The Flavor Structure of Antiquark Distributions in Nucleons and Nuclei

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

Flavor structure of the proton sea



Actually, the nucleon sea is full of surprises ²

<u>Outline</u>

- 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 dependence of $\overline{d}(x) \overline{u}(x)$
- Preliminary results on Fermilab SeaQuest Drell-Yan experiment

Based on work in collaboration with Wen-Chen Chang, Prog. Part. Nucl. Phys. 79 (2014) 95 Search for the "intrinsic" quark sea In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm

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

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



"extrinsic sea"

"intrinsic sea"

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

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



Gunion and Vogt (hep-ph/9706252); Barger, Halzen and Keung (PRD 25 (1982) 112) **Tantalizing evidence for intrinsic charm** (subjected to the uncertainties of charmedquark parametrization in the PDF, however)

6

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 "intrinsic" light-quark sea $|p\rangle = P_{3q} |uud\rangle + P_{5q} |uudQ\bar{Q}\rangle + \cdots$

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

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

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

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

x-distribution for "intrinsic" light-quark sea $|p\rangle = P_{3q} |uud\rangle + P_{5q} |uudQ\bar{Q}\rangle + \cdots$

Brodsky et al. (BHPS) give the following probability for quark *i* (mass m_i) to carry momentum x_i

$$P(x_1, \dots, x_5) = N_5 \delta(1 - \sum_{i=1}^5 x_i) [m_p^2 - \sum_{i=1}^5 \frac{m_i^2}{x_i}]^{-2}$$



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 \overline{Q} (\overline{c} , \overline{s} , \overline{d}) numerically How to separate the "intrinsic sea" from the "extrinsic sea"?

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

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



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.



Complimentality between DIS and Drell-Yan



Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)



Comparison between the $\overline{d}(x) - \overline{u}(x)$ 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 Q²=54 GeV²

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

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

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 $s(x) + \overline{s}(x)$ distribution

Extraction of the intrinsic strange-quark sea from the HERMES $s(x) + \overline{s}(x)$ data



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

The data appear to consist of two different components (intrinsic and extrinsic?)

HERMES collaboration, Phys. Lett. B666, 446 (2008)

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



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

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

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

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

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

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

 $\overline{d} + \overline{u} - s - \overline{s}$ has no contribution from extrinsic sea $(g \rightarrow \overline{q}q)$ and is sensitive to "intrinsic sea" only Comparison between the $\overline{u}(x) + \overline{d}(x) - \overline{s}(x) - \overline{s}(x)$ data with the intrinsic 5-q model



 $d(x) + \overline{u}(x)$ from CTEQ6.6 $s(x) + \overline{s}(x)$ from HERMES

$$\overline{u} + \overline{d} - s - \overline{s}$$
 has

no contribution

from extrinsic sea

A valence-like *x*-distribution is observed

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



 $d(x) + \overline{u}(x)$ from CTEQ6.6 $s(x) + \overline{s}(x)$ from HERMES

 $\overline{u} + \overline{d} - s - \overline{s}$ $\sim P_5^{uudu\overline{u}} + P_5^{uudd\overline{d}} - 2P_5^{uuds\overline{s}}$ (not sensitive to extrinsic sea)

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

$$P_5^{uud\bar{u}} + P_5^{uud\bar{d}} - 2P_5^{uud\bar{s}} = 0.314$$

20

Extraction of the various five-quark components for light quarks



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

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

$$P_{5}^{uudd\overline{d}} = 0.240; P_{5}^{uudu\overline{u}} = 0.122; P_{5}^{uuds\overline{s}} = 0.024$$
Expect $P_{5}^{uudc\overline{c}} \sim 0.0025$

$$O_{1} = O_{1} = O_{1} = O_{1} = O_{1} = O_{1} = O_{2} = O_{1} = O_{2} = O_$$

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?

week ending 21 DECEMBER 2012

Connected-Sea Partons

Keh-Fei Liu,1 Wen-Chen Chang,2 Hai-Yang Cheng,2 and Jen-Chieh Peng3



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

CS and DS have different Bjorken-x and flavor dependencies

• *x* – dependence: at small *x*, CS ~ $x^{-1/2}$; DS ~ x^{-1}

• Flavor dependence: \overline{u} and \overline{d} have both CS and DS; $s + \overline{s}$ is entirely DS ²⁴



SU(3)-flavor independent

Can one separate the "connected sea" from the "disconnected sea" for $\overline{u} + \overline{d}$?

A) Lattice QCD shows that disconnected sea is roughly
 SU(3)-flavor independent

$$R = \frac{\langle x \rangle_{s+\overline{s}}}{\langle x \rangle_{u+\overline{u}}} = 0.857(40) \text{ for disconnected sea}$$

B) $[\overline{u}(x) + \overline{d}(x)]_{\text{disconnected sea}} = [s(x) + \overline{s}(x)]/R$ (since s, \overline{s} is entirely from the disconnected sea) C) $[\overline{u}(x) + \overline{d}(x)]_{\text{connected sea}} =$ $[\overline{u}(x) + \overline{d}(x)]_{\text{PDF}} - [\overline{u}(x) + \overline{d}(x)]_{\text{disconnected sea}_{26}}$

Connected-Sea Partons



Connected sea component for u
(x) + d(x) is valence-like
For u
+ d
, momenta carried by CS and DS are roughly equal, at Q²=2.5 GeV²

Does d / \overline{u} drop below 1 at large x?



Sign change of $\overline{d}(x) - \overline{u}(x)$ at $x \sim 0.25$? (or $\overline{d}(x) / \overline{u}(x) < 1$ at $x \sim 0.25$?)

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

Meson cloud model

Chiral-quark soliton model

Statistical model

х



Revisit the NMC measurement of the Gottfried Sum rule



New Muon Collaboration (NMC) obtains $S_G = 0.235 \pm 0.026$ (Significantly lower than 1/3 !) $\Rightarrow \overline{d} \neq \overline{u}$?

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

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



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



Drell-Yan Experiment at Fermilab

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





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

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

First preliminary result from E906



Nuclear Modifications of Structure Function F₂



Drell-Yan Experiment at Fermilab

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



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

Conclusions

- Evidences for the existence of "intrinsic" light-quark seas $(\overline{u}, \overline{d}, \overline{s})$ in the nucleons.
- Clear evidence for intrinsic charm remains to be found.
- The concept of connected and disconnected seas in Lattice QCD offers useful insights on the flavor- and *x*-dependencies of the sea.
- Ongoing and future Drell-Yan and Semi-Inclusive DIS experiments should provide useful new information.

Latest HERMES result on xS(x)



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



Wen-Chen Chang and JCP, PRD 92, 054020 (2015)

