Sivers Function: Status + Plans

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E1039 Collaboration Meeting
(24-October-2019)

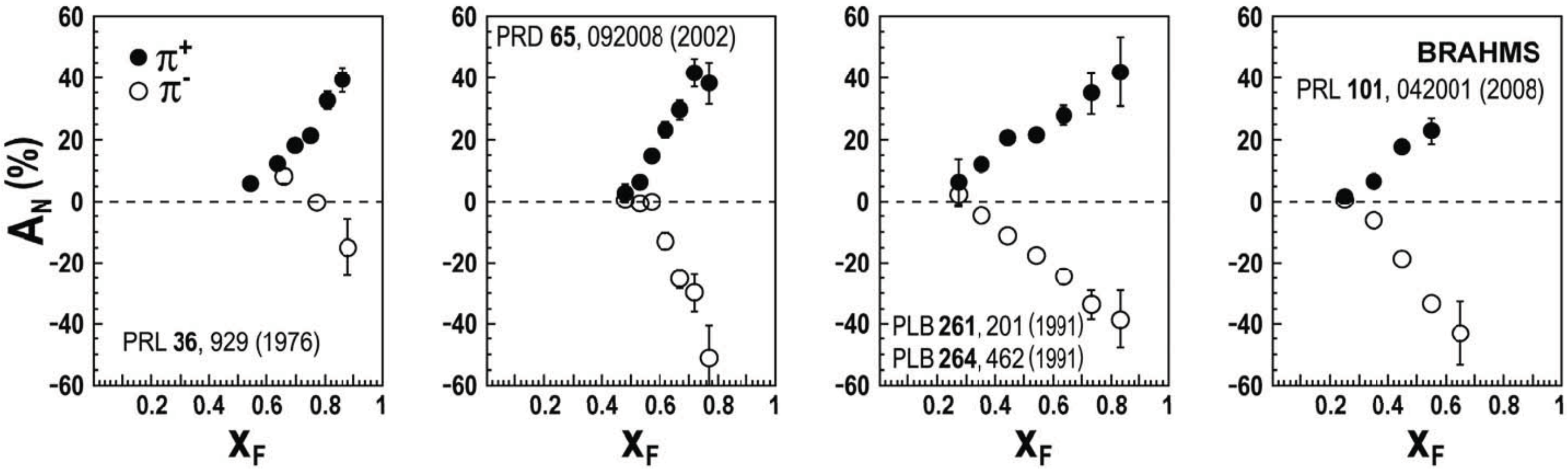
- Introduction
- SIDIS measurements
- Sign Change
- Star and COMPASS measurements
- DY at Fermilab

This work is supported by NSF

Sivers and Transverse Single Spin Asymmetries (SSA)

- Sivers suggested in 1990 “that the k_T distribution of a quark in a hadron could have an azimuthal asymmetry when the initial hadron has transverse polarization”
  → explanation for (huge) SSA for forward meson production in hadron-hadron interactions observed over a wide range of c.m. energies

$\sqrt{s}$ = ANL – 4.9 GeV | BNL – 6.6 GeV | FNAL – 20 GeV | BNL – 62.4 GeV



C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009

2 issues:

- at hard (enough) scales, SSA’s expected to go to zero (pQCD)
- Collins claims: $f_{1T}^{\perp}=0$ because QCD is time-reversal invariant NPB396,161(1993)

Sivers and Transverse Single Spin Asymmetries (SSA)

- Sivers suggested in 1990 "that the k_T distribution of a quark in a hadron could have an azimuthal asymmetry when the initial hadron has transverse polarization"
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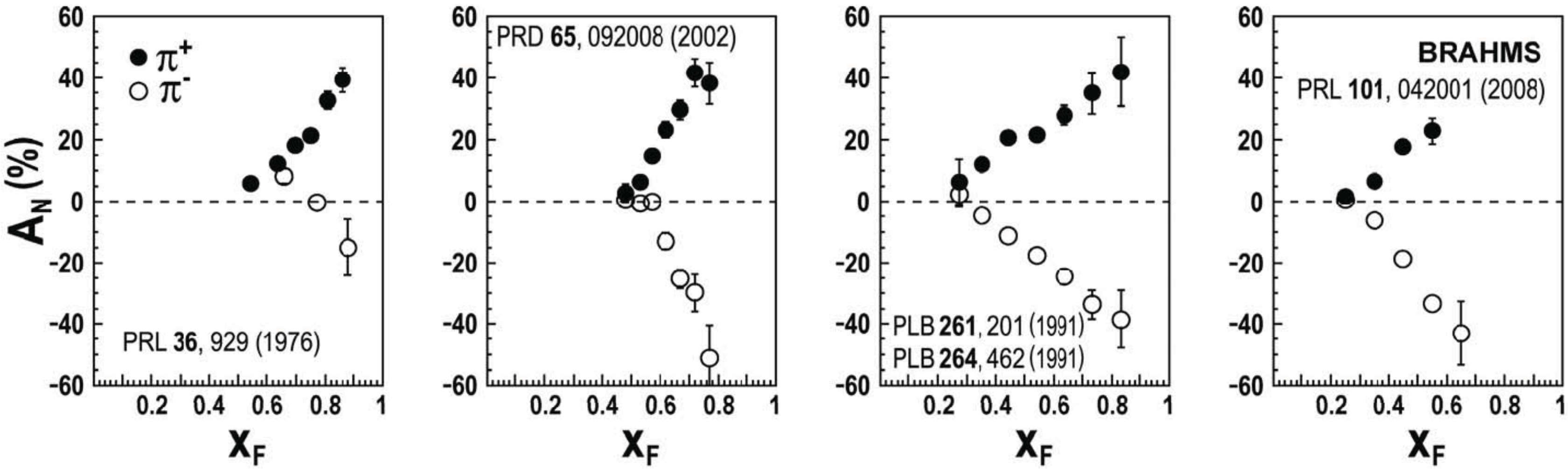


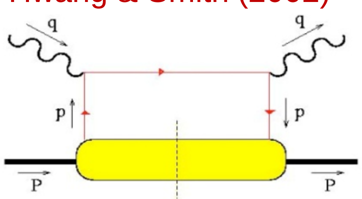
C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009

- SSA cannot come from perturbative subprocess xsec at high energies
  - → *q* helicity flip suppressed by $m_q/\sqrt{s}$
  - → at hard (enough) scales, SSA's must arise from soft physics
- Collins was wrong: Sivers effect is T-odd → allowed at leading order PLB536,43(2002)

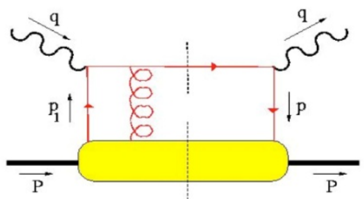
Sivers Function

- T-odd observables
  - ➡ SSA observable $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2)$ odd under naïve Time-Reversal
  - ➡ since QCD amplitudes are T-even, must arise from interference (between spin-flip and non-flip amplitudes with different phases)
- should all be completely suppressed in perturb hard scattering subprocess xsec
- A T-odd function like $f_{1T}^{\perp}$ must arise from interference (How?)

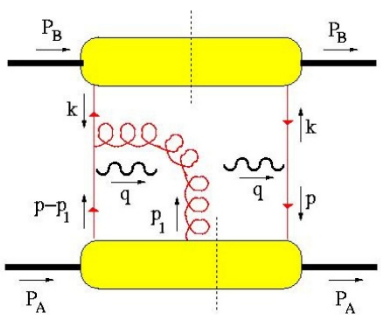
Brodsky, Hwang & Smith (2002)



can interfere with



and produce a T-odd effect!
(also need $L_z \neq 0$)



e.g. Drell-Yan)

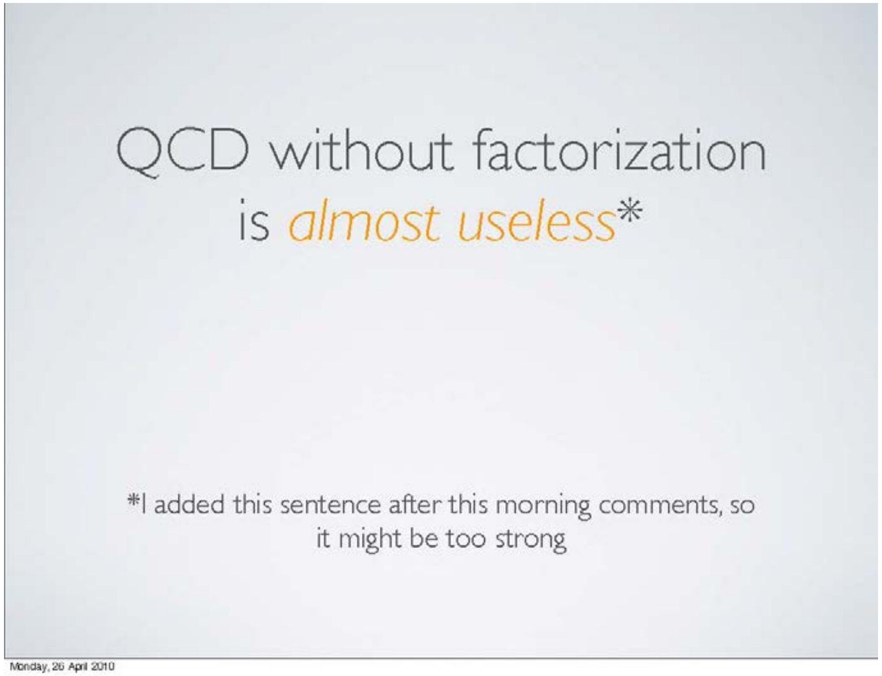
- ➡ soft gluons: "gauge links" required for color gauge invariance
- ➡ such soft gluon re-interactions with the soft wavefunction are final (or initial) state interactions … and maybe process dependent!
- ➡ leads to sign change: $f_{1T}^{\perp}\Big|_{SIDIS} = - f_{1T}^{\perp}\Big|_{DY}$

The Sign Change

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

- fundamental prediction of QCD (in non-perturbative regime)
  → goes to heart of gauge formulation of field theory

- Importance of factorization in QCD:

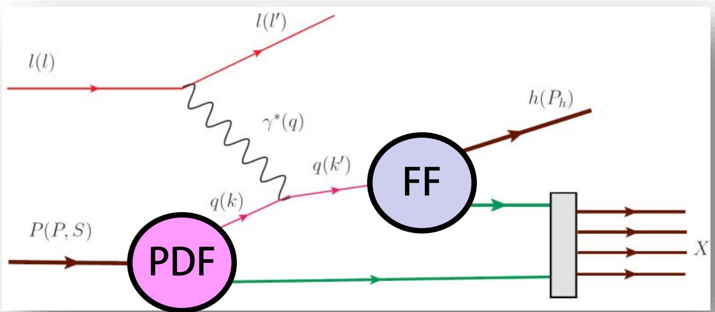


A. Bacchetta , DY workshop, CERN, 4/10

Factorization and Universality (SIDIS - DY)

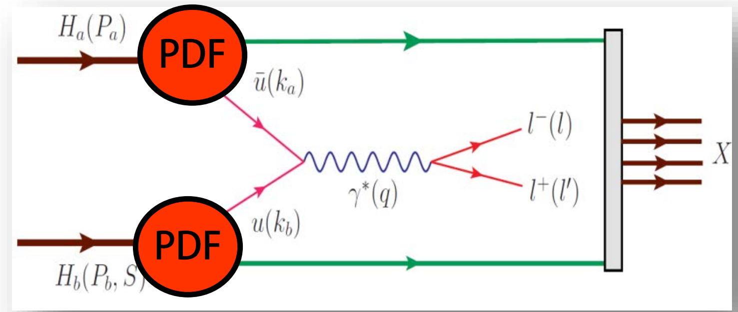
SIDIS

$\mathrm{PDF} \otimes \mathrm{FF}$



DY

$\mathrm{PDF} \otimes \mathrm{PDF}$



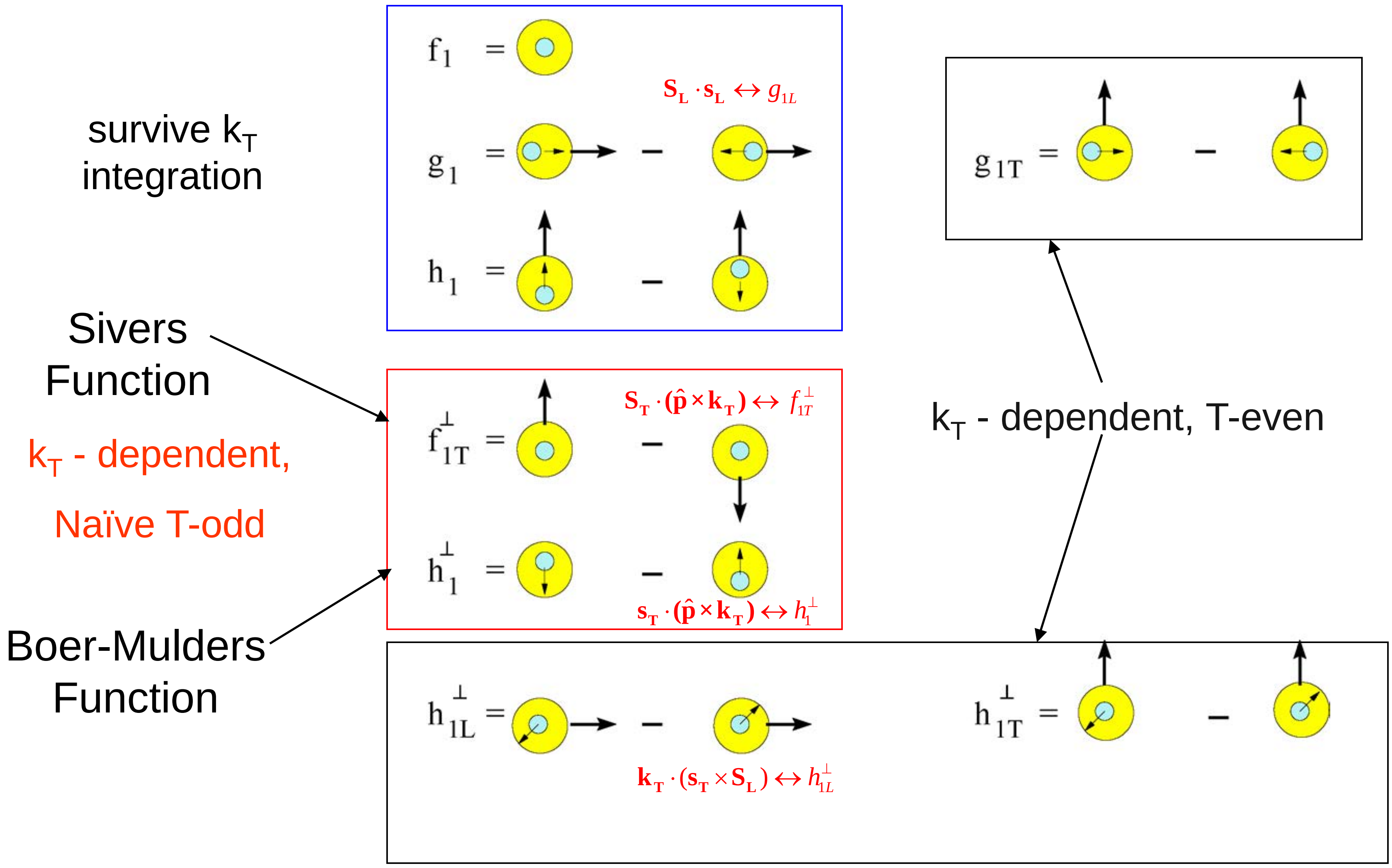
credit: A. Kotzinian

Probe Universality

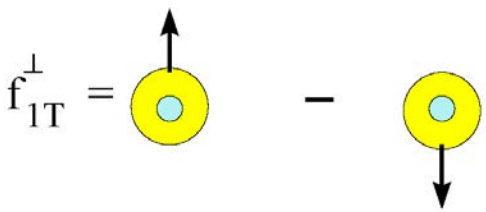
are TMD PDFs in SIDIS identical to TMD PDFs in DY?

Test using unpolarized experiments, transverse SSA and DSA

Transverse Momentum Distributions (Introduction)

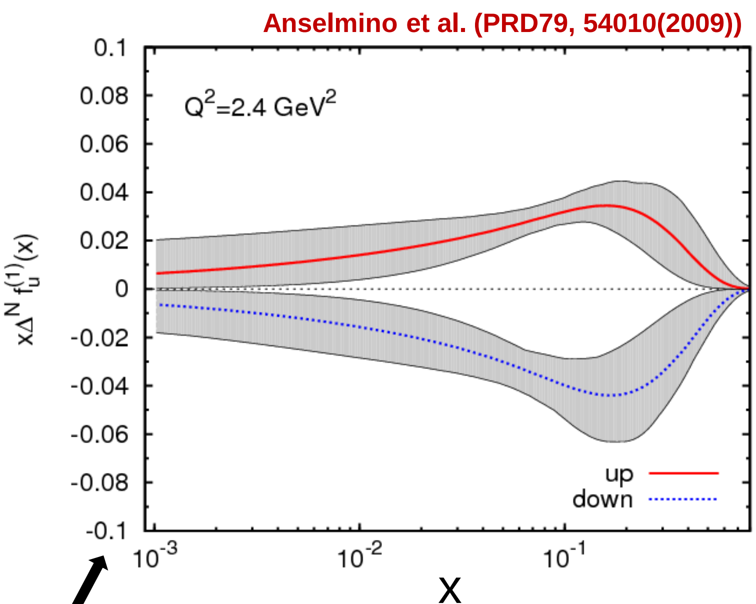


TMDs: Sivers Function



cannot exist w/o quark **OAM**

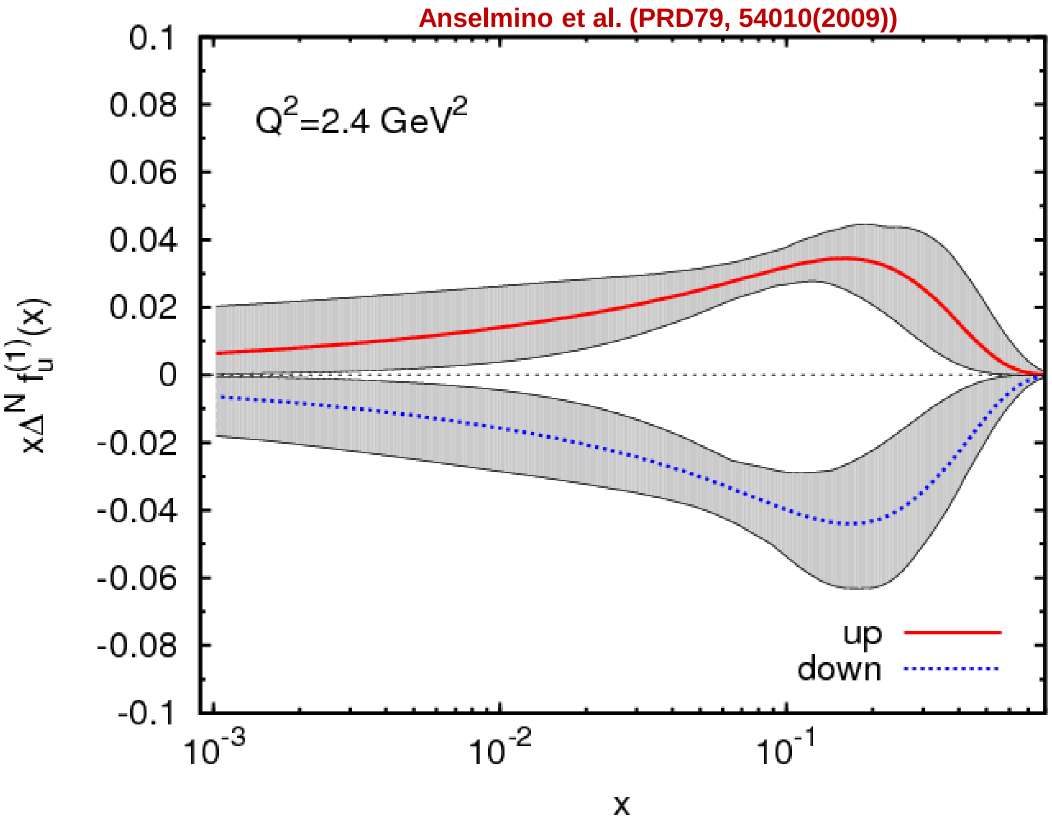
- describes transverse-momentum distribution of unpolarized quarks inside transversely polarized proton
- captures non-perturbative spin-orbit coupling effects inside a polarized proton
- Sivers function is odd under "naïve time-reversal"
  - ➞ operation that reverses all vectors and pseudo-vectors but does not exchange initial and final states
- leads to
  - ➞ $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS
  - ➞ $\sin\phi_b$ asymmetry in Drell-Yan
- measured in SIDIS (HERMES, COMPASS, Jlab)

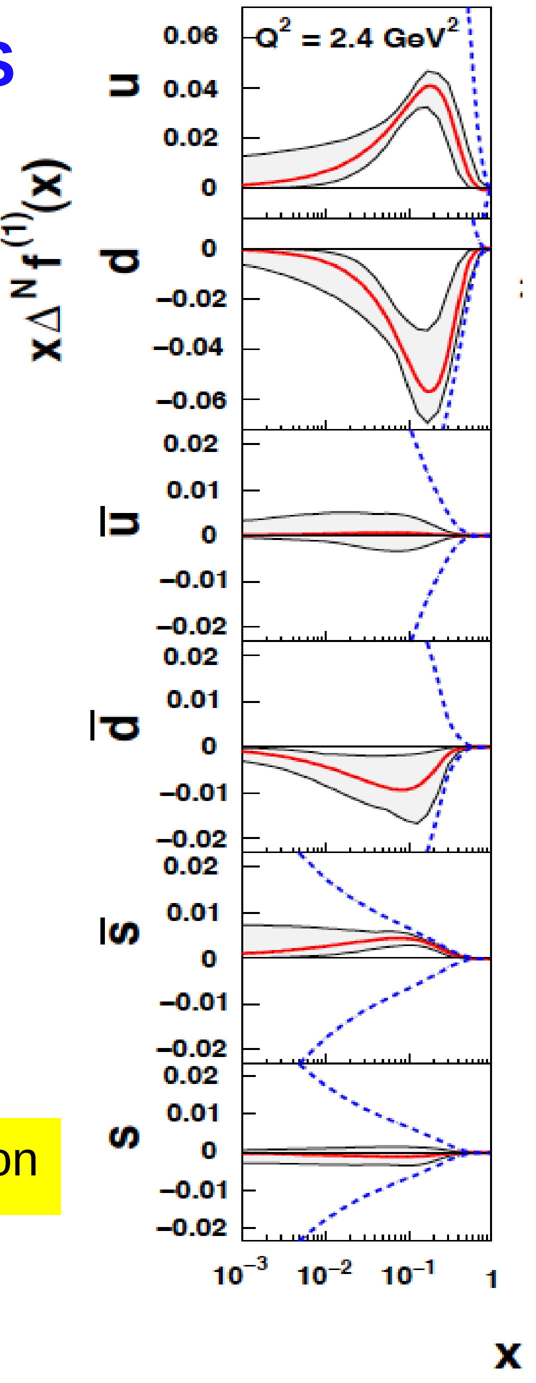


First moment of Sivers functions:

- ➞ u- and d-Sivers have opposite signs, of roughly equal magnitude
- ➞ u-Sivers slightly smaller than d-Sivers

First Moments of Sivers Function from SIDIS

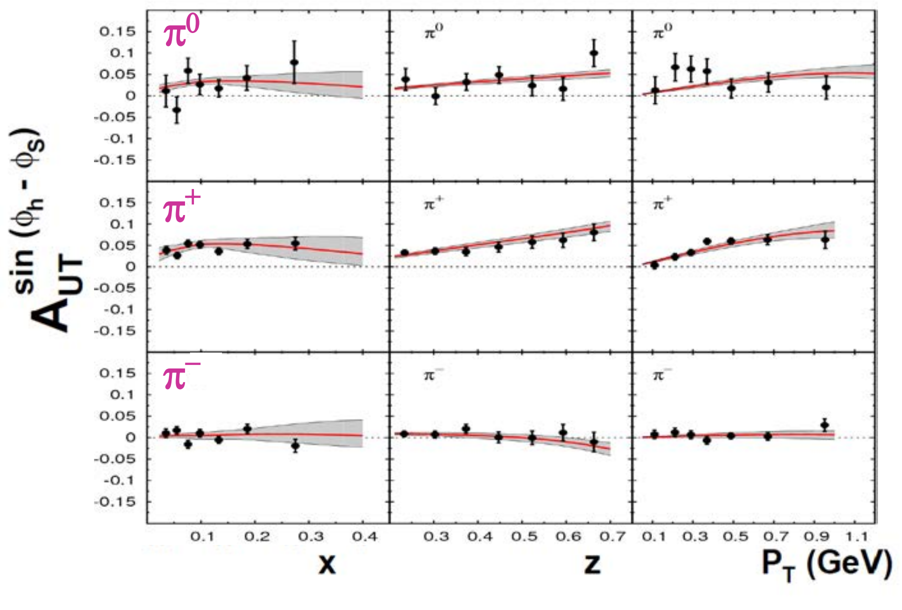




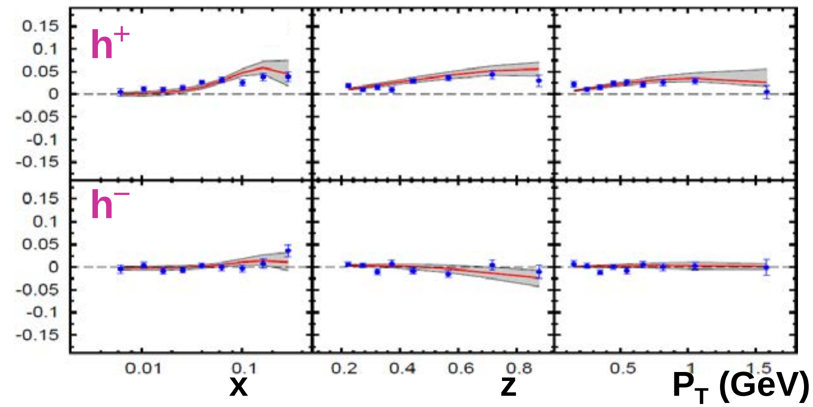
existing SIDIS data poorly constrain sea-quark Sivers function

Sivers Asymmetry in SIDIS: HERMES & COMPASS

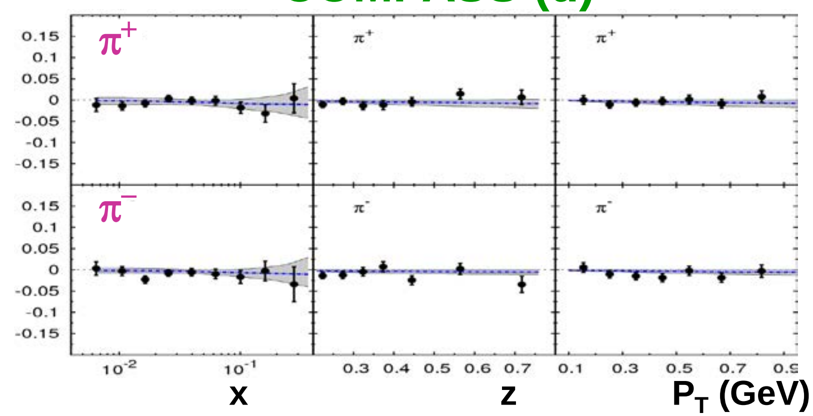
HERMES (p)



COMPASS (p)



COMPASS (d)

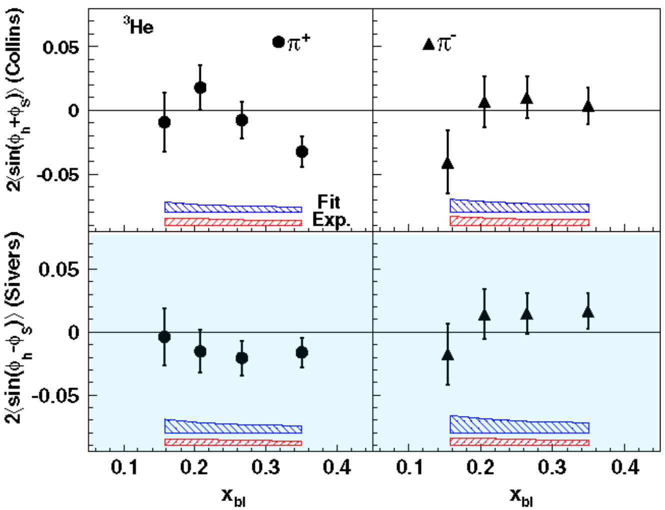


- Global fit to sin ($\phi_h - \phi_S$) asymmetry in SIDIS (HERMES (p), COMPASS (p), COMPASS (d))

Comparable measurements needed in Drell-Yan process

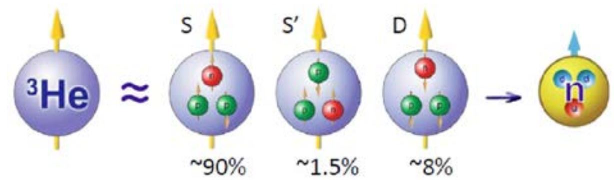
Sivers Asymmetry in SIDIS: JLab

JLab (^{3}He)

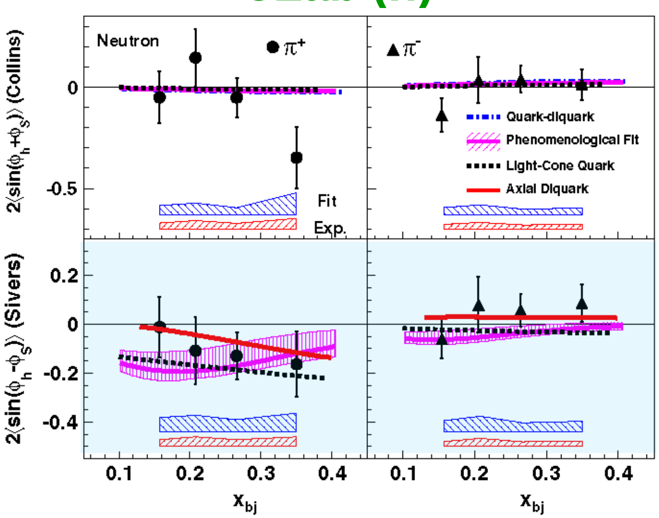


X. Qian etal, PRL107 072003(2011)

- u and d Sivers functions have opposite sign
  - ➡ for proton: $\pi^+ > 0$, then for ^{3}He: $\pi^+ < 0$
  - ➡ at the same time: π^- for ^{3}He should be smaller than π^+



JLab (n)

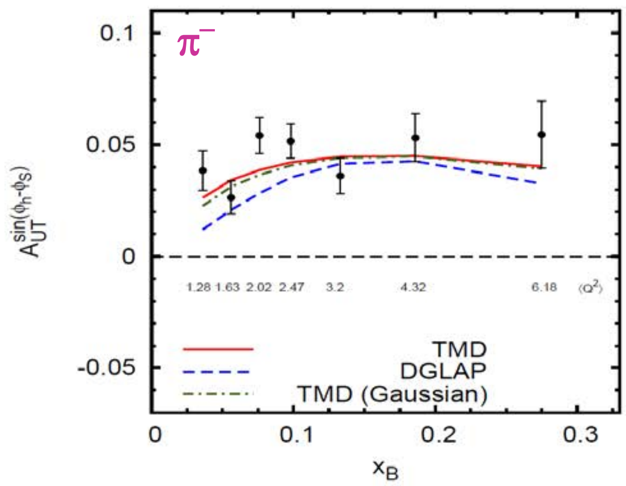


- Neutron Sivers SSA:
  - ➡ nuclear effects in ^{3}He small for n TMD study
  - ➡ $\pi^+ < 0$ neutron
  - ➡ agrees with Torino fit

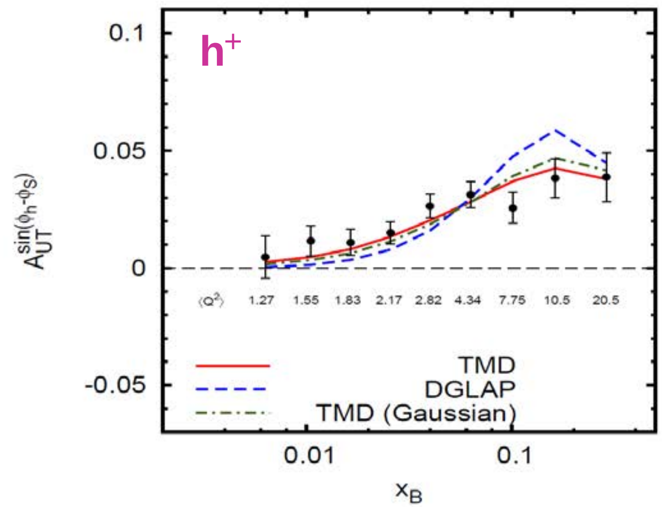
blue band: model (fitting) uncertainties
red band: other systematic uncertainties

QCD Evolution of Sivers Function

HERMES (p)

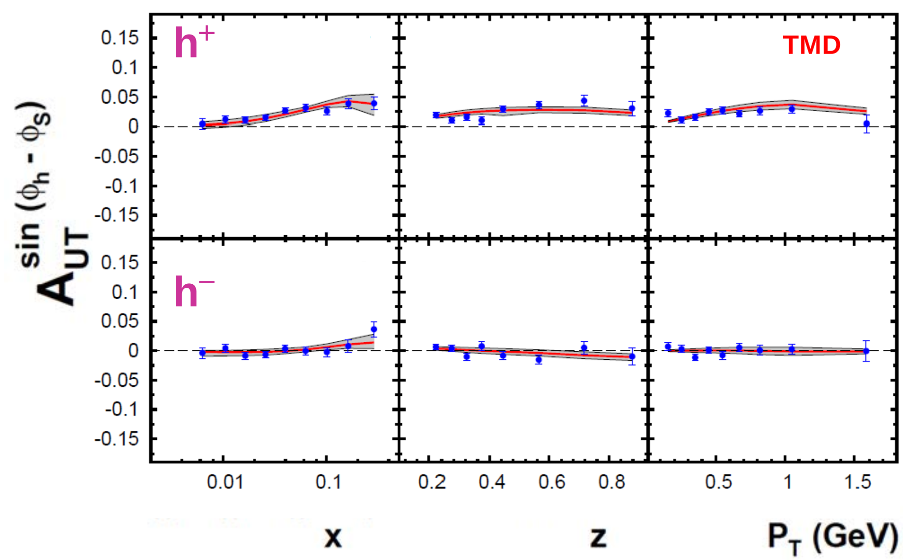


COMPASS (p)



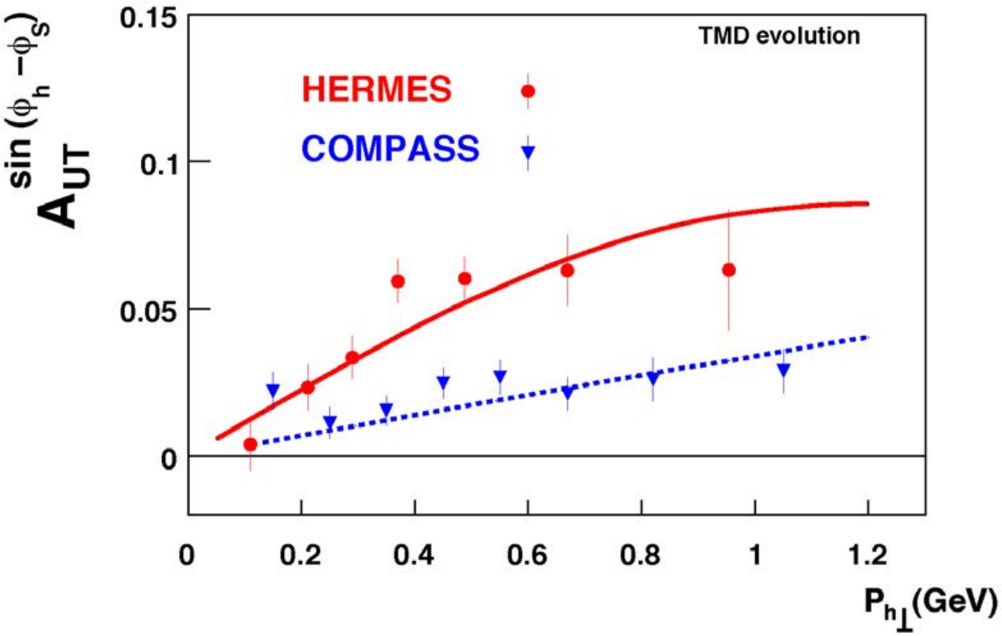
Anselmino et al. (arXiv:1209.1541 [hep-ph])

- Initial global fits by Anselmino group included DGLAP evolution only in collinear part of TMDs (not entirely correct for TMD-factorization)
- Using TMD Q^2 evolution:
  → agreement with data improves



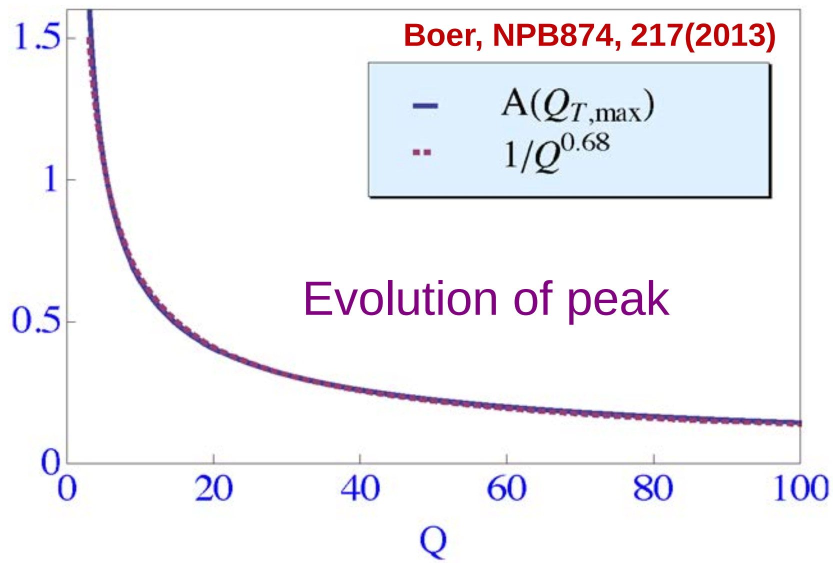
TMD Evolution of Sivers Asymmetry

Aybat et al, PRL108, 242003(2012)



Evolution from HERMES to COMPASS energy scale is required and works well

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto \mathcal{A}(Q_T, Q)$$

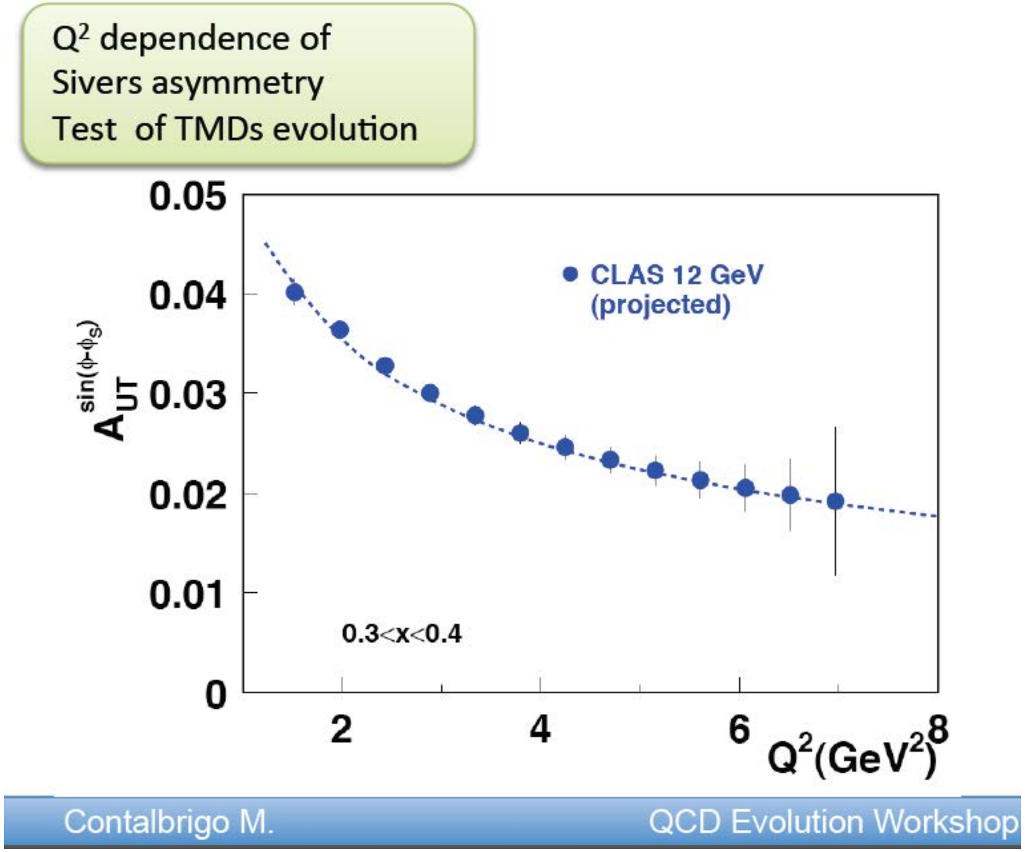


peak of Sivers asymmetry decreases as $1/Q^{0.7}$

testing this drop needs a large Q range (requires an EIC)

TMD Evolution of Sivers Asymmetry (JLAB 12 GeV)

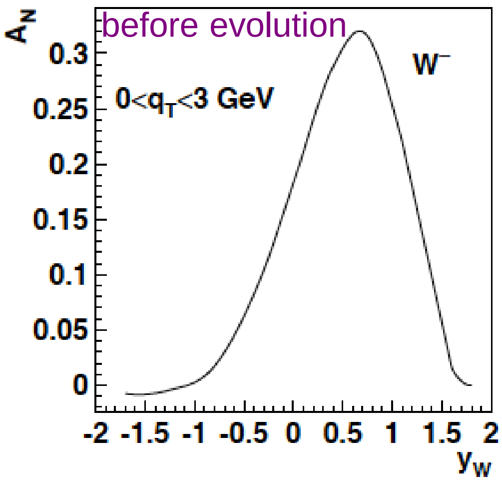
At low Q^2, (<20 GeV^2), Q^2 evolution dominated by so-called non-perturbative Sudakov factor S_{NP} **(Anselmino, PRDD86, 014028(2012))**



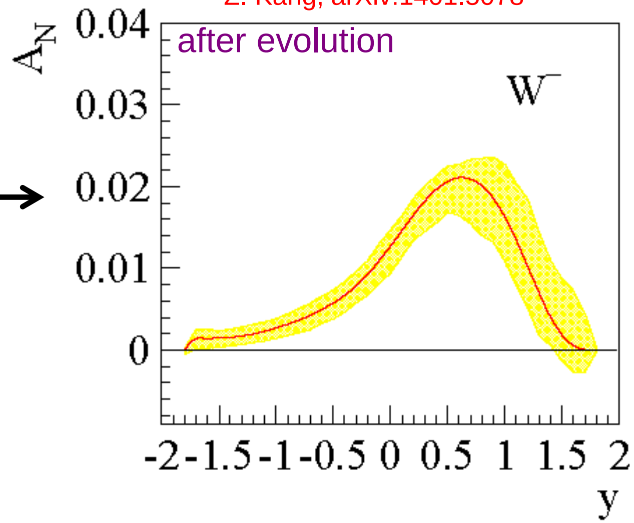
precise low Q^2 data can help determine form and size of S_{NP}

TMD Evolution of Sivers Asymmetry (W^-)

Z. Kang, arXiv:0903.3629



Z. Kang, arXiv:1401.5078



- much stronger than any other known evolution effects
- but needs input from data to constrain non-pertubative part in evolution
- **can be done at RHIC?**
- STAR predicted 2% measurement!

A_N(**DY**) Q^2: 16 – 80 GeV^2 <p_t>: 1-2 GeV

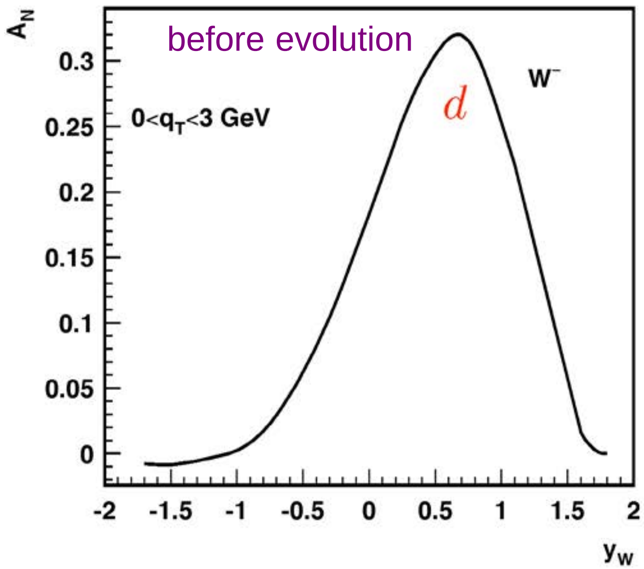
A_N(**$W^{\pm}$,Z^0**) Q^2: **6,400** GeV^2 <p_t>: 3-4 GeV

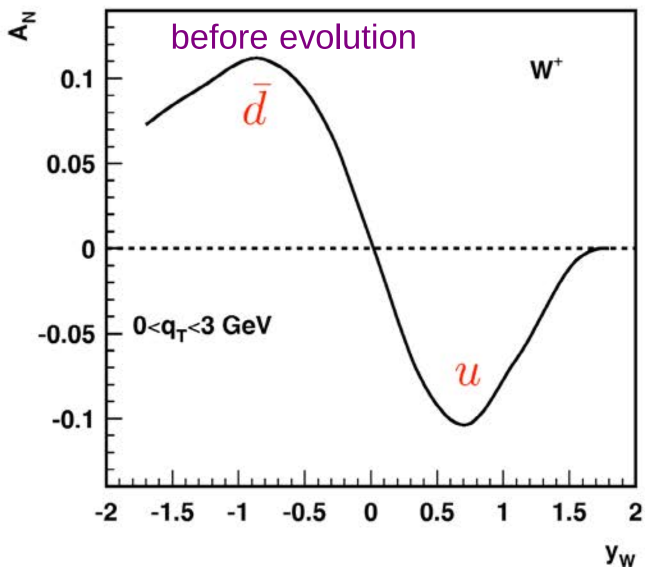
$$A_N \propto \frac{1}{Q^{0.7}}$$

Comparison of extracted TMD (Sivers) can provide strong constraint on TMD evolution

$W^{-/+}$ Sivers Asymmetry

Z. Kang, arXiv:0903.3629

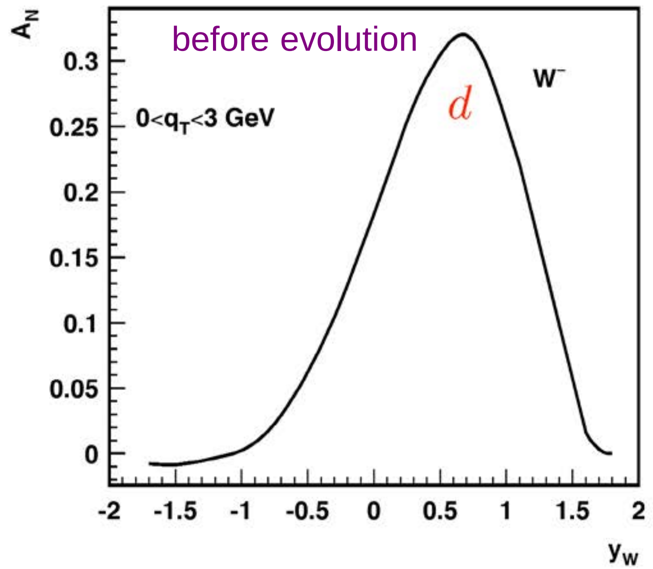


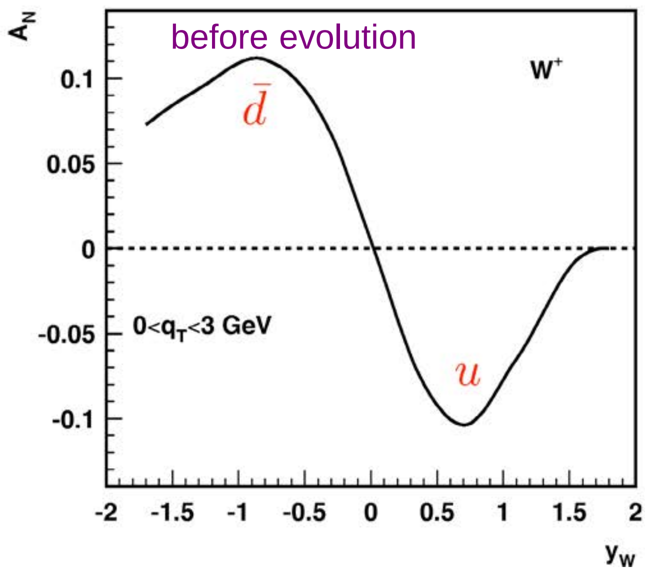


- W^+ and W^- could probe different flavor of u and d Sivers function
- $W^{-/+}$ Sivers asymmetry large (much larger than for DY production)
  - ➡ u and d Sivers functions have opposite sign
    - ✓ partially cancel in DY, but contribute to W^+ and W^- separately
    - ✓ large W^- caused by large d Sivers
- Problem: (TSA of inclusive lepton from W decay)
  - ➡ unobserved neutrino blurs the final-state azimuthal distributions
  - ➡ need to integrate over momentum of (anti) neutrino
    - ✓ **can we cleanly make direct measurement of Sivers function?**

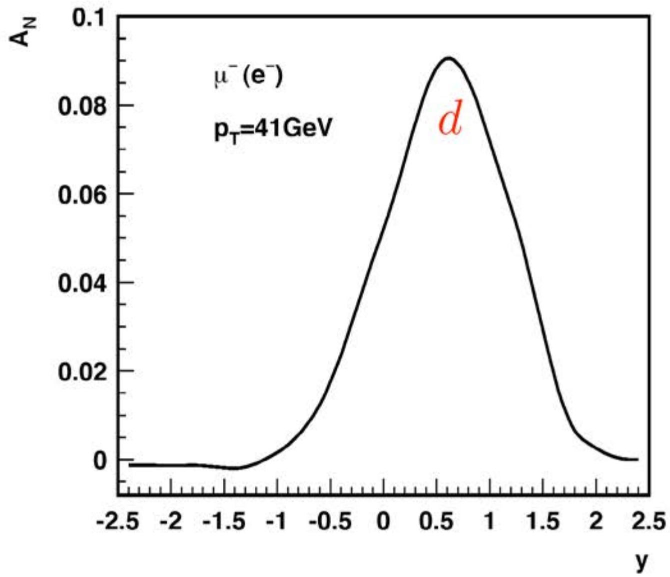
$W^{-/+}$ Sivers Asymmetry

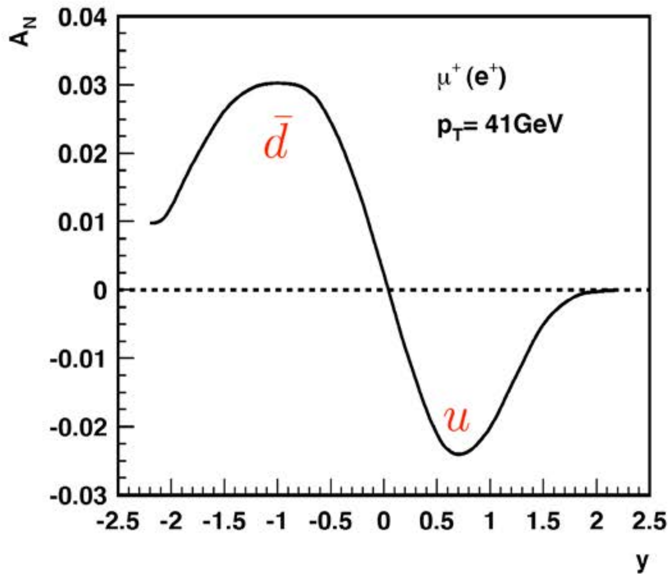
Z. Kang, arXiv:0903.3629





- Inclusive lepton TSSA from decayed W: similar feature, but diluted





Sivers Program at STAR

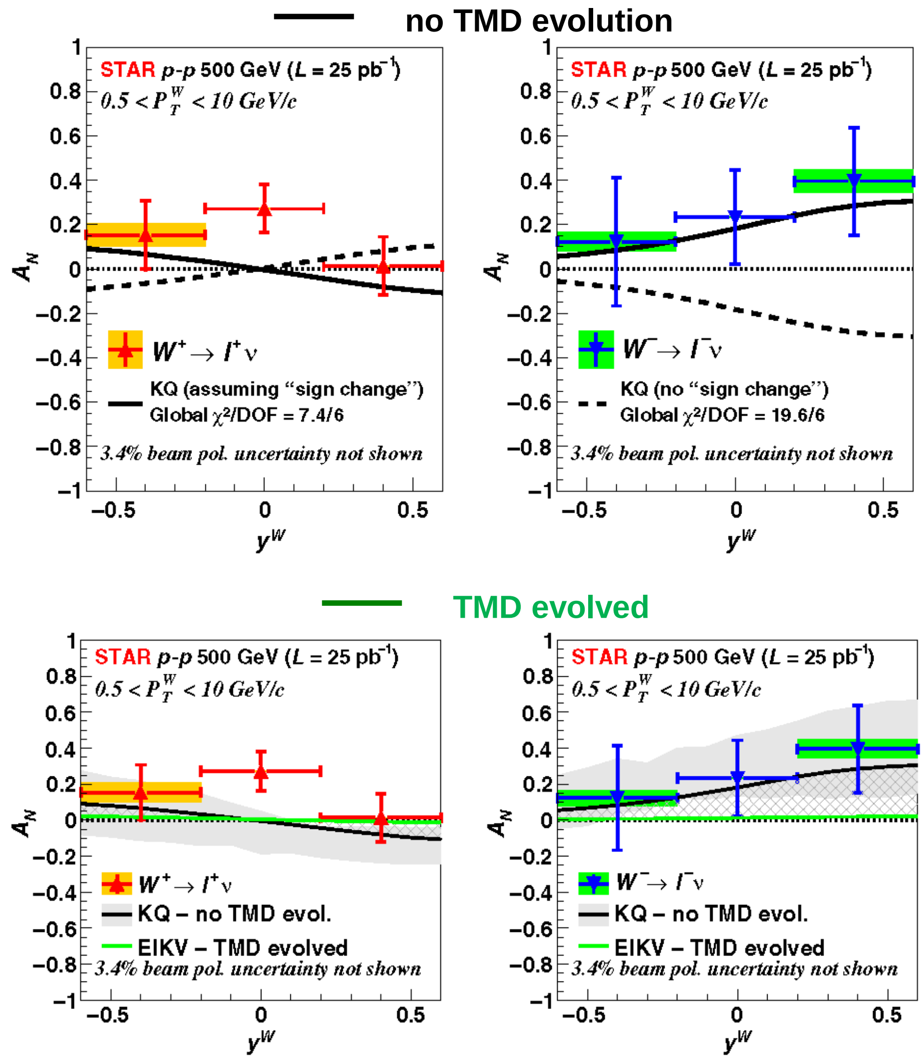
- **RHIC p+p (500 GeV):** $W^{+/-}$ TSSA

$$A_N(W^+) \sim \left(\Delta^N f_{u/p^\uparrow} \otimes f_{\bar{d}/p} + \Delta^N f_{\bar{d}/p^\uparrow} \otimes f_{u/p}\right)$$

$$A_N(W^-) \sim \left(\Delta^N f_{\bar{u}/p^\uparrow} \otimes f_{d/p} + \Delta^N f_{d/p^\uparrow} \otimes f_{\bar{u}/p}\right)$$

- **Sivers asymmetry:**
  - ➞ quark flavor identified
  - ➞ high Q^2 (6,400)
  - ➞ statistically limited: O(10%)
  - ➞ data favor sign-change

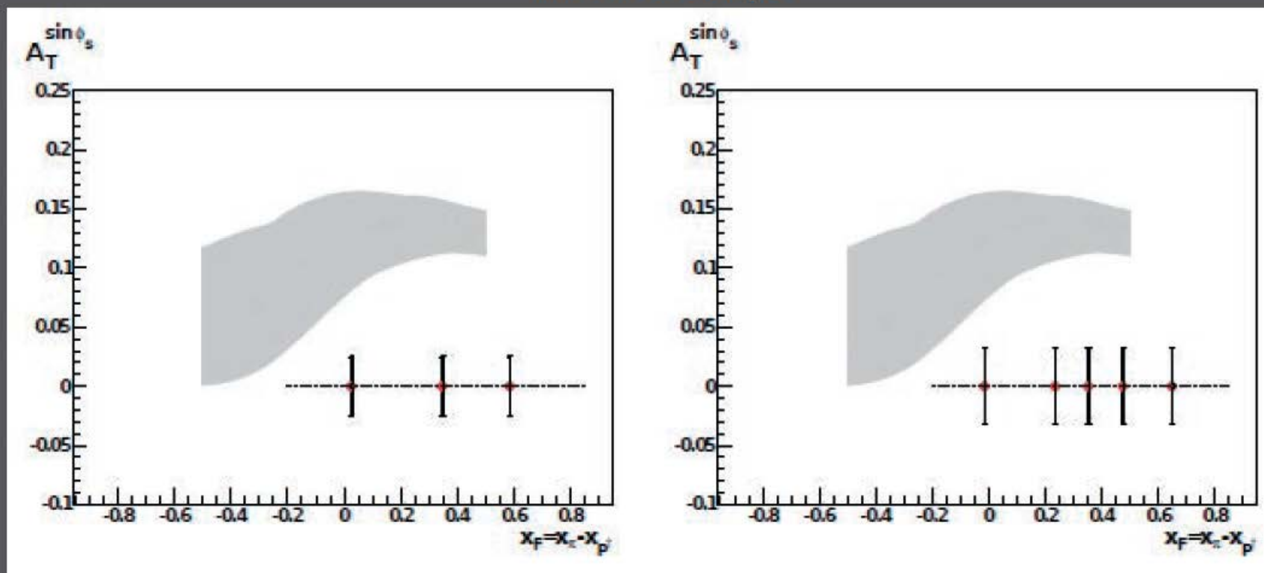
    if TMD **evolution** effects **small**
  - ➞ more data from 2017 (400 pb^{-1}) soon



PRL **116** (2016) 132301

COMPASS Predictions

2 years of data taking
DY 4.-9. GeV/c²



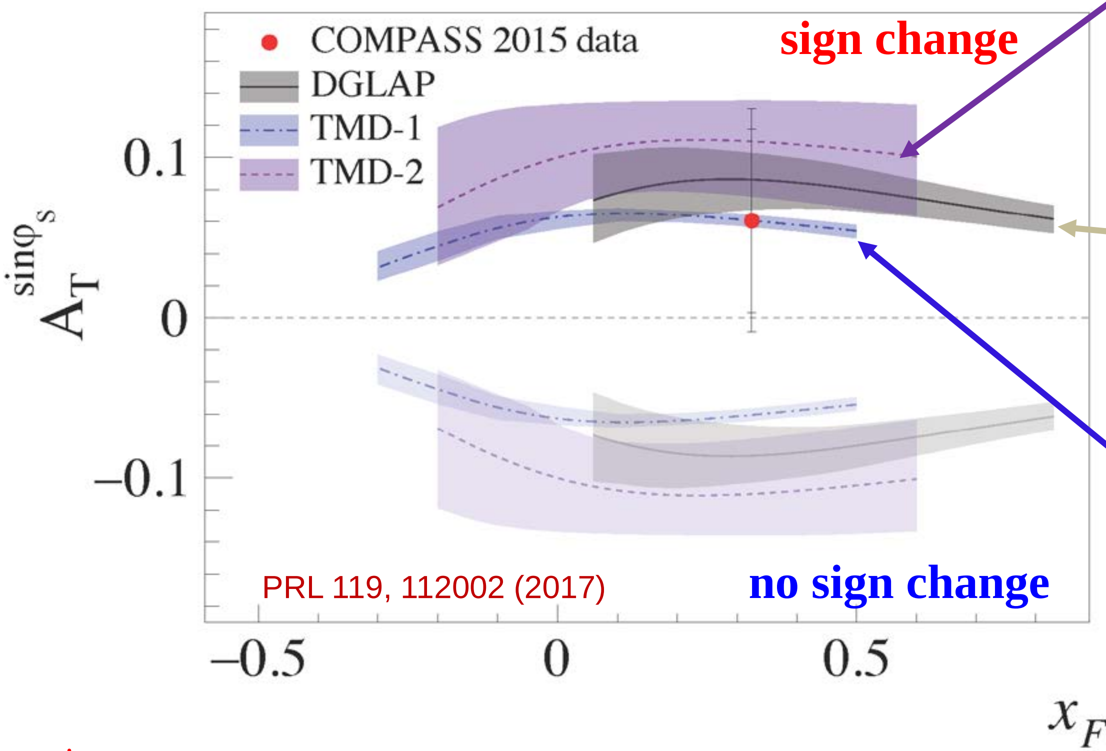
Expected statistical error of the Sivers asymmetry for a measurement in three (left) and five (right) bins in x_F assuming two years of data taking

M. Chiosso, Santa-Fe DY workshop Nov 2010

$\delta A_N \approx 0.02$ for one data point

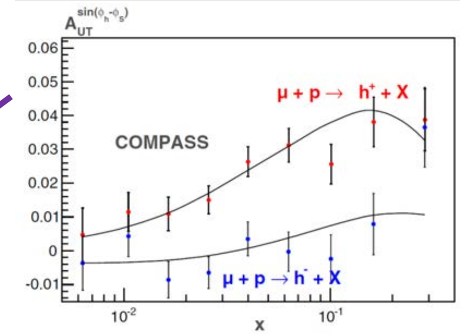
COMPASS 2015 Results

- COMPASS: 190 GeV π^- beam on transverse polarized H target (NH_3)
  - ➡ 2015 data (4 months)
  - ➡ Transverse target polarization ~80%
  - ➡ **consistent w/ sign change!**

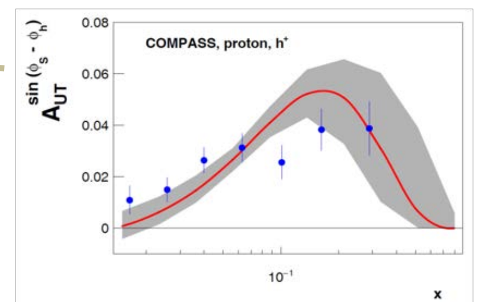


$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

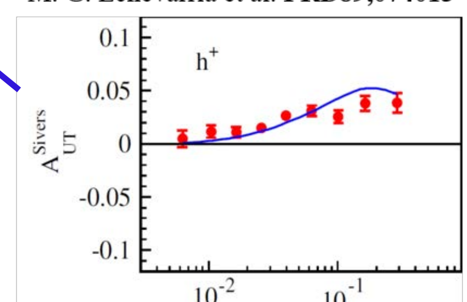
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



DGLAP (2016)
M. Anselmino et al. **JHEP 1704, 046**



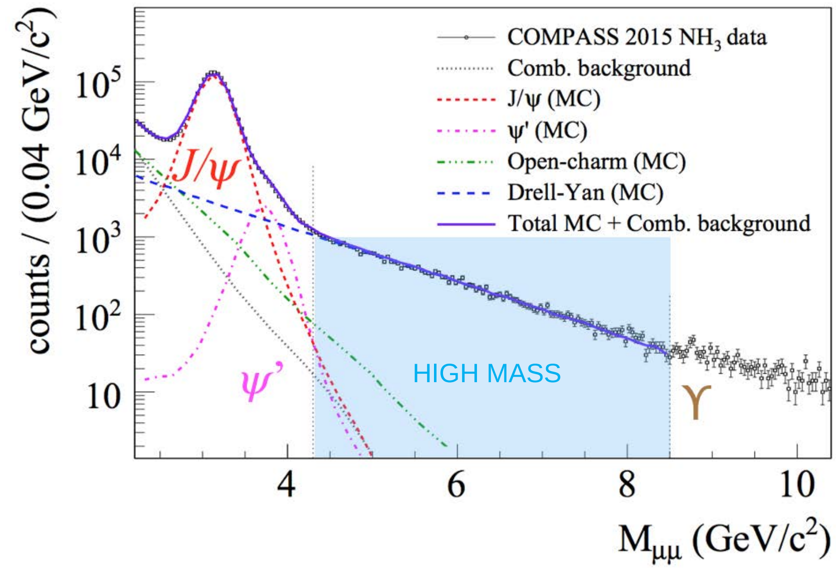
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**

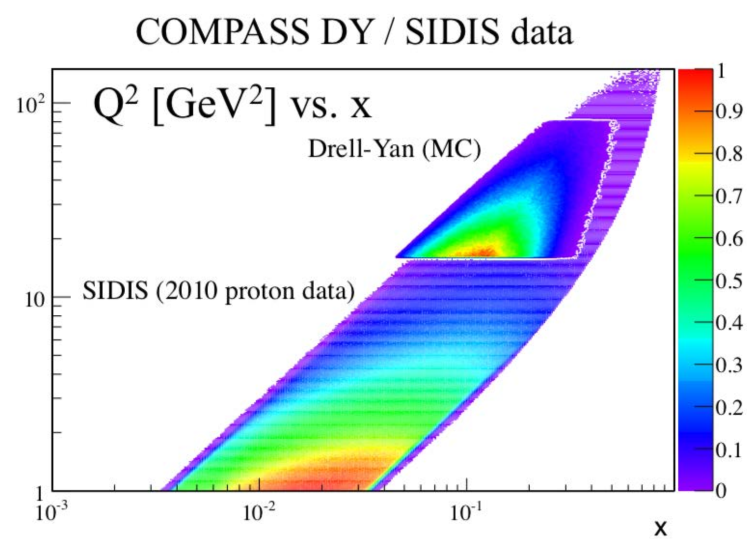


Ref: W.C. Chang (Academia Sinica) & J-C Peng (UIUC)

Kinematic Coverage

- Drell-Yan analysis: mass range 4.3 - 8.5 GeV/c^2 ("high mass range")
  - ➞ only 4% background in this mass range
  - ➞ DY events [$M(\mu^+\mu^-) > 4$ GeV/c^2): ~35,000
- Phase space for Drell-Yan and SIDIS partially overlap in the x-Q^2 plane
  - ➞ average Q^2 in Drell-Yan is about 2x that in SIDIS
  - ➞ allows to minimize the impact of uncertainties from TMD scale evolution
  - ➞ overlap in kinematic regions of COMPASS Drell-Yan and SIDIS data allows for direct comparisons of TMD amplitudes
- COMPASS probes proton's valence quarks in Drell-Yan and SIDIS

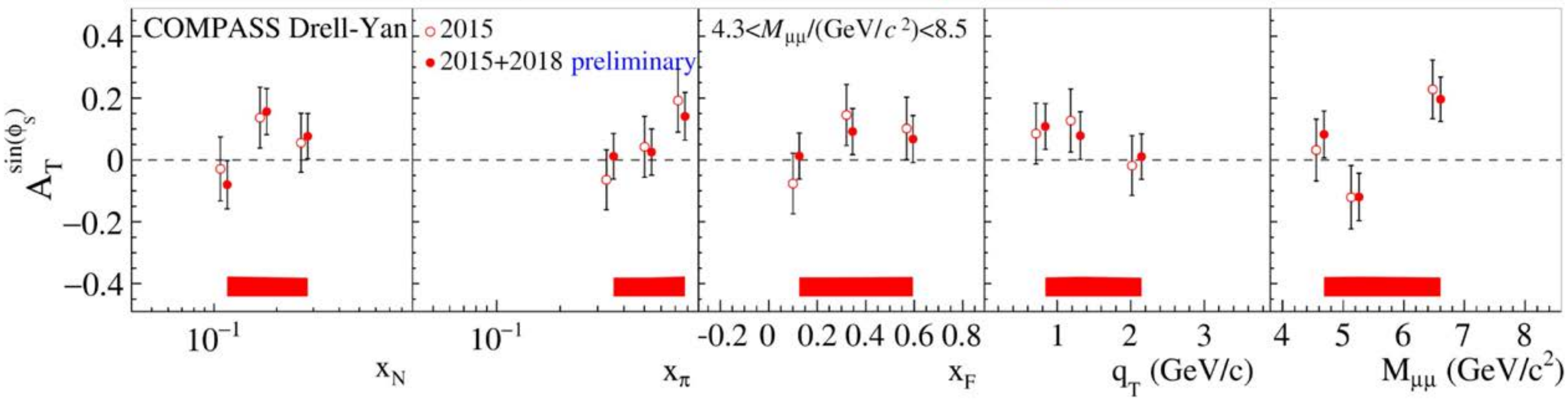




Ref: M. Meyer-Condea Sinica) & R. Heitz (UIUC)

Updated COMPASS Result

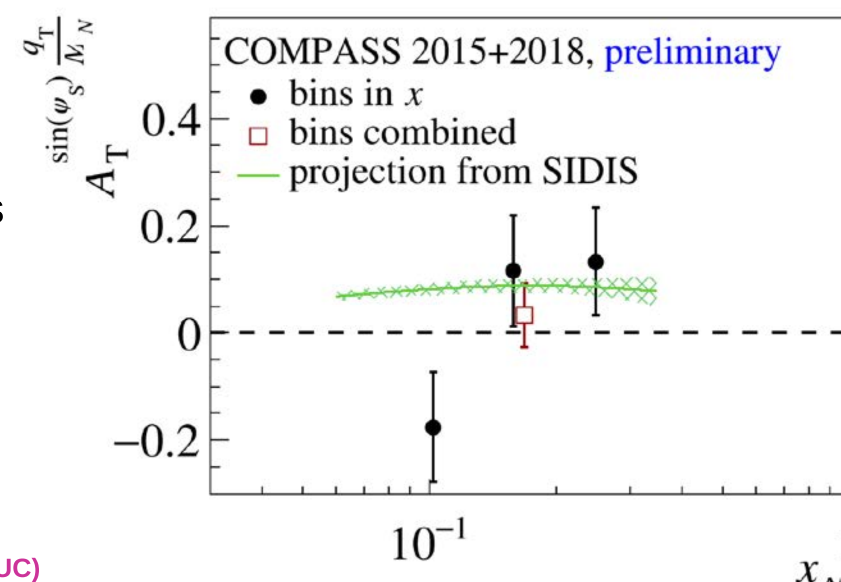
- **COMPASS 2015 (PRL 119 (2017) + 2018 (~50%)**
  - ➡ (2015 = 4 months; 2018 = 5 months of data taking)



- **q_T/M weighted asymmetries**
  - ➡ access to direct product of TMD PDFs
  - ➡ no assumption on k_T dependence of TMDs

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q(1)}$$



Ref: M. Meyer-Conde (UIUC)

(Un)Polarized Drell Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\ s^{-1}$)		P_b or P_t (f)	rFOM[#]	Timeline
COMPASS (CERN)	$\pi^- + p^\uparrow$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 – 0.3$	2×10^{33}		$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2015-2016, 2018
J-PARC (high-p beam line)	$\pi^- + p$	10-20 GeV $\sqrt{s} = 4.4\text{-}6.2$	$x_b = 0.2 – 0.97$ $x_t = 0.06 – 0.6$	2×10^{31}		---	---	>2020? under discussion
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 – 0.5$ $x_b = 0.05 – 0.6$	8×10^{31} 6×10^{32}		$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021?
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$ $x_t = 0.1 – 0.45$	3.4×10^{35}		---	---	2012 – 2017
SpinQuest[‡] (FNAL: E-1039)	$p + p^\uparrow$ $p + d^\uparrow$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 – 0.45$	3.0×10^{35} 3.5×10^{35}		$P_t = 85\%$ f = 0.176	0.15	2019-2021+
Pol beam DY[§] (FNAL: E-1027)	$p^\uparrow + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$	2×10^{35}		$P_b = 60\%$	1	>2021?

[‡] *8 cm NH_3 target* / [§] *L= $1 \times 10^{36}\ cm^{-2}\ s^{-1}$ (LH_2 tgt limited) / L= $2 \times 10^{35}\ cm^{-2}\ s^{-1}$ (10% of MI beam limited)*
**not constrained by SIDIS data* / [#] rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

W. Lorenzon (U-Michigan) 8/2019

Recent, Current and Future DY Program at FNAL

Unpolarized Beam and Target w/ SeaQuest detector

- **E-906/SeaQuest**: 120 GeV p from Main Injector on LH_2, LD_2, C, Fe, W targets → **high-x Drell Yan**
- Science run: March 2014 - July 2017

  ➡ dbar/ubar asymmetry, nuclear dependence, quark energy loss, Tam-Tung relation,…

Unpolarized Beam and polarized Target (w/ upgraded SeaQuest detector)

- **E-1039/SpinQuest**: SeaQuest w/ pol NH_3/ND_3 targets: 2019-2021

  ➡ probe sea quark distributions

Polarized Beam and polarized Target

→ development of **high-luminosity** facility for **polarized Drell Yan**

- **E-1027**: pol p beam on (un)pol tgt (2021+?)

  ➡ **Sivers sign change** (valence quark)

  ➡ TMD physics program complementary to future EIC program

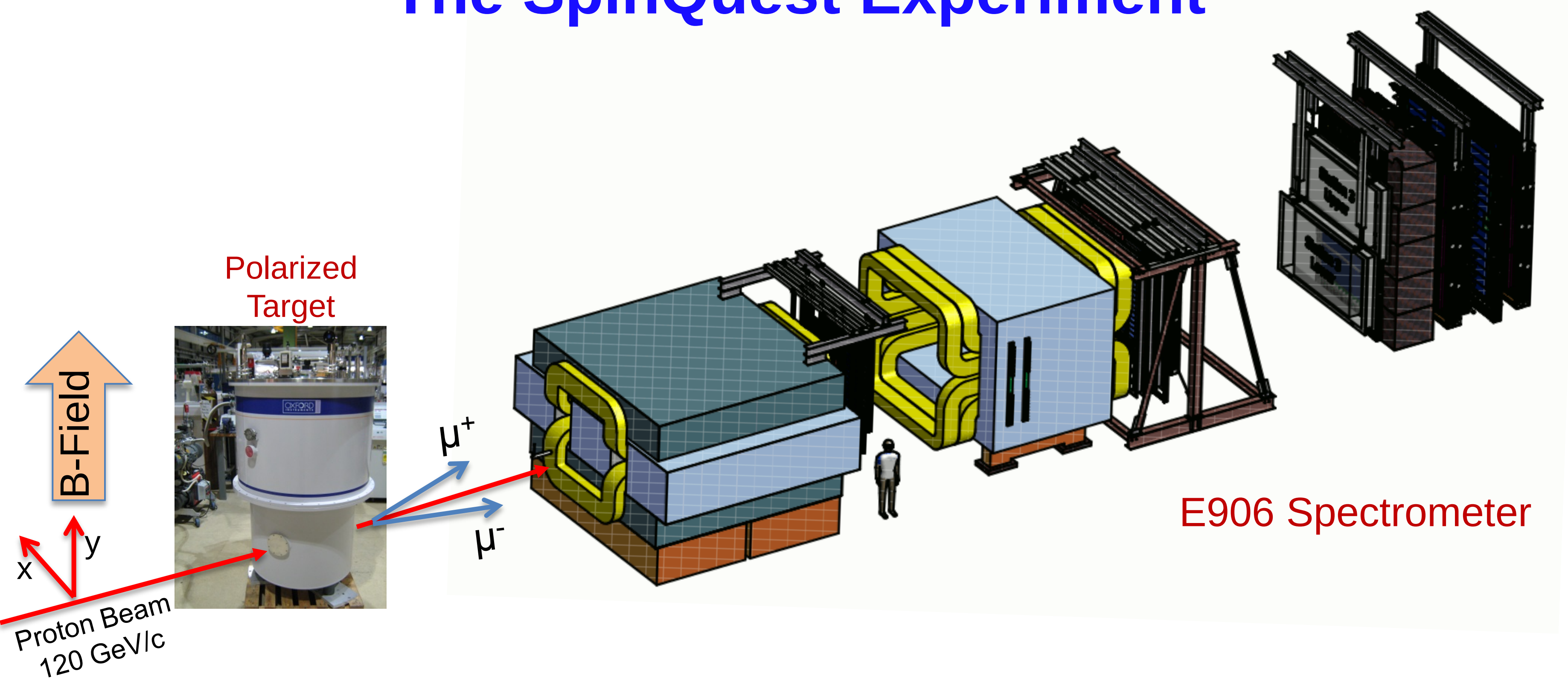
Other opportunities

- **E-1067/DarkQuest**

  ➡ parasitic dark photon search (2016-2021+)

  ➡ dedicated run? (2021+?)

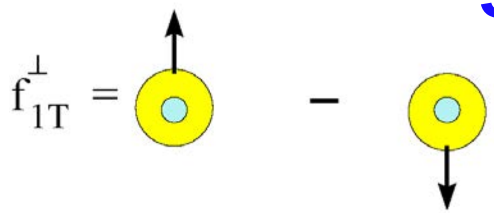
The SpinQuest Experiment



- replace unpolarized E906 target w/ polarized target
  → LANL and UVA effort
- move polarized target ~3m upstream
  → improves target-dump separation
  → moves acceptance to lower x_2

L_{int} **= 1.82 *10^{42}/cm^2 NH_3 / 2.11 *10^{42}/cm^2 ND_3** for 2 years

Sivers Function and Spin Crisis



cannot exist w/o quark **OAM**

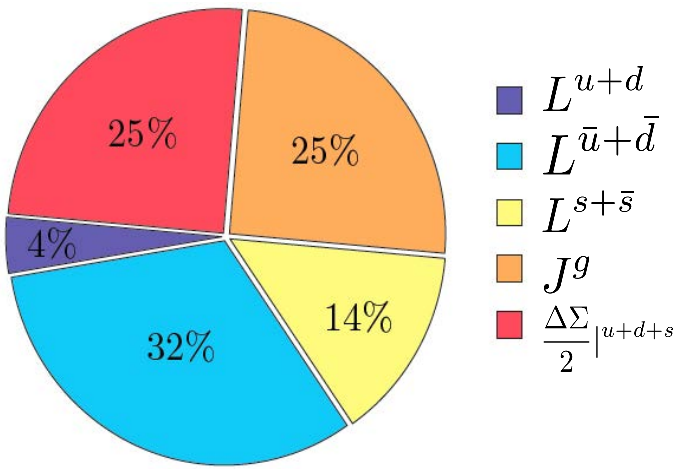
- describes transverse-momentum distribution of unpolarized quarks inside transversely polarized proton
- connection b/w Sivers function and OAM is yet model-dependent

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$\frac{1}{2}\Delta\Sigma \approx 25\%;\quad \Delta G \approx 20\%$

$L \approx$ unmeasured

Lattice QCD:



How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD: Transverse Momentum Distribution

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

$\Delta\Sigma_q \approx 25\%$

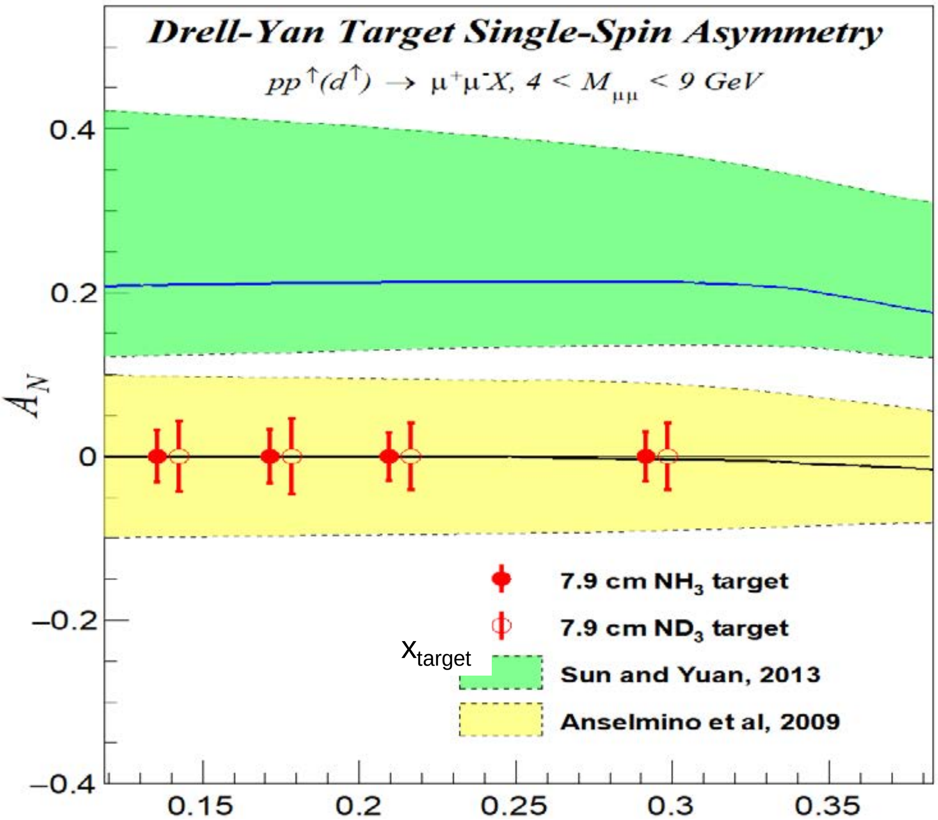
$2\,L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\,J_g \approx 25\%$

K.-F. Liu *et al* arXiv:1203.6388

Projected DY Transverse Single Spin Asymmetry

E1039 proposal



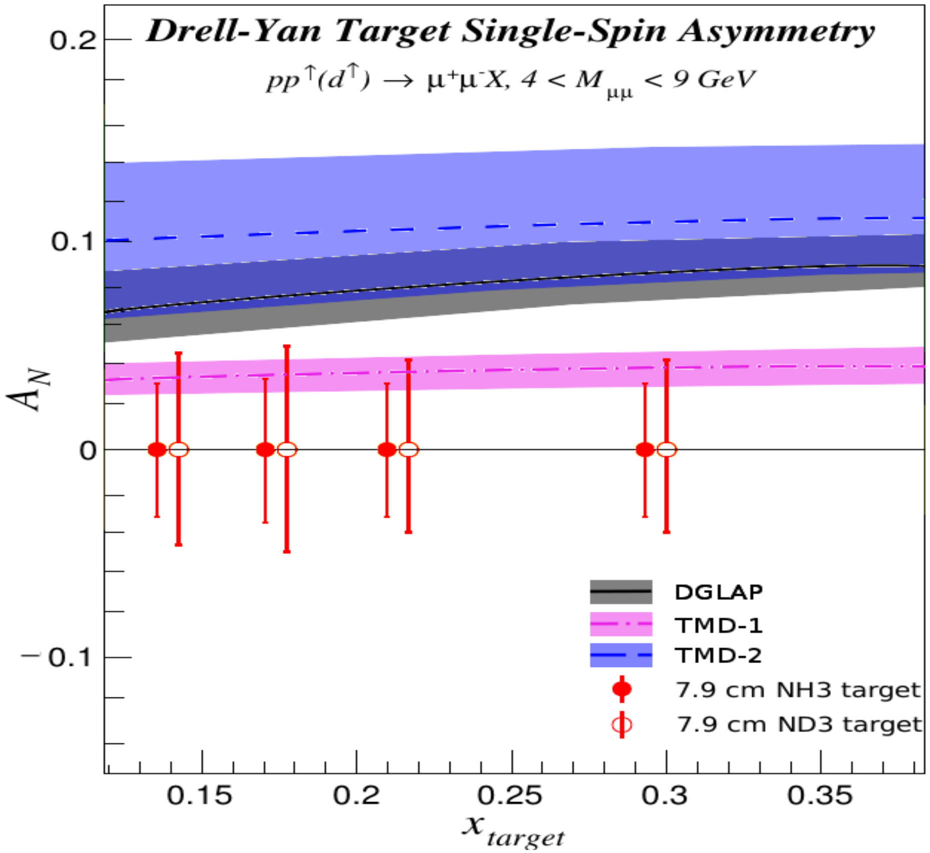
- existing SIDIS data poorly constrain sea-quark Sivers function (Anselmino)
- significant Sivers asymmetry expected from meson-cloud model (Sun & Yuan)

- **determine sign and value of sea quark Sivers asymmetry**
- **measure sea quark Sivers flavor dependence (H & D targets)**

If $A_N \neq 0$, **major discovery**:
"Smoking Gun" evidence for $L_{\bar{u},\bar{d}} \neq 0$

Projected DY Transverse Single Spin Asymmetry

E1039 proposal



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- significant Sivers asymmetry expected from meson-cloud model (Sun & Yuan)

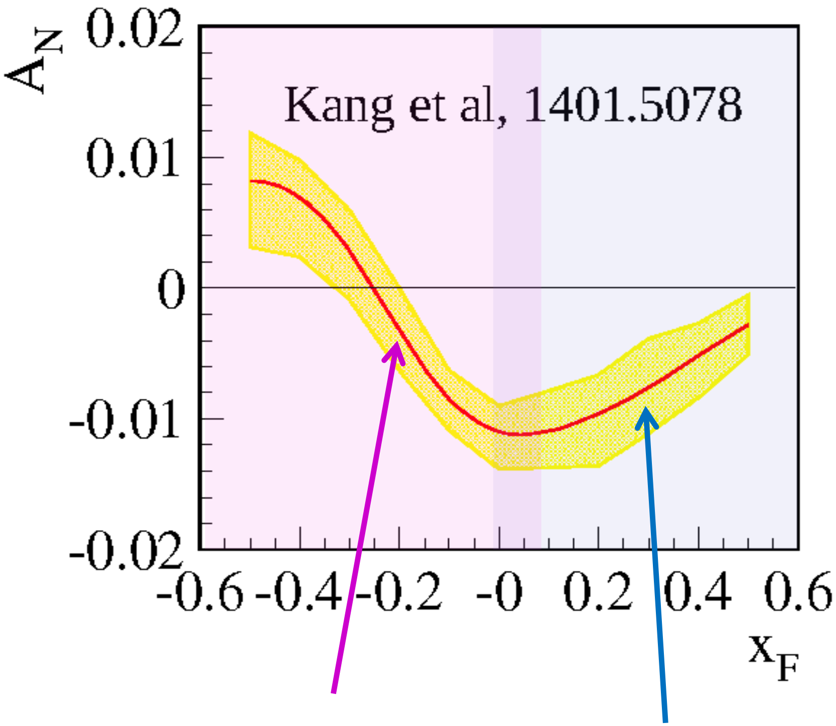
- **determine sign and value of sea quark Sivers asymmetry**
- **measure sea quark Sivers flavor dependence (H & D targets)**

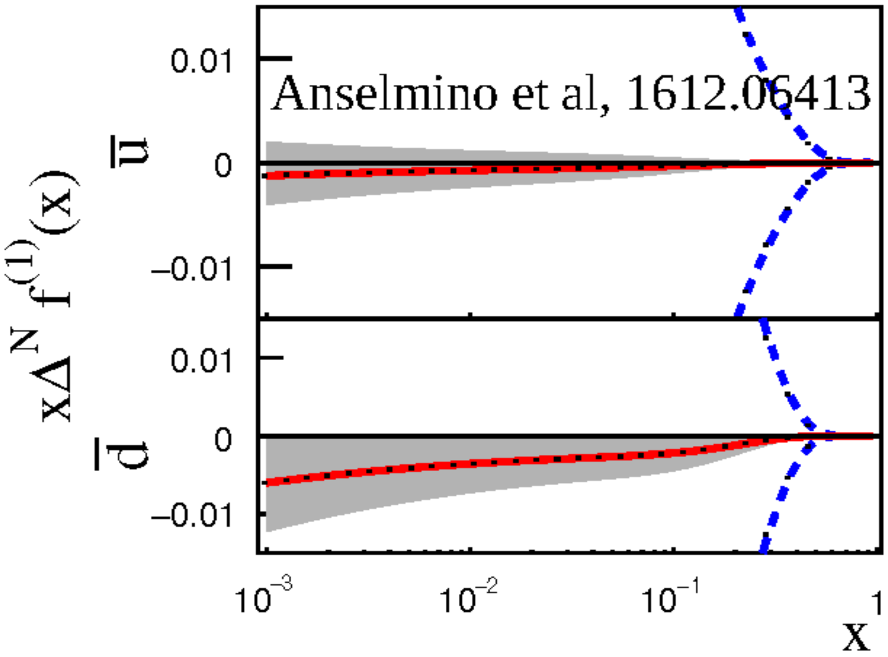
DGLAP: M. Anselmino et al arXiv:1612.06413
TMD-1: M. G. Echevarria et al arXiv:1401.5078
TMD-2: P. Sun and F. Yuan arXiv:1308.5003

If $A_N \neq 0$, **major discovery**:
“Smoking Gun” evidence for $L_{\bar{u},\bar{d}} \neq 0$

Projected DY Transverse Single Spin Asymmetry

More recent calculations





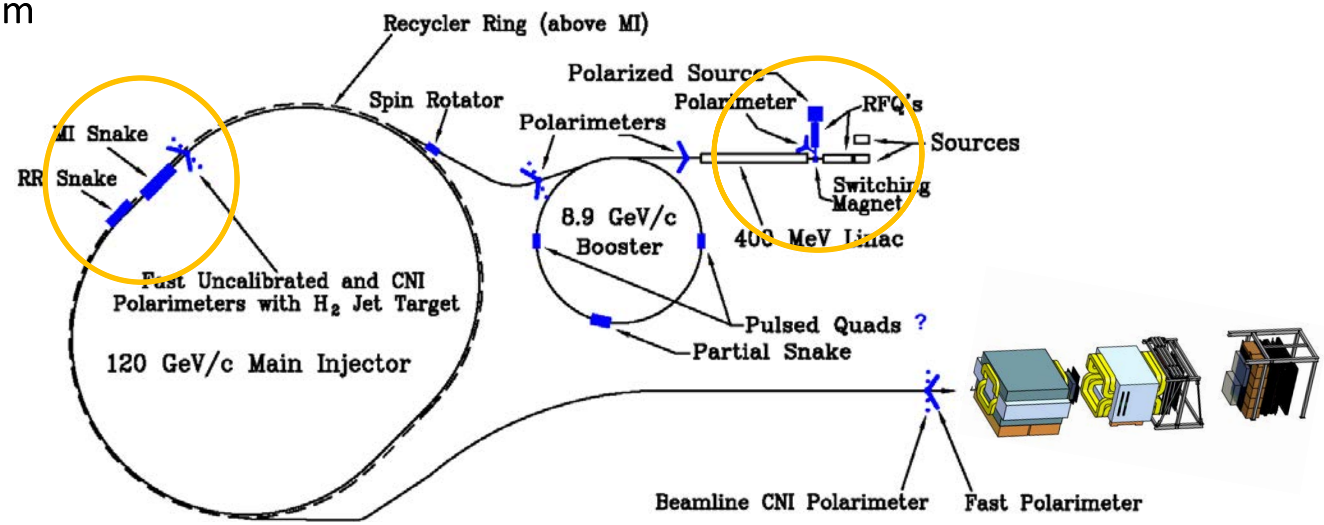
$-0.6 < x_F < 0.1$
sea quarks
(E-1039)

$0 < x_F < 0.6$
valence quarks
(E-1027)

Let's Polarize the Beam at Fermilab (E-1027)

The Plan:

- Use SpinQuest Spectrometer
- Add polarized beam

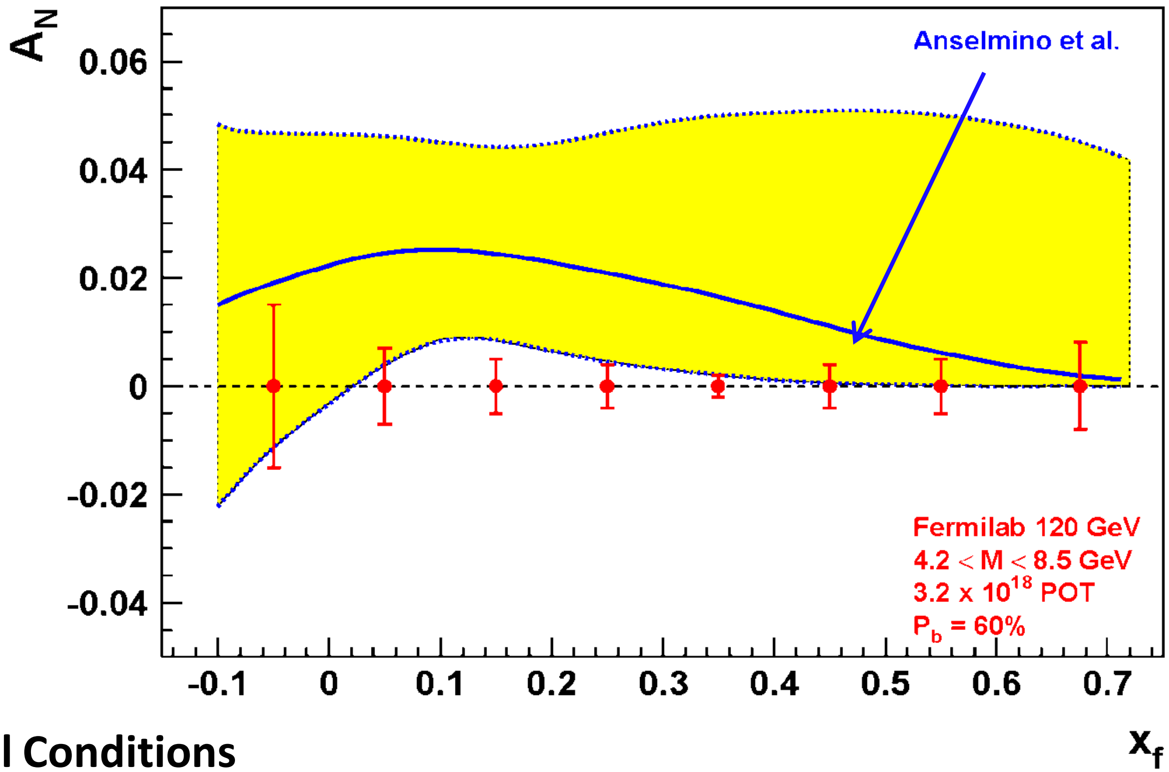


- **Fermilab (best place for polarized DY):**
  - ⟶ very high luminosity, large x-coverage (primary beam, fixed target)
- **Measure sign-change in Sivers Function:**
  - ⟶ sign, size and shape of Sivers function
  - ⟶ and TMD evolution
- **Access to valence quarks**

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

Expected Precision from E-1027 at Fermilab

- Probe **Valence Quark Sivers Asymmetry** with a polarized proton beam at SeaQuest



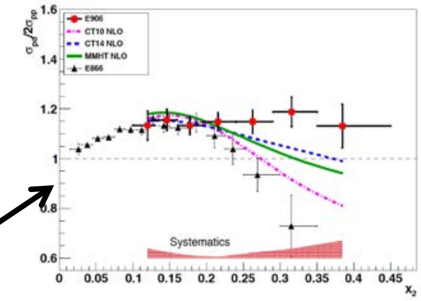
1.3 Mio
DY events
with no
dilution

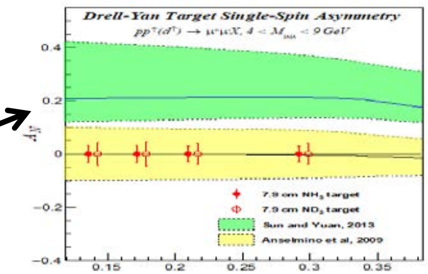
- **Experimental Conditions**
  - same as SeaQuest
  - luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: $I_{av} = 15$ nA)
  - 3.2×10^{18} total protons for 5×10^5 min: (= 2 yrs at 50% efficiency) with $P_b = 60\%$

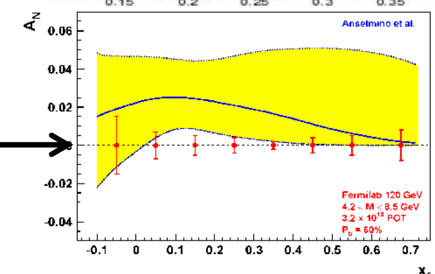
Can measure not only sign, but also the size & probably shape of the Sivers function!
as well as TMD evolution!

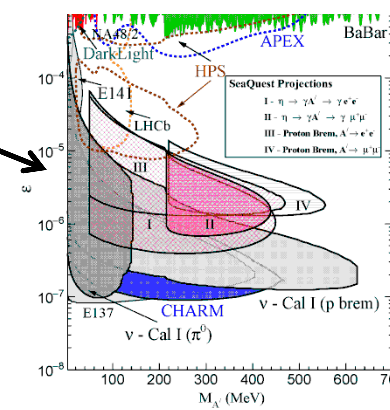
Fermilab - Summary and Outlook

Experiments	Timeline	Interactions	Physics
E906 (SeaQuest)	2014 - 2017	p + LH_2 / LD_2 p + C, Fe, W	dbar/ubar, nucl dep quark dE/dx
E1039 (SpinQuest)	2019 – 2021+	p + pol NH_3 p + pol ND_3	sea-quark Sivers, TMD
E1027	2021+ (?)	pol p + LH_2 or pol p + pol NH_3	valence quark Sivers, sign change, TMDs
E1067 (DarkQuest)	2016 - 2021+ (para.) 2021+ (dedicated?)	p + any target	dark photon, dark Higgs, dark Z, …









Ref: M. Liu (LANL)

Conclusions

- Sivers function has received a lot of attention since it was first announced in 1990
- Collins tried to kill it, but it survived
- It has been measured with good precision with SIDIS at HERMES, COMPASS and Jlab, and more recently even at STAR
- It has a prominent role in verifying the sign-change
  - → so far, only for valence quarks
  - → we have seen first results from COMPASS and STAR on the sign-change
  - → but statistics still poor
  - → will need polarized beam at Fermilab to make a definitive measurement
  - → or wait for the EIC
- Now entering an era where we will have first measurement of a sea quark Sivers function (answer some of the questions):
  - → is there significant orbital angular momentum?
  - → what is the role of the sea quarks?
  - → how much do they contribute to the nucleon spin?

Thank You

SpinQuest/E1039 Collaboration

- Relatively small collaboration
  - → 36 full members, 76 affiliate members
  - → 14 institutions and Fermilab

Abilene Christian University	Tokyo Institute of Technology
Argonne National Laboratory	University of Colorado, Boulder
KEK	University of Illinois, Urbana-Champaign
Los Alamos National Laboratory	University of Michigan
Mississippi State University	University of New Hampshire
New Mexico State University	University of Virginia
RIKEN	Yamagata University

  - → and growing

- US collaborators supported by NSF and DoE Medium Energy

Leading order DY Cross Section

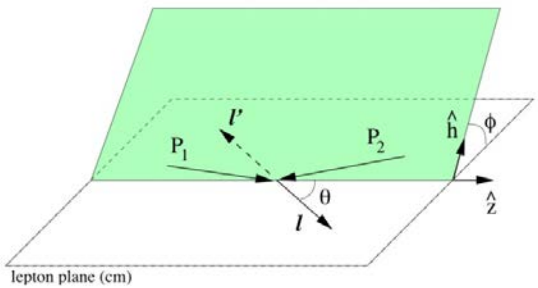
- DY cross section at LO:

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{4q^2\sqrt{(P_b\cdot P_t)^2 - M_p^2}}$$

$$\Big\{ \Big[\left(1+\cos^2\theta\right) F_{UU}^1 + \left(1-\cos^2\theta\right) F_{UU}^2 + \sin 2\theta \cos\phi\, F_{UU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{UU}^{\cos 2\phi} \Big]$$

$$+ \; S_L \Big[\sin 2\theta \sin\phi\, F_{LU}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{LU}^{\sin 2\phi} \Big]$$

$$+ \; S_T \Big[\sin\phi_b \Big(\left(1+\cos^2\theta\right) F_{TU}^1 + \left(1-\cos^2\theta\right) F_{TU}^2 + \sin 2\theta \cos\phi\, F_{TU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{TU}^{\cos 2\phi} \Big) + \cos\phi_b \Big(\sin 2\theta \sin\phi\, F_{TU}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{TU}^{\cos 2\phi} \Big) \Big] \Big\}$$



Sivers Mechanism

Sivers function

$$F_{TU}^1 = -\mathcal{C}\left[\frac{\mathbf{q}_T\cdot \mathbf{k}_{T,b}}{q_T M_p} f_{1T}^{\perp}\left(x_b, \mathbf{k}_{T,b}^2\right) \bar{f}_1\left(x_t, \mathbf{k}_{T,t}^2\right) \right]$$

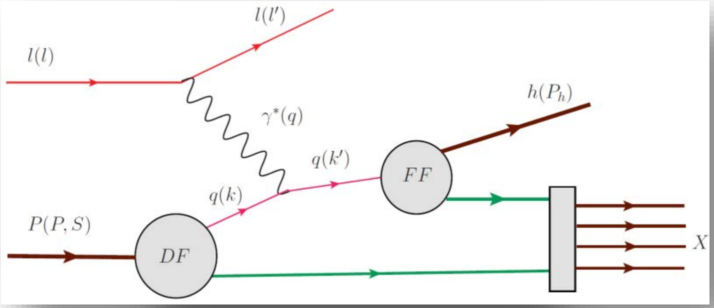
→ with the asymmetry amplitude:

$$A_{TU}^{\sin\phi_b} = \frac{F_{TU}^1}{F_{UU}^1}$$

SIDIS vs Drell Yan

- SIDIS and Drell-Yan have similar physics reach:
  - ➞ tools to probe quark and antiquark structure of nucleon
  - ➞ electromagnetic probes

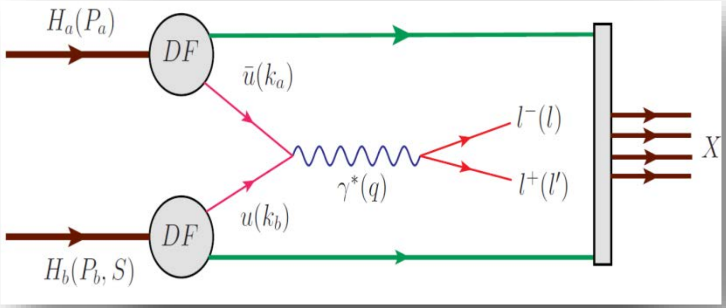
SIDIS (spacelike) virtual photon



Quintessential probe of hadron structure:

- ➞ relatively simple to measure and calculate
- ➞ QCD final state effects
- ➞ fragmentation process
- ➞ **no quark-antiquark selectivity**

Drell-Yan (timelike) virtual photon



credit: A. Kotzinian

Cleanest probe to study hadron structure:

- ➞ no QCD final state effects
- ➞ no fragmentation process
- ➞ production of two TMD parton distribution functions
- ➞ **ability to select sea quark distribution**
- ➞ hadron beam: $\sigma(DY) / \sigma(nuclear) \approx 10^{-7}$

Complementarity between SIDIS and Drell Yan

- Complementarity is emphasized by (LO): (Arnold,Metz,Schlegel:PRD79,034005(2009))
  - ➡ in SIDIS: there is 1 $F_{U(L),T}$ per TMD
  - ➡ in DY: at least 2 $F_{(U)T}$ per TMD
    - → same TMDs can be measured in different $F_{(U)T}$
    - → allowing cross checks of TMD extraction & even of underlying formalism TMD

- Systematic study of quark TMDs in Drell Yan
  - ➡ requires double-polarization
  - ➡ only then can all 8 leading twist TMD be measured

- Double-Spin Drell Yan
  - ➡ Measure DY with both Beam and Target polarized
    - ⟶ broad spin physics program possible
    - ⟶ truly complementary to spin physics programs at Jlab and RHIC and EIC

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma^{LO}_{SIDIS}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\right.$$

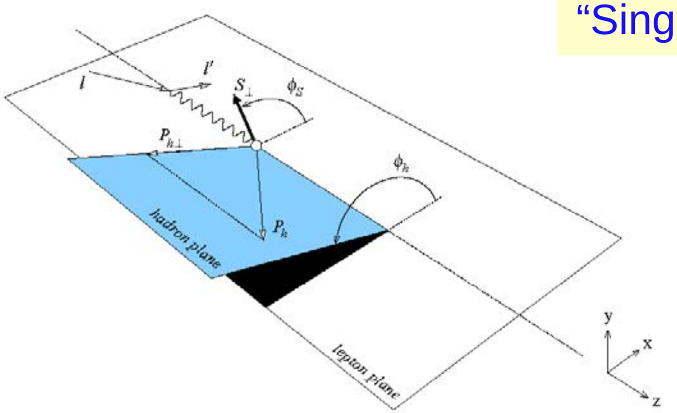
$$+\ S_T\begin{bmatrix}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\ \sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\ \sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{bmatrix}$$

DY

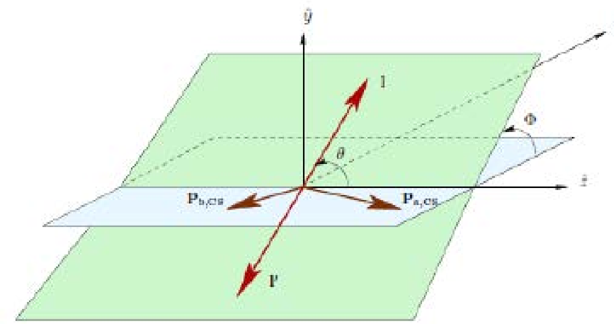
$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\left\{ 1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}\right.$$

$$\left. +\ S_T\begin{bmatrix}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\begin{pmatrix}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{pmatrix}\end{bmatrix}\right\}$$

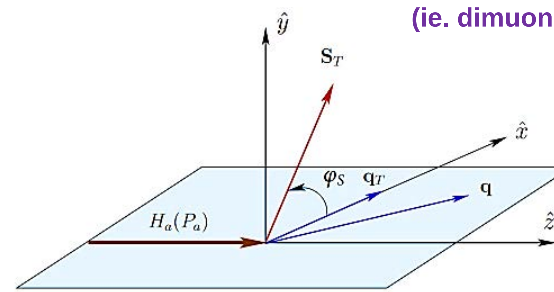
Measure magnitude of azimuthal modulations in cross section:
"Single Spin Asymmetries"



target rest frame



Collins-Soper frame
(ie. dimuon c.m. frame)



target rest frame

credit: M. Chiosso & B. Parsamyan

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma^{LO}_{SIDIS}}{dxdydzdp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\Big\{ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)$$

$$+ S_T\begin{bmatrix}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{bmatrix}$$

DY

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\Big\{ 1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}$$

$$+ S_T\begin{bmatrix}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\begin{pmatrix}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{pmatrix}\end{bmatrix}\Big\}$$

$A_{UU}^{\cos 2\phi_h}$	$\propto$	$h_1^{\perp q}\otimes H_{1q}^{\perp h}$	
$A_{UT}^{\sin(\phi_h-\phi_s)}$	$\propto$	$f_{1T}^{\perp q}\otimes D_{1q}^{h}$	
$A_{UT}^{\sin(\phi_h+\phi_s)}$	$\propto$	$h_1^{q}\otimes H_{1q}^{\perp h}$	
$A_{UT}^{\sin(3\phi_h-\phi_s)}$	$\propto$	$h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$	

PDF	$\otimes$	FF
BM	$\otimes$	CF
Sivers	$\otimes$	FF
Transv	$\otimes$	CF
Pretz	$\otimes$	CF

beam PDF	$\otimes$	target PDF
BM	$\otimes$	BM
f_1	$\otimes$	Sivers
BM	$\otimes$	Transv
BM	$\otimes$	Pretz

$A_T^{\cos 2\varphi_{cs}}$	$\propto$	$h_1^{\perp q}\otimes h_1^{\perp q}$
$A_T^{\sin\varphi_s}$	$\propto$	$f_1^{q}\otimes f_{1T}^{\perp q}$
$A_T^{\sin(2\varphi_{cs}-\varphi_s)}$	$\propto$	$h_1^{\perp q}\otimes h_{1T}^{\perp q}$
$A_T^{\sin(2\varphi_{cs}+\varphi_s)}$	$\propto$	$h_1^{\perp q}\otimes h_1^{q}$

within QCD TMD framework:

$$h_1^{\perp q}\big|_{SIDIS} = -h_1^{\perp q}\big|_{DY} \qquad f_{1T}^{\perp q}\big|_{SIDIS} = -f_{1T}^{\perp q}\big|_{DY}$$

$$h_1^{q}\big|_{SIDIS} = h_1^{q}\big|_{DY} \qquad h_{1T}^{\perp q}\big|_{SIDIS} = h_{1T}^{\perp q}\big|_{DY}$$

Drell Yan Advantage

- Complementarity is emphasized by (LO): (Arnold,Metz,Schlegel:PRD79,034005(2009))
  - ➞ in SIDIS: there is 1 $F_{U(L),T}$ per TMD
  - ➞ in DY: at least 2 $F_{(U)T}$ per TMD

→ same TMDs can be measured in different $F_{(U)T}$
→ allowing cross checks of TMD extraction
& even of underlying formalism

SIDIS asymmetry	PDF ⊗ FF			beam PDF ⊗ target PDF			DY asymmetry
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$	BM	⊗	CF	BM	⊗	BM	$A_T^{\cos 2\varphi_{cs}} \propto h_1^{\perp q} \otimes h_1^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers	⊗	FF	f_1	⊗	Sivers	$A_T^{\sin\varphi_s} \propto f_1^{q} \otimes f_{1T}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transv	⊗	CF	BM	⊗	Transv	$A_T^{\sin(2\varphi_{cs}-\varphi_s)} \propto h_1^{\perp q} \otimes h_{1T}^{\perp q}$
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretz	⊗	CF	BM	⊗	Pretz	$A_T^{\sin(2\varphi_{cs}+\varphi_s)} \propto h_1^{\perp q} \otimes h_1^{q}$

$$A_T^{\sin\varphi_s} = \frac{F_T^1}{F_U^1}$$

Differences compared to RHIC

- **Most significant difference**:
  Ramp time of **Main Injector < 0.7 s**, at **RHIC 1-2 min**
  - ➞ warm magnets at MI vs. superconducting at RHIC
    - → pass through all depolarizing resonances much more quickly
- Beam remains in **MI ~5 s**, in **RHIC ~8 hours**
  - ➞ extracted beam vs. storage ring
  - ➞ much less time for cumulative depolarization
- Disadvantage compared to RHIC — no institutional history of accelerating polarized proton beams
  - ➞ Fermilab E704 had polarized beams through hyperon decays