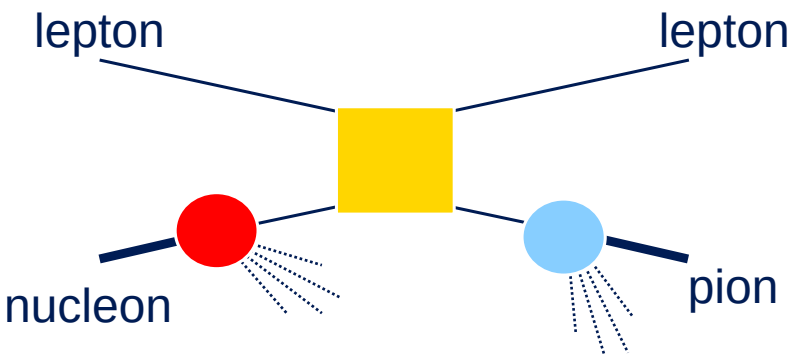
Spin asymmetries for vector boson production in polarized p+p collisions

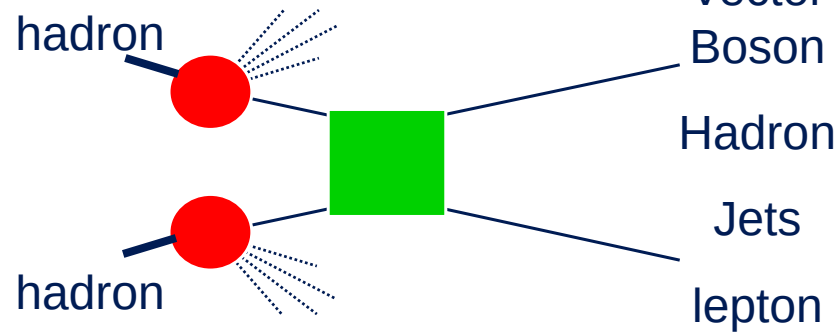
Outline • Sivers and g_{1T} • W/Z cross section in TMD • Phenomenology • Outlook

Jin Huang (Brookhaven National Lab)
Zhongbo Kang (Los Alamos National Lab)
Ivan Vitev (Los Alamos National Lab)
Hongxi Xing (Los Alamos National Lab)

Access TMDs through Hard Processes

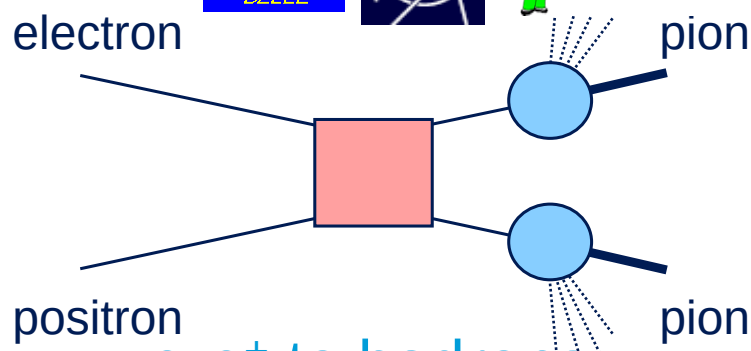


SIDIS



Hadron-Hadron (DY, Jet, IFF, etc.)

- Hard cross sections
- Fragmentation functions
- Parton distribution functions



e^-e^+ to hadrons

Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
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

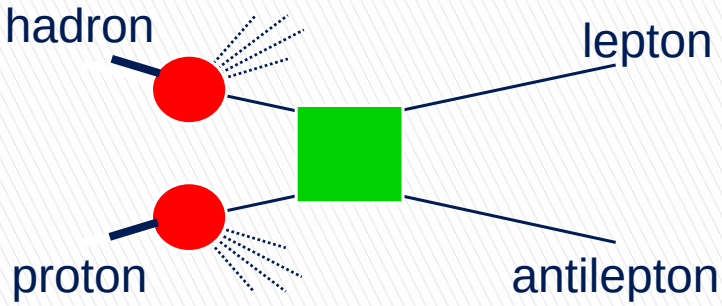
: Focus of this talks

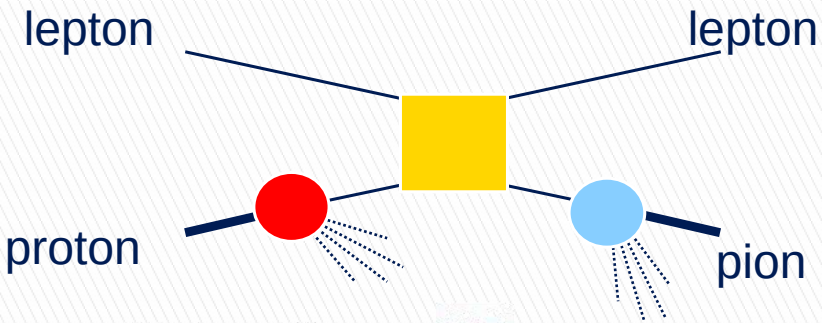
The well-known Sivers effect and modified universality

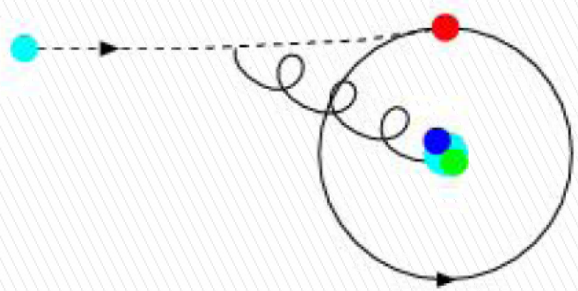
$f_{1T}^{\perp}$ =

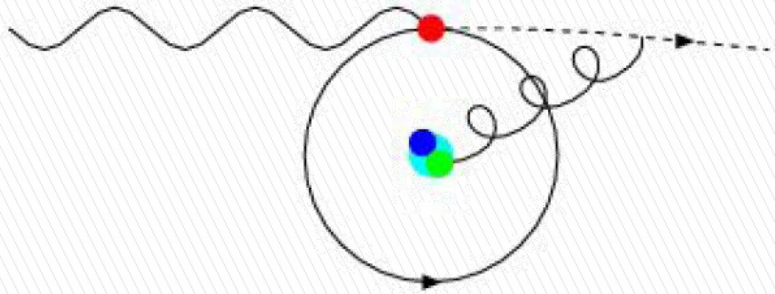
- Test of sign reversal of Sivers function in SIDIS VS Drell-Yan is critical for the TMD factorization approach.

$$f_{1T}^{\perp}(\mathrm{DY}) \stackrel{?}{=} -f_{1T}^{\perp}(\mathrm{SIDIS})$$









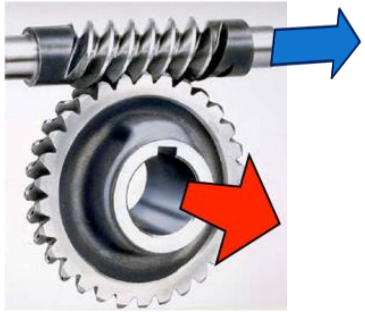
ISI in Drell-Yan is repulsive

FSI in SIDIS is attractive

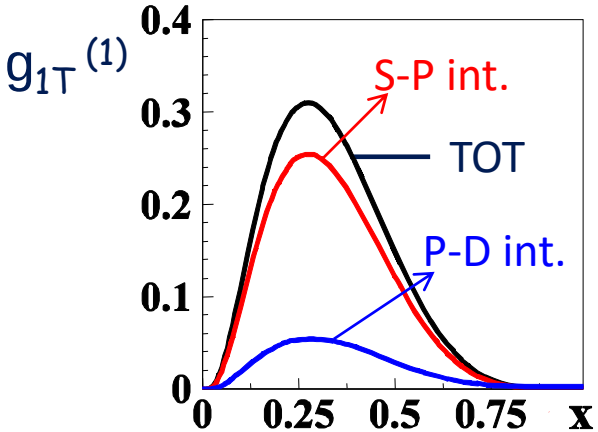
Illustration courtesy to M. Burkardt

Trans-Helicity Functions

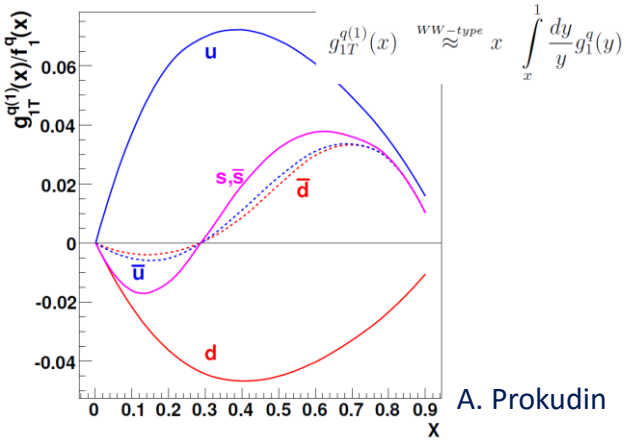
- g_{1T} = 
- Leading twist TMD PDFs, off-diagonal and only survive if p_T!=0
- The only T-even and Chiral-even off-diagonal TMD
  - Expect universal between DY and SIDIS
  - Do not need Chiral-odd FF
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers 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



Worm Gear

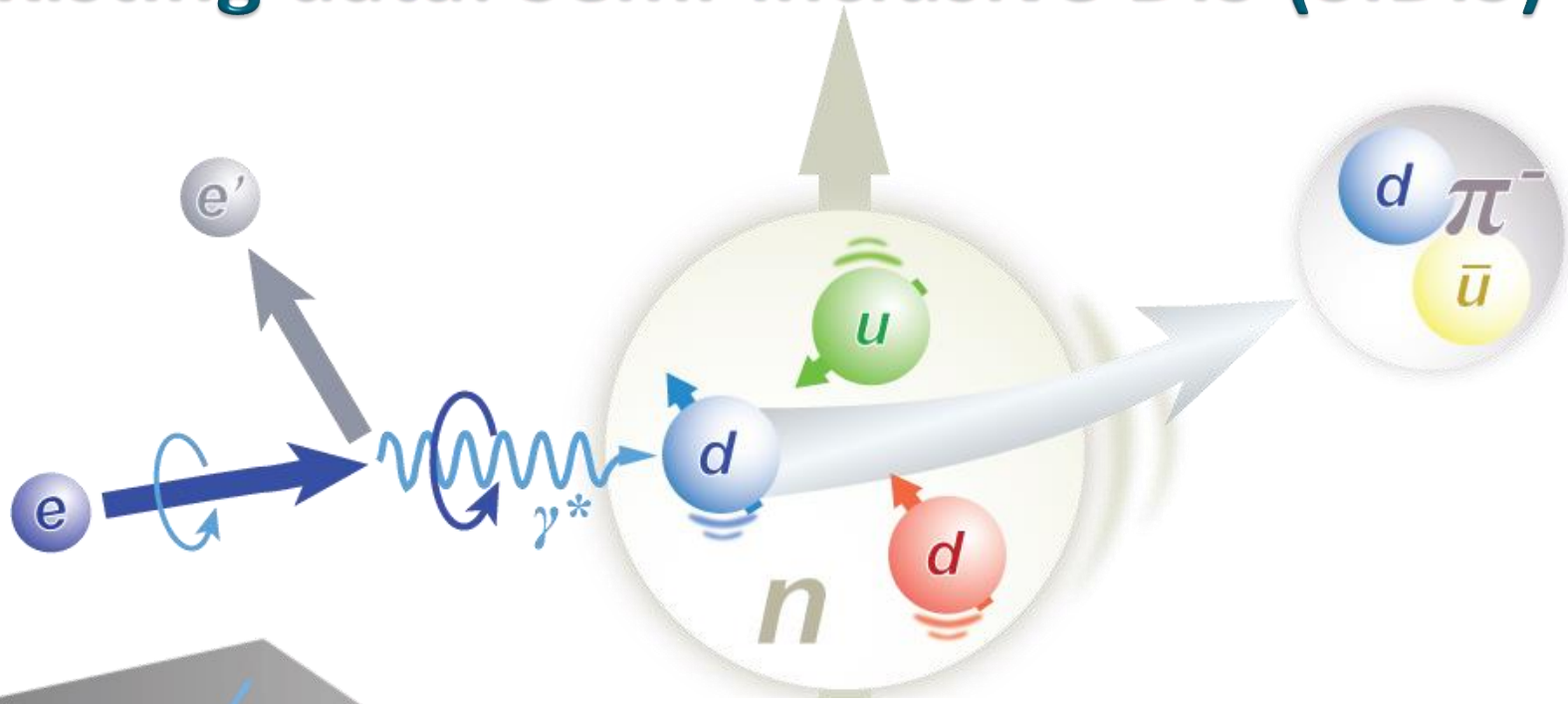


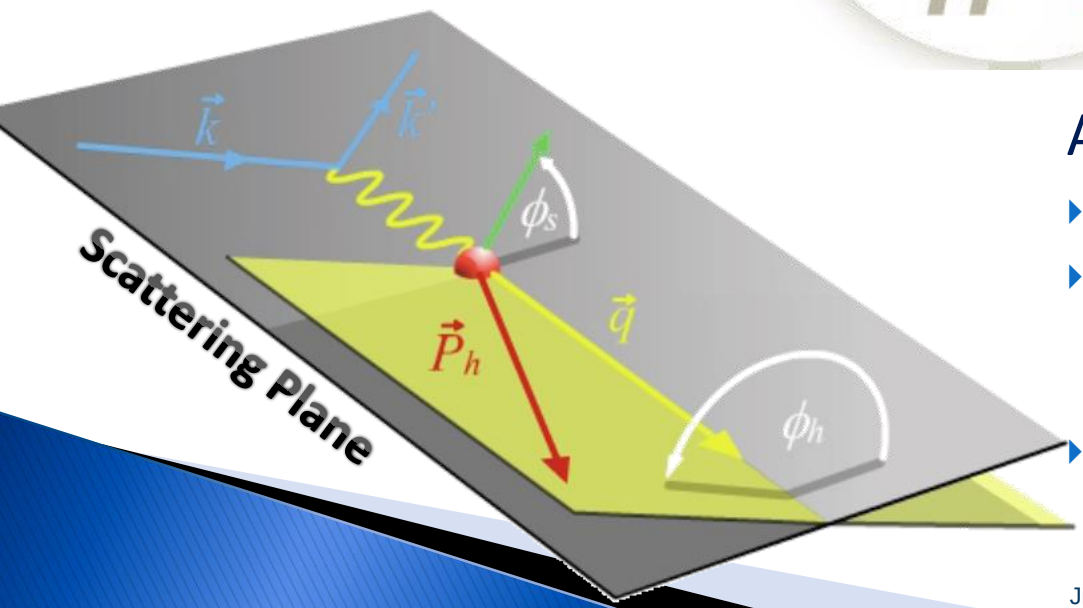
Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008



A. Prokudin

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

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

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

$$+\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

$$+ S_T \lambda_e [\sqrt{1-\varepsilon^2}\cos(\phi_h - \phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]$$

$$+ S_L \lambda_e [\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

$$+ S_L [\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$

$$+ S_T [\varepsilon\sin(\phi_h + \phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+\sin(\phi_h - \phi_S)\cdot(F_{UT}^{\sin(\phi_h-\phi_S)} + \ldots)$$

$$+\varepsilon\sin(3\phi_h - \phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]\}$$

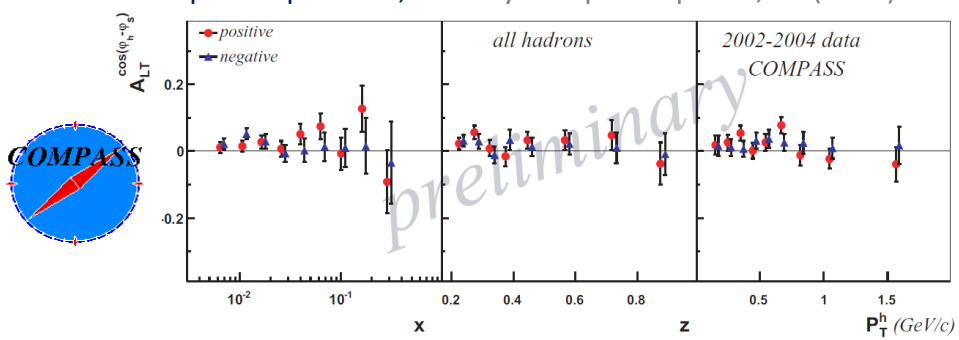
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} g_{1T} \otimes D_1\right]$$

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

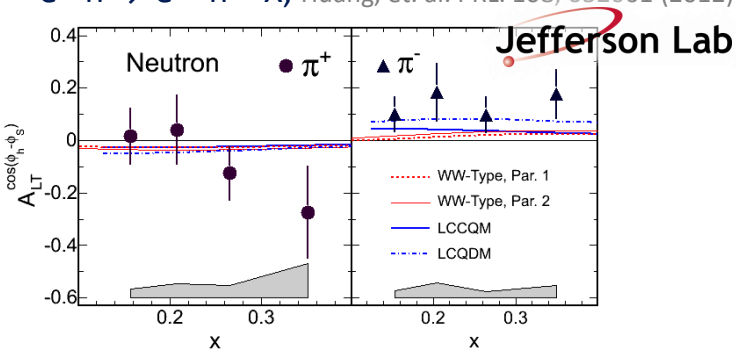
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Existing data: Access g_{1T} in SIDIS

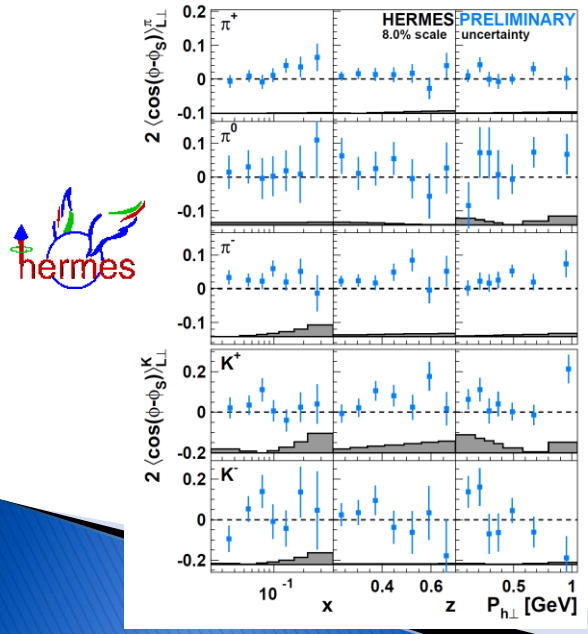
μ+D → μ + h + X, Eur. Phys. J. Spec. Top. 162, 89 (2008).



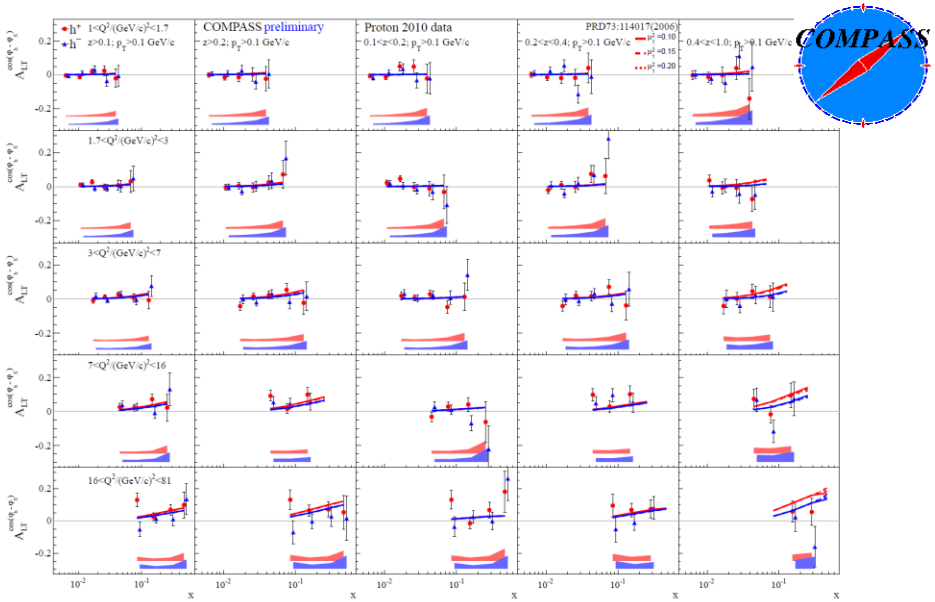
e+ n → e + h + X, Huang, et. al. PRL. 108, 052001 (2012)



e+p → e + h + X, arXiv:1107.4227 [hep-ex]

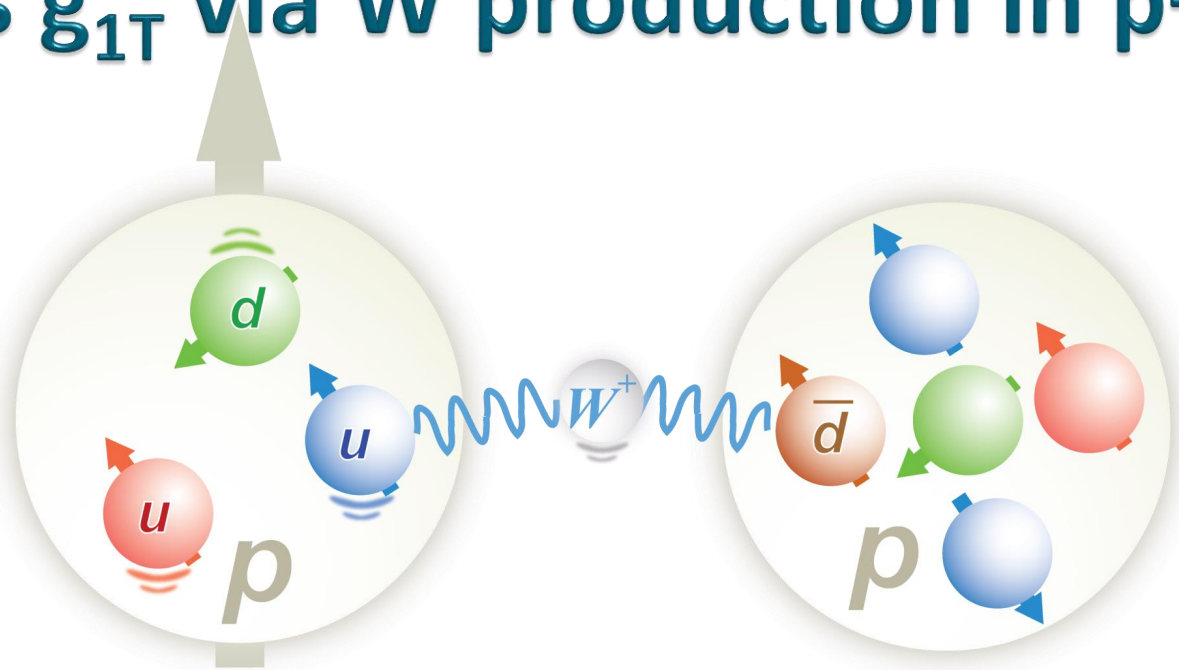


μ +p → μ + h + X, arXiv:1504.01599 [hep-ex]



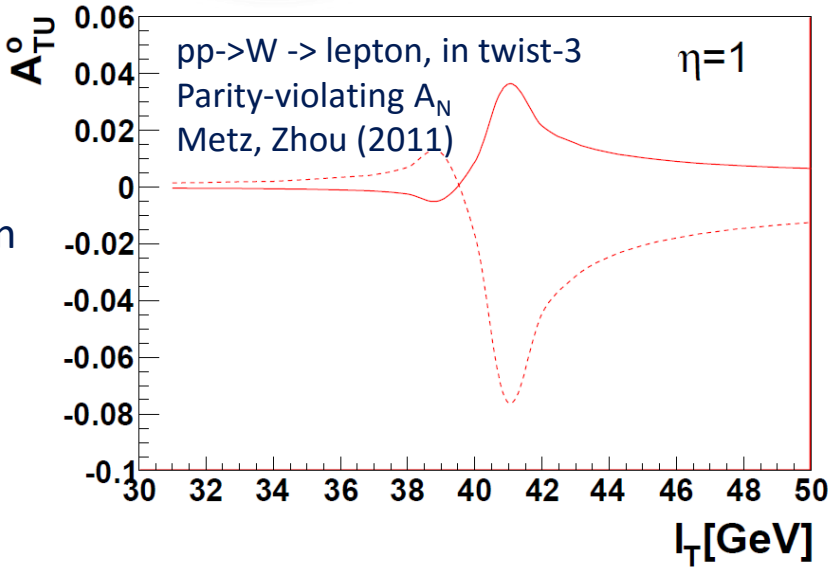
- Also a central piece for JLab12/SoLID SIDIS program.

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



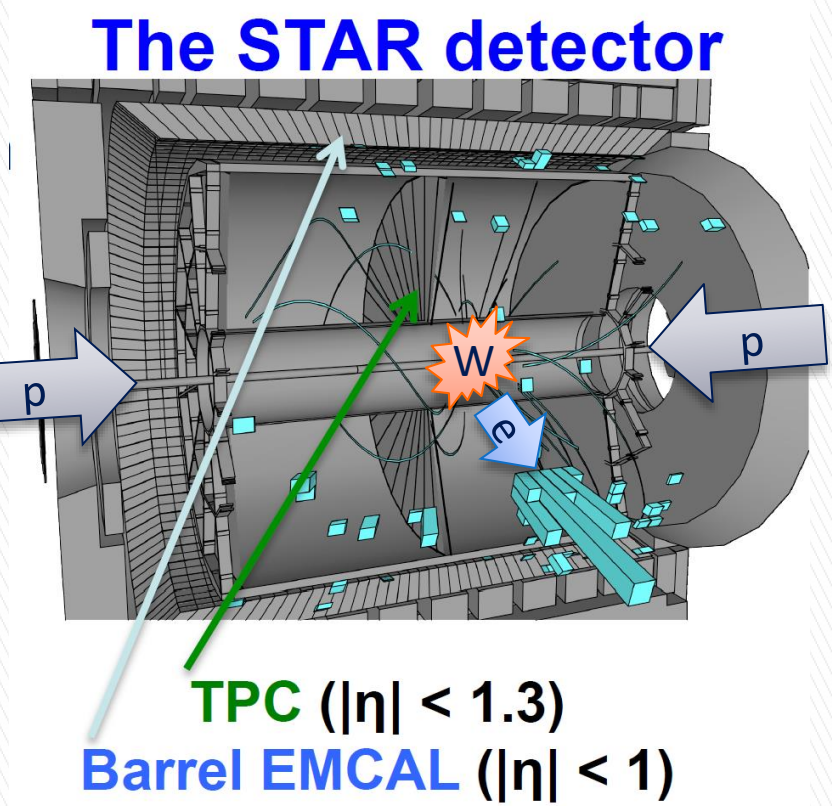
Accessing g_{1T} from W-boson production

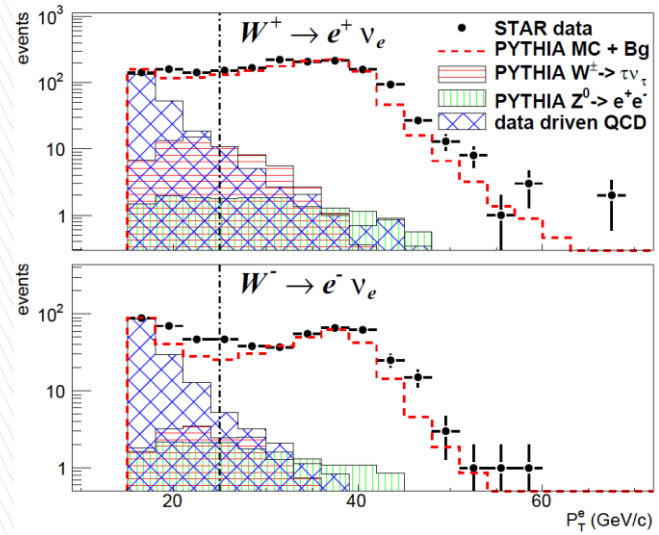
- W-boson couple to left-chirality quark, which provided 100% analyzing power to quark spin (parity-violating observables)
- Flavor separation via charge-selection of W boson
- However, previous asymmetry estimation for the decay lepton on show asymmetry near Jacobian Peak [Kang, Qiu(2009), Boer, den Dunnen, Kotzinian (2011), Metz, Zhou (2011)]

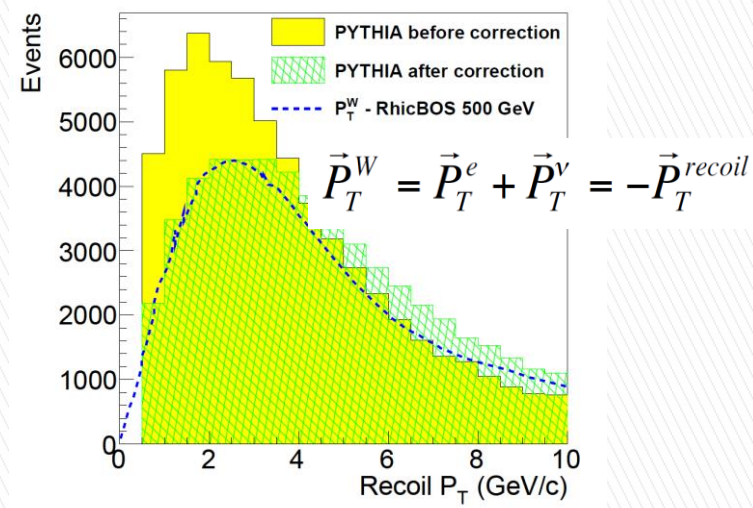


RHIC/STAR collaboration recently established W-boson kinematic reco in polarized p+p

- STAR, Phys. Rev. Lett. 116, 132301
- See also last talk by E. Aschenauer





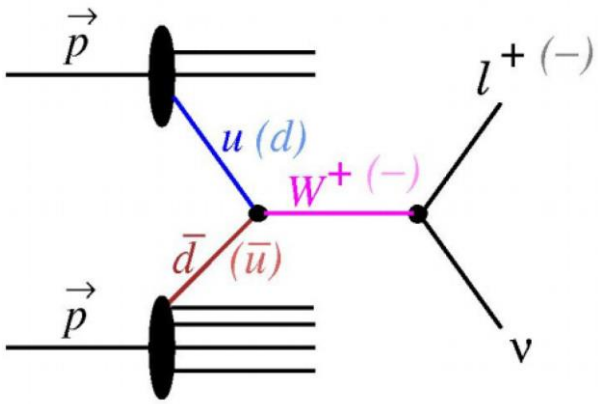


$p^{\uparrow}p \to W + X$ in STAR

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

Differencial Cross section for polarized p+p → W + X

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



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

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

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

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

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

Connection to experimental observables

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

pp → W/Z/γ* + X, integrated over vector boson decay

$$\frac{d\sigma^W}{dyd^2\vec{q}_T} = \sigma_0^W \Big\{ F_{UU} + S_{AL} F_{LU} + S_{BL} F_{UL} + S_{AL} S_{BL} F_{LL}$$
$$+ |\vec{S}_{AT}| \left[\sin(\phi_V - \phi_{S_A}) F_{TU}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TU}^{\cos(\phi_V - \phi_{S_A})} \right]$$
$$+ |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{UT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{UT}^{(\cos\phi_V - \phi_{S_B})} \right]$$
$$+ |\vec{S}_{AT}| S_{BL} \left[\sin(\phi_V - \phi_{S_A}) F_{TL}^{\sin(\phi_V - \phi_{S_A})} + \cos(\phi_V - \phi_{S_A}) F_{TL}^{\cos(\phi_V - \phi_{S_A})} \right]$$
$$+ S_{AL} |\vec{S}_{BT}| \left[\sin(\phi_V - \phi_{S_B}) F_{LT}^{\sin(\phi_V - \phi_{S_B})} + \cos(\phi_V - \phi_{S_B}) F_{LT}^{\cos(\phi_V - \phi_{S_B})} \right]$$
$$+ |\vec{S}_{AT}| |\vec{S}_{BT}| \left[\cos(2\phi_V - \phi_{S_A} - \phi_{S_B}) F_{TT}^{\cos(2\phi_V - \phi_{S_A} - \phi_{S_B})} + \cos(\phi_{S_A} - \phi_{S_B}) F_{TT}^1 \right.$$
$$\left. + \sin(2\phi_V - \phi_{S_A} - \phi_{S_B}) F_{TT}^{\sin(2\phi_V - \phi_{S_A} - \phi_{S_B})} + \sin(\phi_{S_A} - \phi_{S_B}) F_{TT}^2 \right] \Big\}.$$

Parity violating : only probed by weak boson.

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

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

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

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

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

$$\mu = M_V$$

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

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

DSSV

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

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

Anselmino et al.

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

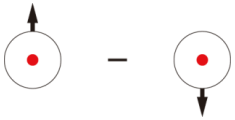
$$g_{1T}^{q(1)}(x) \approx x\int_x^1 \frac{dz}{z}g_{1L}^q(z)$$

Kotzinian et al.

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

Single transverse spin asymmetries in week boson production

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

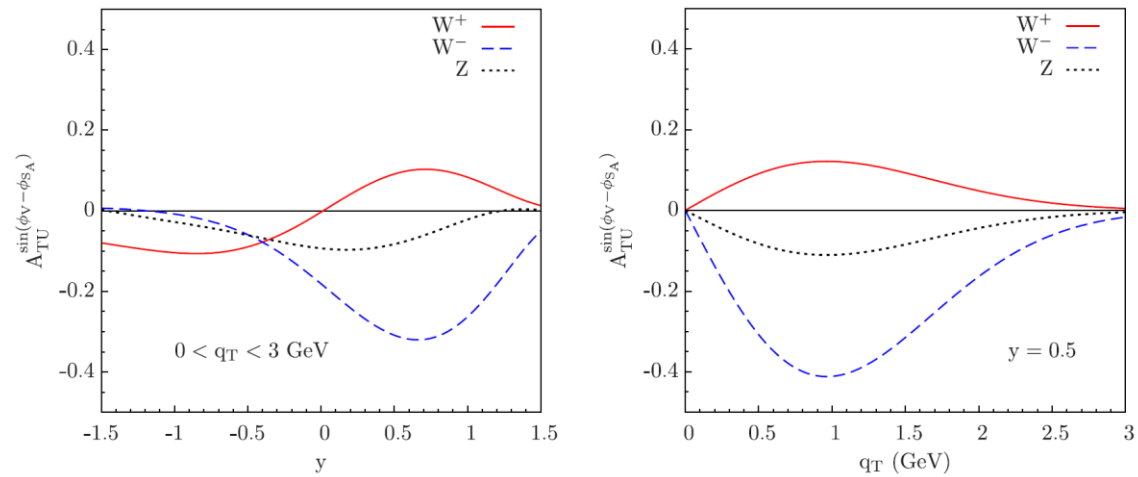
$f_{1T}^{\perp}$ = 

via parity-conserving SSA

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

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

(Reverse sign def. to traditional A_N)

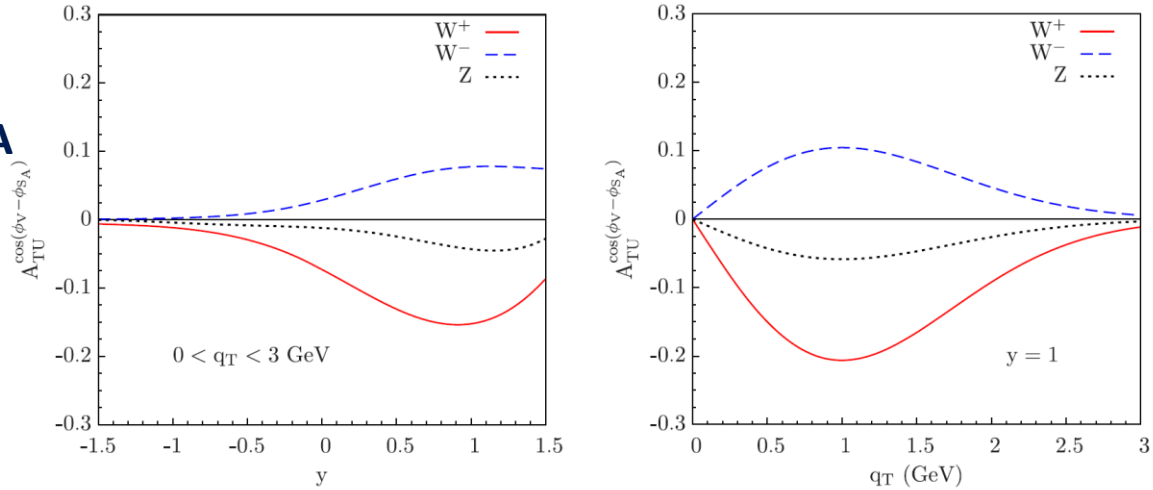


g_{1T} = 

via **unique parity-violating SSA**

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

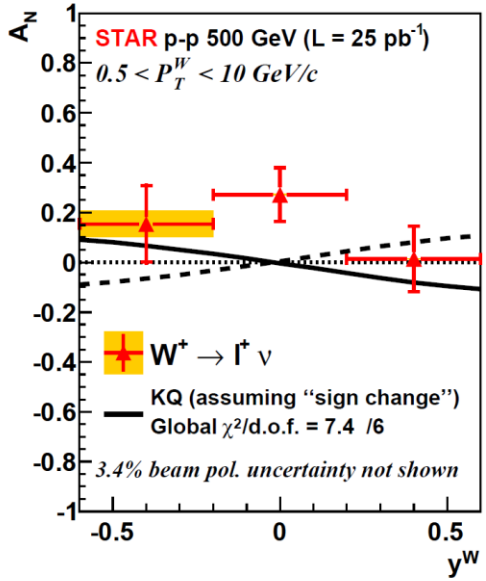
$$A_{TU}^{\cos(\phi_V-\phi_{S_A})} = \frac{F_{TU}^{\cos(\phi_V-\phi_{S_A})}}{F_{UU}},$$

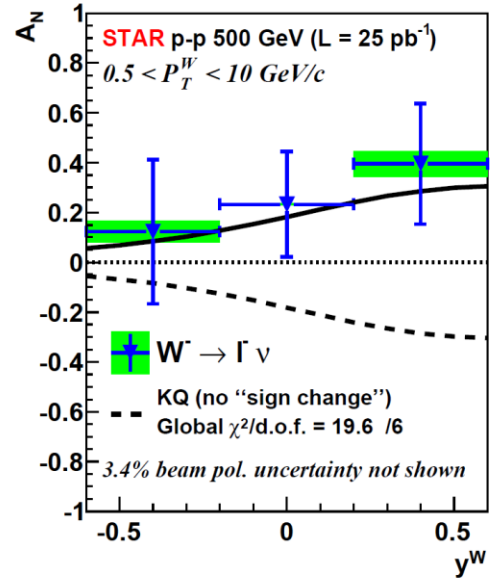


Published RHIC data

$f_{1T}^{\perp}$ = 

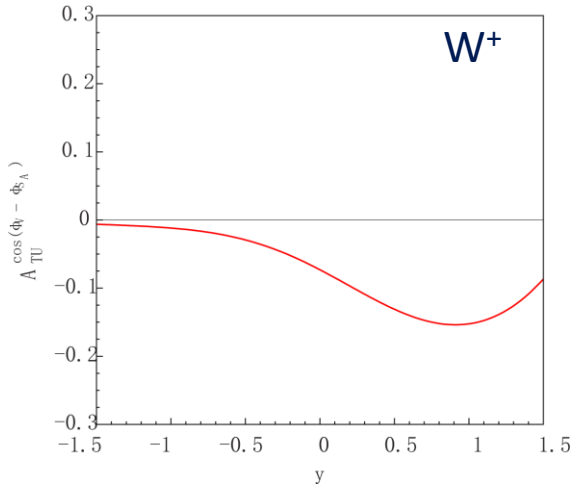
via parity-conserving SSA
STAR, Phys. Rev. Lett. 116, 132301
See also last talk by E. Aschenauer

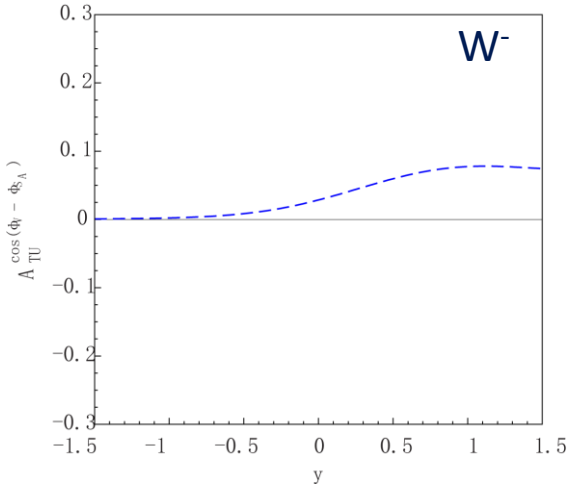




g_{1T} = 

via **unique parity-violating SSA**
our prediction (no evolution),
Huang, Kang, Vitev, Xing,
PRD 93 (2016)

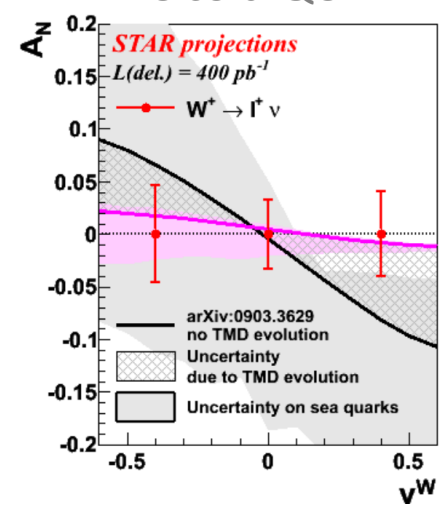


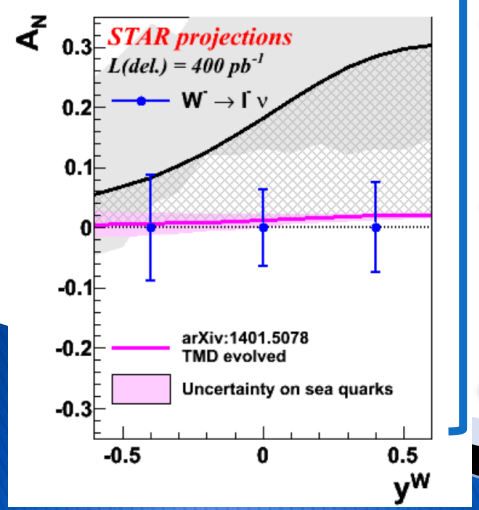


Experimental outlook: RHIC/STAR W in Run 2017

$p^{\uparrow}p \rightarrow W + X \rightarrow (e+\nu)+X$, transversely polarized p+p collision @ $\sqrt{s}$ = 510 GeV

STAR projection in RHIC cold-QCD WP

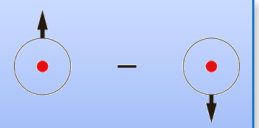




Measured at same time

P-conserving A_N | P-violating A_N

Probing TMD PDFs

$f_{1T}^{\perp}$ =  g_{1T} = 

Modified universality for off-diagonal TMD

Sign change? | Universal?

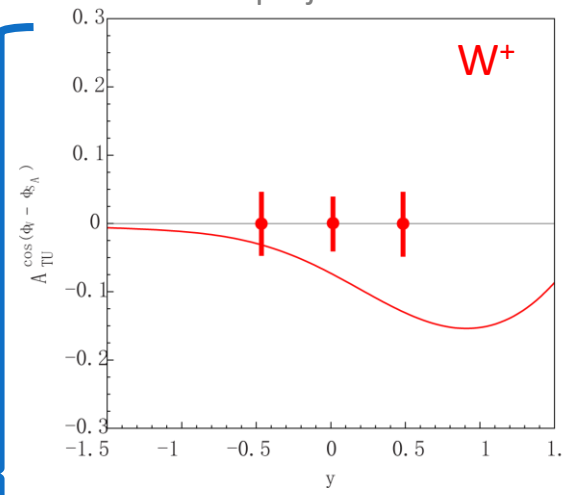
Study evolution for TMD

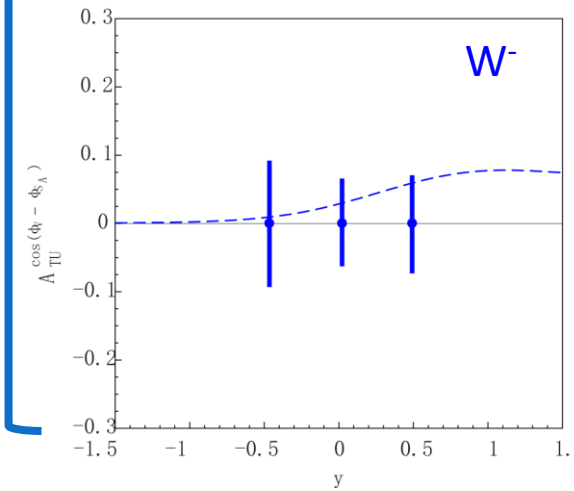
Similar scale of evolution?

Model relation to OAM

Im(S * P) | Re(S * P)

Jin's naive expectation for STAR 2017 projection
Based on AN projection on the left





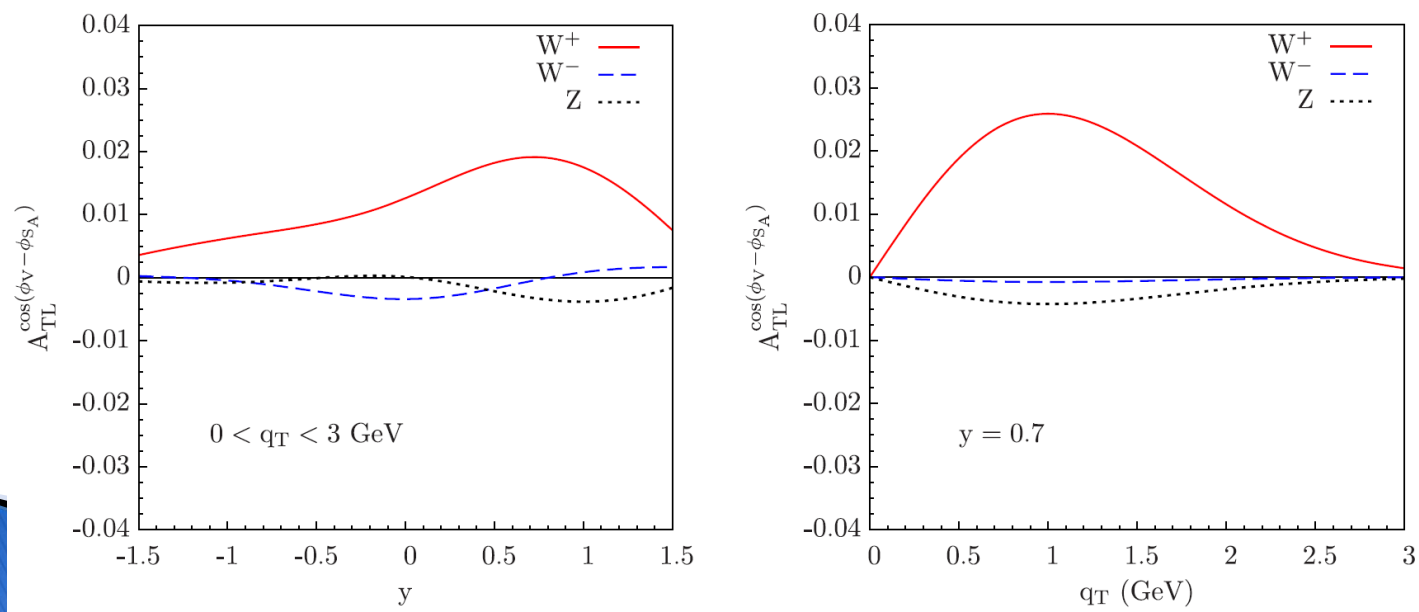
Jin Huang et. al.

Parity-conserving Double spin asymmetries, A_{LT}

- Parity-conserving modulation on LT-double spin observable → g_{1L} = 

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

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

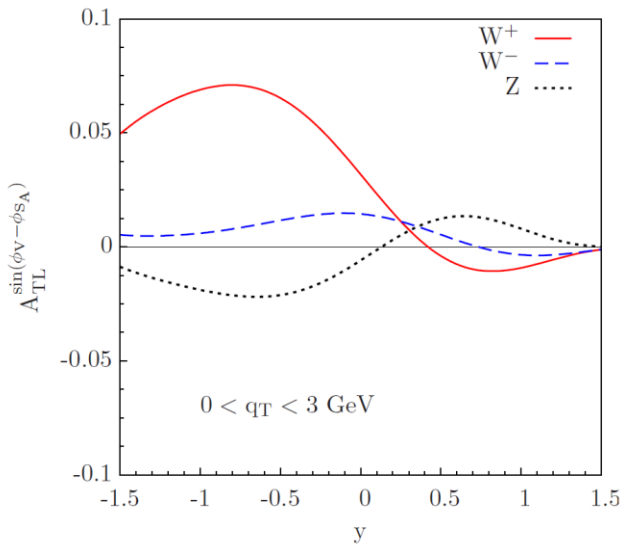


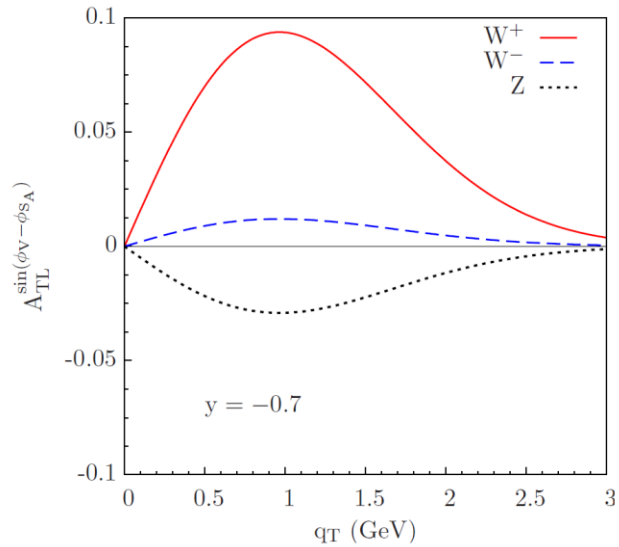
Parity-conserving Double spin asymmetries, A_{LT}

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

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

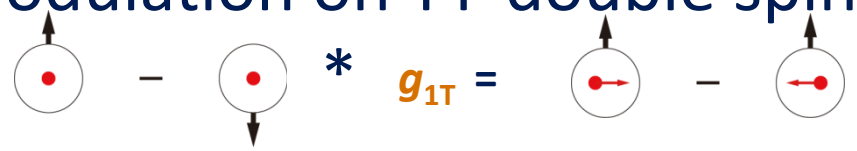
$$A_{TL}^{\sin(\phi_V-\phi_{S_A})}(y) = -A_{LT}^{\sin(\phi_V-\phi_{S_B})}(-y)$$





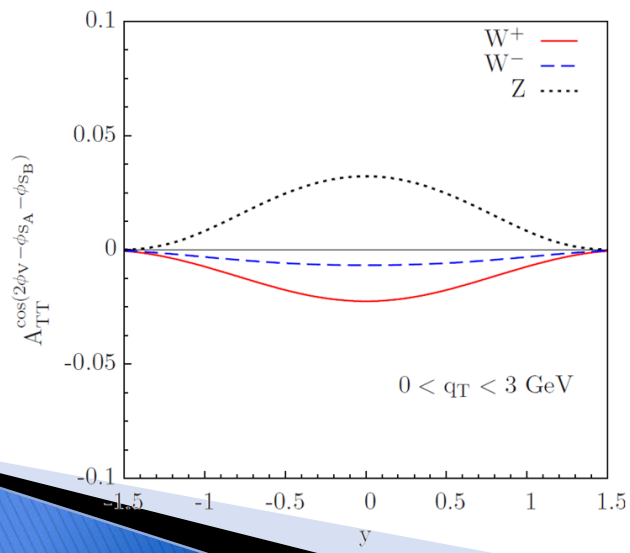
Parity-conserving Double spin asymmetries, A_{TT}

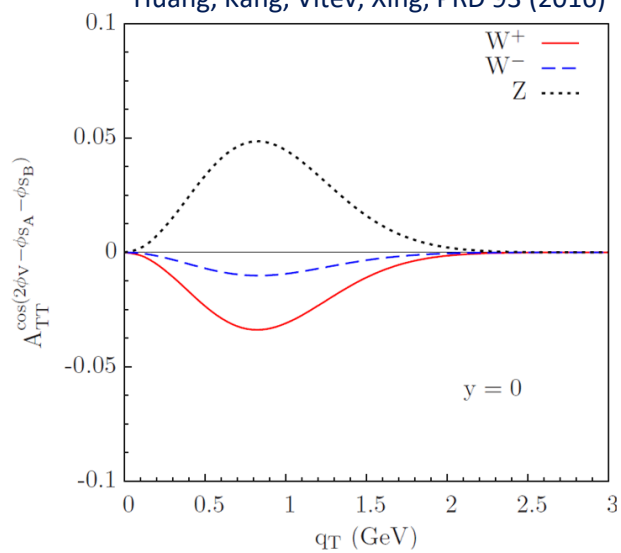
- Modulation also expected in TT-double spin asymmetry
- Parity-conserving modulation on TT-double spin observable → $f_{1T}^{\perp}$ = – * g_{1T} = –



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

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



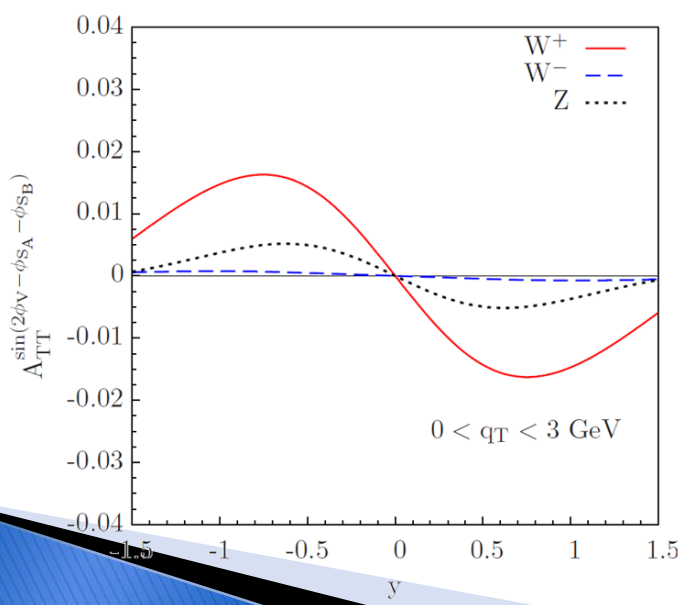


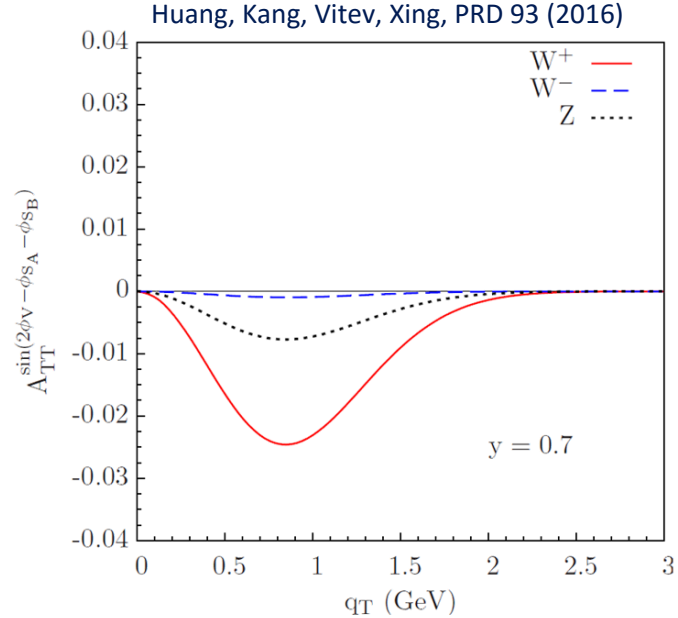
Parity-violating Double spin asymmetries, A_{TT}

- Parity-violating modulation on TT-double spin observable also →

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

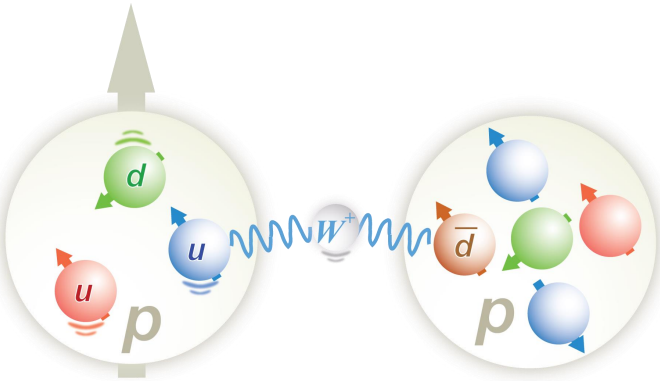
Huang, Kang, Vitev, Xing, PRD 93 (2016)

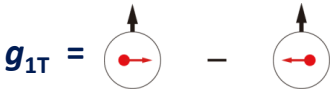




Summary

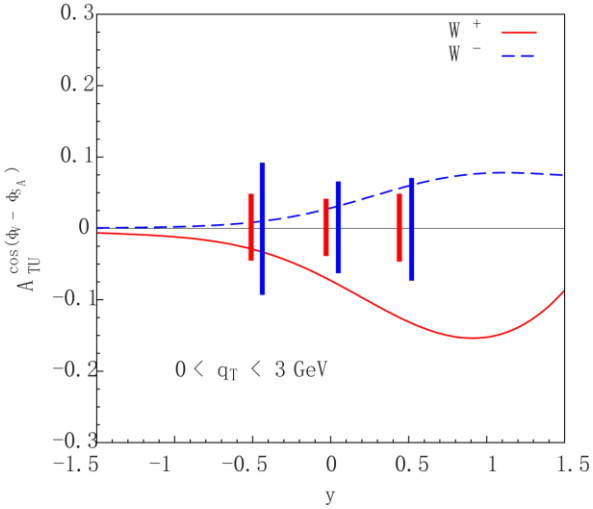
- Within TMD factorization formalism, we presented the cross sections for weak boson production in polarized pp collisions. And estimated the spin asymmetries at the top RHIC energy.
- Unique opportunity of probe g_{1T} via parity violating single transverse spin asymmetry
- The W spin physics program 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.
- We thank E. C. Aschenauer, A. Metz, D. Pitonyak, and M. Schlegel for helpful comments.





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

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



- 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

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

Satisfying the multi-D natural of this study.

Comparable precision for SSA

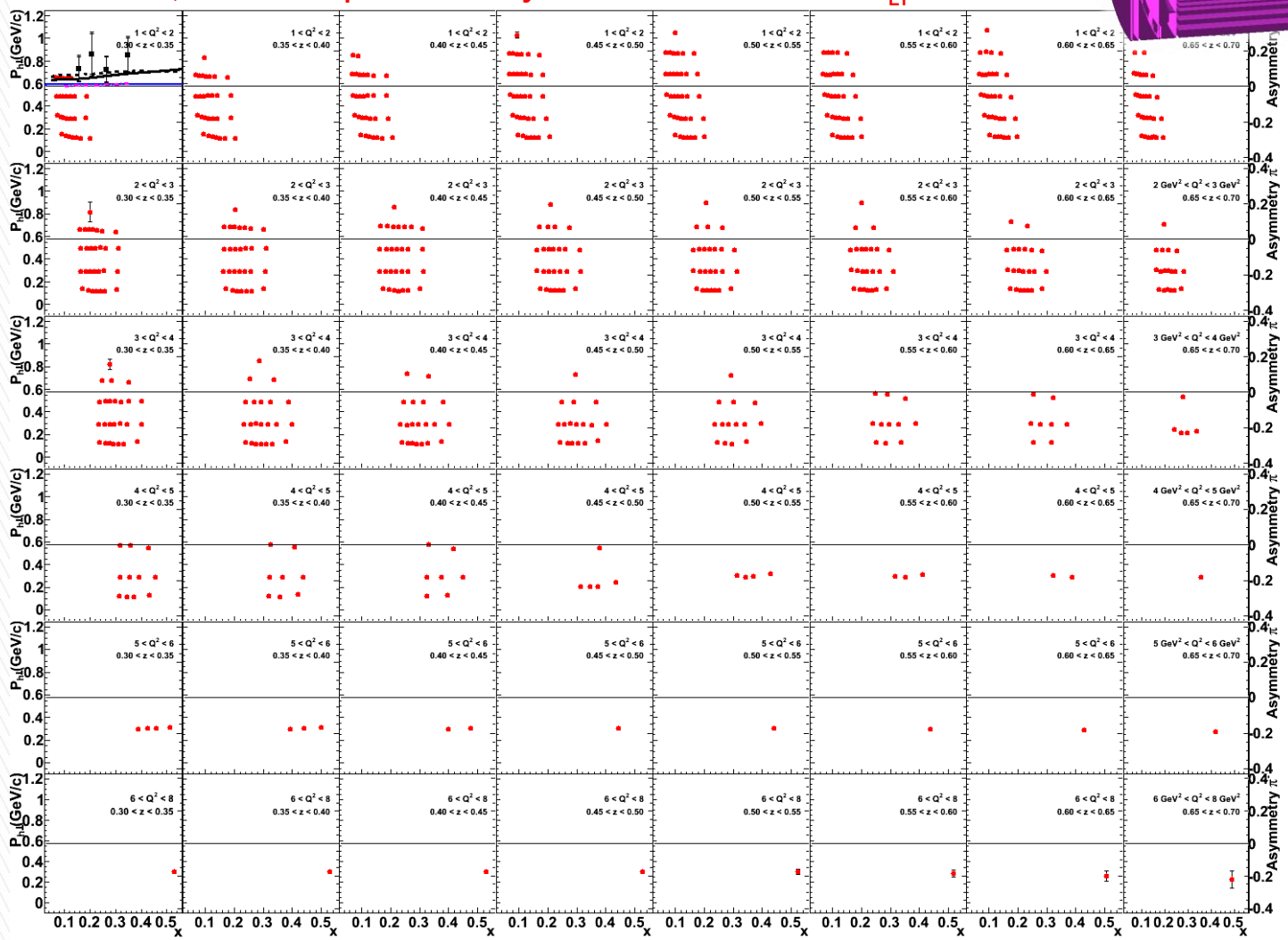
z= 0.3~0.7

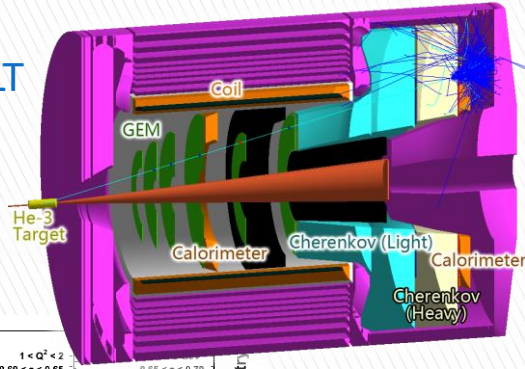
x_{bj}

data point: Projection for neutron A_{LT} of π^-

Q^2 = 1~8 GeV^2

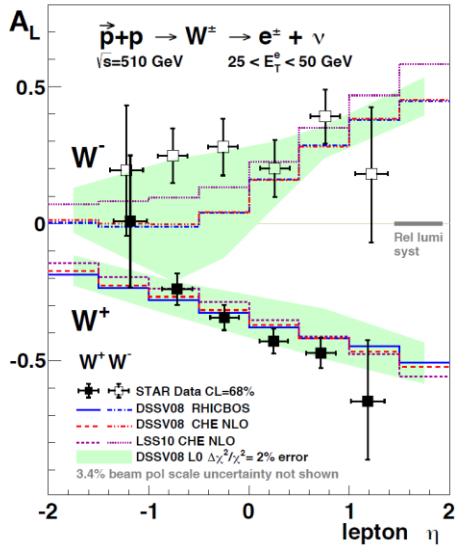
$P_{h\perp}$ (GeV/c)

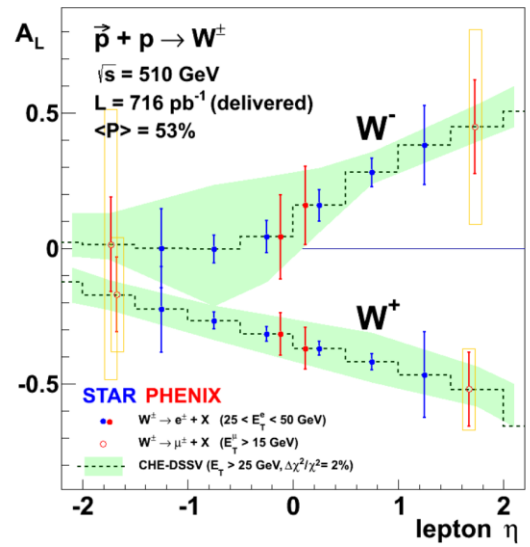




What about A_{LU}

Observed decay lepton from vector boson RHIC data/projection





For observed vector boson
Huang, Kang, Vitev, Xing, PRD 93 (2016)