Intrinsic Sea and Flavor Structure of Nucleon Sea

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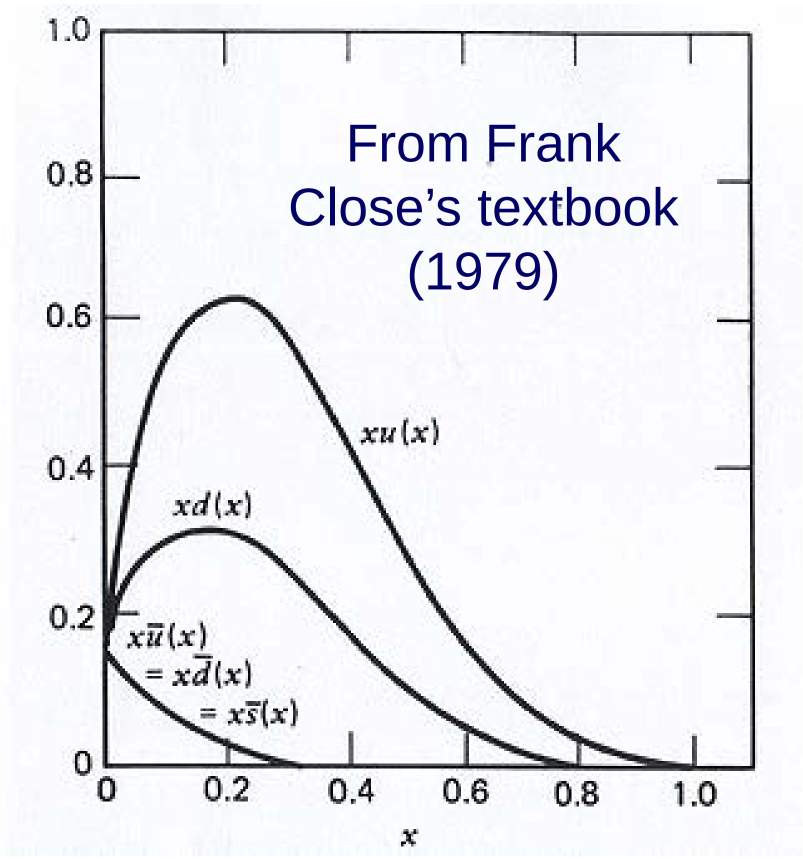
INT Workshop on
"The Flavor Structure of Nucleon Sea"

Oct. 2-13, 2017

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

at the small-x region

Actually, the nucleon sea is full of surprises

Outline

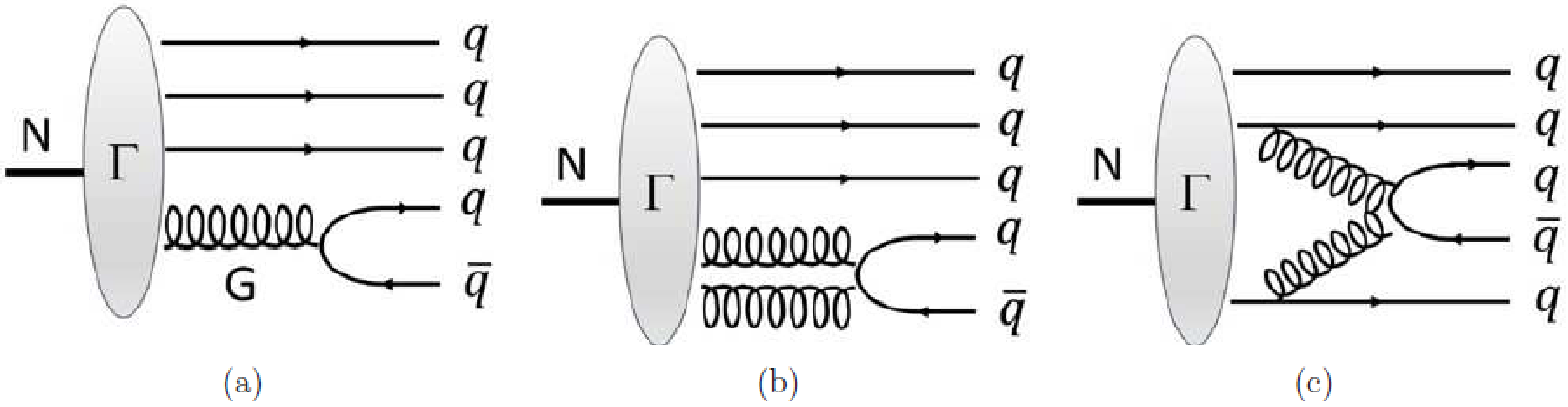
- Extraction of "intrinsic" $\bar{u}$, $\bar{d}$, and $\bar{s}$ sea in the nucleons
- Separation of "connected sea" from "disconnected sea" for light-quark sea
- Bjorken-x dependence of $\bar{d}(x) - \bar{u}(x)$ and $s(x)$
- Flavor structure of kaon valence quark

Search for the "intrinsic" quark sea

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

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

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



"extrinsic sea"

"intrinsic sea"

Search for the "intrinsic" quark sea

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

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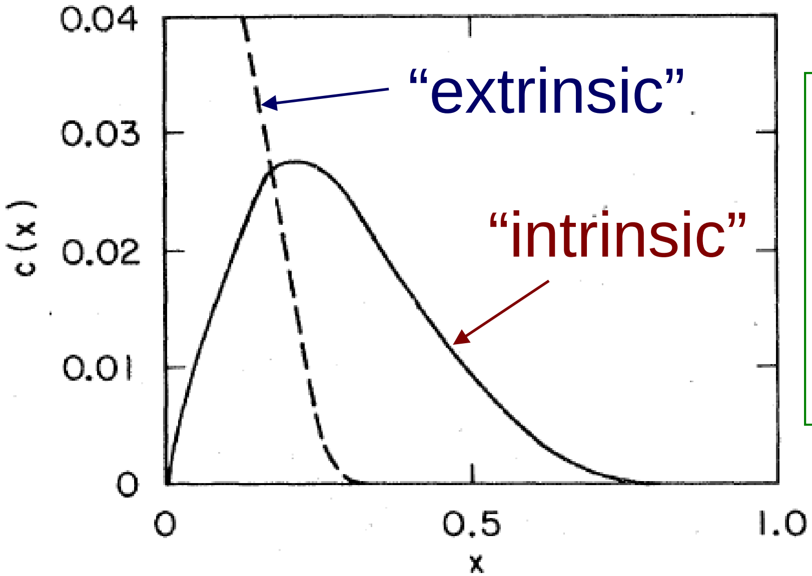
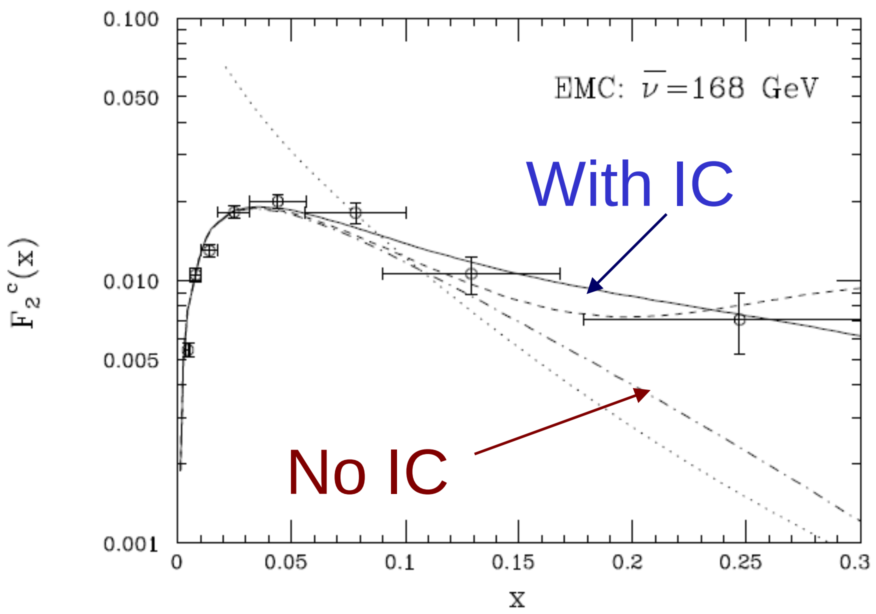


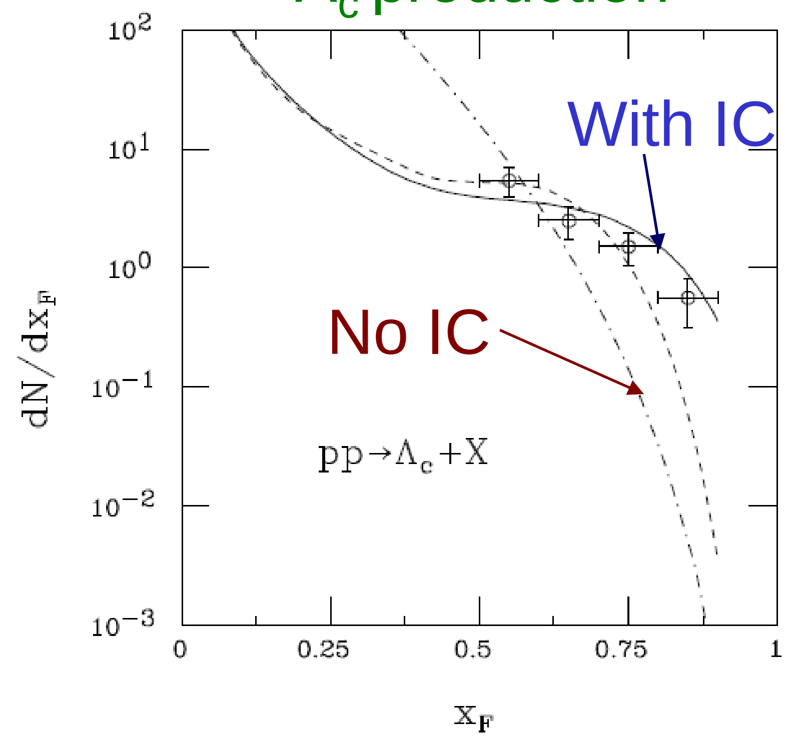
The "intrinsic charm" in $| uudc\overline{c}\rangle$ can lead to large contribution to charm production at large x

“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

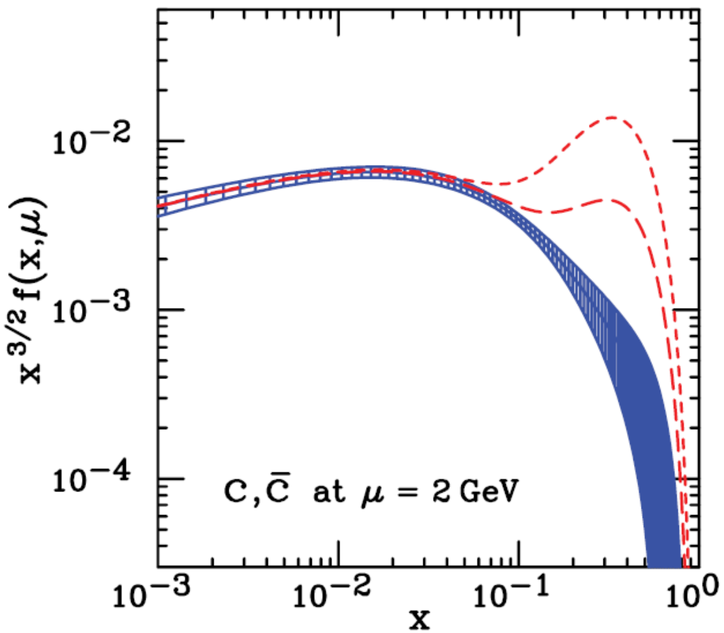
(subjected to the uncertainties of charmed-quark parametrization in the PDF, however)

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)

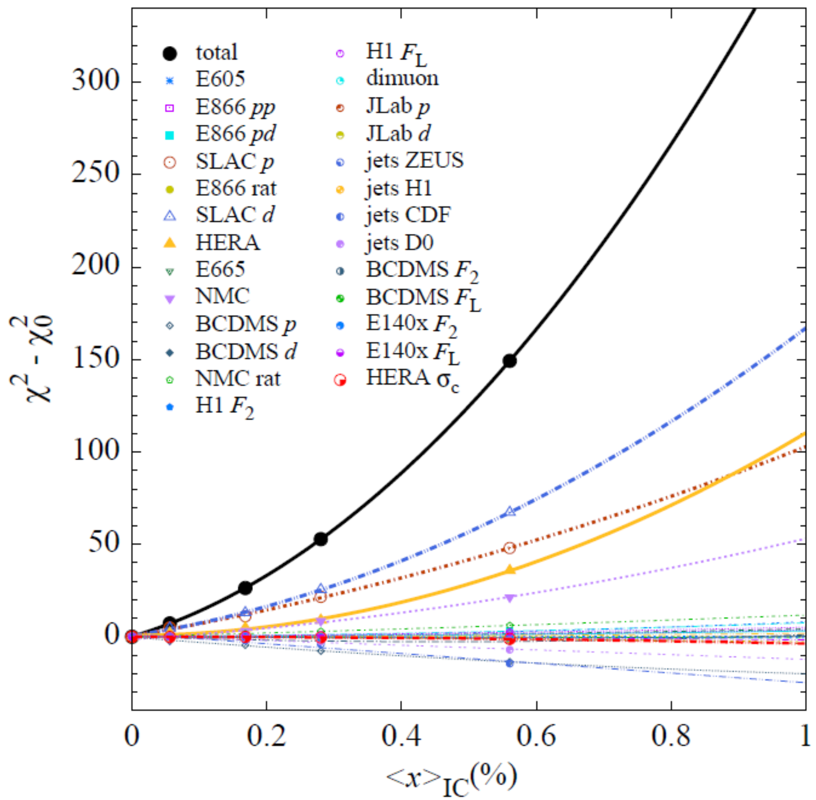
We find that the range of IC is constrained to be from zero (no IC) to a level 2 – 3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

No conclusive evidence for intrinsic-charm

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], W. Melnitchouk[1]

Phys.Rev.Lett. 114 (2015) 082002



previous global analyses. The expanded data set places more stringent constraints on the momentum carried by IC, with $\langle x \rangle_{IC}$ at most 0.5% (corresponding to an IC normalization of $\sim 1\%$) at the 4σ level for $\Delta\chi^2 = 1$. We also critically assess the impact of older EMC measurements of F_2^c at large

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

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

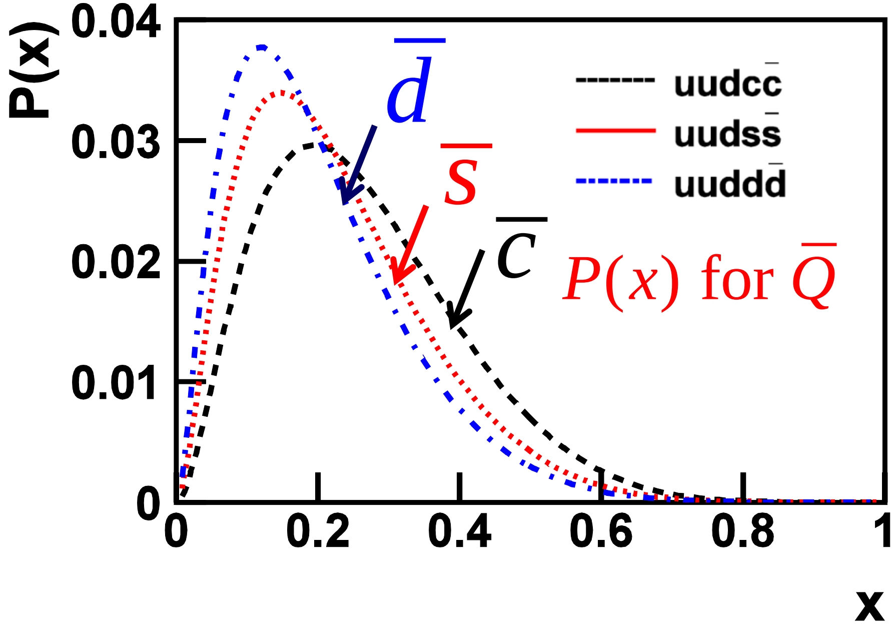
The "intrinsic" sea for lighter quarks has larger probabilities!

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):

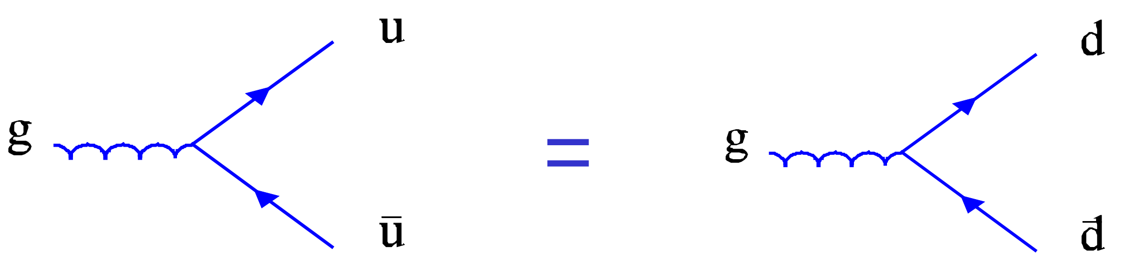
$$P(x_5) = \frac{1}{2}\tilde{N}_5 x_5^2[(1-x_5)(1+10x_5+x_5^2) - 2x_5(1+x_5)ln(1/x_5)$$

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"

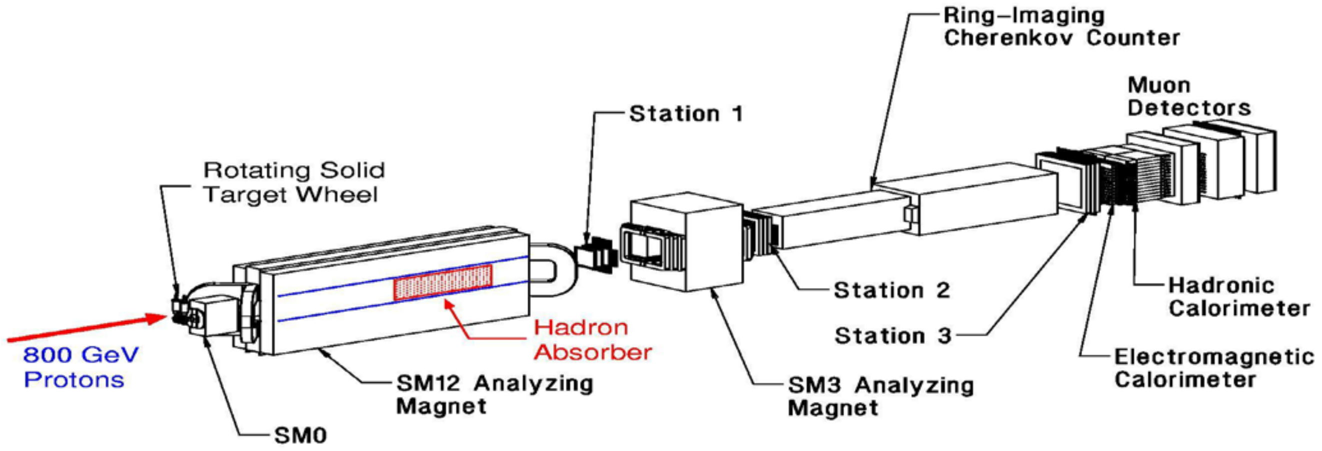
$$\bar{d} - \bar{u} \text{ has no contribution from extrinsic sea } (g \rightarrow \bar{q}q)$$
$$\text{and is sensitive to "intrinsic sea" only}$$



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

Fermilab Dimuon Experiments

(E605 / 772 / 789 / 866 / 906)

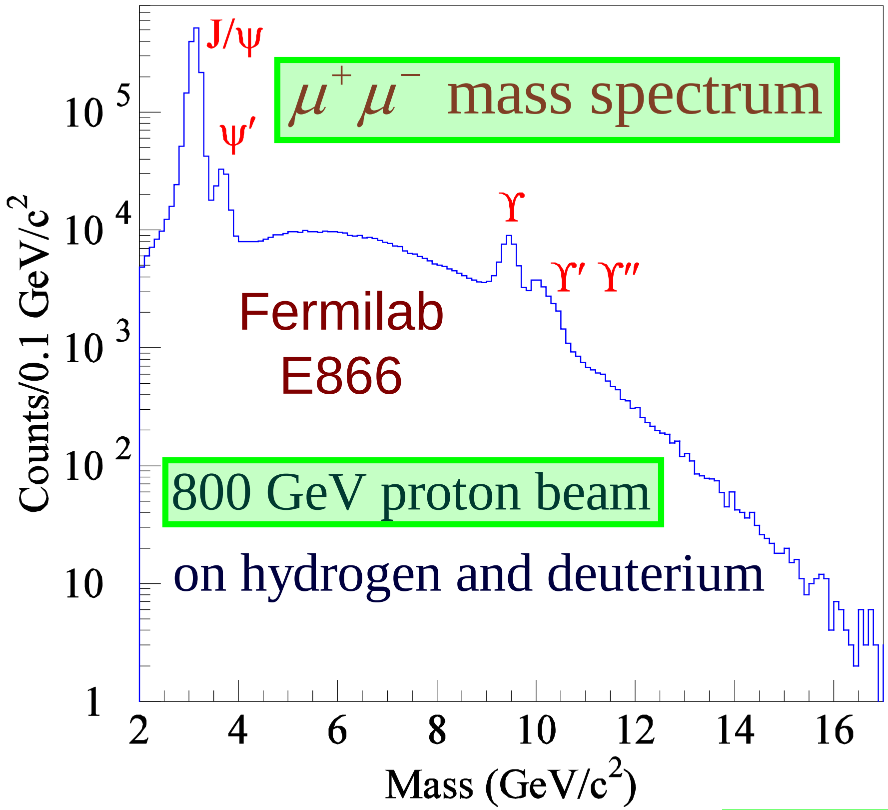


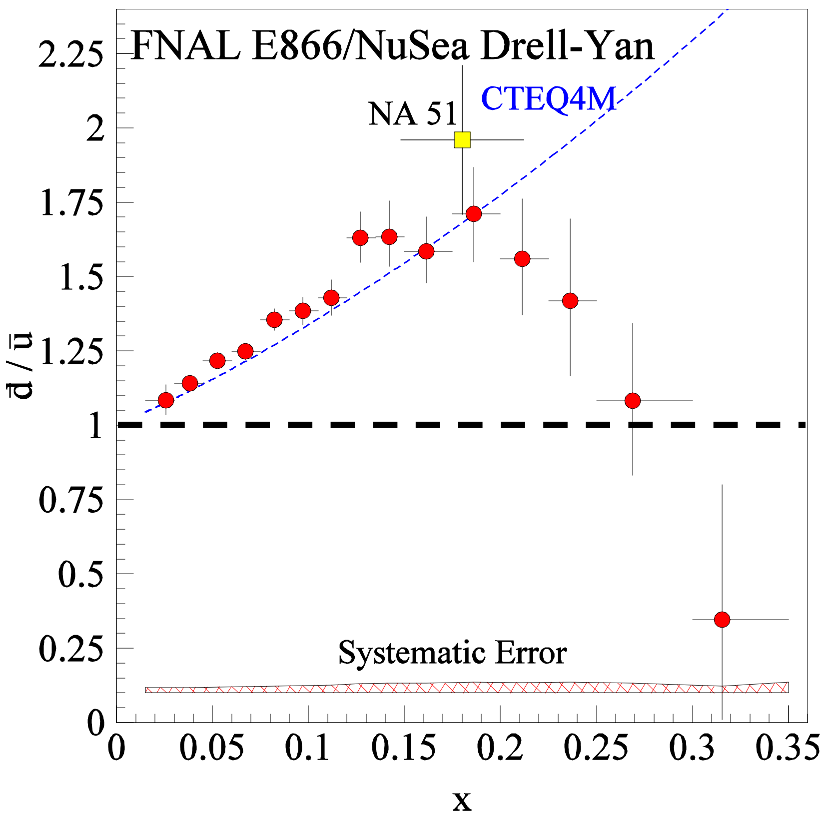
1) Fermilab E772 (proposed in 1986 and completed in 1988)
   "Nuclear Dependence of Drell-Yan and Quarkonium Production"
2) Fermilab E789 (proposed in 1989 and completed in 1991)
   "Search for Two-Body Decays of Heavy Quark Mesons"
3) Fermilab E866 (proposed in 1993 and completed in 1996)
   "Determination of $\bar{d} / \bar{u}$ Ratio of the Proton via Drell-Yan"
4) Fermilab E906 (proposed in 1999, completed in 2017)
   "Drell-Yan with the FNAL Main Injector"

EXPERIMENT E789- Moving Cable at Meson.
"The Snake".

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

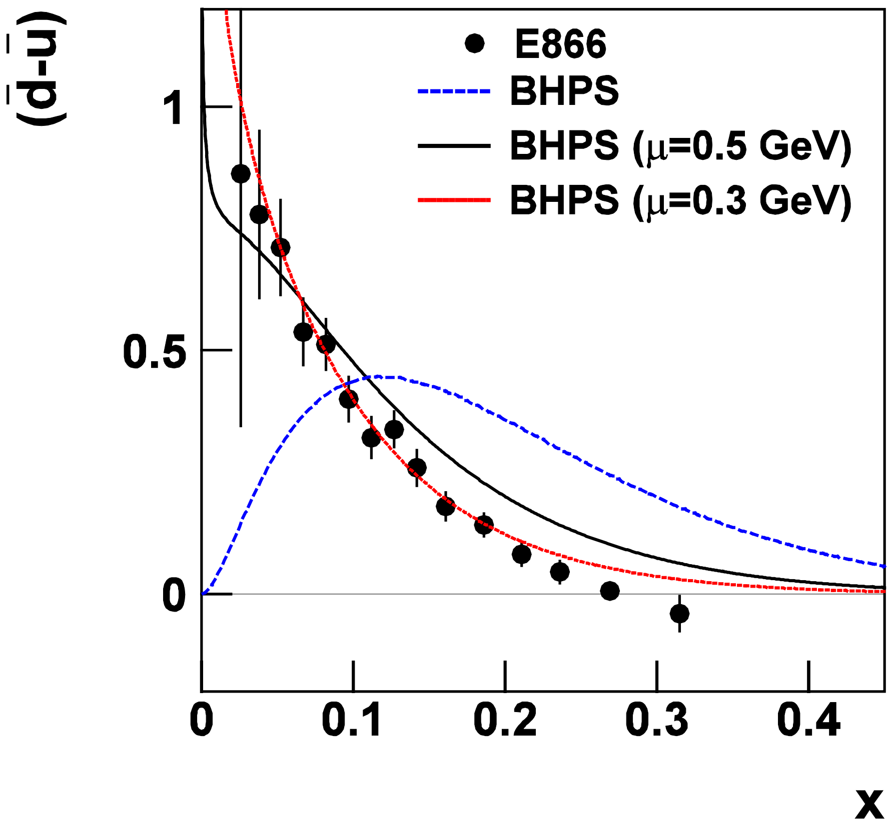
$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$





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

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



(Wen-Chen 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

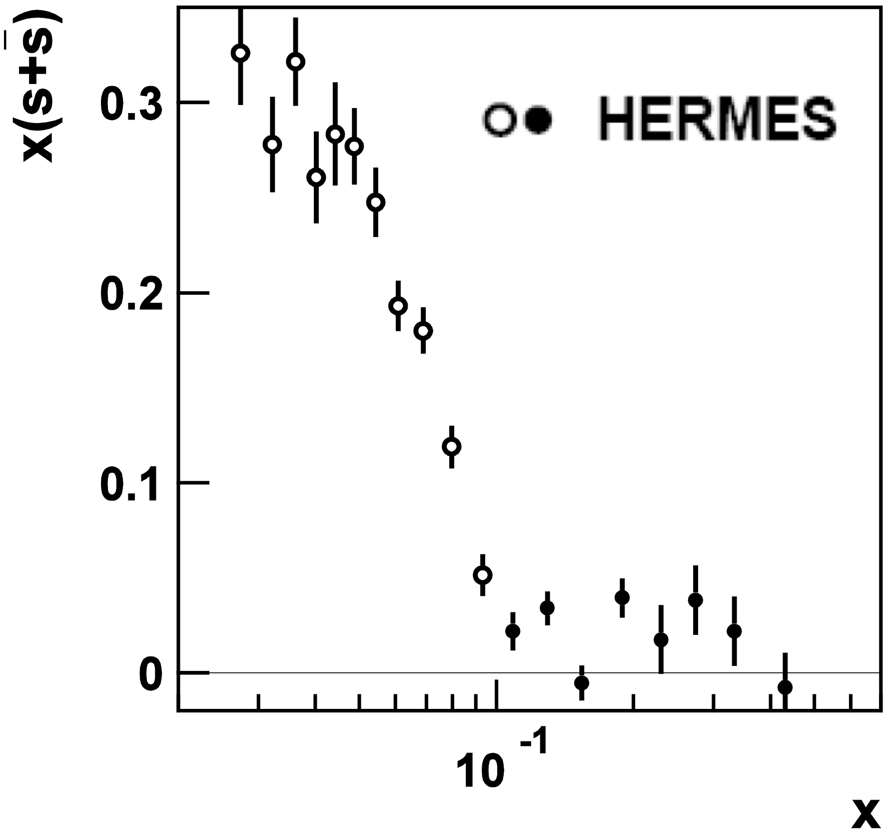
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

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

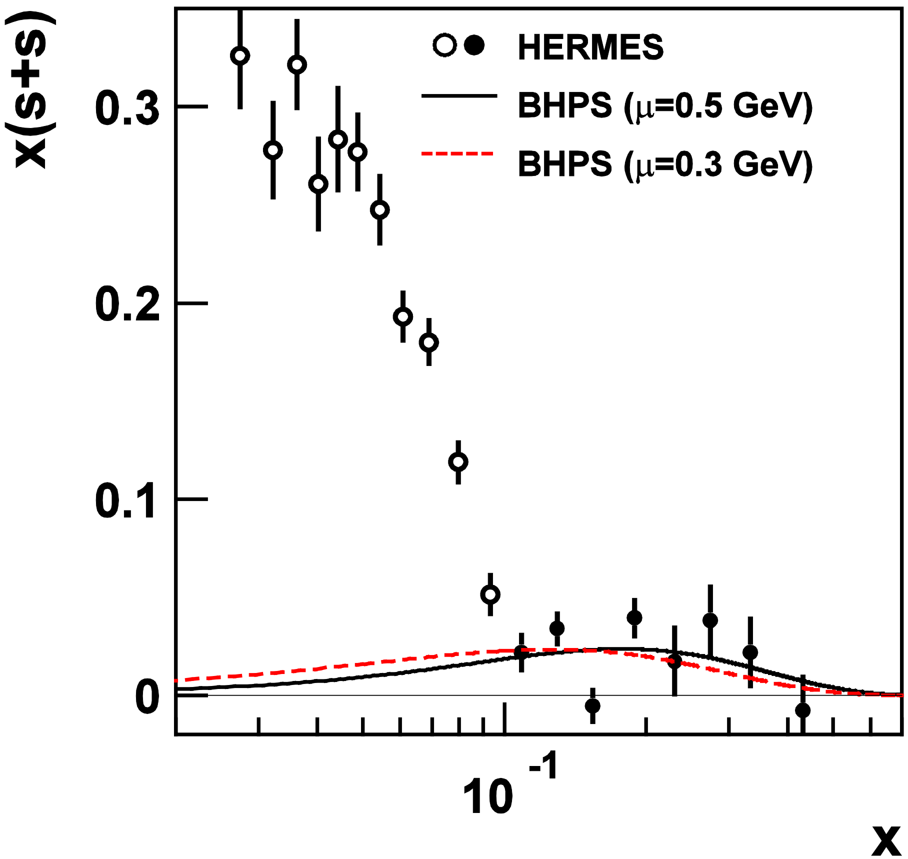


$s(x)+\overline{s}(x)$ extracted from HERMES Semi-inclusive DIS kaon data at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$

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

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

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



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

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

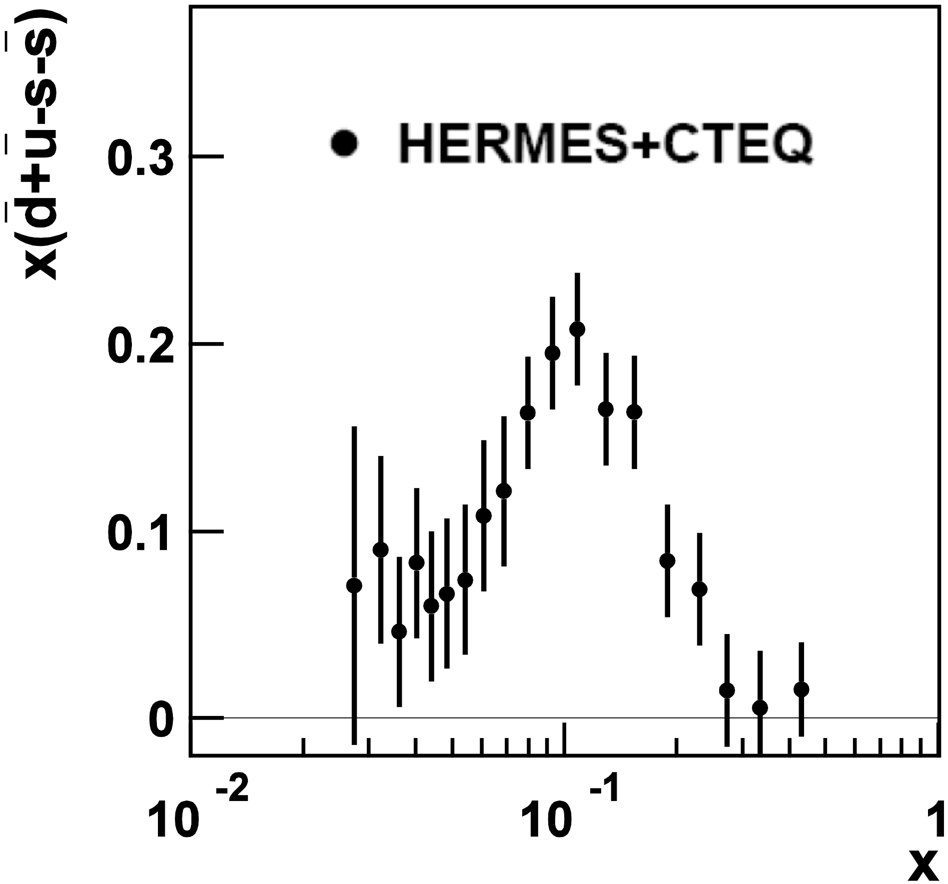
$$P_5^{uuds\bar{s}} = 0.024$$

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

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

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

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



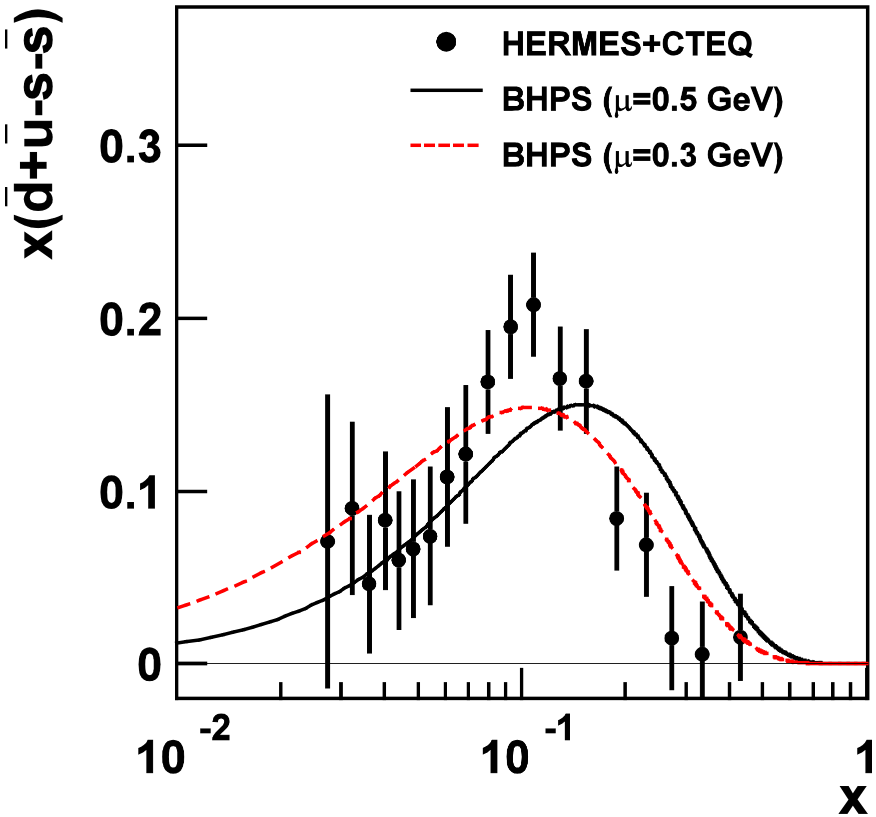
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

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

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

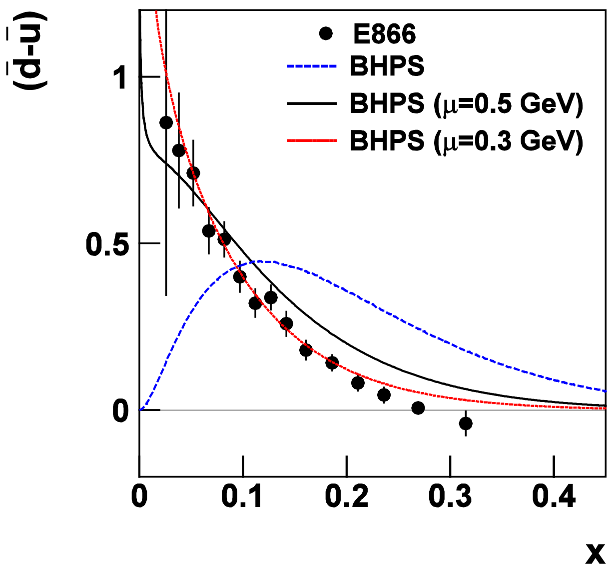
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

(not sensitive to extrinsic sea)

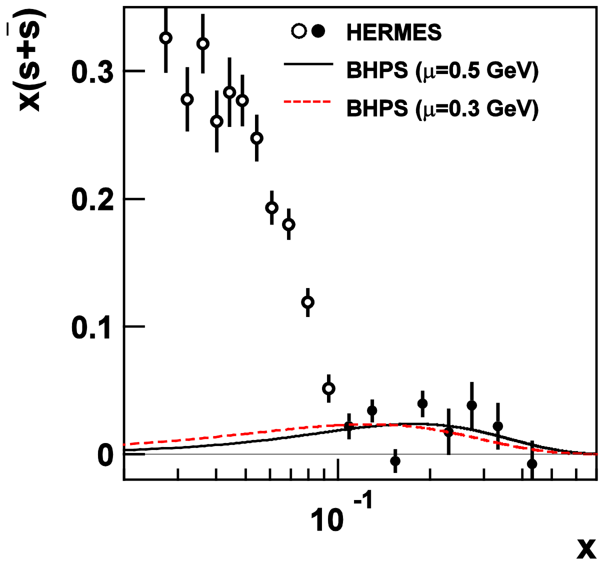
(W. Chang and JCP, PL B704, 197(2011))

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

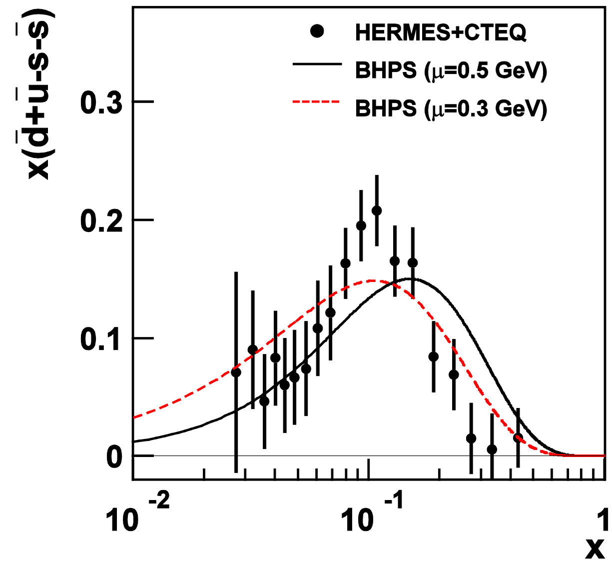
Extraction of the various five-quark components for light quarks



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



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



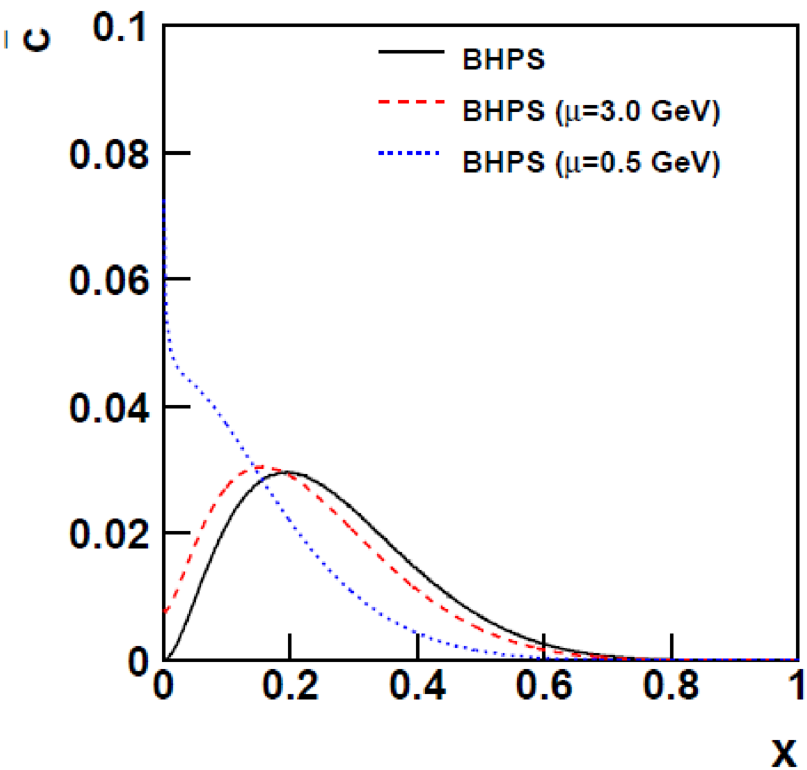
$$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$$

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

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

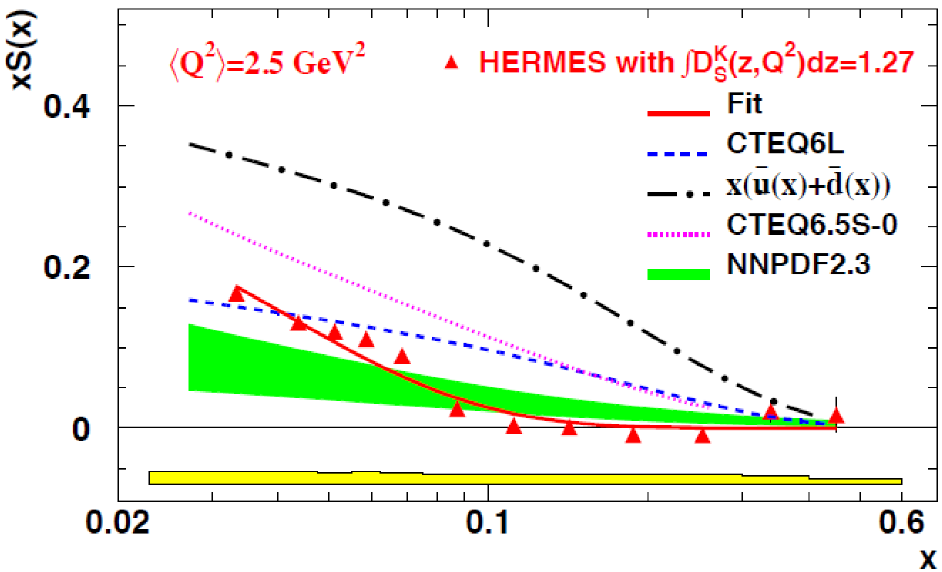
$$P_5^{uud d\bar{d}} = 0.240; \;\; P_5^{uud u\bar{u}} = 0.122; \;\; P_5^{uud s\bar{s}} = 0.024$$

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



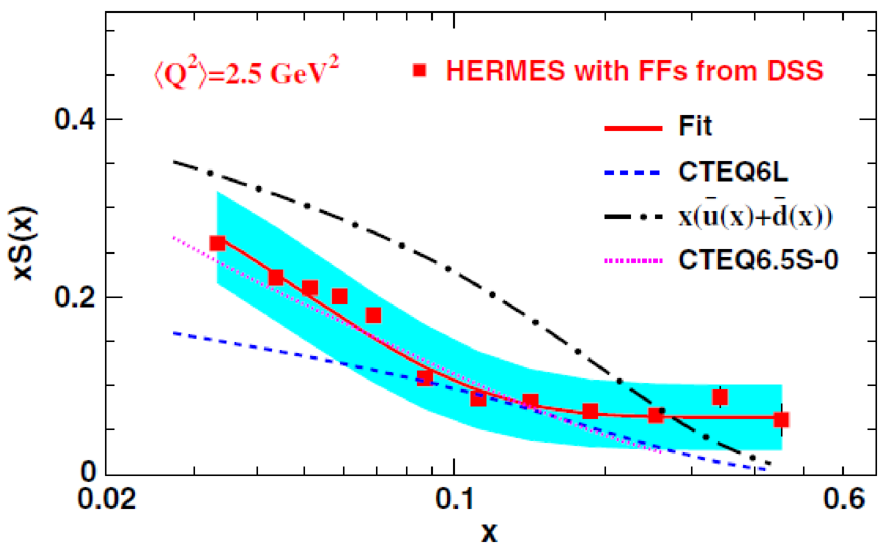
- Calculation assumes $P_5^{uud c\bar{c}} = 0.01$
- Q^2 - evolution could shift the x-distribution to smaller x

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

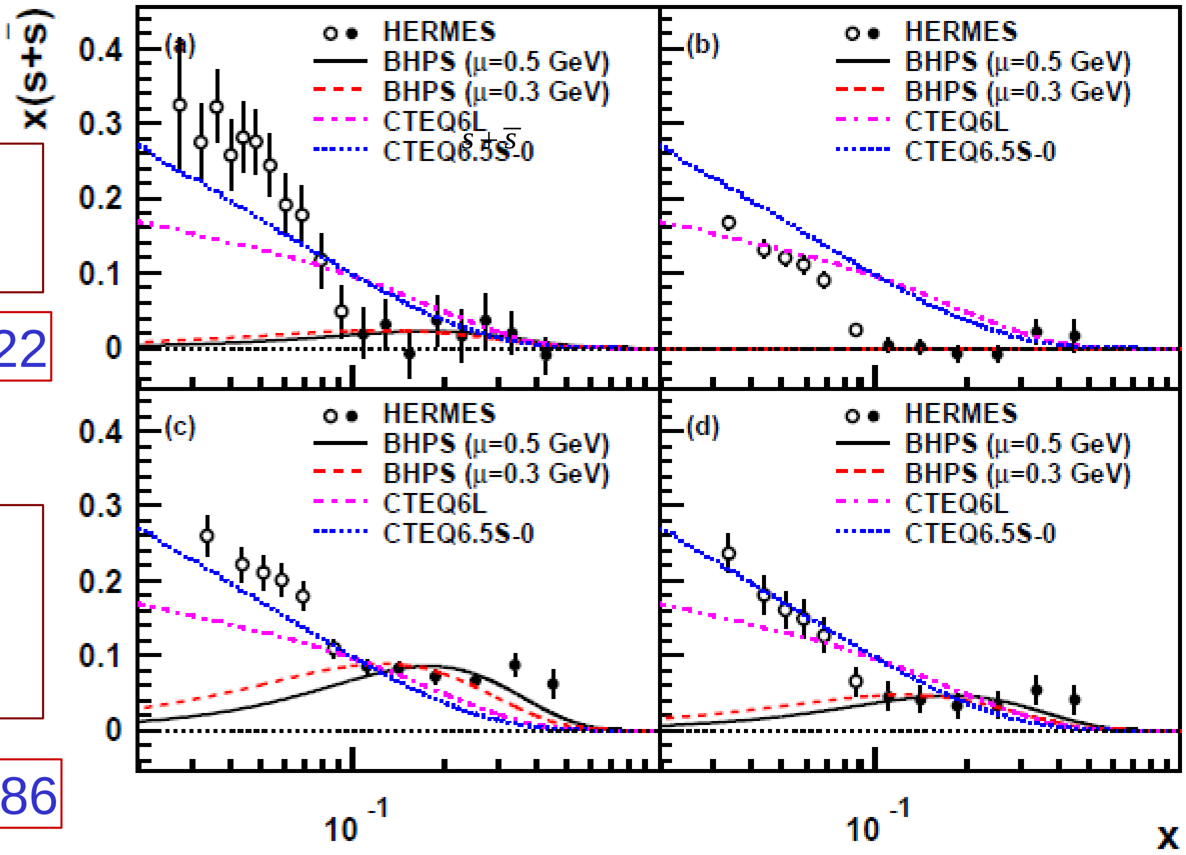
Dependence of $s+\bar{s}$ extraction on the kaon fragmentation functions

2008 HERMES

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

2014 HERMES DSS FF

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



2014 HERMES

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

2014 HERMES Intermediate FF

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

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

Future Possibilities

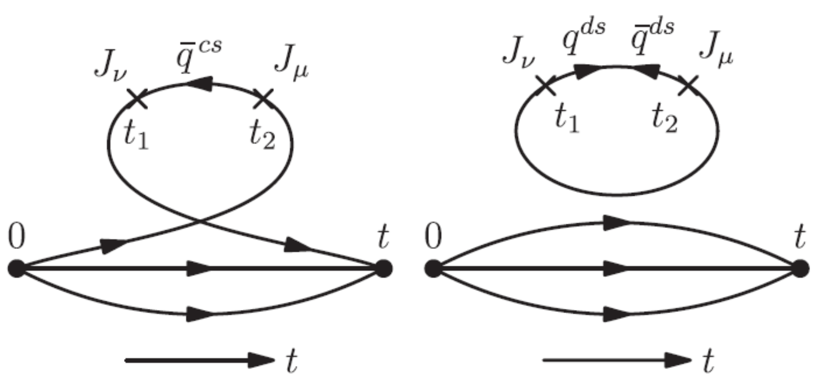
- Search for intrinsic charm and beauty at LHC.
- Spin-dependent observables of intrinsic sea?
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and meson cloud?
- Connection between intrinsic sea and lattice QCD formalism?

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 Disconnected sea



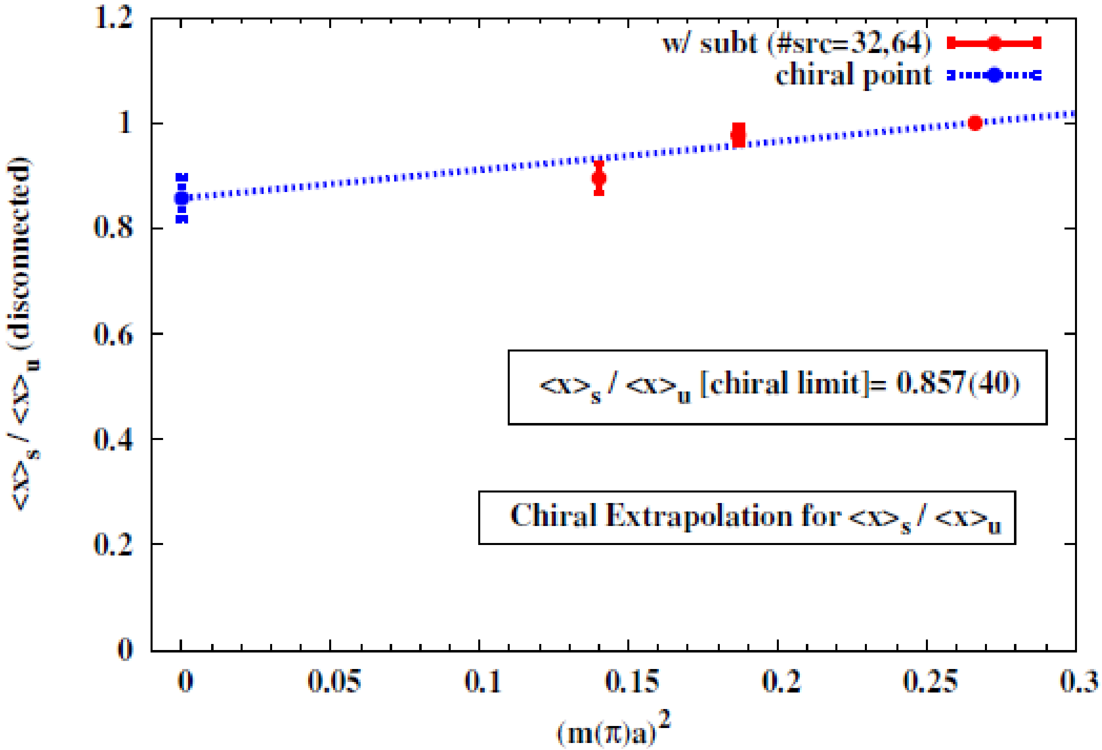
(valence-like) (sea-like)

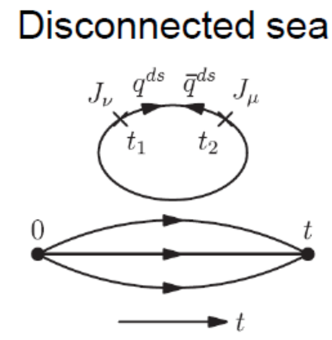
Two sources of sea:
Connected sea (CS) and Disconnected sea (DS)

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; $s+\bar{s}$ is entirely DS

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





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

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)

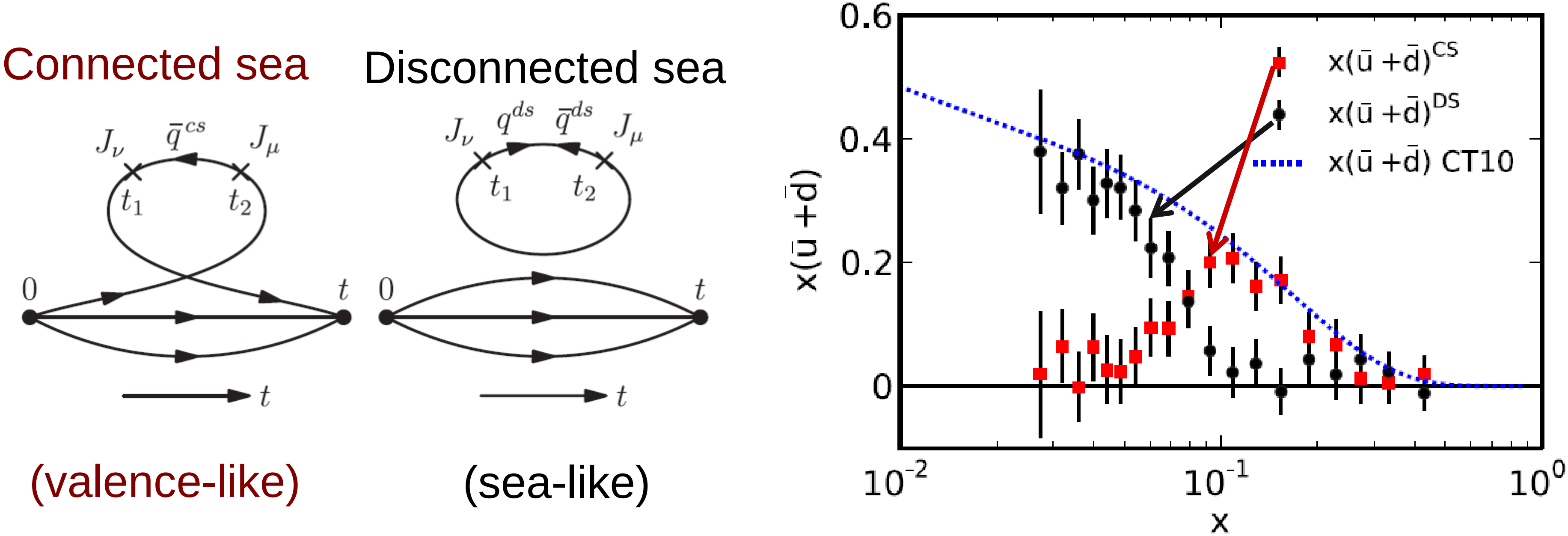
C) $[\bar{u}(x) + \bar{d}(x)]_{\text{connected sea}} =$

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

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

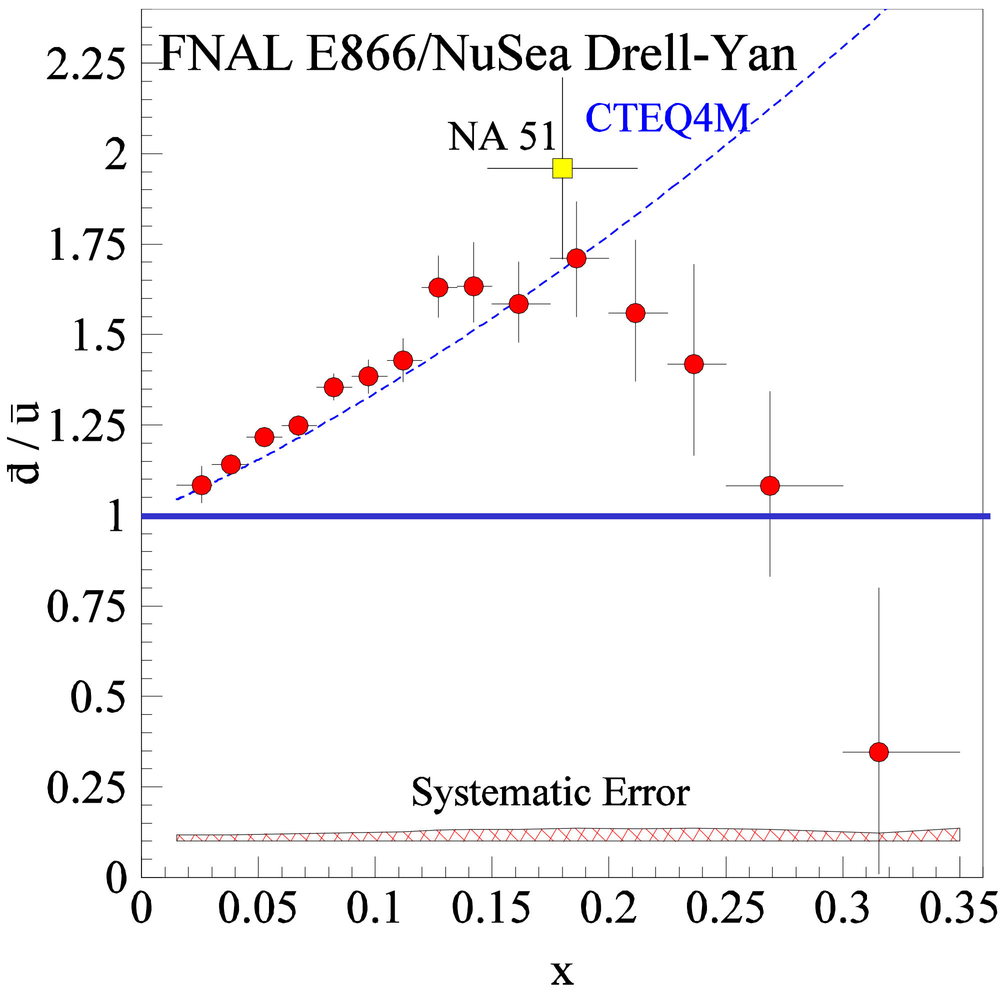
Connected-Sea Partons

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



- Connected sea component for $\bar{u}(x)+\bar{d}(x)$ is valence-like
- For $\bar{u}+\bar{d}$, momenta carried by CS and DS are roughly equal, at $Q^2=2.5\ \mathrm{GeV}^2$

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



No existing models can explain sign-change

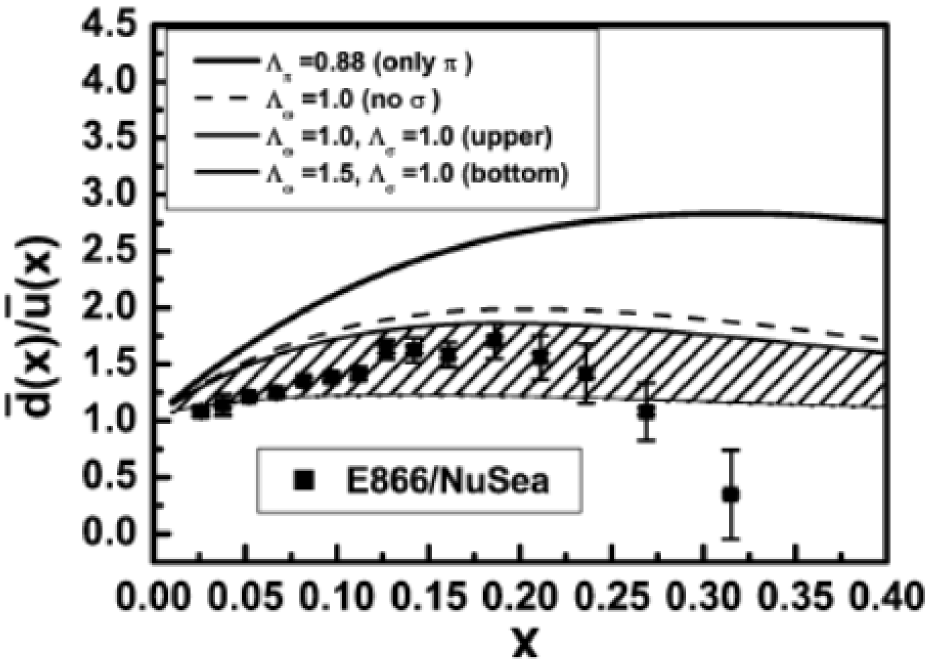
for $\bar{d}(x)-\bar{u}(x)$ at any value of x

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

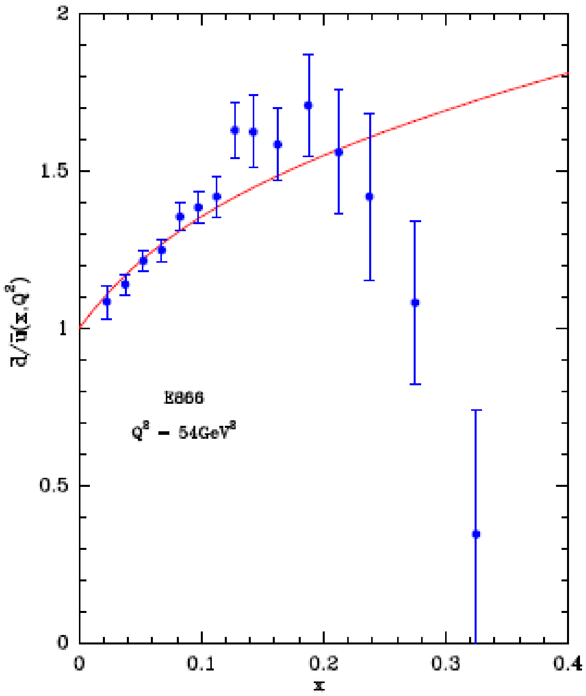
(or $\bar{d}(x)/\bar{u}(x) < 1$ at $x \sim 0.25$?)

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

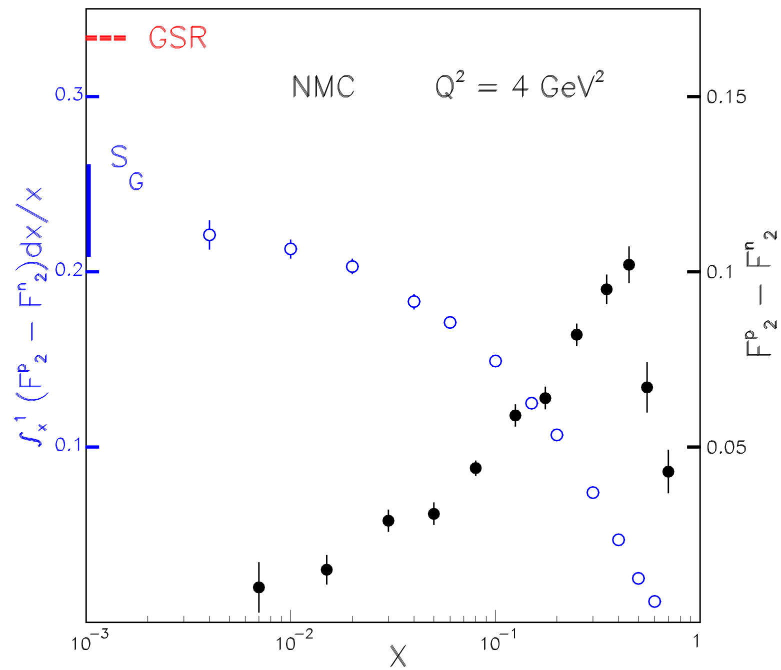
Meson cloud model



Statistical model



Revisit the NMC measurement of the Gottfried Sum rule



The Gottfried Sum Rule

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

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

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

New Muon Collaboration (NMC) obtains

$S_G = 0.235 \pm 0.026$

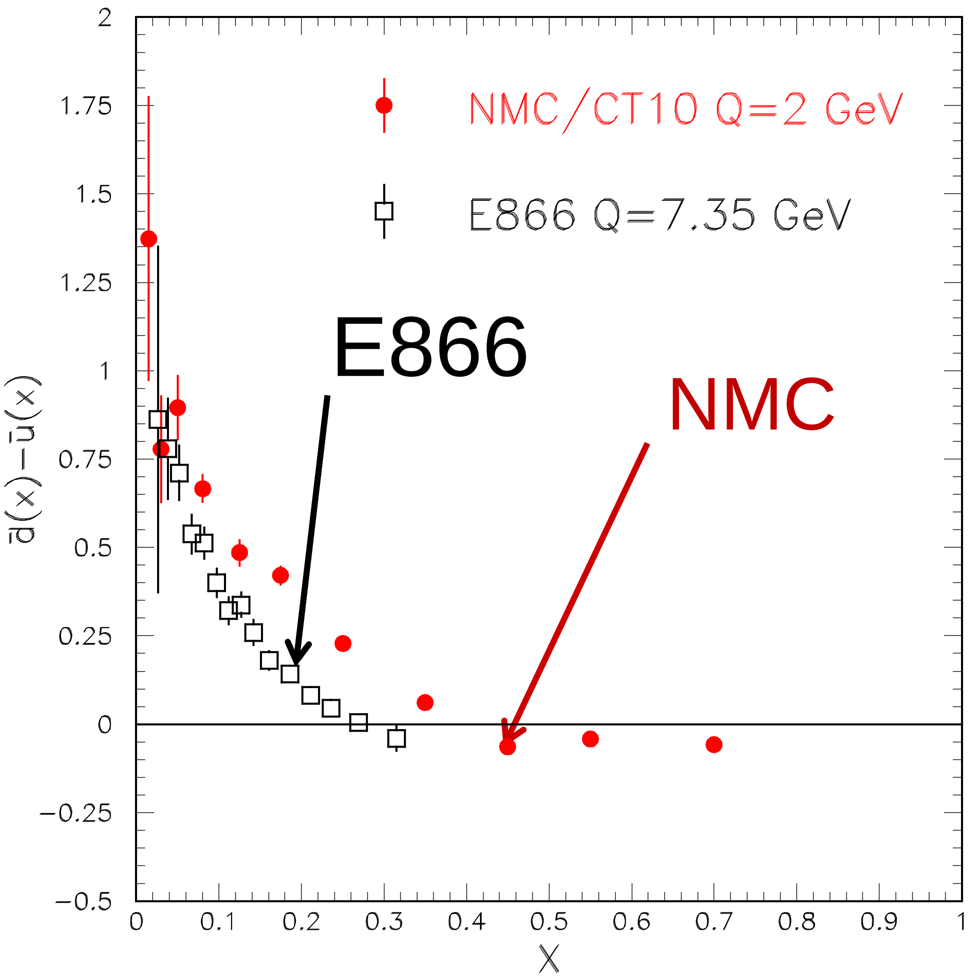
(Significantly lower than 1/3 !)

$\Rightarrow \bar{d} \neq \bar{u}\,?$

Why not look at $F_2^p(x) - F_2^n(x)$ directly?

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

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

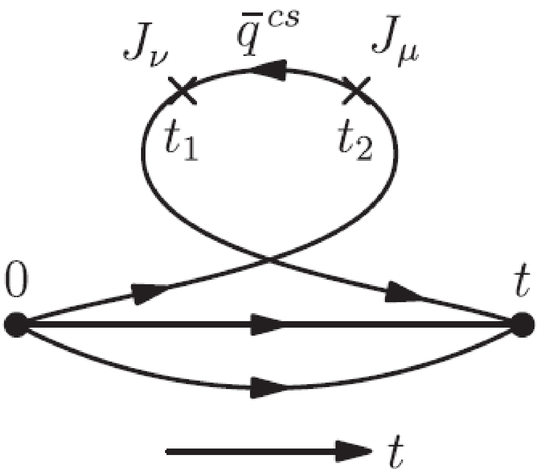


The NMC data, together with the recent PDF, also suggested that $\bar{d}(x) - \bar{u}(x) < 0$ at large x !

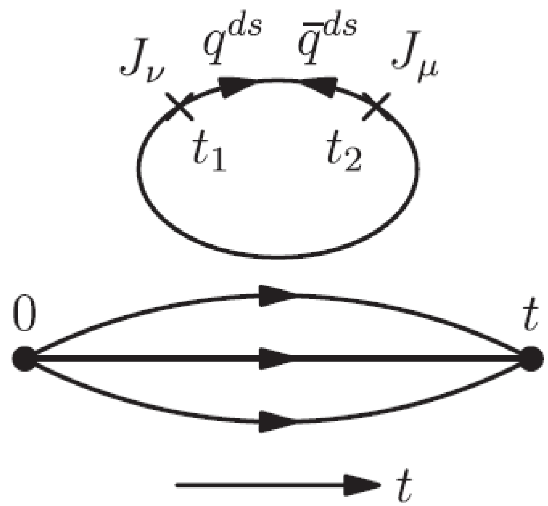
(JCP, W.C. Chen, H.Y. Cheng, T.J. Hou, K.F. Liu, J.W. Qiu, Phys Lett B736 (2014) 411

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

Connected sea | Disconnected sea



(valence-like)



(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??

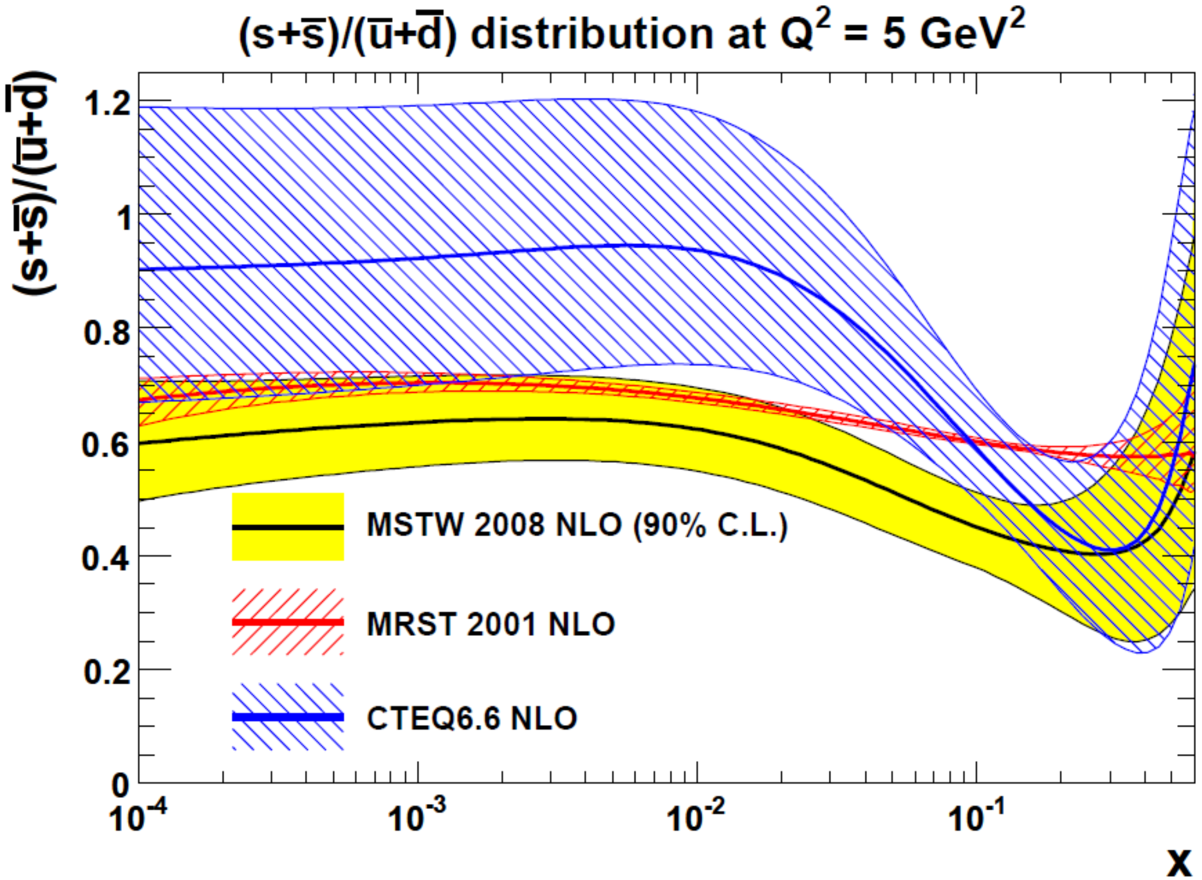
(since there are two u valence quarks and one d valence quak)

Result from SeaQuest is forthcoming

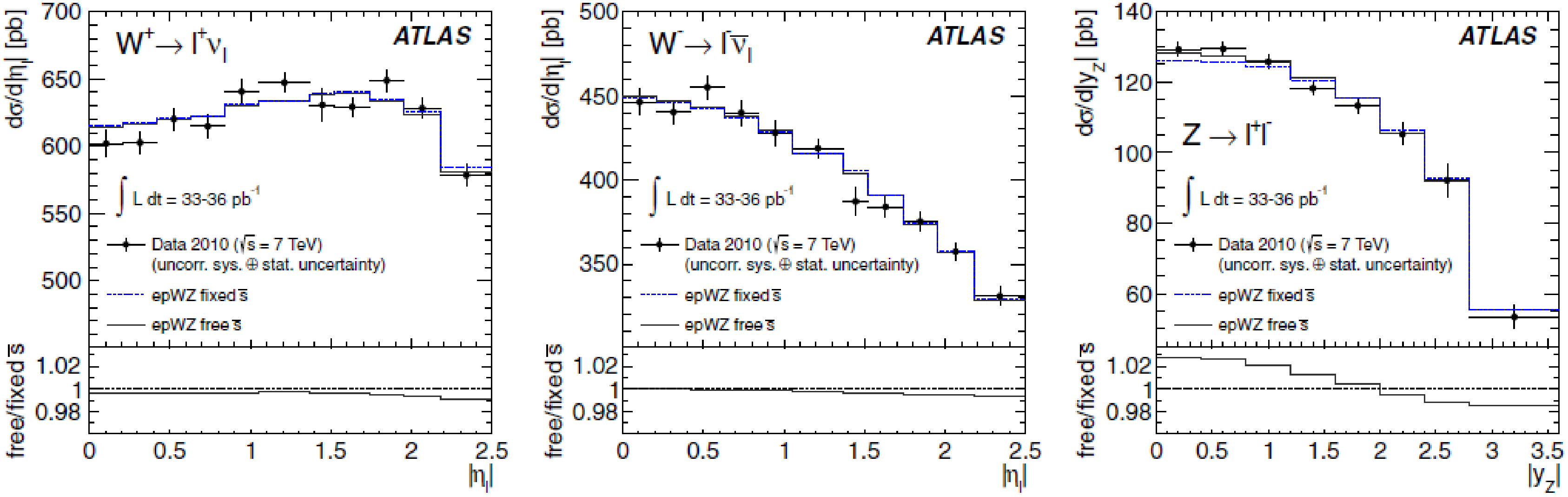
Is $s(x)+\bar{s}(x)=\bar{u}(x)+\bar{d}(x)$?

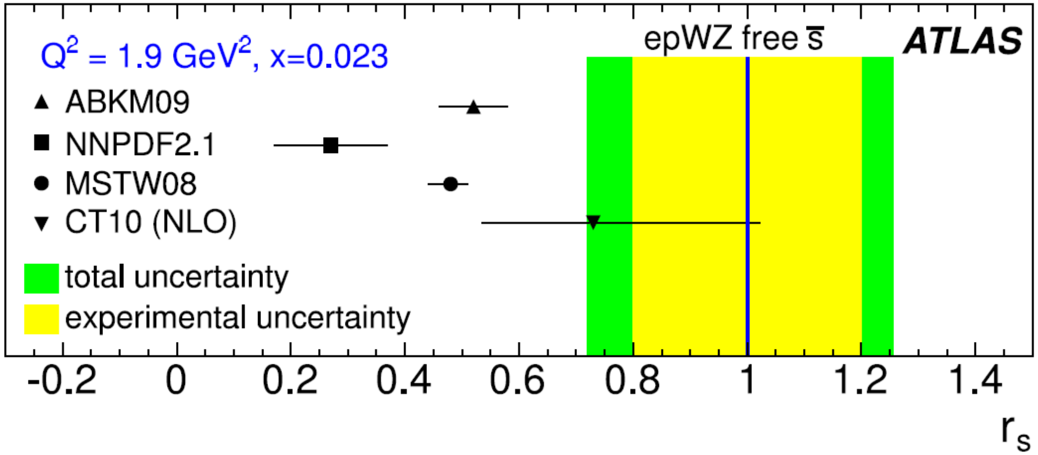
Expectation:

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





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

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

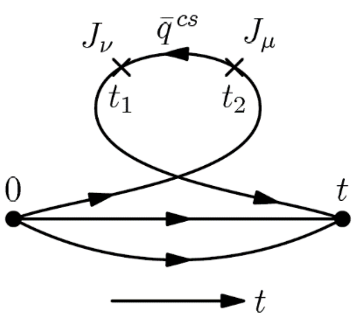
Aad et al., PRL 109 (2012) 012001

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

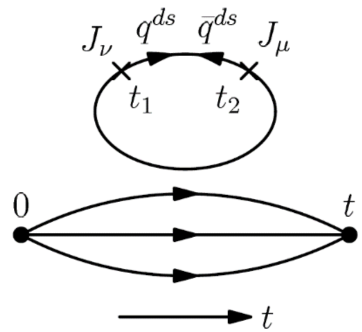
Can be well understood from Lattice QCD
(PRL 109 (2012)252002)

Connected sea



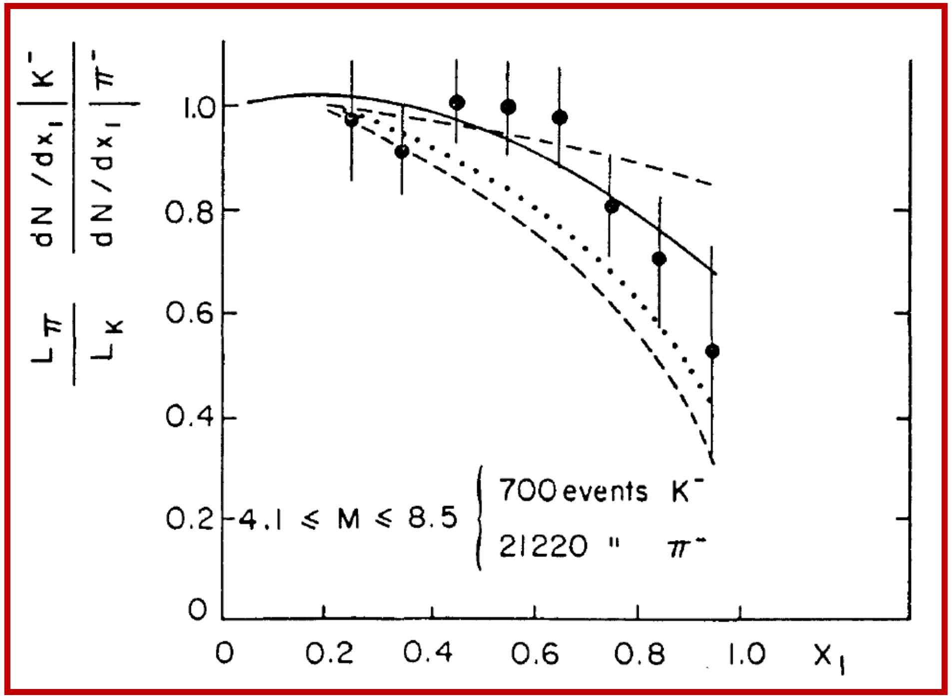
Generate "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger *x*

Disconnected sea



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

Kaon PDF from $(K^- + D)/(\pi^- + D)$ Drell-Yan ratios



From NA3; 150 GeV, Pt target

$$R = \frac{\sigma_{DY}(K^- + D)}{\sigma_{DY}(\pi^- + D)}$$

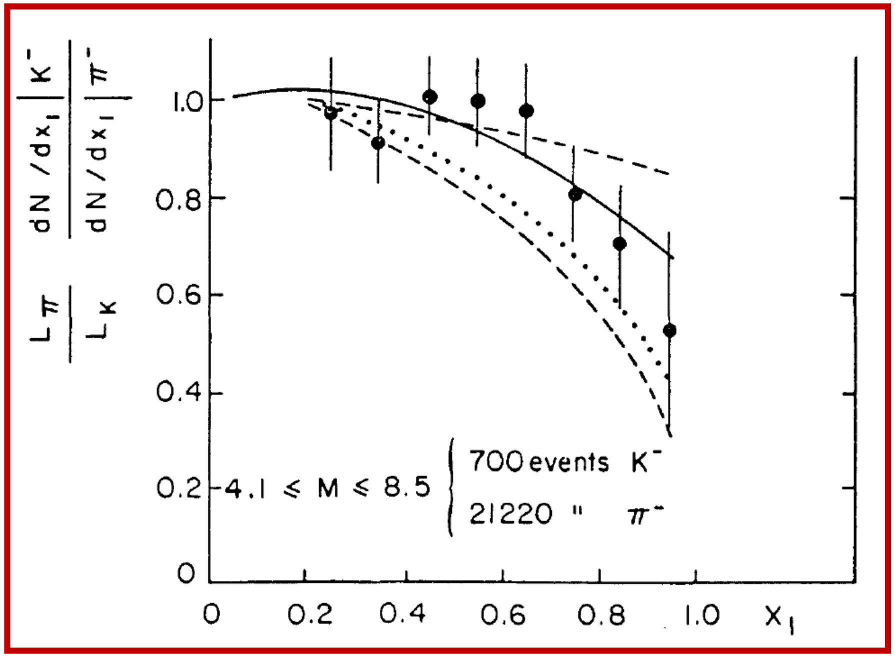
$$\simeq \frac{4V_K^u(x_1)V_N(x_2) + 4V_K^u(x_1)S_N(x_2) + V_K^s(x_1)s_p(x_2) + 5S_K(x_1)V_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2)} \simeq \frac{V_K^u(x_1)}{V_\pi(x_1)}$$

$R \simeq (1-x)^{0.18\pm0.07} \Rightarrow$ softer u-valence in kaon than in pion

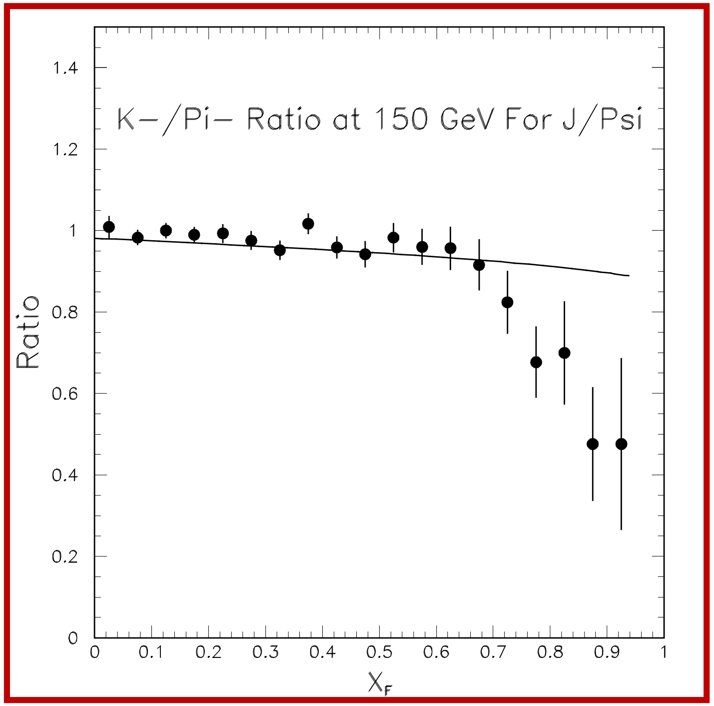
$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y

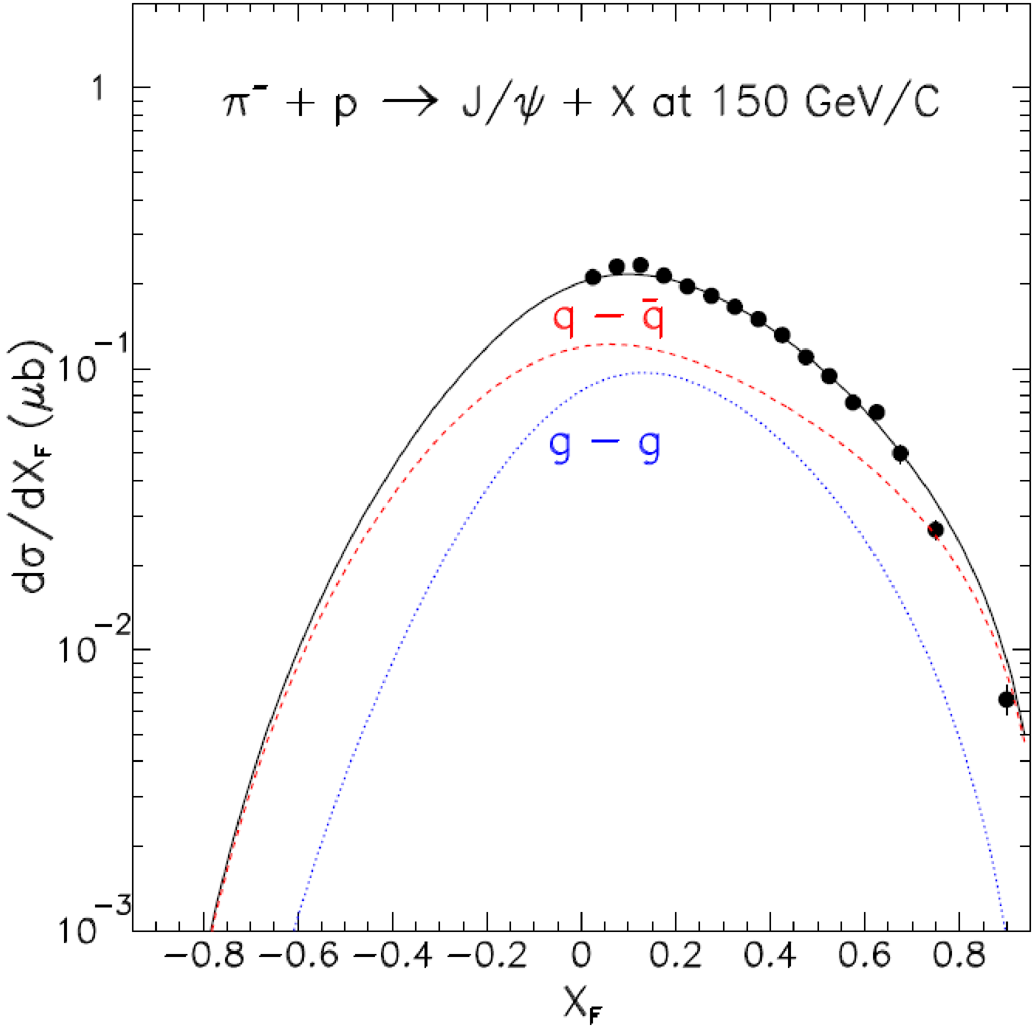


Ratios for J/Ψ



Similar behavior at large x_F for D-Y and J/Ψ production?

J/Ψ Production in the Color-evaporation model

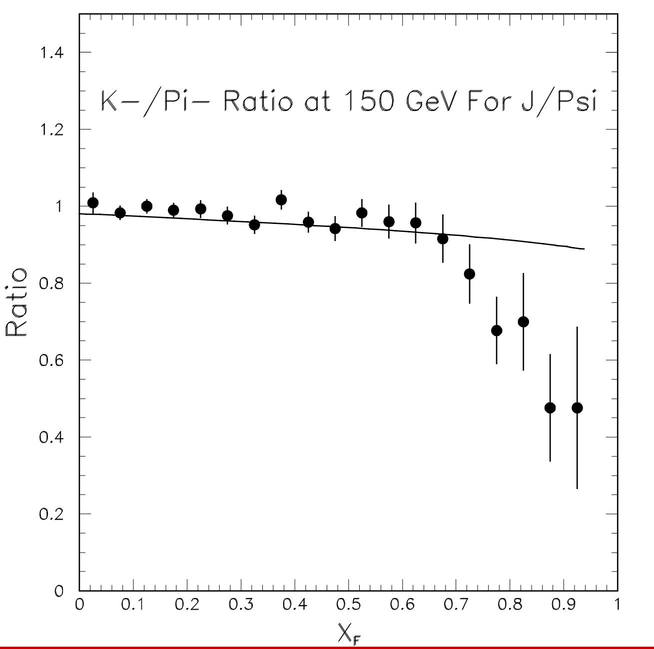


$q-\bar{q}$ annihilation dominates at forward x_F

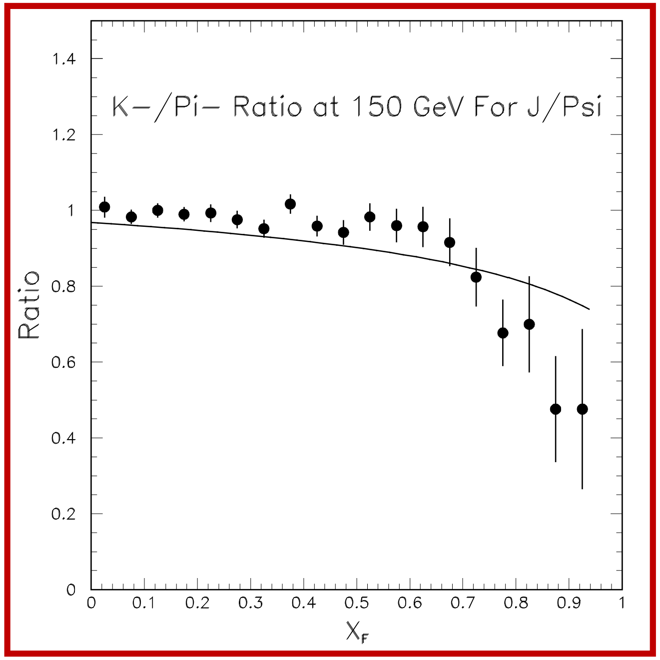
Comparison between data and CEM calculations

$(K^- + \mathrm{Pt})/(\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

same pdf for K^- and π^-



modified pdf for K^-



Modified kaon PDF has the ubar valence quark distribution multiplied by $(1\text{-}x)^{0.18}$ and the strange quark distribution divided by $(1\text{-}x)^{0.18}$

The K/π ratios of J/Ψ production at large x_F might indicate a softer $\bar{u}$ in K^- than in the pion, similar to the D-Y data?

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 concept of connected and disconnected seas in Lattice QCD offers useful insights on the flavor- and *x*-dependencies of the sea.
- Flavor structure of the meson PDFs remains to be studied and should provide useful new information.