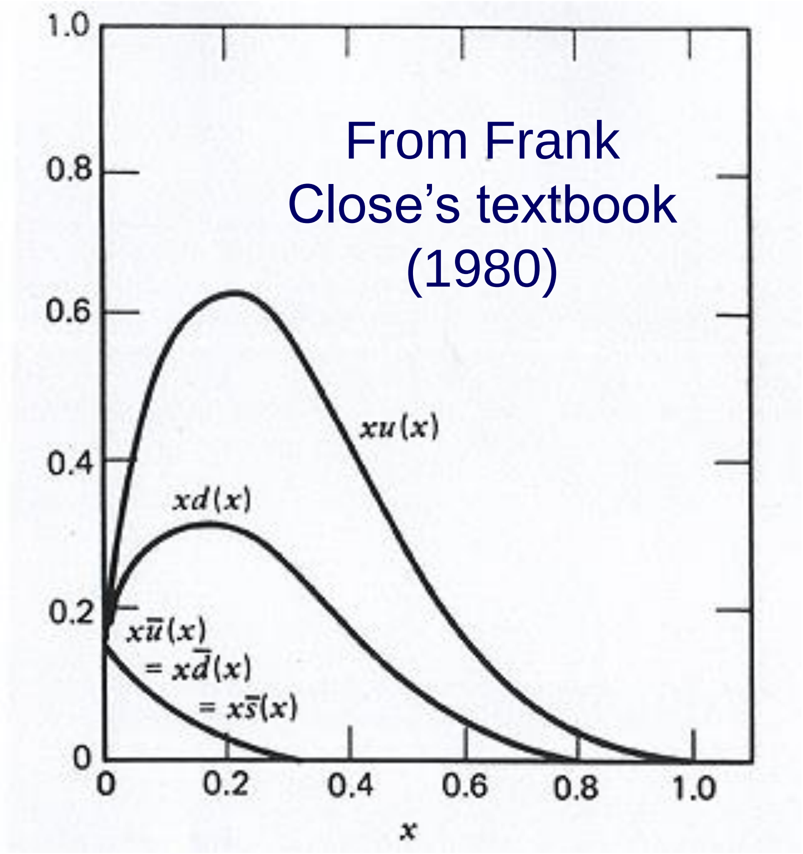
The Flavor Structure of the Nucleon Sea

Jen-Chieh Peng

University of Illinois at Urbana-Champaign
and
Institute of Physics, Academia Sinica

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

Flavor structure of the proton sea



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

$SU(3)$ 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
- Separation of “connected sea” from “disconnected sea” for light-quark sea
- Bjorken-x dependencies of $\bar{d}(x) - \bar{u}(x)$ and $[s(x) + \bar{s}(x)]/[(\bar{u}(x) + \bar{d}(x)]$

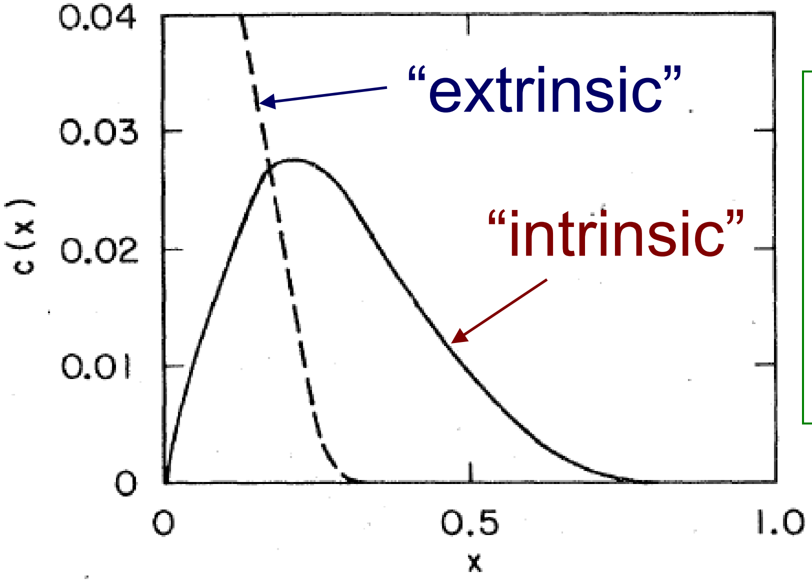
Based on work in collaboration with Wen-Chen Chang,
Hai-Yang Cheng, Keh-Fei Liu, and Jian-Wei Qiu

Search for the “intrinsic” quark sea

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

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

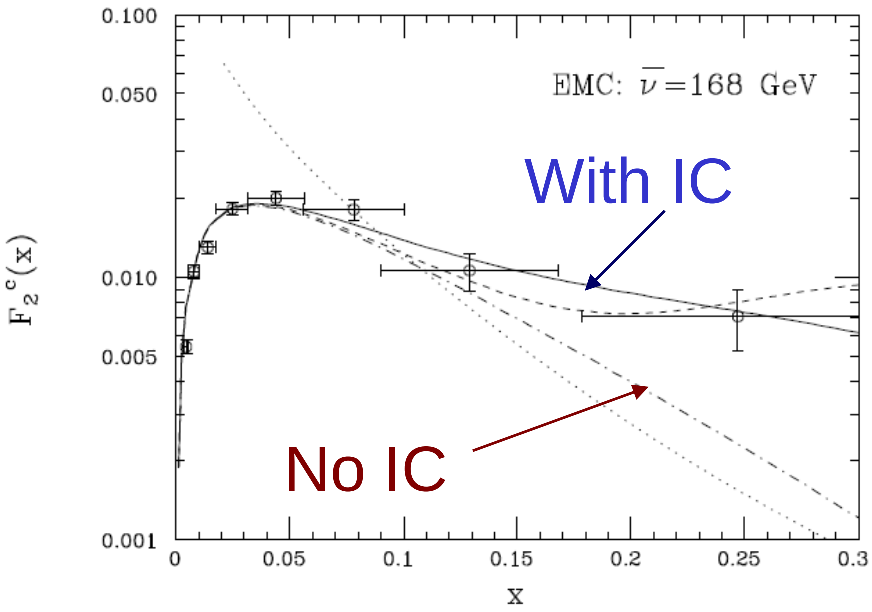
The "intrinsic"-charm from $| uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \rightarrow c\bar{c}$)



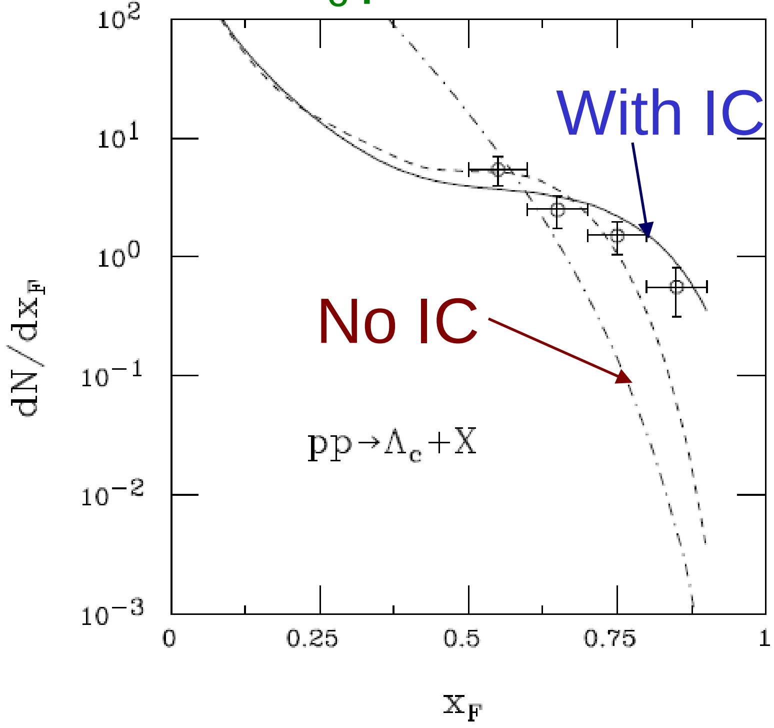
The "intrinsic charm" in $| uudc\bar{c}\rangle$ can lead to large contribution to charm production at large x

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

DIS data



Λ_c production

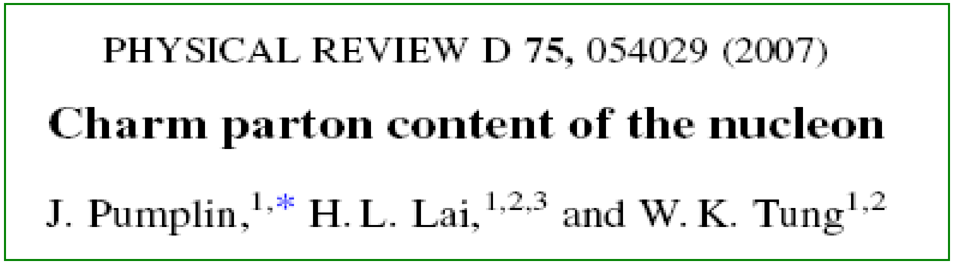


Gunion and Vogt (hep-ph/9706252);
Barger, Halzen and Keung (PRD 25 (1982) 112)

Tantalizing evidence for intrinsic charm

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

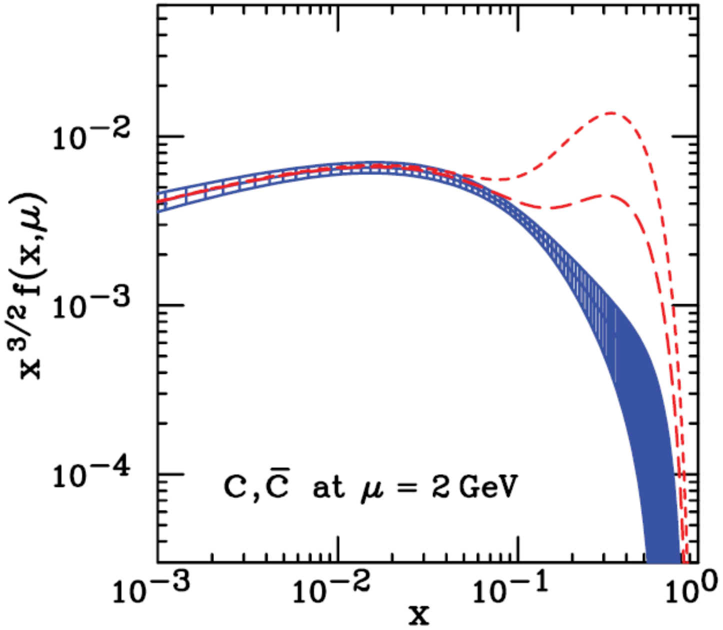
A global fit by CTEQ to extract intrinsic-charm



PHYSICAL REVIEW D 75, 054029 (2007)

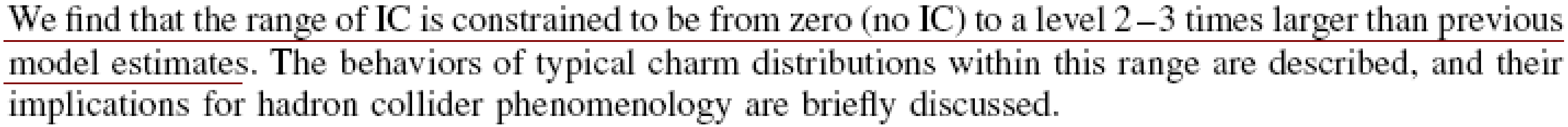
Charm parton content of the nucleon

J. Pumplin,[1,*] H. L. Lai,[1,2,3] and W. K. Tung[1,2]



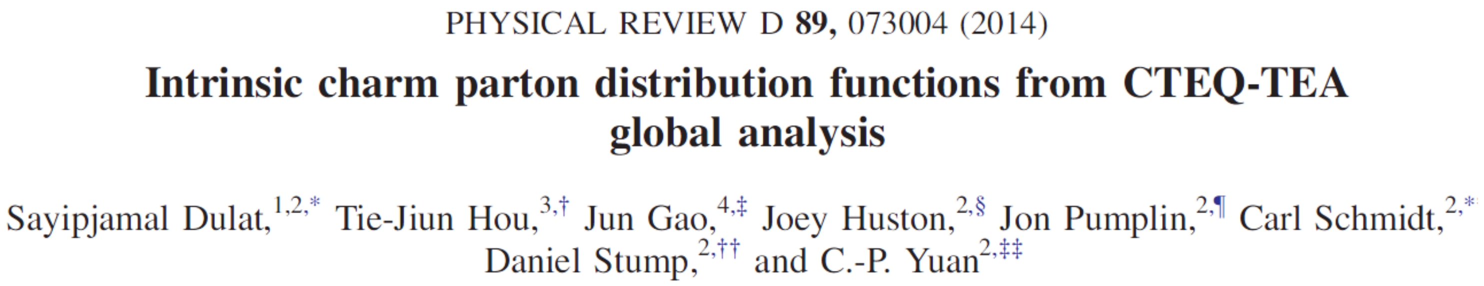
Blue band corresponds to CTEQ6 best fit, including uncertainty

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.

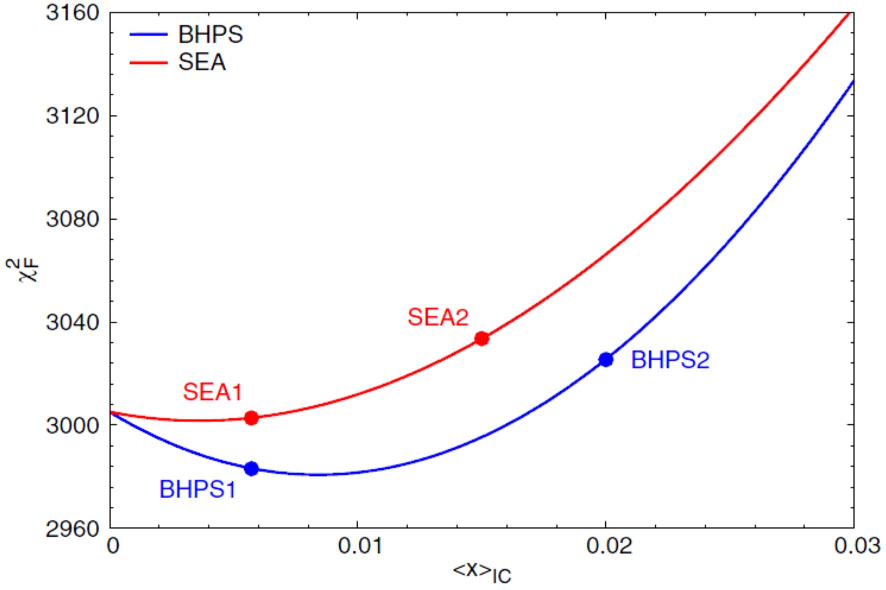
No conclusive evidence for intrinsic-charm

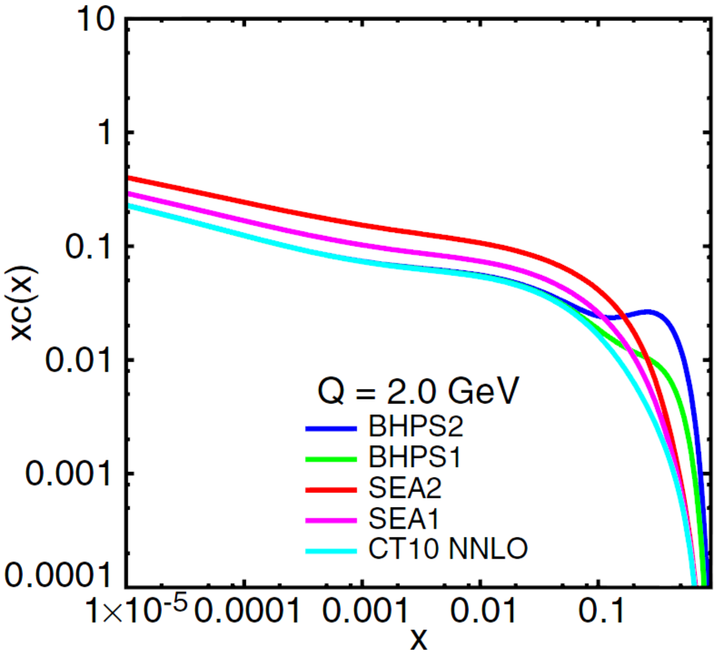


PHYSICAL REVIEW D **89**, 073004 (2014)

Intrinsic charm parton distribution functions from CTEQ-TEA global analysis

Sayipjamal Dulat,[1,2,*] Tie-Jiun Hou,[3,†] Jun Gao,[4,‡] Joey Huston,[2,§] Jon Pumplin,[2,¶] Carl Schmidt,[2,*]
Daniel Stump,[2,††] and C.-P. Yuan[2,‡‡]





$$\langle x \rangle_{IC} \equiv \int_0^1 [c(x) + \bar{c}(x)]dx$$

$$\langle x \rangle_{IC} \leq 2.5\,\%$$

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: $|uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uuds\bar{s}\rangle$?

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

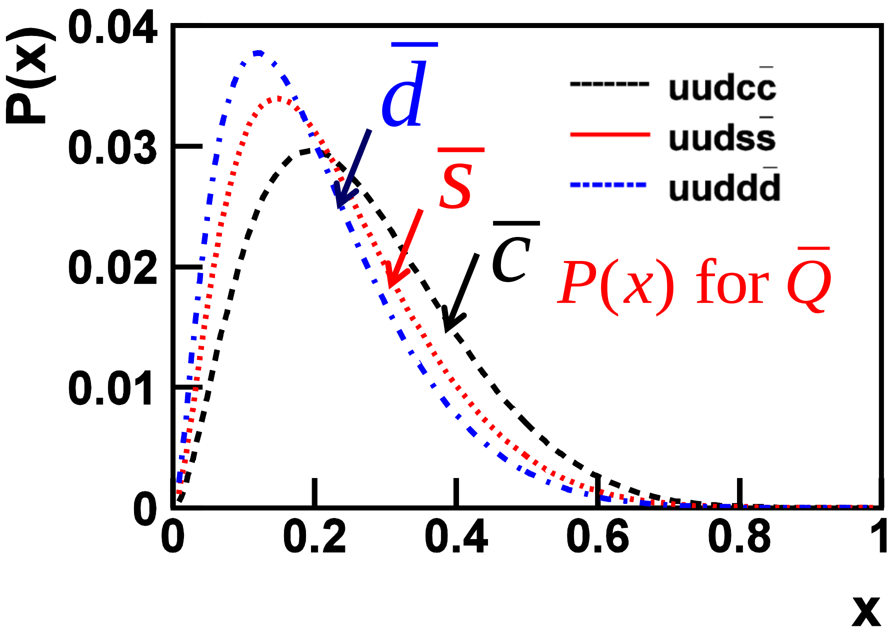
The “intrinsic” sea for lighter quarks have larger probabilities!

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”?

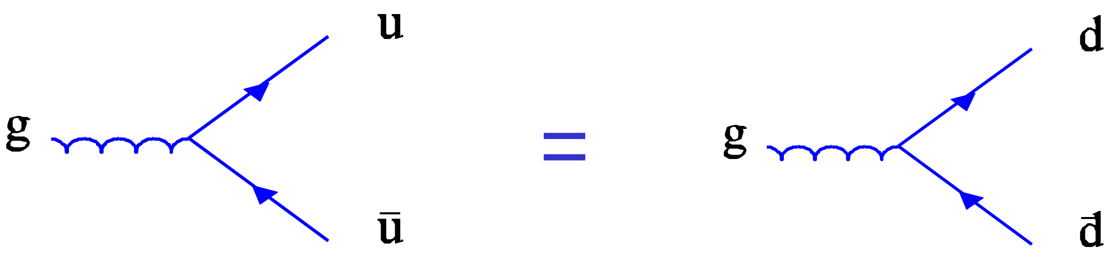
- Select experimental observables which have no contributions from the “extrinsic sea”
- “Intrinsic sea” and “extrinsic sea” are expected to have different *x*-distributions
  - Intrinsic sea is “valence-like” and is more abundant at larger *x*
  - Extrinsic sea is more abundant at smaller *x*

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

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

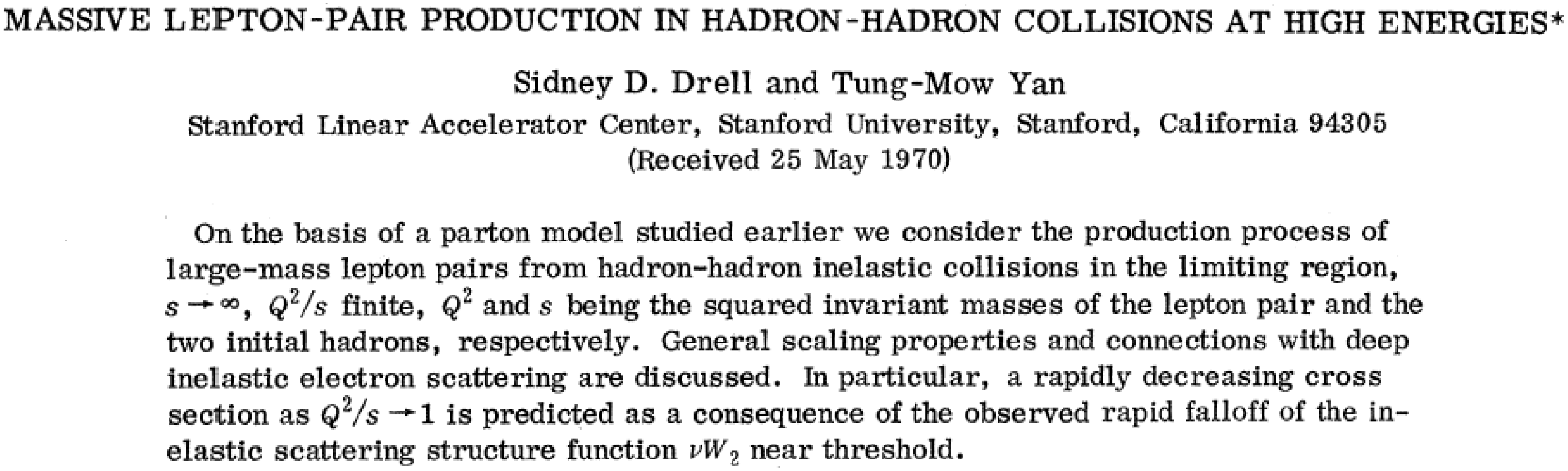
$$\bar{d} - \bar{u} \text{ has no contribution from extrinsic sea } (g \to \bar{q}q)$$

$$\text{and is sensitive to "intrinsic sea" only}$$



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

The Drell-Yan Process

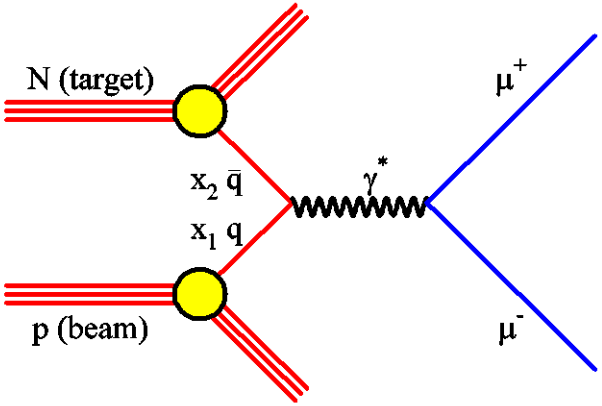


MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 25 May 1970)

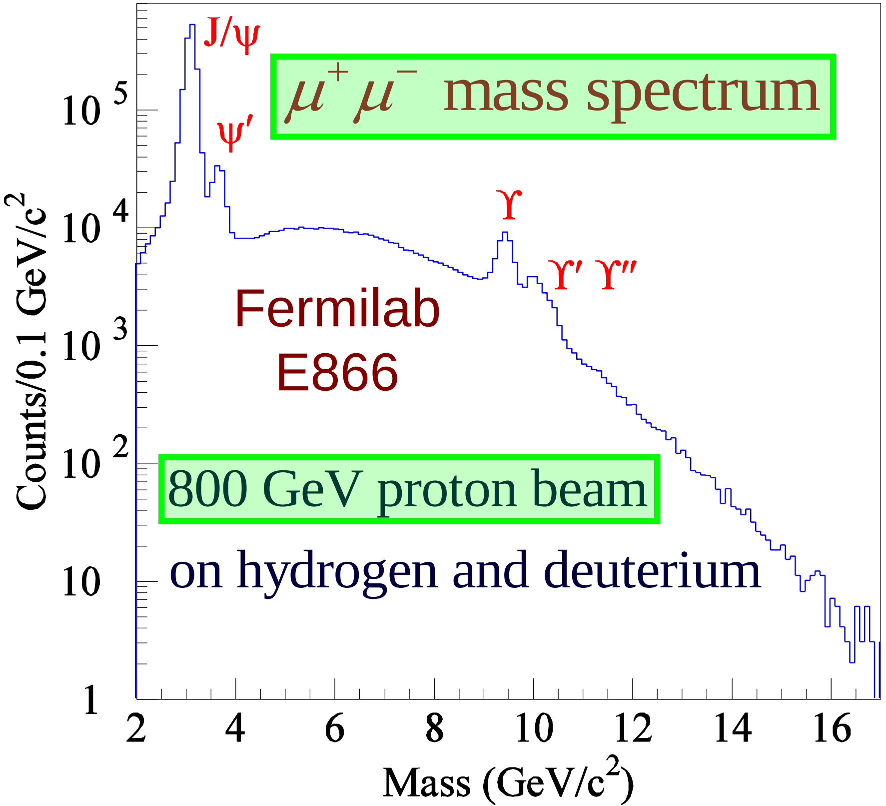
On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \rightarrow \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \rightarrow 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



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

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

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

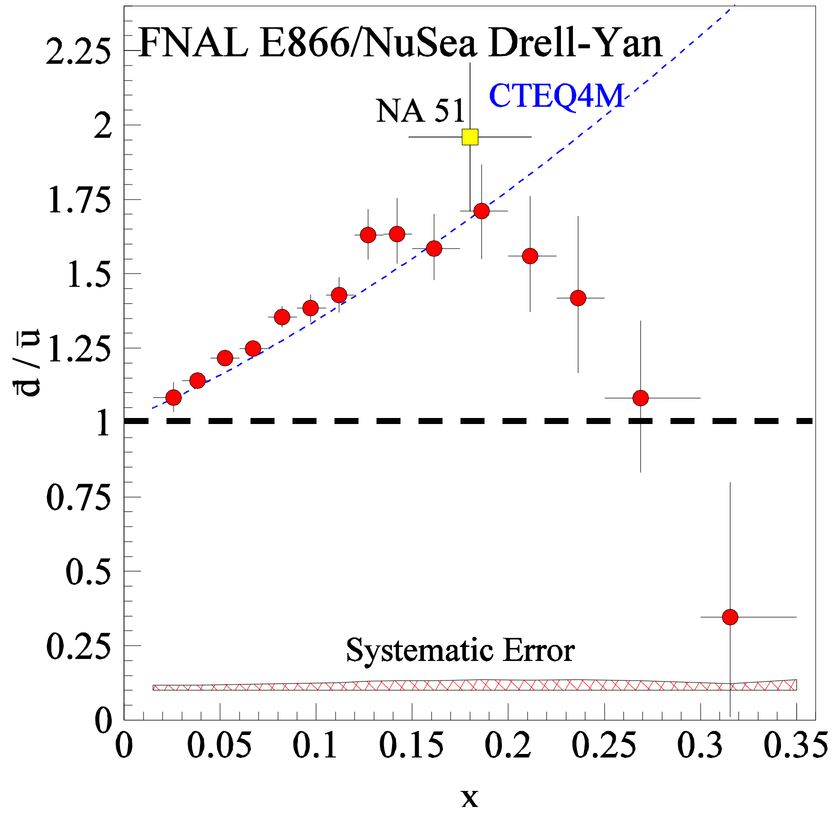


$\mu^+\mu^-$ mass spectrum

Fermilab E866

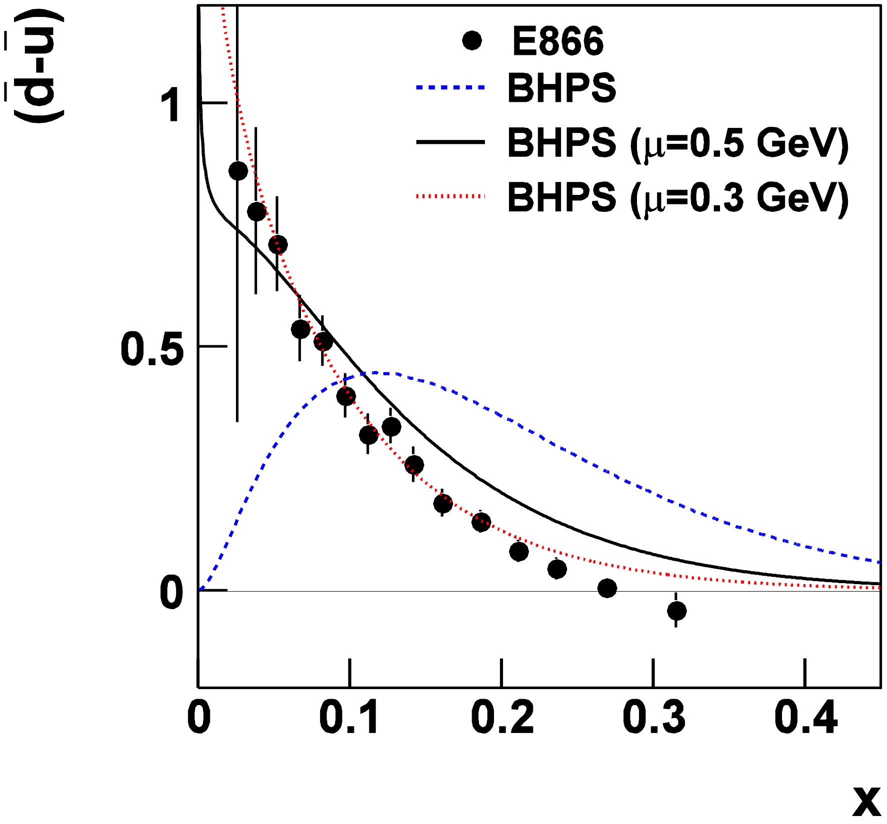
800 GeV proton beam

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 GeV^2

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

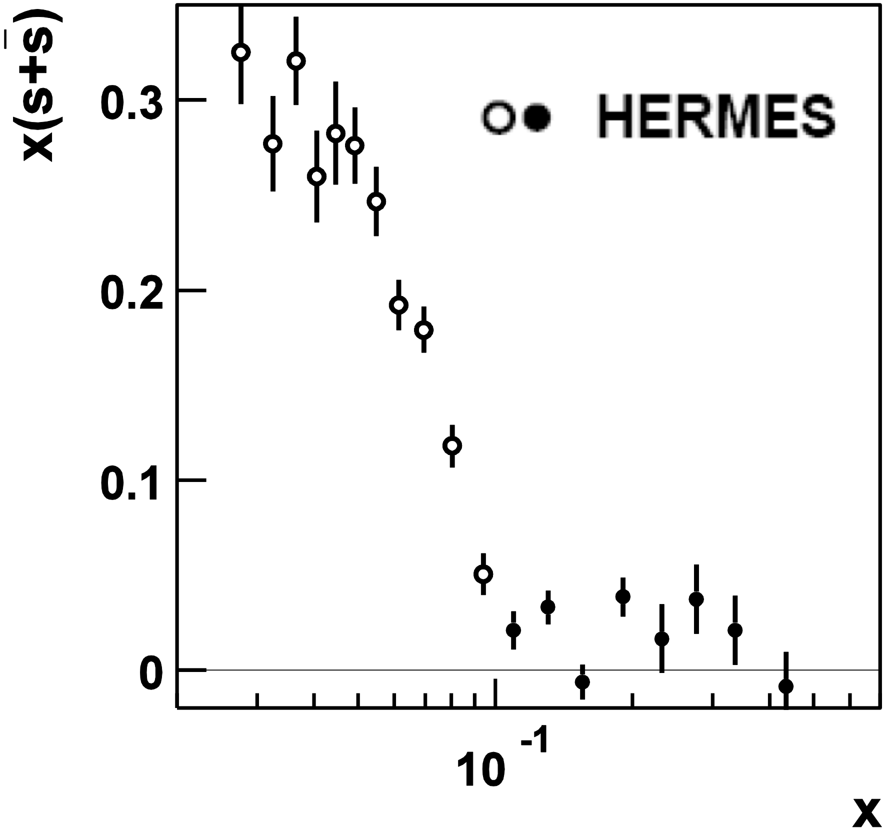
$$\boxed{P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118}$$

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

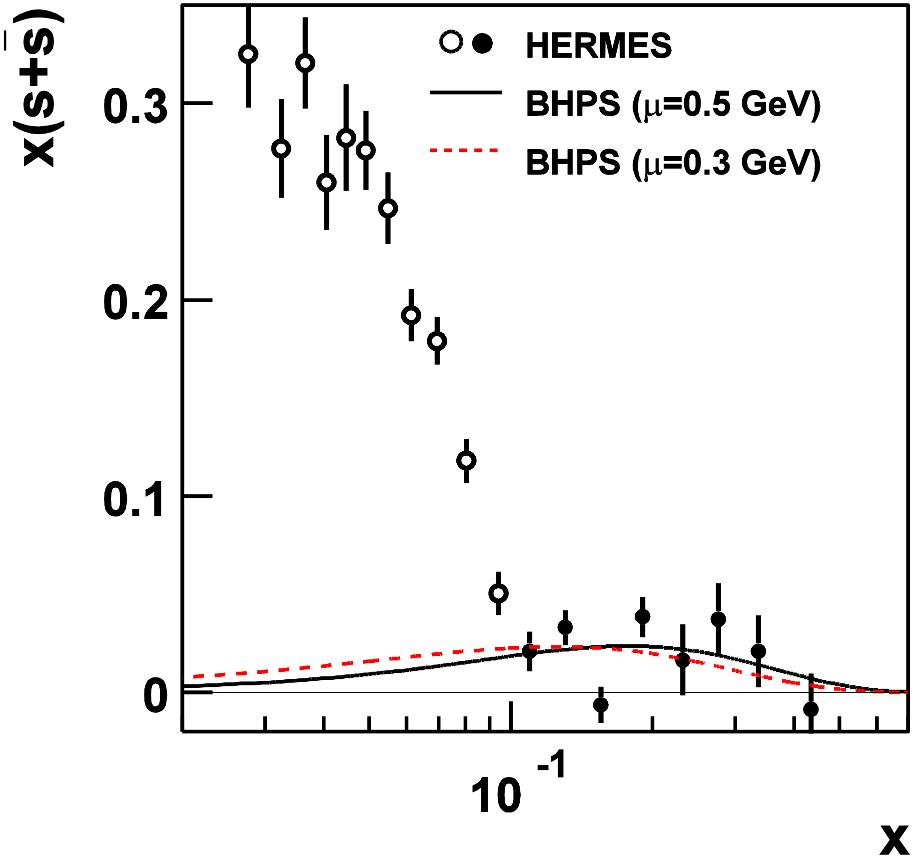


$s(x)+\bar{s}(x)$ extracted from HERMES Semi-inclusive DIS kaon data at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$

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

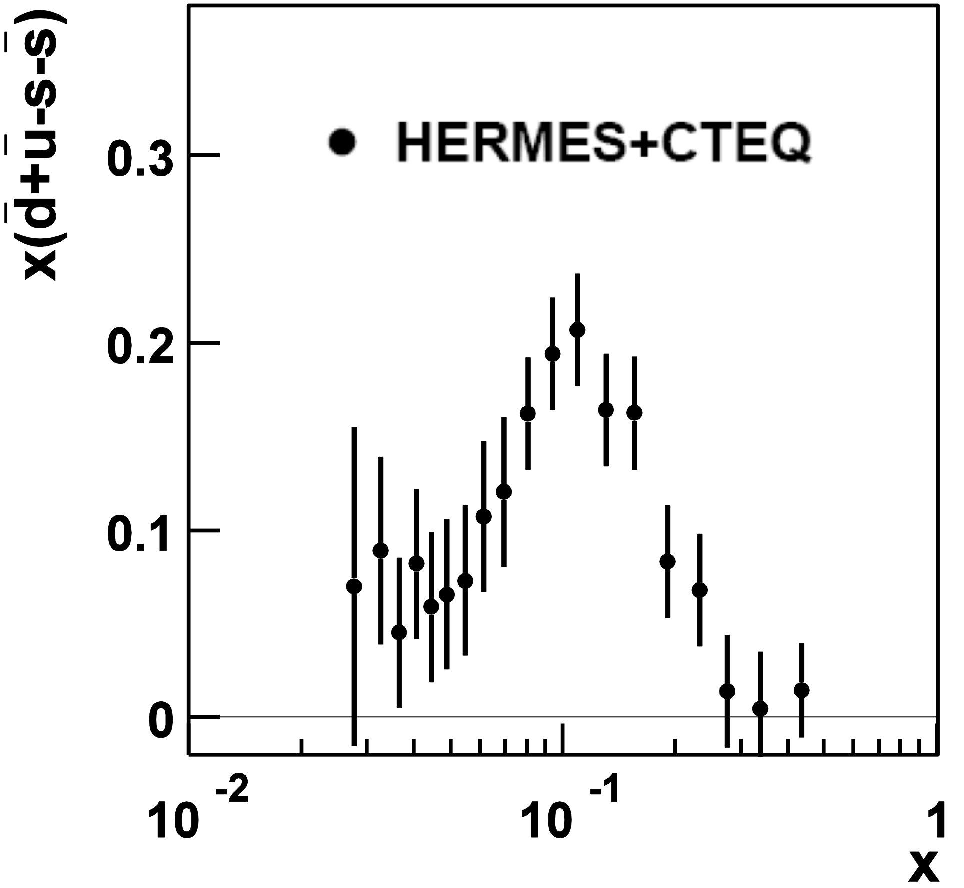
$$\boxed{P_5^{uuds\bar{s}} = 0.024}$$

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

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

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

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



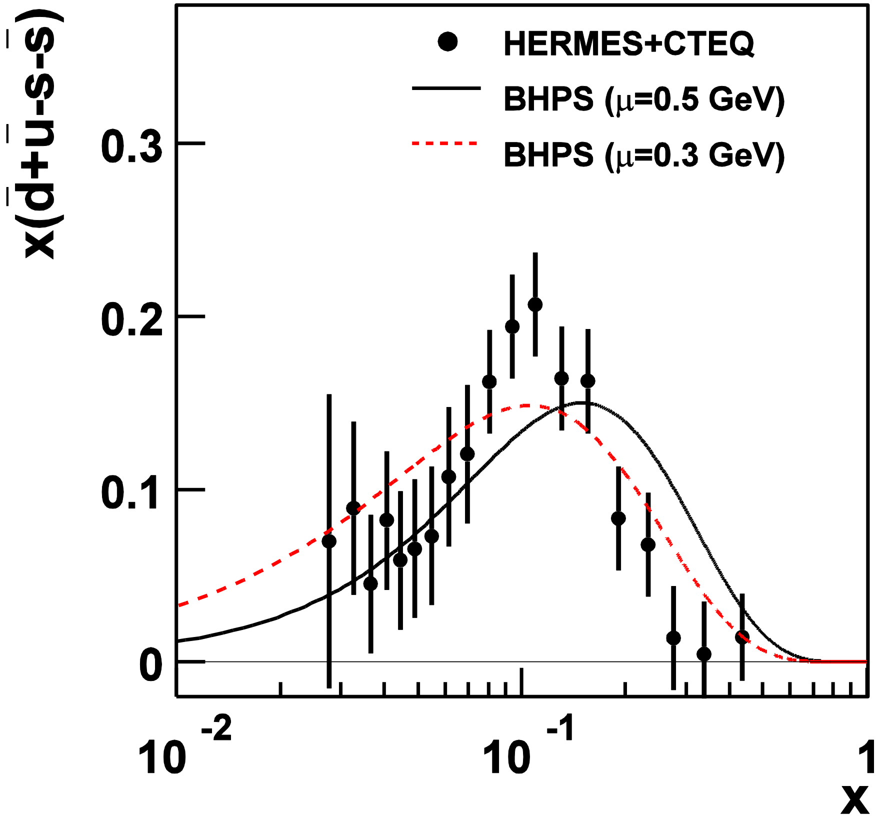
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

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

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

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

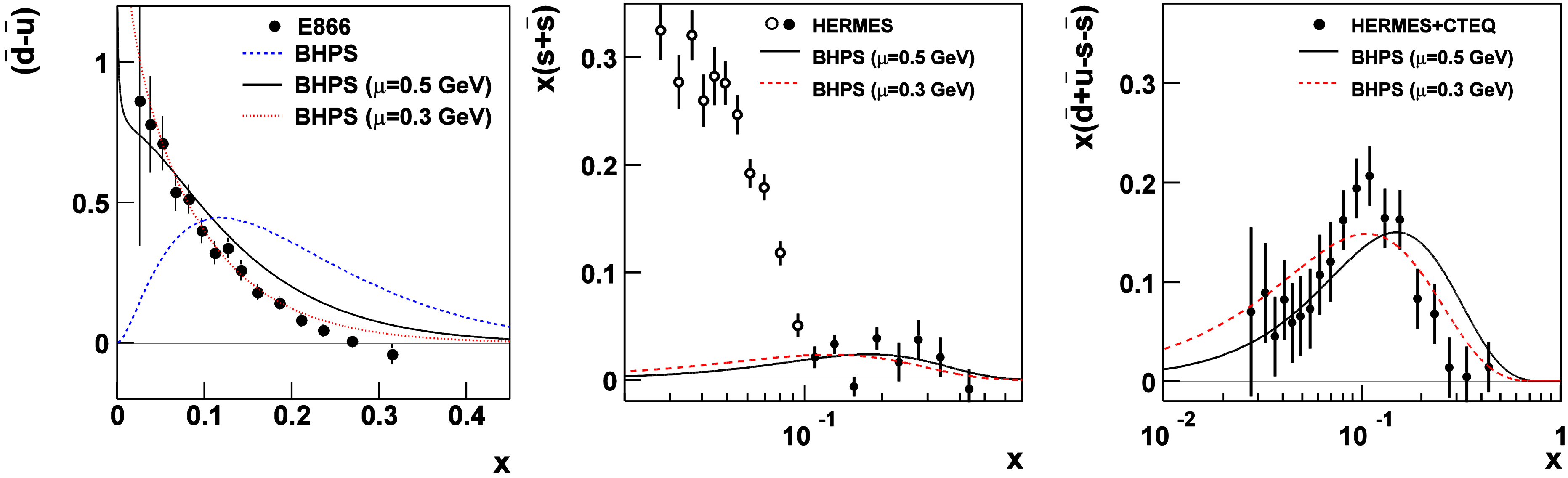
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

(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



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

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

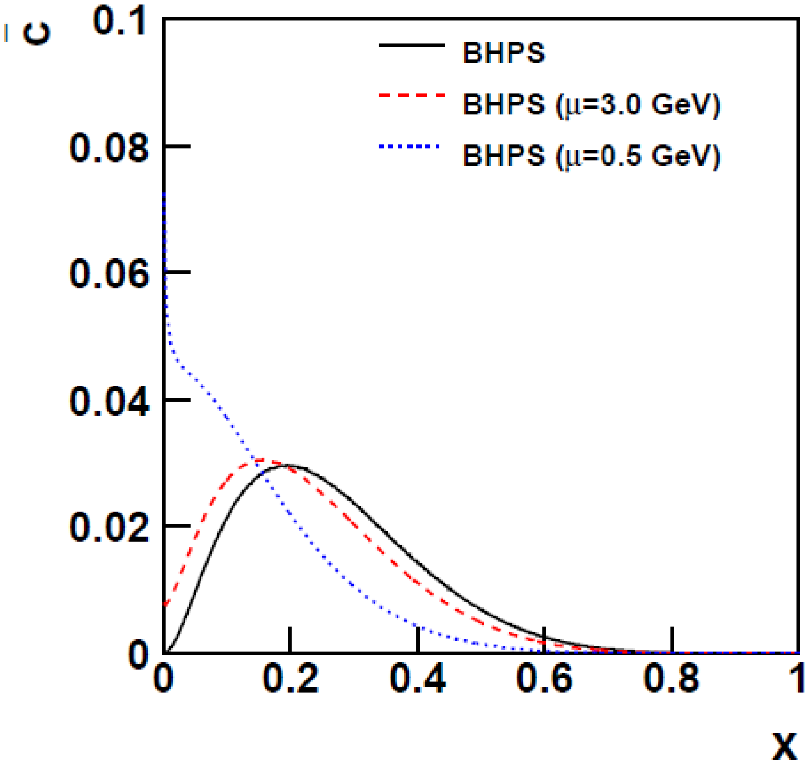
$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$

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

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

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

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

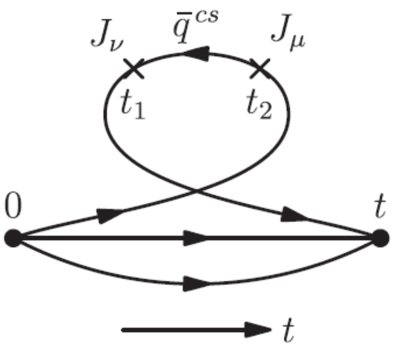
- Search for intrinsic charm and beauty at RHIC and LHC.
- Spin-dependent observables of intrinsic sea?
- Global fits including intrinsic u, d, s sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

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

Connected-Sea Partons

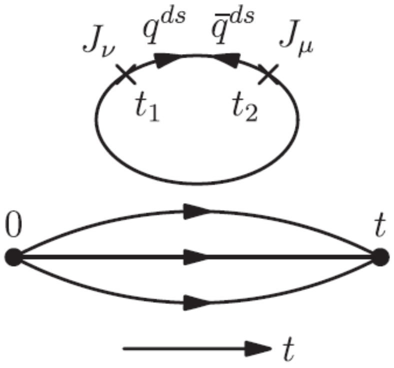
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea



(valence-like)

Disconnected sea



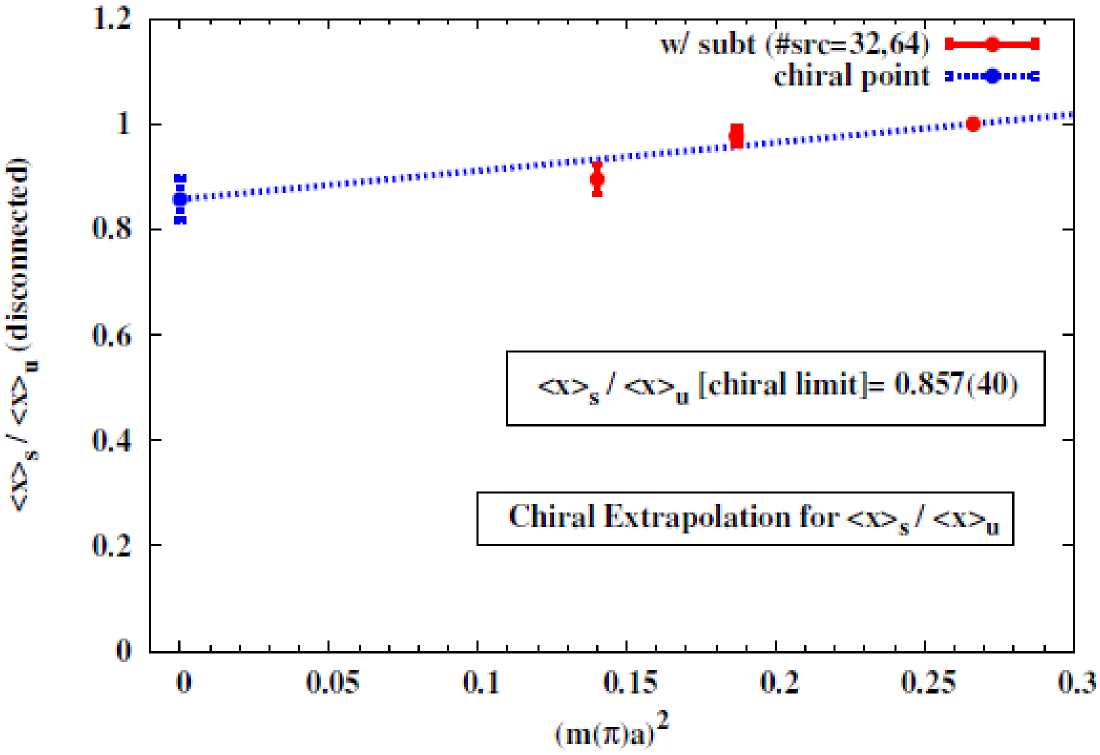
(sea-like)

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

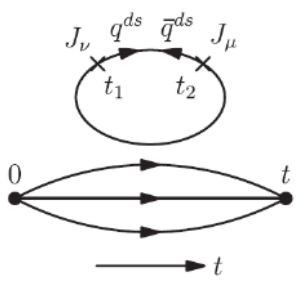
CS and DS have different Bjorken-x and flavor dependences

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

(since $s,\bar{s}$ is entirely from the disconnected sea)

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

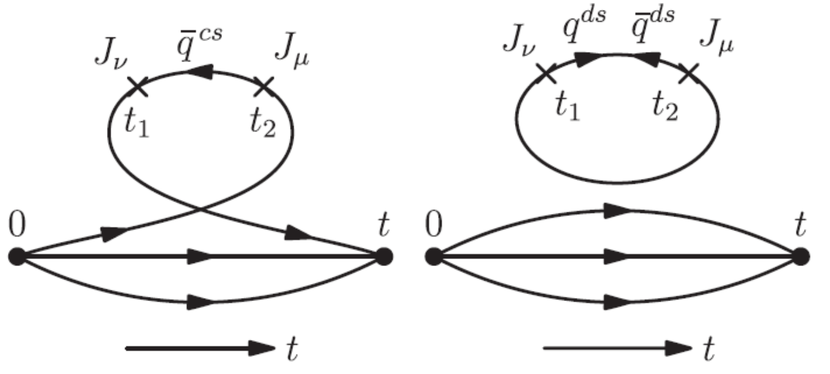
$$[\bar{u}(x)+\bar{d}(x)]_{\text{PDF}}-[\bar{u}(x)+\bar{d}(x)]_{\text{disconnected sea}}$$

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

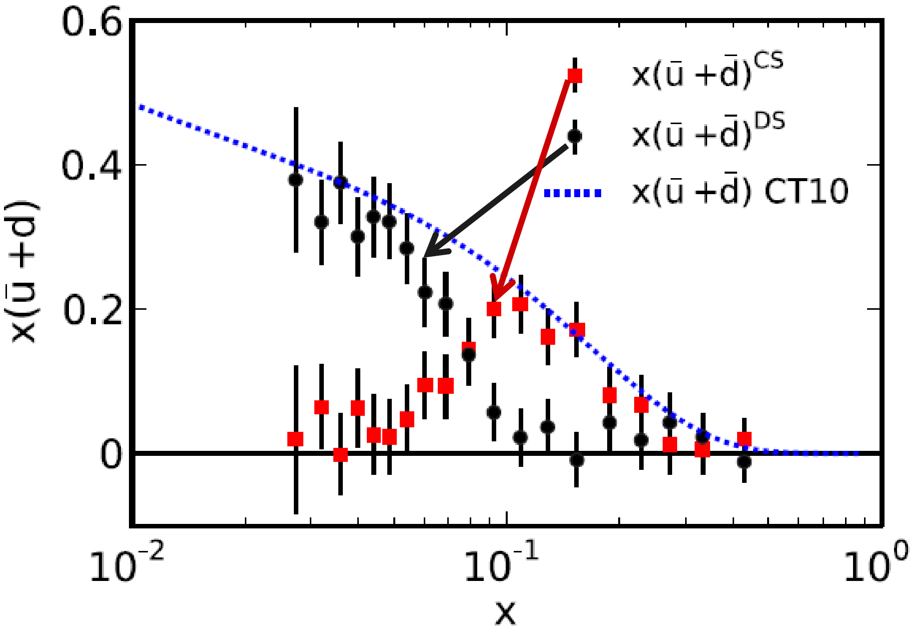
Connected-Sea Partons

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

Connected sea Disconnected sea

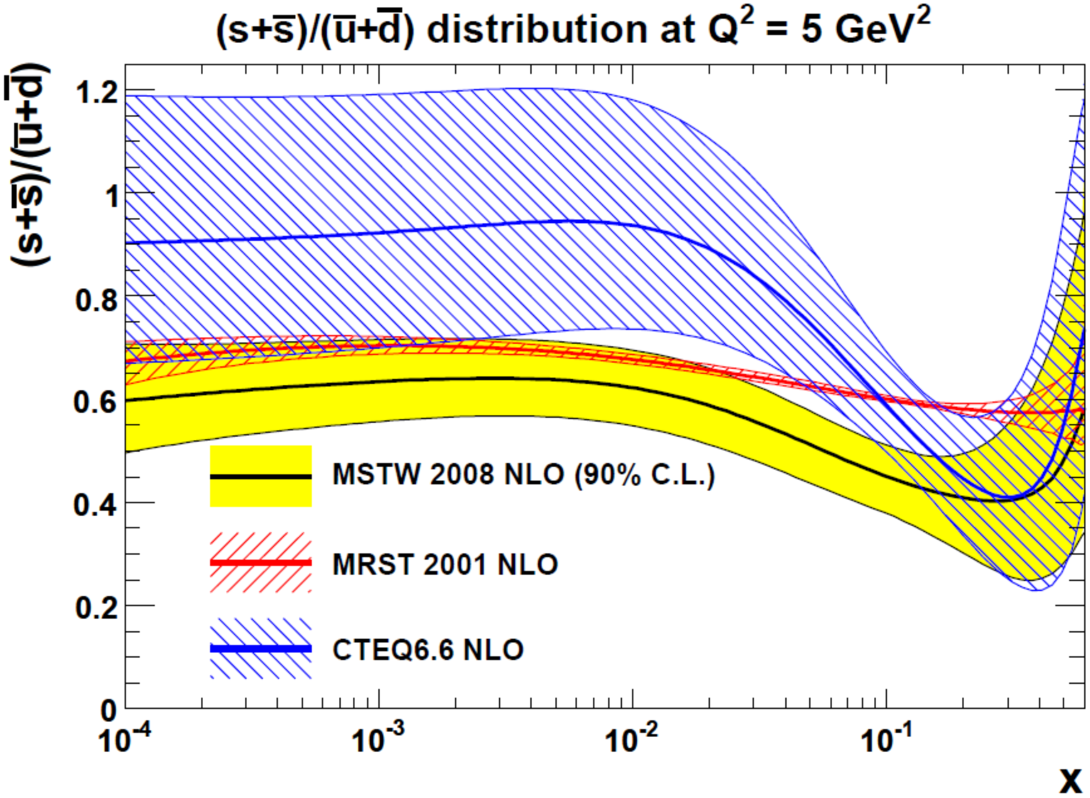


(valence-like) (sea-like)



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



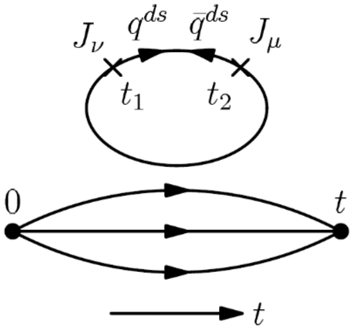
- CTEQ6.6 suggests an SU(3) symmetric sea at small x?
- A strong $x-$dependence for the $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$ ratio?

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*

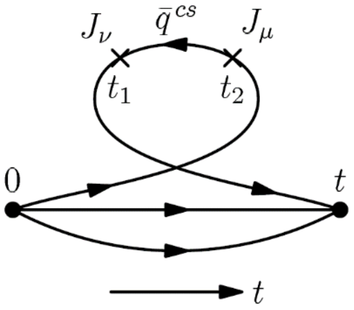
Can be understood from Lattice QCD (PRL 109 (2012)252002)

Disconnected sea



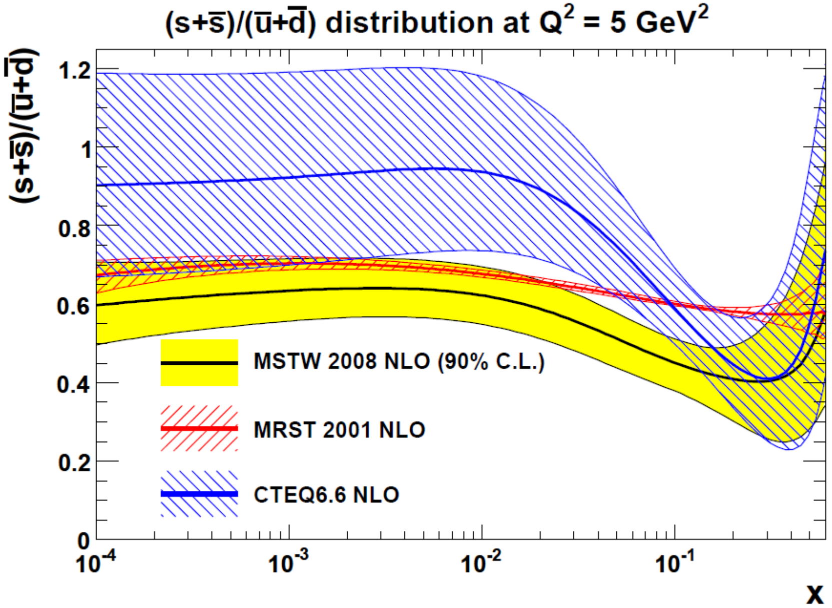
Generate roughly symmetric $s(x), \bar{s}(x), \bar{u}(x)$ and $\bar{d}(x)$ at small *x*

Connected sea

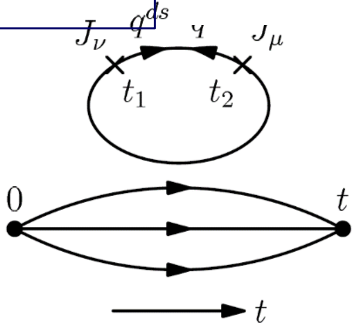


Generate additional "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger *x*

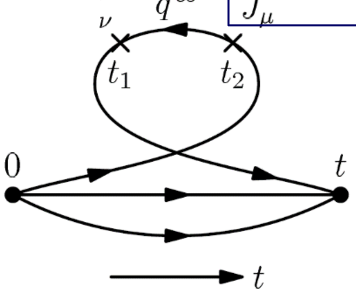
The x-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$



Disconnected sea



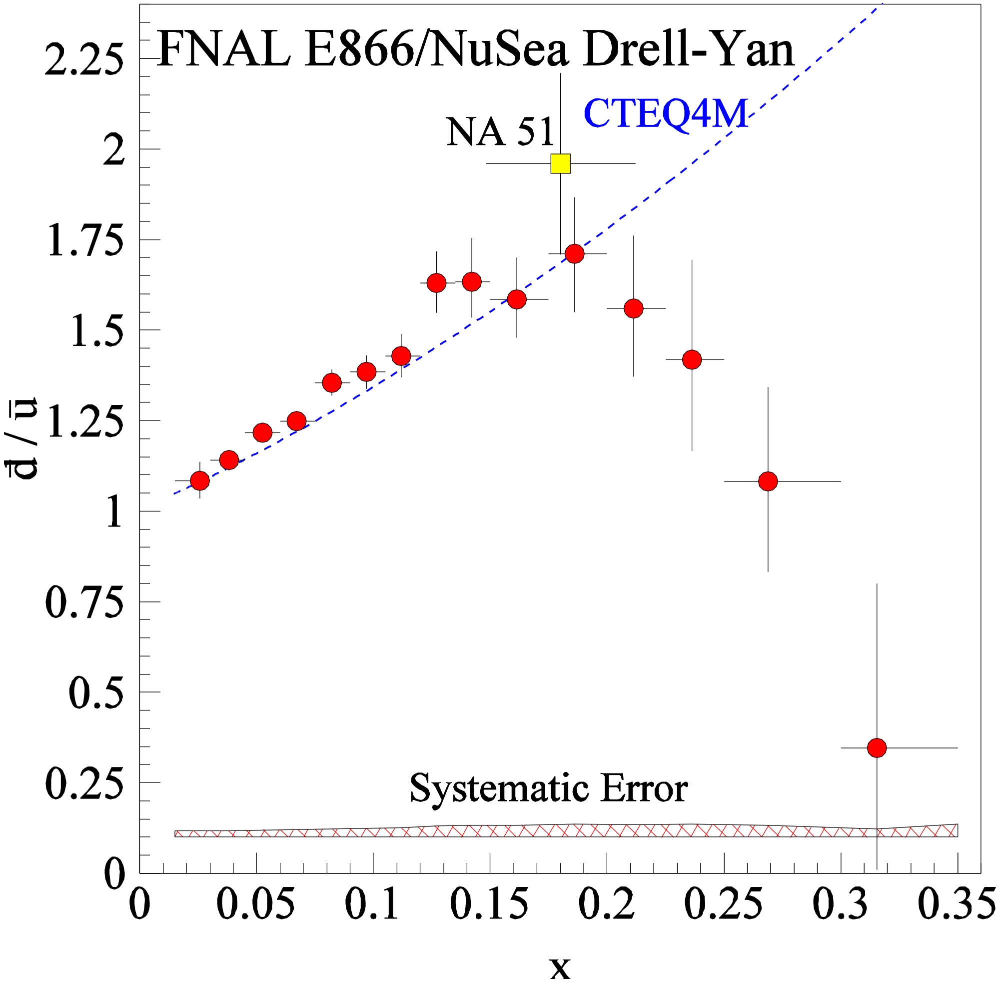
Connected sea



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

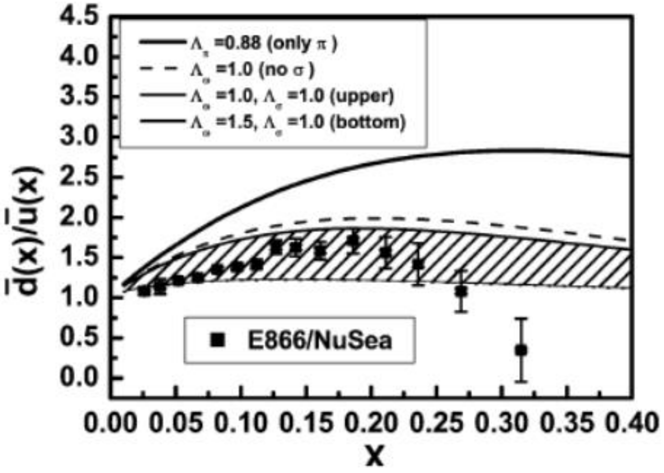
for $\bar{d}(x)-\bar{u}(x)$ at any value of x

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

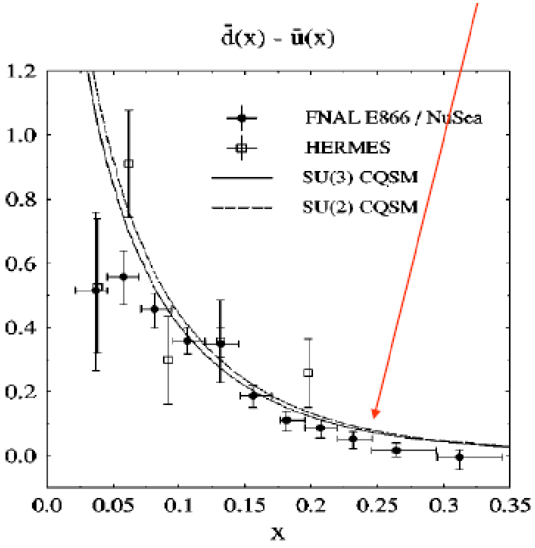
(or $\bar{d}(x)/\bar{u}(x)<1$ at $x\sim 0.25$?)

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

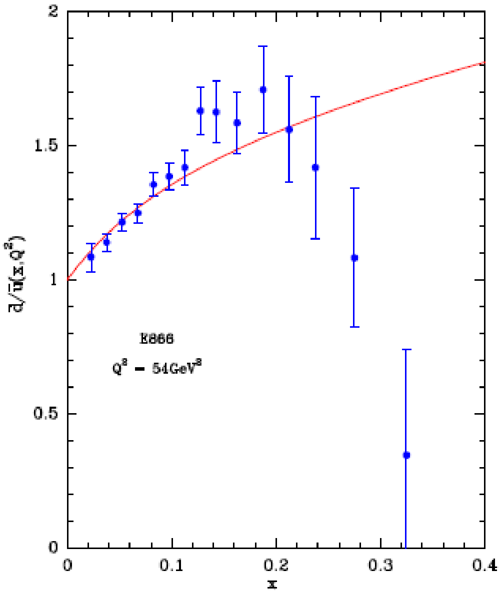
Meson cloud model



Chiral-quark soliton model

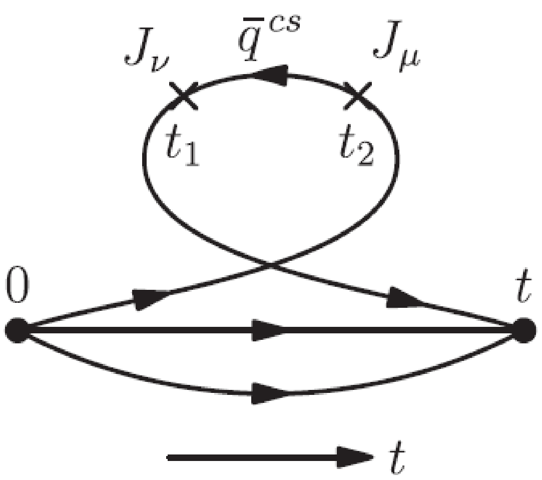


Statistical model



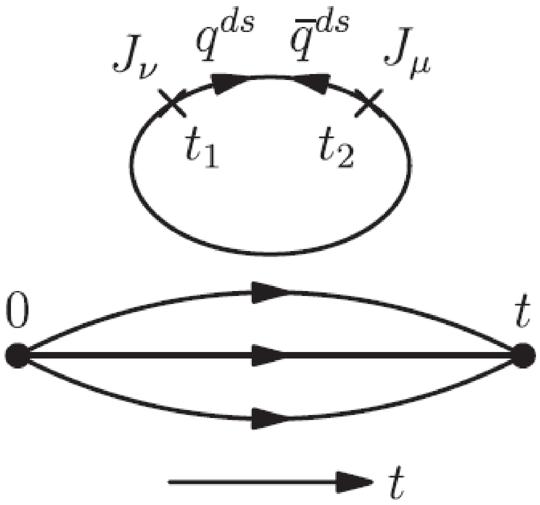
What mechanism could lead to $\bar{u} > \bar{d}$ at $x > 0.25$?

Connected sea



(valence-like)

Disconnected sea



(sea-like)

(JCP, W.C. Chen,
H.Y. Cheng, T.J. Hou,
K.F. Liu, J.W. Qiu,
Phys Lett B736 (2014) 411)

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

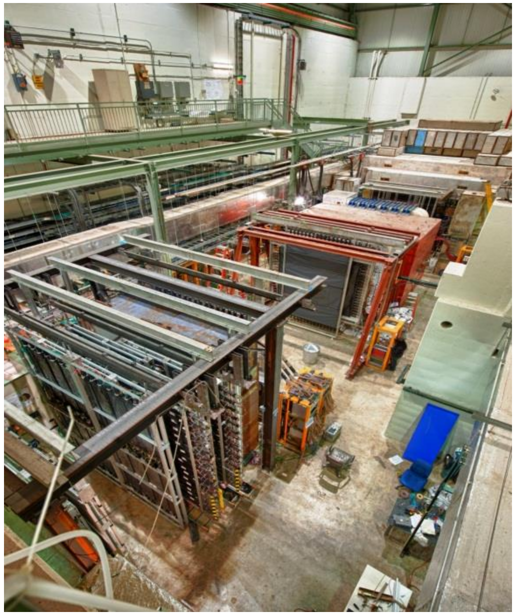
$(u \rightarrow \bar{u} + u + u,\ d \rightarrow \bar{d} + d + d)$ ($\bar{q}$ has the same flavor as q for CS)

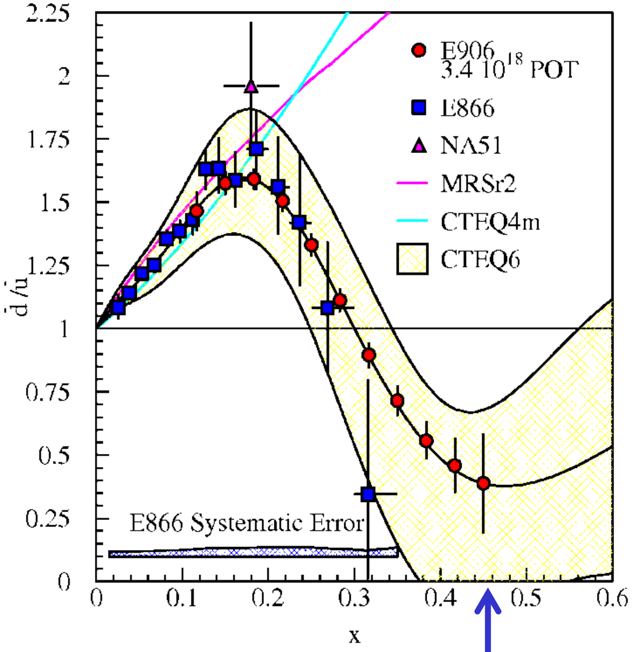
$\Rightarrow$ Connected sea could lead to $\bar{u} > \bar{d}$ at certain x region??

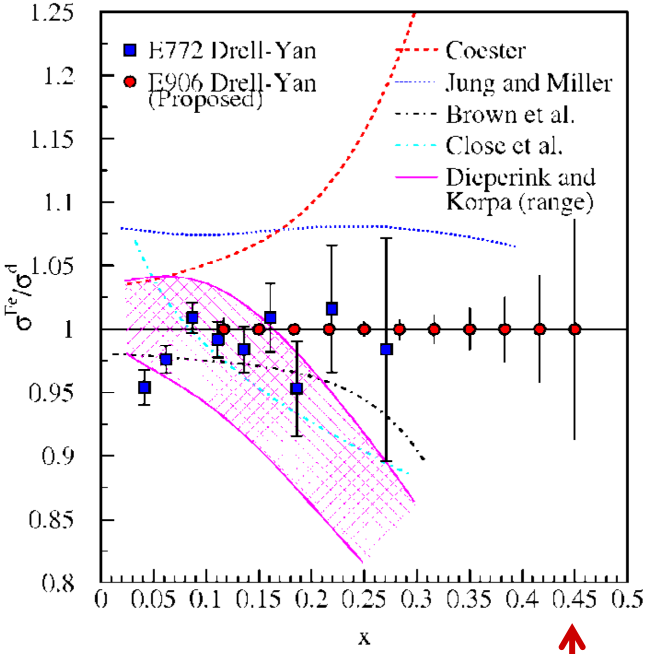
(since there are two u valence quarks and one d valence quak)

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 $x \sim 0.45$

- Commission run took place in February – April 2012
- 2-year production run expected in 2014-2016

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.

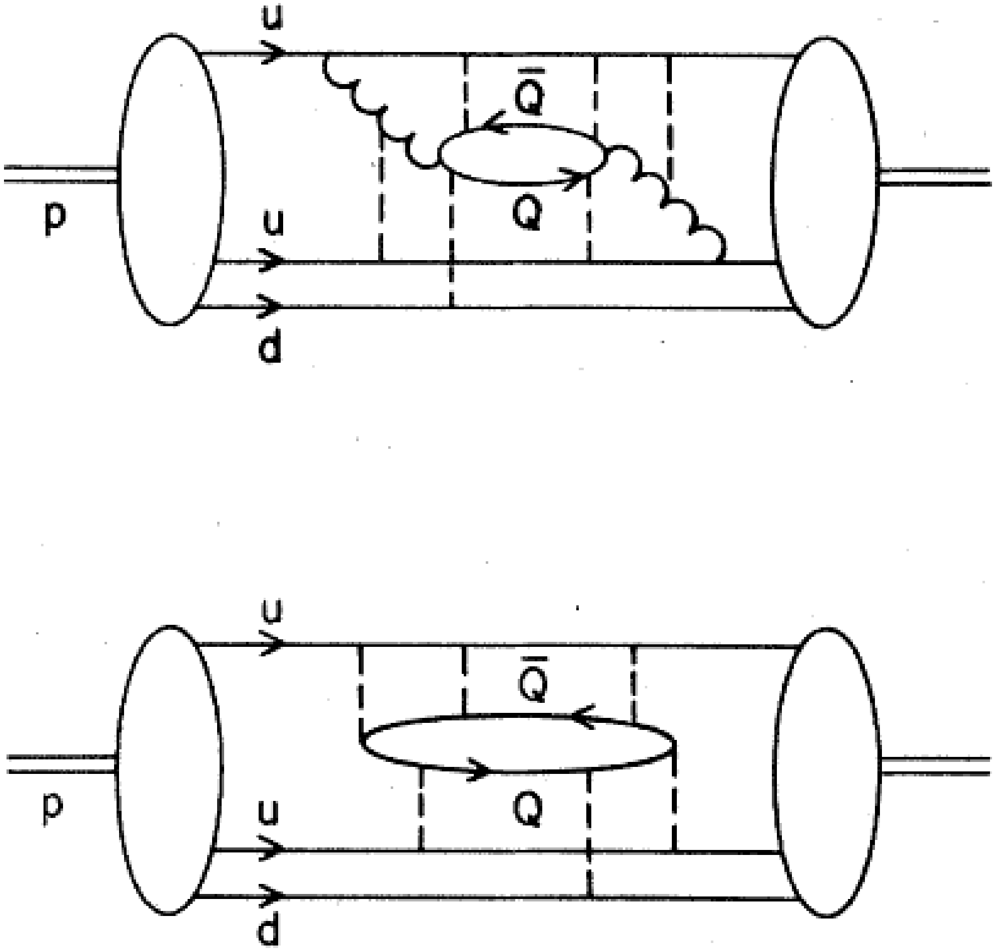
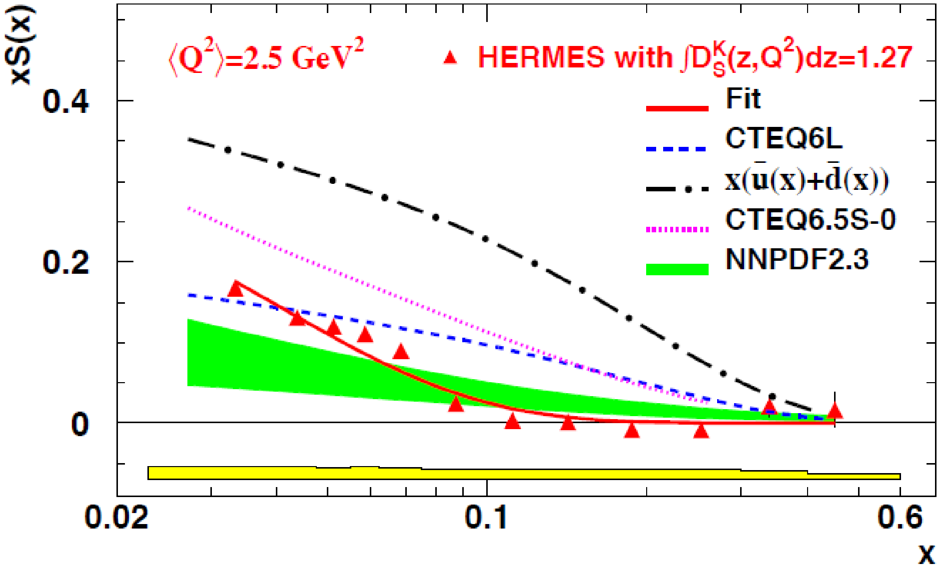


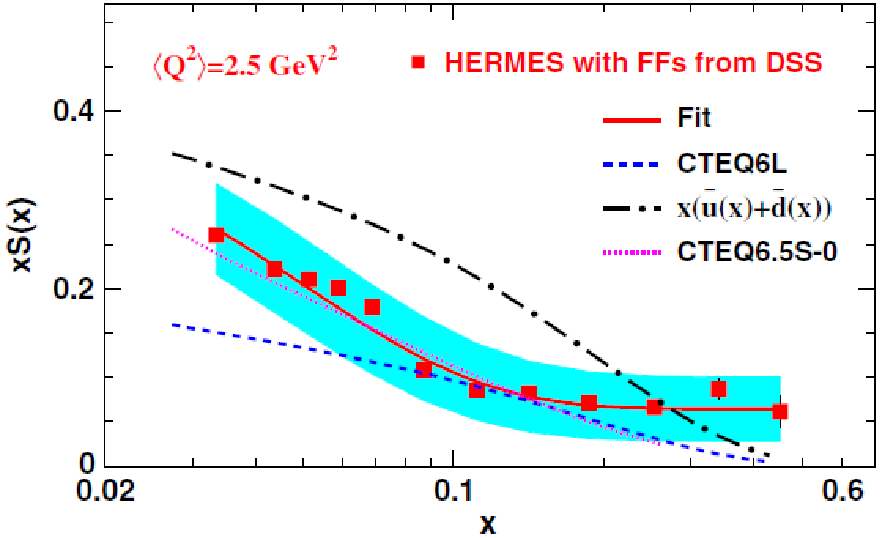
FIG. 1. Diagrams which give rise to the intrinsic heavy quarks ($Q\bar{Q}$) within the proton. Curly and dashed lines represent transverse and longitudinal-scalar (instantaneous) gluons, respectively.

Latest HERMES result on $xS(x)$



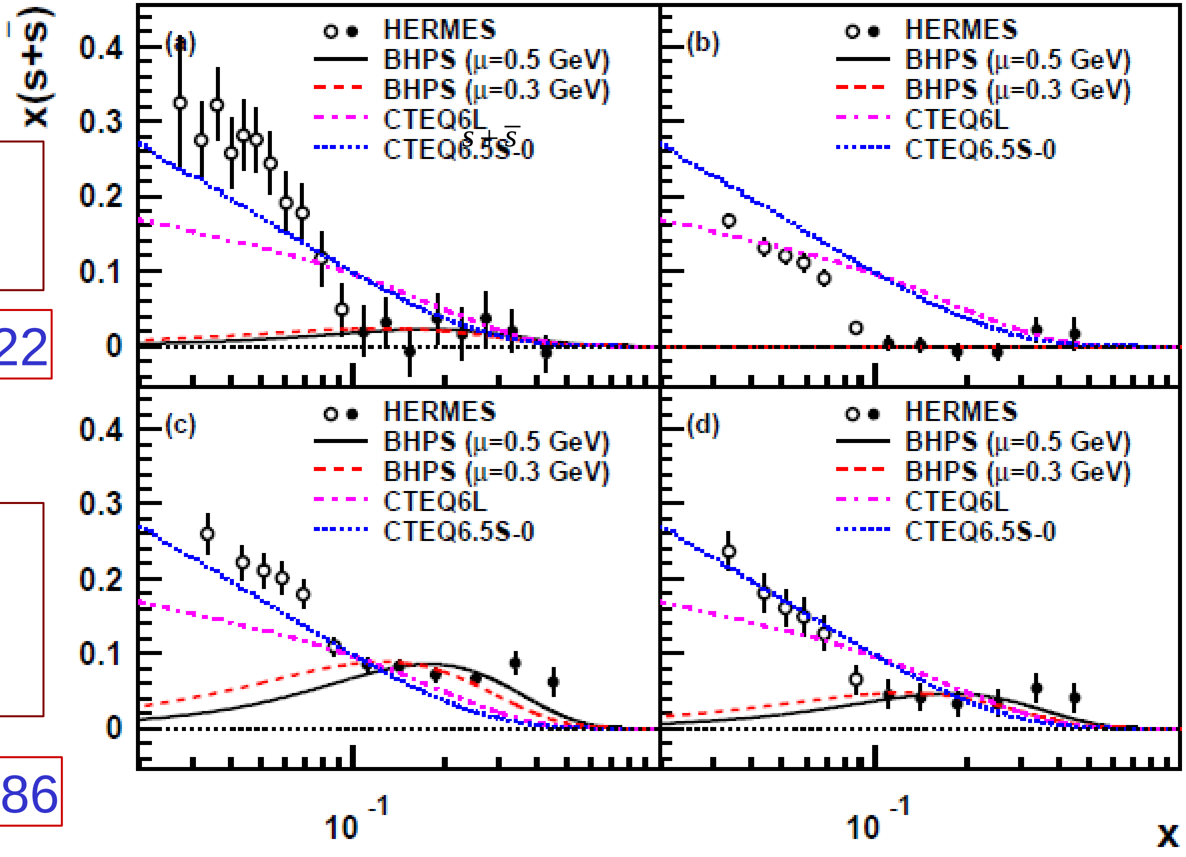
New 2014 result obtained with HERMES kaon fragmentation function

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

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

2014
HERMES

$P_5^{uuds\bar{s}}$=0.00

2014
HERMES
DSS FF

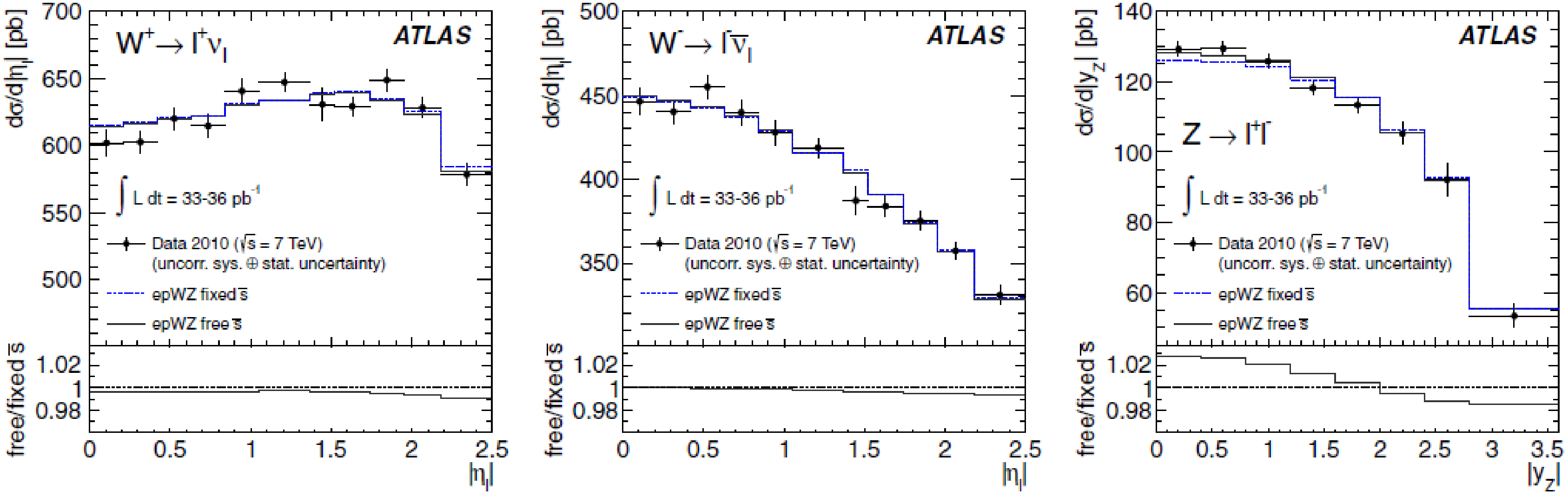
$P_5^{uuds\bar{s}}$=0.086

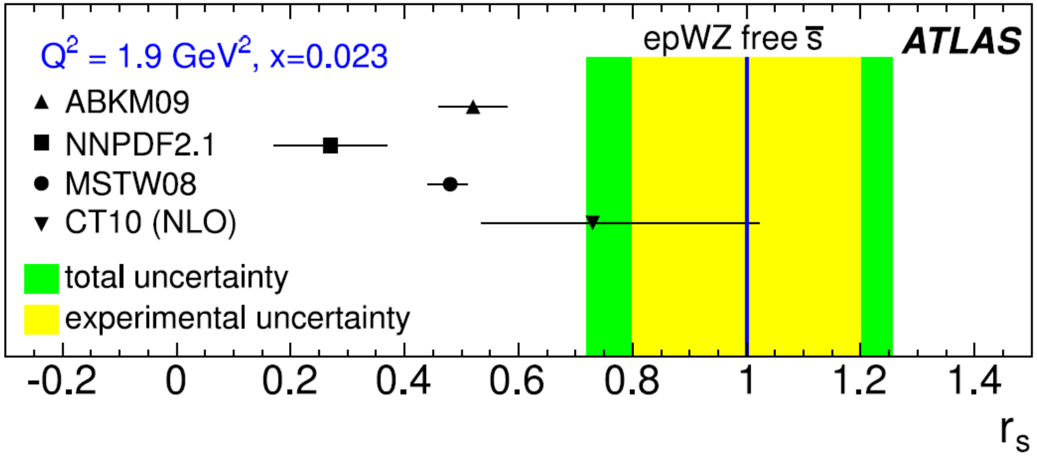
2014
HERMES
Intermediate
FF

$P_5^{uuds\bar{s}}$=0.046

Wen-Chen Chang and JCP, arXiv: 1410.7027

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

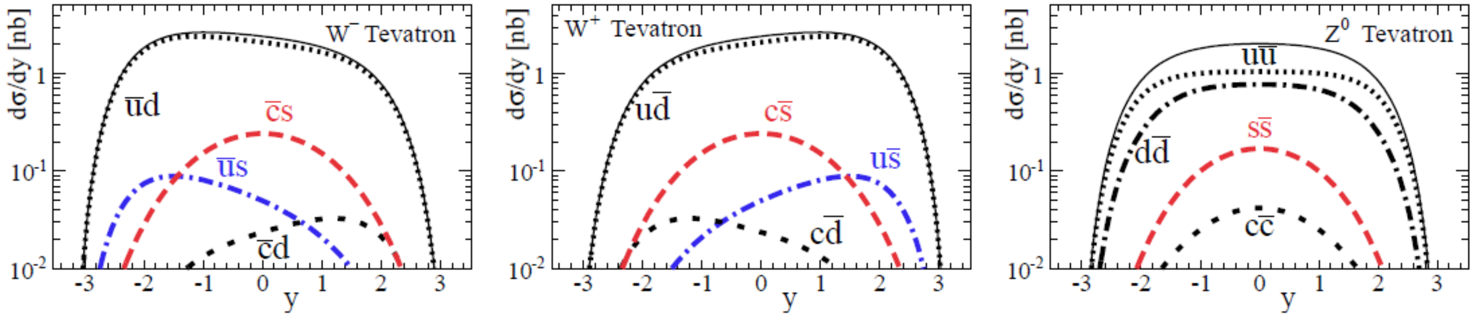
Strange sea from inclusive W/Z production

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

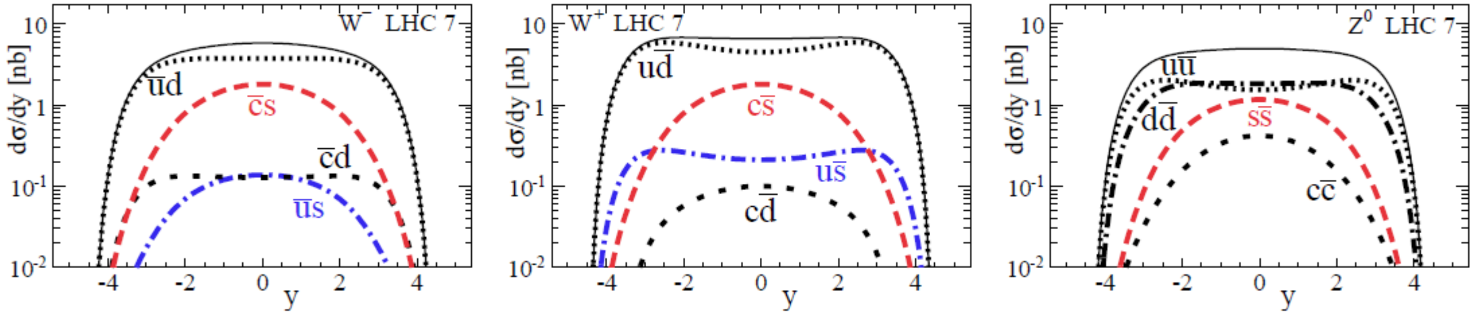
$$W^+:\ \ (u \text{ or } c) + (\bar{d} \text{ or } \bar{s}) \rightarrow W^+$$

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

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



(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

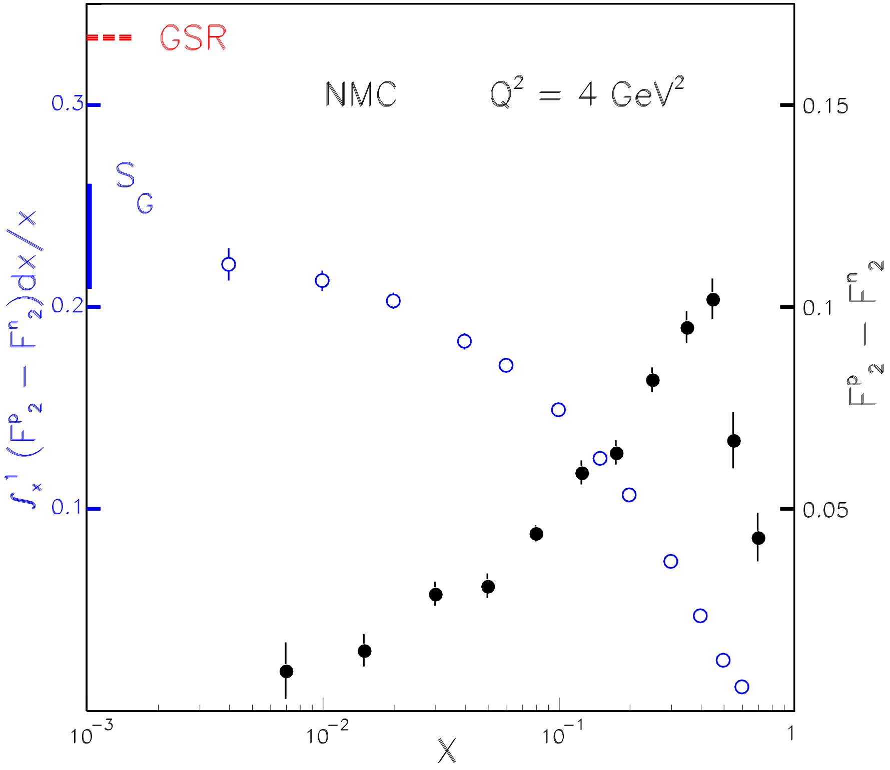
Revisit the NMC measurement of the Gottfried Sum rule

The Gottfried Sum Rule

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

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

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



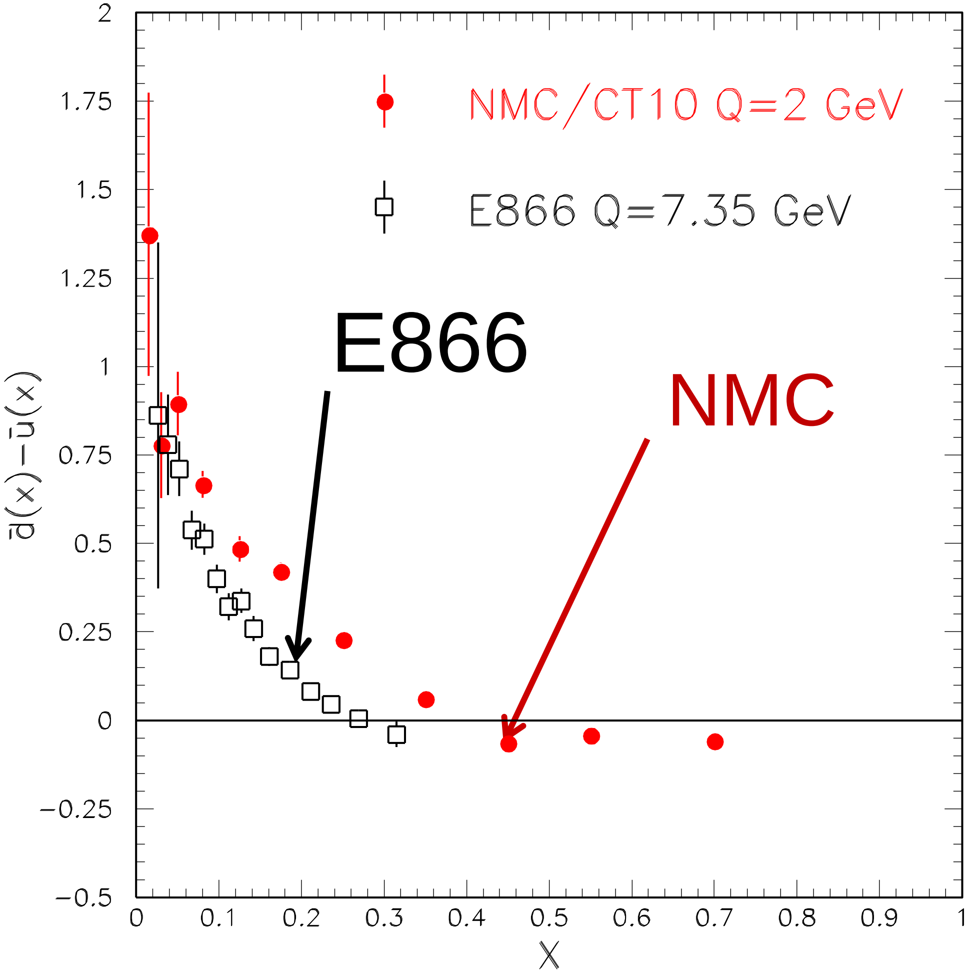
New Muon Collaboration (NMC) obtains

S_G = 0.235 ± 0.026

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

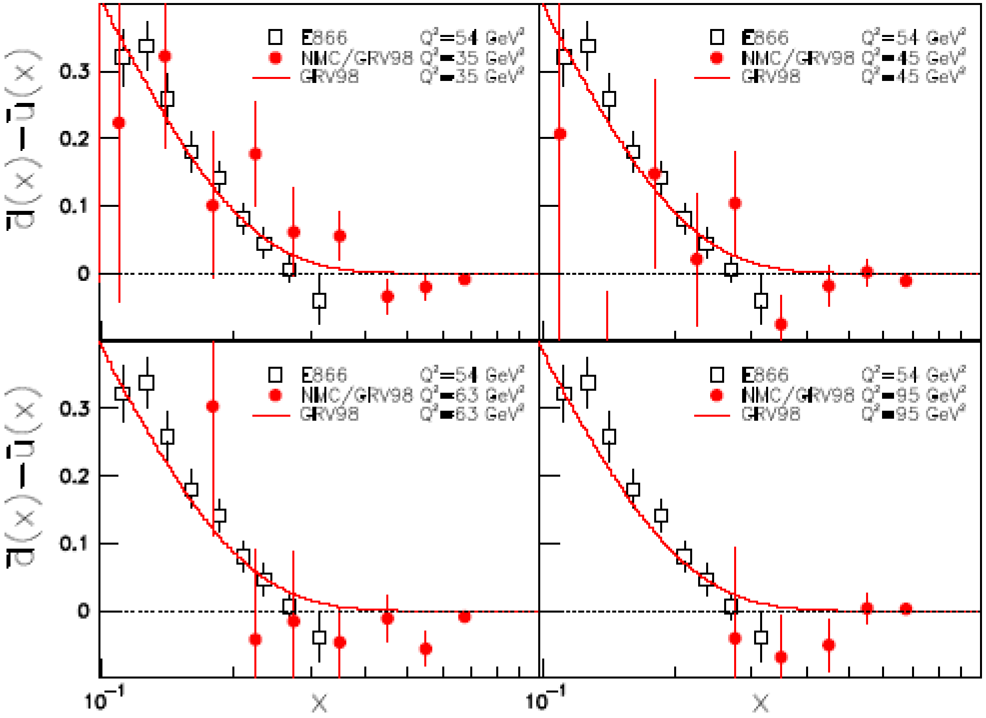
Extracting $\bar{d}(x)-\bar{u}(x)$ from the NMC data

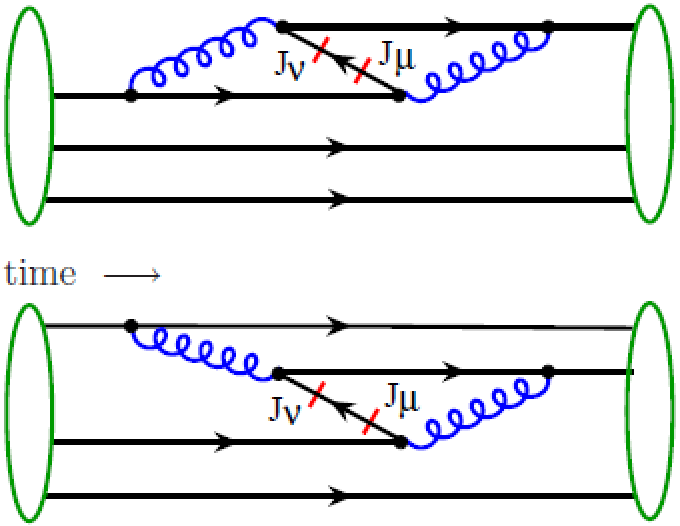
$$\boxed{\bar{d}(x)-\bar{u}(x)=[u_V(x)-d_V(x)]_{CT10}/2-3/2*[F_2^p(x)/x-F_2^n(x)/x]_{NMC}}$$



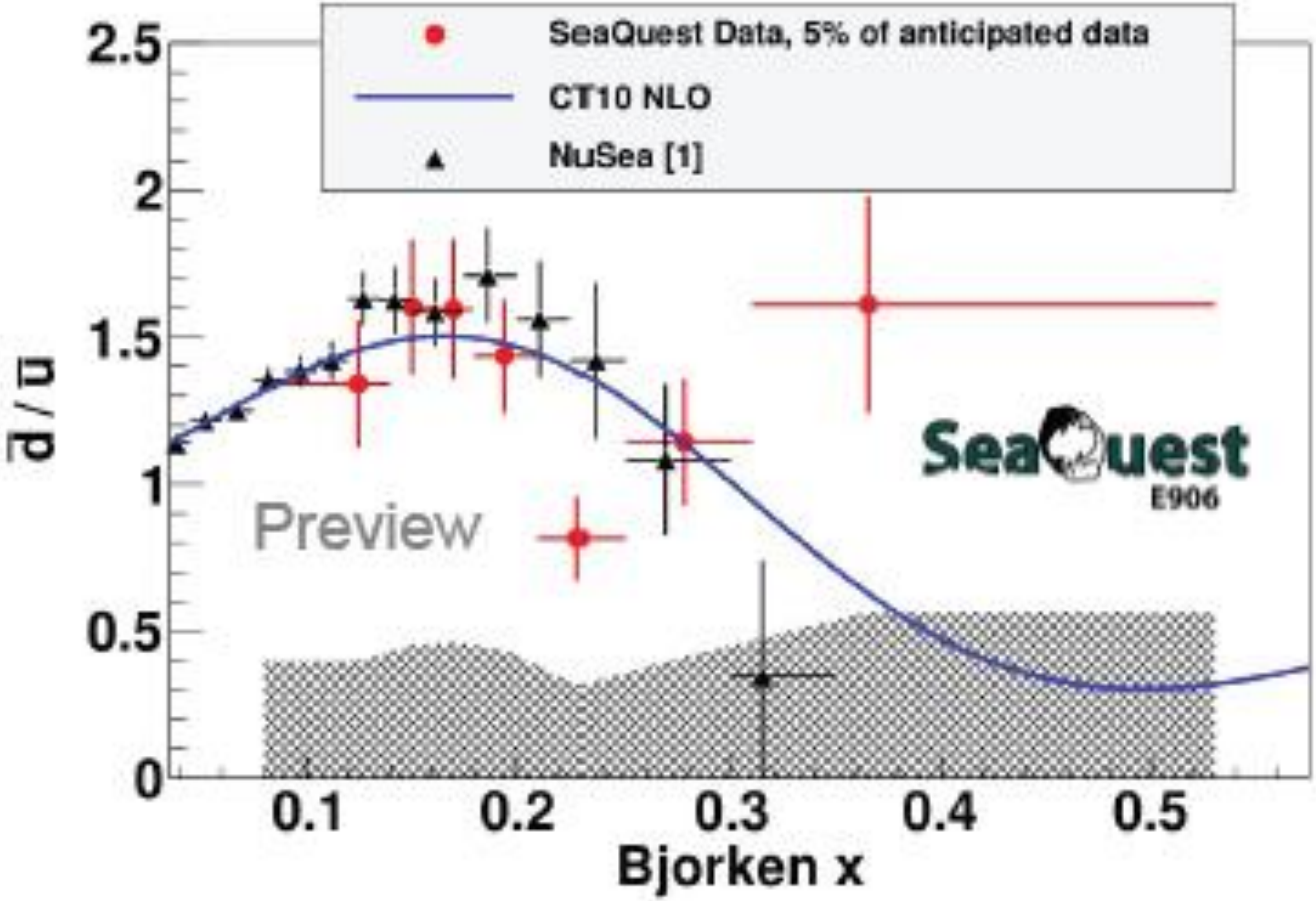
The NMC data, together with the recent PDF, already suggest that $\bar{d}(x)-\bar{u}(x)<0$ at large x!

(JCP, W.C. Chen, H.Y. Cheng, T.J. Hou, K.F. Liu, J.W. Qiu, Phys Lett B736 (2014) 411

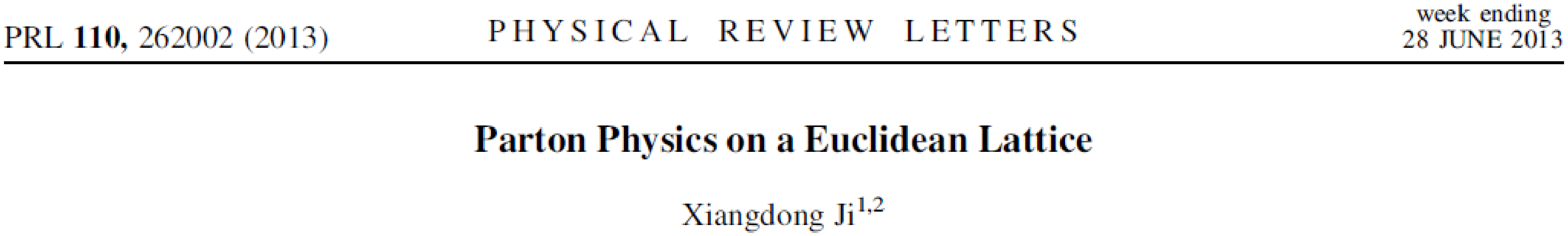

E866 Q²=54 GeV²
NMC/GRV98 Q²=35 GeV²
GRV98 Q²=35 GeV²
E866 Q²=54 GeV²
NMC/GRV98 Q²=45 GeV²
GRV98 Q²=45 GeV²
E866 Q²=54 GeV²
NMC/GRV98 Q²=63 GeV²
GRV98 Q²=63 GeV²
E866 Q²=54 GeV²
NMC/GRV98 Q²=95 GeV²
GRV98 Q²=95 GeV²
d̄(x)−ū(x)
0.3
0.2
0.1
0
10⁻¹
x


Jν
Jμ
time →
Jν
Jμ

First preliminary result from E906



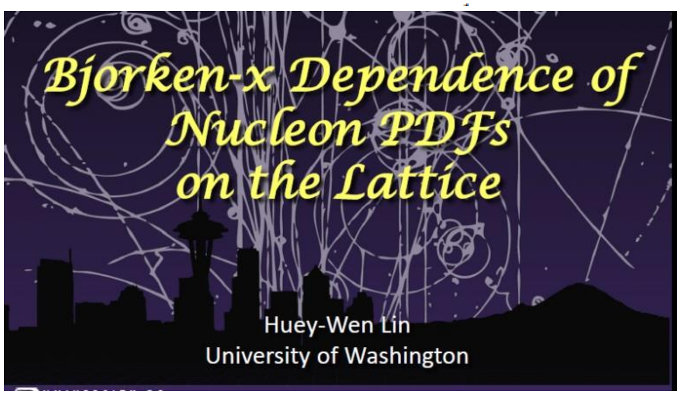
Recent progress in LQCD suggests the possibility to calculate the *x*-dependence of parton distributions



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

Parton Physics on a Euclidean Lattice

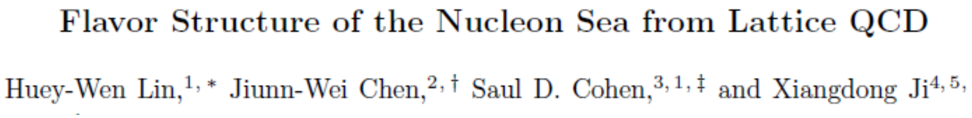
Xiangdong Ji[1,2]



Bjorken-x Dependence of Nucleon PDFs on the Lattice

Huey-Wen Lin
University of Washington

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



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)