Intrinsic Strange and Charm Quark Distributions in the Nucleons

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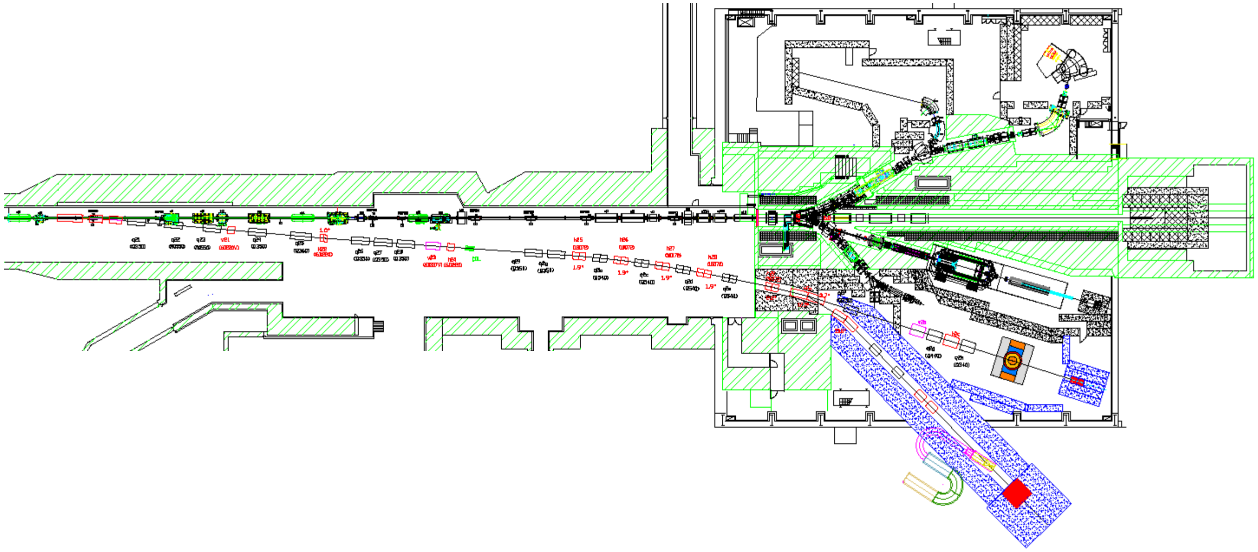
Workshop on "Hadron physics with high-momentum hadron beams at J-PARC"
KEK, Tsukuba, Japan, March 12, 2015



Outline

- Status of the search for intrinsic charm in the nucleons
- Search for intrinsic $\bar{u}$, $\bar{d}$, and $\bar{s}$ sea in the nucleons
- Opportunities for studying intrinsic strange and charm seas at J-PARC

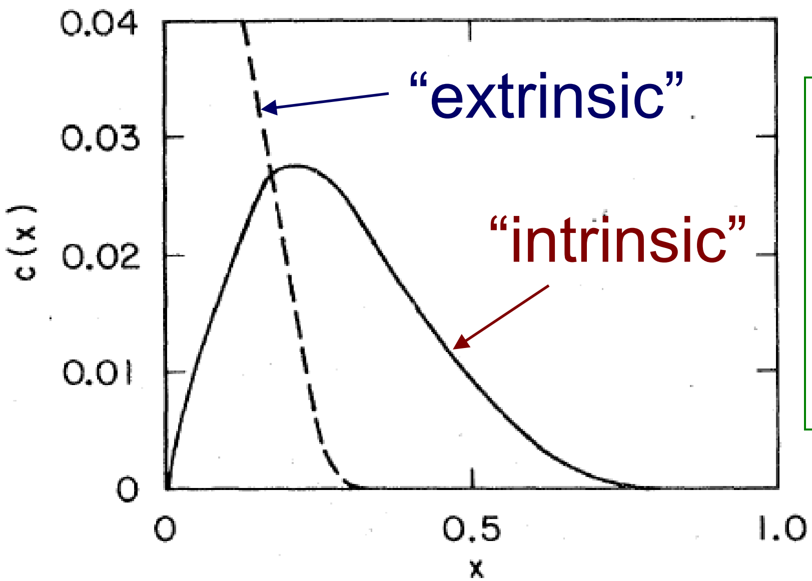
Based on work in collaboration with Wen-Chen Chang
arXiv: 1406.1260; and arXiv: 1410.7027

Search for the "intrinsic" sea

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

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

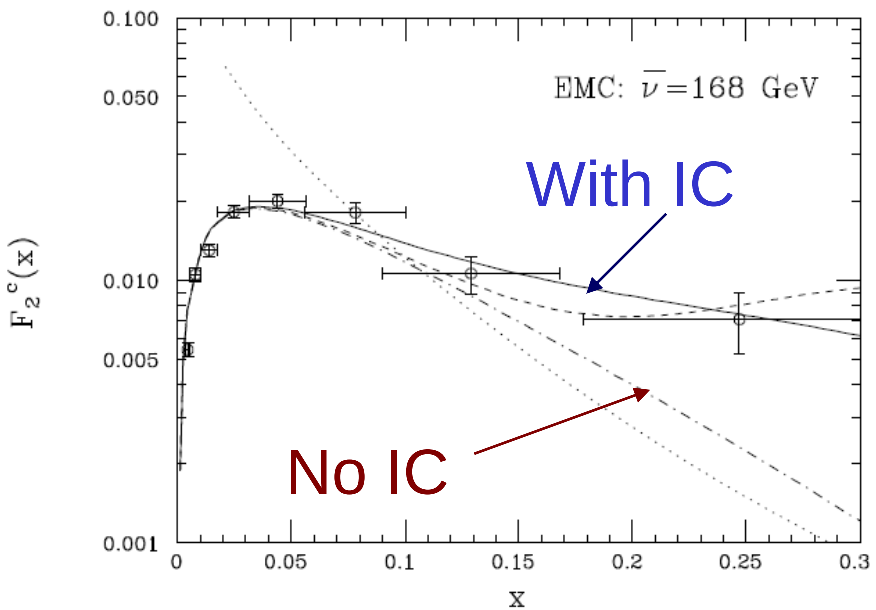
The "intrinsic"-charm from $|uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \to c\bar{c}$)



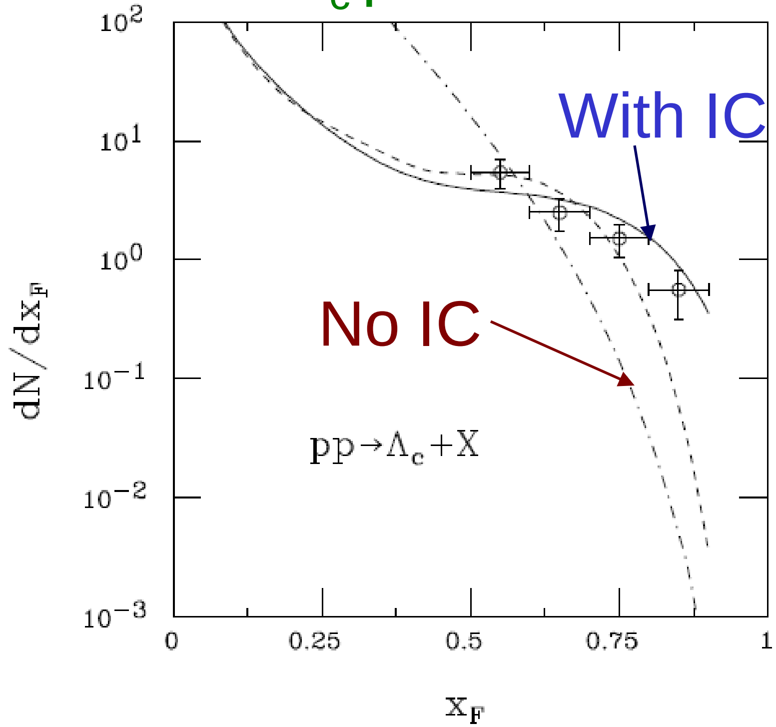
The "intrinsic charm" in $|uudc\bar{c}\rangle$ can lead to large contribution to charm production at large x

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

DIS data



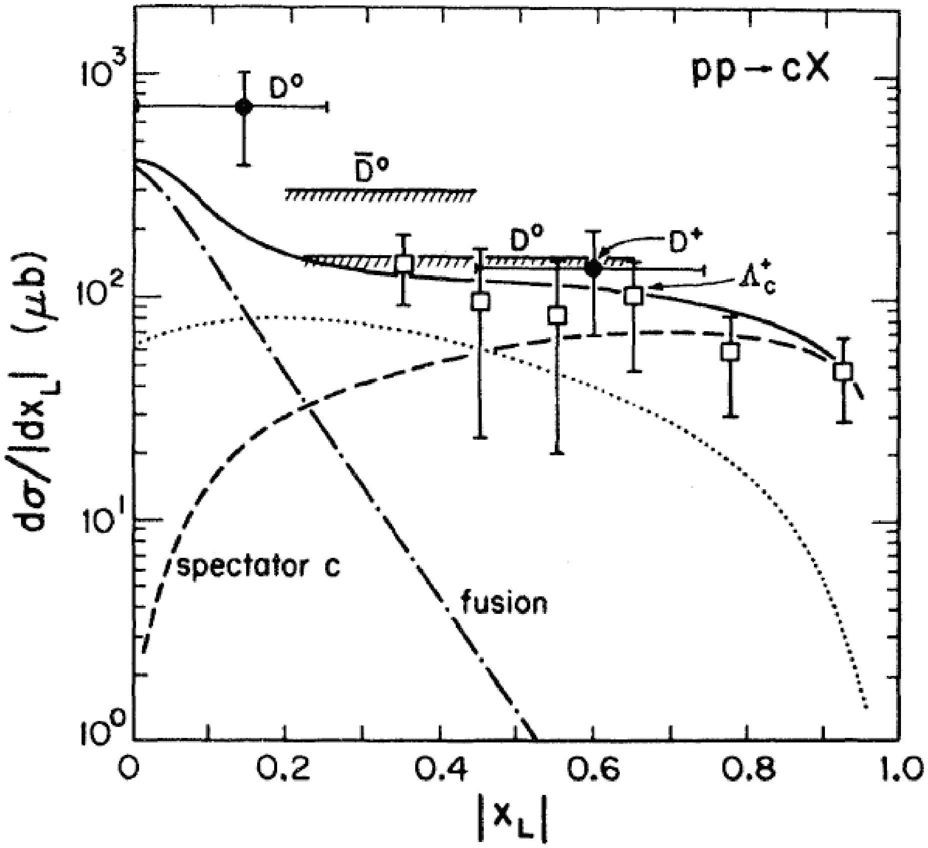
Λ_c production



Gunion and Vogt (hep-ph/9706252)

Tantalizing evidence for intrinsic charm

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

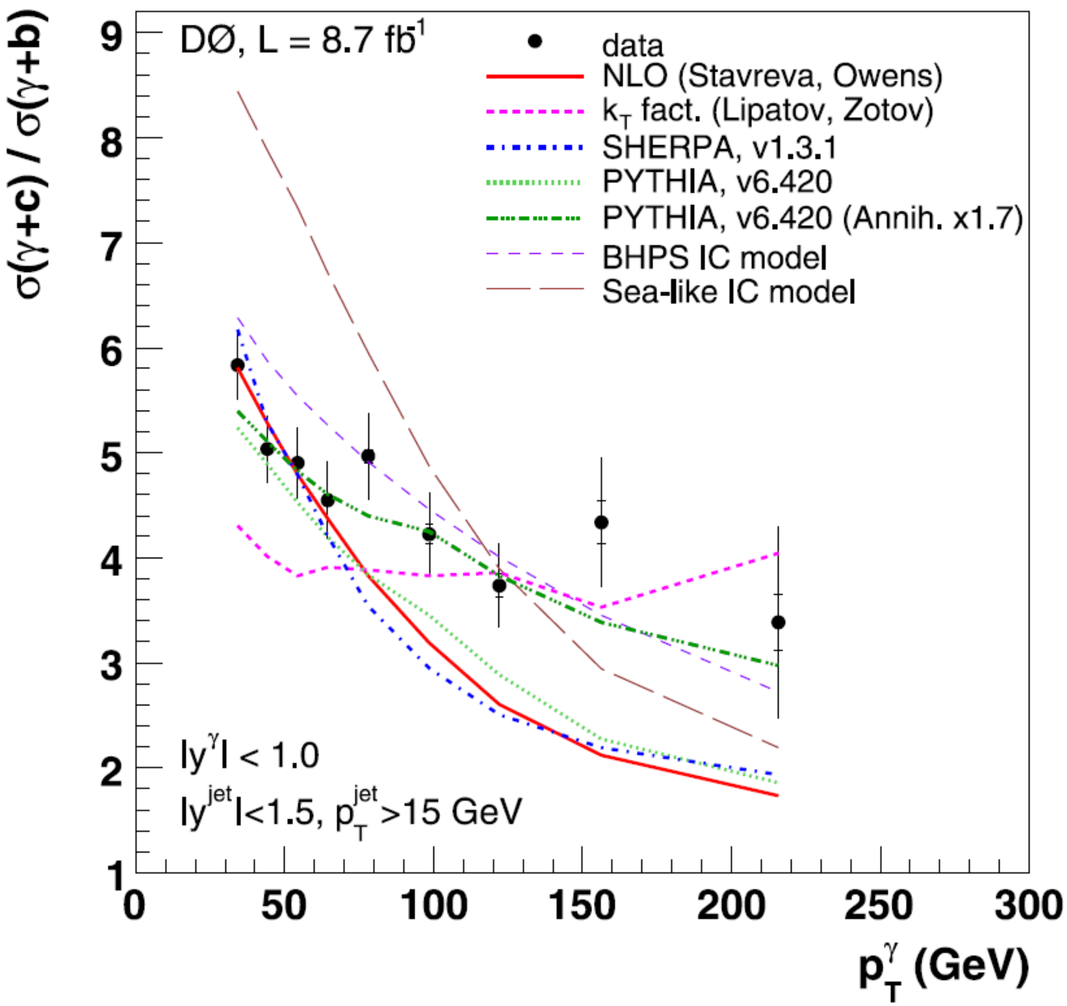


Barger, Halzen, Keung

Evidence for charm at large x

(Slide from Stan Brodsky)

Ratio of $\gamma + c$ and $\gamma + b$ cross sections in $\bar{p} + p$ at 1.96 TeV at D0



Phys. Lett. B 719 (2013) 354

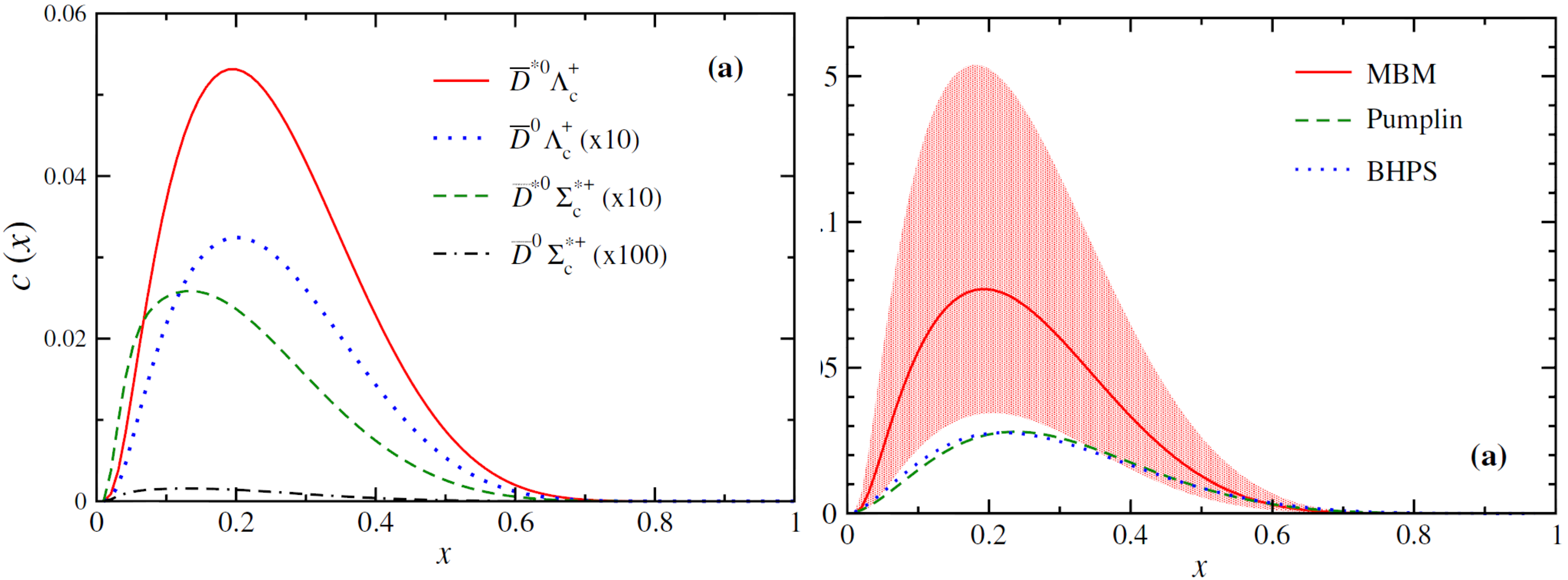
"The BHPS model agrees with data at p^{γ}_{T} > 80 GeV"

PHYSICAL REVIEW D **89**, 074008 (2014)

Phenomenology of nonperturbative charm in the nucleon

T. J. Hobbs,[1*] J. T. Londergan,[1] and W. Melnitchouk[2]

Meson-baryon model: $p \to D^0 Y_C^*$



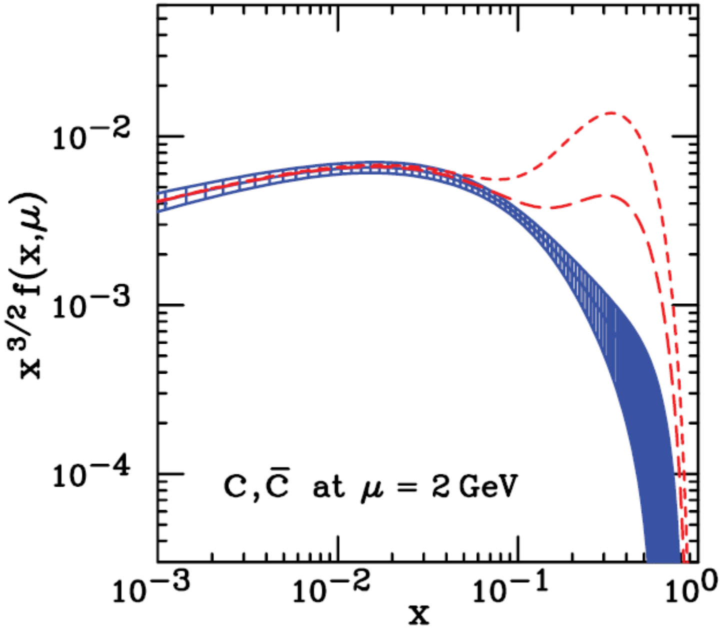
Meson-Baryon model predicts intrinsic C(x) roughly twice larger than BHPS model

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)

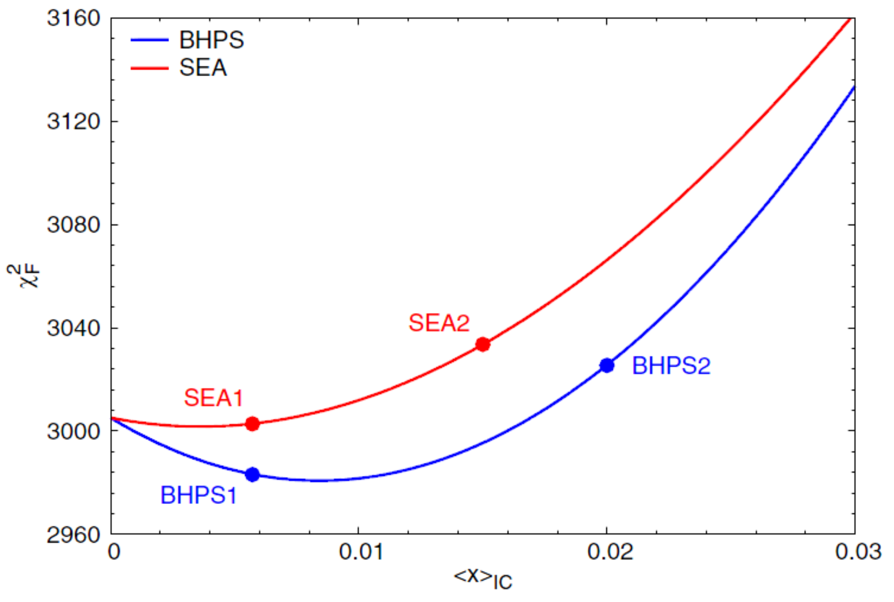
We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

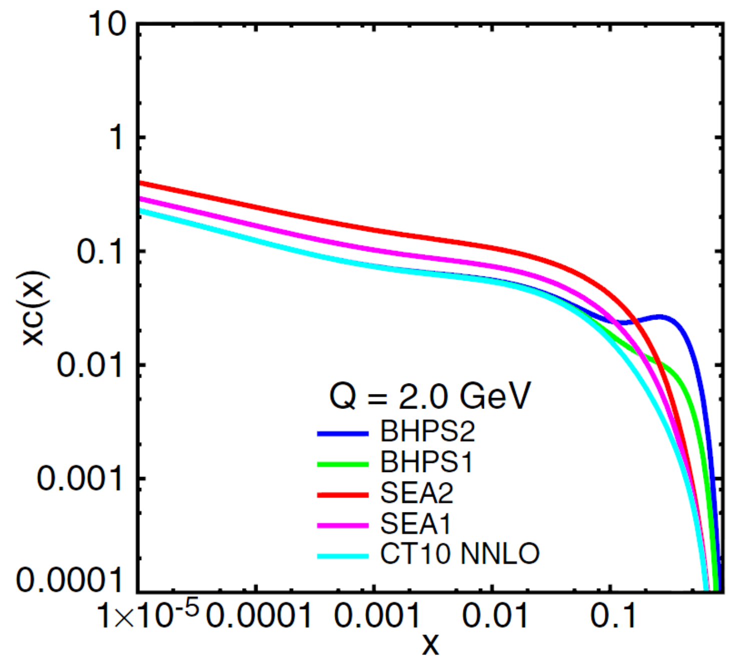
No conclusive evidence for intrinsic-charm

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,‡‡]





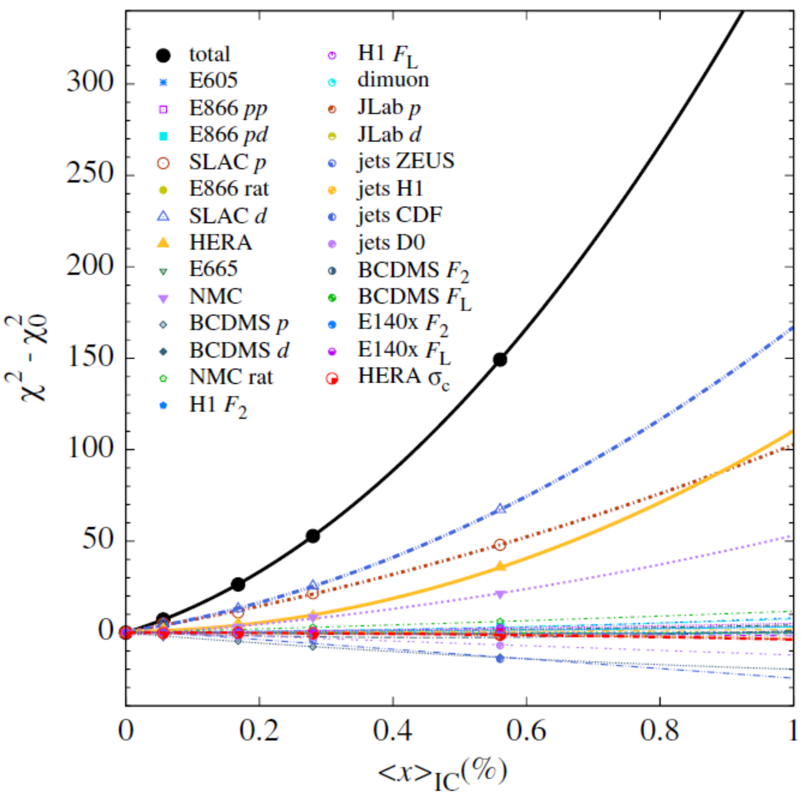
$$\langle x \rangle_{IC} \equiv \int_0^1 [c(x) + \bar{c}(x)]dx$$

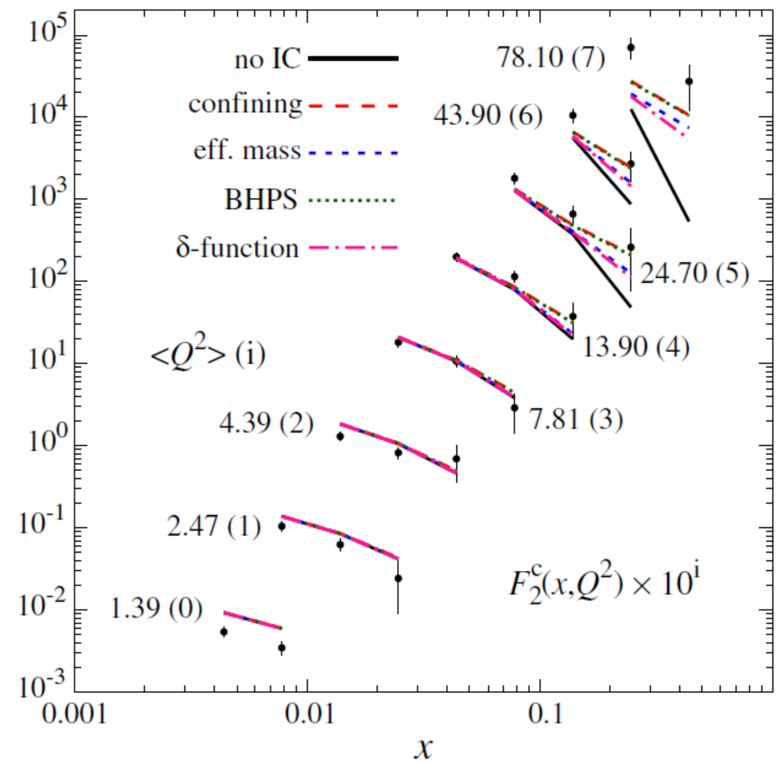
$$\langle x \rangle_{IC} \leq 2.5\,\%$$

PRL 114, 082002 (2015) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2015

New Limits on Intrinsic Charm in the Nucleon from Global Analysis of Parton Distributions

P. Jimenez-Delgado,[1] T. J. Hobbs,[2,3] J. T. Londergan,[2] and W. Melnitchouk[1]





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

$$\langle x \rangle_{IC} < 0.5\,\% \text{ at } 4\sigma$$

Tension between EMC and HERA data

Search for the "intrinsic" light-quark sea

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

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

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

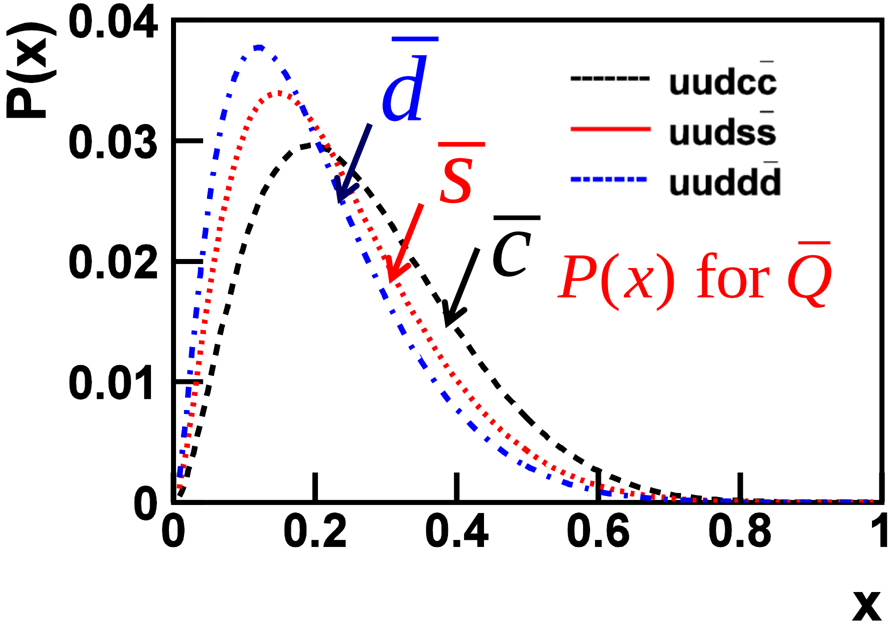
Are there experimental evidences for the intrinsic light-quark sea: $|uudu\bar{u}\rangle, |\,uudd\bar{d}\rangle, |\,uuds\bar{s}\rangle$?

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

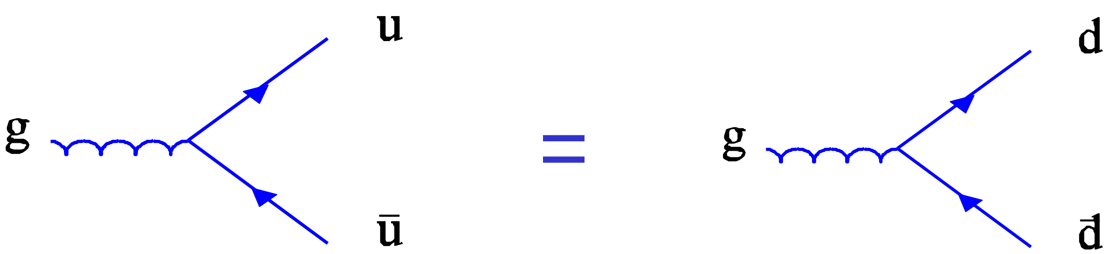
How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no (or small) 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

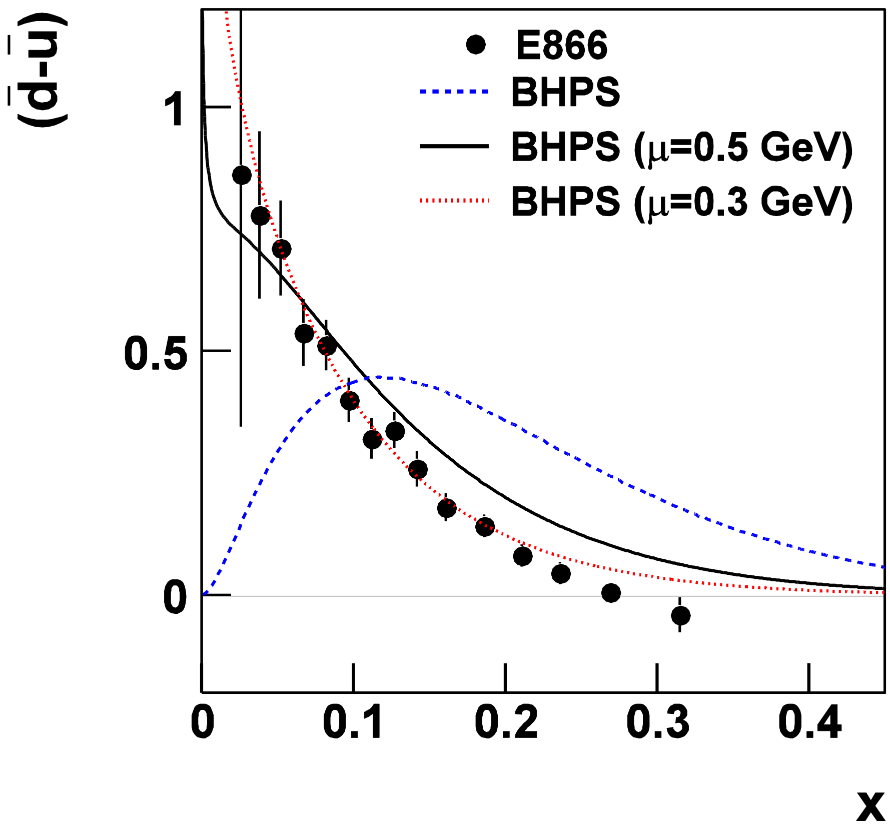
How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no (or small) contributions from the "extrinsic sea"

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



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

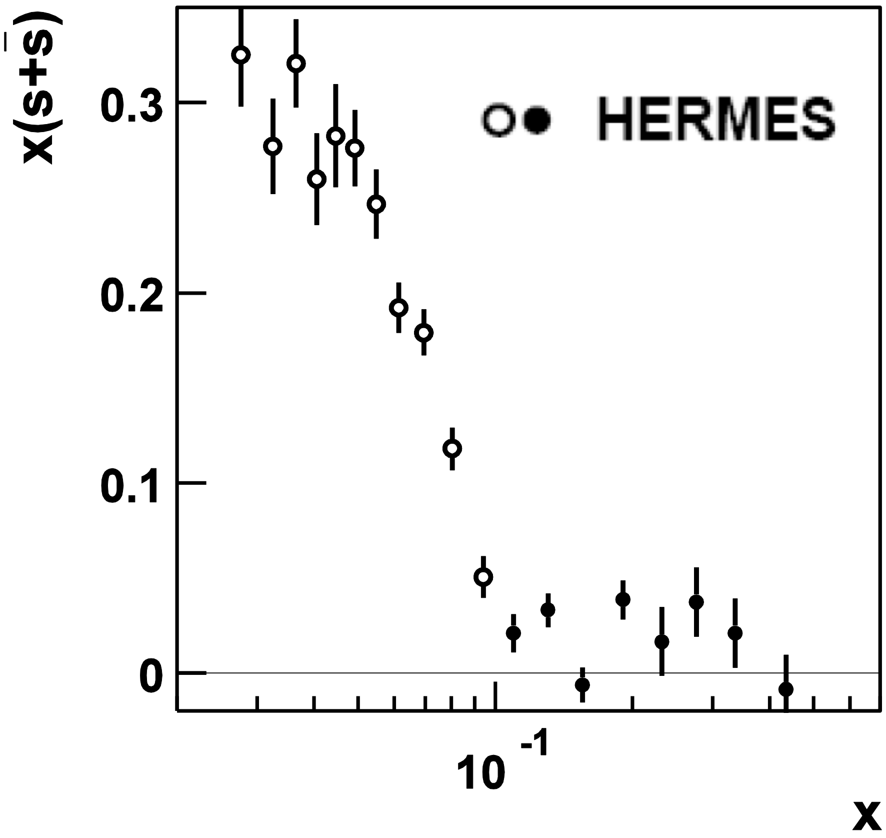
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

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

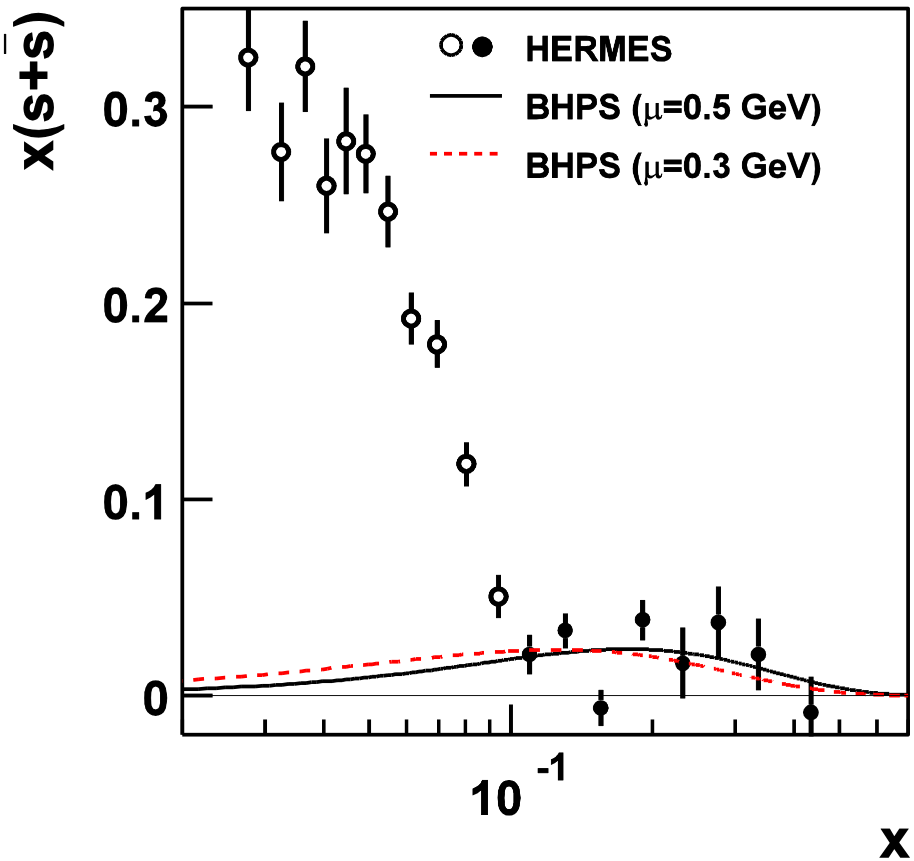


$s(x)+\bar{s}(x)$ extracted from HERMES Semi-inclusive DIS kaon data at $\langle Q^2 \rangle = 2.5\ \text{GeV}^2$

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

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

Comparison between the $s(x)+\bar{s}(x)$ 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 $\langle Q^2 \rangle = 2.5\ \text{GeV}^2$

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

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

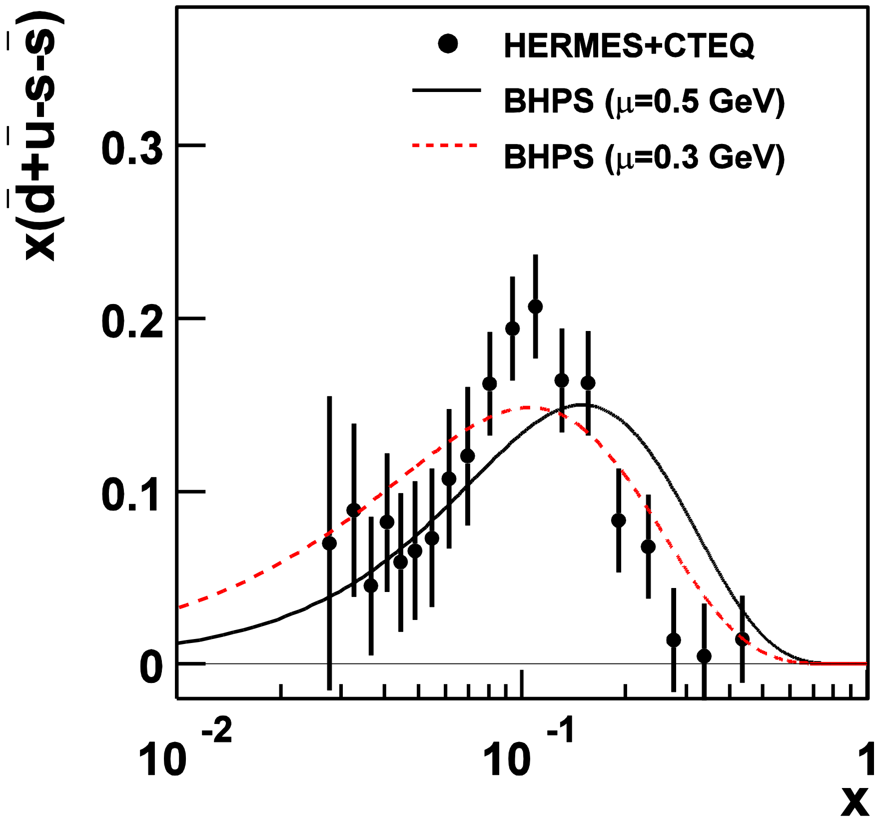
How to separate the "intrinsic sea" from the "extrinsic sea"?

- Select experimental observables which have no (or small) contributions from the "extrinsic sea"

$\bar{d} + \bar{u} - s - \bar{s}$ has small contribution from extrinsic sea $(g \to \bar{q}q)$

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

A valence-like x-distribution is observed

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

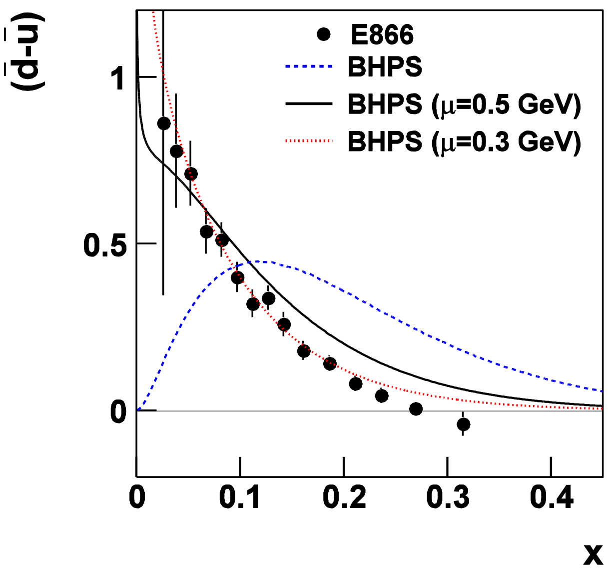
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

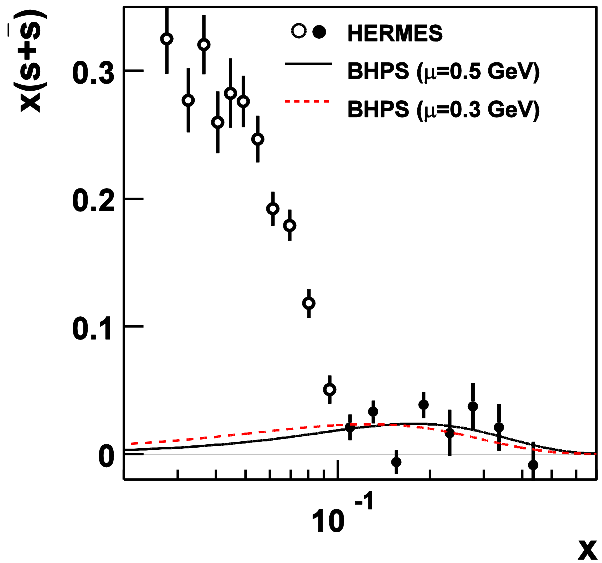
(not sensitive to extrinsic sea)

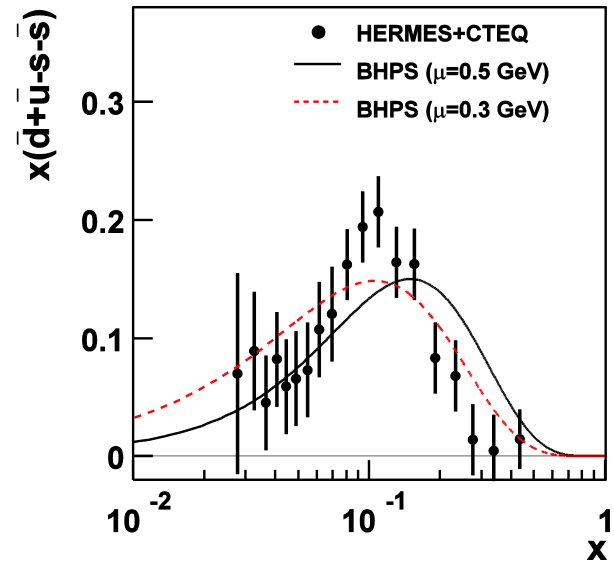
(W. Chang and JCP, PL B704, 197(2011))

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

Extraction of the various five-quark components for light quarks







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

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

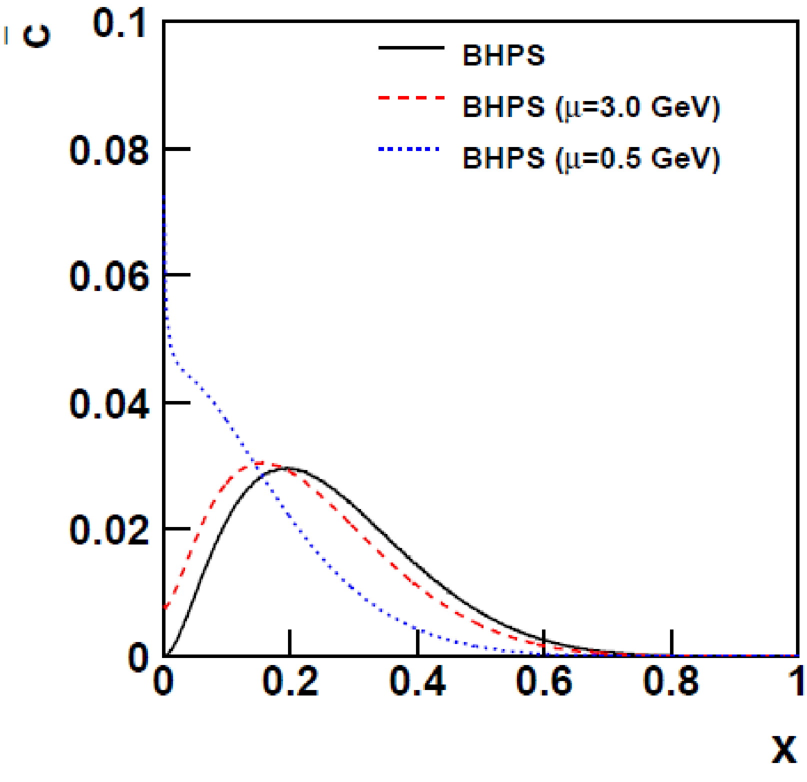
$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$

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

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

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

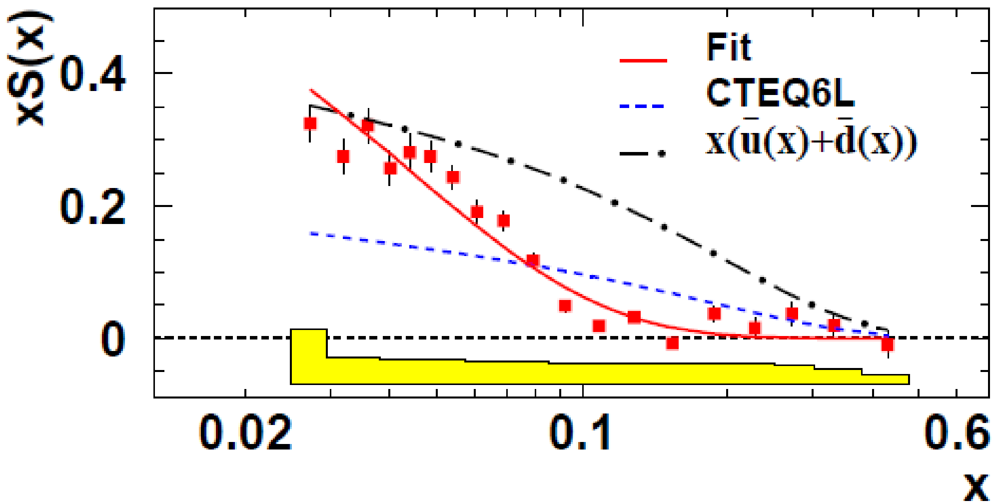
Expect $P_5^{uudc\bar{c}} \sim 0.0025$



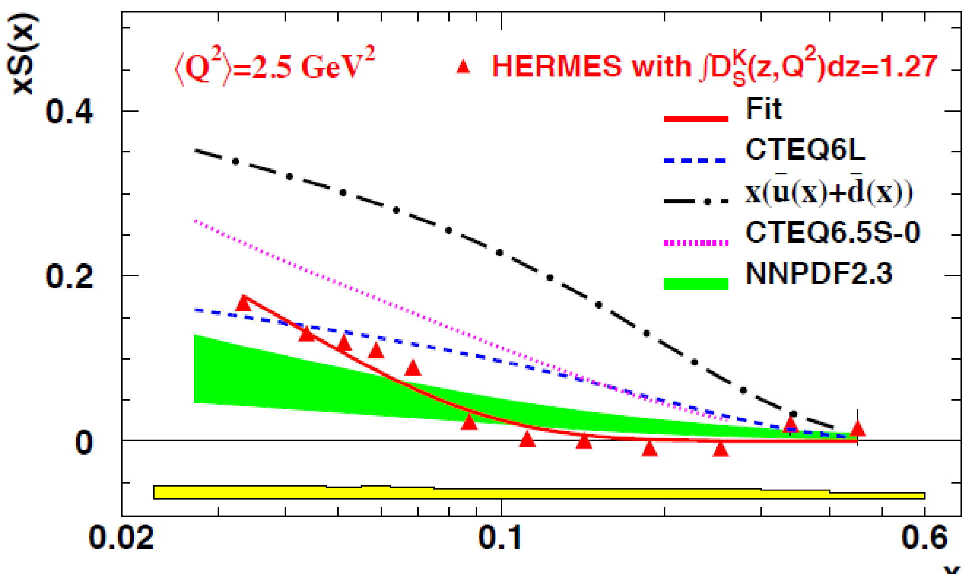
- Calculation assumes $P_5^{uudc\bar{c}} = 0.01$
- Q^2- evolution could shift the x-distribution to smaller x

Latest HERMES result on $xS(x)$

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



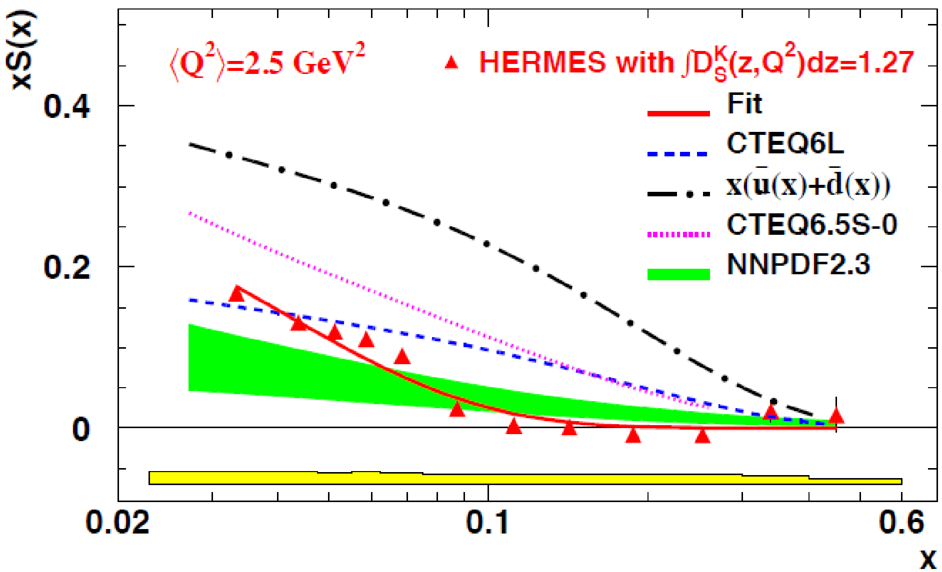
2008 result



2014 result
(PRD 89 (2014) 097101)

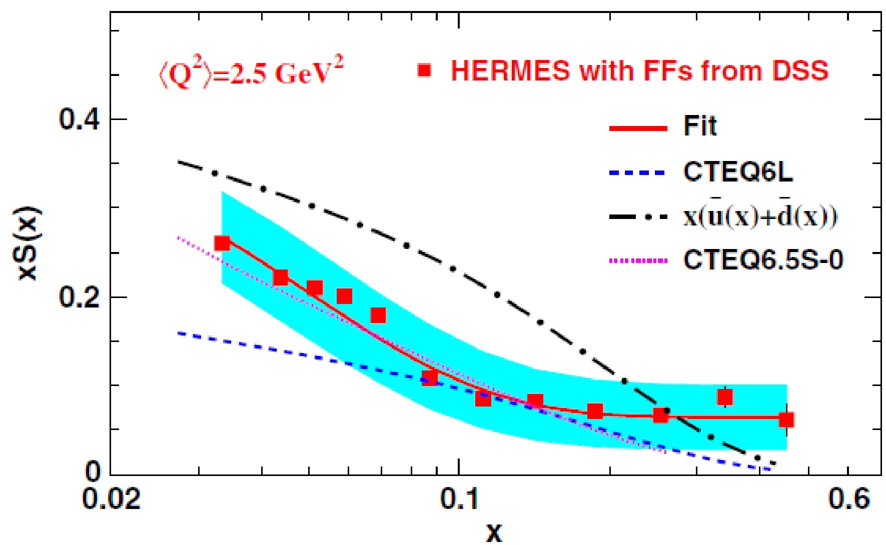
Vanishing strange quark content at x > 0.1 !!

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

Role of kaon fragmentation functions in the extraction of $S(x)$

$$S(x) = \frac{Q(x)\left[5\,\frac{dN^K}{dN^{DIS}}(x) - \int_{0.2}^{0.8} D_Q^K(z)dz\right]}{\int_{0.2}^{0.8} D_S^K(z)dz - 2\,\frac{dN^K}{dN^{DIS}}(x)}$$

$\frac{dN^K}{dN^{DIS}}(x)$ is from HERMES measurement of kaon multiplicity

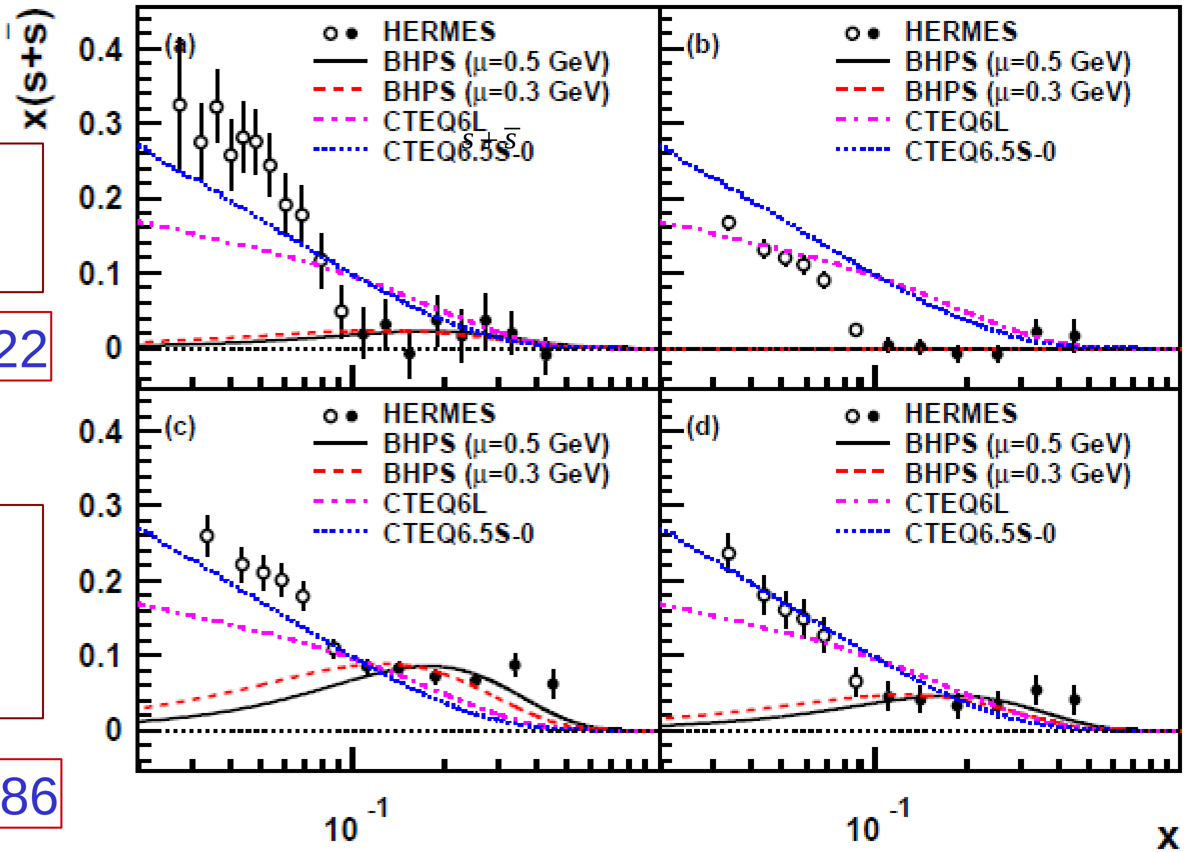
$\int_{0.2}^{0.8} D_S^K(z)dz$ and $Q(x)$ are from DSS and CTEQ6L global fits

$\int_{0.2}^{0.8} D_Q^K(z)dz = 0.514$ is determined from HERMES

$\int_{0.2}^{0.8} D_Q^K(z)dz = 0.435$ from the DSS global fit

The “truth” might be somewhere in-between

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

Future Possibilities on Intrinsic Sea

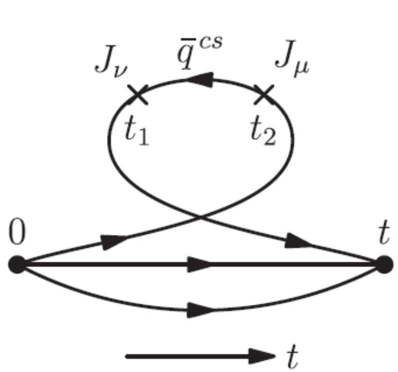
- Search for intrinsic charm and beauty at RHIC and LHC.
- Intrinsic gluons in the nucleons?
- Spin-dependent observables of intrinsic sea?
- Global fits including intrinsic u, d, s sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and lattice QCD formalism?

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

Connected-Sea Partons

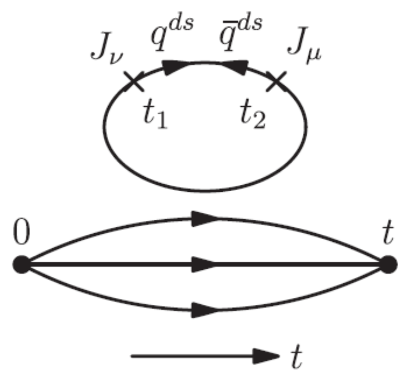
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea



(valence-like)

Disconnected sea



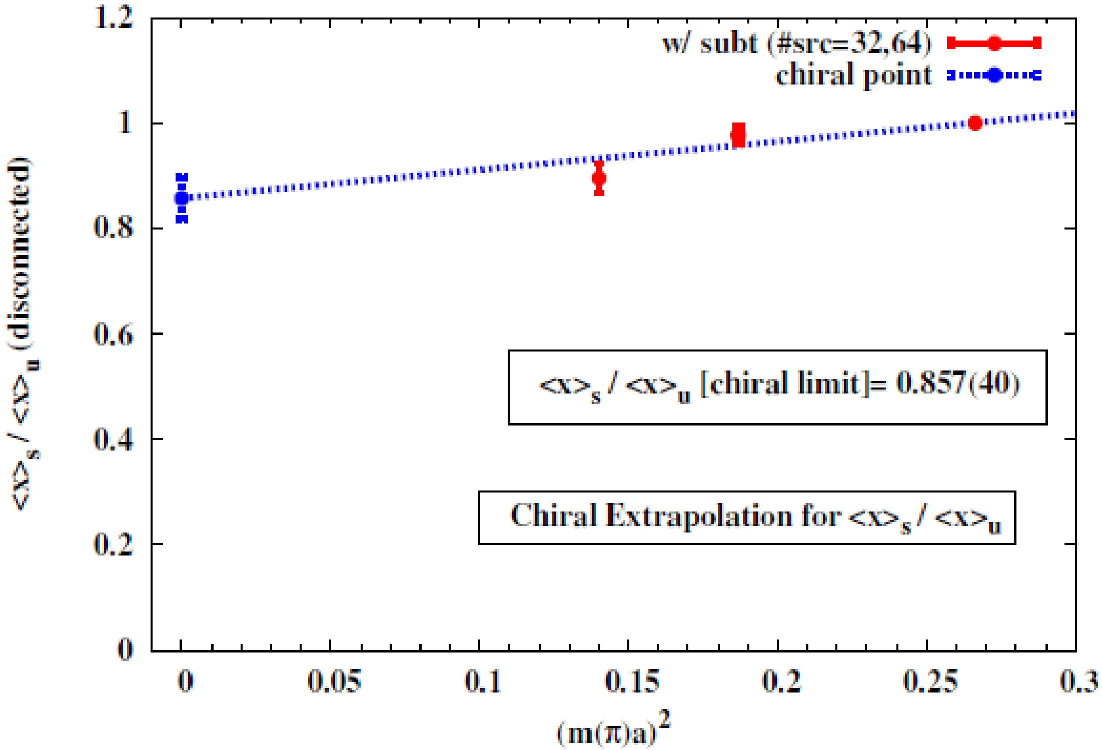
(sea-like)

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

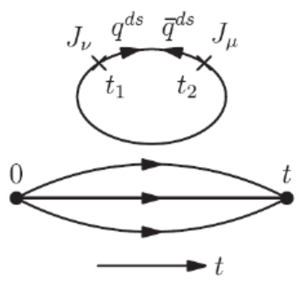
CS and DS have
different Bjorken-x and
flavor dependencies

- $x-$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) $\boxed{\text{Lattice QCD shows that disconnected sea is roughly SU(3)-flavor independent}}$

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

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

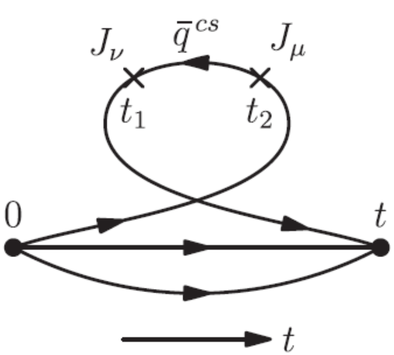
$$[\bar{u}(x) + \bar{d}(x)]_{\text{PDF}} - [\bar{u}(x) + \bar{d}(x)]_{\text{disconnected sea}}$$

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

Connected-Sea Partons

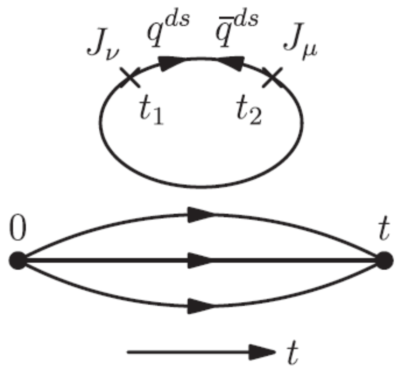
Keh-Fei Liu,[1] Wen-Chen Chang,[2] Hai-Yang Cheng,[2] and Jen-Chieh Peng[3]

Connected sea

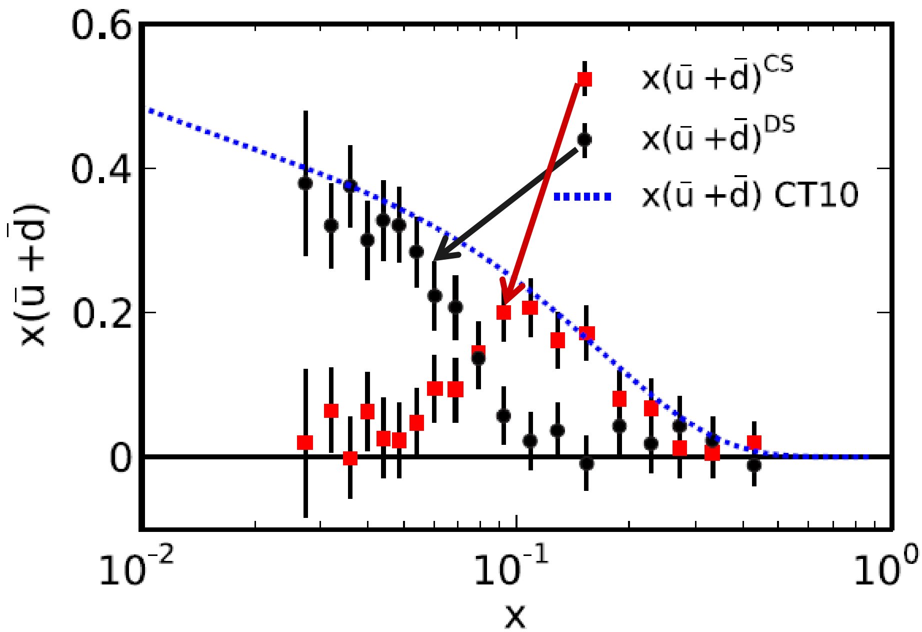


(valence-like)

Disconnected sea

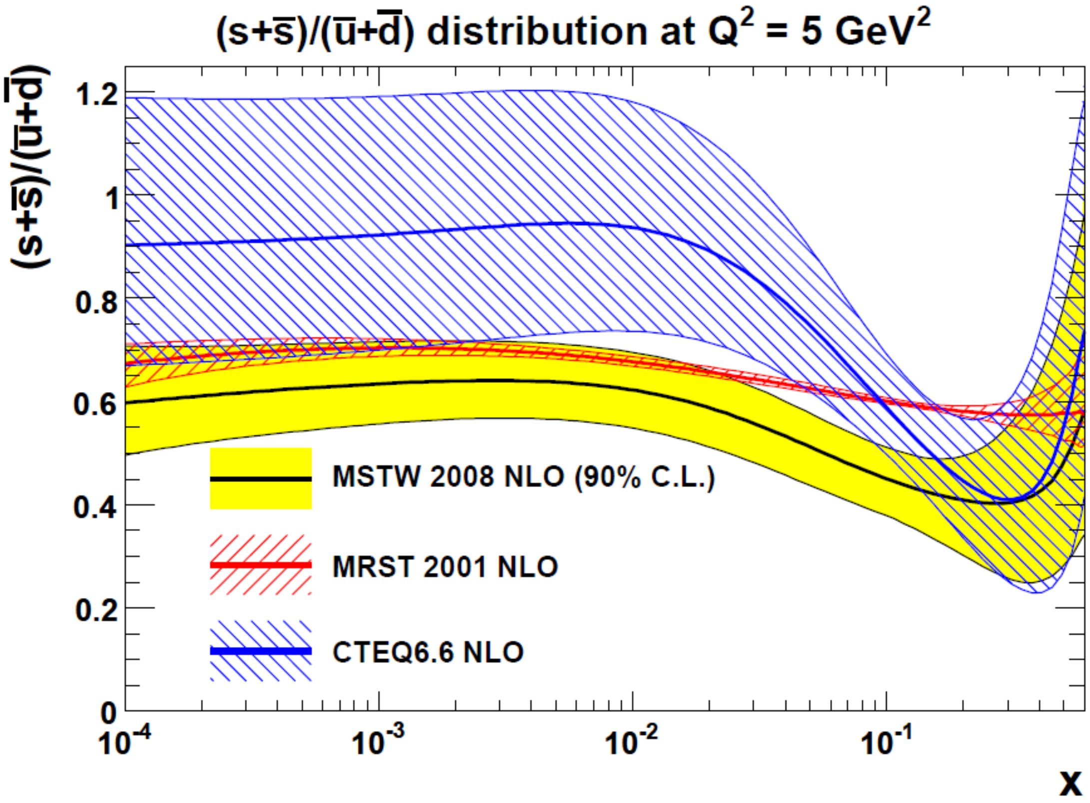


(sea-like)



- 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?

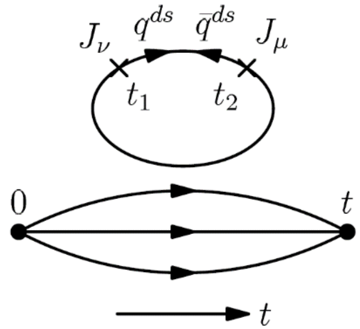
  (Also see Alekhin et al., arXiv: 1404.6469)

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

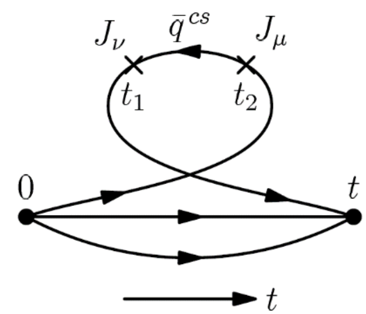
Can be understood from Lattice QCD (PRL 109 (2012)252002)

Disconnected sea



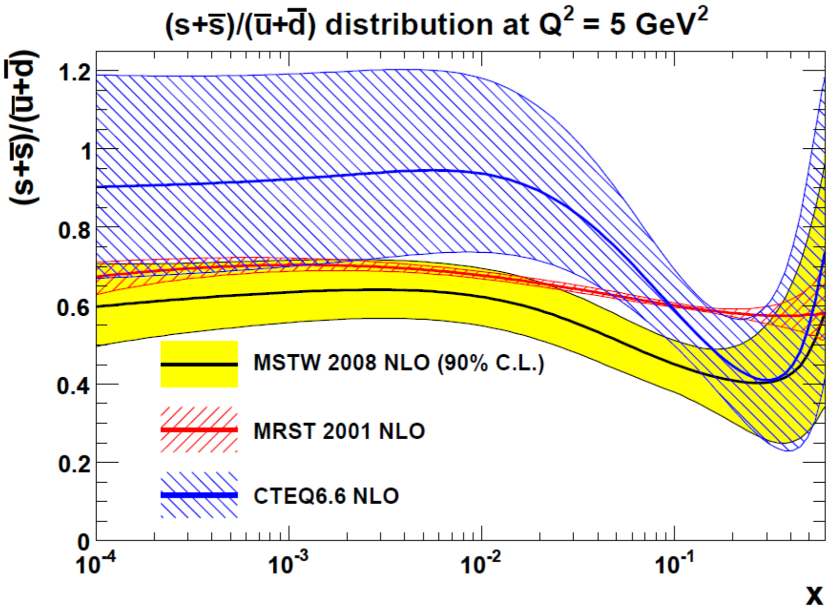
Generate roughly symmetric $s(x), \bar{s}(x), \bar{u}(x)$ and $\bar{d}(x)$ at small x

Connected sea

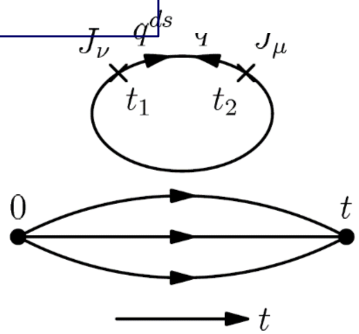


Generate additional "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger x

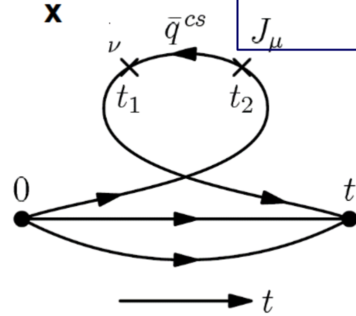
The x-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$



Disconnected sea



Connected sea



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

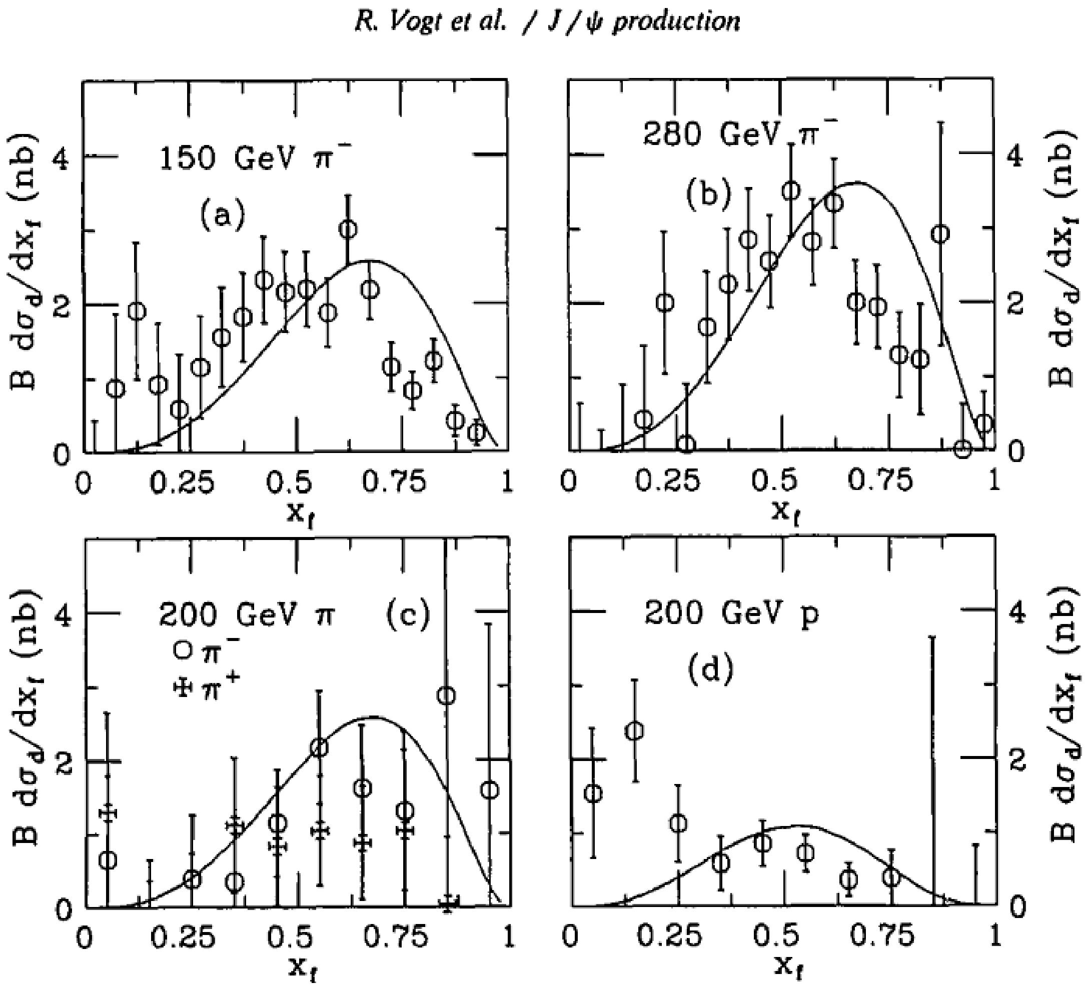
Generate additional "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger x

Opportunities at J-PARC for intrinsic sea

- Search for intrinsic charm components in the pions $|\pi^-\rangle = |d\bar{u}\rangle + |c\bar{c}d\bar{u}\rangle + \cdots$
- J/Ψ production at forward rapidity with pion beam could be sensitive to the intrinsic charm in the pion beam
- The intrinsic charm component in the pion might have relatively large contribution to J/Ψ production near threshold

Comparison between the “diffractive” J/Ψ production with intrinsic charm calculation

(Vogt, Brodsky, Hoyer)

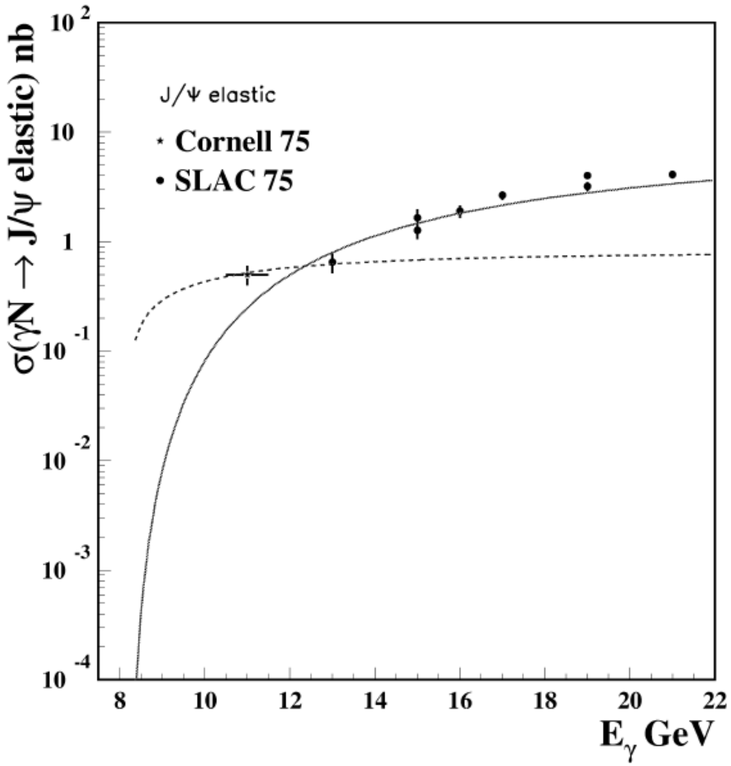


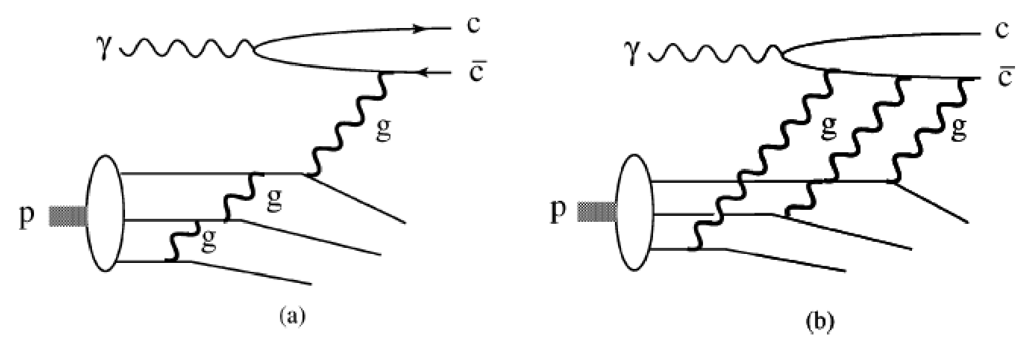
Threshold J/Ψ production via intrinsic charm

Photoproduction of charm near threshold

S.J. Brodsky [a], E. Chudakov [b], P. Hoyer [c], J.M. Laget [d,*]

(PL B498 (2001) 23)





Higher-twist diagram (b) can become important near threshold energy

Conclusions

- Evidences for the existence of "intrinsic" light-quark seas $(\bar{u}, \bar{d}, \bar{s})$ in the nucleons.
- Clear evidence for intrinsic charm (beauty) remains to be found.
- The flavor- and *x*-dependencies of the nucleon sea provide strong constraints on theoretical models.
- Ongoing and future Drell-Yan (Fermilab, COMASS, RHIC, ...) and SIDIS experiments (JLab, EIC,...) and experiments at J-PARC will provide important new inputs.