Pion and Kaon Structure at an EIC
Argonne National Lab, June 2, 2017

π/K structure & sea quarks in the proton:
constraints from chiral EFT & global QCD analysis

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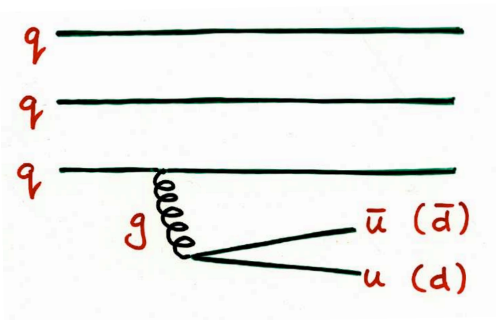
Outline

- Motivation: $\bar{d} - \bar{u}$ asymmetry
- PDF constraints from chiral symmetry in QCD / chiral EFT
- Tagged neutron DIS — implications for pion models and pion PDF extraction
- Strange quarks and hyperon production
- Outlook

Light quark sea

- From text-books: perturbative QCD expected to generate symmetric $q\bar{q}$ sea via gluon radiation into $q\bar{q}$ pairs

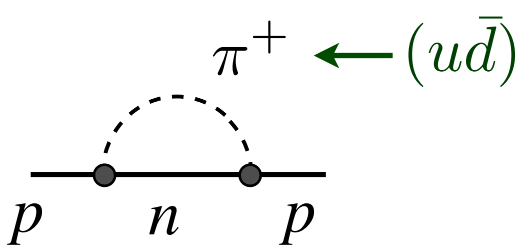


$\rightarrow$ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

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

Ross, Sachrajda (1979)

- (Almost) from text-books: Thomas suggested that chiral symmetry of QCD ("low energy") should have consequences for antiquark PDFs in the nucleon ("high energy")

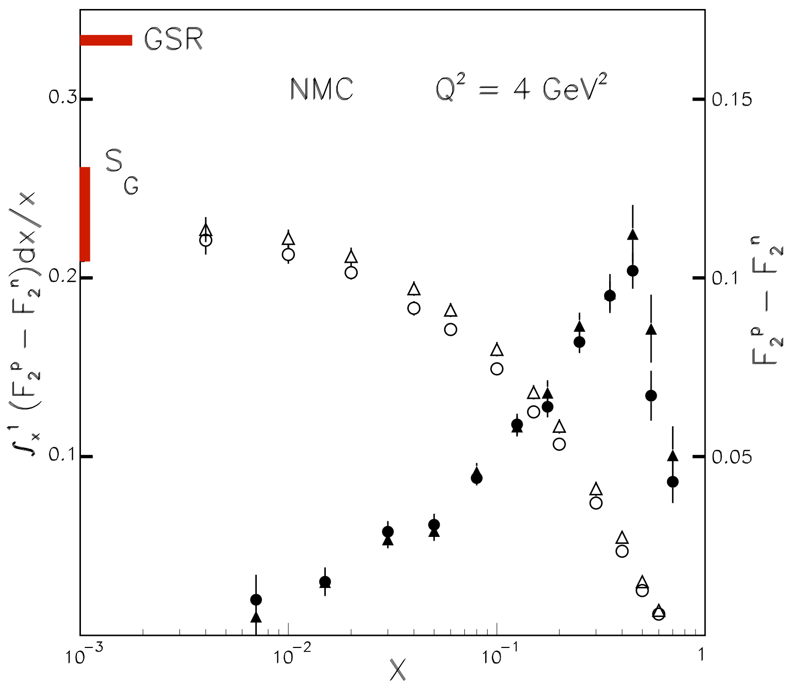


$\rightarrow$ $\bar{d} > \bar{u}$

Thomas (1984)

Light quark sea

- First clear experimental support for $\bar{d} \neq \bar{u}$ came from measurement of Gottfried sum observed by NMC

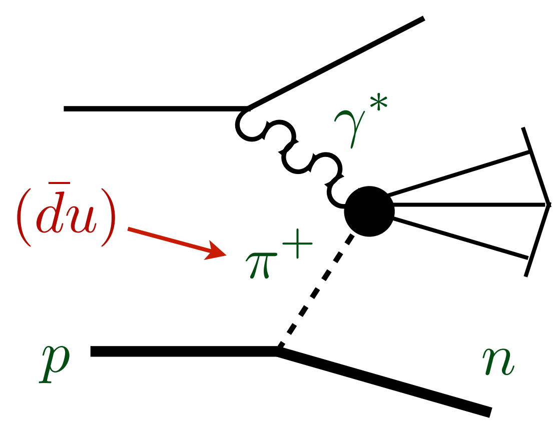


NMC (1991, 1994)

$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,(\bar{d} - \bar{u})$$
$$= 0.235(26)$$

→ violation of "Gottfried sum rule"!

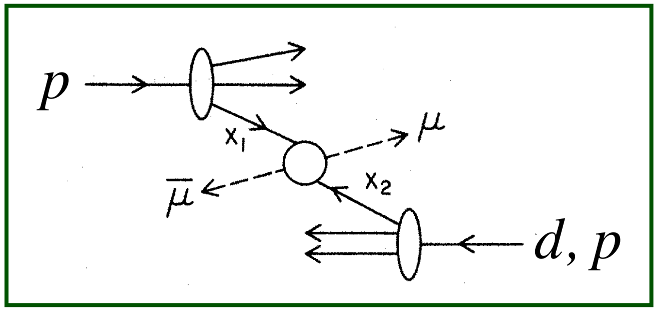
→ Sullivan process — DIS from pion cloud of the nucleon



Sullivan (1972)

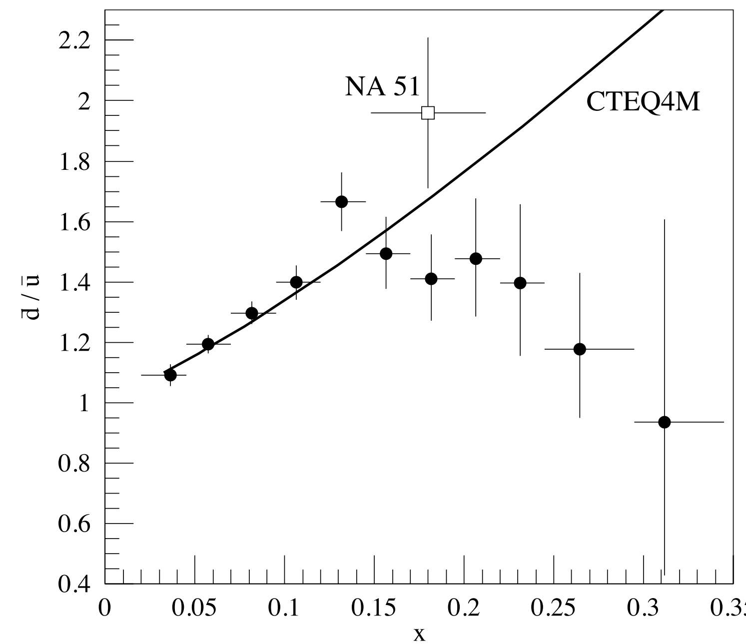
Light quark sea

- x dependence of $\bar{d} - \bar{u}$ asymmetry established in Fermilab E866 pp/pd Drell-Yan experiment



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

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



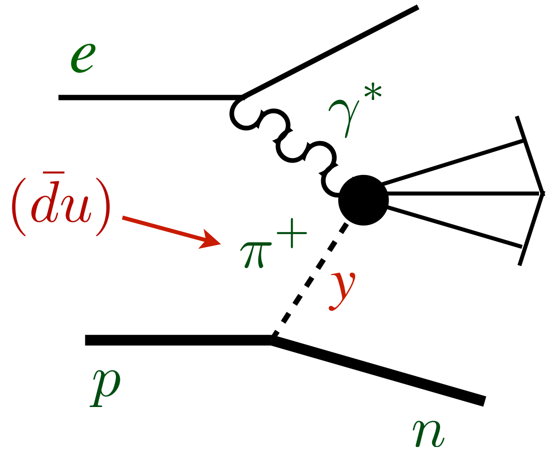
E866 (2001)

→ strong enhancement of $\bar{d}$ at $x \sim 0.1 - 0.2$

→ intriguing behavior at large x hinting at possible sign change of $\bar{d} - \bar{u}$

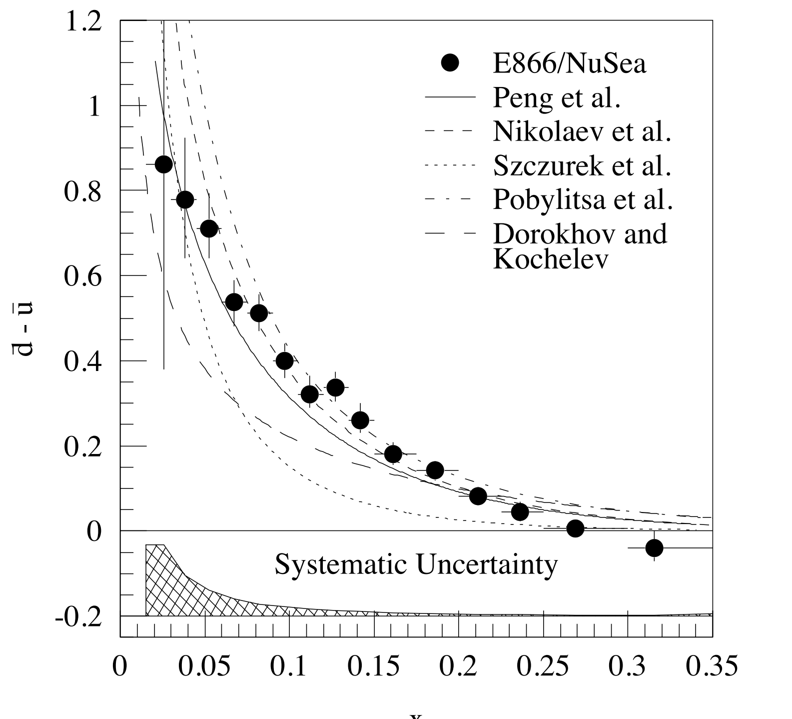
Light quark sea

- General agreement with pion loop models



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

$p \to \pi^+ n$ splitting function
("flux factor")



PRD64, 052002 (2001)

→ shape qualitatively reproduced by most models (except at high x),

— but *is there a direct connection with QCD?*

Chiral effective field theory

- Rigorous connection with QCD established via chiral EFT

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

Weinberg (1967)

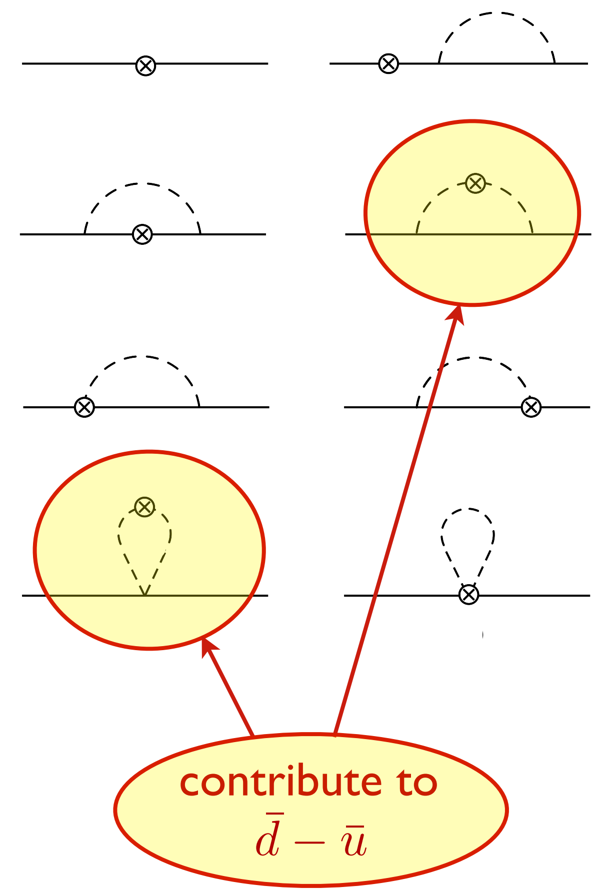
→ lowest order πN interaction includes pion rainbow and tadpole contributions

→ 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

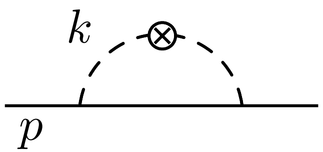
$$q(x) = \sum_h \int_x^1 \frac{dy}{y}\,f_h(y)\,q_v^h(x/y)$$



Ji, WM, Thomas (2013)

Chiral effective field theory

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



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

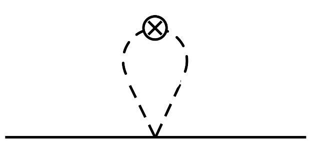
has on-shell $(y = k^+/p^+ > 0)$ and $\delta(y)$ contributions!

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

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

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

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



$\longrightarrow$ contributes to lowest moment, but not at $x > 0$

Salamu, Ji, WM, Wang (2015)

Chiral effective field theory

- Expand moments of PDFs (splitting functions) in powers of m_π

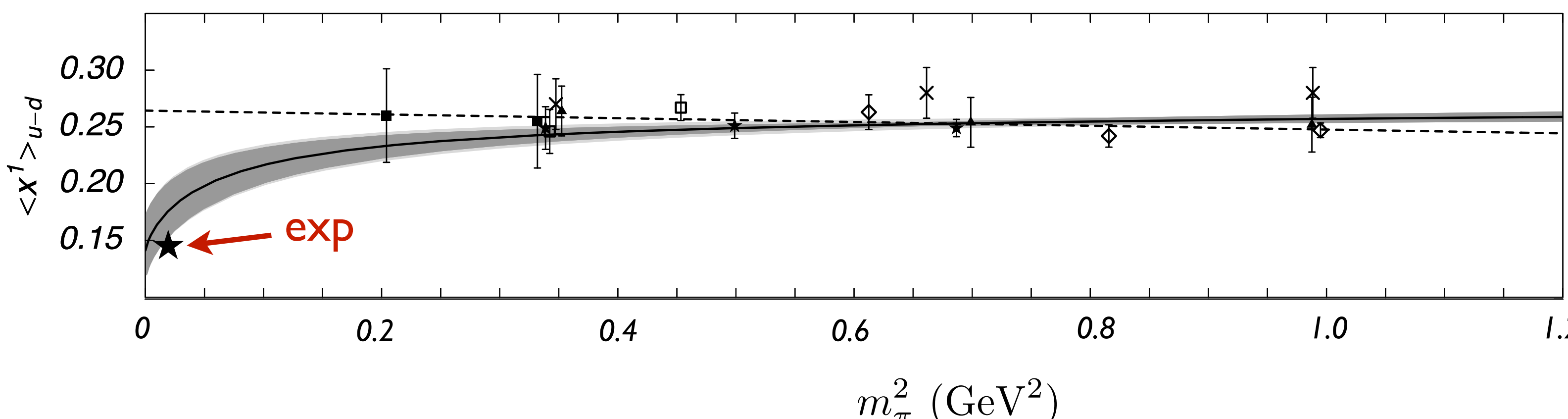
→ coefficients of leading nonanalytic (LNA) terms, reflecting infrared behavior, are *model-independent!*

→ QCD therefore *predicts* a nonzero asymmetry from π loops

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

Thomas, WM, Steffens (2000)

→ nonanalytic behavior vital for understanding lattice data on PDF moments at low m_π



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

Detmold, WM, Thomas (2001)

Chiral effective field theory

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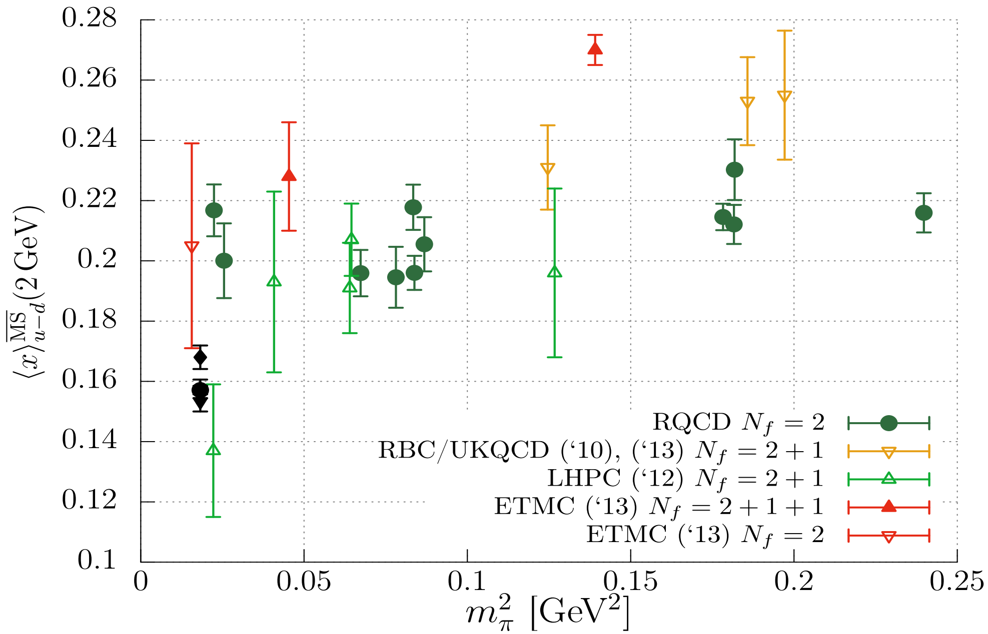


Bali et al. (2014)

Chiral effective field theory

- For point-like nucleons and pions, integrals divergent

  → finite size of nucleon provides natural regularization scale (but does not prescribe form of regularization)

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

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

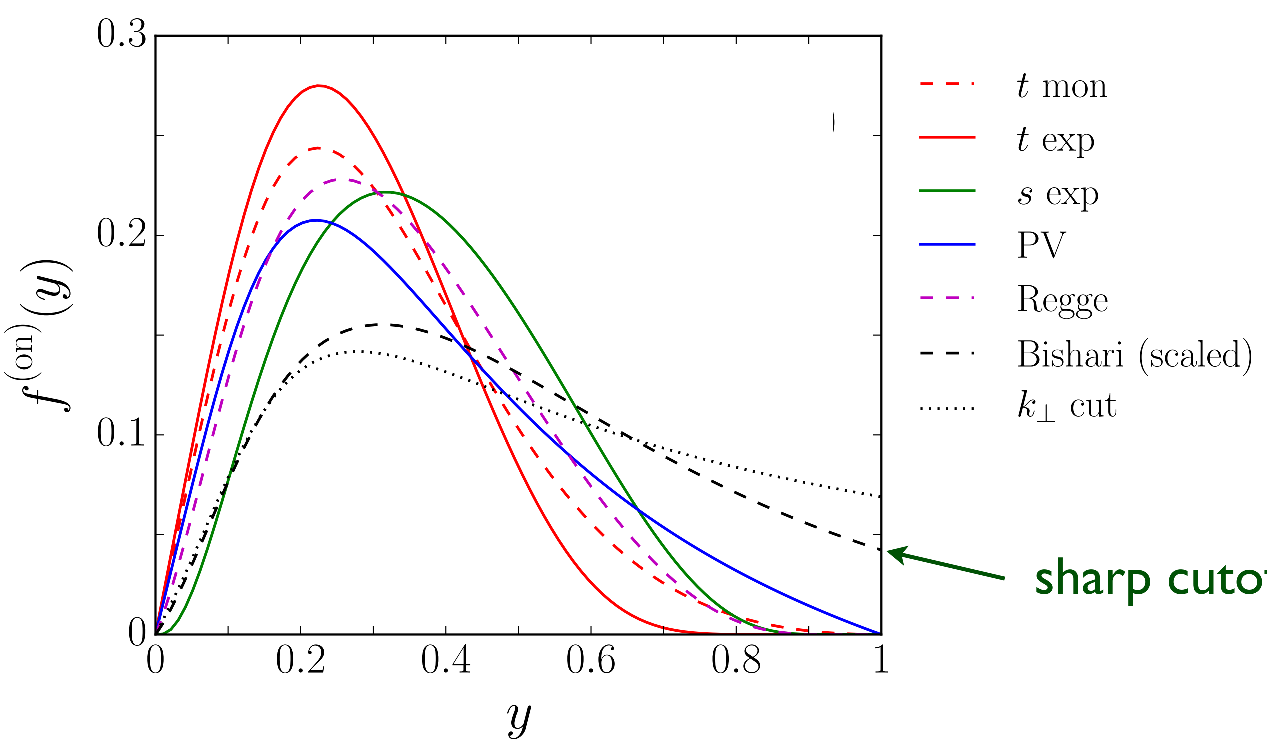
$\mathcal{F} = \left(\dfrac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ t monopole

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

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

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

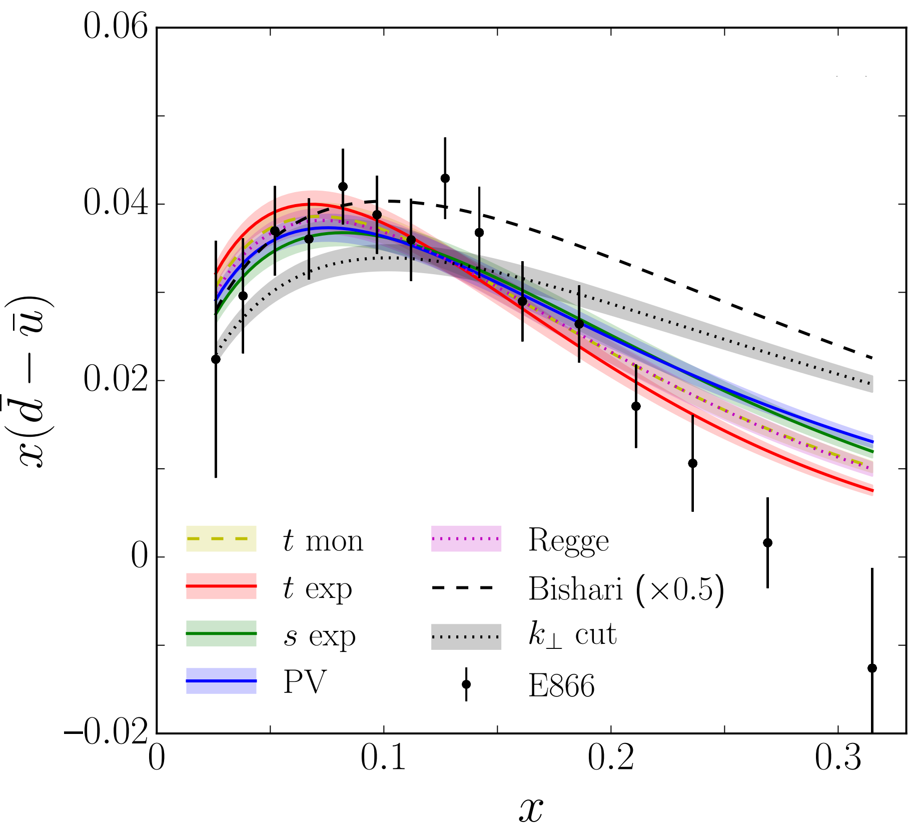
e.g. on-shell function



sharp cutoffs

Chiral effective field theory

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



average pion "multiplicity"

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

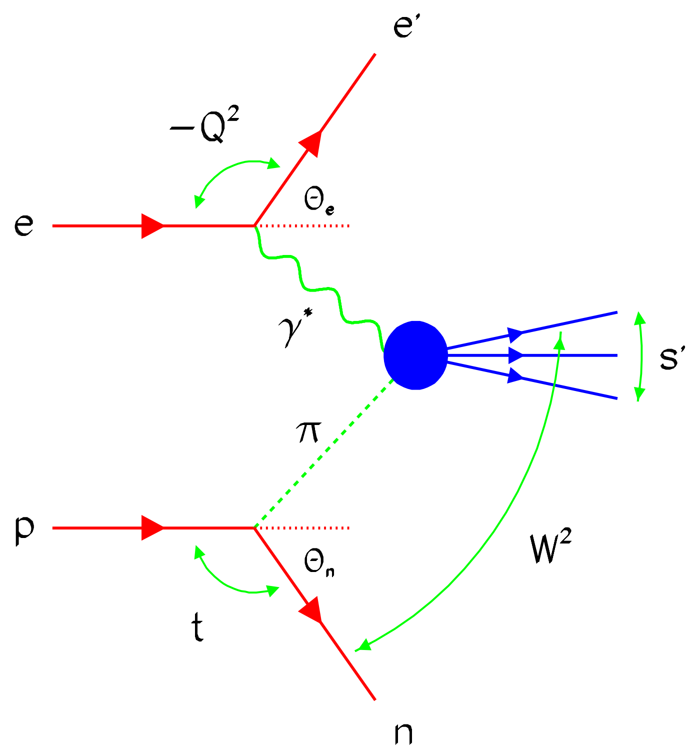
$$\sim \; 0.25 - 0.3$$

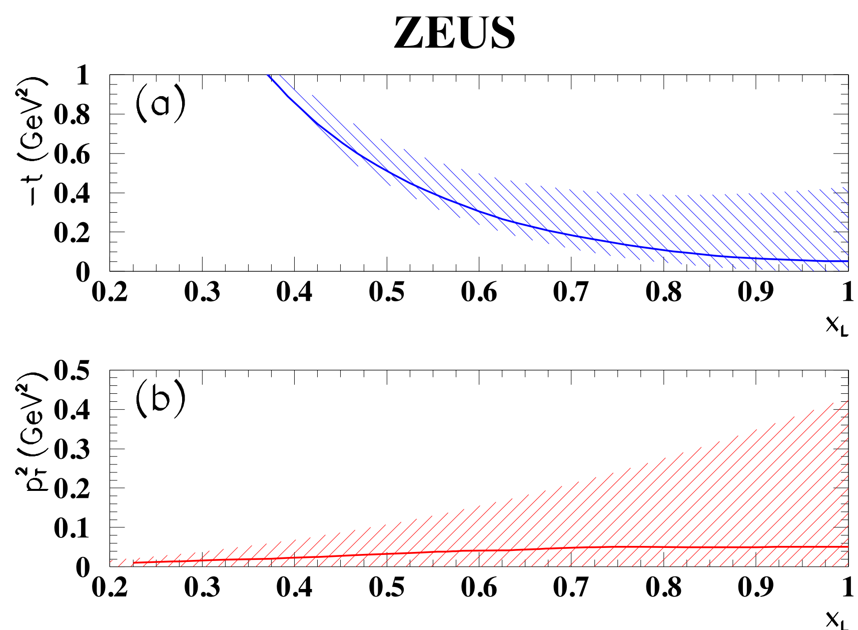
→ with exception of $k_\perp$ cutoff and Bishari models, all others give reasonable fits, $\chi^2 \lesssim 1.5$

→ 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





$x_L \approx 1 - y$

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

→ simultaneous fit never previously been performed!

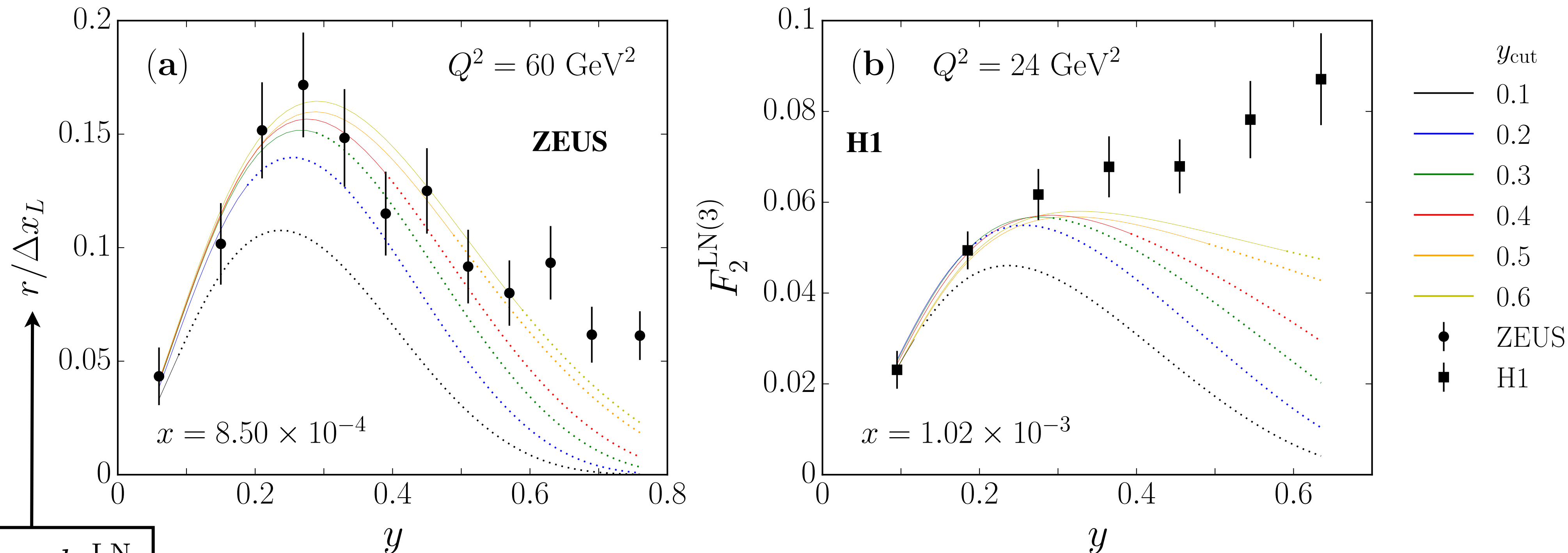
Leading neutron production at HERA

- 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.

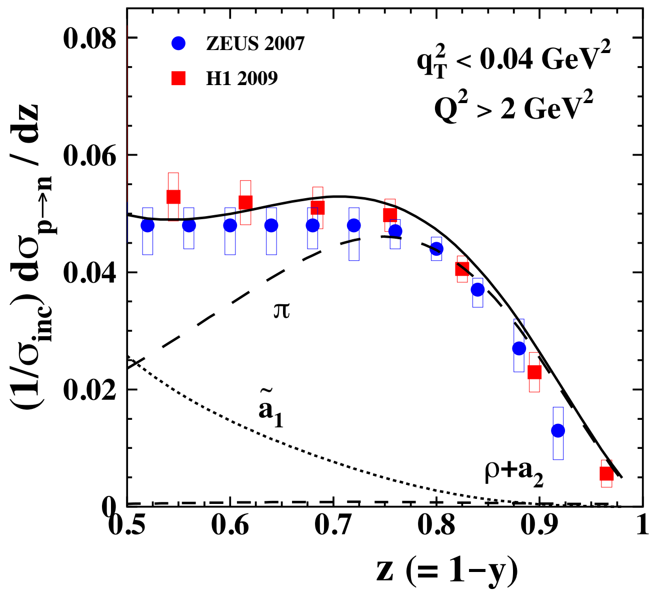


$$r = \frac{d\sigma^{\rm LN}}{d\sigma^{\rm inc}}$$

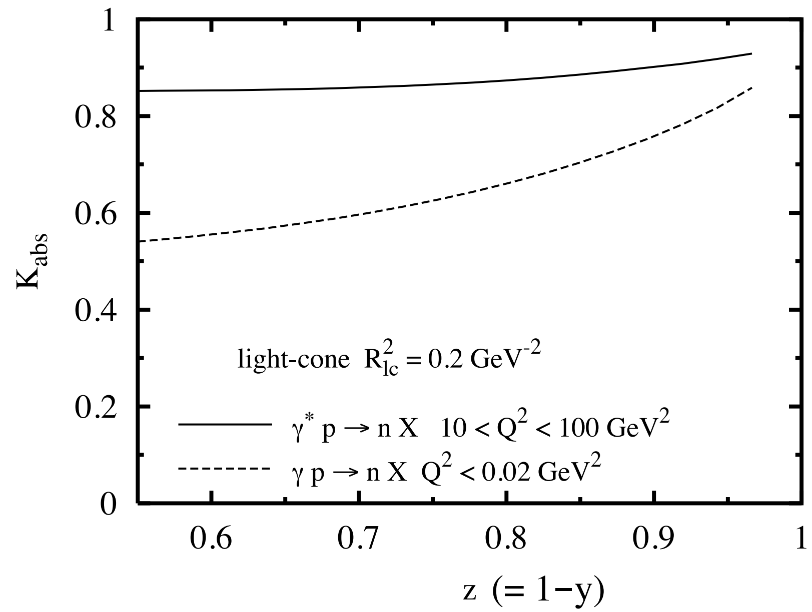
$\longrightarrow$ quality of fit depends on range of y fitted

Leading neutron production at HERA

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



Kopeliovich et al. (2012)

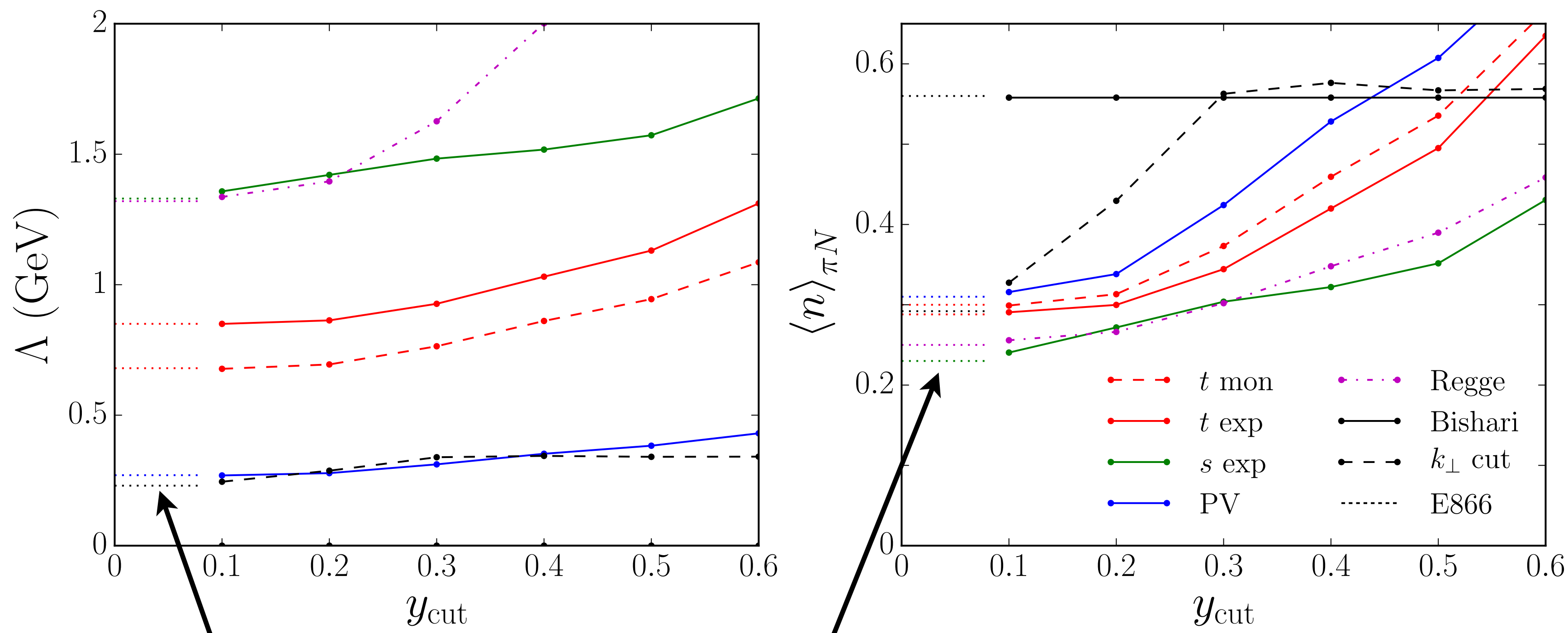


D'Alesio, Pirner (2000)

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

Leading neutron production at HERA

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

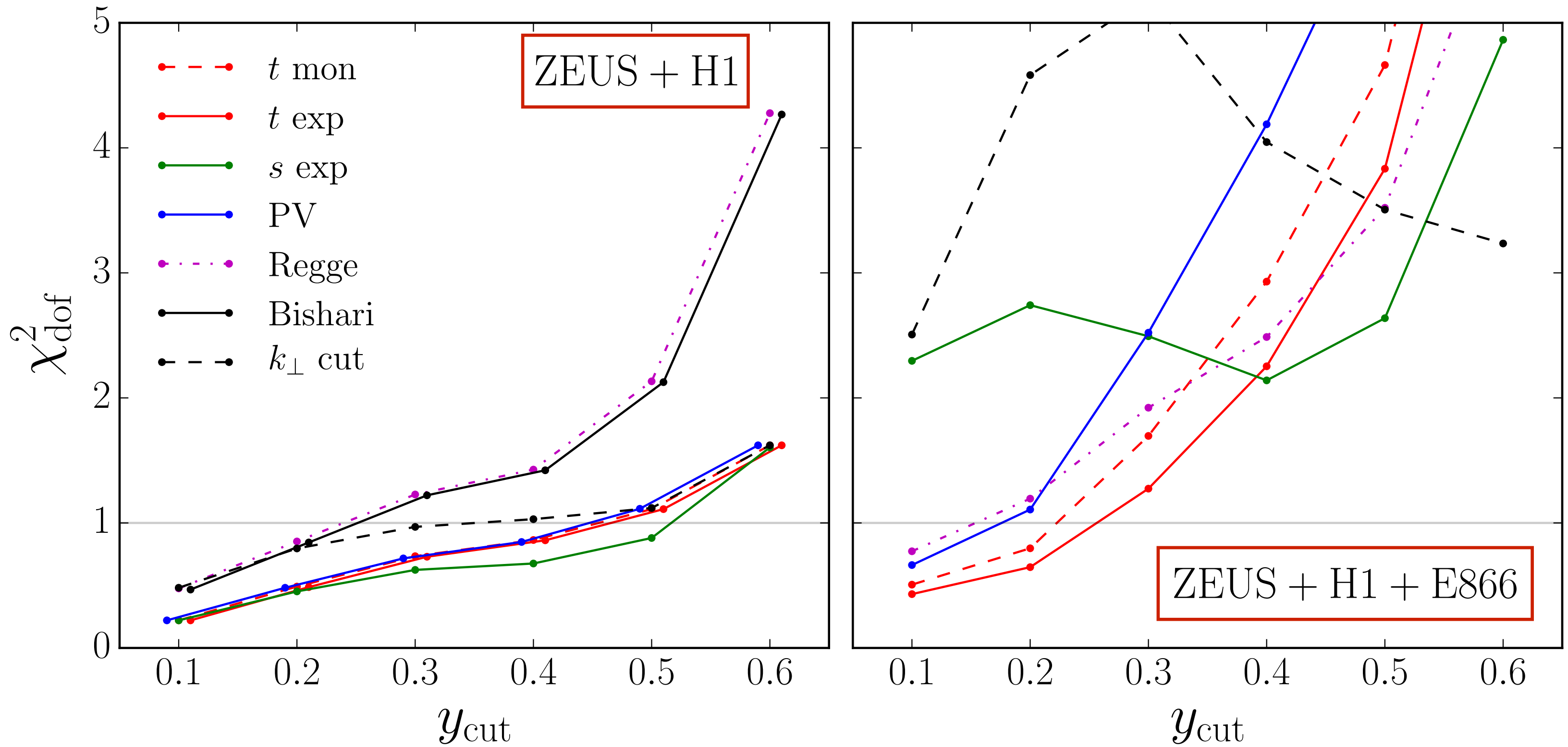


values from fit to E866 data only

$\longrightarrow$ 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



Leading neutron production at HERA

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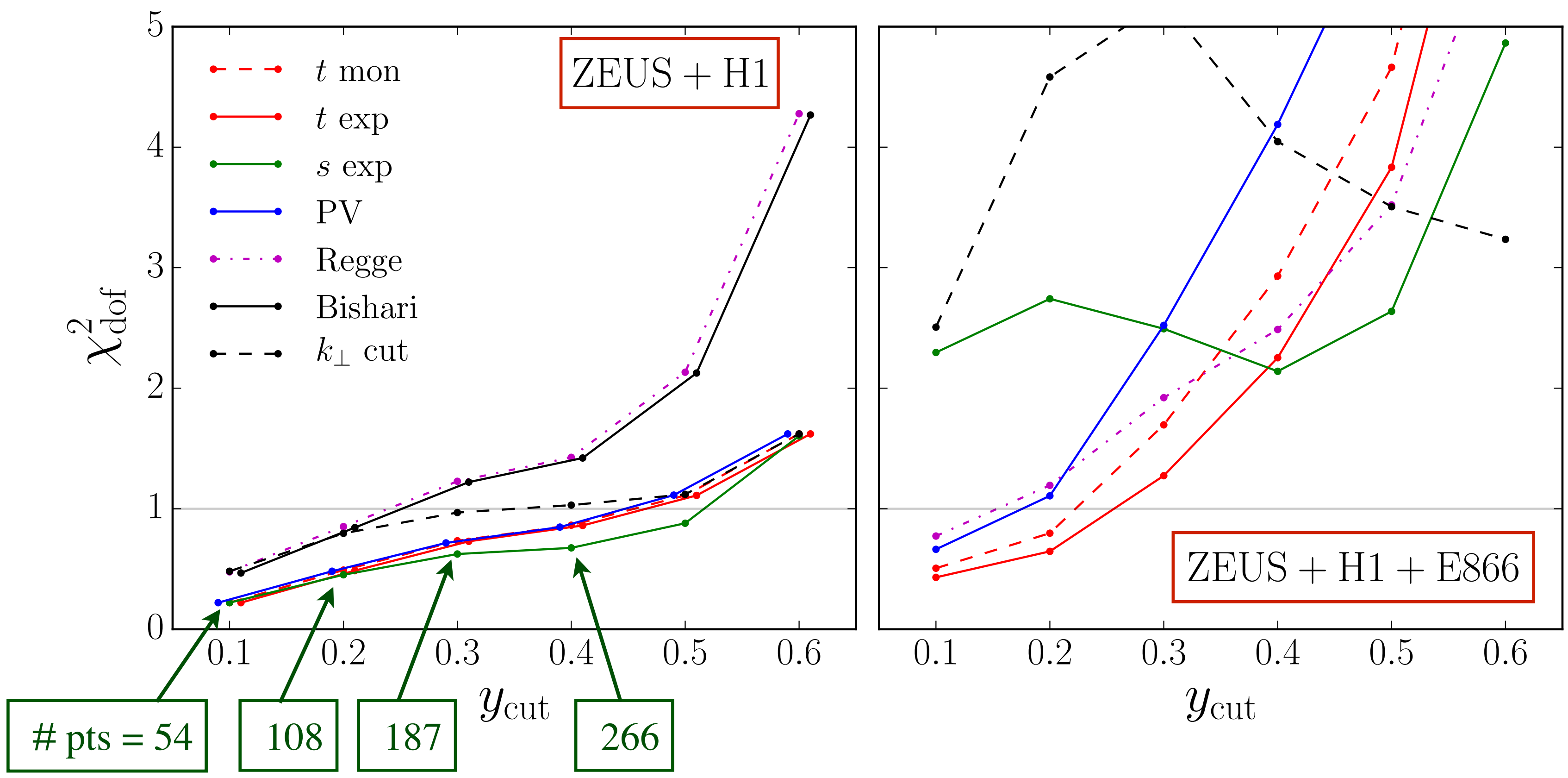
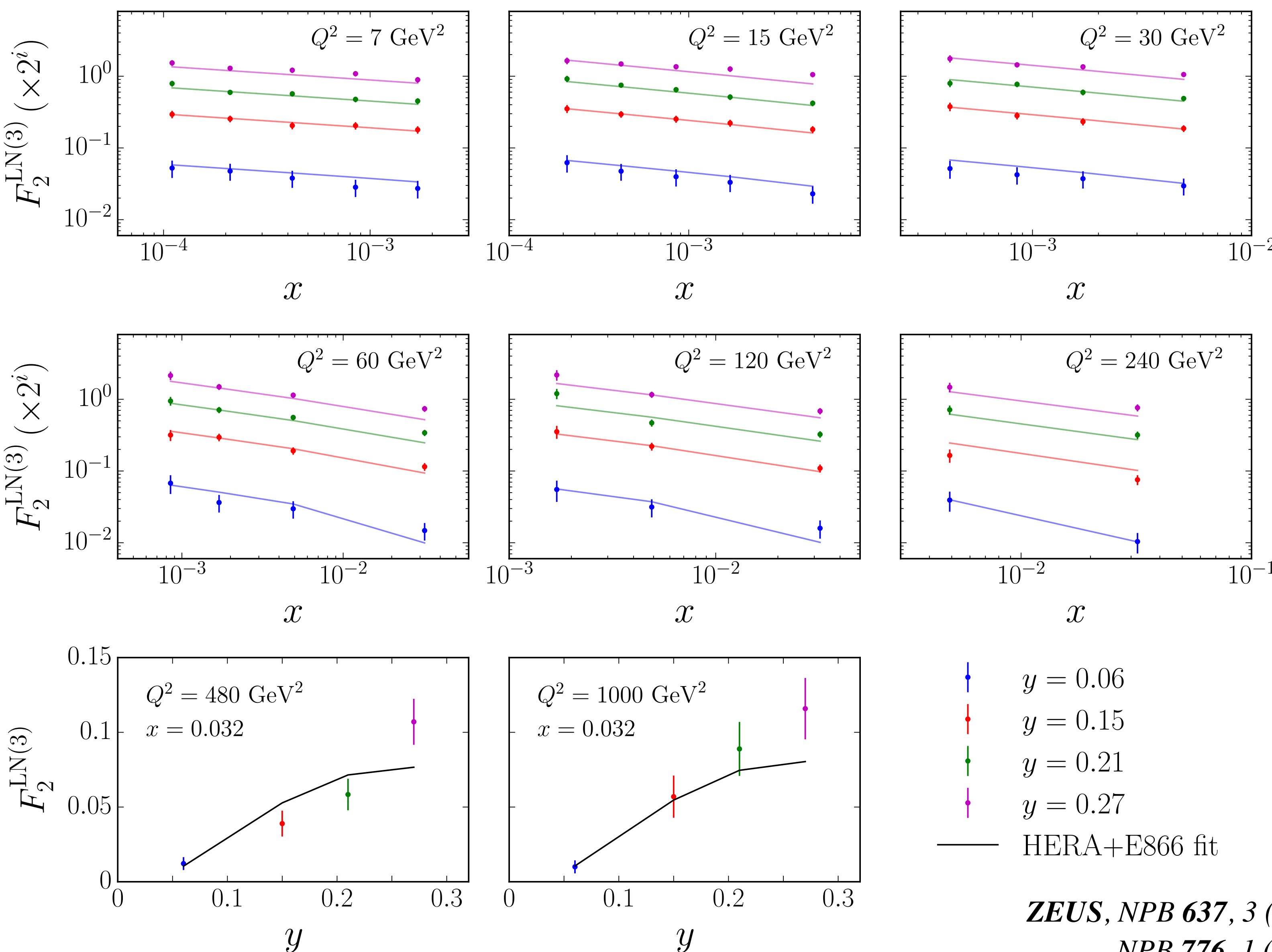


→ best fits for largest number of points afforded by t-dependent exponential (and t monopole) regulators

Leading neutron production at HERA

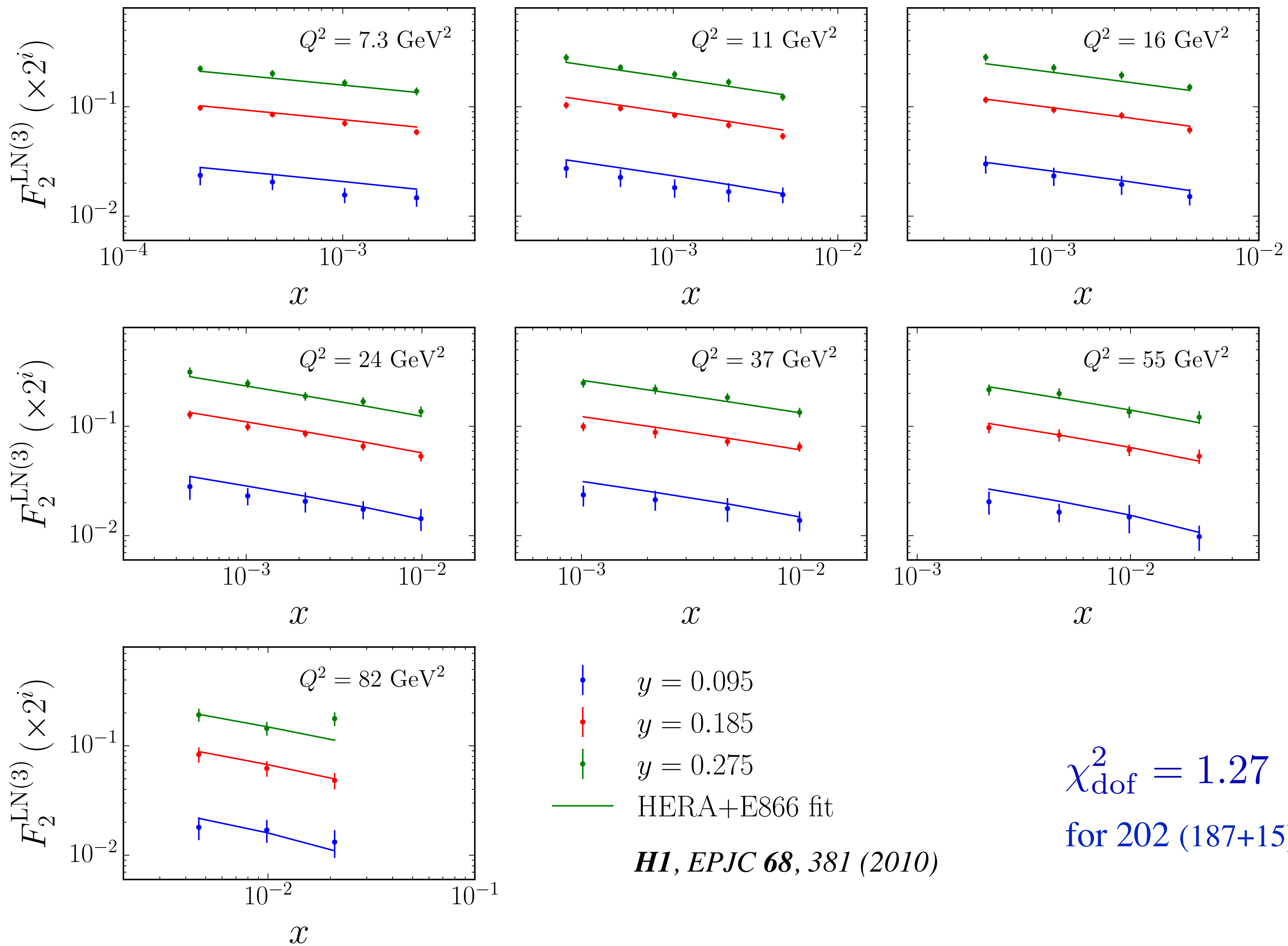
- Fit to ZEUS LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)



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

Leading neutron production at HERA

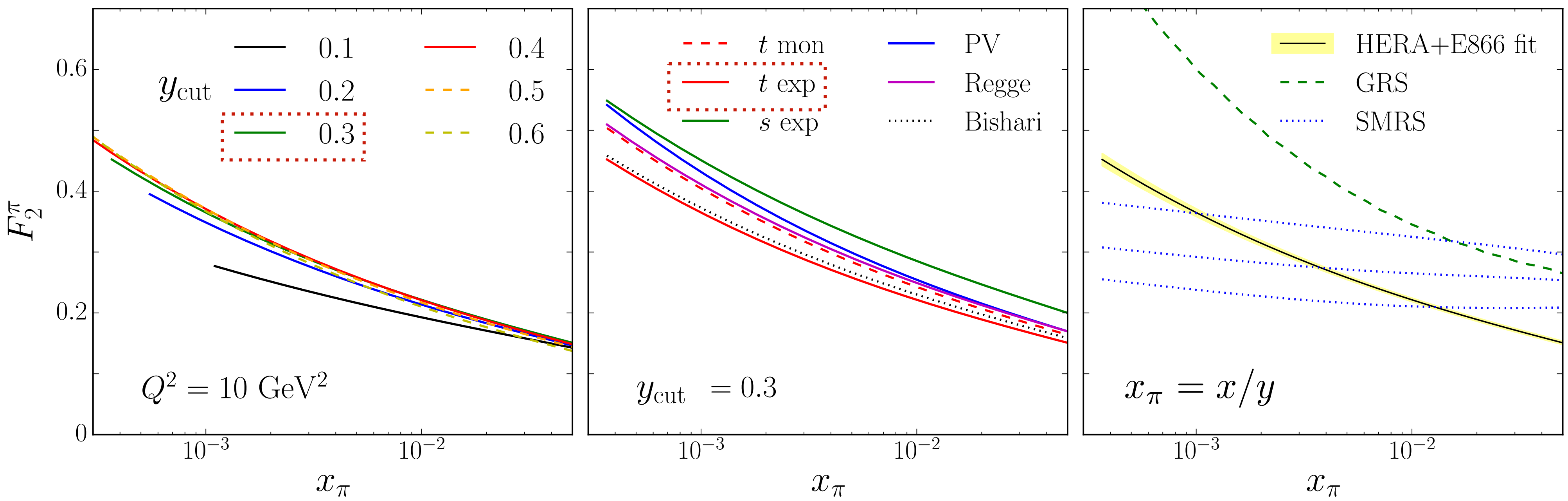
- Fit to H1 LN spectra for $y_{\mathrm{cut}} = 0.3$ (t-dependent exponential)



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

for 202 (187+15) points

Extracted pion structure function

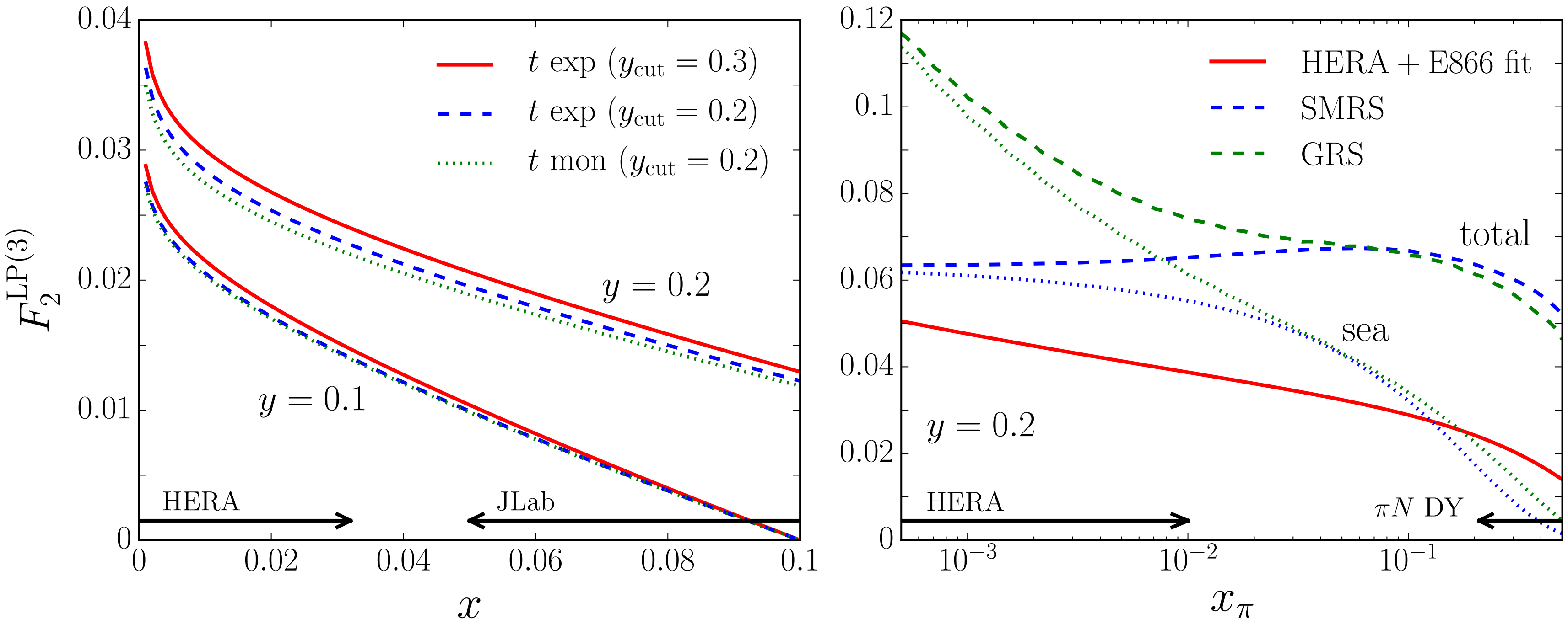


$$F_2^\pi = N\, x_\pi^a\, (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta$$
$$\eta \sim \log(\log Q^2)$$

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



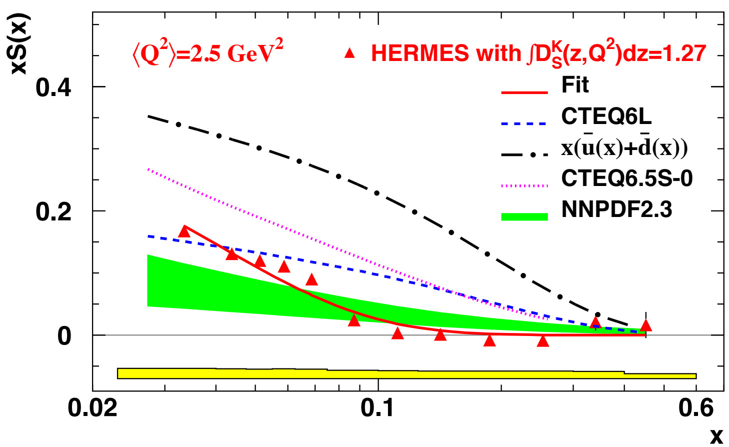
→ JLab TDIS experiment can fill gap in x_π coverage between HERA and πN Drell-Yan kinematics

Strange quarks

- Traditionally, strange quark PDFs most directly determined from $\mu^+\mu^-$ production in $\nu(\bar{\nu})\,A$ DIS $(W^+ s \to c \;/\; W^- \bar{s} \to \bar{c})$

  → but significant uncertainty from nuclear corrections, semileptonic branching ratio uncertainty

  → tension with HERMES semi-inclusive K-production data?



historically, strange to nonstrange ratio

$$\kappa = \frac{s+\bar{s}}{\bar{u}+\bar{d}} \sim 0.2-0.5$$

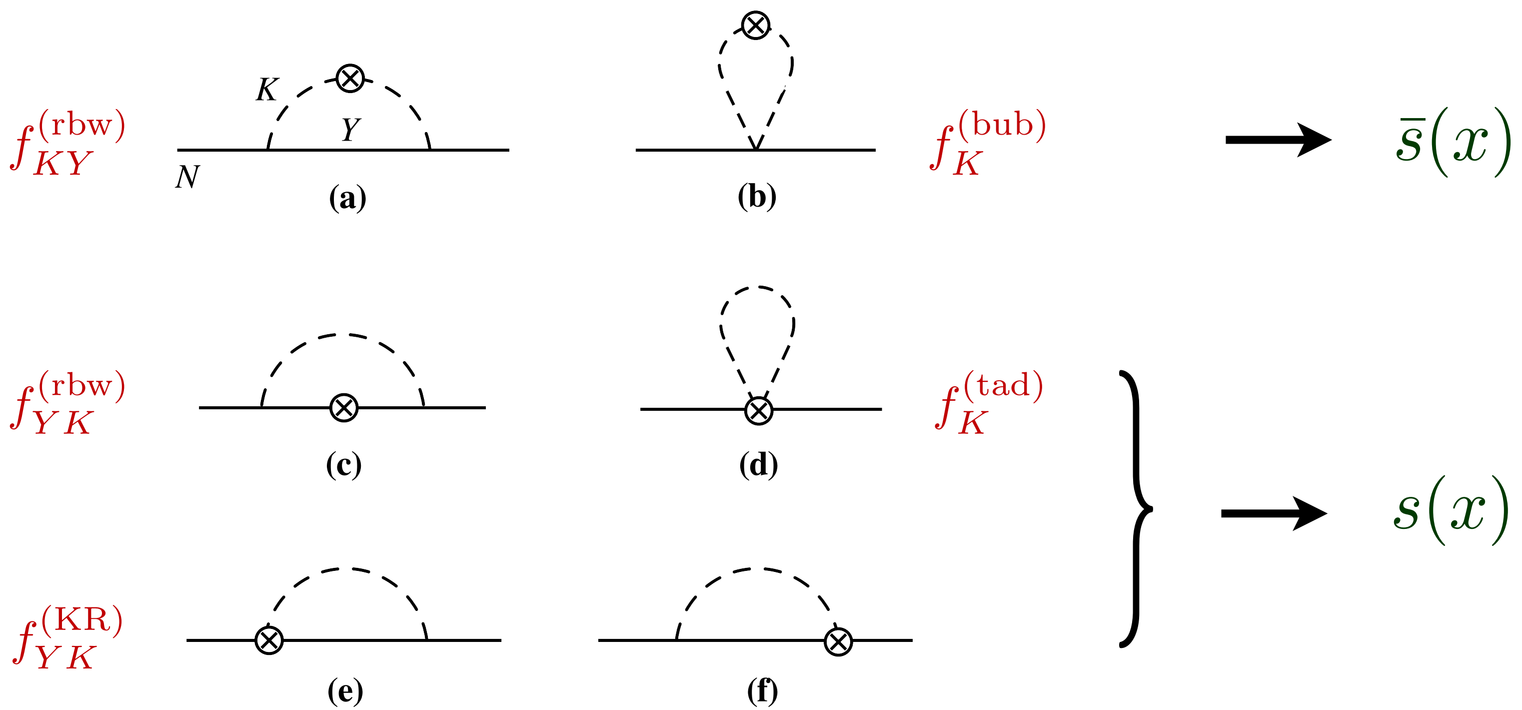
- Some indication of strange–antistrange asymmetry from $\nu/\bar{\nu}$ DIS data

$$S^- = \int_0^1 dx\, x(s-\bar{s}) = (2.0 \pm 1.4)\times 10^{-3}$$

NuTeV (2007)

Strange quarks

- Chiral SU(3) effective theory analysis suggests natural mechanism for generating strange asymmetry



→ gauge invariance requires the relations

$$f_{YK}^{(\mathrm{rbw})} + f_{YK}^{(\mathrm{KR})} = f_{KY}^{(\mathrm{rbw})}$$

$$f_{K}^{(\mathrm{tad})} + f_{K}^{(\mathrm{bub})} = 0$$

Strange quarks

Convolution representation

$$\bar{s} = \left(f_{KY}^{(\mathrm{rbw})} + f_{K}^{(\mathrm{bub})} \right) \otimes \bar{s}_K$$

$$s = \left(\bar{f}_{YK}^{(\mathrm{rbw})} \otimes s_Y + \bar{f}^{(\mathrm{KR})} \otimes s_Y^{(\mathrm{KR})} \right) + \bar{f}_{K}^{(\mathrm{tad})} \otimes s_K^{(\mathrm{tad})}$$

$\bar{f}(y) \equiv f(1-y)$; $\sim \Delta u, \Delta d$; $\sim u, d$

→ *KY* splitting functions regularized using Pauli-Villars regularization

→ δ-function term requires 2 subtractions (parameters μ_1, μ_2)

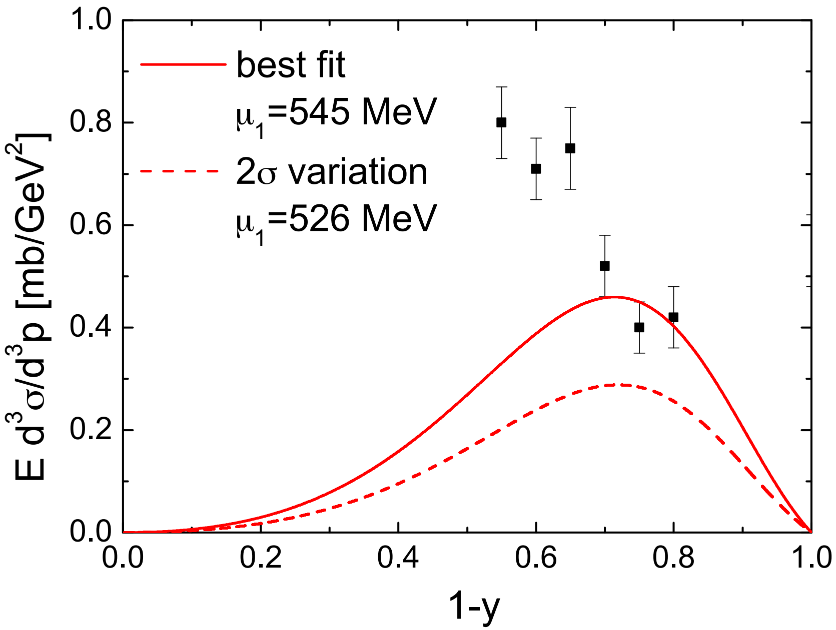
→ since $f_K^{(\mathrm{tad})}(y) \sim \delta(y)$, tadpole term generates *valence-like* strange-quark PDF

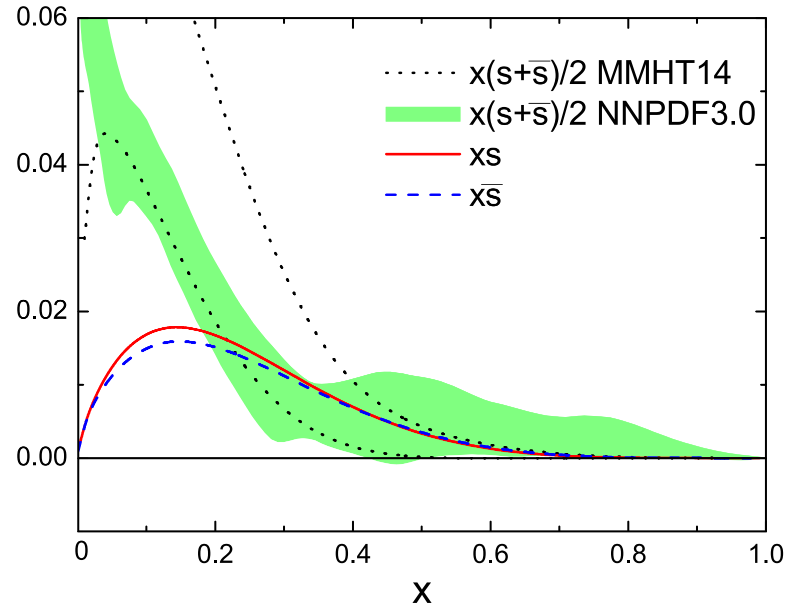
$$\sim \; s_K^{(\mathrm{tad})}(x)$$

X. Wang *et al.*
PRD94, 094035 (2016)

Strange quarks

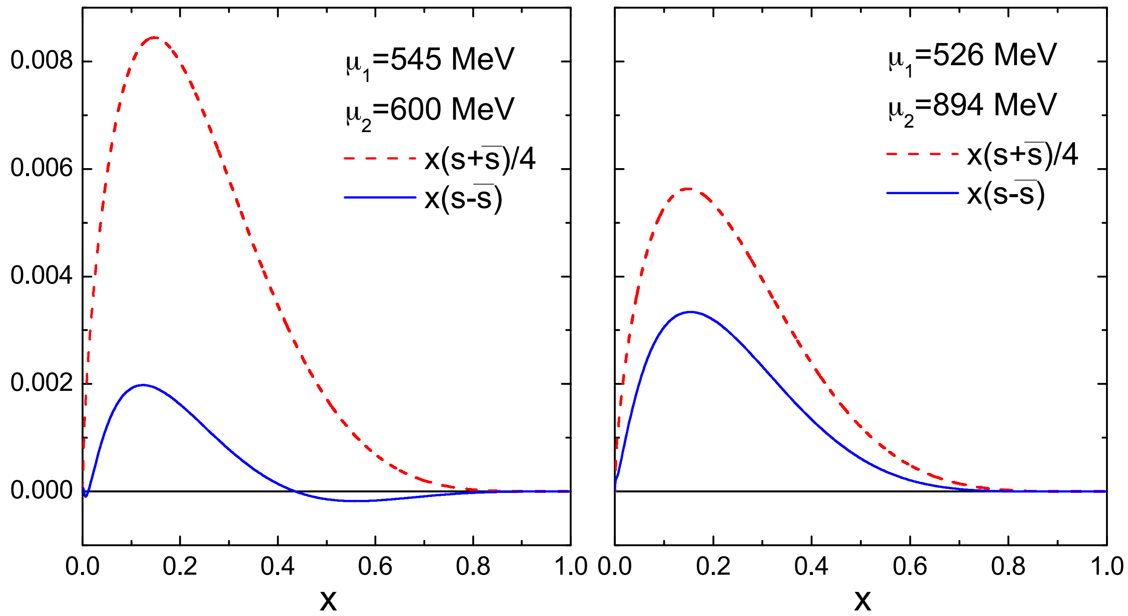
- Constraints on cutoff parameters from $pp \to \Lambda X$ and total $(s+\bar{s})_{\rm loops} \leq (s+\bar{s})_{\rm total}$





Strange quarks

- Gives rise to small but (mostly) positive $s - \bar{s}$ distribution



→ x-weighted difference $S^{-} = (0.4 - 1.1) \times 10^{-3}$

Outlook

- Eagerly await final SeaQuest data!

  $\longrightarrow$ settle question of sign change in $\bar{d} - \bar{u}$ at high x

- Combine "leading neutron" analysis with πN Drell-Yan data to constrain pion PDFs at low and high x

  $\longrightarrow$ talk by Nobuo Sato

- Compare chiral SU(3) predictions for $s - \bar{s}$ asymmetry with future lattice and experimental (SIDIS?) data