Jet production in deep inelastic scattering at HERA

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On behalf of the ZEUS and H1 Collaborations

Preface

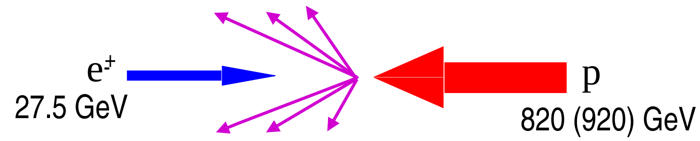
- The HERA collider provides a unique laboratory for the detailed study of the hadronic final state, bridging the gap between e^+e^- and $p\bar{p}$ colliders and completing the coverage of standard model QCD processes.
- It is important understand the QCD final state at HERA in order to maximise the physics potential both at current and future colliders.
- Now a large portfolio of precision jet measurements from HERA – only time to concentrate on a small sub-sample of the recent results.
- High precision data available at high E_T where non-perturbative contributions are small ➡ enables precision tests of our understanding of perturbative QCD.
- Allows the scale variation to be studied over many orders of magnitude in a single environment.

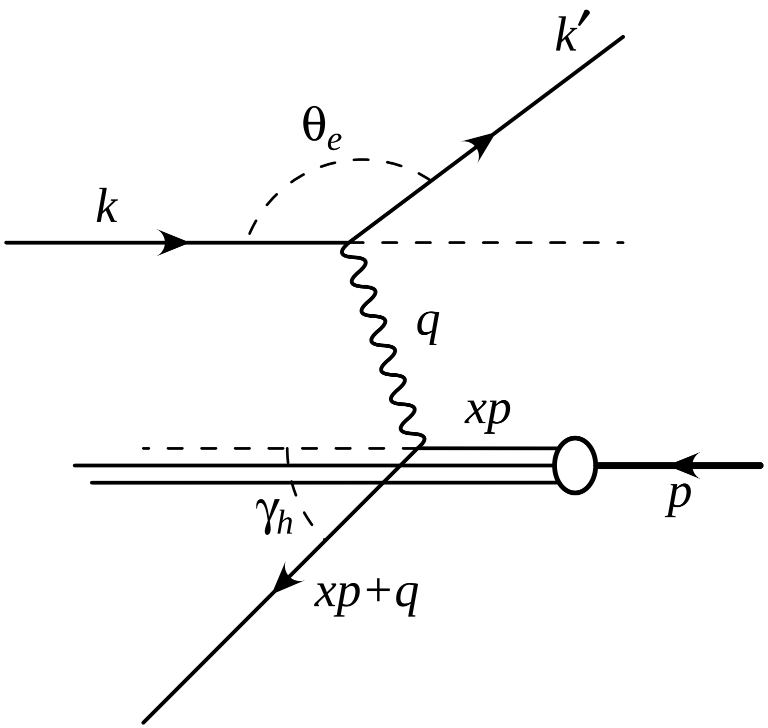
Overview

- Introduction.
- The QCD hard subprocess I - high Q^2,
  - ▷ Extraction of α_s.
  - ▷ Azimuthal asymmetry.
- The QCD hard subprocess II - towards lower Q^2,
  - ▷ Virtual photon structure.
- The QCD hard subprocess III,
  - ▷ Three-jet production in neutral current deep inelastic scattering.
  - ▷ Dijet measurements in charged current deep inelastic scattering.
- Conclusions.

HERA kinematics

- HERA: an ep collider, 27.5 GeV positrons (or electrons) with:
  - ▷ 1994-1997: 820 GeV protons, $\sqrt{s} = 300$ GeV
  - ▷ 1998-2000: 920 GeV protons, $\sqrt{s} = 318$ GeV





- Kinematic variables...
  - ▷ (Negative) squared 4-momentum transfer

$$Q^2 = -(k - k')^2.$$

  - ▷ Bjorken scaling variable

$$x \equiv \frac{Q^2}{2p.q}.$$

  - ▷ Inelasticity

$$y \equiv \frac{p.q}{p.k}.$$

- With ep invariant mass s given by

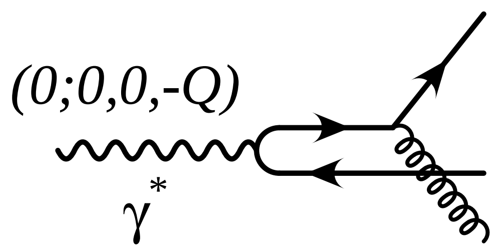
$$Q^2 = sxy.$$

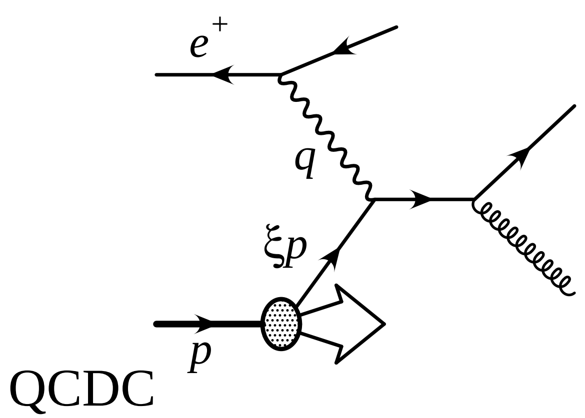
Jets in deep inelastic scattering

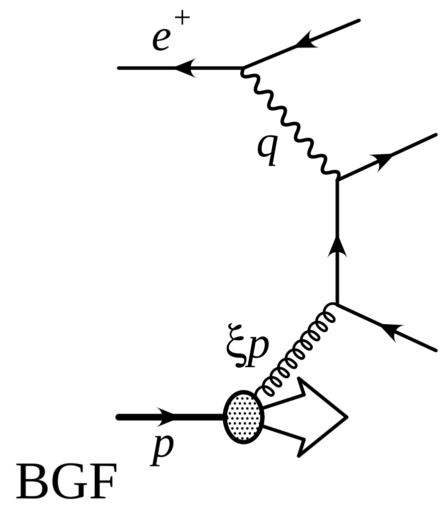
- Factorise jet cross-section into a convolution of PDF's in the proton, f_a, with short distance subprocess, $\mathrm{d}\hat{\sigma}_a$....

$$d\sigma_{\mathrm{jet}} = \sum_{a=q,\bar{q},g} \int \mathrm{d}x \; f_a(x,\mu_F^2) \; \mathrm{d}\hat{\sigma}_a(x,\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2) \times (1+\delta_{\mathrm{had}})$$

- Inclusive jets in LAB frame only $\mathcal{O}(\alpha\alpha_s^0)$ at LO.
- Both inclusive-jet and dijet production with high E_T in the BREIT frame, $\mathcal{O}(\alpha\alpha_s)$ at LO. ⇒ directly sensitive to QCD subprocess and the gluon density in the proton.

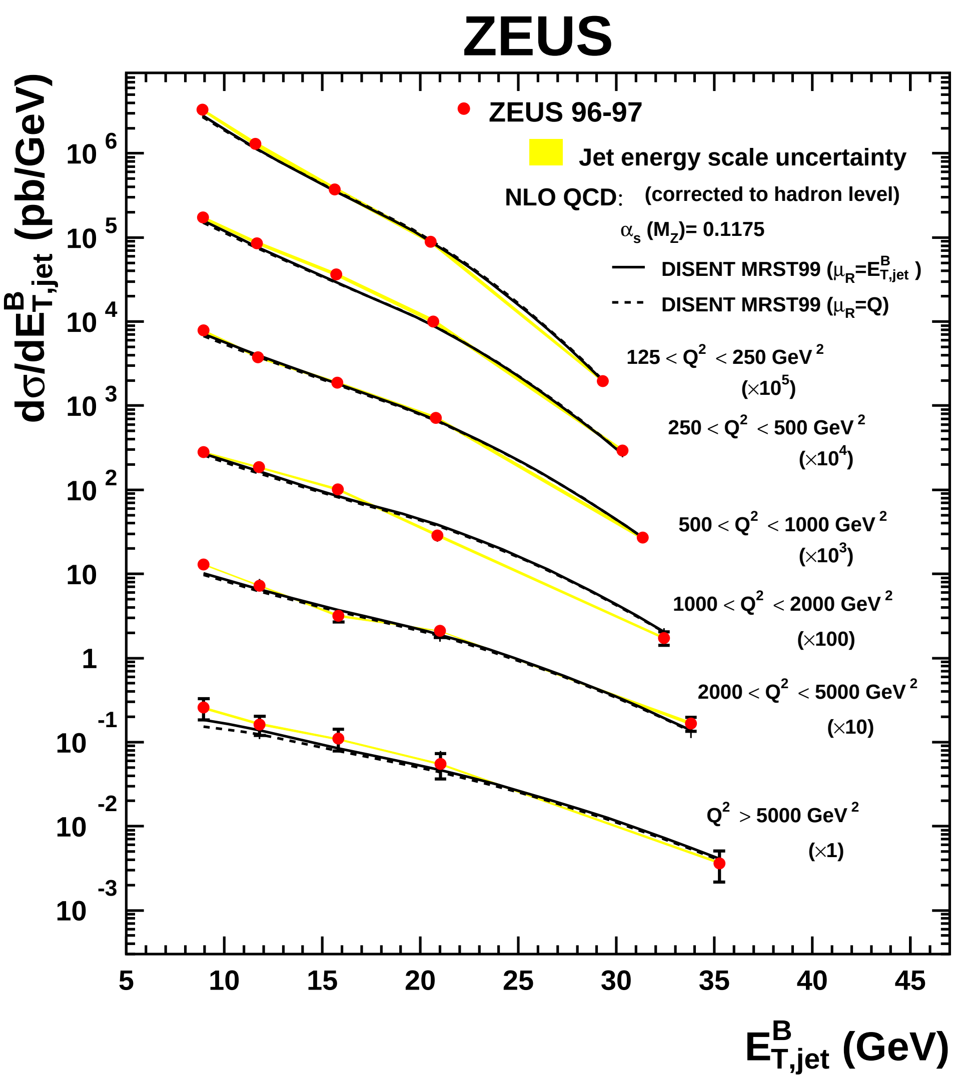






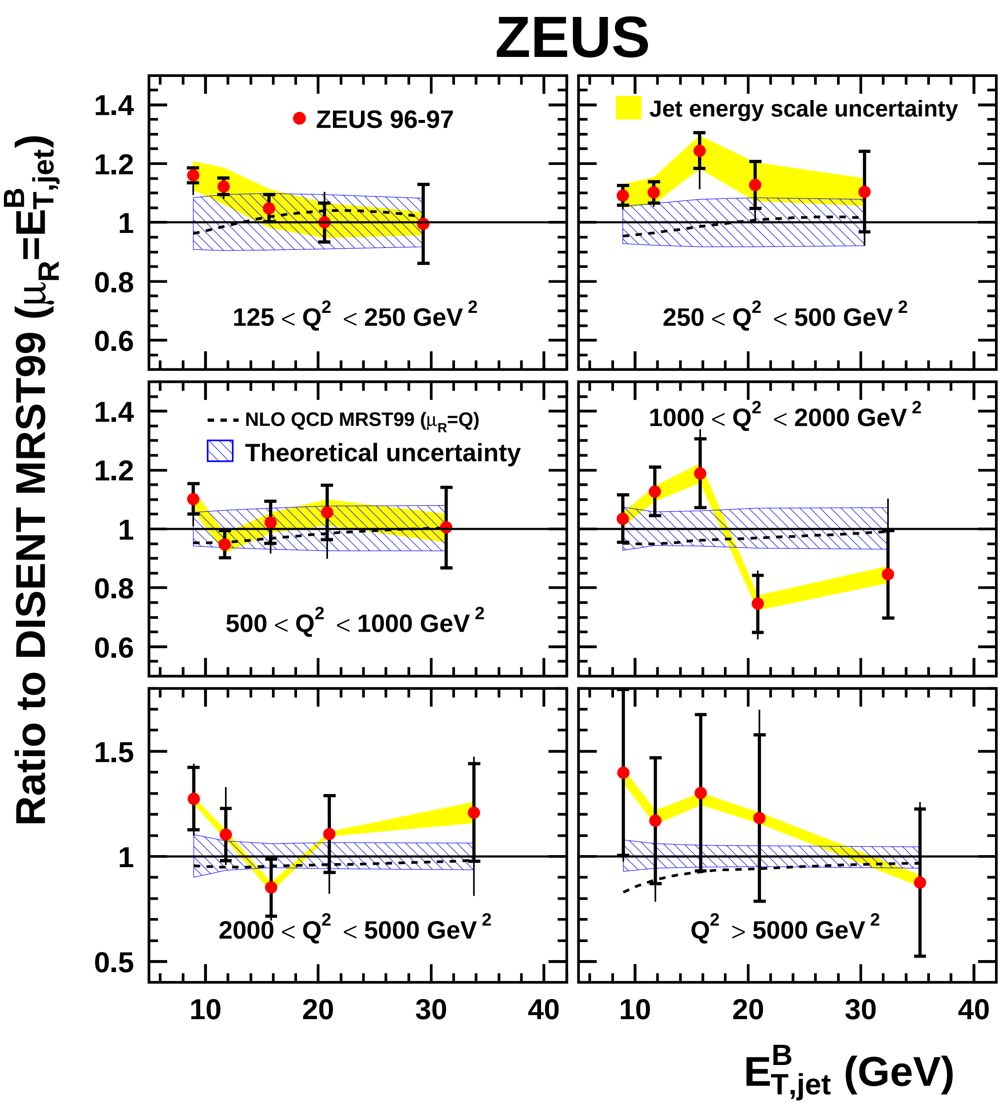
- Large scale variation possible in both Q^2 and E_T ⇒ what is the appropriate scale?

The QCD suprocess I - high Q^2



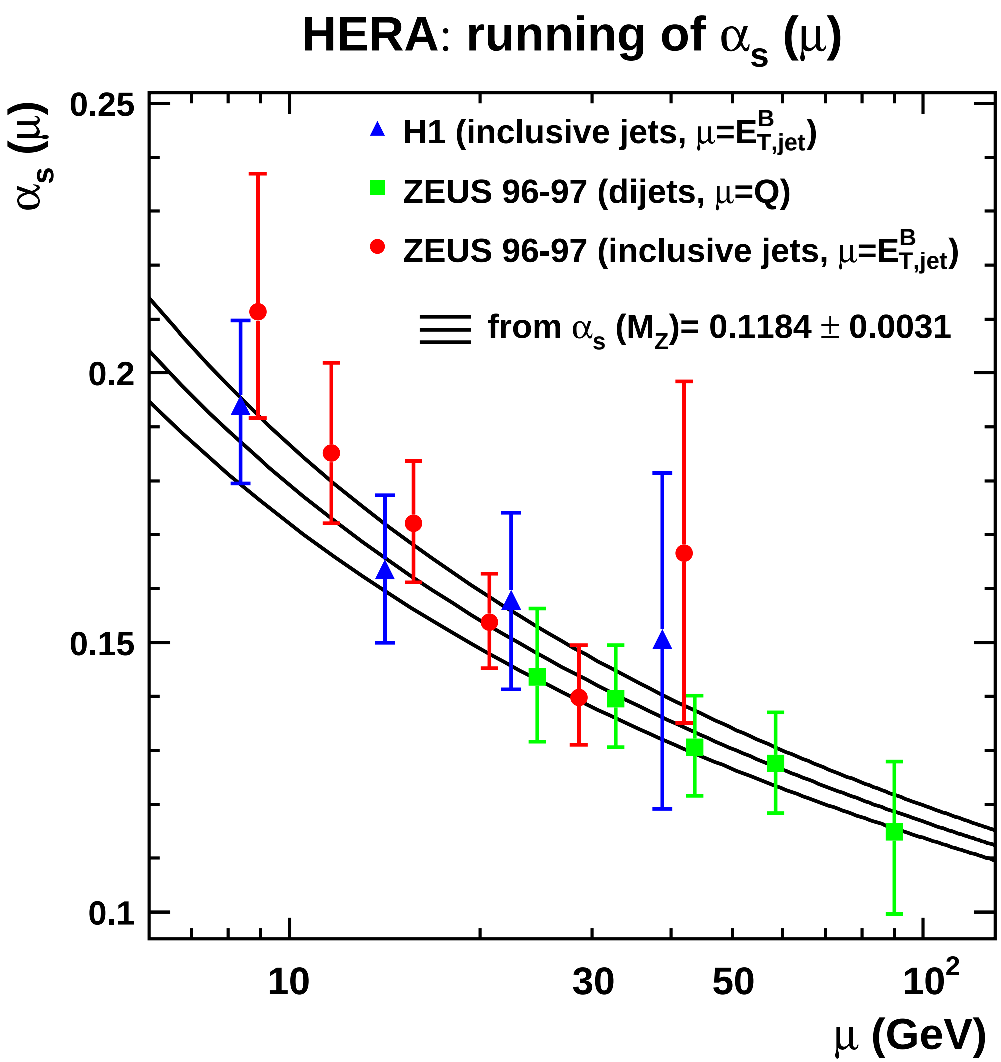
- High $Q^2 > 125\ \text{GeV}^2$
- Inclusive jet cross sections measured in the Breit frame in DIS.
  $$E^{\rm B}_{T,\rm jet} > 8\text{GeV}, \quad -2 < \eta^{\rm B}_{\rm jet} < 1.8$$
- Precision test of our understanding of perturbative QCD
- Agreement with NLO QCD prediction over many orders of magnitude in both Q^2 and $E^{\rm B}_{T,\rm jet}$.

Inclusive jet production (contd.)



- The hatched band shows the NLO scale uncertainty for, $E^B_{T,\text{jet}}/2 < \mu_R < 2E^B_{T,\text{jet}}$.
- At low Q^2 and $E^B_{T,\text{jet}}$, the data are above the predictions of NLO QCD.
- Overall, reasonable agreement within the experimental and theoretical uncertainties ⇒ extraction of the QCD coupling α_s.

Extraction of the QCD coupling – α_s



- Clear running observed with jet E_T.
- H1 value for $150 < Q^2 < 5000\,\mathrm{GeV}^2$,

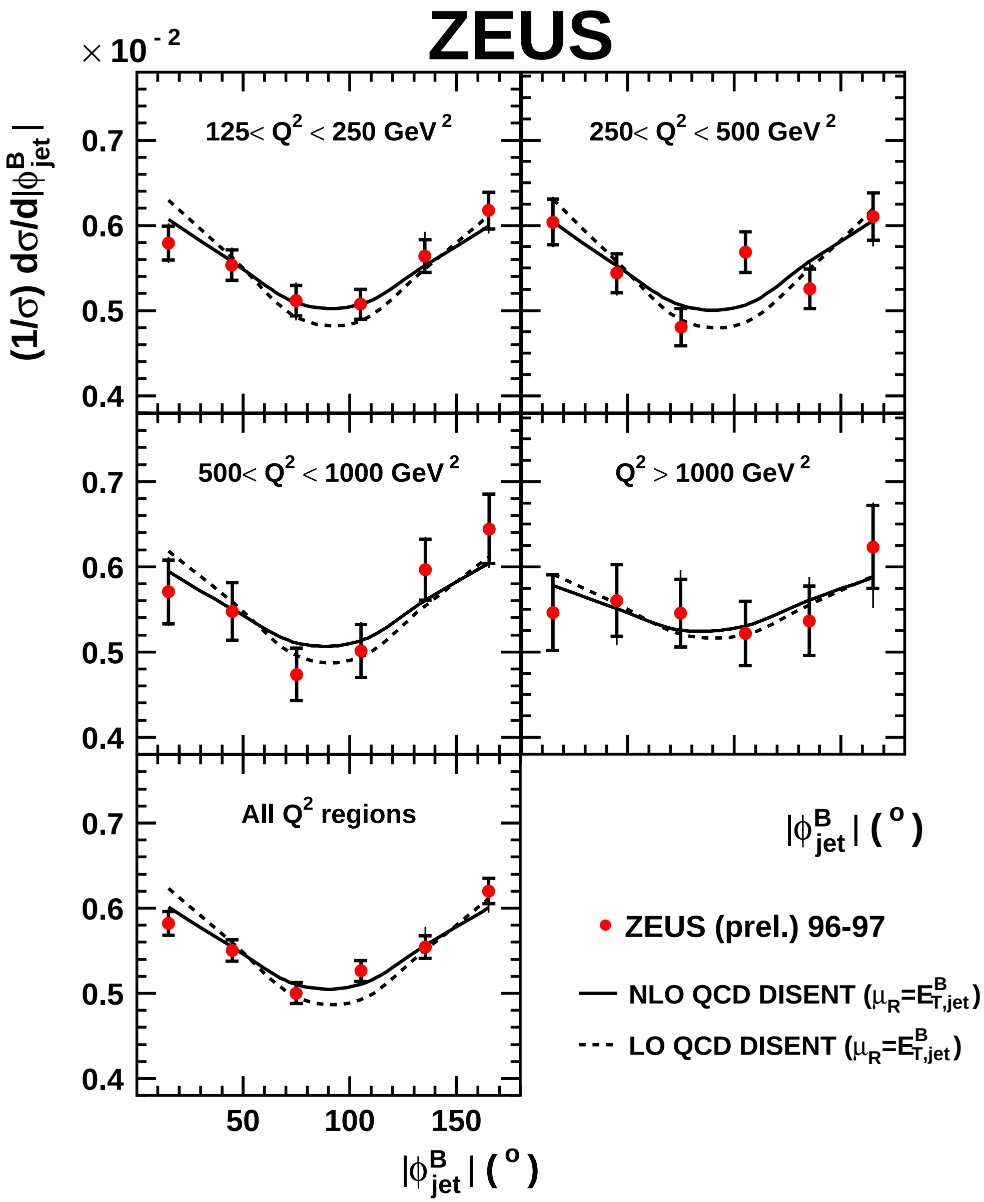
$$\alpha_s(M_Z) = 0.1186 \pm 0.0030(\mathrm{exp.})^{+0.0039}_{-0.0045}(\mathrm{th.})^{+0.0033}_{-0.0023}(\mathrm{pdf})$$

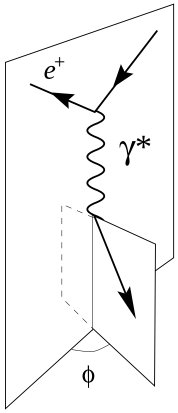
- ZEUS value for high $Q^2 > 500\ \mathrm{GeV}^2$,

$$\alpha_s(M_Z) = 0.1212 \pm 0.0017(\mathrm{stat.})^{+0.0023}_{-0.0031}(\mathrm{syst.})^{+0.0028}_{-0.0027}(\mathrm{th.})$$

- Dominant uncertainty from theory.
- Precision comparable with best measurements from elsewhere.

Jet azimuthal asymmetry





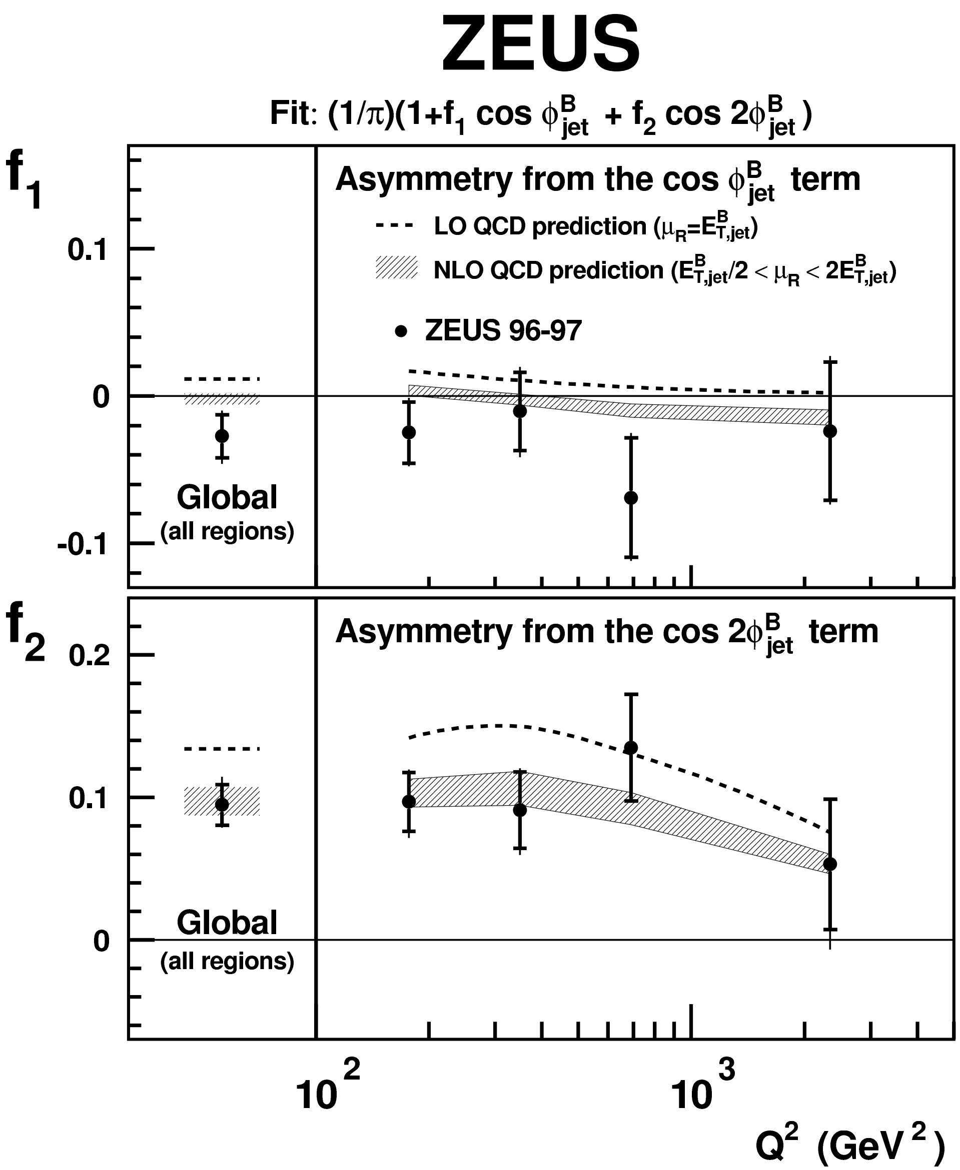
- Angle of jet, ϕ in Breit frame with respect to positron scattering plane,
- Distribution of the form

$$\frac{d\sigma}{d\phi} = A + B\cos\phi + C\cos 2\phi$$

predicted by perturbative QCD.

- Azimuthal dependence largely from the BGF process ⇒ expect Q^2 dependence.
- NLO predictions in agreement with data, decreasing asymmetry with increasing Q^2.
- Asymmetry in jet production observed for the first time in hadronic collisions.

Jet azimuthal asymmetry (contd.)

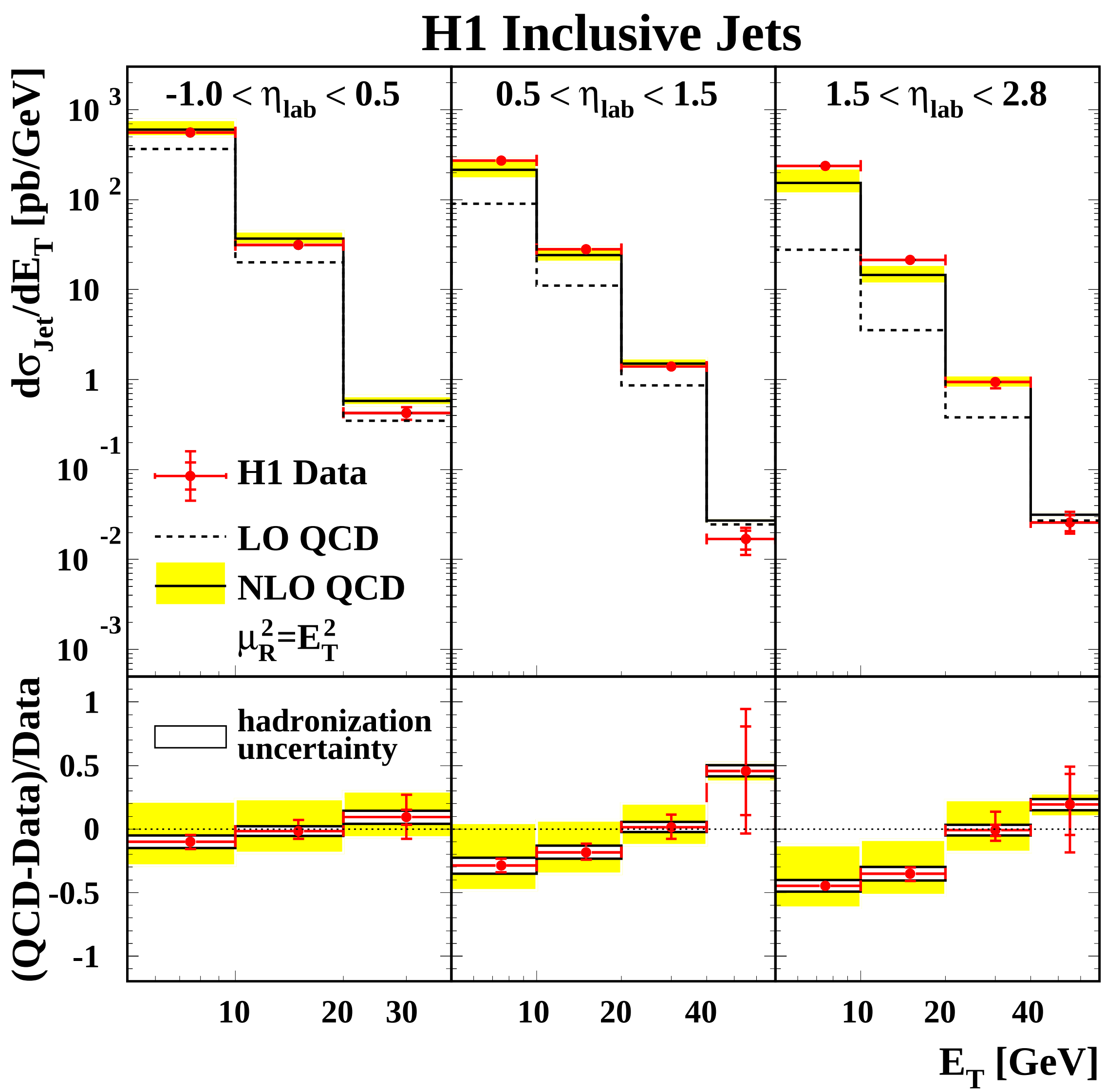


- Asymmetry fitted with functional form

$$\frac{1}{\sigma}\frac{d\sigma}{d\phi^{\rm B}_{\rm jet}} = \frac{1}{\pi}(1 + f_1 \cos\phi^{\rm B}_{\rm jet} + f_2 \cos 2\phi^{\rm B}_{\rm jet}).$$

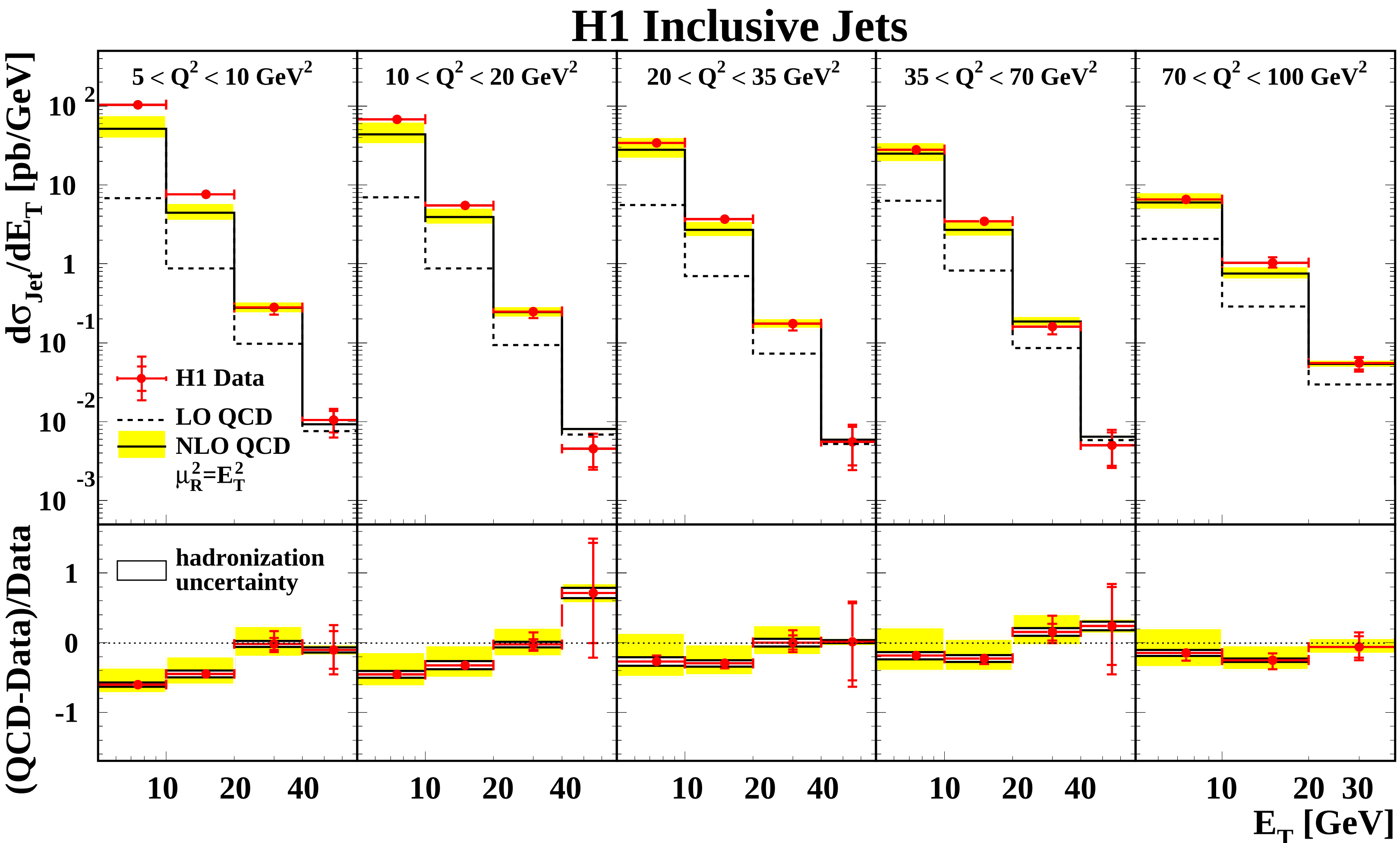
- Fit also for LO and NLO QCD predictions from DISENT.
- Large uncertainty in data ⇒ observed Q^2 dependence not conclusive.
- NLO clearly favoured by the data.

The QCD subprocess II – towards lower Q^2



- Low Q^2 region, $5 < Q^2 < 100\ \text{GeV}^2$
- Standard NLO calculation (DGLAP parton-density evolution).
- NLO corrections large for low E_T and forward η_{lab}.
- Reasonable agreement for backward η_{lab}.
- For forward η_{lab} and low E_T, theory lies below data.

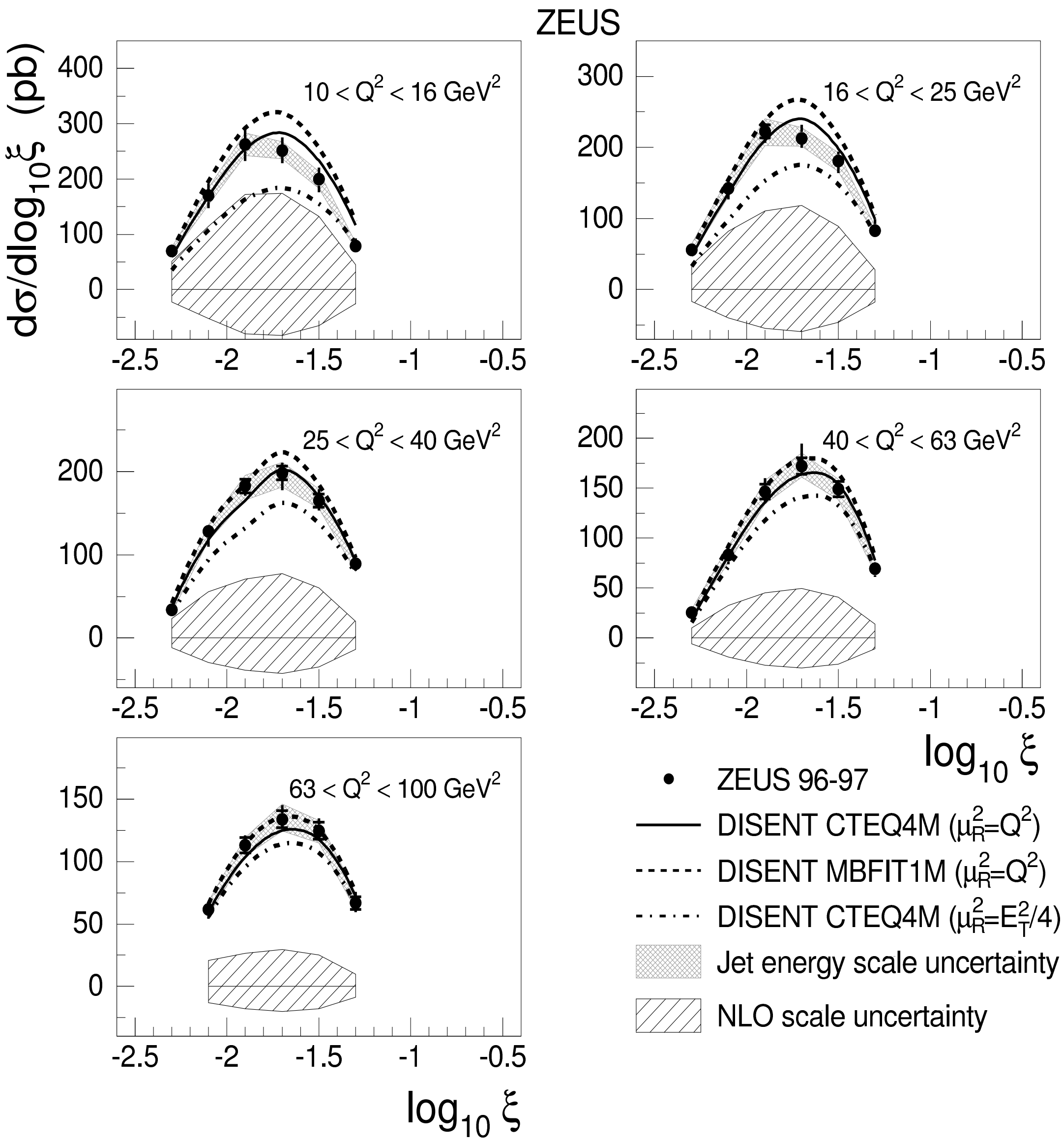
Inclusive jet production – forward region



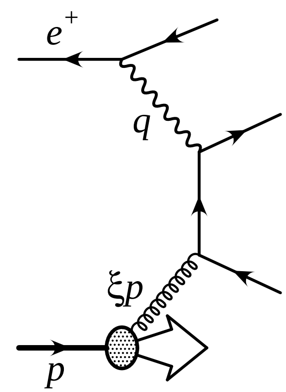
- Examine forward region, $1.5 < \eta_{\mathrm{lab}} < 2.8$.
- Discrepancy between data and NLO large at low Q^2 and low E_T.

  ⇒ what are contributions from uncertainty on the gluon in the proton? virtual photon structure? alternative evolution schemes (CCFM, BFKL)?

Dijet production – gluon density in the proton at low Q^2



- Fraction of the proton momentum entering dijet subprocess related to

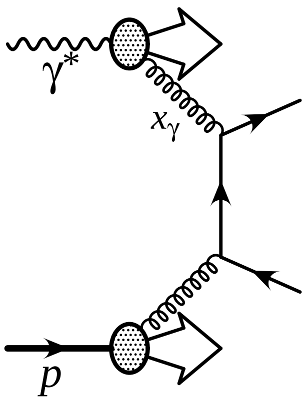


$$\xi \equiv x\left(1 + \frac{M_{\rm jj}^2}{Q^2}\right)$$

- For higher Q^2, NLO predictions similar, gluon is less significant.
- At lower Q^2, small experimental uncertainties, larger sensitivity to the gluon.
- Scale uncertainty is large ⇒ precludes accurate extraction at low Q^2.

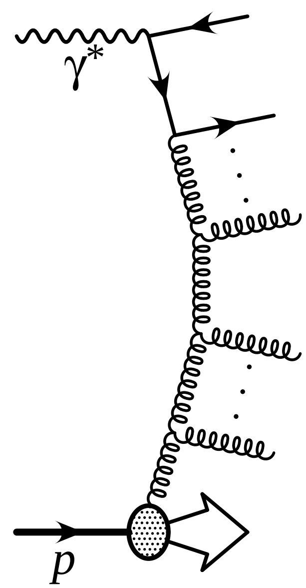
Low Q^2 and virtual-photon structure

- In dijet production, several mechanisms may play a rôle at very low Q^2.

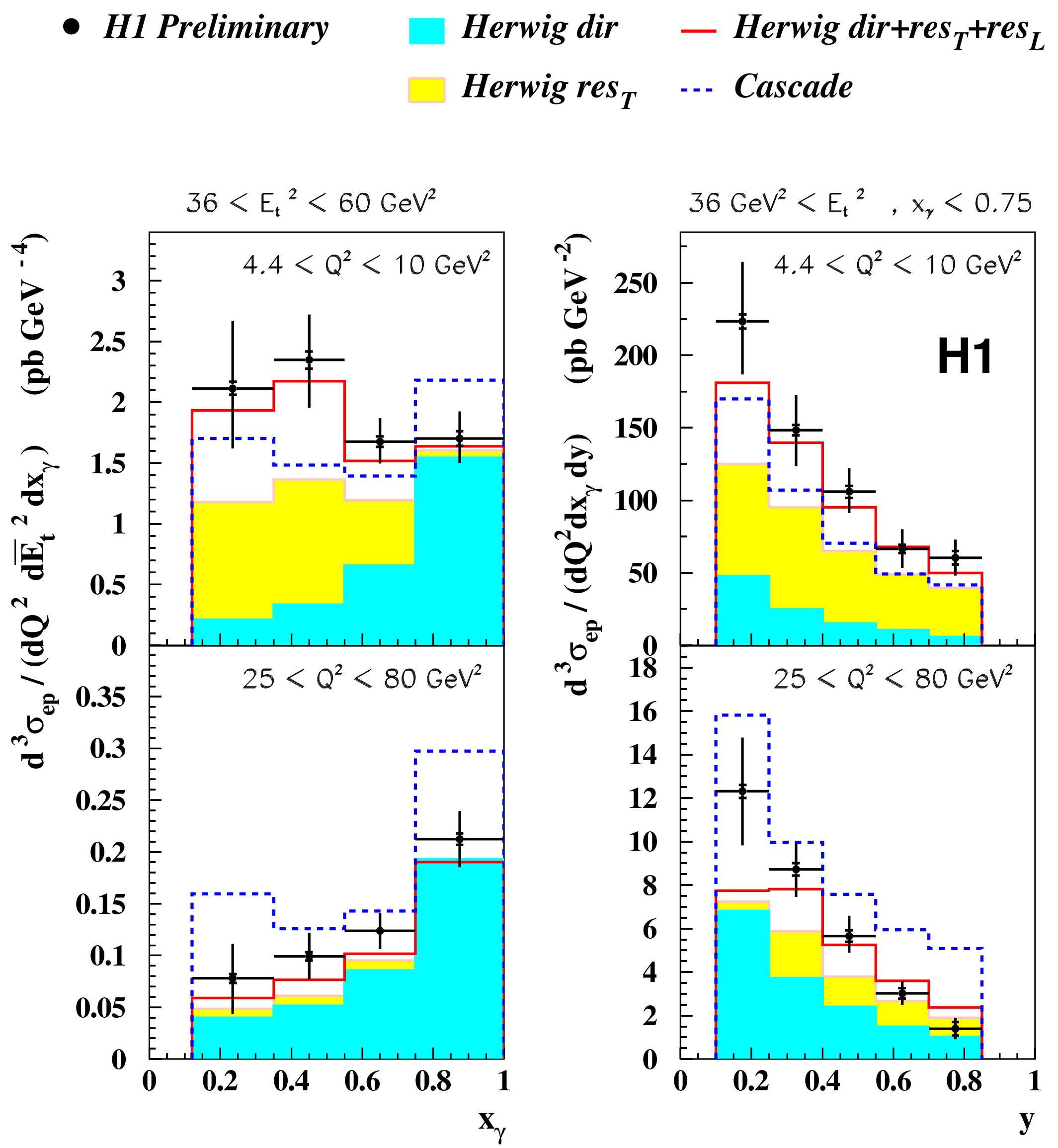


- Formally, when $Q^2 < E_T^2$ photon can be considered to have "resolved" structure ⇒ Photon can interact directly or via a parton from the photon with some fraction $x_\gamma < 1$ of the photon momentum.
- Possible contribution from longitudinally-polarised "resolved" photons ⇒ vanishes as $Q^2 \to 0$ and $y \to 1$.

- Unordered parton evolution, for example CCFM (Cascade), allows the two highest E_T jets in an event to come from anywhere along the ladder
⇒ Qualitatively similar to resolved photon picture, but without explicit photon structure.

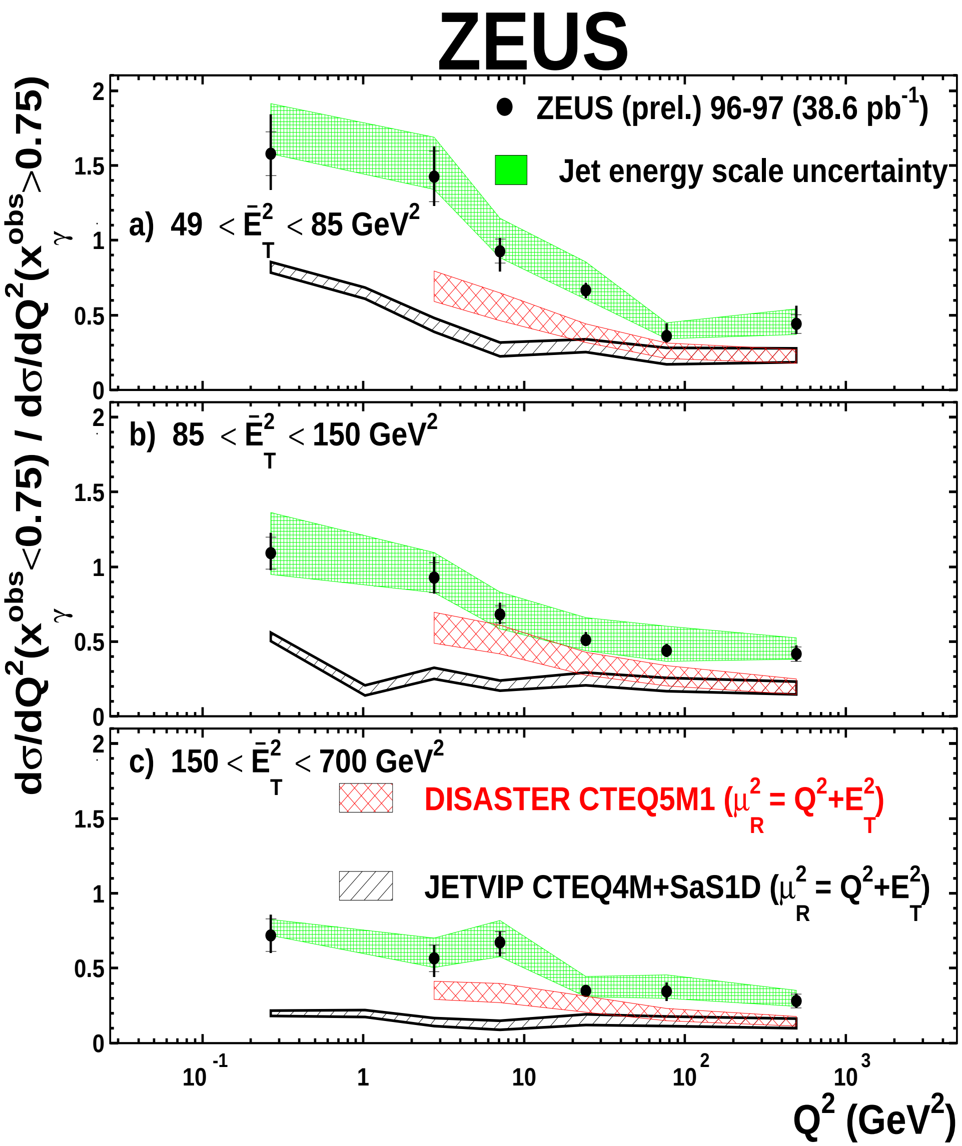


Virtual photon structure



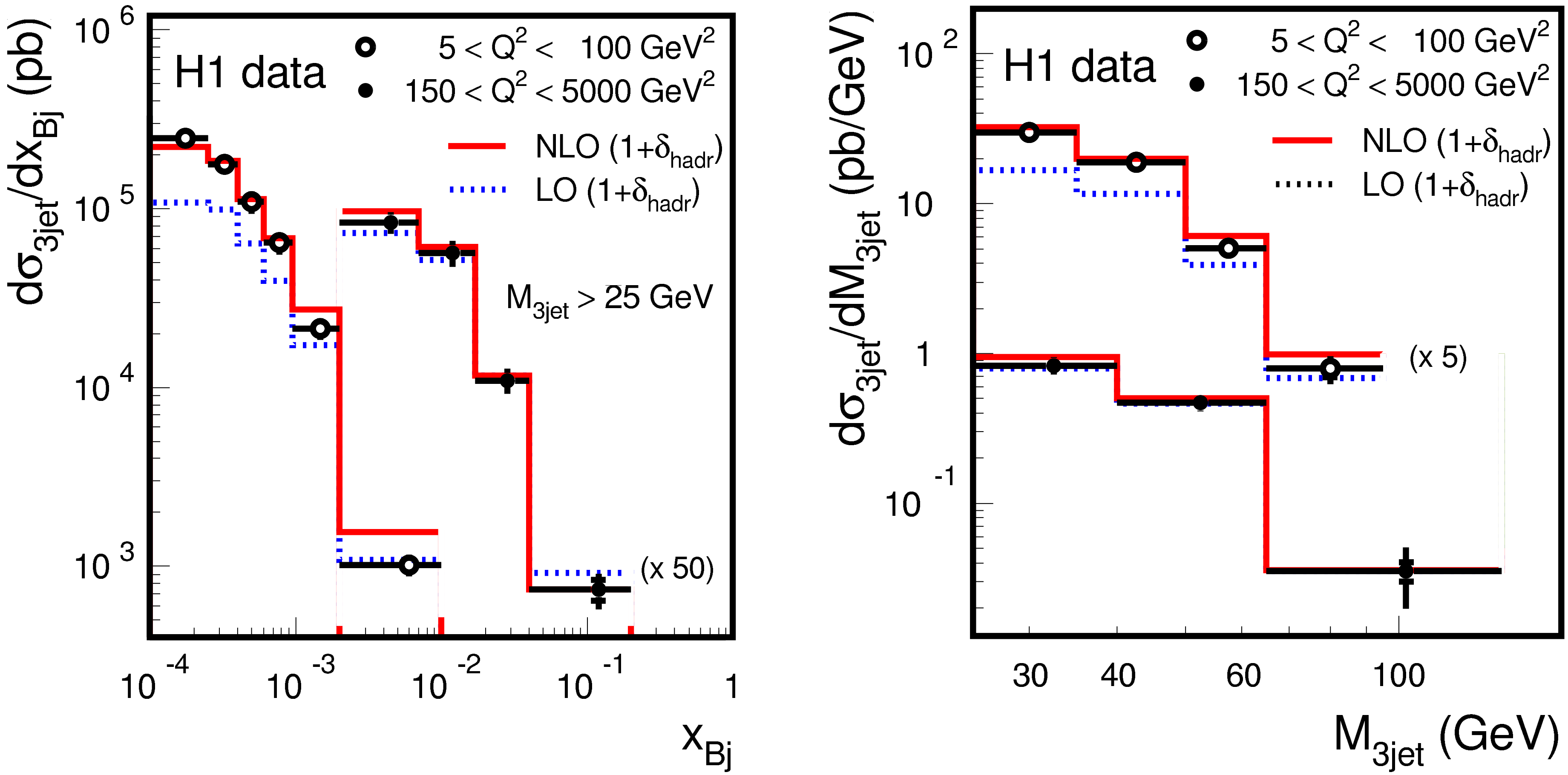
- Data suggest "resolved" component necessary at low Q^2 or when average jet transverse energy, $\bar{E}_T$ is large.
- Leading-order resolved component alone is not adequate.
- Longitudinal resolved photon contribution improves the description.
- Unordered CCFM parton cascade with no resolved photon (Cascade) predicts higher contribution.
- Need NLO comparison...

Virtual photon structure – comparison with NLO theory



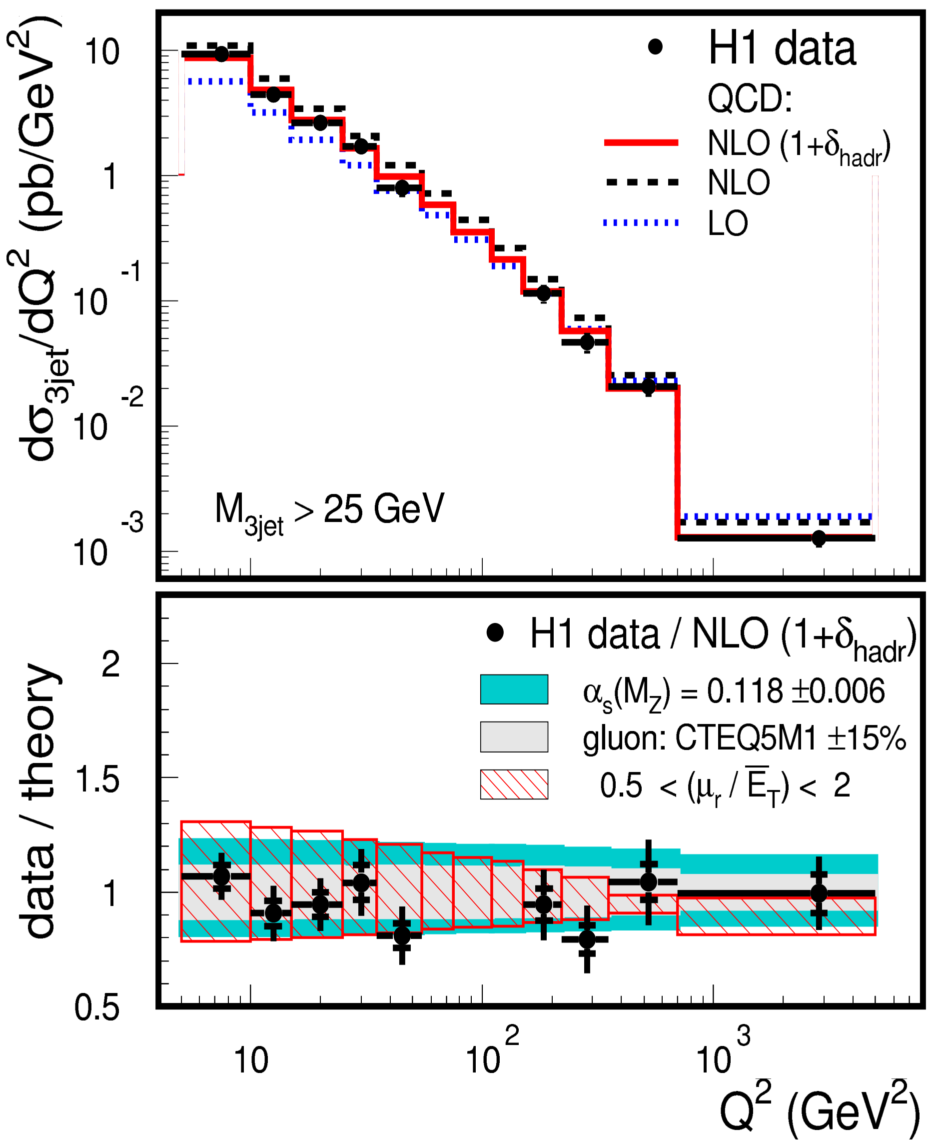
- DISASTER ⇒ NLO DIS no resolved photon.
- DISASTER ratio too low at lower Q^2.
- JetVIP ⇒ Only NLO calculation with resolved virtual photon.
- Expect larger resolved fraction when including resolved virtual photon.
- JetVIP larger direct-enhanced cross section ⇒ even lower fraction.
- Need additional NLO calculations.

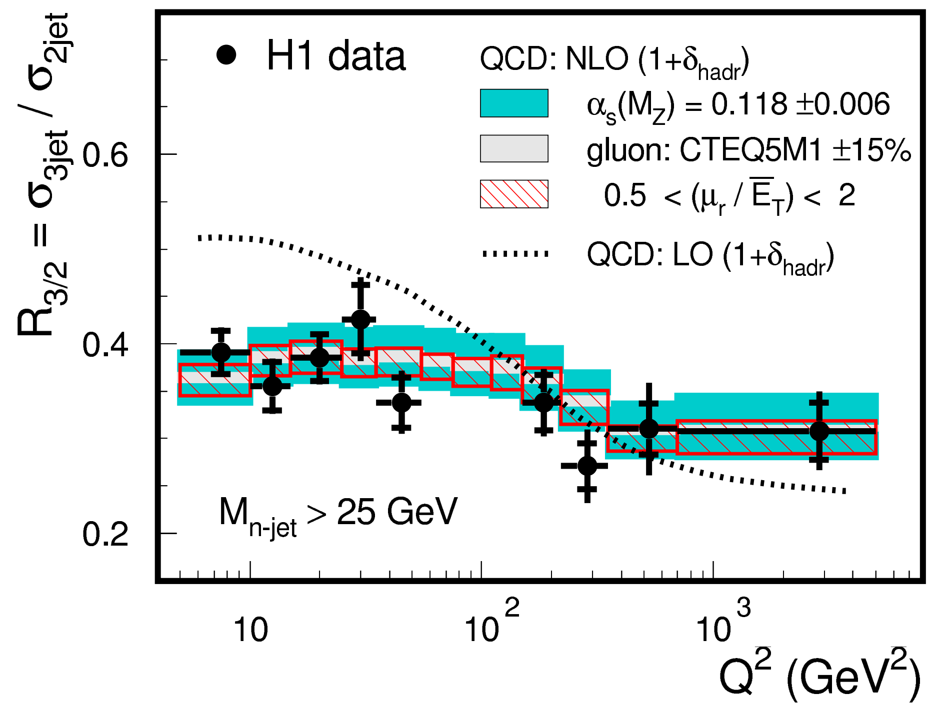
The QCD subprocess III – Three jet production



- Three-jet cross sections in the Breit frame ➡ $\mathcal{O}(\alpha\alpha_s^2)$ process at leading order, $5 < Q^2 < 5000\ \mathrm{GeV}^2$, $-1 < \eta_{\mathrm{lab}} < 2.5$, $M_{\mathrm{3jet}} > 25\ \mathrm{GeV}$
- First comparison with NLO, $\mathcal{O}(\alpha\alpha_s^3)$ calculation ➡ Good agreement over entire phase space region.

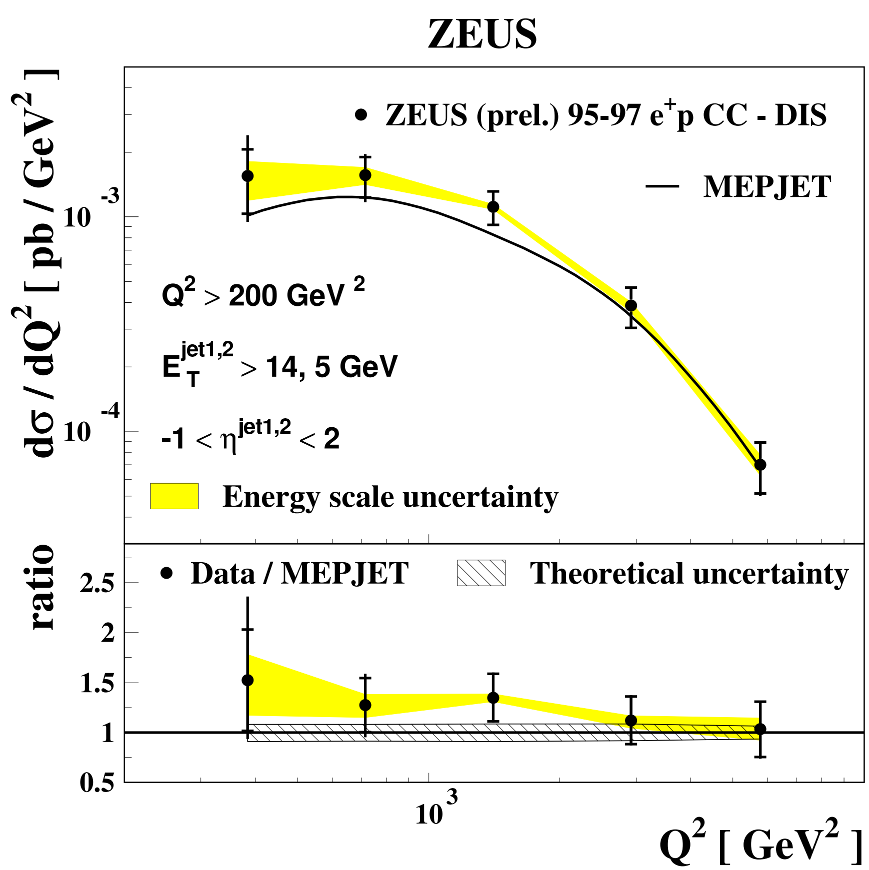
Three jet production – three-to-two jet rate

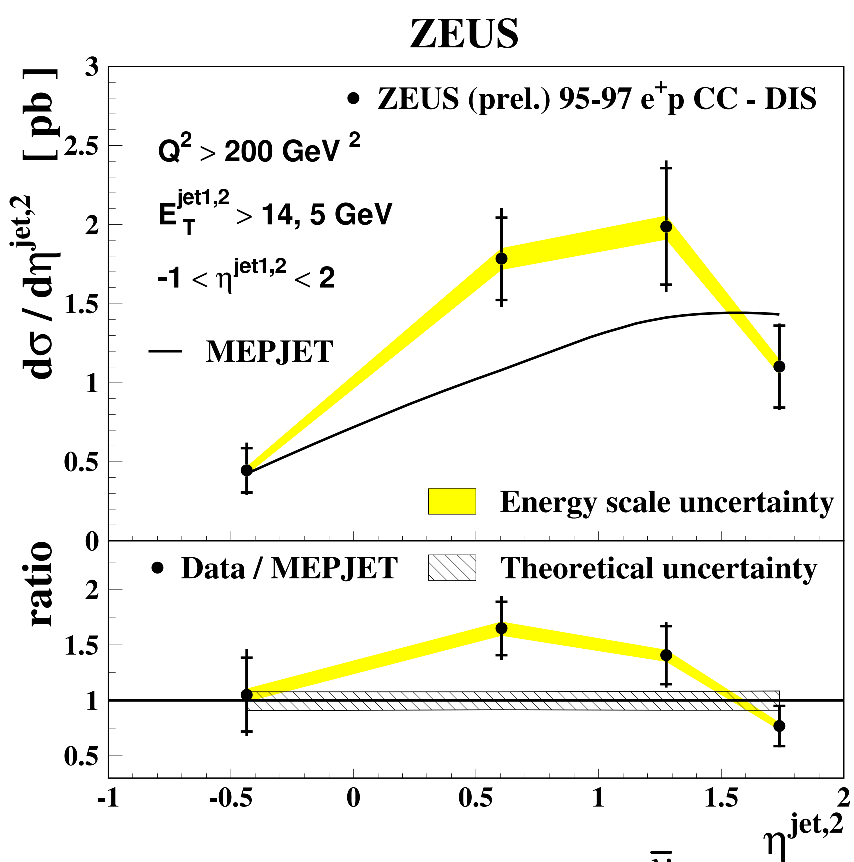




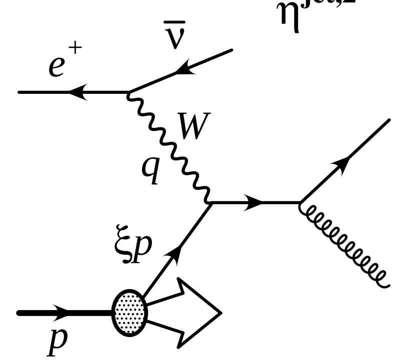
- $R_{3/2}$ ratio of three to two jet cross sections.
- Large NLO corrections, Good agreement between data and NLO calculation.
- Reduced uncertainties and gluon in the proton and renormalisation scale.
- Interesting prospects for extraction of α_s.

Charge current dijet production





- Dijet production in charged current DIS ➡ test of QCD with flavour changing matrix element.
- Comparison with NLO (MEPJET), still dominated by experimental uncertainties, but discrepancy in central pseudorapidity region.



Summary and Outlook

- HERA continues to produce a wealth of precision jet data at high E_T in deep inelastic scattering.
- Scale variation studied over many orders of magnitude in a single environment.
- The QCD coupling constant, α_s, has been extracted with a statistical precision competitive with the world average.
- Theoretical uncertainties now dominate over most of the kinematic range. ➡ what is the appropriate scale, Q^2, E_T^2? Higher order or resummed calculations needed.
- NLO corrections and scale uncertainty large at low Q^2, and in the forward direction. Contribution from resolved photon at lower Q^2 not yet clear.
- NLO QCD is able to describe the data at higher Q^2 over many orders of magnitude.
- Look forward to meeting the challenge of the precision study of QCD at even higher scales with the upgraded HERA machine.