

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

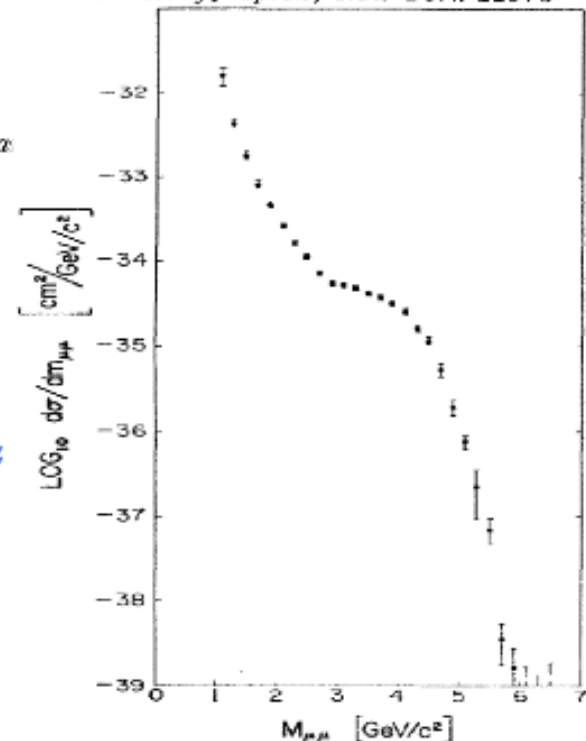
E. Zavattini

CERN Laboratory, Geneva, Switzerland

(Received 8 September 1970)

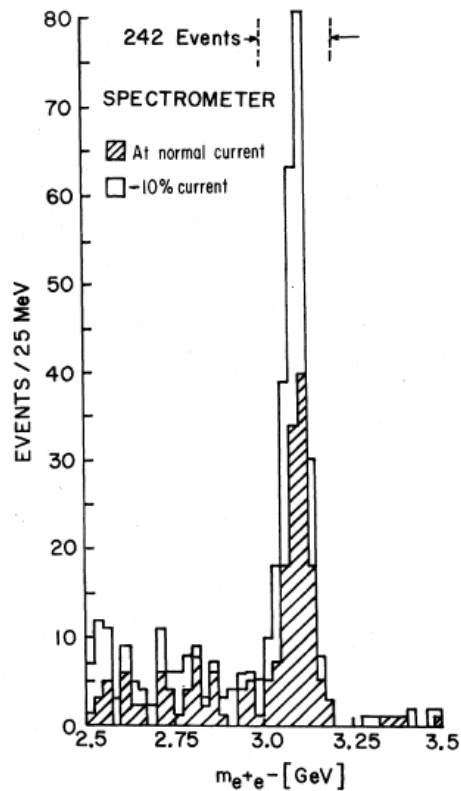
Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7 \text{ GeV}/c^2$ have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5 \text{ cm}^2 (\text{GeV}/c)^{-2}$ 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!

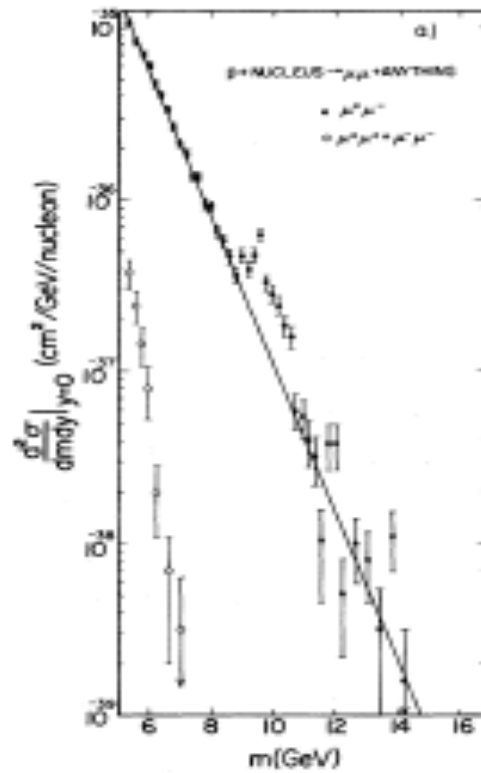


Di-lepton probe: a Powerful Tool for Discovery

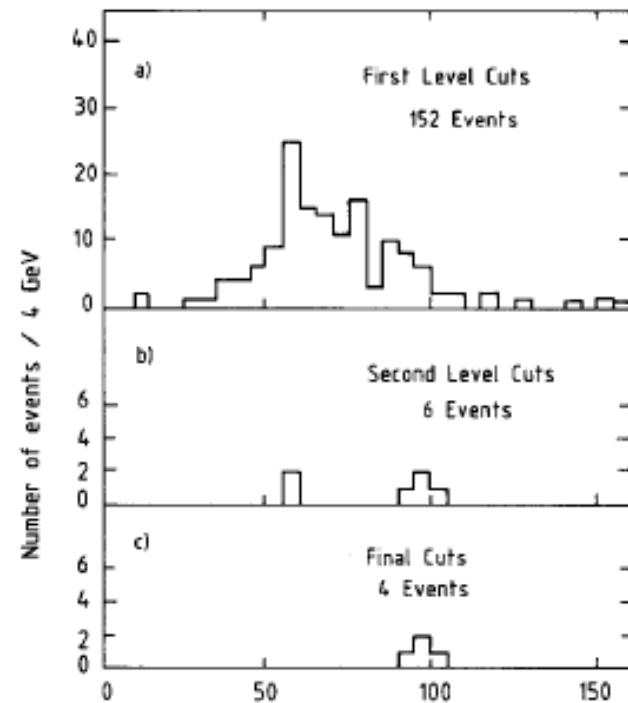
$$J/\Psi \rightarrow e^+e^-$$



$$\Upsilon \rightarrow \mu^+\mu^-$$



$$Z^0 \rightarrow e^+e^-$$



The Drell-Yan Process

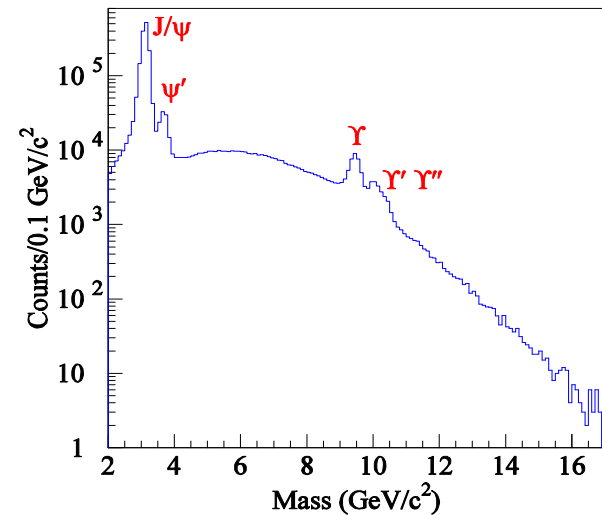
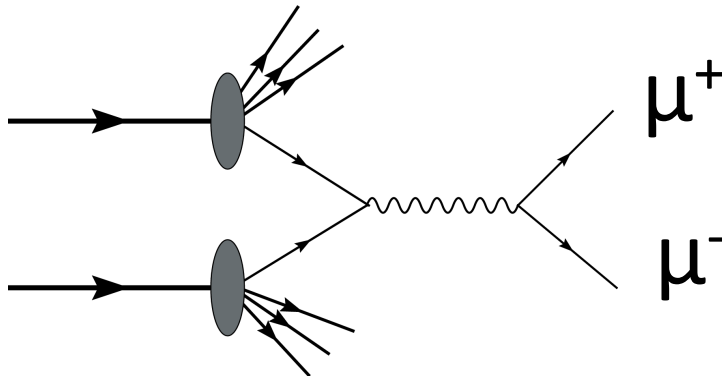
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 25 May 1970)

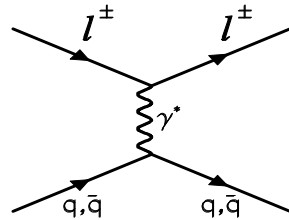
On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \rightarrow \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \rightarrow 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



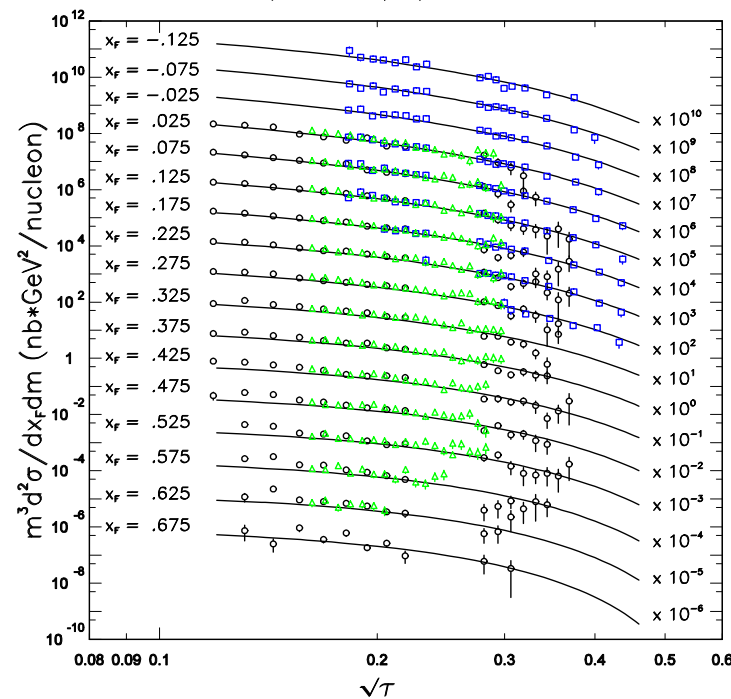
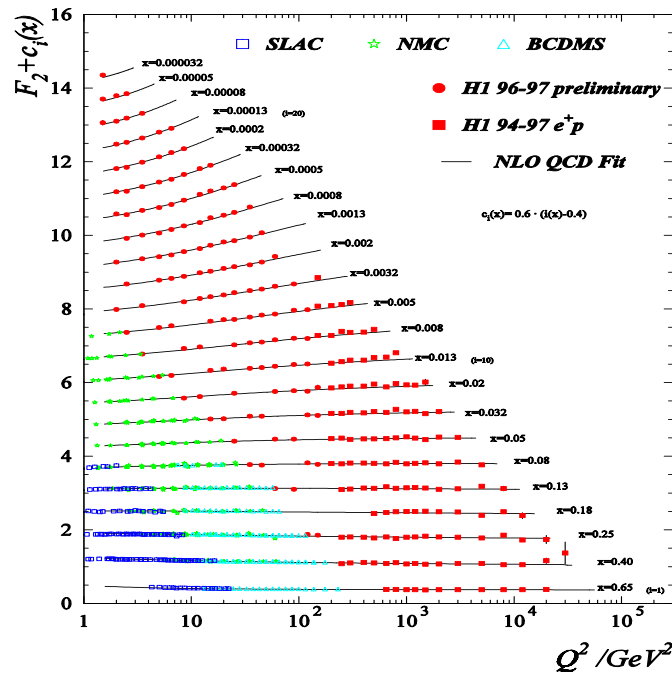
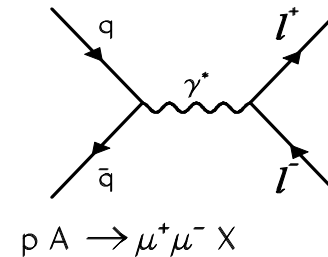
$$\left(\frac{d^2\sigma}{dx_1 dx_2} \right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2} \sum_a e_a^2 [q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1)q_a(x_2)]$$

Complimentarity between DIS and Drell-Yan

DIS



Drell-Yan

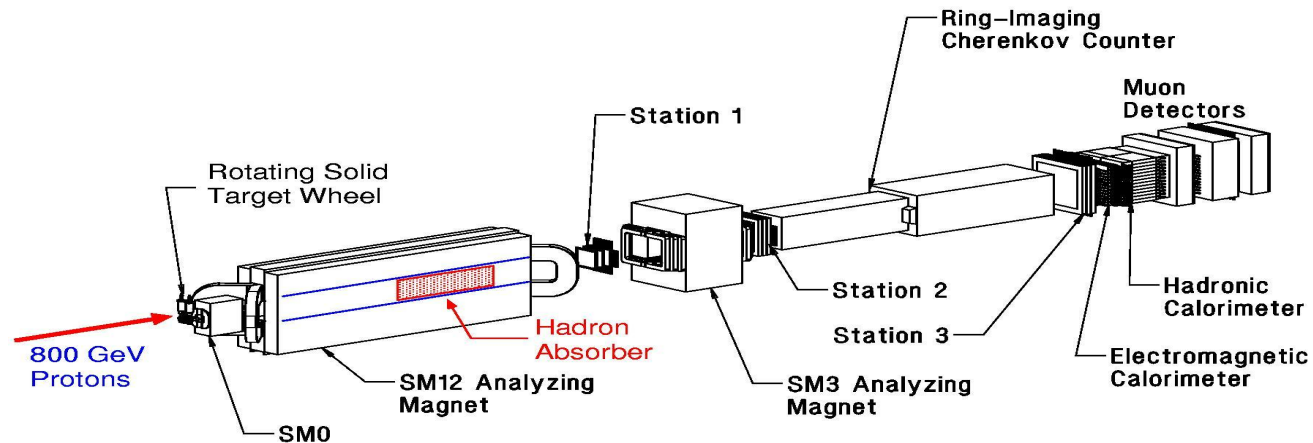


McGaughey,
Moss, Peng,
Ann.Rev.Nucl.
Part. Sci. 49
(1999) 217

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)

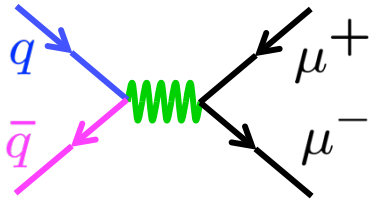
"Determination of $\bar{d}/\bar{u}$ Ratio of the Proton via Drell-Yan"

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

"Drell-Yan with the FNAL Main Injector"

5) RHIC LOI (proposed in 2010)

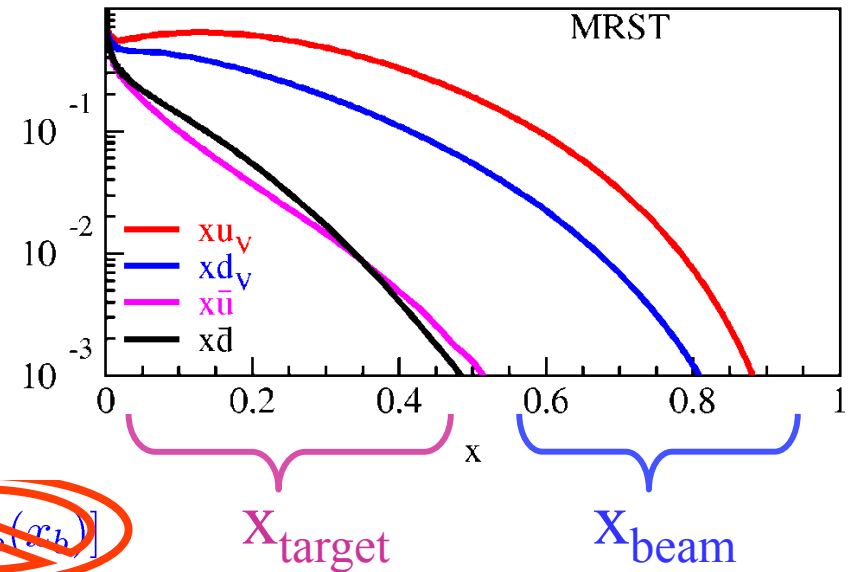
"Polarized Drell-Yan with Internal Target"



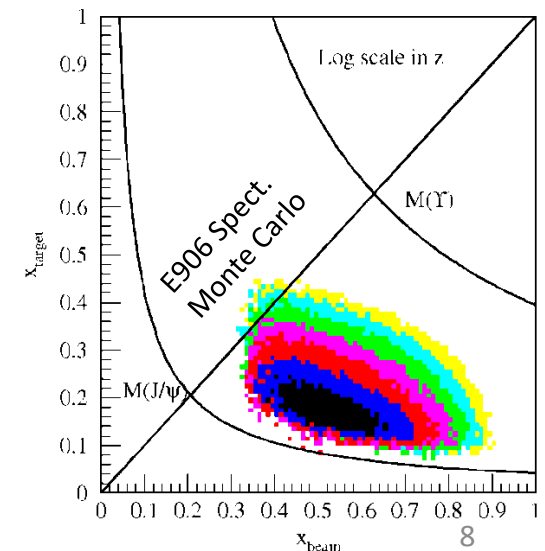
Kinematic of Fixed Target Drell-Yan

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

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [\bar{q}_t(x_t) q_b(x_b) + \cancel{q_t(x_t) \bar{q}_b(x_b)}]$$



- Fixed target kinematics and detector acceptance give $x_b > x_t$
 - ➔ $x_F = 2p_{||}/s^{1/2} \approx x_b - x_t$
 - ➔ Beam valence quarks probed at high x
 - ➔ Target sea quarks probed at low/intermediate x



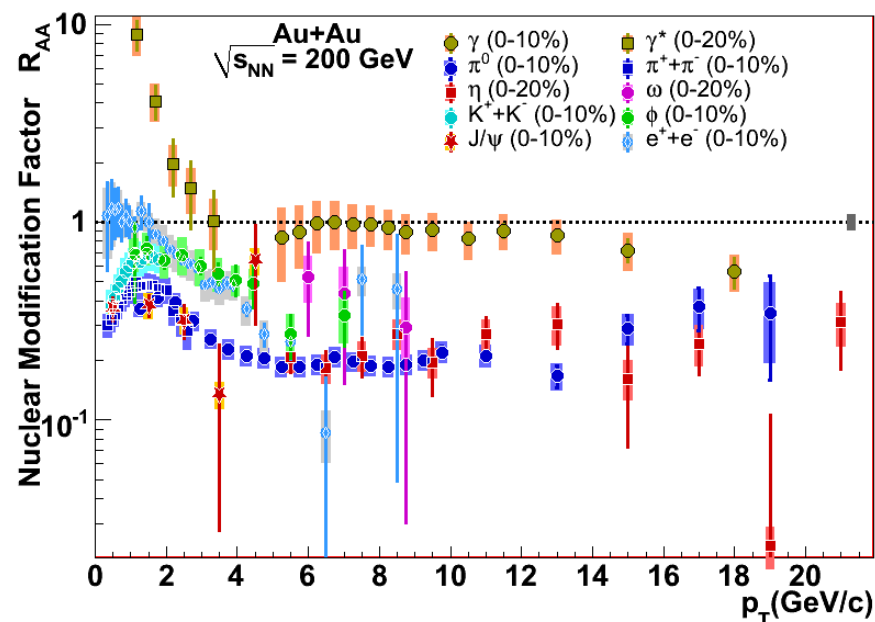
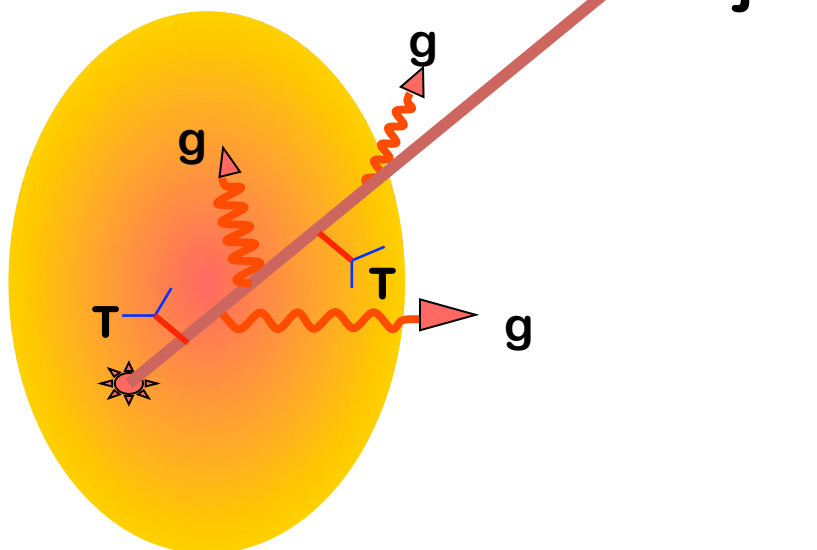
Highlights of Physics from Fermilab Dimuon Experiments

- 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

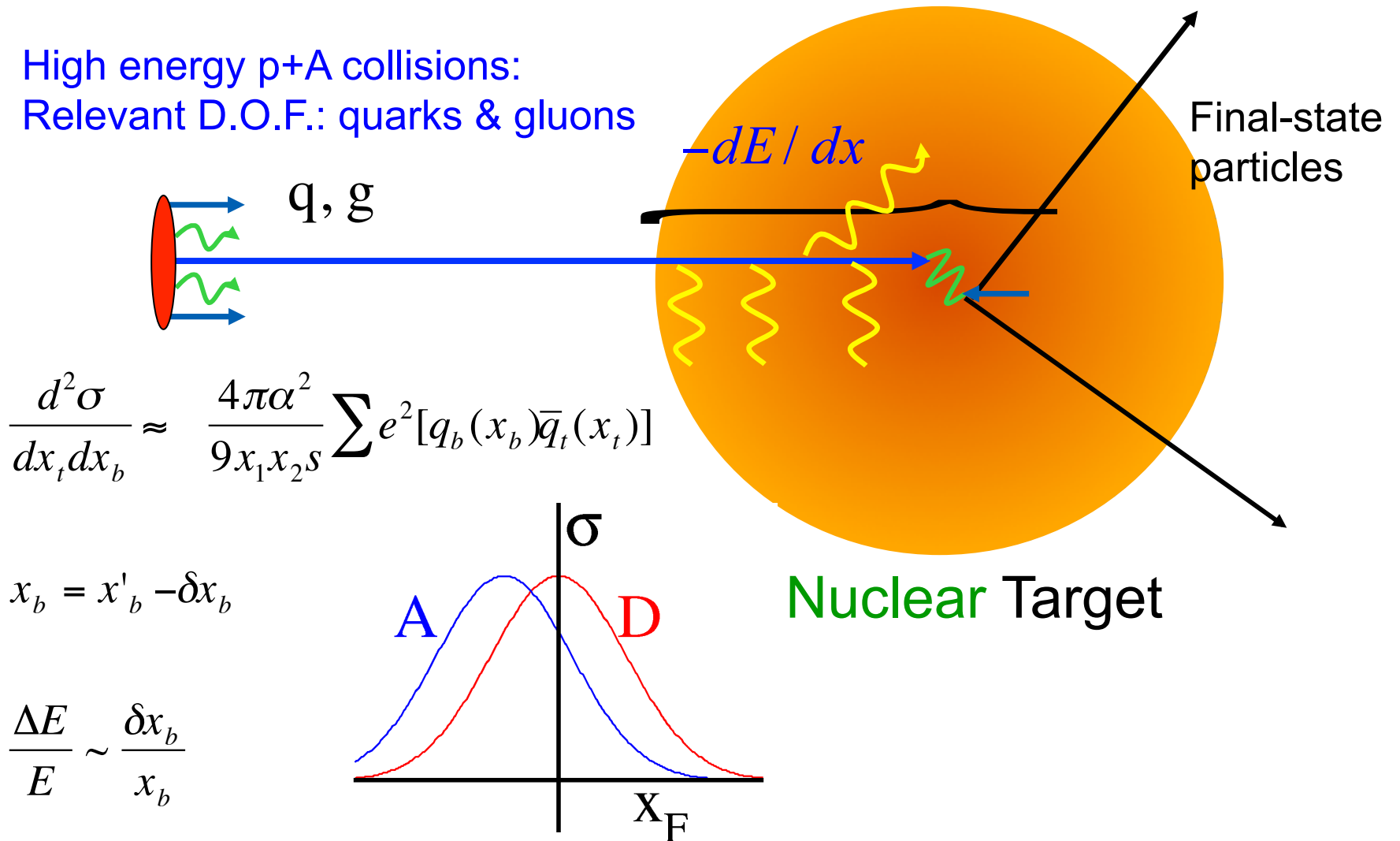
- Parton energy loss has been discovered at RHIC as an excellent probe of the hot/dense matter.
- However, order of magnitude uncertainties in dE/dX

Single Hadron Tomography



Benchmark with DY: Quark Energy Loss in p+A

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



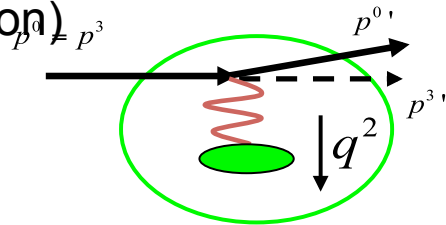
$$\frac{d^2\sigma}{dx_t dx_b} \approx \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [q_b(x_b) \bar{q}_t(x_t)]$$

$$x_b = x'_b - \delta x_b$$

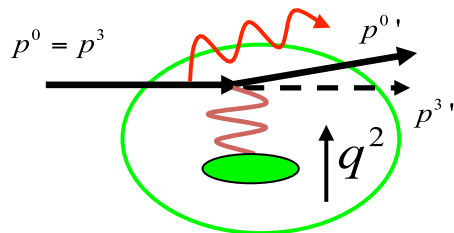
$$\frac{\Delta E}{E} \sim \frac{\delta x_b}{x_b}$$

Energy loss in Electrodynamics

- Collisional energy loss
(ionization and atomic excitation)

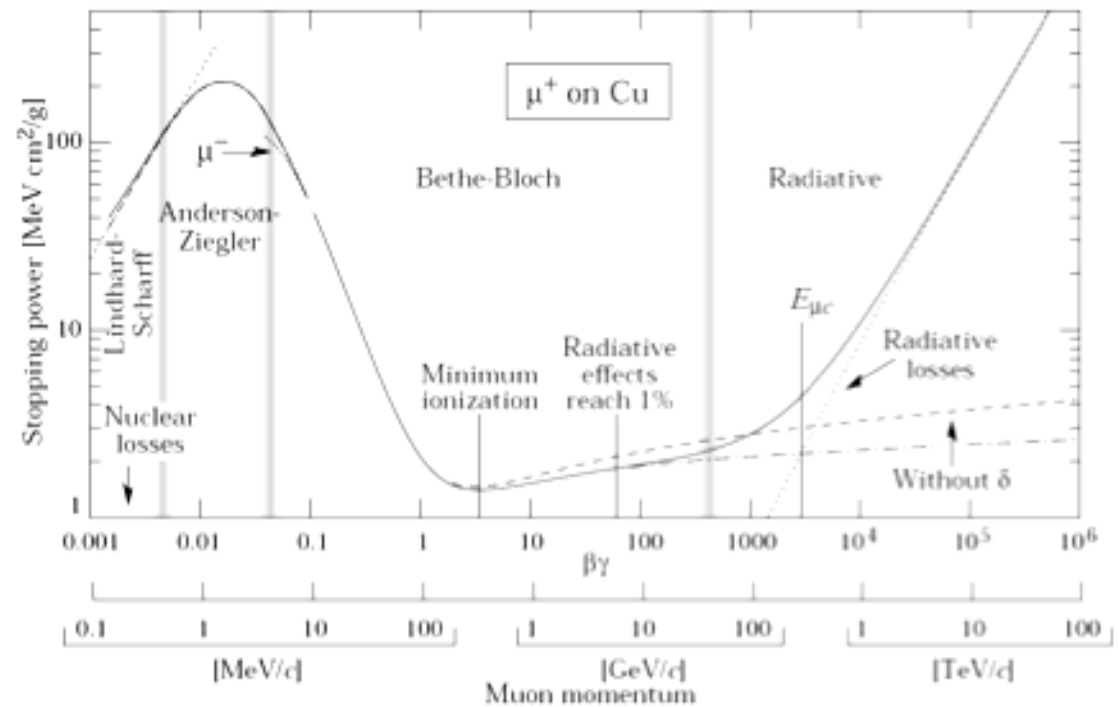


- Radiative energy loss
(photon bremsstrahlung)



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

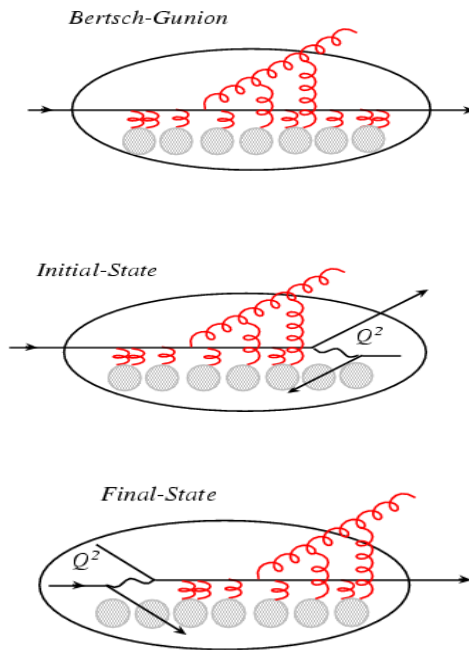
In QCD



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

Process Dependence of Parton Energy Loss

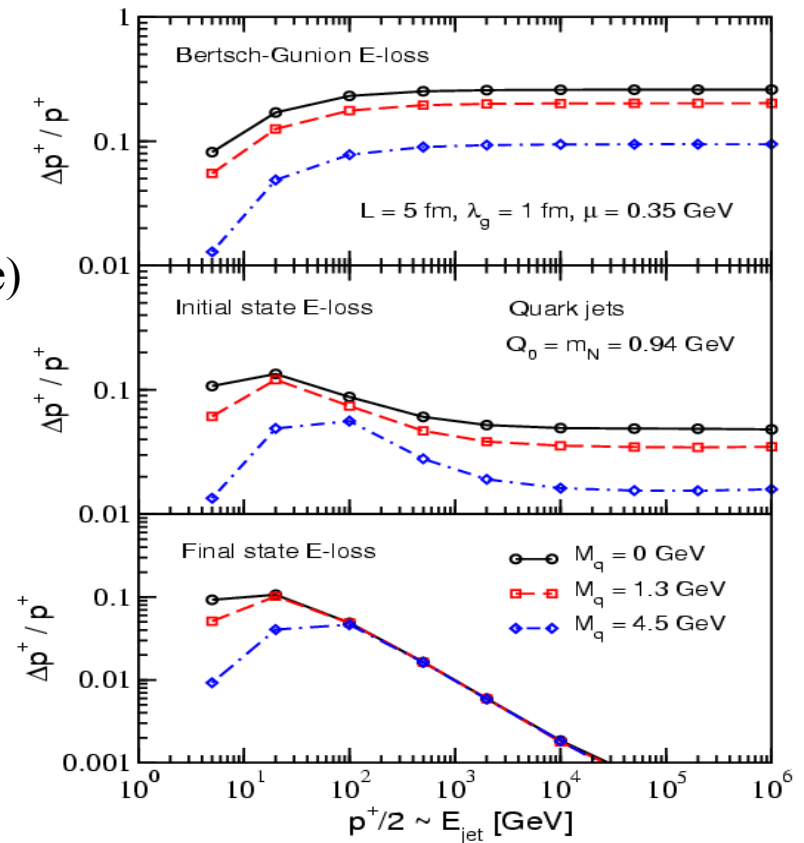
- E-loss in three cases



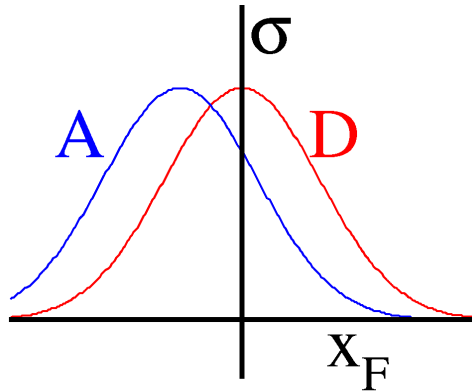
Academic case
(probably inapplicable)

Initial-state E loss:
DY process

Final-state E loss:
SDIS, QGP



Quark Energy Loss in Cold Nuclear Medium



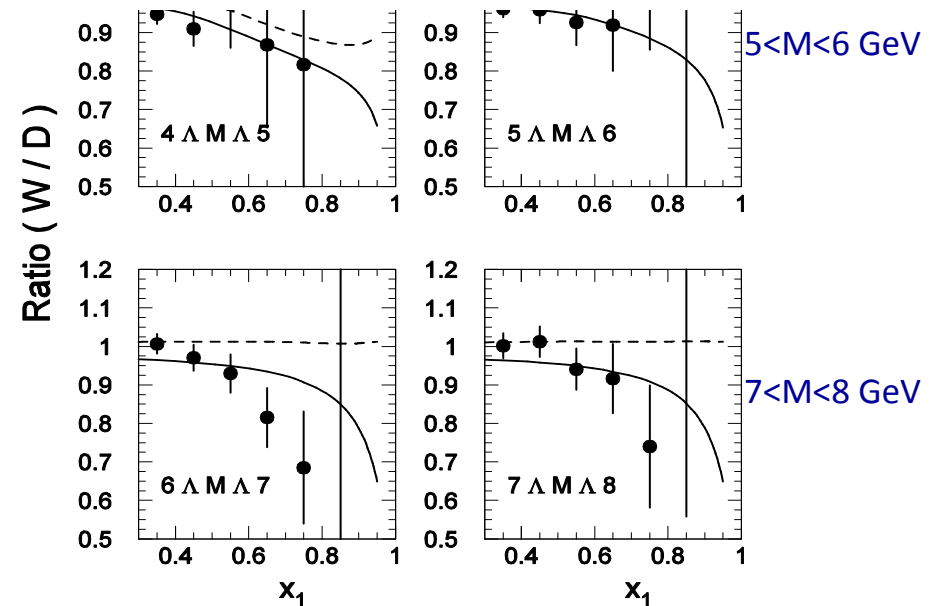
$$\frac{dE}{dx} = 0 \sim 2.5 \text{ GeV/fm}$$

- size of effect $\sim 20\%$
- $\langle dE/dx \rangle$ depends on shadowing correction
- $x_t \sim 10^{-2}$

Drell-Yan @E866

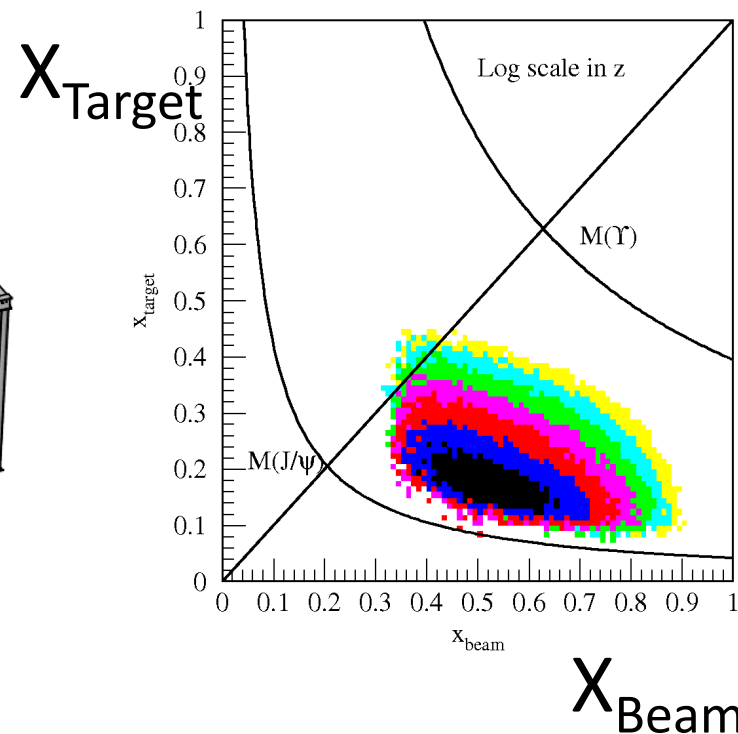
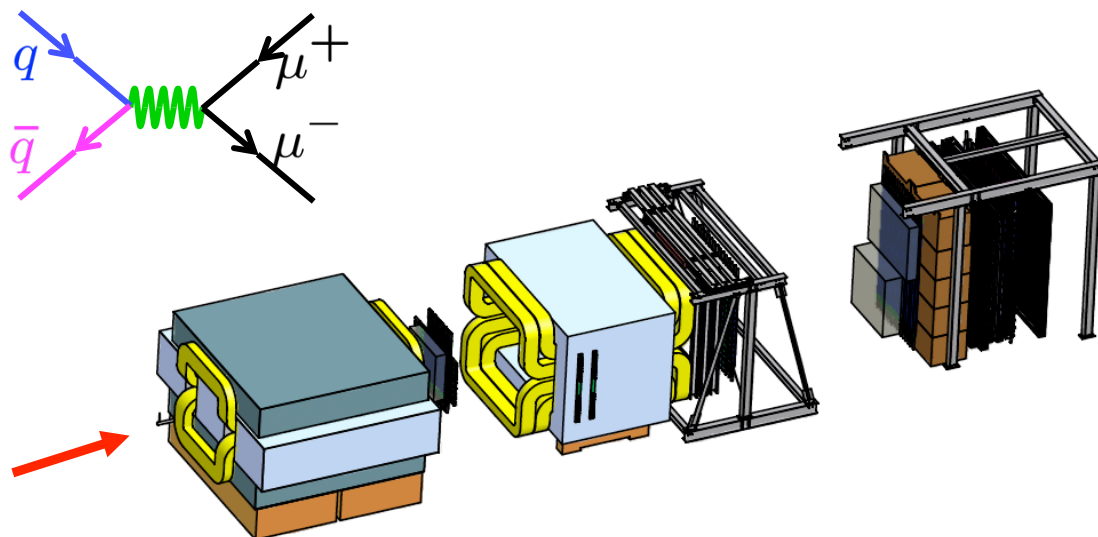
(PRL 86 (2001) 4483)

800GeV p + A



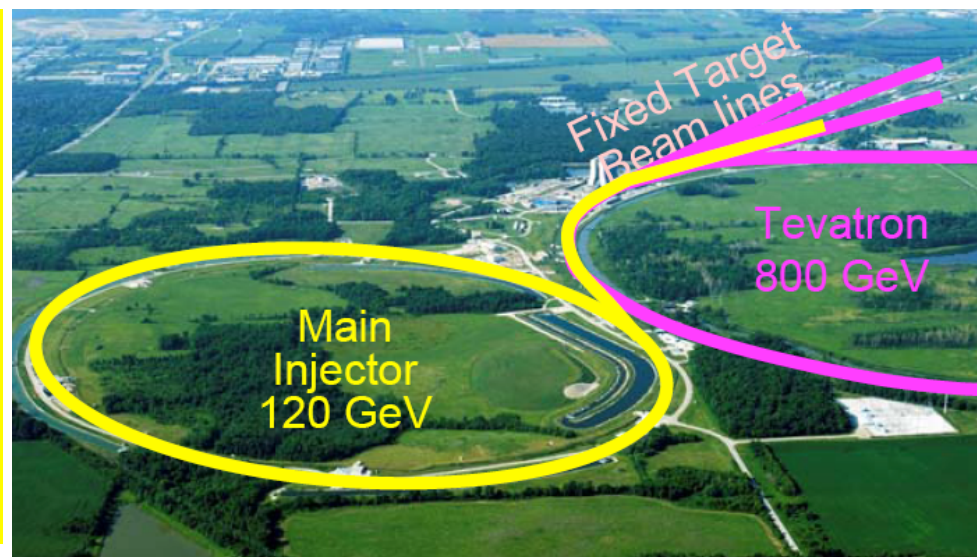
$$\frac{d^2\sigma}{dx_t dx_b} \approx \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [q_b(x_b) \bar{q}_t(x_t)]$$

E906 Drell-Yan:2011-2013



Polarized DY possibility:

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



Experimental Sensitivity to Quark Energy Loss

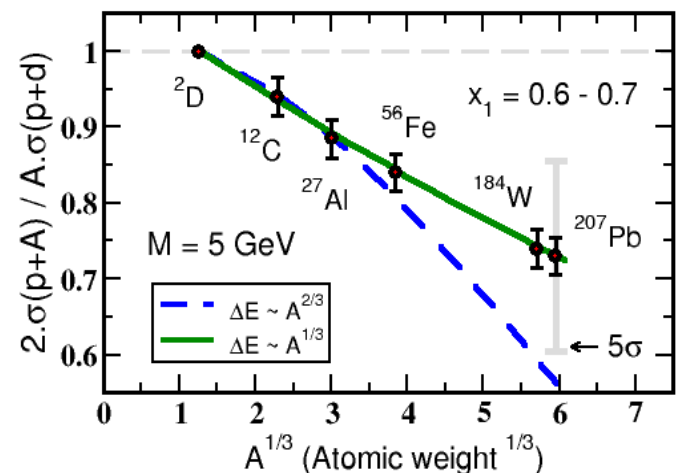
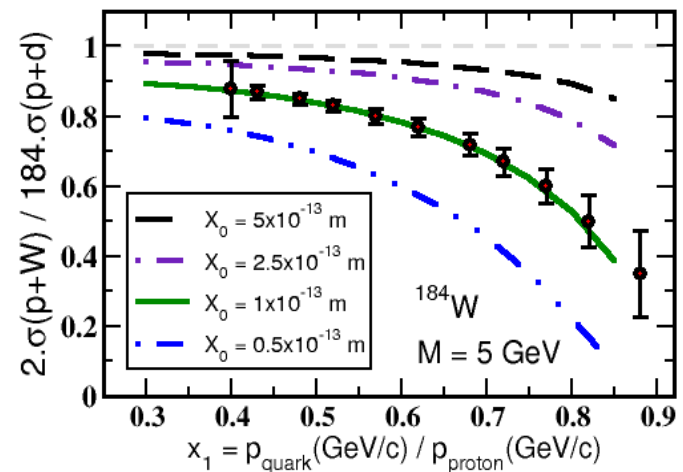
$$-\frac{dE}{dx} = \frac{E}{X_0}$$

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

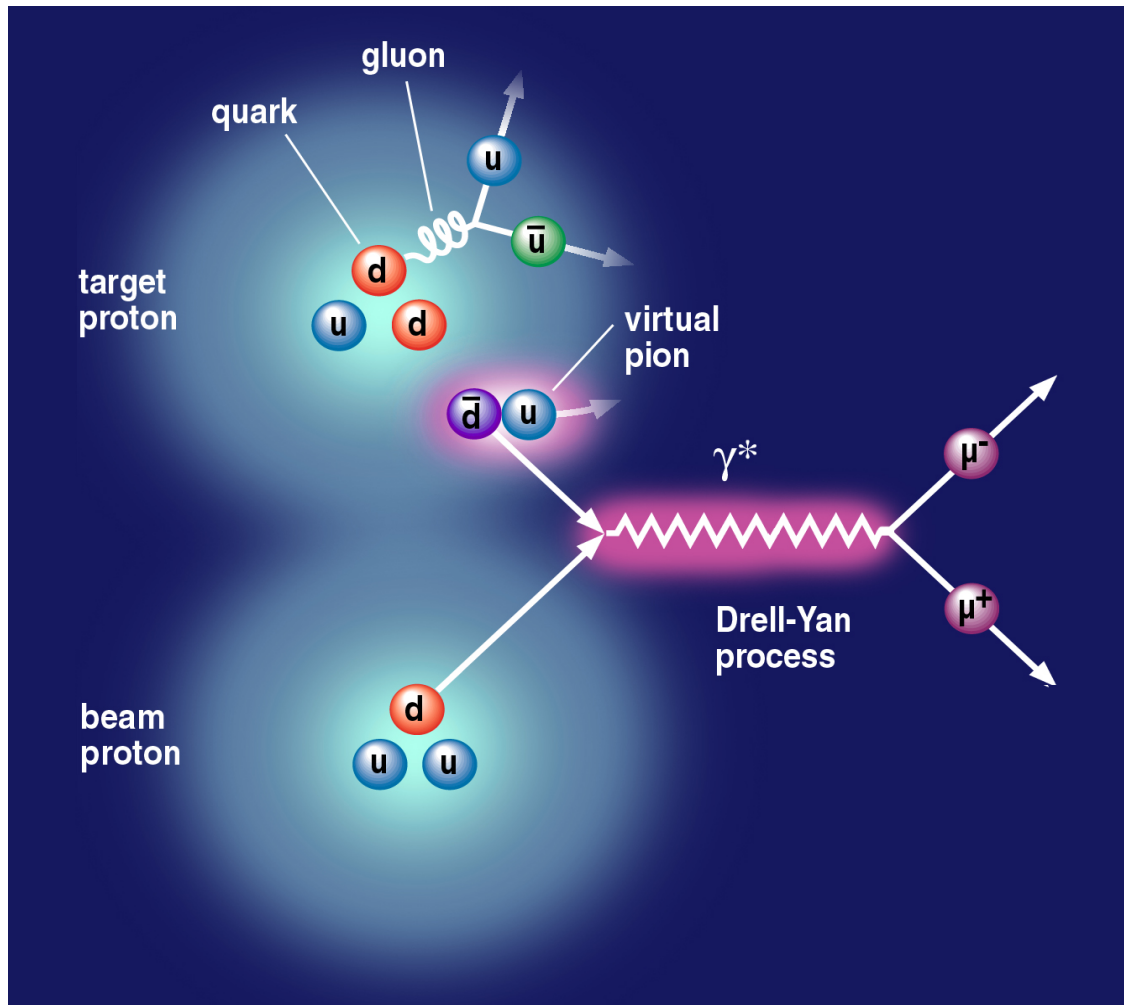
$$\begin{aligned} -\Delta E &\propto A^{1/3} \quad (\text{or } \propto L) \\ -\Delta E &\propto A^{2/3} \quad (\text{or } \propto L^2) \end{aligned}$$

- Benchmark dE/dx models

Quark energy loss **only**



Topic (II): Origin of Sea Quarks



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

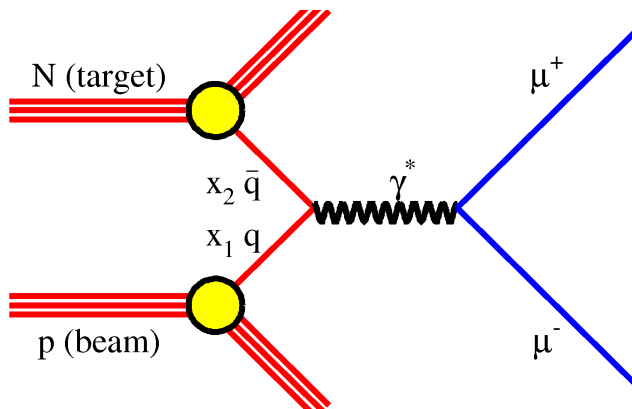
$$\bar{d} \approx \bar{u}$$

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

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

Evidence of Pion Cloud?

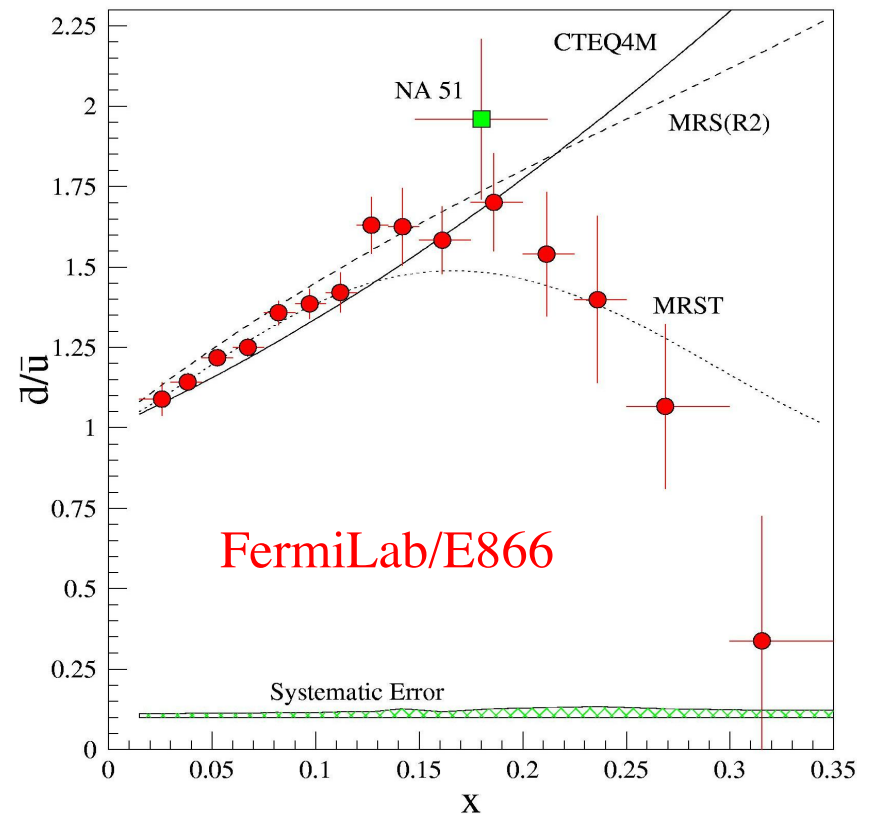
$$pN \rightarrow \mu^+ \mu^- X$$



E866, Phys.Rev. D64 (2001) 052002

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

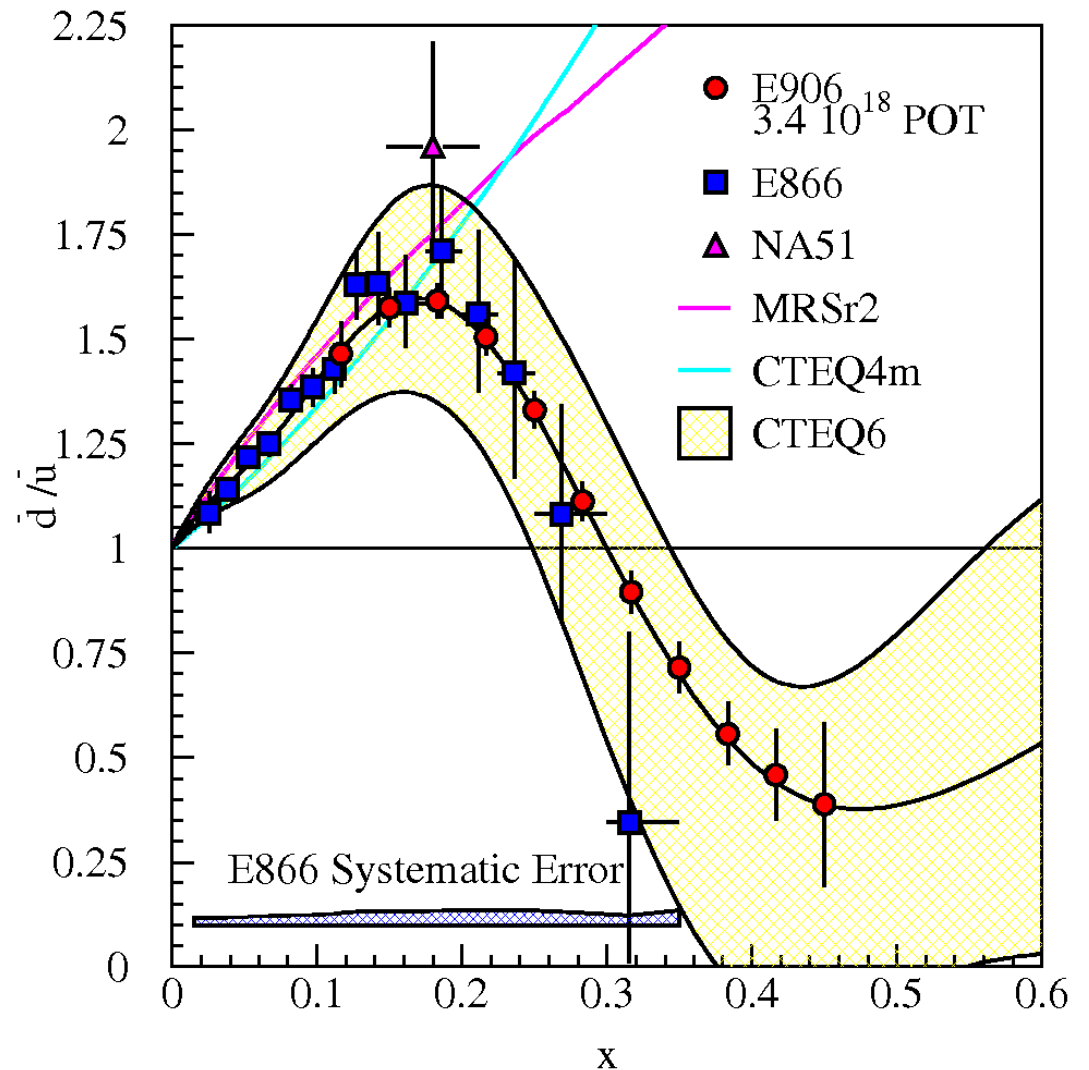
$$\left. \frac{\sigma^{pd}}{2\sigma^{pp}} \right|_{x_b \gg x_t} \approx \frac{1}{2} \left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]$$



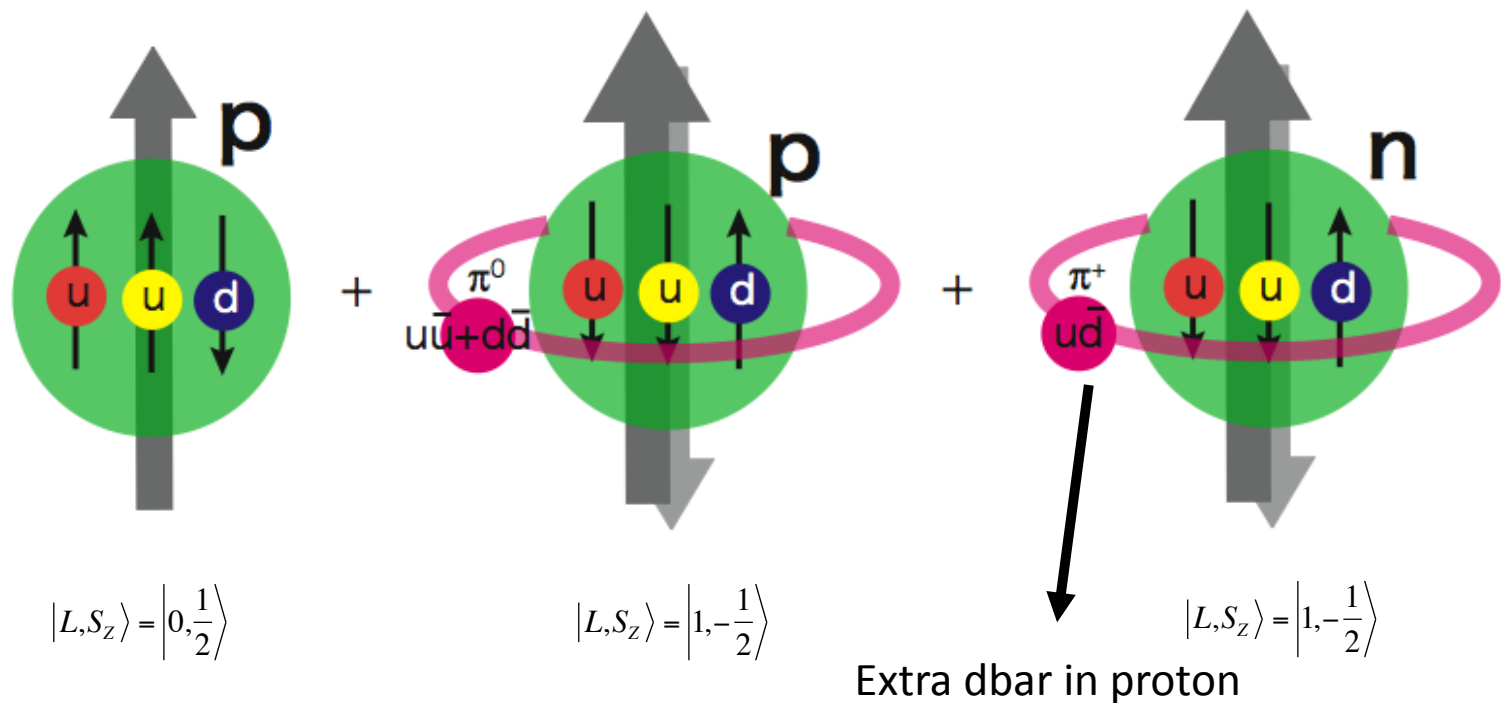
Sea Asymmetry probed by Drell-Yan

E906 Projections for d-bar/u-bar Ratio

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



Pion Cloud Model and the Orbital Angular Momentum?!



Sea Quarks Carry Major Orbital Angular Momentum Component?

Pion Cloud and Orbital Angular Momentum

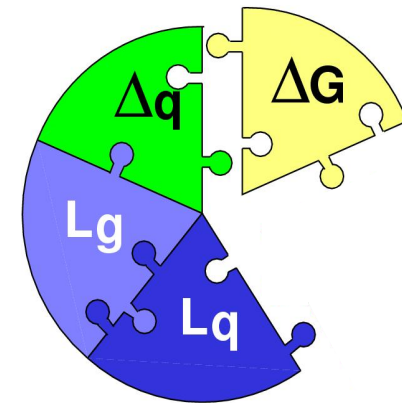
- Spin puzzle, sea quark flavor asymmetry and L_z

G. Garvey, PRC81:055212,2010.

$$|p\rangle = \frac{1}{\sqrt{1+a^2+b^2}} [|p_0\rangle + a(-\sqrt{\frac{1}{3}}|p_0\pi^0\rangle + \sqrt{\frac{2}{3}}|n_0\pi^+\rangle) + b(\sqrt{\frac{1}{2}}|\Lambda_0^{++}\pi^-\rangle - \sqrt{\frac{1}{3}}|\Lambda_0^+\pi^0\rangle + \sqrt{\frac{1}{6}}|\Lambda_0^0\pi^+\rangle)]$$

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

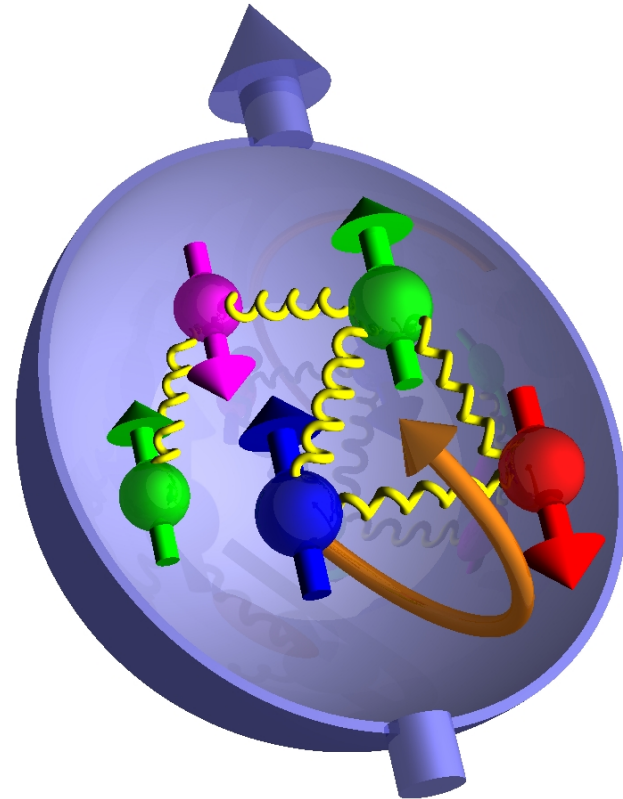
$$\langle p^\uparrow | \hat{L}_z | p^\uparrow \rangle = \frac{2a^2 - b^2}{3(1+a^2+b^2)} = 0.147 \pm 0.027 \sim 30\%[\frac{1}{2}]$$



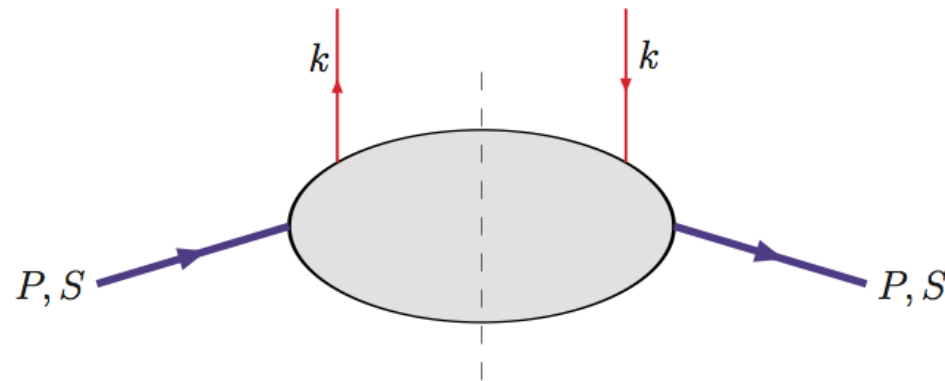
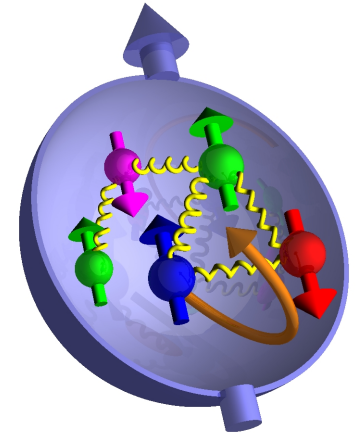
$$\frac{1}{2} = \frac{1}{2} \Delta q + L_q^z + \Delta g + L_g^z$$

Topics (III): Transverse Spin Physics

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



Nucleon Structure @Leading Twist Collinear Approximation (I)



Correlator:

$$\begin{aligned}\Phi_{ij}(k; P, S) &= \sum_X \int \frac{d^3 \mathbf{P}_X}{(2\pi)^3 2E_X} (2\pi)^4 \delta^4(P - k - P_X) \langle PS | \bar{\Psi}_j(0) | X \rangle \langle X | \Psi_i(0) | PS \rangle \\ &= \int d^4 \xi e^{ik \cdot \xi} \langle PS | \bar{\Psi}_j(0) \Psi_i(\xi) | PS \rangle\end{aligned}$$

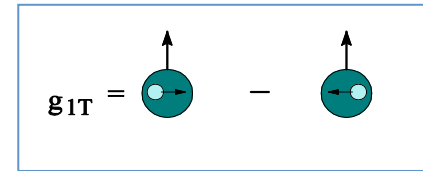
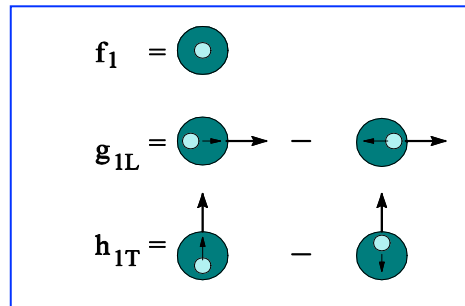
$$\Phi(x, S) = \frac{1}{2} \left[\underbrace{f_1(x)}_{\mathbf{q}} \not{n}_+ + S_L \underbrace{g_{1L}(x)}_{\Delta \mathbf{q}} \gamma^5 \not{n}_+ + \underbrace{h_{1T}}_{\Delta_{\perp} \mathbf{q}} i \sigma_{\mu\nu} \gamma^5 n_+^\mu S_T^\nu \right]$$

Partonic interpretation of hard scatterings
Universal functions

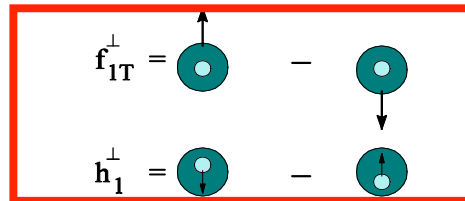
Including k_T ... 5 more (II)

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

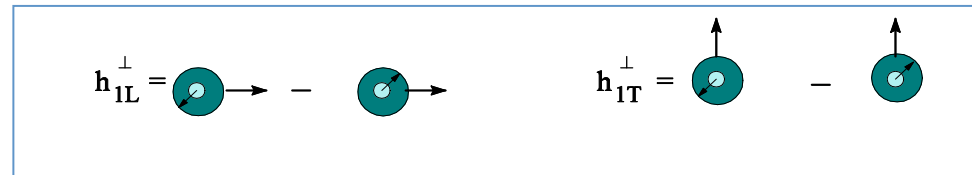
No $K_\perp$
dependence



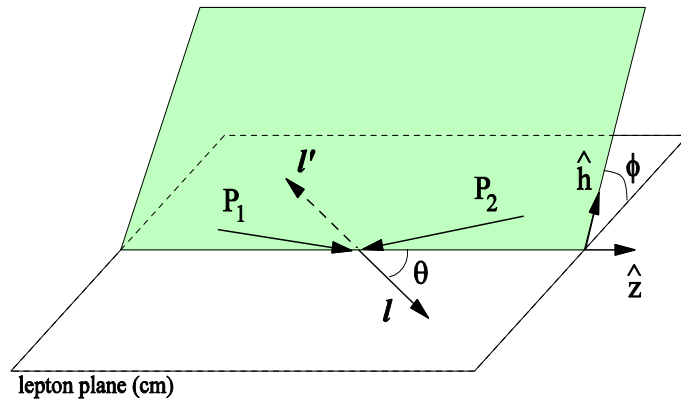
$K_\perp$ - dependent
T-odd



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

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:

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

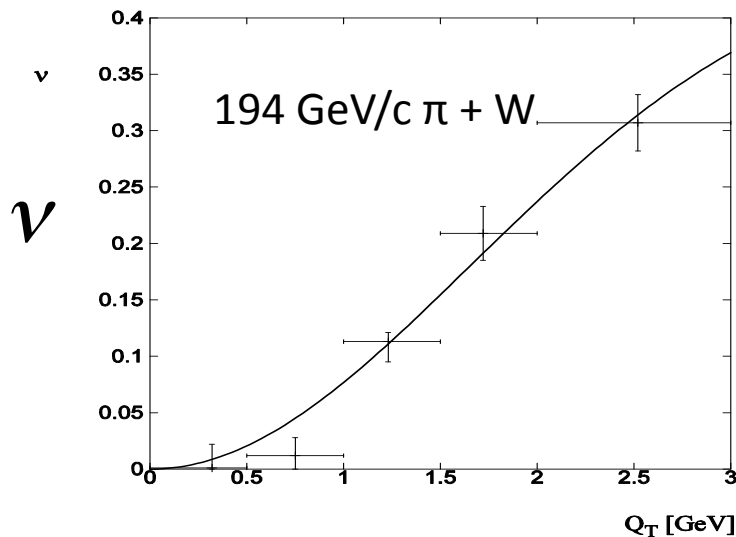
- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY
(Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

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

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



- Observation of large $\cos(2\phi)$ dependence in Drell-Yan with pion beam

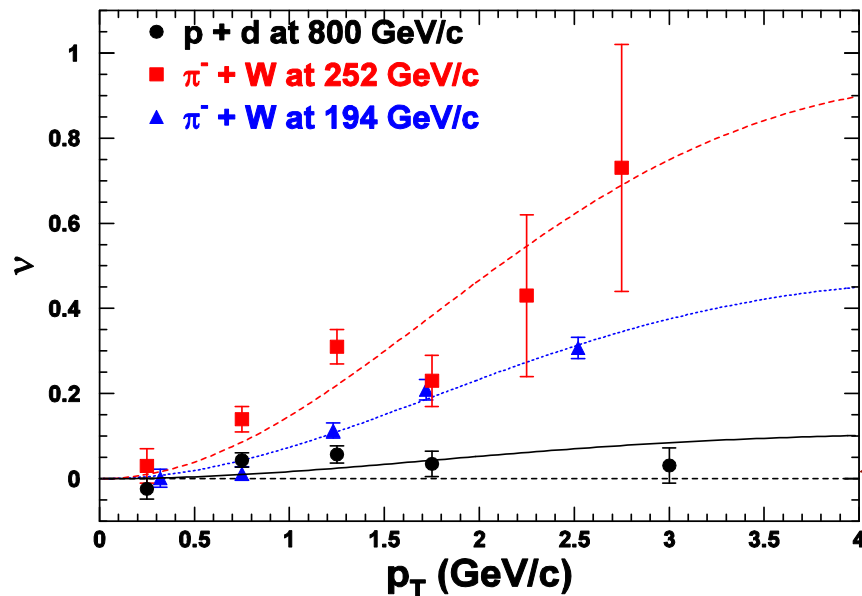
● $\nu \propto h_1^\perp(x_q)h_1^\perp(x_{\bar{q}})$

- How about Drell-Yan with proton beam?

Boer, PRD 60 (1999) 014012

Azimuthal $\cos 2\Phi$ 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 $h_1^\perp$:

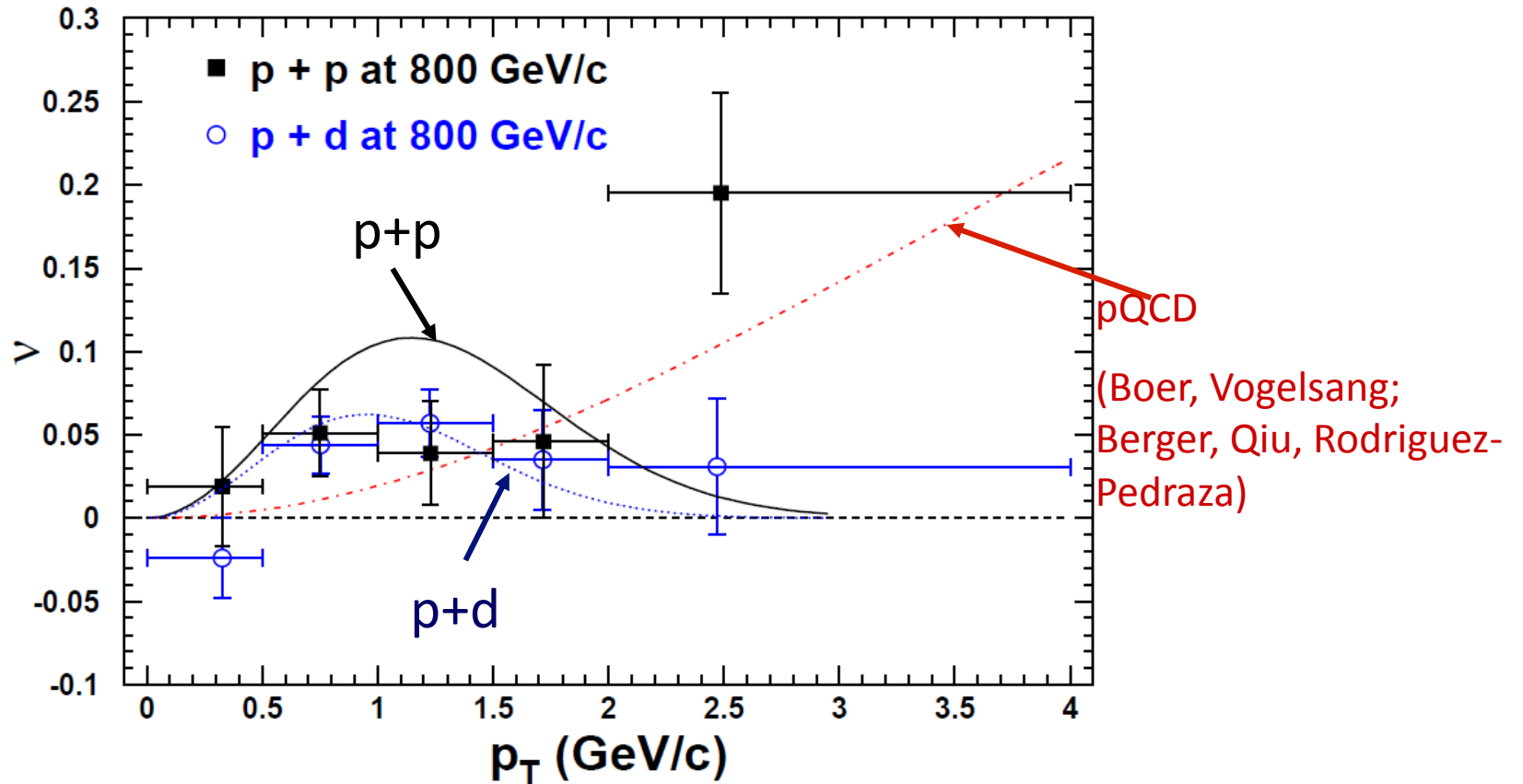
$$\nu(\pi^- W \rightarrow \mu^+ \mu^- X) \sim [\text{valence } h_1^\perp(\pi)] * [\text{valence } h_1^\perp(p)]$$

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

Sea-quark BM functions are much smaller than valence quarks

Results on $\cos 2\Phi$ 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



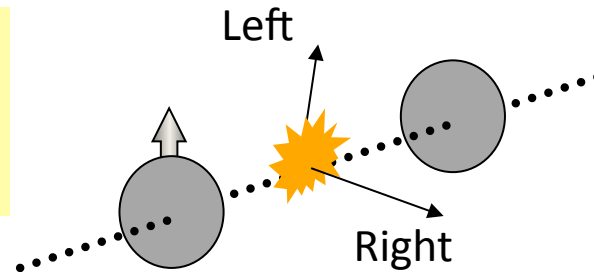
Drawing from D. Sivers @Santa Fe Polarized Drell-Yan Workshop Dinner 10/31-11/1, 2010

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))

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

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

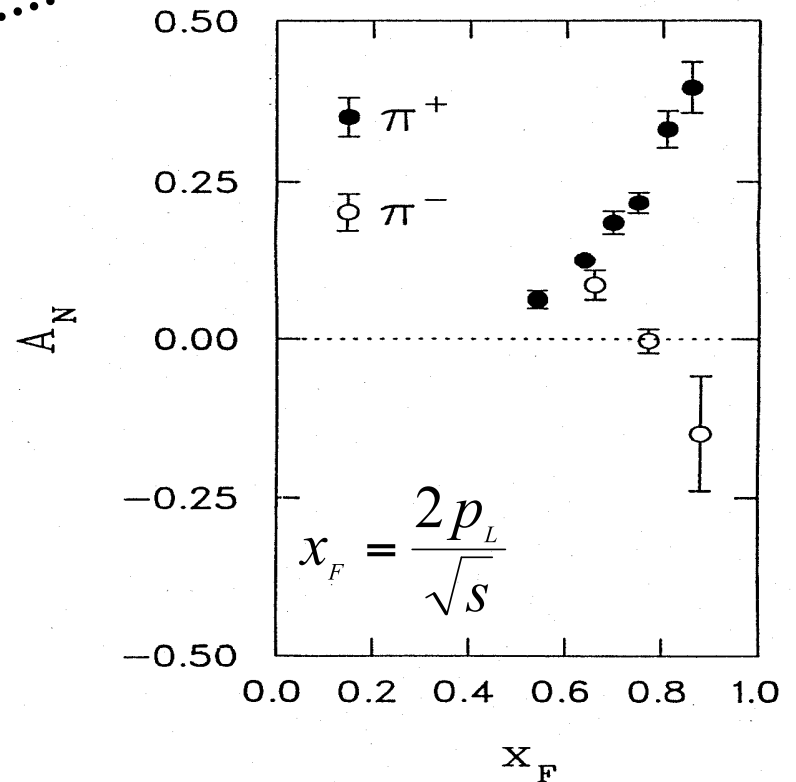
Experiments:

ZGS, AGS, FERMILAB to RHIC

$pp^\uparrow \rightarrow \pi + X$ $A_N \sim O(10^{-1})$ observed

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

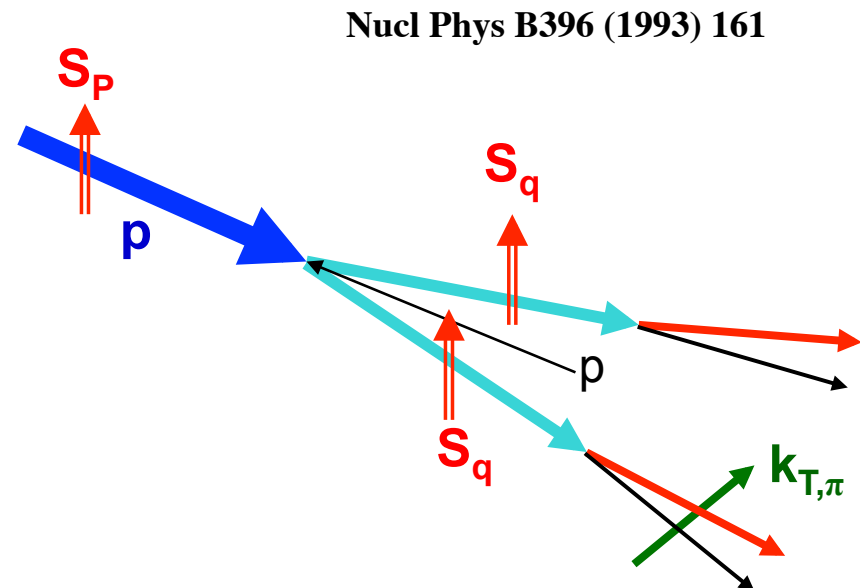
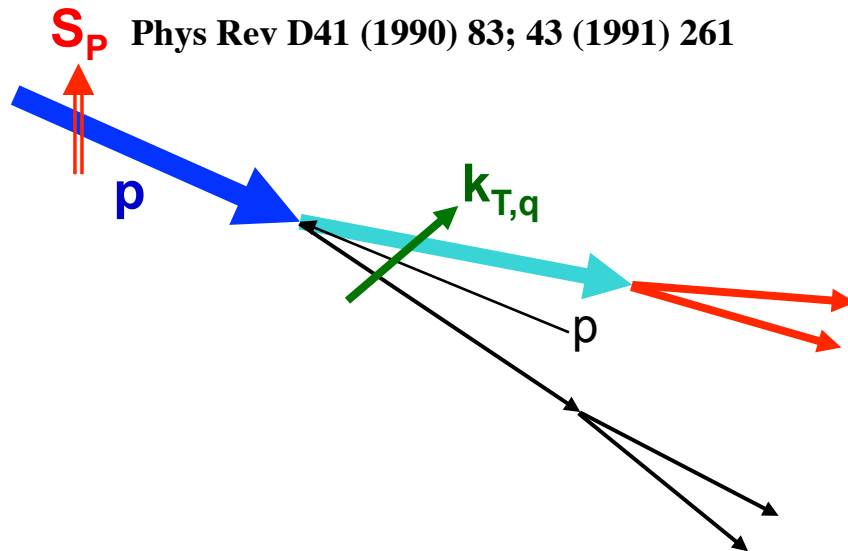
Argonne ZGS, $p_{\text{beam}} = 12 \text{ GeV}/c$



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

Current Understanding of TSSAs (I)

- TMD approach: Transverse Momentum Dependent Distribution Functions
 - **Sivers function**: nucleon spin and parton k_T correlation
 - **Collins function**: spin dependent fragmentation function
 - and lots of others ...

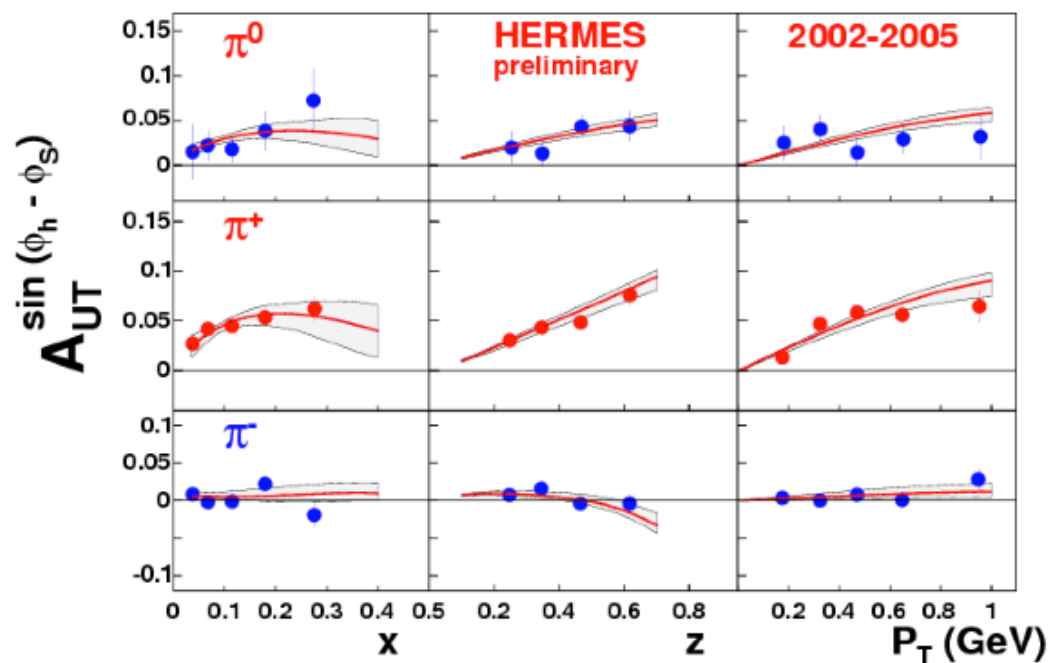




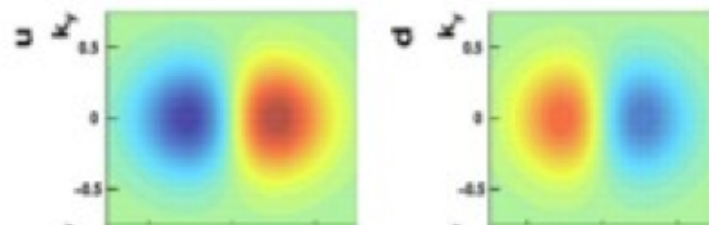
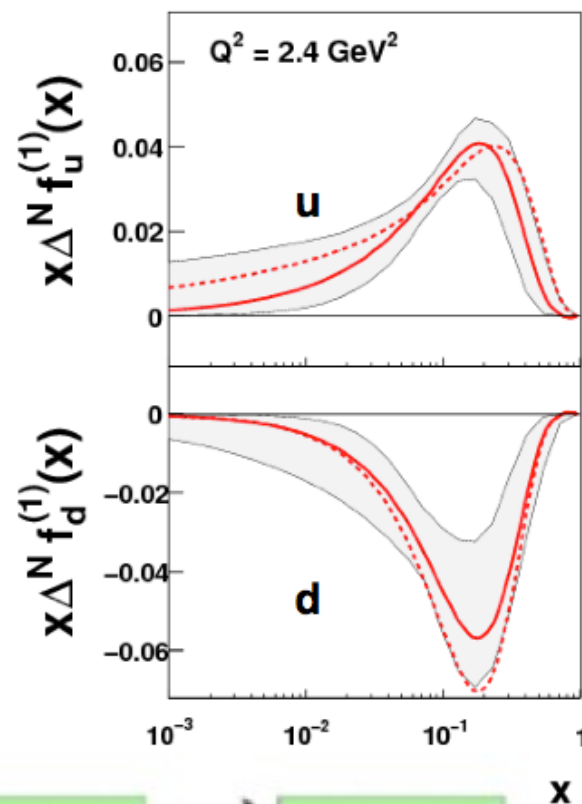
Sivers function from SIDIS

- Extract Sivers function from SIDIS

Anselmino, et.al., 2009

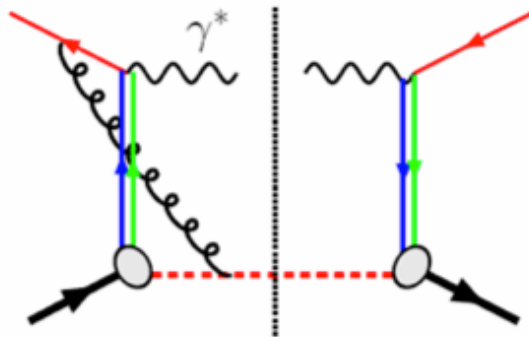


- u and d almost equal size, different sign



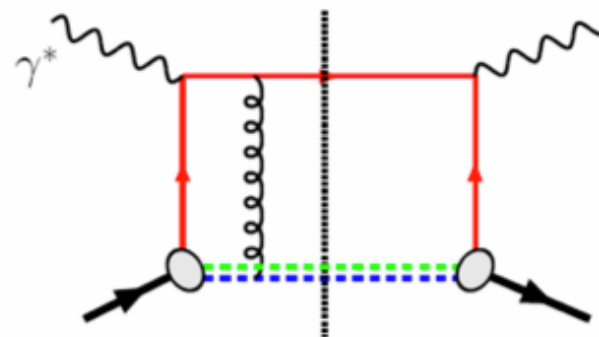
Color Flow in DY and DIS

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



$$p^\uparrow + p \rightarrow [\gamma^* \rightarrow \ell^+ \ell^-] + X$$

DY: repulsive



$$\ell + p^\uparrow \rightarrow \ell + \pi + X$$

SIDIS: attractive

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

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

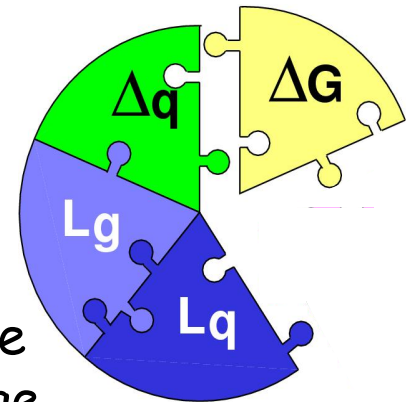
- Test the fundamental prediction of sign change in DY TSSA compared to DIS based on our understanding of the origin of TSSA
 - Test of gauge formulism
 - Test of QCD factorization
- Help to resolve the proton spin puzzle?
 - One expect the observation of Sivers Asymmetry signals the existence of partonic 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

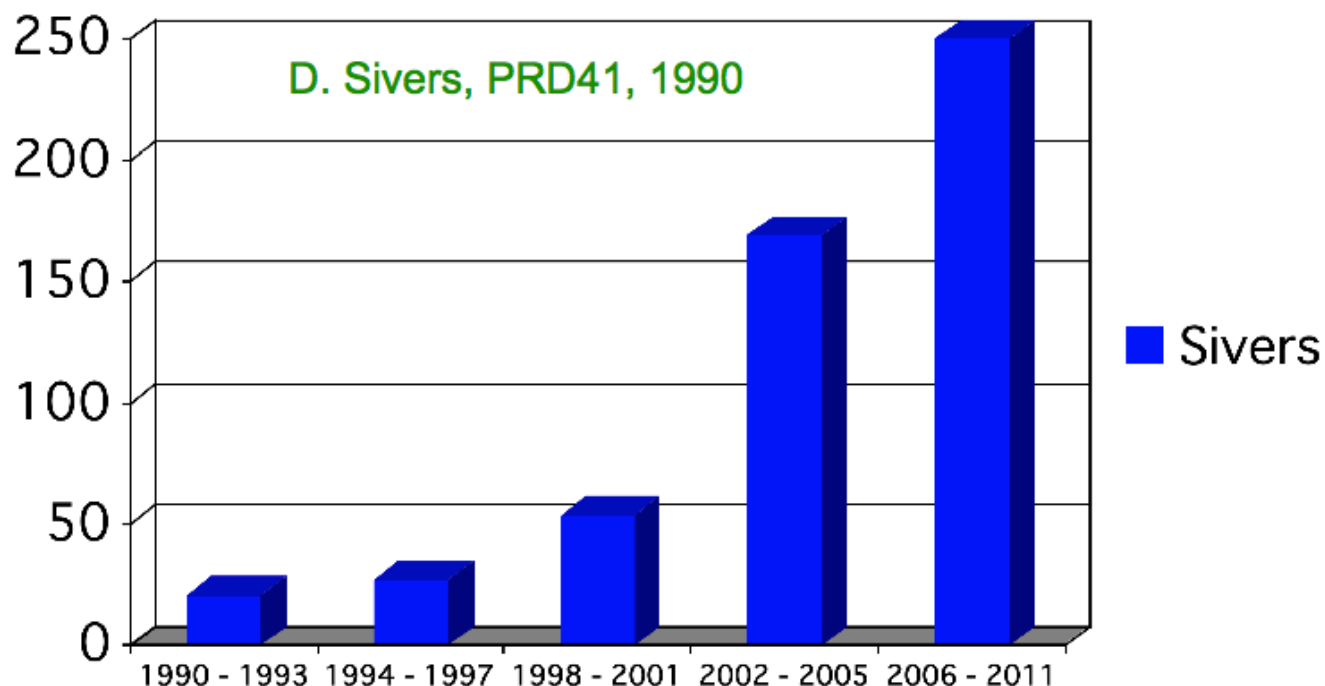
A future challenge





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

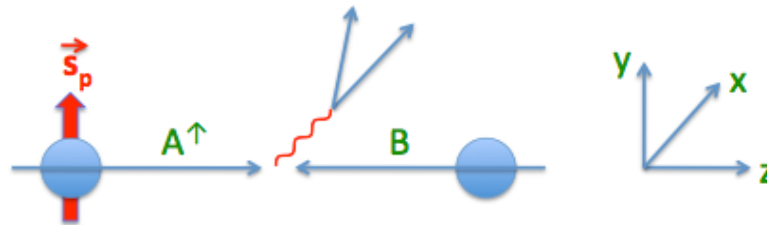
**October 31- November 1, 2010
Hilton of Santa Fe (Fall APS/DNP hotel)
Santa Fe, NM 87501**



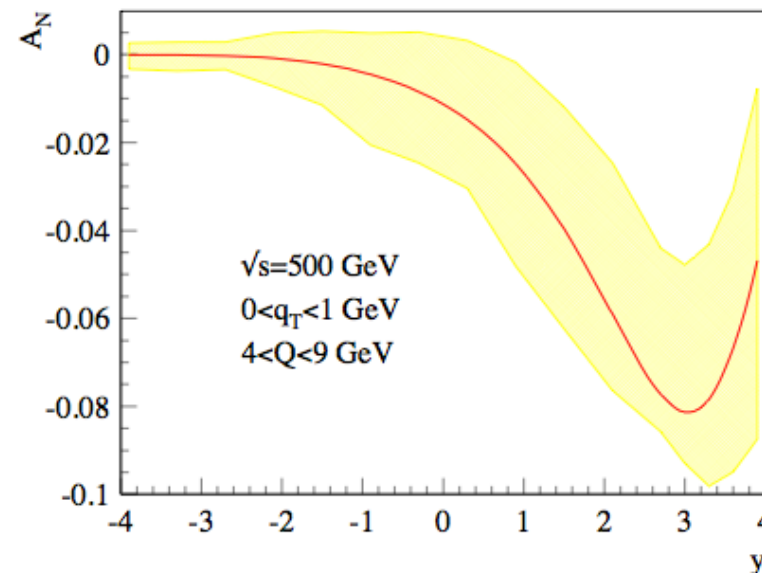
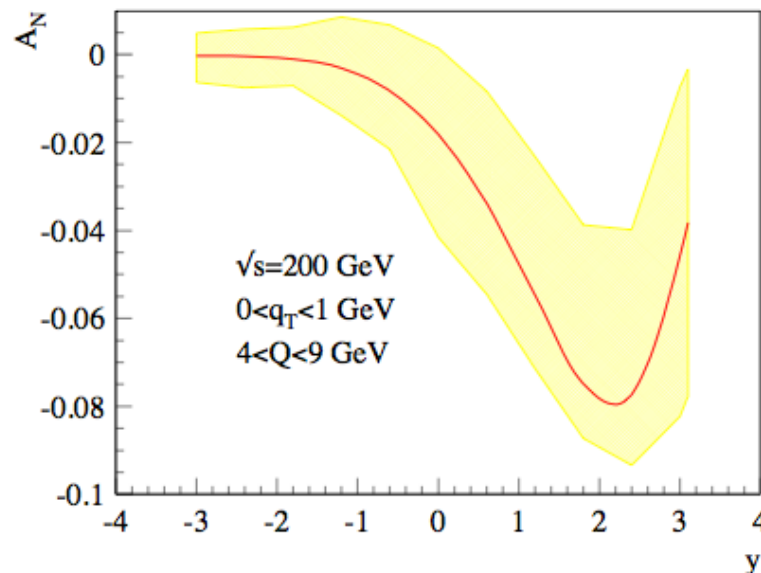
Predictions for Drell-Yan process at RHIC

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

Kang-Qiu, PRD81, 2010



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



Test the Sign Change

Drell-Yan Production @RHIC

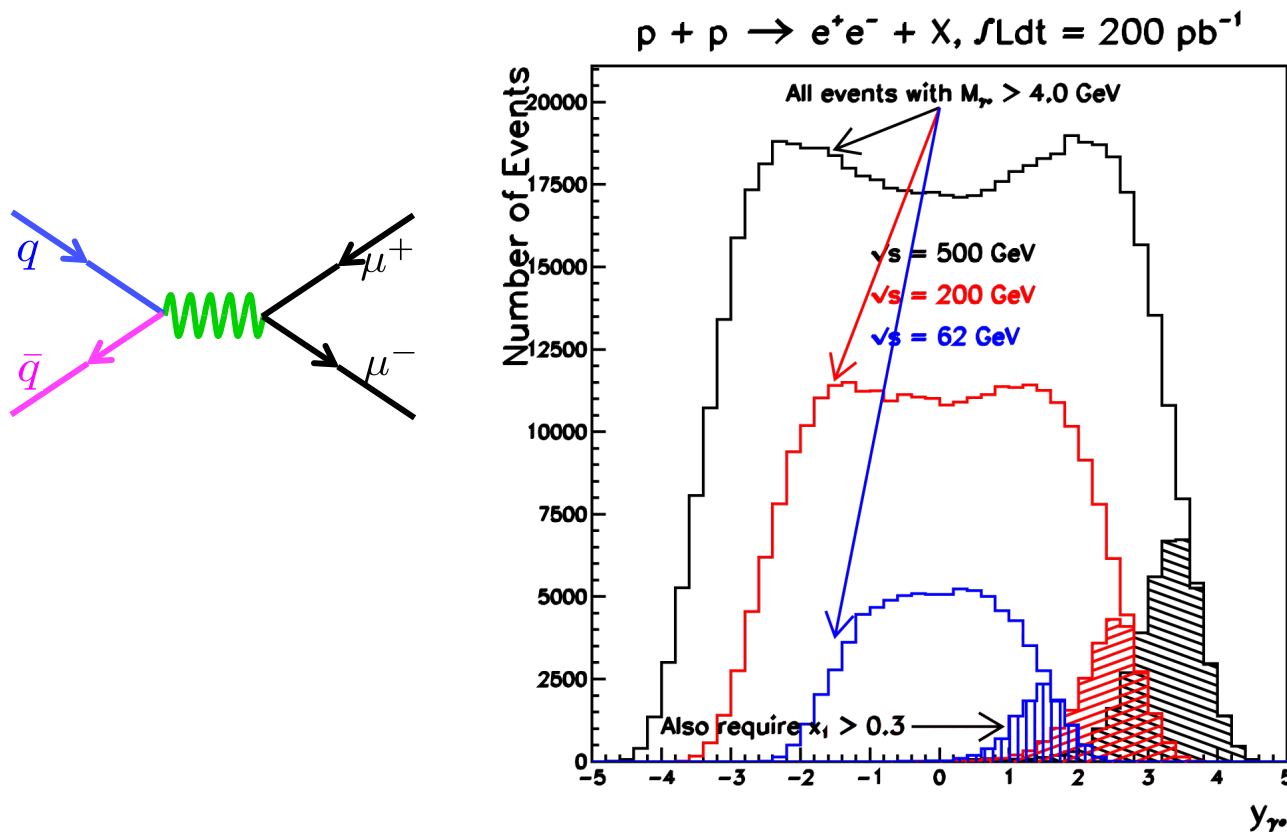


Figure 5: *PYTHIA* simulation of the rapidity distribution of e^+e^- dileptons produced through the Drell-Yan process. The importance of large rapidity to probe the valence region is illustrated by selecting events with $x_1 > 0.3$.

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!)

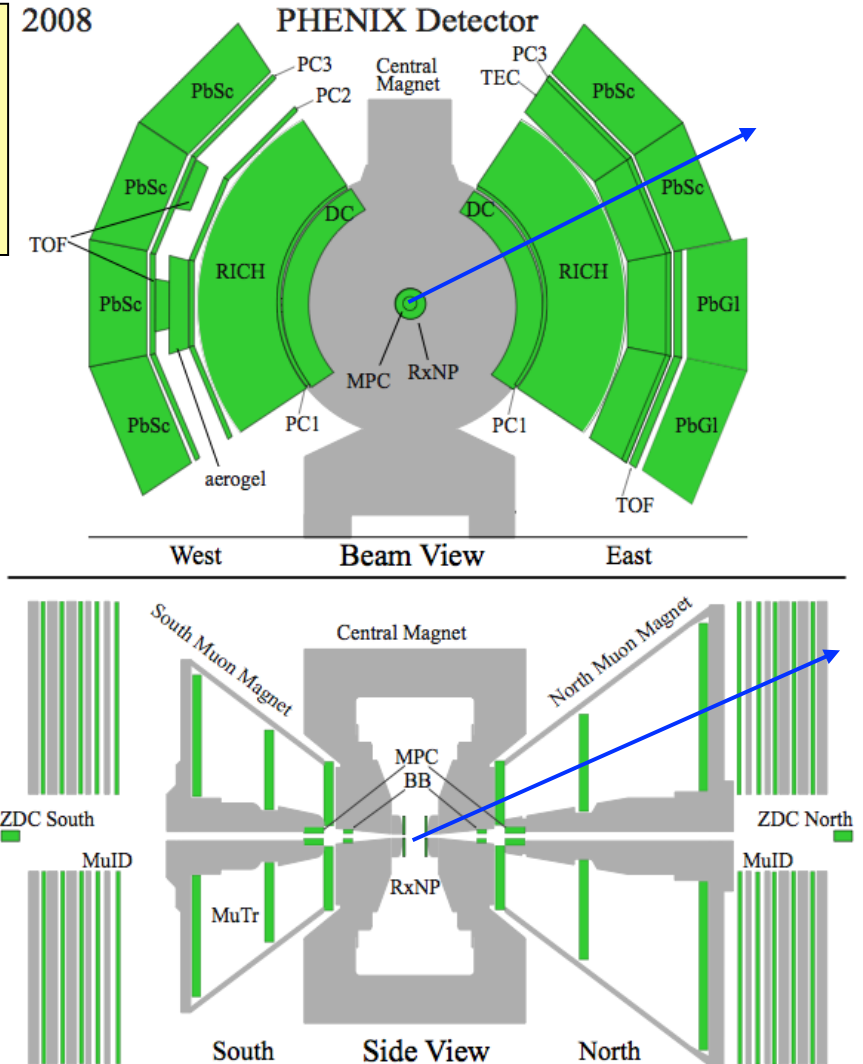
- Measure forward pions

$$3.1 < |\eta| < 3.7$$

2π azimuth

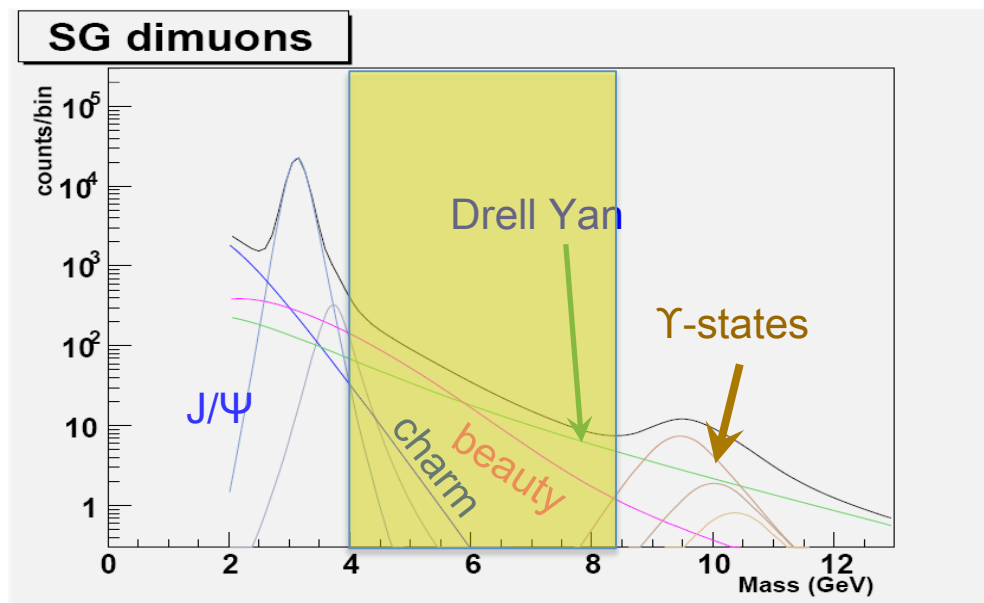
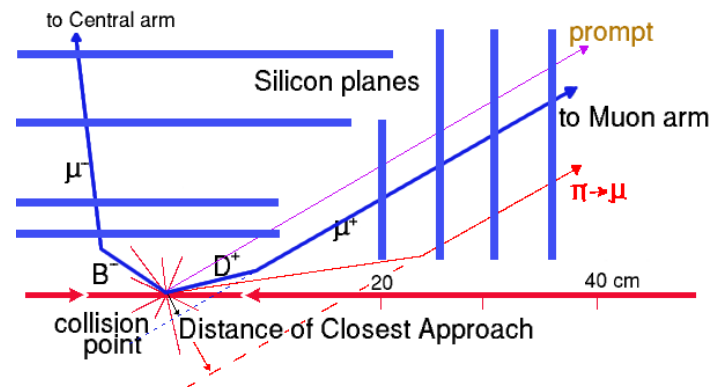
- Relative Luminosity

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

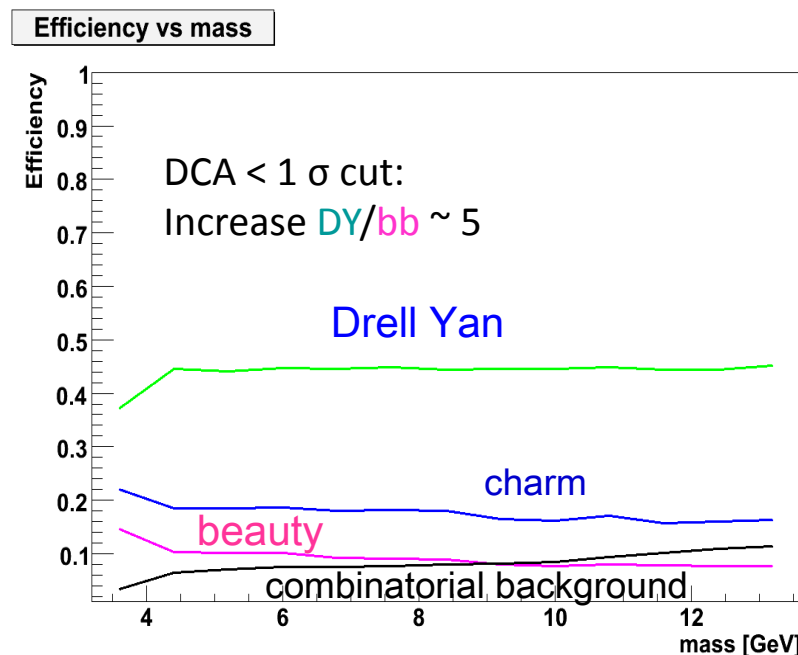


Silicon VTX, Heavy Quark and Drell-Yan

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



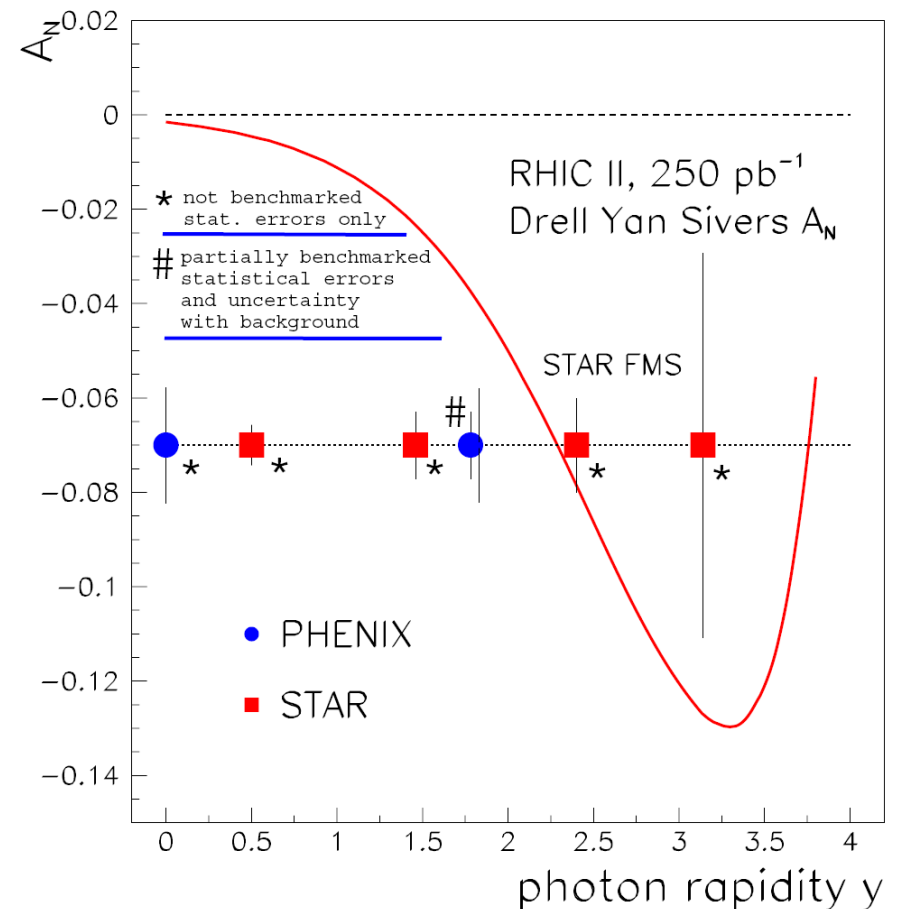
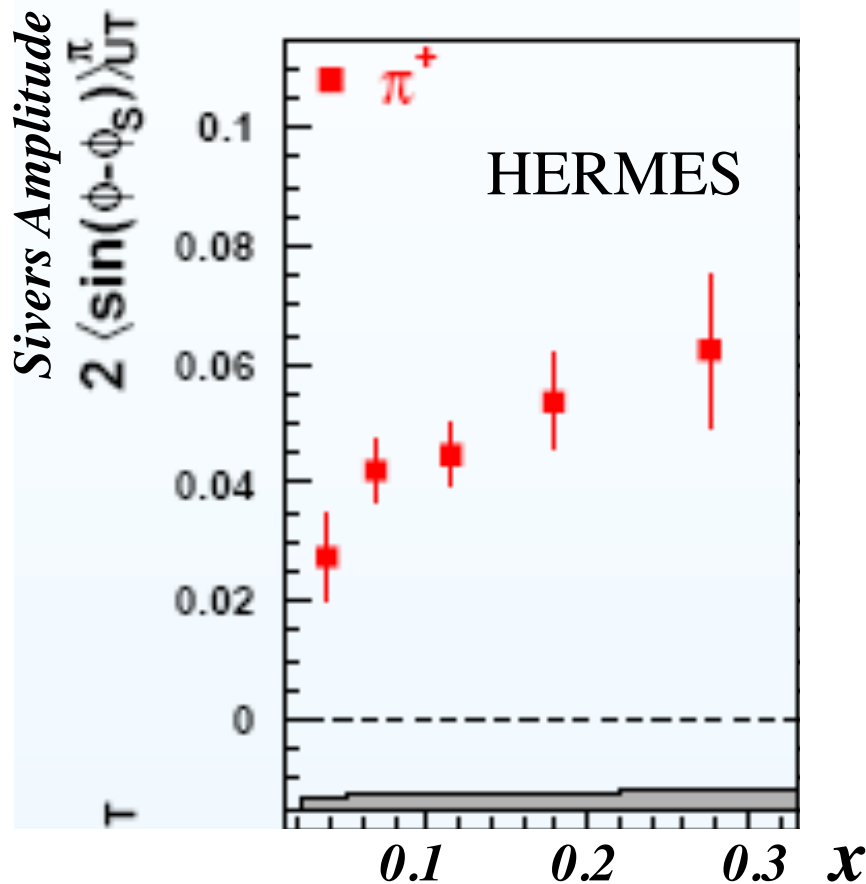
→DY: $4 \text{ GeV} < M < 8 \text{ GeV}$; B-background: use FVTX

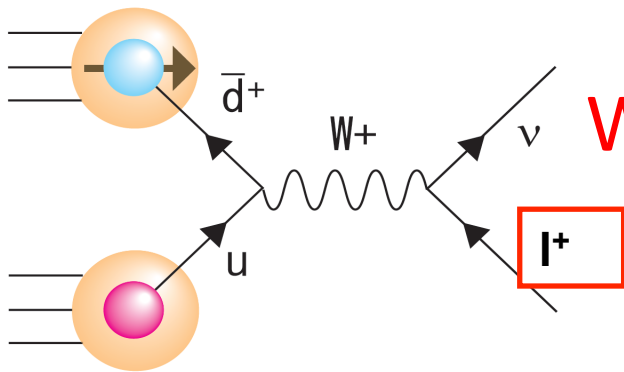


Sivers Asymmetries in SIDIS and DY

“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[±] & Z⁰ 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 Q²
- Expected Statistics @1fb⁻¹ 500GeV

- W[±] → μ[±] ~20K
- Z⁰ → μ⁺μ⁻ ~ 1K

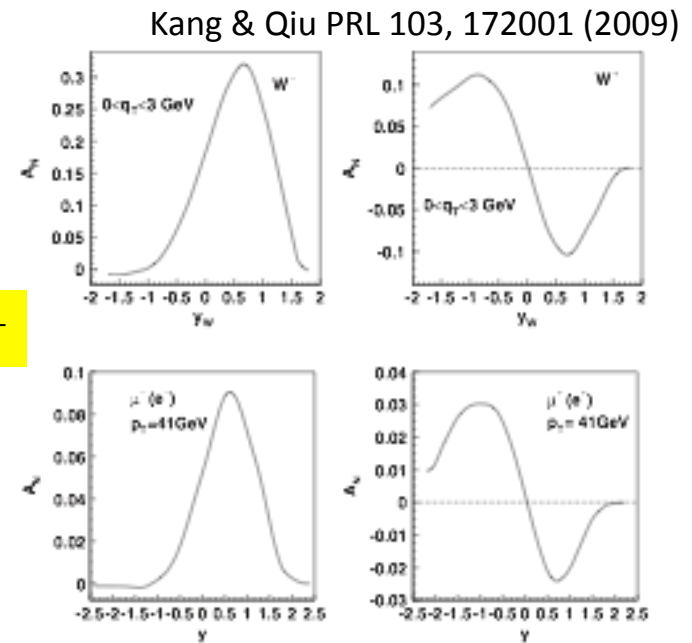
$$W^{\pm}: \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 6300(6900)$$

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

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

$$\approx 6.0\%$$

W[±]



Z⁰

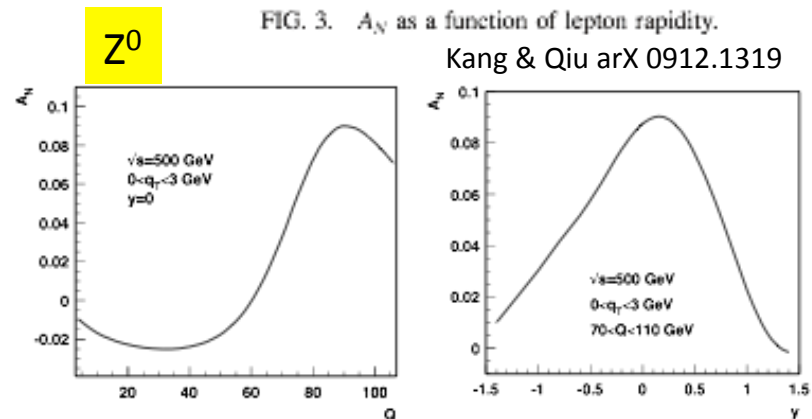
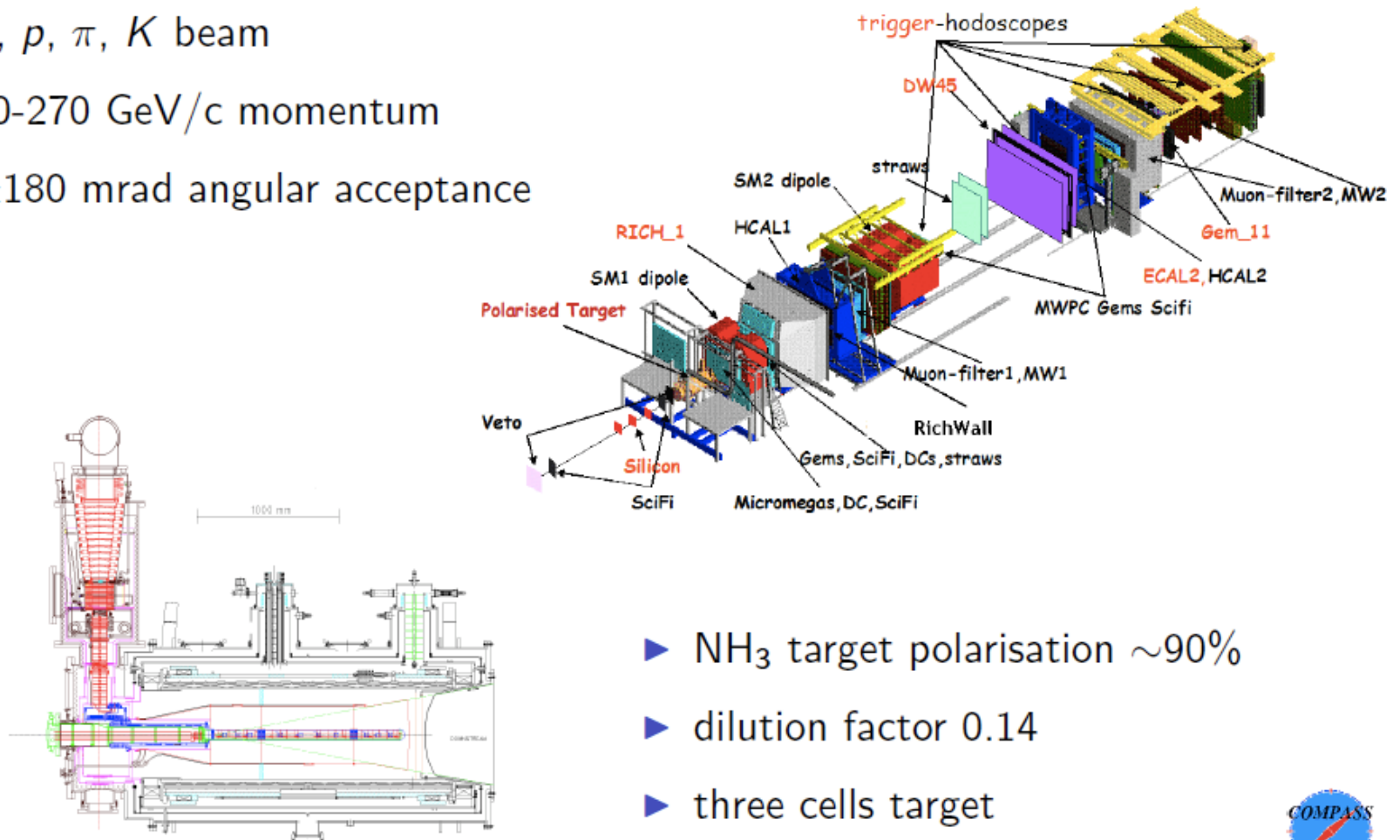


FIG. 3: Left: SSA of lepton pair production as a function of the pair's invariant mass Q . Right: SSA of lepton pair accumulated around Z^0 pole as a function of rapidity y .

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

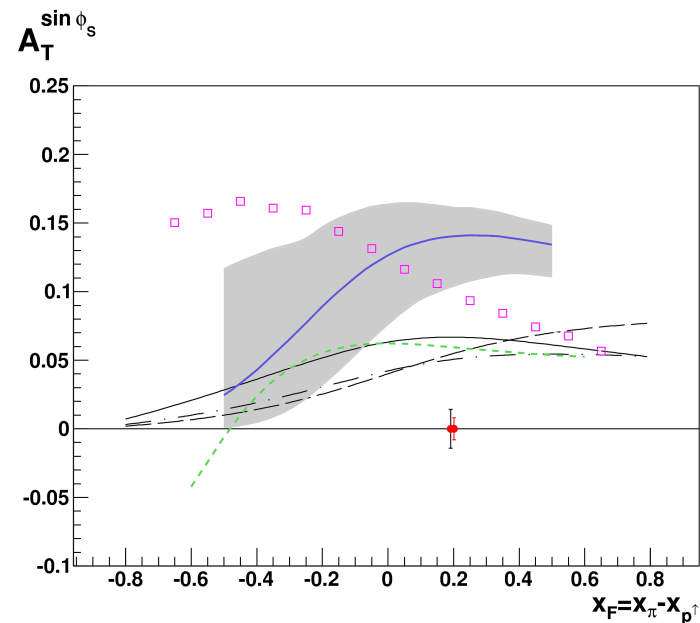
DY@COMPASS projections I

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

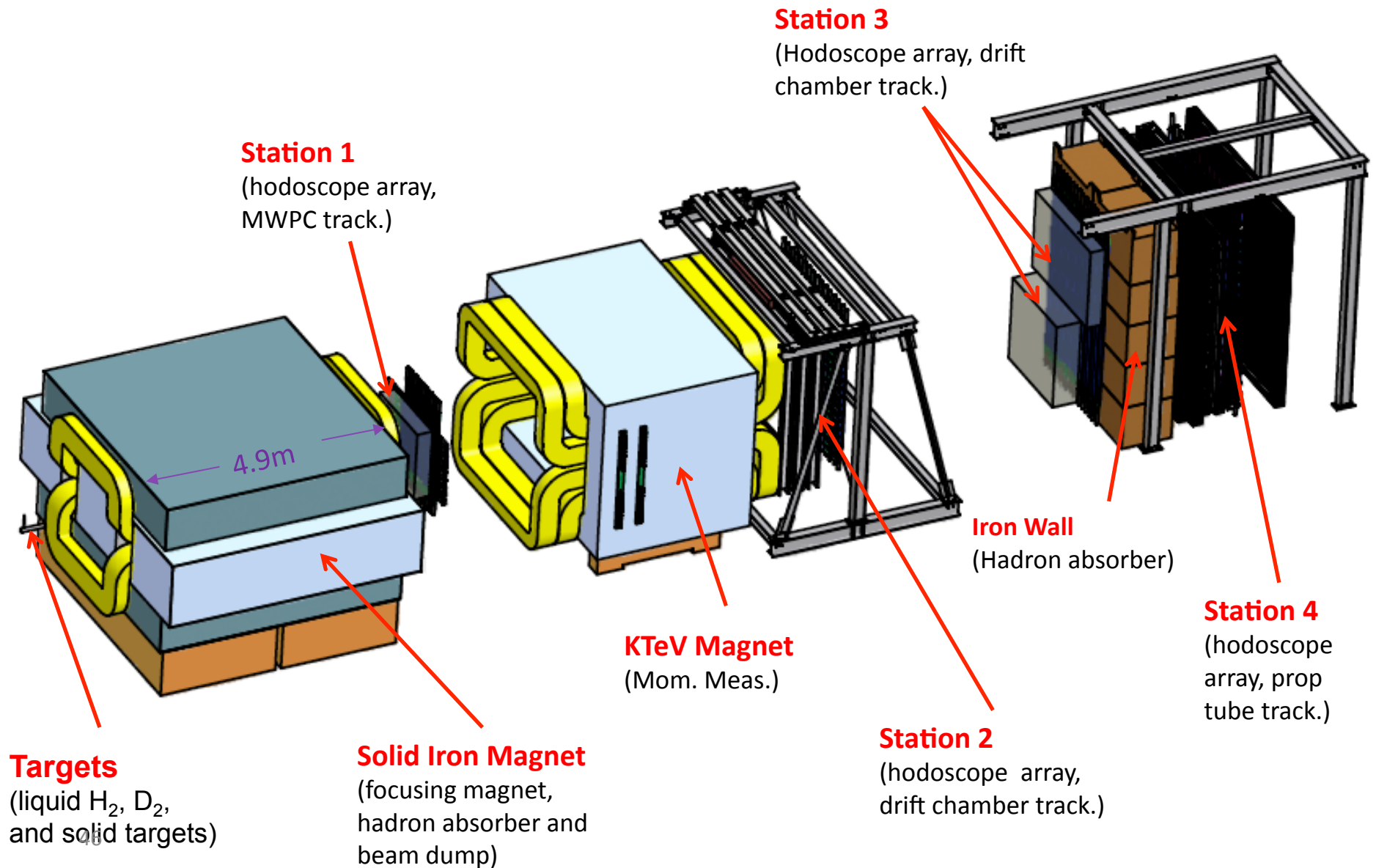
↪ Assuming 2 years of data-taking, one can collect > 200000 DY events in the region $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$.

Predictions for the Siverts asymmetry in the COMPASS phase-space, for the mass region $4. < M < 9 \text{ GeV}/c^2$, 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.

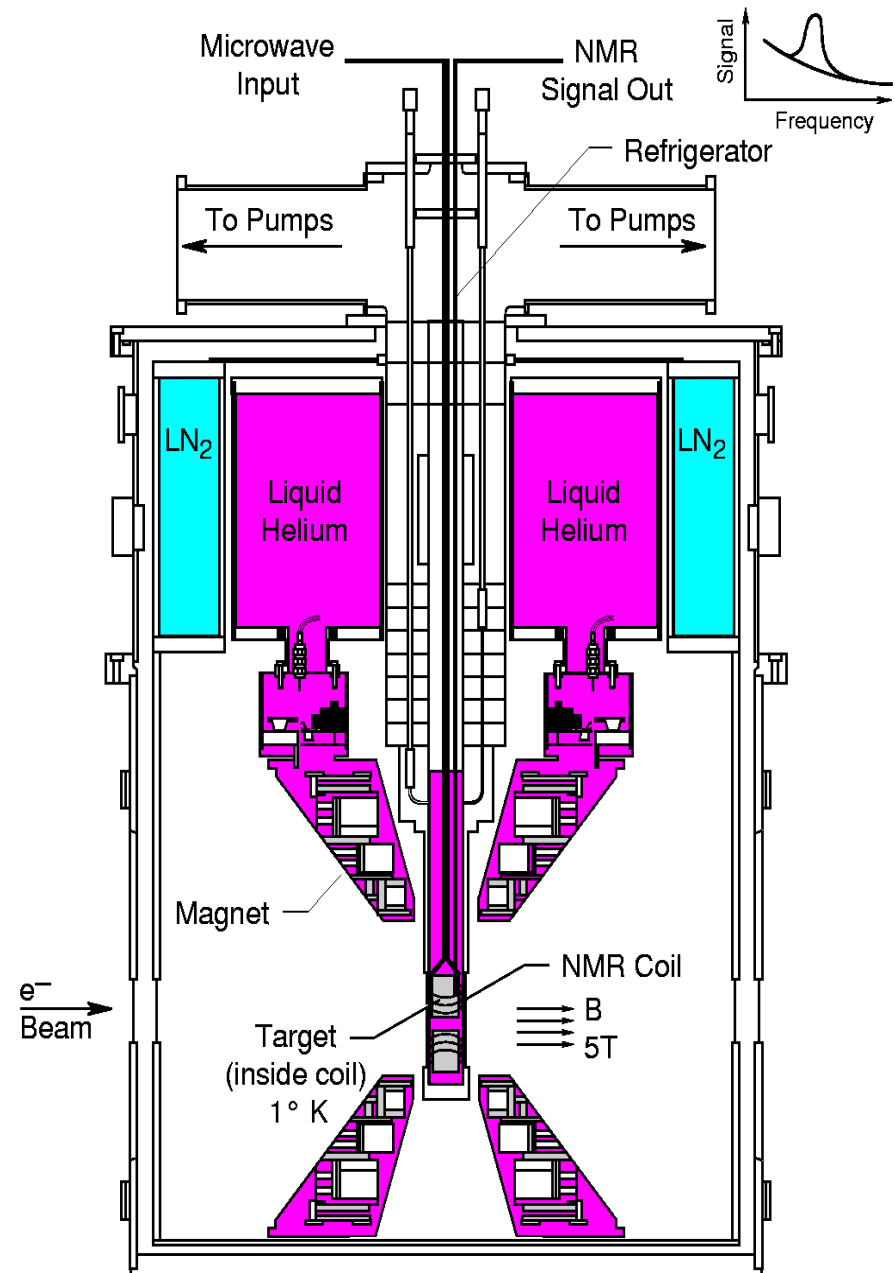


Drell-Yan Spectrometer for E906



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 $\sim B/T$
- Used with high beam intensities – up to ~ 100 nA
- Large capacity pumps
- Polarizations:
 - $p > 90\%$,
 - $d \sim 50\%$
- Able to handle high luminosity
 - up to $\sim 10^{35}$ (Hall C)
 - $\sim 10^{34}$ (Hall B)

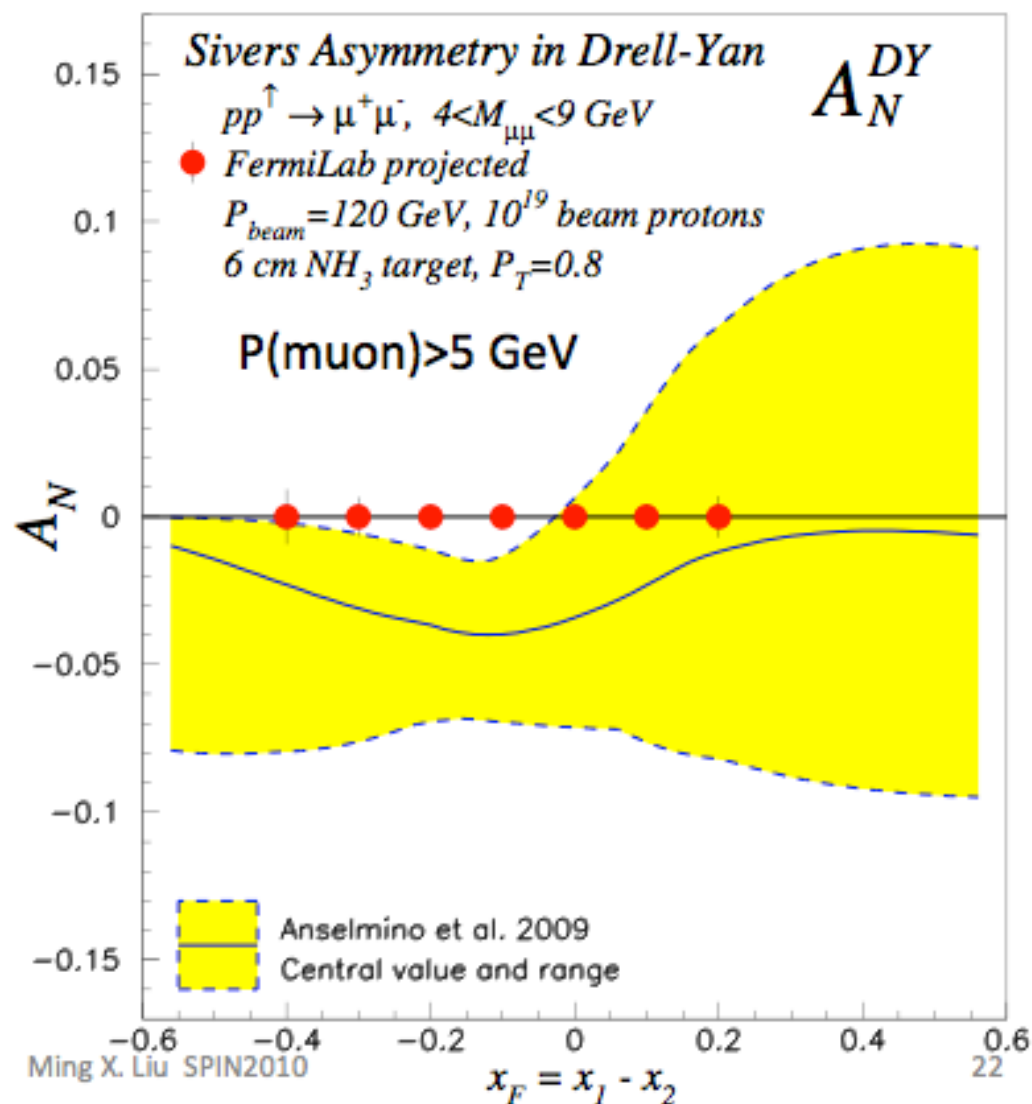
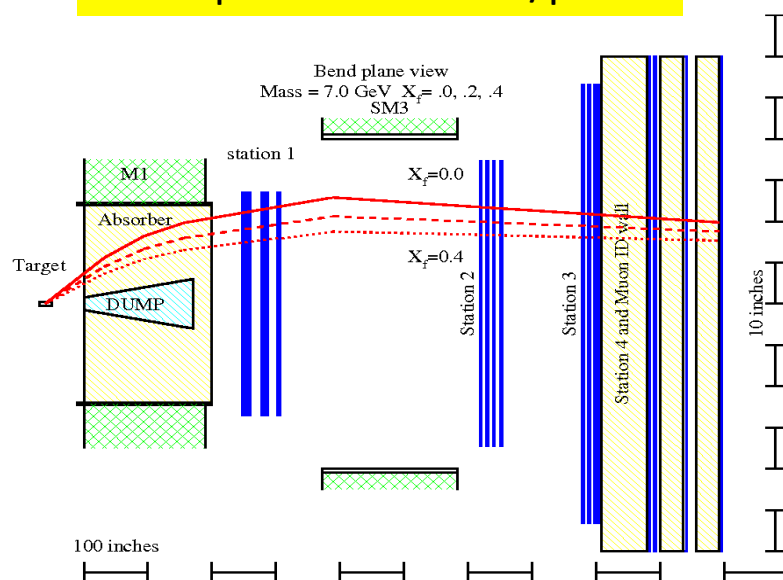


Expected DY A_N Sensitivity @120 GeV.

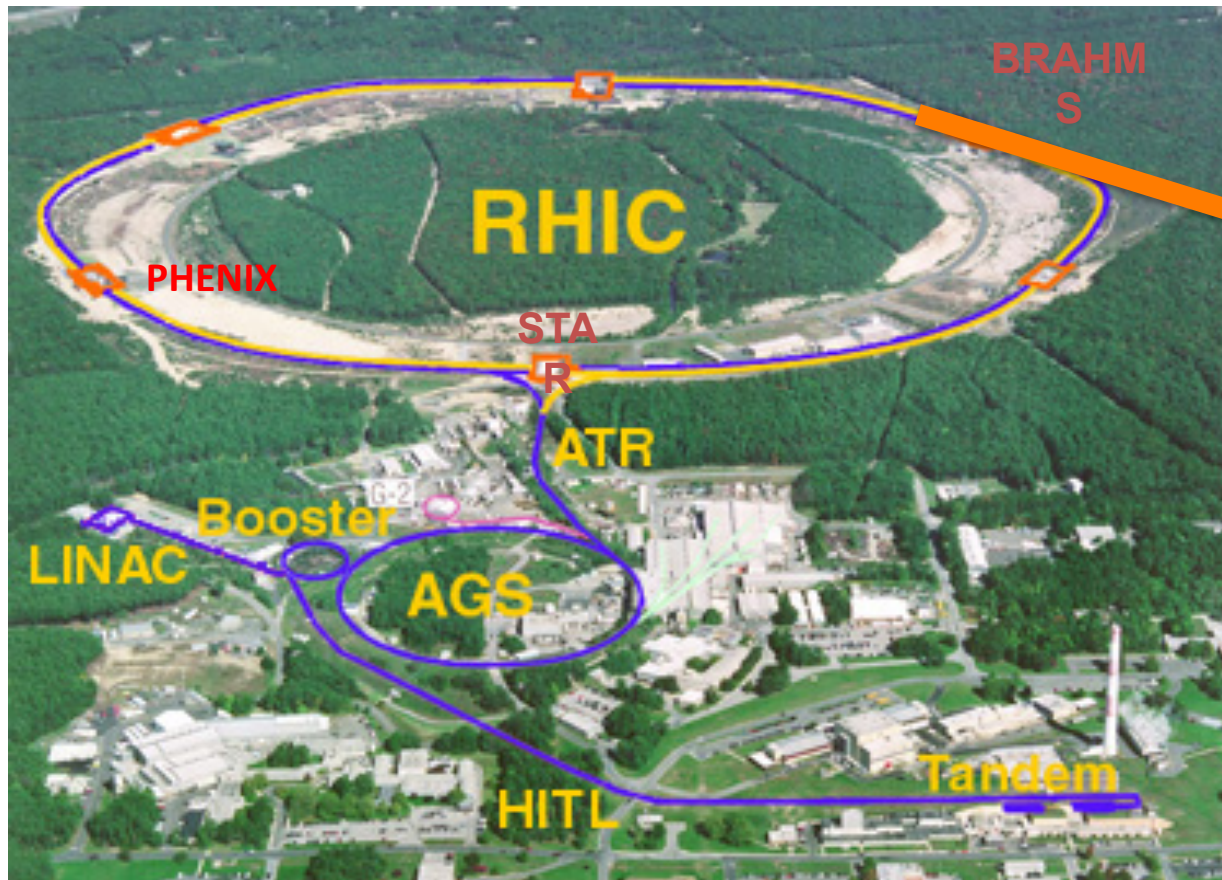
Target

- 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

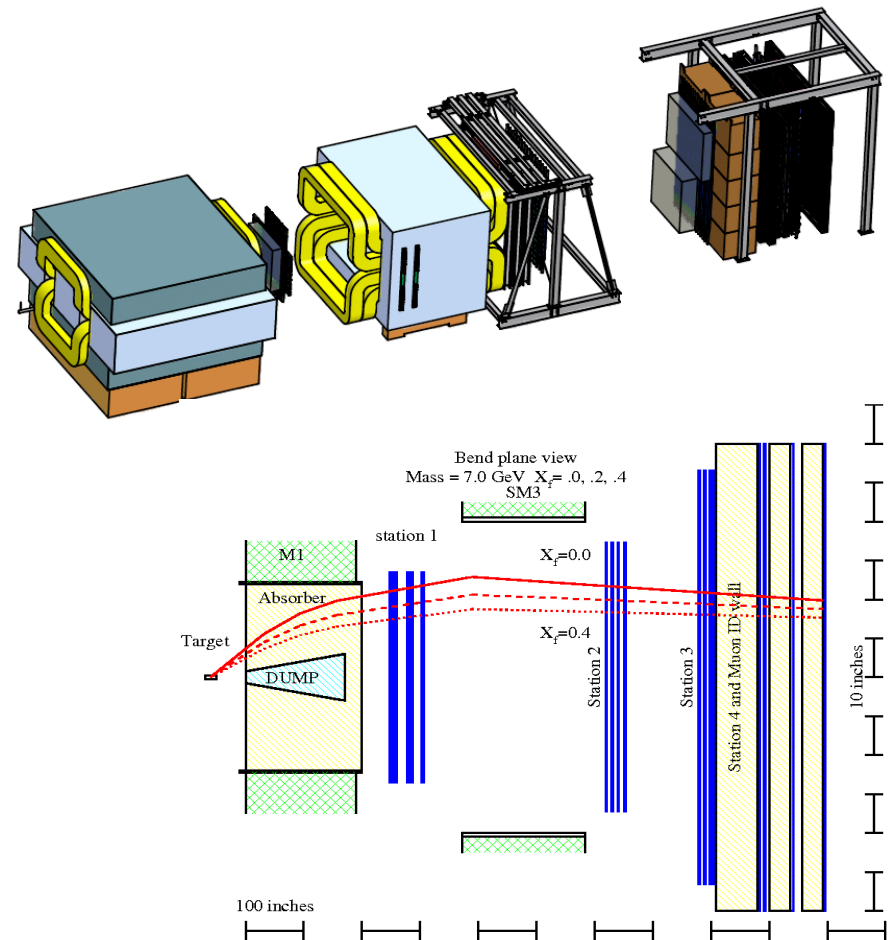
- Parasitic mode
 - Significant beams still left at the end of a store (~50%)
 - Cycle time ~8hr
- Dedicated fixed target
 - Cycle time ~ 1hr
- Dimu x-section @ 250 GeV ($M > 4$) ~20pb

- Targets

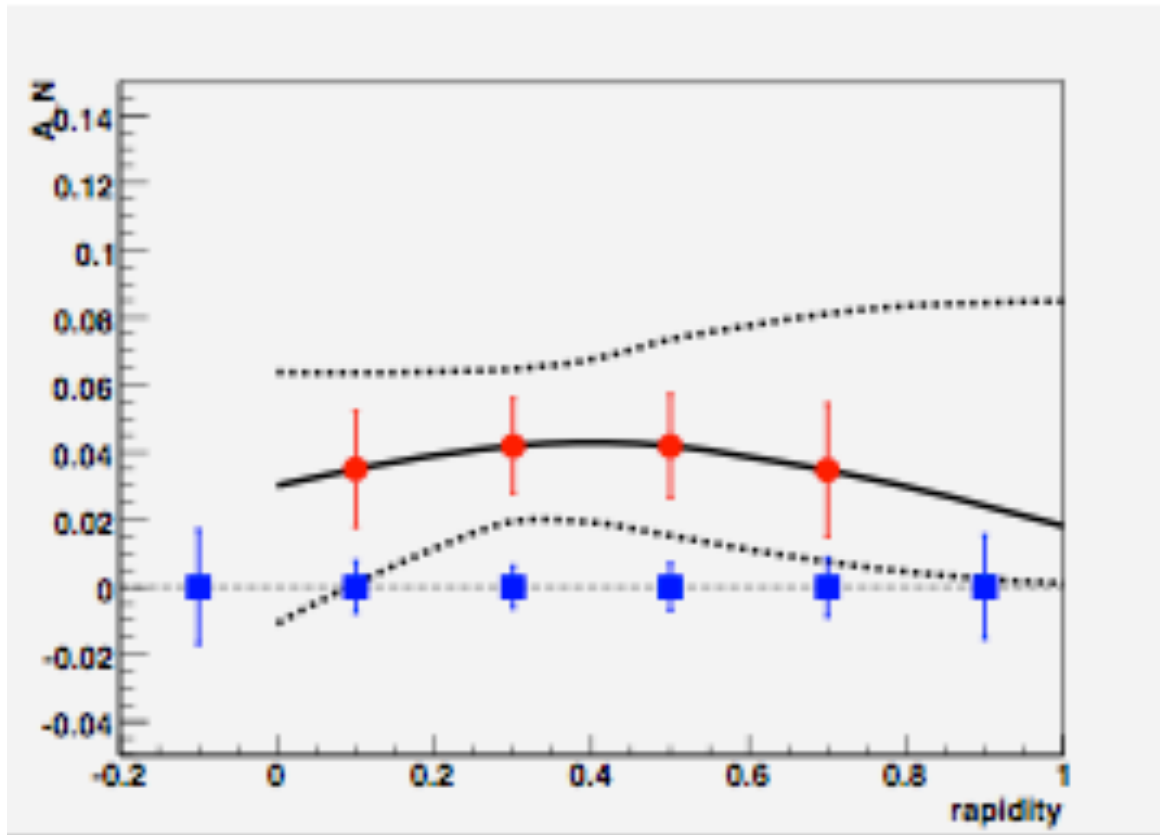
- E906-like unpolarized LH_2 target
 - 51cm LH_2 ($2.1 \times 10^{24}/\text{cm}^2$)
 - Can handle $L \sim 1 \times 10^{36} \text{cm}^{-2} \text{s}^{-1}$
- Polarized solid target
 - UVA/J-Lab/SLAC: $L \sim 10^{35} \text{cm}^{-2} \text{s}^{-1}$

- Advantages

- Polarized beams
- (polarized) targets
- Higher Energy and large x-coverage
- High luminosity



DY A_N Sensitivity @250 GeV Fixed Target



x_F

$4.5 < M < 8 \text{ GeV}$

$q_T < 1 \text{ GeV}$

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	$x_2 = 0.2 - 0.3$	$2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
COMPASS (low mass)	$\pi^\pm + p^\uparrow$	160 GeV $\sqrt{s} = 17.4$ GeV	$x_2 \sim 0.05$	$2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
PAX	$p^\uparrow + p\text{bar}$	collider $\sqrt{s} = 14$ GeV	$x_1 = 0.1 - 0.9$	$2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$
PANDA (low mass)	$p\text{bar} + p^\uparrow$	15 GeV $\sqrt{s} = 5.5$ GeV	$x_2 = 0.2 - 0.4$	$2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
J-PARC	$p^\uparrow + p$	50 GeV $\sqrt{s} = 10$ GeV	$x_1 = 0.5 - 0.9$	$10^{35} \text{ cm}^{-2}\text{s}^{-1}$
NICA	$p^\uparrow + p$	collider $\sqrt{s} = 20$ GeV	$x_1 = 0.1 - 0.8$	$10^{30} \text{ cm}^{-2}\text{s}^{-1}$
SPASCHARM (low mass)	$p + p^\uparrow$	60 GeV $\sqrt{s} = 11$ GeV	$x_2 = 0.05 - 0.2$	
SPASCHARM (low mass)	$\pi^\pm + p^\uparrow$	34 GeV $\sqrt{s} = 8$ GeV	$x_2 = 0.1 - 0.3$	
RHIC PHENIX Muon	$p^\uparrow + p$	collider $\sqrt{s} = 500$ GeV	$x_1 = 0.05 - 0.1$	$2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
RHIC Internal Target phase-1	$p^\uparrow + p$	250 GeV $\sqrt{s} = 22$ GeV	$x_1 = 0.25 - 0.4$	$2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
RHIC Internal Target phase-2	$p^\uparrow + p$	250 GeV $\sqrt{s} = 22$ GeV	$x_1 = 0.25 - 0.4$	$6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

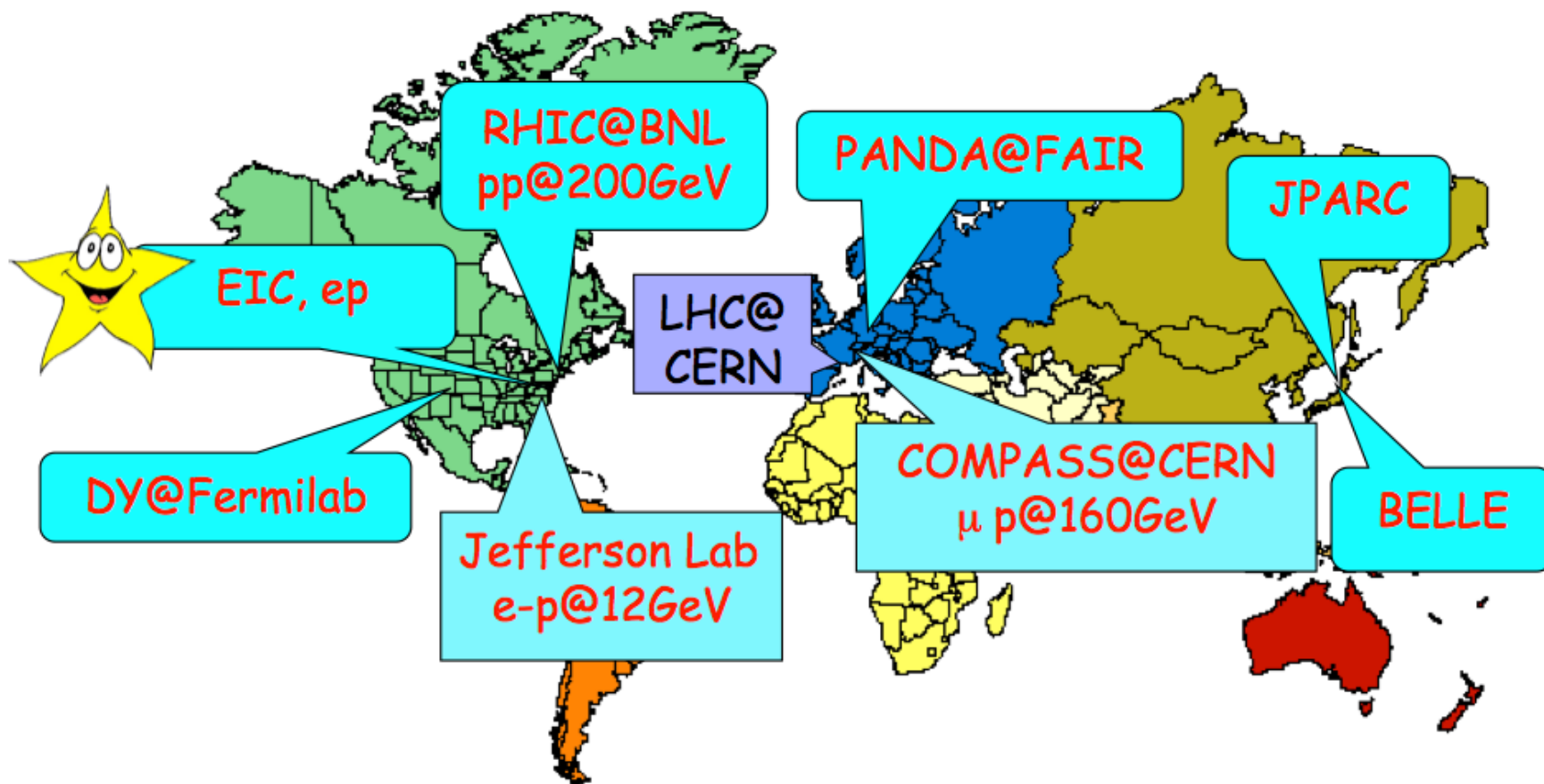
- Polarized DY Dimuon Exp. at Fermilab Main Injector: 120GeV
- RHIC fixed target possibility: 250 GeV

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

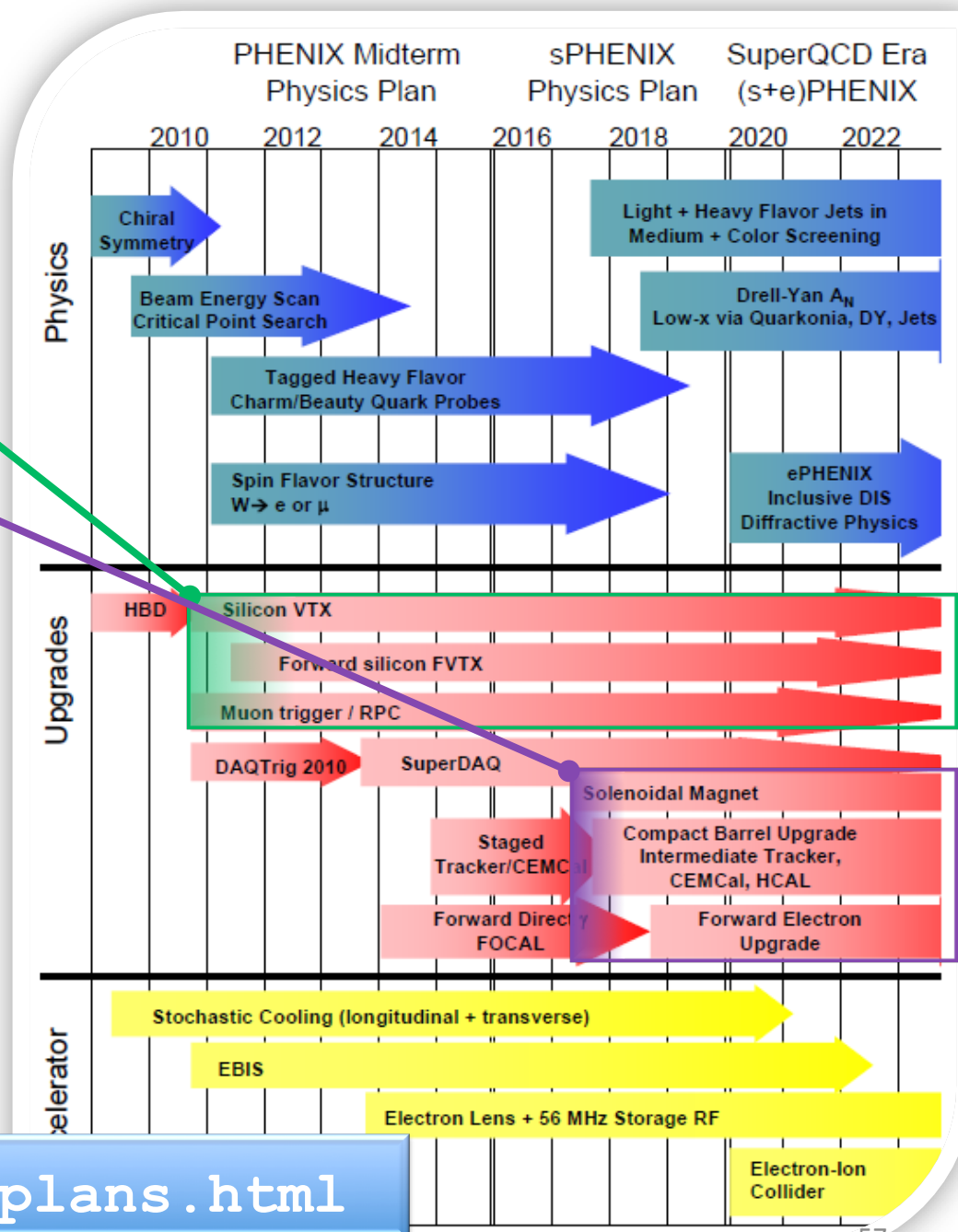
Assume: polarized proton running 2011 to 2014 for W-physics with longitudinal polarization at STAR and PHENIX

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

- ➔ (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

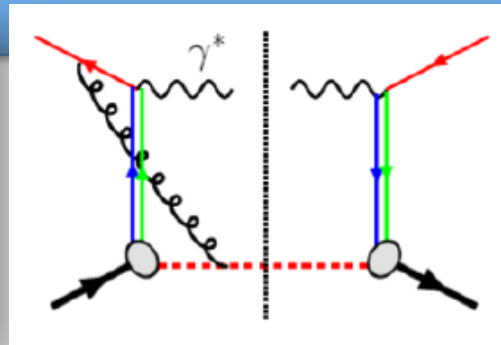
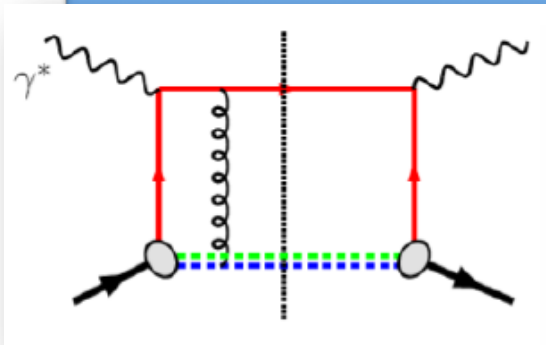
PHENIX Decadal Plan

- 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*



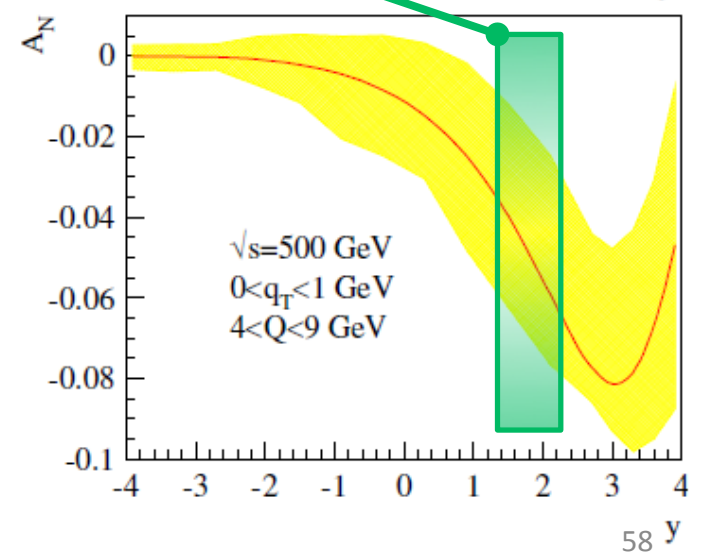
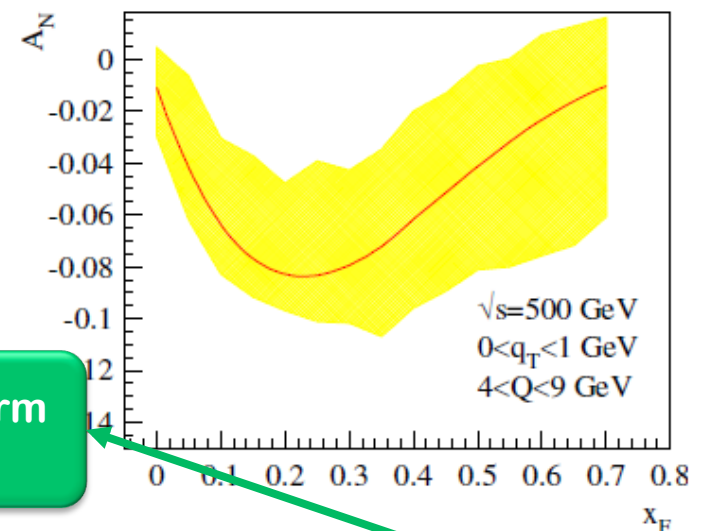
www.phenix.bnl.gov/plans.html

Polarized Drell Yan



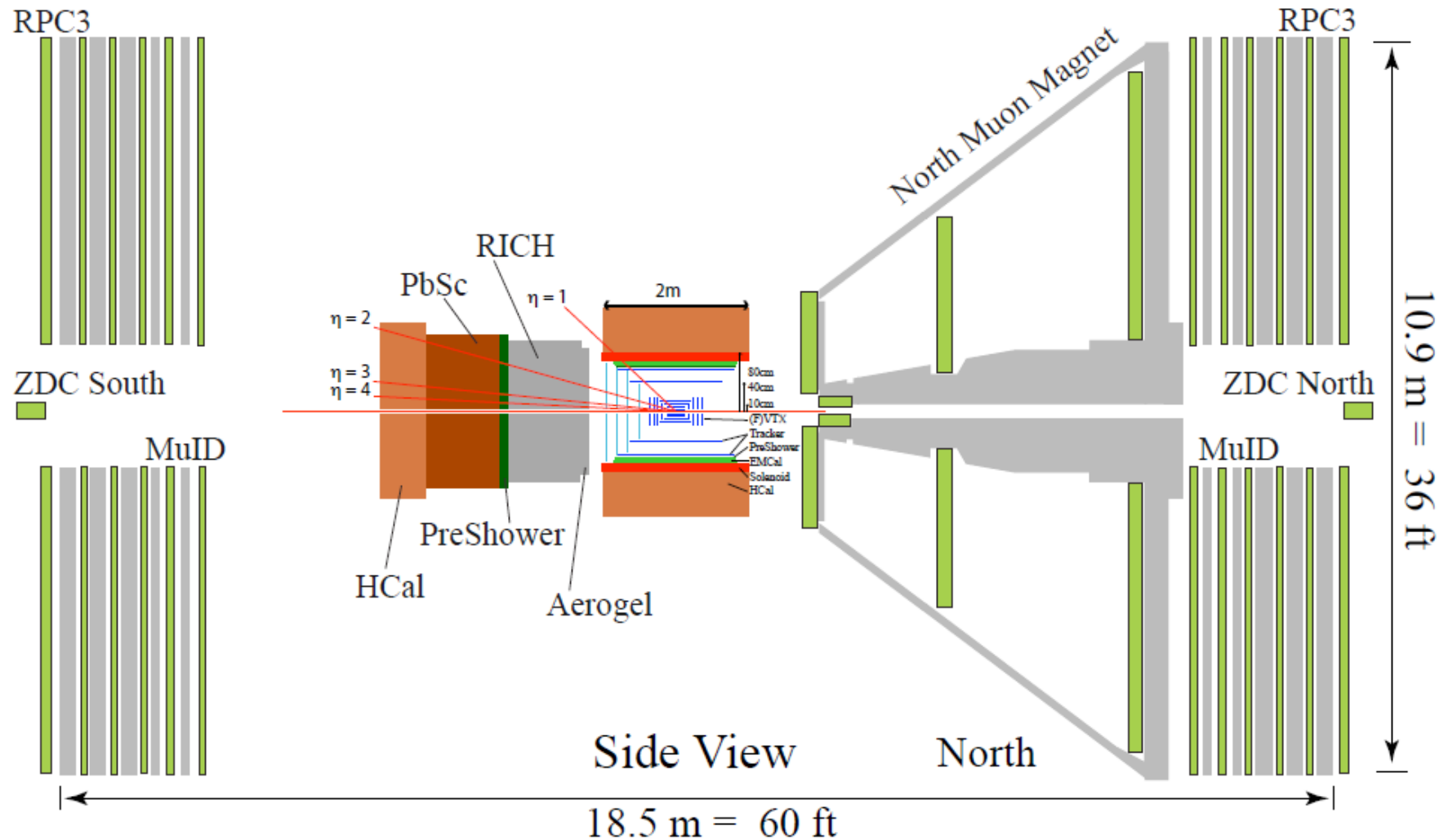
- Solid factorization
- No fragmentation
 - Direct correlation of intrinsic transverse quark momentum to the proton spin
- Fundamental QCD test
 - Sign of asymmetry compared to SIDIS

current Muon arm acceptance

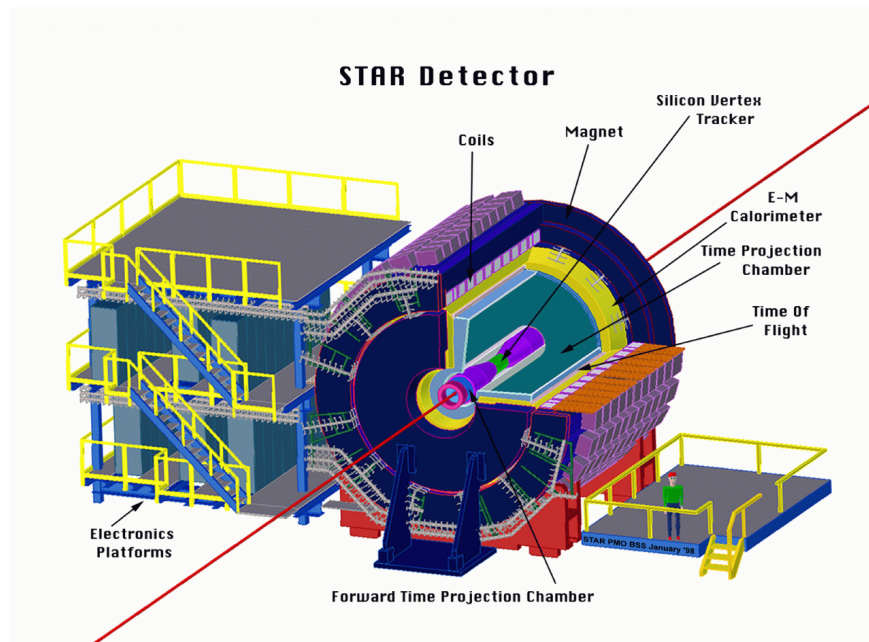


Z. Kang and J. Qiu. Phys. Rev., D81:054020, (2010)

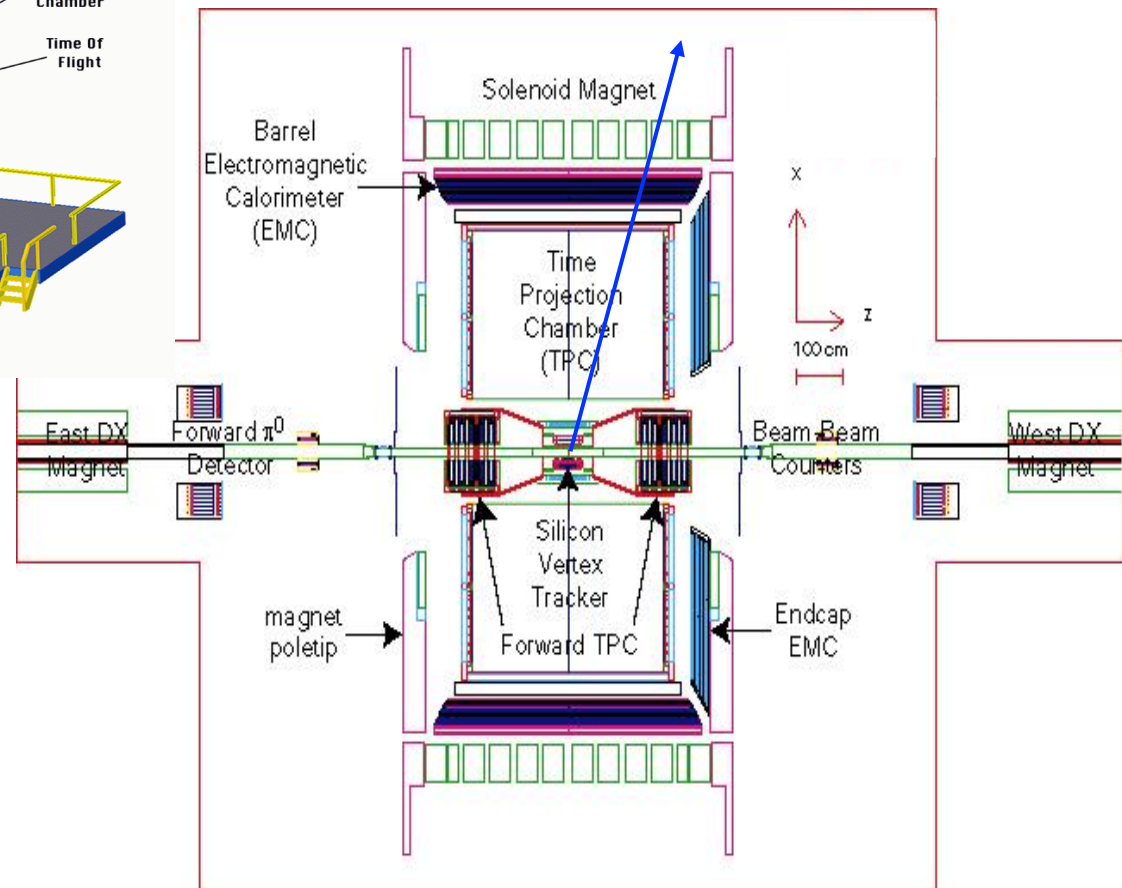
Proposed PHENIX Upgrades



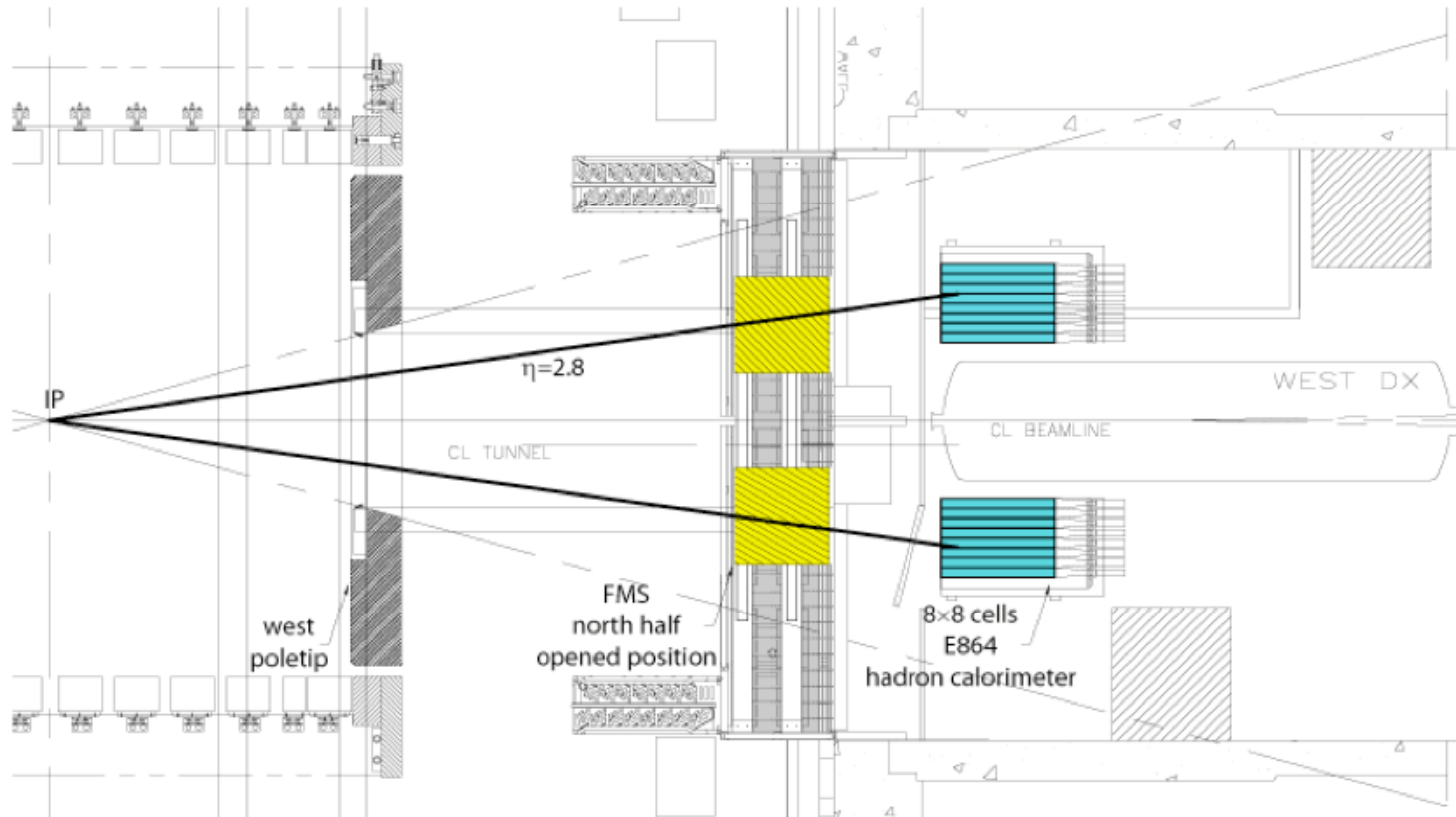
The STAR Detectors



- 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



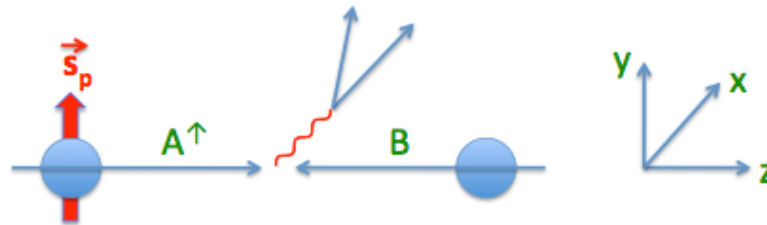
FHC: proposed hadronic calorimetry behind the FMS,
essential towards understanding of forward single-spin asymmetries,
enable forward (anti-)Lambda studies, ...

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.

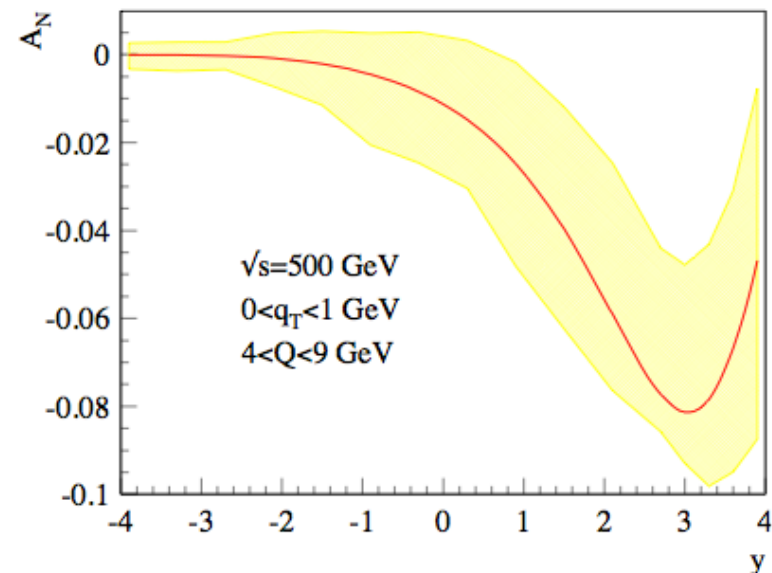
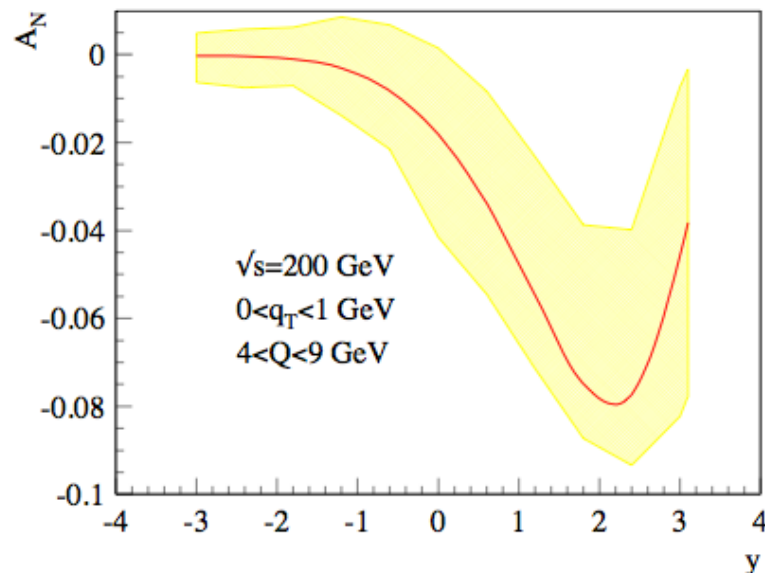
Predictions for Drell-Yan process at RHIC

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

Kang-Qiu, PRD81, 2010

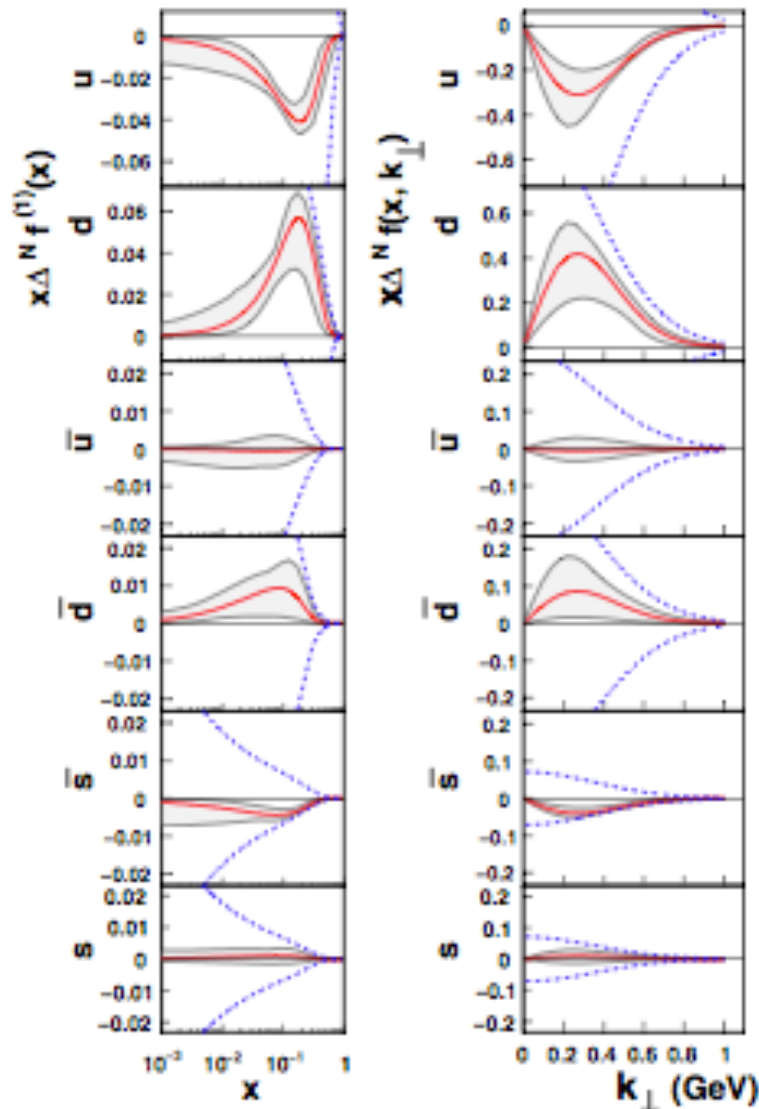


$$A_N \propto \frac{4}{9} \Delta^N u + \frac{1}{9} \Delta^N d < 0$$

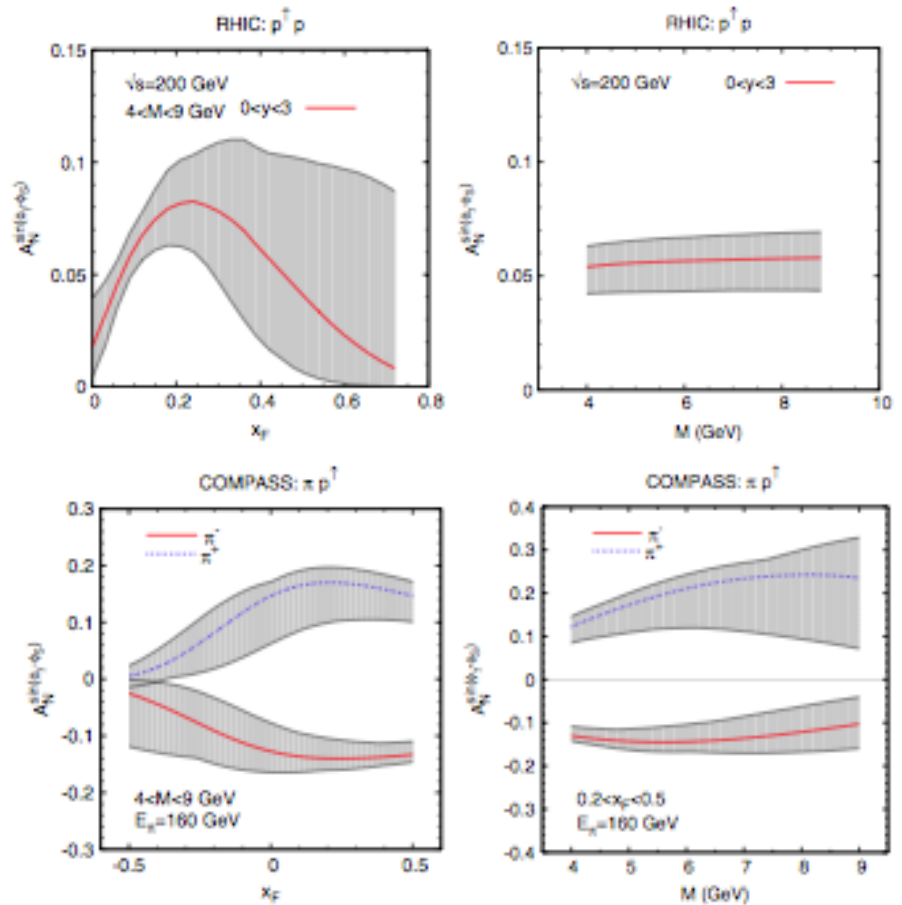


Sivers Functions and DY TSSA

Anselmino et al PRD 79 -54010(2009)



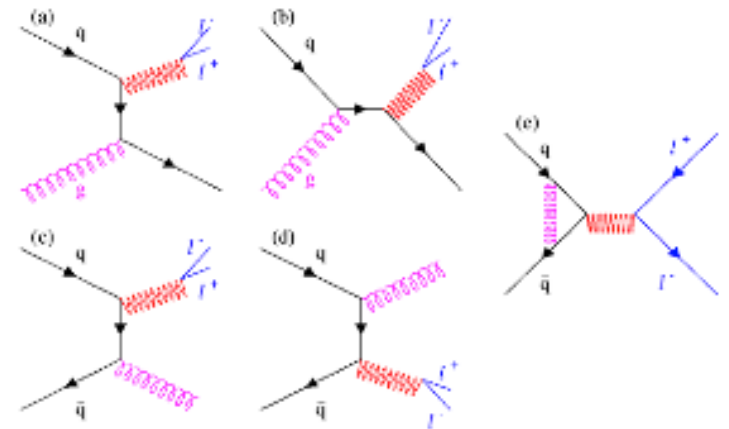
- Expected A_N of DY based on global fit to DIS fit of HERMES and



QCD Correction

K factor collection

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



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).