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First transverse spin asymmetries measured in polarized Drell-Yan at COMPASS

Wen-Chen Chang 章文箴
Institute of Physics, Academia Sinica

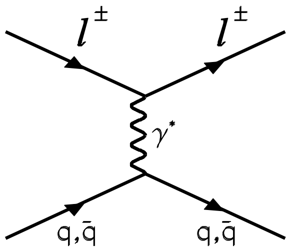
On behalf of COMPASS Collaboration

Outline

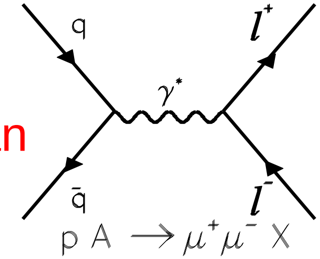
- Transverse momentum dependent distributions (TMDs) and transverse single-spin asymmetries (TSAs)
- Universality test of Sivers Functions: a predicted sign change between SIDIS and Drell-Yan processes
- First measurement of TSAs from the 2015 polarized Drell-Yan runs of COMPASS
- Summary

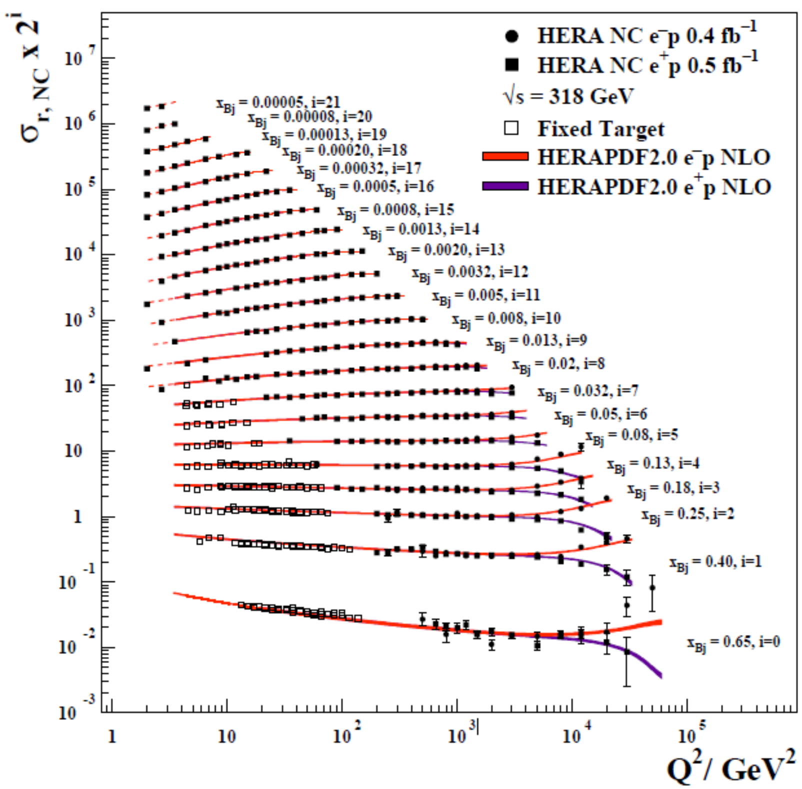
Factorization of Hard Processes

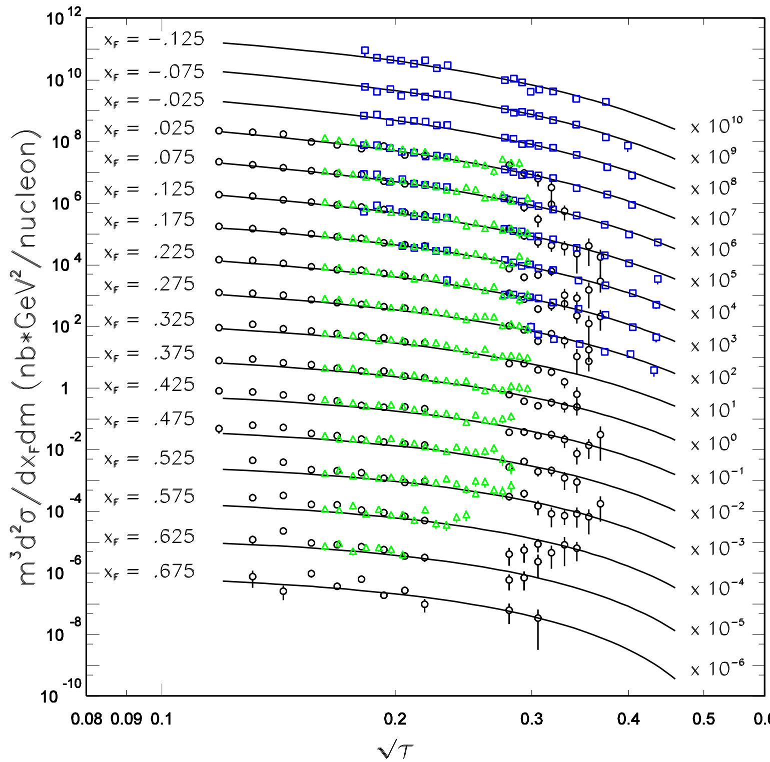
DIS



Drell-Yan

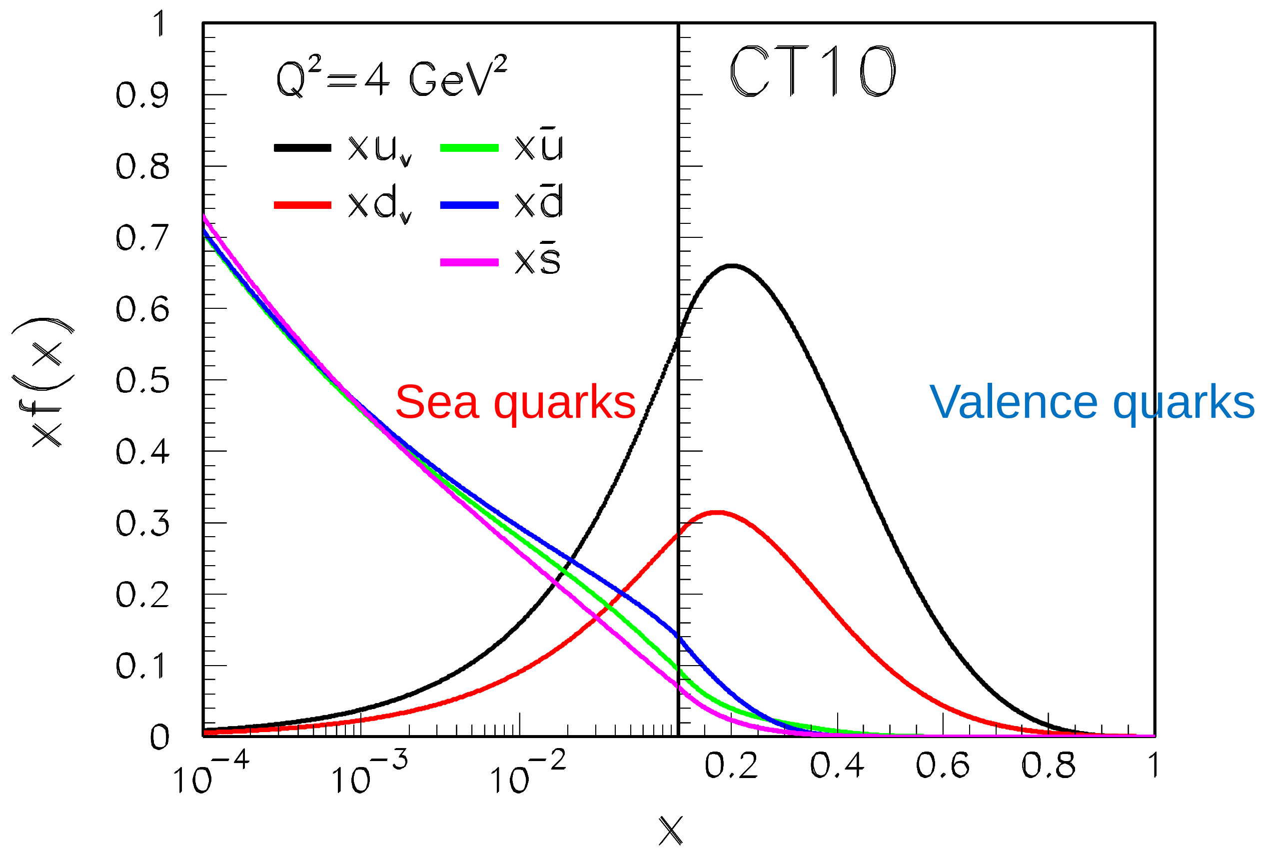






$$\sigma_{proton}(x, Q^2) = f_{parton}(x, Q^2) \otimes \hat{\sigma}_{parton}(Q^2)$$

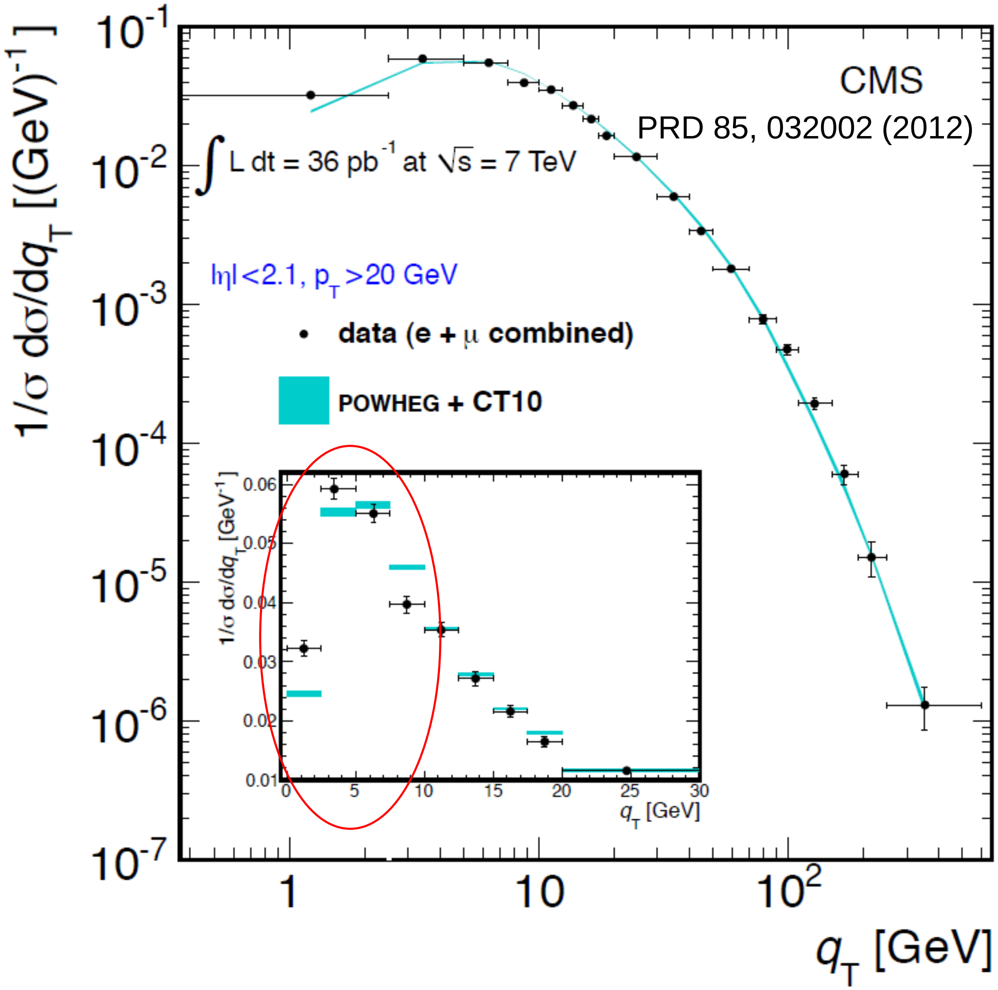
Universality of Parton Density Functions (PDFs)



x: momentum fraction of partons

Why TMDs?

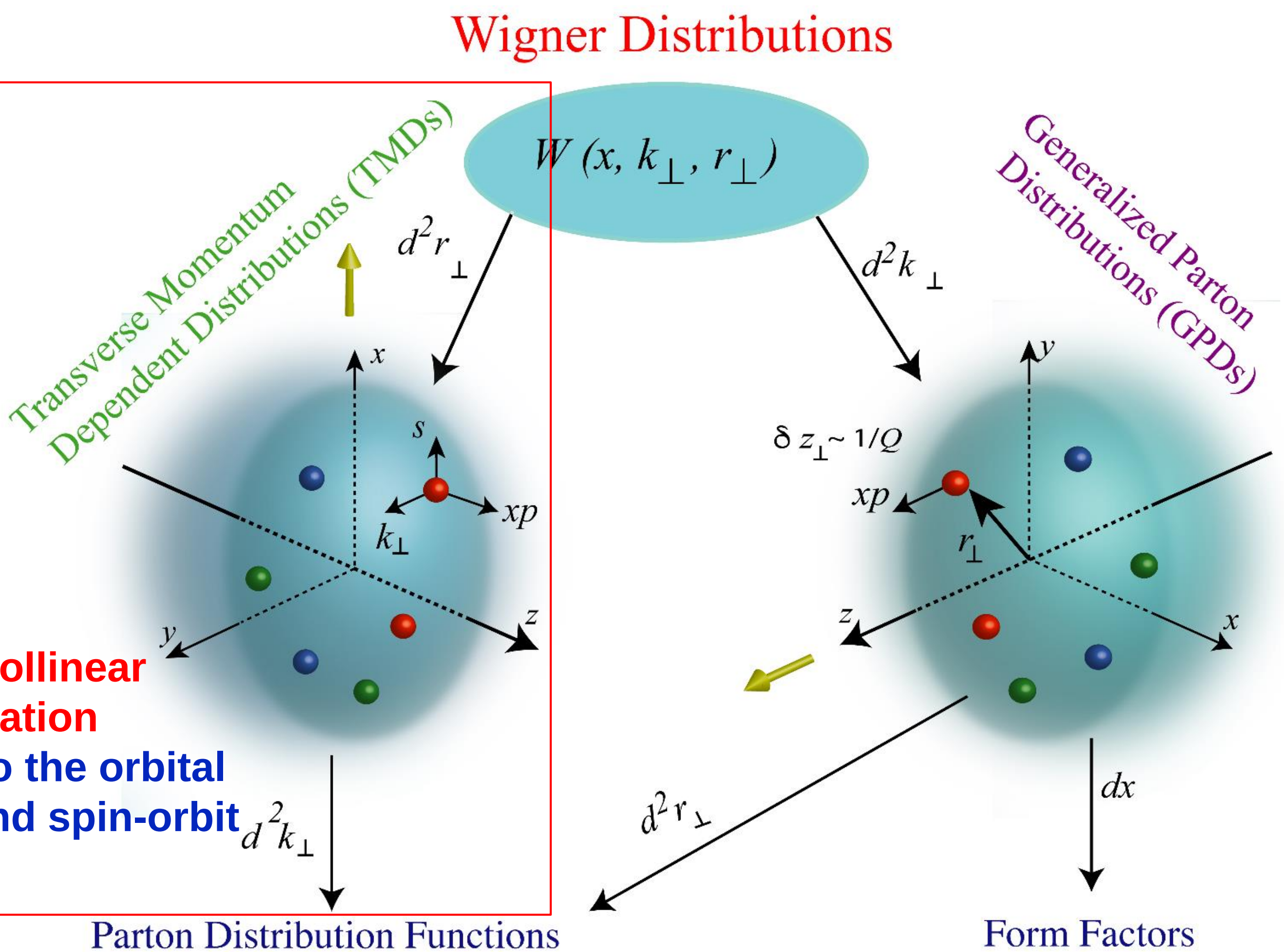
The Z-boson transverse momentum q_T spectrum in pp collisions at the LHC



- At large qT, the NNLO pQCD describes the data better than 10%.
- For qT<10 GeV, pQCD calculation fails: multi-parton QCD radiation.

Angeles-Martinez et al., arXiv: 1507.05267

Multi-dimensional Partonic Structures



- **Beyond collinear approximation**
- **Related to the orbital motion and spin-orbit effects.**

http://www.int.washington.edu/PROGRAMS/17-3/

Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

- spin of the nucleon
- spin of the parton
- k_T of the parton

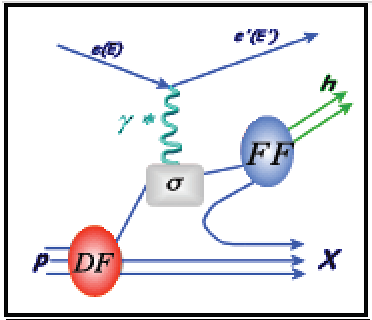
Nucleon \ Quark, Gluon	U	L	T
U	number density $f_1^{q,g}(x,k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x,k_T^2)$
L		Helicity $g_{1L}^{q,g}(x,k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x,k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x,k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x,k_T^2)$	Transversity $h_1^{q,g}(x,k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x,k_T^2)$

Leading-Twist Transverse-momentum Dependent **Fragmentation Function** (TMDs)

- spin of the nucleon
- spin of the parton
- k_T of the parton

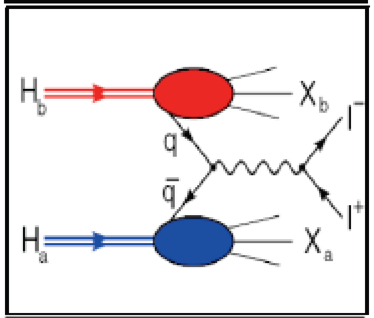
Nucleon \ Quark, Gluon	U	L	T
U	unpolarized $D_1^{q,g}(x, k_T^2)$		Collins $H_1^{\perp q,g}(x, k_T^2)$
L		$G_{1L}^{q,g}(x, k_T^2)$	$H_{1L}^{\perp q,g}(x, k_T^2)$
T	$D_{1T}^{\perp q,g}(x, k_T^2)$	$G_{1T}^{\perp q,g}(x, k_T^2)$	$H_1^{q,g}(x, k_T^2)$ $H_{1T}^{\perp q,g}(x, k_T^2)$

Accessing TMDs



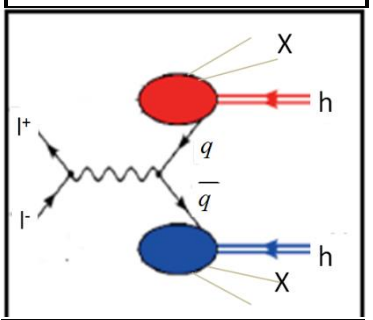
SIDIS: ep → ehX

$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$



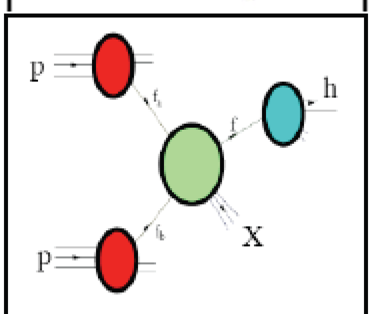
Drell-Yan: pp → e^+e^-X

$$\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$$



Dihadron in e+e-: e^+e^- →h_1 h_2 X

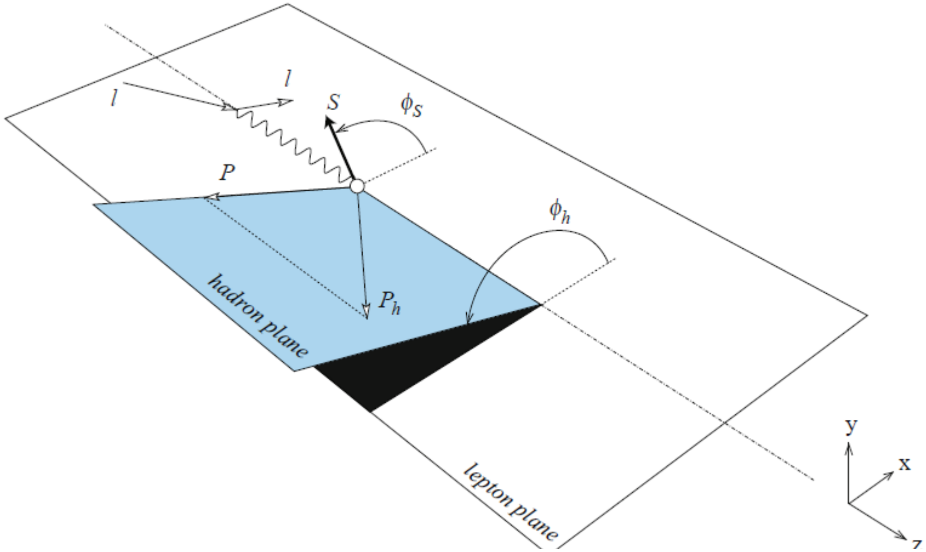
$$\sigma^{ee\to hhX} = \sum_q \sigma^{qq\to ee} \otimes FF \otimes FF$$



Hadron production in pp: pp → hX

$$\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$$

SIDIS cross-sections



$F_{UU}^{\cos(2\phi)}$, $F_{UT}^{\sin(\phi-\phi_S)}$, $F_{UT}^{\sin(\phi+\phi_S)}$:
Structure Functions

$$\sigma(\phi,\phi_S) \equiv \frac{\mathrm{d}^6\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi\,\mathrm{d}\phi_S\,\mathrm{d}P_{hT}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}\cos\phi\,F_{UU}^{\cos\phi}+\epsilon\cos(2\phi)\boxed{F_{UU}^{\cos(2\phi)}}+\lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\sin\phi\,F_{LU}^{\sin\phi}\right]$$

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\,F_{UL}^{\sin\phi}+\epsilon\sin(2\phi)\,F_{UL}^{\sin(2\phi)}\right]+S_L\lambda_e\left[\sqrt{1-\epsilon^2}\,F_{LL}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi\,F_{LL}^{\cos\phi}\right]$$

$$+|S_T|\Big[\sin(\phi-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi-\phi_S)}}+\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)+\epsilon\sin(\phi+\phi_S)\boxed{F_{UT}^{\sin(\phi+\phi_S)}}+\epsilon\sin(3\phi-\phi_S)\,F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\,F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+|S_T|\lambda_e\left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\,F_{LT}^{\cos(\phi-\phi_S)}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\,F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\},$$

Avakian et al., Eur. Phys.J. A52 (2016) 150

Polarization-dependent Terms: Transverse Spin Asymmetry A_{UT}

$$A_{UT} = \frac{F_{UT}}{F_{UU}} = \frac{1}{fS_T} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

f: dilution factor due to non-polarizable component of the target

S_T: polarization degree of transverse spin

- **Advantage**: most of the systematics due to instrumental artifacts cancel.
- **Disadvantage**: the unpolarized structure function F_{UU} has to be well known.

SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)}\, A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h - \phi_S) \right] \end{array} \right\}$$

SIDIS-DY bridge

DY

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$	Worm-gear L	$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$
$A_{LL} \propto g_{1L}^q \otimes D_{1q}^h$, $A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$		Double polarized DY only

(circled): FFs, further constrained by the e+e- process.

Key Issues of TMDs to be Answered/Tested by Experiments

- Signals
- Factorization and universality: different processes
- Properties of QCD evolution: different energies
- Flavor dependence (u, d, $\bar{u}$, $\bar{d}$, s, $\bar{s}$, g): different targets and tagged hadrons

Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

- spin of the nucleon
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Nucleon \ Quark, Gluon	U	L	T
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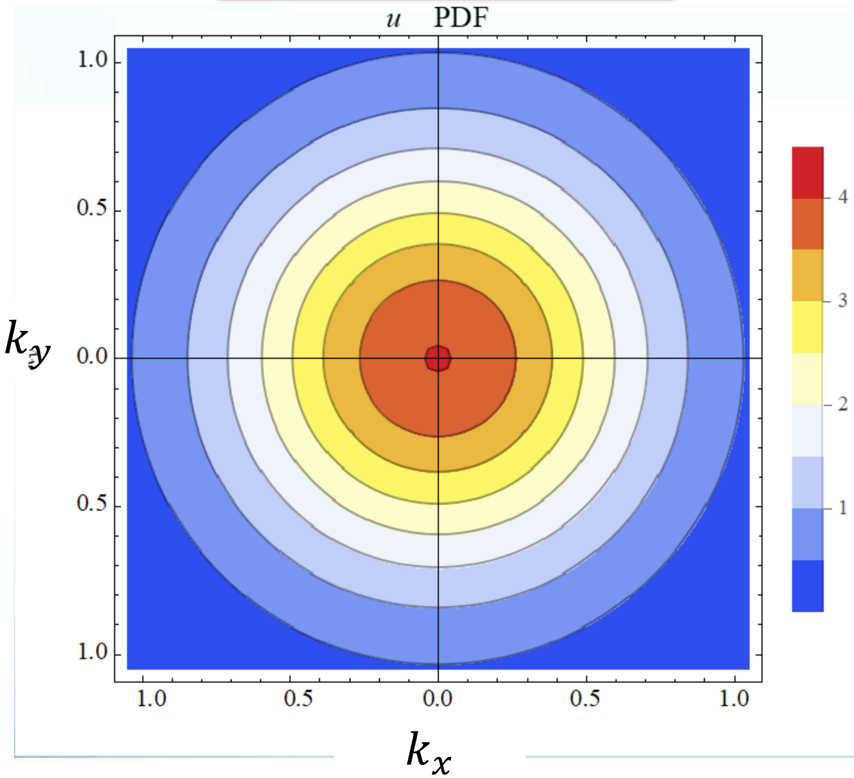
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	**Sivers** $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x, k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x, k_T^2)$

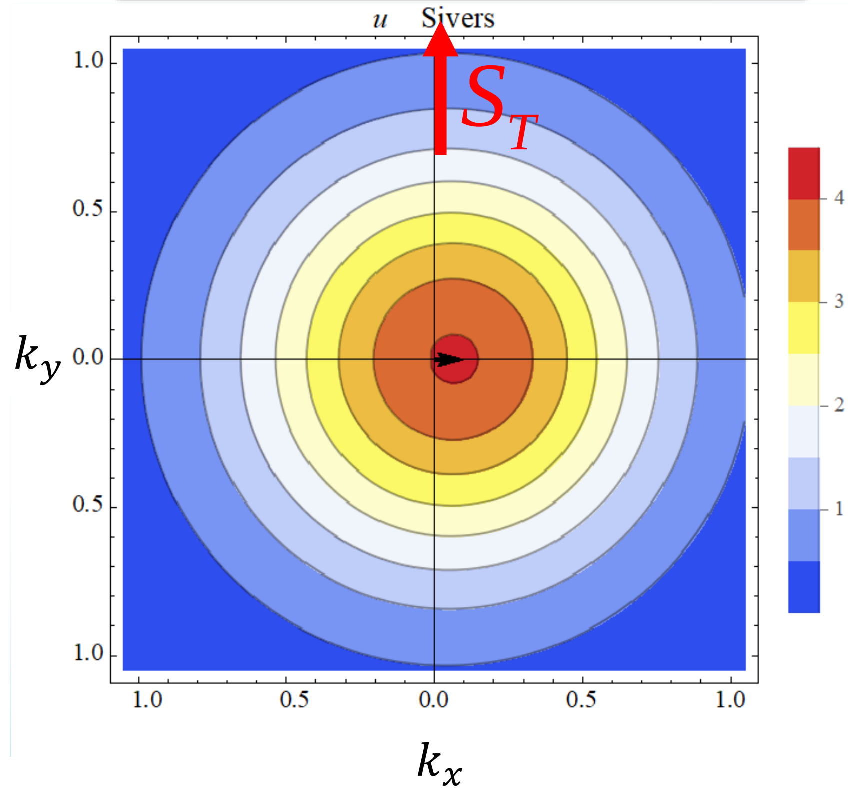
TMD Sivers Function

$$f_{q/p\uparrow}(x,\overrightarrow{k_T},\overrightarrow{S_T}) = f_{q/p}(x,k_T^2) - \frac{1}{M_N} f_{1T}^{\perp q}(x,k_T^2)\overrightarrow{S_T}\cdot(\hat{p}_N \times \overrightarrow{k_T})$$

Unpolarized proton



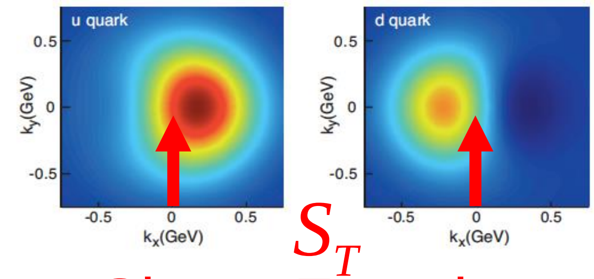
Transversely-polarized proton



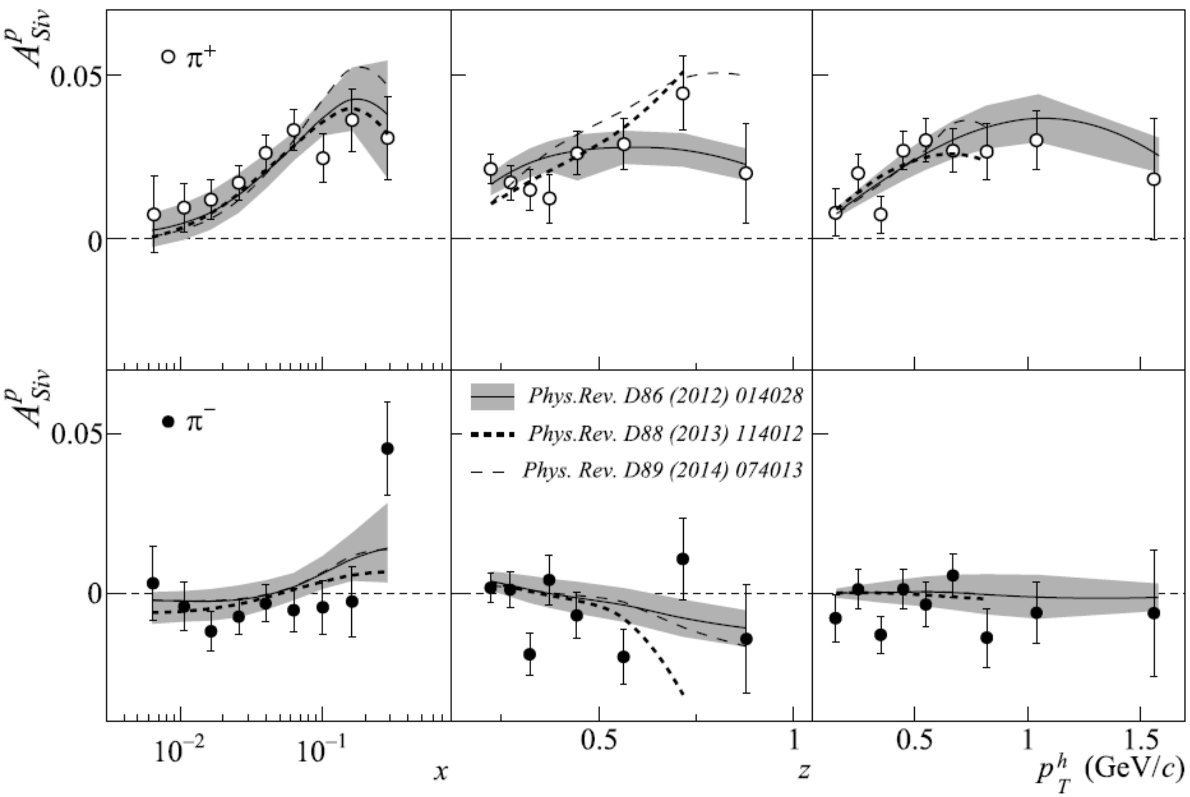
- **A nonzero Sivers function is considered to be strong evidence for the presence of quark orbital angular momentum.**

Nonzero Sivers Asymmetries from SIDIS

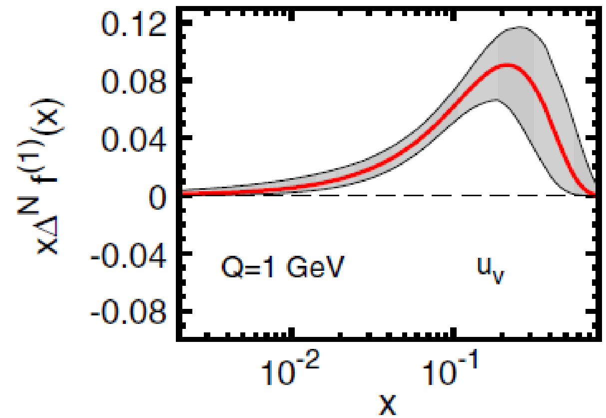
T. Iwata's talk

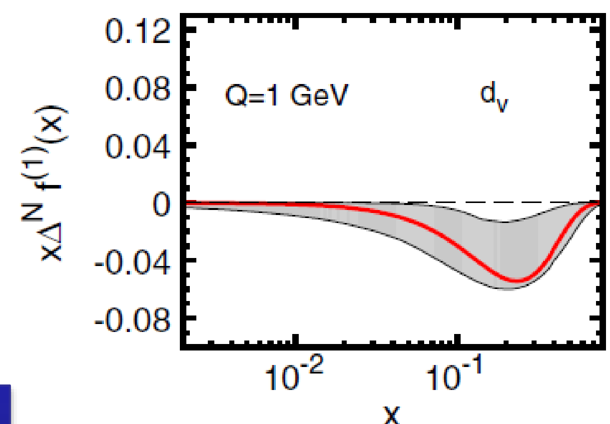


COMPASS, PLB 744 (2015) 250



Sivers Functions





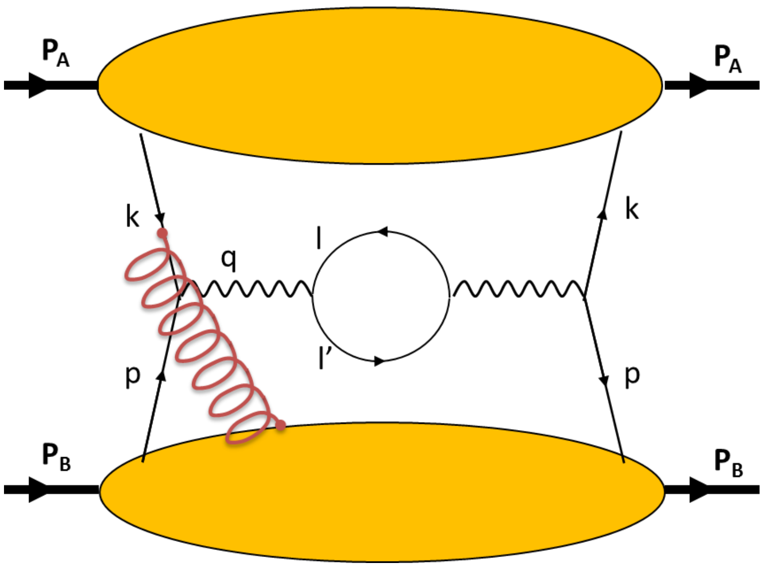
Signals of Sivers functions in SIDIS.
Flavor dependence.

PRD 86, 014028 (2012)
[arXiv:1204.1239]

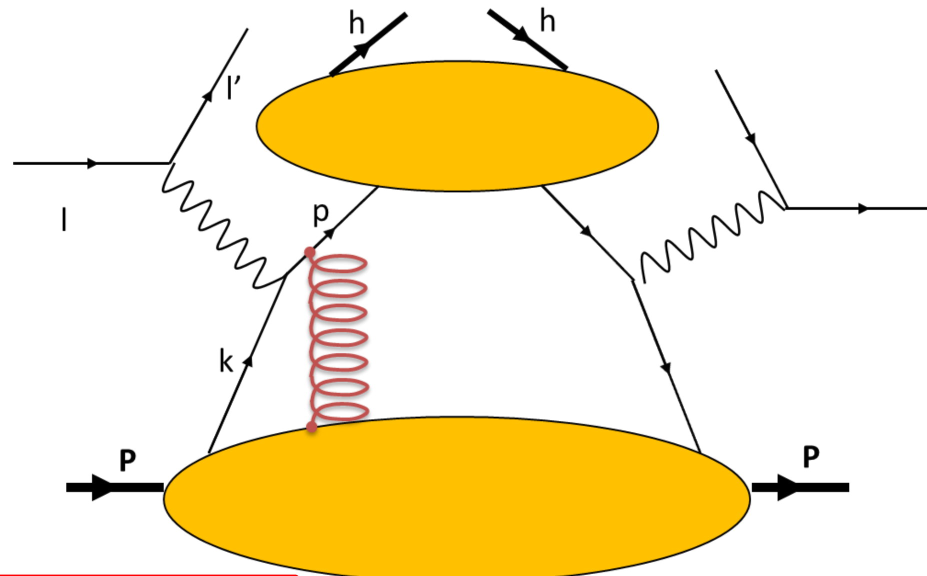
Universality of Sivers Functions

J.C. Collins, Phys. Lett. B 536 (2002) 43
A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656 (2003) 165
D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B 667 (2003) 201
Z.B. Kang, J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001

Drell-Yan



SIDIS

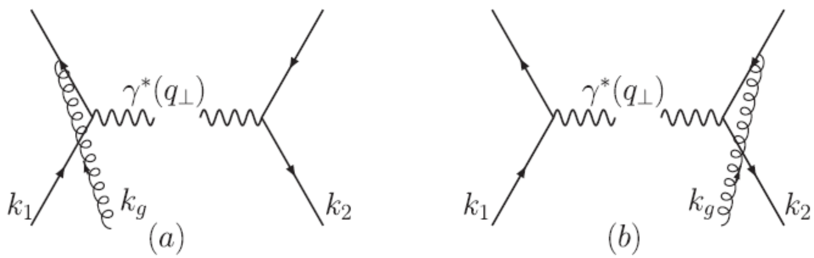


$$\text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}$$

- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Fundamental predictions from TMD physics will be tested.***

"Opposite Sign of SSA for SIDIS and DY" Preserved in NLO QCD

Z-B Kang, B-W Xiao and F. Yuan, PRL 107, 152002 (2011)



- Ji-Ma-Yuan factorization
- Collins-Soper-Sterman resummation

b).

$$\frac{d\Delta\sigma(S_\perp)}{dydQ^2d^2q_\perp} = \sigma_0 \epsilon^{\alpha\beta} S_\perp^\alpha W_{\rm UT}^\beta(Q;q_\perp), \qquad (2)$$

$$W_{\rm UT}^\alpha(Q;q_\perp) = \int \frac{d^2b}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{b}} \tilde{W}_{\rm UT}^\alpha(Q;b) + Y_{\rm UT}^\alpha(Q;q_\perp),$$

$$\left. \Delta C_q^T \right|_{DY} = -\left. \Delta C_q^T \right|_{SIDIS}$$

$q_\perp \ll Q$

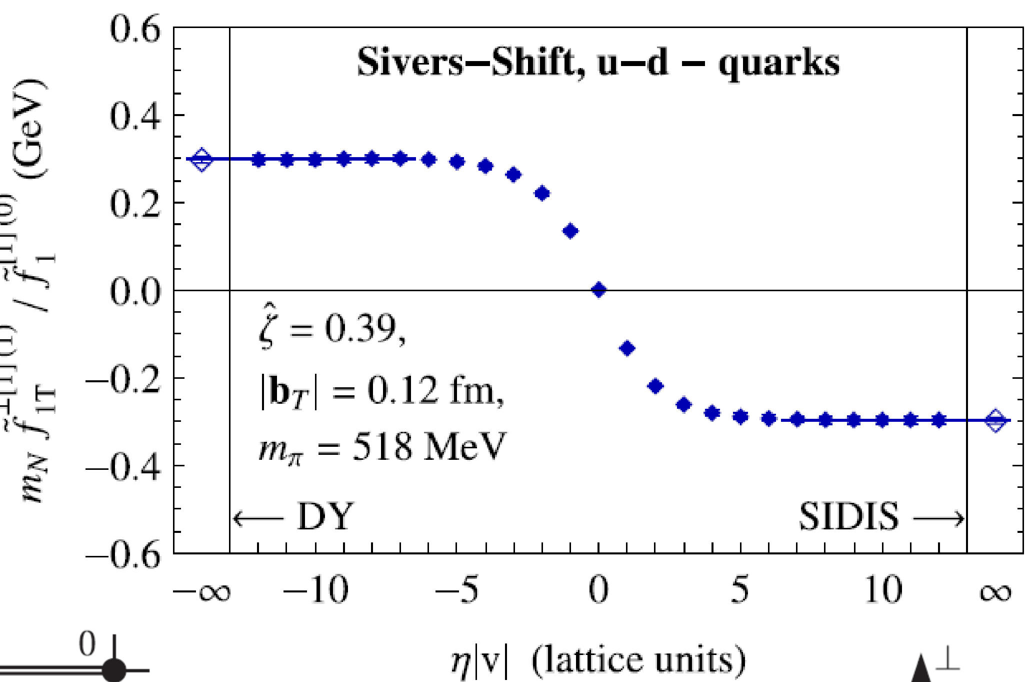
$$\tilde{W}_{\rm UT}^\alpha(Q;b) = e^{-\mathcal{S}_{\rm UT}(Q^2,b)} \tilde{W}_{\rm UT}^\alpha(C_1/b,b)$$

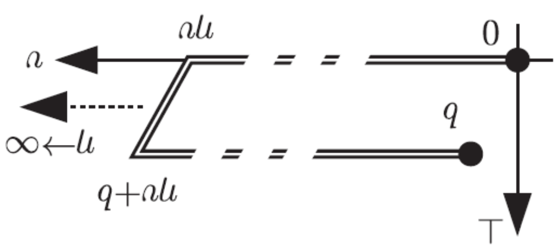
$$= (-ib_\perp^\alpha/2) e^{-\mathcal{S}_{\rm UT}(Q^2,b)} \Sigma_{i,j}$$

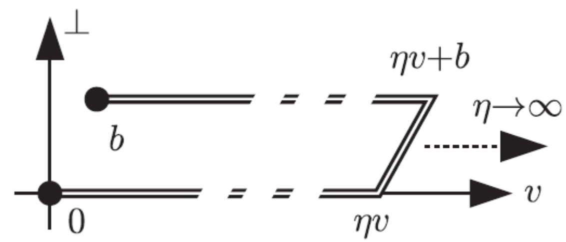
$$\times \Delta C_{qi}^T \otimes f_{i/A}^{(3)}(z_1', z_1'') C_{\bar{q}j} \otimes f_{j/B}(z_2'), \qquad (9)$$

Sivers Function with Lattice QCD

B. U. Musch et al., PRD 85, 094510 (2012)

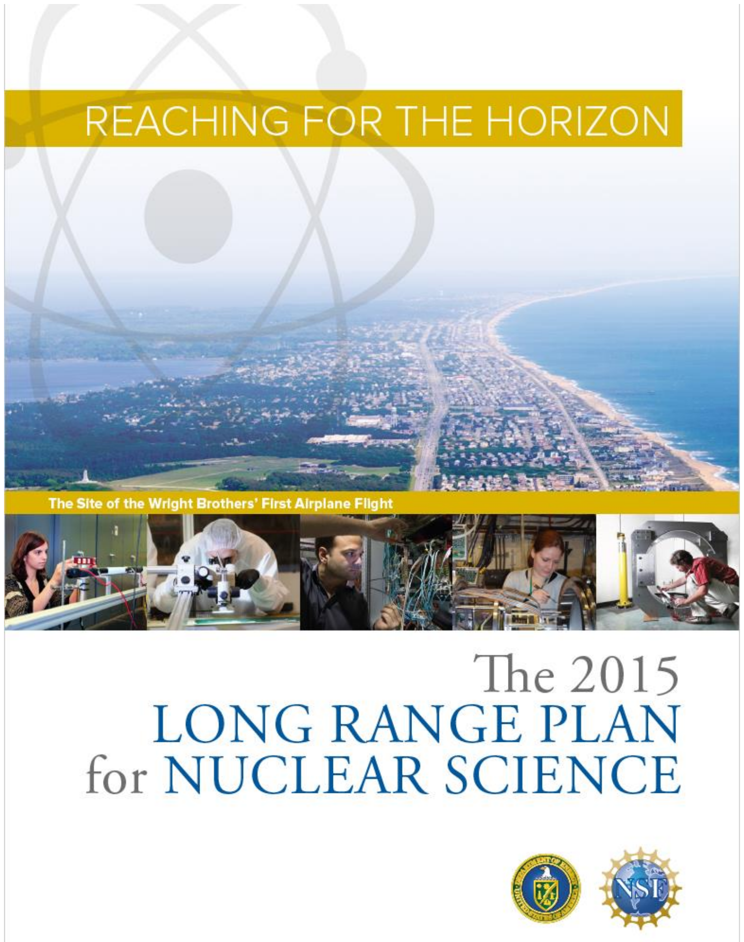






As the vertical gauge link (ηv) goes from ∞ **(SIDIS)** to – ∞ **(Drell-Yan),** the sign of Sivers function reverses.

2015 U.S. Long Range Plan

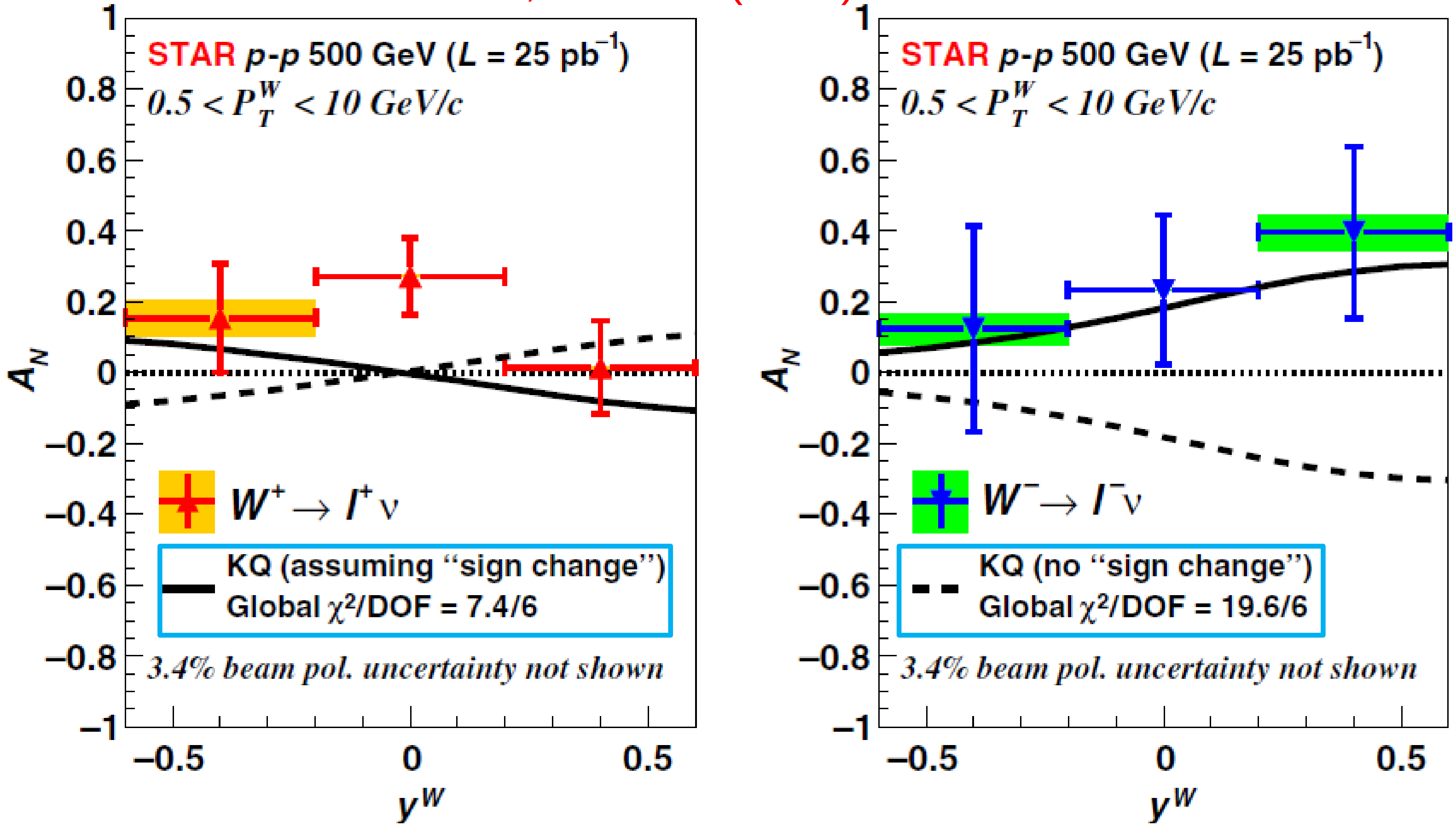


A nonzero Sivers function is considered to be strong evidence for the presence of quark orbital angular momentum. Indeed, it has been measured to be nonzero in the HERMES and JLab experiments. Figure 2.5 shows the unique potential of the JLab 12-GeV program to map the Sivers function for the up quark. The Sivers function has a quite intriguing property predicted by QCD. When measured in SIDIS, it will have one sign, yet when measured in a collision with a proton or pion beam, it should have the opposite sign. This sign change is due to the nature of QCD color interactions and provides an important test of our understanding. It is imperative that the quark Sivers functions that will be measured in SIDIS are also accurately measured with hadron beams, such as the proton beams available at RHIC or Fermilab and the pion beams used by the COMPASS-II experiment at CERN.

https://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

Transverse SSA of W in polarized pp collisions at RHIC

STAR, PRL 116 (2016) 132301



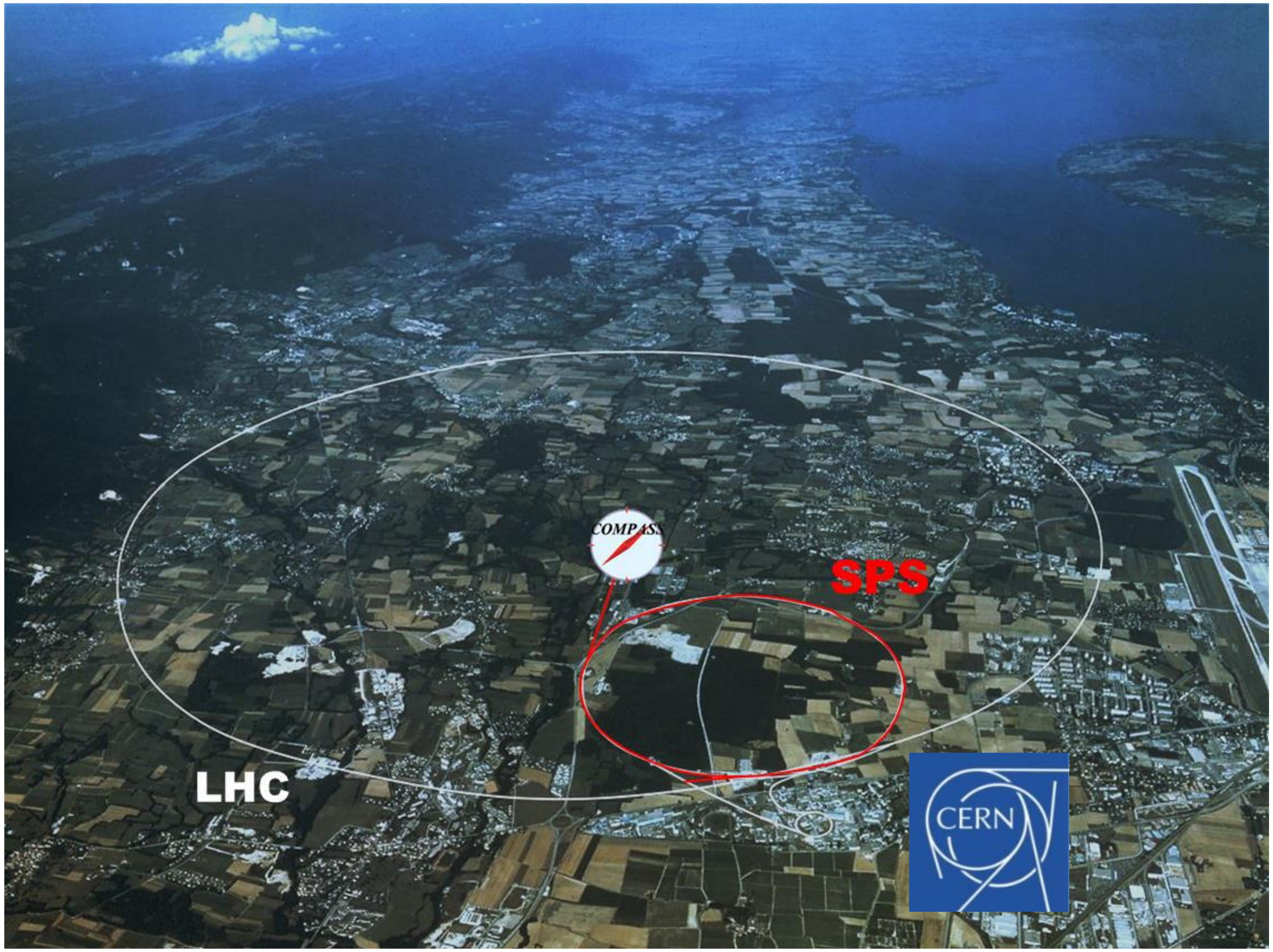
$$A_N = \frac{1}{\langle P \rangle} \frac{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} - \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}}{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} + \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}},$$

COMPASS Collaboration

(Common Muon and Proton Apparatus for Structure and Spectroscopy)

M.G. Perdekamp's talk

- 24 institutions from 13 countries – nearly 250 physicists
- Fixed-target experiment at SPS north area
- Physics programs:
    - Nucleon spin and partonic structures
    - Hadron spectroscopy

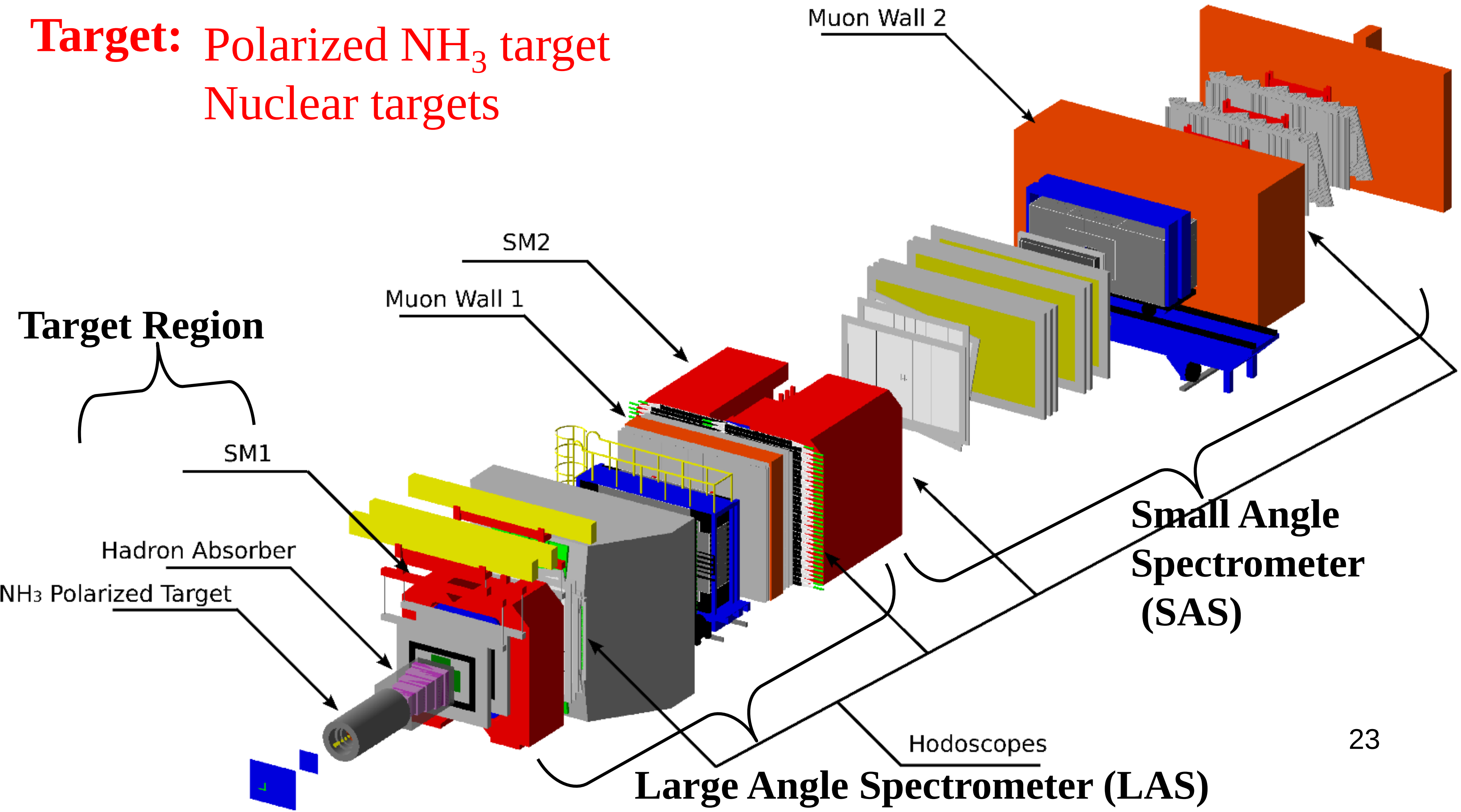


COMPASS Setup (Drell-Yan Runs)

Beam: π^- 190 GeV/c

Target: Polarized NH_3 target

Nuclear targets

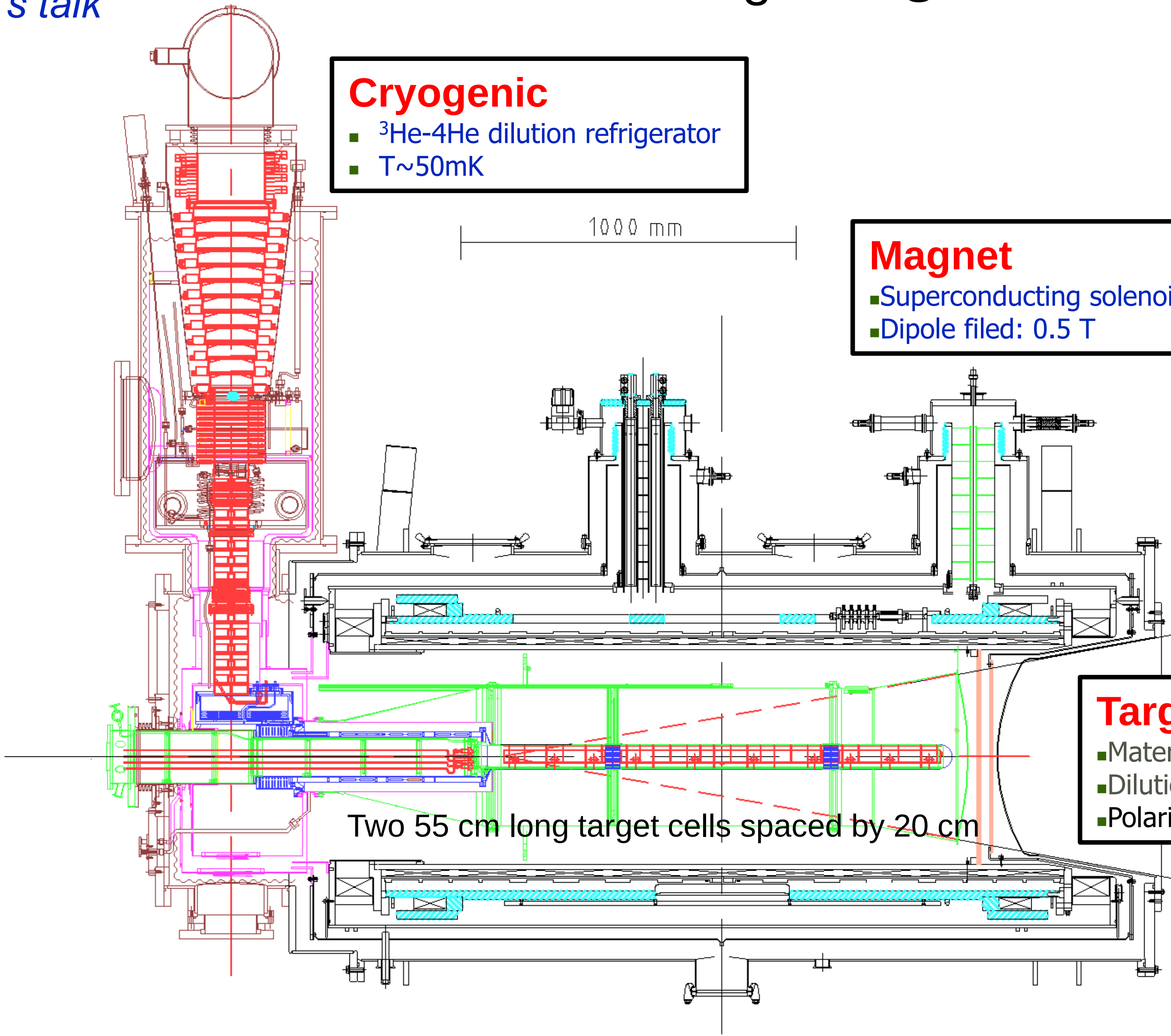


Polarized NH_3 Target

T. Iwata's talk

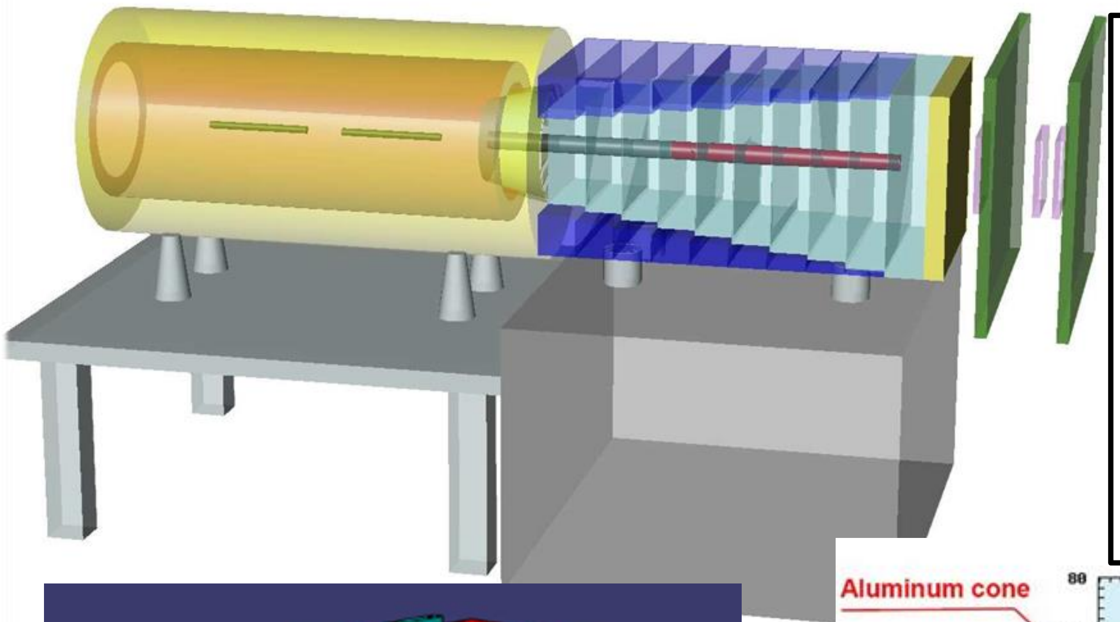
Cryogenic
- ^{3}He-4He dilution refrigerator
- T~50mK

Magnet
- Superconducting solenoid : 2.5 T
- Dipole filed: 0.5 T

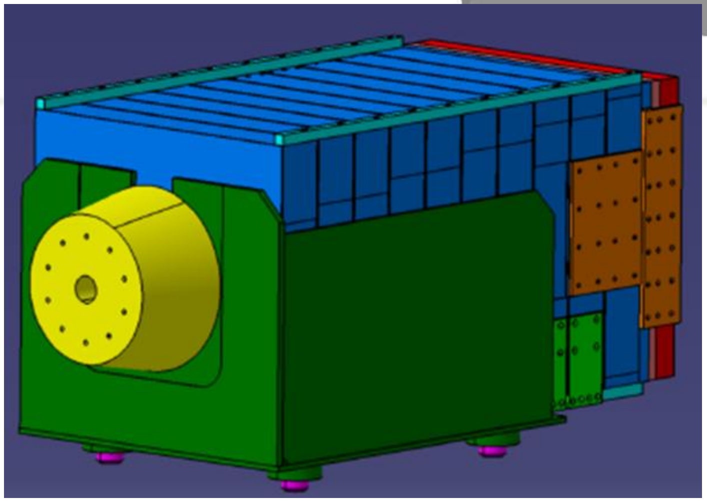


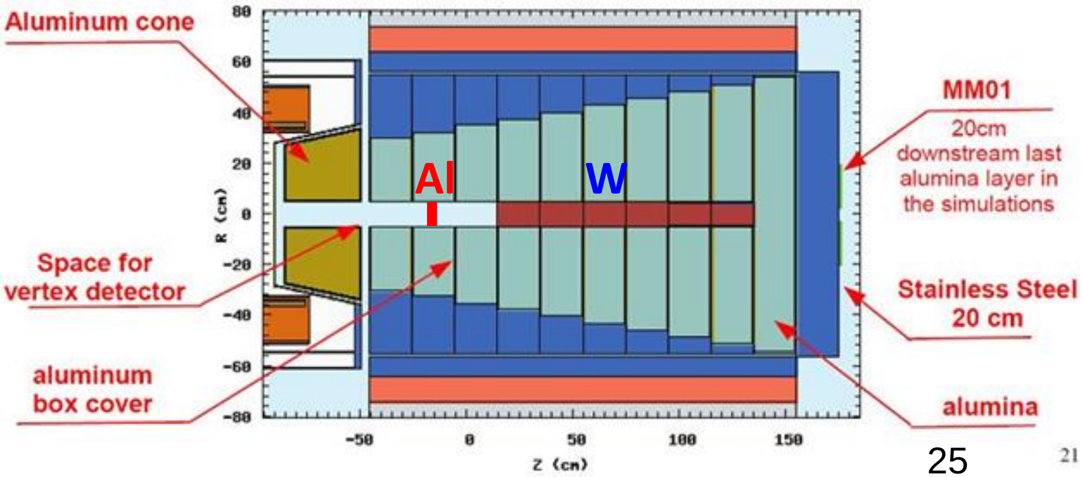
Target
- Materials: p(NH_3)
- Dilution factor: ~0.15
- Polarization: >90%

Hadron Absorber & Nuclear Targets

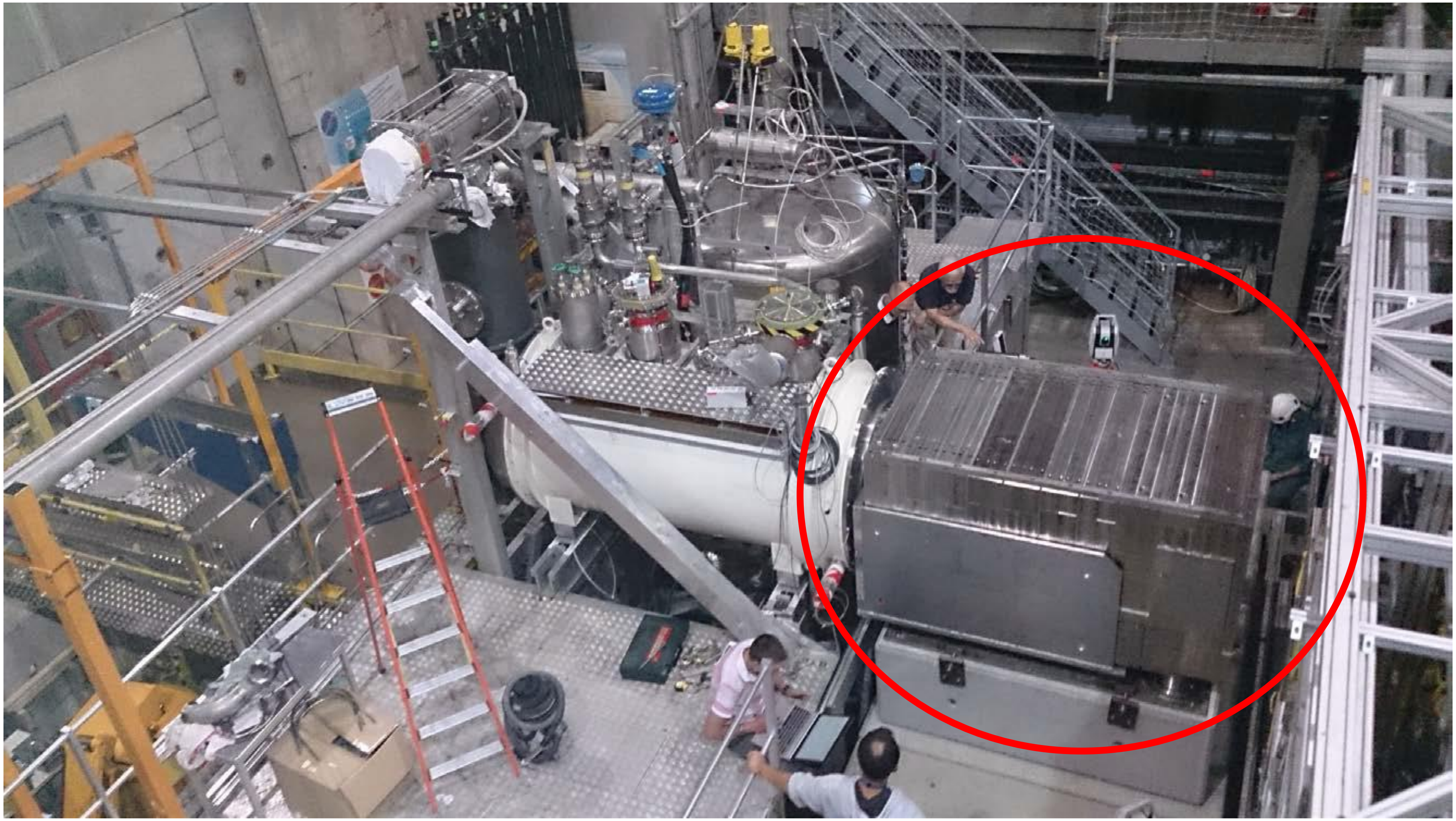


- Absorber: 236 cm long, made of Al_2O_3.
- Radiation lengths (multiple scattering for μ): $x/X_0 = 33.53$
- Hadronic interaction lengths (stopping power for π): $x/\lambda_{int} = 7.25$
- 7 cm Al target
- 120 cm W beam dump





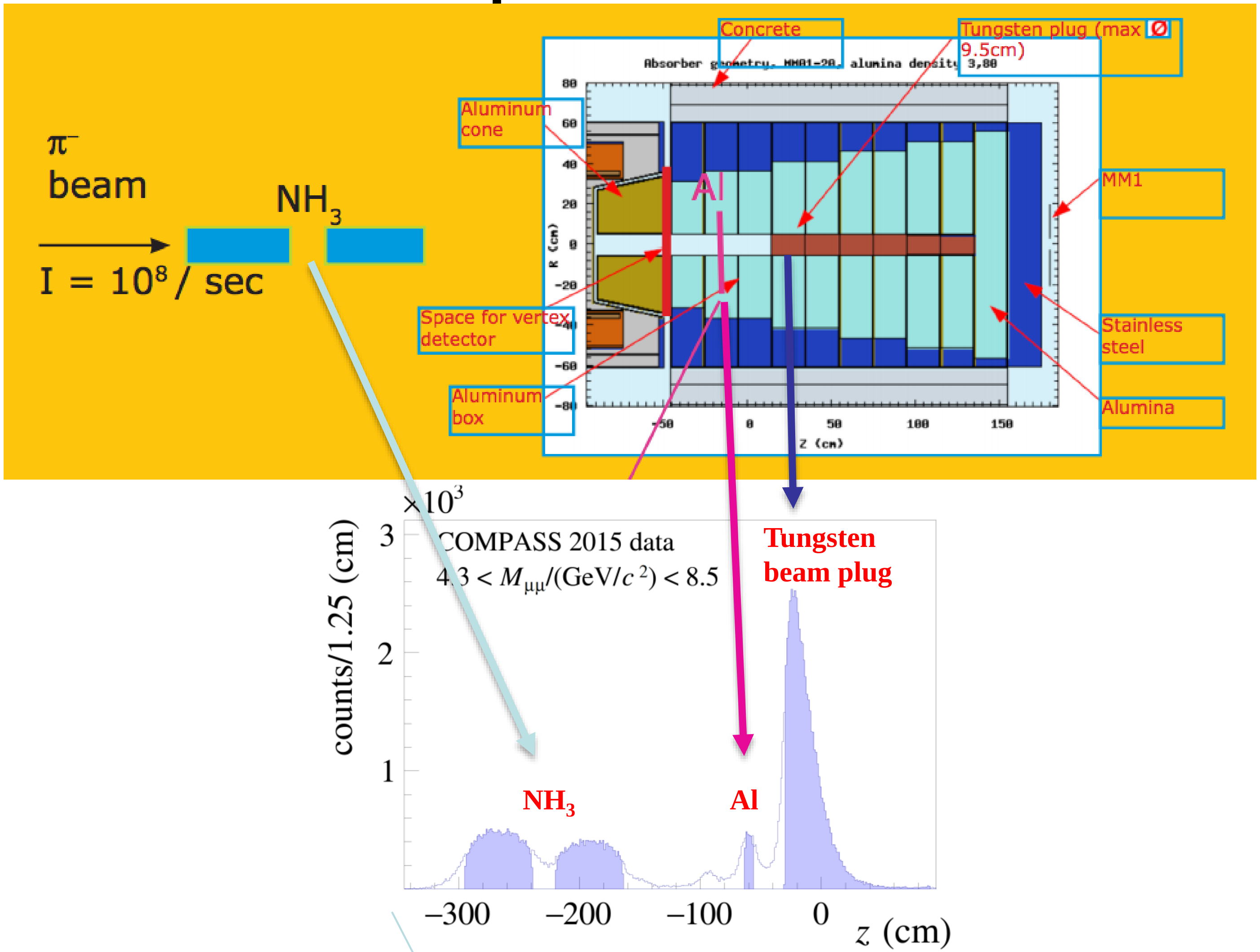
Hadron Absorber & Nuclear Targets



COMPASS-II Transversely Polarized Drell-Yan Program

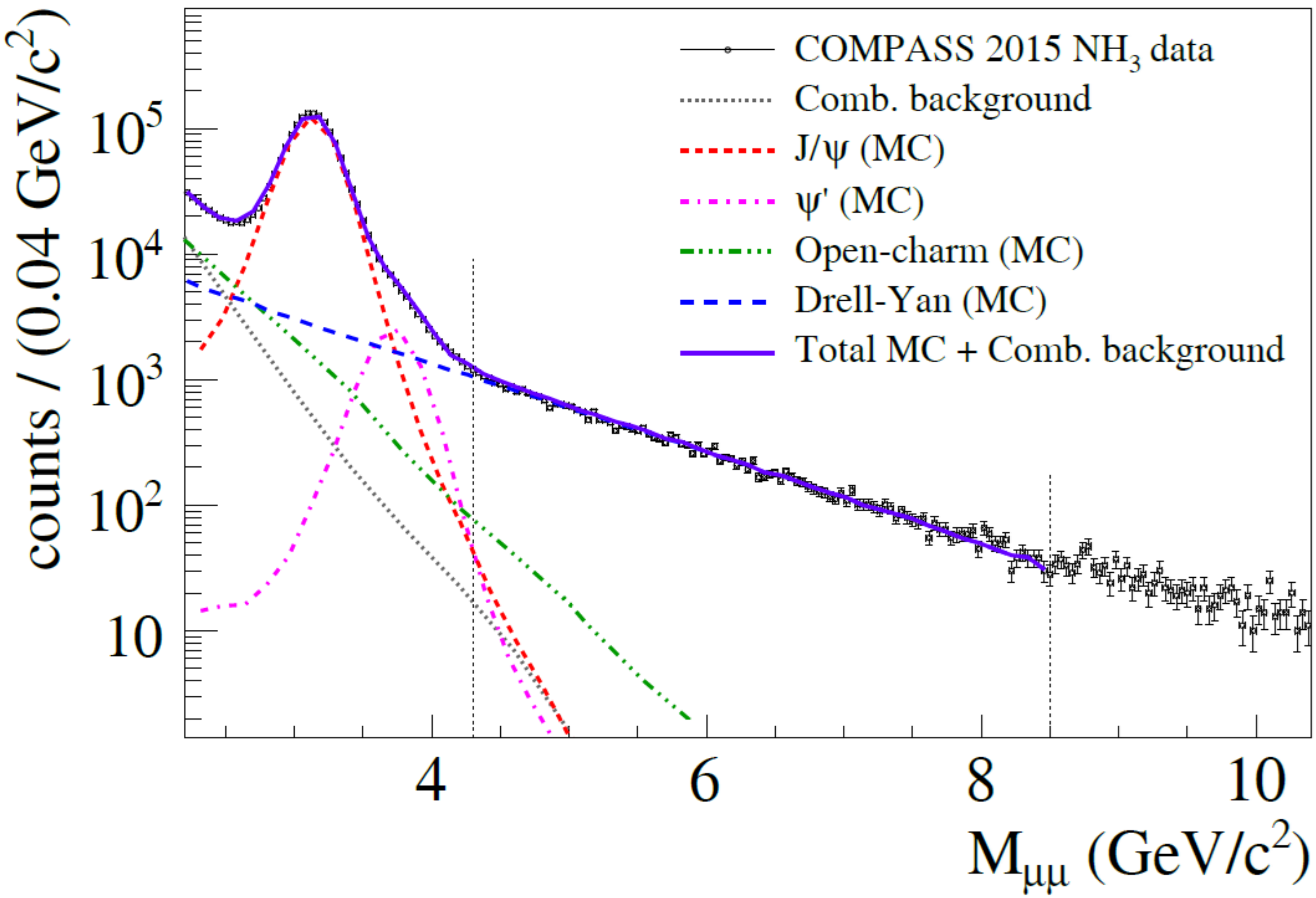
- Schedules:
  - 2014 Oct – Dec: commission Drell-Yan runs
  - 2015: first year of transversely polarized Drell-Yan runs with 190 GeV π^- beam

Dimuon Vertex Distributions (2015 Trans.-pol. Drell-Yan Runs)



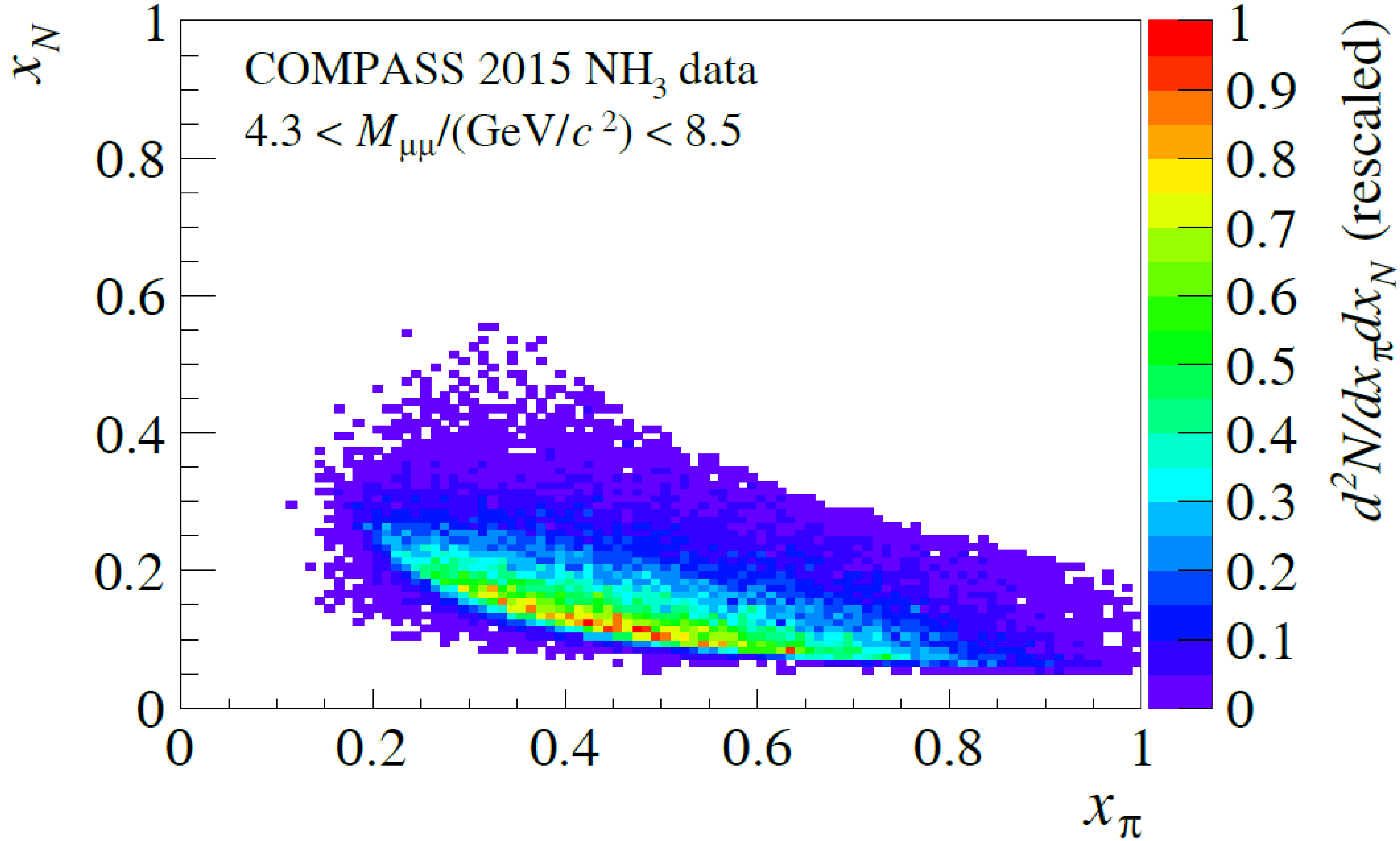
arXiv:1704.00488

Dimuon Invariant-mass Distributions (2015 Trans.-pol. Drell-Yan Runs)



arXiv:1704.00488

Kinematic Acceptance (2015 Trans.-pol. Drell-Yan Runs)

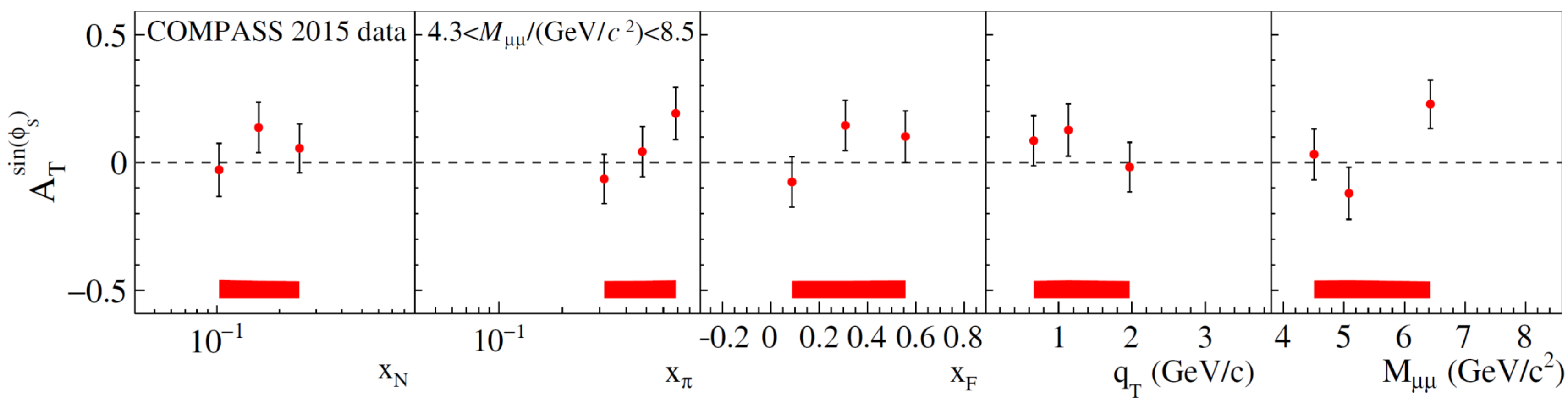


arXiv:1704.00488

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Sivers

$$A_T^{\sin\phi_s} \propto \text{Density } f_1|_\pi \otimes \text{Sivers } f_{1T}^{\perp}|_p$$

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}\left\{\left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi}\cos 2\phi\right)\right.$$
$$+ \left|\vec{S}_T\right|\left[A_T^{\sin\phi_s}\sin\phi_s\right.$$

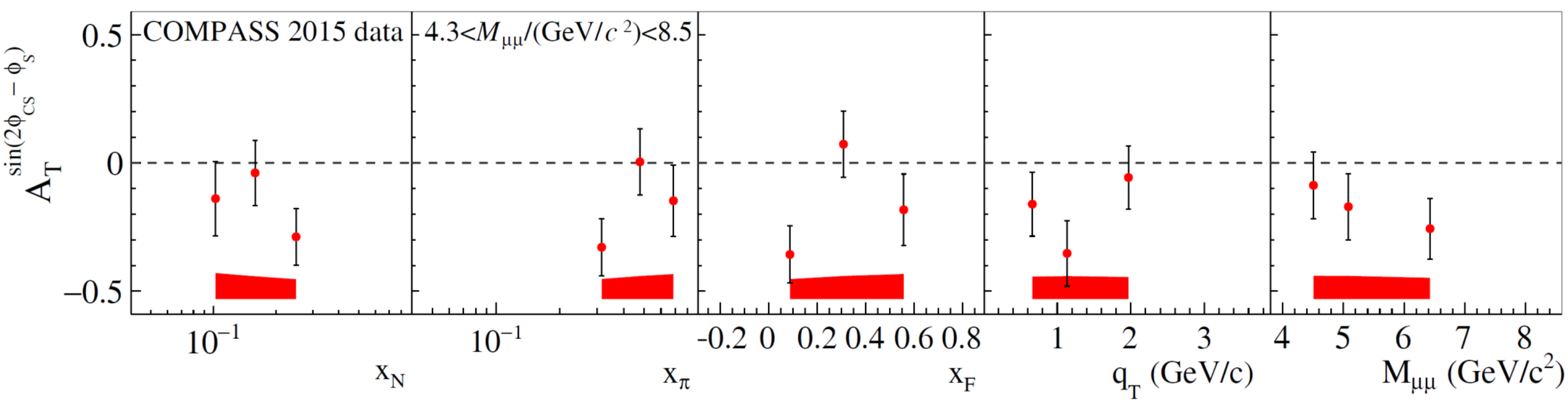


arXiv:1704.00488

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Transversity

$A_T^{\sin(2\phi-\phi_s)} \propto \text{BM } h_1^{\perp}|_{\pi} \otimes \text{Transversity } h_1|_p$

$$\frac{d\sigma^{LO}}{d^4q d\Omega}$$
$$= \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}\left\{\left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi} \cos 2\phi\right)\right.$$
$$+ |\vec{S}_T| \left[A_T^{\sin\phi_s} \sin\phi_s\right.$$

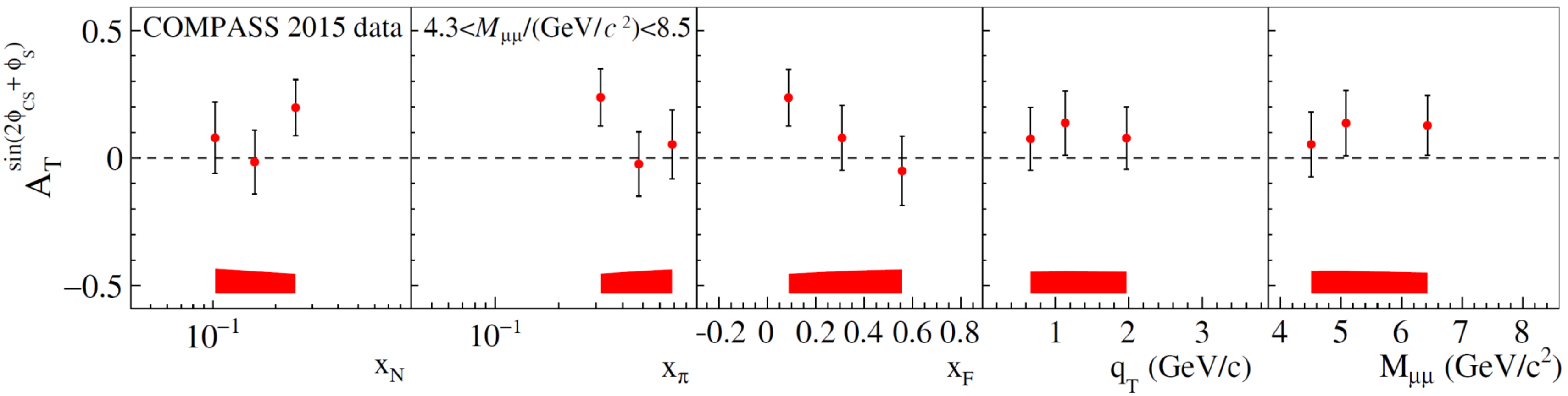


arXiv:1704.00488

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Pretzelosity

$A_T^{\sin(2\phi+\phi_S)} \propto \text{BM } h_1^{\perp}|_{\pi} \otimes \text{Pretzelosity } h_{1T}^{\perp}|_p$

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}\left\{\left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi}\cos 2\phi\right) + |\vec{S}_T|\left[A_T^{\sin\phi_S}\sin\phi_S\right.\right.$$



arXiv:1704.00488

SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right] \end{array} \right\}$$

SIDIS-DY bridge

DY

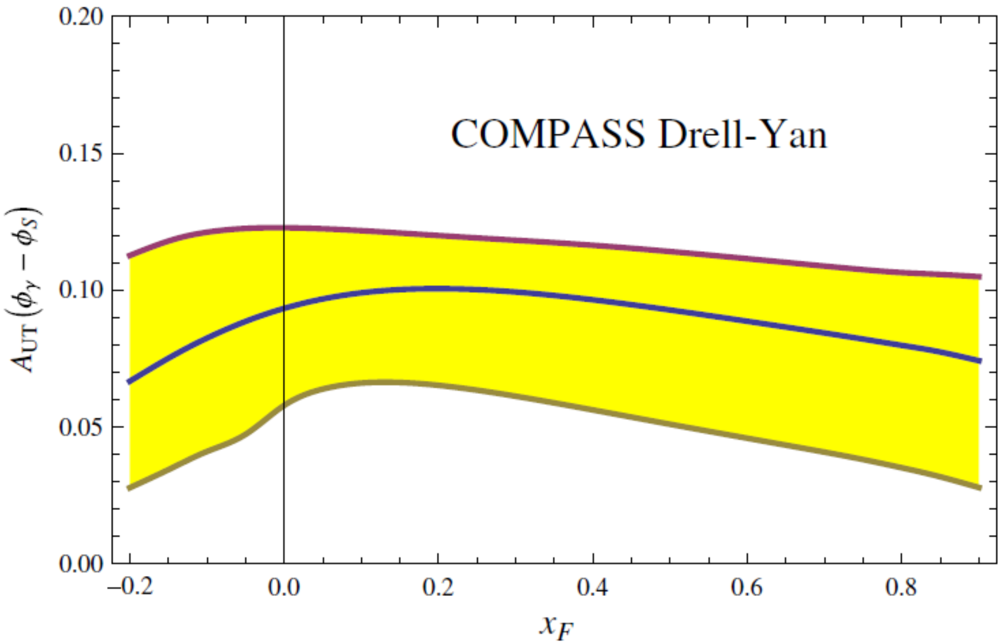
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$

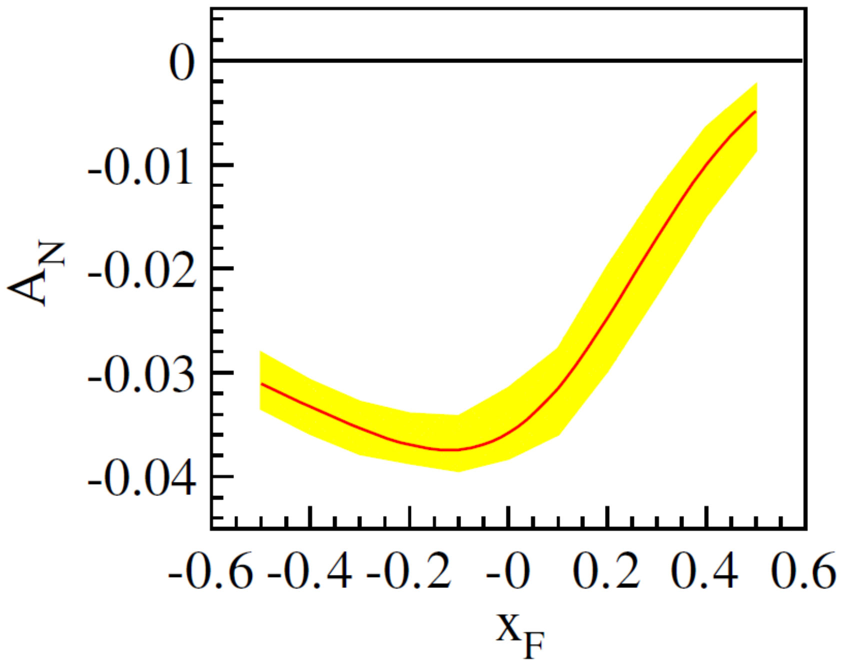
SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h + \phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$
$A_{UT}^{\sin(3\phi_h - \phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$	Worm-gear L	$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$
$A_{LL} \propto g_{1L}^{q} \otimes D_{1q}^{h}$, $A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$		Double polarized DY only

(circled): FFs, further constrained by the e+e- process.

Predicted Sivers Asymmetries in COMPASS with QCD Evolution

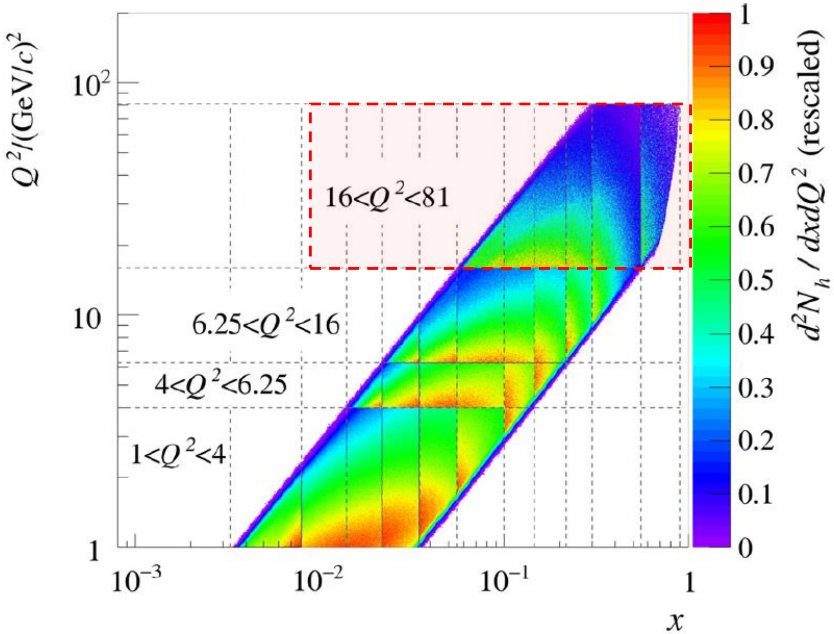


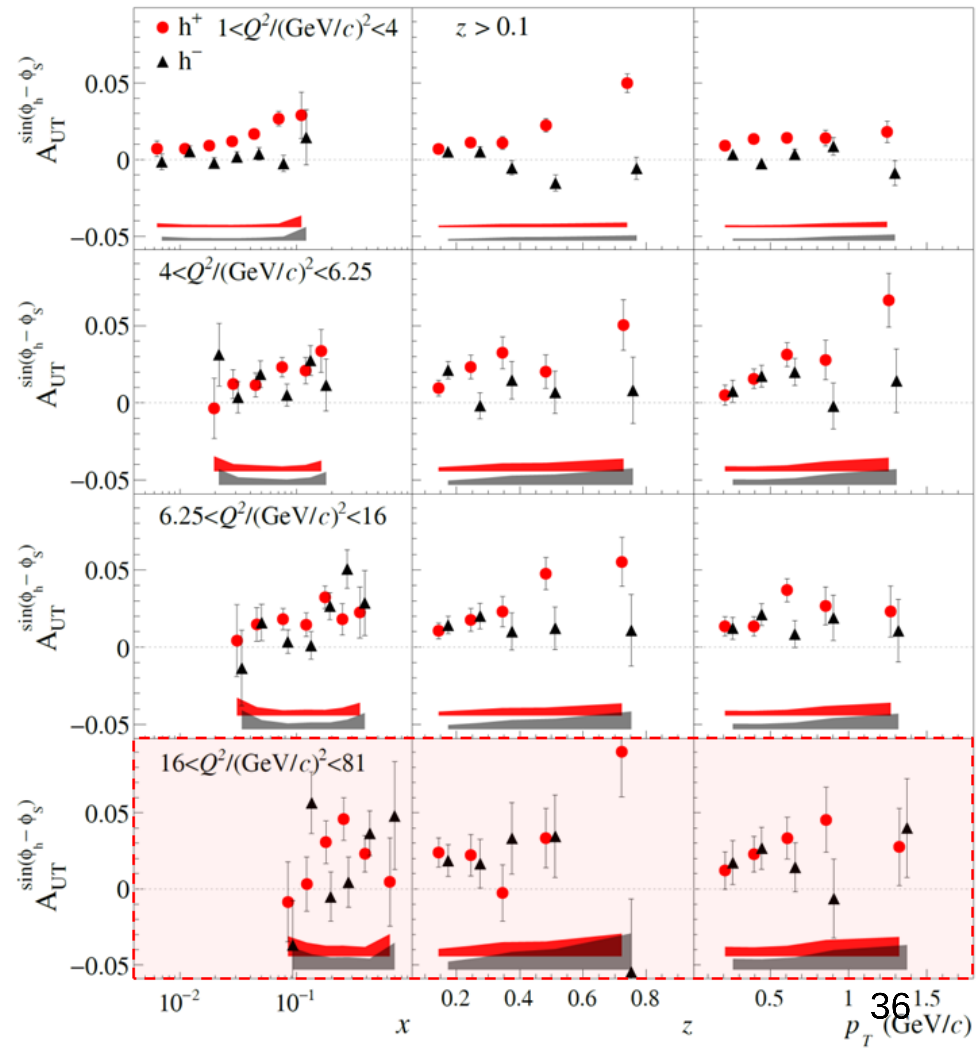
Sun and Yuan,
PRD 88, 114012 (2013)



Echevarria, Idilbi, Kang and Vitev,
PRD 89, 074013 (2014)

Sivers Asymmetries (x, z, p_T^h, Q^2)





Sivers asymmetry extracted in SIDIS at the hard scales of the Drell–Yan process at COMPASS

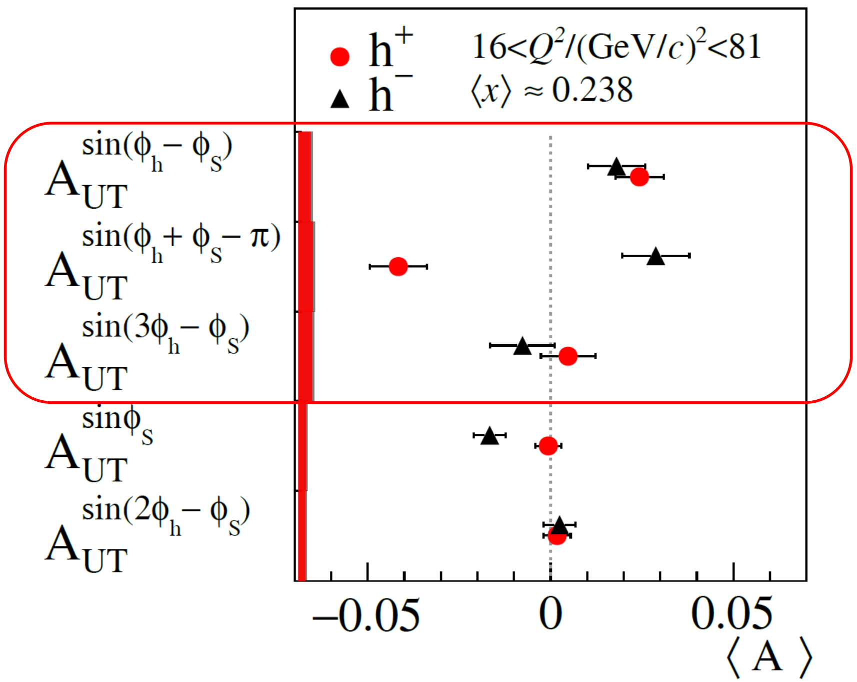
COMPASS, PLB 770 (2017) 138

SIDIS and DY TSAs at COMPASS

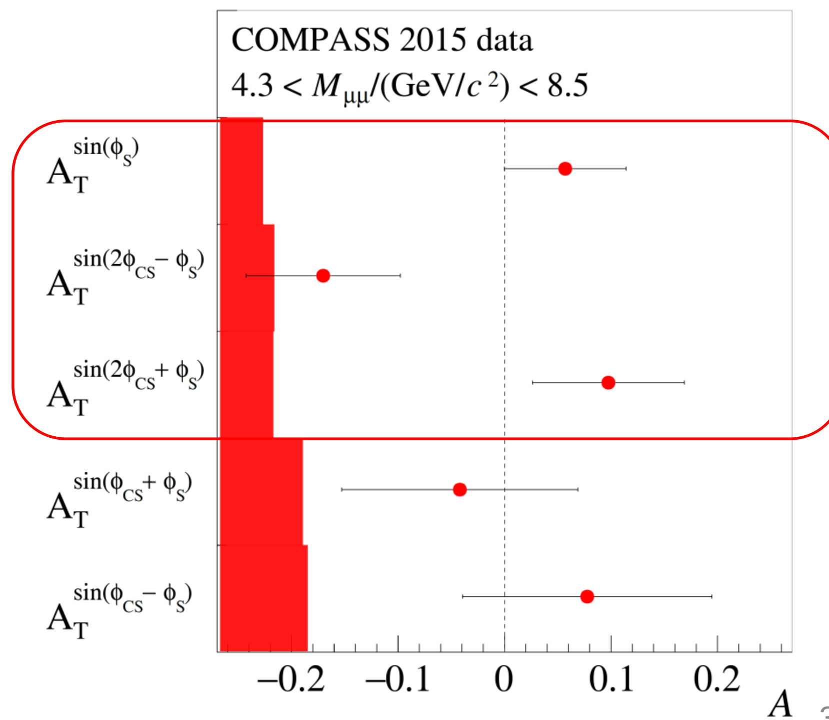
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots + S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \end{bmatrix} \Bigg\}$$

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)\Bigg\{ 1 + \ldots + S_T \begin{bmatrix} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \begin{pmatrix} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{pmatrix} \\ + D_{[\sin 2\theta_{CS}]} \begin{pmatrix} A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) \end{pmatrix} \end{bmatrix} \Bigg\}$$

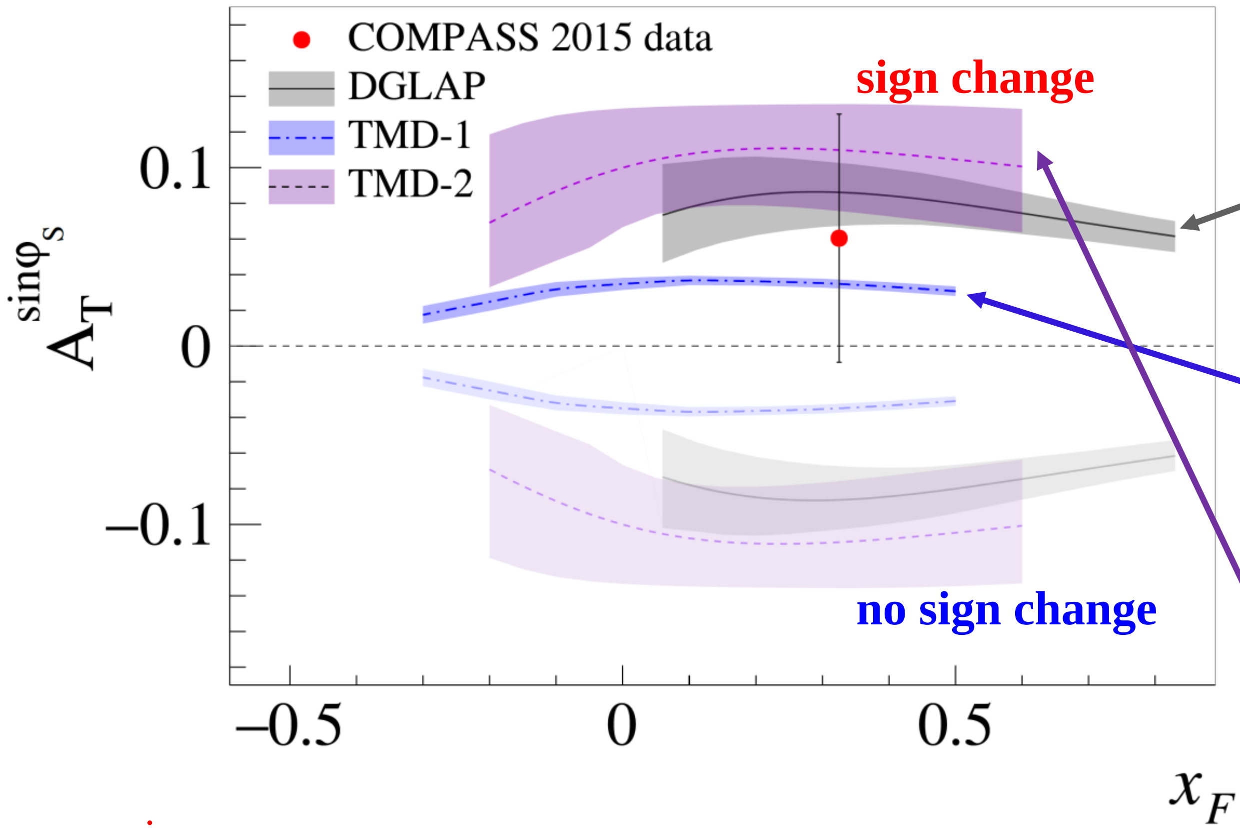
COMPASS, PLB 770 (2017) 138



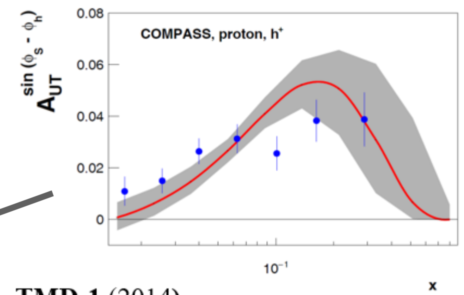
COMPASS, arXiv:1704.00488



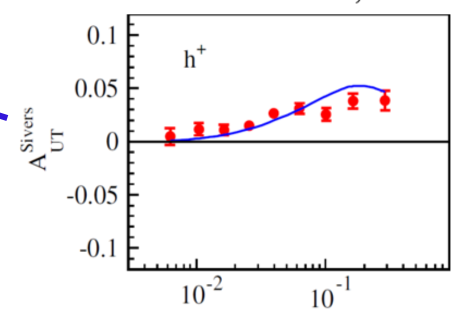
Sivers Asymmetry in Drell-Yan: Hint of Sign Change!



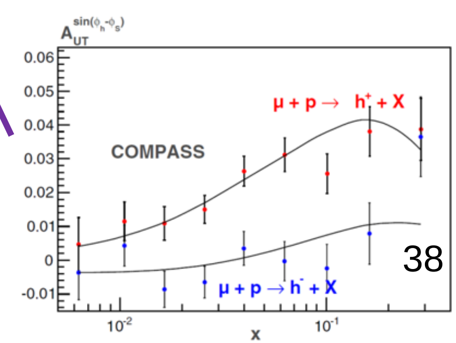
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



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



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



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

arXiv:1704.00488, to appear in PRL.

COMPASS-II Programs

- **2014-2018:**
  - Commissioning of polarized Drell-Yan experiment started in mid-October 2014.
  - 2015: Polarized Drell-Yan program.
  - 2016-2017: DVCS program.
  - 2018: Polarized Drell-Yan program (improved statistics errors of Sivers asymmetries are expected).
- **2020-2024 (under planning) :**
  - Polarized ^{6}LiD target: flavor separation of TMD SSAs.
  - Long LH_2 and nuclei targets: un-polarized pion-induced DY.

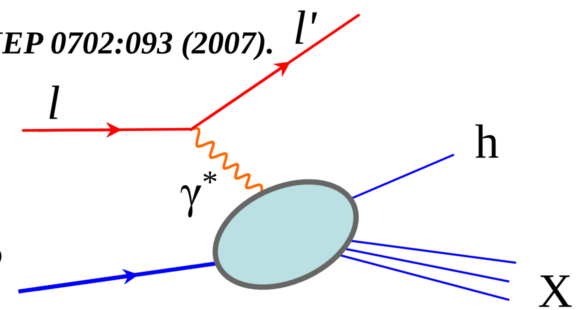
Summary

- In 2015 COMPASS has successfully collected first ever transversely polarized Drell-Yan data:
  - Sivers asymmetry is found to be above zero at about 1 sigma.
  - 1st measurement of the DY Sivers asymmetry is consistent with the predicted change of sign for the Sivers function.
- Other TMDs like transversity and pretzelosity as well as pion BMs are also accessed by TSAs of Drell-Yan process.
- A second year of polarized DY data-taking will take place in 2018. Hopefully it will provide more stringent quantitative test of Sivers universality.

BACKUP SLIDES

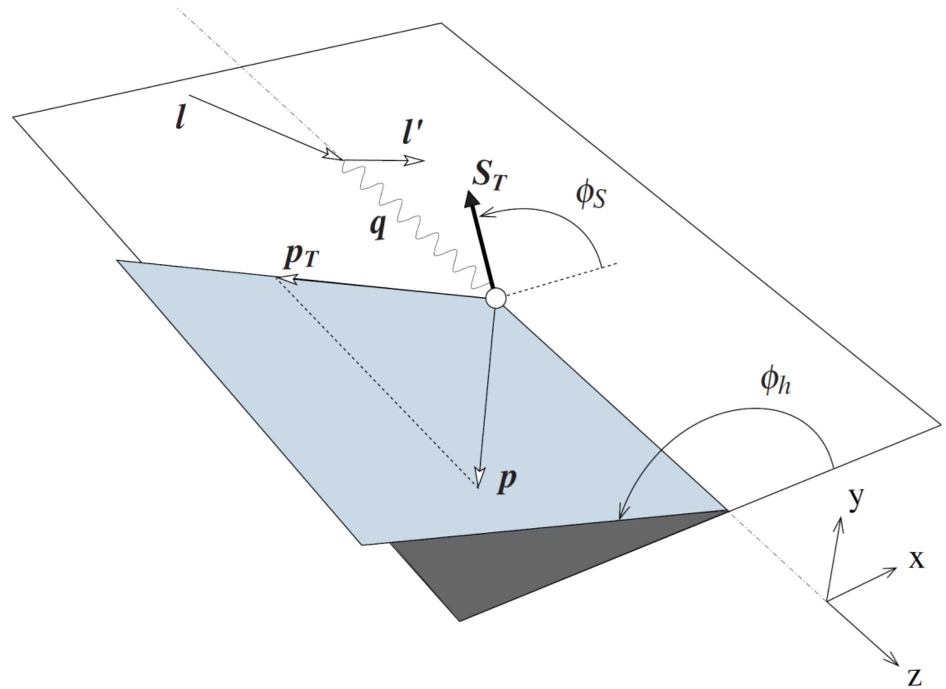
SIDIS x-section

A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).



$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times \left\{ \begin{aligned} & 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ & + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\ & + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\ & + S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\ & + S_T \left[\begin{aligned} & A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ & +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ & +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ & +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ & +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{aligned} \right] \\ & + S_T\lambda \left[\begin{aligned} & \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ & +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ & +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{aligned} \right] \end{aligned} \right\}$$



$$A_{U(L),T}^{w(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

SIDIS x-section and TMDs at twist-2

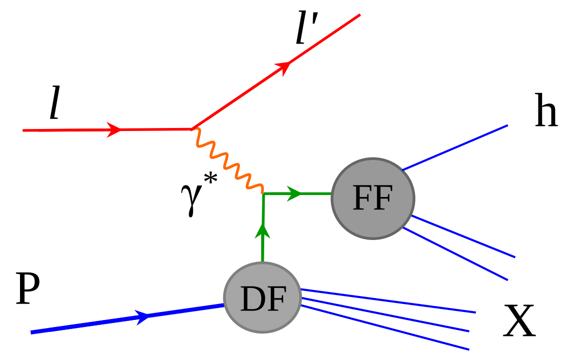
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times \Bigg\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+ S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array}\right]$$

$$+ S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right]\Bigg\}$$



Nucleon \ Quark	U	L	T
U	$f_1^q(x,\mathbf{k}_T^2)$ **number density**		$h_1^{q\perp}(x,\mathbf{k}_T^2)$ **Boer-Mulders**
L		$g_1^q(x,\mathbf{k}_T^2)$ **helicity**	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ **worm-gear L**
T	$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ **Sivers**	$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ **Kotzinian-Mulders worm-gear T**	$h_1^q(x,\mathbf{k}_T^2)$ **transversity**; $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ **pretzelosity**

+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

SIDIS x-section: transverse spin dependent part

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \ldots \right.$$

$$+ S_T \left[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h - \phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h - \phi_S) \right]$$

$$\left. + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h - \phi_S) + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h - \phi_S) \right] \right\}$$

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{LT}^{\cos(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

Twist-2

Twist-3

Eight transverse-spin-dependent azimuthal asymmetries (TSA) appear in SIDIS x-section

- Four “twist-2” TSAs
  (Sivers, Collins, pretzelosity, Kotzinian-Mulders)
- Four “higher-twist”

SIDIS and single-polarized DY x-sections

SIDIS

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\Bigg\{ 1+\ldots$$

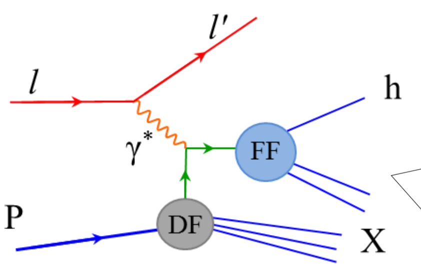
$$+\ S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S} \sin\phi_S \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \end{array} \right]$$

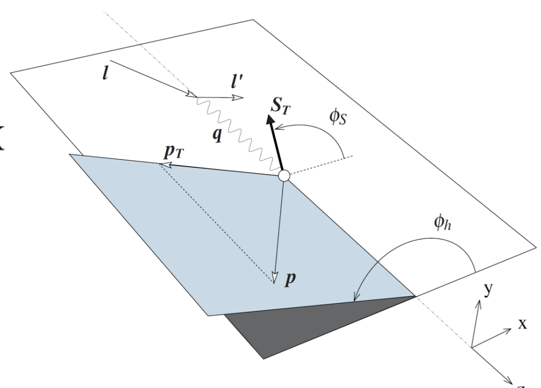
$$+\ S_T\lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos\phi_S} \cos\phi_S \\ +\ \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \end{array} \right] \Bigg\}$$

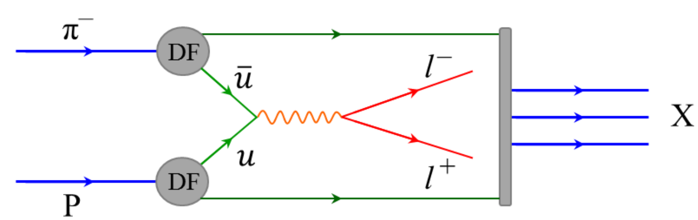
DY

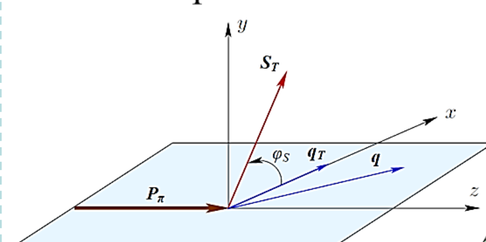
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1+F_U^2\right)$$

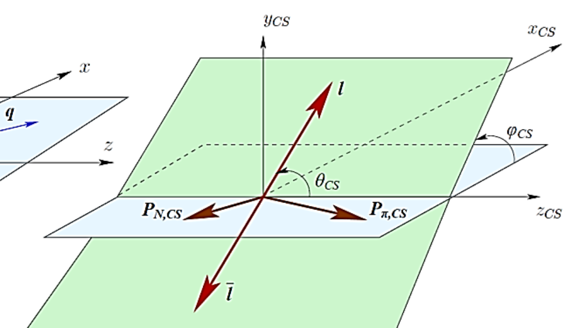
$$\times \left\{ \begin{array}{l} 1+A_U^1\cos^2\theta_{CS} \\ +\ \sin 2\theta_{CS}\,A_U^{\cos\varphi_{CS}}\cos\varphi_{CS} + \sin^2\theta_{CS}\,A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\ +\ S_L\left[\sin 2\theta_{CS}\,A_L^{\sin\varphi_{CS}}\sin\varphi_{CS} + \sin^2\theta_{CS}\,A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS}\right] \\ +\ S_T\left[\begin{array}{l} \left(A_T^{\sin\varphi_S} + \cos^2\theta_{CS}\,\tilde{A}_T^{\sin\varphi_S}\right)\sin\varphi_S \\ +\sin^2\theta_{CS}\left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S) \\ +\ A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S) \end{array}\right) \\ +\sin 2\theta_{CS}\left(\begin{array}{l} A_T^{\sin(\varphi_{CS}-\varphi_S)}\sin(\varphi_{CS}-\varphi_S) \\ +\ A_T^{\sin(\varphi_{CS}+\varphi_S)}\sin(\varphi_{CS}+\varphi_S) \end{array}\right) \end{array} \right] \end{array} \right\}$$



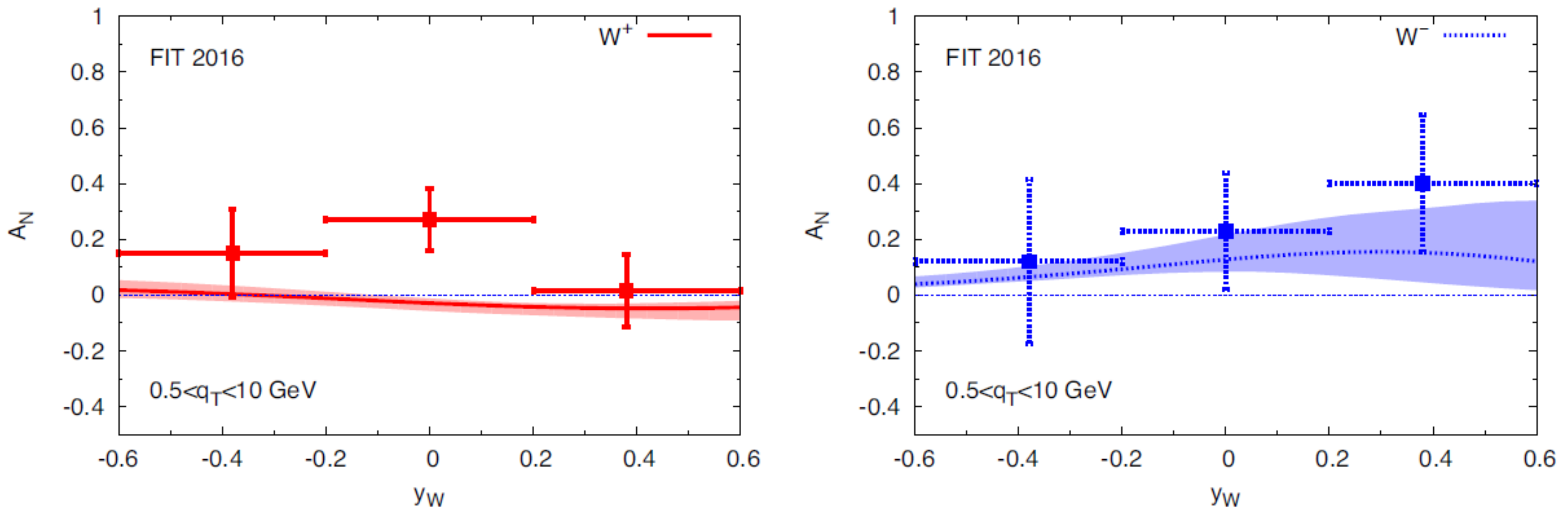








Predicted Sivers asymmetry A_N, assuming a sign change of the SIDIS Sivers functions



Anselmino et al., , JHEP04 (2017) 046 [arXiv:1612.06413]

Signals of Sivers functions in W production.
Hints of (non)universality.