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Pion structure from leading neutron electroproduction

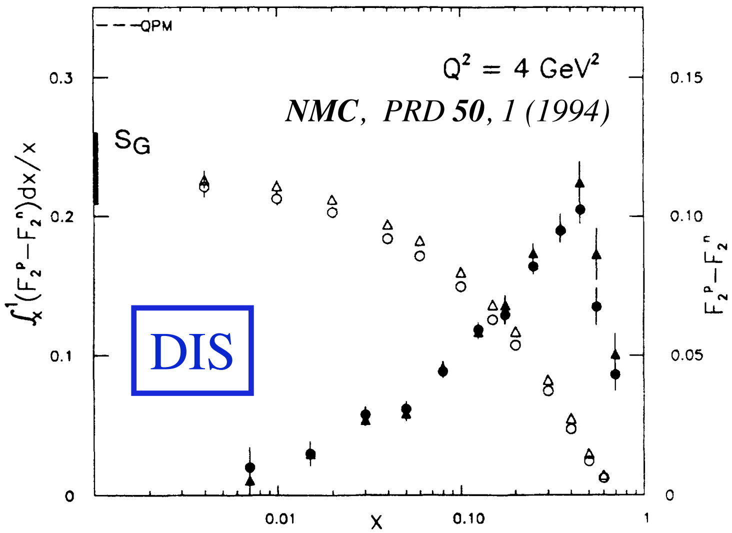
Wally Melnitchouk

Jefferson Lab

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

SU(2) flavor asymmetry

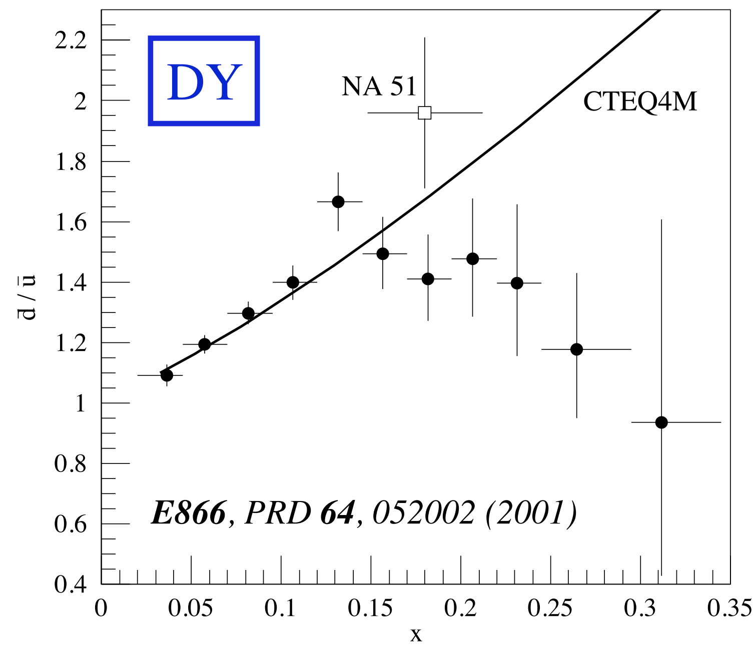
- One of the seminal discoveries of last 25 years has been the SU(2) flavor asymmetry in the proton sea, $\bar{d} \neq \bar{u}$



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

$$= 0.235(26)$$

violation of Gottfried sum rule



$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right) \qquad x_b \gg x_t$$

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

SU(2) flavor asymmetry

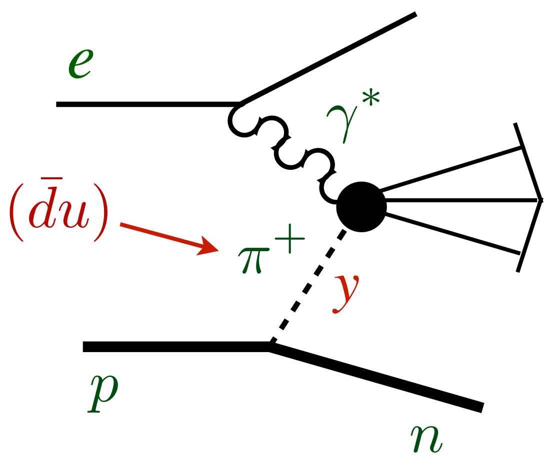
- One of the seminal discoveries of last 25 years has been the SU(2) flavor asymmetry in the proton sea, $\bar{d} \neq \bar{u}$

  → paradigm shift – nucleon *not* simply 3 valence quarks + homogenous $\bar{q}q$ sea!

  → vital role played by nonperturbative dynamics, *e.g.* chiral symmetry breaking & nucleon's pion cloud

  → asymmetry actually predicted a decade earlier from "Sullivan" process

*A.W. Thomas, PLB **126**, 97 (1983)*



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

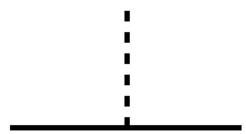
pion momentum distribution in nucleon, or $p \to \pi^+ n$ "splitting function"

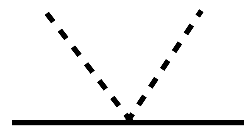
Chiral effective theory

- Splitting function can be computed in chiral effective theory of QCD ($e.g.$ chiral perturbation theory)

- At lowest order, effective (low-energy) πN Lagrangian

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





$g_A = 1.267$

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

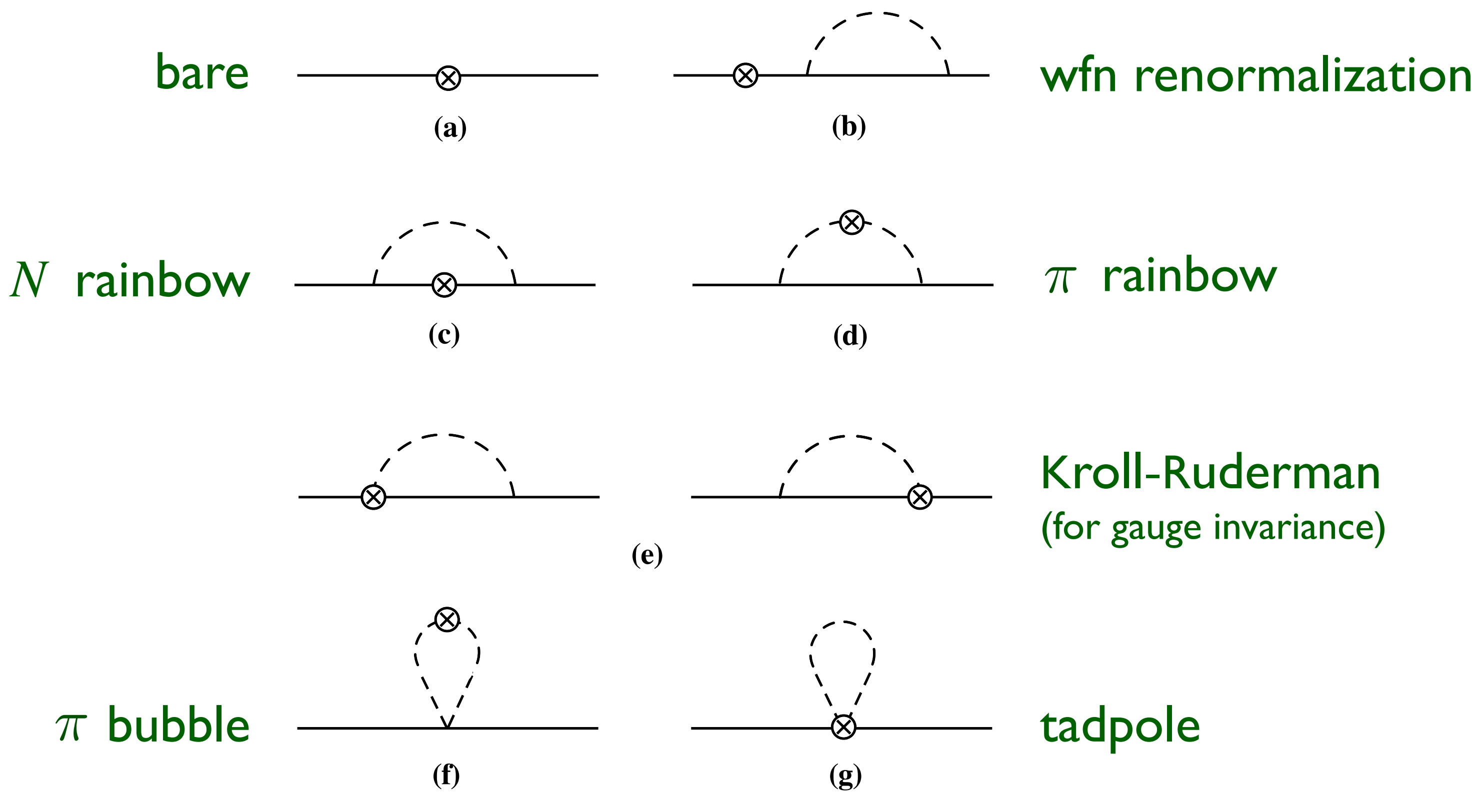
$$= -g_{\pi NN}\,\bar{\psi}_N\, i\gamma_5 \vec{\tau}\cdot\vec{\pi}\,\psi_N \ + \ \sigma NN \text{ term } \ + \ \text{higher order}$$

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

→ pseudoscalar interaction often used for simplicity – results generally different from pseudovector theory

Chiral effective theory

- Coupling of e.m. current to nucleon dressed by pions



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

Chiral effective theory

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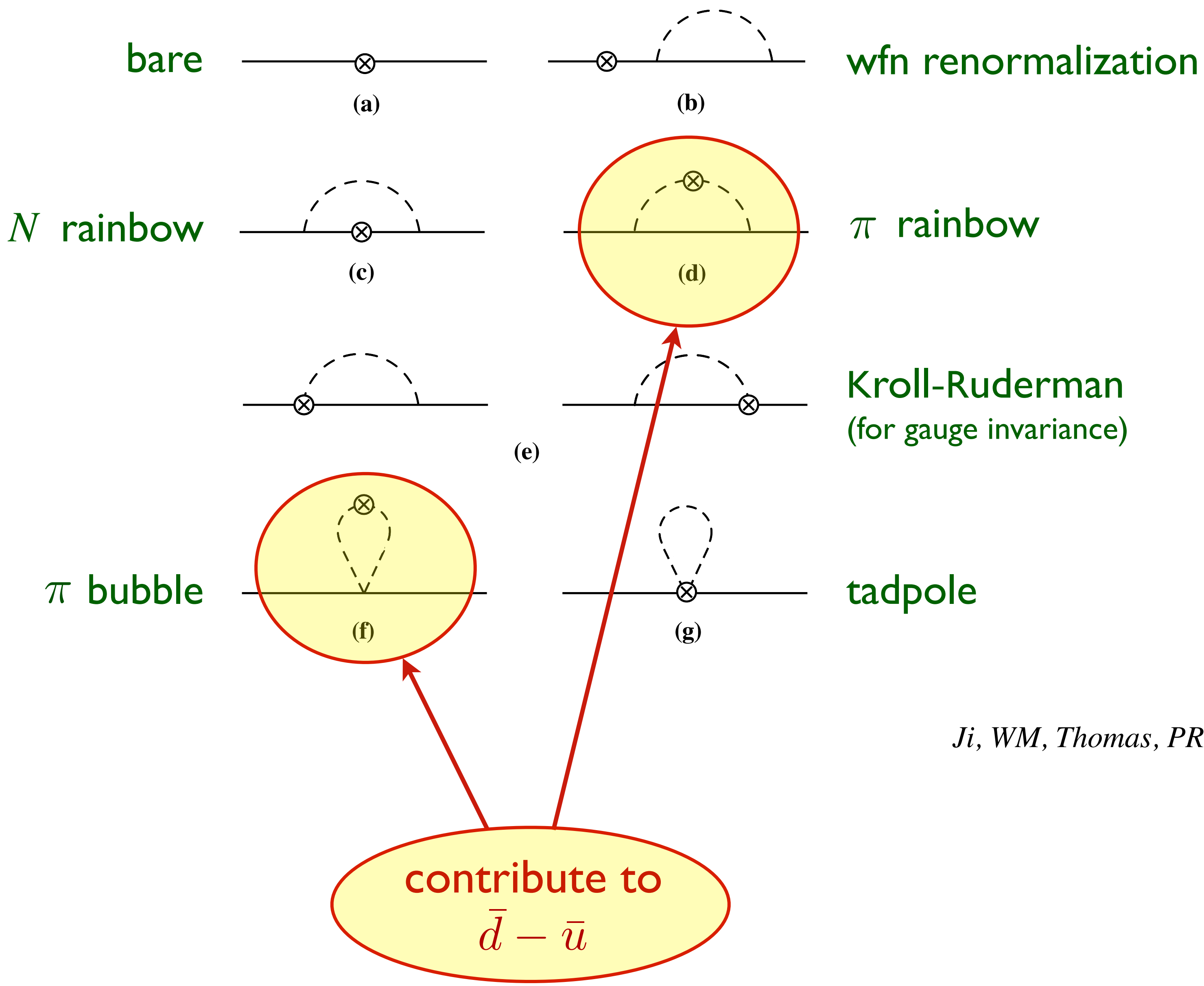
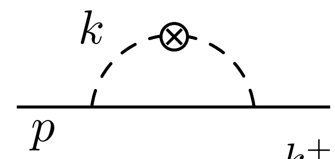


Ji, WM, Thomas, PRD ***88****, 076005 (2013)*

Pion splitting functions

- Splitting function for pion rainbow diagram has on-shell and δ-function contributions



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

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

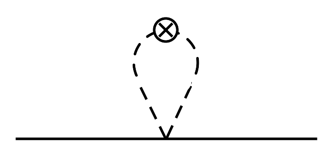
equivalent in PV & PS theories

$$f^{(\delta)}(y) = \frac{g_A^2}{4(4\pi f_\pi)^2} \int dk_\perp^2 \, \log\left(\frac{k_\perp^2 + m_\pi^2}{\mu^2}\right) \delta(y) \, \mathcal{F}^2$$

singular $y = 0$ term only in PV theory

- Bubble diagram contributes only at $y = 0$ (hence $x = 0$)

$$f^{(\mathrm{bub})}(y) = \frac{8}{g_A^2} \, f^{(\delta)}(y)$$



Salamu, Ji, WM, Wang
PRL ***114****, 122001 (2015)*

Pion splitting functions

- Infrared behavior is model independent

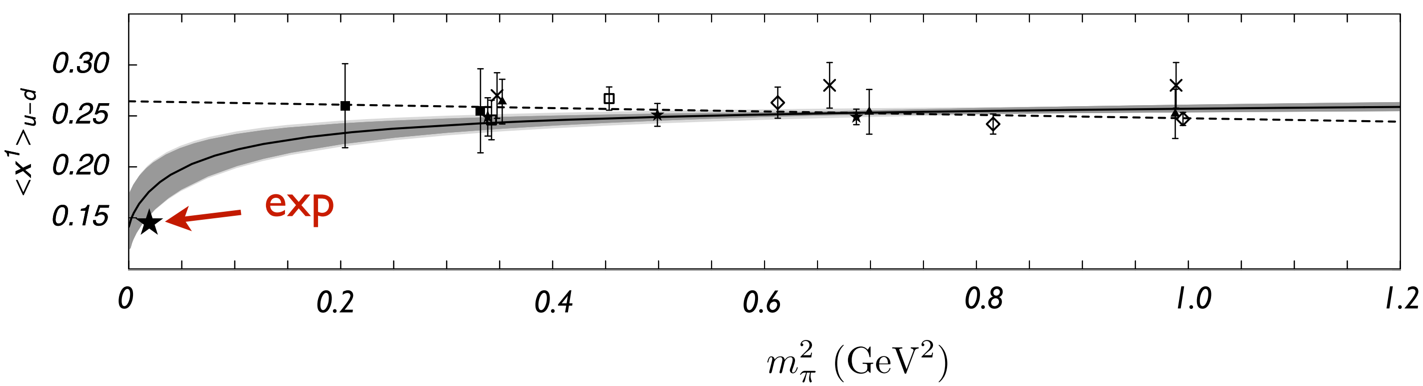
→ leading nonanalytic (LNA) structure of moments

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

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

→ can only be generated by pion loops – nonzero π cloud contribution predicted by QCD!

→ vital *e.g.* for chiral extrapolation of lattice data



Detmold et al.
PRL ***87****, 172001 (2001)*

Pion splitting functions

- Ultraviolet-divergent integrals for point-like particles
- Finite size of nucleon provides natural scale to regularize integrals, but does not prescribe form of regularization

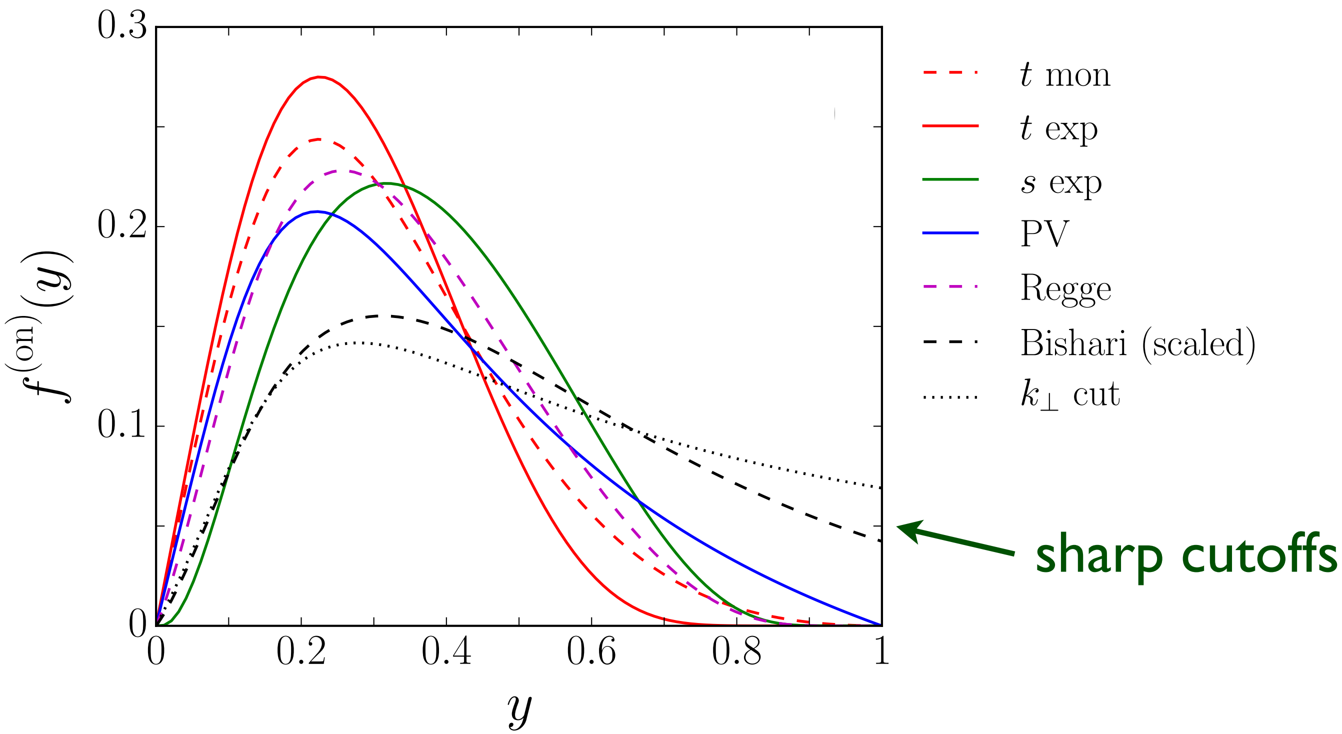
$\longrightarrow$ freedom in choosing regularization prescription

$\mathcal{F} = \Theta(\Lambda^2 - k_\perp^2)$	$k_\perp$ 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
$\mathcal{F} = y^{-\alpha_\pi(t)}$	Bishari

Pion splitting functions

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

e.g. on-shell function

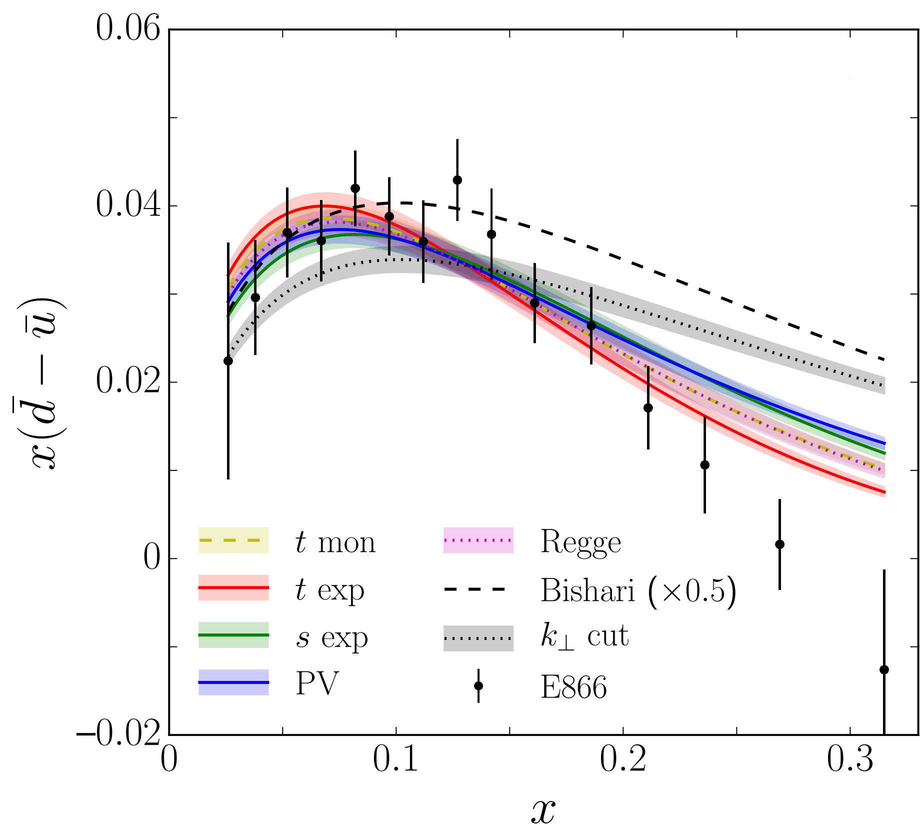


- At $x > 0$, only on-shell part contributes

$$(\bar{d} - \bar{u})(x) \;=\; [2f^{(\mathrm{on})} \otimes \bar{q}_v^\pi](x)$$

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

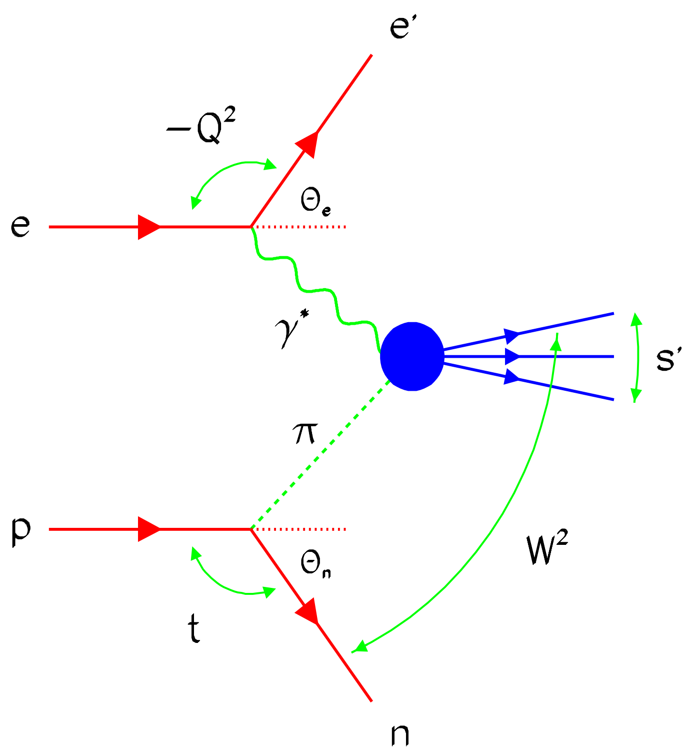
- Is pion cloud the only explanation for the asymmetry?

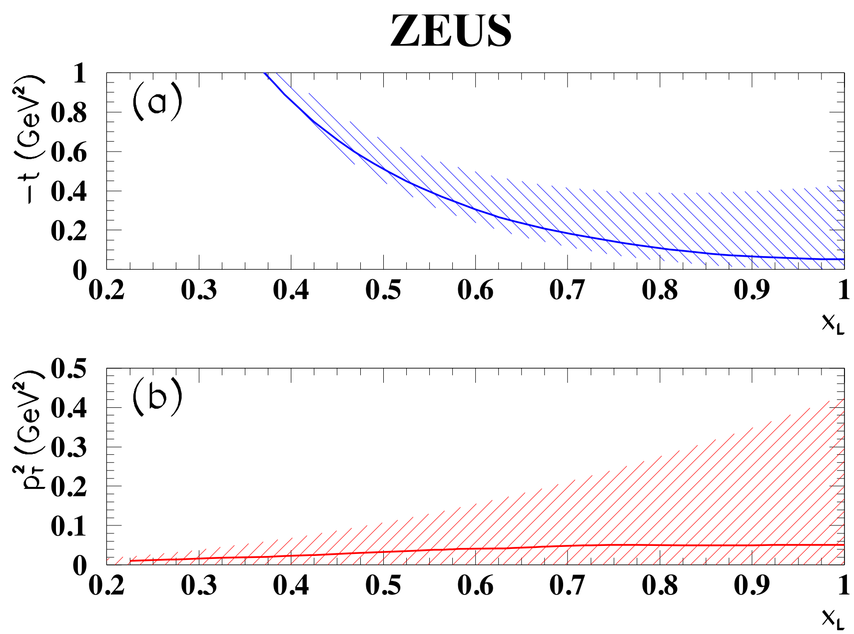
  → are there other data that can discriminate between different mechanisms?

  → 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, $\theta_n < 0.8\ \mathrm{mrad}$





$x_L \approx 1 - y$

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

→ simultaneous fit never previously been performed

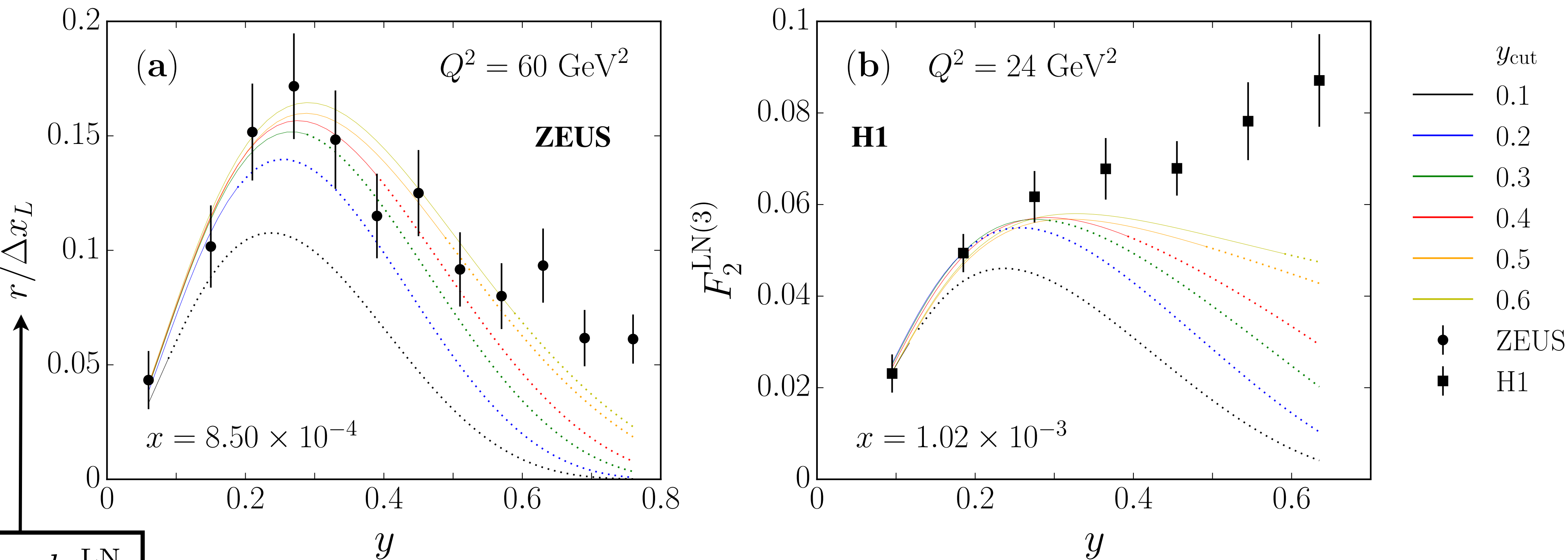
Leading neutron production at HERA

- 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.

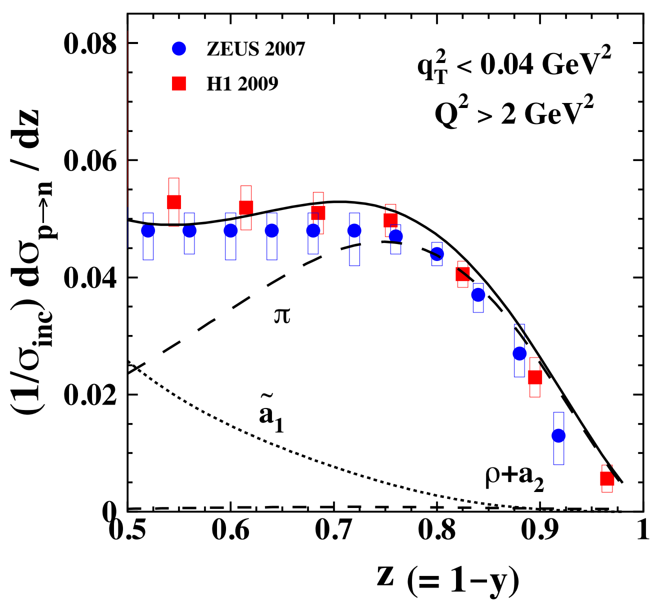


$$r = \frac{d\sigma^{\rm LN}}{d\sigma^{\rm inc}}$$

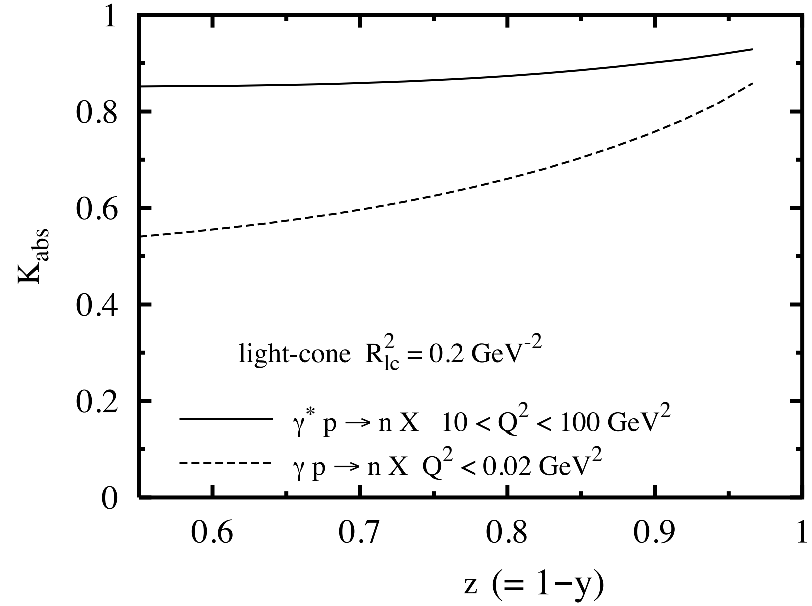
→ quality of fit depends on range of y fitted

Leading neutron production at HERA

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



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

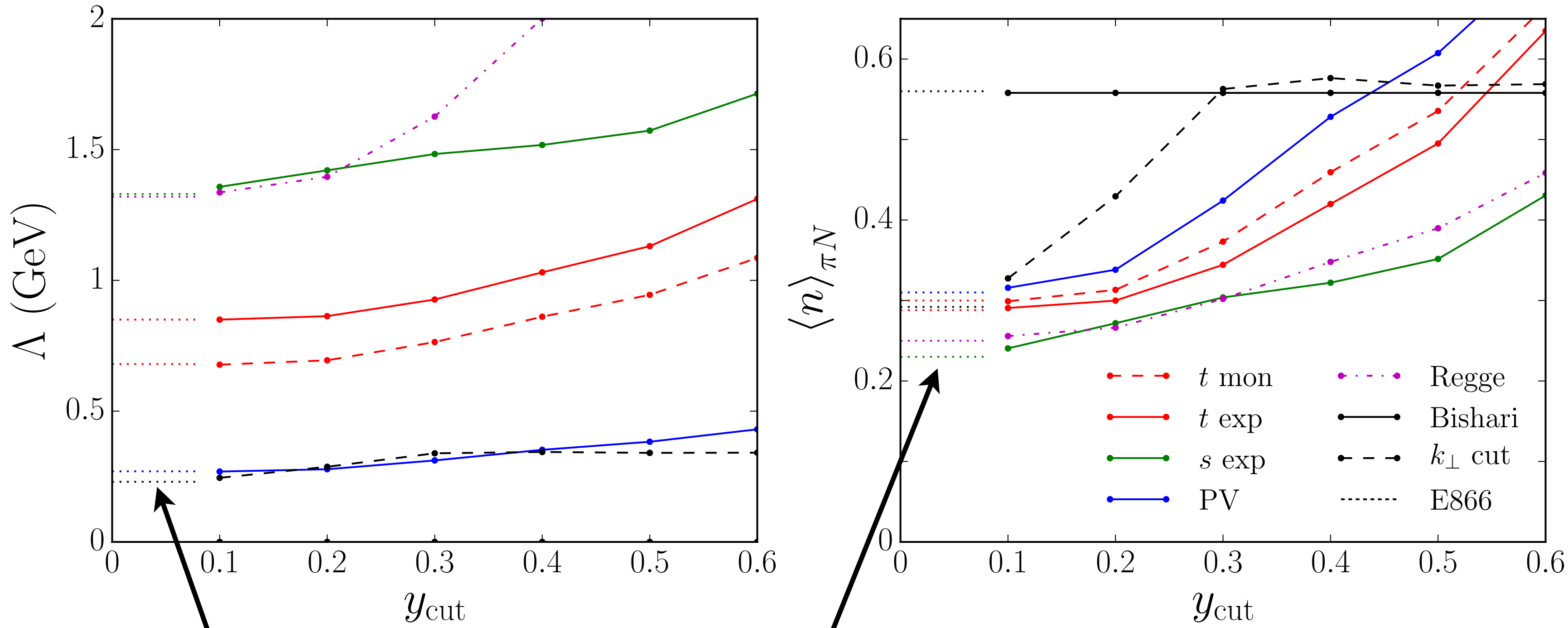


D'Alesio, Pirner, EPJA ***7****, 109 (2000)*

- 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 $y_{\rm cut}$

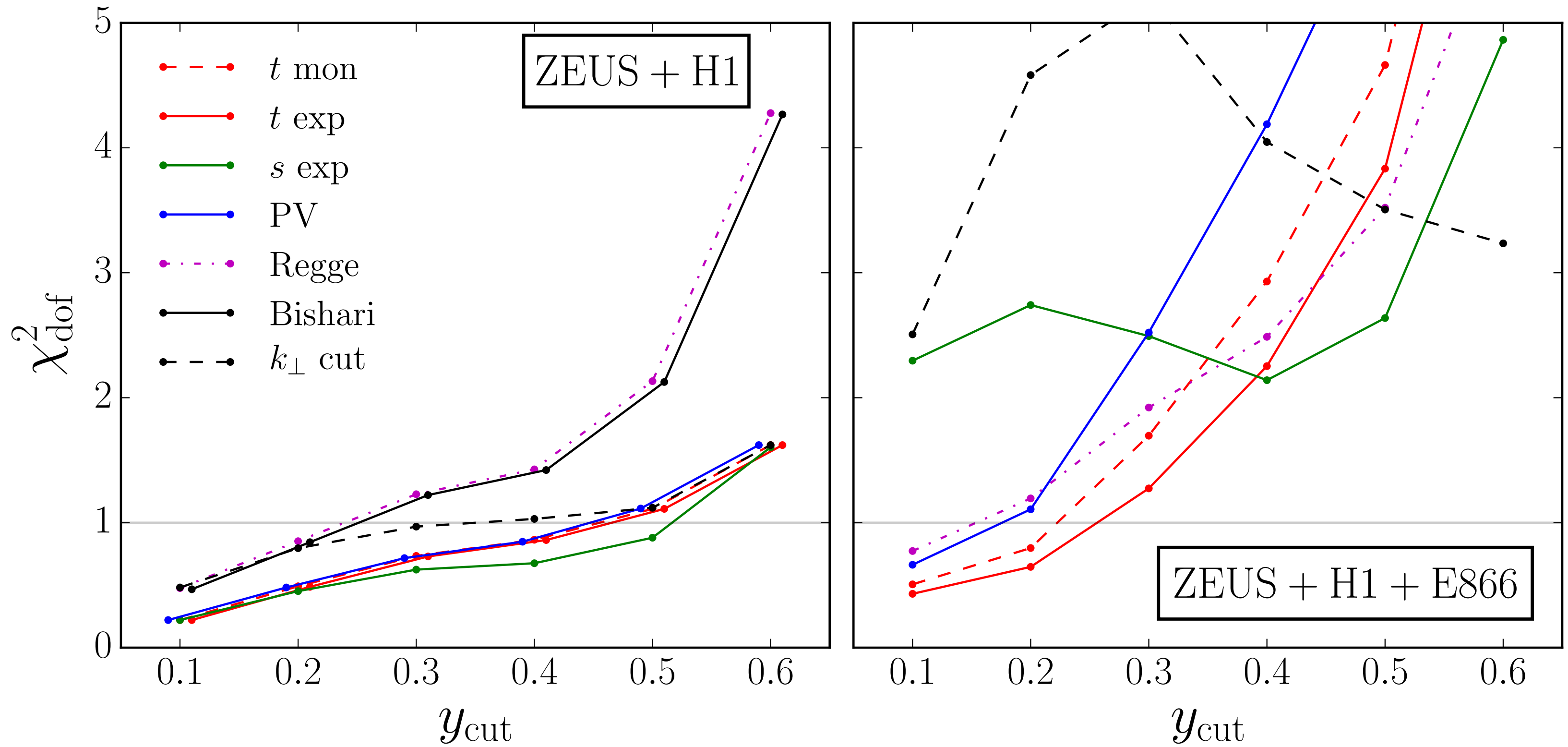


values from fit to E866 data only

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

Leading neutron production at HERA

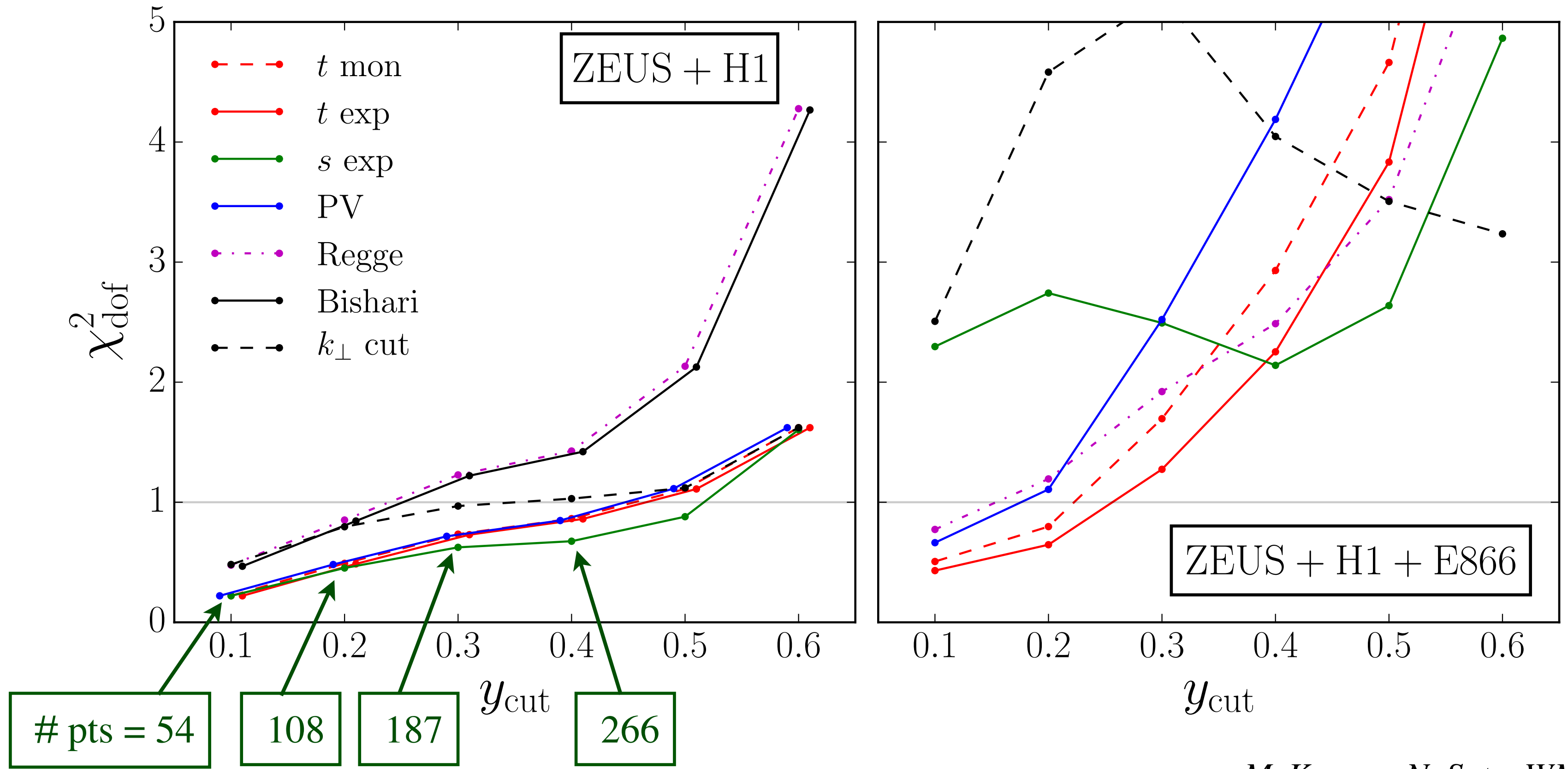
- Combined fit to HERA LN and E866 Drell-Yan data



McKenney, N. Sato, WM, C. Ji
*PRD **93**, 700205 (2016)*

Leading neutron production at HERA

Combined fit to HERA LN and E866 Drell-Yan data



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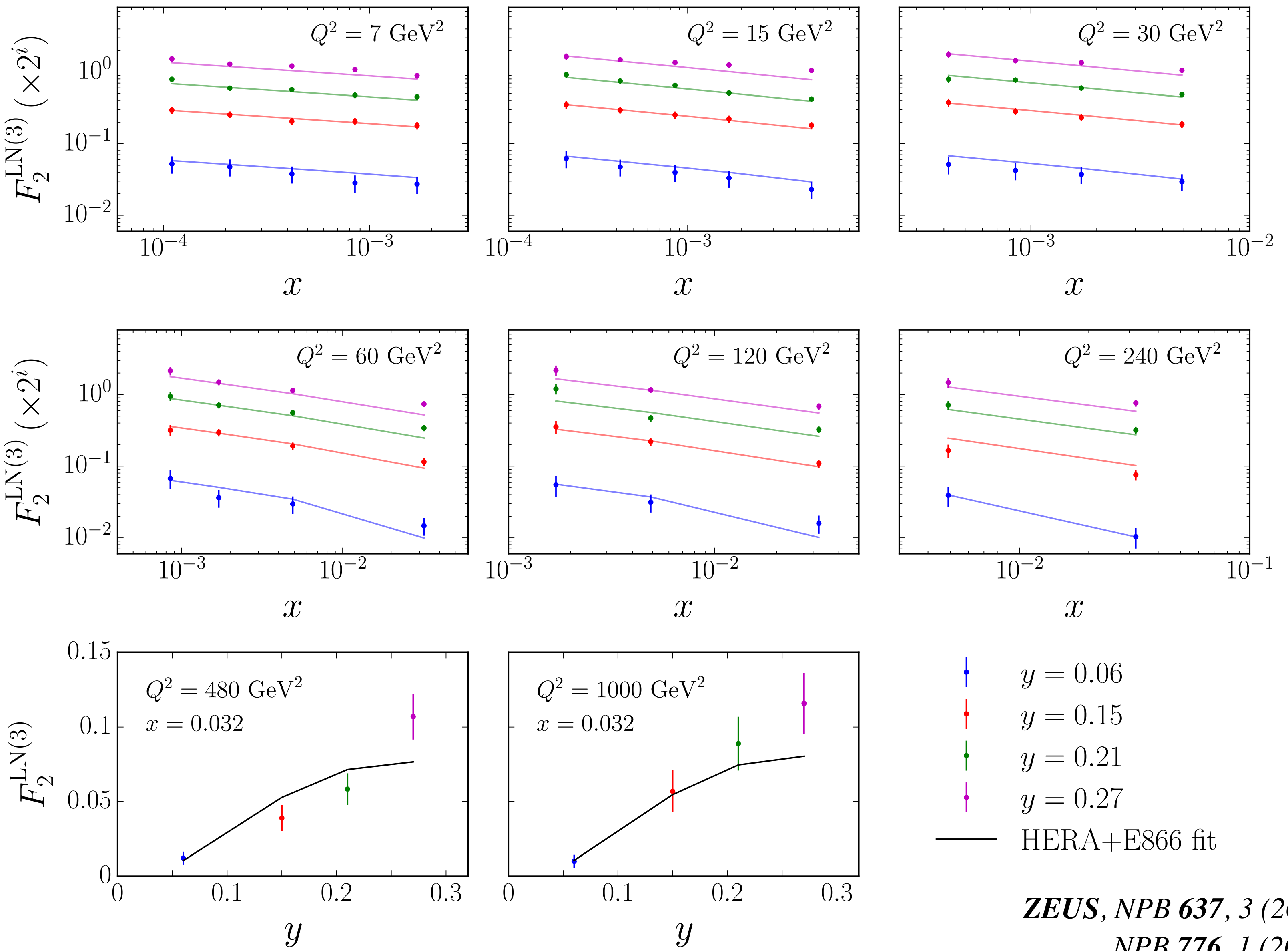
*PRD **93**, 700205 (2016)*

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

Leading neutron production at HERA

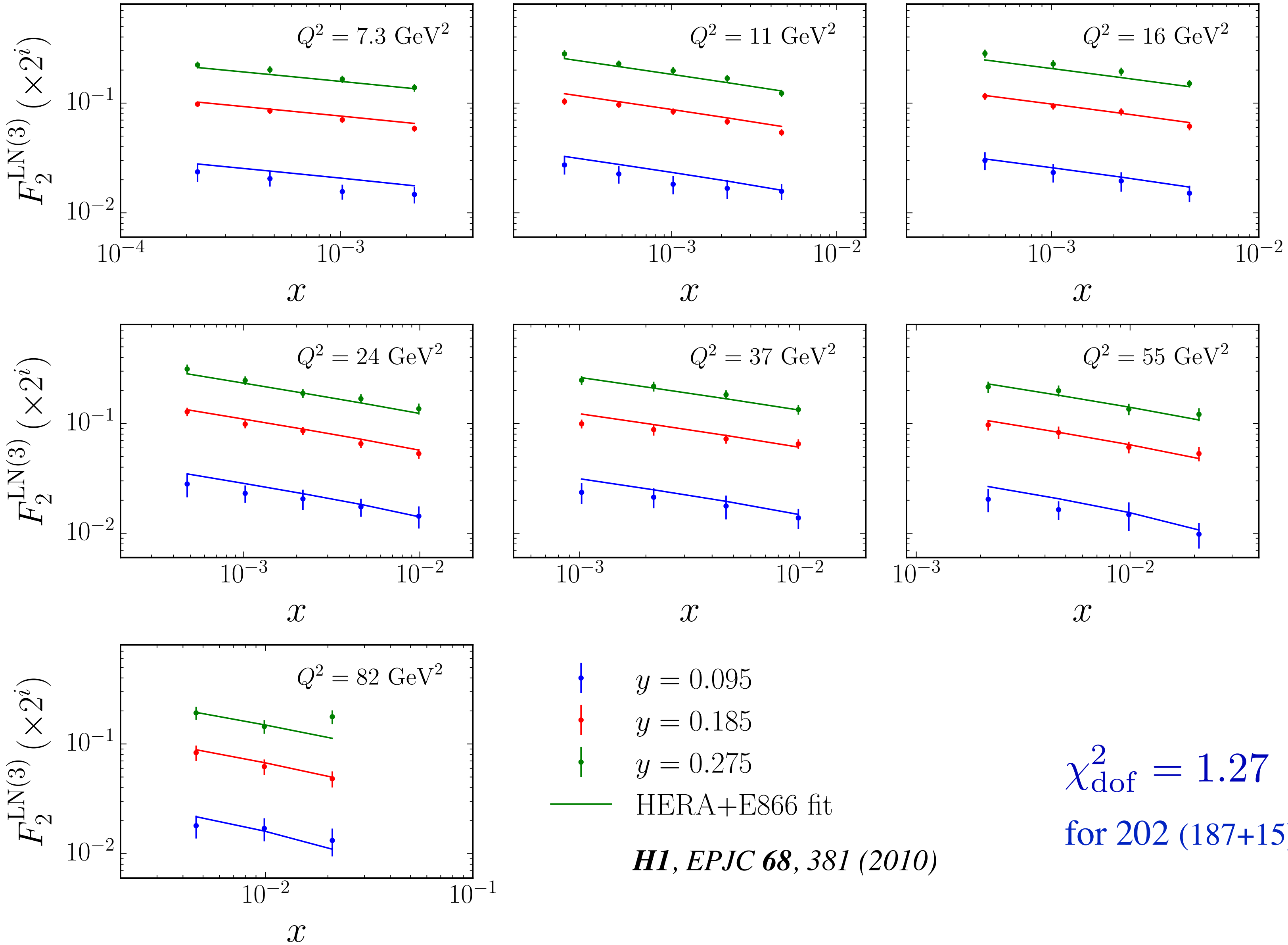
- Fit to ZEUS LN spectra for $y_{\mathrm{cut}} = 0.3$ (t-dependent exponential)



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

Leading neutron production at HERA

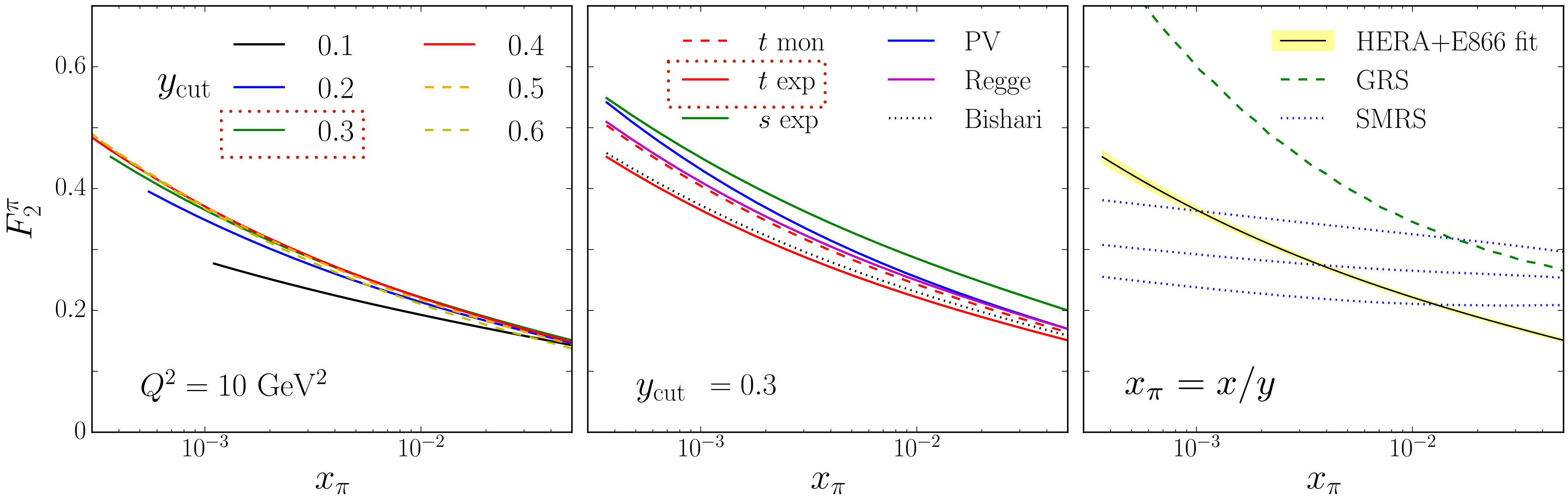
- Fit to H1 LN spectra for $y_{\rm cut} = 0.3$ (*t*-dependent exponential)



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

for 202 (187+15) points

Extracted pion structure function



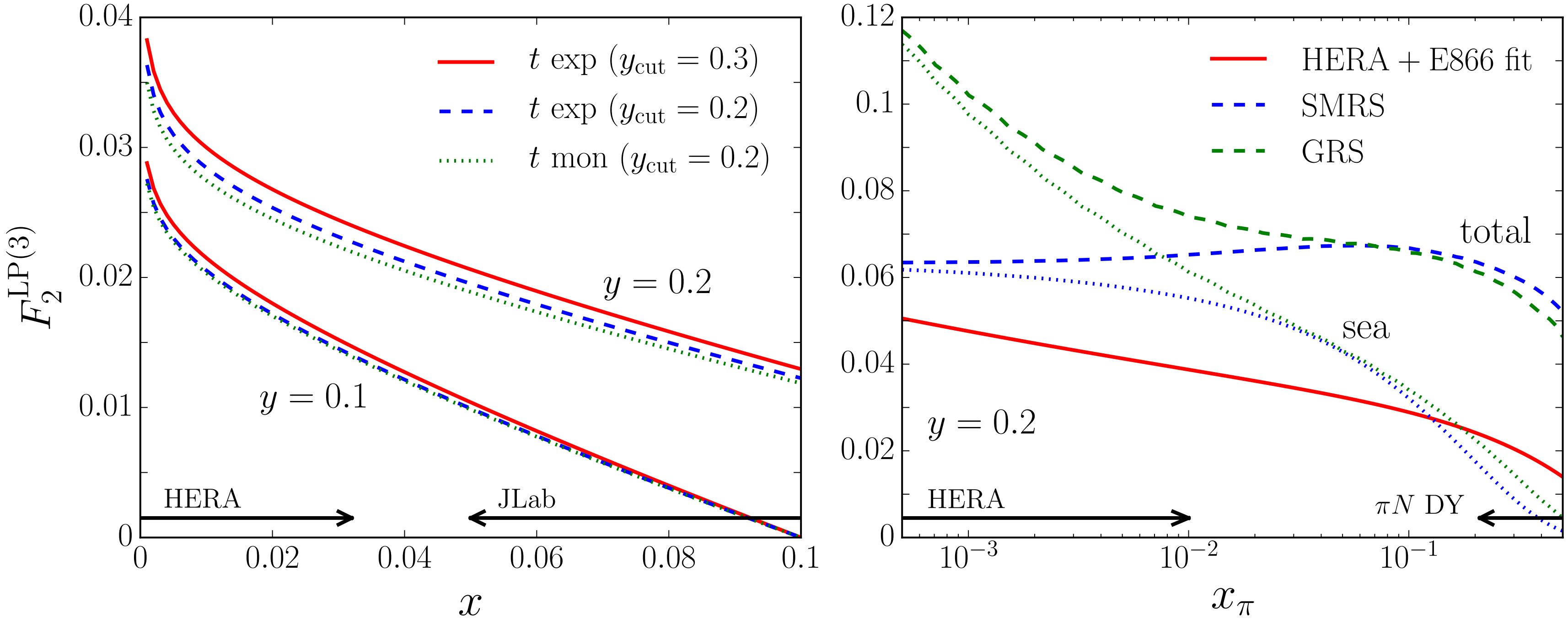
$$F_2^\pi = N\, x_\pi^a\, (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta$$
$$\eta \sim \log(\log Q^2)$$

McKenney, N. Sato, WM, C. Ji
*PRD **93**, 700205 (2016)*

→ 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



$$F_2^{\rm LP(3)} = f_{\pi^- p}(y)\, F_2^\pi(x_\pi, Q^2)$$

McKenney, N. Sato, WM, C. Ji
PRD ***93****, 700205 (2016)*

→ JLab TDIS ("tagged" DIS, $e\,d \to e\,p\,p\,X$) 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 $10^{-4} \lesssim x_\pi \lesssim 1$