New Opportunities of "High" Energy QCD Hadron Physics with Drell-Yan at Fermilab

Ming X. Liu (Los Alamos)

Jen-Chieh Peng (UIUC)

- Study novel strong interaction phenomena (parton model)
- New Fundamental tests of QCD

Outline

- A brief review of Drell-Yan experiments: Hadron Physics @Fermilab

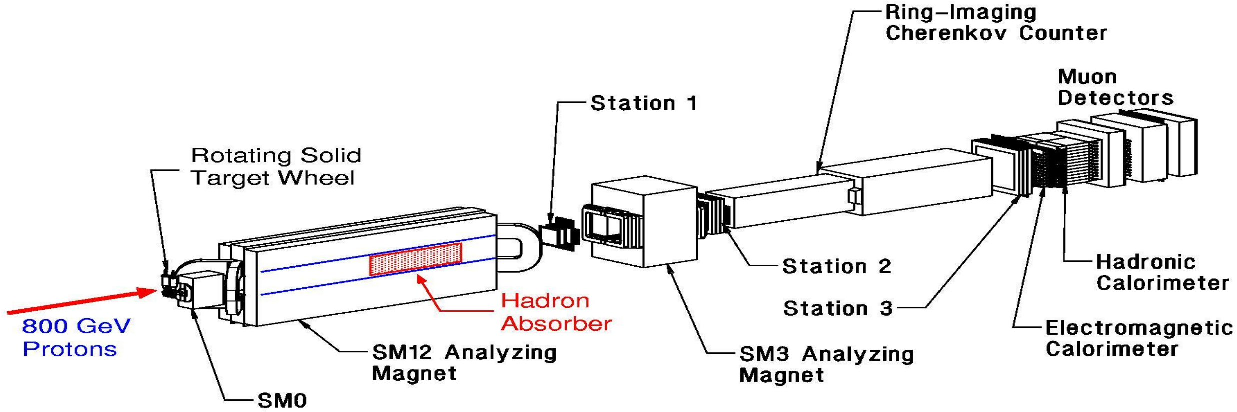
- High energy (parton) QCD hadron physics – recent development
  - Nucleon parton model and novel QCD dynamics
  - Transverse Momentum Dependent PDF & FF functions (TMD)
  - Drell-Yan TSSA and "sign change"

- New opportunities of QCD physics at Fermilab
  - Drell-Yan, Open charm, Lambda …
    - anti-protons @8GeV, (120GeV?)
    - Proton @120GeV

  - Polarized Program?!
    - QCD color-charge flow and transverse spin effect in hard scatterings

Fermilab Dimuon Spectrometer: Fixed Target Drell-Yan

(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"

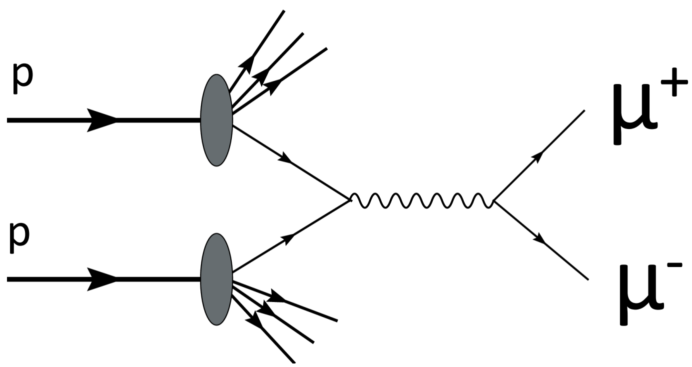
Polarized Drell-Yan at Fermilab after E906?

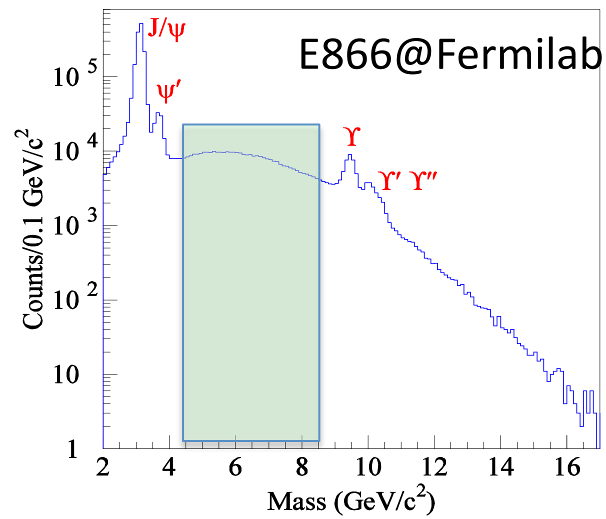
The Drell-Yan Process

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.

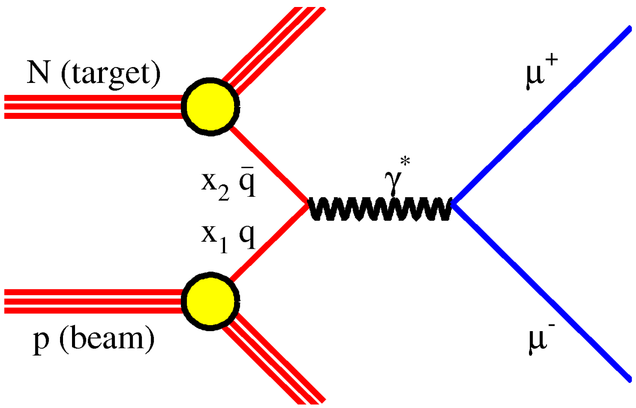




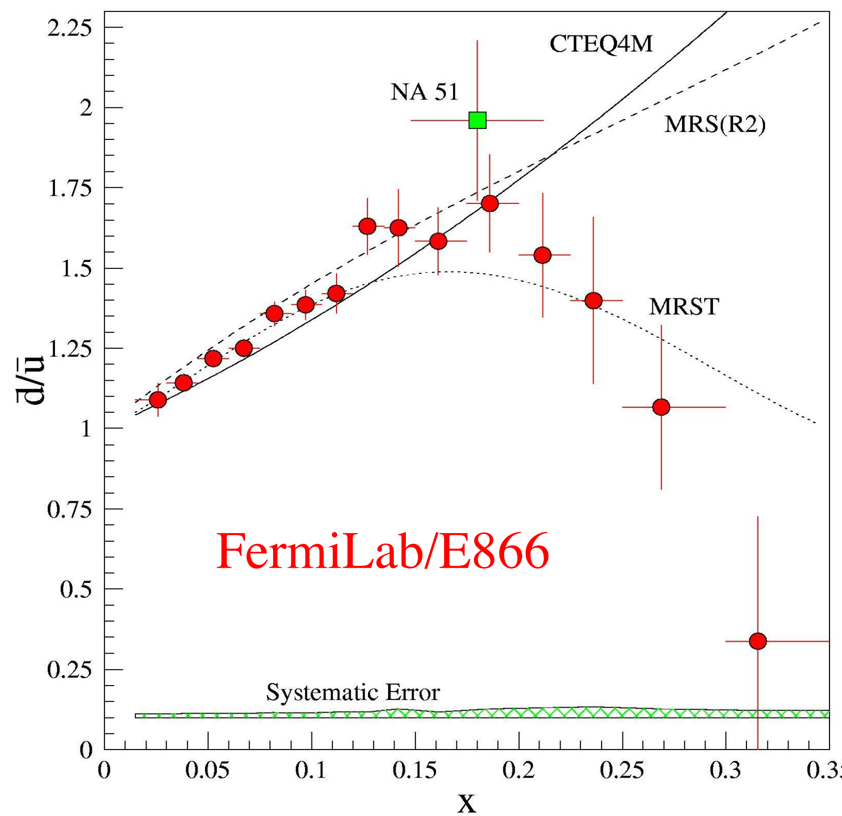
$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2) \right]$$

Fermilab E866 Highlight: sea quark asymmetry

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



E866, Phys.Rev. D64 (2001) 052002

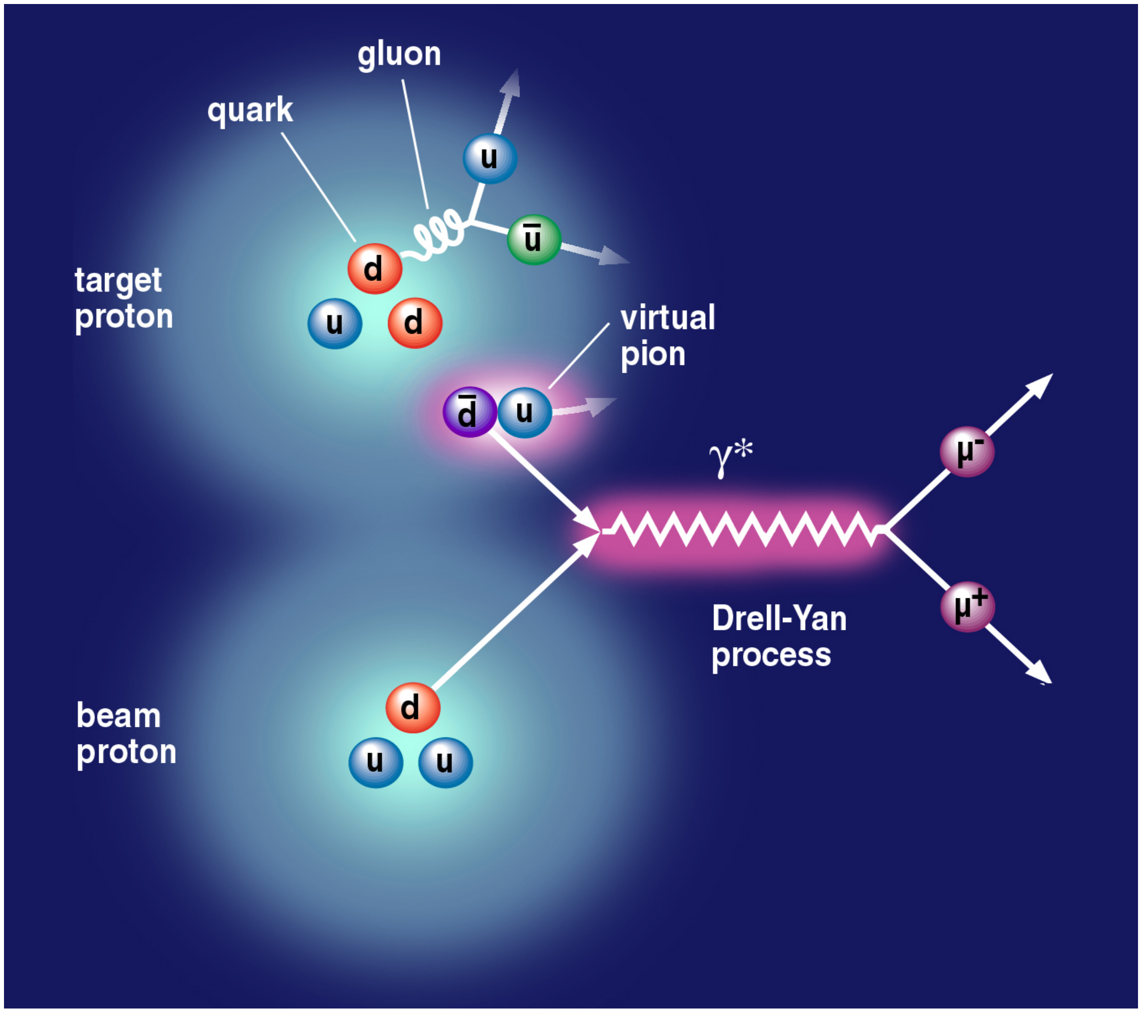


$$\sigma_{DY} \propto \sum_i e_i^2 \left[q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t) \right]$$

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Sea Asymmetry probed by Drell-Yan

Nucleon Structure and Vacuum Quantum Fluctuation



$$g \rightarrow u + \bar{u}, \quad g \rightarrow d + \bar{d}$$

$$\bar{d} \approx \bar{u}$$

$$p(uud) \rightarrow n(udd) + \pi^{+}(u\bar{d})$$

$$\bar{d} > \bar{u}$$

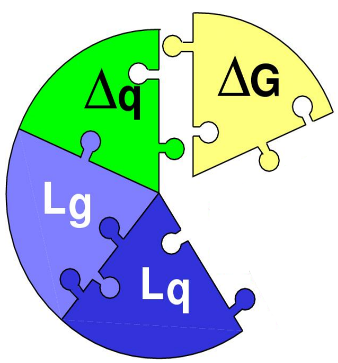
Surprises in Hadron (Spin) Physics (I)

the QCD challenge of "Too Small"

- Proton Spin Puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_q + \Delta L_g$$

$$\Delta\Sigma \sim 0.3! \quad (\sim 1.0 \text{ expected})$$



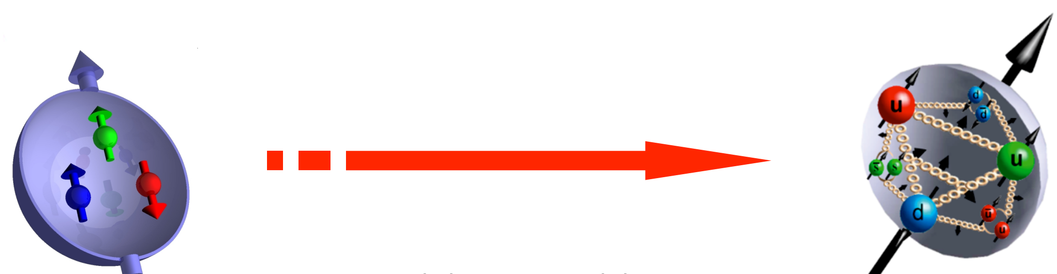
- Spin Physics @RHIC, J-Lab, CERN, JPARC …
  - Gluon polarization

$$\Delta G = \int_0^1 dx \cdot \Delta g(x)$$

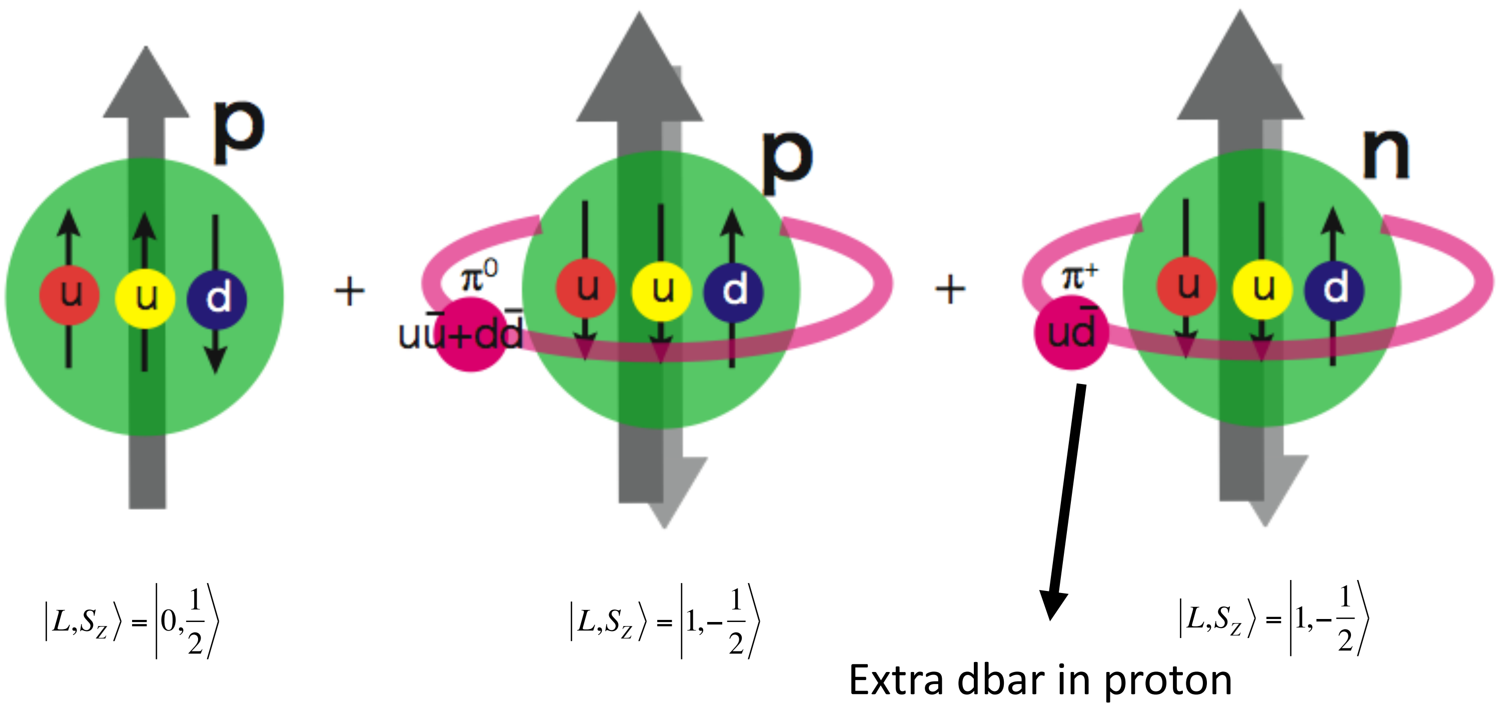
  - Quark polarization

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \ldots$$

  - Orbital angular mom.?



Pion Cloud Model and the Orbital Angular Momentum?!



Sea Quarks Carry Major Orbital Angular Momentum Component?

Pion Cloud and Orbital Angular Momentum

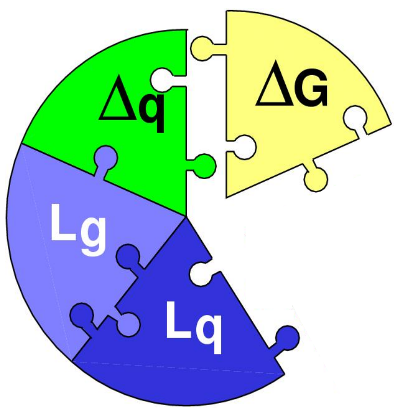
- "Proton spin puzzle", sea quark flavor asymmetry and L_Z

G. Garvey, PRC81:055212,2010.

$$|p\rangle = \frac{1}{\sqrt{1+a^2+b^2}}[|p_0\rangle + a(-\sqrt{\frac{1}{3}}|p_0\pi^0\rangle + \sqrt{\frac{2}{3}}|n_0\pi^+\rangle) + b(\sqrt{\frac{1}{2}}|\Delta_0^{++}\pi^-\rangle - \sqrt{\frac{1}{3}}|\Delta_0^{+}\pi^0\rangle + \sqrt{\frac{1}{6}}|\Delta_0^{0}\pi^+\rangle)]$$

$$I_{fasy} = \int_0^1 dx[\bar{d}(x) - \bar{u}(x)] = \frac{2a^2 - b^2}{3(1+a^2+b^2)} = 0.147 \pm 0.027$$

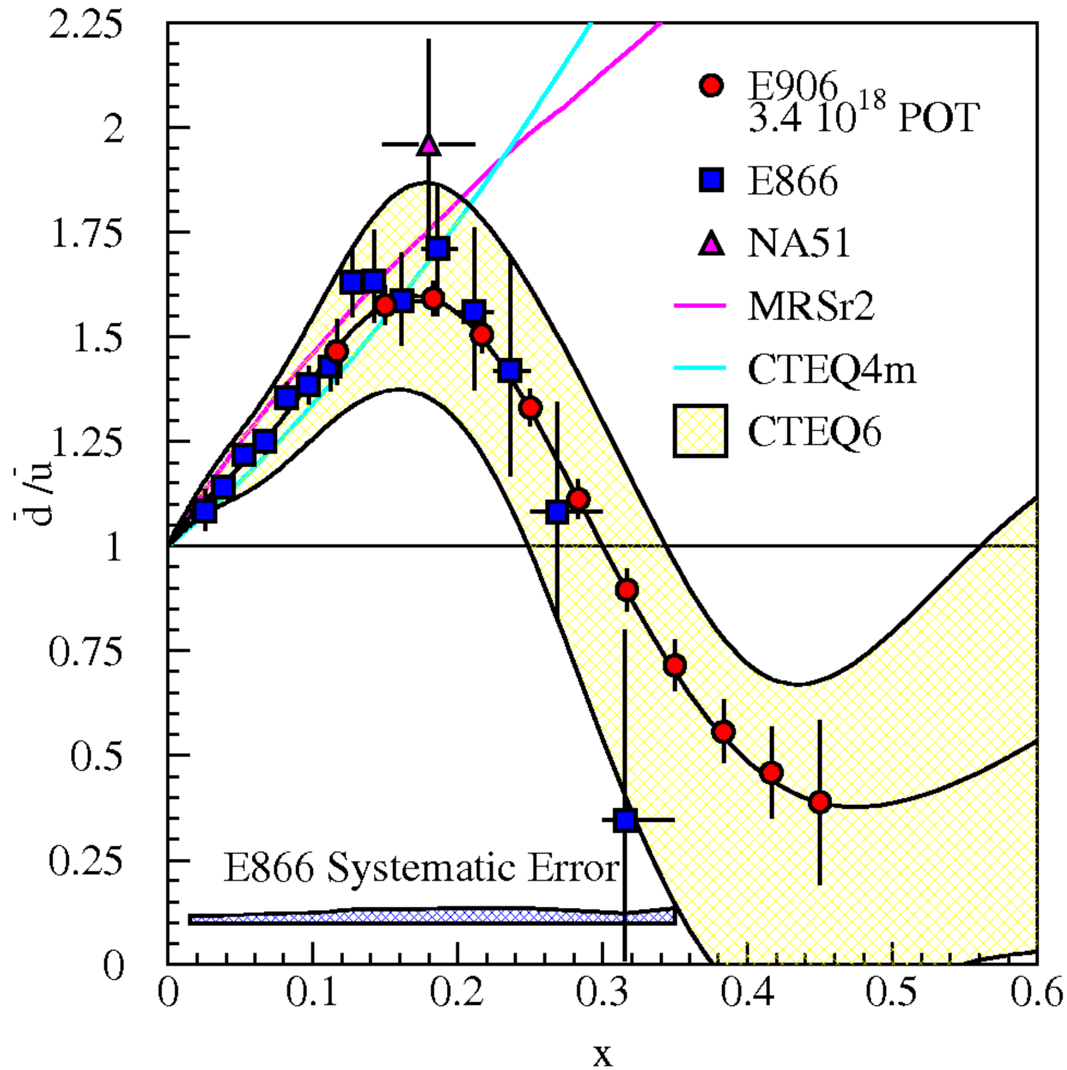
$$\langle p^\uparrow | \hat{L}_Z | p^\uparrow \rangle = \frac{2a^2 - b^2}{3(1+a^2+b^2)} = 0.147 \pm 0.027 \sim 30\%[\frac{1}{2}]$$



$$\frac{1}{2} = \frac{1}{2}\Delta q + L_q^z + \Delta g + L_g^z$$

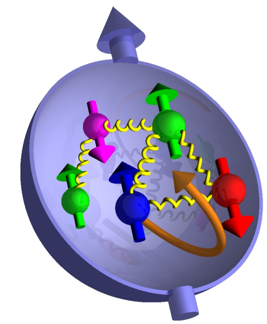
E906 Projections for d-bar/u-bar Ratio

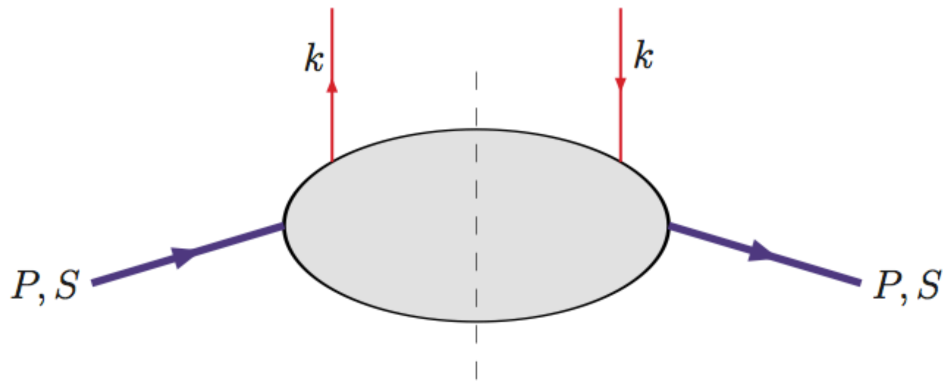
- SeaQuest will extend these measurements and reduce statistical uncertainty
- SeaQuest expects systematic uncertainty to remain at ≈1% in cross section ratio
- 5 s slow extraction spill each minute
- Intensity:
  - 2 x 10^{12} protons/s
  - 1 x 10^{13} protons/spill



Nucleon Quark Structure, TMD

Beyond Leading-Twist Collinear Approximation





Correlator:

$$\Phi_{ij}(k;P,S) = \sum_X \int \frac{d^3 \boldsymbol{P}_X}{(2\pi)^3\, 2E_X} (2\pi)^4\, \delta^4(P-k-P_X) \langle PS|\overline{\Psi}_j(0)|X\rangle\langle X|\Psi_i(0)|PS\rangle$$

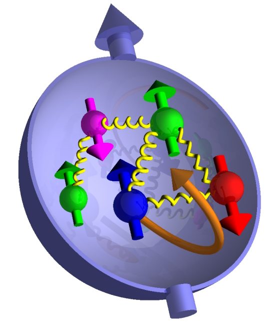
$$= \int d^4\xi\, e^{ik\cdot\xi} \langle PS|\overline{\Psi}_j(0)\Psi_i(\xi)|PS\rangle$$

$$\Phi(x,S) = \frac{1}{2}\left[f_1(x)\, \not{n}_+ + S_L\, g_{1L}(x)\, \gamma^5\, \not{n}_+ + h_{1T}\, i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu\right]$$

q Δq $\Delta_T q$

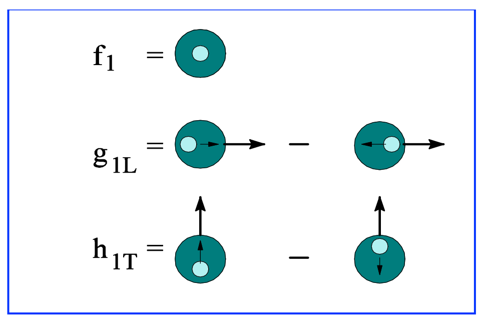
- Partonic interpretation of hard scatterings
- Universal functions

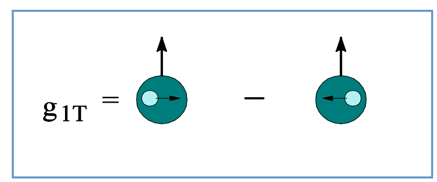
Including k_T … TMDs



$$\Phi(x,\boldsymbol{k}_\perp) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \Big(S_L g_{1L} + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} g_{1T}^\perp \Big) \gamma^5 \not{n}_+$$
$$+ h_{1T} i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu + \Big(S_L h_{1L}^\perp + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} h_{1T}^\perp \Big) \frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M}$$
$$+ h_1^\perp \frac{\sigma_{\mu\nu} k_\perp^\mu n_+^\nu}{M} \Big]$$

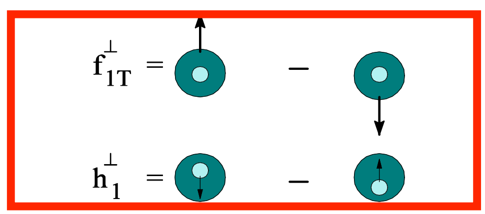
No $K_\perp$ dependence





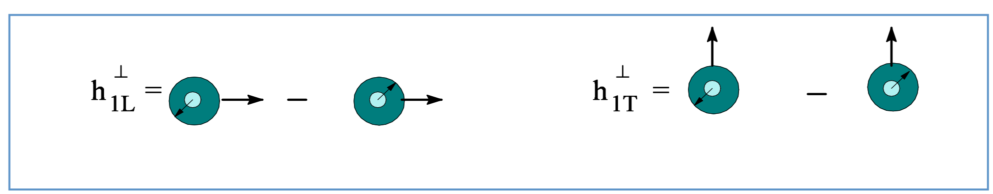
$K_\perp$ - dependent

T-odd



$K_\perp$ - dependent

T-even



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

Three transverse quantities:

1) Nucleon transverse spin

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

2) Quark transverse spin

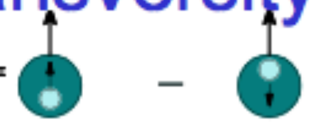
$\vec{s}_{\perp}^{q}$

3) Qaurk transverse momentum

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

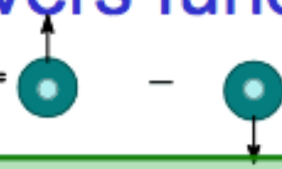
⇒ Three different correlations

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

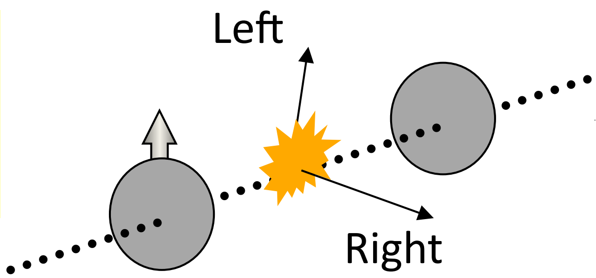
35

Surprises in Hadron (Spin) Physics (II)

the QCD challenge of "Too Large"

Transverse Single Spin Asymmetries A_N

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$



Theory Expectation:

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N ~ $O(10^{-4})$ theory

Experiments:

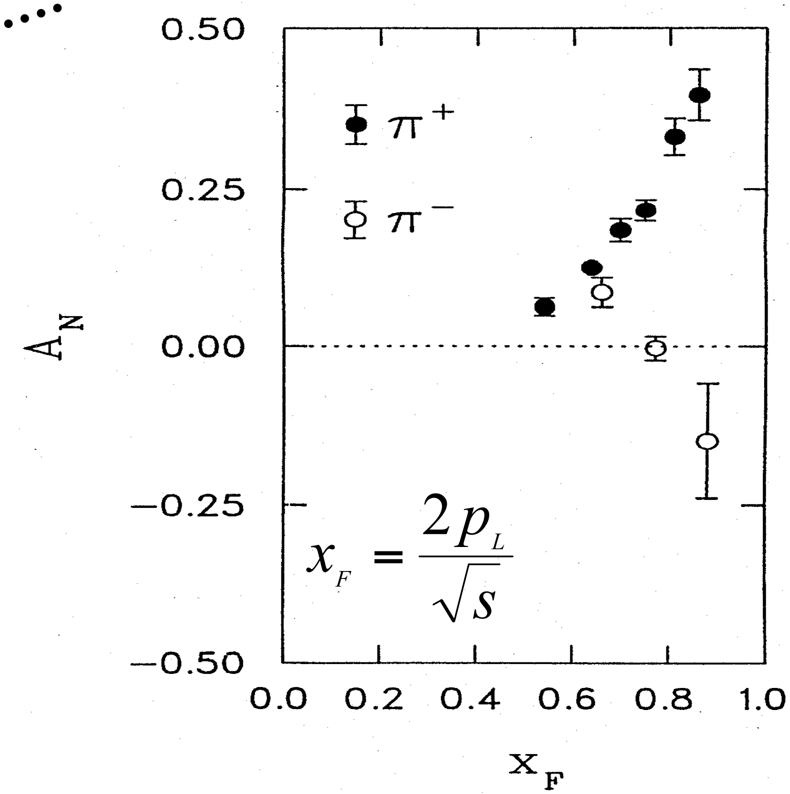
ZGS, AGS, FERMILAB to RHIC

$$pp^{\uparrow} \rightarrow \pi + X$$

A_N ~ $O(10^{-1})$ observed

$$\sqrt{s} = 5 \sim 500 \text{ GeV}$$

Argonne ZGS, p_{beam} = 12 GeV/c

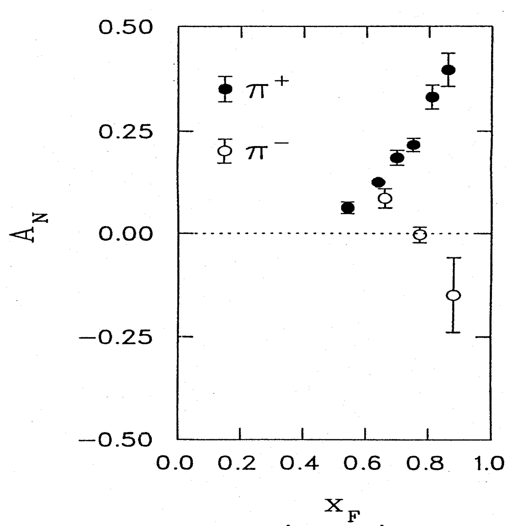


W.H. Dragoset et al., PRL36, 929 (1976)

Transverse SSA's

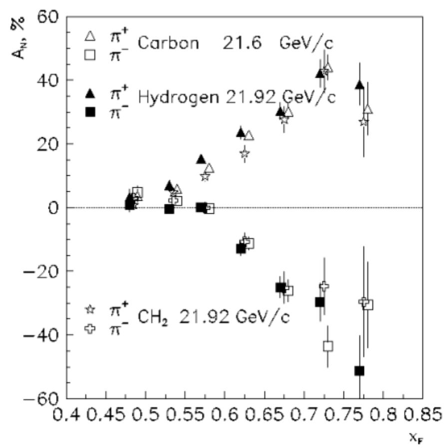
from low to high energies

ZGS 12 GeV beam



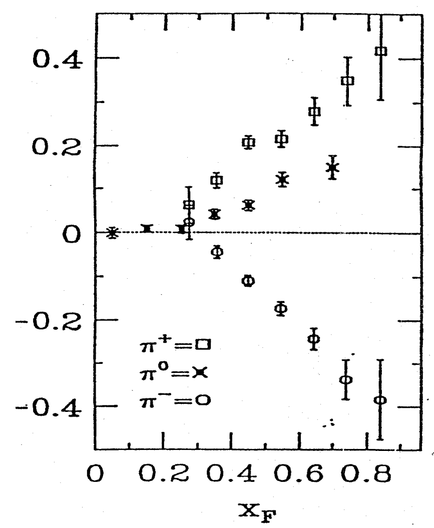
PRL36, 929 (1976)

AGS 22 GeV beam



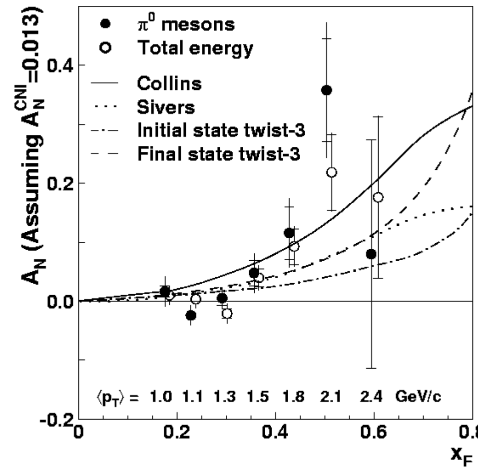
PRD65, 092008 (2002)

FNAL 200 GeV beam



PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC 20,000 GeV beam



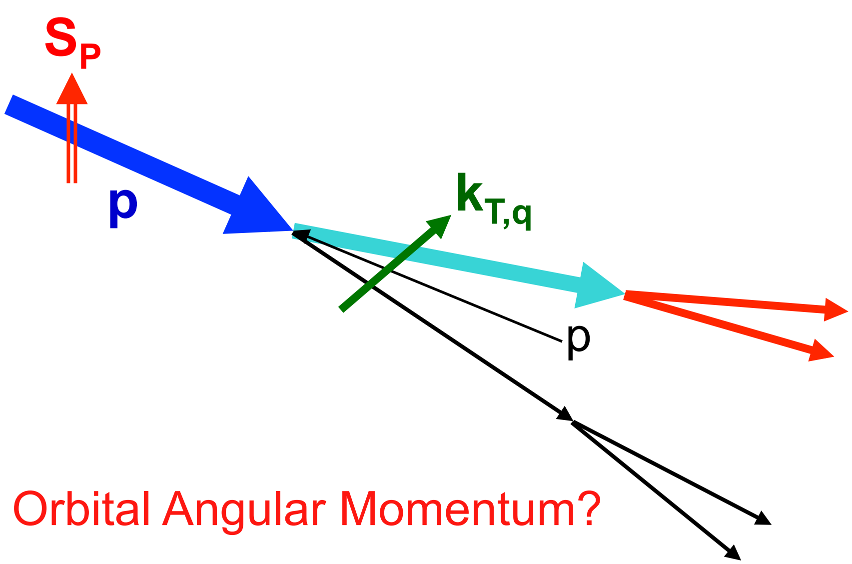
PRL (2004)

Non-Perturbative cross section → Perturbative cross section

Possible Mechanisms …

Sivers mechanism: Correlation between nucleon spin and parton k_T

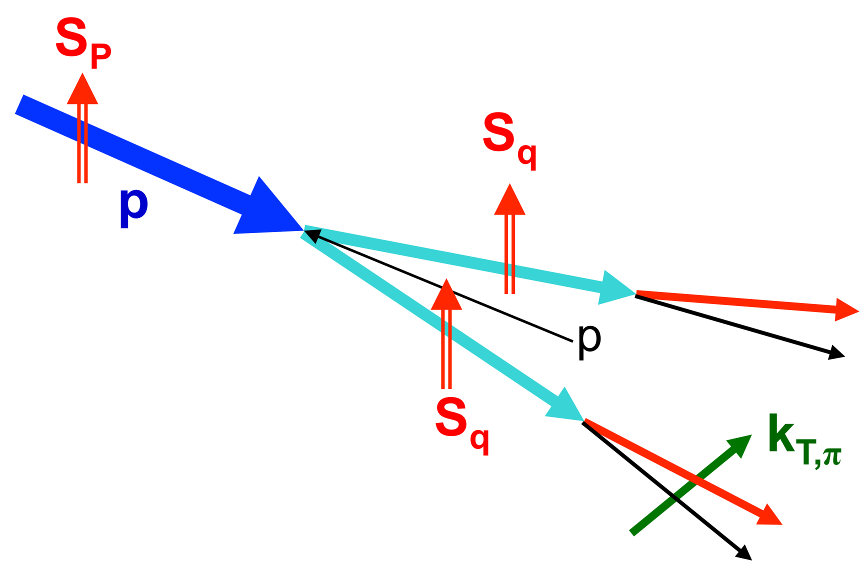
Phys Rev D41 (1990) 83; 43 (1991) 261



Orbital Angular Momentum?

Collins mechanism: Transversity (quark polarization) * asymmetry in the jet fragmentation

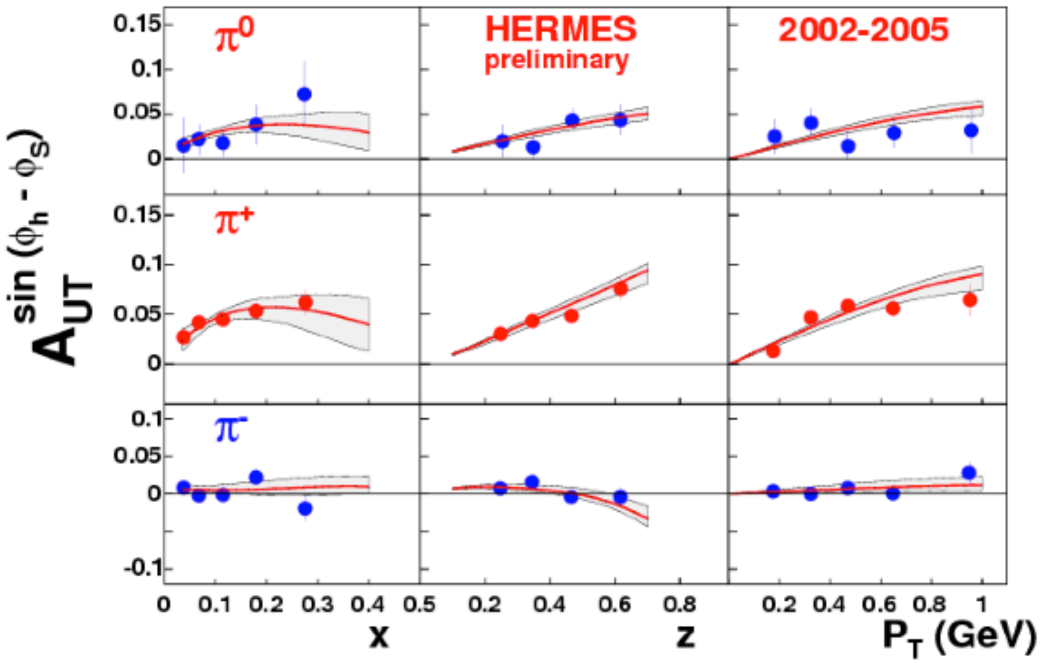
Nucl Phys B396 (1993) 161

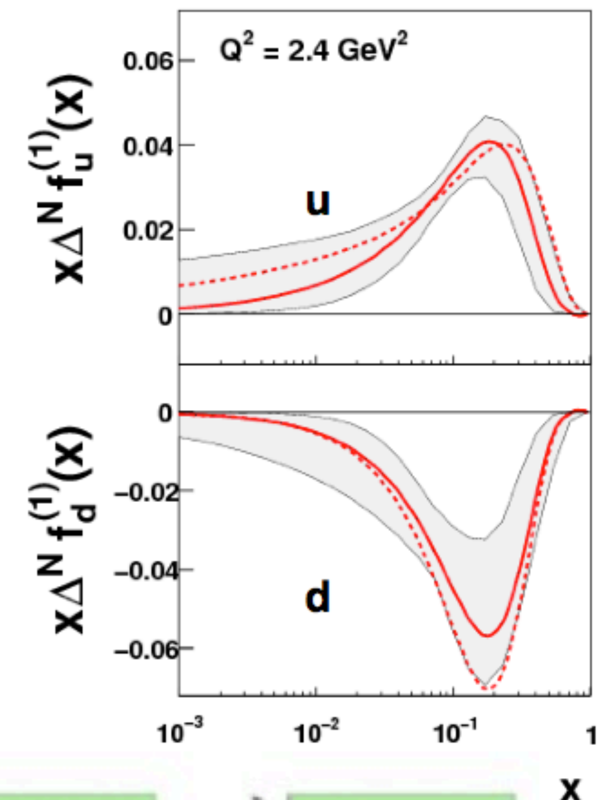


Sivers function from SIDIS

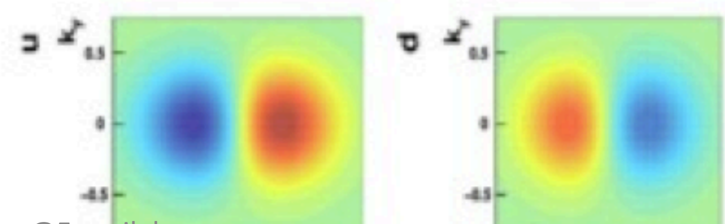
- Extract Sivers function from SIDIS

Anselmino, et.al., 2009



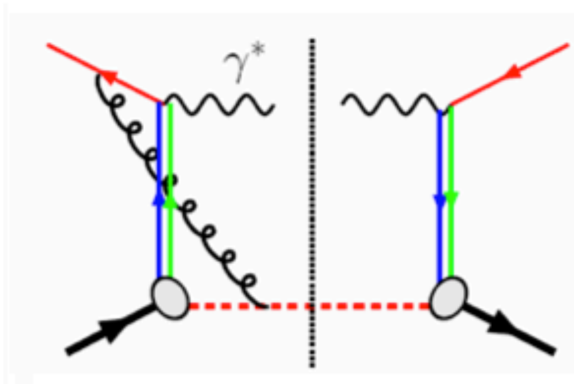


- u and d almost equal size, different sign



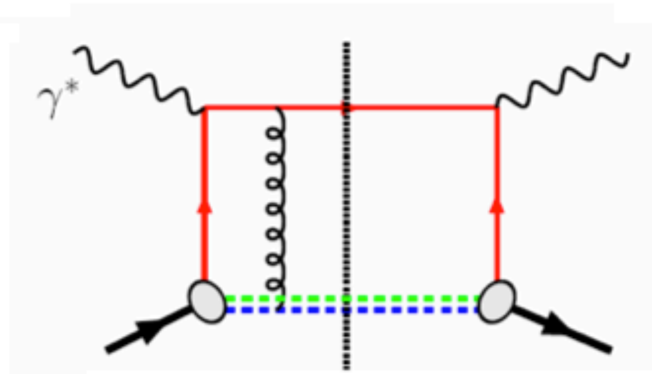
Sivers Functions in DY and DIS

- The sign change – a new fundamental test of color gauge formalism



$$p^{\uparrow} + p \to [\gamma^* \to \ell^+\ell^-] + X$$

DY: repulsive



$$\ell + p^{\uparrow} \to \ell + \pi + X$$

SIDIS: attractive

$$\Delta^N f_{q/h^{\uparrow}}^{\mathrm{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h^{\uparrow}}^{\mathrm{DY}}(x, k_\perp)$$

Collins '02

Twist-3: sign change from gluonic-pole in hard parts

In the overlapped region – consistent description

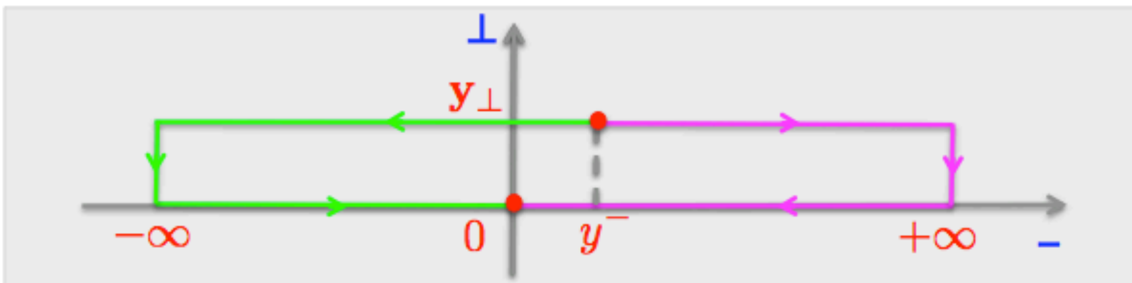
Ji, Qiu, Vogelsang, Yuan '06
Bacchetta, Boer, Diehl, Mulders '08

Non-universality of the Sivers function

- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3}\, e^{ixp^+y^- - i\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\, \boxed{\text{Gauge link}}\, \frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

  - SIDIS: $\Phi_n^\dagger(\{+\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(+\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{+\infty,y^-\},\mathbf{y}_\perp)$
  - DY: $\Phi_n^\dagger(\{-\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(-\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{-\infty,y^-\},\mathbf{y}_\perp)$

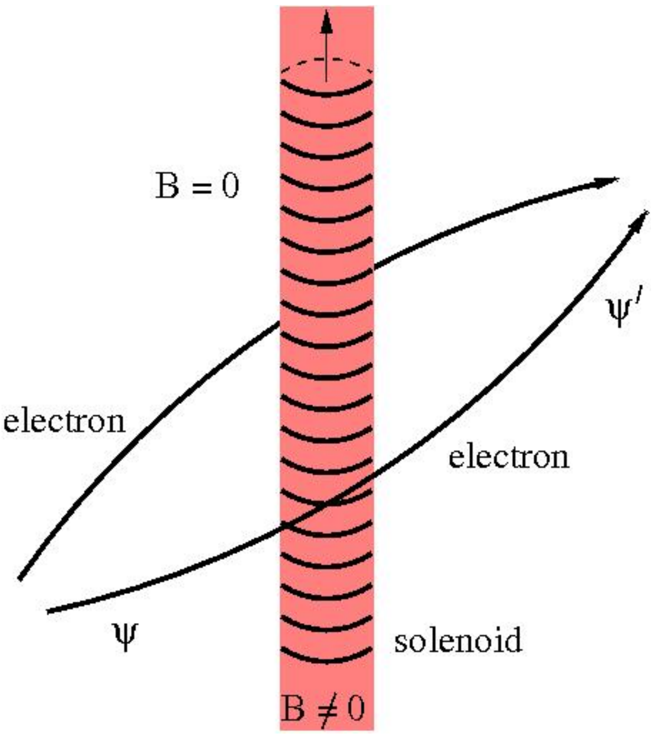


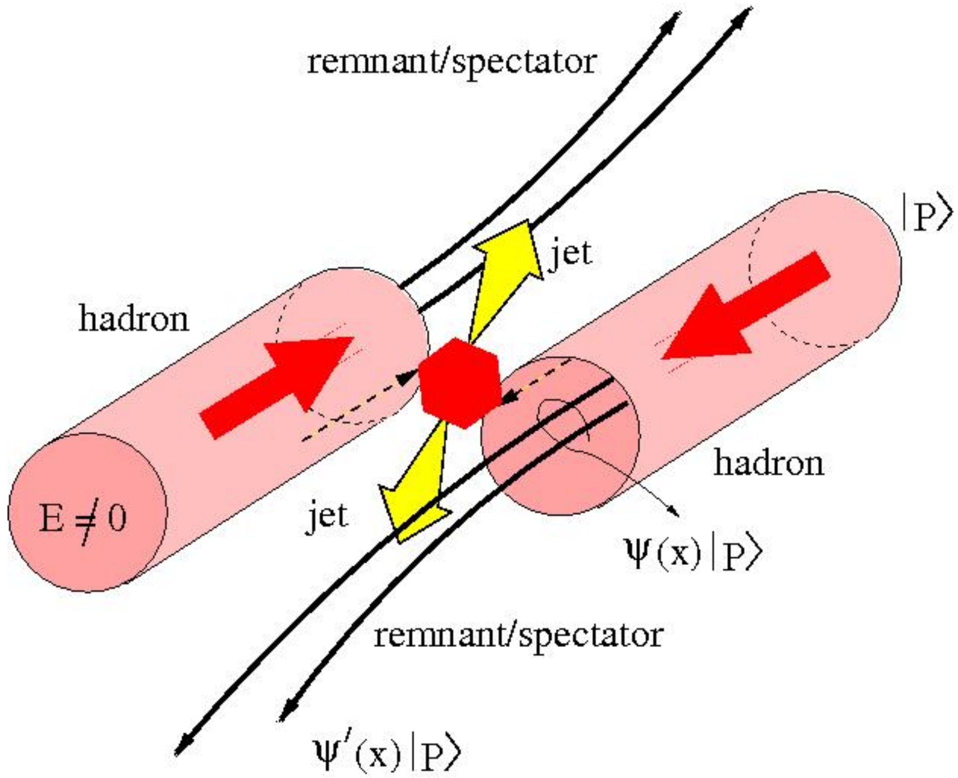
Wilson Loop ~ $\exp\left[-ig\int_\Sigma d\sigma^{\mu\nu}F_{\mu\nu}\right]$ Area is NOT zero

- For a fixed spin state:

$$f_{q/h^\uparrow}^{\text{SIDIS}}(x,\mathbf{k}_\perp,\vec{S}) \neq f_{q/h^\uparrow}^{\text{DY}}(x,\mathbf{k}_\perp,\vec{S})$$

Featuring: phases in gauge theories



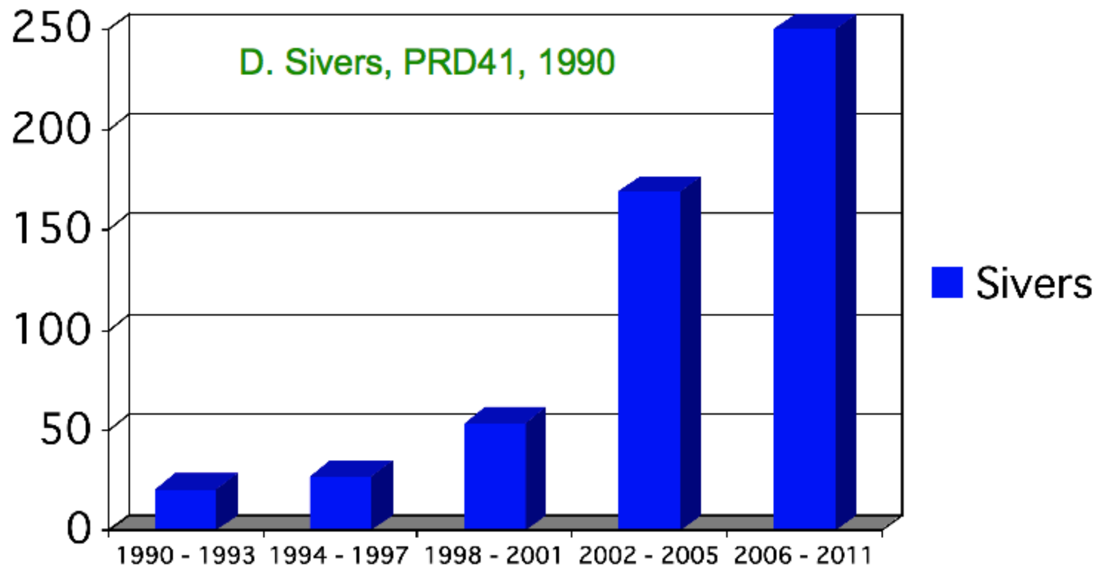


$$\psi' = e^{ie\int ds.A}\psi$$

$$\psi_i(x)\left|P\right\rangle = e^{-ig\int_x^{x'} ds_\mu A^\mu}\psi_i(x')\left|P\right\rangle$$

Transverse spin physics: birth and growth

- Historically transverse spin physics has been a source of much controversy
  - Early days (before 1980s), it was thought to be not very interesting
  - Recently it has become a very active research branch
- Citations tell the story: Sivers function - birth and growth



Apr 4, 2011 Zhongbo Kang, RBRC/BNL 2

=> Probe Sivers Functions via Polarized DY!

Transversity and TMDs can be probed via DY

Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}\bar{h}_1^{\perp}\cos(2\phi)$

Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

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

Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

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

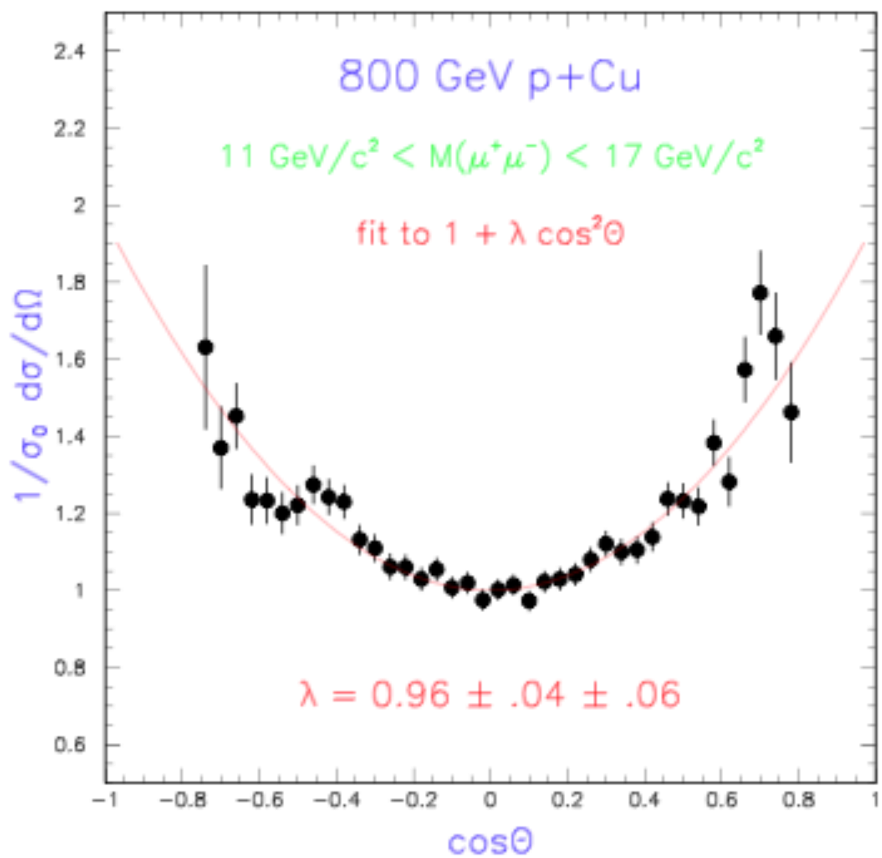
- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

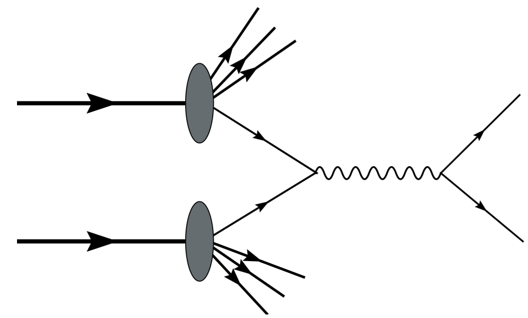
Remains to be tested experimentally!

Drell-Yan angular distribution

Decay Angular Distribution of "naïve" Drell-Yan:

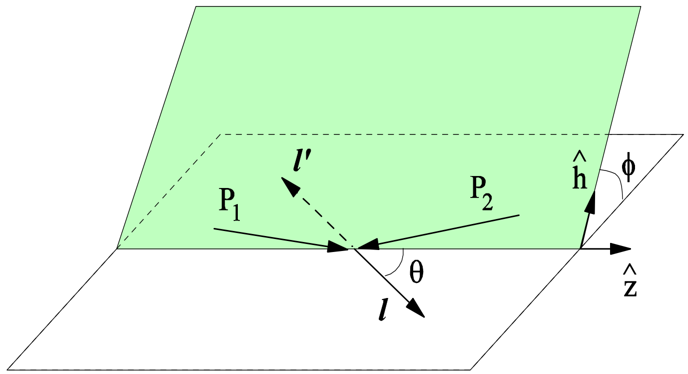
$$\frac{d\sigma}{d\Omega} = \sigma_0(1+\cos^2\theta)$$





Data from Fermilab E772

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:

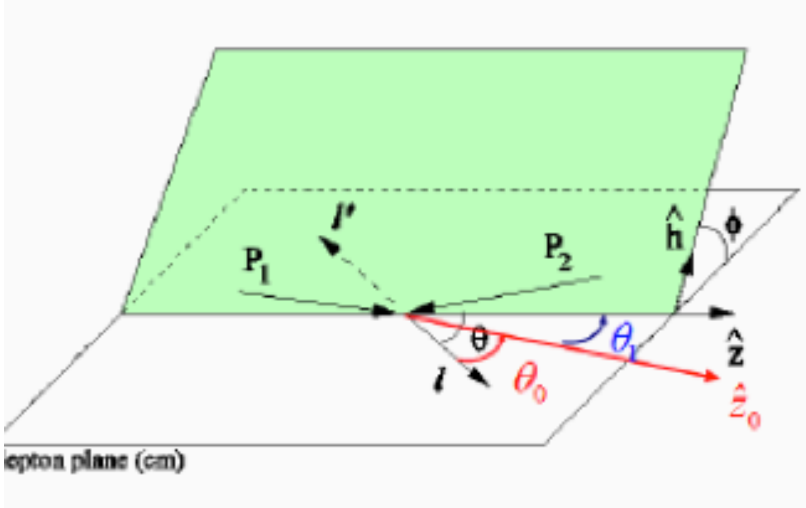
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

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

A simple geometric derivation of the generalized Lam-Tung relation (a la Oleg Teryaev)

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



In the γ^* rest frame:

$\hat{z}$ signifies the Collins-Soper frame

$\hat{z}_0$ is along the collinear $q-\bar{q}$ axis

Leptons are emitted with uniform azimuthal distribution, and with θ_0 dependence:

$$d\sigma \sim 1+\lambda_0\cos^2\theta_0$$

($\lambda_0 = 1$ for spin-1/2 quark;
$\lambda_0 = -1$ for spin-0 quark)

$$\cos\theta_0 = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos\phi$$

$$d\sigma \sim 1+\lambda_0(\cos\theta\cos\theta_1+\sin\theta\sin\theta_1\cos\phi)^2$$
$$=[1+(\lambda_0/2)\sin^2\theta_1]+\cos^2\theta[\lambda_0\cos^2\theta_1-(\lambda_0/2)\sin^2\theta_1]$$
$$+\sin 2\theta\cos\phi[(\lambda_0/2)\sin 2\theta_1]+\sin^2\theta\cos 2\phi[(\lambda_0/2)\sin^2\theta_1]$$

Decay angular distributions in pion-induced Drell-Yan

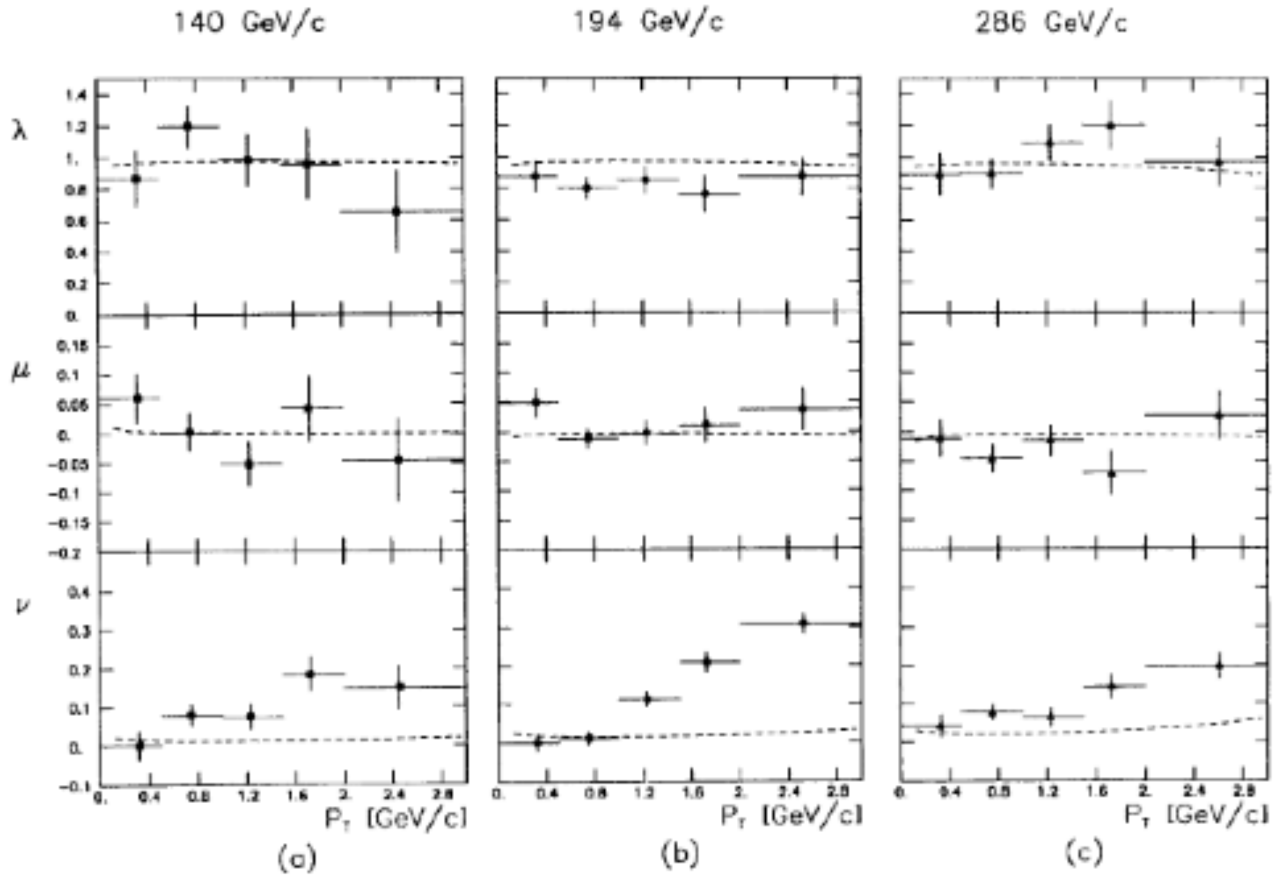


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. a 140 GeV/c; b 194 GeV/c; c 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + W$

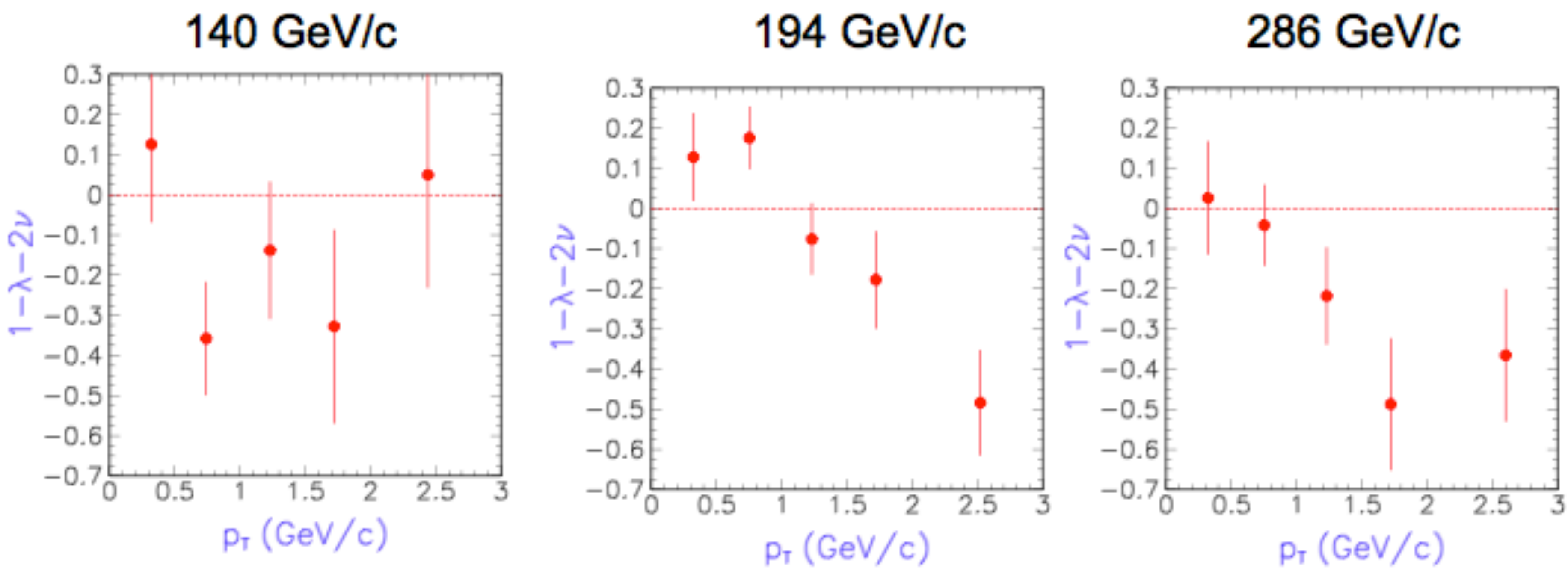
Z. Phys. 37 (1988) 545

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?



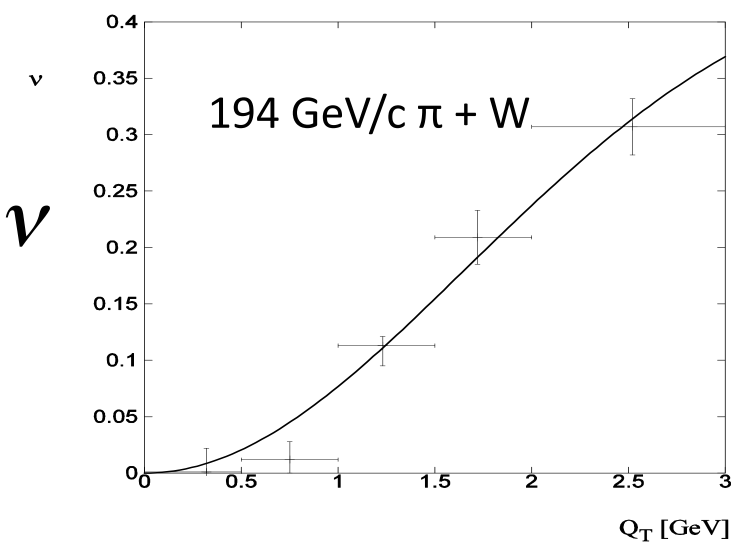
Data from NA10 (Z. Phys. 37 (1988) 545)

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

Unpolarized Beam DY and 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

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



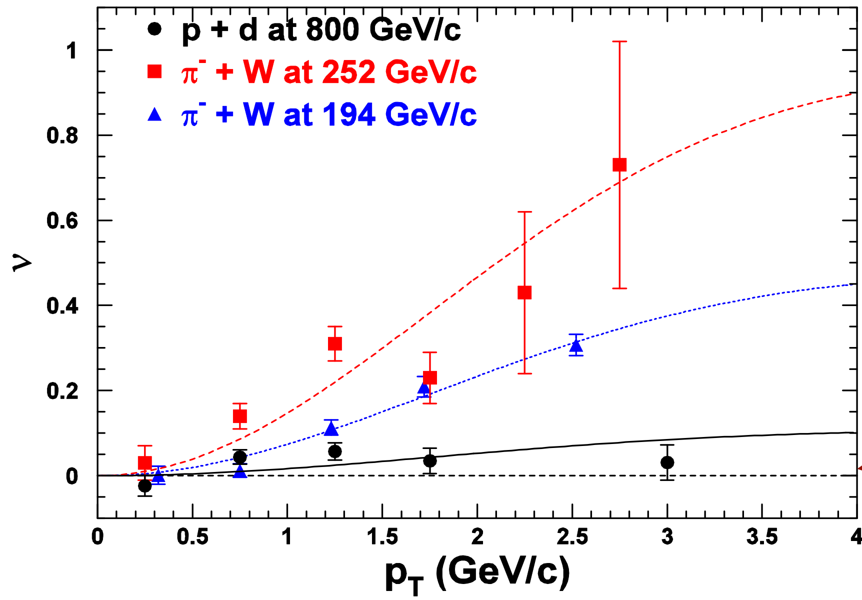
Boer, PRD 60 (1999) 014012

- Observation of large cos(2Φ) dependence in Drell-Yan with pion beam

$$\nu \propto h_1^\perp(x_q)h_1^\perp(x_{\bar{q}})$$

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

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



Small ν is observed for p+d 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 $h_1^{\perp}(p)$]

More data expected from E906 soon!

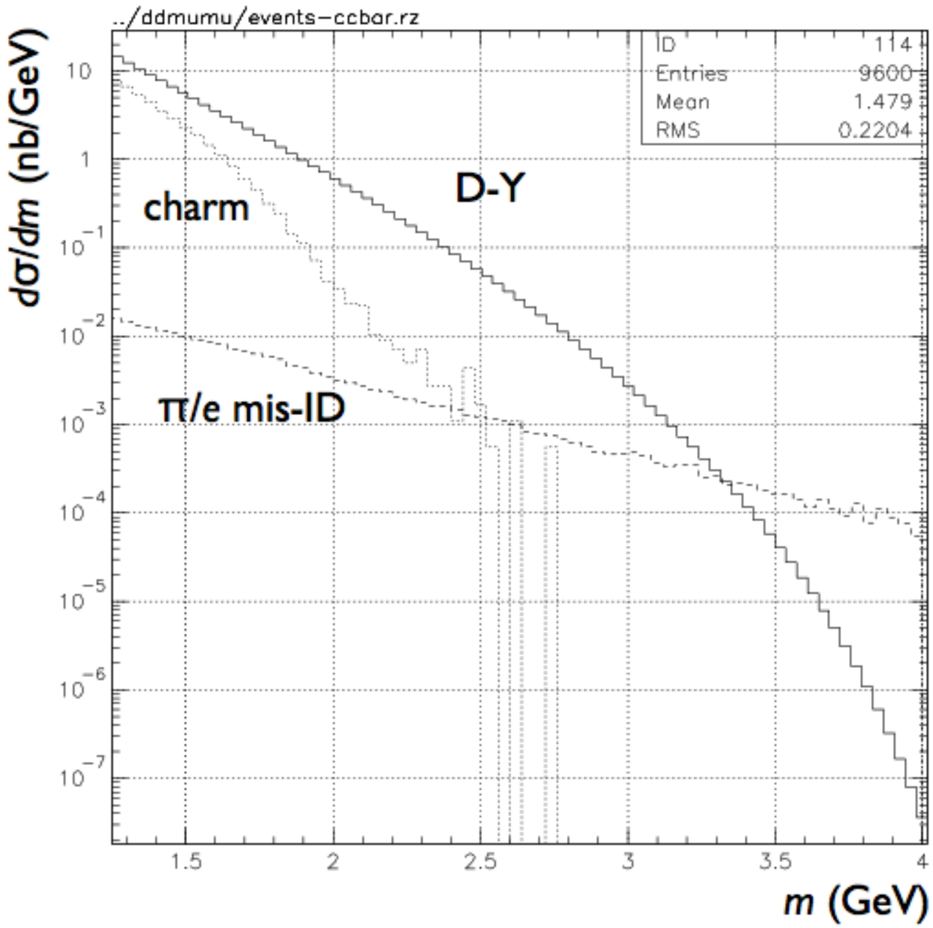
Sea-quark BM functions are much smaller than valence quarks

29

Drell-Yan with anti-protons at Fermilab

- pbar-p:
  - (valence – valence) interaction!
- Expect large TMD effects
  - Possible "strong violation" of Lam-Tung relation?
  - Quark Boer-Mulder functions in p and pbar

$\bar{p}p$ Drell-Yan



Compare signal with main backgrounds

- Low energy is advantageous:
  - ➡ less charm background
  - ➡ fewer pions to confuse
  - ➡ allows measurement in new kinematic region

New Opportunities for Polarized Program at Fermilab

- Anti-proton on polarized proton target – Transverse Single Spin Asymmetry
  - Possible with polarized frozen proton target (BNL, J-Lab etc.)
  - Drell-Yan TSSA sign change!
  - Open charm TSSA: charm vs anti-Charm!
  - Lambda polarization

- High density polarized proton target (NH3)
  - Polarized Drell-Yan with E906 spectrometer
    - 120GeV (polarized) proton beam
  - Antiproton beams 120GeV?

Proposed Future Polarized DY Exp's

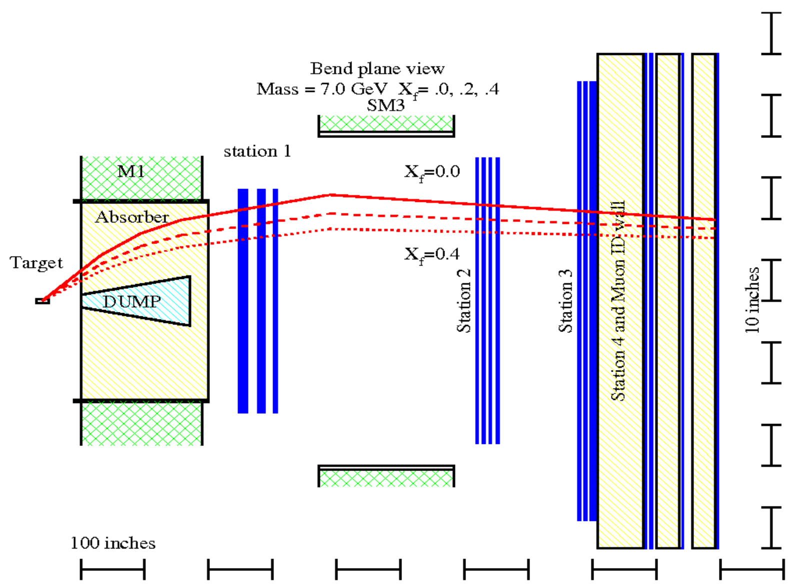
Y. Goto 4/2010 CERN DY

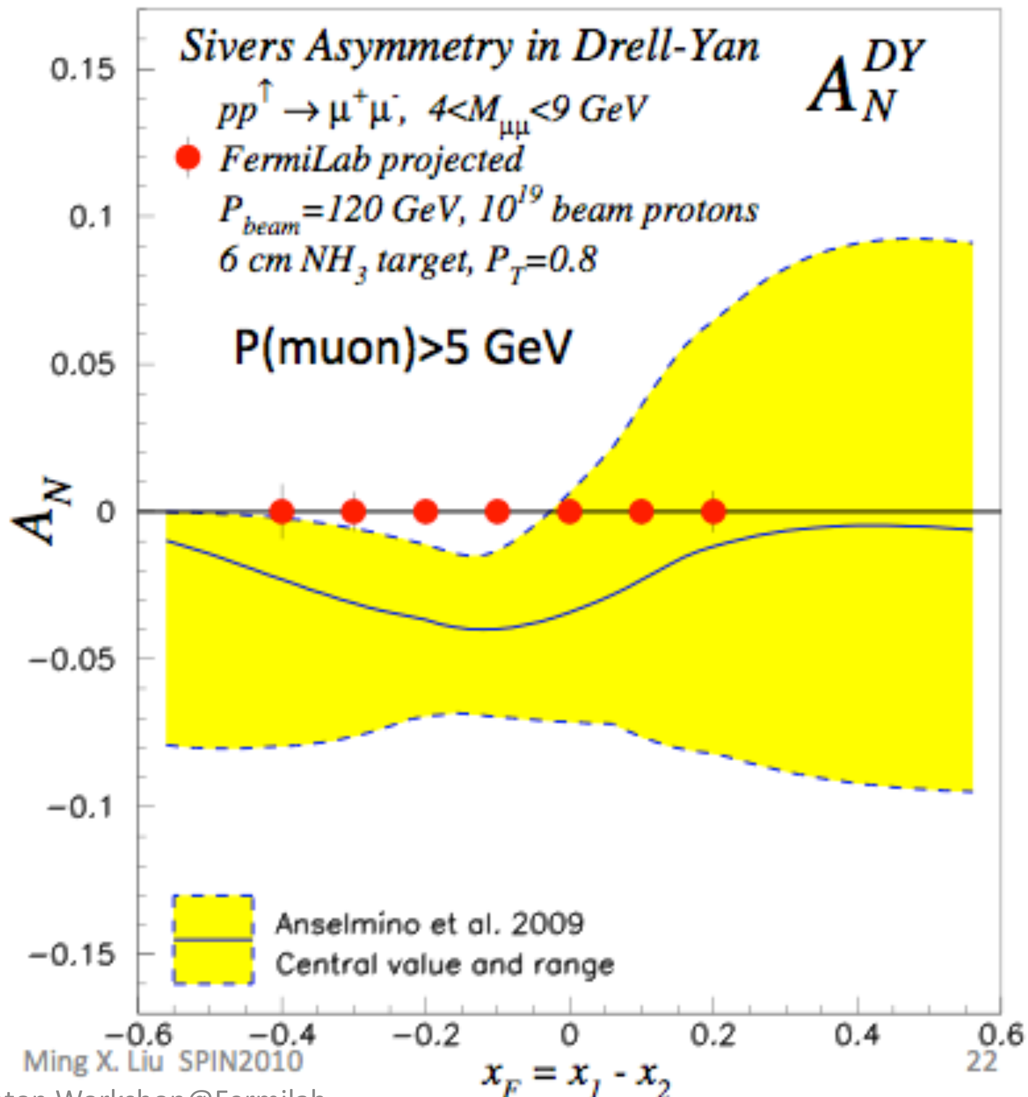
experiment	particles	energy	x1 or x2	luminosity
COMPASS	$\pi\pm$ + p↑	160 GeV √s = 17.4 GeV	x2 = 0.2 – 0.3	2×10^{33} $cm^{-2}s^{-1}$
COMPASS (low mass)	$\pi\pm$ + p↑	160 GeV √s = 17.4 GeV	x2 ~ 0.05	2×10^{33} $cm^{-2}s^{-1}$
PAX	p↑ + pbar	collider √s = 14 GeV	x1 = 0.1 – 0.9	2×10^{30} $cm^{-2}s^{-1}$
PANDA (low mass)	pbar + p↑	15 GeV √s = 5.5 GeV	x2 = 0.2 – 0.4	2×10^{32} $cm^{-2}s^{-1}$
J-PARC	p↑ + p	50 GeV √s = 10 GeV	x1 = 0.5 – 0.9	10^{35} $cm^{-2}s^{-1}$
NICA	p↑ + p	collider √s = 20 GeV	x1 = 0.1 – 0.8	10^{30} $cm^{-2}s^{-1}$
SPASCHARM (low mass)	p + p↑	60 GeV √s = 11 GeV	x2 = 0.05 – 0.2	
SPASCHARM (low mass)	$\pi\pm$ + p↑	34 GeV √s = 8 GeV	x2 = 0.1 – 0.3	
RHIC PHENIX Muon	p↑ + p	collider √s = 500 GeV	x1 = 0.05 – 0.1	2×10^{32} $cm^{-2}s^{-1}$
RHIC Internal Target phase-1	p↑ + p	250 GeV √s = 22 GeV	x1 = 0.25 – 0.4	2×10^{33} $cm^{-2}s^{-1}$
RHIC Internal Target phase-2	p↑ + p	250 GeV √s = 22 GeV	x1 = 0.25 – 0.4	6×10^{34} $cm^{-2}s^{-1}$

- **Polarized DY Dimuon Exp. at Fermilab Main Injector: 120GeV**
- **RHIC fixed target possibility: 250 GeV**

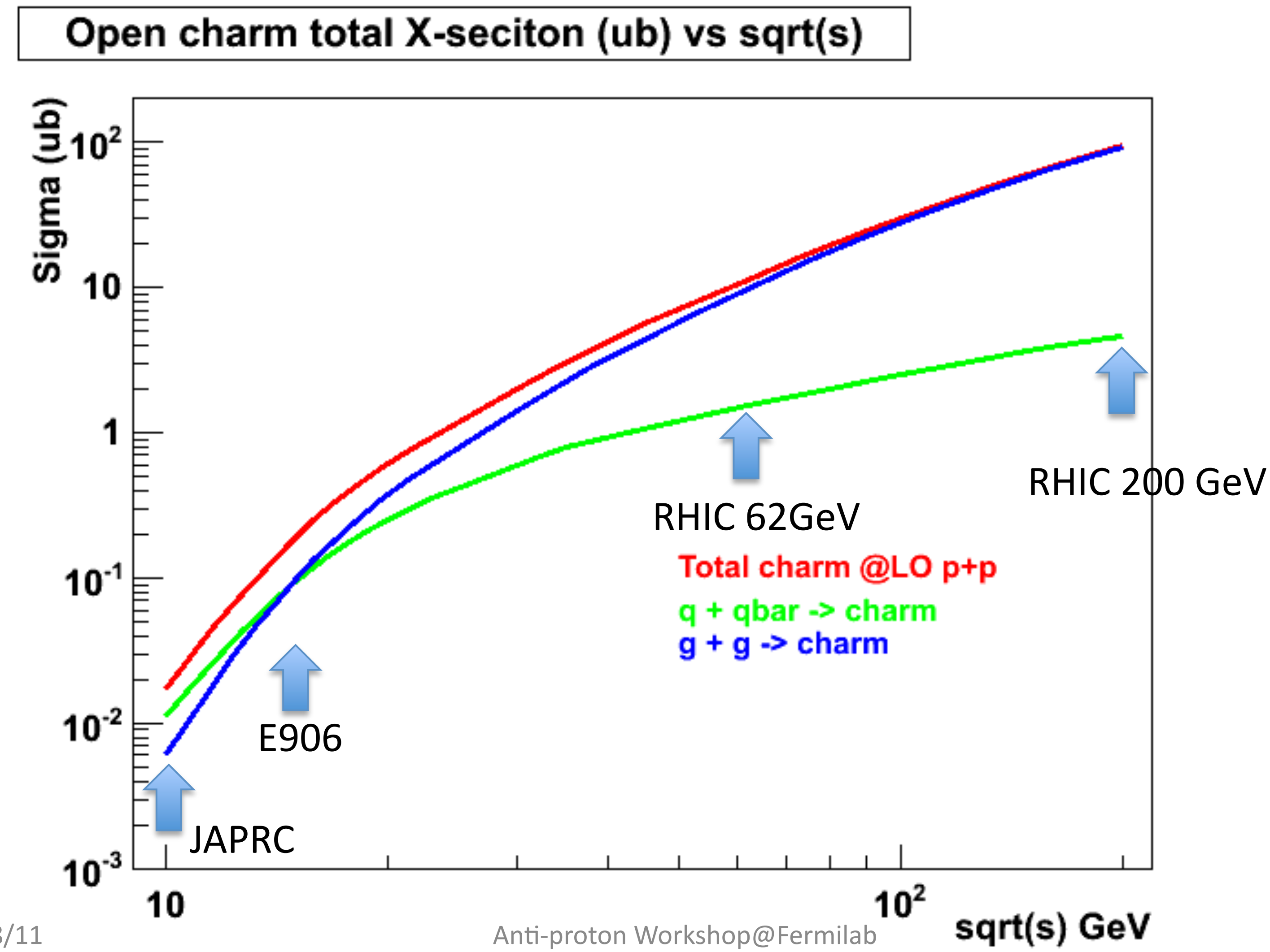
Polarized Drell-Yan @Fermilab?

- Polarized Target?
    - 6 cm NH_3
    - 10^{19} proton
- Polarized beam?





Open Charm Production in p+p with PYTHIA (LO)



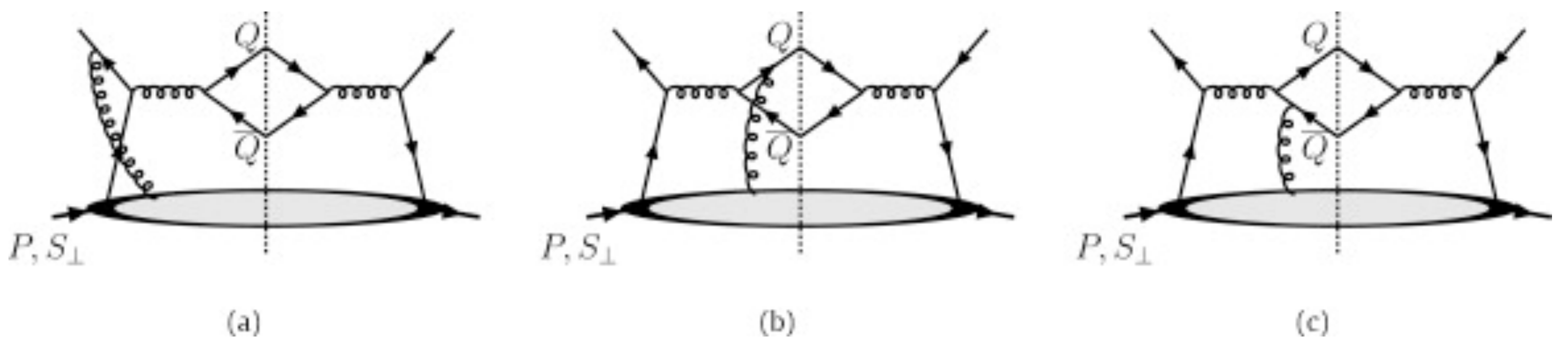
Heavy Quark TSSA pbar-p @Fermilab

Twist-3 quark-gluon correlation fun.

- Different color factors for charm and anti-charm A_N

$$q + \overline{q} \rightarrow c\overline{c}$$

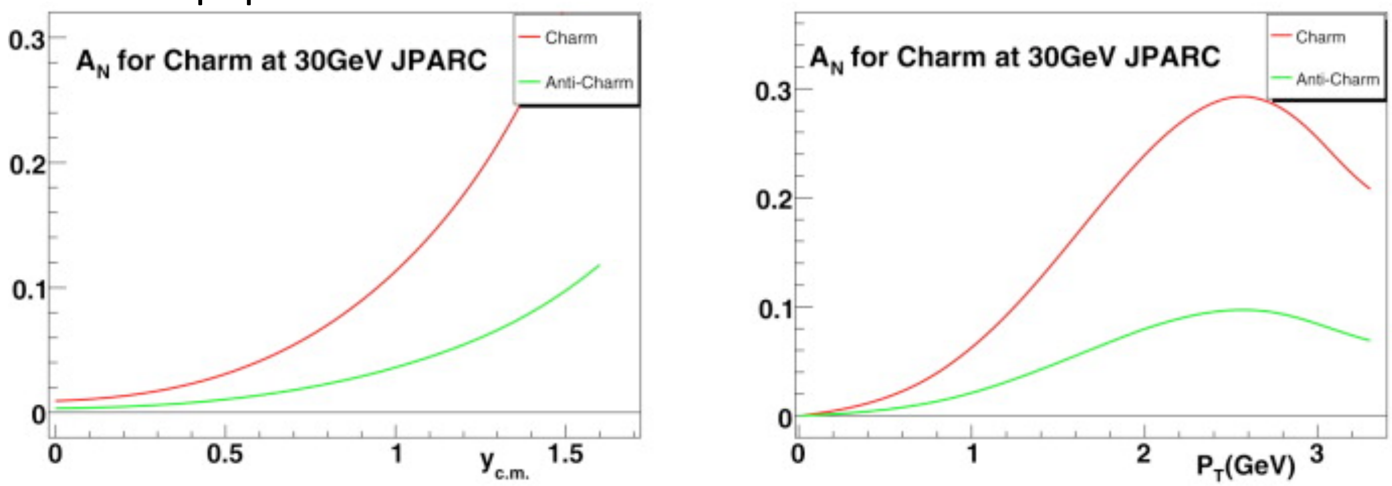
F. Yuan and J. Zhou PLB 668 (2008) 216-220



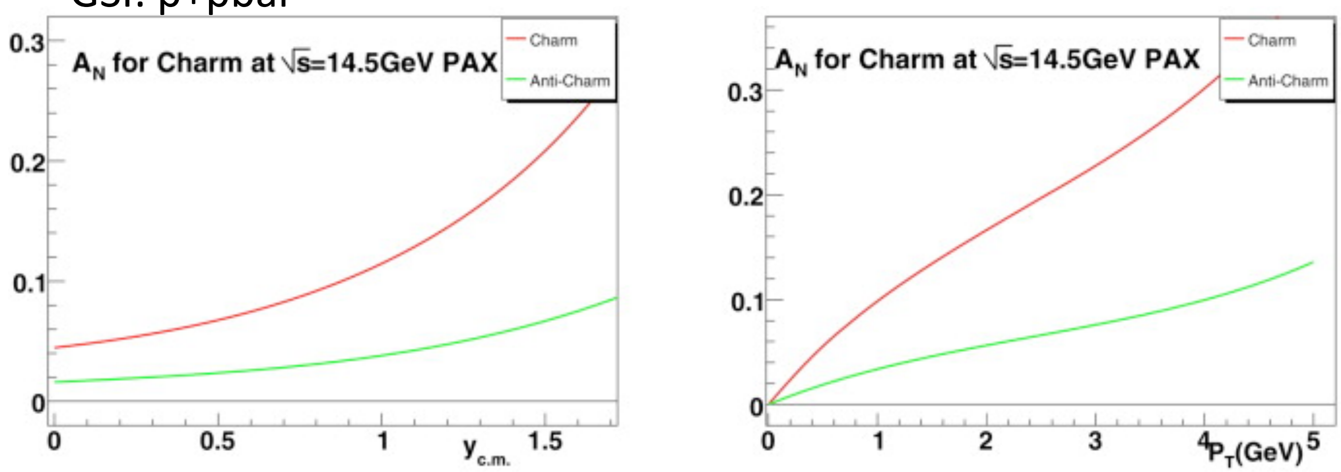
Initial state	Charm	anti-Charm
$\sim \frac{1}{2N_C^2}$	$\sim \frac{N_C^2 - 2}{2N_C^2}$	$\sim \frac{2}{2N_C^2}$

$$A_N : \bar{p} + p\,(q + \bar{q}) \rightarrow c(\bar{c}) + X$$

JPARC p+p



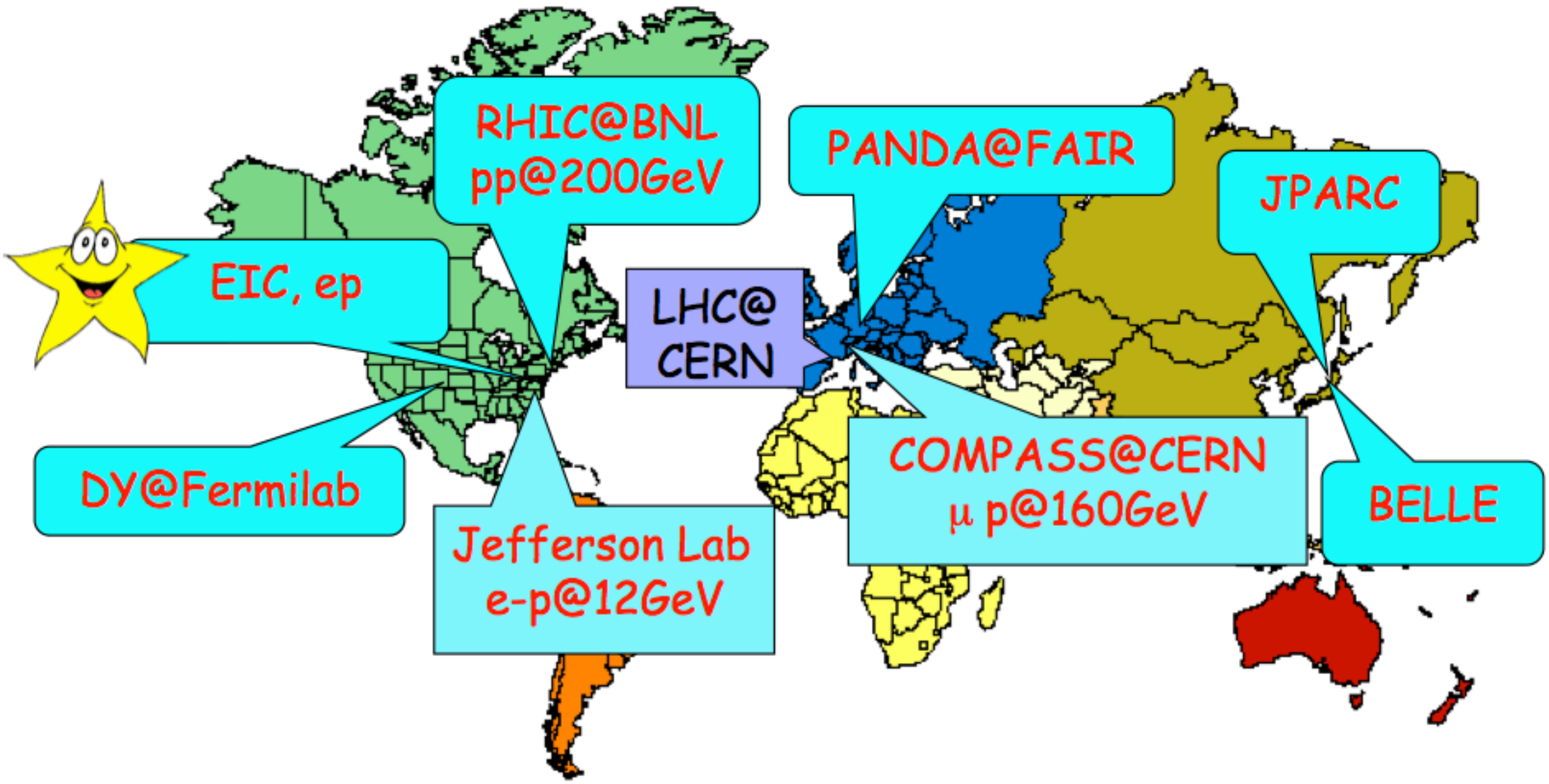
GSI: p+pbar



Summary and Outlook

- Drell-Yan with (anti)proton beams at Fermilab will provide unique and timely opportunity to study critical issues in understanding of QCD dynamics in hadronic interactions
  - TMDs: Boer-Mulders, Lam-Tung relations…
  - Novel QCD dynamics
- Polarized Drell-Yan program could further advance our understanding of strong interactions and novel spin related phenomena
  - TSSAs in Drell-Yan,
  - open (anti)charm
  - Lambda …
- A new fundamental test of QCD color gauge formalism
  - TSSA sign change (or not) in Boer-Mulders and Sivers functions in p(bar)-p compared to what observed in polarized DIS
  - QCD A-B effect

World Map of QCD Facilities



The magic of sign change

Drawing from D. Sivers @Santa Fe Polarized Drell-Yan Workshop 10/31-11/1, 2010

Backup slides

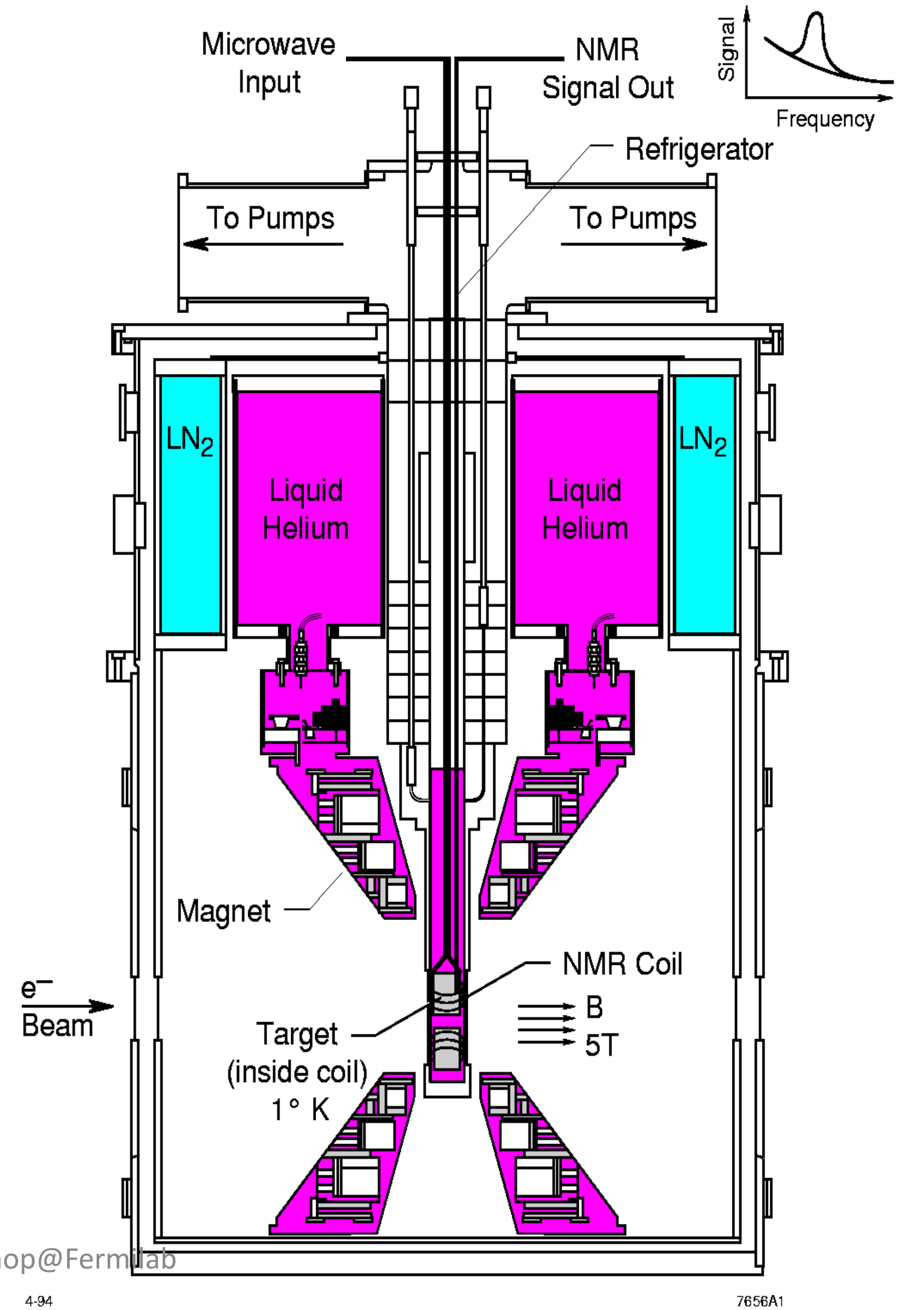
The Intensity Frontier

UVA/J-Lab/SLAC Polarized proton/deuteron target

D. Crabb MENU10

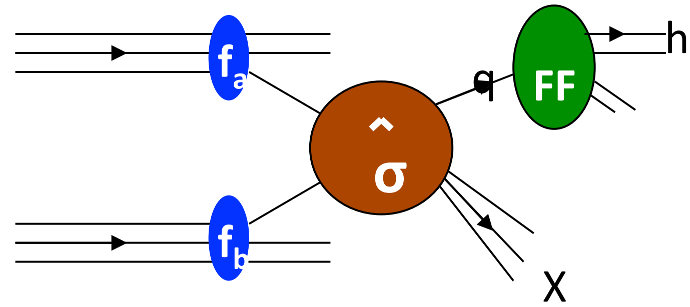
- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization
- Operate at 5 T and 1 K. Pol ~ B/T
- Used with high beam intensities – up to ~100 nA
- Large capacity pumps
- Polarizations:
  - p > 90%,
  - d ~ 50%

- Able to handle high luminosity
  - up to ~ 10^{35} (Hall C)
    ~ 10^{34} (Hall B)



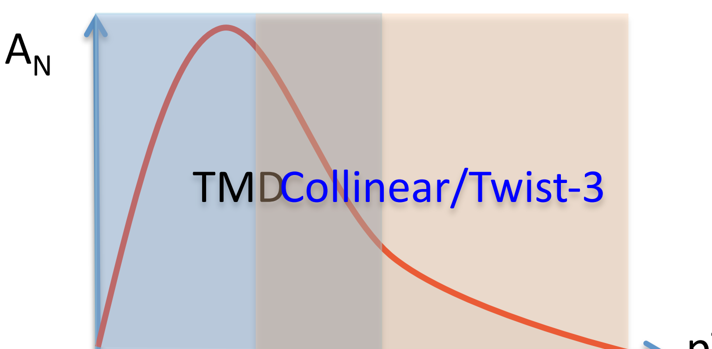
Theory: K_T vs Collinear Factorization

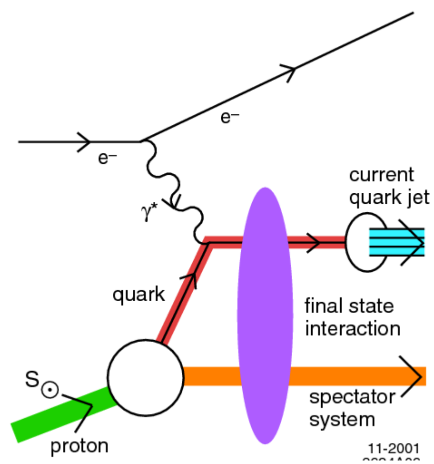
- Tran. Mom. Dep. Funs
  - Sivers Fun
  - Collins Fun

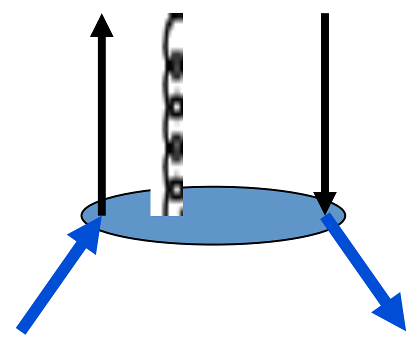


$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to h + X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1, k_{q,T}) \cdot q_j(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

- Twist-3 collinear
  - Quark-gluon correl.
  - Gluon-gluon correl.







Time-reversal modified universality of the Sivers function

- Relation between Sivers functions in SIDIS and DY
  - From P and T invariance:

$$f_{q/h^\uparrow}^{\rm SIDIS}(x, \mathbf{k}_\perp, \vec{S}) = f_{q/h^\uparrow}^{\rm DY}(x, \mathbf{k}_\perp, -\vec{S})$$

    - **Spin-averaged parton distribution function is universal**

$$f_{q/h}(x, k_\perp) = \frac{1}{2}\left[f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) + f_{q/h^\uparrow}(x, \mathbf{k}_\perp, -\vec{S})\right]$$

  - From the definition of Sivers function:

$$\Delta^N f_{q/h^\uparrow}(x, k_\perp)\, \vec{S}\cdot\hat{p}\times\hat{\mathbf{k}}_\perp = f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) - f_{q/h^\uparrow}(x, \mathbf{k}_\perp, -\vec{S})$$

  - One can derive:

$$\Delta^N f_{q/h^\uparrow}^{\rm SIDIS}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\rm DY}(x, k_\perp)$$

Most critical test for TMD approach to SSA

Future avenues for checking sign change in Drell-Yan

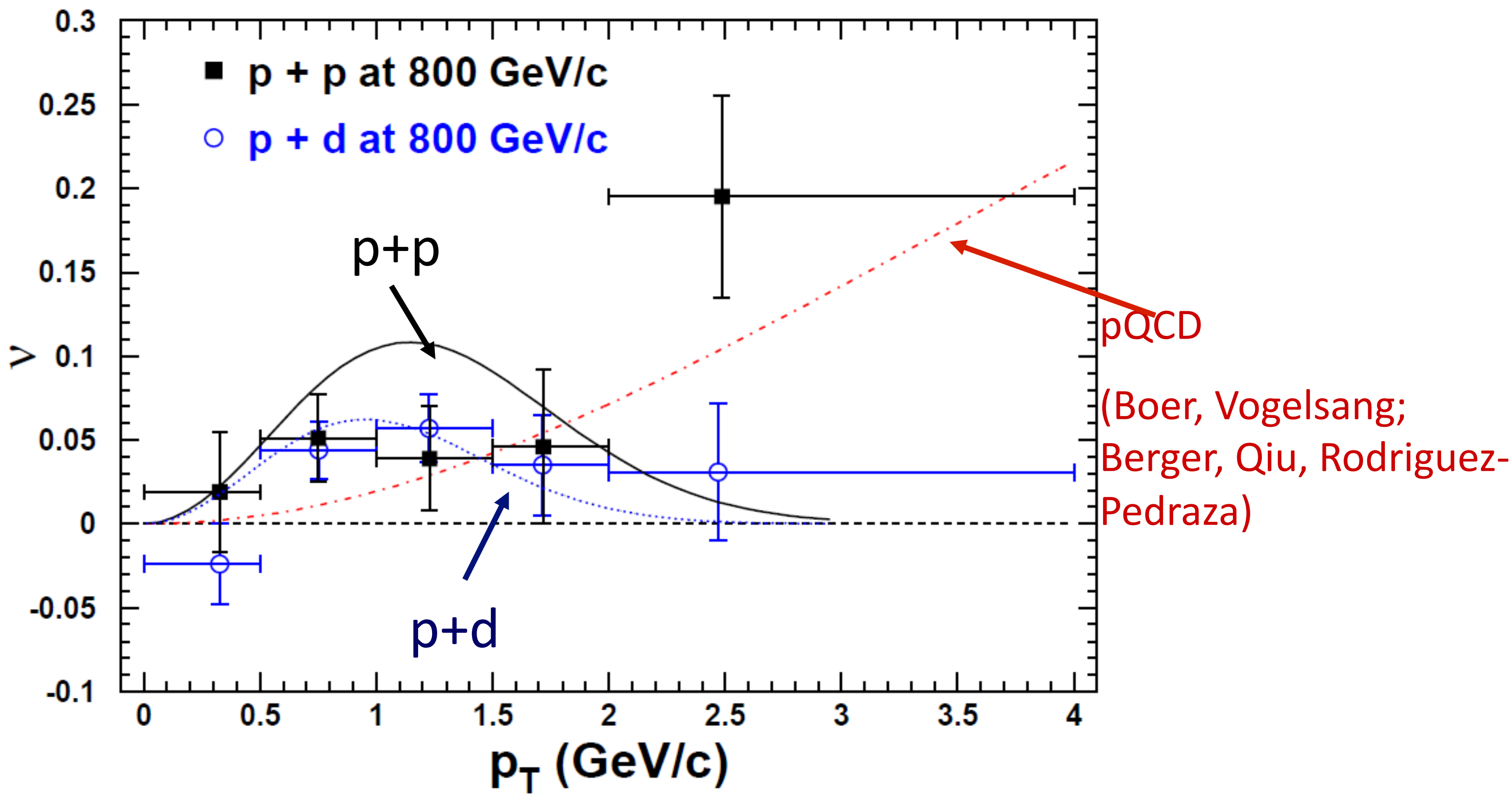
- AnDY program (IP2) at RHIC: 2013
- COMPASS-II at CERN: 2013
- PHENIX and STAR at RHIC: after 2017
  - Decadal plan
- Fixed target DY at Fermilab
- Fixed target DY at JPARC

Santa Fe Polarized Drell-Yan Physics Workshop

October 31- November 1, 2010
Hilton of Santa Fe (Fall APS/DNP hotel)
Santa Fe, NM 87501

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.

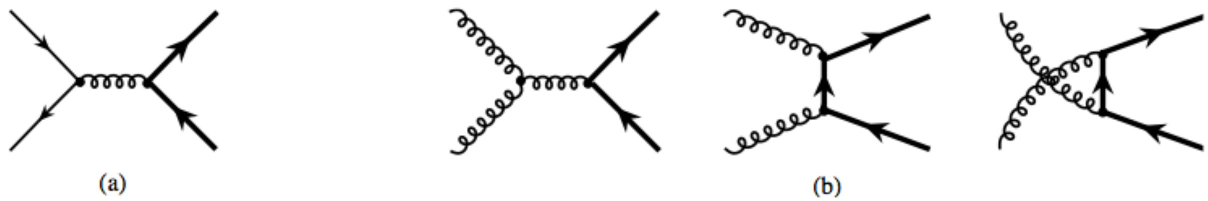
More data are anticipated from Fermilab E906

TSSA in Heavy Quark Production

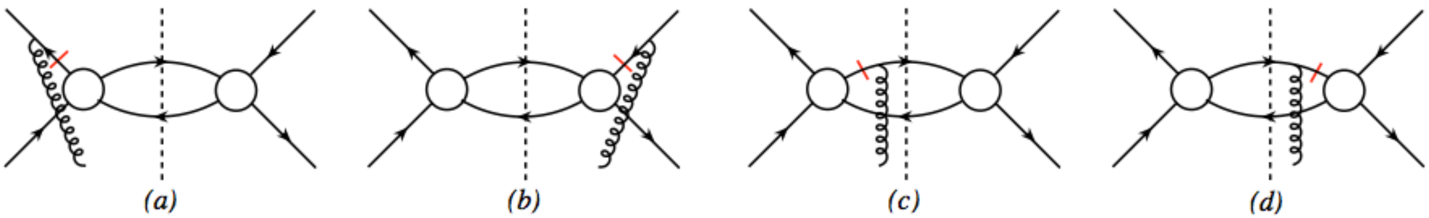
Kang, Qiu, Vogelsang, Yuan, PRD 2008

D-meson production in hadronic collisions

- Two partonic subprocesses:



- Quark-antiquark annihilation:



- Gluon-gluon fusion: