



Forward Jet Production at HERA

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On Behalf of the H1 and ZEUS Collaborations

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Parton Evolution Equations



• Perturbative expansion of evolution equations

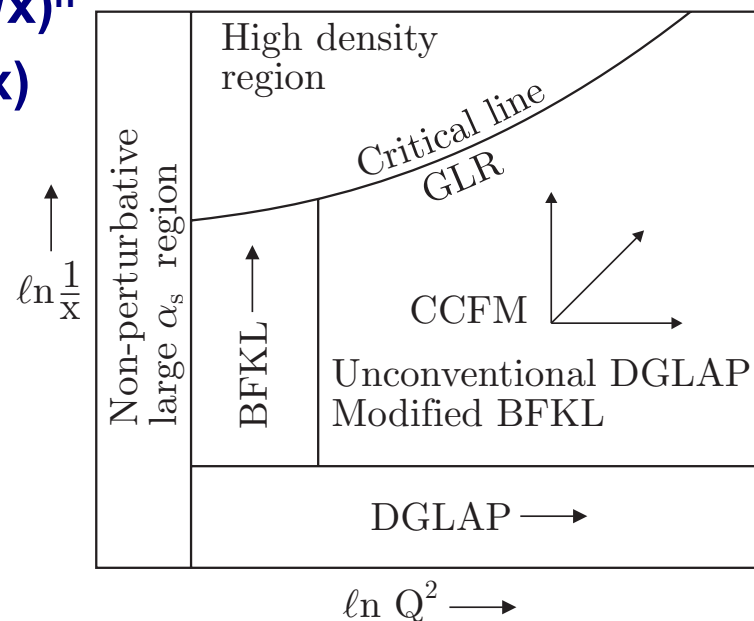
- $\sim \sum_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$
- Cannot be explicitly calculated to all orders

• Equations to calculate QCD evolution

- DGLAP - Resum in $\ln(Q^2)$: $\Sigma(\alpha_s \ln Q^2)^n$
- BFKL - Resum in $\ln(1/x)$: $\Sigma(\alpha_s \ln 1/x)^n$
- CCFM - Resum in $\ln(Q^2)$ and $\ln(1/x)$

• Regions of validity

- DGLAP - Large Q^2 , x not small
- BFKL - Small x , Q^2 not too large
- CCFM - Valid in large x range

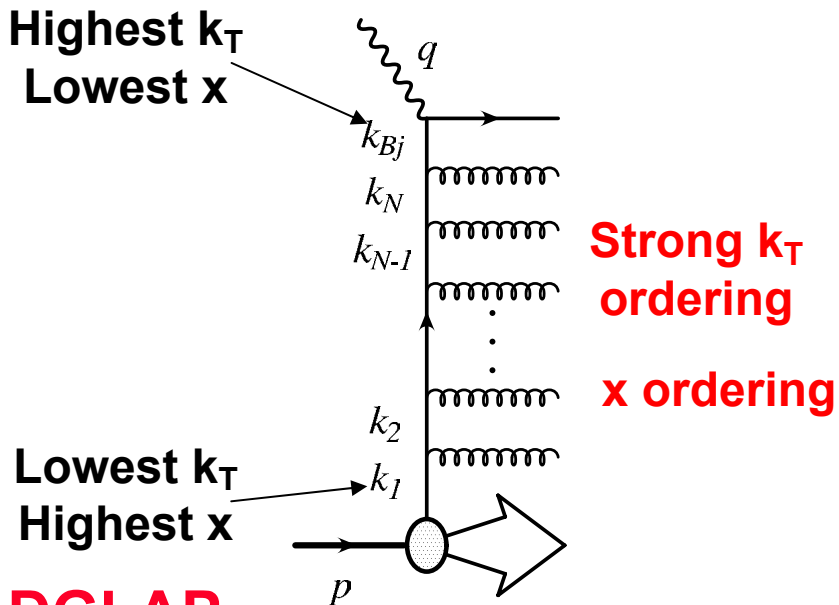




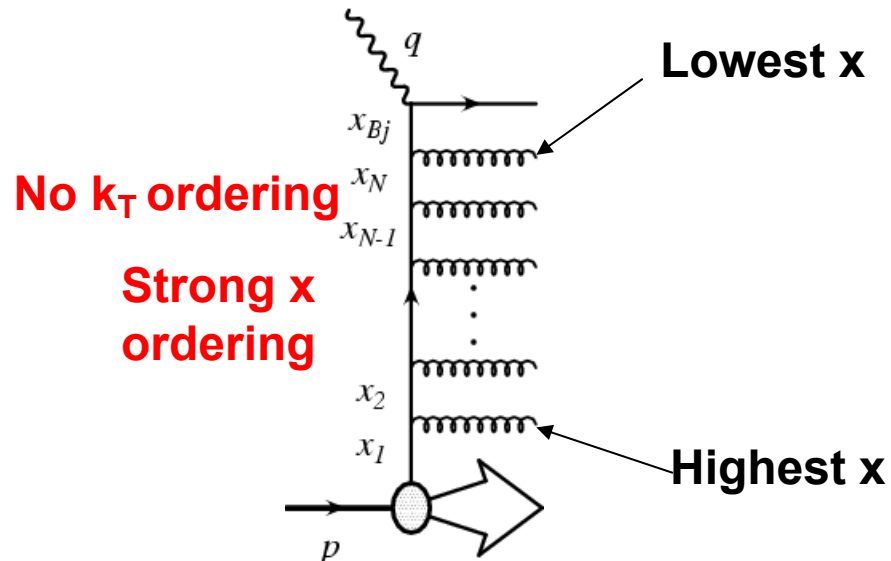
Parton Evolution Equations Gluon Ladder



DGLAP



BFKL



•DGLAP

- Strongly ordered in trans momentum: $k_{T,1} \ll k_{T,2} \ll \dots \ll k_{T,n} \ll Q^2$
- Ordered in x : $x_1 > x_2 > \dots > x_n > x$

•BFKL:

- Strongly ordered in x : $x_1 \gg x_2 \gg \dots \gg x_n \gg x$
- No k_T ordering \rightarrow Eta democracy
- Predicts additional hadrons from high p_T forward partons

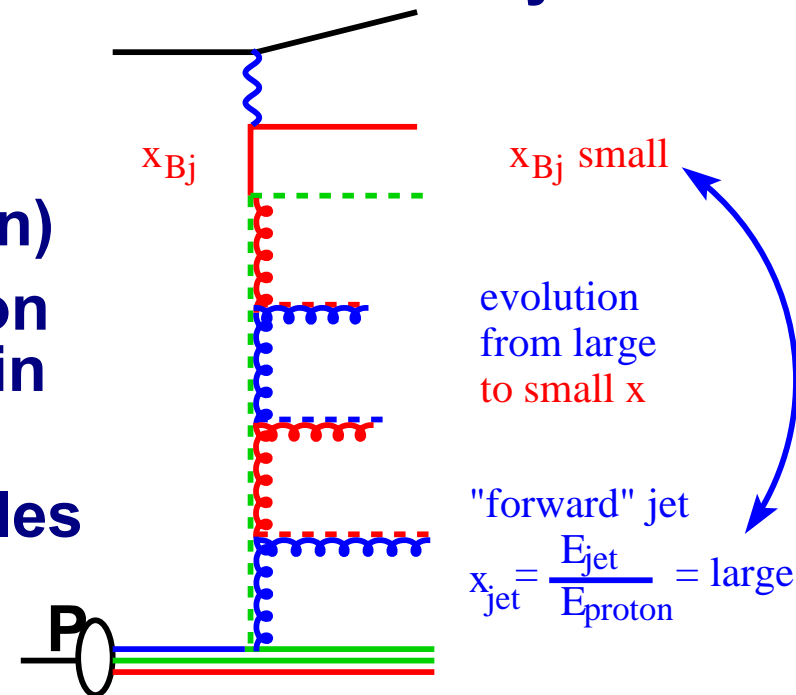
•Experiments: Try to distinguish between evolution equations



Investigate New Parton Dynamics



- **DGLAP Evolution** expected to describe most of HERA kinematic range
 - Find region where DGLAP not guaranteed to be valid
- **Search for signs of BFKL dynamics**
 - Suppress events strongly ordered in virtuality
 - Require Jet $p_T^2 \sim Q^2$
 - Require large $E_{\text{Jet}}/E_{\text{Proton}}$
 - Forward Jet (close to Proton)
 - BFKL predicts larger fraction of small x events will contain high E_T events than DGLAP
 - Can also tag forward Particles





Monte Carlo and Calculations



- **Monte Carlo**
 - **LEPTO**
 - Parton shower: k_T ordered (MEPS) – Uses DGLAP
 - **RAPGAP**
 - Parton shower: k_T ordered (MEPS) – Uses DGLAP
 - Direct γ interactions similar to LEPTO
 - Includes resolved γ interactions
 - **ARIADNE**
 - Parton shower: Color Dipole Model (CDM) – BFKL like
 - **CASCADE**
 - Based on CCFM
 - Set1: $k_{\perp}^{\text{cut}} = 1.33 \text{ GeV}$
 - Set2: $k_{\perp}^{\text{cut}} = 1.88 \text{ GeV}$ and non-singular terms in splitting function included
 - **All models use Lung String Model for Hadronization**
- **NLO QCD Calculations**
 - **DISENT**
 - Fixed order α_s^2

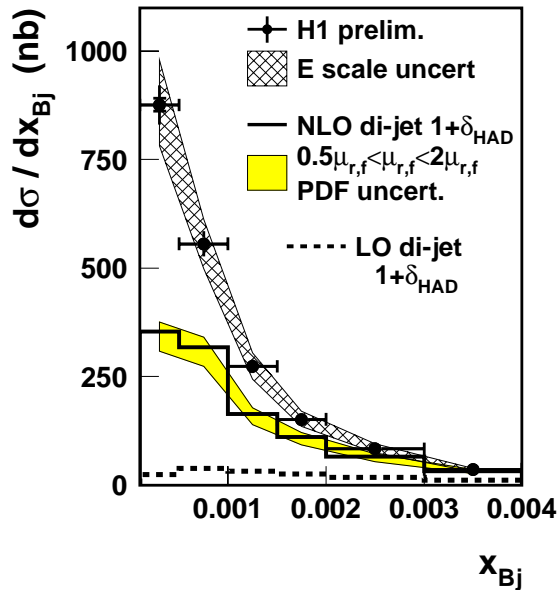


Forward Jet Production at HERA H1 Collaboration



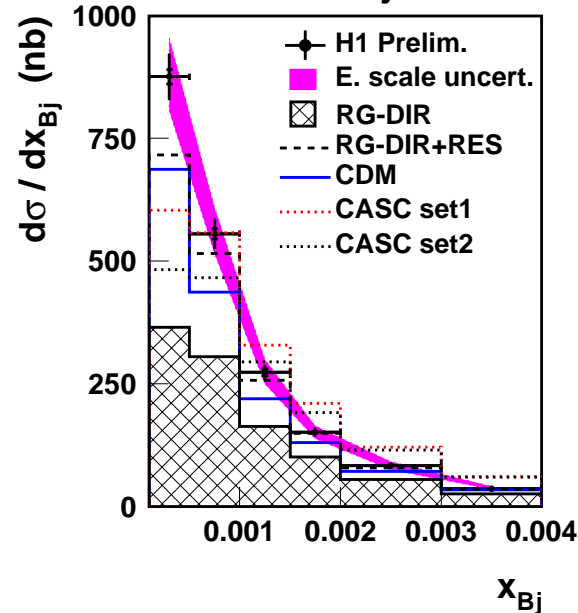
Data vs. NLO

H1 forward jet data



Data vs. MC

H1 forward jet data



Inclusive Forward Jet Production

- DISENT NLO Calculations and RAPGAP (DGLAP) with only direct γ below data
 - Disagreement at low x
- RAPGAP resolved γ model improves agreement
 - Still disagreement at low $x \rightarrow$ Hint of BFKL dynamics?
- ARIANDE (“BFKL-like”) MC and RAPGAP Direct + Resolved (DGLAP) slightly below forward jet data
- CASCADE (CCFM) MC gives poor description of forward jet data

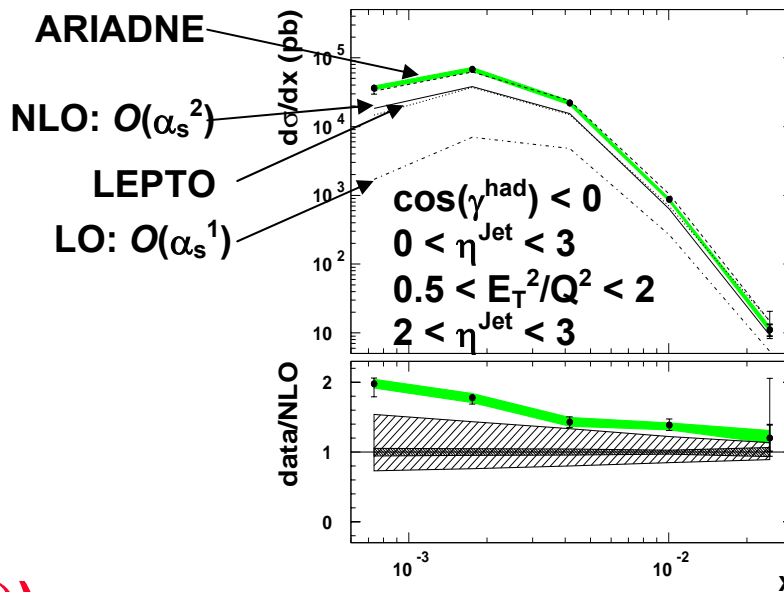
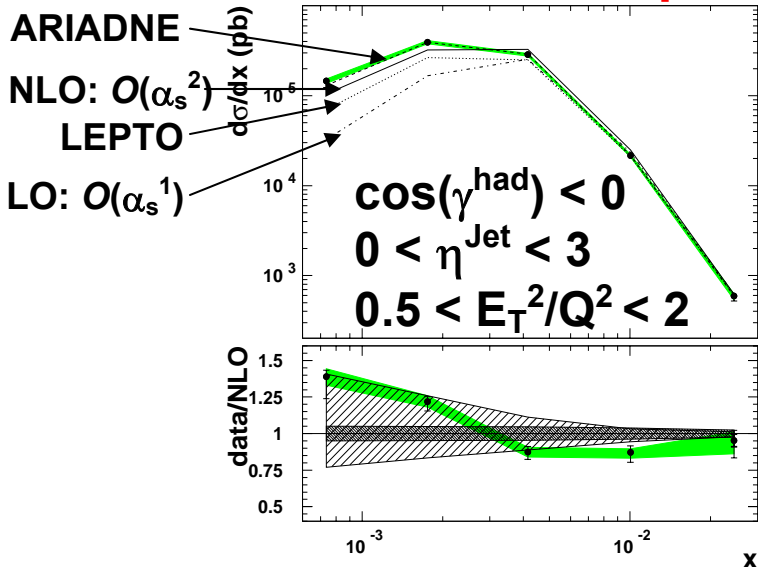


Forward Jet Production at HERA ZEUS Collaboration



BFKL Phase Space

BFKL "Forward" Phase Space



• BFKL Phase Space ($O(\alpha_s^2)$)

- ARIADNE ("BFKL") describes forward jet data, LEPTO (DGLAP) does not
- NLO gives better description of forward jet data than in inclusive region
 - Disagreement still present at low x
 - Disagreement between LO and NLO \rightarrow large corrections from higher order terms

• BFKL Forward Phase Space

- ARIADNE ("BFKL") describes forward jet data, LEPTO (DGLAP) does not
- NLO slightly lower than forward jet data
 - Disagreement between LO and NLO much bigger than in BFKL Phase Space
 - Need for higher order calculations



Very Forward Jets at HERA Data vs. MC (ZEUS)



Data vs. MC

• Very Forward η region

ZEUS

• $2 < \eta^{\text{Jet}} < 3.5$

• Previous H1: $\eta^{\text{Jet}} < 2.7$

• Previous ZEUS: $\eta^{\text{Jet}} < 3.0$

• **ARIADNE describes forward jet data**

• **LEPTO does not describe data**

• Large disagreement at low Q^2 , x

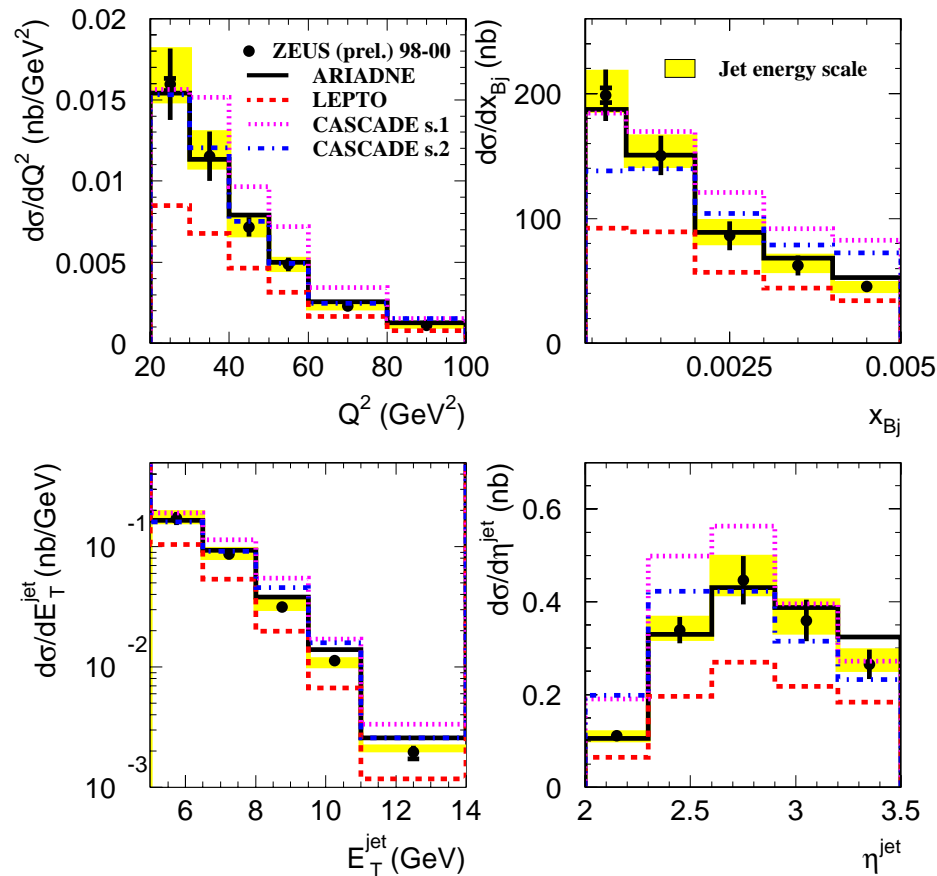
• **CASCADE Set 1**

• Does not describe data

• **CASCADE Set 2**

• Good description of Q^2 and E_T^{Jet}

• Reasonable description of x and η



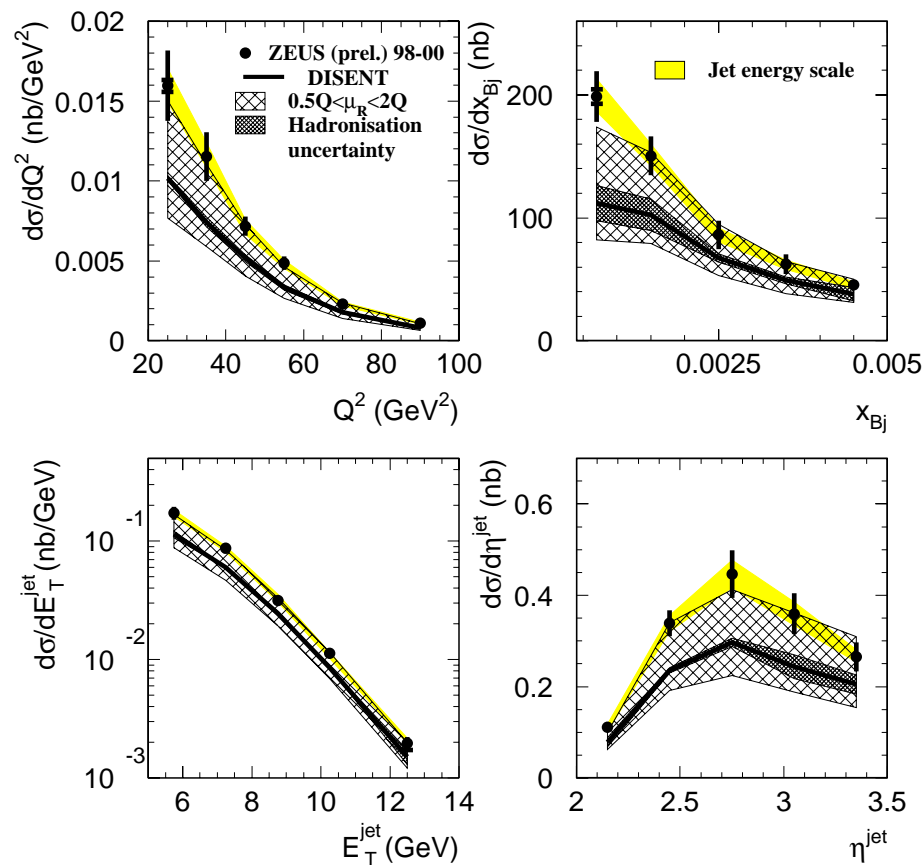


Very Forward Jets at HERA Data vs. NLO (ZEUS)



Data vs. NLO

ZEUS



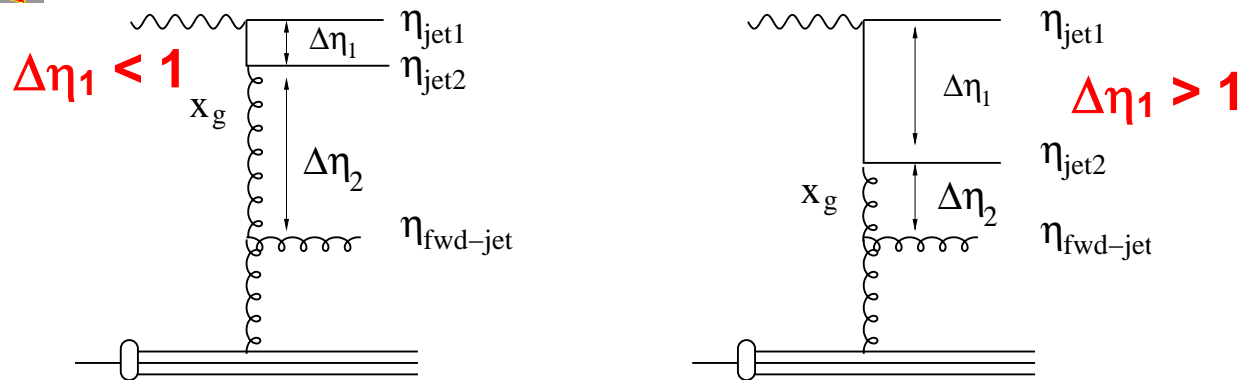
• Very Forward η Region

- $2 < \eta^{\text{Jet}} < 3.5$
- DISENT NLO
 - Describes forward jets data within theoretical uncertainties
 - Large variation with renormalization scale
 - Suggests need for higher order calculations



Forward Jet with Central Dijets

H1 Collaboration



• 2 High- E_T central jets in addition to forward jet

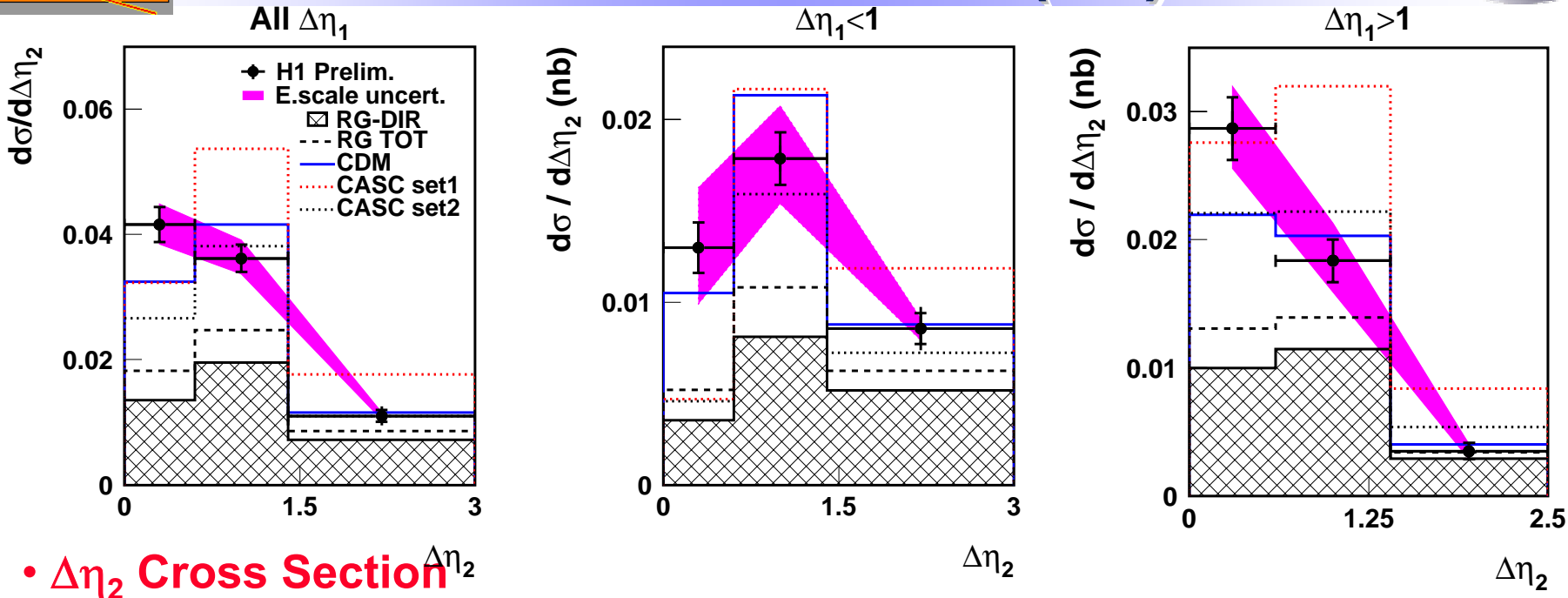
- Jets ordered in η : $\eta_{\text{fwd-Jet}} > \eta_{\text{Jet2}} > \eta_{\text{Jet1}} > \eta_{\text{electron}}$
- η separation
 - Between central jets: $\Delta\eta_1 = \eta_{\text{Jet2}} - \eta_{\text{Jet1}}$
 - Between hadronic system & forward jet: $\Delta\eta_2 = \eta_{\text{fwd-Jet}} - \eta_{\text{Jet2}}$

• Suppress strong k_T ordering by demanding same p_T cut for 3 Jets

- Selects “BFKL region”
- $\Delta\eta_1 < 1$
 - Maximize BFKL phase space
- $\Delta\eta_1 > 1$
 - Separation btw central & forward jets smaller \rightarrow resolved photon region



Forward Jet with Central Dijets Data vs. Models (H1)



• $\Delta\eta_2$ Cross Section

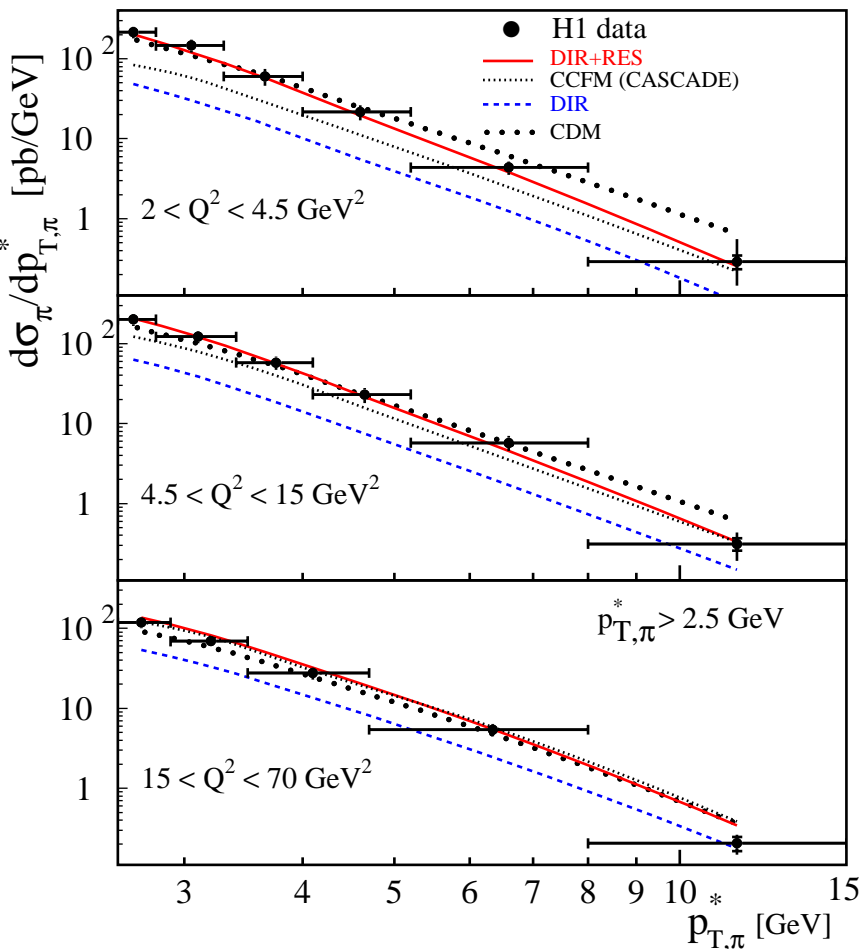
- **RAPGAP Direct + Resolved (DGLAP)**
 - Below data for All $\Delta\eta_1$ and $\Delta\eta_1 < 1$
 - Agrees with data only in highest bin of $\Delta\eta_1 > 1$
- **LEPTO (BFKL-like)**
 - Better agreement for $\Delta\eta_1 < 1$ than $\Delta\eta_1 > 1$
- **CASCADE (CCFM)**
 - Set 1 does not describe data in any region
 - Set 2 Describes data for $\Delta\eta_1 < 1$ except lowest bin, does not describe for $\Delta\eta_1 > 1$



Forward π^0 Production at HERA p_T Distributions (H1)



$p_{T\pi}$ Cross Section

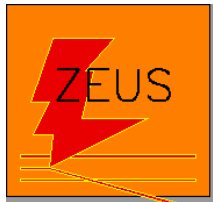


• Measure π^0 instead of Jets

- No ambiguities from Jet algorithm
- Larger uncertainties from hadronization
- BFKL Region: Particle $p_T^2 \sim Q^2$

• Cross Section $p_{T\pi}$

- Data falls steeply as $p_{T\pi}$ increases
- RAPGAP Dir+Res describes π^0 data
- RAPGAP Dir only below π^0 data
- ARIADNE describes π^0 data
- CASCADE
 - Good description at higher Q^2
 - Poor description at lower Q^2

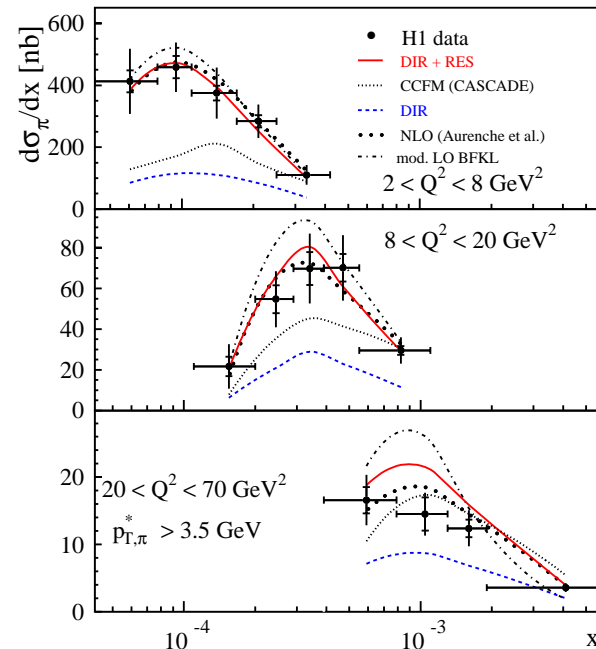
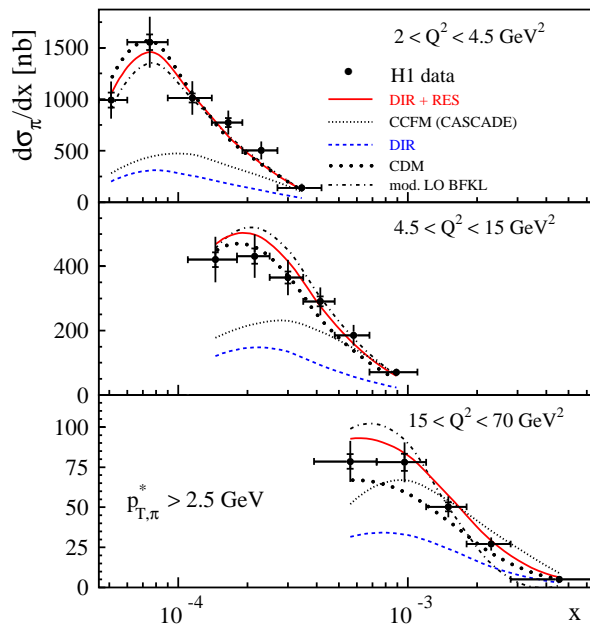


Forward π^0 Production at HERA x Distributions (H1)



x Cross Section with $p_{T\pi} > 2.5$ GeV

x Cross Section with $p_{T\pi} > 3.5$ GeV



• x Cross Section

- RAPGAP Direct + Resolved describe π^0 data well
- RAPGAP Direct only below π^0 data
- CASCADE describes π^0 data only at high x and Q^2
 - Discrepancies at low x not covered by Forward Jet measurement

• x Cross Section with $p_{T\pi} > 3.5$ GeV

- Cross Sections 2-4 times lower
- NLO calculation describes data



Forward Jet Summary



- **BFKL Region Selected**
 - Forward Jets with Jet $p_T^2 \sim Q^2$
 - Forward π^0 with Particle $p_T^2 \sim Q^2$
 - Forward Jet + central dijets with η separations
- **Summary of Agreement between Data and Predictions**
 - MC which describe data
 - ARIADNE (BFKL-like)
 - RAPGAP (DGLAP) Direct + Resolved (except fwd+dijet)
 - MC which do not describe data
 - LEPTO (DGLAP)
 - RAPGAP (DGLAP) Direct only
 - CASCADE (CCFM)
 - NLO gives good description of data
 - Higher order calculations needed to improve agreement
- **Conclusions**
 - DGLAP works everywhere except forward + central dijets
 - Can improve MC agreement with data with any or all of
 - Direct and resolved contributions of DGLAP MC
 - BFKL-like MC
 - NLO