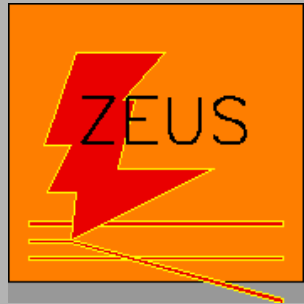


PIC2010 – QCD 2

Precision QCD tests and α_s measurements
(at HERA)



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Karlsruhe
02/09/2010



Why test QCD?

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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: $(17.85 \pm 0.05)\%$, μ : $(17.36 \pm 0.05)\%$

- 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):

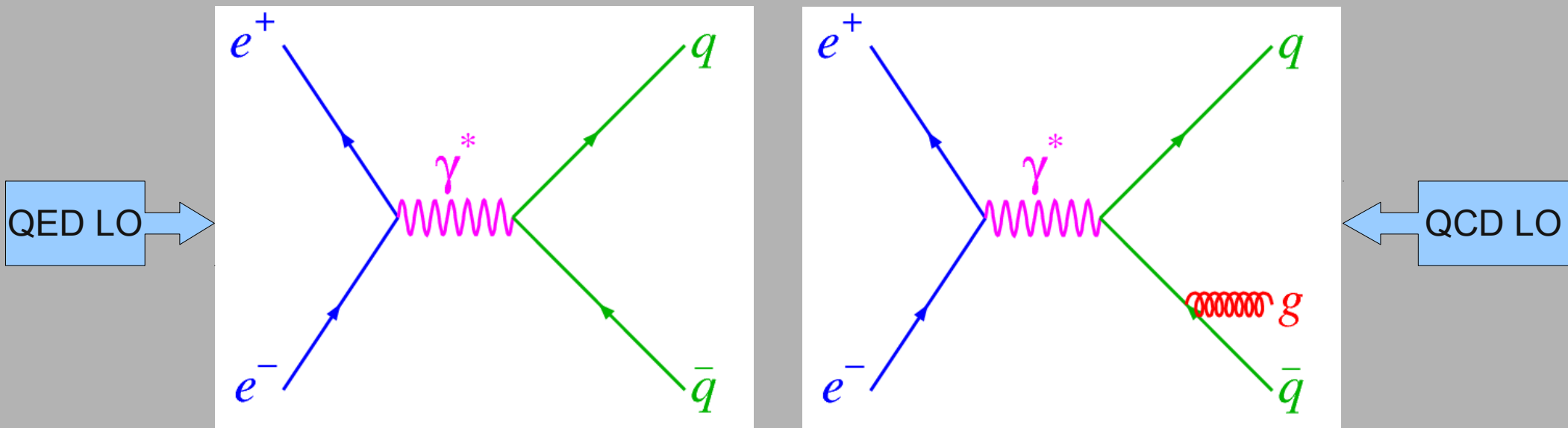
$$\mu^2 \frac{d \alpha_s}{d \mu^2} = \beta(\alpha_s) = -(\beta_0 \alpha_s^2 + \beta_1 \alpha_s^3 + \beta_2 \alpha_s^4 + \dots)$$

- 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)?

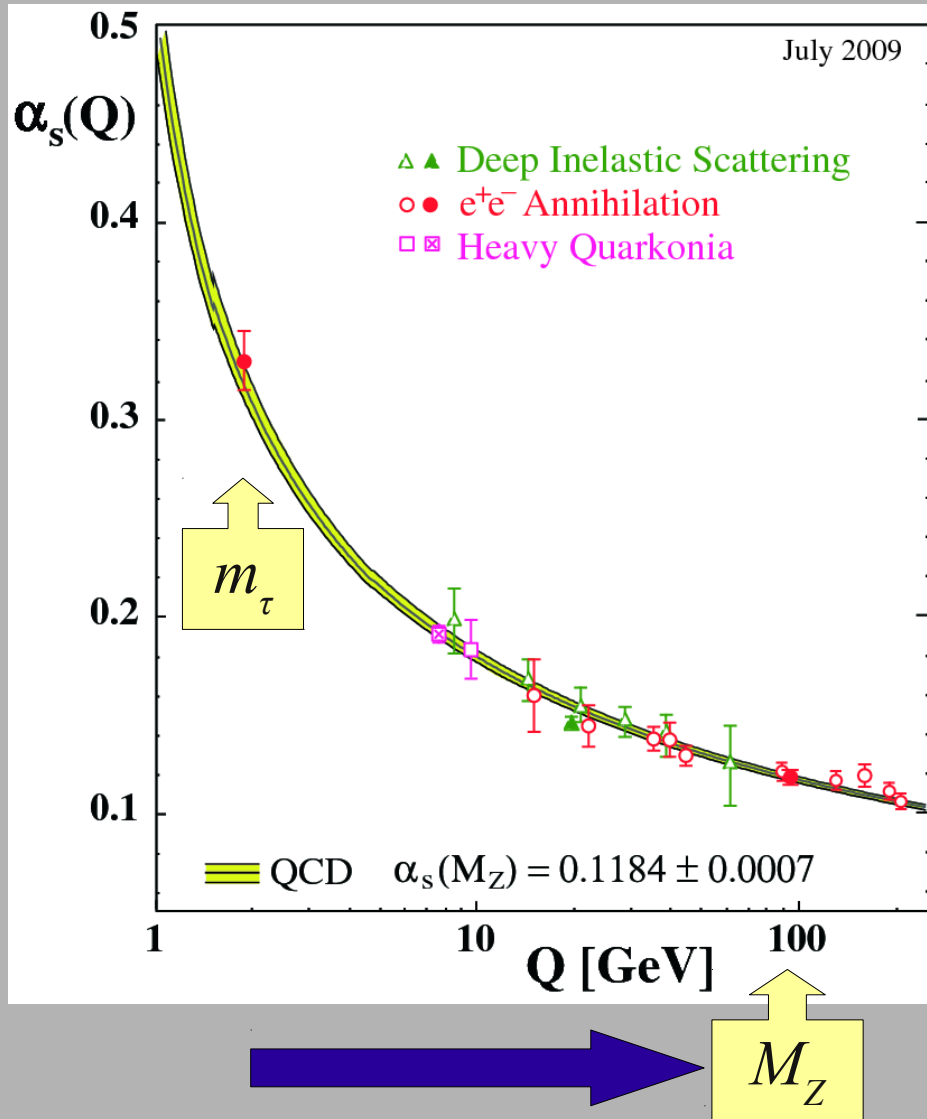


- Usually defined as lowest relevant order in α_S
- In this talk NLO means calculations to α_S^2
- NNLO = next-to-next-to-leading order: N^2LO
- NNNLO = next-to-next-to-next-to...: N^3LO

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
- N³LO: 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:
 $\text{BR}(\Upsilon(1S) \rightarrow \gamma g g) / \text{BR}(\Upsilon(1S) \rightarrow g g g)$
 - 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
arXiv:hep-ex/0512061

How to measure α_s ?

- Take $m(Y(2S)) - m(Y(1S))$
- 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]

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

$$\alpha_s(M_Z) = 0.1224 \pm 0.0039$$

NNLO

- Include α_s in the electroweak fits

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

$$\alpha_s(M_Z) = 0.1193^{+0.0028}_{-0.0027} \pm 0.0005$$

N³LO

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

$$\alpha_s(M_Z) = 0.1172 \pm 0.0051$$

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)

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

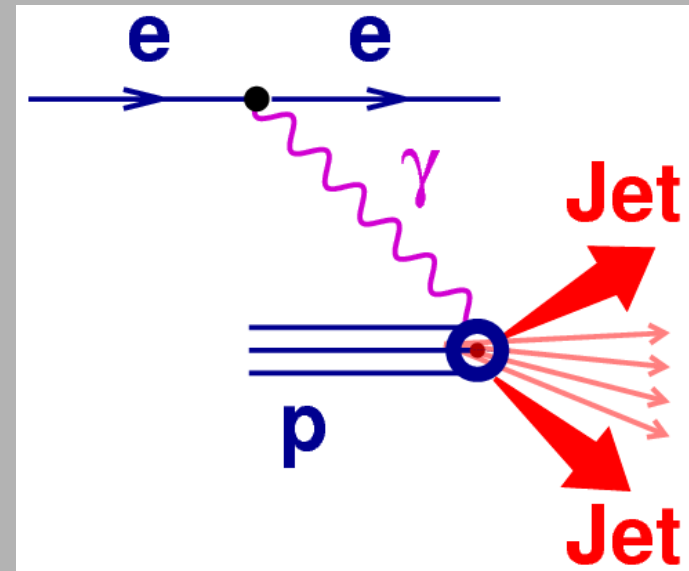
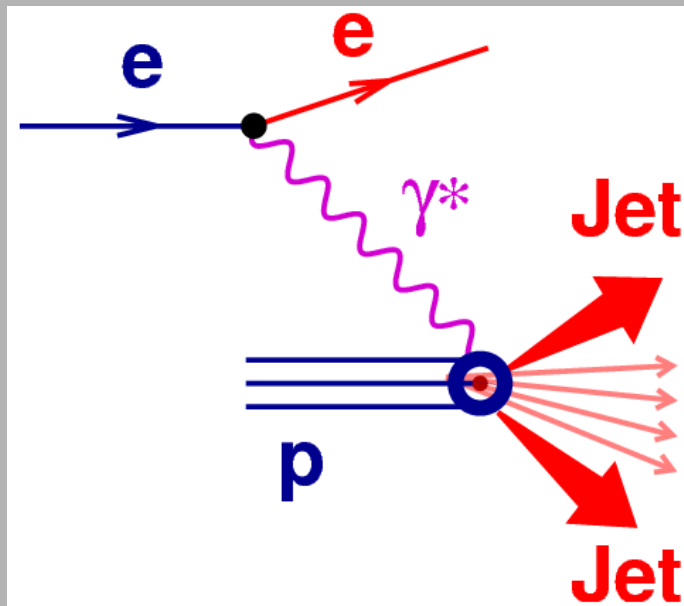
N³LO

- 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



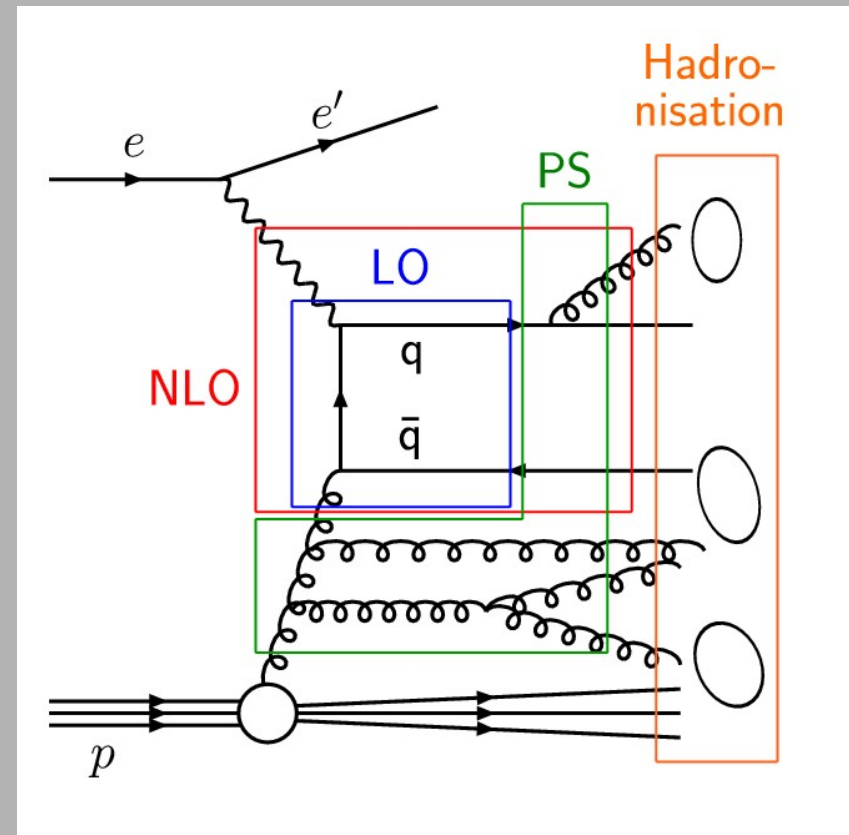
- Cross-section ratios are a good way to reduce systematics

From jets to α_s

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

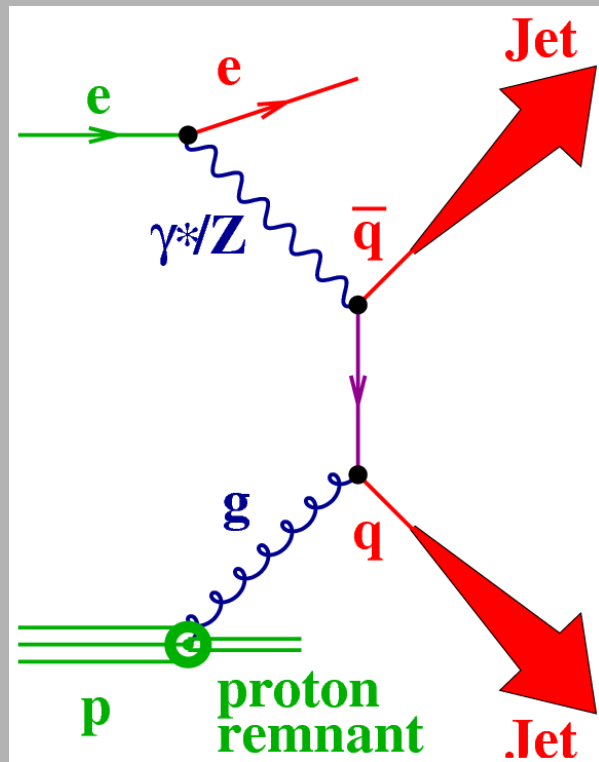
$$d\sigma_{\text{jet}} = \sum_{a=q, \bar{q}, g} \int dx f_a(x, \mu_F) \cdot d\hat{\sigma}_a(x, \alpha_s(\mu_R), \mu_R, \mu_F)$$

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

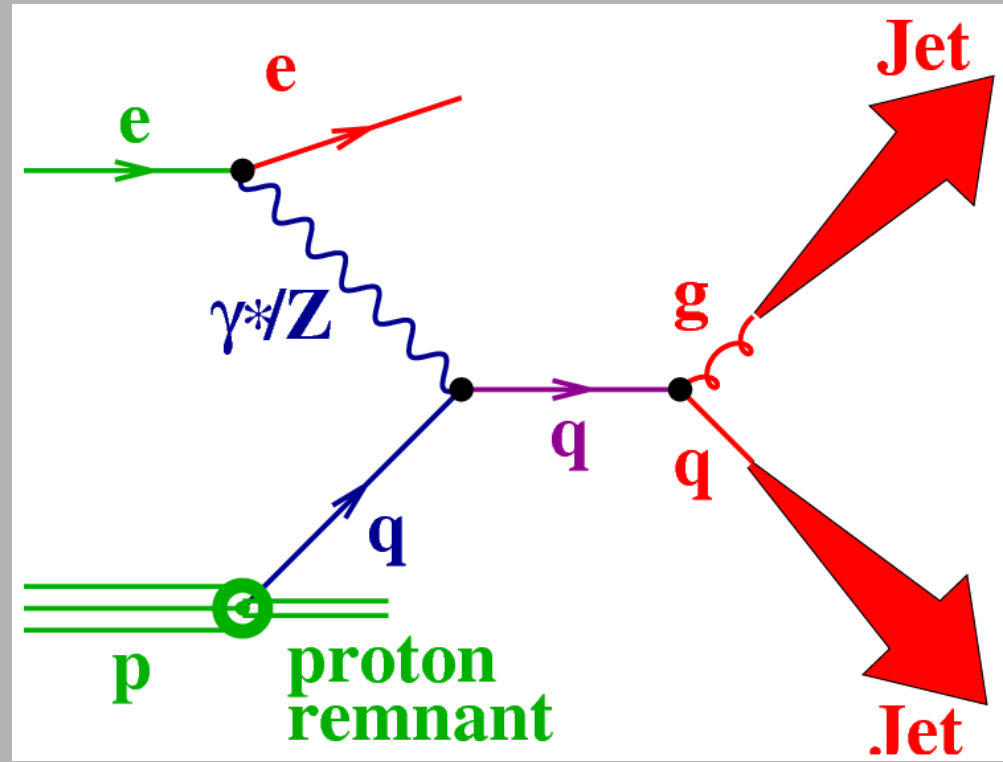


Jets in DIS

- Sources of (di)jet production:



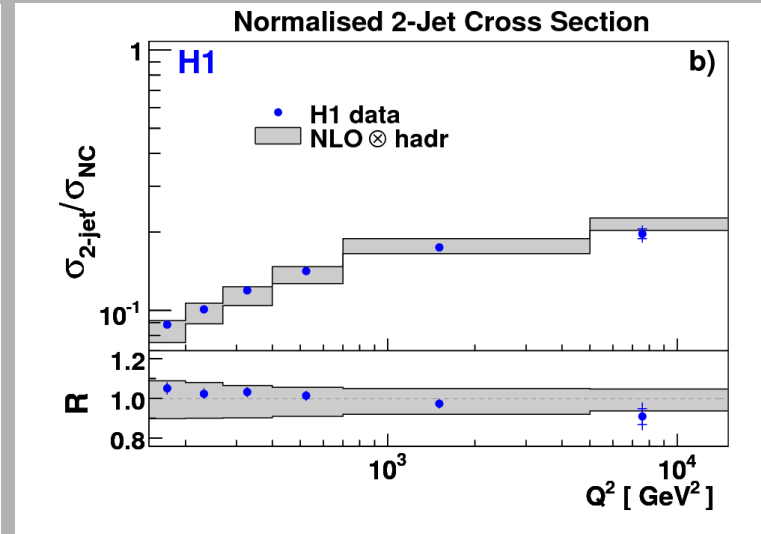
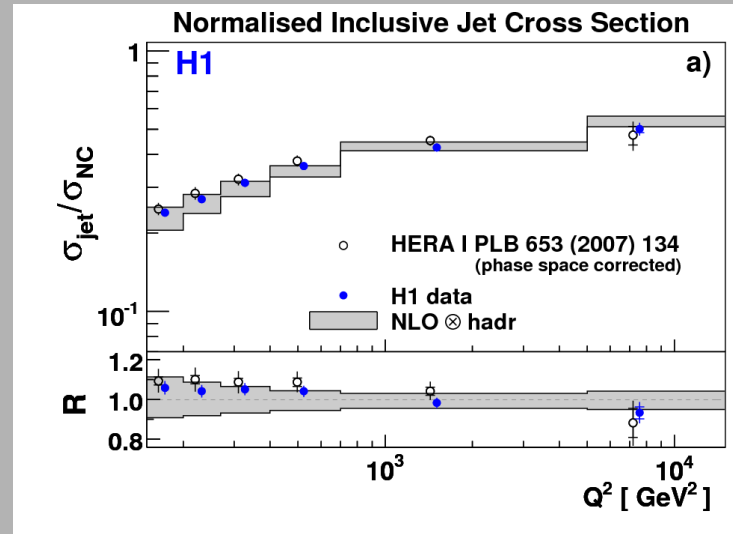
Boson-gluon fusion



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 $\xi = x_{Bj} (1 + M_{jj}/Q^2)$
- Normalise to NC cross-section



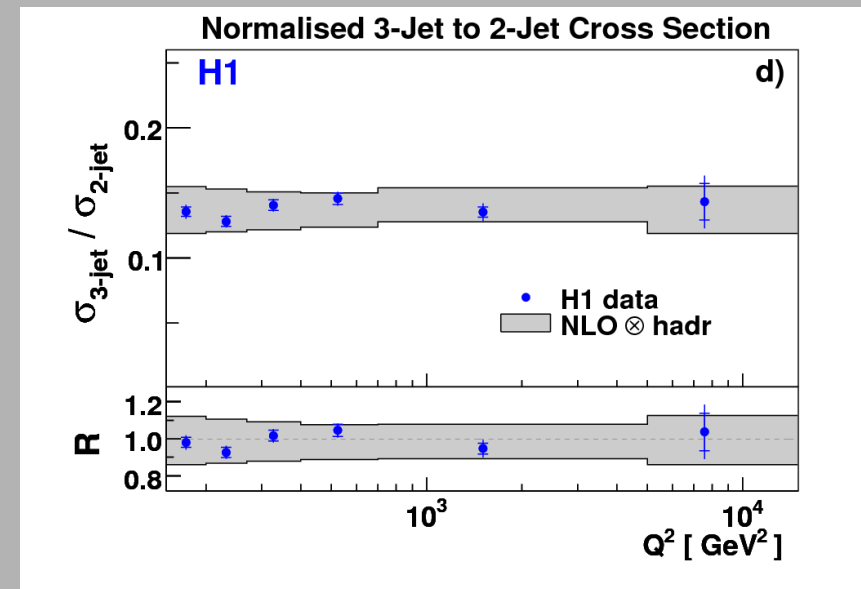
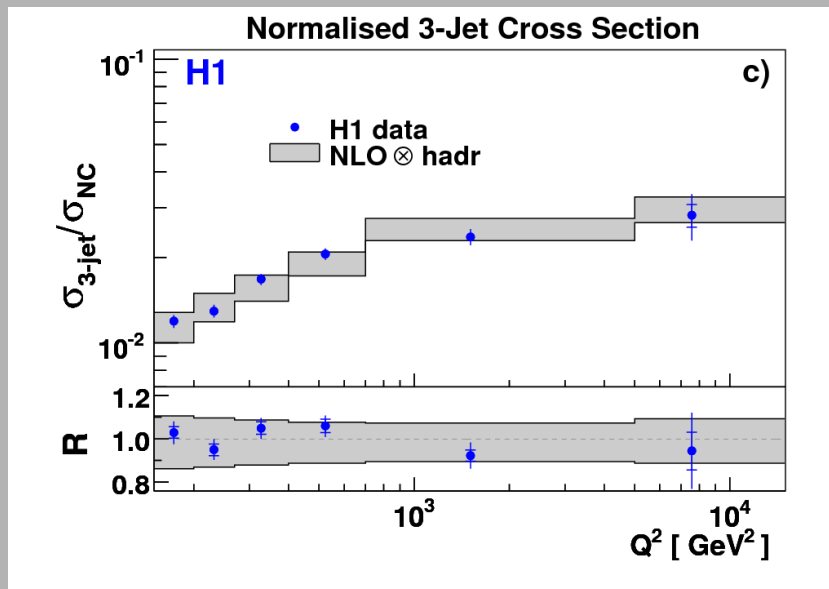
395 pb⁻¹, Event:
 $150 < Q^2 < 15000 \text{ GeV}^2$
 $0.2 < y < 0.7$

Jet:
 $P_T > 7(5) \text{ GeV}$
 $-0.8 < \eta_{\text{lab}} < 2.0$
 k_T algorithm in BF

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

Jets at high Q^2

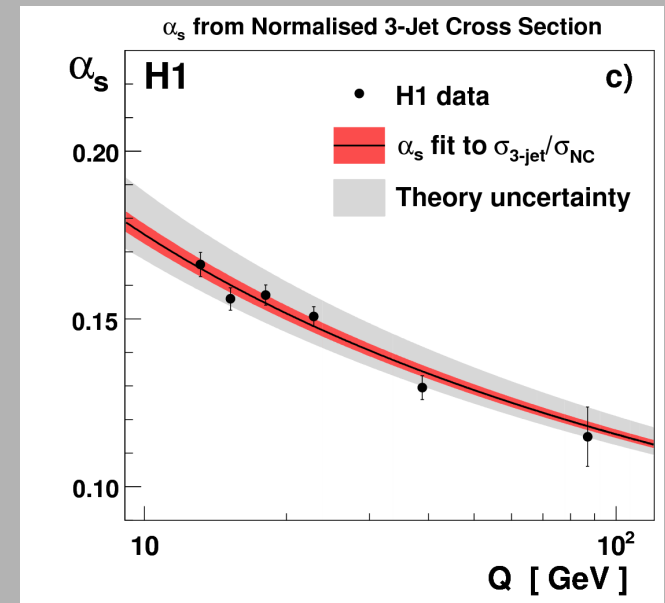
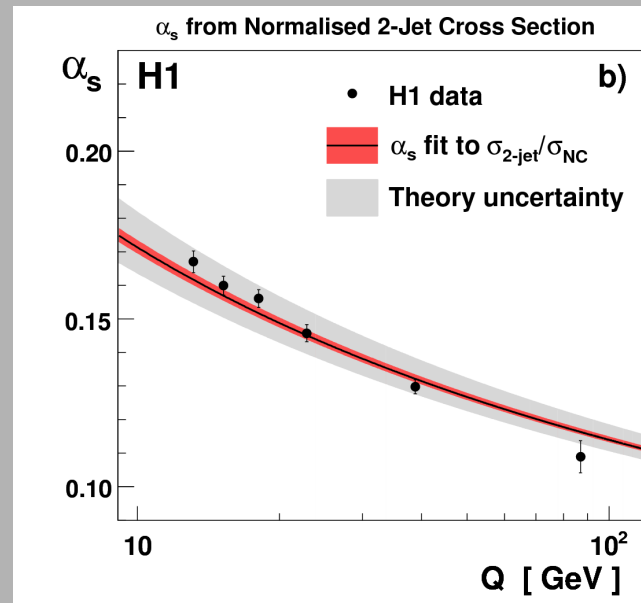
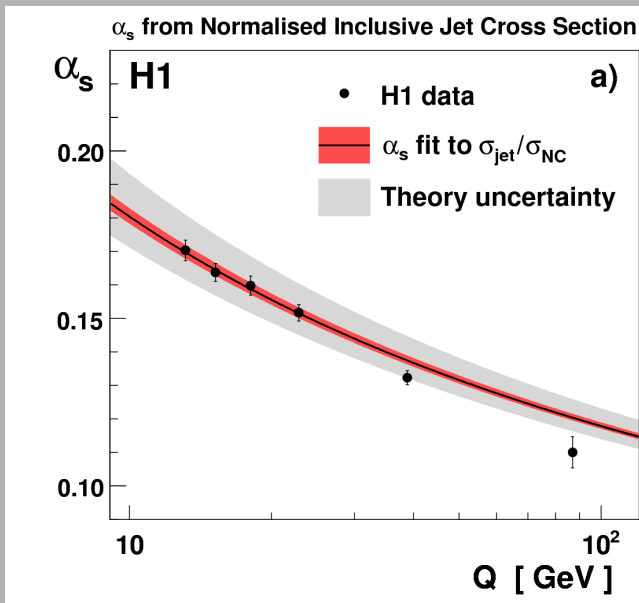
- Plenty of statistics even in 3-jet channel
- NLO uncertainties at 10% level
- Good agreement with predictions over whole Q^2 range



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

Jets at high Q^2

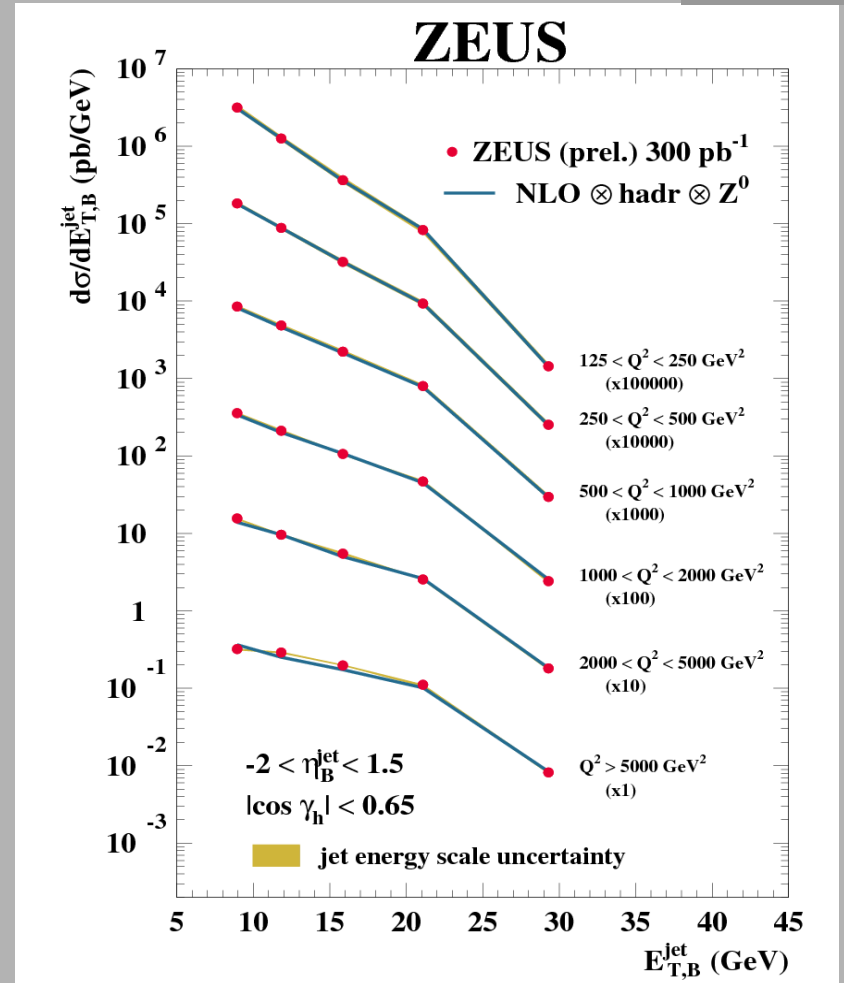
- Each cross-section and cross-section ratio can be used to derive α_s as a function of the scale
- Running of α_s (within a single experiment) clearly seen



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



NLO

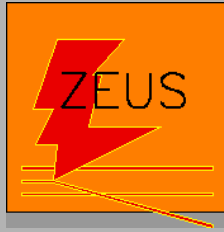
$$\alpha_S(M_Z) = 0.1208 \pm 0.0007 (\text{stat.})_{-0.0031}^{+0.0036} (\text{exp.}) \pm 0.0022 (\text{th.})$$

ZEUS Collab, ZEUS-prel-10-002

300 pb⁻¹, Event:
 $Q^2 > 125 \text{ GeV}^2$
 $|\cos \gamma_h| < 0.65$

Jet:
 $E_T > 8 \text{ GeV}$
 $-2 < \eta_{\text{BF}} < 1.5$
 k_T algorithm in BF

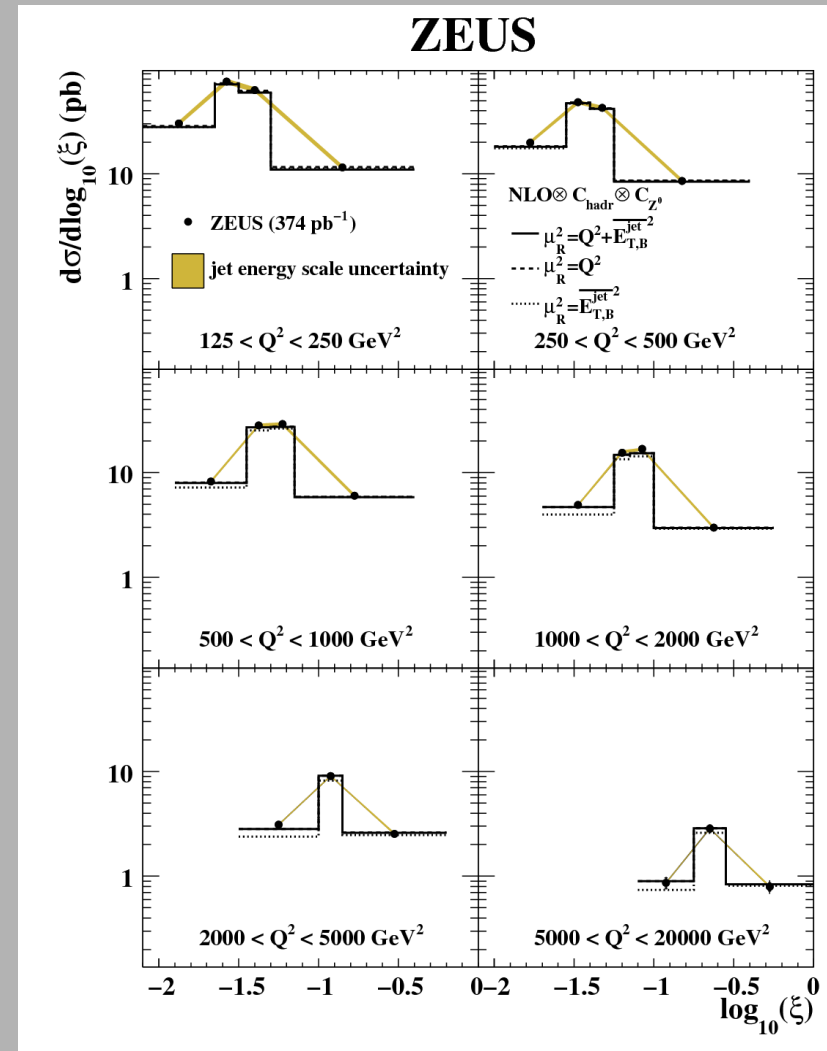
Dijets in NC DIS



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

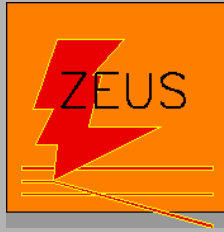
374 pb⁻¹, Event:
 $125 < Q^2 < 20000 \text{ GeV}^2$
 $0.2 < y < 0.6$

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



ZEUS Collab, ZEUS-pub-10-005

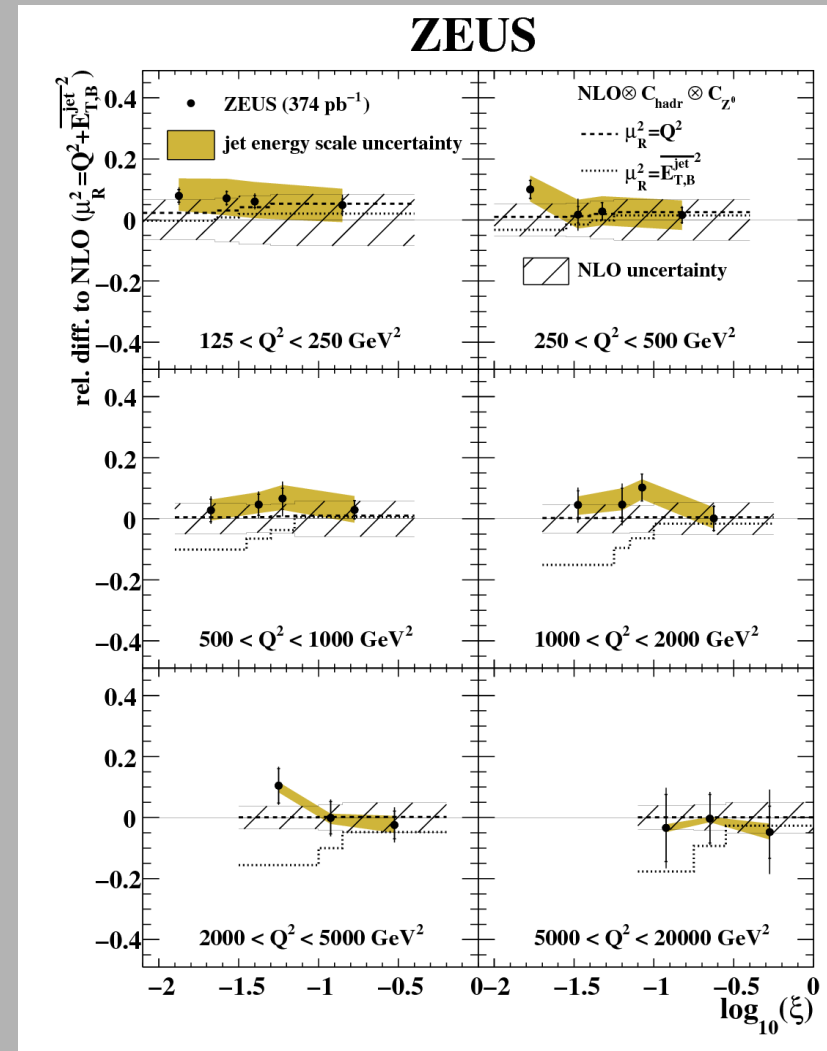
Dijets in NC DIS



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374 pb⁻¹, Event:
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 $0.2 < y < 0.6$

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



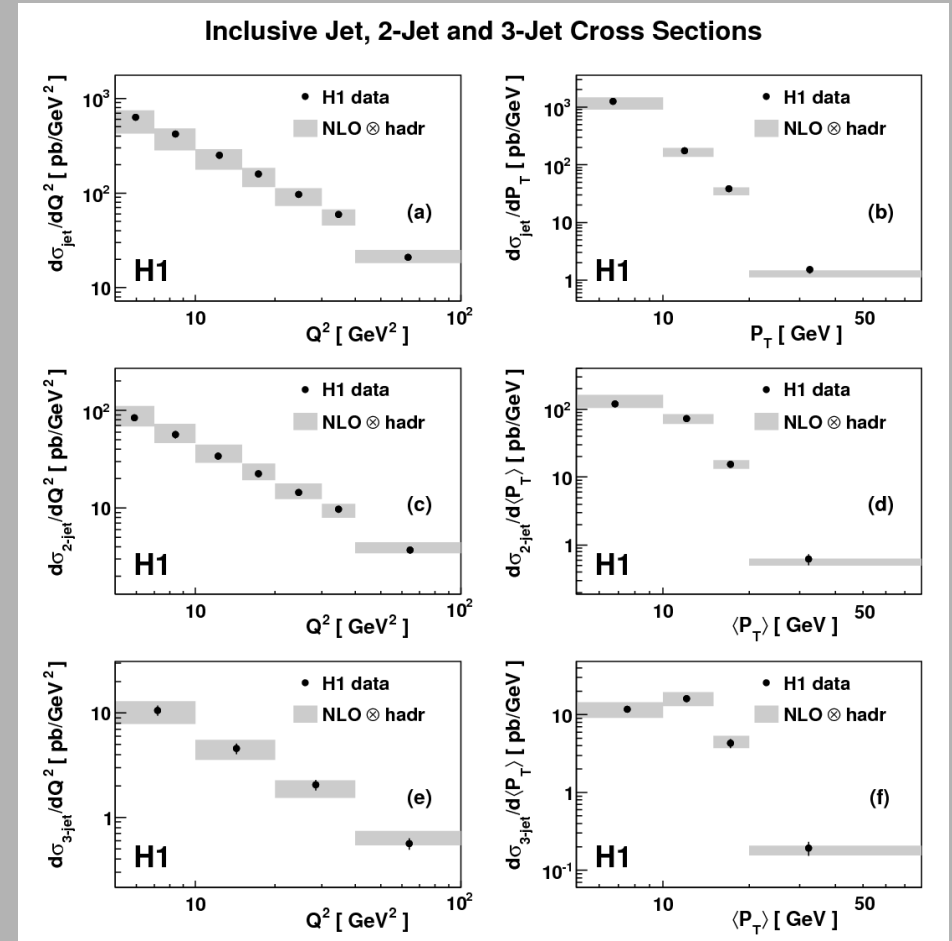
ZEUS Collab, ZEUS-pub-10-005

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:
 $5 < Q^2 < 100 \text{ GeV}^2$
 $0.2 < y < 0.7$

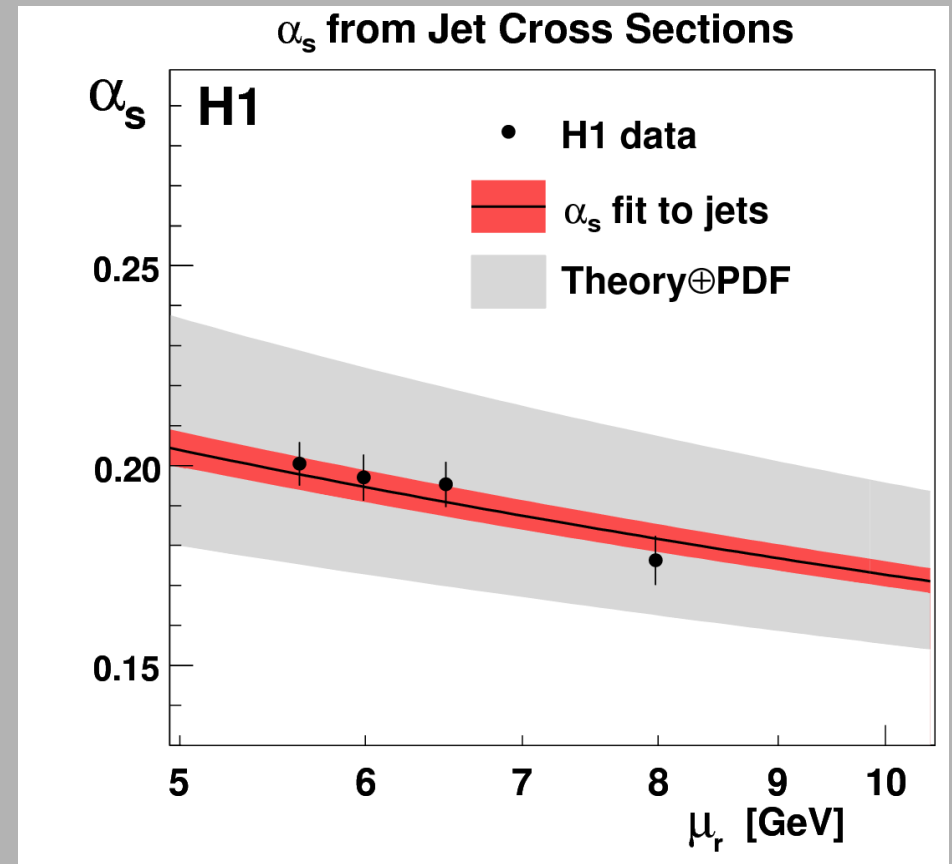
Jet:
 $P_T > 5 \text{ GeV}$
 $-1 < \eta_{\text{lab}} < 2.5$
 k_T algorithm in BF



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

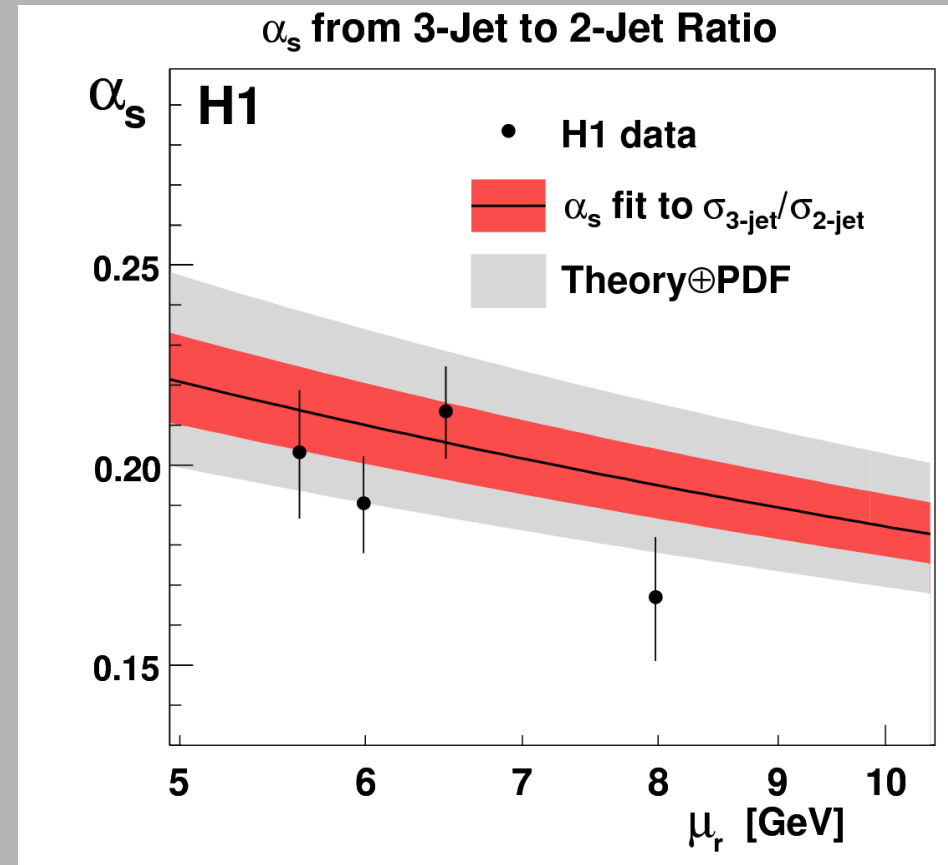
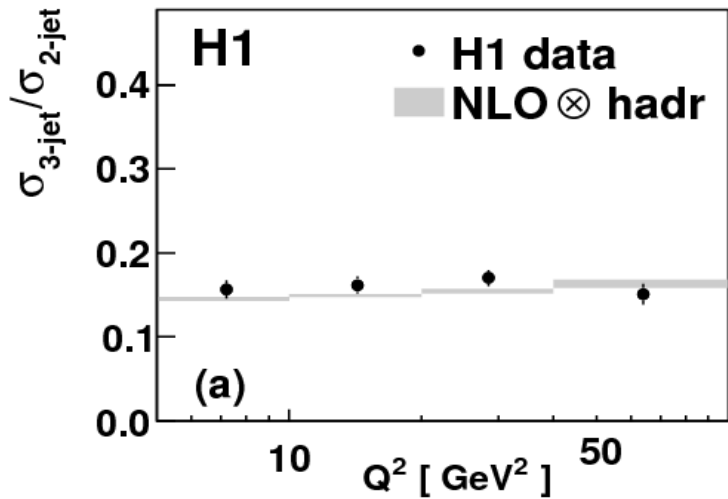


$$\alpha_s(M_Z) = 0.1160 \pm 0.0014 (\text{exp.})_{-0.0079}^{+0.0094} (\text{th.})$$

NLO

Jets at low Q^2

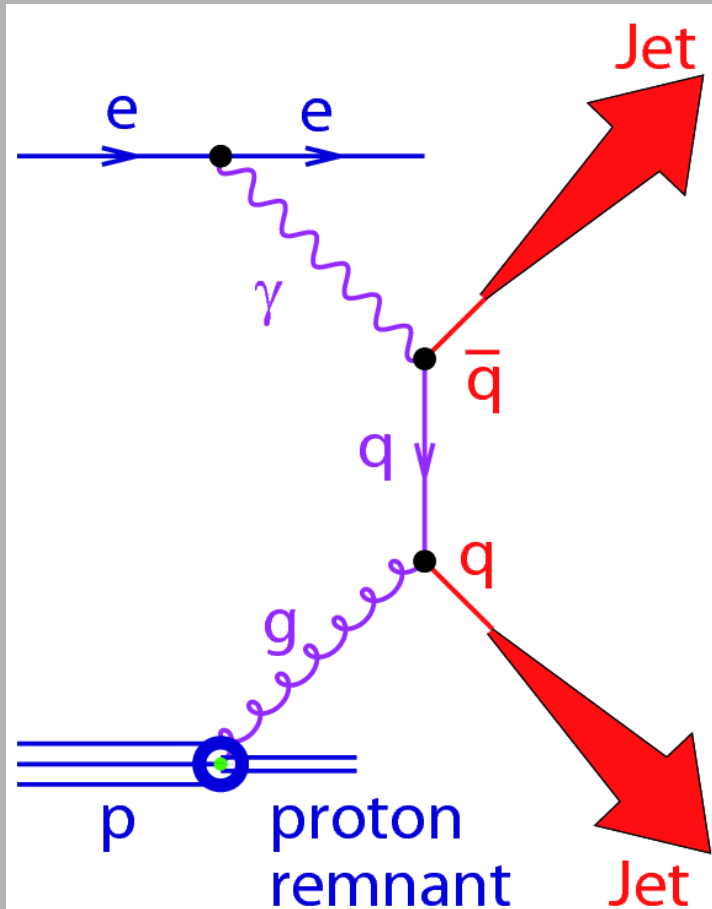
- Shame that precise exp. measurement has large theory error
- Using 3-jet/2-jet ratio reduces theory error



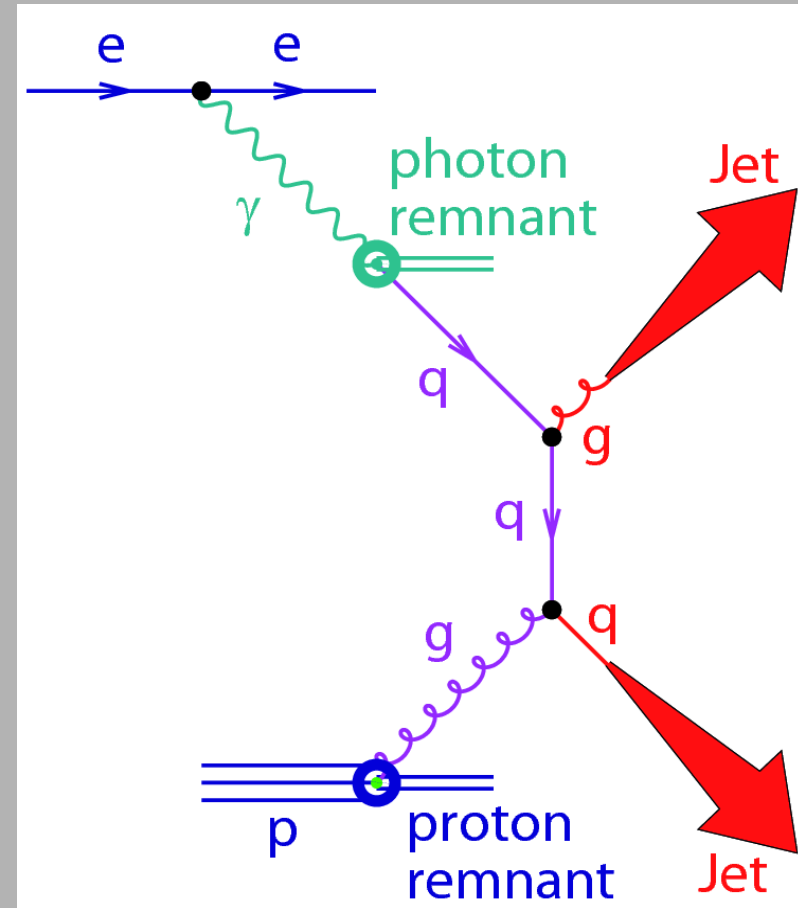
NLO

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

Jets in Photoproduction

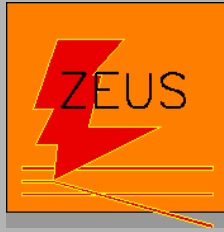


Direct photoproduction

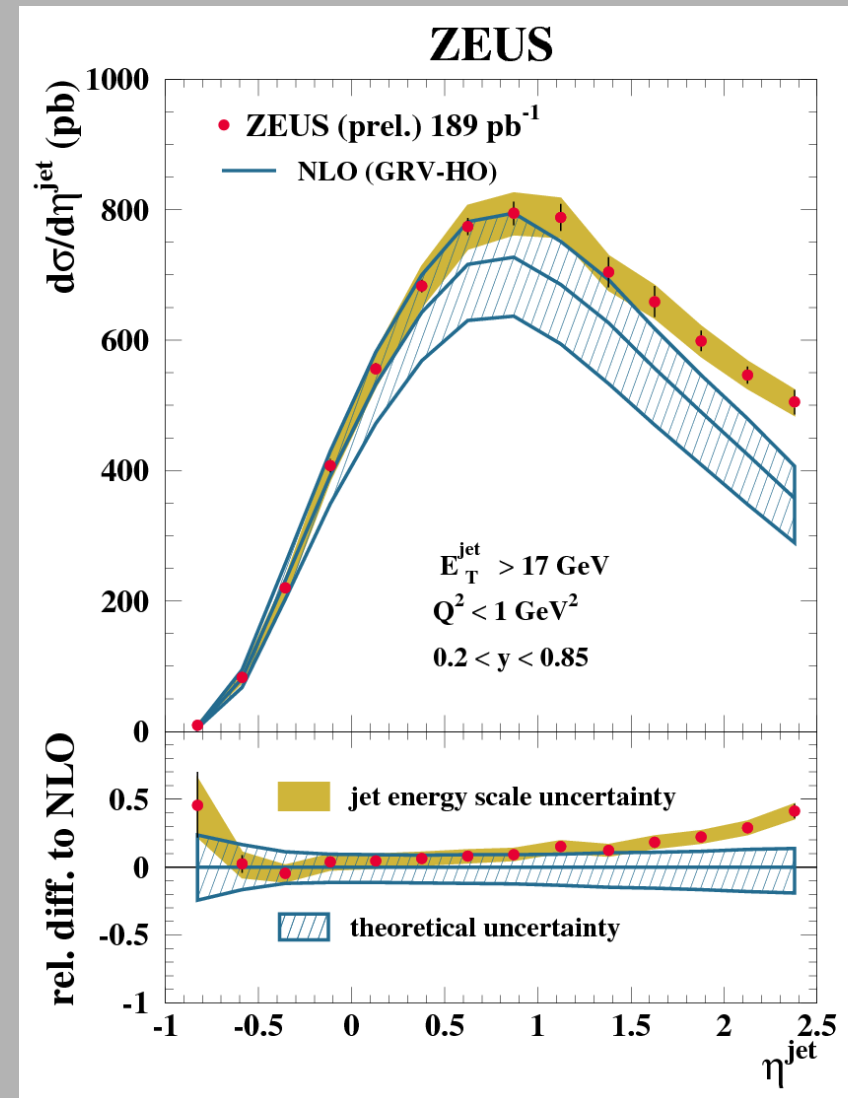


Resolved photoproduction

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



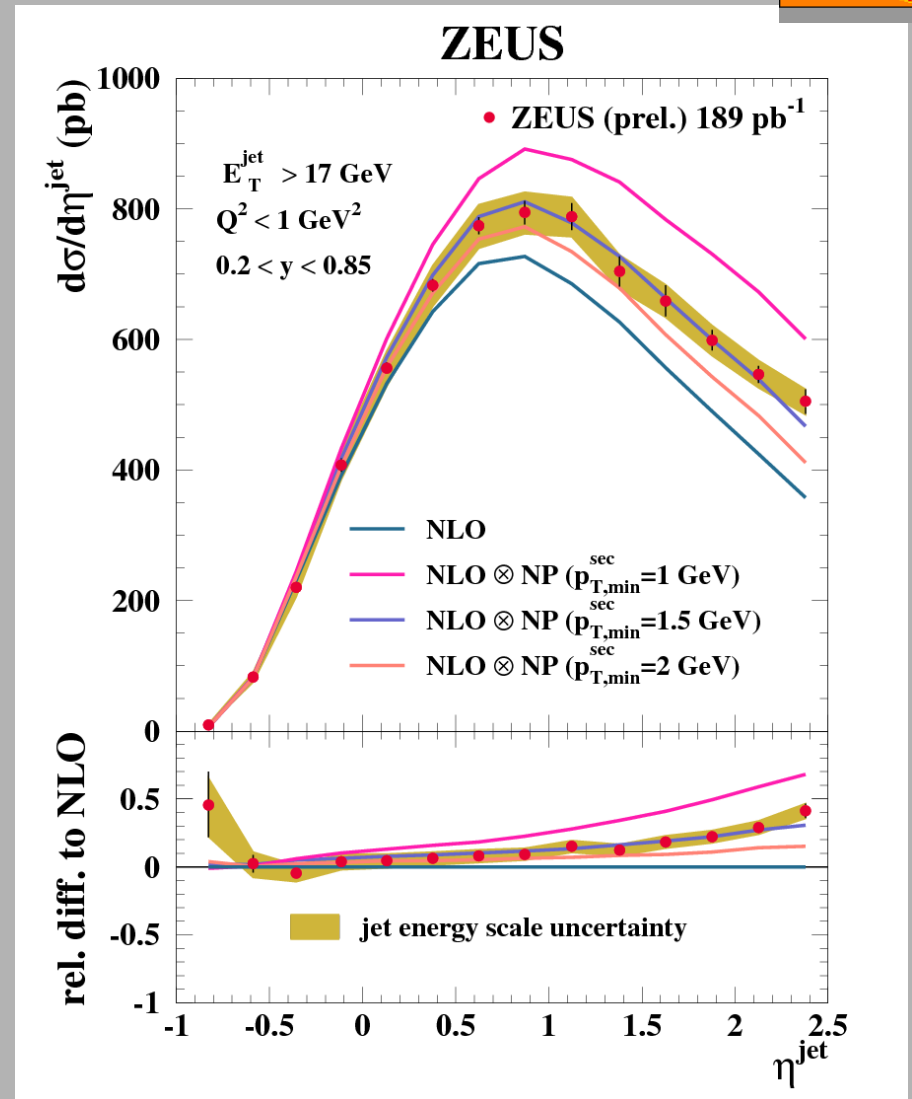
$$\eta = -\ln \tan \theta/2$$

ZEUS Collab, ZEUS-prel-10-003

Jets in Photoproduction



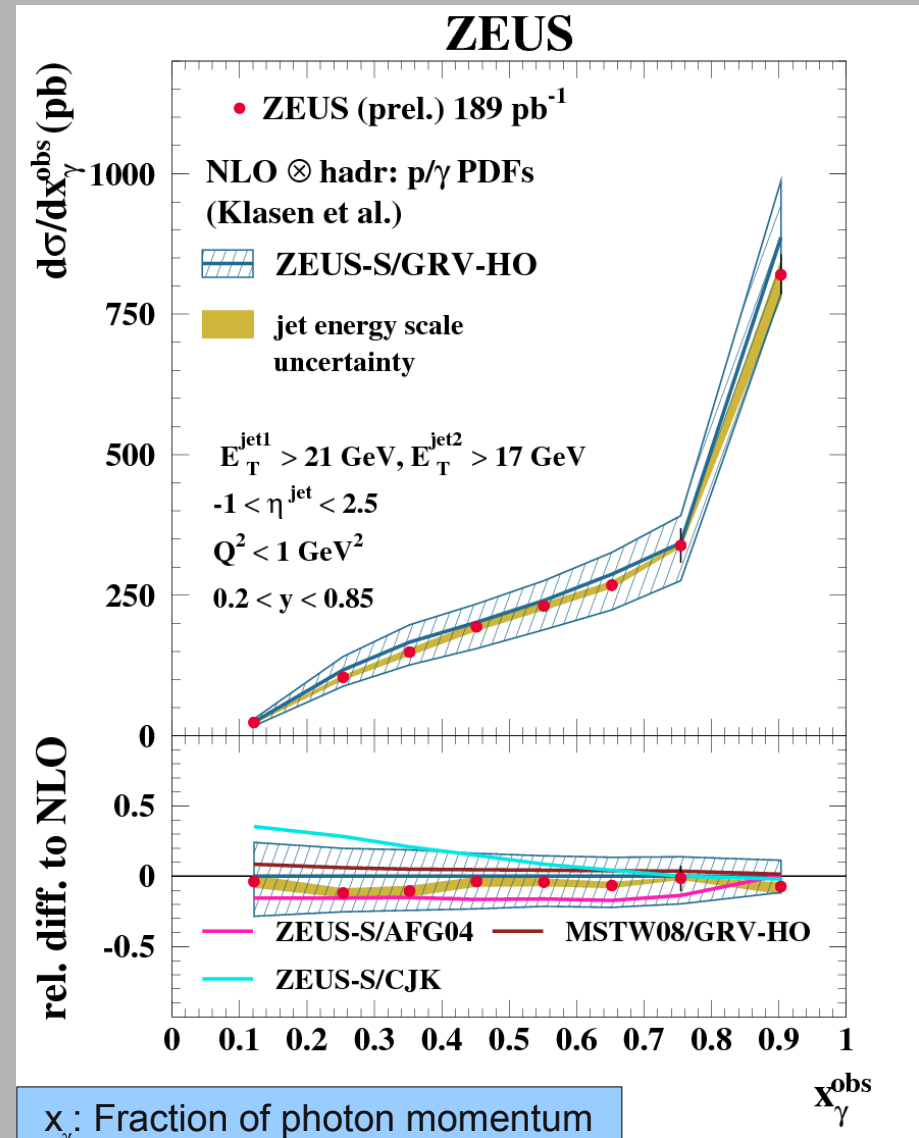
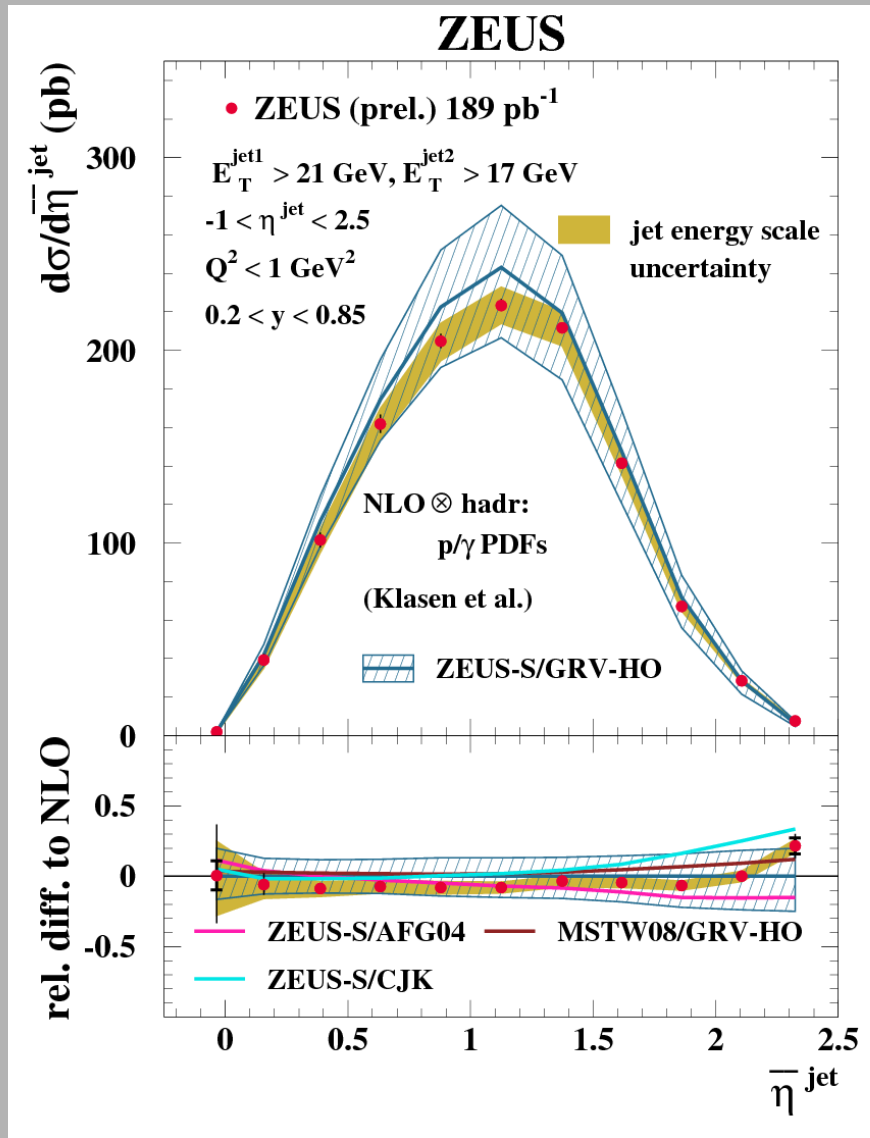
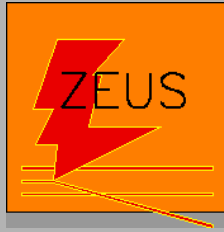
- Include non-perturbative effects using PYTHIA-MI
 - much better agreement at large η
- Size of effect also much reduced for higher E_T^{jet}



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

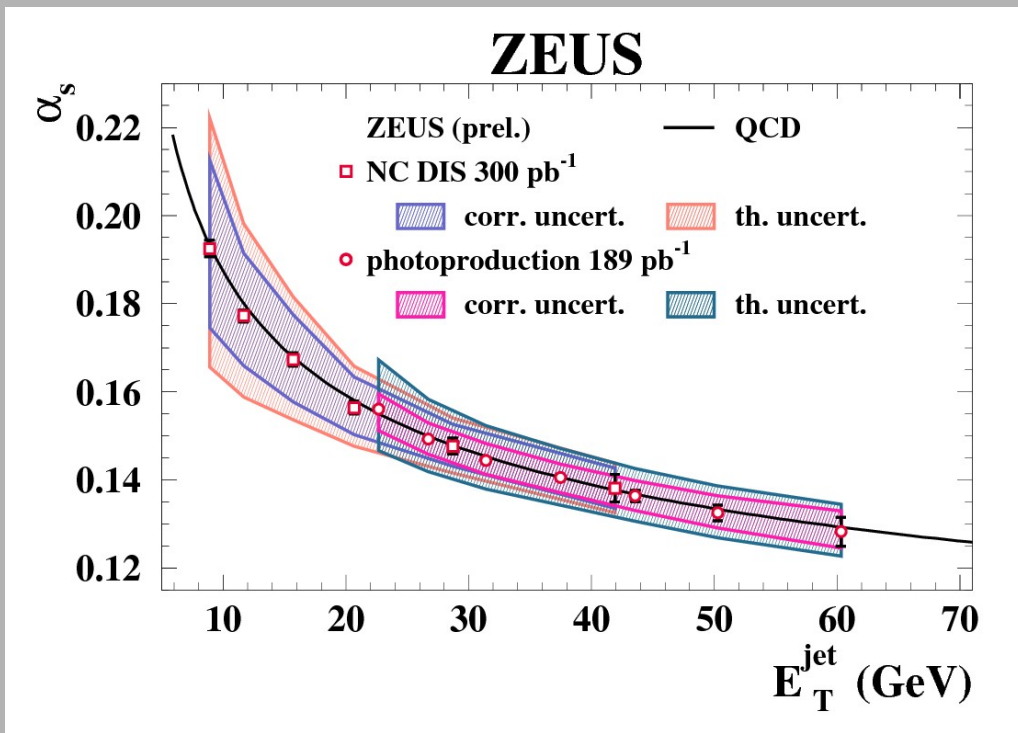
NLO

Dijets in Photoproduction

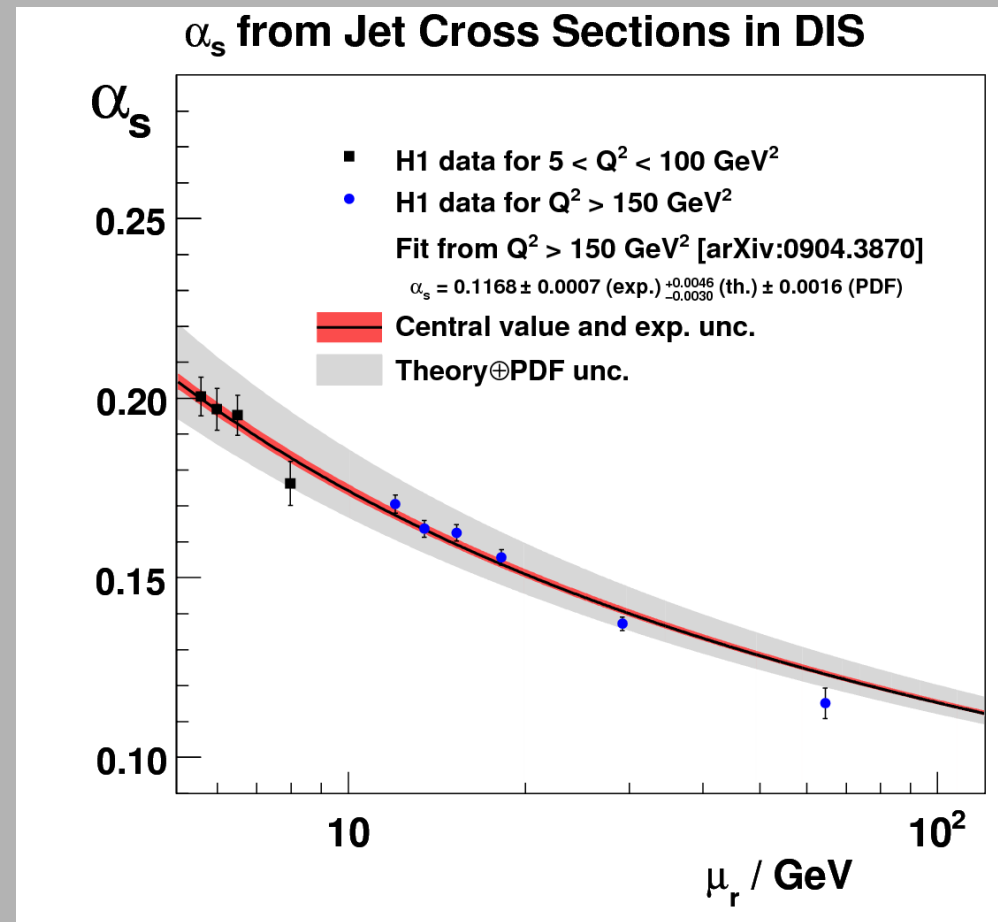


x_γ : Fraction of photon momentum carried by interacting parton

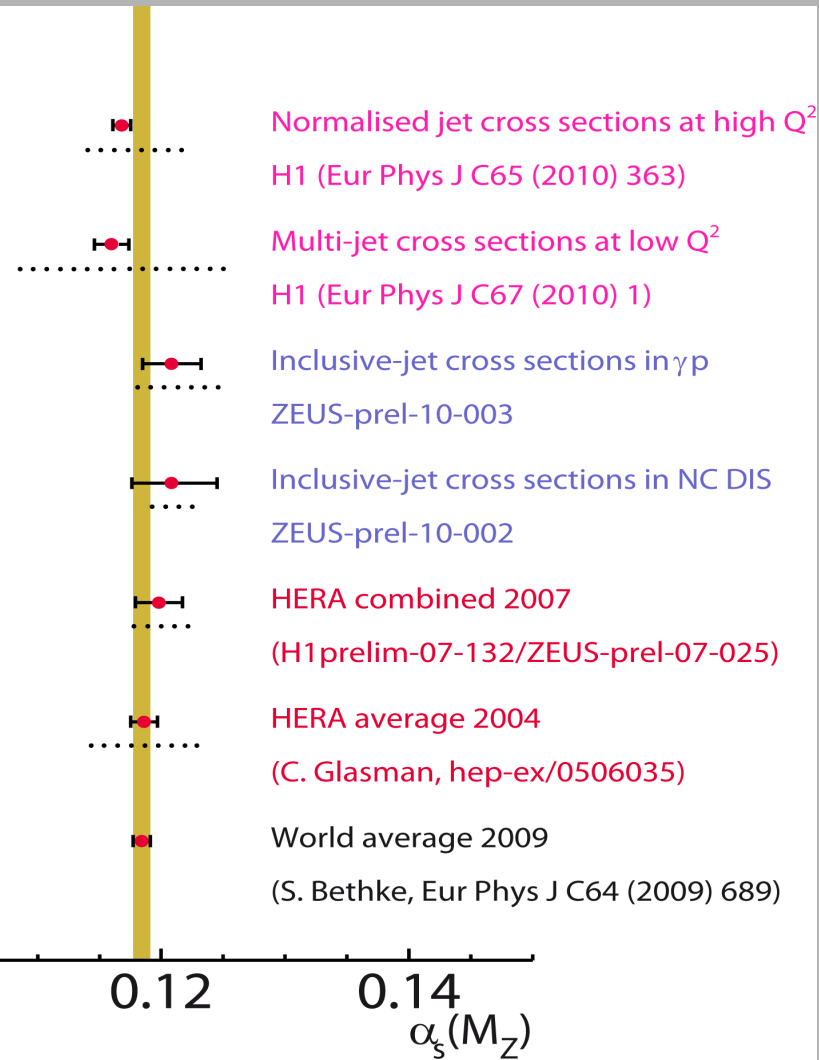
HERA α_s measurements



- DIS and photoproduction measurements in good agreement with each other

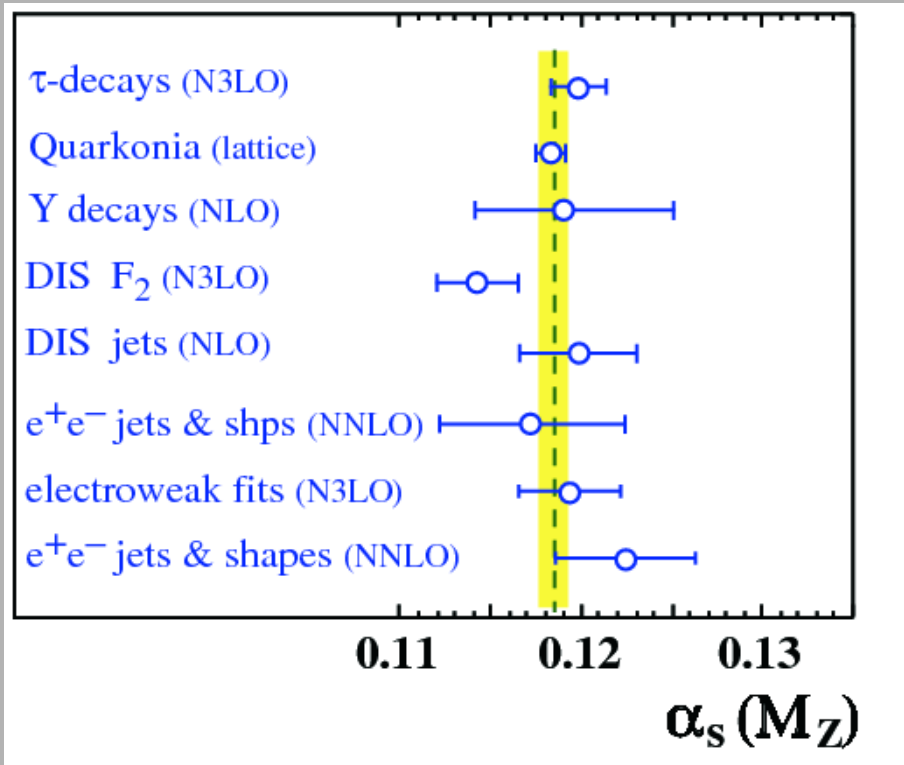


HERA α_s measurements summary

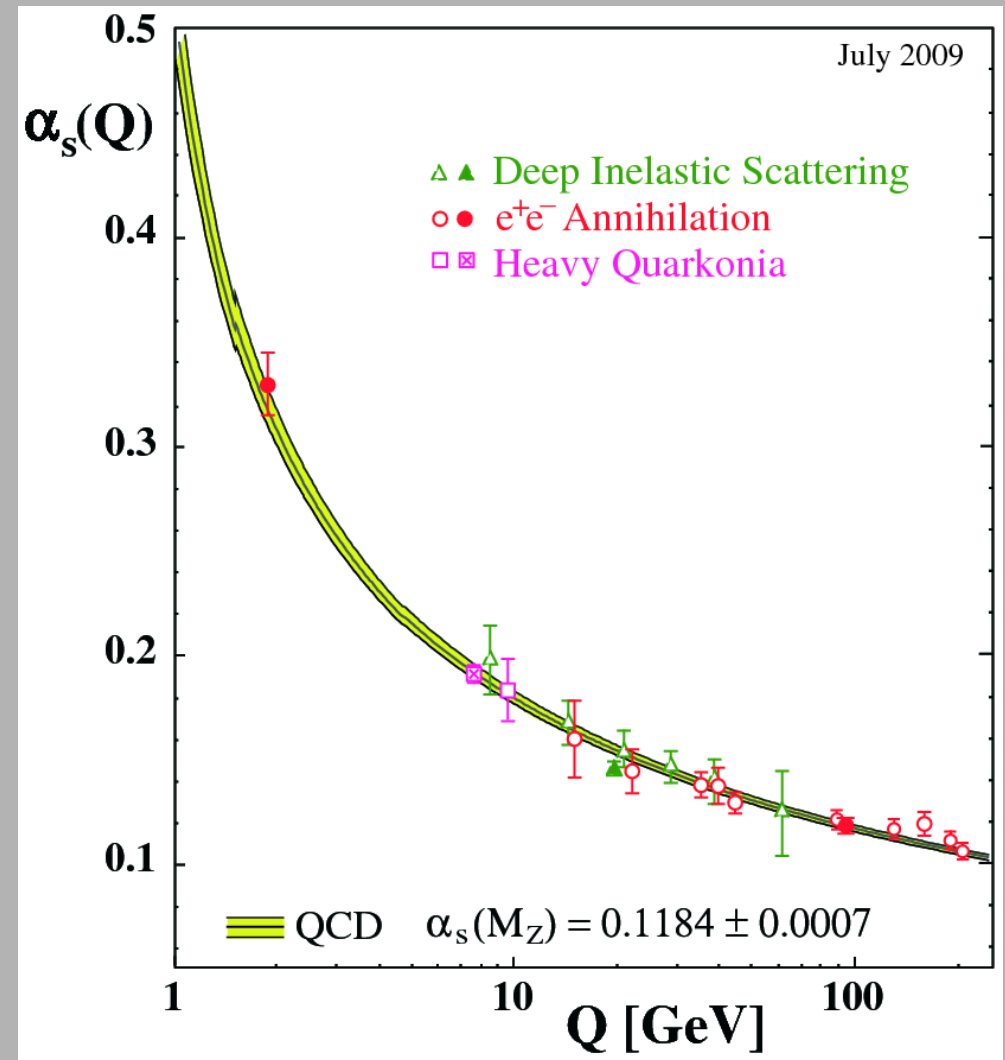


- Compare several precise determinations of α_s
- Trade off between statistics and theoretical uncertainties clearly visible

α_s measurements summary

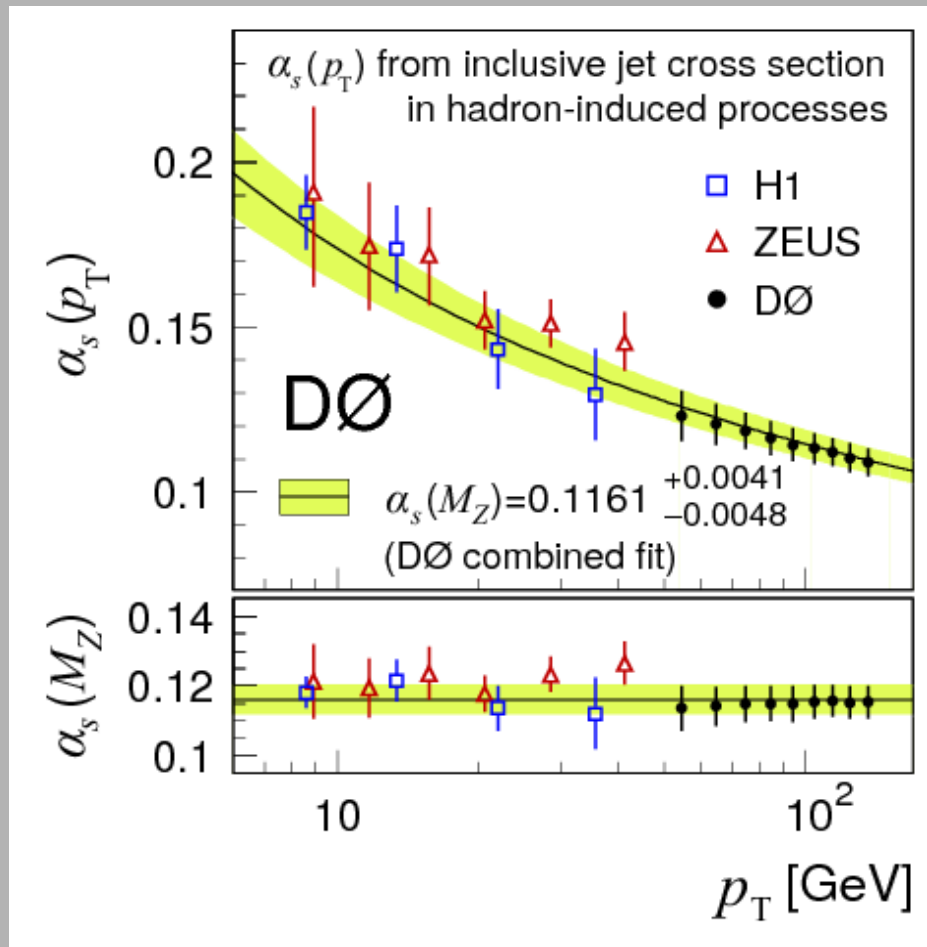


- Most effort on NLO MC generators expended for LHC; similar effort for HERA would be very welcome!



$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

Running at the Tevatron

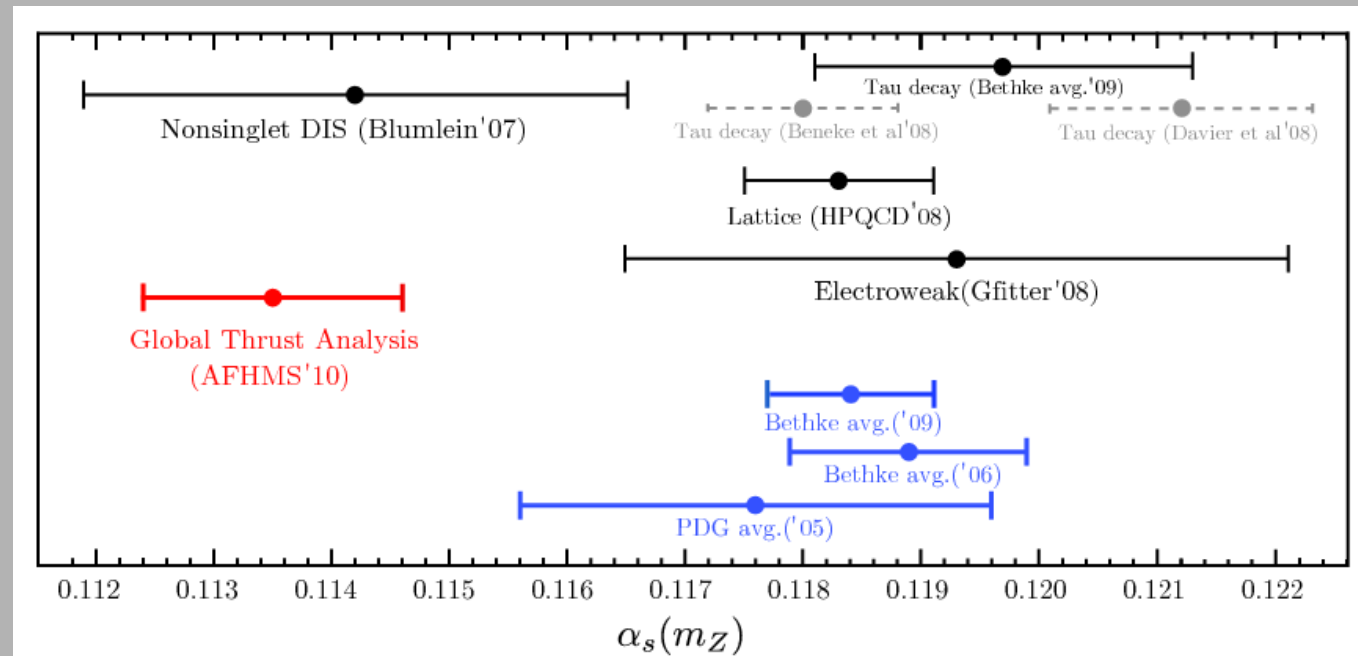


- Careful attention paid to avoid circular reasoning!
 - $g(x)$ and α_s are often correlated
- DØ errors are dominated by correlated experimental uncertainties
- Complementarity of HERA and Tevatron kinematic ranges

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

α_s measurements summary

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



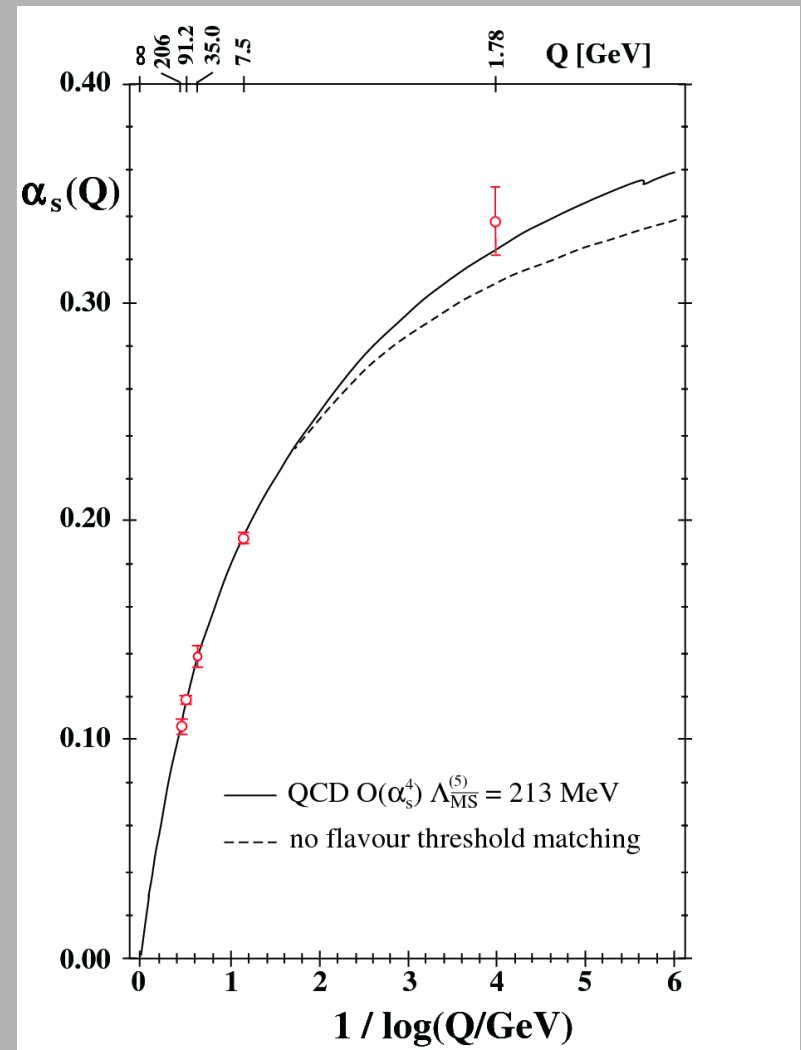
N³LL'

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

R. Abbate et al., arXiv:1006.3080

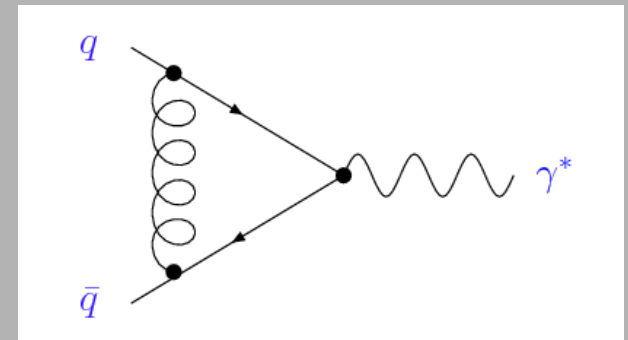
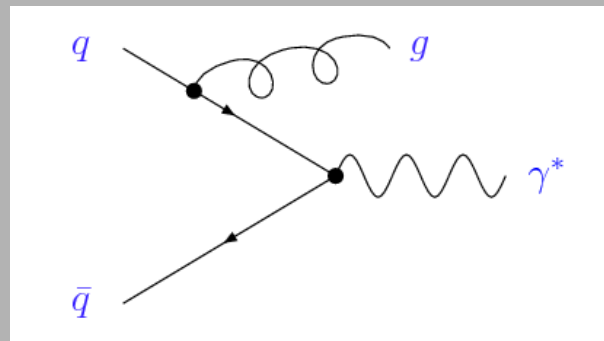
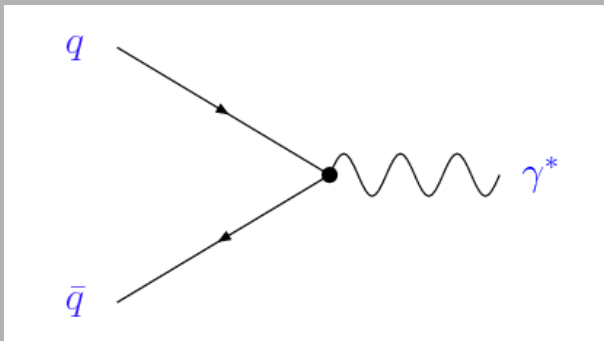
Does α_S run as expected?

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



Precision QCD tests

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



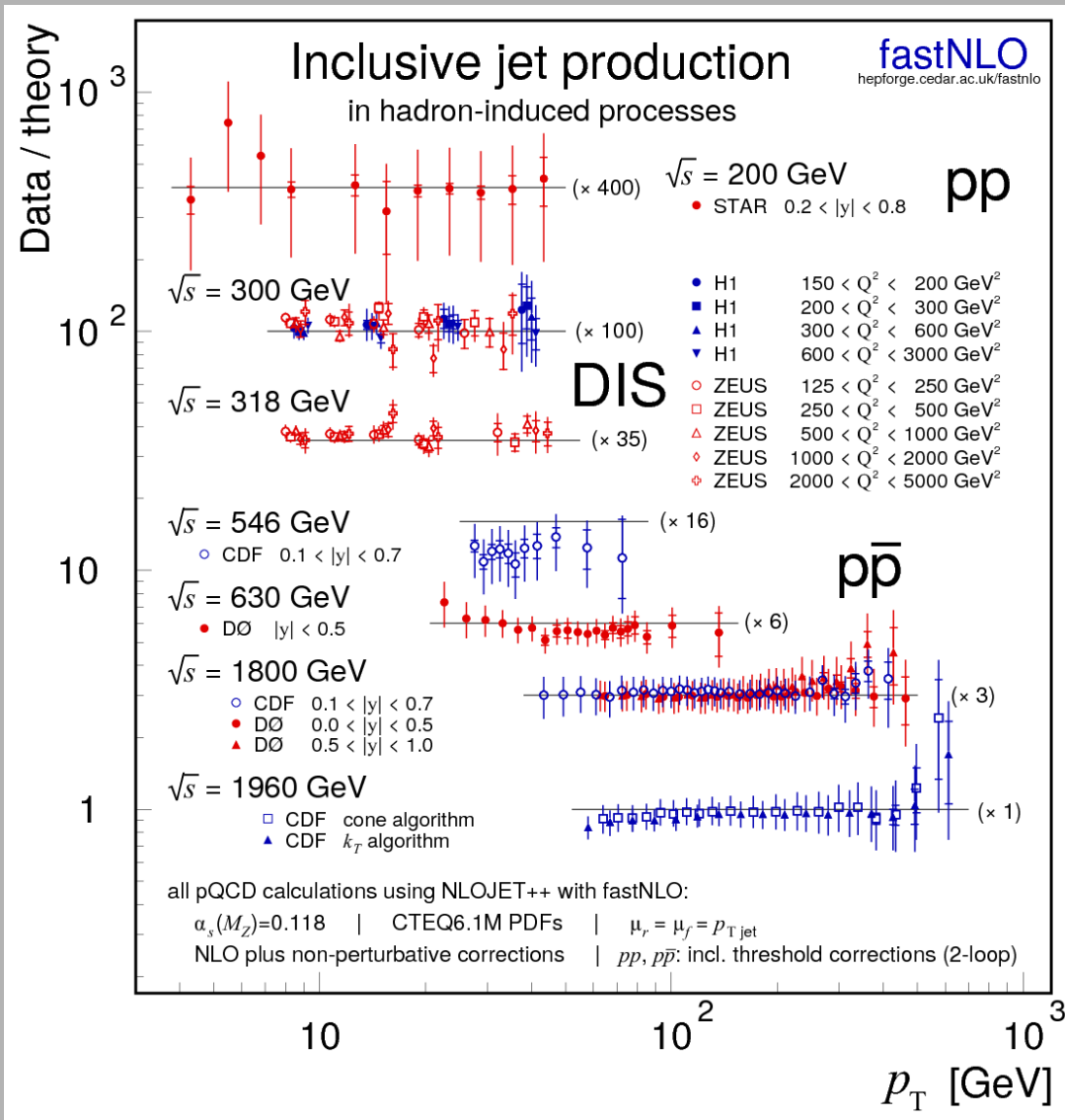
- Improve if summed over all orders, but...
 - Absorb most of remaining infinities in renormalisation
- Buzzwords: soft and collinear divergences

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

Even here convergence not as fast as expected!

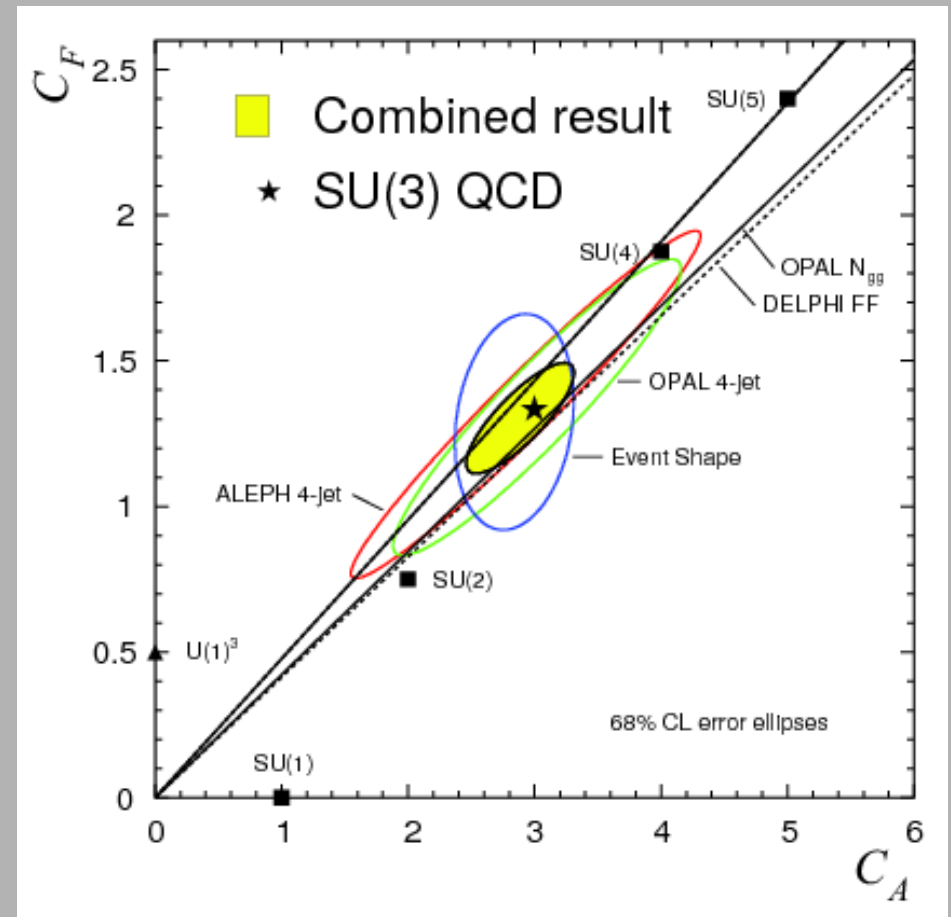
Inclusive jet production



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

Is QCD the right theory?

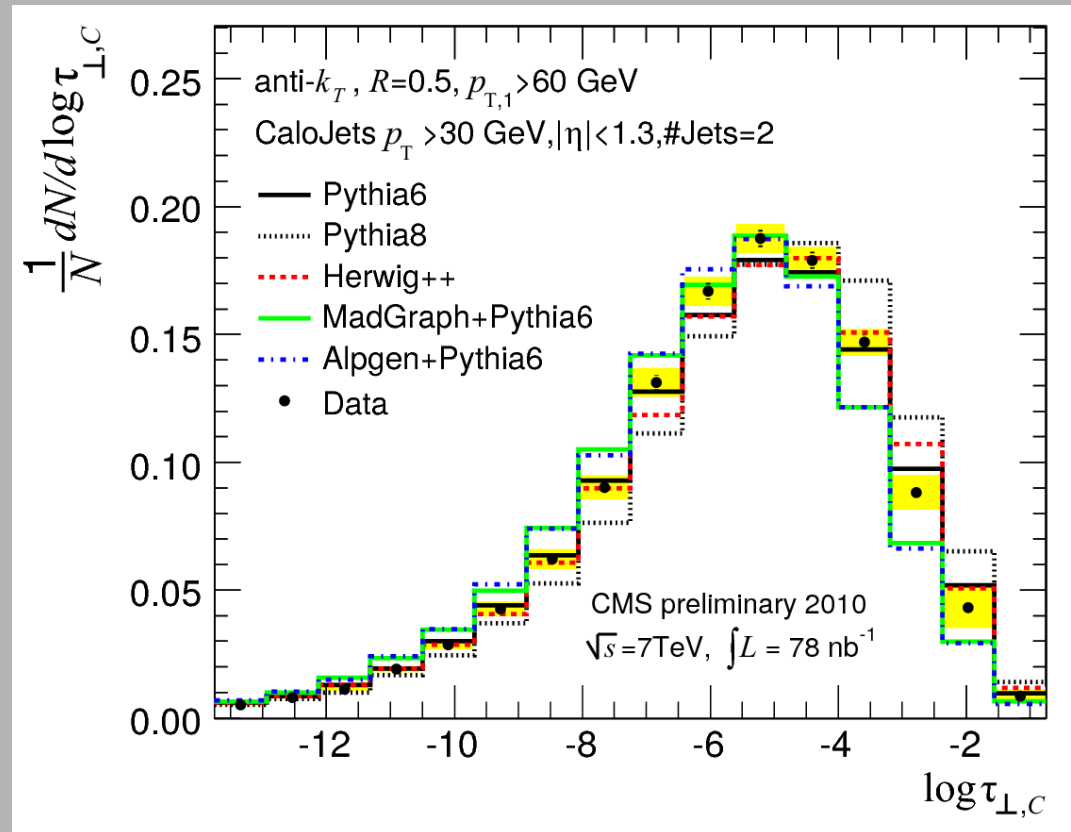
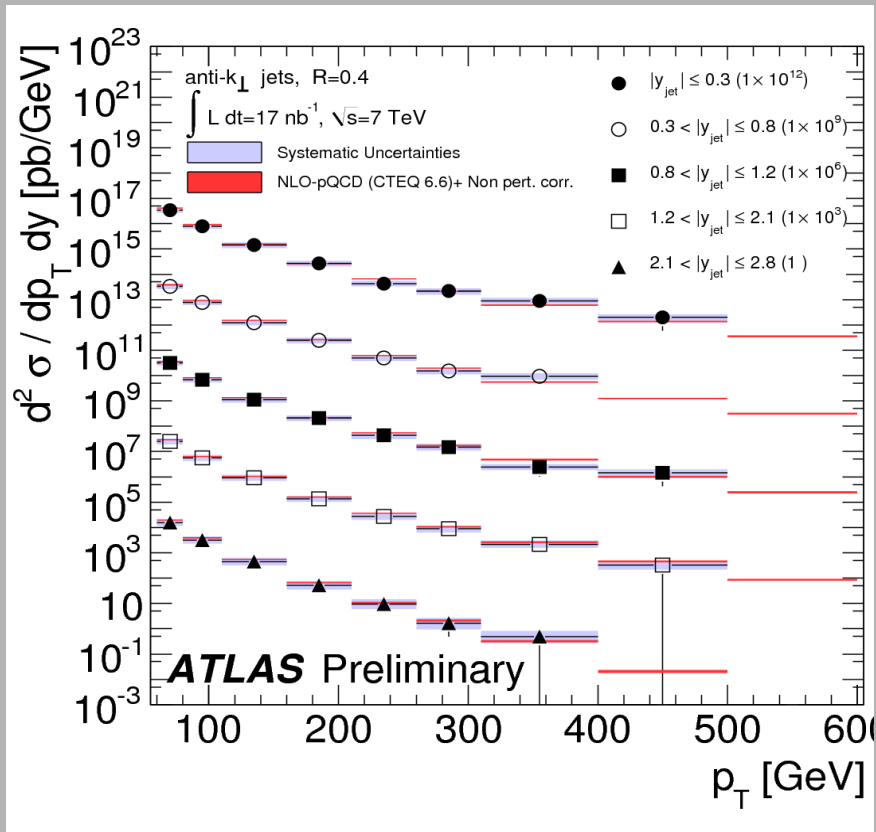
- LEP result from 2004
- e^+e^- collisions
- Look at
 - event shapes
 - $q\bar{q}gg$ final state
- Nice demonstration of consistency of data with SU(3)



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



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

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

Equation motivates commonly adopted approach of varying renormalisation and factorisation scale by $\frac{1}{2}$ and 2

Running of α_s

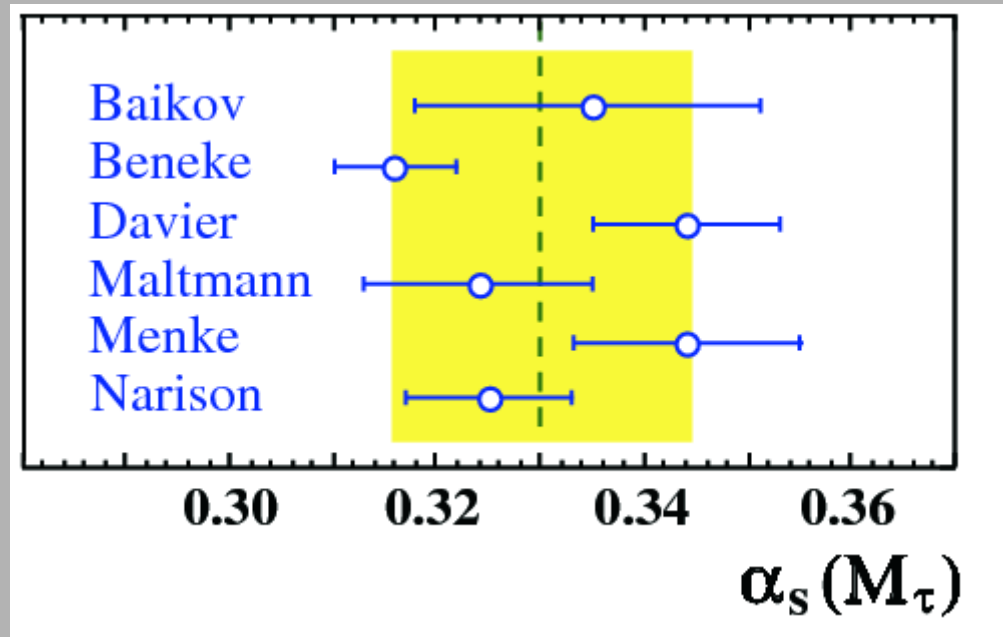
- Running coupling satisfies renormalisation group equation(RGE):

$$\begin{aligned}\mu^2 \frac{d \alpha_s}{d \mu^2} &= \beta(\alpha_s) = -(\beta_0 \alpha_s^2 + \beta_1 \alpha_s^3 + \beta_2 \alpha_s^4 + \dots) & C_F &\equiv (N_c^2 - 1)/(2N_c) = 4/3 \\ b_0 &= (11C_A - 4n_f T_R)/(12\pi) & C_A &\equiv N_c = 3 \\ &= (33 - 2n_f)/(12\pi) & T_R &= 1/2 \\ b_1 &= (153 - 19n_f)/(24\pi^2)\end{aligned}$$

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

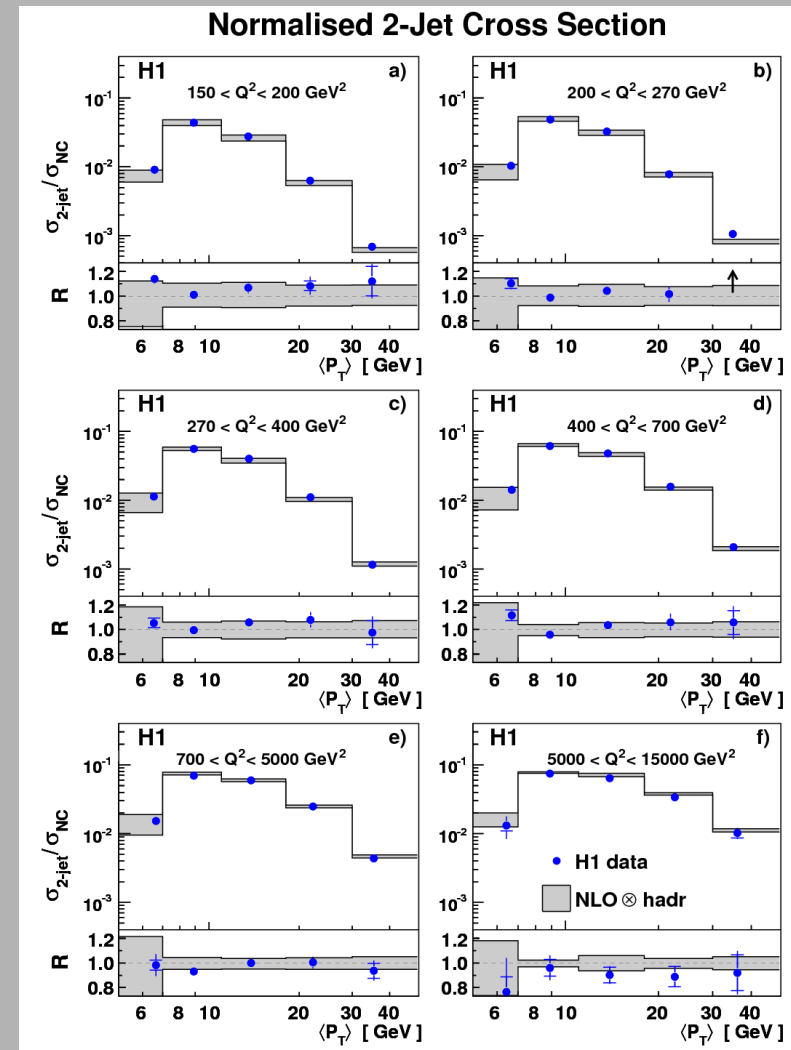
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2) \beta_0 \ln(Q^2/\mu^2)} \quad \text{or} \quad \alpha_s(Q^2) = \frac{1}{\beta_0 \ln(Q^2/\Lambda^2)}$$

α_S from τ measurements



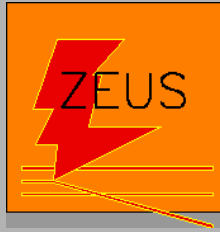
Jets at high Q^2

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

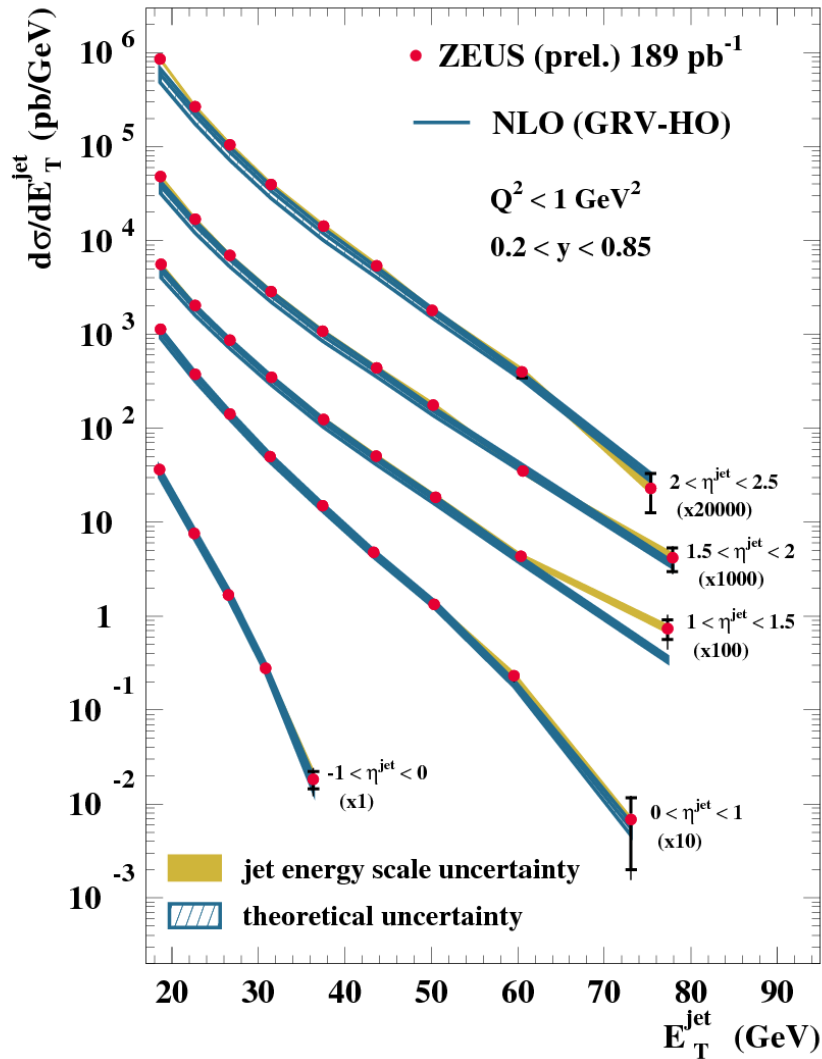


H1 Collab, Eur Phys J. C 65 (2010) 363

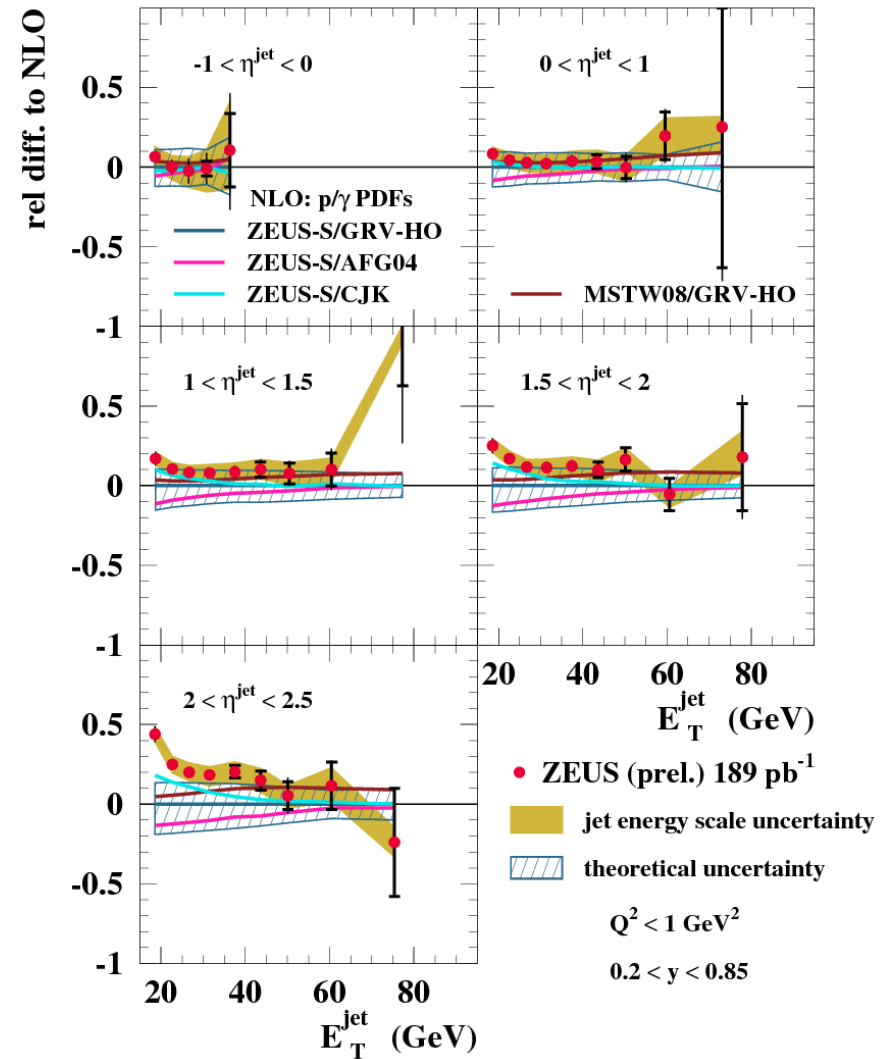
Jets in Photoproduction



ZEUS

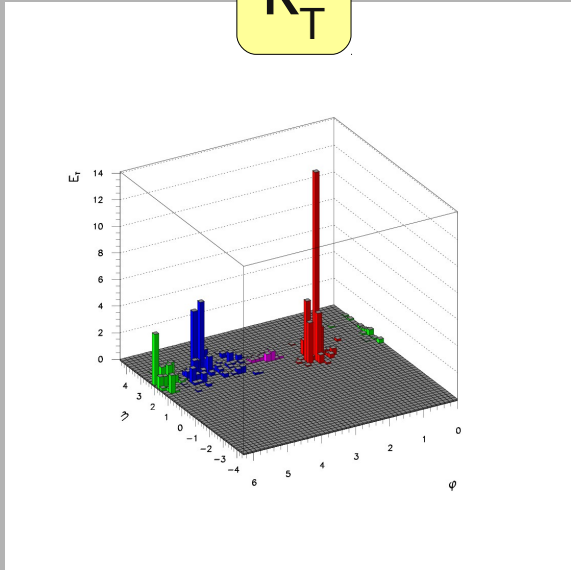


ZEUS

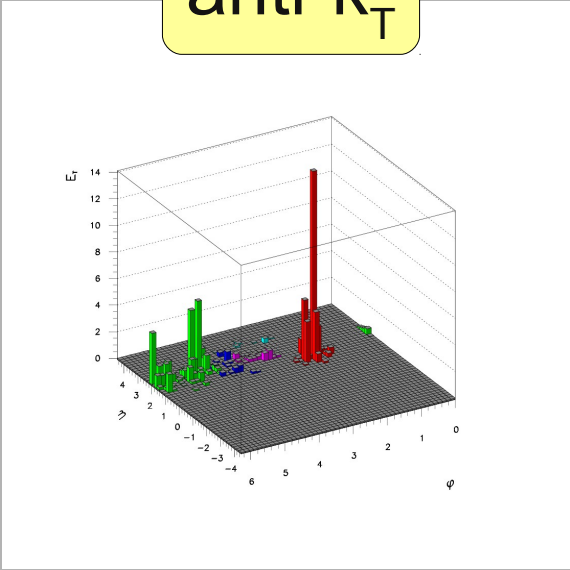


Jet algorithms

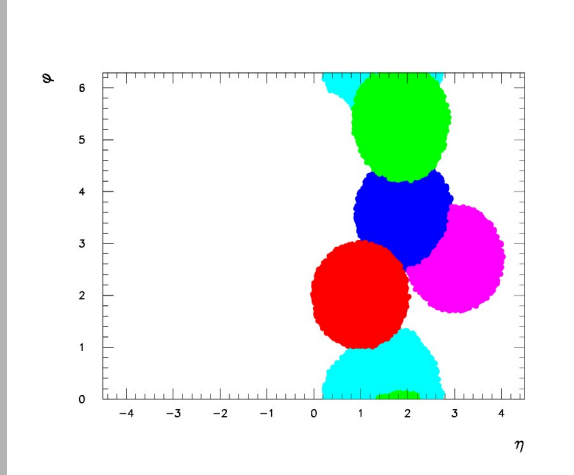
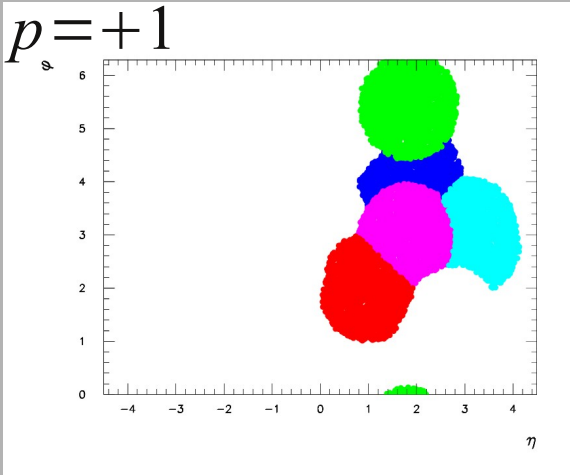
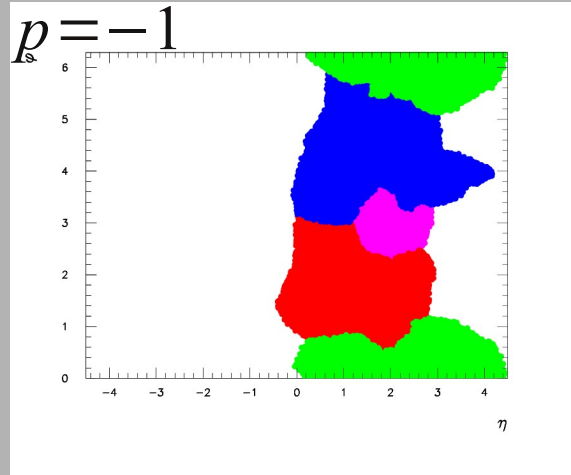
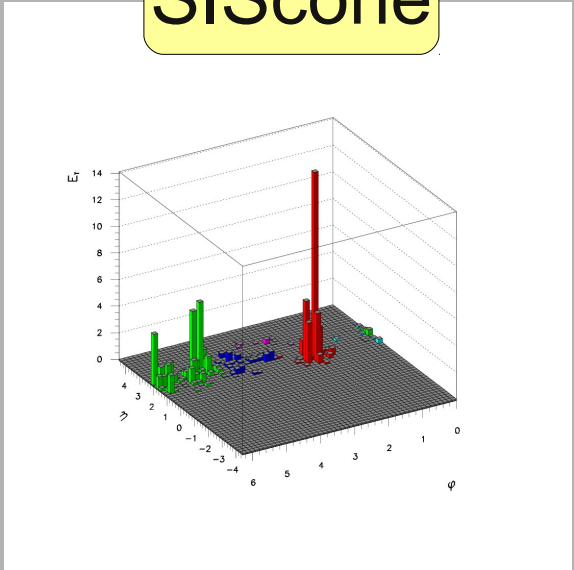
k_T



anti- k_T

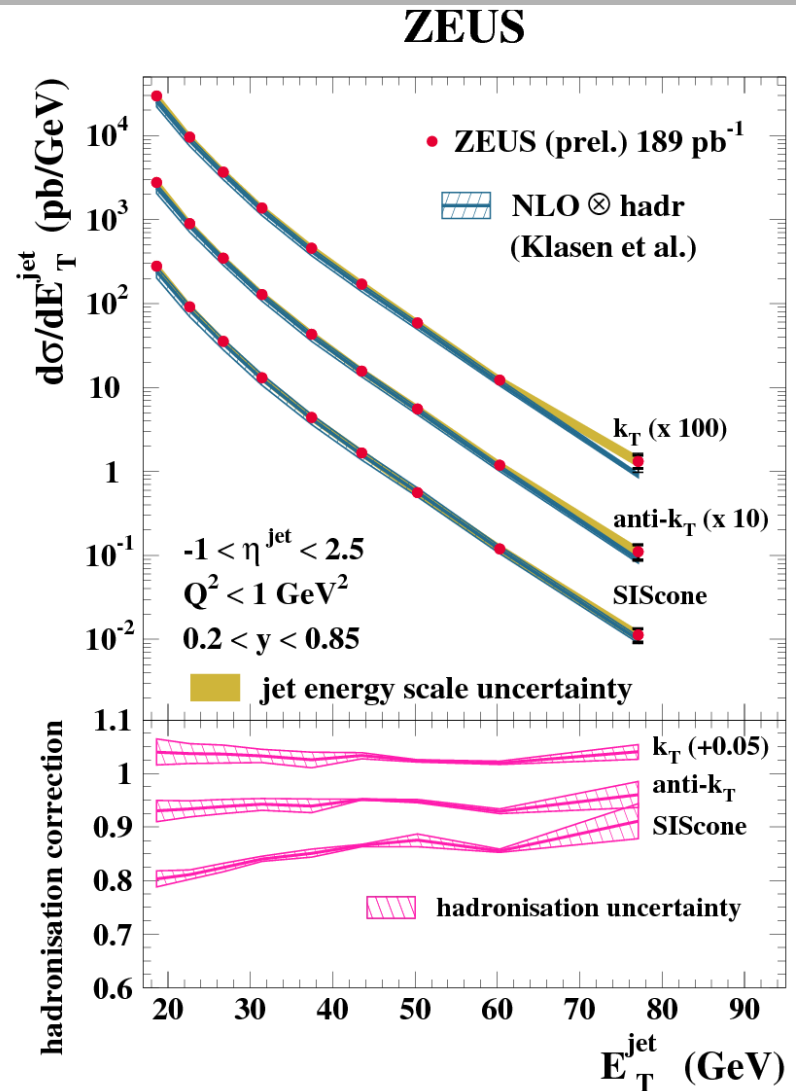
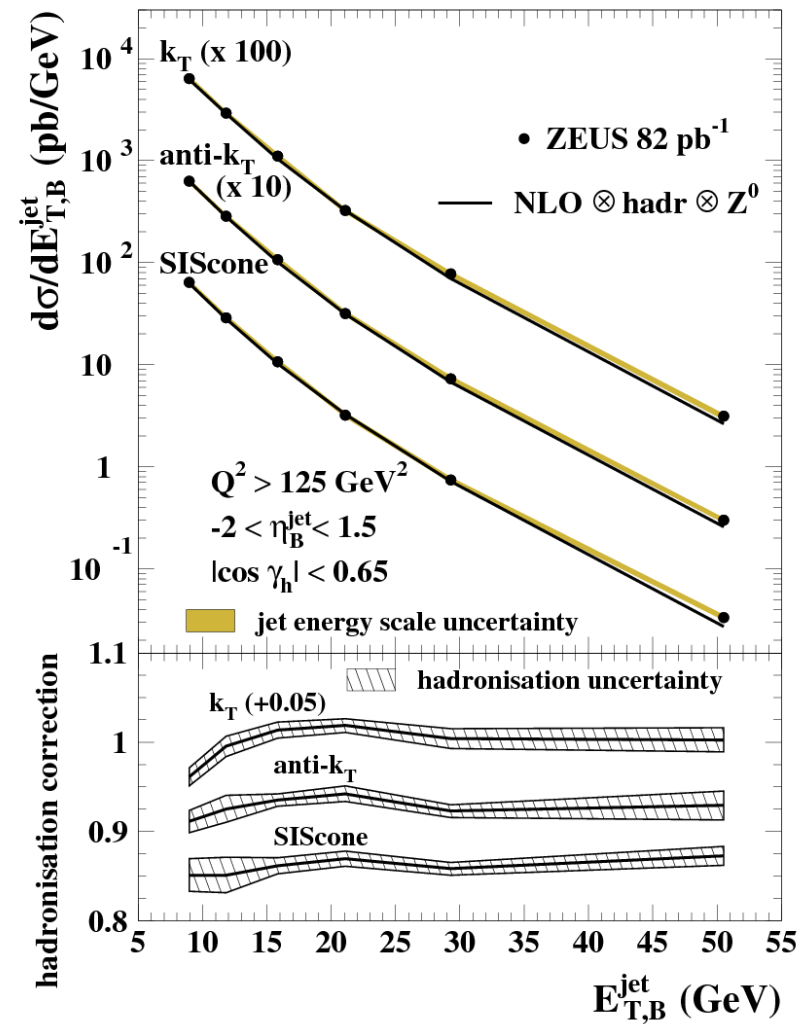


SIScone

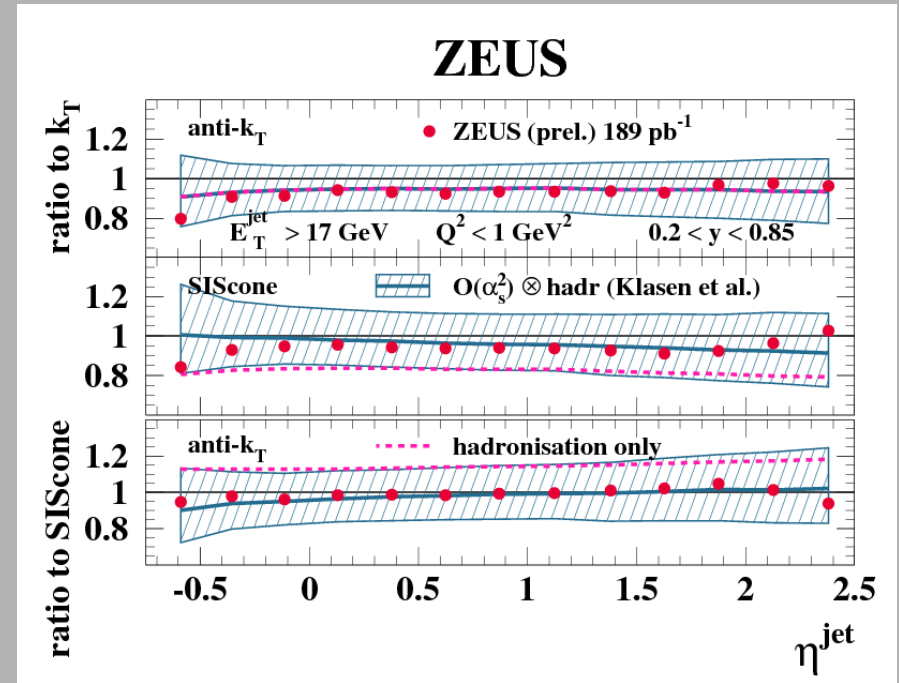
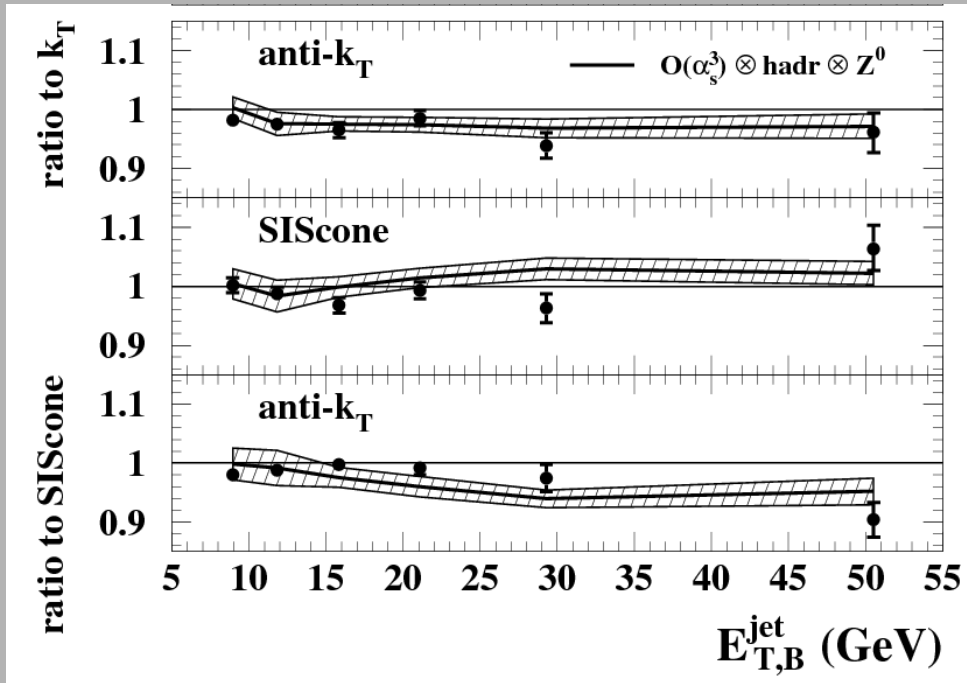


$$d_{ij} = \min[(E_T^i)^{2p}, (E_T^j)^{2p}] \Delta R^2 / R^2$$

Jet algorithms



Cross-section ratios



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