Study of BFKL Dynamics through the jet Angle Correlation, Rapidity Gap between Jets and Forward Jet Production at HERA

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On behalf of the ZEUS and H1 Collaborations

Low x Workshop

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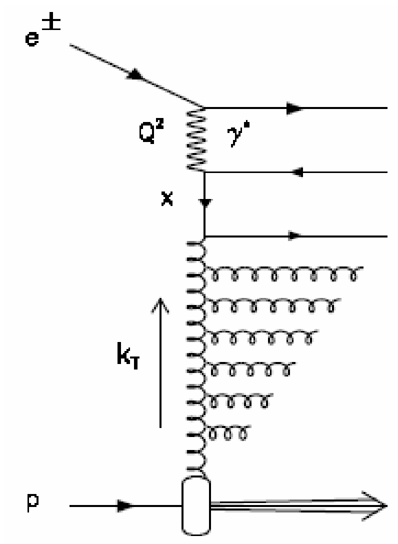
O U T L I N E:

- QCD Dynamics at Low *x*
- MC Modes and QCD Calculations
- Inclusive Forward Jet Measurement (with ZEUS)
- Decorrelation of Dijets at Low x and Q^2
- Photoproduction of Events with Rapidity Gaps Between Jets at ZEUS
- Conclusions

QCD Dynamics at Low *x*

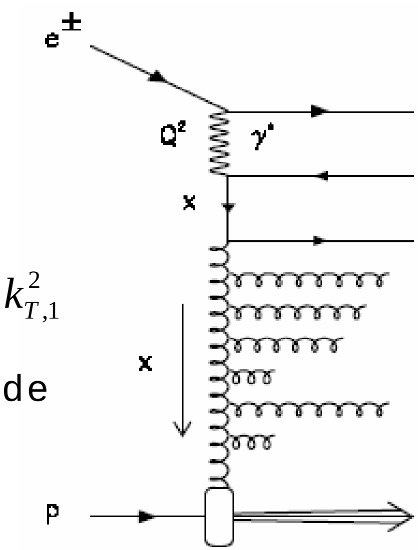


DGLAP

Evolution & resummation in powers of *lnQ2*

$$Q^2 >> k_{T,n}^2 >> ... >> k_{T,2}^2 >> k_{T,1}^2$$

The DGLAP gluon cascade is strongly ordered in k_T and ordered in x



BFKL

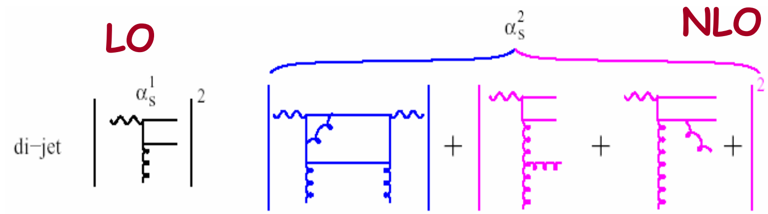
Evolution & resummation in powers of *ln(1/x)*

$$x_1 >> x_2 >> ... >> x_n >> x$$

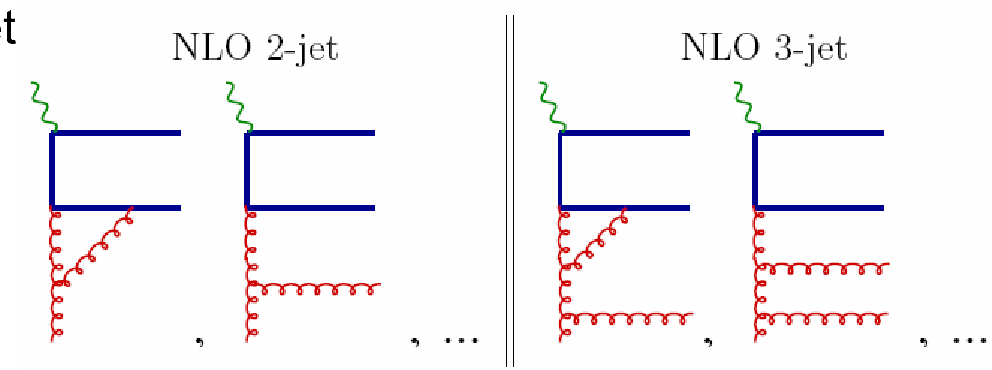
The BFKL is only strongly ordered in x

- **DGLAP** (**D**okshitzer-**G**ribov-**L**ipatov-**A**ltarelli-**P**arisi) is expected to break down at low *x* and Q^2 region
- **BFKL** (**B**alitsky-**F**adin-**K**uraev-**L**ipatov) can be applicable at low x
- **CCFM (C**iafaloni-**C**atani-**F**iorani-**M**archesini) describes an evolution in both Q^2 and *x* and approches BFKL at low *x* and DGLAP at high Q^2; angular ordering

MC Models and QCD Calculations



- DISENT: Fixed order QCD partonic cross section, on mass shell ME + DGLAP



- NLOJET++: calculate (2+1)- and (3+1)-jet cross sections at NLO level

- LEPTO: LO ME+PS , (DGLAP)
  - Strong ordering in k_T

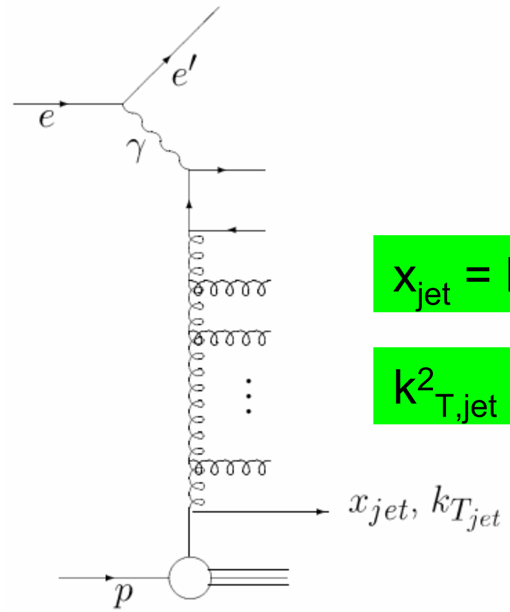
- ARIADNE: LO, an implementation of Color Dipole Model (CDM)
  - Independently radiating dipoles formed by quarks and emitted gluons
  - Random walk in k_T like in BFKL

- CASCADE: LO off mass shell ME + parton shower based on k_T factorized CCFM evolution model
  - Angular ordering in parton emission
  - Examples of unintegrated gluon densities fits *A0*, *J2003 set 1* (with new treatment of soft region) and *J2003 set 2* (fit form includes non singular terms)

ZEUS Inclusive Forward Jet Measurements

DIS kinematical range

95-97 Data, L≅38 pb^{-1}	98-00 Data, L≅ 82 pb^{-1}
$Q^2 > 25$ GeV^2	$20 < Q^2 < 100$ GeV^2
No restriction	$0.0004 < x_{Bj} < 0.005$
$y > 0.04$	$0.04 < y < 0.7$



$x_{jet} = k_{z,jet}/p \gg x_{Bj}$

$k^2_{T,jet} \sim Q^2$

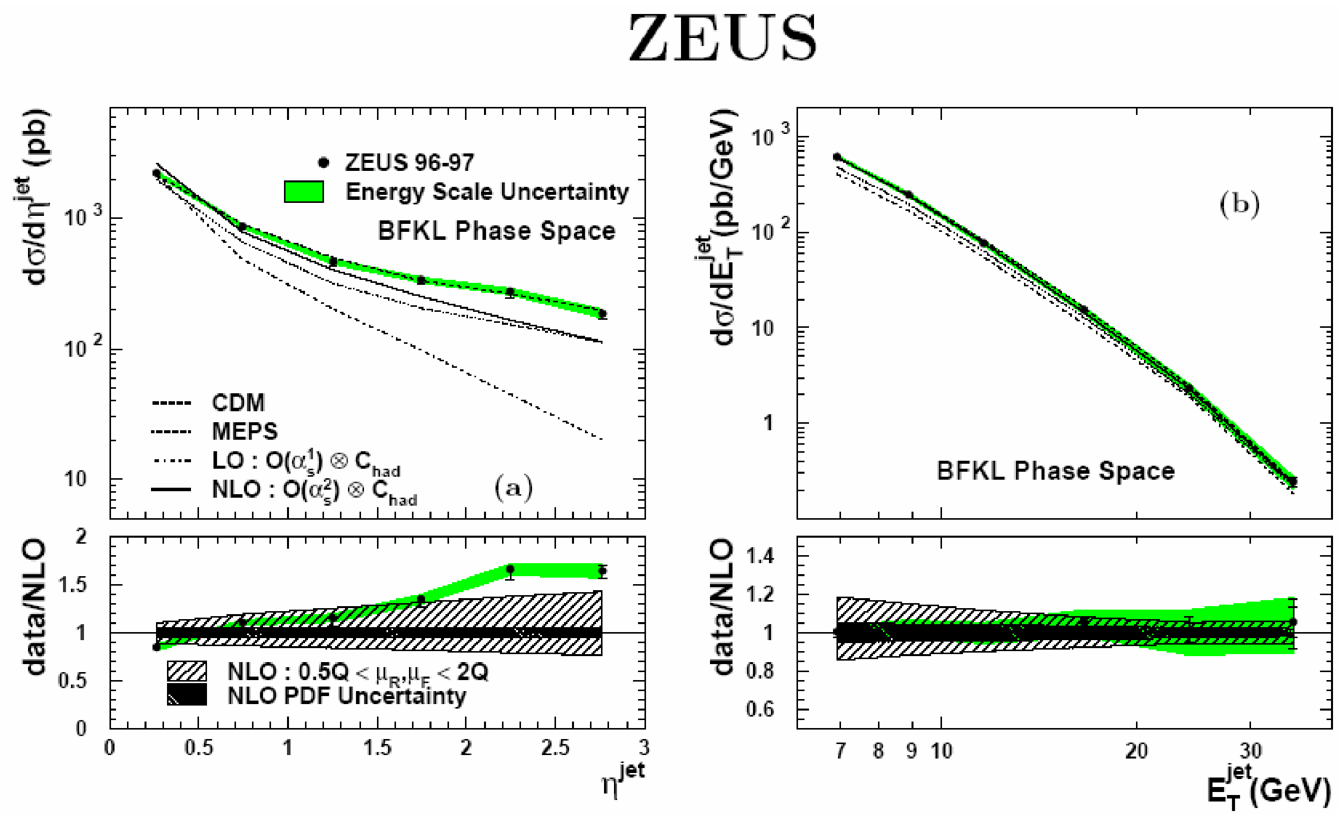
Forward Jet selection

Jet finding with inclusive K_T algorithm in Lab frame	Jet finding with inclusive K_T algorithm in Breit frame
$E_{T,jet} > 6$ GeV	$E_{T,jet} > 5$ GeV
No restriction	$x_{jet} > 0.036$
$0.5 < E^2_{T,jet}/Q^2 < 2$	$0.5 < E^2_{T,jet}/Q^2 < 2$
$0 < \eta^{jet} < 3$	$2 < \eta^{jet} < 3.5$
$\cos\gamma_{had} < 0$ suppresses QPM	

- Jet carries a large fraction of longitudinal momentum of proton in order to maximise phase space for BFKL evolution

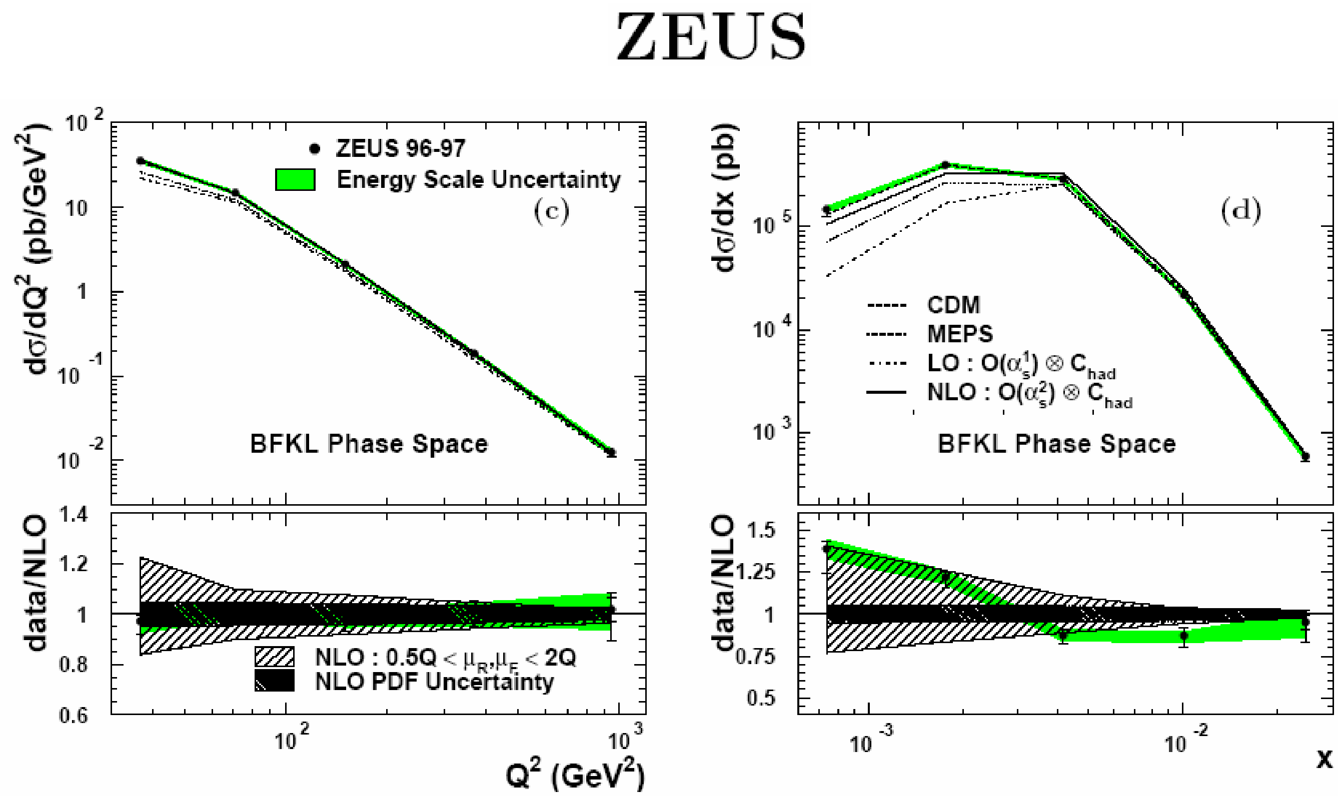
- DGLAP type of evolution is suppressed, leaving no room for strong ordering in transverse momenta

Inclusive Forward Jet Measurement (Phys. Lett. B 632 (2006) 13-26)



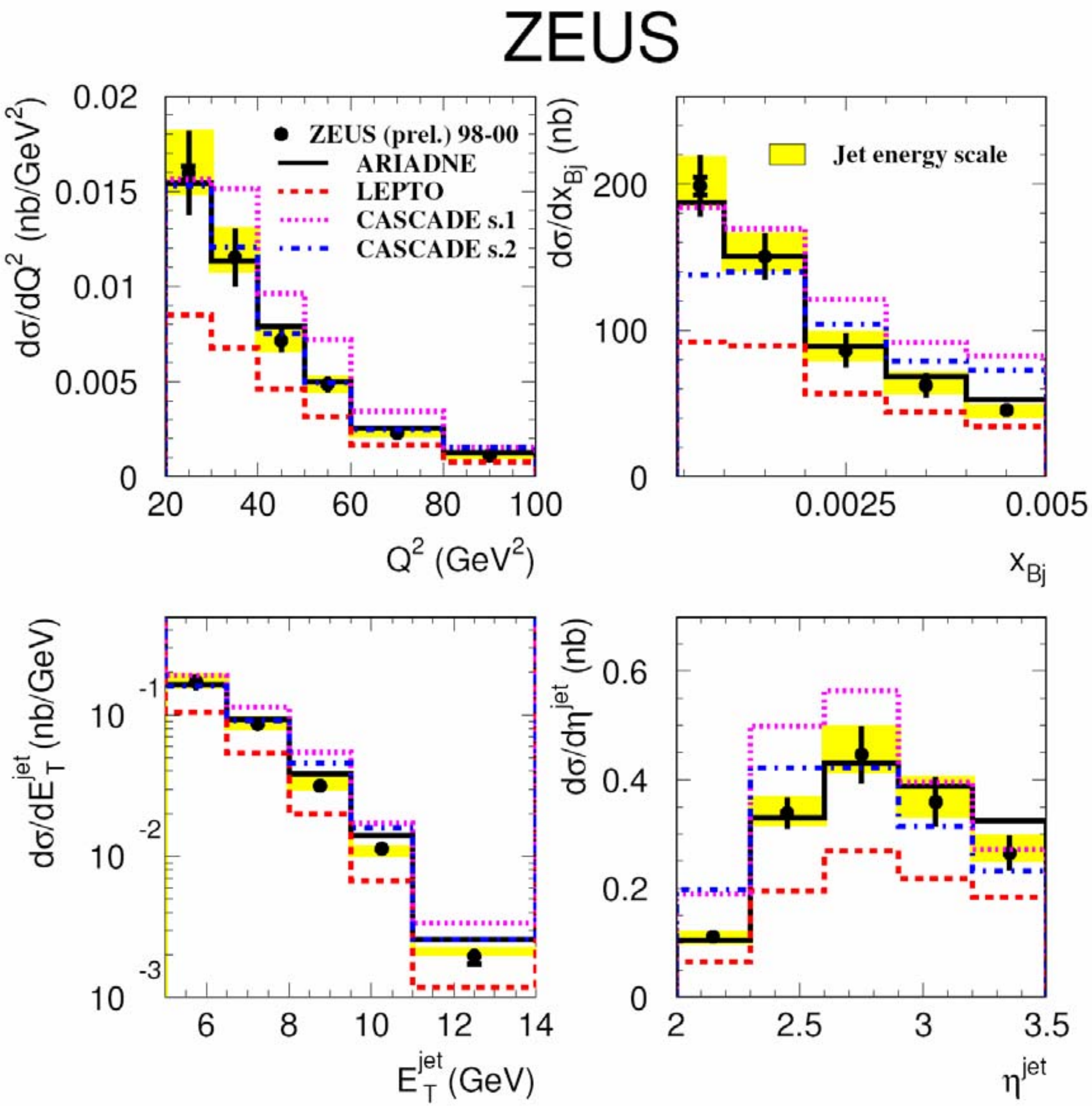
- NLO gives a good description of E_T^{jet} dependence
- Discrepancy between data and NLO in the forward region $1.5 < \eta^{jet} < 3$; this region is more sensitive to higher order radiations (estimation of uncertainty from higher orders is large)

Inclusive Forward Jet Measurement



- NLO predictions lower than data at low x_{Bj} but still within theoretical uncertainties. Gives a good description of Q^2 dependence
- CDM describes all measured cross sections
- ME+PS: LEPTO (DGLAP) fails for low x_{Bj} and Q^2

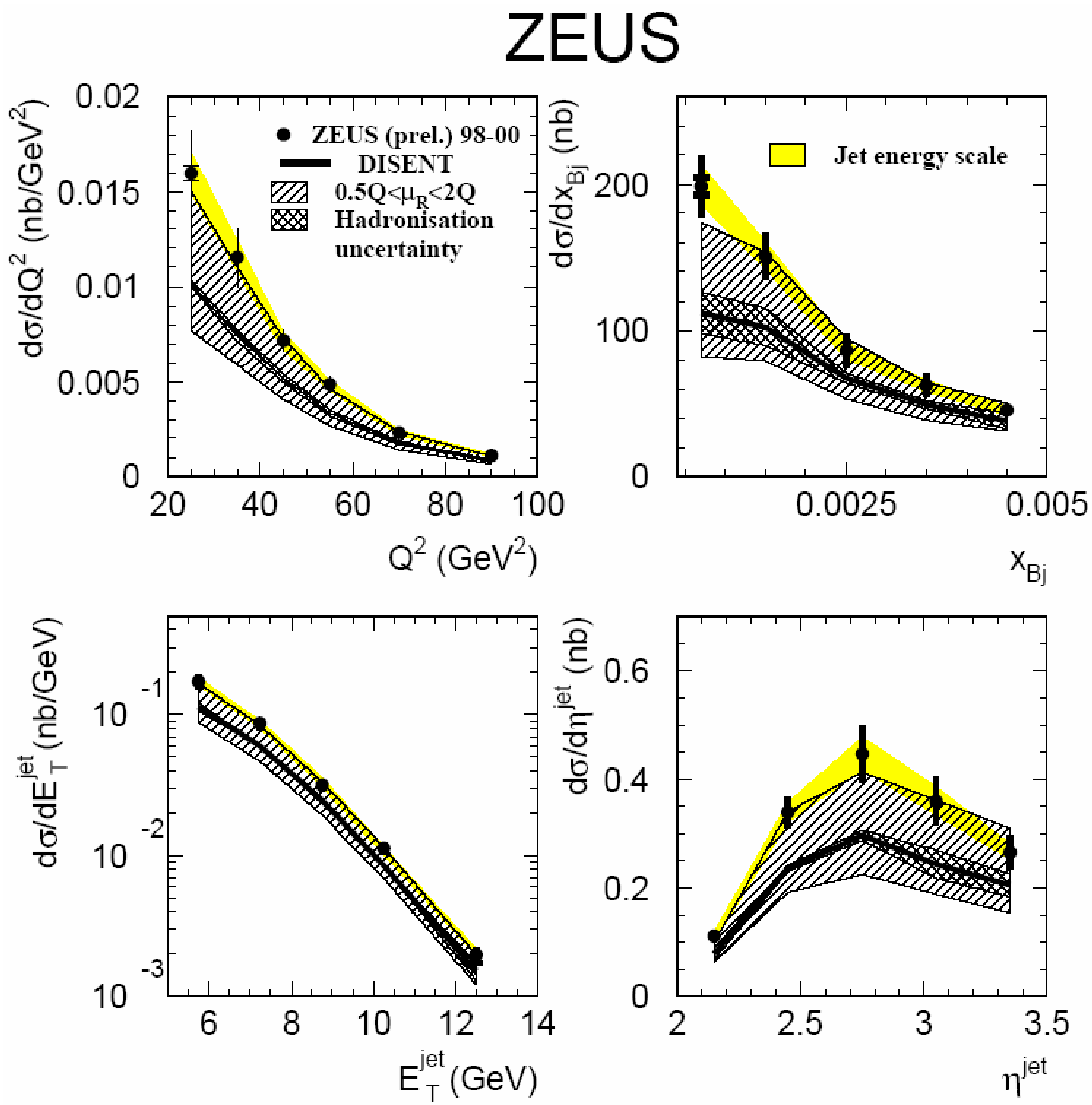
Inclusive Forward Jet Measurement



Measurement extended to $2<\eta^{jet}<3.5$

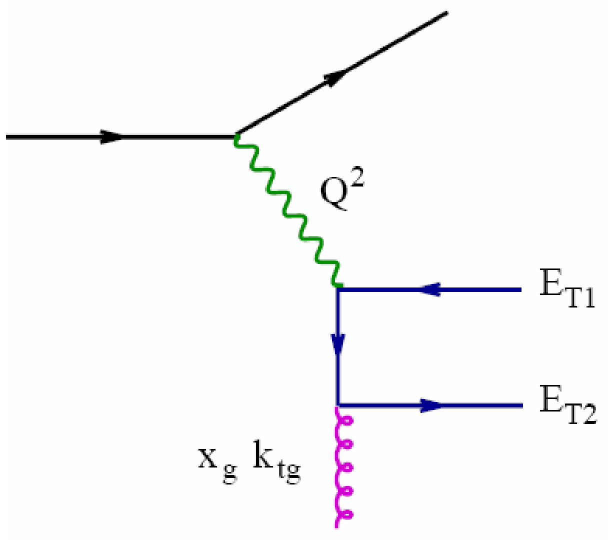
- CASCADE *set1* disagrees with all cross sections
- CASCADE *set2* (with non singular terms) is in a good agreement with data in Q^2 and E_T^{jet} but fails to reproduce the shapes of x_{Bj} and η^{jet}
- CDM (ARIADNE) gives a good description of data in all measured cross sections
- LEPTO underestimates data by a factor of 2

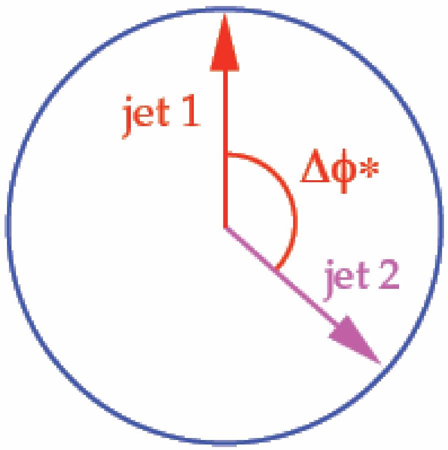
Inclusive Forward Jet Measurement



- Average hadronisation correction obtained with LEPTO and ARIADNE
- Proton PDF CTEQ5D
- NLO predictions lower than data but within theoretical uncertainties (except very low x_{Bj})
- Theory has too large uncertainty
- No disagreement with NLO DGLAP has been observed for forward jets

Decorrelation of Dijets at Low x and Q2



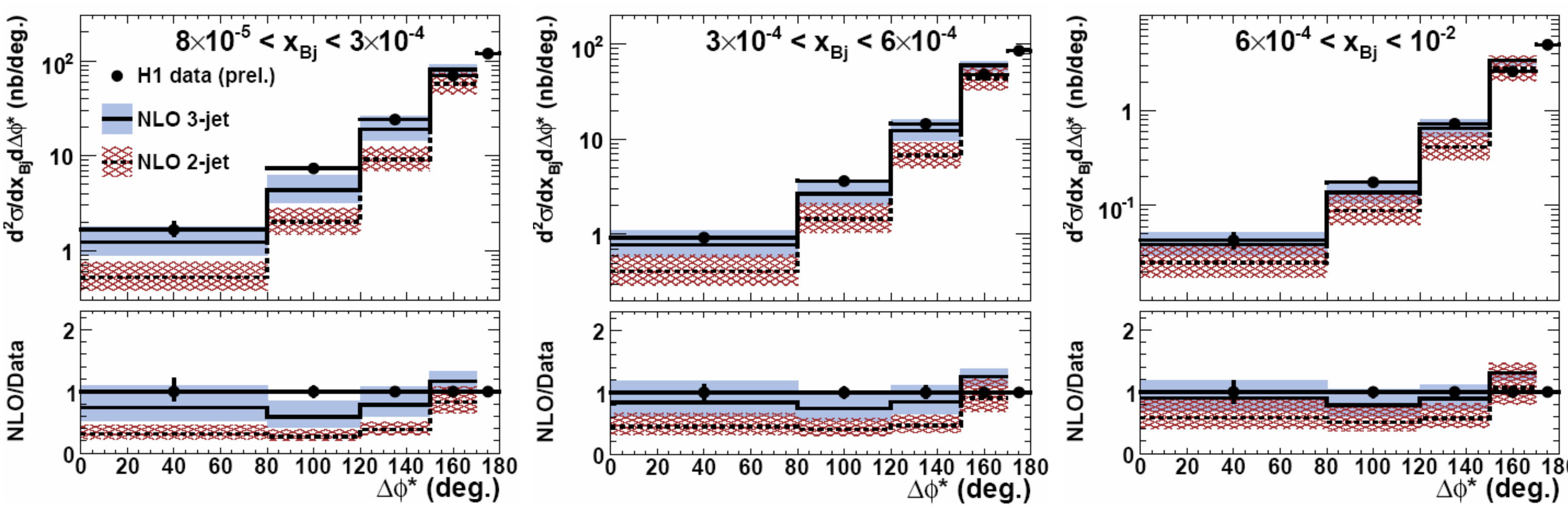


- In LO DGLAP gluon collinear with proton; therefore jets are in a back-to-back azimuthal configuration in HCM; $k_{tg} \approx 0$ and $\Delta\varphi^* \approx 180°$

- Higher order QCD radiation: $k_{tg} \neq 0$ and $\Delta\varphi^* < 180°$

- Alternative parton evolution (BFKL, CCFM) without k_{tg}–ordering leading to $k_{tg} \neq 0$ and broader $\Delta\varphi^*$ spectrum compared to DGLAP ($\Delta\varphi^* < 180°$)

Decorrelation of Dijets at Low x and Q2



99-00 Data, L≅ 64 pb^{-1}

5 < Q^2 < 100 GeV^2

0.1 < y < 0.7

Dijets:

Inclusive k_T algorithm

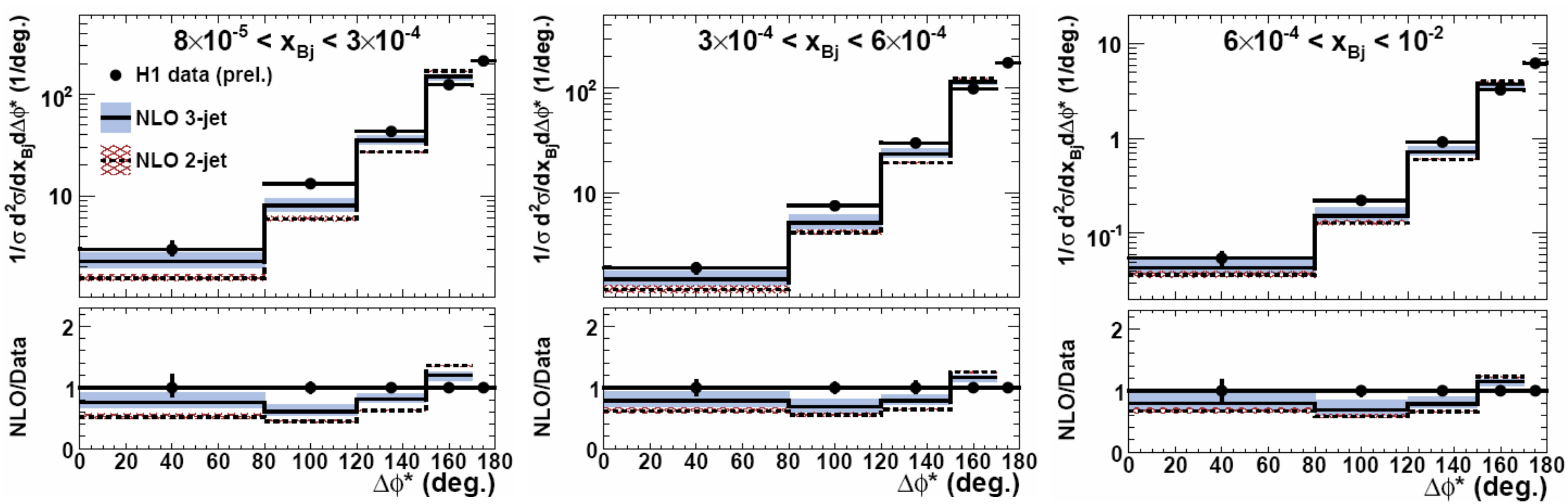
$-1 < \eta_{1,2} < 2.5$ (LAB)

$E^*_T > 5$ GeV (HCM)

- The two jets closest to the scattered electron are chosen as Dijet system
- Infrared sensitivity: no NLO predictions for Δφ* ≈ 180°

- NLO 2-jet : one parton radiation not enough
- NLO 3-jet gives better description of data but systematically low for Δφ* < 150°; agrees within large scale uncertainties (20 - 50%)

Decorrelation of Dijets at Low x and Q2

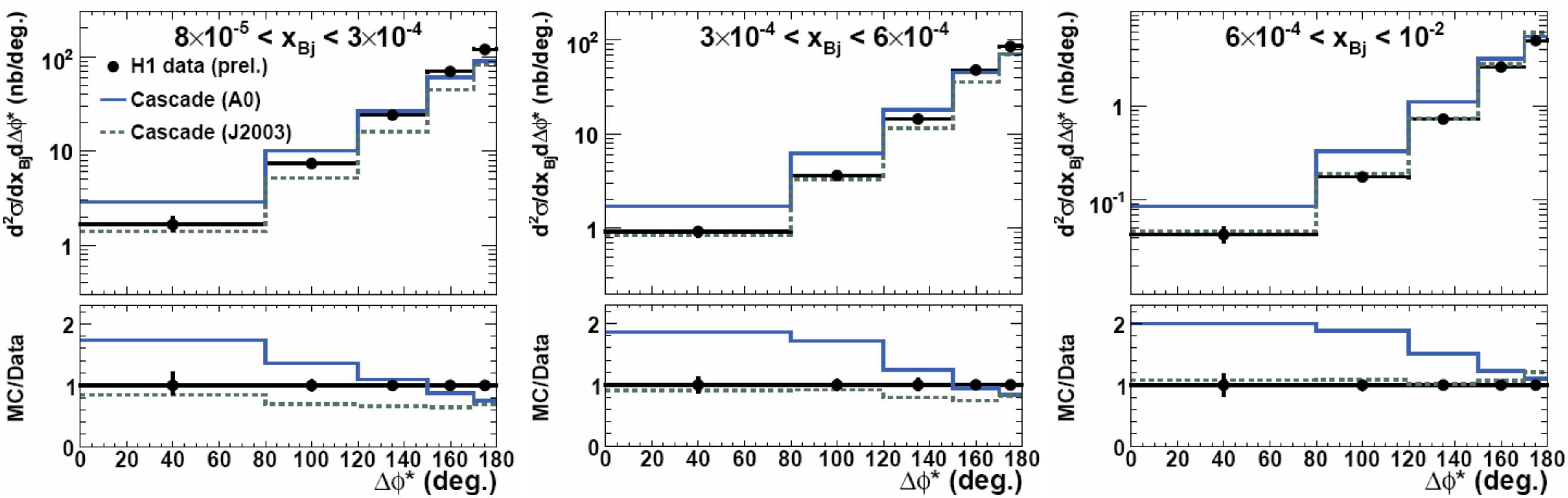


- Normalise to visible cross section in each x_{Bj} bin ($0 < \Delta\varphi^* < 170°$)

Cancellation of scale uncertainties (now 20%)

- NLO 3-jet **is not in agreement with data**

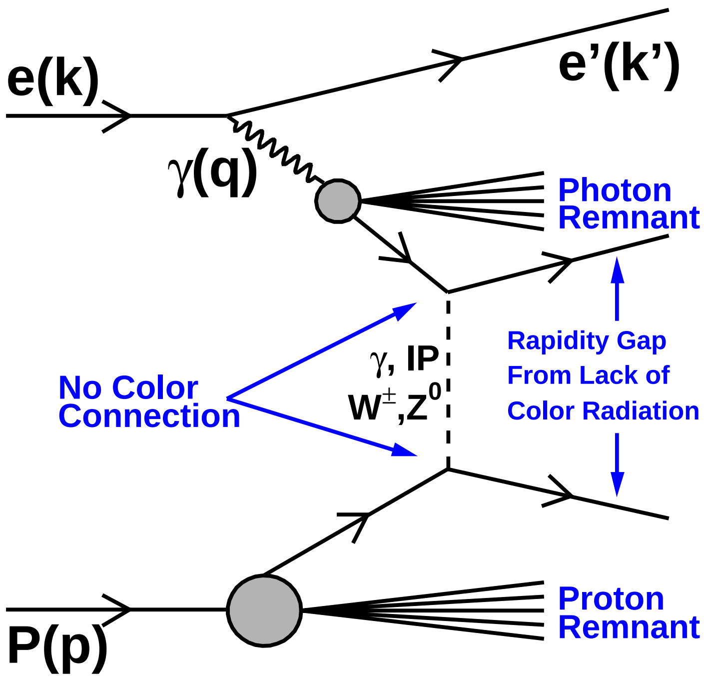
Decorrelation of Dijets at Low x and Q2



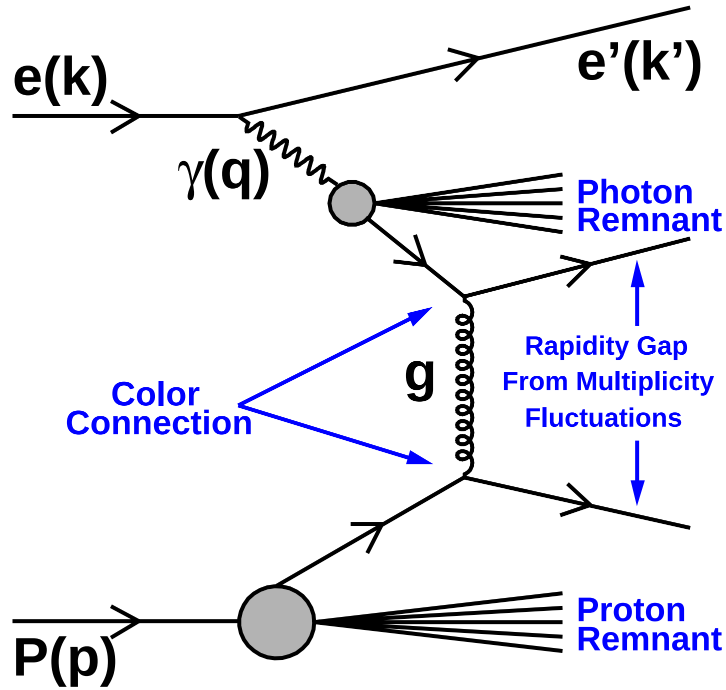
- Sensitivity to unintegrated gluon densities
- Cascade J2003 describes data reasonably well except in lowest x_{Bj} bin
- Cascade A0 fails in all x_{Bj} bins. A0 has too hard k_t-spectrum

Rapidity Gaps Between Jets

Color-Singlet Exchange



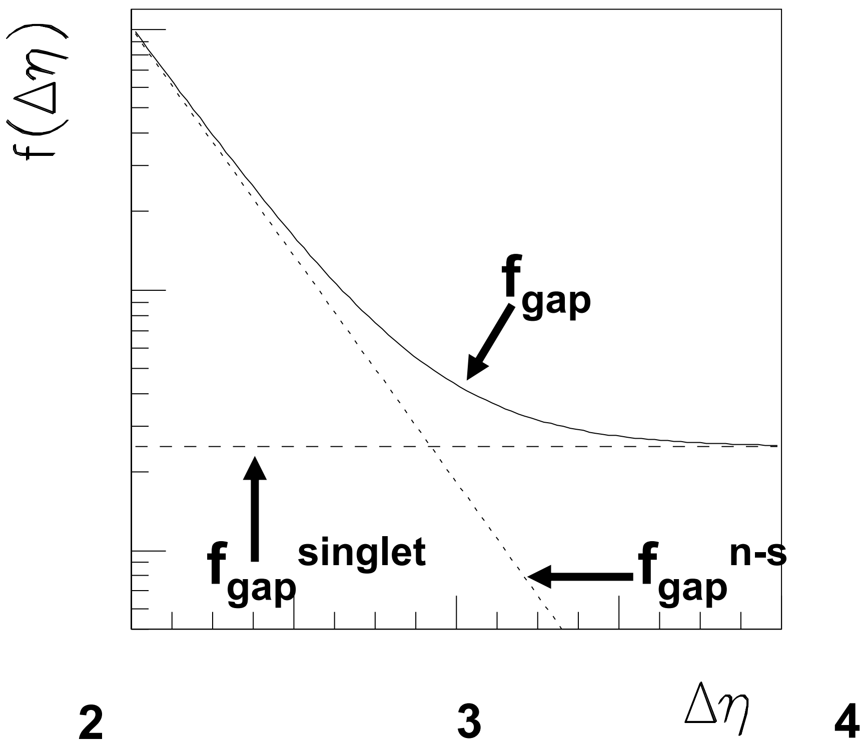
Color-Non-Singlet Exchange



- BFKL-Pomeron is an example of Color-singlet exchange. Non-diffractive fluctuations in particle multiplicity produce gap - Color-non-singlet exchange
- $\Delta\eta$ - distance between leading and trailing jet centers
- E_T^{Gap} - total E_T of jets between leading and trailing jet centers. Gap event has small energy in Gap: $E_T^{Gap} < E_T^{Cut}$

Rapidity Gaps Between Jets

Expectation for Behavior of Gap Fraction (J. D. Bjorken, V. Del Duca, W.-K. Tung)



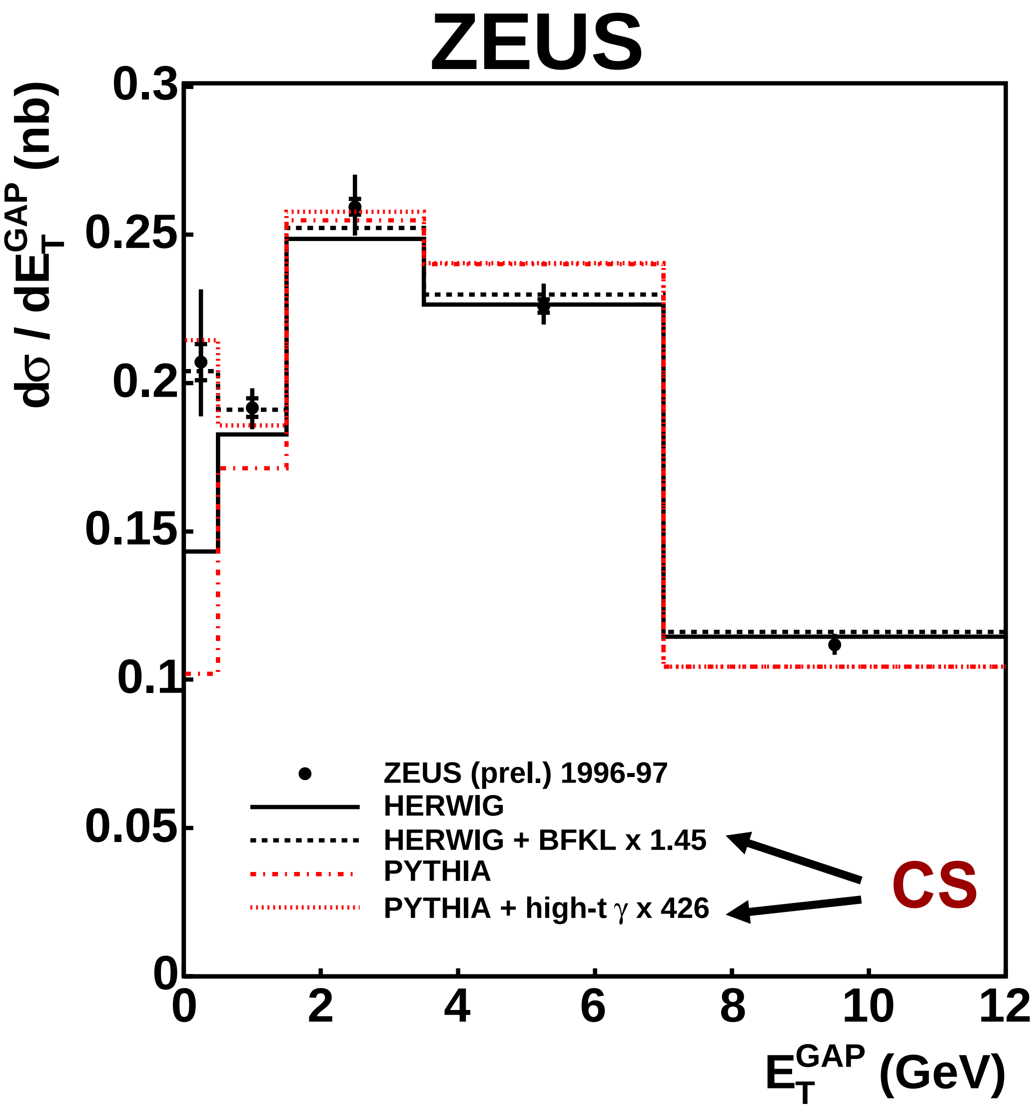
$$f(\Delta\eta) = \frac{d\sigma_{gap} / d\Delta\eta}{d\sigma / d\Delta\eta}$$

- Color Singlet - f(Δη) constant in Δη
- Color Non-Singlet - f(Δη) decreases exponentially with Δη

$$\sigma_{gap} = \sigma_{gap}^{singlet} + \sigma_{gap}^{non-singlet}$$

- σ - all Dijet events with large rapidity separation between jets
- σ_{gap} - all Dijet events with large rapidity separation between jets **&** $E_T^{Gap} < E_T^{Cut}$

Rapidity Gaps Between Jets



- ZEUS 1996-97 Photoproduction Data (38 pb^{-1})

Dijets with Large Rapidity Separation:

$E_T^{1,2} > 6.0, 5.0$ GeV

$|\eta^{1,2}| < 2.4$, $½|\eta^1 + \eta^2| < 0.75$

$2.5 < |\eta1 - \eta2| < 4.0$ (Gap Definition)

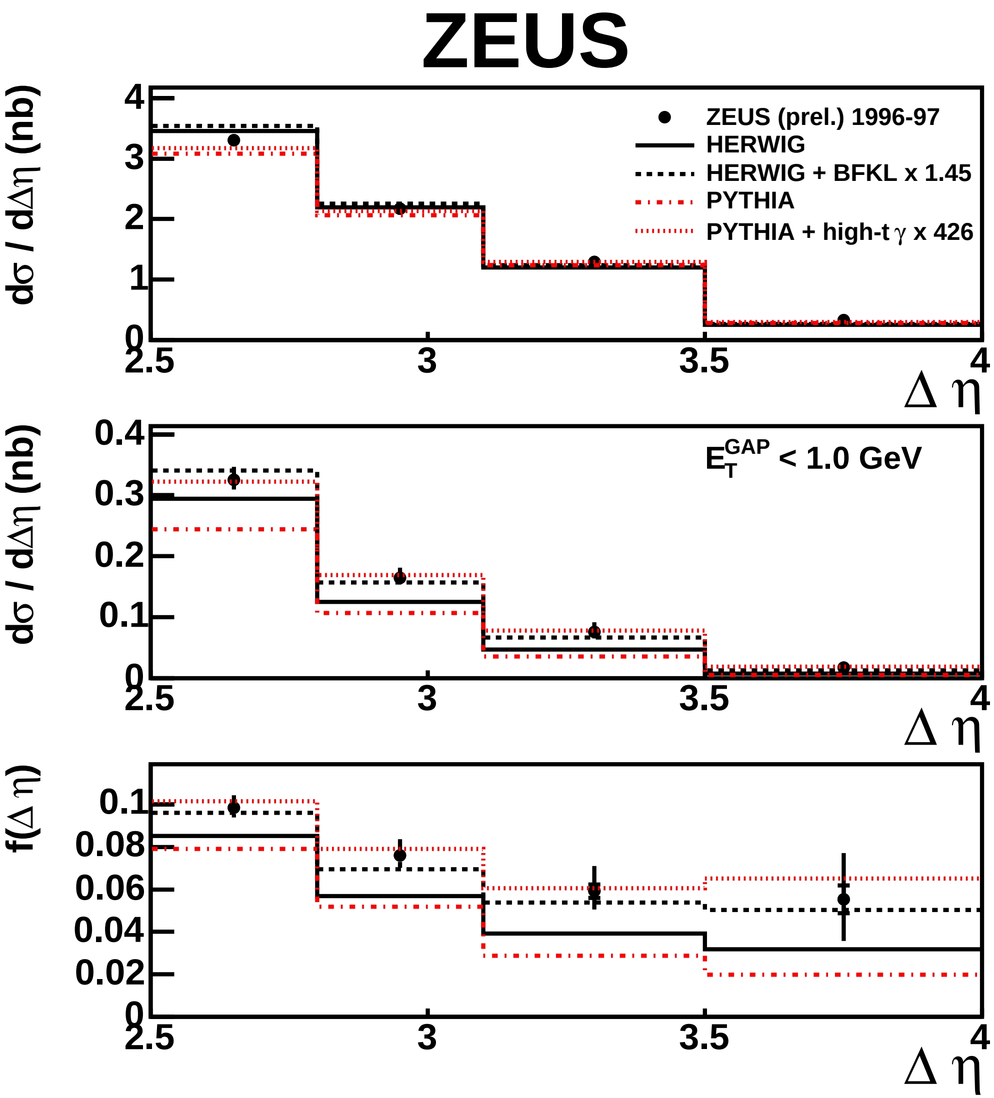
- PYTHIA 6.1 & HERWIG 6.1 to simulate Color-non-singlet and Color-singlet (CS) events
- CS HERWIG - BFKL Pomeron as exchange object
- CS PYTHIA - high-t γ-exchange
- Yield Scale Factors of χ2 minimization :

HER: 1.01*NCS + 1.45*CS

PYT: 1.25*NCS + 426*CS

- High CS Scale Factor in PYTHIA due to high-t γ-exchange

Rapidity Gaps Between Jets



- Minimization of χ^2 in fit to data results in ~3% CS contribution for both PYTHIA & HERWIG
- MC with Color-singlet added describes data

Conclusions

- Study of forward jet production in DIS by ZEUS shows:

i. CDM (ARIADNE) gives a good description of data in all measured cross sections

ii. LO CCFM-based CASCADE does not describe shapes of forward jet cross sections

iii. NLO calculations below data at low Bjorken-x; the agreement is good for very forward jets within large theoretical uncertainties

- Azimuthal decorrelations in Dijet events shows :

Two parton radiation (NLO 3-jet) normalised to visible cross section systematically lower data for $\varphi^* < 150°$ and not within scale uncertainties of NLO 3-jet

- Data demonstrate evidence of ~3% Color-Singlet contribution estimated at the cross section level for entire phase space. MC describe data well after the Color-Singlet contribution is added