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LAWRENCE BERKELEY NATIONAL LABORATORY
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Low-*x* QCD dynamics probed by multijets at HERA

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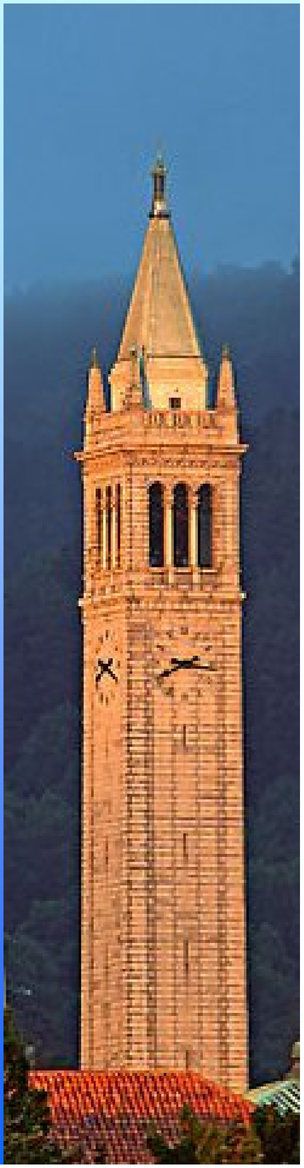
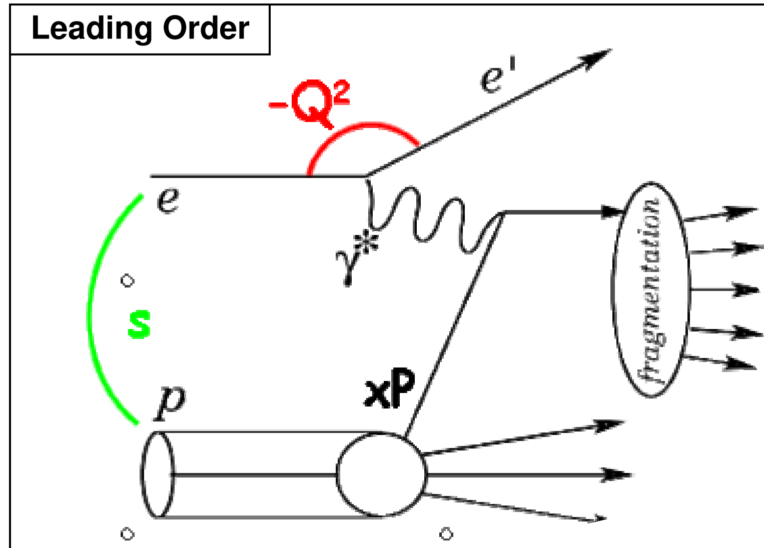
on behalf of the
H1 and ZEUS Collaborations



Outline:

- **Introduction**
- **Multijet production at low-x in DIS**
- **Angular correlation between jets**
- **Forward jets**
- **Three and four-jet final states in PHP**
- **Summary and Outlook**

$e^{\pm}p$ scattering at HERA



$\sqrt{s}$ = 300-318 GeV (Energy C.M.)

Q^2 = Photon Virtuality

x_{Bj} = energy carried by the struck parton in the proton

HERA (1992-2007)

- *820-920 GeV p →← 27 GeV $e^{\pm}$*
- *2001 HERA II Lumi upgrade + polarised $e^{\pm}$*
- *Machine operation ended in June 2007*
- *About 0.5 fb^{-1} per experiment collected*

Q^2 (photon virtuality):

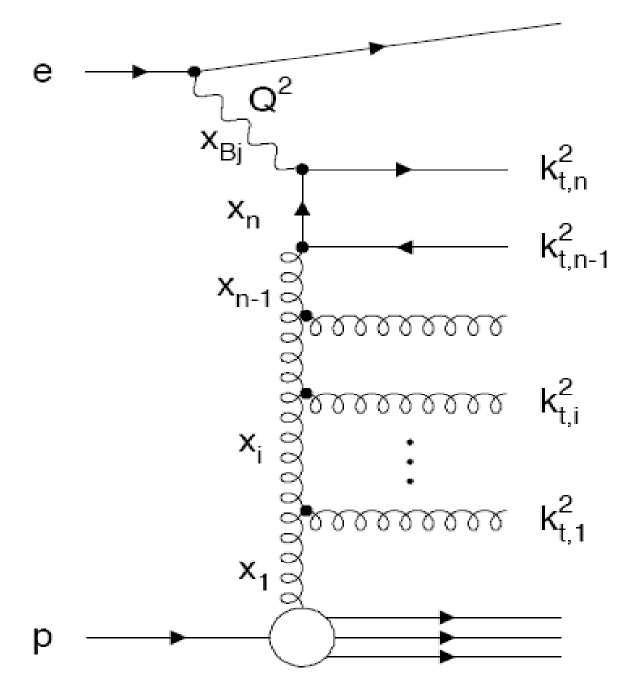
- *Q^2~0 (<1 GeV^2) → Photoproduction: photon-proton scattering*
- *Q^2>1 GeV^2 → Deep Inelastic Scattering (DIS), probing the proton structure*

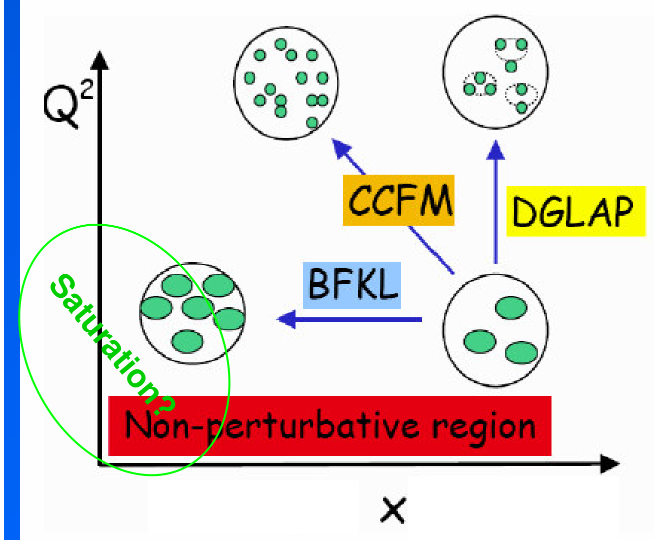
Parton Dynamics at low x in $e^{\pm}p$ collisions

Different approximations to the summation of the perturbative expansion of parton evolution

- ***DGLAP*** $\Sigma(\alpha_s \ln Q^2)^n$
  - *strong ordering in virtuality, i.e.* $k_{t,1}^2 << k_{t,2}^2 << ... << Q^2$
  - *weak ordering in x, i.e.* $x_1 > x_2 > ... > x_{Bj}$
  - *works very well at large* Q^2
  - *expected to fail at low* Q^2 *and x*
- ***BFKL*** $\Sigma(\alpha_s \ln 1/x)^n$
  - *random walk in* k_t
  - *strong ordering in x, i.e.* $x_1 >> x_2 >> ... >> x_{Bj}$
  - *expected to work well at low x*
- ***CCFM*** $\alpha_s \ln Q^2$ & $\alpha_s \ln 1/x$
  - *angular ordering, i.e.* $\theta_1 << \theta_2 << ... << \theta_n$
  - *expected to work at high* Q^2 *and low* Q^2 *and x*

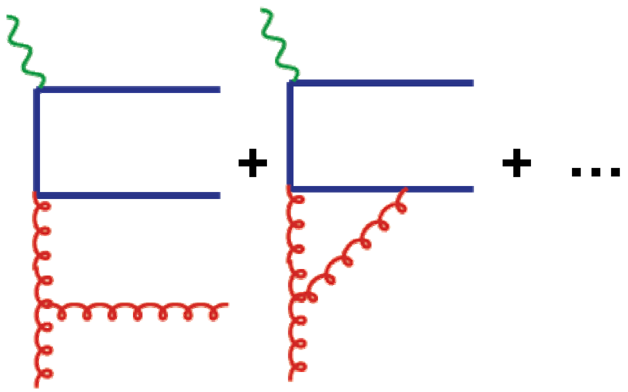
➔ ***DGLAP well established at HERA (PDFs QCD fits,*** F_2***). Look at measurements with better sensitivity to BFKL effects …***





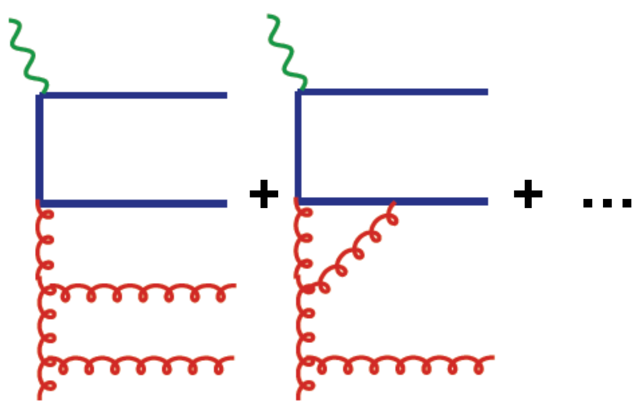
NLO QCD calculations and Monte Carlo Models

Disent, NLOjet++



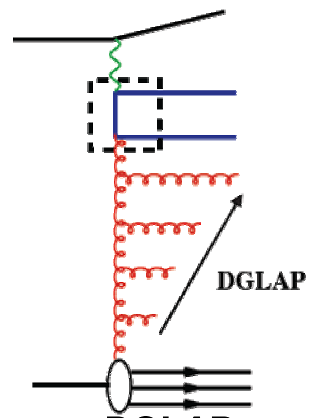
NLO Di-jet (α_S^2)

NLOjet++



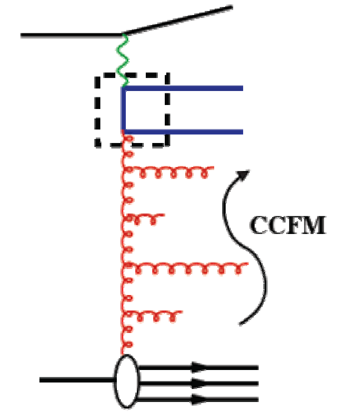
NLO Tri-jet (α_S^3)

Lepto/Rapgap



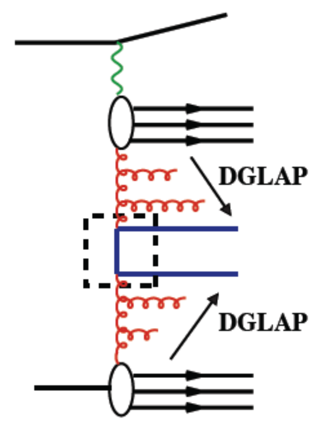
DGLAP
direct photon

Cascade



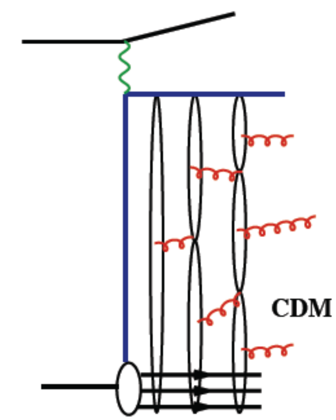
CCFM, angular ordering,
Unintegrated g(x,kt,μ)

Rapgap



DGLAP, direct +
resolved photon

Ariadne/DjangoH



Color Dipole Model
No k_t ordered partons

Multijet at low x

H1-prelim-06-034

H1 99-00 data (44 pb^{-1}):

DIS: 4 $< Q^2 <$ 80 GeV^2;

$10^{-4} < x_{Bj} < 10^{-2}$

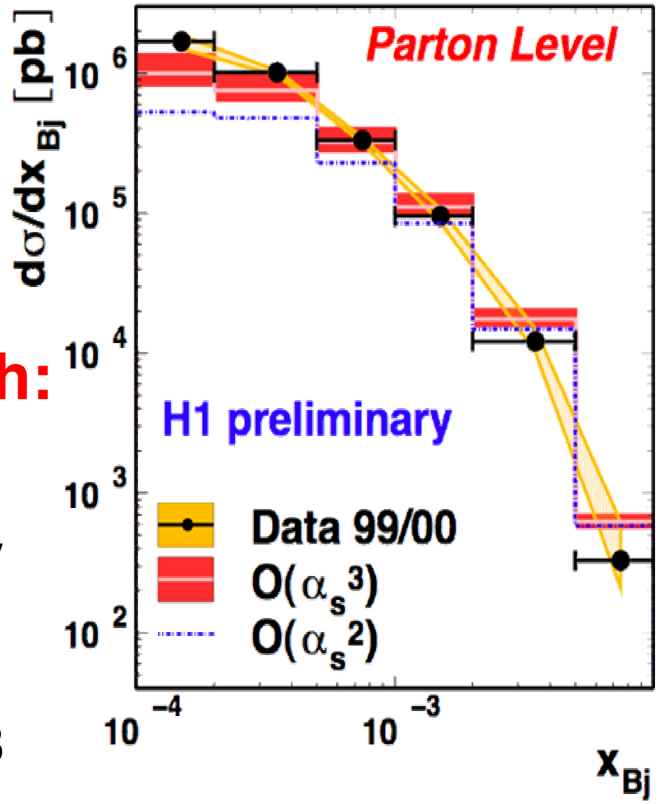
At least 3 jets with:

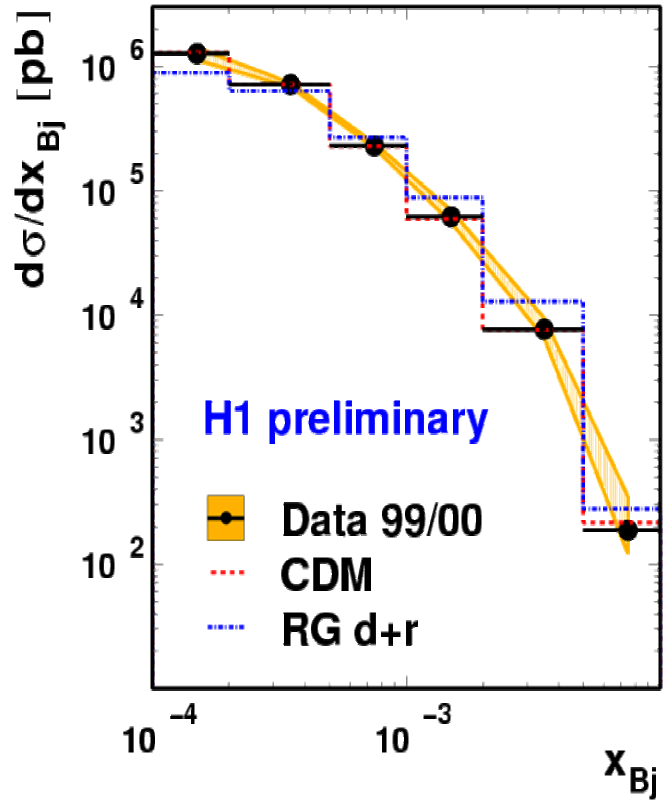
$E_{T\ jet1}$>4 GeV ;

$E_{T\ jet2}+E_{T\ jet3}$>9 GeV

$-1<\eta^{lab}<2.5$;

one jet $-1< \eta^{lab}<1.3$





- NLOjet++ $O(\alpha_S^3)$ gives very good description of the data (with possibly the exception at very low-x)
- CDM (DjangoH) gives also a good description
- Rapgap (Dir+Res) description not as good

Multijet at low x

DESY-07-062

ZEUS 98-00 data (82 pb^{-1}):

DIS: $10 < Q^2 < 100$ GeV^2

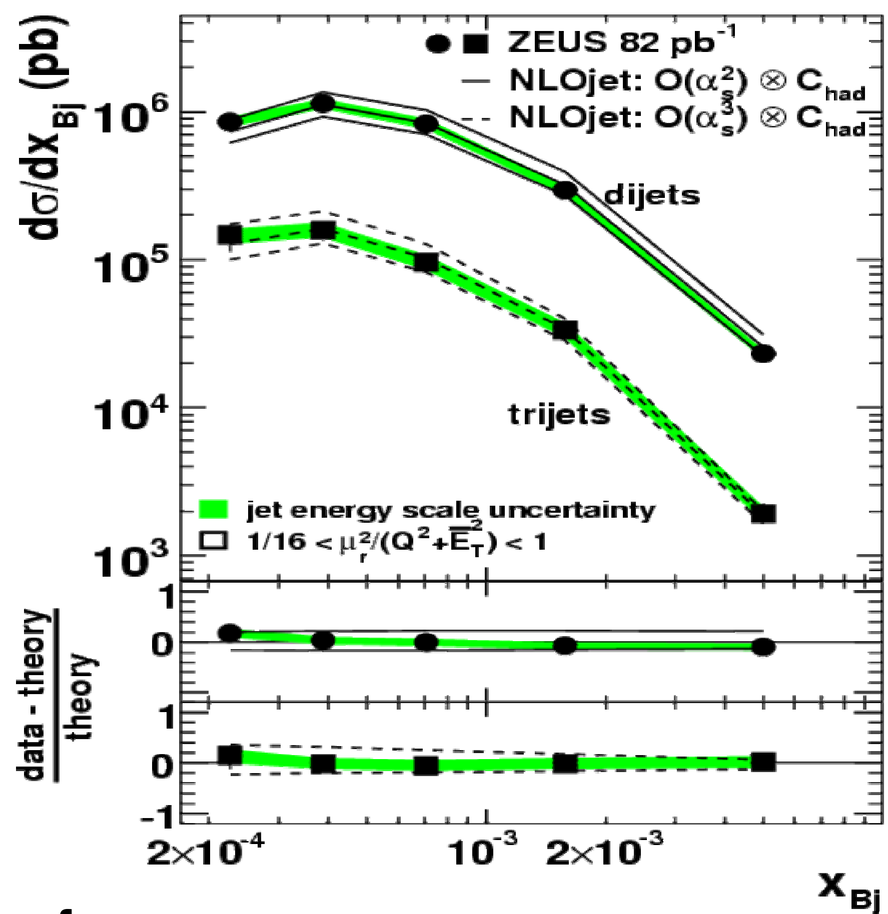
$10^{-4} < x_{Bj} < 10^{-2}$

2 or 3 jets with:

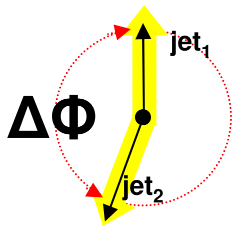
$E_t^{jet1} > 7$ GeV ;

$E_t^{jet2(3)} > 5$ GeV

$-1 < \eta^{lab} < 2.5$



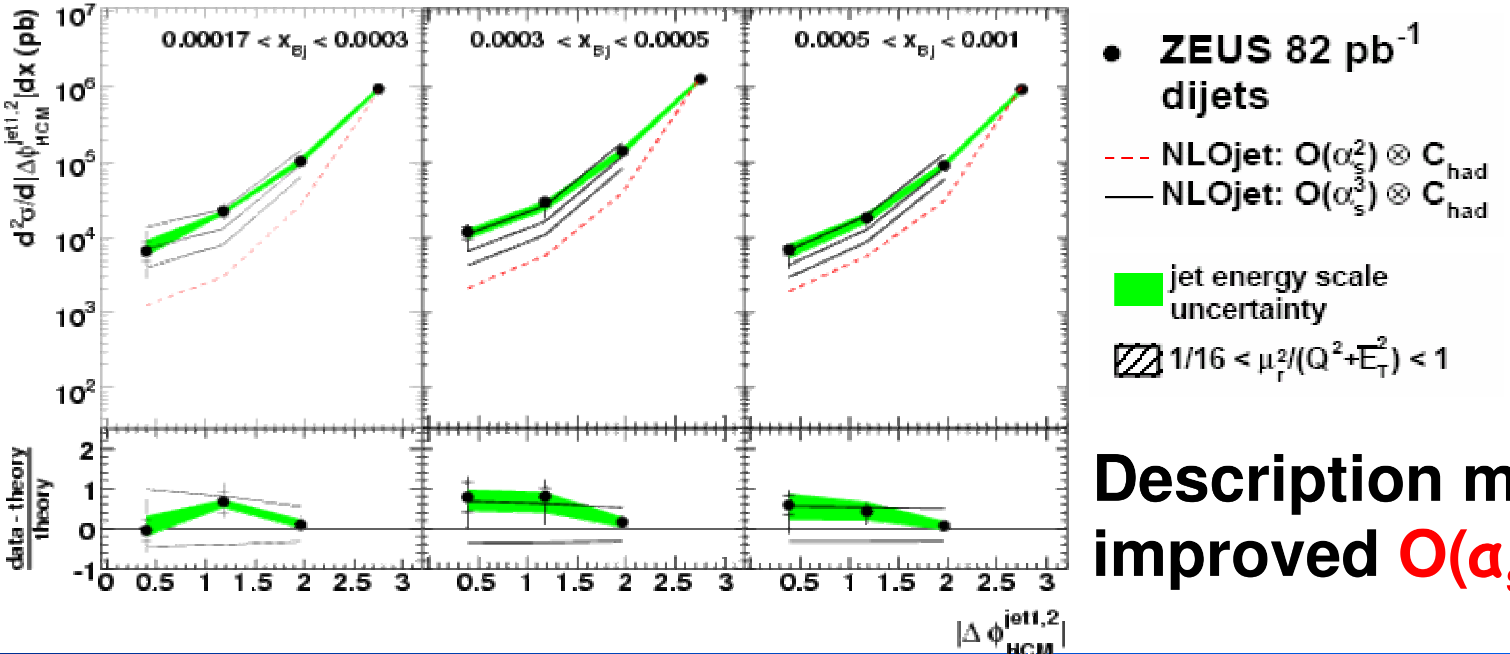
Look in the Hadronic Center of Mass frame:



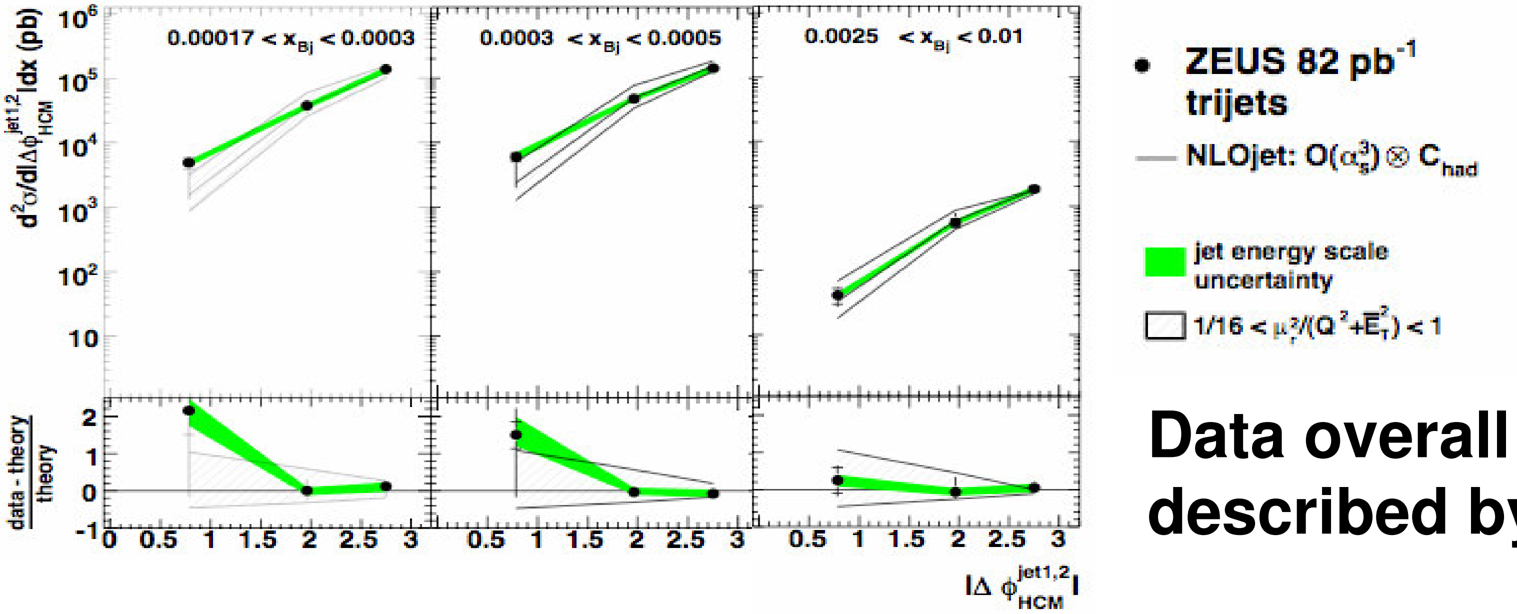
$|\Delta\Phi^{jet1,2}_{T,HCM}|$ = azimuthal separation between the two jets with the highest hadronic center of mass E_T

Multijet at low x

DESY-07-062



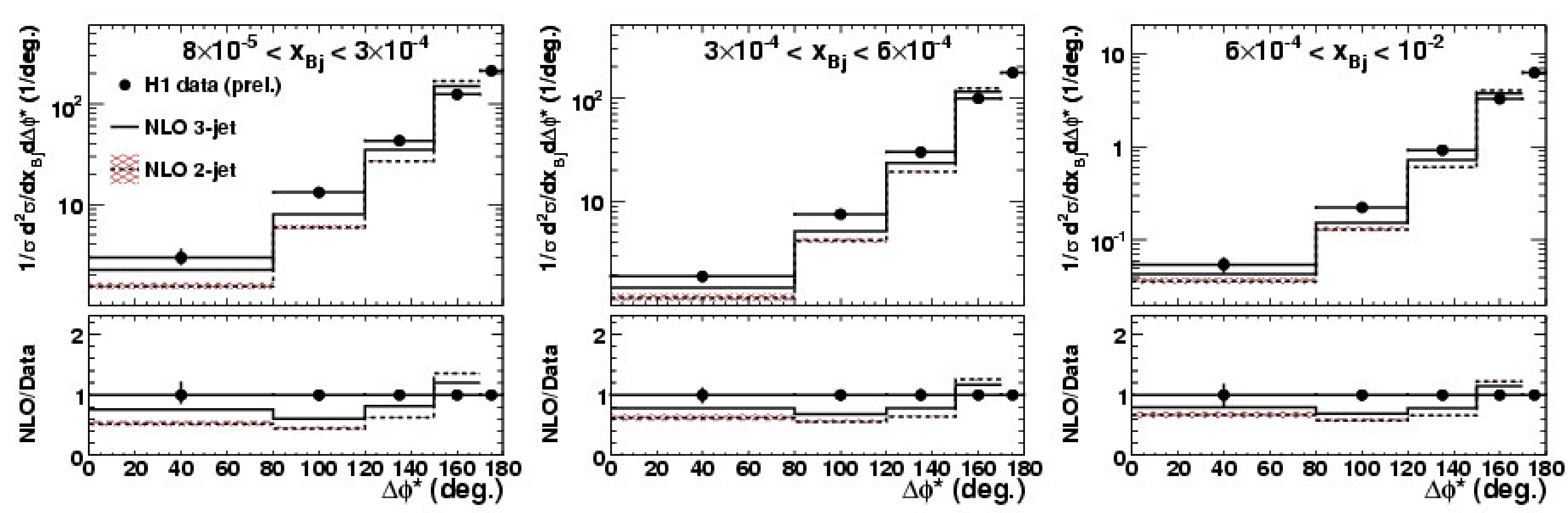
Description much improved O(α$_s^2$)→O(α$_s^3$)



Data overall well described by pQCD

Azimuthal Correlations in Dijets

H1-prelim-06-032



H1 99-00 data (64 pb^{-1}):

DIS: 5 < Q^2 < 100 GeV^2

2 Jets with:

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

$E^*_{Tj} > 5$GeV (HCM)

- Phase space extended toward lowest Q^2 and x_{Bj}
- One-parton-radiation (NLO 2-jet) not enough to describe data
- Two-parton-radiation (NLO 3-jet) systematically low for $\Delta\varphi^* < 150^\circ$

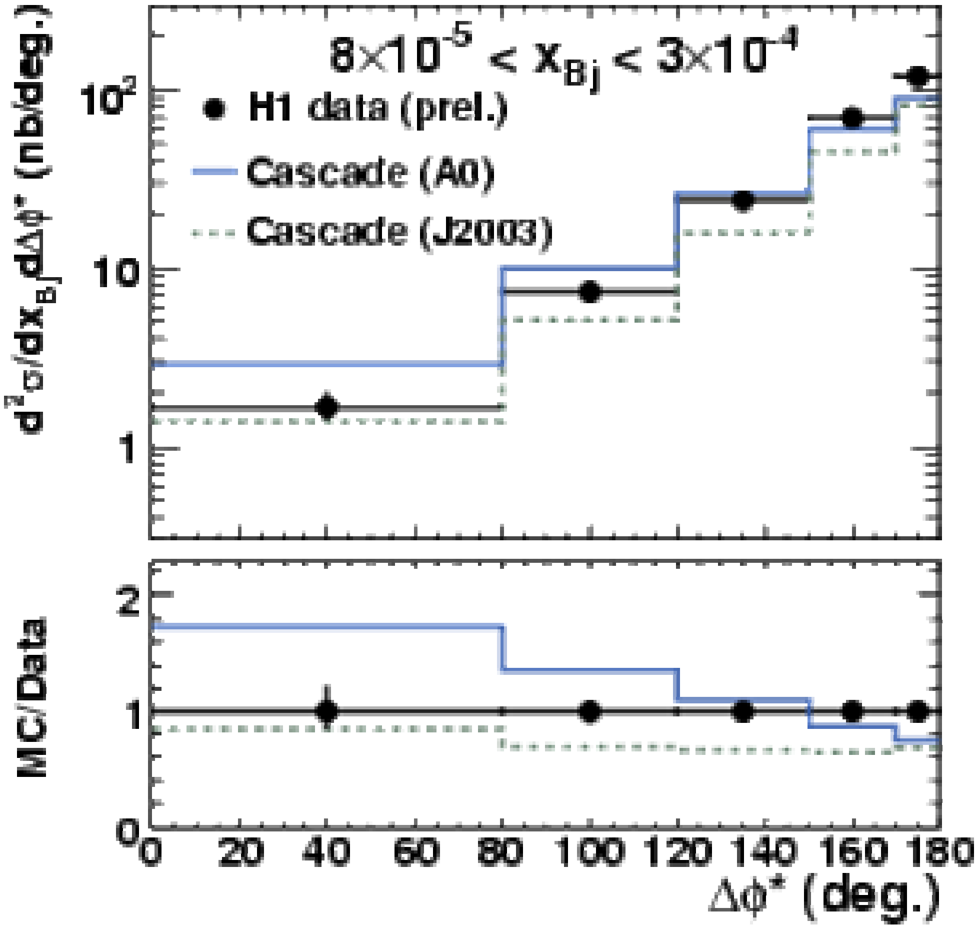
Azimuthal Correlations in Dijets

H1-prelim-06-032

Monte Carlo Models:

- 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

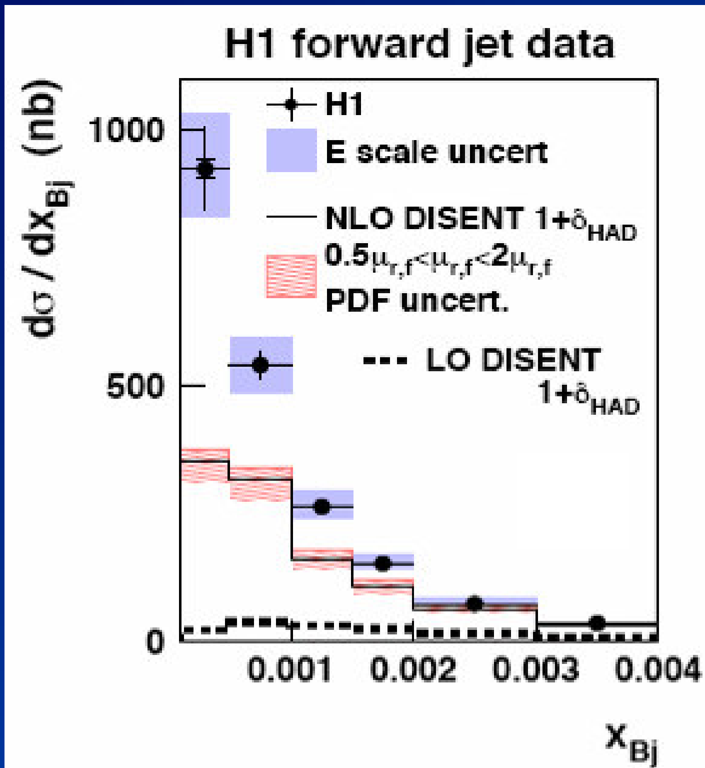
➔ Data show sensitivity to the unintegrated gluon density

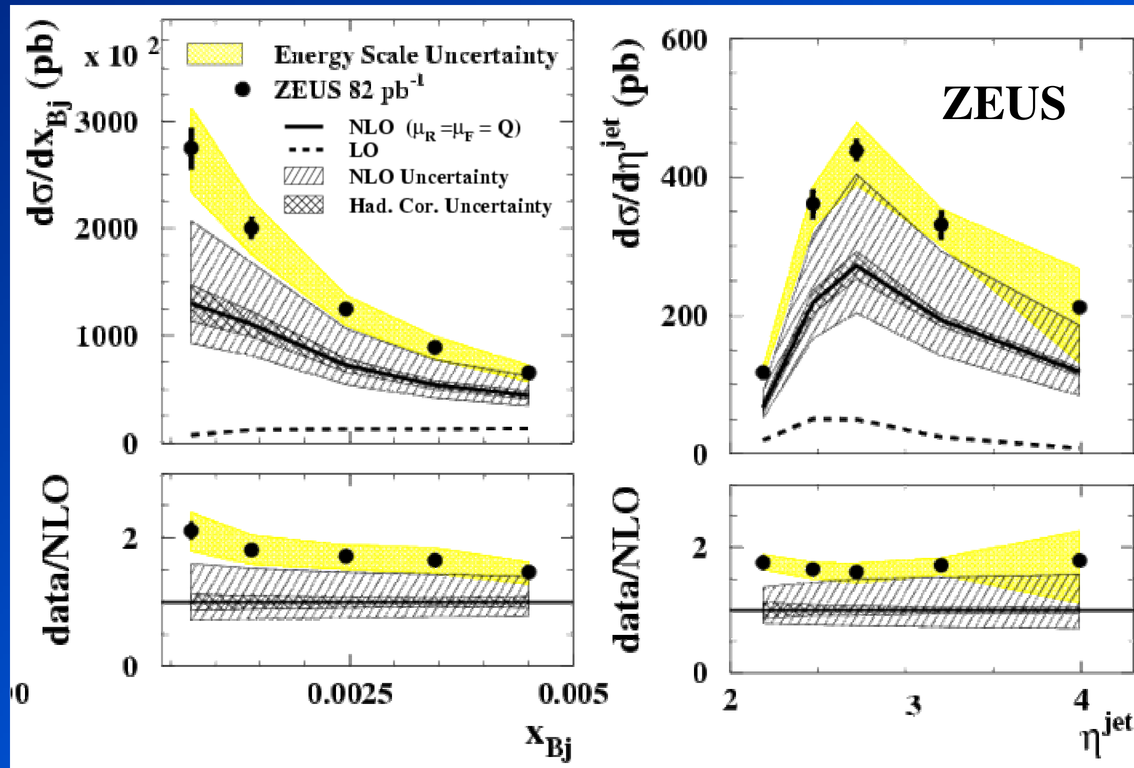


Forward Jets

Eur. Phys. J. C46 (2006) 27

ZEUS: DESY-07-102

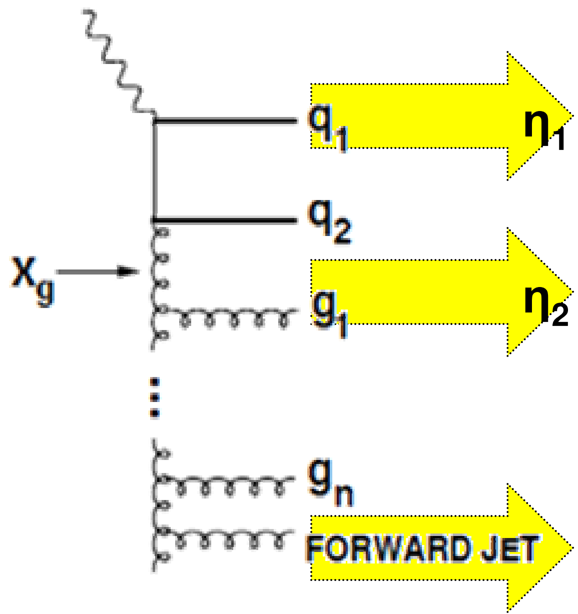


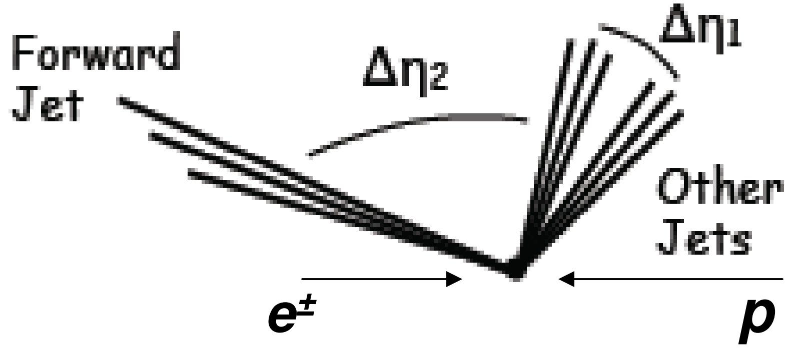


- New measurement ZEUS 98-00 data: $2 < \eta_{jet} <$ **4.3** (FwdPlugCal)
  - DIS: $20 < Q^2 < 100$ GeV^2 ; $10^{-4} < x_{Bj} < 5 \times 10^{-3}$;
  - $x_{jet} > 0.036$ ➔ **Enhance BFKL expected behaviour**
- LO-DGLAP fails completely
- NLO-DGLAP well below data at low *x* (as seen by H1)

Forward jet & dijet

DESY-07-102

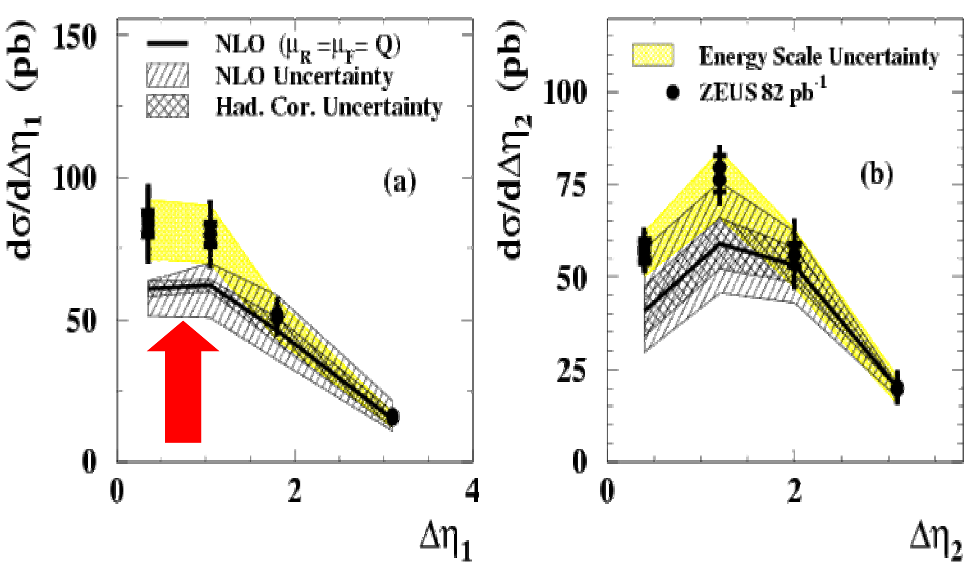


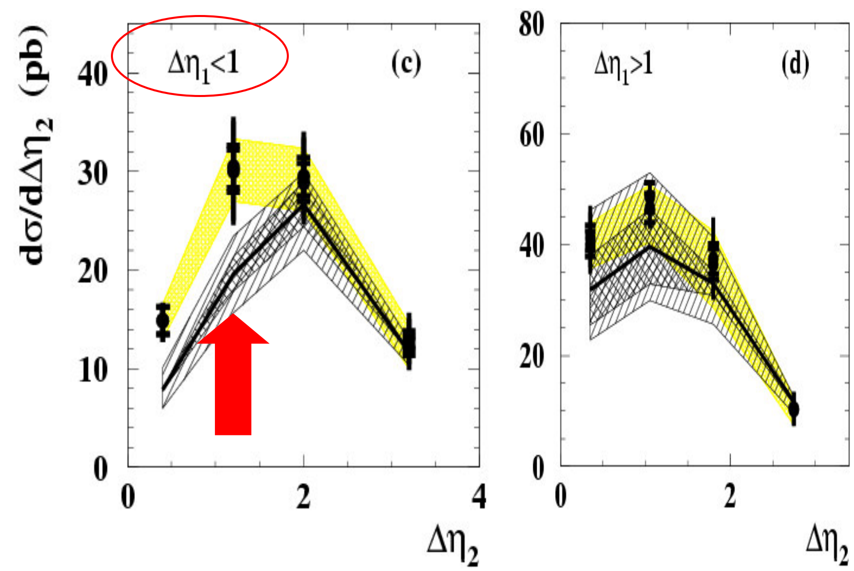


$\Delta\eta_1 = \eta_2 - \eta_1$

$\Delta\eta_2 = \eta_{fwd} - \eta_2$

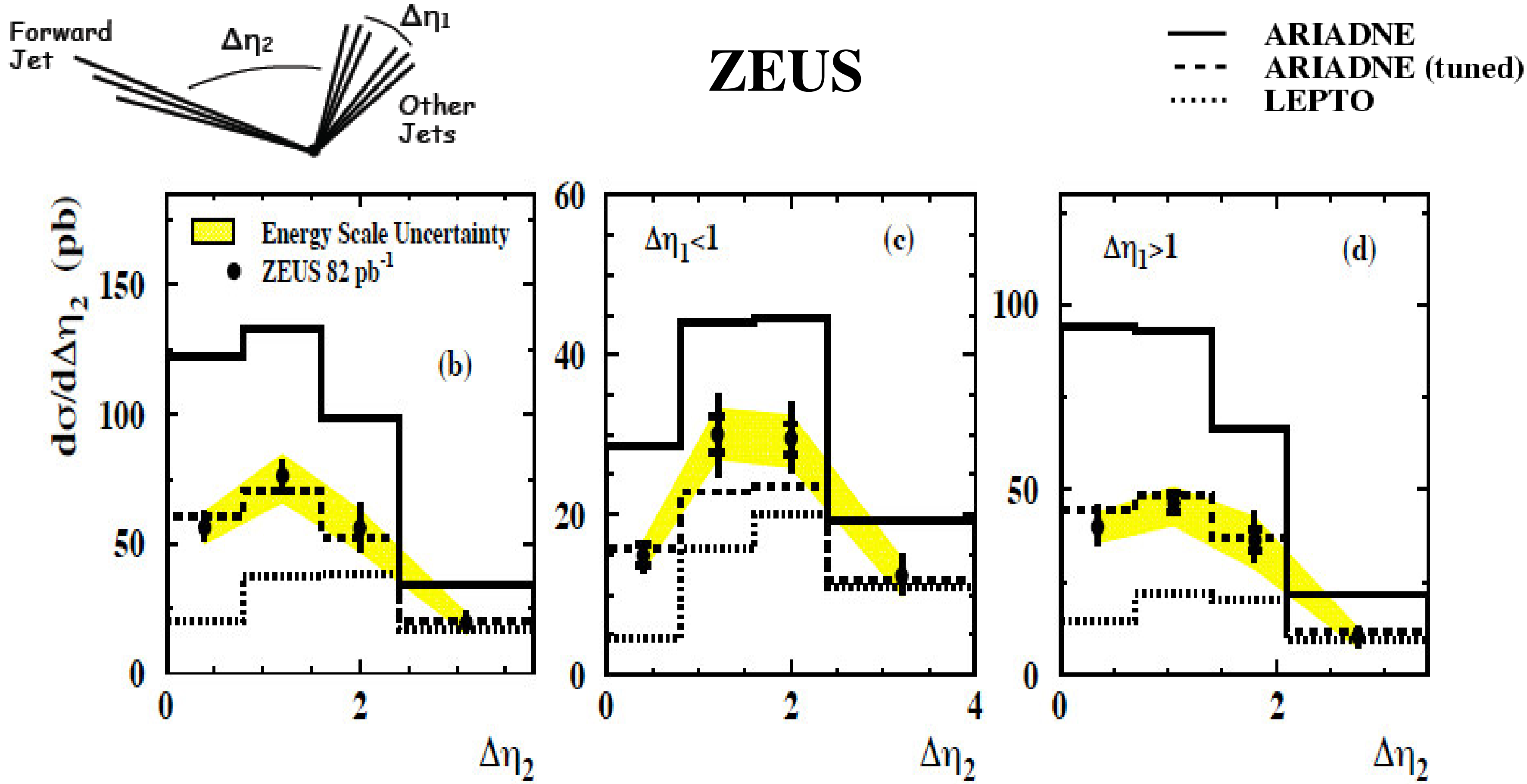
- Discrepancy at low $\Delta\eta_1$ and $\Delta\eta_2$, i.e. when all 3 jets tend to go forward
- Need for additional higher orders or BFKL resummation





Forward Jets & dijet: QCD Models

DESY-07-102



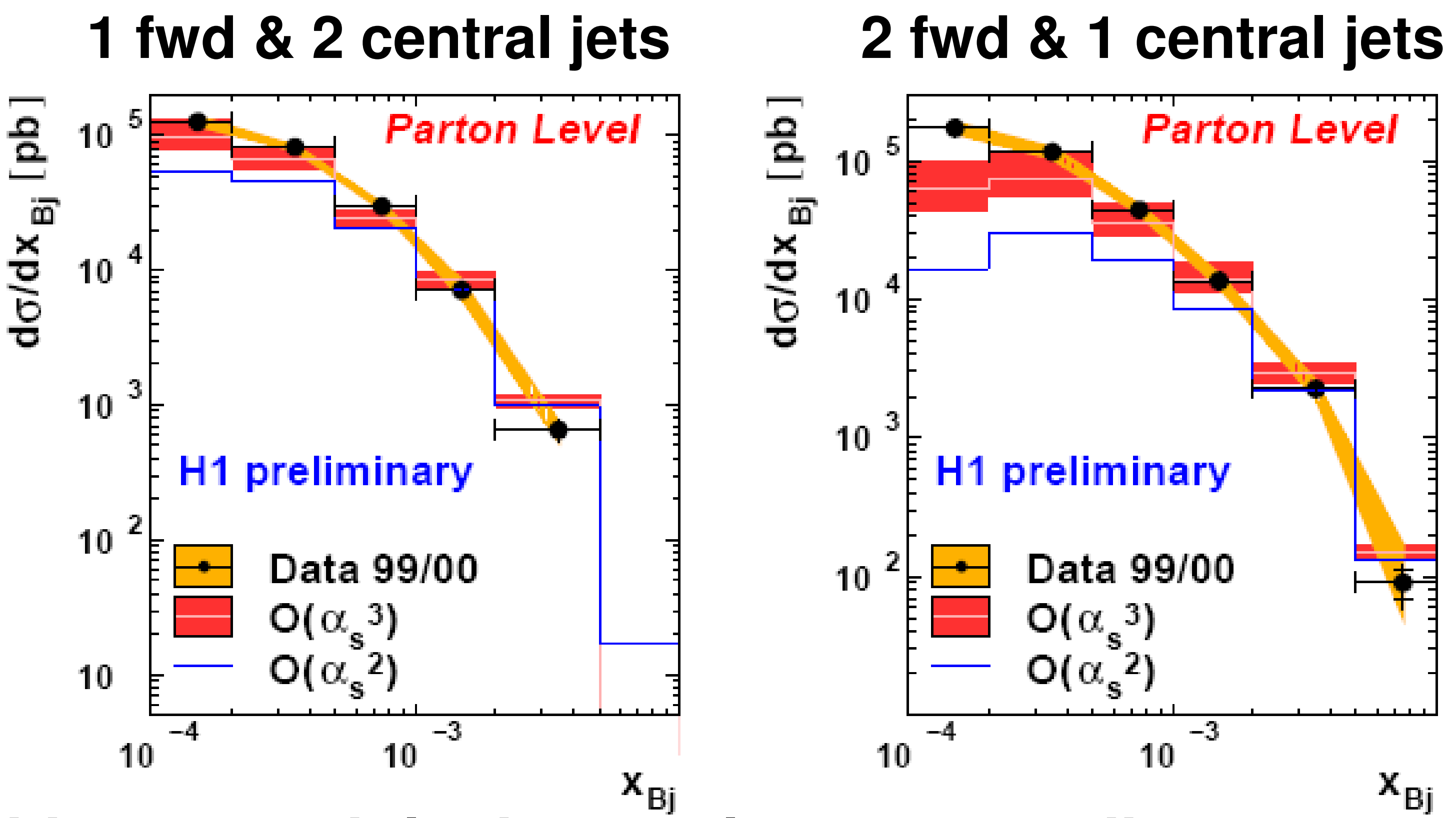
- CDM (Ariadne tuned) describes data reasonably well
- The breaking of k_T ordering is best modeled by CDM

Exclusive Trijets in DIS

H1-prelim-06-034

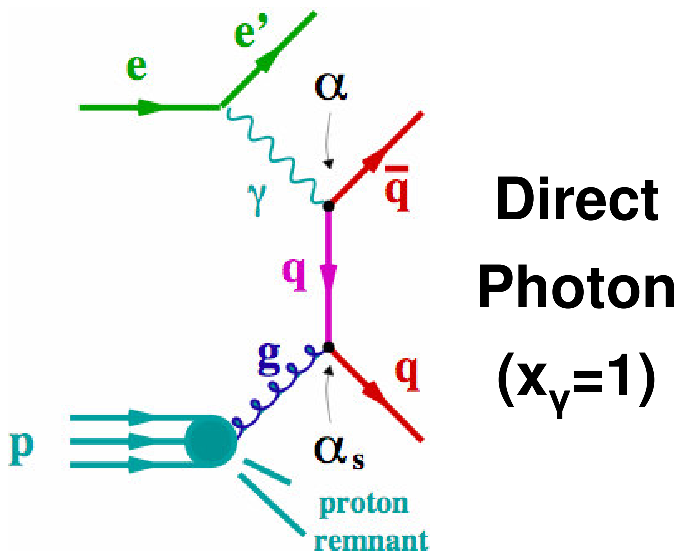
3 jets:

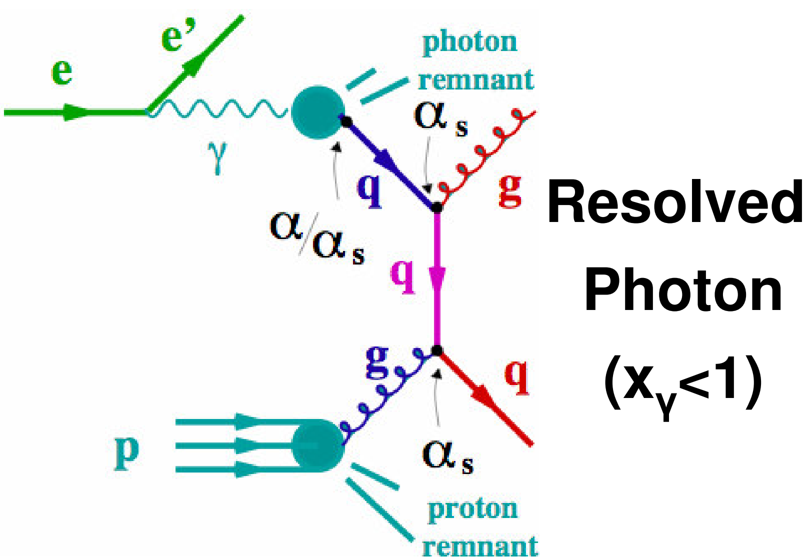
- Forward
  $\eta_{jet} > 1$
- Central:
  $-1 < \eta_{jet} < 1$



- **2 fwd-jets → mainly due to gluons according to MC studies (CDM)**
- **discrepancy at lowest x_{Bj} due to unordered gluon emissions? (NLO also below data for forward η)**

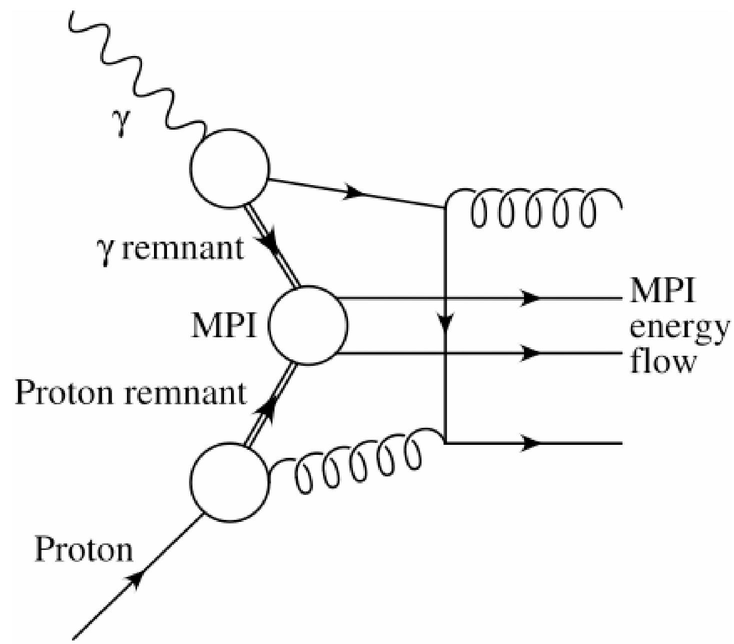
Multijets in Photoproduction





Multi-Parton Interactions (MPI)

- Multijet photoproduction (**resolved γ**) sensitive to MPIs
- 4-jet PHP: the highest order process ever measured at HERA
- No NLO calculation available yet



Multijets in Photoproduction

DESY-07-100

ZEUS HERA I data (121pb^{-1})

Event selection:

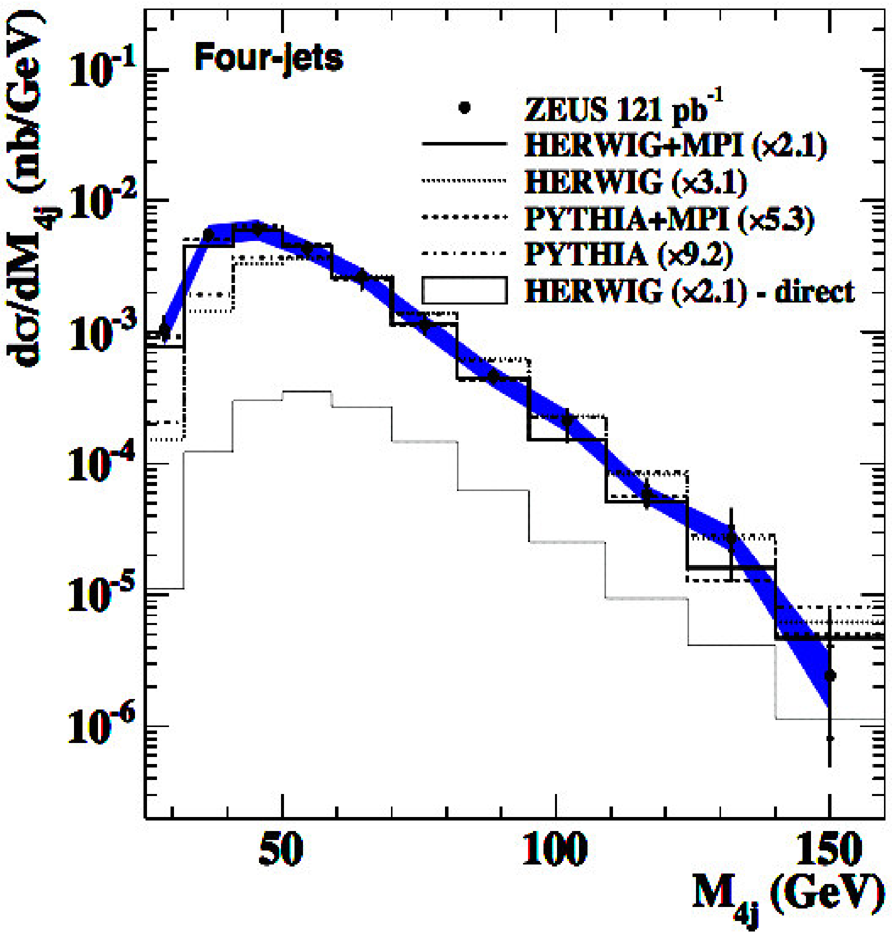
- Photoproduction

  $Q^2<1$ GeV^2

- 3 or 4 jets with

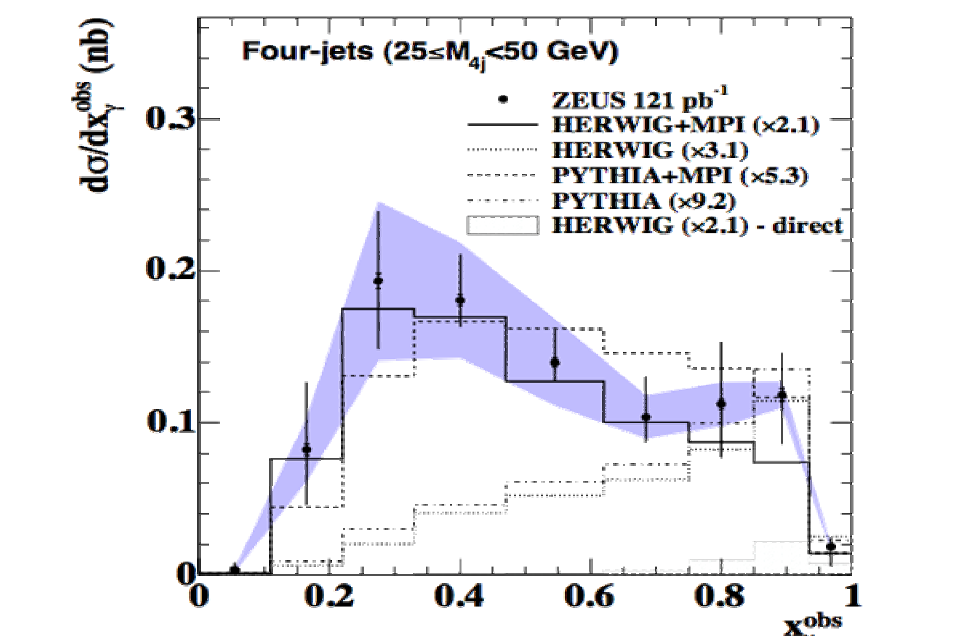
  $|\eta|<2.4$; $E_T>6$ GeV

- Good statistics of 3- and 4-jet events



Multijets in Photoproduction

DESY-07-100



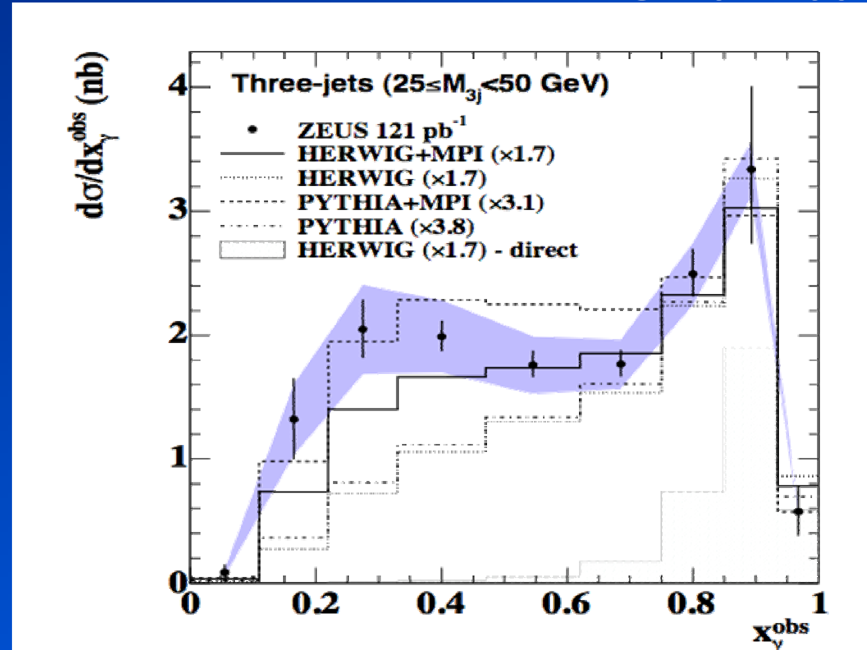
- Two mass regions:

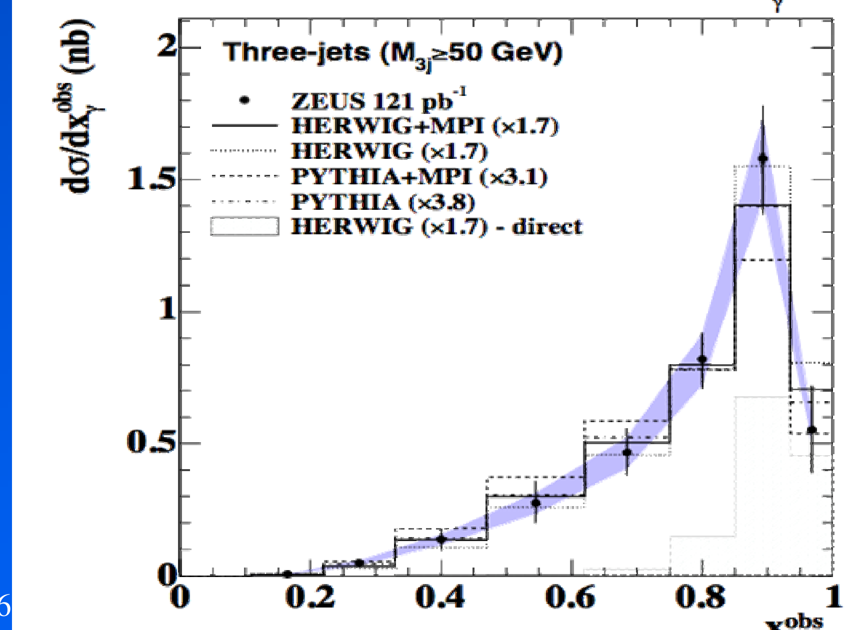
  $25 \leq$ Mnj ≤ 50 GeV

  Mnj ≥ 50 GeV

- Low Mass more sensitive to MPIs (resolved photon)

➔ General improvement adding MPIs to LO MC





Conclusions and Outlook

- HERA provides a versatile testing ground for pQCD
- Multi- and forward- jets production has been measured in the region x_{BJ}~10^{-4} and low Q^2 where NLO DGLAP pQCD is expected to fail
- Agreement between data and QCD calculations well improved when going from $O(\alpha_S^2)$ to $O(\alpha_S^3)$. Nevertheless BFKL enhanced forward jet data at low x_{Bj} are not described by NLO
- CDM as implemented in Ariadne (tuned) provides a good description of most datasets
- Cascade (CCFM) with currently used sets of unintegrated gluon densities fails to describe shape of most distributions; these data could be used to determine the unintegrated gluon distributions.
- Multijet photoproduction data are better described adding Multi-Particle-Interactions to LO Monte Carlos

- HERA data will push further development of the Monte Carlo Models and hopefully stimulate NNLO DGLAP and NLO BFKL calculations
- More precise results expected with the full statistics of HERA $O(1\ fb^{-1})$