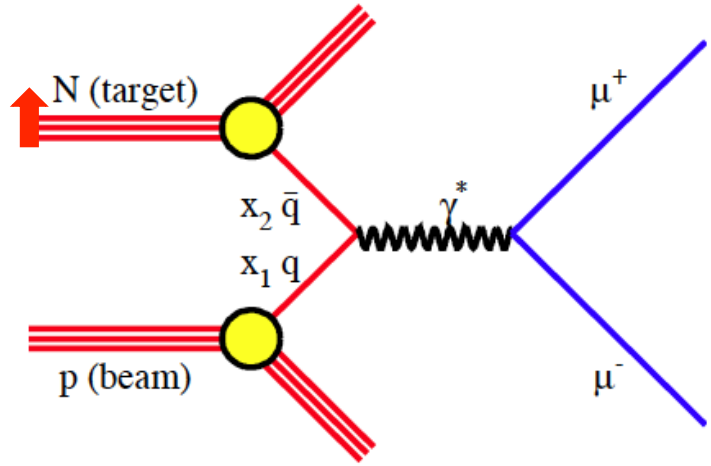
Single-Spin Asymmetries in Drell-Yan Process in p+p Collisions

Fermilab Experiment E-1039



蒋晓东（洛斯阿拉莫斯国家实验室）

Dec. 27th, 2013. Private Discussions@THU

Information on Fermilab E-1039

I have a set of slides on this experiment (Fermilab E-1039), and future polarized Drell-Yan opportunities, please see

http://hepg.sdu.edu.cn/THPPC/conference/spin2013/agenda.html?ver=1.0

Close to the bottom:

Polarized Drell-Yan Experiment at Fermilab

The official version of E-1039 Polarized target LOI as submitted can be found on Fermilab webpage:

http://www.fnal.gov/directorate/program_planning/June2013PACPublic/P-1039_LOI_polarized_DY.pdf

PAC presentation slides and PAC report can be found at:

http://www.fnal.gov/directorate/program_planning/phys_adv_com/pac-members.html

Outline for Today

I will discuss experimental results, physics impacts of the observed single spin asymmetry (SSA) phenomena in:

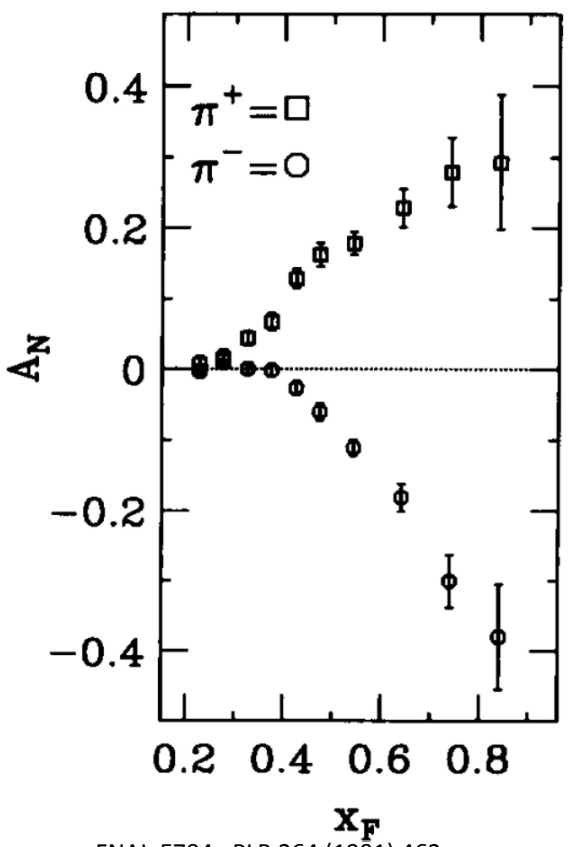
- **Inclusive hadron SSA observed in proton-proton collision at Fermilab and RHIC.**

I will discuss on-going experimental efforts, at Fermilab :

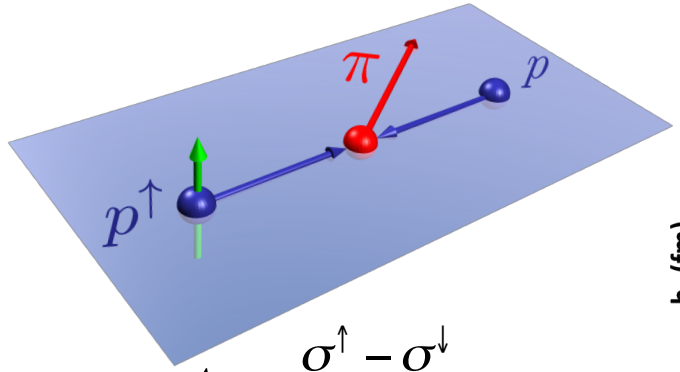
- **Polarized target Drell-Yan experiments (E-1039).**

Quarks can tell left-right in $p\,p^{\uparrow} \to \pi X$

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



FNAL-E704: PLB 264 (1991) 462.

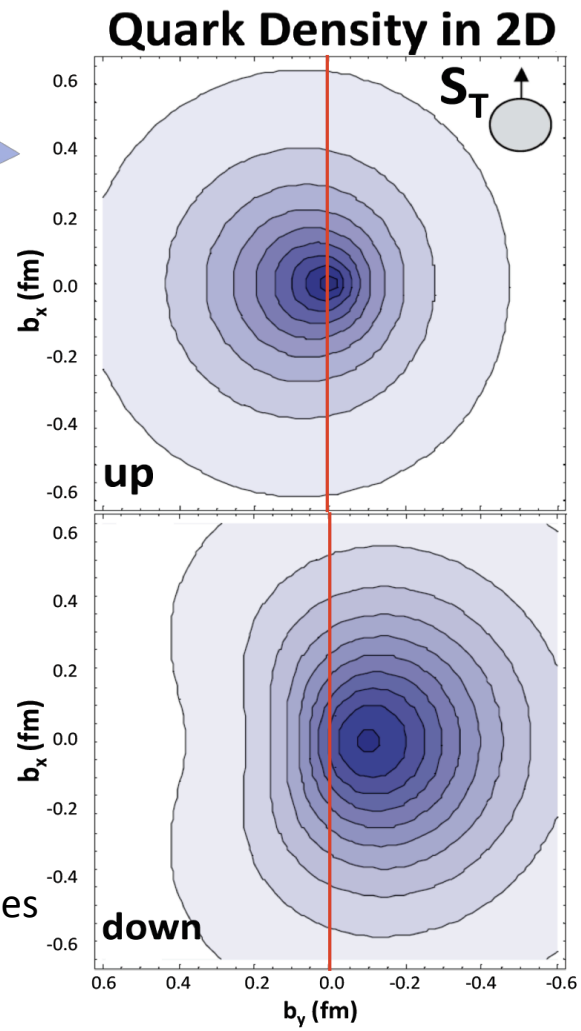


$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

π^+ $(u\bar{d})$ favors left

π^- $(d\bar{u})$ favors right

One explanation (Sivers effect): quark's transverse motion generates a left-right bias.



Lattice QCD PRL98:222001,2007.

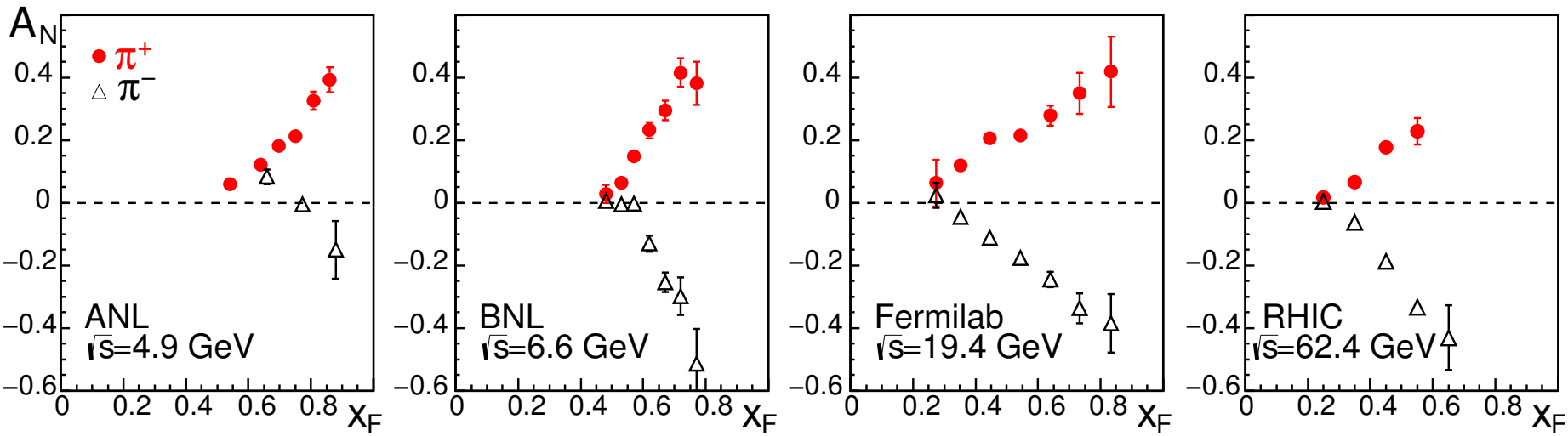
up-quarks favor left (L_u>0), down-quarks favor right (L_d<0).

Viewing along the polarized proton's momentum direction,

π^+ $(u\bar{d})$ favors the left-side, π^- $(d\bar{u})$ favors the right side of the proton spin vector.

Inclusive Hadron Single Spin Asymmetries in p+p

Large, forward A_N in hadron production in p+p have been measured since the mid 70's



Viewing along the polarized proton's momentum direction,

π^+ $(u\bar{d})$ favors the left-side, π^- $(d\bar{u})$ favors the right side of the proton spin vector.

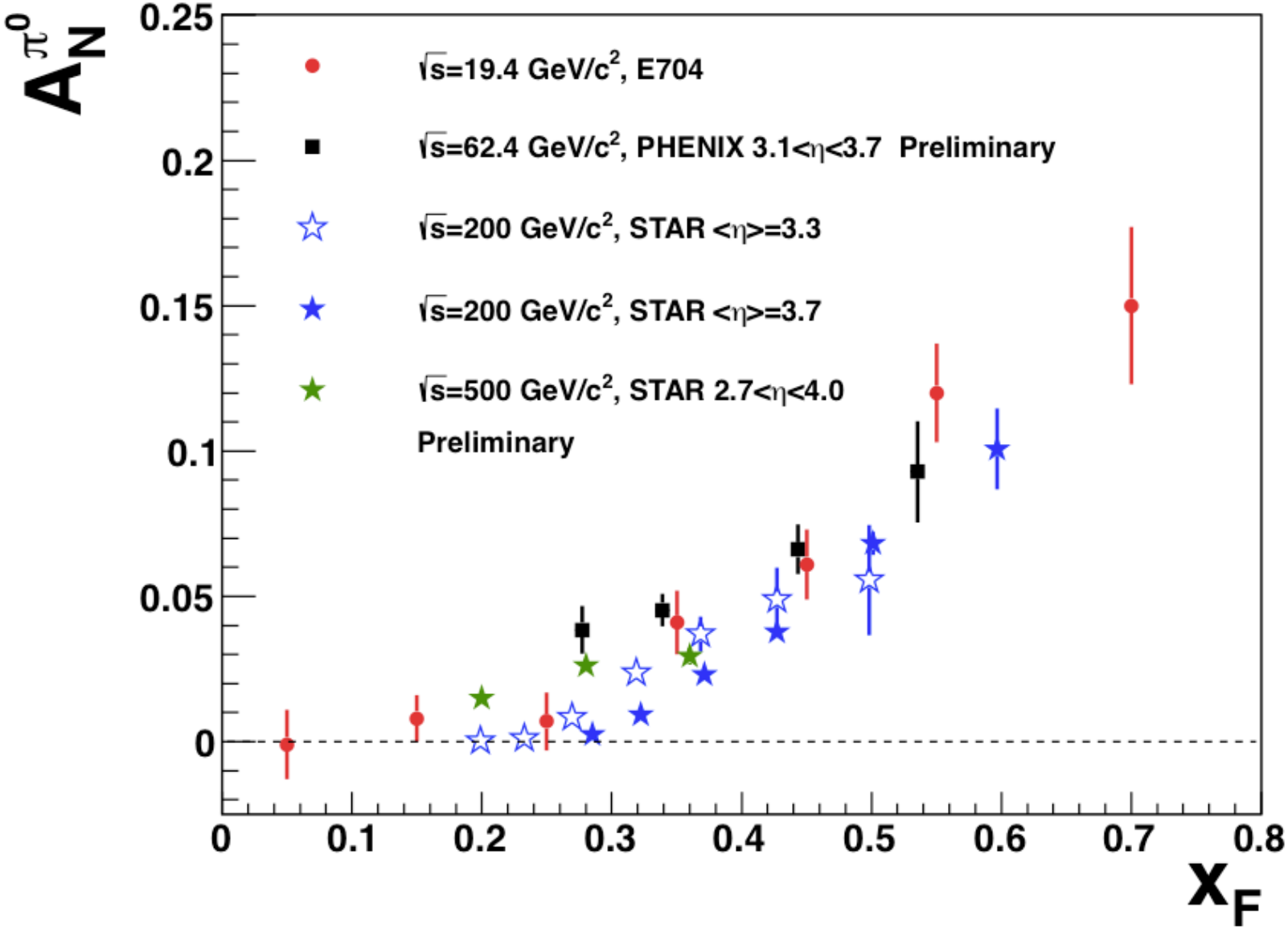
The asymmetries persist from low CM energies to high CM energies.

$$x_F = \frac{2p_L}{\sqrt{s}}$$

A simple (collinear) pQCD calculation tells us that an A_N can exist, but that it should scale like

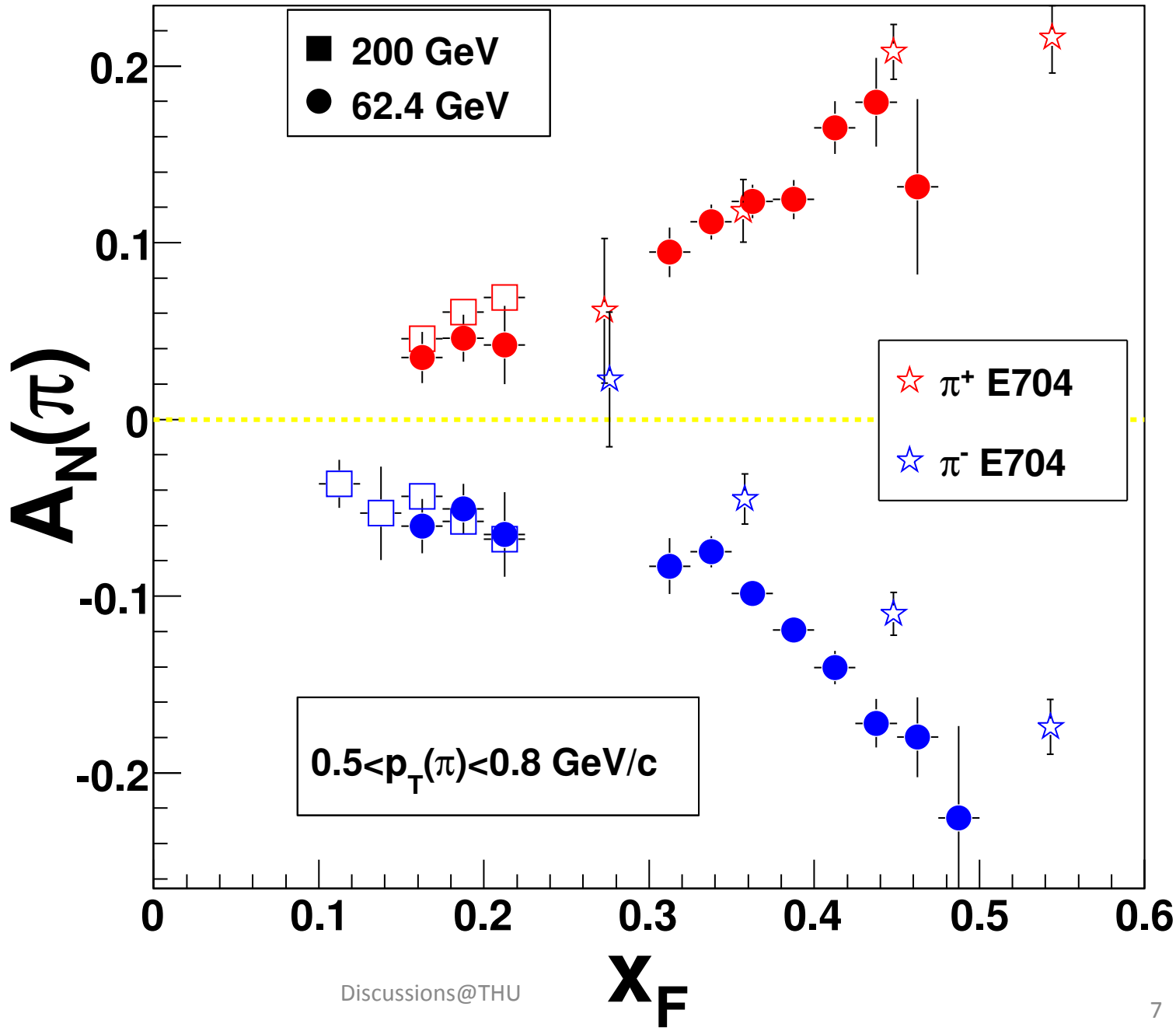
$$A_N \approx \frac{m_q \alpha_S}{p_T}$$

π^0 favors the left side of proton spin vector



At 200 GeV

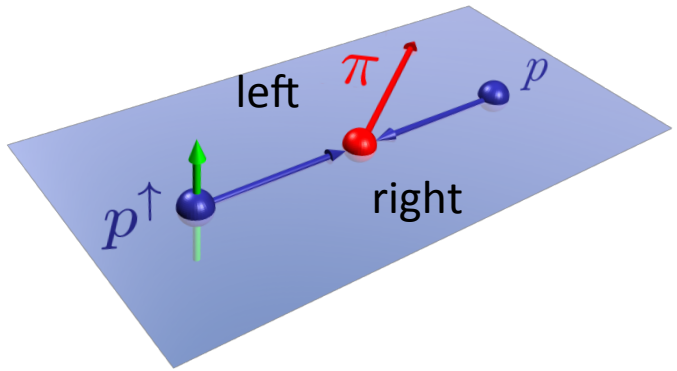
BRAHMS Preliminary



Valence quarks inside a transversely polarized proton have a very clear left-right bias.

Viewing along the polarized proton's momentum direction,

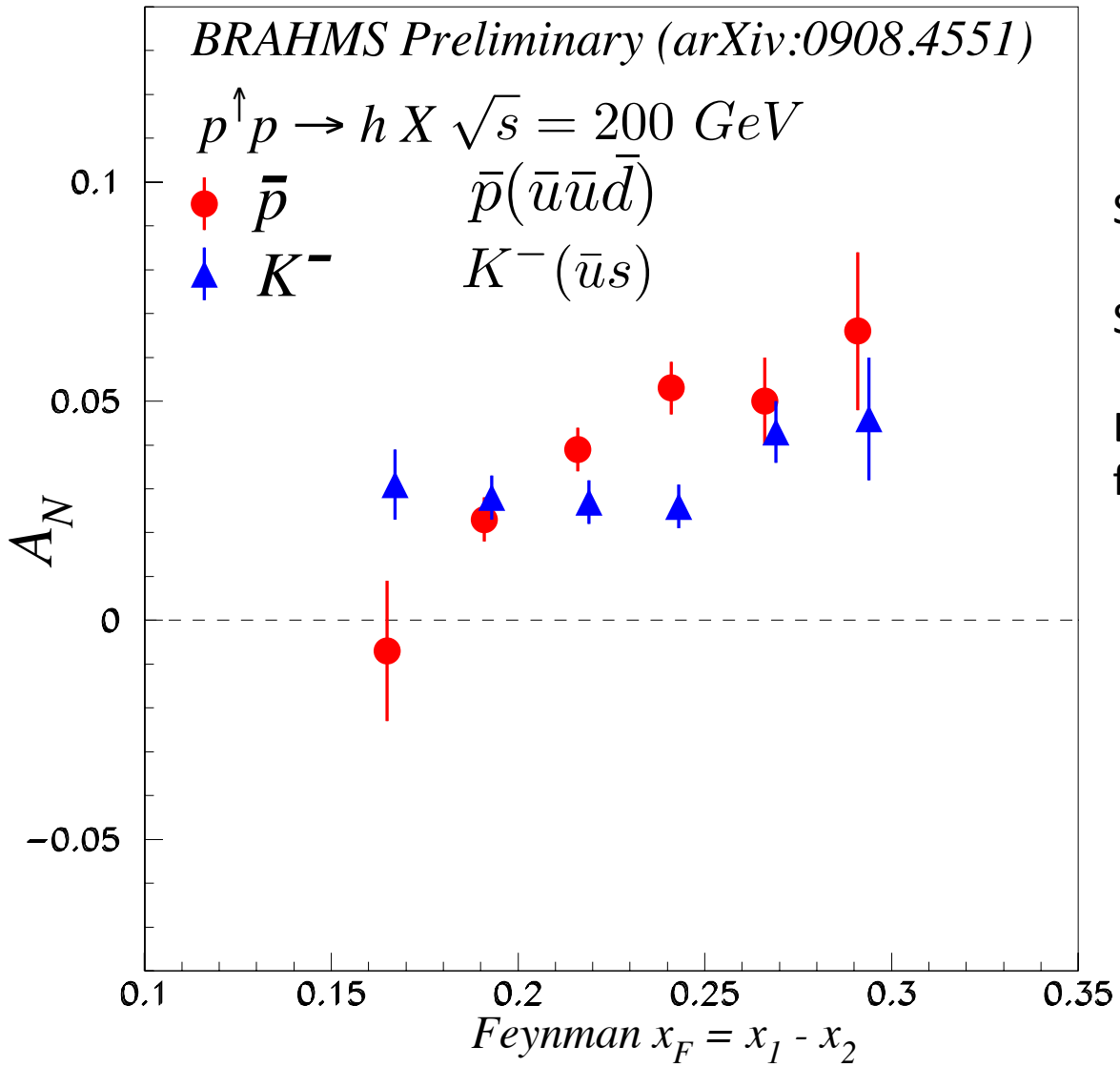
π^+ $(u\bar{d})$ favors the left-side, π^- $(d\bar{u})$ favors the right side of the proton spin vector.



How about sea quarks ?

Do they have a clear left-right bias ?

Hints of Non-Vanishing Sea Quark Sivers Distribution ?



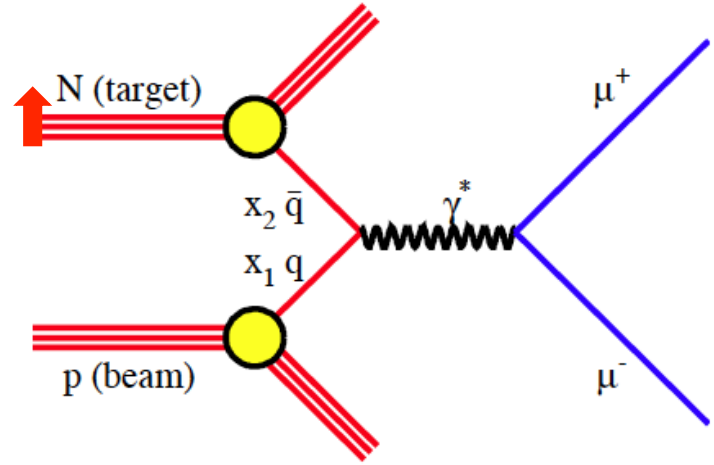
Sea quark generates left-right bias ?

Secondary string-breaking ?

Left-right bias generated through fragmentation process ?

Fermilab E-1039

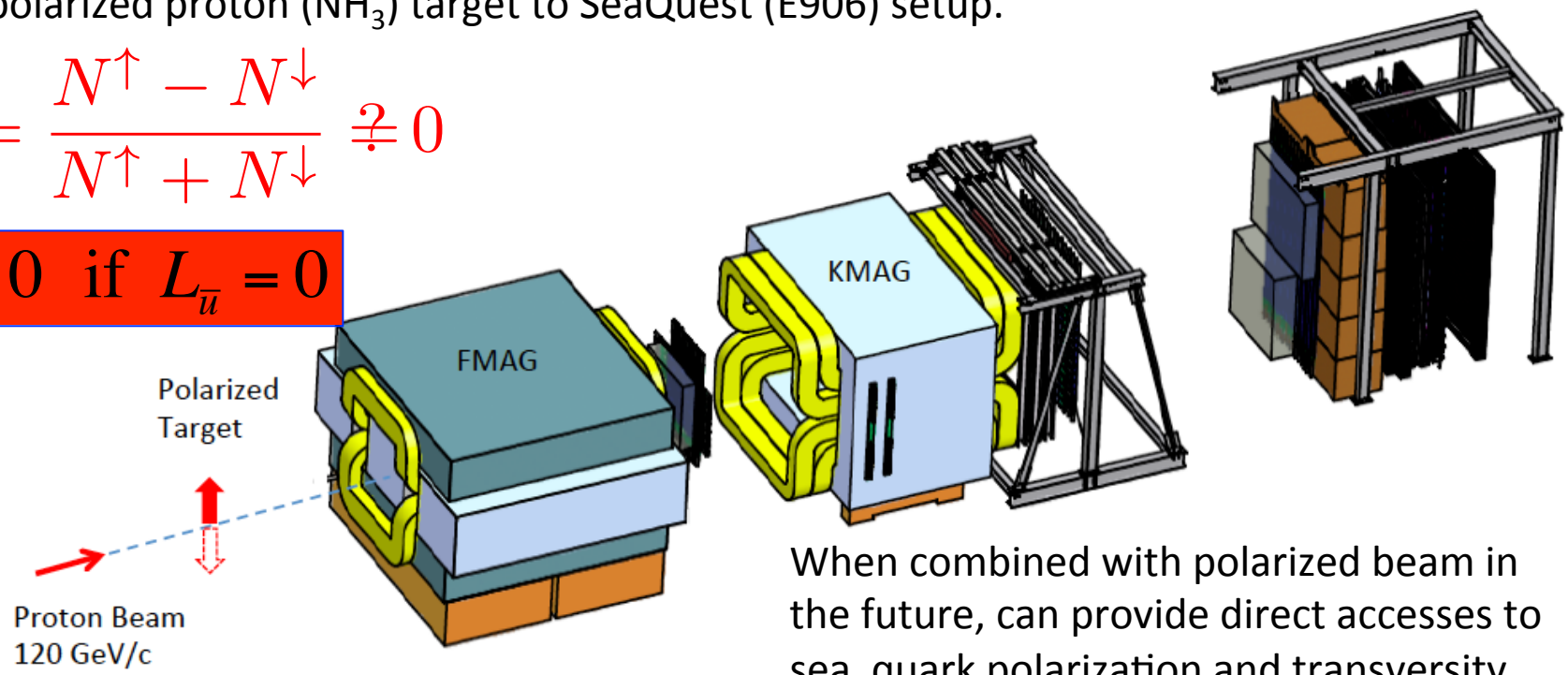
Polarized Target Drell-Yan Single-Spin Asymmetry Measurement to Access Sea Quarks' Angular Momentum



- Measure Drell-Yan yield dependence on the target's spin direction.
- Strong constraints on sea quarks' angular momentum.
- Add a polarized proton (NH_3) target to SeaQuest (E906) setup.

$$A_N = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \stackrel{?}{\neq} 0$$

$$A_N \equiv 0 \;\; \text{if} \;\; L_{\bar{u}} = 0$$



When combined with polarized beam in the future, can provide direct accesses to sea quark polarization and transversity.

- **Nucleon spin puzzle: ~50% of proton spin is not accounted for. Sea quarks' orbital angular momentum could be a major part of the "missing spin".**
- **Quark orbital angular momentum leads to transverse momentum dependent distributions: Sivers distribution.**
- **Polarized target Drell-Yan asymmetry at SeaQuest (E906) provides a clean access to sea quark Sivers distribution.**
- **Experimental setup, polarized target, etc.**

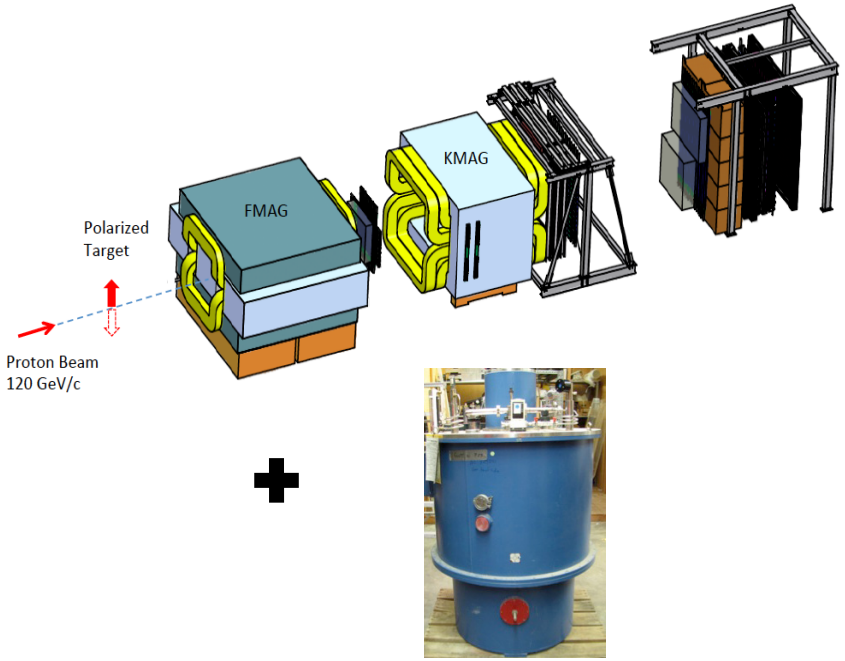
Drell-Yan yields depend on target's spin direction?

$$A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \stackrel{?}{\neq} 0 \qquad A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

$$A_N \equiv 0 \ \text{ if } \ L_{\bar{u}} = 0$$

E-1039 Collaboration:

Co-Spokespersons: A. Klein, X. Jiang
Los Alamos National Laboratory



Collaboration includes experts on

- Drell-Yan: E772, E866, E906
- Polarized target: BNL, SLAC, JLab
- Spin experiments: JLab, HERMES, RHIC

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FNAL Director Granted E-1039 Stage-I Approval

As you can see, the PAC recommends Stage-1 approval for P-1039, contingent on the funding from the DOE Office of Nuclear Physics (NP) for the project and continued minimal impact on the high-priority core program. I accept the PAC recommendation, and grant Stage-1 approval contingent upon funding from the DOE Office of Nuclear Physics. The laboratory management looks forward to discussing with you plans and prospects for obtaining this funding.

Sincerely,

Piermaria Oddone

Letter-Of-Intend (P-1039): submitted May 4th, 2013.
FNAL PAC presentation: June 6th, 2013.
Stage-I approval: June 26th, 2013.

Polarized Drell-Yan SSA: COMPASS, E-1027 and E-1039

	Beam Pol.	Target Pol.	Favored Quarks	Physics Goal
COMPASS $\pi^- p^\uparrow \to \mu^+\mu^- X$	✕	✔	Valence quark	Sign change and size of Sivers distribution for valence quark
E-1027 $p^\uparrow p \to \mu^+\mu^- X$	✔	✕	Valence quark	Sign change and size of Sivers distribution for valence quark
E-1039 $p p^\uparrow \to \mu^+\mu^- X$	✕	✔	Sea quark	Size and sign of Sivers distribution for Sea quarks, if DY $A_N \neq 0$.

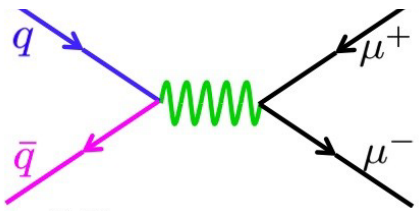
Drell-Yan at SeaQuest (E906): a Clean Access to Sea Quark

$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{4\pi\alpha^2}{9x_b\,x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + \cancel{q_t(x_t)\bar{q}_b(x_b)}\right]$$

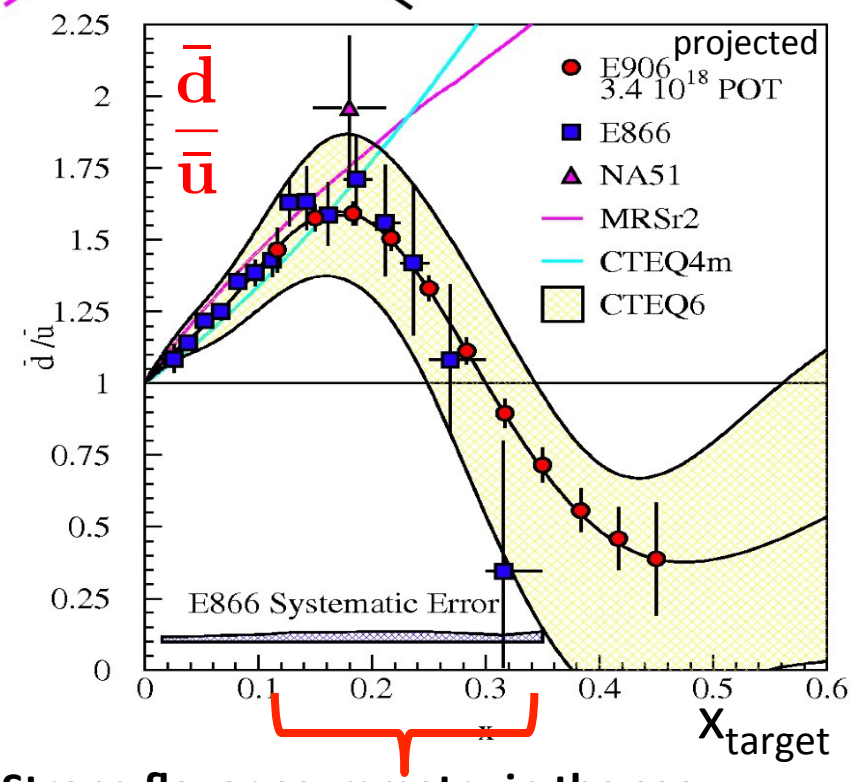
small

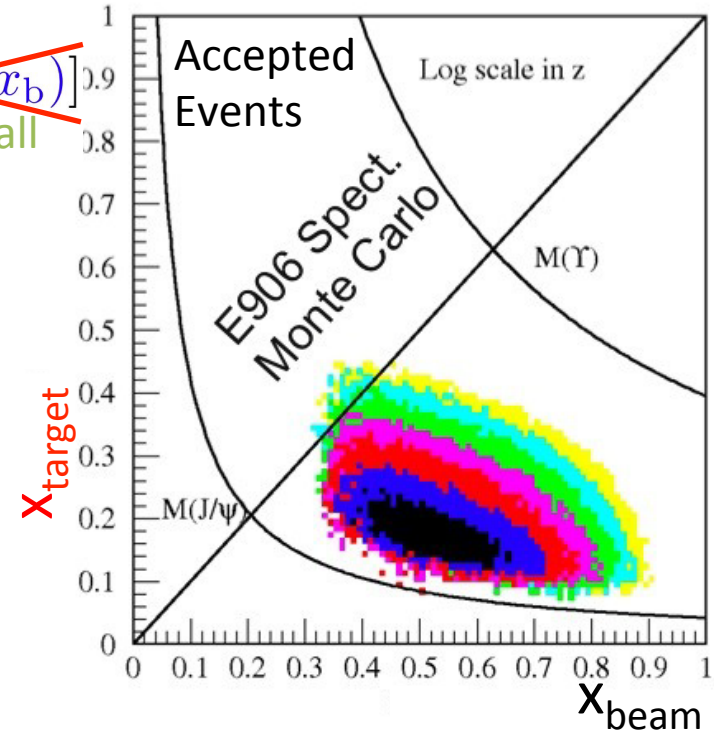
target sea quark

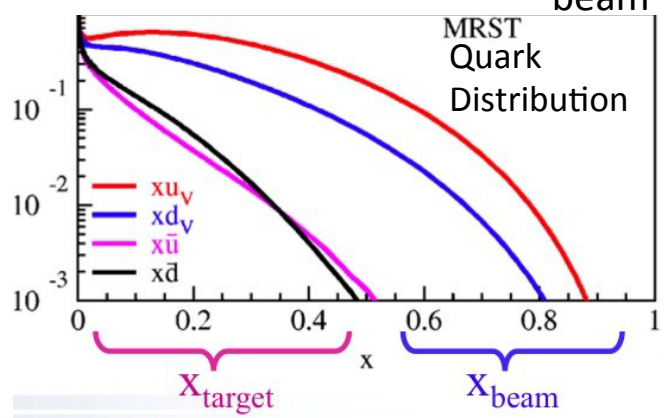
beam valence quark



$\bar{u}_t(x_t) \cdot u_b(x_b)$ dominates







Strong flavor asymmetry in the sea.

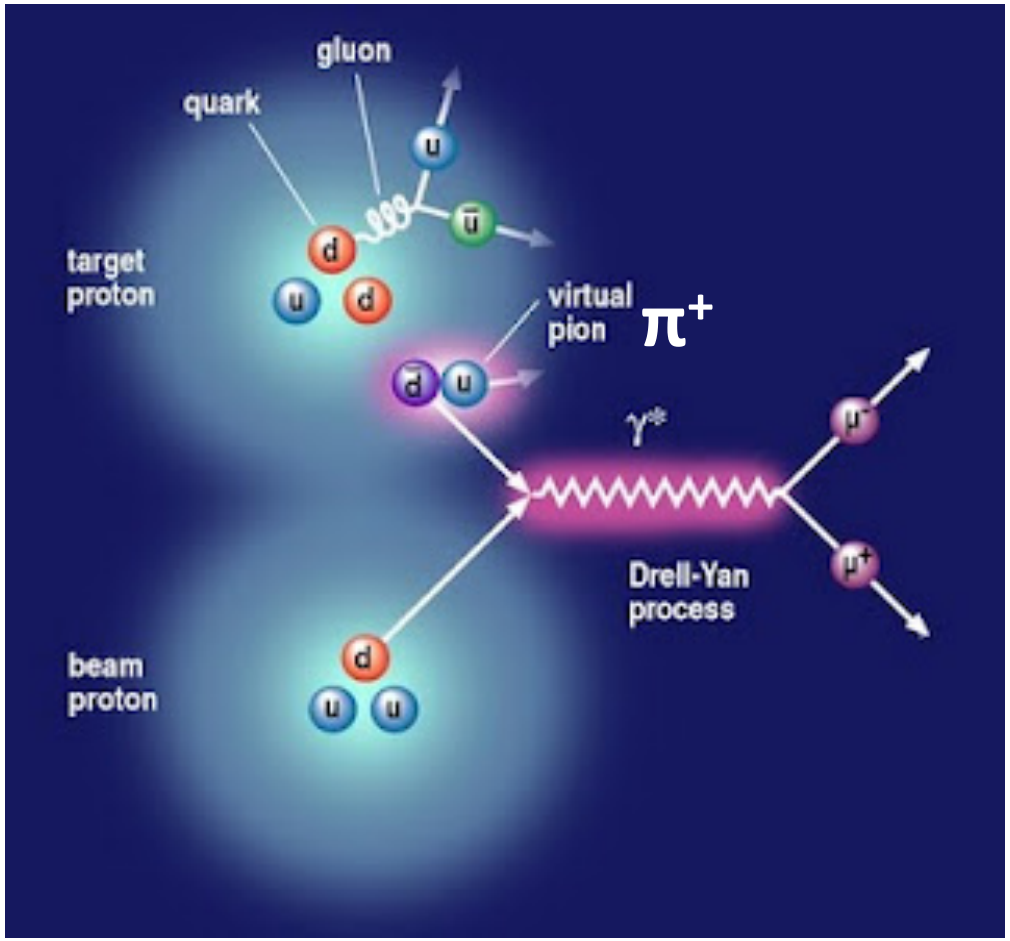
Could sea quarks carry a significant amount of angular momentum ?

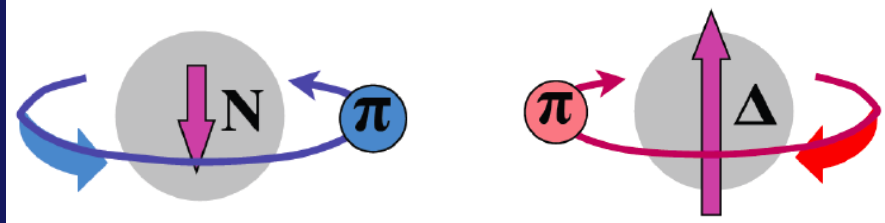
The meson cloud model explains the flavor asymmetry in the sea, and requires quarks to carry angular momentum.

$|p\rangle = p + N\pi + \Delta\pi + \ldots$

Pions $J^p = 0^-$ Negative Parity

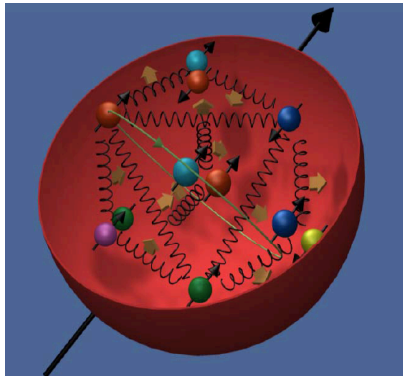
Need **L=1** to get proton's $J^p = \frac{1}{2}^+$





Sea quarks should carry orbital angular momentum.

Quark Orbital Momentum and the Sivers Function

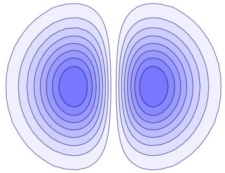


The Sivers function is the distribution of unpolarized quarks in a transversely polarized proton

$$\vec{L} = \vec{b} \times \vec{k}$$

$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S} \cdot (\hat{\mathbf{P}} \times \mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

quark density



Sivers distribution

Sivers distribution was believed to vanish until 2002!

- Naive T-odd, not allowed for collinear quarks. Transverse Mom. Dep. parton distributions (TMD).
- Imaginary piece of interference L_q=0 ✖ L_q=1 quark wave functions.

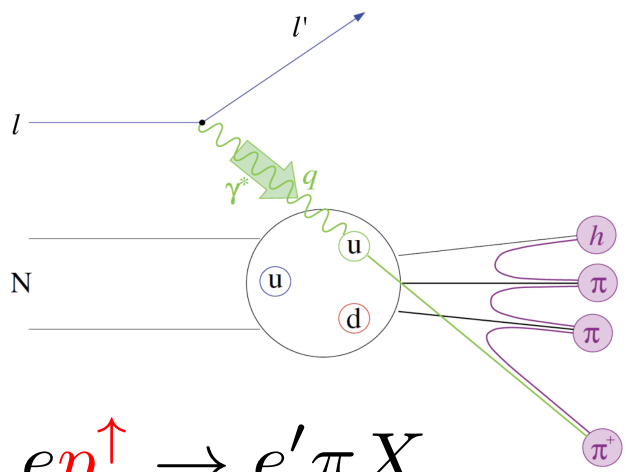
Sivers function = 0 ⇔ L_q=0

Sea quark Sivers function =0 ?

Accessing the quark Sivers distribution

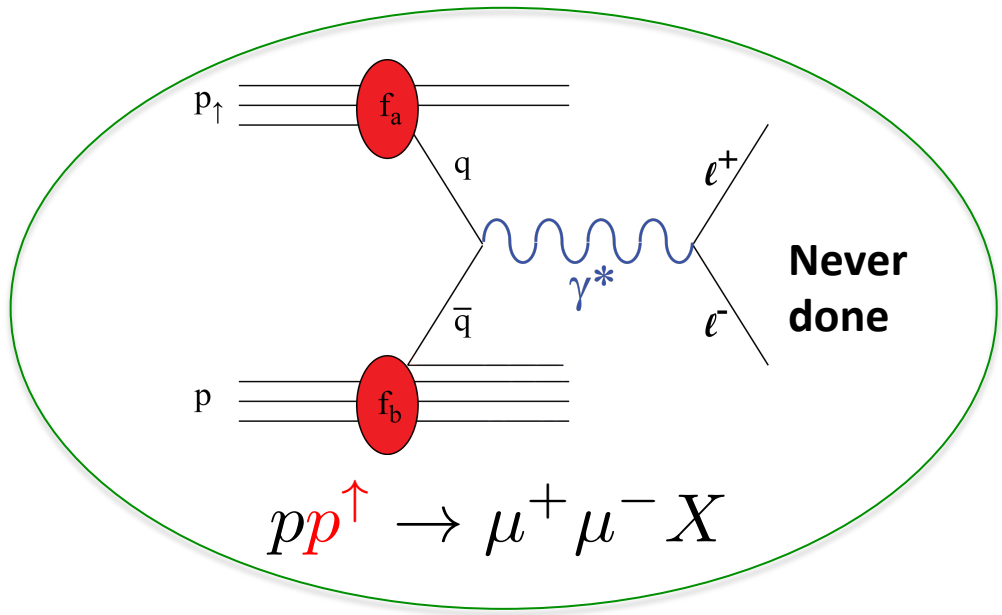
Polarized target experiments

Left-right asymmetry in Semi-Inclusive Deep Inelastic Scattering (SIDIS) on a polarized nucleon



$$ep^{\uparrow} \to e'\pi X$$

Left-right asymmetry in Drell-Yan di-muon production (DY) on a polarized nucleon



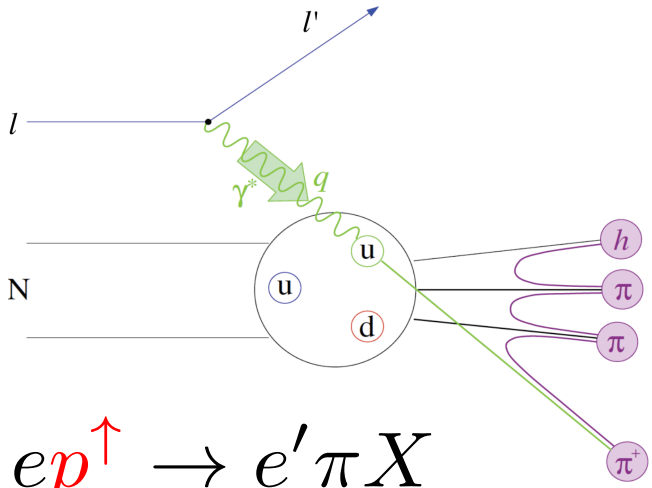
$$pp^{\uparrow} \to \mu^+\mu^- X$$

Cornerstone prediction of QCD

The same quark Sivers distribution in both processes, but with opposite sign

$$f_{1T}^{\perp q}\,|_{SIDIS} = -f_{1T}^{\perp q}\,|_{DY}$$

Asymmetry in Semi-Inclusive DIS



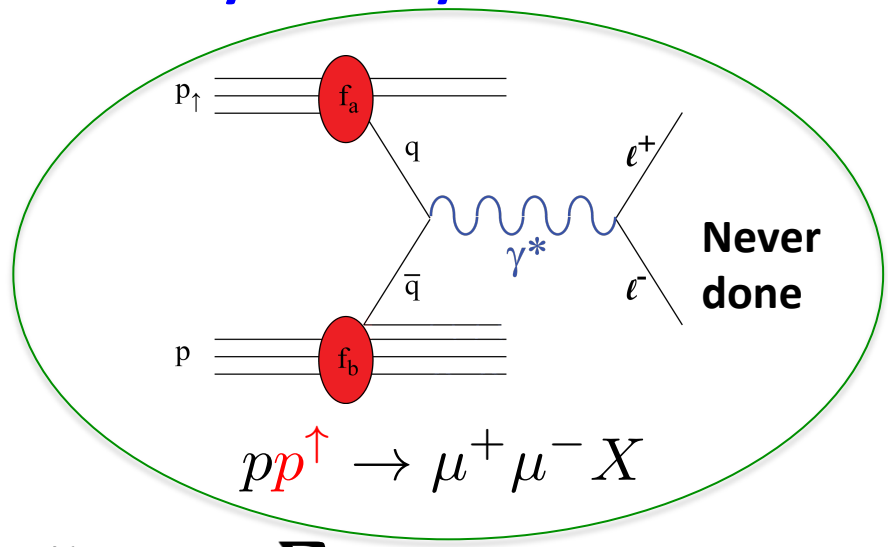
$$ep^{\uparrow} \rightarrow e'\pi X$$

$$d\sigma^{\uparrow\downarrow} = d\sigma_0 \pm \sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)$$

- Involves quark to hadron frag. func.
- Valence and sea quarks are mixed.

$$A_N = \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

Asymmetry in Drell-Yan

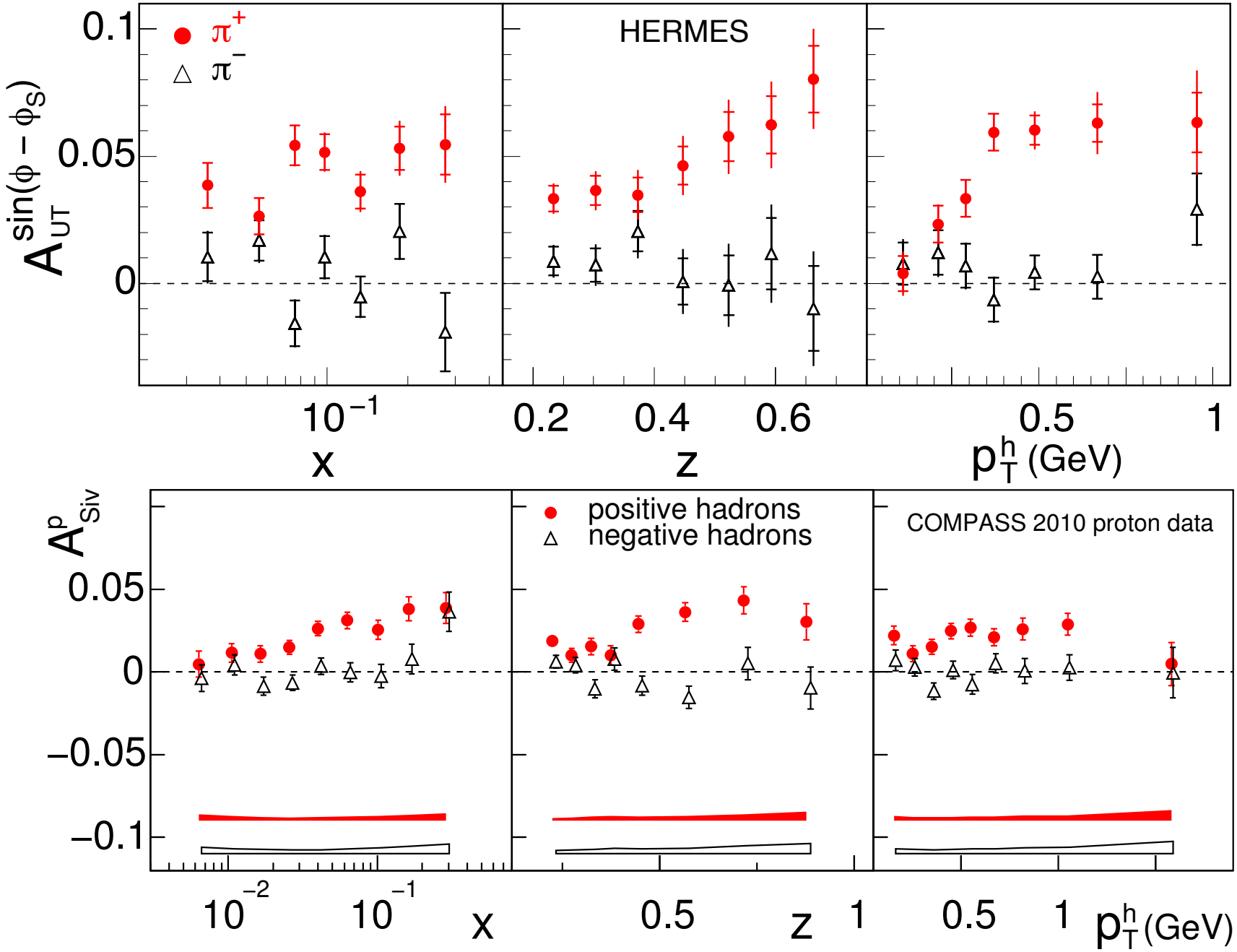


$$pp^{\uparrow} \rightarrow \mu^+\mu^- X$$

$$d\sigma^{\uparrow\downarrow} = d\sigma_0 \pm \sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2]$$

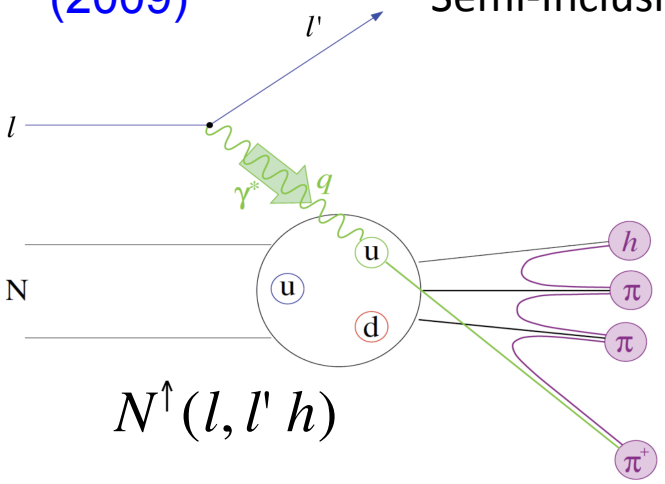
- No quark frag. func. involved.
- Valence and sea quarks can be isolated
  - Pol. Beam➔valence quark (E-1027)
  - Pol. Target➔sea quark (E-1039)

$$A_N = \frac{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2]}$$


HERMES
π^+
π^-
$A_{UT}^{\sin(\phi-\phi_S)}$
0.1
0.05
0
10^{-1}
x
0.2
0.4
0.6
z
0.5
1
p_T^h (GeV)
COMPASS 2010 proton data
positive hadrons
negative hadrons
A_{Siv}^p
0.05
0
−0.05
−0.1
10^{-2}
10^{-1}
x
0.5
z
1
0.5
1
p_T^h (GeV)

Quark Sivers Distributions: fit to HERMES and COMPASS data (2009)

Semi-Inclusive Deep-Inelastic Scattering on transversely polarized targets

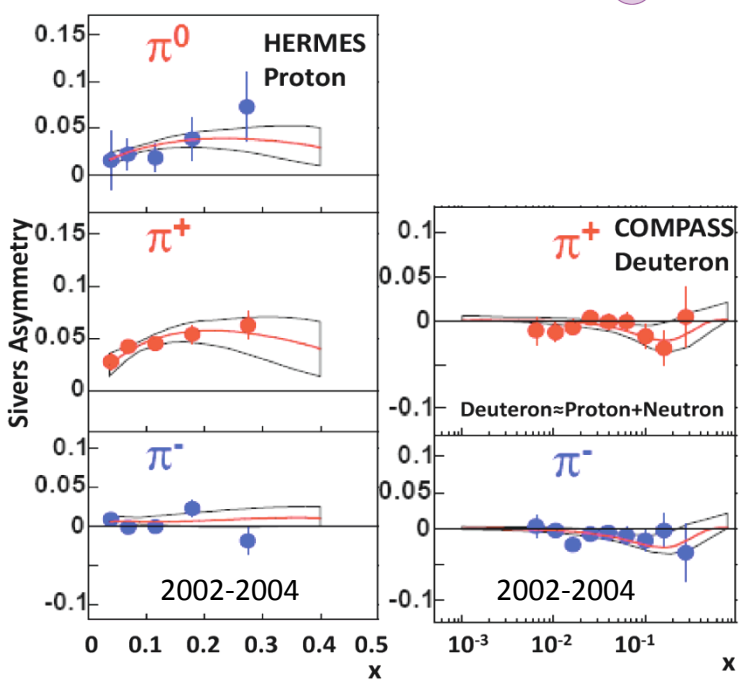


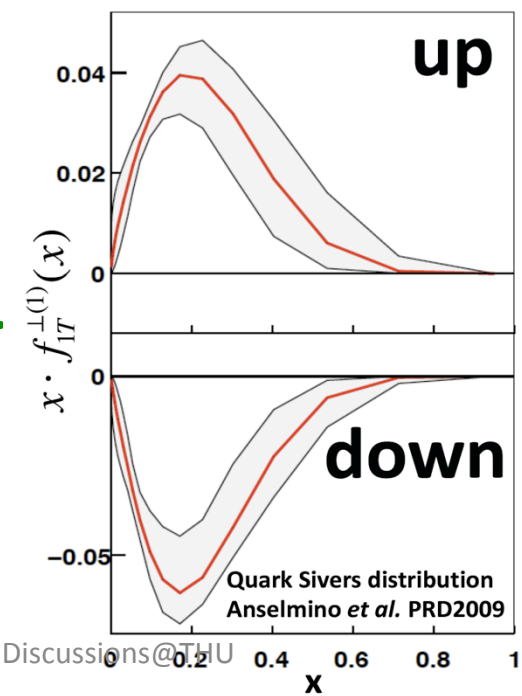
$$N^{\uparrow}(l, l'\, h)$$

$$A_N = \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- **Involves quark fragmentation functions.**
- **Valence quark overwhelmingly dominate.**
- **Limited sensitivity to sea quark leads to zero sea quark Sivers distribution.**

➔ **large uncertainties in Sivers distribution**





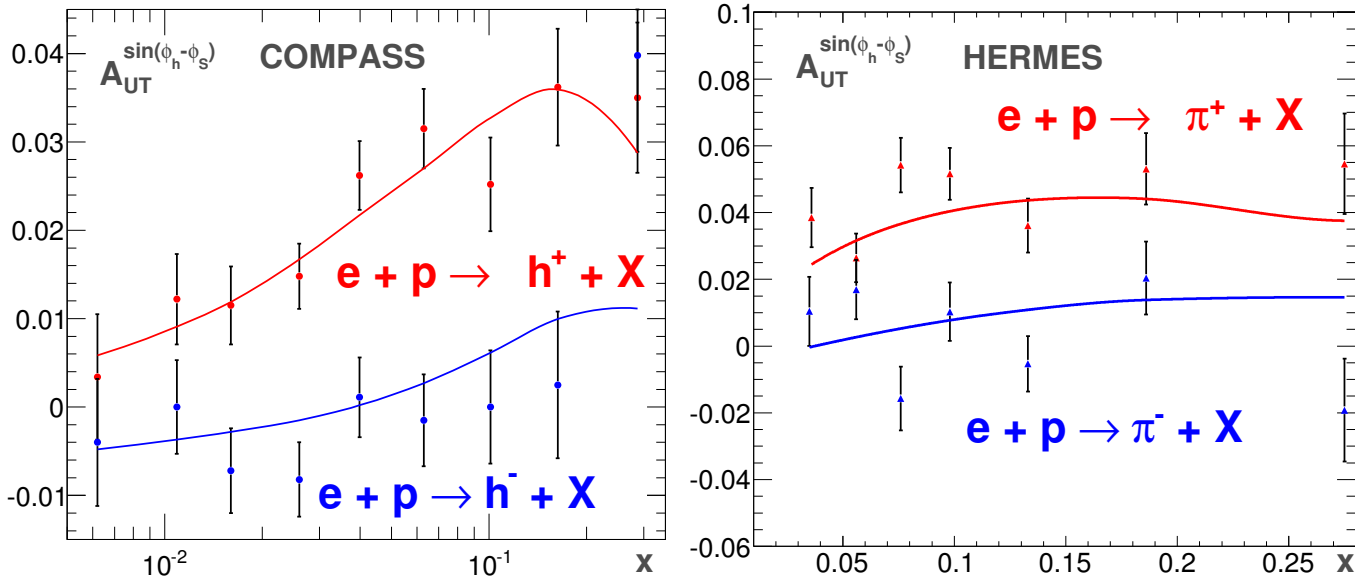
up-quark favors left (L_u>0),

down-quark favors right (L_d<0).

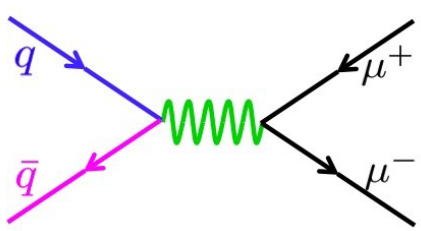
$L_u \approx - L_d$

Quark Sivers Distributions: a new fit includes new data (2013)

Sun and Yuan:
arXiv:1304.5037

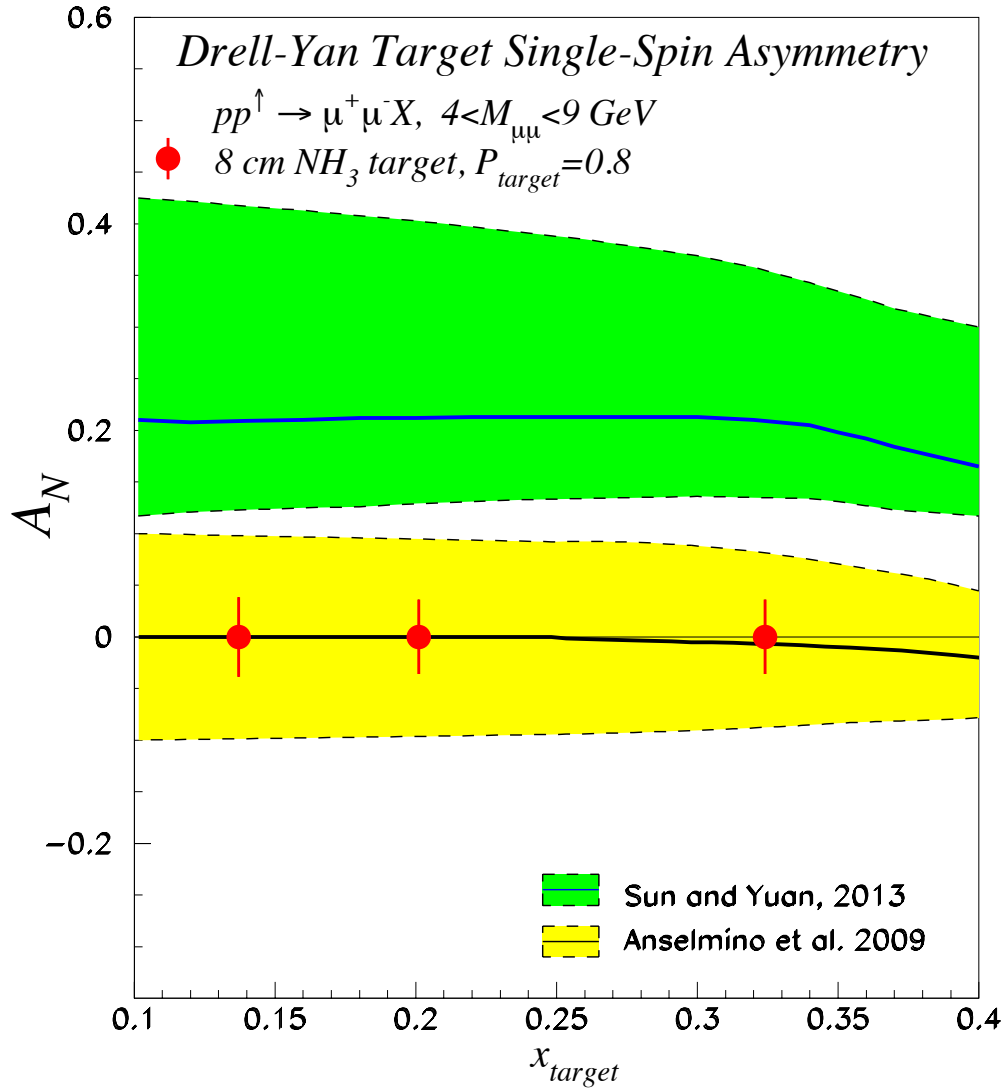


- Include new COMPASS proton target data (2010) and earlier transverse distribution data.
- Take Q^2-evolution effects into account.
- Allow contributions from sea quarks which lead to non-zero ubar Sivers distribution, however with large error bars.
- Predict Drell-Yan target single-spin asymmetry for SeaQuest.



$$A_N^{DY} \propto \frac{u(x_b)\cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b)\cdot \bar{u}(x_t)}$$

Projected Precision with a Polarized Target at SeaQuest



$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

Existing data do not put enough constraints on the sea quark Sivers distribution, neither in sign nor value.

If $A_N \neq 0$, major discovery:

- "Smoking Gun" evidence for $L_{ubar} \neq 0$
- Determine sign and value of ubar Sivers distribution
- Confirm Lattice QCD and Meson Cloud Model expectations
- Help shape physics direction at EIC

If $A_N = 0$:

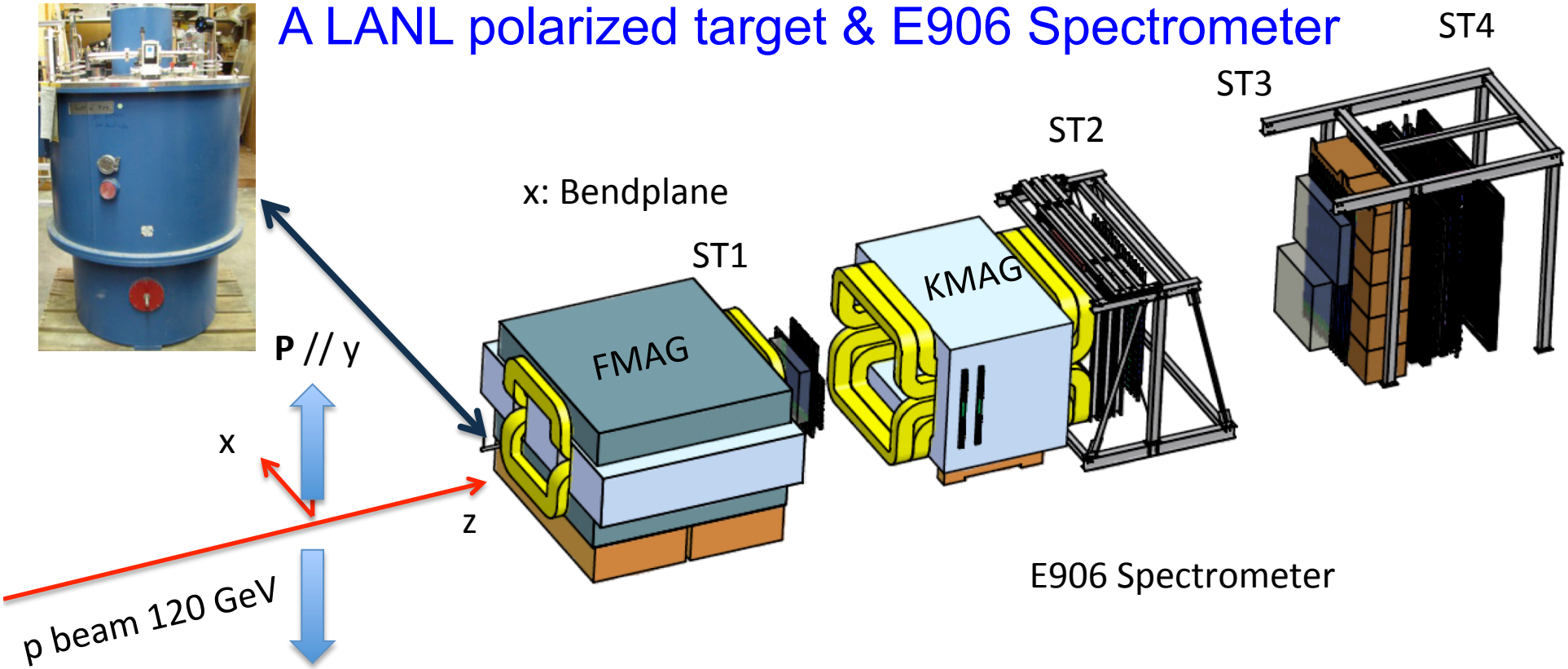
- $L_{ubar} = 0$, spin puzzle more dramatic ?
- Sea flavor asymmetry hard to explain.
- In contradiction to Lattice QCD and Meson Cloud Model.

Statistics shown for one calendar year of running :

$\mathcal{L}_{int}$ = 1.4 *10^{43} /cm^2 ←→ POT = 2.1*10^{18}

Approved for two calendar years of beam time

A LANL polarized target & E906 Spectrometer



- 4 scintillator hodoscope stations (x and y)
- 4 tracking stations (x and stereos)
- Setup close to E906
- $1*10^{13}$ p/spill
- Kinematic Range 4 < M <8 GeV

In a similar set up as in FNAL E906

- **Can perform world's highest luminosity polarized target Drell-Yan measurement at Fermilab's 120 GeV proton beam**

The Polarized Target System (UVa/SLAC/JLab)

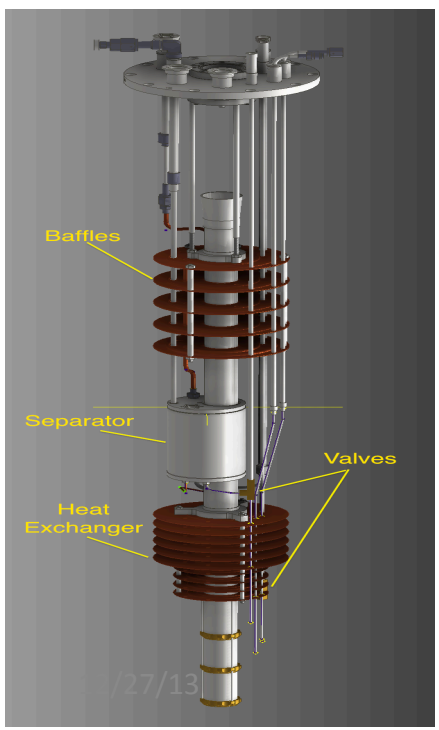
Magnet from LANL

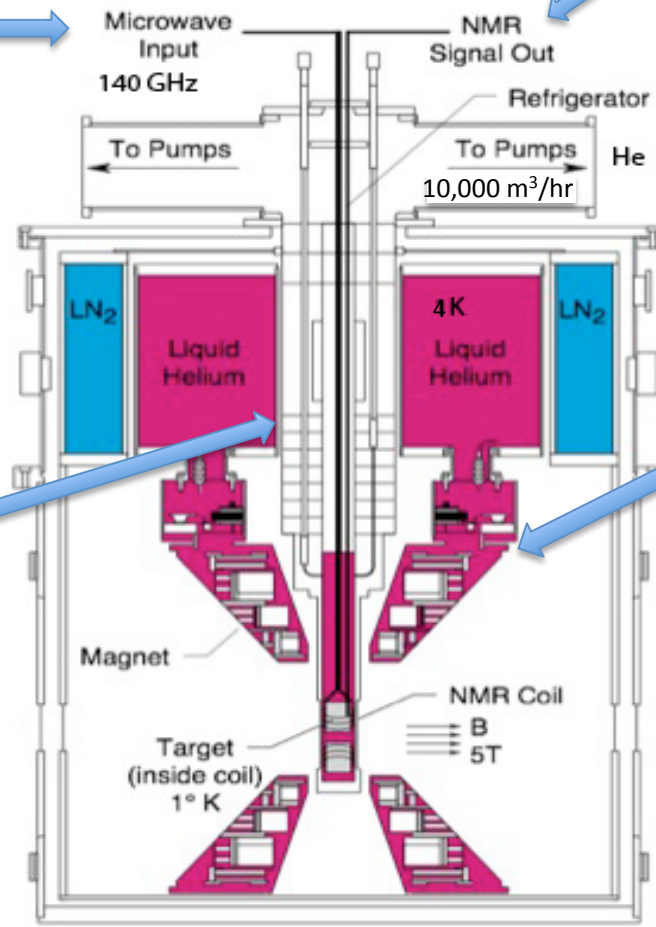
Measure polarization

Microwave: Induces electron spin flips

- Tube + Power equip:

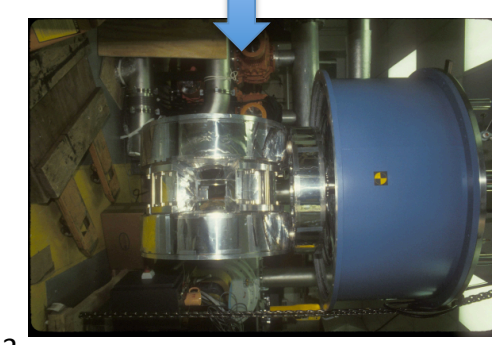
Cryostat: UVa





Roots pump system used to pump on ^{4}He vapor to reach 1K

Superconducting Coils for Magnet: 5T Rotation needed

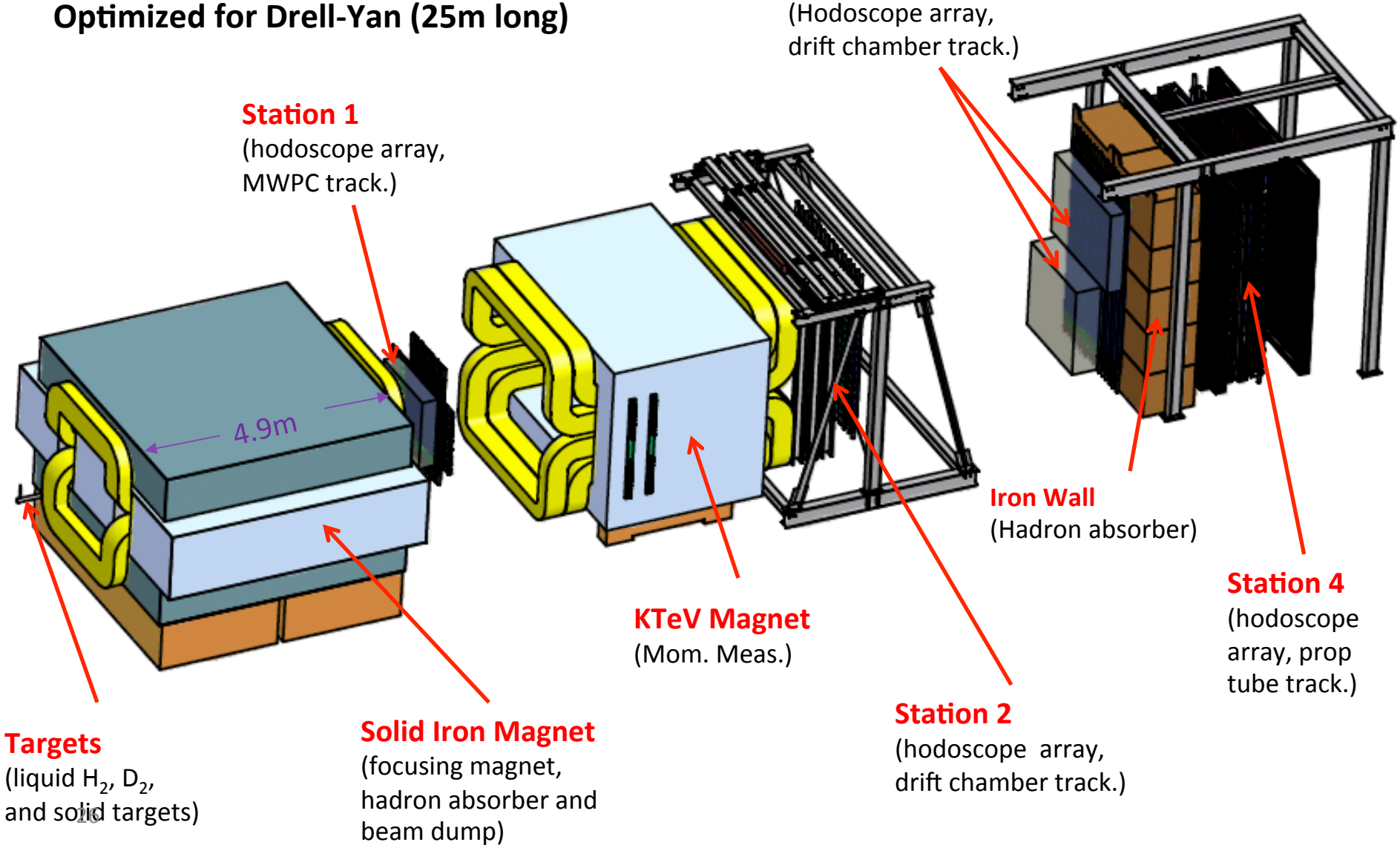


Target material: frozen NH_3

Irradiation @ NIST

Drell-Yan Spectrometer for E906
A simple Spectrometer for SeaQuest

Optimized for Drell-Yan (25m long)



Experiment Layout Top View

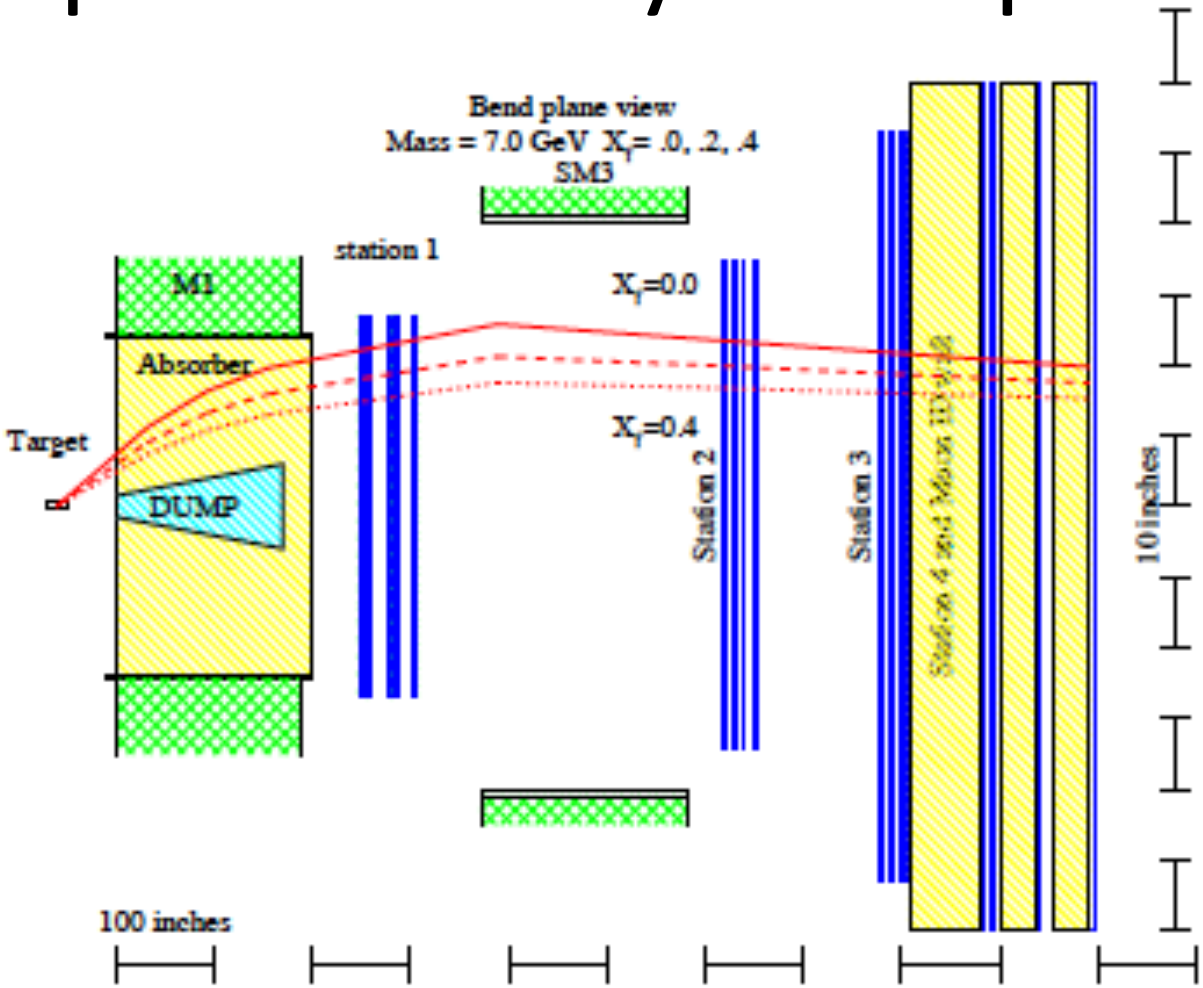


FIG. 12: Bend plane view of the trajectories of one of the two muons resulting from the muonic decay of a 7 GeV virtual photon (which has x_F of 0.0, 0.2 or 0.4) in an 8 T-m spectrometer.

Experiment Layout Side View

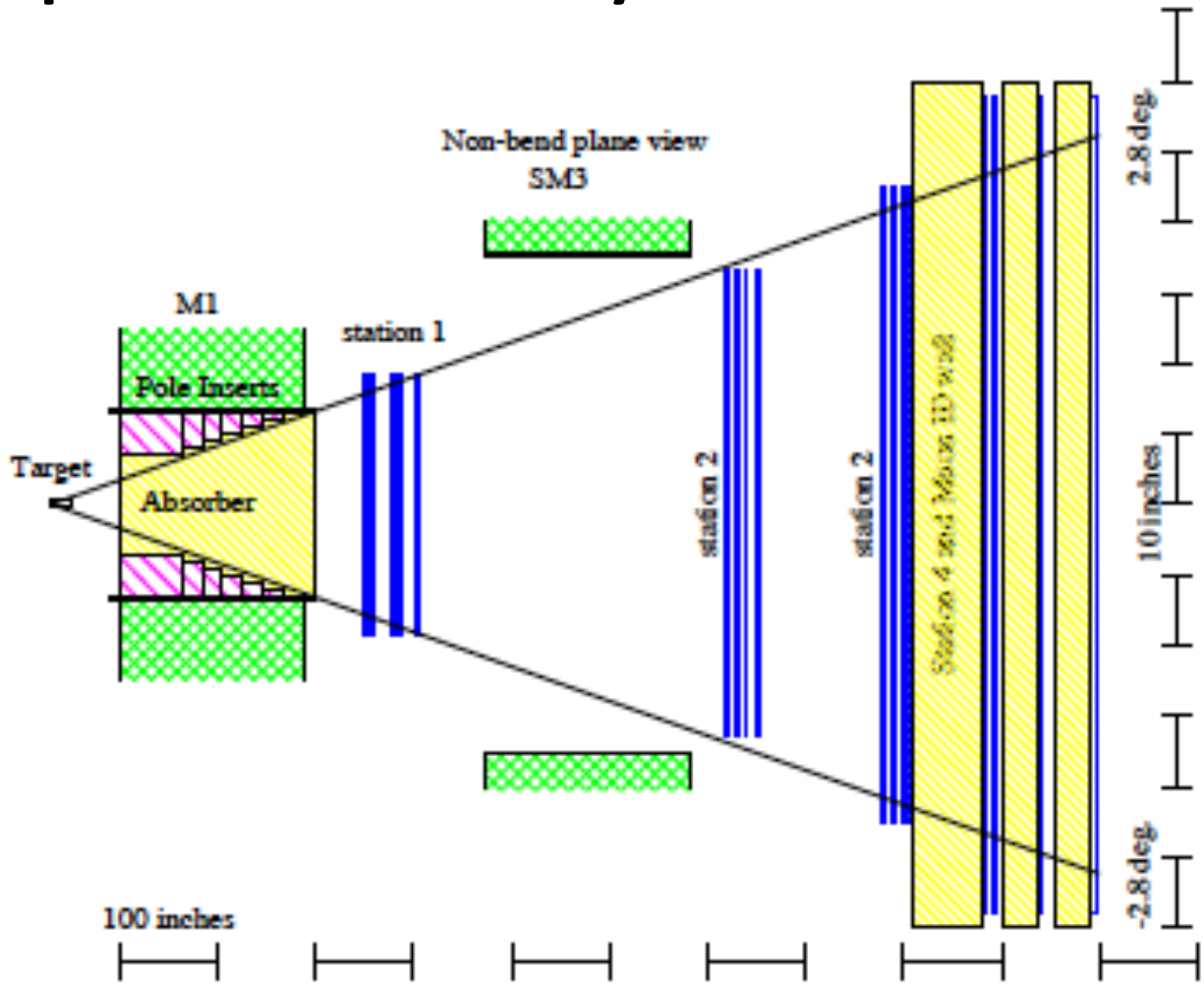
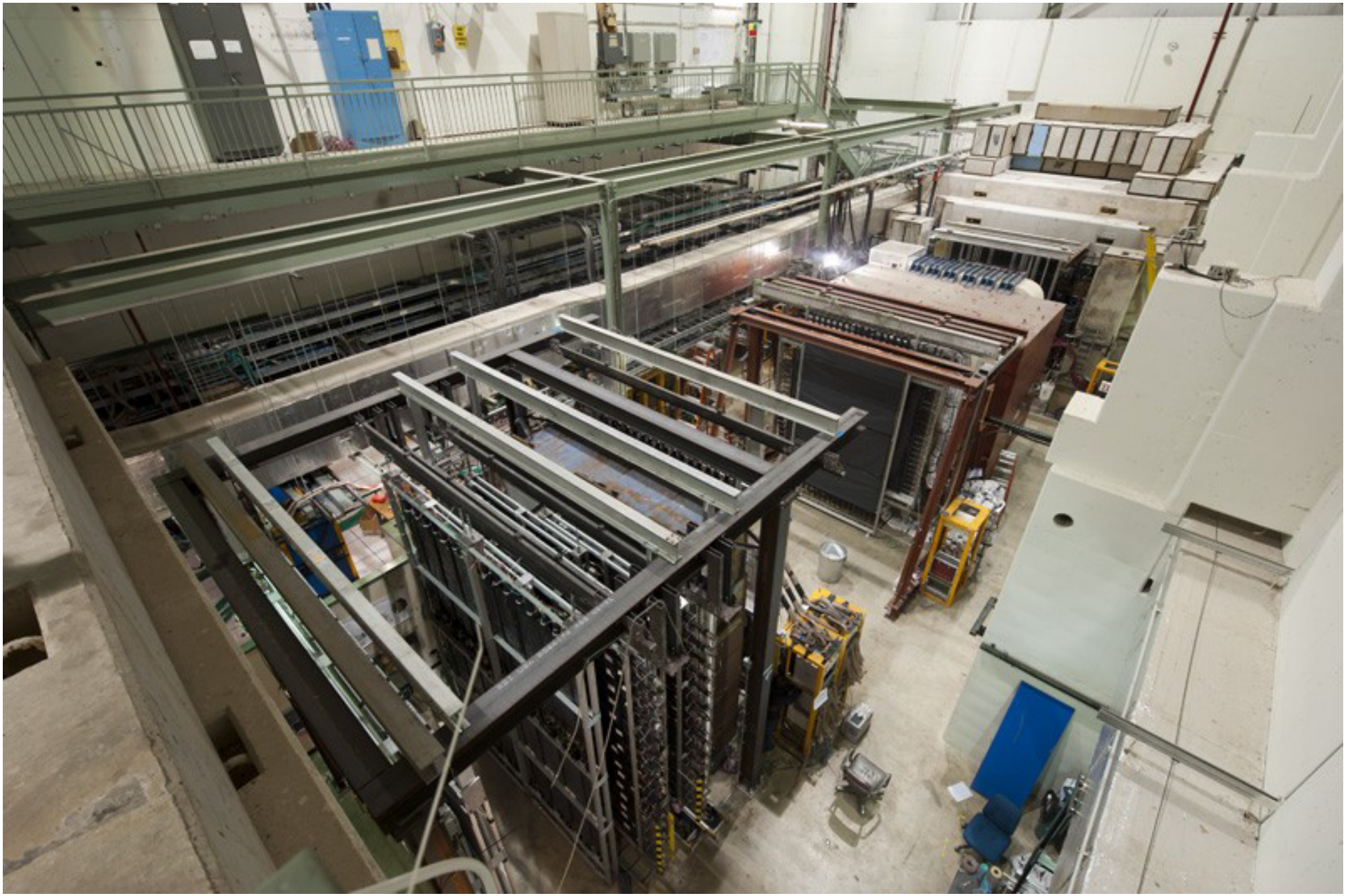


FIG. 13: Non-bend plane view in an 8 T-m spectrometer. Only muons which pass around the beam dump in the bend plane contribute to the acceptance and so the beam dump is not shown.

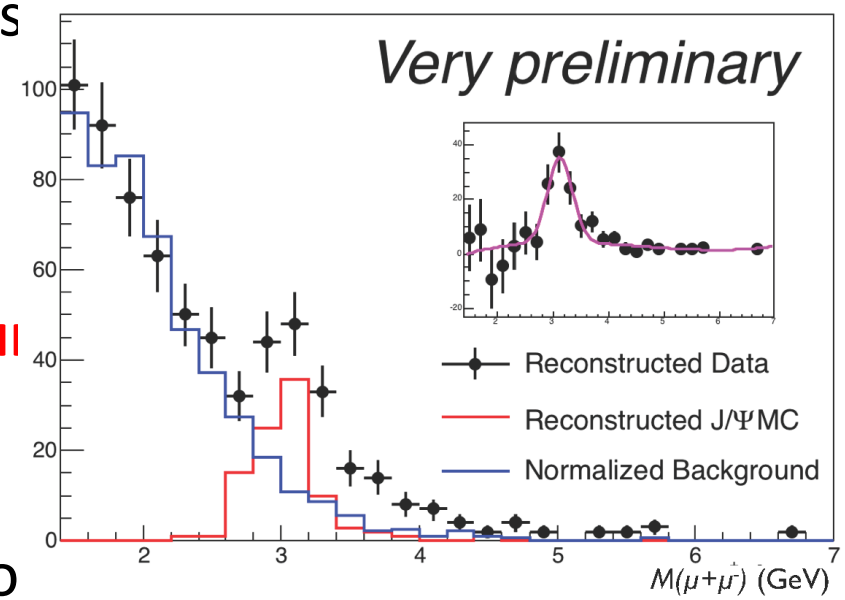


From Commissioning Run to Science Run

- Commissioning Run (late Feb. 2012 – April 30th, 2012)
- First beam in E906 on March 8th, 2012
- Extensive beam tuning by the Fermilab accelerator group
  - 1 x10^{12} protons/s (5 s spill/min)
  - 120 GeV/c
- All the detector subsystems worked
  - improvements for the production run completed
- Main Injector shut down began on May 1st , 2012
- Reconstructable dimuon events s

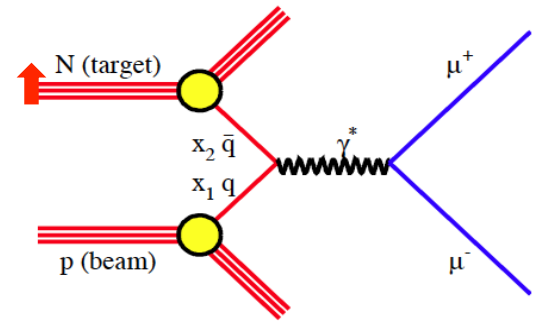
$$M_{J/\Psi} = 3.12 \pm 0.05 \text{ GeV}$$
$$\sigma = 0.23 \pm 0.07 \text{ GeV}$$

A successful commissioning ru



- Science Run started Nov. 2013 fo

Physics Summary of E-1039



- **We know almost nothing about sea quarks angular momentum.**
- **Quark orbital angular momentum leads to quark Sivers distribution.**
- **Identifying a non-vanishing sea quark Sivers distribution could lead to a major breakthrough in nucleon structure.**
- **Polarized target D-Y at Fermilab's SeaQuest provides an unique opportunity to pin down sea quark's angular momentum.**

Does Drell-Yan yield depend on target's spin direction?

$$A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \stackrel{?}{\neq} 0$$

$(A_N \equiv 0 \ \text{ if } L_{\bar{u}} = 0)$

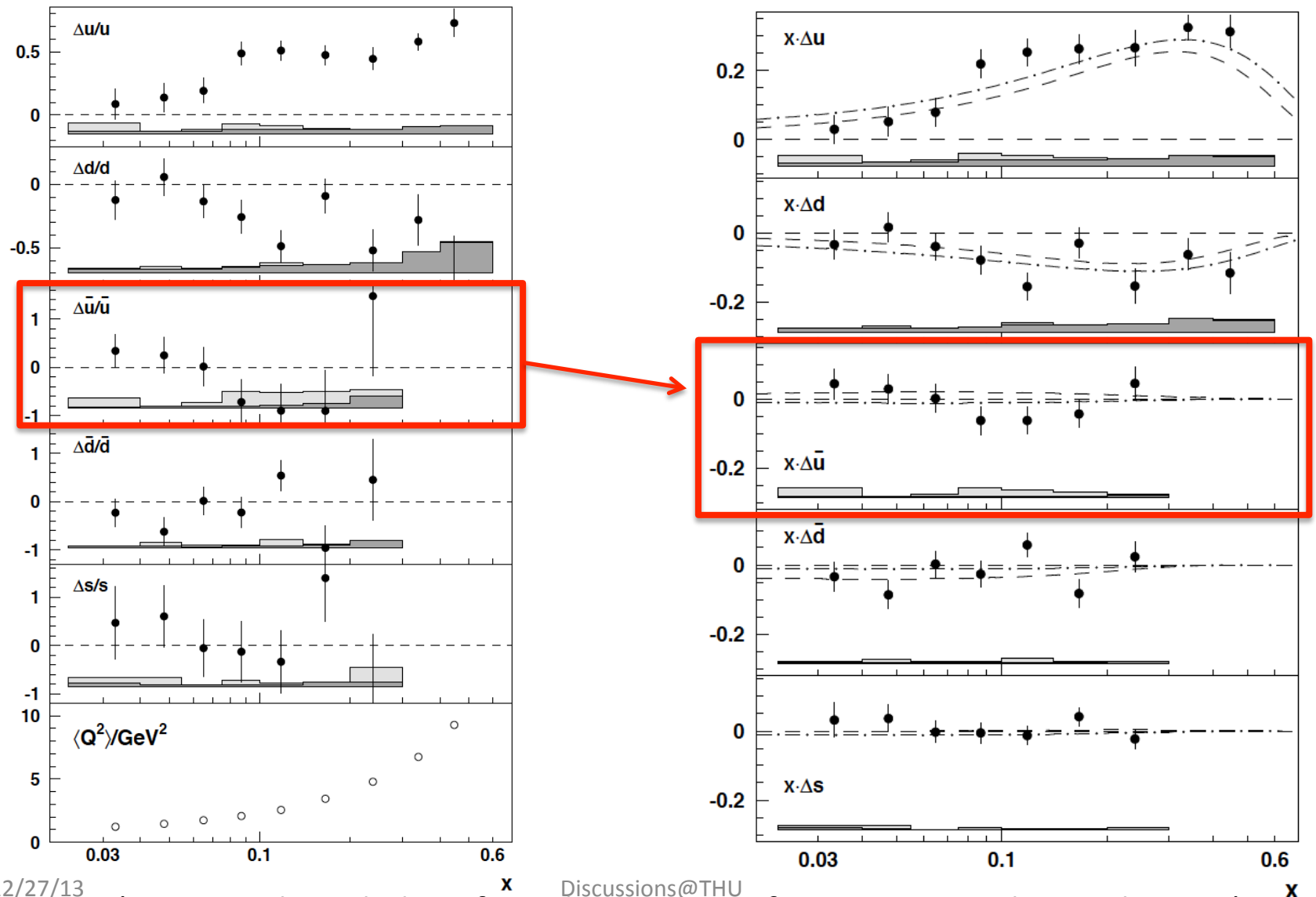
$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

Beyond Drell-Yan Single Spin Asymmetry …

In the longer term future, if we have both polarized beam and polarized target. Drell-Yan double-spin asymmetry can provide accesses to sea quark's

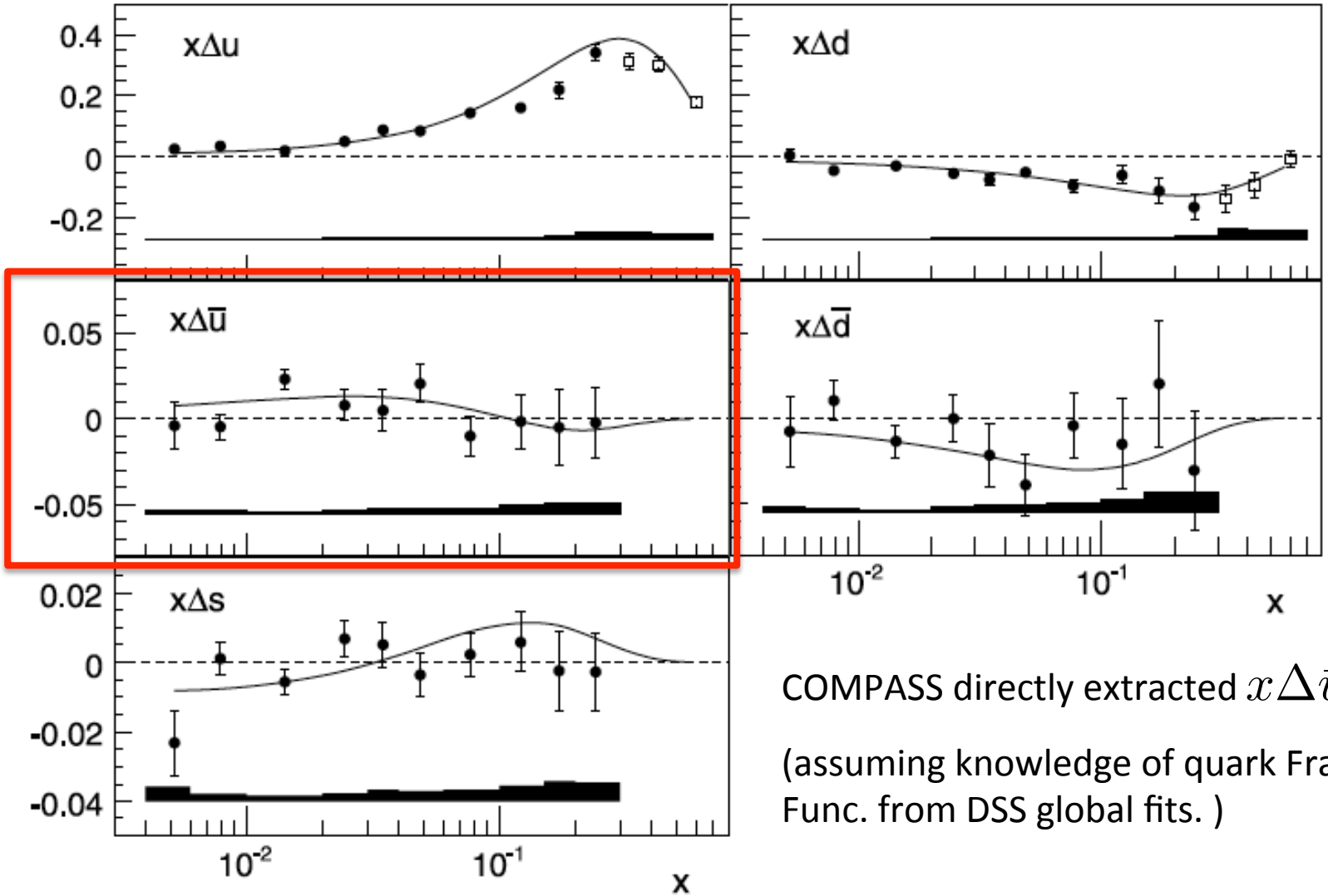
- **Polarization (A_{LL})**
- **Transversity (A_{TT})**

HERMES 2005 Results of Spin-Flavor Decomposition: from SIDIS Double-Spin Asymmetries



(assuming knowledge of quark Frag. Func. from Monte Carlo simulations.)

COMPASS 2010 Spin-Flavor Decomposition

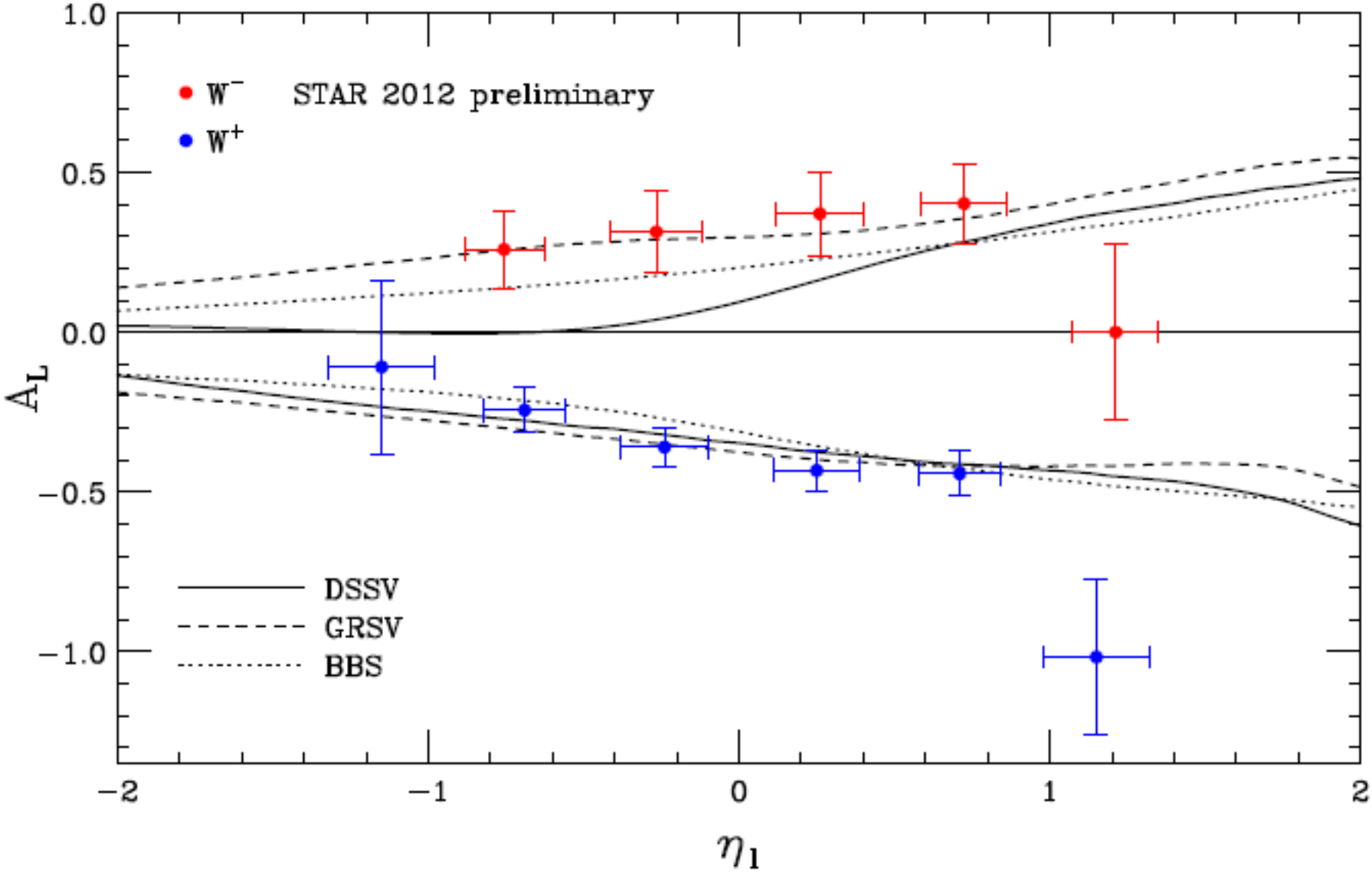


COMPASS directly extracted $x\Delta\bar{u}$

(assuming knowledge of quark Frag. Func. from DSS global fits.)

COMPASS data are not shown in fsPHENIX plot, not sure how to propagate error bars to $\Delta\bar{u}/\bar{u}$

STAR Data



Soffer, Trento Nucleon Sea Workshop, July, 2013

We define Drell-Yan longitudinally polarized beam-target double-spin asymmetry A_{LL} as:

$$A_{LL}^{DY} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta\sigma_{DY}}{\sigma_{DY}}$$

i.e, the ratio of the difference over the sum (or asymmetry) between the spin-aligned and spin-anti-aligned Drell-Yan cross sections, at the Leading Order, we have:

$$A_{LL}^{DY} = -\frac{\sum_q e_q^2\{\Delta q(x_1)\Delta\bar{q}(x_2) + \Delta\bar{q}(x_1)\Delta q(x_2)\}}{\sum_q e_q^2\{q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\}}$$

$$A_{pp} \approx -\frac{\Delta u_1}{u_1}\frac{\Delta\bar{u}_2}{\bar{u}_2} \qquad A_{pn} \approx -\frac{\Delta u_1}{u_1}\frac{\Delta\bar{d}_2}{\bar{d}_2}$$

if anti-quarks carry no spin ➔ $A_{LL}^{DY} \equiv 0$!!!

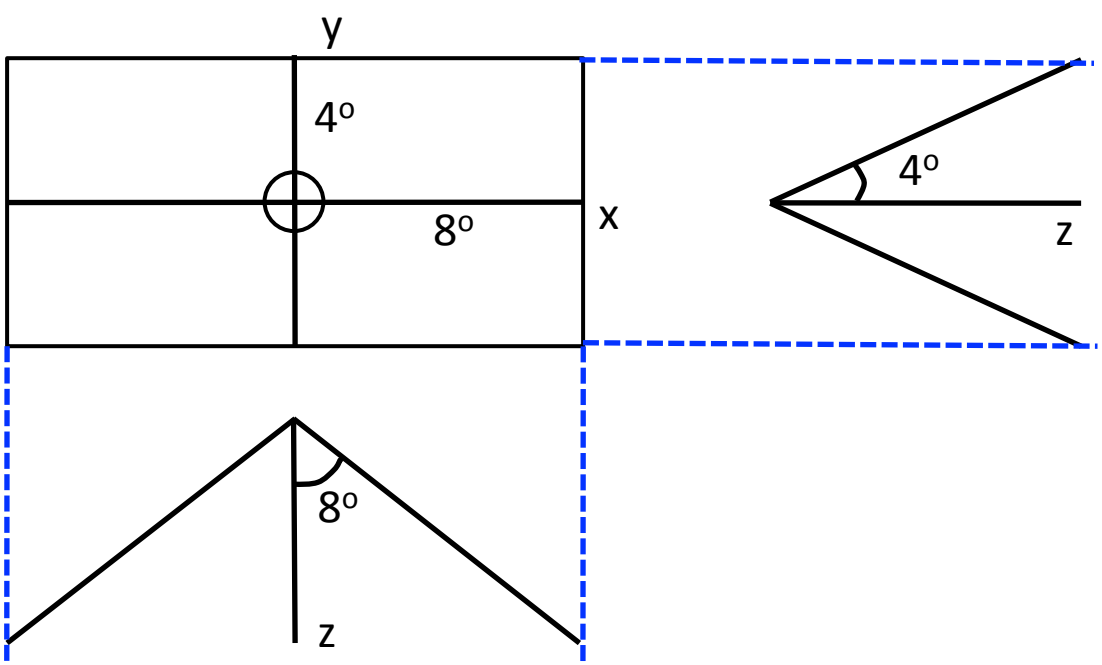
$$A_{LL}^{DY} = -\frac{\sum_q e_q^2\{\Delta q(x_1)\Delta\bar{q}(x_2) + \Delta\bar{q}(x_1)\Delta q(x_2)\}}{\sum_q e_q^2\{q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\}}$$

$$A_{pp} = -\frac{4\Delta u_1\Delta\bar{u}_2 + \Delta d_1\Delta\bar{d}_2 + \ldots}{4u_1\bar{u}_2 + d_1\bar{d}_2 + \ldots}$$

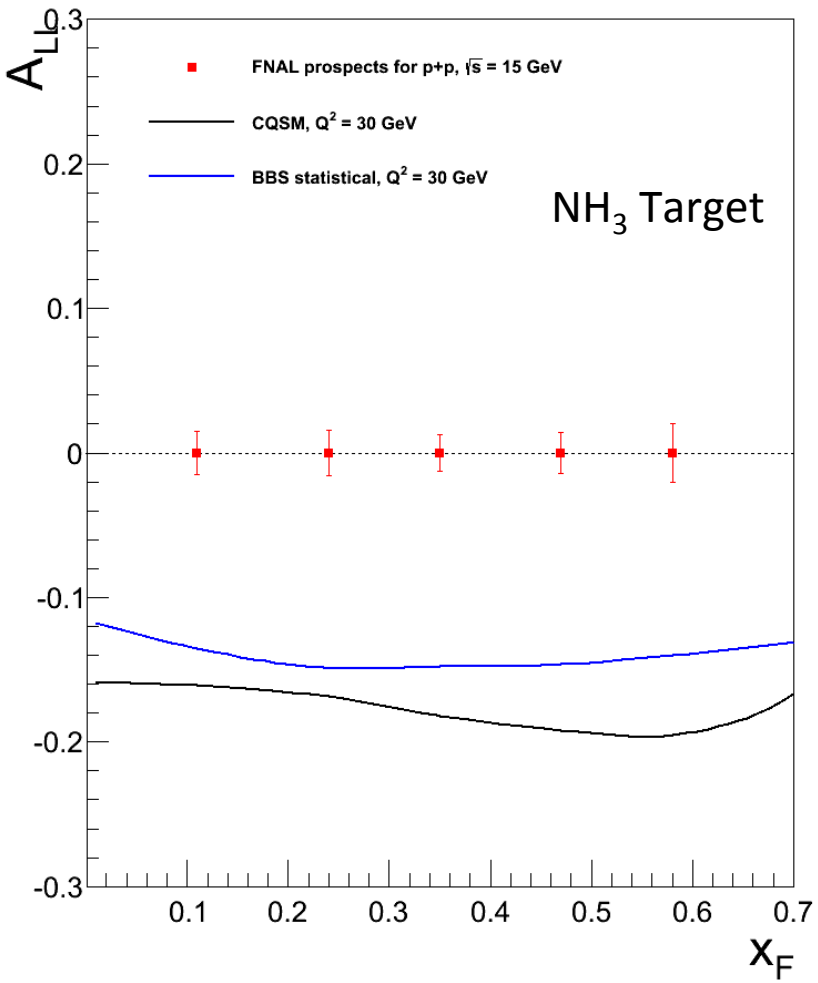
$$A_{pn} = -\frac{4\Delta u_1\Delta\bar{d}_2 + \Delta d_1\Delta\bar{u}_2 + \ldots}{4u_1\bar{d}_2 + d_1\bar{u}_2 + \ldots}$$

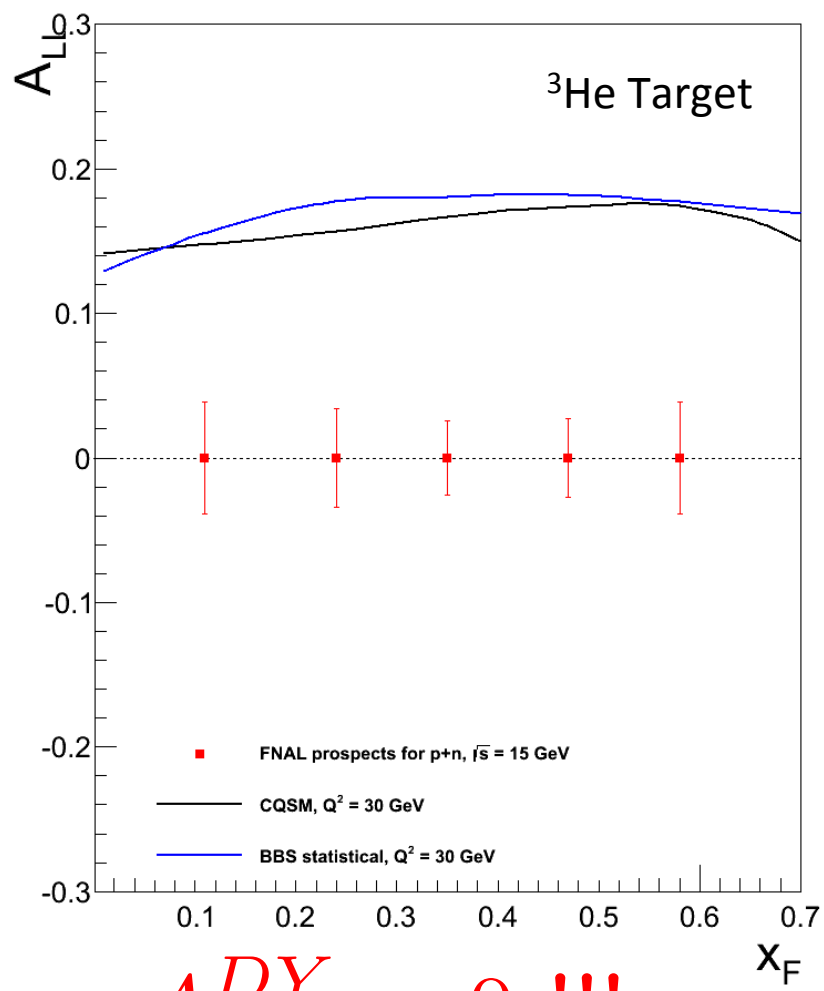
Geometry of an "ideal" spectrometer for FNAL Drell-Yan

- Vertical acceptance ±4 degree
- Horizontal acceptance ±8 degree
- Beam line ±1 degree



FNAL "prospected data" vs. theory predictions

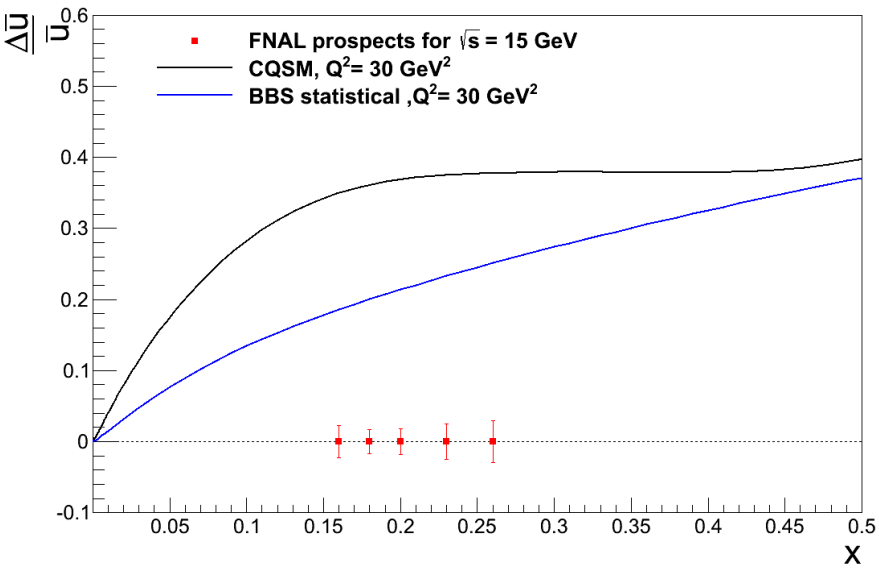


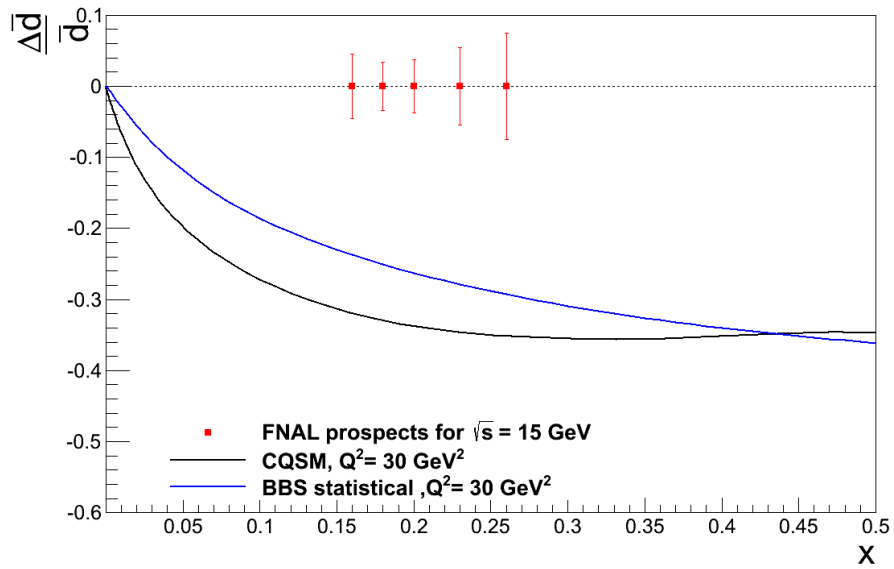


if anti-quarks carry no spin ➔ $A_{LL}^{DY} \equiv 0$!!!

Chiral Quark Soliton Model: Wakamatsu, 2010 BBS statistical model: Soffer et al 2004.

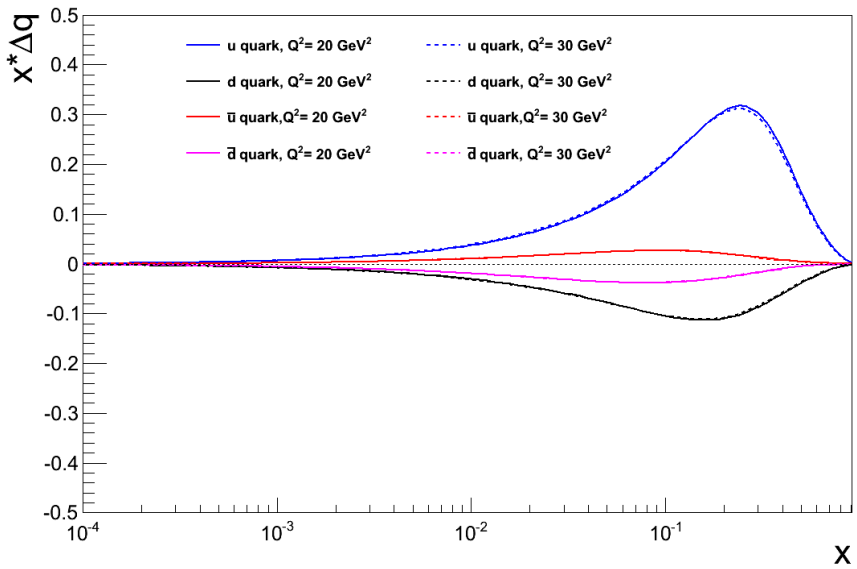
Translate into Δubar/ubar, Δdbar/dbar - Fermilab kinematics

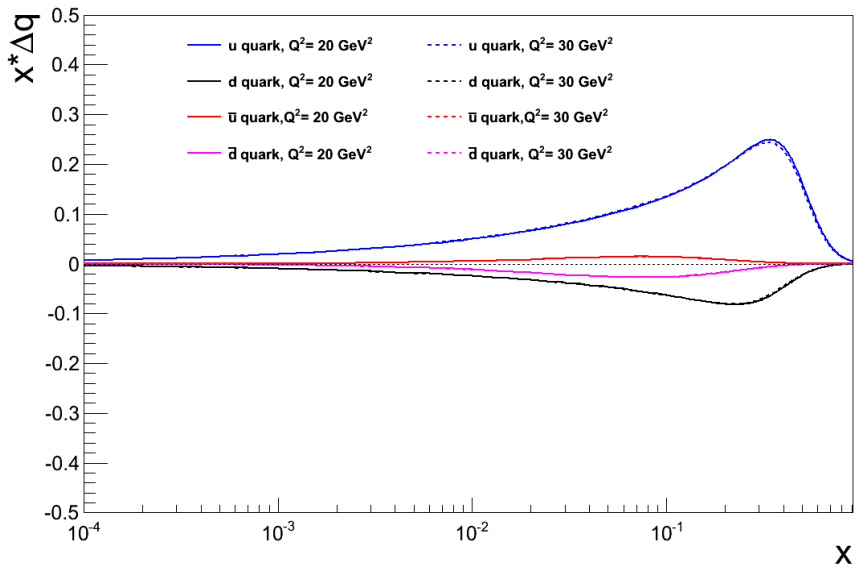




Chiral Quark Soliton Model: Wakamatsu, 2010. BBS statistical model: Soffer et al 2004.

Polarized PDF

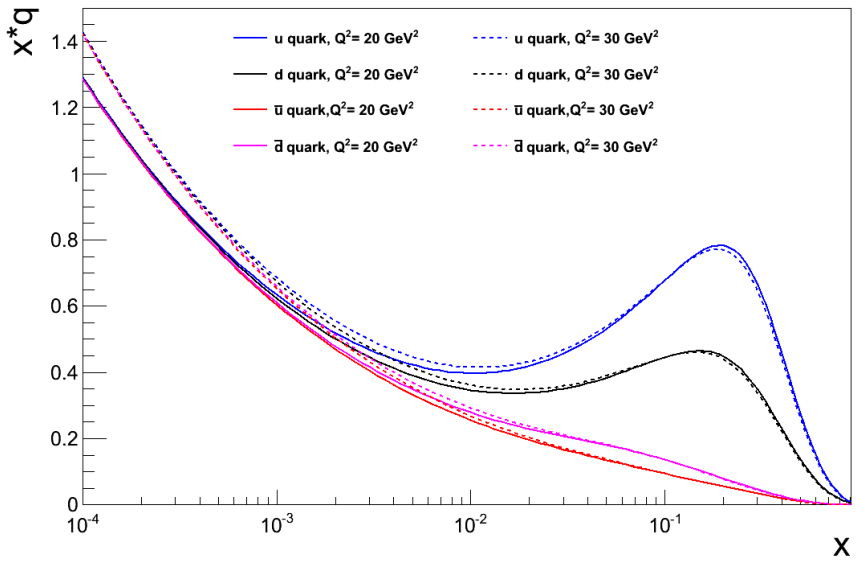




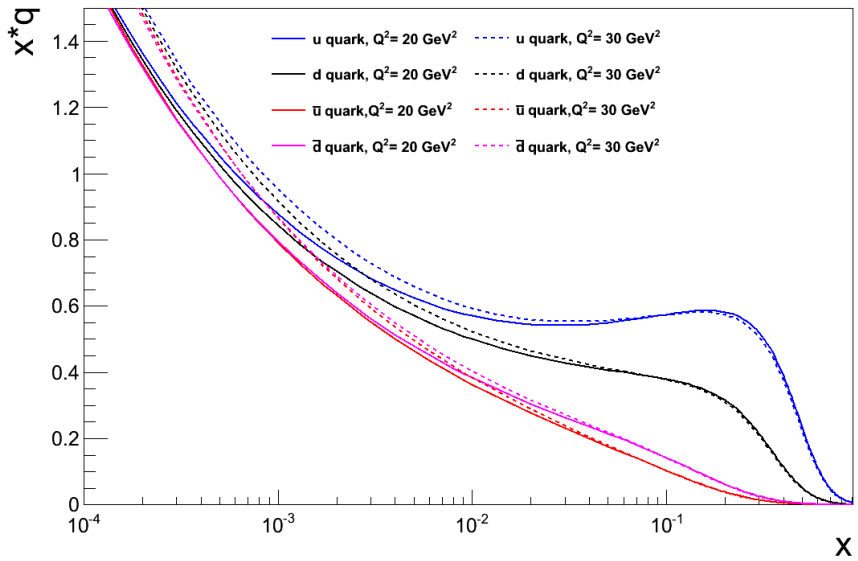
Chiral Quark Soliton Model: Wakamatsu, 2010.

BBS statistical model: Soffer et al 2004.

Unpolarized PDF

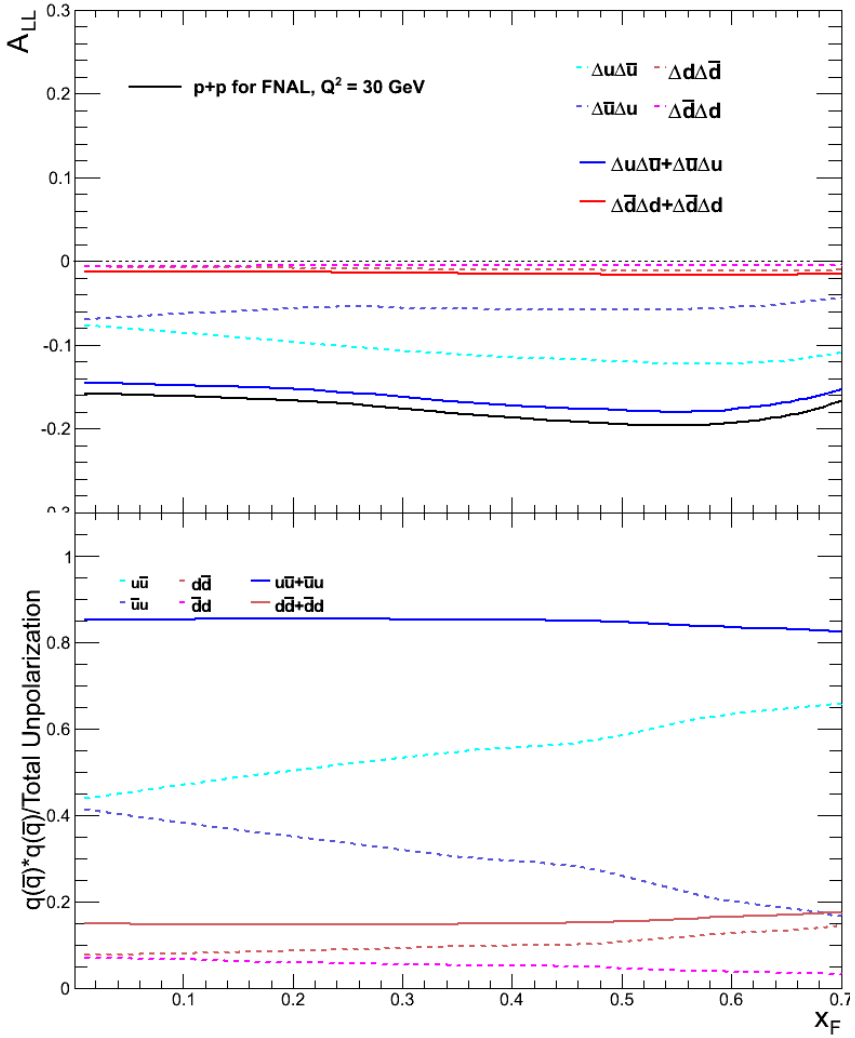


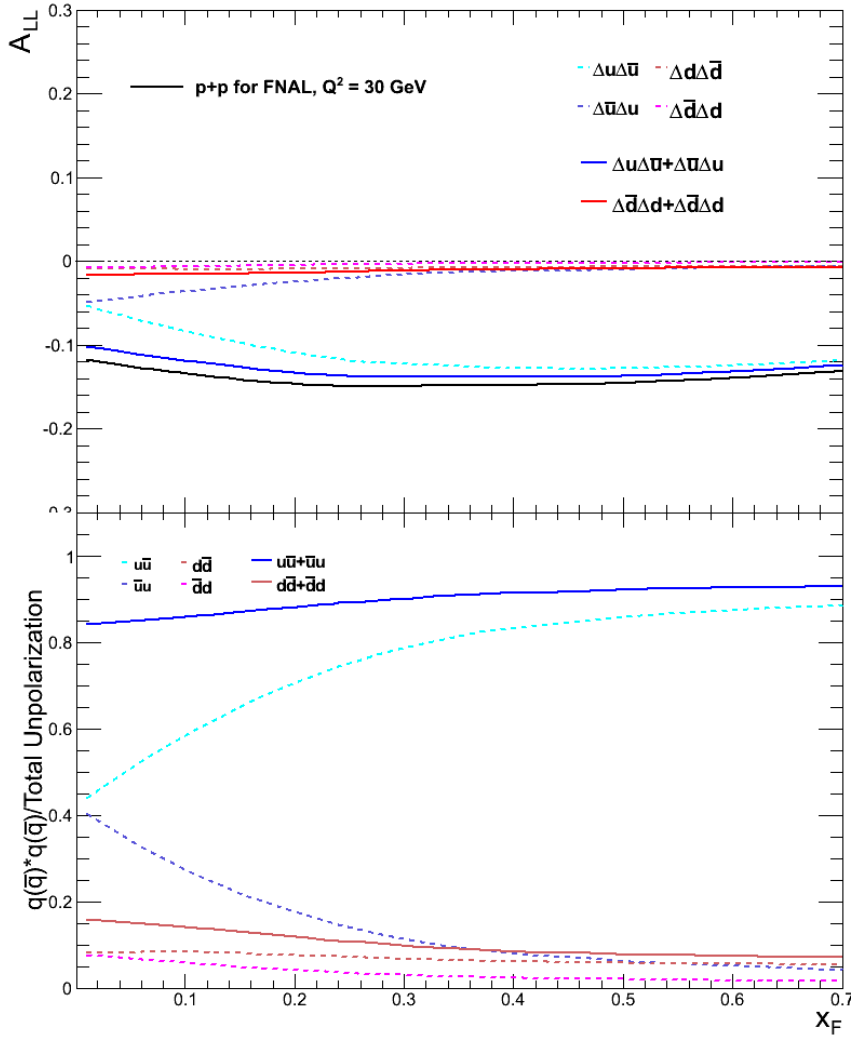
Chiral Quark Soliton Model: Wakamatsu, 2010.



BBS statistical model: Soffer et al 2004.

A_{LL} of FNAL p+p DY Break into Flavors





Chiral Quark Soliton Model: Wakamatsu, 2010.

BBS statistical model: Soffer et al 2004.

A_{TT} to Access Transversity

$$A_{TT}^{DY} = \frac{\sin^2\theta\cos 2\phi}{1+\cos^2\theta} \cdot \frac{\sum_q e_q^2\{\delta q(x_1)\delta\bar{q}(x_2) + \delta\bar{q}(x_1)\delta q(x_2)\}}{\sum_q e_q^2\{q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\}}$$

where θ is the polar angle of either lepton in the rest frame of the virtual photon, and ϕ is the azimuthal angle between the direction of the polarization and the normal to the plane of the di-lepton decay.

<cos(2ϕ)>≈2/π, if cover all DY azimuthal angles.

$$\left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle = 0.821$$ for the "idea spectrometer" setup.

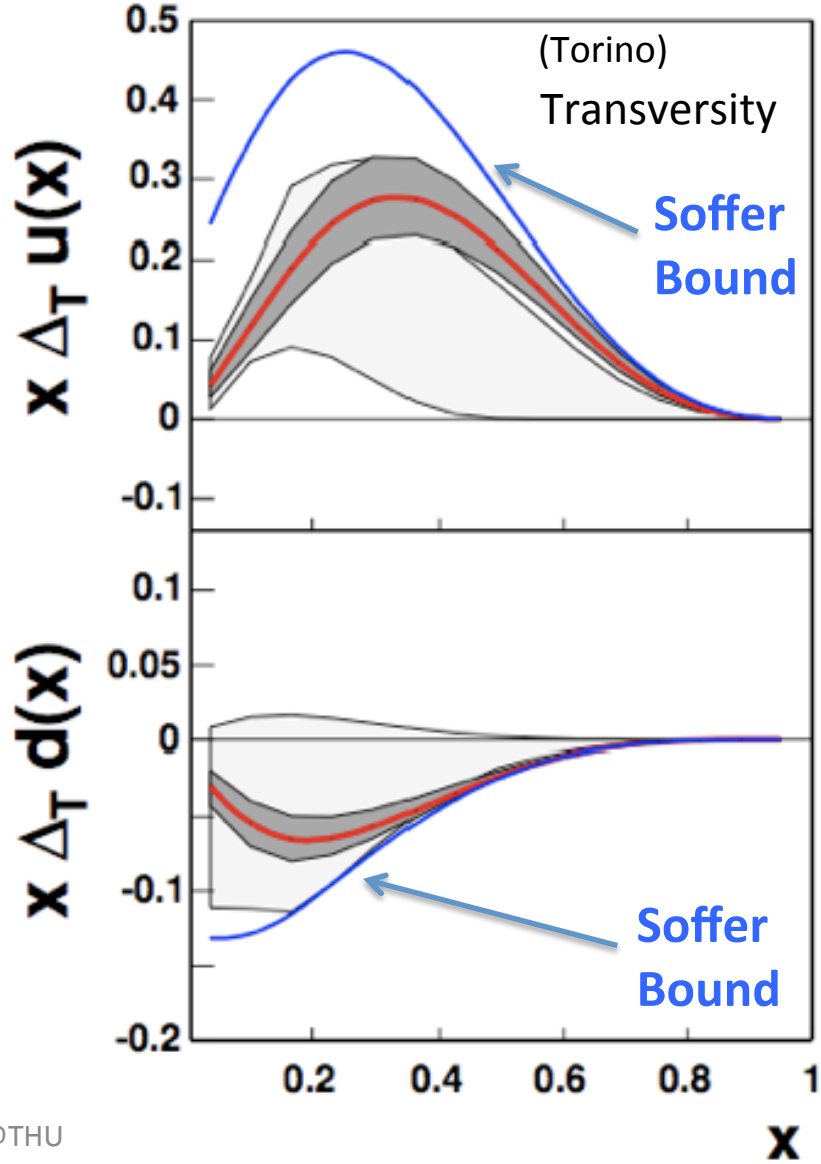
Lacking knowledge on sea transversity, we took the Soffer (positivity) bounds for anti-quark:

$$\delta q(x) \leq \frac{1}{2}|q(x) + \Delta q(x)| \qquad \delta\bar{q}(x) \leq \frac{1}{2}|\bar{q}(x) + \Delta\bar{q}(x)|$$

Valance quark transversity from Anselmino group's fit.

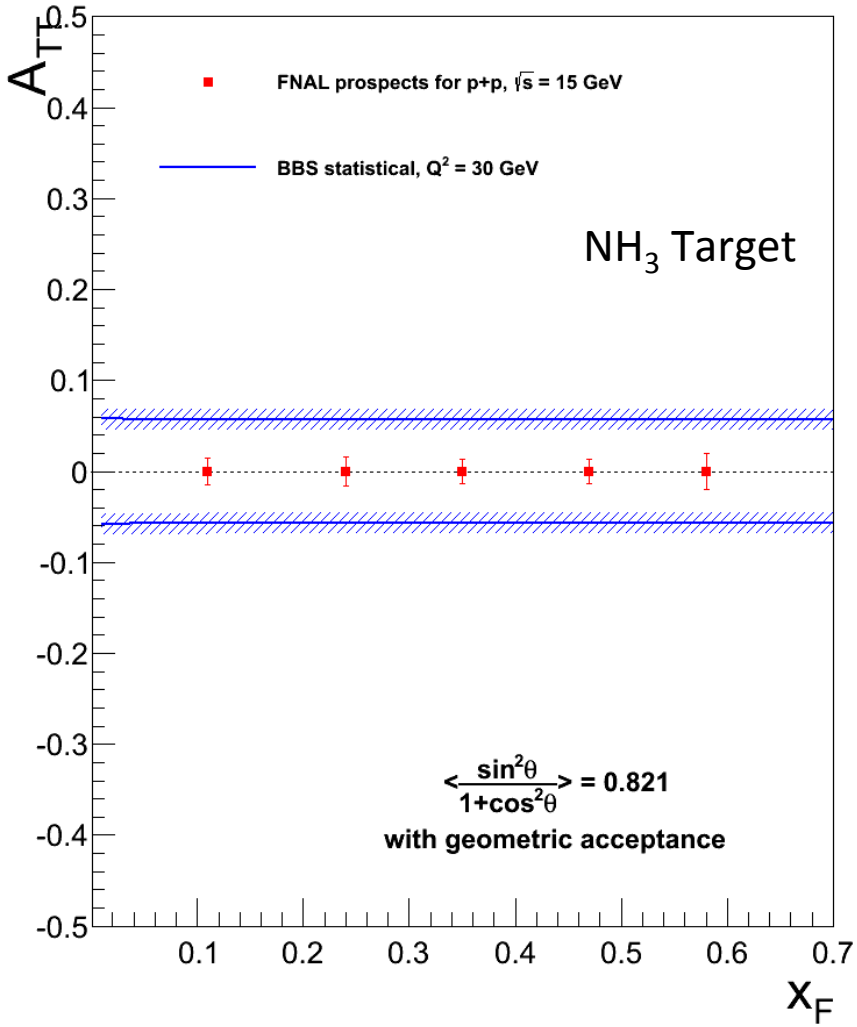
Existing Fits: Quark Transversity:

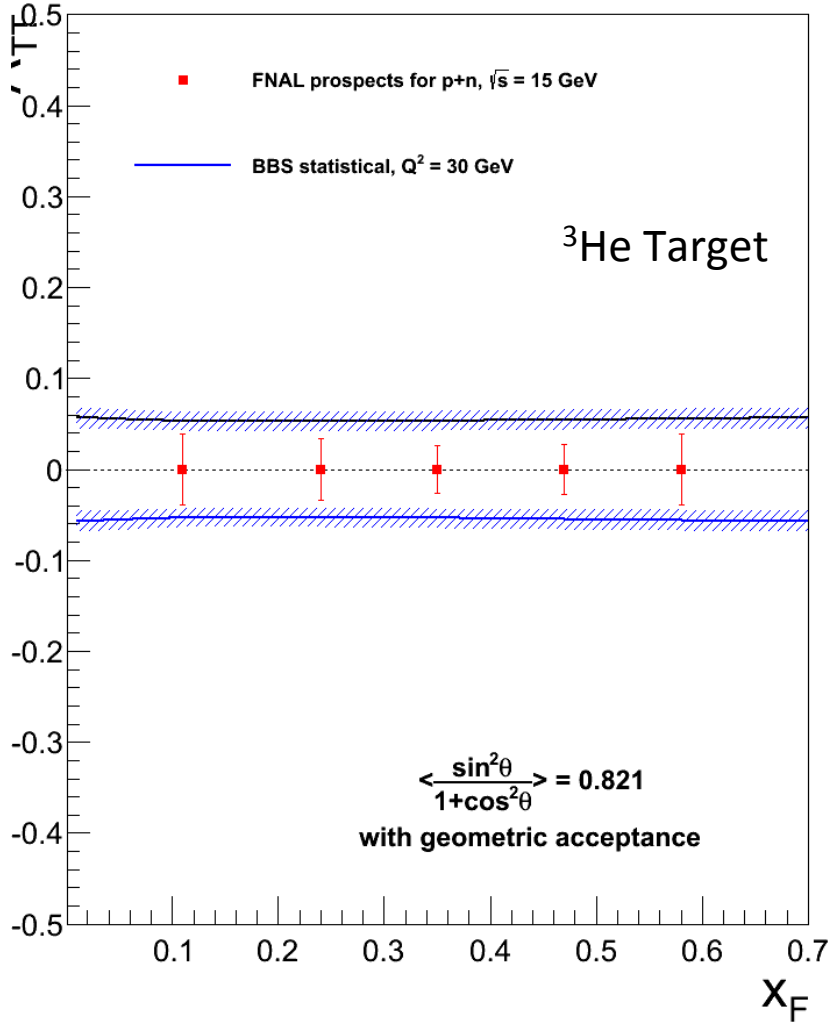
fit of semi-inclusive DIS data



From Collins asymmetry of semi-inclusive DIS (HERMES proton, COMPASS deuteron), and BELLE's correlation asymmetry in $e^+e^- \rightarrow \pi^+\pi^-$

A_{TT} FNAL "prospected data" vs. theory predictions





My Questions:

(Reliable) Predictions
or upper bounds for :

- **Sea quark polarization ?**
- **Sea quark transversity ?**
- **Sea quark Sivers distribution ?**

Summary-I

Polarized Target Drell-Yan at FNAL

E-1039 Polarized target SSA, access sea quark Sivers.

- **Sea Quark Angular Momentum (A_{UT})**

In the future, with both polarized beam and target:

- **Sea Quark Polarization (A_{LL})**
- **Sea Quark Transversity (A_{TT})**

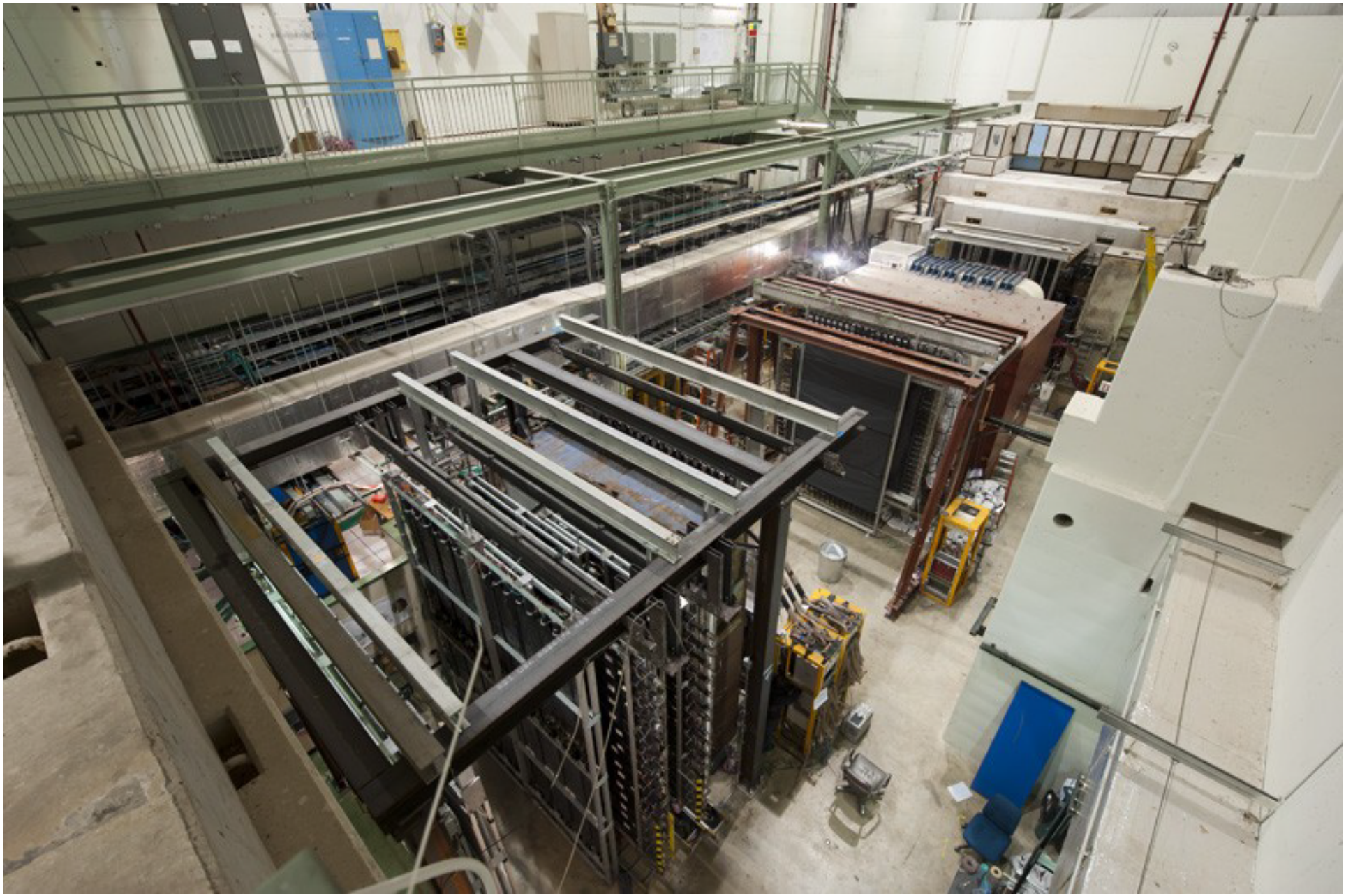
Outline for Wednesday

I will discuss experimental results, physics impacts, interpretations, and the connections of the observed single spin asymmetry (SSA) phenomena in:

- Inclusive hadron SSA observed in proton-proton collision at Fermilab and RHIC.
- Target SSA in semi-inclusive deep inelastic scattering (SIDIS).
- **New Jefferson Lab results of polarized target SSA in inclusive hadron production e+N->h+X (arXiv_1311:1866)**

I will also discuss on-going and future experimental efforts, including :

- Polarized target Drell-Yan experiments at Fermilab (E-1039).
- **Forward jet production asymmetry in p+p with the upgraded PHENIX experiment at RHIC.**

I will raise my own questions to PKU colleagues during the seminar for discussions.

Backup Slides