# Flavor and ***x***-dependence of the Nucleon Sea

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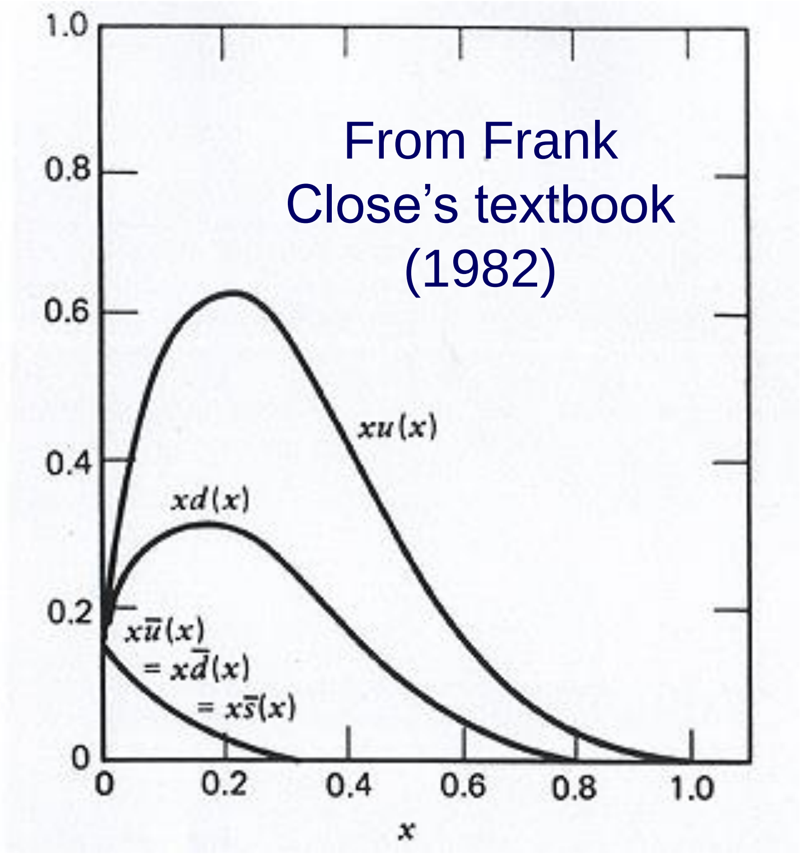
# There was a time when nucleon sea was nice and simple……

## Flavor structure of the proton sea



From Frank Close’s textbook (1982)

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

$SU(3)$ symmetric sea

Actually, the nucleon sea is full of surprises

# Outline

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

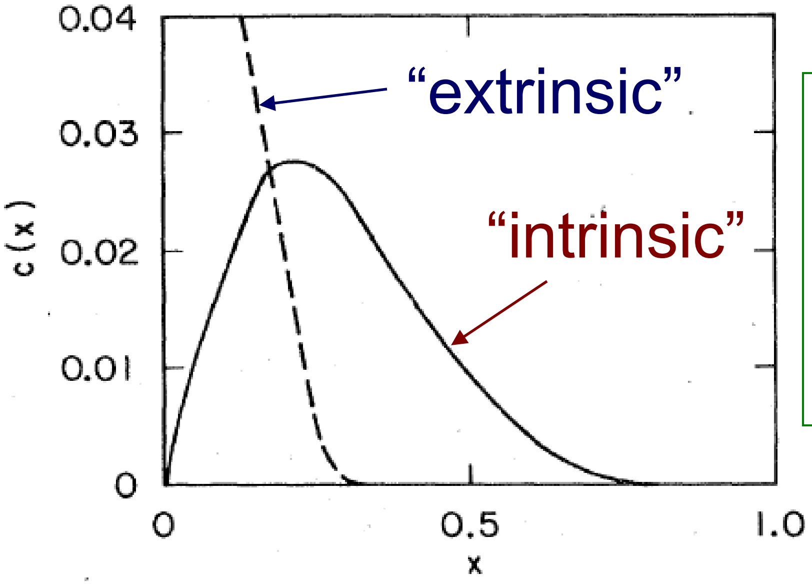
Based on a review article: “Flavor Structure of the Nucleon Sea”,
Wen-Chen Chang and Jen-Chieh Peng, arXiv: 1406.1260

# Search for the "intrinsic" quark sea

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

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

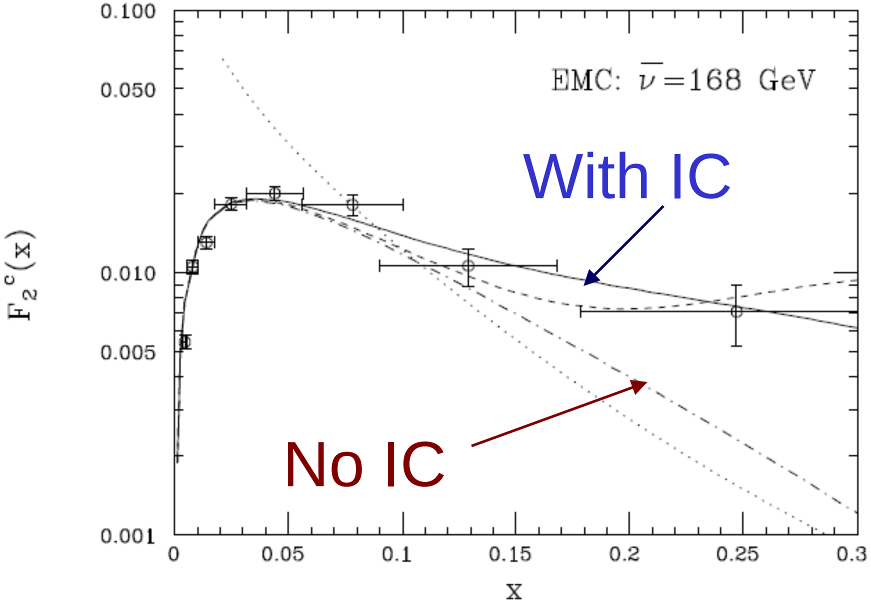
The "intrinsic"-charm from $|uudc\bar{c}\rangle$ is "valence"-like and peak at large $x$ unlike the "extrinsic" sea $(g \to c\bar{c})$



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)

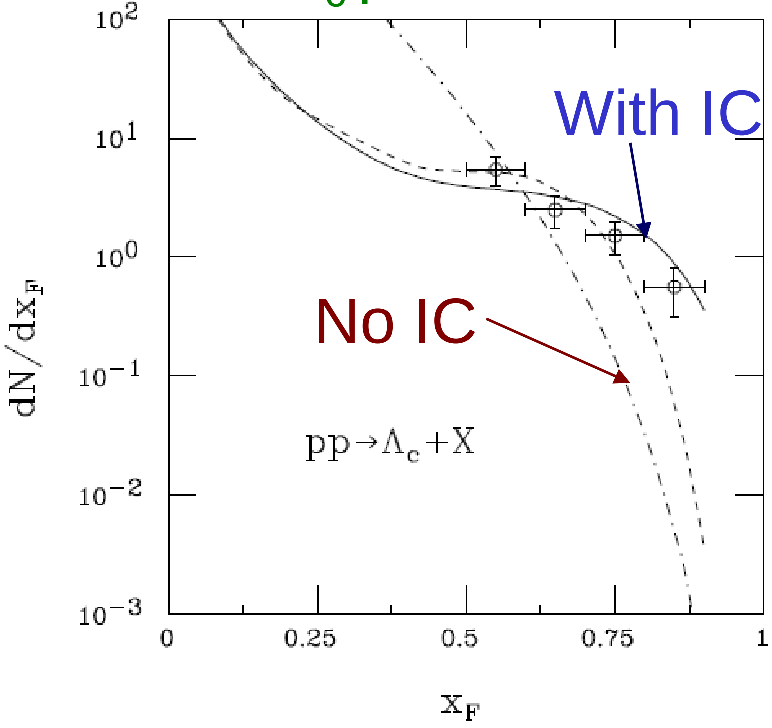
DIS data



With IC

No IC

$\Lambda_c$ production



With IC

No IC

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

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

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

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

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

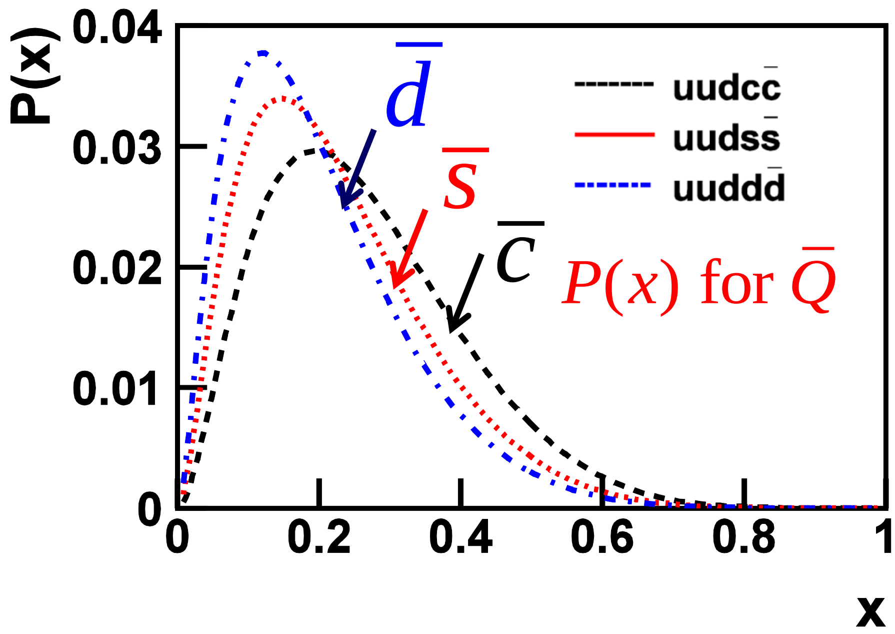
The "intrinsic" sea for lighter quarks have larger probabilities!

# *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”?

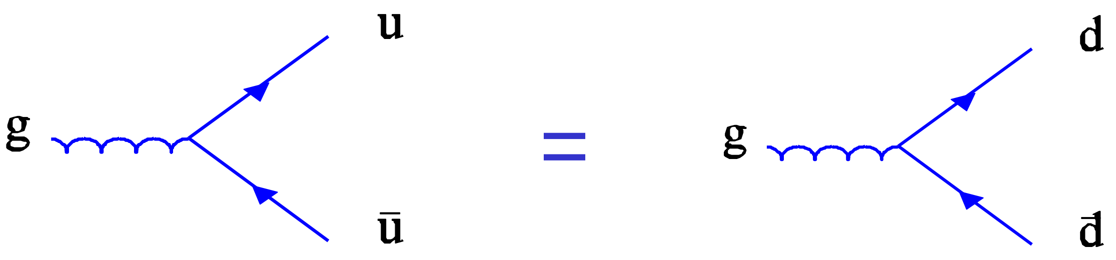
- Select experimental observables which have no contributions from the “extrinsic sea”
- “Intrinsic sea” and “extrinsic sea” are expected to have different *x*-distributions
  - Intrinsic sea is “valence-like” and is more abundant at larger *x*
  - Extrinsic sea is more abundant at smaller *x*

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

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

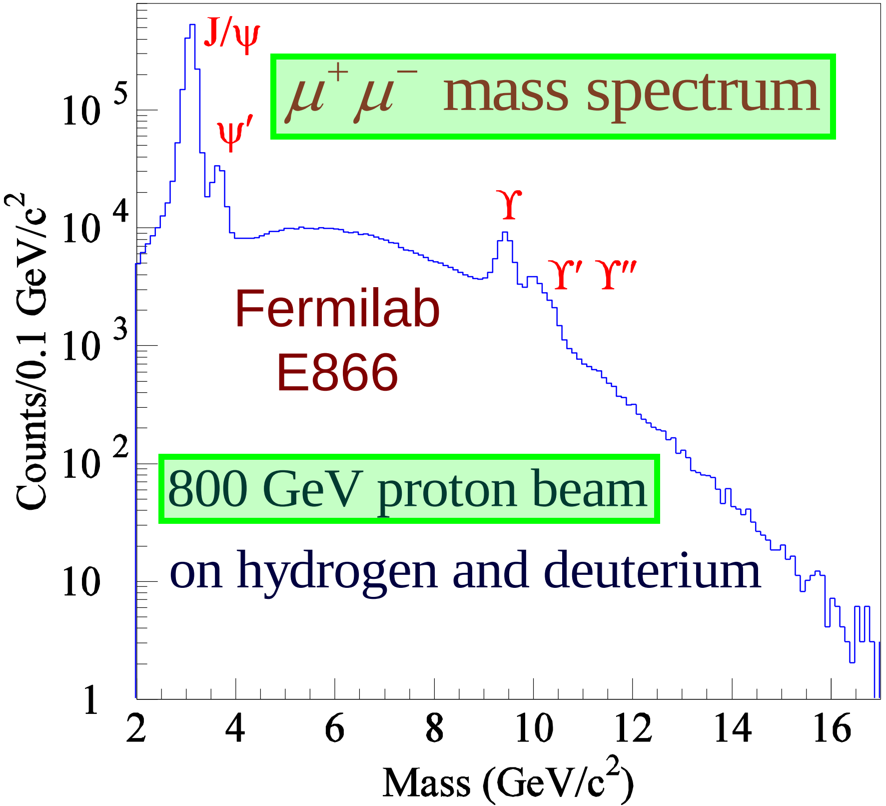
$\bar{d}-\bar{u}$ has no contribution from extrinsic sea $(g \rightarrow \bar{q}q)$

and is sensitive to "intrinsic sea" only



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

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

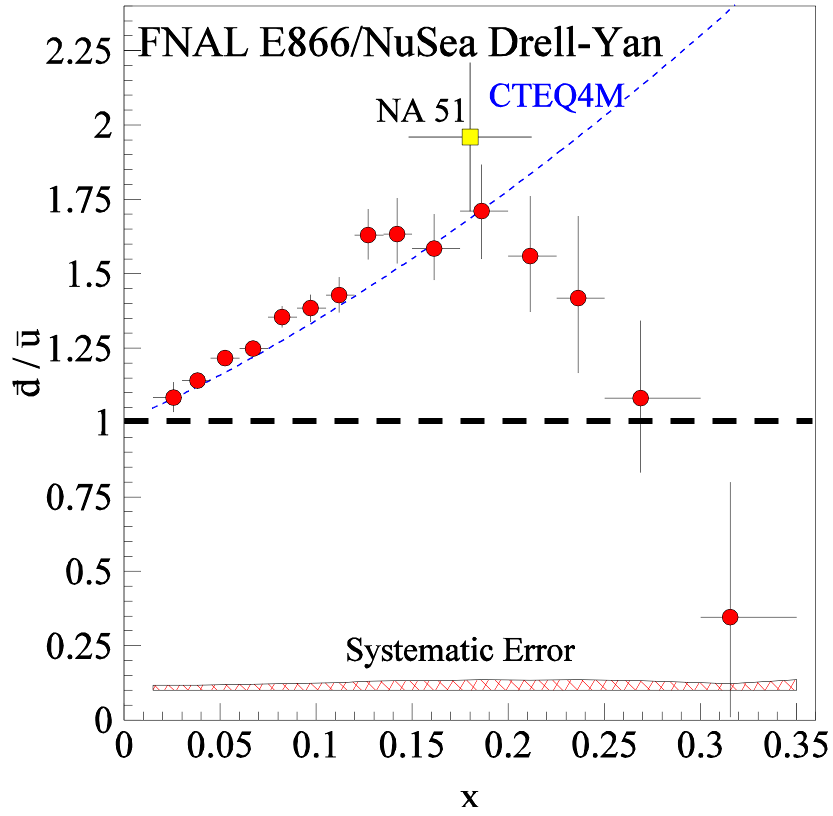


$\mu^+\mu^-$ mass spectrum

Fermilab
E866

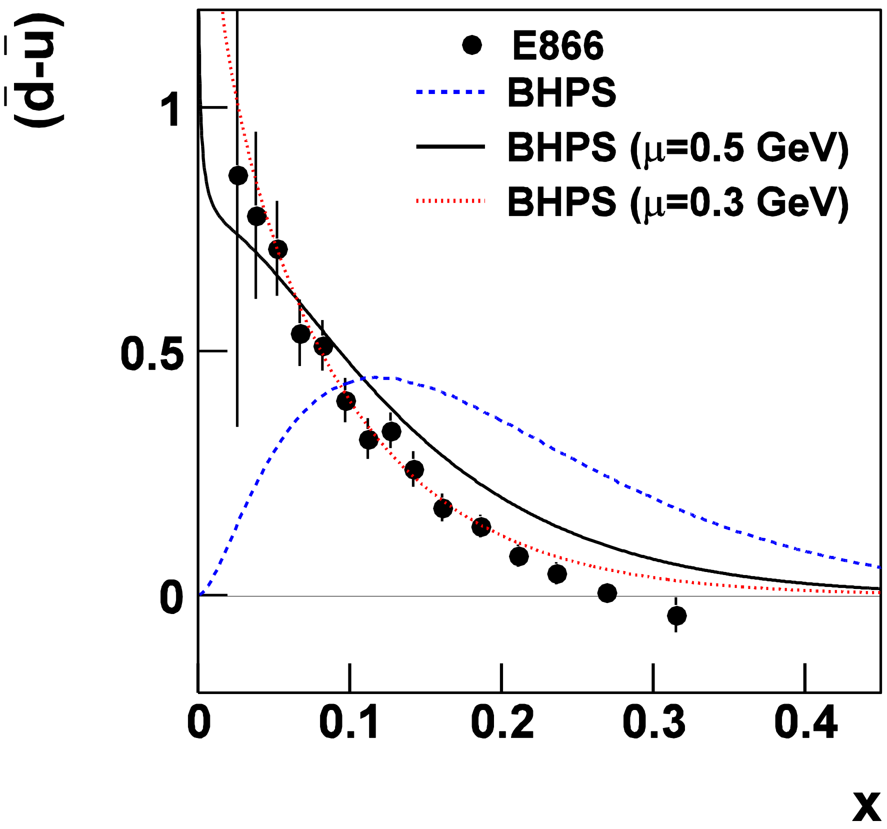
800 GeV proton beam

on hydrogen and deuterium



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 $\mathrm{GeV}^2$

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

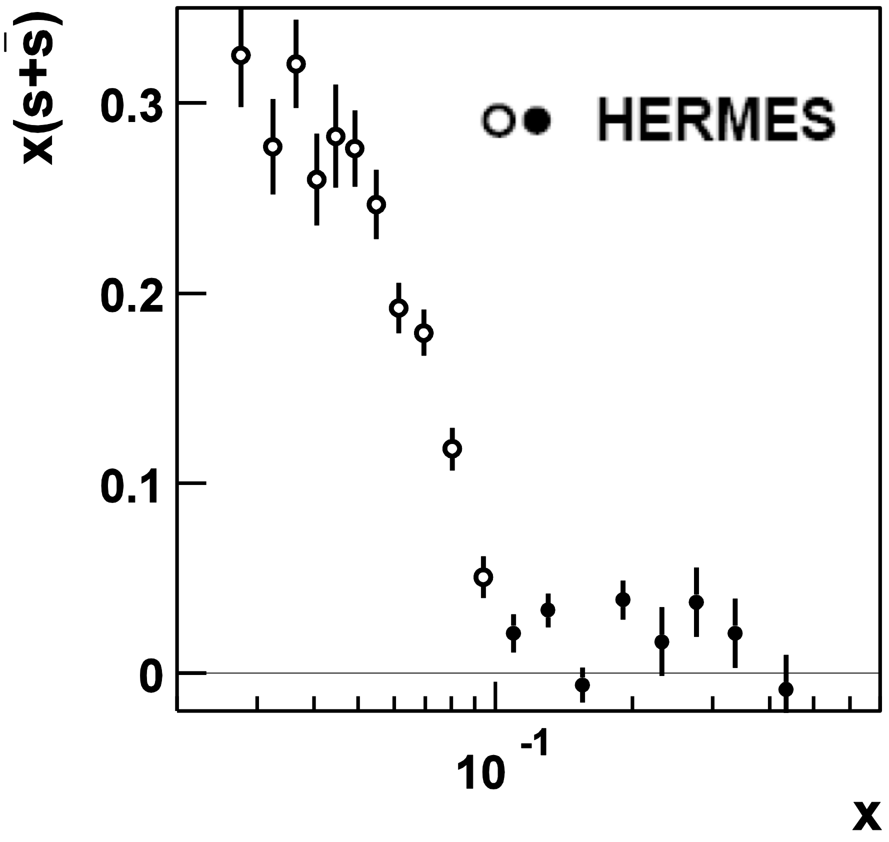
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

# 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

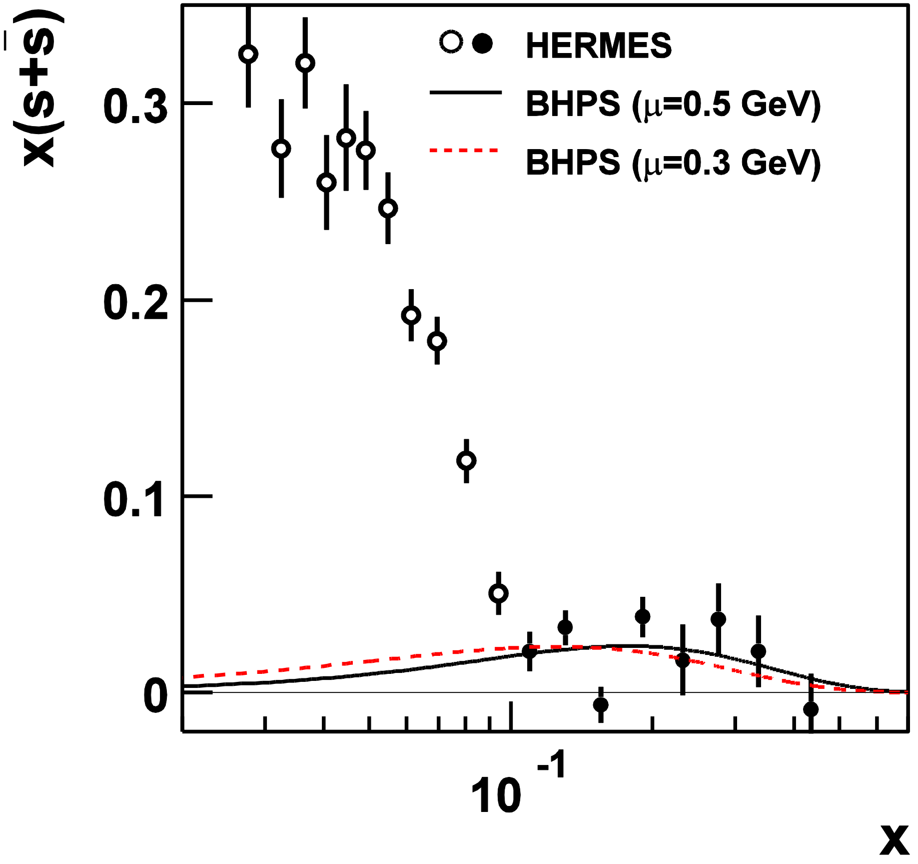


$s(x)+\bar{s}(x)$ extracted from HERMES Semi-inclusive DIS kaon data at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$

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

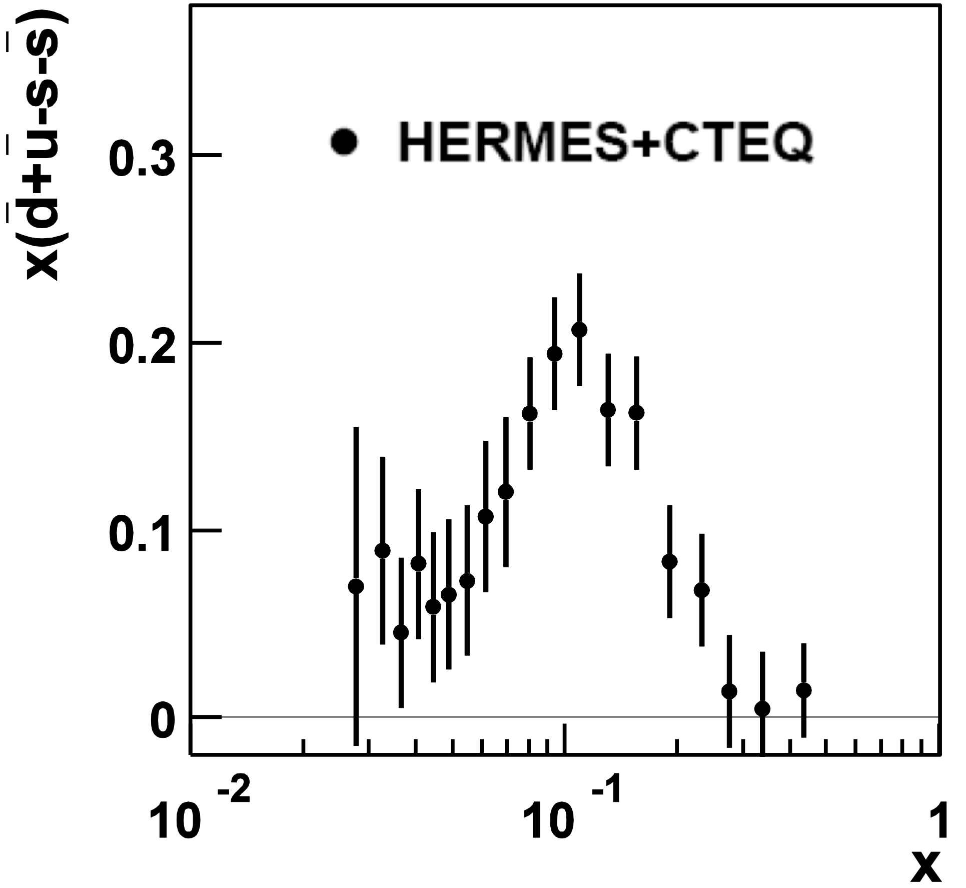
$$P_5^{uuds\bar{s}} = 0.024$$

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

- Select experimental observables which have no 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



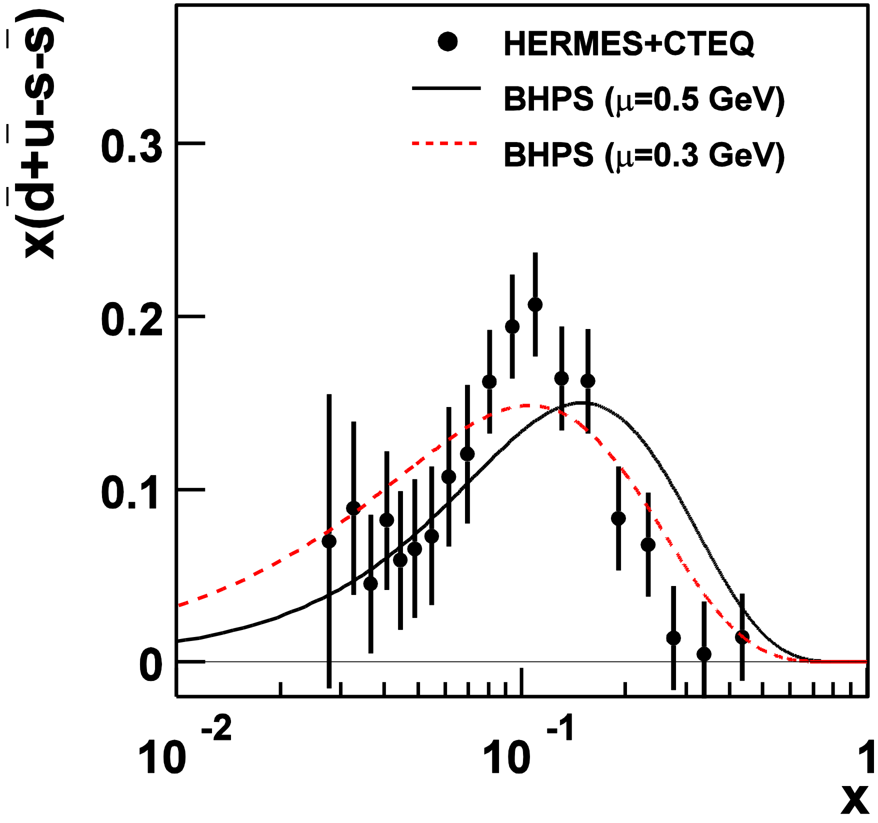
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

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



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

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

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

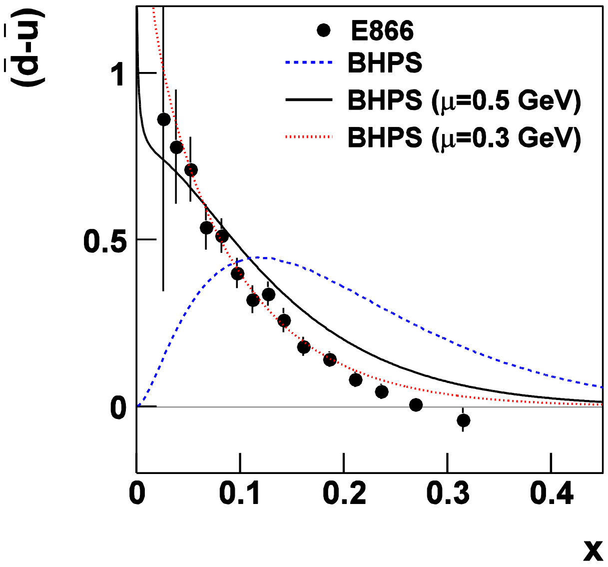
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

(not sensitive to extrinsic sea)

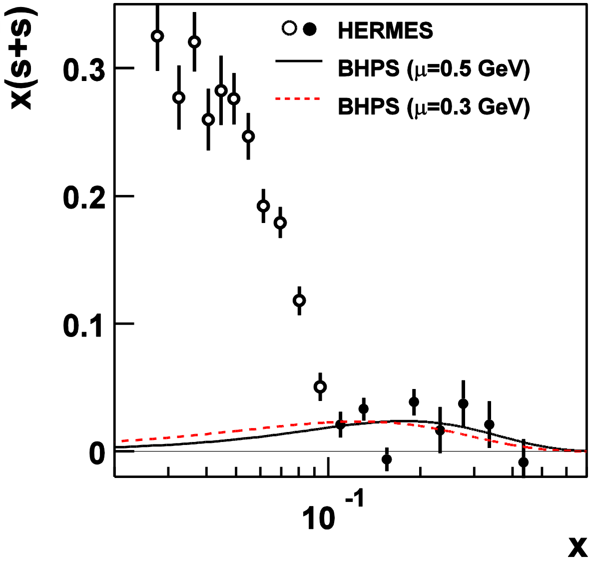
(W. Chang and JCP, PL B704, 197(2011))

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

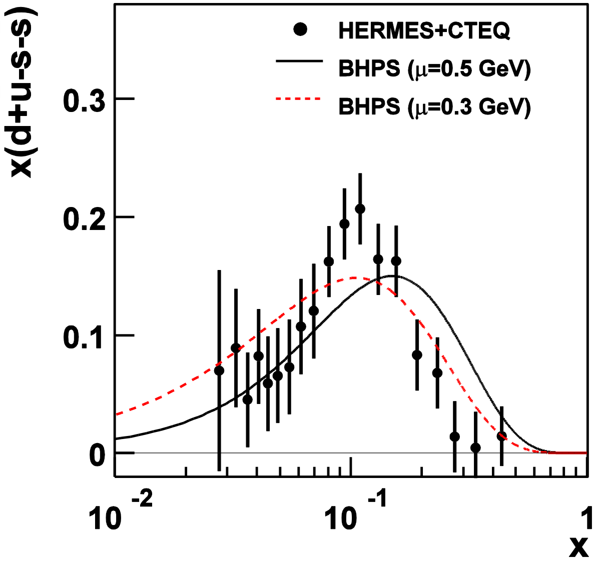
# Extraction of the various five-quark components for light quarks



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



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



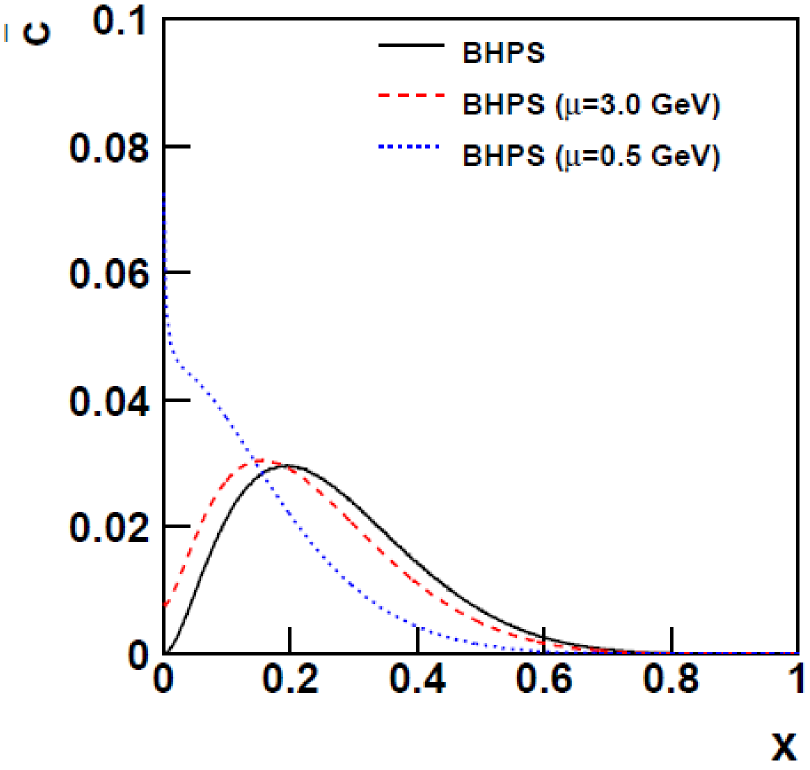
$$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$$

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

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

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

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

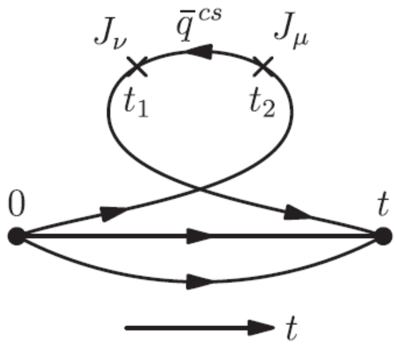
- Search for intrinsic charm and beauty at RHIC and LHC.
- Intrinsic gluons in the nucleons (Hoyer and Roy)?
- Spin-dependent observables of intrinsic sea?
- Global fits including intrinsic u, d, s sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?


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

# Connected-Sea Partons

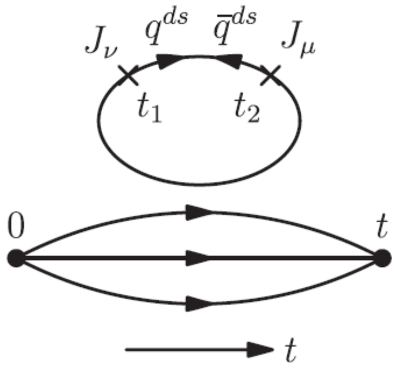
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea



(valence-like)

Disconnected sea



(sea-like)

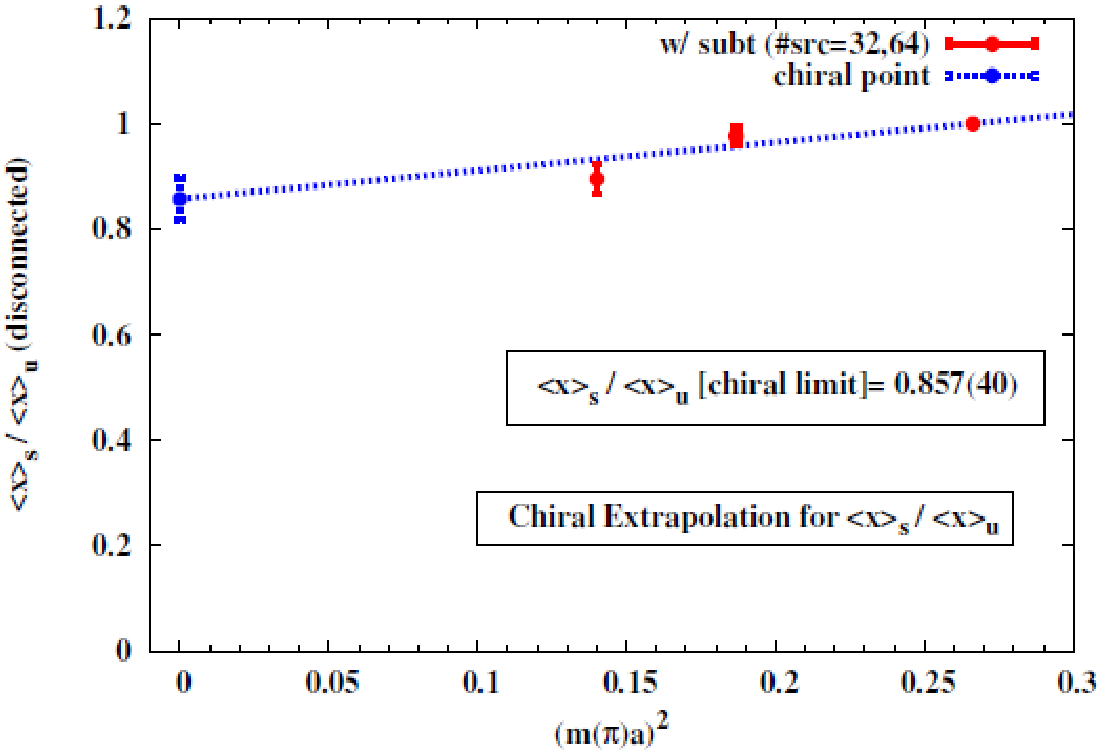
Two sources of sea:

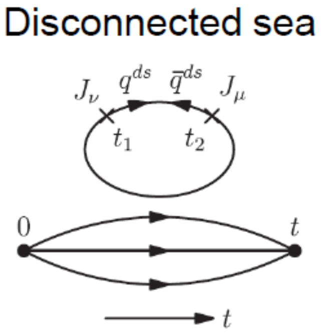
Connected sea (CS) and Disconnected sea (DS)

CS and DS have different Bjorken-x and flavor dependences

- $x$ – 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 $\bar{u} + \bar{d}$ ?





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

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

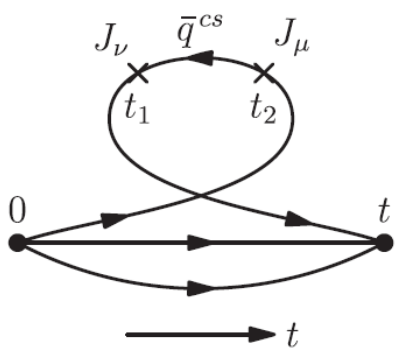
$$[\bar{u}(x) + \bar{d}(x)]_{\text{PDF}} - [\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}}$$

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

# Connected-Sea Partons

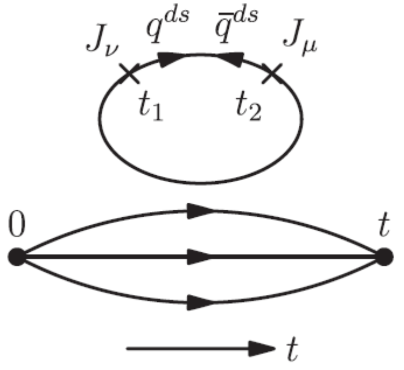
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea

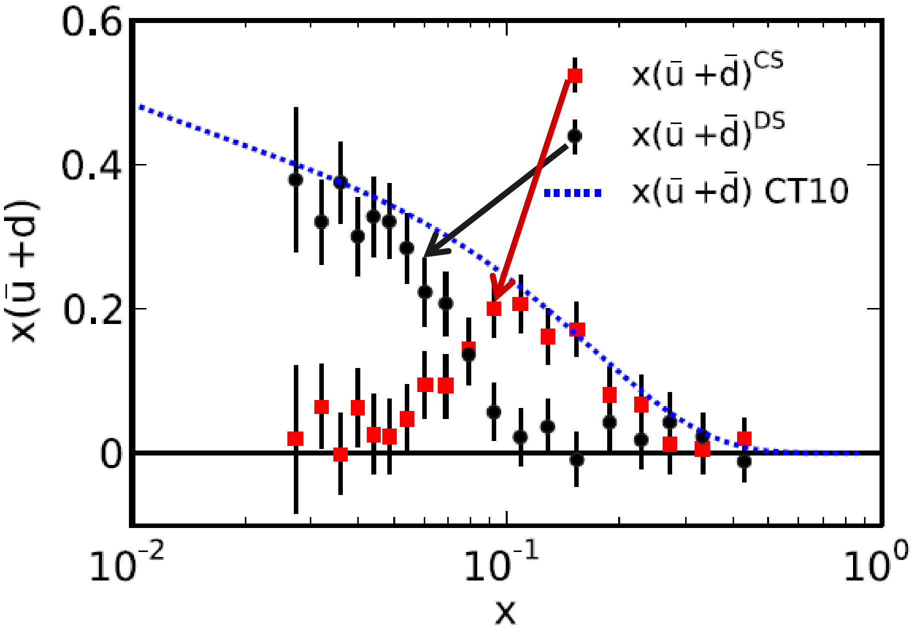


(valence-like)

Disconnected sea

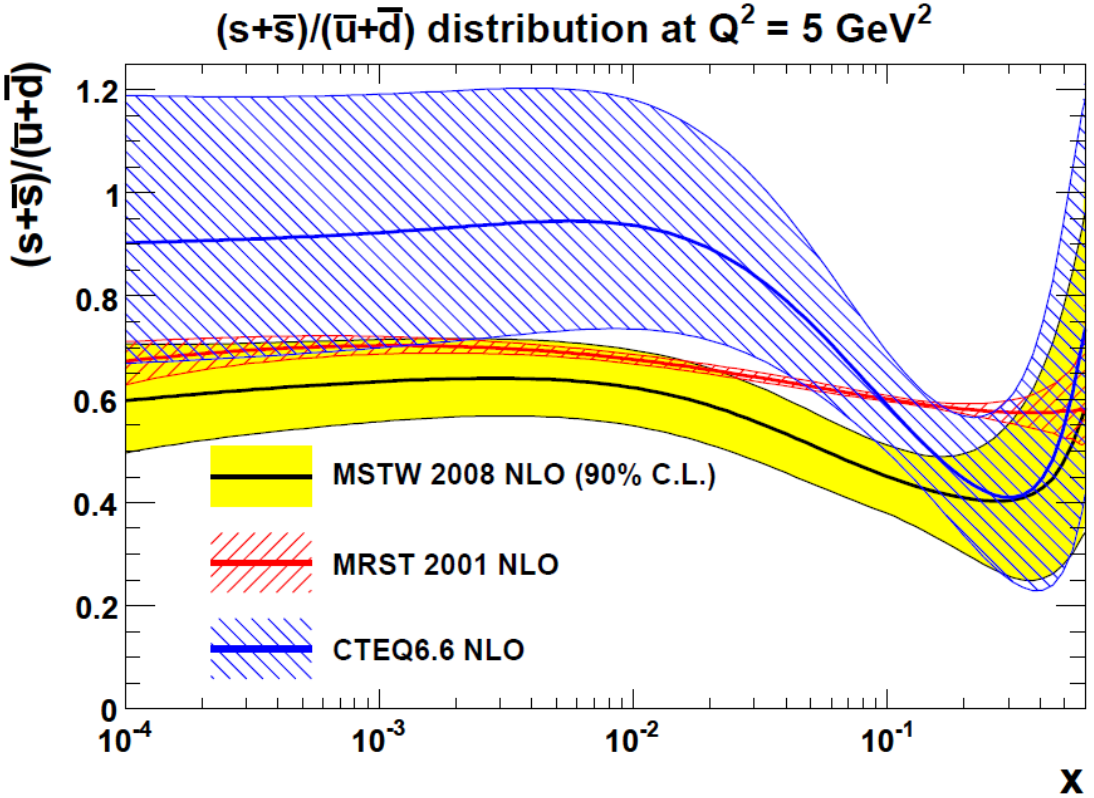


(sea-like)



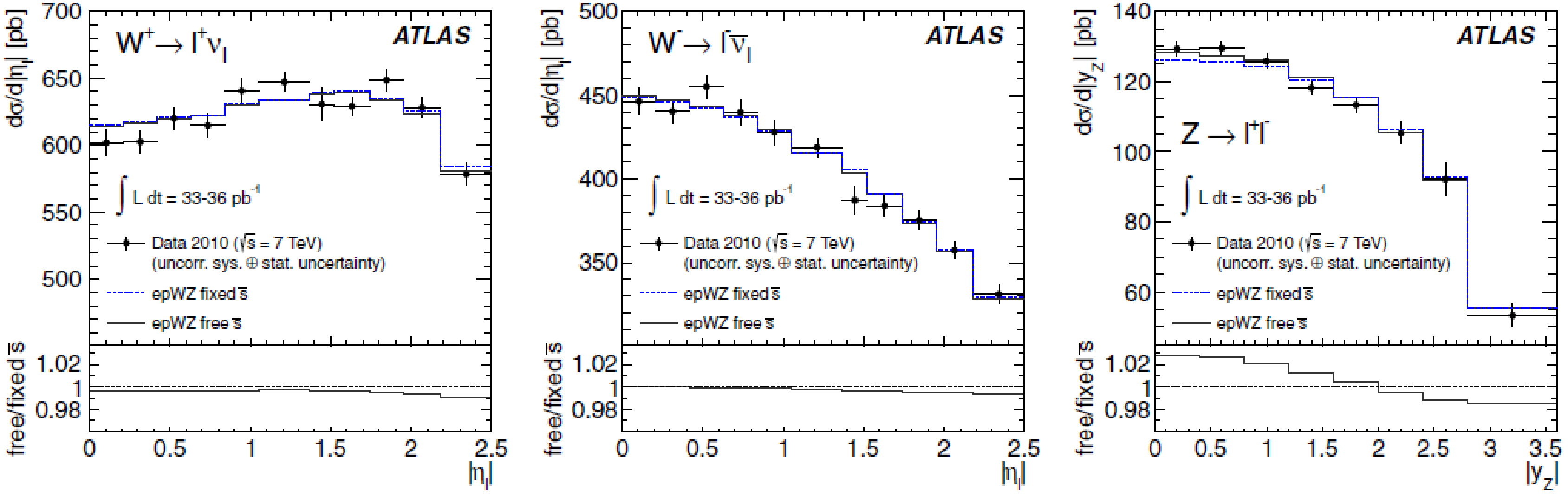
- Using input from lattice QCD, one can separate the connected sea from the disconnected sea for $\bar{u}(x)+\bar{d}(x)$
- For $\bar{u}+\bar{d}$ at $Q^2$=2.5 GeV$^2$, momenta carried by CS and DS are roughly equal

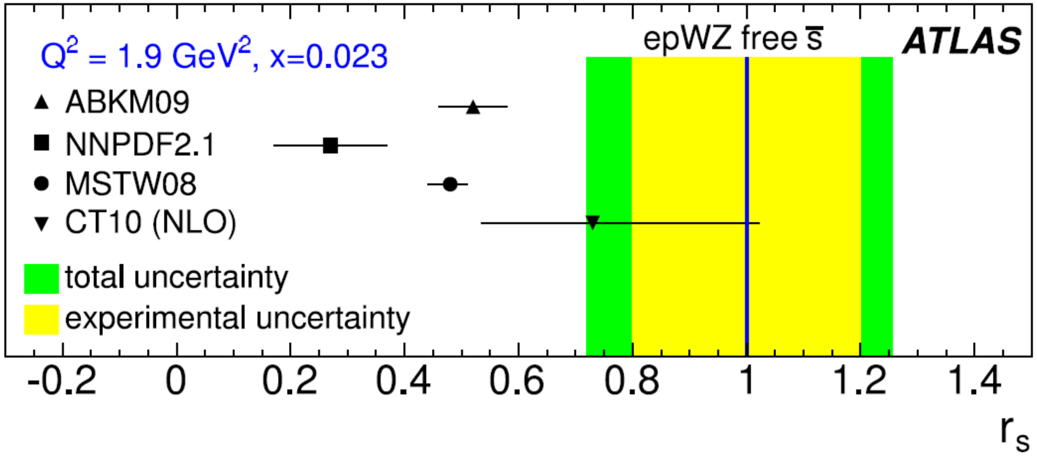
# What is the $x$-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$?



- 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?

# ATLAS W/Z production suggests SU(3) symmetric sea?





$$r_s = (s+\bar{s})/2\bar{d} = 1.00^{+0.09}_{-0.10}$$

at $x$=0.013, $Q^2 = M_Z^2$

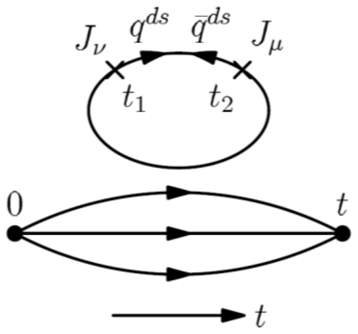
Aad et al., PRL 109 (2012) 012001

# 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*

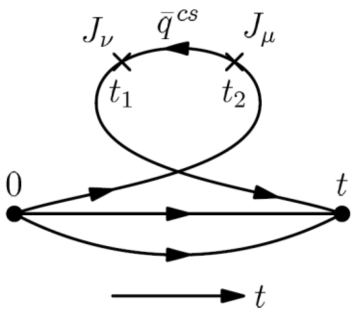
Can be understood from Lattice QCD (PRL 109 (2012)252002)

Disconnected sea



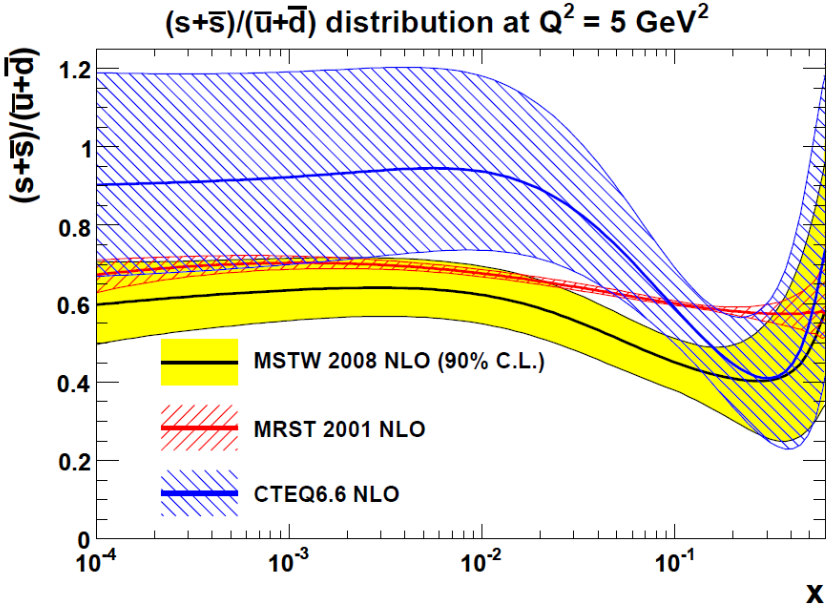
Generate roughly symmetric $s(x), \bar{s}(x), \bar{u}(x)$ and $\bar{d}(x)$ at small *x*

Connected sea

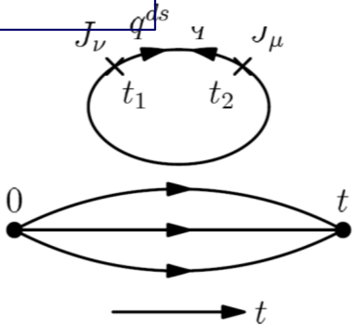


Generate additional "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger *x*

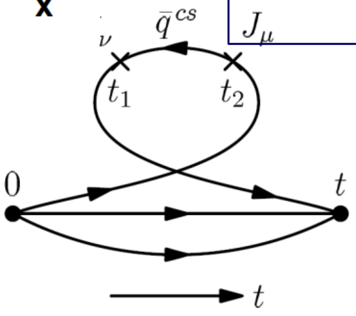
# The $x$-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$



Disconnected sea



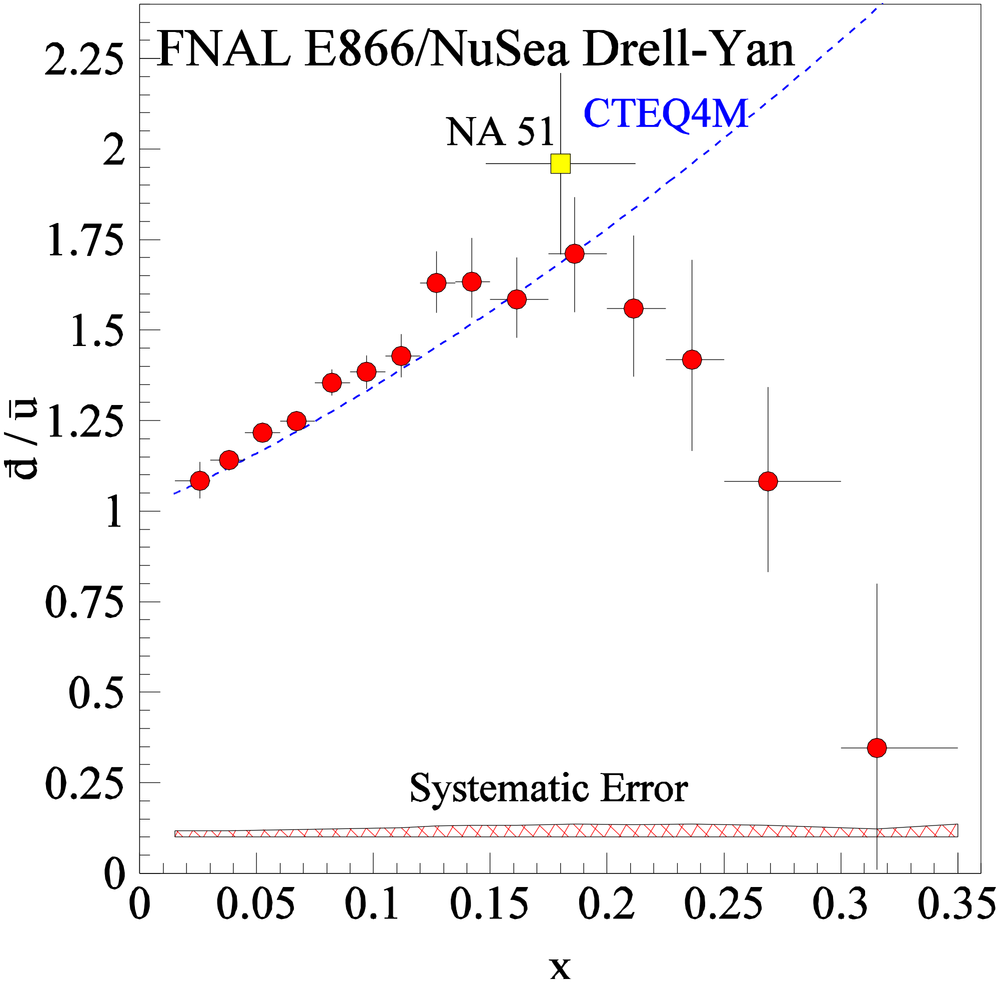
Connected sea



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

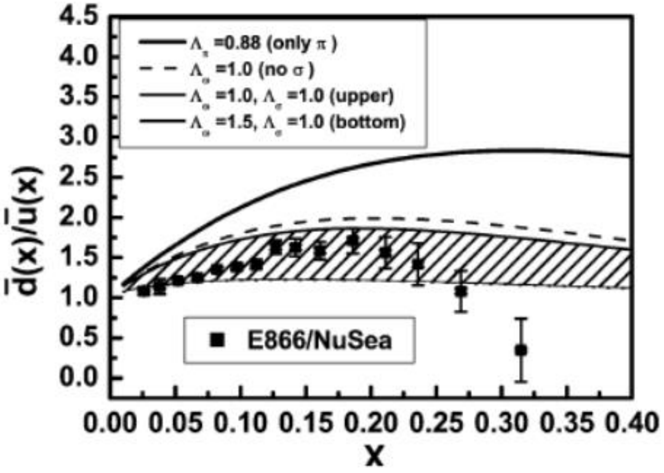
for $\bar{d}(x) - \bar{u}(x)$ at any value of $x$

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

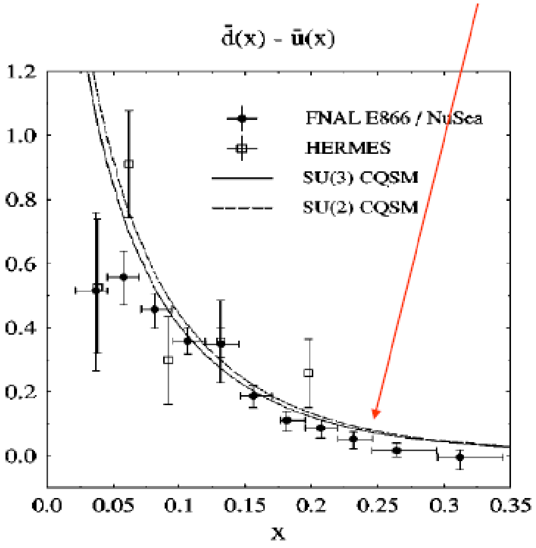
# (or $\bar{d}(x) / \bar{u}(x) < 1$ at $x \sim 0.25$?)

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

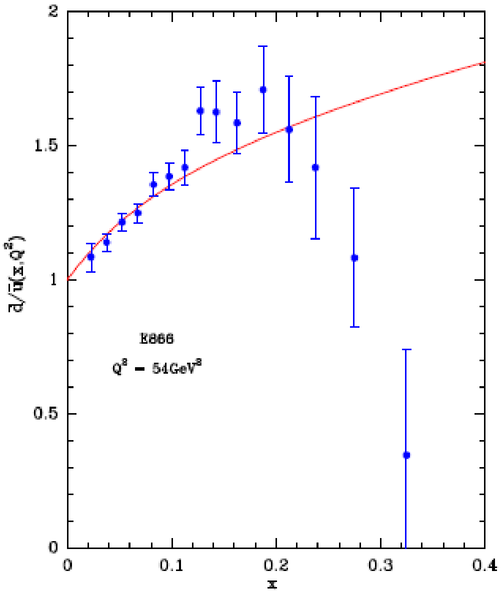
Meson cloud model



Chiral-quark soliton model



Statistical model



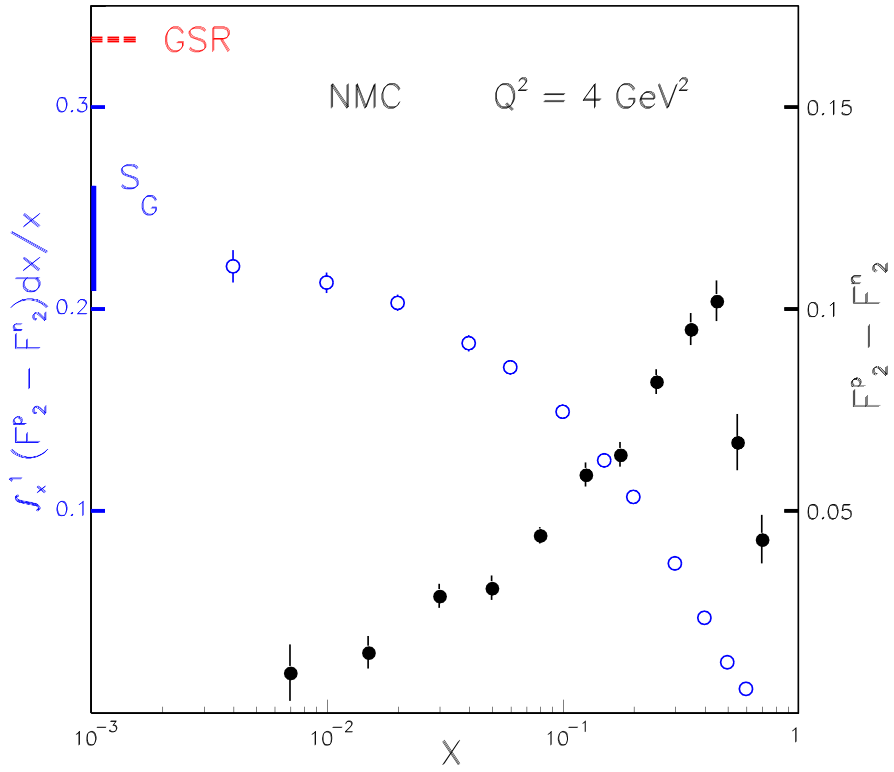
# Revisit the NMC measurement of the Gottfried Sum rule

The Gottfried Sum Rule

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

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

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



New Muon Collaboration (NMC) obtains

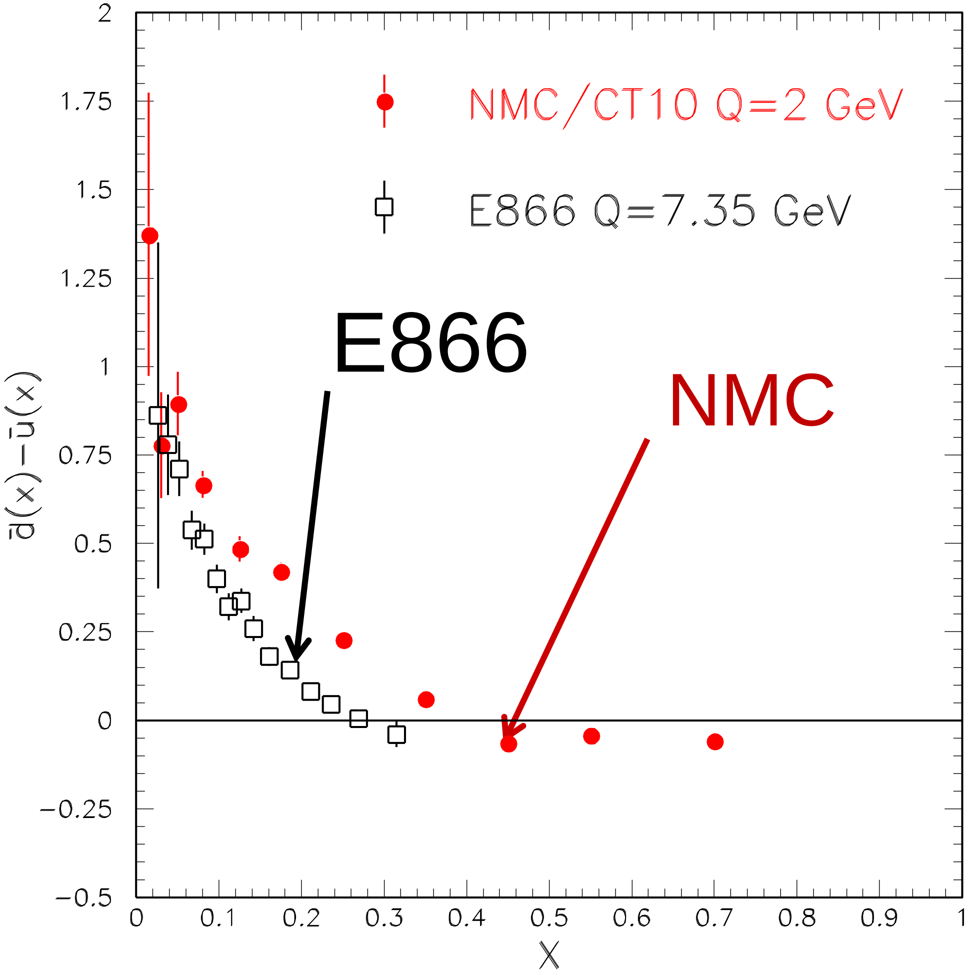
$S_G$ = 0.235 ± 0.026

**( Significantly lower than 1/3 ! )**

$$\boxed{\Rightarrow \bar{d} \neq \bar{u}\ ?}$$

# Extracting $\bar{d}(x)-\bar{u}(x)$ from the NMC data

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

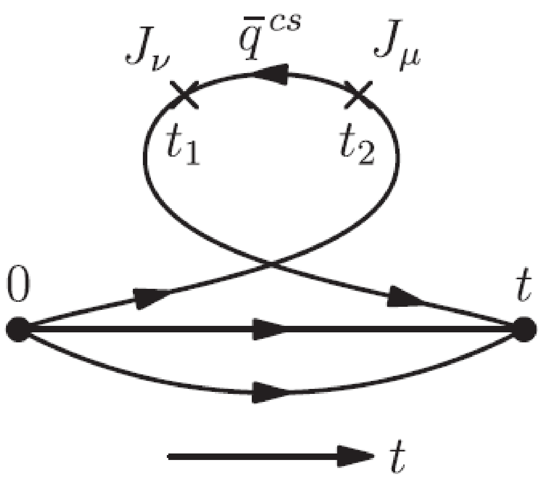


The NMC data, together with the recent PDF, already suggest that $\bar{d}(x)-\bar{u}(x)<0$ at large $x$!

(JCP, Chen, Liu, Qiu, et al. arXiv: 1401.1705)

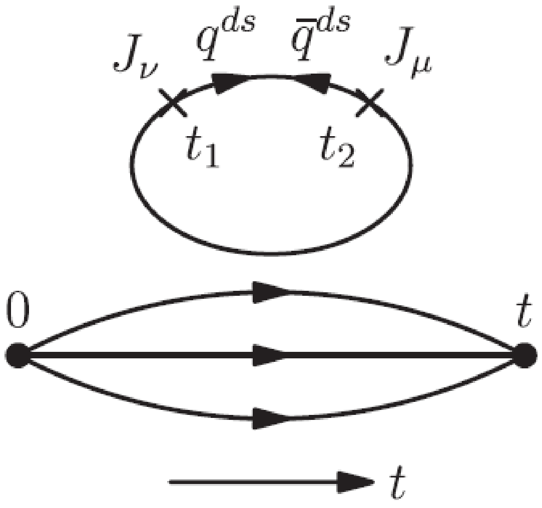
# What mechanism could lead to $\bar{u} > \bar{d}$ at $x > 0.25$?

Connected sea



(valence-like)

Disconnected sea



(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)

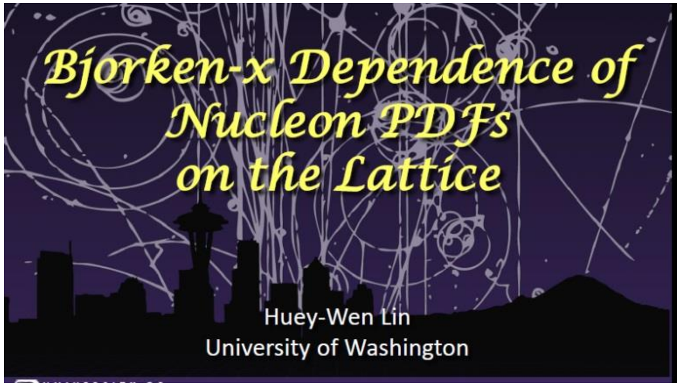
# Recent progress in LQCD suggests the possibility to calculate the *x*-dependence of parton distributions

PRL **110,** 262002 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

**Parton Physics on a Euclidean Lattice**

Xiangdong Ji[1,2]

The *x*-dependence of the quark and antiquark distributions can be calculated (not just their moments)



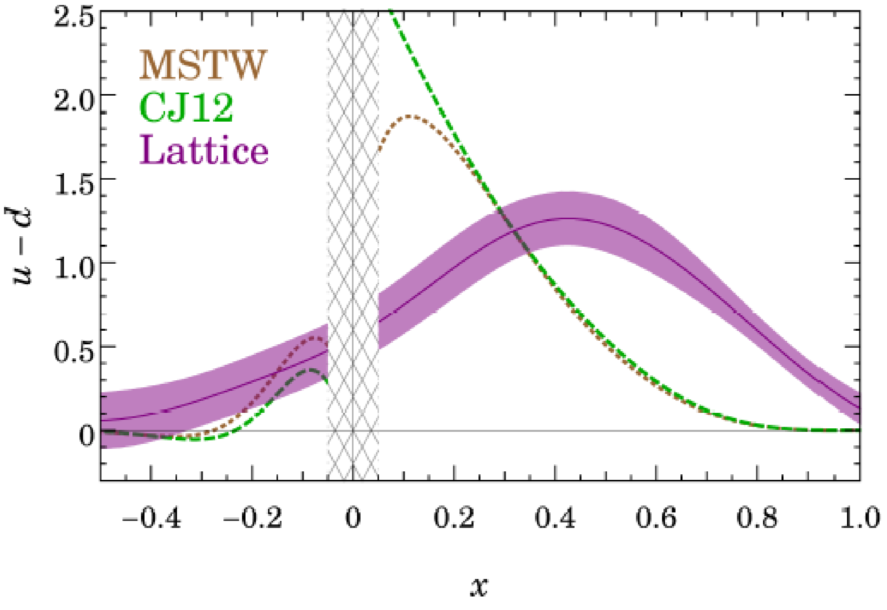
*Bjorken-x Dependence of Nucleon PDFs on the Lattice*

Huey-Wen Lin
University of Washington

Flavor Structure of the Nucleon Sea from Lattice QCD

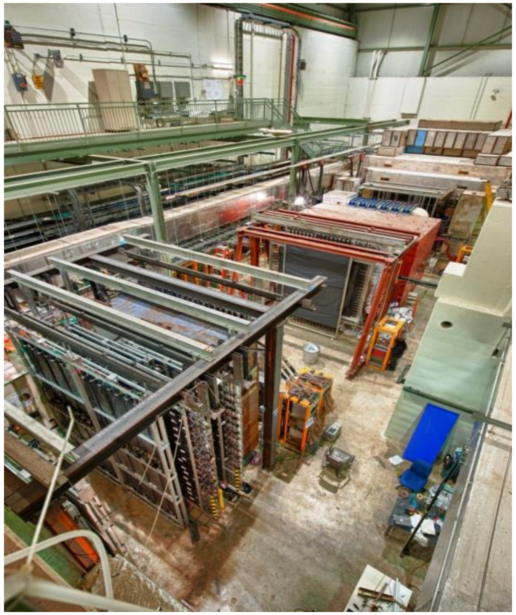
Huey-Wen Lin,[1,*] Jiunn-Wei Chen,[2,†] Saul D. Cohen,[3,1,‡] and Xiangdong Ji[4,5,]

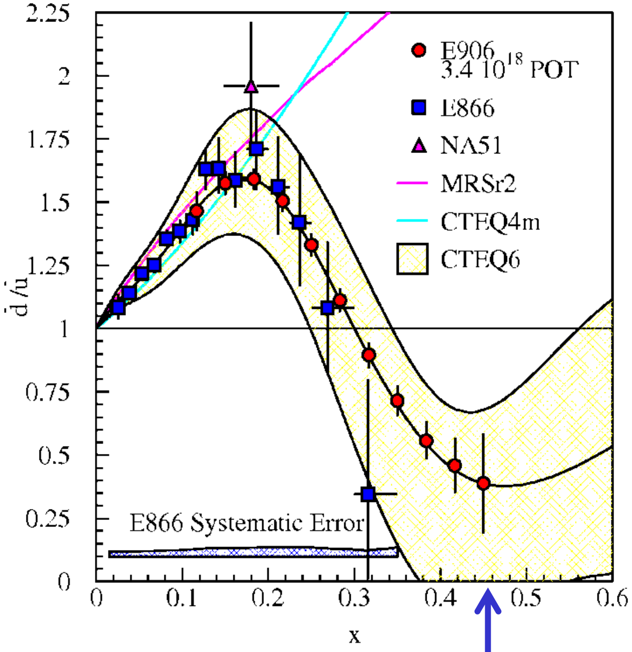
(arXiv: 1402.1462)

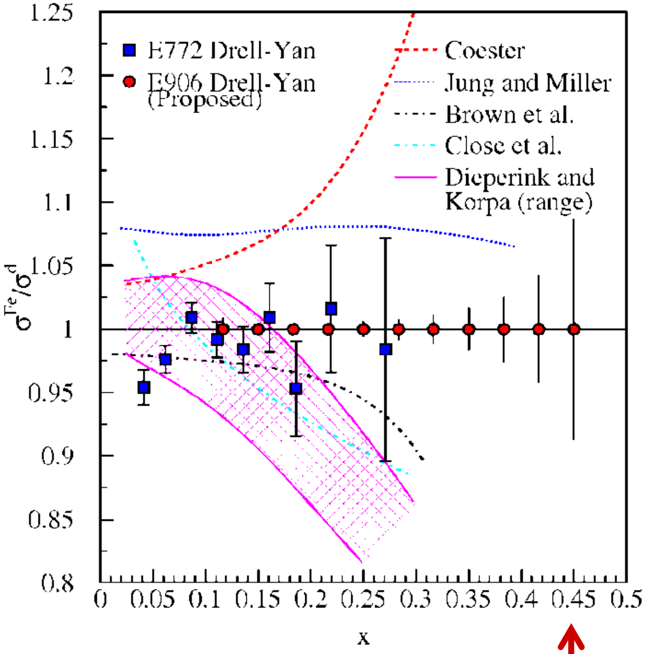


# Drell-Yan Experiment at Fermilab

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







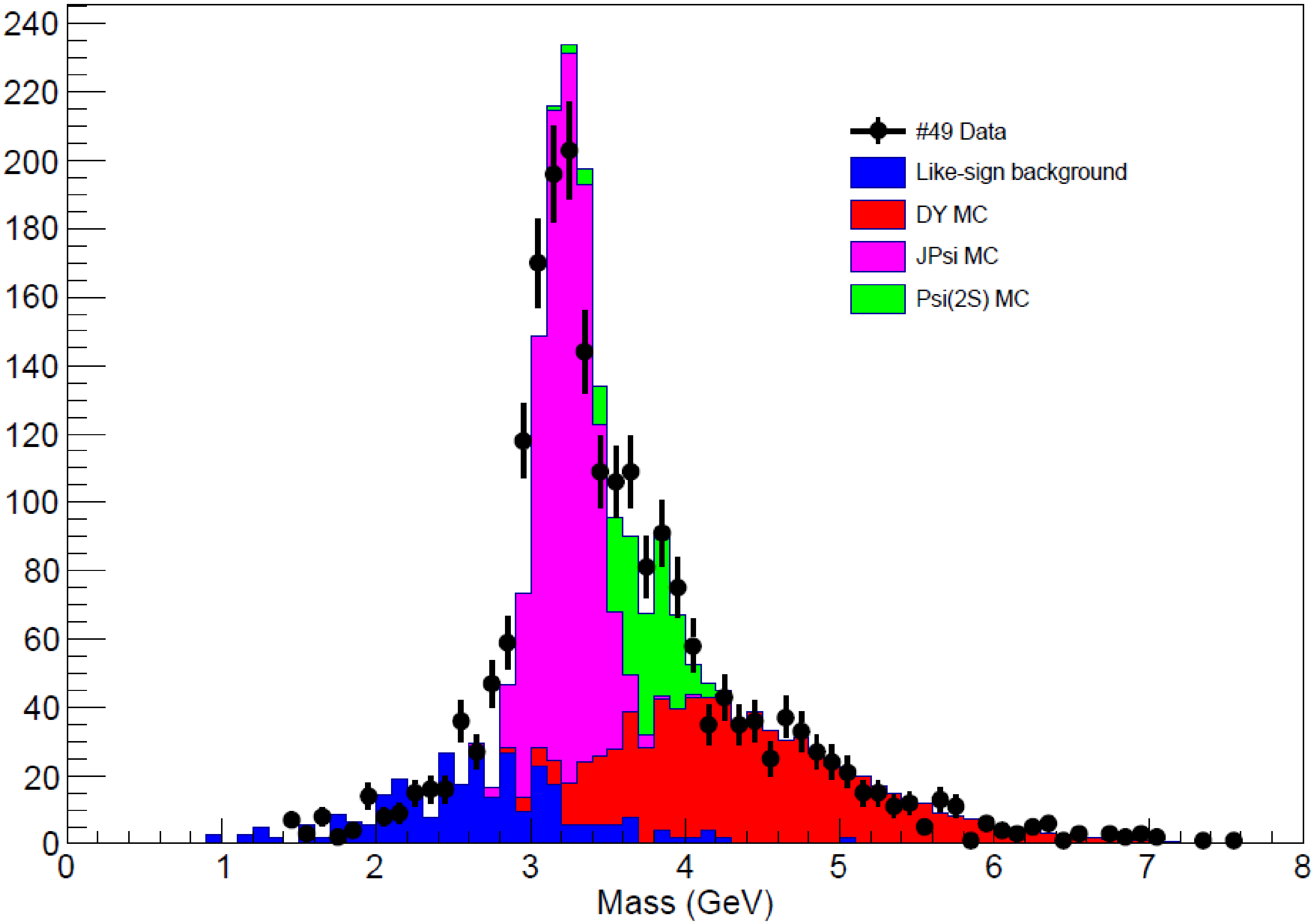
Main goals: 1) Measure $\bar{d}\,/\,\bar{u}$ flavor asymmetry up to $x$ ~ 0.45

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

- Commission run took place in February – April 2012
- 2-year production run expected in 2014-2015

# Dimuon mass spectra from SeaQuest/E906

(Preliminary analysis of a small fraction of data)



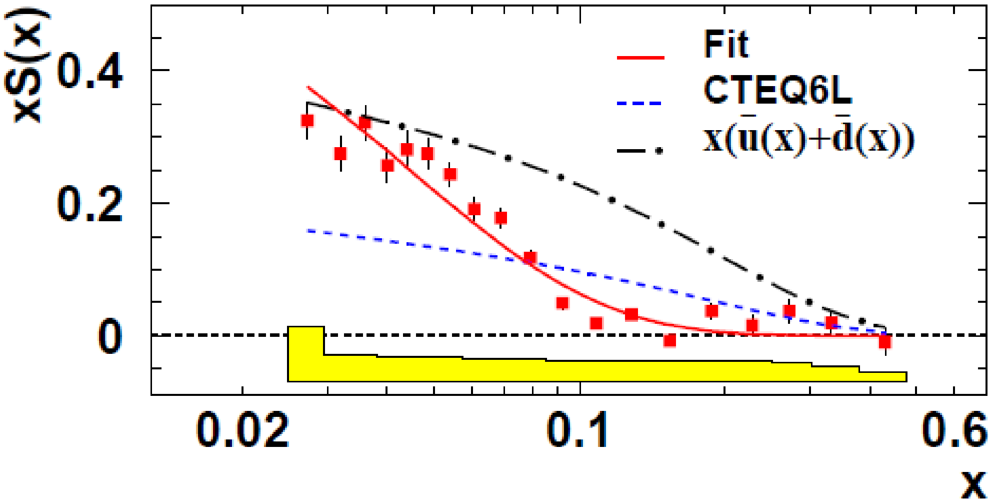
Physics run started Feb. 2014

# Conclusions

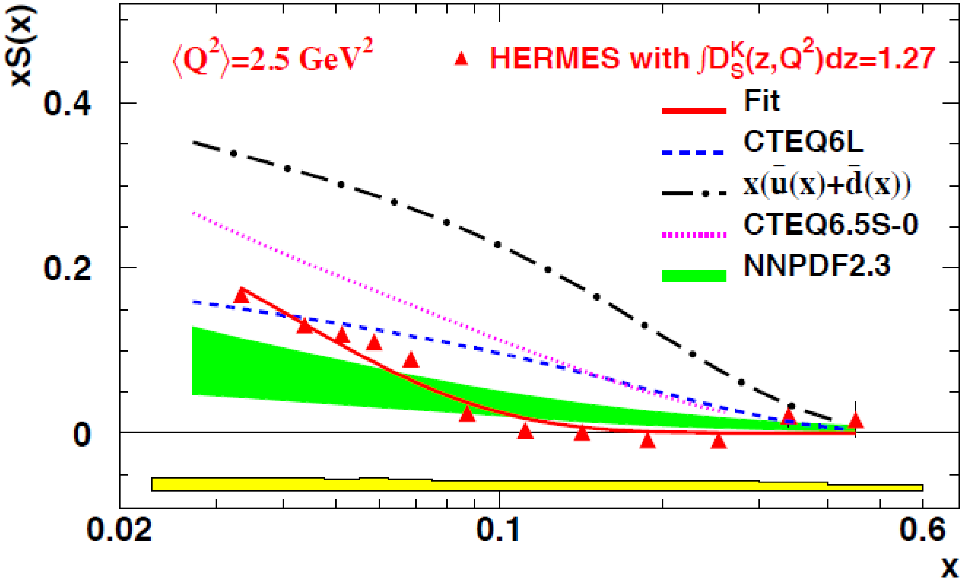
- Evidences for the existence of "intrinsic" light-quark seas $(\bar{u}, \bar{d}, \bar{s})$ in the nucleons.
- Clear evidence for intrinsic charm remains to be found.
- The flavor structures of the nucleon sea and their Bjorken-$x$ dependence provide strong constraints on theoretical models.
- The concept of connected and disconnected seas in Lattice QCD offers useful insights on the flavor- and $x$-dependences of the sea.
- Ongoing and future Drell-Yan and SIDIS experiments will provide crucial new information.

# Backup Slides

# Latest HERMES result on *S(x)*

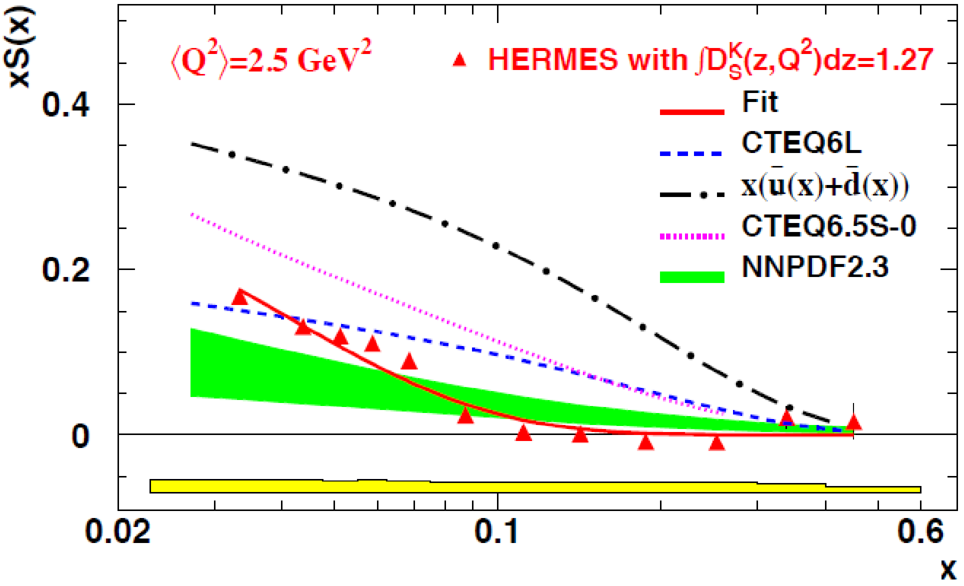


Old result



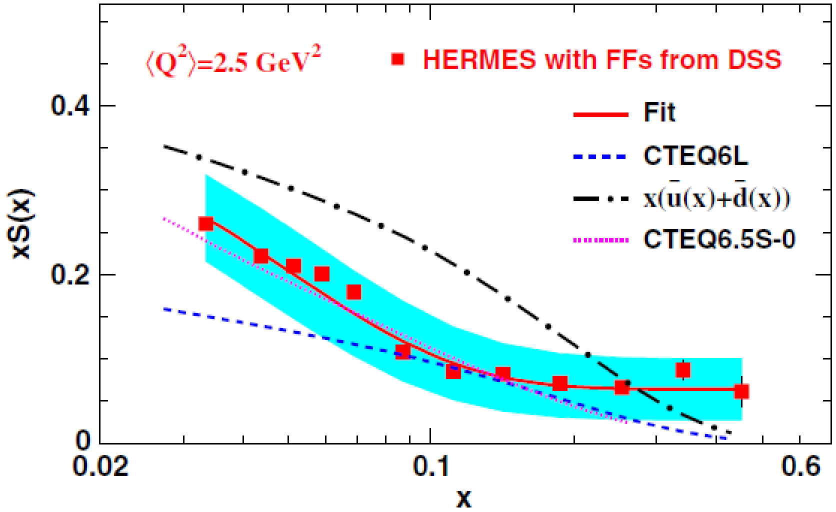
New result

# Latest HERMES result on *S(x)*



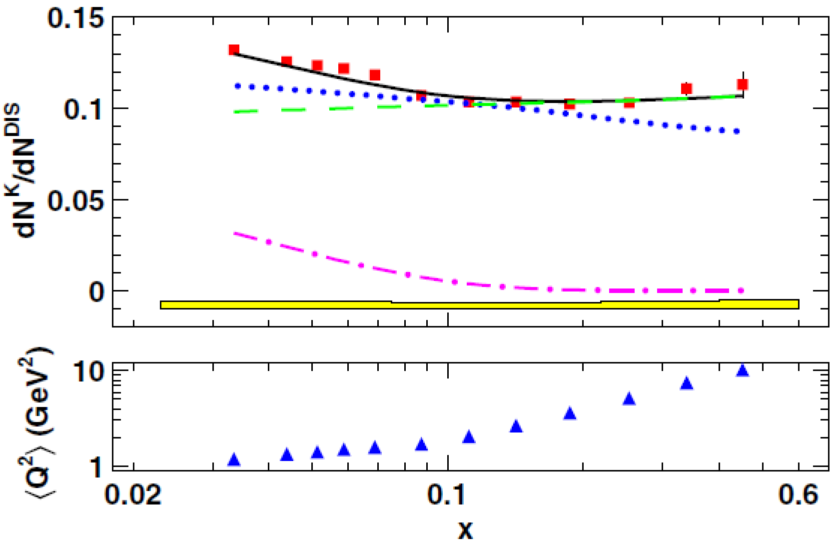
New result

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

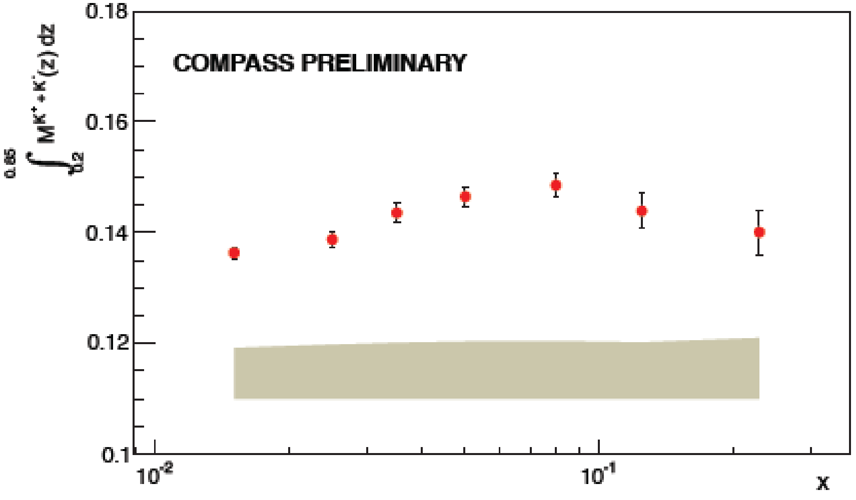


New result obtained with a different kaon fragmentation function

# HERMES versus COMPASS kaon SIDIS data



New HERMES result

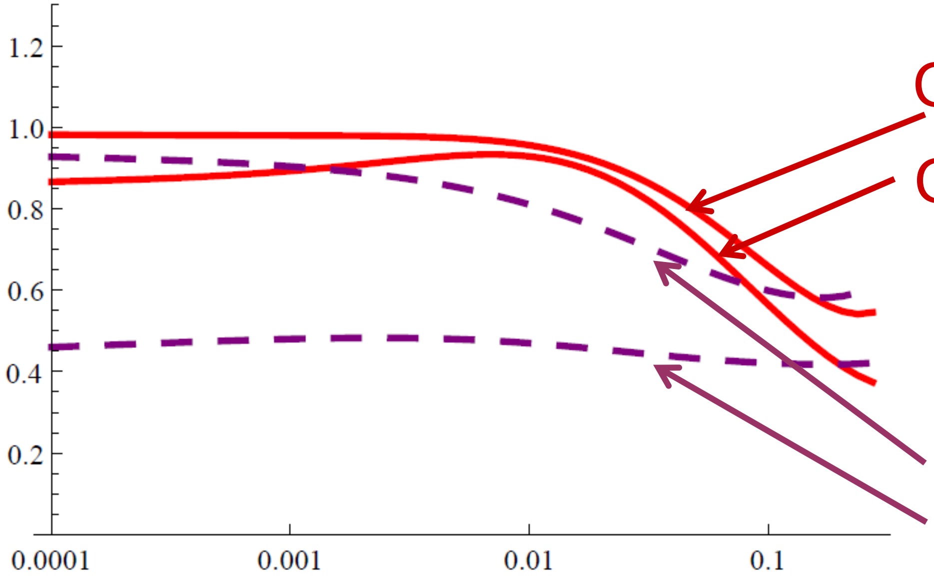


Preliminary COMPASS result looks different !

# Strange sea content is strongly $Q^2$ dependent

$$\kappa(x,Q) = \frac{2s(x,Q)}{\bar{u}(x,Q)+\bar{d}(x,Q)}$$

Kusina et al., PRD 85 (2012) 094028



CTEQ 6.6

Q=80 GeV

Q=1.5 GeV

CTEQ 6.1

Q=80 GeV

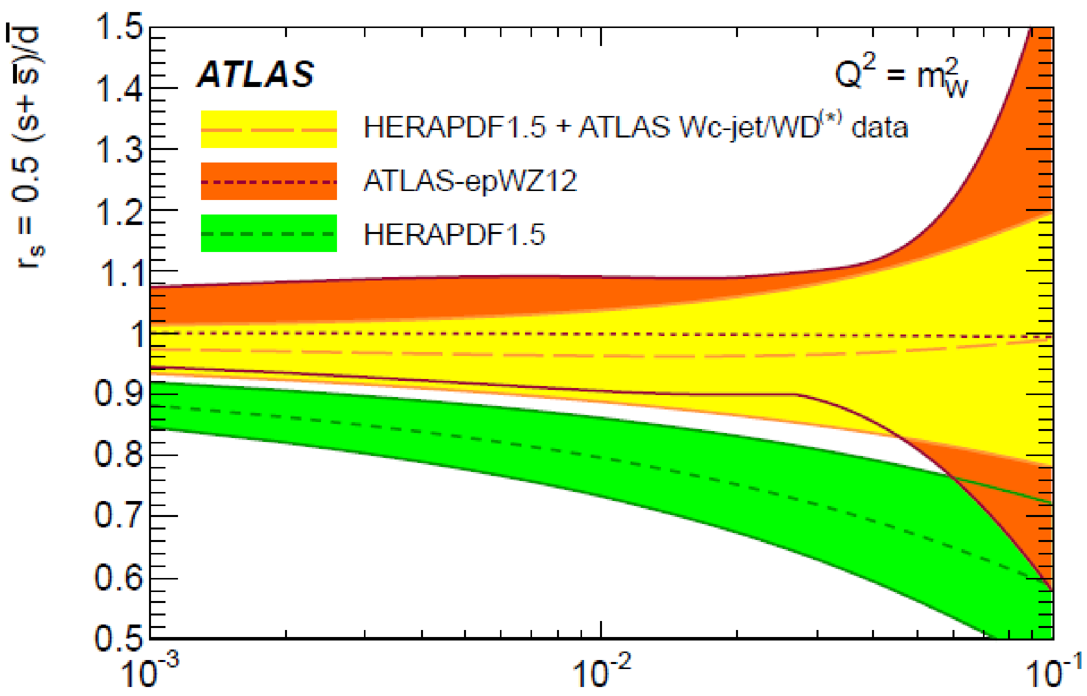
Q=1.5 GeV

Figure 5: $\kappa(x, Q)$ vs. $x$ showing the evolution from low to high scales. The solid (red) lines are for CTEQ6.6, and the dashed (purple) lines are for CTEQ6.1. The lower

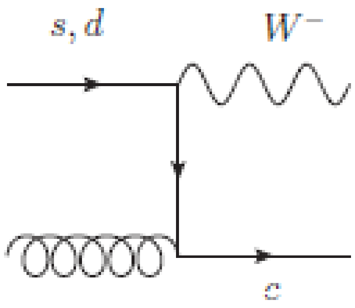
W/Z productions are sensitive to $s(x), \bar{s}(x)$ at very large $Q^2$ scale ($Q^2 = M_{W/Z}^2$), dominated by perturbative roughly SU(3) symmetric sea!

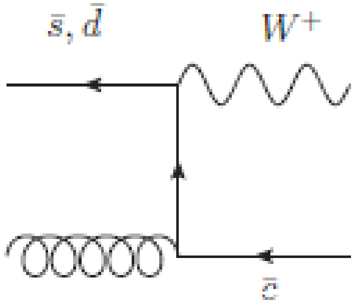
## Measurements at low $Q^2$ are very important

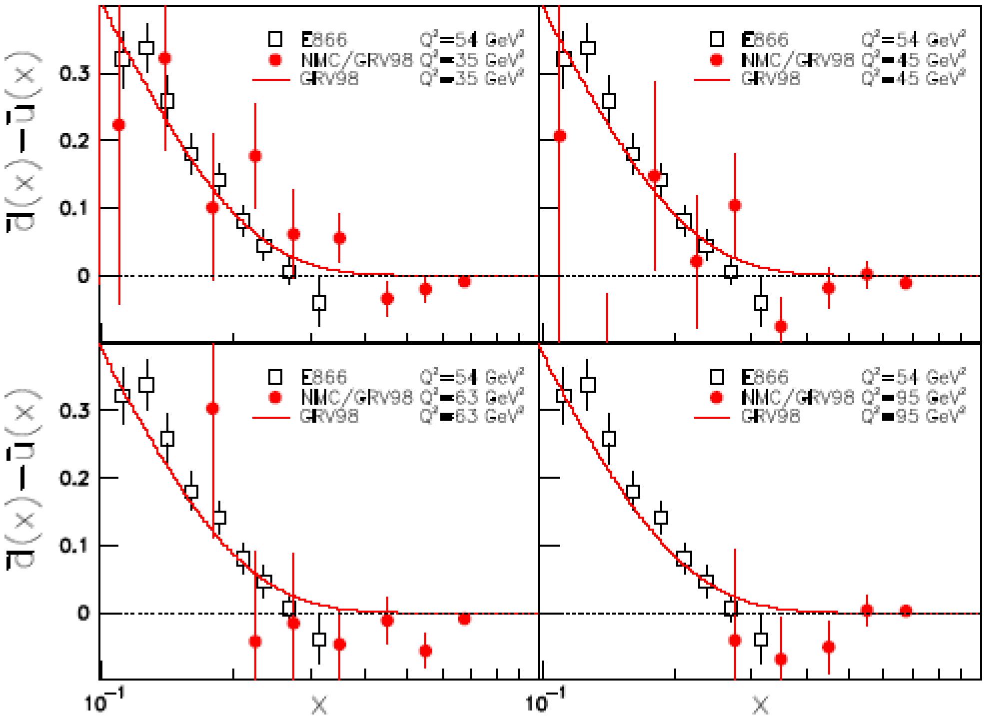
# W plus c-jet production at LHC



arXiv:1402.6263






$\bar{d}(x)-\bar{u}(x)$
0.3
0.2
0.1
0
E866 $Q^2$=54 GeV$^2$
NMC/GRV98 $Q^2$=35 GeV$^2$
GRV98 $Q^2$=35 GeV$^2$
E866 $Q^2$=54 GeV$^2$
NMC/GRV98 $Q^2$=45 GeV$^2$
GRV98 $Q^2$=45 GeV$^2$
E866 $Q^2$=54 GeV$^2$
NMC/GRV98 $Q^2$=63 GeV$^2$
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E866 $Q^2$=54 GeV$^2$
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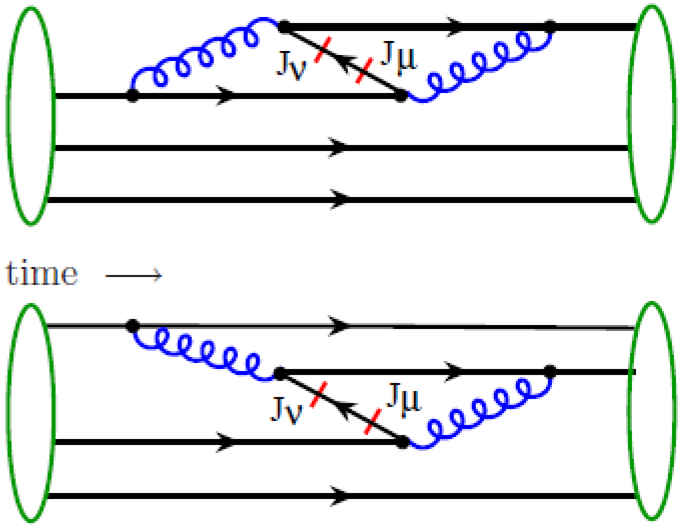
GRV98 $Q^2$=95 GeV$^2$
$10^{-1}$
x
$10^{-1}$
x


Jν
Jμ
time ⟶
Jν
Jμ

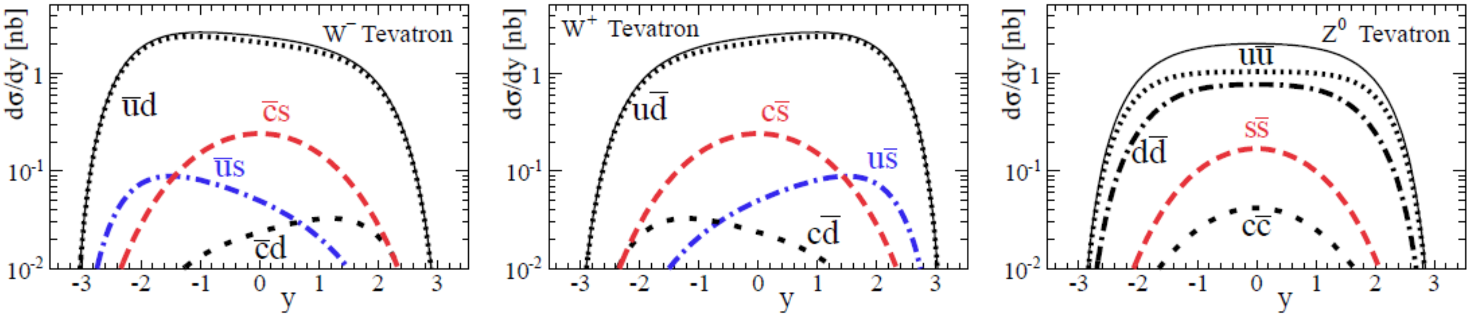
# Strange sea from inclusive W/Z production

Inclusive $W\,/\,Z$ production at Tevatron/LHC

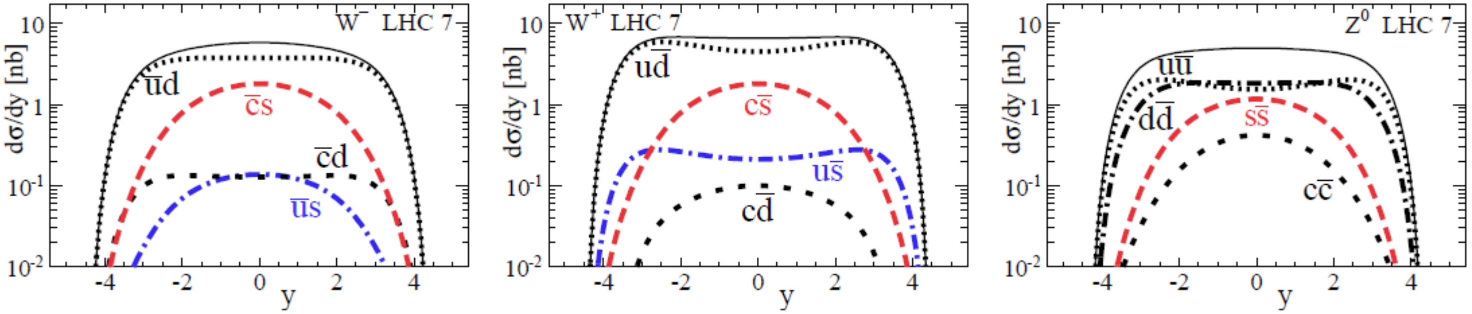
$$W^+:\ (u \text{ or } c) + (\bar{d} \text{ or } \bar{s}) \rightarrow W^+$$

$$W^-:\ (\bar{u} \text{ or } \bar{c}) + (d \text{ or } s) \rightarrow W^-$$

$$Z^0:\ s + \bar{s} \rightarrow Z^0$$



(a) $d\sigma/dy$ for $W^-$ (left), $W^+$ (middle), $Z^0$ (right) boson production at the Tevatron.



(b) $d\sigma/dy$ for $W^-$ (left), $W^+$ (middle), $Z^0$ (right) boson production at the LHC with $\sqrt{S} = 7$ TeV.

Kusina et al., PRD 85 (2012) 094028