High-Energy Hadron Physics with Dilepton Production

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

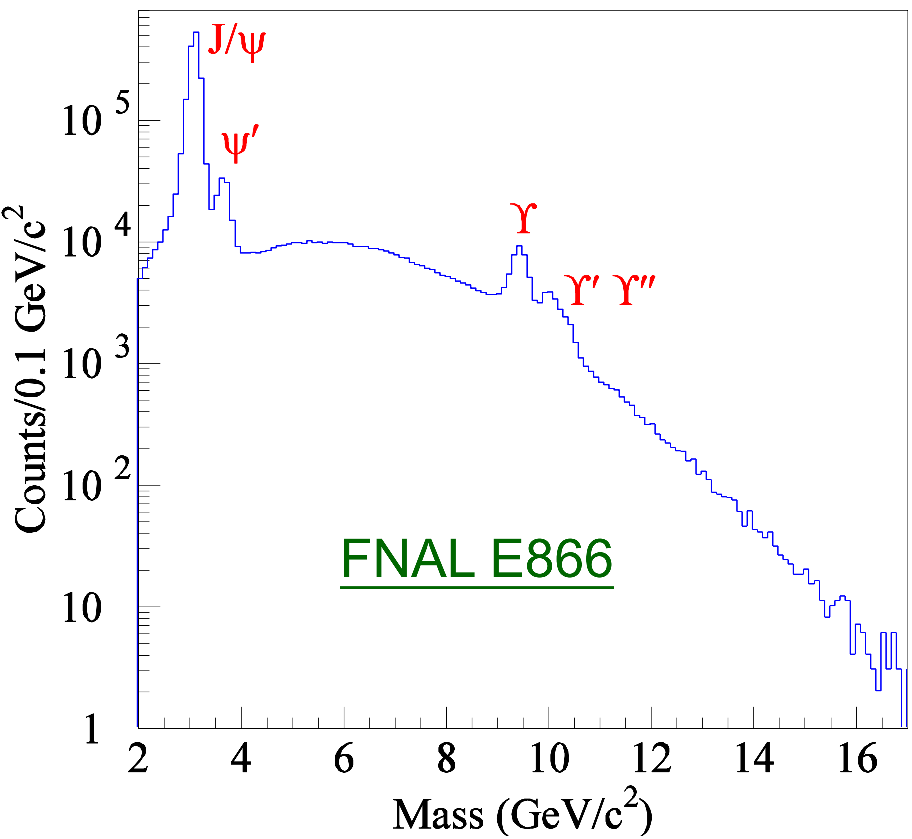
KEK Theory Center Workshop on “Hadron Physics with High-Momentum Hadron Beams at J-PARC”
KEK, January 15-18, 2013

Challenge and opportunities of dilepton experiments at J-PARC

- Challenge
  - Beam energies are relatively low (30-50 GeV ptoton, and secondary pion, kaon, antiproton at lower energies)
- Opportunities
  - Very few existing data at this energy region
  - Some novel hadron physics topics could be well studied at relatively low energies
  - Polarized beam/target offers new possibilities

Dilepton production in hadron-hadron collision

$p + p(d) \rightarrow \mu^+\mu^- x$ at 800 GeV/c



Two components in the dilepton mass spectrum

(a) Continuum: Drell-Yan process

- Electromagnetic process
- Quark - antiquark annihilation

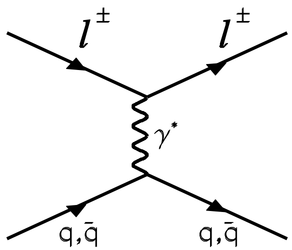
(b) Vector mesons: J/ψ, Y

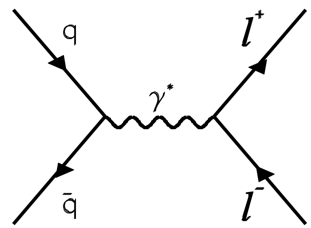
- Strong interaction
- Gluon - gluon fusion

  (quark - antiquark annihilation)

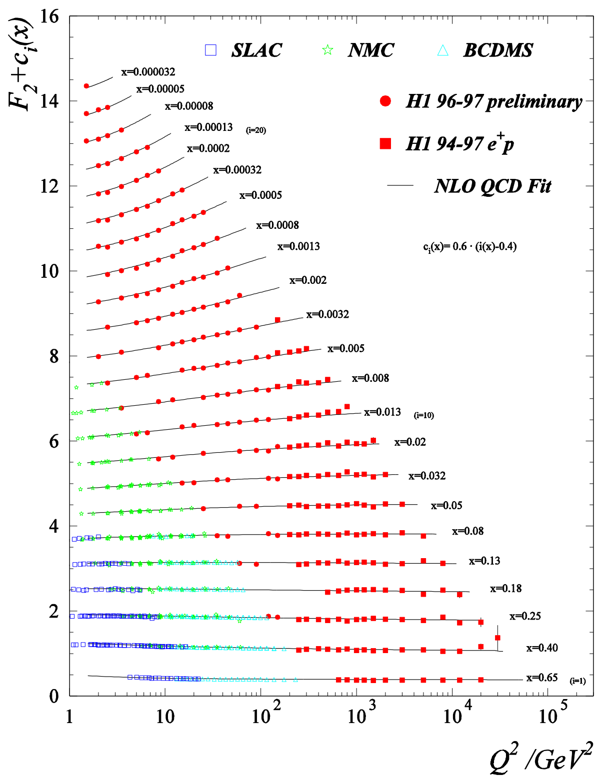
Complimentality between DIS and Drell-Yan

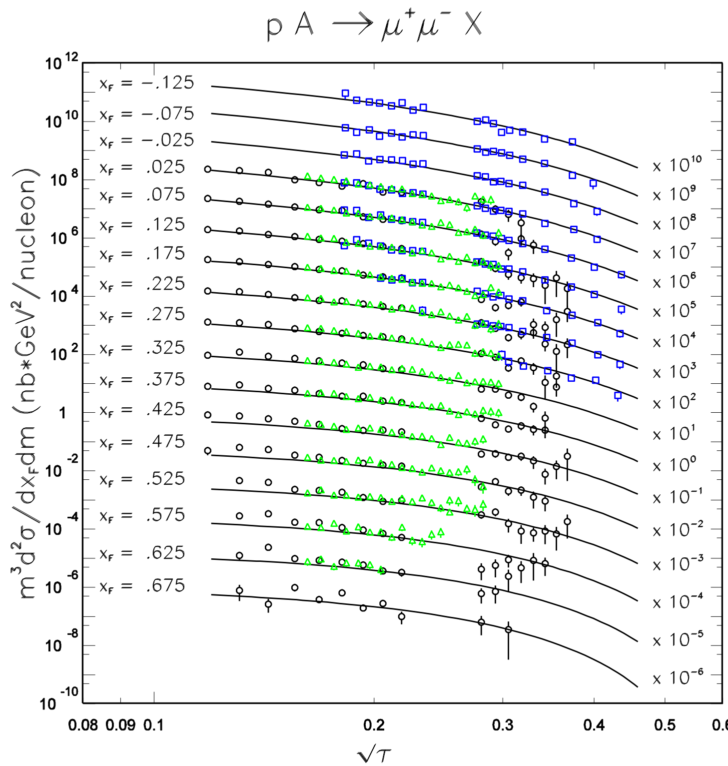
DIS





Drell-Yan





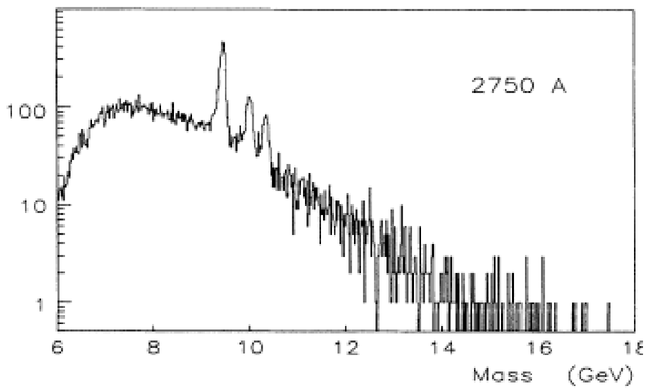
Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

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

Lepton-pair production provides unique information on parton distributions

$p + W \rightarrow \mu^+ \mu^- X$

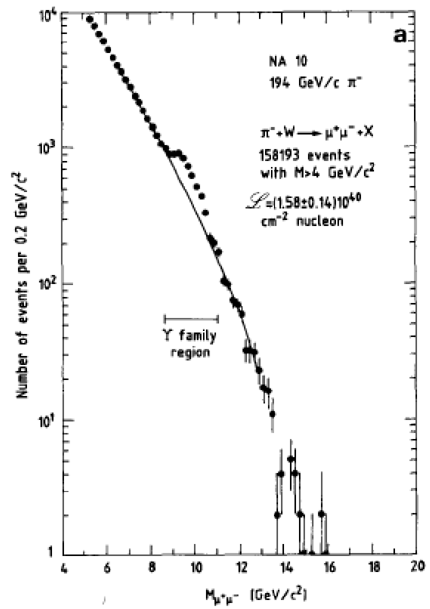
800 GeV/c



Probe antiquark distribution in nucleon

$\pi^- + W \rightarrow \mu^+ \mu^- X$

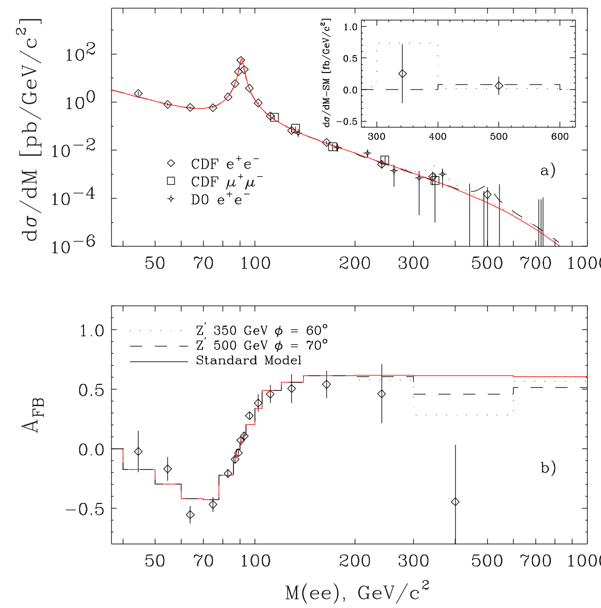
194 GeV/c



Probe antiquark distribution in pion

$\bar{p} + p \rightarrow l^+ l^- X$

1.8 TeV

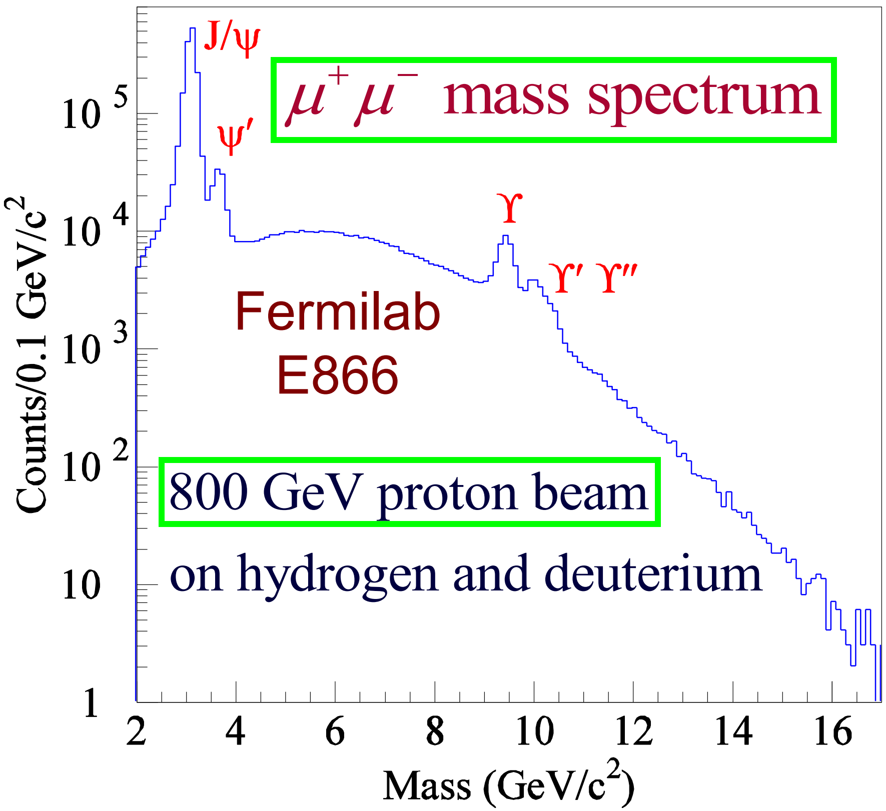


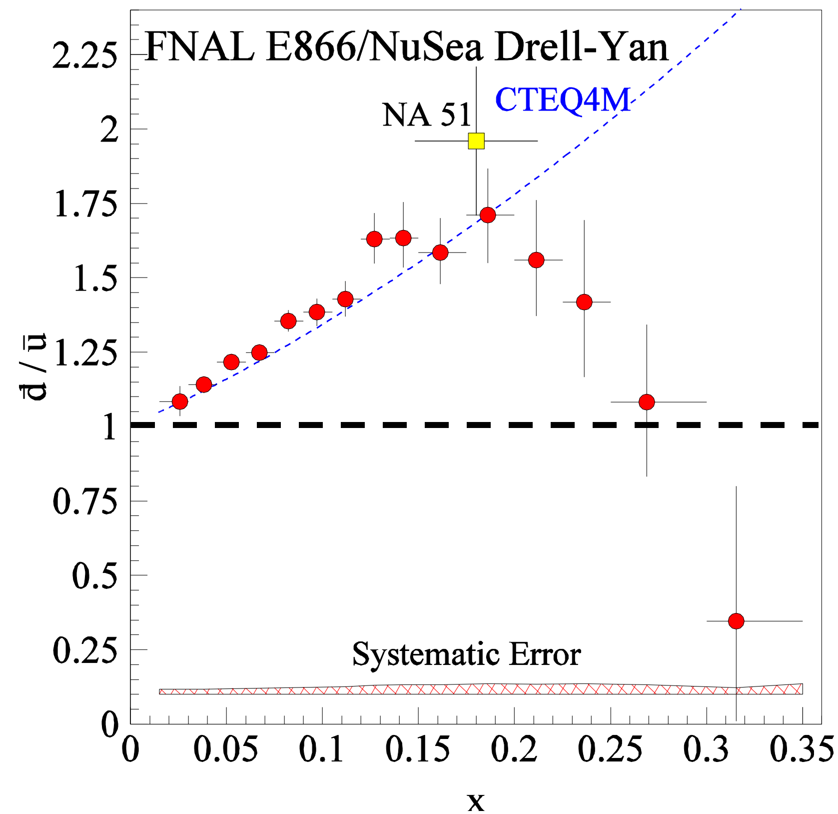
Probe antiquark distributions in antiproton

Unique features of D-Y: antiquarks, unstable hadrons…

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

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

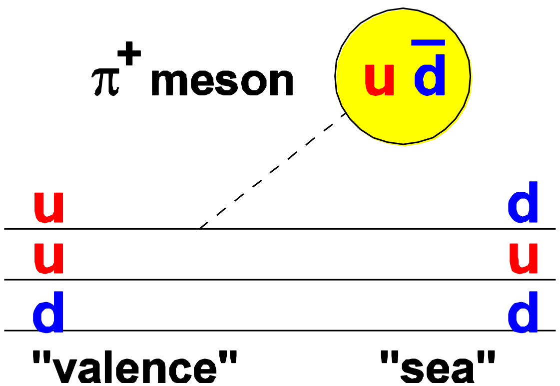




$at\ x_1 > x_2:$ Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \sim \frac{1}{2}\left(1 + \bar{d}(x_2)/\bar{u}(x_2)\right)$

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

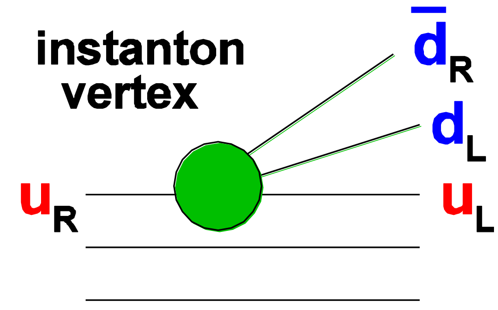
Meson Cloud Models



Chiral-Quark Soliton Model

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

Instantons



(For reviews, see Speth and Thomas (1997), Kumano Phys Report (hep-ph/9702367))

These models also have implications on

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

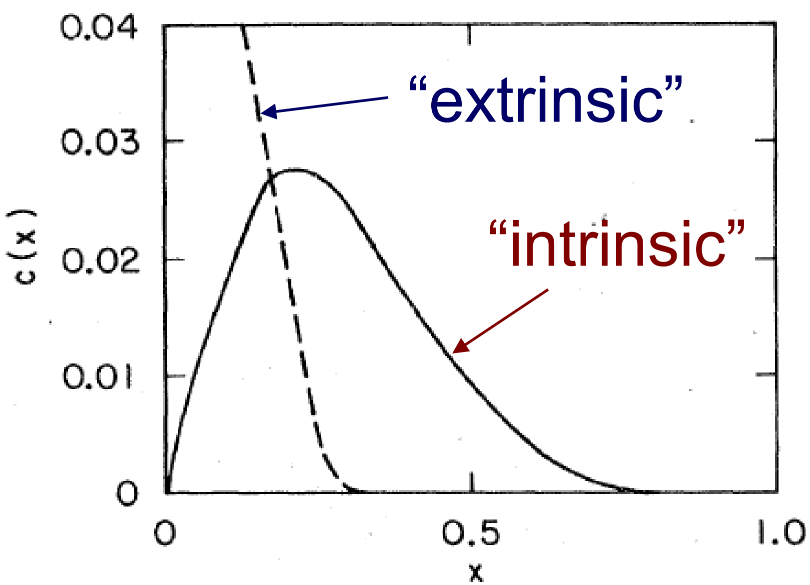
Meson cloud has significant contributions to sea-quark distributions

Implications on the "intrinsic" quark sea

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

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

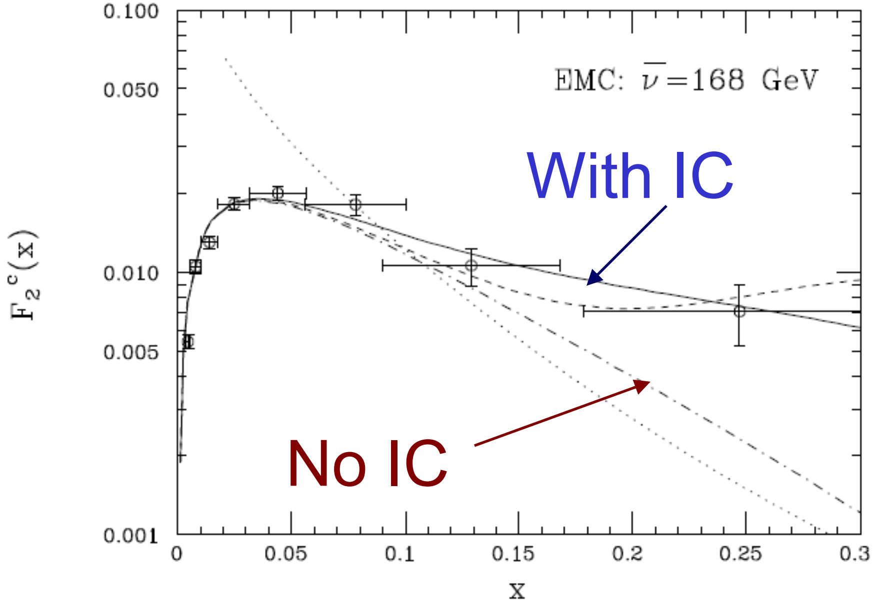
The "intrinsic"-charm from $|uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \to c\bar{c}$)



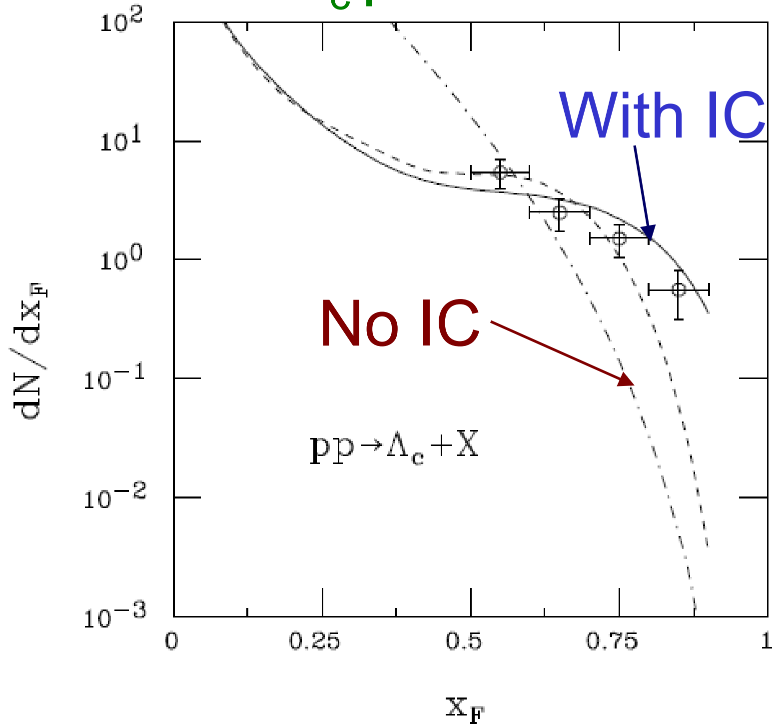
The $|uudc\bar{c}\rangle$ intrinsic-charm can lead to large contribution to charm production at large x

Evidence for the "intrinsic" charm (IC)

DIS data



Λ_c production



Gunion and Vogt (hep-ph/9706252)

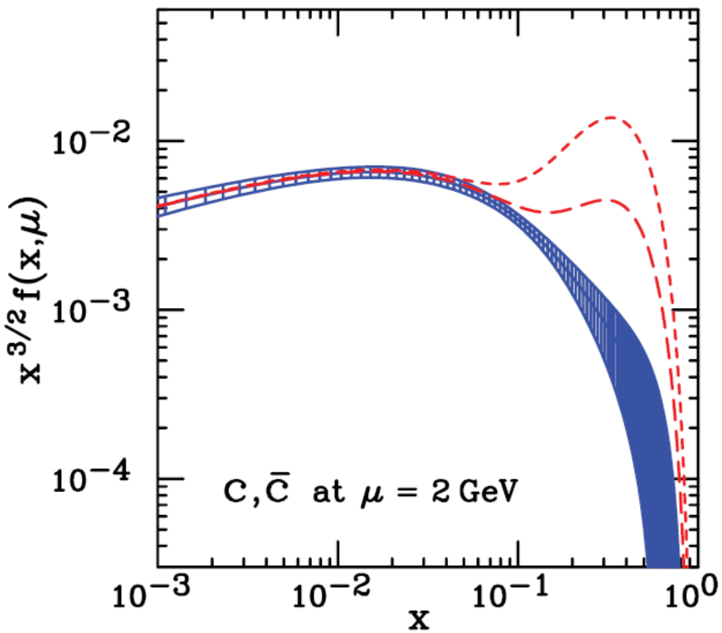
(Evidence is subjected to the uncertainties of charmed-quark parametrization in the PDF)

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 lighter "intrinsic" quark sea

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

No conclusive 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 ?

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

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

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

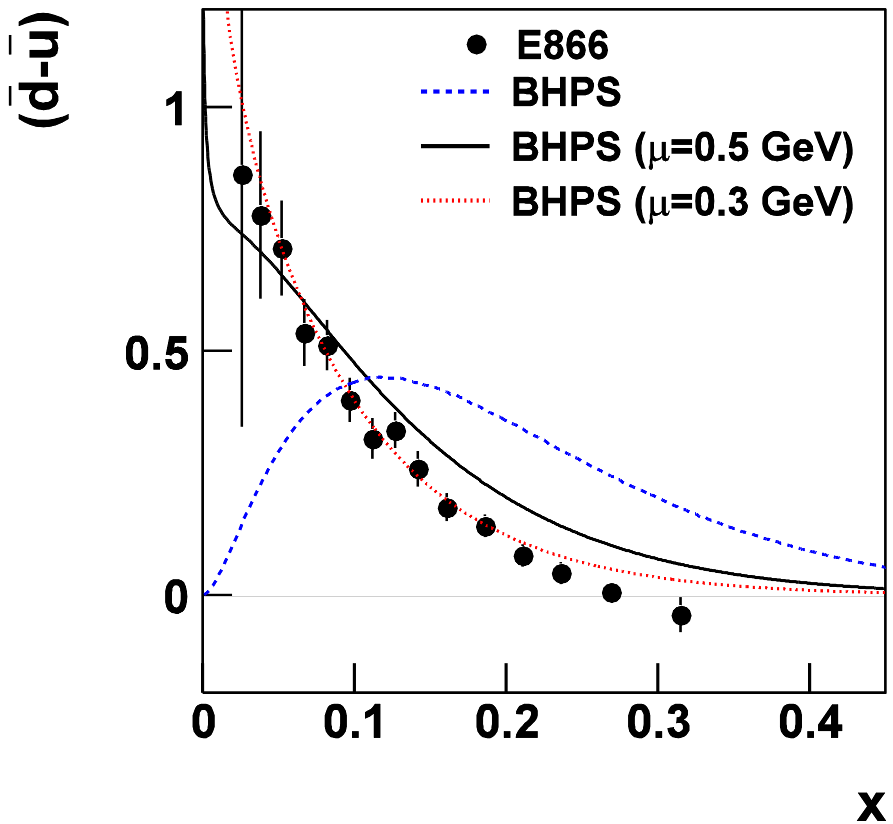
- Select experimental observables which have no contributions from the "extrinsic sea"
- "Intrinsic sea" and "extrinsic sea" are expected to have different x-distributions
  - Intrinsic sea is "valence-like" and is more abundant at larger x
  - Extrinsic sea is more abundant at smaller x

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

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

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

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

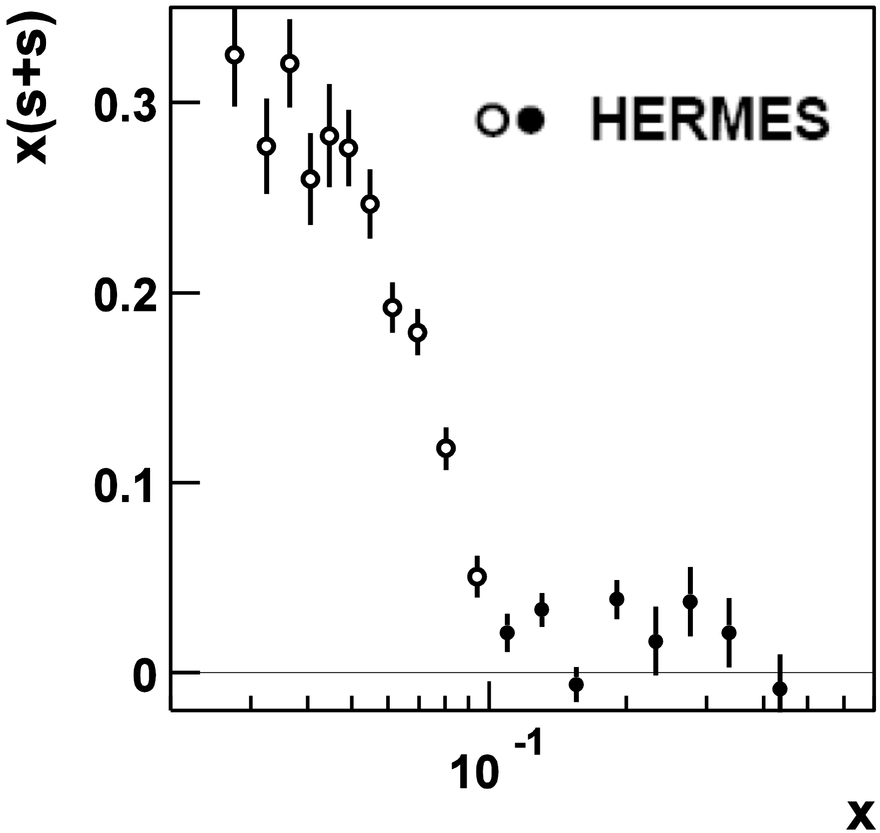
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

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

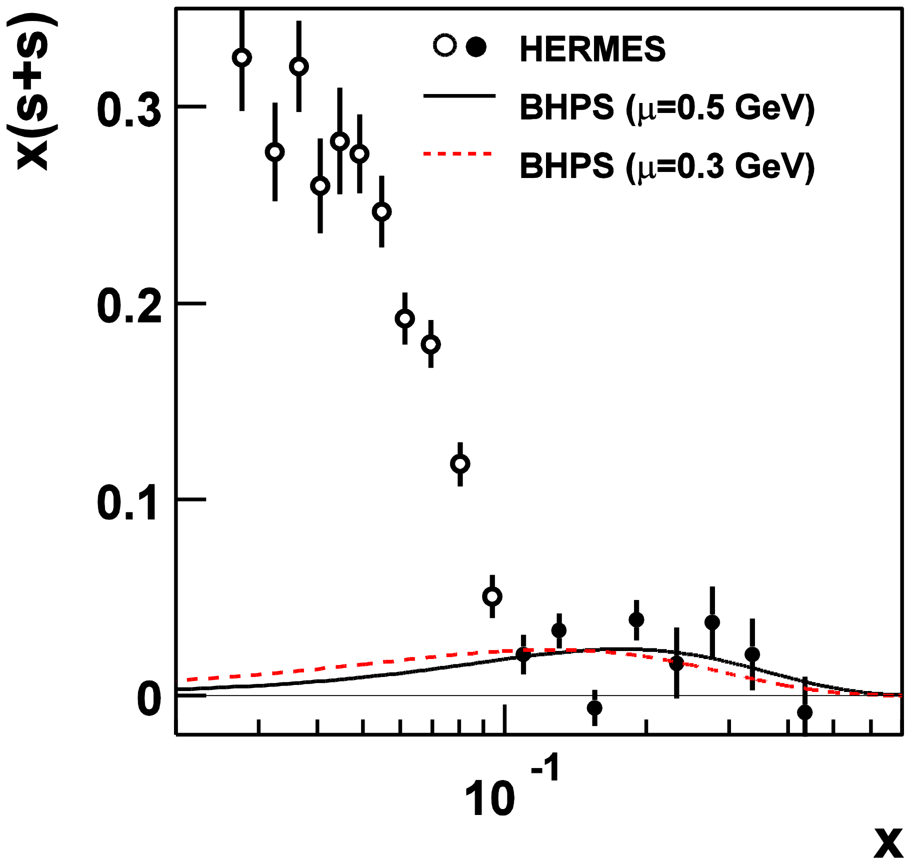


$s(x)+\overline{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$

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 $\langle Q^2 \rangle = 2.5$ GeV^2

Assume $x > 0.1$ data are dominate by intrinsic sea (and $x < 0.1$ are from QCD sea)

This allows the extraction of the intrinsic sea for strange quarks

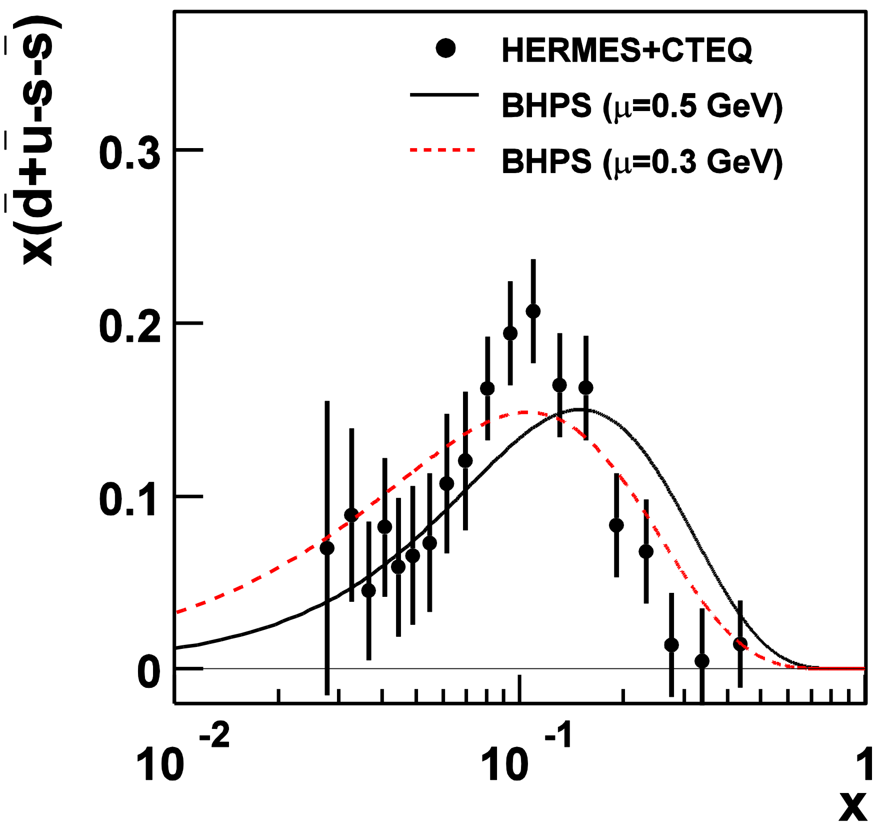
$$P_5^{uuds\bar{s}} = 0.024$$

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

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

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

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

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

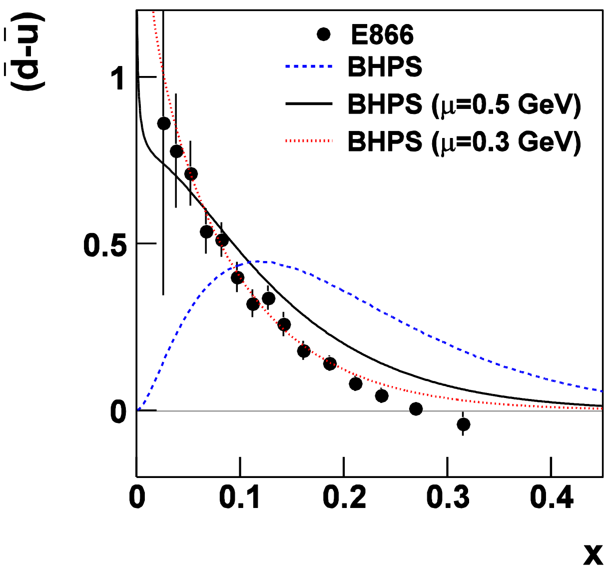
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

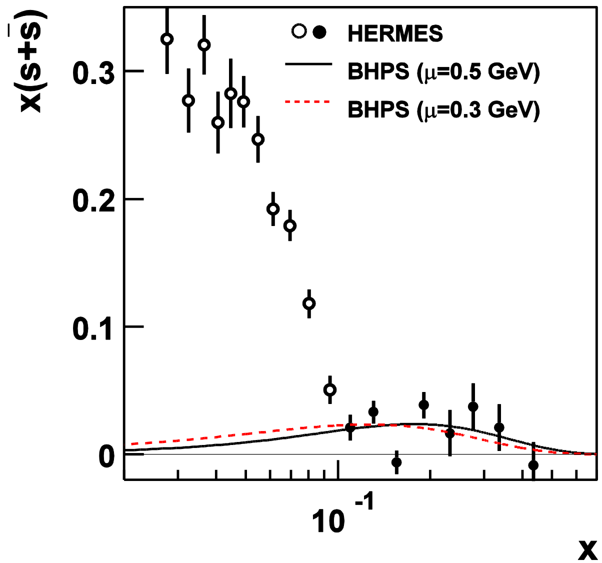
(not sensitive to extrinsic sea)

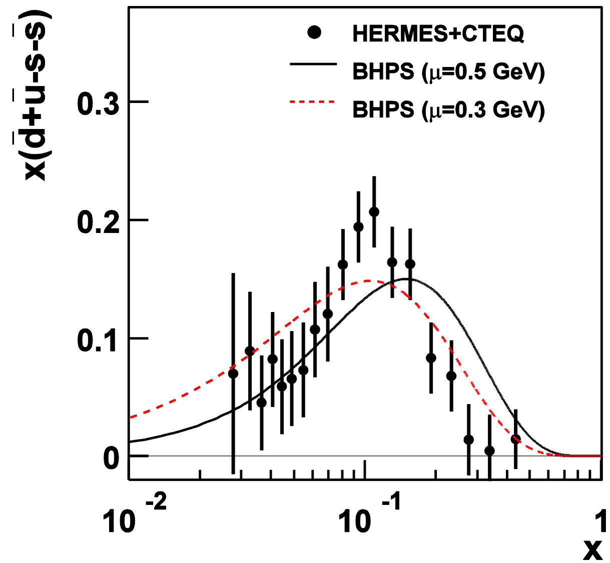
(W. Chang and JCP, PL B704, 197(2011))

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

Extraction of the various five-quark components for light quarks







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

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

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

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

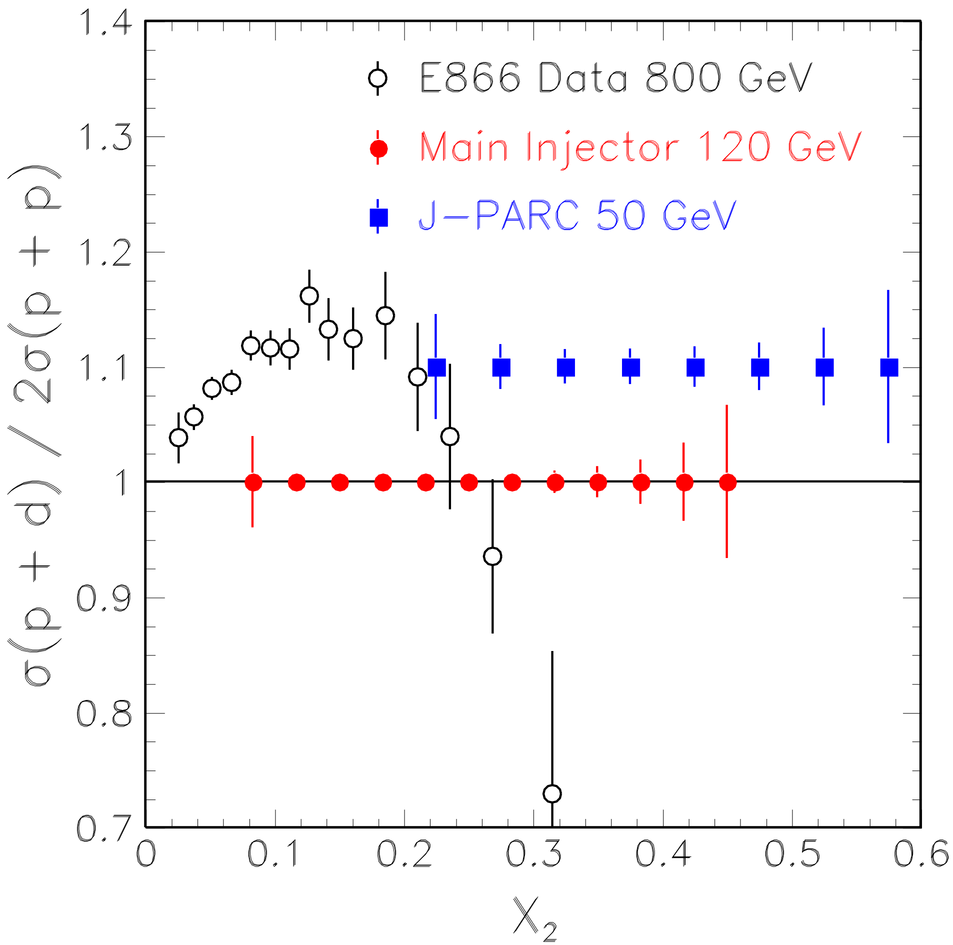
Future Prospect (Experimental)

- dbar-ubar for large x region at the Fermilab E906 andd J-PARC Drell-Yan experiments.
- Kaon production in SIDIS at COMPASS and 12 GeV Jlab/EIC for more information on s and s-bar?
- Kaon-induced Drell-Yan at J-PARC for probing s and s-bar?
- Open-charm production at forward rapidity at RHIC and LHC.
- J/ψ production at forward x_F in p-A collision at J-PARC?

$\bar{d}\,/\,\bar{u}$ at large x?

DY cross section is ~ 16 time larger at 50 GeV than at 800 GeV

$$\frac{d\sigma_{DY}}{dx_1 dx_2} \sim \frac{1}{s} \text{ at fixed } x_1, x_2$$



10^{12} protons per spill (3 s)

50-cm long $LH_2\,/\,LD_2$ targets

60-day runs for each targets

assuming 50% efficiency

$p + p$ D-Y at 50 GeV also directly measure $\bar{u}$ at large x

J-PARC P-04

(Peng and Sawada)

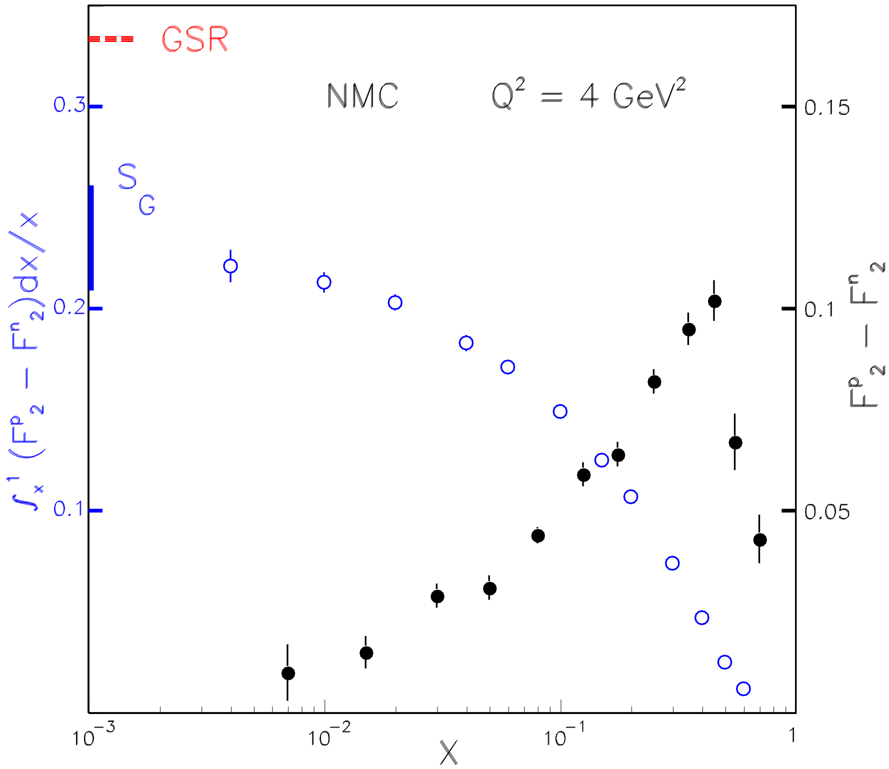
Revisit the NMC measurement of the Gottfried Sum rule

The Gottfried Sum Rule

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

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

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



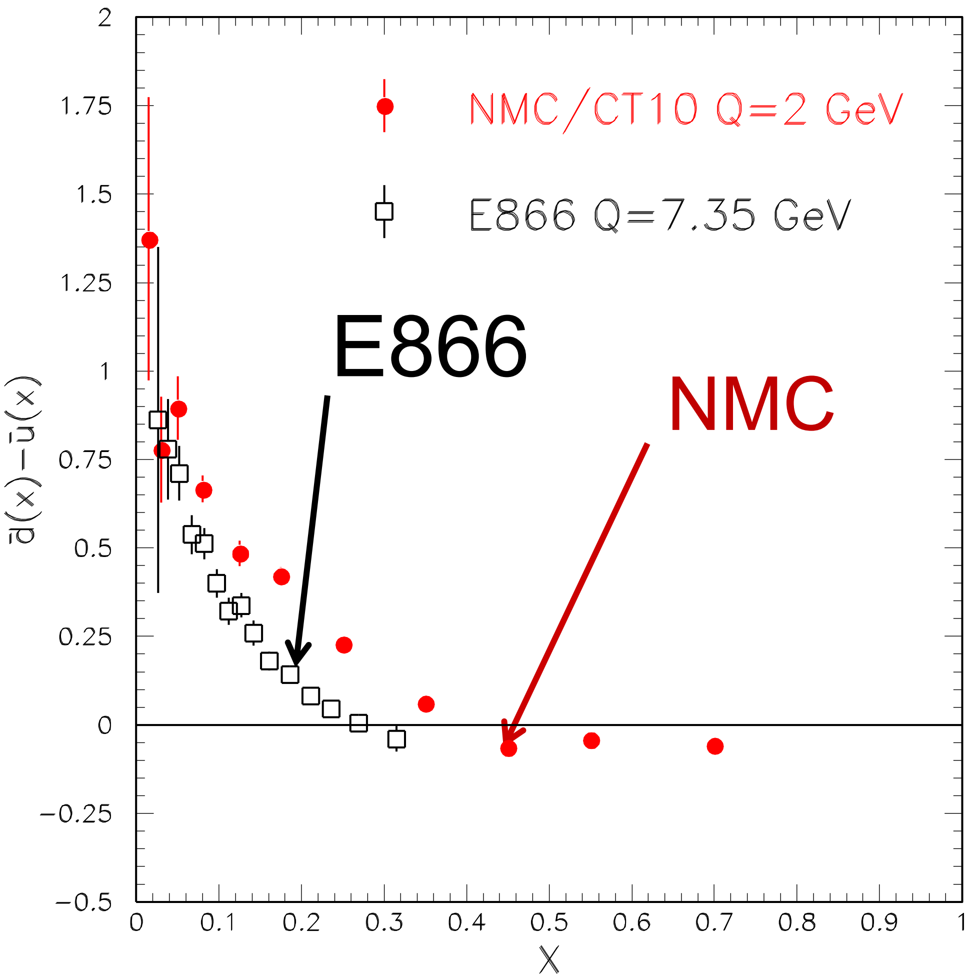
New Muon Collaboration (NMC) obtains

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

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

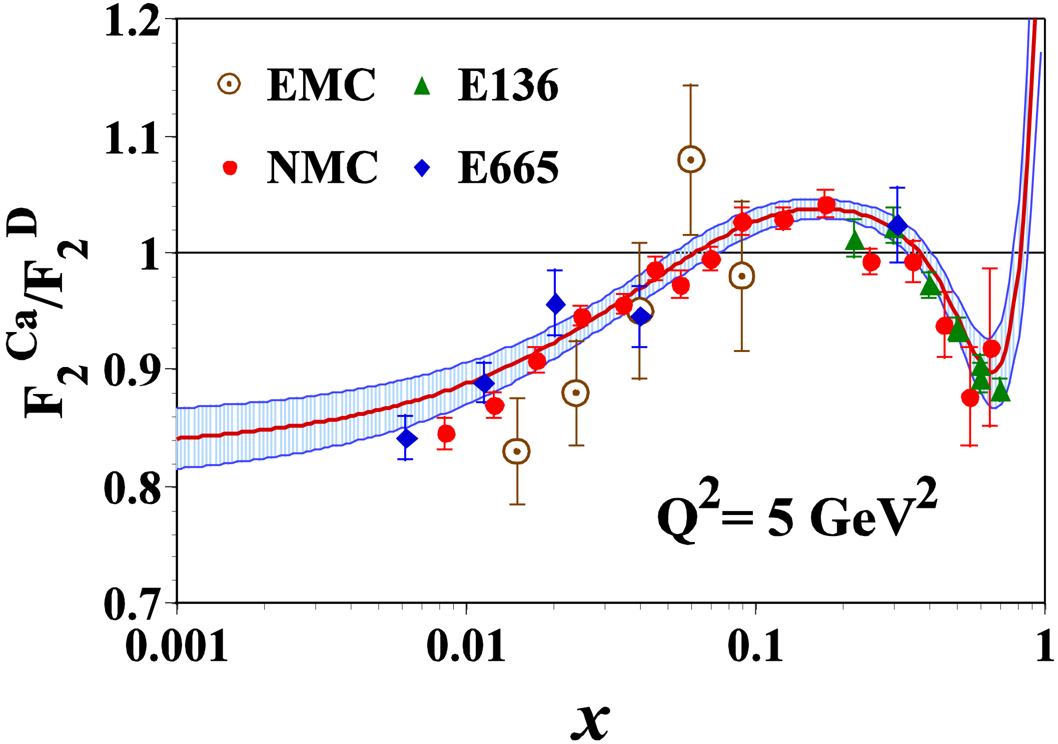


The NMC data, together with the recent PDF, already suggest that $\bar{d}(x)-\bar{u}(x)<0$ at large x!

(W.C. Chen, K.F. Liu, JCP)

Modification of Parton Distributions in Nuclei

EMC effect observed in DIS

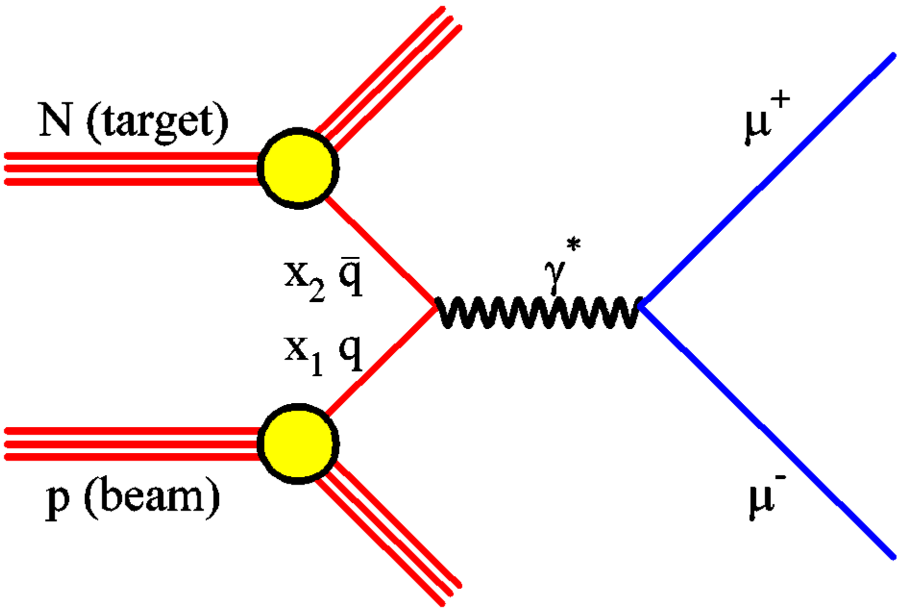


(Ann. Rev. Nucl. Part. Phys., Geesaman, Sato and Thomas)

F_2 contains contributions from quarks and antiquarks

How are the antiquark distributions modified in nuclei?

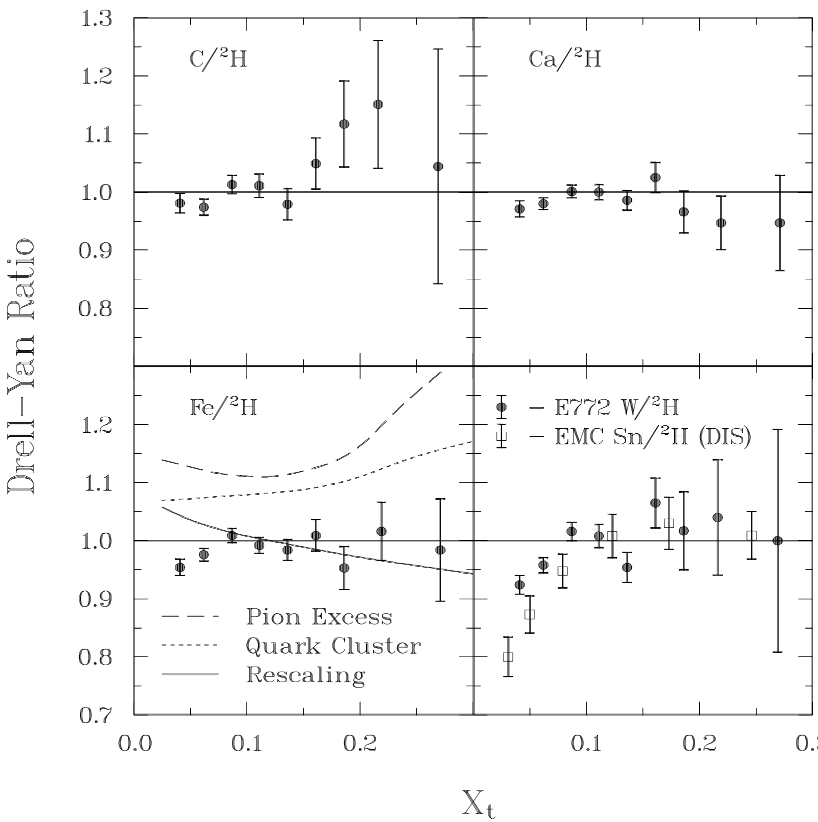
Drell-Yan on nuclear targets



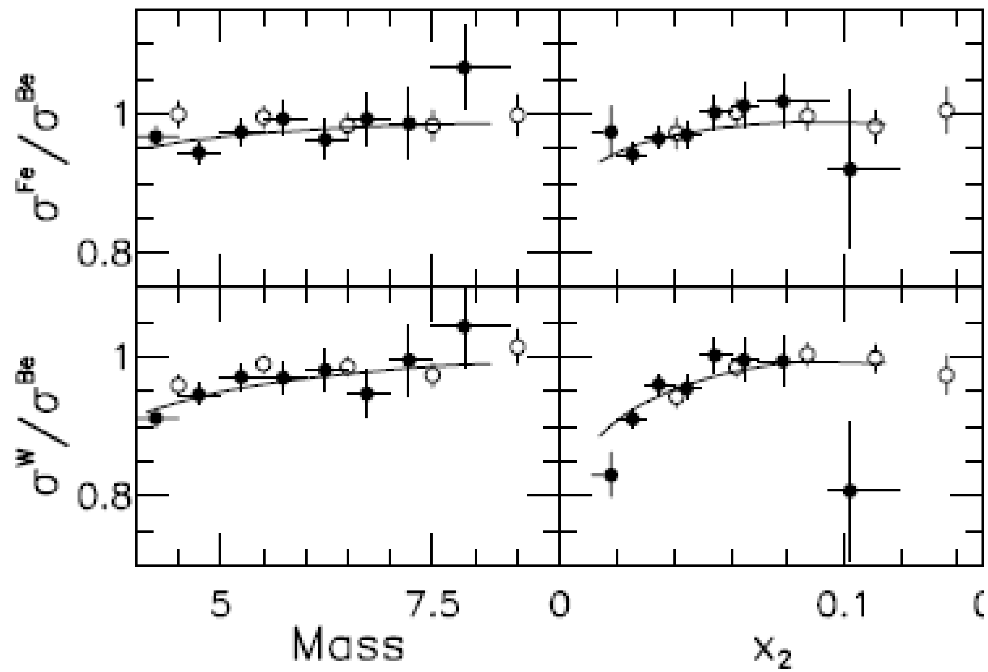
$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

The x-dependence of $\bar{u}_A(x)/\bar{u}_N(x)$ can be directly measured

Drell-Yan on nuclear targets



PRL 64 (1990) 2479



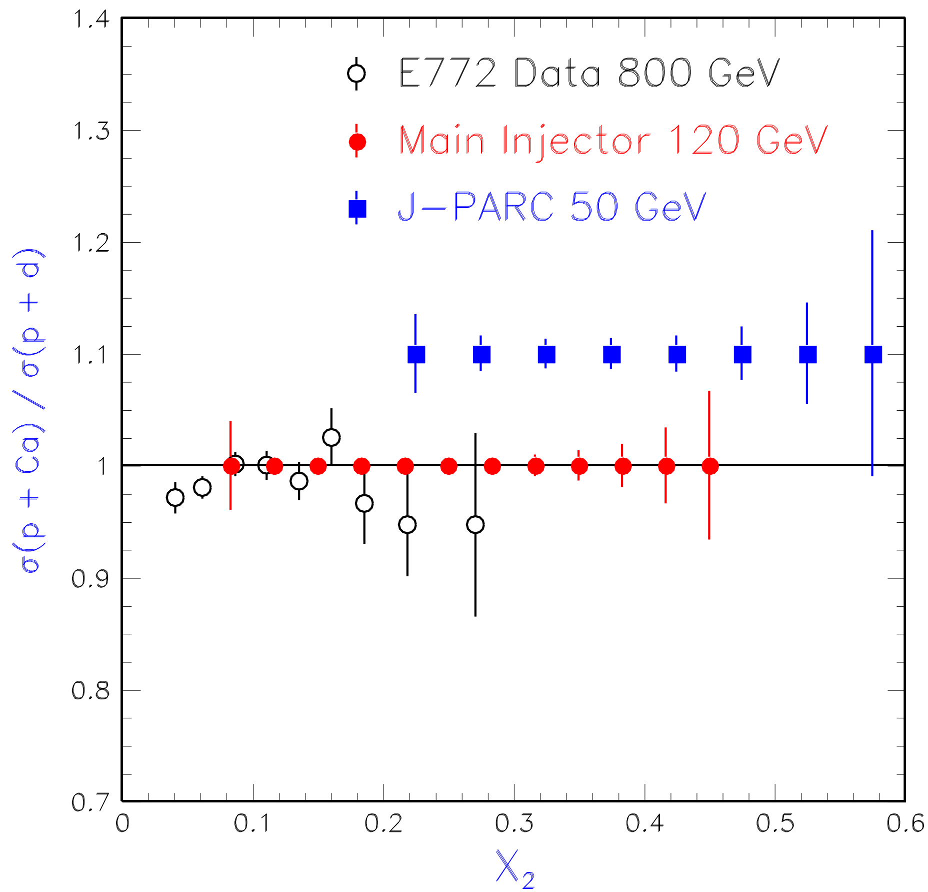
PRL 83 (1999) 2304

No evidence for enhancement of antiquark in niclei !?

The Drell-Yan data place strong constraints on EMC models

Modification of Antiquark Distributions in Nuclei

Nuclear dependence of Drell-Yan at larger *x* at J-PARC?



10^{12} protons per spill (3 s)

50-cm long LH_2 / LD_2 targets

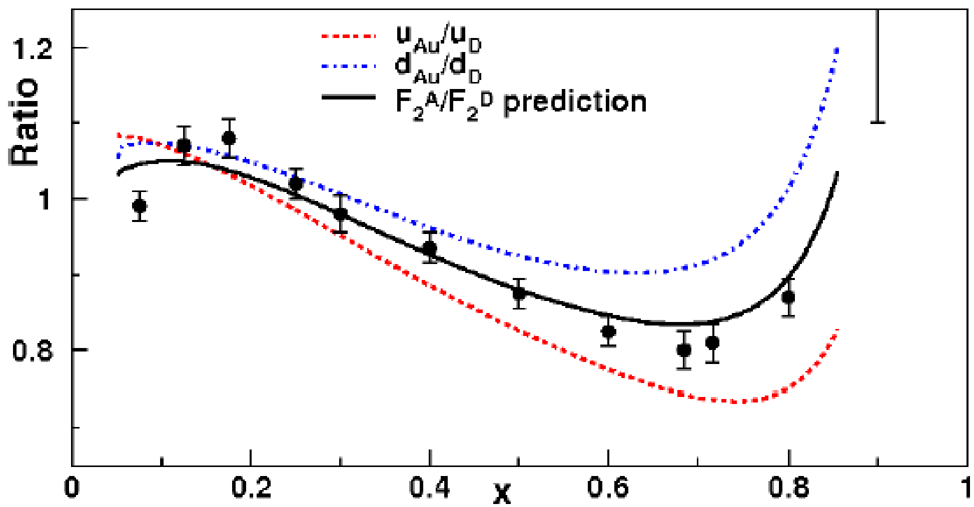
60-day runs for each targets

assuming 50% efficiency

J-PARC P-04
(Peng and Sawada)

Sensitive to $\bar{u}$ distribution in nuclei

Flavor dependence of the EMC effects ?



Isovector mean-field generated in Z≠N nuclei can modify nucleon's *u* and *d* PDFs in nuclei

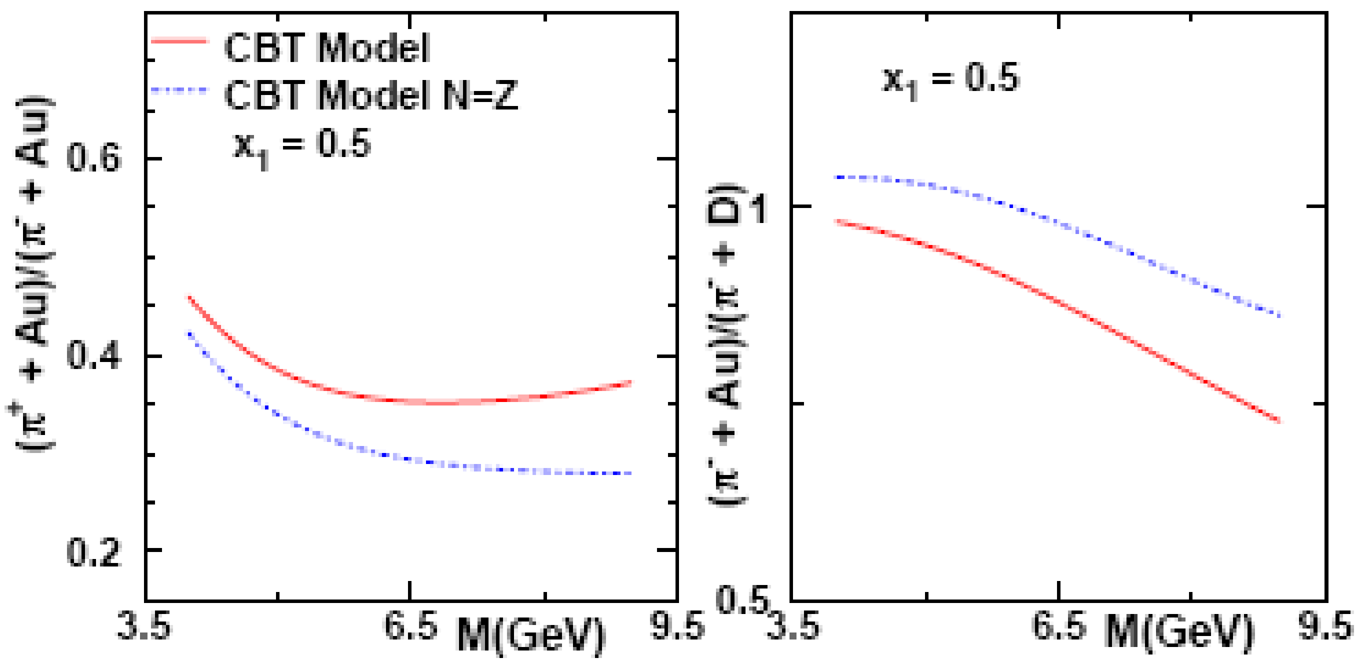
Cloet, Bentz, and Thomas, arXiv:0901.355
(see also Kumano et al.)

How can one check this prediction?

- SIDIS (Semi-inlusive DIS) and PVDIS (Parity-violating DIS)
- Pion-induced Drell-Yan

Pion-induced Drell-Yan and the flavor-dependent EMC effect

$$\frac{\sigma^{DY}(\pi^{+}+A)}{\sigma^{DY}(\pi^{-}+A)} \approx \frac{d_A(x)}{4u_A(x)}; \qquad \frac{\sigma^{DY}(\pi^{-}+A)}{\sigma^{DY}(\pi^{-}+D)} \approx \frac{u_A(x)}{u_D(x)}$$



160 GeV pion beam

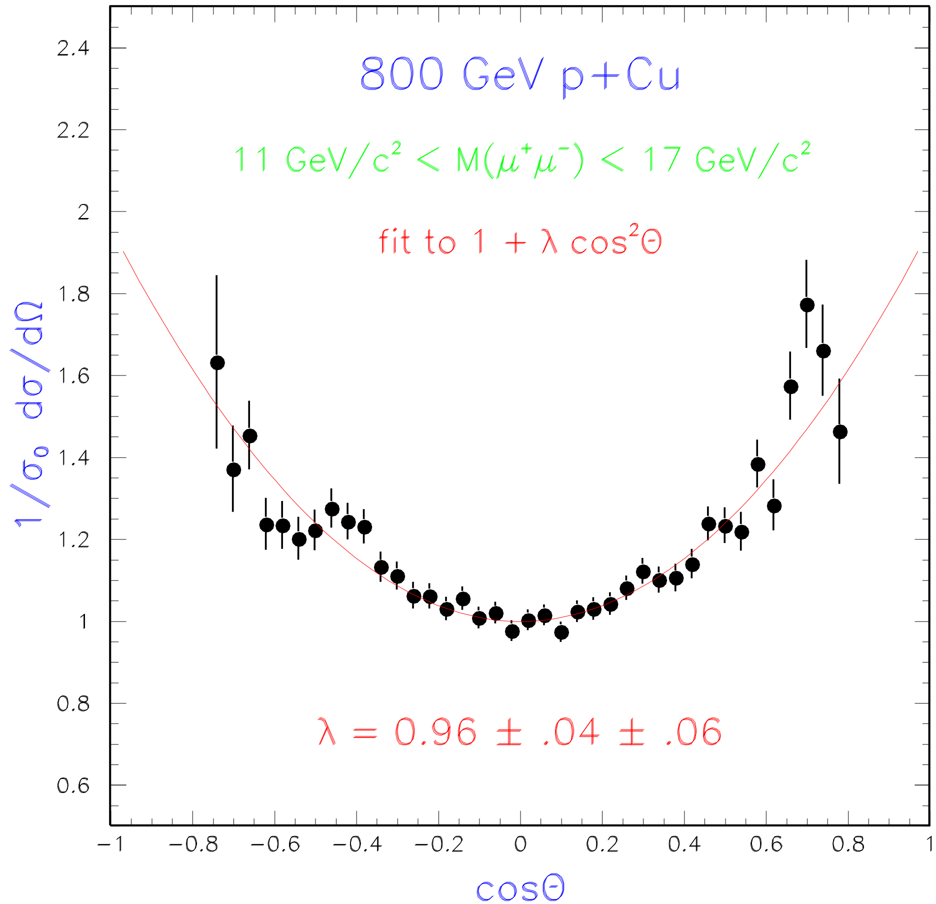
(D. Dutta, JCP, Cloet, Gaskell)

Drell-Yan data from COMPASS and J-PARC with pion beams could provide important new information

Drell-Yan angular distribution

Decay Angular Distribution of "naïve" Drell-Yan:

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \cos^2 \theta)$$

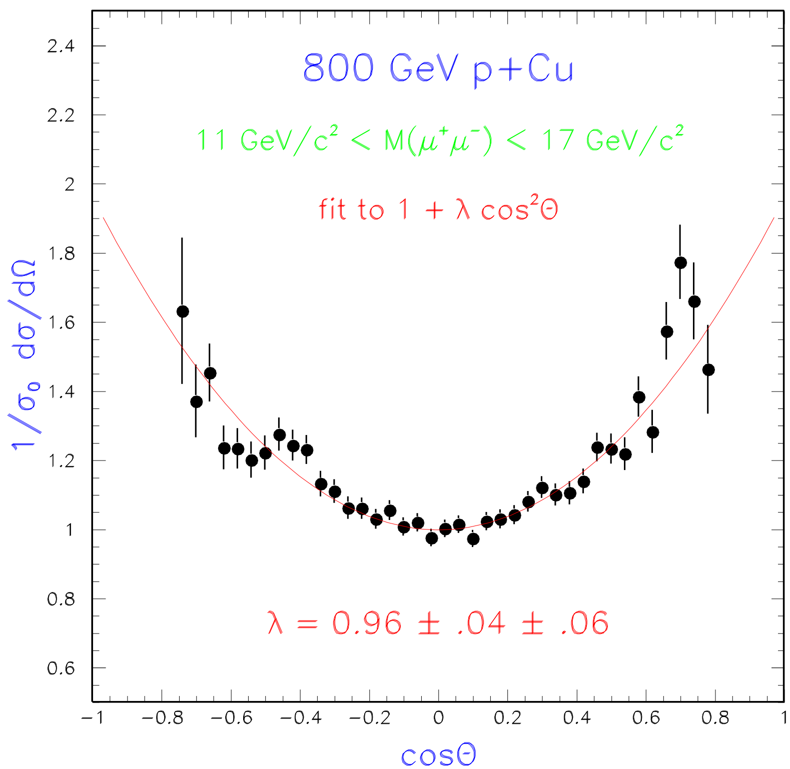


Data from Fermilab E772

Parity violation in Drell-Yan?

Forward-backward asymmetry in decay angular distribution of Drell-Yan:

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \boxed{a\cos\theta} + b\cos^2\theta)$$



Interference between γ and Z^0 diagrams can lead to non-zero parity-violating $\cos\theta$ term

Parity violation in D-Y can probe Weinberg angles at low Q^2

Parity violation in Drell-Yan?

Forward-backward asymmetry in decay angular distribution of Drell-Yan:

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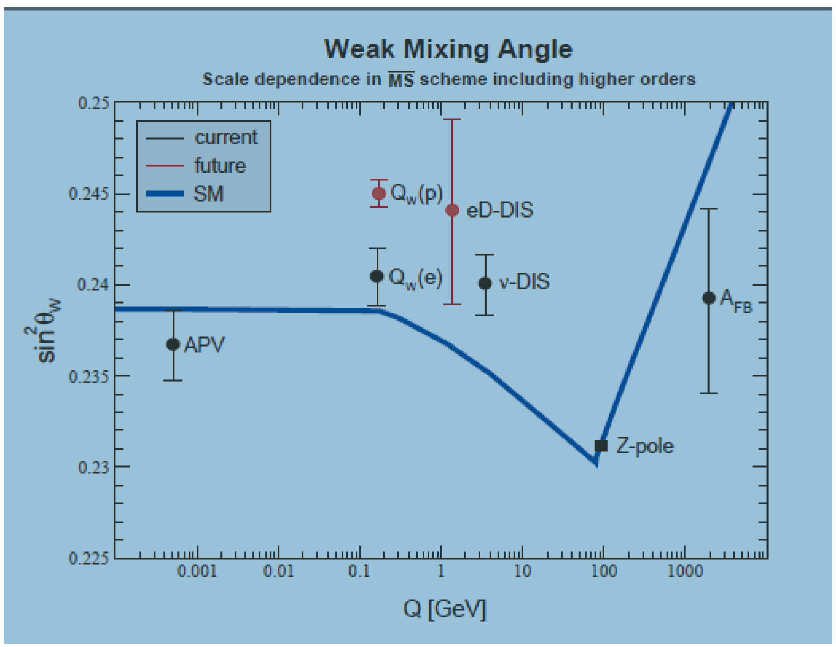
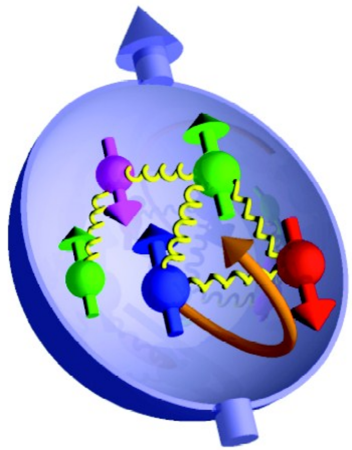


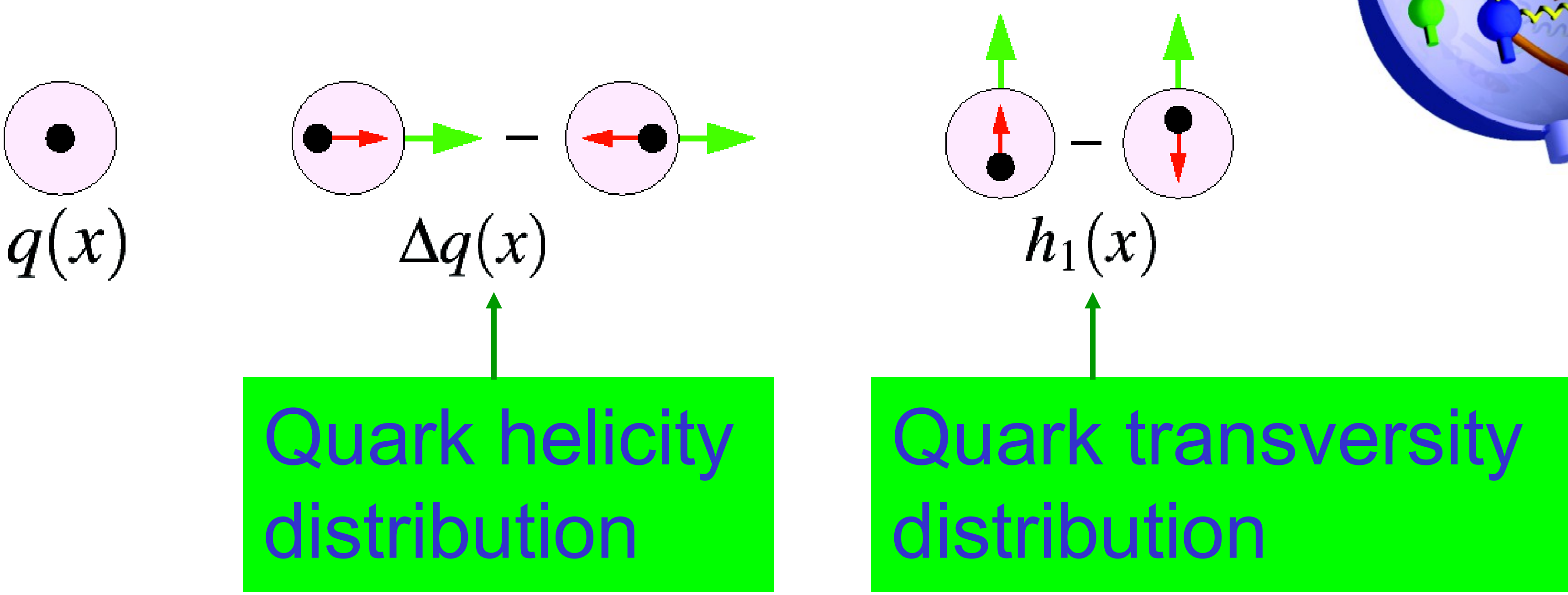
Interference between γ and Z^0 diagrams can lead to non-zero parity-violating $\cos\theta$ term

Parity violation in D-Y can probe Weinberg angles at low Q^2 (Never been studied yet)

Polarized Drell-Yan with polarized proton beam?

- Polarized Drell-Yan experiments have never been done before
- Provide unique information on the quark (antiquark) spin





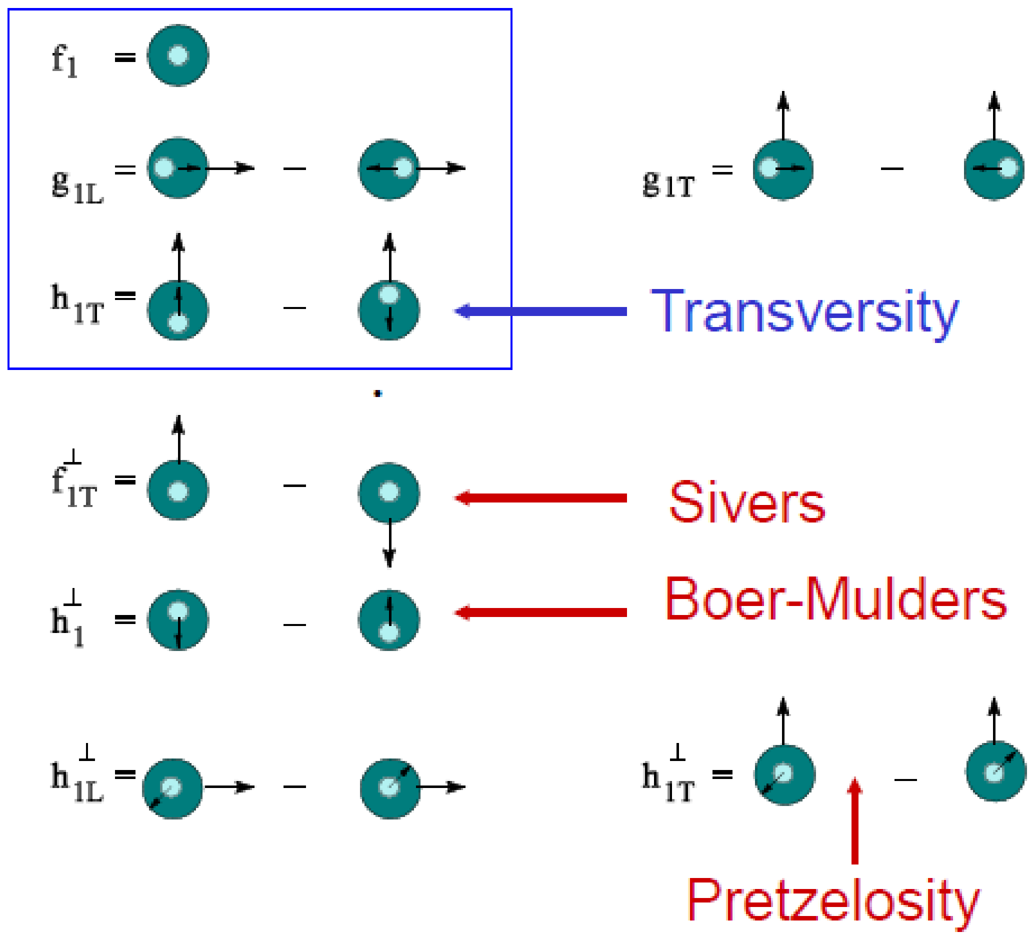
Drell-Yan and Transverse Momentum Dependent (TMD) Quark Distributions

Leading-Twist Quark Distributions

(A total of eight distributions)

Three would remain after $k_\perp$ integration

The other five are transverse momentum ($k_\perp$) dependent (TMD)



Three parton distributions describing quark's transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_\perp^N$

2) Quark transverse spin

$\vec{s}_\perp^q$

3) Quark transverse momentum

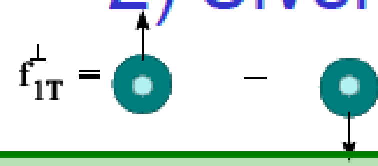
$\vec{k}_\perp^q$

$\Rightarrow$ Three different correlations

1) Transversity, Pretzelosity

Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function



Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

3) Boer-Mulders function

Correlation between $\vec{s}_\perp^q$ and $k_\perp^q$

Transversity and Transverse Momentum Dependent PDFs are also probed in Drell-Yan

a) Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}}) \cos(2\phi)$

b) Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$$A_N^{DY} \propto f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})$$

c) Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

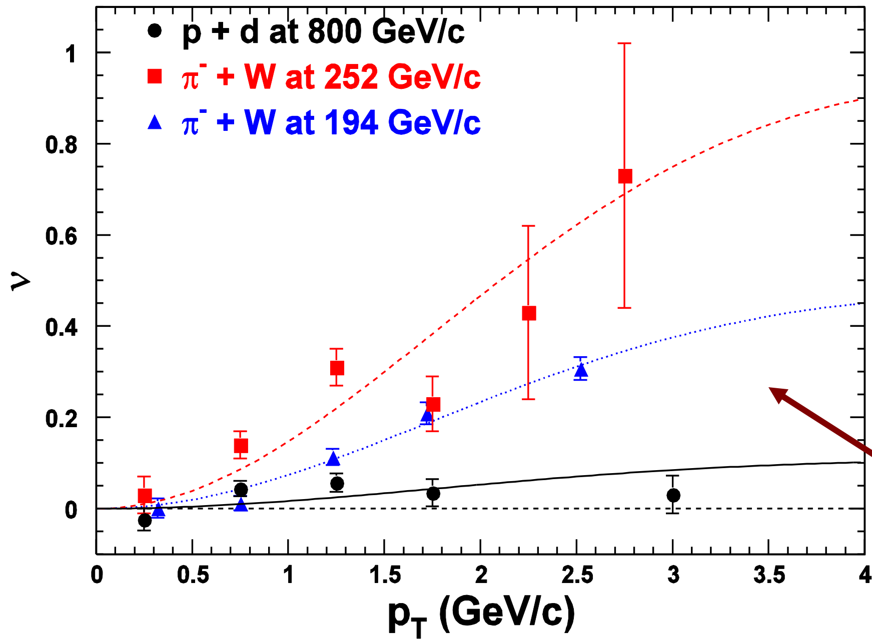
$$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$$

- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

Azimuthal cos2Φ Distribution in π+W and p+d Drell-Yan

E866 Collab., Lingyan Zhu et al.,
PRL 99 (2007) 082301; PRL 102 (2009) 182001



Boer-Mulders function from unpolarized DY

$$d\sigma_{DY} \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}}) \cos(2\phi)$$

$$d\sigma_{DY} \propto \nu \cos(2\phi)$$

Large ν is observed for pion DY, but small ν for proton DY

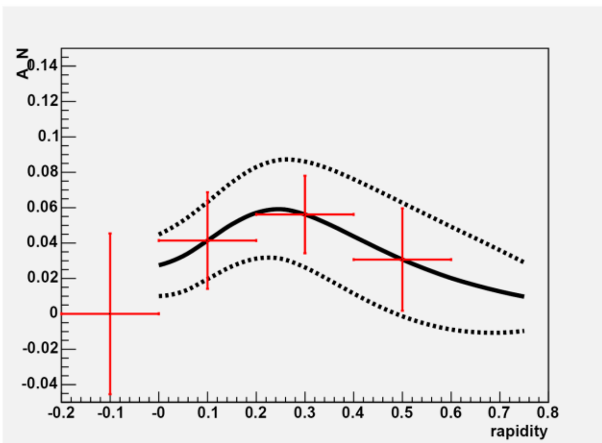
Sea-quark BM functions are much smaller than valence quarks

Can be further explored at J-PARC

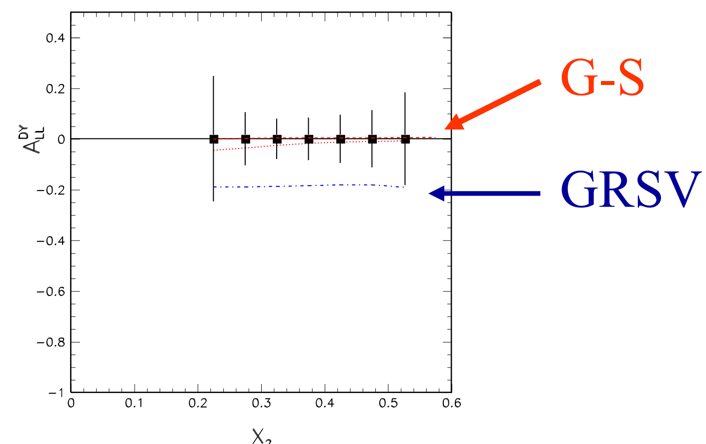
Spin physics with dimuons at J-PARC
(See Y. Goto's talk)

Single-spin asymmetry (A_N) measurements for orbital angular momentum

– Drell-Yan, J/Ψ



D-Y A_{LL} at 50 GeV



Drell-Yan A_N (Ji et al.)

-sensitive to Sivers effect at low $q_T << Q$

-sensitive to higher-twist effect at high $q_T \sim Q$

-Sivers function in Drell-Yan is expected to have a sign opposite to that in DIS.

Other measurements

– Drell-Yan A_{LL} for sea-quark polarization
– Drell-Yan A_{TT} for transversity
– Unpolarized Drell-Yan for Boer-Mulders function
– A_{LL} for J/Ψ for gluon polarization

Outstanding questions to be addressed by future Drell-Yan experiments

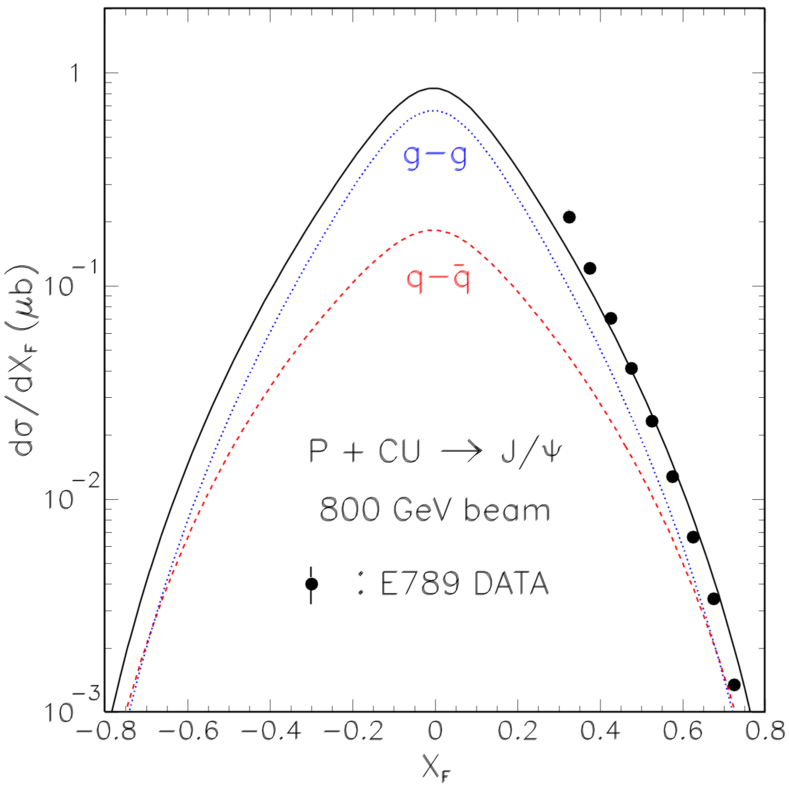
- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan

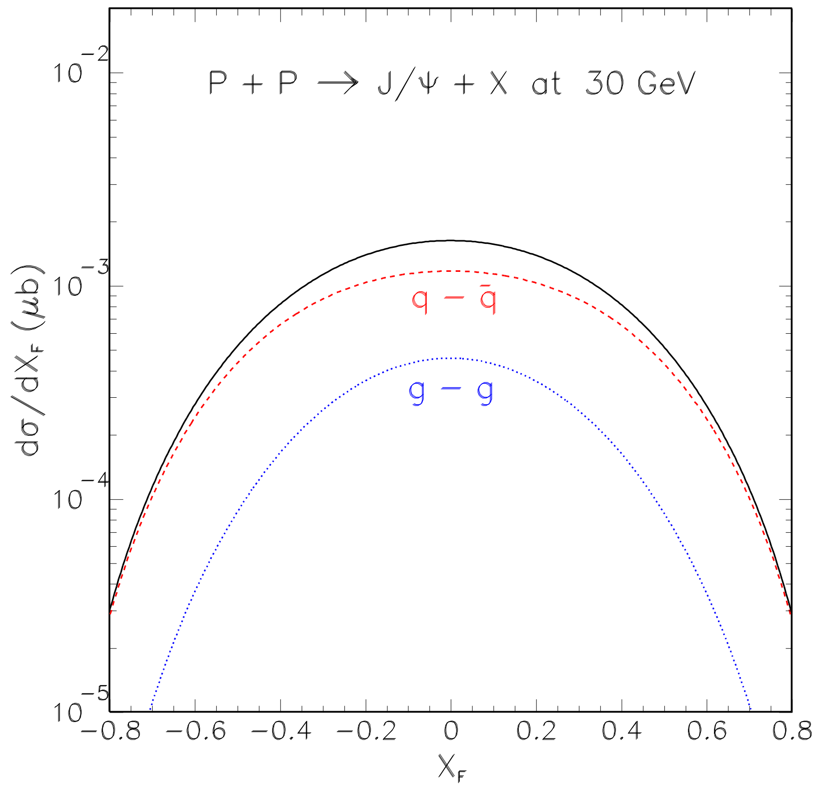
Can be studied at COMPASS, RHIC, FAIR, JPARC, JINR, etc

J/Ψ Production at 30 GeV

At 800 GeV, J/Ψ production is dominated by gluon-gluon fusion

At 30 GeV J/Ψ production is dominated by quark-antiquark annihilation





J/Ψ production at 30 GeV is sensitive to quark and antiquark distributions

Summary

- The Drell-Yan process is a powerful experimental tool complimentary to the DIS for exploring quark structures in nucleons and nuclei.
- A rich physics program in Drell-Yan and J/Ψ production can be pursued at J-PARC.
- Unique information on flavor structures of quarks and quark sea, and on the novel transverse-momentum dependent parton distributions can be obtained with Drell-Yan experiments.