The Hadronic Final State and Parton Dynamics at HERA

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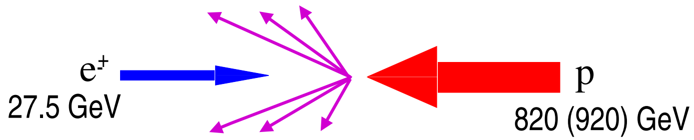
On behalf of the ZEUS and H1 Collaborations

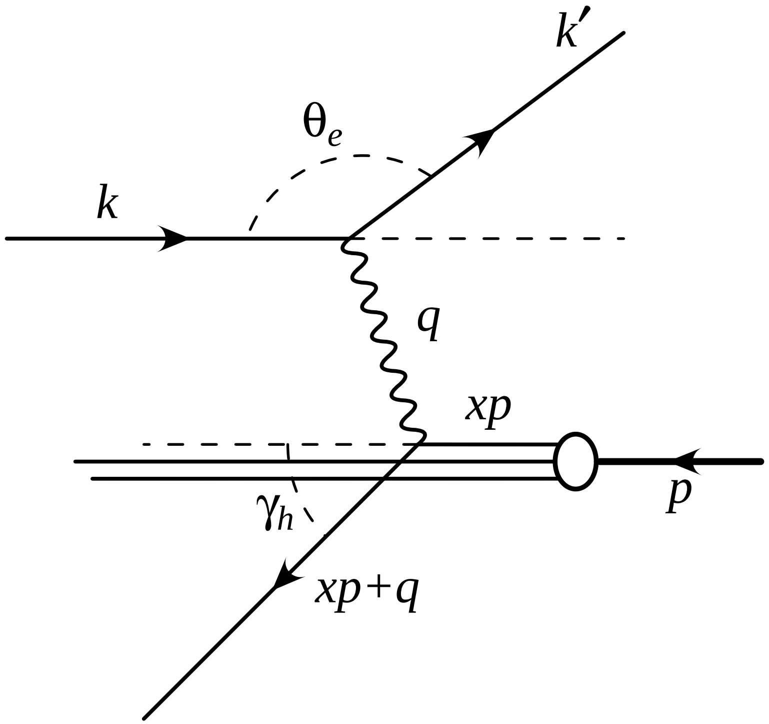
By way of introduction...

- The HERA collider provides a unique laboratory for the study of the hadronic final state.
- High transverse energy jet data are now very precise, typically experimental systematic uncertainties are below 5% and non-perturbative effects are small...
  - ▷ Precision tests of our understanding of QCD.
  - ▷ Where theoretical uncertainties are small, allows extraction of QCD parameters.
  - ▷ Constraints on proton parton distribution functions.
- Study sub-processes directly proportional to α_s.
- Explore low Q^2 transition region, and processes where alternative parton evolution schemes may apply ➡ only briefly alluded to here, for even more details see talk by Didar.

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





- (Negative) squared 4-momentum transfer

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

- Bjorken scaling variable

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

- Inelasticity

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

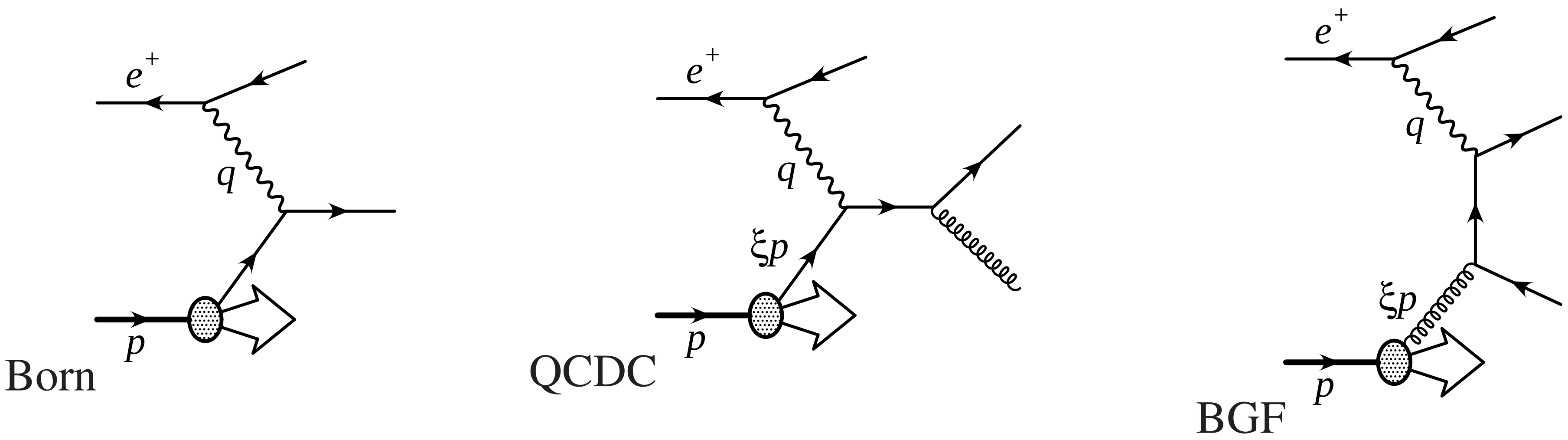
- Total hadronic centre-of-mass energy squared

$$W^2 = (q + p)^2 = ys - Q^2$$

Jets in deep inelastic scattering

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

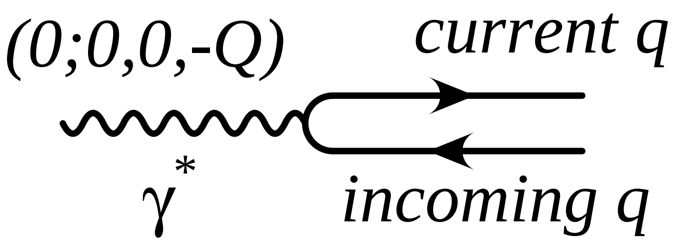
$$d\sigma_{\mathrm{jet}} = \sum_{a=q,\bar{q},g} \int \mathrm{d}x\, f_a(x,\mu_F^2) \times \mathrm{d}\hat{\sigma}_a(x,\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2) \times (1+\delta_{\mathrm{had}})$$



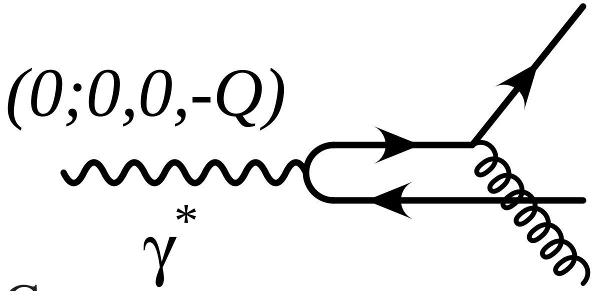
- Longitudinally invariant k_T algorithm (Catani et al).
  ➡ At high E_T hadronisation effects are small ➡ more reliable QCD predictions.
- Large scale variation possible in both Q^2 and E_T.

Jet production in the Breit frame

- Breit frame ➡ purely space-like photon.



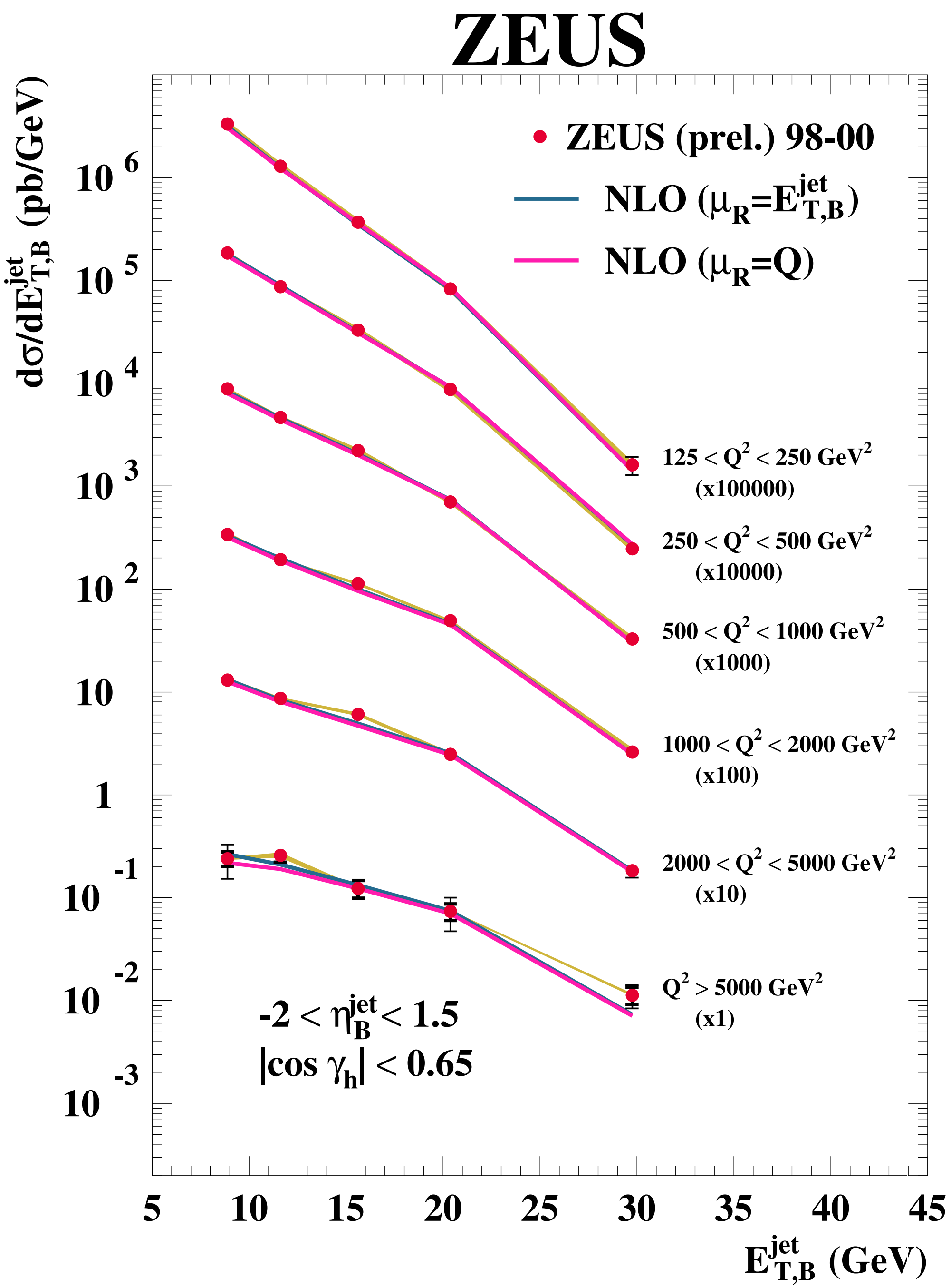
Born



QCDC

- Inclusive jet production in LAB frame $\mathcal{O}(\alpha\alpha_s^0)$ at lowest order.
- Inclusive jets with high E_T in the Breit frame, $\mathcal{O}(\alpha\alpha_s)$ at lowest order.
  - ▷ Suppresses Born contribution (in Breit frame current quark has no E_T).
  - ▷ No cuts on sub-leading jet (can be unobserved)
    ➡ Theory has better infrared behaviour, smaller renormalisation scale uncertainty.
  - ▷ Leading order contributions from $\gamma^* g \to q\bar{q}$ and $\gamma^* q \to qg$ ➡ Directly sensitive to the gluon distribution within the proton and to QCD subprocess at $\mathcal{O}(\alpha\alpha_s)$.

Inclusive jet production at high E_T

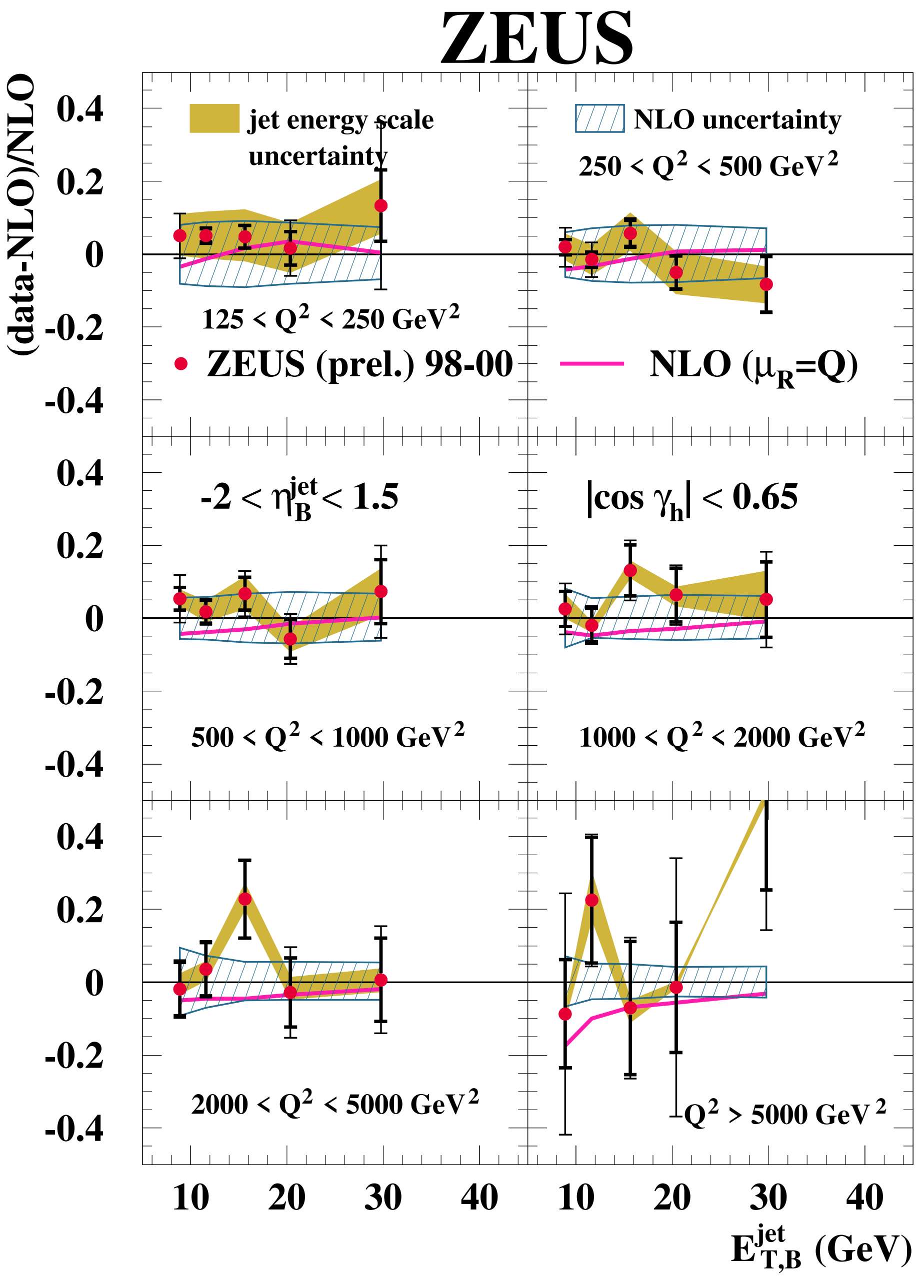


- High $Q^2 > 125$ GeV^2
- Inclusive jet cross sections measured in the Breit frame

$$E^{\rm B}_{T,\rm jet} > 8\rm GeV, \quad -2 < \eta^{\rm B}_{\rm jet} < 1.5$$

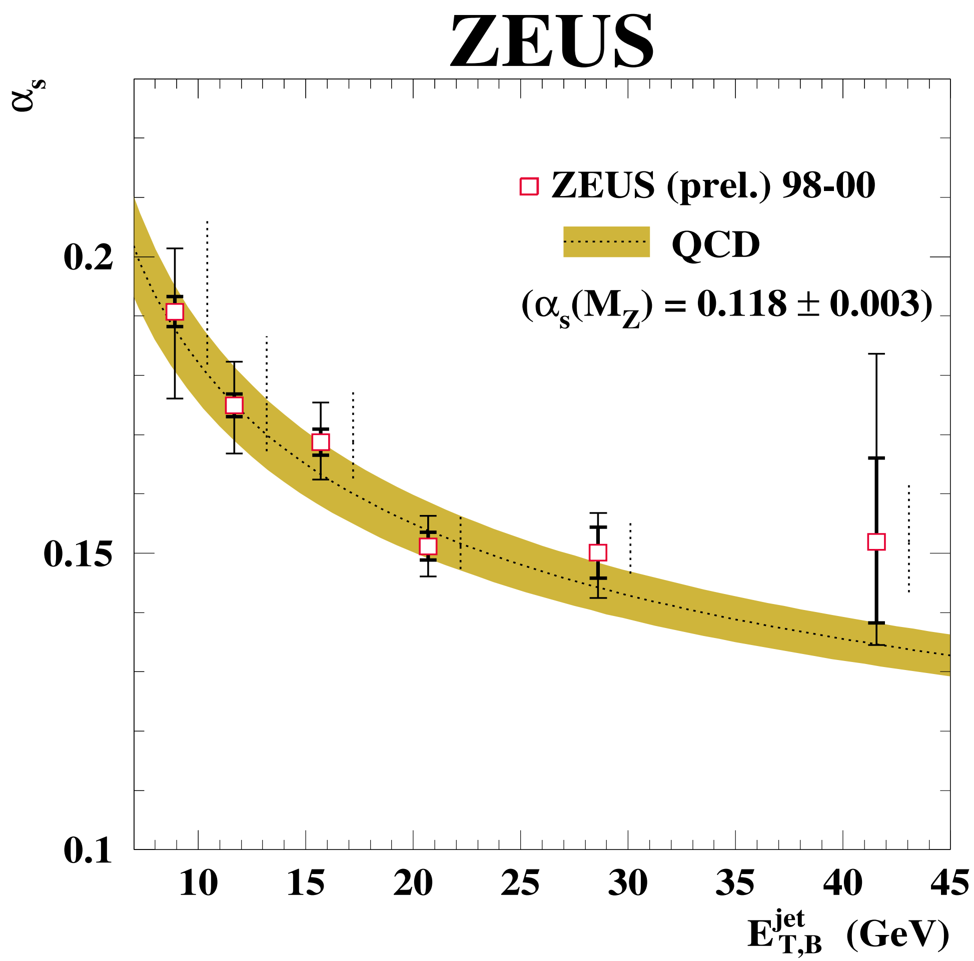
- Again, reasonable agreement with NLO (DISENT) over both Q^2 and $E^{\rm B}_{T,\rm jet}$.

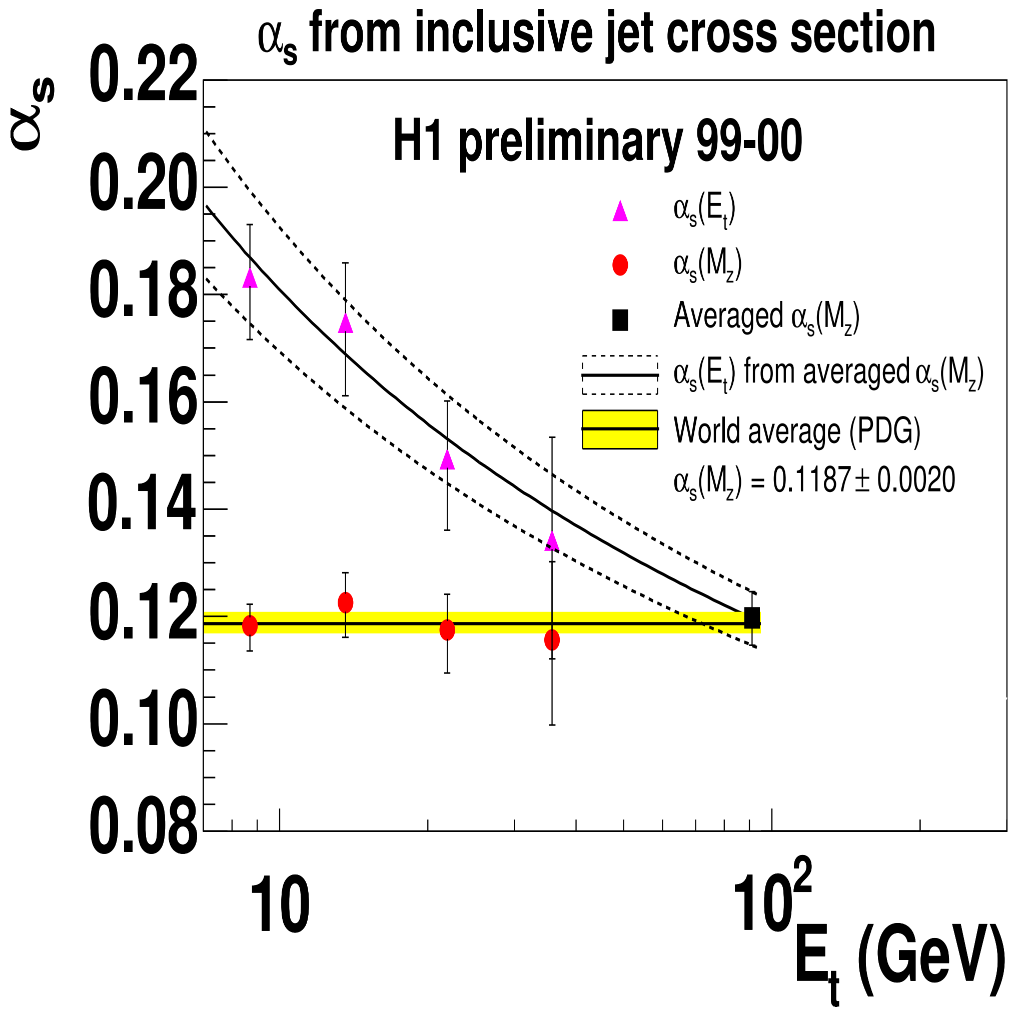
Inclusive jet production at high E_T



- Hatched band: NLO scale uncertainty for, $E^{\rm B}_{T,\rm jet}/2 < \mu_R < 2E^{\rm B}_{T,\rm jet}$.
- Better agreement with $\mu_R = E^{\rm B}_{T,\rm jet}$.
- NLO scale uncertainty $\pm 5\%$.
- Hadronisation uncertainty $< \ 1\%$.
- Overall, reasonable agreement within the experimental and theoretical uncertainties ⇒ extraction of the QCD coupling α_s.

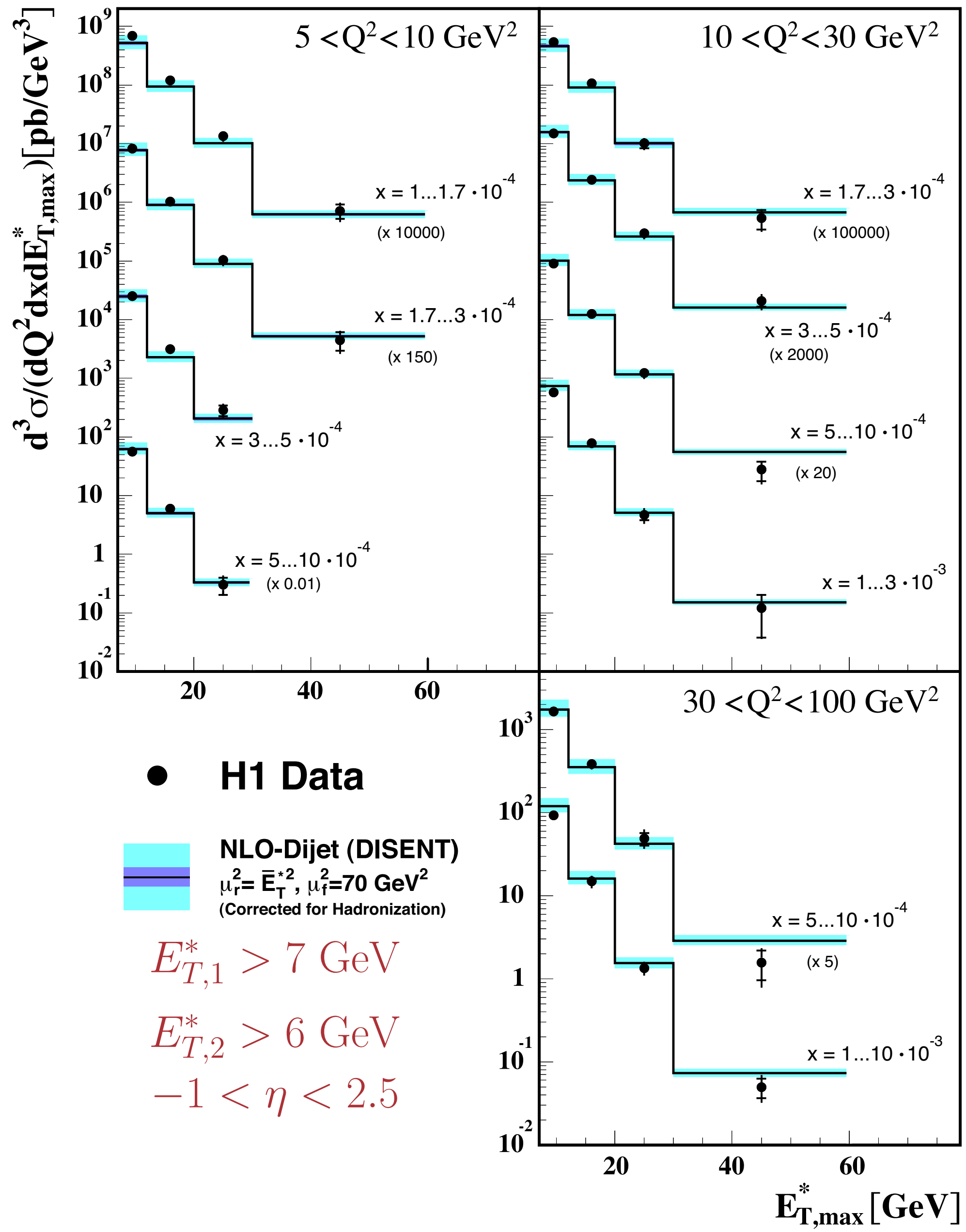
Extraction of the strong coupling constant





- H1 value $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\text{exp})^{+0.0046}_{-0.0048}(\text{th})$
- ZEUS value $\alpha_s(M_Z) = 0.1196 \pm 0.0011(\text{stat})^{+0.0019}_{-0.0025}(\text{exp})^{+0.0029}_{-0.0017}(\text{th.})$

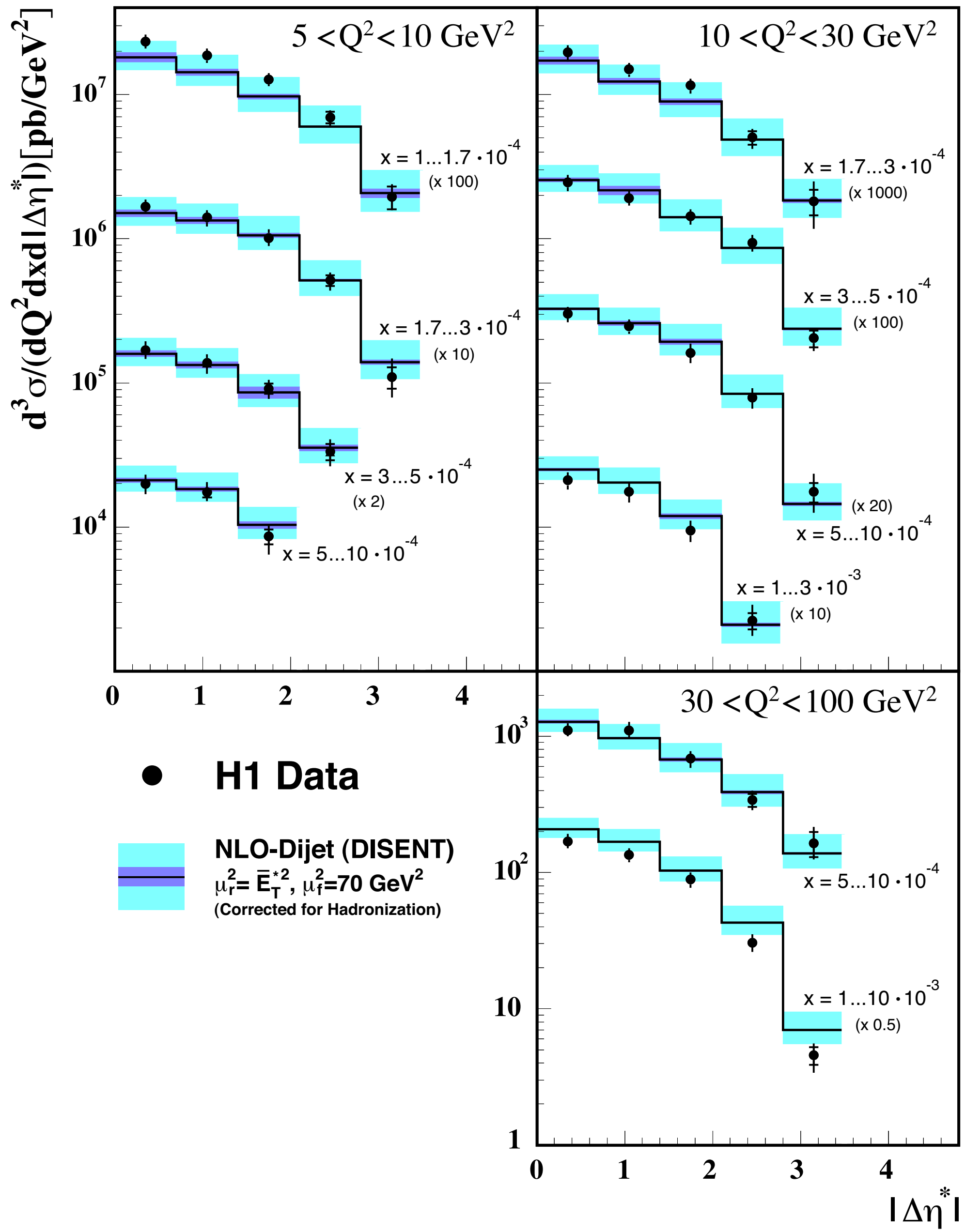
Lower Q^2 - Triple differential Dijet cross section



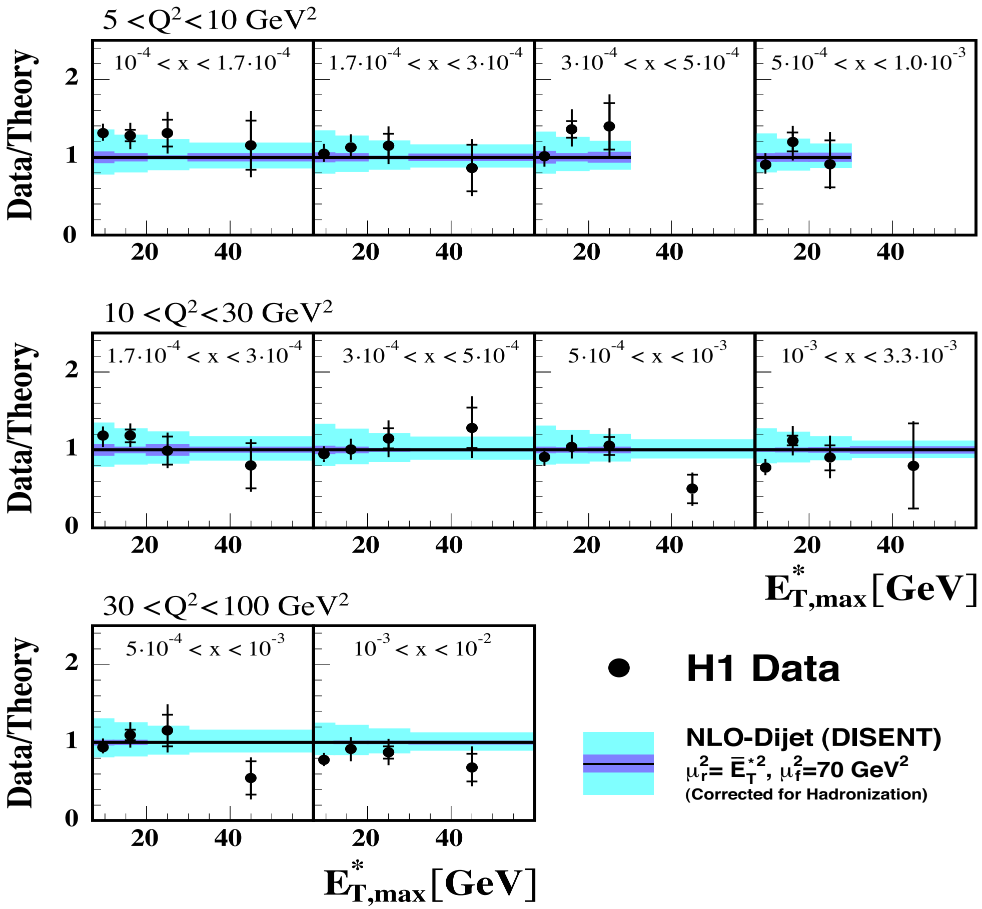
$E^*_{T,1} > 7$ GeV

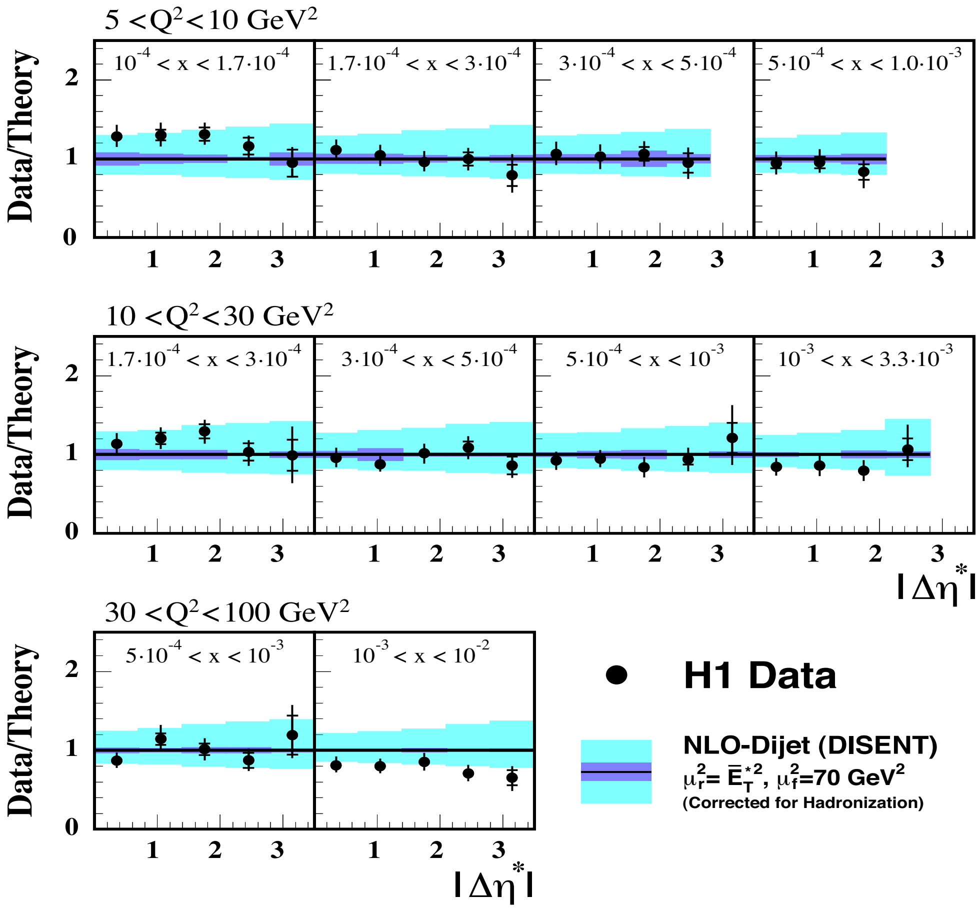
$E^*_{T,2} > 6$ GeV

$-1 < \eta < 2.5$



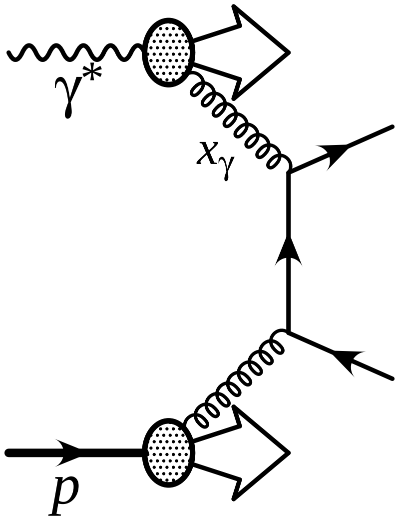
DIS Jet production at lower Q^2





- Scale uncertainty $\sim$20 % at lower Q^2, E_T^*.
- Reasonable agreement with NLO prediction, data lie above theory for low E_T^* and central η^*.
- More details on the these data, see talk by Didar.

Low Q^2 and virtual-photon structure

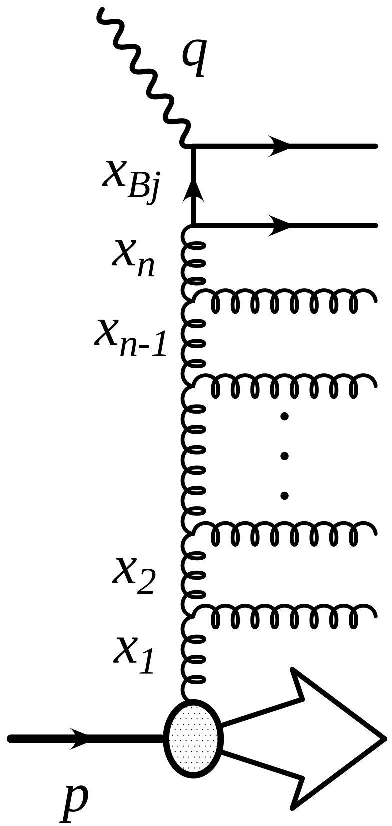


- In dijet production, at very low Q^2, we have $Q^2 < E_T^2$ ➡ large logarithms of $\ln E_T/Q^2$, ➡ formally resum into "resolved" photon structure.
  ➡ Photon can interact directly or via a parton with some momentum fraction $x_\gamma < 1$.
- Possible contribution from longitudinally-polarised "resolved" photons ➡ vanishes as $Q^2 \to 0$ and $y \to 1$.

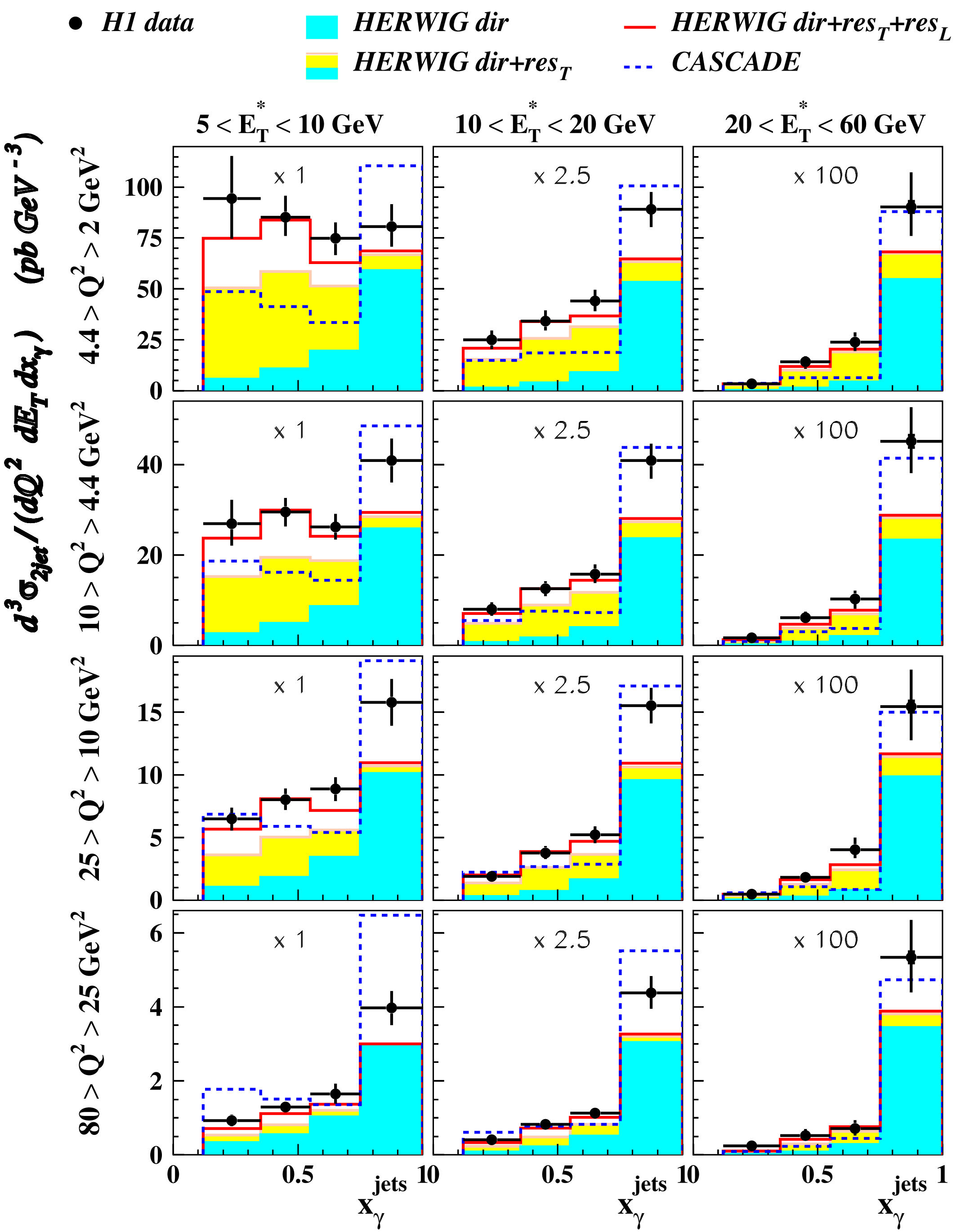
- Virtual photon PDF's modeled using
  - ▷ Leading Log part of real photon ➡ $\ln E_T/\Lambda_{\rm QCD}$
  - ▷ Assymtotic behaviour from perturbative QCD ➡ $\ln E_T/Q$

Alternative evolution schemes

- Unordered parton evolution, eg CCFM (CASCADE),
  - ▷ Strong order in x: $x_1 \gg x_2 \gg ... \gg x_{Bj}$, unordered in k_T.
  - ▷ Allows the highest two E_T jets in an event to come from anywhere along the ladder.
- Uses only unintegrated gluon density in the proton.
- Qualitatively similar to resolved photon picture, but without explicit photon structure.

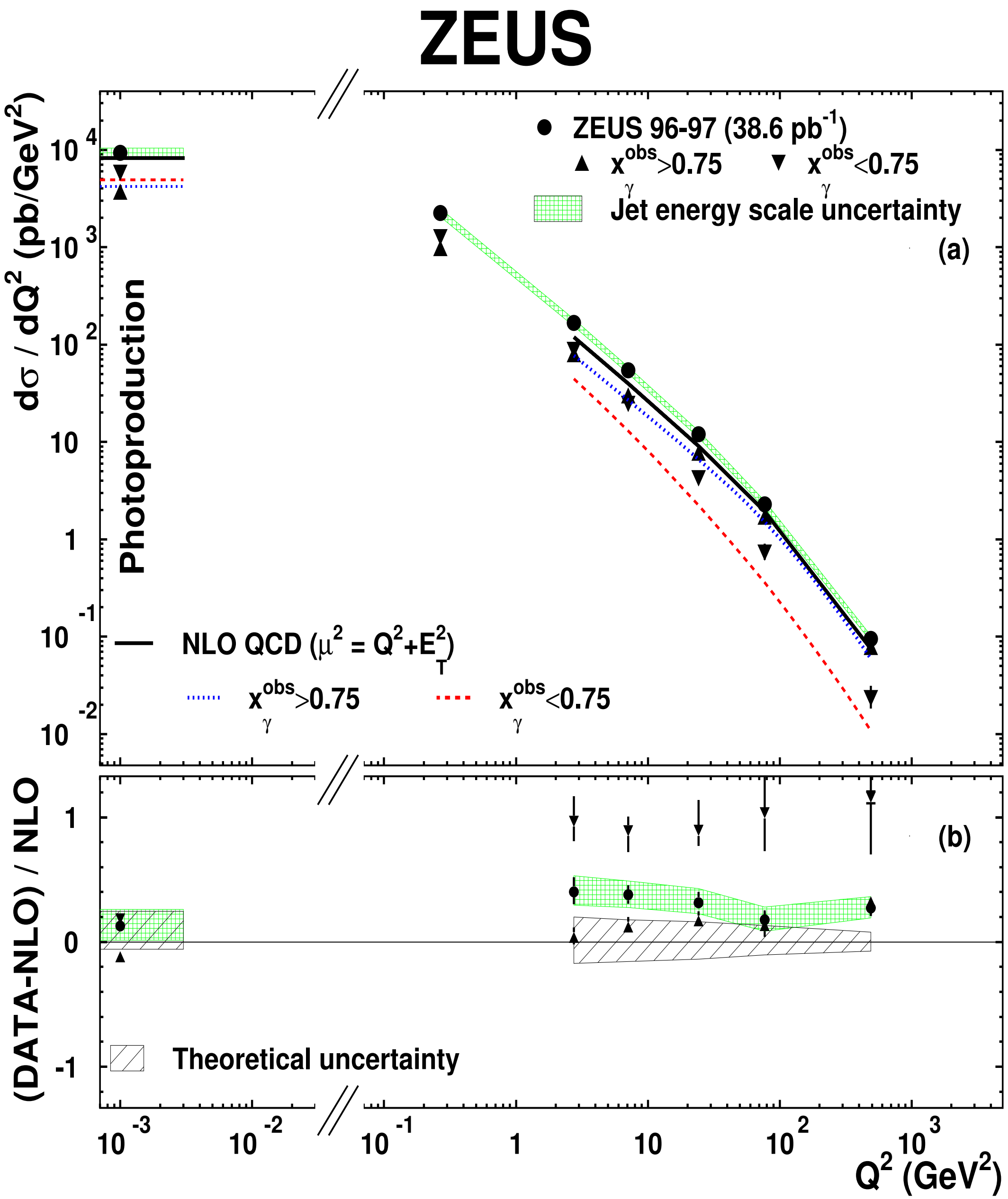


Virtual photon structure



- Data suggest "resolved" component neccessary at low Q^2 or when $\bar{E}_T$ is large.
- Leading-order resolved component alone is not adequate.
- Longitudinally polarised photon improves the description.
- Unordered CCFM parton cascade with NO resolved photon predicts higher contrbution.

Virtual photon structure – comparison with NLO theory

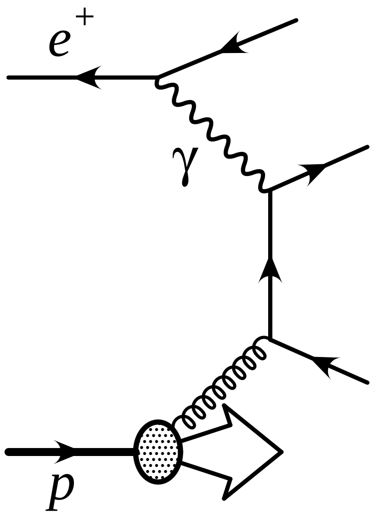


- $E_T^{\text{jet1,2}} > 7.5, 6.5$ GeV.
- $-3 < \eta_{\gamma^* p}^{\text{jet}} < 0$
- NLO DIS calculation ➡ no resolved photon.
- Ratio of direct enhanced to resolved enhanced too low at lower Q^2.
- Expect larger resolved fraction when including resolved virtual photon.
- Need additional NLO calculations at lower Q^2.

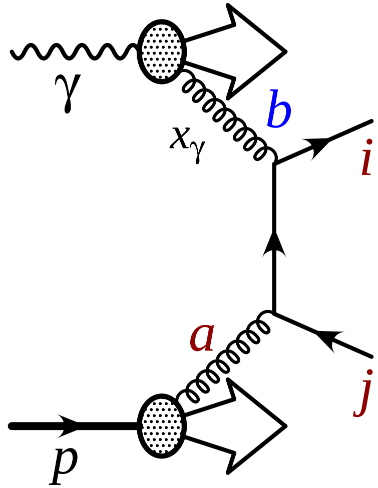
Photoproduction at HERA

- Photoproduction, very low photon virtuality $\sim 10^{-3}$ GeV^2 ➡ perturbatively calculable when there is a hard scale provided by high transverse energy jets.
- To $\mathcal{O}(\alpha\alpha_s)$, two types of process contribute to the high E_T jet production.

Direct



Resolved

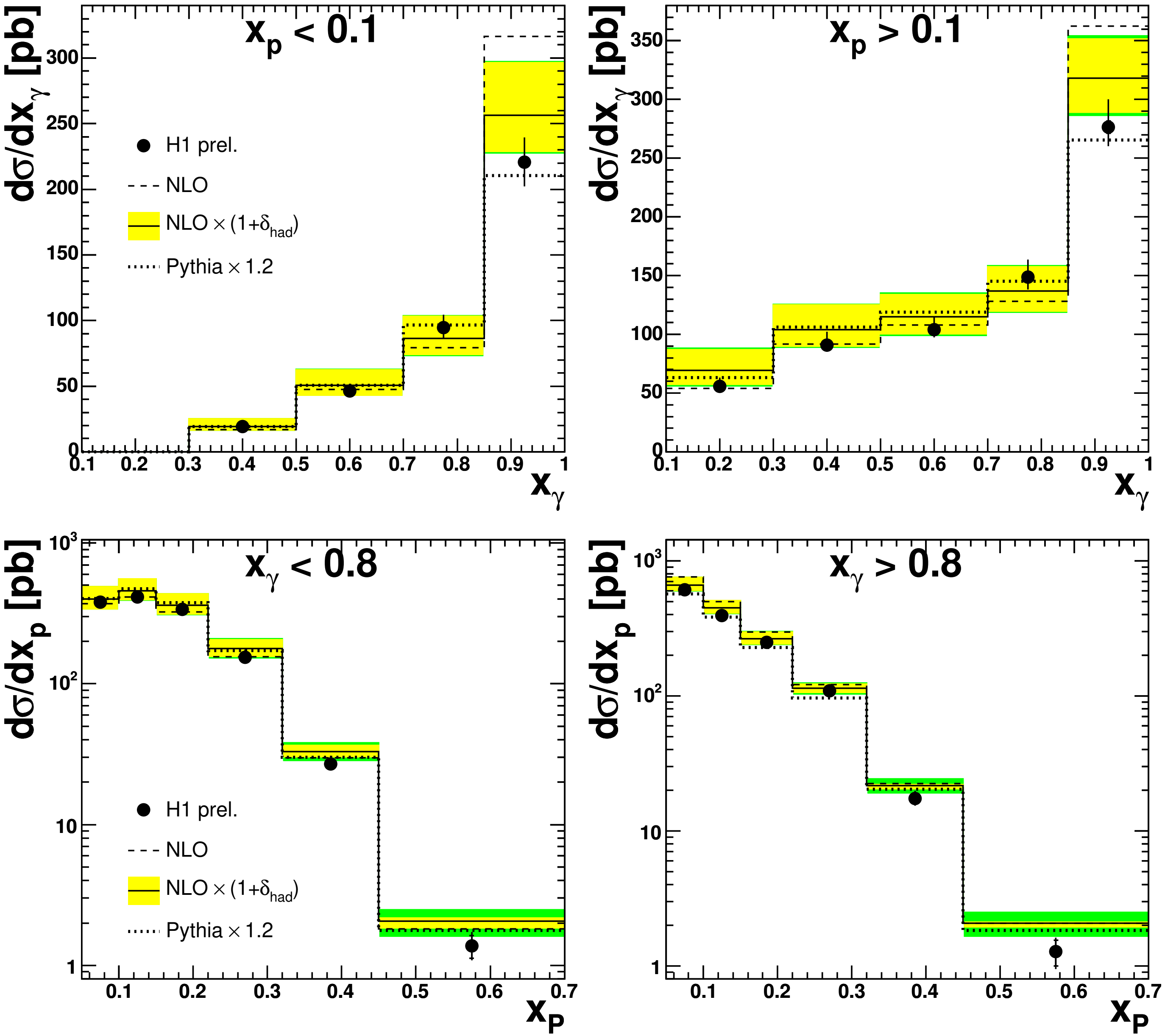


$$d\sigma^{res}(\gamma p \rightarrow ij) = \sum_{ab} \int_y dy f_{e\rightarrow\gamma}(y) \int_{x_p} dx_p f_{p\rightarrow a}(x_p, t) \int_{x_\gamma} dx_\gamma f_{\gamma\rightarrow b}(x_\gamma, t) d\sigma(ab \rightarrow ij)$$

Photon flux, $f_{e\rightarrow\gamma}(y)$, PDF's in the proton, $f_{p\rightarrow a}(x_p, t)$, and photon, $f_{\gamma\rightarrow b}(x_\gamma, t)$.

- In leading order picture, two jets, balanced in E_T, back to back in ϕ.

Inclusive Dijet production in Photoproduction



- $Q^2 < 1\ \mathrm{GeV}^2$
- $E_{\mathrm{T,jet1,2}} > 25,\ 15\ \mathrm{GeV}$
- $-0.5 < \eta_{\mathrm{jet}} < 2.75$
- x_γ the fraction of the photon energy entering the hard scatter.

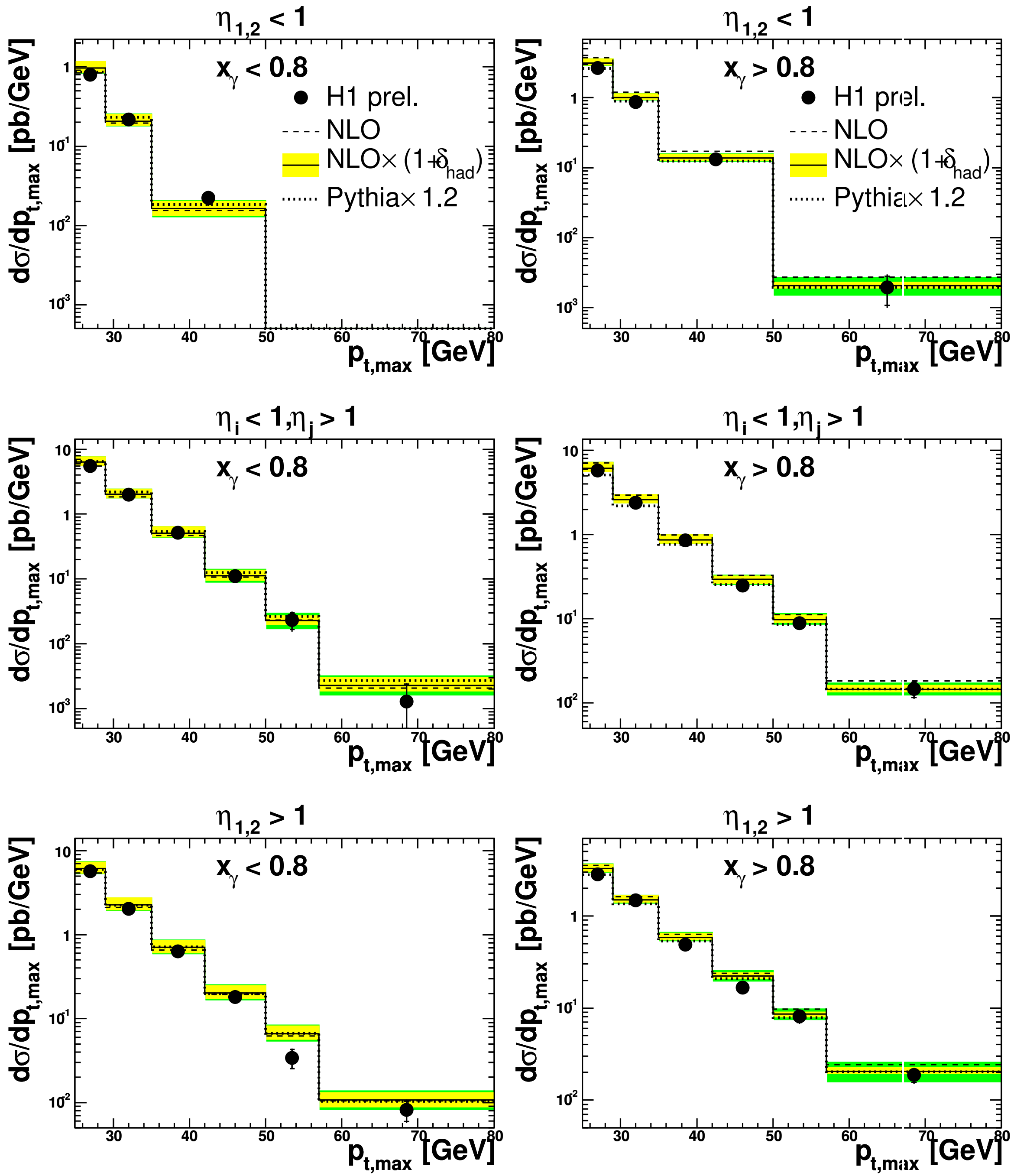
  $x_P < 0.1$ - γg enhanced,
  $x_P > 0.1$ - γq enhanced.

- x_{p} the fraction of the proton energy entering the hard scatter.

  $x_\gamma > 0.8$ - direct enhanced,
  $x_\gamma < 0.8$ - resolved enhanced,

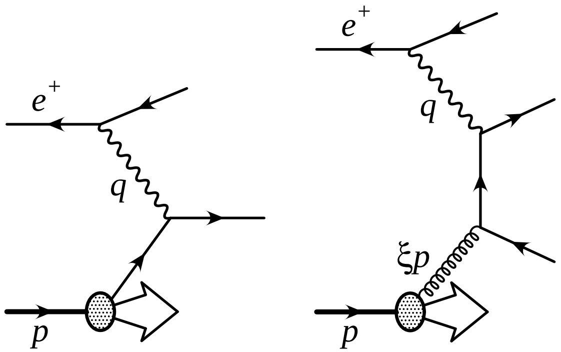
- Reasonable agreement with theory ⇒ look more differentially.

Inclusive Dijet Photoproduction



- Scale uncertainty dominant at low P_T (yellow band).
- at higher P_T, PDF uncertainty dominates.
- Generally good decription over complete phase space.

Extracting the proton parton densities using jet data



- PDF fits using only inclusive DIS data sensitive only indirectly to the gluon density through higher-order term.
- Multijet data directly sensitive to the gluon distribution and α_s at their leading order.

- NLO jet calculations have existed for some time, but use in PDF fitting prohibative

  ➡ must perform convolution over x and Q^2, eg for DIS ...

$$d\sigma_{\text{jet}} = \sum_{a=q,\bar{q},g} f_a(x, \mu_F^2) \otimes d\hat{\sigma}_a(x, \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

  for each iteration through the PDF parameter space, where $d\hat{\sigma}$ involves non-analytic integration over the phase space including the jet algorithm to cancel the IR divergences.

- Deconvolute the PDF and α_s from the matrix elements in the calculation on a grid of ξ and Q^2

$$d\sigma_i^{\text{jet}} = \sum_{n=1,2} \sum_{a=q,\bar{q},g} \sum_j \sum_k f_a(\xi_k, Q_j^2) \times \alpha_s^n(Q_j^2) \times G_{i,a,n,\xi_k,Q_j^2}$$

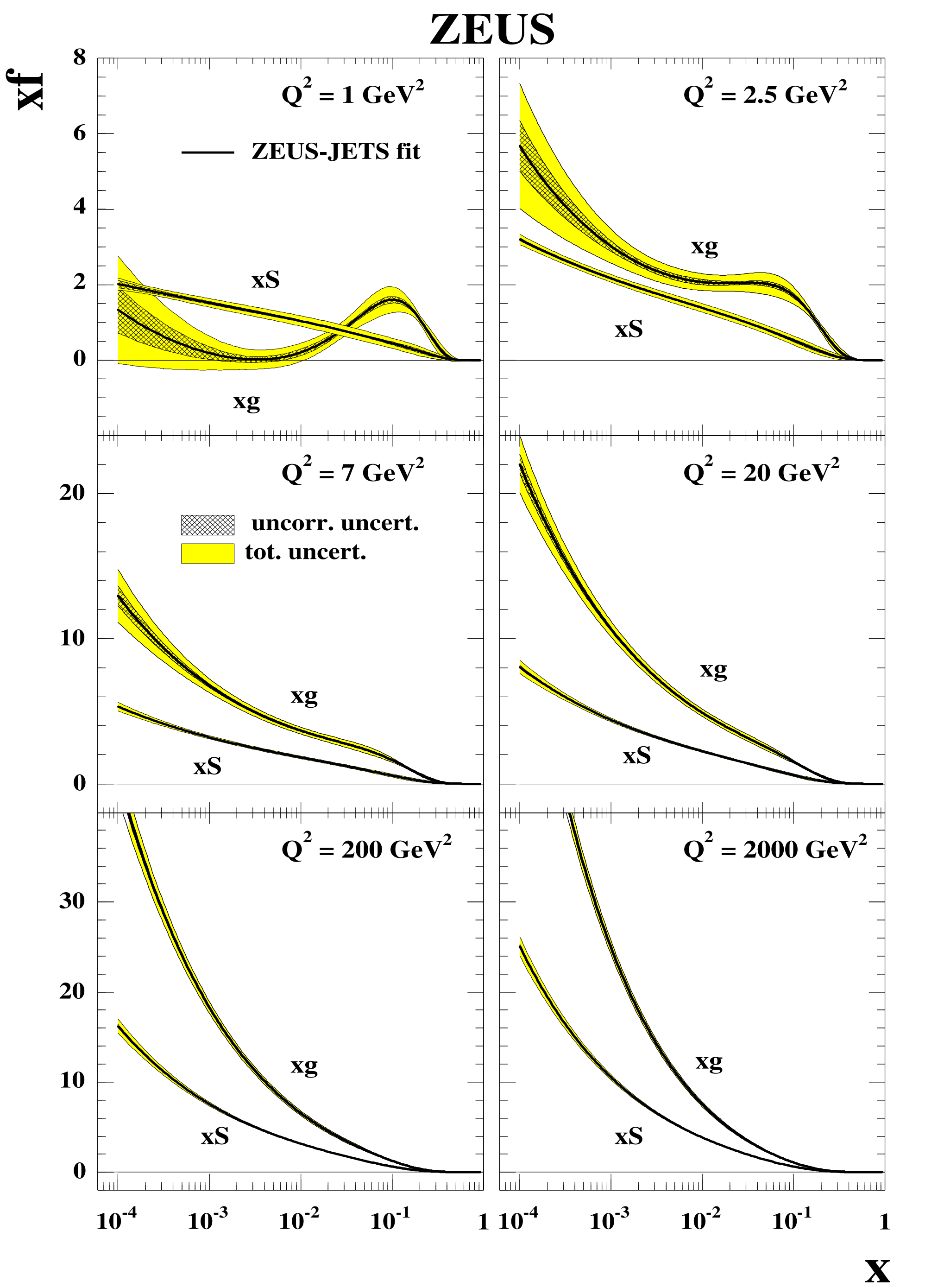
  ▷ Allows NLO calculations (DIS and Photoproduction) to be done once,

  ▷ Convolution to be done by fast summation ➡ suitable for iterative fit.

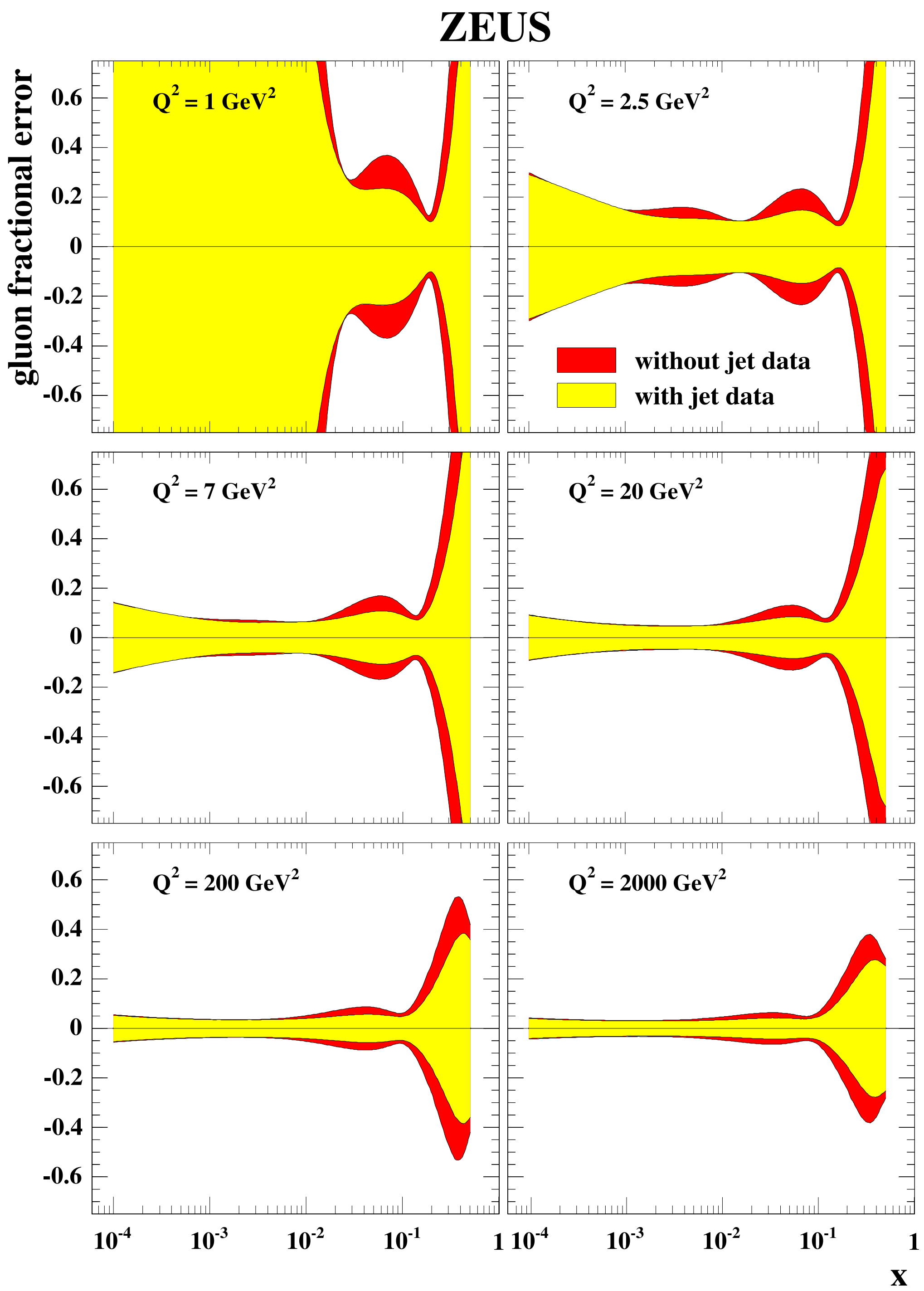
- Jet calculations can be done for any PDF set and any value of α_s to better than 0.5% accuracy!

The gluon distribution from jet data

- Principle data sets for the ZEUS-jets fit...
  - ▷ Published ZEUS Inclusive neutral and charged current DIS data.
  - ▷ Published ZEUS inclusive DIS jets (96-97 data) – (Preliminary 98-00 inclusive jets shown here)
  - ▷ Published ZEUS 96-97 Dijet photoproduction.
- NC and CC data constrain the quarks.
- Jet data constrain the medium x gluon (and α_s).
- No tension between inclusive and jet data ⇒ factorisation.

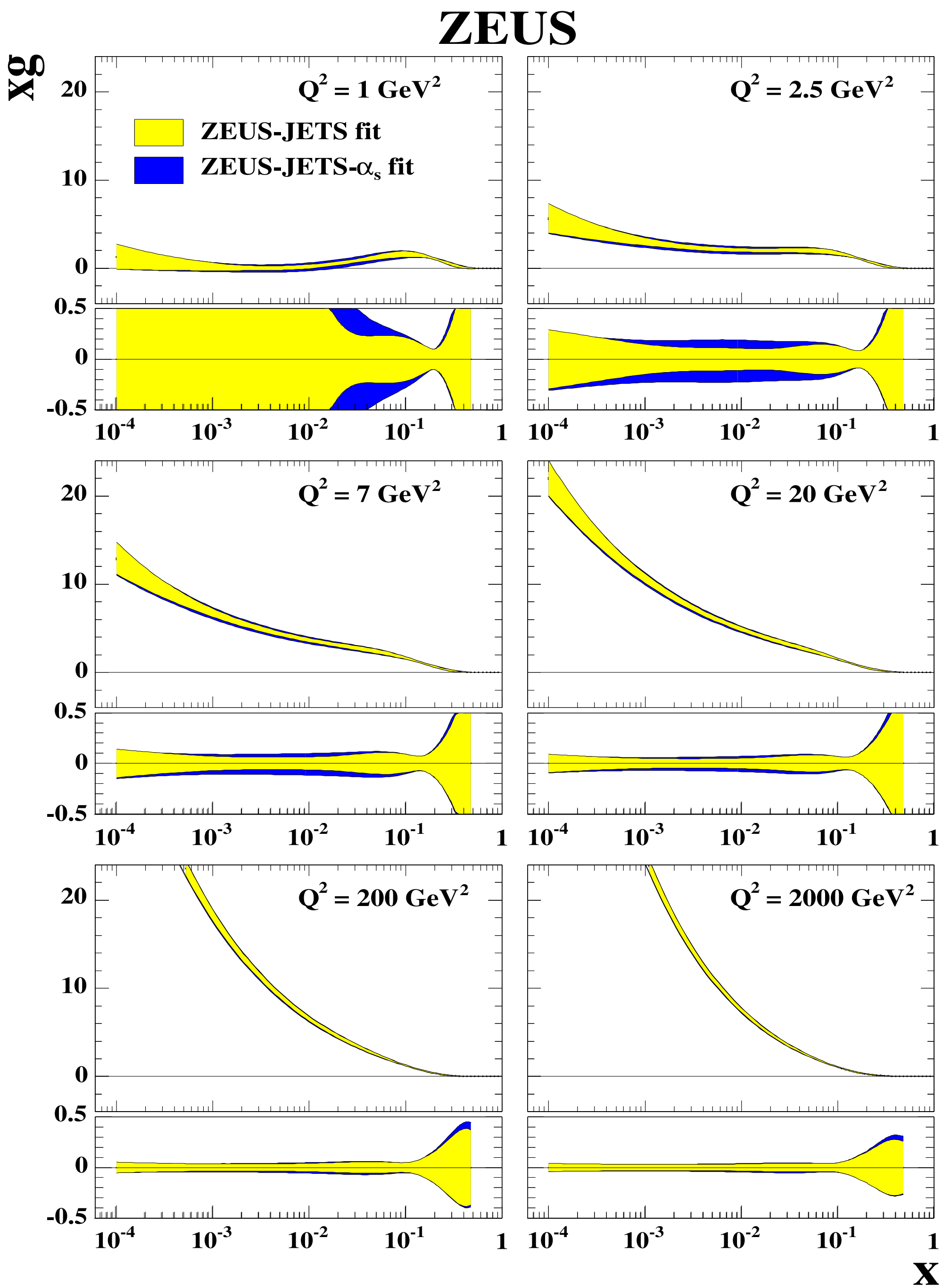


The gluon distribution from jet data



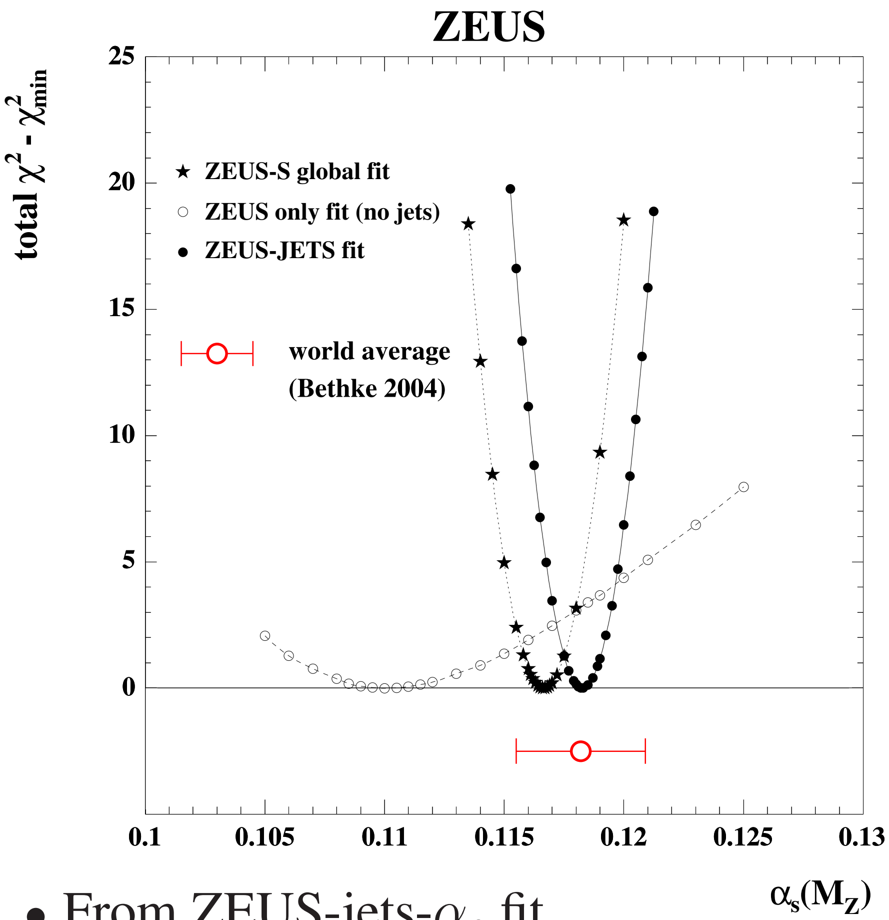
- Significant reduction in the gluon uncertainty ⇒ around factor of 2 for medium x, still significant improvement for high x.

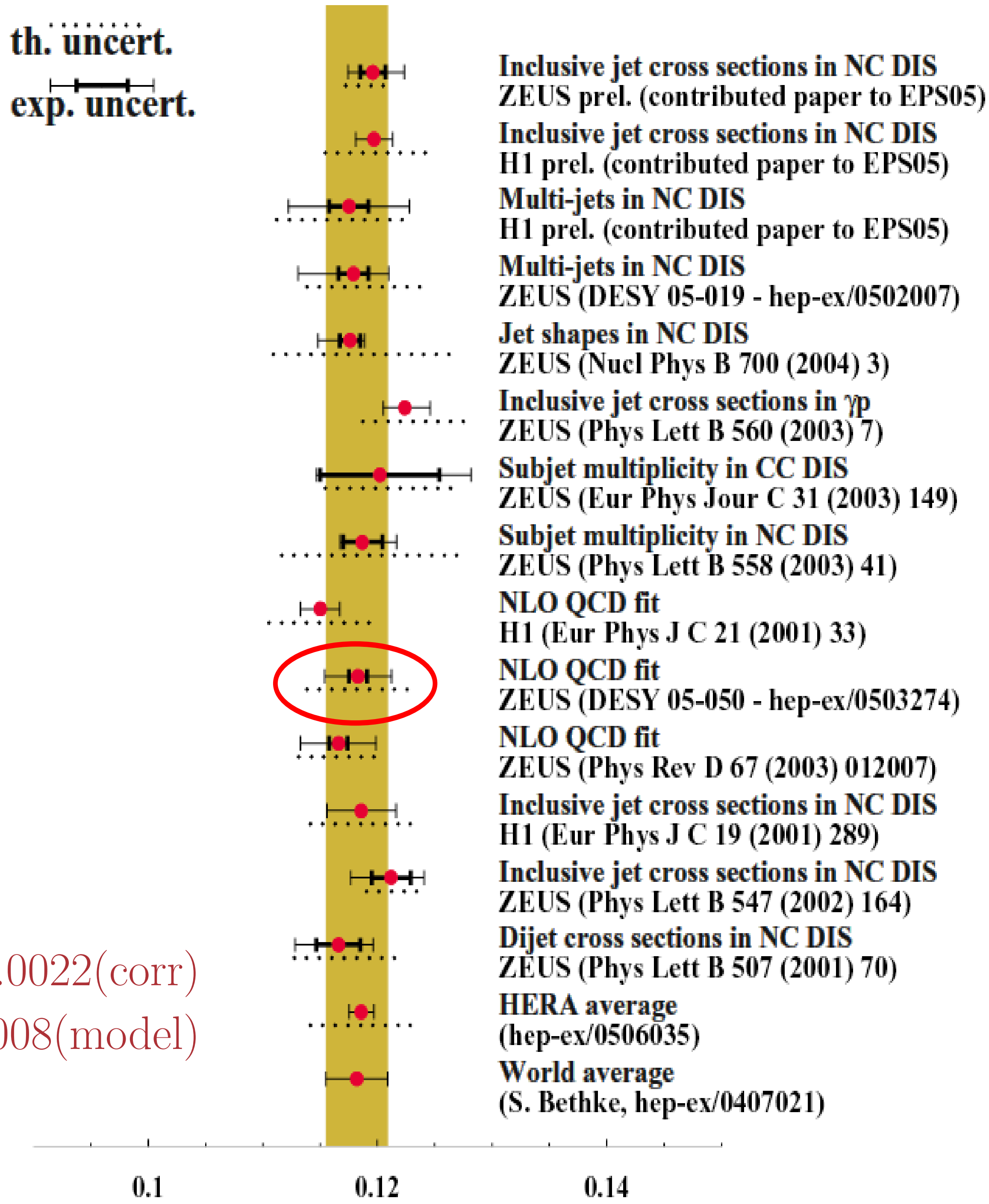
The strong coupling constant



- Jet cross sections sensitive to α_s through
  - ▷ quark density, $\gamma^* q \to qg$,
  - ▷ gluon density $\gamma^* g \to q\bar{q}$.
- Allows simultaneous determination of α_s and gluon density which are not strongly correlated.
  ➡ gluon does not become unconstrained when α_s is a free parameter in the fit.

The strong coupling constant





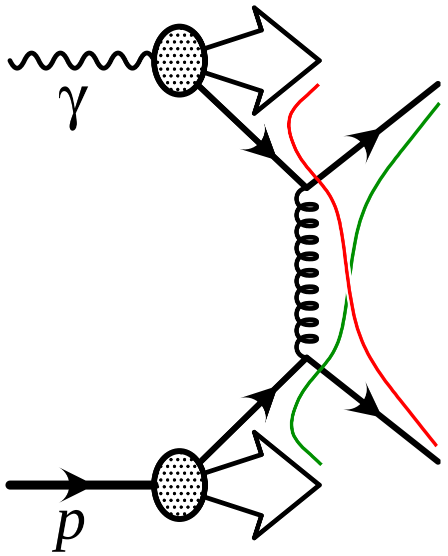
- From ZEUS-jets-α_s fit

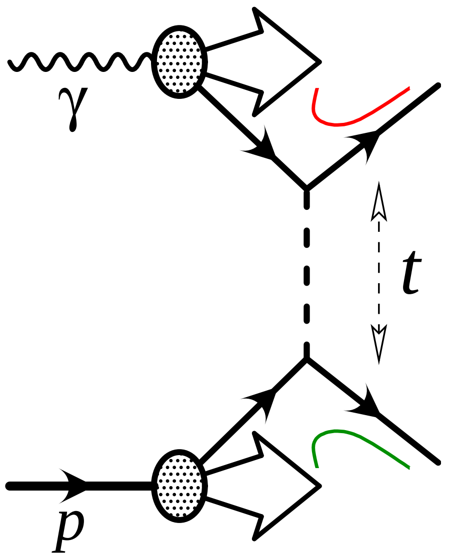
$$\alpha_s(M_Z) = 0.1183 \pm 0.0007(\text{uncorr}) \pm 0.0022(\text{corr}) \pm 0.0016(\text{norm}) \pm 0.0008(\text{model})$$

- Estimated uncertainty from terms beyond NLO ± 0.0050

Interjet energy flow in photoprodcution

- Regge phenomenology describes total hadronic cross sections very well (colour singlet - Pomeron - exchange) but not so good for processes with a hard scale.
- "Complete" theory of the strong interaction must be able to reproduce Regge behaviour in the high energy limit ➡ need understanding of the Pomeron within the framework of perturbative QCD.
- In standard QCD dijet production, jets are colour connected across gap
➡ energy flow between jets, gaps exponentially suppressed.





- At large, negative t, colour singlet exchange (CSE) would result in gaps between the jets with little or no energy flow across the gap
➡ not exponentially suppressed.

Experimental signature and gap fraction

- Two highest transverse energy jets, separated in pseudorapidity,

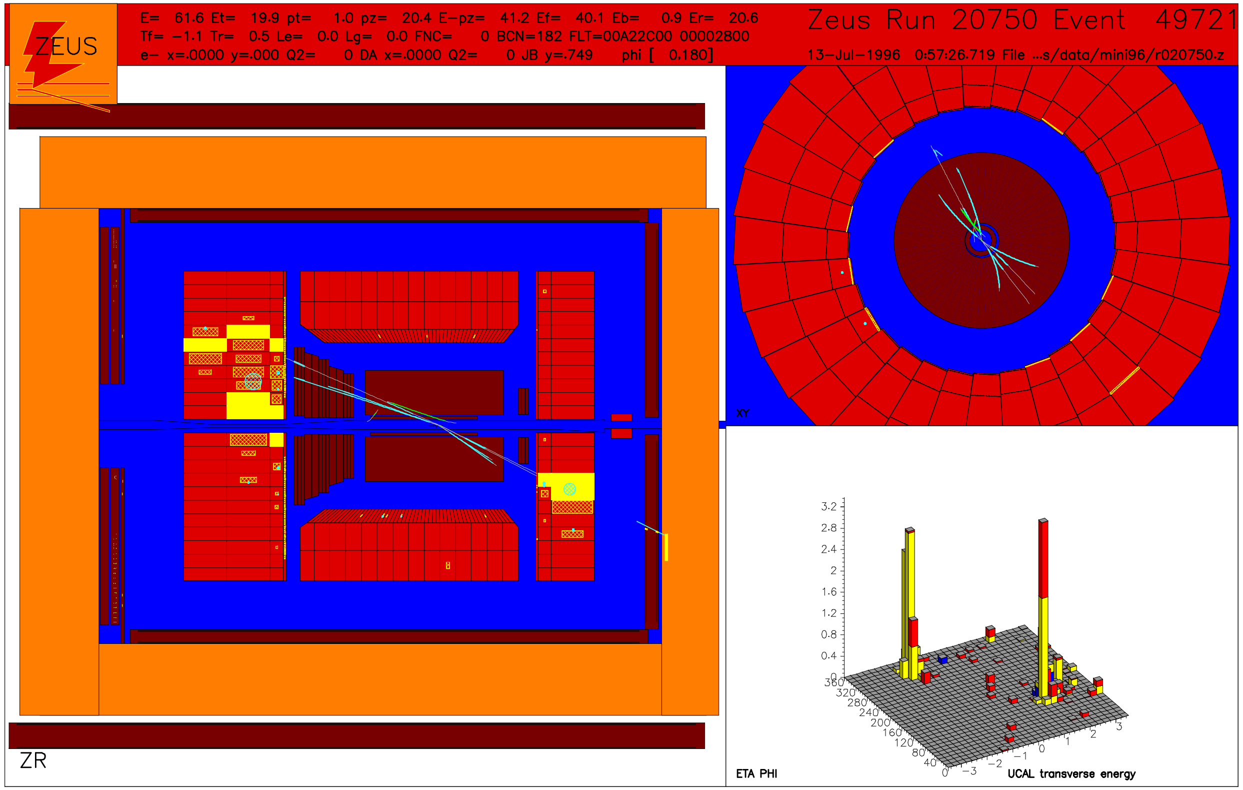
$$\Delta\eta = \eta^{\rm jet}_{\rm forward} - \eta^{\rm jet}_{\rm backward}$$

- Energy flow in the gap

$$E_T^{\rm gap} = \sum_{{\rm jet}\ i} E_T^{{\rm jet}\ i}$$

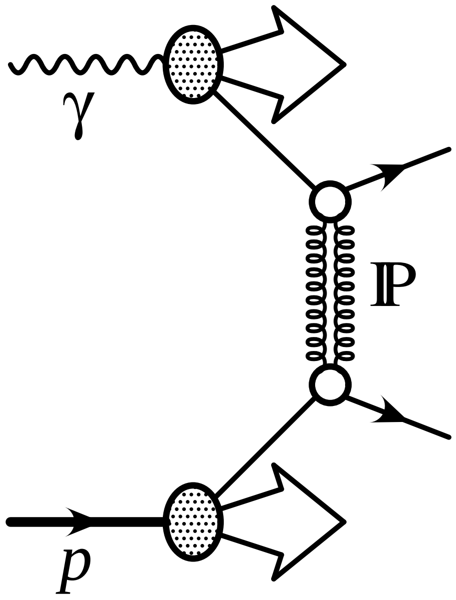
where

$$\eta^{\rm jet}_{\rm backwards} < \eta^{{\rm jet}\ i} < \eta^{\rm jet}_{\rm forward}$$



- Gap event where $E_T^{\rm gap} < E_T^{\rm cut}$, infrared safe, perturbatively calculable when $E_T^{\rm cut} \gg \Lambda_{\rm QCD}$
- Define gap fraction, $f(E_T^{\rm cut}, \Delta\eta)$, for interval $\Delta\eta$, the fraction of events where $E_T^{\rm gap} < E_T^{\rm cut}$.

What is the mechanism of gap formation?



- QCD has no fundamental colour singlet object.
- The large momentum transfer $-t \gg \Lambda^2_{\rm QCD}$ ensures a hard scale at both ends of the exchange ➡ perturbative QCD.
- Can construct perturbative colour singlet using two gluons.
  ➡ Leading Log BFKL approximation colour singlet exchange, two gluons including resummation of $\ln 1/x$ terms (LLA BFKL).
- Calculation from Mueller and Tang,

$$\frac{{\rm d}\sigma(qq \to qq)}{{\rm d}t} = (\alpha_s^{\rm pre.} C_F)^4 \frac{2\pi^3}{t^2} \frac{\exp(2\omega_0 \Delta\eta)}{(7\alpha_s^{\rm den.} C_A \zeta(3)\Delta\eta)^3}$$

- Hard Pomeron intercept, $1+\omega_0$ with $\omega_0 = (\alpha_s C_A/\pi) 4 \ln 2$, couplings $\alpha_s^{\rm pre.}$ and $\alpha_s^{\rm den.}$ free along the ladder.
- Implemention in HERWIG + LLA BFKL, $\omega_0 = 0.45$ ($\alpha_s = 0.17$).

The gap cross section

- Photoproduction region, virtuality and inelasticity,

$$Q^2 < 1\mathrm{GeV}^2, \quad 0.2 < y < 0.85$$

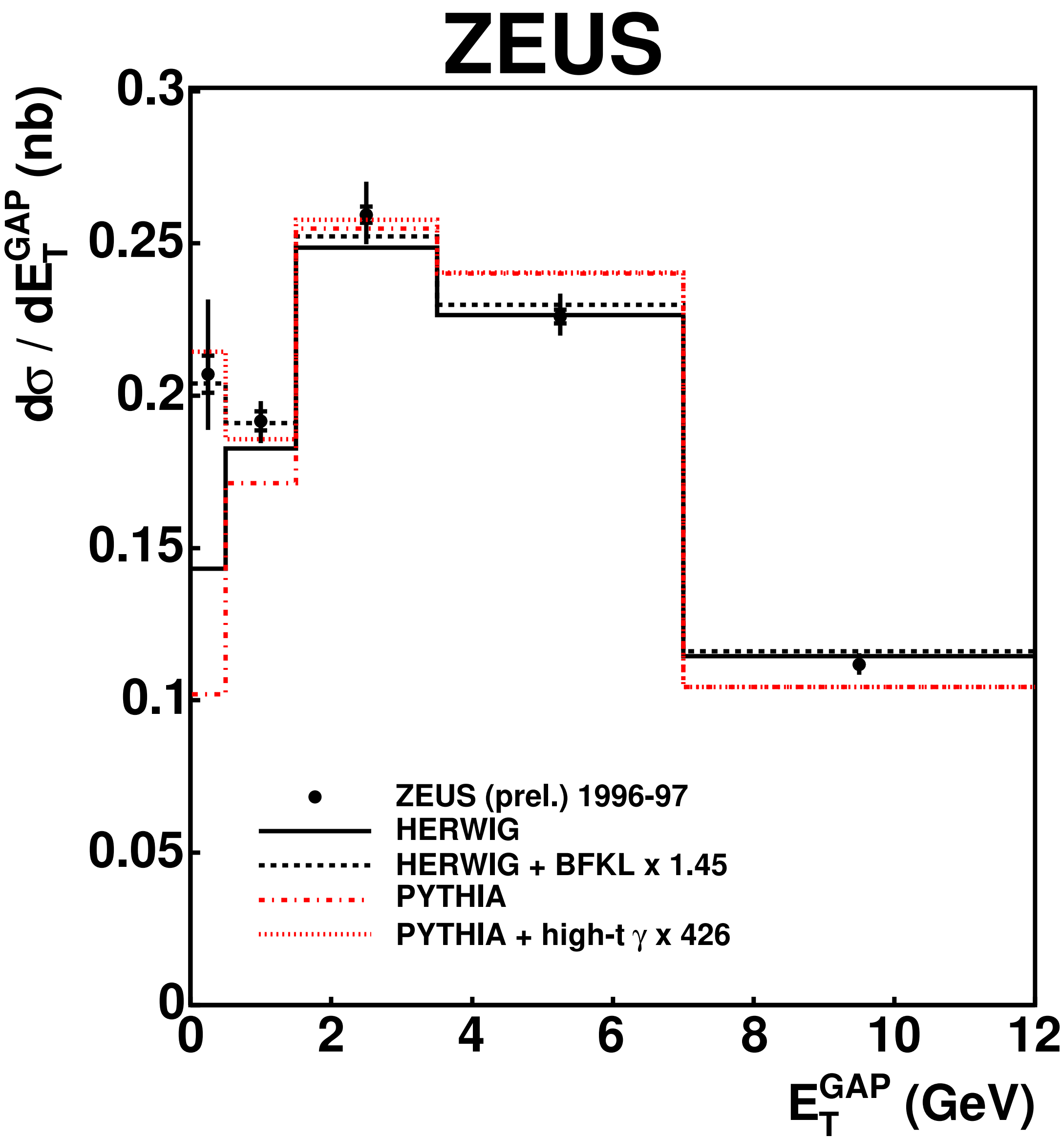
- Require at least two high transverse energy jets,

$$E_T^{\mathrm{jet}1,2} > 6,\ 5\ \mathrm{GeV}$$

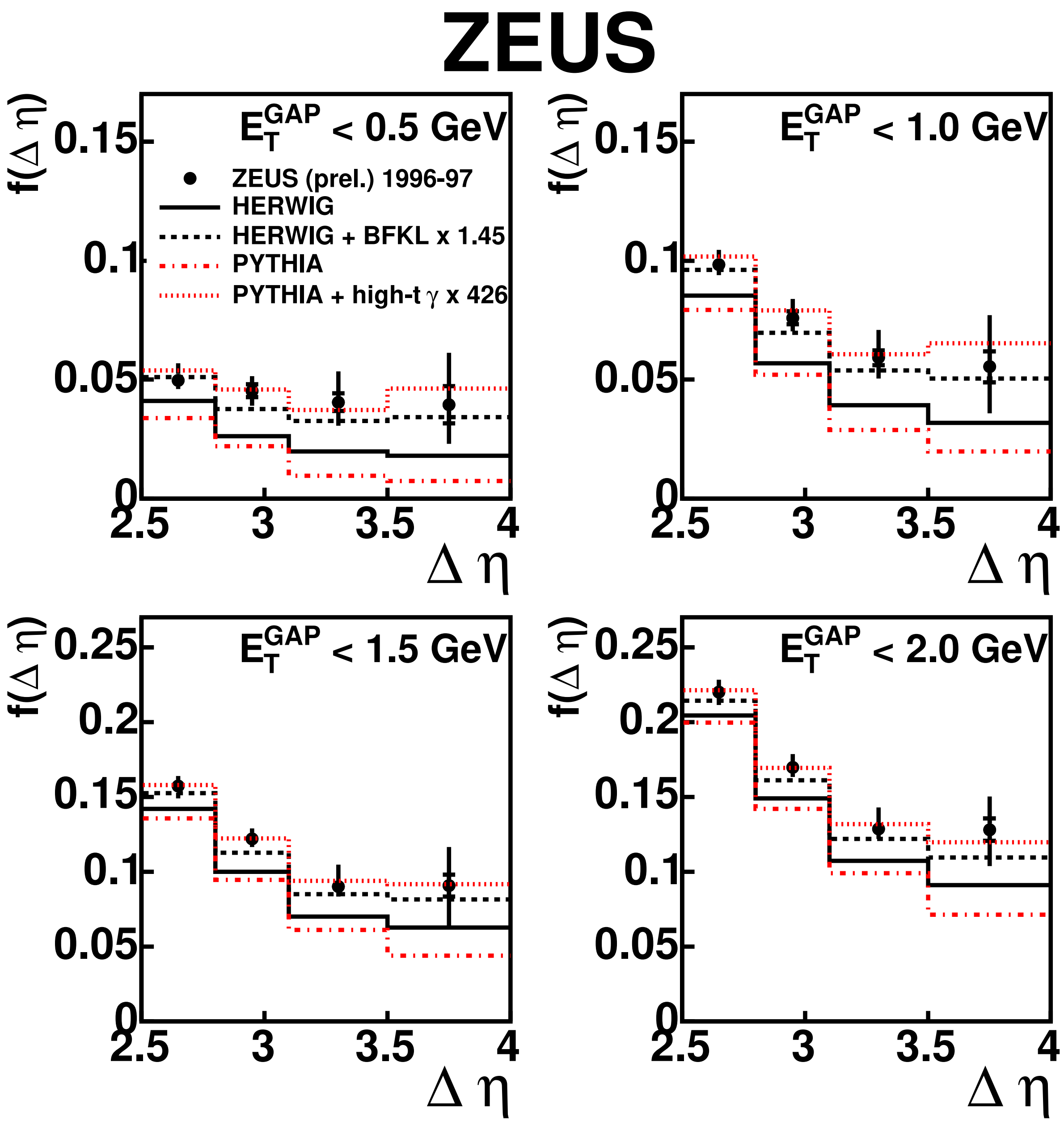
$$|\eta^{\mathrm{jet}1,2}| < 2.4,$$

$$2.5 < \Delta\eta < 4.0$$

- Large difference between models without colour singlet exchange.
- Including colour singlet exchange improves the description at low E_T^{gap}.



The gap fraction versus $\Delta\eta$



- Large differences between standard QCD predictions.
- Models without colour singlet exchange consistent with statistical behaviour.
- Reasonable description when including colour singlet exchange
  ➡ Contribution increases for decreasing E_T^{gap} and increasing $\Delta\eta$.

Summary and outlook

- ZEUS and H1 continue to produce many high precision measurements of the hadronic final state in DIS and photoproduction.
- Theoretical uncertainties continue to dominate over much of the phase space.
- First rigourous use of high precision HERA jet data to extract α_s and constrain the gluon in the proton.
  - ▷ Value from the QCD fit including jet data, using HERA data alone,

$$\alpha_s(M_Z) = 0.1183 \pm 0.0028(\mathrm{exp}) \pm 0.0008(\mathrm{model}) \pm 0.0050(\mathrm{th})$$

  consistent with the world average, $\alpha_s(M_Z) = 0.1182 \pm 0.0027$ (Bethke, 2004)

- Much more data is currently available and around 700 pb^{-1} is expected by the end of HERA-II running which will allow even better constraints on QCD and the structure of the proton.