# Drell-Yan Physics

## An Experimental Overview

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# Outline

- Introduction – a brief review of history
- Recent highlights and future prospects
  - quark energy loss dE/dx in pA
  - Nucleon and nucleus structure
- New opportunity
  - Transverse spin physics

# The First Dimuon Measurements

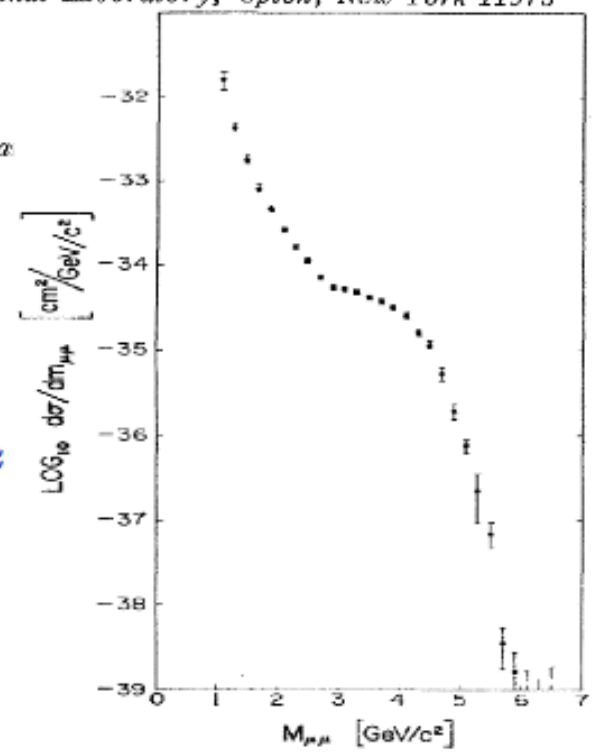
VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

**Observation of Massive Muon Pairs in Hadron Collisions***

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
*Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973*

and

E. Zavattini
*CERN Laboratory, Geneva, Switzerla*
(Received 8 September 1970)

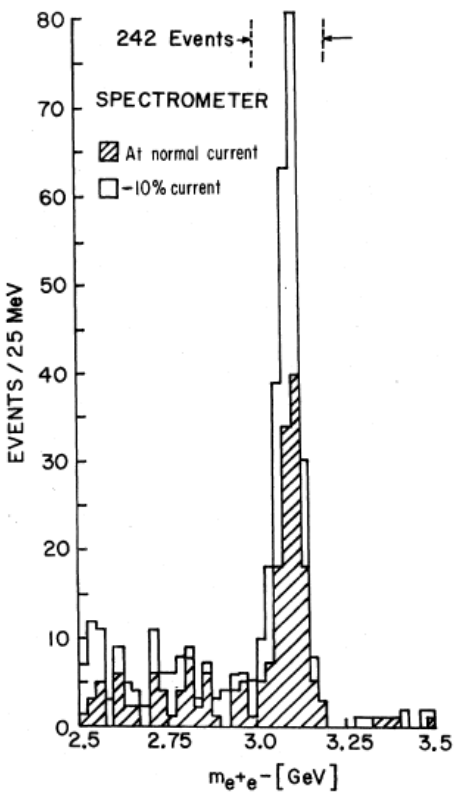


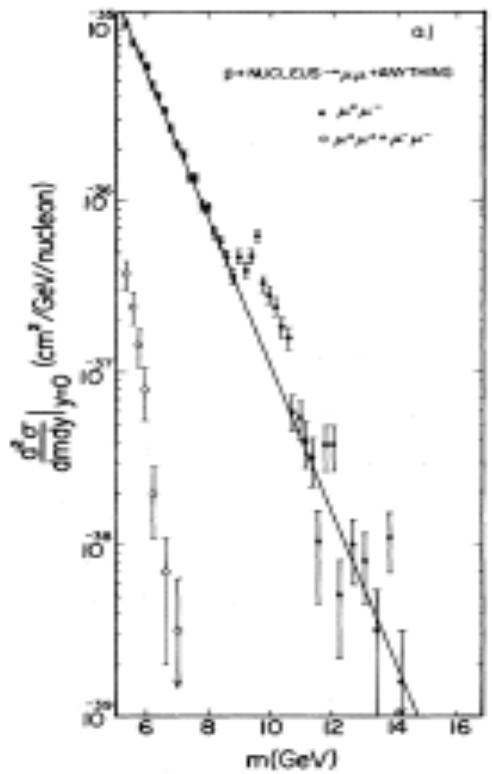

Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c$^2$ have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm$^2$ (GeV/c)$^{-2}$ and exhibits no resonant structure.** The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

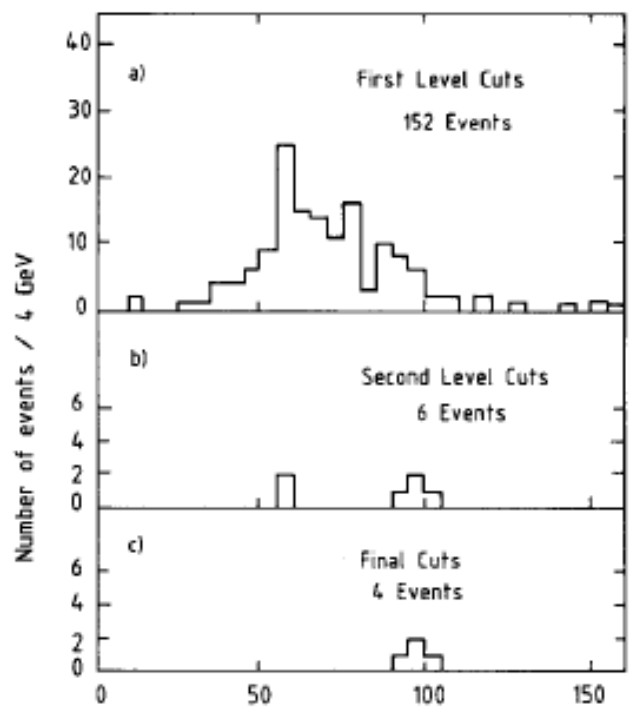
Missed the J/Psi!

# Di-lepton probe: a Powerful Tool for Discovery

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



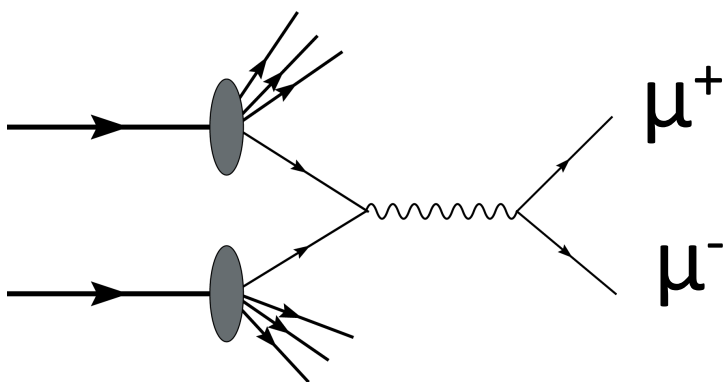



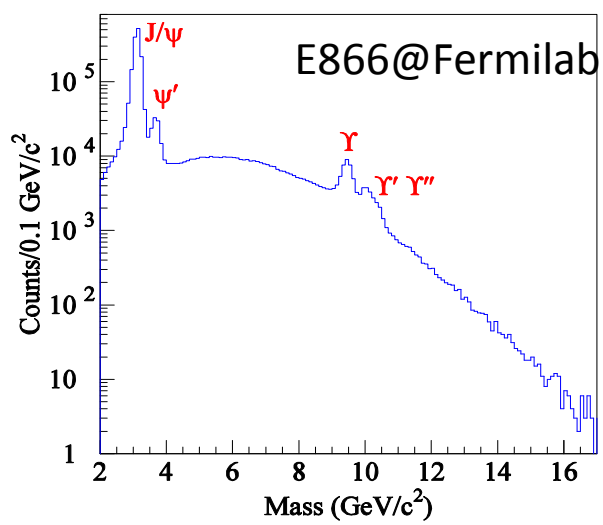
# The Drell-Yan Process

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 $\nu W_2$ near threshold.

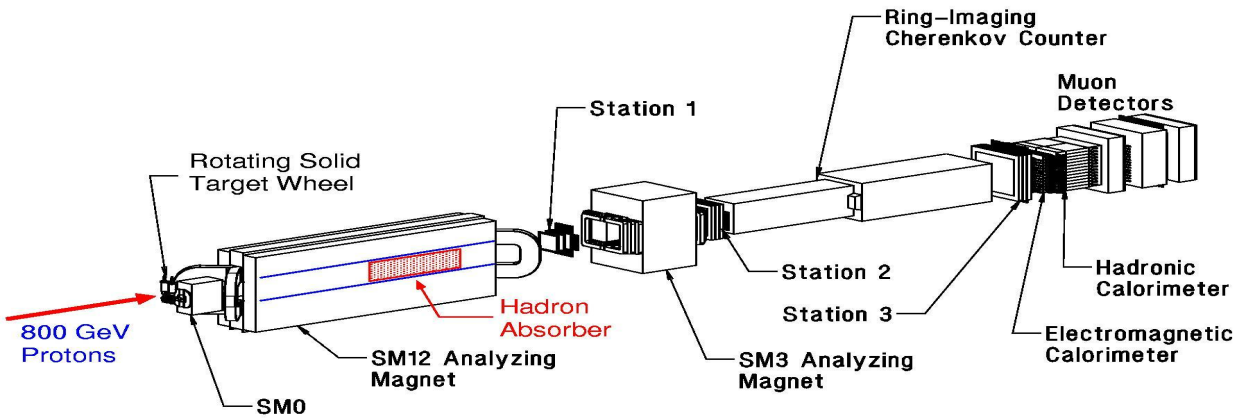



$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2)\right]$$

# Fermilab 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)

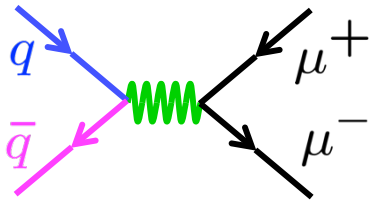
"Determination of $\bar{d}/\bar{u}$ Ratio of the Proton via Drell-Yan"

4) Fermilab E906 (proposed in 1999, will run in 2010-2013)

"Drell-Yan with the FNAL Main Injector"

5) RHIC LOI (proposed in 2010)

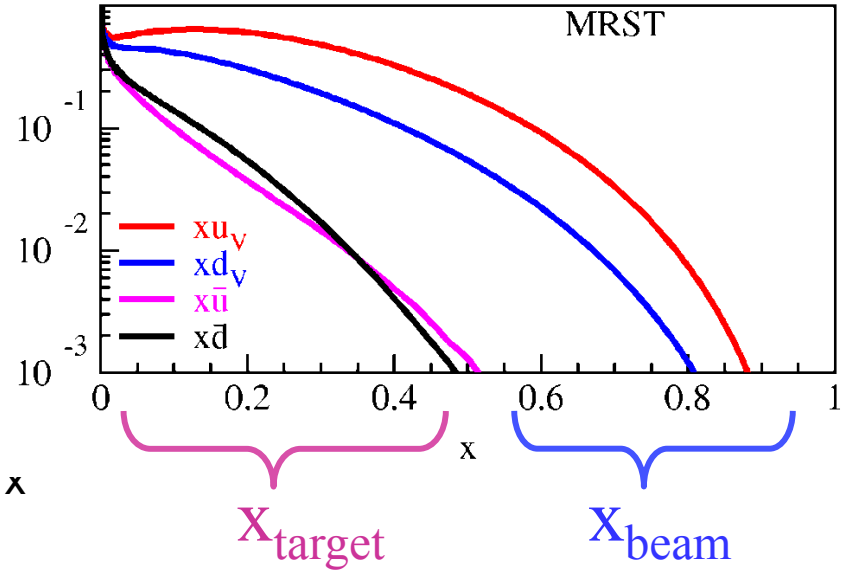
"Polarized Drell-Yan with Internal Target"



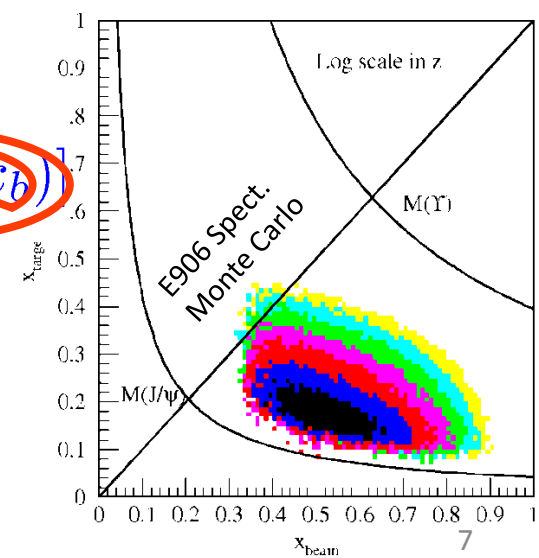

# Kinematic of Fixed Target Drell-Yan

Fixed target kinematics and detector accepta
give $x_b > x_t$

- ➡ $x_F = 2p_{||}^{\gamma}/s^{1/2} \approx x_b - x_t$
- ➡ Beam valence quarks probed at high x
- ➡ Target sea quarks probed at low/intermediate x

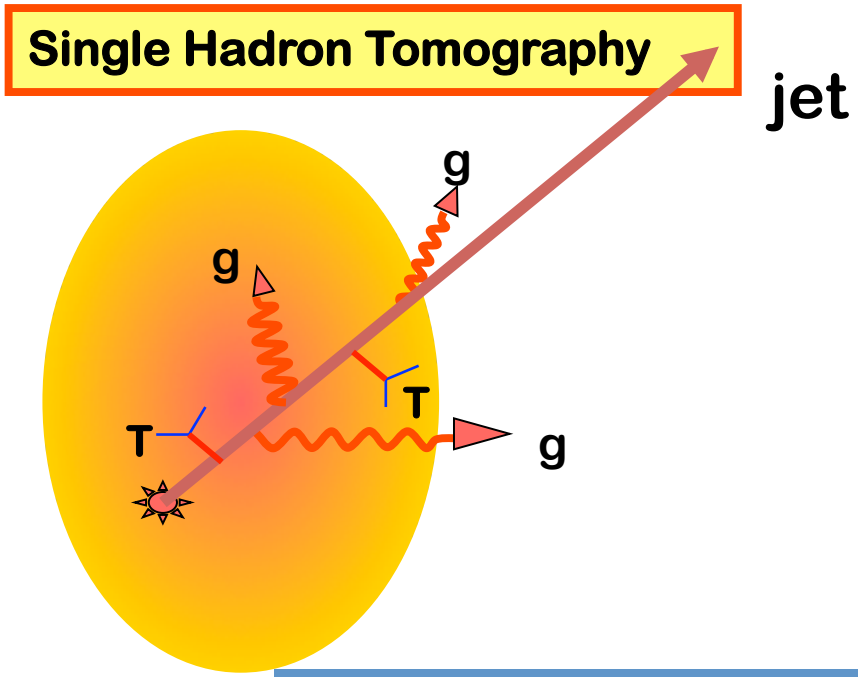


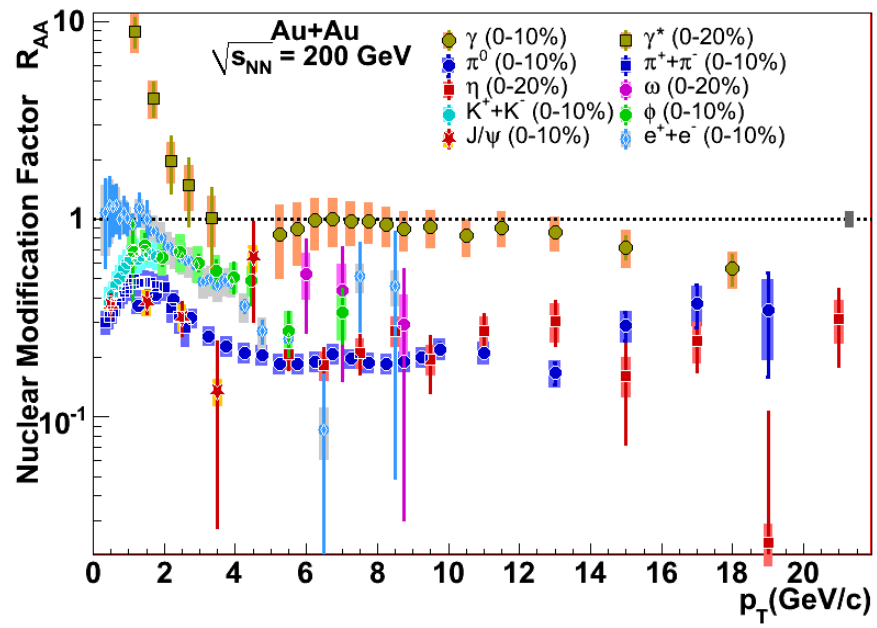

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$



# Topic (I): Energy loss in the Nuclear Medium

- Parton energy loss has been discovered at RHIC as an excellent probe of the hot/dense matter.
- However, order of magnitude uncertainties in dE/dX, model dependent

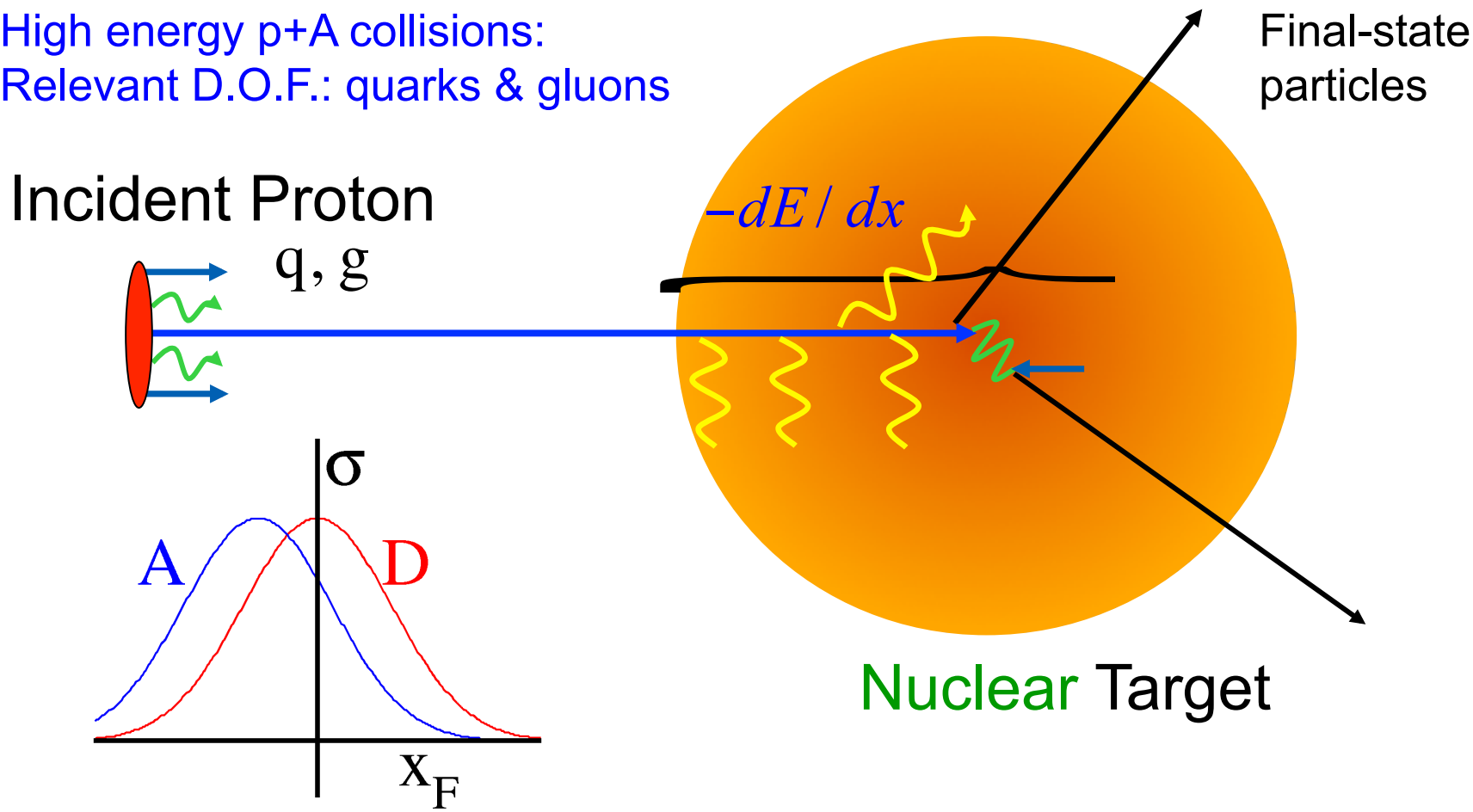


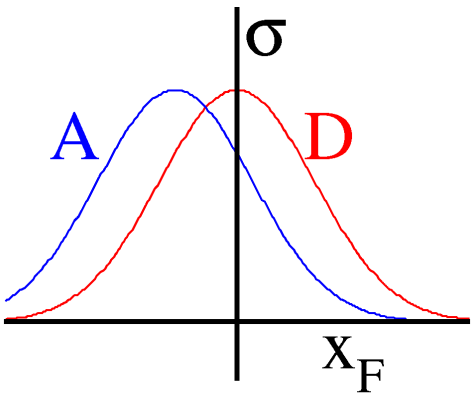

Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

# Benchmark with DY: Quark Energy Loss in p+A

High energy p+A collisions:
Relevant D.O.F.: quarks & gluons



# Quark Energy Loss in Cold Nuclear Medium



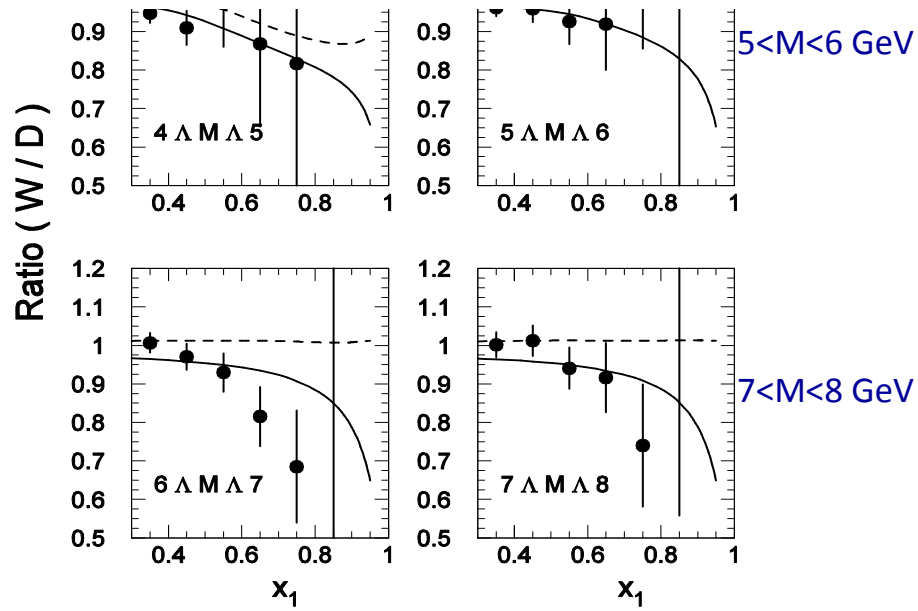

$$\frac{dE}{dx} = 0 \sim 2.5 \quad GeV/fm$$

- depends on shadowing correction
- size of effect ~20%
- $x_t \sim 10^{-2}$

## Drell-Yan @E866

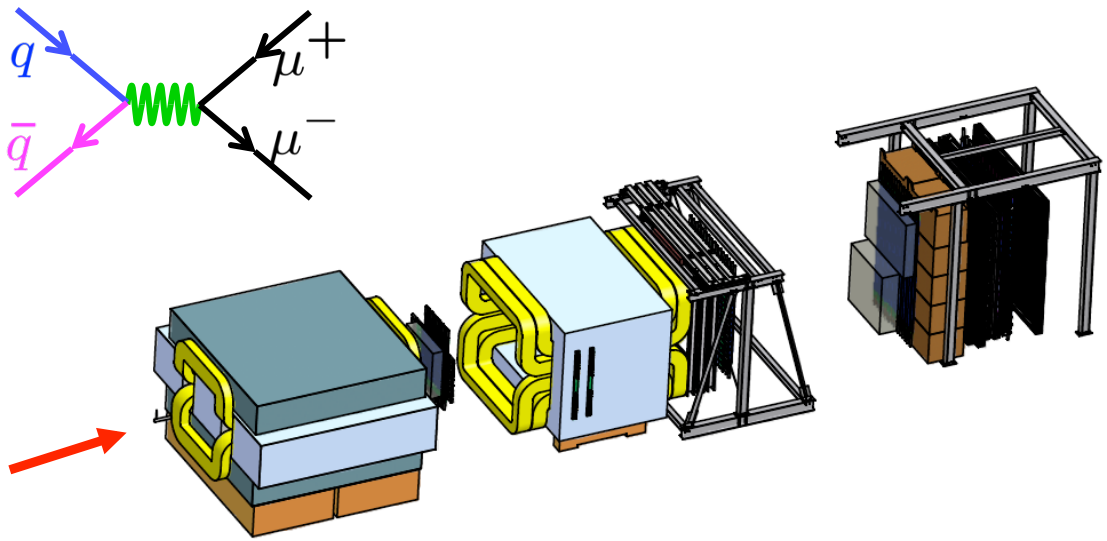
(PRL 86 (2001) 4483)

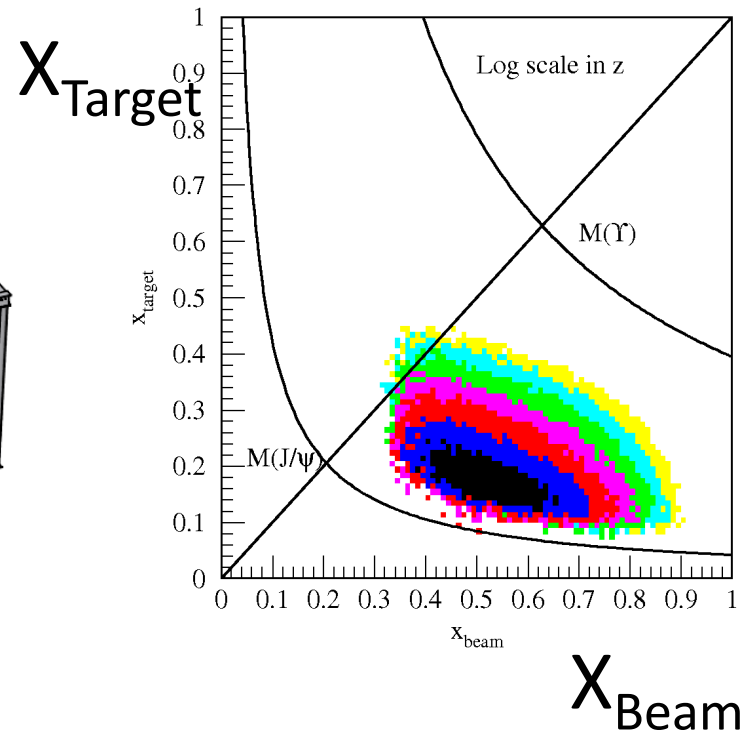
800GeV p + A




$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

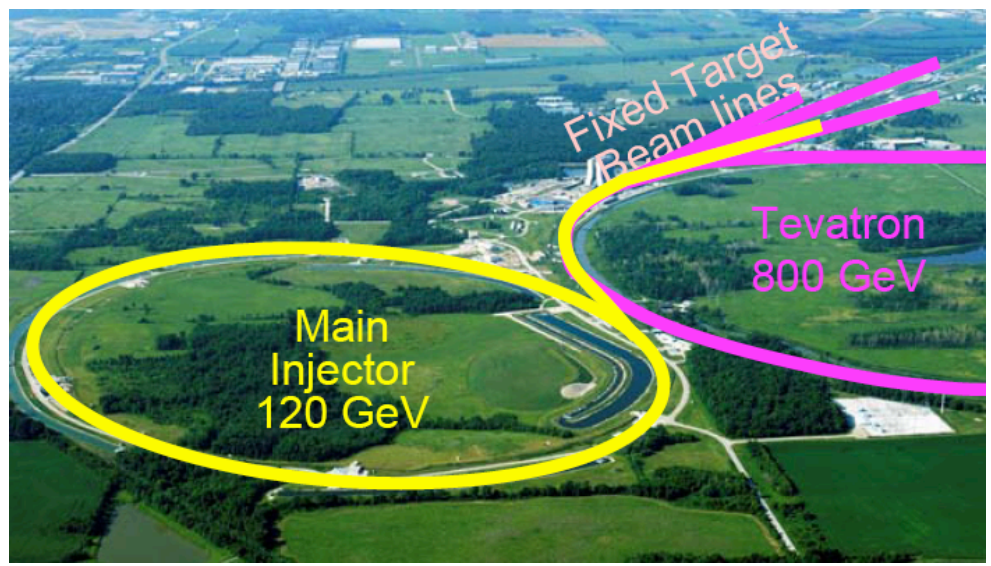
# E906 Drell-Yan:2011-2013




## Polarized DY possibility:

- 120 GeV proton
- p+A: p, d, C, Al, Fe, W
- $X_b$ = 0.3~0.7
- $X_t$ = 0.1~0.3
  - free from shadowing effect



# Experimental Sensitivity to Quark Energy Loss

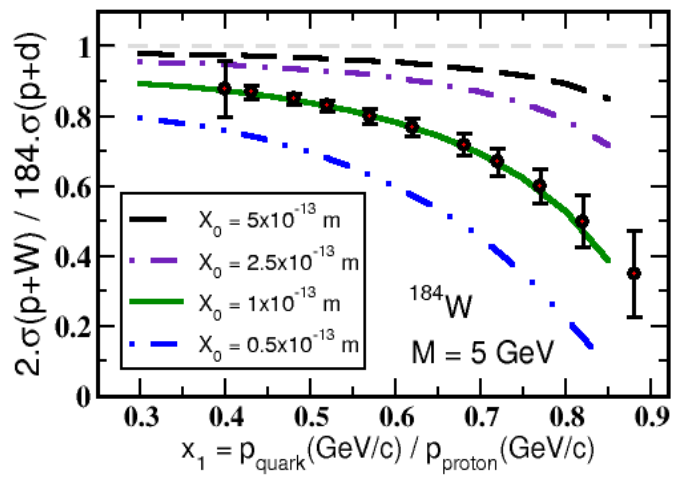
$$-\frac{dE}{dx} = \frac{E}{X_0}$$

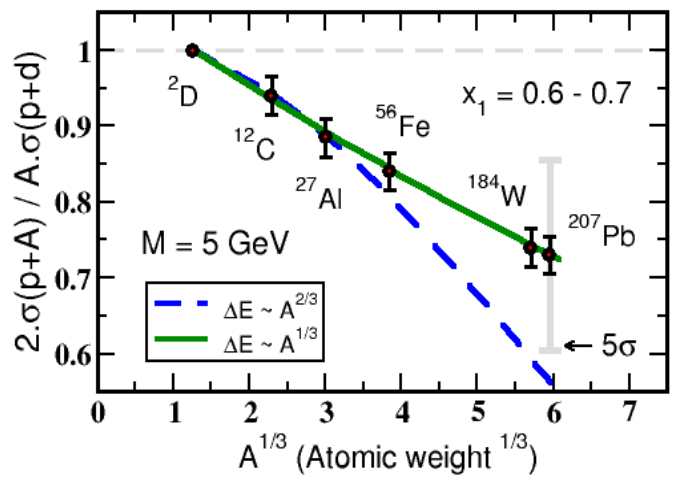
- Shortest radiation length in nature $X_0 = 1 \times 10^{-13}$ m
- Clearly distinguish between leading models for L dependence of E-loss

$$\boxed{\begin{aligned} -\Delta E &\propto A^{1/3} \quad (\text{or} \propto L) \\ -\Delta E &\propto A^{2/3} \quad (\text{or} \propto L^2) \end{aligned}}$$

- Benchmark dE/dx models

**Quark energy loss only**



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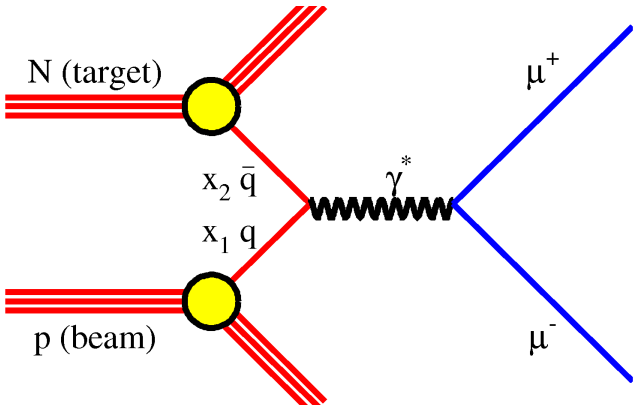
# Topic (II): Origin of Sea Quarks

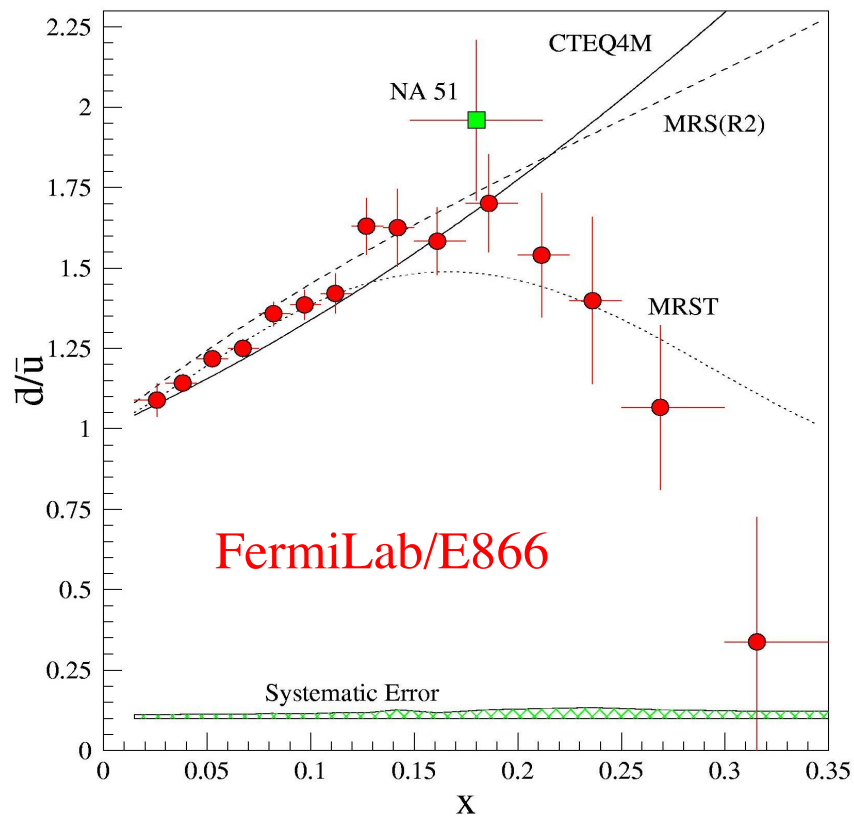
$$pN \to \mu^+\mu^- X$$




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

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

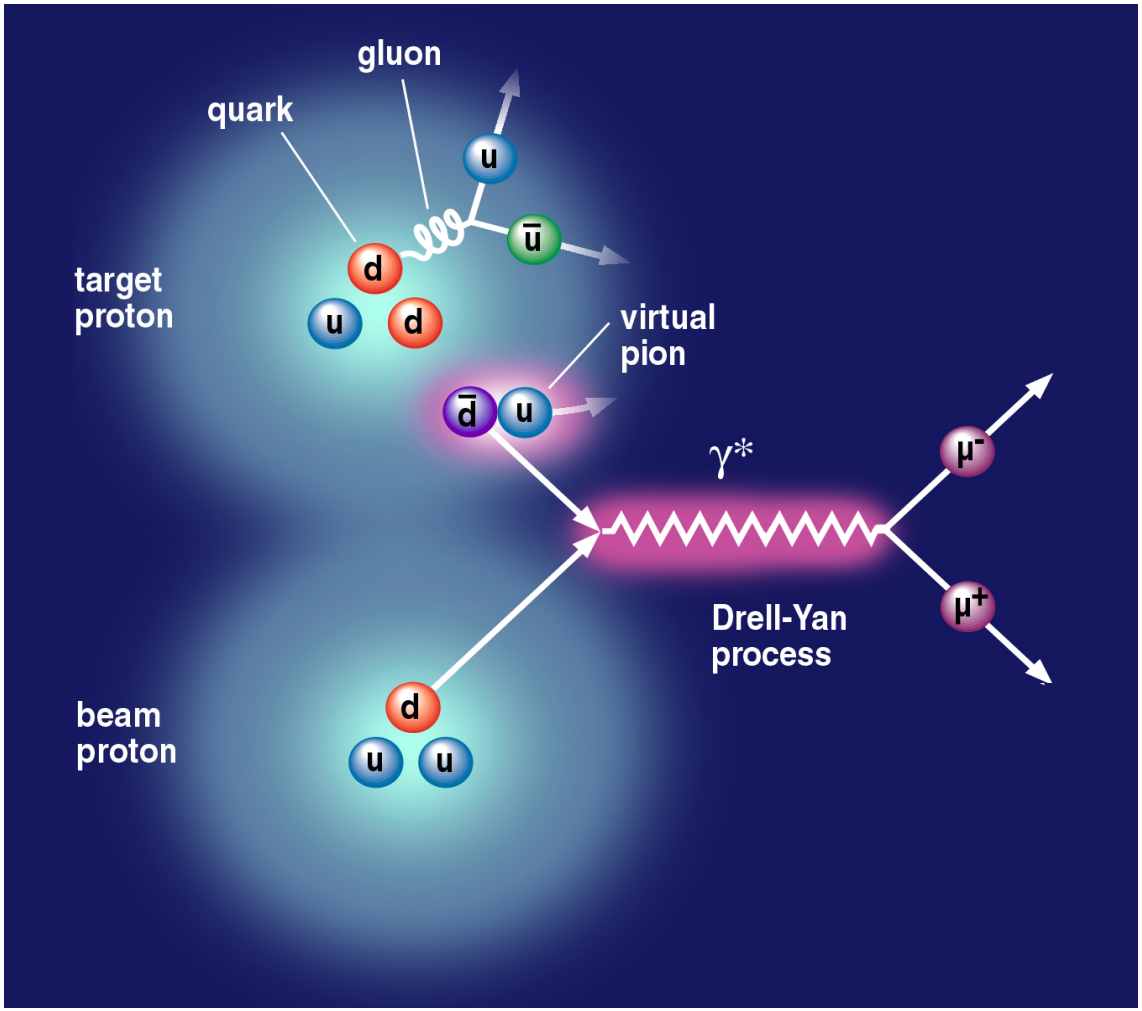
E866, Phys.Rev. D64 (2001) 052002




Sea Asymmetry probed by Drell-Yan

# Nucleon is a Complex System

## Pion cloud and Sea quarks

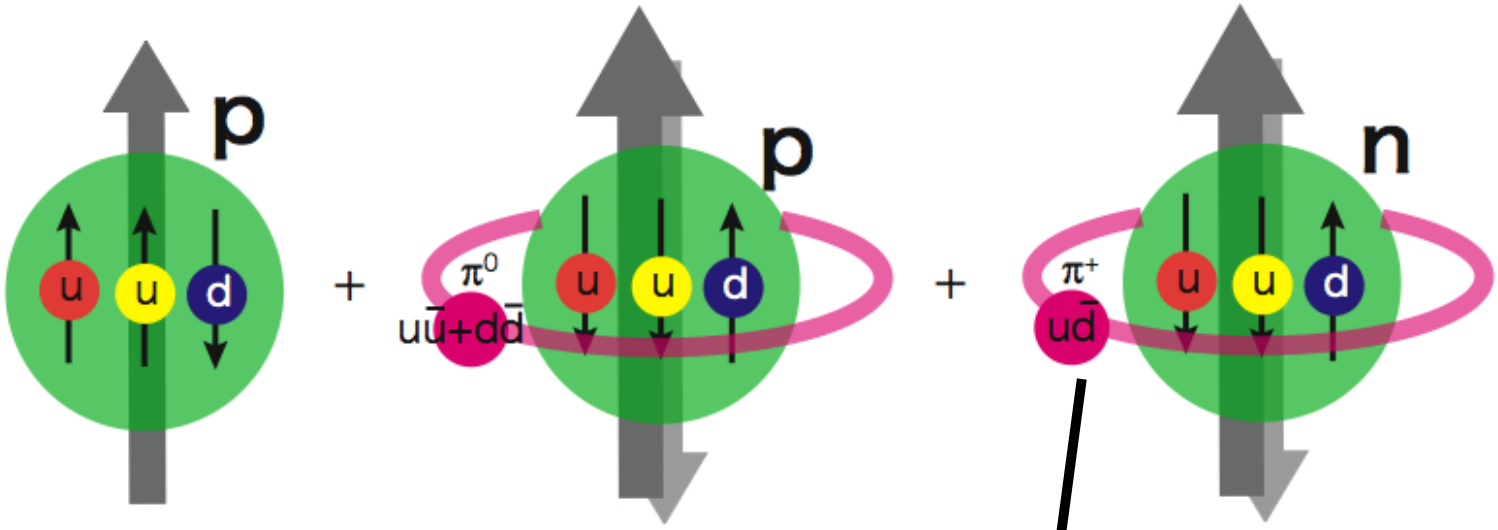



$$g \rightarrow u + \bar{u}$$

$$g \rightarrow d + \bar{d}$$

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

# Pion Cloud Model and the Orbital Angular Momentum?!




$|L,S_Z\rangle = \left|0,\frac{1}{2}\right\rangle$ $\quad$ $|L,S_Z\rangle = \left|1,-\frac{1}{2}\right\rangle$ $\quad$ $|L,S_Z\rangle = \left|1,-\frac{1}{2}\right\rangle$

Extra dbar in proton g.s.

Sea Quarks Carry Major Orbital Angular Momentum Component?

# Pion Cloud and Orbital Angular Momentum

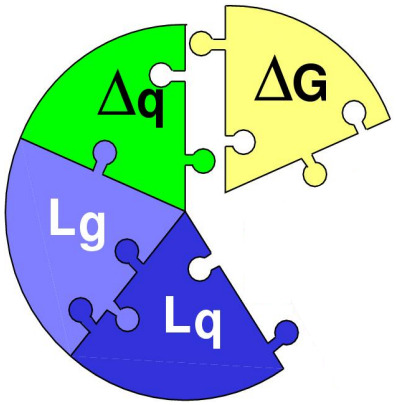
- Spin puzzle, sea quark flavor asymmetry and $L_Z$

**G. Garvey, PRC81:055212,2010**.

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

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

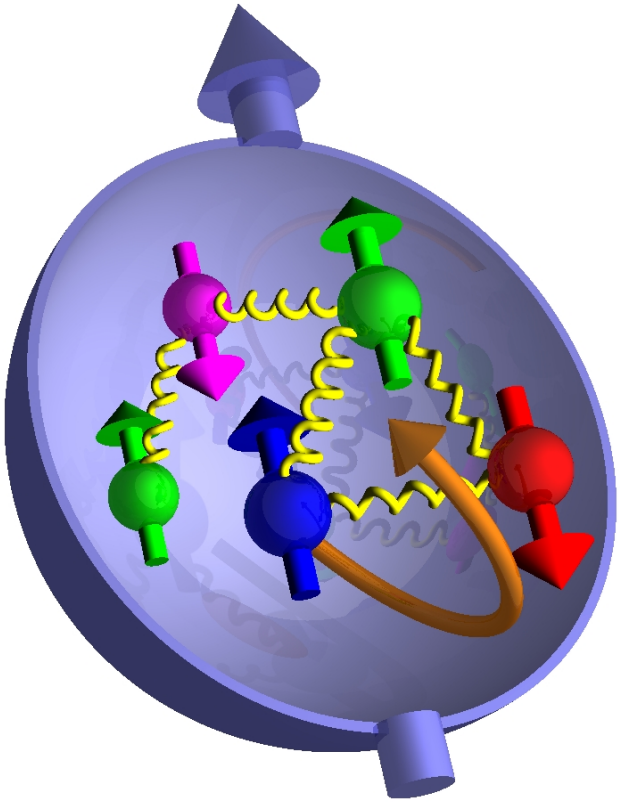
$$\langle p^\uparrow | \hat{L}_Z | p^\uparrow \rangle = \frac{2a^2 - b^2}{3(1+a^2+b^2)} = 0.147 \pm 0.027 \sim 30\%[\frac{1}{2}]$$



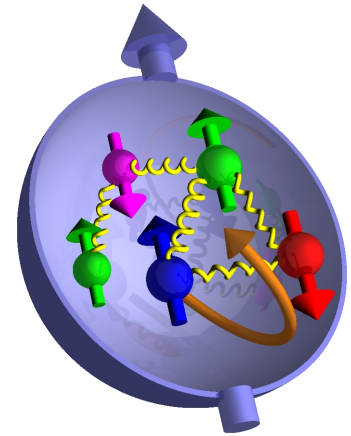

$$\frac{1}{2} = \frac{1}{2}\Delta q + L_q^z + \Delta g + L_g^z$$

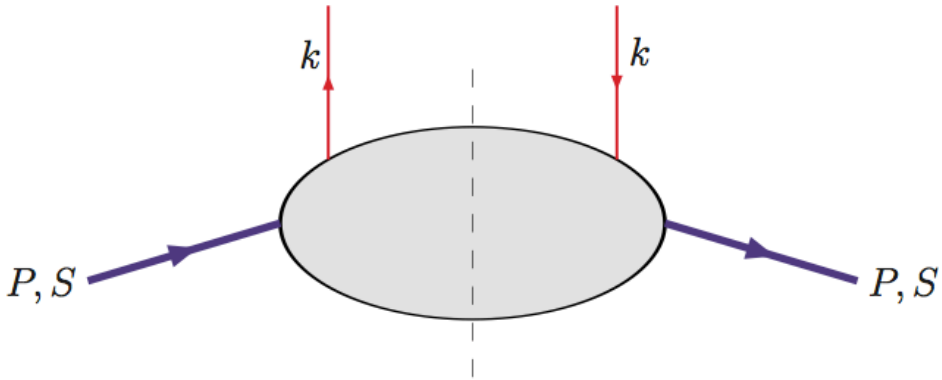
# Topics (III): Transverse Spin Physics

- TMD and the alike: beyond the collinear approximation
  - Sivers functions
  - Collins functinos
  - and more…



# Nucleon Structure @Leading Twist Collinear Approximation (I)






Correlator:

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

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

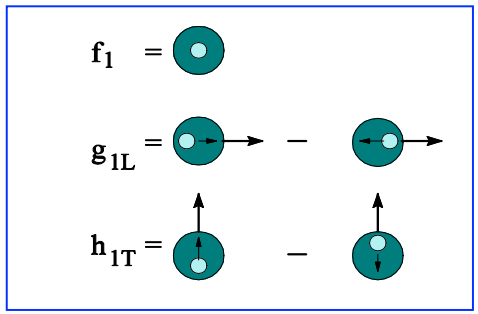
$$\Phi(x,S) = \frac{1}{2}\left[\underbrace{f_1(x)}_{q}\not{n}_+ + S_L \underbrace{g_{1L}(x)}_{\Delta q}\gamma^5 \not{n}_+ + \underbrace{h_{1T}}_{\Delta_T q} i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu\right]$$

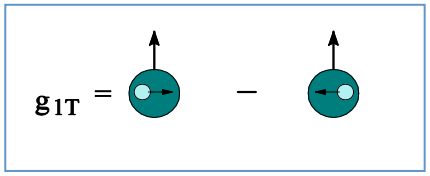
- Partonic interpretation of hard scatterings
- Universal functions

# Including $k_T$ … 5 more (II)

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

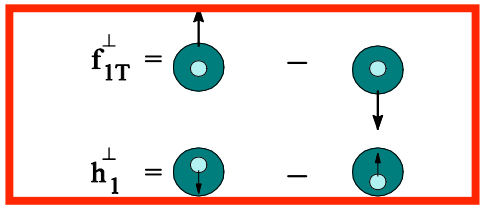
No $K_\perp$ dependence



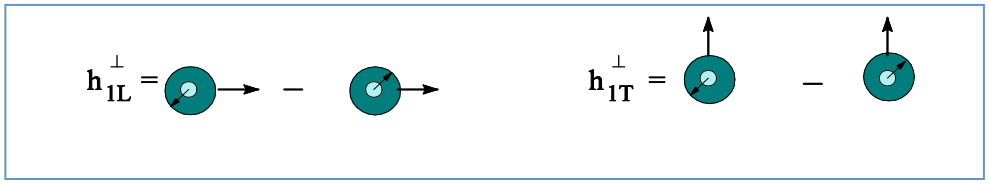

$K_\perp$ - dependent

T-odd




$K_\perp$ - dependent

T-even



# 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:

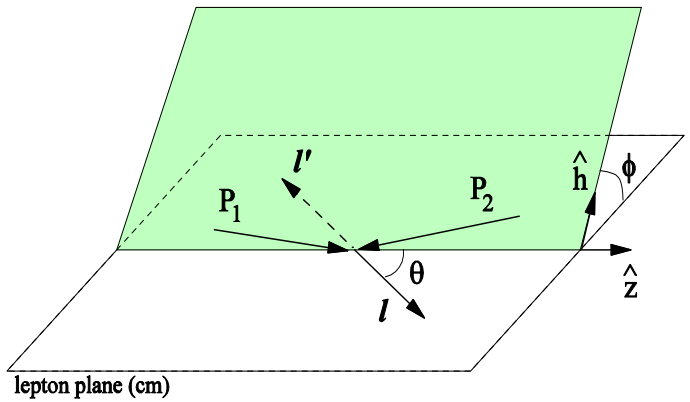
$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$

- 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 Decay Angular Distributions




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

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

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

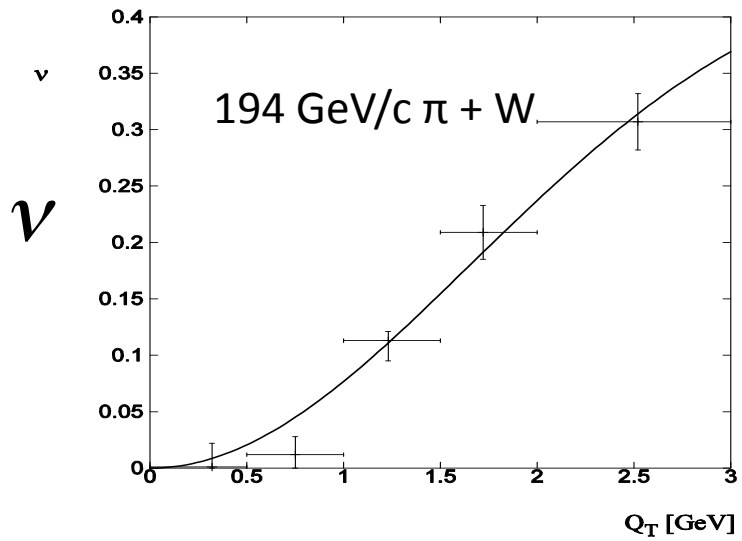
Lam-Tung relation: $1 - \lambda = 2\nu$

- Reflect the spin-1/2 nature of quarks (analog of the Callan-Gross relation in DIS)
- Insensitive to QCD - corrections

# Unpolarized 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

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



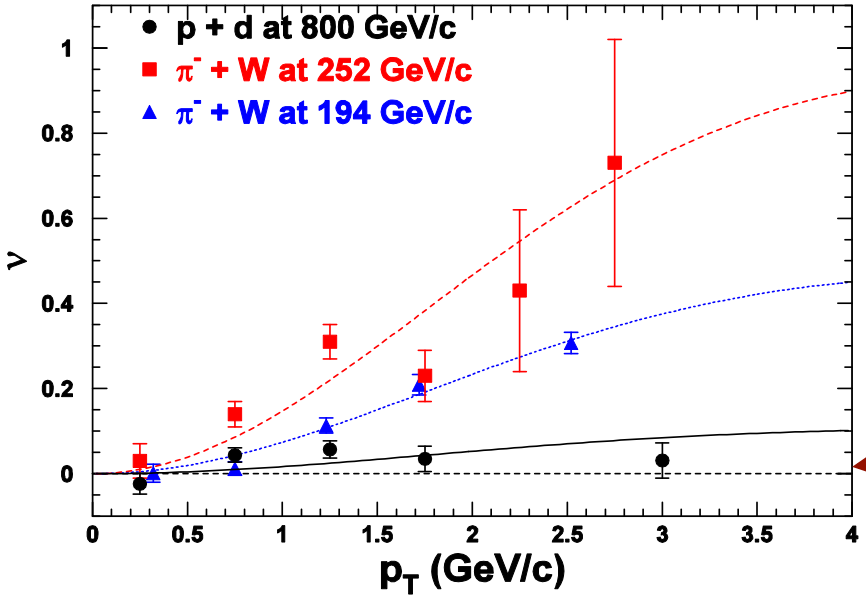

Boer, PRD 60 (1999) 014012

- 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 p+p and p+d Drell-Yan

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




Small $\nu$ 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 $h_1^{\perp}(p)$]

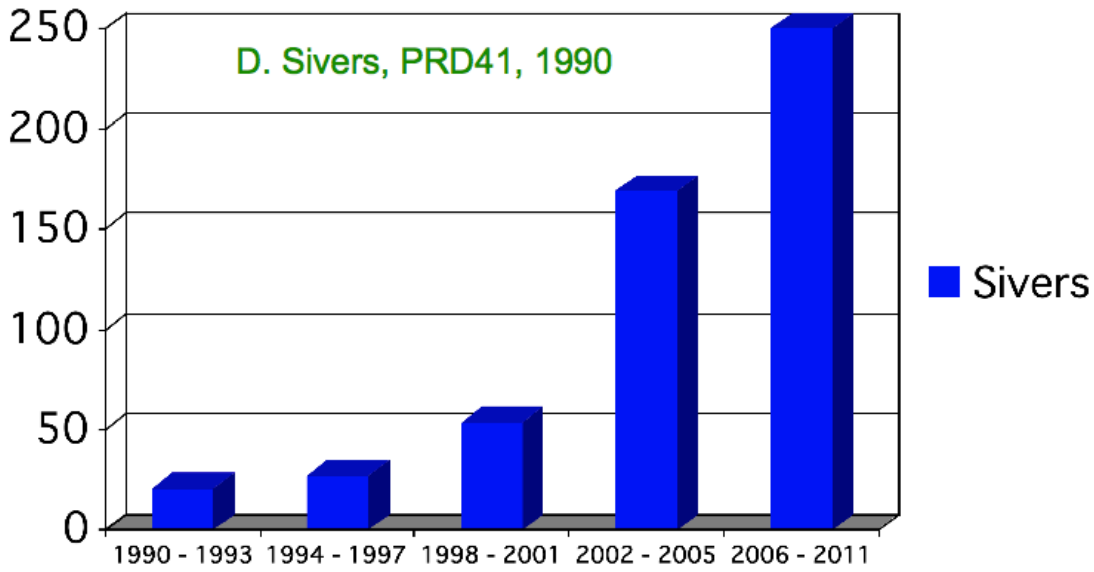
More data expected from E906 soon!

Sea-quark BM functions are much smaller than valence quarks

# Polarized DY to access Sivers Function

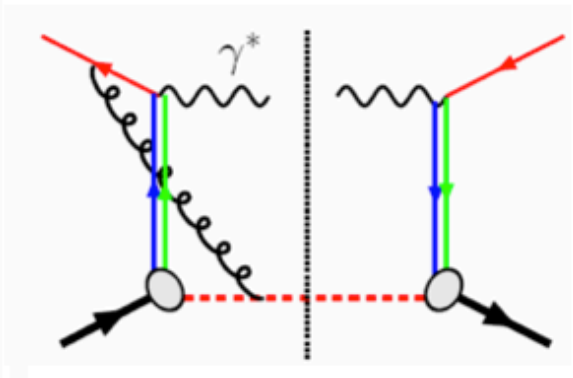
## Transverse spin physics: birth and growth

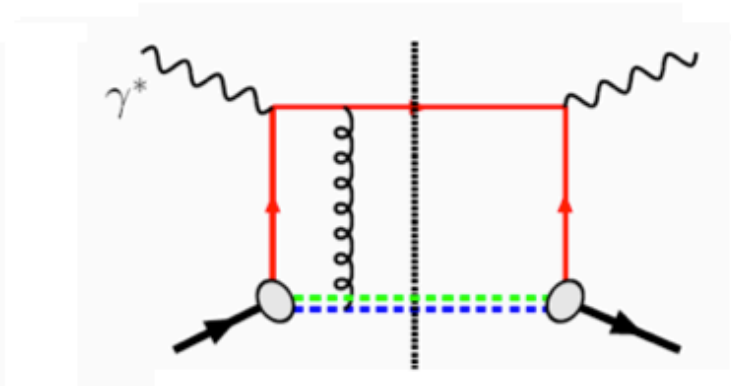
- Historically transverse spin physics has been a source of much controversy
  - Early days (before 1980s), it was thought to be not very interesting
  - Recently it has become a very active research branch
- Citations tell the story: Sivers function - birth and growth



# 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**

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

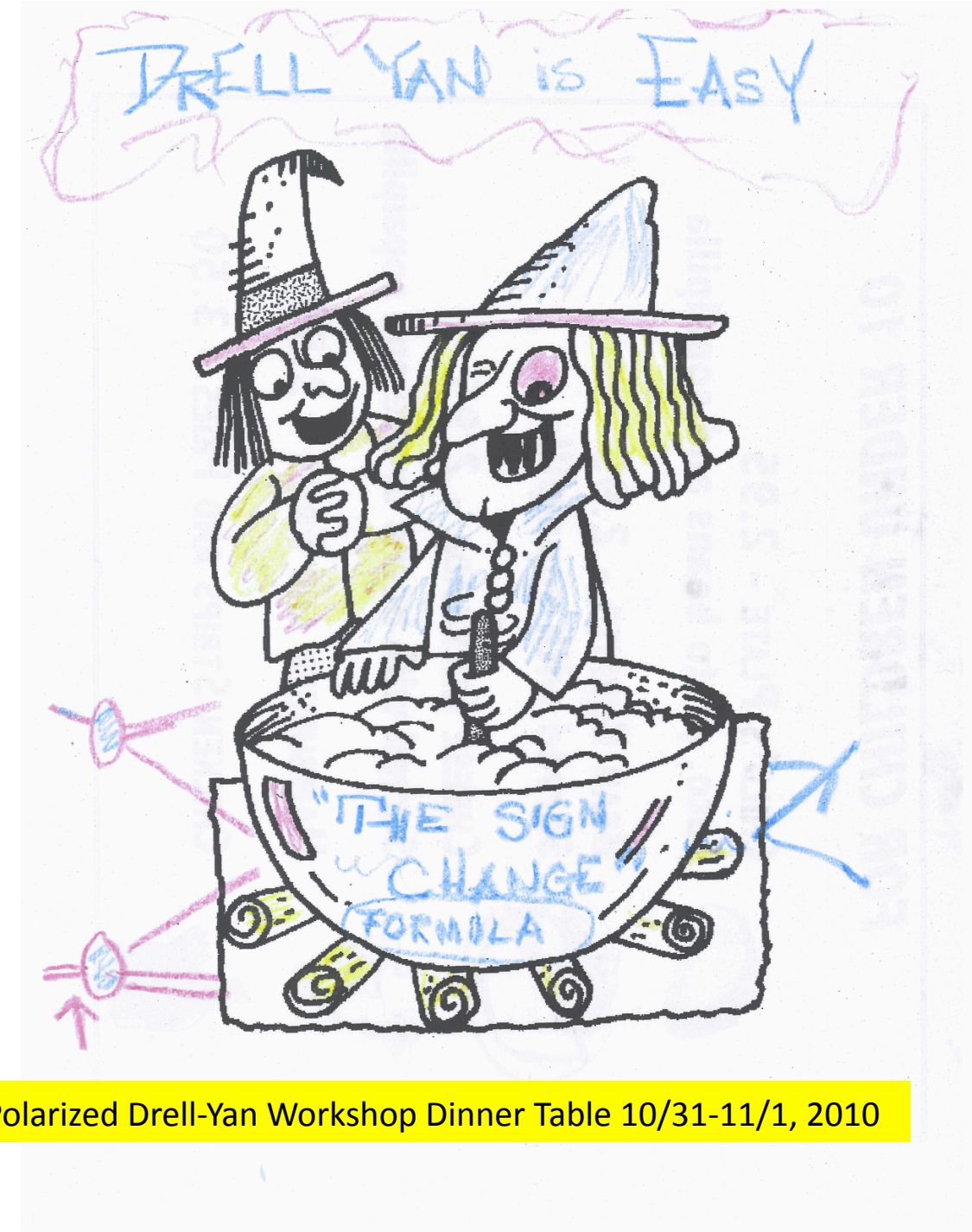
Collins '02

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

# The magic of sign change




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

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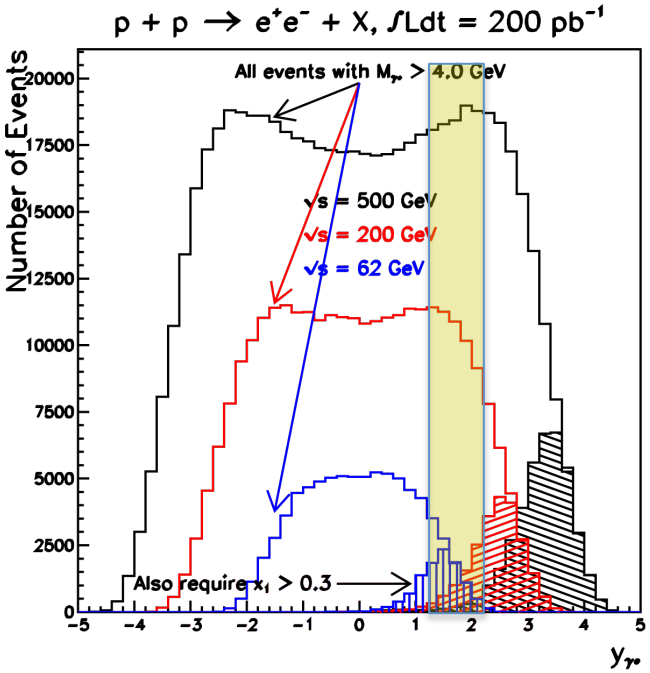
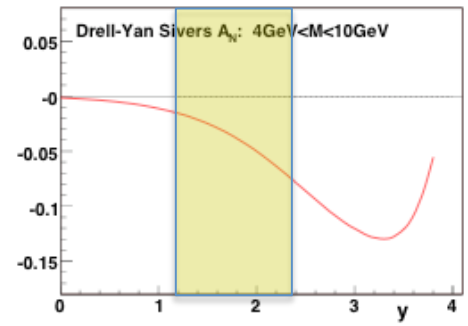
# Test the Sign Change

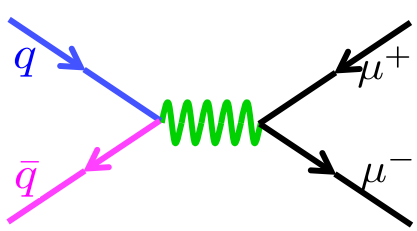
## Drell-Yan Production @RHIC




- $-A_N$ @large XF
- PHENIX muon acceptance
- 1.2 < |y| <2.4
- muon p > 2.5GeV

Figure 5: *PYTHIA simulation of the rapidity distribution of $e^+ e^-$ dileptons produced through the Drell-Yan process. The importance of large rapidity to probe the valence region is illustrated by selecting events with* $x_1 > 0.3$.




$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i e_i^2[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)]$$

$$= \frac{\pi\alpha^2}{9M^2}\sum_i e_i^2[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)]$$

# The PHENIX detector

**Philosophy:**

**High rate capability to measure rare probes, limited acceptance.**

- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes

$|\eta| < 0.35$

$90^\circ + 90^\circ$ azimuth

- 2 forward muon spectrometers
  - Identify and track muons

$1.2 < |\eta| < 2.4$

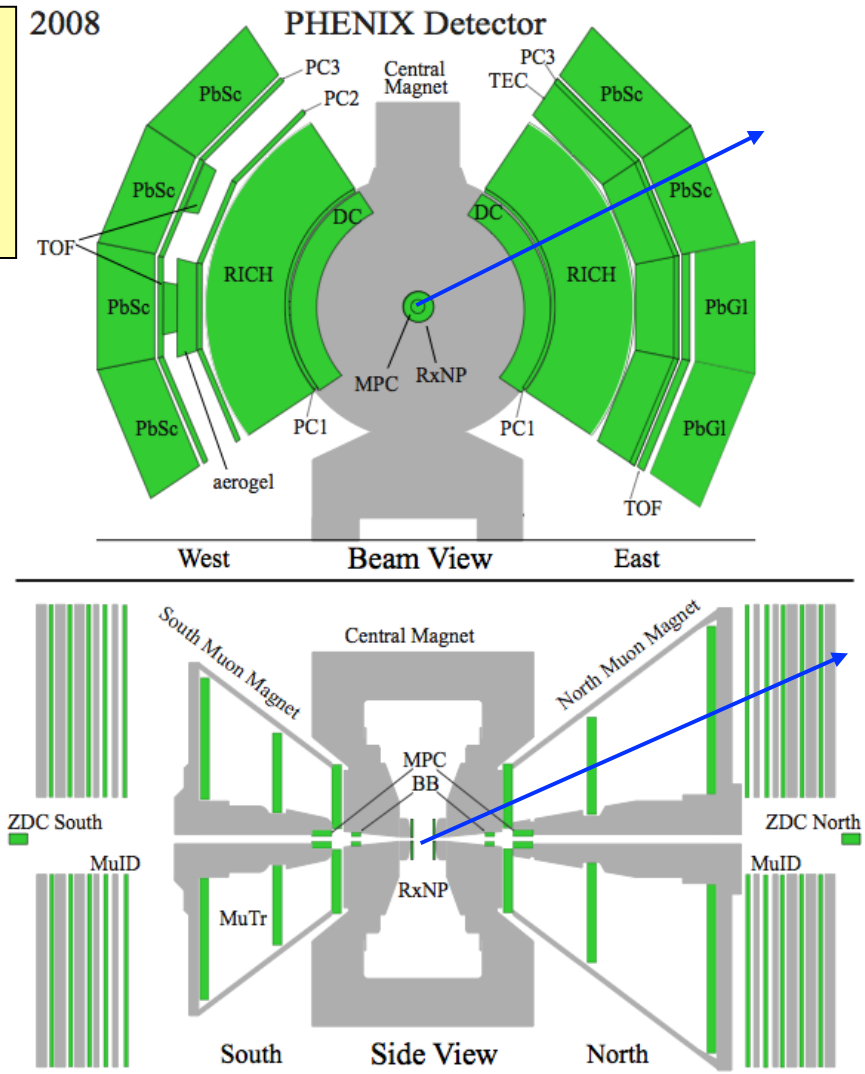
$2\pi$ azimuth

- 2 forward calorimeters (as of 2007!)
  - Measure forward pions

$3.1 < |\eta| < 3.7$

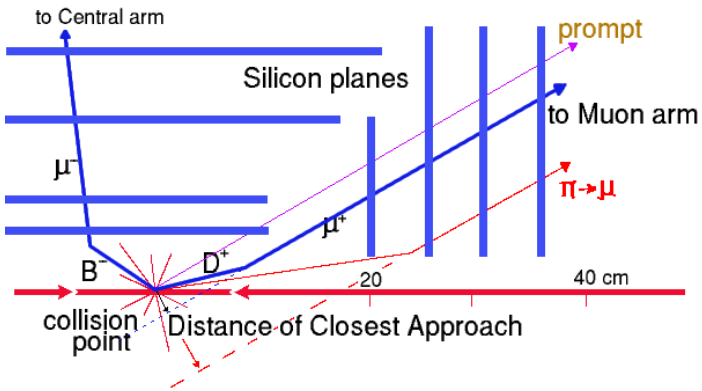
$2\pi$ azimuth

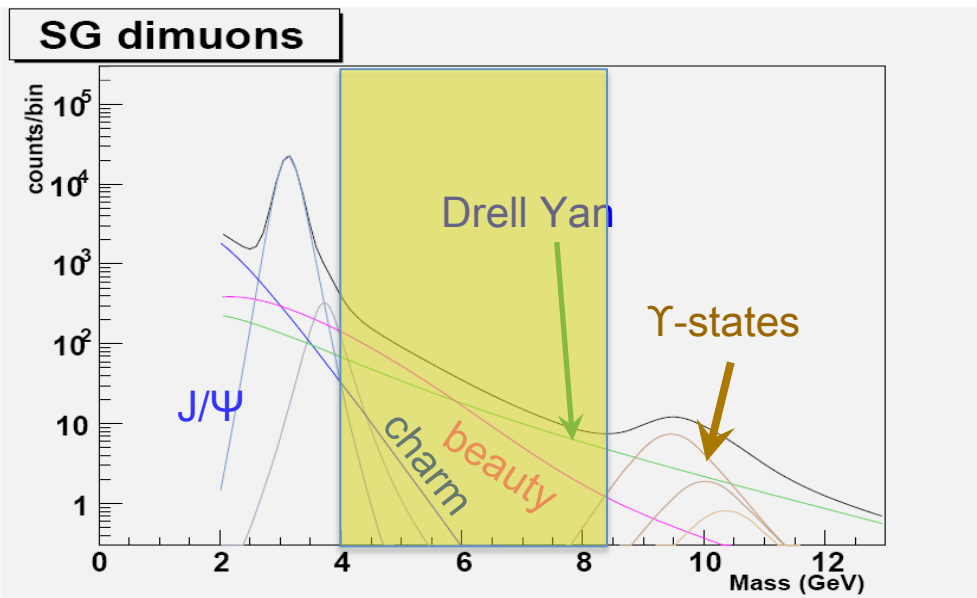
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)

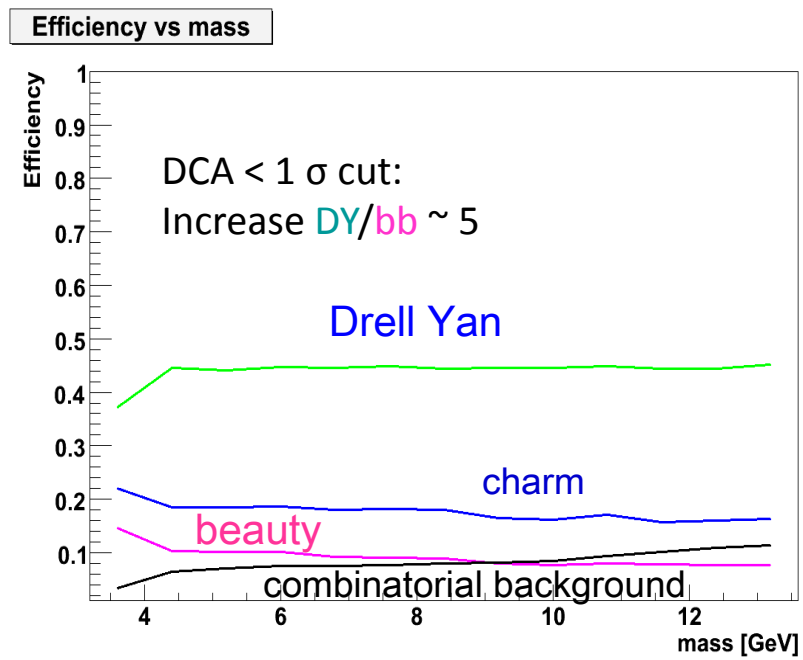


# Silicon VTX, Heavy Quark and Drell-Yan

- Tracking muons with MuTr+FVTX
  - Prompt muons from DY
  - Displaced tracks from π/K and heavy quark decays



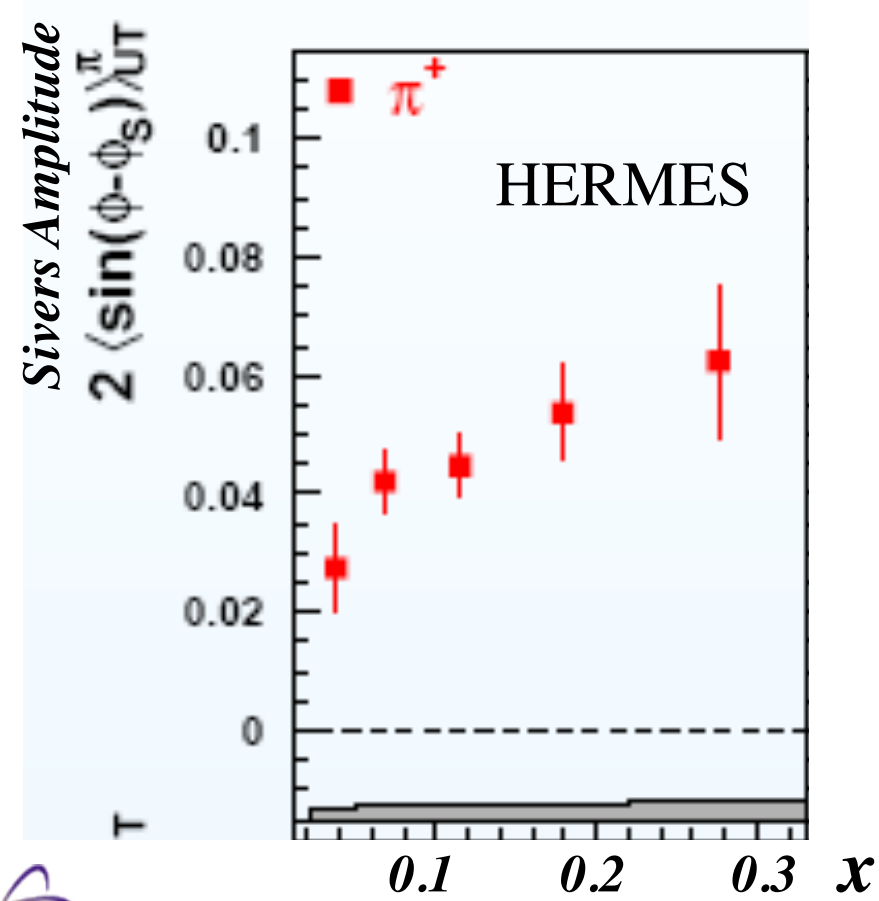



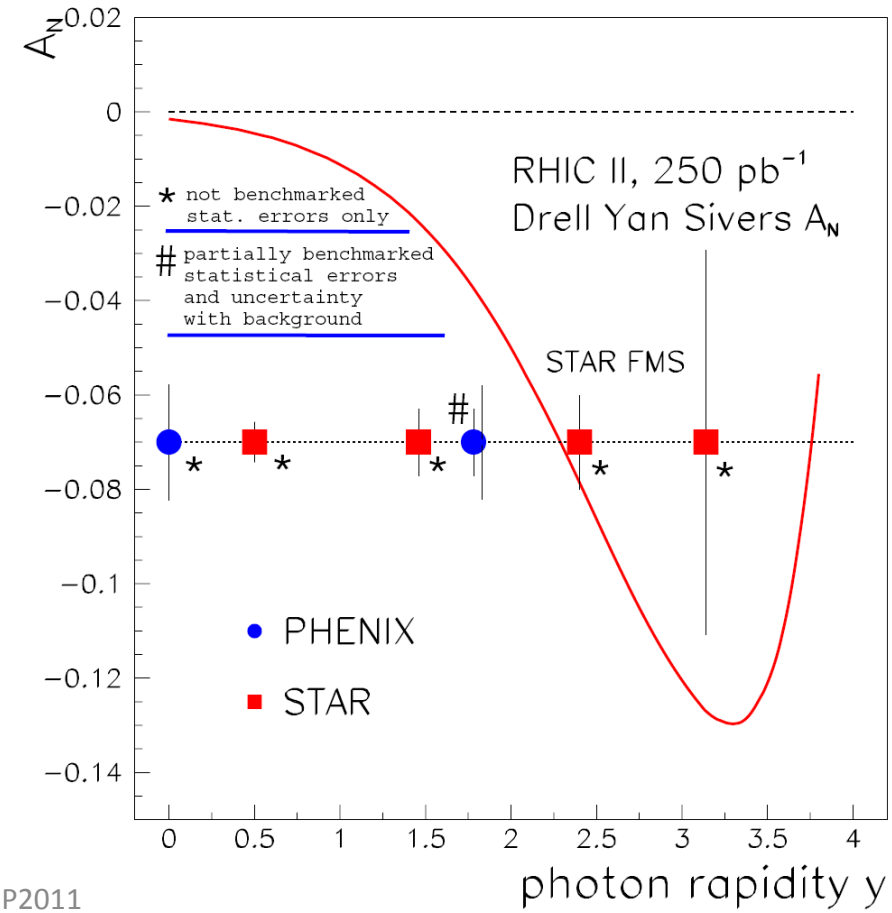

➔DY: 4 GeV < M < 8 GeV; B-background: use FVTX

# Sivers Asymmetries in SIDIS and DY

"Transverse-Spin Drell-Yan Physics at RHIC" (http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf)

- Important test at RHIC of recent fundamental QCD predictions for the Sivers effect, demonstrating… **attractive vs repulsive color charge forces**



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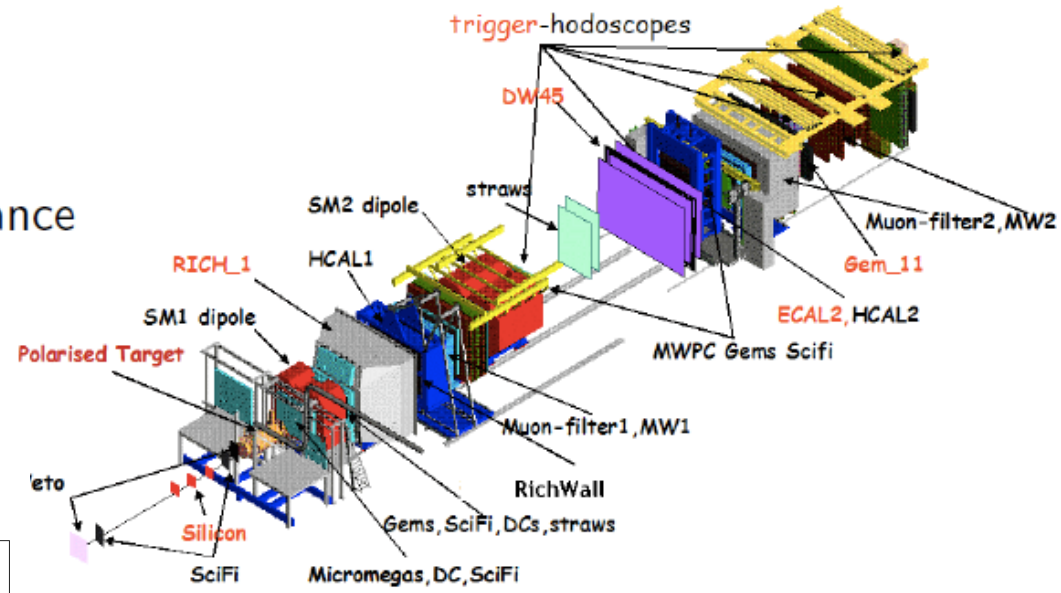
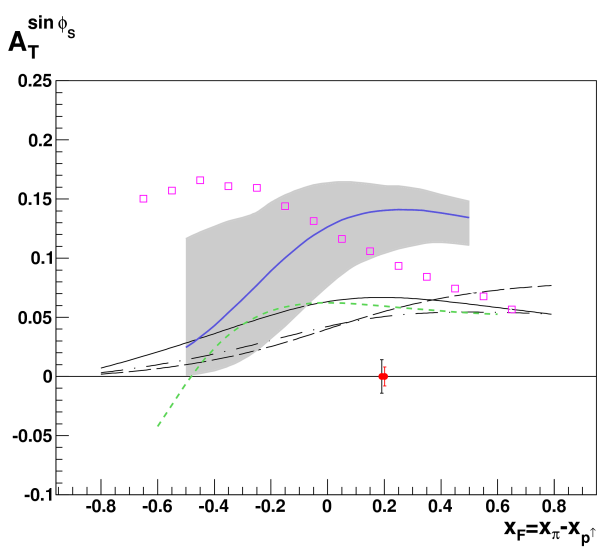
A. Morreale's talk
4/28/2011

# Test the Sign Change

## COMPASS facility at CERN

- $\mu$, $p$, $\pi$, $K$ beam
- 50-270 GeV/c momentum
- $\pm 180$ mrad angular acceptance




- $NH_3$ target polarisation $\sim$90%
- dilution factor 0.14
- three cells target

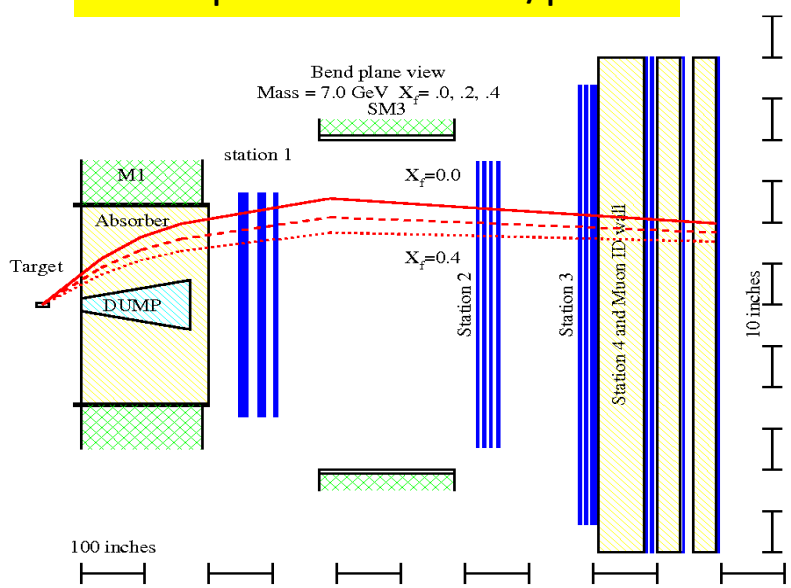
# Polarized DY @ E906/Fermilab?

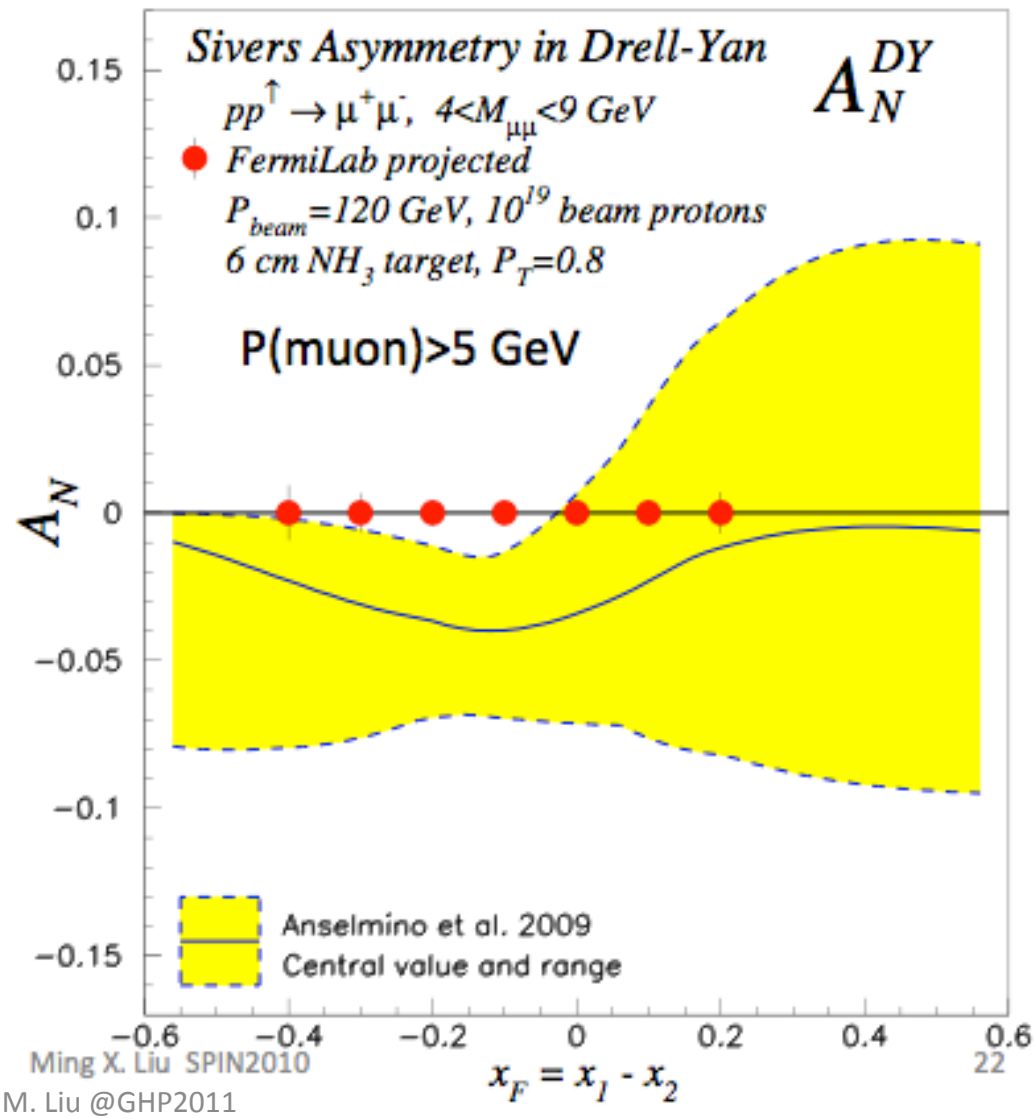
D. Sivers' talk
4/27/2011

## Polarized Target

- 6 cm $NH_3$
- $10^{19}$ proton

Also open charm and J/psi




Ming X. Liu SPIN2010

M. Liu @GHP2011



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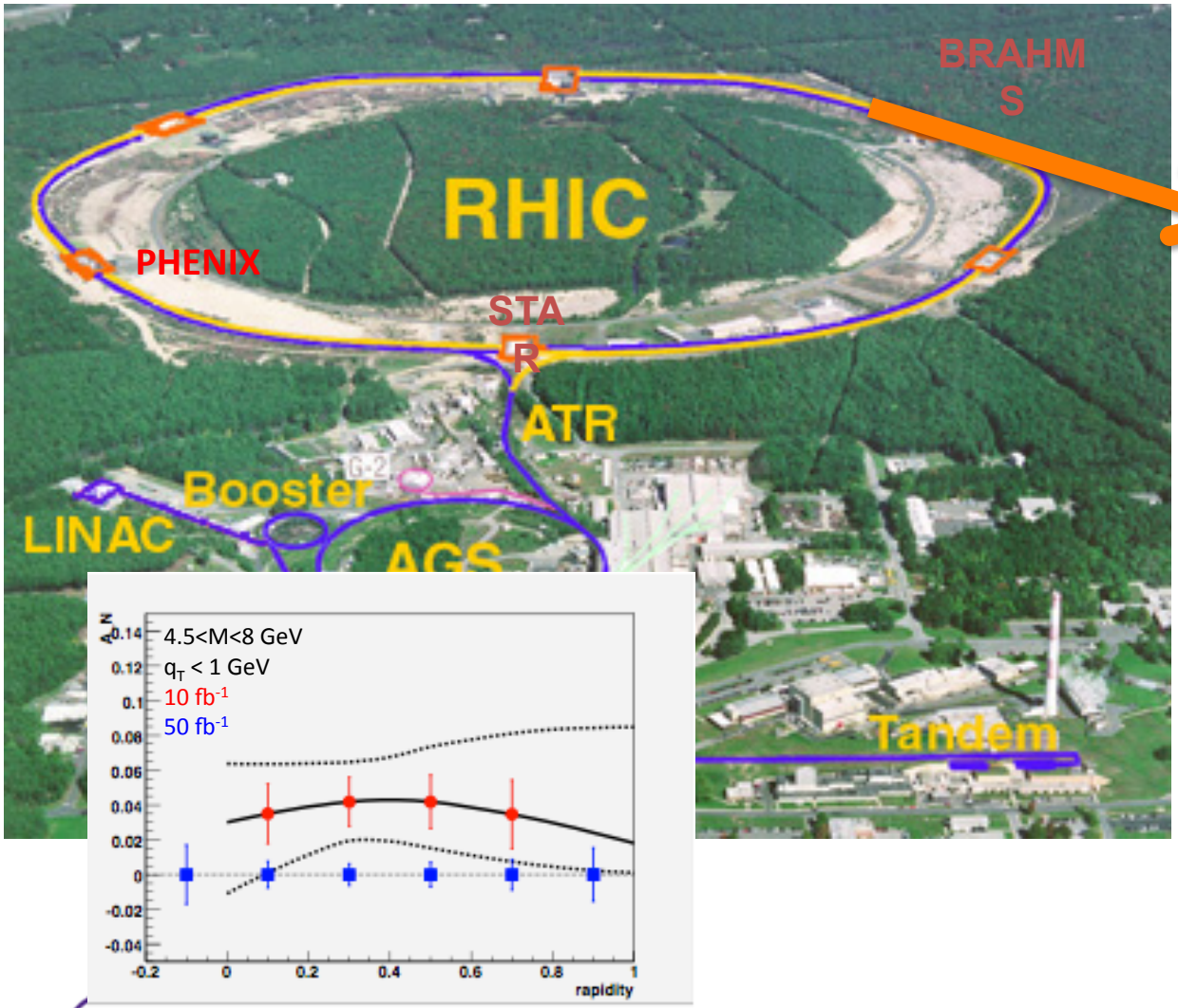
# Polarized DY w/ Fixed Target @RHIC ?




**Polarized fixed target DY exp. with extracted polarized proton beams:**

**Fixed Target DY Exp. @Beam Dump**

1. High density $LH_2$/ $LD_2$ target
2. High density polarized targets
3 Map out x-dep.

- 250 GeV proton beams
- Pol up to 70%

# 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**

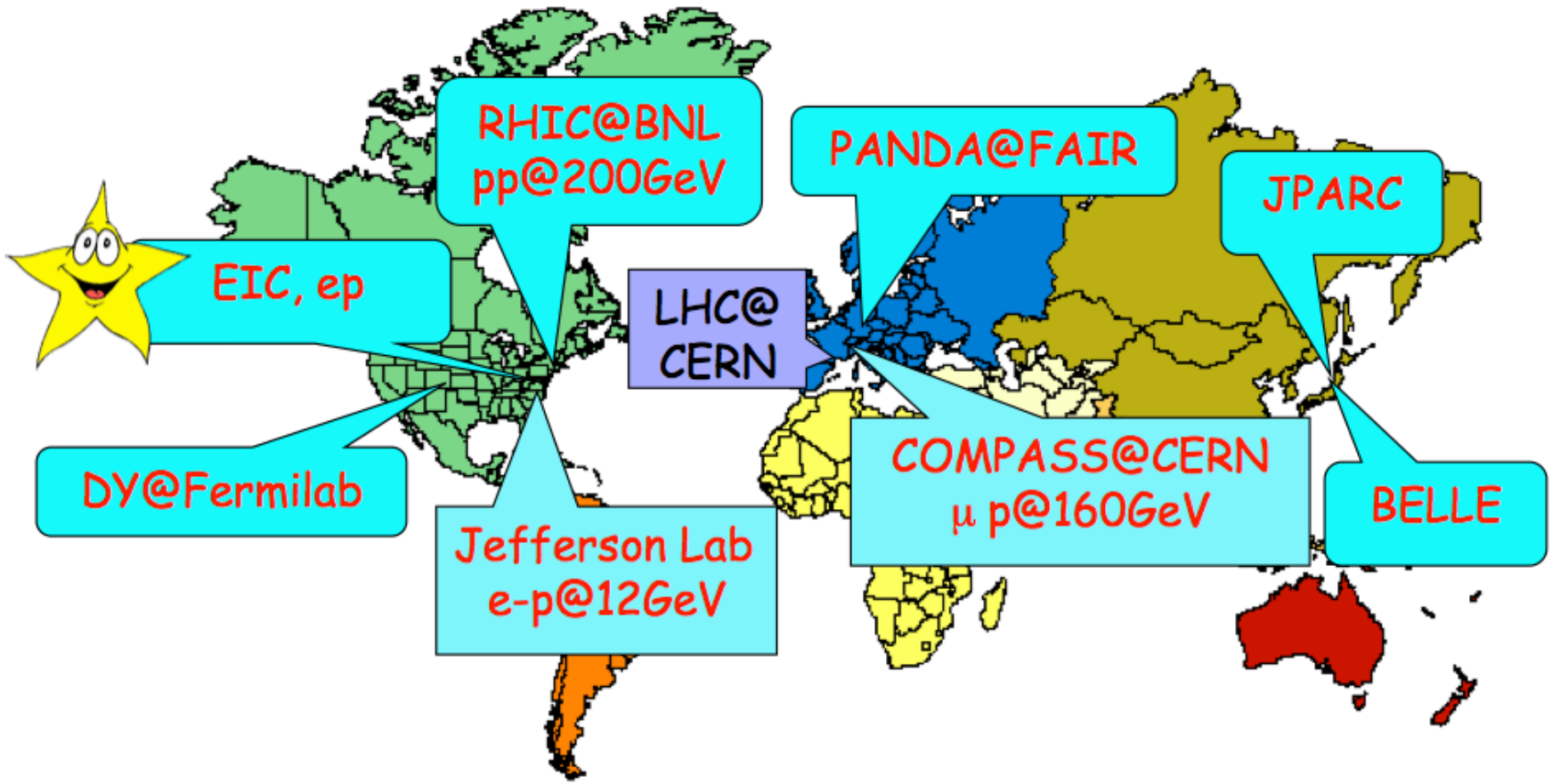
**October 31- November 1, 2010**
**Hilton of Santa Fe (Fall APS/DNP hotel)**
**Santa Fe, NM 87501**

# Summary and Outlook

- Drell-Yan is a powerful tool complimentary to DIS for exploring nucleus structure and QCD dynamics
  - EIC and DY
- Active worldwide programs, current and future Exp's will address many critical issues in hadron spin and flavor physics
  - A new fundamental test of QCD

# backup

# World Map of QCD Facilities



# Proposed Future Polarized DY Exp's

Y. Goto 4/2010 CERN DY

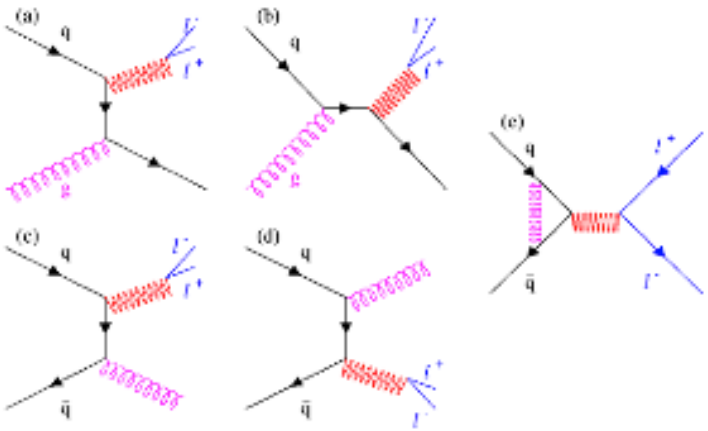
| experiment | particles | energy | x1 or x2 | luminosity |
|---|---|---|---|---|
| COMPASS | $\pi\pm + p\uparrow$ | 160 GeV<br>$\sqrt{s}$ = 17.4 GeV | x2 = 0.2 – 0.3 | $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ |
| COMPASS (low mass) | $\pi\pm + p\uparrow$ | 160 GeV<br>$\sqrt{s}$ = 17.4 GeV | x2 ~ 0.05 |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

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

# QCD Correction

## K factor collection

$$d\sigma^{DY}_{NLO} = K(s, M^2) d\sigma^{DY}_{LO}$$

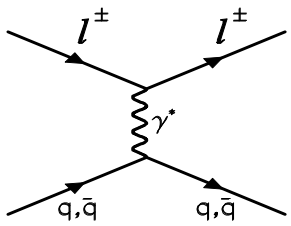


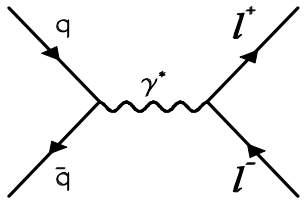
| Group | Beam/target | cm Energy | K |
|---|---|---|---|
| E288 | p/Pt | 27.4 | 1.7 |
| E439 | p/W | 27.4 | 1.6±0.3 |
| CHFMNP | p/p | 44,63 | 1.6±0.2 |
| AABCSY | p/p | 44,63 | 1.7 |
| NA3 | p/Pt | 27.4 | 3.1±0.5±0.3 |
| E537 | $\bar{p}$/W | 15.3 | 2.45±0.12±0.20 |
| NA3 | (p-$\bar{p}$)/Pt | 16.8 | 2.3±0.4 |
| NA3 | $\pi$/Pt | 16.8 | 2.49±0.37 |
| | | 22.9 | 2.22±0.33 |
| E326 | $\pi$/W | 20.6 | 2.70±0.08±0.40 |
| NA10 | $\pi$/W | 19.1 | 2.8±0.1 |
| Goliath | $\pi$/Be | 16.8,18.1 | 2.5 |
| Omega | $\pi$/W | 8.7 | 2.6±0.5 |

Table VII..2. *K* Factors for dilepton experiments (Grosso-Pilcher and Shochet, 1986).

# Complimentality between DIS and Drell-Yan

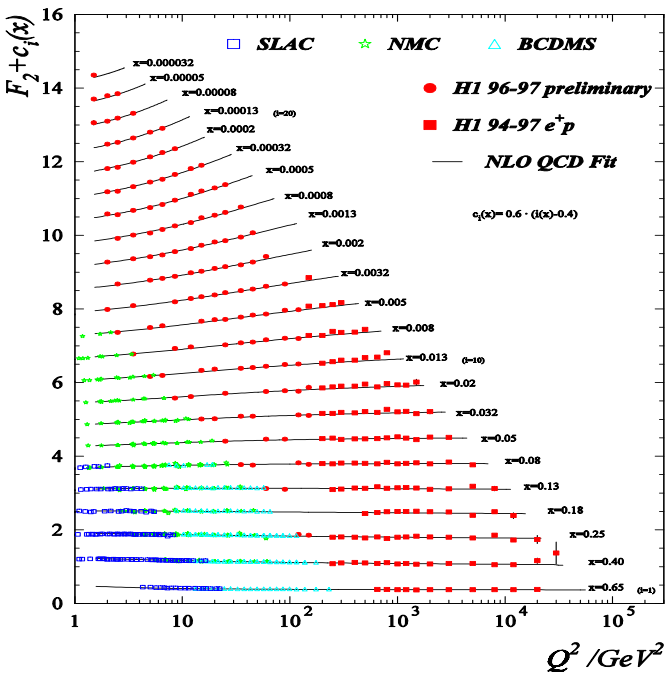
DIS

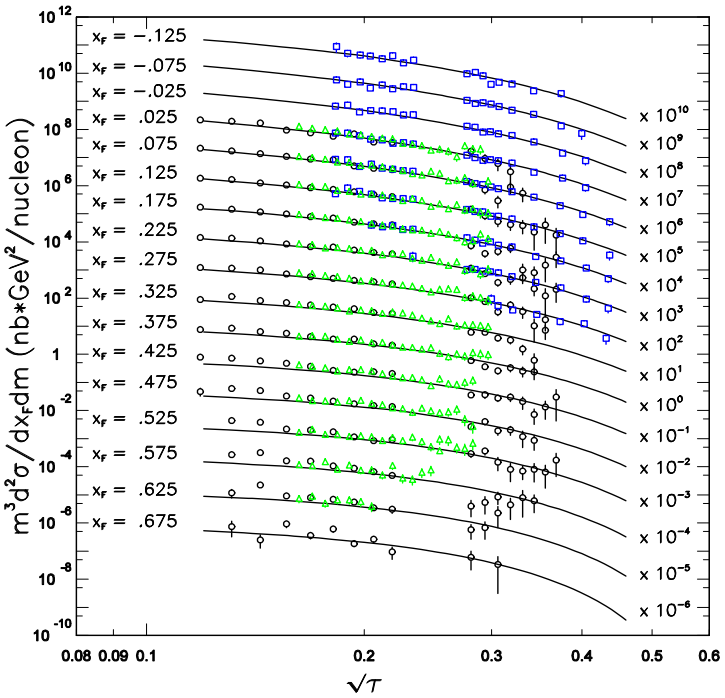



Drell-Yan

$p\,A \rightarrow \mu^+\mu^-\,X$



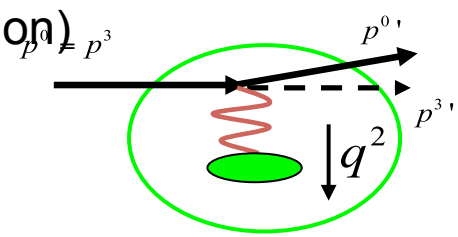

McGaughey, Moss, Peng,

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

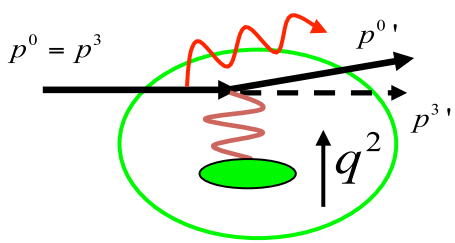
Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

# Energy loss in Electrodynamics

- Collisional energy loss (ionization and atomic excitation)

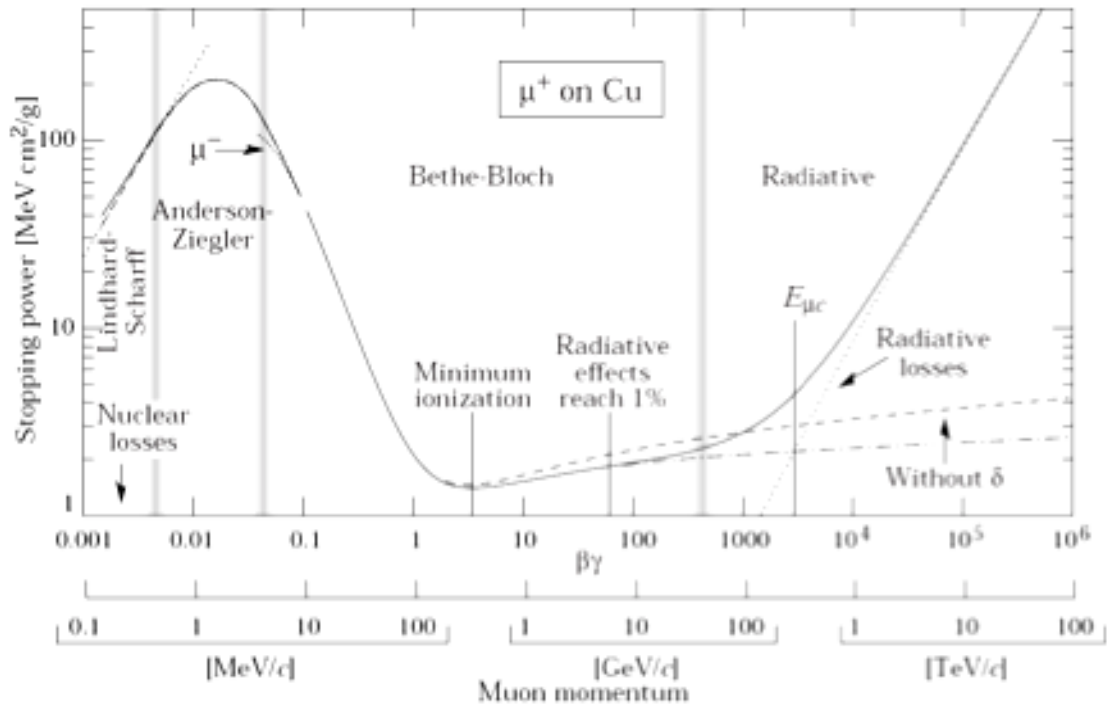



- Radiative energy loss (photon bremsstrahlung)




$\Delta E_{rad} = \Delta E_{col}$ at $\gamma \sim 500$

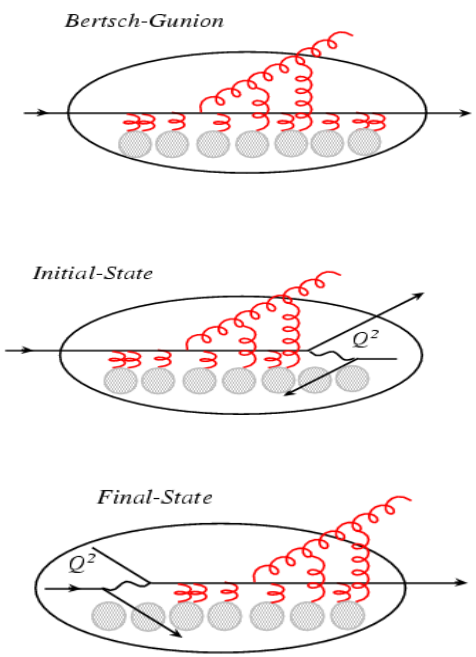
**In QCD**




**PDG, Phys.Lett. B 592, 1-4 (2004)**

# Process Dependence of Parton Energy Loss

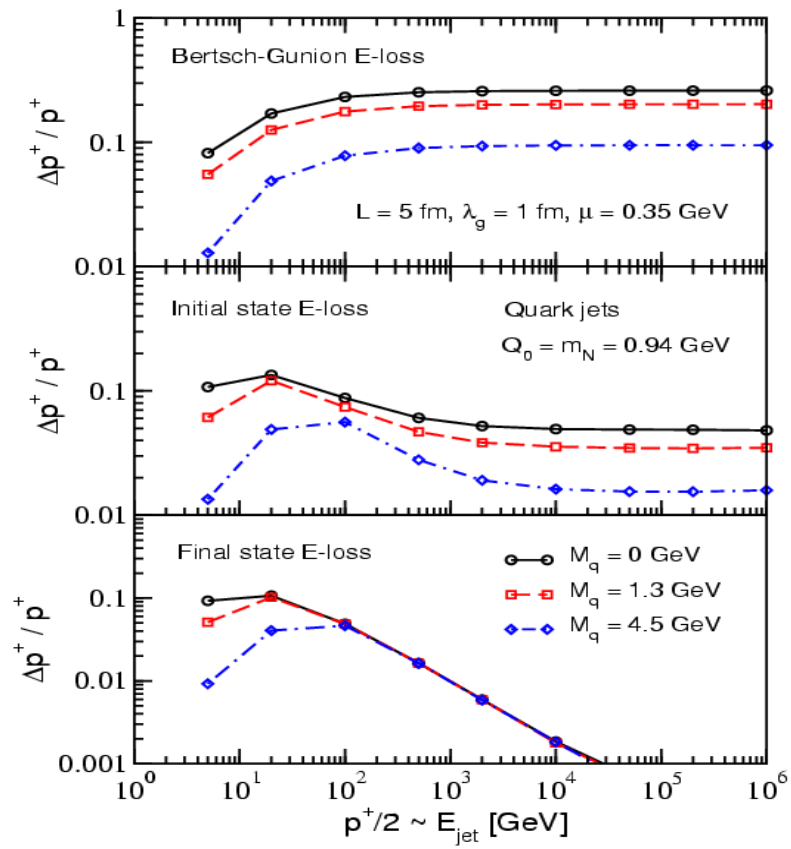
- E-loss in three cases




Academic case
(probably inapplicable)

Initial-state E loss:
DY process

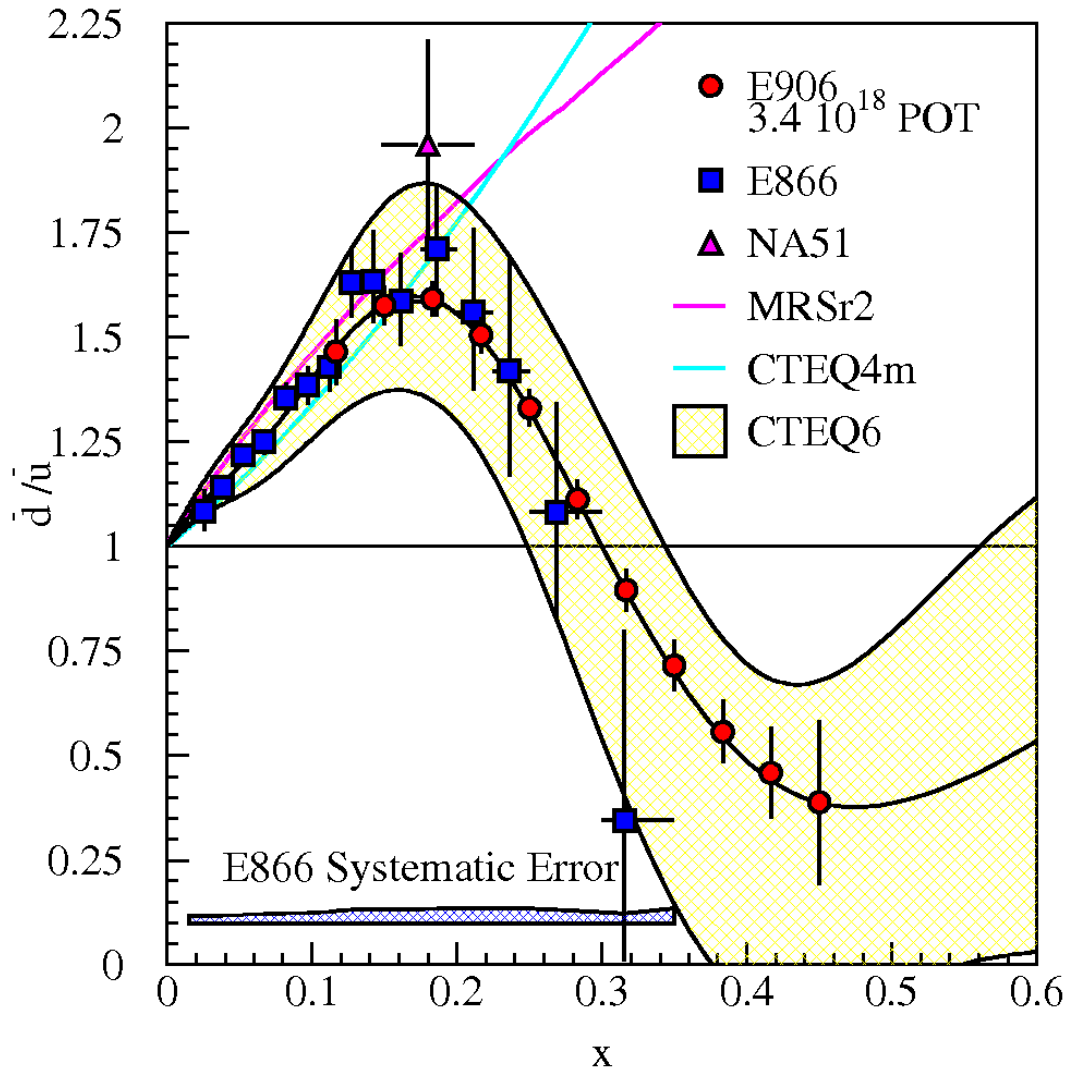
Final-state E loss:
SDIS, QGP




I. Vitev, PRC 75(2007)064906.

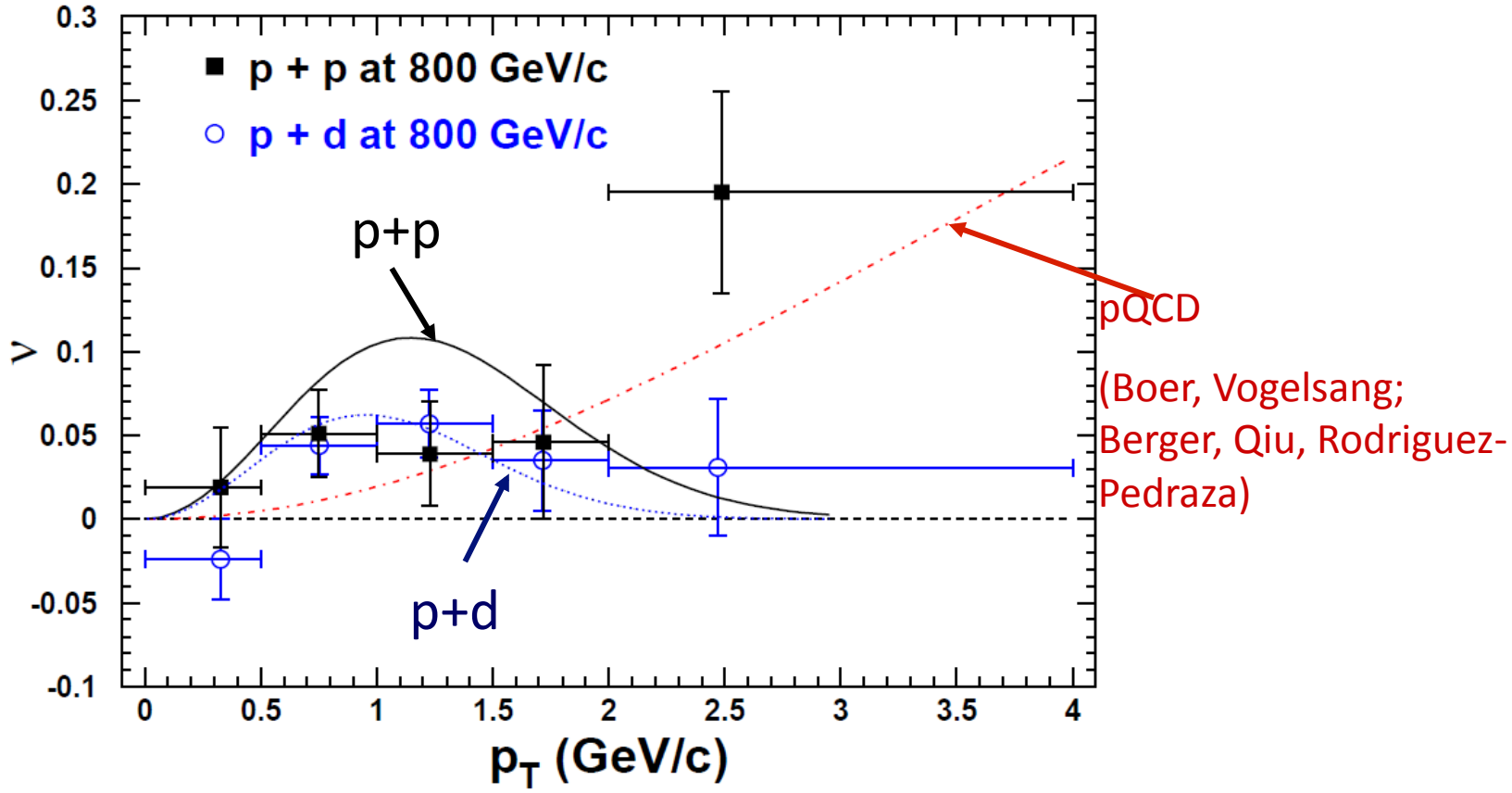
# E906 Projections for d-bar/u-bar Ratio

- 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



# Results on cos2Φ Distribution in p+p Drell-Yan

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

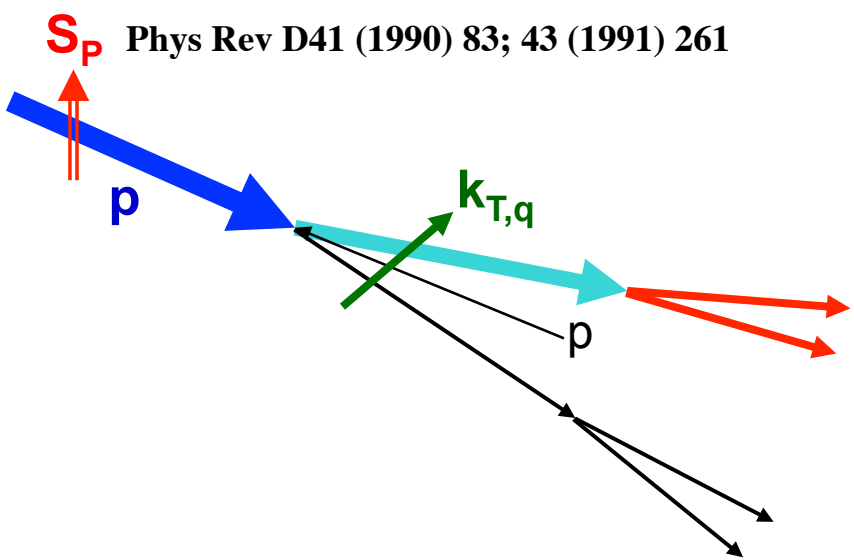


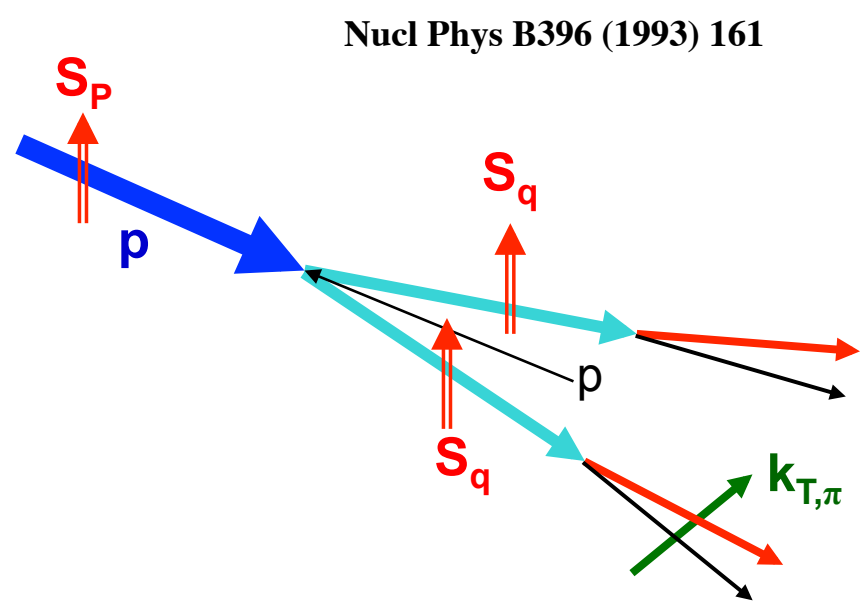

Combined analysis of SIDIS and D-Y by Melis et al.

More data are anticipated from Fermilab E906

# Current Understanding of TSSAs

- TMD approach: Transverse Momentum Dependent Distribution Functions
  - Sivers fucntion: nucleon spin and parton kT correlation
  - Collins function: spin dependent fragmentation function
  - and lots of others …

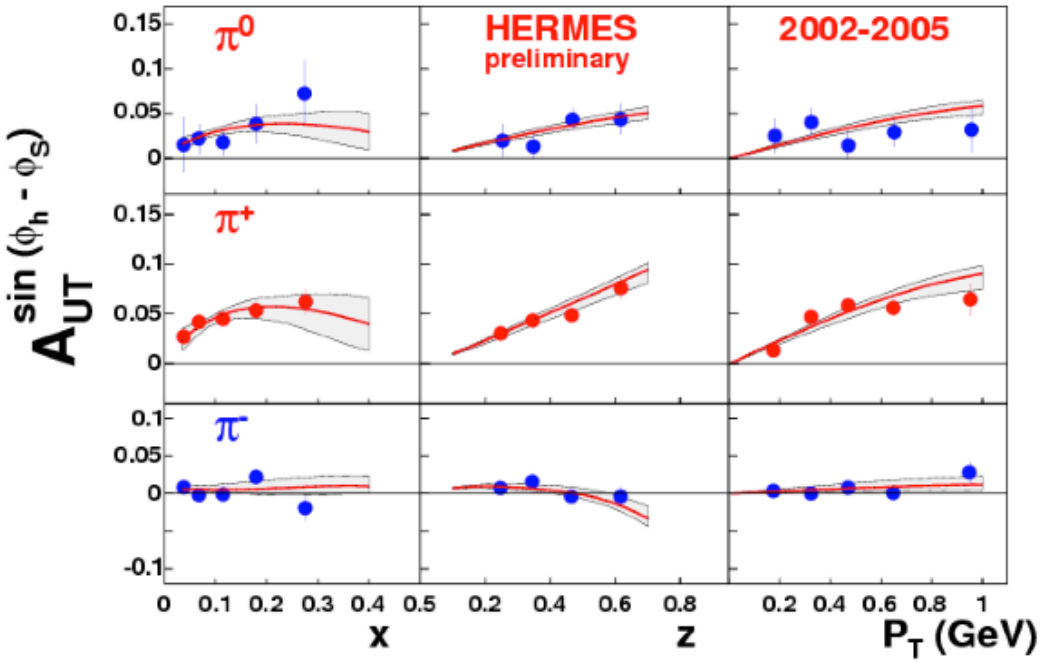


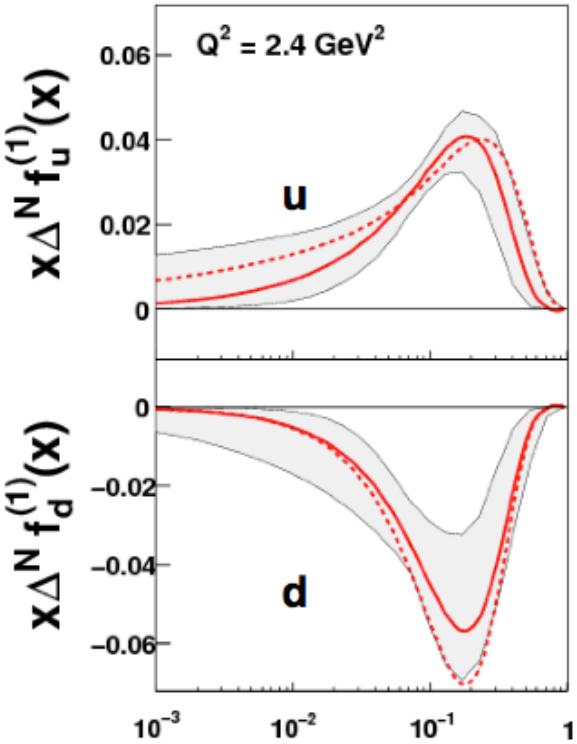



# Sivers function from SIDIS

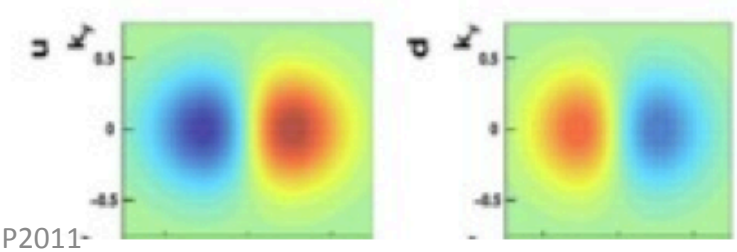
- Extract Sivers function from SIDIS

Anselmino, et.al., 2009




- u and d almost equal size, different sign

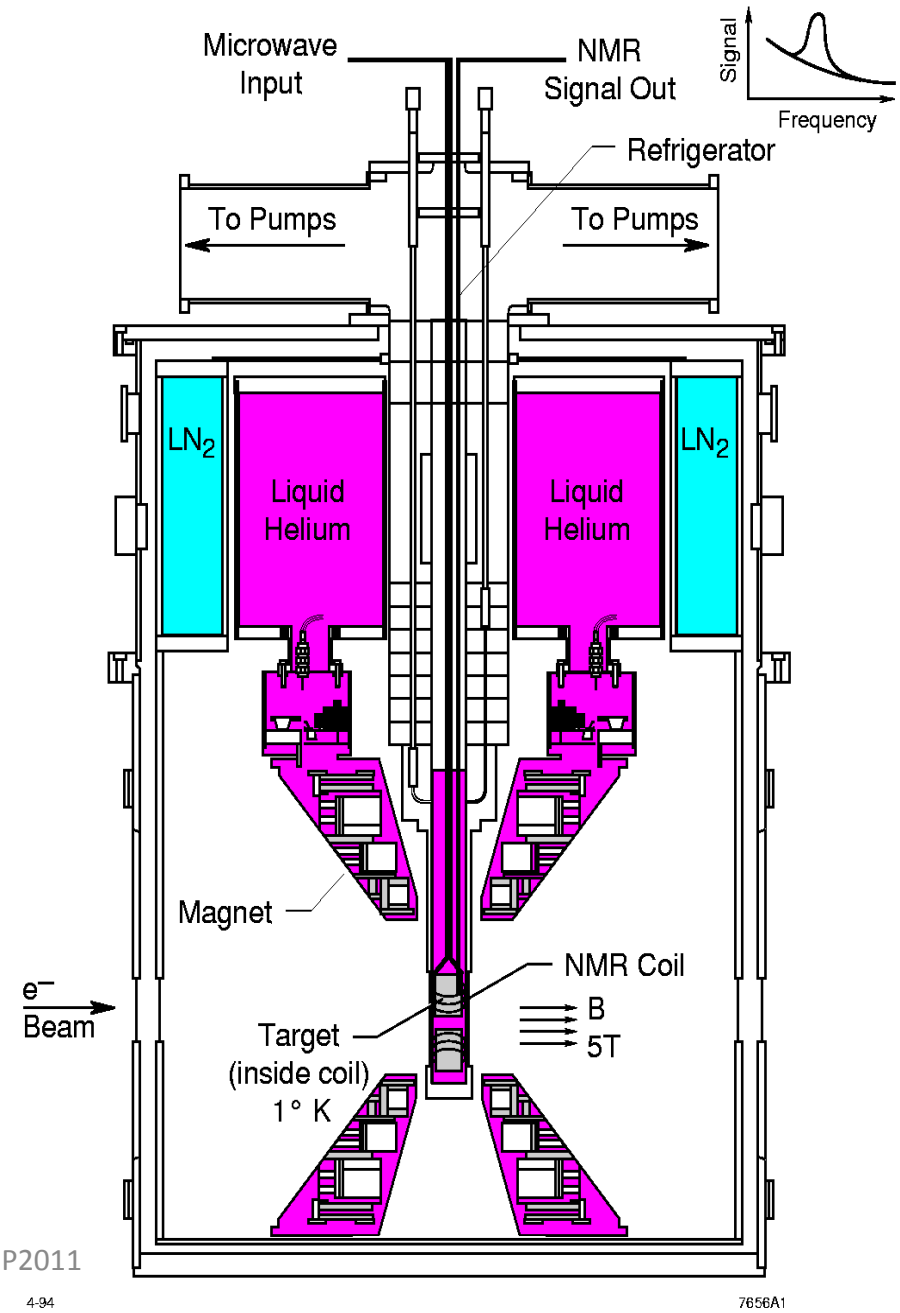


D. Crabb MENU10

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

- 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)




M. Liu @GHP2011

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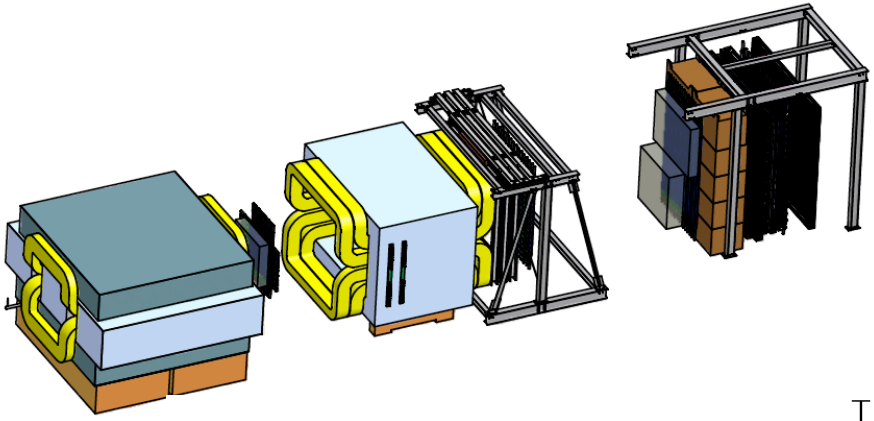
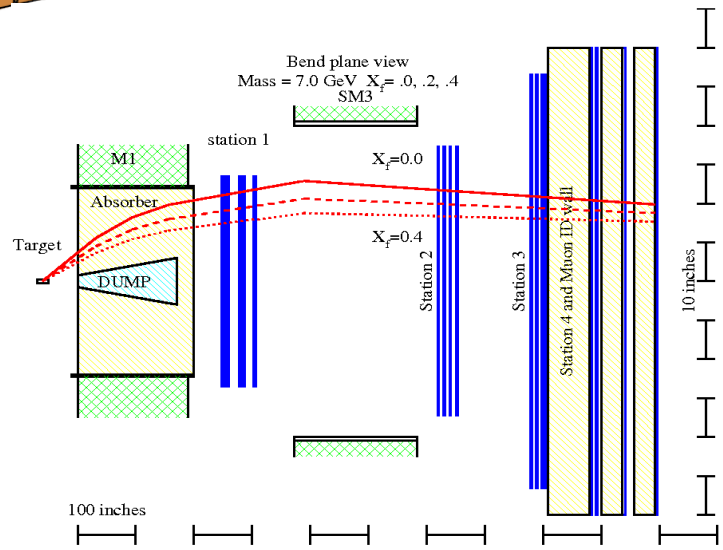
# Fixed Target @RHIC ?

- Beam dump experiment: dimuon channel
  - Parasitic mode
    - Significant beams still left at the end of a store (~50%)
    - Cycle time ~8hr
  - Dedicated fixed target
    - Cycle time ~ 1hr
  - Dimu x-section @ 250 GeV (M>4) ~20pb
- Targets
  - E906-like unpolarized $LH_2$ target
    - 51cm LH2 ($2.1 \times 10^{24}/cm^2$)
    - Can handle L ~ $1 \times 10^{36} cm^{-2} s^{-1}$
  - Polarized solid target
    - UVA/J-Lab/SLAC: L ~$10^{35} cm^{-2} s^{-1}$
- Advantages
  - Polarized beams
  - (polarized) targets
  - Higher Energy and large x-coverage
  - High luminosity





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# RHIC Polarized Protons: Plans

Assume: polarized proton running 2011 to 2014 for W-physics with longitudinal polarization at STAR and PHENIX

| | 2009 | 2011 | 2012 | 2013 | 2014 | Design |
|---|---|---|---|---|---|---|
| Polarization | 35% | 50% | 55% | 60% | 65% | 70% |
| <Luminosity> in $10^{32} cm^{-2} s^{-1}$ | 0.6 | 1.0 | 1.5 | 2.0 | 2.5 | 2.0 |
| | | *longitudinal spin for W-physics and $\Delta G$ with $\int Ldt \sim 300\ pb^{-1}$* | | | | |

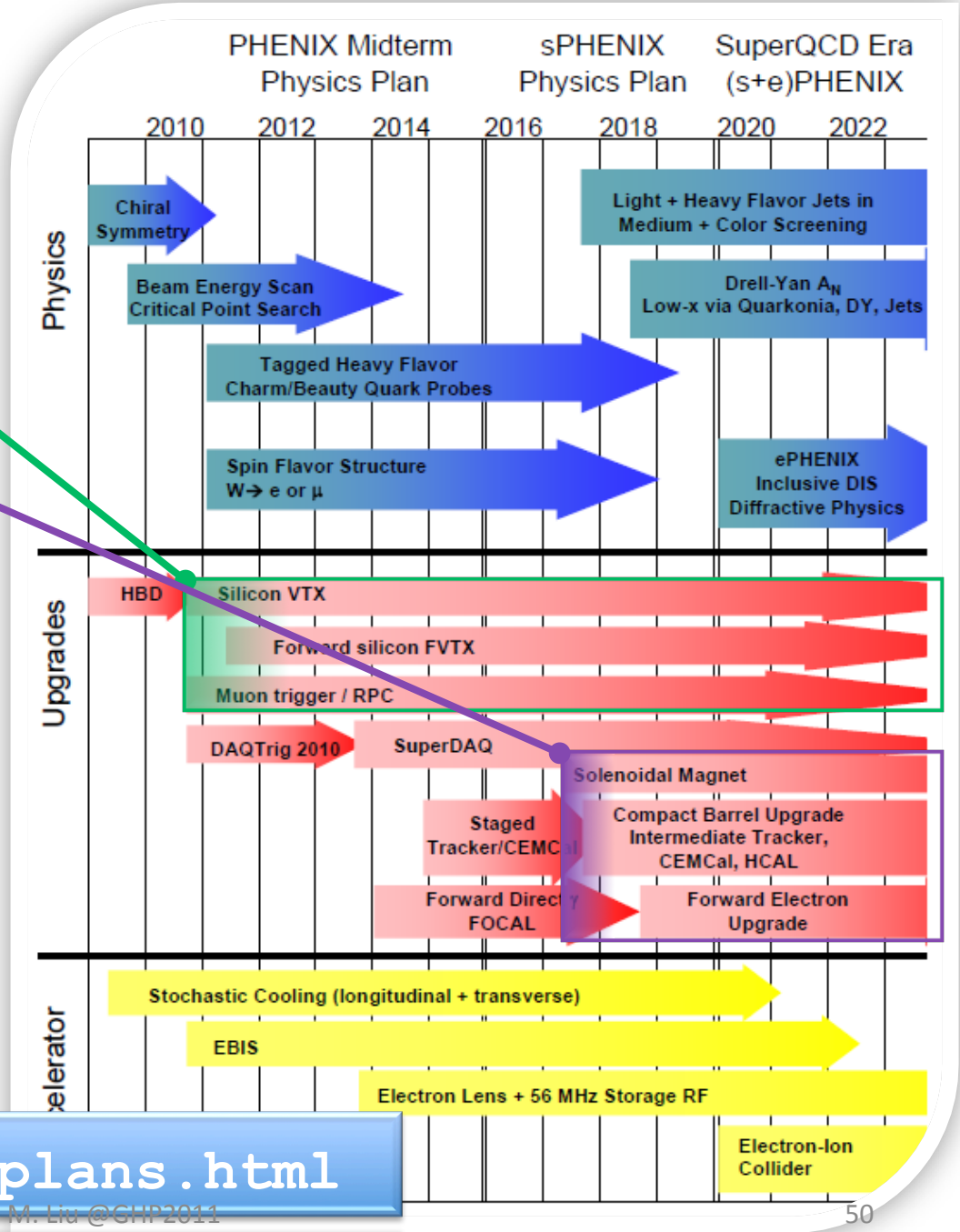
➔ (1) Drell-Yan Program with transverse spin in STAR and PHENIX will not start before run 15 (starting late 2014).

(2) 11-14: Drell-Yan with longitudinal polarization using "W-sample"

(3) Initial ideas for dedicated Drell-Yan experiment at IP-2

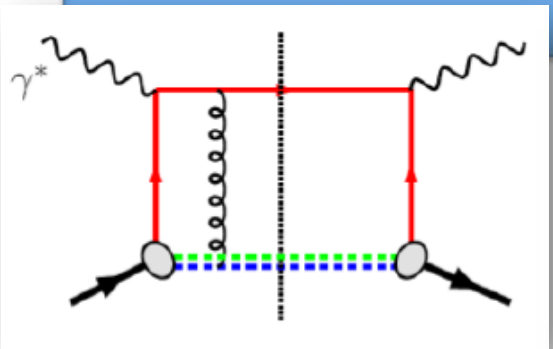
# PHENIX Decadal Plan

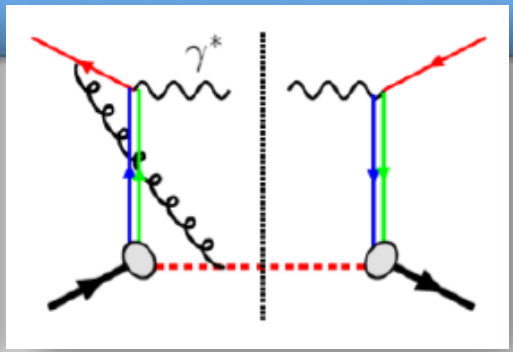
- Midterm upgrades until 2015
- Long term evolution after 2015
- Dynamical origins of spin-dependent interactions
- *New probes of longitudinal spin effects*
- *Measurement with polarized $He^3$ and increased energies*

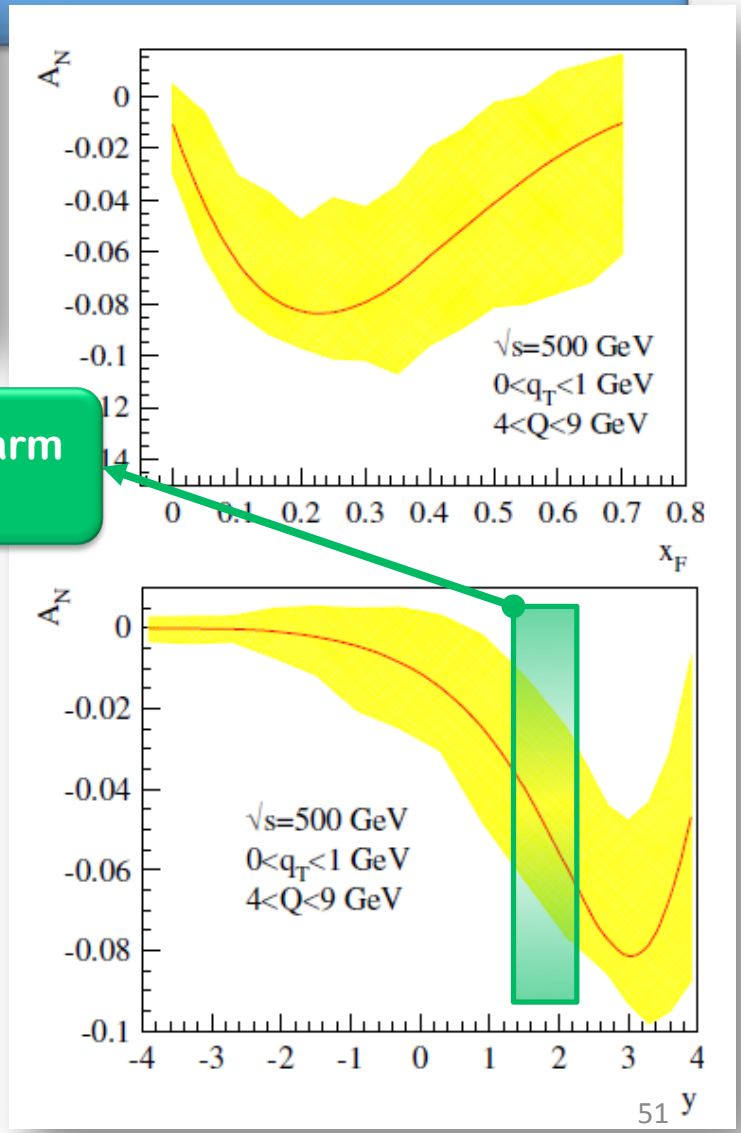



www.phenix.bnl.gov/plans.html

# Polarized Drell Yan




current Muon arm acceptance

- Solid factorization
- No fragmentation
  - Direct correlation of intrinsic transverse quark momentum to the proton spin
- Fundamental QCD test
  - Sign of asymmetry compared to SIDIS

Z. Kang and J. Qiu. Phys. Rev., D81:054020, (2010)



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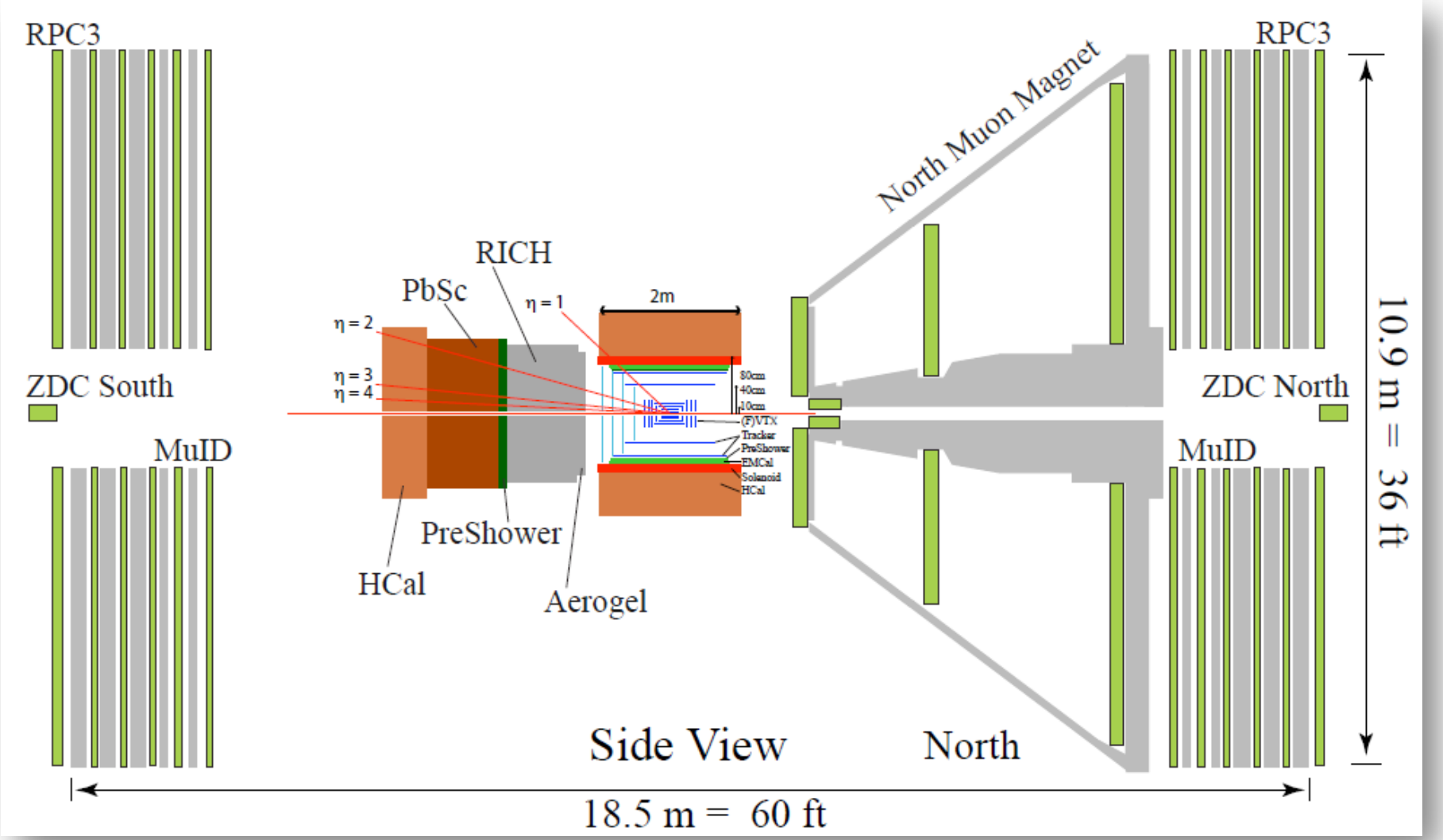
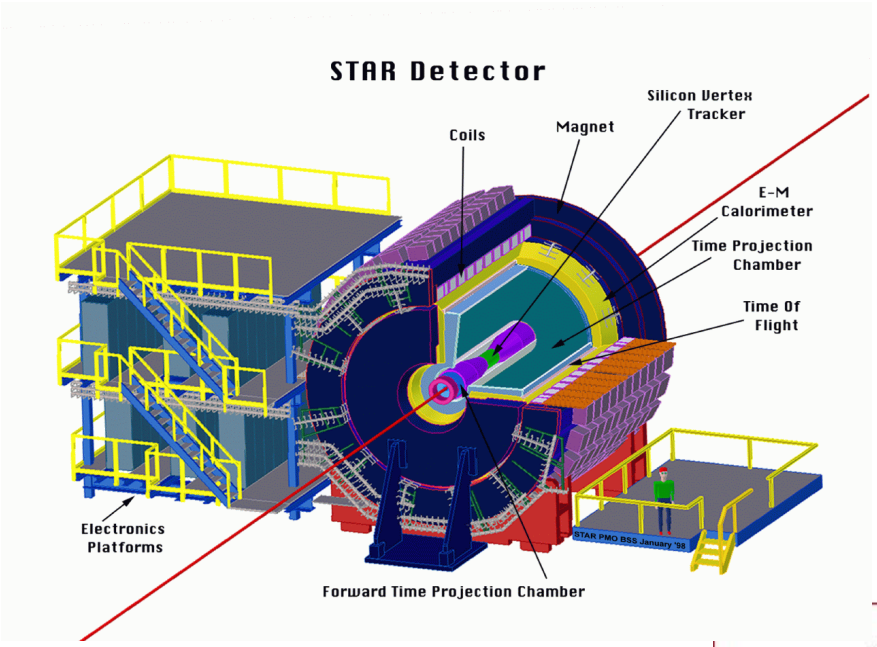
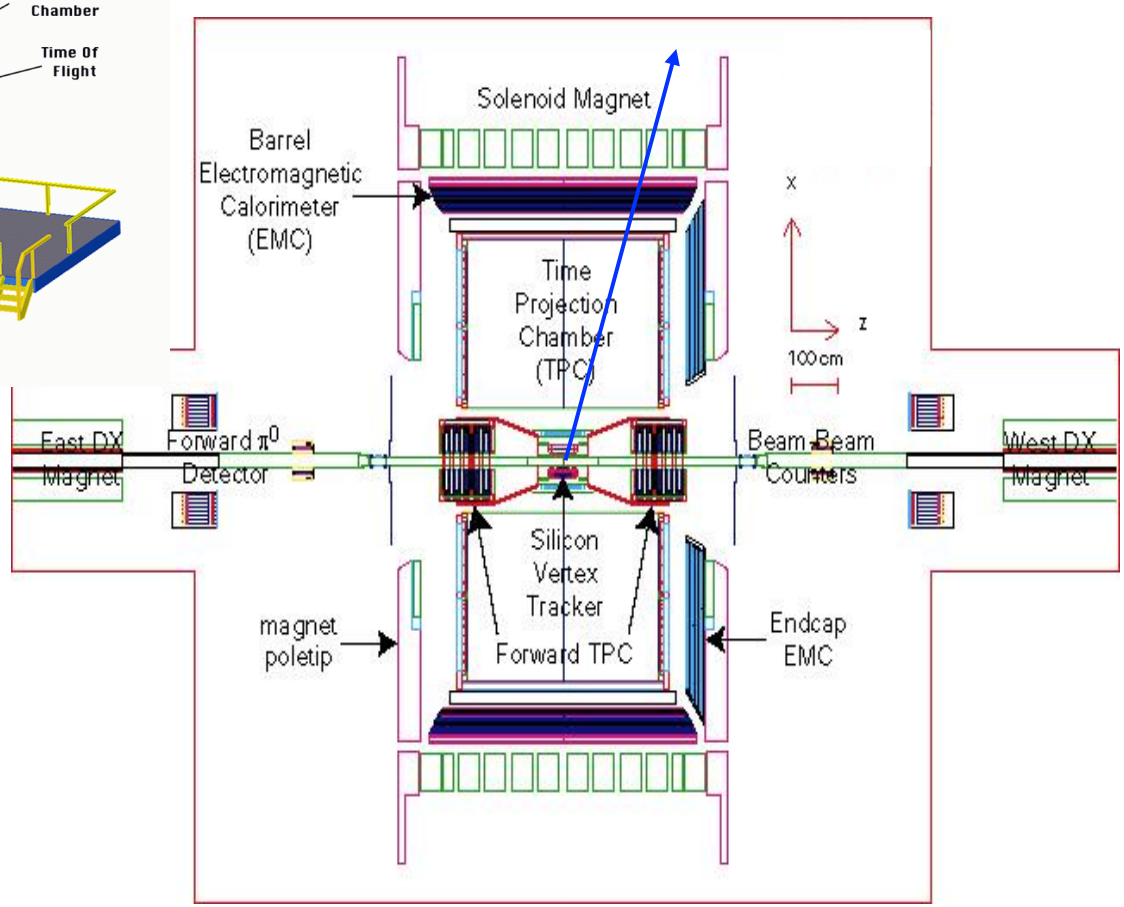
# Proposed PHENIX Upgrades



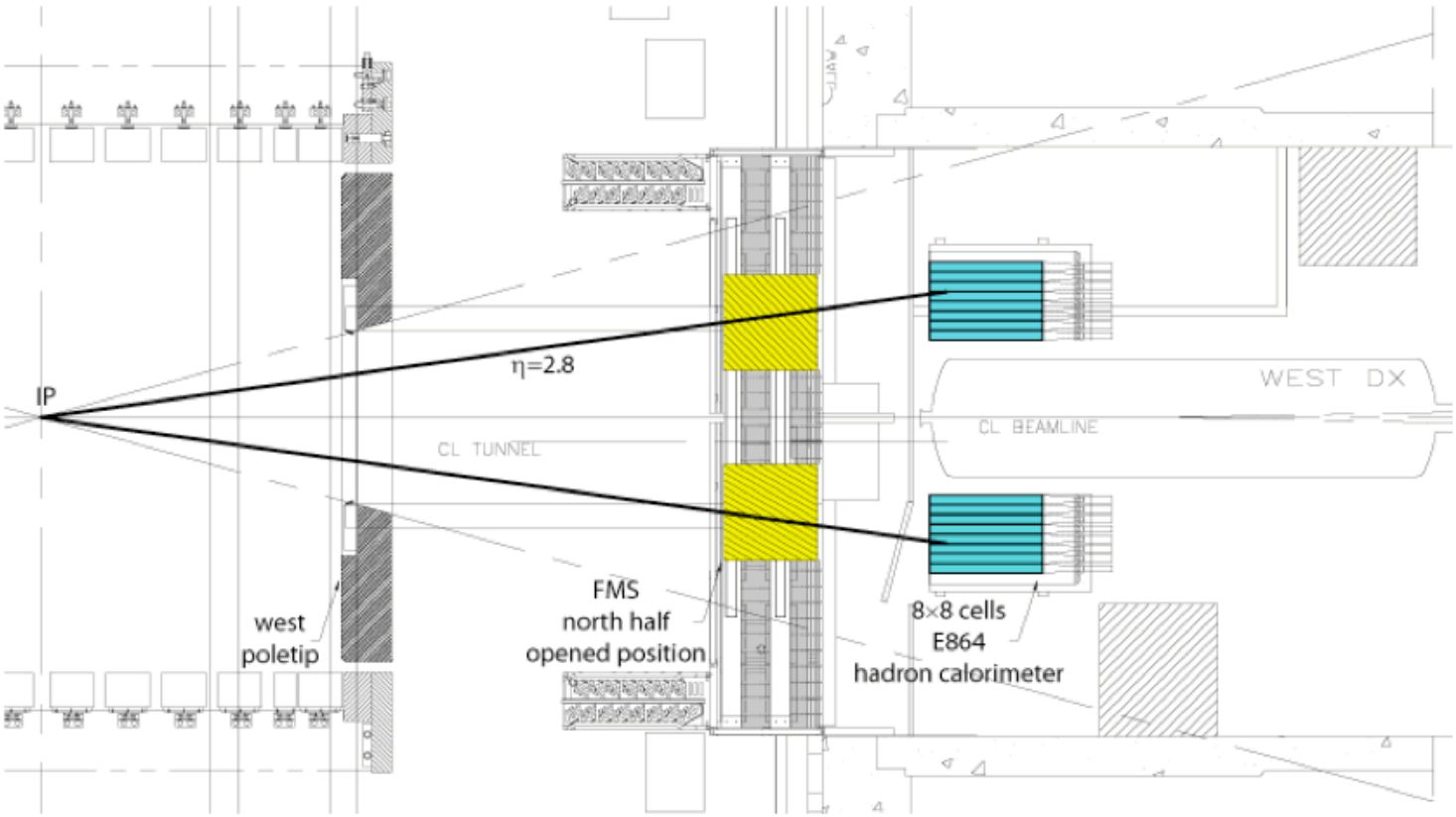
# The STAR Detectors




- Time Projection Chamber $|\eta|<1.6$
- Forward TPC $2.5<|\eta|<4.0$
- Silicon Vertex Tracker $|\eta|<1$
- Barrel EMC $|\eta|<1$
- Endcap EMC $1.0<\eta<2.0$
- Forward Pion Detector $3.3<|\eta|<4.1$

# STAR Experiment - Forward Upgrades



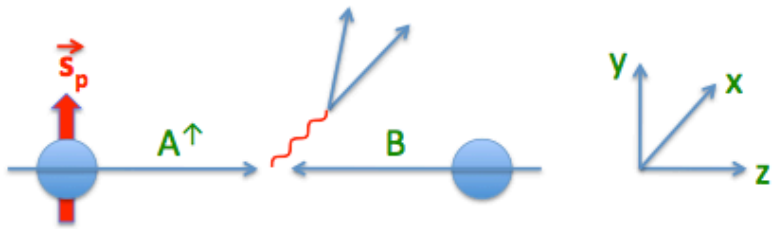

FHC: proposed hadronic calorimetry behind the FMS,
essential towards understanding of forward single-spin asymmetries,
enable forward (anti-)Lambda studies, ...

Would be part of a broader forward upgrade concept that is currently being discussed/studied within STAR,
e.g. extended tracking in the form of additional FGT-like disks,
preshower or TRD, converter, and shower-maximum detector for the FMS,
possibly a RICH to separate protons and advanced trigger.

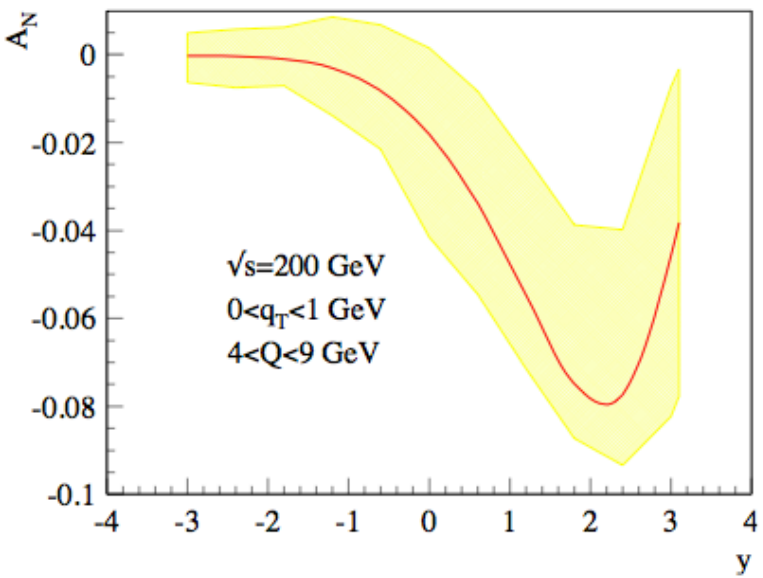
# Predictions for Drell-Yan process at RHIC

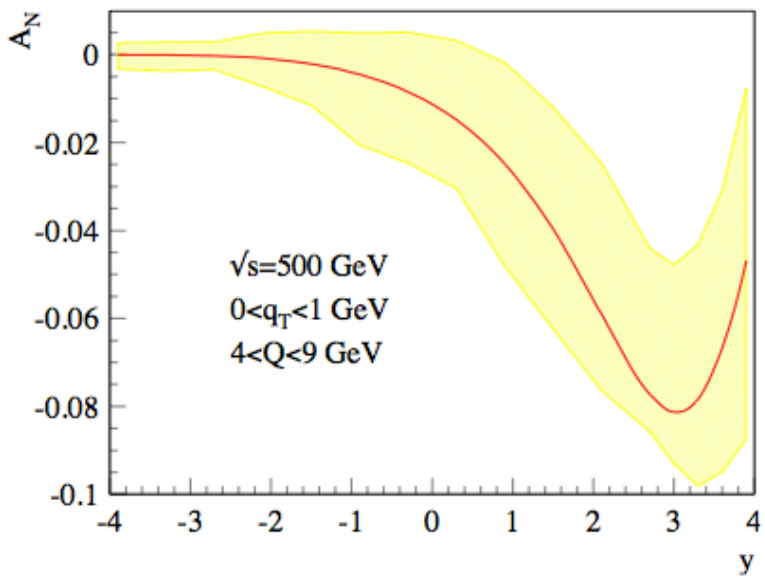
- Reverse the sign of Sivers from SIDIS and make predictions for Drell-Yan production at RHIC

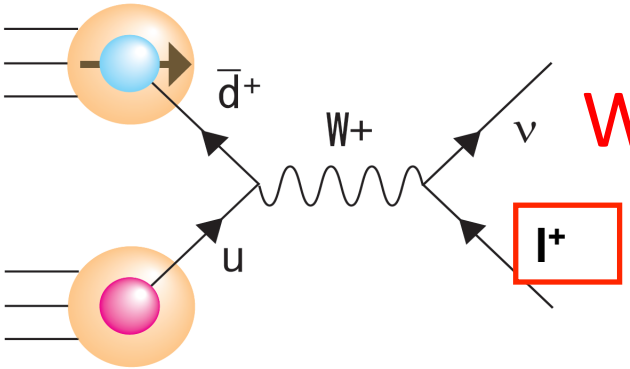
Kang-Qiu, PRD81, 2010




$$A_N \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d < 0$$






# $W^{+/-}$ & $Z^0$ Transverse SSA @500GeV ?

- Latest theoretical progress
  - Test time-reversal universality of Sivers functions with W/Z
  - Expect large asymmetry (from DIS fit)
- Flavor-identified Sivers Funs
  - Very large $Q^2$
- Expected Statistics @1fb$^{-1}$ 500GeV
  - $W^{+/-} \rightarrow \mu^{+/-}$ ~20K
  - $Z^0 \rightarrow \mu^+\mu^-$ ~ 1K

$$W^{\pm}: \quad \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 6300(6900)$$

$$\approx 1.5\%(1.4\%)$$

$$Z^0: \quad \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 380$$

$$\approx 6.0\%$$

Kang & Qiu PRL 103, 172001 (2009)

$W^{+/-}$

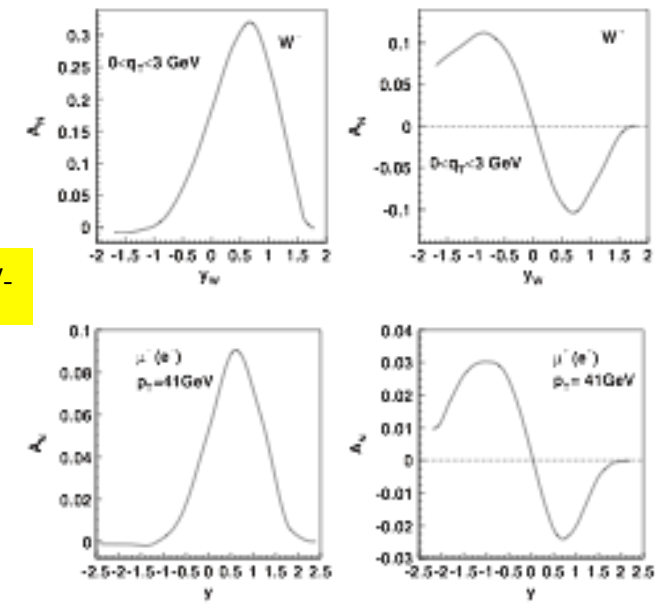



FIG. 3. $A_N$ as a function of lepton rapidity.

$Z^0$

Kang & Qiu arX 0912.1319

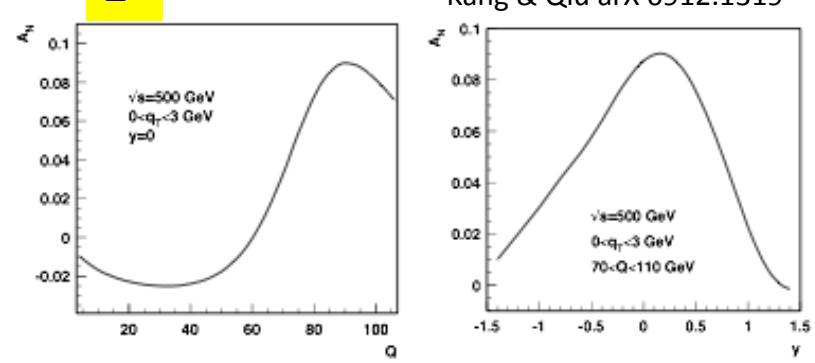



FIG. 3: Left: SSA of lepton pair production as a function of the pair's invariant mass $Q$. Right: SSA of lepton pair accumulated around $Z^0$ pole as a function of rapidity $y$.



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