

Spin asymmetries for vector boson production in polarized p+p collisions

Outline • Sivers and g_{1T} • W/Z cross section in TMD • Phenomenology • Outlook

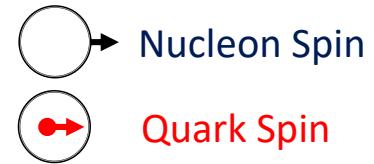
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Leading-Twist TMD PDFs



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ Boer-Mulders
	L		$g_1 =$ Helicity	$h_{1L}^\perp =$ Worm Gear (Kotzinian-Mulders)
	T	$f_{1T}^\perp =$ Sivers	$g_{1T} =$ Worm Gear (trans-helicity)	$h_1 =$ Transversity $h_{1T}^\perp =$ Pretzelosity

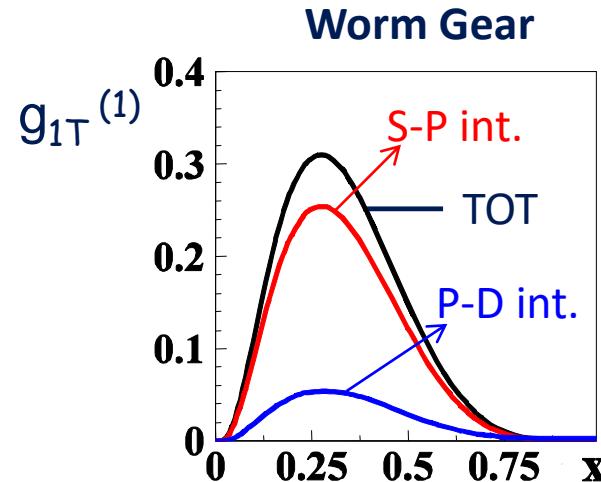
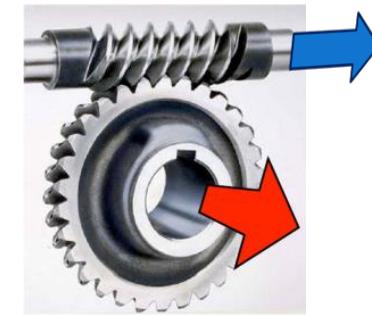


: Focus of this talks

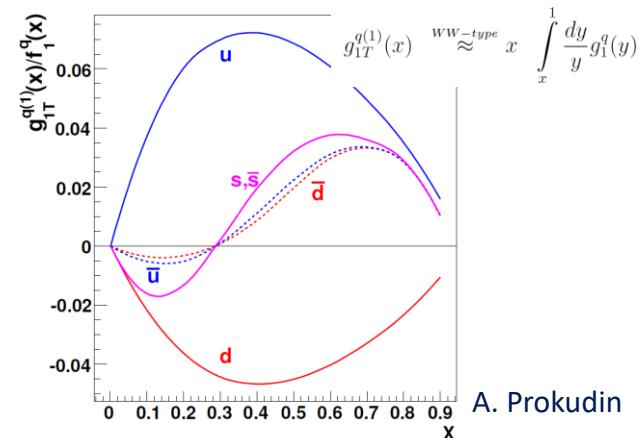
Trans-Helicity Functions

$$g_{1T} = \text{---} - \text{---}$$

- ▶ $g_{1T} =$
- ▶ Leading twist TMD PDFs, off-diagonal and only survive if $p_T \neq 0$
- ▶ The only T-even and Chiral-even off-diagonal TMD
 - Expect universal between DY and SIDIS
 - Do not need Chiral-odd FF
- ▶ Dominated by real part of interference between L=0 (S) and L=1 (P) states
 - Imaginary part \rightarrow Sivers effect
- ▶ Harder to access experimentally when compared to Sivers, need to probe two polarization (usually double dilution).
- ▶ Previous observables require double spin asymmetries A_{LT} in SIDIS or p+p collisions



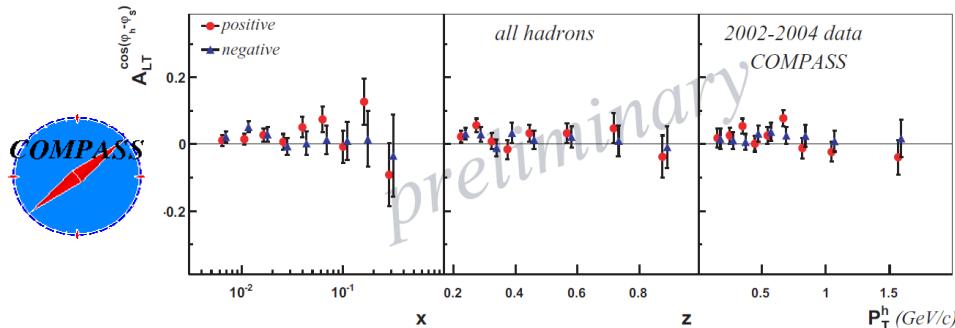
Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008



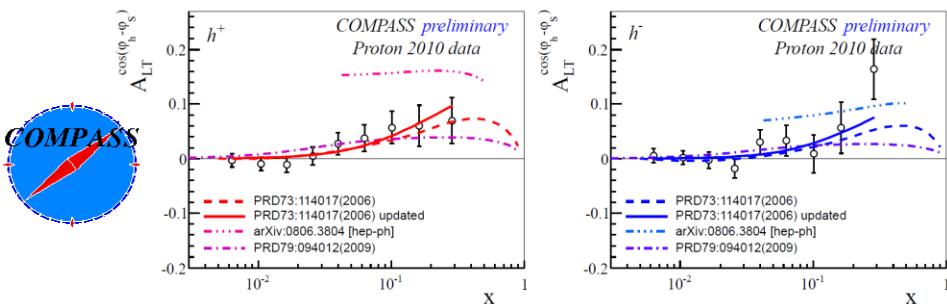
A. Prokudin

Existing data: Access g_{1T} in SIDIS

$\mu + D \rightarrow \mu + h + X$, Eur. Phys. J. Spec. Top. 162, 89 (2008).

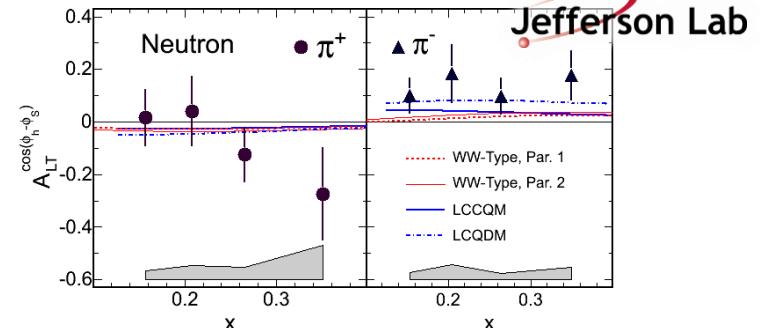


Talk: Monday - Parsamyan
 $\mu + p \rightarrow \mu + h + X$, arXiv:1512.06772, arXiv:1301.6615

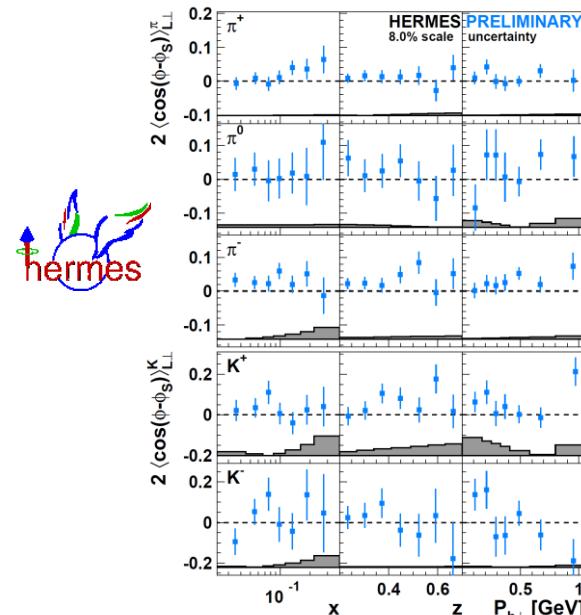


- Also a central piece for JLab12 SIDIS program
 See also Z.W. Zhao – Session Future

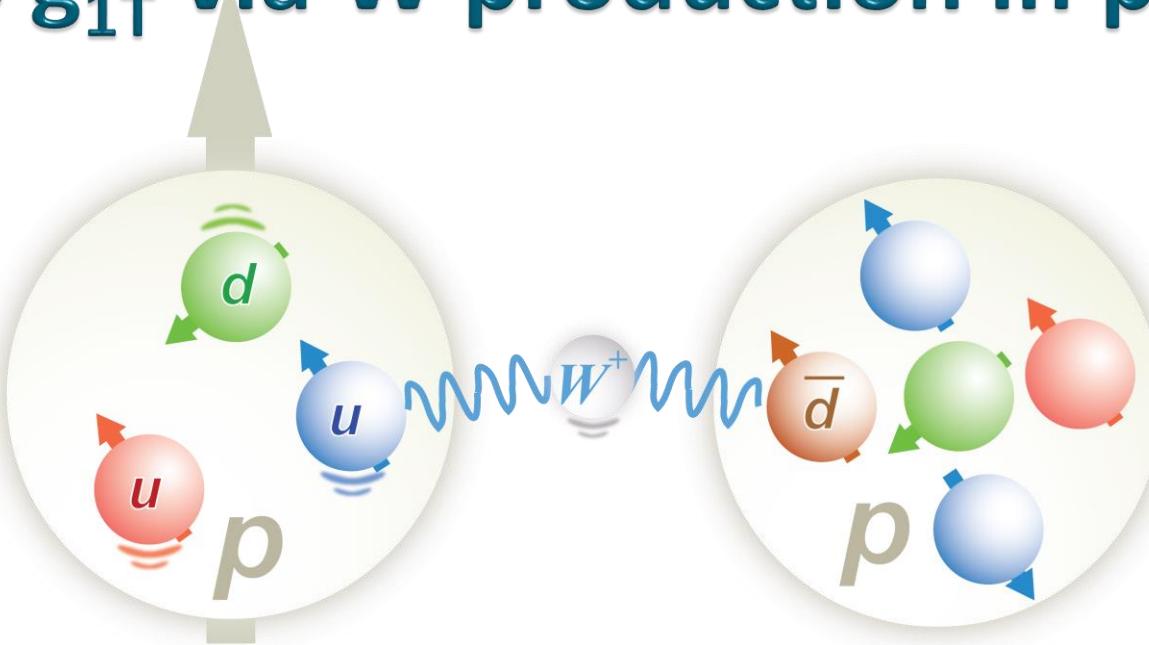
Talk: Monday - Puckett
 $e + n \rightarrow e + h + X$, Huang, et. al. PRL. 108, 052001 (2012)



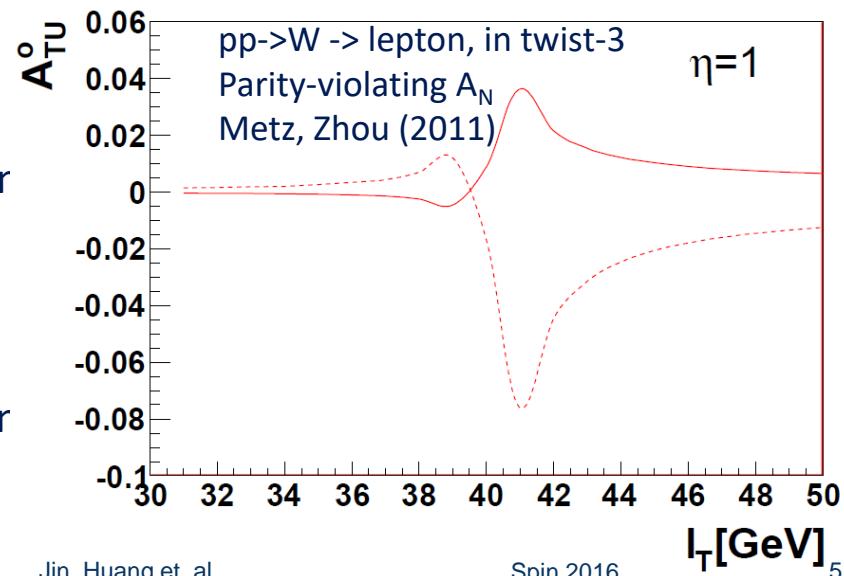
$e + p \rightarrow e + h + X$, arXiv:1107.4227 [hep-ex]



Access g_{1T} via W production in p+p



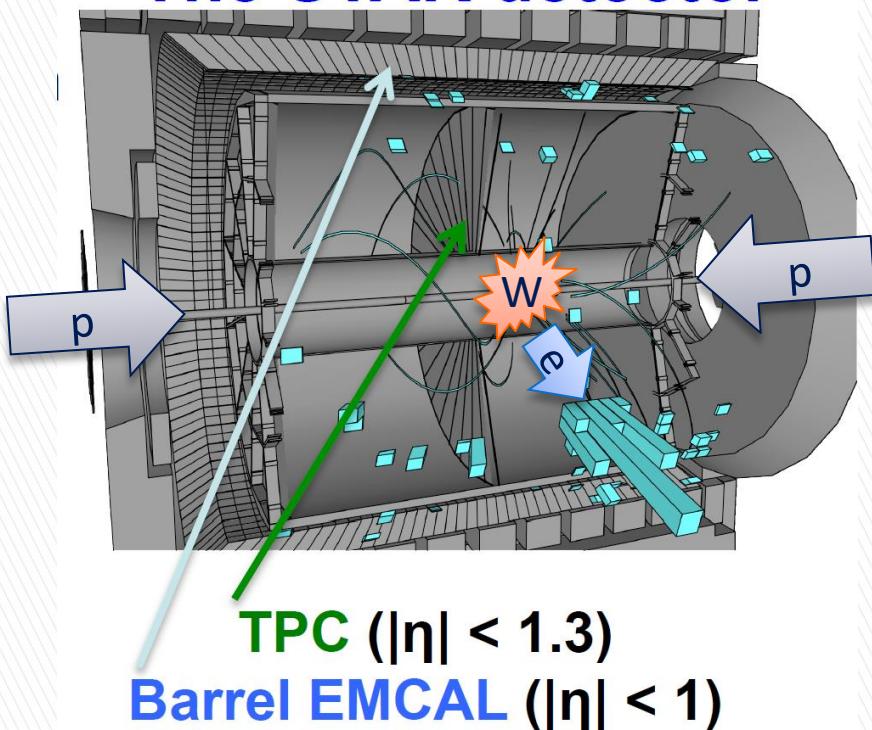
- ▶ W-boson couple to left-chirality quark, which provided 100% analyzing power to quark spin (parity-violating observables)
- ▶ Flavor separation via charge-selection of W boson
- ▶ However, previous asymmetry estimation for the decay lepton on show asymmetry near Jacobian Peak [Kang, Qiu(2009), Boer, den Dunnen, Kotzinian (2011), Metz, Zhou (2011)]
- ▶ g_{1T} also assessable in LT-double spin observable in hard scattering [Metz, Pitonyak, Schaefer, Zhou (2012)]



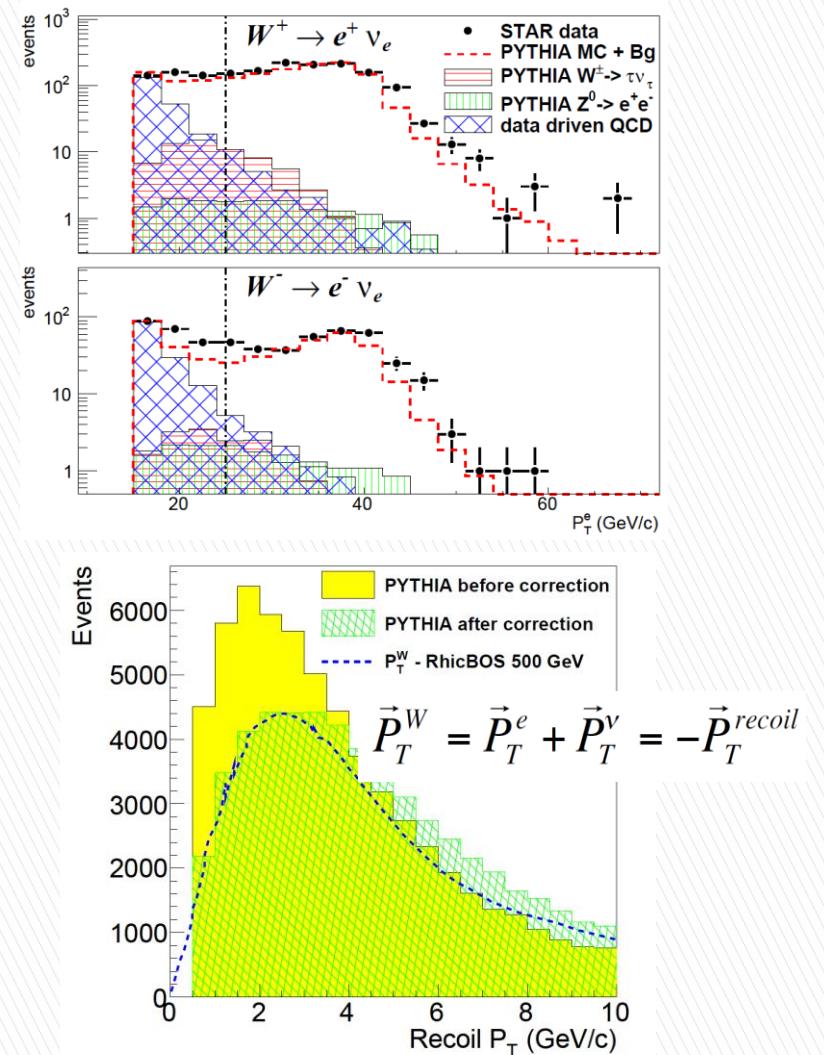
RHIC/STAR collaboration recently established
W-boson kinematic reco in polarized p+p

- STAR, Phys. Rev. Lett. 116, 132301
- See also Monday talk by Akio Ogawa

The STAR detector



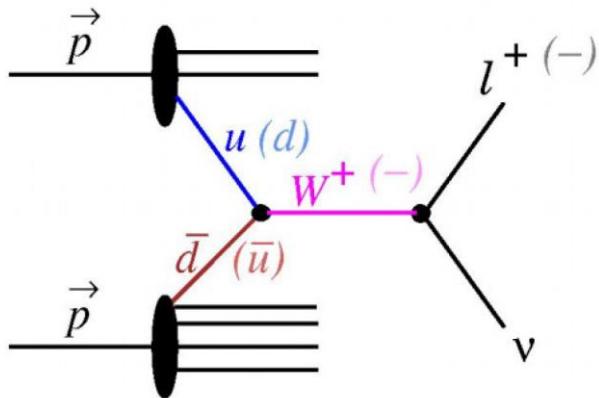
$p^\uparrow p \rightarrow W + X$ in STAR



STAR Run11 data,
Phys. Rev. Lett. 116, 132301

Differential Cross section for polarized p+p → V + X

- In kinematic region of $q_T \ll M_V$, therefore TMD factorization applies.
- Observe boson kinematics after integrating over decays.



$$\frac{d\sigma^W}{dy d^2\vec{q}_T} = \frac{\pi G_F M_W^2}{2\sqrt{2}S} \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{M_W^2} \right) \boxed{W^{\mu\nu}(P_A, S_A, P_B, S_B)}$$

Huang, Kang, Vitev, Xing, PRD 93 (2016)

$$W^{\mu\nu}(P_A, S_A, P_B, S_B) = \frac{1}{N_c} \sum_{q,q'} |V_{qq'}|^2 \int d^2\vec{k}_{aT} d^2\vec{k}_{bT} \delta^2(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT}) \\ \times \text{Tr} \left[\gamma^\mu (v_q - a_q \gamma^5) \Phi^q(x_a, \vec{k}_{aT}, S_A) \gamma^\nu (v_q - a_q \gamma^5) \bar{\Phi}^{q'}(x_b, \vec{k}_{bT}, S_B) \right]$$

$$\Phi^{q[\gamma^+]} = f_1^q(x_a, \vec{k}_{aT}^2) - \frac{\epsilon_T^{ij} k_{aT}^i S_{AT}^j}{M_A} f_{1T}^{\perp q}(x_a, \vec{k}_{aT}^2),$$

$$\Phi^{q[\gamma^+ \gamma^5]} = S_{AL} g_{1L}^q(x_a, \vec{k}_{aT}^2) + \frac{\vec{k}_{aT} \cdot \vec{S}_{AT}}{M_A} g_{1T}^q(x_a, \vec{k}_{aT}^2)$$

Connection to experimental observables

Huang, Kang, Vitev, Xing, PRD 93 (2016)

$\text{pp} \rightarrow W/Z/\gamma^* + X$, integrated over vector boson decay

$$\frac{d\sigma^W}{dy d^2\vec{q}_T} = \sigma_0^W \left\{ F_{UU} + S_{AL} F_{LU} + S_{BL} F_{UL} + S_{AL} S_{BL} F_{LL} \right.$$

$$+ |\vec{S}_{AT}| \left[\sin(\phi_V - \phi_{S_A}) F_{TU}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TU}^{\cos(\phi_V - \phi_{S_A})} \right]$$

$$+ |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{UT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{UT}^{\cos(\phi_V - \phi_{S_B})} \right]$$

$$+ |\vec{S}_{AT}| S_{BL} \left[\sin(\phi_V - \phi_{S_A}) F_{TL}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TL}^{\cos(\phi_V - \phi_{S_A})} \right]$$

$$+ S_{AL} |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{LT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{LT}^{\cos(\phi_V - \phi_{S_B})} \right]$$

$$+ |\vec{S}_{AT}| |\vec{S}_{BT}| \left[\cos(2\phi_V - \phi_{S_A} - \phi_{S_B}) F_{TT}^{\cos(2\phi_V - \phi_{S_A} - \phi_{S_B})} + \cos(\phi_{S_A} - \phi_{S_B}) F_{TT}^1 \right. \\ \left. + \sin(2\phi_V - \phi_{S_A} - \phi_{S_B}) F_{TT}^{\sin(2\phi_V - \phi_{S_A} - \phi_{S_B})} + \sin(\phi_{S_A} - \phi_{S_B}) F_{TT}^2 \right] \left. \right\}.$$

Parity violating : only probed by weak boson.

For W, bonus++: 100% analyzing power on quark helicity + quark flavor tagging

$$F_{TU}^{\sin(\phi_V - \phi_{S_A})} = \mathcal{C}^W \left[(v_q^2 + a_q^2) \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} f_{1T}^\perp \bar{f}_1 \right],$$

$$F_{TU}^{\cos(\phi_V - \phi_{S_A})} = -\mathcal{C}^W \left[2v_q a_q \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} g_{1T} \bar{f}_1 \right],$$

$$A_{TU}^{\sin(\phi_V - \phi_{S_A})} = \frac{F_{TU}^{\sin(\phi_V - \phi_{S_A})}}{F_{UU}},$$

$$A_{TU}^{\cos(\phi_V - \phi_{S_A})} = \frac{F_{TU}^{\cos(\phi_V - \phi_{S_A})}}{F_{UU}},$$

Phenomenology study

- ▶ Assumptions:
 - No TMD evolution
 - Gauss ansatz for k_T -dependence

- ▶ Parametrizations of TMDs:

$$f_1^q(x, k_T^2) = f_1^q(x) \frac{1}{\pi \langle k_T^2 \rangle_{f_1}} e^{-k_T^2 / \langle k_T^2 \rangle_{f_1}},$$

CTEQ 6

$$\mu = M_V$$

$$\langle k_T^2 \rangle_{f_1} = \langle k_T^2 \rangle_{g_{1L}} = 0.25 \text{ GeV}^2$$

$$g_{1L}^q(x, k_T^2) = g_{1L}^q(x) \frac{1}{\pi \langle k_T^2 \rangle_{g_{1L}}} e^{-k_T^2 / \langle k_T^2 \rangle_{g_{1L}}},$$

DSSV

$$\frac{k_T}{M} f_{1T}^{\perp q}(x, k_T^2) = -\mathcal{N}_q(x) h(k_T) f_1^q(x, k_T^2)$$

$$f_{1T}^{\perp q}(x, k_T^2)|_{\text{DY/W/Z}} = -f_{1T}^{\perp q}(x, k_T^2)|_{\text{SIDIS}}$$

Anselmino et al.

$$\frac{1}{2M^2} g_{1T}^q(x, k_T^2) = g_{1T}^{q(1)}(x) \frac{1}{\pi \langle k_T^2 \rangle_{g_{1T}}^2} e^{-k_T^2 / \langle k_T^2 \rangle_{g_{1T}}}$$

Kotzinian et al.

$$\langle k_T^2 \rangle_{g_{1T}} = 0.15 \text{ GeV}^2$$

$$g_{1T}^{q(1)}(x) \approx x \int_x^1 \frac{dz}{z} g_{1L}^q(z)$$

Single transverse spin asymmetries in weak boson production

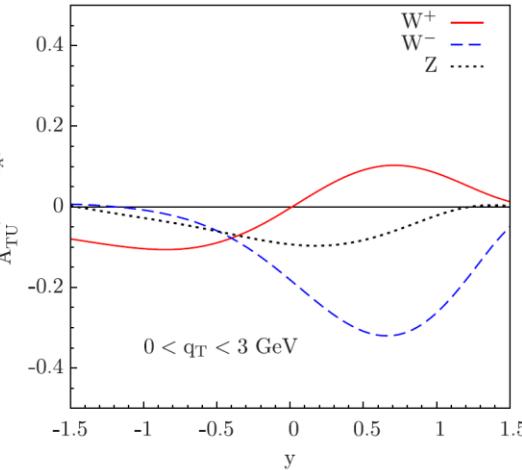
$$f_{1T}^\perp = \text{circle with dot up} - \text{circle with dot down}$$

via parity-conserving SSA

$$F_{TU}^{\sin(\phi_V - \phi_{SA})} = \mathcal{C}^W \left[(v_q^2 + a_q^2) \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} f_{1T}^\perp \bar{f}_1 \right]$$

$$A_{TU}^{\sin(\phi_V - \phi_{SA})} = \frac{F_{TU}^{\sin(\phi_V - \phi_{SA})}}{F_{UU}}$$

(Reverse sign def. to traditional A_N)

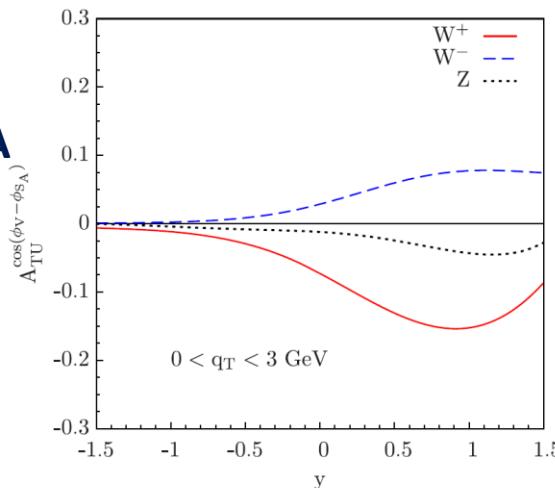


$$g_{1T} = \text{circle with dot up} - \text{circle with dot right}$$

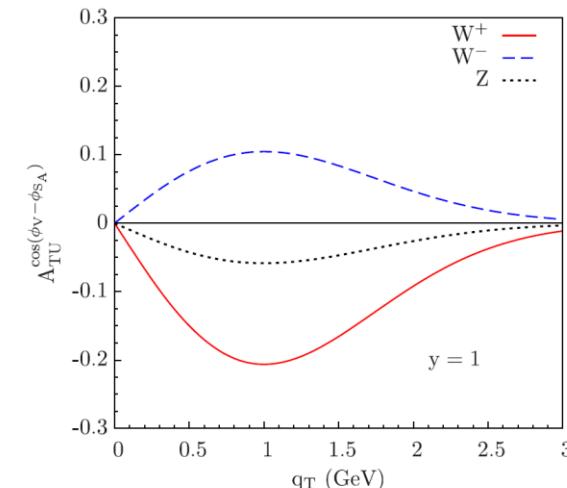
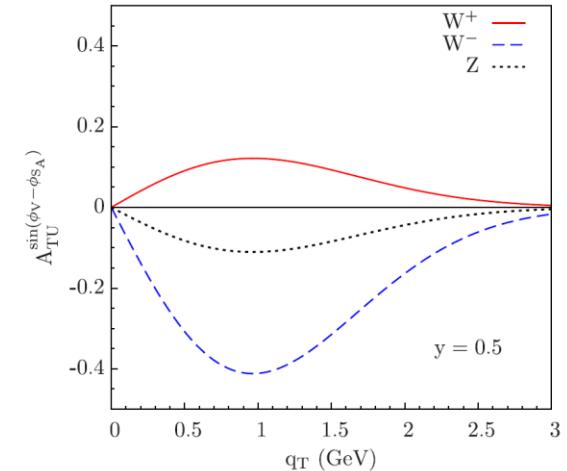
via unique parity-violating SSA

$$F_{TU}^{\cos(\phi_V - \phi_{SA})} = -\mathcal{C}^W \left[2v_q a_q \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} g_{1T} \bar{f}_1 \right],$$

$$A_{TU}^{\cos(\phi_V - \phi_{SA})} = \frac{F_{TU}^{\cos(\phi_V - \phi_{SA})}}{F_{UU}},$$



Huang, Kang, Vitev, Xing, PRD 93 (2016)



Published STAR data Run2011

$$f_{1T}^{\perp} = \text{circle with dot} - \text{circle with dot}$$

via parity-conserving SSA

STAR, Phys. Rev. Lett. 116, 132301

See Monday talk by Akio Ogawa

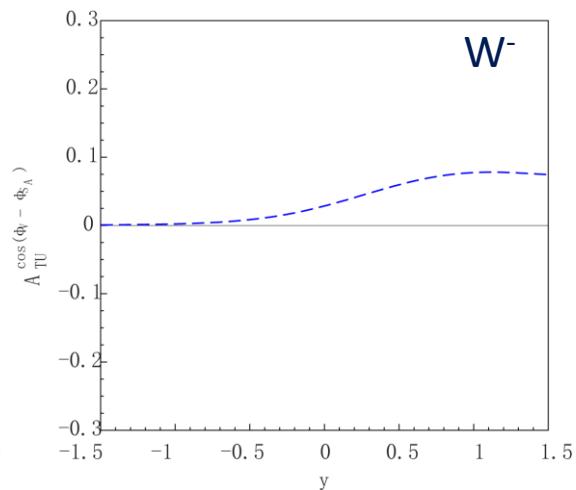
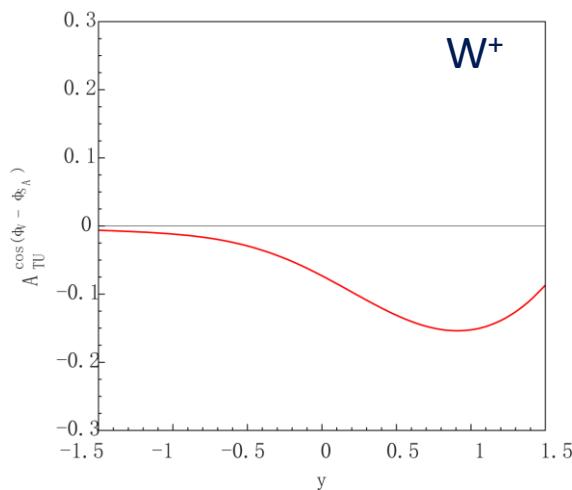
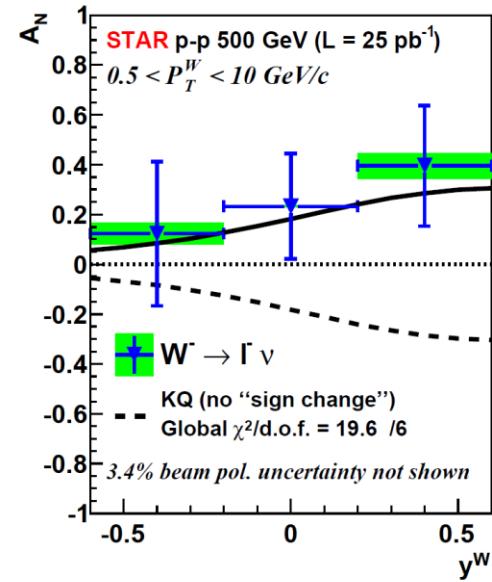
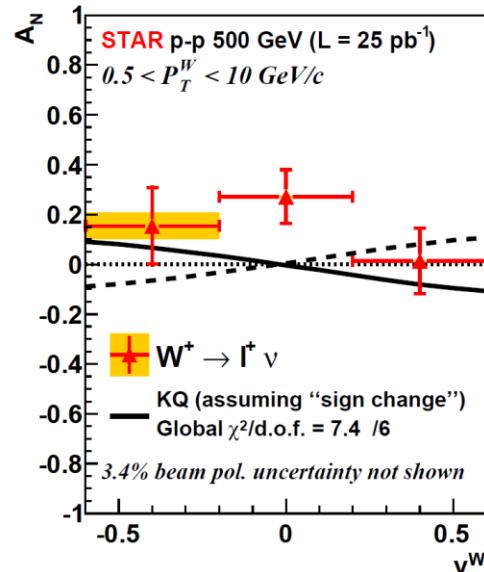
$$g_{1T} = \text{circle with dot} - \text{circle with dot}$$

via unique parity-violating SSA

Our prediction (no evolution)

Huang, Kang, Vitev, Xing,

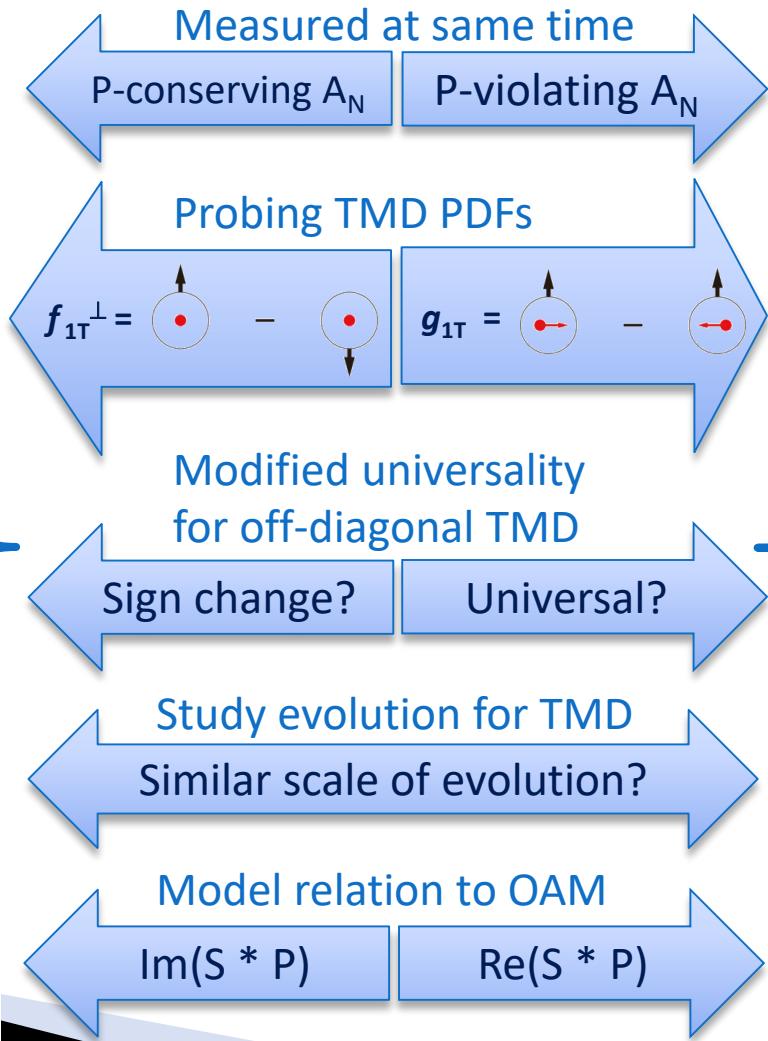
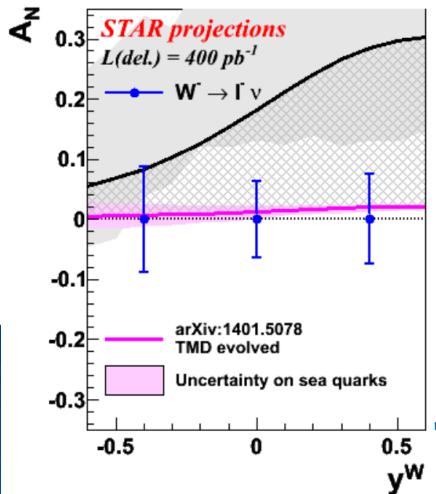
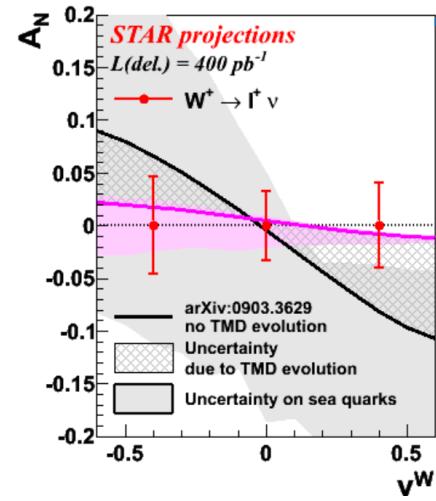
PRD 93 (2016)



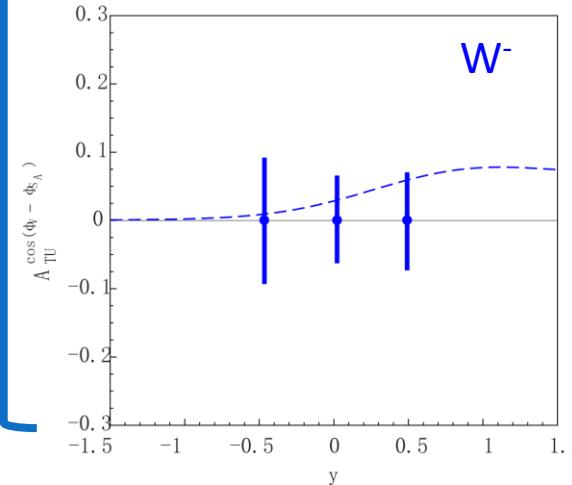
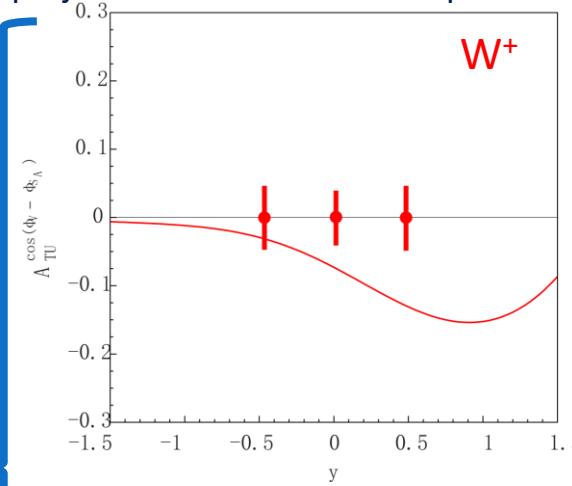
Experimental outlook: RHIC/STAR W in Run 2017

STAR projection

RHIC cold-QCD WP
arXiv:1602.03922

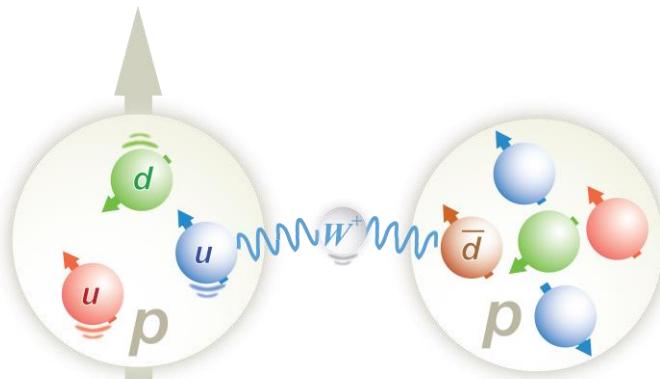


- **Curve:** Huang, Kang, Vitev, Xing, PRD 93 (2016)
- **Points:** Jin's naïve expectation of STAR Run17 projection based on Sivers A_N projection in RHIC Cold QCD plan



Summary

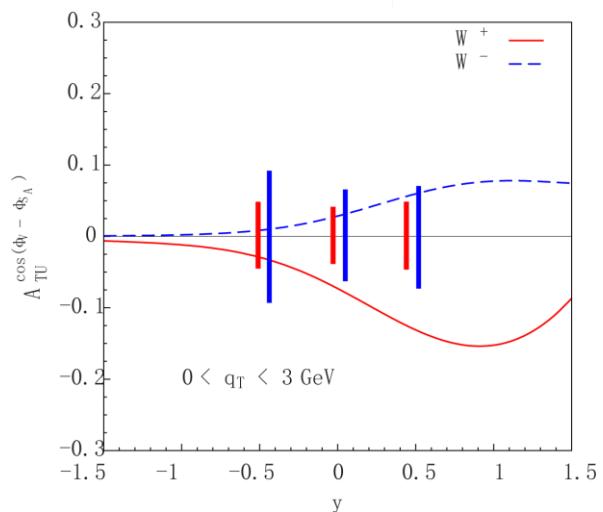
- Within TMD factorization formalism, we presented the cross sections for **weak boson production in polarized pp collisions**. And estimated the spin asymmetries at the top RHIC energy.
- Unique opportunity of probe g_{1T} via parity violating single transverse spin asymmetry
- Double spin asymmetry calculation in our paper
- The W spin physics program at RHIC could be viewed as truly **multi-purpose**: flavor separation, tests the universality properties of TMDs, constrains the TMD evolution effects, and probes the sea quark TMDs. Expecting high statistics data in future RICH runs.
- We thank E. C. Aschenauer, A. Metz, D. Pitonyak, and M. Schlegel for helpful comments.



$$g_{1T} = \text{---} - \text{---}$$

$$F_{TU}^{\cos(\phi_V - \phi_{S_A})} = -\mathcal{C}^W \left[2v_q a_q \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} g_{1T} \bar{f}_1 \right],$$

$$A_{TU}^{\cos(\phi_V - \phi_{S_A})} = \frac{F_{TU}^{\cos(\phi_V - \phi_{S_A})}}{F_{UU}},$$



- Curve: Huang, Kang, Vitev, Xing, PRD 93 (2016)
- Points: Jin's naïve expectation of STAR Run17 projection based on Sivers A_N projection in RHIC Cold QCD plan

Extra information

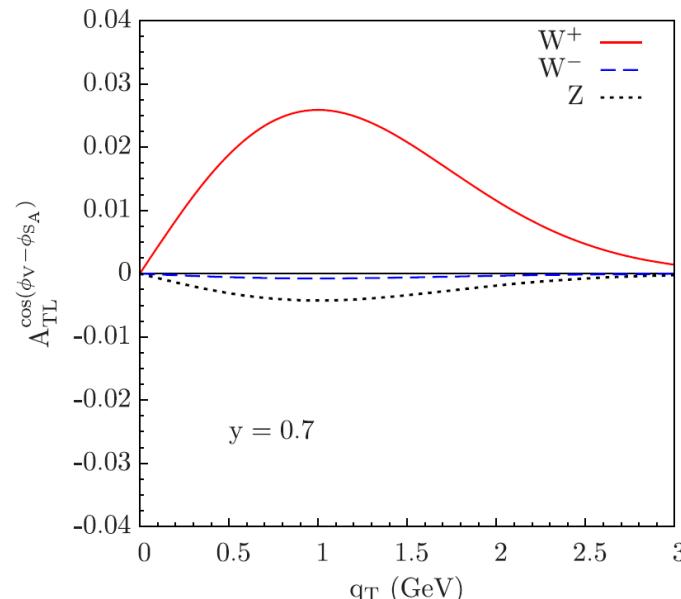
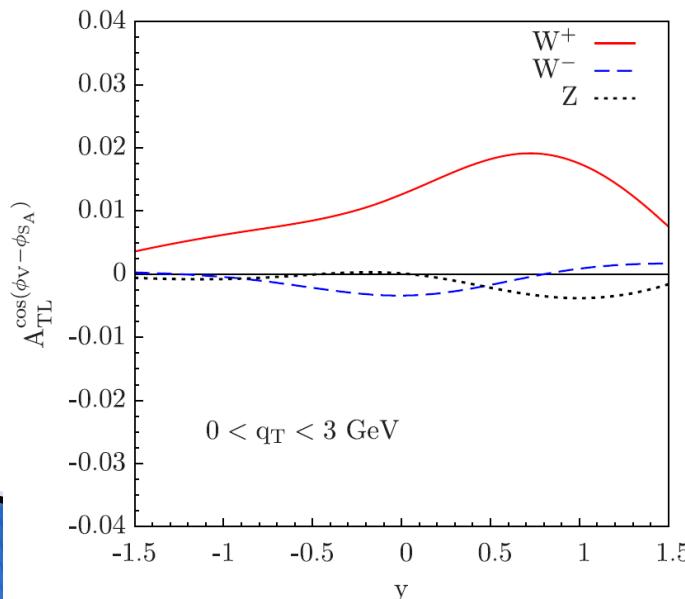


Parity-conserving Double spin asymmetries, A_{LT}

- ▶ Parity-conserving modulation on LT-double spin observable $\rightarrow g_{1L} = \text{Diagram with left arrow} - \text{Diagram with right arrow} * g_{1T} = \text{Diagram with up arrow} - \text{Diagram with down arrow}$

$$A_{TL}^{\cos(\phi_V - \phi_{S_A})} = \frac{F_{TL}^{\cos(\phi_V - \phi_{S_A})}}{F_{UU}}, \quad F_{TL}^{\cos(\phi_V - \phi_{S_A})} = -\mathcal{C}^W \left[(v_q^2 + a_q^2) \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} g_{1T} \bar{g}_{1L} \right],$$

$$A_{TL}^{\cos(\phi_V - \phi_{S_A})}(y) = A_{LT}^{\cos(\phi_V - \phi_{S_B})}(-y)$$

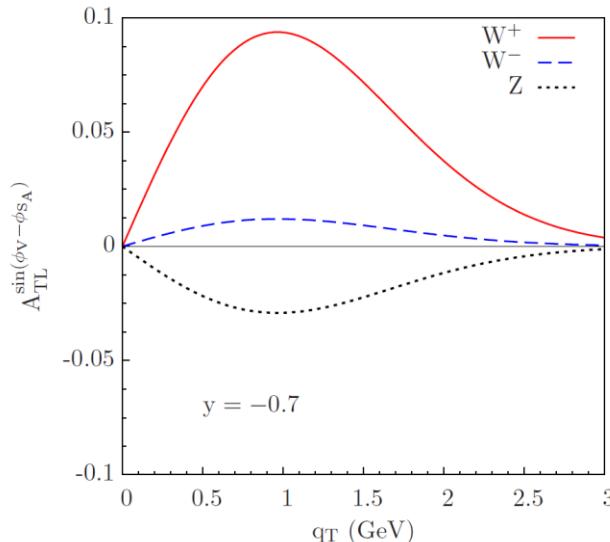
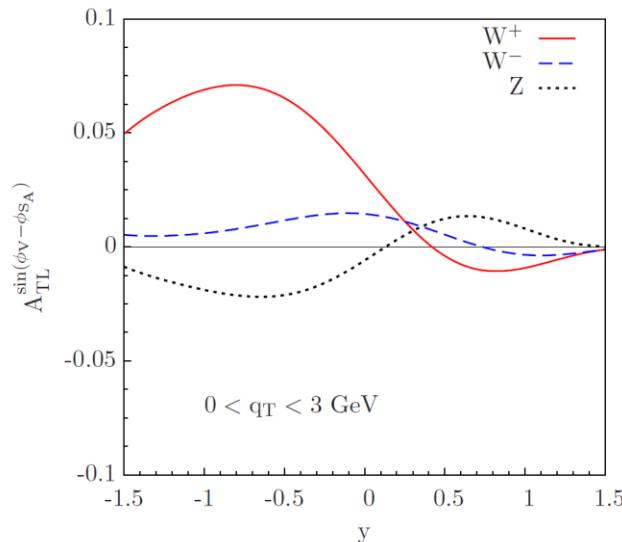


Parity-conserving Double spin asymmetries, A_{LT}

- ▶ Parity-violating modulation on LT-double spin observable → $f_{1T}^\perp = \text{ } \begin{array}{c} \text{ } \\ \text{ } \end{array} - \text{ } \begin{array}{c} \text{ } \\ \text{ } \end{array} * \text{ } g_{1T} = \text{ } \begin{array}{c} \text{ } \\ \text{ } \end{array} - \text{ } \begin{array}{c} \text{ } \\ \text{ } \end{array}$

$$A_{TL}^{\sin(\phi_V - \phi_{SA})} = \frac{F_{TL}^{\sin(\phi_V - \phi_{SA})}}{F_{UU}}, \quad F_{TL}^{\sin(\phi_V - \phi_{SA})} = \mathcal{C}^W \left[2v_q a_q \frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} f_{1T}^\perp \bar{g}_{1L} \right],$$

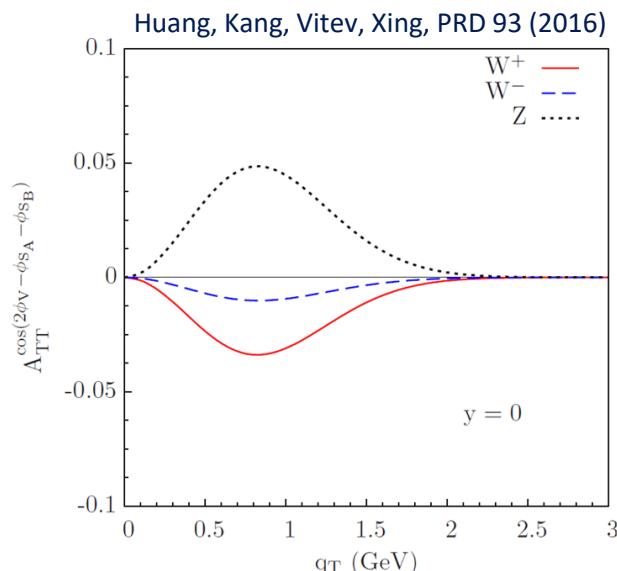
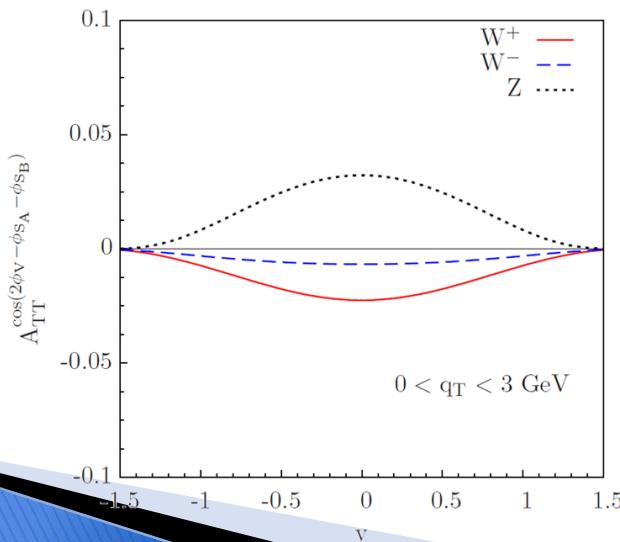
$$A_{TL}^{\sin(\phi_V - \phi_{SA})}(y) = -A_{LT}^{\sin(\phi_V - \phi_{SB})}(-y)$$



Parity-conserving Double spin asymmetries, A_{TT}

- ▶ Modulation also expected in TT-double spin asymmetry
- ▶ Parity-conserving modulation on TT-double spin observable → $f_{1T}^\perp = \text{Diagram with up arrow and red dot} - \text{Diagram with down arrow and red dot}$ * $g_{1T} = \text{Diagram with up arrow and red dot with horizontal arrow} - \text{Diagram with up arrow and red dot}$

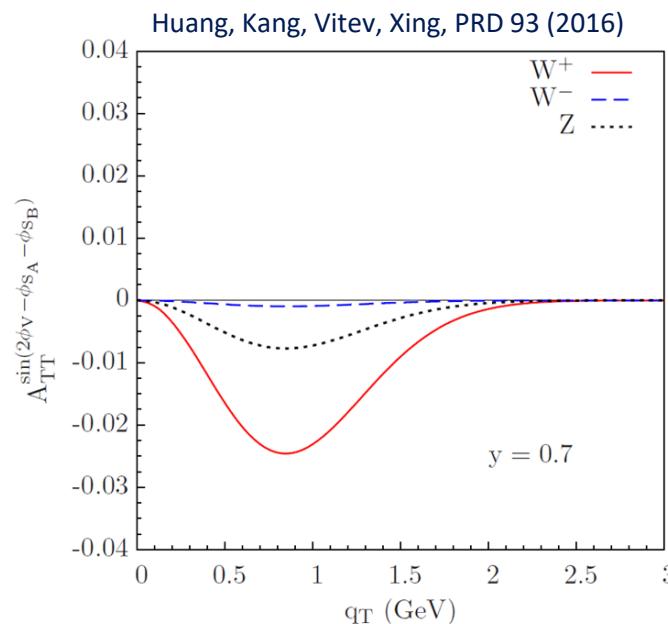
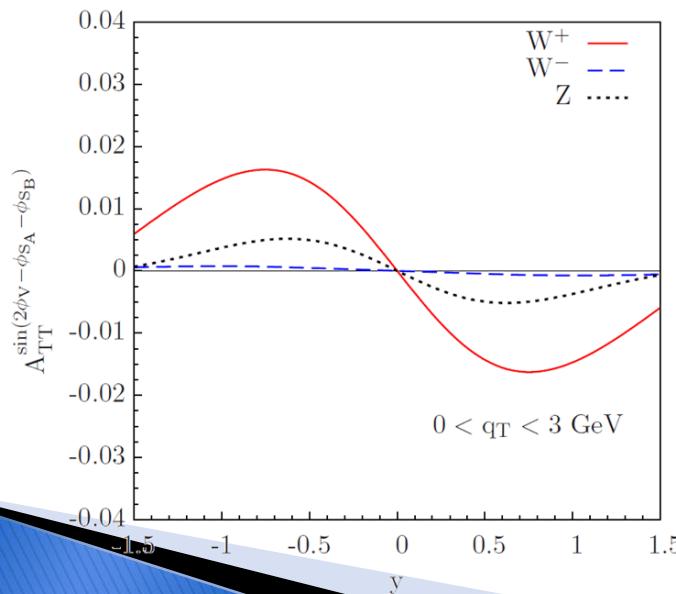
$$F_{TT}^{\cos(2\phi_V - \phi_{SA} - \phi_{SB})} = \mathcal{C}^W \left[(v_q^2 + a_q^2) \frac{2\vec{k}_{aT} \cdot \hat{q}_T \vec{k}_{bT} \cdot \hat{q}_T - \vec{k}_{aT} \cdot \vec{k}_{bT}}{2M_A M_B} (f_{1T}^\perp \bar{f}_{1T}^\perp - g_{1T} \bar{g}_{1T}) \right],$$



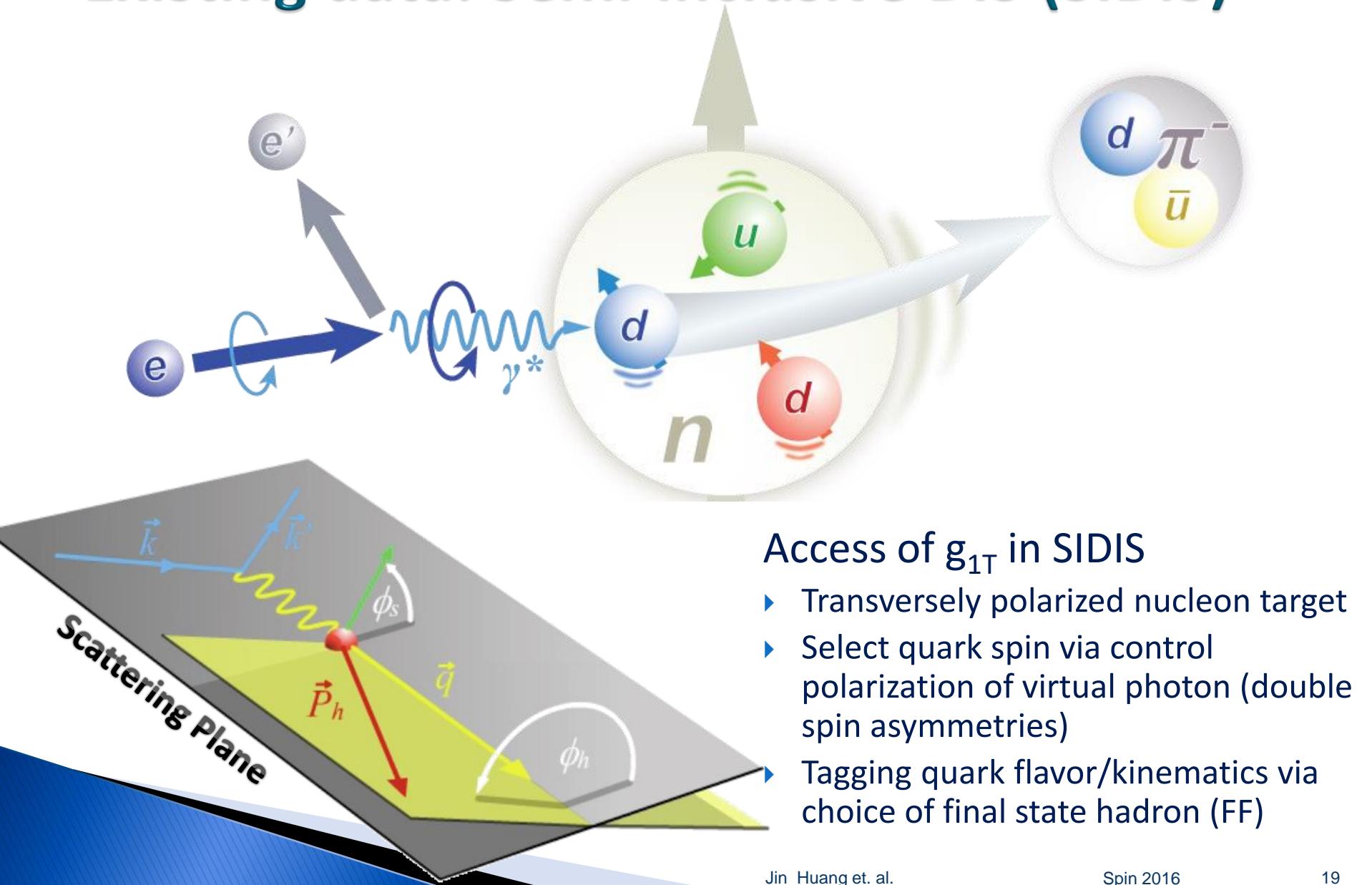
Parity-violating Double spin asymmetries, A_{TT}

- ▶ Parity-violating modulation on TT-double spin observable also → $f_{1T}^\perp =$  - $* g_{1T} =$ 

$$F_{TT}^{\sin(2\phi_V - \phi_{SA} - \phi_{SB})} = \mathcal{C}^W \left[v_q a_q \frac{2\vec{k}_{aT} \cdot \hat{q}_T \vec{k}_{bT} \cdot \hat{q}_T - \vec{k}_{aT} \cdot \vec{k}_{bT}}{M_A M_B} (f_{1T}^\perp \bar{g}_{1T} + g_{1T} \bar{f}_{1T}^\perp) \right],$$



Existing data: Semi-inclusive DIS (SIDIS)

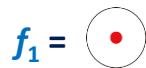


Access of g_{1T} in SIDIS

- ▶ Transversely polarized nucleon target
- ▶ Select quark spin via control polarization of virtual photon (double spin asymmetries)
- ▶ Tagging quark flavor/kinematics via choice of final state hadron (FF)

Access g_{1T} in SIDIS Cross Section

$$\frac{d\sigma}{dxdydzd\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)}.$$



$$\{F_{UU,T} +$$

Boer-Mulder

$$h_1^\perp = \text{Diagram with vertical spin} - \text{Diagram with horizontal spin} + \varepsilon \cos(2\phi_h) \cdot F_{UU}^{\cos(2\phi_h)} + \dots$$

Worm Gear

$$g_{1T} = \text{Diagram with vertical spin} - \text{Diagram with horizontal spin} + S_T \lambda_e [\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) \cdot F_{LT}^{\cos(\phi_h - \phi_S)} + \dots]$$

Helicity

$$g_1 = \text{Diagram with vertical spin} - \text{Diagram with horizontal spin} + S_L \lambda_e [\sqrt{1-\varepsilon^2} \cdot F_{LL} + \dots]$$

Worm Gear

$$h_{1L}^\perp = \text{Diagram with vertical spin} - \text{Diagram with horizontal spin} + S_L [\varepsilon \sin(2\phi_h) \cdot F_{UL}^{\sin(2\phi_h)} + \dots]$$

Transversity

$$h_{1T} = \text{Diagram with vertical spin} - \text{Diagram with horizontal spin} + S_T [\varepsilon \sin(\phi_h + \phi_S) \cdot F_{UT}^{\sin(\phi_h + \phi_S)} + \dots]$$

Sivers

$$f_{1T}^\perp = \text{Diagram with vertical spin} - \text{Diagram with horizontal spin} + \sin(\phi_h - \phi_S) \cdot (F_{UT}^{\sin(\phi_h - \phi_S)} + \dots)$$

Pretzelosity

$$h_{1T}^\perp = \text{Diagram with vertical spin} - \text{Diagram with horizontal spin} + \varepsilon \sin(3\phi_h - \phi_S) \cdot F_{UT}^{\sin(3\phi_h - \phi_S)} + \dots \}$$

$$F_{LT}^{\cos(\phi_h - \phi_S)} = \left[\frac{\hat{h} \cdot \mathbf{p}_T}{M} g_{1T} \otimes D_1 \right]$$

$$A_{LT}^{\cos(\phi_h - \phi_S)} \equiv \sqrt{1 - \varepsilon^2} \frac{F_{LT}^{\cos(\phi_h - \phi_S)}}{(1 + \varepsilon R) F_{UU,T}}$$

S_L, S_T : Target Polarization; λ_e : Beam Polarization

JLab/SoLID E12-11-007 Full projection, neutron A_{LT}

Satisfying the multi-D natural of this study.

$z = 0.3 \sim 0.7$ Comparable precision for SSA

