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

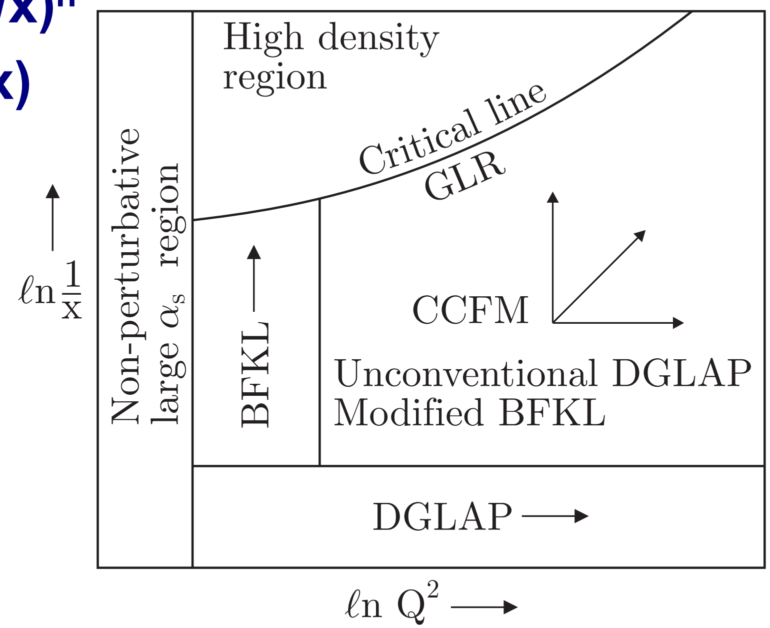
- $\sim \Sigma_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$
- Cannot be explicitly calculated to all orders

•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

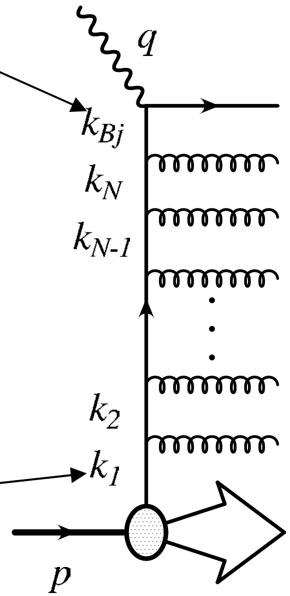
- DGLAP - Large Q^2, x not small
- BFKL - Small x, Q^2 not too large
- CCFM - Valid in large x range



Parton Evolution Equations
Gluon Ladder

DGLAP

Highest k_T
Lowest x



Lowest k_T
Highest x

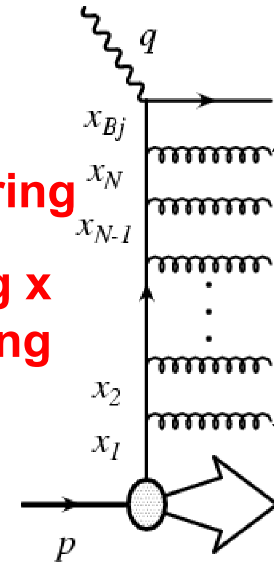
Strong k_T ordering

x ordering

BFKL

No k_T ordering

Strong x ordering



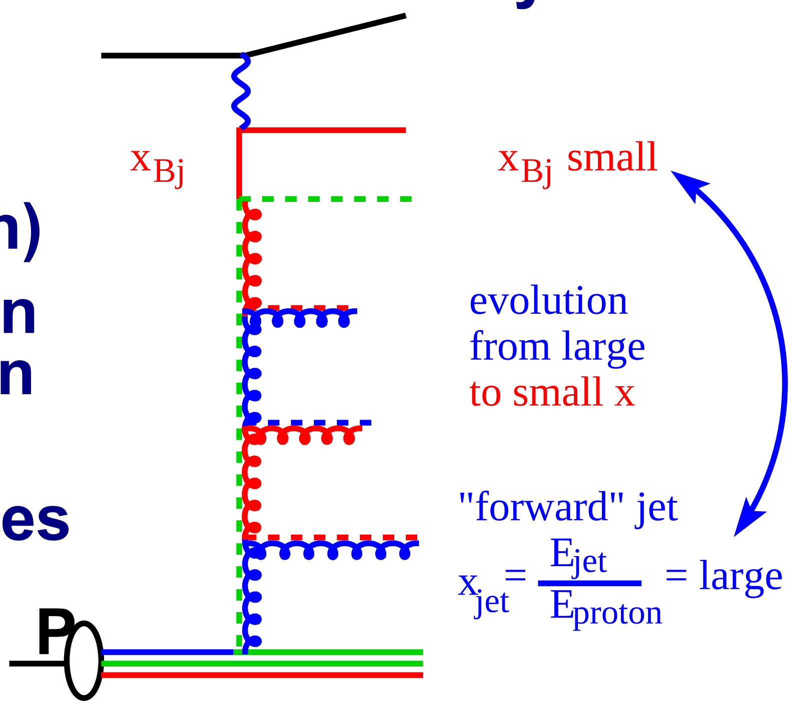
Lowest x

Highest x

- **DGLAP**
  - Strongly ordered in trans momentum: $k_{T,1} << k_{T,2} << \ldots << k_{T,n} << Q^2$
  - Ordered in x: $x_1 > x_2 > \ldots > x_n > x$
- **BFKL:**
  - Strongly ordered in x: $x_1 >> x_2 >> \ldots >> x_n >> x$
  - No k_T ordering → 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_{Jet}/E_{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

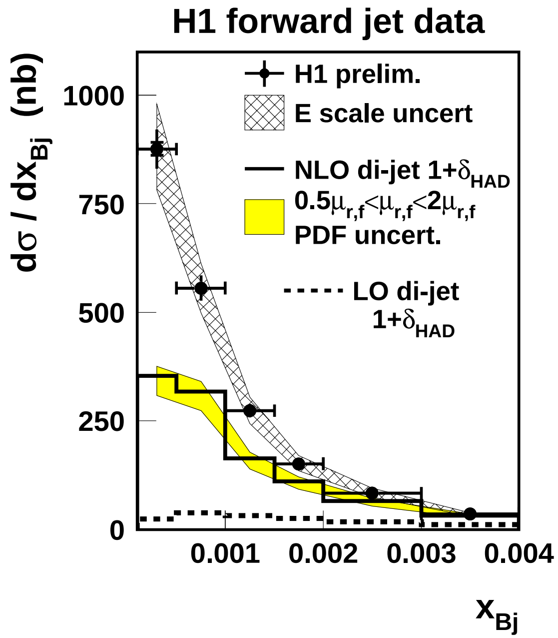


Monte Carlo and Calculations

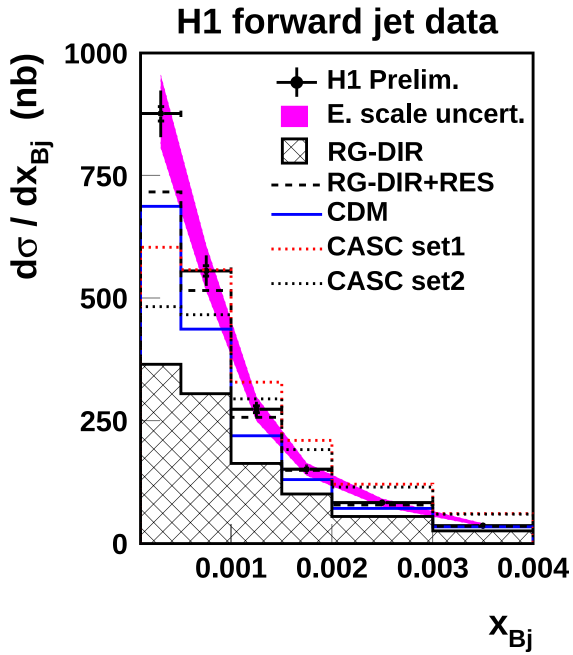
- Monte Carlo
  - LEPTO
    - Parton shower: k_T ordered (MEPS) – Uses DGLAP
  - RAPGAP
    - Parton shower: k_T ordered (MEPS) – Uses DGLAP
    - Direct γ interactions similar to LEPTO
    - Includes resolved γ interactions
  - ARIADNE
    - Parton shower: Color Dipole Model (CDM) – BFKL like
  - CASCADE
    - Based on CCFM
    - Set1: $k_\perp^{cut}$ = 1.33 GeV
    - Set2: $k_\perp^{cut}$ = 1.88 GeV and non-singular terms in spliting 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



Data vs. MC

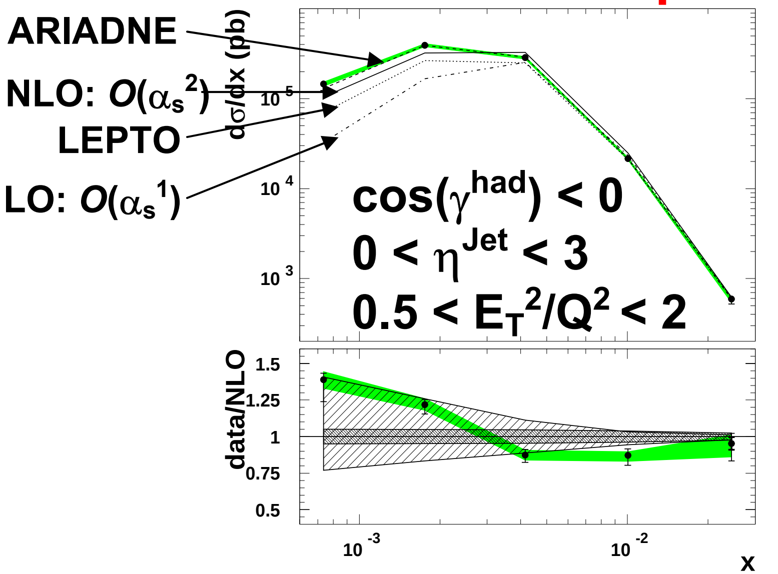


•Inclusive Forward Jet Production

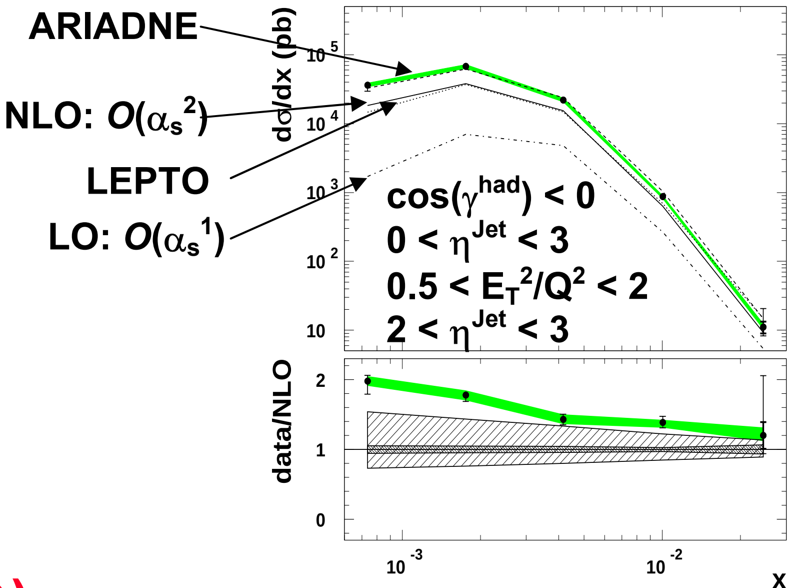
- **DISENT NLO Calculations and RAPGAP (DGLAP) with only direct γ below data**
  - Disagreement at low x
- **RAPGAP resolved γ model improves agreement**
  - Still disagreement at low x → Hint of BFKL dynamics?
- **ARIANDE (“BFKL-like”) MC and RAPGAP Direct + Resolved (DGLAP) slightly below forward jet 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 ($O(\alpha_s^2)$)

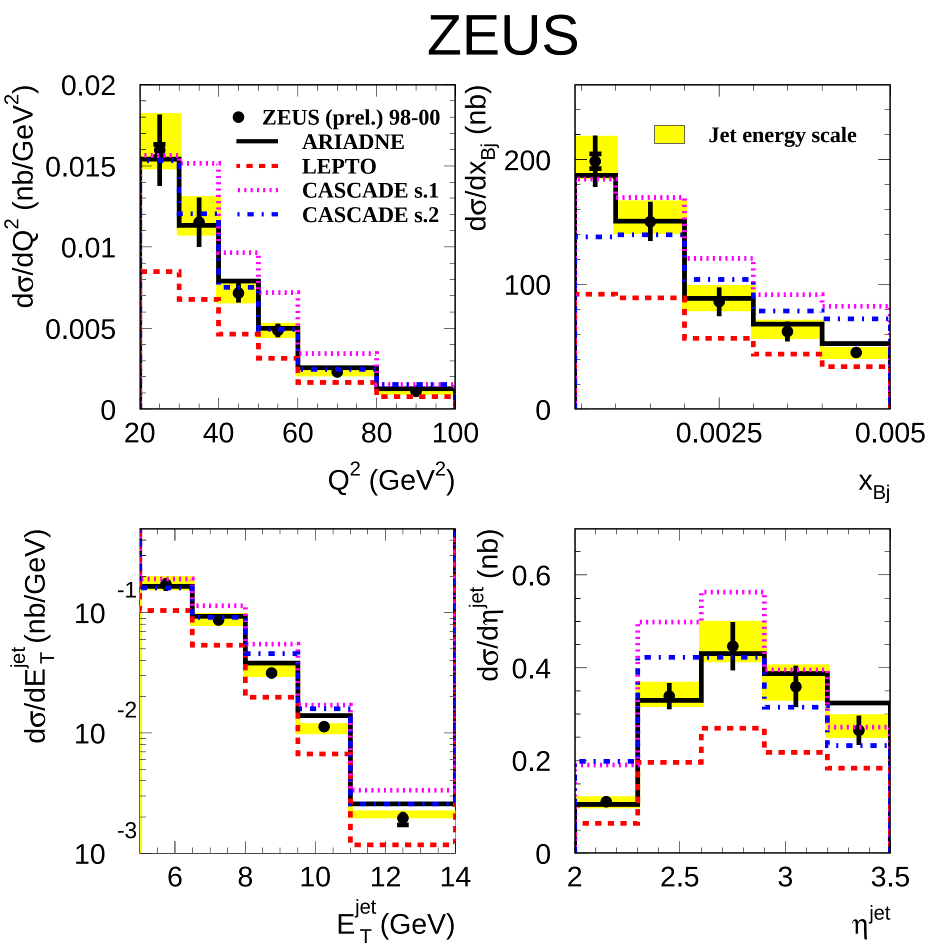
- ARIADNE ("BFKL") describes forward jet data, LEPTO (DGLAP) does not
- NLO gives better description of forward jet data than in inclusive region
  - Disagreement still present at low x
  - Disagreement between LO and NLO → large corrections from higher order terms

•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)

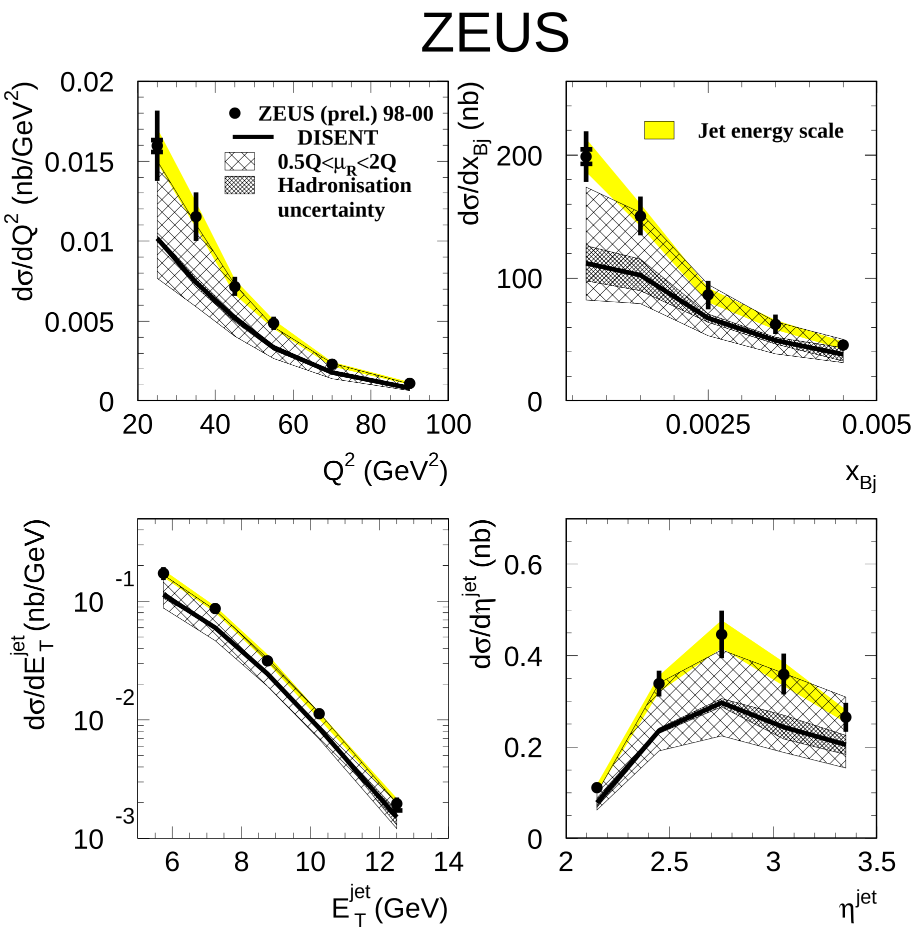
Data vs. MC



•Very Forward η region

- **$2 < \eta^{Jet} < 3.5$**
  - Previous H1: $\eta^{Jet} < 2.7$
  - Previous ZEUS: $\eta^{Jet} < 3.0$
- **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

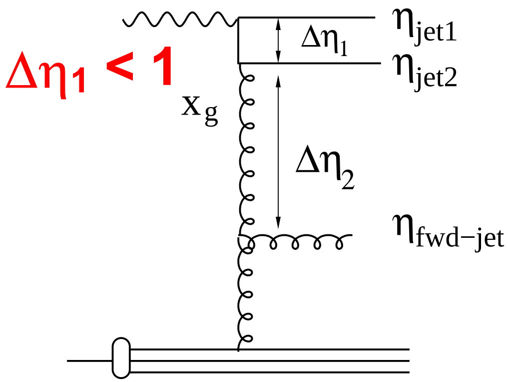
Data vs. NLO

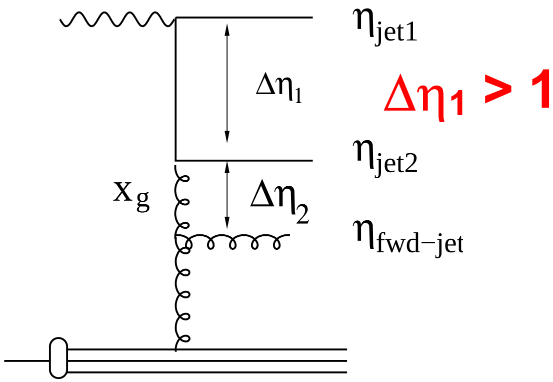


•Very Forward η Region

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

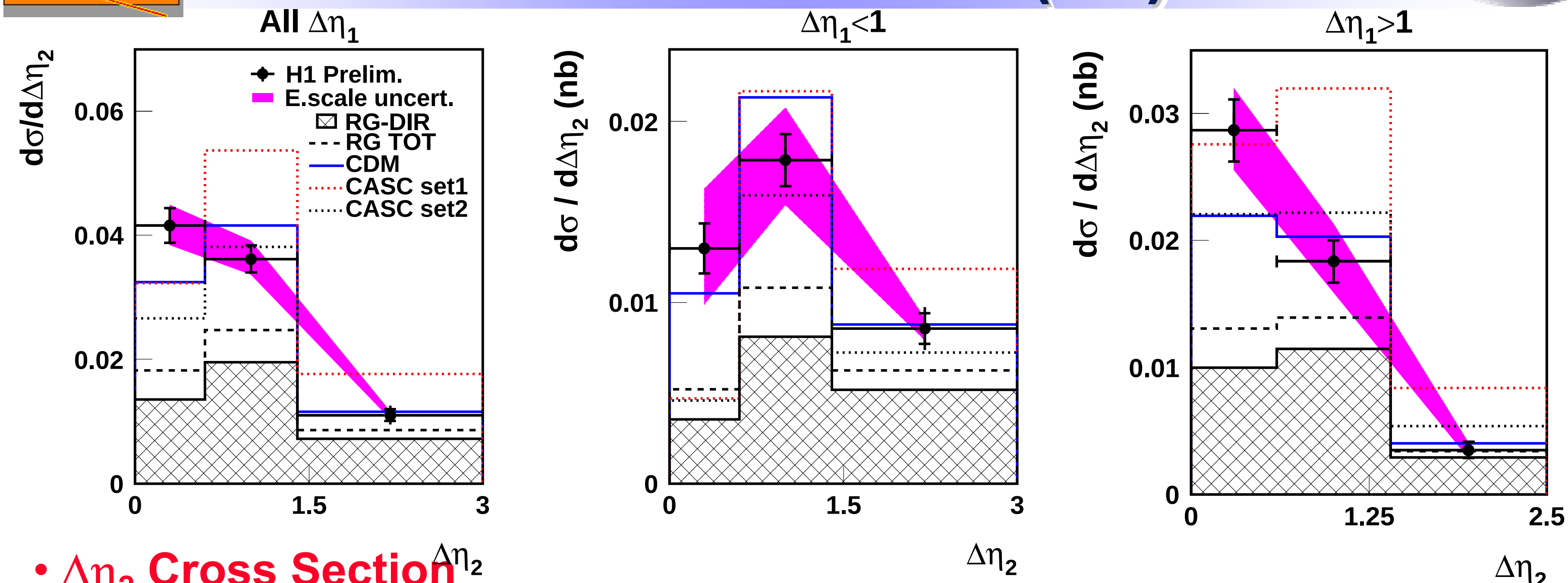
Forward Jet with Central Dijets
H1 Collaboration





- **2 High-E_T central jets in addition to forward jet**
  - **Jets ordered in η: $\eta_{fwd\text{-}Jet} > \eta_{Jet2} > \eta_{Jet1} > \eta_{electron}$**
  - **η separation**
    - Between central jets: $\Delta\eta_1 = \eta_{Jet2} - \eta_{Jet1}$
    - Between hadronic system & forward jet: $\Delta\eta_2 = \eta_{fwd\text{-}Jet} - \eta_{Jet2}$
- **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 → resolved photon region**

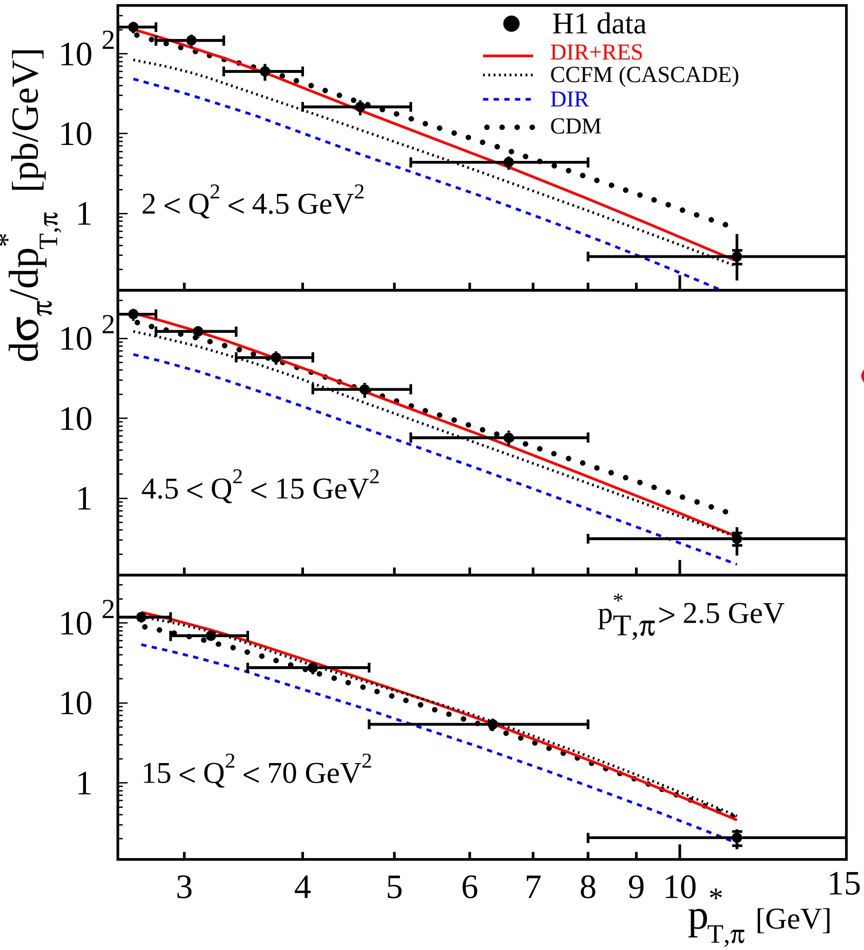
Forward Jet with Central Dijets Data vs. Models (H1)



- **$\Delta\eta_2$ 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)

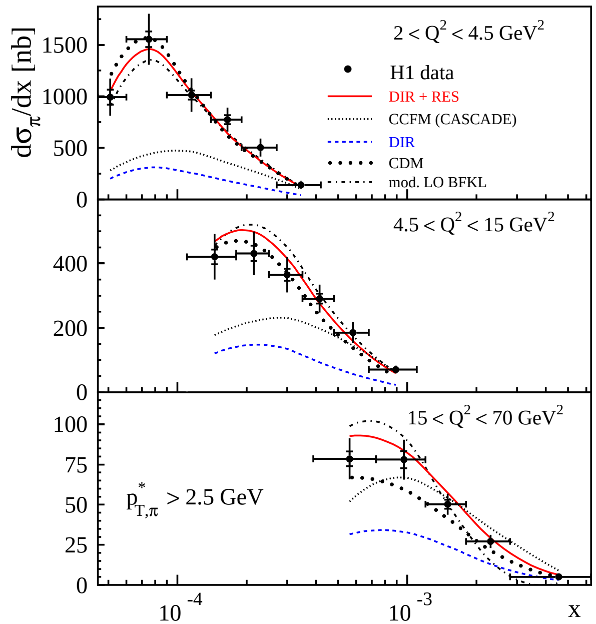
$p_{T\pi}$ Cross Section



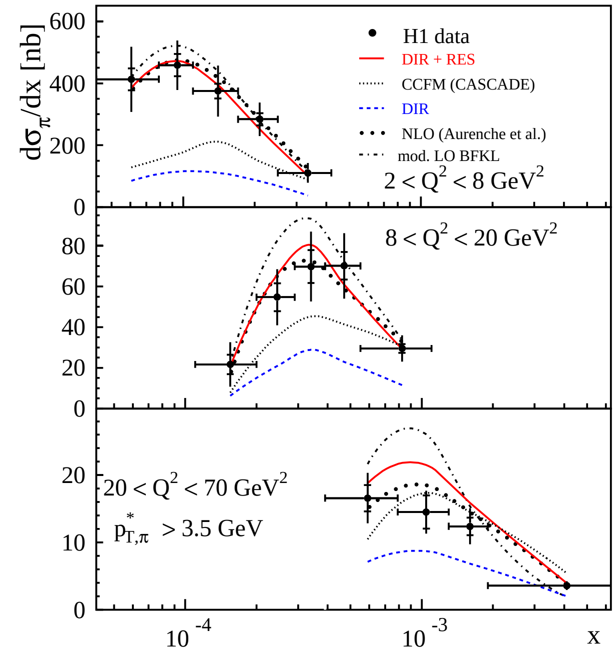
- **Measure π^0 instead of Jets**
  - **No ambiguities from Jet algorithm**
  - **Larger uncertainities from hadronization**
  - **BFKL Region: Particle $p_T^2 \sim Q^2$**
- **Cross Section $p_{T\pi}$**
  - **Data falls steeply as $p_{T\pi}$ increases**
  - **RAPGAP Dir+Res describes π^0 data**
  - **RAPGAP 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