Probing quark structures of nucleons and nuclei with the Drell-Yan process

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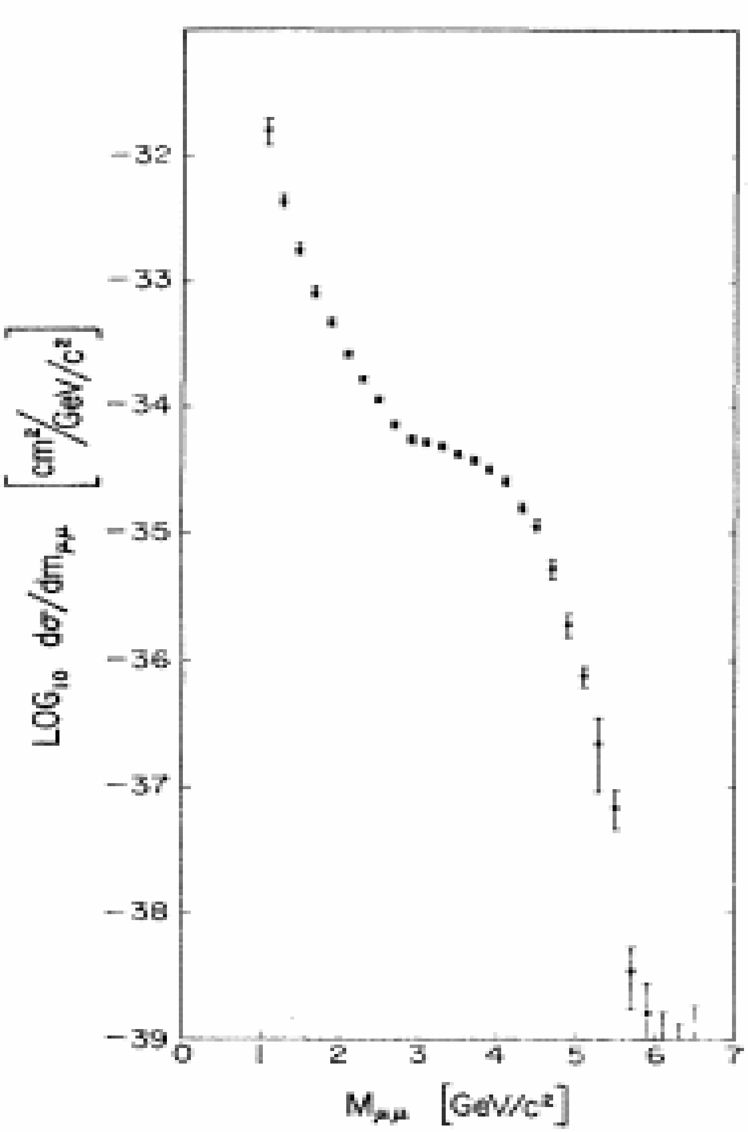
Outline

- Brief historical review
- Recent highlights of Drell-Yan experiments
- Future prospect for Drell-Yan experiments at Fermiab, CERN, RHIC, GSI, J-PARC, etc.

First Dimuon Experiment



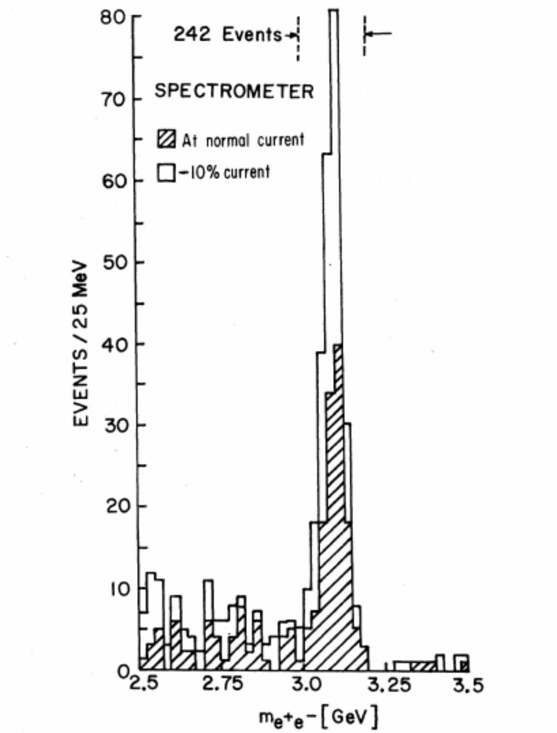
$p + U \to \mu^+ + \mu^- + X$ 29 GeV proton

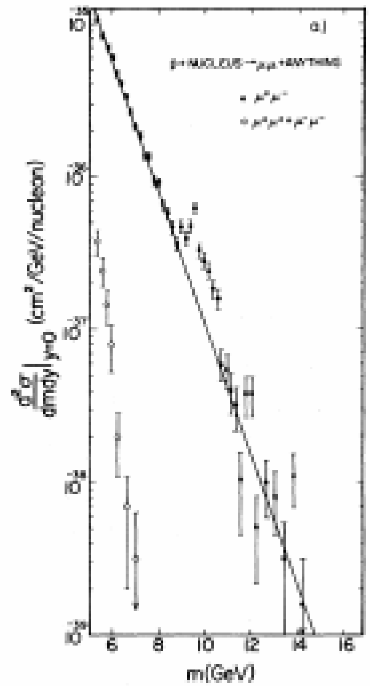
Lederman et al. PRL 25 (1970) 1523

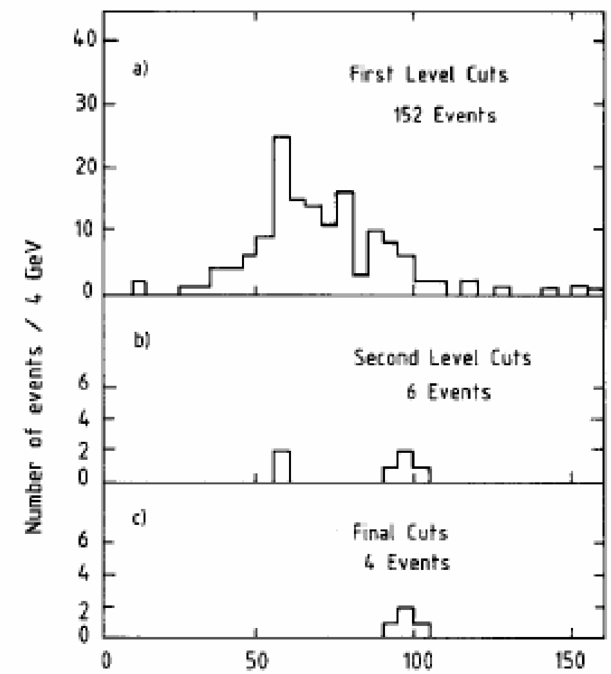
- Experiment originally designed to search for neutral weak boson (Z^0)
- Missed the J/Ψ signal !

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

$J/\Psi \rightarrow e^+e^-$ $\quad\quad$ $\Upsilon \rightarrow \mu^+\mu^-$ $\quad\quad$ $Z^0 \rightarrow e^+e^-$





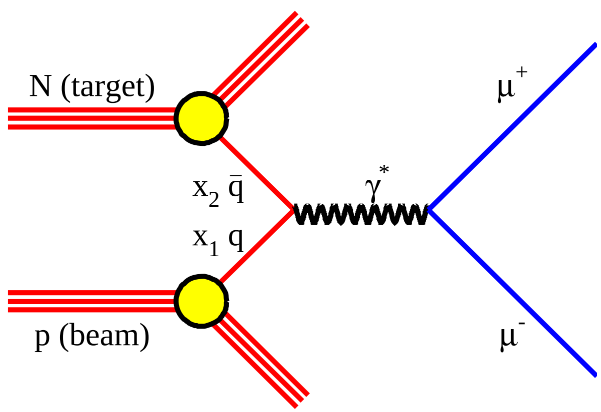


The Drell-Yan Process

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.

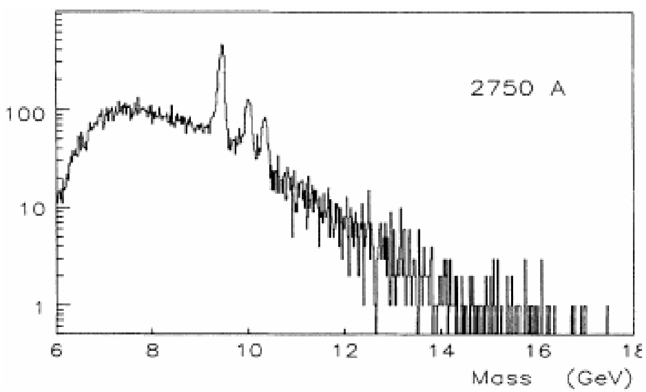


$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2) \right]$$

Lepton-pair production also provides unique information on parton distributions

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

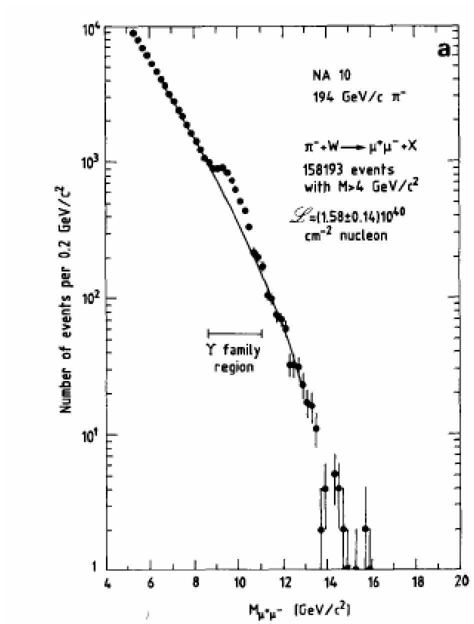
800 GeV/c



Probe antiquark distribution in nucleon

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

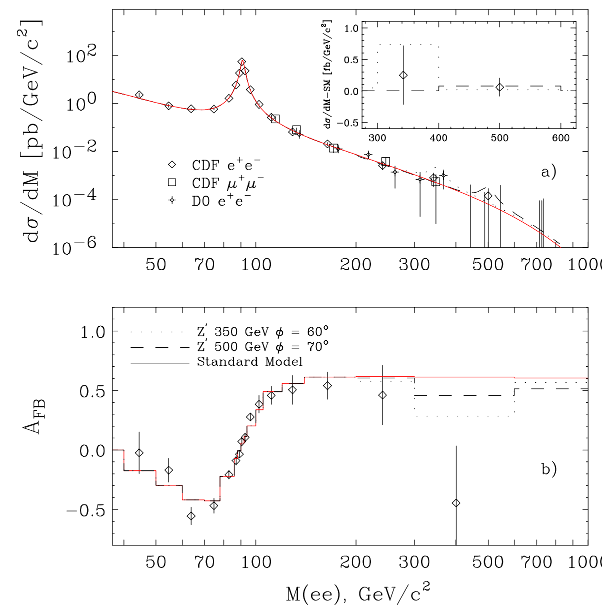
194 GeV/c



Probe antiquark distribution in pion

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

1.8 TeV

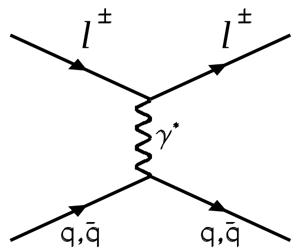


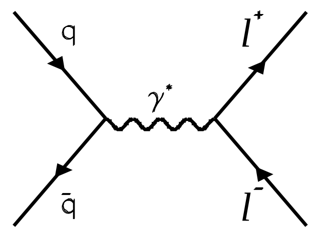
Probe antiquark distributions in antiproton

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

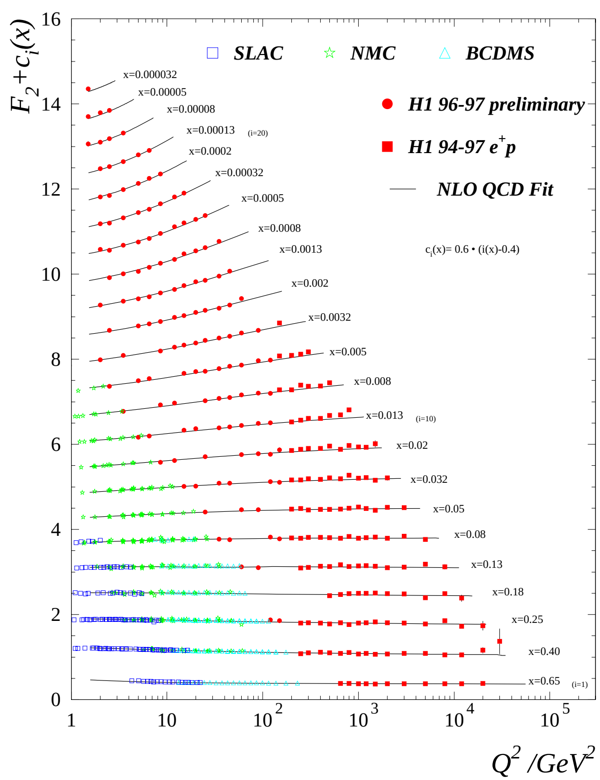
Complimentality between DIS and Drell-Yan

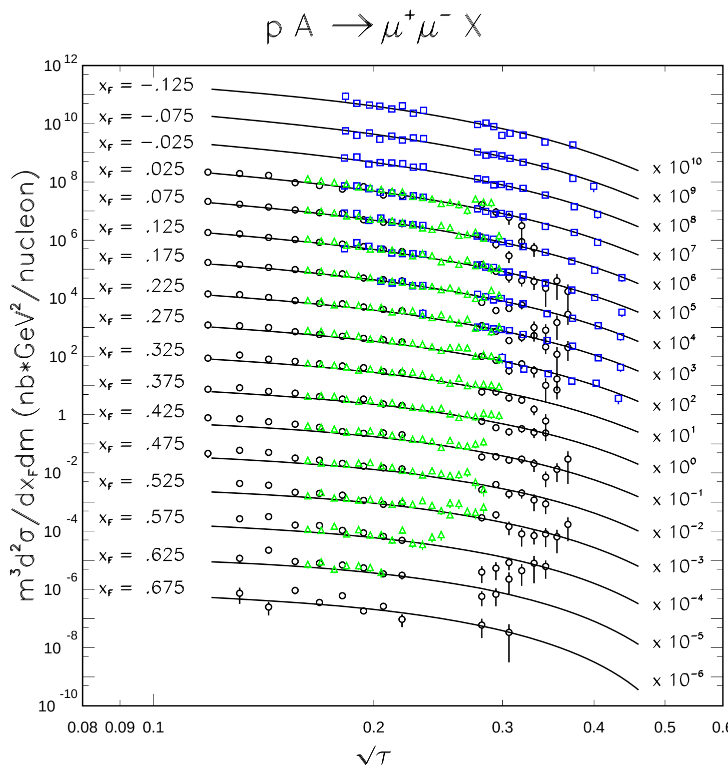
DIS





Drell-Yan





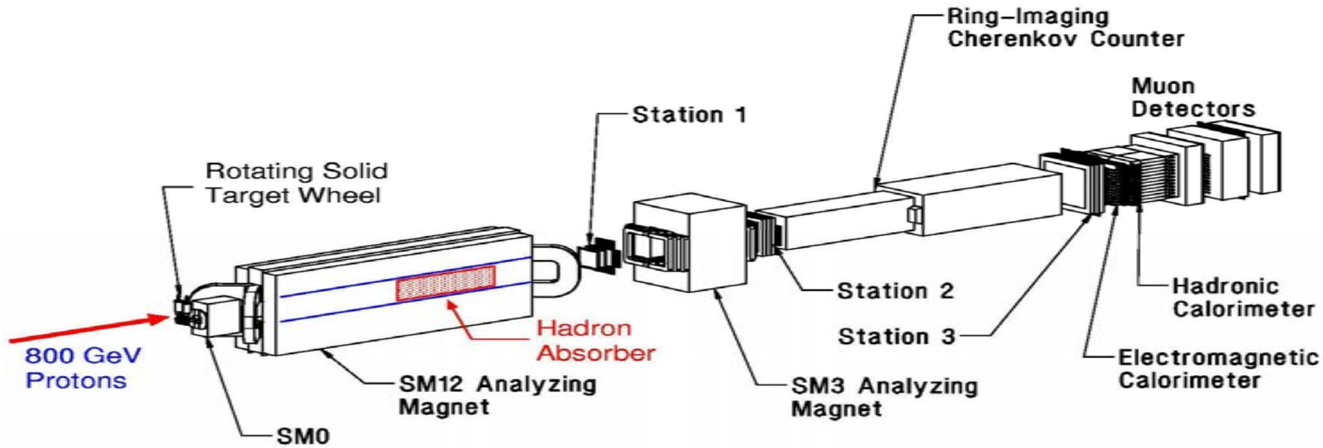
McGaughey, Moss, JCP,

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 (factorization, universality)

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 2010-2013)
   "Drell-Yan with the FNAL Main Injector"
5) RHIC LOI (proposed in 2010)
   "Polarized Drell-Yan with Internal Target"

Physics results from Fermilab dimuon experiments

1) Drell - Yan process :

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

2) Quarkonium production :

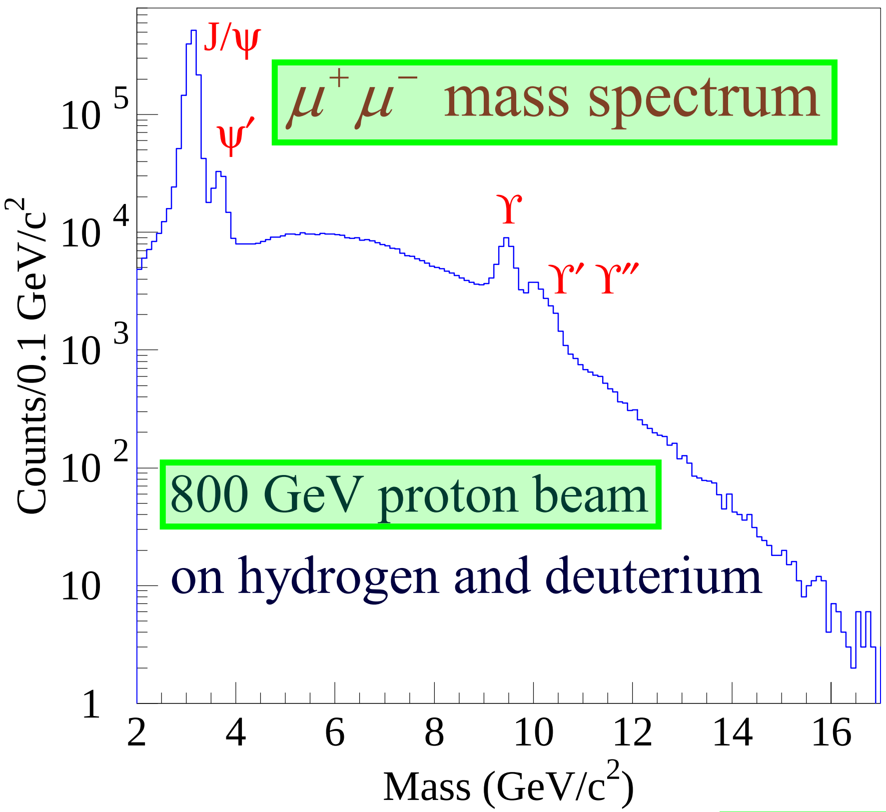
- Pronounced nuclear dependence
- Production mechnism and polarizations
- Gluon distributions in the nucleons

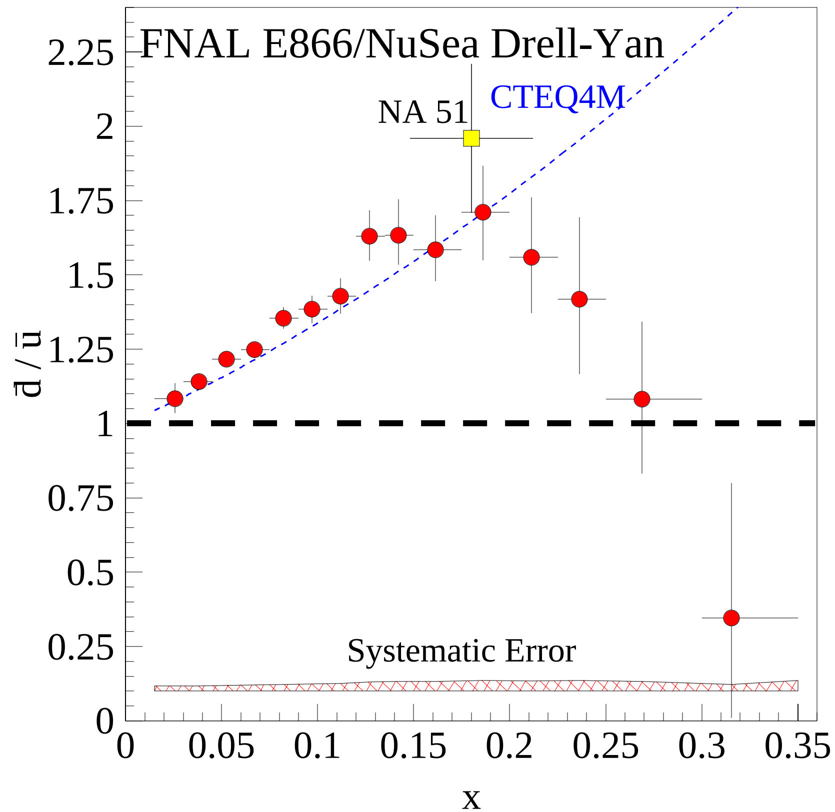
3) Heavy quark production :

- Open charm production
- B-meson production

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

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

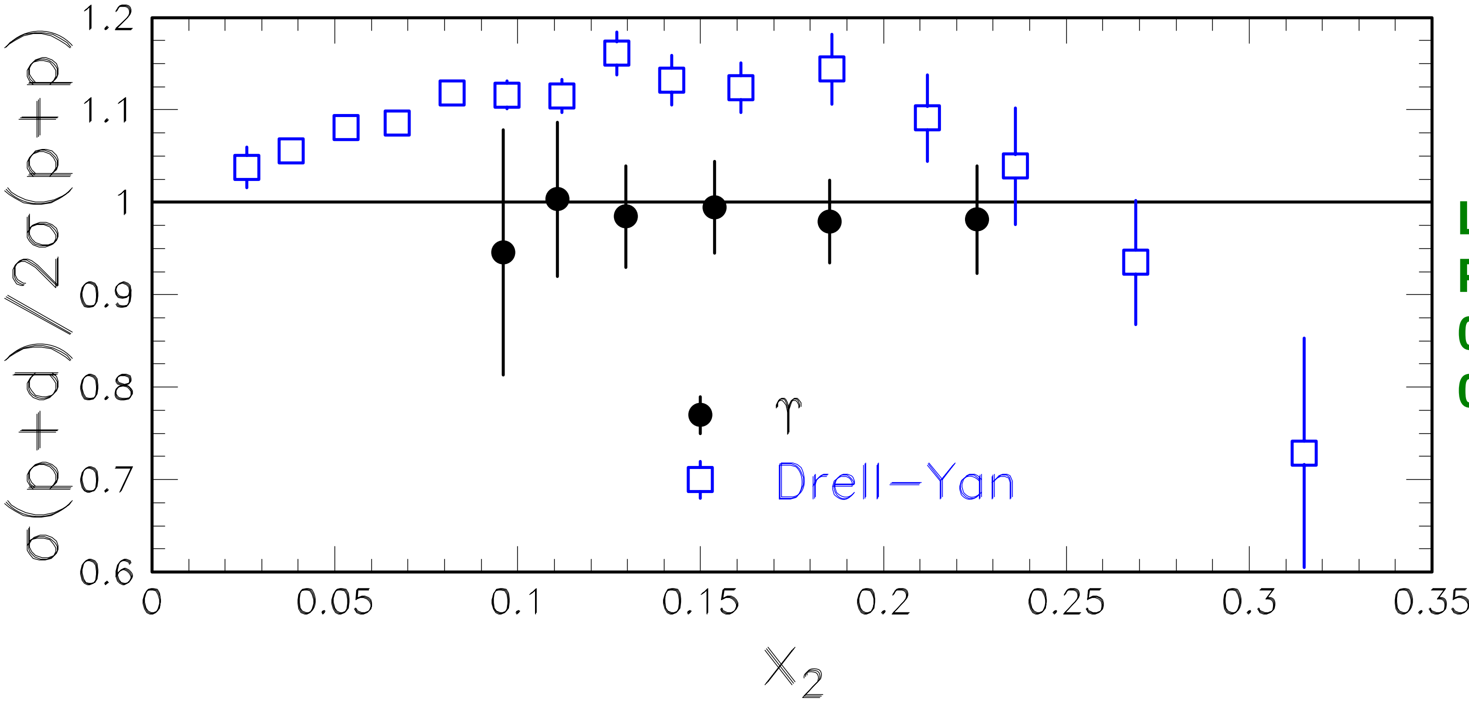




at $x_1 > x_2$: Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \approx \frac{1}{2}\left(1+\bar{d}(x_2)/\bar{u}(x_2)\right)$

Gluon distributions in proton versus neutron?

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



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

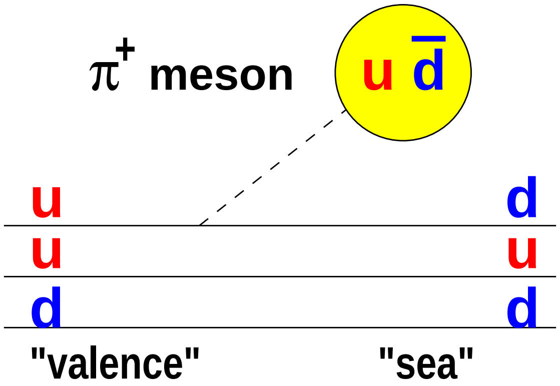
$$Drell-Yan: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+\bar{d}(x)/\bar{u}(x)]/2$$

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

Gluon distributions in proton and neutron are very similar

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

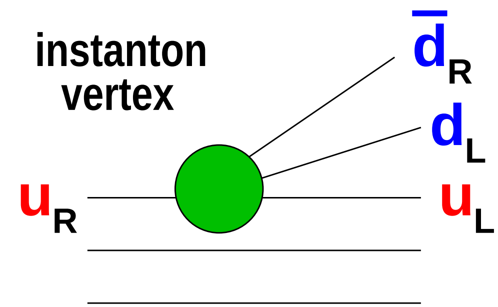
Meson Cloud Models



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))

These models also have implications on

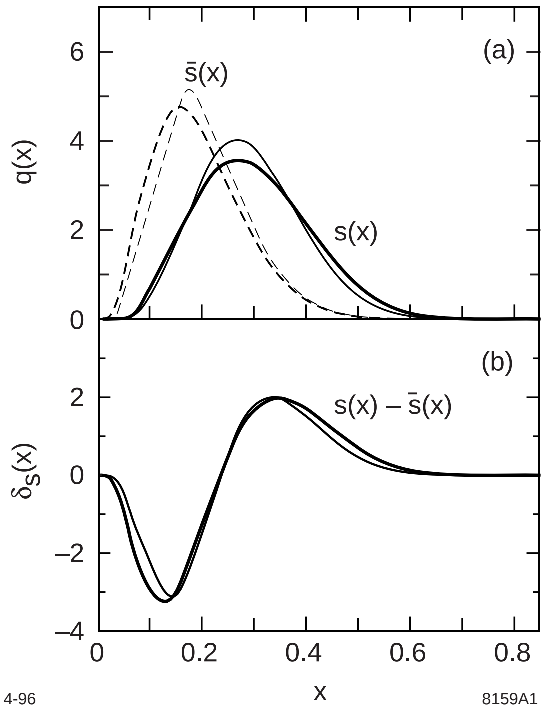
- asymmetry between $s(x)$ and $\bar{s}(x)$
- flavor structure of the polarized sea

Meson cloud has significant contributions to sea-quark distributions

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

Meson cloud model

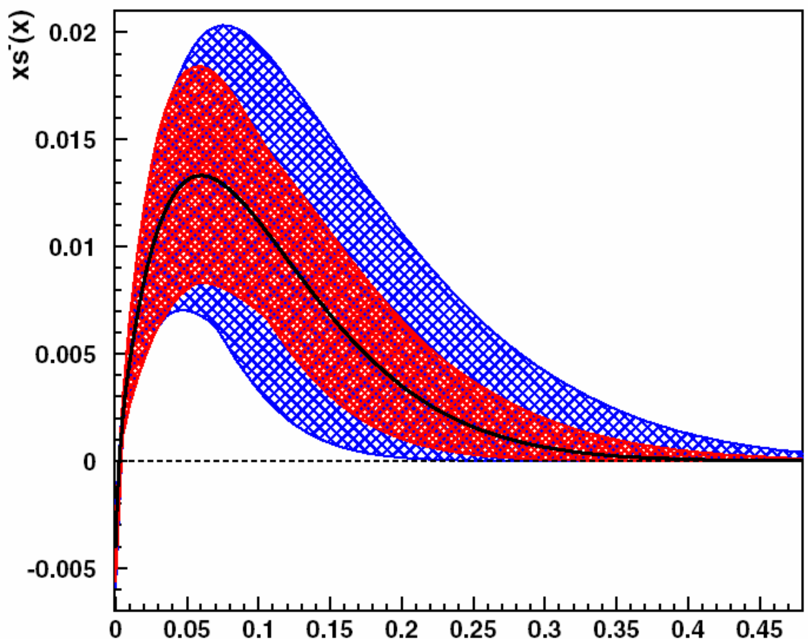
$$p \rightarrow K^+ \Lambda$$
$$(u\bar{s})\,(uds)$$



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

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

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

- 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

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

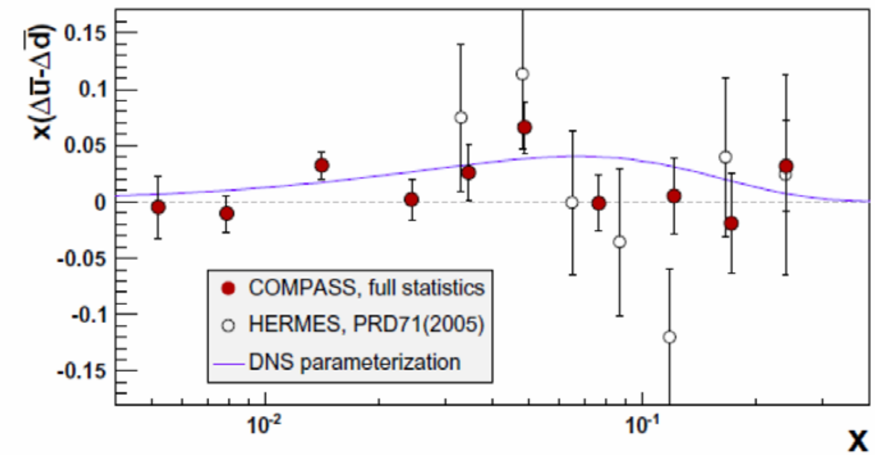
Is $\Delta\bar{u} = \Delta\bar{d}$?

- 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)

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

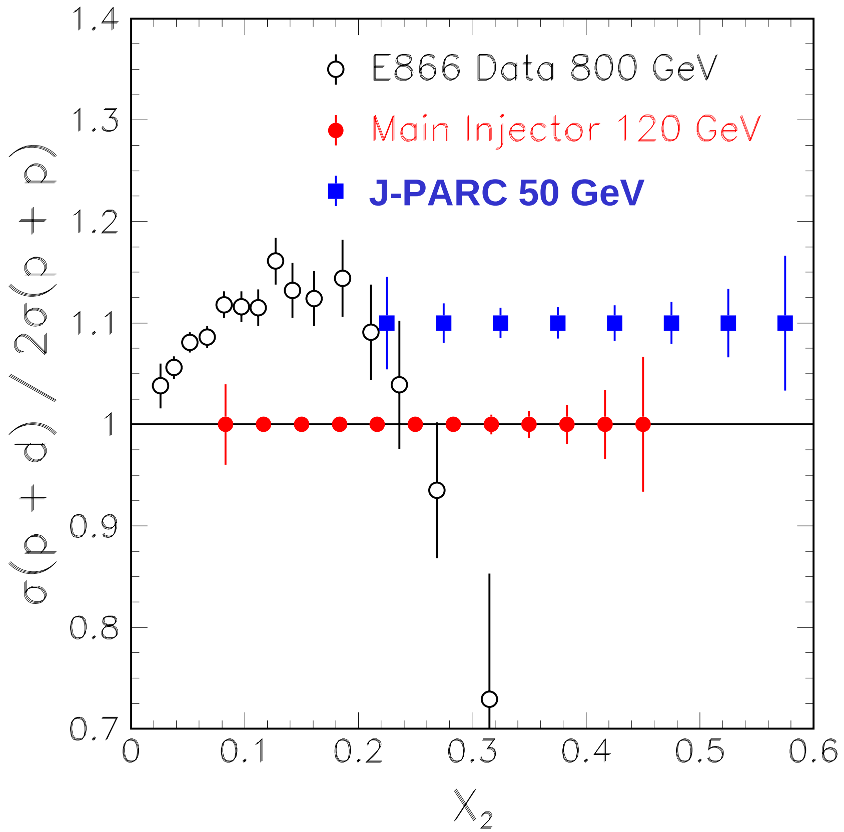
More results expected from JLab and RHIC-spin

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

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

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

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

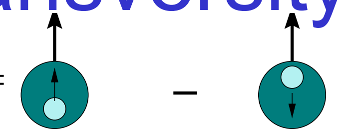
$\vec{s}_{\perp}^{q}$

3) Quark transverse momentum

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

⇒ 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

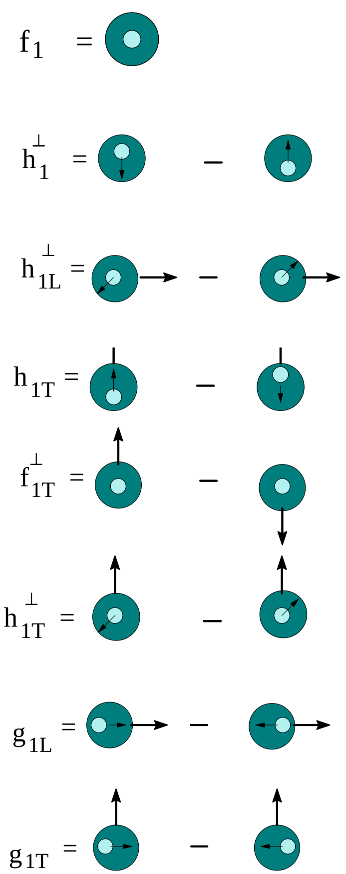
$h_{1}^{\perp} =$  –

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

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

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

Boer-Mulders | **Transversity** | **Sivers**



Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

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

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

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

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

Polarzied beam and target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

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

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)

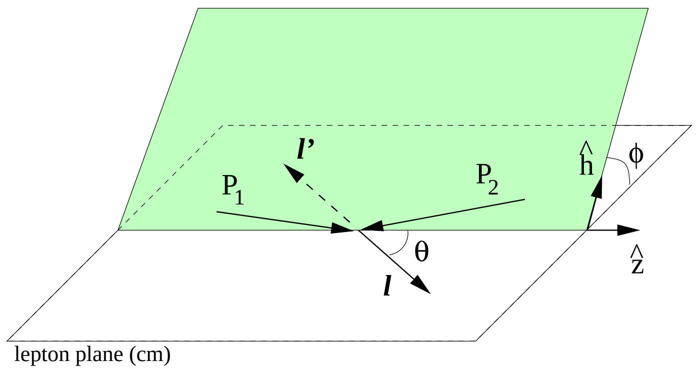
Remains to be tested experimentally!

A variety of novel parton distribution functions can be probed with polarized Drell-Yan

- Ralston and Soper (NP B152 (1979) 109) (Transversity with D-Y)
- 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



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:

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

Lam-Tung relation (C.S. Lam and Wu-ki Tung): $1-\lambda=2\nu$

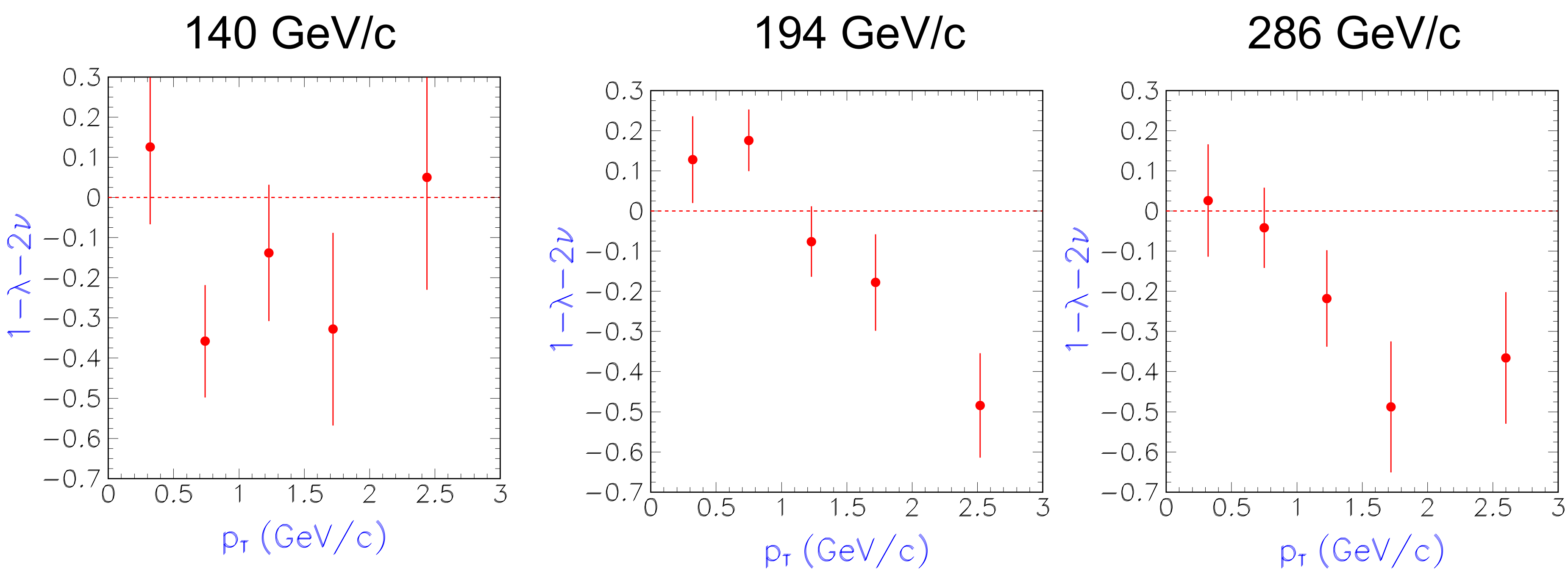
– Reflect the spin-1/2 nature of quarks

(analog of the Callan-Gross relation in DIS)

– Insensitive to QCD - corrections

Decay angular distributions in pion-induced Drell-Yan

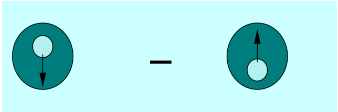
Is the Lam-Tung relation violated?



Data from NA10 (Z. Phys. 37 (1988) 545)

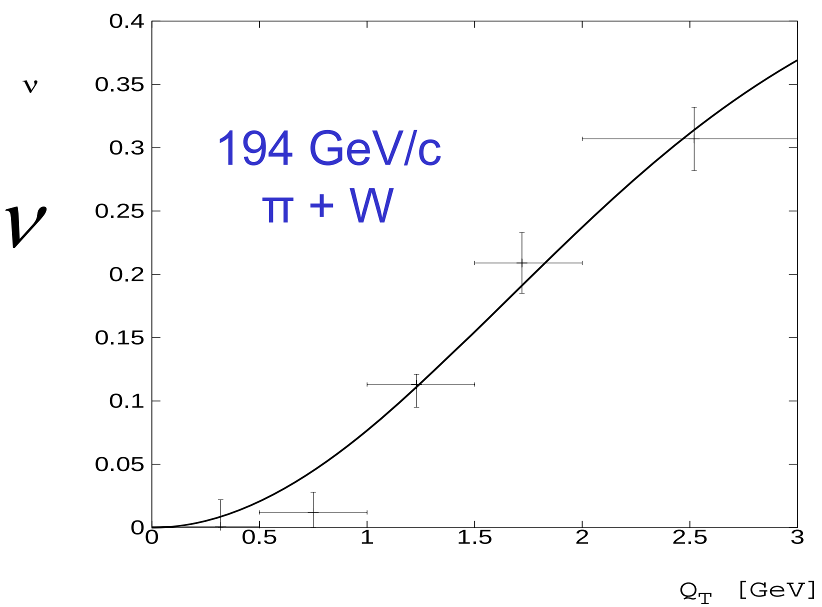
Violation of the Lam-Tung relation suggests new mechanisms with non-perturbative origin

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(2ϕ) dependence in Drell-Yan

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

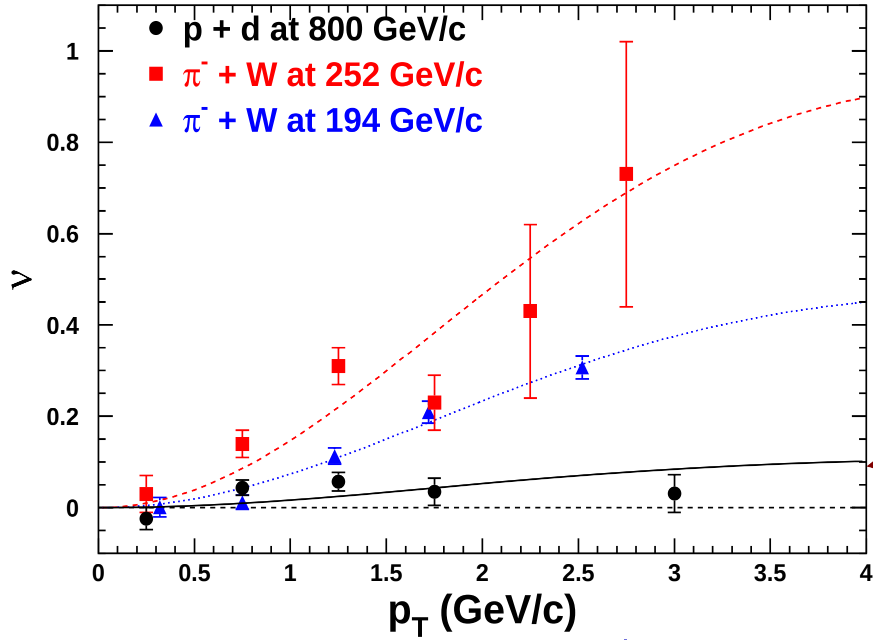


Boer, PRD 60 (1999) 014012

- Observation of large cos(2Φ) 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 $h_1^{\perp}$:

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

$\nu(pd \to \mu^+\mu^- X) \sim$ [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:

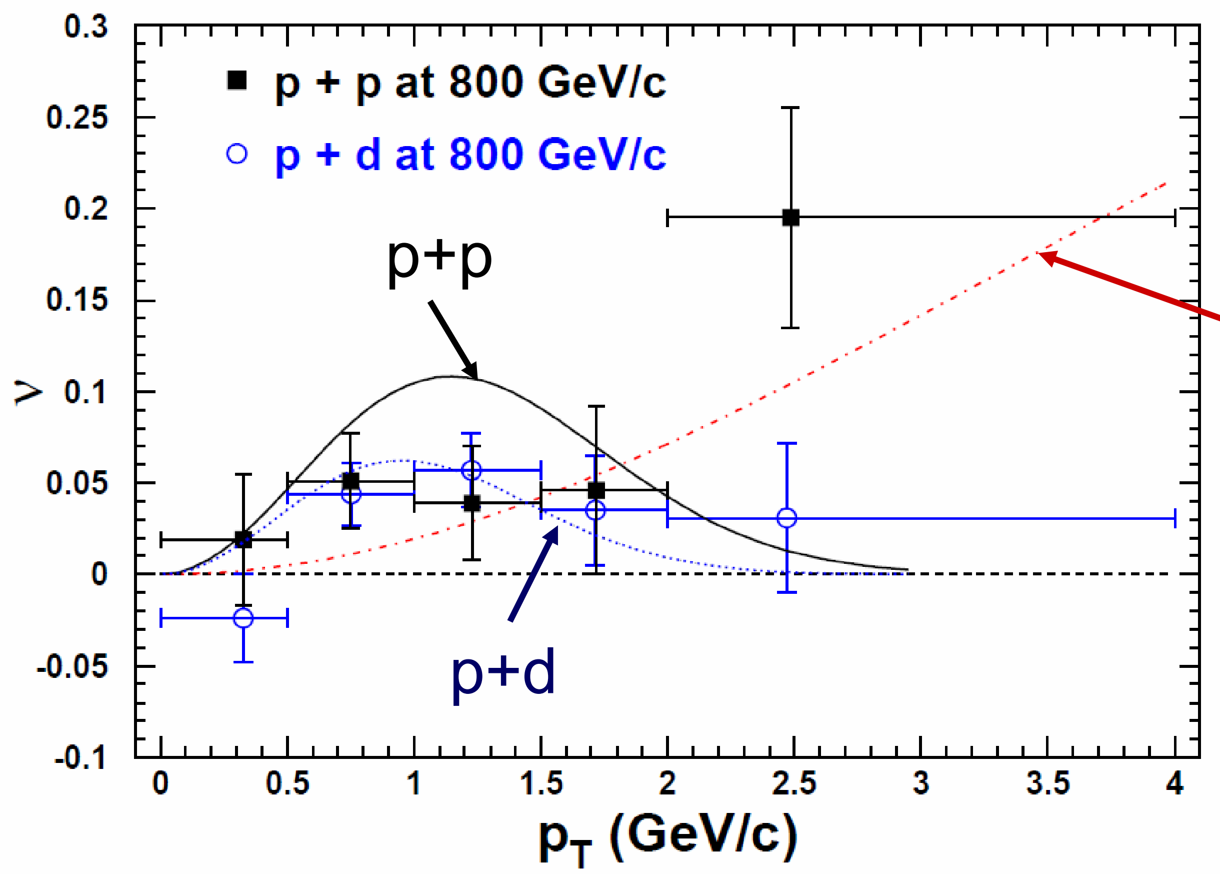
$$h_1^{\perp,q}(x, p_\perp^2) = H_q x^c (1-x) f_1^q(x) \exp(-p_\perp^2 / p_{BM}^2)$$

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

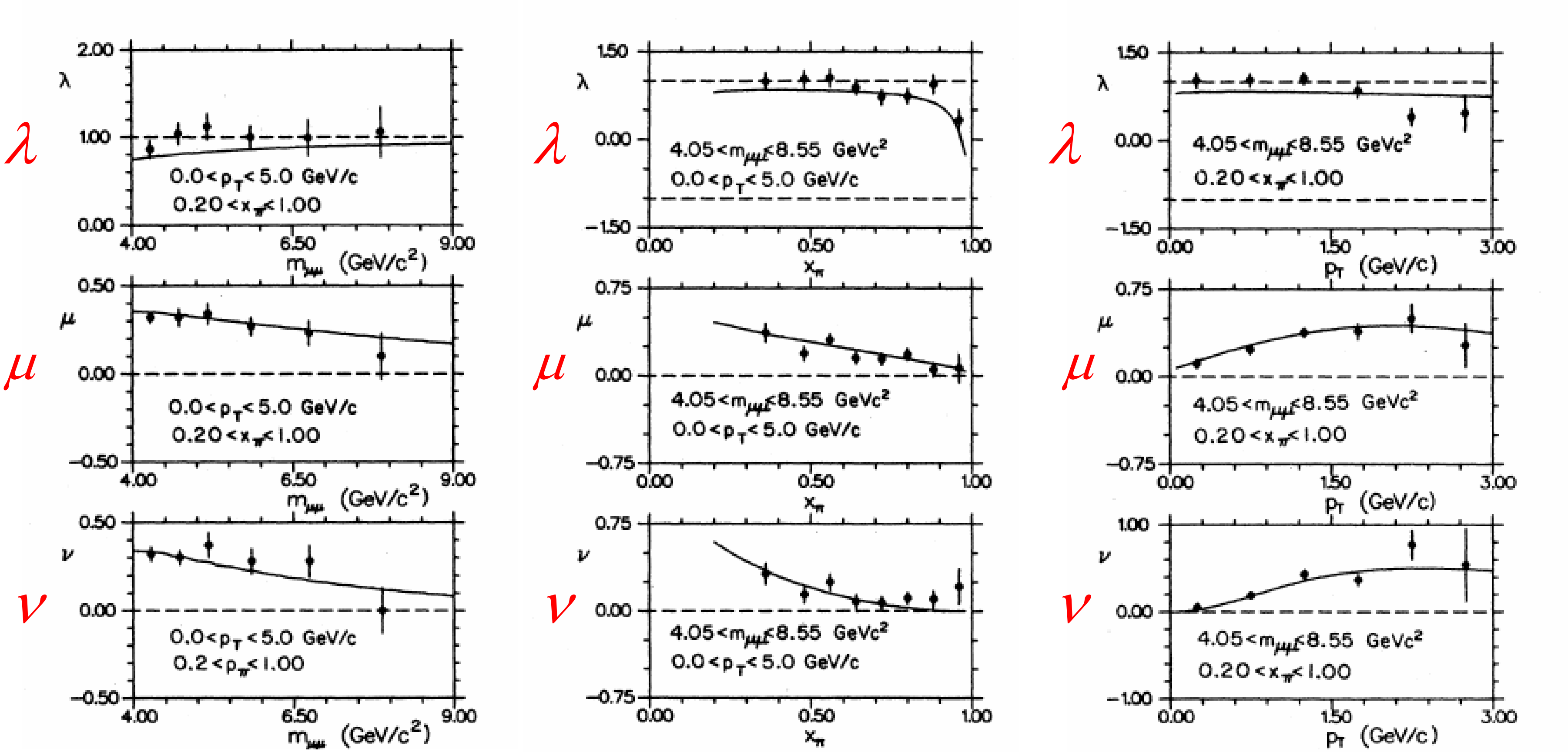


QCD
(Boer, Vogelsang;
Berger, Qiu,
Rodriguez-
Pedraza)

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

Decay angular distributions in pion-induced Drell-Yan

E615 Data 252 GeV $\pi^- + W$ Phys. Rev. D 39 (1989) 92



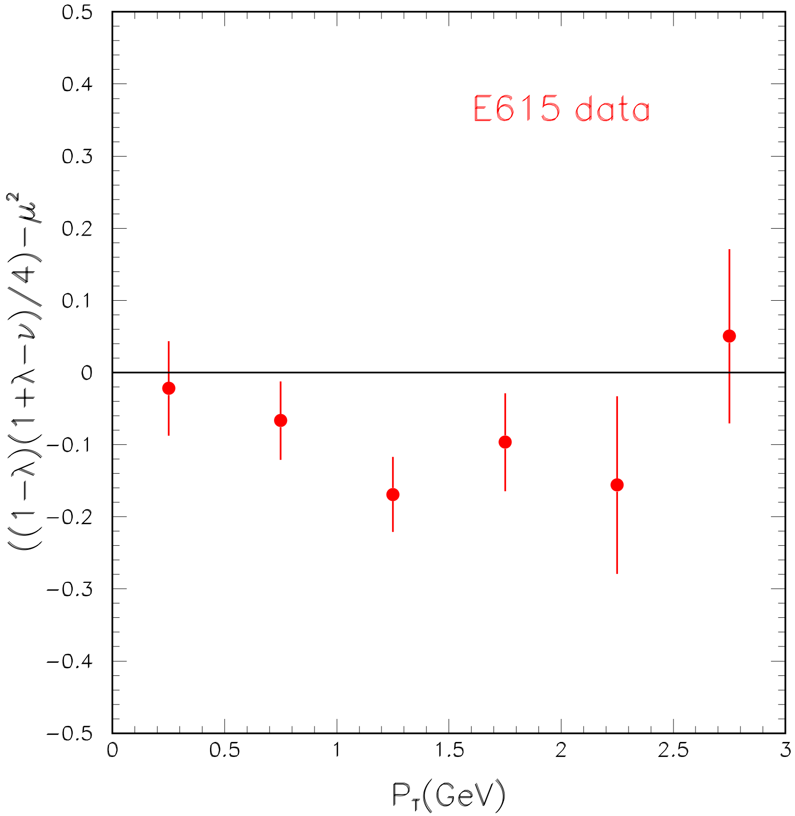
$m_{\mu\mu}(\text{GeV/c}^2)$ x_π $p_T\,(\text{GeV/c})$

$\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$ and they vary with $m_{\mu\mu}$, p_T, and x_π

$\mu^2 \leq (1-\lambda)(1+\lambda-\nu)/4$ predicted by O. Teryaev based on positivity

Is the $\mu^2 \le (1-\lambda)(1+\lambda-\nu)/4$ inequality valid?

$$(1-\lambda)(1+\lambda-\nu)/4-\mu^2 \ge 0\,?$$

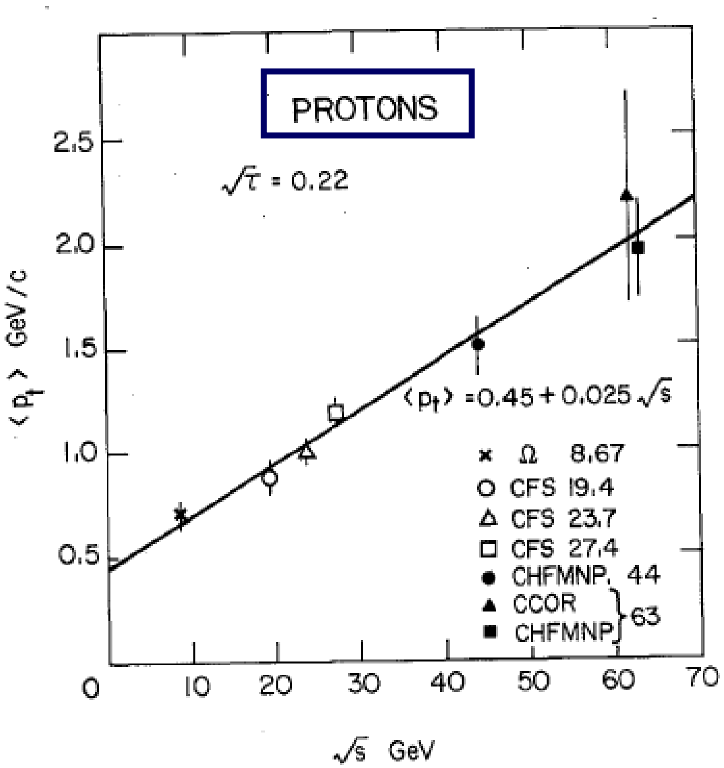


The inequality appears to be violated!

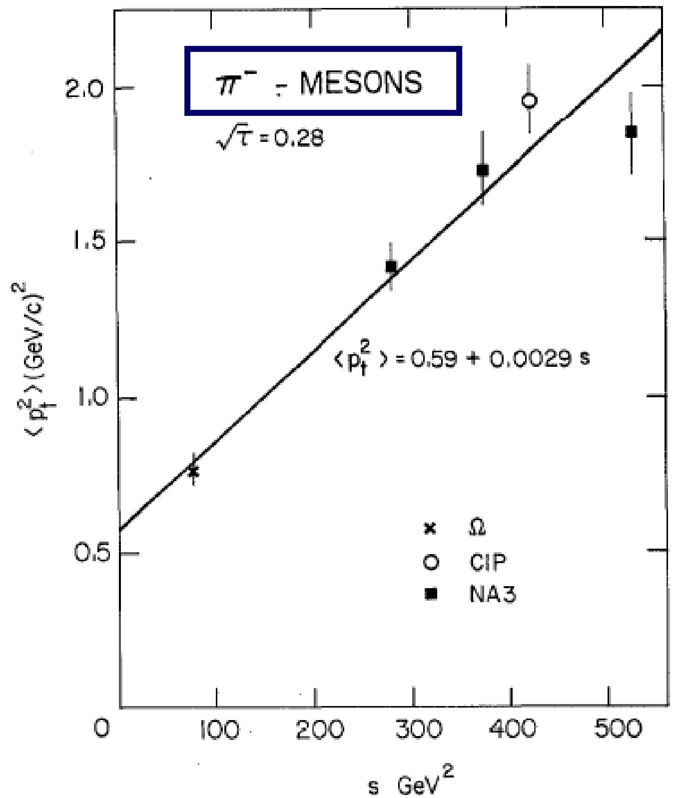
Our knowledge of D-Y azimuthal angular dependence is still incomplete

Intrinsic k_T distribution from Drell-Yan

$$\langle p_T \rangle = 0.45 + 0.025\sqrt{s}$$



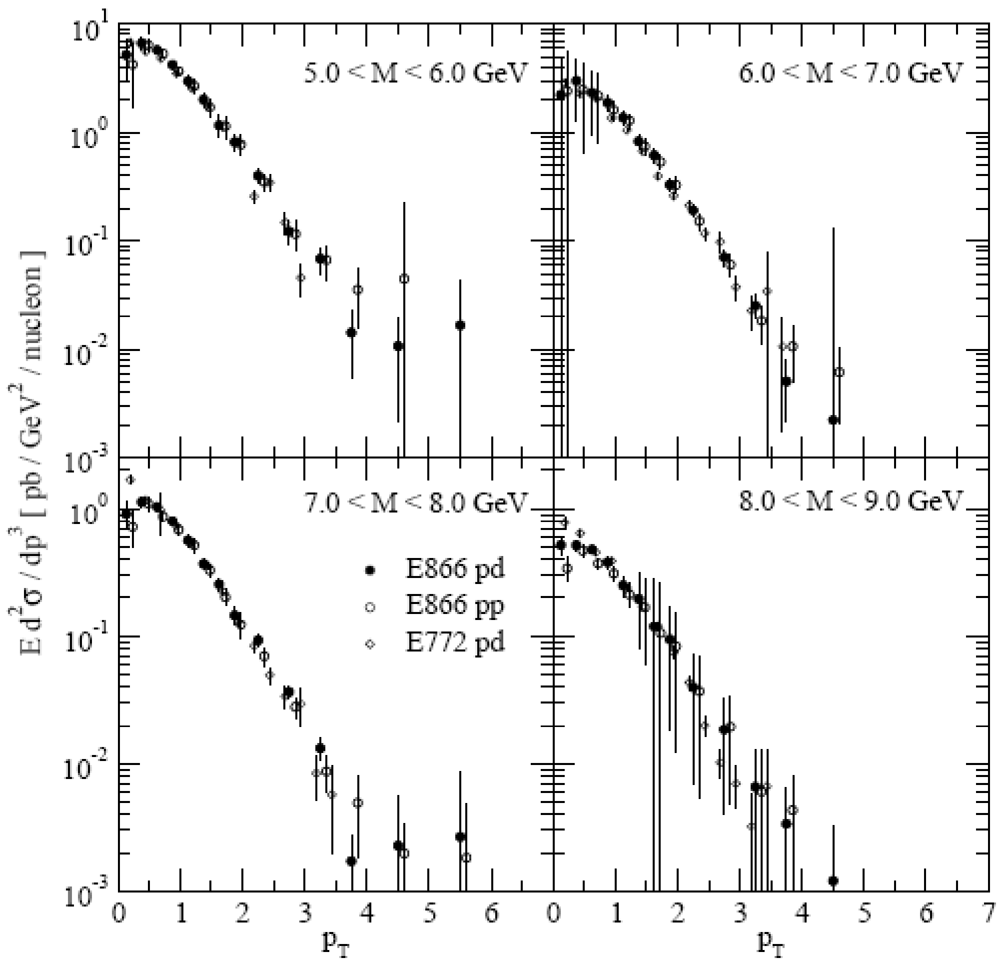
$$\langle p_T^{\ 2} \rangle = 0.59 + 0.0029\, s$$



<p_T> is significantly larger for D-Y with pion than proton beam

See recent work by Schweitzer, Teckentrup, Metz, PRD 81 (2010) 094019

Does the intrinsic k_T distribution depends on the quark flavor?

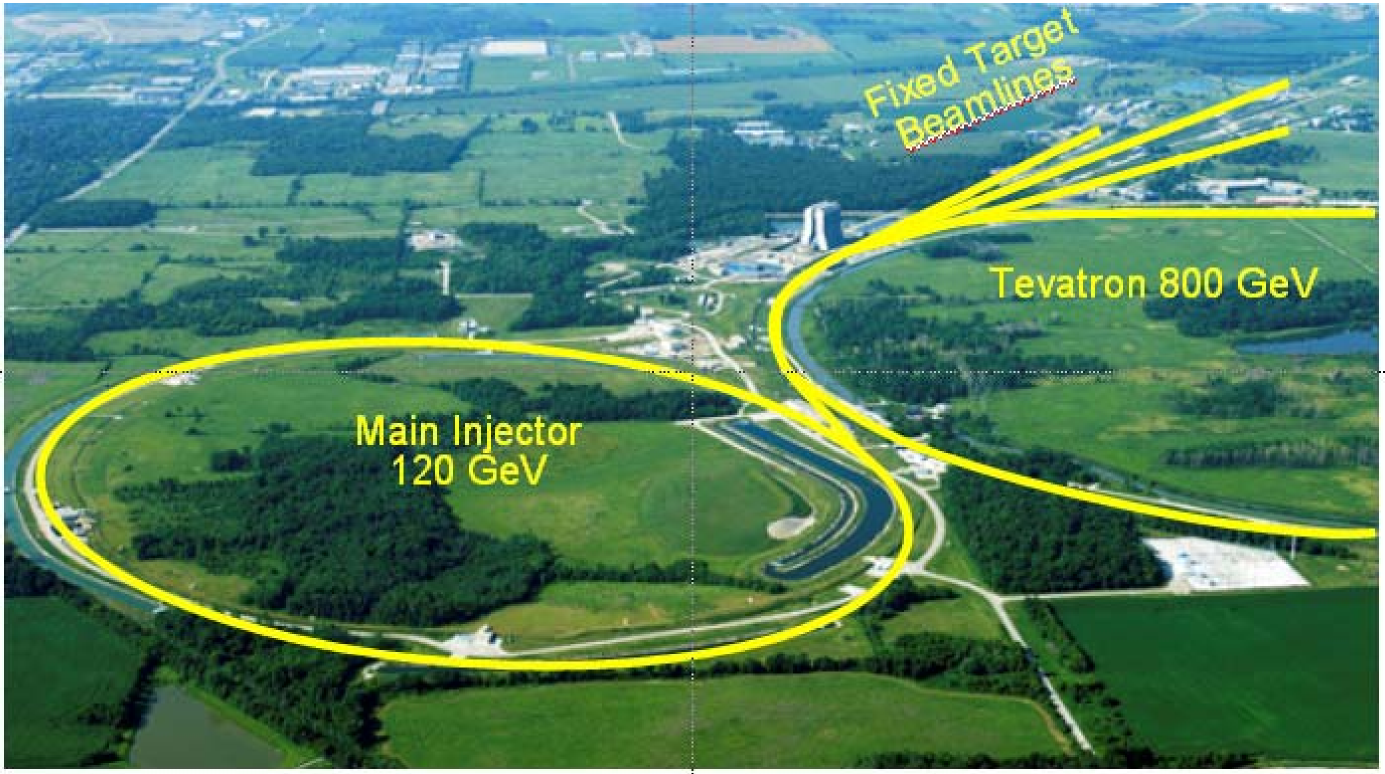


- E866 $p+d$
- E866 $p+p$

Drell-Yan data

The p+p and p+d E866 Drell-Yan data indicate no flavor-dependence for intrinsic k_T distribution

Fermilab E906 dimuon experiment (Geesaman, Reimer et al., expected to run ~2010-2013)



- Main goal is to measure the flavor asymmetry for the sea

- Boer-Mulders can also be studied

NM4/KTeV Hall

drift chambers

Draft 2010-13 Fermilab Accelerator Experiments' Run Schedule

Typically Revised Annually - This Version from October, 2009

Calendar Year		2010	2011	2012	2013
Tevatron Collider		CDF & DZero	CDF & DZero	OPEN	OPEN
Neutrino Program	B	MiniBooNE	MiniBooNE		OPEN
	B	OPEN	OPEN		MicroBooNE
	MI	MINOS	MINOS		OPEN
	MI	MINERvA	MINERvA		MINERvA
	MI	ArgoNeuT			
	MI		NOvA		NOvA
SY 120	MT	Test Beam	Test Beam		Test Beam
	MC	OPEN	OPEN		OPEN
	NM4	E-906/Drell-Yan	E-906/Drell-Yan		E-906/Drell-Yan

Letter of Intent

Measurement of Dimuons from Drell-Yan Process with Polarized Proton Beams and an Internal Target at RHIC

May 21, 2010

M. Brooks[4], A. Deshpande[6,7], N. Doshita[9], Y. Fukao[5], D. F. Geesaman[1], Y. Goto[5,6], M. Grosse Perdekamp[2], T. Iwata[9], X. Jiang[4], K. Kondo[9], G. Kunde[4], M. J. Leitch[4], M. X. Liu[4], P. L. McGaughey[4], Y. Miyachi[8,9], I. Nakagawa[5,6], K. Nakano[5,8], K. Okada[6], J.-C. Peng[2], P. E. Reimer[1], J. Rubin[1], N. Saito[3], S. Sawada[3], R. Seidl[6], T.-A. Shibata[8], and A. Taketani[5,6]

[1] *Argonne National Laboratory, Argonne, Illinois 60439, USA*
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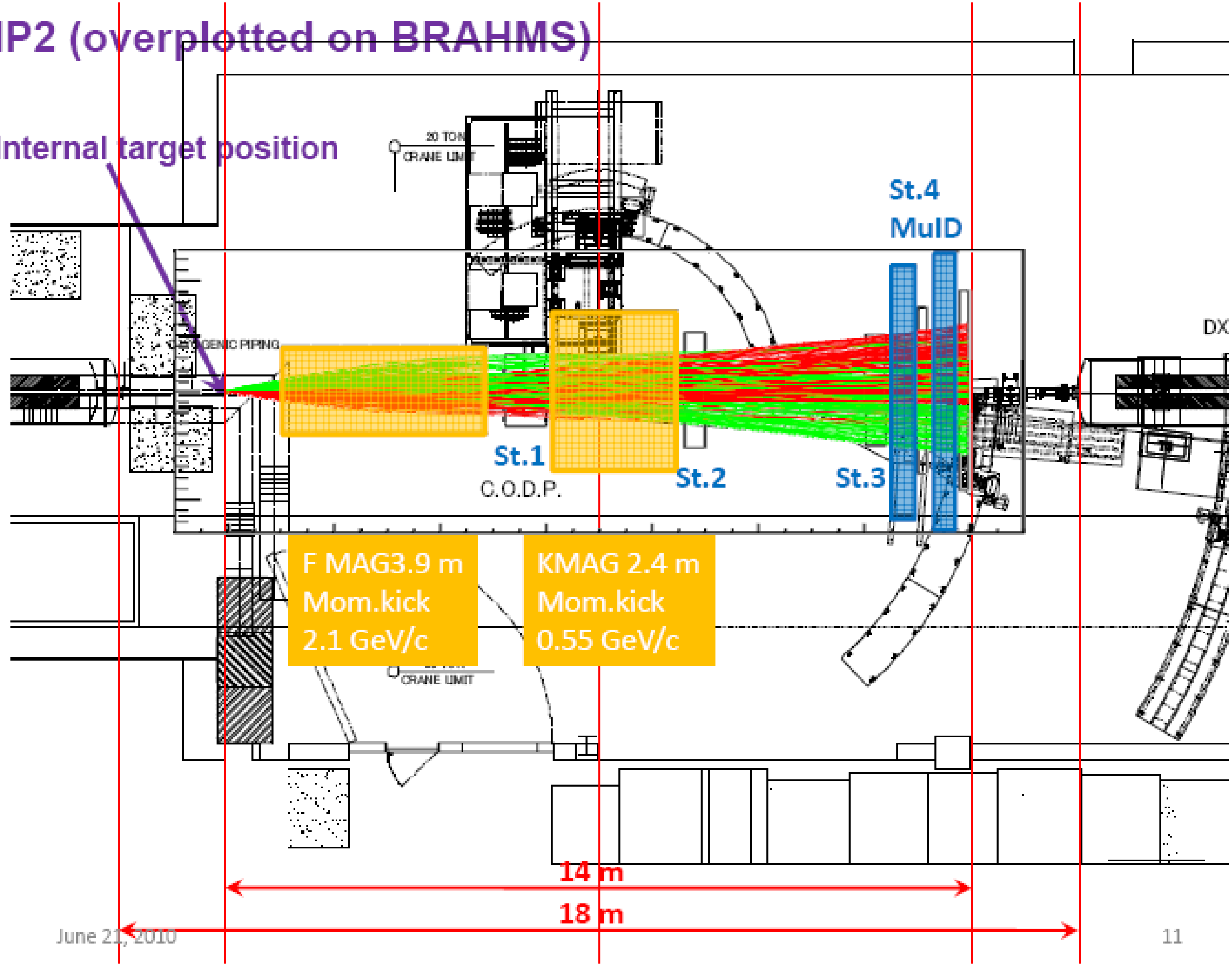
[6] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[7] *Stony Brook University, SUNY, Stony Brook, New York 11794, USA*
[8] *Tokyo Institute of Technology, Tokyo 152-8551, Japan*
[9] *Yamagata University, Yamagata 990-8560, Japan*

IP2 (overplotted on BRAHMS)

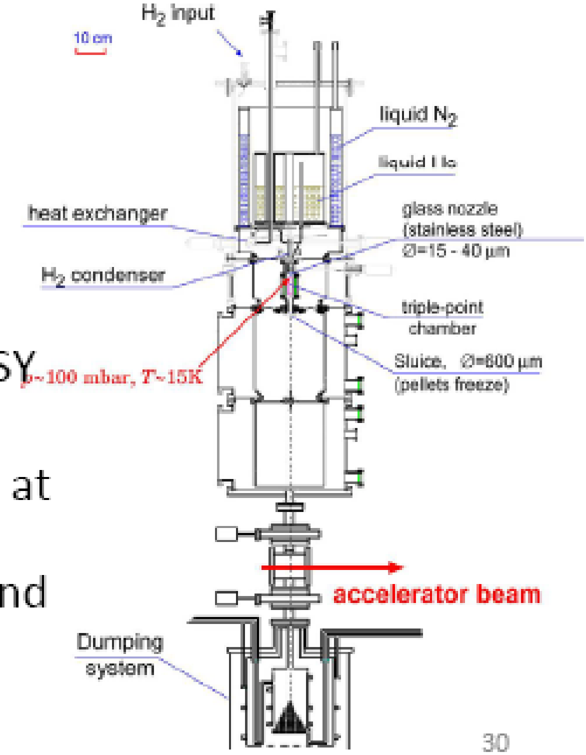


June 21, 2010

11

Internal target

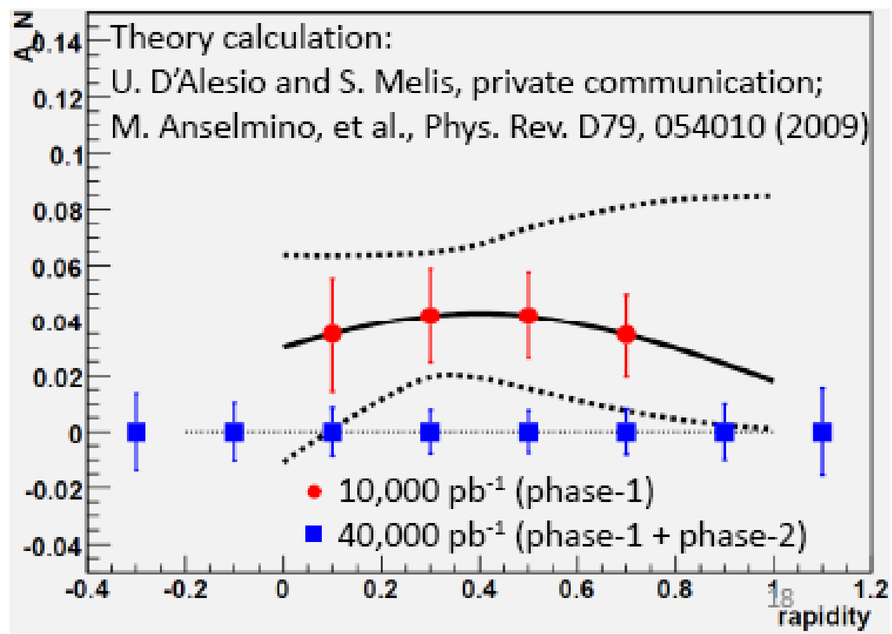
- Cluster-jet target
  - H_2, D_2, N_2, CH_4, Ne, Ar, Kr, Xe, …
  - $10^{14} – 10^{15}$ atoms/cm^2
  - Prototype of the PANDA target is operational at the Univ. of Muenster with a thickness of 8×10^{14} atoms/cm^2
- Pellet target
  - H_2, D_2, N_2, Ne, Ar, Kr, Xe, …
  - $10^{15} – 10^{16}$ atoms/cm^2
  - First generation target was developed in Uppsala and is in use with the WASA@COSY experiment
  - Prototype of the PANDA target is available at Juelich which has been developed in collaboration with Moscow groups (ITEP and MPEI)



Experimental sensitivities

- Phase-1 (parasitic operation)
  - $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$
  - 10,000 pb^{-1} with 5×10^6 s ~ 8 weeks, or 3 years (10 weeks × 3) of beam time by considering efficiency and live time
- Phase-2 (dedicated operation)
  - $L = 3 \times 10^{34}\ cm^{-2}s^{-1}$
  - 30,000 pb^{-1} with 10^6 s ~ 2 weeks, or 8 weeks of beam time by considering efficiency and live time

Measure not only the sign of the Sivers function but also the shape of the funcion



PAC recommends preparation of full proposal

Future prospect for Drell-Yan experiments

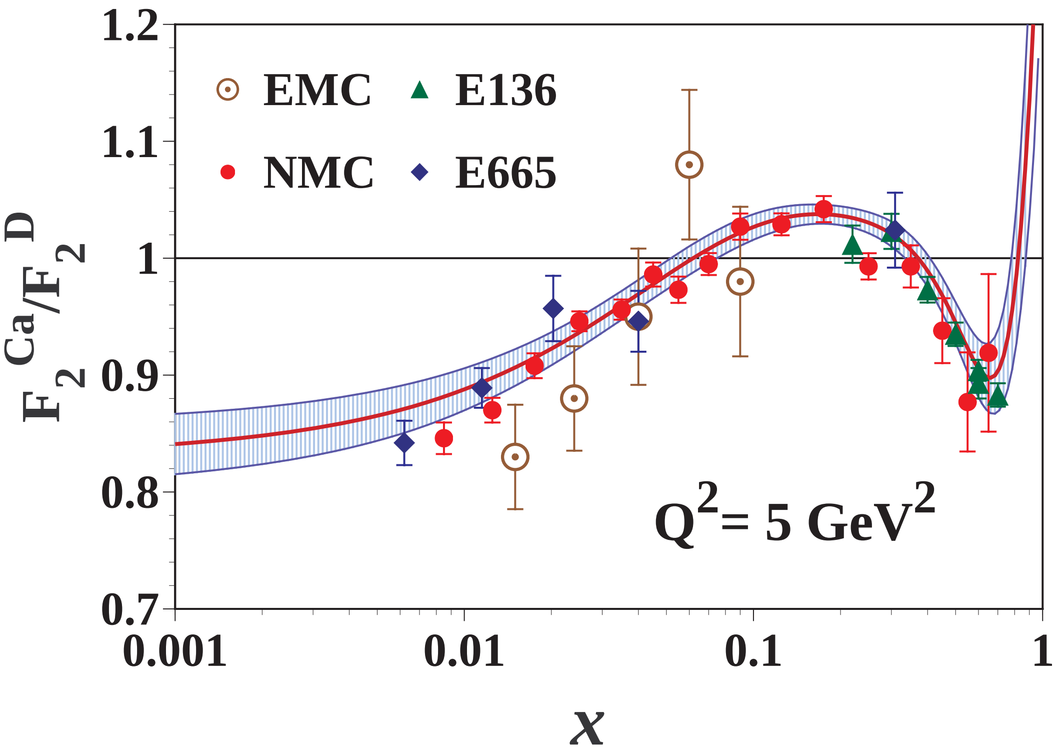
- Fermilab p+p, p+d, p+A
  - Unpolarized beam and target
- RHIC
  - Doubly and singly polarized p+p collision
- COMPASS
  - π-p and π-d with polarized targets
- FAIR
  - Polarized antiproton-proton collision
- J-PARC
  - Possibly polarized proton beam and target
- JINR
  - NICA with polarized target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

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



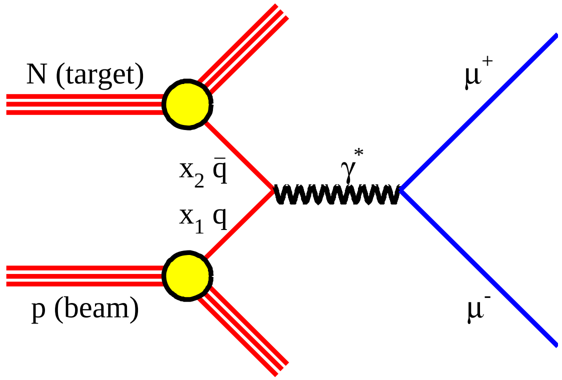
(Ann. Rev. Nucl. Part. Phys., Geesaman, Sato and Thomas)

Extensive study by Kumano et al. and Strikman et al.

F_2 contains contributions from quarks and antiquarks

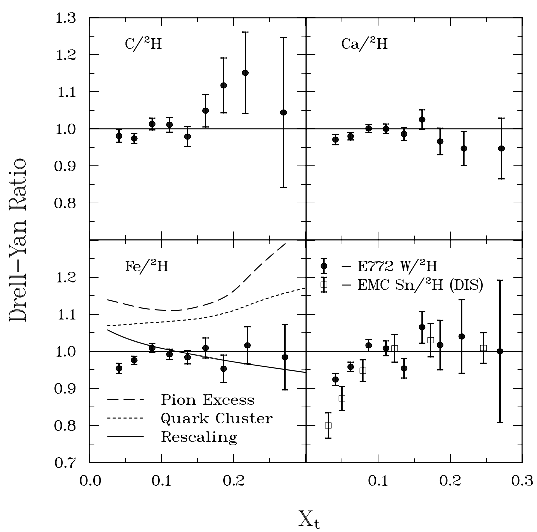
How are the antiquark distributions modified in nuclei?

Drell-Yan on nuclear targets

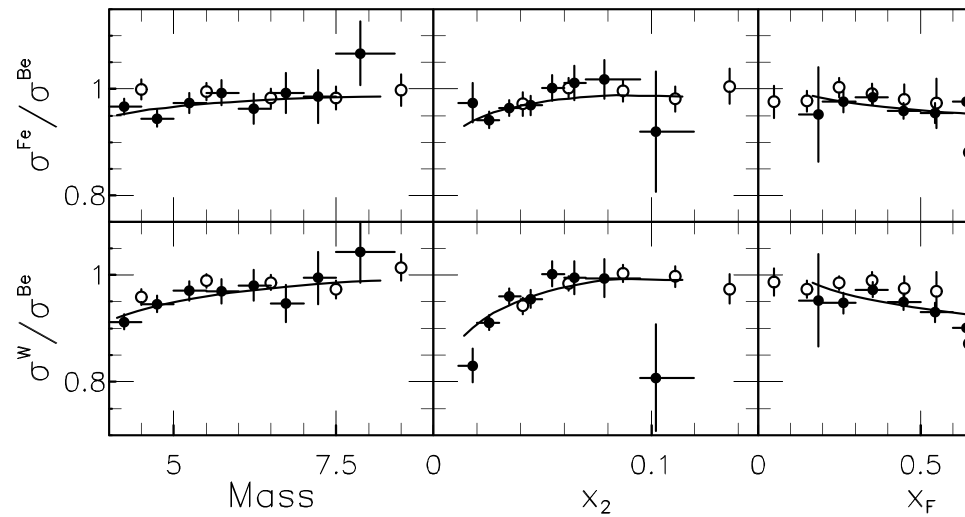


$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

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



PRL 64 (1990) 2479

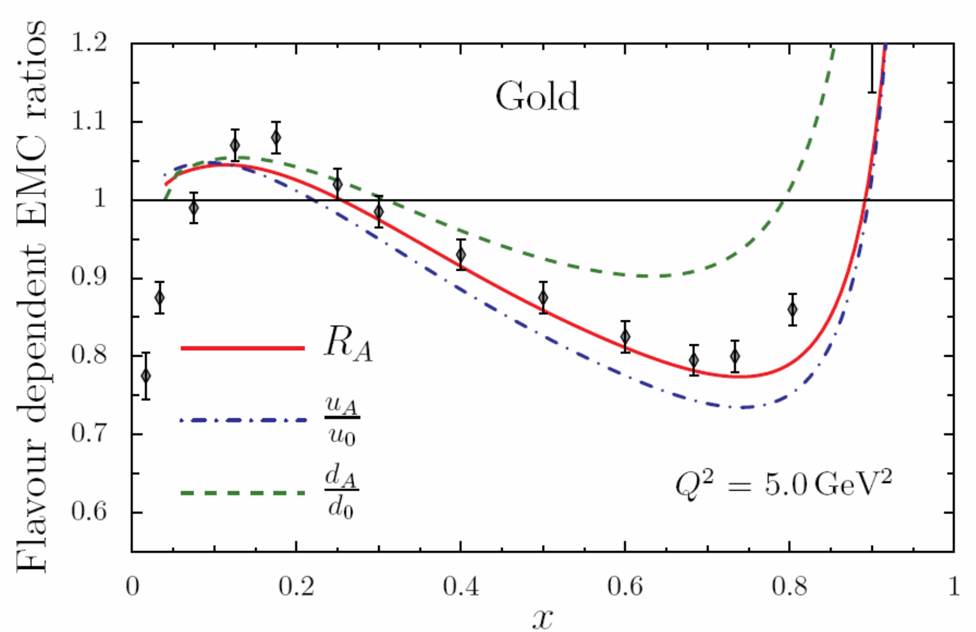


PRL 83 (1999) 2304

No evidence for enhancement of antiquark in niclei !?

E906 will extend the measurement to larger *x*

Flavor dependence of the EMC effects ?



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

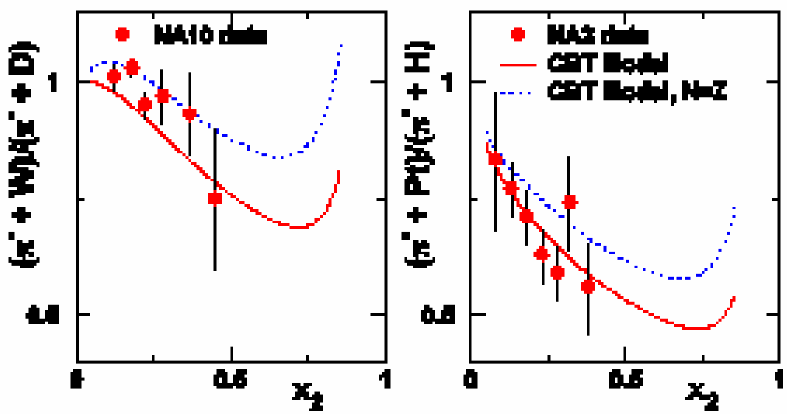
Cloet, Bentz, and Thomas, arXiv:0901.3559

How can one check this prediction?

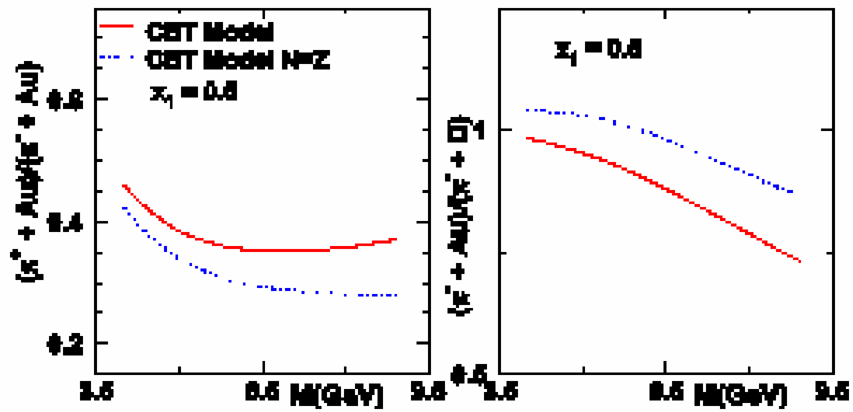
- SIDIS (JLab proposal) and PVDIS P.Souder)
- Pion-induced Drell-Yan

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

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



Red (blue) curve corresponds to flavor-dependent (independent) EMC



New data from COMPASS or Fermilab with pion beams could provide important new information

(D. Dutta, JCP, Cloet, Gaskell, arXiv: 1007.3916)

Summary

- The Drell-Yan process is a powerful experimental tool complimentary to the DIS for exploring quark structures in nucleons and nuclei.
- Unique information on flavor structures of sea-quark has been obtained with Drell-Yan experiments. First results on TMD have also been extracted.
- On-going and future Drell-Yan experiments at various hadron facilities can address many important unresolved issues in the spin and flavor structures of nucleons and nuclei.