Next Generation Nuclear Physics with JLab12 and EIC
Florida International University
February 10, 2016

Pion structure from leading neutron electroproduction

Wally Melnitchouk

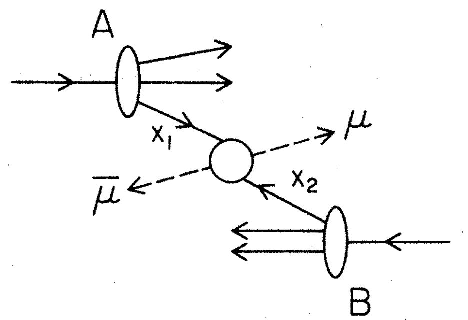
Jefferson Lab

with Chueng Ji (NCSU), *Josh McKinney* (UNC),
Nobuo Sato (JLab), *Tony Thomas* (Adelaide)

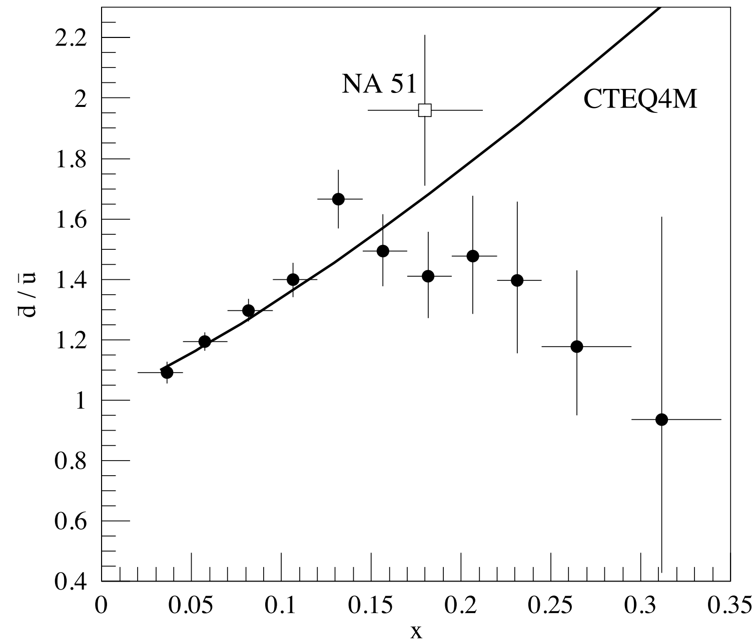
Flavor asymmetry

- 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)*

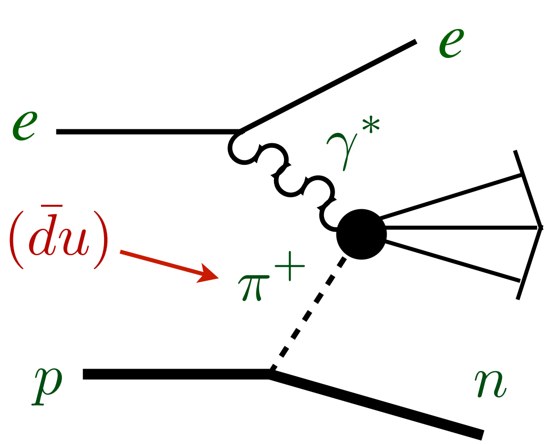
→ for $x_b \gg x_t$

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

Flavor asymmetry

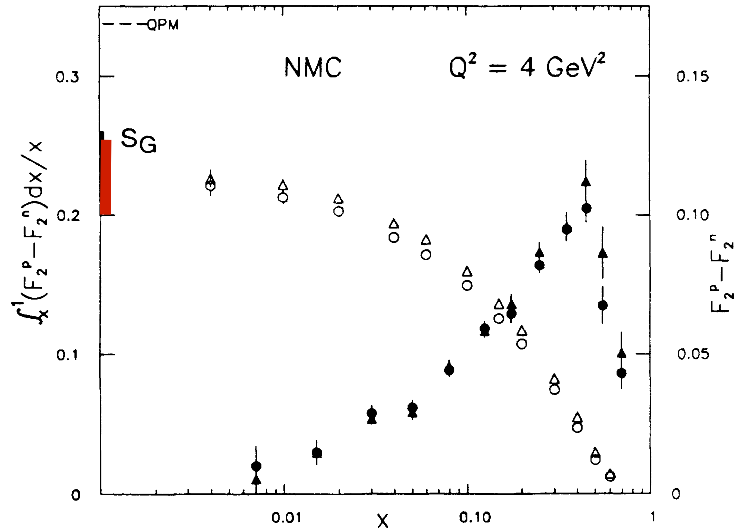
- Large flavor asymmetry in proton sea suggests important role of chiral symmetry in high-energy reactions

→ Sullivan process in DIS



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

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



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

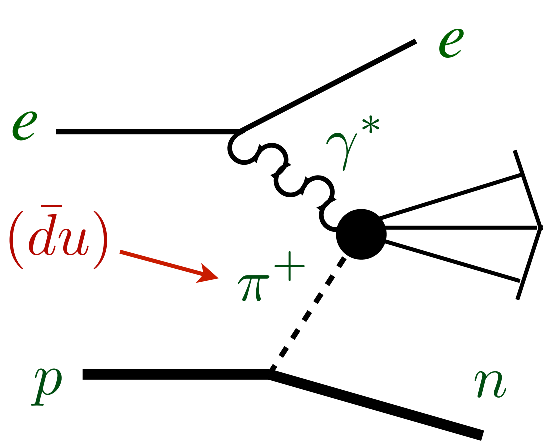
$$= 0.235(26)$$

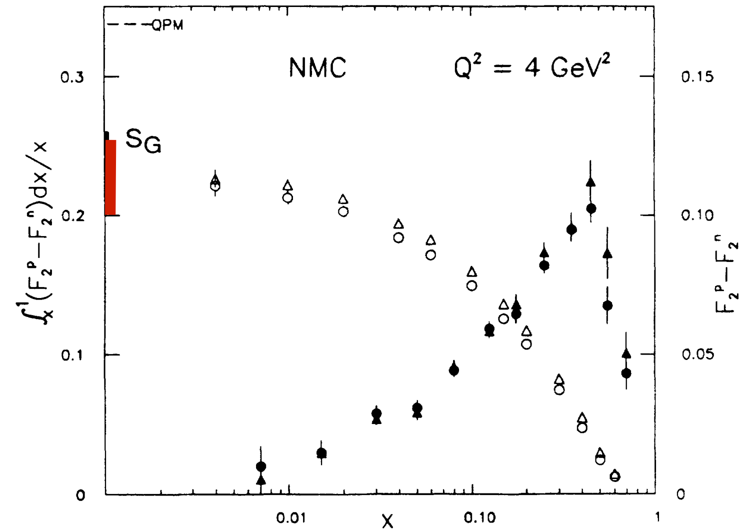
NMC, PRD ***50****, 1 (1994)*

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

- Chiral expansion of moments of $f_\pi(y)$

→ model-independent leading nonanalytic (LNA) behavior

$$\langle x^0 \rangle_{\bar{d}-\bar{u}} \equiv \int_0^1 dx\,(\bar{d}-\bar{u}) = \frac{2}{3}\int_0^1 dy\, f_\pi(y)$$
$$= \frac{2g_A^2}{(4\pi f_\pi)^2} m_\pi^2 \log(m_\pi^2/\mu^2) \;+\; \text{terms analytic in } m_\pi^2$$

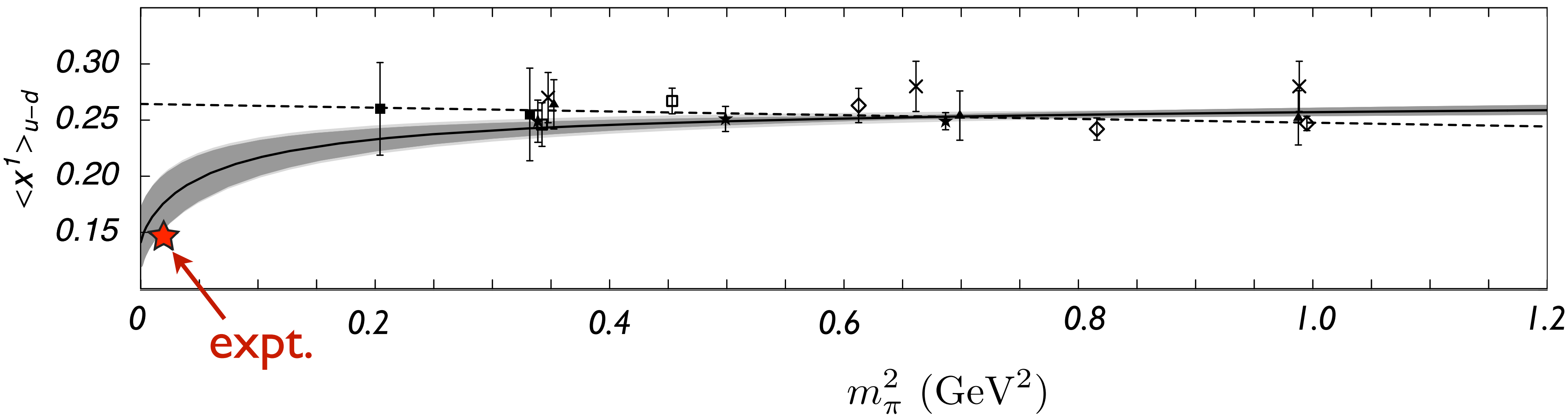
Thomas, WM, Steffens
PRL ***85****, 2892 (2000)*

→ can *only* be generated by pion cloud

→ nonzero π cloud contribution *predicted* by QCD!

Connection with QCD

- Nonanalytic behavior vital for chiral extrapolation of lattice data



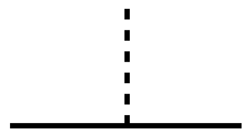
Detmold, WM, Negele, Renner, Thomas
*PRL **87**, 172001 (2001)*

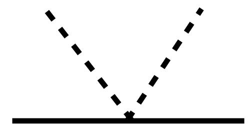
→ allows lattice QCD calculations (at unphysical m_π) to be reconciled with experiment

Chiral effective theory

- Effective low-energy theory of pions & nucleons

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





$g_A = 1.267$

$f_\pi = 93$ MeV

→ lowest order approximation of chiral perturbation theory Lagrangian

→ *cf.* pseudoscalar (PS) Lagrangian

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

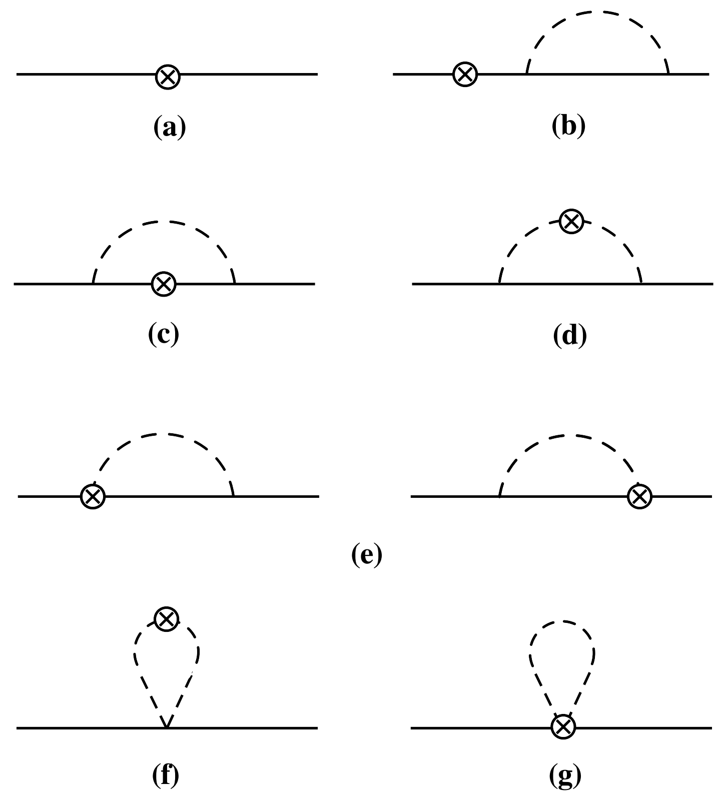
Weinberg, PRL ***18****, 88 (1967)*

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

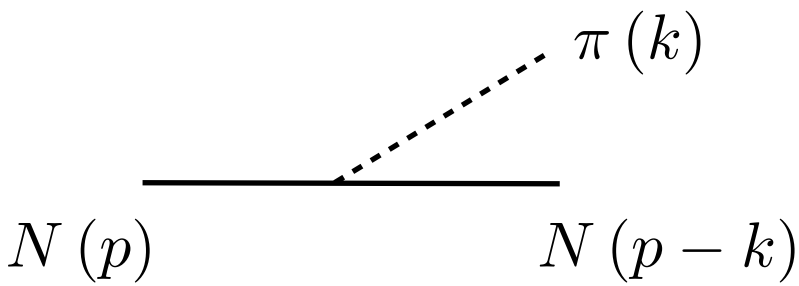
→ $e.g.$ for N rainbow contribution,

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

*C. Ji, WM, Thomas, PRD **88**, 076005 (2013)*

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:

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

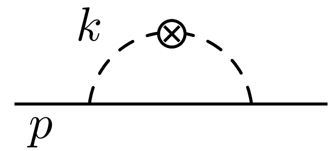
where

$$f_\pi(y) = f^{(\text{on})}(y) + f^{(\delta)}(y)$$

$$f_N(y) = f^{(\text{on})}(y) + f^{(\text{off})}(y) - f^{(\delta)}(y)$$

$$f_{\text{KR}}(y) = f^{(\text{off})}(y) - 2f^{(\delta)}(y)$$

$$f_{\text{tad}}(y) = -f_{\text{bub}}(y) \ = \ 2f^{(\text{tad})}(y)$$



has on-shell $(y > 0)$ and $\delta(y)$ contributions!

Pion splitting functions

- Summary of splitting functions:

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

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

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

on-shell contribution equivalent to PS ("Sullivan")

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

N rainbow & KR contain new off-shell contribution

Pion splitting functions

- Summary of splitting functions:

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

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

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

KR needed for gauge invariance
$$(1 - Z_1^\pi) + (1 - Z_1^{\text{KR}}) = (1 - Z_1^N)$$

singular $y = 0$ contribution only in PV theory

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

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

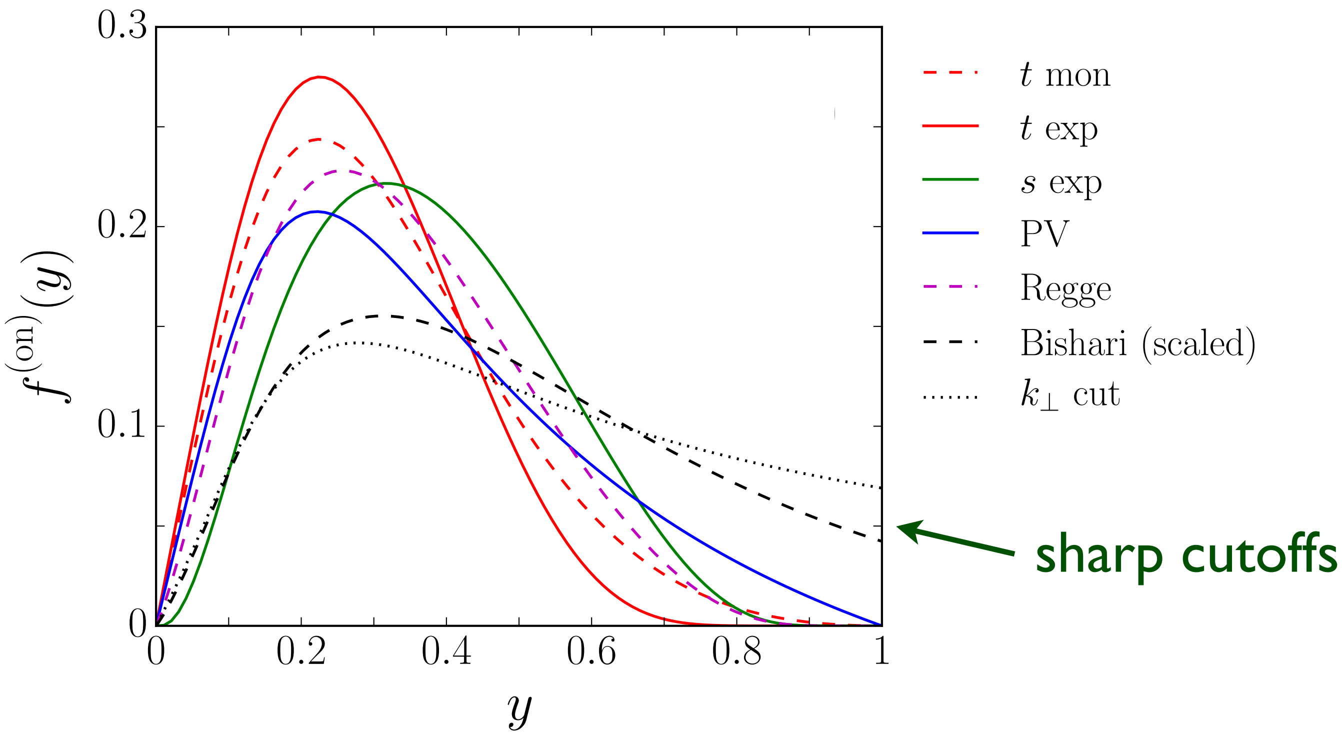
  $\longrightarrow$ freedom in choosing regularization prescription
  (long-distance physics independent of choice!)

$\mathcal{F} = \Theta(\Lambda^2 - k_\perp^2)$	$k_\perp$ cutoff
$\mathcal{F} = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$	monopole in $t \equiv k^2 = -\frac{k_\perp^2 + y^2 M^2}{1-y}$
$\mathcal{F} = \exp\left[(t - m_\pi^2)/\Lambda^2\right]$	exponential in t
$\mathcal{F} = \exp\left[(M^2 - s)/\Lambda^2\right]$	exponential in $s = \frac{k_\perp^2 + m_\pi^2}{y} + \frac{k_\perp^2 + M^2}{1-y}$
$\mathcal{F} = \left[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$	Pauli-Villars
$\mathcal{F} = y^{-\alpha_\pi(t)} \exp\left[(t - m_\pi^2)/\Lambda^2\right]$	Regge

UV regularization

- Detailed shape of splitting function depends on regularization, but common general features

e.g. on-shell function



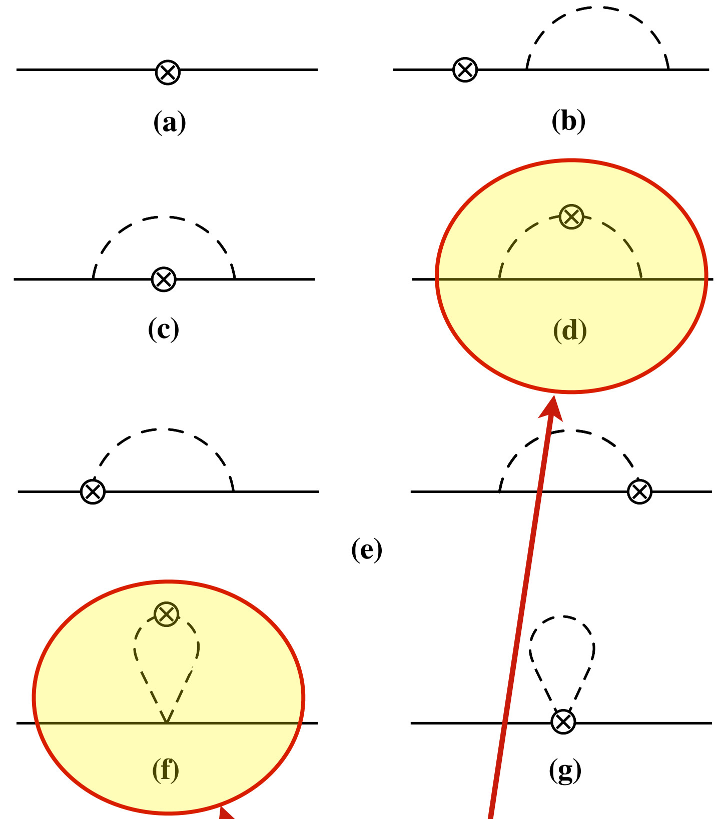
- If "bare" nucleon has symmetric sea, then only pion coupling diagrams contribute

$$\bar{d} - \bar{u} = [f_{\pi^+} + f_{\rm bub}] \otimes \bar{q}_\pi$$

Flavor asymmetry

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

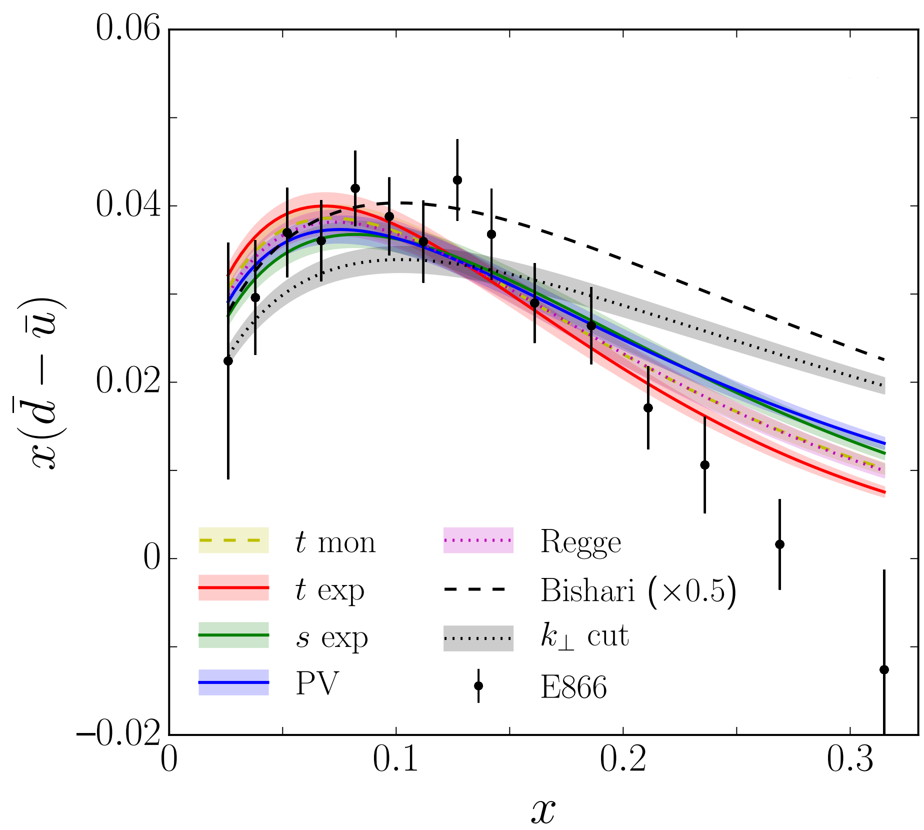
→ $e.g.$ for N rainbow contribution,

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

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

Flavor asymmetry

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



average pion "multiplicity"

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

$$\sim\ 0.25 - 0.3$$

→ 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

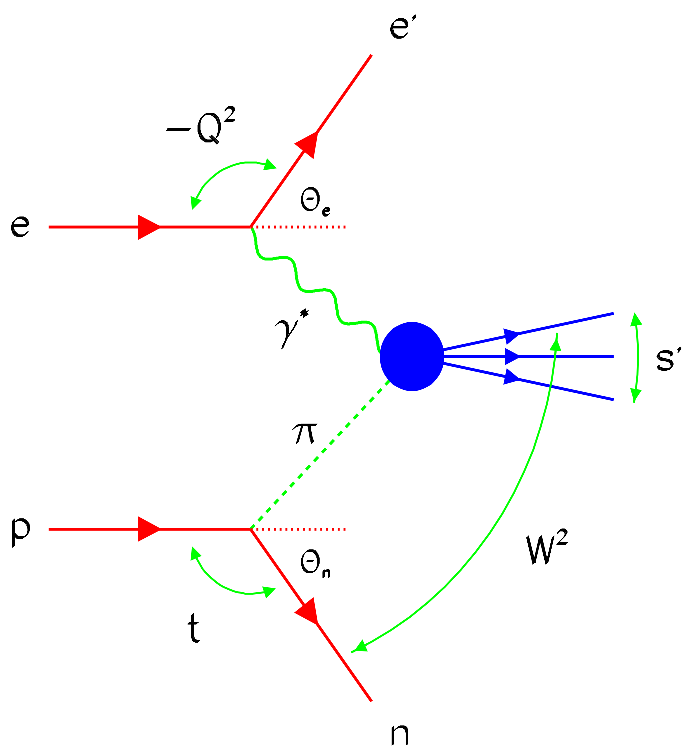
- Is pion cloud the only explanation for the asymmetry?

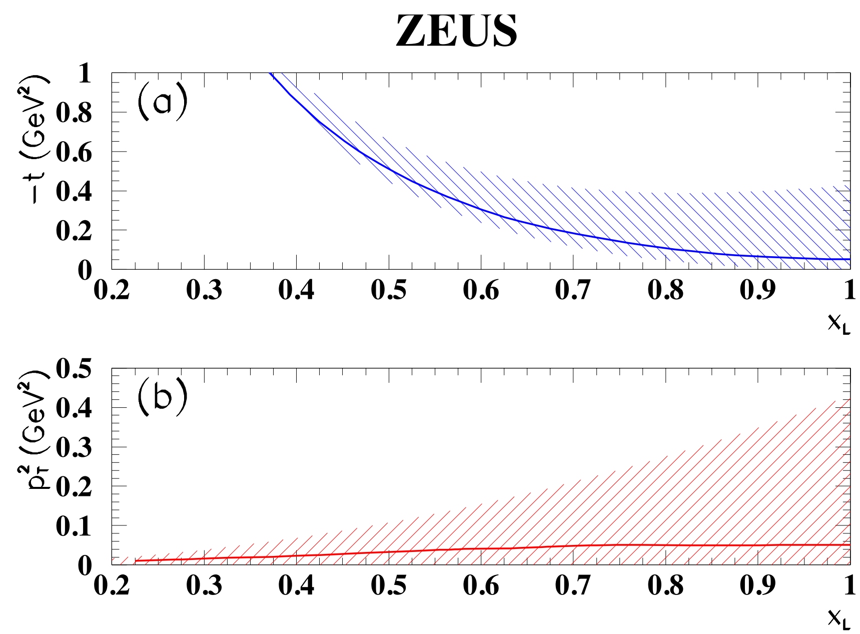
  → are there other data that can discriminate between different mechanisms?

  → 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!

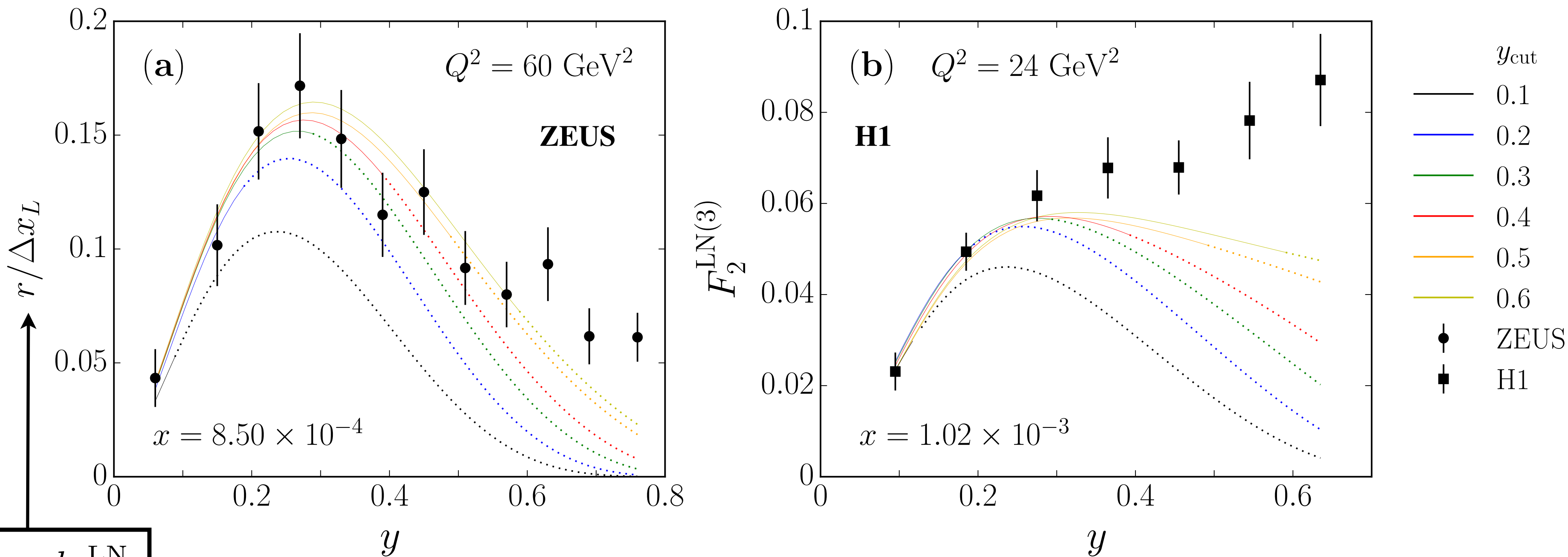
Leading neutron production at HERA

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

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

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

e.g.

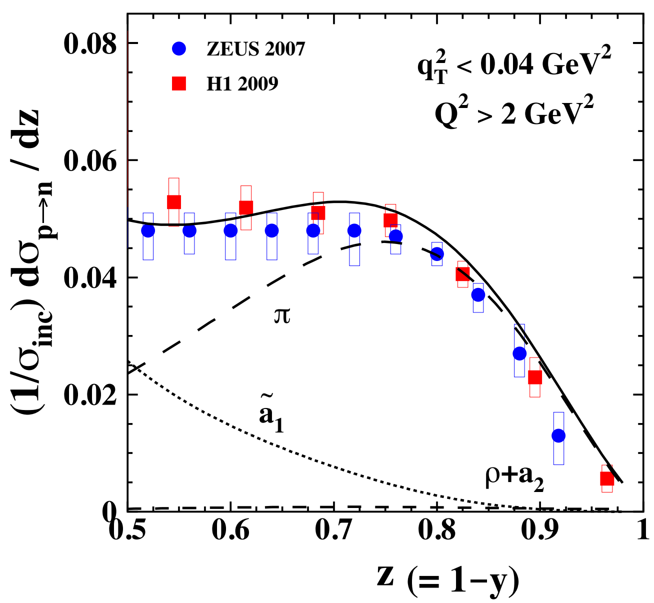


$$r = \frac{d\sigma^{\rm LN}}{d\sigma^{\rm inc}}$$

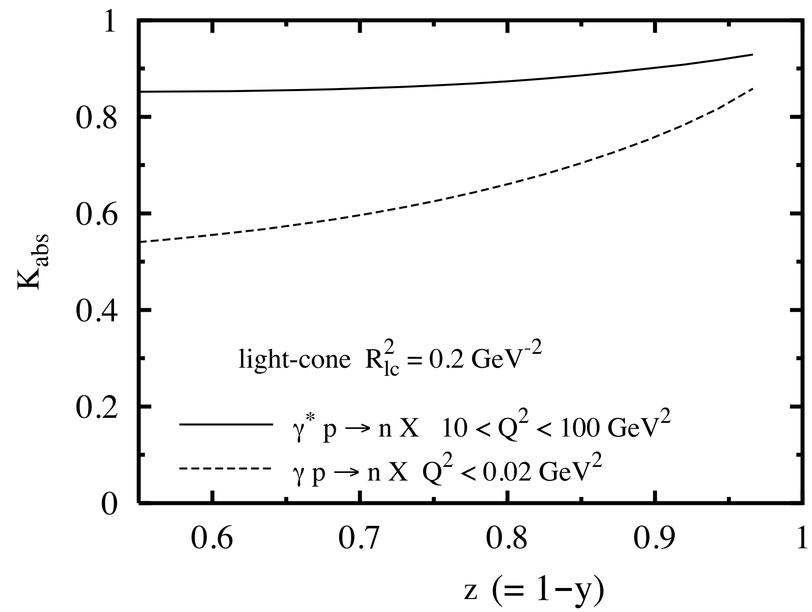
→ quality of fit depends on range of y fitted

Leading neutron production at HERA

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



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

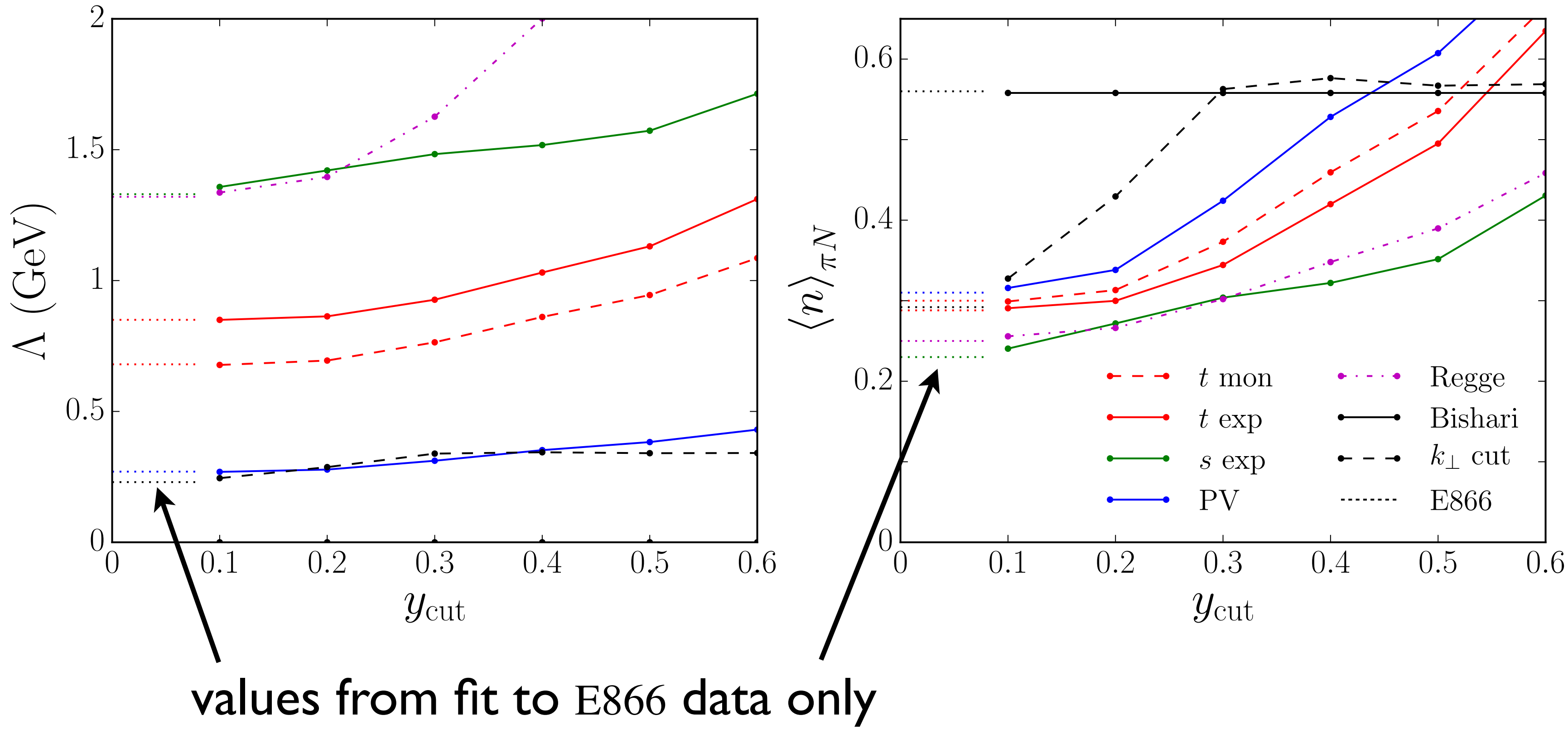


*D'Alesio, Pirner, EPJA **7**, 109 (2000)*

- 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

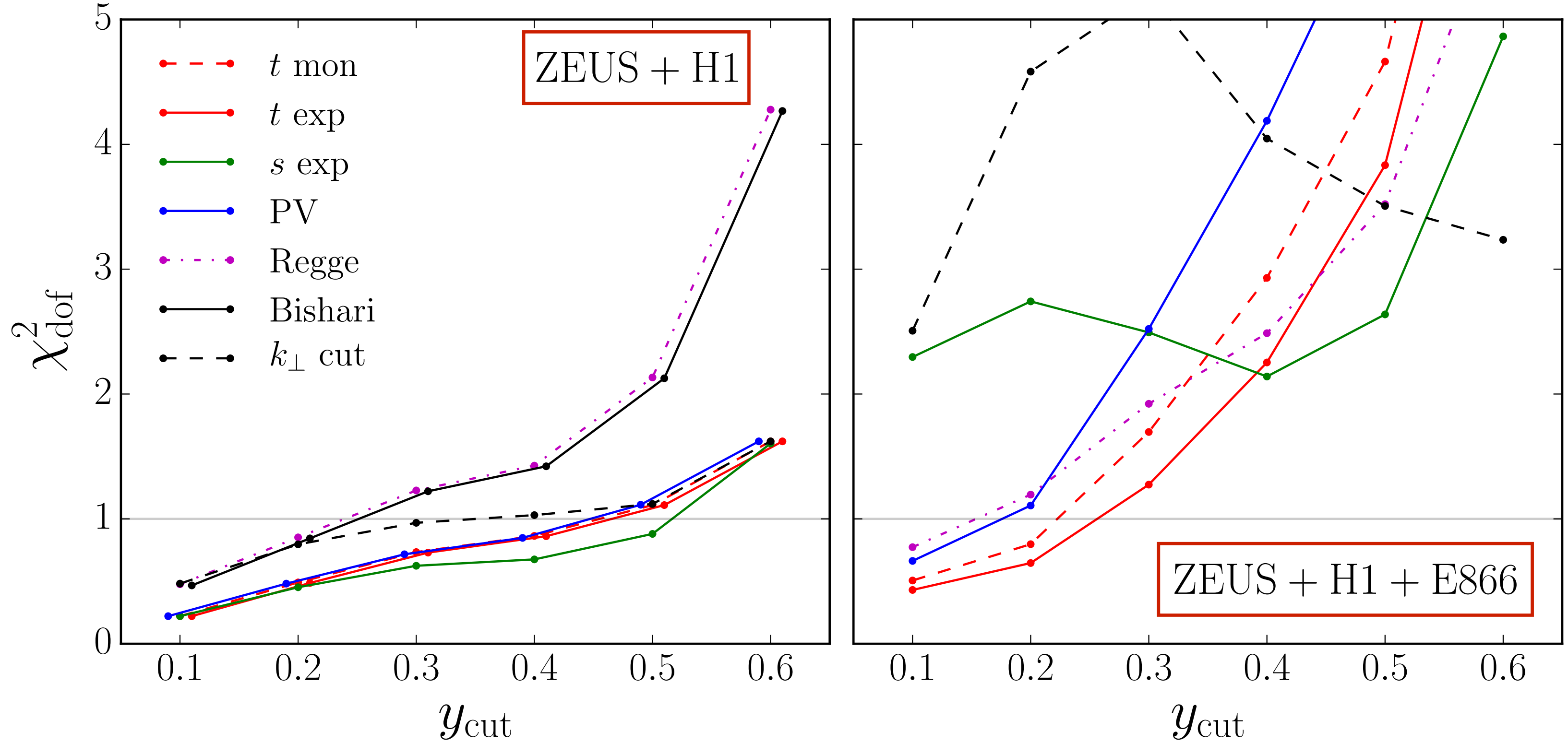
- Fit requires higher momentum pions with increasing y_{cut}



→ larger values of y_{cut} more in conflict with E866 data

Leading neutron production at HERA

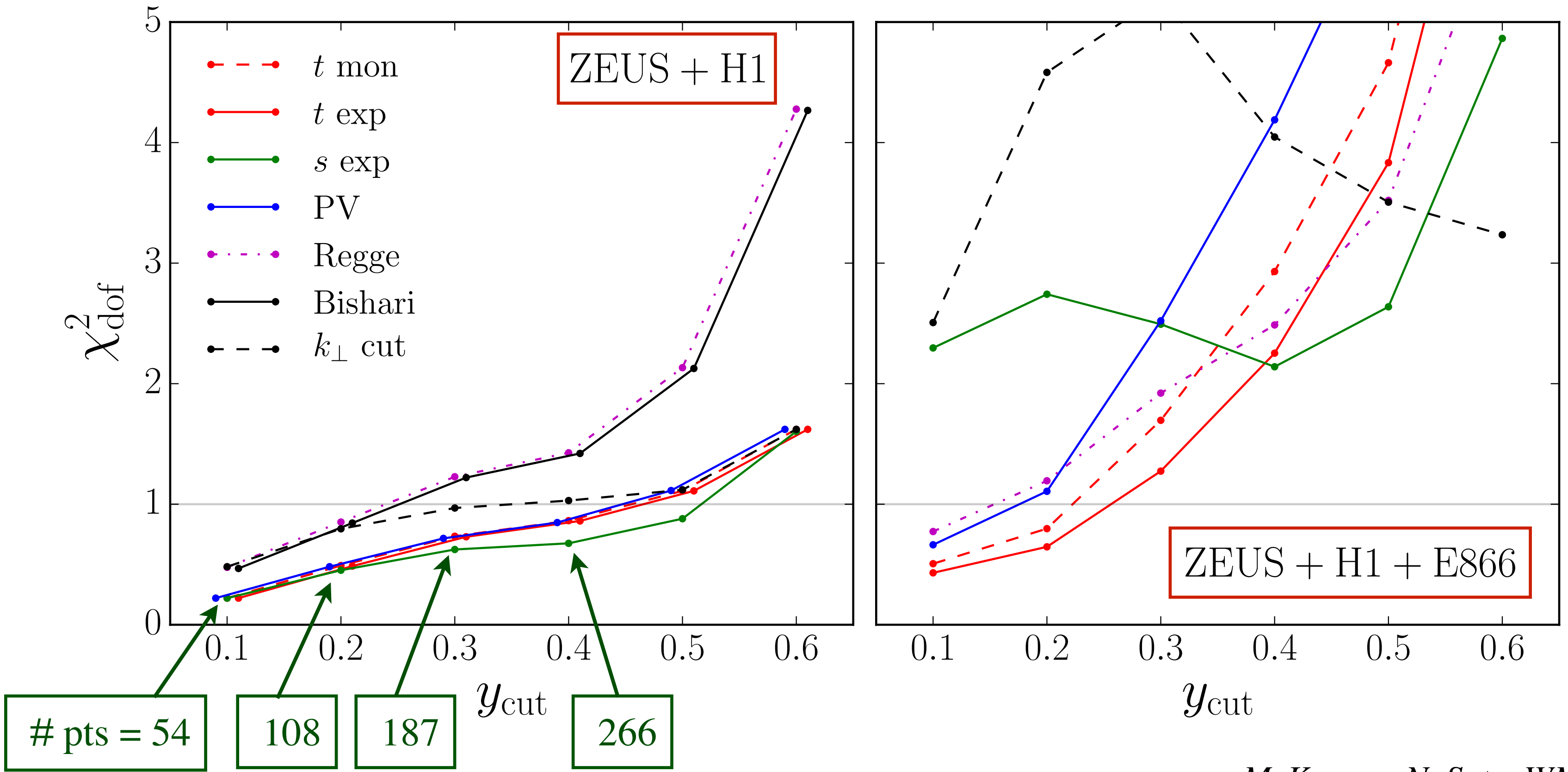
- Combined fit to HERA LN and E866 Drell-Yan data



McKenney, N. Sato, WM, C. Ji
PRD (2016), arXiv:1512.04459

Leading neutron production at HERA

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

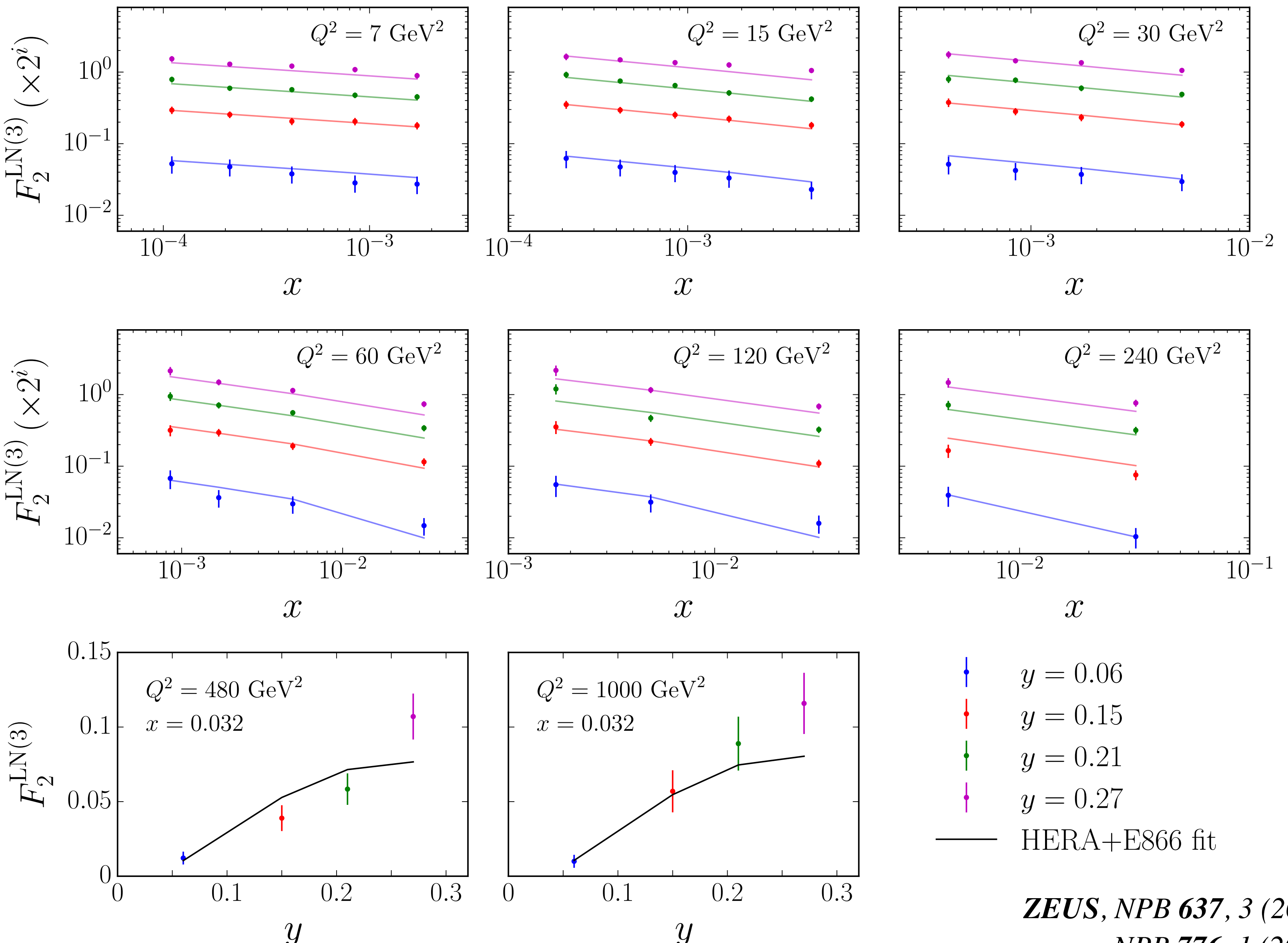


McKenney, N. Sato, WM, C. Ji
PRD (2016), arXiv:1512.04459

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

Leading neutron production at HERA

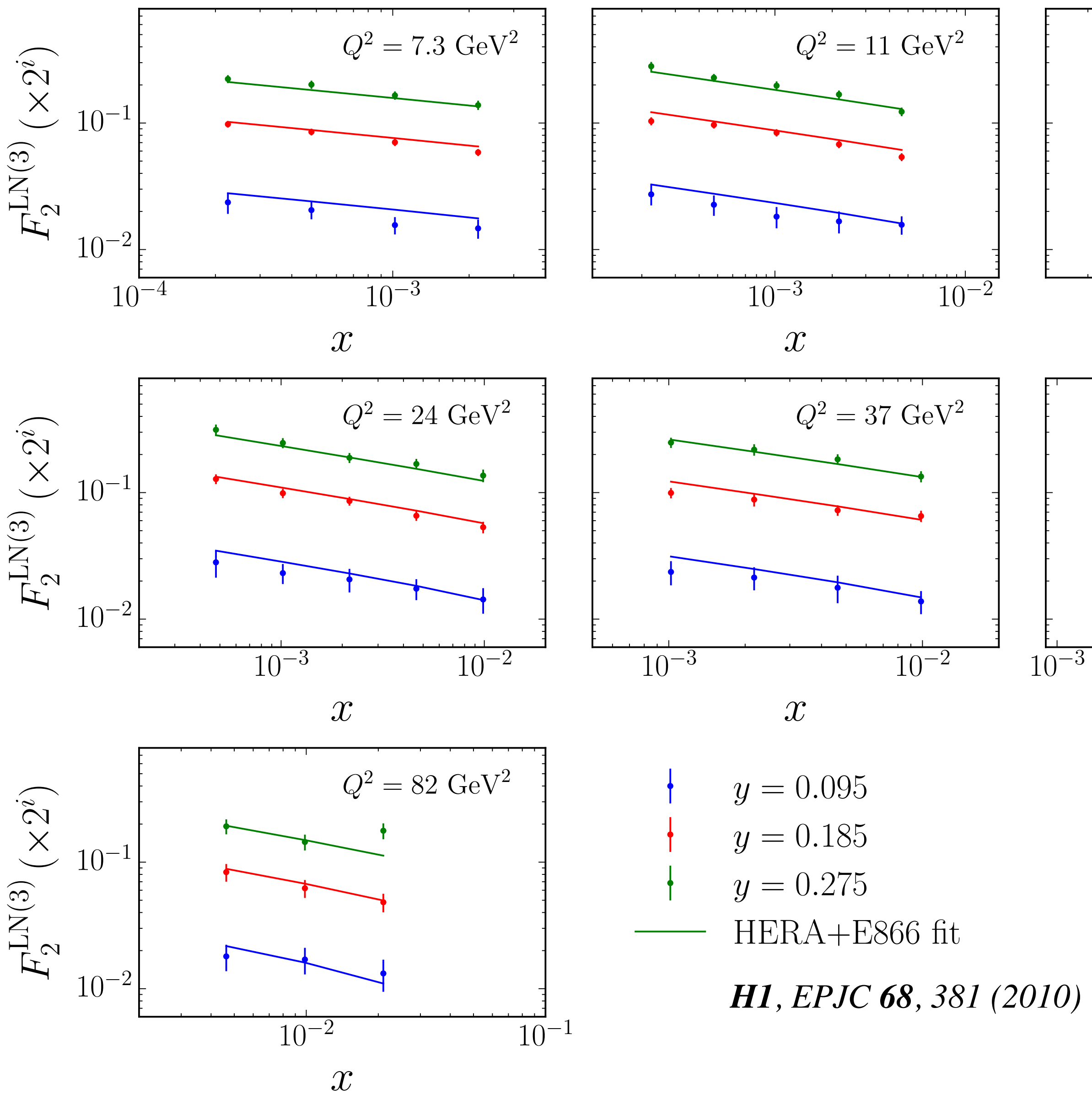
- Fit to ZEUS LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)



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

Leading neutron production at HERA

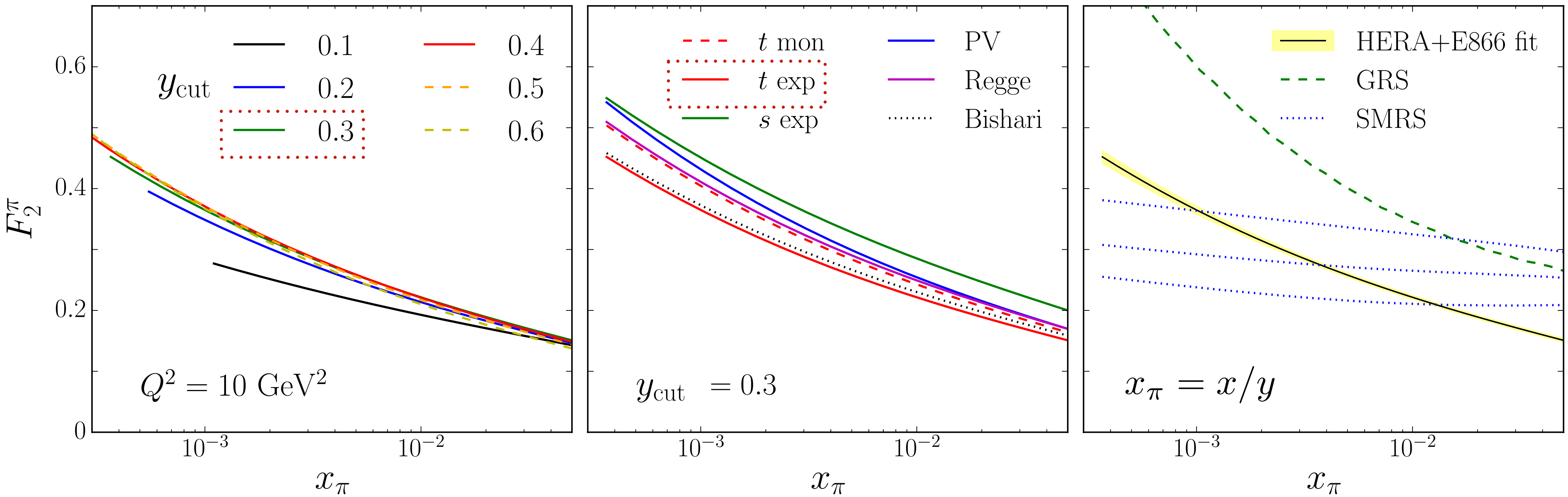
- Fit to H1 LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)



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

for 202 (187+15) points

Extracted pion structure function



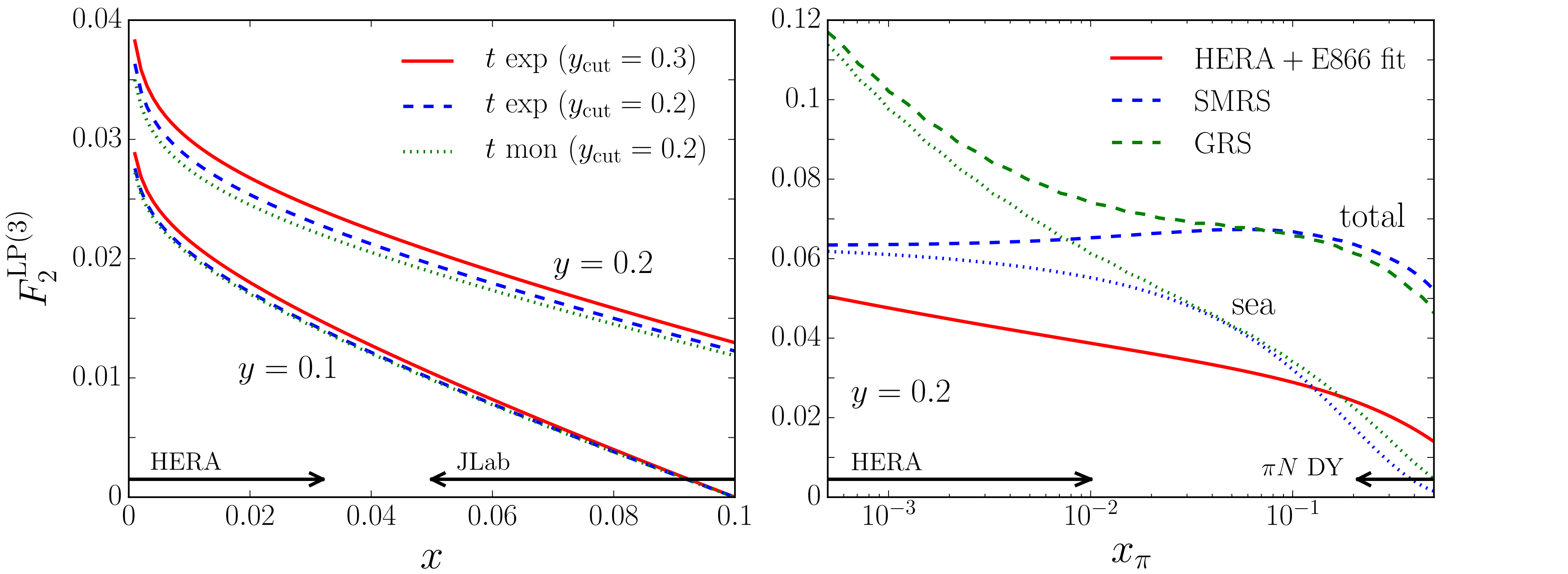
$$F_2^\pi = N\, x_\pi^a\, (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta$$
$$\eta \sim \log(\log Q^2)$$

McKenney, N. Sato, WM, C. Ji
PRD (2016), arXiv:1512.04459

→ stable values of F_2^π at $4\times10^{-4} \lesssim x_\pi \lesssim 0.03$ 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



McKenney, N. Sato, WM, C. Ji
PRD (2016), arXiv:1512.04459

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

Outlook

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

  → 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 $10^{-4} \lesssim x_\pi \lesssim 1$