Intrinsic Strangeness at Large X

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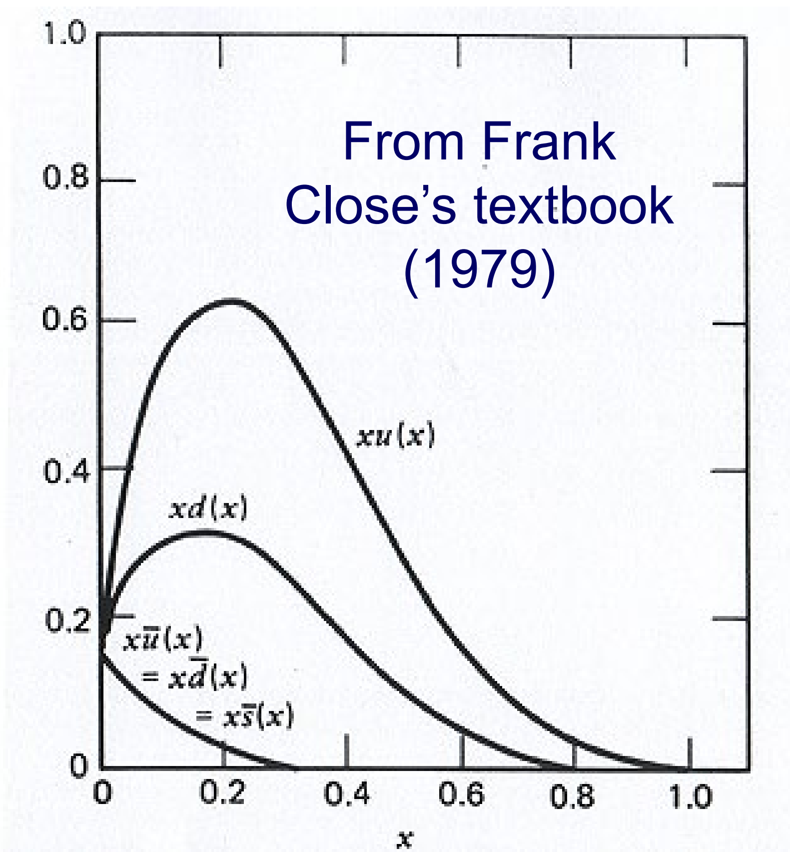
University of Illinois at Urbana-Champaign

CFNS Workshop on
"Target Fragmentation Physics with EIC"

September 28-30, 2020

There was a time when nucleon sea was nice and simple……

Flavor structure of the proton sea

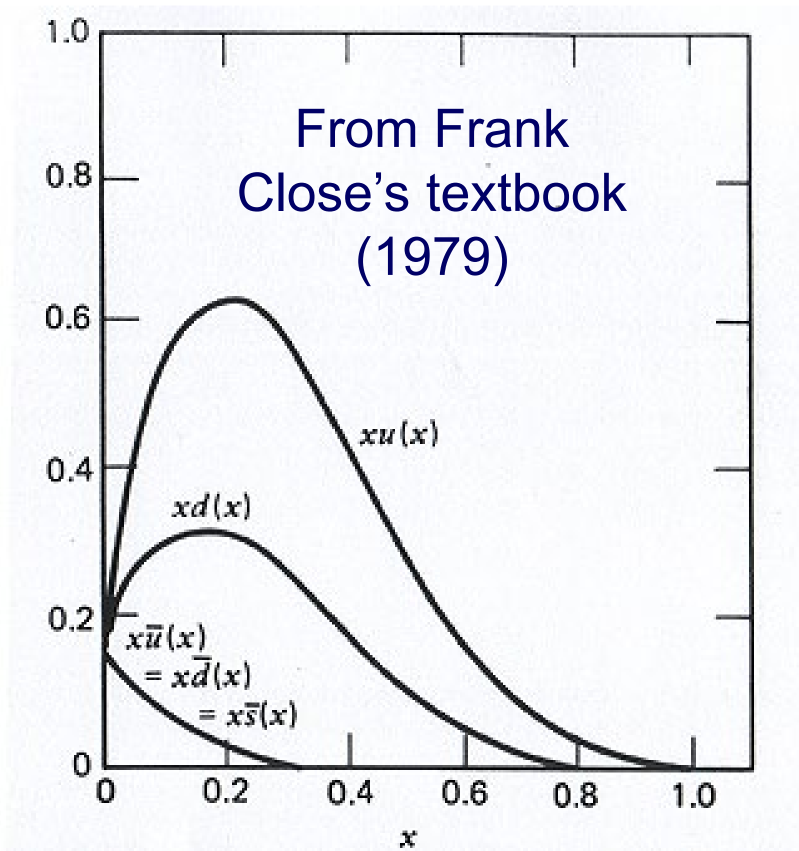


$$\bar{u}(x) = \bar{d}(x) = \bar{s}(x) = s(x)$$

$SU(3)$ symmetric sea at the small-x region

Actually, the nucleon sea is full of surprises

Flavor structure of the parton distributions in the proton



Questions

- $Is\ \ \bar{u}(x) = \bar{d}(x)?$
- $Is\ \ \bar{s}(x) = \bar{u}(x)?$
- $Is\ \ \bar{s}(x) = s(x)?$
- $Is\ \ \bar{u}_p(x) = \bar{d}_n(x)?$
- $Is\ \ u_{Sea}(x) = \bar{u}(x)?$
- $Is\ \ u_p(x) = d_n(x)?$

Outline

- Concept of "intrinsic" sea versus "extrinsic" sea in hadrons
- Extraction of "intrinsic" $\bar{u}$, $\bar{d}$, and $\bar{s}$ sea in the nucleons
- Separation of "connected sea" from "disconnected sea" for light-quark sea
- Latest result on the "intrinsic" $\bar{u}$, $\bar{d}$ distribution at large *x*

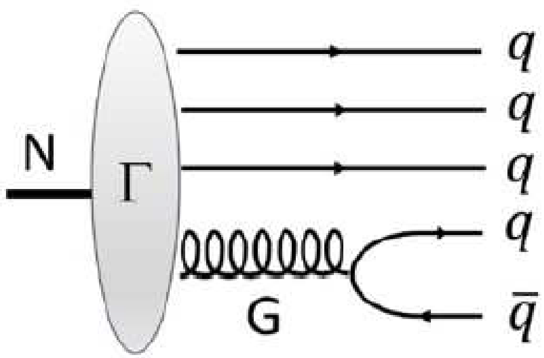
Based on work in collaboration with Wen-Chen Chang

Search for the "intrinsic" quark sea

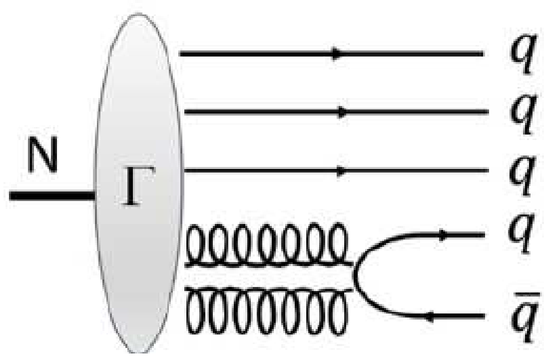
In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm

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

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



(a)



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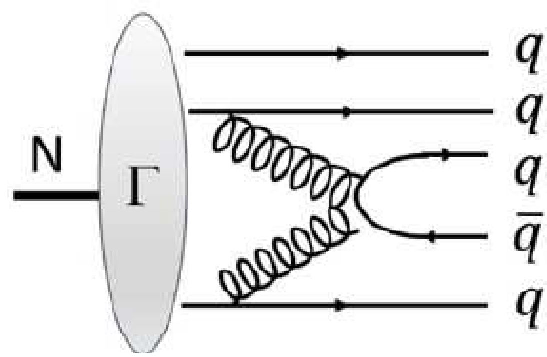

(c)

"extrinsic sea"

"intrinsic sea"

Search for the "intrinsic" quark sea

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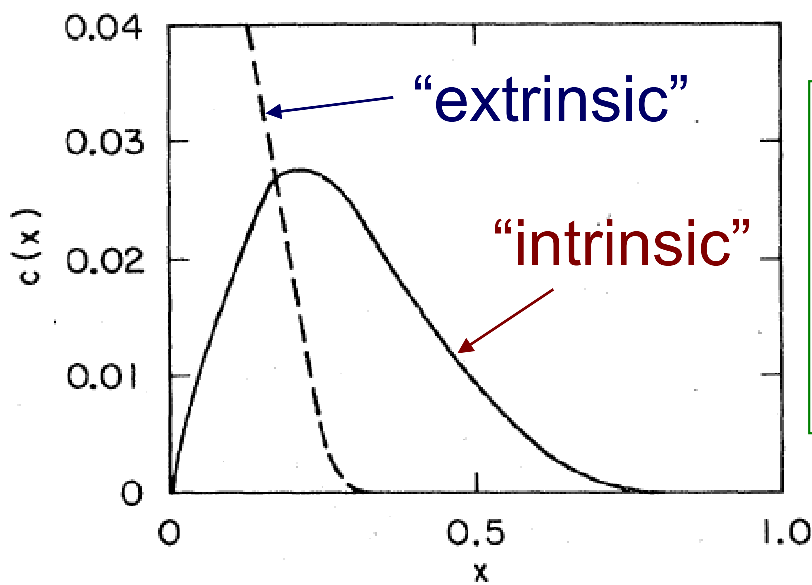
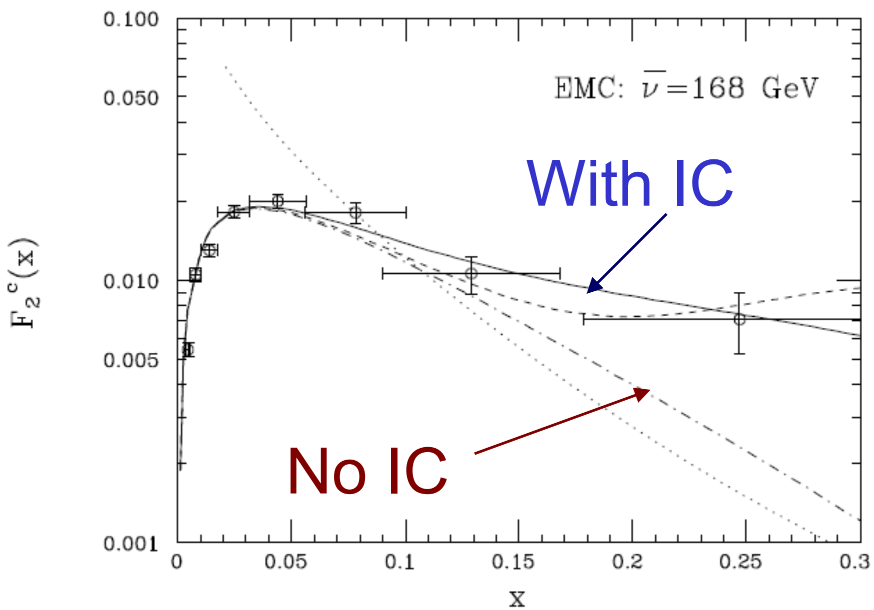


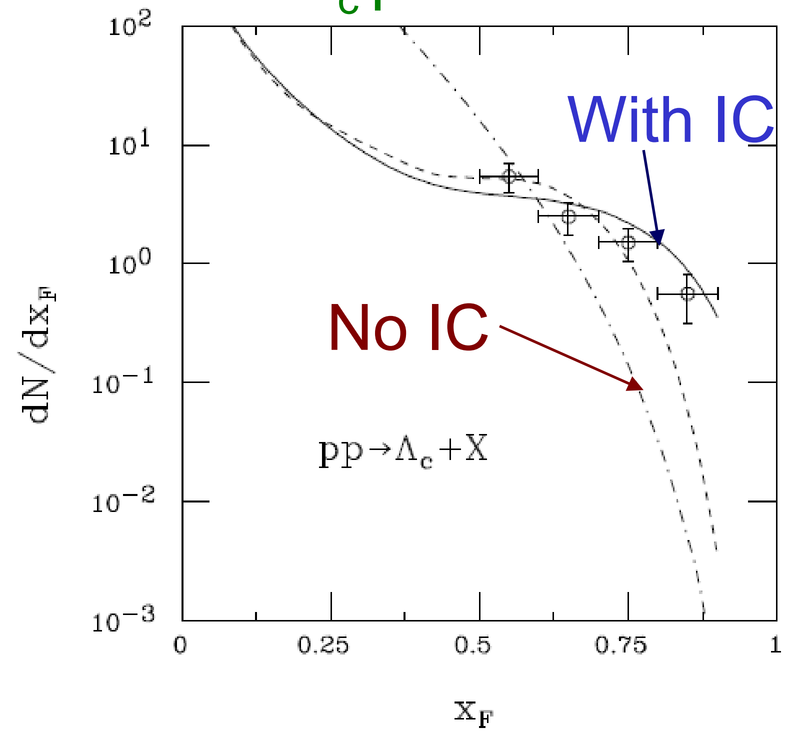
The "intrinsic charm" in $| uudc\overline{c}\rangle$ can lead to large contribution to charm production at large x

“Evidence” for the “intrinsic” charm (IC)

DIS data



Λ_c production



Gunion and Vogt (hep-ph/9706252);
Barger, Halzen and Keung (PRD 25 (1982) 112)

Tantalizing evidence for intrinsic charm

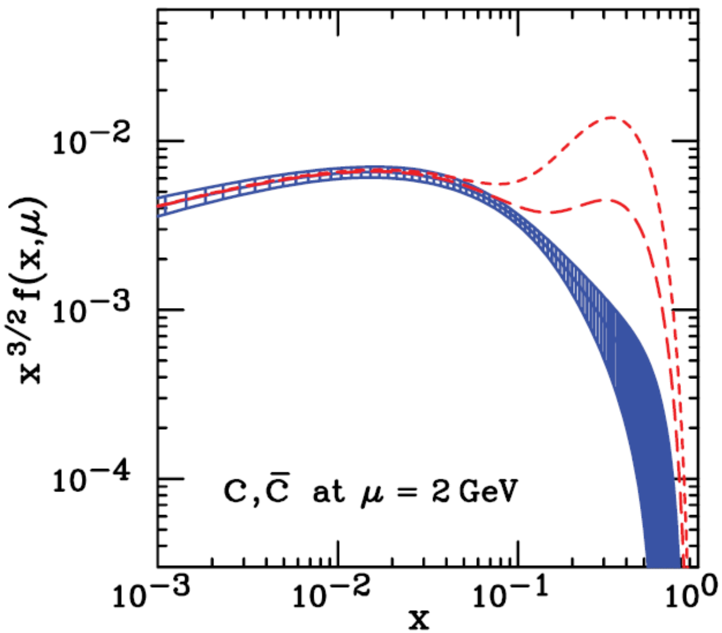
(subjected to the uncertainties of charmed-quark parametrization in the PDF, however)

A global fit by CTEQ to extract intrinsic-charm

PHYSICAL REVIEW D 75, 054029 (2007)

Charm parton content of the nucleon

J. Pumplin,[1,*] H. L. Lai,[1,2,3] and W. K. Tung[1,2]



Blue band corresponds to CTEQ6 best fit, including uncertainty

Red curves include intrinsic charm of 1% and 3% (χ^2 changes only slightly)

We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

No conclusive evidence for intrinsic-charm

Search for the "intrinsic" light-quark sea

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

Some tantalizing, but not conclusive, experimental evidence for intrinsic-charm so far

Are there experimental evidences for the intrinsic light-quark sea: $|uudu\bar{u}\rangle, | uudd\bar{d}\rangle, | uuds\bar{s}\rangle$?

$$\boxed{P_{5q}^2 \sim 1 / m_Q^2}$$

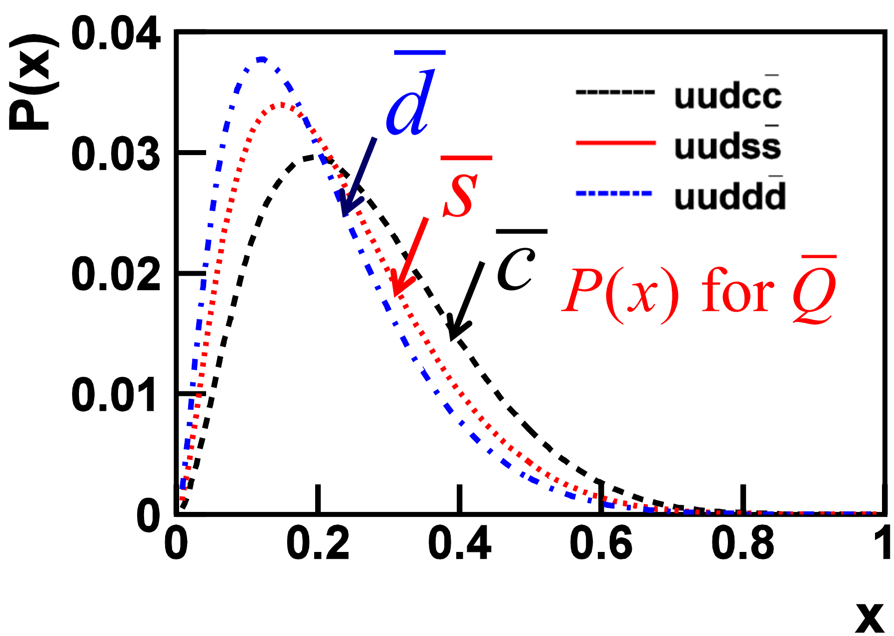
The "intrinsic" sea for lighter quarks have larger probabilities!

x-distribution for "intrinsic" light-quark sea

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

Brodsky et al. (BHPS) give the following probability for quark i (mass m_i) to carry momentum x_i

$$P(x_1,\cdots,x_5) = N_5\delta(1-\sum_{i=1}^{5} x_i)[m_p^2 - \sum_{i=1}^{5}\frac{m_i^2}{x_i}]^{-2}$$



In the limit of large mass for quark Q (charm):

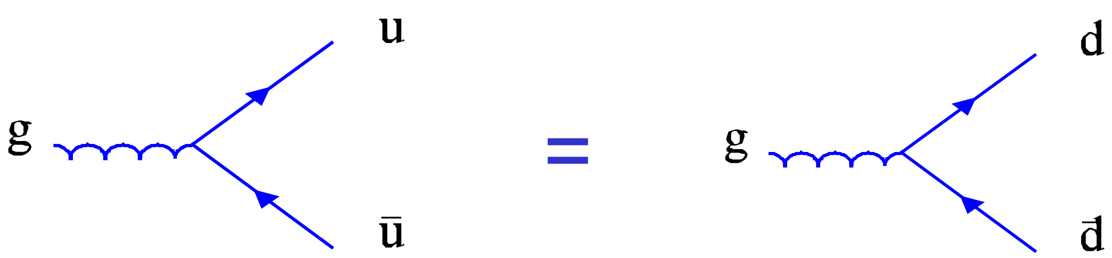
$$P(x_5) = \frac{1}{2}\tilde{N}_5 x_5^2[(1-x_5)(1+10x_5+x_5^2) - 2x_5(1+x_5)ln(1/x_5)]$$

One can calculate $P(x)$ for antiquark $\bar{Q}$ $(\bar{c}, \bar{s}, \bar{d})$ numerically

How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no contributions from the "extrinsic sea"

$$\bar{d} - \bar{u} \text{ has no contribution from extrinsic sea } (g \rightarrow \bar{q}q)$$
$$\text{and is sensitive to "intrinsic sea" only}$$



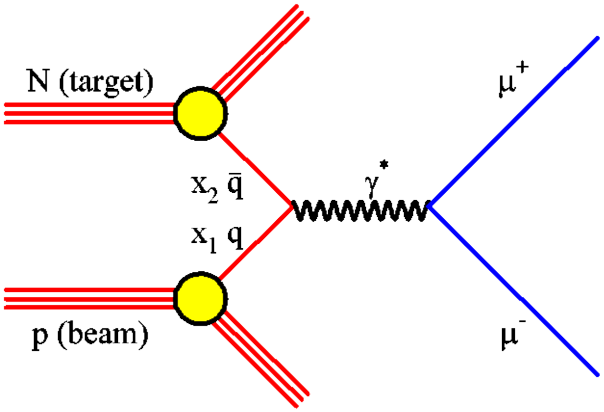
$\boxed{\text{How to measure } \bar{d} - \bar{u}\text{ ?}}$

The Drell-Yan Process

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

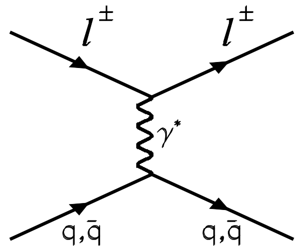
On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

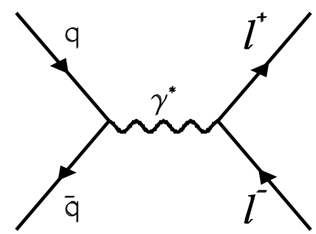


$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2) \right]$$

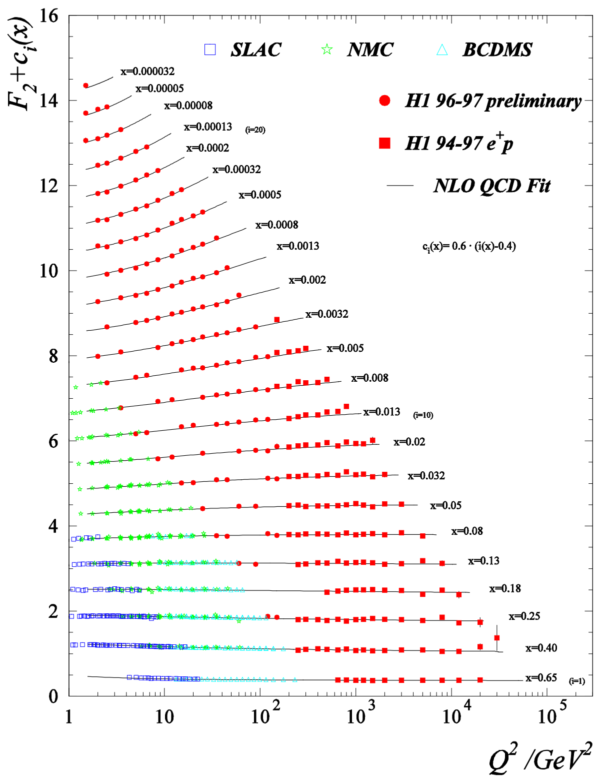
Complimentality between DIS and Drell-Yan

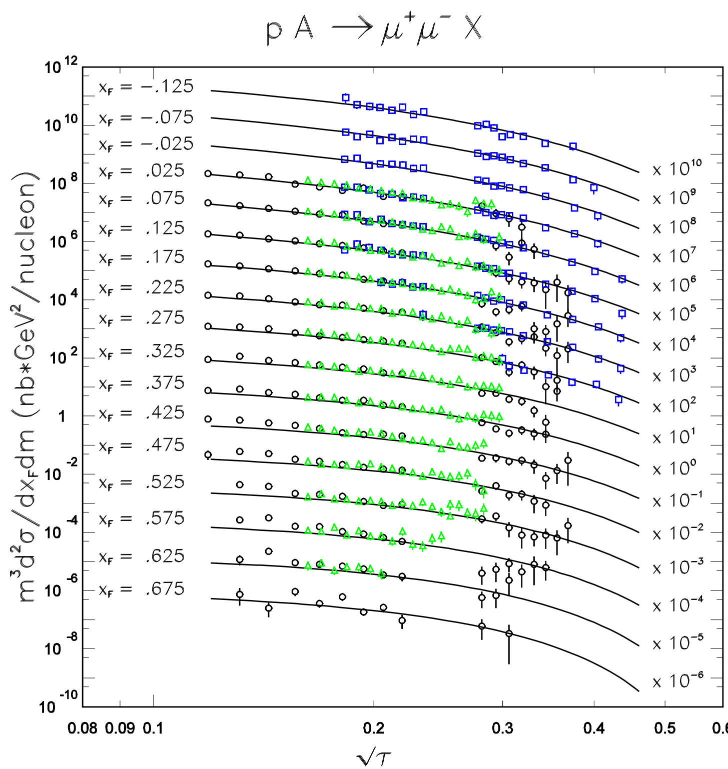
DIS





Drell-Yan





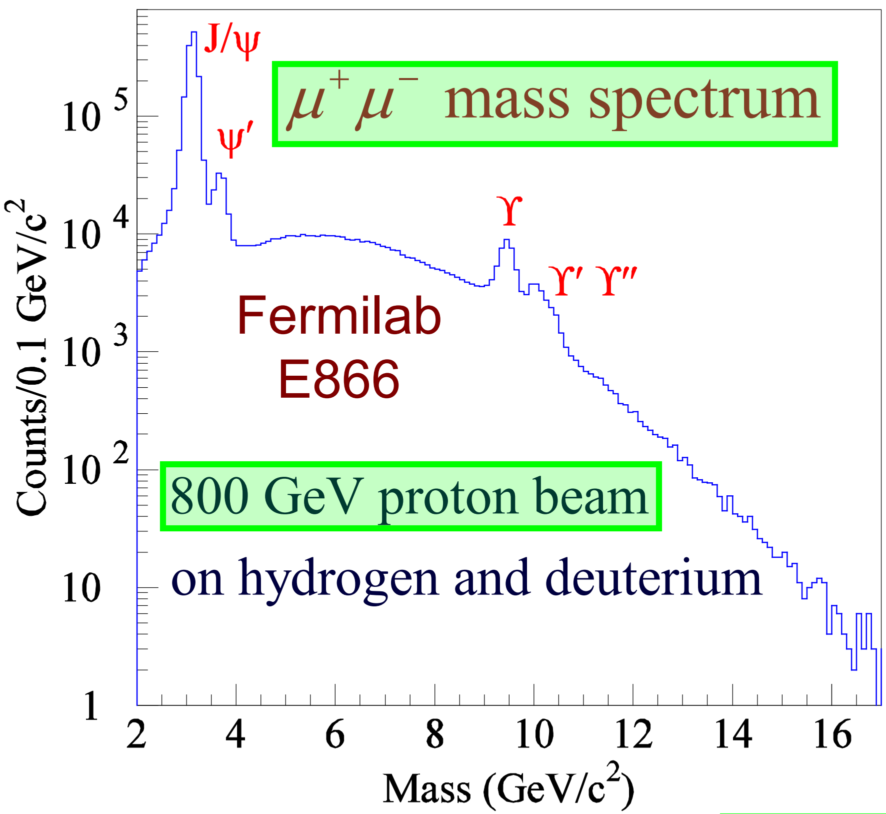
Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

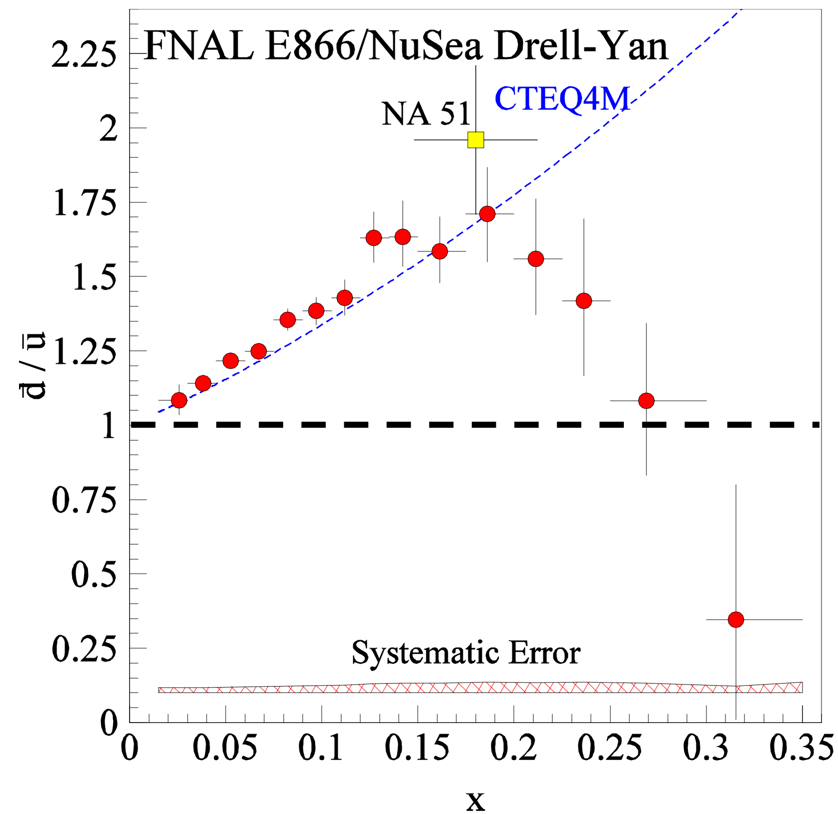
Prog. Part. Nucl. Phys. 76 (2014) 43 (JCP, J. Qiu)

Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

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

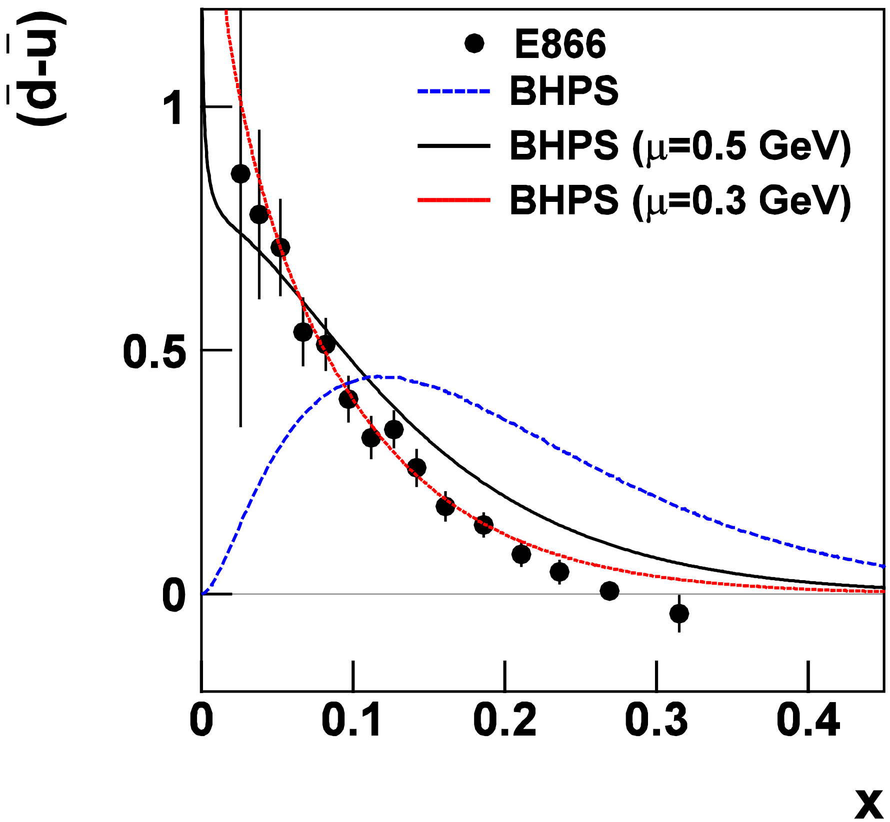
$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2) \right]$$





at $x_1 > x_2$: Drell-Yan: $\sigma^{pd} / 2\sigma^{pp} \sim \frac{1}{2}\left(1 + \bar{d}(x_2)/\bar{u}(x_2)\right)$

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



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

The data are in good agreement with the BHPS 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

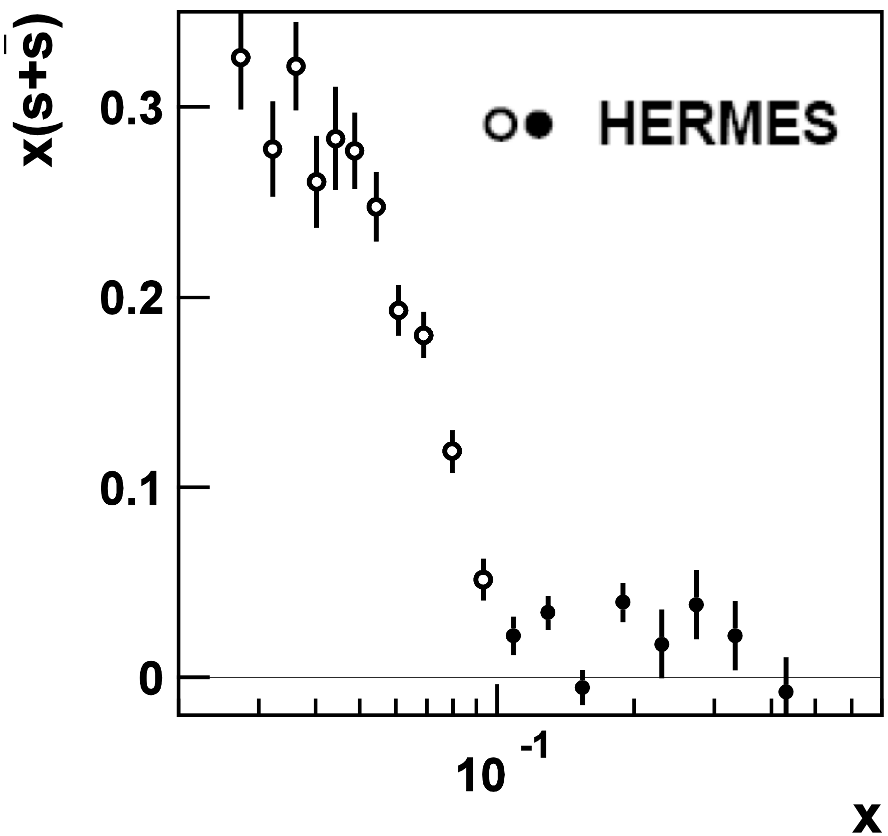
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

How to separate the "intrinsic sea" from the "extrinsic sea"?

- "Intrinsic sea" and "extrinsic sea" are expected to have different x-distributions
  - Intrinsic sea is "valence-like" and is more abundant at larger x
  - Extrinsic sea is more abundant at smaller x

An example is the $s(x)+\bar{s}(x)$ distribution

Extraction of the intrinsic strange-quark sea from the HERMES $s(x)+\overline{s}(x)$ data

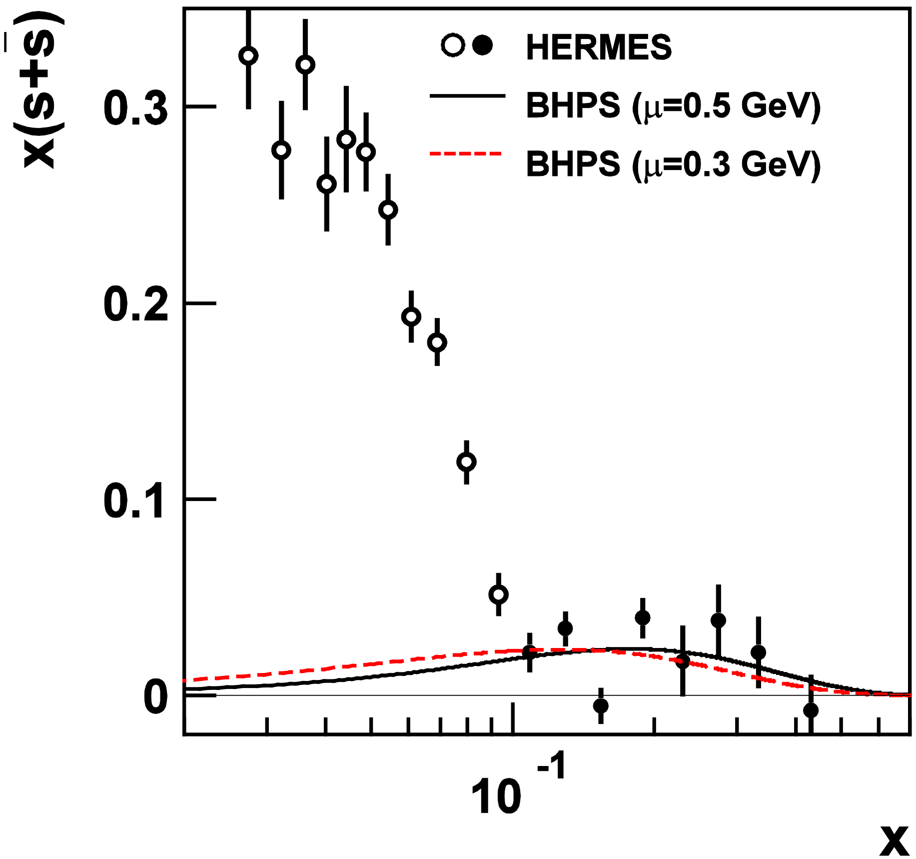


$s(x)+\overline{s}(x)$ extracted from HERMES Semi-inclusive DIS kaon data at $\langle Q^2 \rangle = 2.5\ \mathrm{GeV}^2$

The data appear to consist of two different components (intrinsic and extrinsic?)

HERMES collaboration, Phys. Lett. B666, 446 (2008)

Comparison between the $s(x)+\overline{s}(x)$ data with the intrinsic 5-q model



(W. Chang and JCP, PL B704, 197(2011))

$s(x)+\overline{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$

Assume $x > 0.1$ data are dominated by intrinsic sea (and $x < 0.1$ are from QCD sea)

This allows the extraction of the intrinsic sea for strange quarks

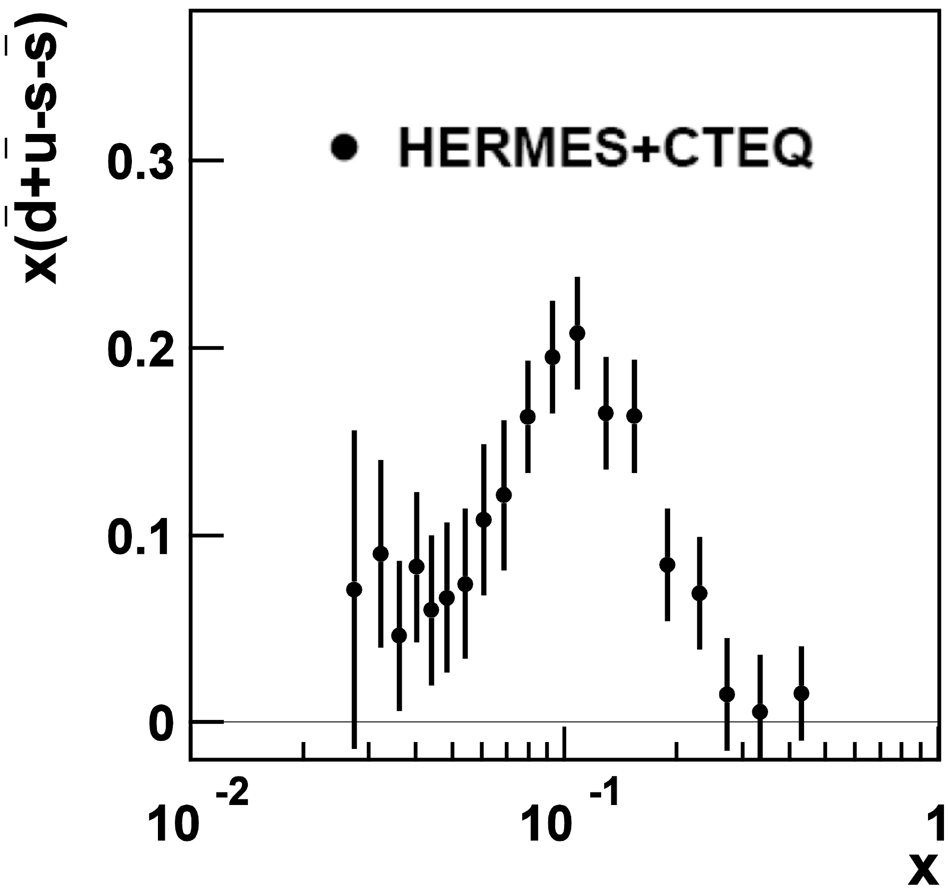
$$\boxed{P_5^{uuds\bar{s}} = 0.024}$$

How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no contributions from the "extrinsic sea"

$$\boxed{\begin{array}{c}\bar{d} + \bar{u} - s - \bar{s} \text{ has no contribution from extrinsic sea } (g \to \bar{q} q) \\ \text{and is sensitive to " intrinsic sea" only}\end{array}}$$

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



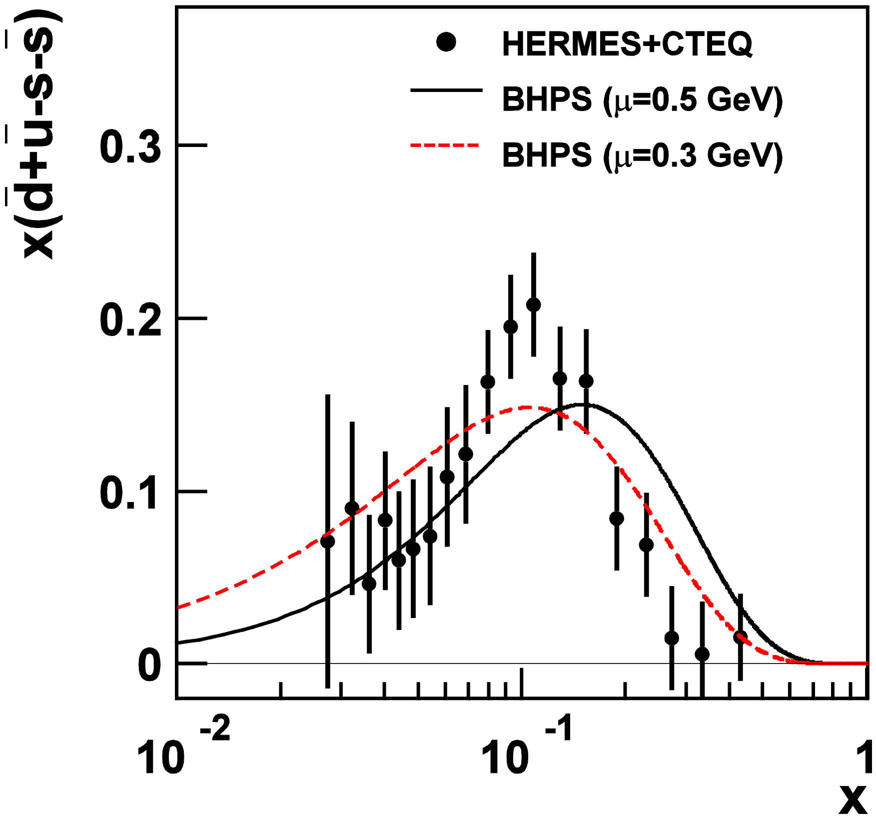
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

$s(x)+\bar{s}(x)$ from HERMES

$\bar{u}+\bar{d}-s-\bar{s}$ has no contribution from extrinsic sea

A valence-like x-distribution is observed

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



$\overline{d}(x)+\overline{u}(x)$ from CTEQ6.6

$s(x)+\overline{s}(x)$ from HERMES

$$\overline{u}+\overline{d}-s-\overline{s}$$

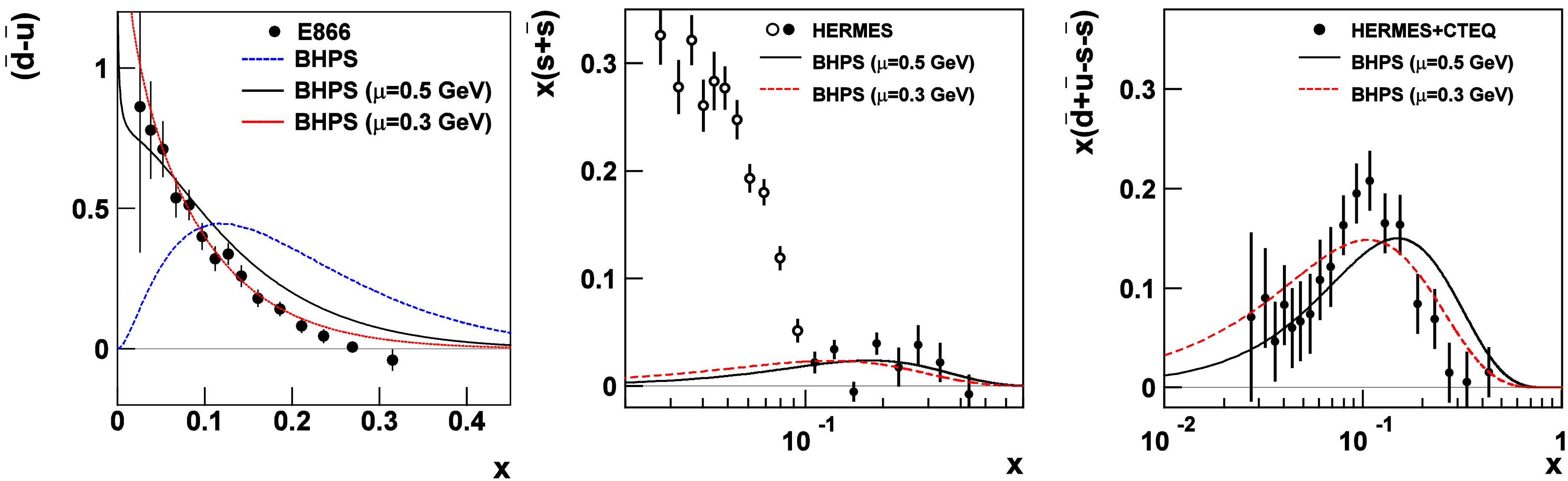
$$\sim P_5^{uudu\overline{u}}+P_5^{uudd\overline{d}}-2P_5^{uuds\overline{s}}$$

(not sensitive to extrinsic sea)

(W. Chang and JCP, PL B704, 197(2011))

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

Extraction of the various five-quark components for light quarks



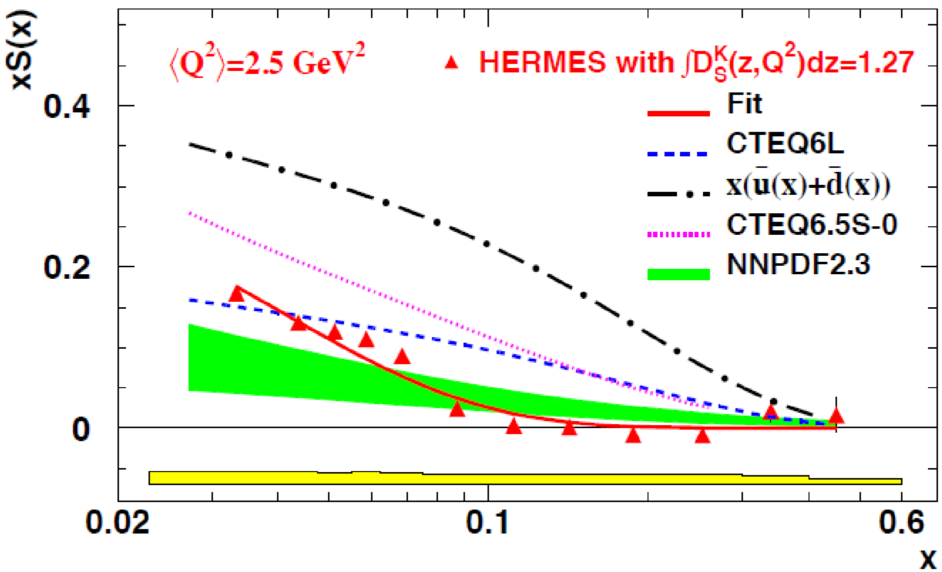
$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$

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

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

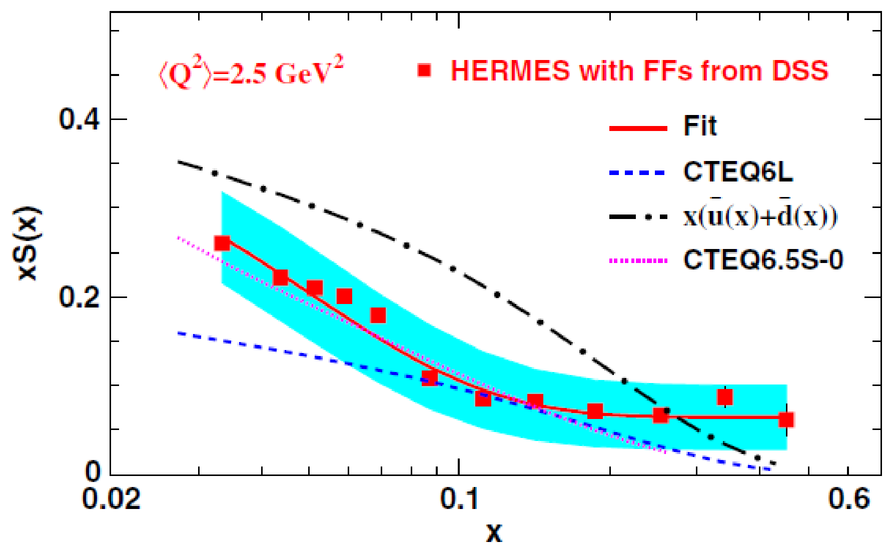
$$P_5^{uudd\bar{d}} = 0.240;\ \ P_5^{uudu\bar{u}} = 0.122;\ \ P_5^{uuds\bar{s}} = 0.024$$

Latest HERMES result on $xS(x)$



New 2014 result obtained with HERMES kaon fragmentation function

PHYSICAL REVIEW D **89,** 097101 (2014)



New 2014 result obtained with the DSS kaon fragmentation function

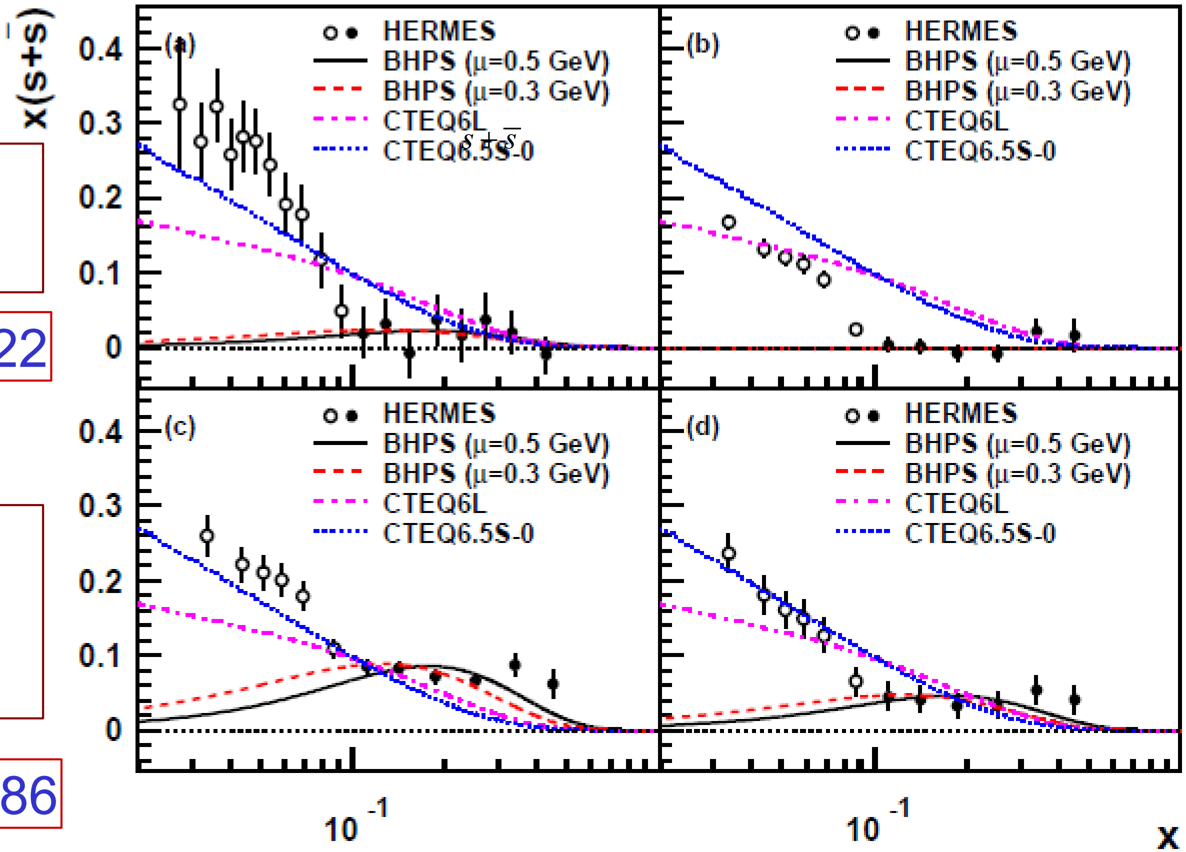
Dependence of $s+\bar{s}$ extraction on the kaon fragmentation functions

2008 HERMES

$P_5^{uuds\bar{s}}$=0.022

2014 HERMES

$P_5^{uuds\bar{s}}$=0.00



2014 HERMES DSS FF

$P_5^{uuds\bar{s}}$=0.086

2014 HERMES Intermediate FF

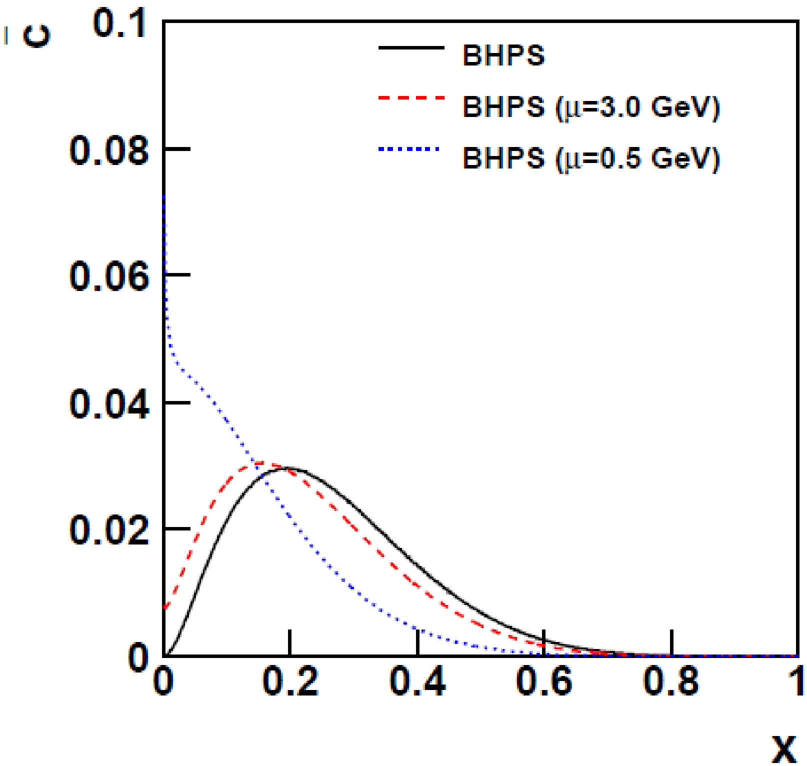
$P_5^{uuds\bar{s}}$=0.046

Wen-Chen Chang and JCP, PRD 92, 054020 (2015)

What are the implications on the intrinsic charm content in the proton?

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

Expect $P_5^{uudc\bar{c}} \sim 0.0025$



- Calculation assumes $P_5^{uudc\bar{c}} = 0.01$
- Q^2- evolution could shift the x-distribution to smaller x

Future Possibilities

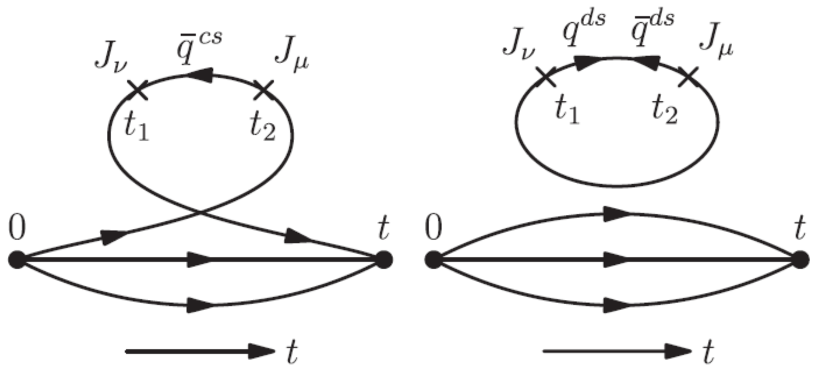
- Search for intrinsic strange and charm at EIC and LHC.
- Spin-dependent observables of intrinsic sea?
- Global fits including intrinsic u, d, s sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

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 Disconnected sea



(valence-like) (sea-like)

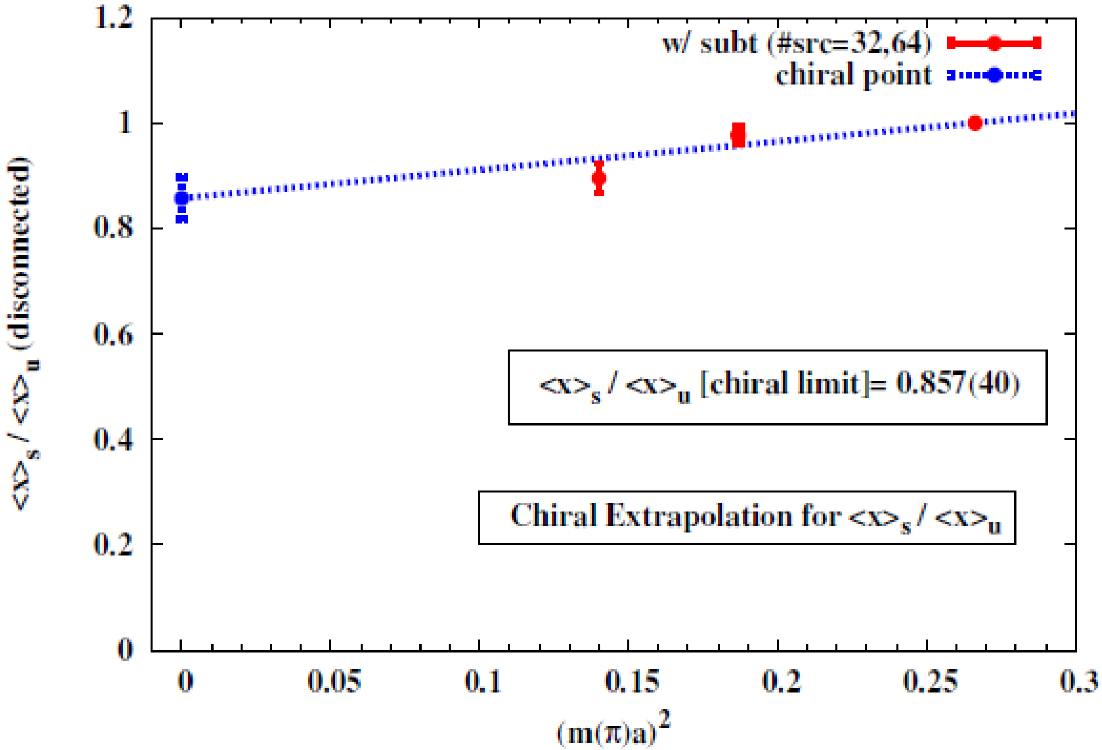
Two sources of sea:
Connected sea (CS) and
Disconnected sea (DS)

CS and DS have
different Bjorken-x and
flavor dependencies

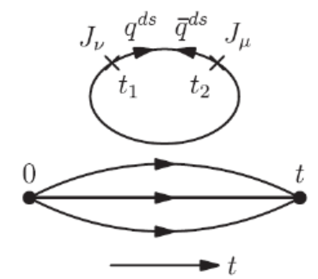
- x – dependence: at small x, CS $\sim x^{-1/2}$; DS $\sim x^{-1}$
- Flavor dependence: $\bar{u}$ and $\bar{d}$ have both CS and DS;

$s+\bar{s}$ is entirely DS

Can one separate the "connected sea" from the "disconnected sea" for $\bar{u} + \bar{d}$?



Disconnected sea



$$R = \frac{\langle x \rangle_{s+\bar{s}}}{\langle x \rangle_{u+\bar{u}}} = 0.857(40)$$

for disconnected sea

(Doi et al., Pos lattice 2008, 163.)

Lattice QCD shows that disconnected sea is roughly SU(3)-flavor independent

Can one separate the "connected sea" from the "disconnected sea" for $\bar{u} + \bar{d}$?

A) Lattice QCD shows that disconnected sea is roughly SU(3)-flavor independent

$$R = \frac{\langle x \rangle_{s+\bar{s}}}{\langle x \rangle_{u+\bar{u}}} = 0.857(40) \text{ for disconnected sea}$$

B) $[\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}} = [s(x) + \bar{s}(x)] / R$

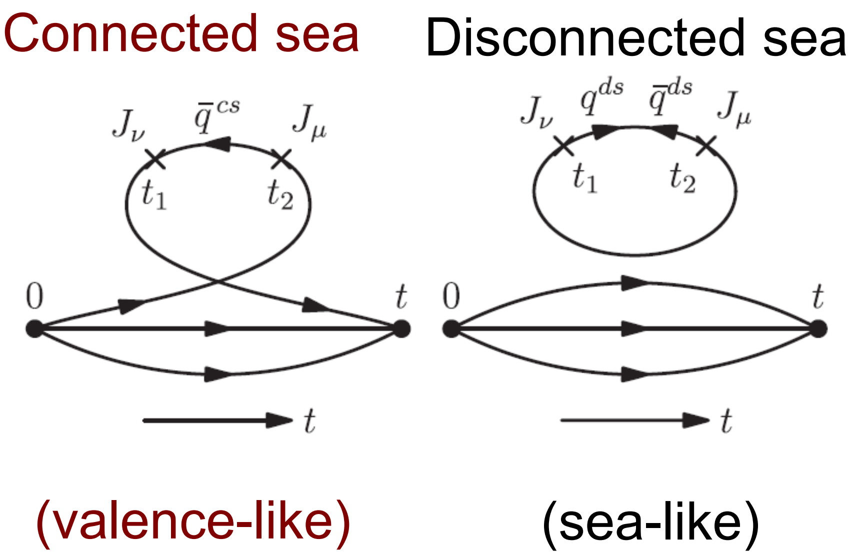
(since $s, \bar{s}$ is entirely from the disconnected sea)

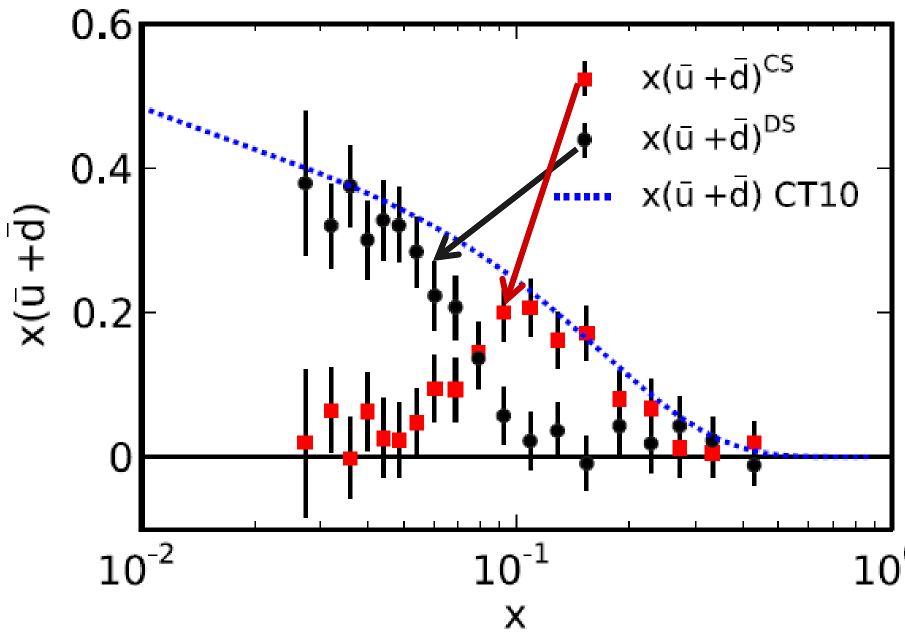
C) $[\bar{u}(x) + \bar{d}(x)]_{\text{connected sea}} =$

$[\bar{u}(x) + \bar{d}(x)]_{\text{PDF}} - [\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}}$

Connected-Sea Partons

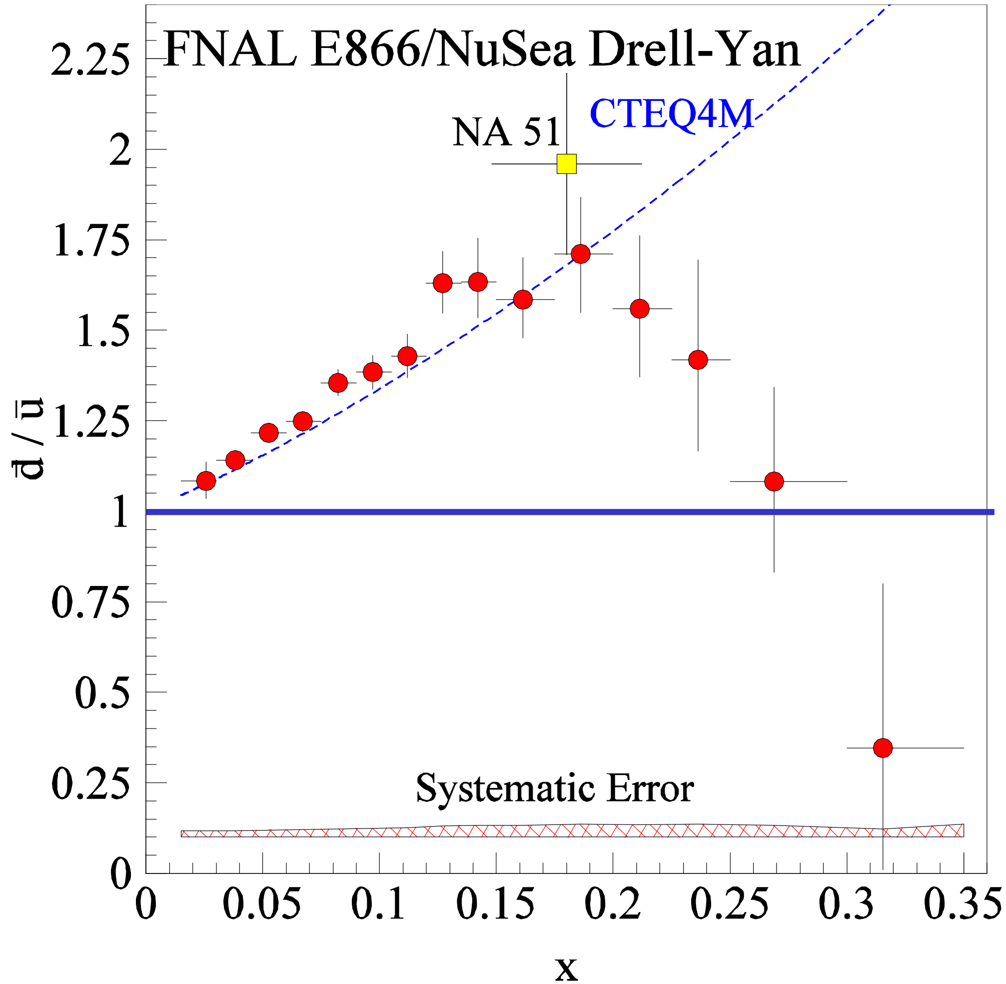
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]





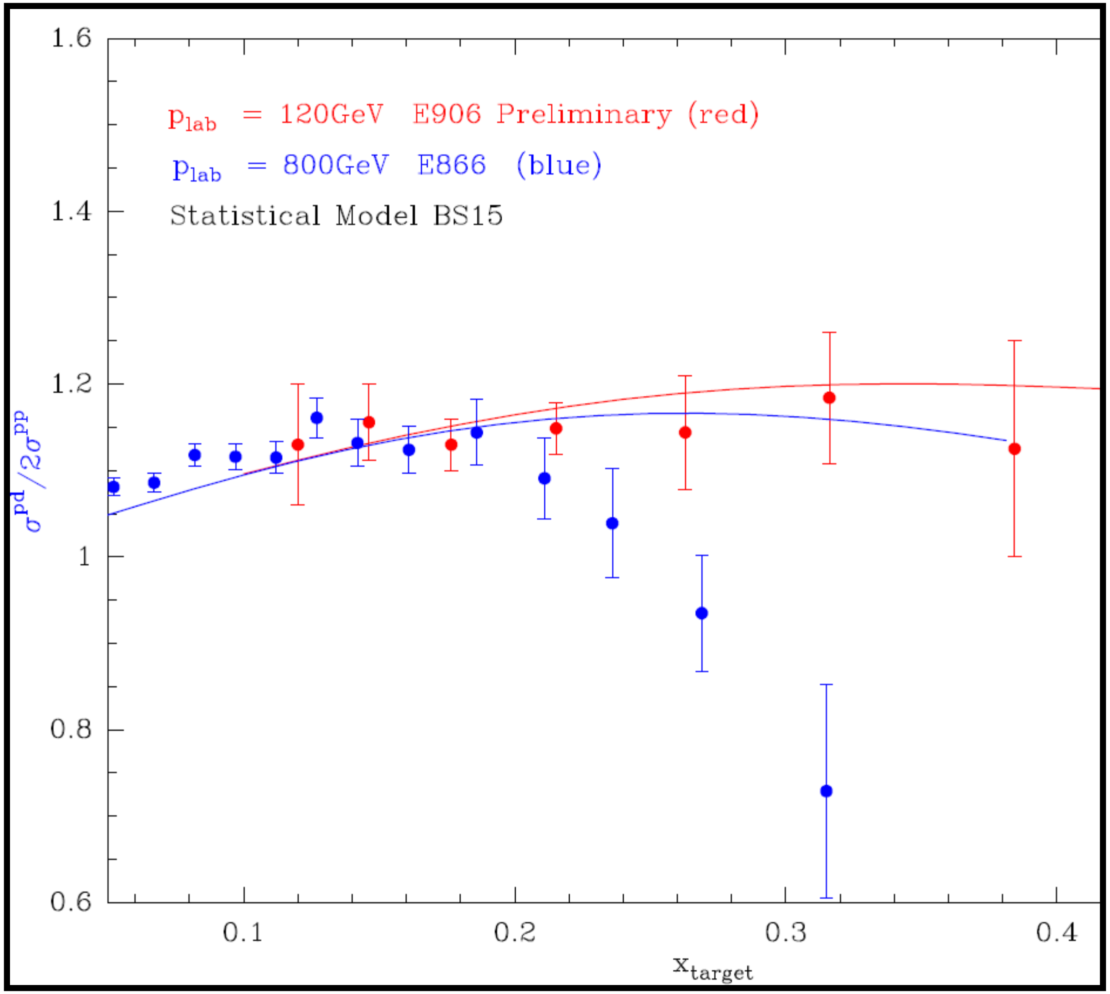
- Connected sea component for $\bar{u}(x)+\bar{d}(x)$ is valence-like
- For $\bar{u}+\bar{d}$, momenta carried by CS and DS are roughly equal, at Q^2=2.5 GeV^2

Does $\bar{d}\,/\,\bar{u}$ drop below 1 at large x?



No existing models can explain sign-change

for $\bar{d}(x) - \bar{u}(x)$ at any value of x



The E906 result shows that $\bar{d}(x) > \bar{u}(x)$ continues to be true at the highest x, suggesting the importance of intrinsic sea at high x

Possible measurements at EIC

- Semi-inclusive DIS with kaons

$$e + p \rightarrow e' + K + x$$

- Semi-inclusive DIS with charmed mesons

$$e + p \rightarrow e' + D + x$$

- TDIS with forward-going hyperons

$$e + p \rightarrow e' + \Lambda + x$$

Conclusions

- Evidences for the existence of "intrinsic" light-quark seas $(\bar{u}, \bar{d}, \bar{s})$ in the nucleons.
- Clear evidence for intrinsic charm remains to be found.
- The concept of connected and disconnected seas in Lattice QCD offers useful insights on the flavor- and x-dependencies of the sea.
- Future target fragmentaion measurements at JLab and EIC could provide useful new information on intrinsic strange.