Flavor Structure of the Nucleon Sea

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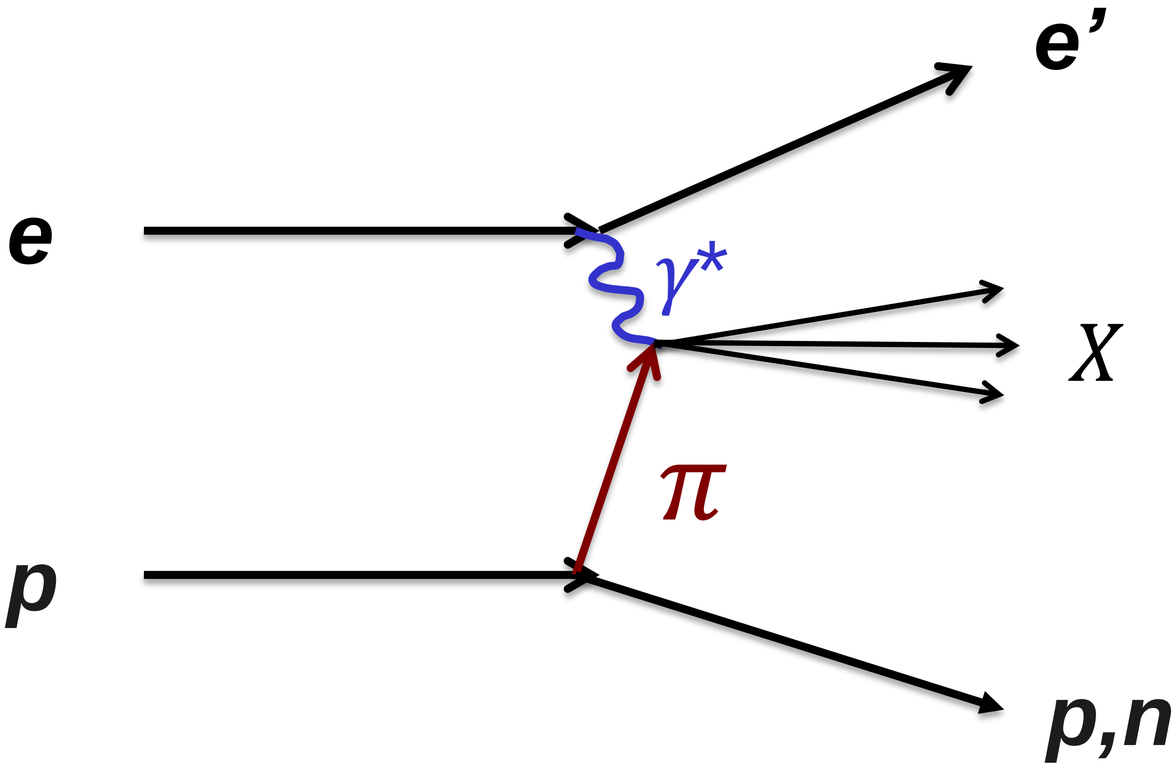
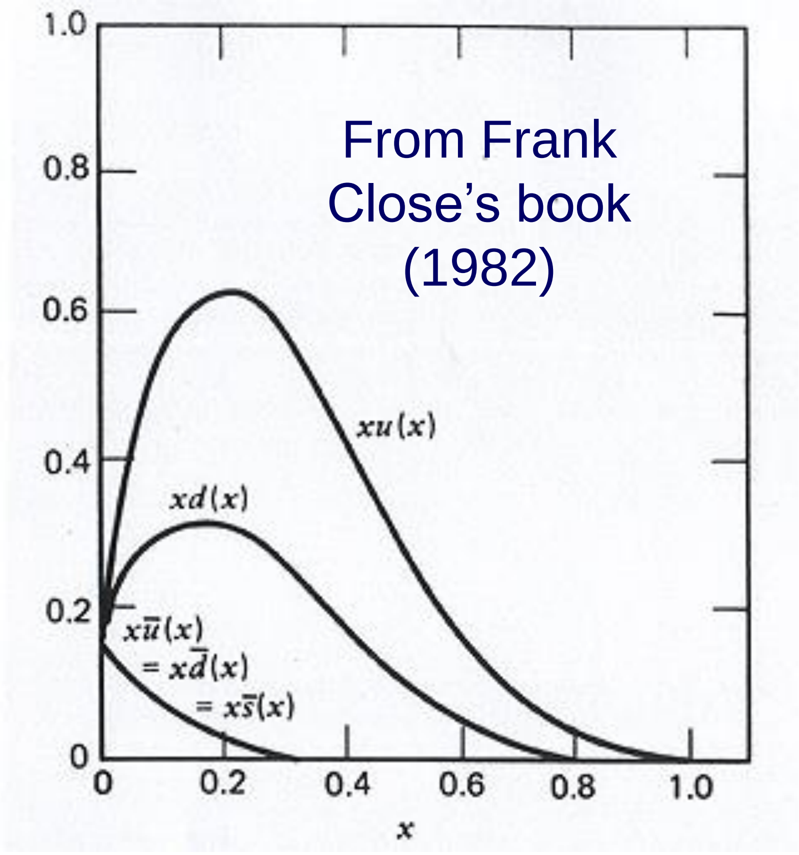
Workshop on "Exploring Hadron Structure with Tagged Structure Function", Jefferson Lab, Jan. 16-18, 2014



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

Flavor structure of the proton sea



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

$SU(3)$ symmetric sea

Is $\bar{u} = \bar{d}$ in the proton?

Expect $\bar{d} = \bar{u}$ if sea quarks are produced in $g \to q\bar{q}$

Can be tested using the Gottfried Sum Rule

$$I_2^p = \int_0^1 F_2^p(x)/x \, dx = \sum_i (Q_i^p)^2 = 1$$

"Prof. Bjorken and I constructed the sum rules in the hope of destroying the quark model"

(Gottfried, 1967)

Gottfried Sum Rule (modified)

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

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

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

Is $\bar{u} = \bar{d}$ in the proton?

The Gottfried Sum Rule

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

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

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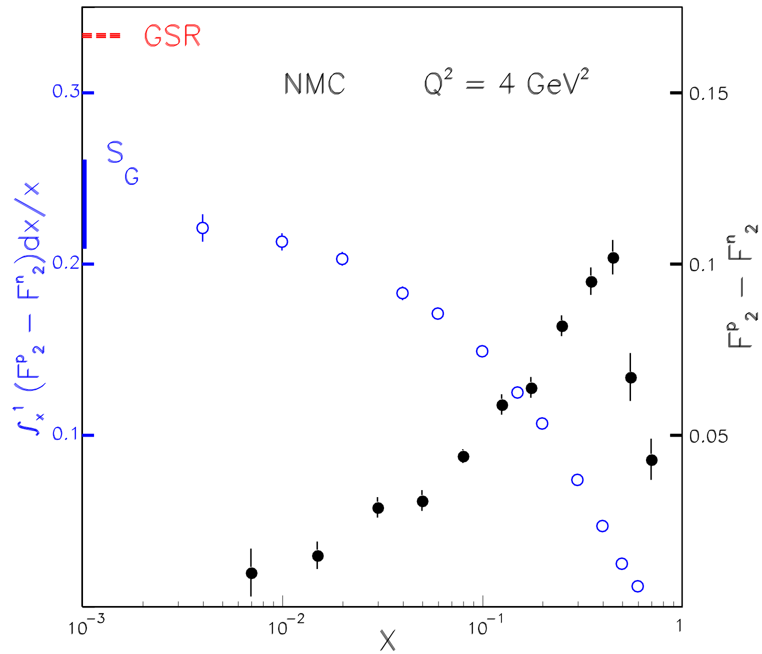


New Muon Collaboration (NMC) obtains

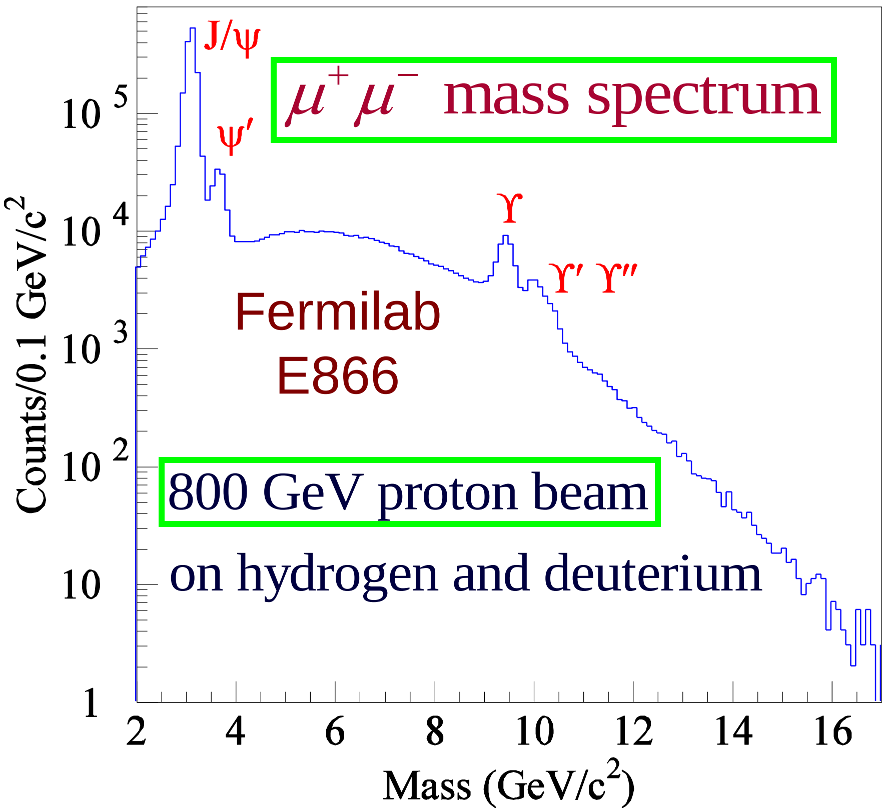
$S_G = 0.235 \pm 0.026$ **(Significantly lower than 1/3 !)**

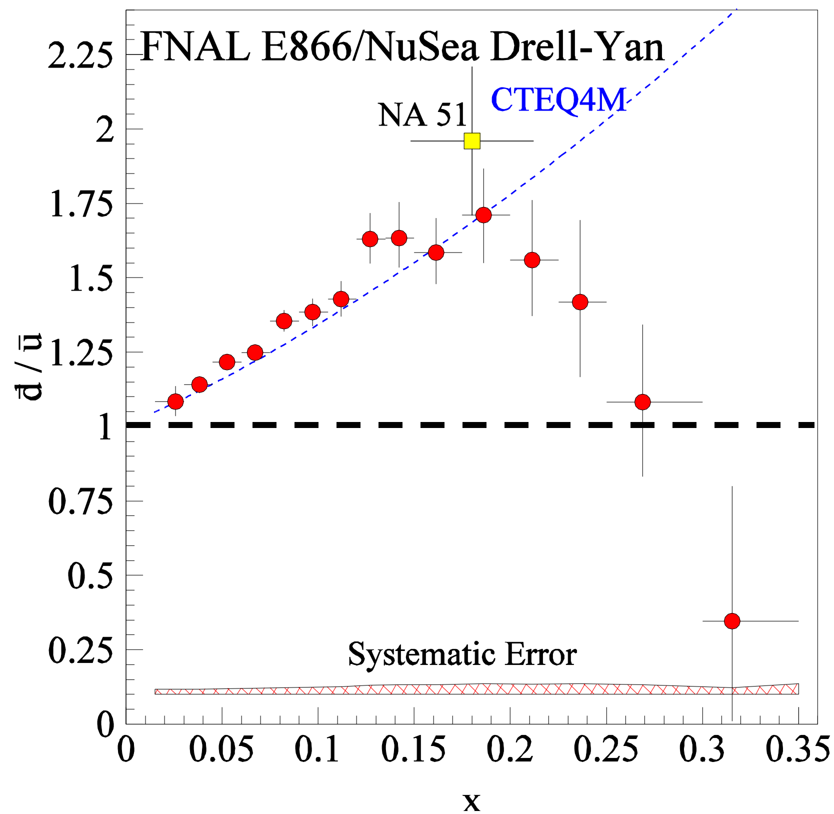
$$\Rightarrow \int_0^1 (\bar{d}(x) - \bar{u}(x))\,dx = 0.148 \pm 0.04$$

Need independent methods to check the $\bar{d}/\bar{u}$ asymmetry and to measure the *x*-dependence

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

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

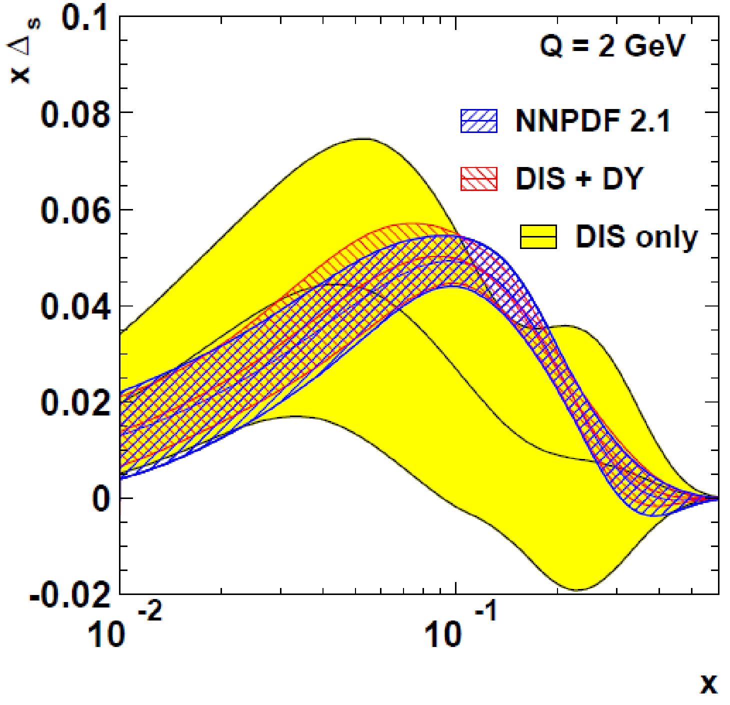


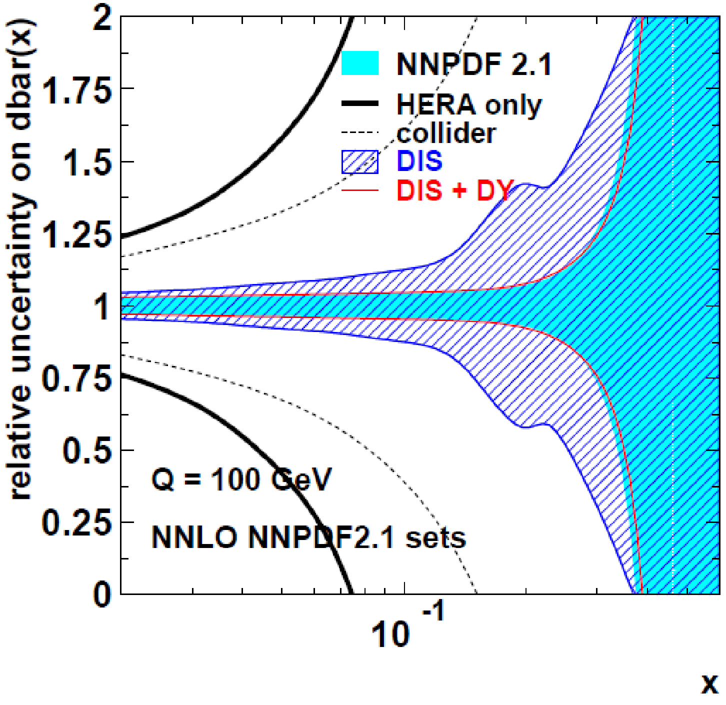


at $x_1 > x_2$: Drell-Yan: $\boxed{\sigma^{pd}/2\sigma^{pp} \sim \frac{1}{2}(1+\bar{d}(x_2)/\bar{u}(x_2))}$

Impact of the Drell-Yan data for constraining the $\bar{d}$ and $\bar{u}$ $\boldsymbol{x}$-distributions

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

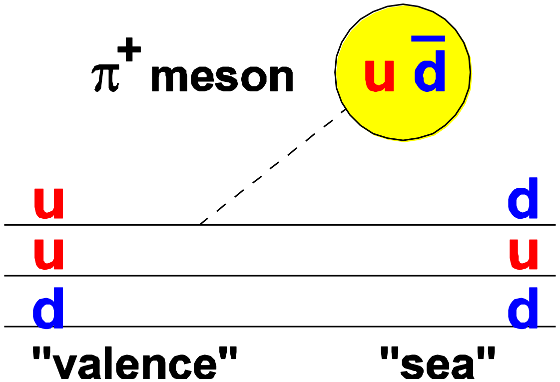




Drell-Yan is very effective in determining the $\bar{d}(x)$ and $\bar{u}(x)$

Origins of $\bar{u}(x) \neq \bar{d}(x)$?

Meson Cloud Models



Chiral-Quark Soliton Model

- nucleon = chiral soliton
- expand in 1/*Nc*
- Quark degrees of freedom in a pion mean-field

Instantons

Statistical

Pauli-blocking

Intrinsic sea

Theory: Thomas, Miller, Kumano, Ma, Londergan, Henley, Speth, Hwang, Melnitchouk, Nikolaev, Soffer, Wakamatsu, Liu, Cheng/Li, etc.

(For reviews, see Speth and Thomas (1997), Kumano (hep-ph/9702367), Garvey and Peng (nucl-ex/0109010))

Theses models also have implications on

- asymmetry between $s(x)$ and $\bar{s}(x)$
- flavor structure of the polarized sea

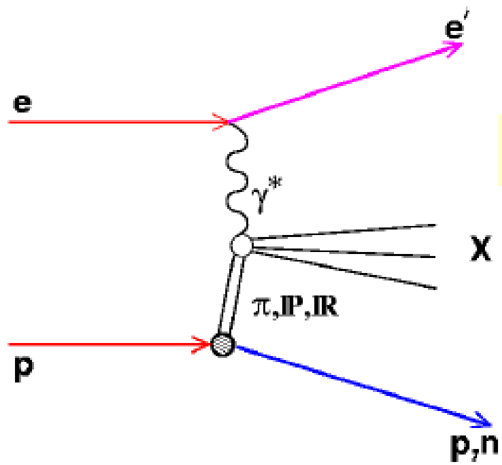
Meson cloud has significant contributions to sea-quark distributions

Measuring the pion cloud with leading neutron DIS

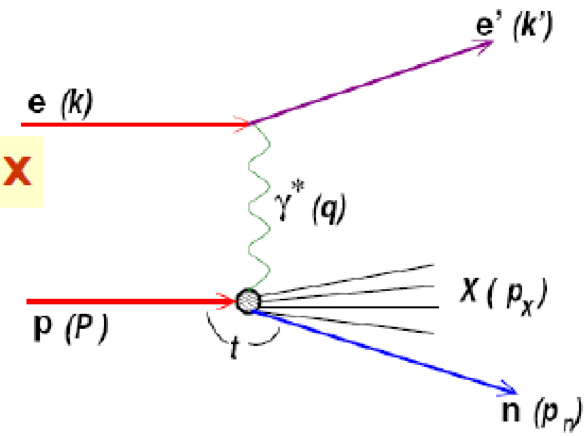
(From talk by Povh)

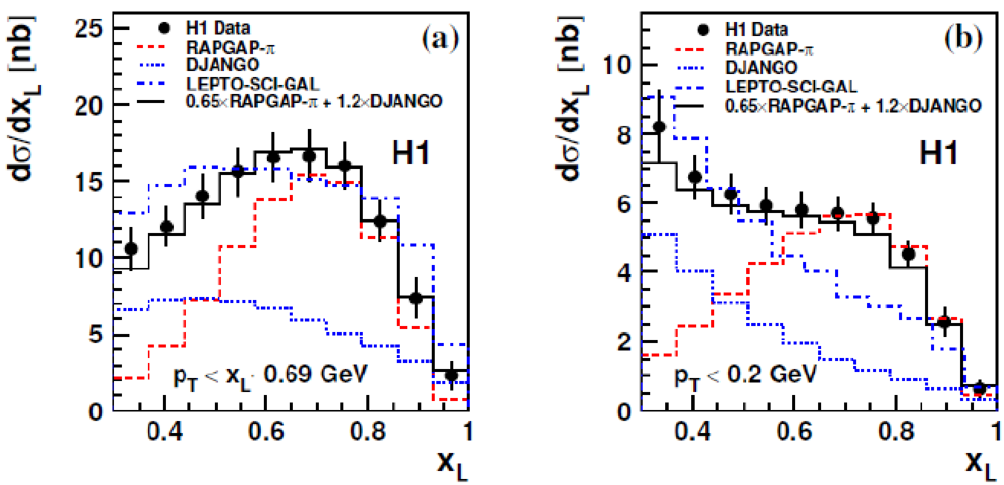
Leading neutron

Significant fraction of ep scattering events contains a high energy forward neutron produced at very small angles.



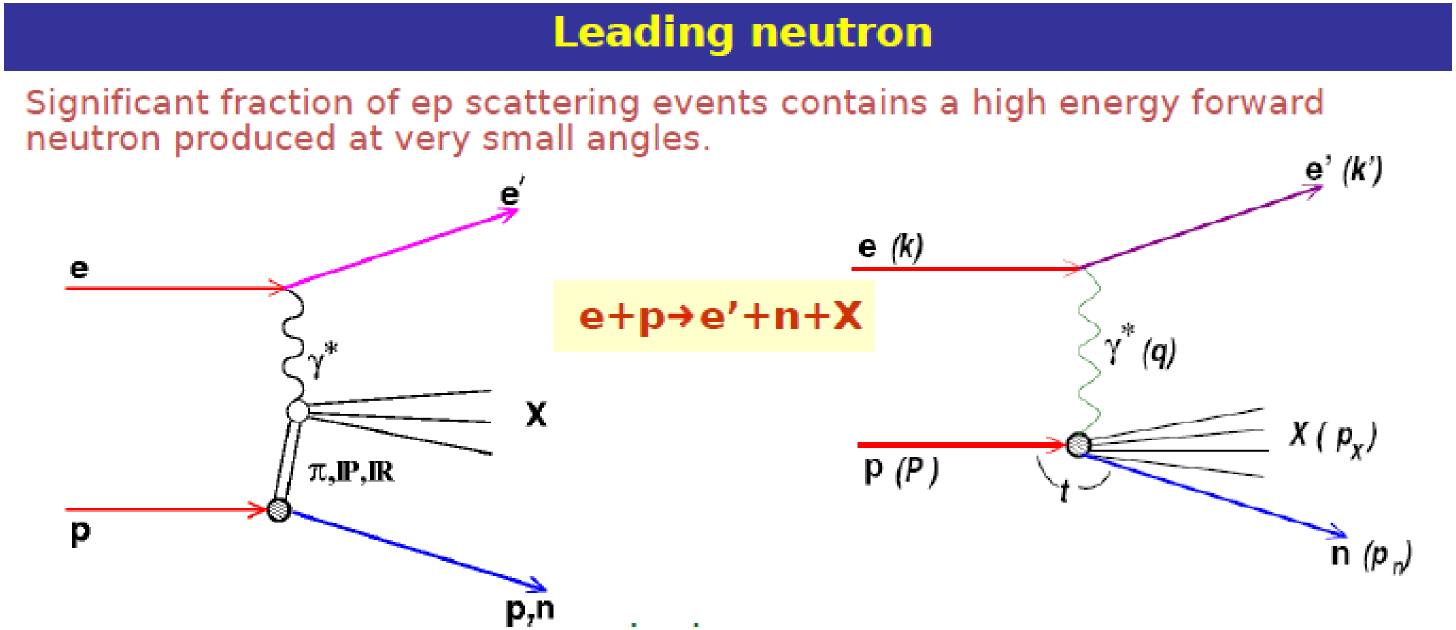
e+p→e'+n+X





	$\int_0^1 (\bar{d}(x,Q^2) - \bar{u}(x,Q^2))dx$
Drell-Yan	0.118 ± 0.038
GSR	0.176 ± 0.038
$p \to n\pi^+$	$0.165 \pm$ systematic

Measuring the pion cloud with leading neutron DIS



Future possibilities:

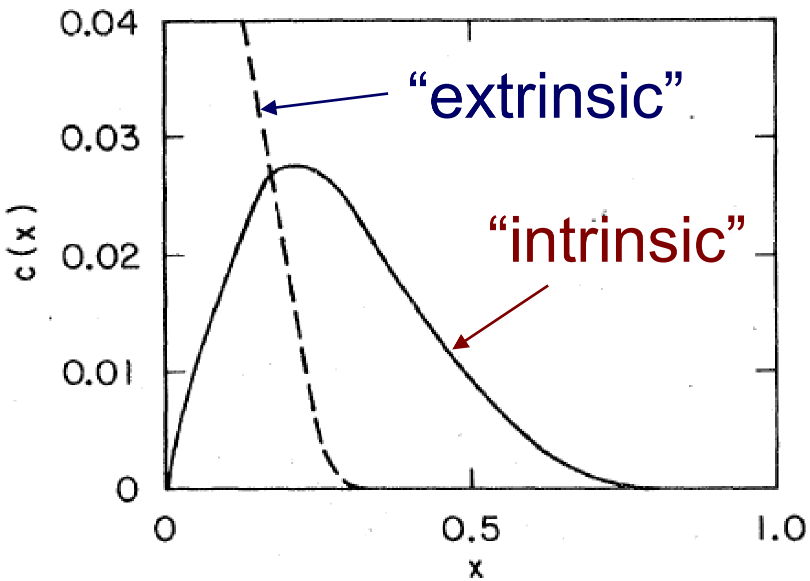
- Tagged forward neutron/proton DIS at 12 GeV JLab and EIC (Measure valence quark distributions of pion cloud)
- Tagged forward Lambda DIS to probed the kaon cloud
- Tagged forward neuron/proton Drell-Yan at RHIC/LHC

Implications on the "intrinsic" quark sea

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

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

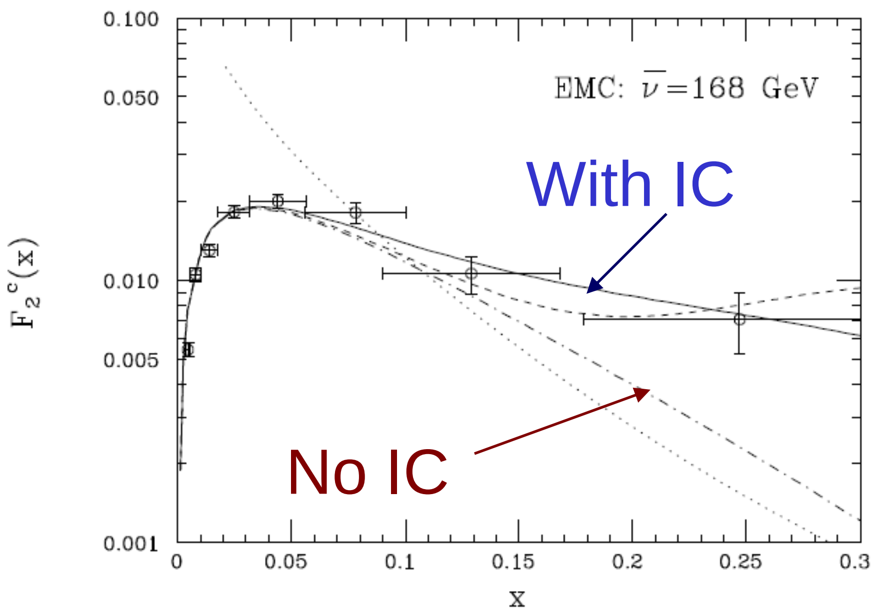
The "intrinsic"-charm from $|\,uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \to c\bar{c}$)



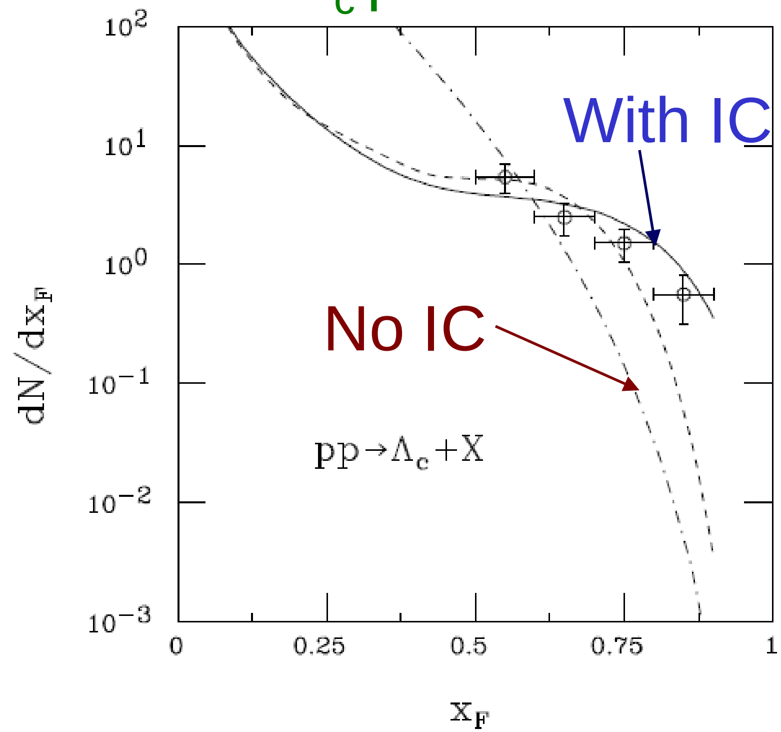
The $|\,uudc\bar{c}\rangle$ intrinsic-charm can lead to large contribution to charm production at large x

Evidence for the "intrinsic" charm (IC)

DIS data



Λ_c production



Gunion and Vogt (hep-ph/9706252)

(Evidence is subjected to the uncertainties of charmed-quark parametrization in the PDF)

Search for the lighter "intrinsic" quark sea

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

Some tantalizing 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 ?

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

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

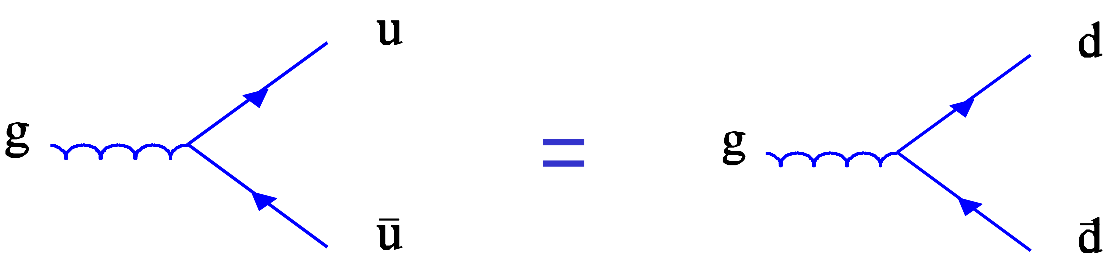
How to separate the "intrinsic sea" from the "extrinsic sea"?

- 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

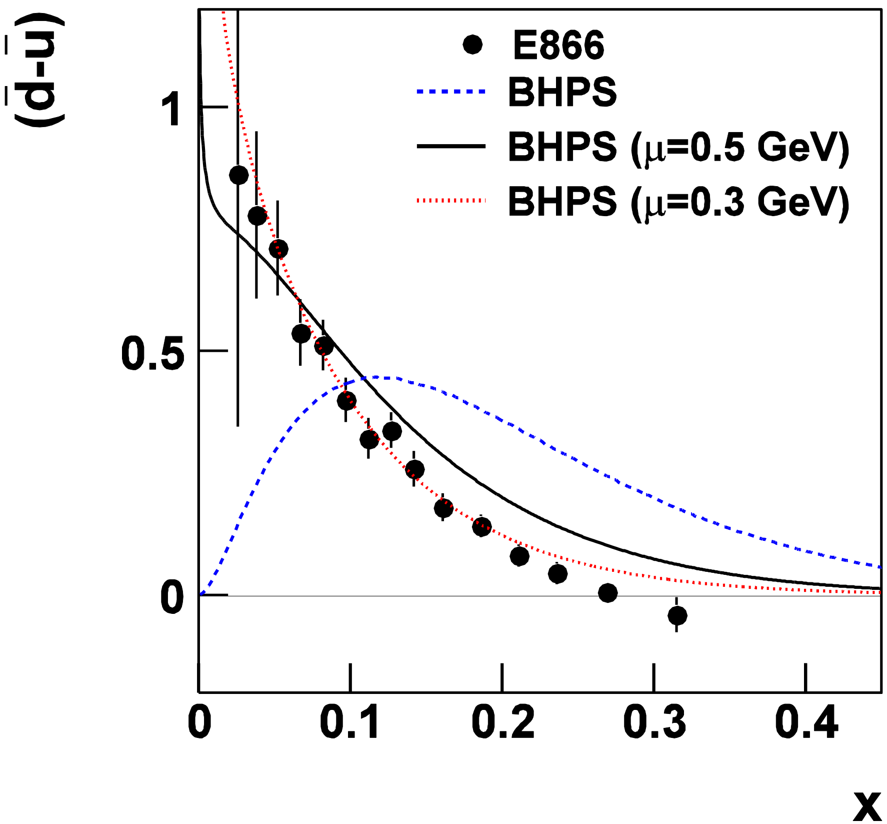
How to separate the "intrinsic sea" from the "extrinsic sea"?

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

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



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



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

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

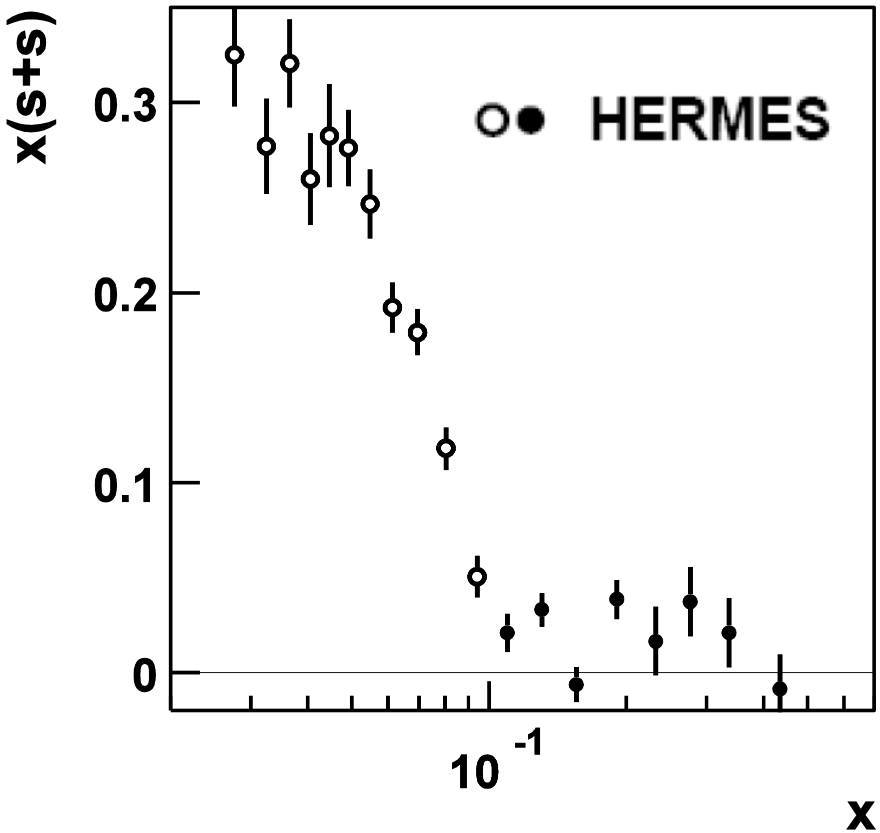
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

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

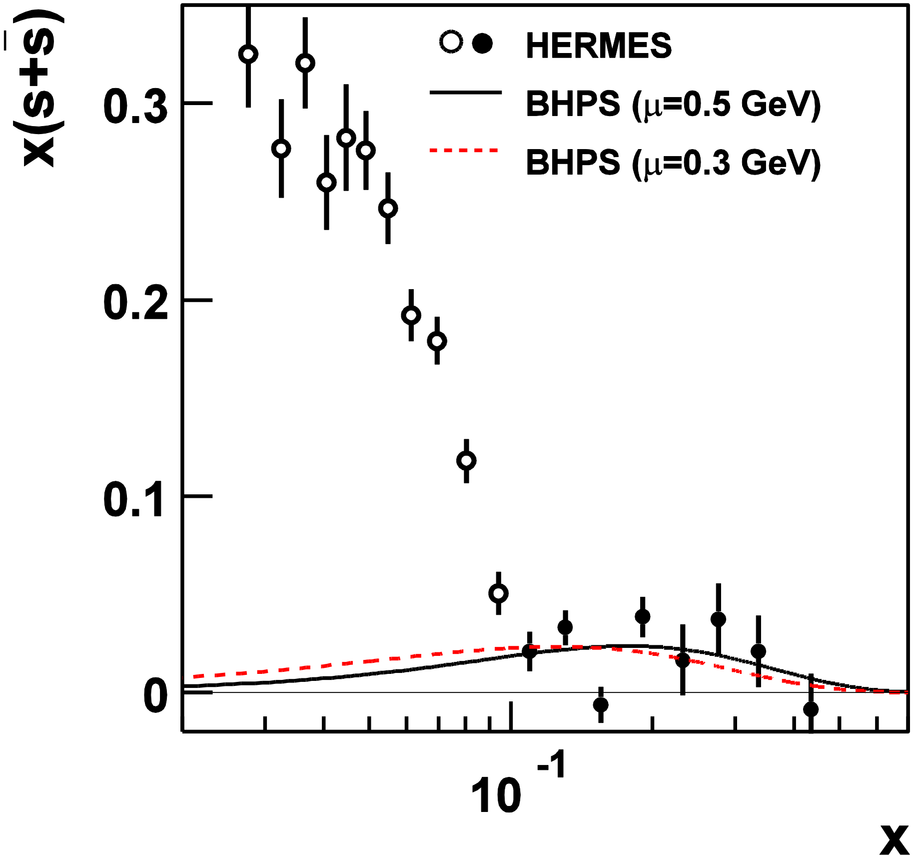


$s(x)+\bar{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2 \rangle = 2.5\ \mathrm{GeV}^2$

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 dominated by intrinsic sea (and $x < 0.1$ are from extrinsic sea)

This allows the extraction of the intrinsic sea for strange quarks

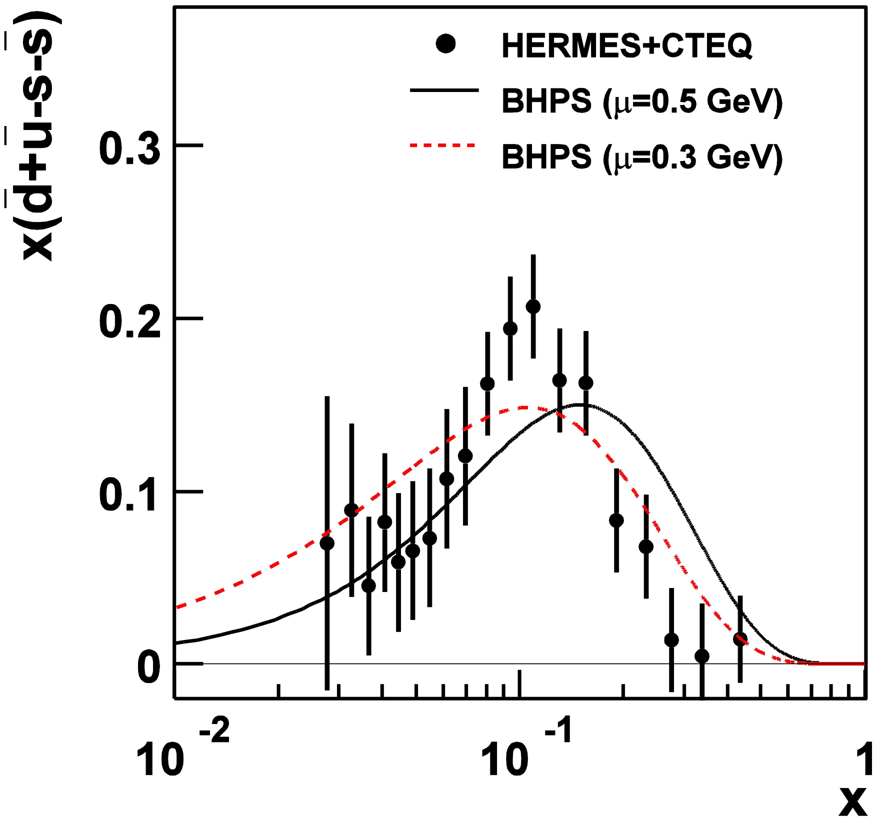
$$\boxed{P_5^{uud s\bar{s}} = 0.024}$$

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

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

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

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

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

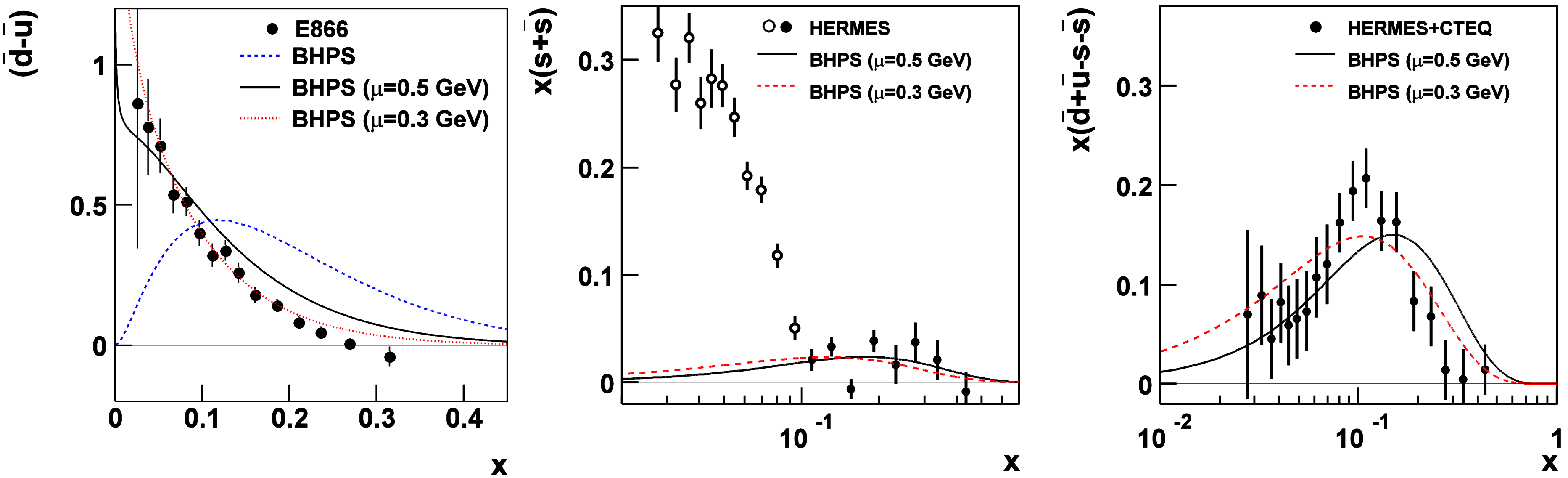
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

(not sensitive to SU(3)-symmetric 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



$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118 \qquad P_5^{uuds\bar{s}} = 0.024 \qquad P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$$

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

Future Possibilities

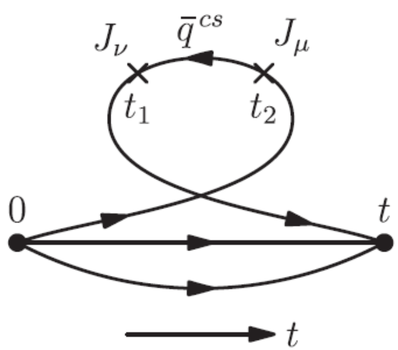
- Search for intrinsic charm and beauty at RHIC and LHC.
- Intrinsic gluons in the nucleons?
- Spin-dependent observables of intrinsic sea?
- Global fits including intrinsic u, d, s sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

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

Connected-Sea Partons

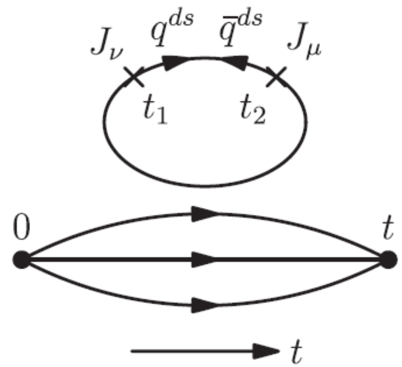
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea



(valence-like)

Disconnected sea



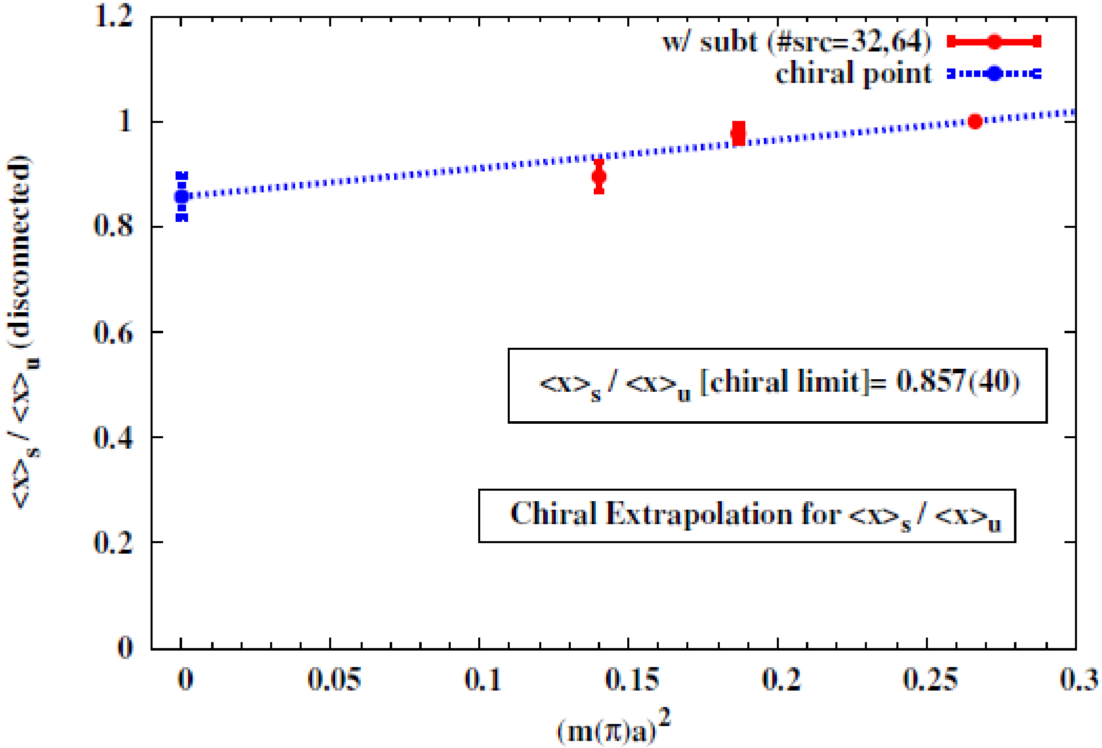
(sea-like)

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

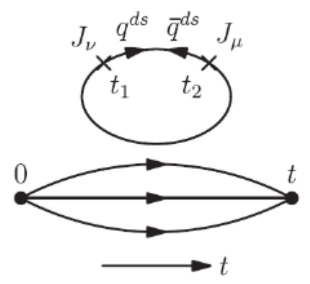
CS and DS have
different Bjorken-x and
flavor dependences

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

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Connected-Sea Partons

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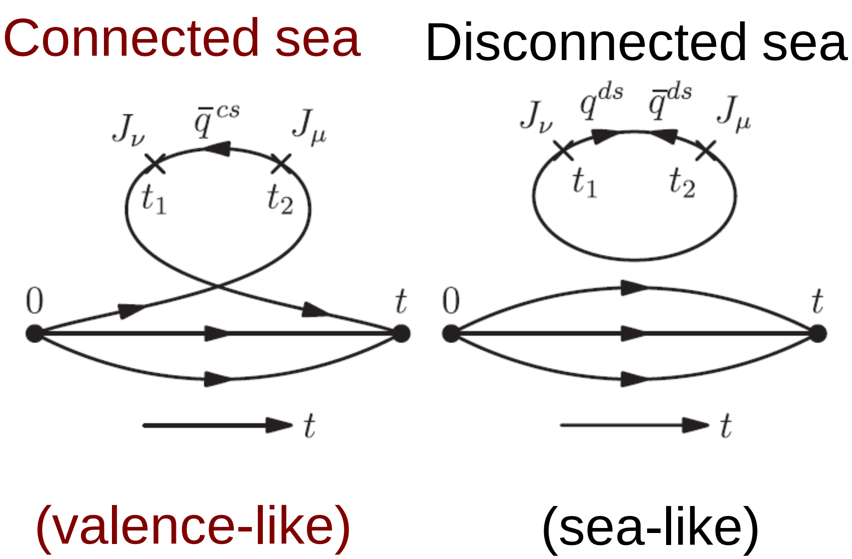
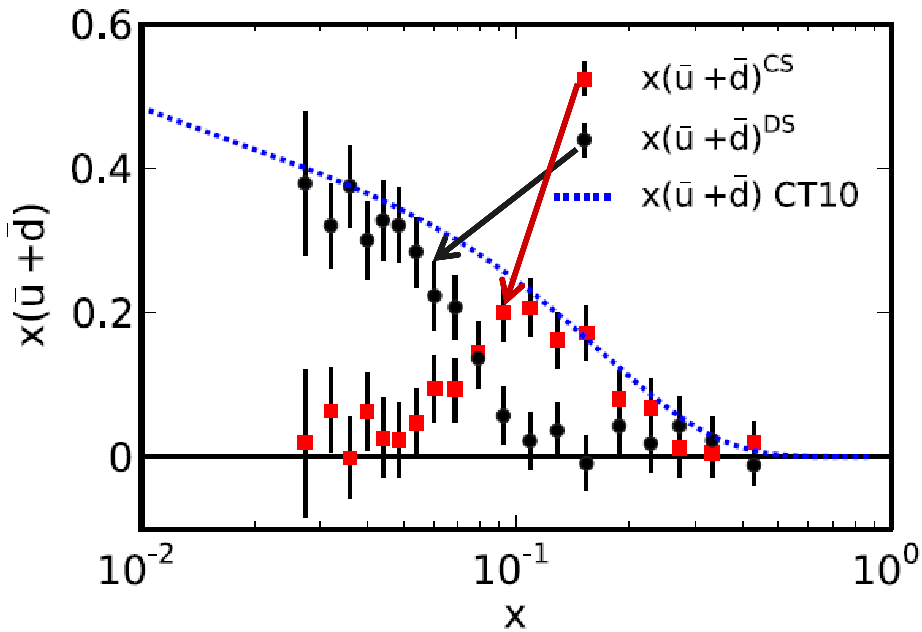
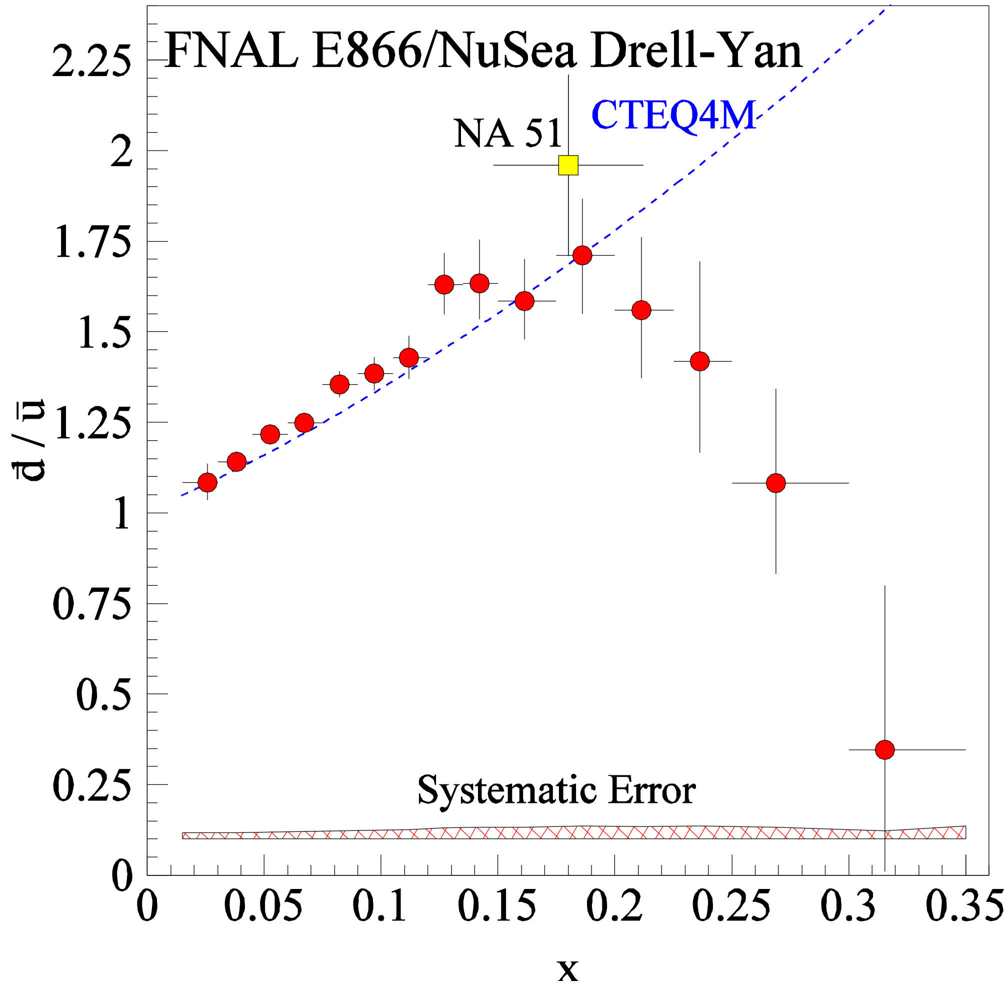




- Using input from lattice QCD, one can separate the connected sea from the disconnected sea for $\bar{u}(x)+\bar{d}(x)$
- For $\bar{u}+\bar{d}$ at Q^2=2.5 GeV^2, momenta carried by CS and DS are roughly equal

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



No existing models can explain sign-change

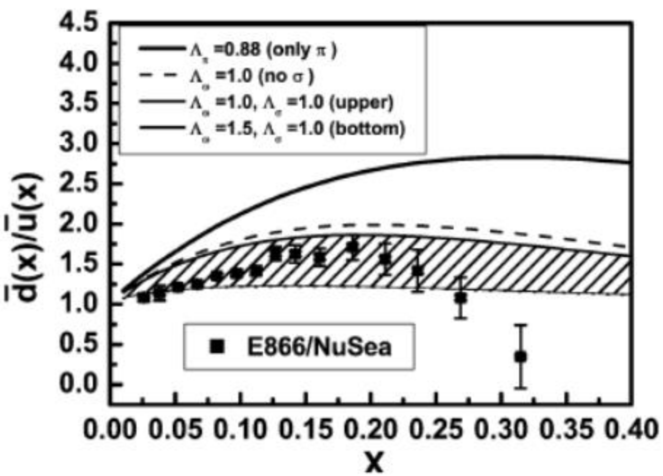
for $\bar{d}(x) - \bar{u}(x)$ at any value of x

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

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

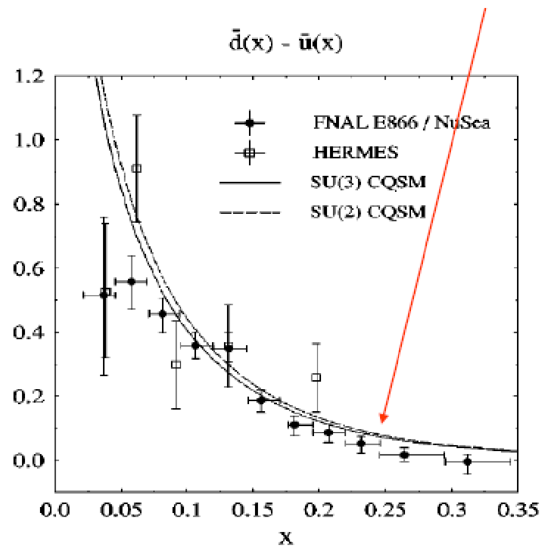
Why is it interesting? (no models can explain it yet!)

Meson cloud model



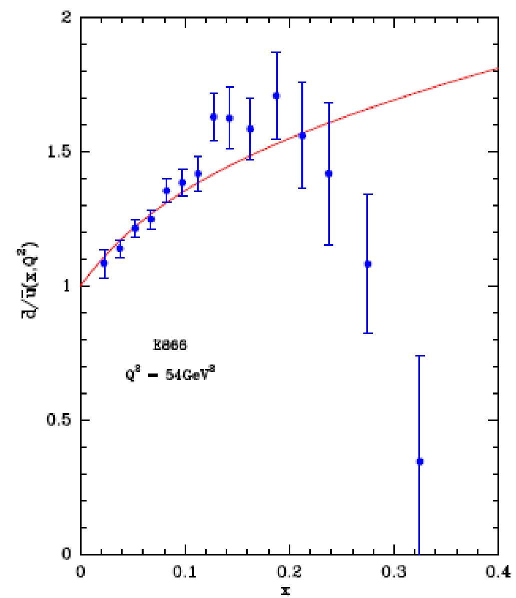
From Alberg

Chiral-quark soliton model



From Wakamatsu

Statistical model



From Soffer's

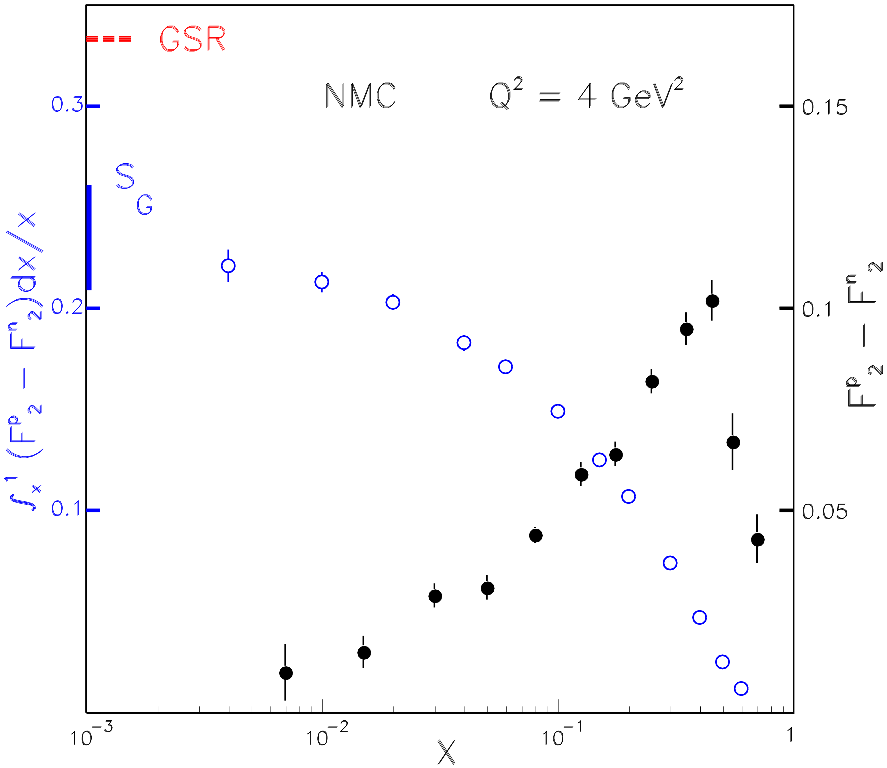
Revisit the NMC measurement of the Gottfried Sum rule

The Gottfried Sum Rule

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

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

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



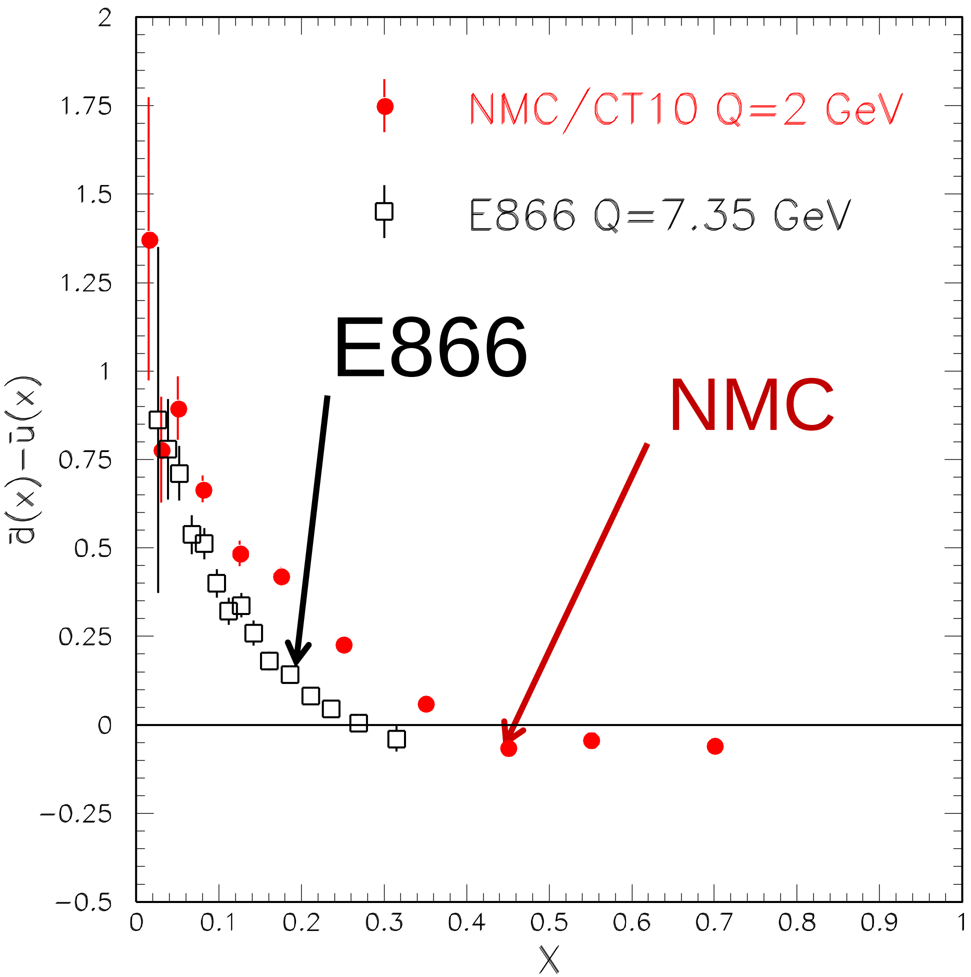
New Muon Collaboration (NMC) obtains

S_G = 0.235 ± 0.026

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

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

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

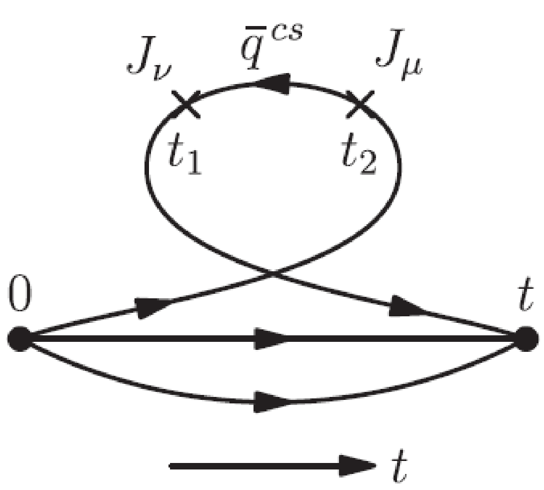


The NMC data, together with the recent PDF, already suggest that $\bar{d}(x)-\bar{u}(x)<0$ at large x!

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

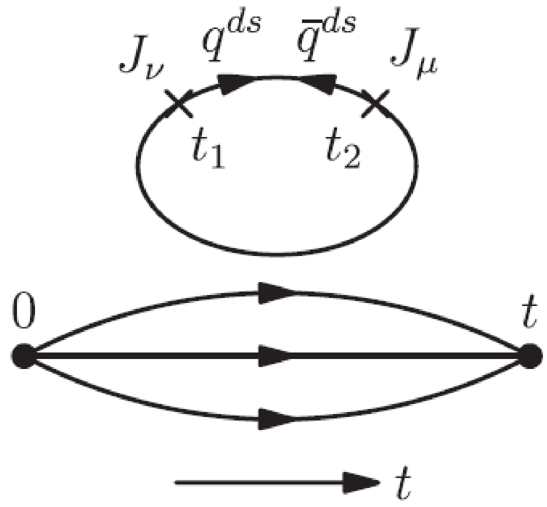
What mechanism could lead to $\bar{u} > \bar{d}$ at $x > 0.25$?

Connected sea



(valence-like)

Disconnected sea



(sea-like)

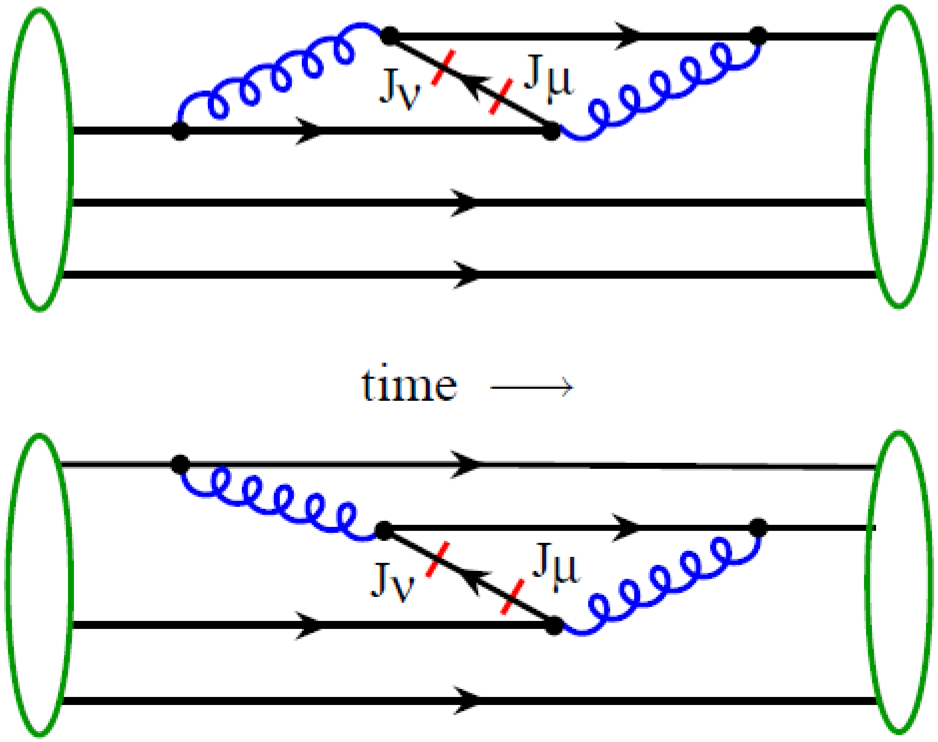
$\bar{u}(x) \neq \bar{d}(x)$ can only come from connected sea (CS)

$(u \rightarrow \bar{u} + u + u,\ d \rightarrow \bar{d} + d + d)$ ($\bar{q}$ 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)

Some diagrams could lead to $\bar{u}(x) > \bar{d}(x)$

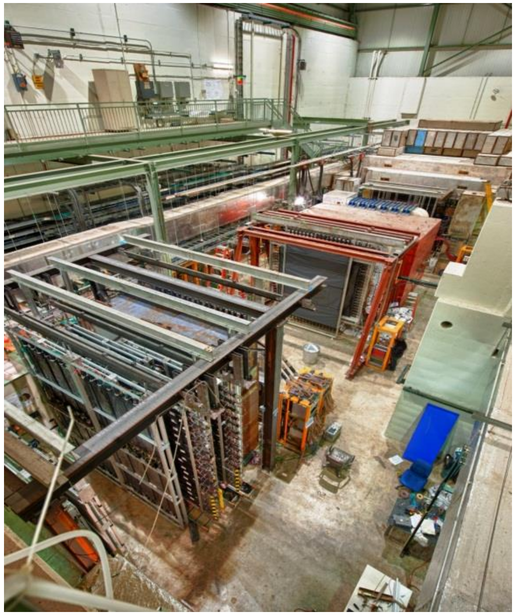


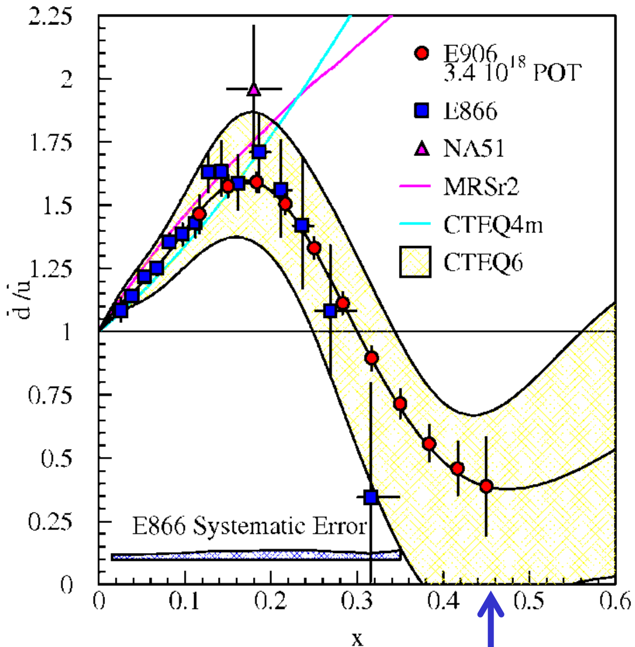
Both diagrams favor ubar over dbar

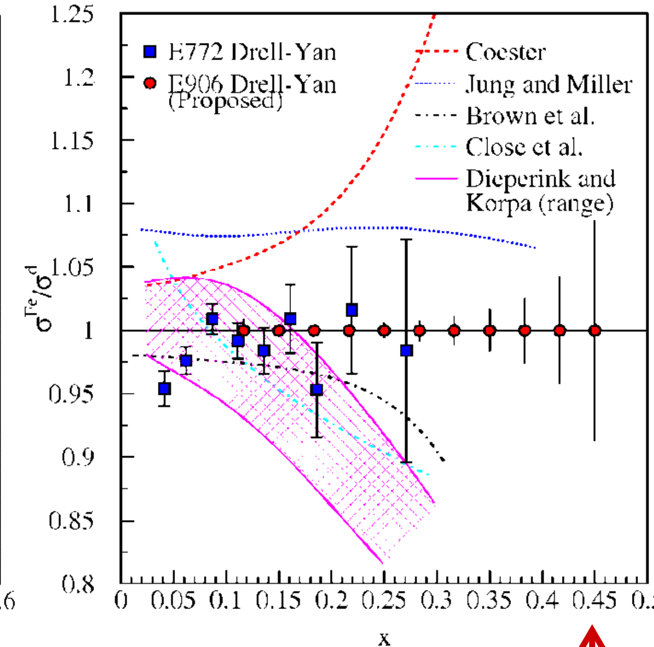
(JCP, Chen, Liu, Qiu, et al, arXiv: 1401.1705)

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 $x \sim 0.45$

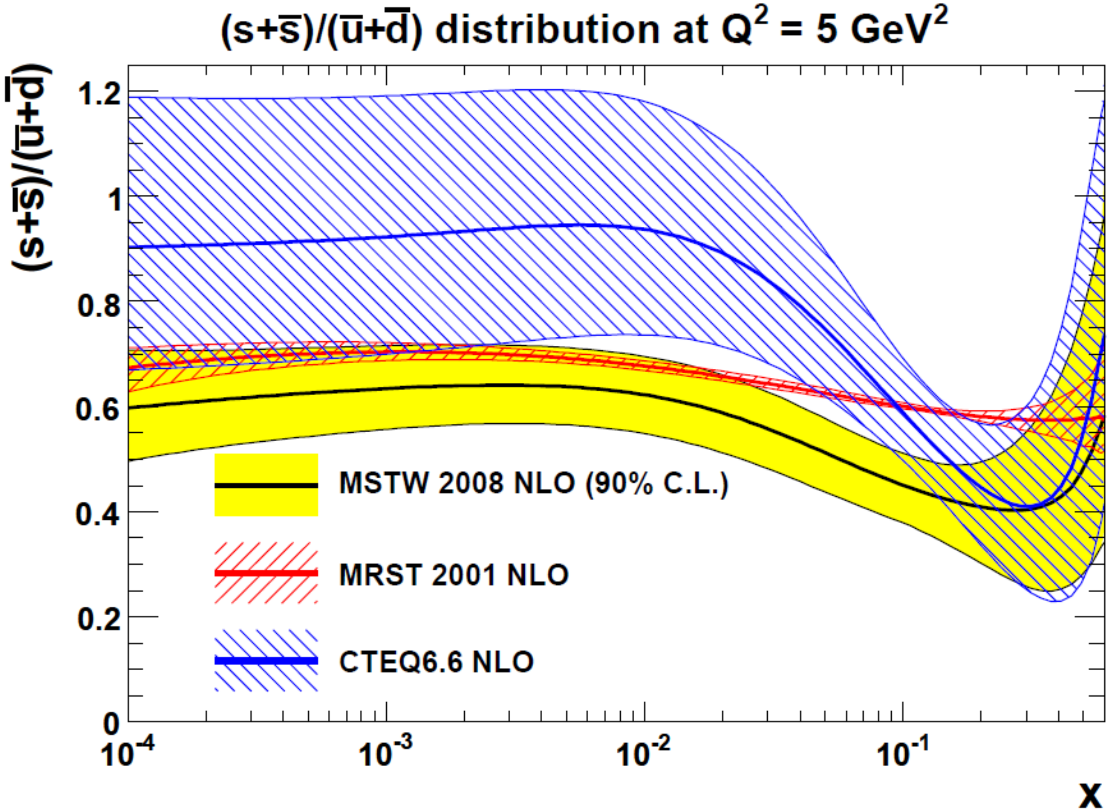
2) Measure EMC effect of antiquarks up to $x \sim 0.45$

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

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



The ratio of $(s(x)+\bar{s}(x))/(\bar{u}(x)+\bar{d}(x))$ is strongly x-dependent!

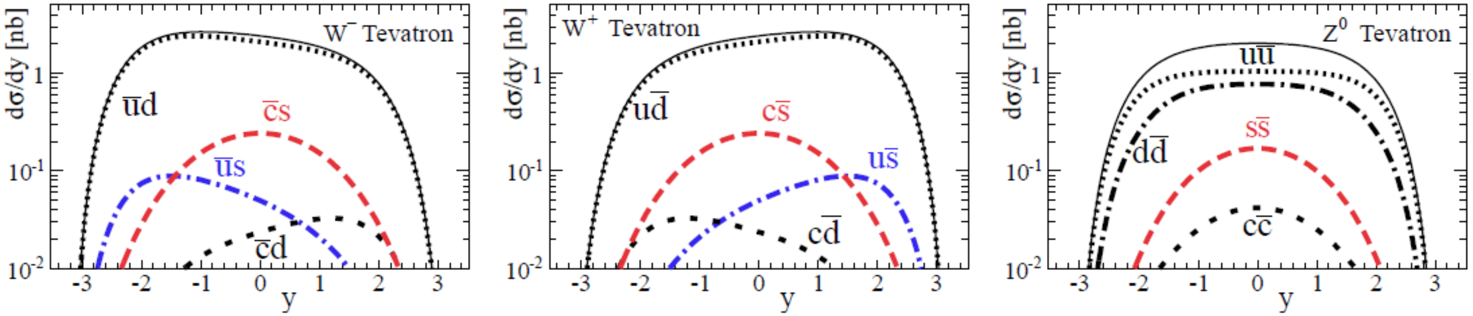
Strange sea from inclusive W/Z production

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

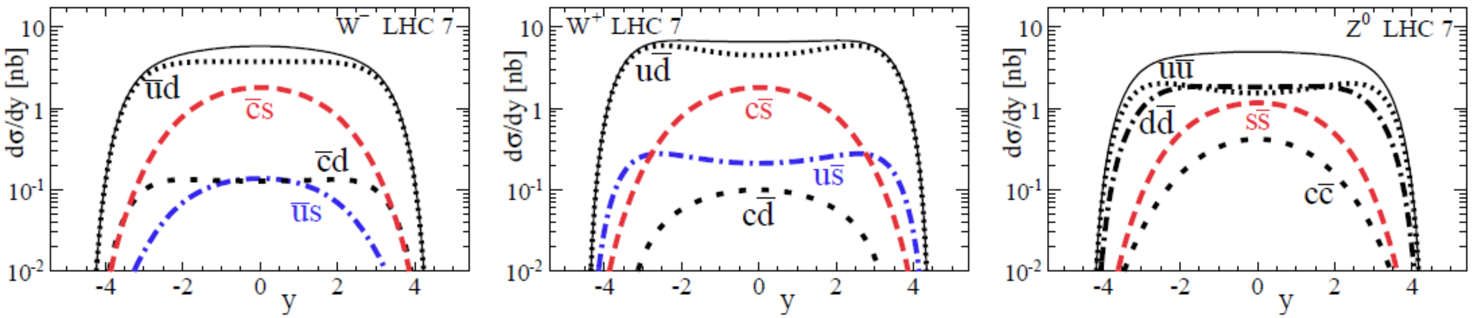
$$W^+:\ (u \text{ or } c) + (\bar{d} \text{ or } \bar{s}) \to W^+$$

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

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



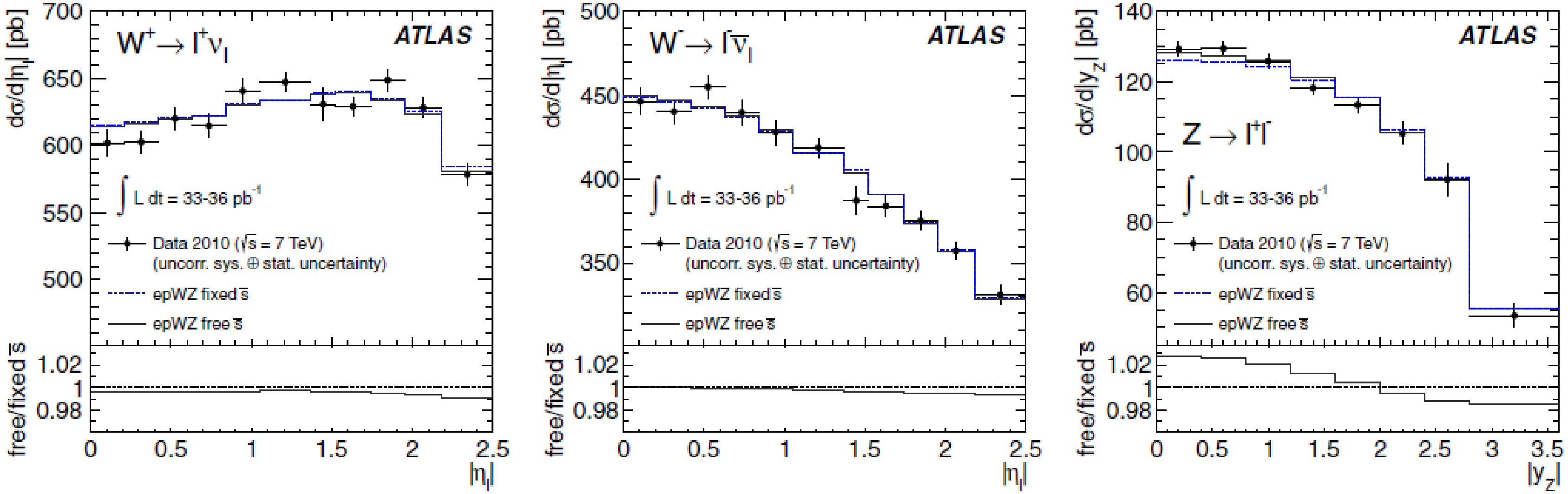
(a) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the Tevatron.

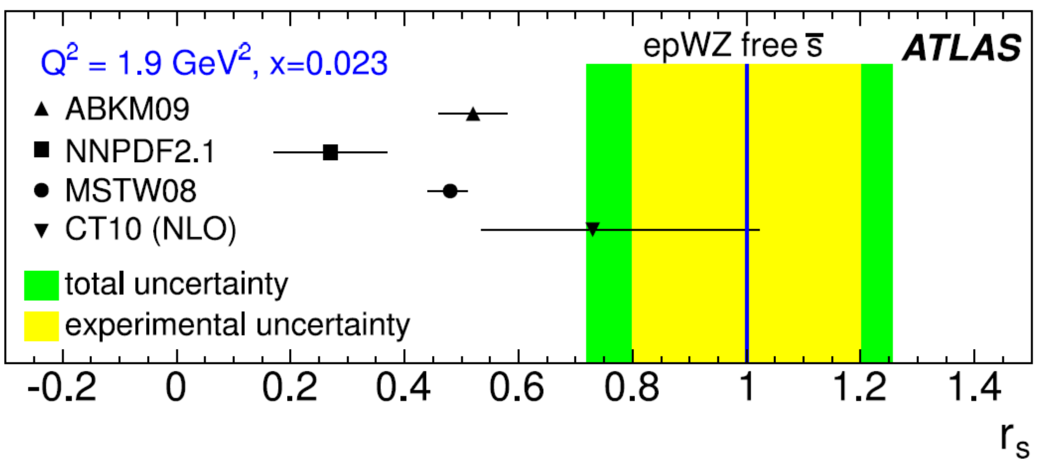


(b) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the LHC with $\sqrt{S} = 7$ TeV.

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, $Q^2 = M_Z^2$

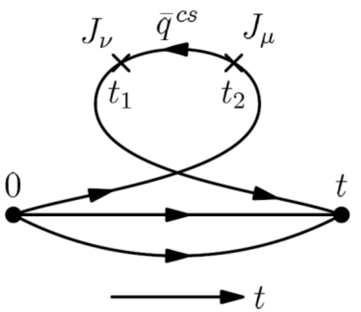
Aad et al., PRL 109 (2012) 012001

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

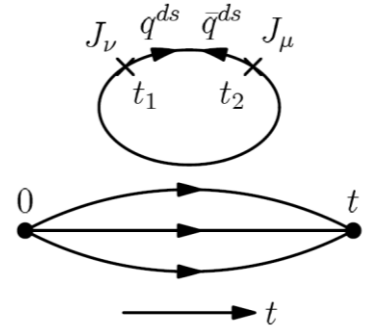
Can be well understood from Lattice QCD
(PRL 109 (2012)252002)

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

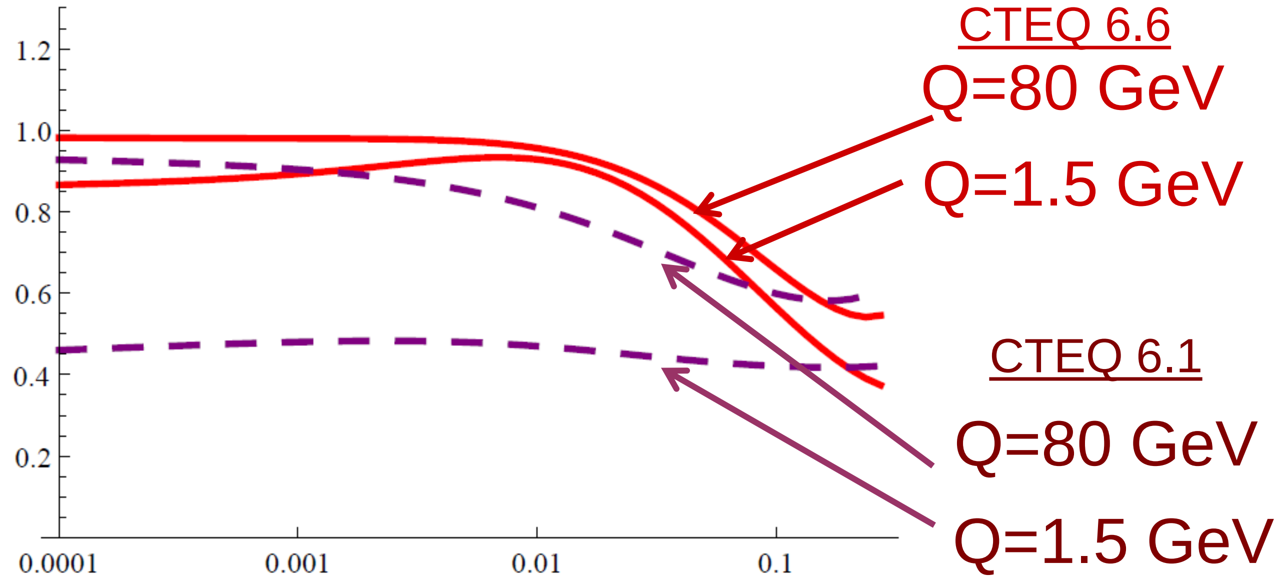


Figure 5: $\kappa(x,Q)$ vs. x showing the evolution from low to high scales. The solid (red) lines are for CTEQ6.6, and the dashed (purple) lines are for CTEQ6.1. The lower

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.
- Further search for intrinsic charm is of much interest.
- 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 new information on nucleon sea and meson structure.