Leading Baryon Production in ep Scattering at HERA

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Reporting for H1 and ZEUS

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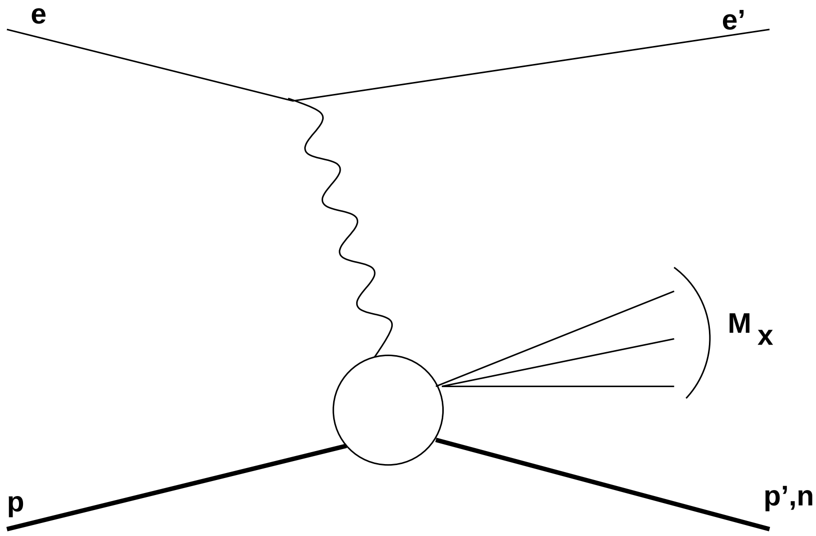
DIS2000

Overview

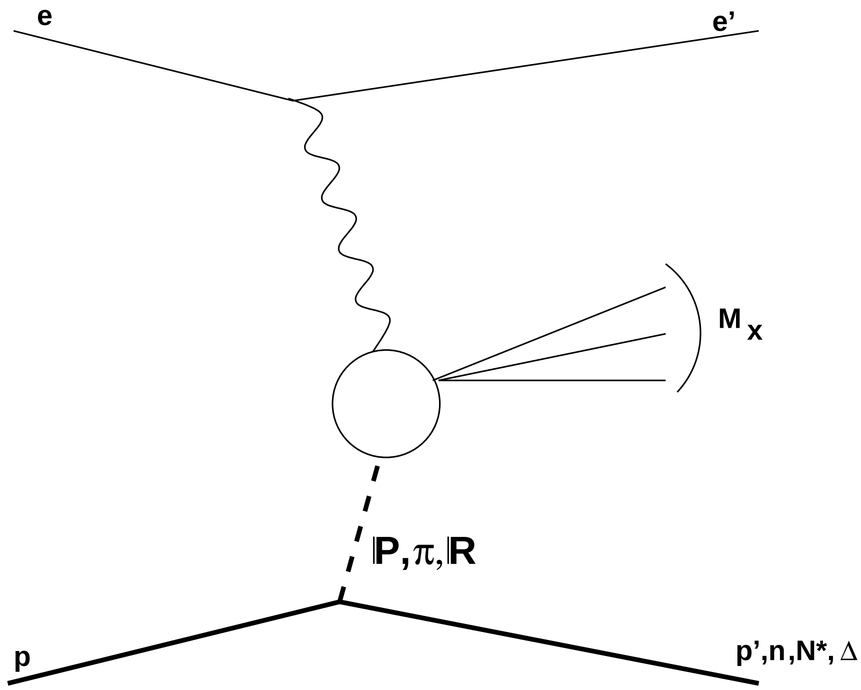
- Introduction
- Detectors and Data Samples
- Leading Baryon Production in DIS
- Leading Neutron Production in Photoproduction
- Leading Neutron p_T Distributions
- Summary
- First some notation:
  - LB = Leading Baryon
  - LP = Leading Proton
  - LN = Leading Neutron

Motivation

- Baryons from hadronization of p remnant:



- Baryons from exchange of virtual $I\!P$, π, $I\!R$:



Motivation

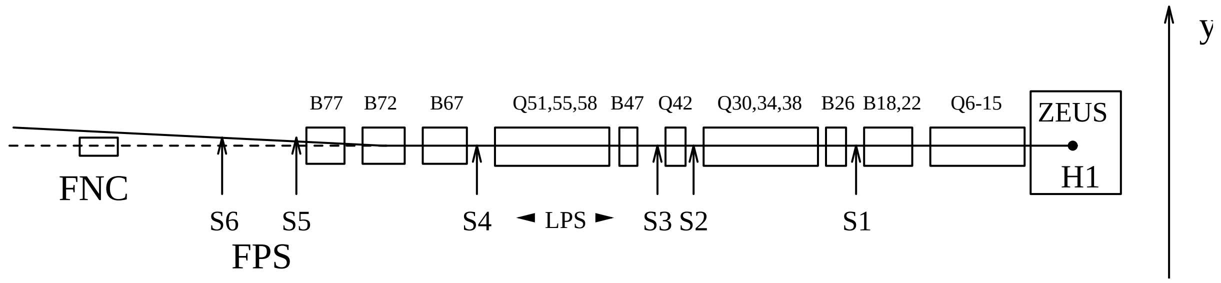
- Leading baryons characterized by:
  - Fraction of incoming proton energy carried: $x_L = E_{p'}/E_p$ (also denoted z)
  - Four-momentum transfer squared t of exchanged particle, or transverse momentum p_T of baryon
- In exchange models, e.g. π exchange, cross section factorizes:

$$\sigma(ep \to e'nX) = f_{\pi/p}(x_L, p_t^2)\sigma(e\pi \to e'X)$$

- Measuring leading baryons rate, x_L, p_T in ep scattering can:
  - Compare hadronization and particle exchange models
  - Test factorization hypothesis
  - Differentiate different particle exchange models

Detectors

- Downstream in proton direction from HERA IR:



- Vertical bend at z=+70m serves as:
  - Analyzing magnet for proton spectrometers (FPS,LPS)
  - Sweeping magnet for neutron calorimeters (FNC)
- H1 FPS: $\sigma_{x_L} \approx 1\%$, $\sigma_{p_T} < 70$ MeV
- H1 FNC: $\sigma_E/E \approx 20\%$, 1996-1997
- ZEUS LPS: $\sigma_{x_L} \approx 1\%$, $\sigma_{p_T} \approx 5$ MeV, 1995
- ZEUS FNC: $\sigma_E/E \approx 70\%/\sqrt(E)$, 1995-1997
- ZEUS FNT: $\sigma_x \approx 2.5$ mm, 1999 (more later . . .)

Tests of Factorization

- In exchange picture (e.g. π) cross section factorizes:

$$\sigma(ep \to e'NX) = f_{\pi/p}(x_L, p_t^2)\sigma(e\pi \to e'X)$$

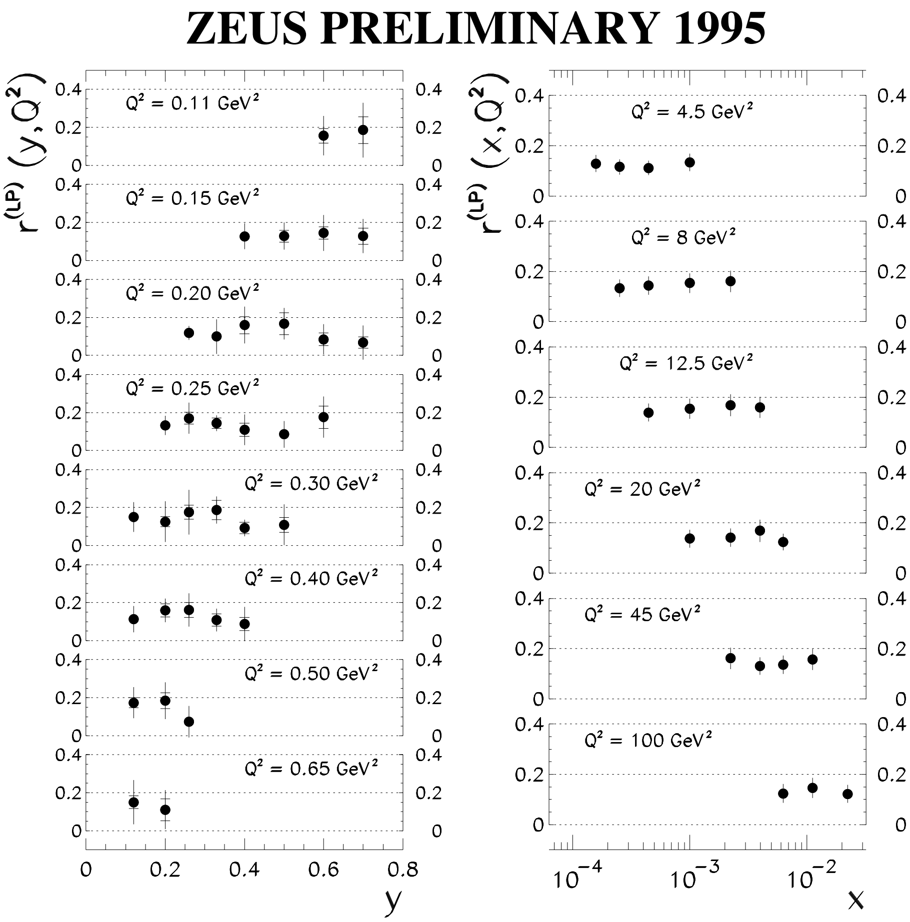
- Similar dependence of $\sigma(ep)$ and $\sigma(e'\pi)$ on DIS variables
- $\Rightarrow$ Expect fraction of events with leading baryon independent of DIS variables
- Study fraction of events with leading baryon as function of:
  - Q^2
  - x_{BJ} (high Q^2) or y (low Q^2)
  - LPS data corrected for acceptance, $r^{LP} = F_2^{LP}/F_2$
  - Neutron data not corrected for FNC acceptance, independent of DIS variables

ZEUS DIS Data

- Medium to high Q^2:
  - e^+ in central detector
  - $Q^2 > 4$ GeV^2
  - Higher maximum Q^2 with larger FNC data sample
- Low Q^2:
  - e^+ in Beam Pipe Calorimeter
  - $0.1 < Q^2 < 0.65$ GeV^2
- Leading Protons:
  - $0.60 < x_L < 0.97$ (see M. Capua's talk for results on $x_L \approx 1$ diffractive events)
  - $p_T^2 < 0.5$ GeV^2
- Leading Neutrons:
  - $x_L > 0.6$
  - $\theta_n < 0.8$ mrad (limited by geometric aperture)

Tests of Factorization

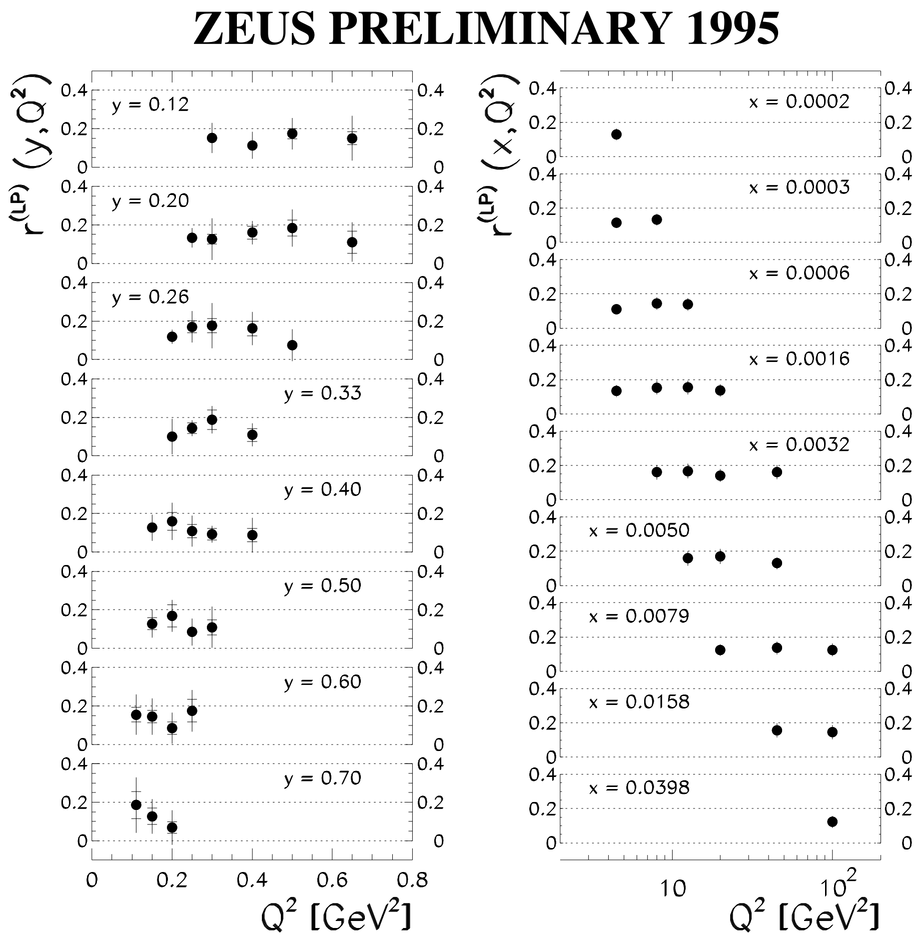
- LP production as function of x_{BJ} or y:



- LP production independent of x_{BJ} or y $\Rightarrow$ Consistent with factorization

Tests of Factorization

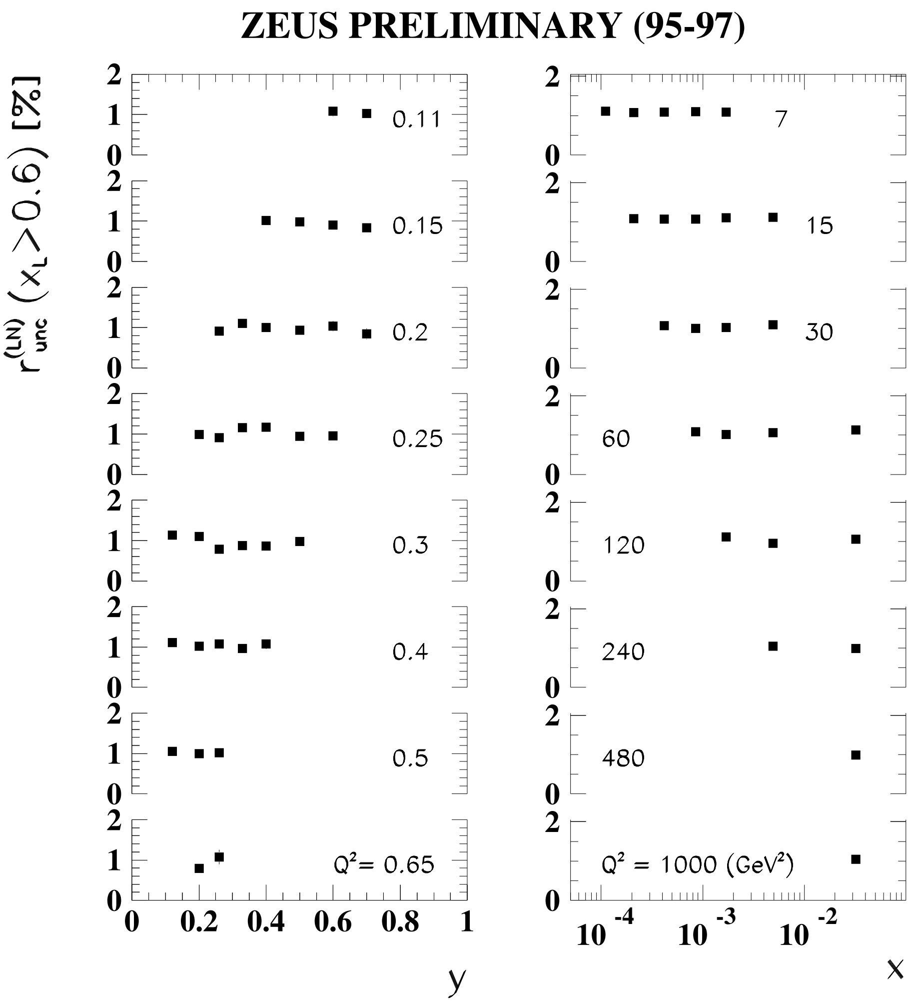
- LP production as function of Q^2:



- LP production independent of Q^2 $\Rightarrow$ Consistent with factorization

Tests of Factorization

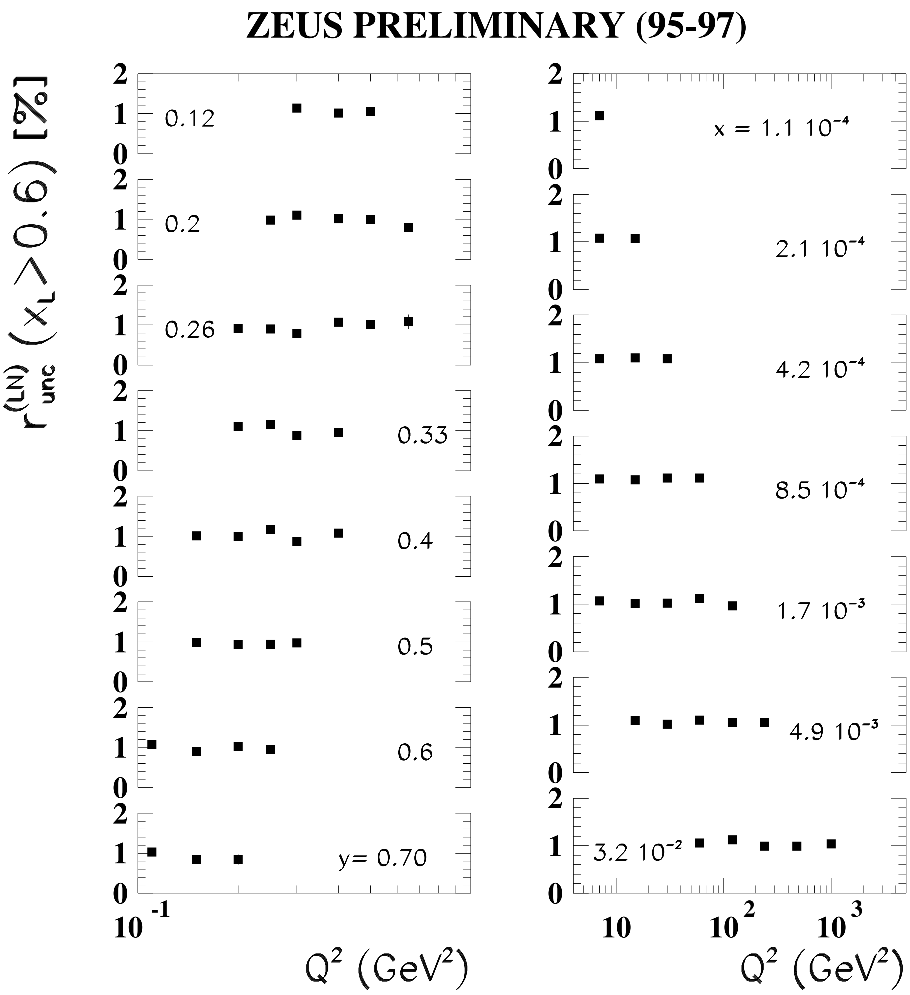
- LN production as function of x_{BJ} or y:



- LN production independent of x_{BJ} or y $\Rightarrow$ Consistent with factorization

Tests of Factorization

- LN production as function of Q^2:



- LN production independent of Q^2 over 4 orders of magnitude

$\Rightarrow$ Consistent with factorization

Tests of Factorization

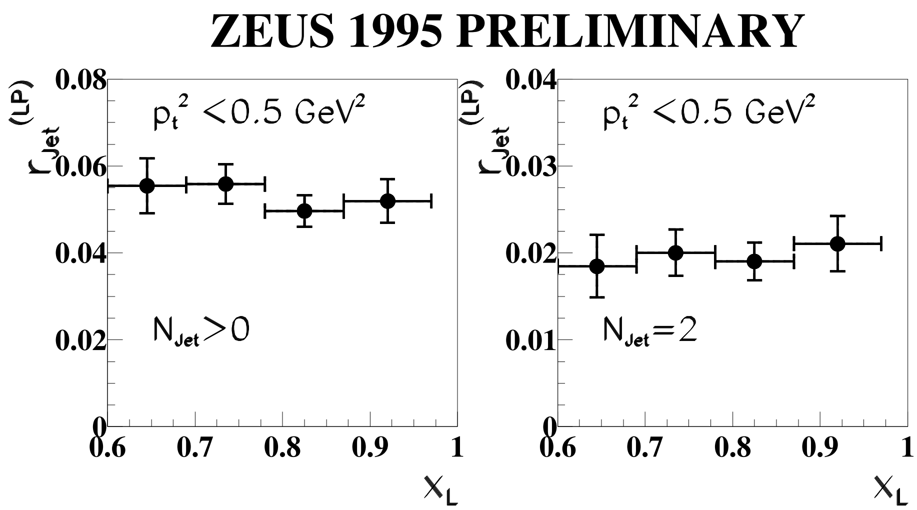
- In exchange picture cross section for some subset of LB events (e.g. jets) also factorizes:

$$\sigma^{jet}(ep \to e'NX) = f_{\pi/p}(x_L, p_t^2)\sigma^{jet}(e\pi \to e'X)$$

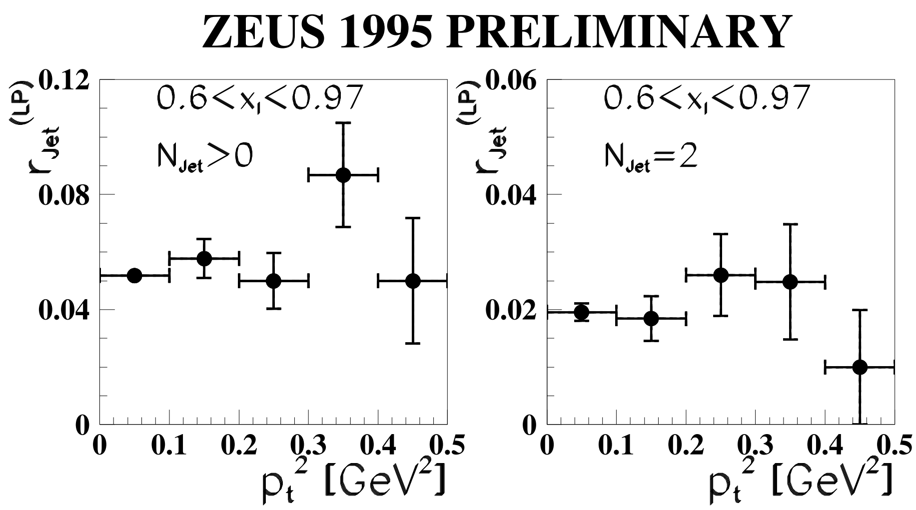
- Expect fraction of LB events with jets to be indepenent of LB variables x_L, p_T (flux factors cancel)
- ZEUS has measured fraction of LP events with jets as a function of x_L and p_T^2:
  - Select jets with k_t algorithm
  - $E_T^{jet} > 4$ GeV
  - $-2 < \eta^{jet} < 2.2$
  - Look for at least one jet or exactly 2 jets
  - Jet finding, detector smearing of jet variables independent of LB variables, no correction applied

Tests of Factorization

- Fraction of LP events with jet(s) as function of x_L:



- Fraction of LP events with jet(s) as function of p_T^2:



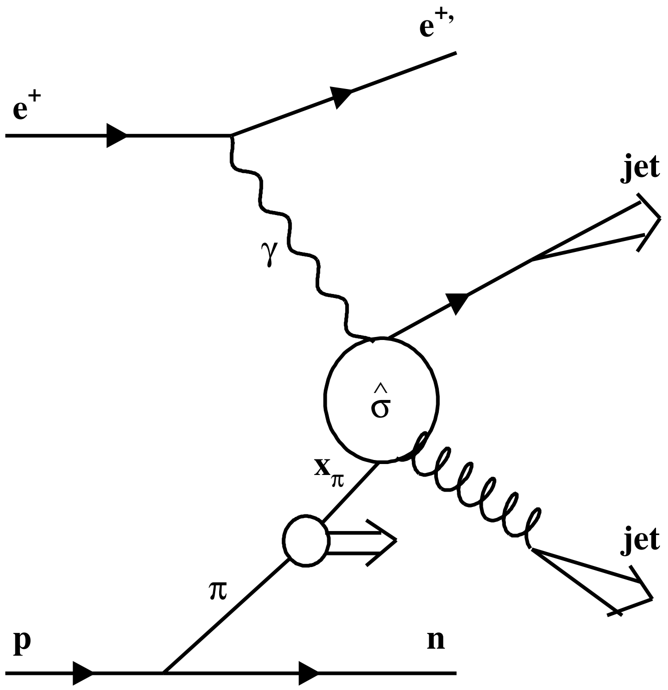
- Jet production independent of x_L and p_T^2 $\Rightarrow$ Consistent with factorization

Neutrons in Dijet Photoproduction

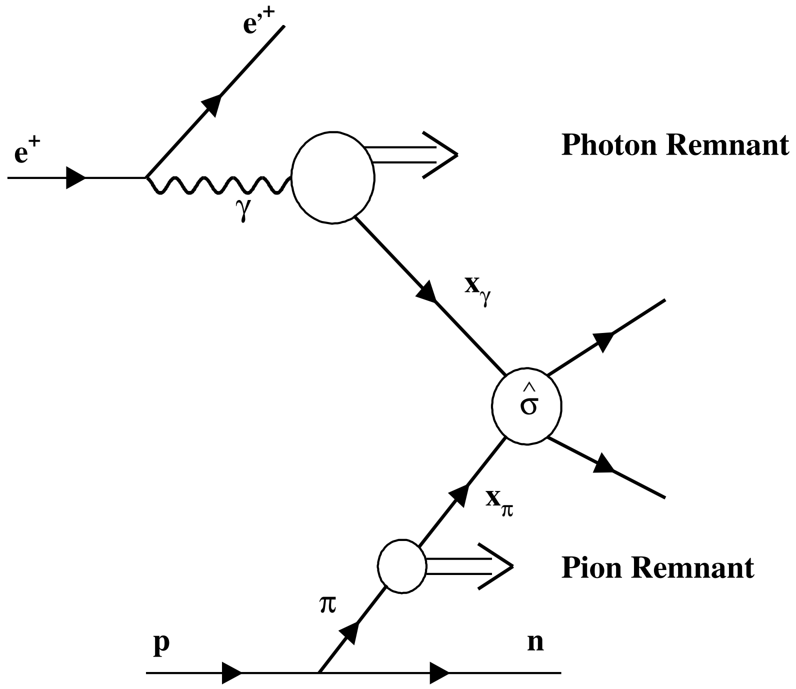
- Neutrons have also been measured in dijet photoproduction
- New results from this data:
  - Further tests of factorization
  - Tests of MC models
  - Sensitivity to $F_2^{\pi}(x_{\pi})$?
- Photoproduction quantities from jet variables:
  - x_{γ} = fraction of photon momentum carried by initial state parton participating in hard scattering
  - x_{π} = fraction of pion momentum carried by initial state parton participating in hard scattering ($x_{\pi} = \beta$ in diffractive lingo)

Neutrons in Dijet Photoproduction

- Direct photoproduction has $x_\gamma \approx 1$:



- Resolved photoproduction has $x_\gamma < 1$:

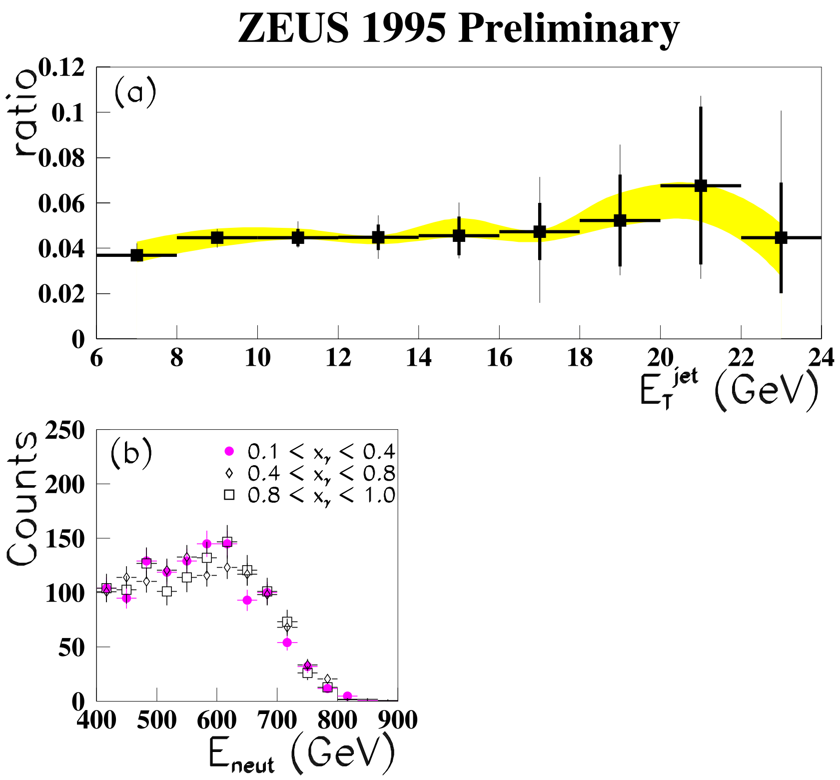


Dijet Photoproduction Data Sets

- H1 data:
  - Tagged photoproduction $Q^2 < 0.01$ GeV^2
  - $0.3 < y < 0.65$
  - $E_n > 400$ GeV, $\theta_n < 0.8$ mrad
  - Exactly 2 jets (cone algorithm)
  - $E_T^{jet} > 4$ GeV
  - $-1 < \eta^{jet} < 2$
- ZEUS data:
  - Untagged photoproduction $Q^2 < 1$ GeV^2
  - $0.2 < y < 0.8$
  - $E_n > 400$ GeV, $\theta_n < 0.8$ mrad
  - At least 2 jets (k_T algorithm, use 2 highest energy)
  - $E_T^{jet} > 6$ GeV
  - $-2 < \eta^{jet} < 2$

Tests of Factorization

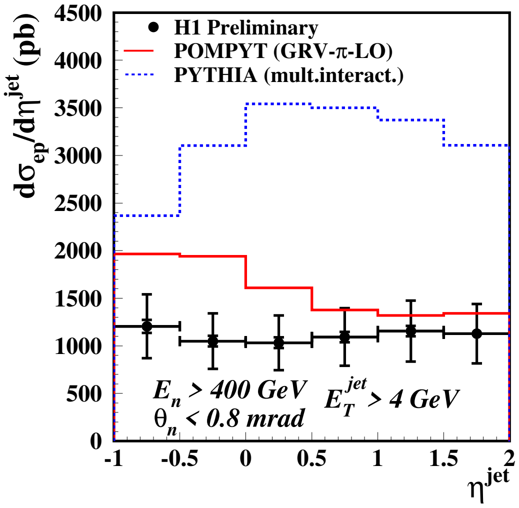
- Two studies made with photoproduction dijets:
  - Fraction of events with LN vs. E_T
  - Compare E_n spectra at different x_γ

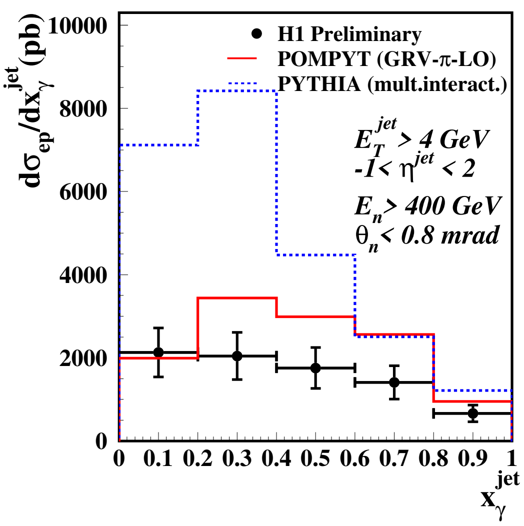


- LN production independent of E_T^{jet} $\Rightarrow$ Consistent with factorization
- LN spectrum independent of x_γ $\Rightarrow$ Consistent with factorization

Tests of MC Models

- POMPYT (with pion exchange, Holtmann flux) reproduces data reasonably well; PYTHIA (w/o pion exchange, with multiple interactions) is way off in normalization:

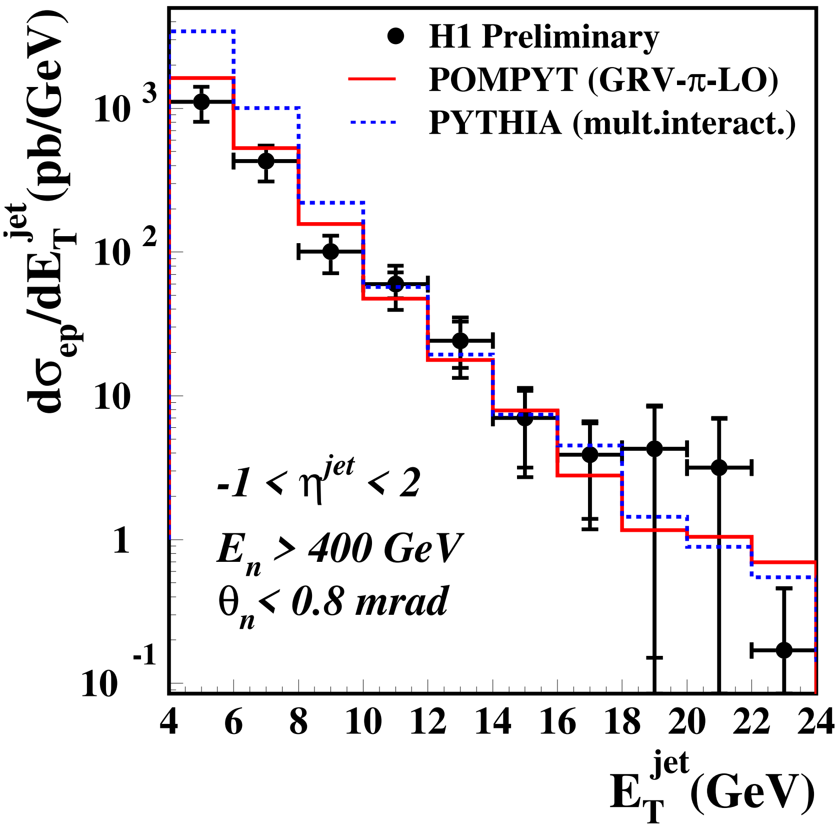




- Note here mostly resolved photoproduction

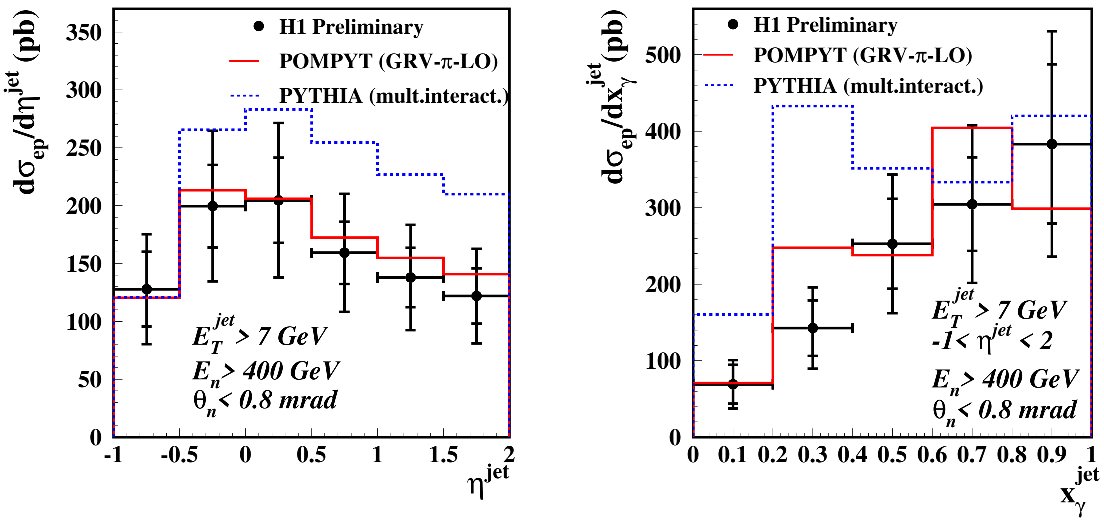
Tests of MC Models

- Excess in Pythia is at lower E_T:



Tests of MC Models

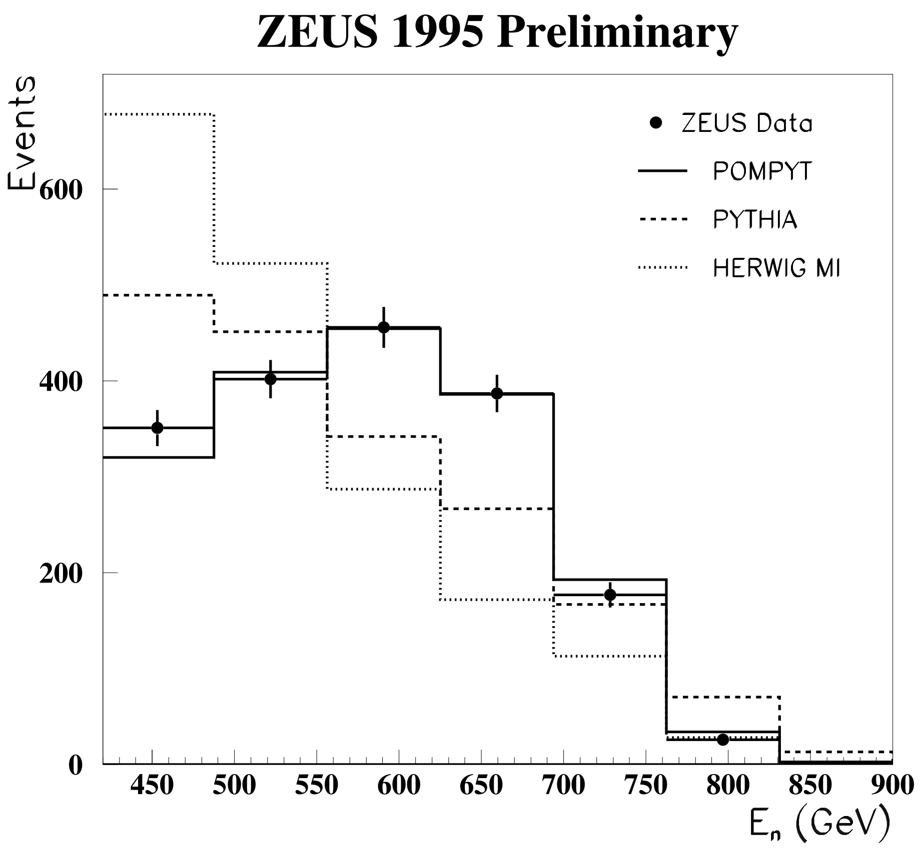
- At higher $E_T > 7$ GeV POMPYT does very well; PYTHIA comes closer:



- In this region there is more direct component

Tests of MC Models

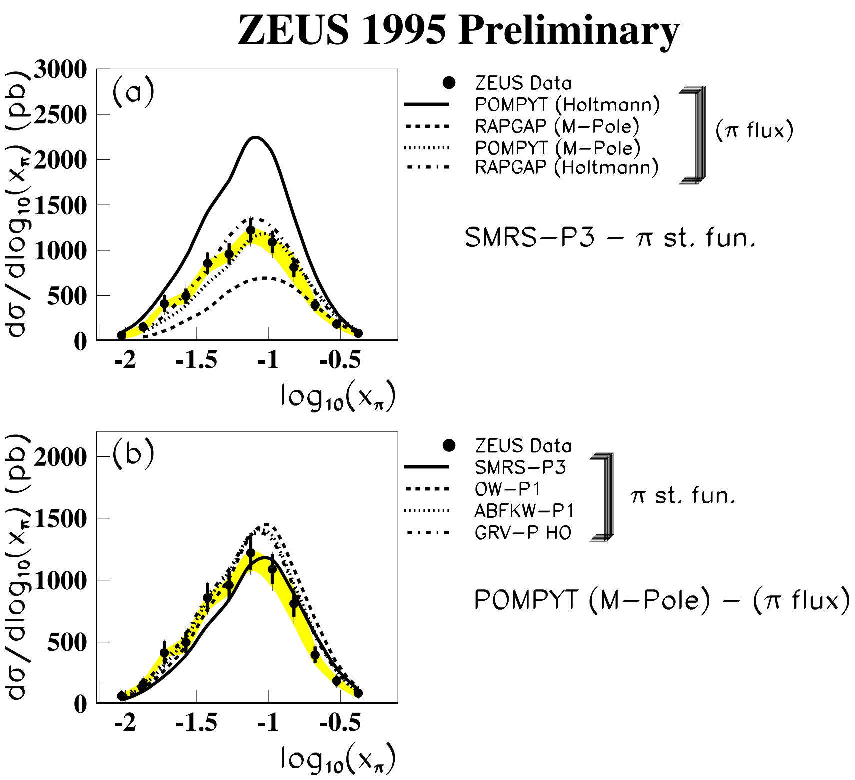
- But MC models with neutrons only from proton remnant fragmentation do not reproduce the shape of the neutron spectrum:



- Here MC curves are area normalized to the data
- Pion exchange reproduces the neutron spectrum

Tests of MC Models

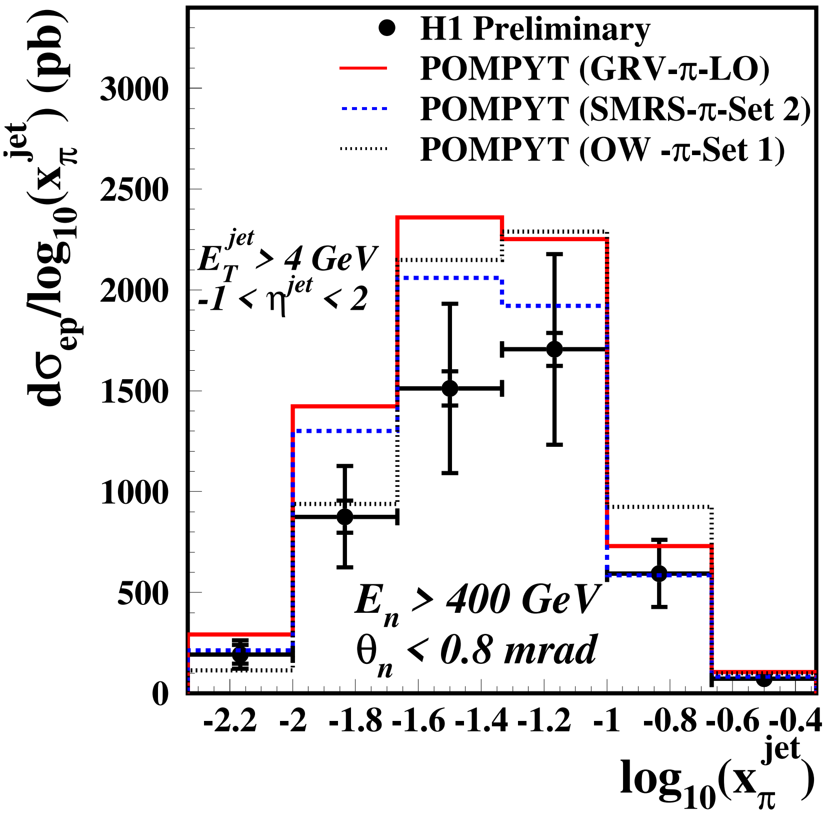
- Normalization of distribution is sensitive to choice of MC, pion flux:



- But the shape of the x_π distribution is not sensitive to parameterization of F_2^π

Tests of MC Models

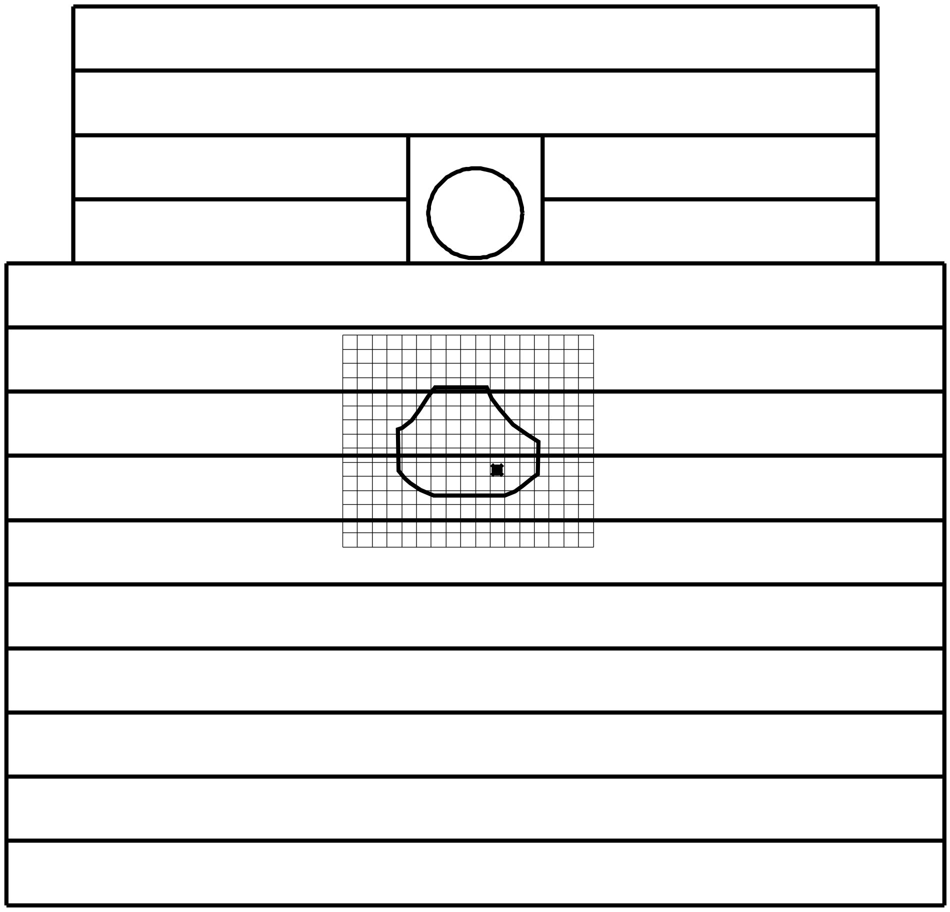
- H1 also sees no sensitivity to F_2^π:



- Dijet photoproduction is not the place to study F_2^π
- F_2^π already measured more directly in DIS (H1 publication)

FNT

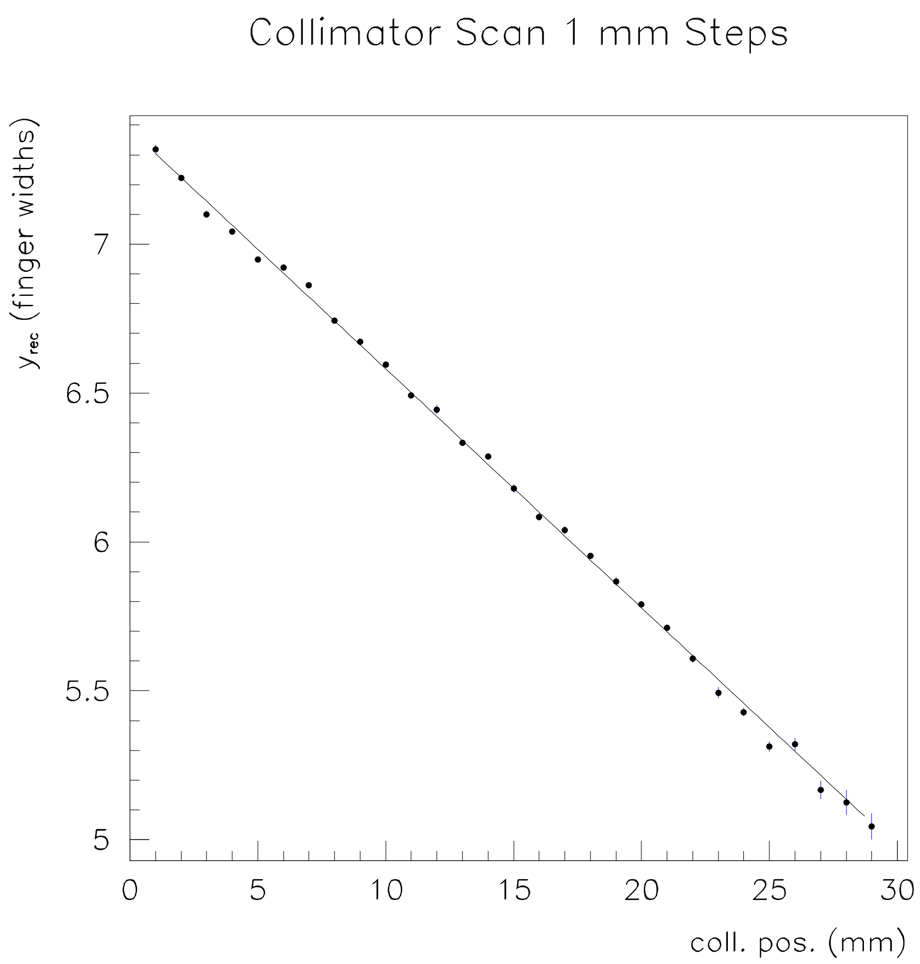
- Forward Neutron Tracker (FNT), position detector installed in ZEUS FNC in 1998:



- 17×15 x–y hodoscope $1\lambda_I$ into FNC
- Scintillators 1.2cm wide

FNT Reconstruction

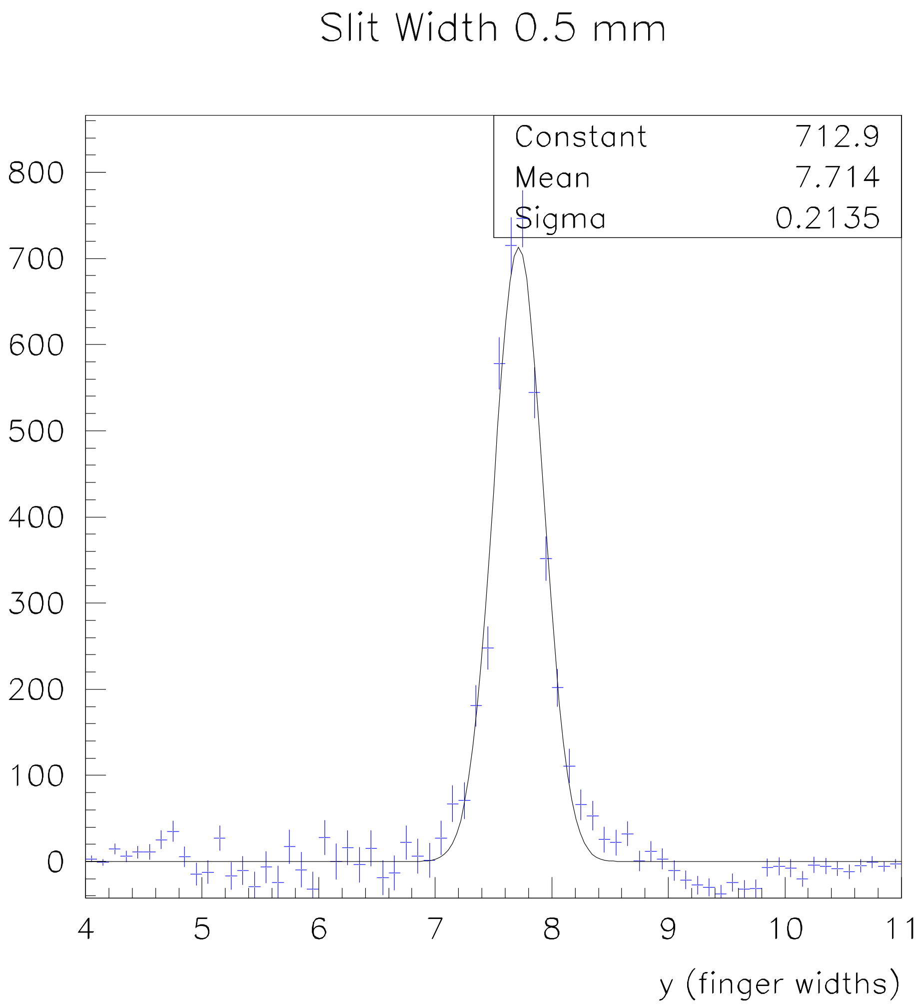
- Select events with energy in FNT, cuts to give clean showers
- Position reconstructed with log-weighted centroid
- Scan with movable collimator in front of FNC:



- Scan allowed tuning of reconstruction, shows linearity, no biases

FNT Reconstruction

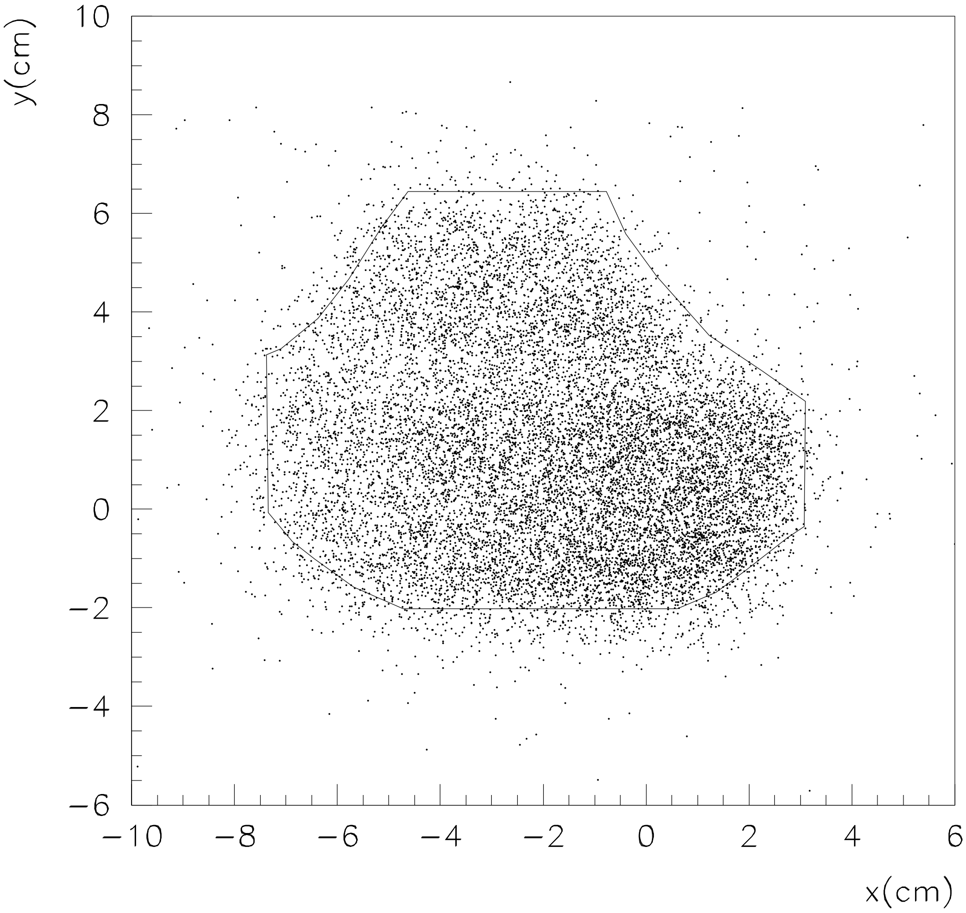
- Data with very narrow slit:



- Well described by gaussian, no tails
- Resolution measured $\sigma = 2.5$ mm. Better than beam divergence, $\sigma_x = 5$ mm, $\sigma_y = 10$ mm

FNT Alignment

- Hit distribution agrees well with beam line MC:



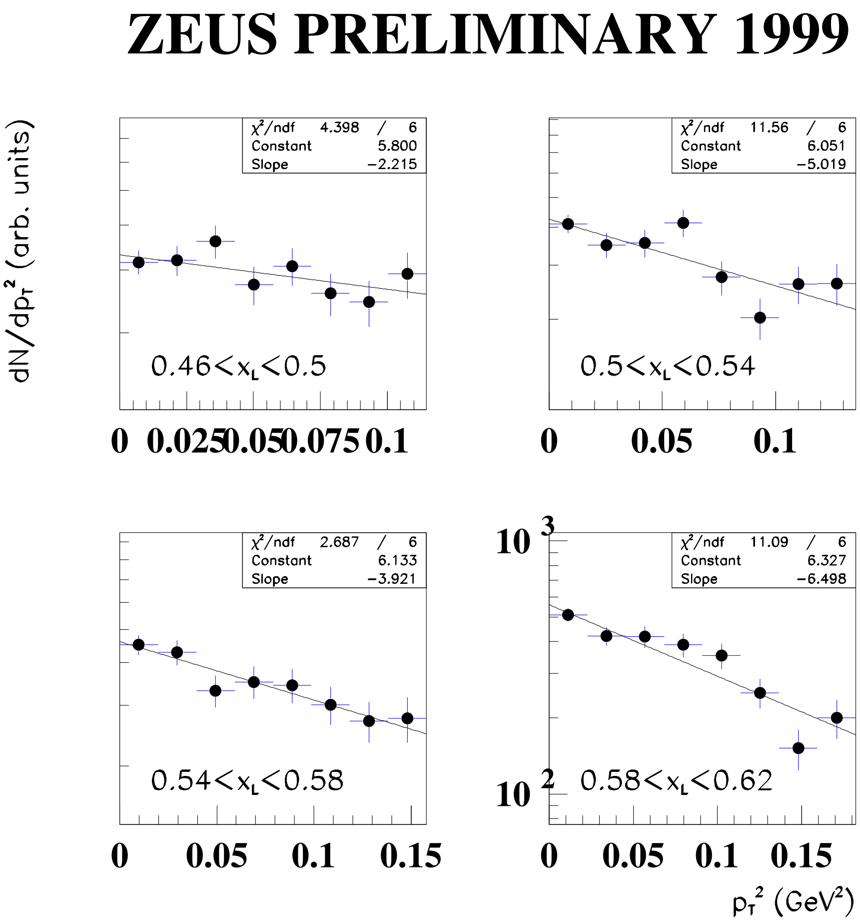
- Beam tilt: beam zero-degree point found by peak of hit distribution

FNT p_T^2 Distributions

- Data: 3 pb^{-1}, DIS $Q^2 > 3$ GeV^2
- Simple MC:
  - Account for geometric aperture
  - Smear for beam divergence
  - Smear for FNT position resolution
  - Smear for FNC energy resolution
  - Simple parameterization of observed x_L, p_T distribution
- Make bin-by-bin corrections in x_L, p_T^2 bins
- Note: due to angular acceptance cutoff, maximum $p_T^2 \propto x_L^2$ (much less than phase space limit)

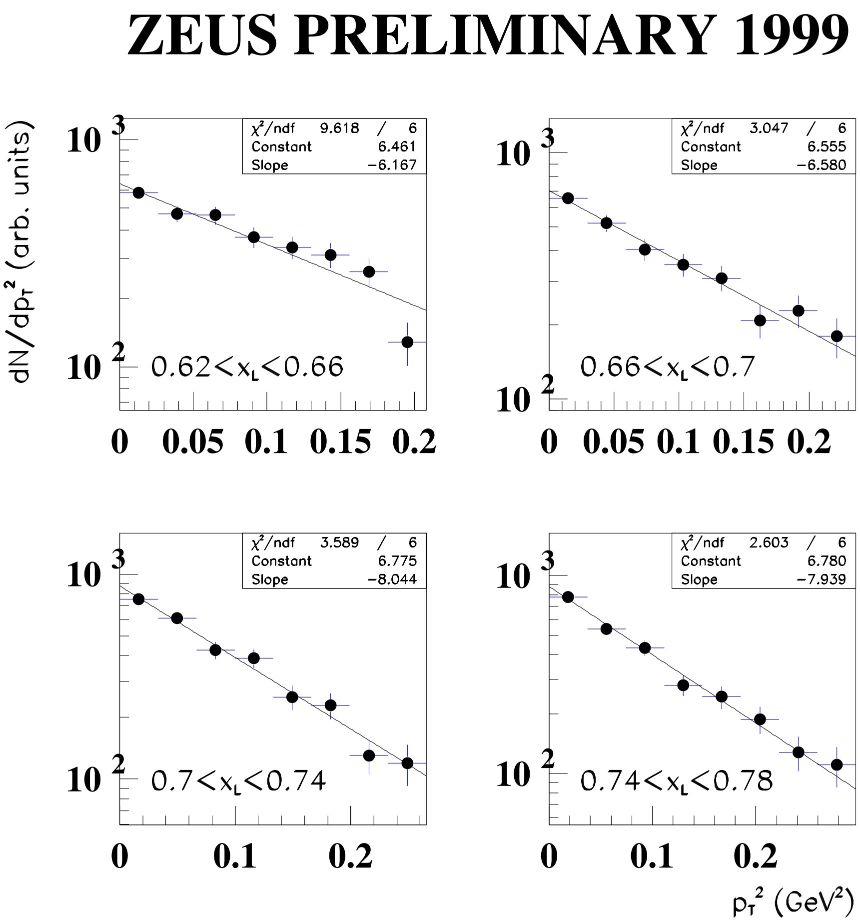
FNT p_T^2 Distributions

- At low x_L p_T^2 distributions are relatively flat:



FNT p_T^2 Distributions

- Distributions are steeper at medium x_L:



FNT p_T^2 Distributions

- Distributions are very steep at highest x_L:

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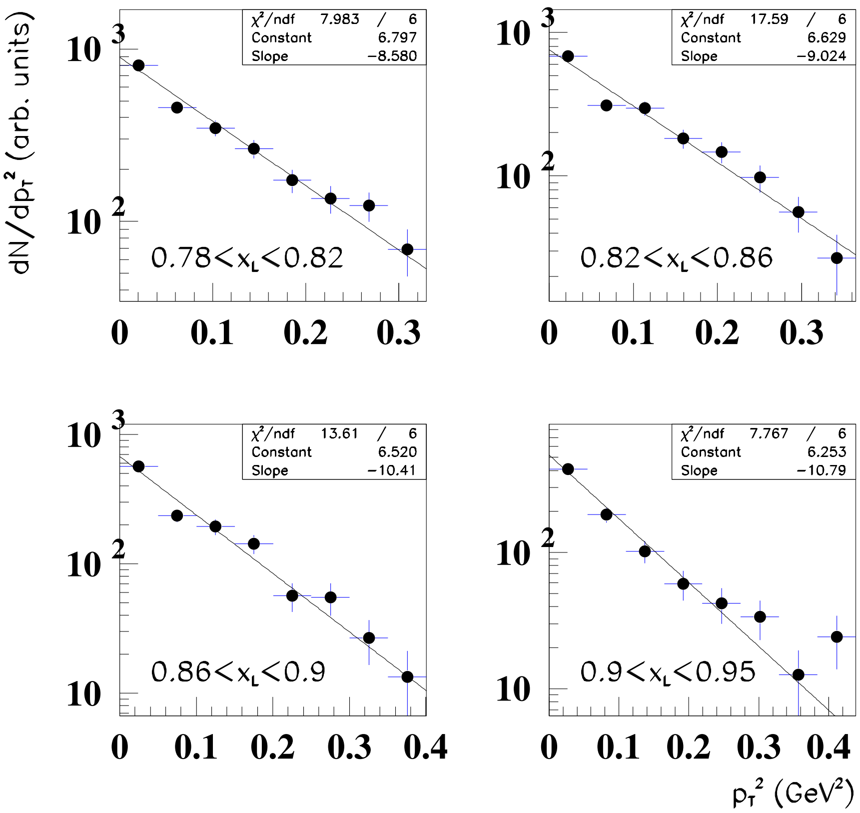
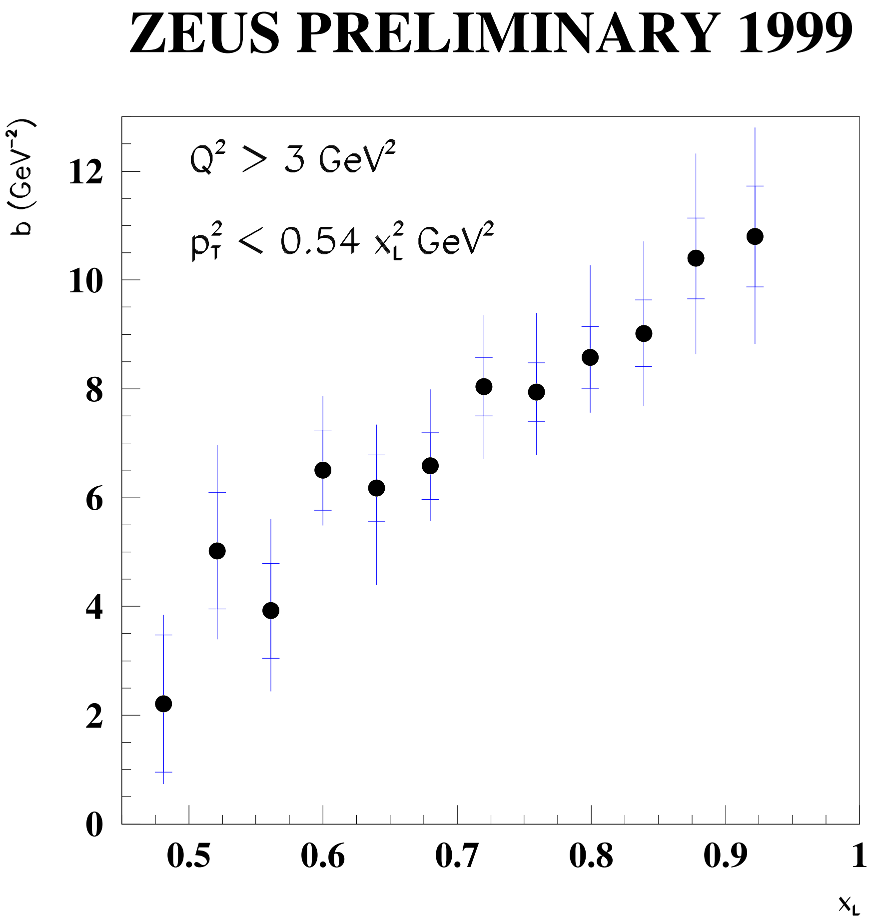


FNT b-Slopes

- p_T^2 distributions are well described by an exponential
- Parameterize $\frac{dN}{dp_T^2} \propto e^{-bp_T^2}$, measure b in each x_L bin
- Sytematic uncertaities:
  - Uncertainty in beam zero-degree point (few mm)
  - Uncertainty in FNC channel-to-channel calibration (few %)

FNT b-Slopes



- b rises roughly linearly across range $x_L = 0.5$–1.0

Comparison to OPE Models

- Several models of One Pion Exchange in the literature
- Have general form:

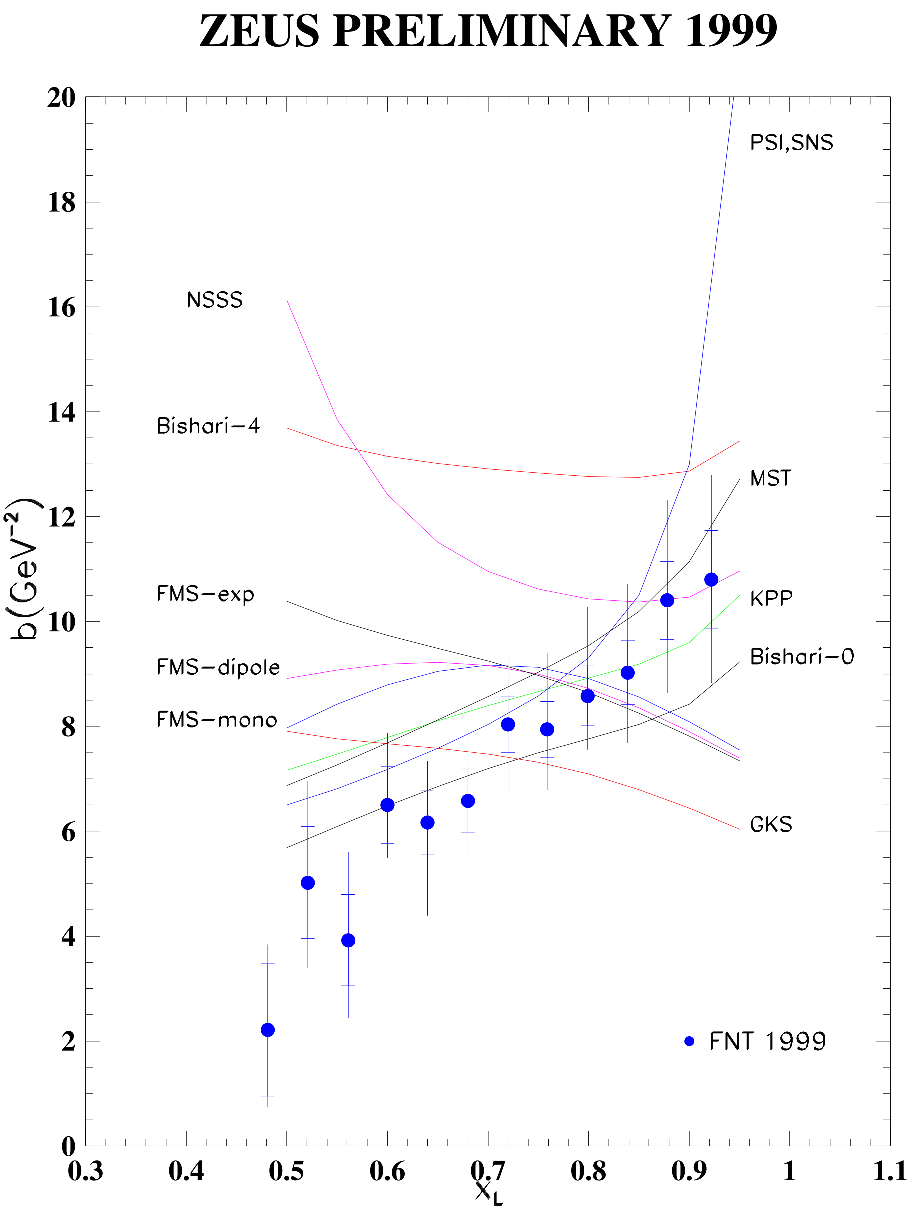
$$\frac{d^2N}{dx_L dt} \propto \frac{-t}{(t - m_\pi^2)^2}(1 - x_L)^{\alpha(t)} F^2(x_L, t)$$

- Here power $\alpha(t)$ and form factor $F(x_L, t)$ are model dependent, and:

$$t = -\frac{p_T^2}{x_L} - \frac{(1 - x_L)(m_n^2 - m_p^2 x_L)}{x_L}$$

- Not exactly an exponential in p_T^2, but can 'fit' models to $e^{-bp_T^2}$ parameterization, compare to data

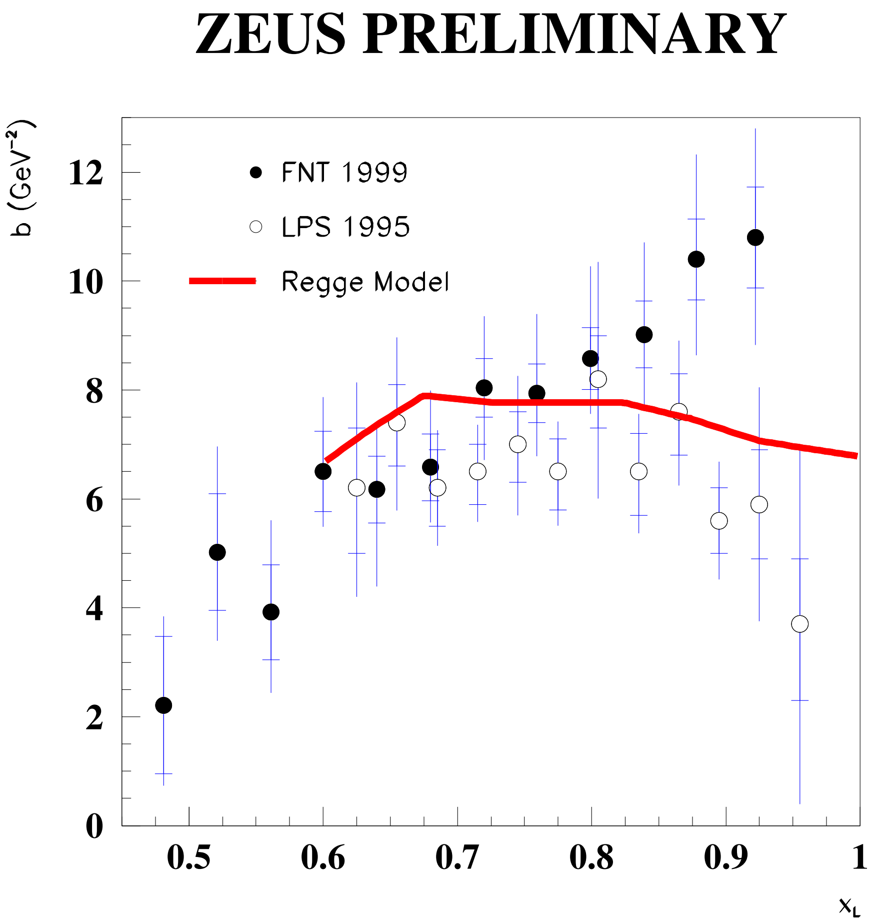
Comparison to OPE Models



- OPE only expected to dominate for $x_L >$ 0.6–0.7
- Data can constrain choice of models
- Data can constrain choice of parameters (e.g. Bishari and KPP curves are same model, different parameters)

Comparison to Leading Protons

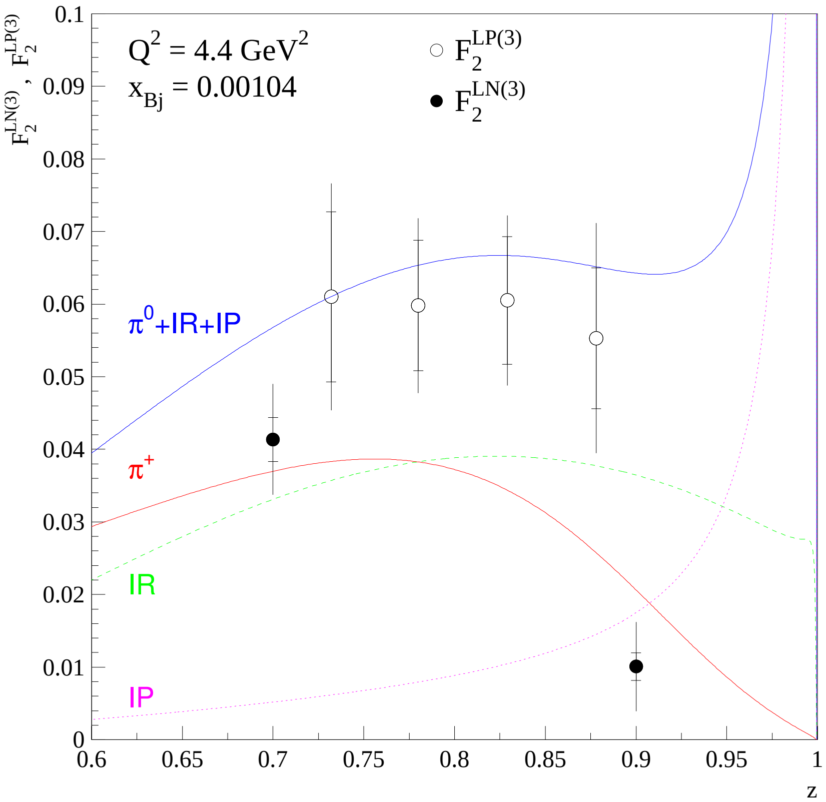
- ZEUS LPS also has b-slopes for leading protons:



- $b(x_L)$ is much flatter for protons than for neutrons
- Proton production expected to proceed through several different exchanged particles, isovector and isoscalar $(\pi^0, I\!P, f_2, \ldots)$
- Different exchanges conspire to give flat $b(x_L)$

Comparison to Leading Protons

- A difference is also seen in the x_L spectra, as shown in H1 publication:



- π^0 contribution to protons is exactly $\frac{1}{2}$ of shown π^+ contribution to neutrons (isospin Clebsch-Gordan)
- Different contributions are need to explain shape and normalization of proton x_L spectrum

Summary

- Factorization(expected in e.g. exchange models):
  - Observed over wide range of kinematic space in DIS
  - Observed in dijet photoproduction
  - Taking out a baryon with a large fraction of E_{beam} doesn't change distributions
  - The lepton and baryon vertices don't know about each other
- Neutrons in dijet photoproduction:
  - MC models w/o π exchange but with MI can reproduce jet distributions in high E_T region, but not neutron spectrum
  - MC models with π exchange do well on both counts
  - Data sensitive to π flux, not sensitive to F_2^π
- Leading neutron p_T^2 distributions:
  - Slope of distribution rises steeply across $x_L = 0.5$–1.0
  - Data can be used to select OPE models, parameters
  - Different from leading protons, different exchange processes