*Large-x ("non-small x") Meeting*
*Jefferson Lab, October 4, 2016*

# Pion structure from leading particle production

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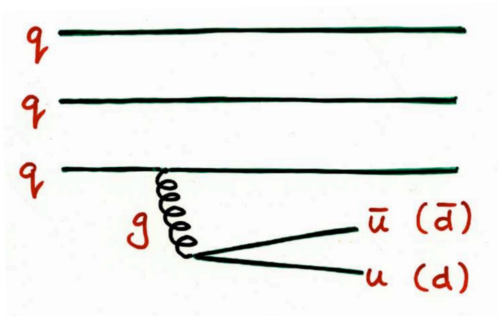
*Nobuo Sato* (JLab), *Tony Thomas* (Adelaide)

# Light quark sea

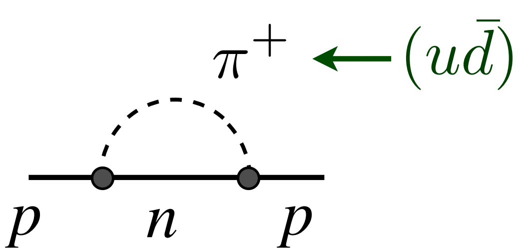
- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)




$\rightarrow$ since $u$ and $d$ quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

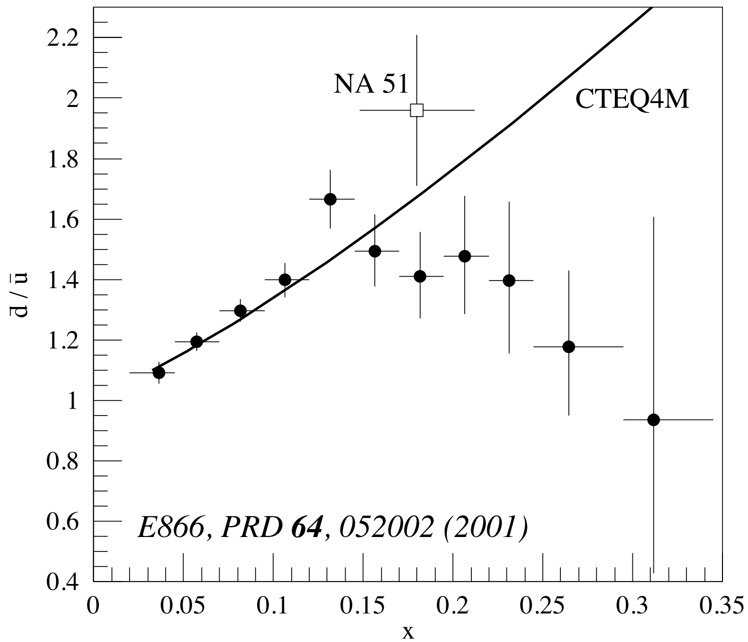
- In 1980s Thomas argued that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

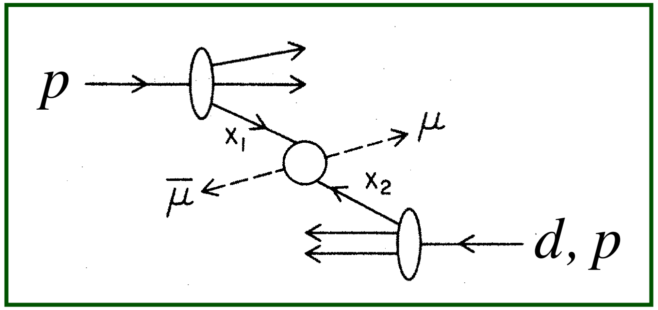



$\rightarrow$ $\boxed{\bar{d} > \bar{u}}$

# Light quark sea

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments




$$\frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2\, q(x_1)\, \bar{q}(x_2) \;+\; (x_1 \leftrightarrow x_2)$$

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$

$\longrightarrow$ strongly suggested role of chiral symmetry and pion cloud as central to understanding of nucleon's quark structure

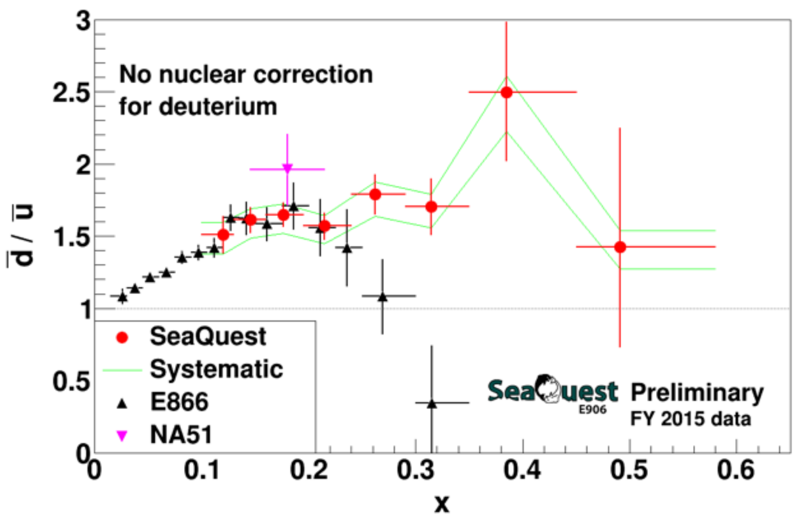
$$(\bar{d} - \bar{u})(x) = (f_\pi \otimes \bar{q}_\pi)\,(x)$$

pion distribution in nucleon

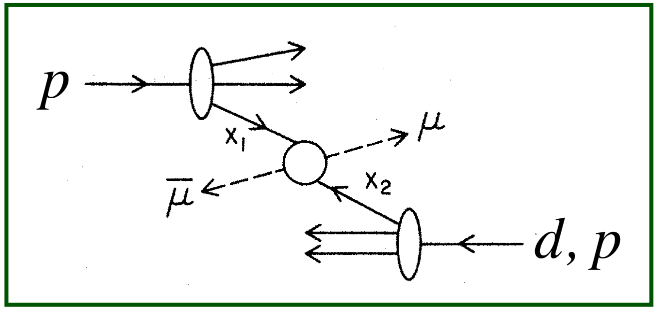
pion PDF

# Light quark sea

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments




*P. Reimer (2016)*

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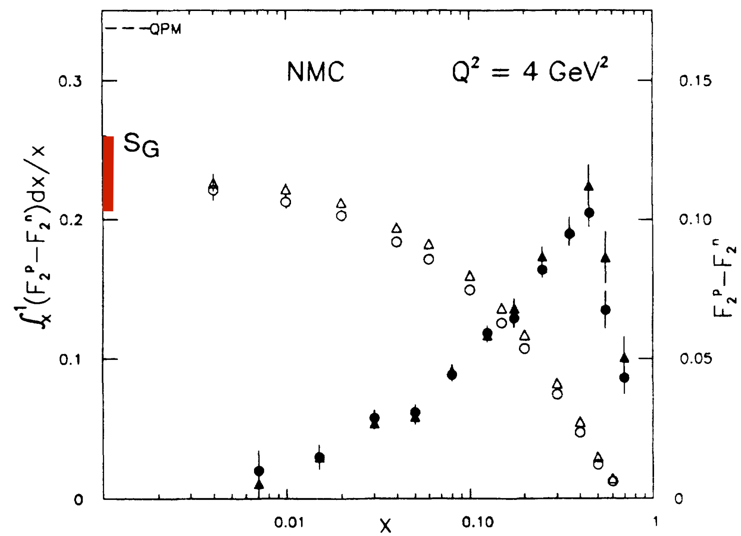


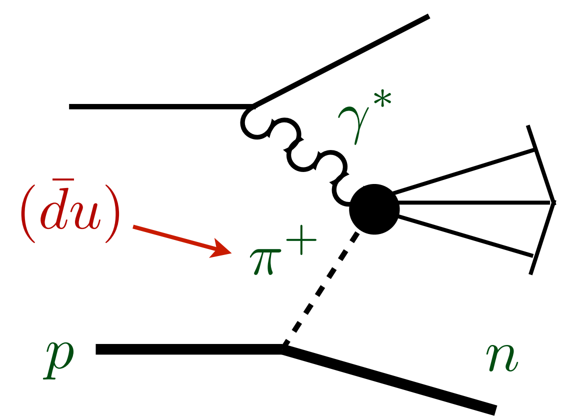

*NMC (1994)*

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

$$= 0.235(26)$$

violation of Gottfried sum rule!

→ Sullivan process — DIS from pion cloud of the nucleon




*Sullivan (1972)*

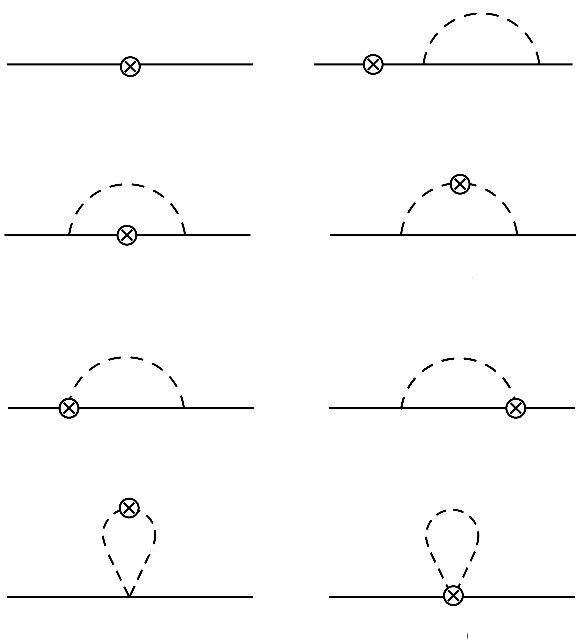
# Chiral effective theory

- Early calculations used phenomenological models
  — more recently rigorous connection with QCD
  established via effective chiral field theory

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

***Weinberg (1967)***

→ lowest order $\pi N$ interaction includes
pion rainbow and tadpole contributions



→ matching quark- and hadron-level operators

$$\mathcal{O}_q^{\mu_1\cdots\mu_n} = \sum_h c_{q/h}^{(n)}\ \mathcal{O}_h^{\mu_1\cdots\mu_n}$$

yields convolution representation

$$q(x) = \sum_h \int_x^1 \frac{dy}{y}\, f_h(y)\, q_v^h(x/y)$$

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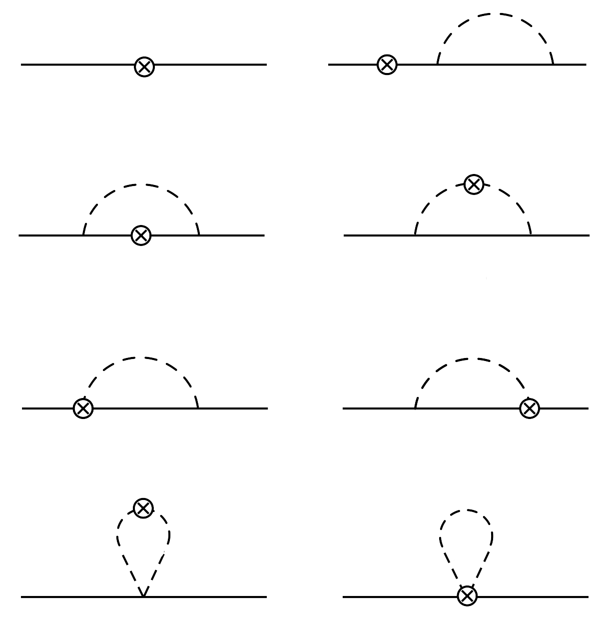
***Weinberg (1967)***

$\longrightarrow$ expanding PDF moments in powers of $m_\pi$, coefficients of leading nonanalytic (LNA) terms are model-independent!

***Thomas, WM, Steffens (2000)***
***Chueng Ji, WM, Thomas (2012)***



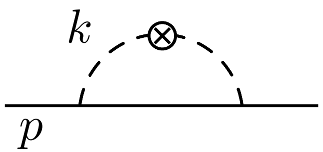
$\longrightarrow$ nonanalytic behavior vital for chiral extrapolation of lattice data on PDF moments

$$\langle x\rangle_{u-d}^{\rm LNA} \sim m_\pi^2 \log m_\pi^2$$

***Detmold et al. (2001)***

# Pion splitting functions

- Spitting functions for various diagrams computed in chiral theory
  *e.g.* pion rainbow diagram




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

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

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

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

- For point-like nucleons and pions, integrals divergent

$\longrightarrow$ finite size of nucleon provides natural regularization scale
(but does not prescribe form of regularization)

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

$\mathcal{F} = \left(\dfrac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ $\quad$ $t$ monopole

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

$\mathcal{F} = \exp\left[(M^2 - s)/\Lambda^2\right]$ $\quad$ $s$-dep. exponential

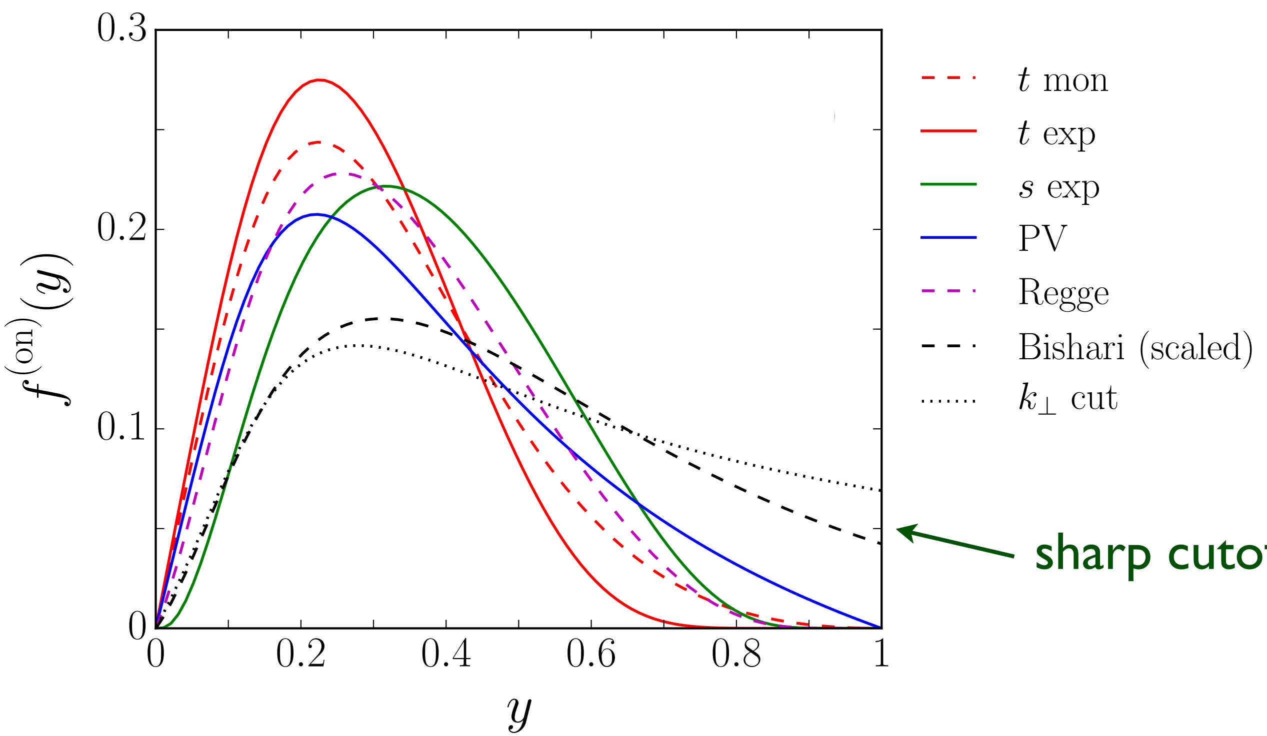
$\mathcal{F} = \left[1 - \dfrac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$ $\quad$ Pauli-Villars

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

# Pion splitting functions

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

*e.g.* on-shell function




sharp cutoffs

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

$\mathcal{F} = \left(\dfrac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ $t$ monopole

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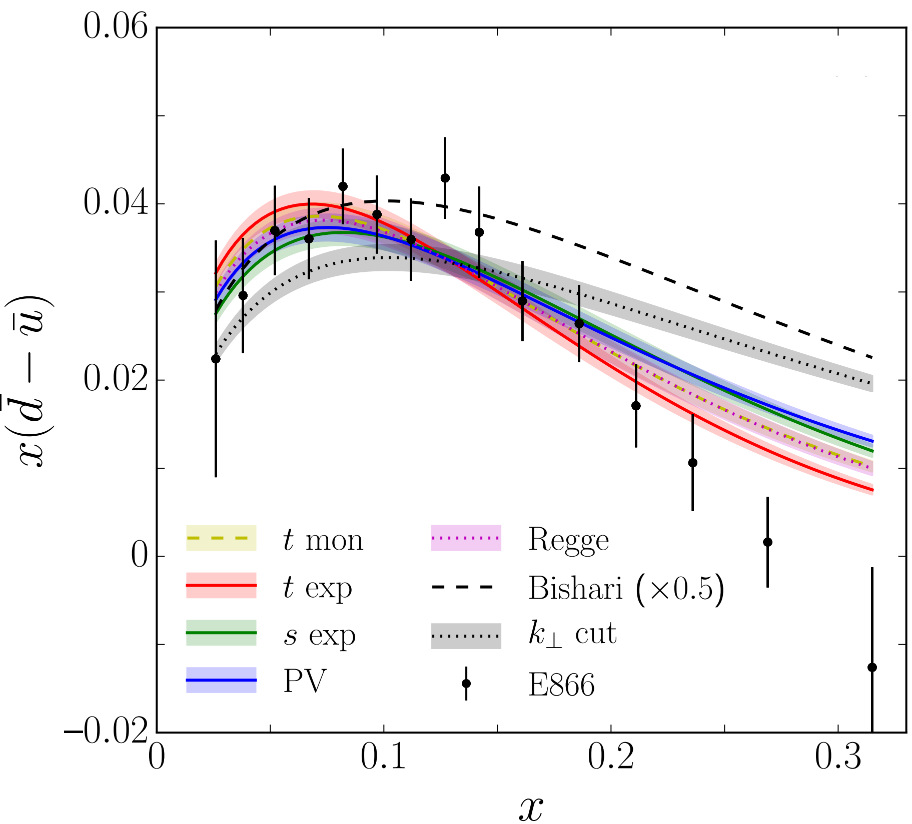
# Pion splitting functions

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




average pion "multiplicity"

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

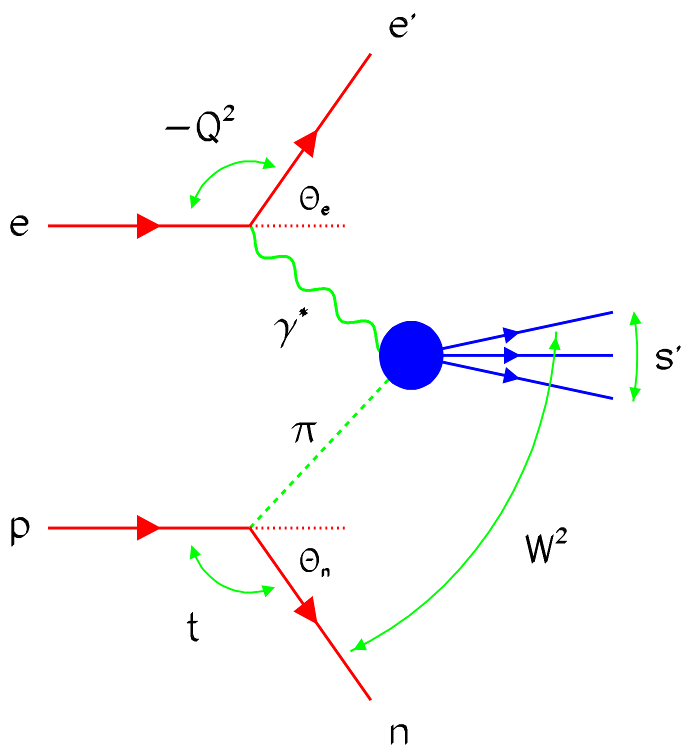
$$\sim\ 0.25 - 0.3$$

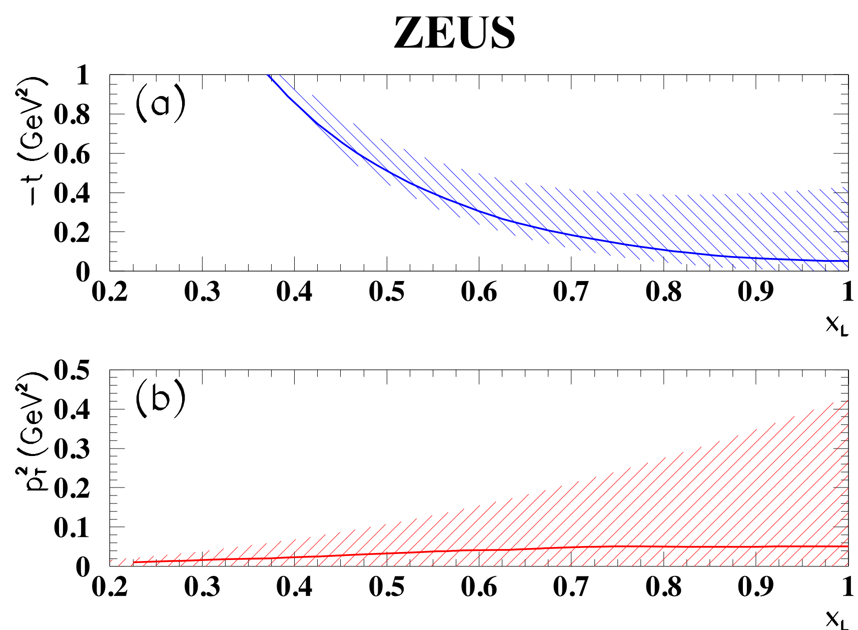
$\longrightarrow$ with exception of $k_\perp$ cutoff and Bishari models, all others give reasonable fits, $\chi^2 \lesssim 1.5$

$\longrightarrow$ are there other data that can be more discriminating?

# Leading neutron production at HERA

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




$$x_L \approx 1 - y$$

$\longrightarrow$ can data be described within same framework as E866 asymmetry?

$\longrightarrow$ simultaneous fit never previously been performed!

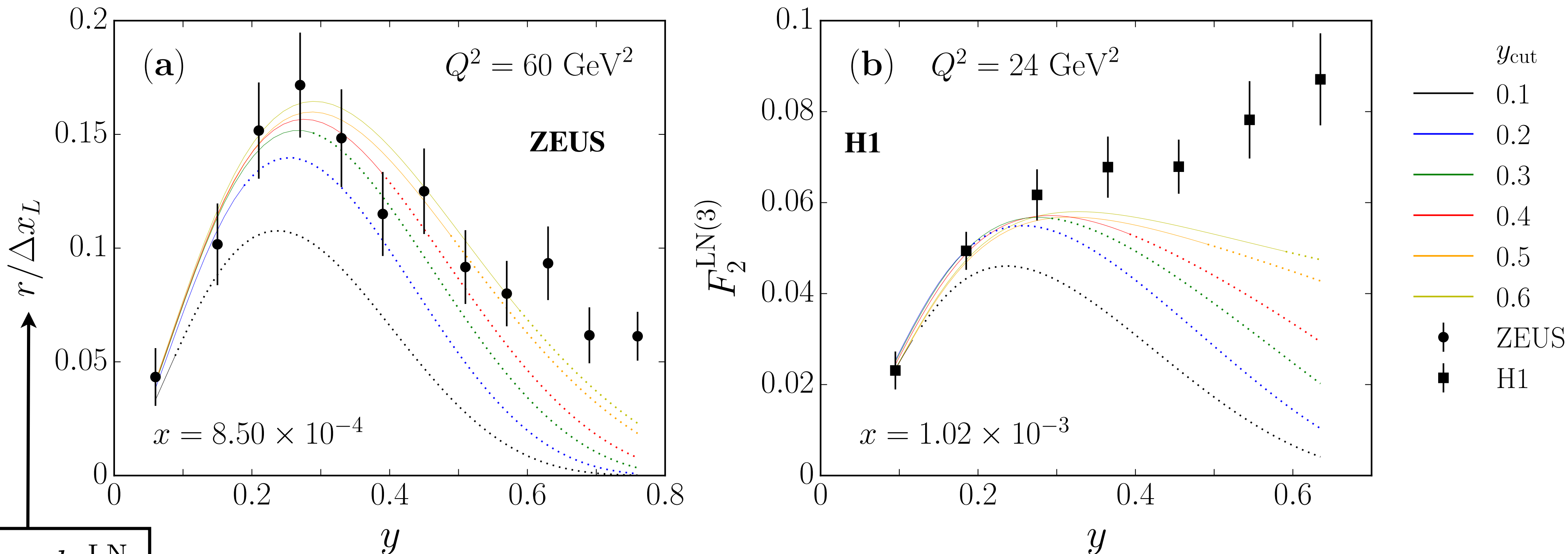
# Leading neutron production at HERA

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

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

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

e.g.

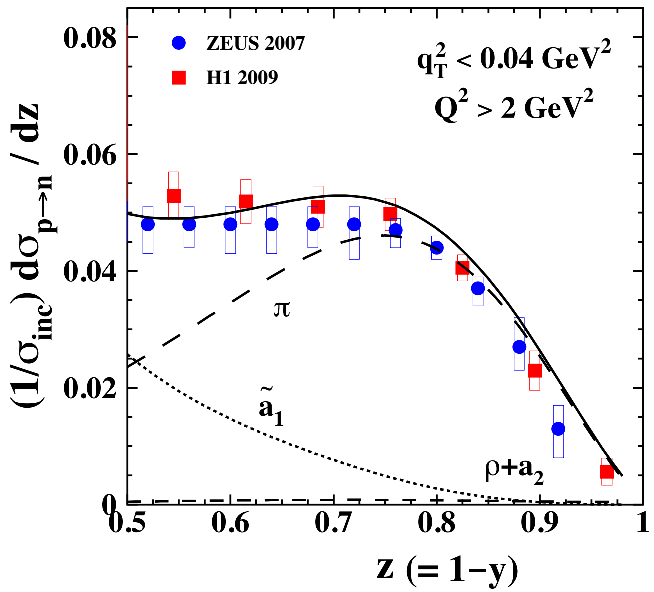



$$\boxed{r = \frac{d\sigma^{\mathrm{LN}}}{d\sigma^{\mathrm{inc}}}}$$

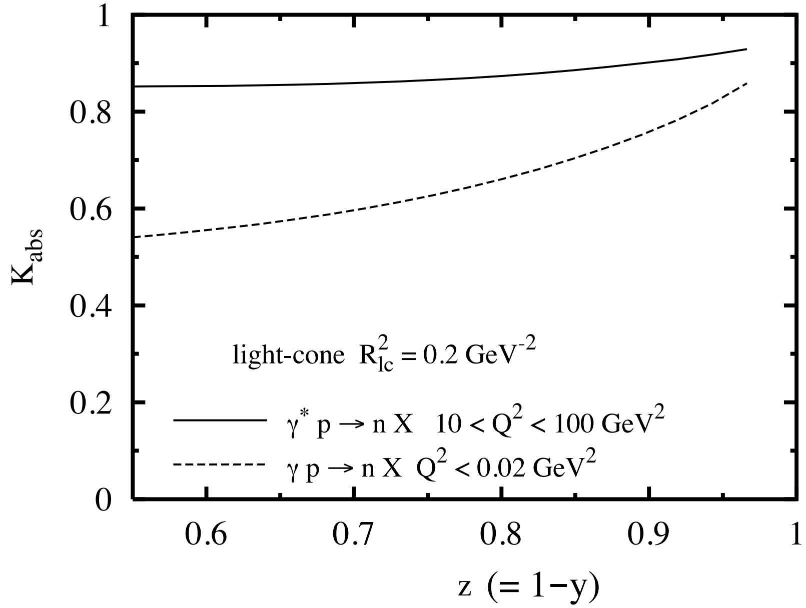
$\longrightarrow$ quality of fit depends on range of $y$ fitted

# Leading neutron production at HERA

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




*Kopeliovich et al. (2012)*

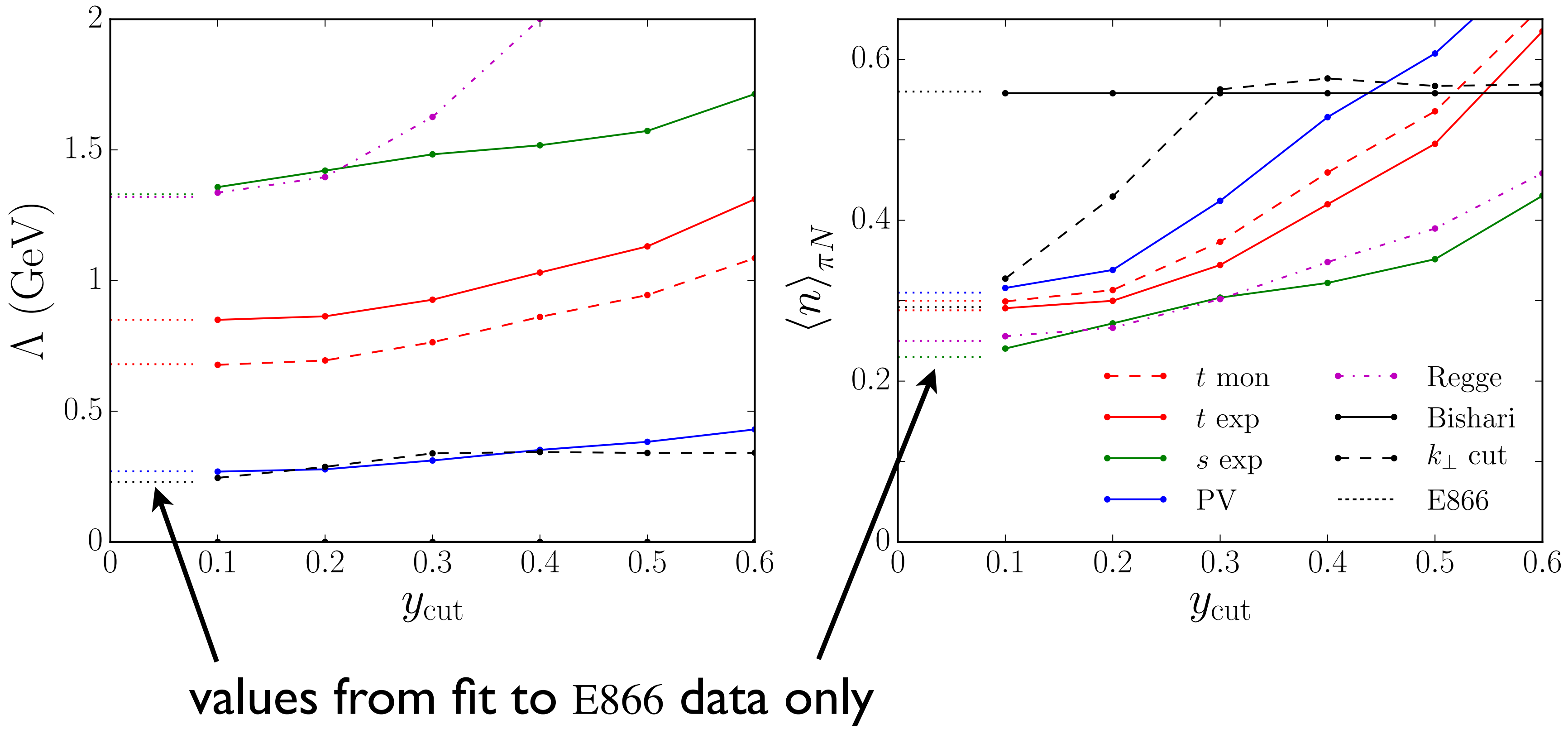



*D'Alesio, Pirner (2000)*

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

# Leading neutron production at HERA

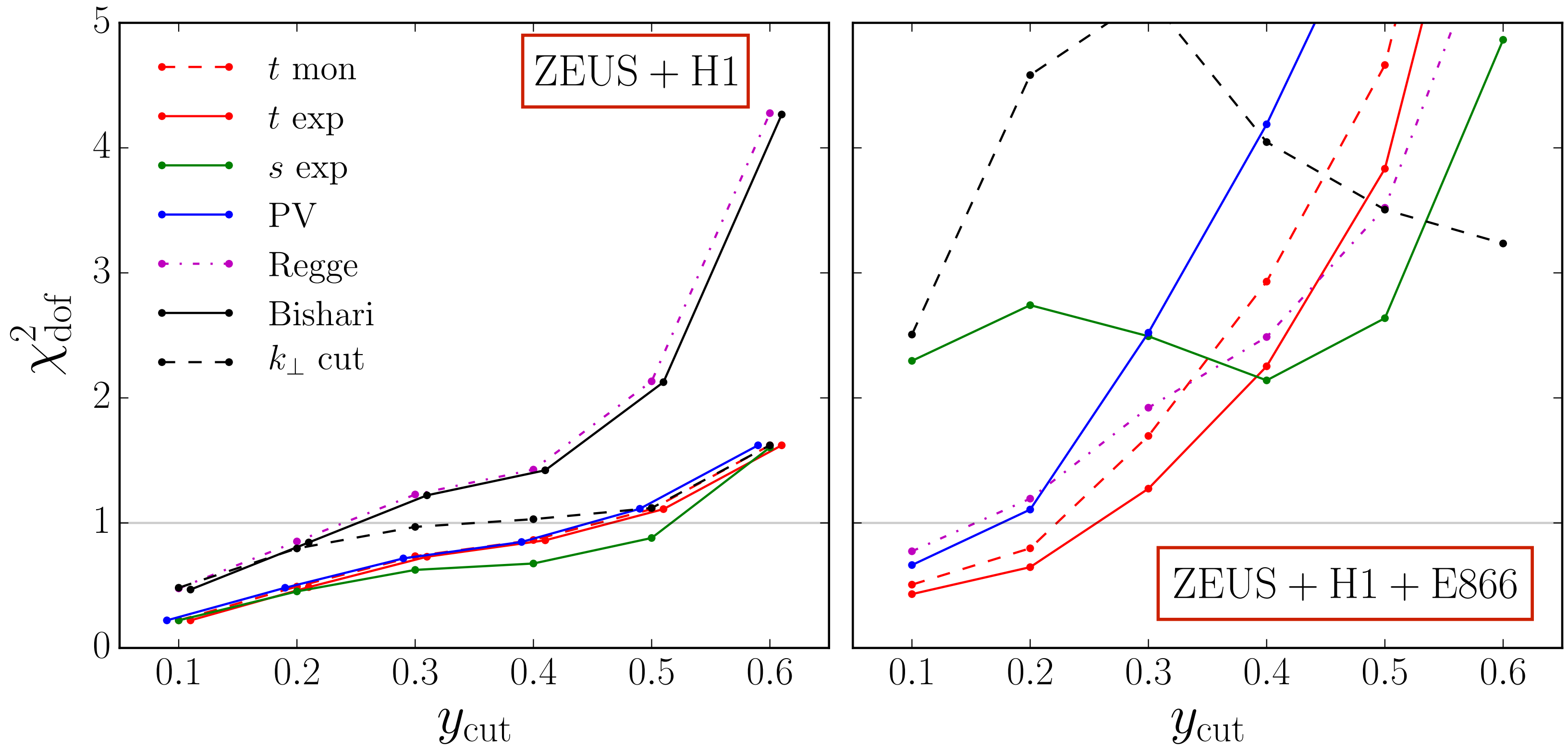
- Fit requires higher momentum pions with increasing $y_{\rm cut}$




$\longrightarrow$ 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, Sato, WM, Ji (2016)*

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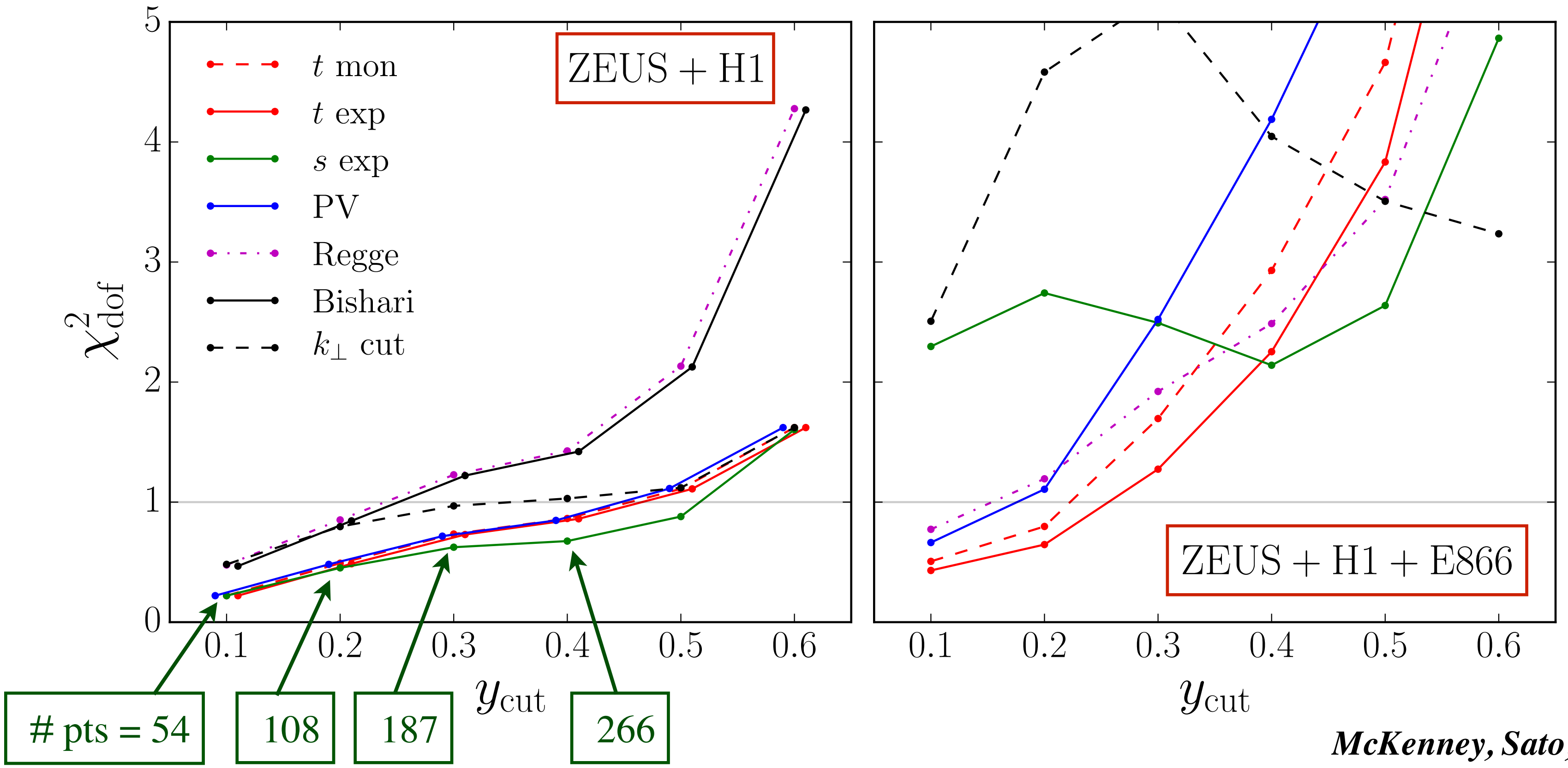
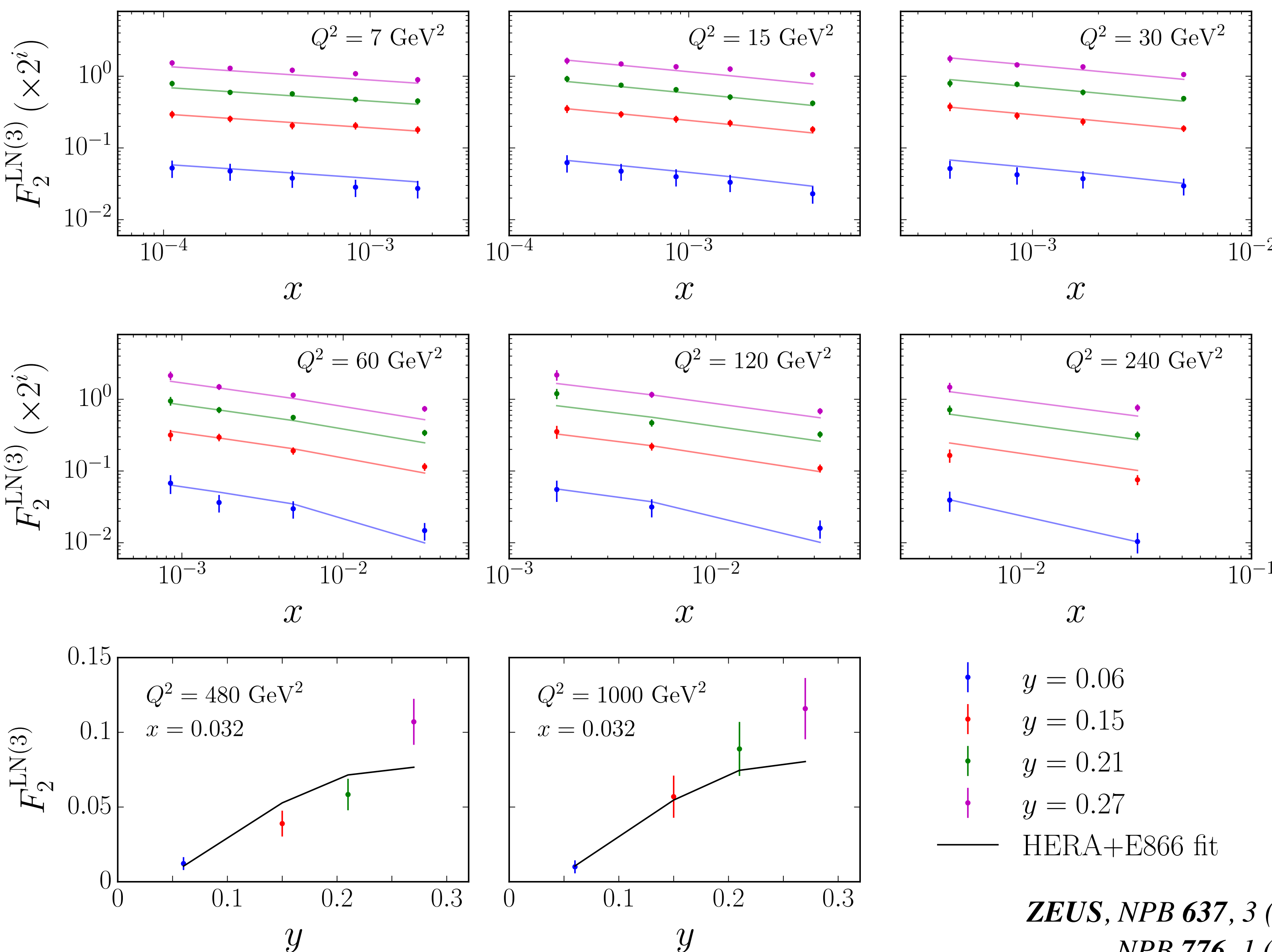



***McKenney, Sato, WM, Ji (2016)***

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

# Leading neutron production at HERA

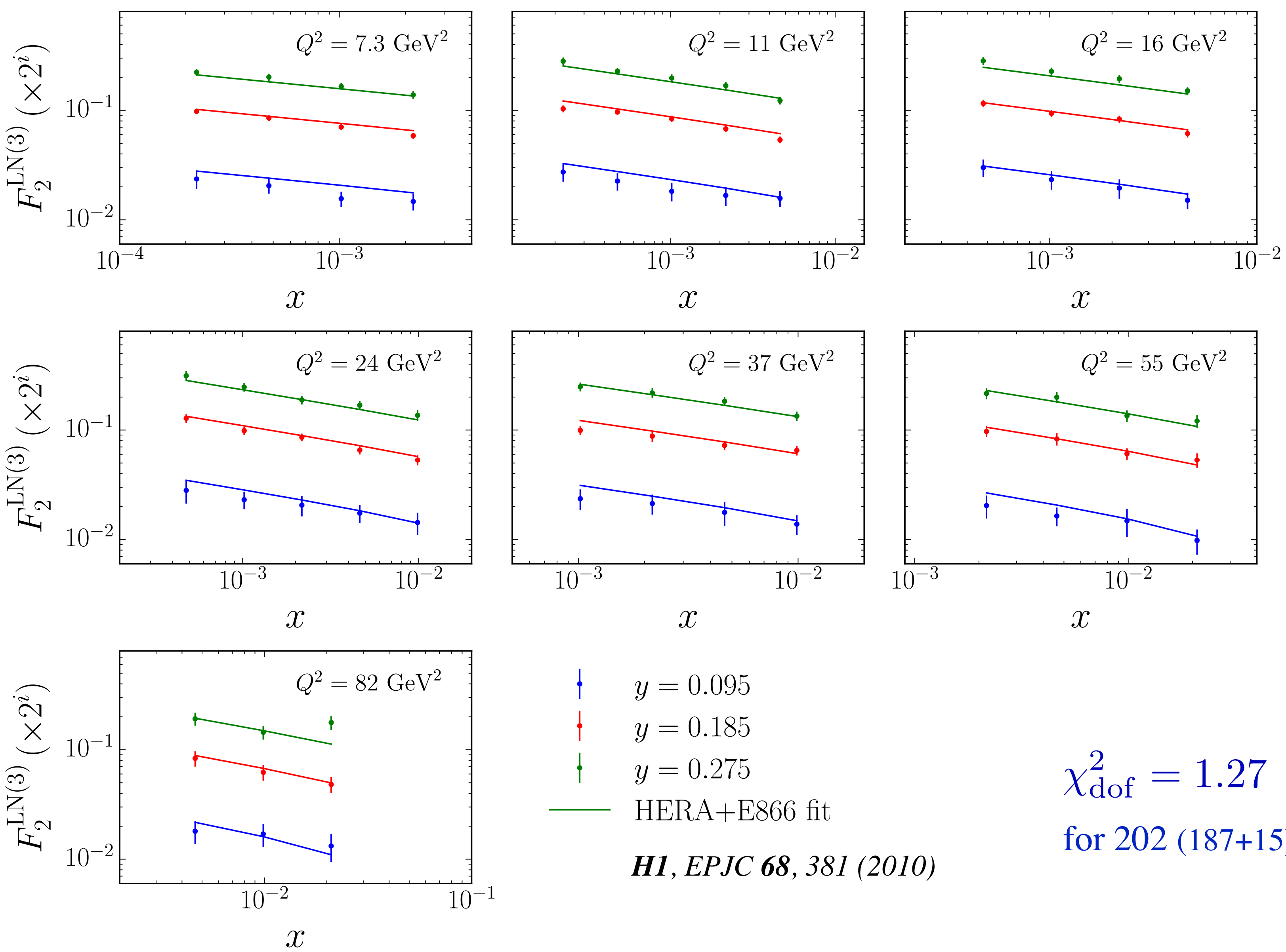
- Fit to ZEUS LN spectra for $y_{\mathrm{cut}} = 0.3$ ($t$-dependent exponential)




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

# Leading neutron production at HERA

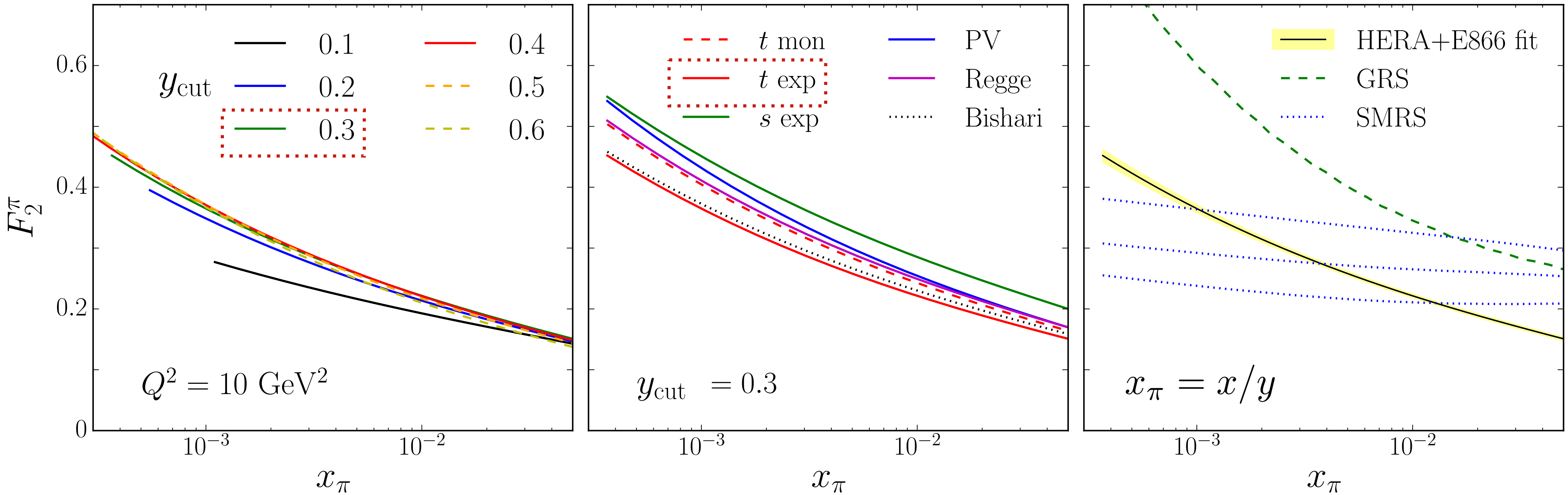
## Fit to H1 LN spectra for $y_{\rm cut} = 0.3$ ($t$-dependent exponential)




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

for 202 (187+15) points

# Extracted pion structure function




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

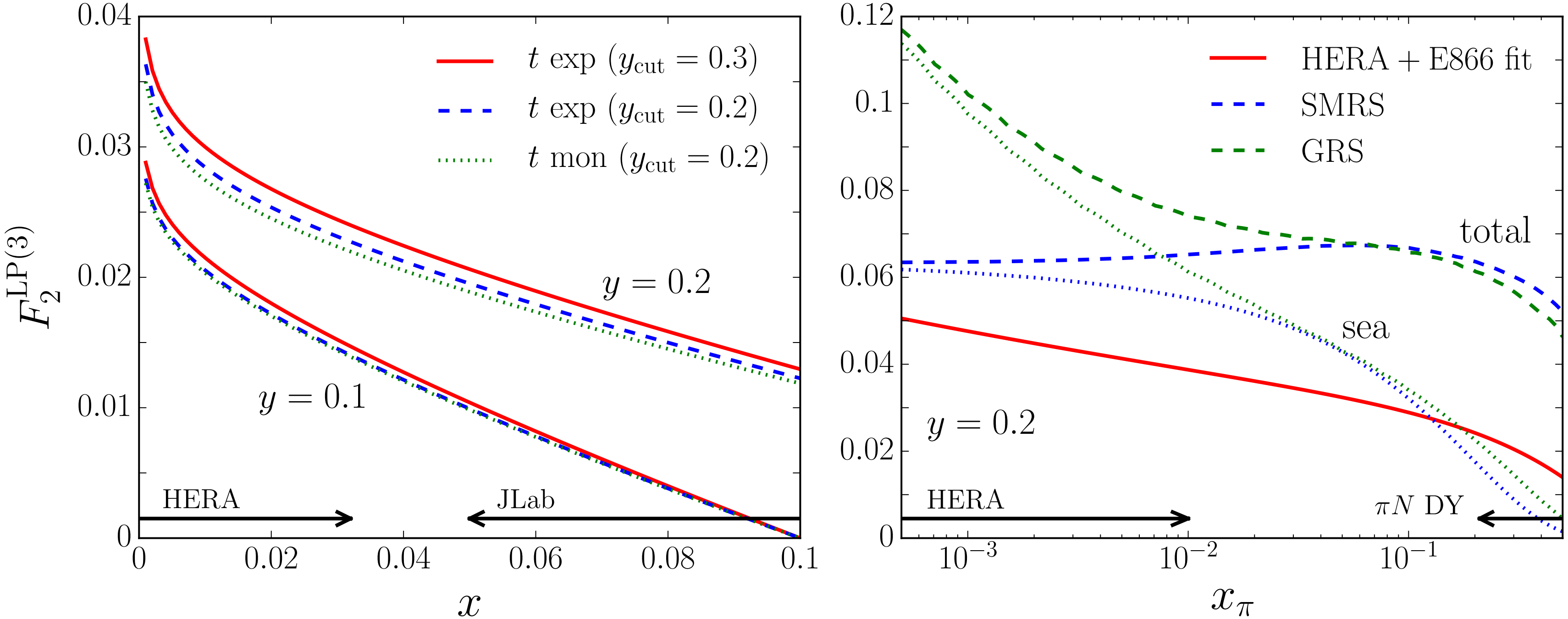
$$\eta \sim \log(\log Q^2)$$

***McKenney, Sato, WM, Ji (2016)***

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

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

# Predictions at TDIS kinematics




***McKenney, Sato, WM, Ji (2016)***

$\longrightarrow$ JLab TDIS experiment can fill gap in $x_\pi$ coverage between HERA and $\pi N$ Drell-Yan kinematics

# Outlook

- Combined analysis can be extended by including $\pi N$ DY data

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

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

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

  $\longrightarrow$ global analysis under way of HERA LN, Drell-Yan $\pi N + pd/pp$ (+ future JLab TDIS data) to determine pion PDFs at all $x$

  ***Patrick Barry, Chueng Ji (NCSU), Nobuo Sato, WM (2016)***