Physics With Leading Neutrons at HERA

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On behalf of the H1 and ZEUS collaborations

- Motivation: One pion exchange
  Absorption (rescattering)
- Leading neutrons (LN) in DIS and photoproduction ($\gamma p$) with dijets:
  rates and kinematic dependences comparison with
  - standard fragmentation models
  - pion exchange models
  - NLO QCD calculations
- $p_T$ spectra of leading neutrons in inclusive DIS & photoproduction:
  - comparison to pion exchange models
  - effects of absorption
- Summary
Motivation: One Pion Exchange

One Pion Exchange: (O.P.E.):
- Proton fluctuates into virtual $\pi$-$n$ system
- Virtual $\pi$ interacts with $\gamma^{(*)}$
- Real $n$ can be detected
- Cross section factorizes:
  \[
  \sigma_{ep\rightarrow eXn}(W^2, Q^2, x_L, t) = f_{\pi/p}(x_L, t)\sigma_{e\pi}(1-x_L)W^2, Q^2)
  \]
- Lepton vertex variables ~ independent of baryon vertex variables

LN can result from 'standard' fragmentation

LN observables (baryon variables):
- $x_L = E_n / E_p$
- $p_T$ or $t = -p_T^2 / x_L - m_N^2 (1-x_L)^2 / x_L$
- Models predict $x_L, p_T^2$ distributions

Lepton variables e.g. DIS:
- $Q^2 = \gamma^* 4$-mom. $^2$
- $W = \gamma^* -p$ c.m. $E$

Lepton vertex variables

\[\gamma^* \to e^- \pi^+ n \rightarrow e^- e' \pi^+ n \rightarrow e^- e' \
\]
Motivation: Rescattering model

- $\gamma$ size $\sim 1/Q$ ($Q = \gamma$ virtuality):
  - $\Rightarrow$ more rescattering at lower $Q^2$; compare DIS ($Q^2 > 0$) and $\gamma p$ ($Q^2 \sim 0$)
- In $\pi$ exchange models, $\langle r_{n\pi} \rangle$ smaller at lower $x_L$:
  - $\Rightarrow$ more rescattering @ lower $x_L$
- Smaller $\langle r_{n\pi} \rangle \sim$ higher $p_T$:
  - $\Rightarrow$ fewer high $p_T n$ in photoproduction, steeper $p_T$ distributions
Motivation: Rescattering

- Ratio of $x_L$ distributions: $\gamma p$/DIS each normalized by inclusive (no LN requirement) cross section
- Observed fewer low $x_L$ neutrons in $\gamma p$ than in DIS ✔
- Same trend in rescattering (absorption) model of D'Alesio & Pirner

Here will compare $p_T^2$ distributions in DIS and $\gamma p$ for the first time
LN detectors:
Forward Neutron Calorimeter (FNC)

- ~100 m from I.P. in proton direction
- Protons bent upward; FNC acceptance at 0°

ZEUS FNC:
- Pb-scintillator sandwich
- $\sigma_{E}/E \approx 70%/\sqrt{E}$
- Position detector hodoscope 1 $\lambda_1$ deep
- $\sigma_{x,y} = 2.3$ mm
- $p_T$ resolution dominated by proton beam spread

H1 FNC:
- Pb-scintillator spaghetti
- $\sigma_{E}/E \approx 20\%$ for $E_n > 300$ GeV
LN with dijets: Data sample & kinematics

- Hadronic final state w/ 2 high $E_T$ jets:
  $$e+p \rightarrow e'+n+jet_1+jet_2+X$$
  $E_{T1} > 7$ GeV, $E_{T2} > 6$ GeV

- Samples in $\gamma p$ ($Q^2 < 0.01$ GeV $^2$) and DIS ($2 < Q^2 < 80$ GeV $^2$) regimes

- Jets characterized by $E_T$, $\eta$ (pseudorapidity)

- Also: $x_\gamma$, fractional momentum of the parton from photon which enters the hard interaction
  - $x_\gamma \sim 1$: direct $\gamma p$, photon pointlike
  - $x_\gamma < 1$: resolved $\gamma p$, photon has structure, size
LN with dijets: Monte Carlo models

<table>
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<th>Photoproduction</th>
<th>DIS</th>
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<td>$\pi$-exchange</td>
<td>RAPGAP-$\pi$, POMPYT</td>
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<td>Inclusive (no $\pi$-exchange)</td>
<td>PYTHIA-MI, PYTHIA</td>
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<td>NLO calculations ($\pi$-exch.)</td>
<td>M.Klasen &amp; G.Kramer</td>
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- RAPGAP, LEPTO 'standard' DIS MC; PYTHIA 'standard' $\gamma p$ MC
- $\text{RAPGAP-}\pi = \text{RAPGAP} + \pi$-exchange
- $\text{POMPYT} = \text{PYTHIA} + \pi$-exchange, similar results as RAPGAP-$\pi$
- $\text{PYTHIA -MI} = \text{PYTHIA} + \text{multi-parton interactions}$; necessary to describe inclusive dijet $\gamma p$
- $\text{LEPTO-SCI} = \text{LEPTO} + \text{soft color interactions}$; LN production enhanced via non-perturbative color rearrangements
- Hadronization corrections applied to NLO calculation, determined from MC
- Here models passed through detector simulation, compared to uncorrected data
LN with dijets: $x_L$ spectra

- Well described by $\pi$-exchange MC models
- 'Standard' DIS models predict too low neutron rate
- 'Standard' $\gamma p$ model PYTHIA w/ multiple interactions predicts too high rate w/o multiple interactions PYTHIA give reasonable description of $x_L$

$$x_L = \frac{E_{FNC}}{E_{p\text{-beam}}}$$
LN with dijets: kinematic dependencies

- Well described by $\pi$-exchange MC models
- PYTHIA describes LN data, but not inclusive $\gamma p$
- LEPTO-SCI too low; PYTHIA-MI too high at low $x_{\gamma}$: too much resolved
- NLO QCD calculation, corrected for hadronization describes the data
LN with dijets: LN ratios

Fraction of inclusive dijet $\gamma p$ with LN: test of factorization

- $f_{\text{LN}}$ almost independent of $E_T^\text{jet}$: factorization
- $f_{\text{LN}}$ strong dependence on $x_\gamma$; not phase space (PYTHIA): factorization breaking
- Fewer LN at low $x_\gamma$, resolved photon region
- Resolved photon 'larger': absorption effect? A calculation would be nice...
LN in DIS: $p_T^2$ distributions

- LN in inclusive DIS regime: $Q^2 > 2 \text{ GeV}^2$
- Limited neutron scattering angle $\Rightarrow p_T^2 < 0.476 x_L^2 \text{ GeV}^2$

Data here corrected for acceptance, resolution

Well described by exponential $\exp(-b p_T^2)$

$b$ characterizes steepness of $p_T^2$ distribution

$b$ consistent with zero for $x_L < 0.3$
LN in DIS: $p_T^2$ distributions

- Numerous models for $\pi$-exchange in the literature
- Essentially different form factors at $p-n-\pi$ vertex
- Parameterized from low energy $pp, \pi p$ data
- Not exponential, but can MC models and fit like data
- None describe data over whole $x_L$ range
- $\pi$-exchange expected to dominate for $0.6 < x_L < 0.9$; Bishari0 closest (also simplest model)
- Varying contributions other than $\pi$-exchange across $x_L$?

References in HEP2005 paper #343
LN in $\gamma p$ & DIS: $p_T^2$ distributions

- Compare LN in DIS and $\gamma p$ ($Q^2 < 0.02$ GeV$^2$) regimes
- Normalize @ $p_T^2 = 0$ GeV$^2$ to compare slopes
- In $\gamma p$ relatively fewer LN at high $p_T^2$
- Qualitatively consistent with expectation from absorption model
Some systematic uncertainties on $b(\gamma p)$, $b$(DIS) cancel in $\Delta b = b(\gamma p) - b$(DIS)

Slopes in $\gamma p$ larger than in DIS for $0.6 < x_L < 0.9$

Qualitatively consistent with expectation from absorption

Quantitative comparison would be nice

$\Rightarrow$ need a calculation...
Summary

'Standard' fragmentation does not describe LN production: generally predict too low LN rate

\( \pi \)-exchange models give reasonable description of LN in \( \gamma p \) & DIS: LN rate, \( x_L \) spectra, kinematic dependencies

\( \pi \)-exchange models in literature do not describe \( p_T \) spectra very well:

- contributions from other processes?

Effects consistent with absorption have been observed:

- LN in inclusive \( \gamma p \), resolved \( \gamma p \) of dijets

New calculations of absorption would be nice:

- \( x_\gamma \), LN \( p_T \) dependencies

An invitation to our calculational colleagues!