Pion Structure Function and SU(2) Flavor Asymmetry

Chueng-Ryong Ji
North Carolina State University

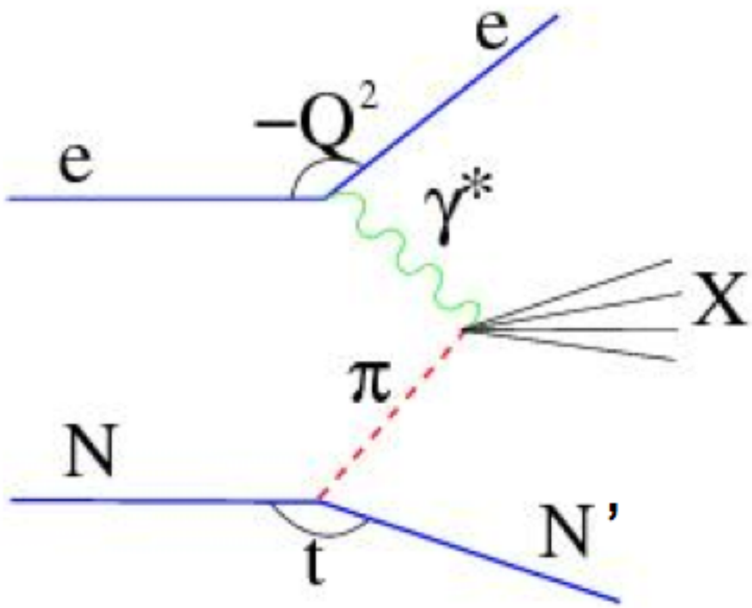
In collaboration with **Wally Melnitchouk** (Jlab),
Josh McKinney (UNC), Nobuo Sato (Jlab), Tony Thomas (Adelaide)

QCD Evolution 2016

Nikhef, June 2, 2016

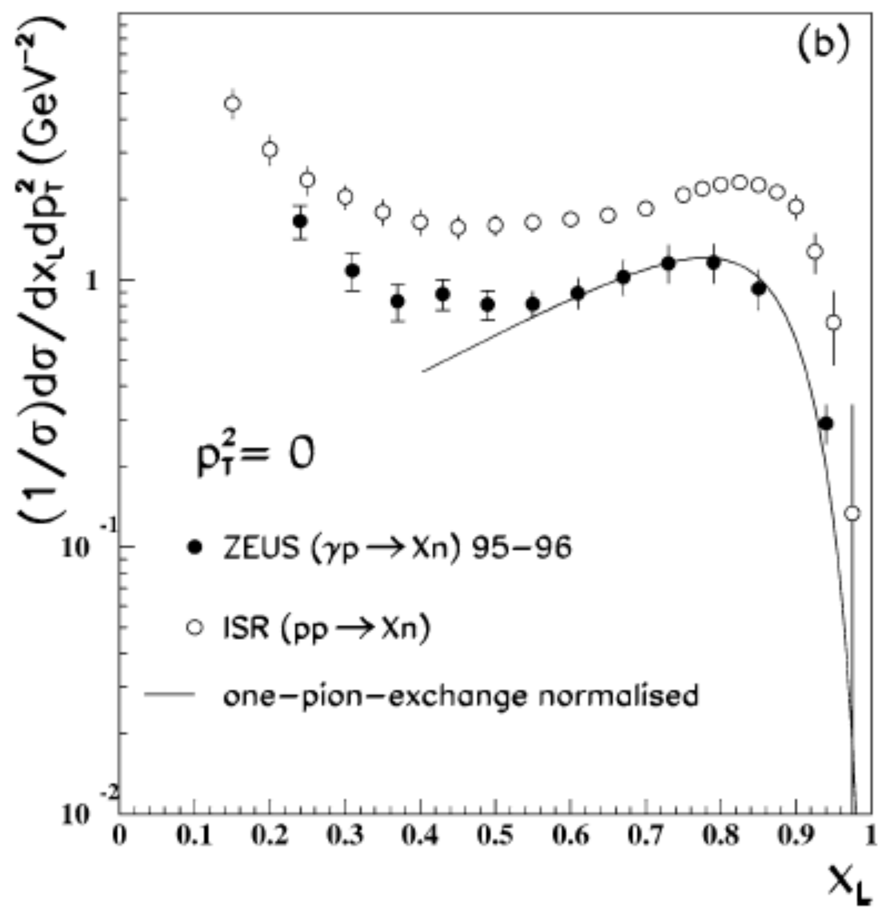
Measurement of Tagged Deep Inelastic Scattering (TDIS)

C.Keppel (Contact person)



$$e + p(or\ n) \rightarrow e' + p + X$$

$$e + D \rightarrow e' + p + p + X$$



Leading neutron production in e^+p collisions at HERA

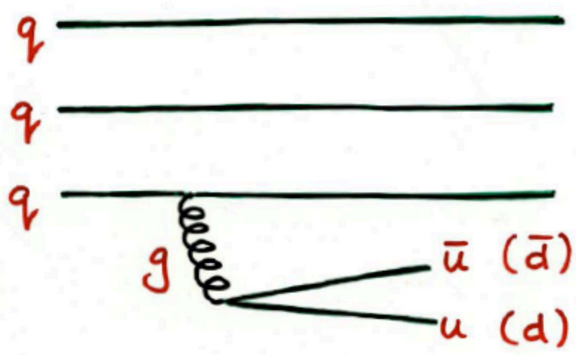
ZEUS Collaboration, NPB 637 (2002) 3–56

Outline

- Flavor Asymmetry in Proton Sea
- Chiral Effective Theory Connection with QCD
- Pion Splitting Functions
- Leading Neutron Electroproduction
- Outlook

Flavor asymmetry

- Antiquarks in the proton "sea" produced predominantly by gluon radiation into quark-antiquark pairs, $g \to q\bar{q}$



→ since u and d quark masses are similar, expect flavor-symmetric sea, $\bar{d} \approx \bar{u}$

- Experimentally, one finds *large excess* of $\bar{d}$ over $\bar{u}$

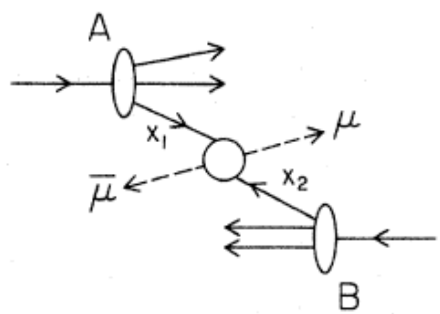
$$\int_0^1 dx\ (\bar{d}(x) - \bar{u}(x)) = 0.118 \pm 0.012$$

E866 (Fermilab), PRD ***64****, 052002 (2001)*

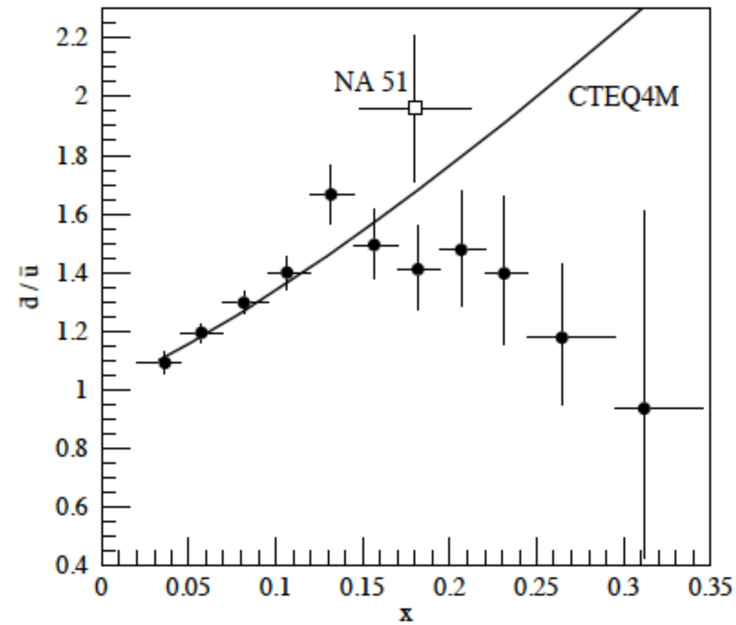
Flavor asymmetry

- Large flavor asymmetry in proton sea suggests important role of chiral symmetry in high-energy reactions

→ Drell-Yan process



$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9Q^2}\sum_q e_q^2\left(q(x_b)\bar{q}(x_t) + \bar{q}(x_b)q(x_t)\right)$$



E866, PRD ***64***, *052002 (2001)*

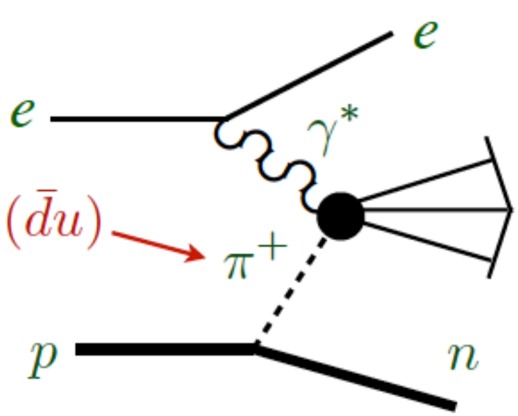
→ for $x_b \gg x_t$

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right) \quad \rightarrow \quad \int_0^1 dx\,(\bar{d} - \bar{u}) = 0.118 \pm 0.012$$

Flavor asymmetry

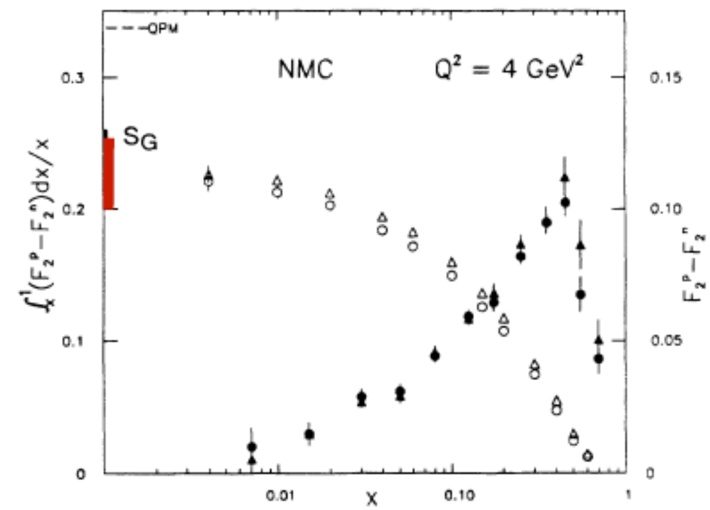
- Large flavor asymmetry in proton sea suggests important role of chiral symmetry in high-energy reactions

→ Sullivan process in DIS



Sullivan, PRD **5**, *1732 (1972)*

$$\boxed{\bar{d} > \bar{u}}$$



$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,(\bar{d} - \bar{u})$$

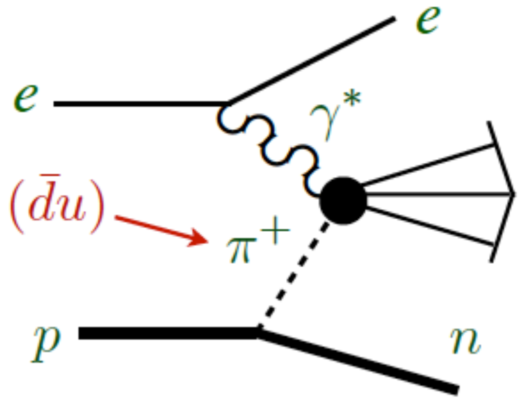
$$= 0.235(26)$$

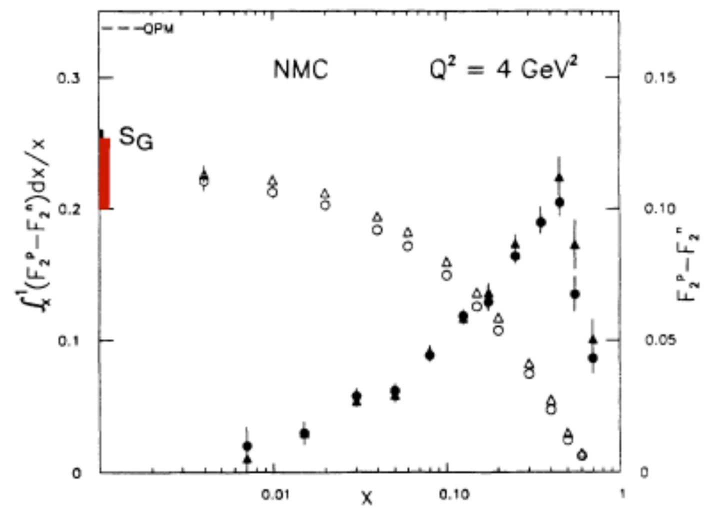
NMC, PRD **50**, *1 (1994)*

Flavor asymmetry

- Large flavor asymmetry in proton sea suggests important role of chiral symmetry in high-energy reactions

→ Sullivan process in DIS





Sullivan, PRD ***5****, 1732 (1972)*
Thomas, PLB ***126****, 97 (1983)*
Miller, Kumano, Strikman, Weiss, ...

$$(\bar{d} - \bar{u})(x) = \frac{2}{3} \int_x^1 \frac{dy}{y}\, f_\pi(y)\ \bar{q}^\pi(x/y)$$

pion light-cone momentum distribution in nucleon

$$f_\pi(y) = \frac{3 g_{\pi NN}^2}{16\pi^2}\, y \int dt \frac{-t\ \mathcal{F}_{\pi NN}^2(t)}{(t - m_\pi^2)^2}$$

connection with QCD?

Connection with QCD

- $(\bar{d}-\bar{u})(x) = \frac{2}{3}\int_x^1 \frac{dy}{y}\, f_\pi(y)\, \bar{q}^\pi(x/y)$ $\quad \boxed{f_\pi(y) = \frac{3g_{\pi NN}^2}{16\pi^2}\, y \int dt \frac{-t\, \mathcal{F}_{\pi NN}^2(t)}{(t-m_\pi^2)^2}}$

$\longrightarrow$ *model-independent* leading nonanalytic (LNA) behavior *consistent with Chiral Symmetry of QCD*.

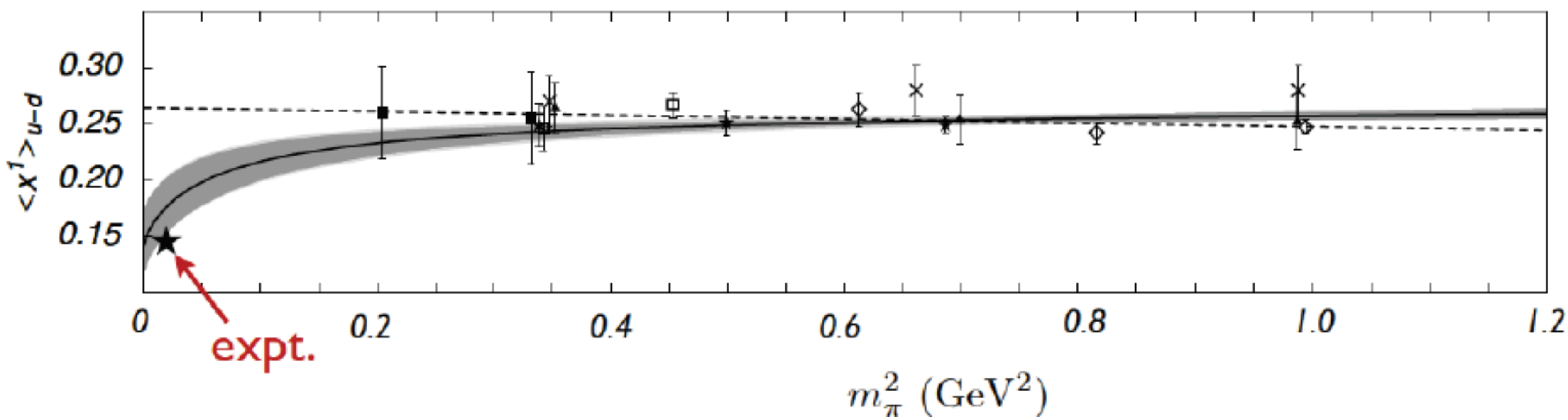
$$\langle x^0 \rangle_{\bar{d}-\bar{u}} \equiv \int_0^1 dx(\bar{d}-\bar{u})$$

$$\boxed{m_\pi^2 f_\pi^2 = -2m_q < \bar{q}q >}$$

$$= \frac{2}{3}\int_0^1 dy\, f_\pi(y) = \frac{2g_A^2}{(4\pi f_\pi)^2} m_\pi^2 \log(m_\pi^2/\mu^2) \;+\; \text{analytic terms}$$

- Nonanalytic behavior vital for chiral extrapolation of lattice data

Thomas, Melnitchouk, Steffens PRL ***85****, 2892 (2000)*



Chiral effective theory

- Effective low-energy theory of pions & nucleons

$$\mathcal{L}_{\pi N} = \frac{g_A}{2f_\pi}\,\bar{\psi}_N \gamma^\mu \gamma_5\, \vec{\tau}\cdot\partial_\mu \vec{\pi}\,\psi_N - \frac{1}{(2f_\pi)^2}\,\bar{\psi}_N \gamma^\mu\, \vec{\tau}\cdot(\vec{\pi}\times\partial_\mu\vec{\pi})\,\psi_N$$

$g_A = 1.267$

$f_\pi = 93\ \mathrm{MeV}$

→ lowest order approximation of chiral perturbation theory Lagrangian

→ *cf.* pseudoscalar (PS) Lagrangian

$$\mathcal{L}_{\pi N}^{\mathrm{PS}} = -g_{\pi NN}\,\bar{\psi}_N\, i\gamma_5 \vec{\tau}\cdot\vec{\pi}\,\psi_N\ + \sigma NN\ \text{term}$$

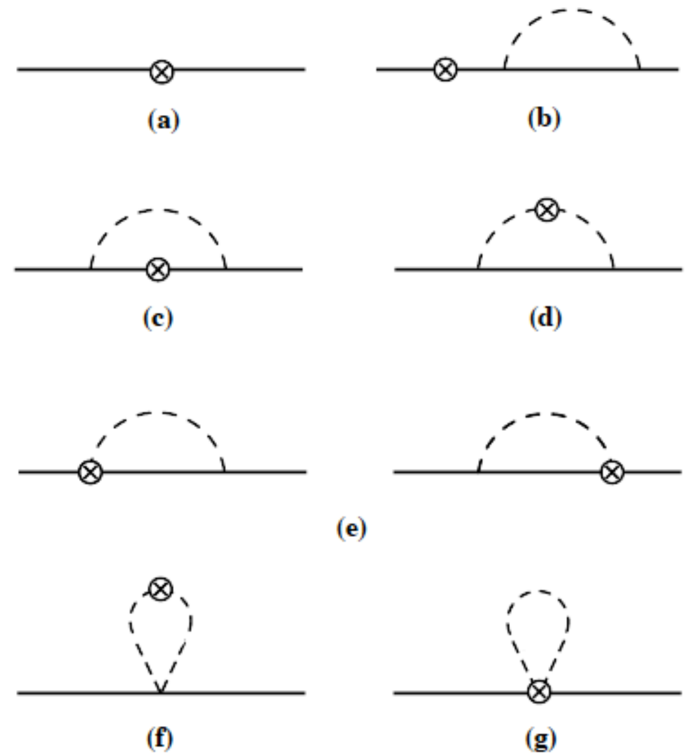
Weinberg, PRL ***18****, 88 (1967)*

gives the classic "Sullivan" result
– full PV theory more complicated!

Chiral effective theory

- Pion cloud corrections to electromagnetic N coupling

  → N rainbow **(c)**, π rainbow **(d)**, Kroll-Ruderman **(e)**, π bubble **(f)**, π tadpole **(g)**



- Vertex renormalization

$$(Z_1^{-1} - 1)\,\bar{u}(p)\,\gamma^\mu\,u(p) = \bar{u}(p)\,\Lambda^\mu\,u(p)$$

→ taking "+" components: $Z_1^{-1} - 1 \approx 1 - Z_1 = \dfrac{M}{p^+}\,\bar{u}(p)\,\Lambda^+\,u(p)$

→ $e.g.$ for N rainbow contribution,

$$\Lambda_\mu^N = -\frac{\partial \hat{\Sigma}}{\partial p^\mu}$$

C.Ji, W. Melnitchouk, A.Thomas, PRD88,076005(2013)

Flavor asymmetry

- Pion cloud corrections to electromagnetic N coupling

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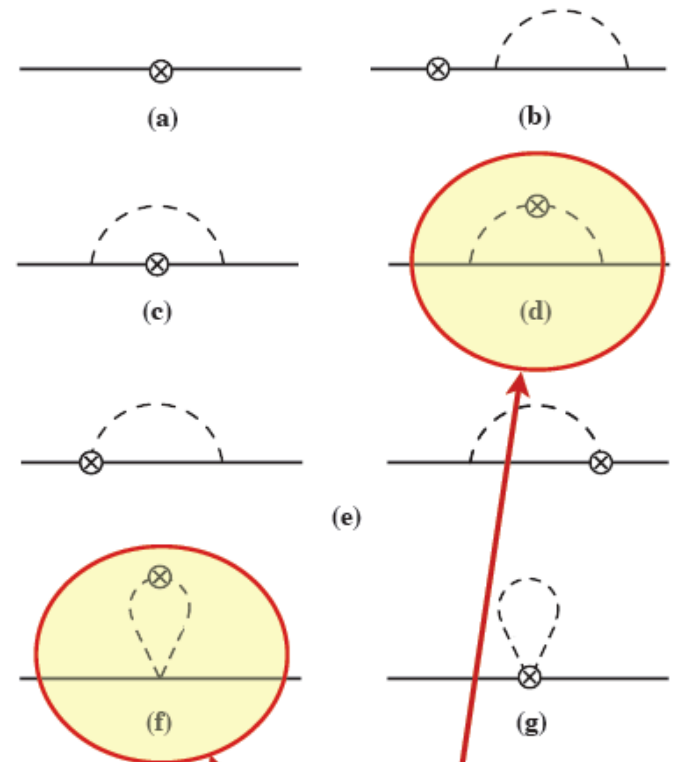

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→ *e.g.* for N rainbow contribution,

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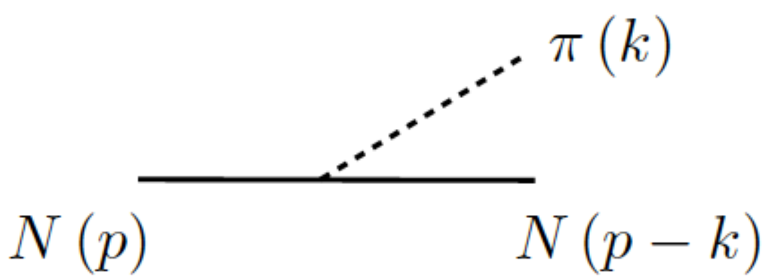
contribute to $\bar{d} - \bar{u}$

Pion splitting functions

- Each diagram can be represented by $N \to N\pi$ "splitting function" $f_i(y)$ (light-cone momentum distribution function)



$$y = \frac{k^+}{p^+}$$

- Vertex renormalization is k^+ moment of $f_i(y)$

$$1 - Z_1^i = \int dy\, f_i(y)$$

Pion splitting functions

- Summary of splitting functions:

$$1 - Z_1^i = \int dy\, f_i(y)$$

where
$$f_\pi(y) = f^{(\mathrm{on})}(y) + f^{(\delta)}(y)$$
$$f_N(y) = f^{(\mathrm{on})}(y) + f^{(\mathrm{off})}(y) - f^{(\delta)}(y)$$
$$f_{\mathrm{KR}}(y) = f^{(\mathrm{off})}(y) - 2f^{(\delta)}(y)$$
$$f_{\mathrm{tad}}(y) = -f_{\mathrm{bub}}(y) \;=\; 2f^{(\mathrm{tad})}(y)$$

with components
$$f^{(\mathrm{on})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2\, \frac{y(k_\perp^2 + y^2 M^2)}{\left[k_\perp^2 + y^2 M^2 + (1-y)m_\pi^2\right]^2}$$
$$f^{(\mathrm{off})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2\, \frac{y}{k_\perp^2 + y^2 M^2 + (1-y)m_\pi^2}$$
$$f^{(\delta)}(y) = \frac{g_A^2}{4(4\pi f_\pi)^2} \int dk_\perp^2\, \log\left(\frac{k_\perp^2 + m_\pi^2}{\mu^2}\right)\delta(y)$$
$$f^{(\mathrm{tad})}(y) = -\frac{4}{g_A^2}\; f^{(\delta)}(y)$$

tadpole & bubble
equal & opposite
$$(1 - Z_1^{\mathrm{tad}}) = -(1 - Z_1^{\mathrm{bub}})$$

UV regularization

- For point-like nucleons and pions, integrals divergent

- Finite size of nucleon provides natural scale to regularize integrals, but does not prescribe form of regularization

  $\longrightarrow$ freedom in choosing regularization prescription
  (long-distance physics independent of choice!)

$$\mathcal{F} = \Theta(\Lambda^2 - k_\perp^2)$$ $k_\perp$ cutoff

$$\mathcal{F} = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$$ monopole in $t \equiv k^2 = -\dfrac{k_\perp^2 + y^2 M^2}{1-y}$

$$\mathcal{F} = \exp\left[(t - m_\pi^2)/\Lambda^2\right]$$ exponential in t

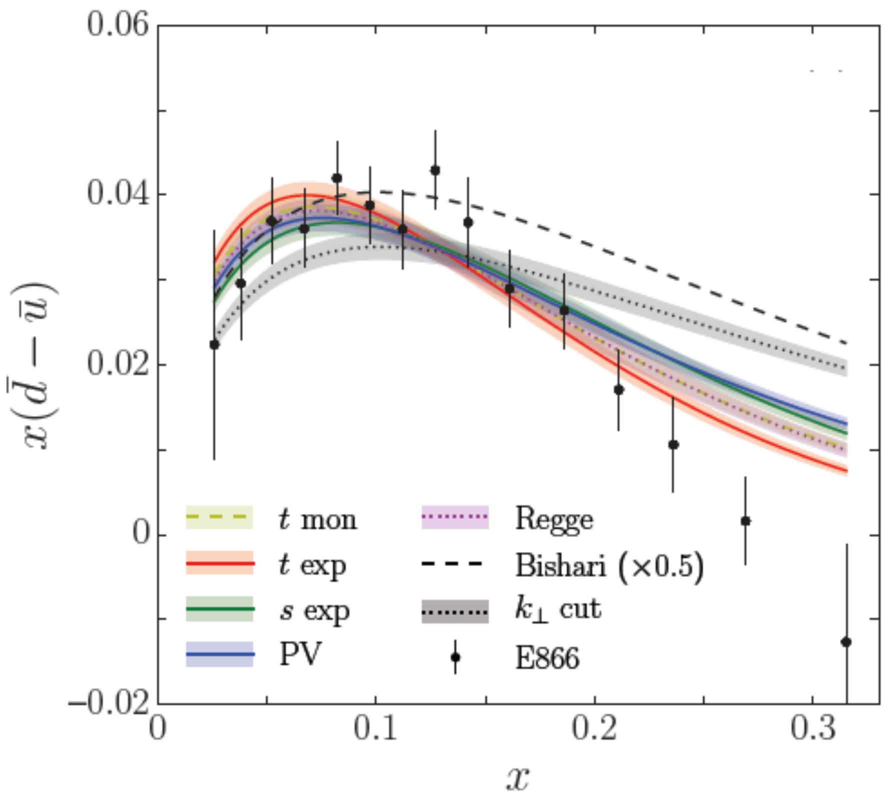
$$\mathcal{F} = \exp\left[(M^2 - s)/\Lambda^2\right]$$ exponential in $s = \dfrac{k_\perp^2 + m_\pi^2}{y} + \dfrac{k_\perp^2 + M^2}{1-y}$

$$\mathcal{F} = \left[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$$ Pauli-Villars

$$\mathcal{F} = y^{-\alpha_\pi(t)} \exp\left[(t - m_\pi^2)/\Lambda^2\right]$$ Regge

Flavor asymmetry

- E866 $\bar{d} - \bar{u}$ data can be fitted with range of regulators



average pion "multiplicity"

$$\langle n \rangle_{\pi N} = 3 \int_0^1 dy\, f_N^{(\mathrm{on})}(y)$$

$$\sim\ 0.25 - 0.3$$

→ with exception of $k_\perp$ cutoff and Bishari models, all others give reasonable fits, $\chi^2 \lesssim 1.5$

→ large-x asymmetry to be probed by FNAL *SeaQuest* expt.

Flavor asymmetry

- E866 $\bar{d} - \bar{u}$ data can be fitted with range of regulators

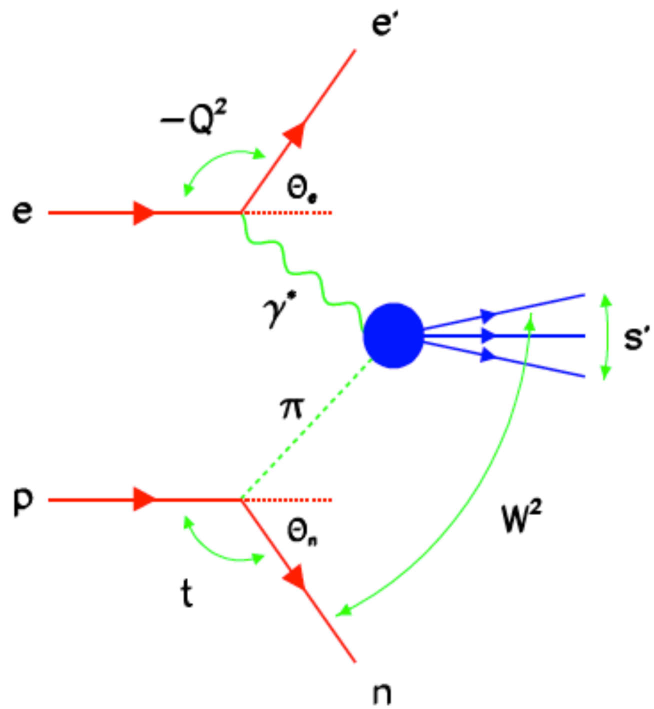
- Is pion cloud the only explanation for the asymmetry?

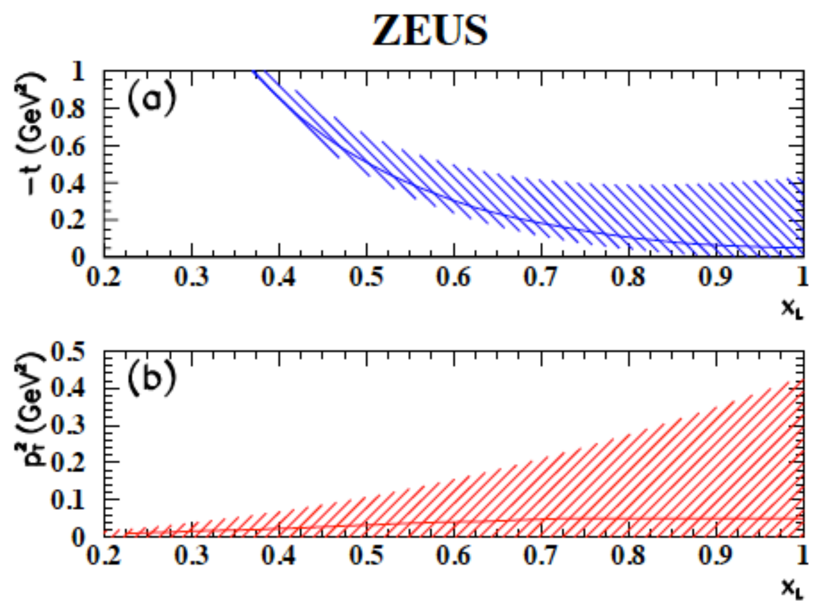
  $\longrightarrow$ are there other data that can discriminate between different mechanisms?

  $\longrightarrow$ semi-inclusive production of "leading neutrons" (LN) at HERA!

Leading neutron production at HERA

- ZEUS & H1 collaborations measured spectra of neutrons produced at very forward angles, $\theta_n < 0.8$ mrad





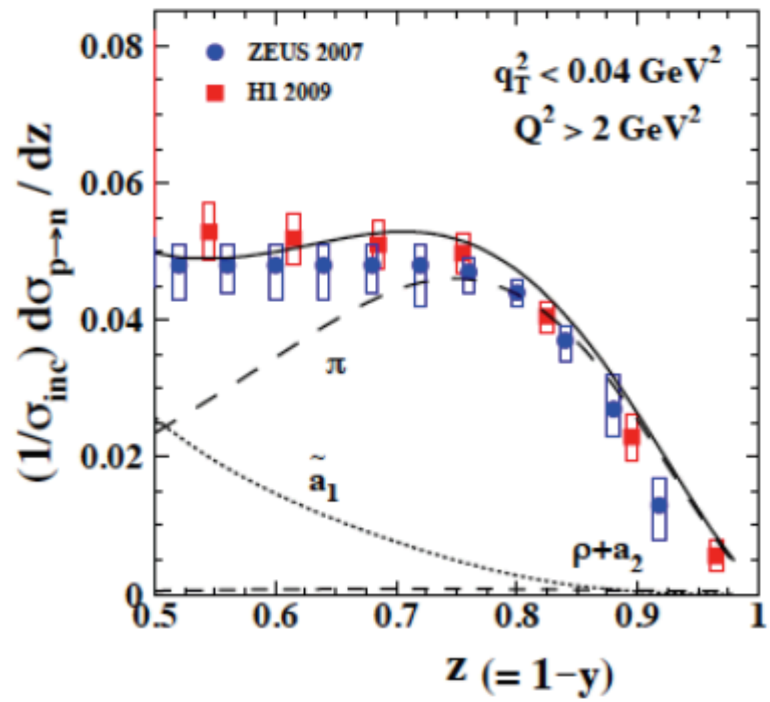
$x_L \approx 1 - y$

→ can data be described within same framework as E866 flavor asymmetry?

→ simultaneous fit never previously been performed!

Leading neutron production at HERA

- At large y non-pionic mechanisms contribute
  ($e.g.$ heavier mesons, absorption)



Kopeliovich et al., PRD **85**, *114025 (2012)*

- To reduce model dependence, fit the value of $y_{\rm cut}$
  up to which data can be described in terms of π exchange

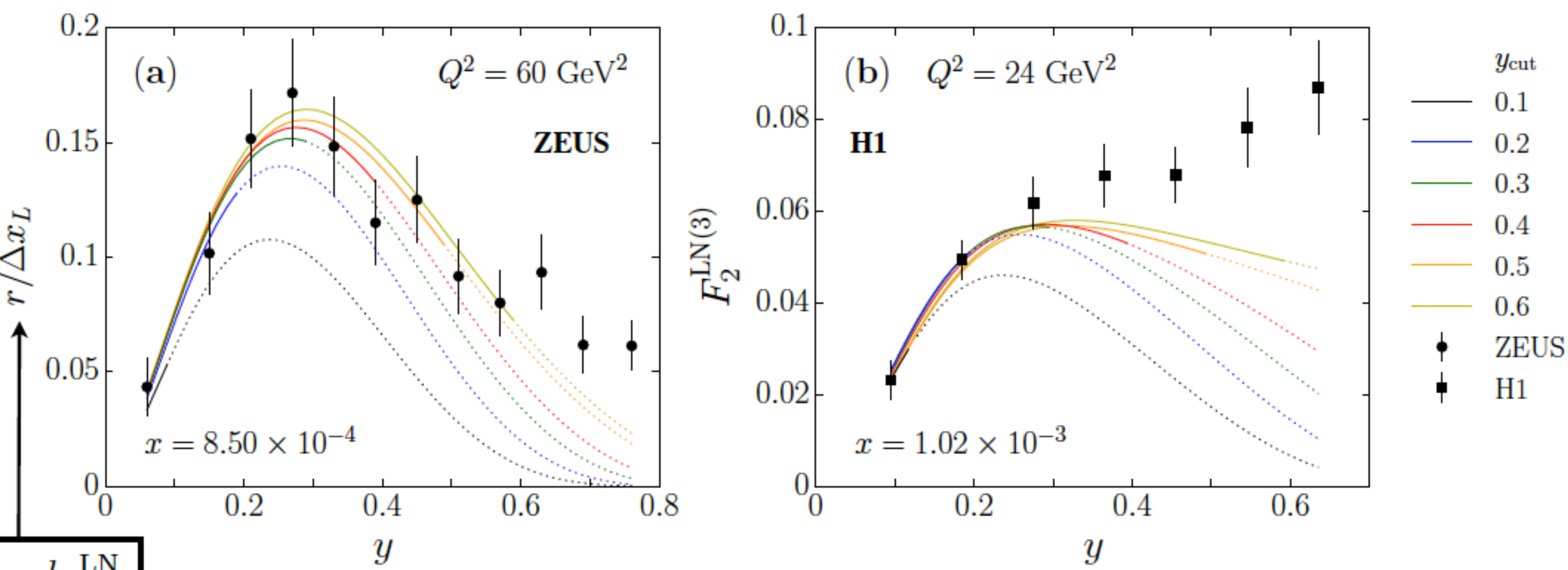
Leading neutron production at HERA

- Measured LN differential cross section (integrated over $p_\perp$)

$$\frac{d^3\sigma^{\rm LN}}{dx\, dQ^2\, dy} \sim F_2^{\rm LN(3)}(x, Q^2, y)$$

$$\boxed{2 f_N^{\rm (on)}(y)\, F_2^\pi(x/y, Q^2)}$$ for π exchange

e.g.

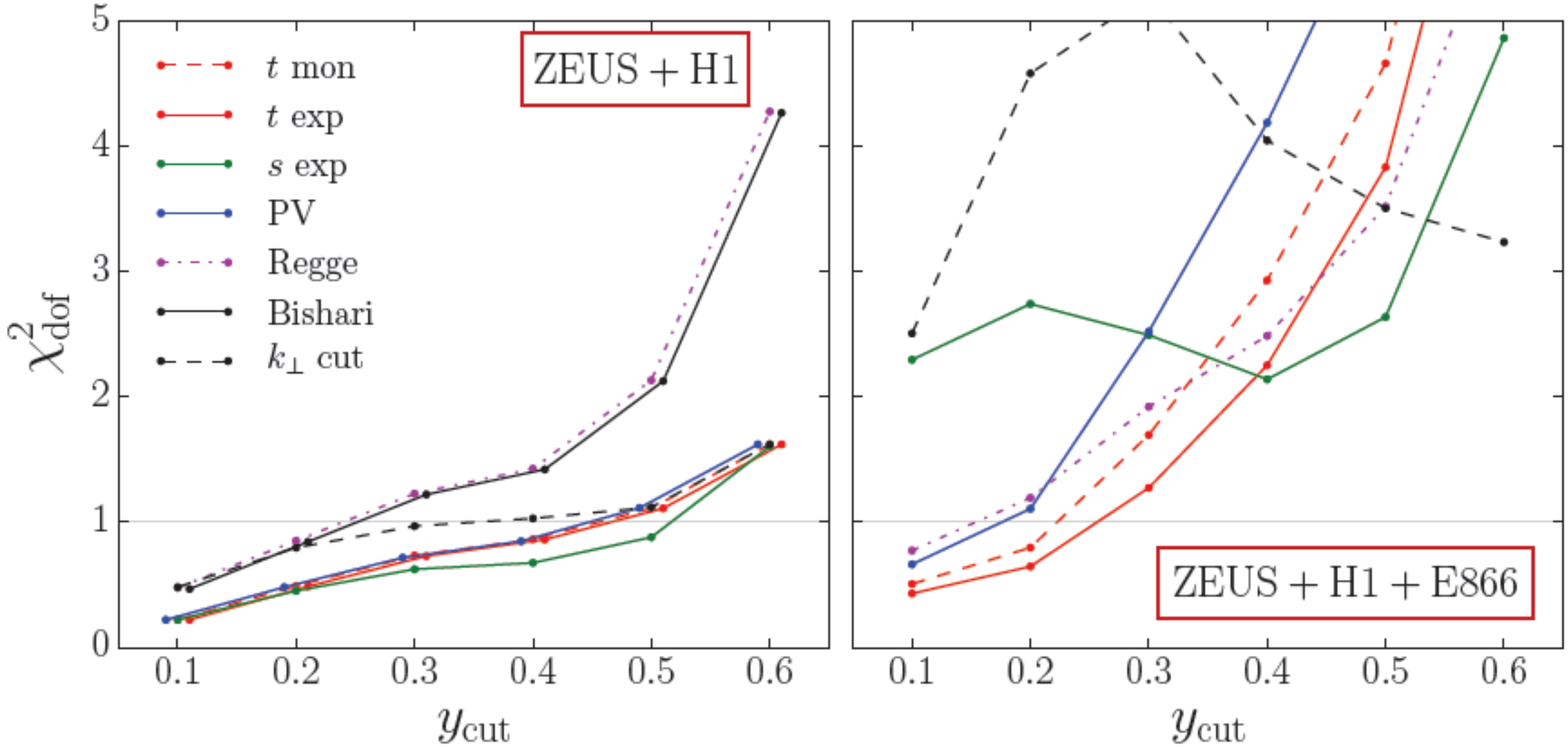


$$\boxed{r = \frac{d\sigma^{\rm LN}}{d\sigma^{\rm inc}}}$$

$\longrightarrow$ quality of fit depends on range of y fitted

Leading neutron production at HERA

- Combined fit to HERA LN and E866 Drell-Yan data

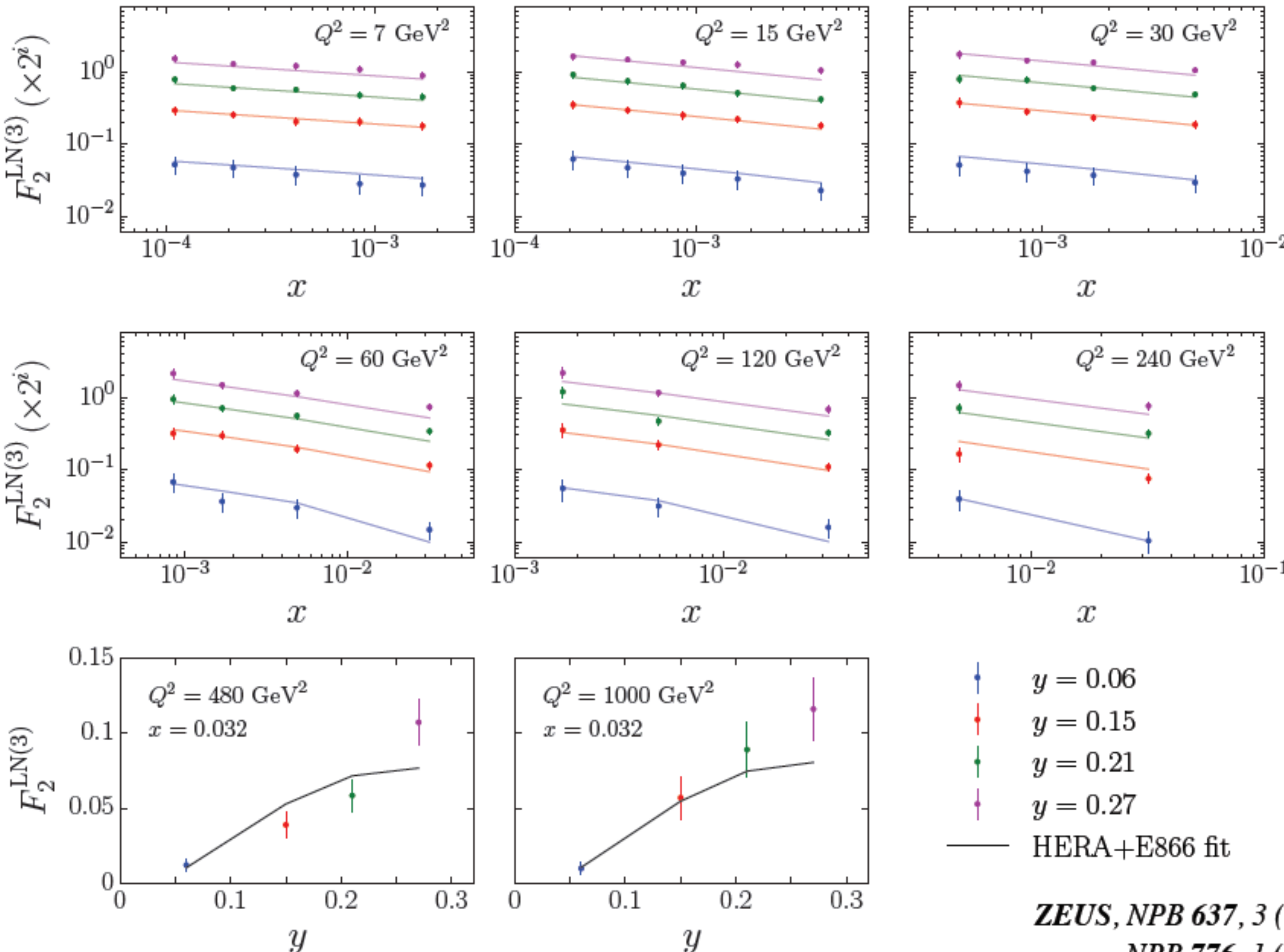


J. McKenney, N. Sato, W. Melnitchouk, C.Ji, PRD93, 054011 (2016)

→ best fits for largest number of points afforded by t-dependent exponential (and t monopole) regulators

Leading neutron production at HERA

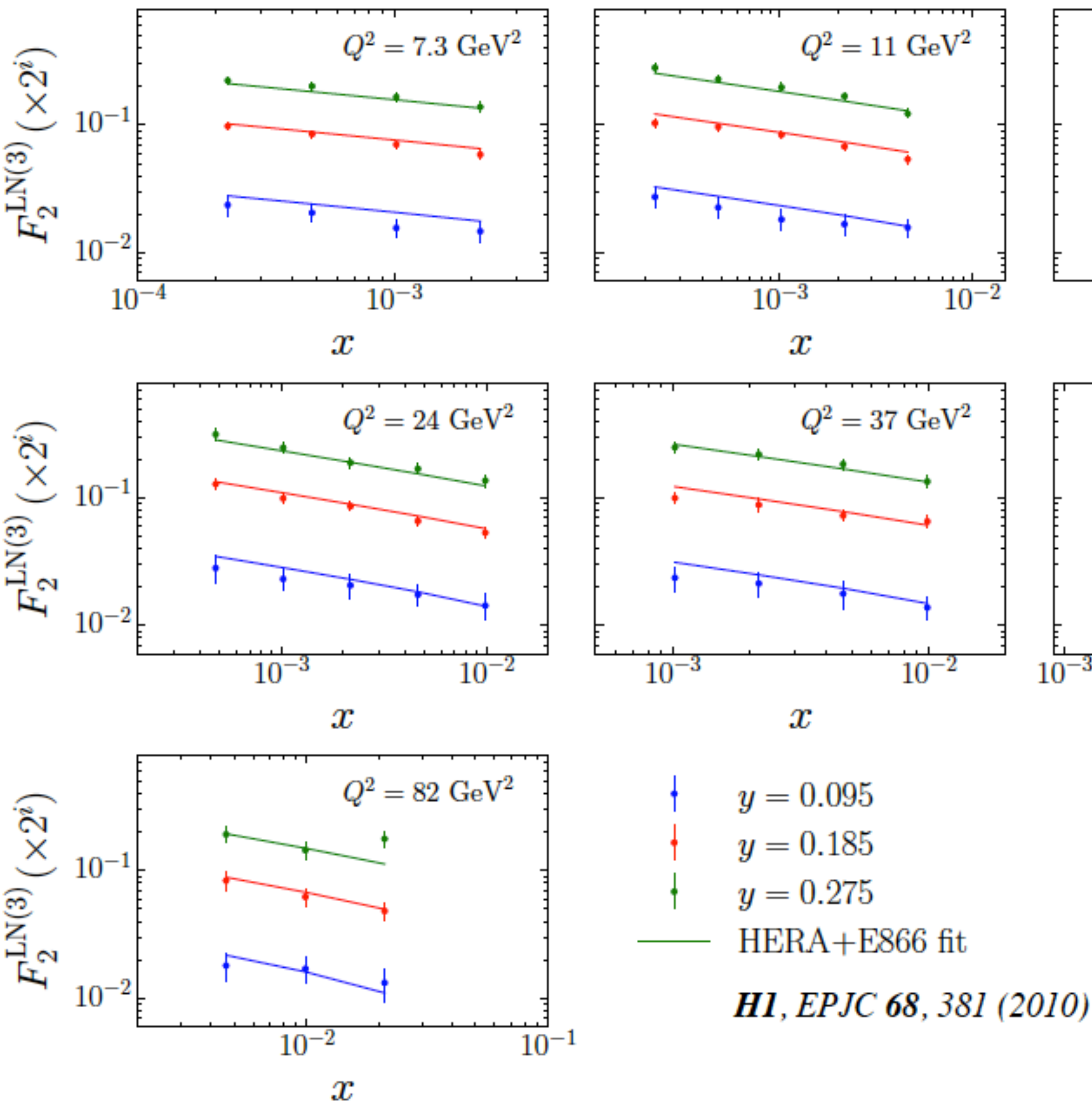
- Fit to ZEUS LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)



ZEUS, *NPB* ***637***, *3 (2002)*
NPB ***776***, *1 (2007)*

Leading neutron production at HERA

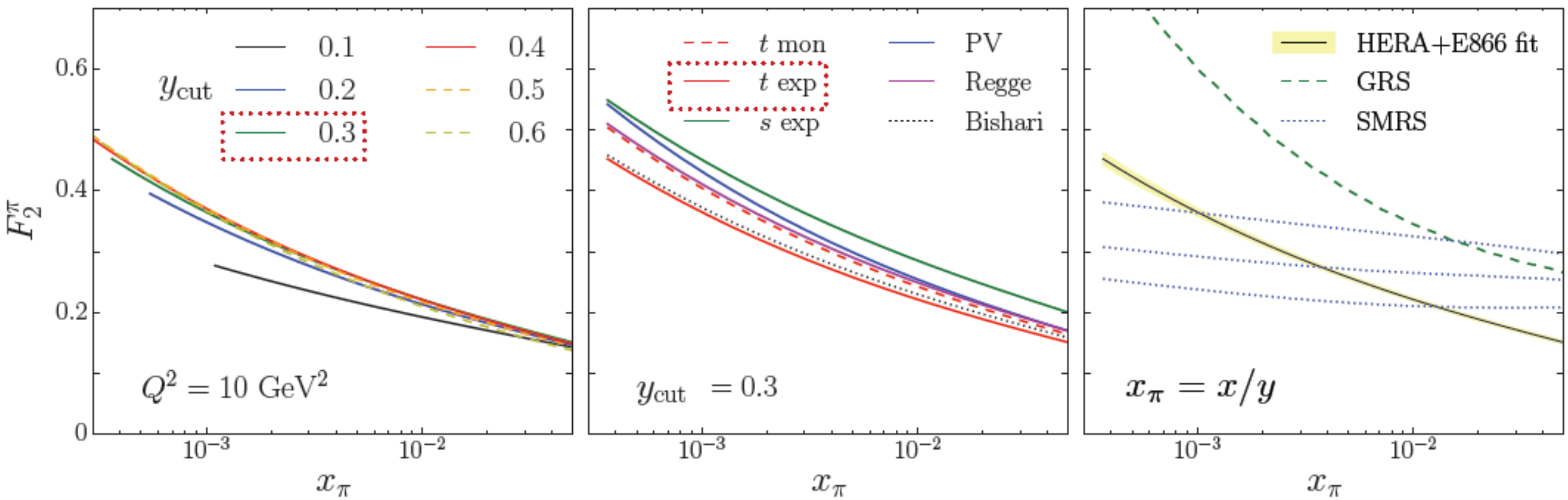
- Fit to H1 LN spectra for $y_{\mathrm{cut}} = 0.3$ (t-dependent exponential)



$\chi^2_{\mathrm{dof}} = 1.27$

for 202 (187+15) points

Extracted pion structure function



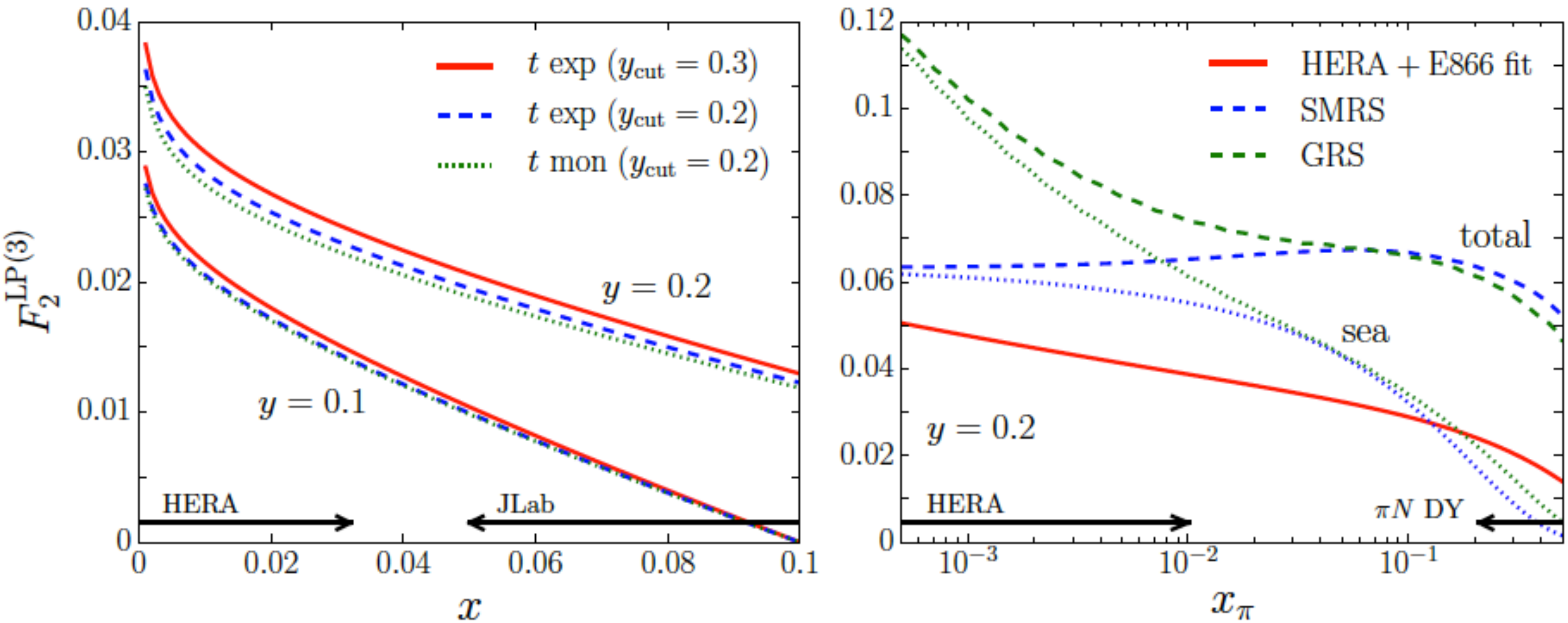
$$F_2^\pi = N\, x_\pi^a\, (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta$$

$$\eta \sim \log(\log Q^2)$$

→ stable values of F_2^π at $4 \times 10^{-4} \lesssim x_\pi \lesssim 0.03$ from combined fit

→ shape similar to GRS fit to πN Drell-Yan data (for $x_\pi \gtrsim 0.2$), but smaller magnitude

Predictions at TDIS kinematics



→ JLab TDIS experiment can fill gap in x_π coverage between HERA and πN Drell-Yan kinematics

J. McKenney, N. Sato, W. Melnitchouk, C.Ji, PRD93, 054011 (2016)

Outlook

- Combined analysis can be extended by including also πN Drell-Yan data

  $\longrightarrow$ constrain large-x_π region $(x_\pi \gtrsim 0.2)$

- Generalize parametrization by fitting individual pion valence and sea quark PDFs, rather than F_2^π

- Ultimate goal will be to use all data sensitive to pion structure (including TDIS, EIC?) to constrain pion PDFs over full range $10^{-4} \lesssim x_\pi \lesssim 1$