Drell-Yan Physics

An Experimental Overview

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Los Alamos National Lab

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

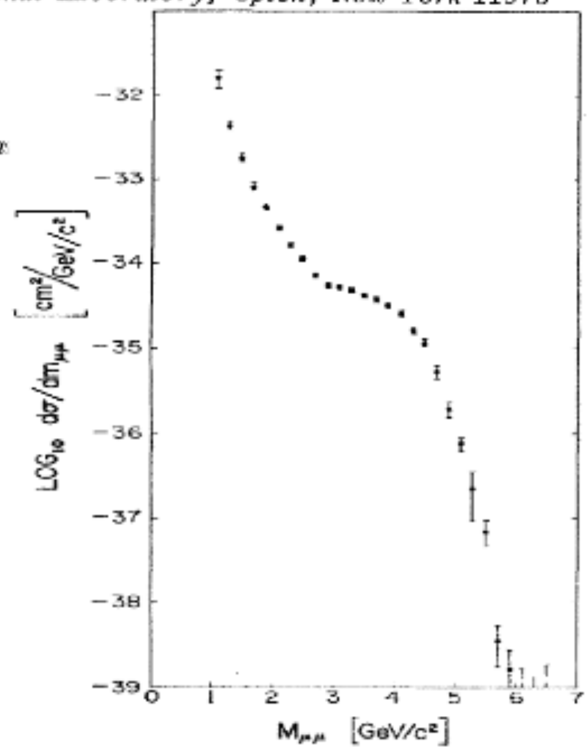
VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

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)

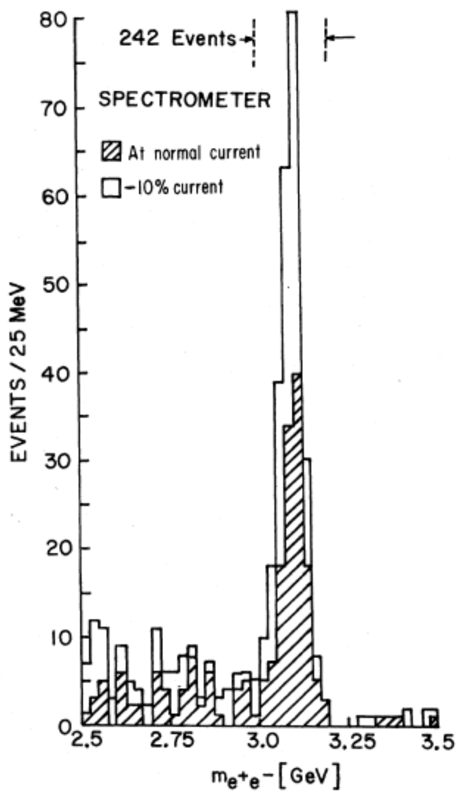


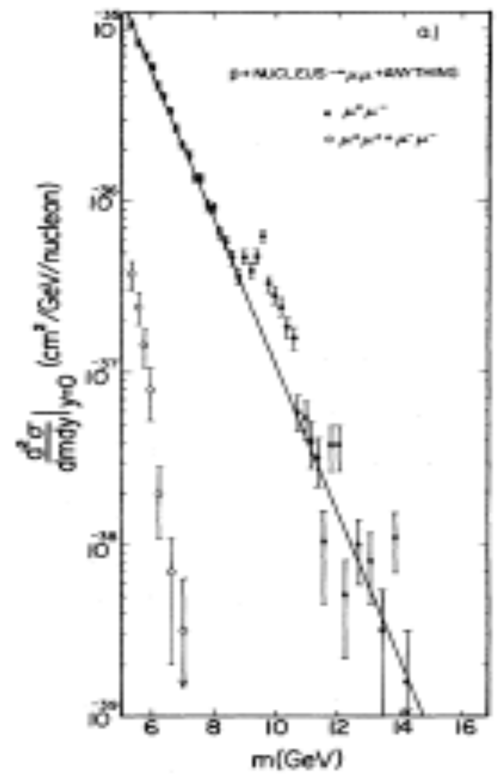
Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c² have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm² $(GeV/c)^{-2}$ and exhibits no resonant structure.** The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

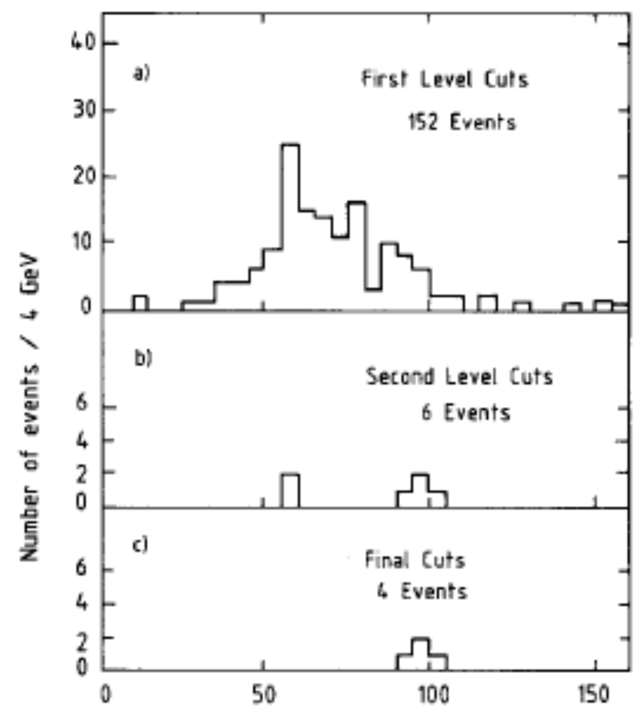
Missed the J/Psi!

Di-lepton probe: a Powerful Tool for Discovery

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





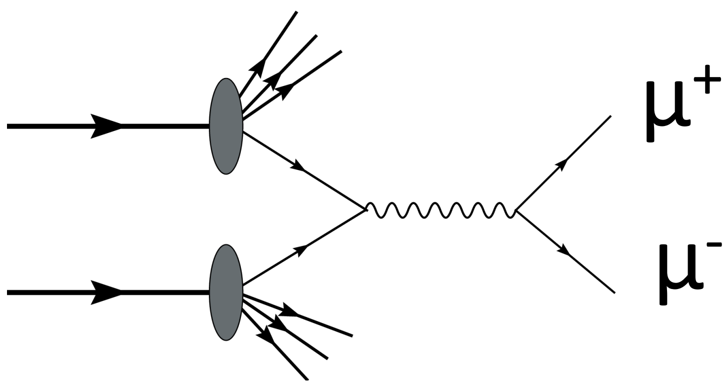


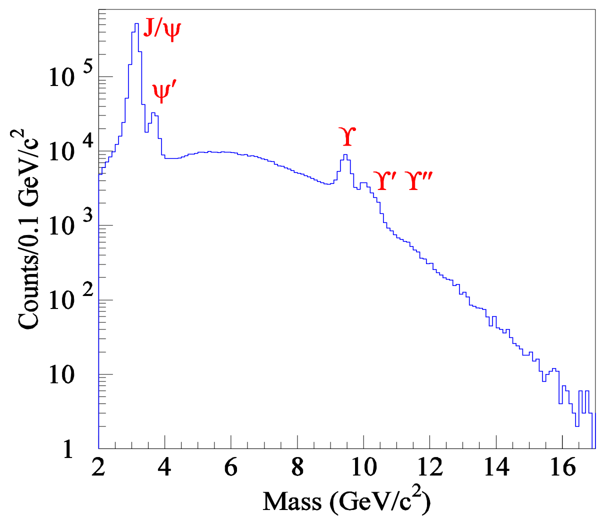
The Drell-Yan Process

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 νW_2 near threshold.

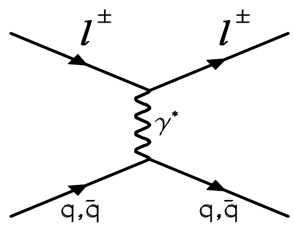


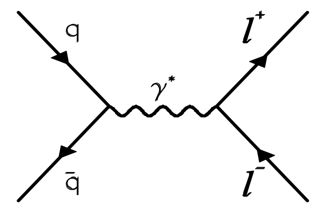


$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9\, s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2) \right]$$

Complimentality between DIS and Drell-Yan

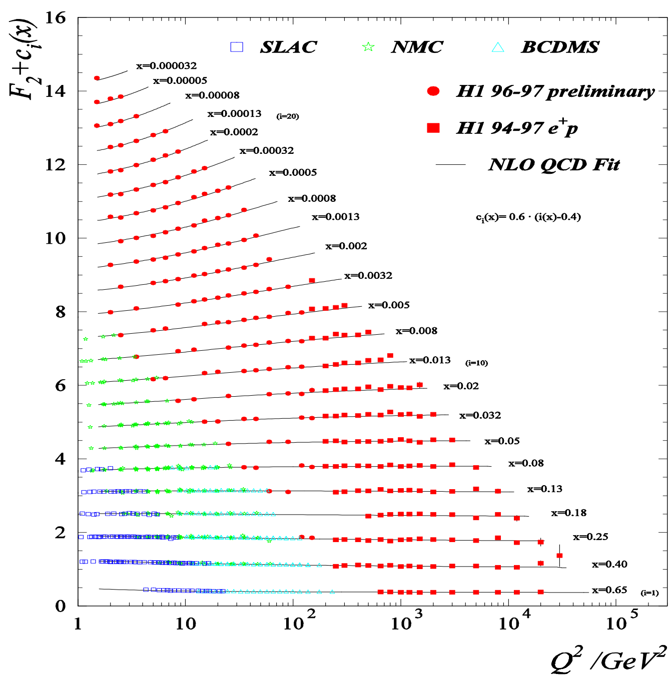
DIS

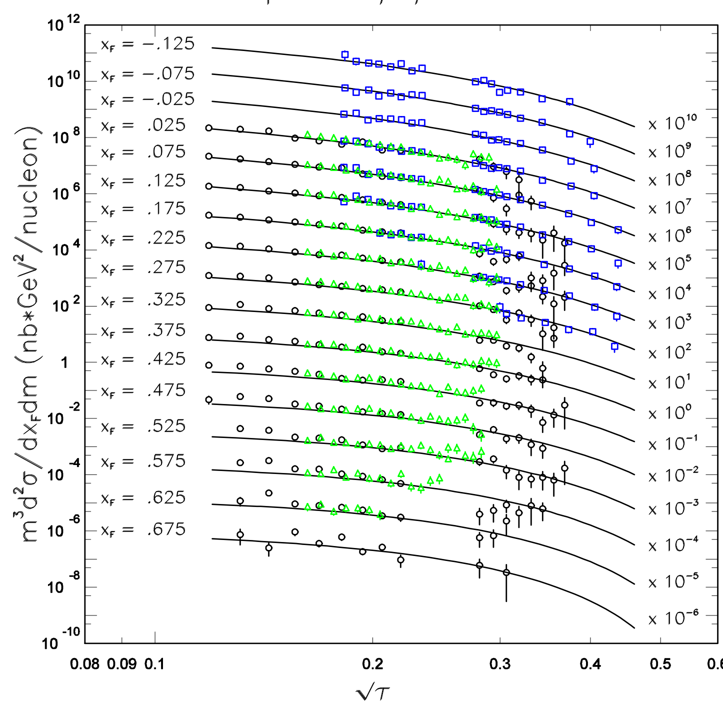




Drell-Yan

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





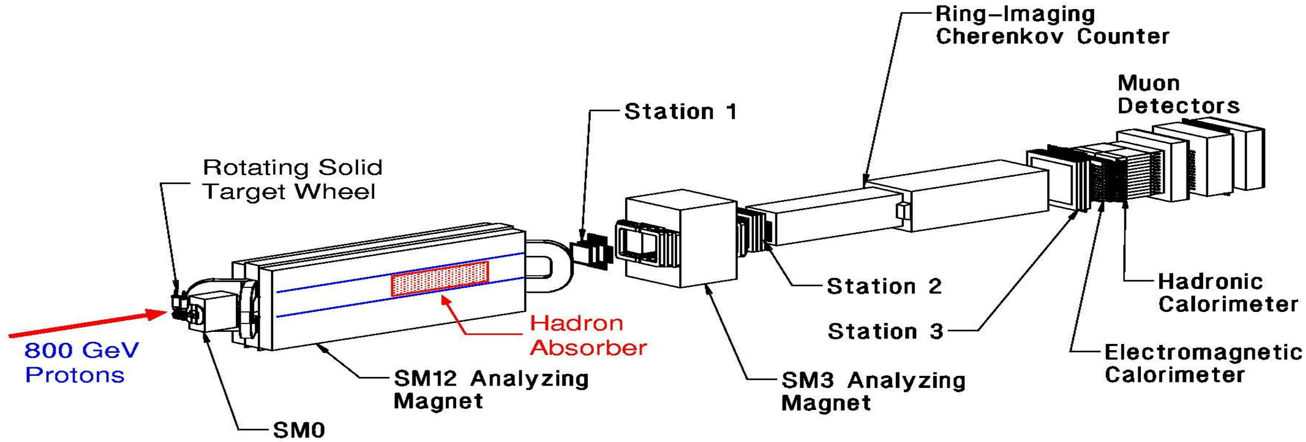
McGaughey, Moss, Peng,

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

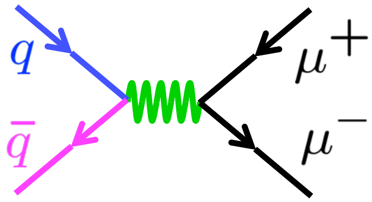
Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

Fermilab Dimuon Spectrometer: Fixed Target Drell-Yan

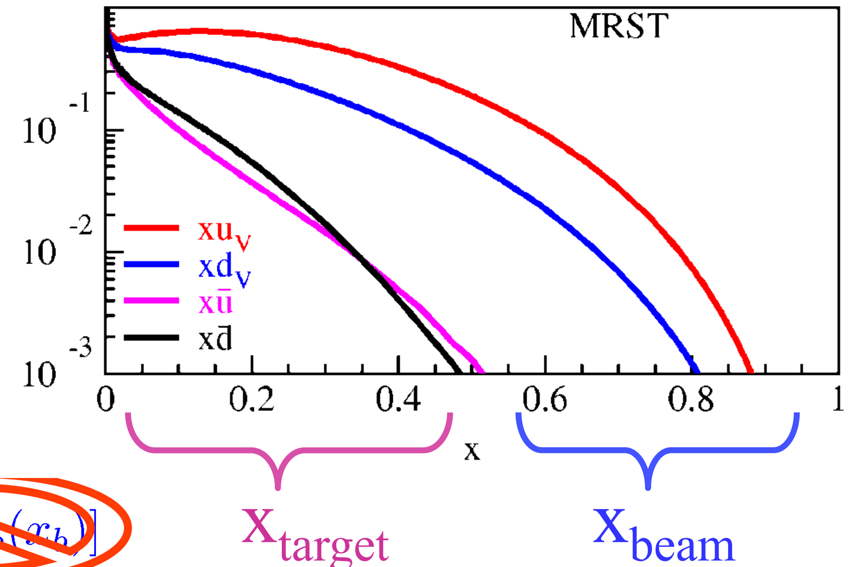
(E605 / 772 / 789 / 866 / 906)



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"



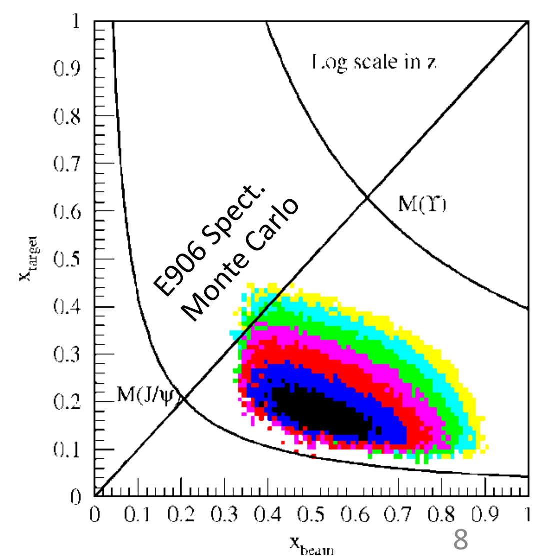
Kinematic of Fixed Target Drell-Yan



- Measure yields of $\mu^+\mu^-$ pairs from different targets: p+p, p+A
- Determine x_b, x_t
- Measure differential cross section

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

- Fixed target kinematics and detector acceptance 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

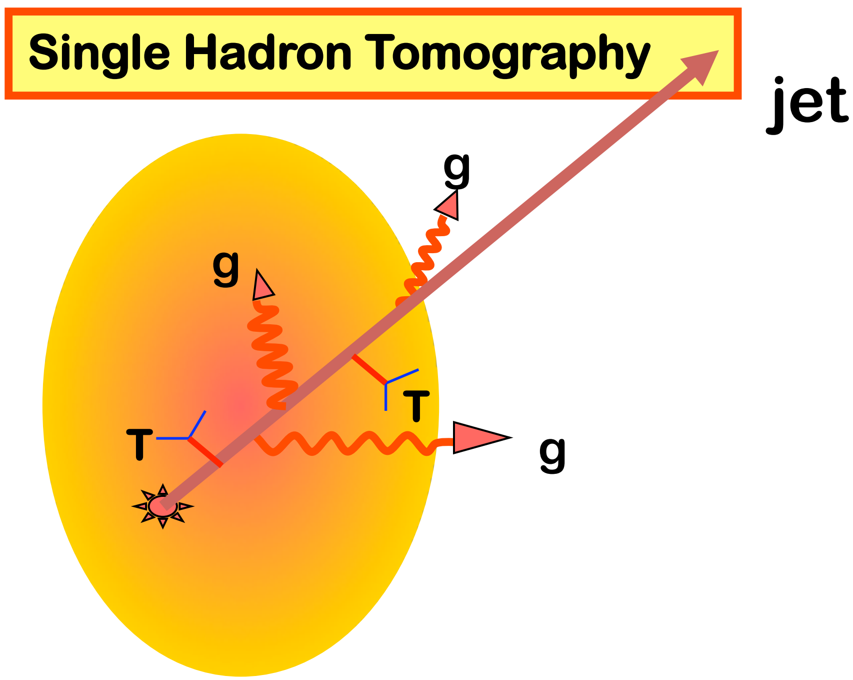


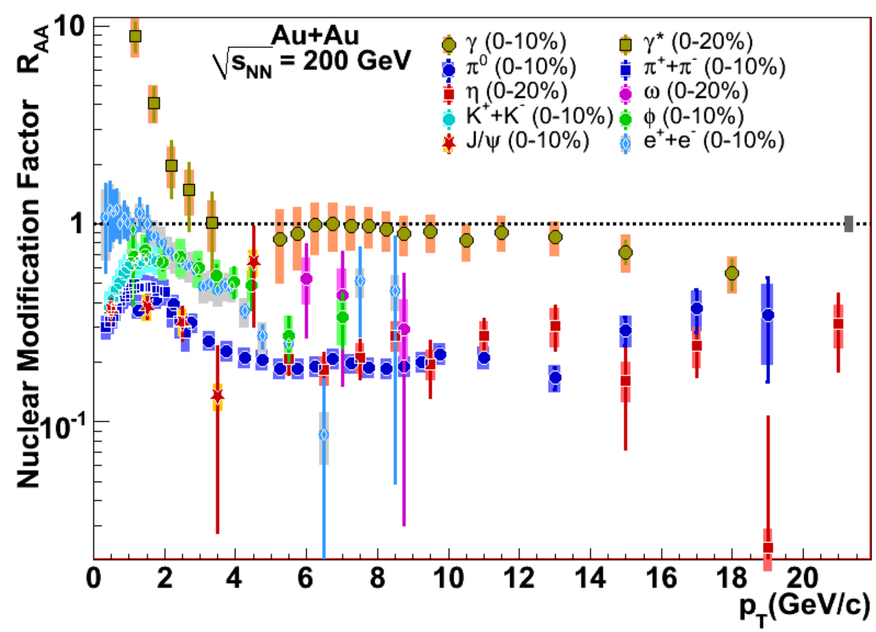
Highlights of Physics from Fermilab Dimuon Experiments

- Quark energy loss in nuclear medium
- Sea quarks and gluons in nucleons and nuclei
- Transverse spin physics
  - Drell-Yan angular distributions
  - Transverse Single Spin Asymmetry: DY vs DIS

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

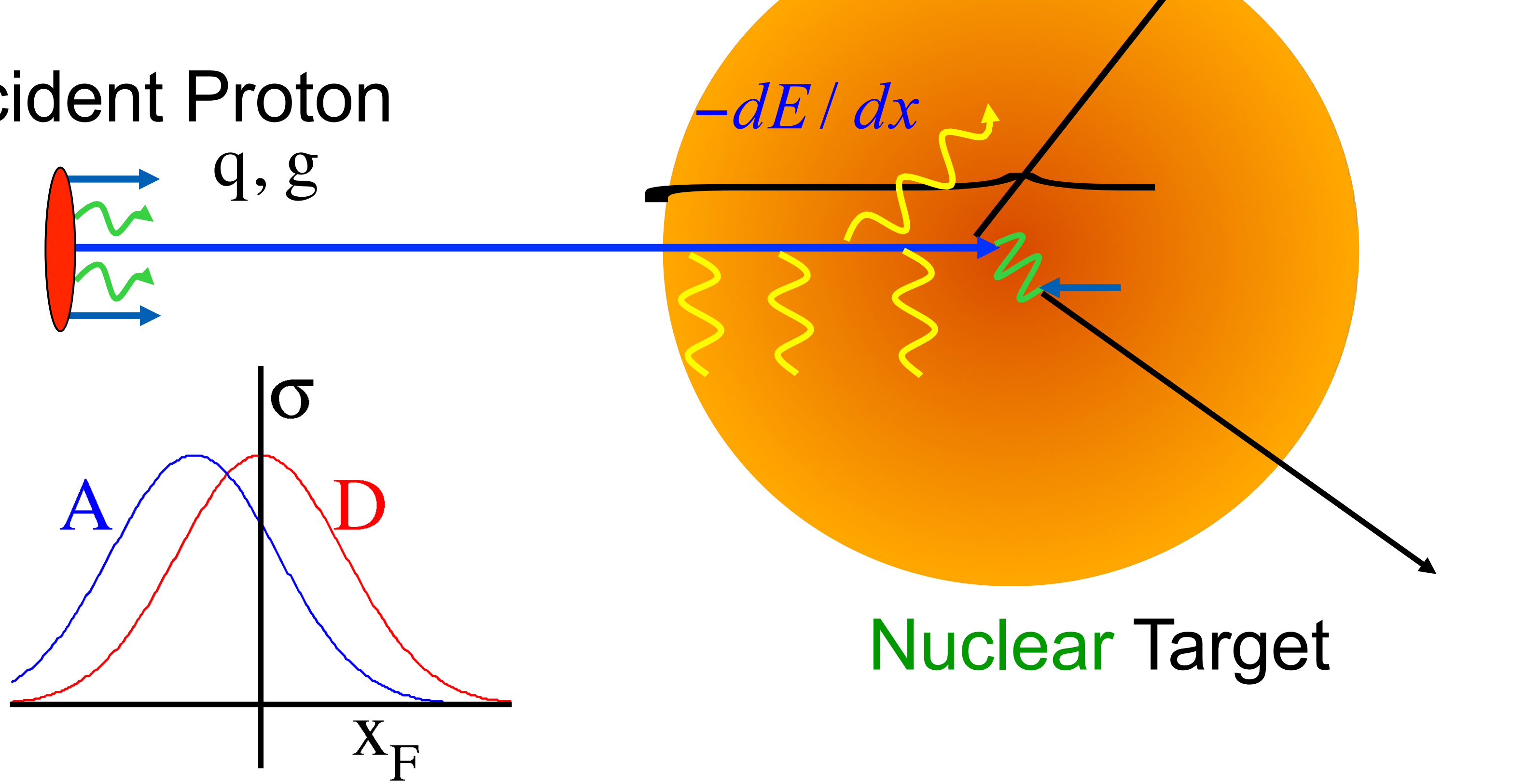




Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

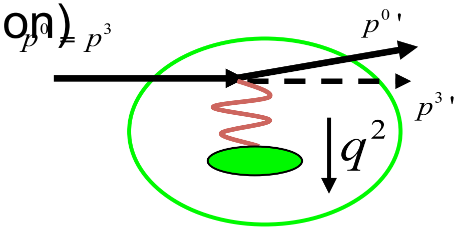
Benchmark with DY: Quark Energy Loss in p+A

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

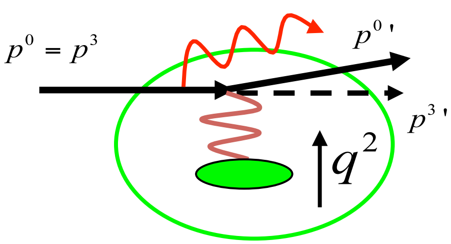


Energy loss in Electrodynamics

- Collisional energy loss (ionization and atomic excitation)

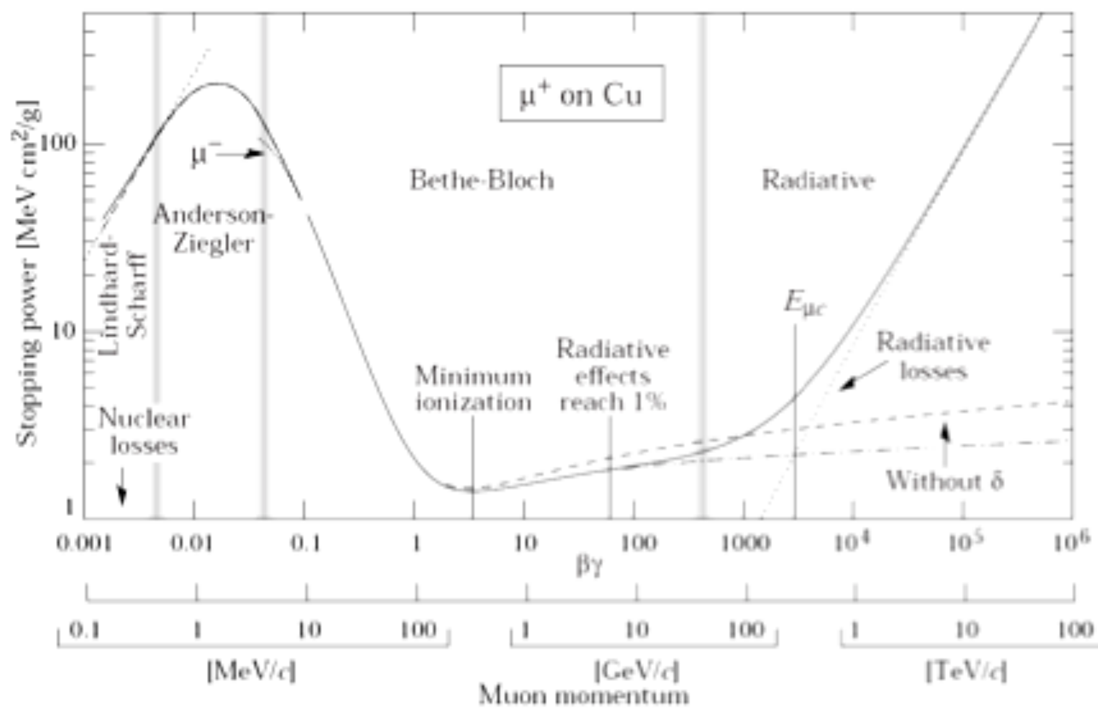


- Radiative energy loss (photon bremsstrahlung)



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

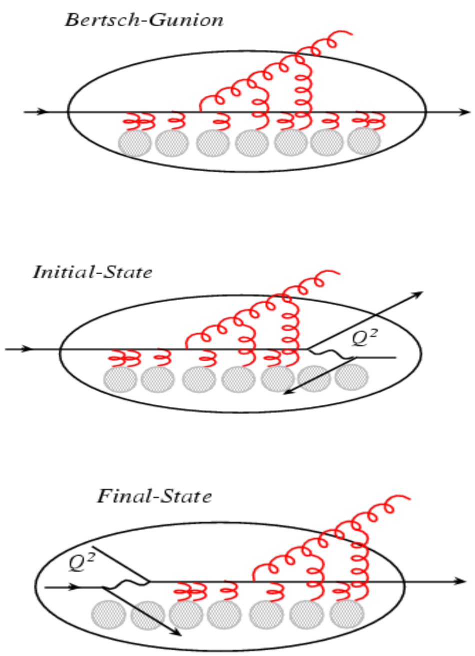
In QCD



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

Process Dependence of Parton Energy Loss

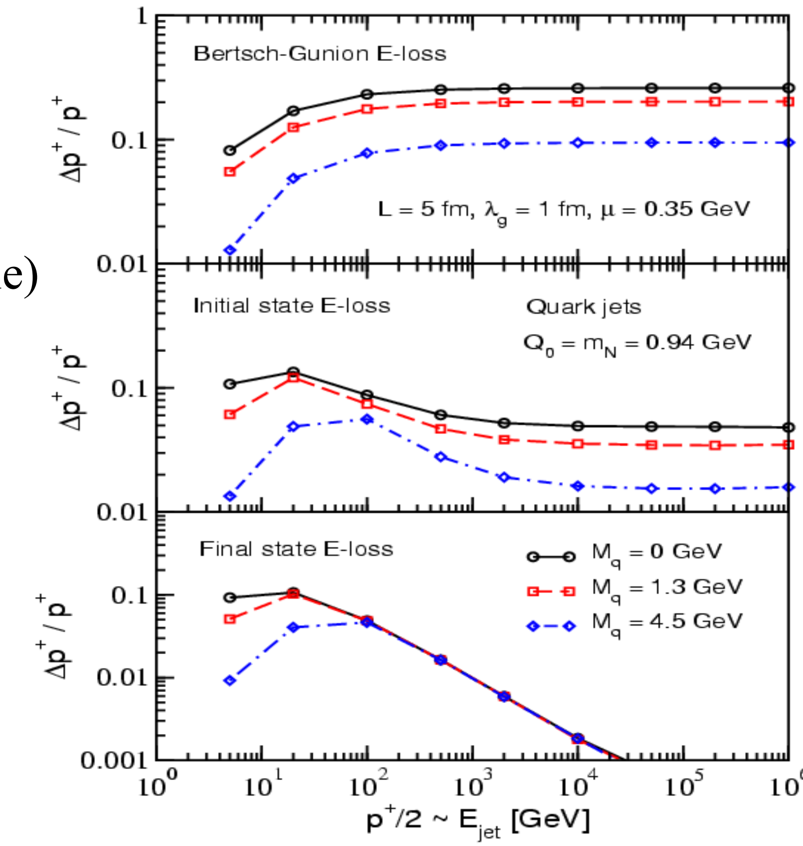
- E-loss in three cases



Academic case
(probably inapplicable)

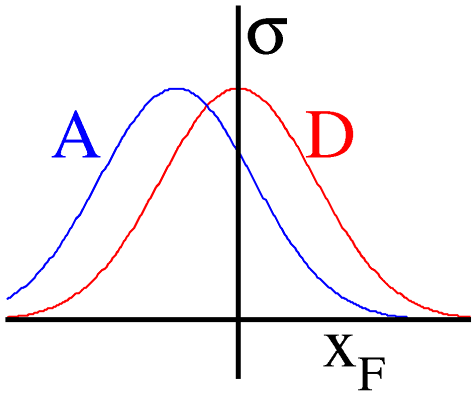
Initial-state E loss:
DY process

Final-state E loss:
SDIS, QGP



I. Vitev, PRC 75(2007)064906.

Quark Energy Loss in Cold Nuclear Medium



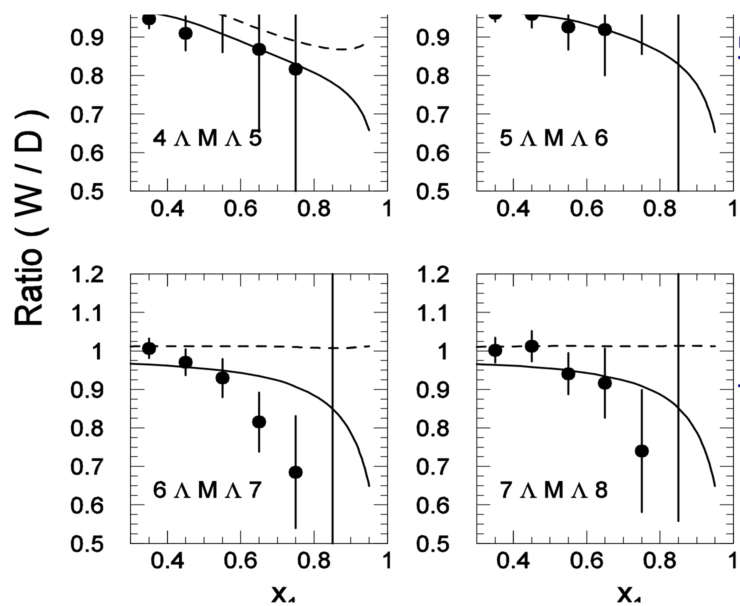
$$\frac{dE}{dx} \simeq 2.5 \pm 0.6 \text{ GeV/fm}$$

(depends on shadowing correction)

Drell-Yan @E866

(PRL 86 (2001) 4483)

800GeV p + A

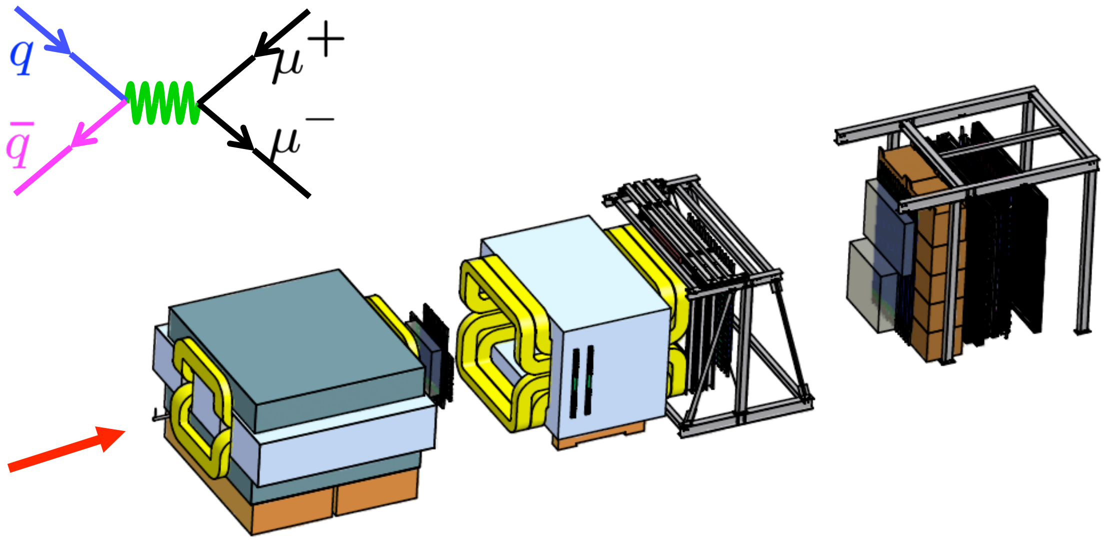


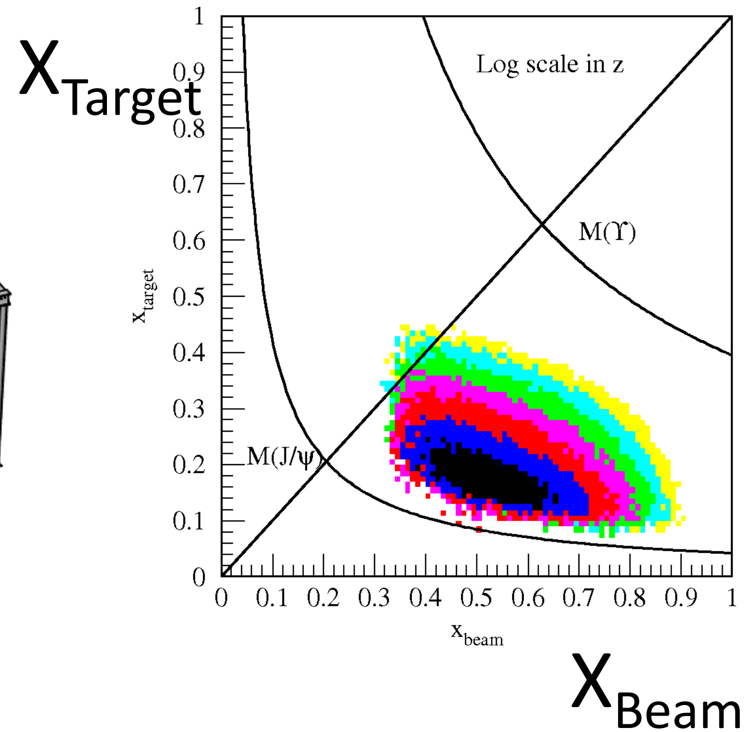
5<M<6 GeV

7<M<8 GeV

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

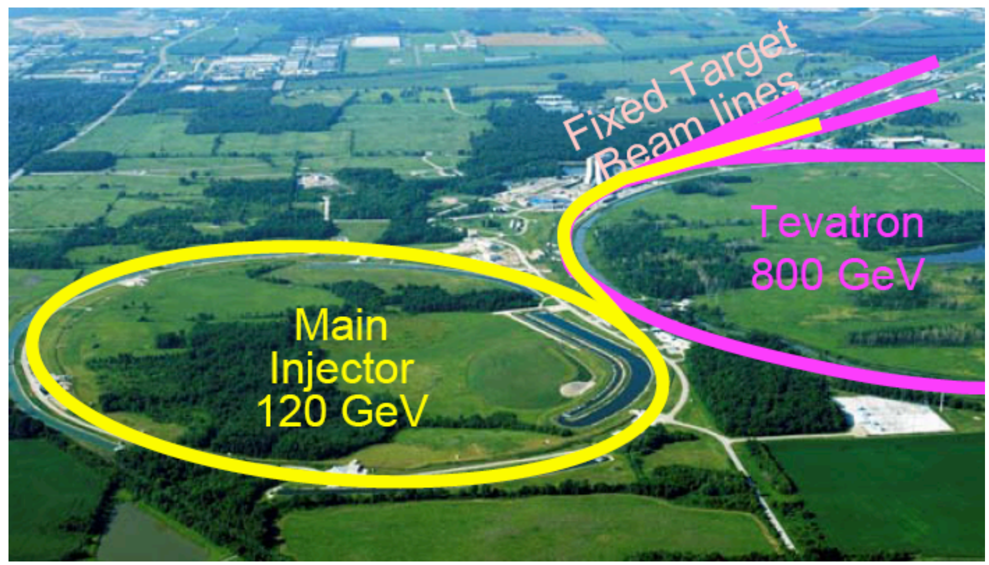
E906 Drell-Yan:2011-2013





Polarized DY possibility:

- 120 GeV proton
- p+A: p, d, C, Al, Fe, W
- X_1 = 0.3~0.7
- X_2 = 0.1~0.3
  - free from shadowing effect



Experimental Sensitivity to Quark Energy Loss

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

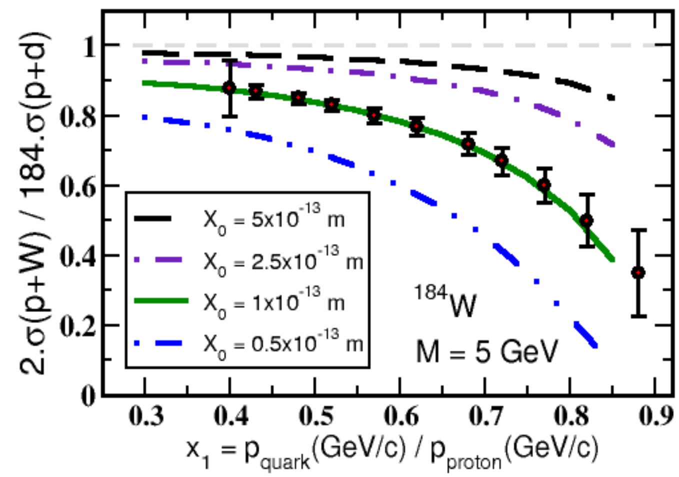
- Shortest radiation length in nature $X_0 = 1 \times 10^{-13}$ m

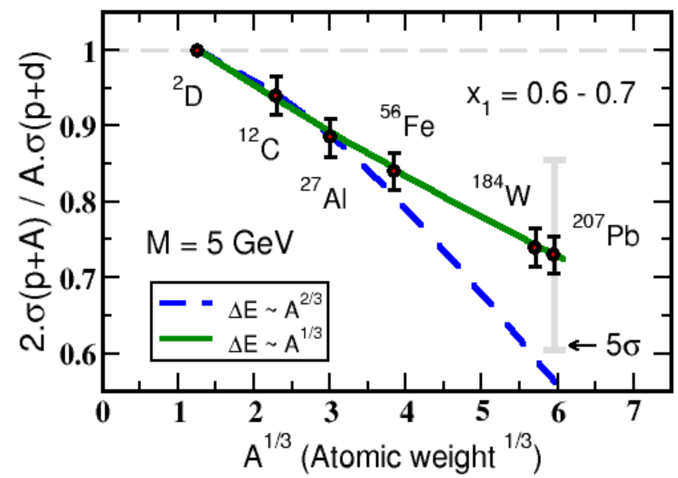
- Clearly distinguish between leading models for L dependence of E-loss

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

- Benchmark dE/dx models

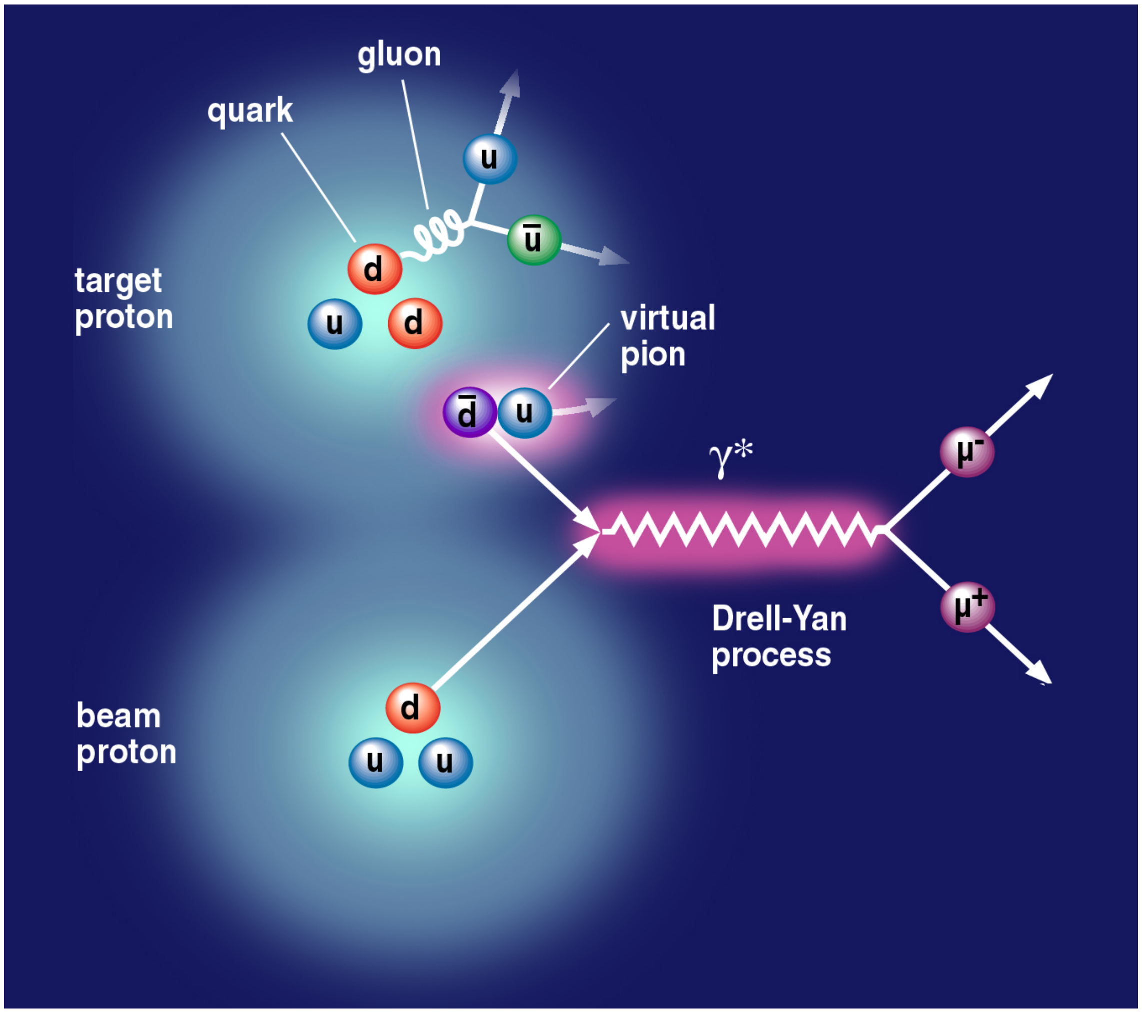
Quark energy loss only





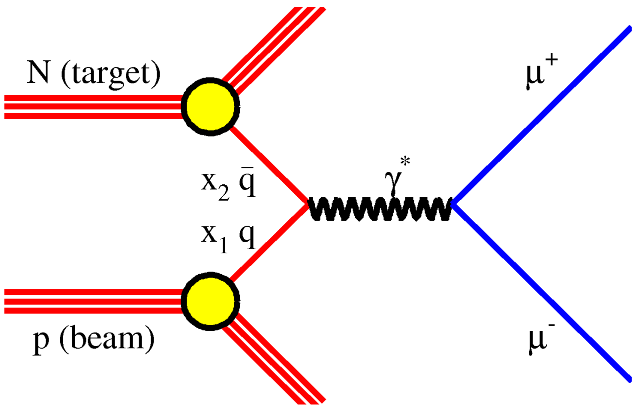
Topic (II): Nucleon is a Complex System

Origin of Sea Quarks



Evidence of Pion Cloud?

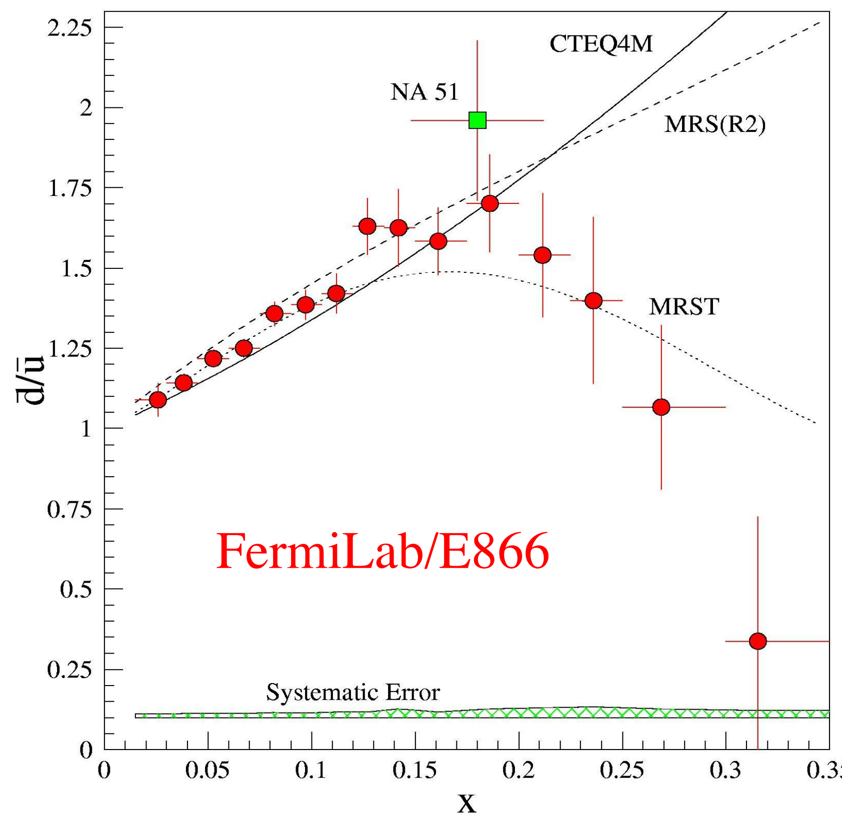
$$pN \to \mu^+\mu^- X$$



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

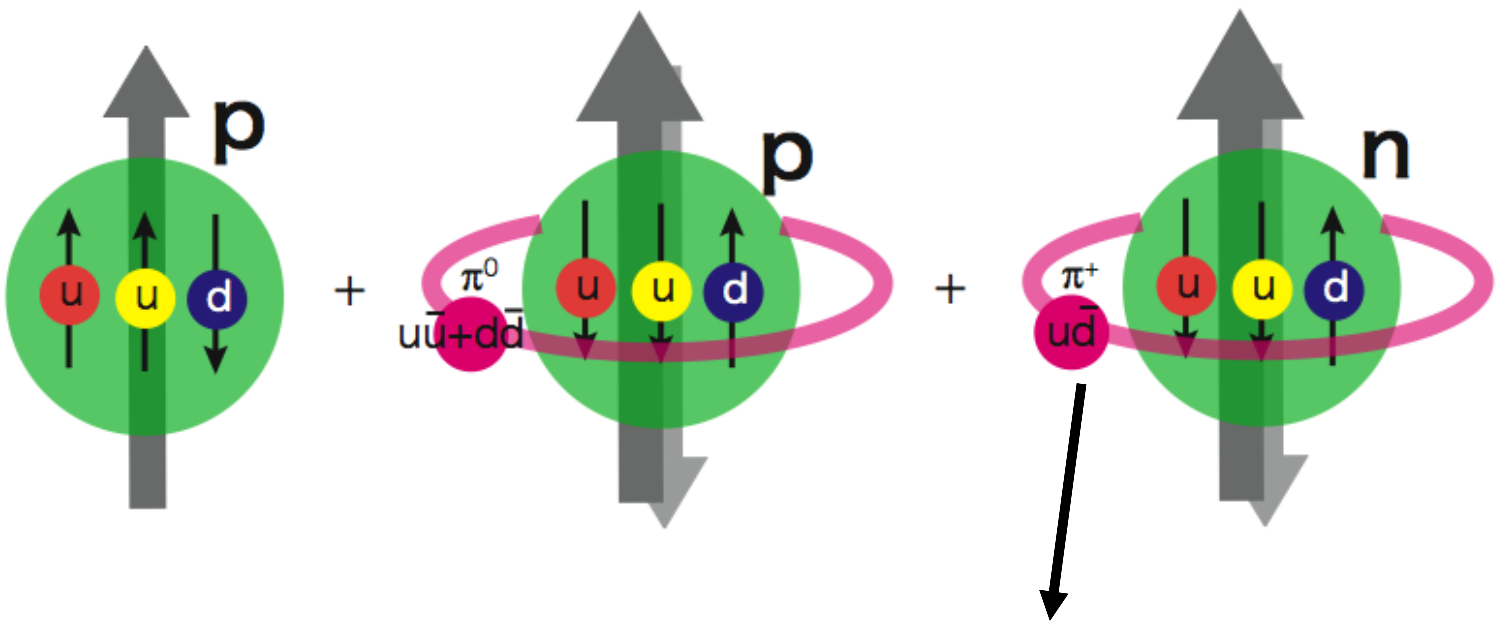
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

E866, Phys.Rev. D64 (2001) 052002



Sea Asymmetry probed by Drell-Yan

Pion Cloud Model and the Orbital Angular Momentum?!



Extra dbar in proton g.s.

Sea Quarks Carry Major Orbital Angular Momentum Component?

Pion Cloud and Orbital Angular Momentum

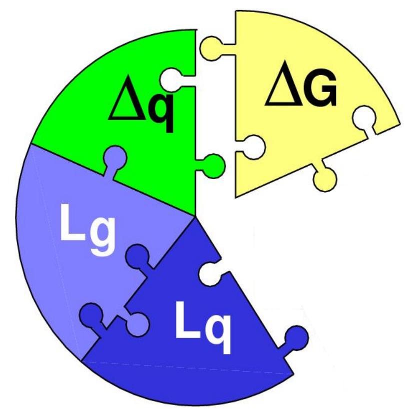
- Spin puzzle, sea quark flavor asymmetry and L_Z

G. Garvey, PRC81:055212,2010.

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

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

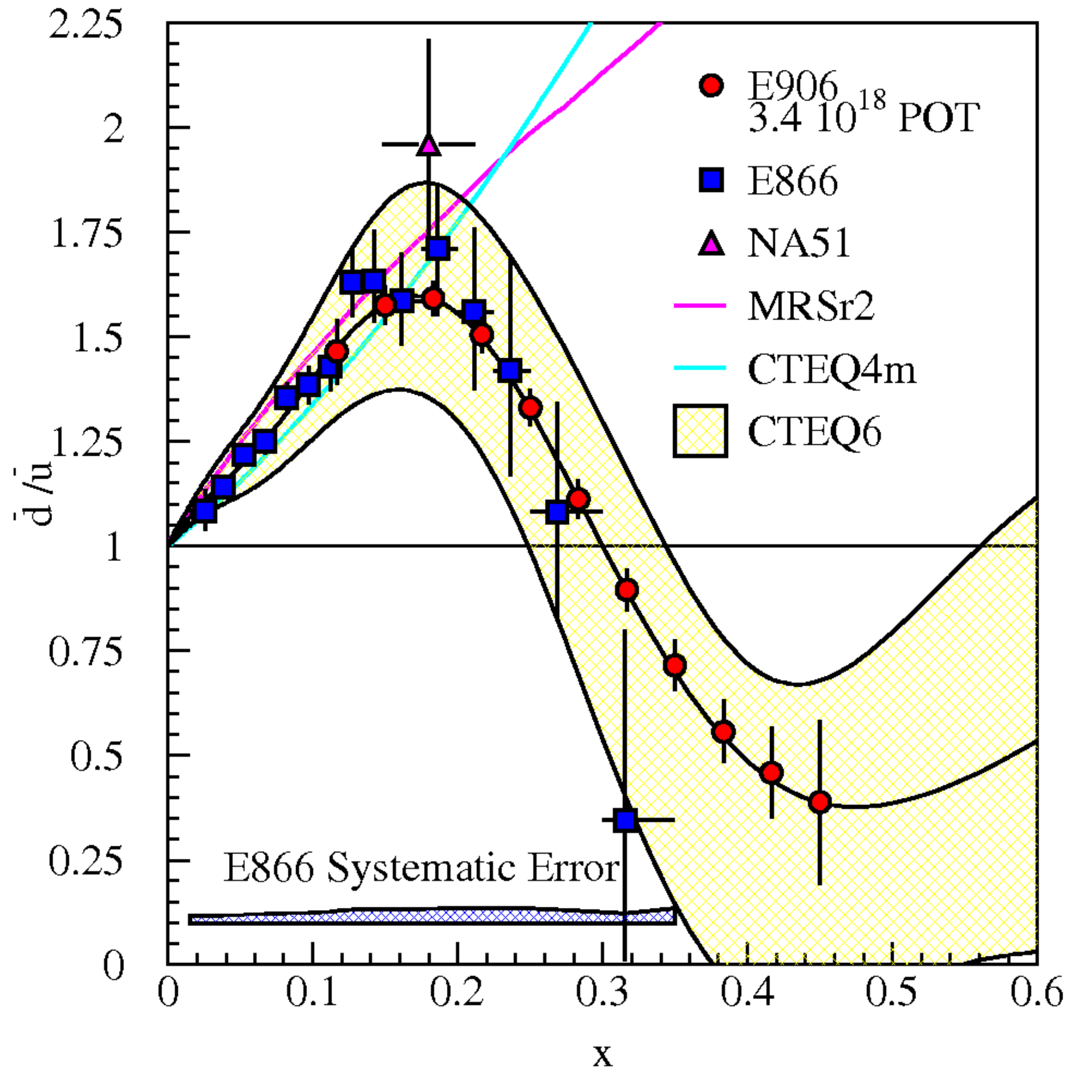
$$\langle p^\uparrow | \hat{L}_Z | p^\uparrow \rangle = \frac{2a^2 - b^2}{3(1+a^2+b^2)} = 0.147 \pm 0.027 \sim 30\%[\frac{1}{2}]$$



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

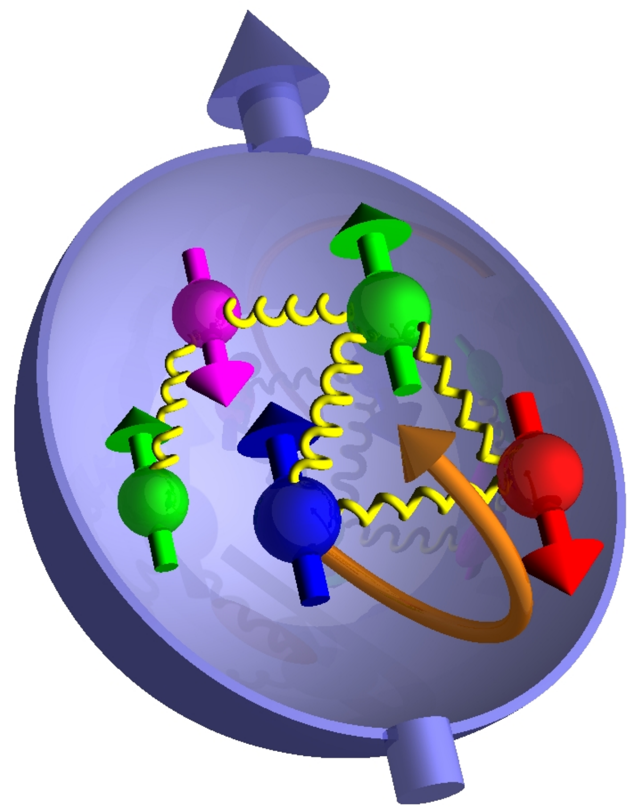
E906 Projections for d-bar/u-bar Ratio

- 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:
  - 2×10^{12} protons/s
  - 1×10^{13} protons/spill

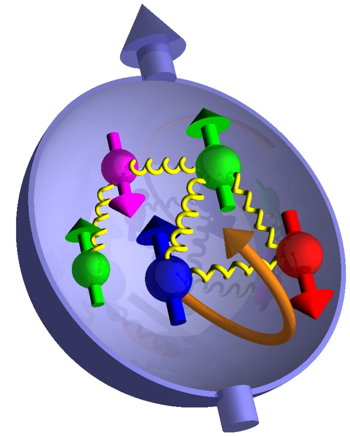


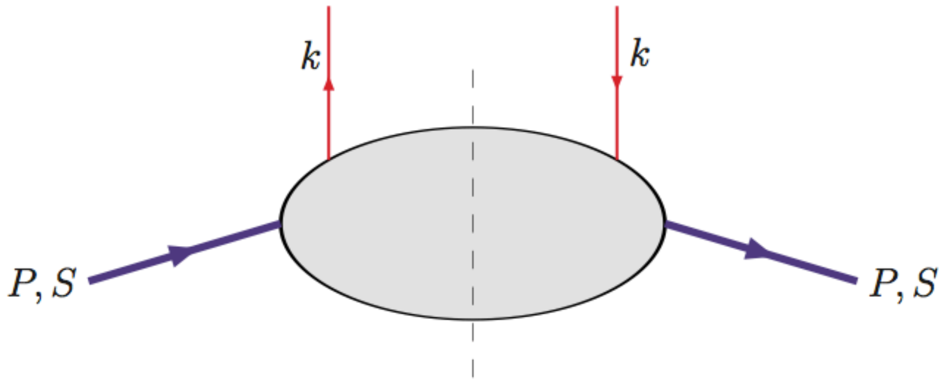
Topics (III): Transverse Spin Physics

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



Nucleon Structure @Leading Twist
Collinear Approximation (I)





Correlator:

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

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

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

Partonic interpretation of hard scatterings
Universal functions

Including k_T … 5 more (II)

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

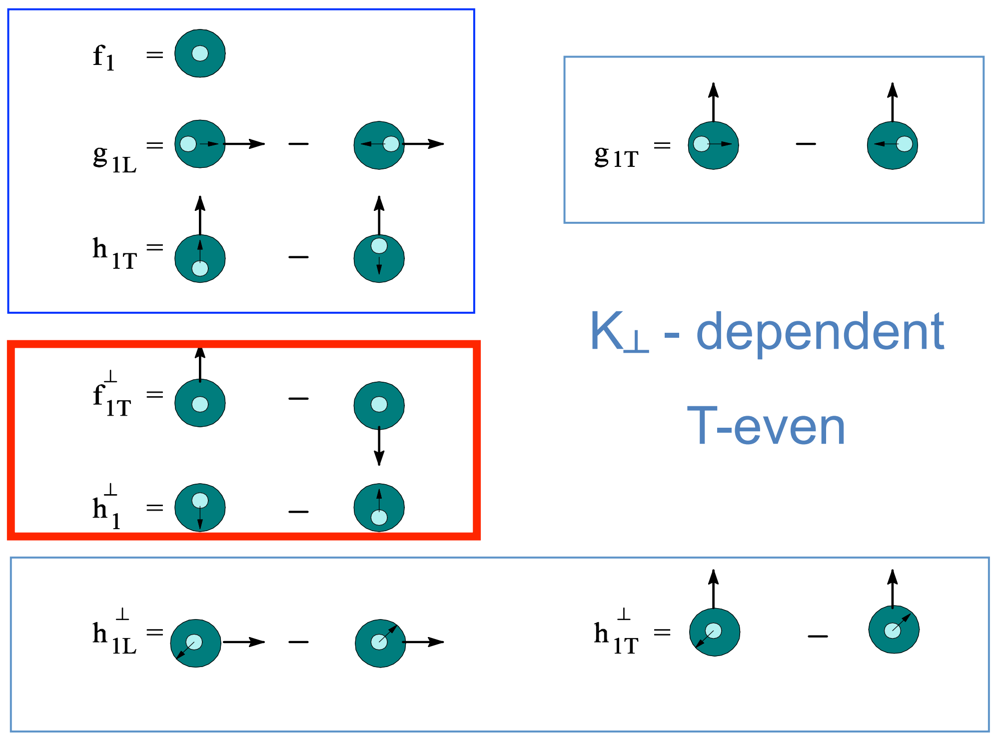
No $K_\perp$ dependence

$K_\perp$ - dependent

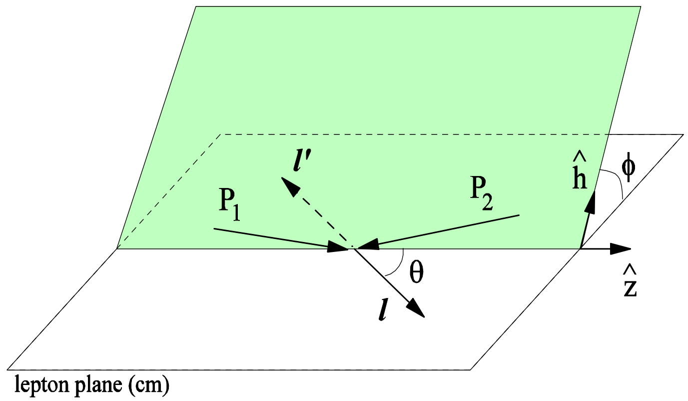
T-odd

$K_\perp$ - dependent

T-even



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

Transversity and TMDs can be probed via DY

Boer-Mulders functions:

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

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:

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

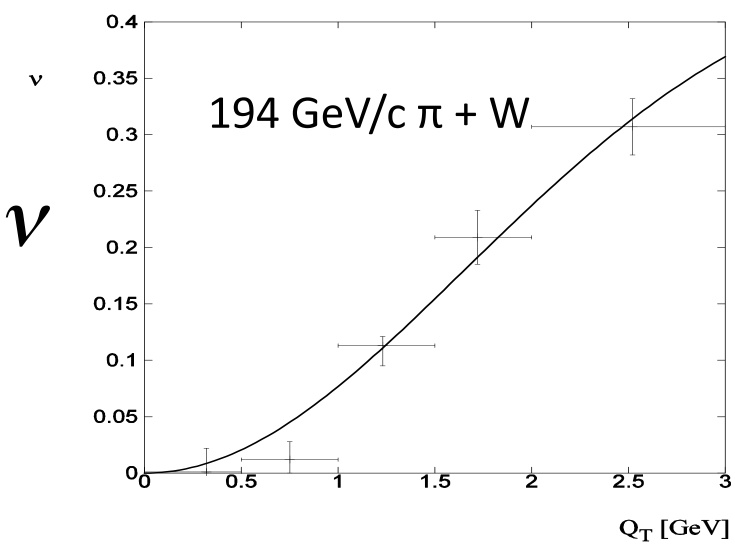
- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

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(2ϕ) dependence in Drell-Yan

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

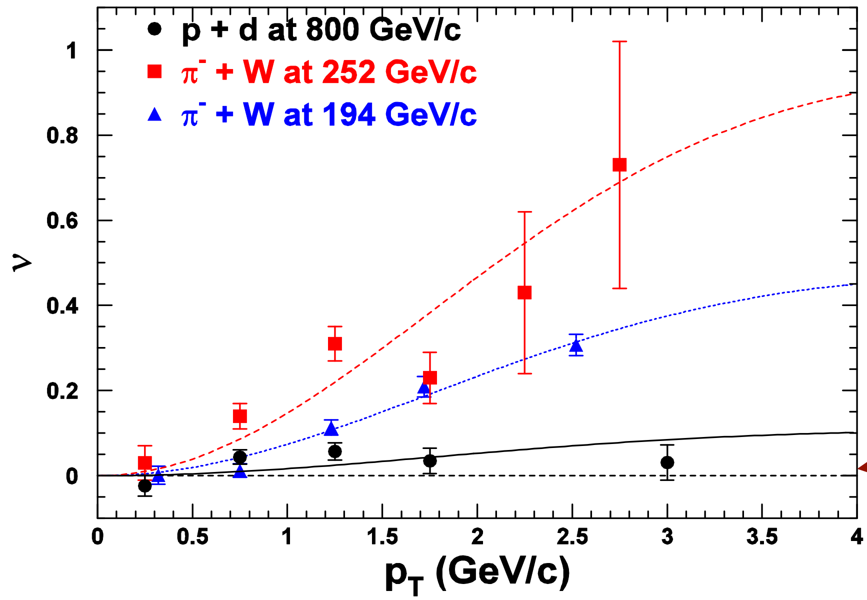


Boer, PRD 60 (1999) 014012

- 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 $h_1^\perp(p)$]

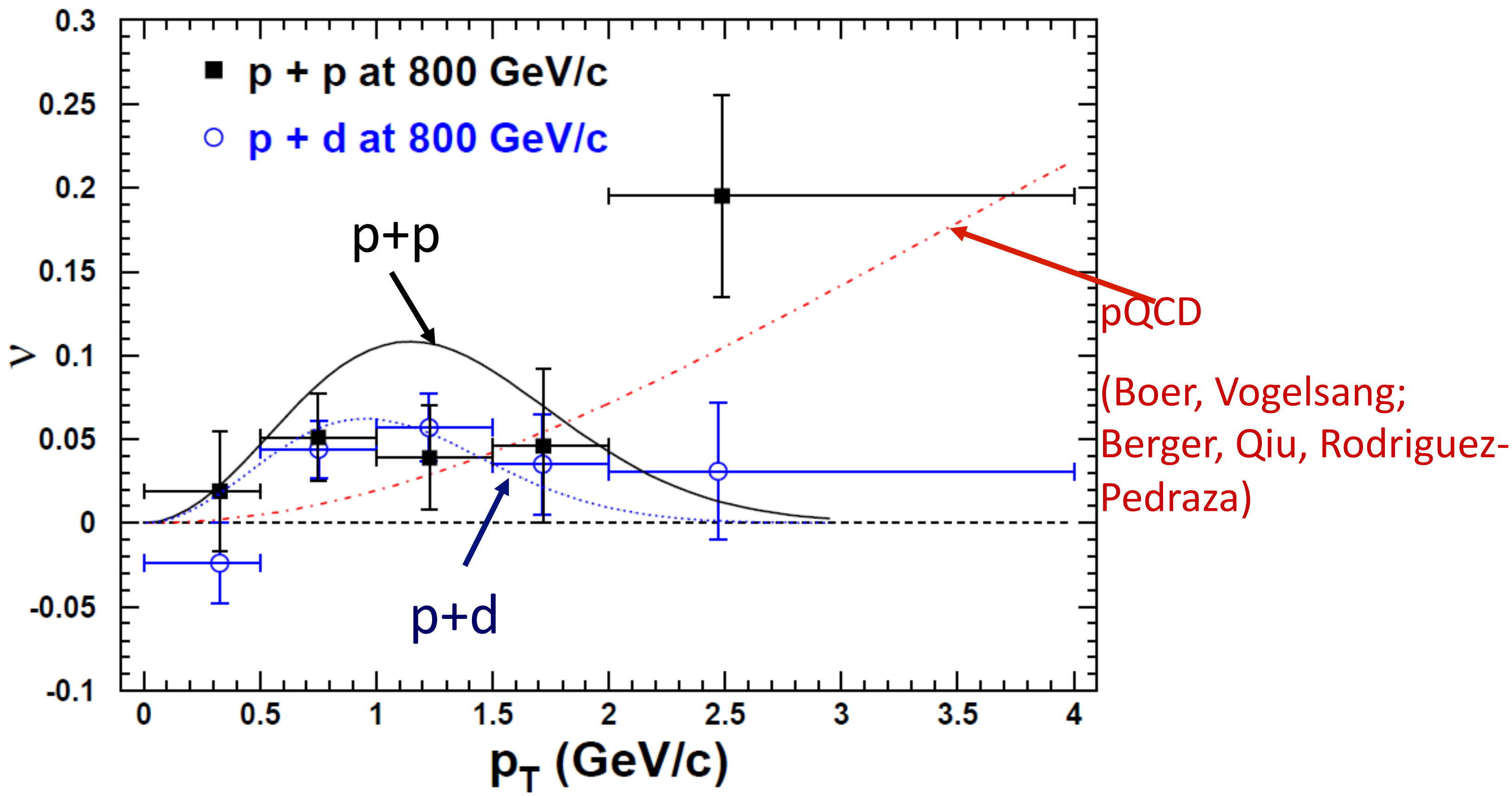
$\nu(pd \to \mu^+\mu^- X) \sim$ [valence $h_1^\perp(p)$] * [sea $h_1^\perp(p)$]

Sea-quark BM functions are much smaller than valence quarks

28

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

Future: Polarized DY?

The magic of sign change

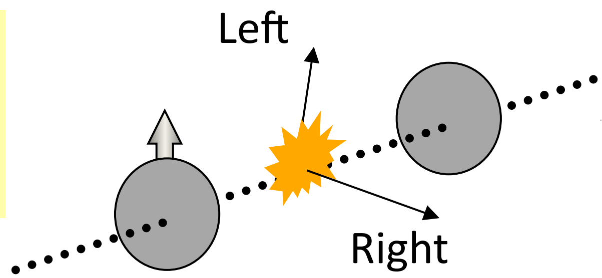
Drawing from D. Sivers @Santa Fe Polarized Drell-Yan Workshop Dinner 10/31-11/1, 2010

Surprises in Spin Physics

the challenge of "Too Big"

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:

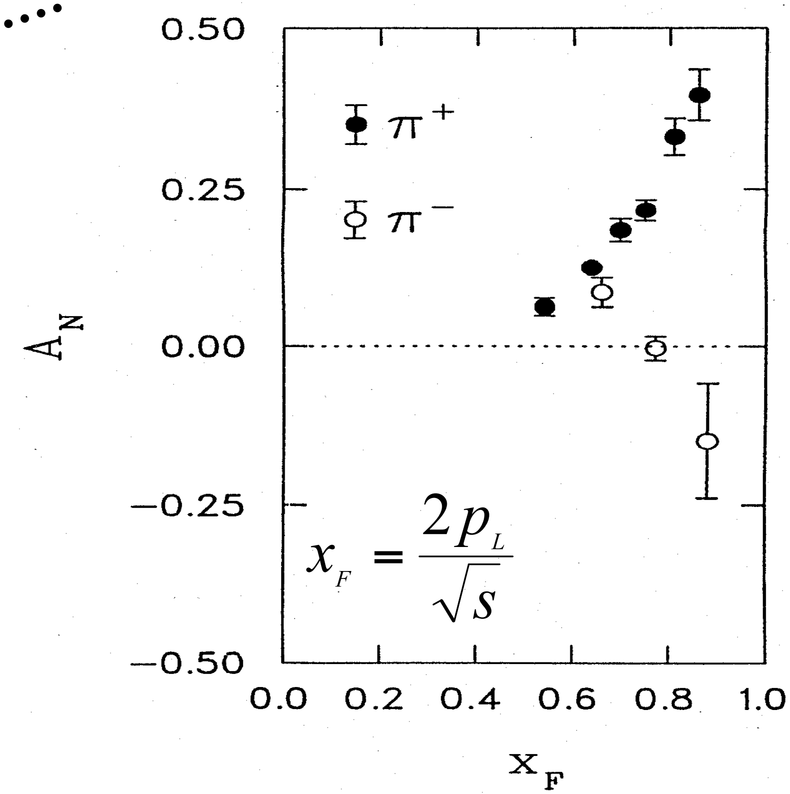
ZGS, AGS, FERMILAB to RHIC

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

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

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

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

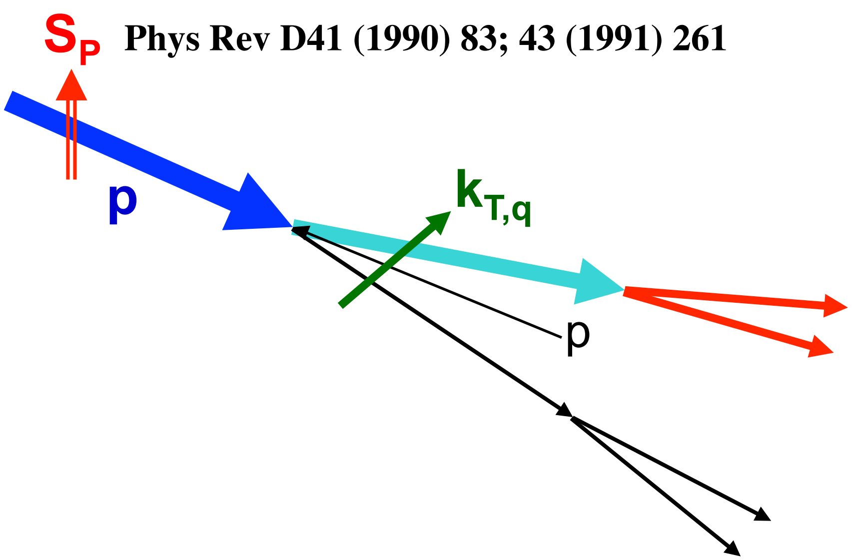


W.H. Dragoset et al., PRL36, 929 (1976)

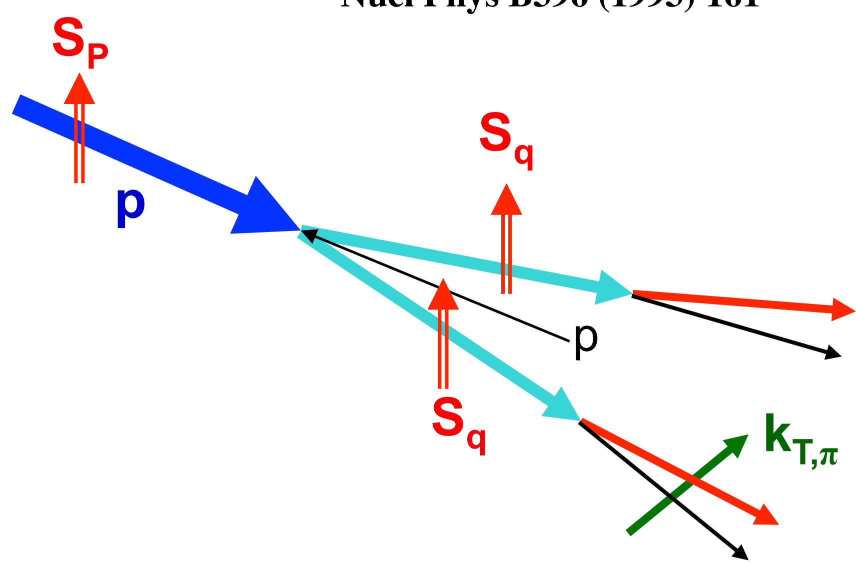
Current Understanding of TSSAs (I)

- 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 …

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



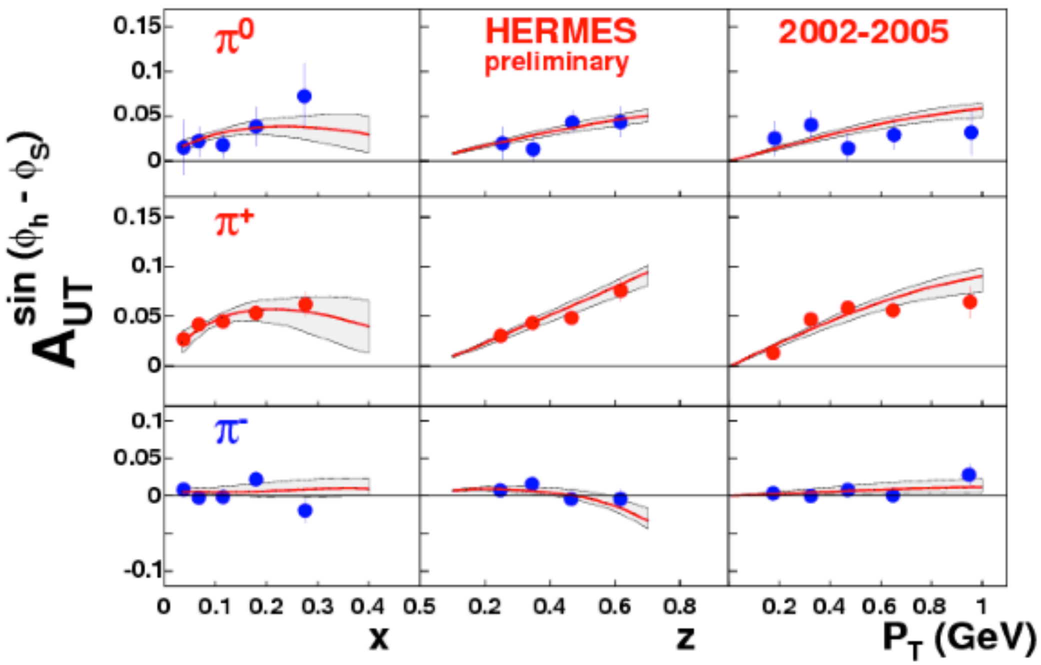
Nucl Phys B396 (1993) 161

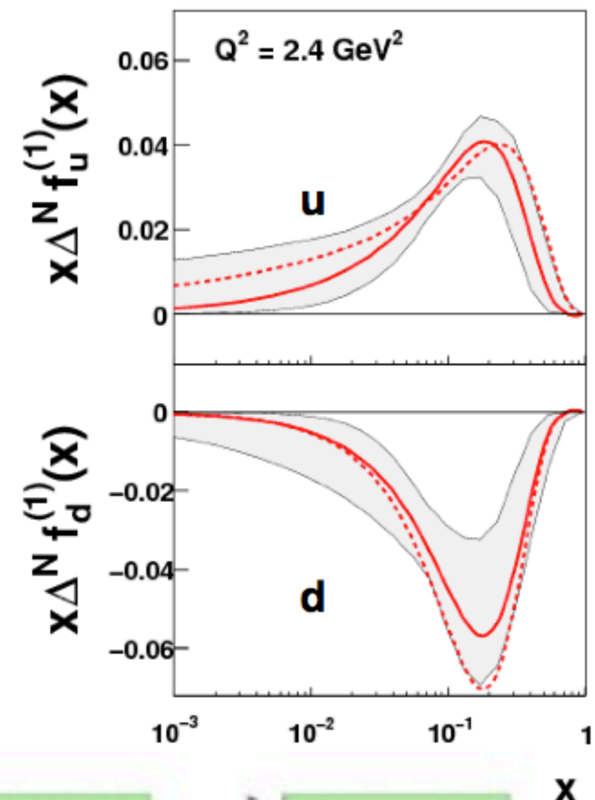


Sivers function from SIDIS

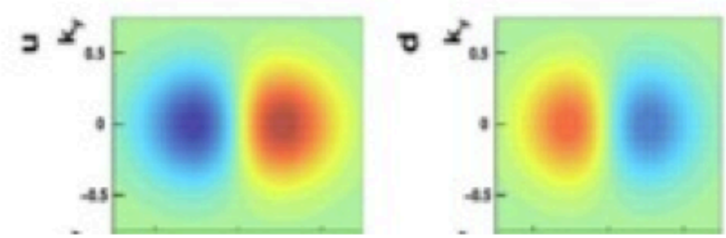
- Extract Sivers function from SIDIS

Anselmino, et.al., 2009



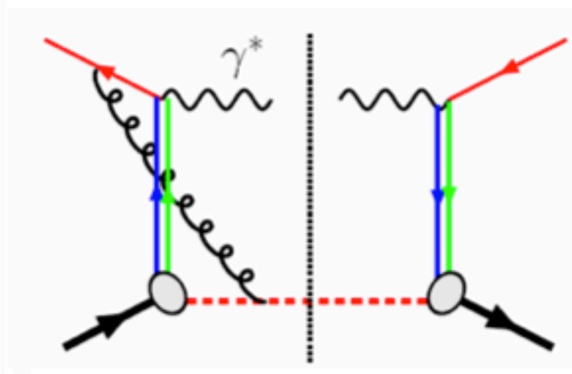


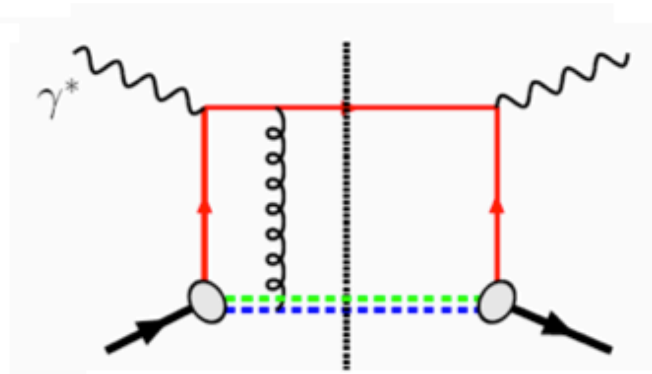
- u and d almost equal size, different sign



Color Flow 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

Importance of Drell-Yan TSSA

- Test the fundamental prediction of sign change in DY TSSA compared to DIS based on our understanding of the origin of TSSA
  - Test of gauge formulism
  - Test of QCD factorization

$$f_{1T}^{\perp}(x,k_T)\Big|_{SIDIS} = -f_{1T}^{\perp}(x,k_T)\Big|_{DY}$$

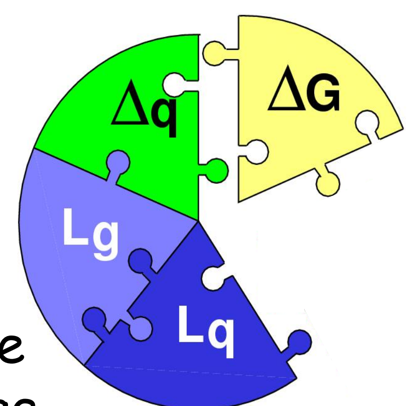
- Help to resolve the proton spin puzzle?
  - One expect the observation of Sivers Asymmetry signals the existence of partonic orbital angular momentum

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

only ~30% of spin

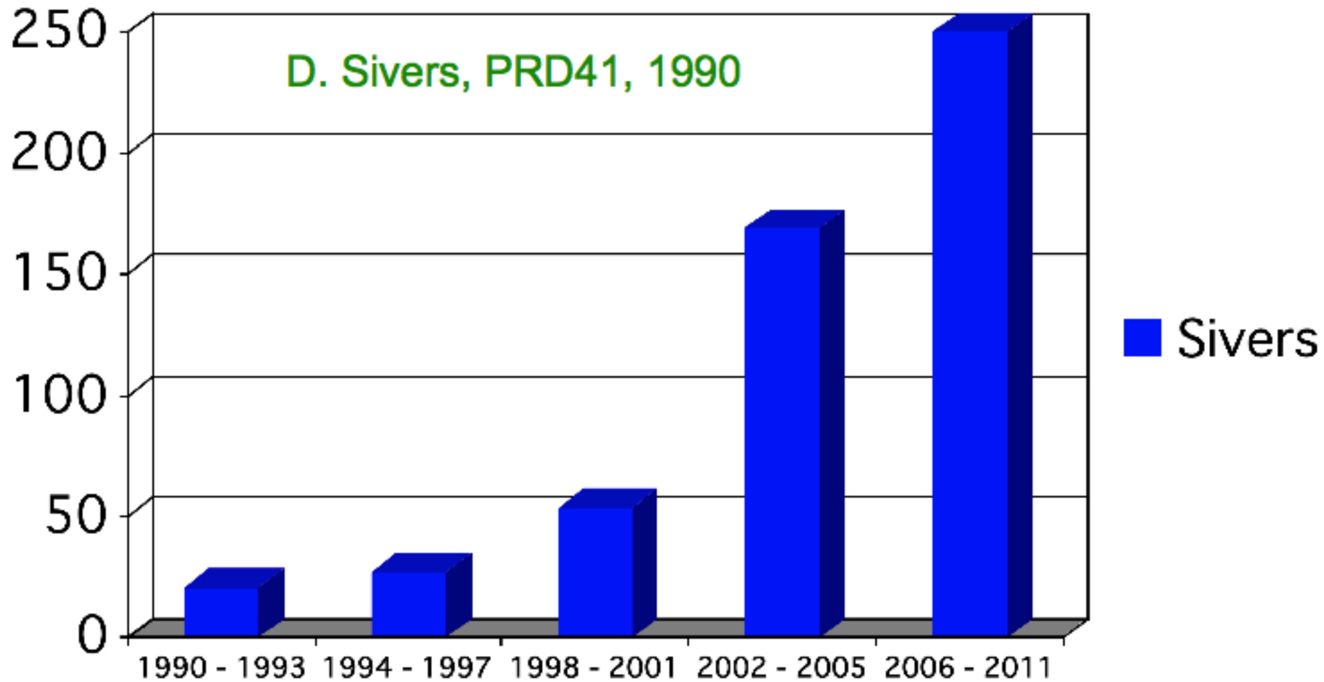
Beginning to be measured at RHIC

A future challenge



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



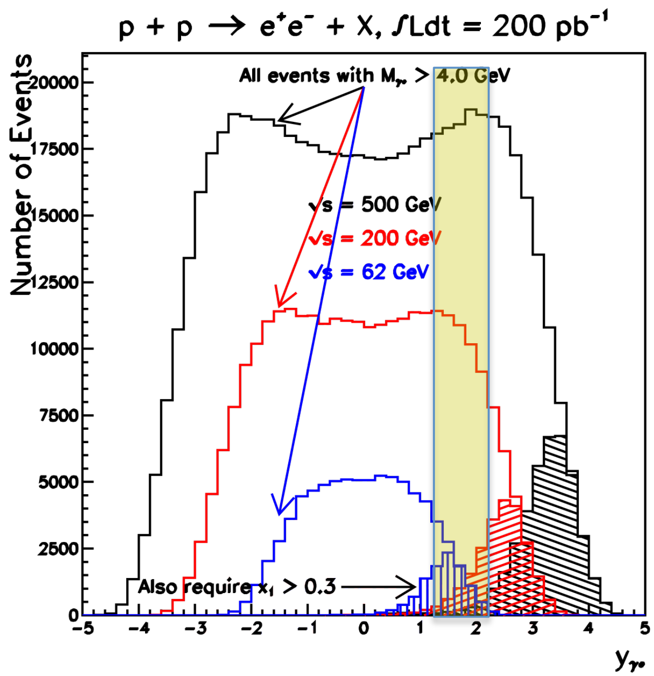
Future avenues for checking sign change in Drell-Yan

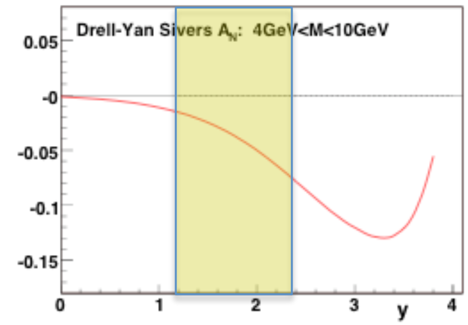
- AnDY program (IP2) at RHIC: 2013
- COMPASS-II at CERN: 2013
- PHENIX and STAR at RHIC: after 2017
  - Decadal plan
- Fixed target DY at Fermilab
- Fixed target DY at JPARC

Santa Fe Polarized Drell-Yan Physics Workshop

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

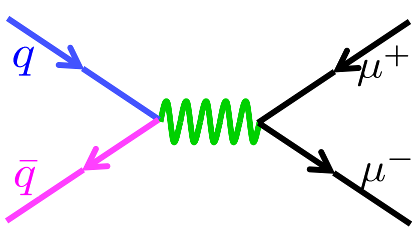
Drell-Yan Production @RHIC





- 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

$1.2 < |\eta| < 2.4$

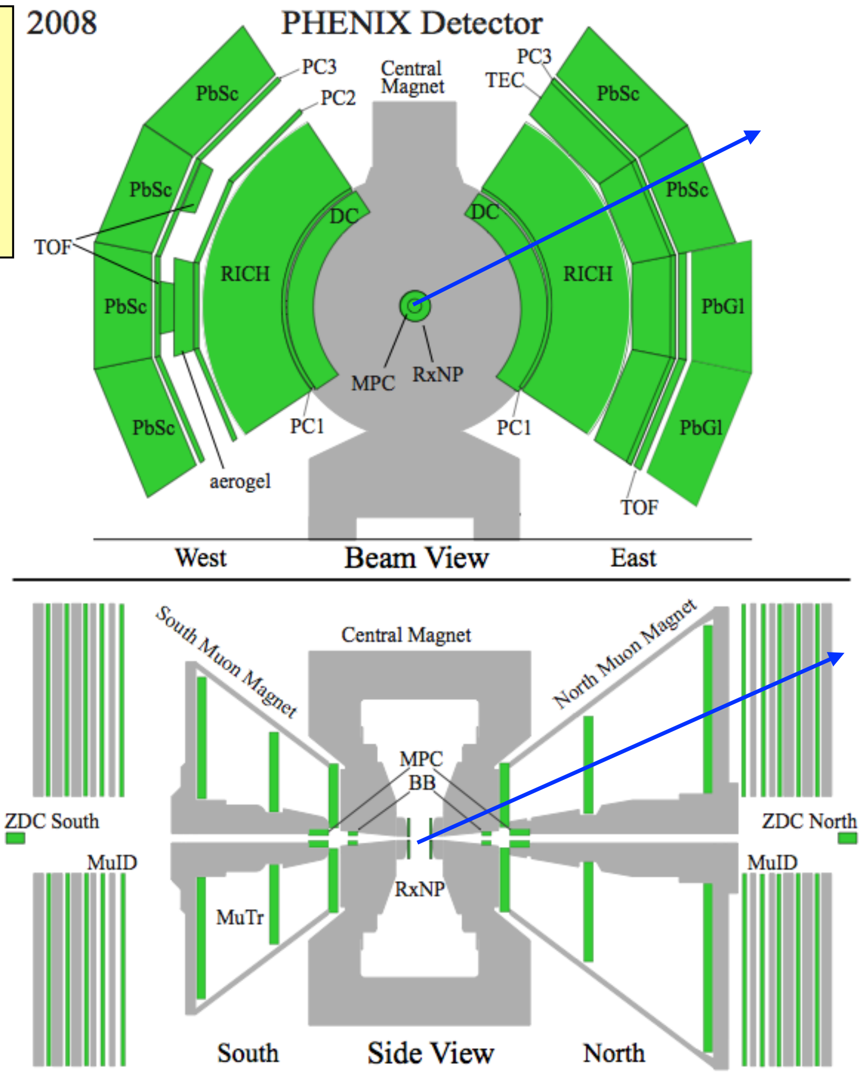
2π azimuth

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

$3.1 < |\eta| < 3.7$

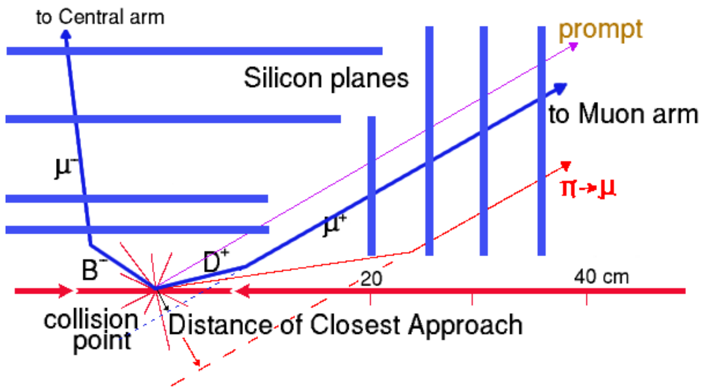
2π azimuth

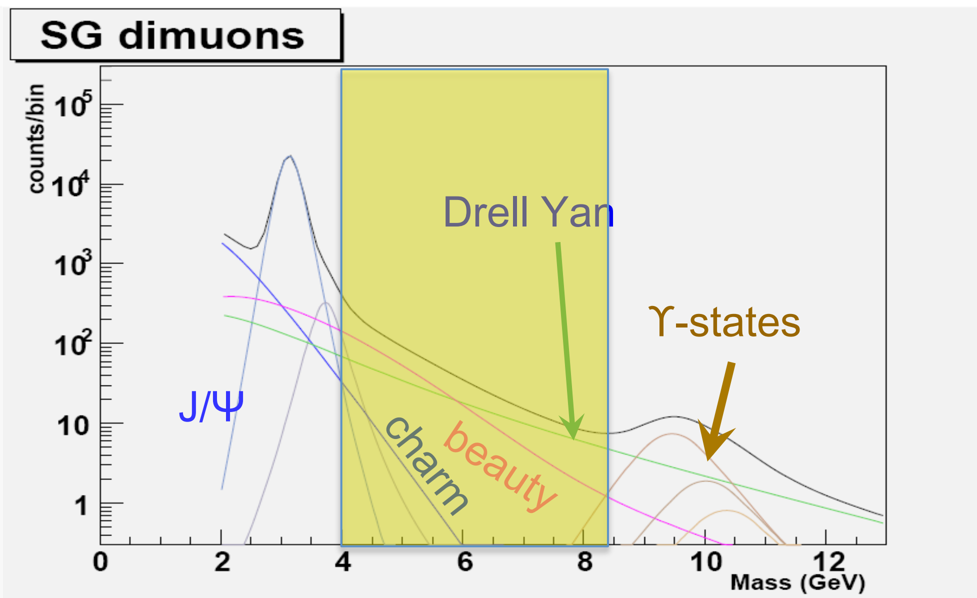
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)

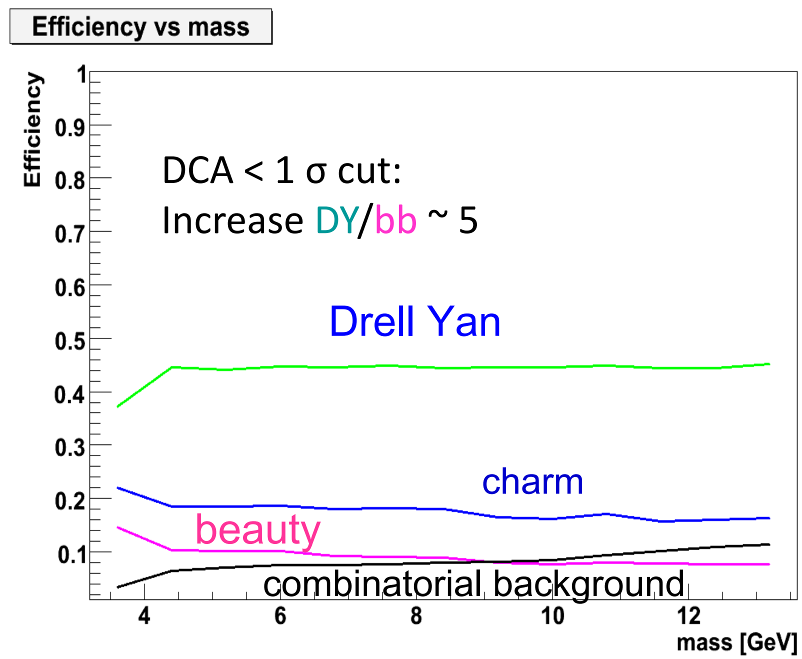


Silicon VTX, Heavy Quark and Drell-Yan

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





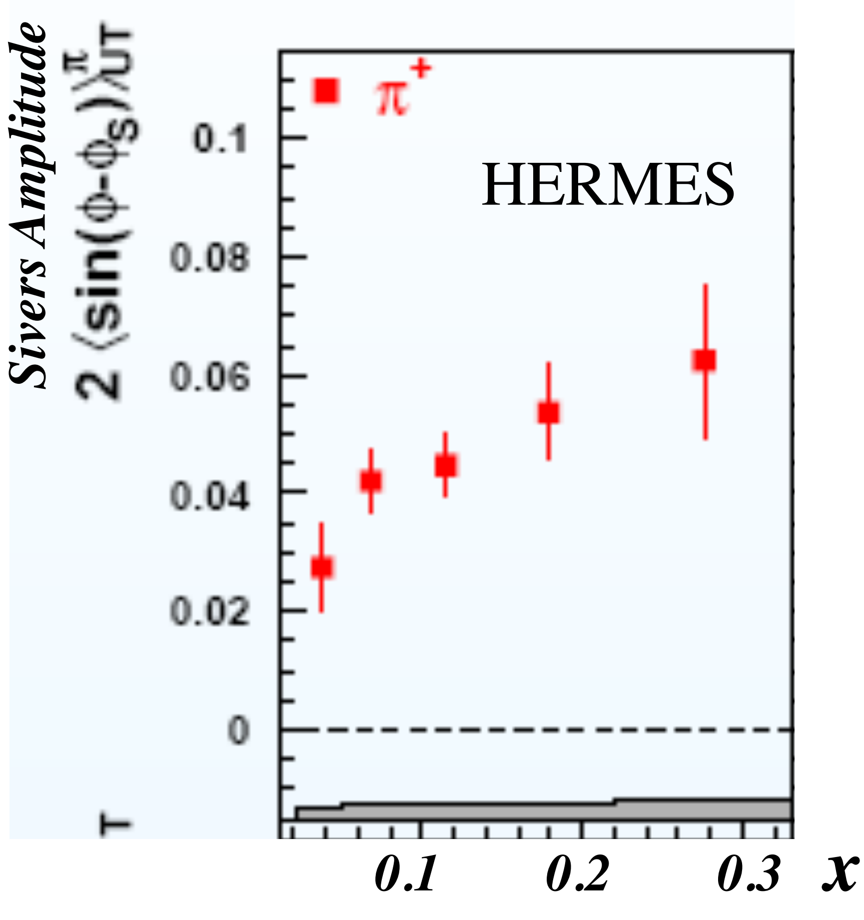


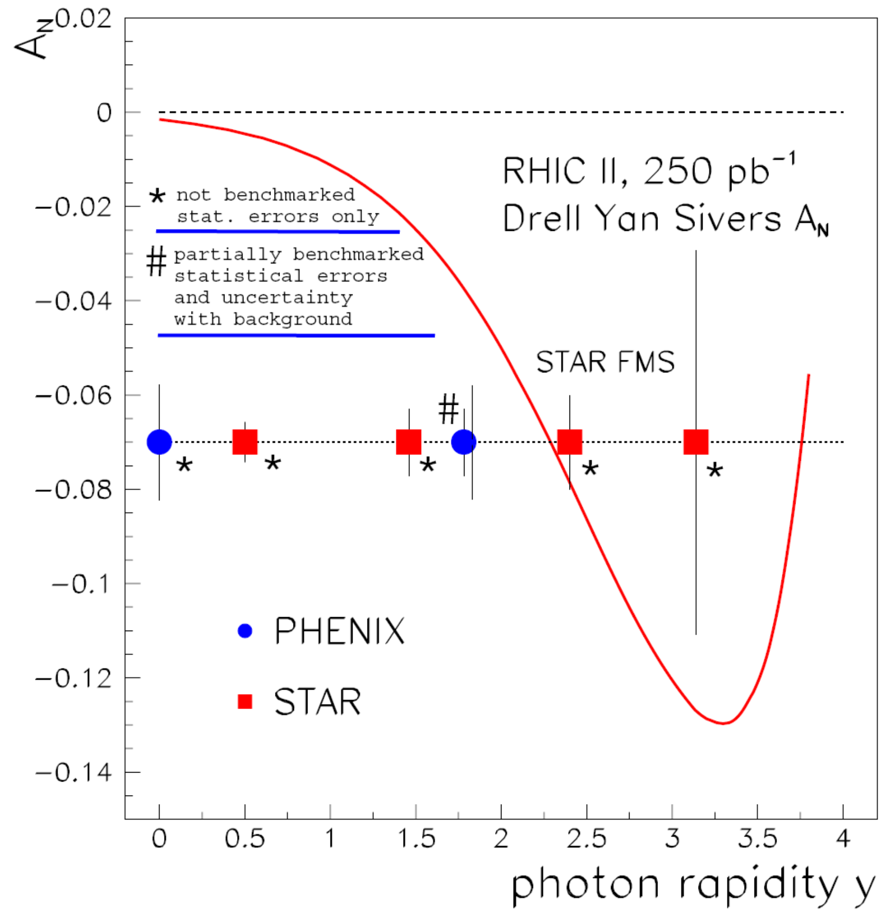
➔DY: 4 GeV < M < 8 GeV; B-background: use FVTX

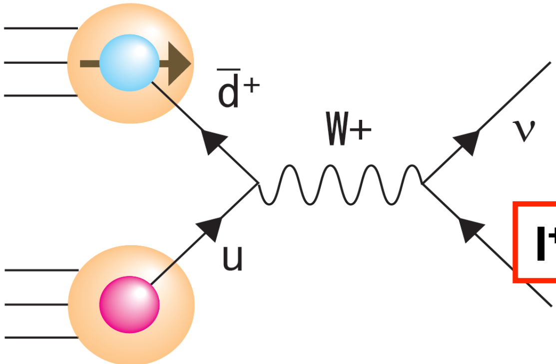
Sivers Asymmetries in SIDIS and DY

"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







$W^{+/-}$ & 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
  - $W^{+/-} \to \mu^{+/-}$ ~20K
  - $Z^0 \to \mu^+\mu^-$ ~ 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)

$W^{+/-}$

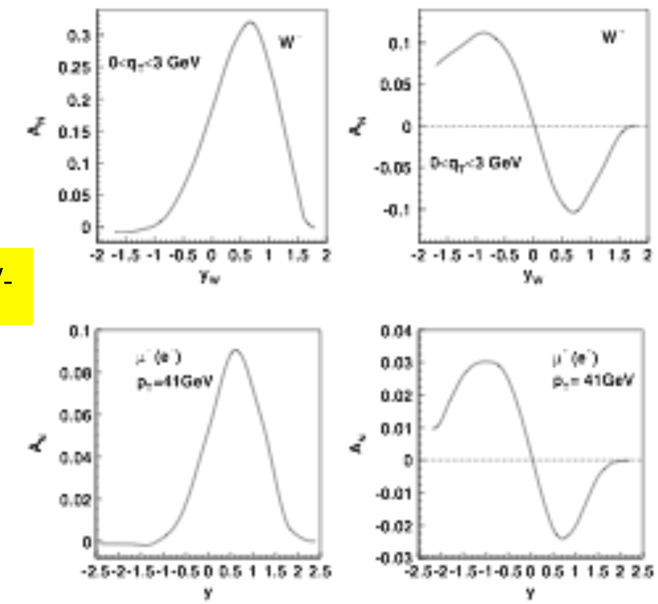


FIG. 3. A_N as a function of lepton rapidity.

Kang & Qiu arX 0912.1319

Z^0

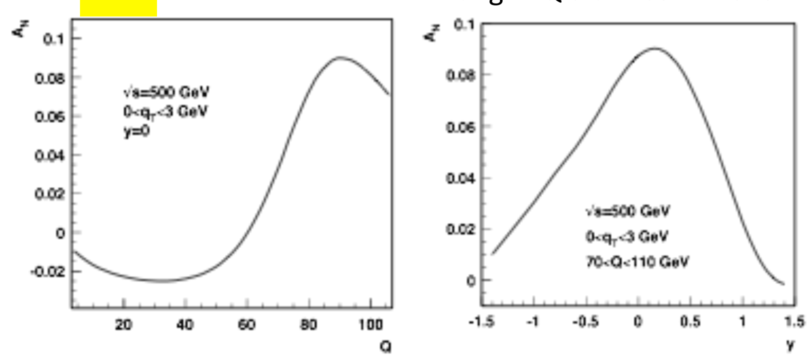
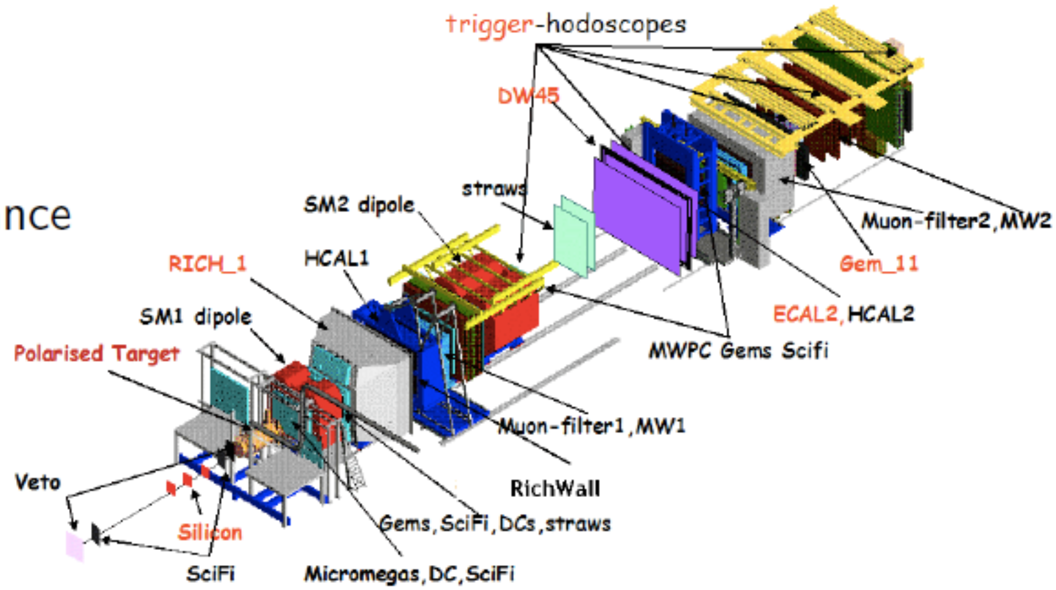
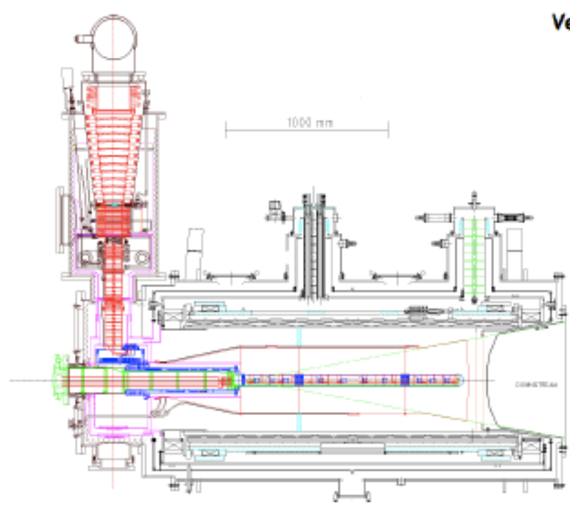


FIG. 3: Left: SSA of lepton pair production as a function of the pair's invariant mass Q. Right: SSA of lepton pair accumulated around Z^0 pole as a function of rapidity y.

COMPASS facility at CERN (SPS) II

- μ, p, π, K beam
- 50-270 GeV/c momentum
- ± 180 mrad angular acceptance





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

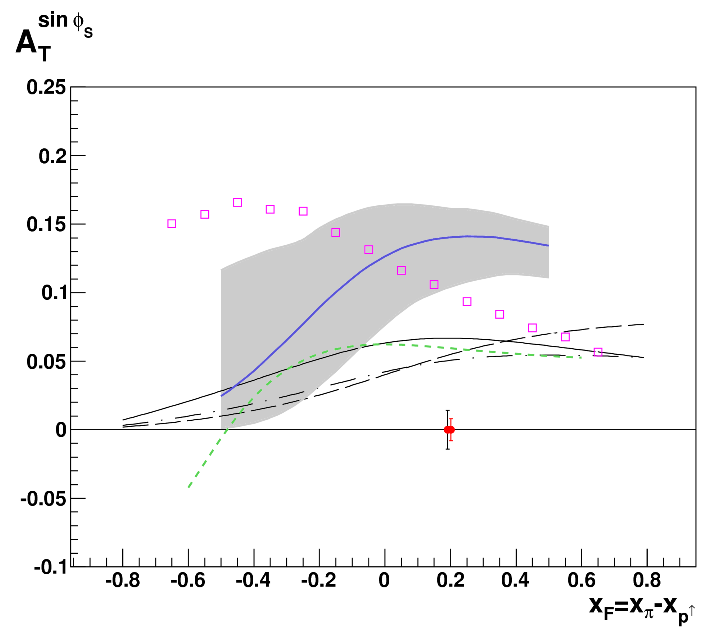
DY@COMPASS projections I

With a beam intensity $I_{beam} = 6 \times 10^7$ particles/second,
a luminosity of $L = 1.7 \times 10^{33}\ cm^{-2}s^{-1}$ can be obtained.

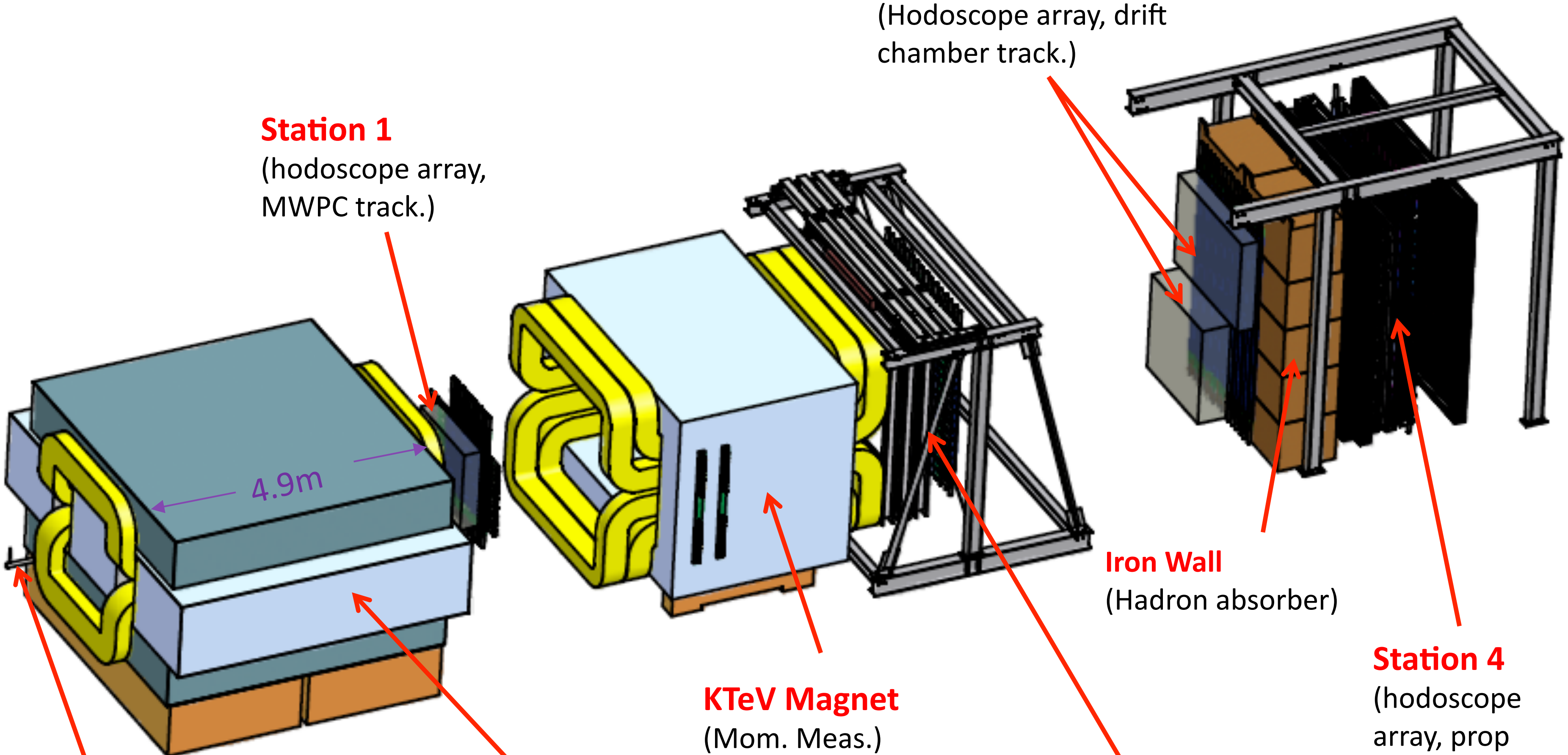
$\hookrightarrow$ Assuming 2 years of data-taking, one can collect > 200000 DY events in the region $4 < M_{\mu\mu} < 9.$ GeV/c^2.

Predictions for the Sivers asymmetry in the COMPASS phase-space, for the mass region $4. < M < 9.$ GeV/c^2, compared to the expected statistical errors of the measurement:

– solid and dashed: Efremov et al, PLB612(2005)233;
– dot-dashed: Collins et al, PRD73(2006)014021;
– solid, dot-dashed: Anselmino et al, PRD79(2009)054010;
– boxes: Bianconi et al, PRD73(2006)114002;
– short-dashed: Bacchetta et al, PRD78(2008)074010.



Drell-Yan Spectrometer for E906

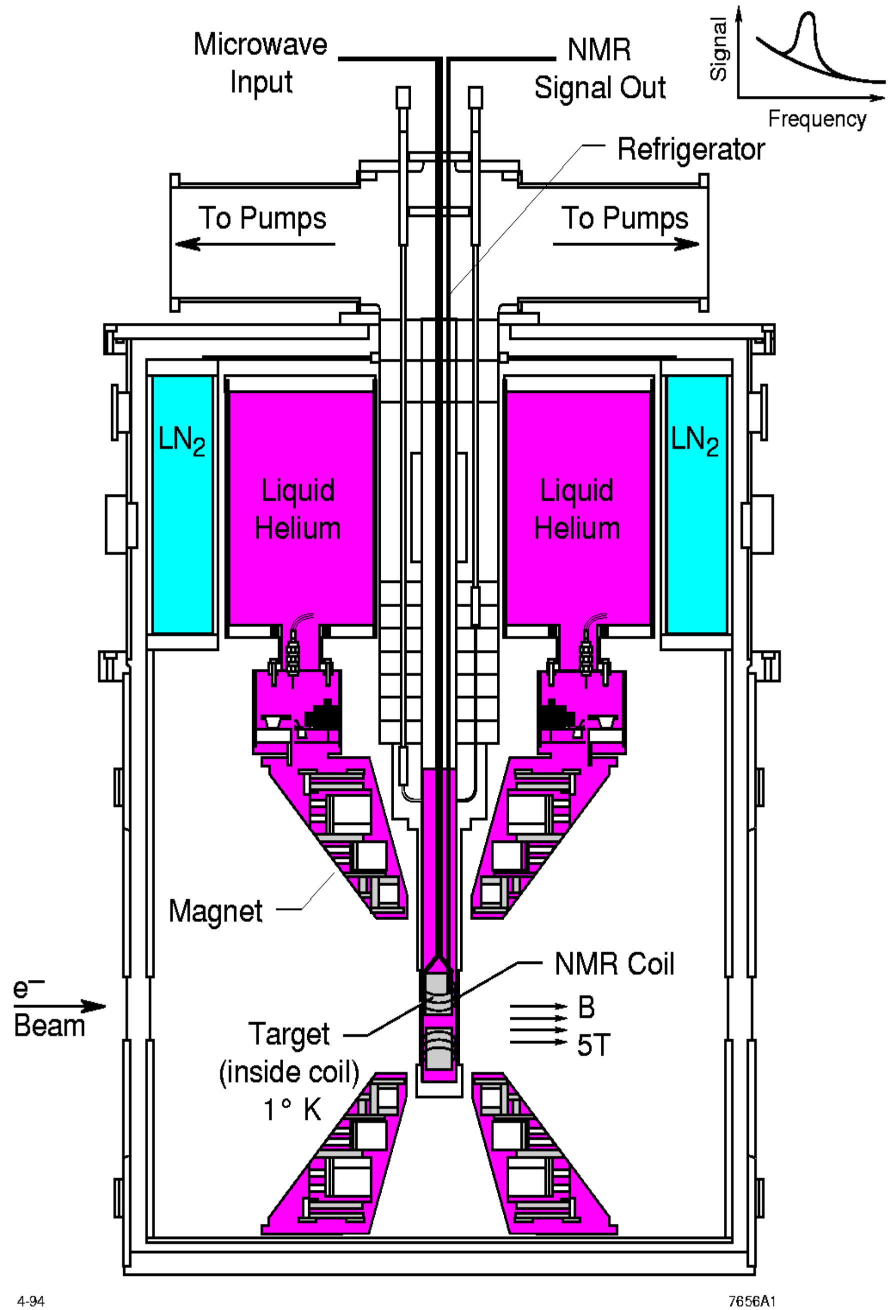


D. Crabb MENU10

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)

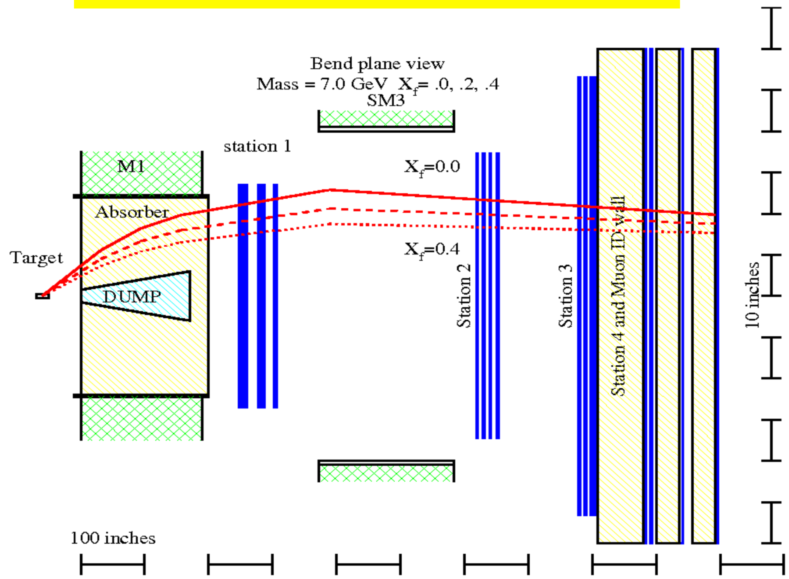


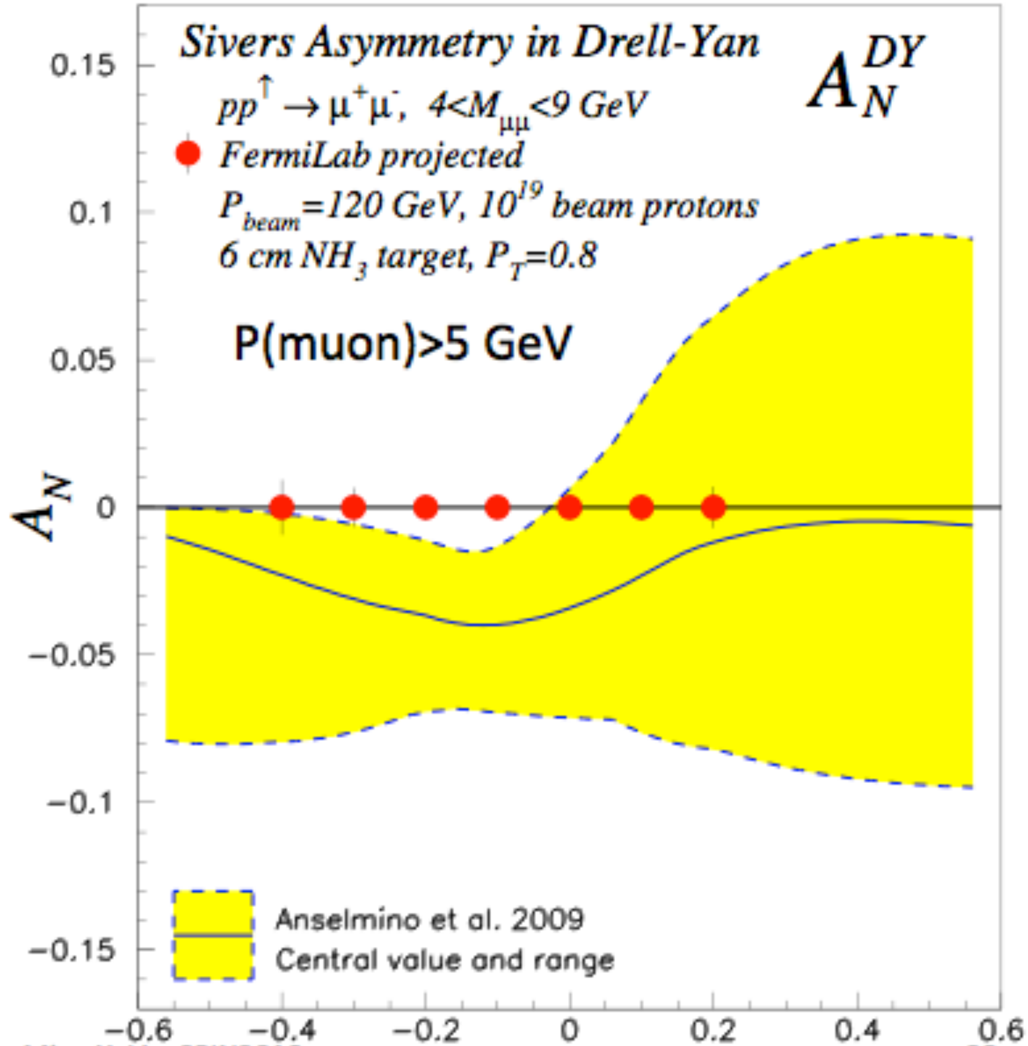
Expected DY A_N Sensitivity @120 GeV.

Target

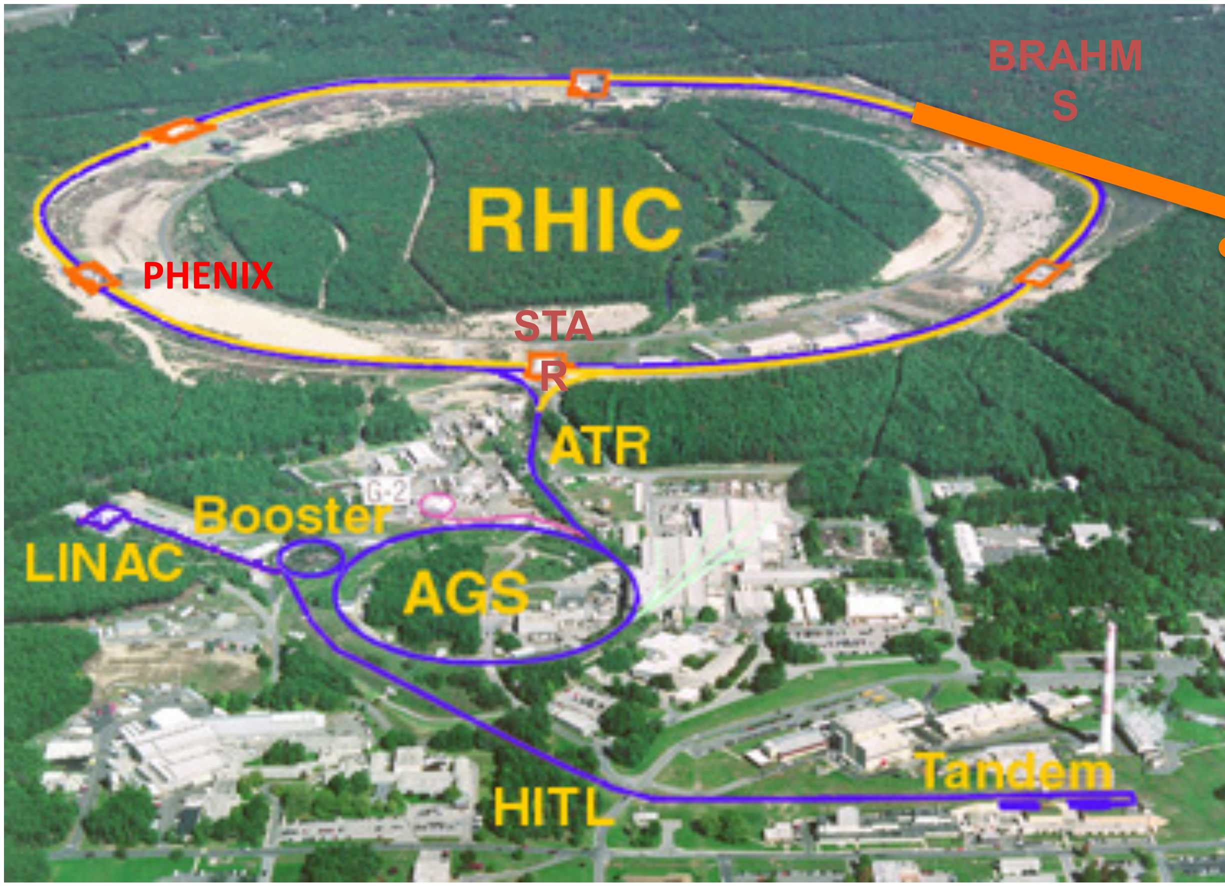
- 6 cm NH_3
- 10^{19} proton

Also open charm and J/psi





Polarized DY w/ Fixed Target @RHIC ?



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

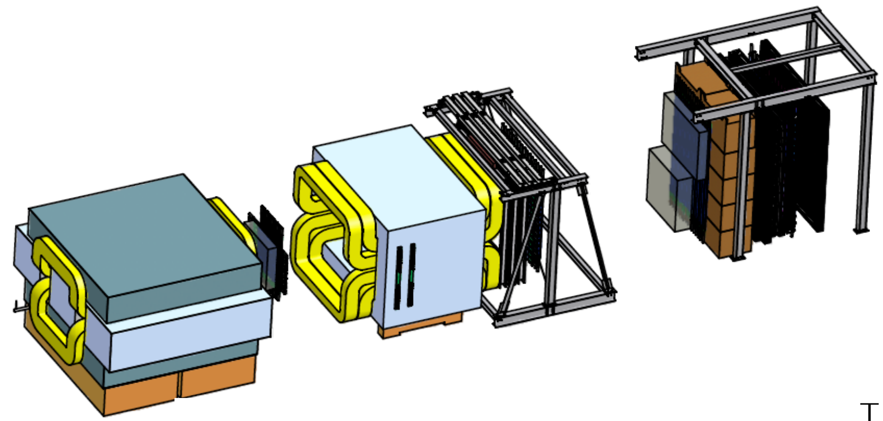
Fixed Target DY Exp. @Beam Dump

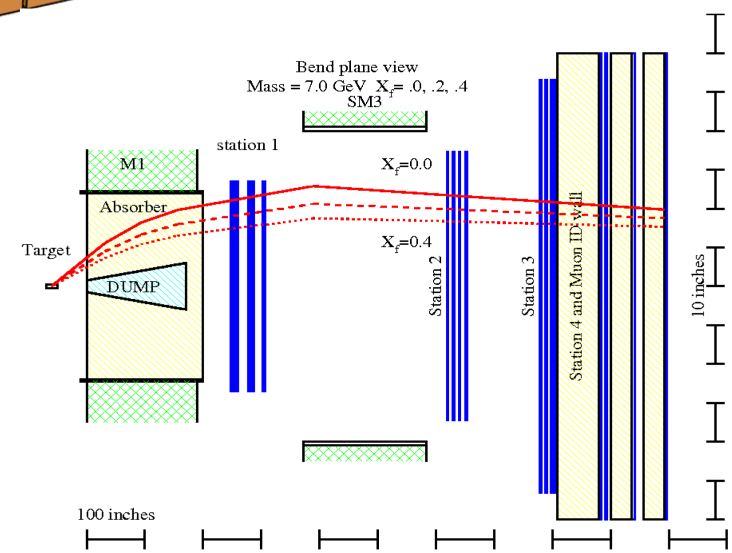
1. High density LH_2/ LD_2 target
2. High density polarized targets
3 Map out x-dep.

- 250 GeV proton beams
- Pol up to 70%

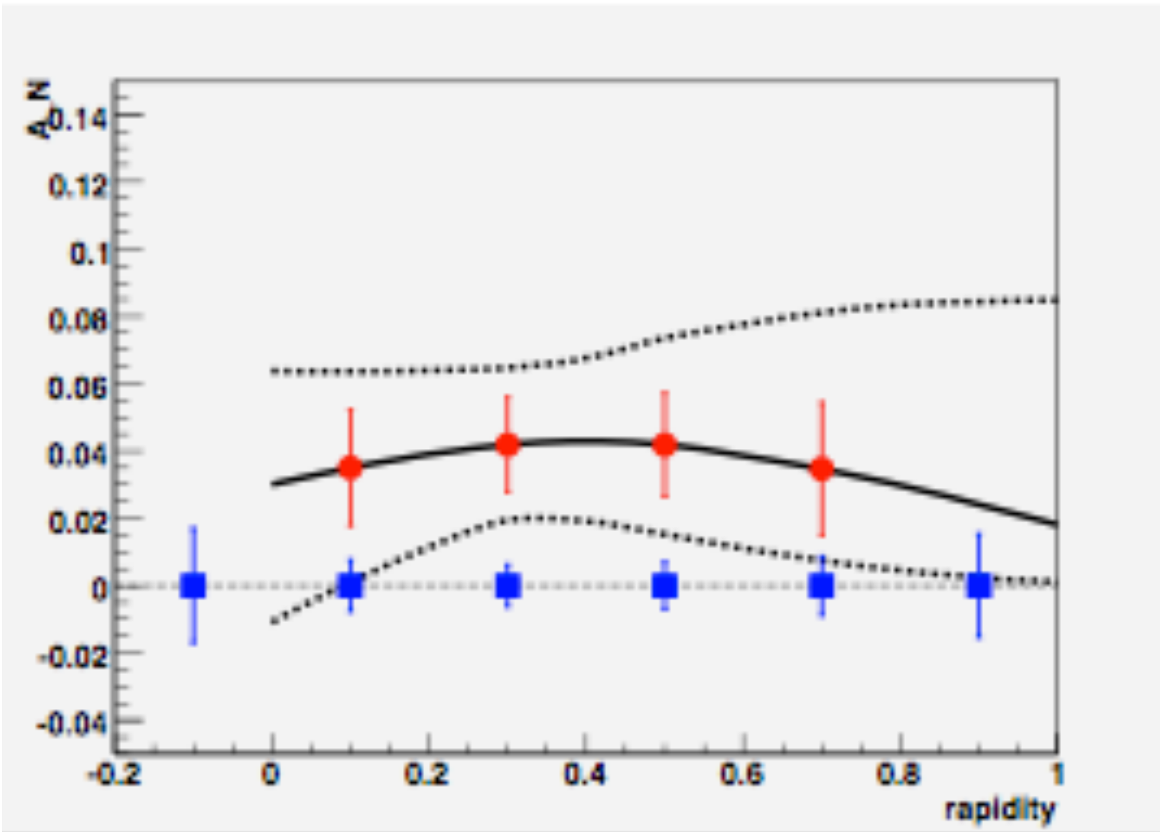
Fixed Target @RHIC ?

- 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 ($2.1\times10^{24}/cm^2$)
    - Can handle L ~ $1\times10^{36} cm^{-2}s^{-1}$
  - 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





DY A_N Sensitivity @250 GeV Fixed Target



x_F

4.5<M<8 GeV

q_T < 1 GeV

10 fb^{-1}

50 fb^{-1}

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

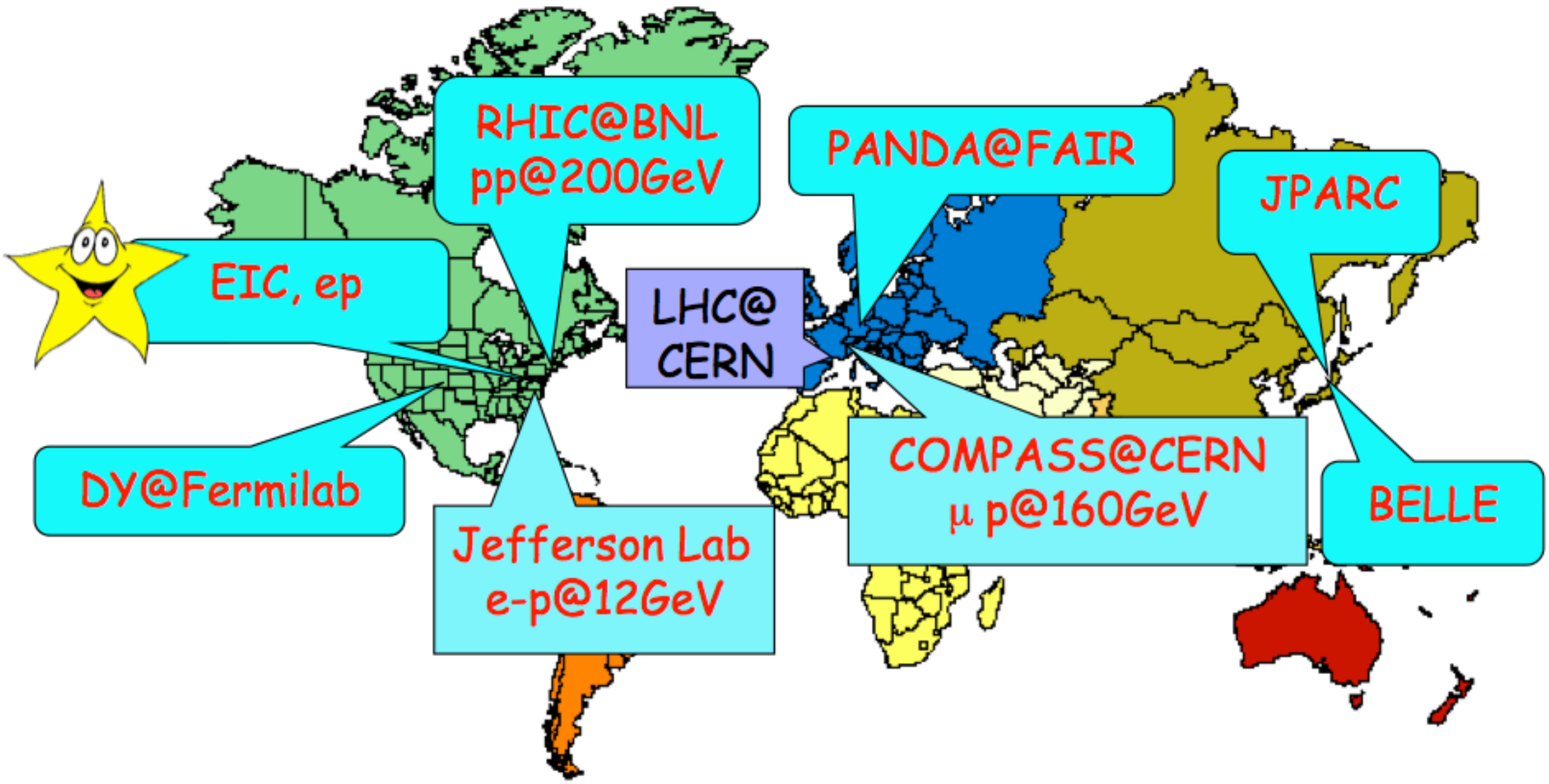
- **Polarized DY Dimuon Exp. at Fermilab Main Injector: 120GeV**
- **RHIC fixed target possibility: 250 GeV**

Summary and Outlook

- Drell-Yan is a powerful tool complimentary to DIS for exploring nucleus structure
- Very interesting results obtained from DY in the past
- Active worldwide programs, current and future Exps will address many critical issues in hadron spin and flavor physics

backup

World Map of QCD Facilities



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 ΔG with $\int Ldt \sim 300\ pb^{-1}$				

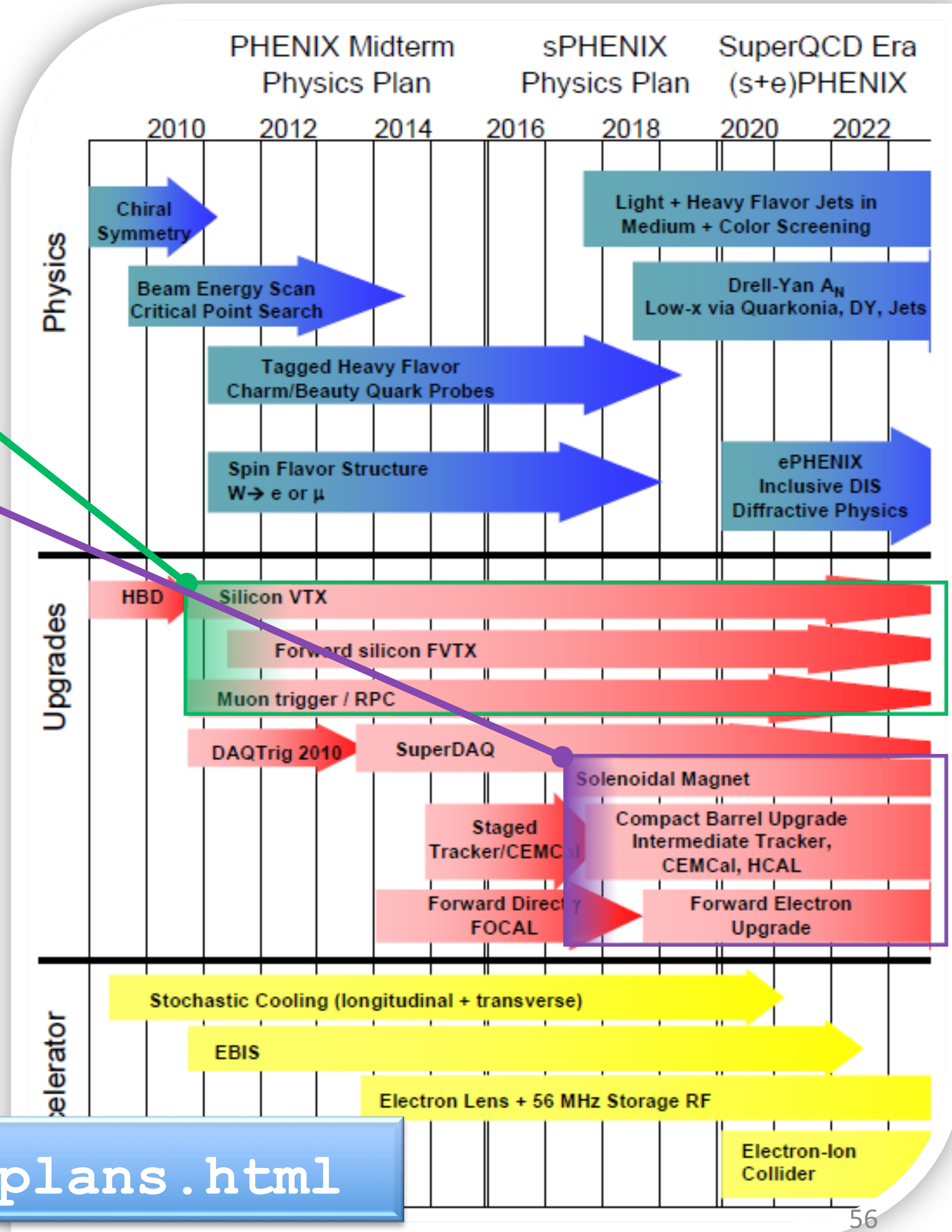
➔ (1) Drell-Yan Program with transverse spin in STAR and PHENIX will not start before run 15 (starting late 2014).

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

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

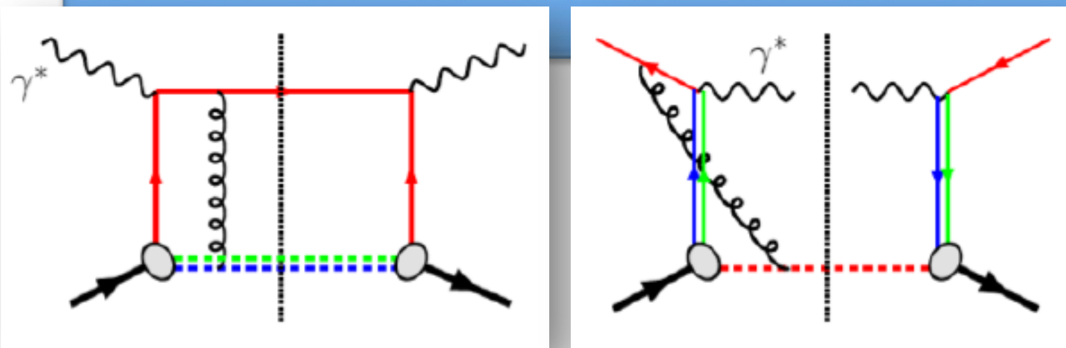
PHENIX Decadal Plan

- ○ 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*

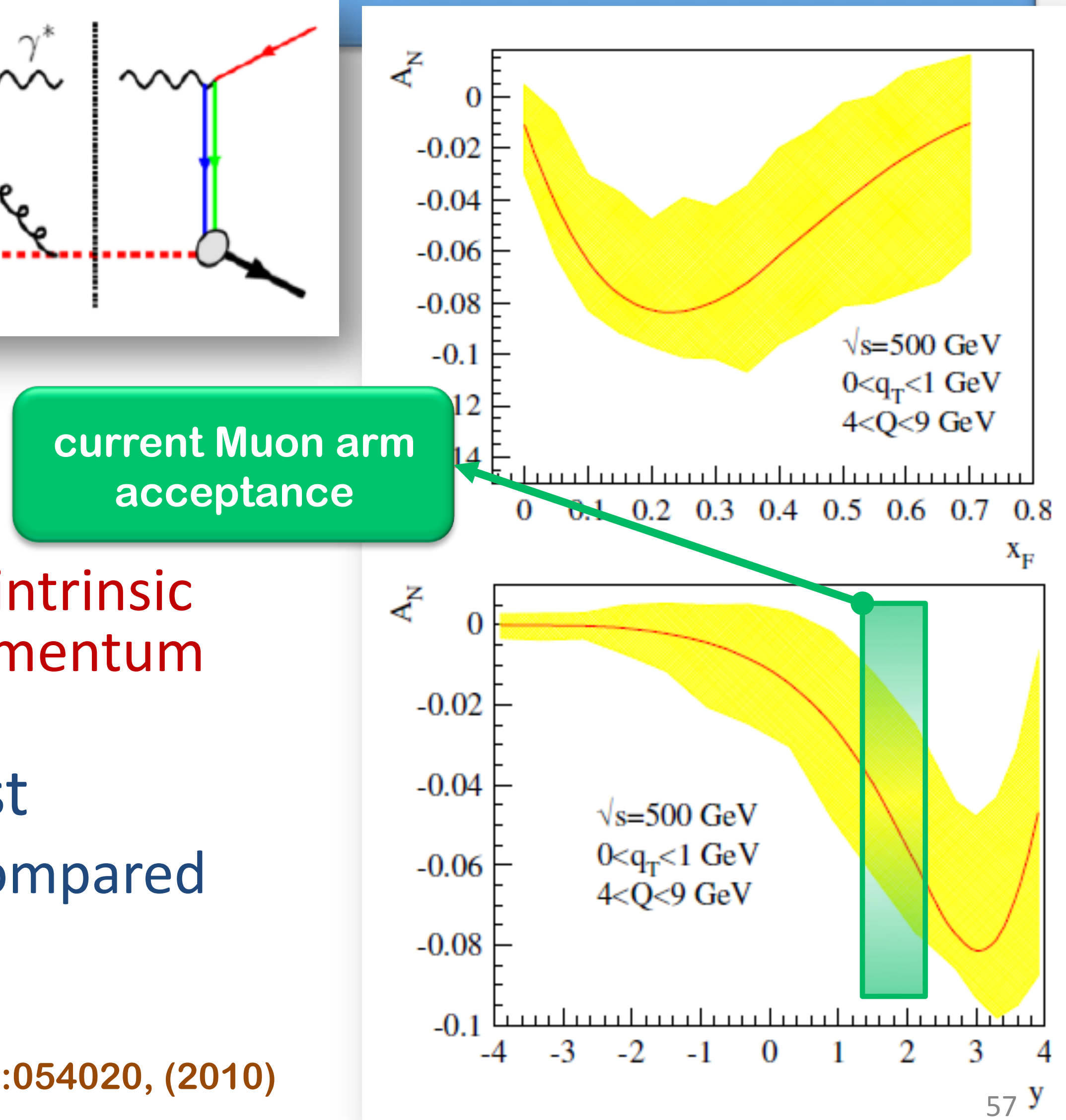


www.phenix.bnl.gov/plans.html

Polarized Drell Yan

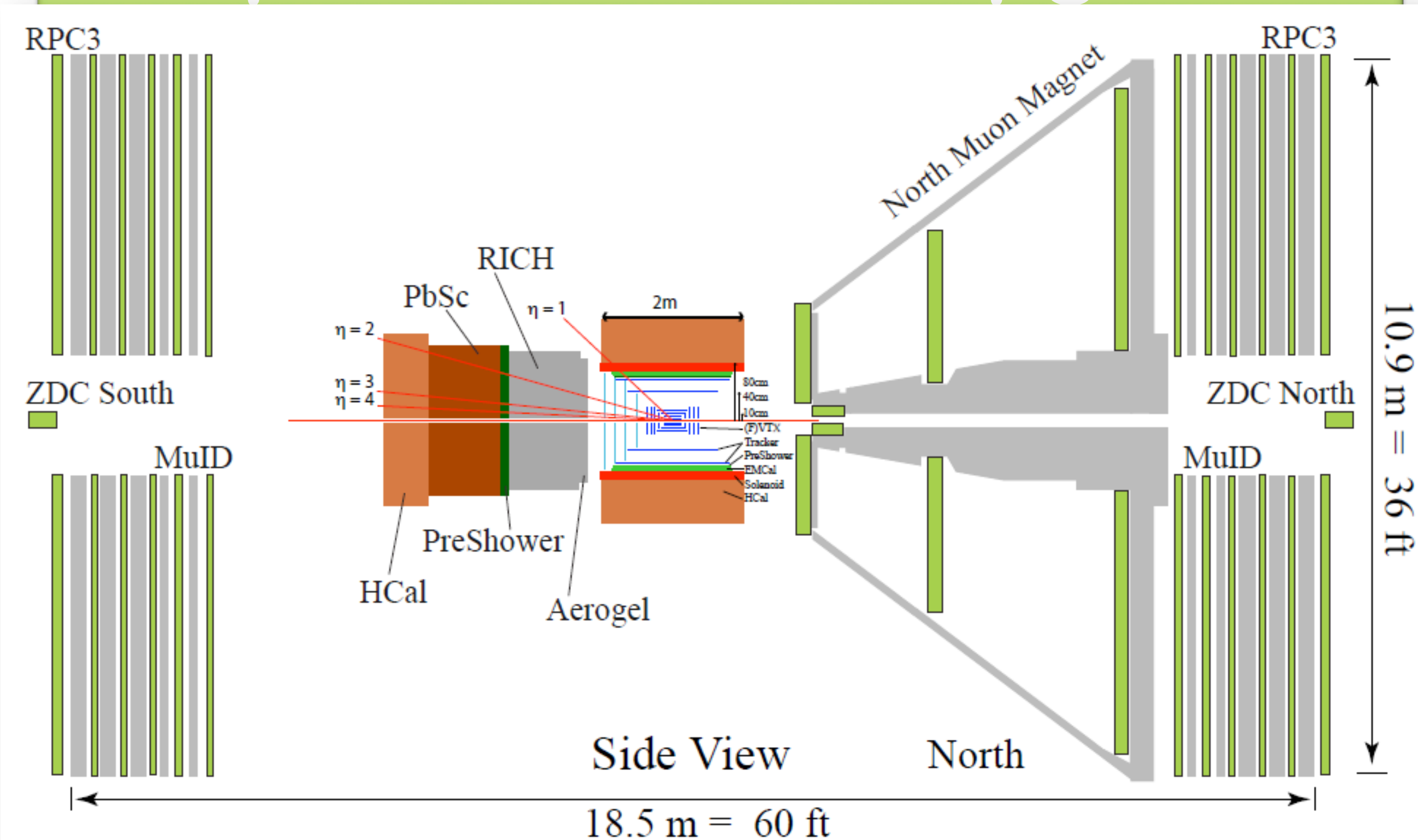


- Solid factorization
- No fragmentation
  - Direct correlation of intrinsic transverse quark momentum to the proton spin
- Fundamental QCD test
  - Sign of asymmetry compared to SIDIS

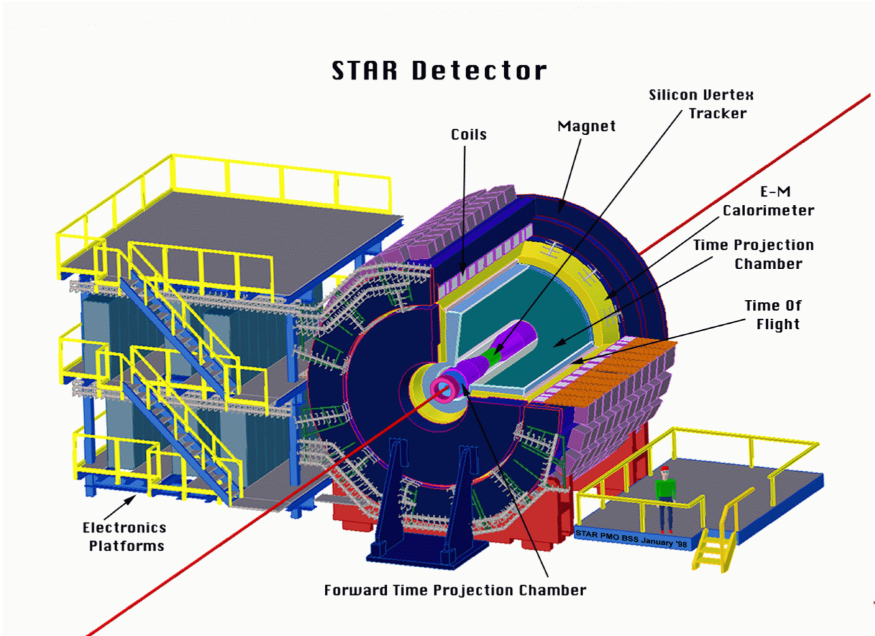


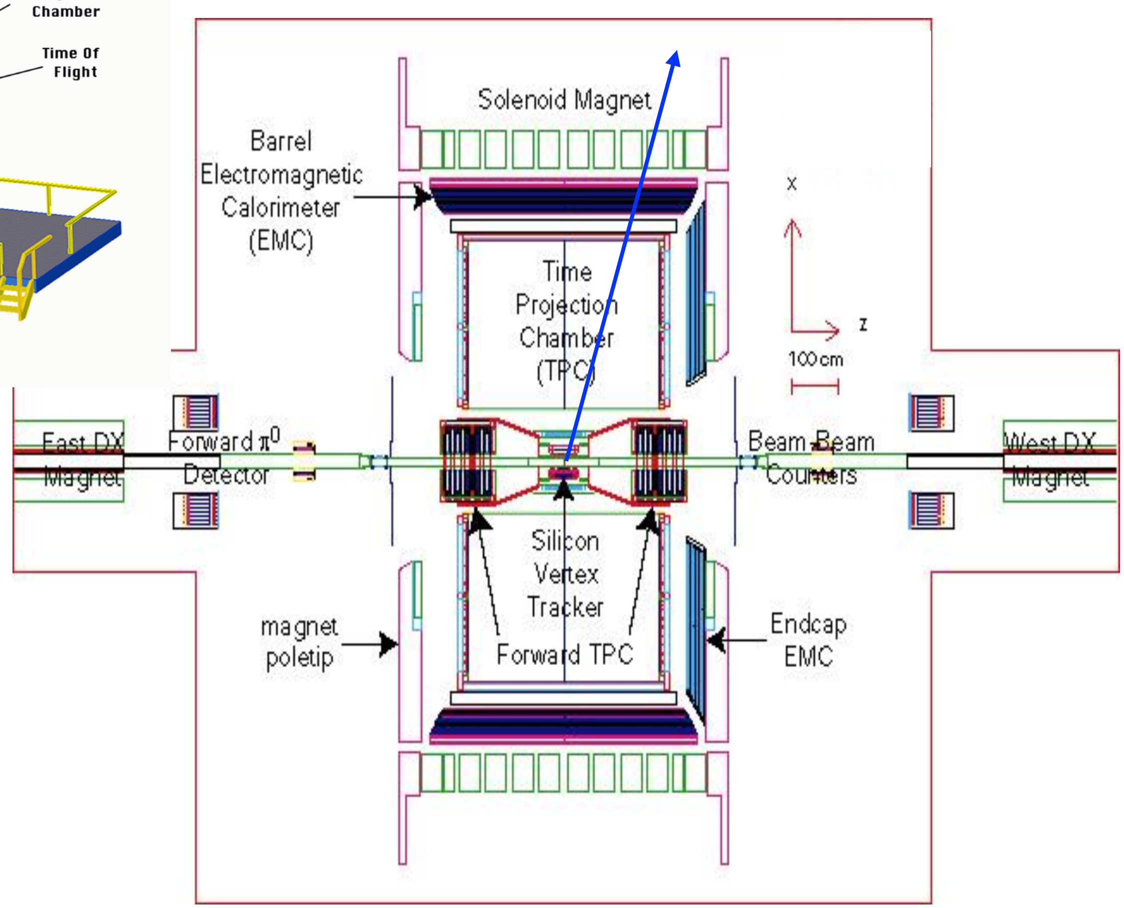
Z. Kang and J. Qiu. Phys. Rev., D81:054020, (2010)

Proposed PHENIX Upgrades



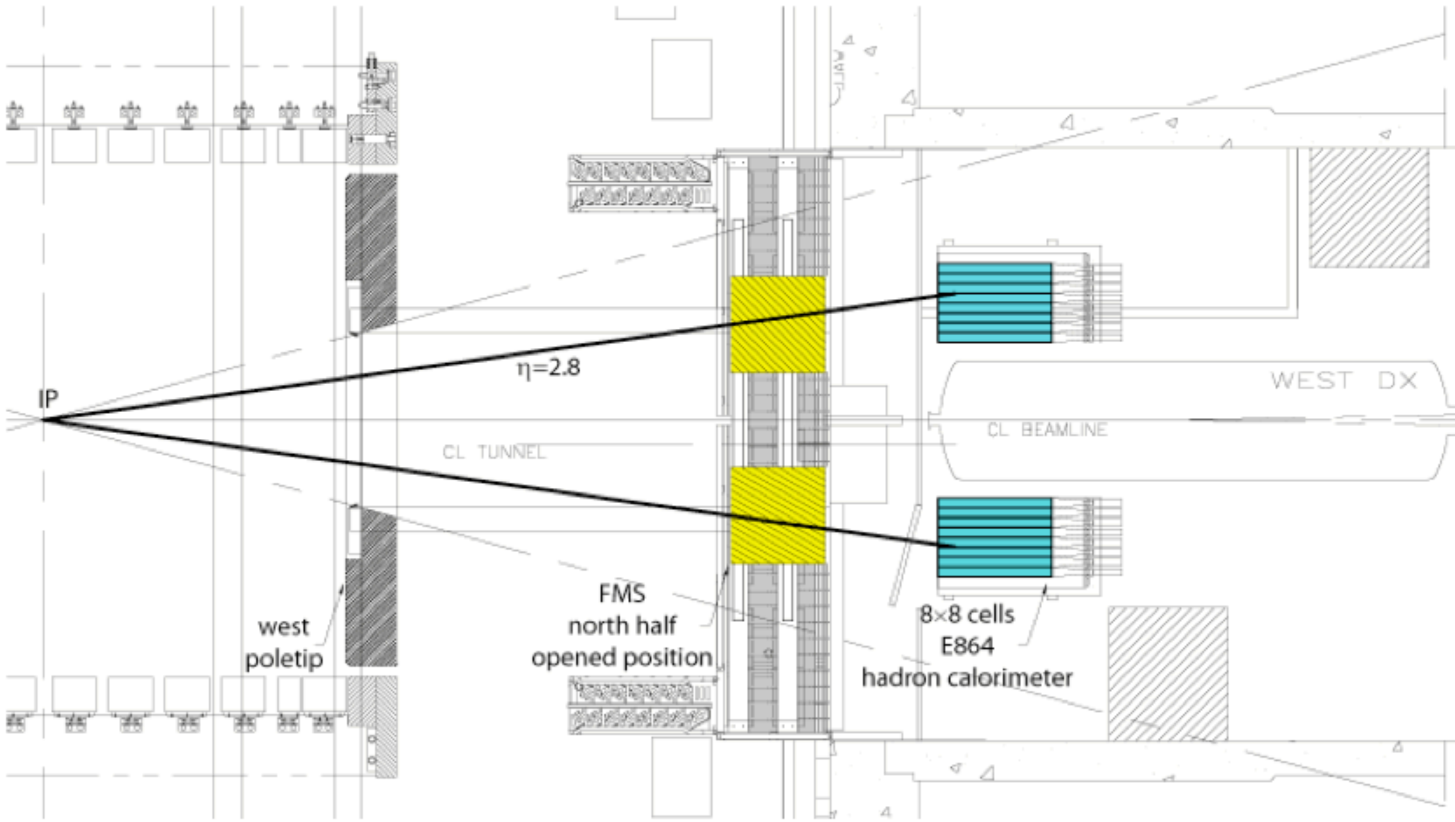
The STAR Detectors





- 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



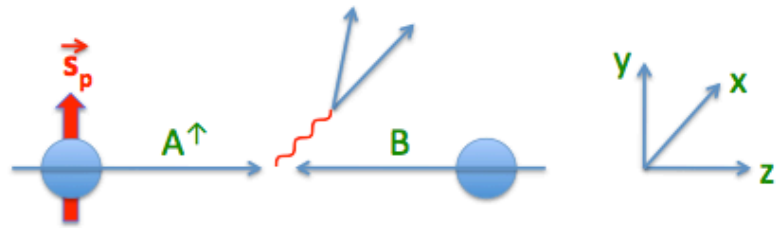
FHC: proposed hadronic calorimetry behind the FMS,
essential towards understanding of forward single-spin asymmetries,
enable forward (anti-)Lambda studies, ...

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.

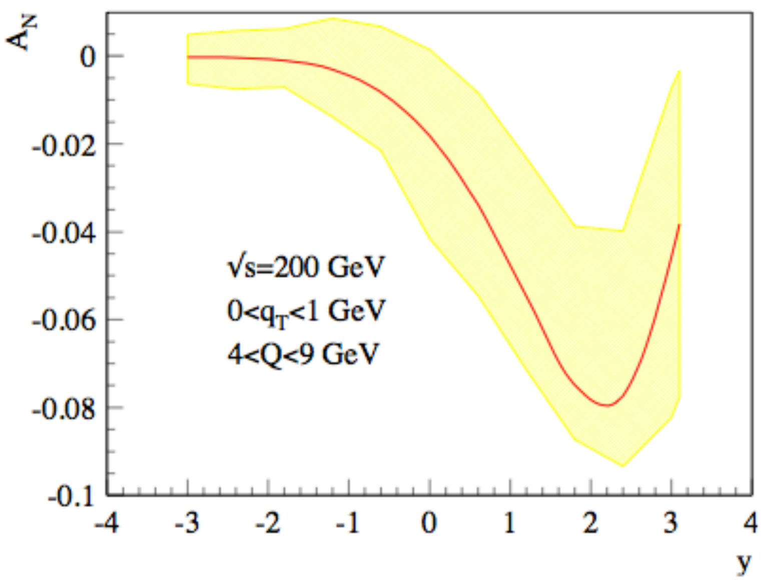
Predictions for Drell-Yan process at RHIC

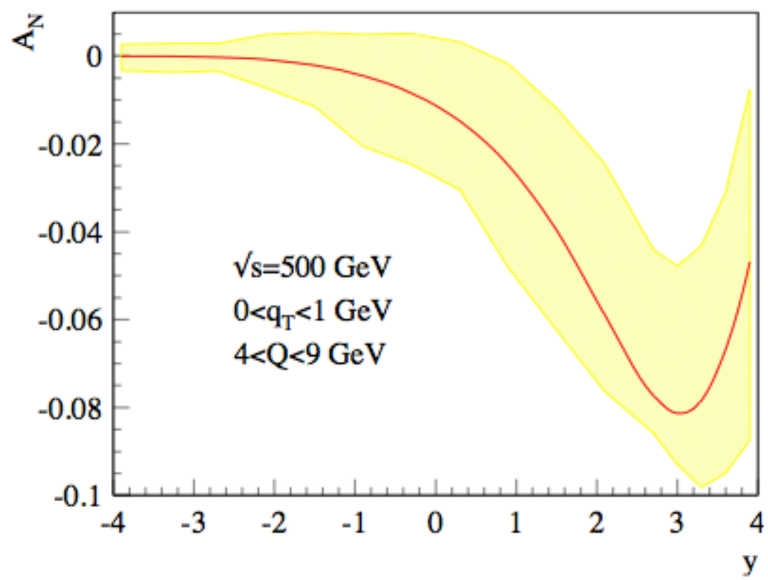
- Reverse the sign of Sivers from SIDIS and make predictions for Drell-Yan production at RHIC

Kang-Qiu, PRD81, 2010



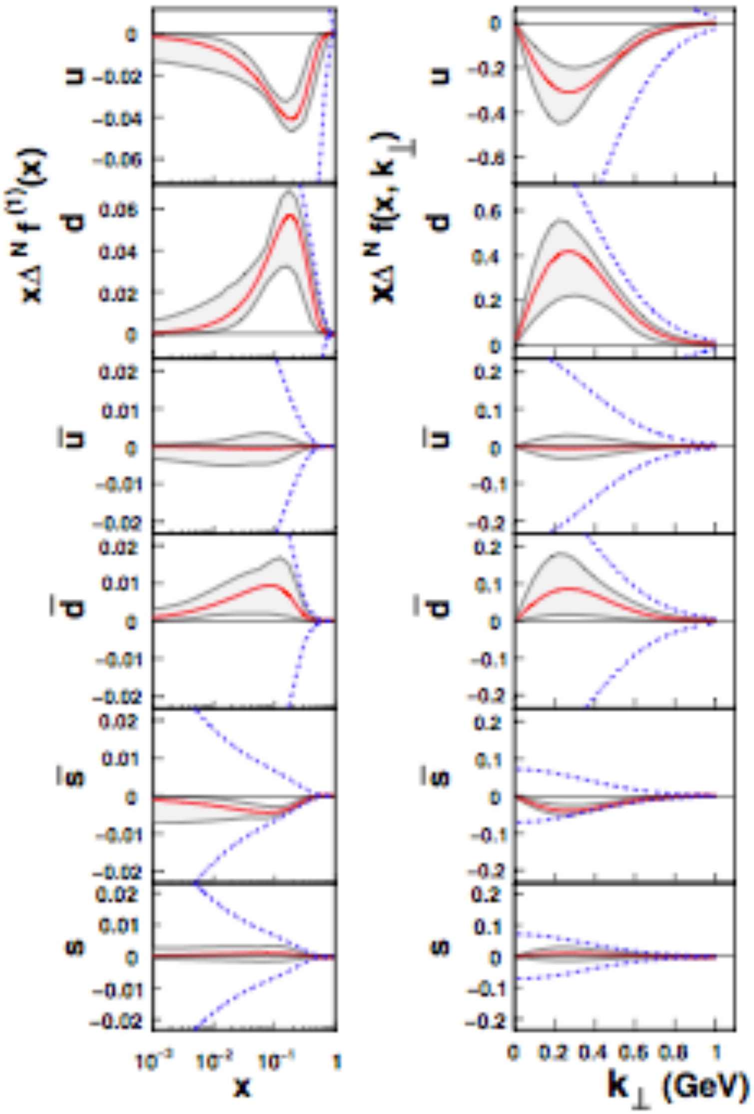
$$A_N \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d < 0$$



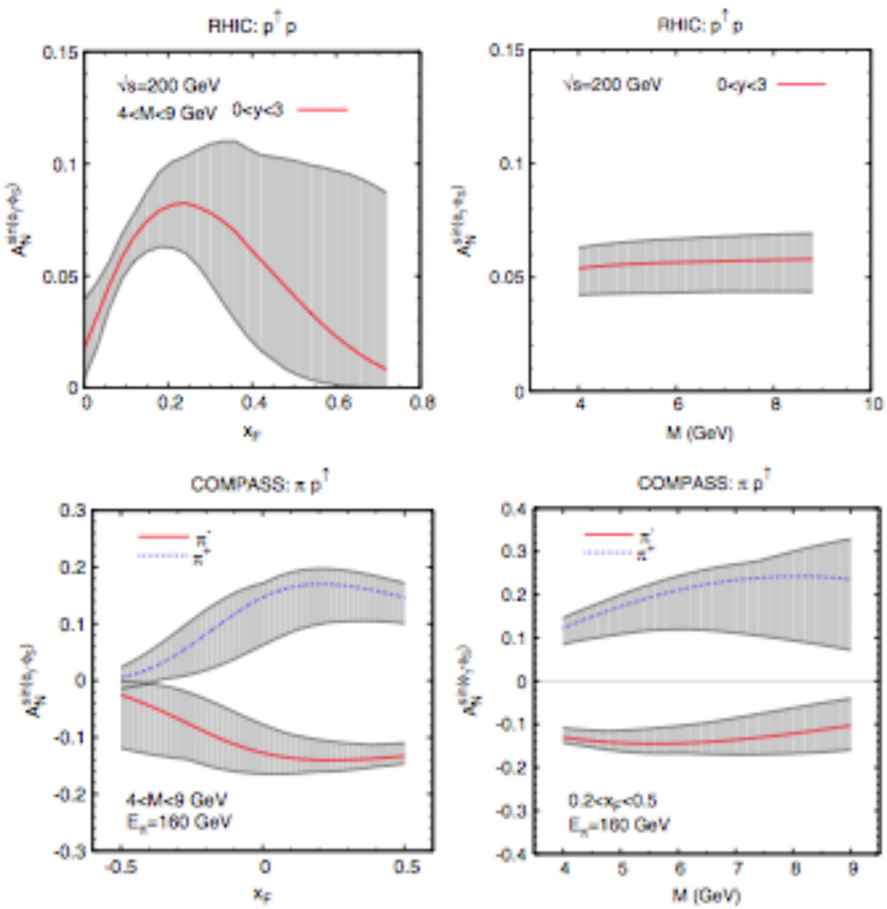


Sivers Functions and DY TSSA

Anselmino et al PRD 79 -54010(2009)



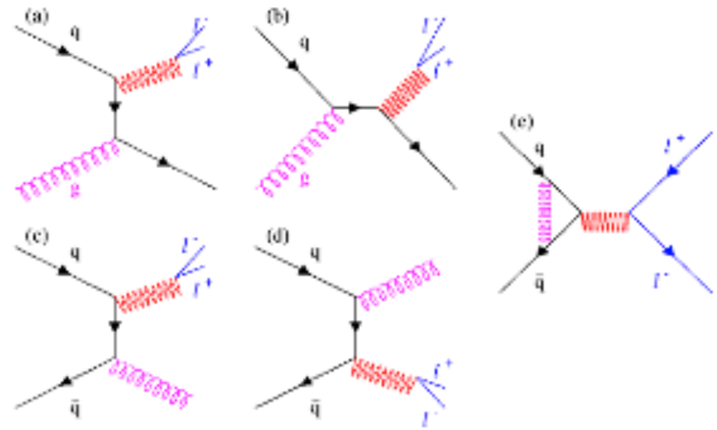
- Expected A_N of DY based on global fit to DIS fit of HERMES and



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	π/Pt	16.8	2.49±0.37
		22.9	2.22±0.33
E326	π/W	20.6	2.70±0.08±0.40
NA10	π/W	19.1	2.8±0.1
Goliath	π/Be	16.8,18.1	2.5
Omega	π/W	8.7	2.6±0.5

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