QCD Dynamics at Low-x_{Bj} in ep Collisions at HERA

Results from ZEUS and H1

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on behalf of the ZEUS and H1 collaborations

- Dijet and Trijet Correlations
- Inclusive Forward Jet Production

Rencontres de Moriond: March 22 2007, Italy

Testing Parton Evolution: Jets at low x_{Bj}

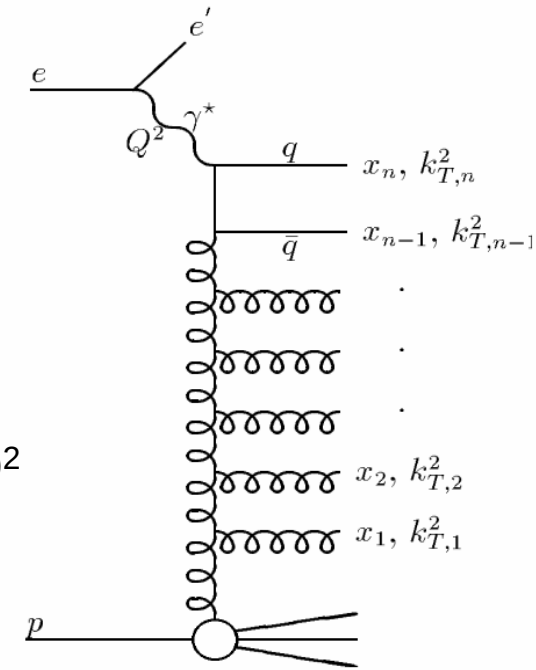
Moving to LHC:

- **Are extracted PDFs usable in the LHC kinematic range ($1 > x > 10^{-6}$) ?**
- **Does DGLAP evolution work sufficiently to extrapolate?**

Study QCD evolution schemes with jets at low x_{Bj} at HERA

$$10^{-4} < x_{Bj} < 10^{-2} \qquad 5 < Q^2 < 100\,GeV^2$$

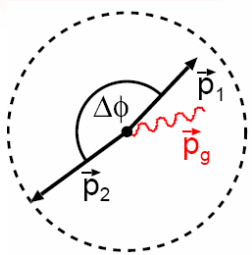
- **Jets found with k_T algorithm in inclusive mode**
- **DGLAP: sums over ln(Q^2) terms (LEPTO, RAPGAP, DISENT, NLOjet++)**
  - ordering in both k_T and x
  - well tested over large range of Q^2
- **BFKL: sums over ln(1/x) terms (~ ARIADNE (CDM))**
  - Strong ordering in x, but not ordered in k_T
    - More energetic forward jets
    - Jets less correlated in energies, angles
- **CCFM: k_T factorization (CASCADE)**
  - Evolution in Q^2, x
    - Approaches BFKL for low x_{Bj}, DGLAP for high Q^2
  - angular ordering (instead of k_T ordering)
  - uses unintegrated parton densities



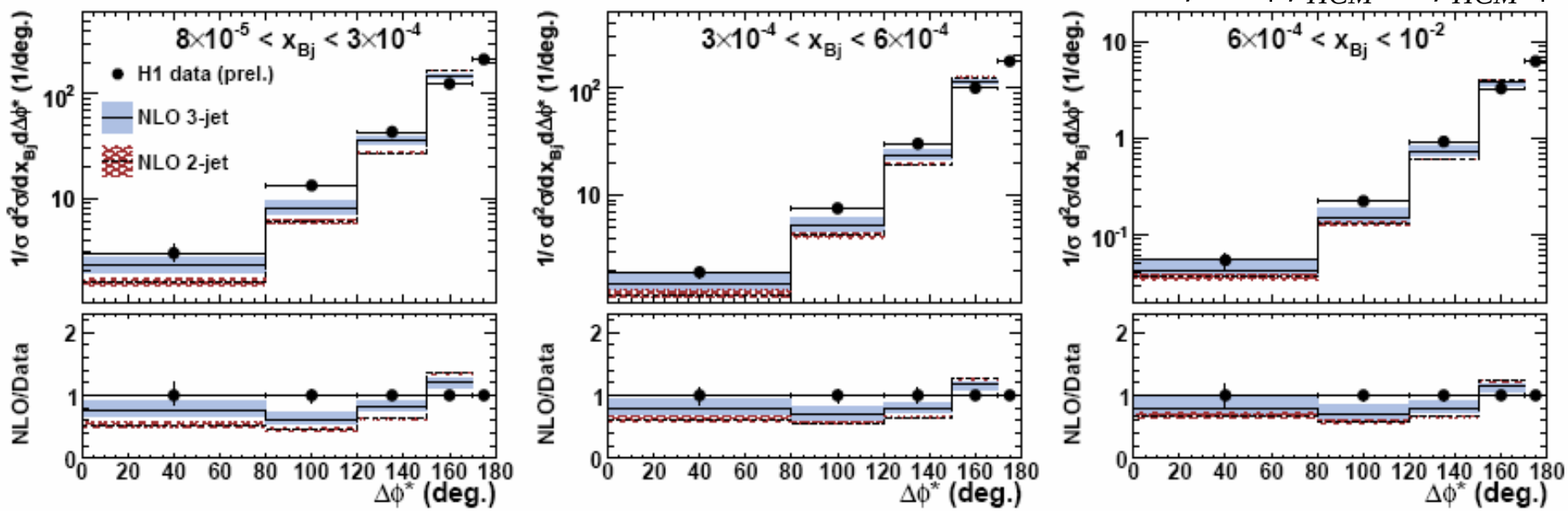
First examine DGLAP NLO calculations

H1 Dijet Azimuthal Correl. vs. x_{Bj}

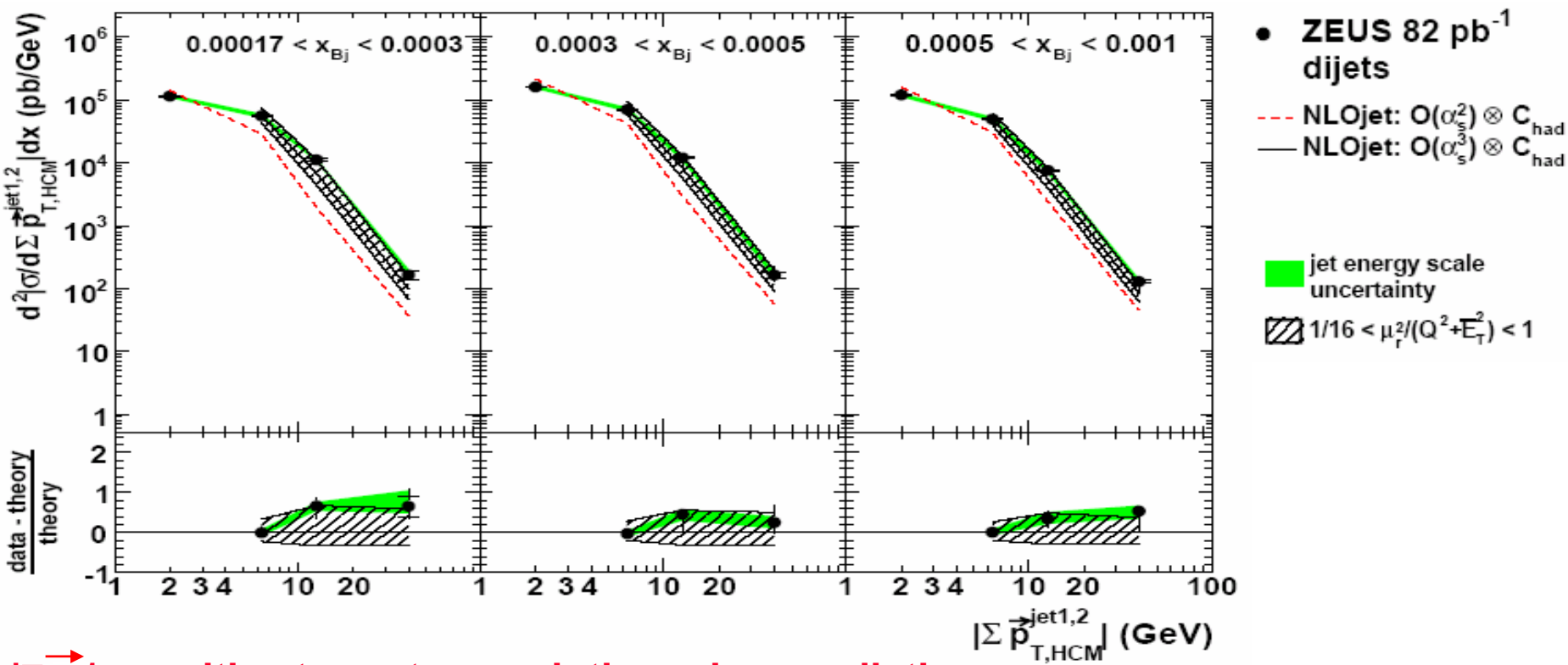
- Examine $\Delta\phi^*$ correlation of dijets at low x_{Bj}
- $\Delta\phi^*$ Sensitive to parton evolution scheme, gluon radiation
  - Jets are back-to-back without gluon emission
- Test DGLAP calculations from NLOjet
  - Normalize to visible cross section for $\Delta\phi^* < 170$ in each bin of x_{Bj}
    - Cancellation of renormalization scale uncertainties
  - Disagreement between data, NLOjet calculations at low x_{Bj}, low $\Delta\phi^*$
    - Kinematic region where DGLAP needs checking



$$\Delta\phi^* = |\phi^{jet1}_{HCM} - \phi^{jet2}_{HCM}|$$



ZEUS Dijet p_T Correlations vs. x_{Bj}



$|\Sigma\vec{p_T}|$ sensitive to parton evolution, gluon radiation

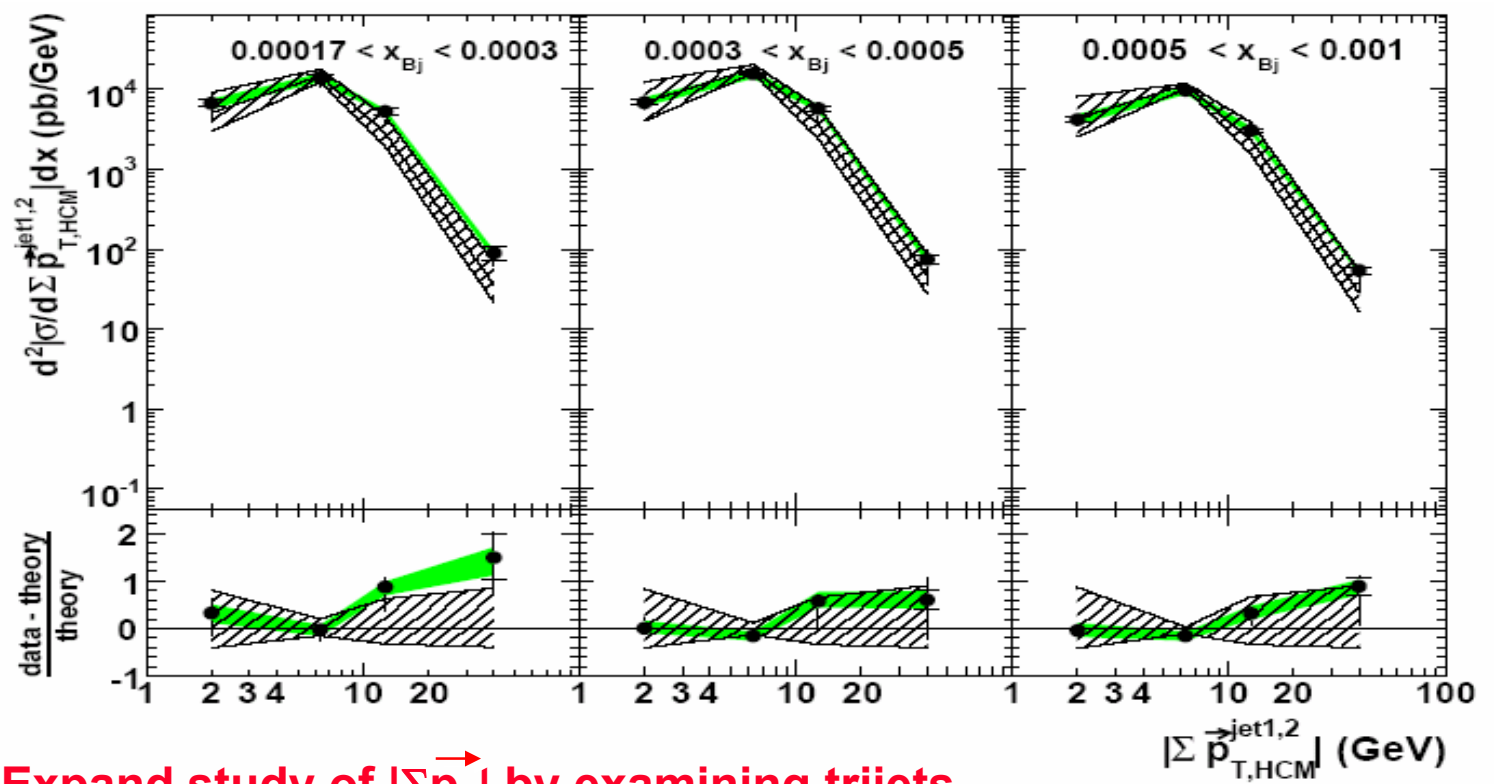
- **$|\Sigma\vec{p_T}| = 0$ without gluon radiation**

NLOjet (DGLAP) calculations at $O(\alpha_s^2)$ do not describe dijet data at low x_{Bj}

NLOjet calculations at $O(\alpha_s^3)$ describe data, even at low x_{Bj}

- **Higher order terms important at low x_{Bj}**
  - Allows for more gluon emission

ZEUS Trijet p_T Correlations vs. x_{Bj}



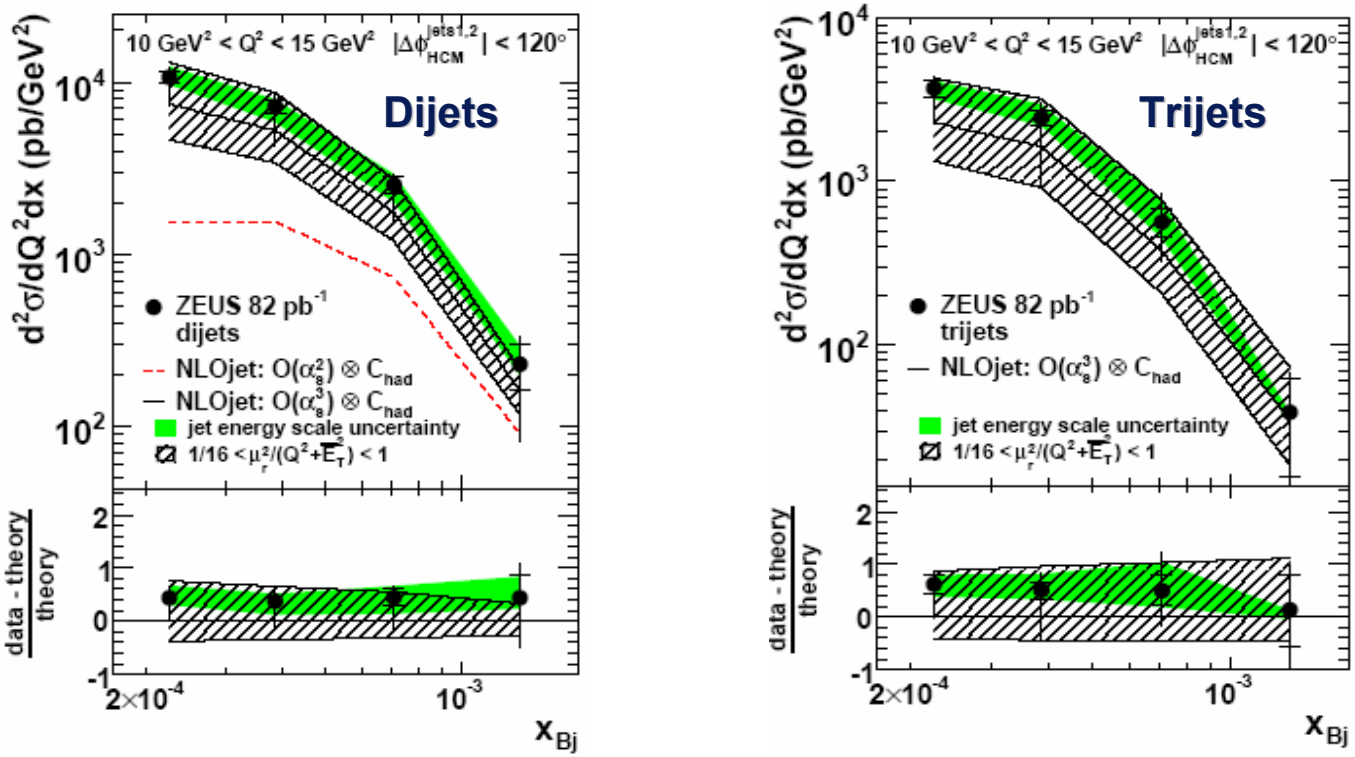
Expand study of $|\Sigma \vec{p}_T|$ by examining trijets

- **Higher order measurement ($O(\alpha_s^2)$ at LO)**

NLOjet calculations at $O(\alpha_s^3)$ describe the data

- **Better description at higher values of x_{Bj}**
  - Higher-order NLO calculations not available
  - Effect much less pronounced than for dijets vs. $O(\alpha_s^2)$ NLOjet calculations

ZEUS 2,3-jet Azimuthal Correl. vs. Q^2, x_{Bj}



$\Delta\phi^* < 120° \rightarrow$ high-E_T forward jet

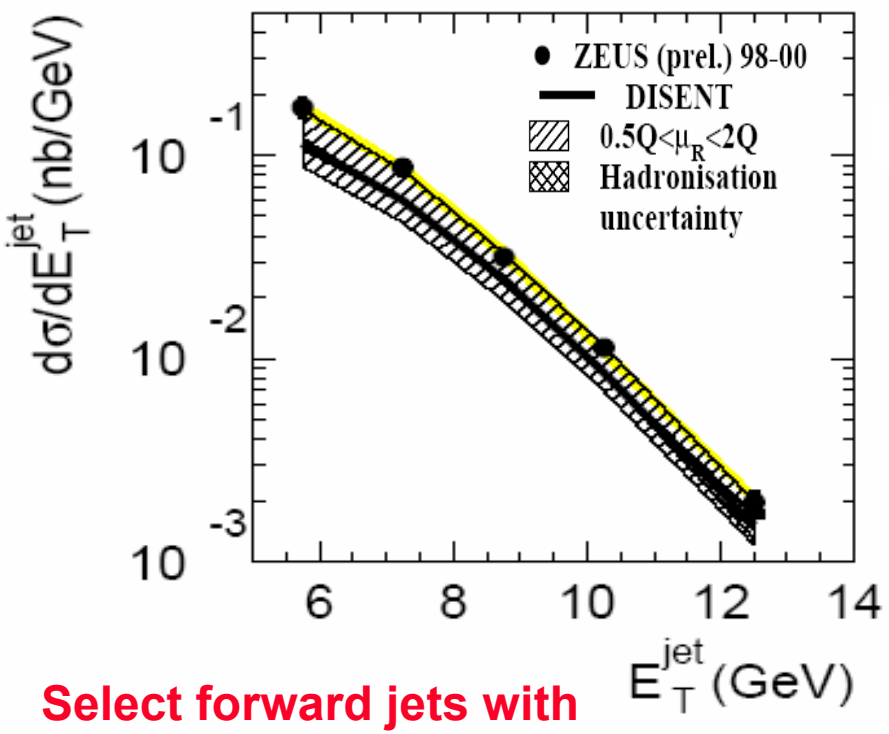
- Measurements sensitive both to angular correlations, forward jets

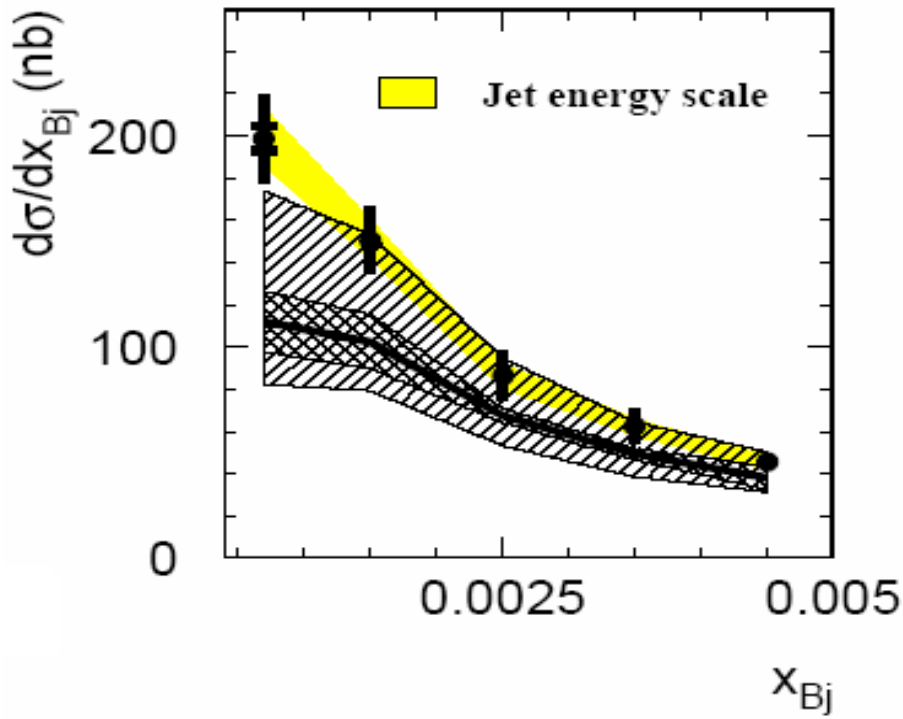
NLOjet calculations at O(α_s^3) describe dijet, trijet data, even at low x_{Bj}

- Dijets at low x_{Bj}: O(α_s^3) calcs for dijets ~ 10 x O(α_s^2) calcs

For phase space tested, DGLAP works when higher-order terms included

ZEUS Inclusive Forward Jets: NLO Calculations





Select forward jets with
$2 < \eta < 3.5$, $x_{jet} > 0.036$

- **DISENT NLO predictions in agreement with data within theoretical uncertainties**
  - Theoretical uncertainty increases at lower Q^2, x_{Bj}
    - Higher-order terms important

ZEUS inclusive forward jets described by DISENT NLO DGLAP calcs.

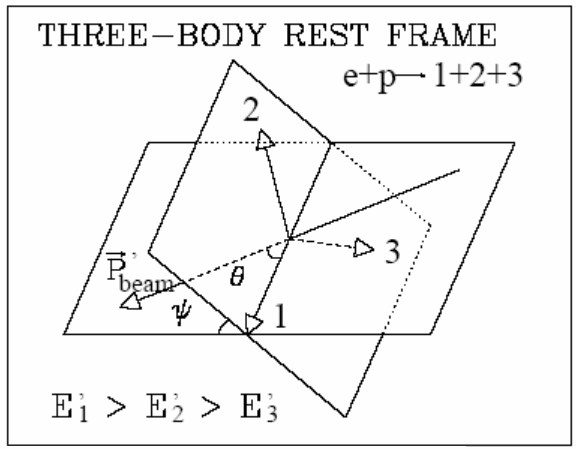
H1 Trijet Correlations

Parton evolution for multijet events examined:

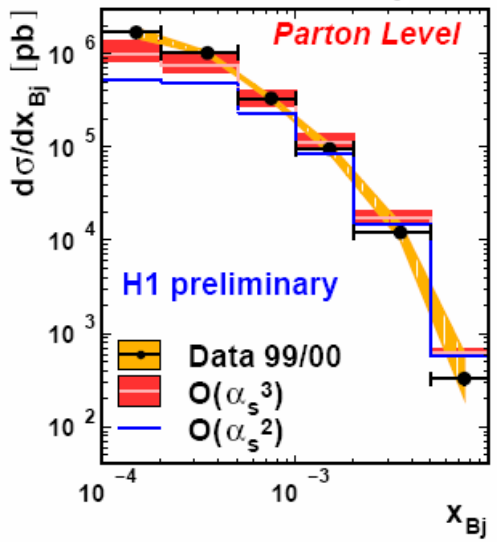
- **Angular correlations**
- **Normalized jet energies** $X_i = \dfrac{E_i}{\sum_j E_j}$

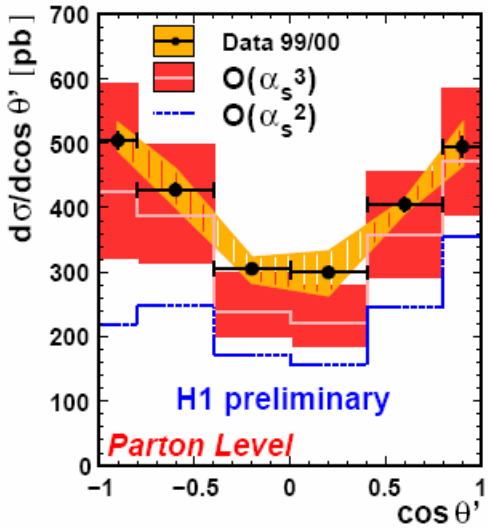
For

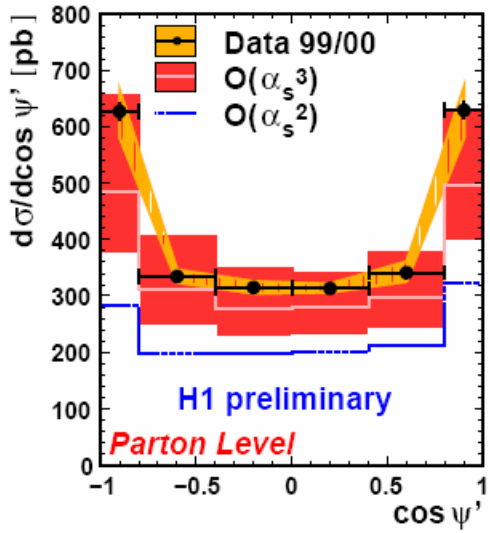
- **Inclusive trijet**
- **Trijet with 1, 2 forward jets**



Inclusive Trijets







Inclusive trijet data generally well-described by NLOjet calculations at $O(\alpha_s^3)$

- **Data above calculations at low x_{Bj}**

H1 Forward Trijet Measurements

Select forward jets with

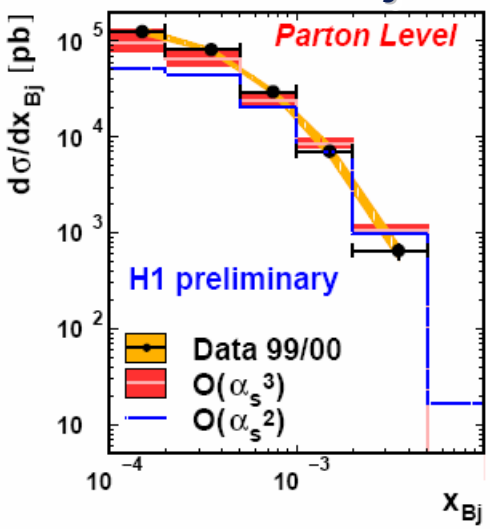
- $x_{jet} > 0.035$, $\theta_{jet} < 20°$

2 forward jets: disagreement with NLOjet at low x_{Bj} for $d\sigma/dx_{Bj}$

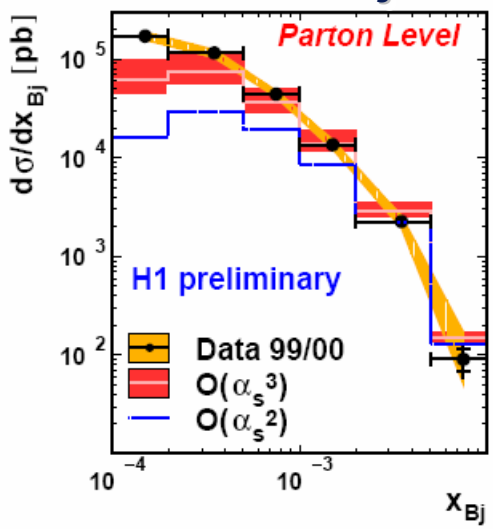
- **More gluons expected with 2 forward jets**
- **More sensitive to higher-order terms**
  - Jets selected to favor more gluon emission

NLOjet describes angular correlations well within theorectical uncertainties

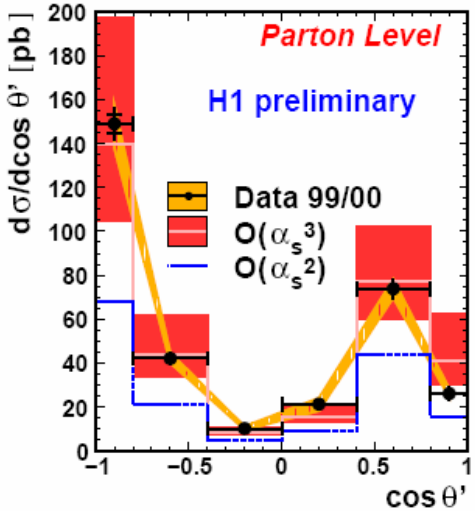
1 forward jet

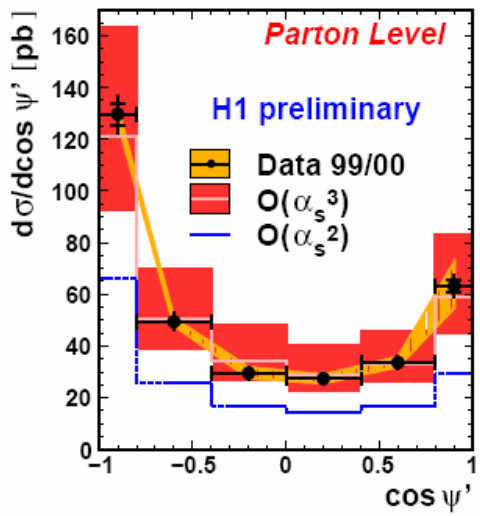


2 forward jets



2 forward jets

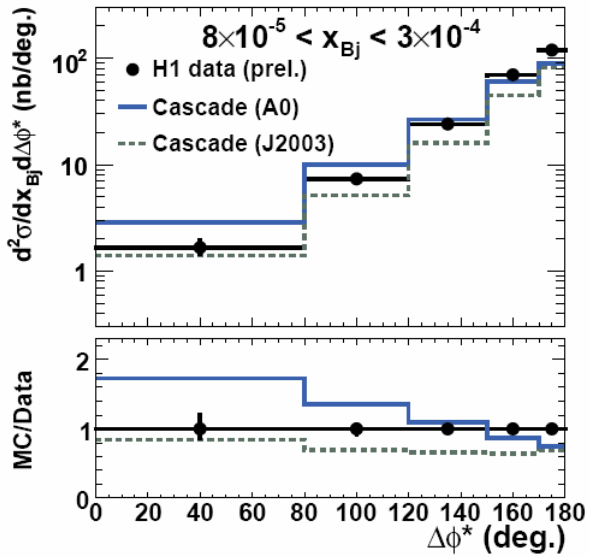




Leading-Order Models: Dijet Azim. Correl, Incl. Forward Jets

H1 dijet azimuthal correlations:

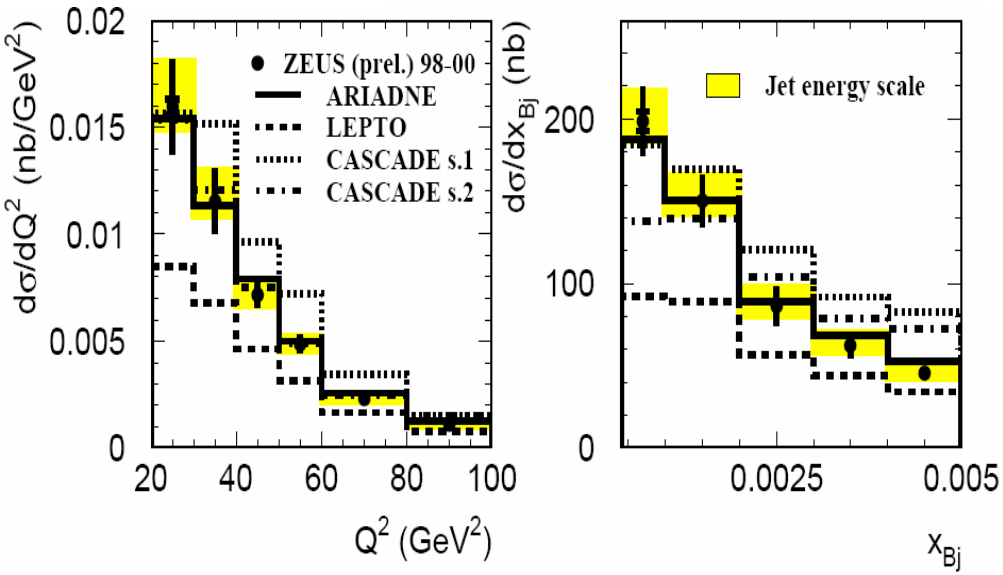
- Expect broader $\Delta\phi^*$ spectrum from BFKL, CCFM
- CASCADE with J2003 pdf set describes data at higher x_{Bj}
  - CASCADE predictions dependent on unintegrated gluon PDF
- All models fail to describe $\Delta\phi^*$ at low x_{Bj}



ZEUS inclusive forward jets:

Expect more forward jets with BFKL, CCFM at low x_{Bj}

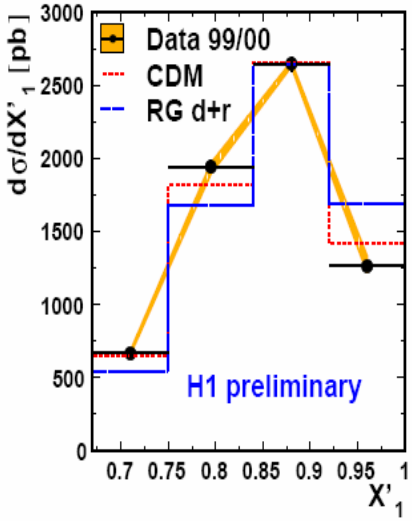
- LEPTO (DGLAP) consistently below measurements
- CASCDE (CCFM) inconsistent in description of data
  - Better description from J2003 set 2 than set 1
- ARIADNE (CDM, ~BFKL) gives best overall description

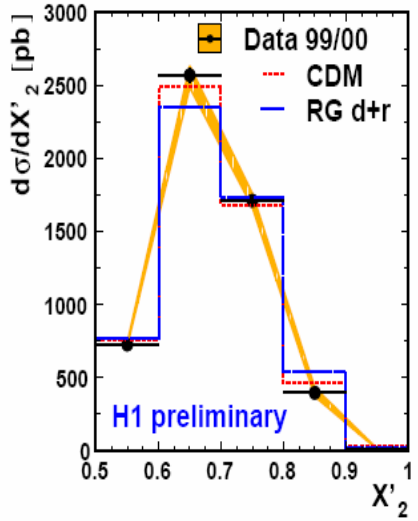


Leading-Order Models: H1 Inclusive Trijet Correlations

Trijet sample

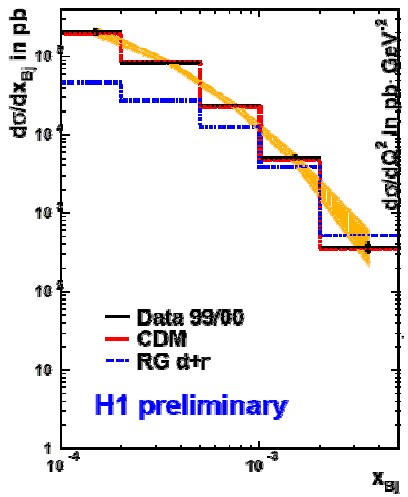
- Scaled jet energies better described by CDM (~BFKL) than RAPGAP (DGLAP)
- Both CDM and RAPGAP (DGLAP + res. photon) fail to describe both angular correlations

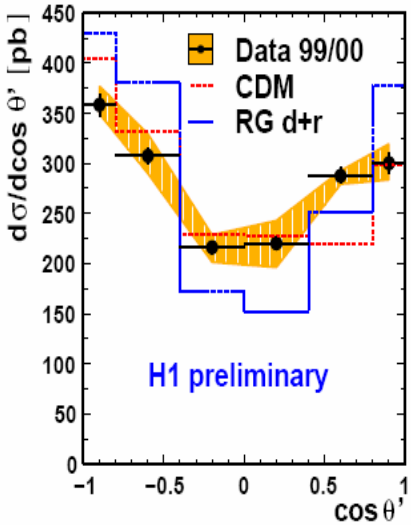


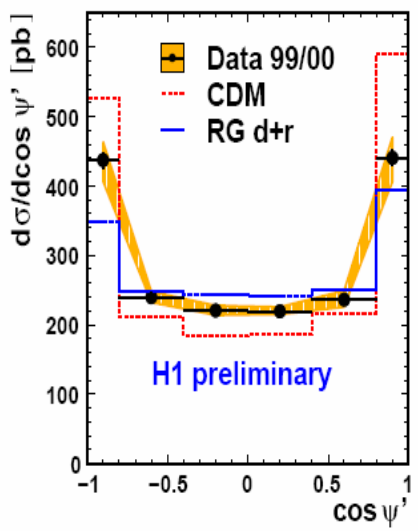


Four-jet sample

- CDM provides better description overall
- No NLO calculations available







Summary: Low-x_{Bj} Dynamics at HERA

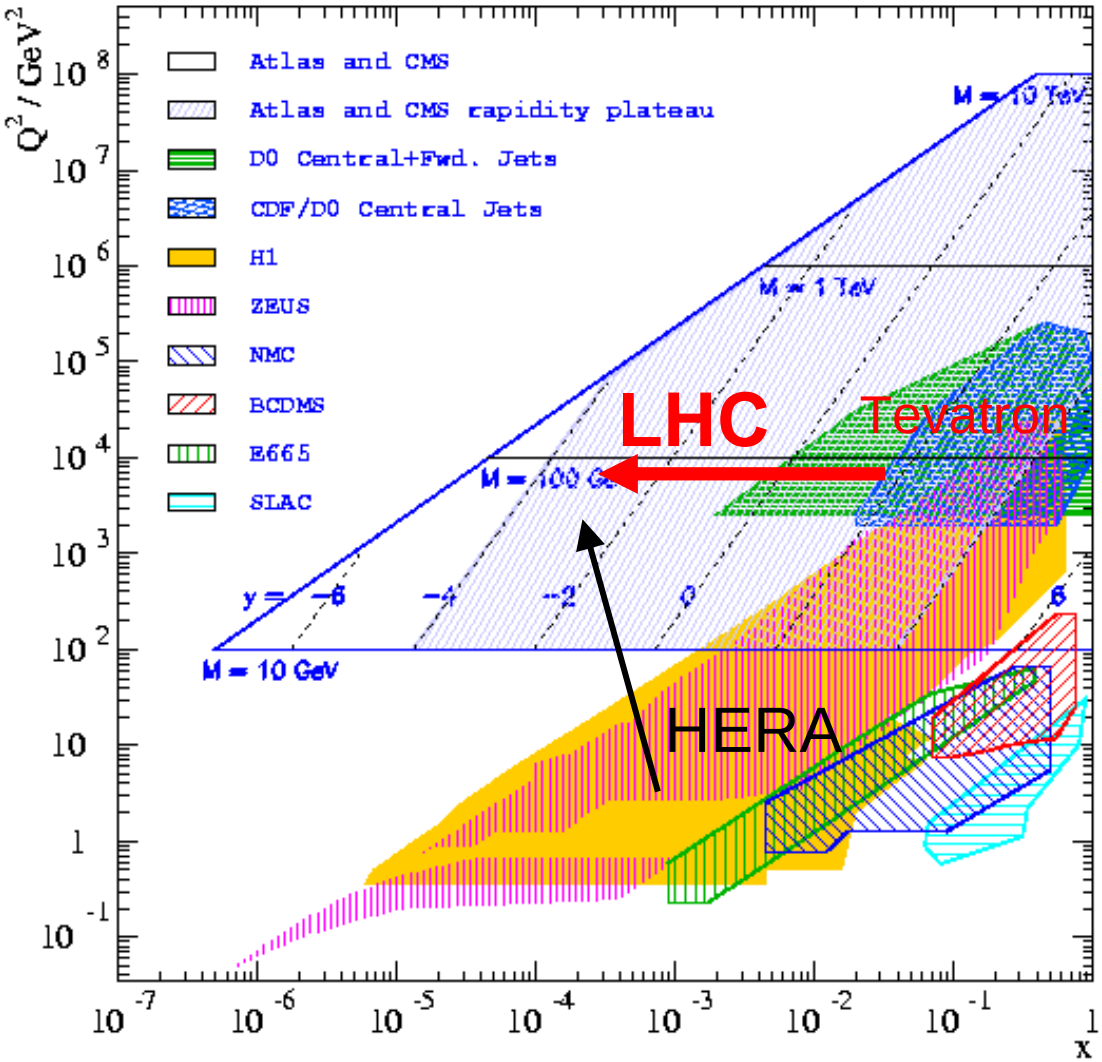
- **DGLAP NLO calculations describe data in general**
  - **Higher-order terms important at low Q^2, x_{Bj}**
  - **NLO calculations do not describe**
    - Dijet azimuthal correlations, when normalized to visible cross section
    - Trijet cross sections for trijets with 2 forward jets at very small x_{Bj}
- **Leading-order models describe data inconsistently**
  - **DGLAP-based models consistently fail to describe inclusive forward jet measurements, dijet and trijet correlations**
  - **CASCADE (CCFM) dependent on unintegrated PDF. Fails to describe inclusive forward jet cross sections**
  - **CDM (~BFKL) gives best overall description, but fails to describe dijet azimuthal correlations, trijet angular correlations**

LHC implications:

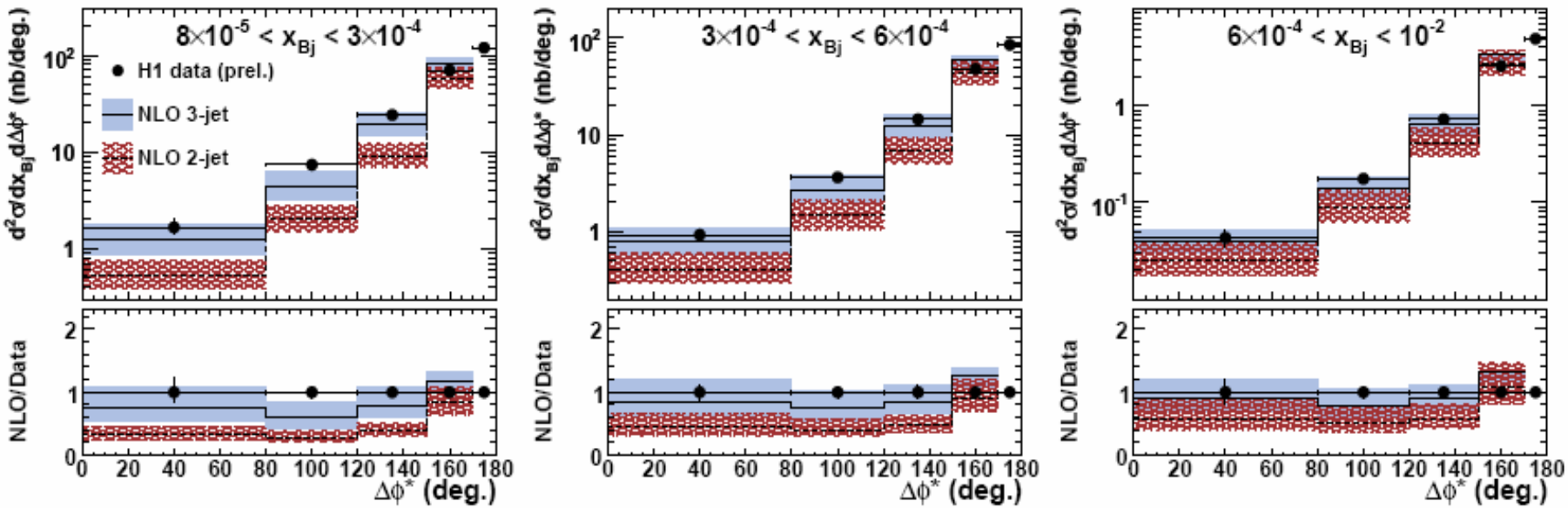
- **LHC low-x limit: ~10^{-6}**
- **Tevatron low-x limit: ~10^{-3}**
- **HERA analyses have tested QCD evolution to x_{Bj} ~ 10^{-4}**

Backup Slides

Kinematic Coverage of Colliders



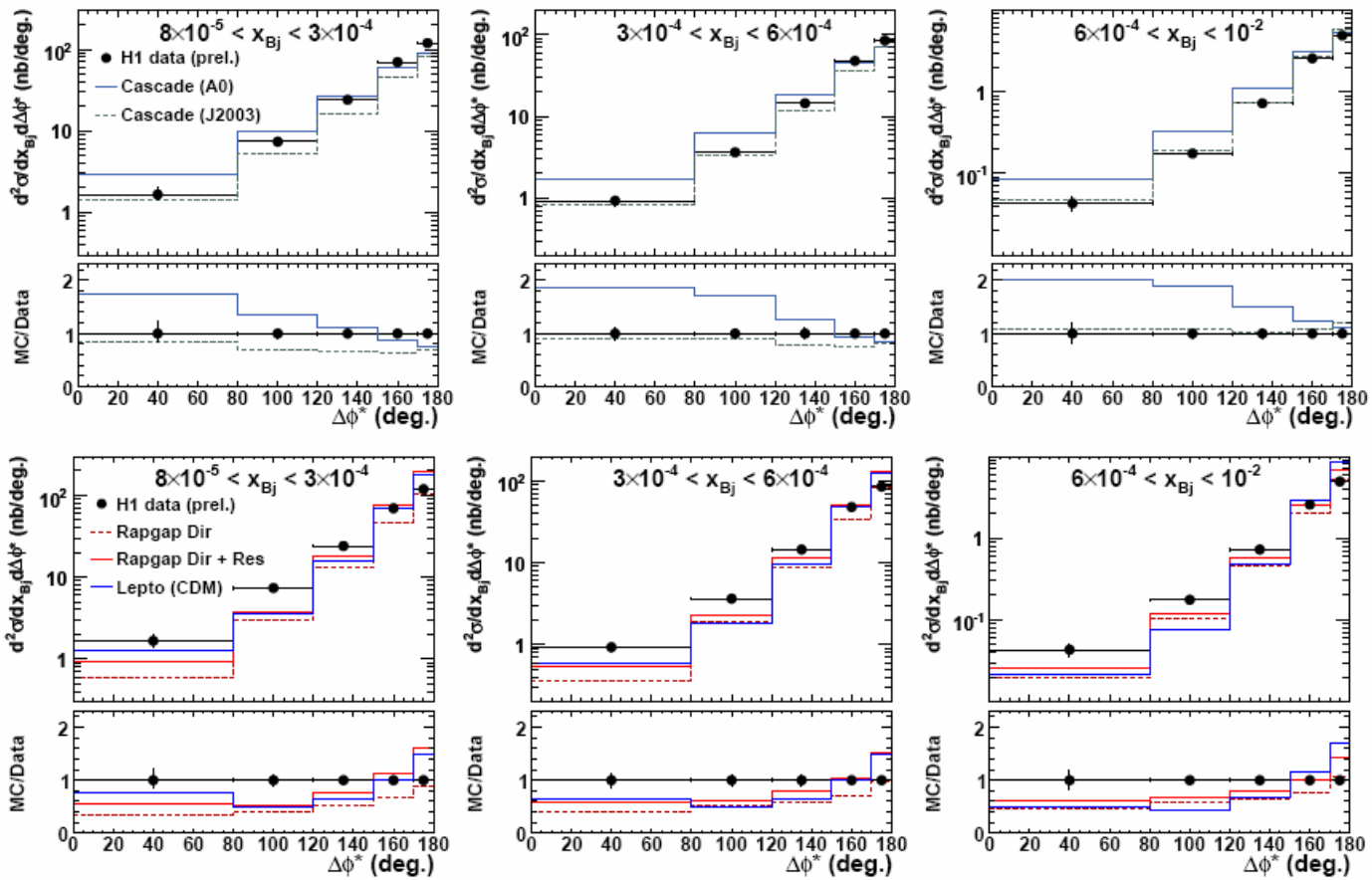
H1 Dijet Azimuthal Correl. vs. x_{Bj}



Without normalization to visible cross section

- **Reasonable description of dijet data from NLO 3-jet calculation**
- **Large theoretical uncertainties**

H1 Dijet Azimuthal Correlations: Complete LO Results



CASCADE (CCFM)

LEPTO (CDM)
→ *used with ARIADNE*
RAPGAP dir (DGLAP)

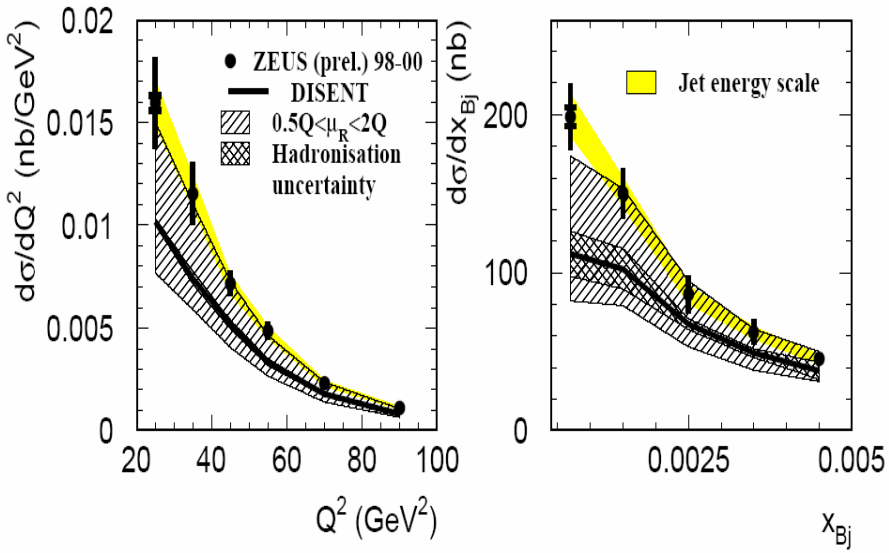
RAPGAP res (+ resolved photon)

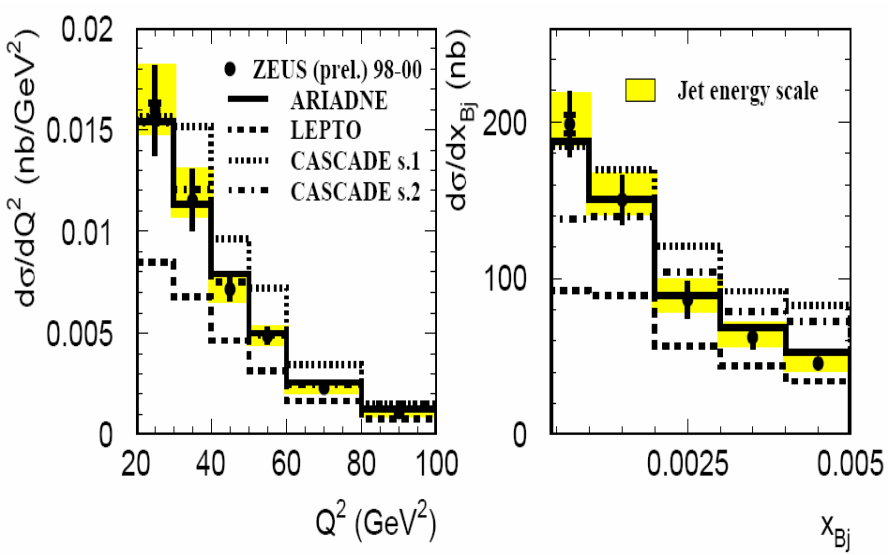
CASCADE with J2003 pdf set describes data at higher x_{Bj}

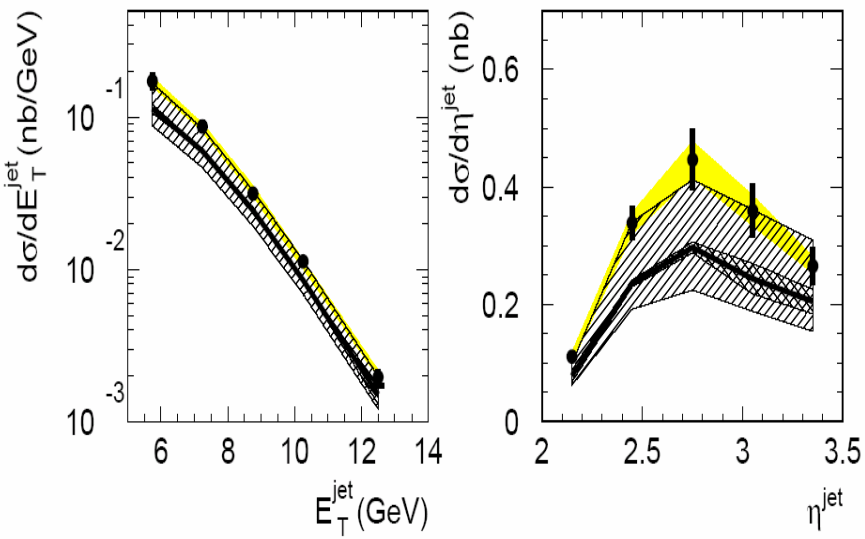
CDM, RAPGAP (dir and res) fail to describe low-$\Delta\phi^*$ regions

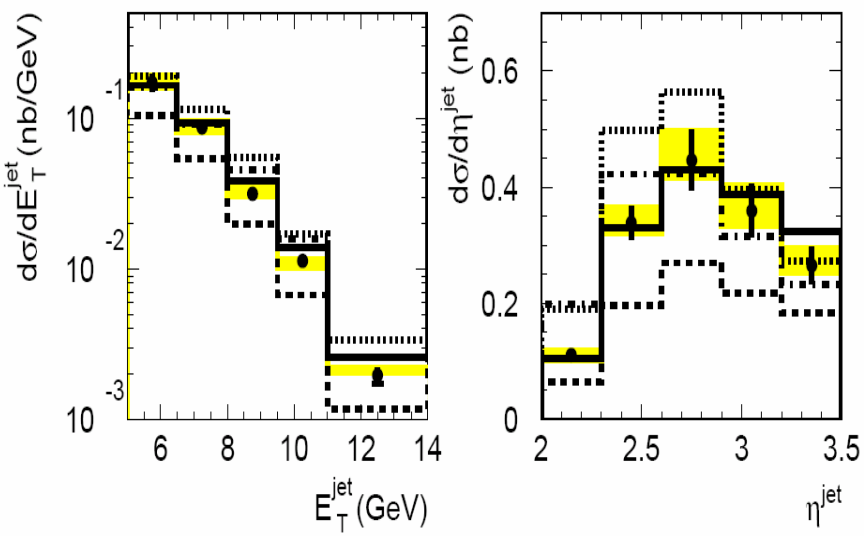
- **CDM has slightly better description at low x_{Bj}**

ZEUS Forward Jets: Complete Results









ZEUS Dijet and Trijet p_T Correlations vs. x_{Bj}