Leading Baryon Production at HERA

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Outline:

- Leading proton production in DIS.
  (ZEUS Collaboration)

- Leading neutron production in DIS.
  (H1 Collaboration)

- Leading neutron in dijet photoproduction.
  (ZEUS Collaboration)
Introduction

• Significant fraction of $ep$ scattering events contain a leading proton or leading neutron (LB) in the final state carrying a substantial portion of the energy of the incoming proton: $e+p \rightarrow e+LB+X$
• Different production models are available

Leading baryon can come from “standard fragmentation”
• implemented in MC models (Lund String)

Leading baryon can be produced via exchange of virtual particle:
• leading protons: $IP, IR, \pi_0$
  (isoscalar + isovector)
• leading neutrons: $\pi^+, \rho^+, a_2$
  (isovector)
Lepton variables:
\[ Q^2 = -(k-k')^2 \]
\[ x = Q^2/(2Pq) \]
\[ y = s/(xQ^2) \]

Leading baryon variables:
\[ x_L = E_{LB}/E_p \]
\[ t = (P-P_{LB})^2 \text{ (or } p_T^2) \]

In the exchange model the cross sections factorise, e.g. for one pion exchange (OPE)

\[ \sigma(ep \rightarrow e'NX) = f_{\pi/p}(x_L, t) \times \sigma(e\pi \rightarrow e'X) \]

- \( f_{\pi/p}(x_L, t) \) - pion flux:
  probability to emit pion from the proton with given \( x_L, t \)

- LB production independent of photon vertex
- probe structure of exchanged particle
- models predict factorisation violation – rescattering

\[ \sigma(e\pi \rightarrow e'X) \] - cross-section of \( e\pi \) scattering
Detectors used for measurement of LB

**ZEUS FNC+FNT**
- 14 towers, 17x15 grid of the FNT hodoscopes, $\sigma_E/E \approx 0.7/\sqrt{E}$
- Acceptance window $\theta < 0.75\text{÷}0.8$ mrad
- Position resolution 2-3mm

**H1 FNC**
- 4 sections
- 32 channels
- $\sigma_E/E \approx 0.63/\sqrt{E} \pm 2\%$

**ZEUS LPS**
- 6 stations with $\mu$-strip detectors
- Hit position resolution $\sim 30\mu$m
- $\sigma_{xL} < 1\%$, $\sigma_{pT} \sim$ few MeV
- Momentum accuracy $< 1\%$

**Acceptance limited by beam apertures and detector size.**

$p_T$ resolution is dominated by $p_T$ spread of proton beam (50-100 MeV).

“Leading Baryon Production at HERA”, Vitaliy Dodonov, EPS HEP 2009, July 2009, Krakow
Leading Proton production in DIS

(DESY-08-176, to be published in JHEP)
LP production in DIS:

$d\sigma_{LP}/dx_L$ normalised to the inclusive DIS cross section

- clear diffractive peak at $x_L \to 1$
- proton yield flat below $x_L \approx 0.95$
- consistent with earlier low $Q^2$ data

$12.8 \text{ pb}^{-1}$
$Q^2 > 3 \text{ GeV}^2$
$p_T^2 < 0.5 \text{ GeV}^2$
$45 < W < 225 \text{ GeV}$
$x_L > 0.32$
Comparison LP, LN yields

LP production in DIS:

- Restricted to a common $p_T^2$ range where the detector acceptances overlap
- For pure isovector (e.g. pion) particle exchange one expects: $LP = \frac{1}{2} LN$
- Data suggest: $LP = 2 LN$

Additional IR contributions are needed to account for the observed LP rates
LP production in DIS:

\[ d^2\sigma_{LP}/dx_L dp_T^2 \text{ (nb/(GeV^2))} \]

Fit by:

\[ \frac{1}{\sigma_{inc}} \frac{d\sigma_{LP}}{dp_T^2 dx_L} = a(x_L) \cdot e^{-b(x_L)p_T^2} \]

- clear different trends for LP and LN
- similar slopes for \( x_L \approx 0.65-0.8 \)
LP production in DIS:

**Rates to inclusive DIS**

**Structure function $F_2^{LP(2)}$**

\[
\frac{d^2 \sigma(ep \rightarrow eXp)}{dx \, dQ^2} = \frac{4 \pi \alpha^2}{x \, Q^4} \left[ 1 - y + \frac{y^2}{2} \right] \cdot F_2^{LP(2)}(x, Q^2)
\]

$r^{LP(2)}$ is approximately constant vs $x$ and $Q^2$ with average value $\sim 0.24$

same trend as inclusive $F_2$ is observed
Comparison to models

**Standard fragmentation MC**

- **ZEUS**
  - $p_t^2 < 0.5 \text{ GeV}^2$
  - $Q^2 > 3 \text{ GeV}^2$
  - $45 < W < 225 \text{ GeV}$

**Model with multiple exchanges**

- **ZEUS**
  - $p_t^2 < 0.5 \text{ GeV}^2$
  - $Q^2 > 3 \text{ GeV}^2$
  - $45 < W < 225 \text{ GeV}$

**LP production in DIS:**

- Standard fragmentation MC
- Model with multiple exchanges

- **Comparison**
  - Good description of diff. peak but all fail at low $x_L$
  - Slopes are too low at low $x_L$
  - Good description of LP yield and slope by adding different exchanges
  - Reggeon dominant at medium $x_L$
Leading Neutron production in DIS
The triple differential reduced cross section is given by:

\[
\frac{d^3 \sigma (ep \rightarrow enX)}{dQ^2 dx dx_L} = \frac{4 \pi \alpha^2}{x Q^4} \left[1 - y + \frac{y^2}{2}\right] \cdot F_2^{LN}(Q^2, x, x_L)
\]

- DJANGO (standard fragmentation) predicts too low cross section, also \(x_L\) spectrum shape is too different.
- RAPGAP \(\pi^+\)-exchange describes data well for \(x_L > 0.7\).
- Mixture of the DJANGO and the RAPGAP MC's can be used to describe data in the whole kinematic region.

\[122 \text{ pb}^{-1}\]
\[6 < Q^2 < 100 \text{ GeV}^2\]
\[p_T^2 < 0.04 \text{ GeV}^2\]
\[0.32 < x_L < 0.95\]
LN production in DIS:

\( F_2(Q^2,x) \) from the H1 parameterisation (Eur.Phys.J.C21 (2001) 33)

\[ \frac{F_2^{LN}(Q^2,x,x_L)}{F_2(Q^2,x)} \] is mostly flat in \( Q^2 \) and \( x \)

\( F_2^{LN}(Q^2,x,x_L)/F_2(Q^2,x) \) is similar to the Leading Proton measurement

"Leading Baryon Production at HERA", Vitaliy Dodonov,

EPS HEP 2009, July 2009, Krakow
Estimate for Pion Structure Function from $F_2^{LN}$

In the $\pi$-exchange picture leading neutron production cross section can be expressed as the product of the pion flux and the pion structure function $F_2^{\pi}$ from the measured $F_2^{LN}$:

$$\sigma_{ep \rightarrow enX}(\beta, Q^2, x_L, t) = f_{\pi^+/p}(x_L, t) \times \sigma_{e\pi \rightarrow eX}(\beta, Q^2), \text{ where } \beta = x / (1 - x_L)$$

Assuming that pion exchange is dominating at $x_L \approx 0.7$ and $p_T < 0.2$ GeV we can estimate $F_2^{\pi}$ from the $F_2^{LN(3)}$ measurement according to:

$$F_2^{LN(3)}(\beta, Q^2, x_L) = \Gamma_\pi(x_L) \times F_2^{\pi}(\beta, Q^2)$$

where $\Gamma_\pi$ is integrated over $t$ pion flux

Using pion flux

$$f_{\pi^+/p} = \frac{1}{2\pi} \frac{g_{p\pi n}^2}{4\pi} (1 - x_L) \frac{-t}{(m_\pi^2 - t)^2} \exp\left(-R_{\pi n}^2 \frac{m_\pi^2 - t}{1 - x_L}\right) \Rightarrow \text{ at } x_L = 0.73 \quad \Gamma_\pi = 0.131$$

(Other pion flux form-factors give other values of $\Gamma_\pi \Rightarrow$ global normalisation factor on $F_2^{\pi}$)

No background subtraction or absorption correction applied
Pion Structure Function from $F_2^{\text{LN}}$

Data compared to parameterisations:
- 2/3 of proton $F_2$
- GRV-$\pi$ LO (revisited)
- ABFKW-$\pi$ Set 1 NLO

The $F_2^{\pi}$ exhibits a rise with $Q^2$ (i.e. scaling violation) and steep rise with decreasing $\beta$. Similar to pion and proton structure functions parameterisations.
Leading Neutron with Dijet in photoproduction
LN + dijets in $\gamma p$:

Absorption effects increase from high $Q^2 \Rightarrow \gamma p$, i.e. hard $\Rightarrow$ soft scale

A hard scale in $\gamma p$ can be introduced by requiring high $E_T$ jets

$40 \text{ pb}^{-1}, \ Q^2 < 1 \text{ GeV}^2, \ p_T^2 < 0.475 \ x_L^2 \text{ GeV}^2, \ x_L > 0.2, \ E_T^{\text{jet}1} > 7.5 \text{ GeV}, \ E_T^{\text{jet}2} > 6.5 \text{ GeV}, \ -1.5 < \eta^{\text{jet}1,2} < 2.5$
LN + dijets in $\gamma p$:

- **Strong dependence of ratio on $x_\gamma$ (also on $W$, $x_p$).**
- Seem that resolved photon is suppressed in neutron events.

**ZEUS**

$W$ – total energy of photon-proton system

$$x_\gamma = \frac{\sum_{\text{jets}} (E-p_z)}{2yE_e}$$

$$x_p = \frac{\sum_{\text{jets}} (E+p_z)}{2E_p}$$
LN + dijets in \( \gamma p \):

**p_T^2** distributions in \( x_L \) bins; slopes

Well described by exponential fall-off in \( p_T^2 \)

\[
\frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dp_T^2 dx_L} = a(x_L) \cdot e^{-b(x_L)p_T^2}
\]

similar slopes in DIS and \( \gamma p + \text{dijet} \)

\( b(x_L) \) - slopes

**ZEUS**

- ZEUS 40 pb\(^{-1}\)
  - \( ep \rightarrow e\bar{\nu}Xn \)
  - \( Q^2 < 1 \text{ GeV}^2 \)
  - Fit \( d\sigma/dp_T^2 \propto \exp(-bp_T^2) \)

- ZEUS 40 pb\(^{-1}\)
  - \( ep \rightarrow e\bar{\nu}Xn \)
  - \( Q^2 > 2 \text{ GeV}^2 \)

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EPS HEP 2009, July 2009, Krakow
Comparison with Models

**LN + dijets in $\gamma p$:**

\[
x_{\pi} > 0.1 \Rightarrow \text{OK also at lower } x_{\pi}
\]

- RAPGAP $\pi$-exchange only and PYTHIA-SCI describe data poor
- Pion exchange is dominating mechanism at high $x_L$
- Full RAPGAP gives good description of data

\[
x_{\pi} = x_p / (1 - x_L)
\]
**LN + dijets in $\gamma p$:**

“LN + dijet in $\gamma p$” vs “LN in DIS” vs “LN in $\gamma p$”

**ZEUS**

- Protoproduction with jets is suppressed vs DIS at low $x_L$
  $\Rightarrow$ consistent with rescattering models

- Effect not prominent in photoproduction with high $E_T$ jets

- Phase space limitation: dijets in the final state leave little room for energetic high $x_L$ neutrons

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**“Leading Baryon Production at HERA”, Vitaliy Dodonov, EPS HEP 2009, July 2009, Krakow**
Leading Baryons are good testing ground to study soft vs hard physics

- Precise measurements of LB $x_L$ and $p_T^2$ presented in DIS, $\gamma p$ with dijets.
- Fragmentation MC-models without meson exchange do not describe the data.
- Models with virtual meson exchange describe data better.
- $F_{2}^{LP}/F_{2}$ and $F_{2}^{LN}/F_{2}$ ratios are independent of $x$ and $Q^2$.
- For LN production, pion structure $F_{2}^{\pi}$ estimated and compared with parameterisations of pion structure function.
- Reintroducing hard scale in $\gamma p$ with high $E_T$ jets: absorption effect not prominent.
Backup slides
The world's only electron/positron-proton collider at DESY, Hamburg.

\[ E_e = 27.6 \text{ GeV}, \ E_p = 920 \text{ GeV} \ (\text{also 820, 460 and 575 GeV}). \ \sqrt{s} \text{ up to 320 GeV}. \]
DATA Sets

- **ZEUS:** Leading Proton production in DIS:
  
  \[12.8 \text{ pb}^{-1}, \ Q^2 > 3 \text{ GeV}^2, \ p_T^2 < 0.5 \text{ GeV}^2, \ x_L > 0.32, \ 45 < W < 225 \text{ GeV}\]

- **H1:** Leading Neutron production in DIS:
  
  \[122 \text{ pb}^{-1}, \ 6 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2, \ p_T^2 < 0.04 \text{ GeV}^2, \ 0.32 < x_L < 0.95\]

- **ZEUS:** Leading Neutron + Dijets in photoproduction:
  
  \[40 \text{ pb}^{-1}, \ Q^2 < 1 \text{ GeV}^2, \ p_T^2 < 0.475 x_l^2 \text{ GeV}^2, \ x_L > 0.2, \ 130 < W < 280 \text{ GeV}, \]
  \[E_T^{\text{jet1}} > 7.5 \text{ GeV}, \ E_T^{\text{jet2}} > 6.5 \text{ GeV}, \ -1.5 < \eta^{\text{jet1,2}} < 2.5\]

**DIS and γp have very different inclusive cross sections** \(\sigma_{\text{inc}}\)

\[=> \text{for sensible comparisons look at} \ \sigma_{LB}/\sigma_{\text{inc}}\]

Additional benefit: systematic uncertainties of central detector cancel

\[=> \text{Most measured by ZEUS LB cross sections are relative to inclusive ones}\]
LN + dijets in γp:

Consider $X_{BP} = \text{fraction of p-energy available for LN production}$

$X_{BP}$ dist. is different in DIS and dijet γp:

much less energy available in dijet γp for LN production

Reweight DIS LN $x_L$ dist. to match the $X_{BP}$ dist. in dijet γp

- suppression at high $x_L$ dist. mostly gone
- large suppression at low $x_L$ seen in γp without jets not there

Differences in the $x_L$ spectra due to kinematic suppression.

For fixed $X_{BP}$, same LN rate and $x_L$ spectrum