Parton Distribution Functions

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

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Outline

- Unpolarized parton distrbutions
  - Flavor structures of the valence and sea quark contents of the nucleons and nuclei
- Transverse momentum dependent (TMD) distributions
  - Transversity and other novel TMDs

Flavor and spin structures of the nucleons

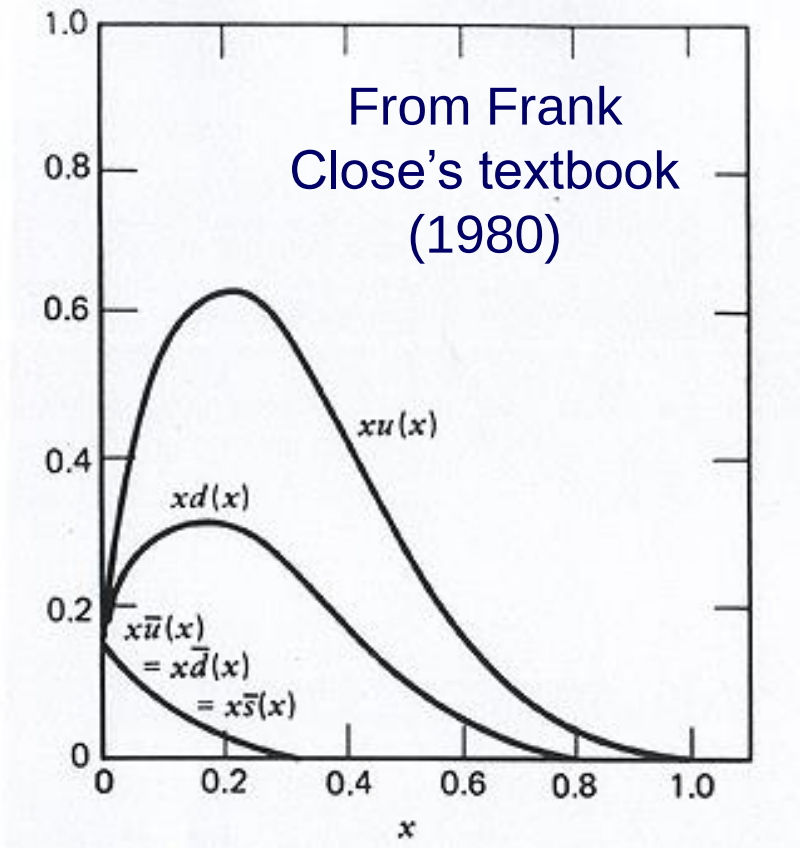
Why is it interesting?

- 99.97% of the visible mass of the Universe is composed of protons and neutrons
- QCD at the confinement scale remains to be better understood
- The progress of lattice QCD calculations allow direct comparison between the experiments and theory
- They provide crucial inputs for describing hard processes in high energy collisions such as at LHC (p+p collider)

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

Flavor structure of the proton sea

$\bar{u}(x) = \bar{d}(x) = \bar{s}(x) = s(x) \Rightarrow SU(3)$ symmetric sea



Questions

- Is $u_V(x) = 2d_V(x)$?
- Is $\bar{u}(x) = \bar{d}(x)$?
- Is $\bar{s}(x) = \bar{u}(x)$?
- Is $\bar{s}(x) = s(x)$?
- Is $u_p(x) = d_n(x)$?
- Is $g_p(x) = g_n(x)$?

Actually, the nucleon is full of surprises !!

Is $\bar{u} = \bar{d}$ in the Proton?

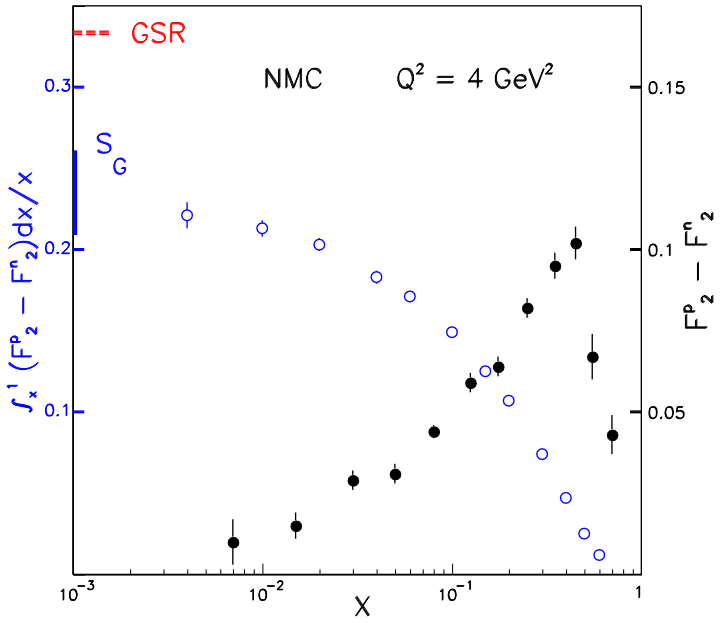
Expect $\bar{d} = \bar{u}$ if sea quarks are produced in $g \rightarrow q\bar{q}$

The Gottfried Sum Rule

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

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

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



New Muon Collaboration (NMC) obtains

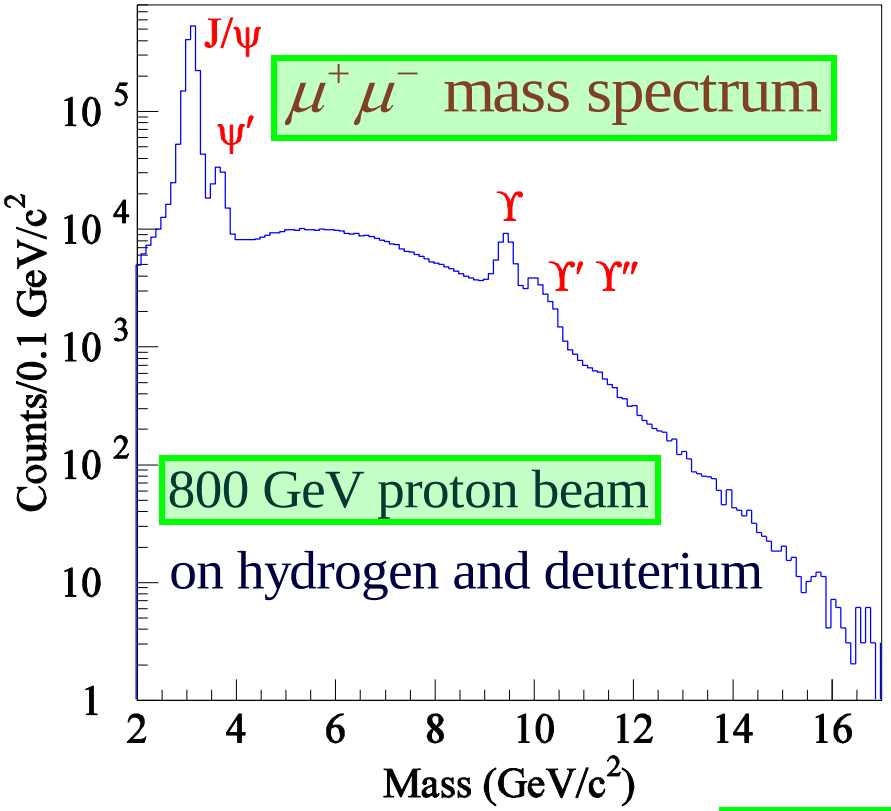
$S_G = 0.235 \pm 0.026$

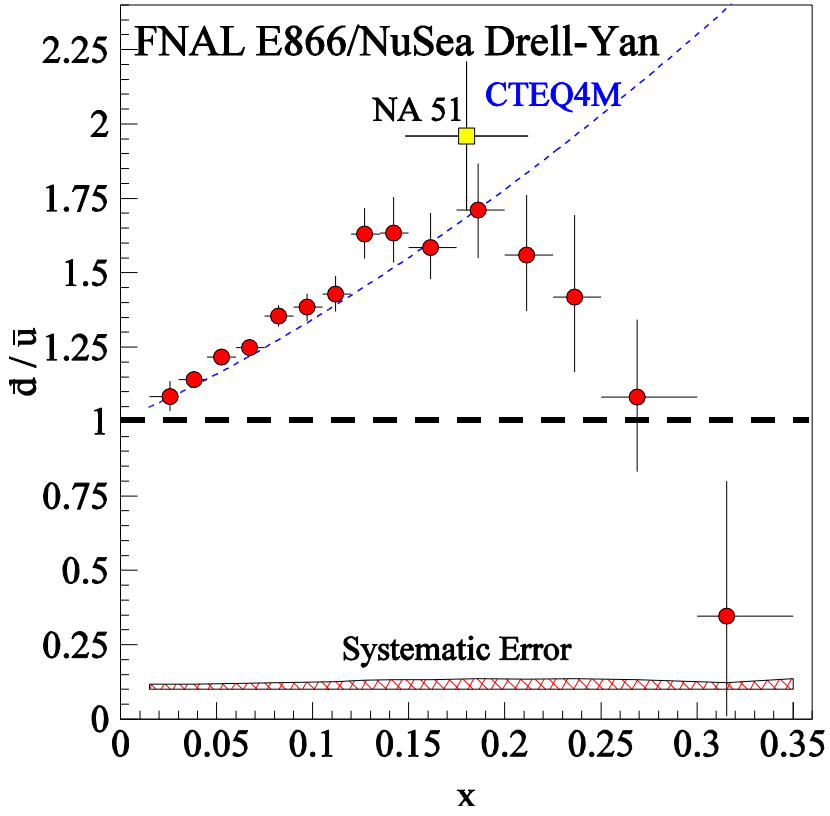
(Significantly lower than 1/3 !)

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

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

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

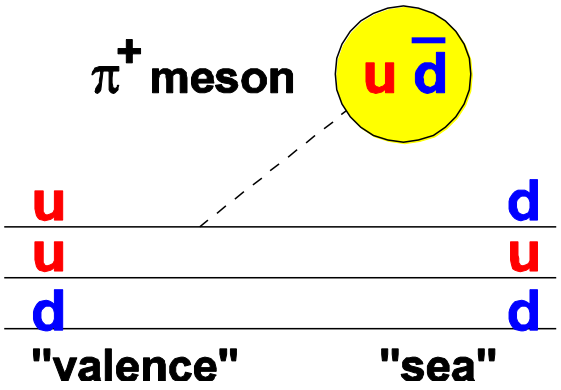




Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \approx \frac{1}{2}(1+\bar{d}(x_2)/\bar{u}(x_2))$

Some Theoretical Models for $\bar{d}$ / $\bar{u}$ Asymmetry

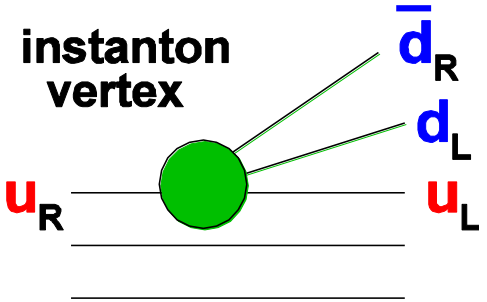
Meson Cloud Models



Chiral-Quark Soliton Model

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

Instantons



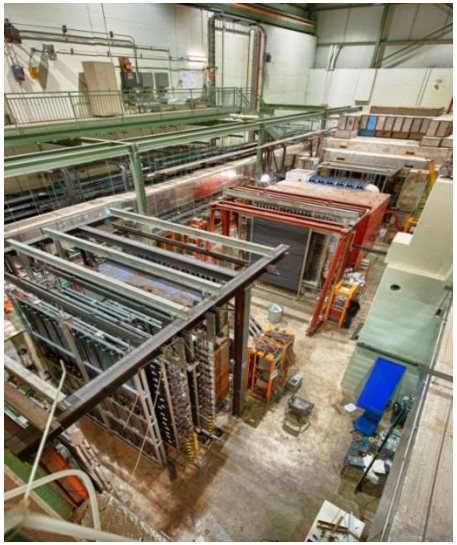
Meson cloud has significant contributions to sea-quark distributions

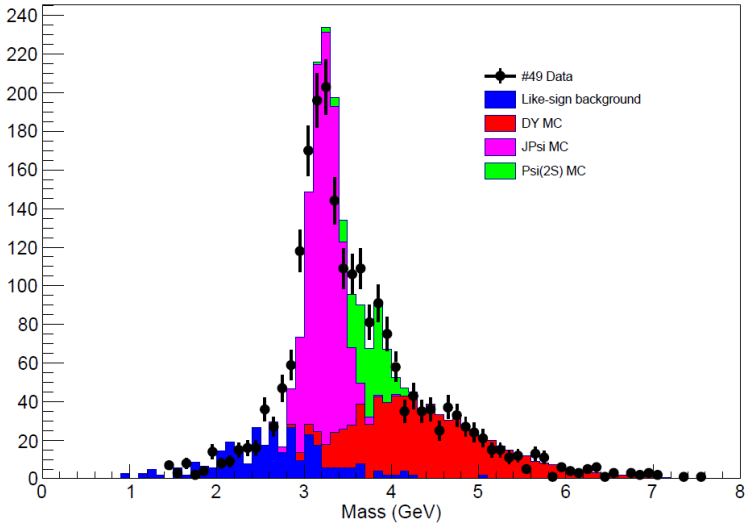
These models also have specific predictions on

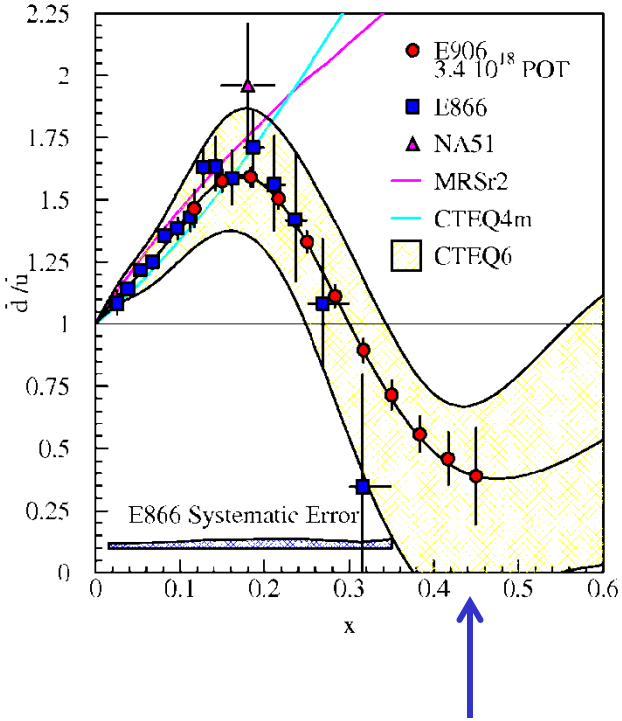
- Asymmetry between $s(x)$ and $\bar{s}(x)$
- Asymmetry between $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$

Is there a sign-reversal for $\bar{d}(x) - \bar{u}(x)$ at large x?

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





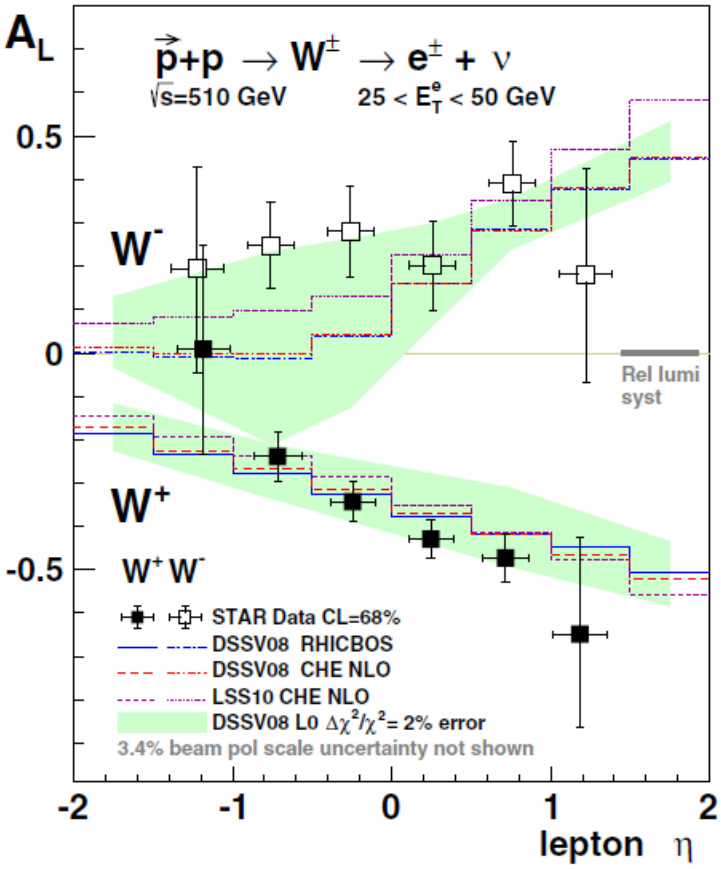


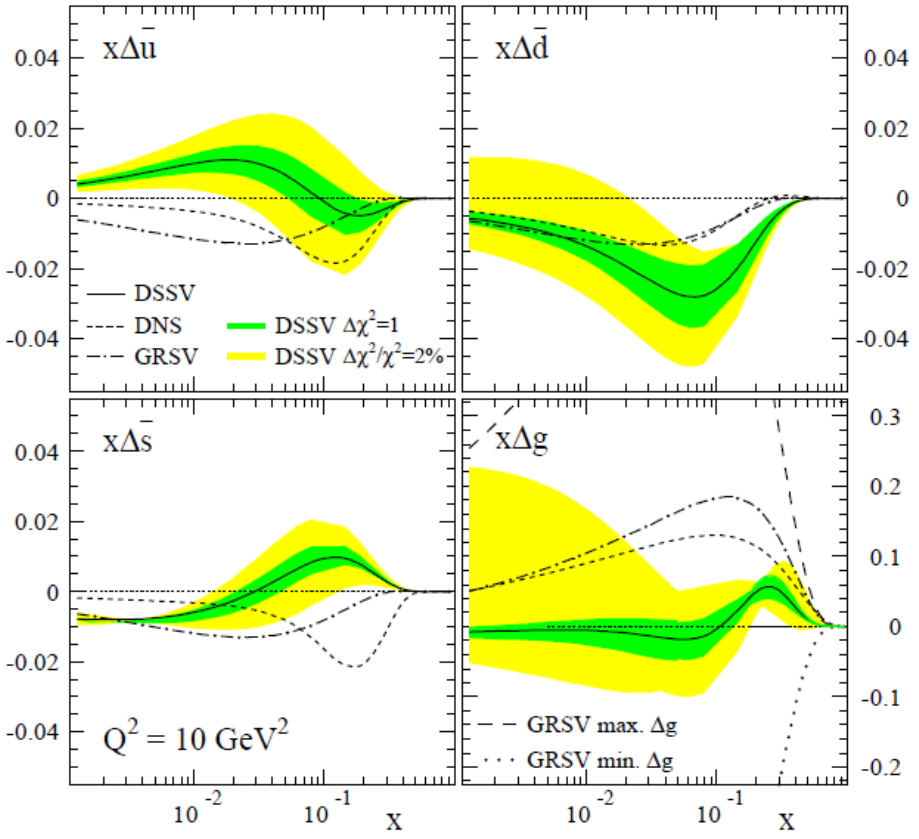
Main goals: 1) Measure $\bar{d}/\bar{u}$ flavor asymmetry up to $x \sim 0.45$

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

Is the sea-quark polarization flavor symmetric?

W production at RHIC clearly shows $\Delta\bar{u}(x) / \Delta\bar{d}(x)$ asymmetry





Data show $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$ in agreement with chiral soliton model

Ratios of $d(x)/u(x)$ at large x?

$$|p\rangle\uparrow = \frac{1}{\sqrt{2}}u\uparrow(ud)_{S=0,S_Z=0} + \frac{1}{\sqrt{18}}u\uparrow(ud)_{S=1,S_Z=0} - \frac{1}{3}u\downarrow(ud)_{S=1,S_Z=1}$$
$$-\frac{1}{3}d\uparrow(uu)_{S=1,S_Z=0} + \frac{\sqrt{2}}{3}d\downarrow(uu)_{S=1,S_Z=1}$$

1) SU(6) symmetry

$$\frac{d}{u} = \frac{1}{2} \qquad \frac{F_2^n}{F_2^p} = \frac{2}{3}$$

2) Dominance of $S=0$ diquark configurations (Close, Carlitz)

Ignoring terms with $S=1$ diquarks, then

$$\frac{d}{u} = 0 \qquad \frac{F_2^n}{F_2^p} = \frac{1}{4}$$

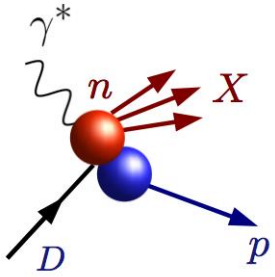
2) Dominance of $S_Z=0$ diquark configurations (Farrar, Jackson)

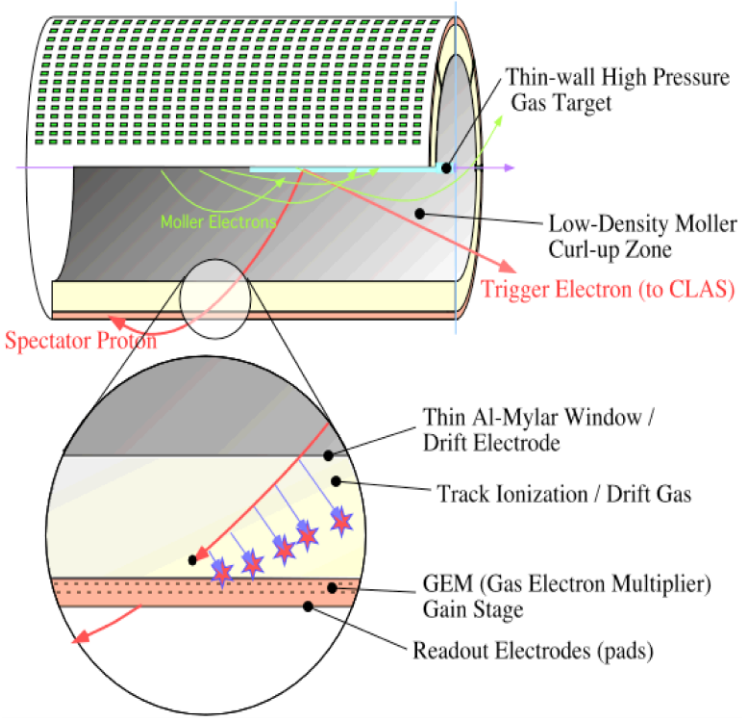
Ignoring terms with $S_Z=1$ diquarks, then

$$\frac{d}{u} = \frac{1}{5} \qquad \frac{F_2^n}{F_2^p} = \frac{3}{7}$$

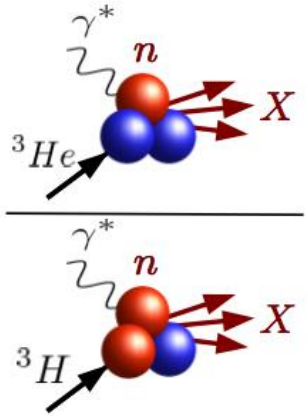
How to make a precise measurement of $d(x)/u(x)$?

1) "spectator tagging" (BONUS experiment)





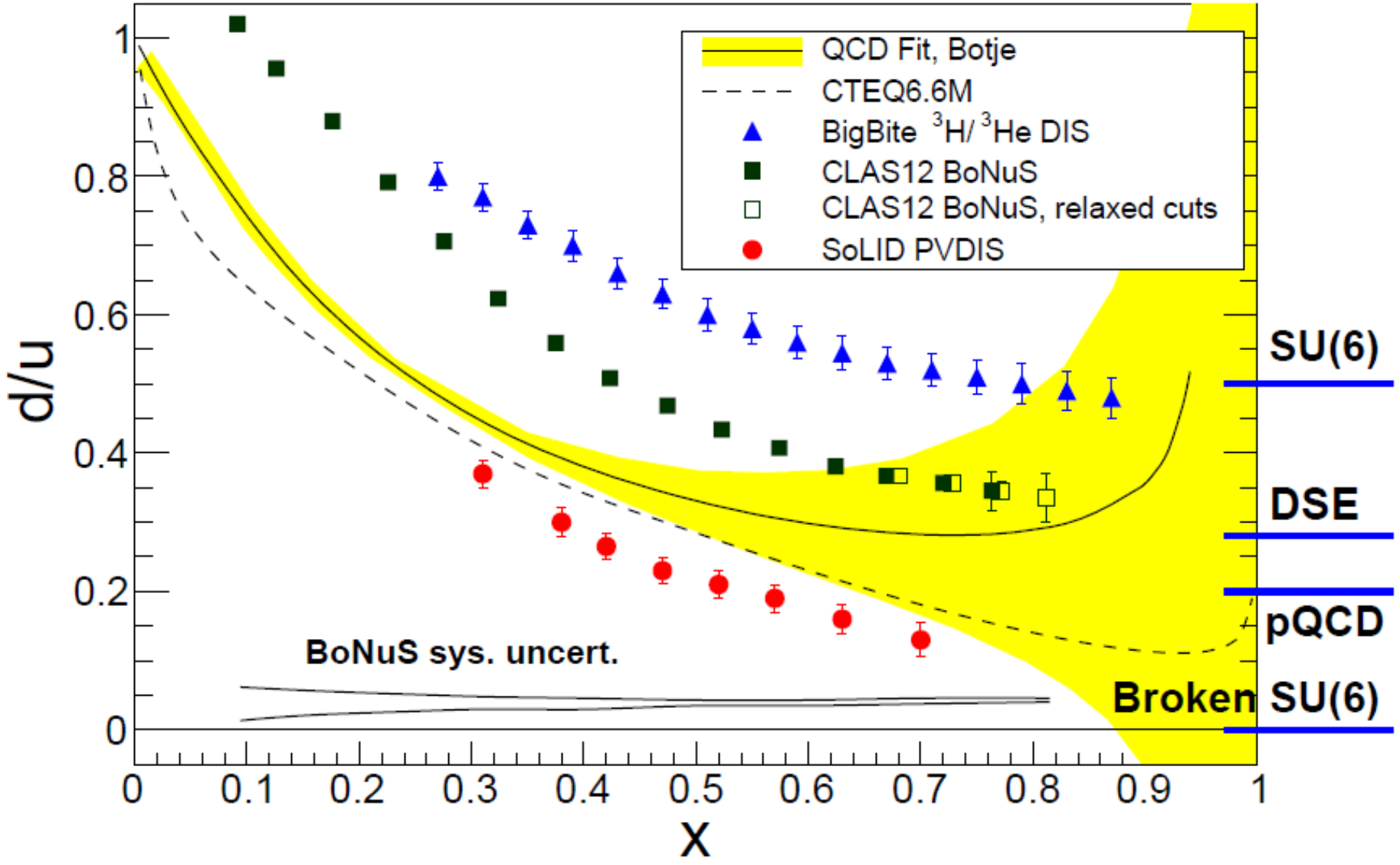
2) "Super ratio ^{3}He/^{3}H" (Marathon experiment)



– Extract F_2^n/F_2^p from ratio of measured ^{3}He/^{3}H structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

Projected 12 GeV d/u Extractions

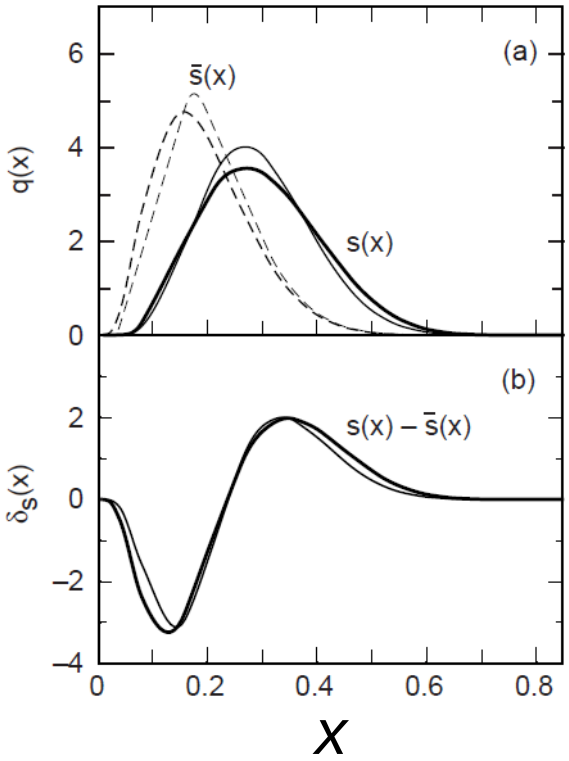


Is $s(x) = \bar{s}(x)$?

Meson cloud model

$p \to K^+ \Lambda$

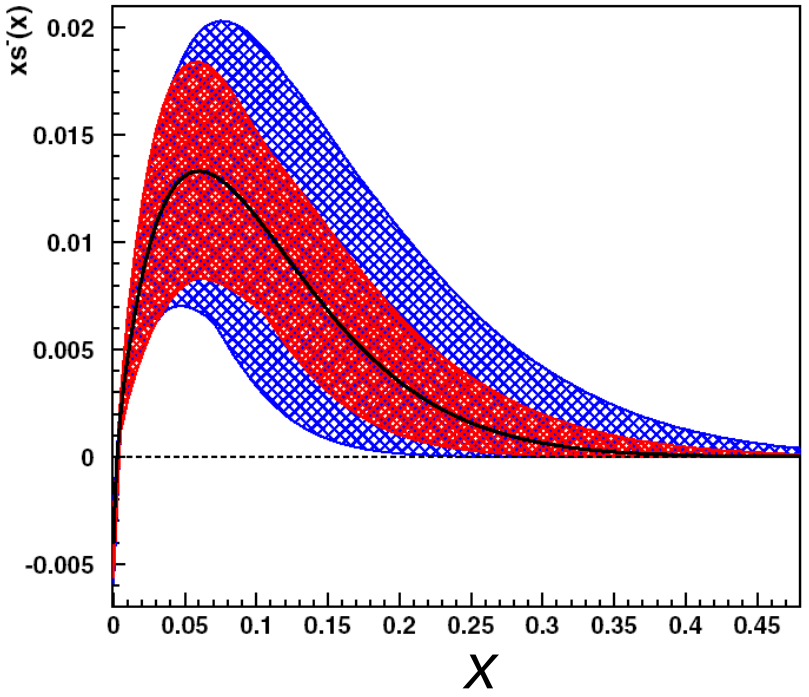
$(u\bar{s})\,(uds)$



Thomas / Brodsky and Ma

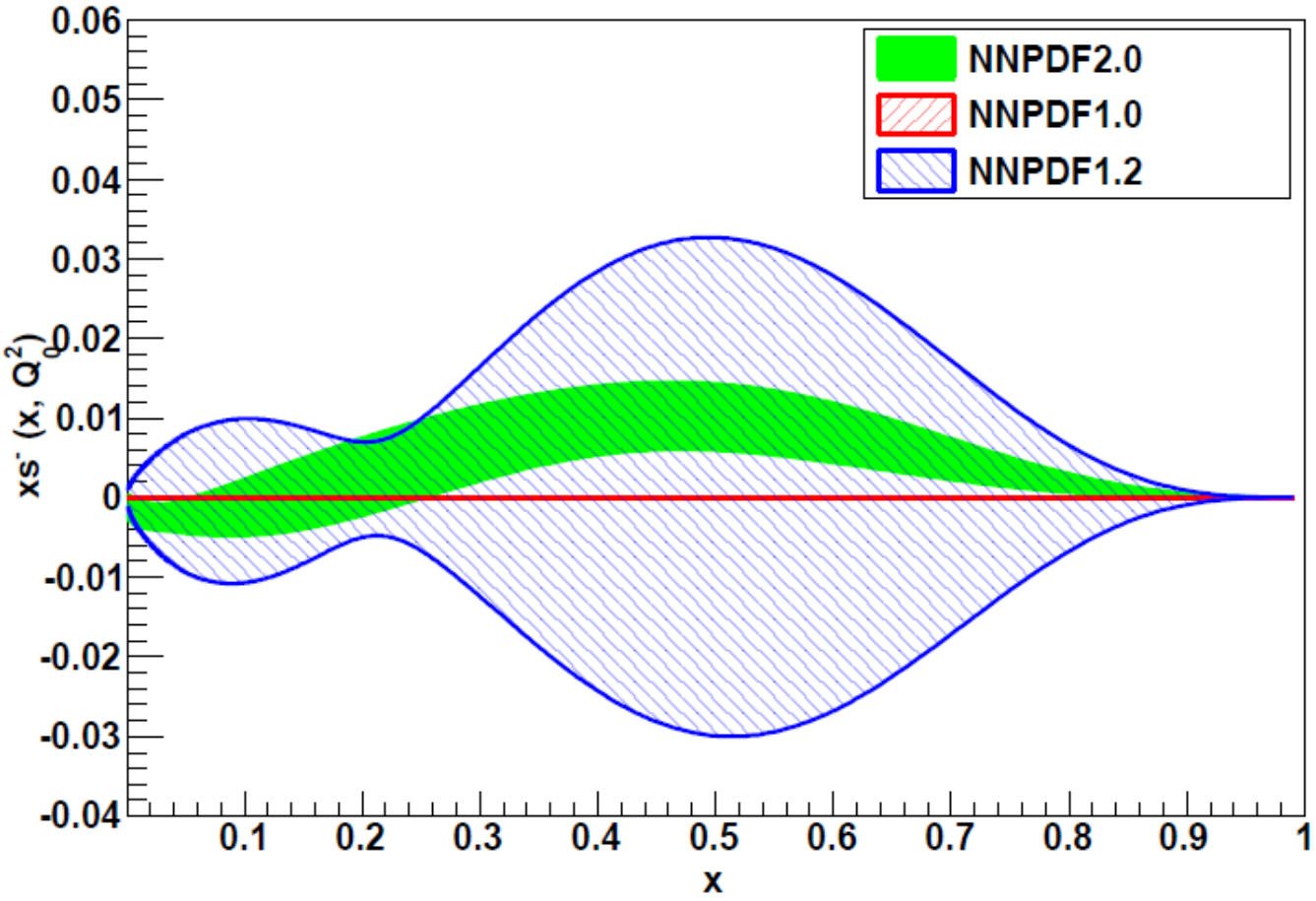
Analysis of neutrino DIS data

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



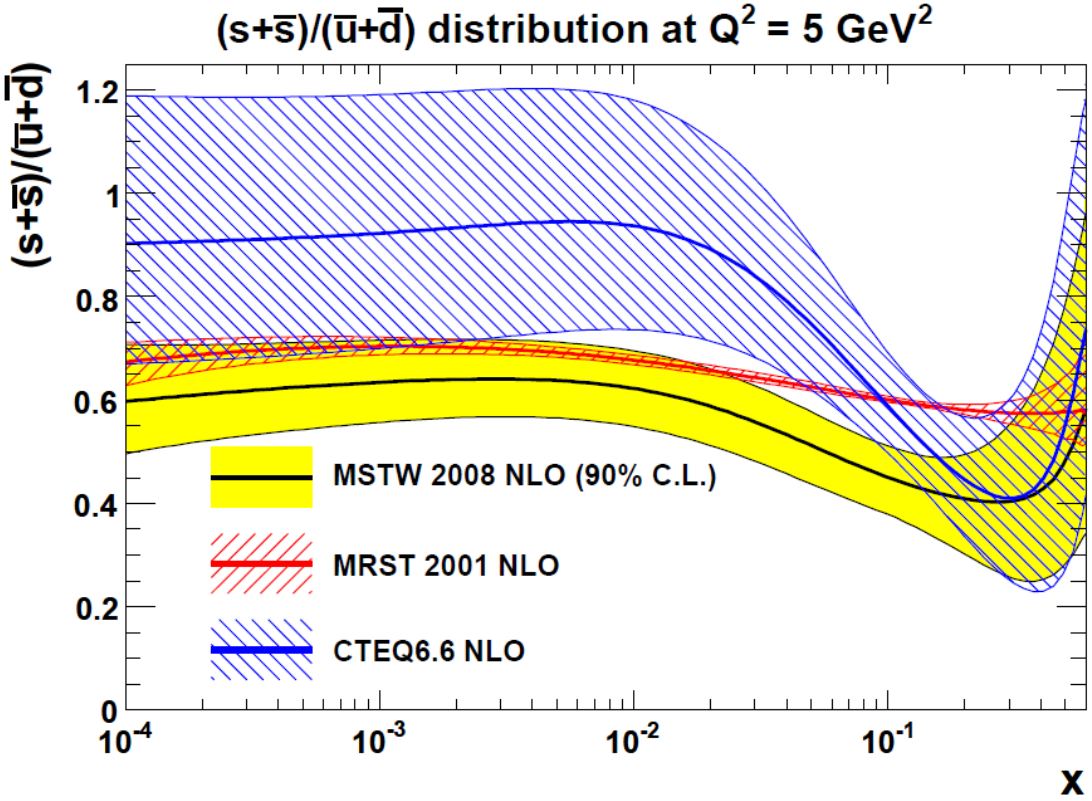
NuTeV, PRL 99 (2007) 192001

$s(x) - \bar{s}(x)$ from NNPDF global fits



NNPDF2.0 analysis includes fixed-target Drell-Yan and Tevatron W and Z data

What is the x-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$?

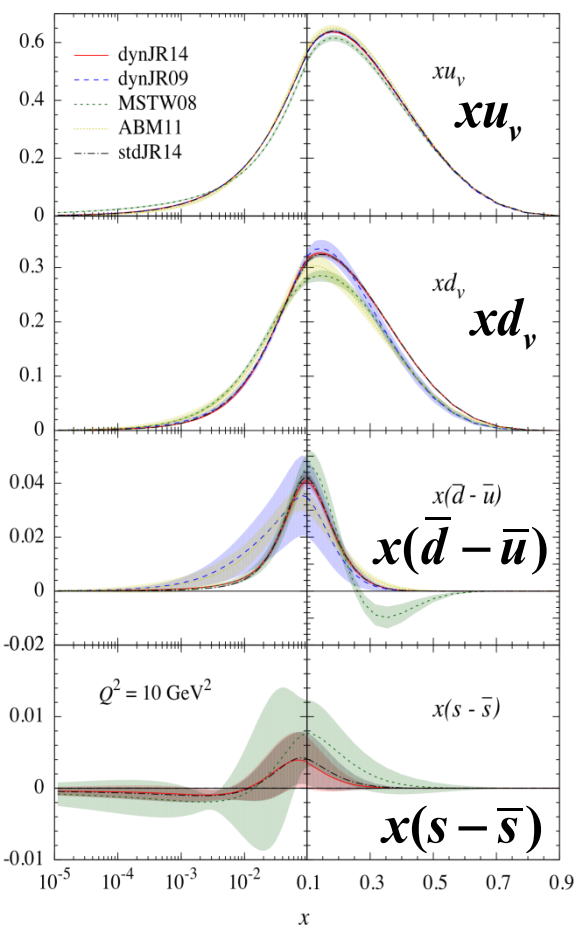


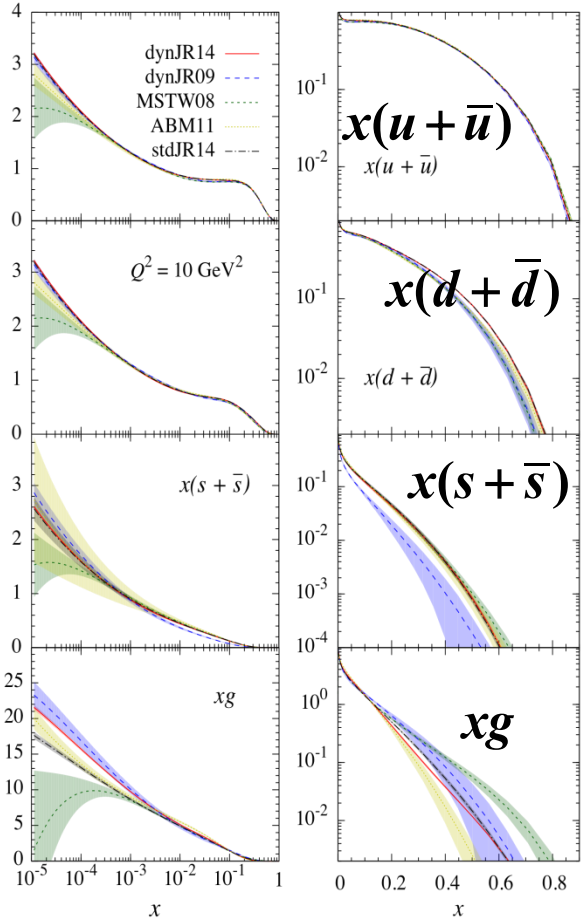
- CTEQ6.6 suggests an SU(3) symmetric sea at small x?
- A strong $x-$dependence for the $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$ ratio?
- New kaon semi-inclusive DIS data at JLab 12 GeV and at EIC will be crucial

Proton parton distributions from JR14

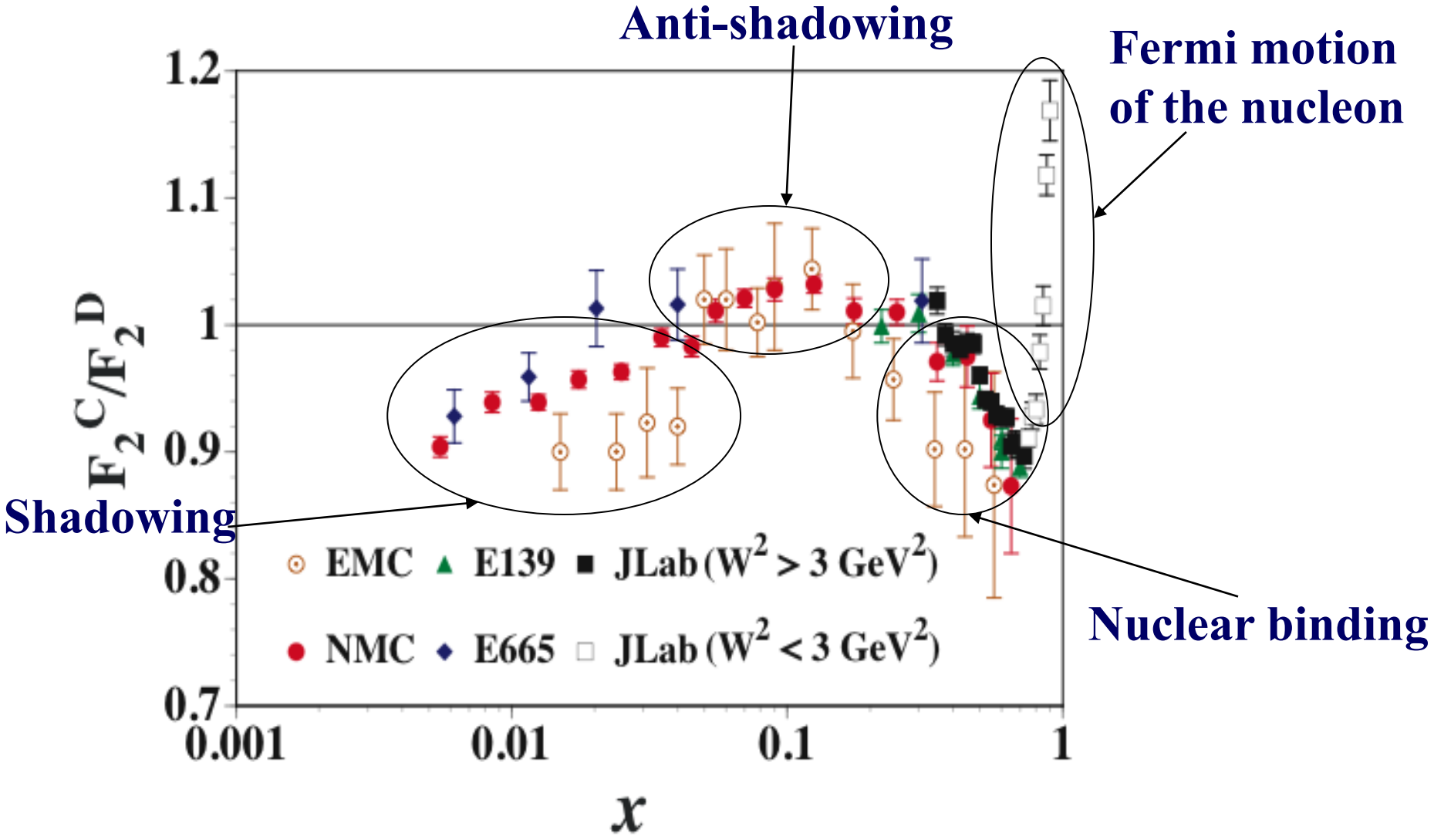
P. Jimenez-Delgado, E. Reya, PRD 89 (2014) 074049

	NDP
HERA σ [39]	621
H1 F_2 [41]	63
H1 F_L [41]	63
HERA σ^c [40]	52
SLAC p [16]	504
SLAC d [16]	517
BCDMS p [18]	351
BCDMS d [19]	254
NMC p, d [17]	516
NMC d/p [44]	177
E665 p, d [21]	106
JLab p [43]	91
JLab d [43]	91
BCDMS F_2 [42]	10
BCDMS F_L [42]	10
SLAC 140x F_2 [42]	2
SLAC 140x F_L [42]	2
dimuon [30,31]	180
E605 [29]	136
E866 pp [46]	138
E866 pd [46]	159
E866 pd/pp [47]	39
CDF jet [48]	64
D0 jet [49]	96
ZEUS jet [50]	30
H1 jet [51]	24
total	4296/4030





Nuclear Modifications of Structure Function F_2

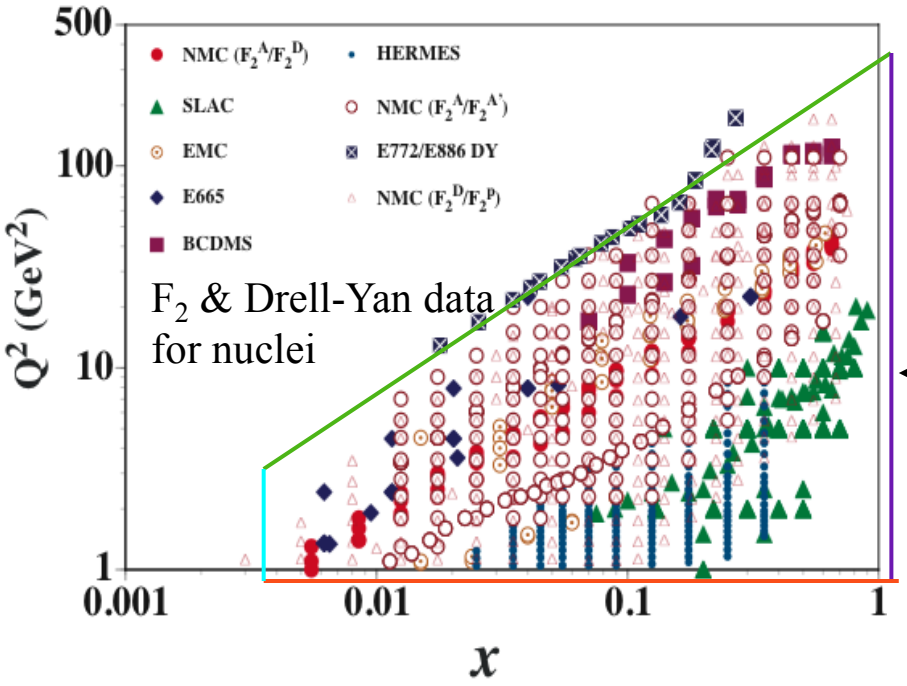


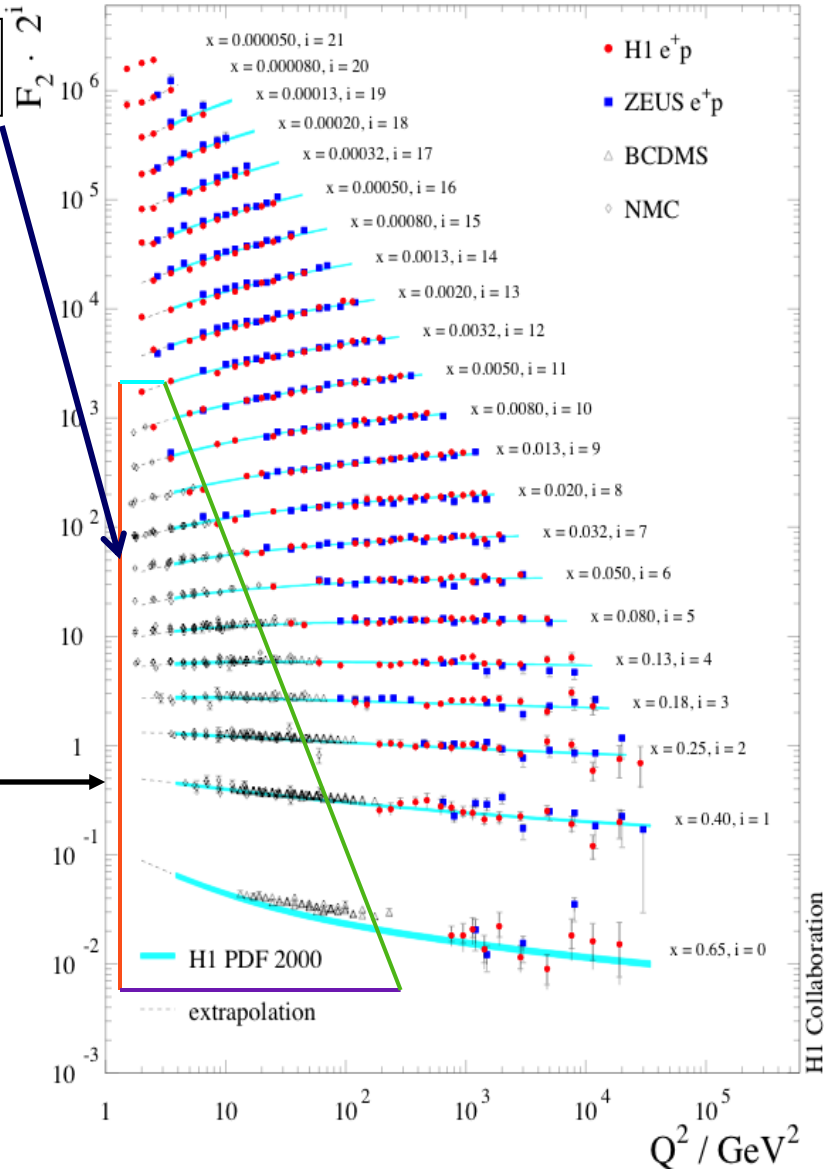
Connection with SRC? Flavor-dependent EMC effect?

Existing Nuclear Data are limited in Q^2 and x

region of existing nuclear data

EIC and p-A collision will explore new region

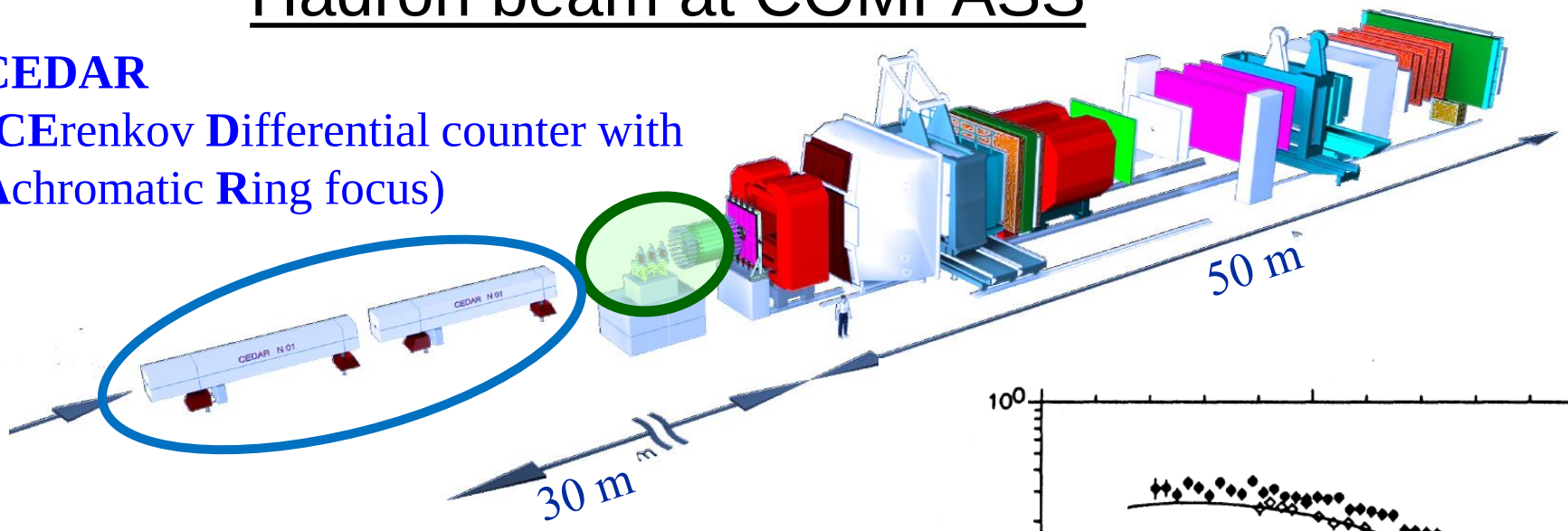




Measure Meson PDF with Drell-Yan Process

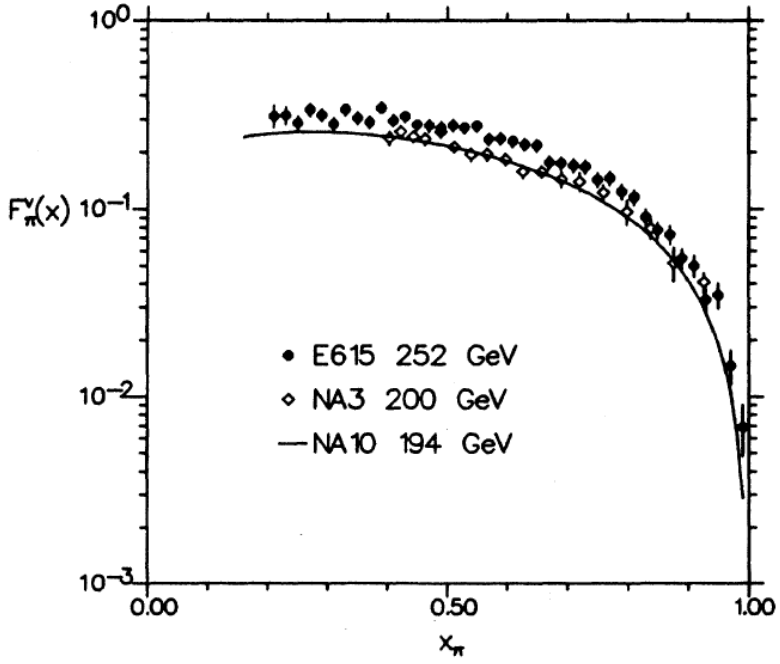
Hadron beam at COMPASS

CEDAR
(**CE**renkov **D**ifferential counter with **A**chromatic **R**ing focus)

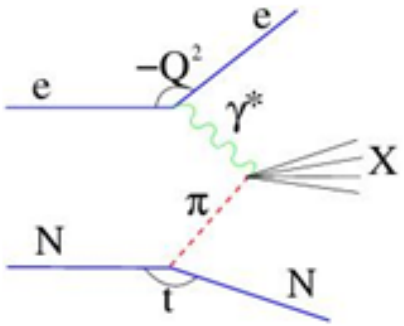


Projected D-Y events in 140 days

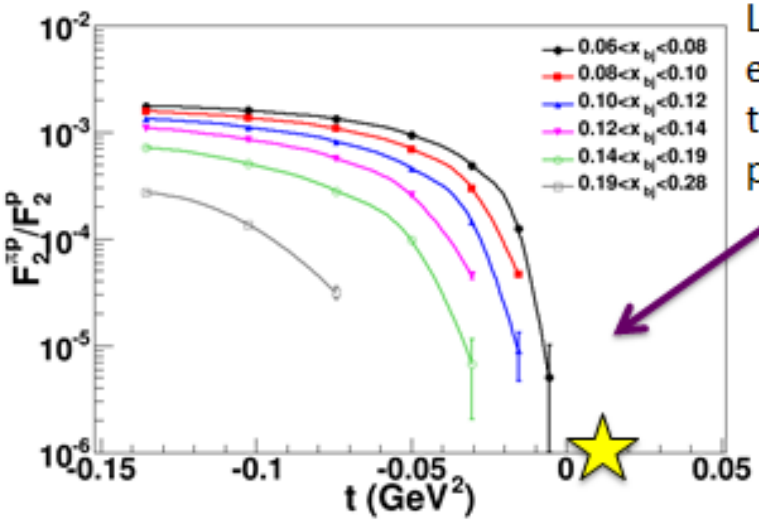
	NH_3	Al (7cm)	W
π^- beam	285,000	55,100	549,000
K^- beam	3,570	710	7,570
$\bar{p}$ beam	2,570	450	3,640



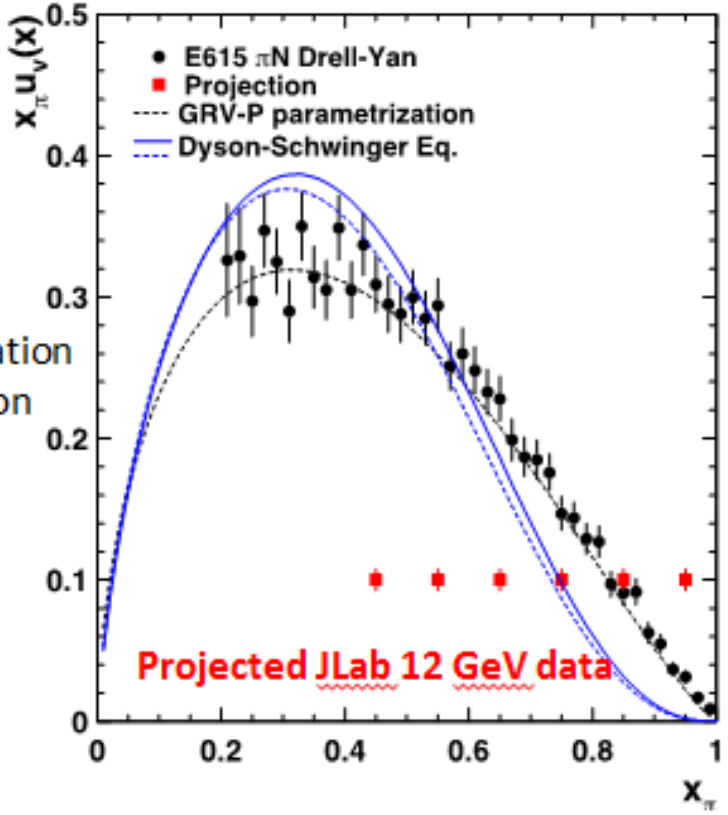
DIS from the Pion Cloud with Nucleon Tagging?



$$N(e, e'N')X$$



Low t extrapolation to the pion pole



Transverse structures of the nucleons

Why is it interesting?

- Transverse degrees of freedom offer new insights on the nucleon structure
- TMDs provide stringent tests for various nucleon models
- The progress of lattice QCD calculations allow direct comparison with the experiments
- Novel parton distributions are accessible by experiments using lepton as well as hadron beams

Three parton distributions describing 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

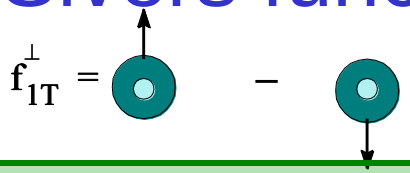
$\vec{k}_\perp^{\,q}$

$\Rightarrow$ Three different correlations

1) Transversity

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

2) Sivers function



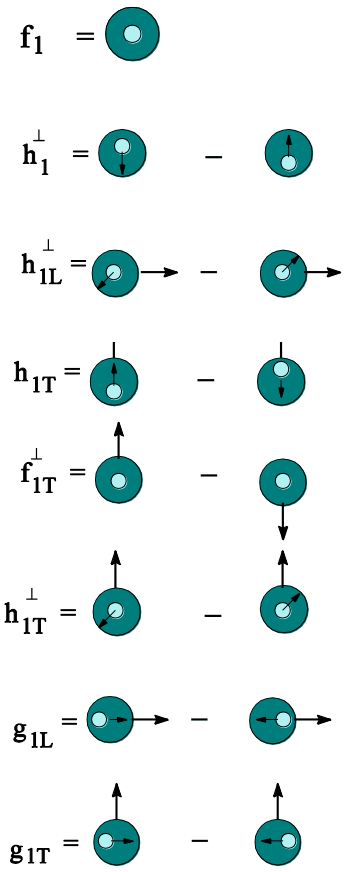
Correlation between $\vec{S}_\perp^{\,N}$ and $\vec{k}_\perp^{\,q}$

3) Boer-Mulders function

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

Transversity and TMD PDFs are probed in Semi-Inclusive DIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$



$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

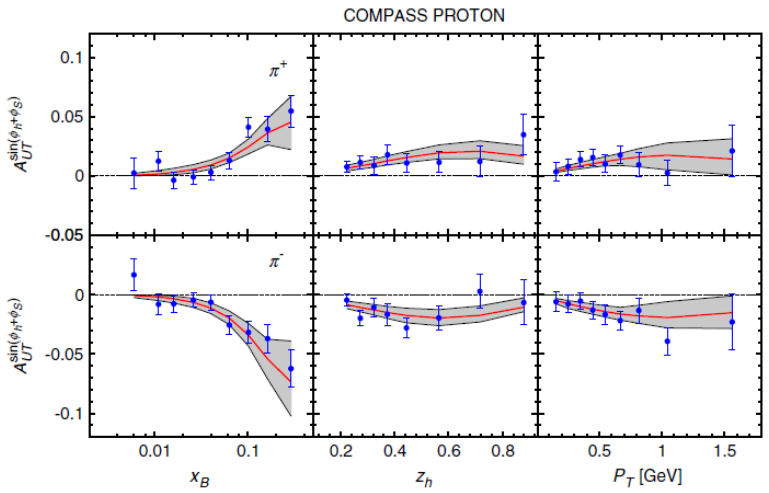
Polarzied beam and target

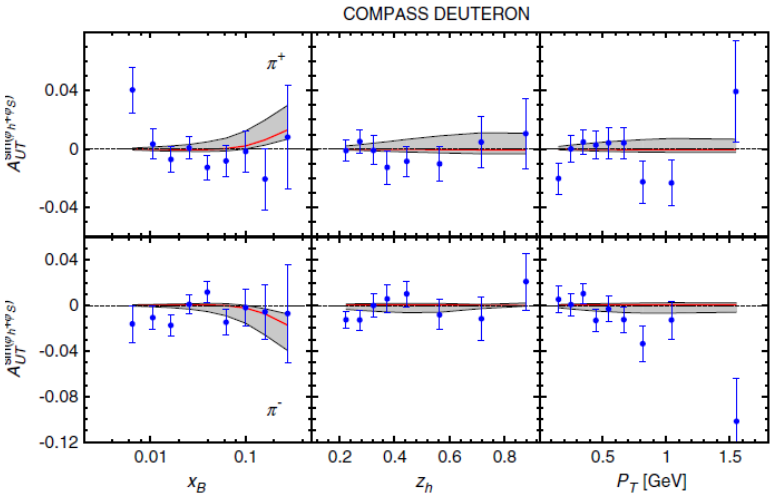
S_L and S_T: Target Polarizations; λe: Beam Polarization

Extraction of Transversity and Collins fragmentation function from SIDIS and Belle data

Torino group, Anselmino et al., PRD 87, 094019 (2013)

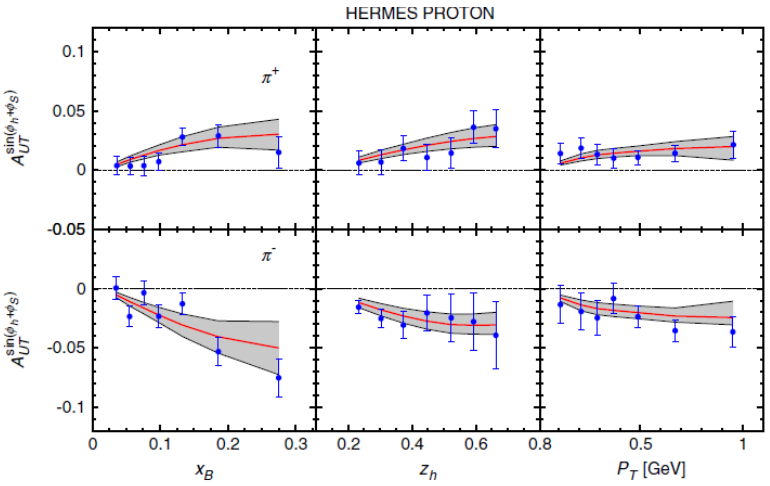
SIDIS on *p*

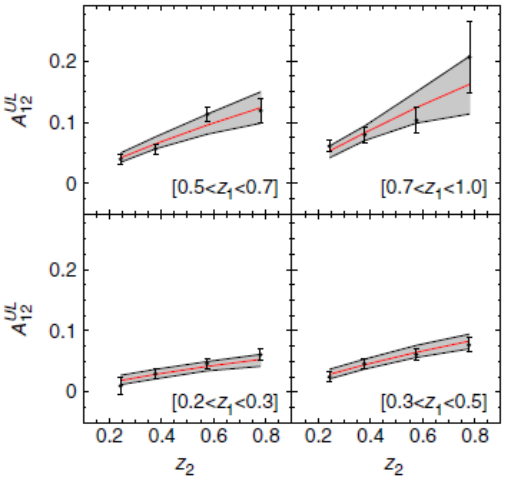




SIDIS on *d*

SIDIS on *p*



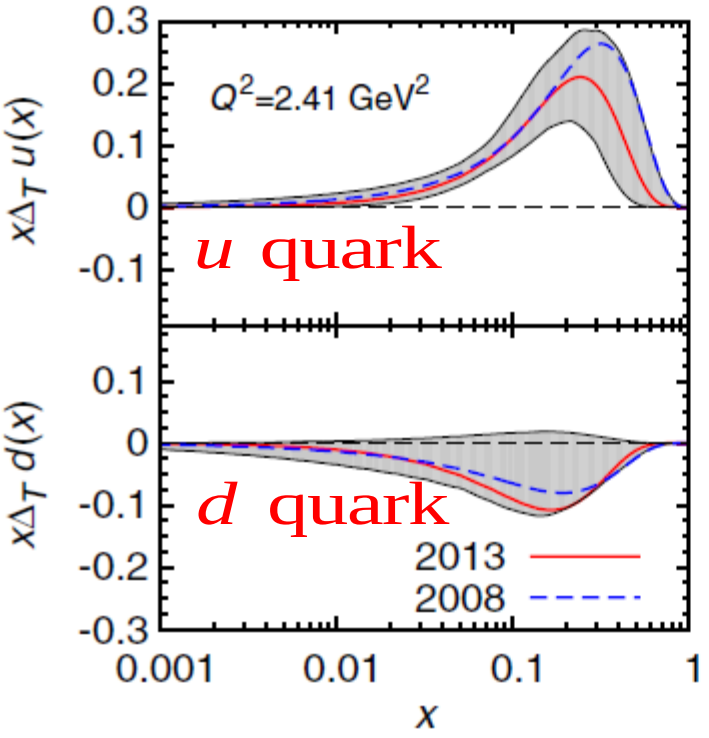


Belle e^+e^-

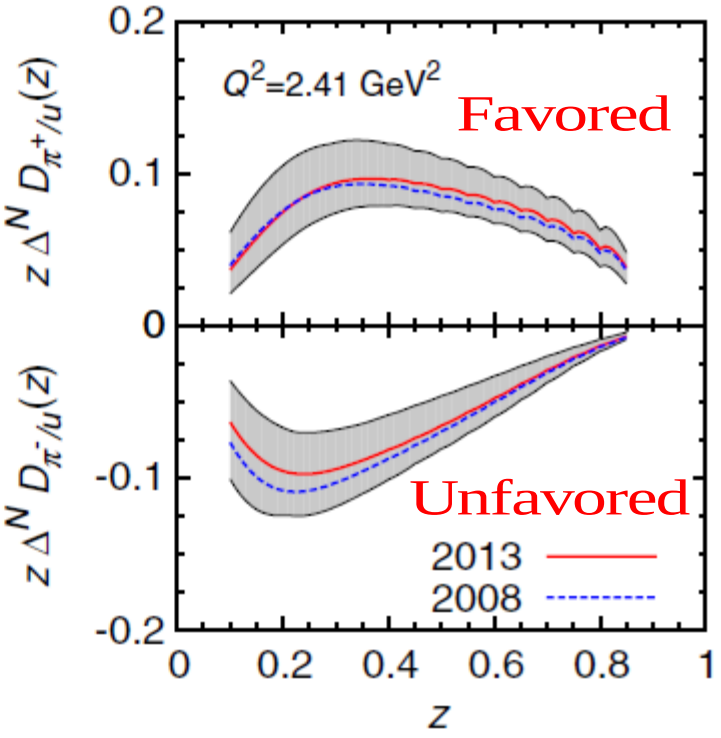
Extraction of Transversity and Collins fragmentation function from SIDIS and Belle data

Torino group, Anselmino et al., PRD 87, 094019 (2013)

Transversity



Collins pion FF



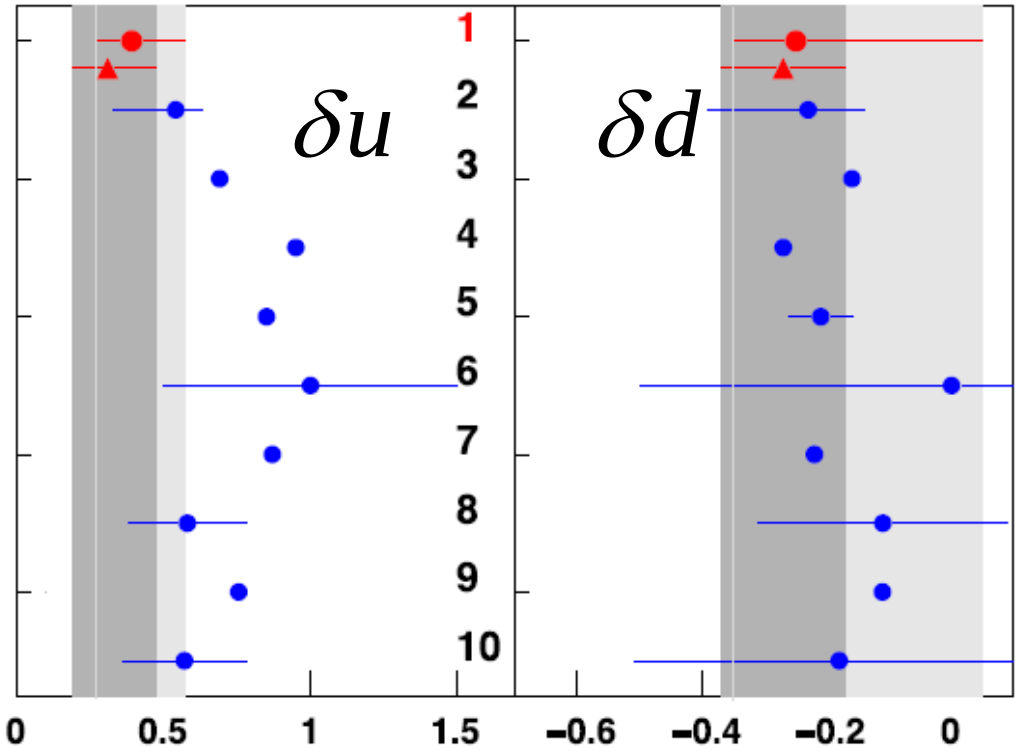
Extraction of nucleon tensor charge

Torino group, Anselmino et al., PRD 87, 094019 (2013)

$\bullet\ \delta u = 0.39^{+0.18}_{-0.12}$ $\quad\bullet\ \delta d = -0.25^{+0.30}_{-0.10}$

$\blacktriangle\ \delta u = 0.31^{+0.16}_{-0.12}$ $\quad\blacktriangle\ \delta d = -0.27^{+0.10}_{-0.10}$

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$



1 : Extractions from global fits (using two different Collins FF parameterizations)

2-10: Predictions from various models (including LQCD)

- Tensor charges are smaller than axial charge
- Difference between data and theory could be partly caused by neglecting sea transversity in the extraction?

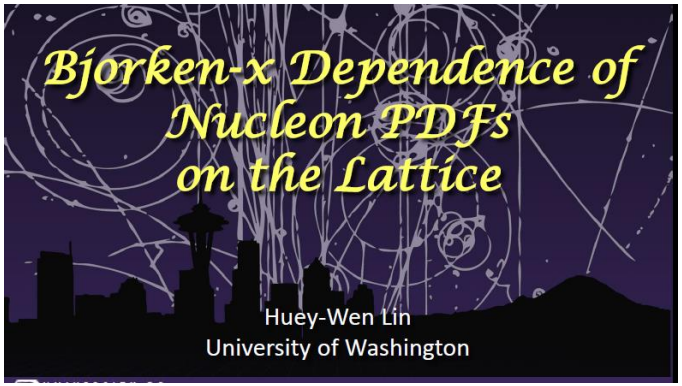
$\Delta u = 0.787$ $\qquad \Delta d = -0.319$

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]



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

Transversity Distribution

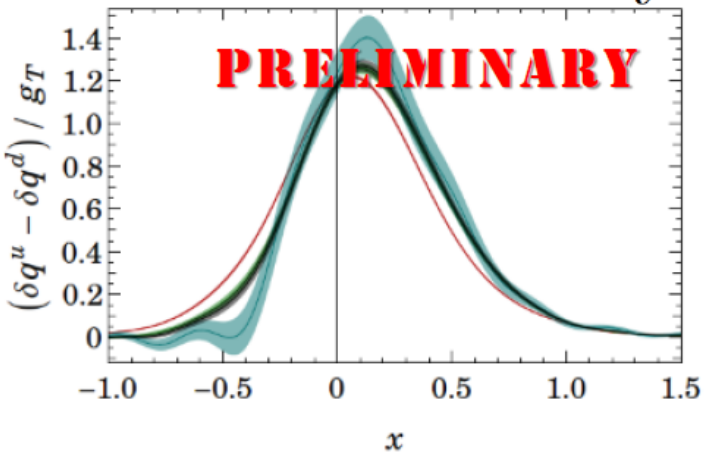
§ Exploratory study

- We found $\delta\bar{u} < \delta\bar{d}$ with large sea asymmetry
- Chiral quark-soliton model

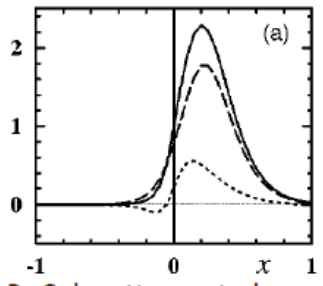
$$\int dx \frac{\delta\bar{u}(x) - \delta\bar{d}(x)}{g_T} \approx -0.320\,(18)$$

$$\int dx \left(\delta\bar{u}(x) - \delta\bar{d}(x)\right) \approx -0.082$$

B. Dressler et al., hep-ph/9809487



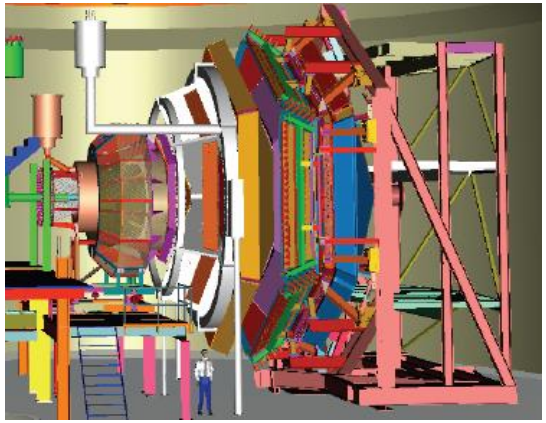
CQS model



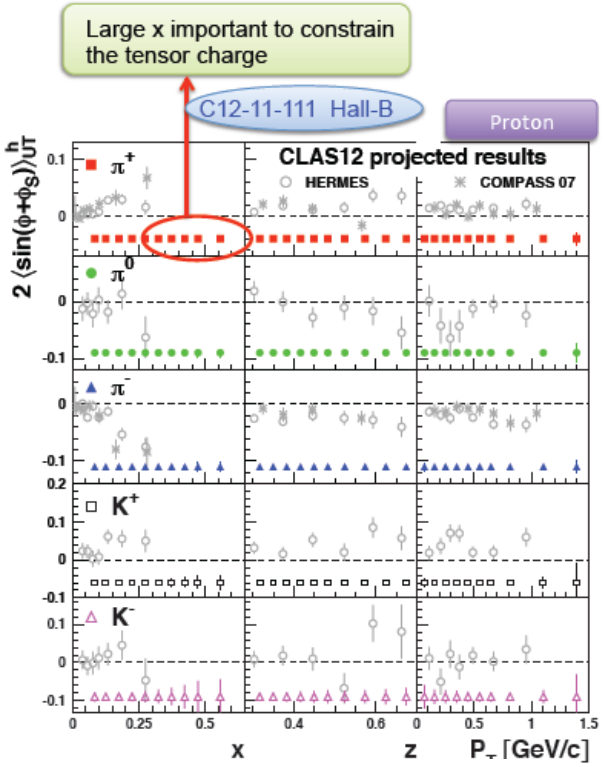
P. Schweitzer et al. PRD 64, 034013 (2001)

Predicts large sea-quark transversity!

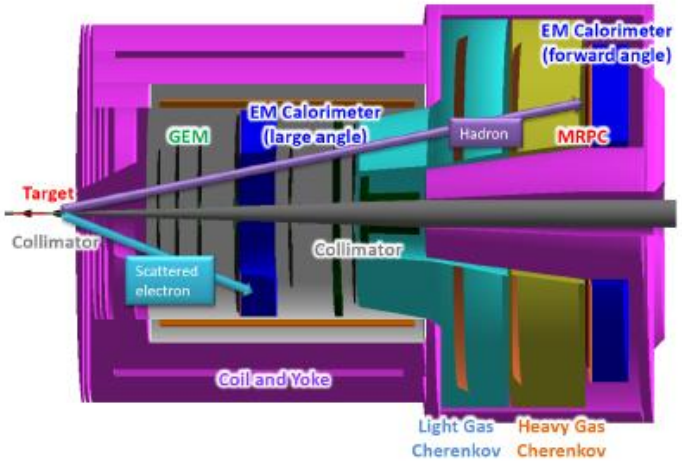
Transversity at Jlab 12-GeV

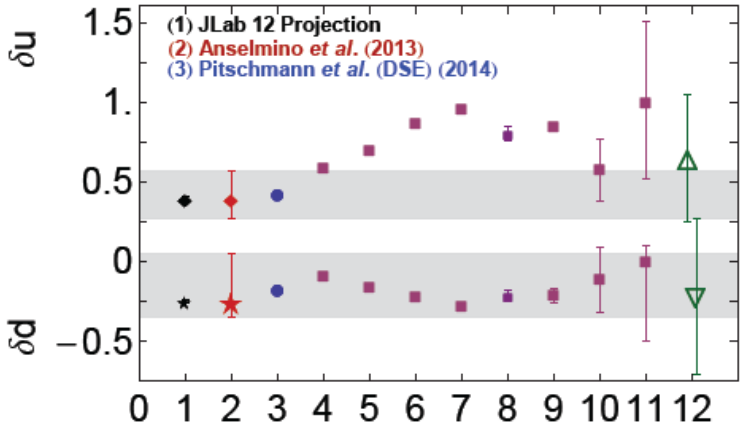


Hall-B



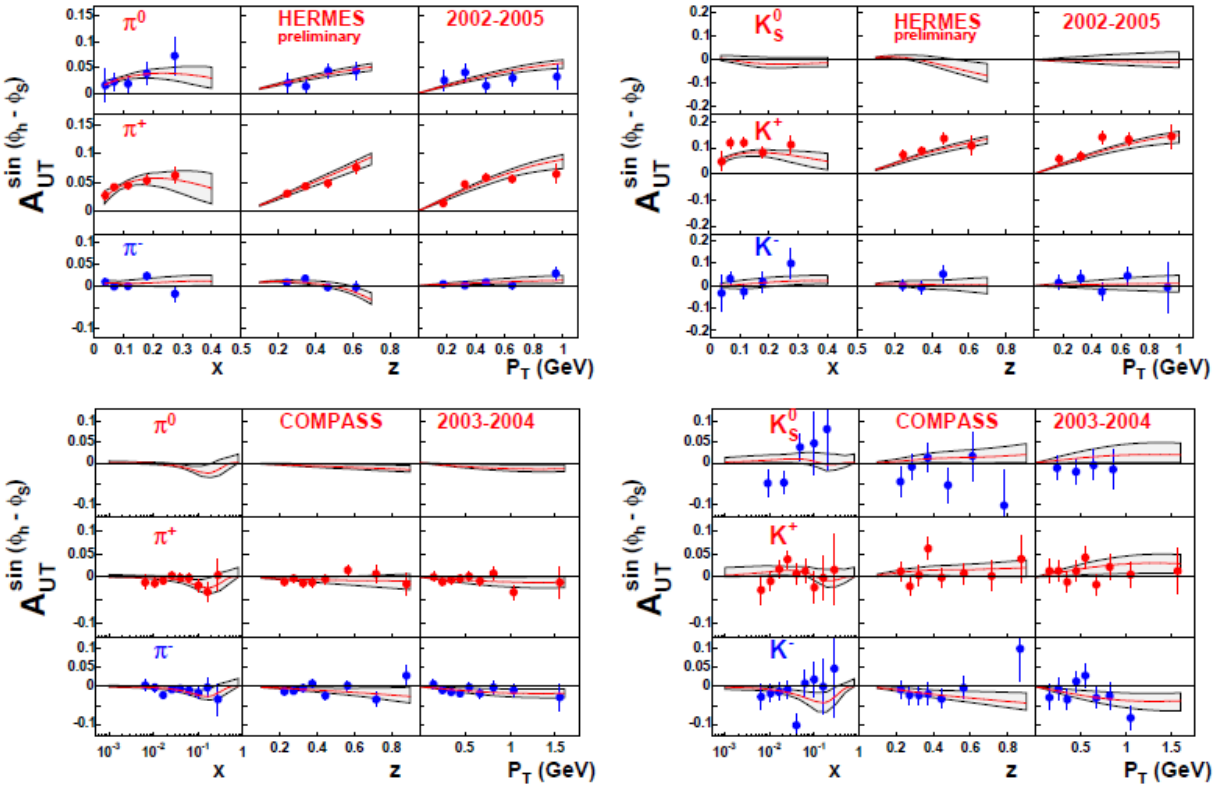
Extensive SIDIS program with SoliD in Hall-A

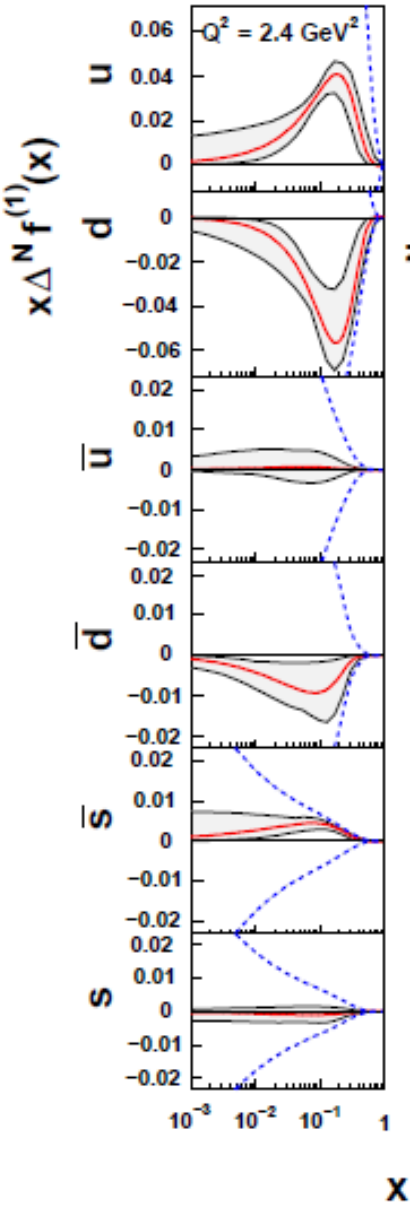




Extraction of Sivers function from SIDIS data

Torino group, Anselmino et al.,
Eur. Phys. J. A39 (2009) 89



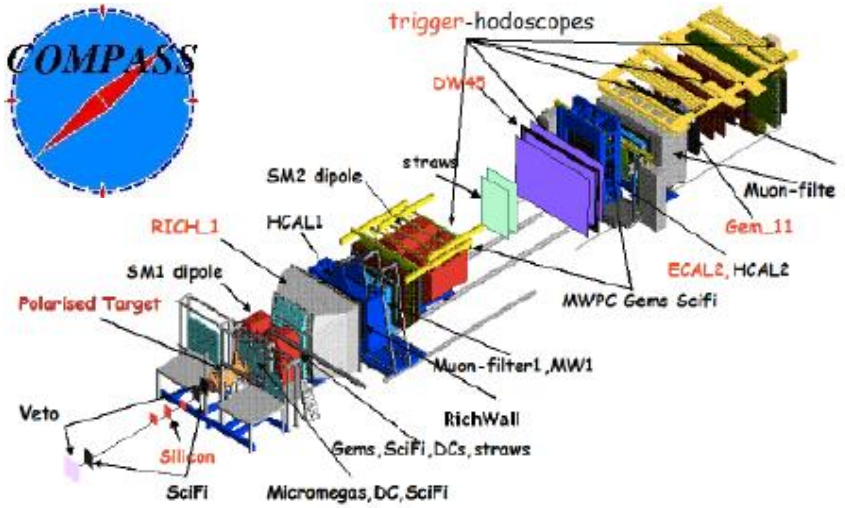


- u – and d - quark Sivers functions have opposite signs
- Sea-quark Sivers functions are non-zero (from K^+ data)

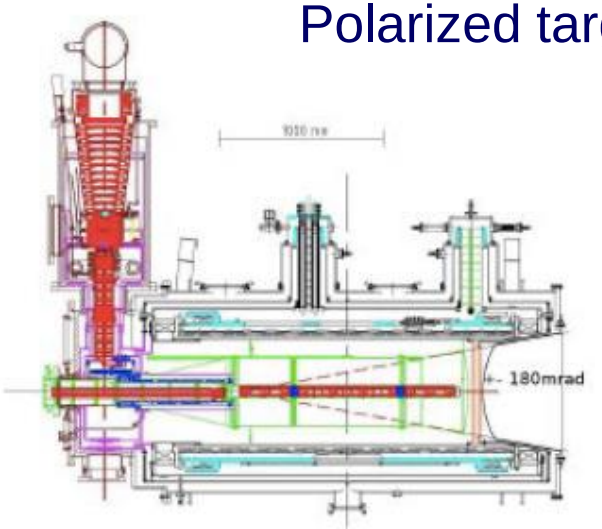
Outstanding questions on Sivers function

- Does Sivers function change sign between DIS and Drell-Yan?
- Sign and magnitude of the sea-quark Sivers functions?
- Q^2-evolution of the Sivers function?

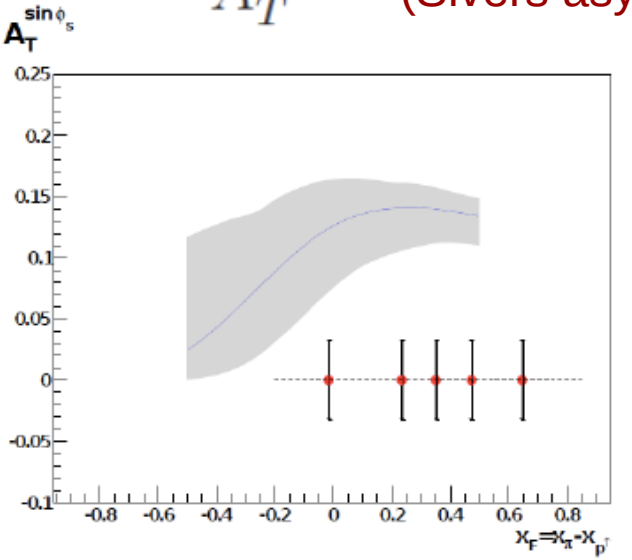
Polarized Drell-Yan with 190 GeV/c pion beam



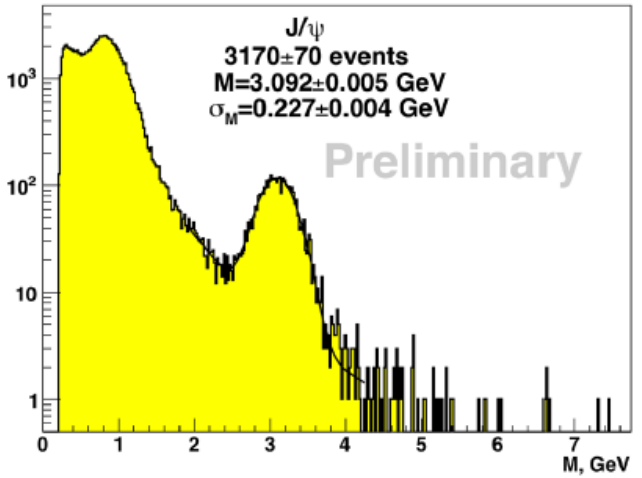
Polarized target



$A_T^{\sin\phi_S}$ (Sivers asymmetry)



COMPASS DY beam test 2009

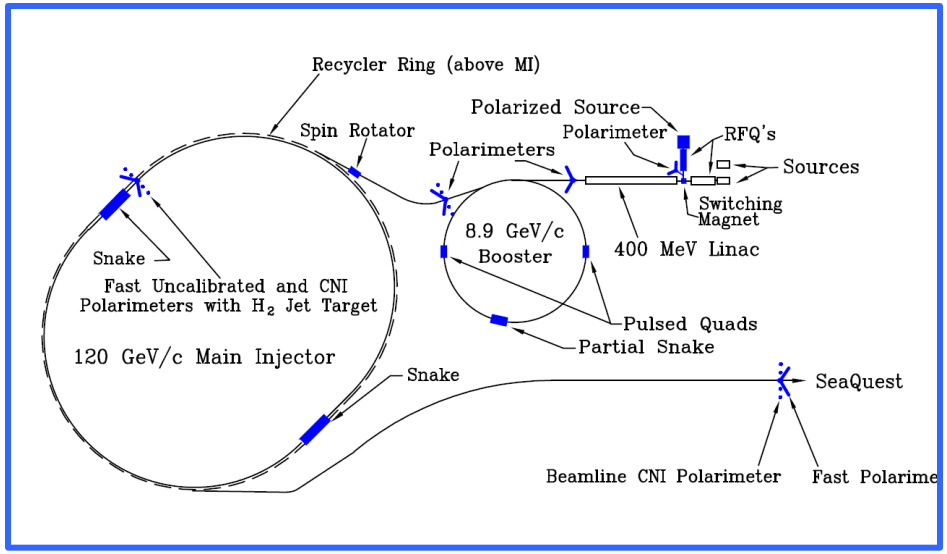


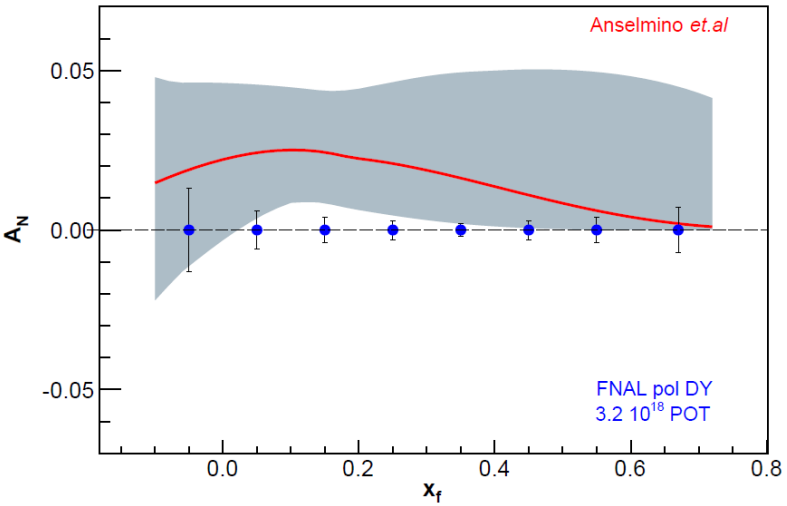
Expect data-taking in 2014-2015

Proposal to measure Sivers in polarized Drell-Yan at Fermilab

Proposal (P-1027) (Polarized Drell-Yan with polarized proton beam)

(W. Lorenzon, P. Reimer, et al.)





Main goals: 1) Accelerate polarized proton beam at the Main Injector

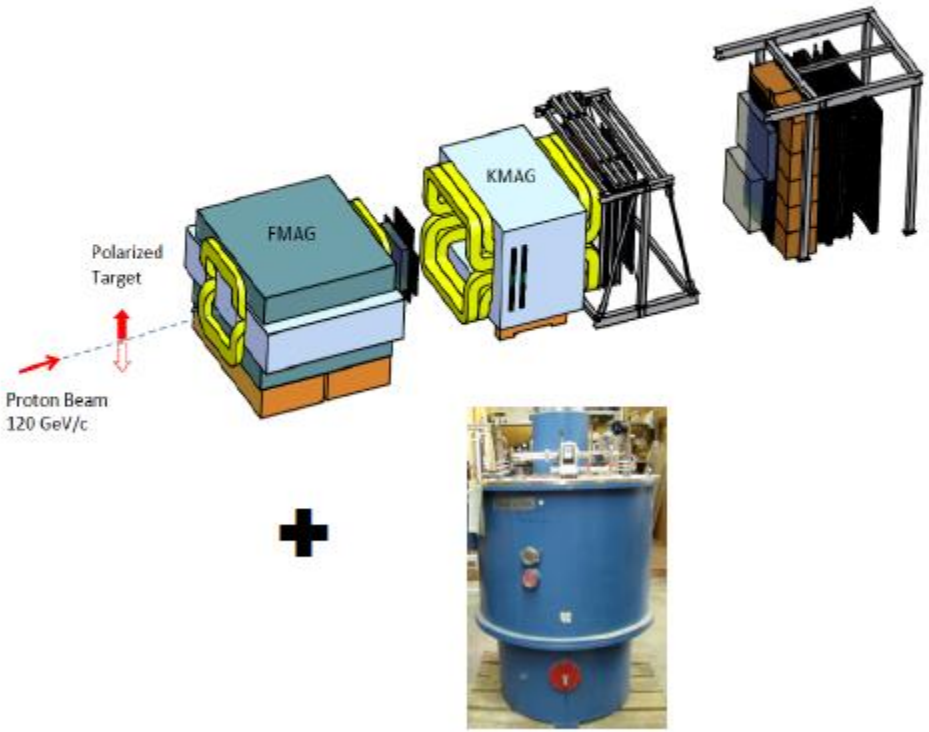
2) Test "sign-change" of T-odd Sivers function in Drell-Yan

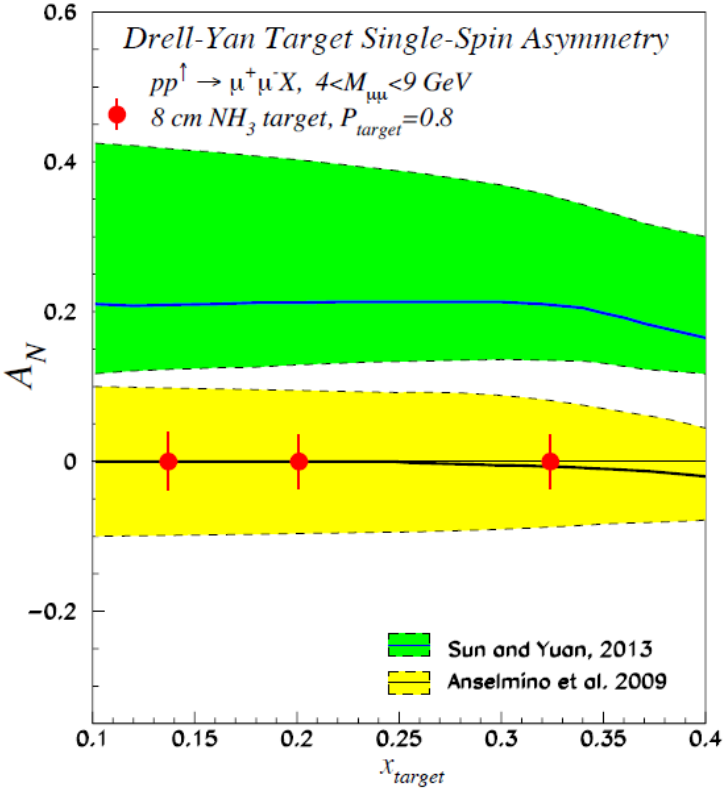
- Propose using the existing dimuon spectrometer
- Possibility of polarized target is also being considered

Another proposal to measure sea-quark Sivers in polarized Drell-Yan at Fermilab

P-1039 Collaboration:

Co-Spokespersons: A. Klein, X. Jiang
Los Alamos National Laboratory





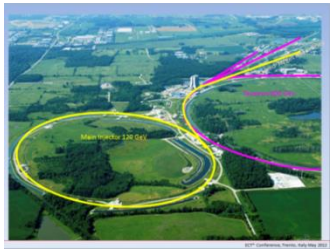
Statistics shown for one calendar year of running :
$\mathcal{L}$ = 1.4 *10^{43} /cm^2 ←→ POT = 2.1*10^{18}

Request for two calendar years of beam time

Global interest in polarized Drell-Yan measurements

- Fermilab (proton beam, unpolarized, polarized beam/target possible)
- COMPASS (pion beam, polarized target)
- FAIR (polarized antiproton beam)
- RHIC (polarized proton beam)
- J-PARC (proton beam, polarzied beam possible)
- JINR NICA (proton beam)

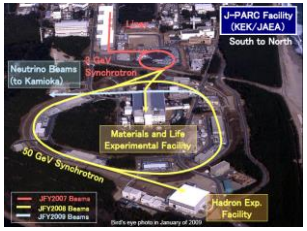
Fermilab



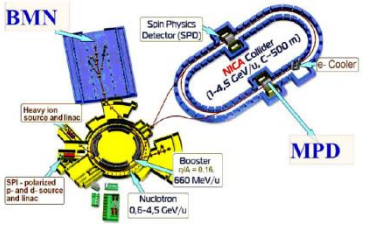
COMPASS

RHIC

J-PARC



NICA



Summary

- Significant progress has been made in measuring and understanding the flavor and momentum dependencies of parton distributions in the nucleon.
- Exciting physics opportunities await us with existing and future electron and hadron facilities to further advance our knowledge on hadron structure and QCD.