Jet Production at HERA and the Measurement of α_s

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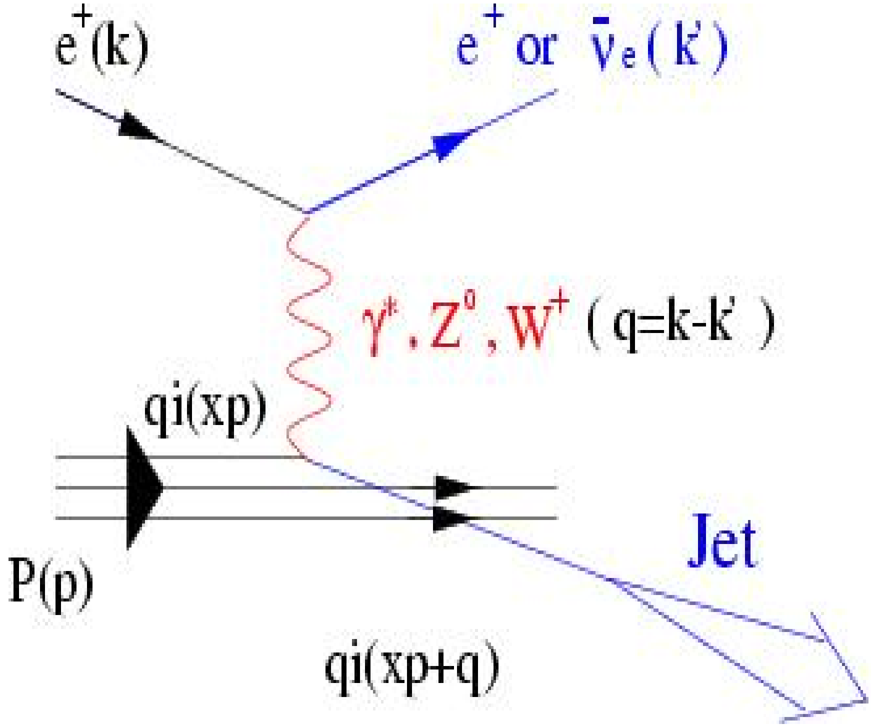
HERA Kinematics



Neutral Current: $e^+ p \rightarrow e^+ X(\gamma, Z^0)$

$Q^2 = -q^2$ •virtuality of the exchanged photon

$x = \frac{Q^2}{2p \cdot q}$ •fractional momentum carried by the struck quark (QPM)

$y = \frac{p \cdot q}{p \cdot k}$ •inelasticity, relative energy of electron transferred to the proton (in proton rest frame)

$s = \sqrt{(p+k)^2}$ •c.m. energy of ep system

Jet Production in Neutral Current Deep Inelastic ep scattering

$$\sigma^{jet} = \sum_{a=q,\bar{q},g} \int dx \cdot f_a(x,\mu_F,\alpha_s) \cdot d\sigma_a(x,\mu_F,\mu_R,\alpha_s(\mu_R)) \cdot (1+\delta_{had})$$

Parton distribution of the proton

Determined experimentally

Evolution predicted from QCD

Hard scattering cross section

Calculable from pQCD

Fragmentation: hadronisation

Corrections (C_{had}). Small for hard scale jets

Jet measurements at HERA allow:

- to constrain PDFs
- to study PDF evolution – parton dynamics
- precision tests of QCD + accurate determination of α_s
- many other studies

← this talk

PDF evolution: DGLAP

- **DGLAP** describes the evolution of PDFs with μ_F (=Q^2)

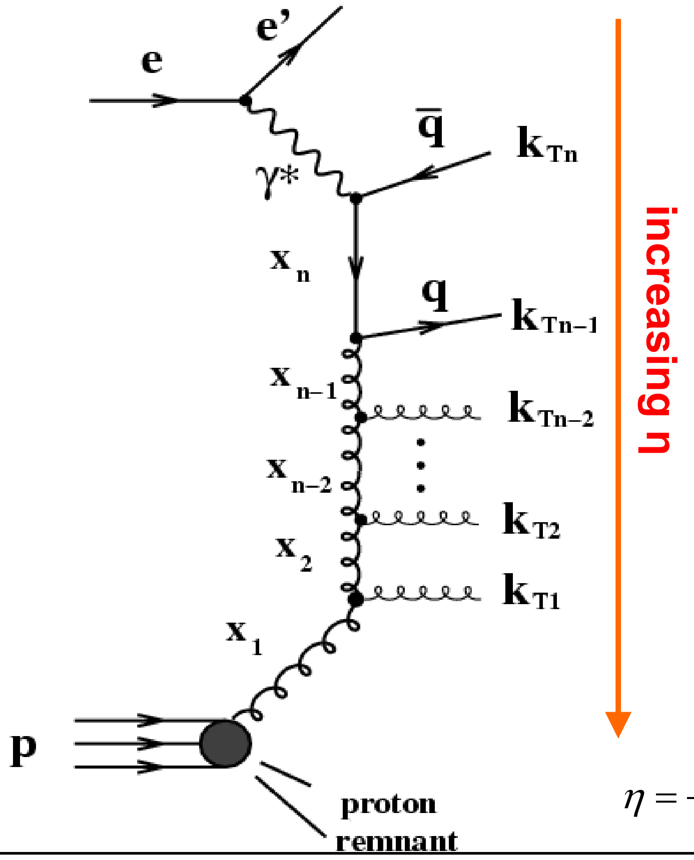
$$\frac{d}{d\ln(Q^2)}\begin{pmatrix} q \\ g \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{bmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{bmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$

- Perturbative expansion in terms of **$\alpha_s\ln(Q^2)$**

$$x = x_n < x_{n-1} < \ldots < x_1$$

- Assumes strong ordering in virtuality of the exchanged parton cascade

$$Q^2 = k_{T,n}^2 >> \ldots >> k_{T,1}^2$$



$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- DGLAP Very successful in describing HERA experimental measurements at high scales (Q^2,E_T)
- Terms at low x neglected. DGLAP valid at high scales but expected to break down at low x and low scales.

QCD at low x: BFKL & CCFM

BFKL

- describes evolution of PDFs with x

•Perturbative expansion in terms of **$\alpha_s \ln(1/x)$**

•No strong k_T ordering assumed: η-democracy

•Off-Shell matrix elements and unintegrated

gluon distribution

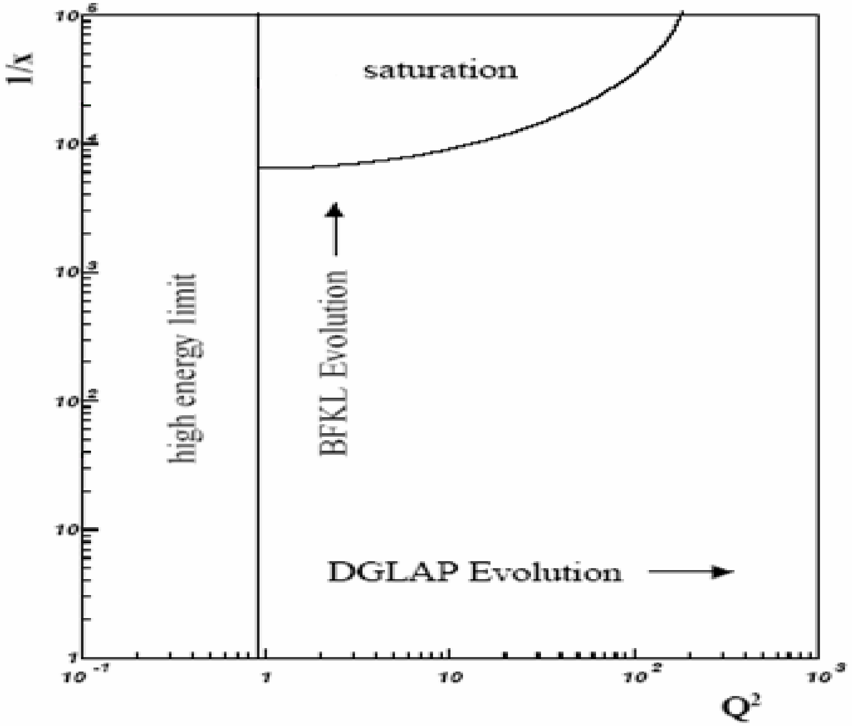
Differences with DGLAP:

▪Jet production at low x

▪ More partons (jets) with higher *k_T (E_T)* in forward region with BFKL than with DGLAP

▪DGLAP: Scattered partons correlated in Energy, azimuthal and polar angles

▪BFKL: Scattered partons not necessarily strongly correlated



CCFM

•resummes terms in both $\log(Q^2)$ and $\log(1/x)$

•Angular ordering of real emissions

•Valid over whole x range

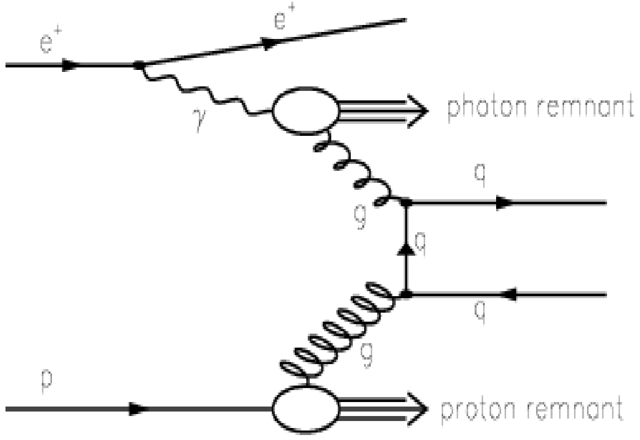
•Approaches DGLAP at large x and BFKL at low x

QCD at low x: other approaches

Virtual Photon Structure

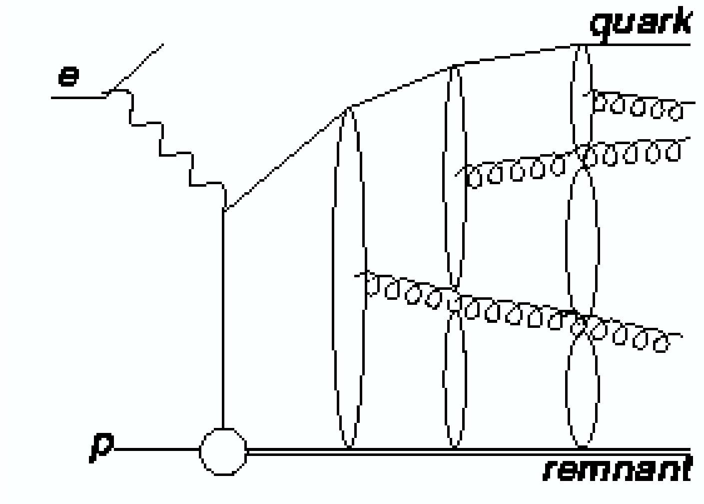
Mimic higher order QCD effects with second k_T-ordered parton cascade on the photon side => photon structure

Resolved contribution important for $E_T^2 > Q^2$



Color Dipole Model

- Gluons emitted from color field between quark-antiquark pairs
- Color dipoles radiate independently
- Gluons not necessarily k_T ordered (BFKL-like)



pQCD calculations and MCs

Fixed order DGLAP calculations

DISENT
- **up to O(α_s^2)**

NLOJET
- **up to O(α_s^3)**

Monte Carlo generators

CASCADE
- **Based on CCFM evolution**
  - k_T factorized unintegrated parton distributions
  - off mass shell matrix elements

RAPGAP
- **DGLAP evolution**
  - approximates higher orders in LO calc
  - Resolved photon component added to simulate events at low x

ARIADNE
- **Color Dipole Model (CDM)**

LEPTO
- **Matrix Element + Parton Shower (MEPS)**
  - Parton cascade: approximate higher orders in LO calc
  - Radiated gluons k_T-ordered (DGLAP-based)
  - Only direct photon process

Both Ariadne and Lepto use Lund String Model to simulate hadronization

Forward Jet Production

- $5<Q^2<85$ GeV^2
- Inclusive jets

  $E_{T,jet}>3.5$GeV, $7.0<\theta_{jet}<20$ ($1.74<\eta_{jet}<2.8$)
- $0.5< E_{T,jet}/Q^2<5$, $x_{jet}>0.035$

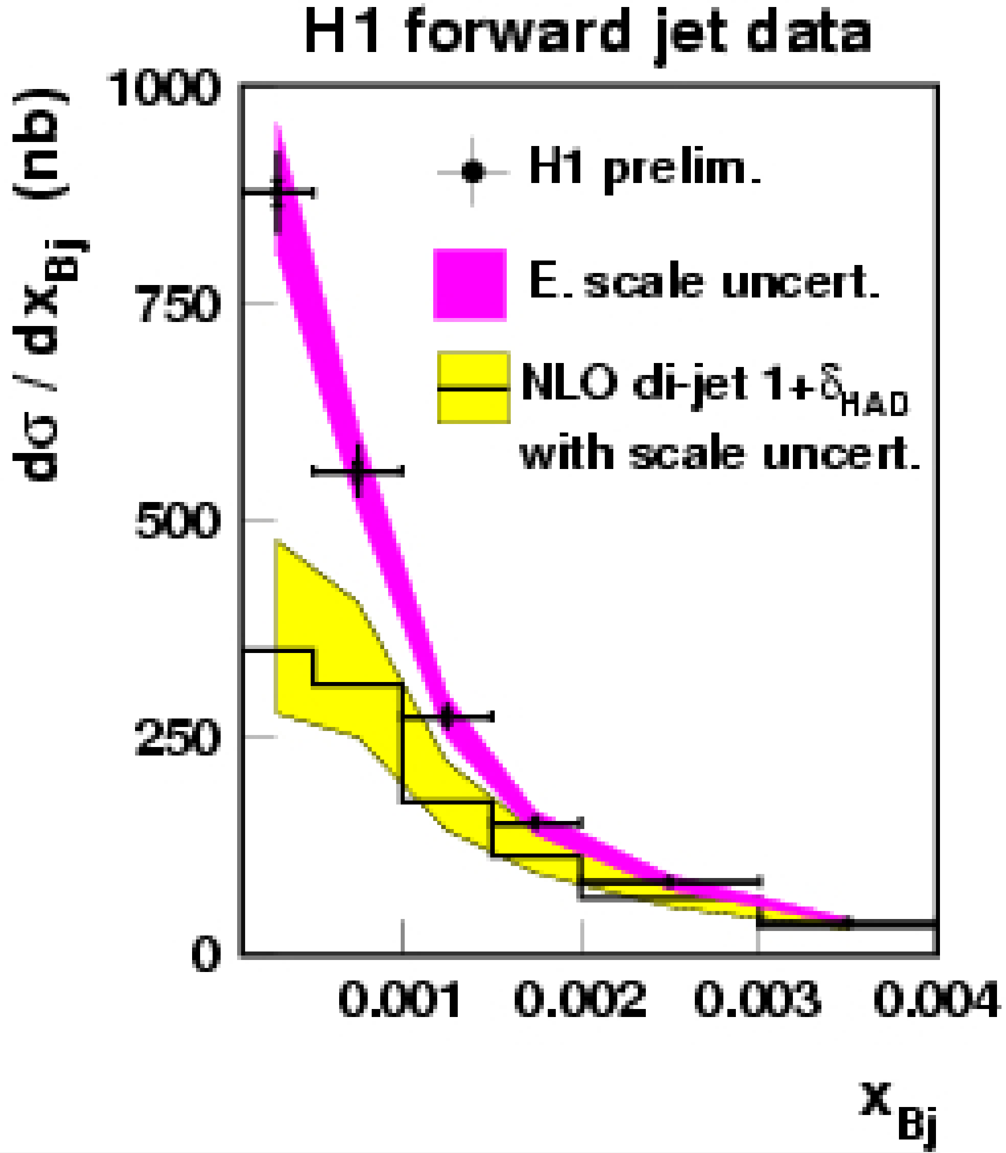
$$x_{jet} = \frac{E_{jet}}{E_{proton}}$$

Comparison to NLO

DISENT NLO prediction $\mu_R = \left\langle E^2_{T,jet} \right\rangle = 45 GeV^2$

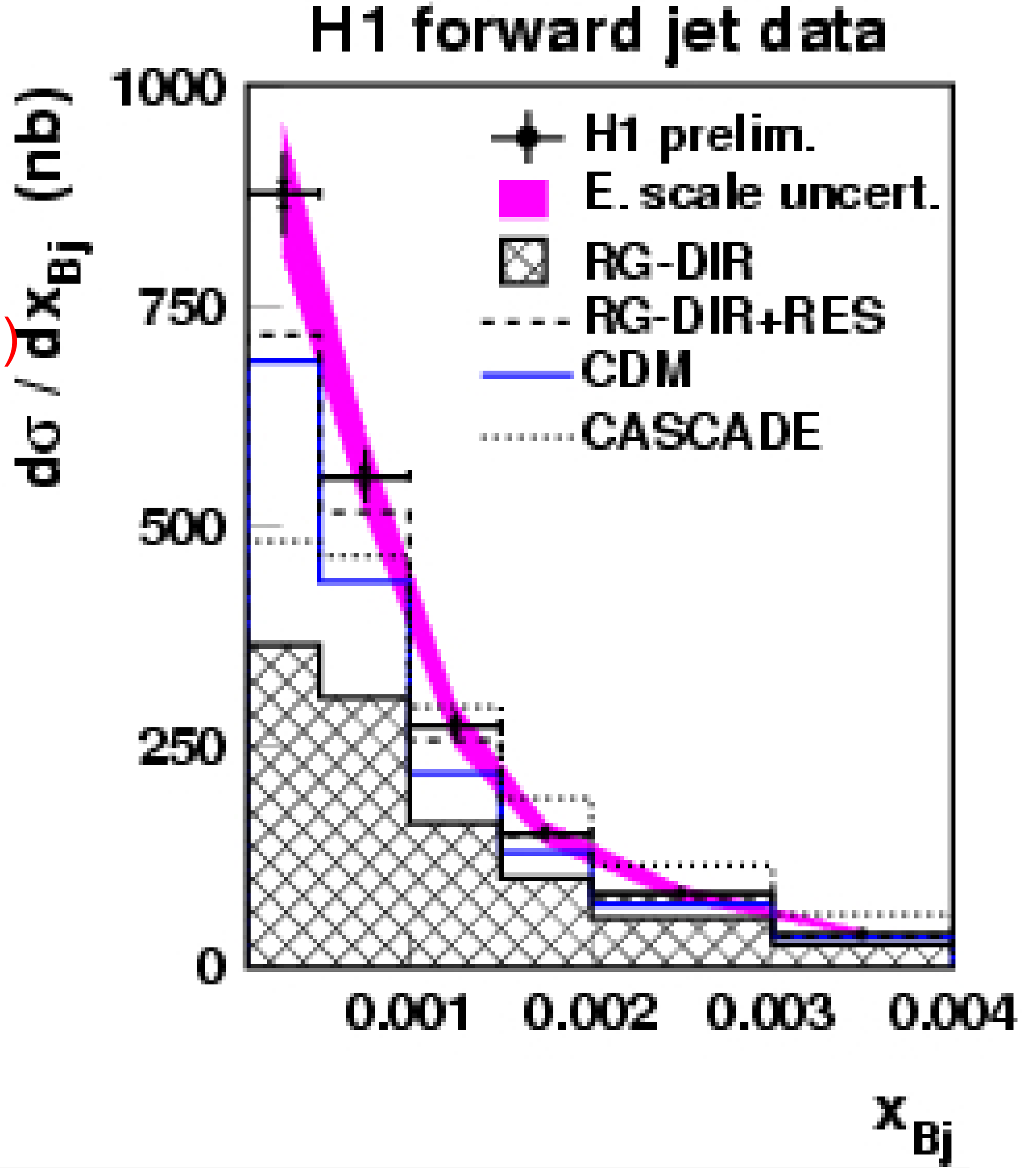
CTEQ6M proton PDFs

Scale uncertainty: $E^2_{T,jet}/4 < \mu^2_R < 4E^2_{T,jet}$



- NLO DGLAP fall below the data at low x
- Better agreement at high x
- DGLAP NLO uncertainty increases at low x

Forward Jet Production



Comparison to MC models

Description of data from DGLAP (RAPGAP – SaS1D for the photon PDFs) significantly improves when resolved photon processes are included

The CDM (Ariadne) show similar behaviour to DIR+RES DGLAP

CCFM model (Cascade) fails to describe data

Forward Jet Production

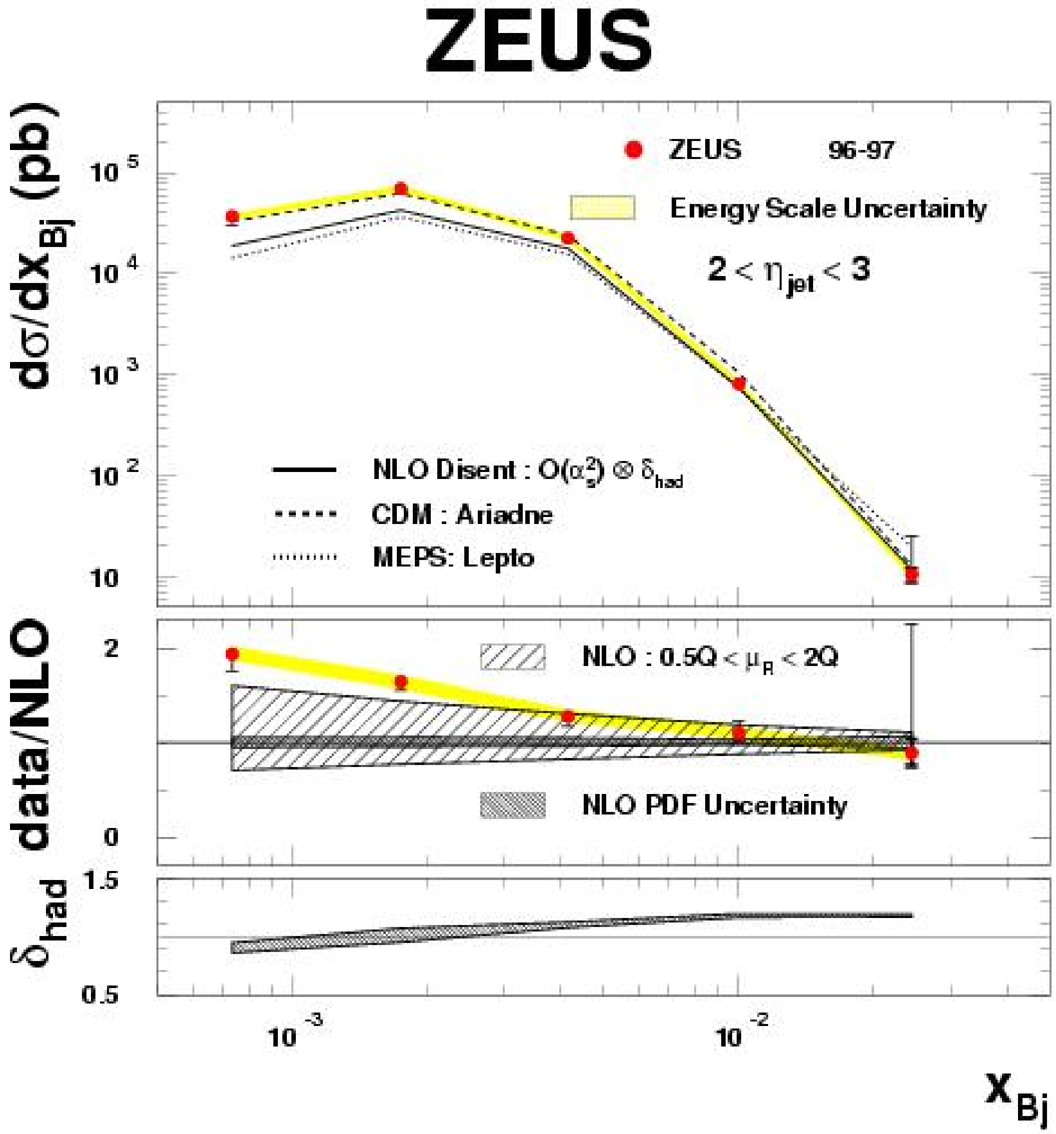
$Q^2>25$ GeV^2, $y>0.04$

$E_{T,jet}>6$GeV, $2<\eta_{jet}<3$

$\cos(\gamma_H)<0$, $0.5<Q^2/(E_{T,jet})^2<2$

γ_H = hadronic angle (QPM: angle of struck quark)

- Fixed order NLO and MEPS describe data at high x but underestimate the lower x measurement.
- Uncertainty of NLO increases in lower x region → missing ln(1/x) terms?
- CDM gives reasonable description of data.



Inclusive dijets at low x: Azimuthal Asymmetry

$10^{-4}<x<10^{-2}$, $5<Q^2<100$ GeV^2

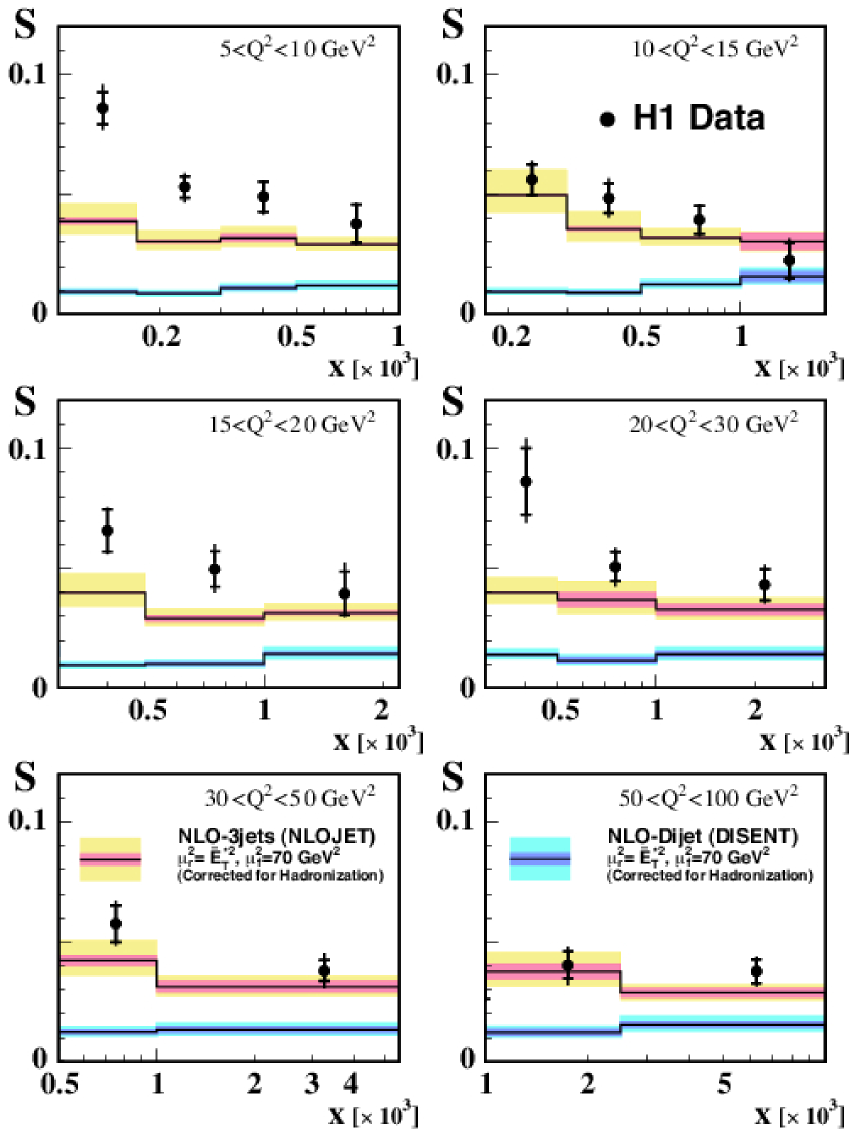
γ^*P c.m.f $E_{T,jet1,2}>7$, 5 GeV $-1<\eta_{jet}<2.5$

$$S = \frac{\int_0^{120^o} N_{dijet}(\Delta\phi^*, x, Q^2)\, d\Delta\phi^*}{\int_0^{180^o} N_{dijet}(\Delta\phi^*, x, Q^2)\, d\Delta\phi^*}$$

Rise of S towards low x most prominent in lowest Q^2 bin

Disent (DGLAP $O(\alpha_s^2)$) shows no rise towards low x and does not describe the data – at LO would expect S=0

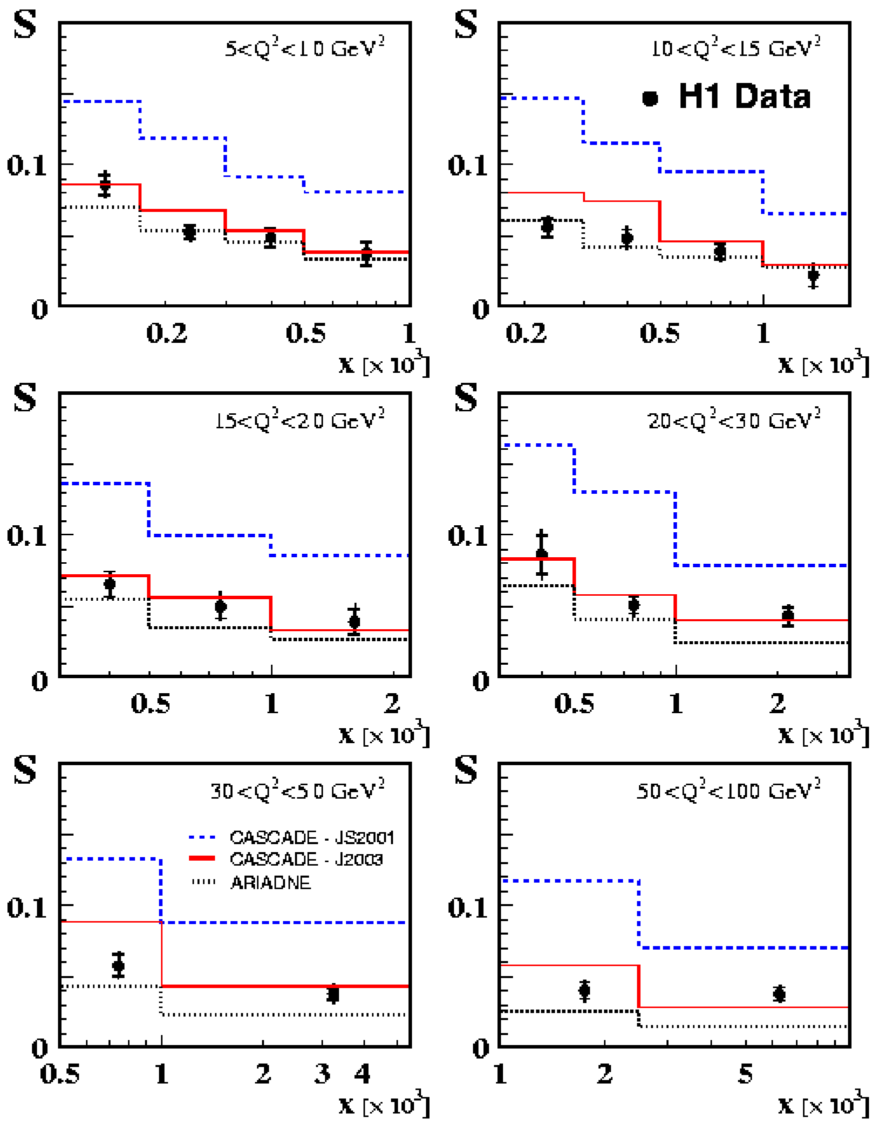
NLOJet (DGLAP $O(\alpha_s^3)$) describe data at large Q^2 and large x but fails to describe rise towards low x, especially at low Q^2



Inclusive dijets at low x: Azimuthal Asymmetry

- CDM (Ariadne) gives good description of data at low x and low Q^2 but fails at higher Q^2

- CCFM (Cascade) predictions with the JS2003 unintegrated PDFs describes data well, while with JS2001 overshoot data.



Conclusions: Parton Dynamics at low x

- DGLAP based calculations fail to reproduce HERA data at low x and forward jet pseudorapidities

- DGLAP + Models including resolved photon component give a better description of the data

- CDM also gives a reasonable description of the data

- CCFM based MC shows strong sensitivity to unintegrated gluon distributions

- Improved (BFKL based) calculations would help to perform decisive tests.

Multijet Production

Kinematic Range

$10\ \mathrm{GeV}^2 < Q^2 < 5000\ \mathrm{GeV}^2$

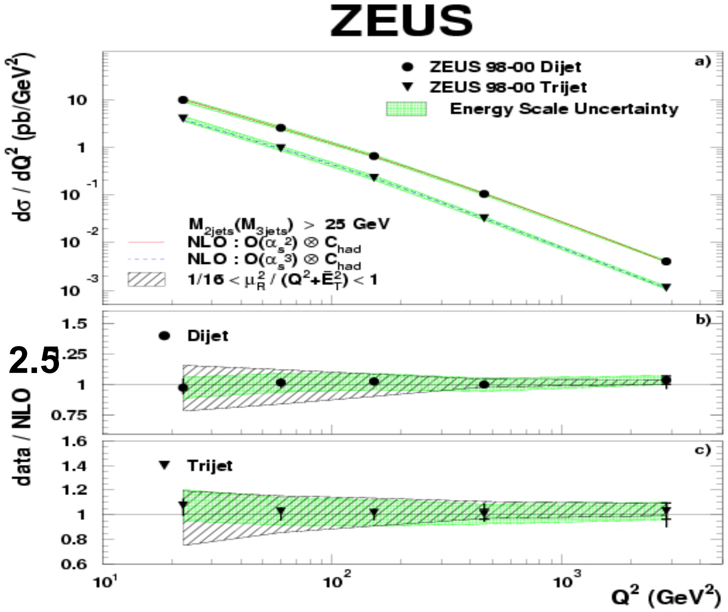
$0.04 < y < 0.6$, $\cos(\gamma_H) < 0.7$

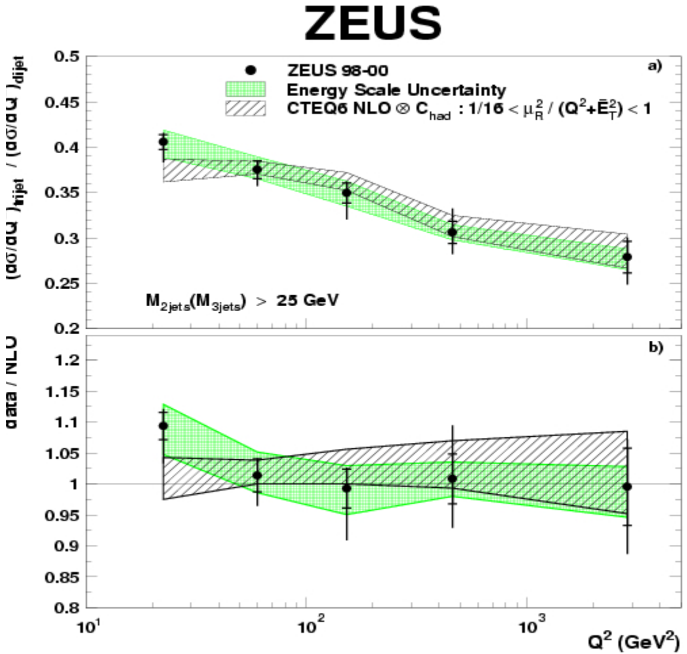
Jet Reconstruction

$E_{T,\mathrm{jetBRT}} > 5$ GeV, $-1 < \eta_{\mathrm{jetLAB}} < 2.5$

Inv. mass $M_{2,3\mathrm{jet}} > 25$GeV

NLOJet: $\mu_R^2 = \mu_F^2 = (E_T^2 + Q^2)/4$
CTEQ6 PDF, $\alpha_s = 0.1179$
Dijet NLO: $O(\alpha_s^2)$
Trijet NLO: $O(\alpha_s^3)$





$R_{3/2} = \sigma_{\mathrm{trijet}}/\sigma_{\mathrm{dijet}}$ ($O(\alpha_S)$)

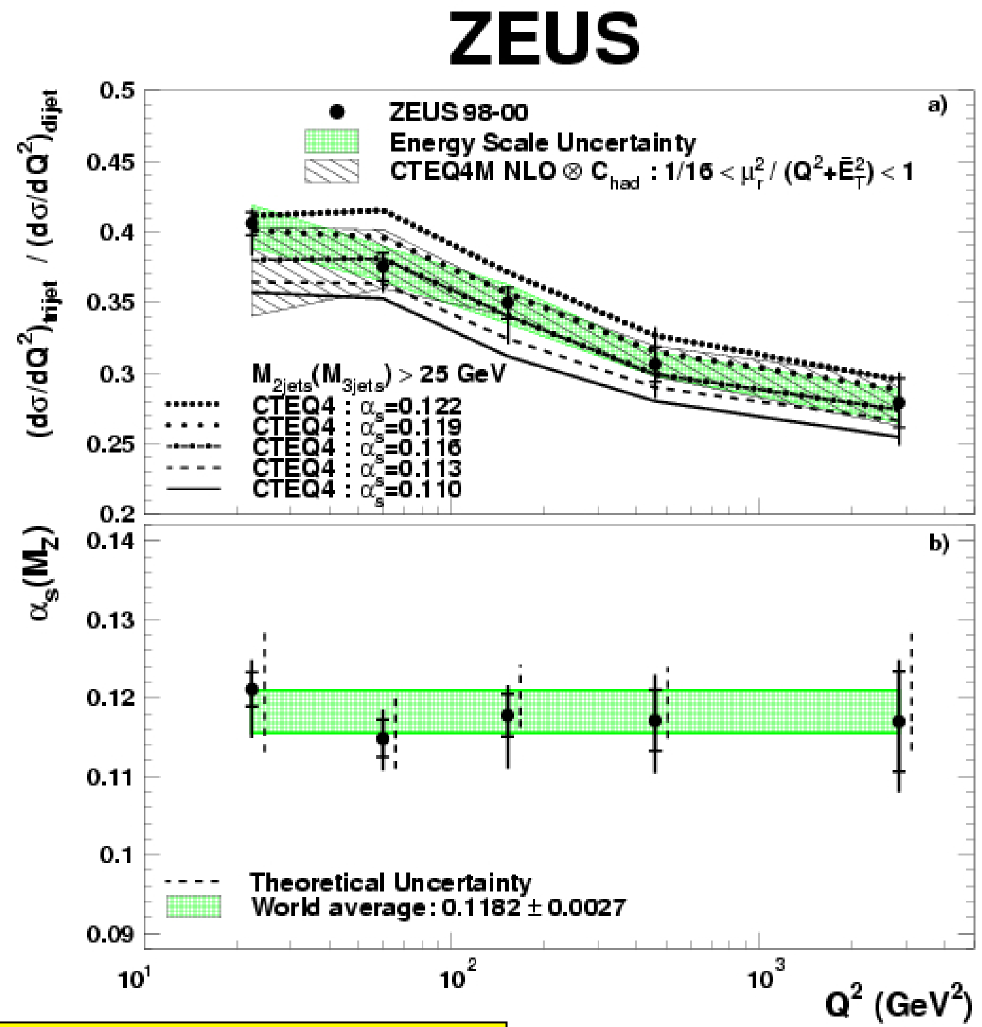
- NLOJet describes as dijet and trijet cross sections over 3 orders of magnitude in Q^2
- NLO uncertainties become large at low Q^2

- Correlated systematic uncertainties substantially reduced
- Scale dependence reduced
- Very sensitive test of QCD calculation
- NLO describes data over large range of scales

Multijet Production: α_s measurement

Procedure:

- Run NLOJET with several α_S values and fit with a linear function for each Q^2 bin
- Use this function to establish correlation of $R_{3/2}$ with $\alpha_S(M_z)$
- Extract α_S for each Q^2 bin and determine combined value with χ^2-fit.



The value of strong coupling constant α_s at the conventional scale of M_Z=91.9 GeV is measured to be:

$$\alpha_S(M_Z) = 0.1179 \pm 0.0013(\mathrm{stat.})\ ^{+0.0028}_{-0.0046}\ (\mathrm{syst.})\ ^{+0.0064}_{-0.0046}\ (\mathrm{th.})$$

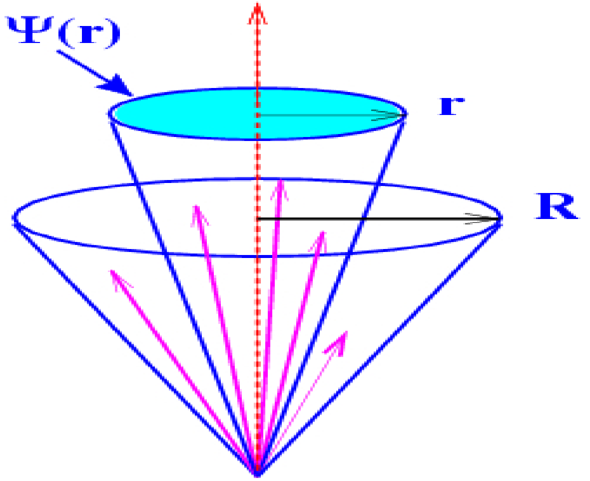
Substructure dependence of Jet Cross Sections

The integrated jet shape is the the fraction of the jet transverse energy that lies in a cone of radius r in the η-φ plane

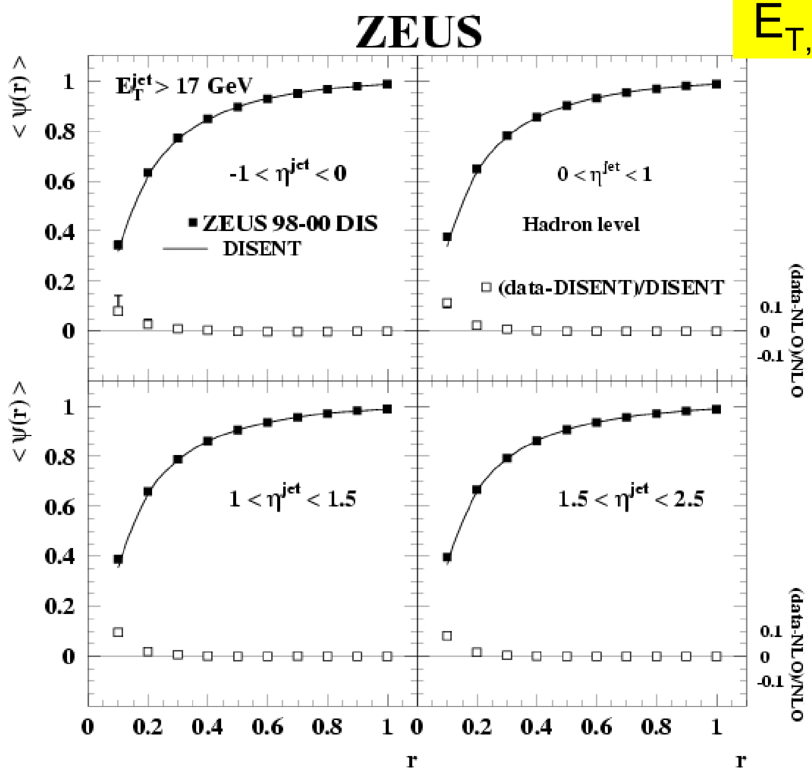
ZEUS 98-00 DIS

$Q^2>125\mathrm{GeV}^2$, inclusive jets

$E_{T,jet}>17\mathrm{GeV}, -1<\eta_{jet}<2.5$



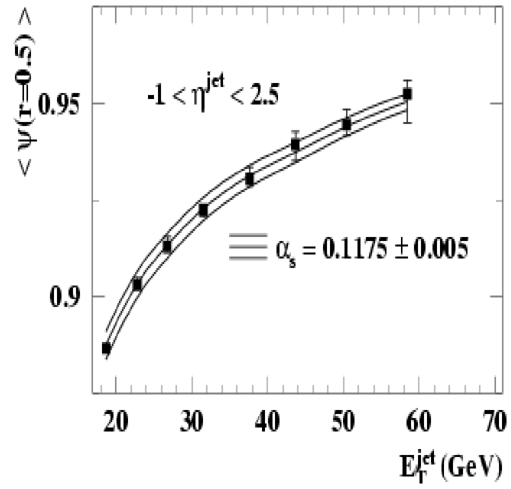
$$\langle\Psi(r)\rangle = \frac{1}{N_{jets}} \cdot \sum_{jets} \frac{E_T(r)}{E_T^{jet}}$$



•Good description of ψ(r) by NLO

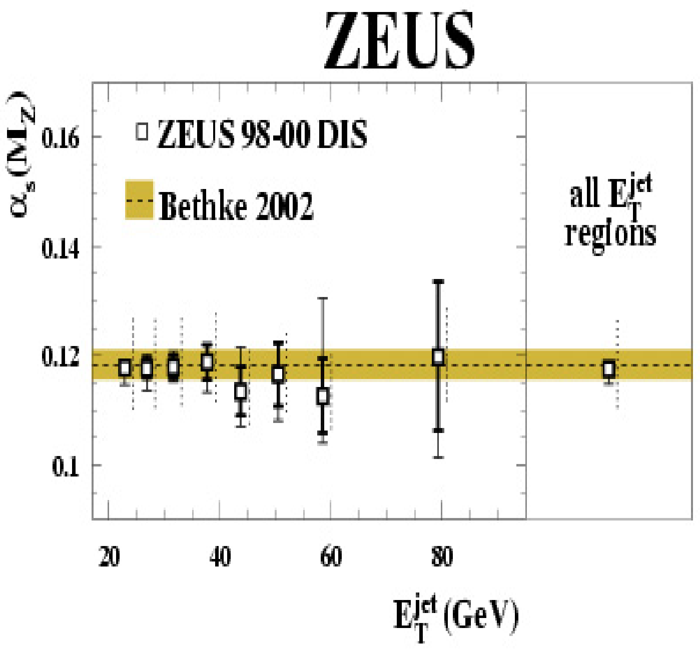
Substructure dependence of Jet Cross Sections

- NLO Calculations give very good description of ψ dependence with $E_{T,jet}$



- Sensitivity to α_s used for its determination

$$\alpha_S(M_Z) = 0.1176 \pm 0.0009(\text{stat.})\ {}^{+0.0009}_{-0.0026}\ (\text{syst.})\ {}^{+0.0091}_{-0.0072}\ (\text{th.})$$



- Statistical and experimental systematic errors are small. Theoretical errors are dominating.

Conclusions: Precision Tests of QCD and α_S Measurements

- ➢Jet data are very precise at high transverse energy where the experimental uncertainties and non-perturbative effects are small.
- ➢Multijet and Jet Substructure studies
  - ❑ Precision tests of perturbative QCD
  - ❑ Extraction of α_s with high precision
  - ❑ HERA α_s measurements well in agreement with world average
  - ❑ Need improved calculations for better accuracy
- ➢HERA – unique laboratory for jet physics