Workshop on Deep Inelastic Scattering and Related Topics
Birmingham, April 4, 2017

Insights into sea quark asymmetries from global PDF analysis

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CTEQ-Jefferson Lab (CJ) collaboration
http://www.jlab.org/CJ

Outline

- Asymmetries between various PDFs $(\bar{d}-\bar{u},\ s-\bar{s},\ \Delta\bar{u}-\Delta\bar{d}\ldots)$ reveal nonperturbative structure of the nucleon

- $\bar{d}-\bar{u}$ asymmetry and chiral symmetry in QCD: a brief history

- Evidence of sign change at large x?

- New (preliminary) $\mathrm{SeaQuest}$ data

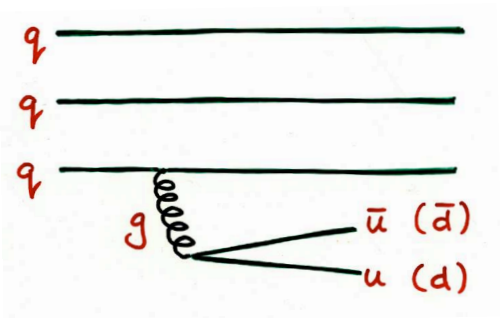
  $\longrightarrow$ constraint on $\bar{d}-\bar{u}$ at large x

  $\longrightarrow$ implications for pion cloud models and pion structure function extraction

- Outlook

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)

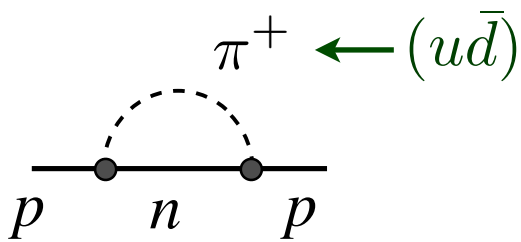


$\longrightarrow$ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

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

Ross, Sachrajda (1979)

- Thomas suggested that chiral symmetry of QCD (important at low energy) should have consequences for antiquark PDFs in nucleon (measured at high energy)

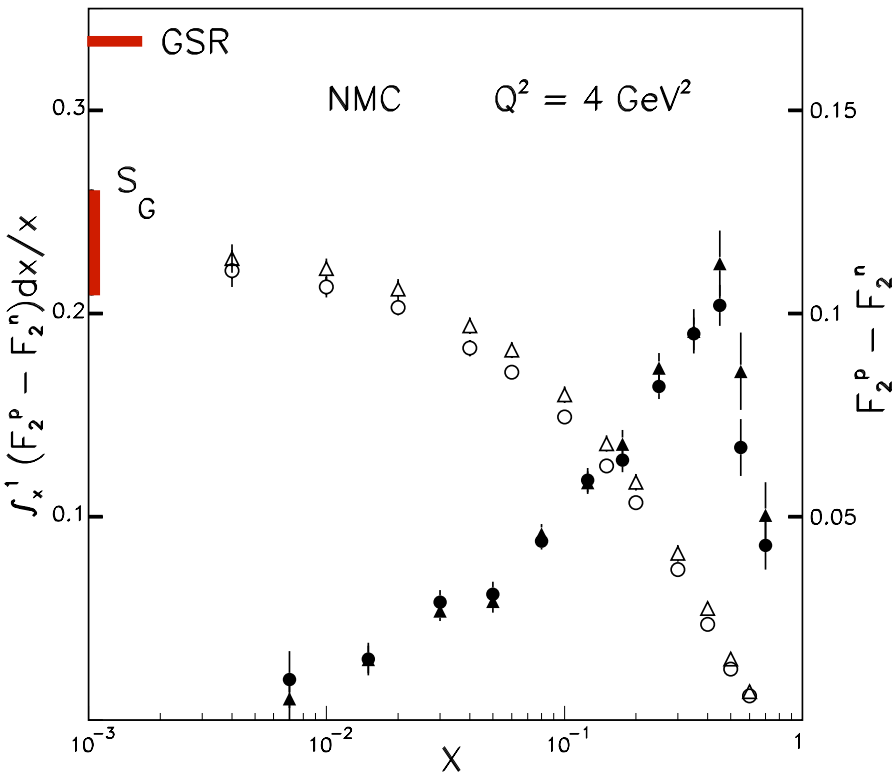


$\longrightarrow$ $\bar{d} > \bar{u}$

A.W. Thomas (1984)

Light quark sea

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



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

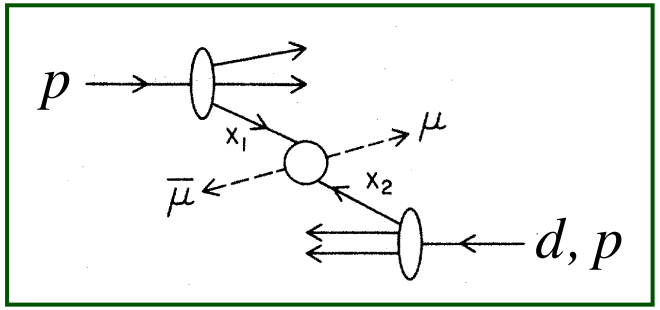
$$S_G \equiv \int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = 0.235 \pm 0.026$$

NMC (1991, 1994)

$\longrightarrow$ clear evidence for $\bar{d} - \bar{u} > 0$ (or at least integrated value)

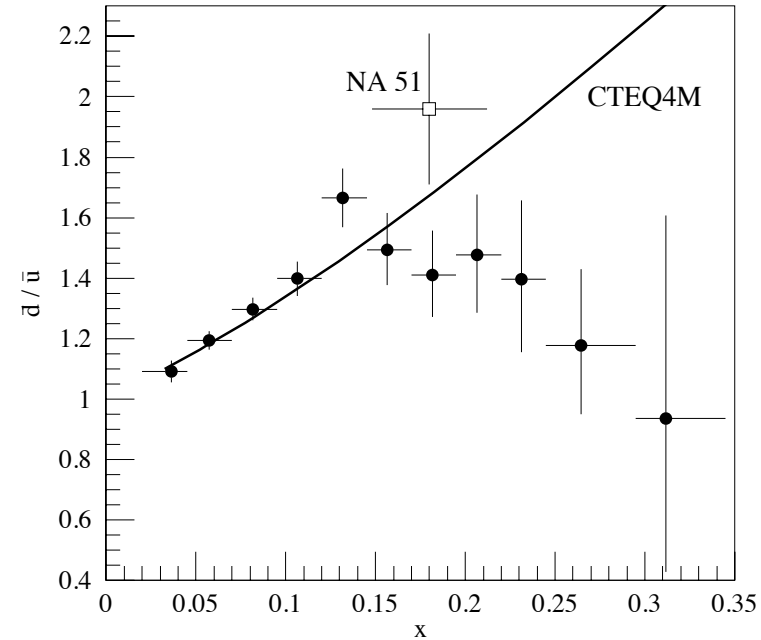
Light quark sea

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



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

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

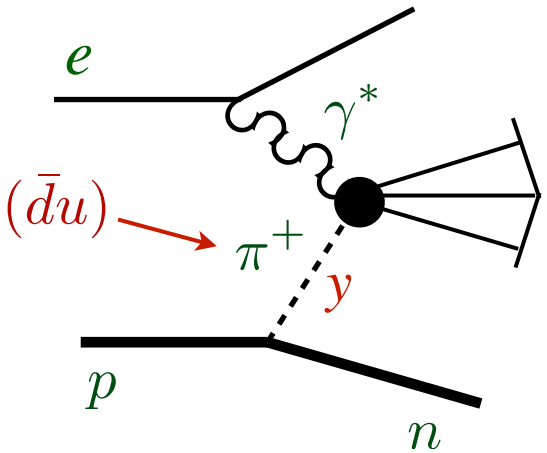


E866 (2001)

$\longrightarrow$ strong enhancement of $\bar{d}$ at $x \sim 0.1 - 0.2$, but intriguing behavior at large x hinting at possible sign change of $\bar{d} - \bar{u}$

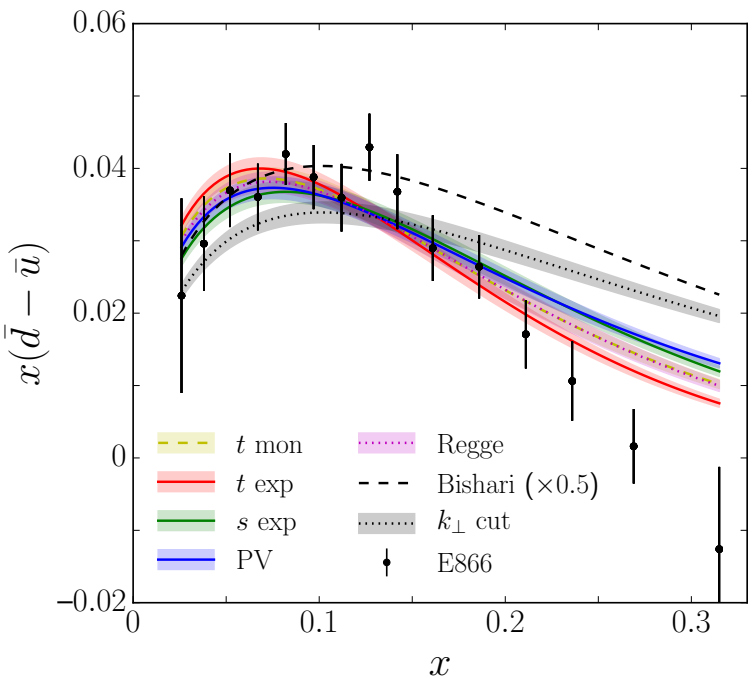
Light quark sea

- 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



→ shape qualitatively reproduced by most models (except at high x), but is there a direct connection with QCD?

Chiral EFT

- Recently rigorous connection with QCD established via chiral effective 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)

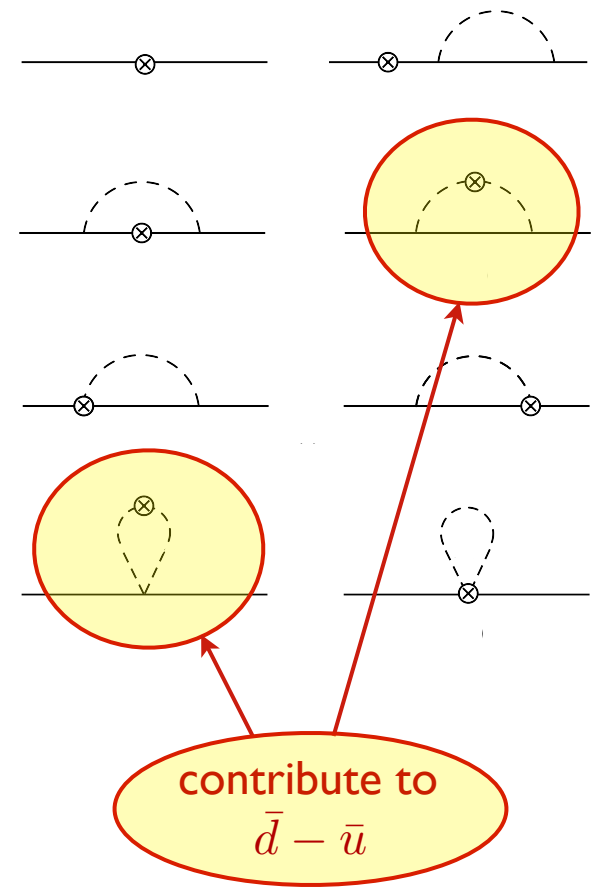
→ lowest order πN interaction includes pion rainbow and tadpole contributions

→ 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 EFT

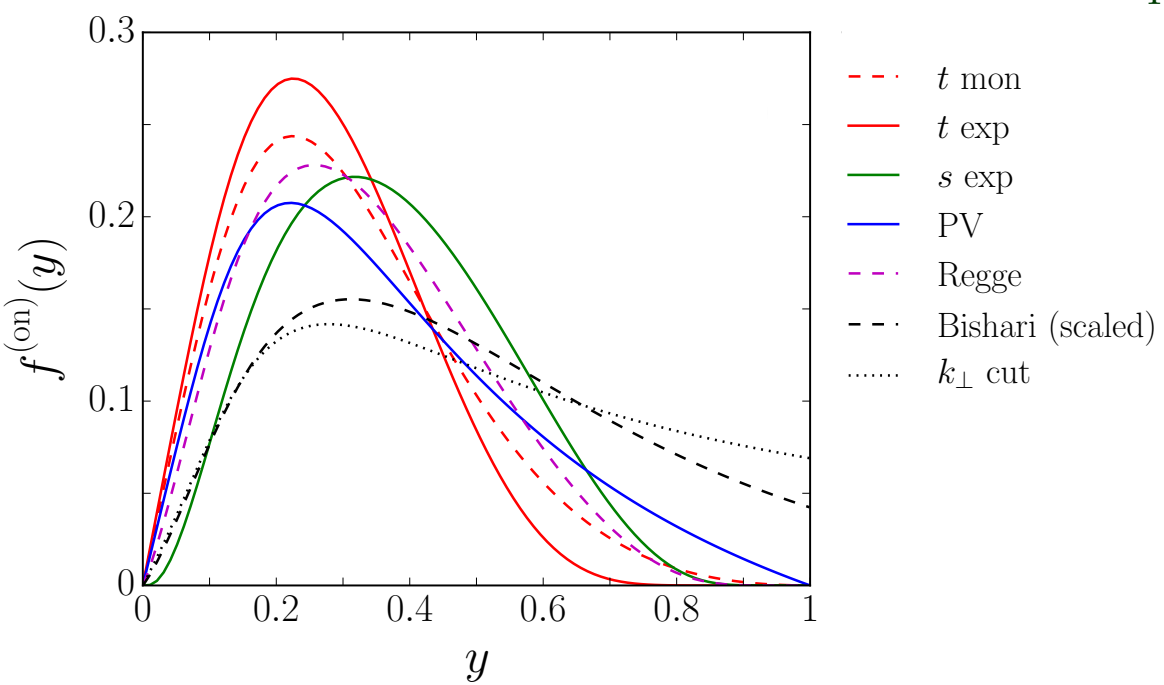
- Recently rigorous connection with QCD established via chiral effective field theory

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

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

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

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



UV regulator

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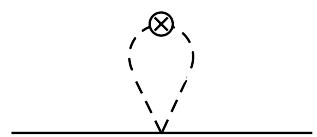
- Bubble diagram contributes only at $y = 0$ (hence $x = 0$)

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



Salamu, Ji, WM, Wang (2015)

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

Chiral EFT

- Expand moments of PDFs in powers of m_π

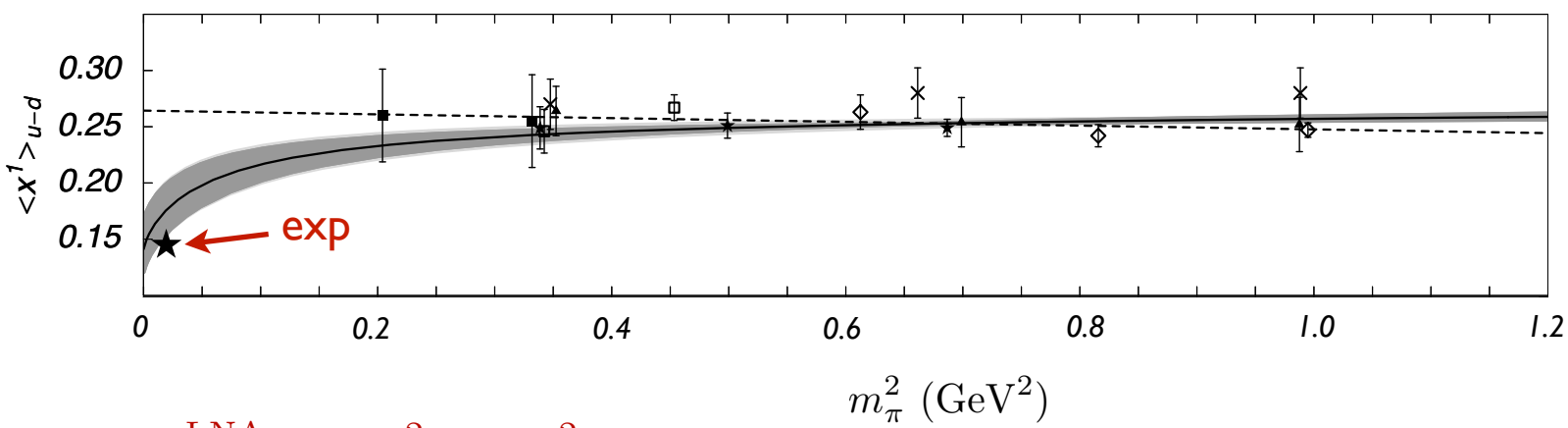
→ coefficients of leading nonanalytic (LNA) terms, reflecting infrared behavior, are model-independent!

→ 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 chiral extrapolation of lattice data on PDF moments from large m_π



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

Detmold et al. (2001)

Chiral EFT

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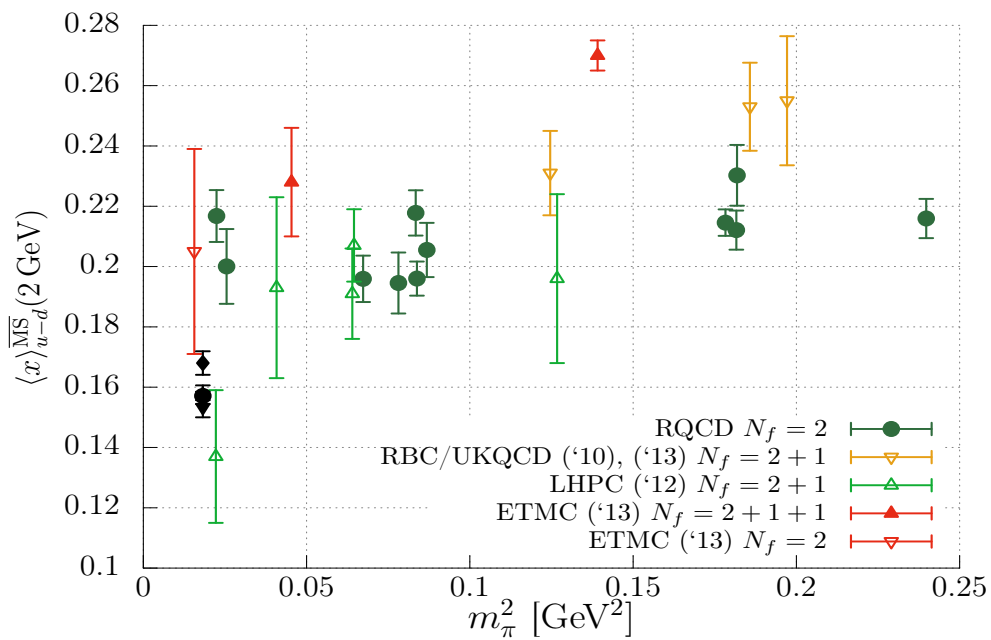


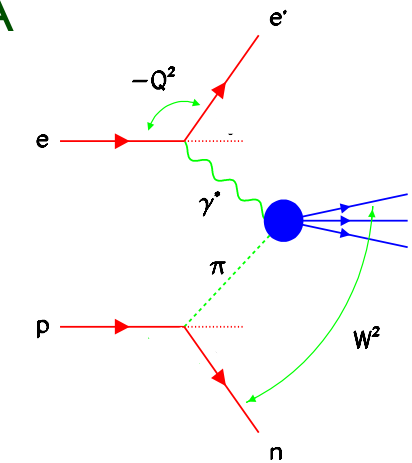
Bali et al. (2014)

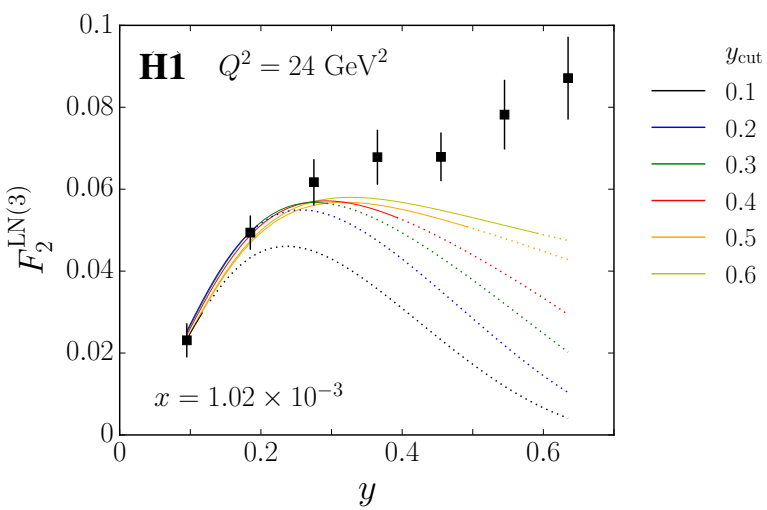
Constraints from leading neutrons

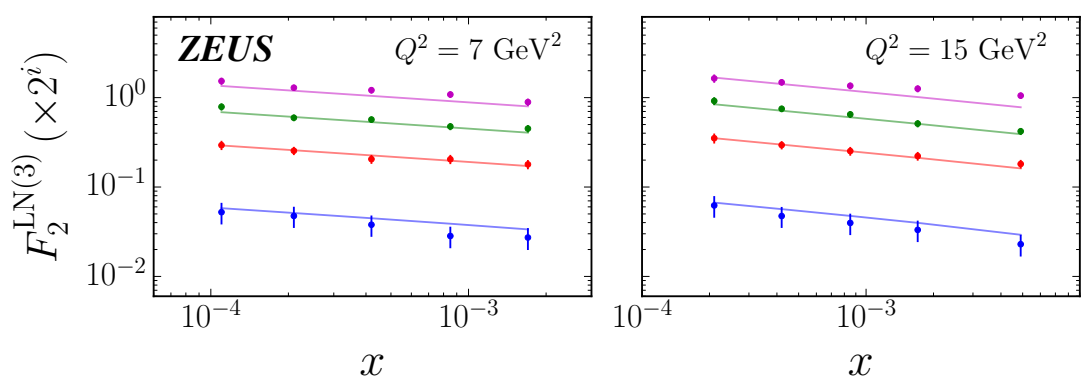
- Drell-Yan $\bar{d} - \bar{u}$ data can be described with range of UV regulators (shapes of pion splitting functions)

  → semi-inclusive production of "leading neutrons" at HERA can discriminate between different shapes

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







McKinney, Ji, WM, Sato (2016)

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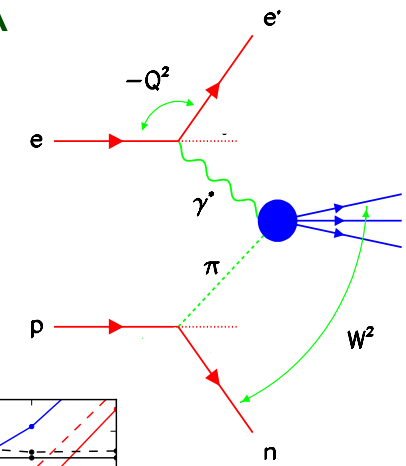

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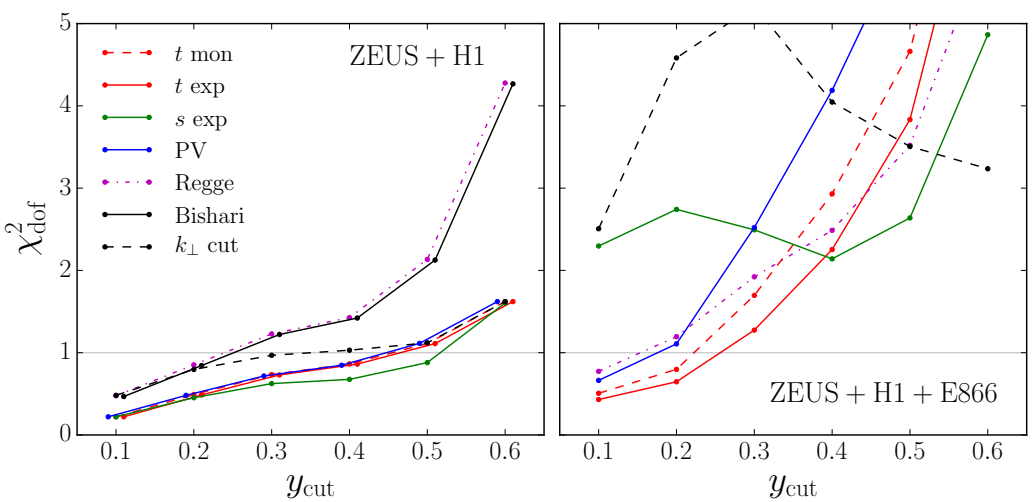

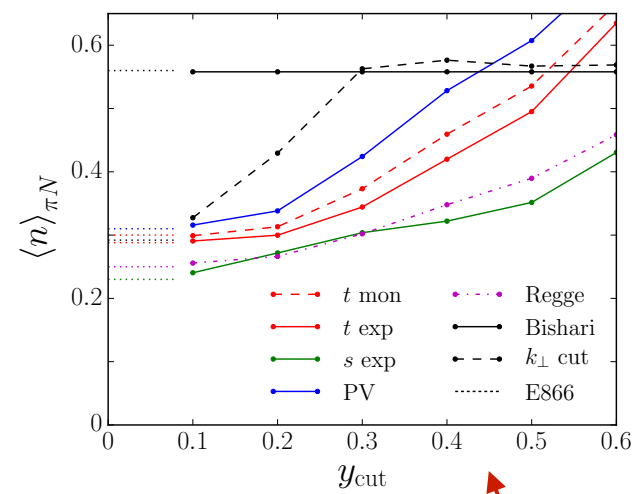

average pion "multiplicity"

$$\langle n \rangle_{\pi N} = 3 \int_0^1 dy\, f_N^{\rm (on)}(y) \sim 0.3$$

→ best fit to combined ZEUS/H1 & DY data for t-dependent exponential regulator

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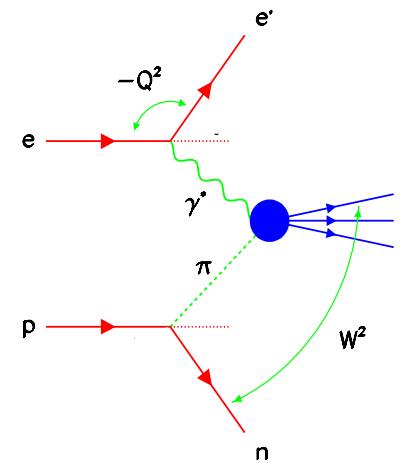
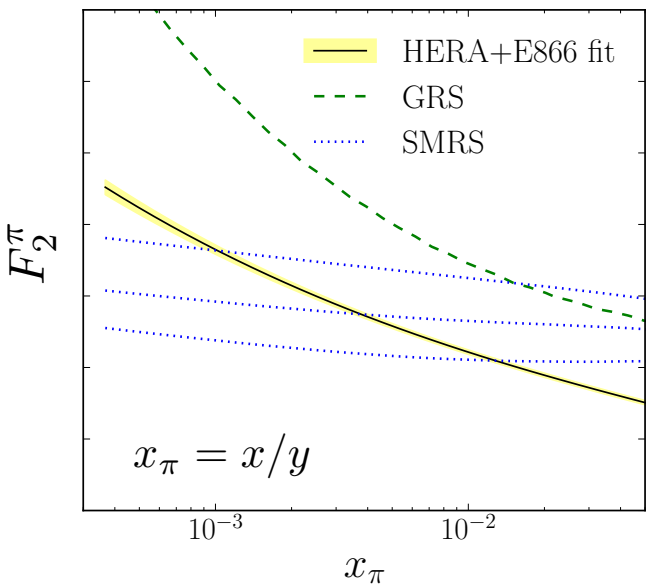




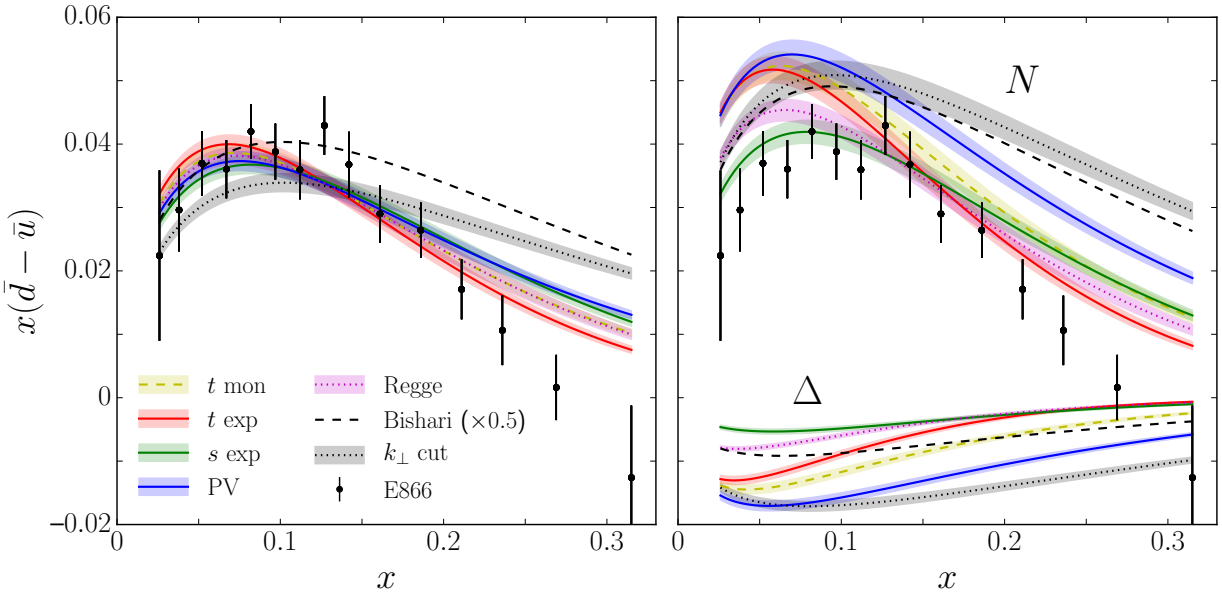
→ constrain shape of F_2^π at $10^{-4} \lesssim x_\pi \lesssim 0.03$ from combined HERA + Drell-Yan fit

→ global analysis under way of HERA LN, Drell-Yan πN + pd/pp (+ upcoming JLab TDIS data) to determine pion PDFs at all x

→ ***C. Keppel (Thu 9:40 am — WG1)***

Sign change at large x?

- E866 data has driven successful phenomenology through interplay of PDFs and chiral physics



… but lingering question of possible sign change of $\bar{d}-\bar{u}$ at high x

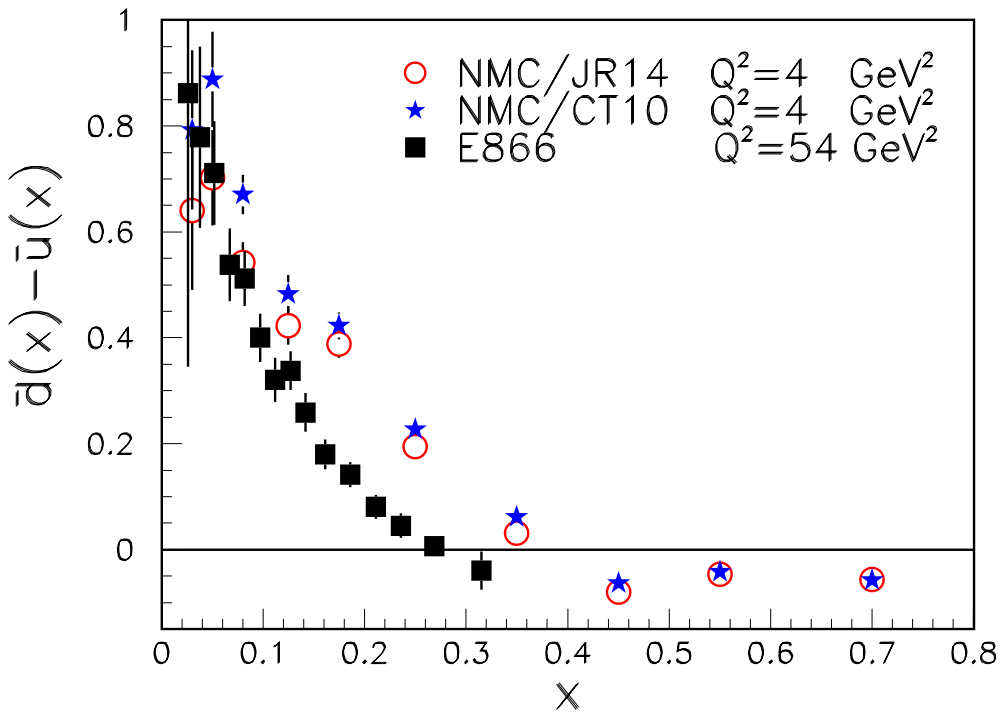
→ sign change cannot be accommodated within chiral EFT framework since (negative) Δ contribution << (positive) N contribution

→ evidence for other mechanisms?

Sign change at large x?

- "Independent evidence for $\bar{d} - \bar{u}$ sign change at $x \sim 0.3$" from NMC

Peng et al., PLB 736 (2014) 411



$$\bar{d} - \bar{u} \equiv \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

$\longrightarrow$ conclusions based on LO analysis … how robust?

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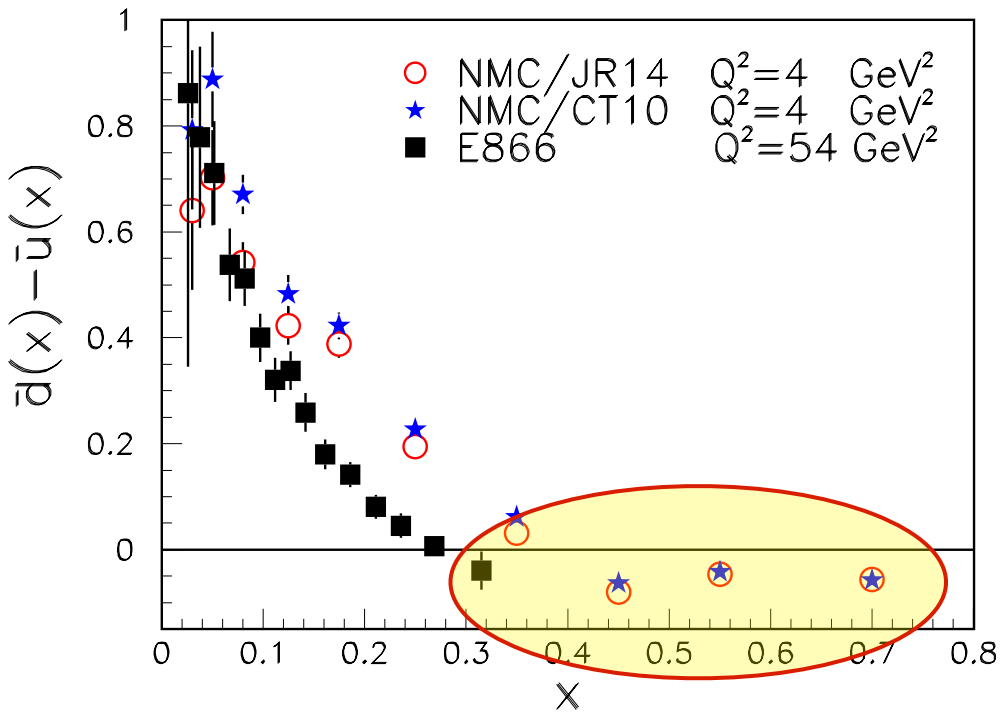

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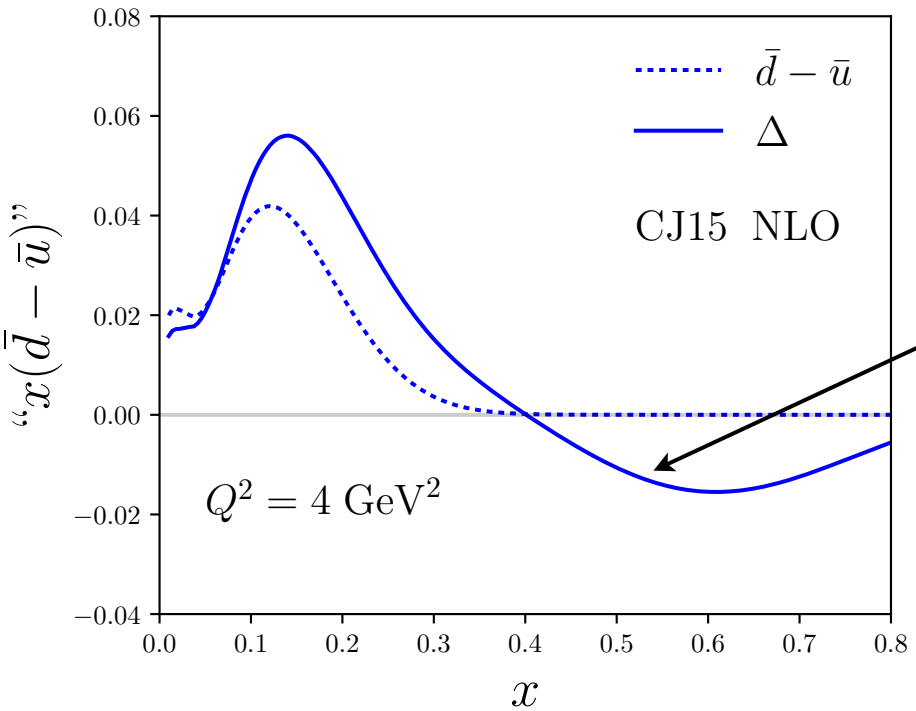
Sign change at large x?

- At higher order can easily generate zero crossing in

$$\Delta \equiv \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

with no $\bar{d} - \bar{u}$ asymmetry!



"sign change" for NMC data

→ no evidence of sign change from DIS data!

Sign change at large x?

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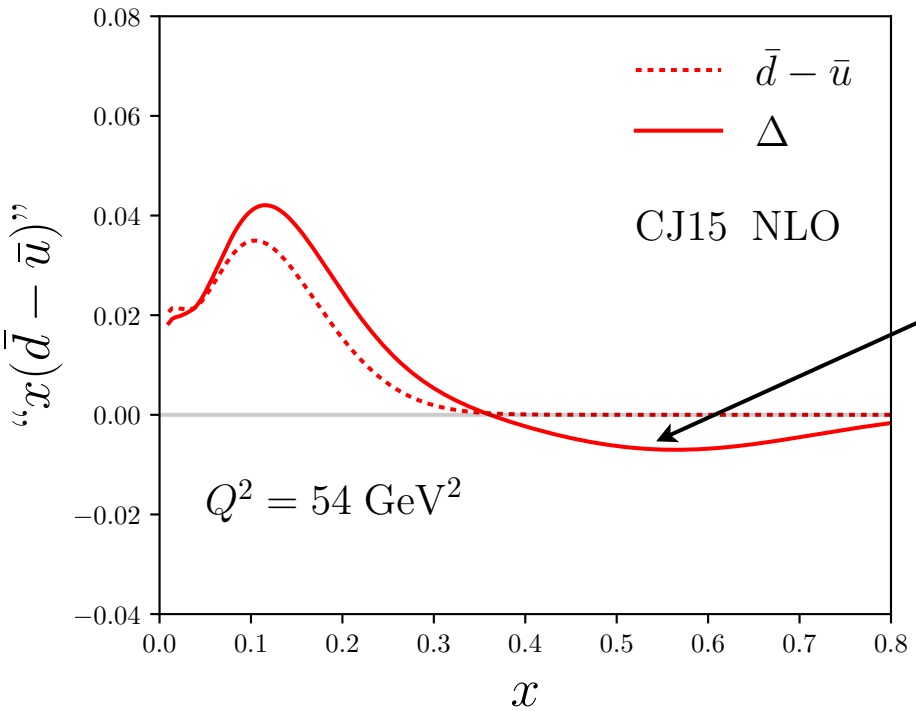
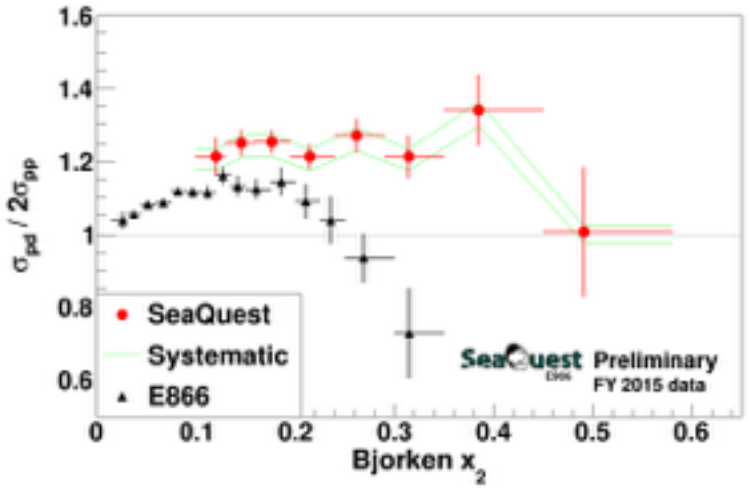
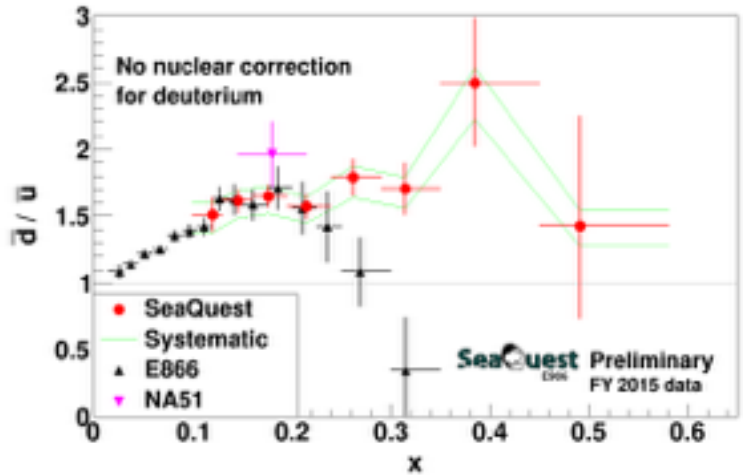


persists at E866 kinematics

Sign change at large x?

- Preliminary data from SeaQuest (E906) Drell-Yan experiment at Fermilab shows no evidence for sign change

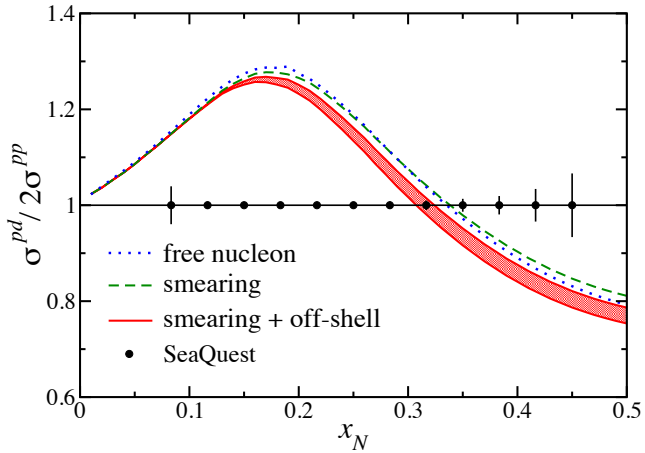




P. Reimer (2016)

→ SeaQuest data consistent with E866 data up to $x \sim 0.2$, remains above unity up to $x \sim 0.5$

→ Results not significantly affected if include nuclear corrections

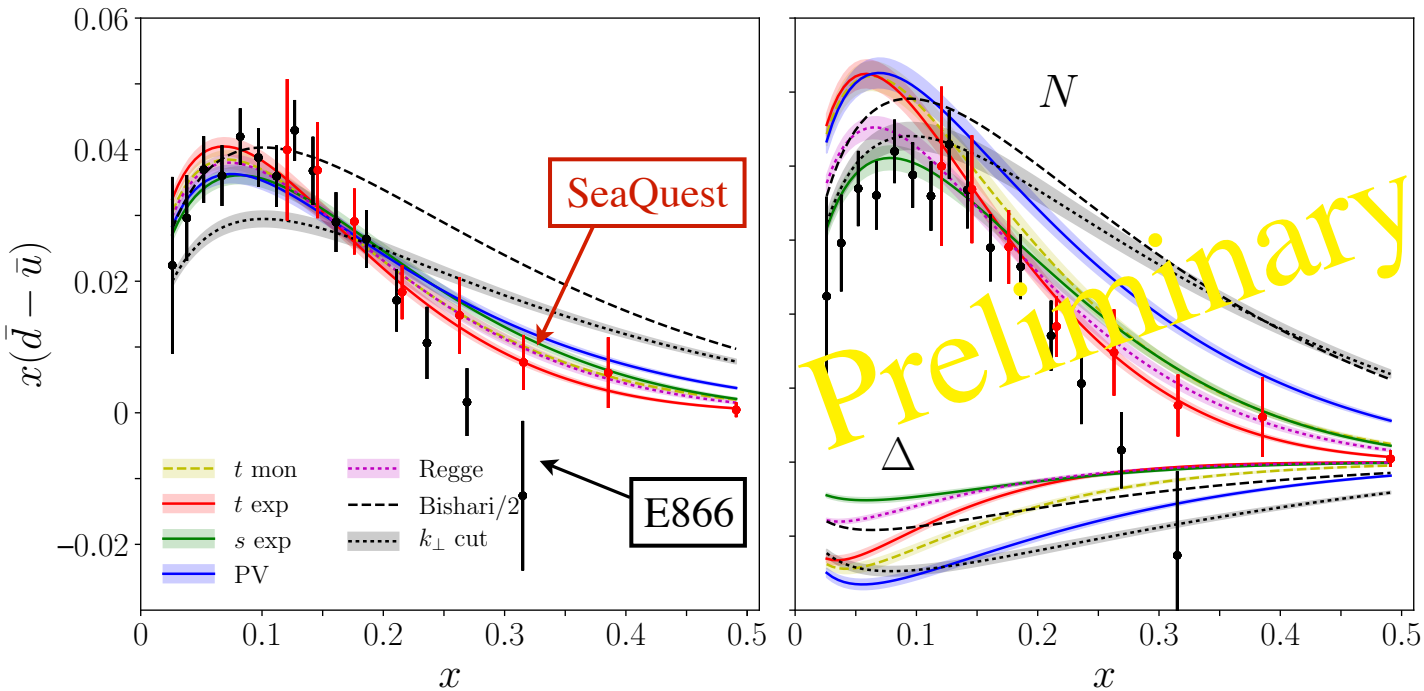


Ehlers, Accardi, Brady, WM (2014)

Sign change at large x?

- Consequences for chiral analysis?

→ including both E866 and preliminary SeaQuest data in fit …



Barry, Sato, WM et al. (2017)

	E866	E866 + SeaQuest
$\chi^2_{\rm dof}$	**1.2**	**0.8**
Λ (GeV)	**0.85**	**0.85**
$\langle n \rangle_{\pi N}$	**0.29**	**0.29**

→ Improved fit, but almost no effect on shape!

Outlook

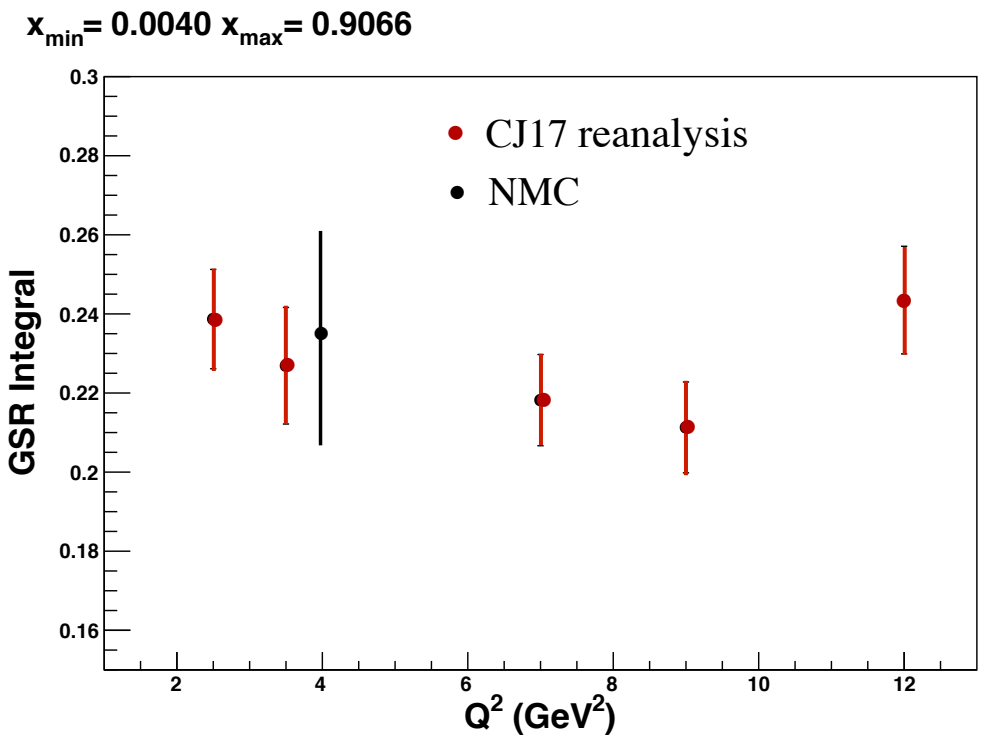
- Eagerly await final SeaQuest data!

  $\longrightarrow$ 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

  $\longrightarrow$ upcoming "tagged DIS" experiment at JLab $\longrightarrow$ ***C. Keppel (Thu 9:40 am – WG1)***

- Extend to strangeness sector to analyze $s - \bar{s}$ asymmetry within chiral SU(3) EFT framework



Niculescu et al. (2016)