Flavor and *X*-dependence of the Nucleon Sea

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Outline

- Extraction of "intrinsic" $\bar{u}$, $\bar{d}$, and $\bar{s}$ sea from Drell-Yan and semi-inclusive DIS experiments
- Separation of "connected sea" from "disconnected sea" for $\bar{u}(x) + \bar{d}\,(x)$
- Bjorken-x dependencies of $\bar{d}(x) - \bar{u}(x)$ and $[s(x) + \bar{s}(x)]/[(\bar{u}(x) + \bar{d}(x)]$

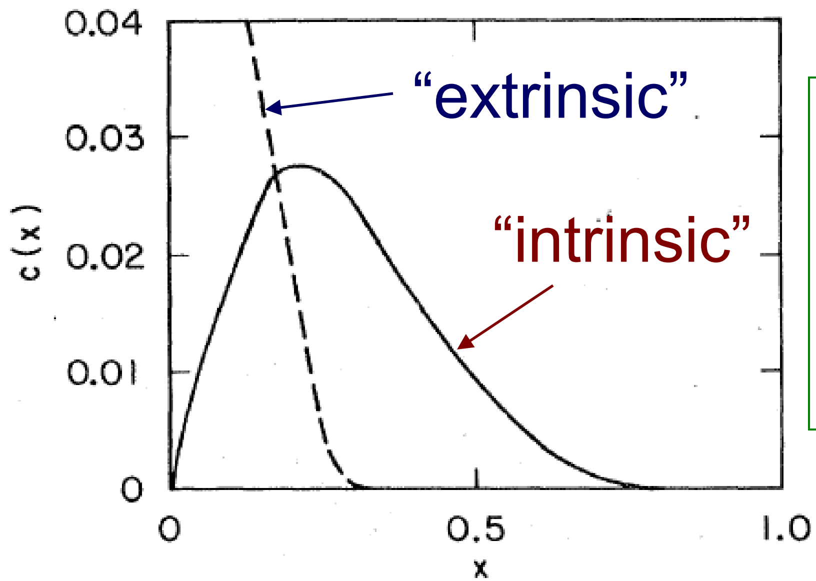
Based on a review paper: "Flavor Structure of the Nucleon Sea", Wen-Chen Chang and JCP, arXiv: 1406.1260 ; and the preprint arXiv: 1410.7027

Search for the "intrinsic" quark sea

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

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

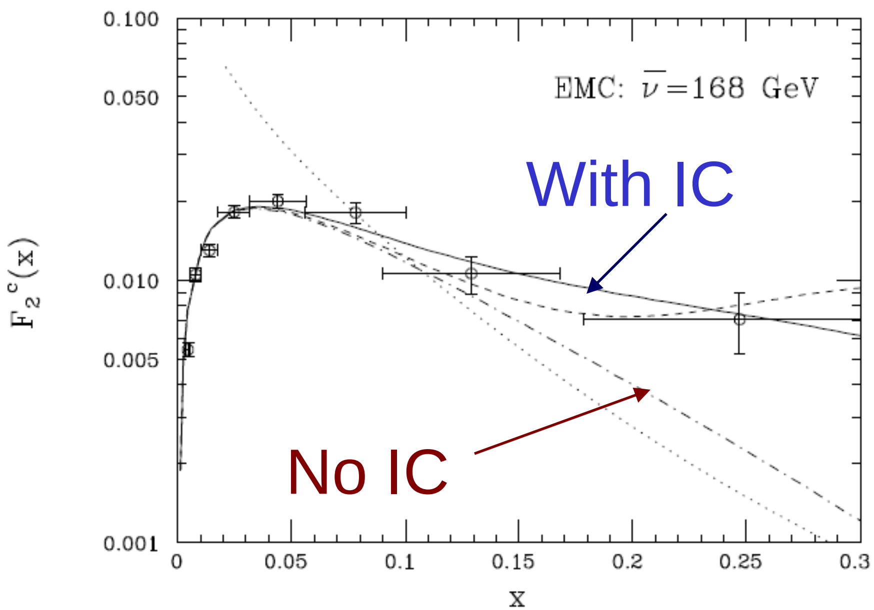
The "intrinsic"-charm from $|uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \to c\bar{c}$)



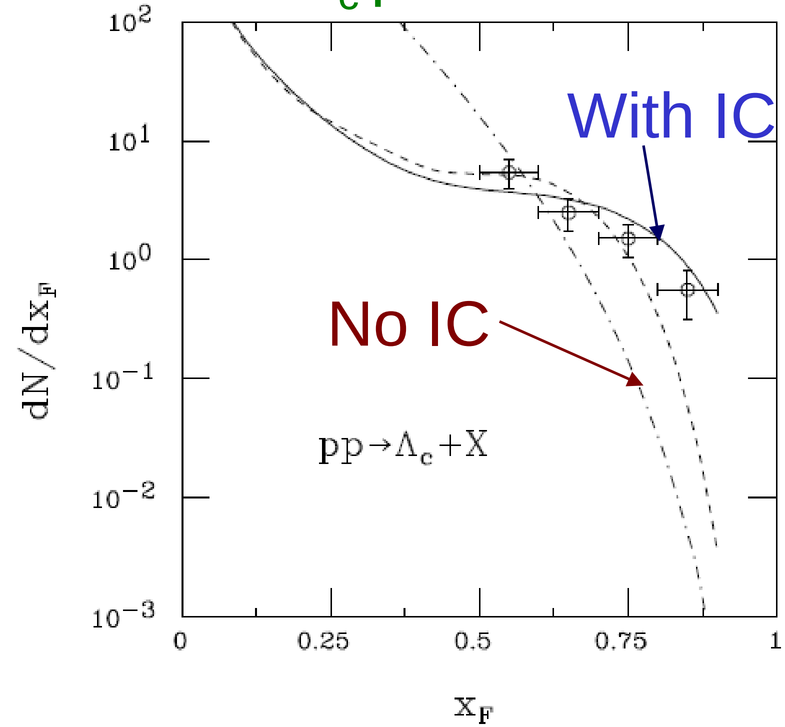
The "intrinsic charm" in $|uudc\bar{c}\rangle$ can lead to large contribution to charm production at large x

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

DIS data



Λ_c production



Gunion and Vogt (hep-ph/9706252)

Tantalizing evidence for intrinsic charm

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

Search for the "intrinsic" light-quark sea

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

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

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

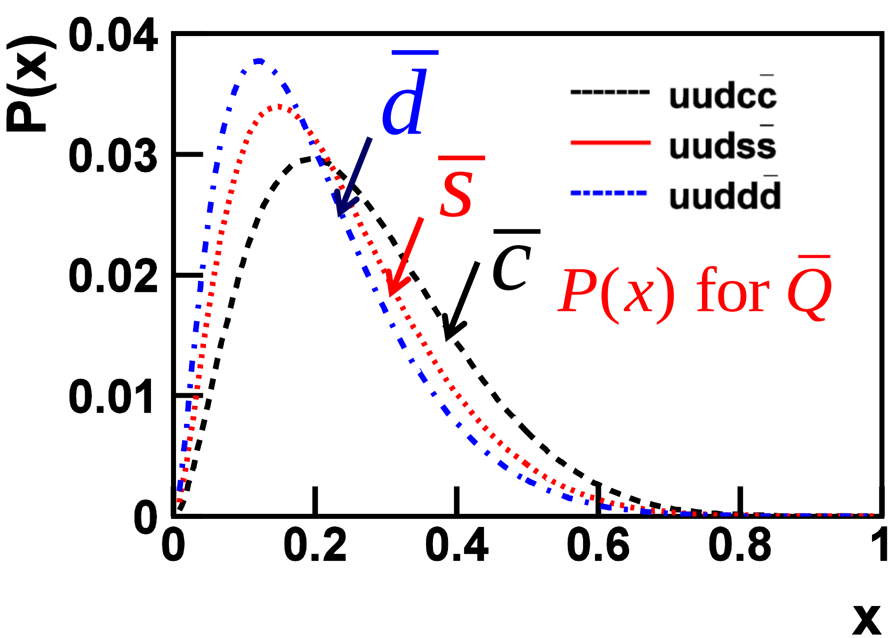
Are there experimental evidences for the intrinsic light-quark sea: $|uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uuds\bar{s}\rangle$?

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

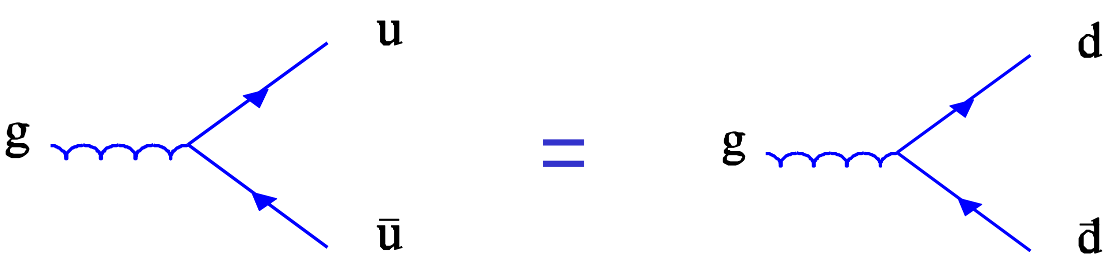
How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no (or small) contributions 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

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

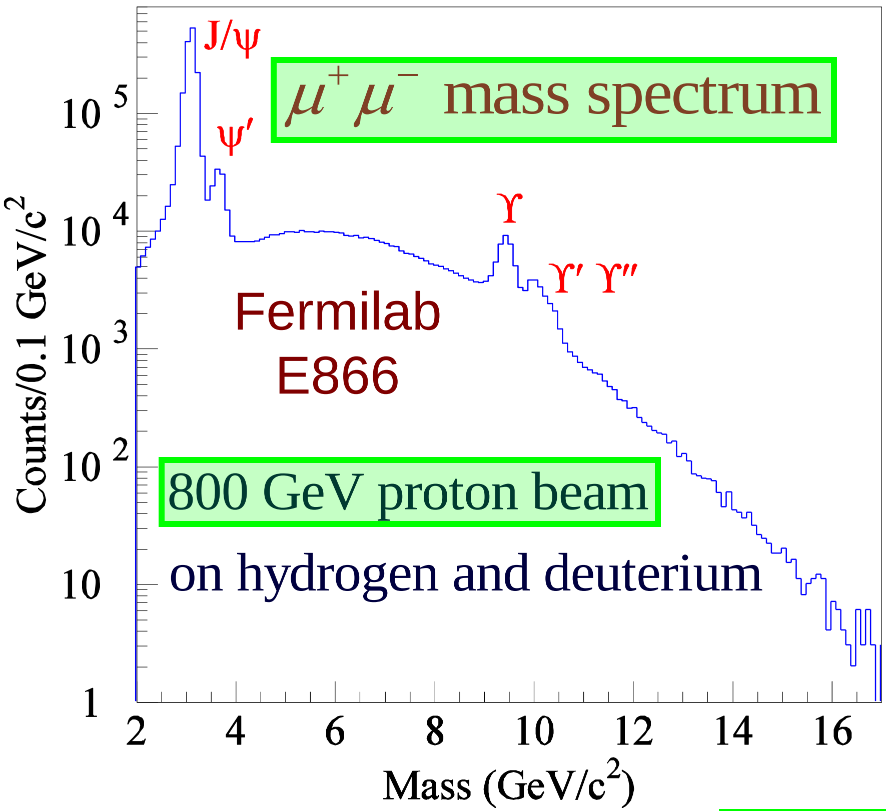
- Select experimental observables which have no (or small) contributions from the "extrinsic sea"

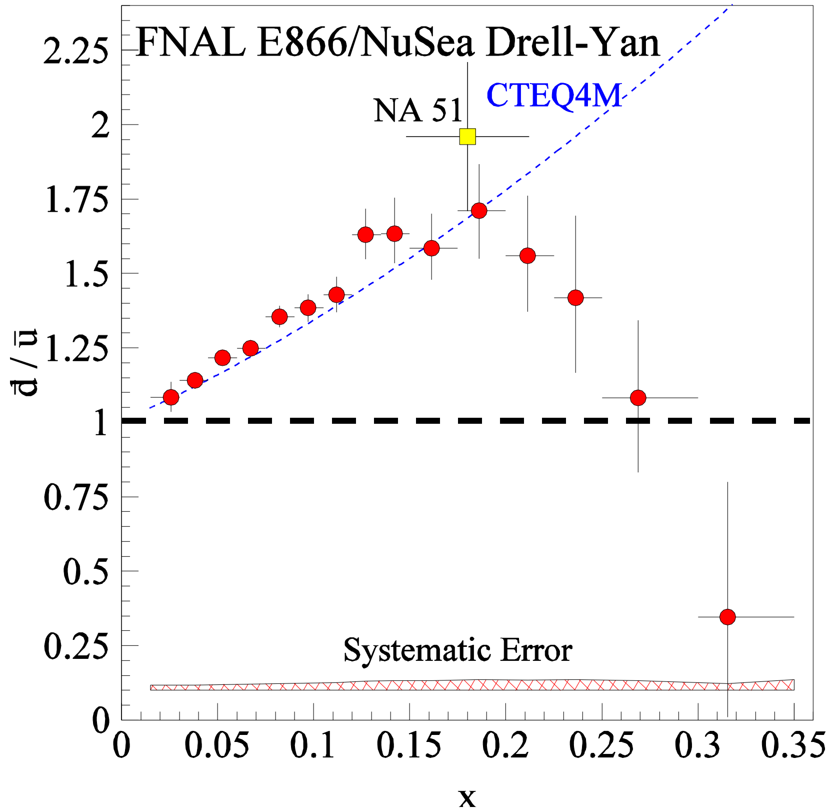
$\bar{d} - \bar{u}$ has no contribution from extrinsic sea ($g \to \bar{q}q$) in LO, and is sensitive to "intrinsic sea" only



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

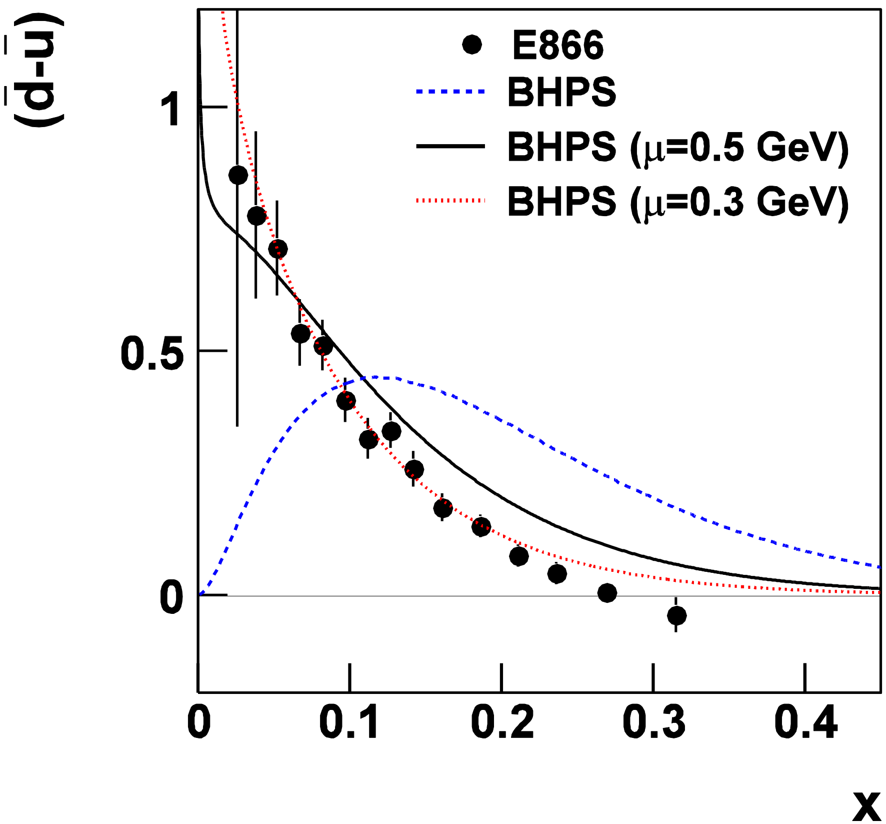
$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2)\right]$$





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

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

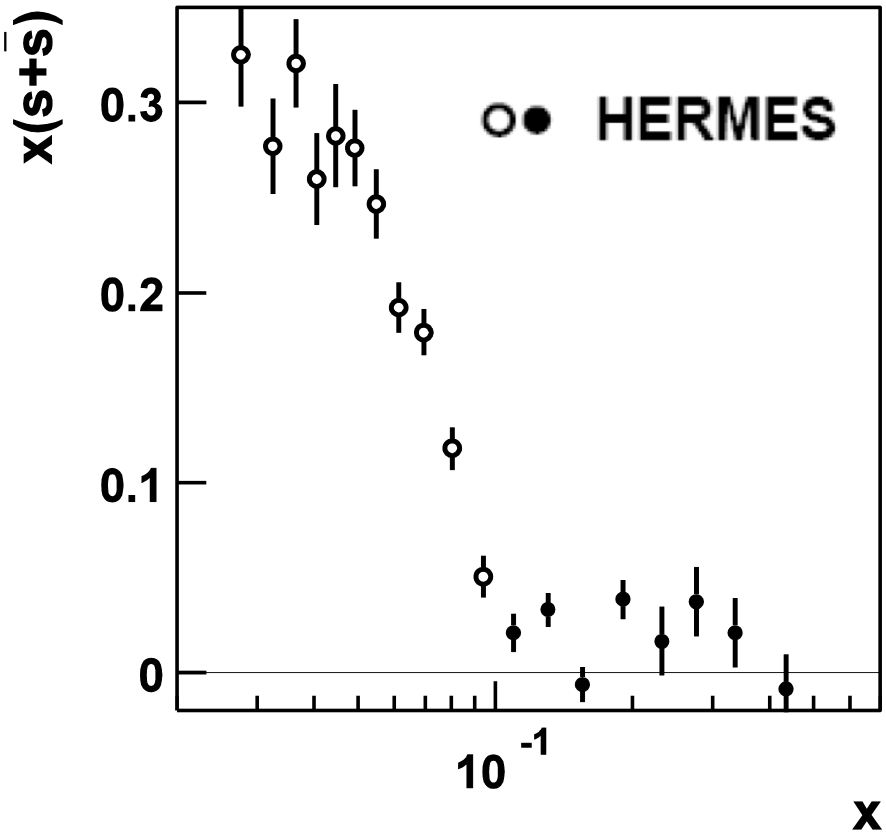
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

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

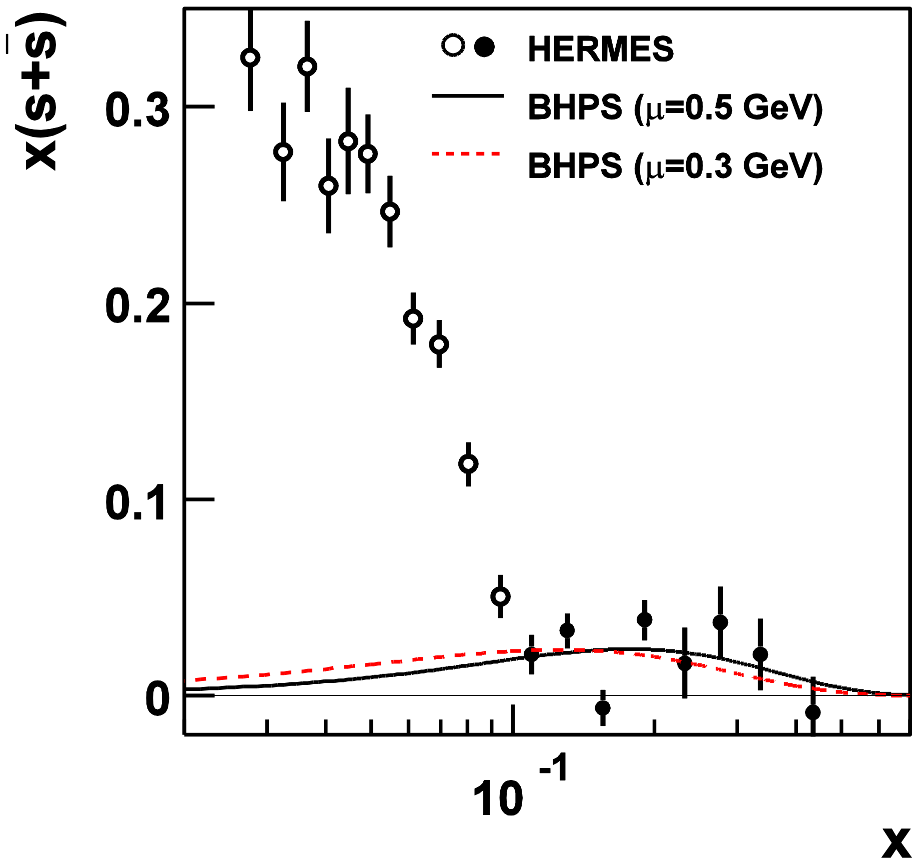


$s(x)+\bar{s}(x)$ extracted from HERMES Semi-inclusive DIS kaon data at $\langle Q^2 \rangle = 2.5\ \mathrm{GeV}^2$

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



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

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

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

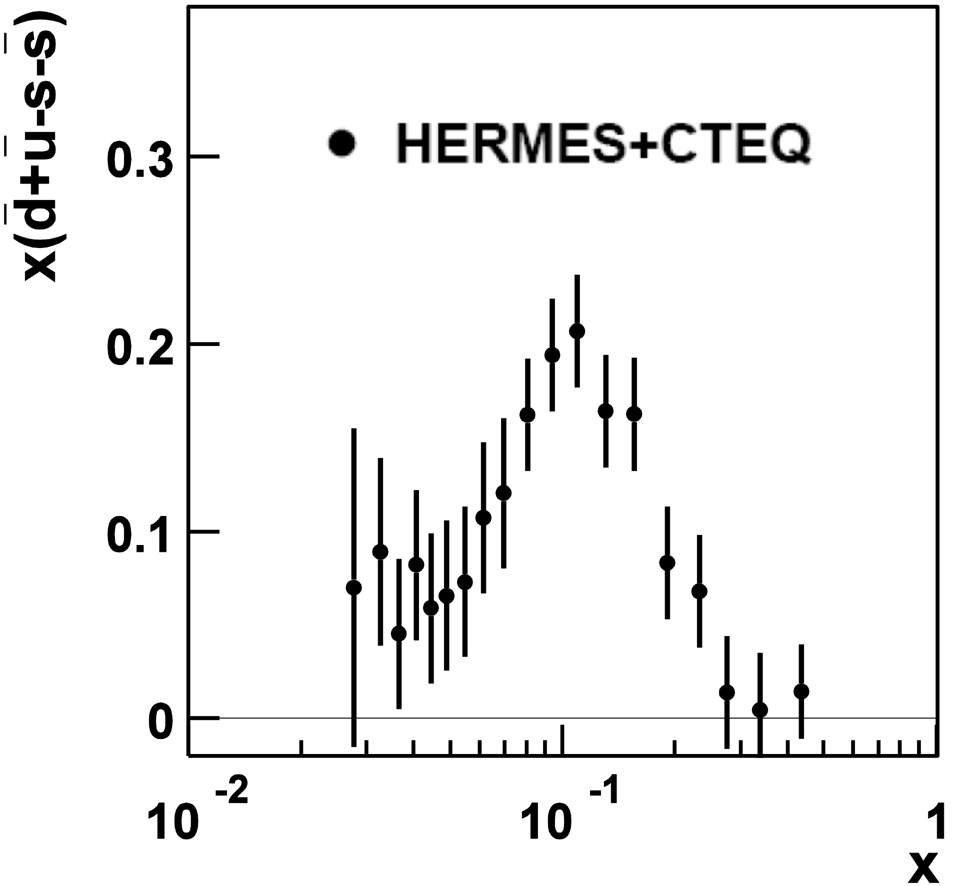
How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no (or small) contributions from the "extrinsic sea"

$\bar{d} + \bar{u} - s - \bar{s}$ has small contribution from extrinsic sea $(g \to \bar{q}q)$

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 BHPS model



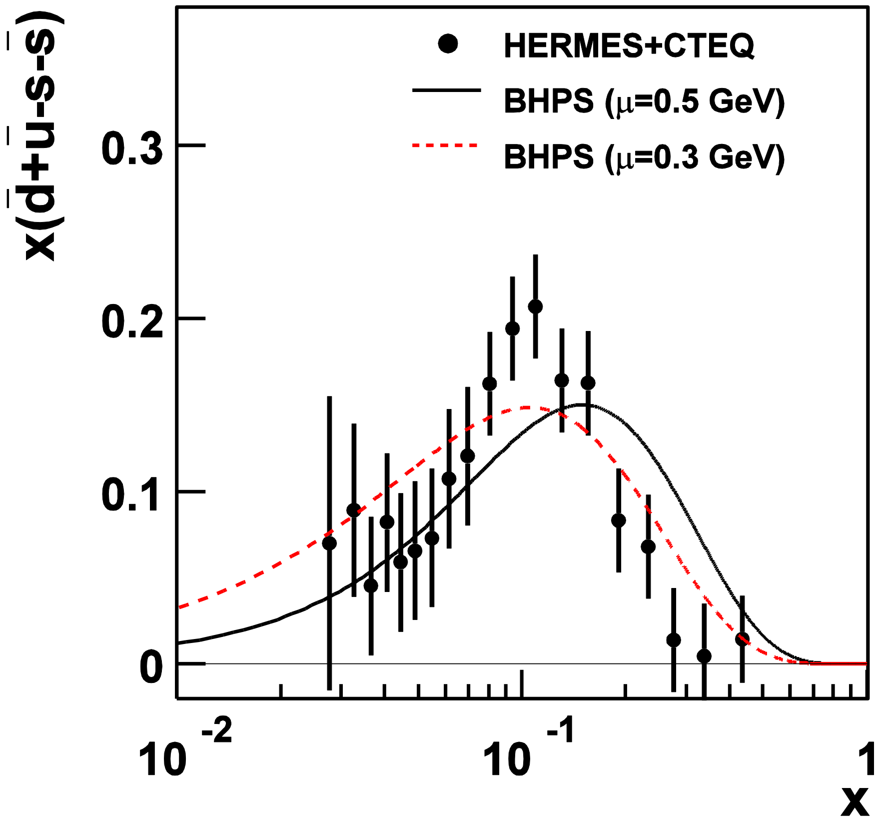
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

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

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

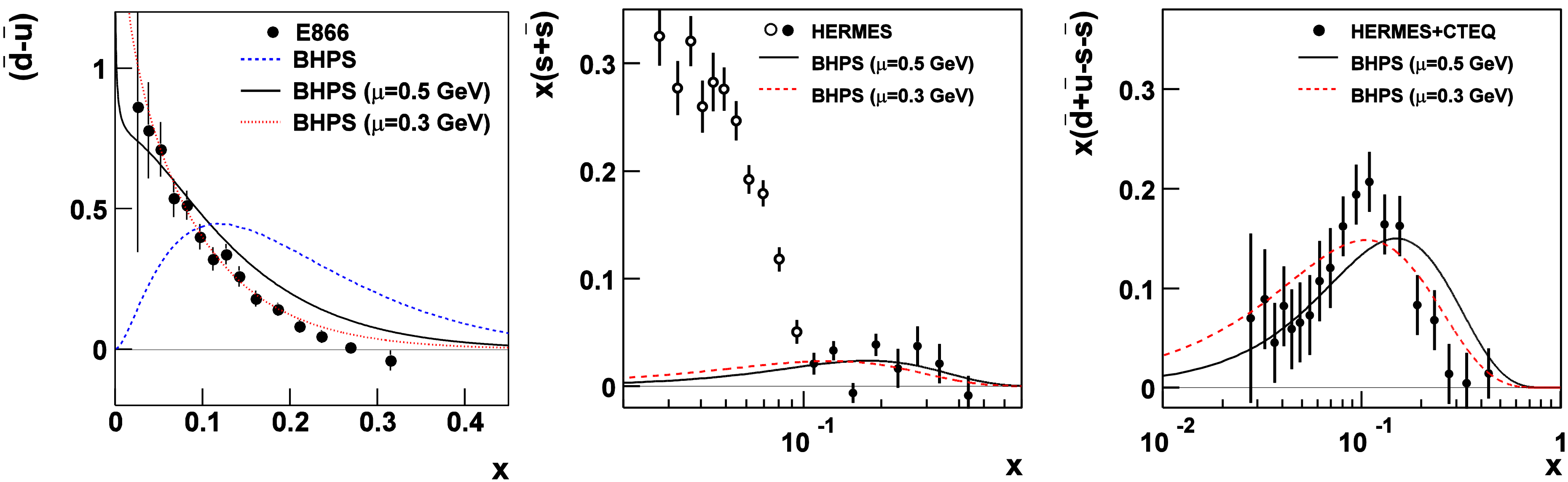
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

(not sensitive to extrinsic sea)

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

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

Extraction of the various five-quark components for light quarks



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

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

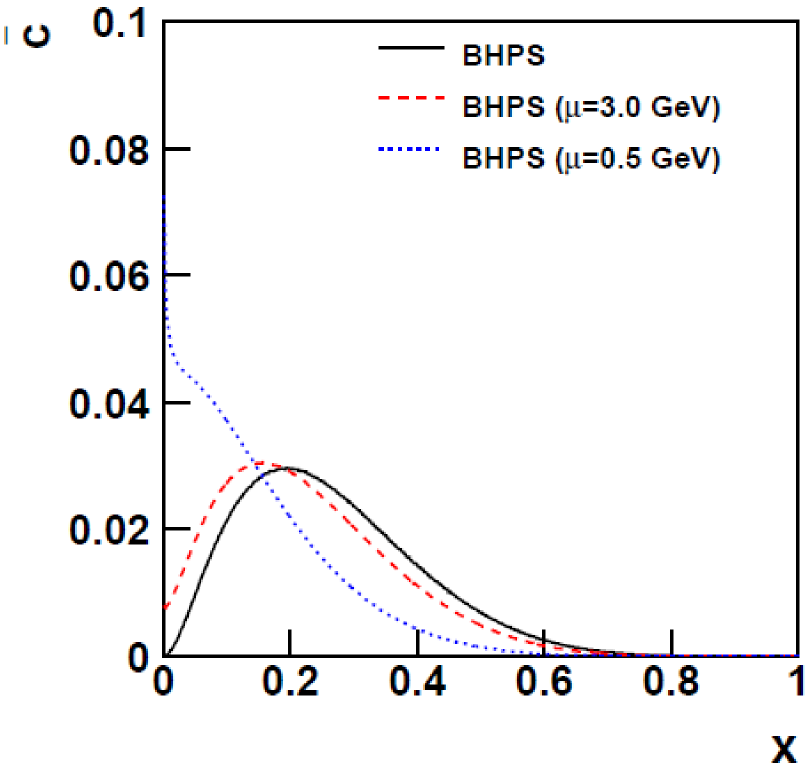
$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$

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

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

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

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



See Jimenez-Delgado, Hobbs, Londergan, Melnitchouk, 1408.1708

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

Future Possibilities on Intrinsic Sea

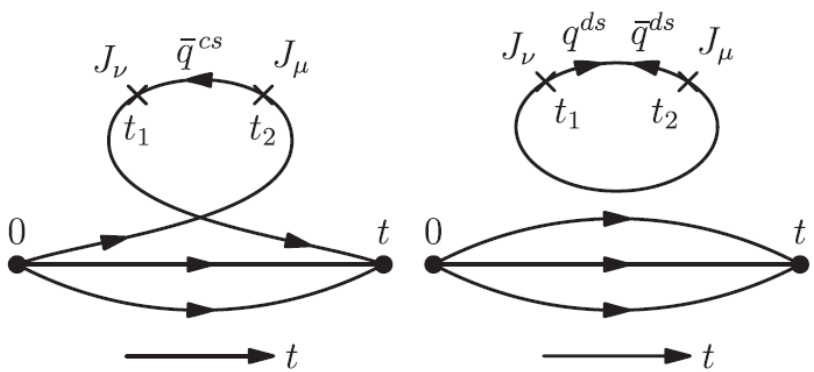
- Search for intrinsic charm and beauty at RHIC and LHC.
- Intrinsic gluons in the nucleons?
- Spin-dependent observables of intrinsic sea?
- Global fits including intrinsic u, d, s sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

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



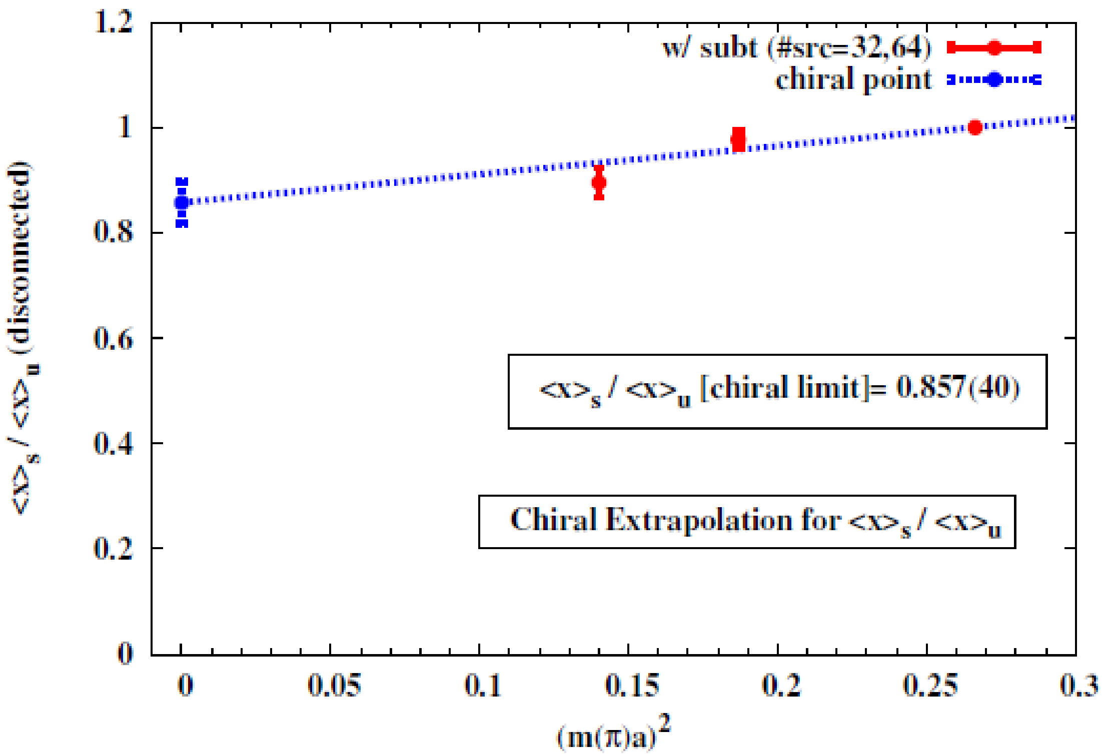
(valence-like) (sea-like)

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

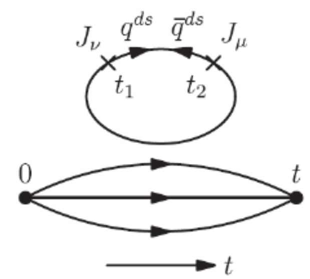
CS and DS have different Bjorken-x and flavor dependencies

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

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

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Connected-Sea Partons

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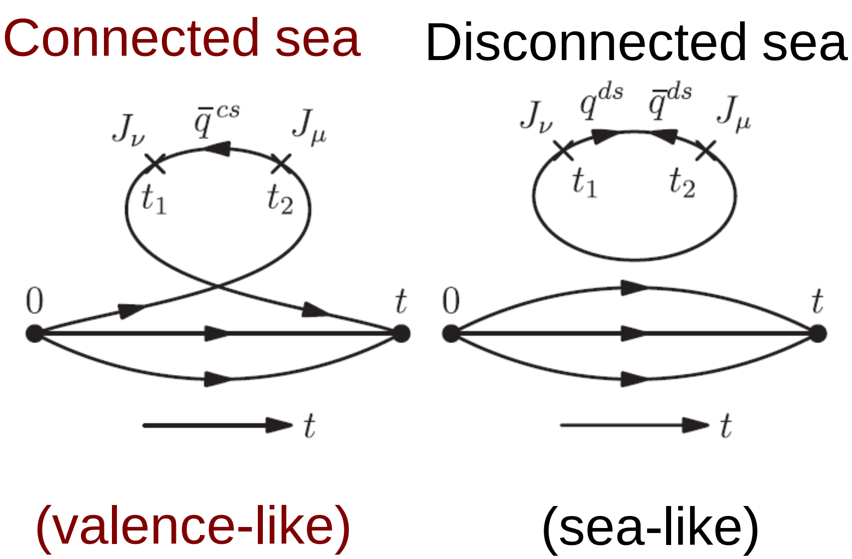
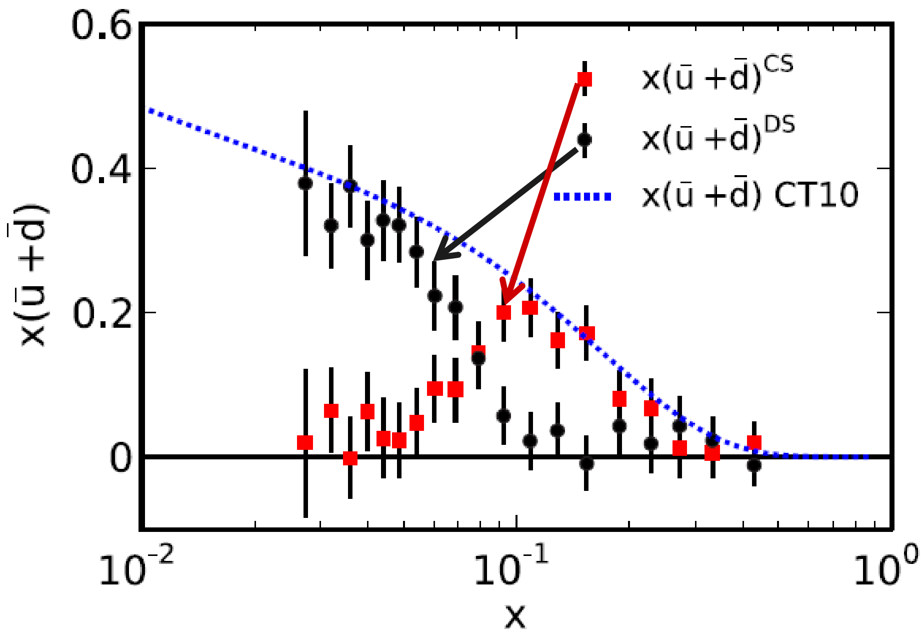
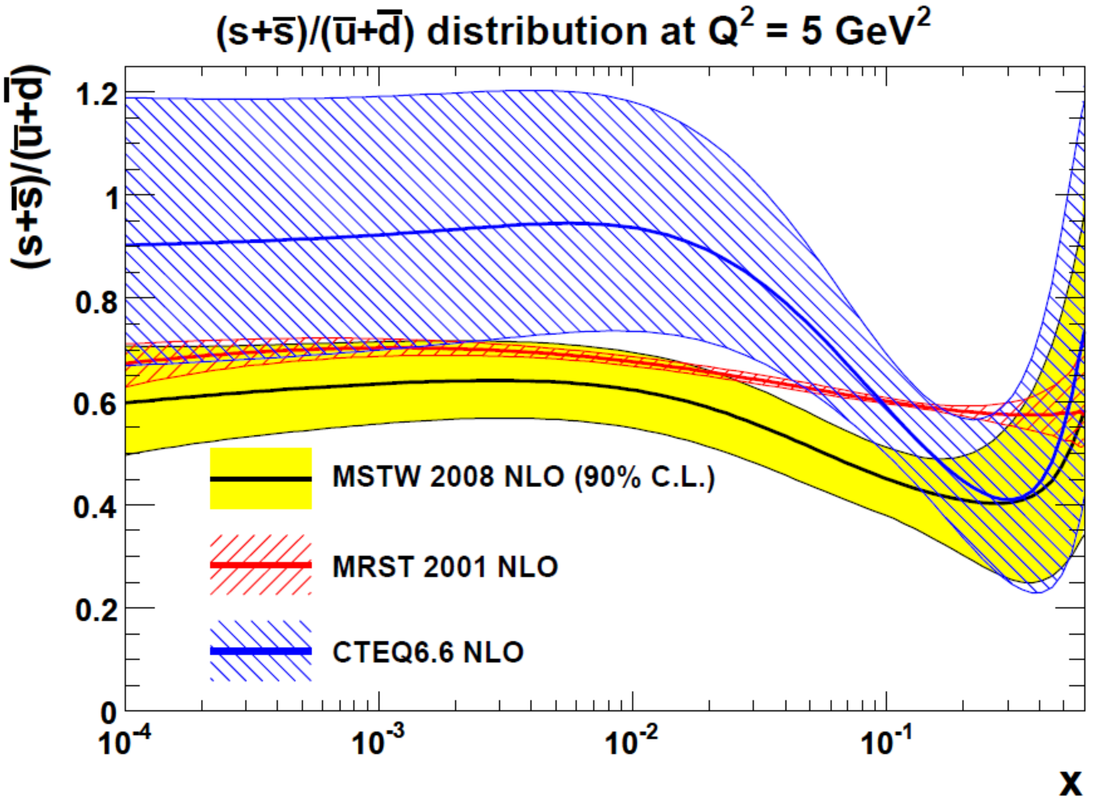




- Using input from lattice QCD, one can separate the connected sea from the disconnected sea for $\bar{u}(x)+\bar{d}(x)$
- For $\bar{u}+\bar{d}$ at Q^2=2.5 GeV^2, momenta carried by CS and DS are roughly equal

What is the x-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$?



- CTEQ6.6 suggests an SU(3) symmetric sea at small x?
- A strong $x-$dependence for the $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$ ratio?

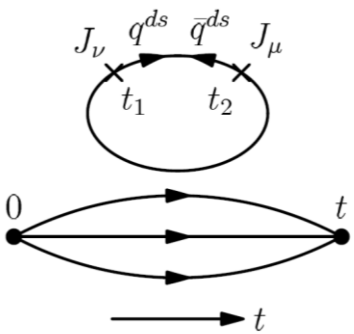
  (Also see Alekhin et al., arXiv: 1404.6469)

Flavor structure of nucleon sea is strongly x dependent

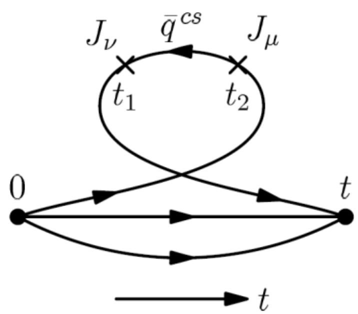
- Sea is roughly SU(3) symmetric at small x
- Sea is SU(3) asymmetric at large x

Can be understood from Lattice QCD (PRL 109 (2012)252002)

Disconnected sea



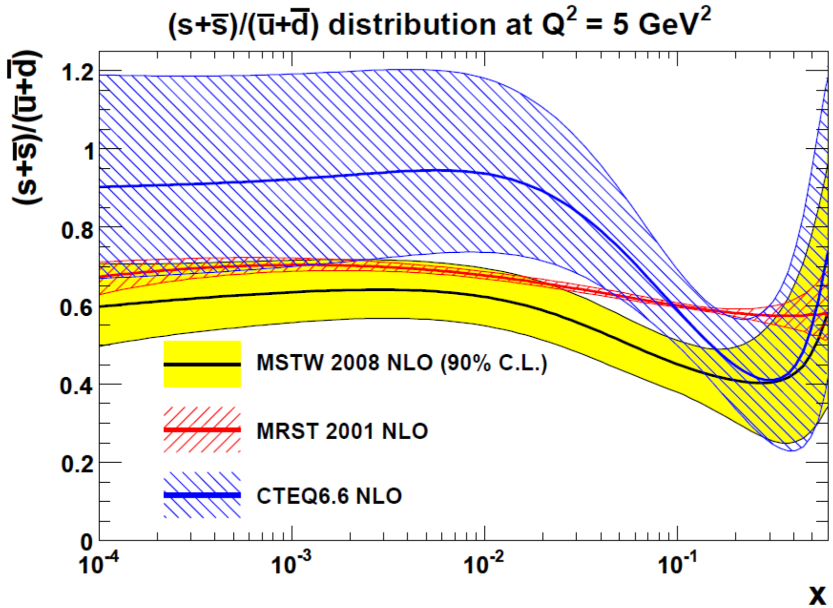
Connected sea



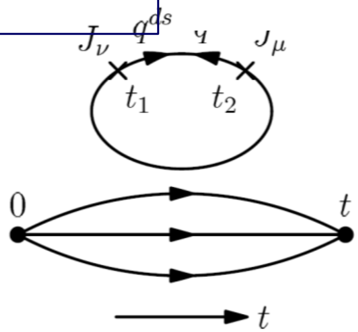
Generate roughly symmetric $s(x), \bar{s}(x), \bar{u}(x)$ and $\bar{d}(x)$ at small x

Generate additional "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger x

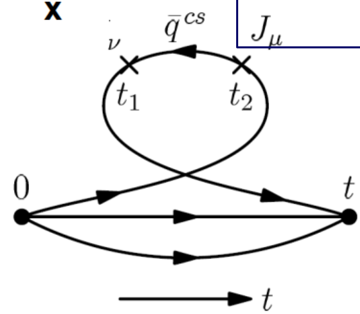
The x-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$



Disconnected sea



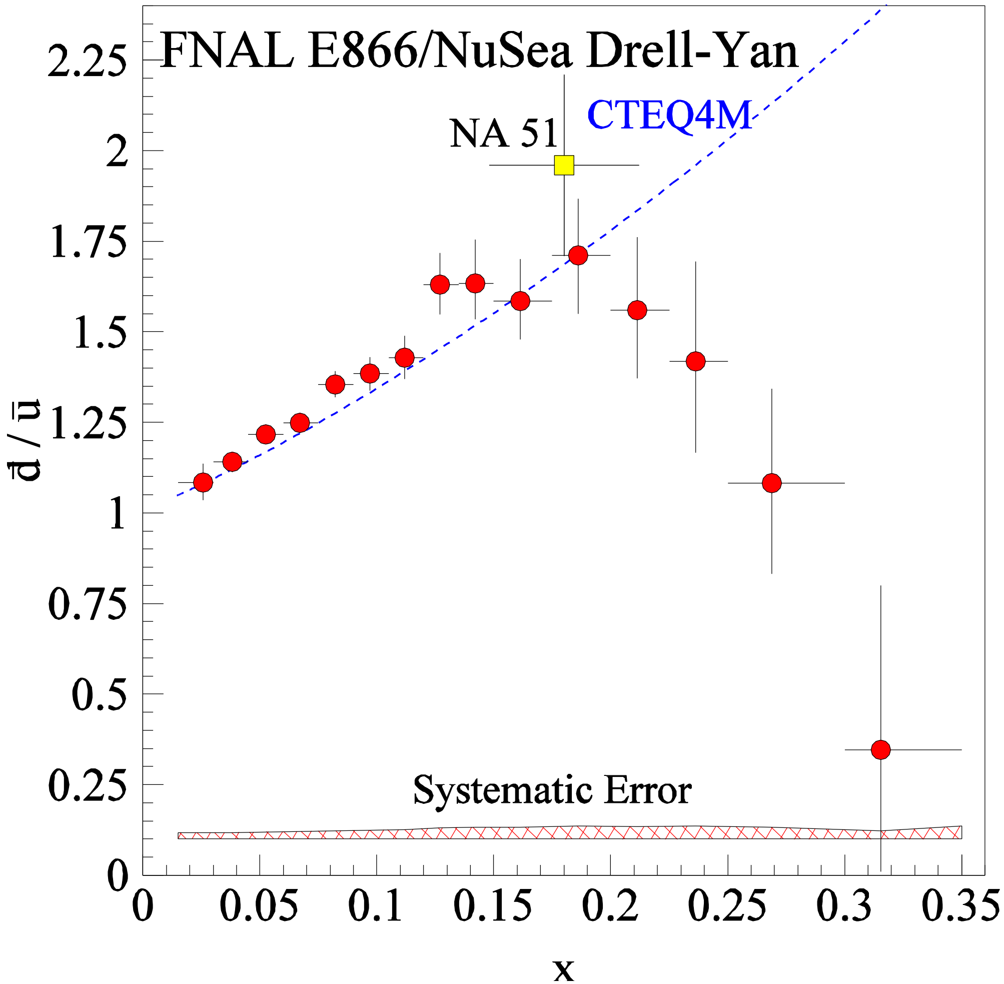
Connected sea



Generate roughly symmetric $s(x), \bar{s}(x), \bar{u}(x)$ and $\bar{d}(x)$ at small x

Generate additional "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger x

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



No existing models can explain sign-change

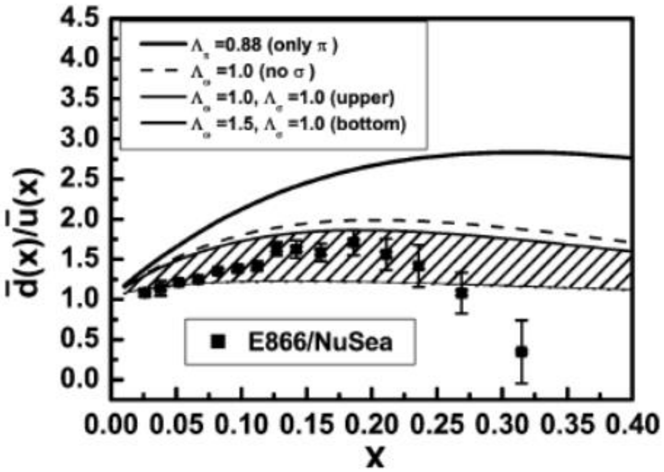
for $\bar{d}(x)-\bar{u}(x)$ at any value of x

Sign change of $\bar{d}(x) - \bar{u}(x)$ at $x \sim 0.25$?

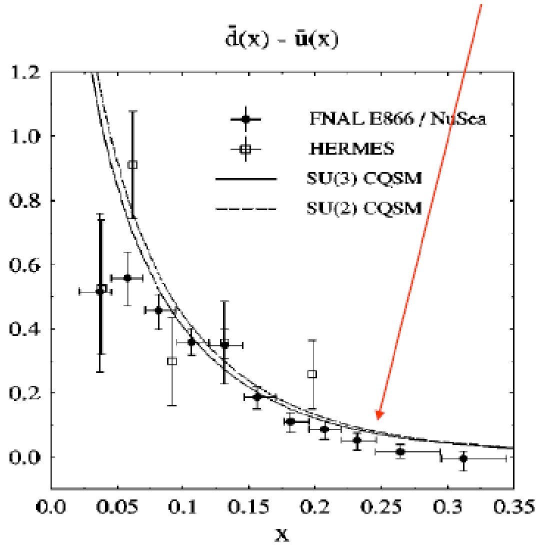
(or $\bar{d}(x)/\bar{u}(x) < 1$ at $x \sim 0.25$?)

Why is it interesting? (no models can explain it yet!)

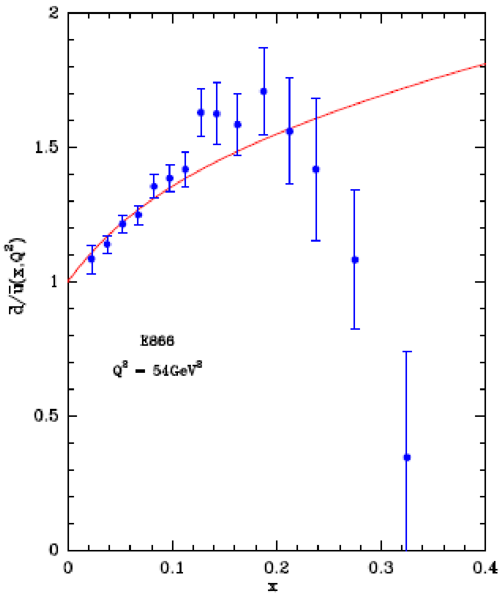
Meson cloud model



Chiral-quark soliton model

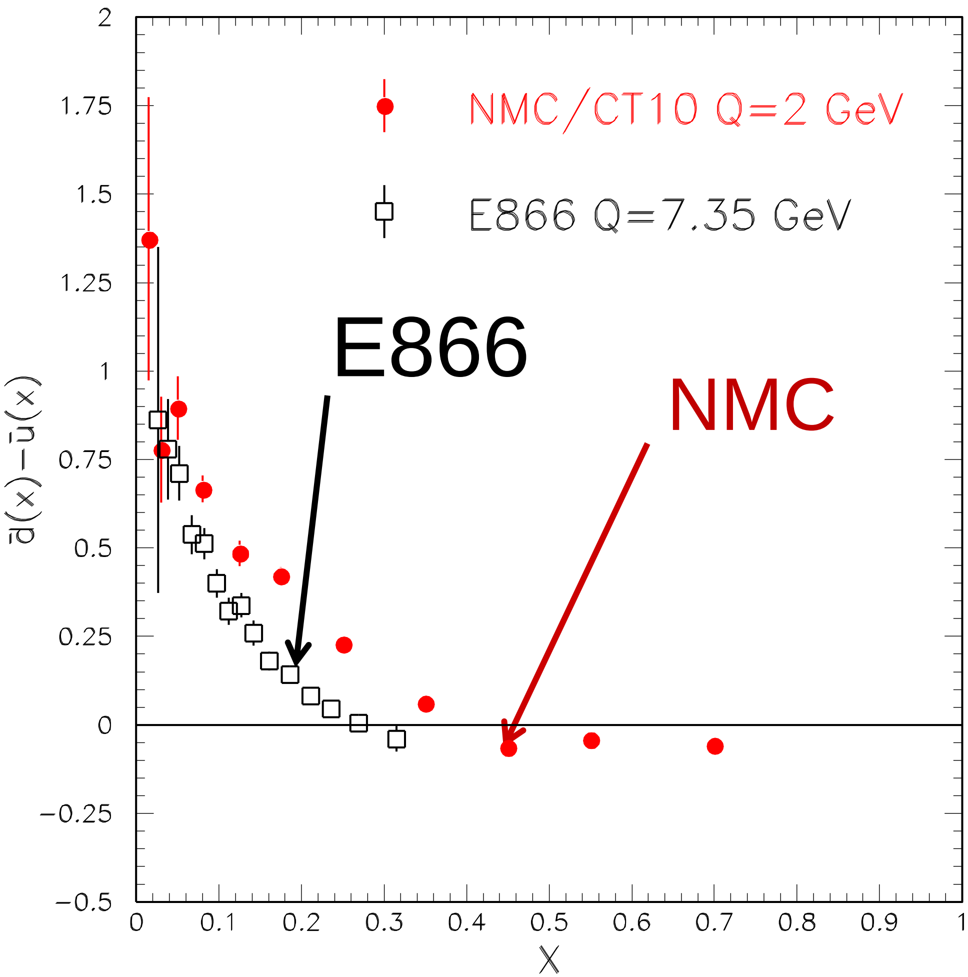


Statistical model



Extracting $\bar{d}(x)-\bar{u}(x)$ from the NMC $F_2^p - F_2^n$ data

$$\bar{d}(x)-\bar{u}(x) = [u_V(x)-d_V(x)]_{CT10}/2 - 3/2 * [F_2^p(x)/x - F_2^n(x)/x]_{NMC}$$

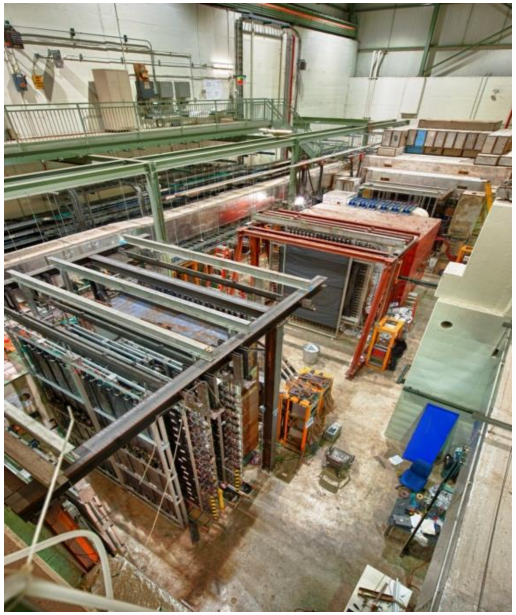


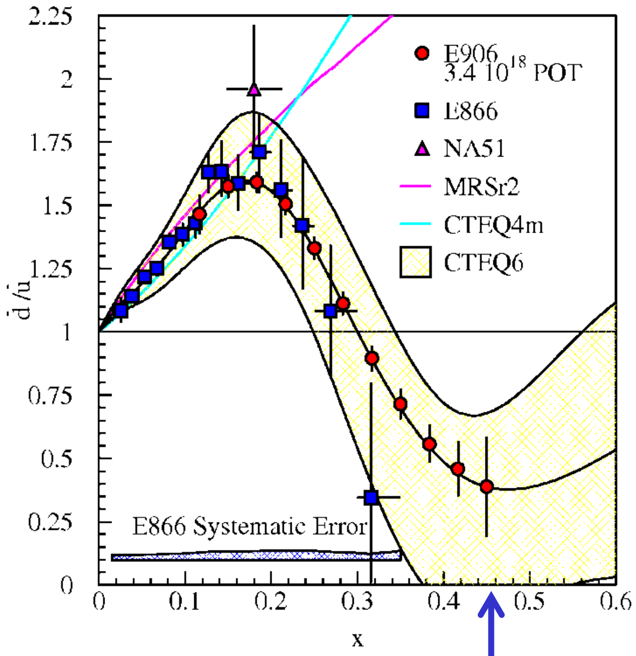
The NMC data, together with the recent PDF, already suggest that $\bar{d}(x)-\bar{u}(x) < 0$ at large x!

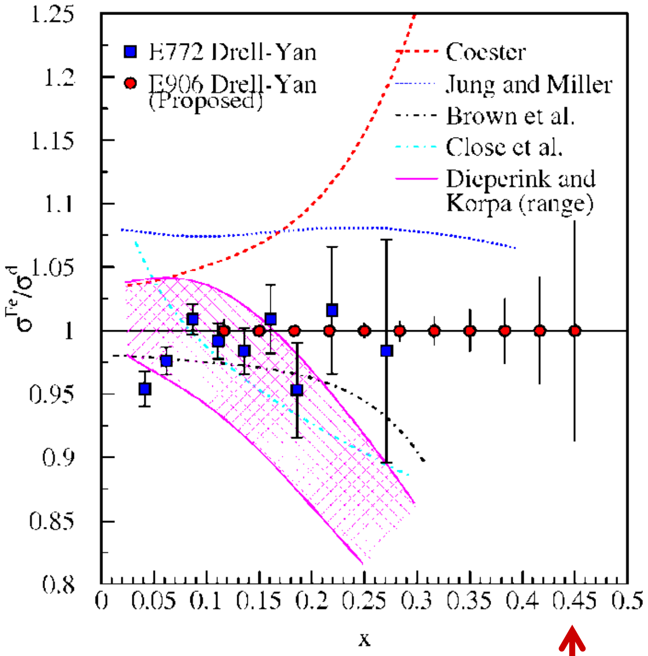
(JCP, Chen, Liu, Qiu, et al. PL B736 (2014) 411; arXiv: 1401.1705)

Drell-Yan Experiment at Fermilab

SeaQuest Experiment (Unpolarized Drell-Yan using 120 GeV proton beam)







Main goals: 1) Measure $\bar{d}\,/\,\bar{u}$ flavor asymmetry up to $x \sim 0.45$

2) Measure EMC effect of antiquarks up to $x \sim 0.45$

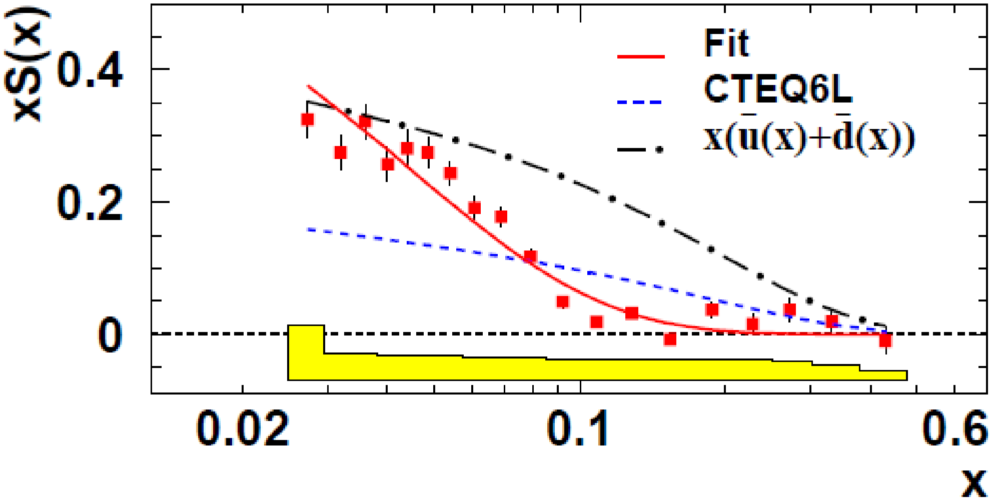
Data-taking started Feb. 2014 (Paul Reimer's talk)

Conclusions

- Evidences for the existence of "intrinsic" light-quark seas ($\bar{u}, \bar{d}, \bar{s}$) in the nucleons.
- Clear evidence for intrinsic charm (beauty) 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.
- The flavor- and *x*-dependencies of the nucleon sea provide strong constraints on theoretical models.
- Ongoing and future Drell-Yan (Fermilab, COMASS, RHIC, ...) and SIDIS experiments (JLab, EIC,...) will provide new inputs.

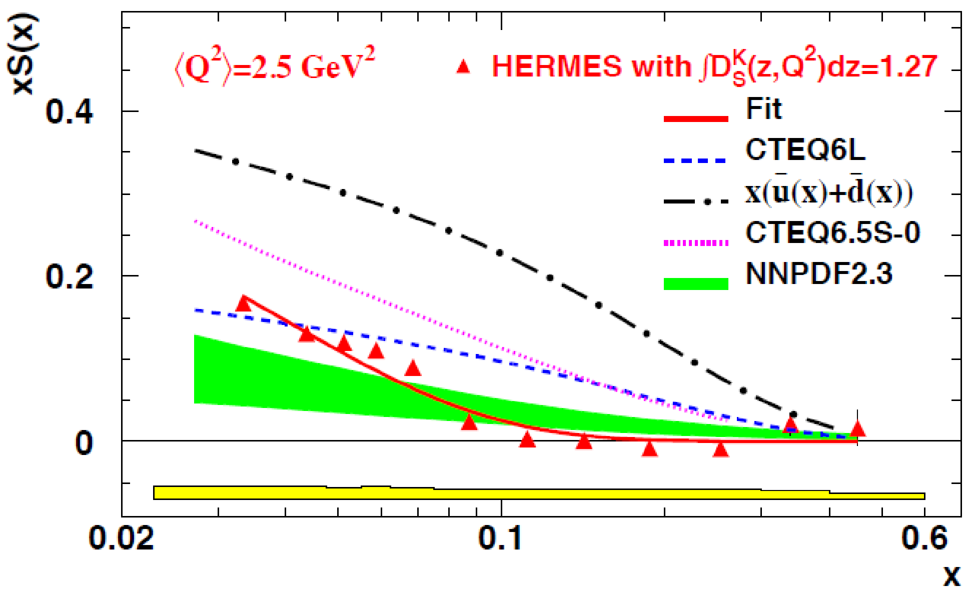
Backup Slides

Latest HERMES result on $xS(x)$



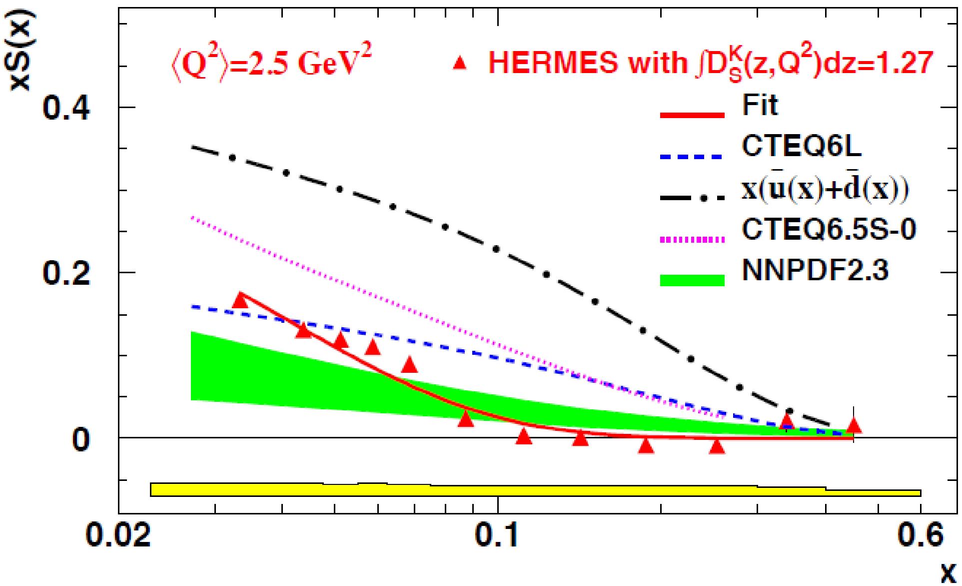
$S(x) \equiv s(x) + \bar{s}(x)$

2008 result



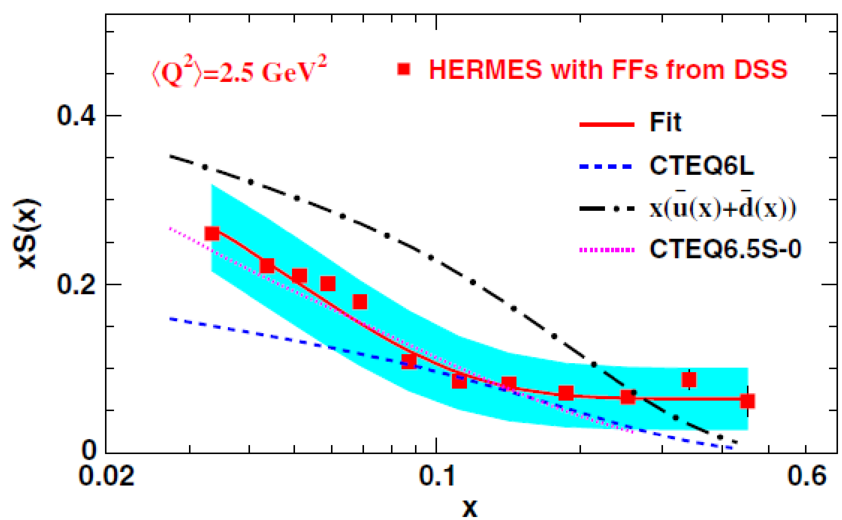
2014 result
(PRD 89 (2014) 097101)

Latest HERMES result on $xS(x)$



2014 result obtained with HERMES kaon fragmentation function

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

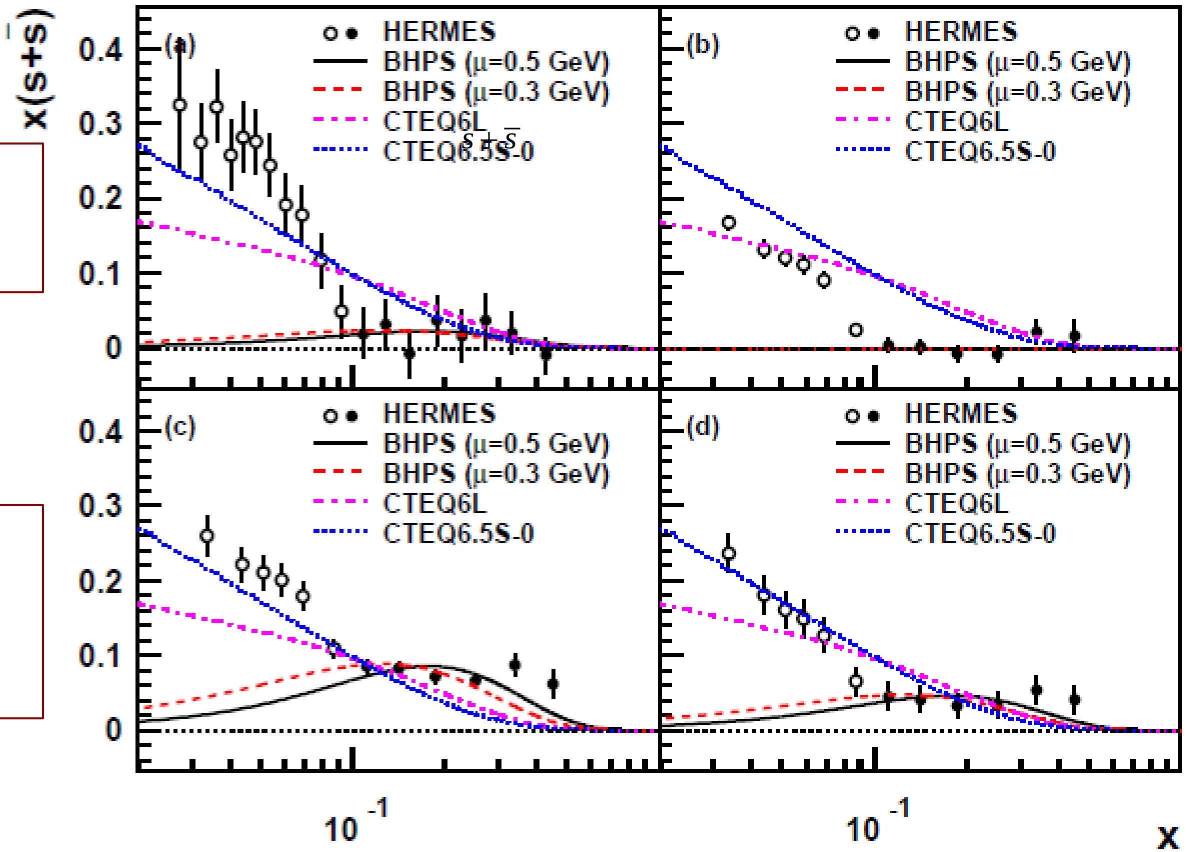


New 2014 result obtained with the DSS kaon fragmentation function

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

2008
HERMES

2014
HERMES
DSS FF



2014
HERMES

2014
HERMES
Intermediate
FF

Wen-Chen Chang and JCP, arXiv: 1410.7027

$xS(x)$	μ (GeV)	$\mathcal{P}_5^{u\bar{u}}$	$\mathcal{P}_5^{d\bar{d}}$	$\mathcal{P}_5^{s\bar{s}}$
HERMES2008	0.5	0.120 (0.128, 0.112)	0.238 (0.246, 0.230)	0.022
HERMES2008	0.3	0.161 (0.174, 0.145)	0.279 (0.292, 0.263)	0.029
HERMES2014 set1	0.5	0.178 (0.187, 0.167)	0.296 (0.305, 0.285)	0.000
HERMES2014 set1	0.3	0.229 (0.242, 0.211)	0.347 (0.360, 0.329)	0.000
HERMES2014 set2	0.5	0.125 (0.131, 0.124)	0.243 (0.249, 0.242)	0.086
HERMES2014 set2	0.3	0.194 (0.202, 0.188)	0.312 (0.320, 0.306)	0.111
HERMES2014 set3	0.5	0.145 (0.152, 0.139)	0.263 (0.270, 0.257)	0.046
HERMES2014 set3	0.3	0.211 (0.223, 0.198)	0.329 (0.341, 0.316)	0.059

Table 1: The extracted values of $\mathcal{P}_5^{u\bar{u}}$, $\mathcal{P}_5^{d\bar{d}}$ and $\mathcal{P}_5^{s\bar{s}}$ from E866 [16], CTEQ6.6 [21] and four sets of HERMES's data (HERMES2008 and HERMES2014 set1, set2 and set3) assuming two initial scales (μ) for the BHPS five-quark distributions. The results of $\mathcal{P}_5^{u\bar{u}}$ and $\mathcal{P}_5^{d\bar{d}}$ using CTEQ6.5S-0 [25] and CTEQ6L [15] PDFs are also shown in parenthesis.

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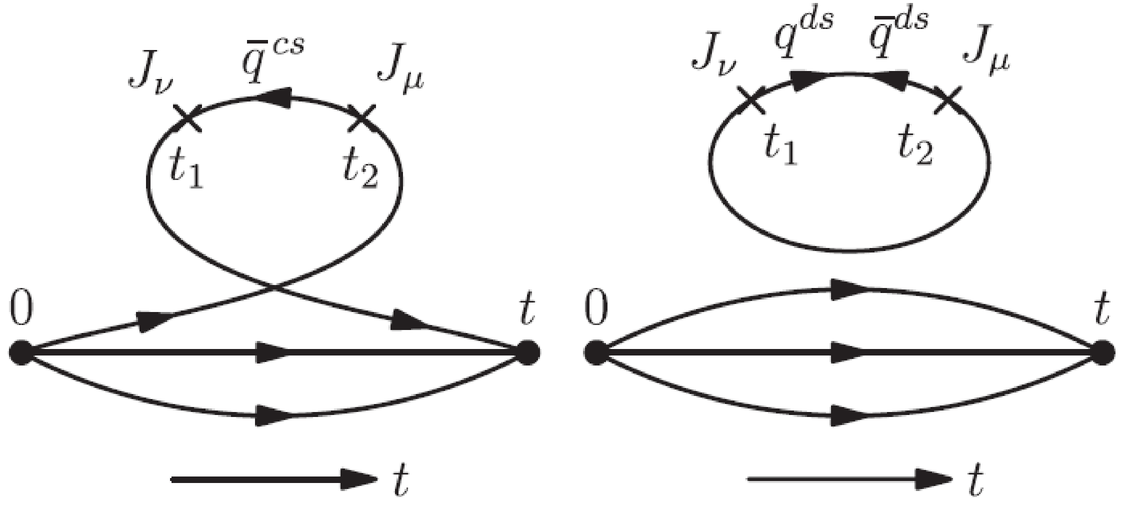
What mechanism could lead to $\bar{u} > \bar{d}$ at $x > 0.25$?

Connected sea — Disconnected sea



(valence-like) — (sea-like)

$\bar{u}(x) \neq \bar{d}(x)$ can only come from connected sea (CS)

$(u \to \bar{u} + u + u,\ d \to \bar{d} + d + d)$ ($\bar{q}$ has the same flavor as q for CS)

$\Rightarrow$ Connected sea could lead to $\bar{u} > \bar{d}$ at certain x region??

(since there are two u valence quarks and one d valence quak)