

# SIDIS and Intrinsic Sea at Mid-x

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Workshop on “Science at Mid-x: Anti-Shadowing  
and the Role of the Sea”

Jefferson Lab, July 22-23, 2022

# Outline

- “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
- Possible connections between PDFs and FF (fragmentation functions)

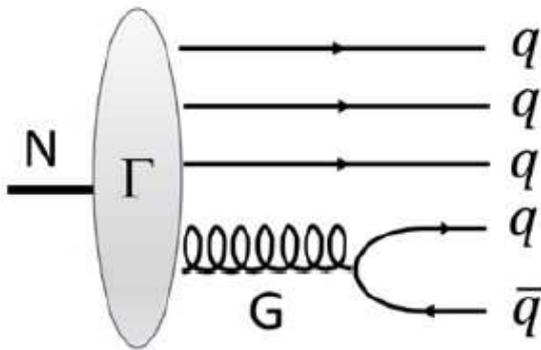
Work in collaboration with Wen-Chen Chang

# Search for the “intrinsic” quark sea

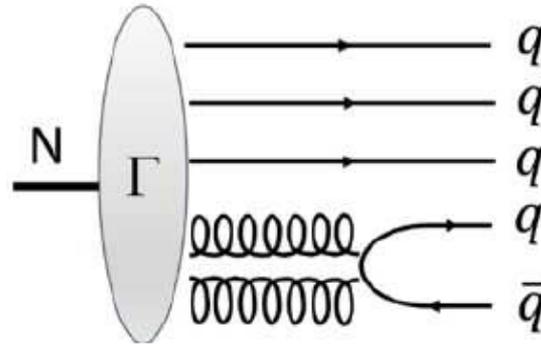
In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of “intrinsic” charm

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

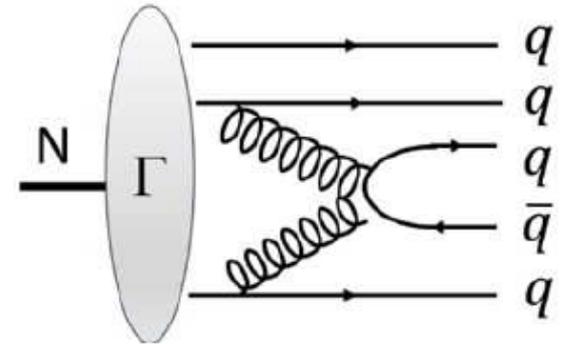
The "intrinsic"-charm from  $|uudc\bar{c}\rangle$  is "valence"-like and peak at large  $x$  unlike the "extrinsic" sea ( $g \rightarrow c\bar{c}$ )



(a)



(b)



(c)

“extrinsic sea”

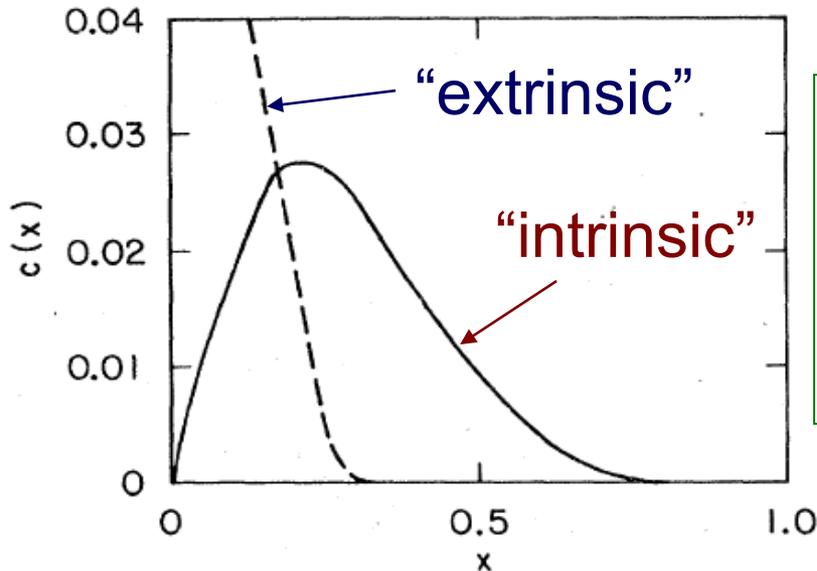
“intrinsic sea”

# Search for the “intrinsic” quark sea

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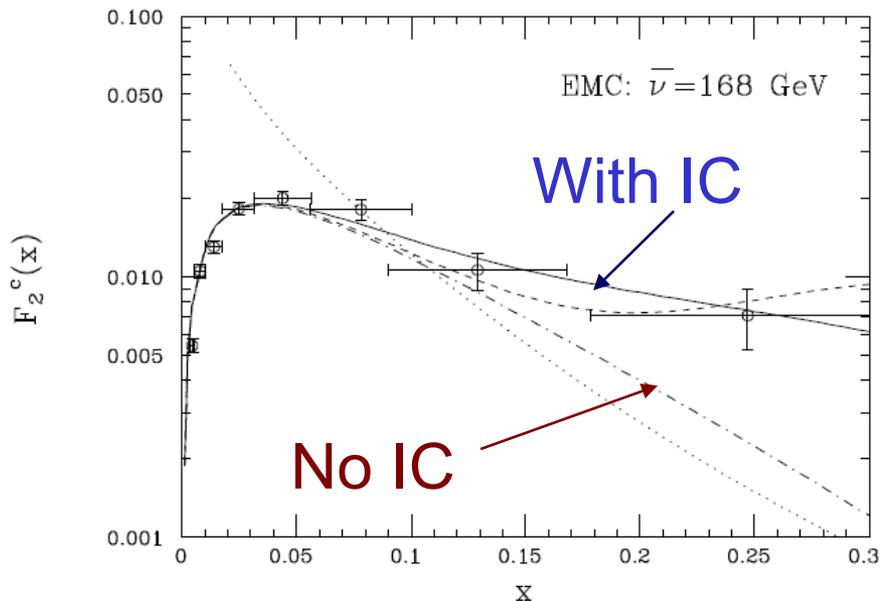
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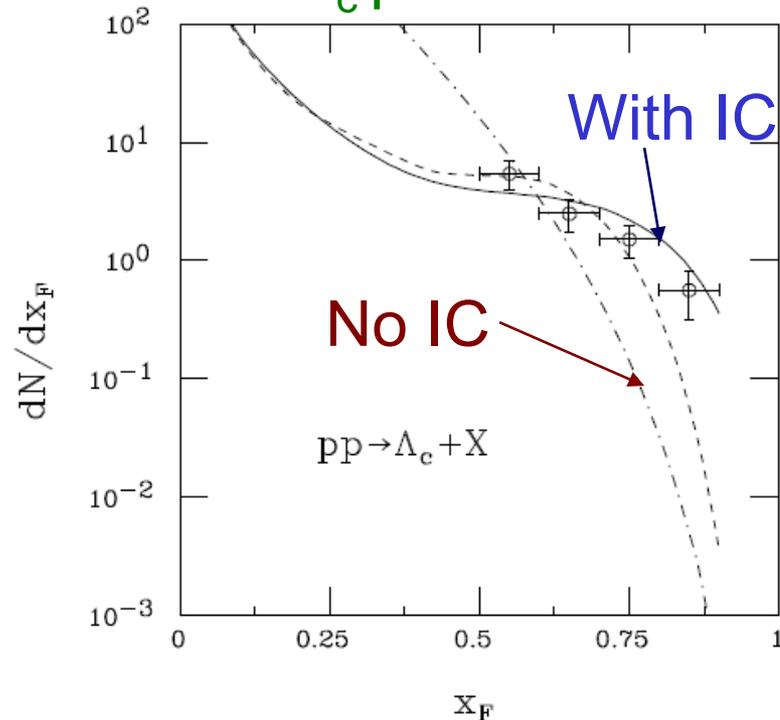
The “intrinsic charm” in  $|uudc\bar{c}\rangle$  can lead to large contribution to charm production at large  $x$

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

DIS data



$\Lambda_c$  production



Gunion and Vogt (hep-ph/9706252);

Barger, Halzen and Keung (PRD 25 (1982) 112)

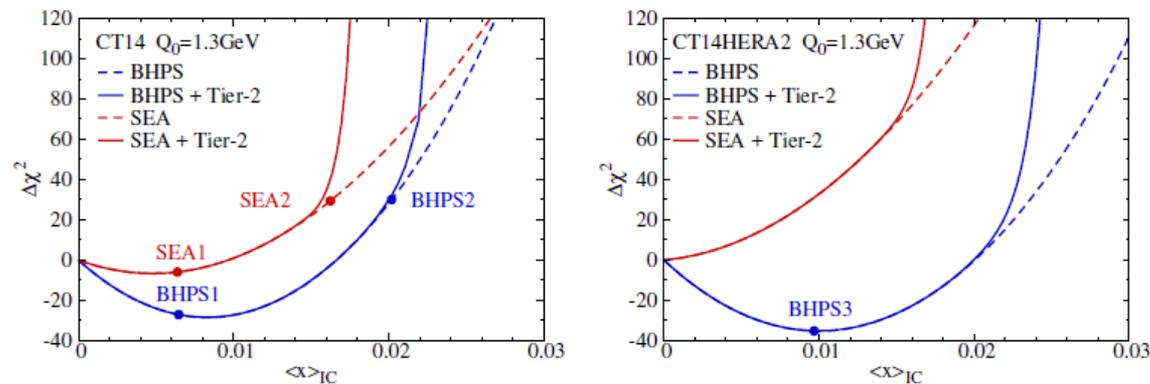
**Tantalizing evidence for intrinsic charm**

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

# A recent global fit by CTEQ-TEA to extract intrinsic-charm (JHEP02 (2018) 059)

## CT14 intrinsic charm parton distribution functions from CTEQ-TEA global analysis

Tie-Jiun Hou,<sup>a</sup> Sayipjamal Dulat,<sup>b,c,d</sup> Jun Gao,<sup>e</sup> Marco Guzzi,<sup>f,g</sup> Joey Huston,<sup>d</sup> Pavel Nadolsky,<sup>a</sup> Carl Schmidt,<sup>d</sup> Jan Winter,<sup>d</sup> Keping Xie<sup>a</sup> and C.-P. Yuan<sup>d</sup>

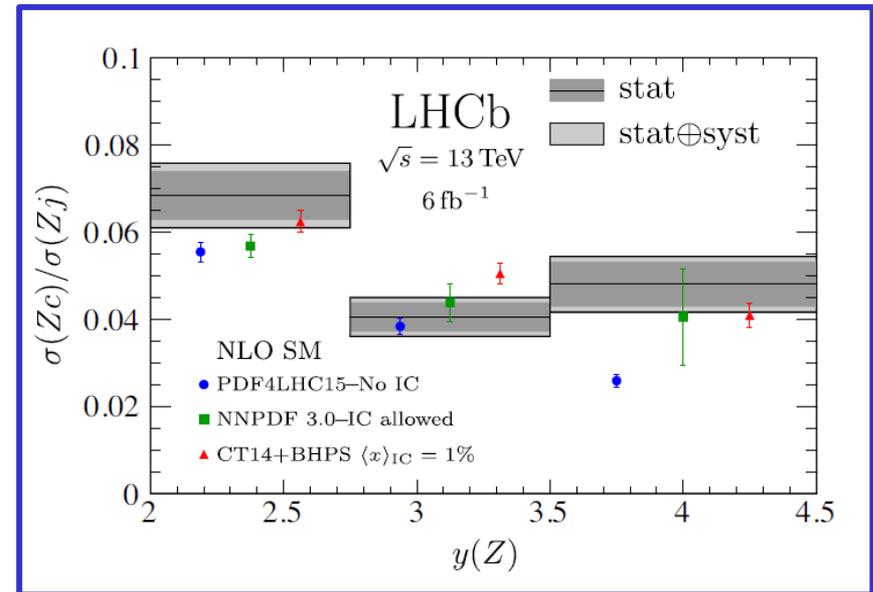
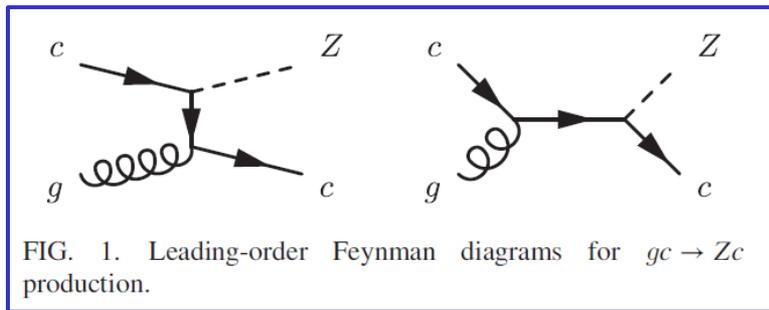


We see from figure 5 that large amounts of intrinsic charm are disfavored for all models under scrutiny. A mild reduction in  $\chi^2$ , however, is observed for the BHPS fits, roughly at  $\langle x \rangle_{IC} = 1\%$ , both in the CT14 and CT14HERA2 frameworks.

No conclusive evidence for intrinsic-charm  
(However, possible new evidence from LHC) 6

## Study of Z Bosons Produced in Association with Charm in the Forward Region

R. Aaij *et al.*\*  
(LHCb Collaboration)



charm jets is determined in intervals of Z-boson rapidity in the range  $2.0 < y(Z) < 4.5$ . A sizable enhancement is observed in the forwardmost  $y(Z)$  interval, which could be indicative of a valencelike intrinsic-charm component in the proton wave function.

“...However, conclusion about whether the proton contains valence-like intrinsic charm can only be drawn after incorporating these results into global PDF analyses”

# Search for the “intrinsic” light-quark sea

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

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

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

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

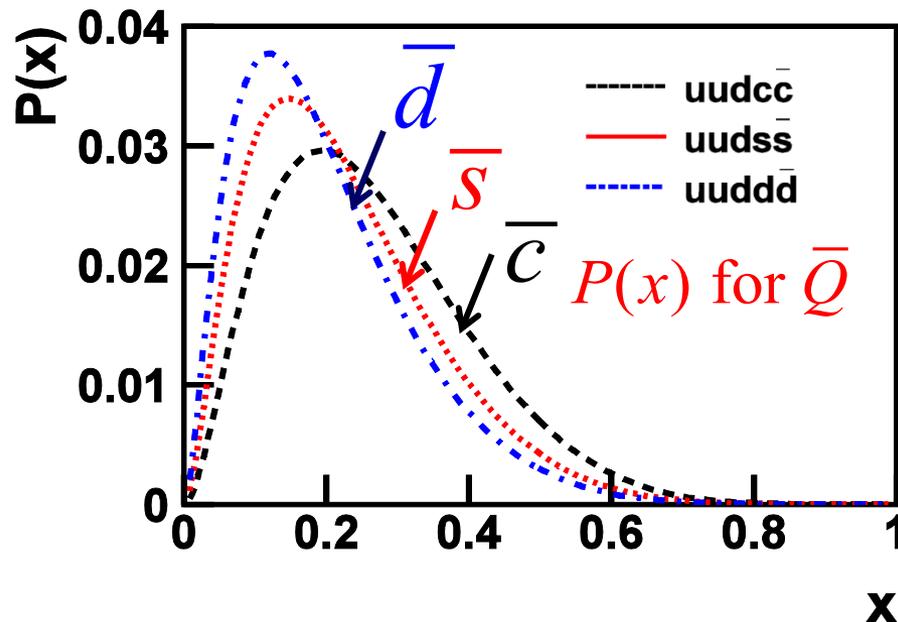
The “intrinsic” sea for lighter  
quarks have larger probabilities!

# $x$ -distribution for “intrinsic” light-quark sea

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

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

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



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

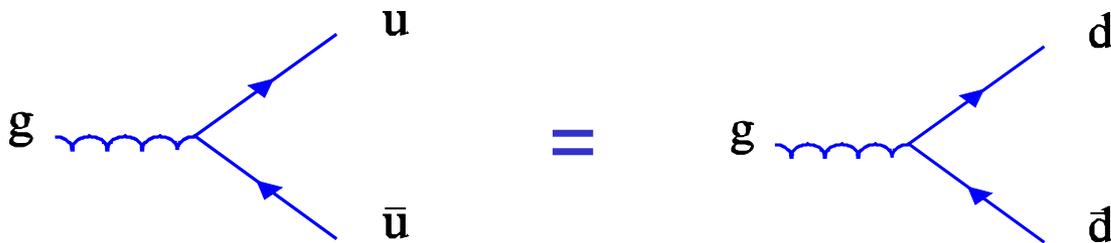
$$P(x_5) = \frac{1}{2} \tilde{N}_5 x_5^2 [(1-x_5)(1+10x_5+x_5^2) - 2x_5(1+x_5)\ln(1/x_5)]$$

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”?

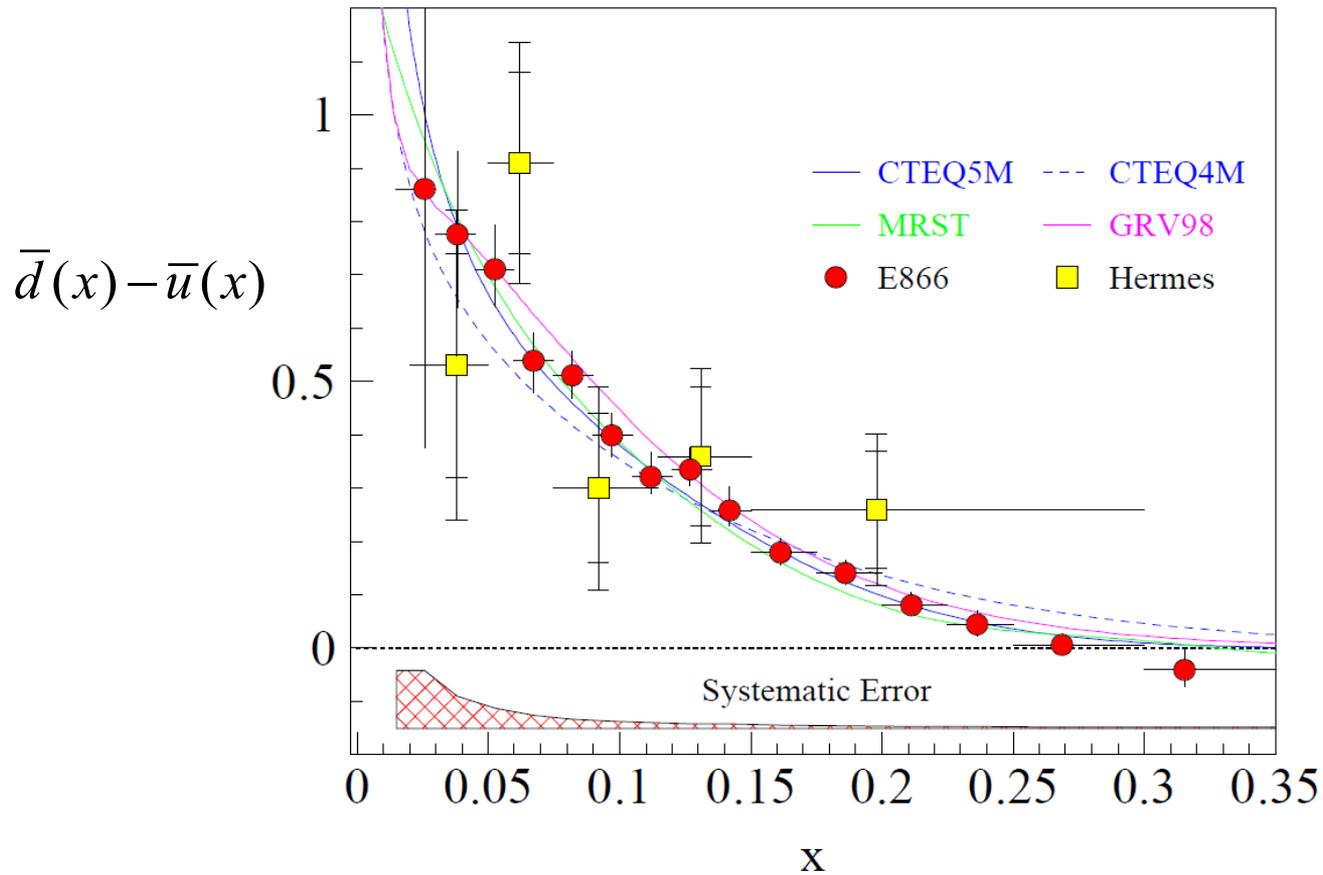
- Select experimental observables which have no contributions from the “extrinsic sea”

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



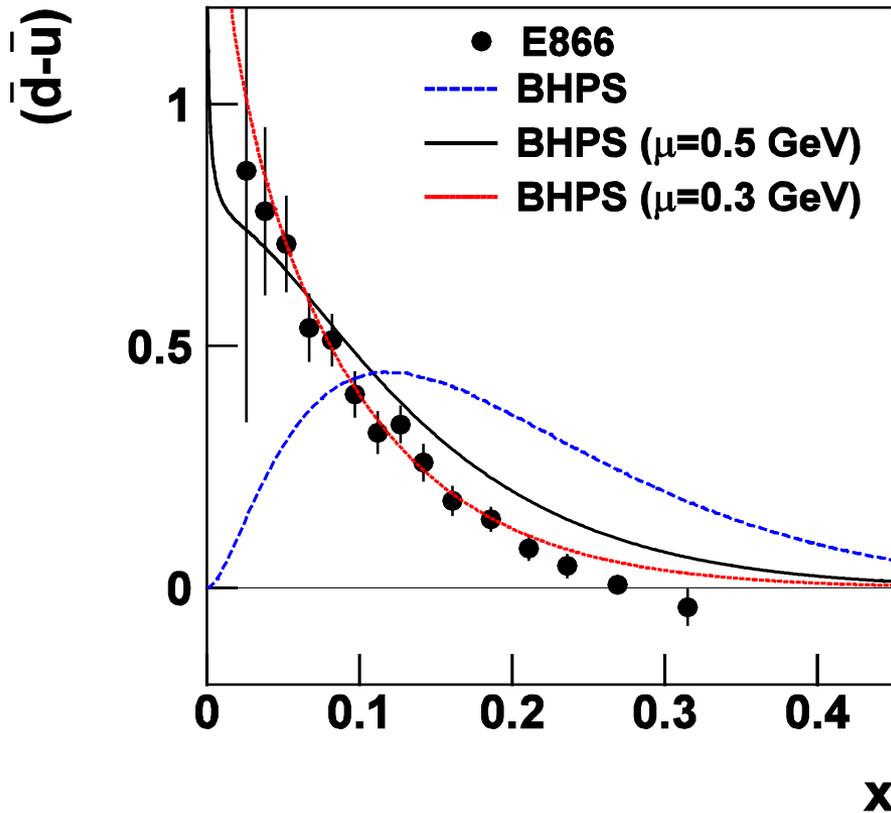
How to measure  $\bar{d} - \bar{u}$  ?

# $\bar{d}(x) - \bar{u}(x)$ from SIDIS and Drell-Yan



HERMES SIDIS data, PRL 81, 5519 (1998)  
Drell-Yan data from Fermilab E866

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



The data are in good agreement with the BHPS model after evolution from the initial scale  $\mu$  to  $Q^2=54 \text{ GeV}^2$

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

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

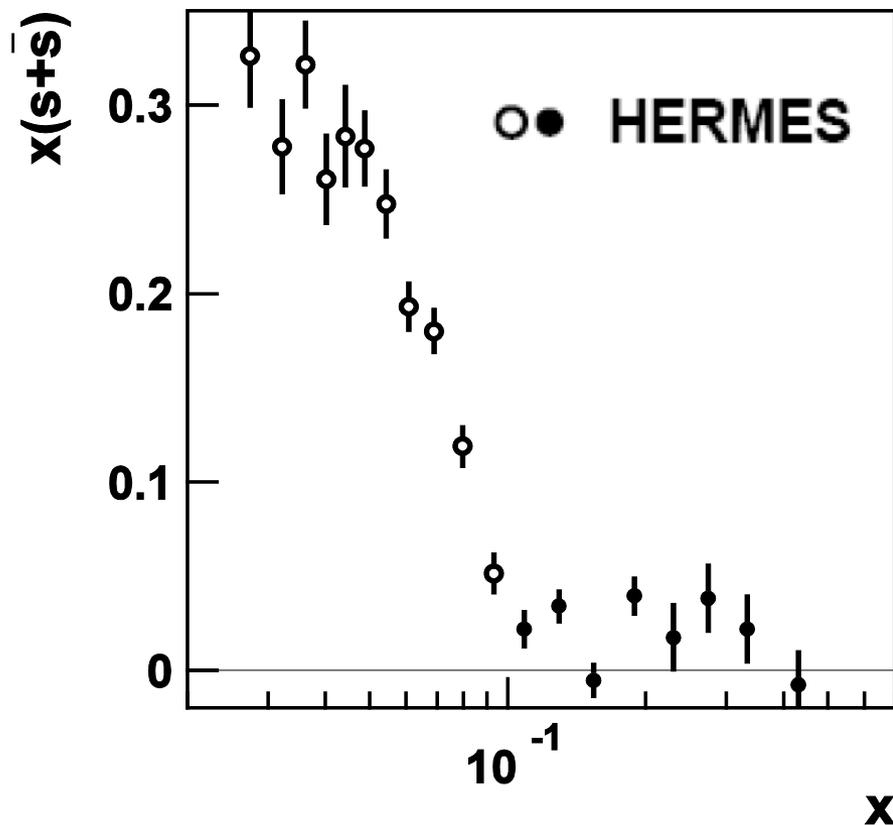
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

# 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 $s(x) + \bar{s}(x)$ data

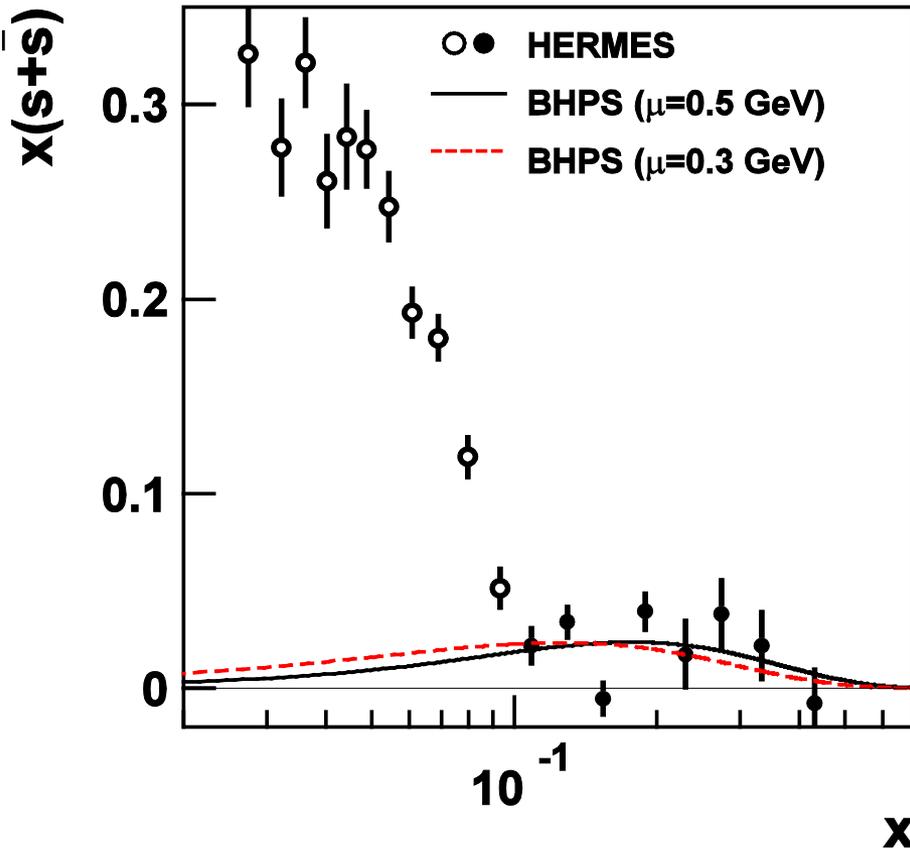


$s(x) + \bar{s}(x)$  extracted from  
HERMES Semi-inclusive DIS  
kaon data at  $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$

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

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

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



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

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

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

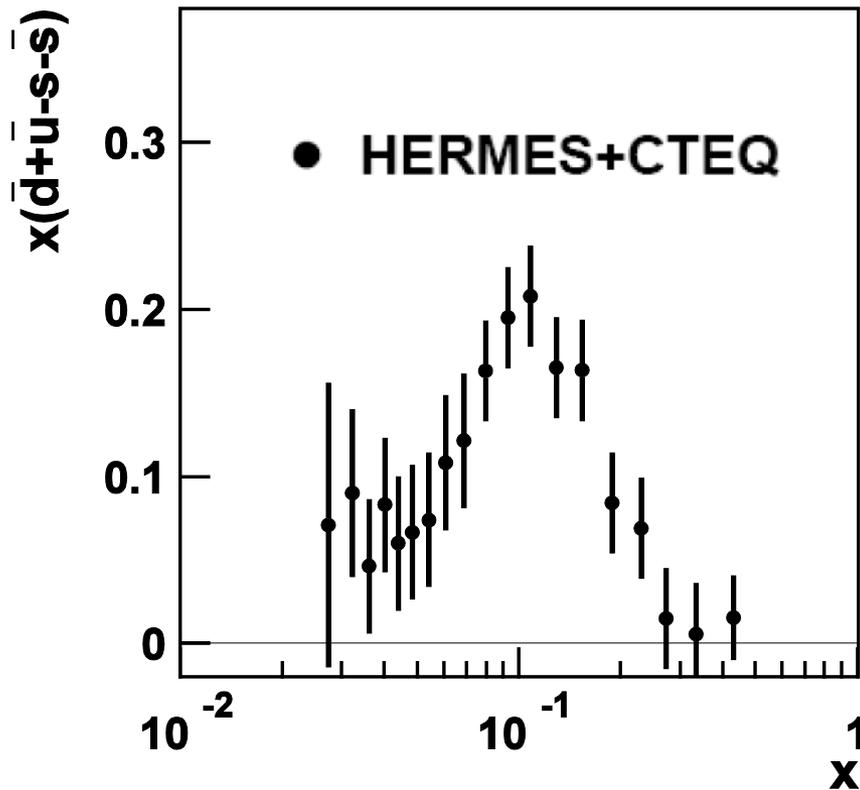
$$P_5^{uuds\bar{s}} = 0.024$$

# How to separate the “intrinsic sea” from the “extrinsic sea”?

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

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

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

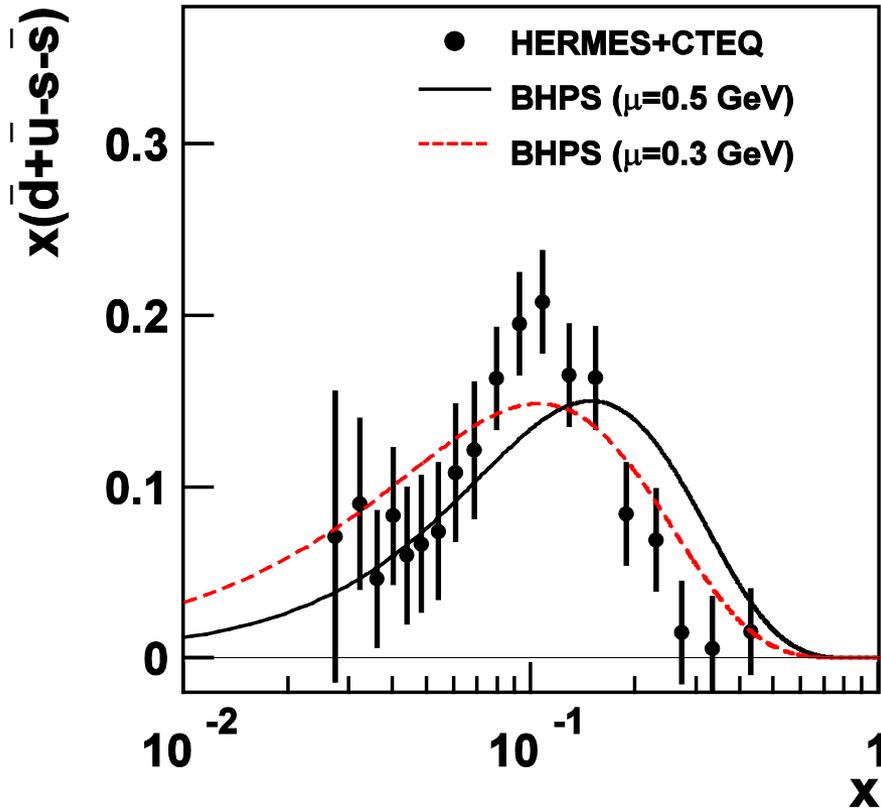


$\bar{d}(x) + \bar{u}(x)$  from CTEQ6.6  
 $s(x) + \bar{s}(x)$  from HERMES

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

A valence-like  $x$ -distribution is observed

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



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

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

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

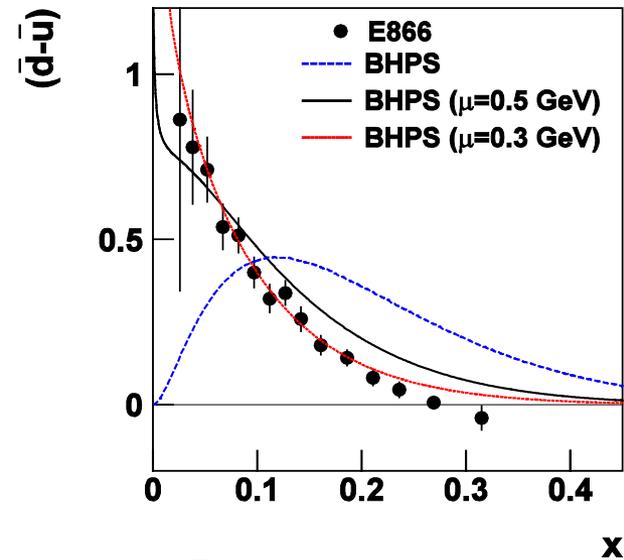
(not sensitive to extrinsic sea)

A valence-like distribution peaking at  $x \sim 0.1$  is observed

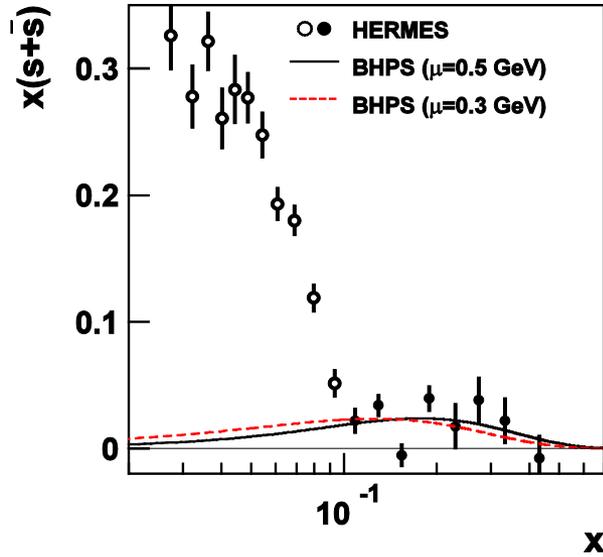
(W. Chang and JCP, PL B704, 197(2011))

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

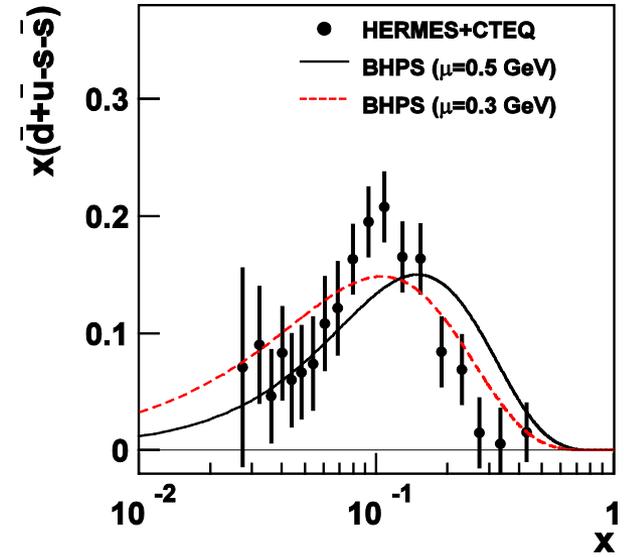
# Extraction of the various five-quark components for light quarks



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



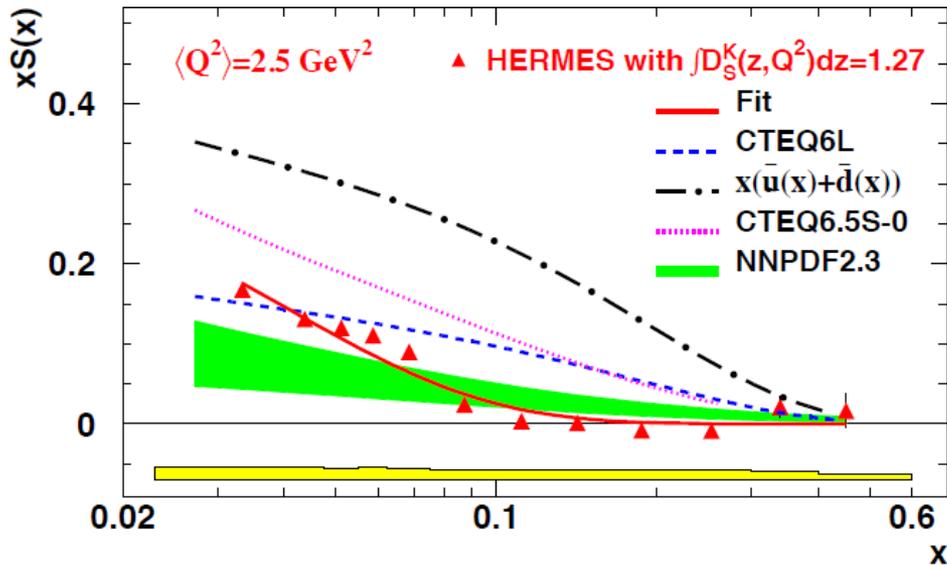
$$P_5^{uuds\bar{s}} = 0.024$$



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

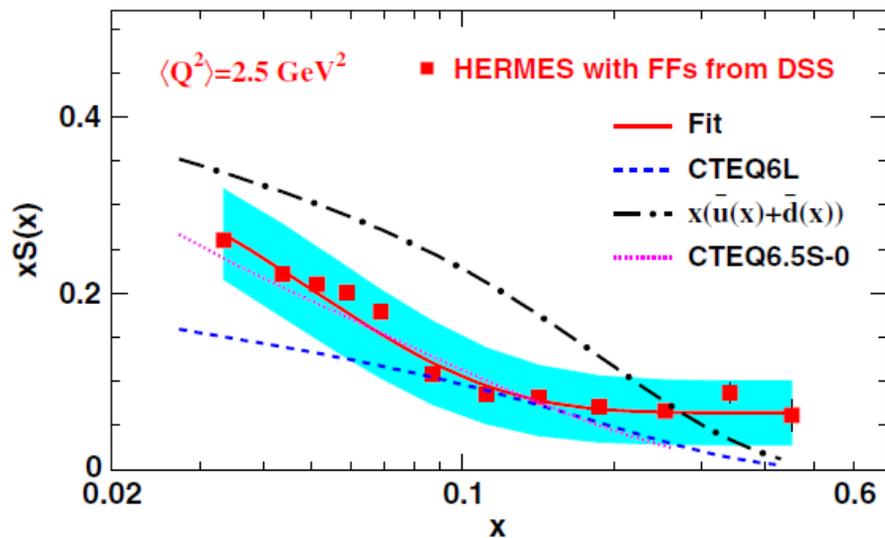
$$P_5^{uudd\bar{d}} = 0.240; \quad P_5^{uudu\bar{u}} = 0.122; \quad P_5^{uuds\bar{s}} = 0.024$$

# Latest HERMES result on $xS(x)$



Newer 2014 result obtained with HERMES kaon fragmentation function

PHYSICAL REVIEW D 89, 097101 (2014)



Newer 2014 result obtained with the DSS kaon fragmentation function

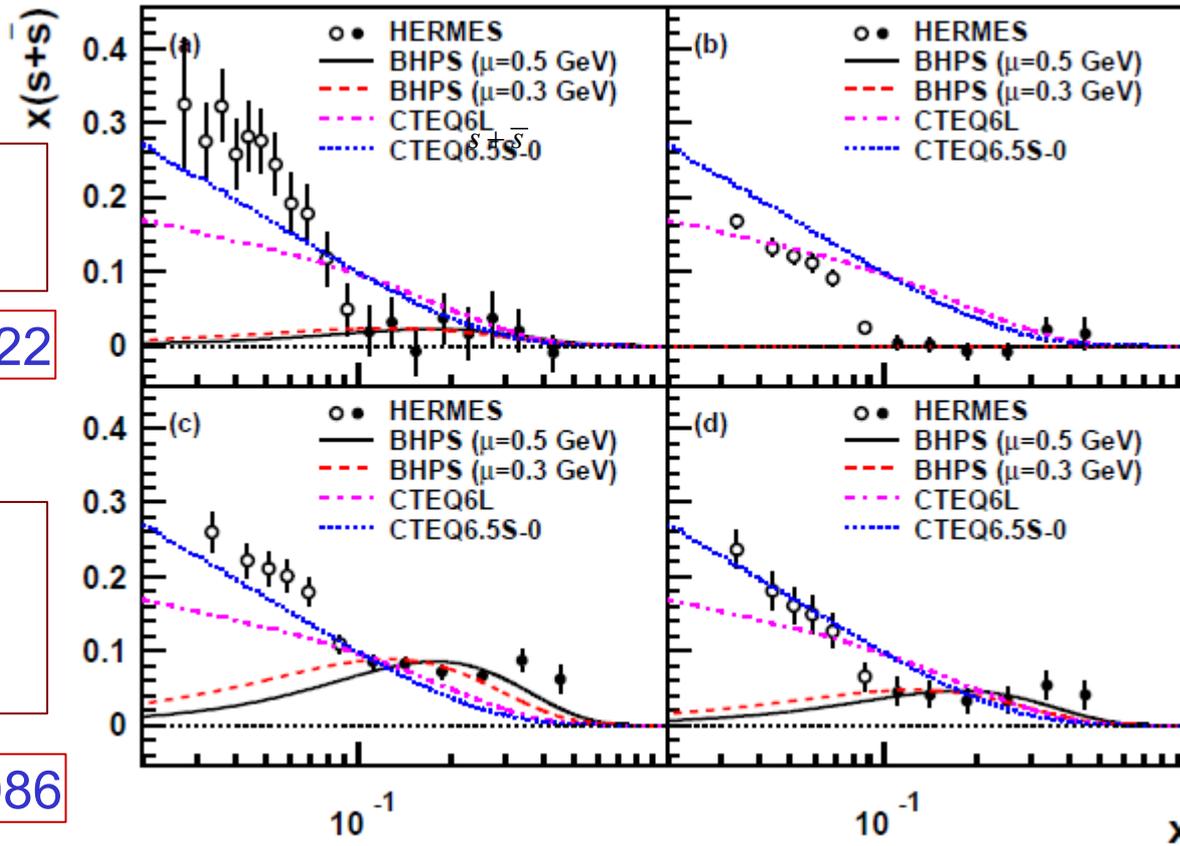
# Dependence of $s + \bar{s}$ extraction on the kaon fragmentation functions

2008  
HERMES

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

2014  
HERMES  
DSS FF

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



2014  
HERMES

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

2014  
HERMES  
Intermediate  
FF

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

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

# Other possible implications

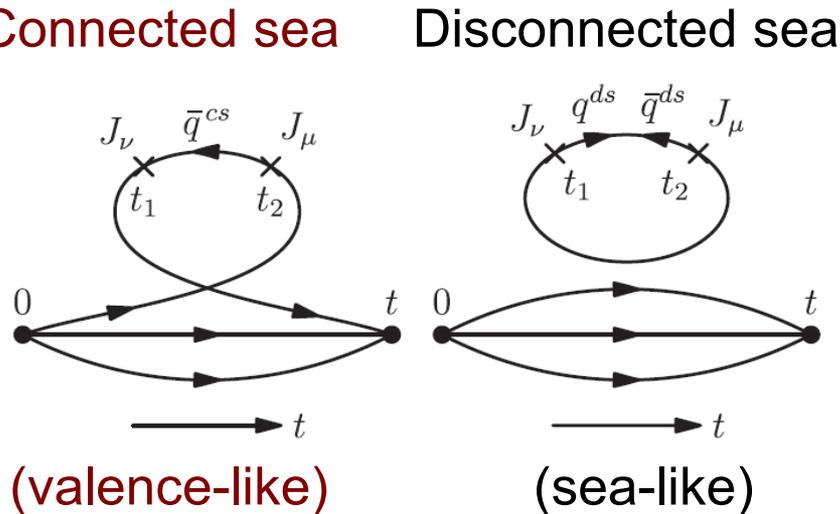
- Search for intrinsic strange sea with SIDIS at JLab.
- Spin-dependent observables of intrinsic sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

## Connected-Sea Partons

Keh-Fei Liu,<sup>1</sup> Wen-Chen Chang,<sup>2</sup> Hai-Yang Cheng,<sup>2</sup> and Jen-Chieh Peng<sup>3</sup>

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  $\bar{u} + \bar{d}$  ?

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

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

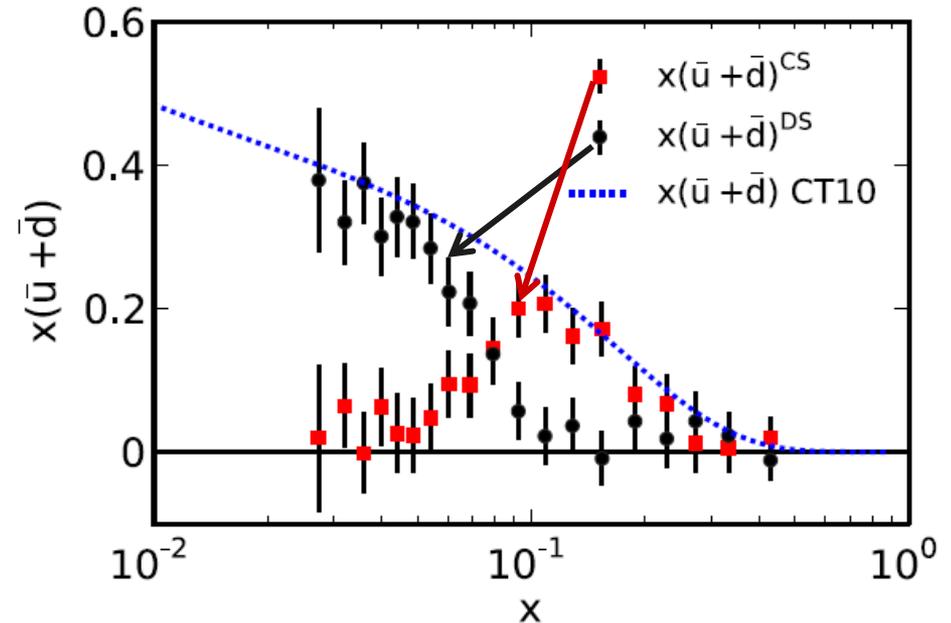
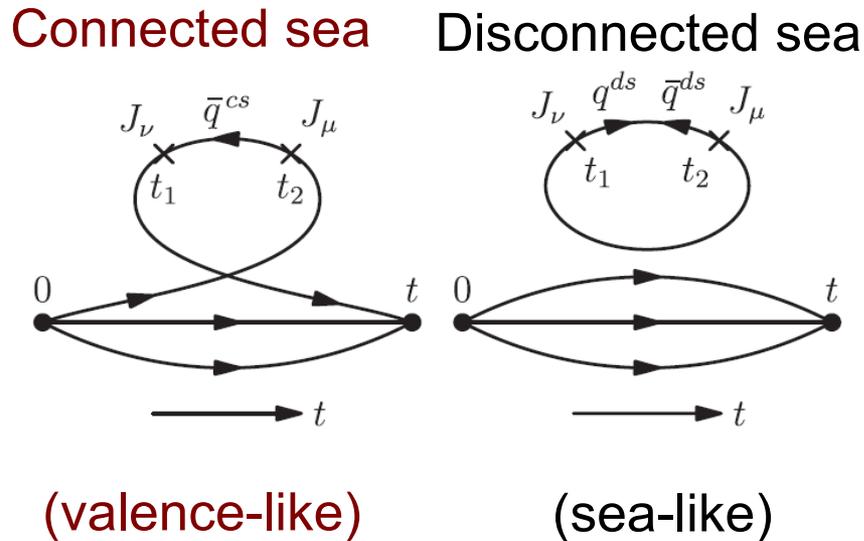
$$\text{B) } [\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}} = [s(x) + \bar{s}(x)] / R$$

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

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

## Connected-Sea Partons

Keh-Fei Liu,<sup>1</sup> Wen-Chen Chang,<sup>2</sup> Hai-Yang Cheng,<sup>2</sup> and Jen-Chieh Peng<sup>3</sup>



- 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  $Q^2 = 2.5 \text{ GeV}^2$
- A recent preprint performed the first global fit (CT18CS), with separate CS and DS (T. Hou et al., arXiv:2206.02431)

# Connections between PDFs and fragmentation functions (FFs)

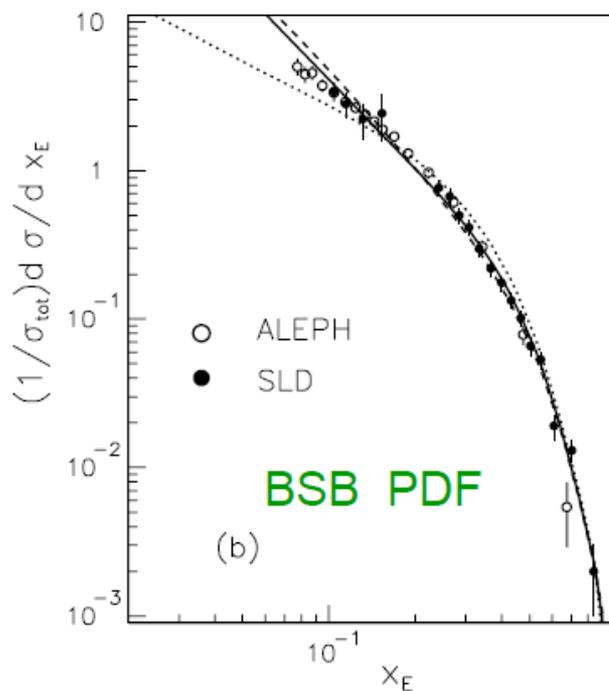
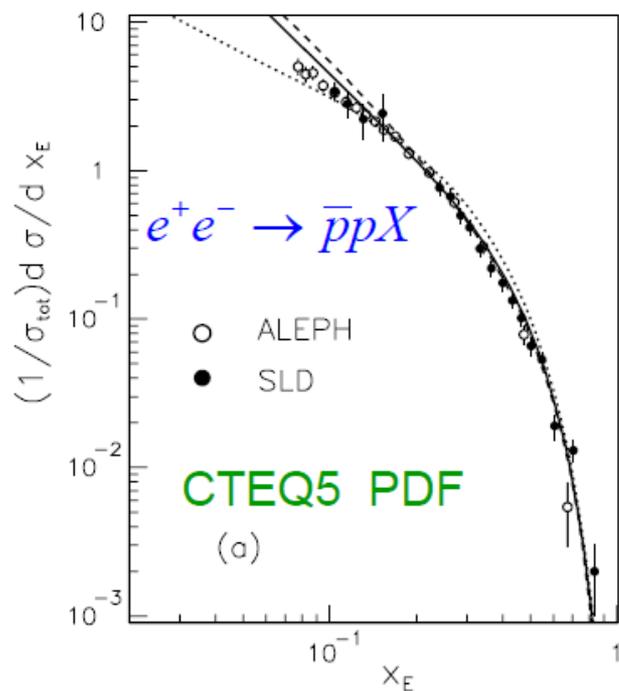
- Gribov-Lipatov "reciprocity" relation at  $z \rightarrow 1$

$$D_q(z) = zq(z)$$

- Implications on the flavor structure of the proton fragmentation functions?
- Flavor structure of the meson fragmentation functions?

Ma, Schmidt, Soffer, Yang assumes the following relations between fragmentation function and parton distributions:

$$D_v(z) = C_v z^\alpha q_v(z); \quad D_s(z) = C_s z^\alpha q_s(z)$$



Dotted:  $C_v = 1, C_s = 0, \alpha = 0$

Solid:  $C_v = 1, C_s = 1, \alpha = 0.5$

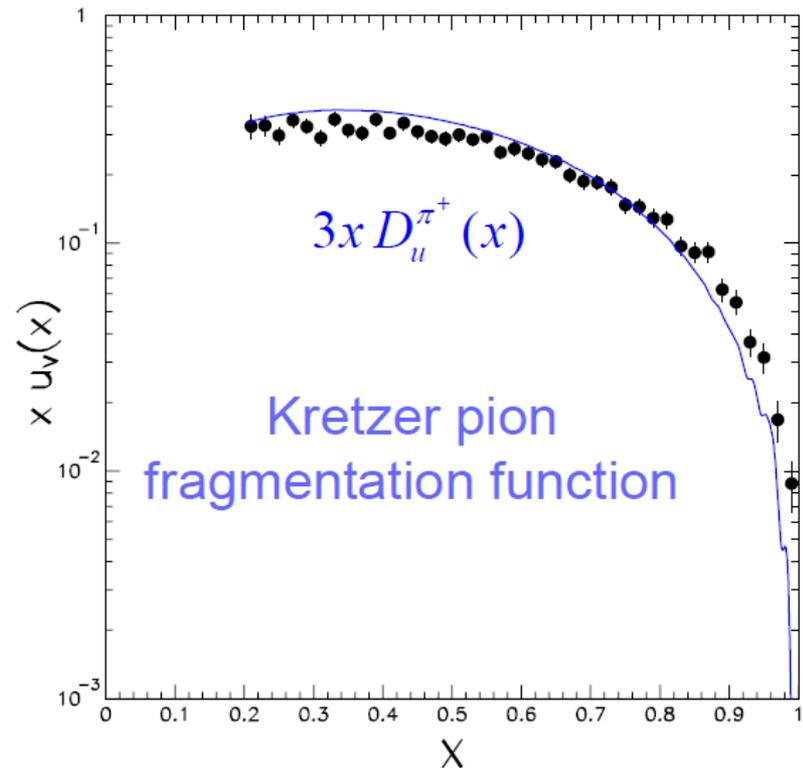
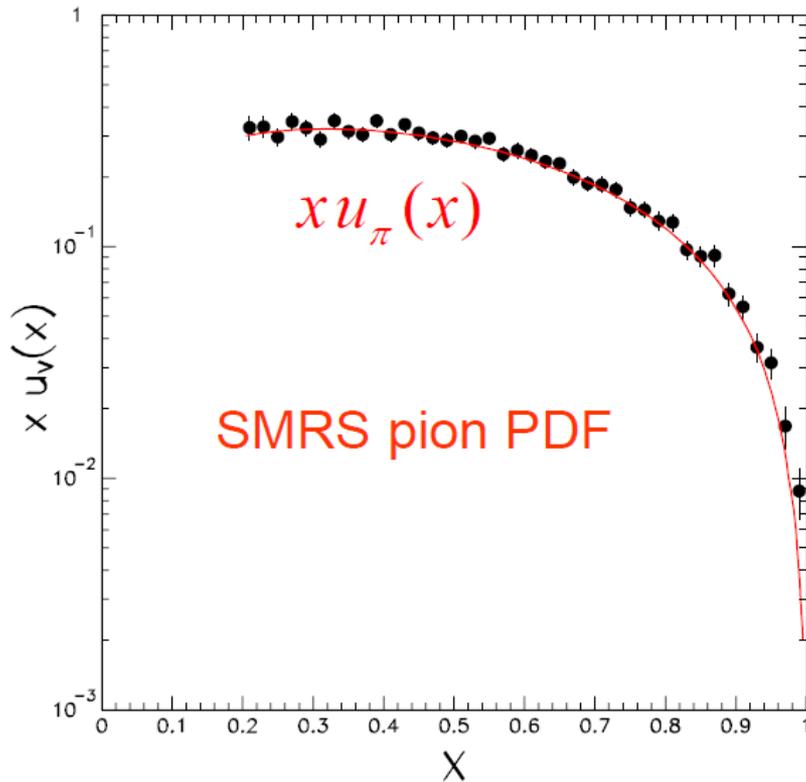
Dashed:  $C_v = 1, C_s = 3, \alpha = 1$

(hep-ph/0208122)

The proton FFs used in the calculation are from the proton PDFs

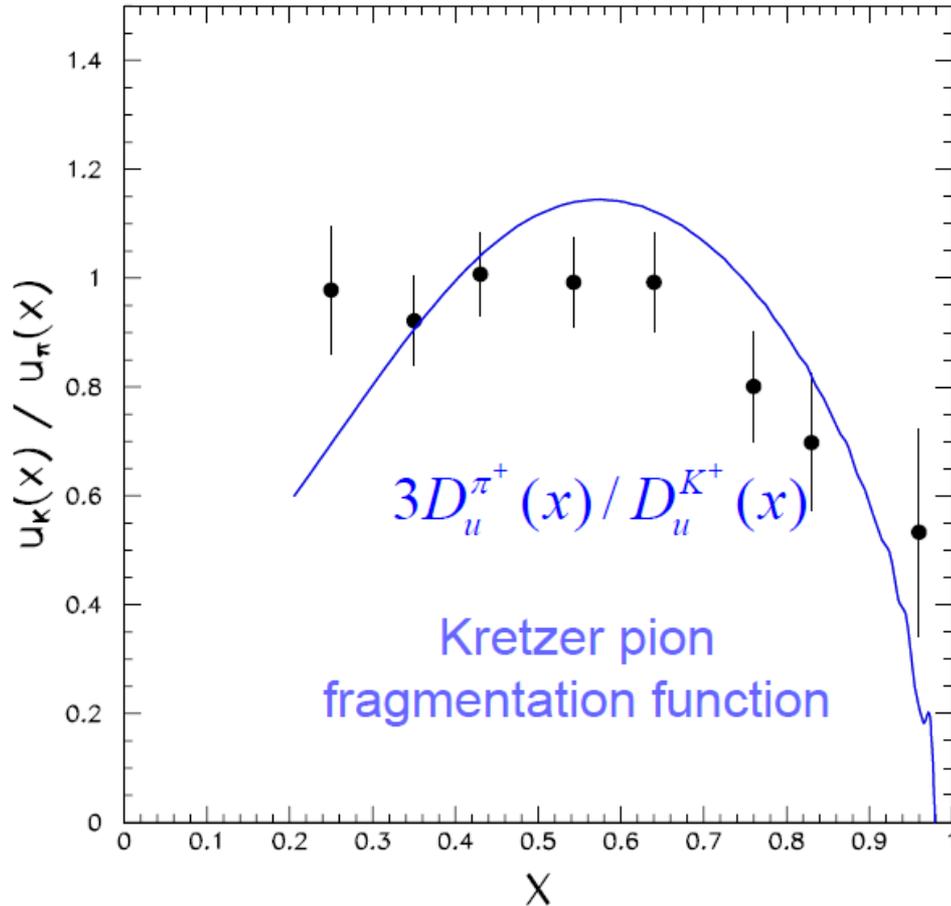
# Connection between PDF and FF for mesons?

## Pion valence quark distribution from E615 Drell-Yan



# Connection between PDF and FF for mesons?

$u_K(x) / u_\pi(x)$  from NA3 Drell-Yan experiment



# 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 SIDIS measurements at JLab could provide very useful new information on intrinsic strange sea.**
- Possible connection between PDFs and FFs for mesons could be further explored with SIDIS at JLab.