Flavor Structure of Hadron Sea and SIDIS

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Workshop on “TMD Studies: from JLab to EIC”
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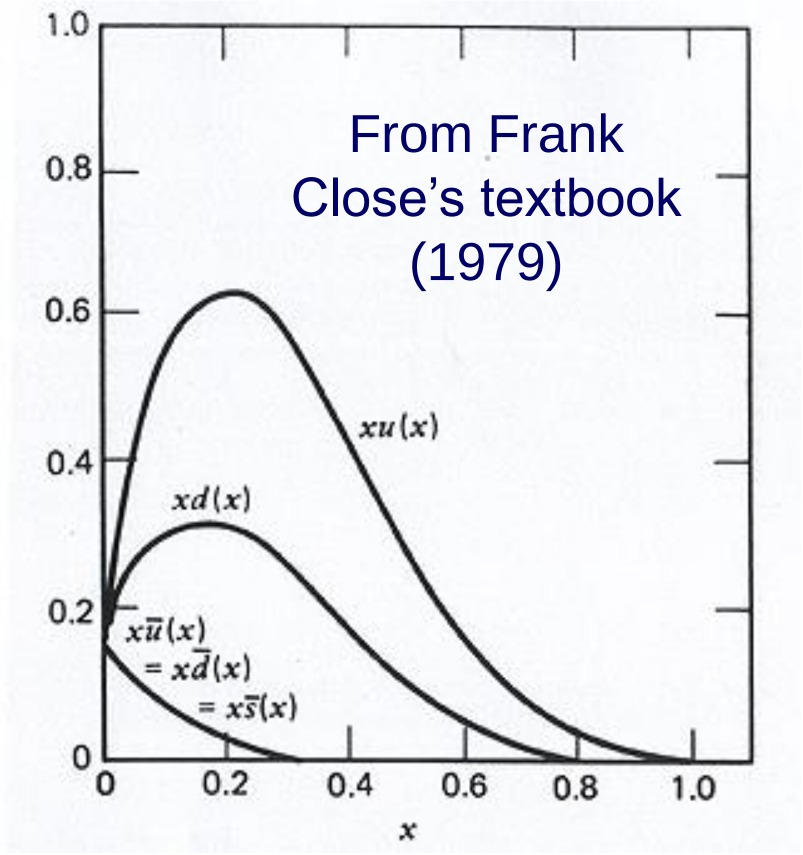
Flavor structure of the parton distributions in the proton



Questions

- $\bar{u}(x) = \bar{d}(x)$?
- $\bar{s}(x) = \bar{u}(x)$?
- $\bar{s}(x) = s(x)$?
- $\bar{u}_p(x) = \bar{d}_n(x)$?
- $u_V(x) = 2d_V(x)$?
- $u_p(x) = d_n(x)$?
- $g_p(x) = g_n(x)$?

Analogous questions can be raised for the helicity and TMD parton distributions

Is $\bar{u} = \bar{d}$ in the proton?

Expect $\bar{d} = \bar{u}$ if sea quarks are produced in $g \to q\bar{q}$

$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$

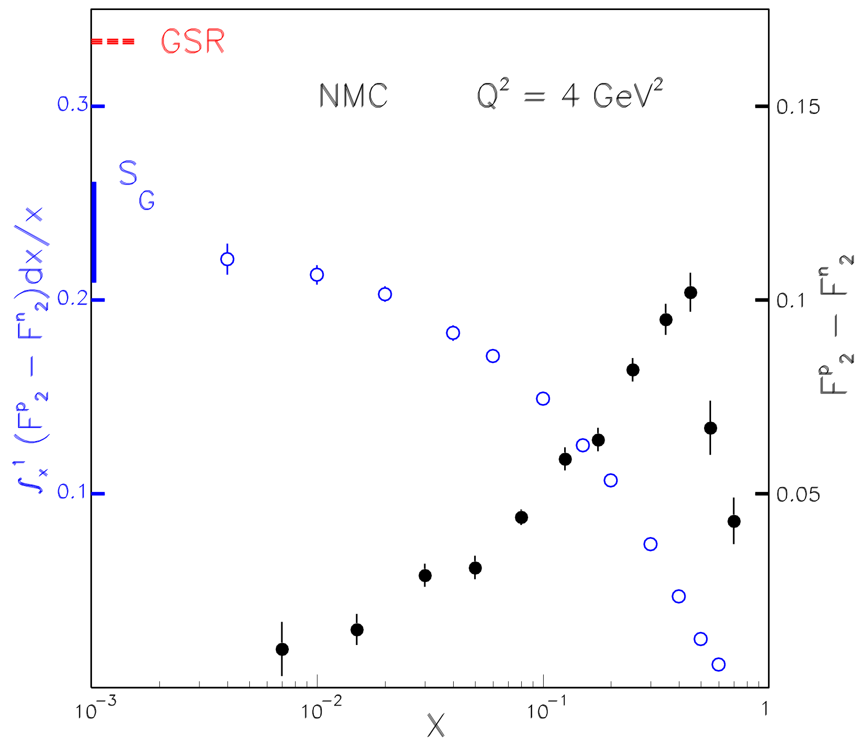
$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\;dx$$

$$= \frac{1}{3} \qquad (\text{if } \bar{u}_p = \bar{d}_p)$$

New Muon Collaboration (NMC) obtains

$S_G = 0.235 \pm 0.026$

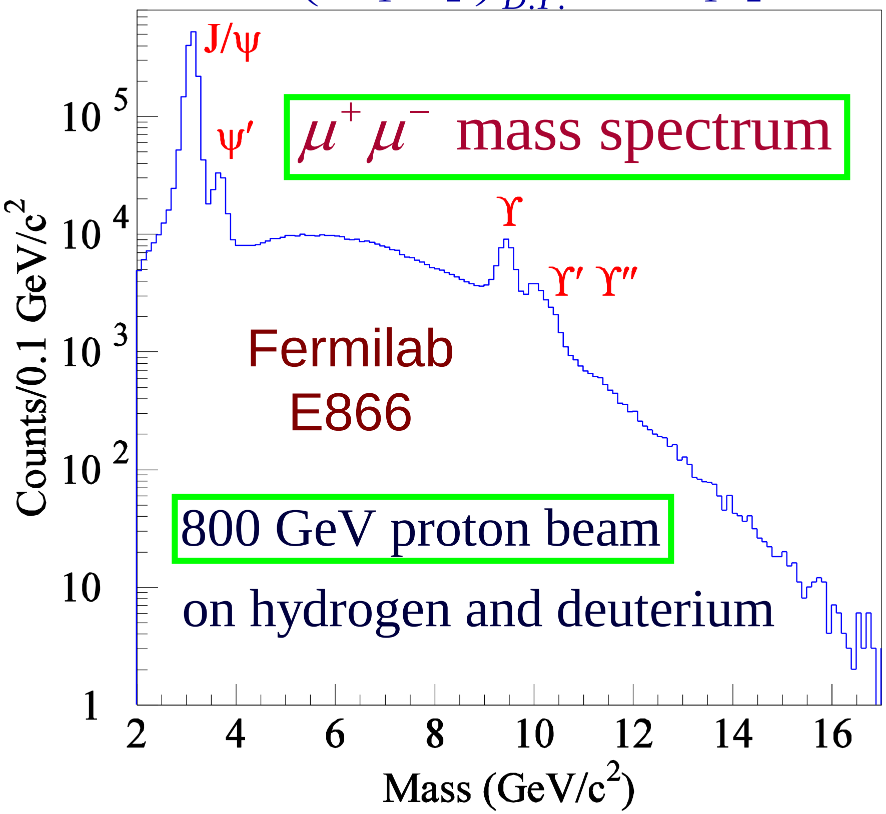
$$\Rightarrow \int_0^1 (\bar{d}(x) - \bar{u}(x))\;dx = 0.148 \pm 0.04$$

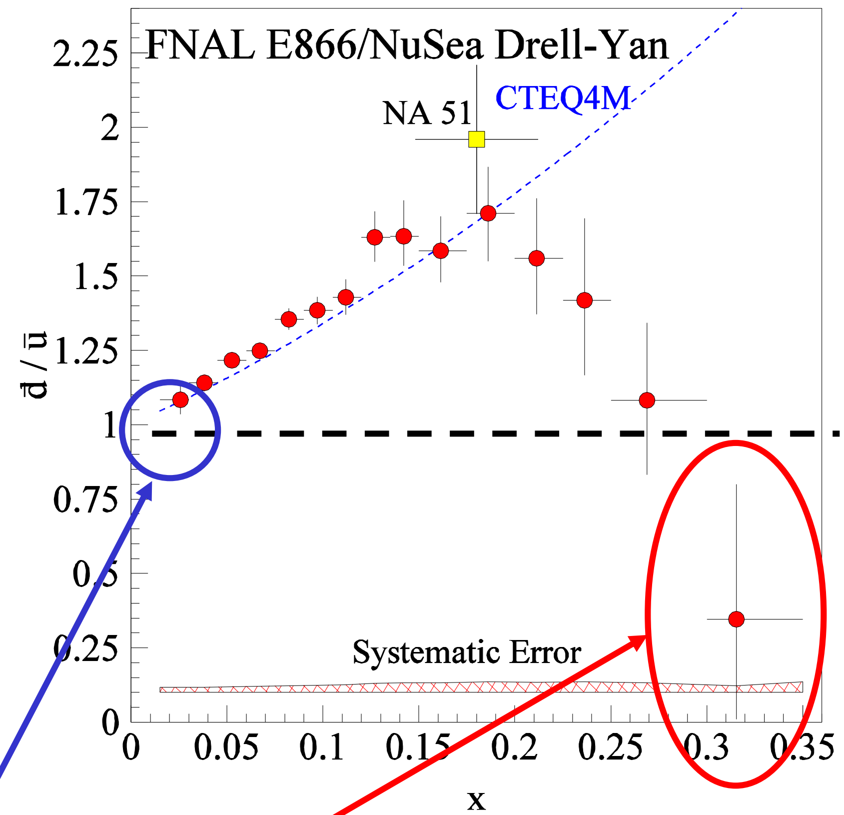


Need independent methods to check the $\bar{d}/\bar{u}$ asymmetry and to measure the x-dependence

$\bar{d}/\bar{u}$ flavor asymmetry from Drell-Yan

$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$

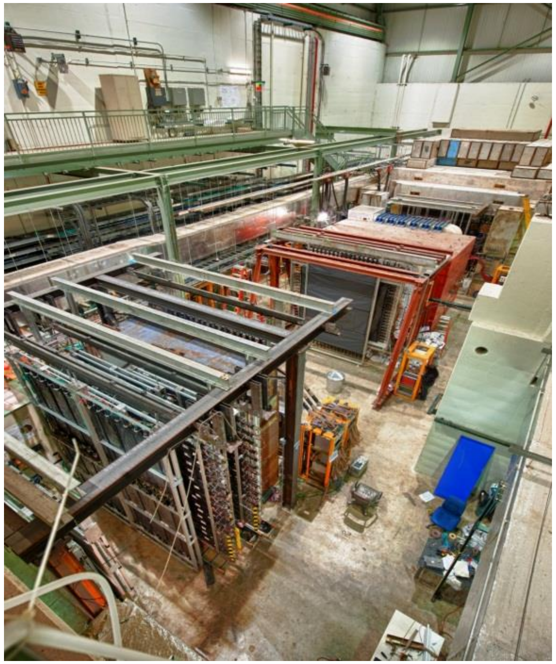


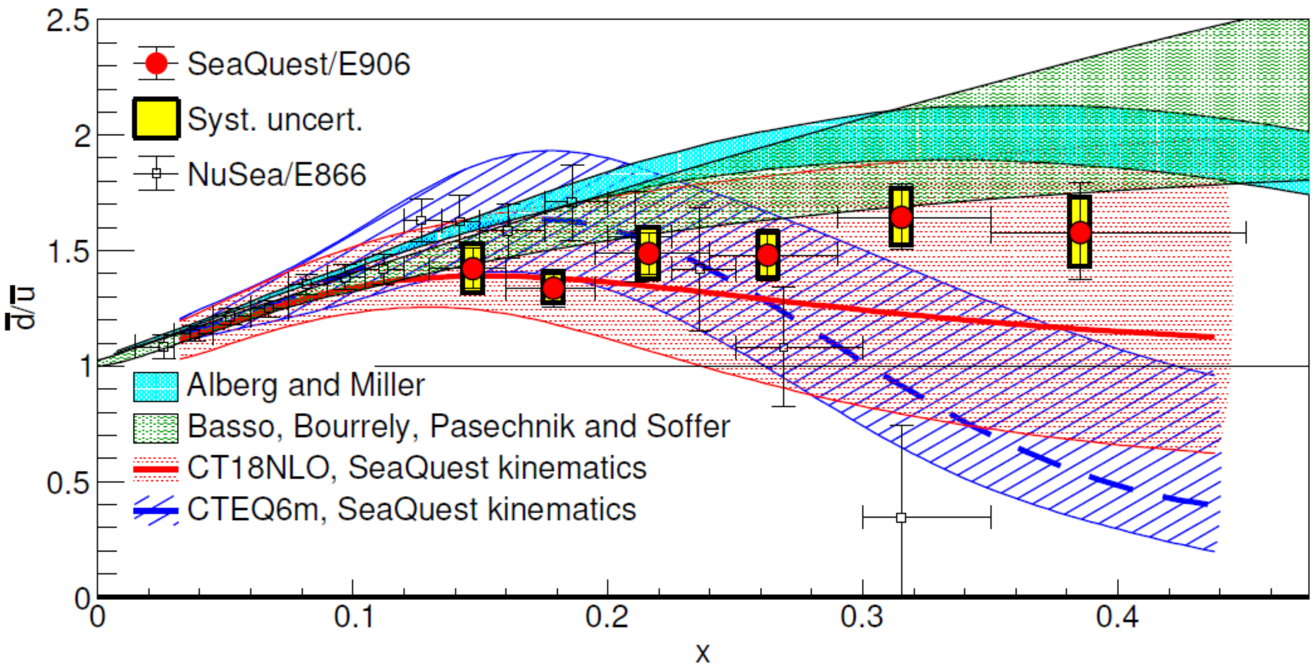


The data suggest $\bar{d}/\bar{u} \to 1$ at small x, but more data are needed

The data suggest $\bar{d}/\bar{u} < 1$ at large x, but better data are needed

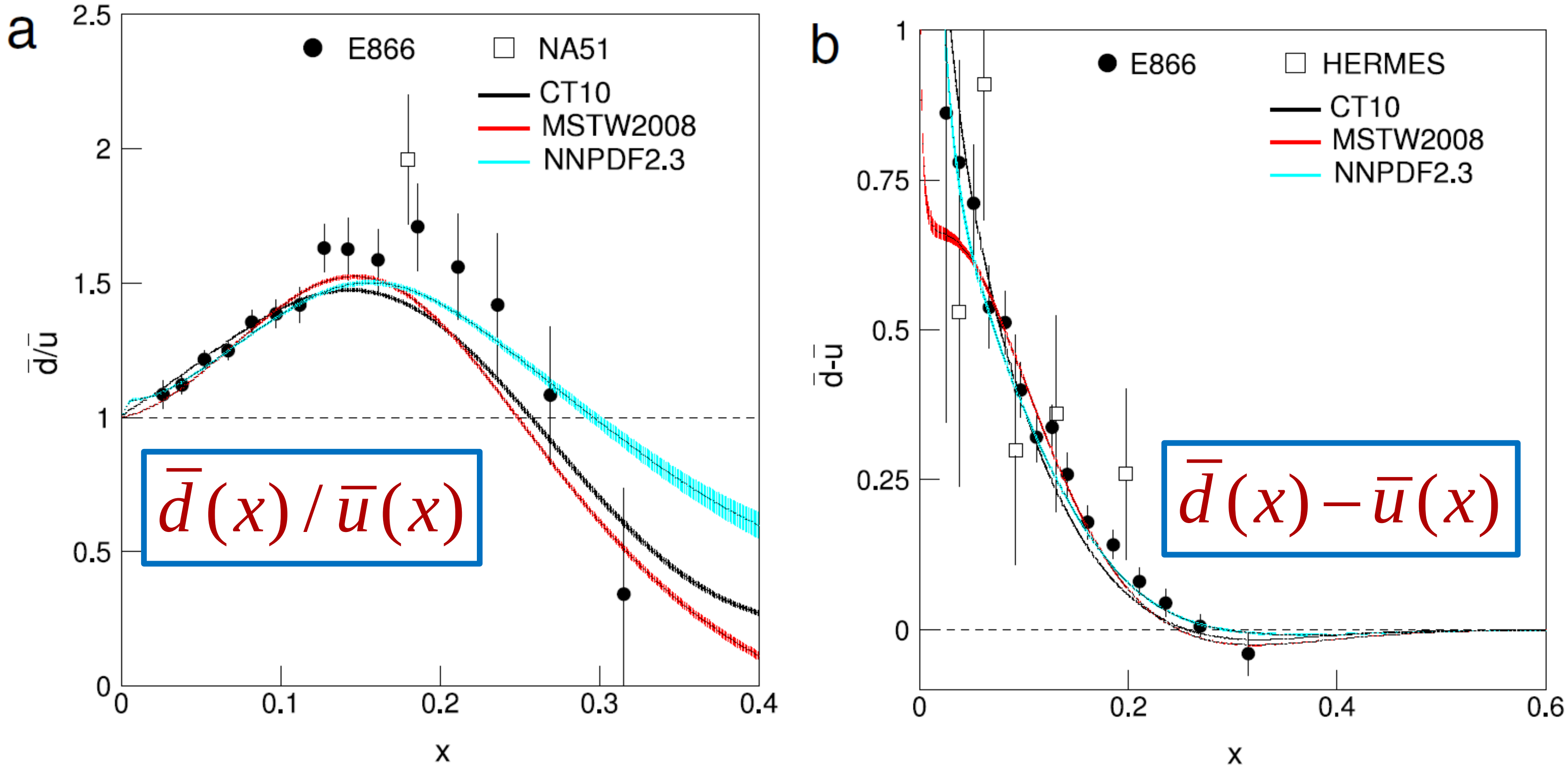
First physics results from SeaQuest (Nature, 590, (2021) 561)





- A new spectrometer was constructed for data collected with 120 GeV proton beam
- The $\bar{d}(x)/\bar{u}(x)$ ratio is found to be greater than 1 for the entire range of $0.13 < x < 0.45$
- The SeaQuest finding is in agreement with meson-cloud and statistical models
- The new data will further constrain future nucleon PDFs

From $\bar{d}(x)/\bar{u}(x)$ to $\bar{d}(x)-\bar{u}(x)$

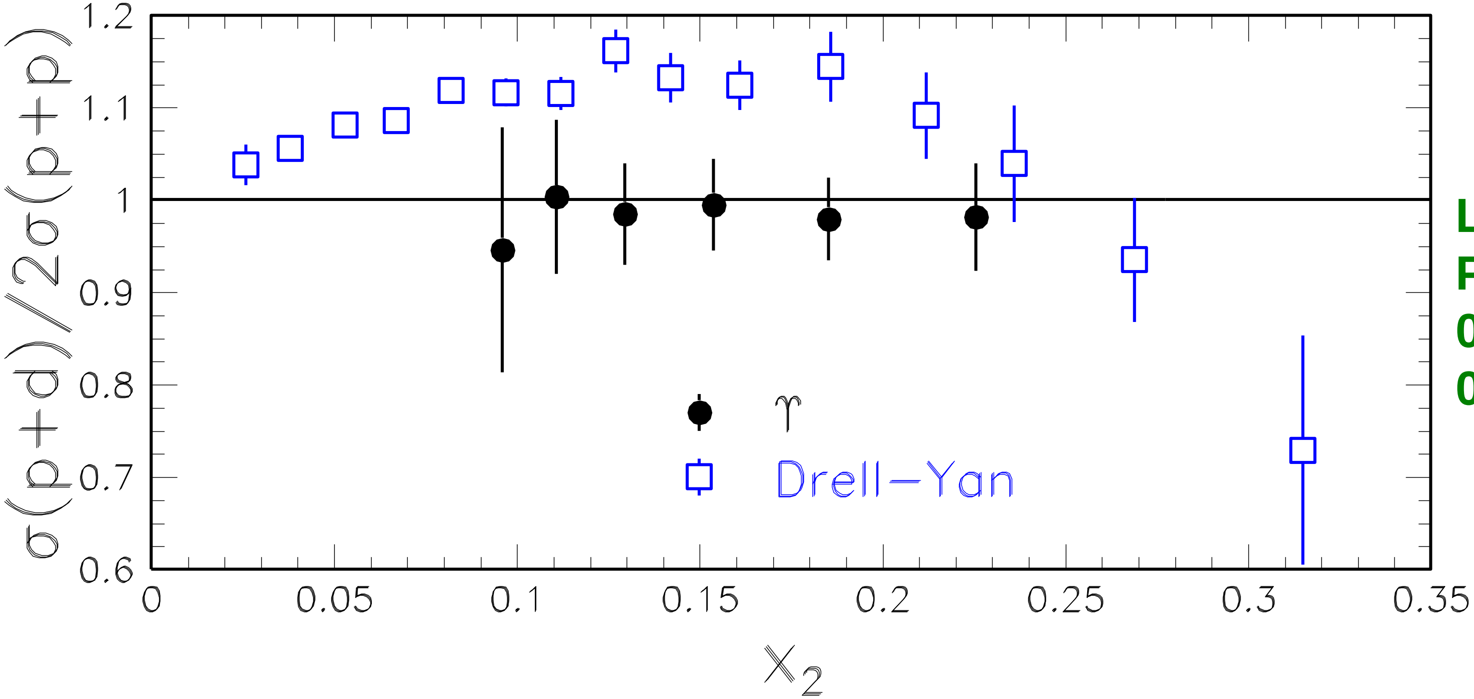


- SIDIS with pion production can give $\bar{d}(x)-\bar{u}(x)$ versus x, anlogous to Drell-Yan
- pQCD $g \to q\bar{q}$ process should give $\bar{d}(x)=\bar{u}(x)$, and does not contribute to $\bar{d}(x)-\bar{u}(x)$
- $\bar{d}(x)-\bar{u}(x)$ rises at small $x \Rightarrow$ future measurment of SIDIS at EIC would be crucial for determining the small - x contribution to the Gottfried Sum Rule

Gluon distribution in proton versus in neutron

$$(g_p(x) = g_n(x)?)$$

$$\text{E866 data}: \sigma(p+d \to \Upsilon X)/2\sigma(p+p \to \Upsilon X)$$



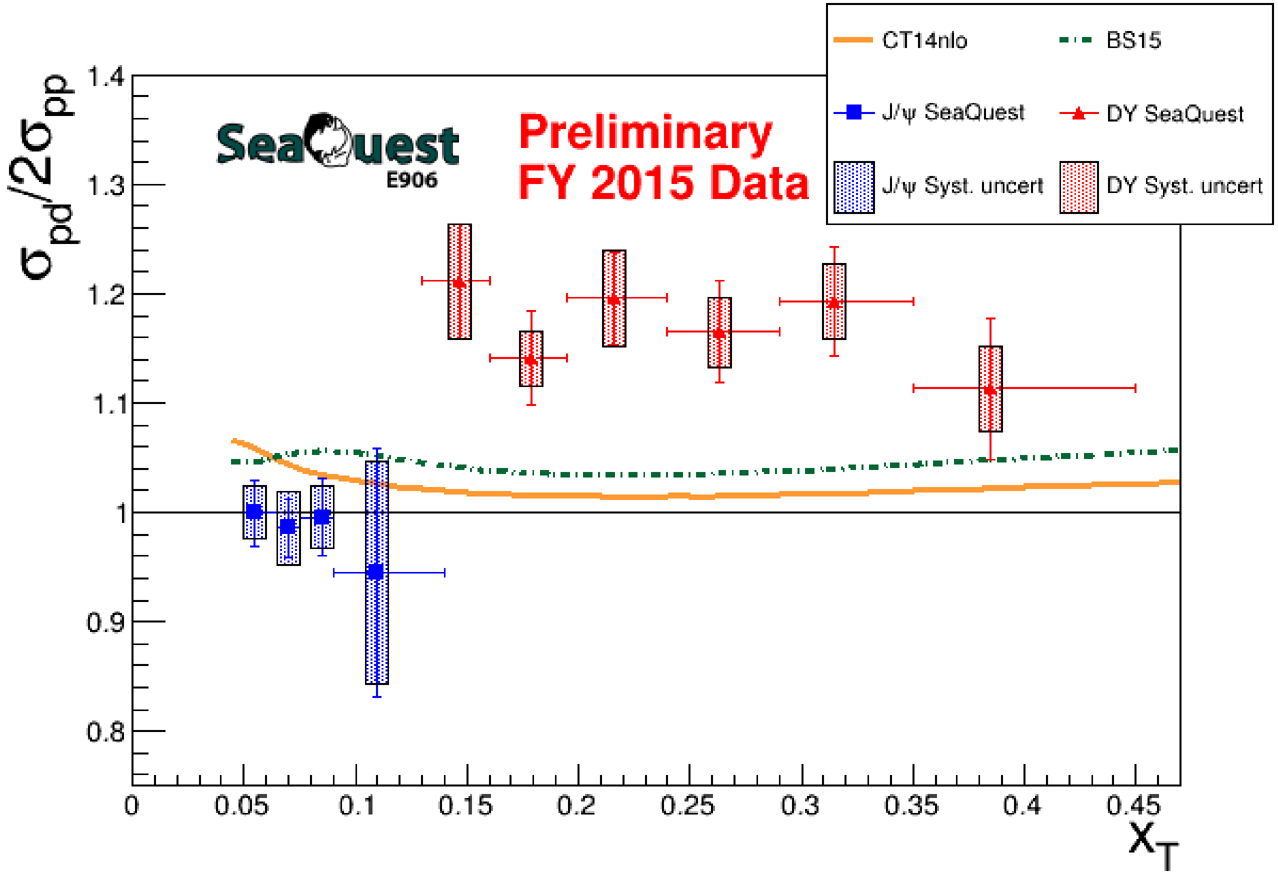
Lingyan Zhu et al., PRL, 100 (2008) 062301 (arXiv: 0710.2344)

$$Drell-Yan: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+\bar{d}(x)/\bar{u}(x)]/2$$

$$J/\Psi, \Upsilon: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+g_n(x)/g_p(x)]/2$$

Gluon distributions in proton and neutron are very similar

$\sigma_{pd}/2\sigma_{pp}$ for Drell-Yan and J/Ψ in SeaQuest

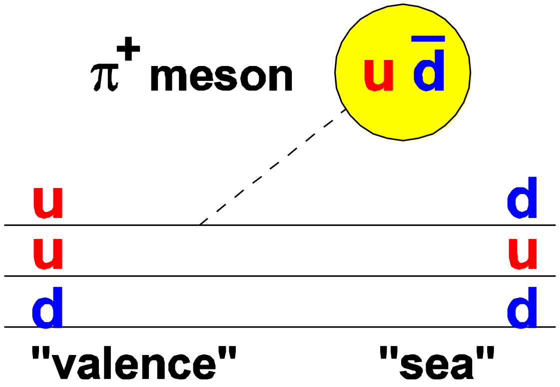


- J/Ψ production is dominated by gluon-gluon fusion process
- J/Ψ ratio should be 1, if gluon content of proton is the same as neutron
- The data show distinct difference for Drell-Yan and J/Ψ cross section ratios

We might test $g_p(x) = g_n(x)$ at small x at EIC?

Origins of $\bar{u}(x) \neq \bar{d}(x)$?

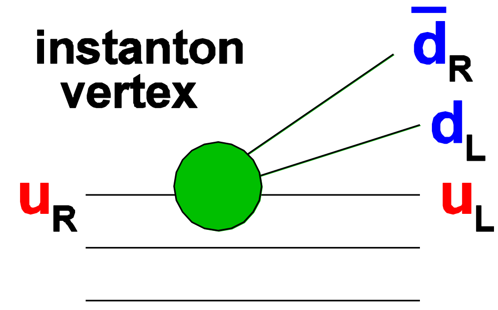
Meson Cloud Models



Chiral-Quark Soliton Model

- nucleon = chiral soliton
- expand in 1/*Nc*
- Quark degrees of freedom in a pion mean-field

Instantons



Theory: Thomas, Miller, Kumano, Ma, Londergan, Henley, Speth, Hwang, Melnitchouk, Liu, Cheng/Li, etc.

(For reviews, see Speth and Thomas (1997), Kumano (hep-ph/9702367), Garvey and Peng (nucl-ex/0109010), Chang and Peng (1406.1260))

Theses models also have implications on

- asymmetry between $s(x)$ and $\bar{s}(x)$
- flavor structure of the polarized sea

Meson cloud has significant contributions to sea-quark distributions

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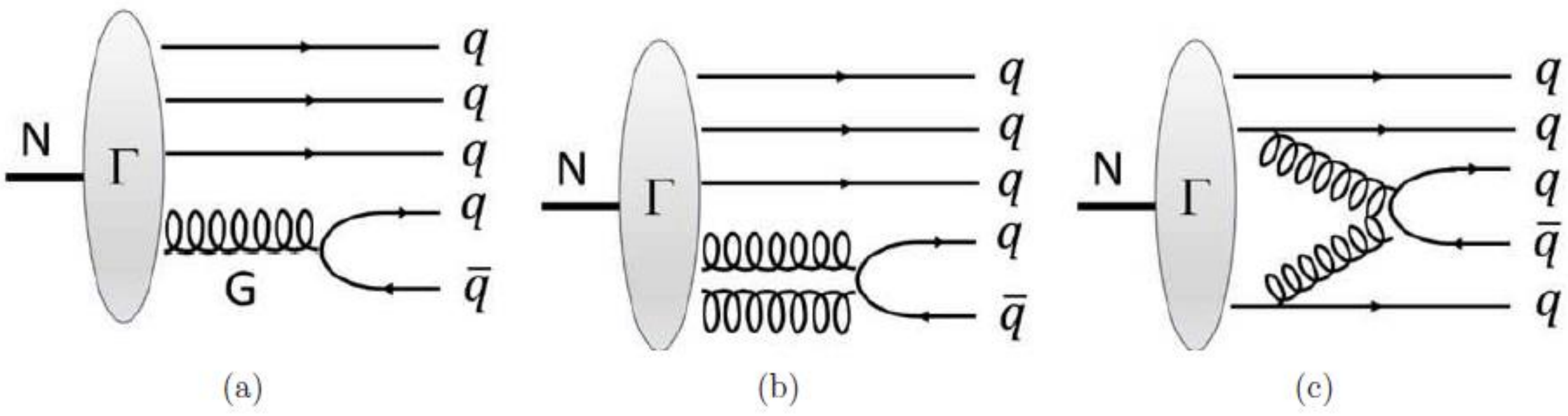
Search for the "intrinsic" quark sea

In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm

$$|\, p\rangle = P_{3q}\,|\,uud\rangle + P_{5q}\,|\,uudQ\bar{Q}\rangle + \cdots\cdots$$

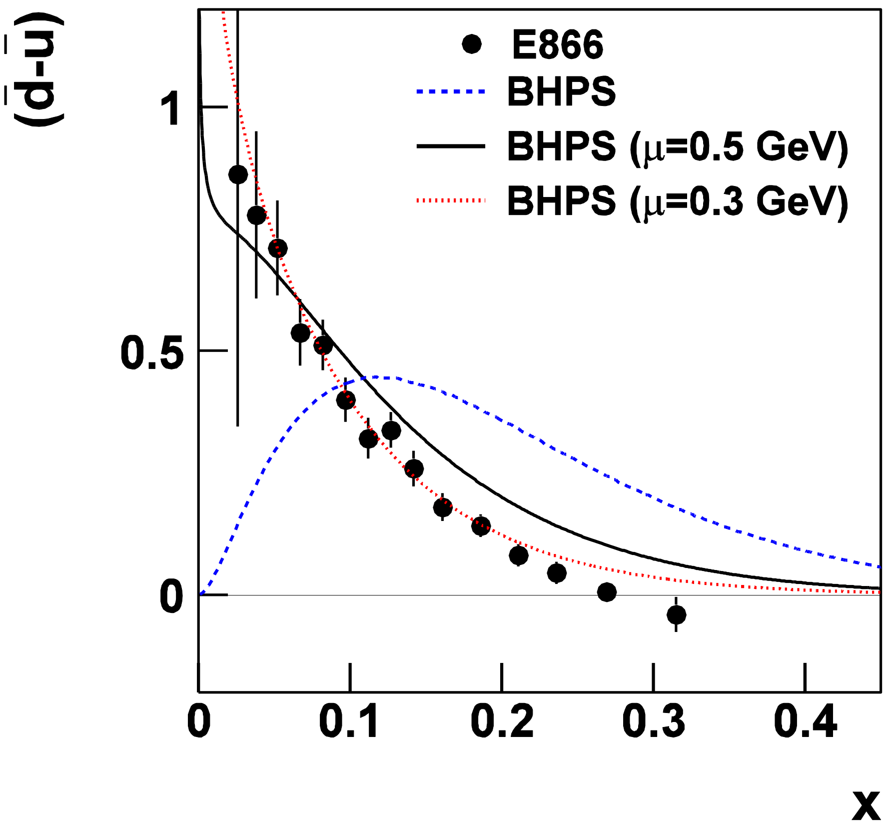
The "intrinsic"-charm from $|\,uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \rightarrow c\bar{c}$)



"extrinsic sea"

"intrinsic sea"

Comparison between the $\bar{d}(x)-\bar{u}(x)$ data with the intrinsic 5-q model



(W. Chang and JCP , PRL 106, 252002 (2011))

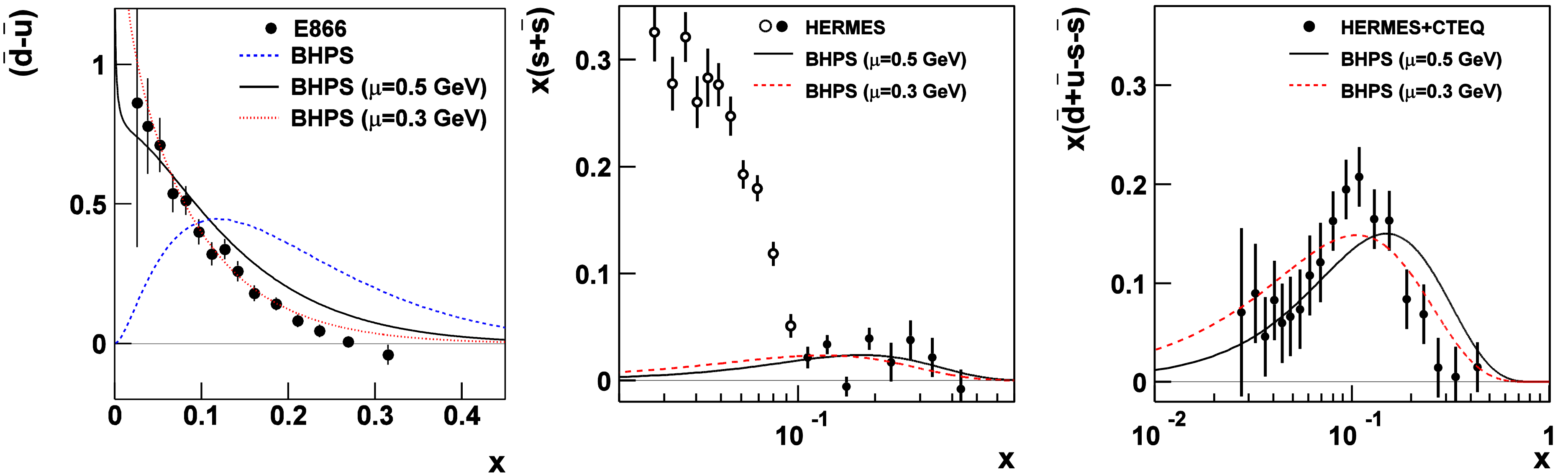
The data are in good agreement with the 5-q model after evolution from the initial scale μ to Q^2=54 GeV^2

The difference in the two 5-quark components can also be determined

$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

Extraction of the various light-quark intrinsic-sea components

$\bar{d}(x)-\bar{u}(x)$ | $s(x)+\bar{s}(x)$ | $\bar{d}(x)+\bar{u}(x)-s(x)-\bar{s}(x)$



$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$

$P_5^{uuds\bar{s}} = 0.024$

$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$

$$P_5^{uudd\bar{d}} = 0.240;\ \ P_5^{uudu\bar{u}} = 0.122;\ \ P_5^{uuds\bar{s}} = 0.024$$

New SIDIS data on kaon production at JLab and EIC would be crucial for determining $s(x)$ and $\bar{s}(x)$

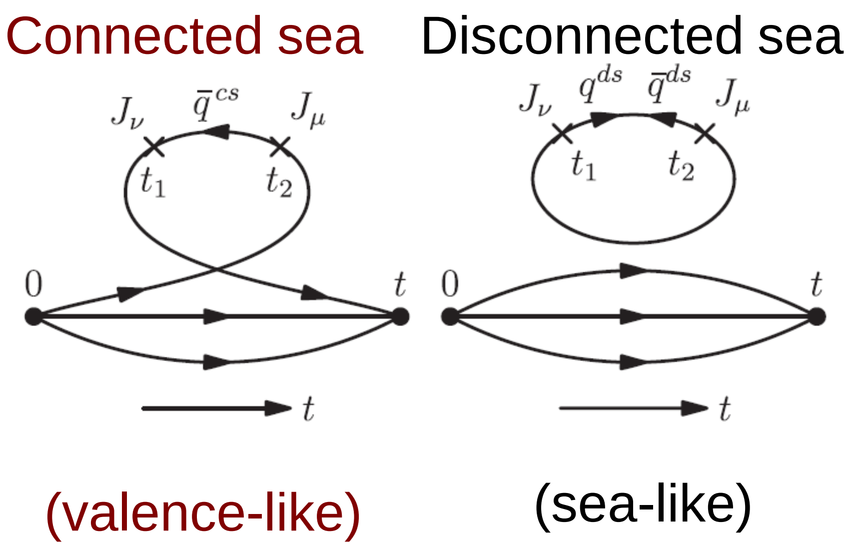
Future possibilities

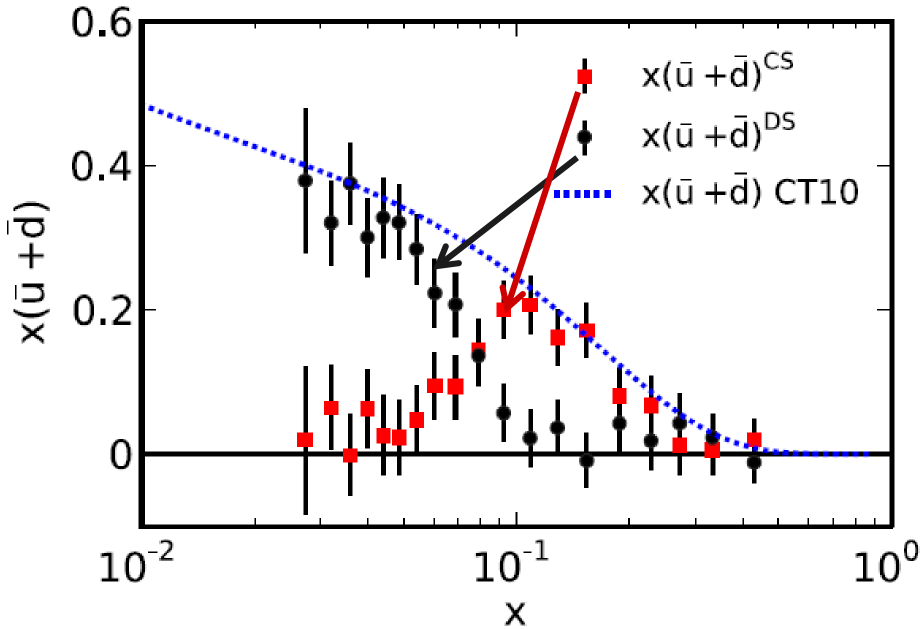
- Search for intrinsic charm and beauty at LHC and EIC?
- Intrinsic sea for mesons?
- Spin-dependent observables of intrinsic sea?
- Connection between the 5-quark model and lattice QCD calculations?

PRL 109, 252002 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

Connected-Sea Partons

Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]





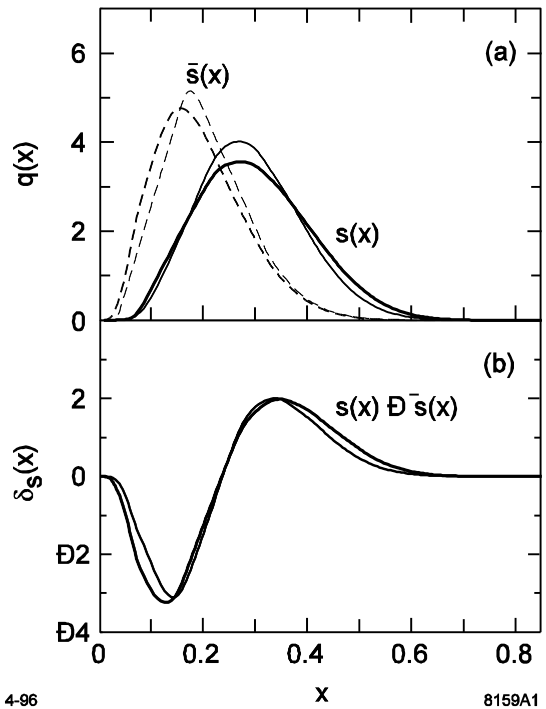
- Connected sea component for $\bar{u}(x)+\bar{d}(x)$ is valence-like
- For $\bar{u}+\bar{d}$, momenta carried by CS and DS are roughly equal, at Q^2=2.5 GeV^2

CTEQ is currently performing an independent study.
More SIDIS data from Jlab and EIC would be great

$s(x) = \bar{s}(x)$?

Meson cloud model

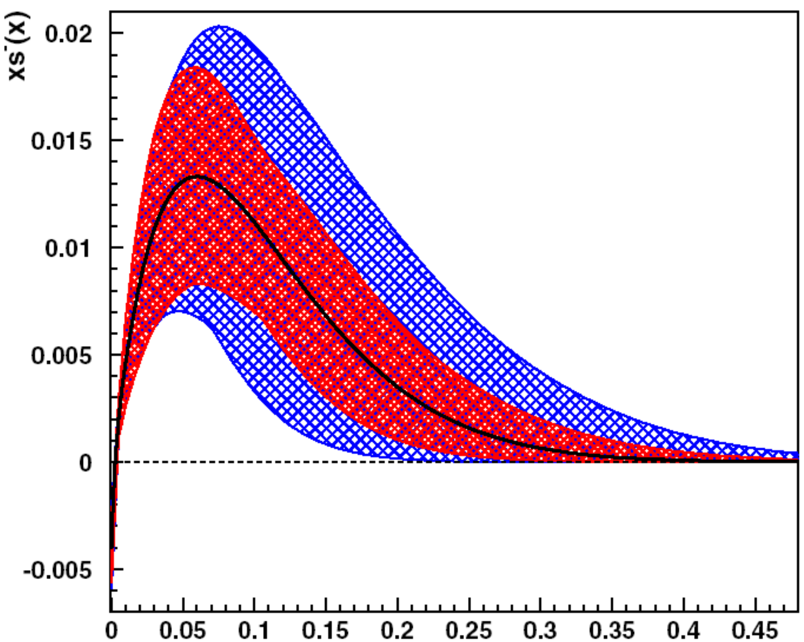
$$p \to K^+ \Lambda$$
$$(u\bar{s})\,(uds)$$



Thomas / Brodsky and Ma

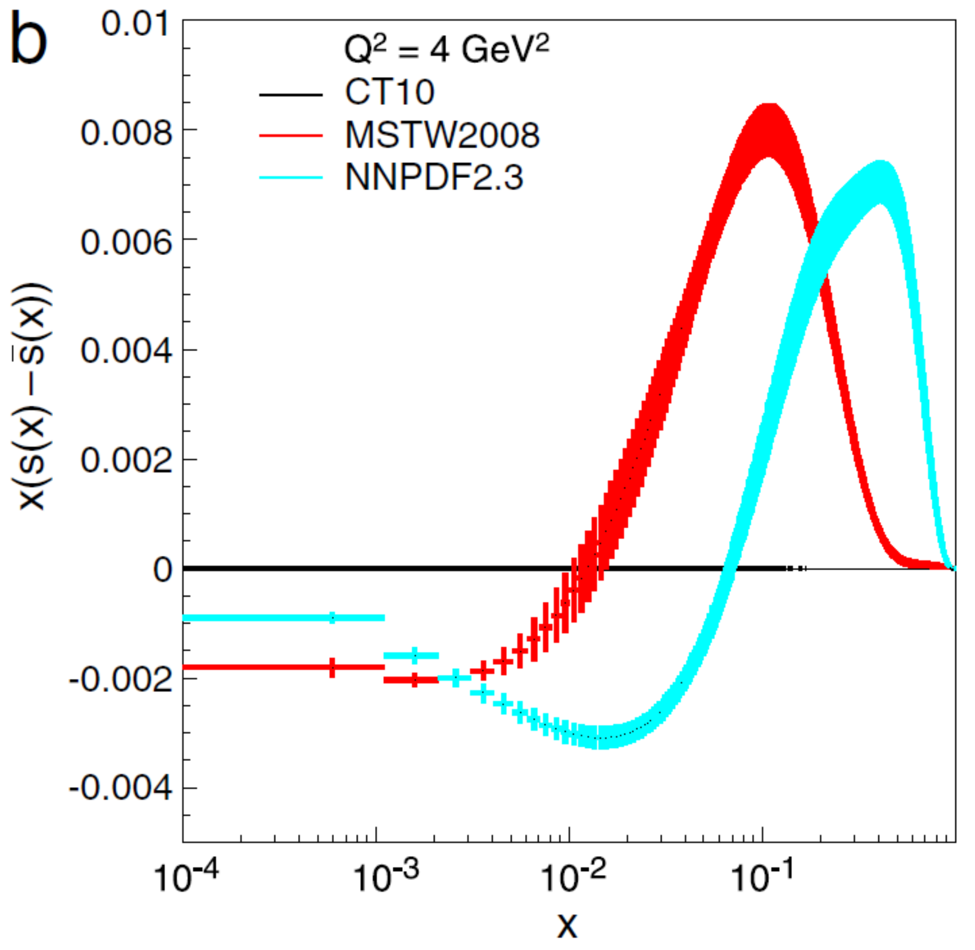
Analysis of neutrino DIS data

$$x(s - \bar{s})$$



NuTeV, PRL 99 (2007) 192001

$x(s(x) - \bar{s}(x))$ from global fits



New SIDIS data on kaon production at JLab and EIC would be crucial for determining $s(x)$ and $\bar{s}(x)$

Sea-quark helicity flavor asymmetry

Prediction of various theoretical models on the integral $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$.

Model	I_Δ prediction	Ref.
Meson cloud (π-meson)	0	[31,127]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[117]
Meson cloud ($\pi - \rho$ interf.)	$= -6\int_0^1 g^p(x)dx$	[118]
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[119]
Meson cloud (ρ-meson)	<0	[120]
Meson cloud ($\pi - \sigma$ interf.)	$\simeq 0.12$	[132]
Pauli-blocking (bag-model)	$\simeq 0.09$	[119]
Pauli-blocking (ansatz)	$\simeq 0.3$	[128]
Pauli-blocking	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[129]
Chiral-quark soliton	0.31	[130]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12}[\bar{d}(x) - \bar{u}(x)]dx$	[131]
Instanton	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[123]
Statistical	$\simeq \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.12$	[41]
Statistical	$> \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx > 0.12$	[126]

W. Chang and JCP (1406.1260)

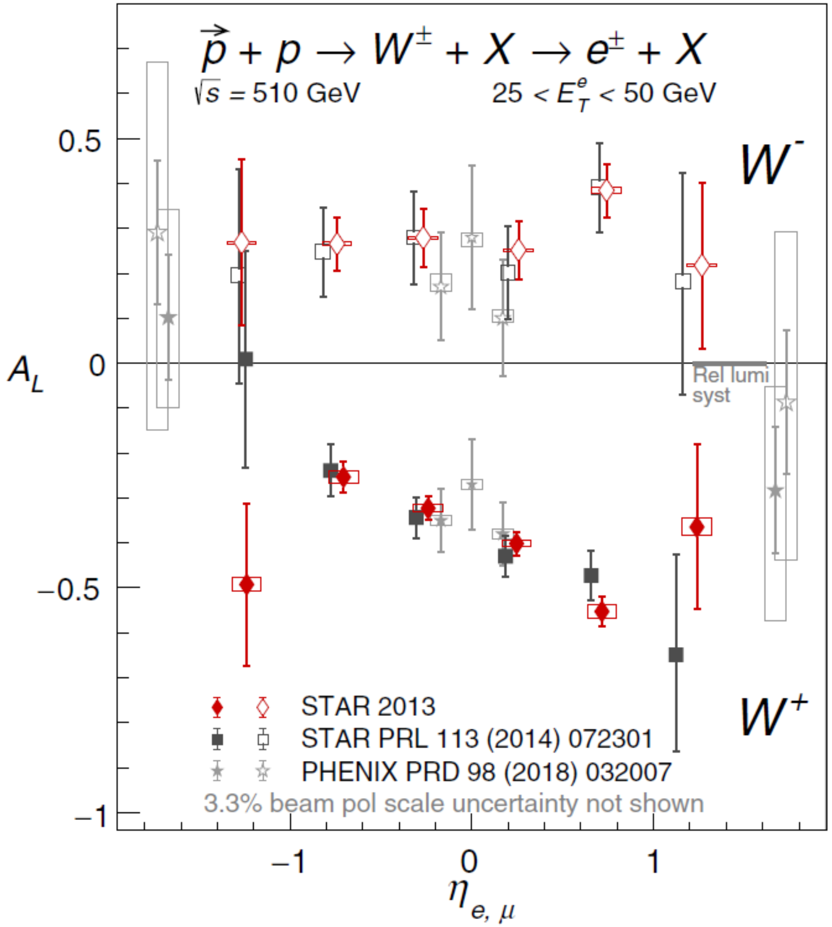
Meson Cloud Model

$$u\uparrow \to \pi^0(u\bar{u}) + u\downarrow \qquad u\uparrow \to K^+(u\bar{s}) + s\downarrow; \qquad \Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta\bar{s}(x) = 0$$

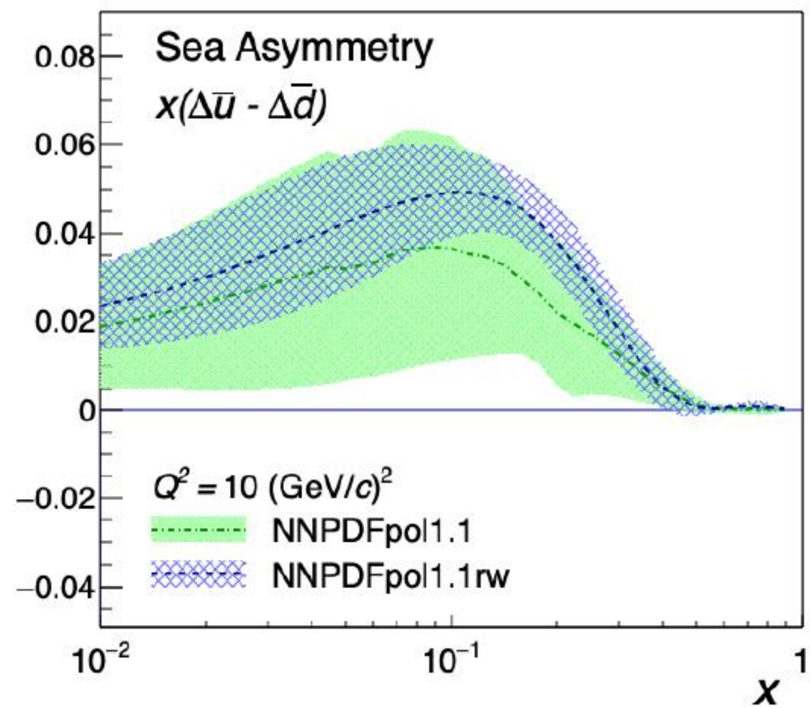
Chiral-Quark Soliton Model and Statistical Model

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) > \bar{d}(x) - \bar{u}(x)$$

$\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ from $W^{\pm}$ production at RHIC-spin



$x\Delta\bar{u}(x) - x\Delta\bar{d}(x)$



$\Delta\bar{u} > \Delta\bar{d}$ consistent with some models and lattice QCD

Need longitudinally polarizied SIDIS for pion production at JLab and EIC

Three parton distributions describing quark's transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_\perp^N$

2) Quark transverse spin

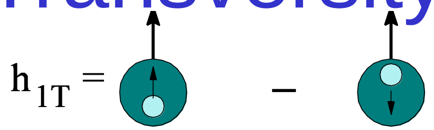
$\vec{s}_\perp^q$

3) Quark transverse momentum

$\vec{k}_\perp^q$

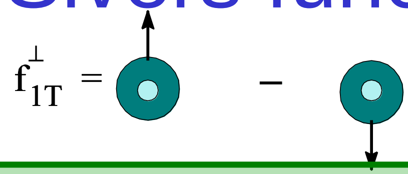
$\Rightarrow$ Three different correlations

1) Transversity



Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function



Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

3) Boer-Mulders function

Correlation between $\vec{s}_\perp^q$ and $\vec{k}_\perp^q$

Some remaining questions on transversity to be addressed by future experiments

- Magnitude and sign of the sea-quark transversity?
- Sea-quark flavor asymmetry for transversity (similar to the unpolarized sea and the helicity sea)?
- Other methods to extract the transversity (without using the Collins fragmentation functions)?
- Verify the expected slower Q^2-evolution with data at much higher Q^2 ?

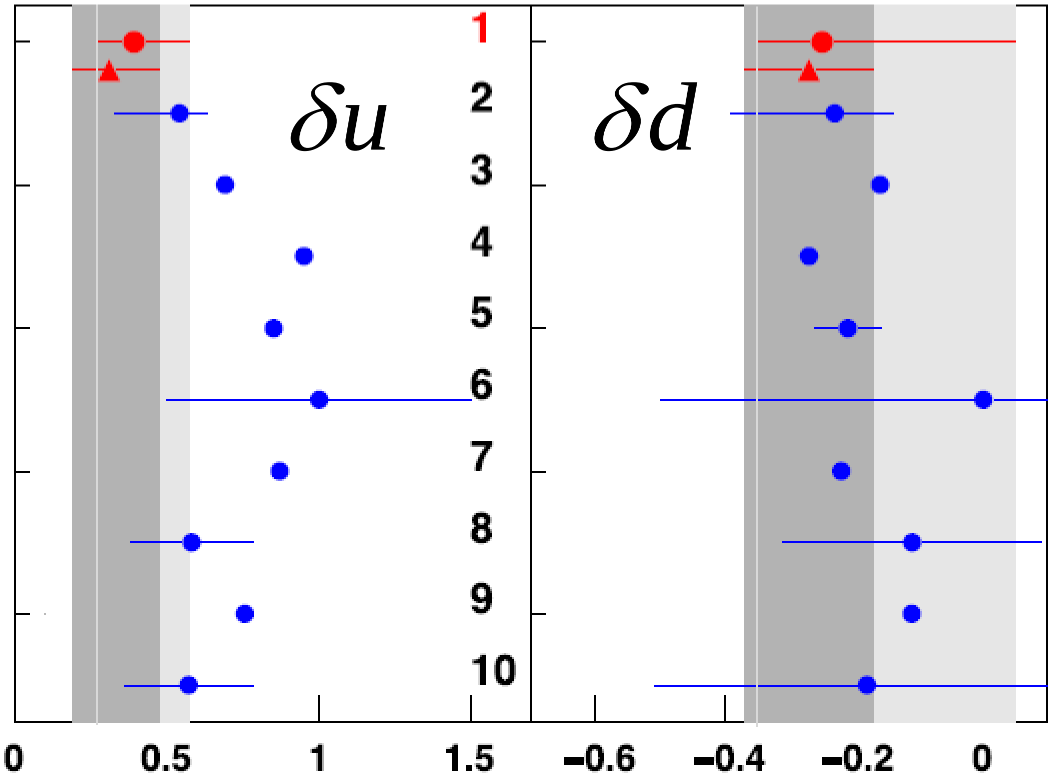
Extraction of nucleon tensor charge

Torino group, Anselmino et al., PRD 87, 094019 (2013)

● $\delta u = 0.39^{+0.18}_{-0.12}$ ● $\delta d = -0.25^{+0.30}_{-0.10}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$



$\Delta u = 0.787$ $\Delta d = -0.319$

1 : Extractions from global fits (using two different Collins FF parameterizations)

2-10: Predictions from various models (including LQCD)

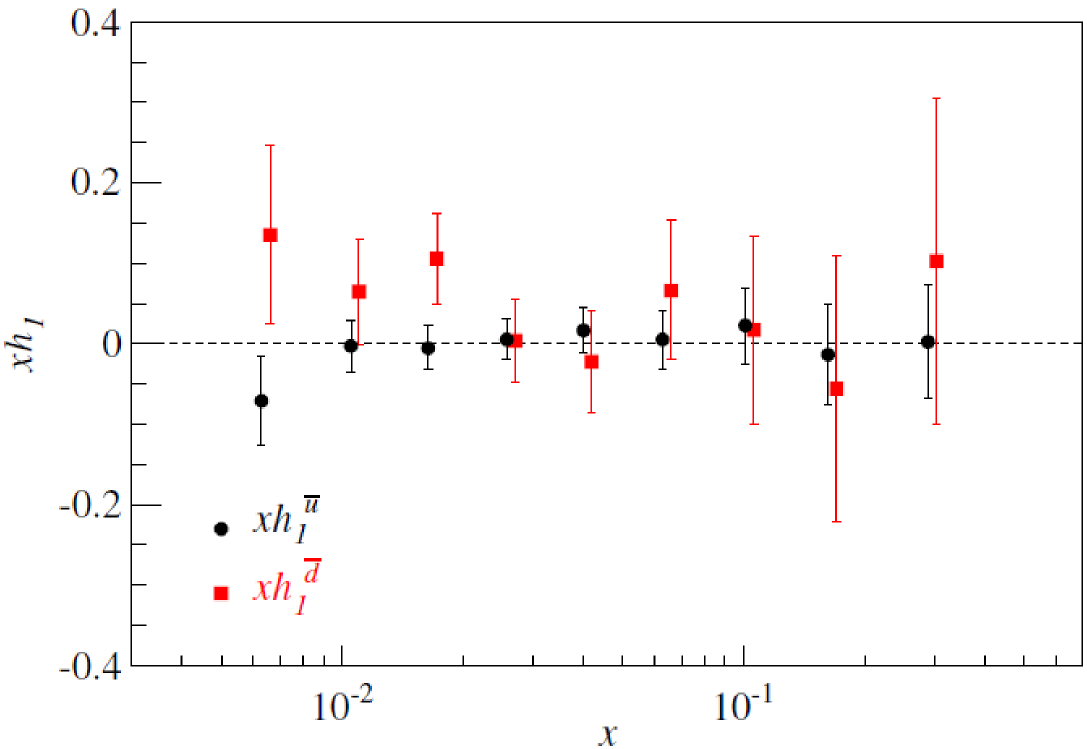
- Tensor charges are smaller than axial charge
- Discrepancy could be caused by neglecting sea transversity in the fit

Extraction of sea-quark transversity in SIDIS

PHYSICAL REVIEW D **91,** 014034 (2015)

Extracting the transversity distributions from single-hadron and dihadron production

Anna Martin,[1] Franco Bradamante,[1] and Vincenzo Barone[2]



- Large uncertainties in sea-quark transversity from SIDIS data
- Future data at JLab and EIC are needed

Measuring transversity in the Drell-Yan process

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U (1 + S_T\{D_1 A_T^{\sin\varphi_S} \sin\varphi_S + D_2[A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S)]\}).$$

D_2 : depolarization factor

φ_S : azimuthal angle between $\vec{q}_T$ and $\vec{S}_T$

φ_{CS} : azimuthal angle of μ^- in the Collins-Soper frame

$A_T^{\sin(2\phi_s-\phi_S)} \propto$ BM $h_1^\perp|_p \otimes$ Transversity $h_1|_p$

E1039/SpinQuest can measure the sea-quark transversity

Conclusion

- Many important questions in the flavor structure of the nucleon sea remain to be answered
- JLab and EIC offer exciting opportunities in the near and longer-term future.