Intrinsic Sea of the Nucleons

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Workshop on “Opportunities with JLAB Energy and Luminosity Upgrade”

ECT* Trento, Italy, September 26-30, 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
- Opportunities at JLab Upgrade and at EIC for intrinsic sea

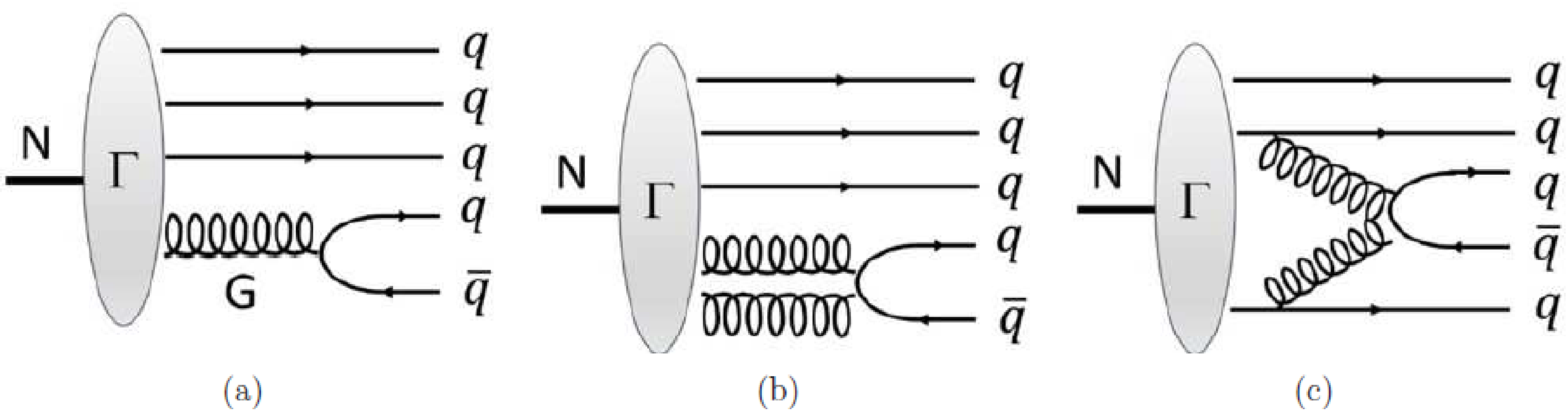
Work in collaboration with Wen-Chen Chang

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 ($g \rightarrow c\bar{c}$)



"extrinsic sea"

"intrinsic sea"

Search for the "intrinsic" quark sea

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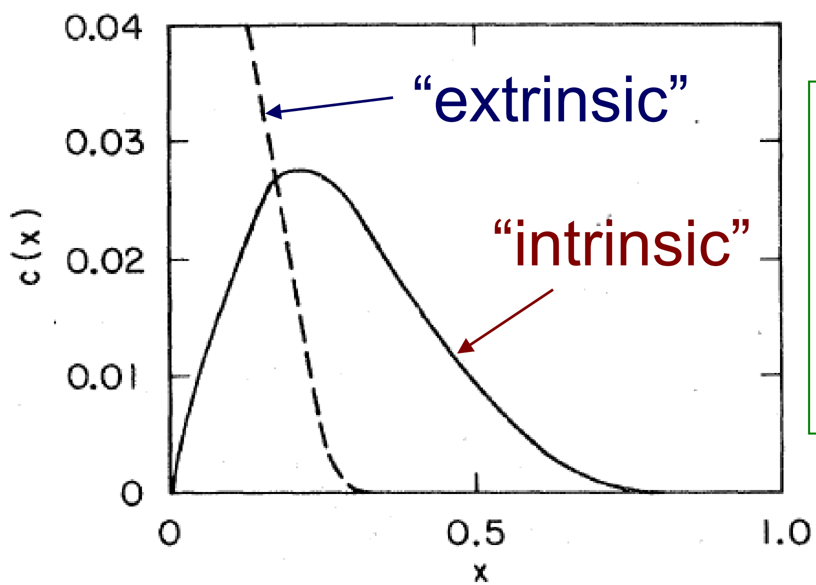
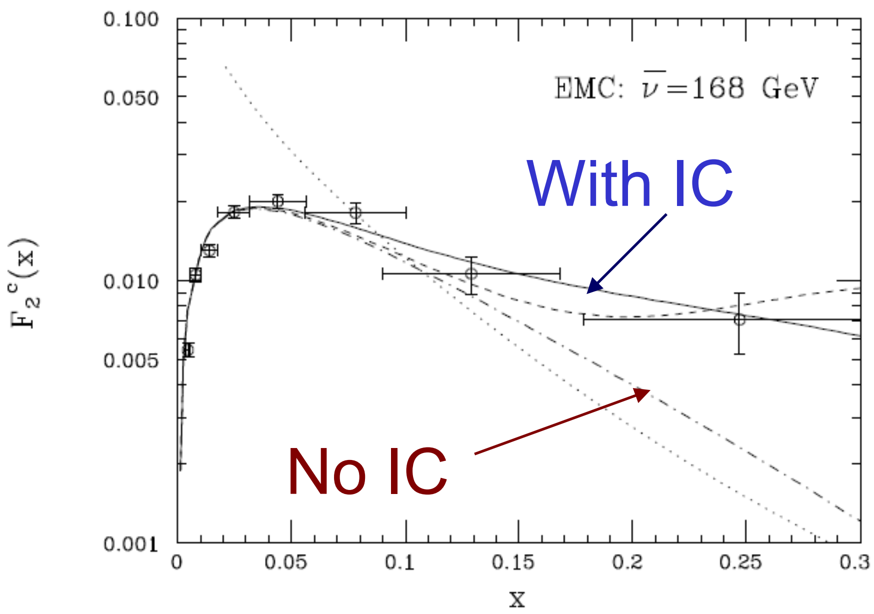


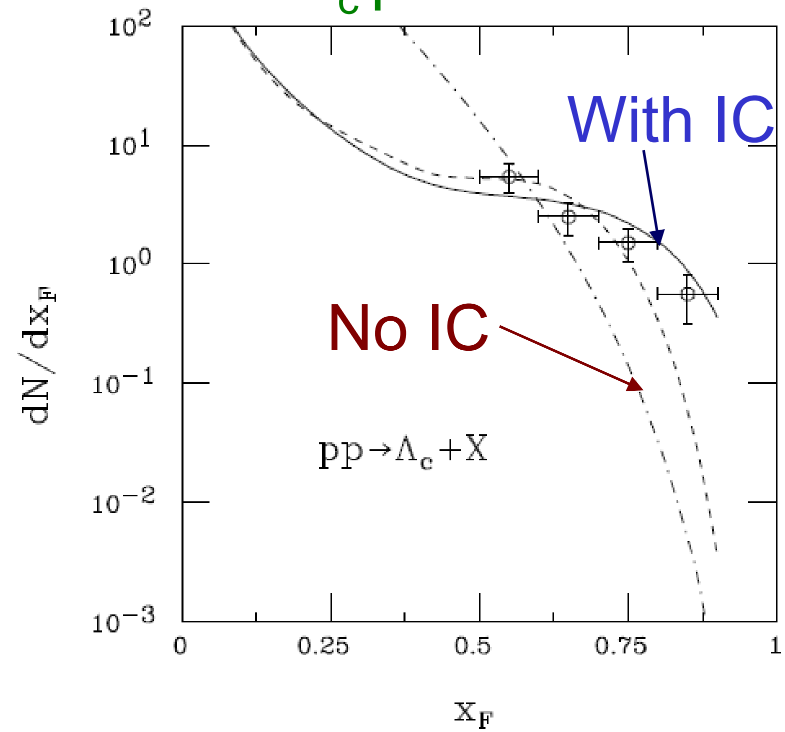
The "intrinsic charm" in $|\, uudc\bar{c}\rangle$ can lead to large contribution to charm production at large x

"Evidence" for the "intrinsic" charm (IC)

DIS data



Λ_c production



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

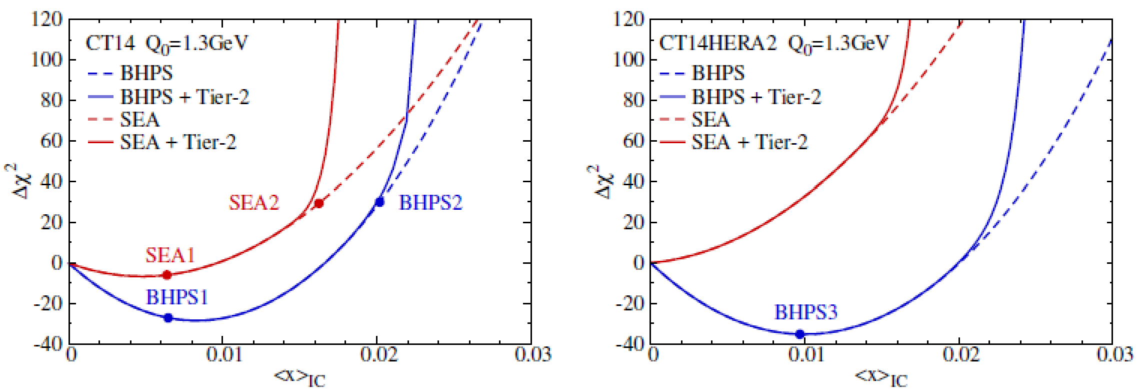
Tantalizing evidence for intrinsic charm

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

A 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,[a] Sayipjamal Dulat,[b,c,d] Jun Gao,[e] Marco Guzzi,[f,g] Joey Huston,[d] Pavel Nadolsky,[a] Carl Schmidt,[d] Jan Winter,[d] Keping Xie[a] and C.-P. Yuan[d]



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

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

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

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

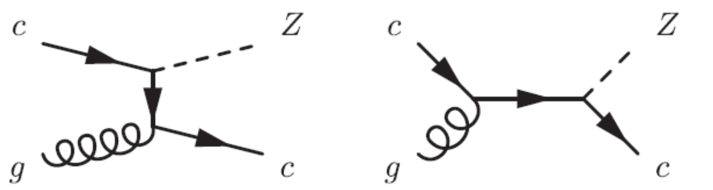
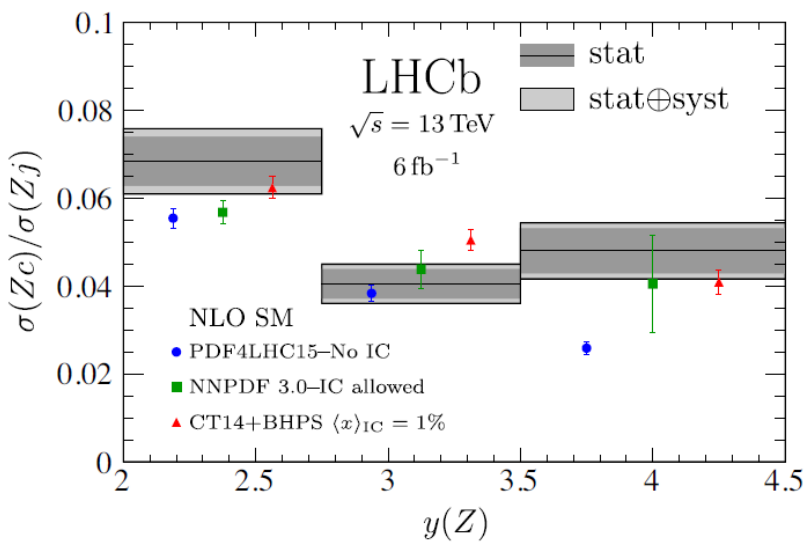


FIG. 1. Leading-order Feynman diagrams for $gc \to Zc$ production.



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

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

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

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

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

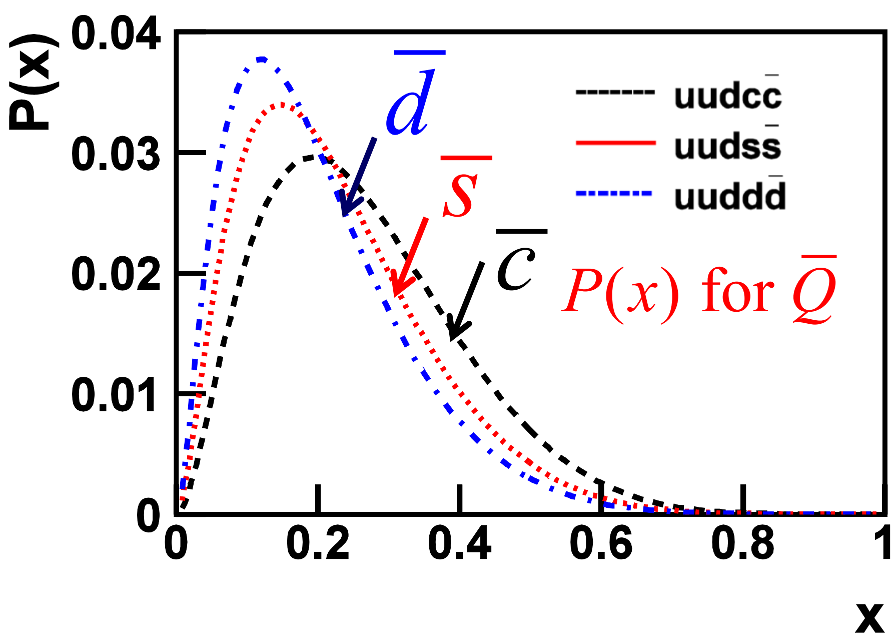
The "intrinsic" sea for lighter quarks have larger probabilities!

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

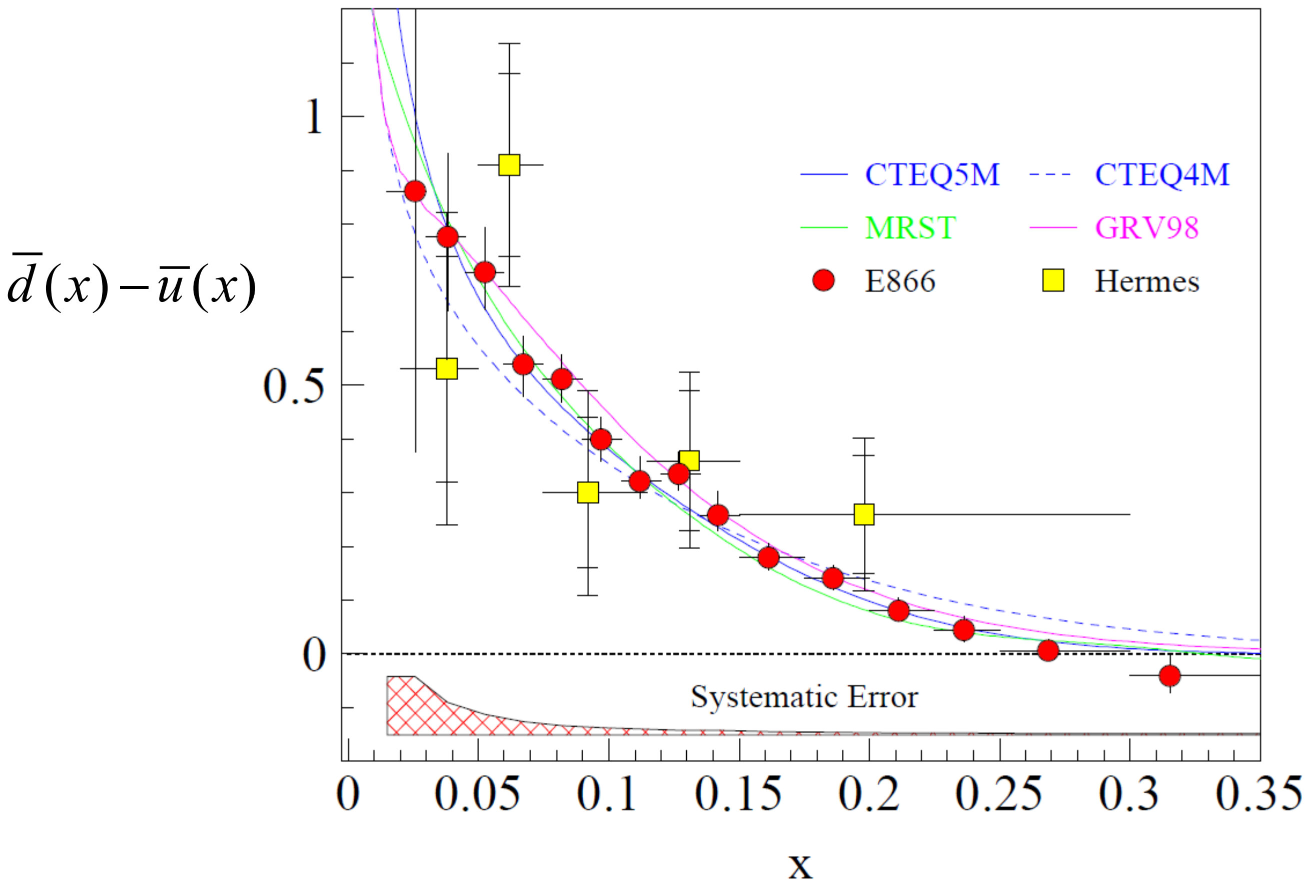
How to separate the "intrinsic sea" from the "extrinsic sea"?

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

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

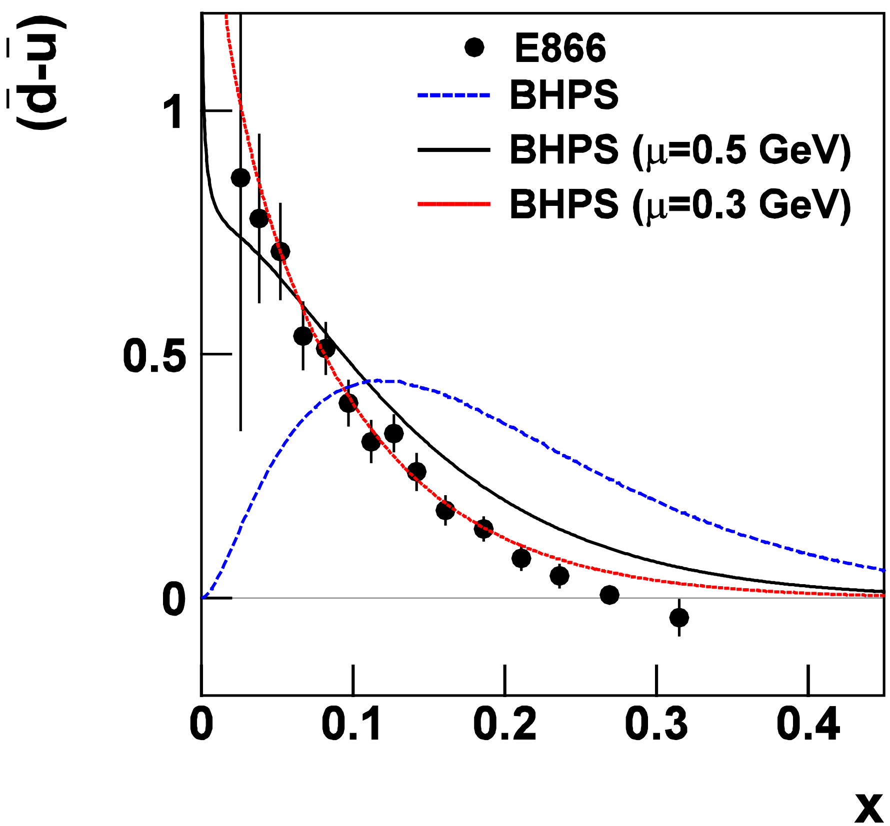
How to measure $\bar{d}$ - $\bar{u}$?

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



(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

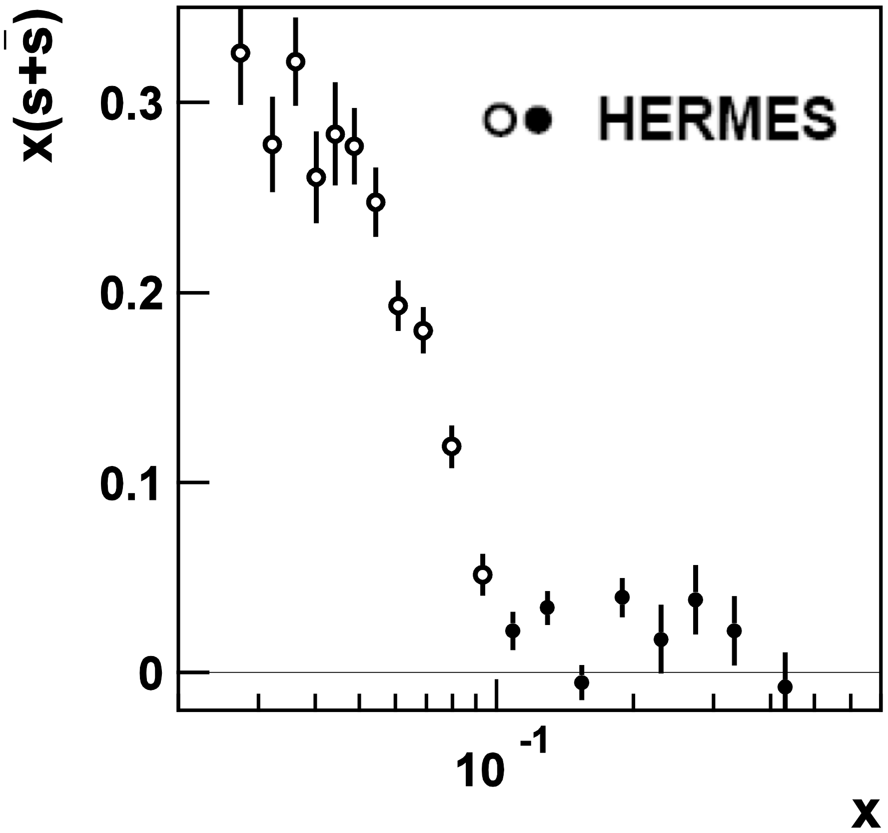
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

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

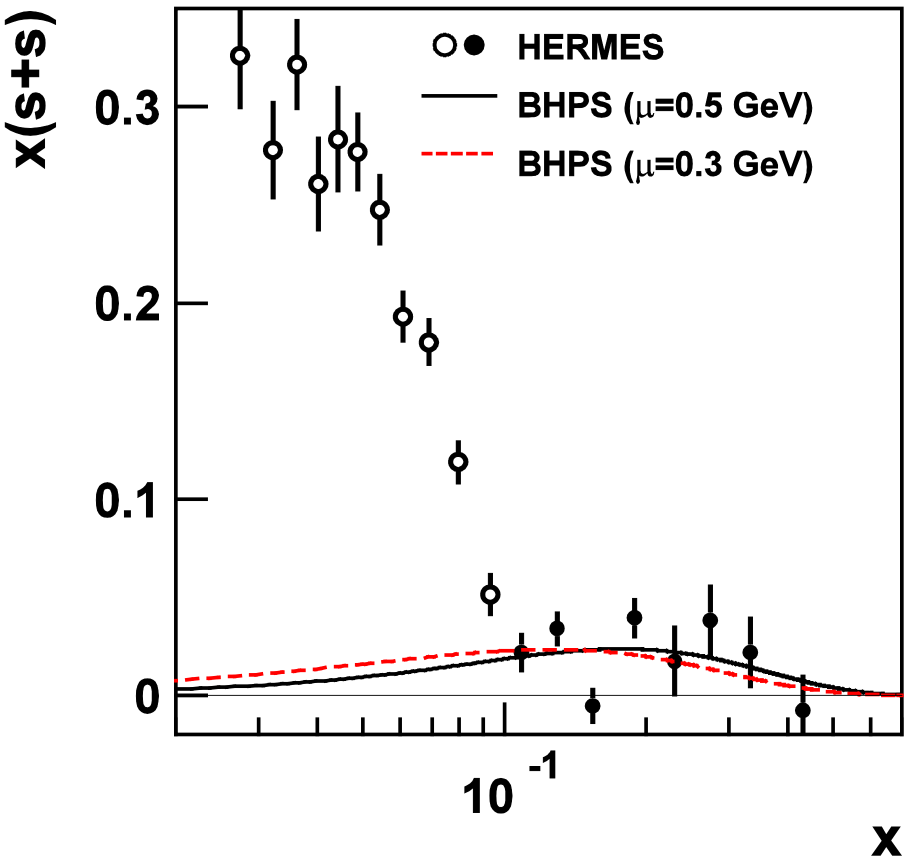


$s(x)+\bar{s}(x)$ extracted from HERMES Semi-inclusive DIS kaon data at $\langle Q^2 \rangle = 2.5\ \mathrm{GeV}^2$

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

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

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



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

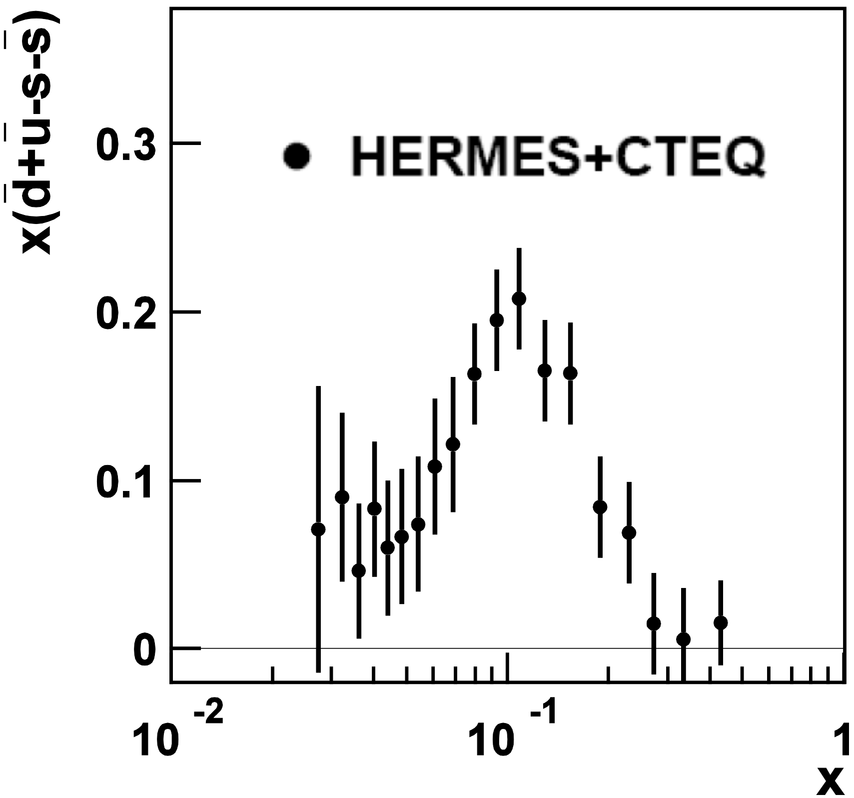
$$P_5^{uuds\bar{s}} = 0.024$$

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

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

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

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



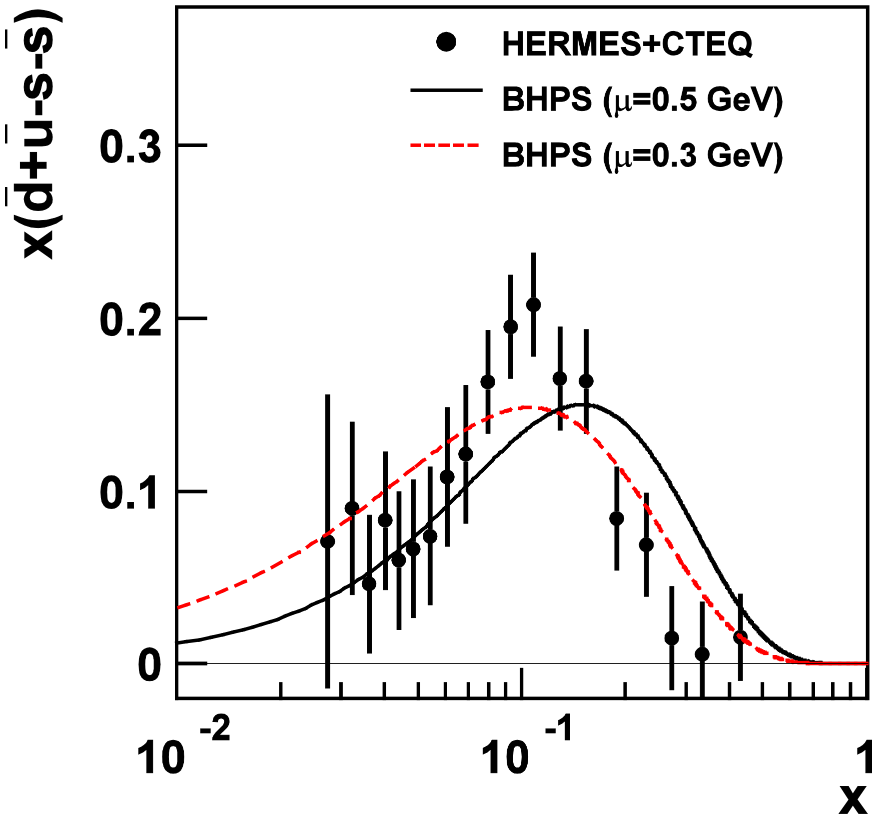
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

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



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

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

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

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

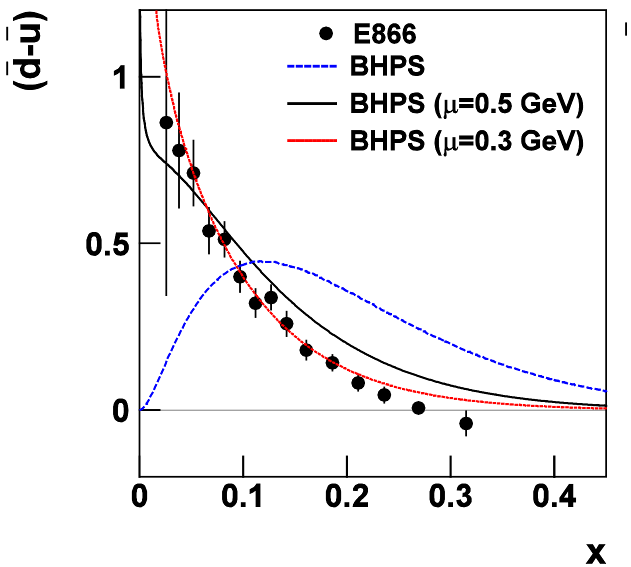
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

(not sensitive to extrinsic sea)

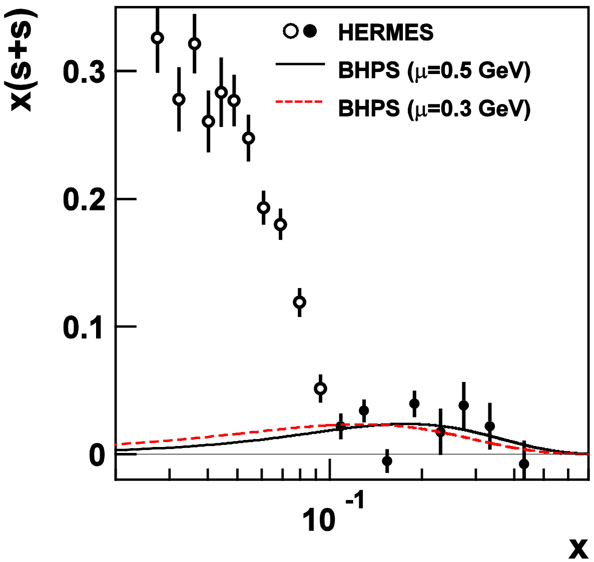
A valence-like distribution peaking at $x\sim 0.1$ is observed

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

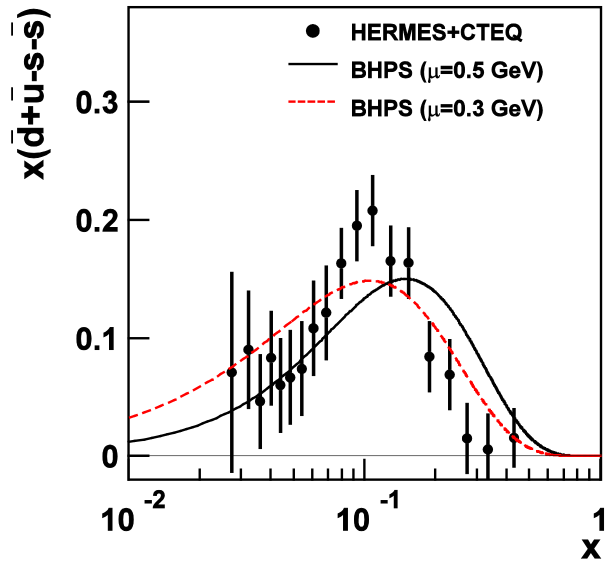
Extraction of the various five-quark components for light quarks



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



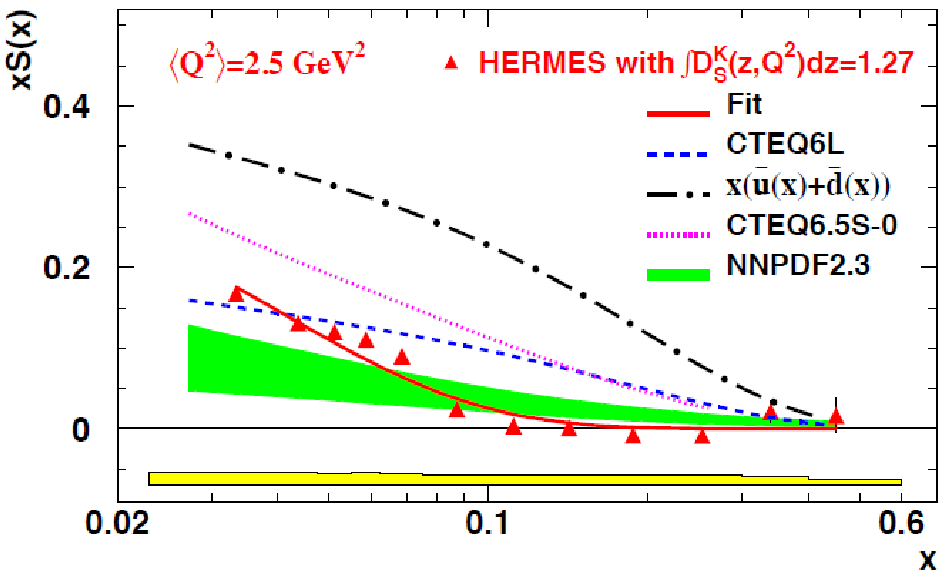
$$P_5^{uuds\bar{s}} = 0.024$$



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

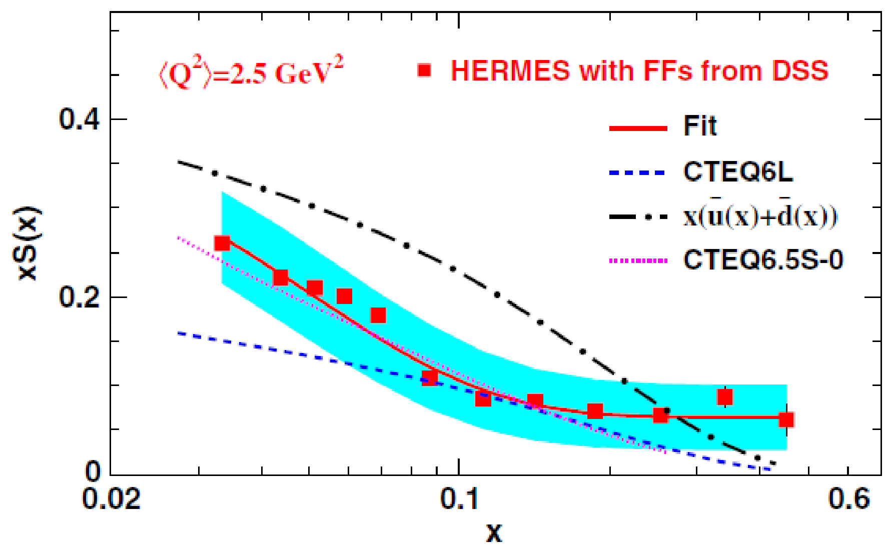
$$P_5^{uudd\bar{d}} = 0.240;\ P_5^{uudu\bar{u}} = 0.122;\ P_5^{uuds\bar{s}} = 0.024$$

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

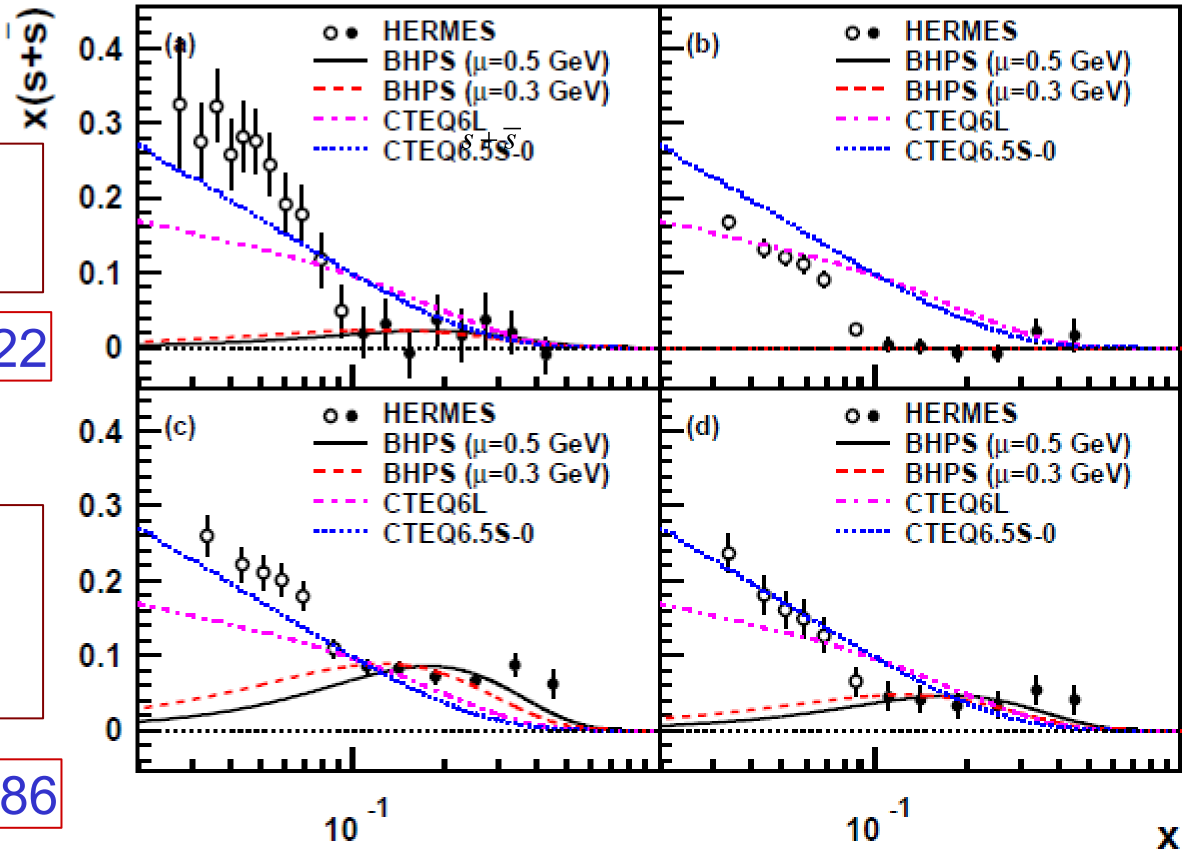
Dependence of $s+\bar{s}$ extraction on the kaon fragmentation functions

2008 HERMES

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

2014 HERMES

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

Other possible implications

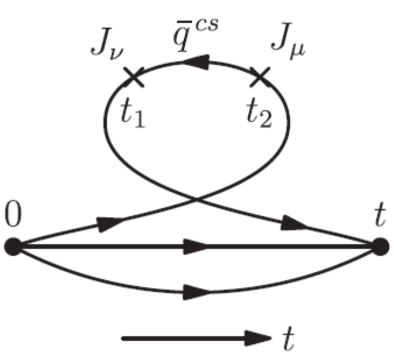
- Search for intrinsic strange sea with SIDIS at JLab.
- Spin-dependent observables of intrinsic sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

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

Connected-Sea Partons

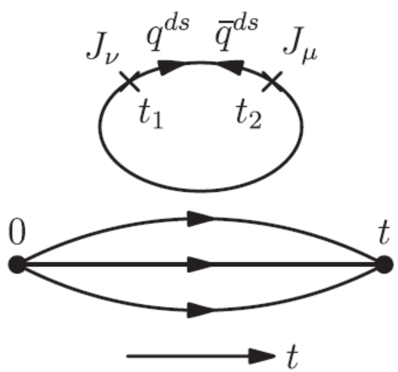
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea



(valence-like)

Disconnected sea



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

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)

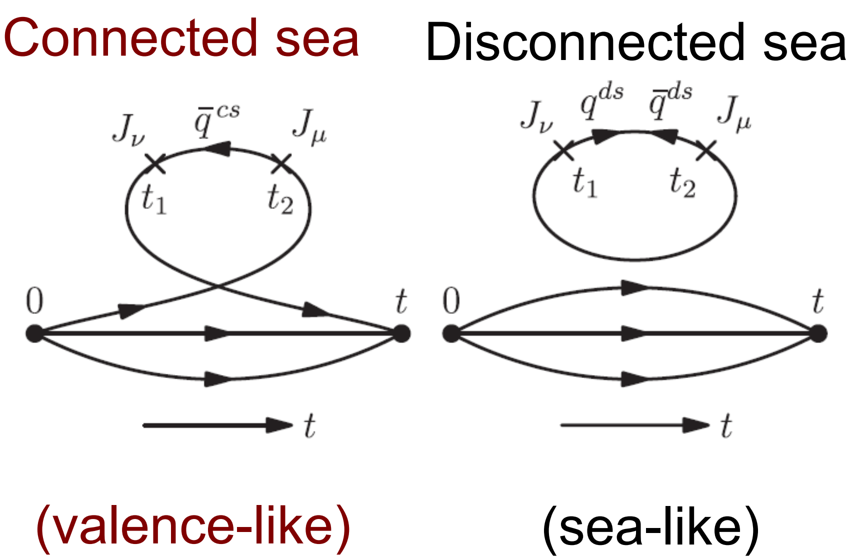
C) $[\bar{u}(x) + \bar{d}(x)]_{\text{connected sea}} =$

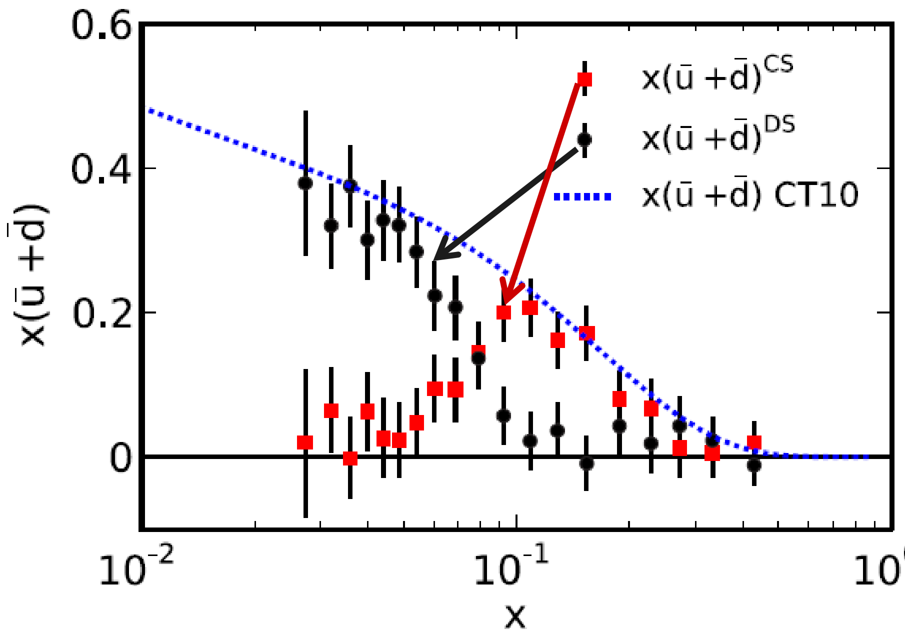
$[\bar{u}(x) + \bar{d}(x)]_{\text{PDF}} - [\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}}$

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
- A recent preprint performed the first global fit (CT18CS), with separate CS and DS (T. Hou et al., arXiv:2206.02431)

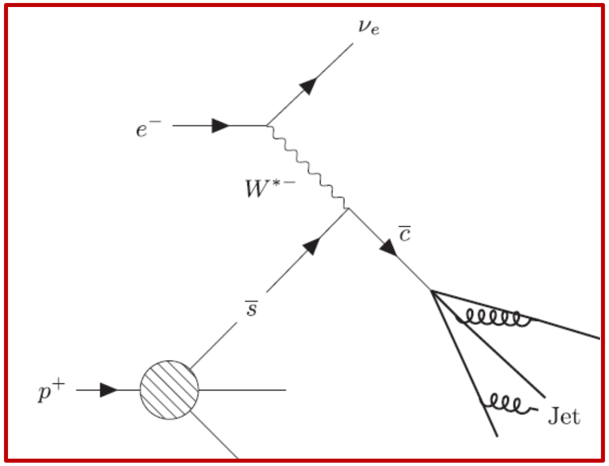
Possibility to search for intrinsic sea at EIC

- Evidences for the existence of "intrinsic" light-quark seas $(\bar{u}, \bar{d}, \bar{s})$ in the nucleons.
- Future SIDIS measurements at EIC could provide very useful new information on intrinsic strange sea.
- Clear evidence for intrinsic charm remains to be found

Charm jets as a probe for strangeness at the future Electron-Ion Collider

Miguel Arratia,[1,2] Yulia Furletova,[2] T. J. Hobbs,[3,4,5] Fredrick Olness,[3] and Stephen J. Sekula[3,*]

PHYSICAL REVIEW D **103,** 074023 (2021)



Article

Evidence for intrinsic charm quarks in the proton

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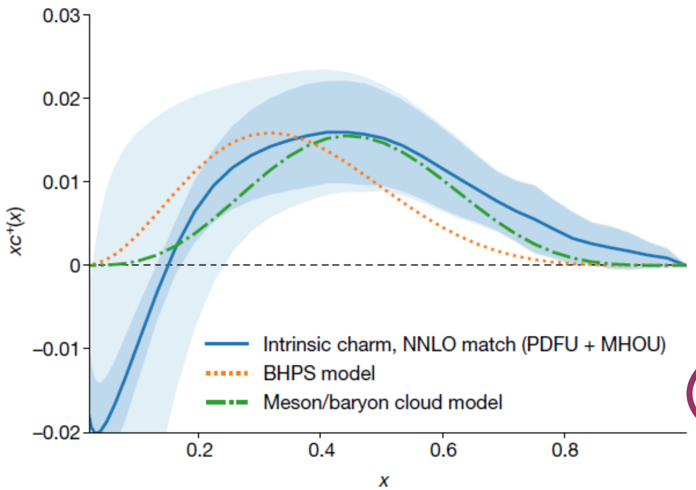
The NNPDF Collaboration*

The theory of the strong force, quantum chromodynamics, describes the proton in terms of quarks and gluons. The proton is a state of two up quarks and one down quark bound by gluons, but quantum theory predicts that in addition there is an infinite number of quark–antiquark pairs. Both light and heavy quarks, whose mass is respectively smaller or bigger than the mass of the proton, are revealed inside the proton in high-energy collisions. However, it is unclear whether heavy quarks also exist as a part of the proton wavefunction, which is determined by non-perturbative dynamics and accordingly unknown: so-called intrinsic heavy quarks[1]. It has been argued for a long time that the proton could have a sizable intrinsic component of the lightest heavy quark, the charm quark. Innumerable efforts to establish intrinsic charm in the proton[2] have remained inconclusive. Here we provide evidence for intrinsic charm by exploiting a high-precision determination of the quark–gluon content of the nucleon[3] based on machine learning and a large experimental dataset. We disentangle the intrinsic charm component from charm–anticharm pairs arising from high-energy radiation[4]. We establish the existence of intrinsic charm at the 3-standard-deviation level, with a momentum distribution in remarkable agreement with model predictions[1,5]. We confirm these findings by comparing them to very recent data on Z-boson production with charm jets from the Large Hadron Collider beauty (LHCb) experiment[6].



Very recent Nature paper on intrinsic charm

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
- Intrinsic charm in the nucleons can be explored at EIC