Energy Flow and Leading Neutron Production at HERA

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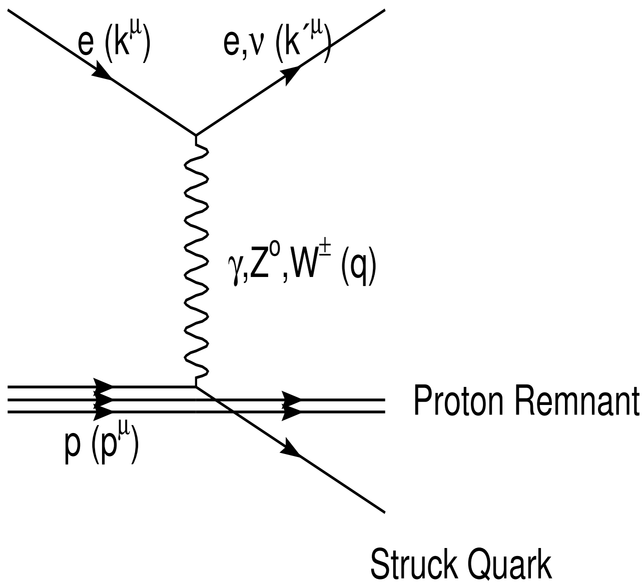
On behalf of H1 and ZEUS Collaborations

XXXV International Symposium on Multiparticle Dynamics 2005

HERA collider

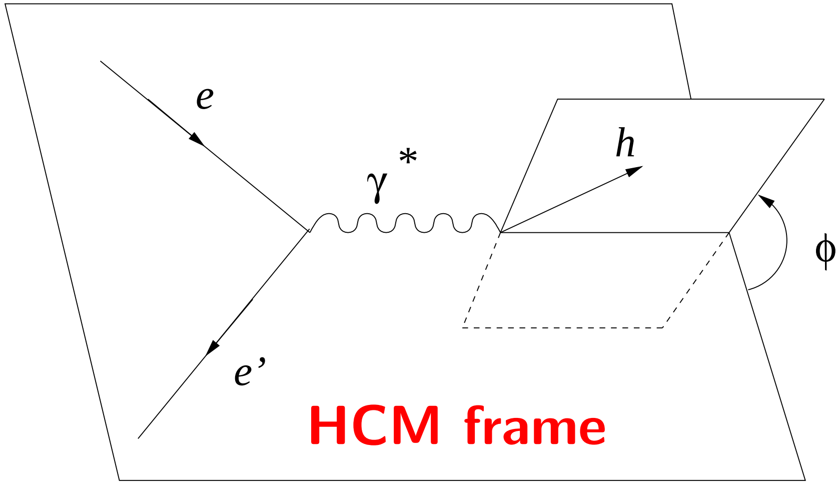
- **HERA ep collider: $E_e = 27.5$ GeV and $E_p = 820$ GeV/920 GeV**
- **DIS kinematics:**



  - **Momentum transfer** $Q^2 = -q^2 = -(k - k')^2$
  - **Bjorken scaling variable** $x = Q^2/(2pq)$
  - **Inelasticity** $y = pq/pk$
  - **Hadronic invariant mass** $W^2 = (p + q)^2 = 2pq - Q^2$

- **Reference frame:**
  - **Hadronic center of mass (HCM) frame: defined by $p + q = 0$**
  - **Lab frame**

Azimuthal angle in e+p $\longrightarrow$ e+h+X



- **Azimuthal asymmetry comes from**
  - **Two-body processes (BGF and QCDC)**
  - **Boson polarization**
  - **Longitudinally polarized electron beam**
  - **Parity violating weak interactions**
  - **Final hadron polarization**
  - **Intrinsic parton momentum in the proton**

- **pQCD prediction:**

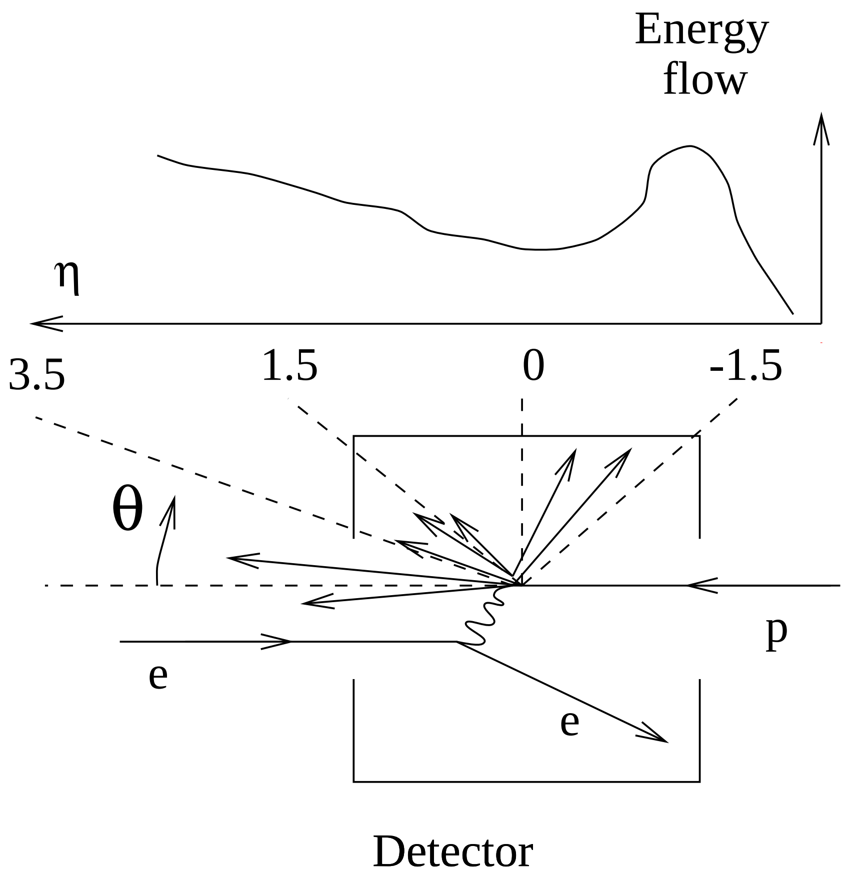
$$\frac{d\sigma^{ep\rightarrow ehX}}{d\phi} = A + B\cos(\phi) + C\cos(2\phi) + D\sin(\phi) + E\sin(s\phi)$$

- **Determine coefficients by 1st moment**

$$\langle\cos(n\phi)\rangle = \frac{\int d\sigma\cos(n\phi)}{\int d\sigma} \qquad \textbf{(n = 1, 2)}$$

$$\langle\cos(\phi)\rangle = \frac{B}{2A} \qquad \langle\cos(2\phi)\rangle = \frac{C}{2A} \qquad \langle\sin(\phi)\rangle = \frac{D}{2A} \qquad \langle\sin(2\phi)\rangle = \frac{E}{2A}$$

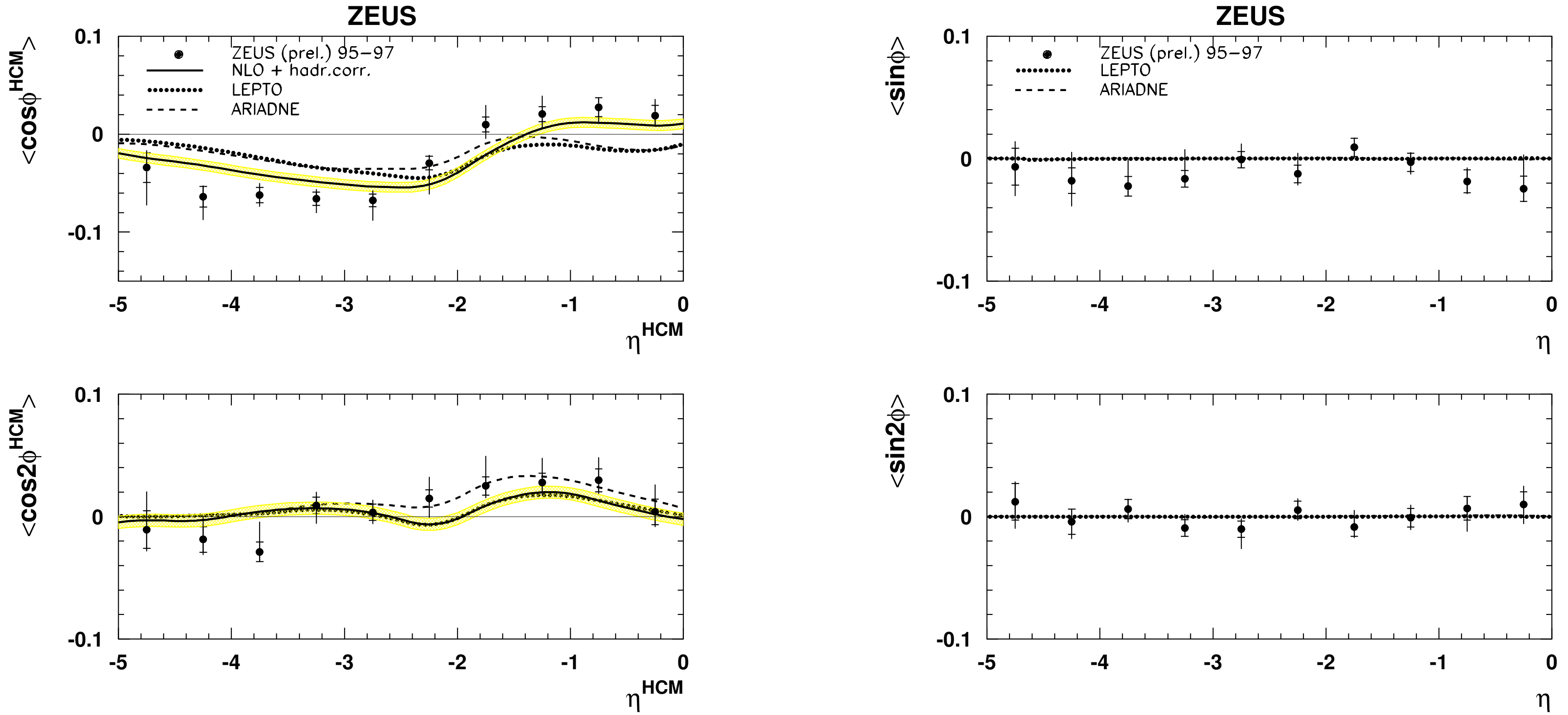
Azimuthal asymmetry: energy flow method



- **Multiplicity method**
  - **using charged hadrons**
  - **ZEUS: PLB481 (2000) 199**
- **Energy flow method**
  - **calorimeter and tracking detector information are used, i.e. charged and neutral hadrons included**
  - **each particle direction is weighted with its energy, hard partons ($E_T^\star$ larger) provides a larger contribution**
  - **calorimeter energy scale is canceled due to mean value**

ZEUS: Azimuthal asymmetry results

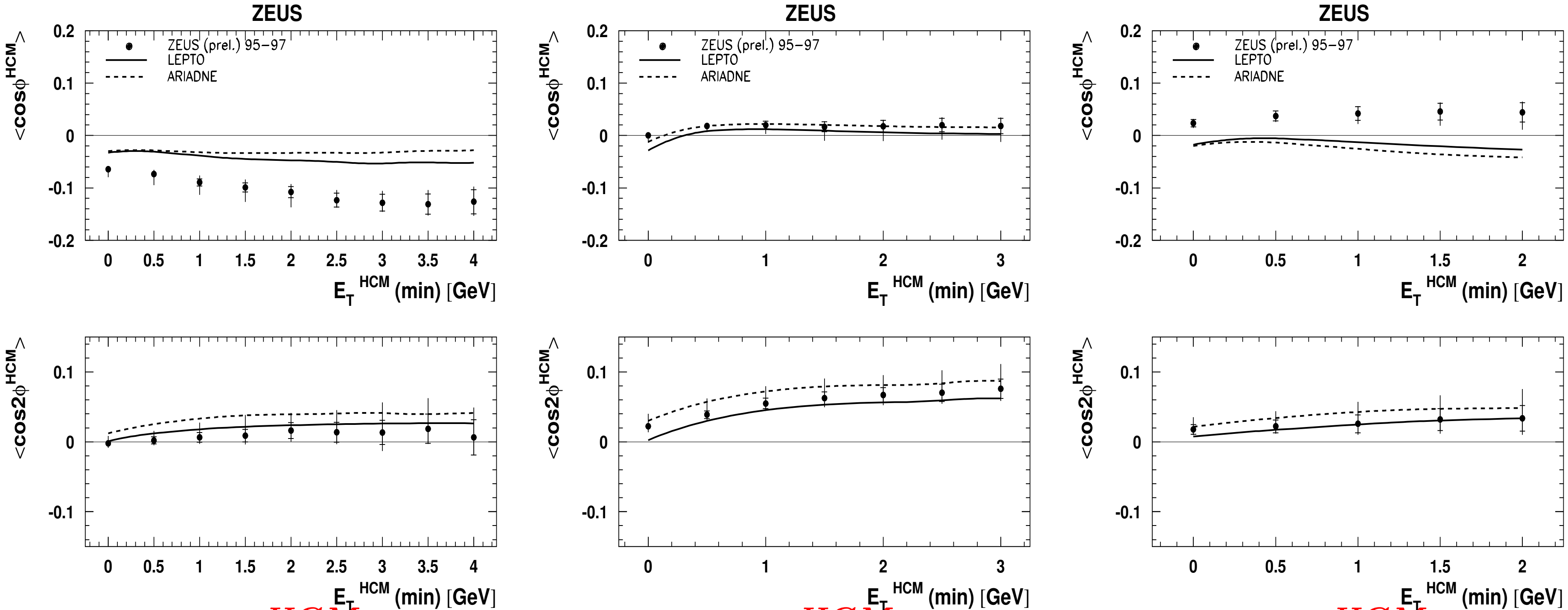
- **ZEUS:** $100 < Q^2 < 8000$ **GeV**^{2}, $0.01 < x < 0.1$ **and** $P_T^{Lab} > 150$ **MeV**



- $\langle\cos\phi\rangle$: **NLO prediction by DISENT describe data points than LO MC programs by LEPTO and ARIADNE**
- $\langle\cos 2\phi\rangle$: **about zero for** $\eta^{HCM} < -2.0$ **and positive for higher** η^{HCM}
- $\langle\sin\phi\rangle$ **and** $\langle\sin 2\phi\rangle$: **small and consistent with zero**

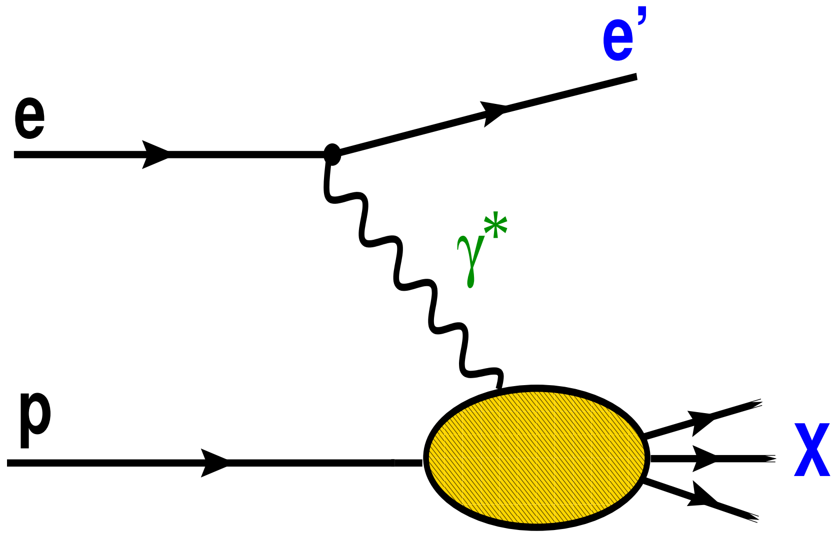
ZEUS: Azimuthal asymmetry results

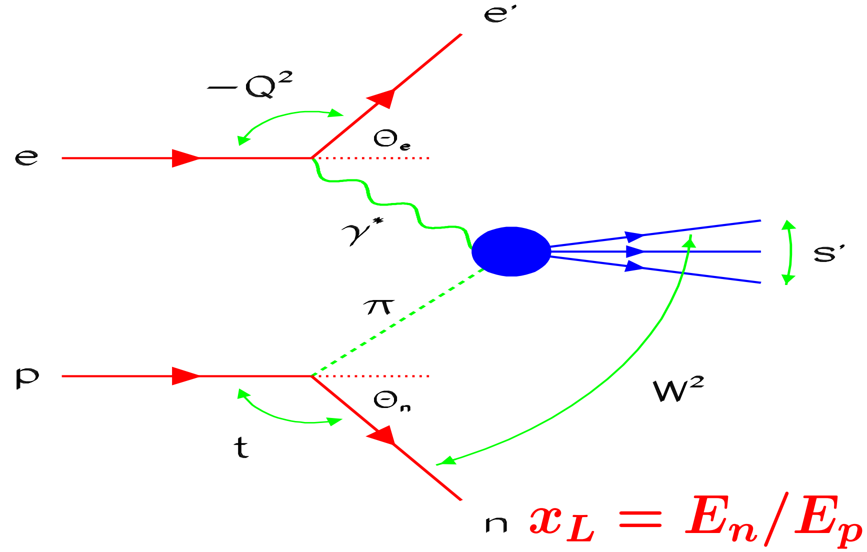
- $\langle \cos n\phi \rangle$ as function of detected hadron's minimum transverse energy E_T^{HCM}(min)
- remove 0th QCD process: Born level contribution
- higher E_T^{HCM}(min): better comparison with pQCD
- $\langle \cos n\phi \rangle$: more negative than LO MC programs by LEPTO and ARIADNE in $-5.0 < \eta^{HCM} < -2.5$. the LO MC programs predictions are in good agreement with data for $-2.5 < \eta^{HCM} < -1.0$



$-5.0 < \eta^{HCM} < -2.5$ $\quad$ $-2.5 < \eta^{HCM} < -1.0$ $\quad$ $-1.0 < \eta^{HCM} < 0.0$

Leading neutron production: e+p $\longrightarrow$ e+n+X





$x_L = E_n/E_p$

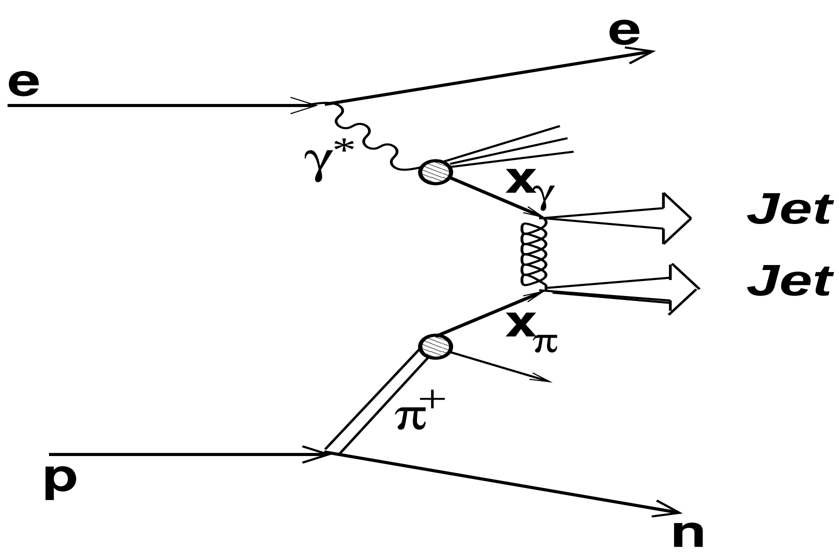
fragmentation of proton remnant — **exchange process**

one pion exchange dominates for $x_L > 0.7$

- **study the neutron production mechanism**
- **Cross section factorizes: $\sigma_{ep\to enX} = f_{\pi/p}(x_L, t) \times \sigma(e\pi \to e'X)$**
  vertex factorization: dependence of cross section on lepton vertex variables independent of baryon vertex variables
- **test of different MC and the parameterizations of pion flux $f_{\pi/p}(x_L, t)$**
- **test of pQCD predictions and vertex factorization**

H1: leading neutron with dijet

- **Leading neutron production in inclusive DIS is well described by pion exchange model and soft color interaction (LEPTO-SCI) model**



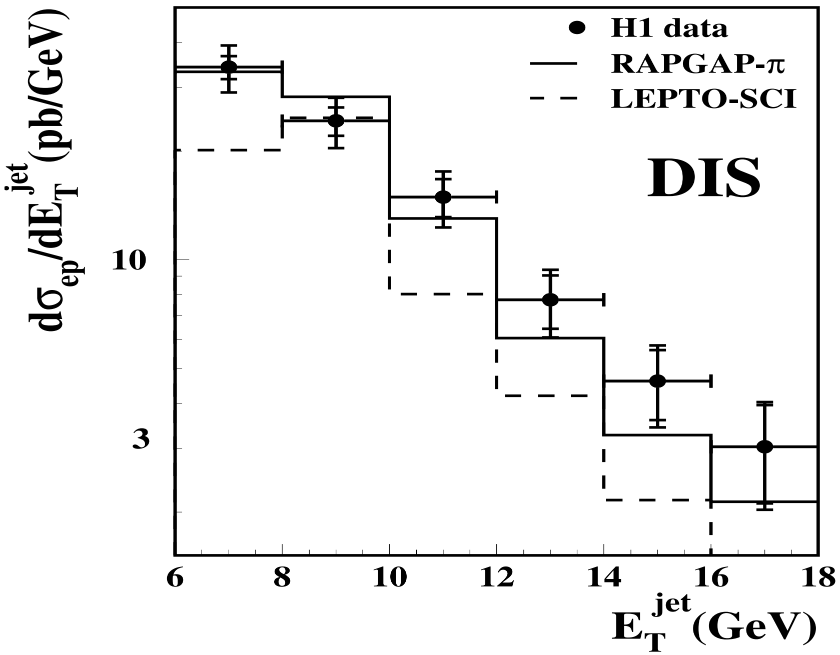
- **events with dijet:**
  $e + p \rightarrow e' + n + jet1 + jet2 + X$
  H1: Eur. Phys. J. C41 (2005) 273

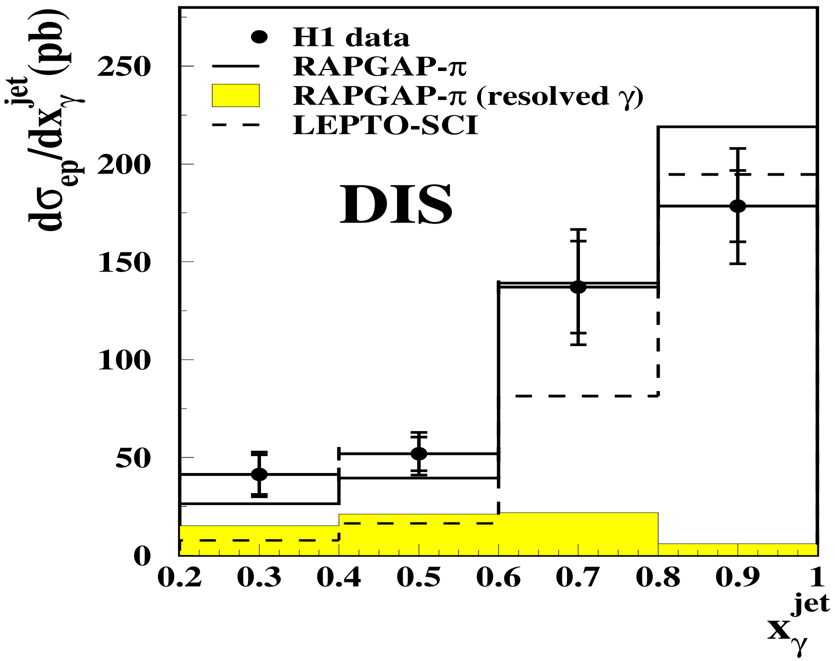
- γp **($Q^2 < 0.01$ GeV^2) and DIS ($2.0 < Q^2 < 80.0$ GeV^2) samples**

- **test of factorization: leading neutron production rate is independent of jet variables ?**

	Photoproduction	DIS
π exchange	RAPGAP-π, POMPYT	RAPGAP-π
inclusive (no π exchange)	PYTHIA-MI, PYTHIA	RAPGAP, LEPTO, LEPTO-SCI
NLO (π exchange)	M.Klasen & G. Kramer	

H1: leading neutron with dijet in DIS





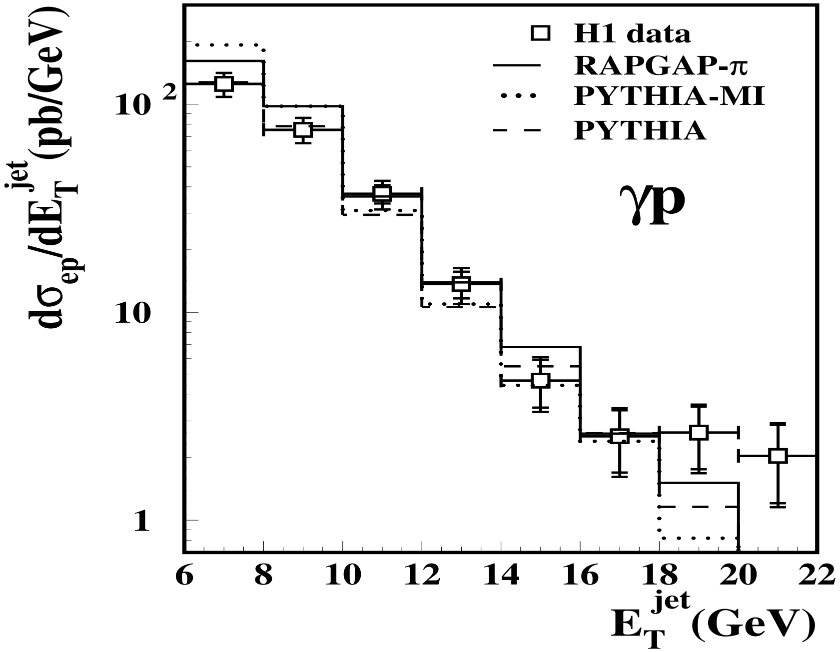
- **data described by π exchange MC model**

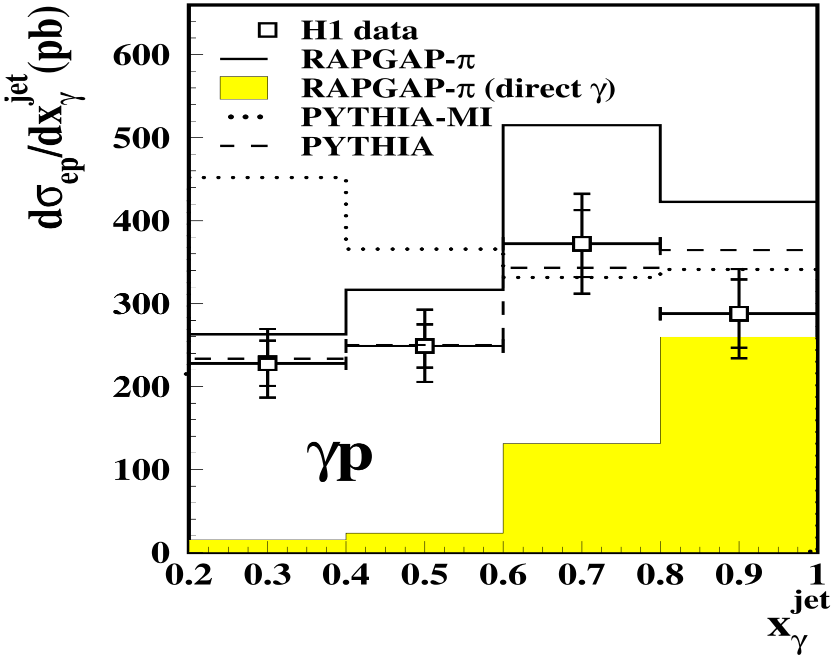
$$x_\gamma^{jets} = \frac{\sum E_{T,i}^{jet} \exp(-\eta_i^{jet})}{2yE_e}$$

- **LEPTO-SCI (LEPTO + soft color interactions) is too low**

- **some contribution from resolved photon is necessary**

H1: leading neutron with dijet in γp



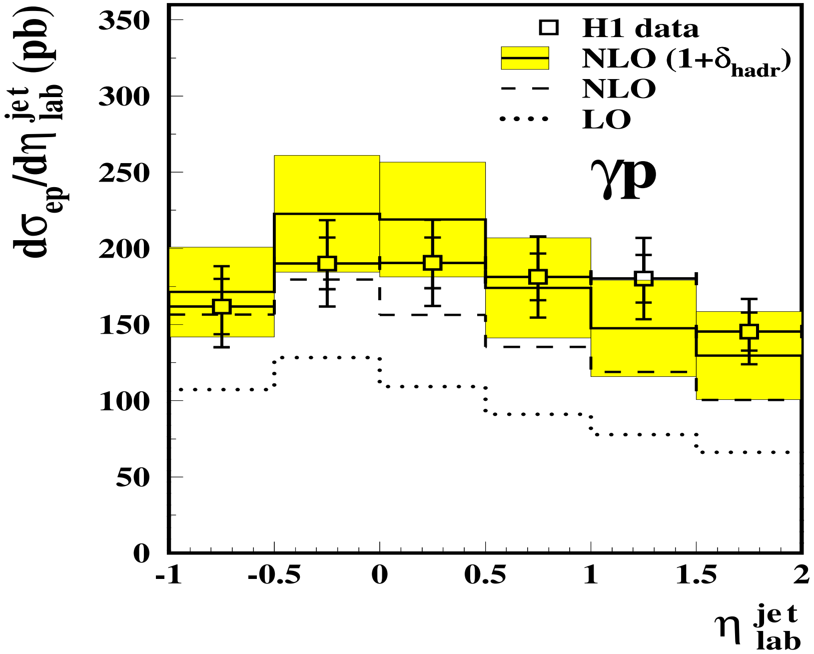


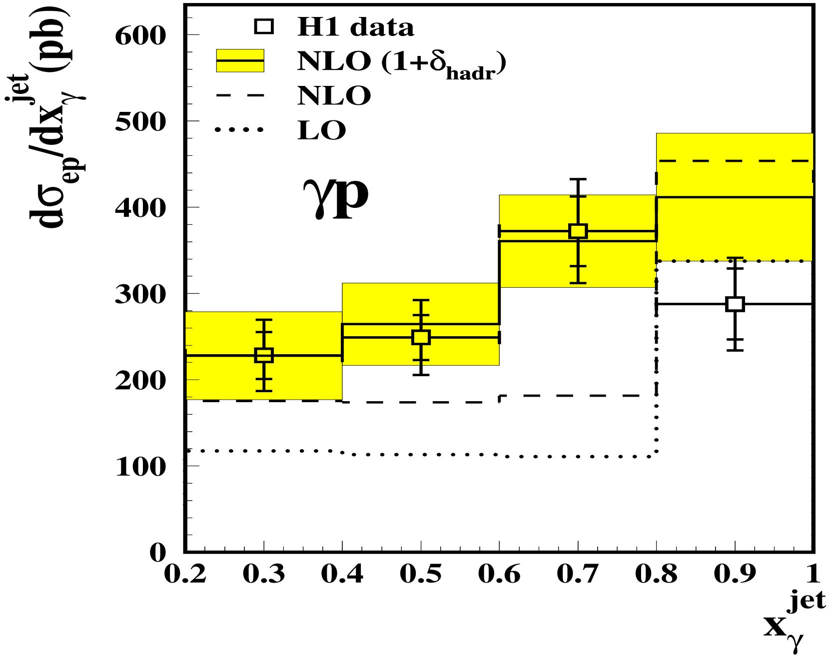
- data described by π exchange MC model

$$x_\gamma^{jets} = \frac{\sum E_{T,i}^{jet}\exp(-\eta_i^{jet})}{2yE_e}$$

- PYTHIA also describe data.
- PYTHIA-MI (PYTHIA + multi-parton interactions) too high at low x_γ, too much resolved

H1: leading neutron with dijet in γp

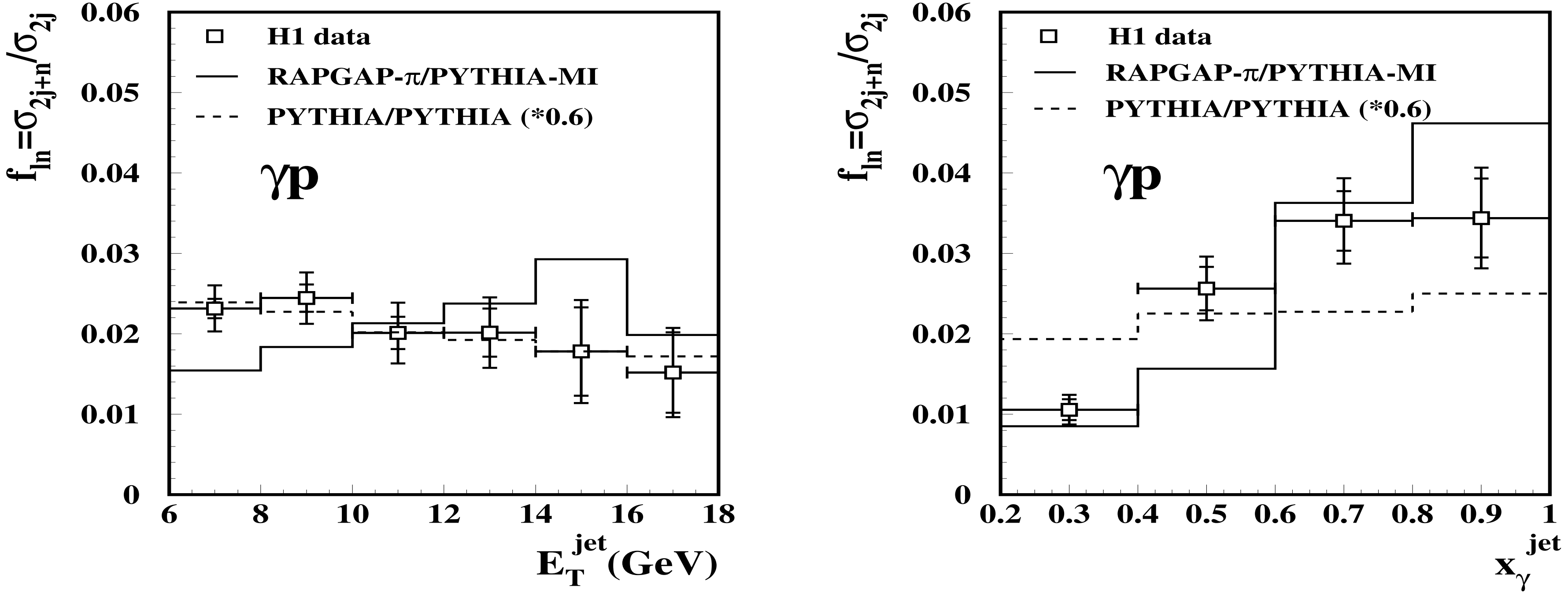




$$x_\gamma^{jets} = \frac{\sum E_{T,i}^{jet} \exp(-\eta_i^{jet})}{2yE_e}$$

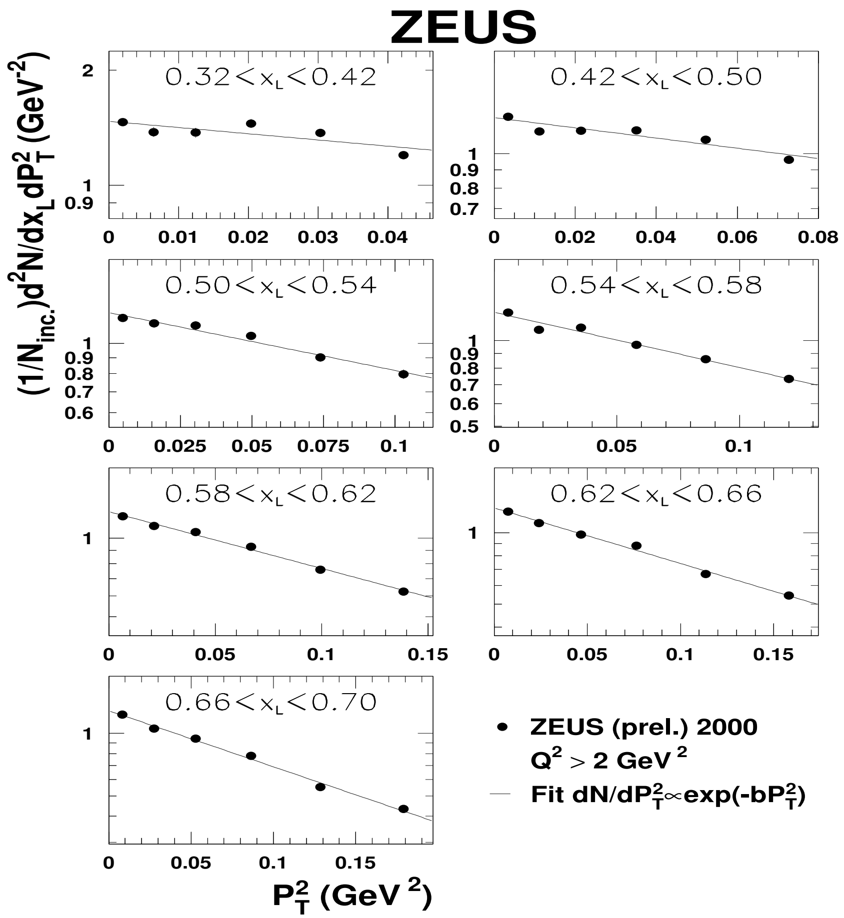
- **NLO QCD predictions based on pion exchange, corrected for hadronization effects, describe the measured data.**

H1: leading neutron with dijet

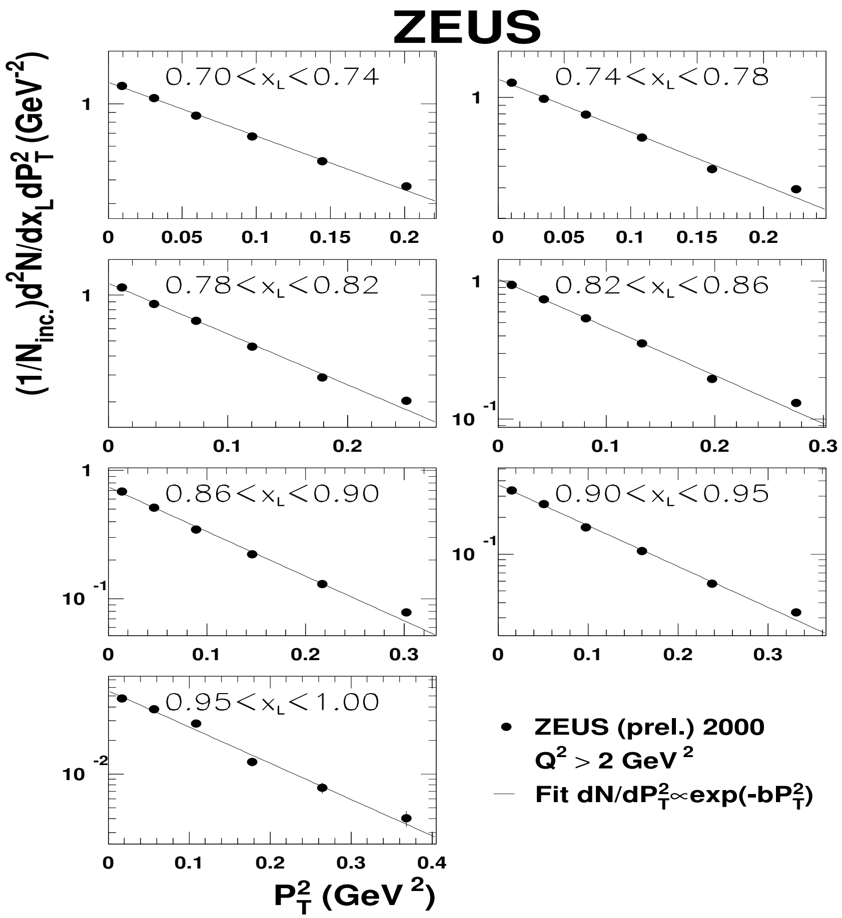


- f_{ln}: ratio of leading neutron to inclusive dijet cross section
- f_{ln} is almost independent of E_T^{jet}: factorization
- f_{ln} shows strong dependence on x_γ^{jet} (also on η^{jet} and x_p^{jet}),
- not phase space effects (PYTHIA), factorization breaking

ZEUS: leading neutron in DIS on p_T^2 distributions



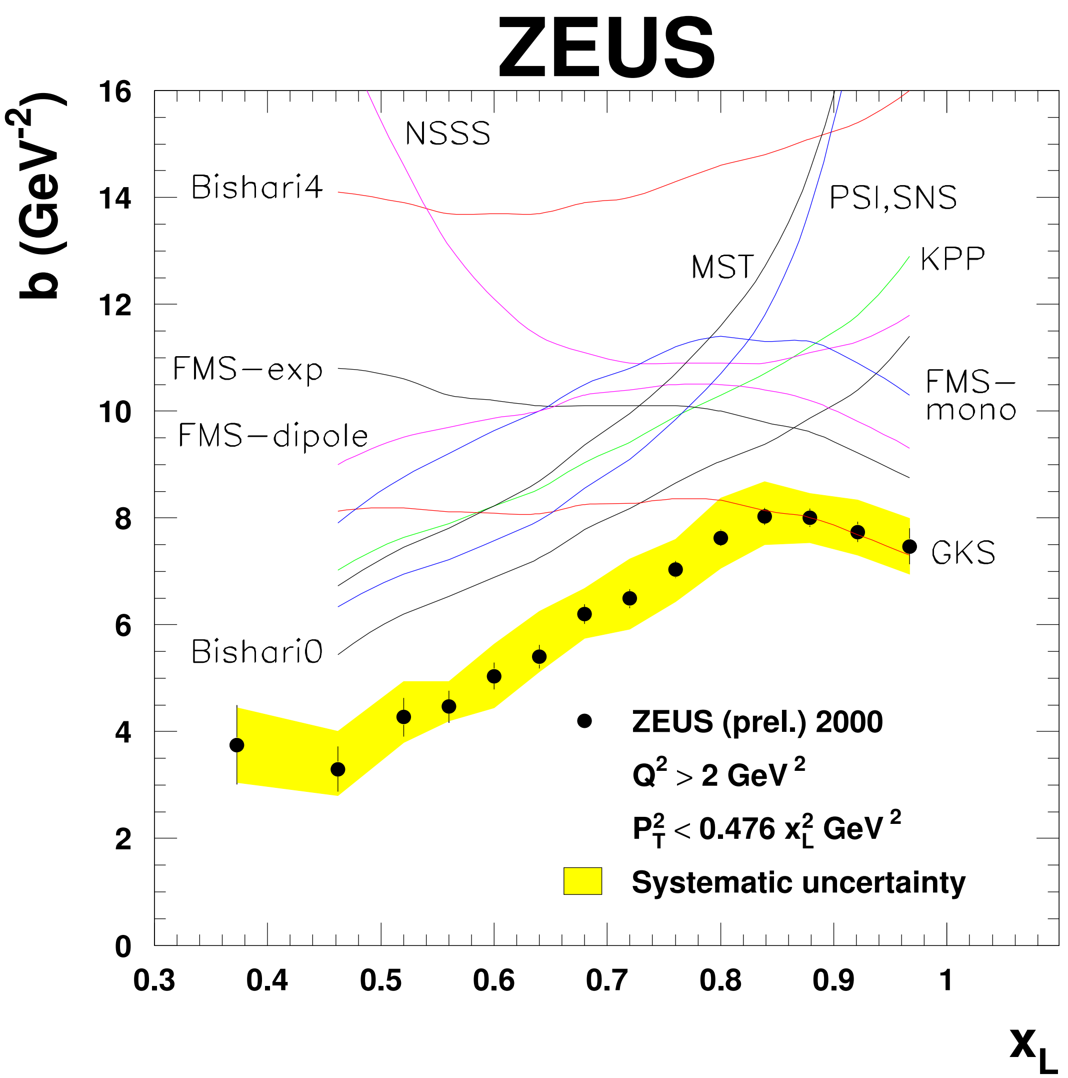
$$\mathbf{0.32 < x_L < 0.70}$$



$$\mathbf{0.70 < x_L < 1.00}$$

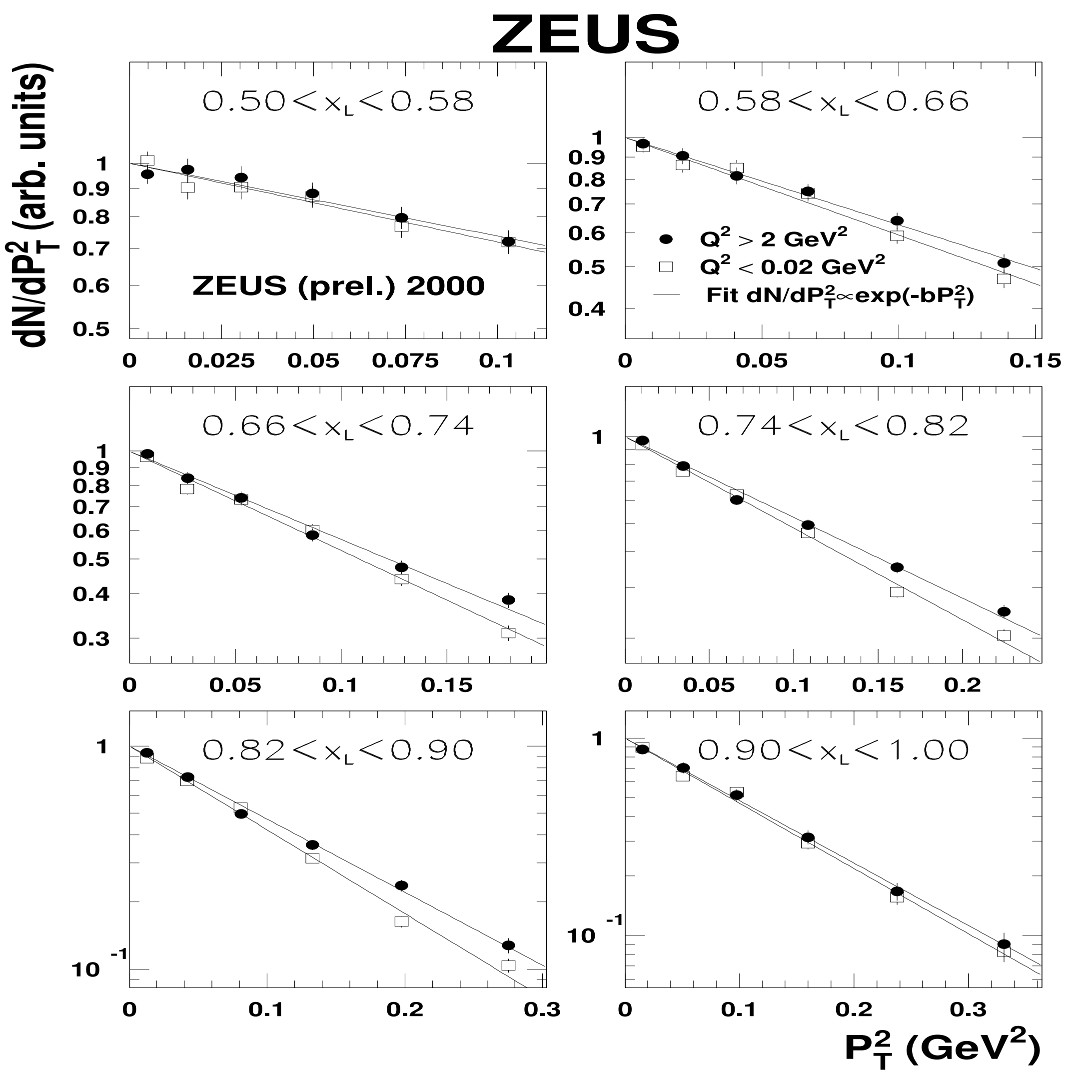
- $\exp(-bp_T^2)$ **well describe data**

ZEUS: leading neutron in DIS on p_T^2 distributions



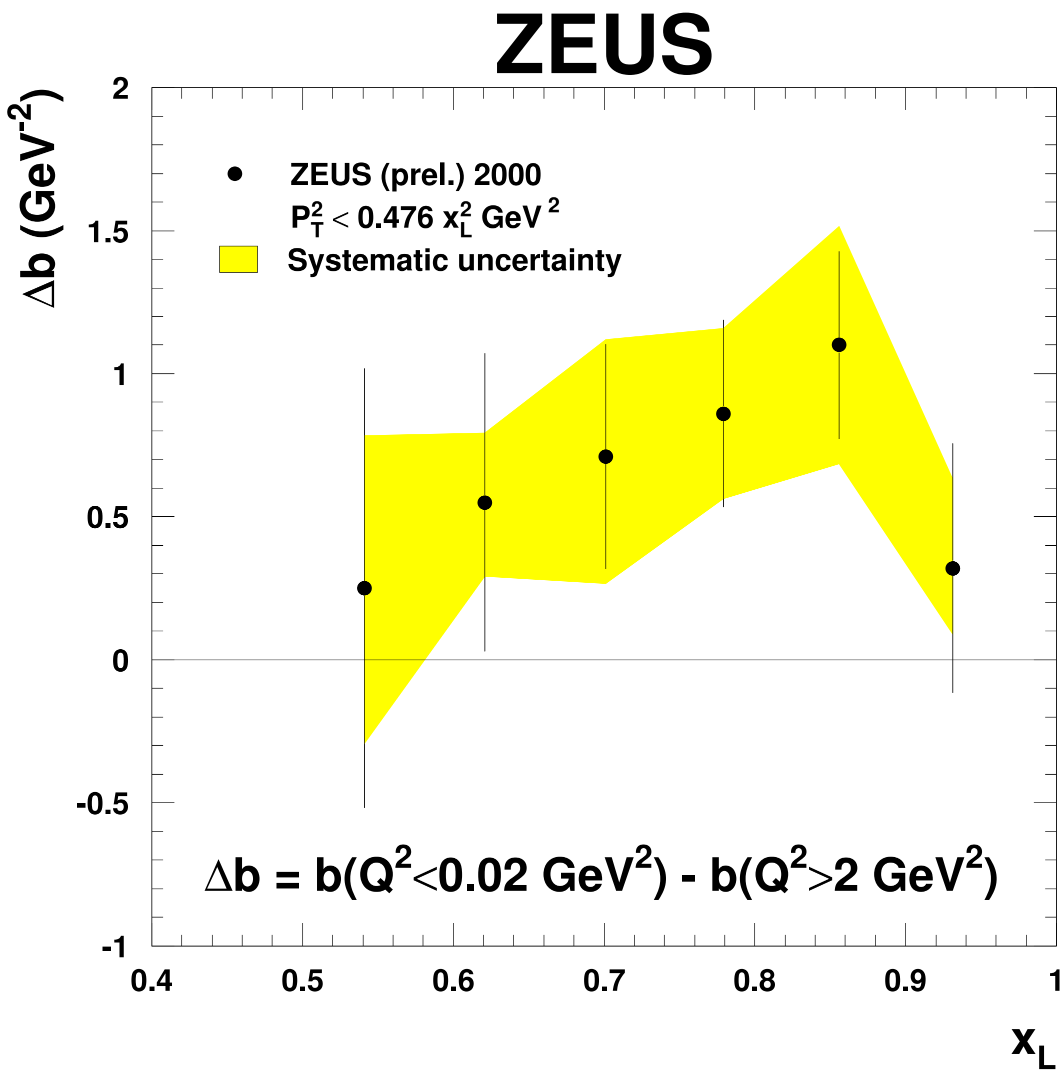
- Numerous model for one pion exchange
- pion flux $f_{\pi/p}$, not exponential in p_T^2, but fit with $\exp(-bp_T^2)$ at fixted x_L. resulting b are theory prediction
- No model describe data over whole x_L range
- one pion exchange expected to dominate for $0.6 < x_L < 0.9$
- reject models and constrain choice of parameters in models

ZEUS: leading neutron in γp and DIS



- leading neutron in γp ($Q^2 < 0.02$ GeV^2) and DIS ($Q^2 > 2.0$ GeV^2) regions
- normalize to unity at $p_T^2 = 0.0$ for comparing slopes
- in γp, distributions are clearly steeper in $0.6 < x_L < 0.9$
- $\exp(-bp_T^2)$ well describe data in γp and DIS

ZEUS: leading neutron in γp and DIS



- for $\Delta b = b(\gamma p) - b(DIS)$, some systematic uncertainties are canceled.
- $b(\gamma p)$ clearly larger than $b(DIS)$ in the range $0.6 < x_L < 0.9$ with $\Delta b = 0.5 - 1.0$ GeV^{-2}
- absorption models: smaller mean size of π-n system $\sim$ higher p_T^2 $\longrightarrow$ fewer high p_T^2 neutron and steeper p_T^2 distributions in photoproduction $\longrightarrow$ confirmed by data points.

Summary

- **Azimuthal asymmetry of hadrons in e+p $\longrightarrow$ e+h+X**
  - **use energy flow method**
  - **NLO program (DISENT) has better agreement with experimental data than LO MC programs. some discrepancies are visible.**
- **leading neutron production with dijet in photoproduction and DIS**
  - π **exchange MC models describe measured data**
  - **NLO prediction by PLB 508 (2001) 259 could describe data in γp**
  - **violation of factorization is observed by dependence of f_{ln} on x_{γ}^{jet}**
- p_T^2 **distribution of leading neutron production**
  - $\exp(-bp_T^2)$ **well describe data in γp and DIS**
  - **no model described measured b over whole range**
  - **the measured b have difference in γp and DIS, and consistent with expections from absorption models**