Recent Results and Future Prospects for Drell-Yan Experiments

Jen-Chieh Peng

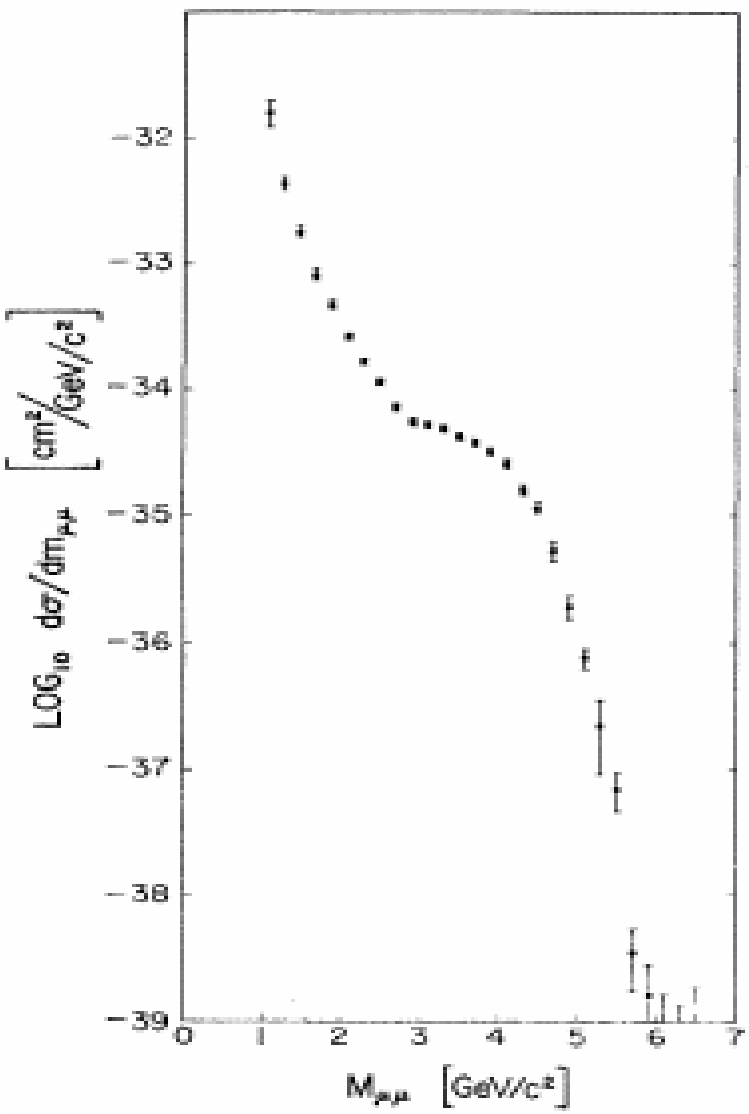
University of Illinois at Urbana-Champaign

RIKEN-BNL Workshop on "Progress in High-P_T Physics at RHIC", BNL, March 17-19, 2010

Outline

- Brief historical review
- Recent highlights of Drell-Yan experiments
- Future prospects for Drell-Yan experiments

First Dimuon Experiment



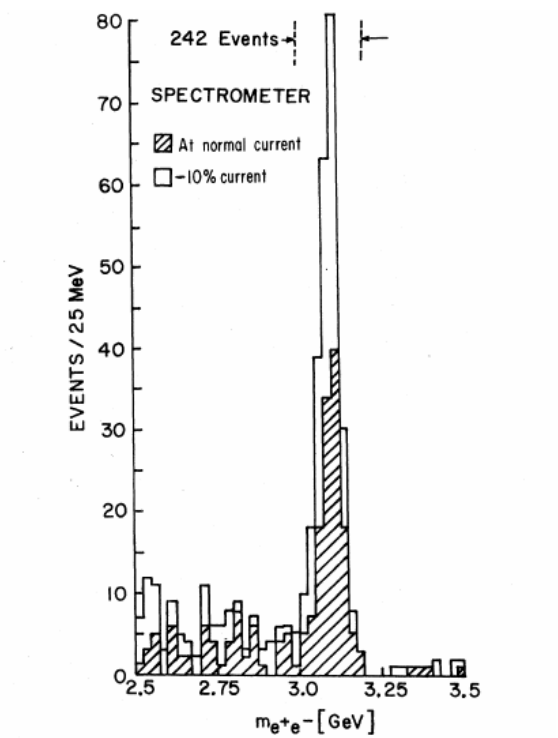
$p + U \rightarrow \mu^{+} + \mu^{-} + X$ 29 GeV proton

Lederman et al. PRL 25 (1970) 1523

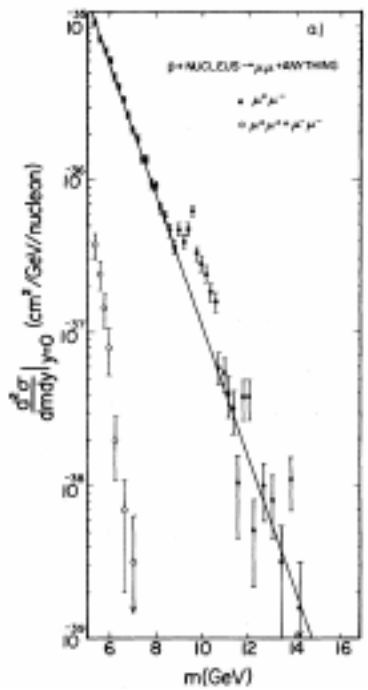
- Experiment originally designed to search for neutral weak boson (Z^0)

Lepton-pair production is a powerful tool for finding new particles

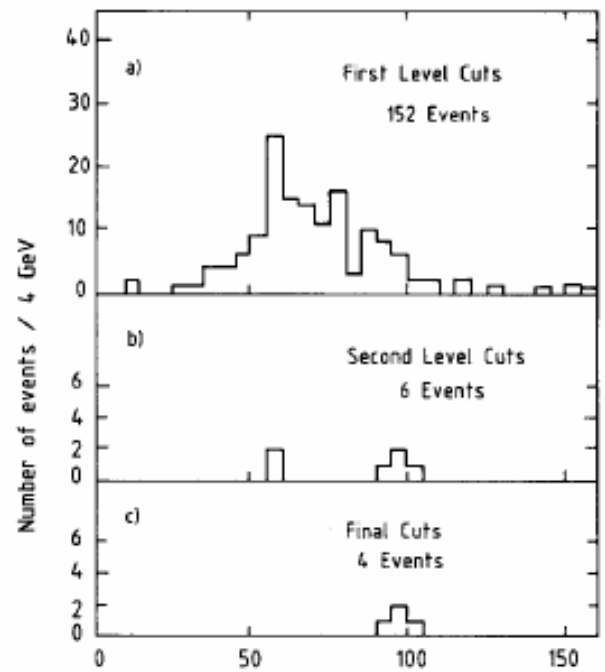
$J/\Psi \rightarrow e^+e^-$



$\Upsilon \rightarrow \mu^+\mu^-$



$Z^0 \rightarrow e^+e^-$

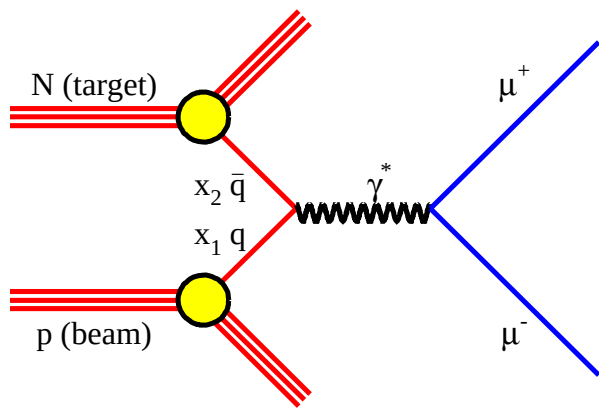


The Drell-Yan Process

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

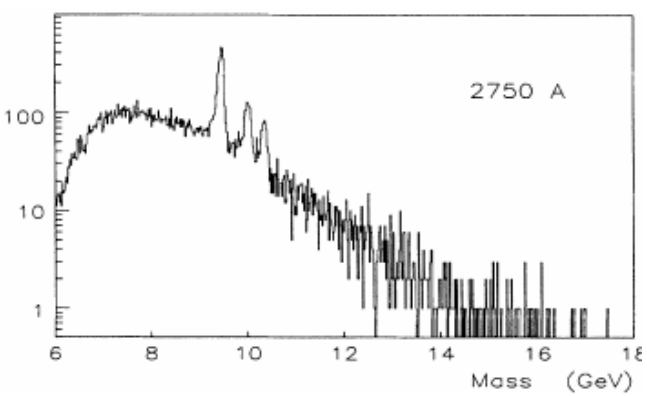


$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2)\right]$$

Lepton-pair production also provides unique information on parton distributions

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

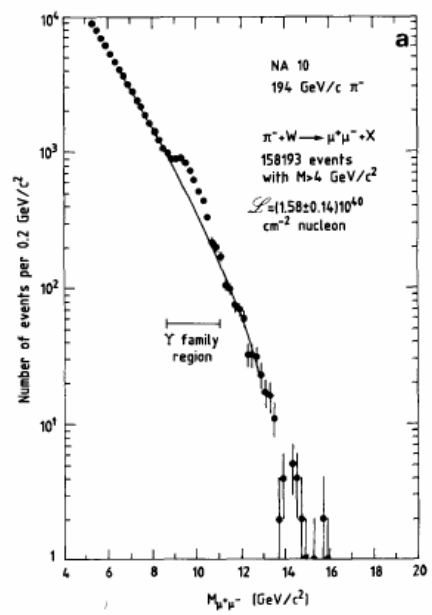
800 GeV/c



Probe antiquark distribution in nucleon

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

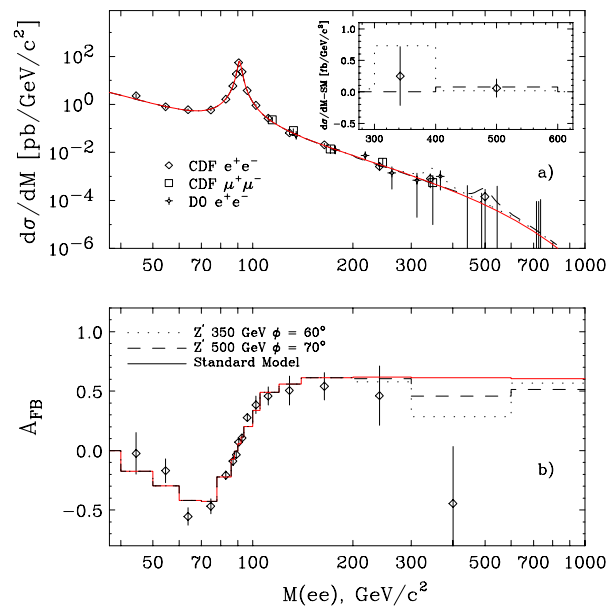
194 GeV/c



Probe antiquark distribution in pion

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

1.8 TeV

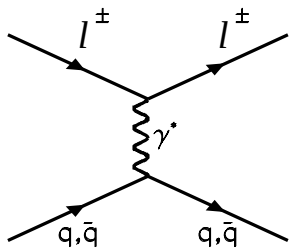


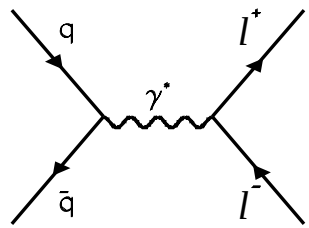
Probe antiquark distributions in antiproton

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

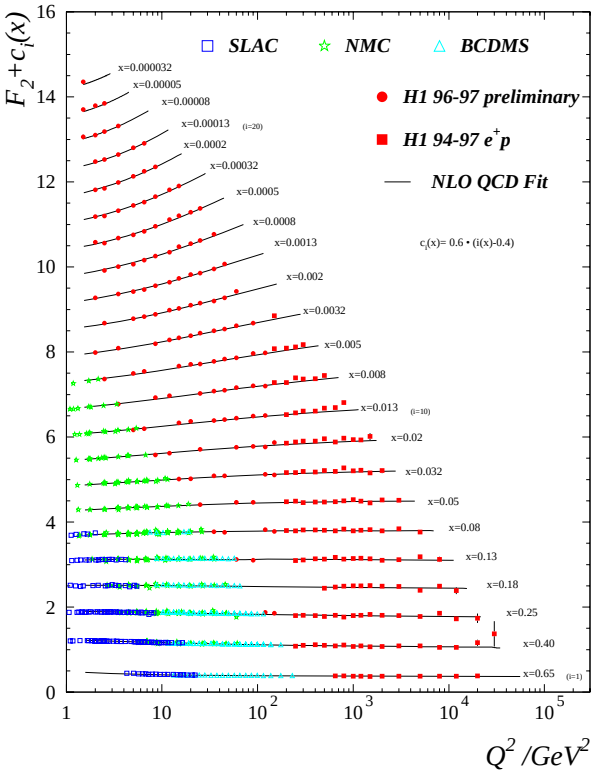
Complimentality between DIS and Drell-Yan

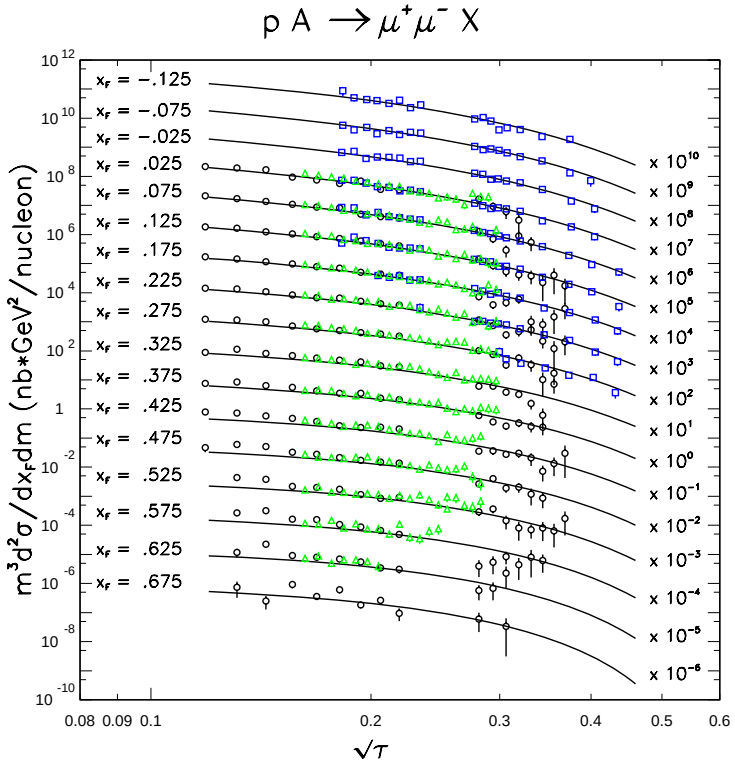
DIS





Drell-Yan





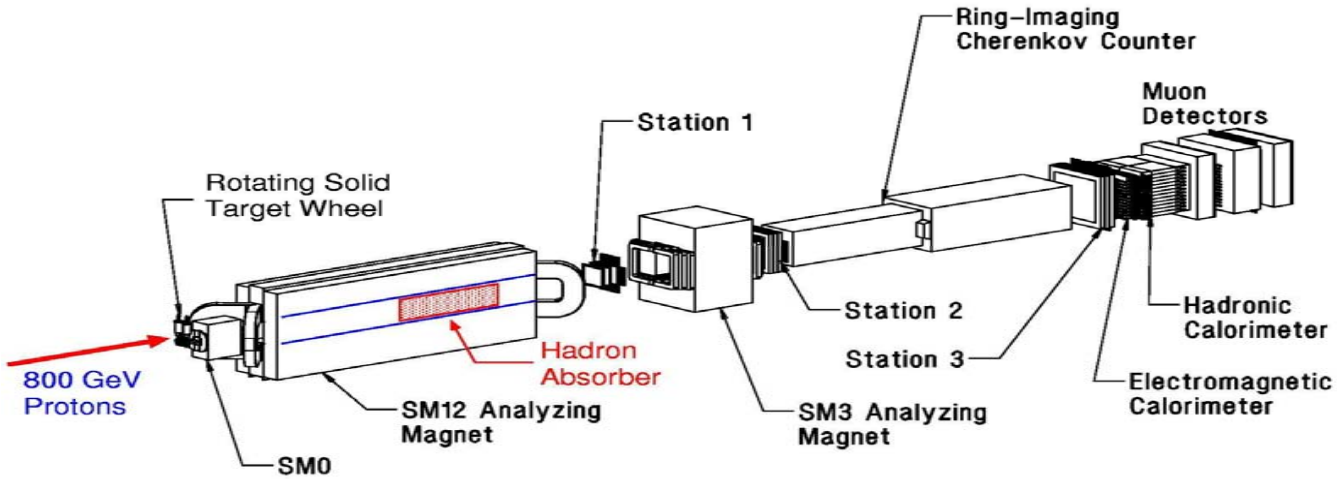
McGaughey, Moss, JCP,

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

Fermilab Dimuon Spectrometer

(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, will run in 2010?)

- "Drell-Yan with the FNAL Main Injector"

Physics results from Fermilab dimuon experiments

1) Drell - Yan process :

- Antiquarks in nuclei and nucleons
- Quark energy loss in nuclear medium
- Drell-Yan angular distributions

2) Quarkonium production :

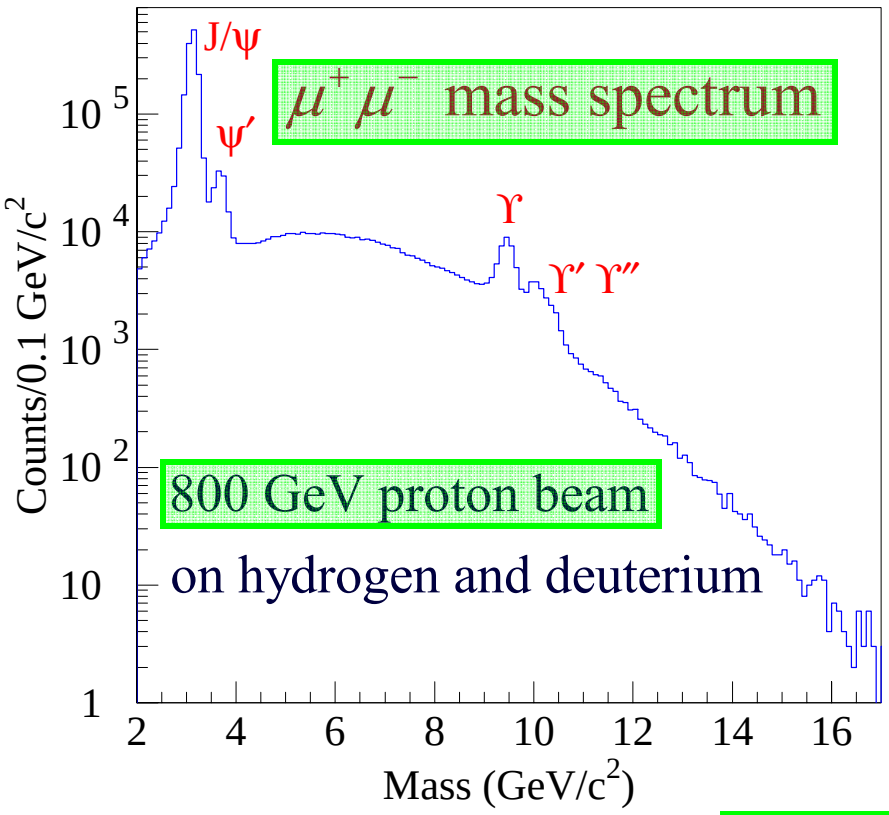
- Pronounced nuclear dependence
- Production mechnism and polarizations
- Gluon distributions in the nucleons

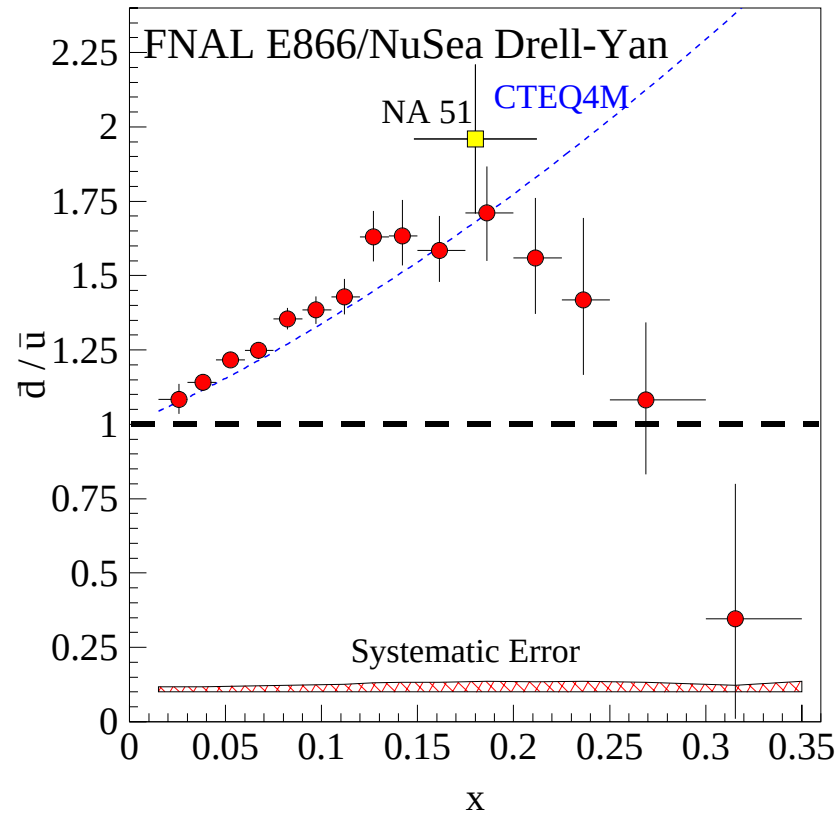
3) Heavy quark production :

- Open charm production
- B-meson production

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

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

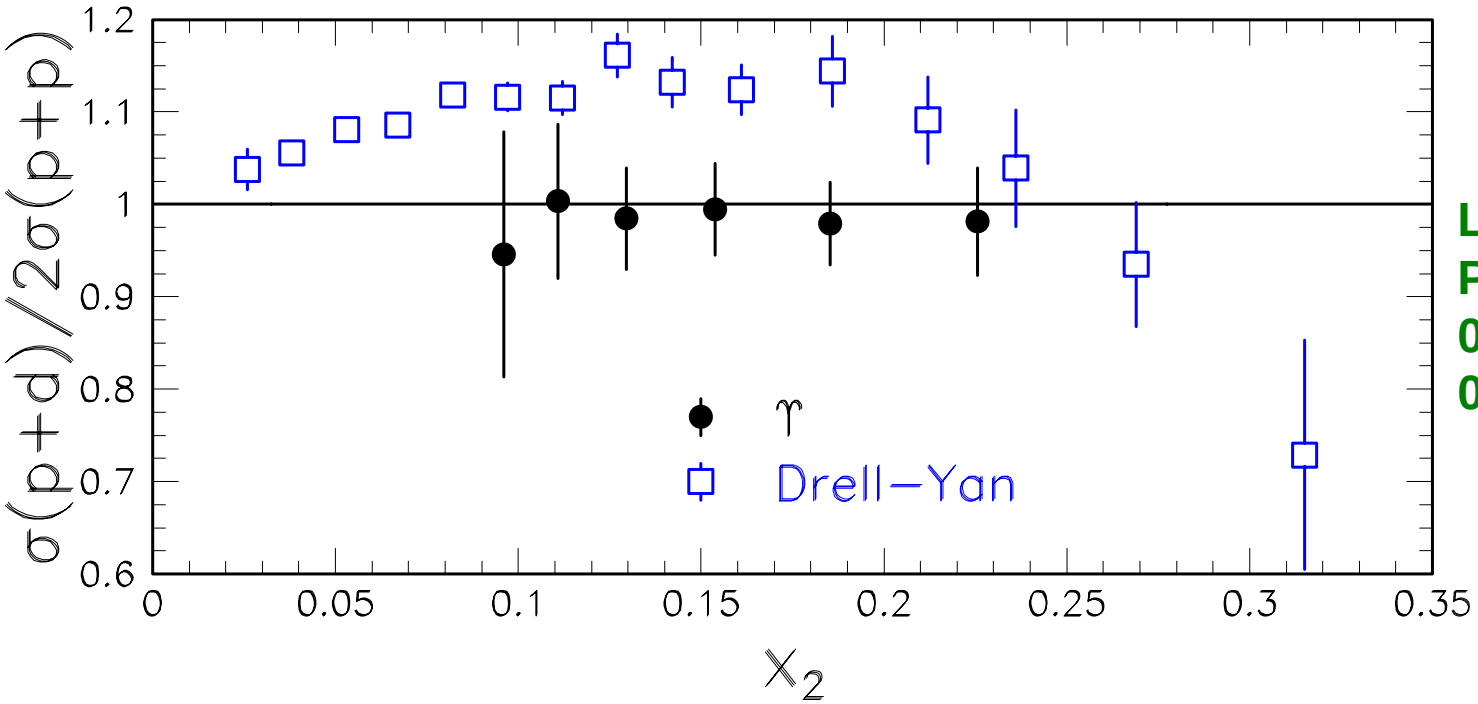




at $x_1 > x_2$: Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \approx \frac{1}{2}(1+\bar{d}(x_2)/\bar{u}(x_2))$

Gluon distributions in proton versus neutron?

$$\text{E866 data}: \sigma(p+d \to \Upsilon X)/2\sigma(p+p \to \Upsilon X)$$



Lingyan Zhu et al., PRL, 100 (2008) 062301 (arXiv: 0710.2344)

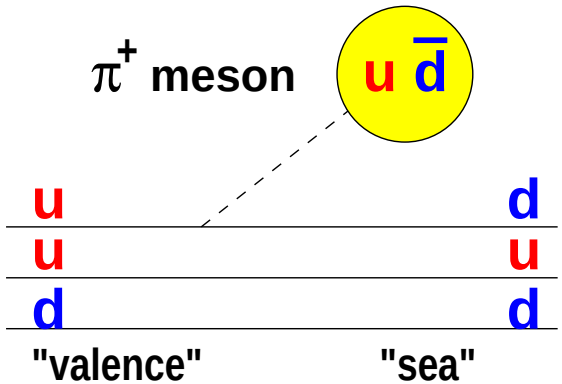
$$Drell-Yan: \quad \sigma^{pd}/2\sigma^{pp} \square [1+\bar{d}(x)/\bar{u}(x)]/2$$

$$J/\Psi, \Upsilon: \quad \sigma^{pd}/2\sigma^{pp} \square [1+g_n(x)/g_p(x)]/2$$

Gluon distributions in proton and neutron are very similar

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

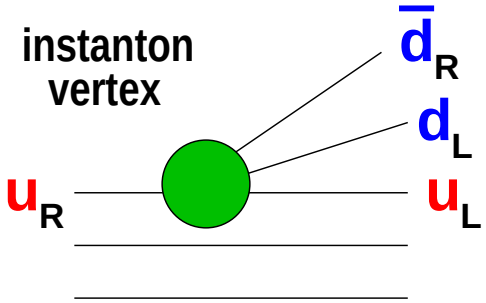
Meson Cloud Models



Chiral-Quark Soliton Model

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

Instantons



Theory: Thomas, Miller, Kumano, Londergan, Henley, Speth, Hwang, Liu, Cheng/Li, Ma, etc.

(For reviews, see Kumano (hep-ph/9702367), Garvey and Peng (nucl-ex/0109010))

Theses models also have implications on

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

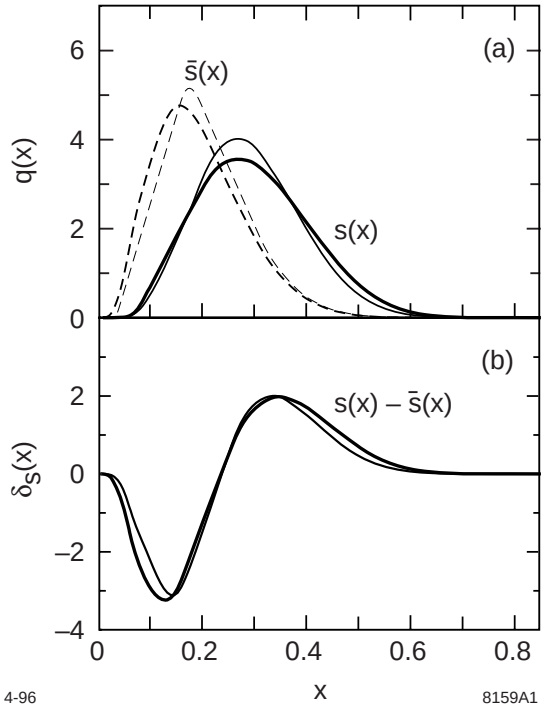
Meson cloud has significant contributions to sea-quark distributions

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

Meson cloud model

$$p \to K^+ \Lambda$$

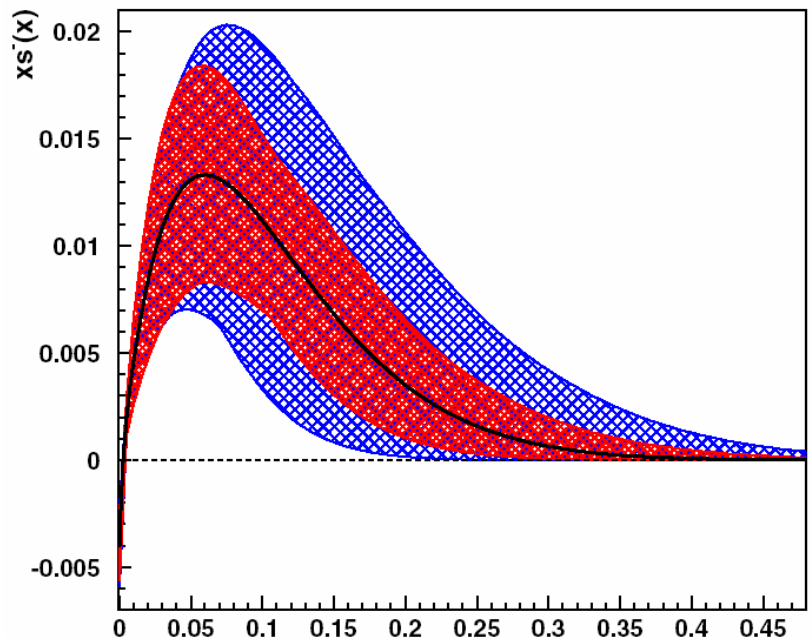
$$(u\bar{s})\,(uds)$$



Thomas / Brodsky and Ma

Analysis of neutrino DIS data

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



NuTeV, PRL 99 (2007) 192001

Spin and flavor are closely connected

- Meson Cloud Model

$$u\uparrow \rightarrow \pi^0(u\bar{u}) + u\downarrow \qquad u\uparrow \rightarrow K^+(u\bar{s}) + s\downarrow$$

- Pauli Blocking Model

A spin-up valence quark would inhibit the probability of generating a spin-down antiquark

- Instanton Model

$$u_L \rightarrow u_R d_R \bar{d}_L, \qquad d_L \rightarrow d_R u_R \bar{u}_L$$

- Chiral-Quark Soliton Model

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) > \bar{d}(x) - \bar{u}(x)$$

- Statistical Model

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) \approx \bar{d}(x) - \bar{u}(x)$$

Predictions of $\int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]\,dx$

Table 2. Prediction of various theoretical models on the integral $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$.

Model	I_Δ prediction	Ref.
Meson cloud (π-meson)	0	[42,43]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[34]
Meson cloud ($\pi - \rho$ interf.)	$= -6\int_0^1 g^p(x)dx$ $\simeq -0.7$	[35]
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[36]
Meson cloud (ρ-meson)	< 0	[37]
Meson cloud ($\pi - \sigma$ interf.)	$\simeq 0.12$	[44]
Pauli-blocking (bag-model)	$\simeq 0.09$	[36]
Pauli-blocking (ansatz)	$\simeq 0.3$	[45]
Pauli-blocking	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ $\simeq 0.2$	[46]
Chiral-quark soliton	0.31	[47]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12}[\bar{d}(x) - \bar{u}(x)]dx$	[48]
Instanton	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ $\simeq 0.2$	[39]
Statistical	$\simeq \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ $\simeq 0.12$	[49]
Statistical	$> \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ > 0.12	[50]

Eur. Phys. J. A18 (2003) 395

First measurements are now available

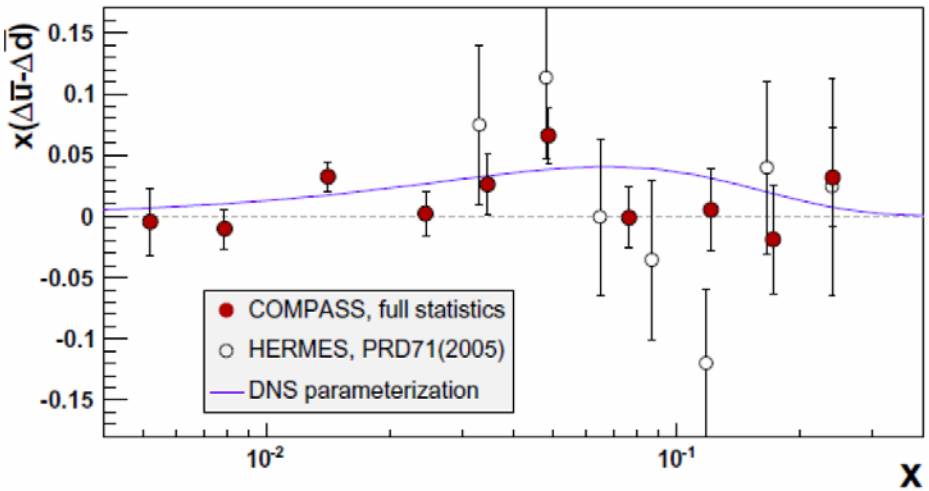
Is $\Delta\bar{u} = \Delta\bar{d}$?

- HERMES (PR D71 (2005) 012003)

$$\int_{0.023}^{0.3} (\Delta\bar{u} - \Delta\bar{d})dx = 0.048 \pm 0.057 \pm 0.028$$

- COMPASS (arXiv: 0909.3729)

$$\int_{0.004}^{0.3} (\Delta\bar{u} - \Delta\bar{d})dx = 0.052 \pm 0.035 \pm 0.013 \text{ at } Q^2 = 3 \text{ GeV}^2$$



- DSSV 2008 (de Florian et al. PRL 101 (2008) 072001)

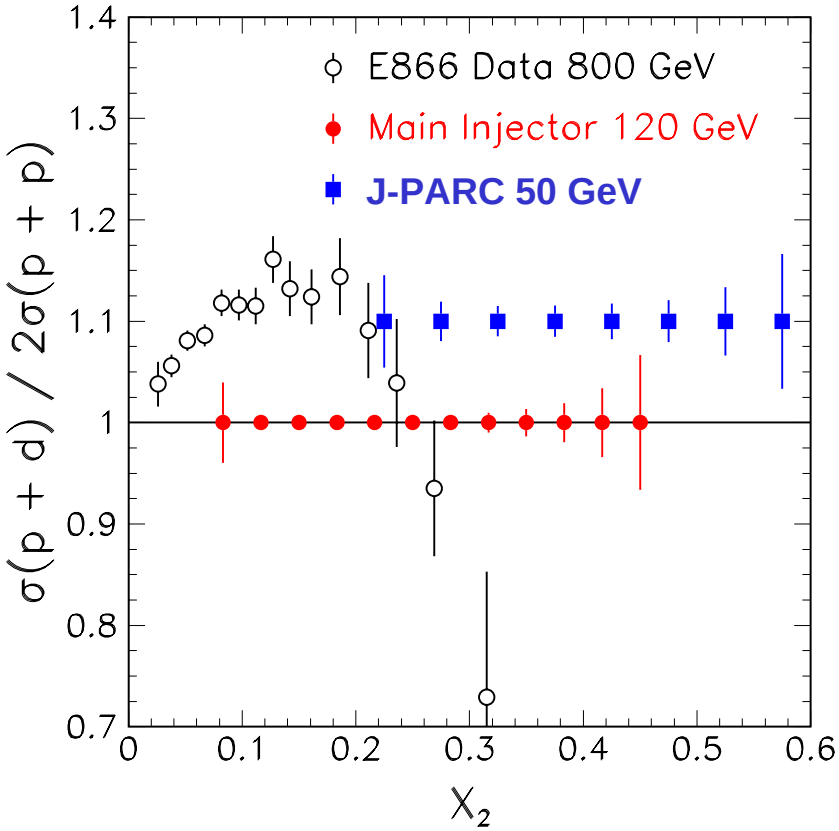
$$\int_{0}^{1} (\Delta\bar{u} - \Delta\bar{d})dx = 0.117 \pm 0.036 \text{ at } Q^2 = 10 \text{ GeV}^2$$

What's next for $\bar{d}/\bar{u}$?

$$\frac{d\sigma_{DY}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{3x_1x_2}\frac{1}{s}\sum_i e_i^2[q_i(x_1)\bar{q}(x_2)+\bar{q}(x_1)q(x_2)]$$

Intriguing $\bar{d}/\bar{u}$ behavior at large x can be studied at lower beam energies

DY cross section is 6 times larger at 120 GeV than at 800 GeV

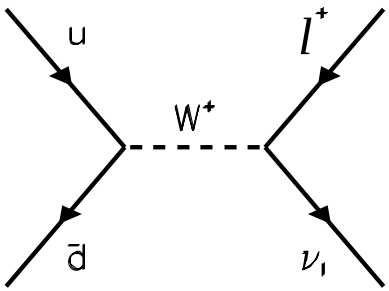


- Fermilab E-906
  (P. Reimer, D. Geesaman et al.)
  120 GeV proton beam
- J-PARC P-04
  (J. Peng, S. Sawada et al.)
  50 GeV proton beam

$\bar{d}/\bar{u}$ from W production at RHIC

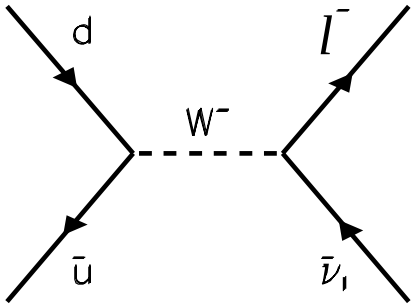
W production in $p-p$ collision (Generalized Drell-Yan)

$p+p \rightarrow W^{+}+x$



$(u+\bar{d} \rightarrow W^{+})$

$p+p \rightarrow W^{-}+x$



$(d+\bar{u} \rightarrow W^{-})$

$$R(x_F) \equiv \frac{\frac{d\sigma}{dx_F}(pp \rightarrow W^{+}X)}{\frac{d\sigma}{dx_F}(pp \rightarrow W^{-}X)} \square \frac{u(x_1)}{d(x_1)} \frac{\bar{d}(x_2)}{\bar{u}(x_2)}$$

No nuclear effects

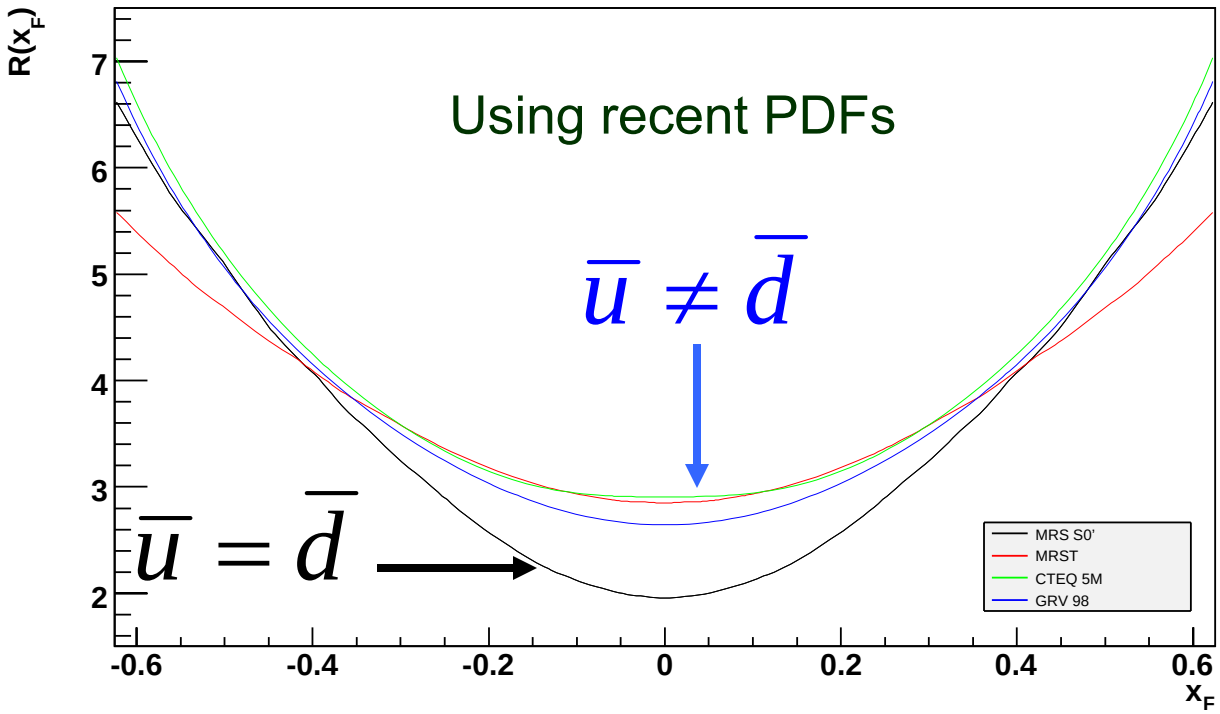
No assumption of charge-symmetry

Large Q^2 scale

Berger; Soffer; etc.

$\bar{d}/\bar{u}$ from W production at RHIC

$$R(x_F) = \frac{d\sigma/dx_F(pp \to W^+ x)}{d\sigma/dx_F(pp \to W^- x)} \quad \text{at } \sqrt{s} = 500 \text{ GeV}$$



Yang, Peng, Perdekamp, Phys. Lett. B680, 231 (2009)

A comparison with D-Y could lead to extraction of CSV effect

$$Is \;\; u_p(x) = d_n(x)? \;\; \bar{u}_p(x) = \bar{d}_n(x)? \text{ etc.}$$

Three parton distributions describe 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

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

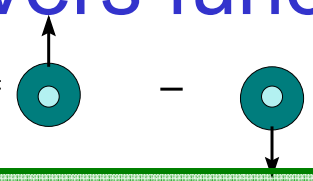
$\Rightarrow$ Three different correlations

1) Transversity

$h_{1T} =$

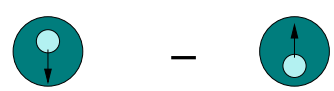
Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function

$f_{1T}^\perp =$ 

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

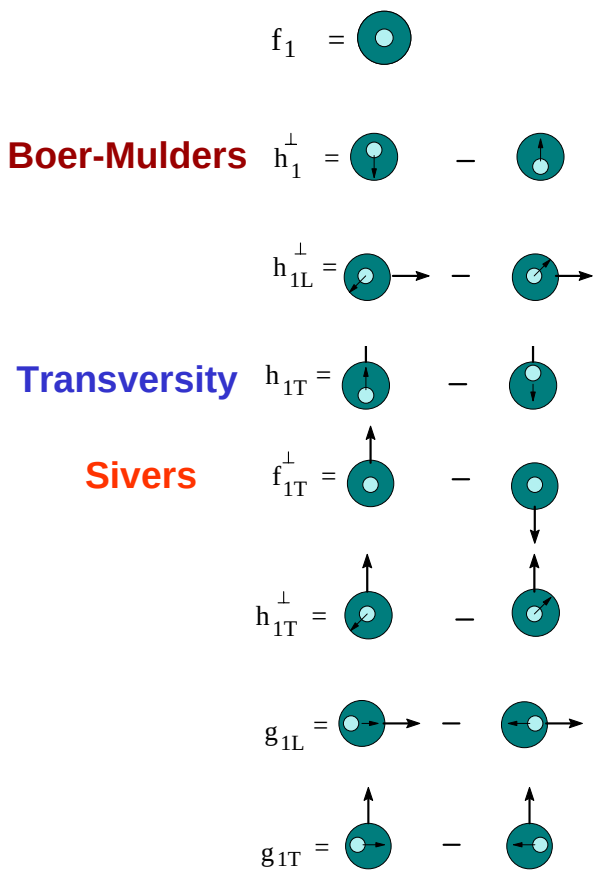
3) Boer-Mulders function

$h_1^\perp =$ 

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

Transversity and Transverse Momentum Dependent PDFs are probed in Semi-Inclusive DIS

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



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

Unpolarized

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

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

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)

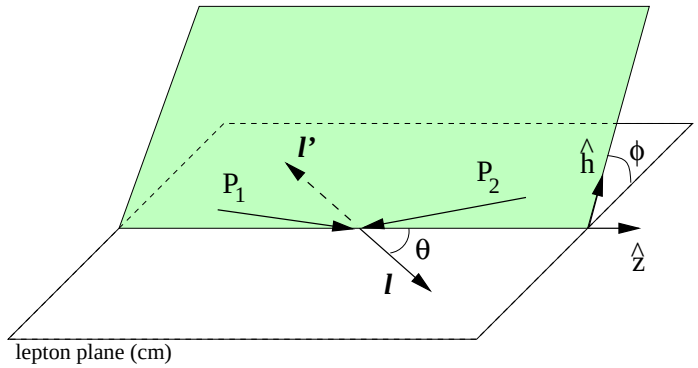
Remains to be tested experimentally!

Transverse Momentum Dependent PDFs with polarized Drell-Yan

- Ralston and Soper (NP B152 (1979) 109)
- Pire and Ralston (PR D28 (1983) 260)
- Tangerman and Mulders (PR D51 (1995) 3357)
- Boer (PR D60 (1999) 014012)
- Arnold, Metz, and Schlegel (PR D79 (2009) 034005)

$$
\begin{aligned}
\sigma_{UU} &\propto f_1 f_1 + \cos 2\phi\, h_1^\perp h_1^\perp\,, \\
\sigma_{LU} &\propto \sin 2\phi\, h_{1L}^\perp h_1^\perp\,, \\
\sigma_{TU} &\propto f_{1T}^\perp f_1 + \sin 2\phi\, h_1 h_1^\perp + \sin 2\phi\, h_{1T}^\perp h_1^\perp\,, \\
\sigma_{LL} &\propto g_{1L} g_{1L} + \cos 2\phi\, h_{1L}^\perp h_{1L}^\perp\,, \\
\sigma_{TL} &\propto g_{1T} g_{1L} + \cos 2\phi\, h_1 h_{1L}^\perp + \cos 2\phi\, h_{1T}^\perp h_{1L}^\perp\,, \\
\sigma_{TT} &\propto f_{1T} f_{1T} + g_{1T} g_{1T} + \cos 2\phi\, h_1 h_1 + \cos 2\phi\, h_1 h_{1T}^\perp + \cos 2\phi\, h_{1T}^\perp h_{1T}^\perp\,.
\end{aligned}
$$

Drell-Yan decay angular distributions



$$h_1 + h_2 \to \gamma^* + x \to l^+ + l^- + x \quad (q + \bar{q} \to \gamma^*)$$

Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

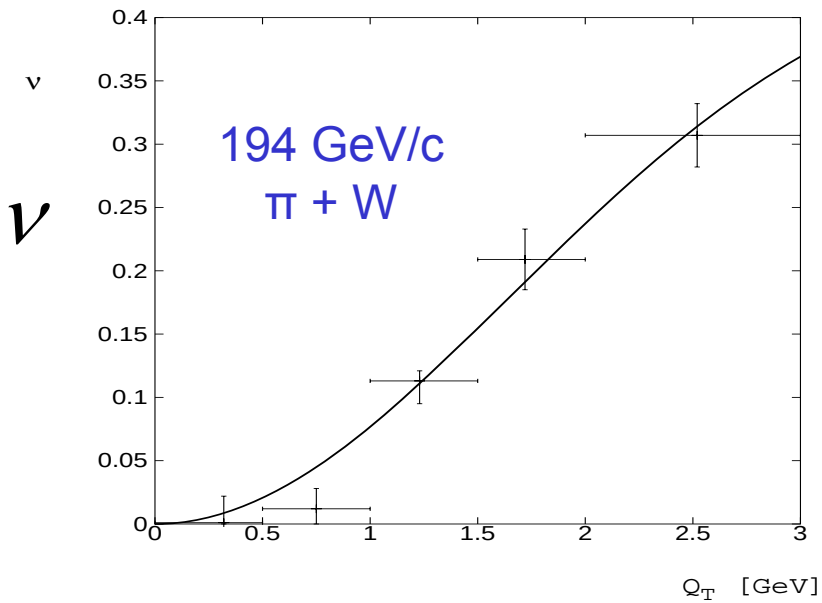
"Naive" Drell-Yan (transversely polarized γ^*, no transverse momentum) $\to \lambda = 1,\ \mu = 0,\ \nu = 0$

In general : $\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$

Boer-Mulders function $h_1^\perp$

- $h_1^\perp$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron
- $h_1^\perp$ is a time-reversal odd, chiral-odd TMD parton distribution
- $h_1^\perp$ can lead to an azimuthal $\cos(2\phi)$ dependence in Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

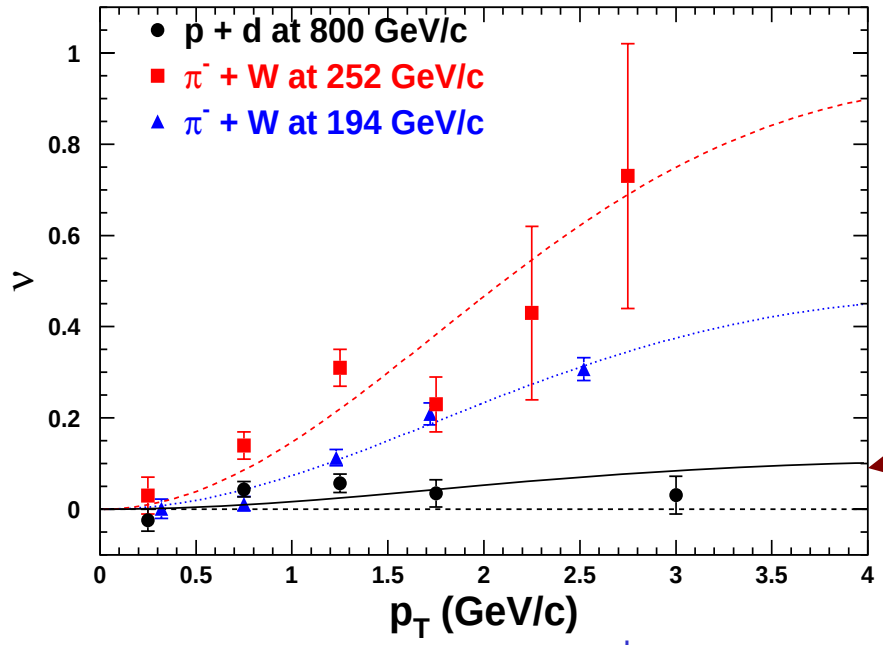


Boer, PRD 60 (1999) 014012

- Observation of large $\cos(2\Phi)$ dependence in Drell-Yan with pion beam
- $\nu \propto h_1^\perp(x_q)h_1^\perp(x_{\bar{q}})$
- How about Drell-Yan with proton beam?

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

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



Small ν is observed for p+d and p+p D-Y

With Boer-Mulders function $h_1^{\perp}$:

$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

$\nu(pd \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

Sea-quark BM functions are much smaller than valence quarks

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, arXiv:0803.1692)

Parametrization of the BM functions:

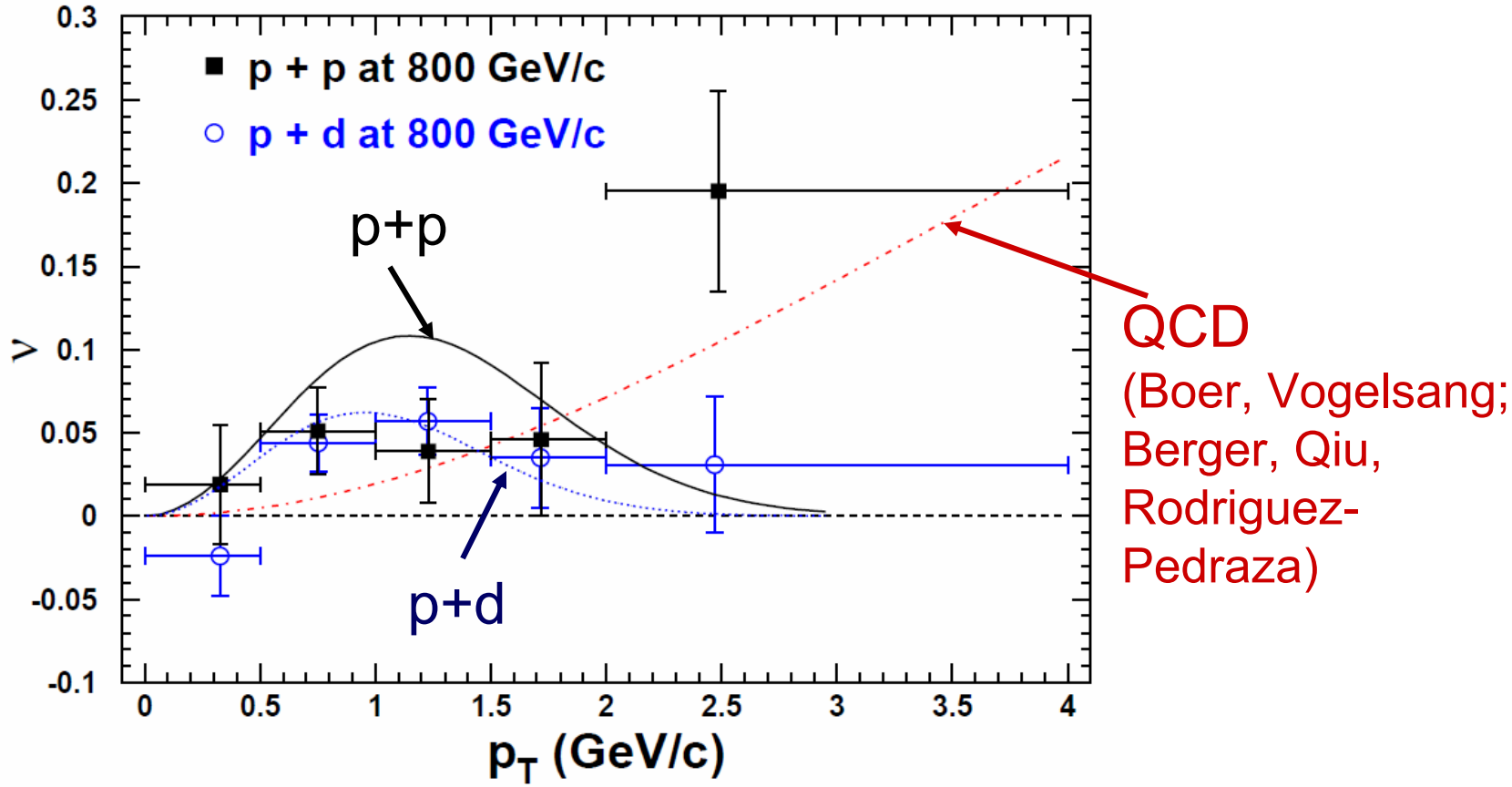
$$h_1^{\perp,q}(x, p_\perp^2) = H_q x^c (1-x) f_1^q(x) \exp(-p_\perp^2 / p_{BM}^2)$$

H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	p_{BM}^2	c	χ^2 / dof
3.99	3.83	0.91	-0.96	0.16	0.45	0.79

- H_u and H_d have the same sign and similar magnitude (in agreement with model calculations (bag-model, quark-diquark, relativistic CQM, Lattice) and the picture given by M. Burkardt)
- $H_{\bar{u}}$ and $H_{\bar{d}}$ are smaller by factor of 4 and have opposite sign

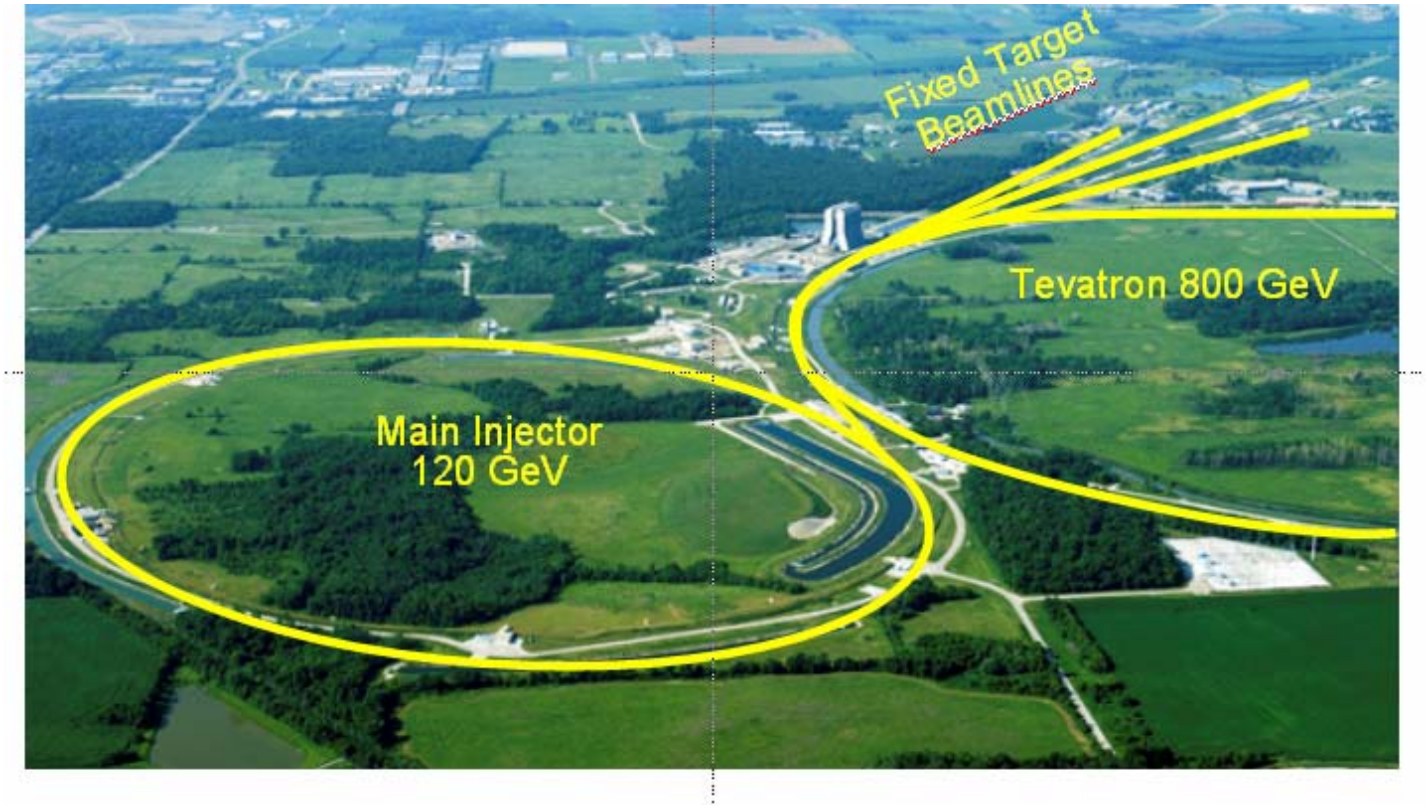
New results on cos2Φ Distribution in p+p Drell-Yan

L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001



- p+p is similar to p+d; More data at higher p_T is needed
- More data are expected soon from Fermilab E906

Fermilab E906 dimuon experiment (Geesaman, Reimer et al., expected to run ~2010-2012)

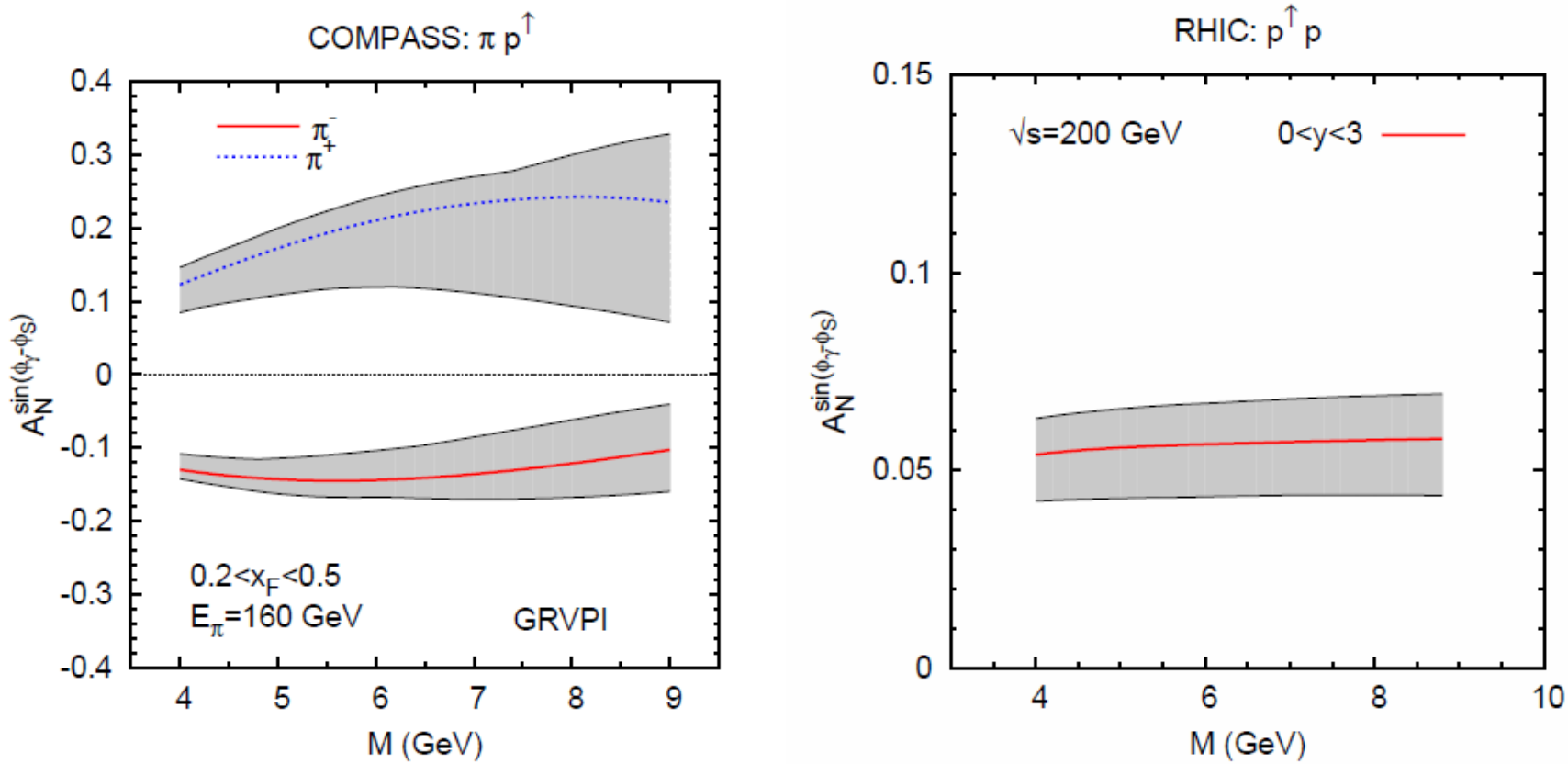


- Main goal is to measure the flavor asymmetry for the sea
- Boer-Mulders can also be studied

Future prospect for Drell-Yan experiments

- Fermilab p+p, p+d, p+A
  - Unpolarized beam and target
- RHIC
  - Doubly and singly polarized p+p collision
- COMPASS
  - π-p and π-d with polarized targets
- FAIR
  - Polarized antiproton-proton collision
- J-PARC
  - Possibly polarized proton beam and target
- JINR
  - NICA with polarized target
- IHEP
  - SPASCHARM with polarized target p-p and π-p

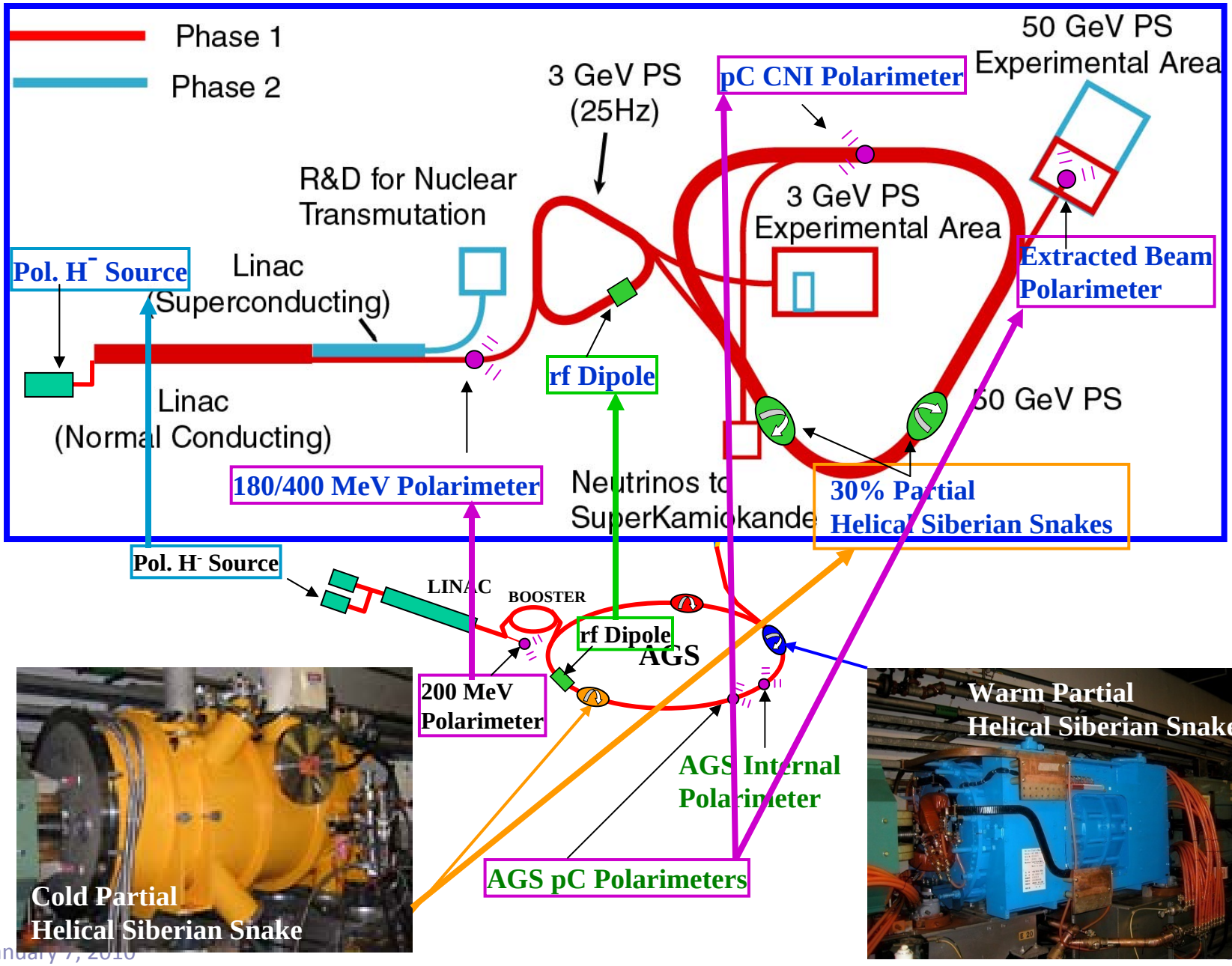
Sivers Effect in Drell-Yan



Anselmino et al., arXiv: 0901.3078

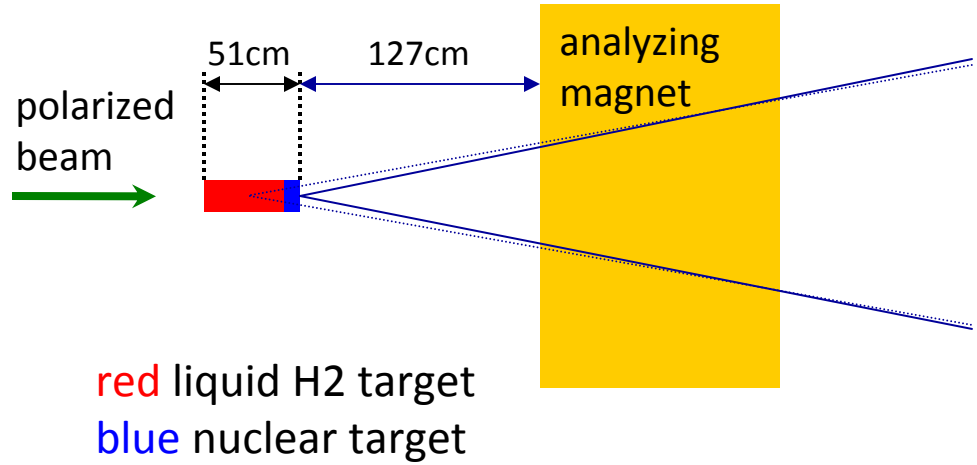
- Use Sivers distributions deduced from SIDIS
- Assume sign change from SIDIS to D-Y

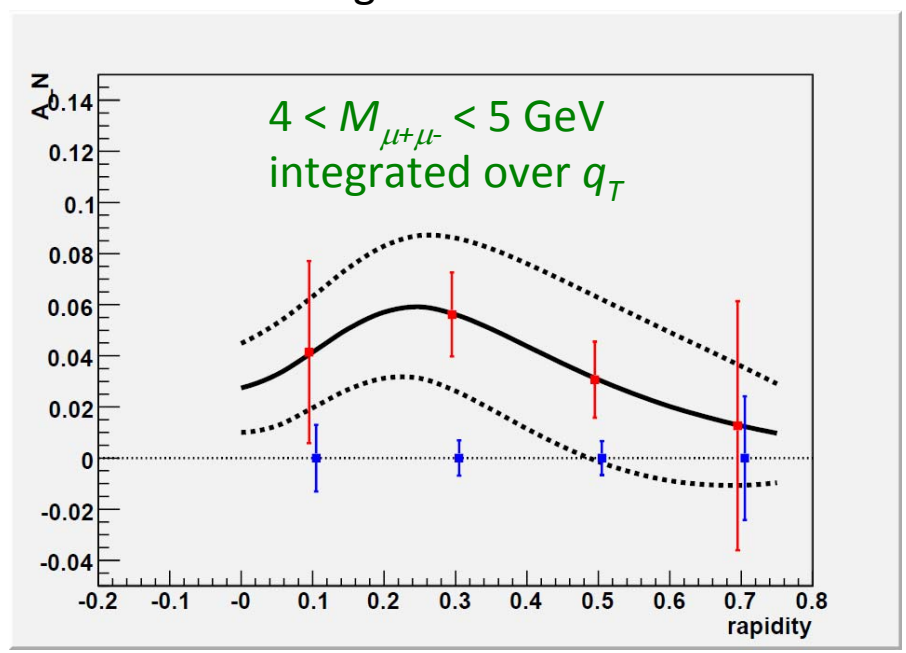
Polarized proton at J-PARC?



Polarized Drell-Yan at J-PARC

- Single transverse-spin asymmetry
  - Sivers effect measurement
- Experimental condition
  - higher beam intensity is possible for unpolarized liquid H_2 target, or nuclear target
    - 5×10^{12} ppp = $2.5\times10^{12}\times2$sec in 1pulse (5sec) possible?
  - PYTHIA simulation
    - 75% polarization beam
    - 120 days, beam on target 5×10^{17} (with 50% duty factor)
    - ~5% liquid H_2 target
      - 10000 fb^{-1} luminosity
    - ~20% nuclear target
      - 40000 fb^{-1} luminosity





Theory calculation by Ji, Qiu, Vogelsang and Yuan based on Sivers function fit of HERMES data (Vogelsang and Yuan: PRD 72, 054028 (2005))

Fixed-target experiments at RHIC

- Internal target
  - Storage cell target (polarized)
    - H_2, D_2, ^3He
    - 10^{14} / cm^2
    - HERMES
  - Cluster jet target
    - H_2, D_2, N_2, CH_4, Ne, Ar, Kr, Xe, .
    - $10^{14} – 10^{15}$ / cm^2
    - CELSIUS (Uppsala), FNAL-E835, Muenster, COSY, GSI, …
  - Pellet target
    - H_2, D_2, N_2, Ne, Ar, Kr, Xe, …
    - $10^{15} – 10^{16}$ / cm^2
    - CELSIUS (Uppsala), COSY, GSI, …

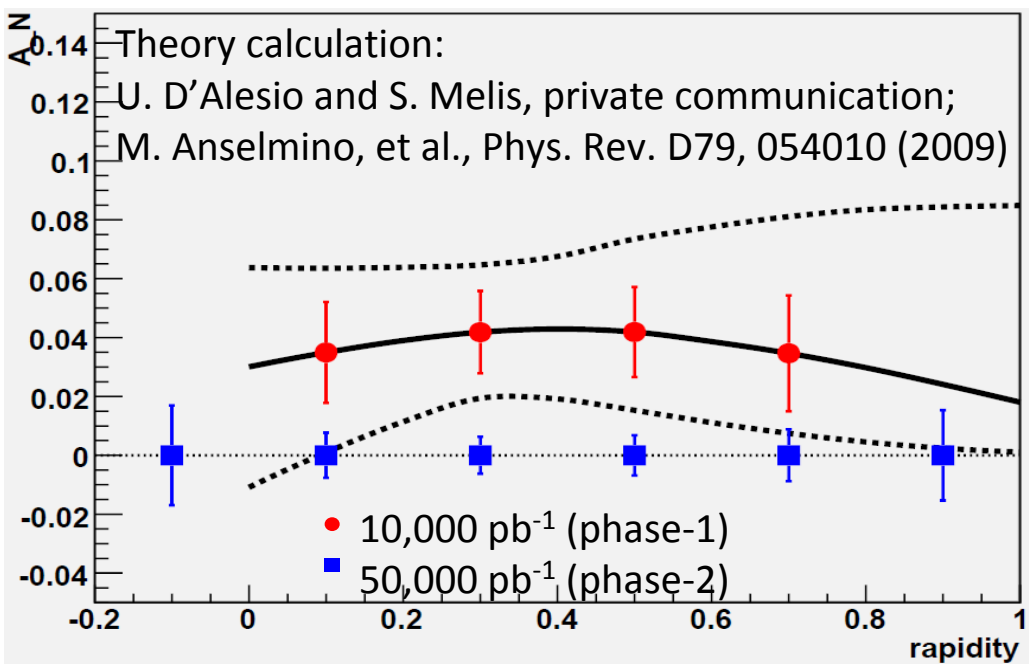
Double-spin experiment possible
Low density = low luminosity
Issue to be used in the RHIC ring

High luminosity
Only single-spin experiment possible

From Y. Goto

- Experimental sensitivity
  - Phase-1 (parasitic operation)
    - $L = 2\times10^{33}$ $cm^{-2}s^{-1}$
    - 10,000 pb-1 with 5×10^{6} s ~ 8 weeks (1 year), or 3 years of beam time by considering efficiency and live time
  - Phase-2 (dedicated operation)
    - $L = 6\times10^{34}$ $cm^{-2}s^{-1}$
    - 50,000 pb-1 with 10^{6} s ~ 2 weeks, or 8 weeks (1 year) of beam time by considering efficiency and live time

From Y. Goto

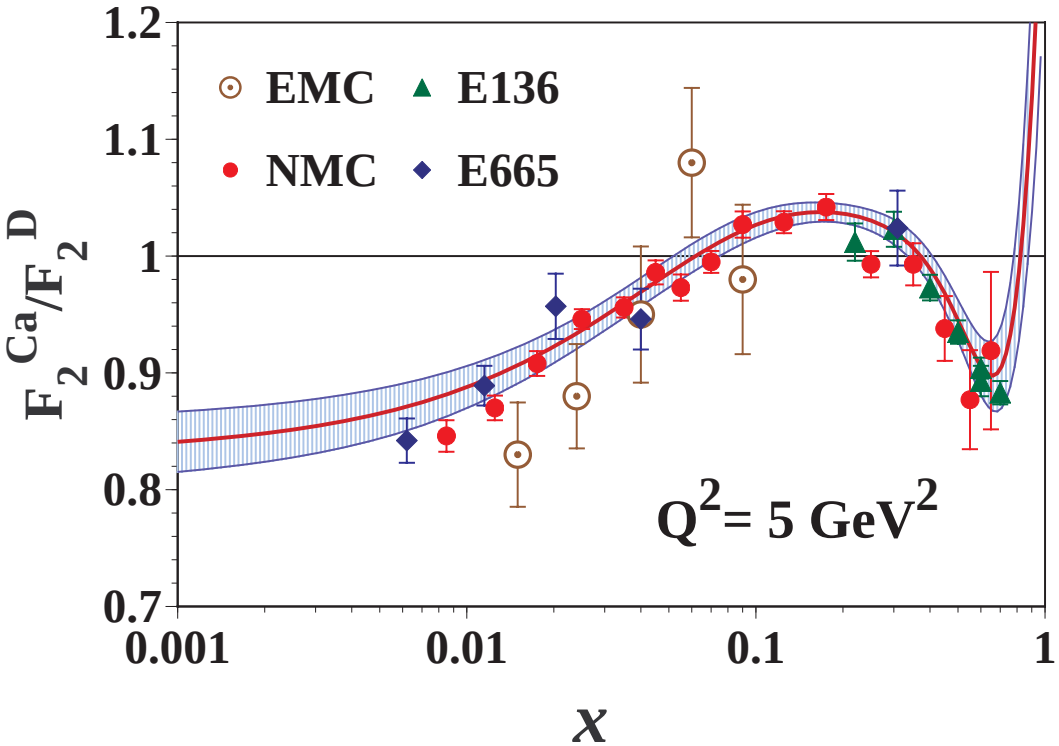


Outstanding questions to be addressed by future Drell-Yan experiments

- 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

Modification of Parton Distributions in Nuclei

EMC effect observed in DIS

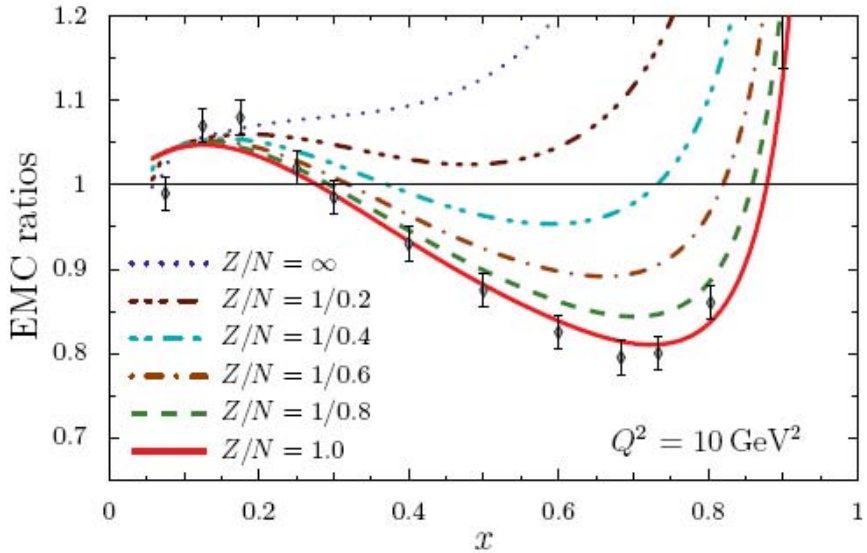


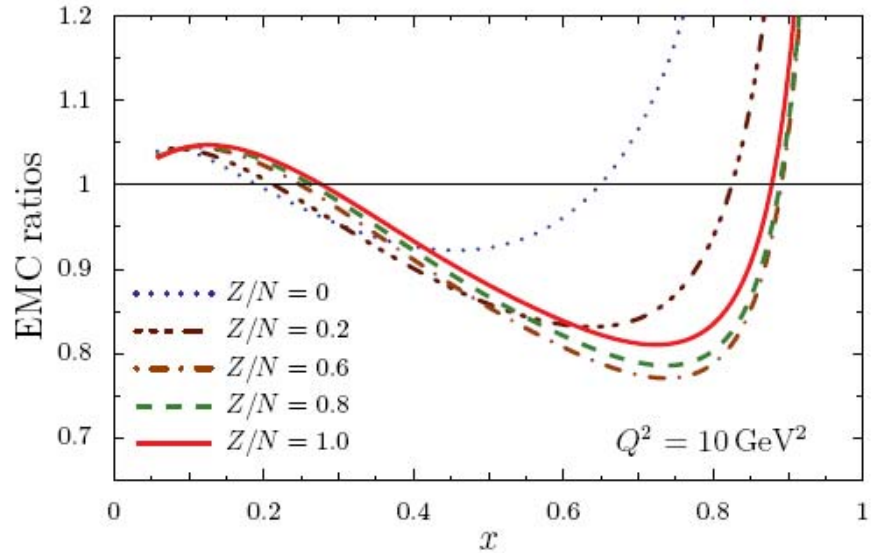
(Ann. Rev. Nucl. Part. Phys., Geesaman, Saito and Thomas)

F_2 contains contributions from quarks and antiquarks

How are the antiquark distributions modified 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

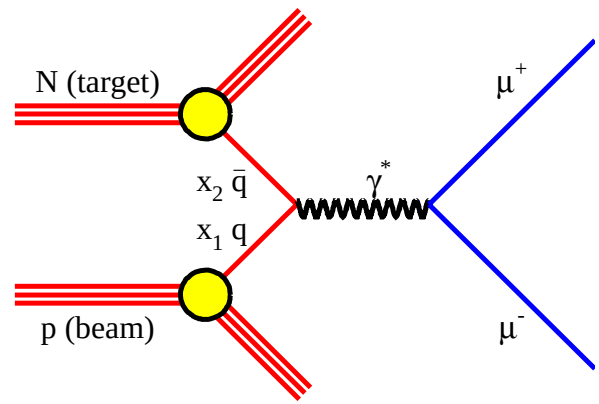
Cloet, Bentz, and Thomas, arXiv:0901.3559

Is $\bar{d}/\bar{u}$ asymmetry also modified in nuclei?

Can one measure $\bar{d}/\bar{u}$ in nuclei?

The Drell-Yan Process:

$$pN \rightarrow \mu^+ \mu^- X$$



Drell-Yan ratios for p-A /p-d :

$$\frac{2\sigma^{pA}}{A\sigma^{pd}} \approx \frac{2}{A}\frac{Z + N\,\bar{d}/\bar{u}}{1+\bar{d}/\bar{u}}$$

Assuming dbar/ubar = 1.5 for the nucleons at x=0.15, then the above ratios are:

1.0 for ^{40}Ca, 1.042 for ^{208}Pb

Can probably be measured at Fermilab E906

Nuclear modification of spin-dependent PDF?

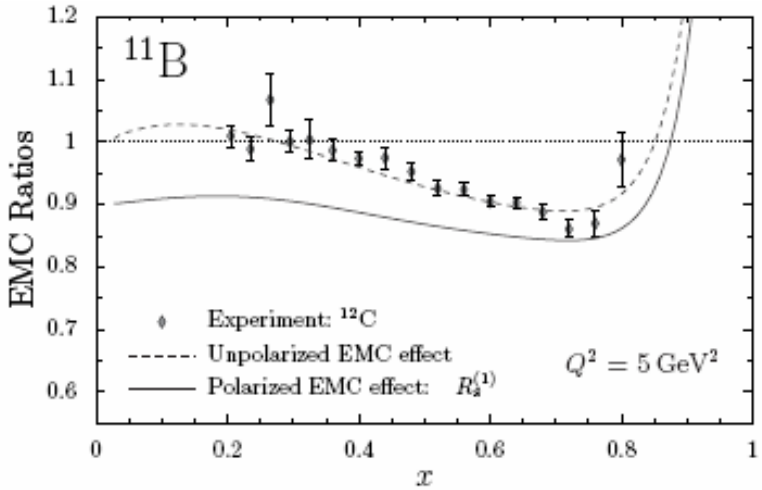


Figure 7: EMC ratios for ^{11}B. The experimental data refer to ^{12}C.

EMC effect for $g_1(x)$

Bentz, Cloet, Thomas et al., arXiv:0711.0392

Remains to be tested by experiments

Measure the nuclear modification of Boer-Mulders functions with Drell-Yan ?
(only unpolarized Drell-Yan is required)

Summary

- Unique information on hadron structures has been obtained with dilepton production experiments using hadron beams.
- On-going and future dilepton production experiments at various hadron facilities can address many important unresolved issues in the spin and flavor structures of nucleons and nuclei.