TMDs and Drell-Yan at Fermilab/J-PARC

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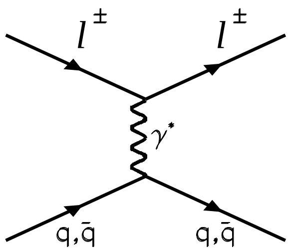
TMD2010 ECT* Workshop
Trento, June 21-25, 2010

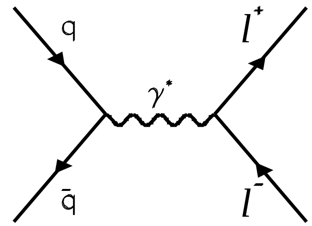
Outline

- Brief review of Drell-Yan at Fermilab
- Plans of Drell-Yan measurements at Fermilab
- Future prospect at J-PARC

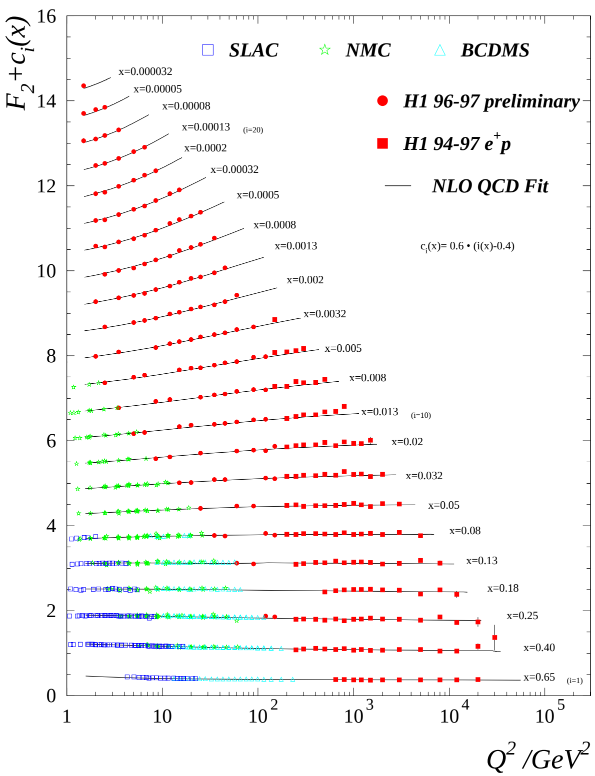
Complimentality between DIS and Drell-Yan

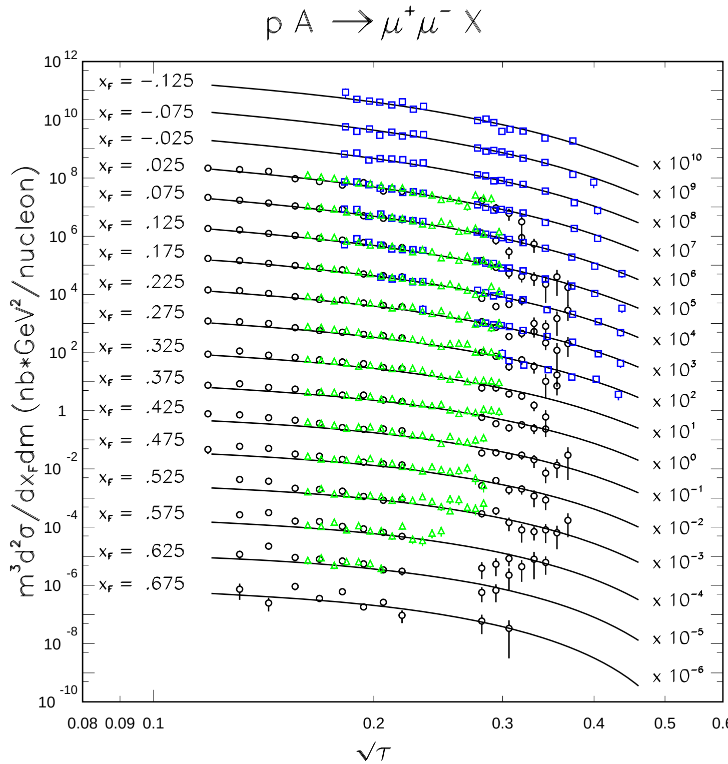
DIS





Drell-Yan





McGaughey, Moss, JCP,

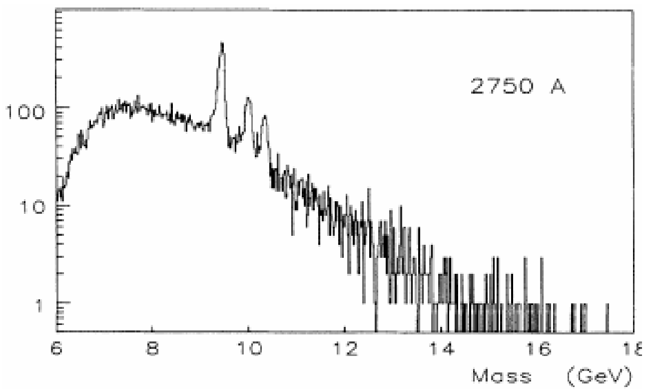
Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons

Lepton-pair production has provided unique information on parton distributions

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

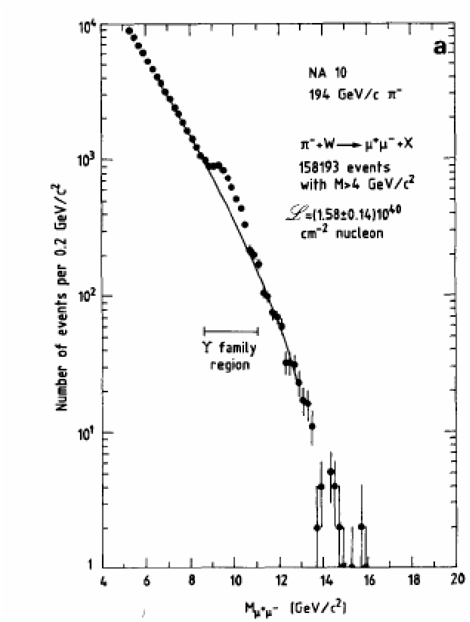
800 GeV/c



Probe antiquark distribution in nucleon

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

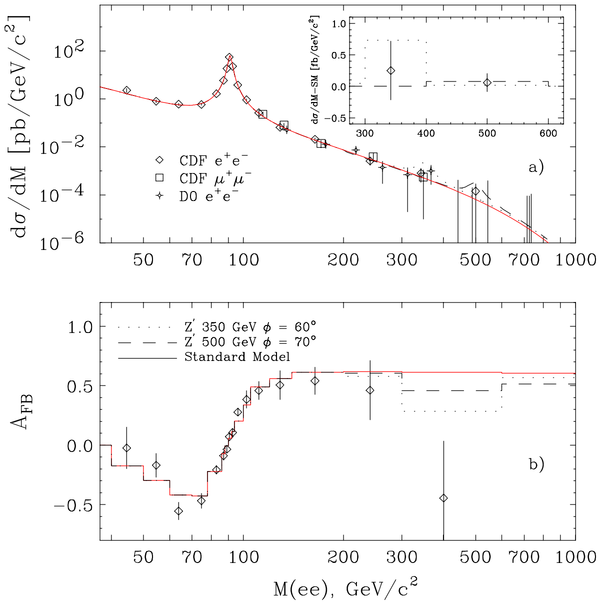
194 GeV/c



Probe antiquark distribution in pion

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

1.8 TeV

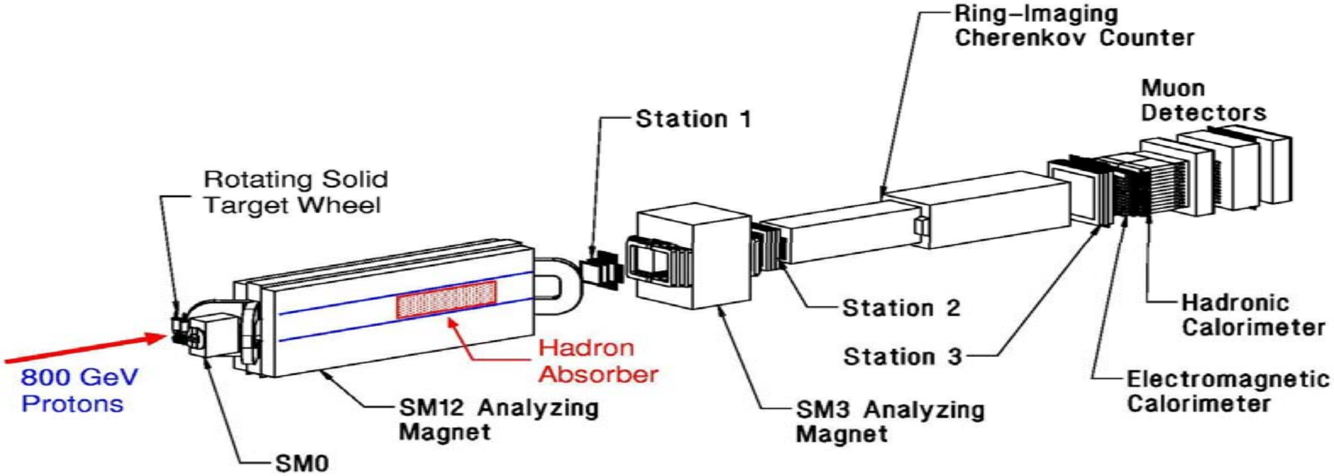


Probe antiquark distributions in antiproton

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

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 :

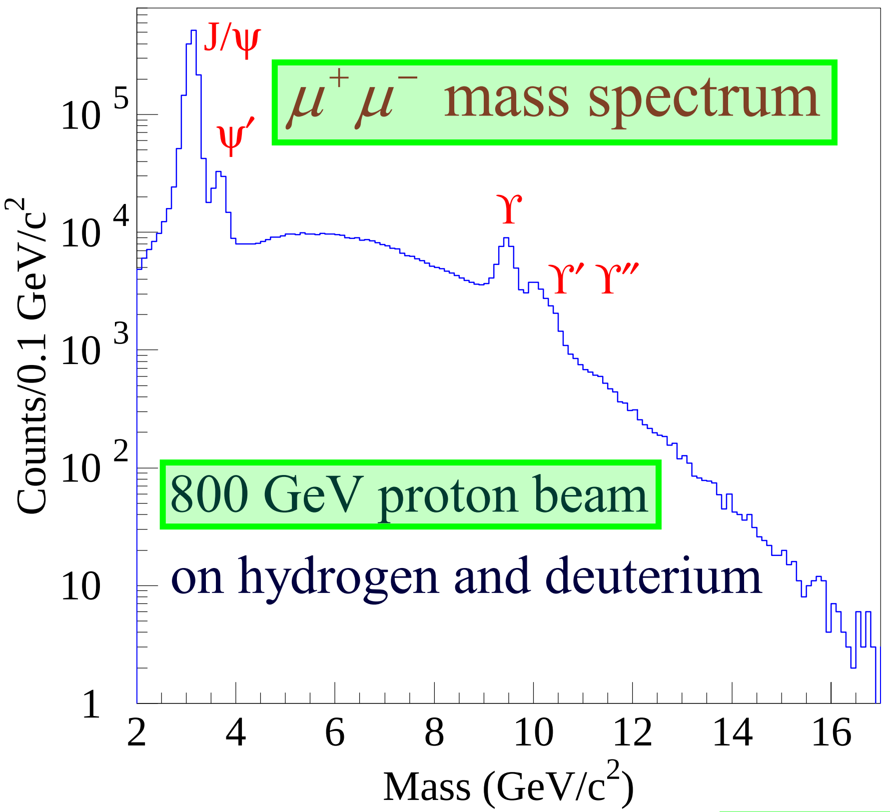
- Pronounced nuclear dependence
- Production mechnism and polarizations
- Gluon distributions in the nucleons

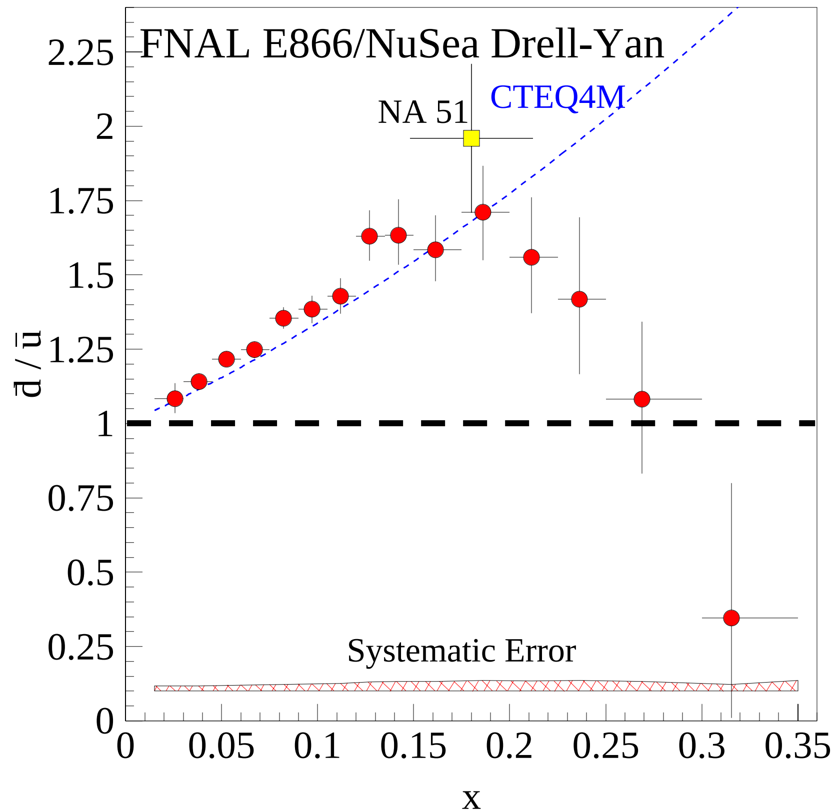
3) Heavy quark production :

- Open charm production
- B-meson production

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

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

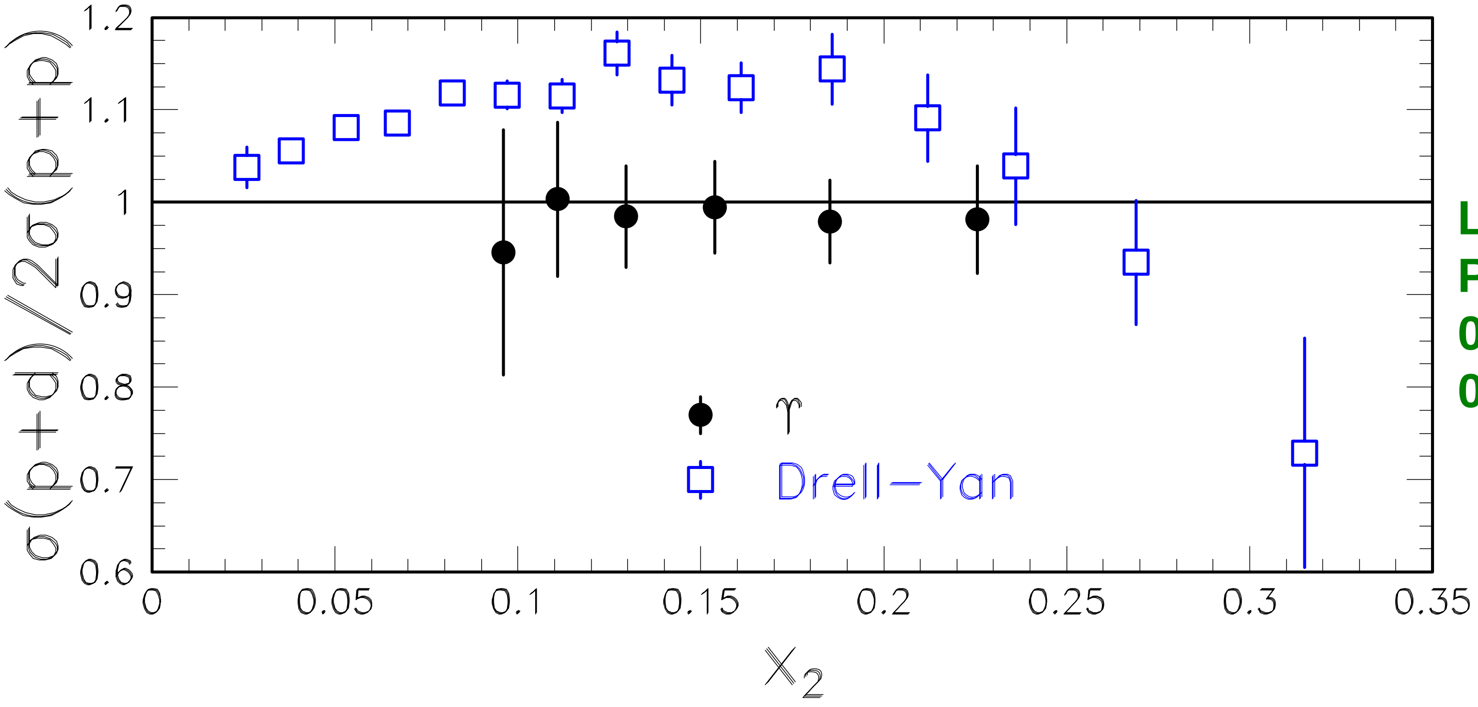




at $x_1 > x_2$: Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \approx \frac{1}{2}\left(1+\bar{d}(x_2)/\bar{u}(x_2)\right)$

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

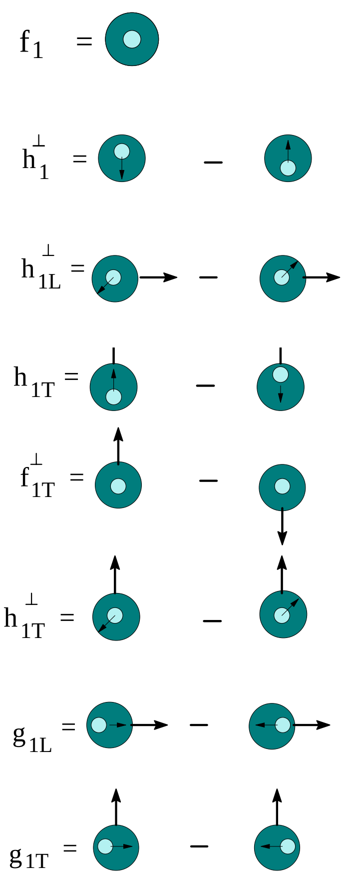
Transversity and Transverse Momentum Dependent PDFs are probed in Semi-Inclusive DIS

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

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)

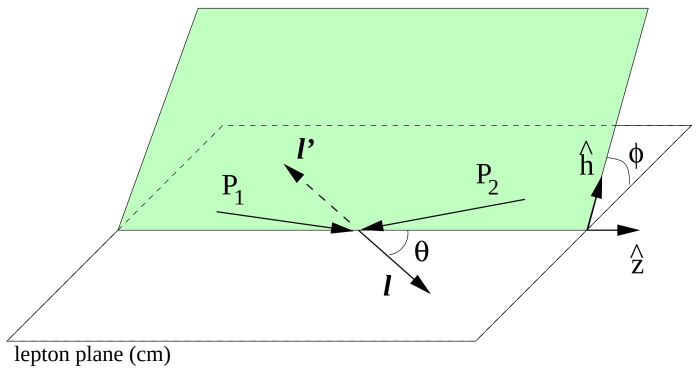
Remains to be tested experimentally!

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



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: $1-\lambda=2\nu$

– 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

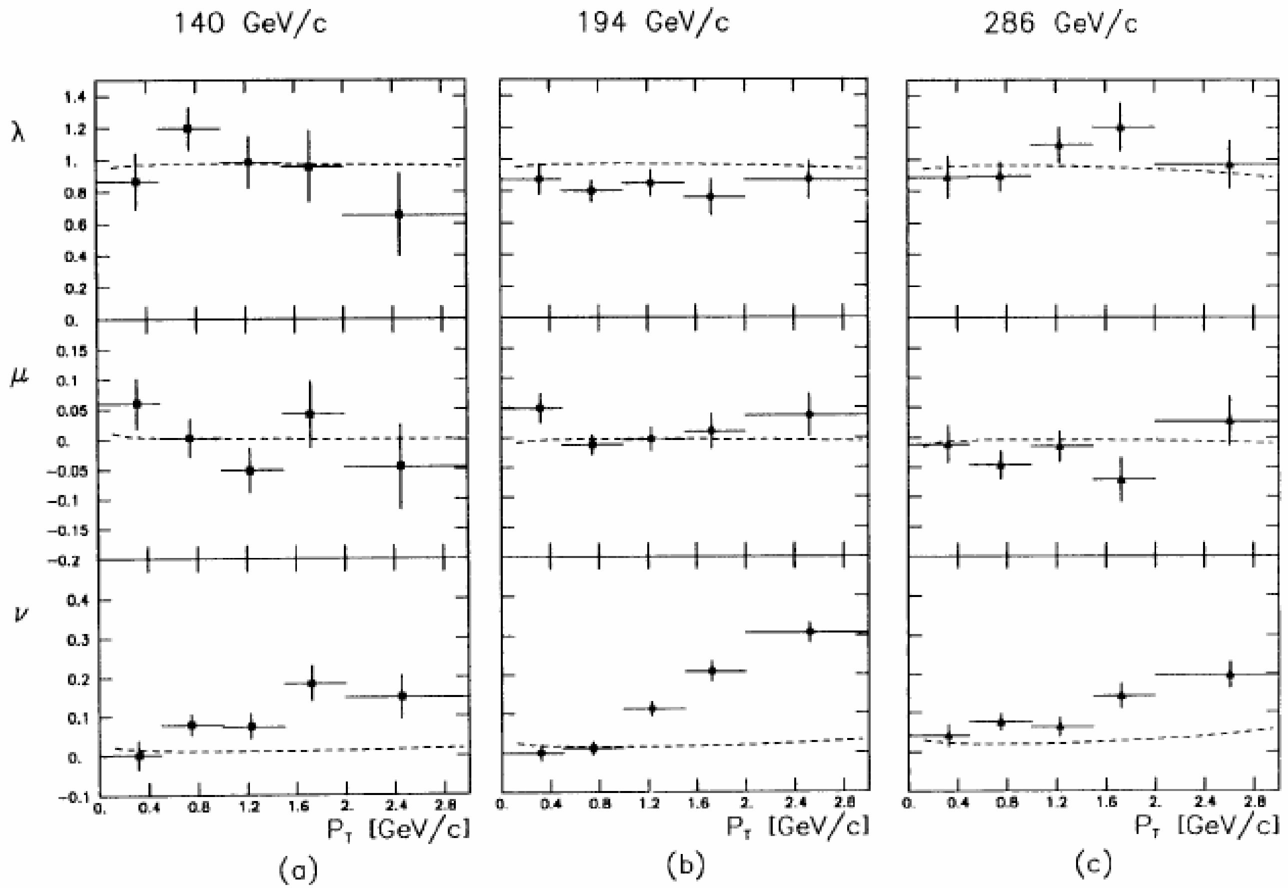


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + W$

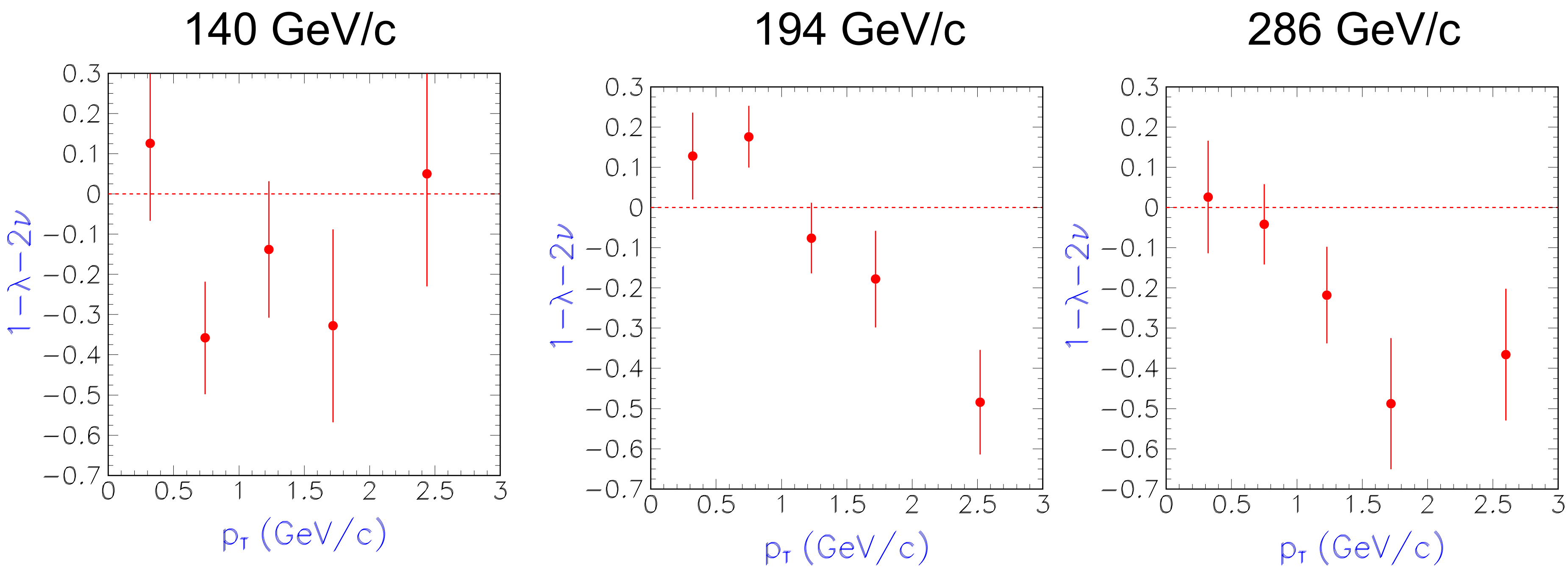
Z. Phys. 37 (1988) 545

Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

Decay angular distributions in pion-induced Drell-Yan

Is the Lam-Tung relation violated?

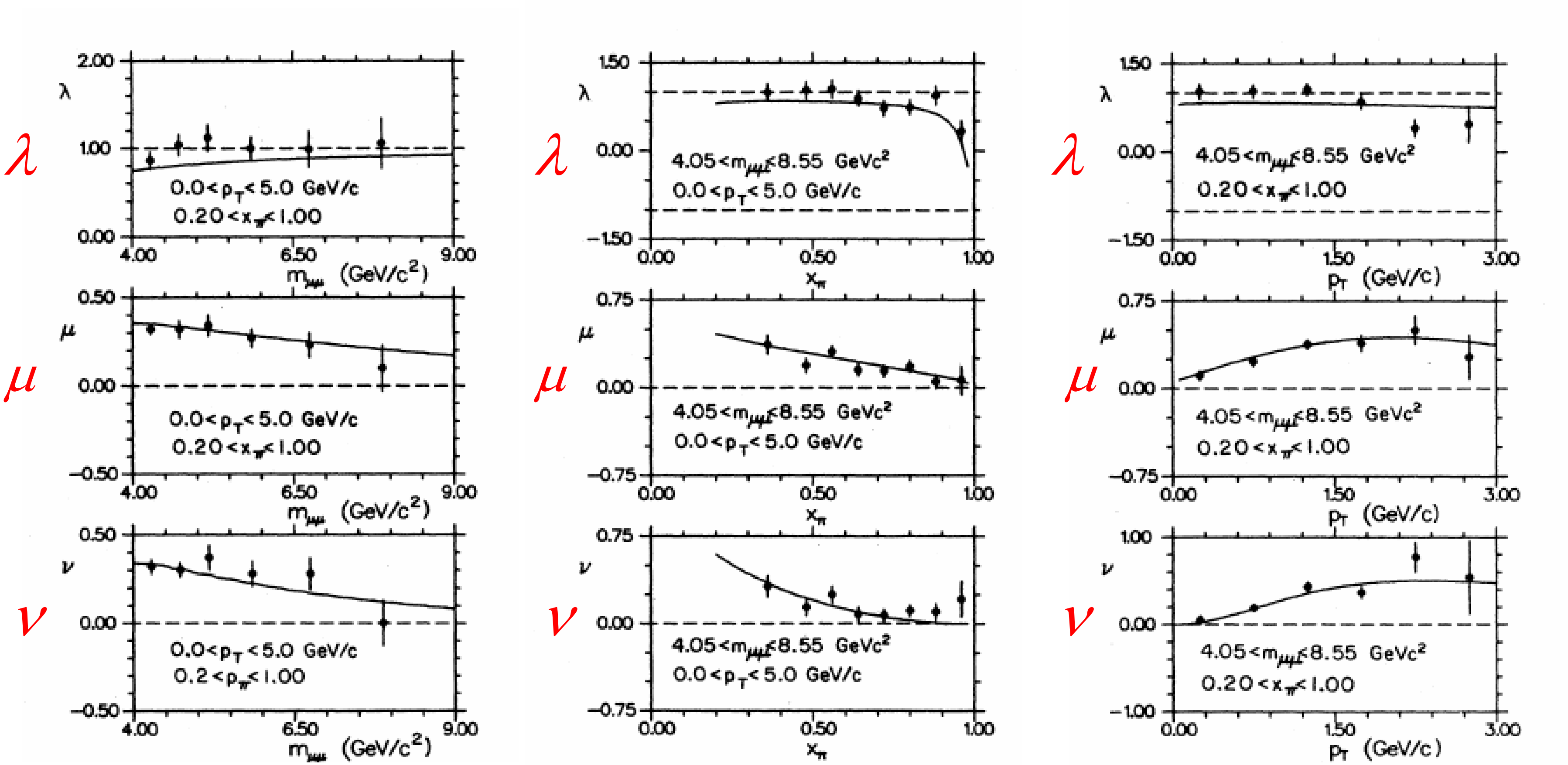


Data from NA10 (Z. Phys. 37 (1988) 545)

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

Decay angular distributions in pion-induced Drell-Yan

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

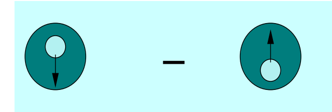


$m_{\mu\mu}$(GeV/c^2) x_π p_T(GeV/c)

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

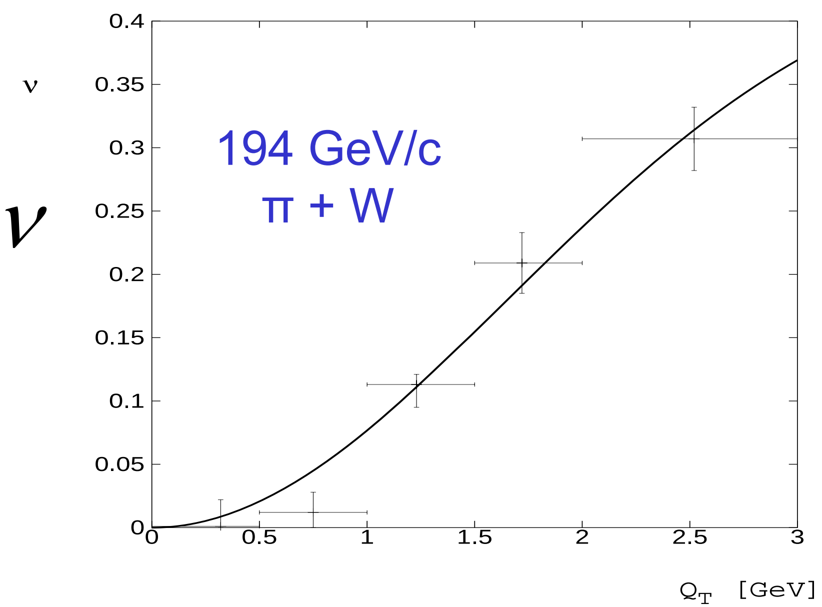
$\mu^2 \leq (1-\lambda)(1+\lambda-\nu)/4$ (O. Teryaev) is also violated

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

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

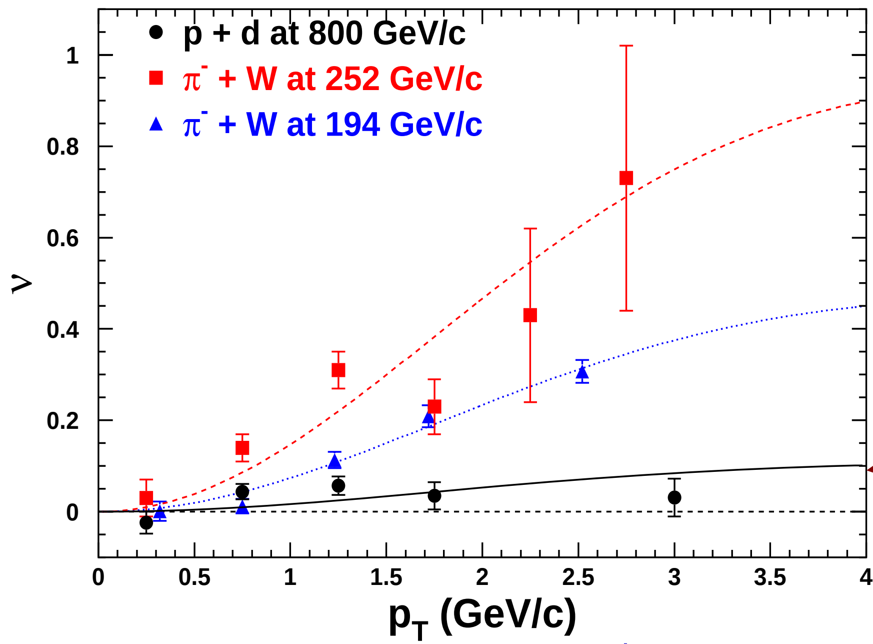


Boer, PRD 60 (1999) 014012

- 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:

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

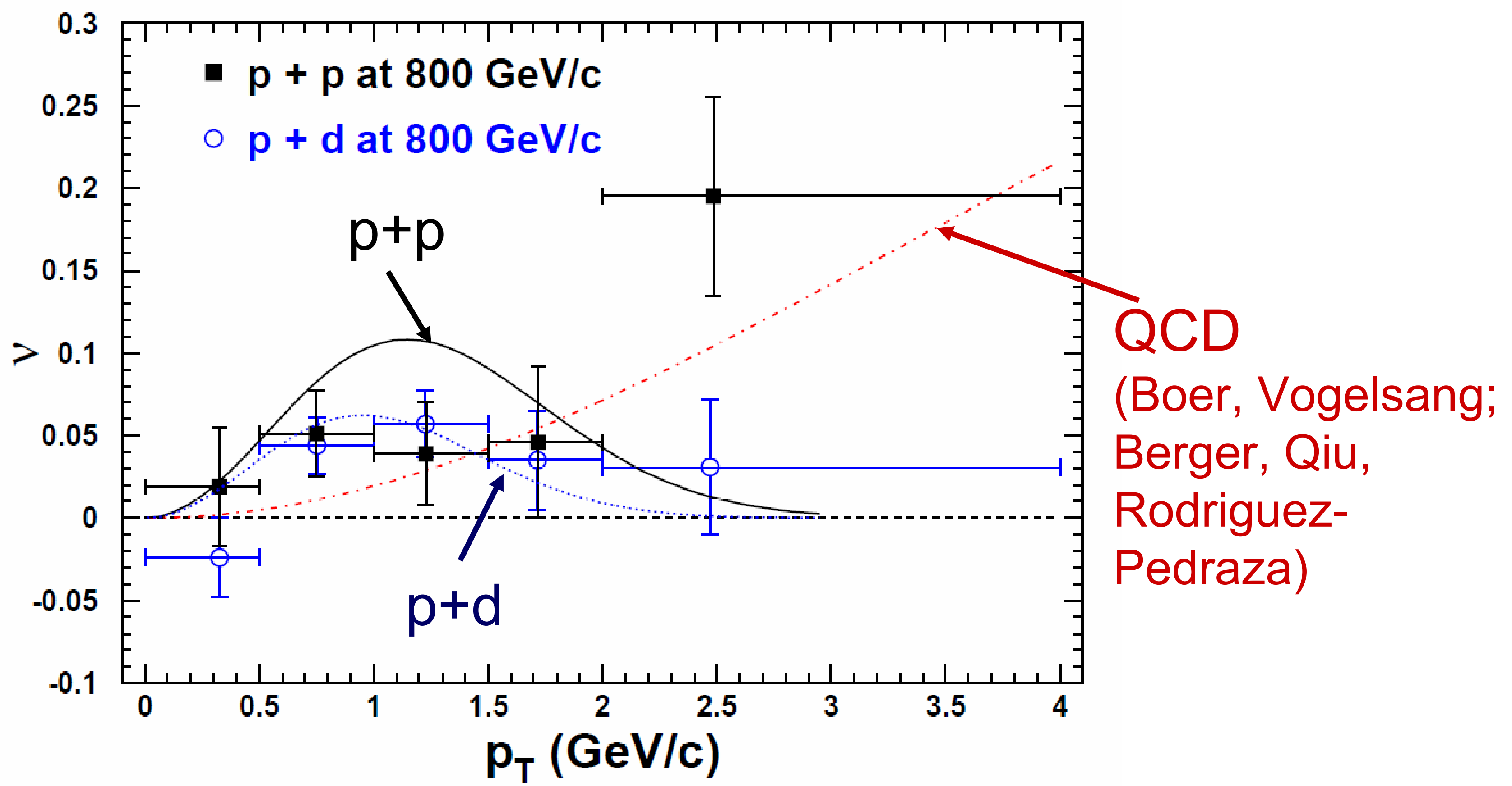
H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	p_{BM}^2	c	χ^2 / dof
3.99	3.83	0.91	-0.96	0.16	0.45	0.79

- 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

Predictions were made for p+p cos(2Φ) distributions

Results on cos2Φ Distribution in p+p Drell-Yan

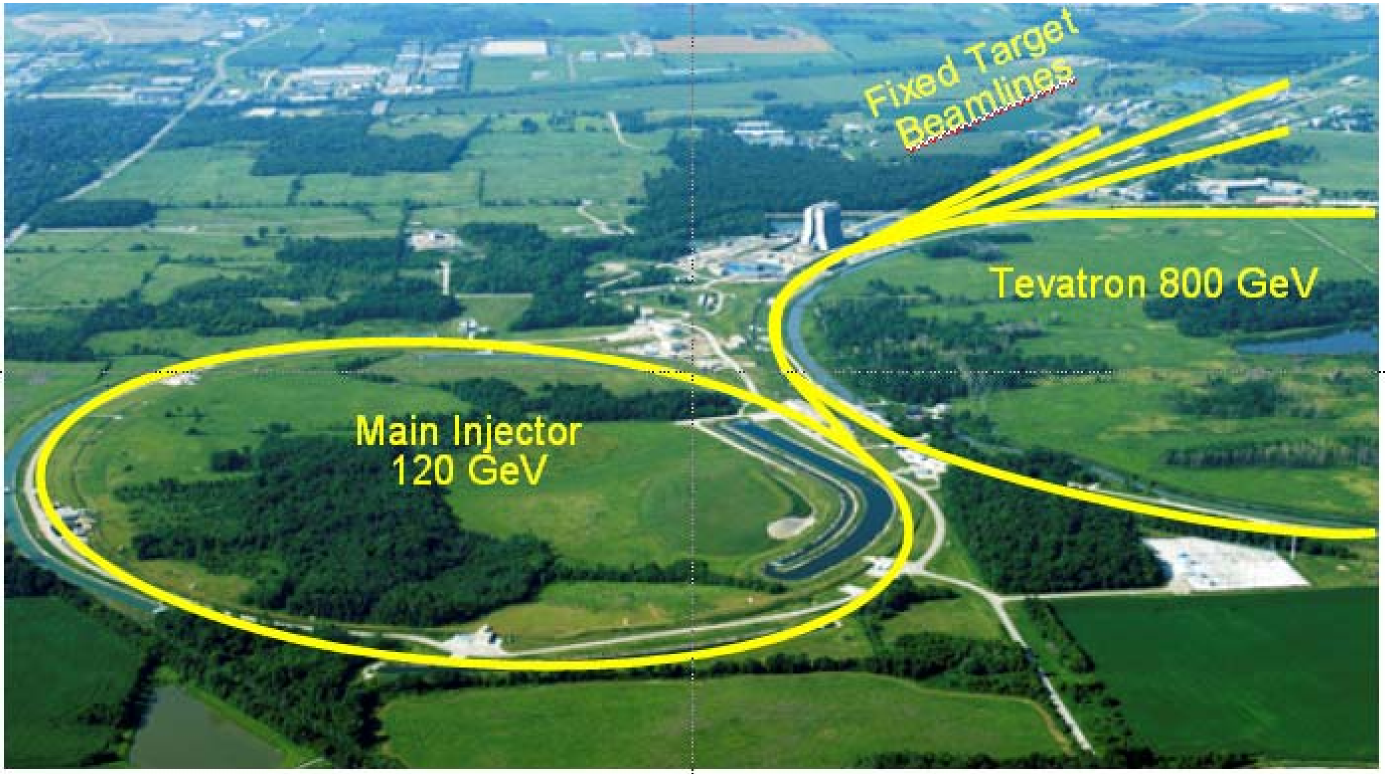
L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001



Combined analysis of SIDIS and D-Y by Melis et al.

More data are anticipated from Fermilab E906

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



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

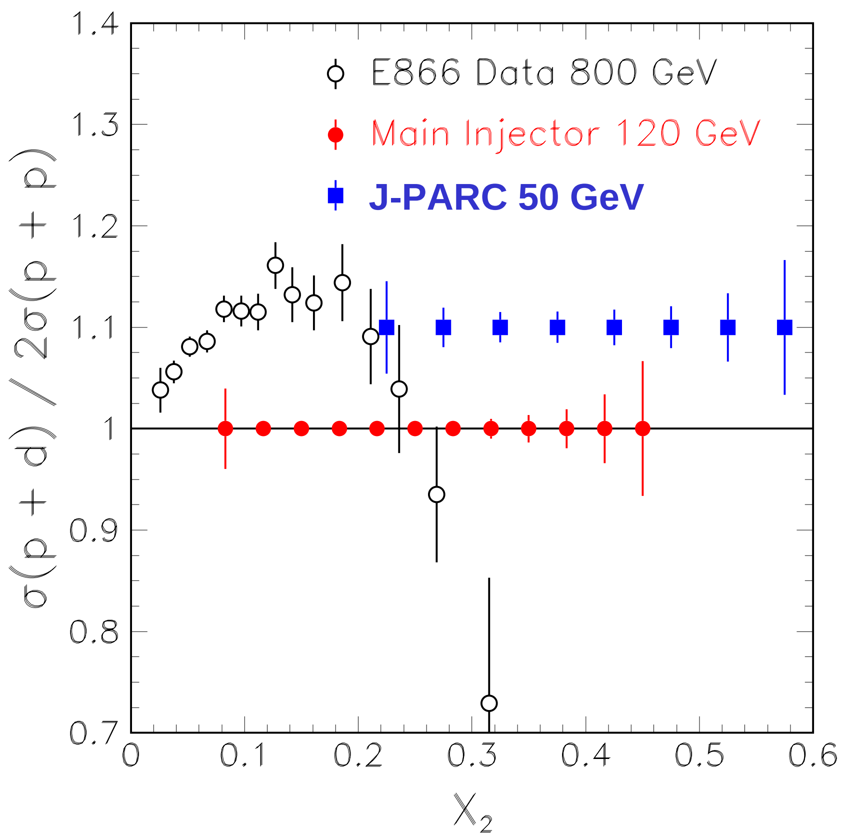
- Boer-Mulders can also be studied

Main goal is to measure $\bar{d}/\bar{u}$ at large x

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

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

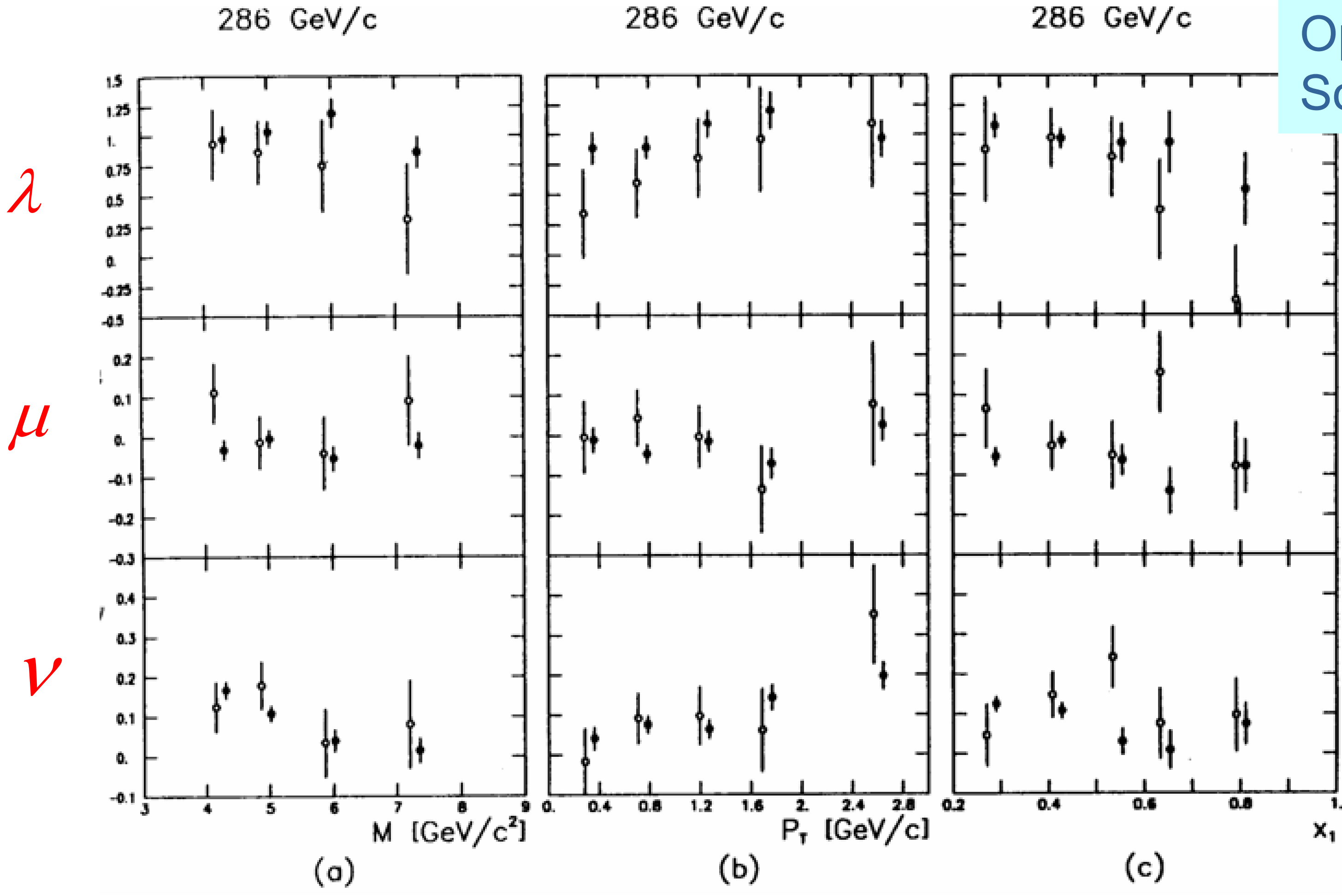
DY cross section is ~ 16 times larger at 50 GeV than at 800 GeV



- 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

Nuclear modification of the B-M function?

Open: Deuterium
Solid: Tungsten



NA10 results

Can be measured in Fermilab E906

Nuclear modification of spin-dependent PDF?

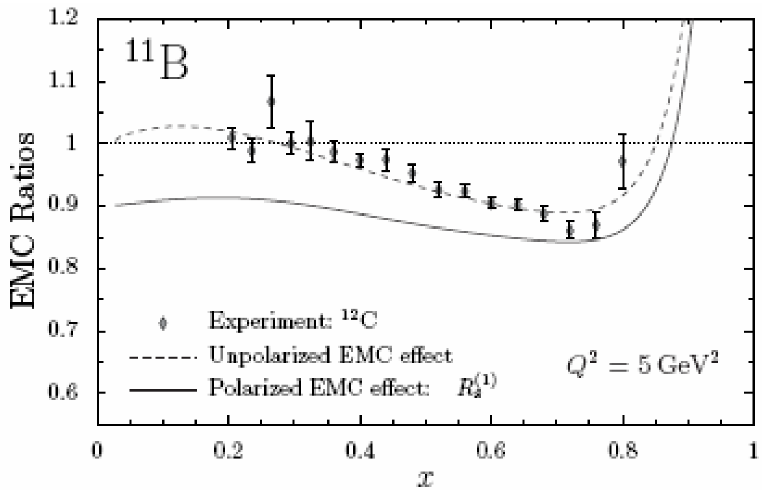


Figure 7: EMC ratios for ^{11}B. The experimental data refer to ^{12}C.

EMC effect for $g_1(x)$

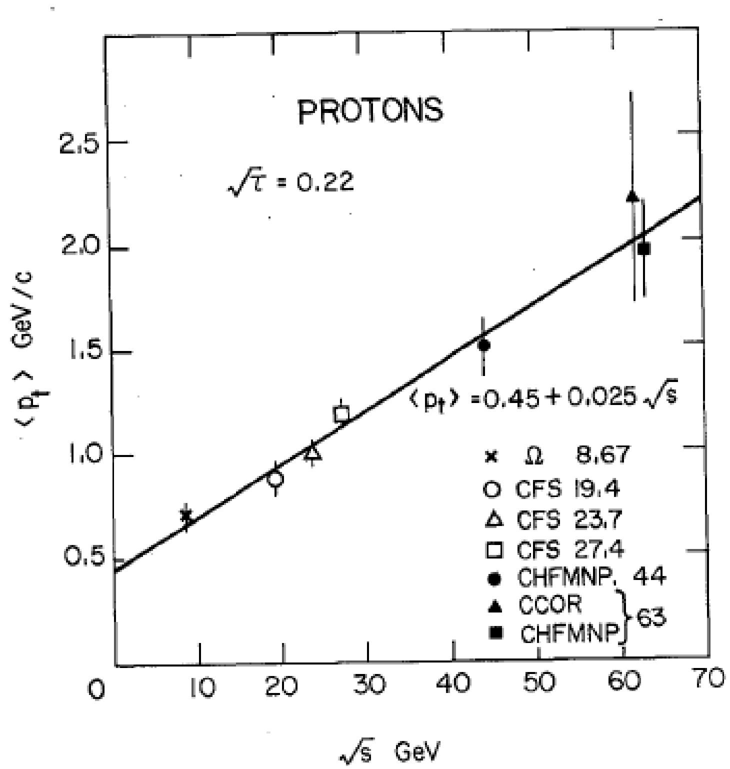
Bentz, Cloet et al., arXiv:0711.0392

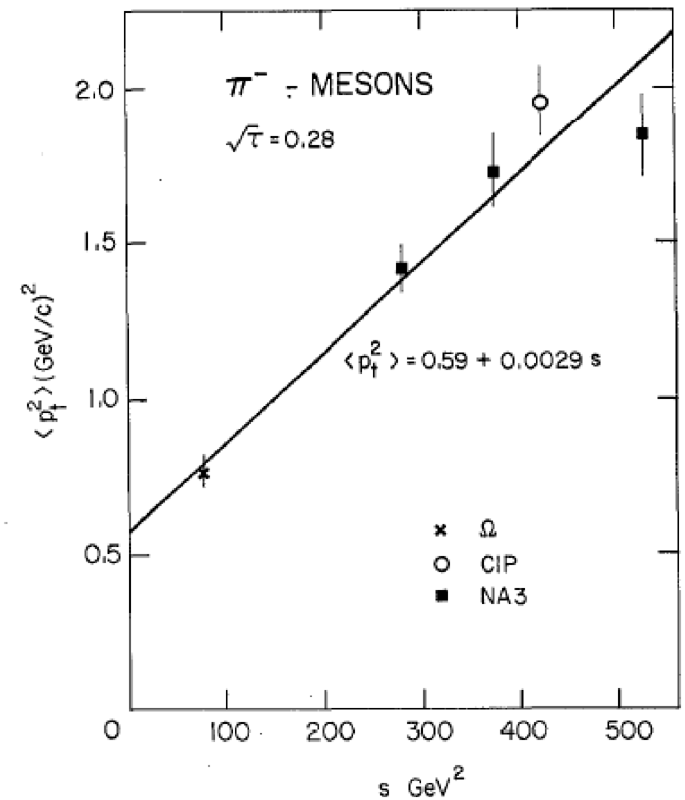
Very difficult to measure !

Easier to measure the nuclear modification of Boer-Mulders functions (only unpolarized targets are required)?

(See Bianconi and Radici, J. Phys. G31 (2005) 645)

Intrinsic k_T distribution from Drell-Yan





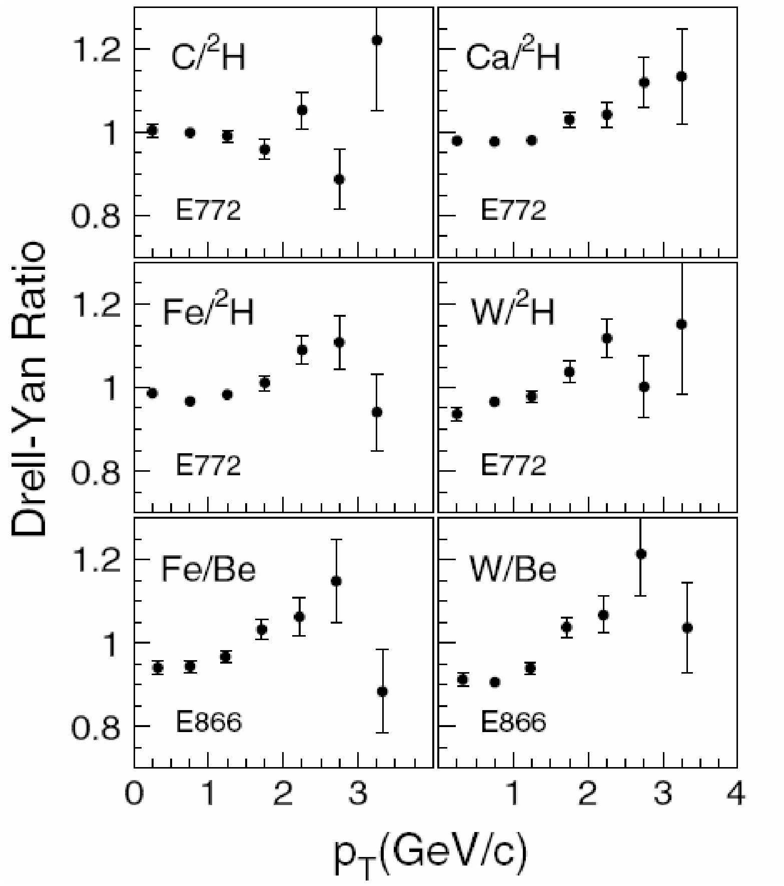
$\langle p_T \rangle$ is significantly larger for D-Y with pion beam than proton beam

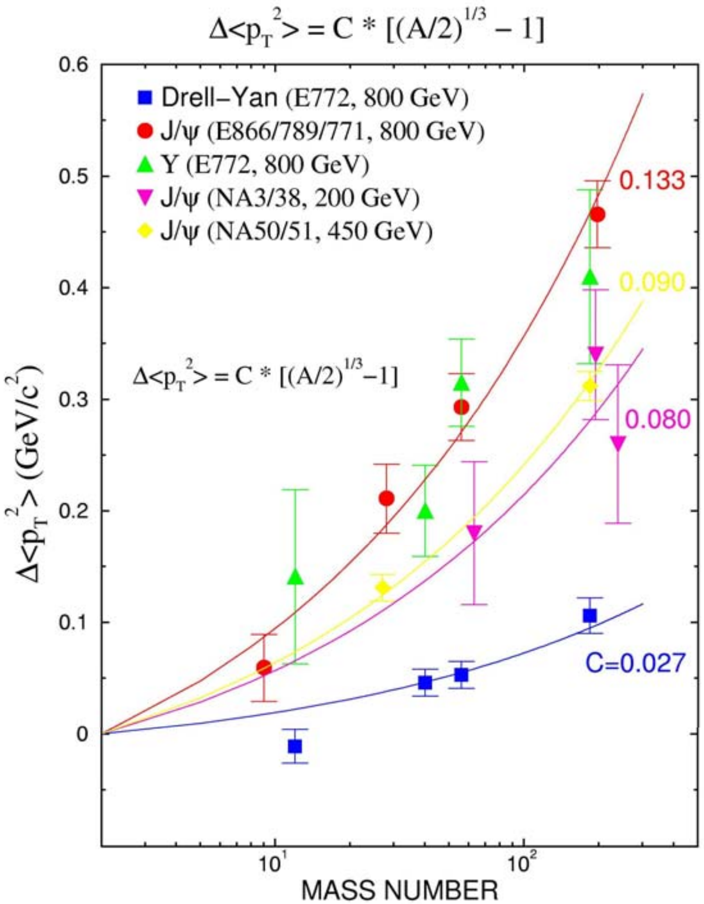
See recent work by Schweitzer, Teckentrup, Metz, PRD 81 (2010) 094019

Modification of k_T distribution in nuclei?

E772/E866 p+A

Harut's talk: evidence in SIDIS





P_T broadening for D-Y is much smaller than for J/Ψ production, due to the absence of Cronin effect

NM4/KTeV Hall

Focusing Magnet

KTeV Magnet

Station 2 and 3 drift chambers

Experiment Schedule

http://www.fnal.gov/directorate/program_planning/schedule/index.html

2010-2011 Fermilab Accelerator Experiments Schedule

This schedule will be updated regularly, as plans change.

Calendar Year		2010	2011
Tevatron Collider		CDF	CDF OPEN
		DZero	DZero OPEN
Neutrino Program	B	MiniBooNE	MiniBooNE #
	MI	MINERvA	MINERvA
		ArgoNeuT	
		MINOS	MINOS
SY 120	MT	Test Beam	Test Beam
	MC	OPEN	OPEN
	NM4	E-906/SeaQuest	E-906/SeaQuest

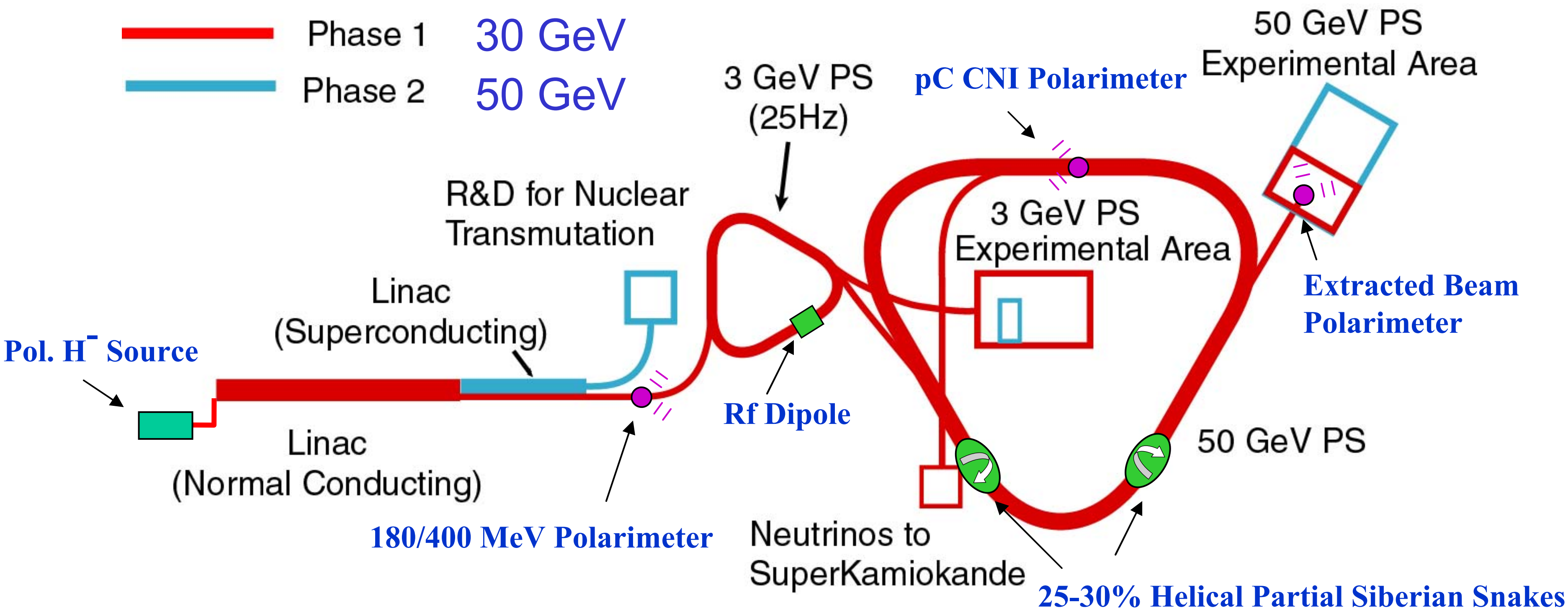
Draft 2010-13 Fermilab Accelerator Experiments' Run Schedule

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
		OPEN	OPEN		MicroBooNE
	MI	MINOS	MINOS		OPEN
		MINERvA	MINERvA		MINERvA
		ArgoNeuT			
				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

Polarized proton beam at J-PARC ?

- **Polarized proton beam at J-PARC with**
  - **Polarized H^- source**
  - **RF dipole at 3 GeV RCS**
  - **Two 30% partial snakes at 50 GeV Main Ring**



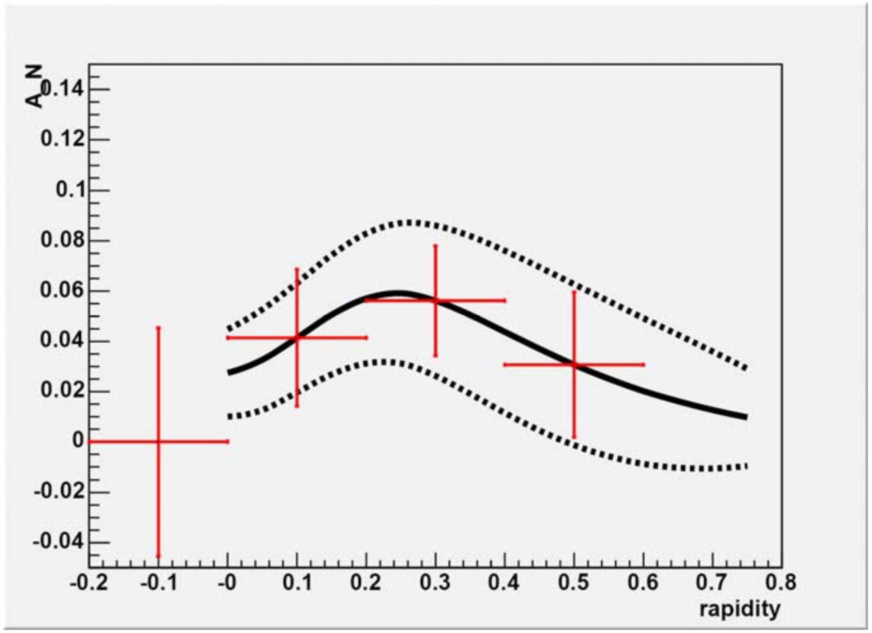
J-PARC dimuon proposals

- P04: measurement of high-mass dimuon production at the 50-GeV proton synchrotron
  - spokespersons: Jen-Chieh Peng (UIUC) and Shinya Sawadas (KEK)
  - collaboration: Abilene Christian Univ., ANL, Duke Univ., KEK, UIUC, LANL, Pusan National Univ., RIKEN, Seoul National Univ., TokyoTech, Tokyo Univ. of Science, Yamagata Univ.
  - including polarized physics program.
- P24: polarized proton acceleration at J-PARC
  - contact persons: Yuji Goto (RIKEN) and Hikaru Sato (KEK)
  - collaboration: ANL, BNL, UIUC, KEK, Kyoto Univ., LANL, RCNP, RIKEN, RBRC, Rikkyo Univ., TokyoTech, Tokyo Univ. of Science, Yamagata Univ.
  - polarized Drell-Yan included as a physics case

Single-spin asymmetry in polarized p-p at J-PARC

Single-spin asymmetry (A_N) can probe Sivers function

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



$$A_N^{DY} = \frac{\sum_q e_q^2 f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})}{\sum_q e_q^2 f_q(x_q) f_{\bar{q}}(x_{\bar{q}})}$$

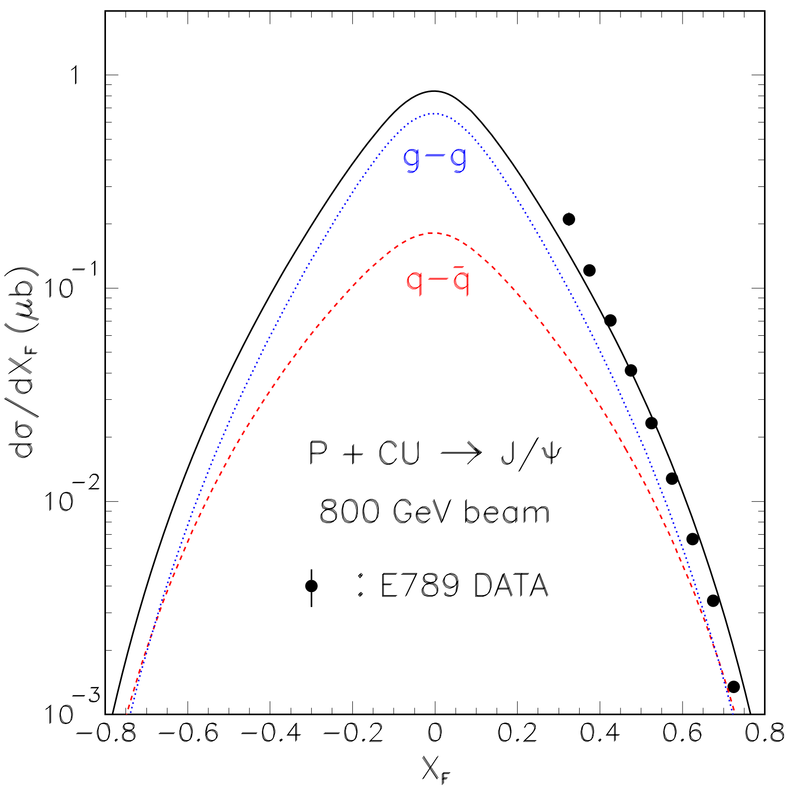
- J/Ψ production could also probe the Sivers function

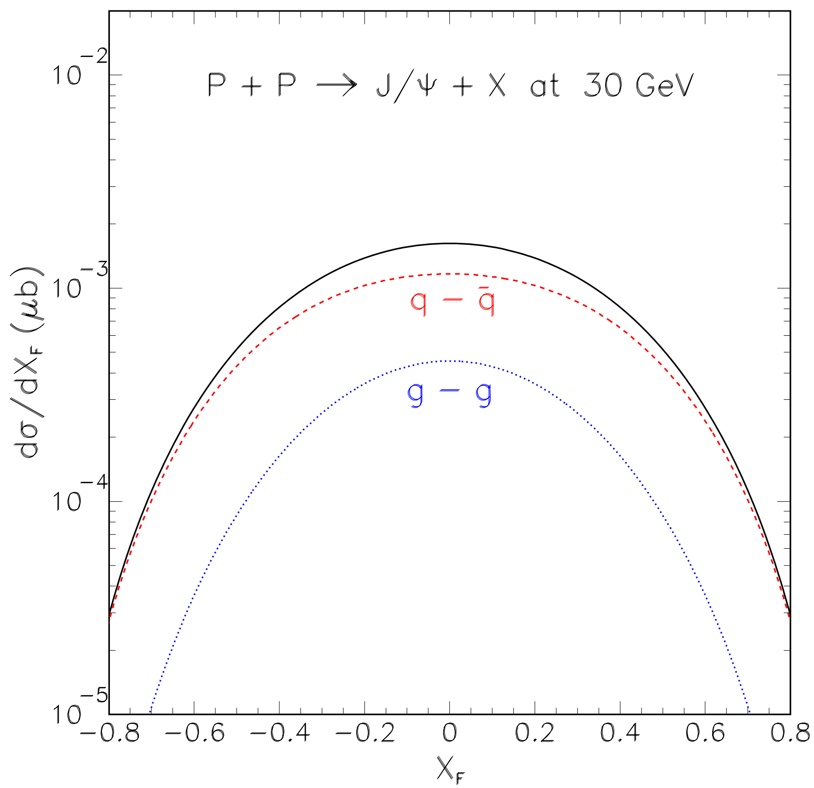
- Much higher statistics could be obtained in J/Ψ production

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

Outstanding questions in TMD 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