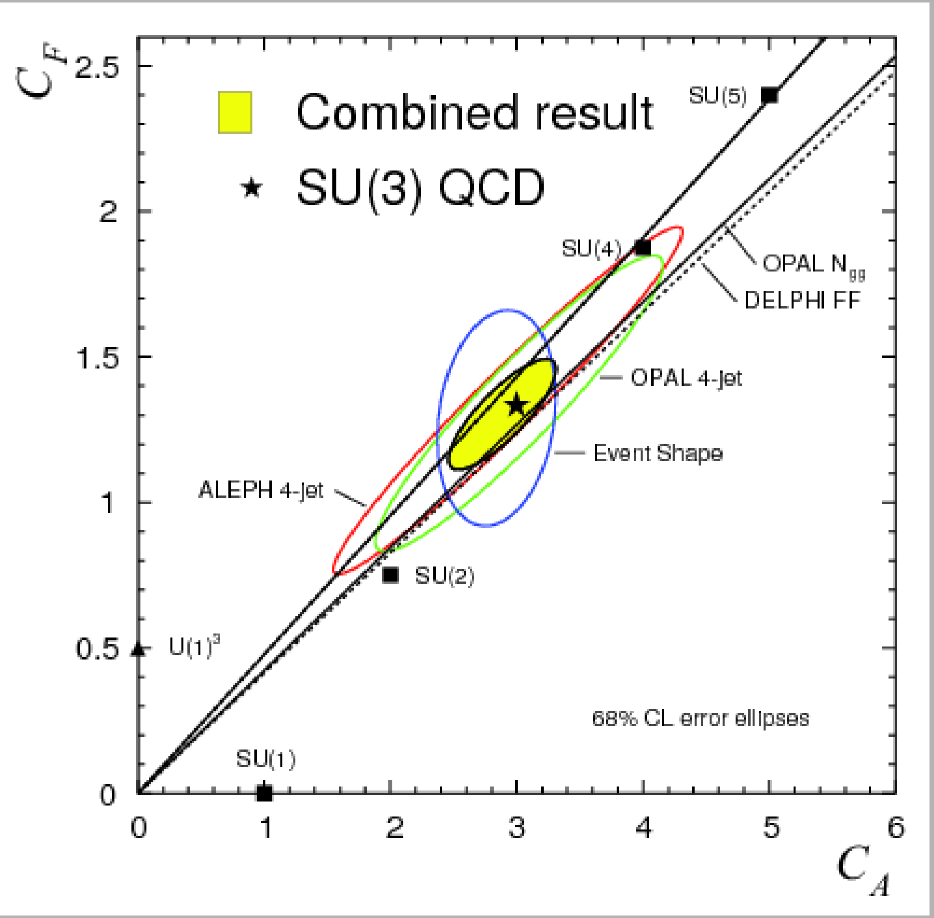
Inclusive jet production



- Compare data with NLO predictions for different process and kinematics
- Remarkably good and consistent agreement seen

Is QCD the right theory?

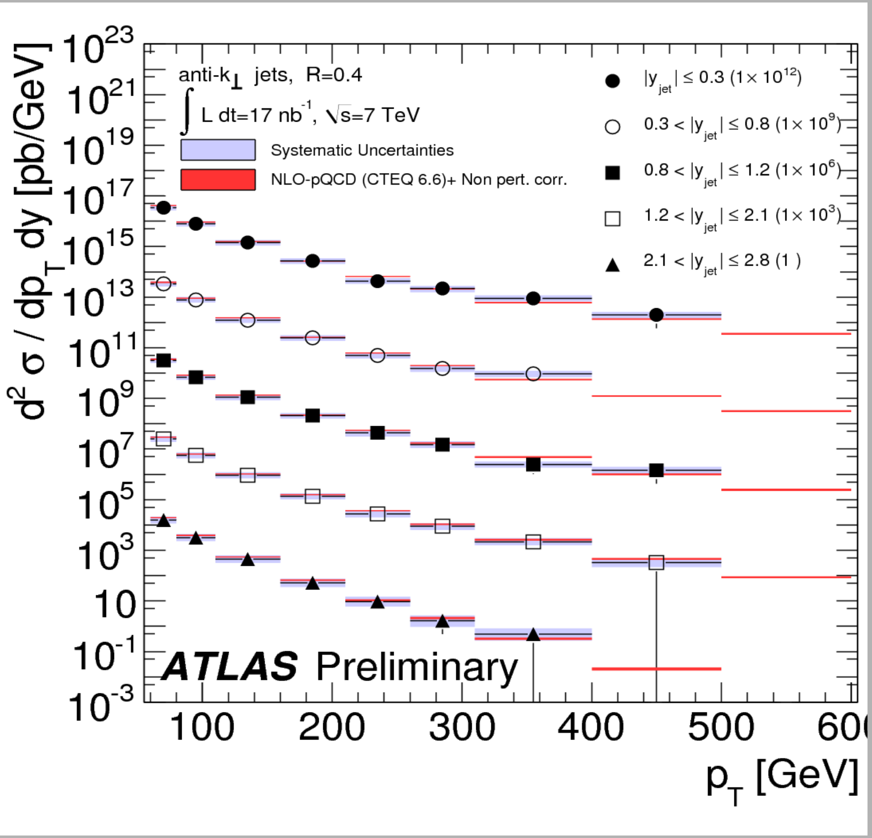
- LEP result from 2004
- e^+e^- collisions
- Look at
  - event shapes
  - $q\bar{q}gg$ final state
- Nice demonstration of consistency of data with SU(3)

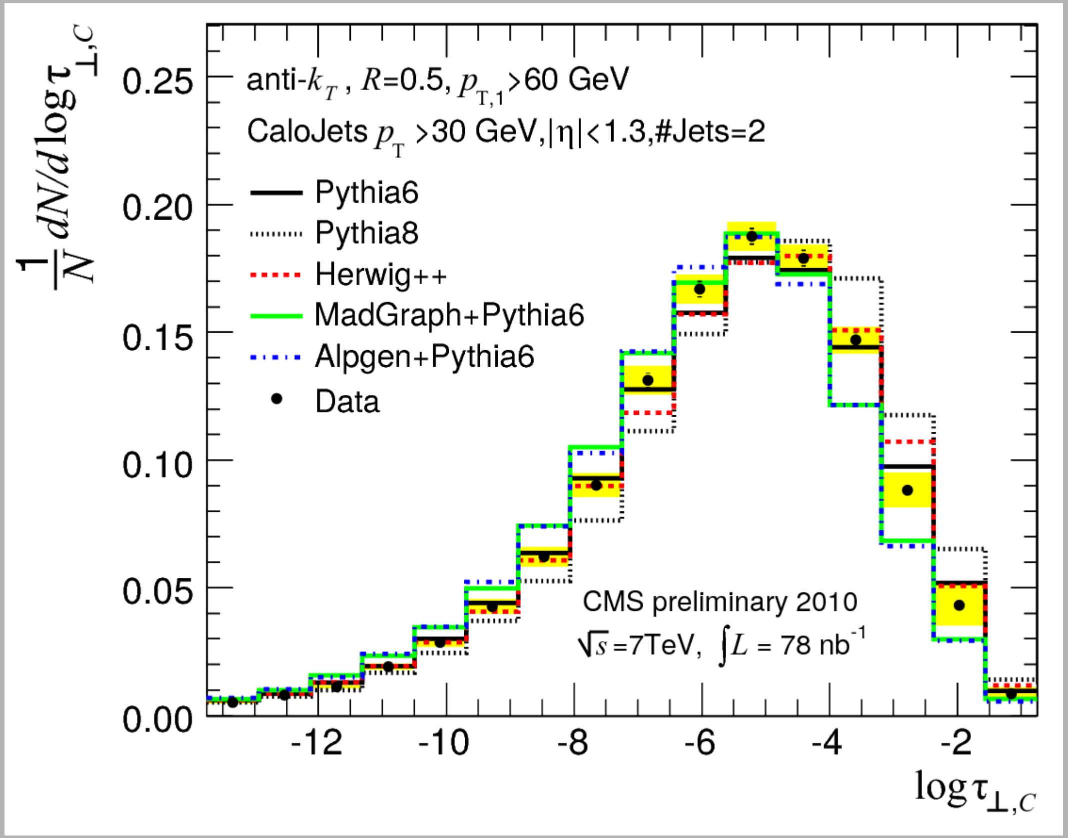


C_F, C_A: colour factors

QCD and LHC

- LHC already has first results on QCD tests
- Huge cross-sections means 100 nb^{-1} are enough to make comparisons with theory





universitätbonn

Summary

- α_s measured with an accuracy of 0.6%
- Many different methods, colliders, experiments give in general very consistent results
  - DIS (and thrust) determinations tend to be a bit lower
- Running of α_s seen within single experiments
- Trend consistent with expectations from asymptotic freedom
- Further precision QCD tests show good agreement between data and predictions
- LHC has entered the game!

Backup

Theory uncertainty

- Assess theory uncertainty by requiring physical observable to be independent of scale for a given order of calculation

$$\frac{d}{d\ln\mu^2}\sigma_{pp\to X}=O(\alpha_S^{l+1})$$

Equation motivates commonly adopted approach of varying renormalisation and factorisation scale by ½ and 2

Running of α_s

- Running coupling satisfies renormalisation group equation(RGE):

$$\begin{aligned} \mu^2 \frac{d\alpha_S}{d\mu^2} &= \beta(\alpha_S) = -(\beta_0 \alpha_S^2 + \beta_1 \alpha_S^3 + \beta_2 \alpha_S^4 + \cdots) \\ b_0 &= (11C_A - 4 n_f T_R)/(12\pi) \\ &= (33 - 2 n_f)/(12\pi) \\ b_1 &= (153 - 19 n_f)/(24\pi^2) \end{aligned}$$

$$\begin{aligned} C_F &\equiv (N_c^2 - 1)/(2N_c) = 4/3 \\ C_A &\equiv N_c = 3 \\ T_R &= 1/2 \end{aligned}$$

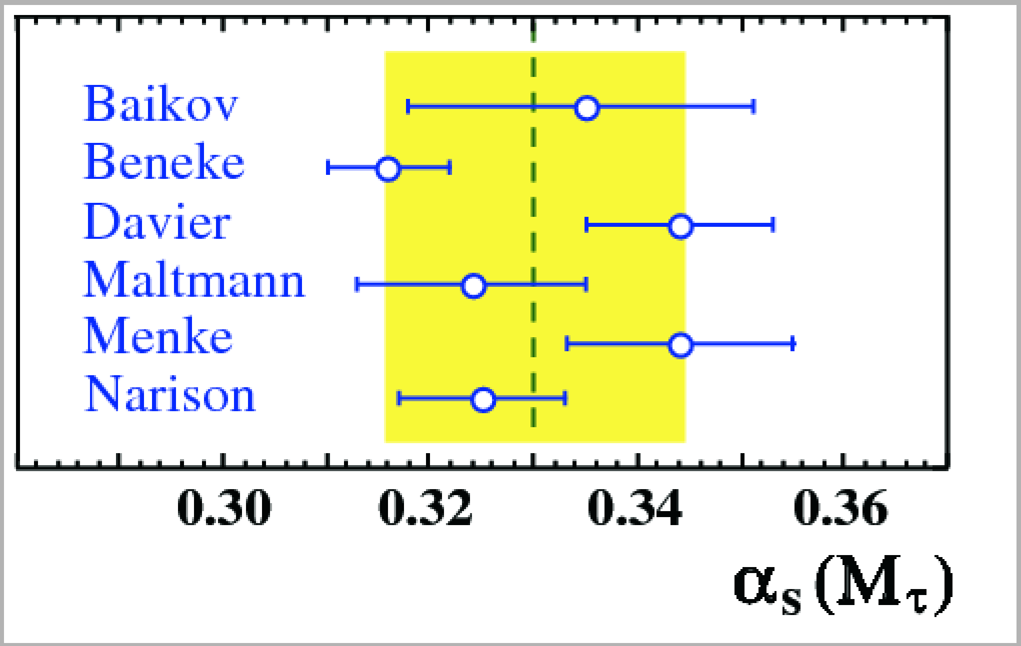
- 1-loop approximation ($\beta_1 = 0$)

$$\alpha_S(Q^2) = \frac{\alpha_S(\mu^2)}{1 + \alpha_S(\mu^2)\beta_0 \ln(Q^2/\mu^2)}$$

or

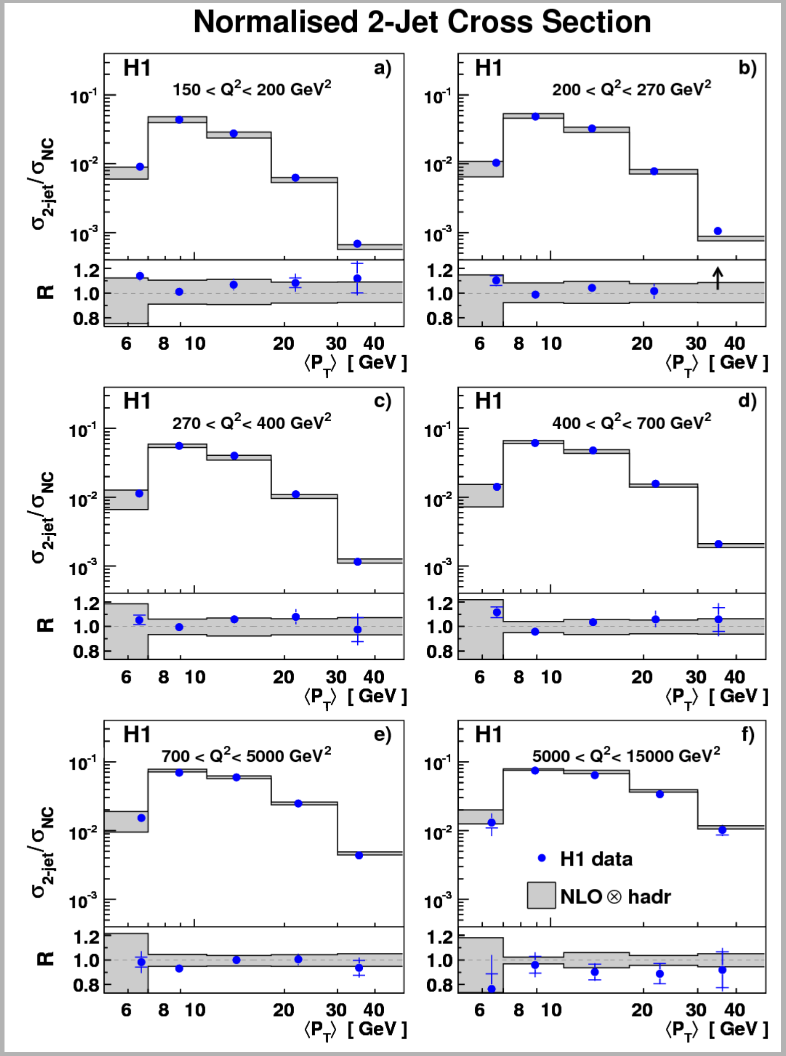
$$\alpha_S(Q^2) = \frac{1}{\beta_0 \ln(Q^2/\Lambda^2)}$$

α_s from τ measurements



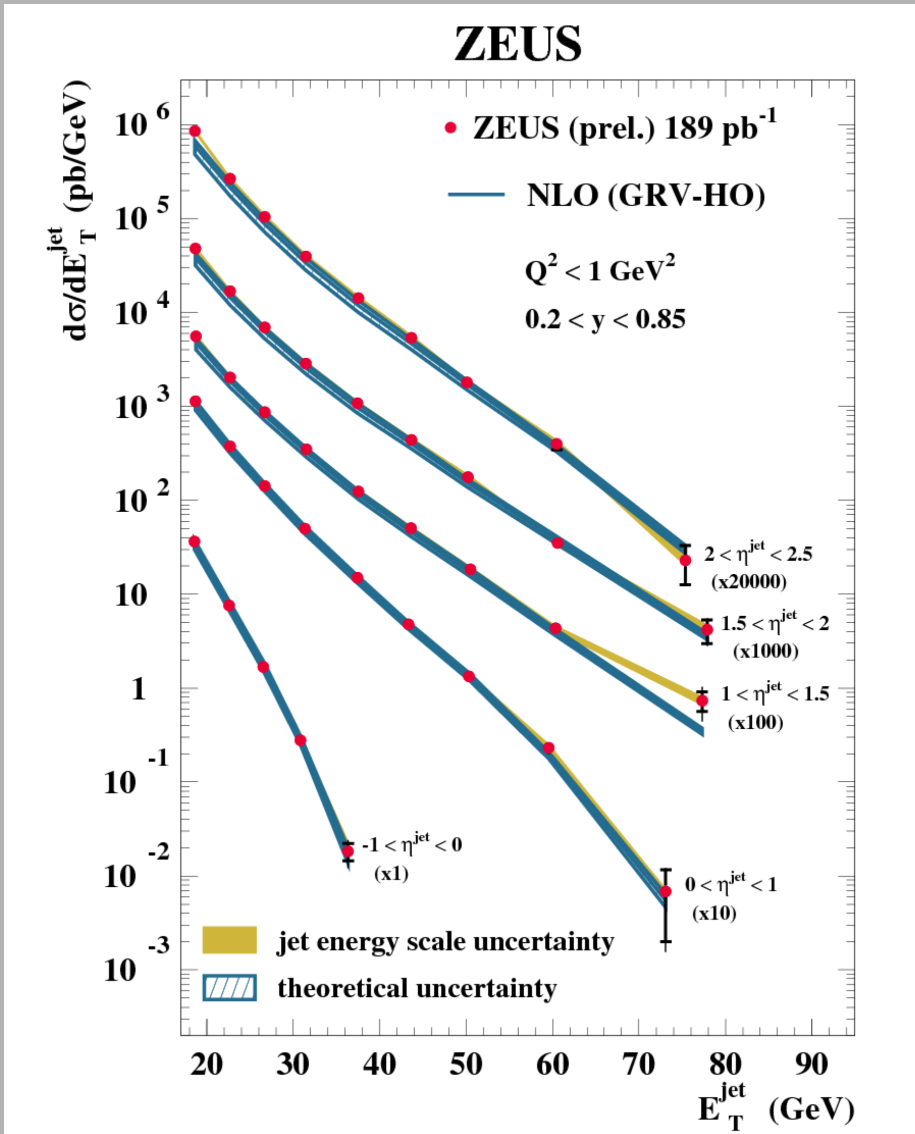
Jets at high Q^2

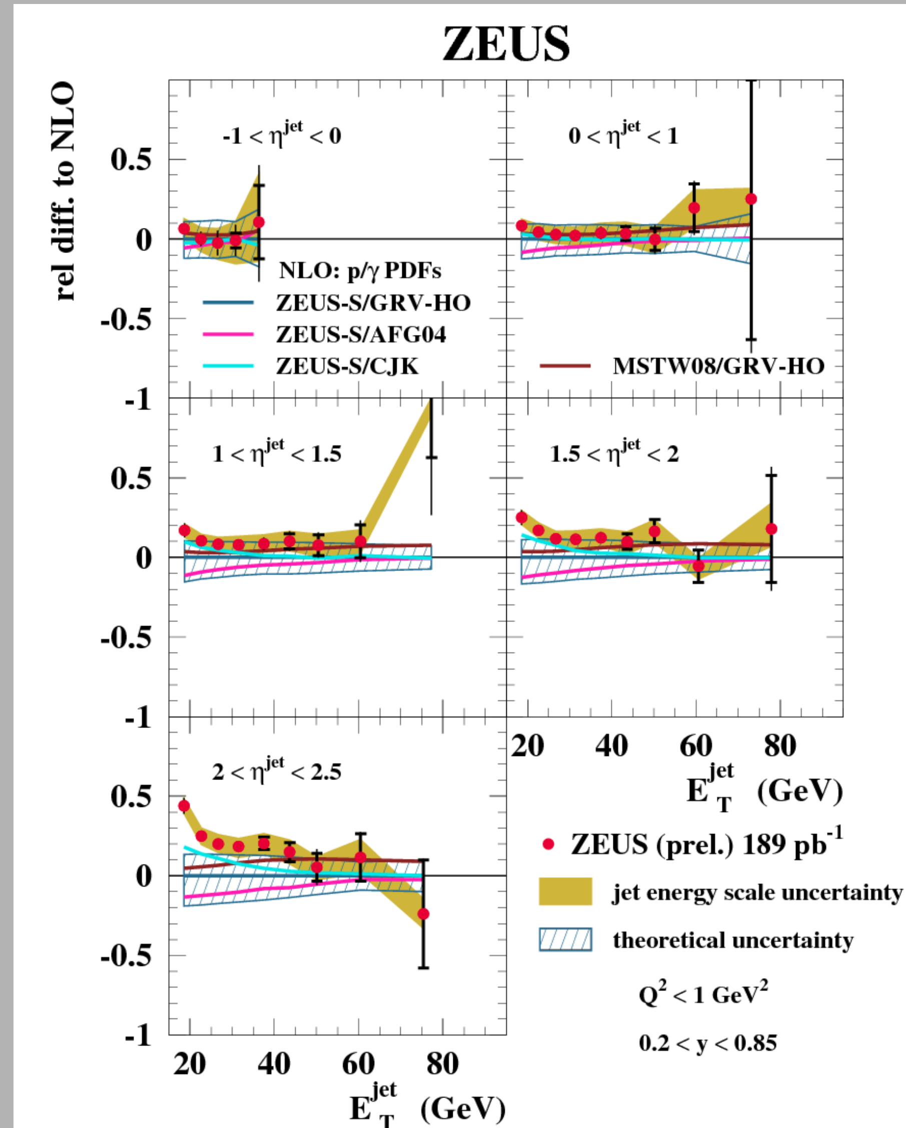
- Compare average P_T^{jet} distribution in different Q^2 ranges
- Again good description by NLO prediction



H1 Collab, Eur Phys J. C 65 (2010) 363

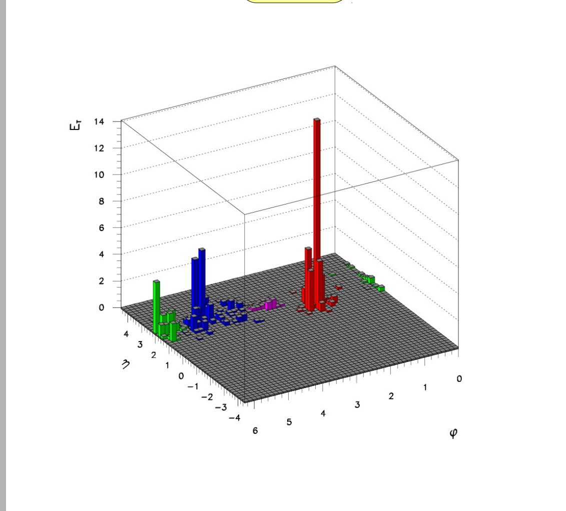
Jets in Photoproduction

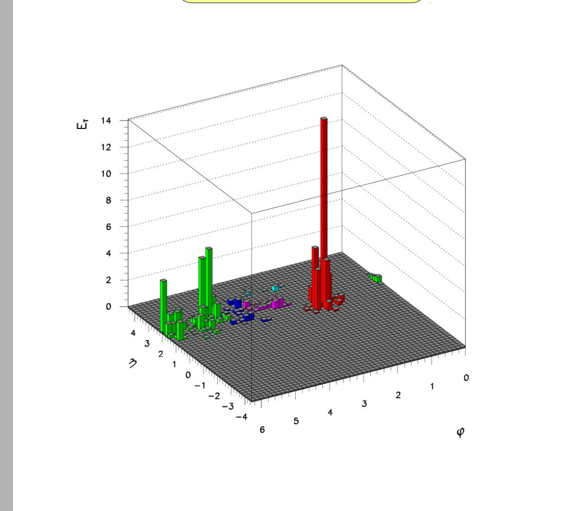


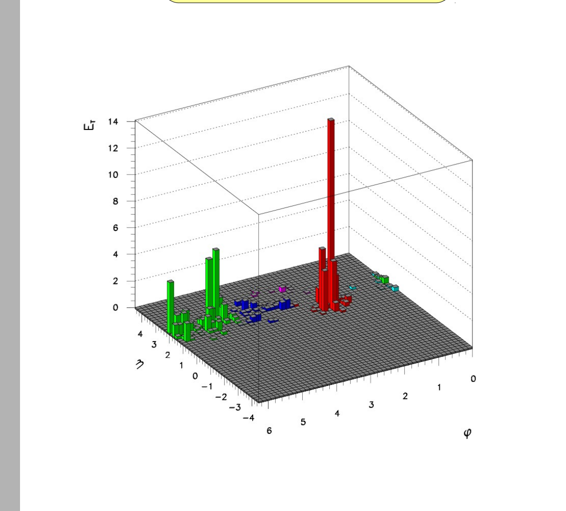


Jet algorithms

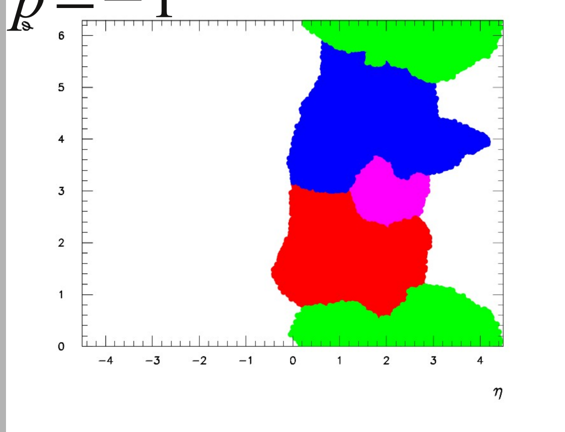
k_T	anti-k_T	SIScone



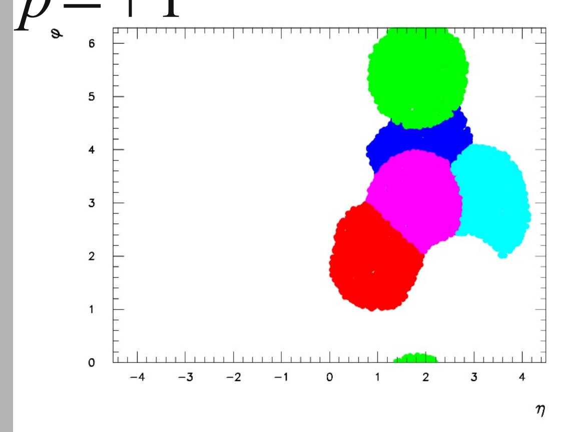


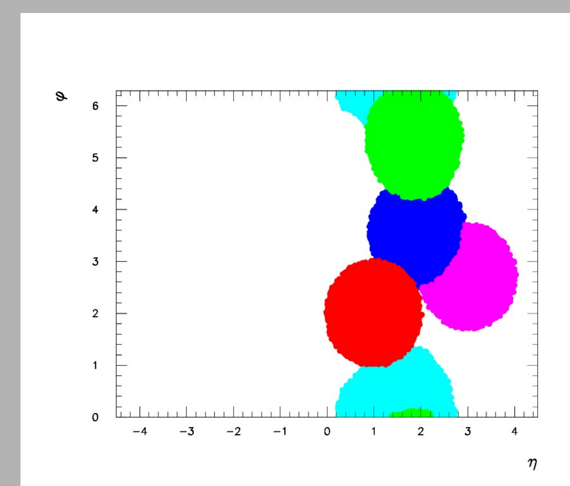


$p = -1$



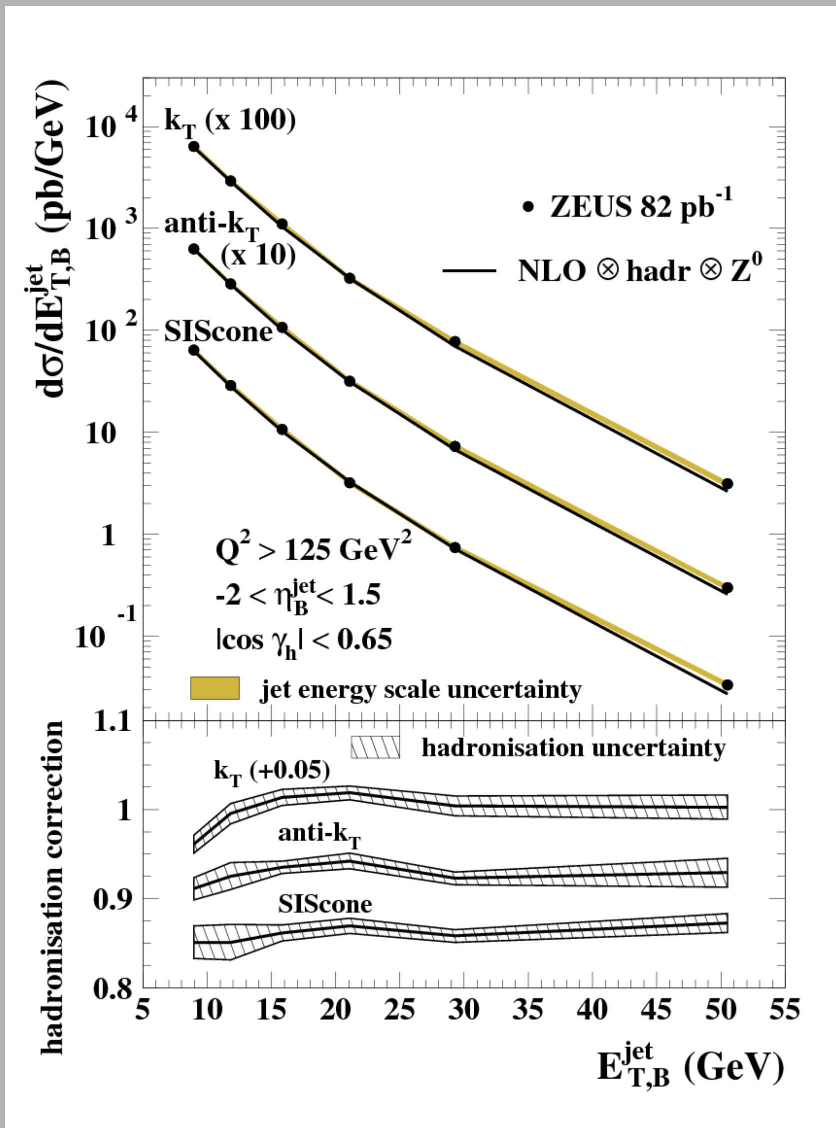
$p = +1$

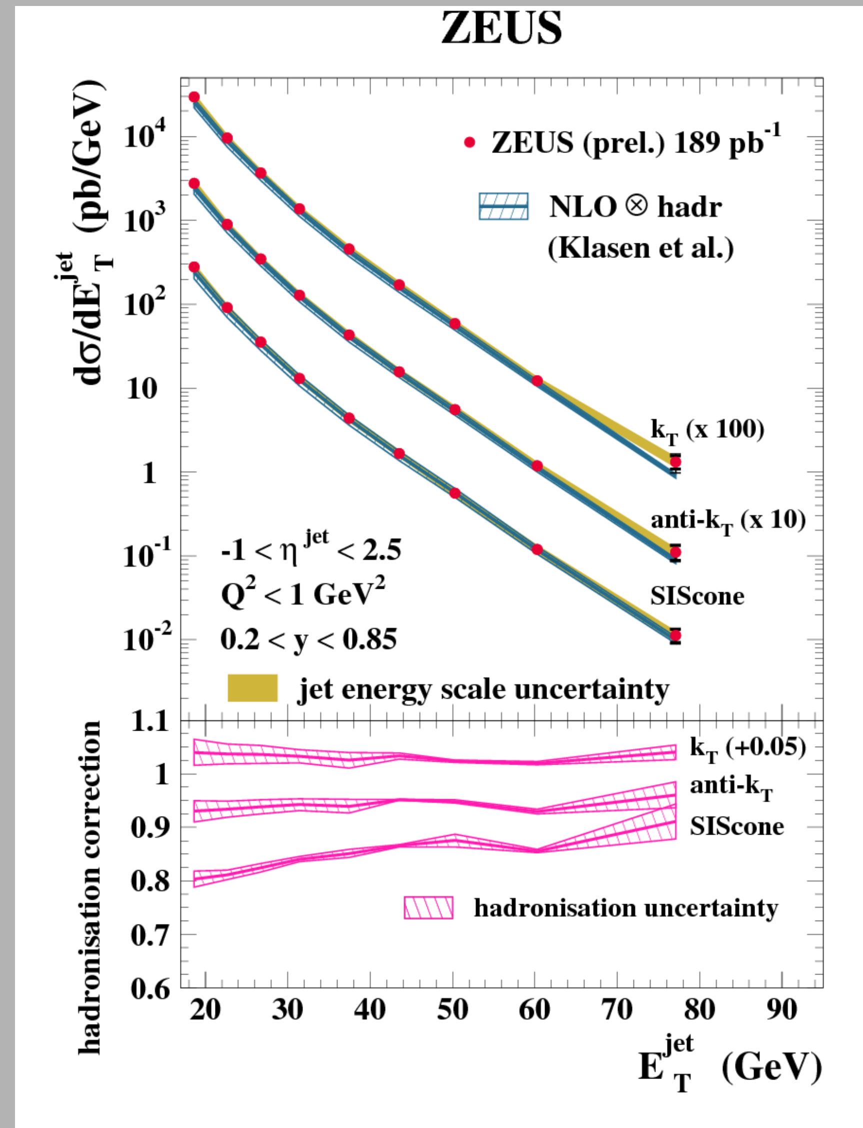




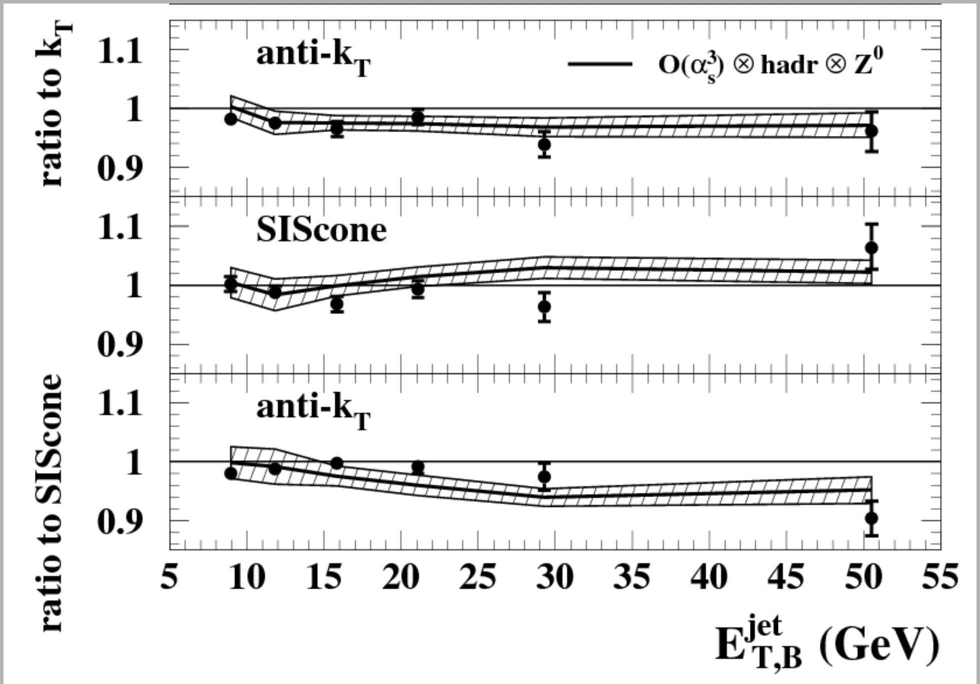
$$d_{ij} = \min[(E_T^i)^{2p}, (E_T^j)^{2p}] \Delta R^2 / R^2$$

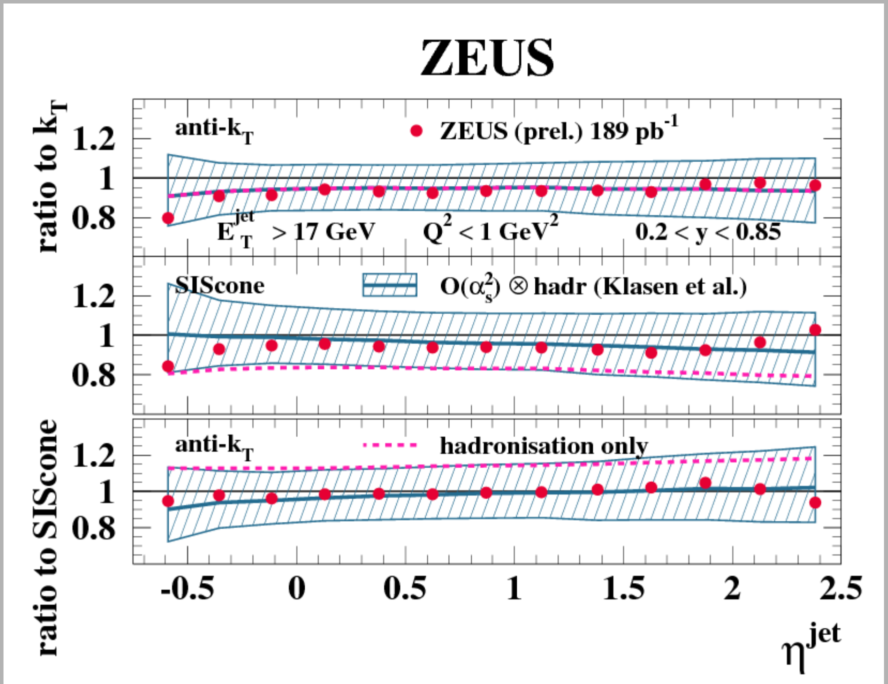
Jet algorithms





Cross-section ratios





- Measured cross-sections with different algorithms similar
- pQCD calculations account adequately for differences in algorithms