Bjorken-*x* dependences of light-quark sea

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

2nd Workshop on "Probing Strangeness in Hard Processes"

LNF, Frascati, November 11-13, 2013

Outline

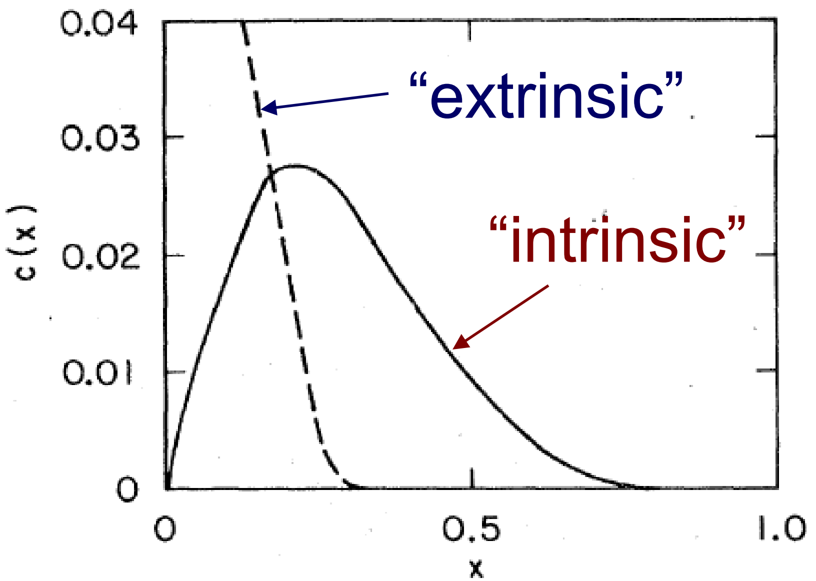
- Extraction of "intrinsic" $\bar{u}$, $\bar{d}$, and $\bar{s}$ sea in the nucleons from Drell-Yan and semi-inclusive DIS experiments
- Separation of "connected sea" from "disconnected sea" for $\bar{u}(x) + \bar{d}\,(x)$
- Bjorken-x and Q^2 - dependences of strange quark distributions

Search for the "intrinsic" quark sea

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

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

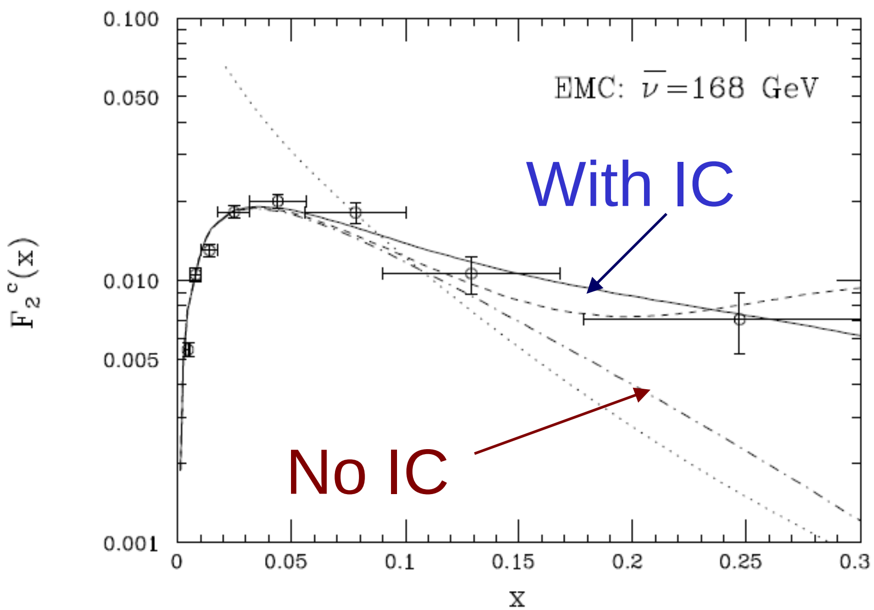
The "intrinsic"-charm from $|uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \rightarrow c\bar{c}$)



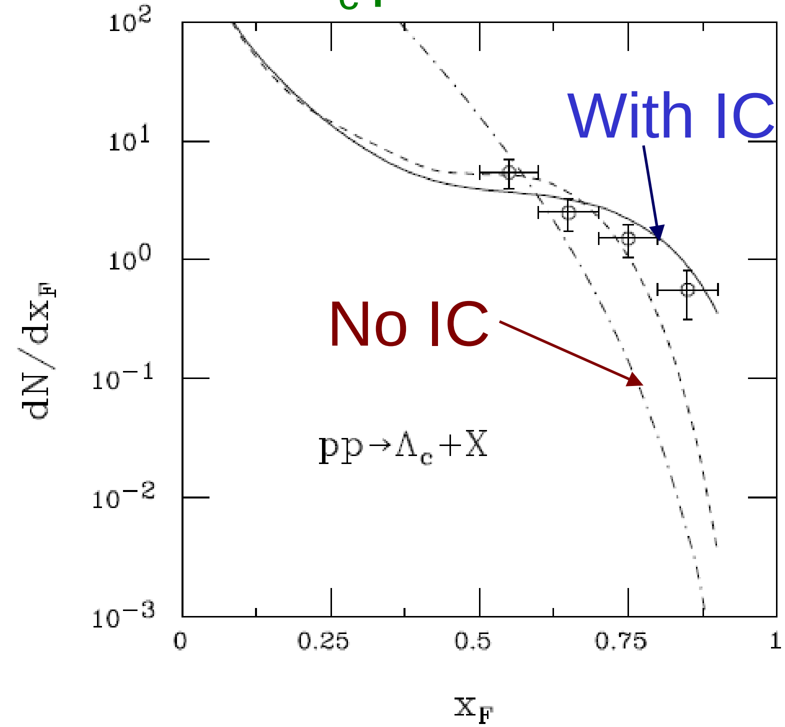
The $|uudc\bar{c}\rangle$ intrinsic-charm can lead to large contribution to charm production at large x

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

DIS data



Λ_c production



Gunion and Vogt (hep-ph/9706252)

“Evidence” appears to be rather weak

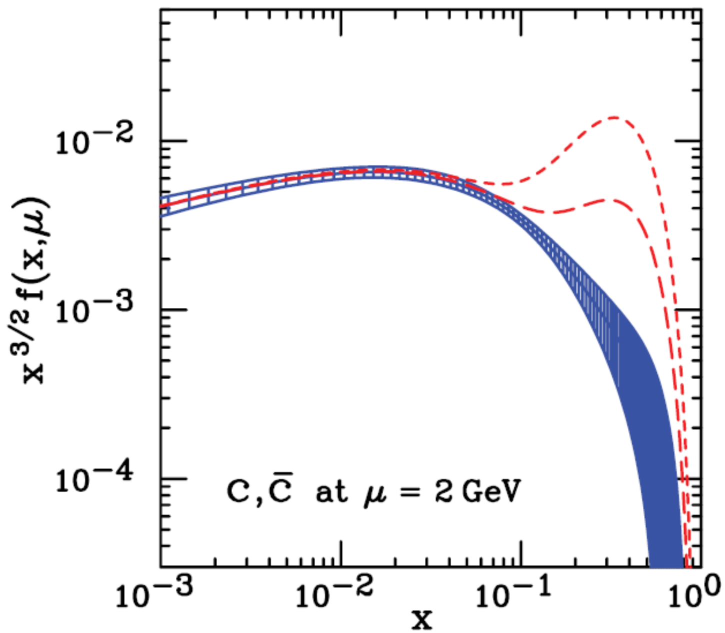
(subject to the uncertainties of charmed-quark parametrization in the PDF)

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 lighter "intrinsic" quark sea

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

No conclusive experimental evidence
for intrinsic-charm so far

Are there experimental evidences for the intrinsic

$|uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uuds\bar{s}\rangle$ 5-quark states ?

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

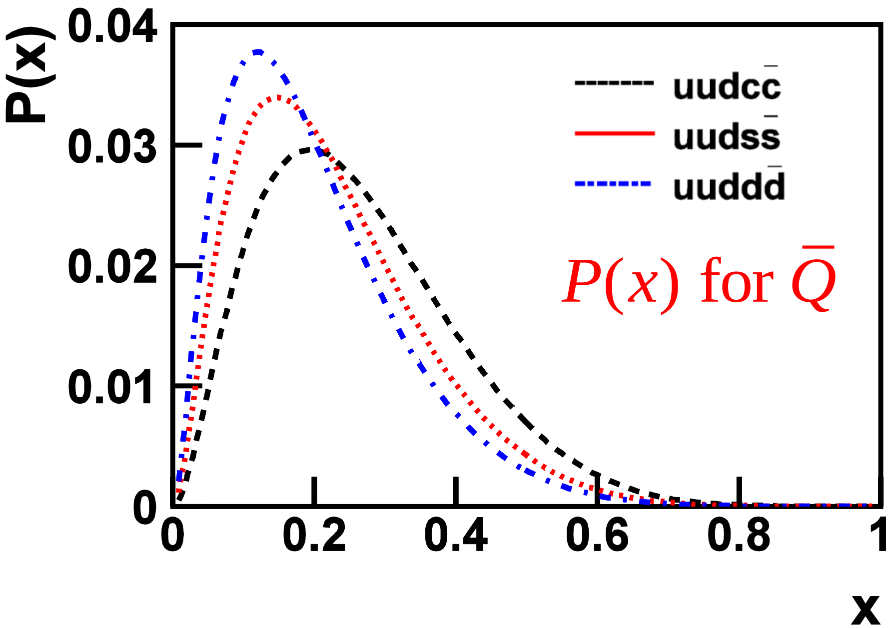
The 5-quark states for lighter
quarks have larger probabilities!

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

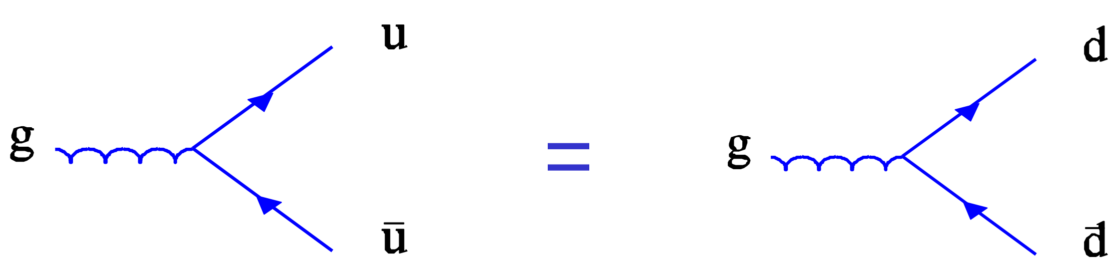
How to separate the "intrinsic sea" from the "extrinsic sea"?

- 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”?

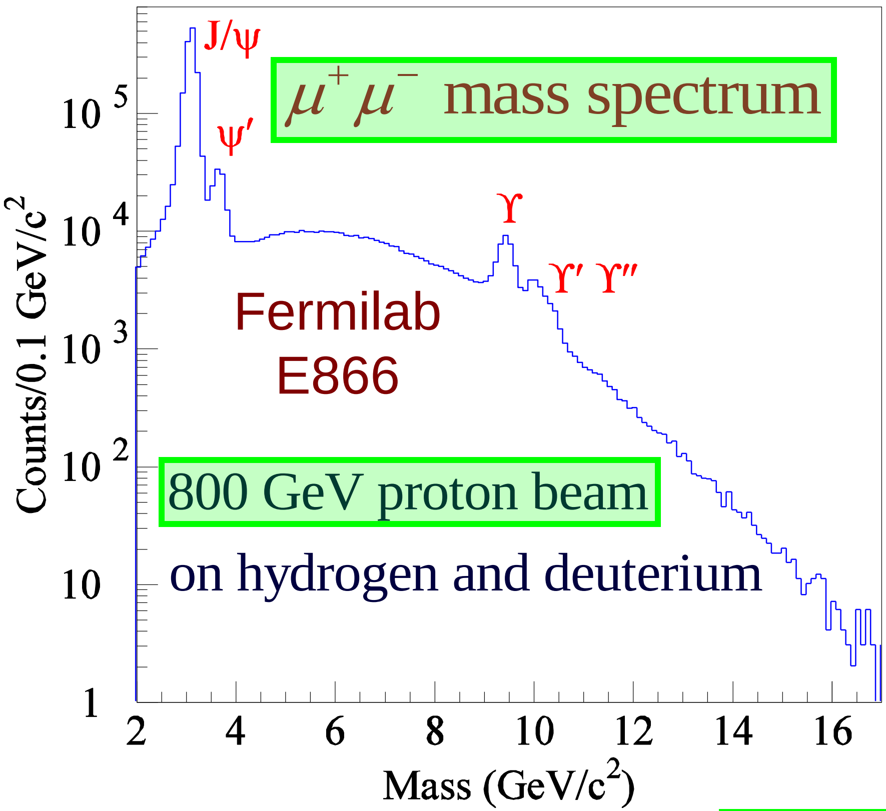
- Select experimental observables which have no contributions from the “extrinsic sea”

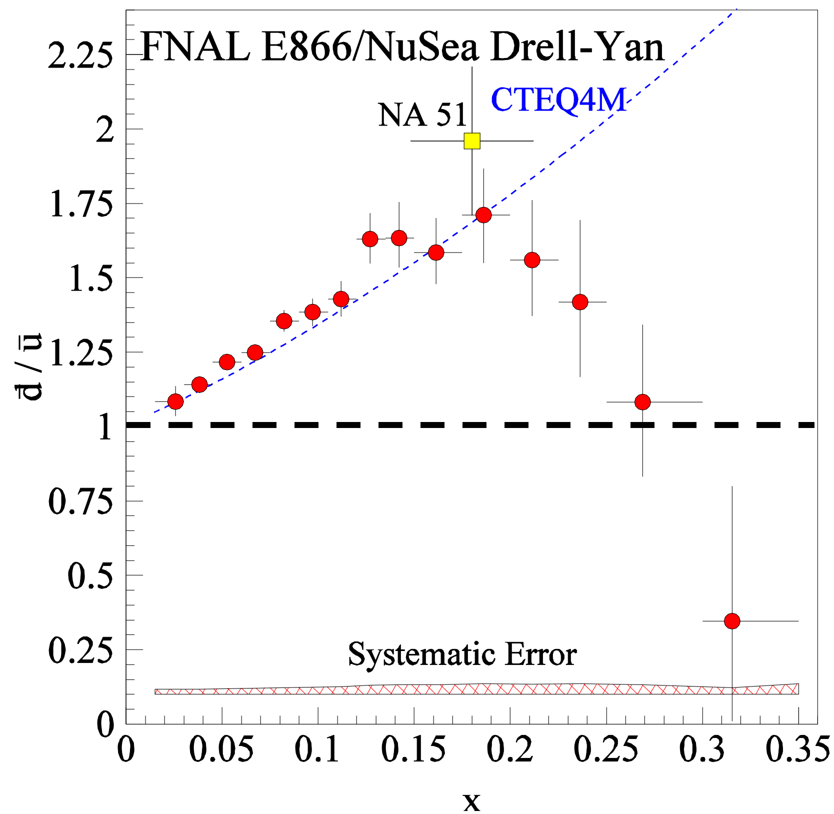
$$\bar{d} - \bar{u} \text{ has no contribution from extrinsic sea } (g \rightarrow \bar{q}q)$$
$$\text{and is sensitive to "intrinsic sea" only}$$



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

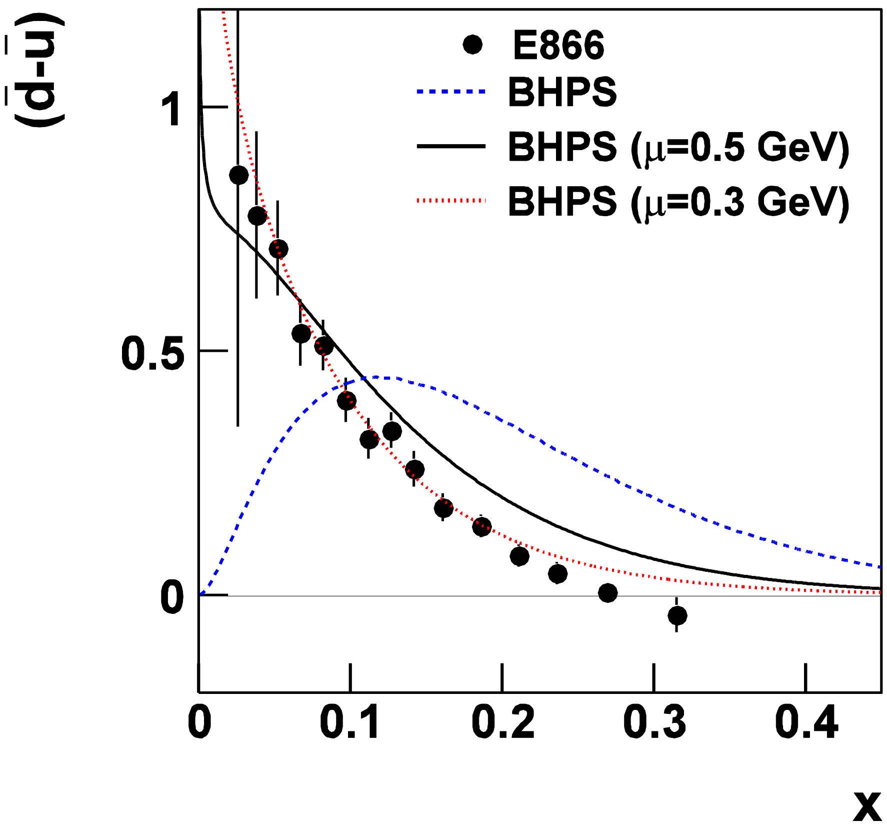
$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$





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

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



The data are in good agreement with the 5-q 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

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

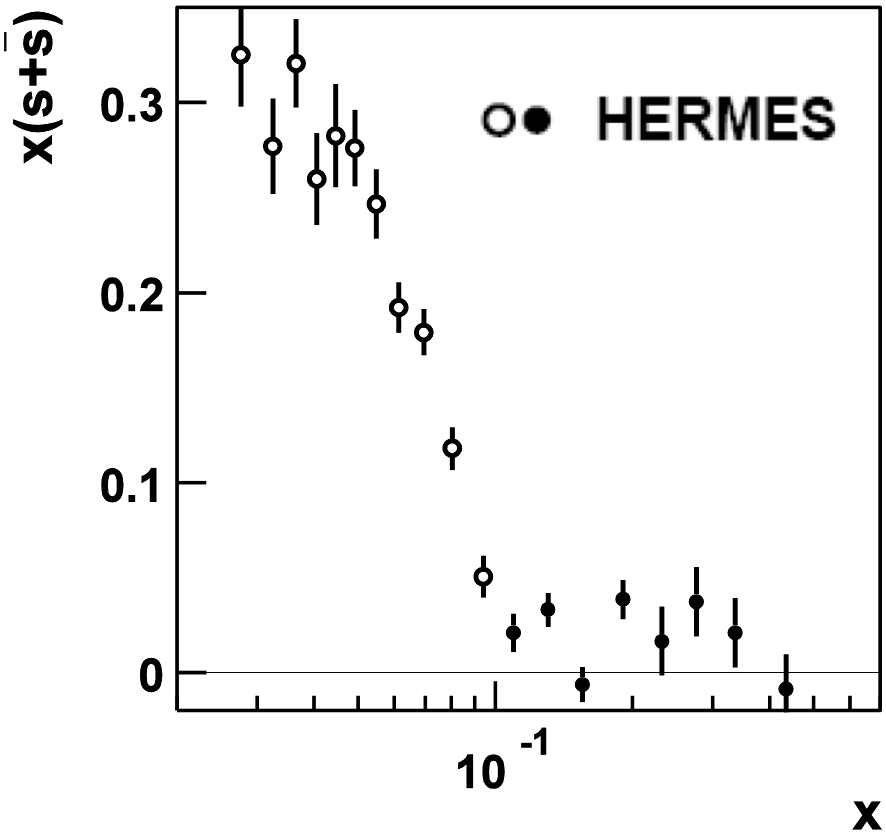
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

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

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

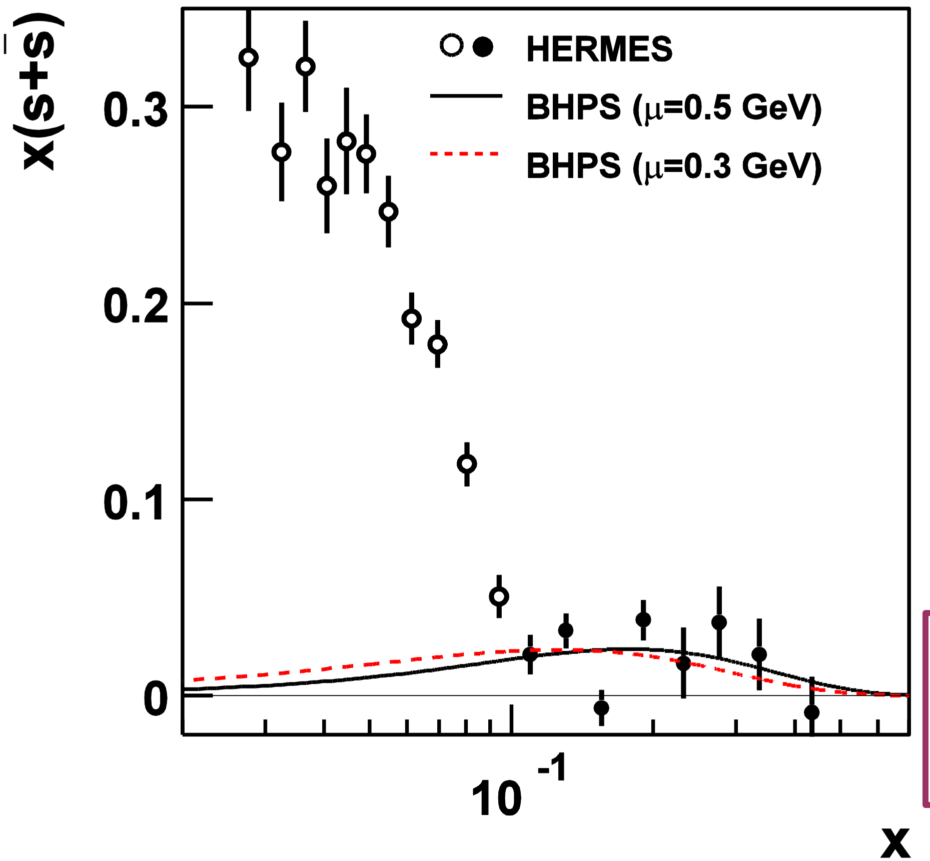


$s(x)+\bar{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2 \rangle = 2.5\ \mathrm{GeV}^2$

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 dominate by intrinsic sea (and $x < 0.1$ are from QCD sea)

This allows the extraction of the intrinsic sea for strange quarks

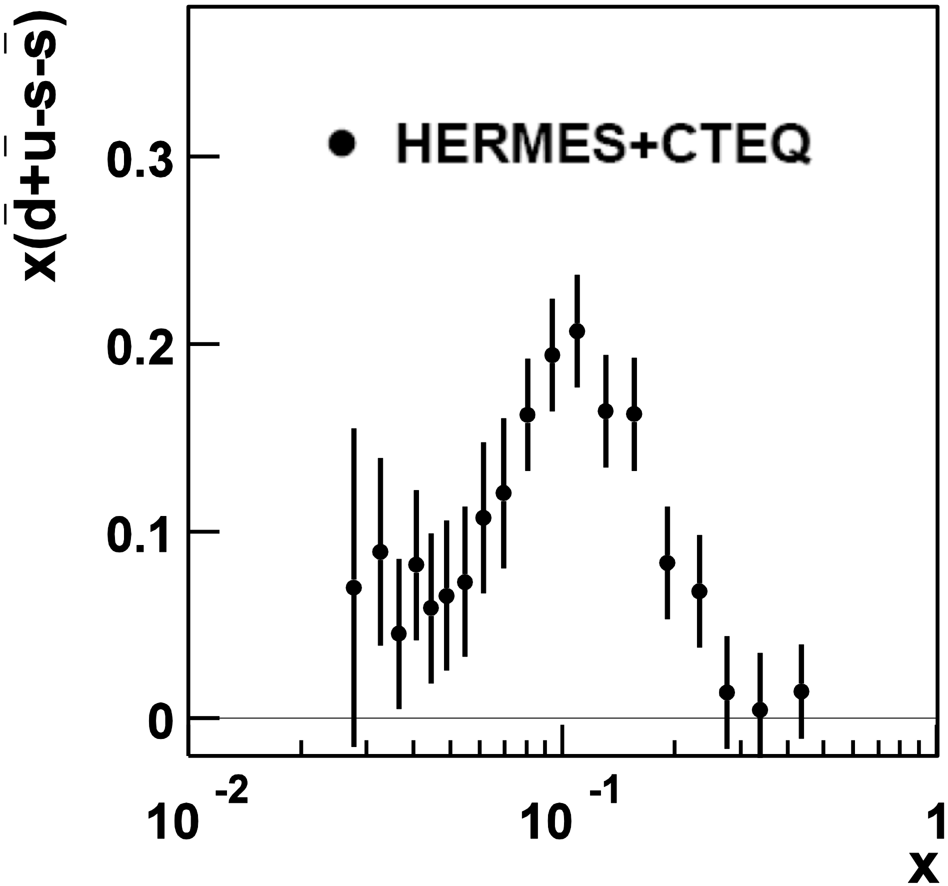
$$P_5^{uud s\bar{s}} = 0.024$$

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



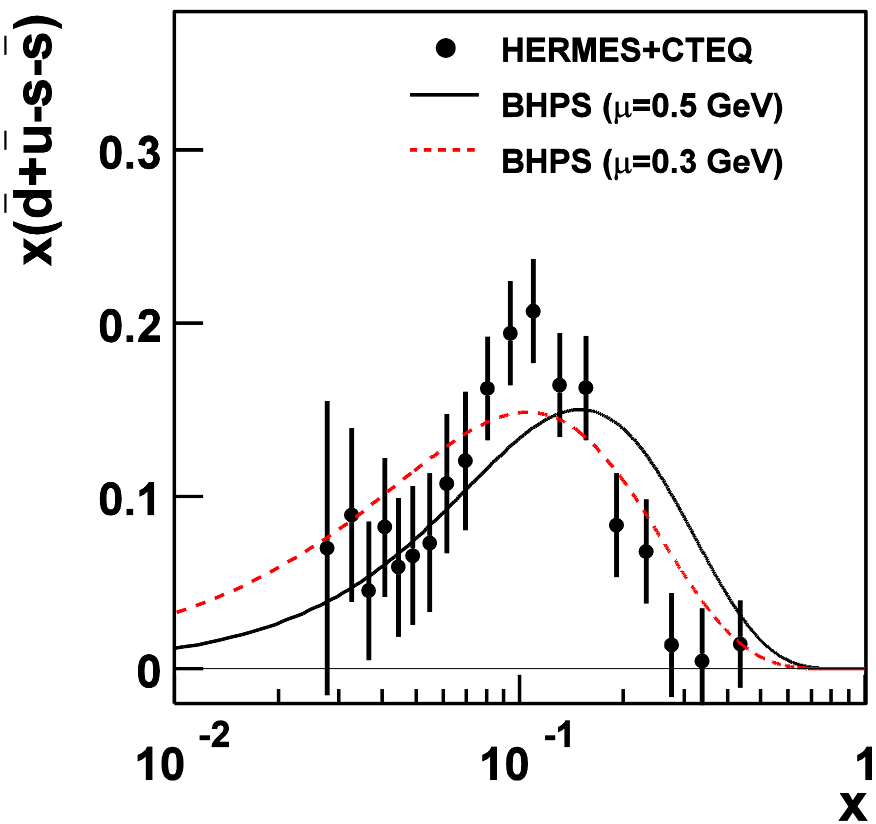
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

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



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

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

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

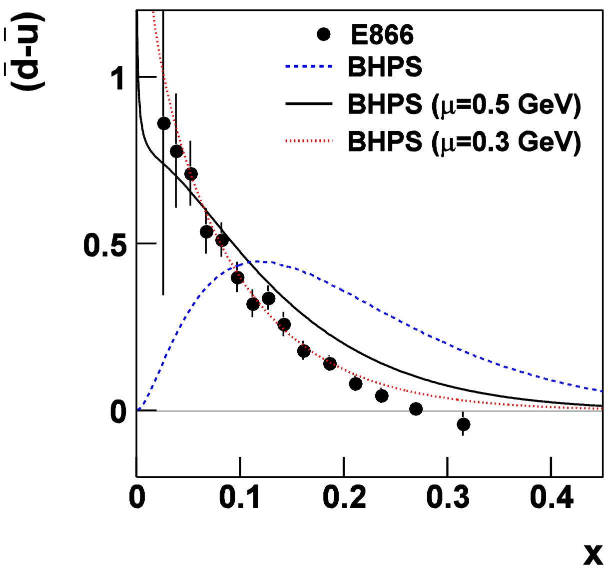
$$\sim P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}}$$

(not sensitive to extrinsic sea)

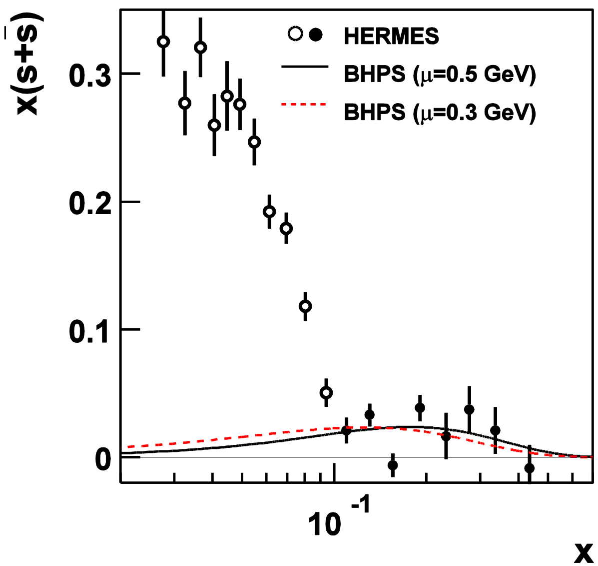
(W. Chang and JCP, PL B704, 197(2011))

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

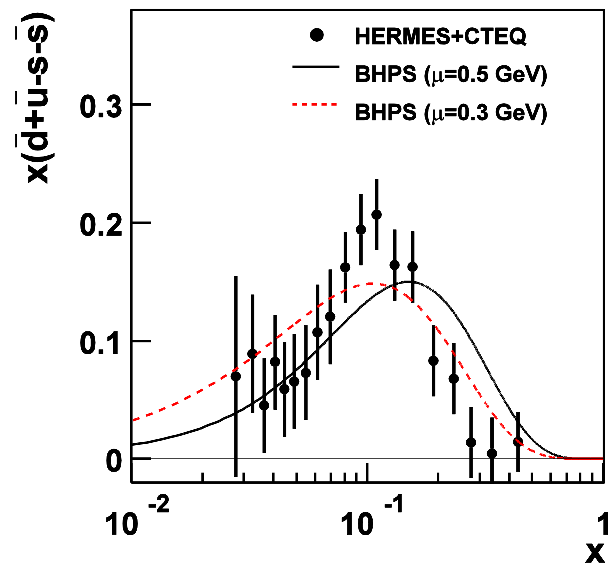
Extraction of the various five-quark components for light quarks



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



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



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

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

Future Possibilities

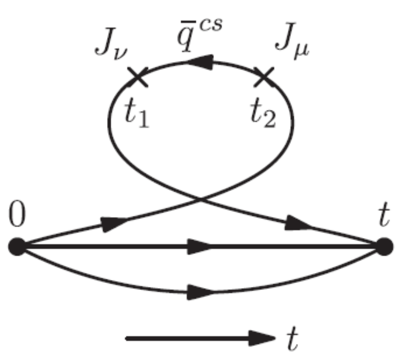
- Search for intrinsic charm and beauty at RHIC and LHC.
- Intrinsic gluons in the nucleons (Hoyer and Roy)?
- Spin-dependent observables of intrinsic sea?
- Global fits including intrinsic u, d, s sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

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

Connected-Sea Partons

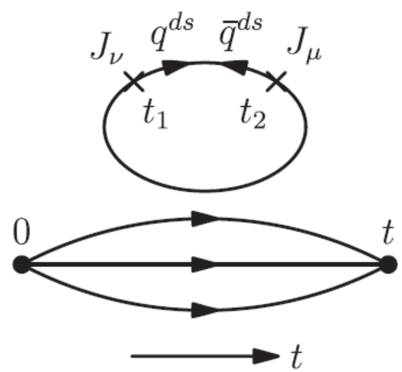
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea



(valence-like)

Disconnected sea



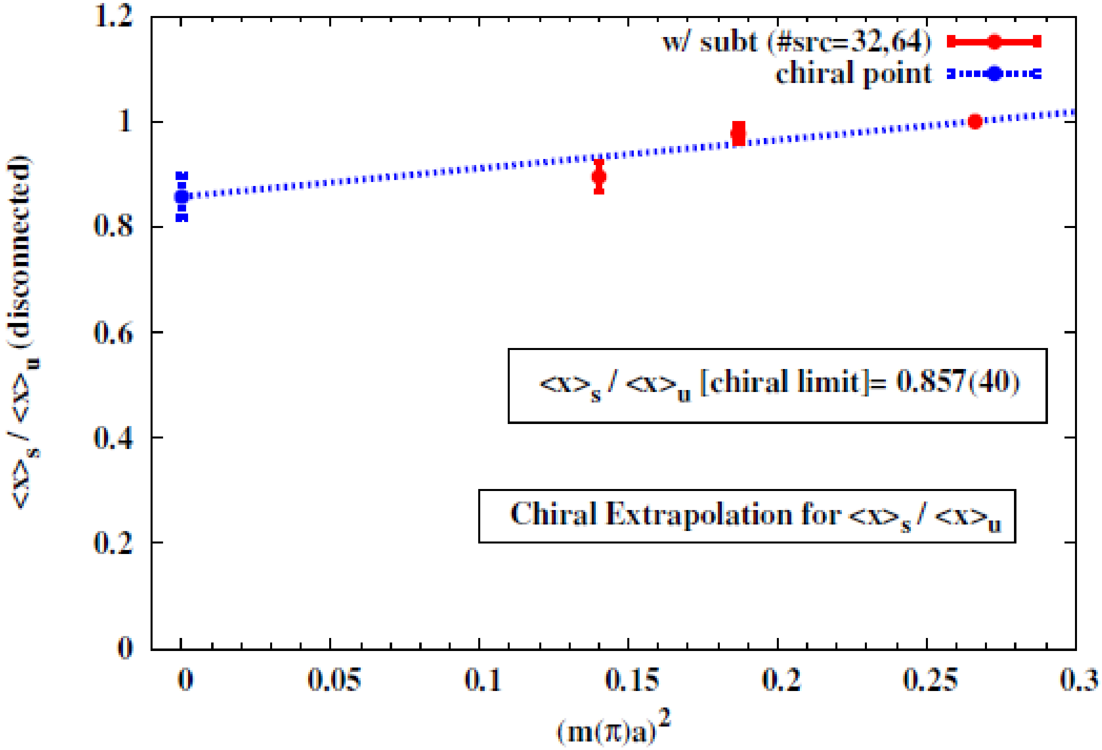
(sea-like)

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

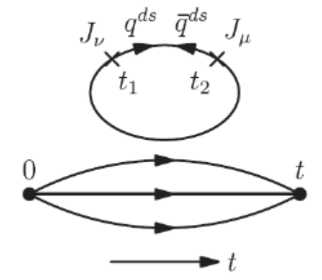
CS and DS have
different Bjorken-x and
flavor dependences

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



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) $$[\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}} = \frac{1}{R}[s(x) + \bar{s}(x)]$$

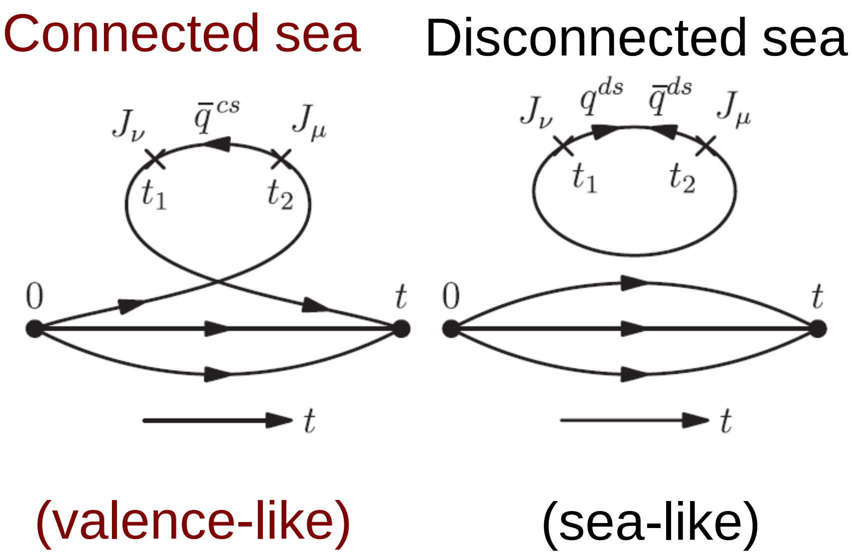
C) $$[\bar{u}(x) + \bar{d}(x)]_{\text{connected sea}} =$$

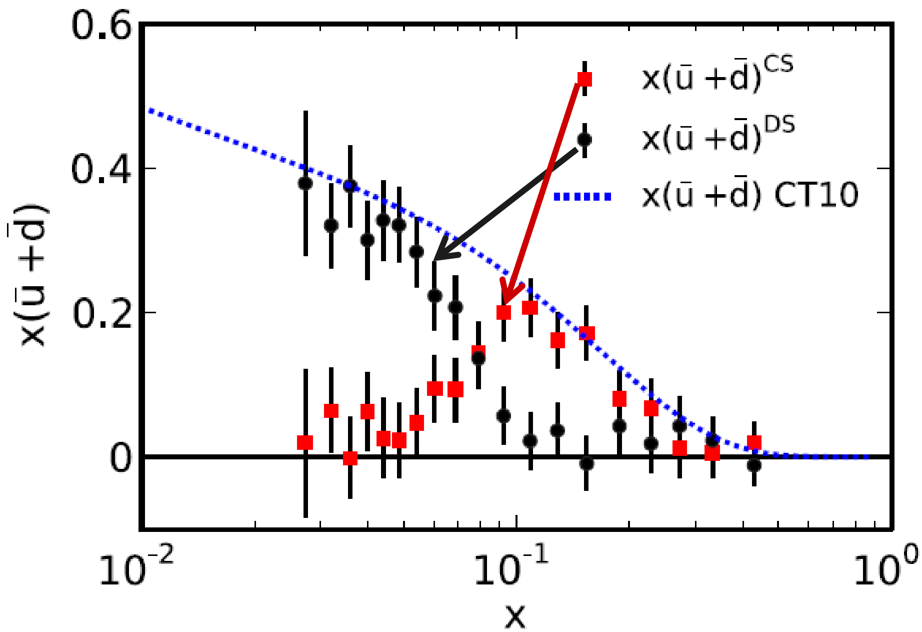
$$[\bar{u}(x) + \bar{d}(x)]_{\text{PDF}} - [\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}}$$

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]



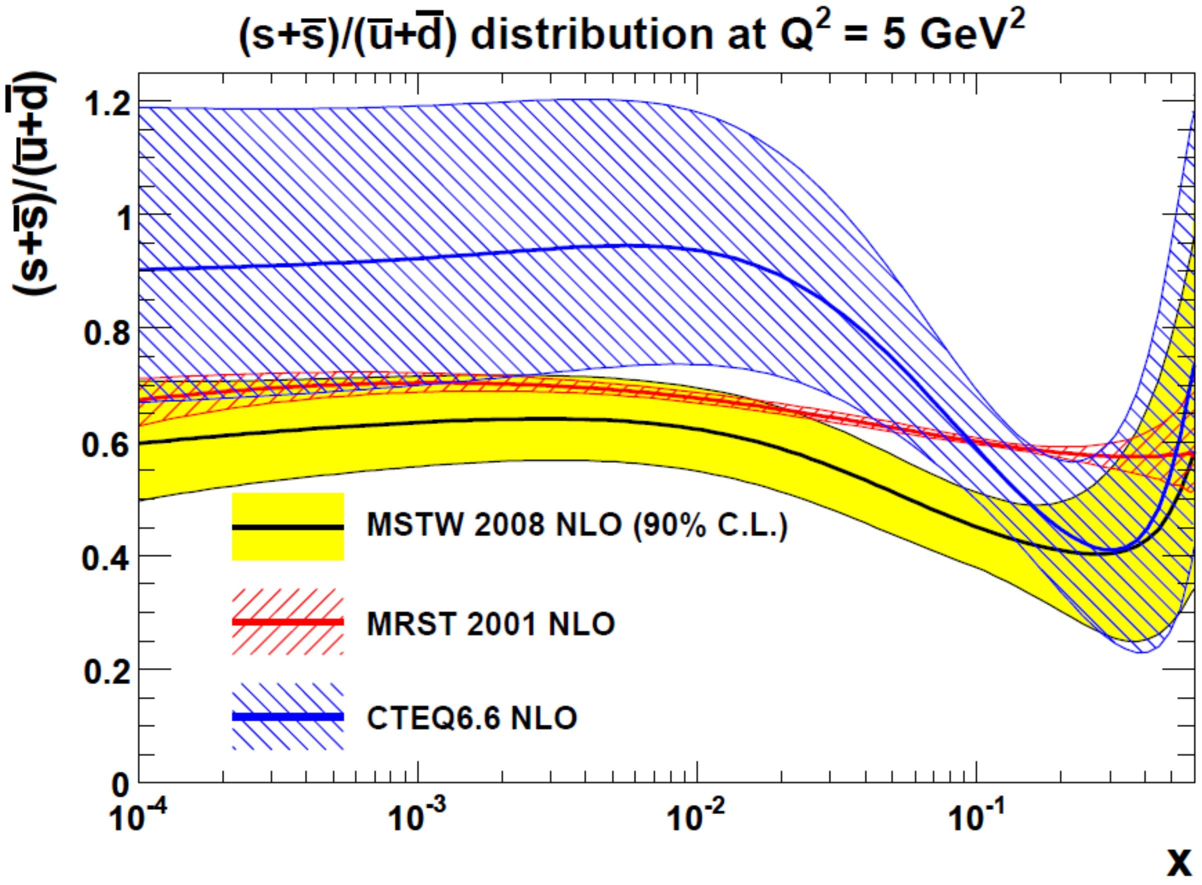


- Using input from lattice QCD, one can separate the connected sea from the disconnected sea for $\bar{u}(x)+\bar{d}(x)$
- For $\bar{u}+\bar{d}$ at Q^2=2.5 GeV^2, momenta carried by CS and DS are roughly equal

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

Expectation:

s and $\bar{s}$ are suppressed relative to $\bar{u}$ and $\bar{d}$ due to larger s-quark mass



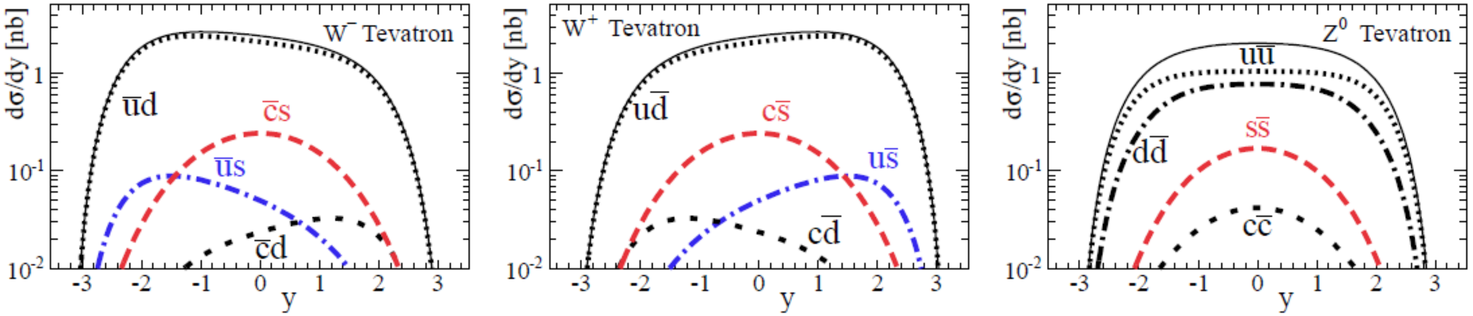
Strange sea from inclusive W/Z production

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

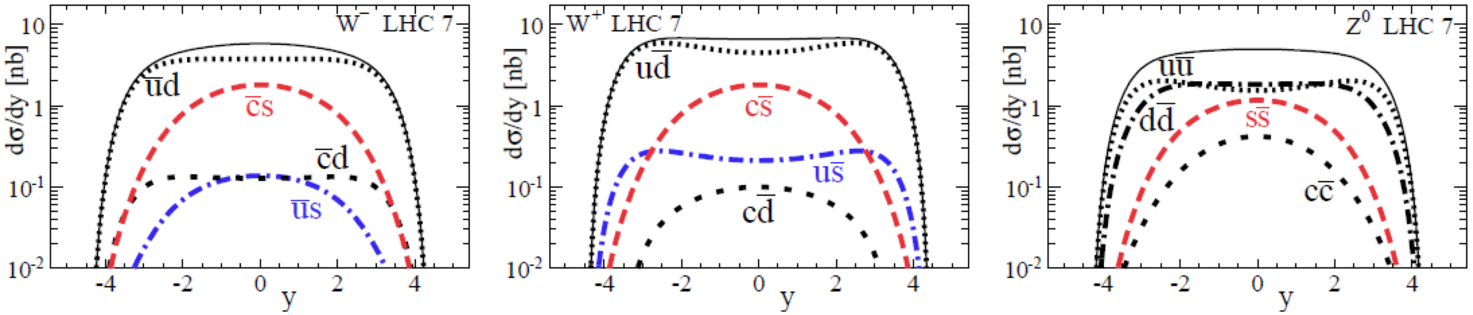
$$W^+:\ \ (u \text{ or } c)+(\bar{d} \text{ or } \bar{s}) \rightarrow W^+$$

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

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



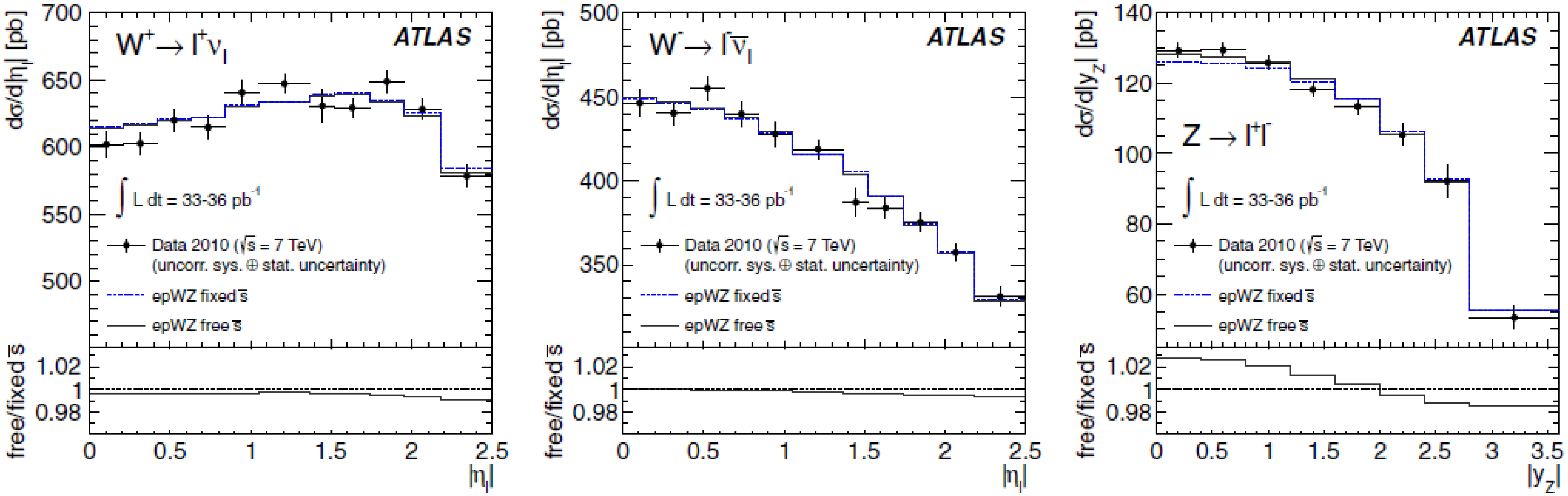
(a) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the Tevatron.

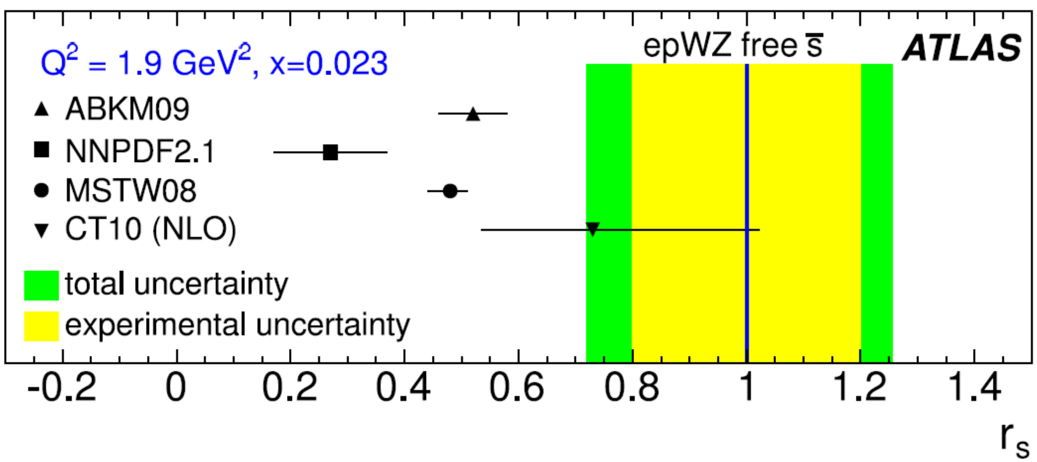


(b) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the LHC with $\sqrt{S}=7$ TeV.

Kusina et al., PRD 85 (2012) 094028

Strange sea from inclusive W/Z production





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

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

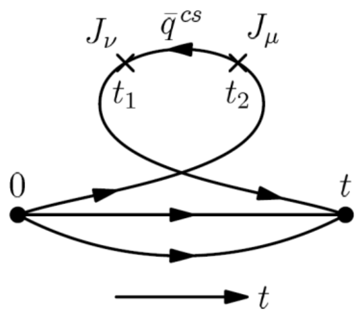
Aad et al., PRL 109 (2012) 012001

Strange sea content is strongly *x* dependent

- Perturbative sea at small *x* is roughly SU(3) symmetric
- Non-perturbative sea at larger *x* is SU(3) asymmetric

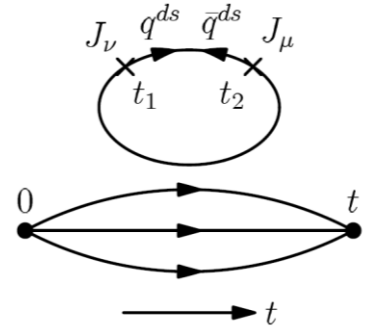
Can be well understood from Lattice QCD
(PRL 109 (2012)252002)

Connected sea



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

Disconnected sea



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

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

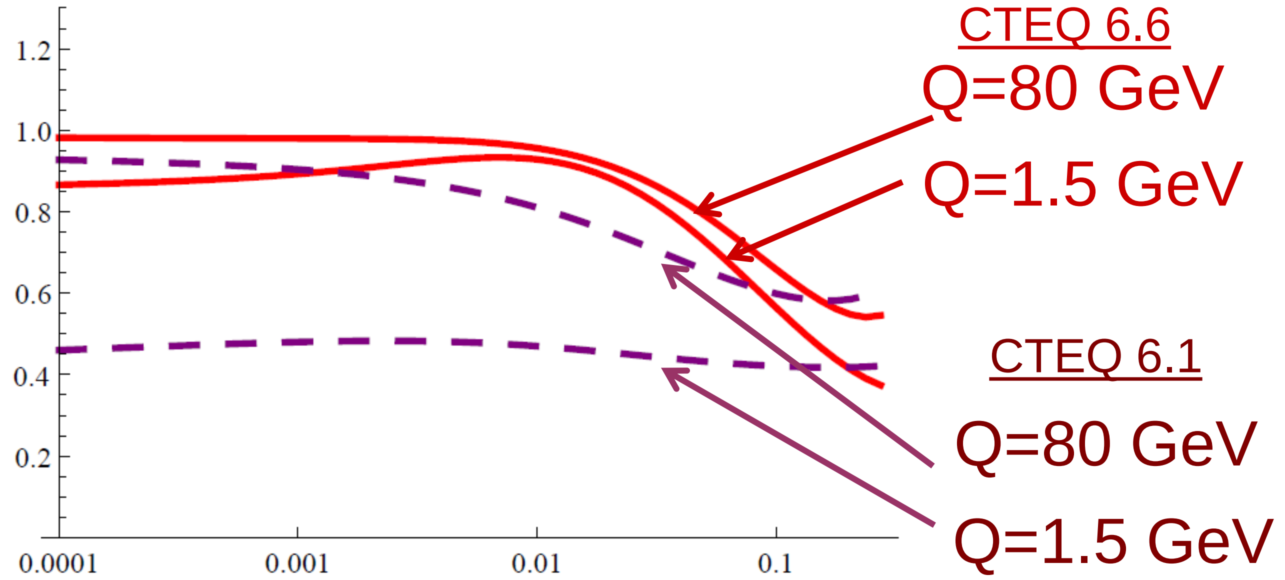


Figure 5: $\kappa(x,Q)$ vs. x showing the evolution from low to high scales. The solid (red) lines are for CTEQ6.6, and the dashed (purple) lines are for CTEQ6.1. The lower

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

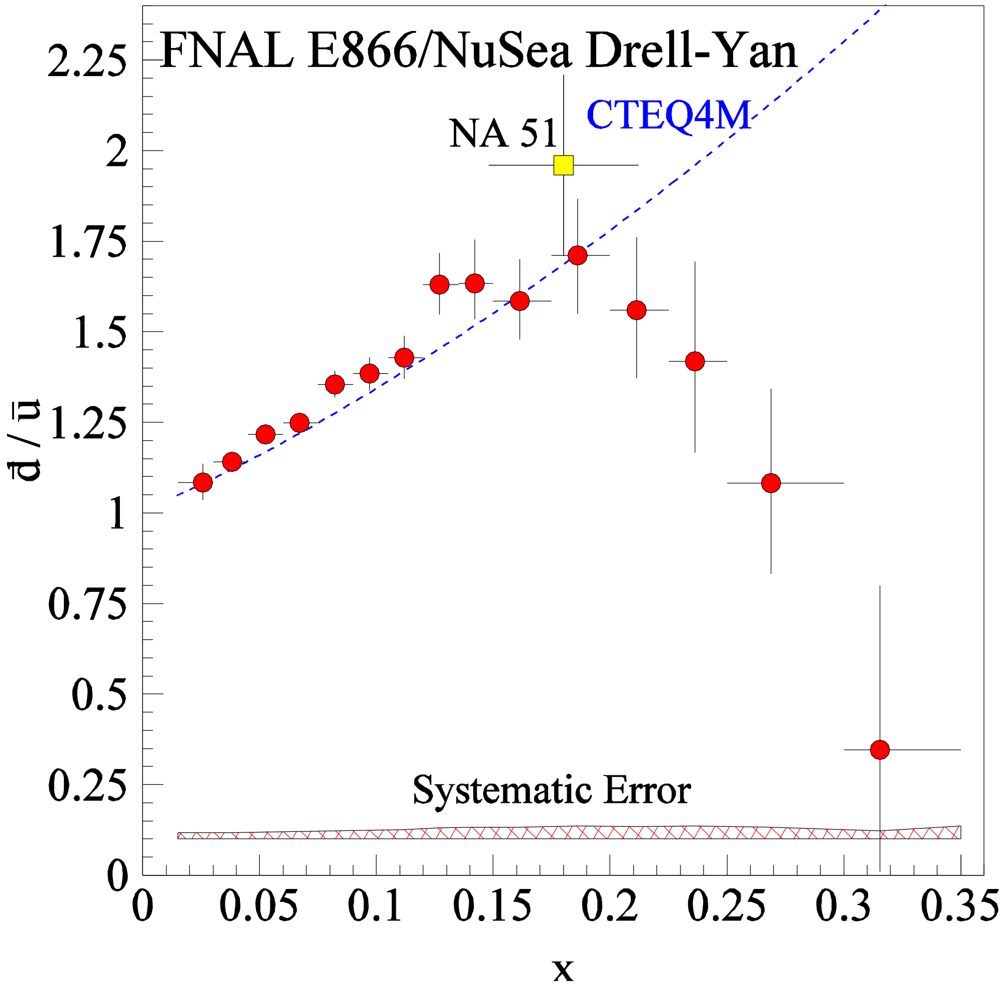
Measurements at low Q^2 are very important

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

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

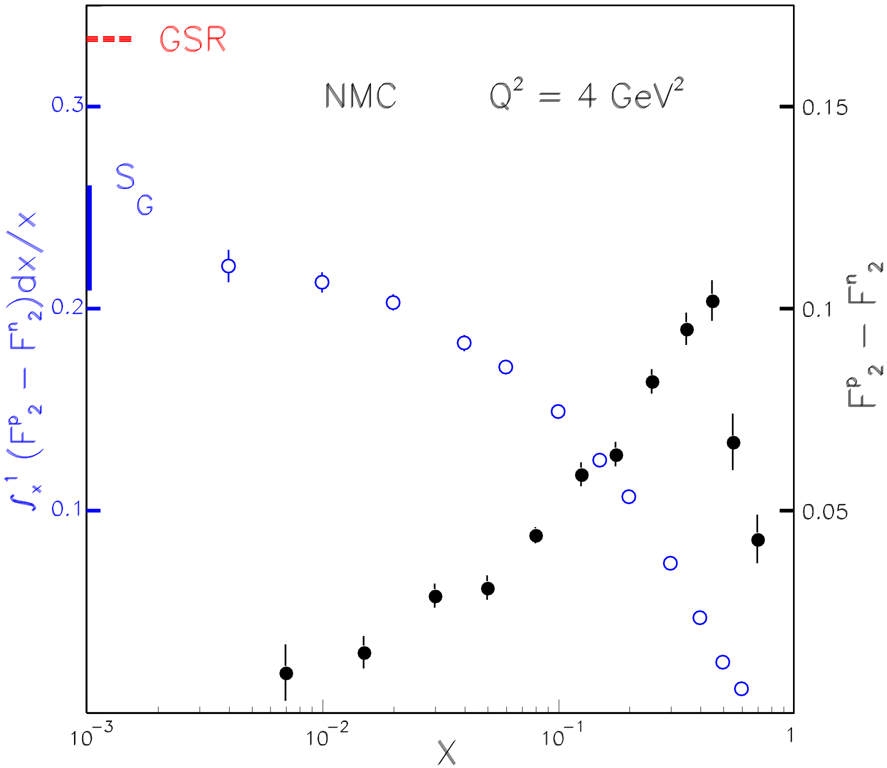
Revisit the NMC measurement of the Gottfried Sum rule

The Gottfried Sum Rule

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

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

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



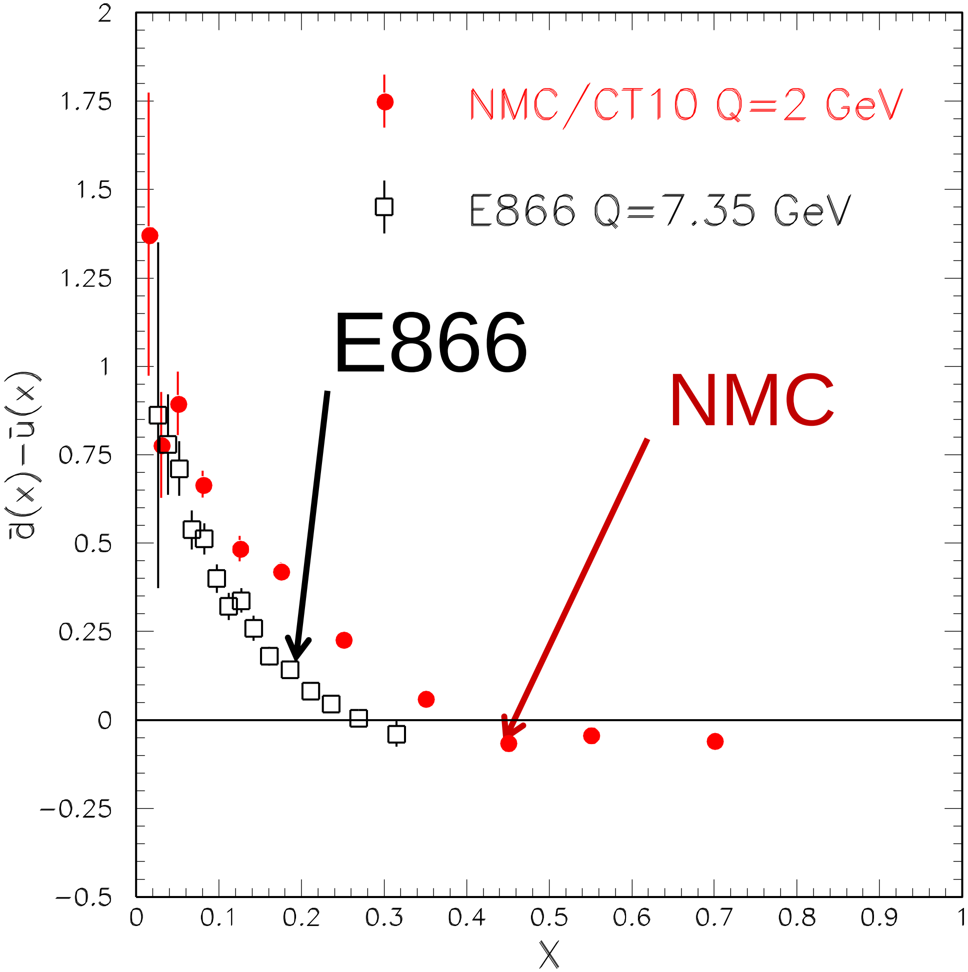
New Muon Collaboration (NMC) obtains

$S_G = 0.235 \pm 0.026$

(Significantly lower than 1/3 !) $\Rightarrow \bar{d} \neq \bar{u}\,?$

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

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

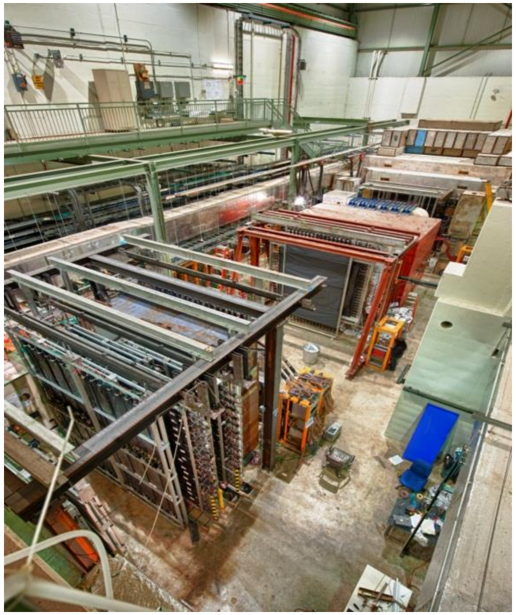


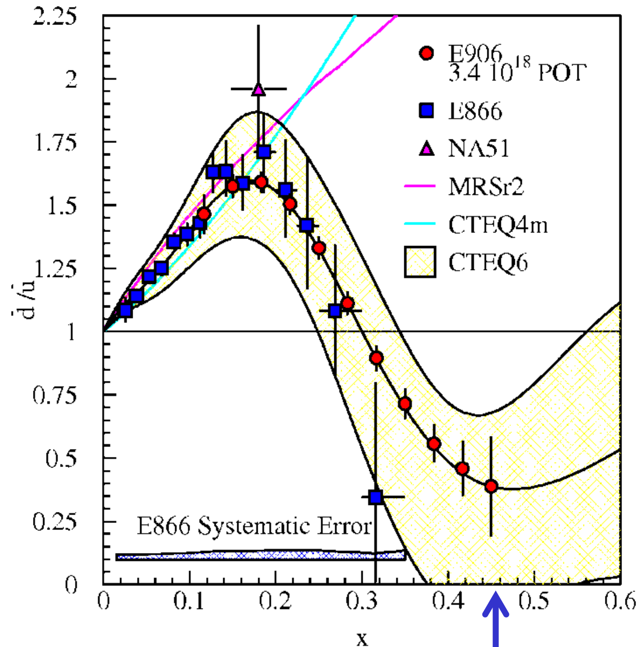
The NMC data, together with the recent PDF, already suggest that $\bar{d}(x)-\bar{u}(x)<0$ at large x!

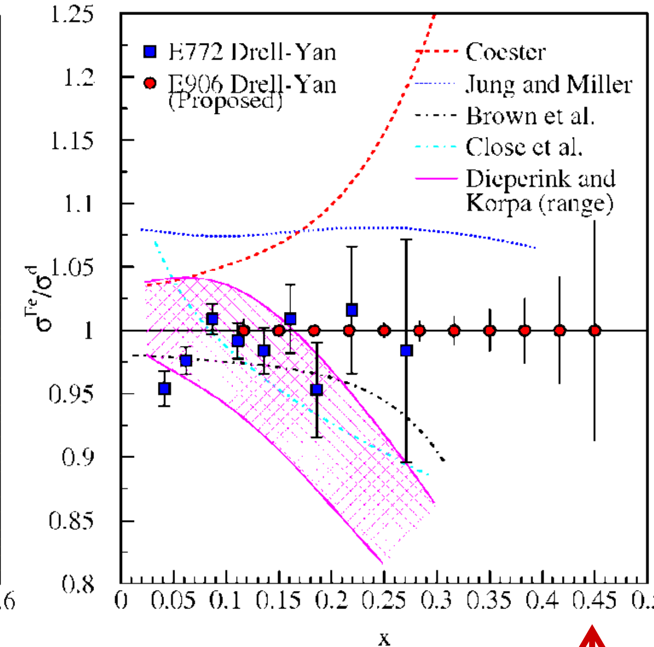
(JCP, W.C. Chen, K.F. Liu)

Drell-Yan Experiment at Fermilab

<u>SeaQuest Experiment</u> (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 2013-2015