Forward Jet Production in DIS at HERA

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On behalf of the ZEUS Collaborations

Workshop on Low-x Physics
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Outline

- DIS Events at HERA
- QCD Dynamics at low x
- NLO QCD Calculations & MC Models
- Inclusive Forward Jet Measurements
- Conclusions

Forward Jet Production in deep inelastic scattering and low-x parton dynamics at HERA
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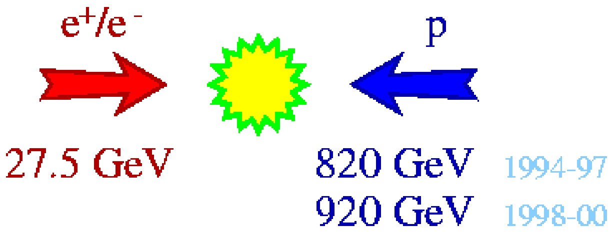
DIS Events at HERA



$$\sqrt{s} = \sqrt{4E_e E_p} \cong 300\ (320)\ GeV$$

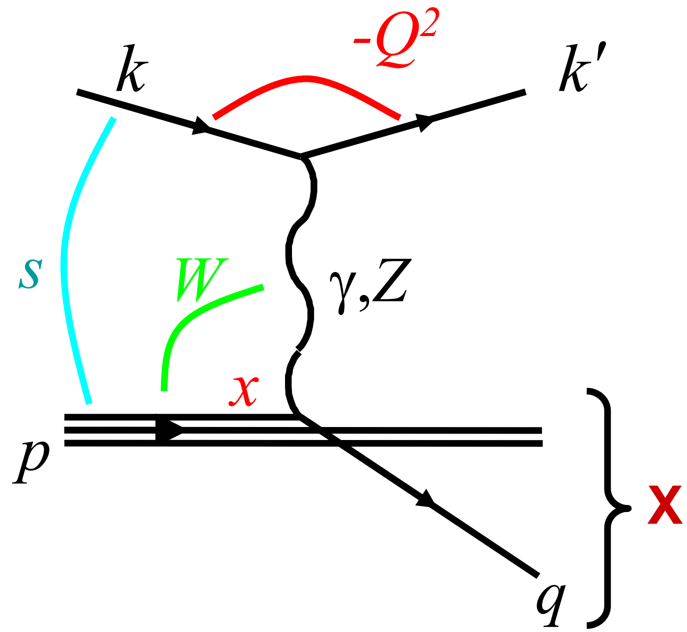
The Lorentz invariant kinematic variables to describe DIS are;

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

$$Q^2 \cong sxy$$

$$x = \frac{Q^2}{2(P.q)} \qquad 0 \le x \le 1$$

$$y = \frac{(P.q)}{(P.k)} \qquad 0 \le y \le 1$$



s: e-p c.m. energy

Q2 = -q2: 4-momentum transfer squared

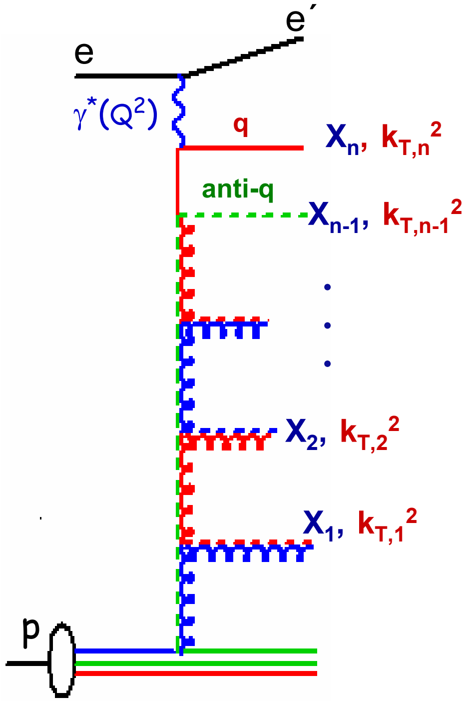
x: fraction of proton momentum carried by struck quark

y: inelasticity parameter

W: γ-p c.m. energy

QCD Dynamics at low x

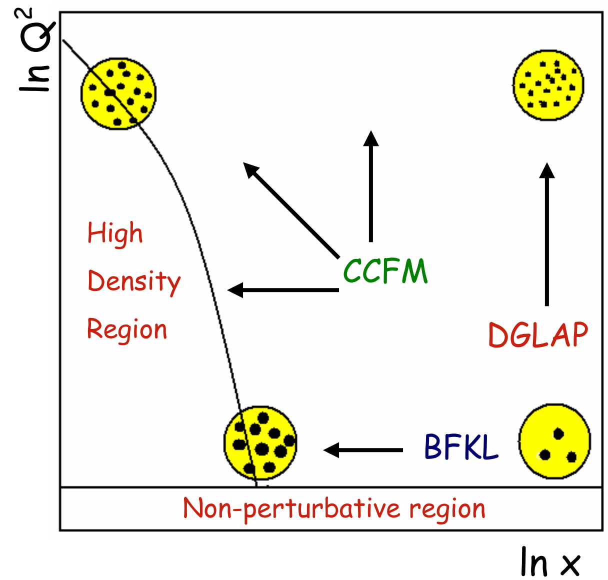
Jet/particle production has been successfully described by DGLAP at high scales (Q^2)



- **DGLAP:** strong k_T ordering

$$\alpha_s(Q^2)\ln(Q^2),\ \alpha_s(Q^2)\ln\frac{1}{x}\approx 1$$

- DGLAP is expected to break down at low scales and low x
- This break down might be observed in forward jet production at HERA



Other approaches to explain parton dynamics at low x ;

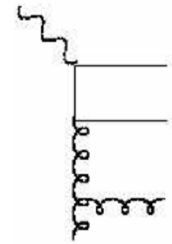
- **BFKL** : no k_T ordering, ordering in x
  Applicable at very low-x

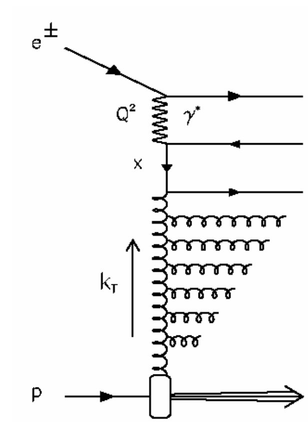
$$\alpha_s(Q^2)\ln(Q^2)\approx 1\ ,\ \alpha_s(Q^2)\ln\frac{1}{x}$$

- **CCFM** : un-integrated PDFs Angular ordering

QCD Calculations and MC Models

DISENT: Fixed order QCD partonic cross section, on mass shell ME + DGLAP , needs to be corrected to hadron level



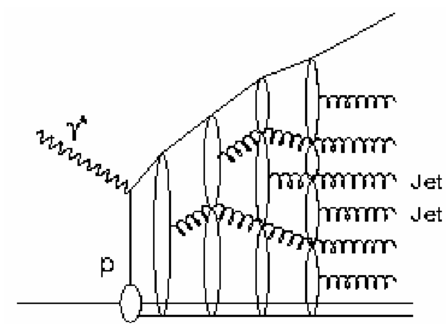


LEPTO: LO ME+PS , (DGLAP)

- → Strong ordering in k_T

ARIADNE: LO, an implementation of Color Dipole Model (CDM)

- → Independently radiating dipoles formed by emitted gluons
- → Random walk in k_T
- → BFKL-like



MC Models

CASCADE: LO off mass shell ME + PS based on k_T factorized CCFM evolution model

→ angular ordering in parton emission

$k_\perp$ is transverse momentum of emitted gluon $k_\perp > k_\perp^{cut}$

CASCADE set1 :

$k_\perp^{cut} = 1.33$ GeV

CASCADE set2 :

$k_\perp^{cut} = 1.18$ GeV

Non-singular terms in CCFM splitting function are also included

All MC models described here use LUND string fragmentation model for hadronization !

Measurement-1

Kinematic range

96-97 Data, $L \cong 38\ pb^{-1}$

$Q^2 > 25\ GeV^2$

No restriction for x_{Bj}

$y > 0.04$

Forward Jet selection

Jet Finding with Inclusive K_T Algorithm in Lab Frame

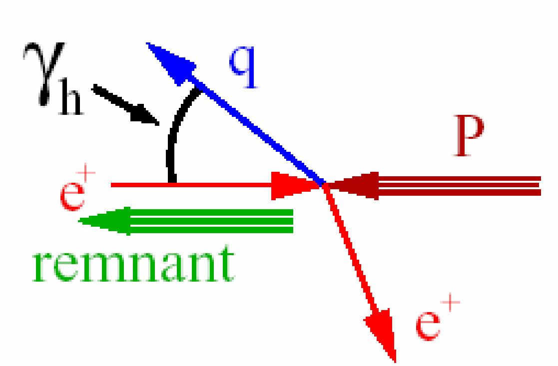
Global phase space

$E_{T,jet} > 6\ GeV$

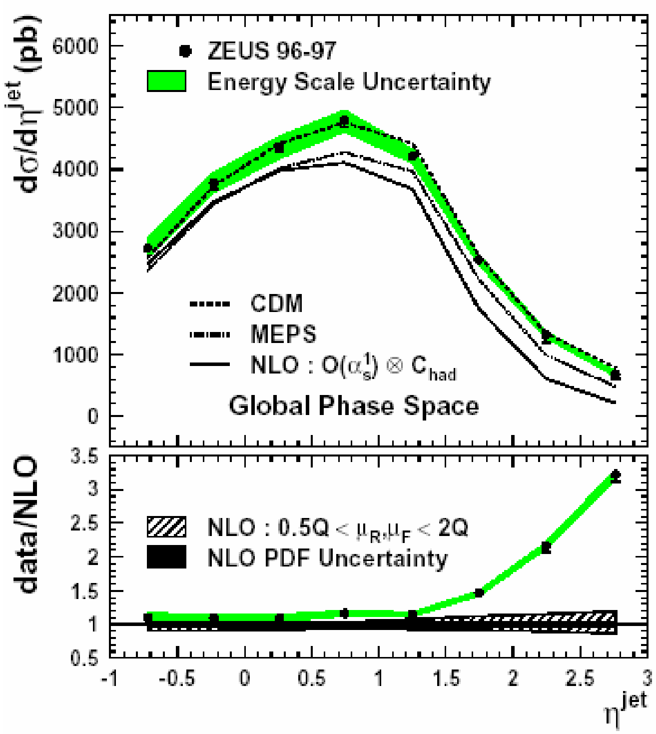
$-1 < \eta^{jet} < 3$

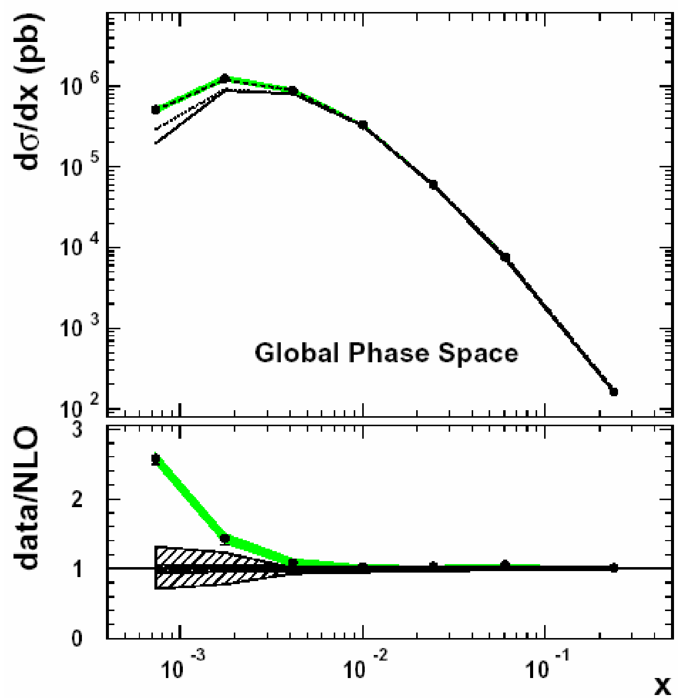
$\eta = -\log(\tan(\theta/2))$

Single jet events (QPM) dominant



Measurement-1 (Global phase space)





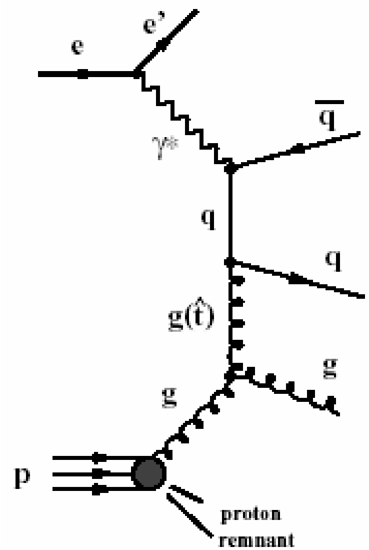
$V^* q \rightarrow q$ QPM

$V^* g \rightarrow q \bar{q}$ BGF

$V^* q \rightarrow q\, g$ QCDC

NLO calculations with $\mu_r^2 = \mu_f^2 = Q^2$, CTEQ6

Corrected to hadron level



CDM is in good agreement with data everywhere.

LEPTO (DGLAP) slightly lower than data but doing good for high x region

Fixed-order QCD calculations describe well low η and high x, BUT lower than data at low-x and in forward region,

Scale variations can not reflect the contributions from gluon exchange in *t-channel which* appear only in the higher orders . . .

Measurement-1

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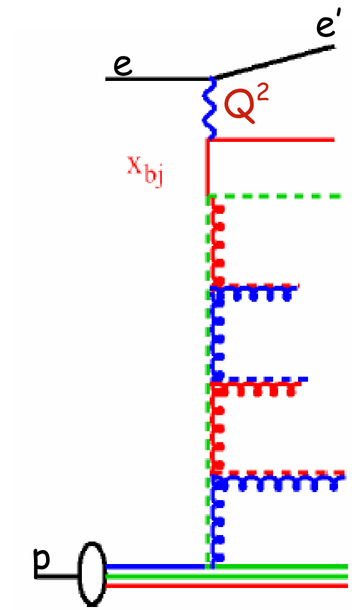


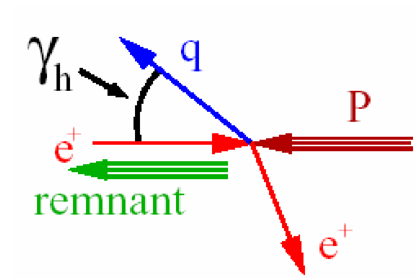
BFKL phase space

$E_{T,jet} > 6$ GeV

$0.5 < E^2_{T,jet}/Q^2 < 2$

$0 < \eta^{jet} < 3$

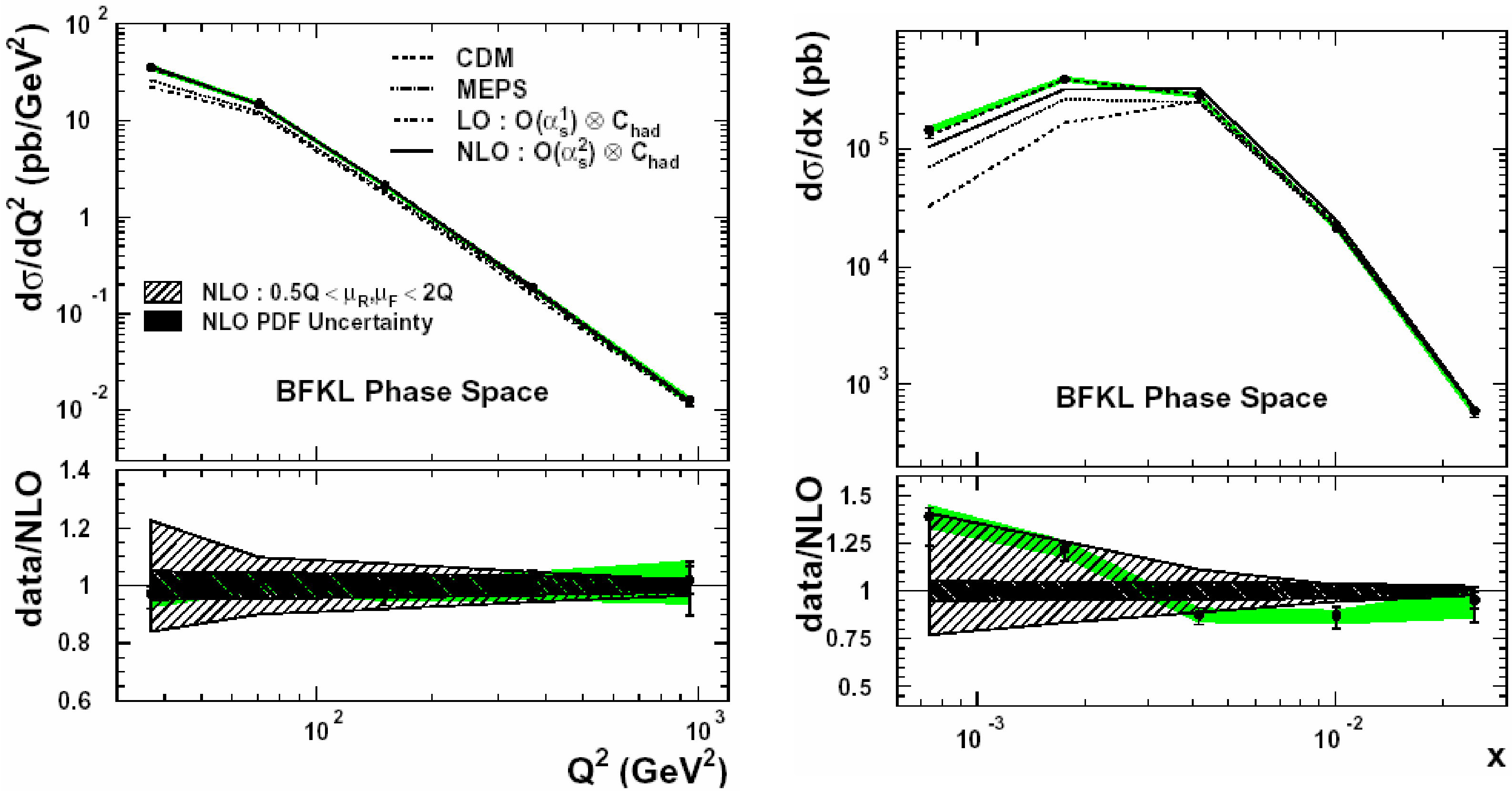
$\cos\gamma_{had} < 0$ Suppresses QPM



$$\cos\gamma = \frac{(\sum_i p_{x,i})^2 + (\sum_i p_{y,i})^2 - (\sum_i (E-p_z)_i)^2}{(\sum_i p_{x,i})^2 + (\sum_i p_{y,i})^2 + (\sum_i (E-p_z)_i)^2}$$

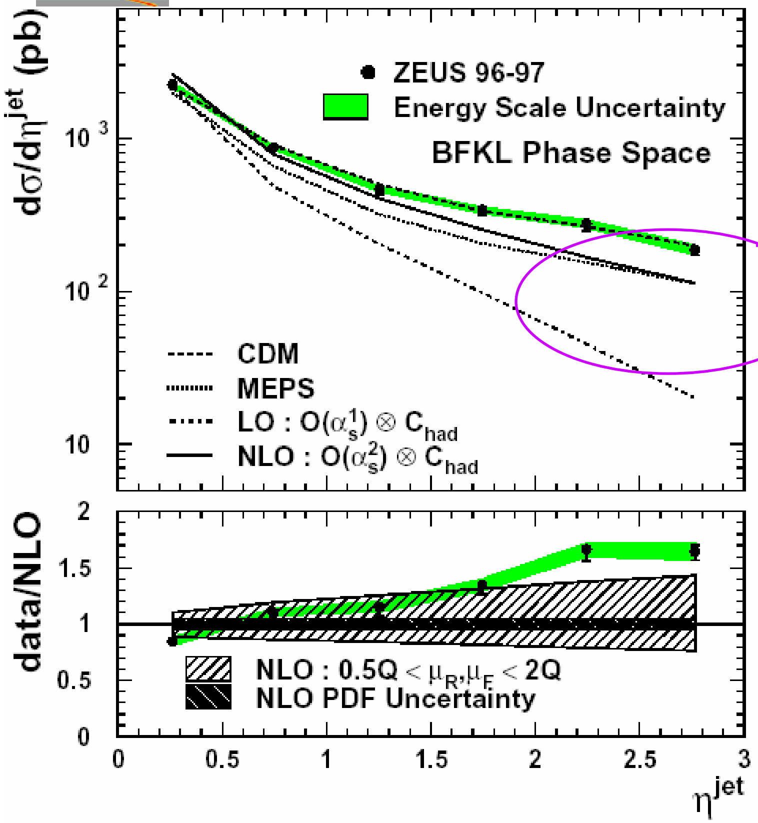
gluon exchange in t-channel is expected to be dominant

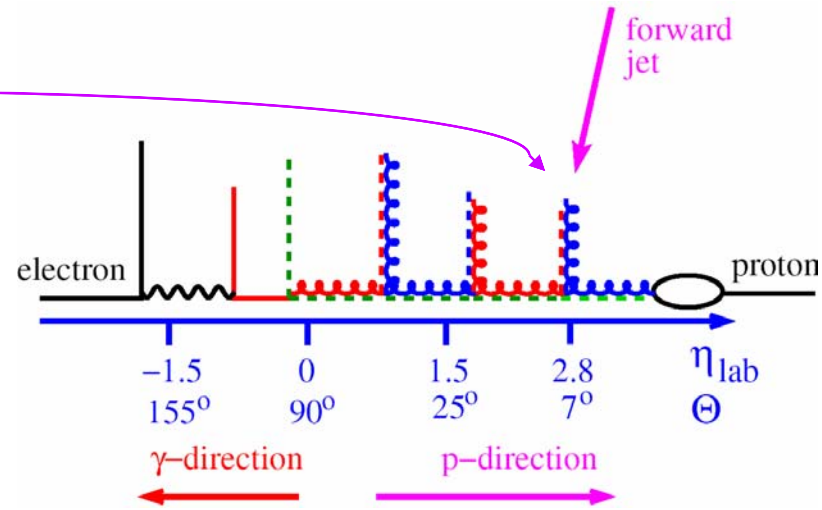
Measurement-1 (BFKL phase space)



- CDM describes both measured cross sections
- ME+PS:LEPTO (DGLAP) fails for low x_{Bj} and Q^2
- NLO calculations give a good description of Q^2 dependence
- From LO: $\mathcal{O}(\alpha_s^1)$ to NLO: $\mathcal{O}(\alpha_s^2)$ brings NLO prediction closer to data at low-x, since in this case gluon exchange in t-channel is included

Measurement-1 (BFKL phase space)





- Large increase of cross sections from $\mathcal{O}(\alpha_s^{\,1})$ to NLO: $\mathcal{O}(\alpha_s^{\,2})$ associated with the contribution from t-channel gluon exchange diagrams
- Discrepancy between data and NLO in the forward region $\eta^{jet}>1.5$, this region is more sensitive to higher order radiations (estimation of uncertainty from higher orders is large)
- CDM describes well measured cross section
- ME+PS:LEPTO (DGLAP) fails in all η^{jet} range

Measurement-2

Kinematical range

98-00 Data, $L \cong 82\ pb^{-1}$

$20 < Q^2 < 100\ GeV^2$

$0.0004 < x_{Bj} < 0.005$

$0.04 < y < 0.7$

Forward Jet selection

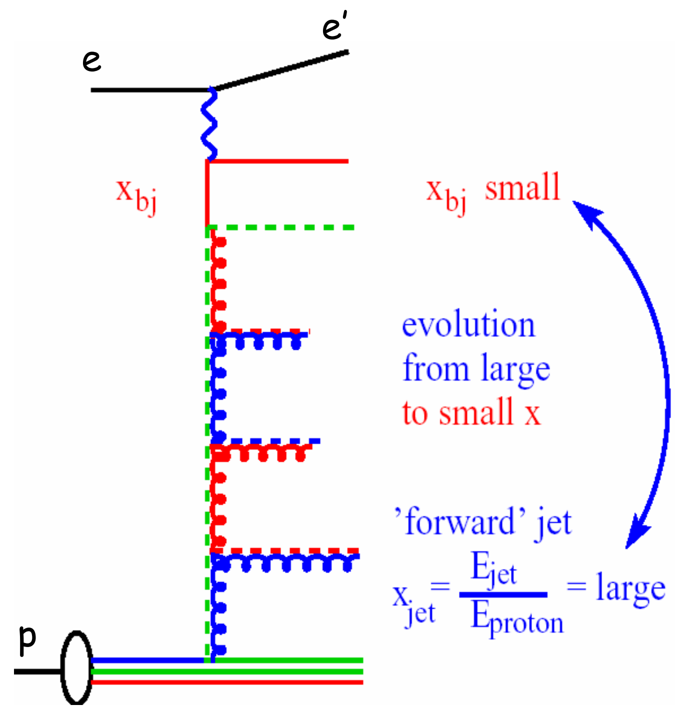
Jet Finding with Inclusive K_T Algorithm in Breit Frame

$E_{T,jet} > 5\ GeV$

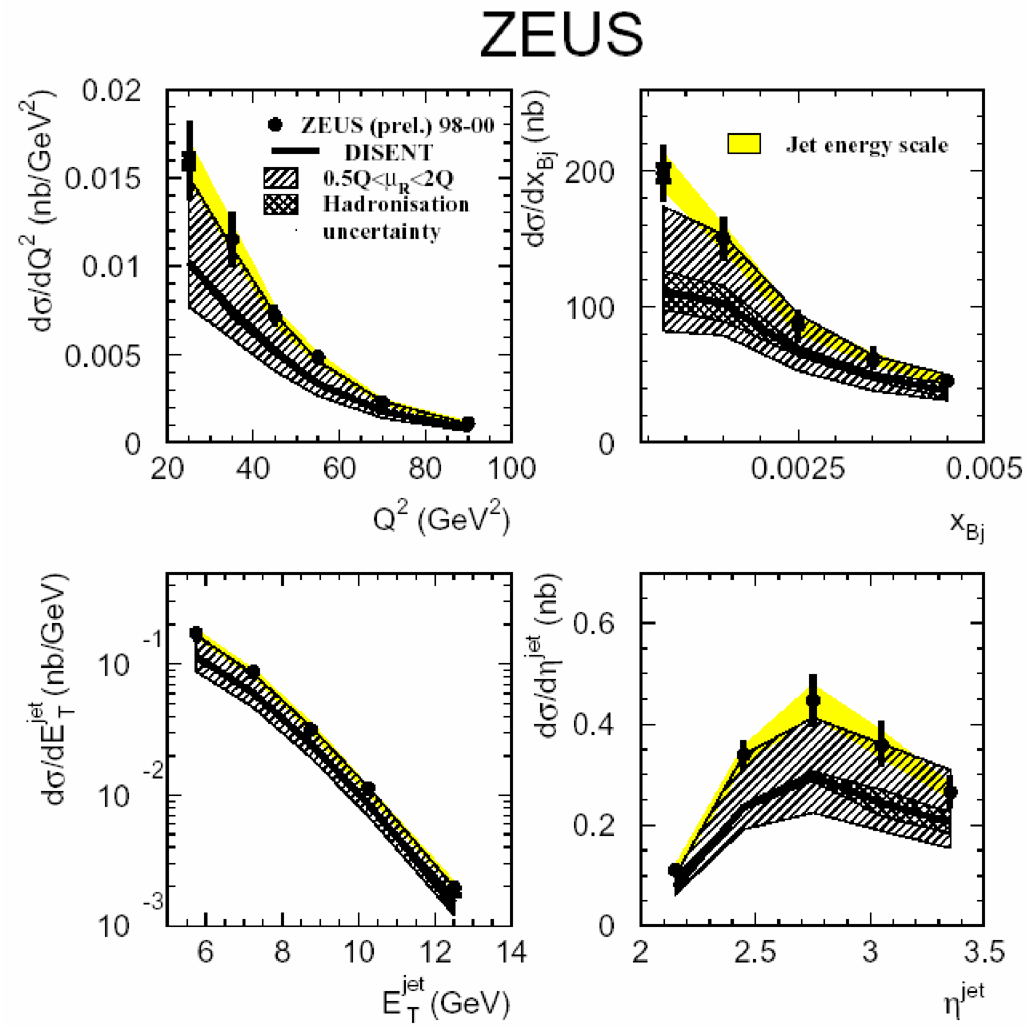
$0.5 < E^2_{T,jet}/Q^2 < 2$ → $E^2_{T,jet} \sim Q^2$ suppress DGLAP evolution

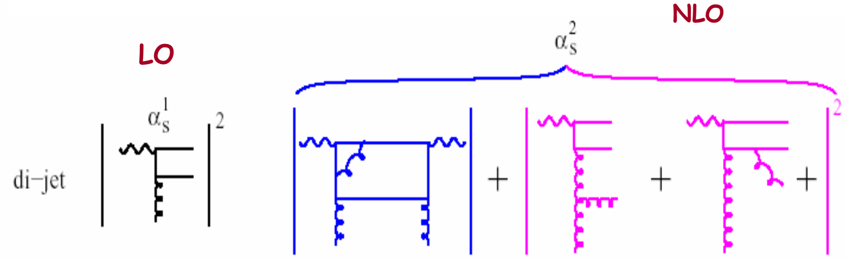
$x_{jet} > 0.036$ → $x_{jet} = E_{jet}/E_{proton} >> x_{Bj}$ enhances BFKL effect

$2 < \eta^{jet} < 3.5$



Measurement-2





$\mu_R^2 = \mu_f^2 = Q^2$

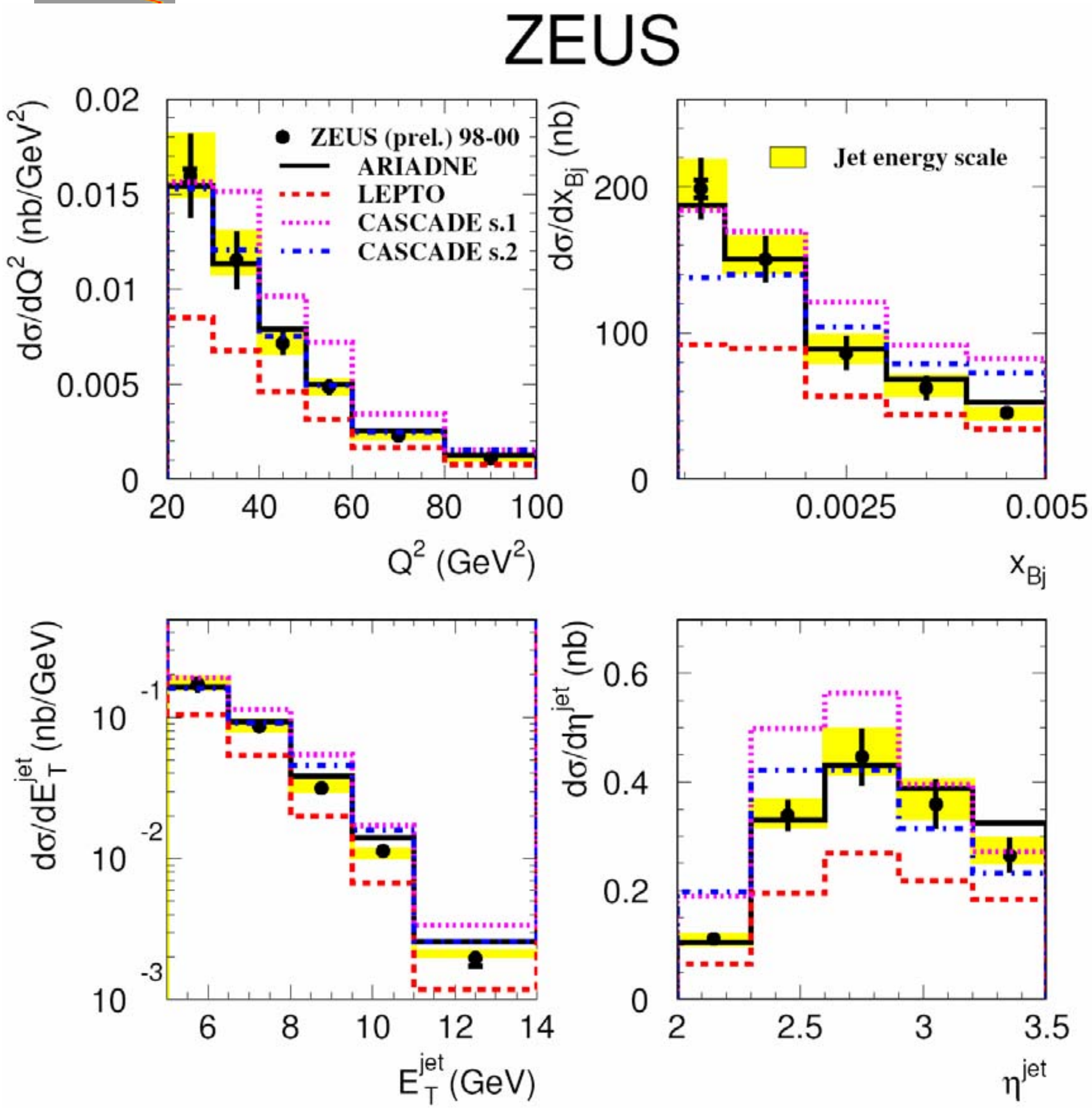
corrected to hadron level

Proton PDF: CTEQ5D

- NLO predictions tend to be below data, however it is within the thr. unc.

- Size of theoretical uncertainties in this phase space region , prevents us to make decisive conclusions

Measurement-2



Look more forward region $2 < \eta^{jet} < 3.5$

- LEPTO:DGLAP describes the shape but not the normalization (fails by a factor of ~ 2)
- CCFM set1 disagrees with all cross sections
- CCFM set2 in good agreement with data in Q^2 and E_T but fails to reproduce the shapes of x_{Bj} and η^{jet}
- CDM gives a good description of data in all measured cross sections } BFKL-like

Conclusions

✓ Parton dynamics at low-x studied in forward jet production in DIS by ZEUS coll.

✓ Lowest-order DGLAP (LEPTO) calculations fail to describe forward jet cross sections

✓ NLO calculations predict lower cross sections at low Bjorken-x and for very forward region, the theoretical uncertainty is large in this phase space, indicating that higher order corrections are needed

✓ Models beyond DGLAP evolution (CCFM, BFKL) look promising in describing parton dynamics at low x , NLO calculations based on BFKL & CCFM needed.

✓ Forward jet measurements can provide constraint on Un-integrated Gluon Densities

Any idea of a new measurement to search for a BFKL signature is welcome !!!!