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

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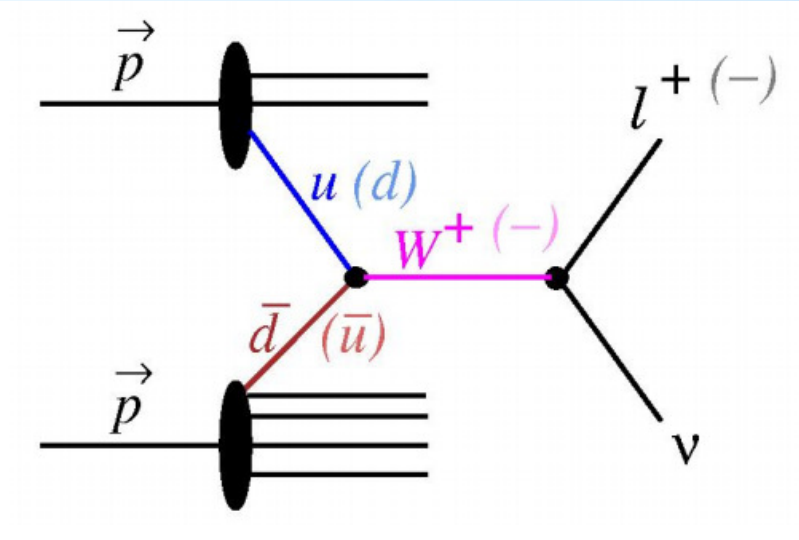
Outline

- Introduction
- Spin dependent cross section
- Phenomenology at RHIC energy
- Summary

Why W-boson spin asymmetries

- Flavor separation for spin dependent parton distribution
- Extract sea quark polarization
- Test sign change for Sivers function
- Excellent constraints on QCD evolution effects

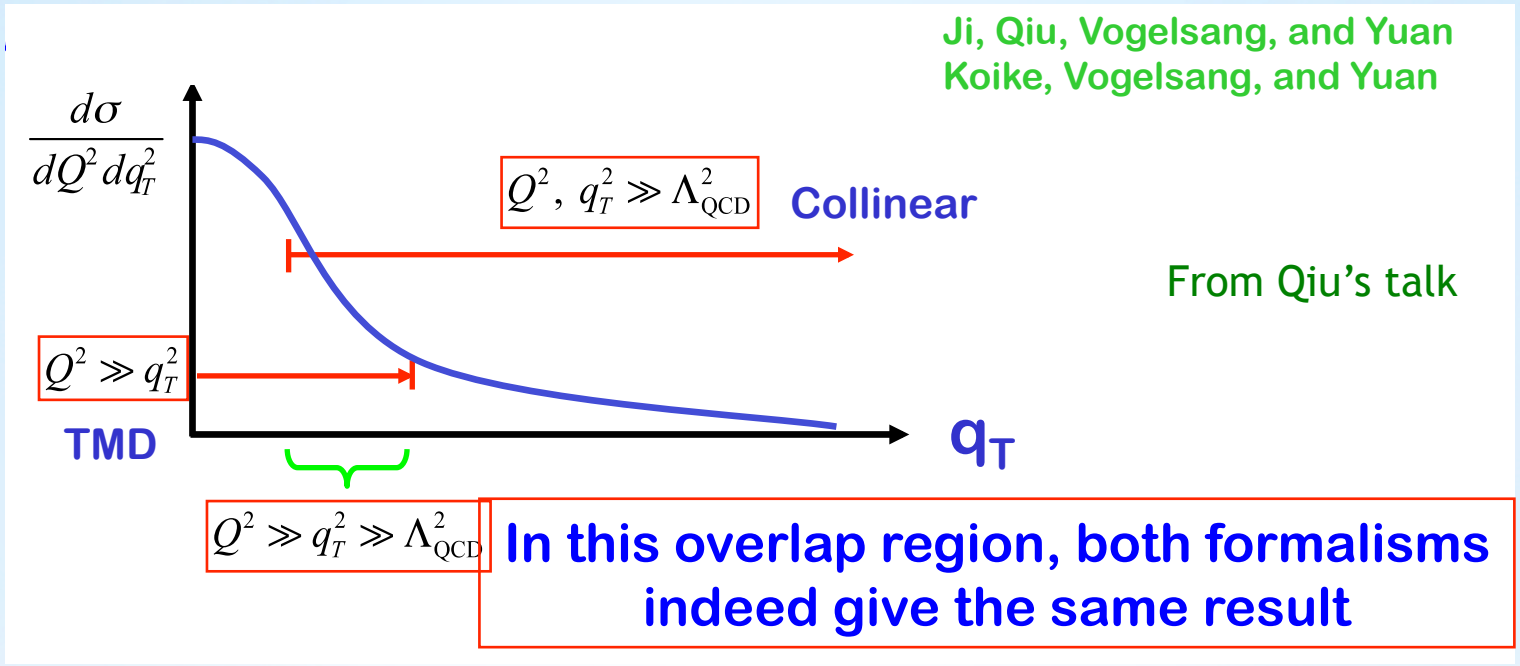


$$u + \bar{d} \to W^+ \to e^+ + \nu$$

$$d + \bar{u} \to W^- \to e^- + \bar{\nu}$$

Rely on QCD factorization!

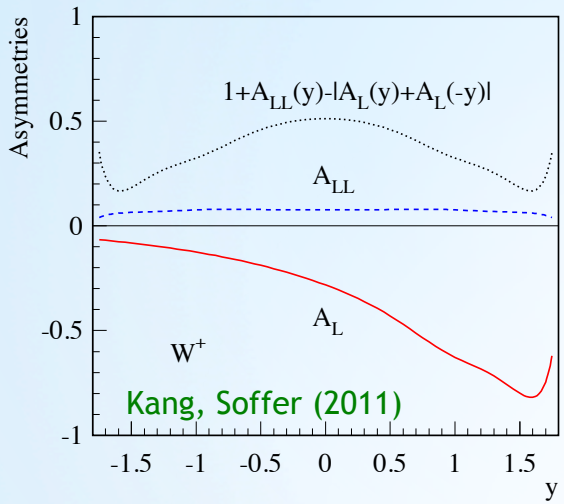
QCD factorization

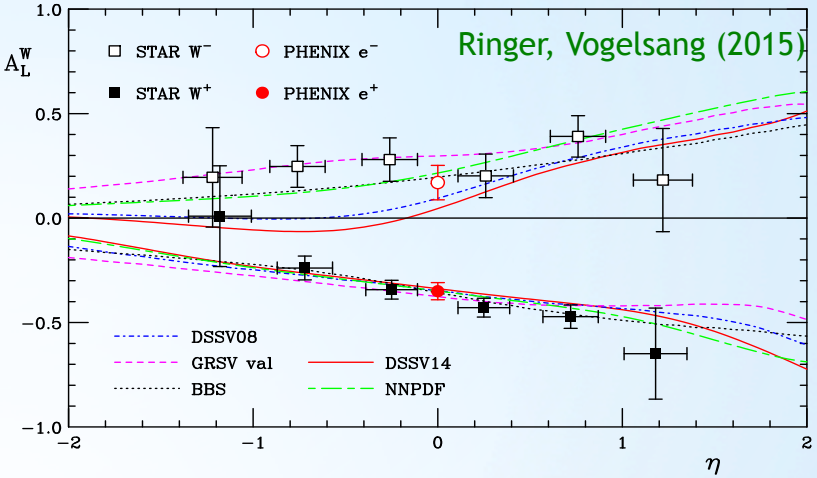


- Low pT - TMD factorization
- High pT - collinear factorization
- pT integrated - collinear factorization

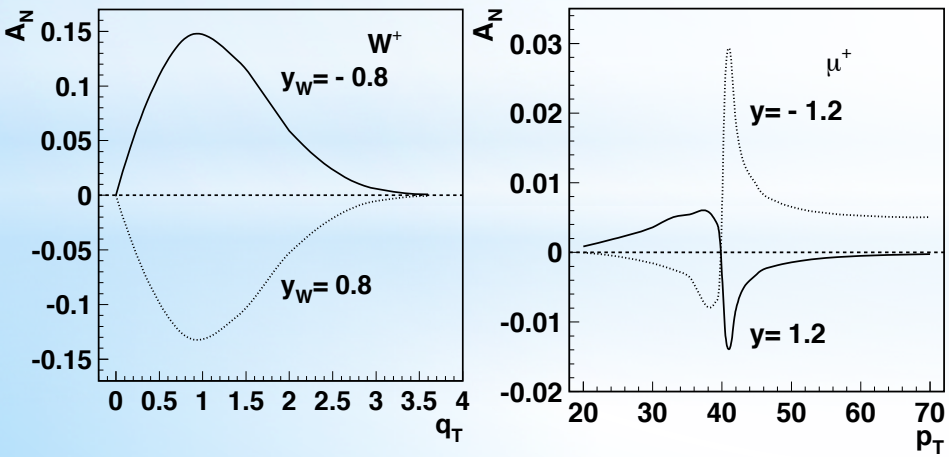
Some examples for W spin asymmetries

- Single longitudinal spin asymmetry

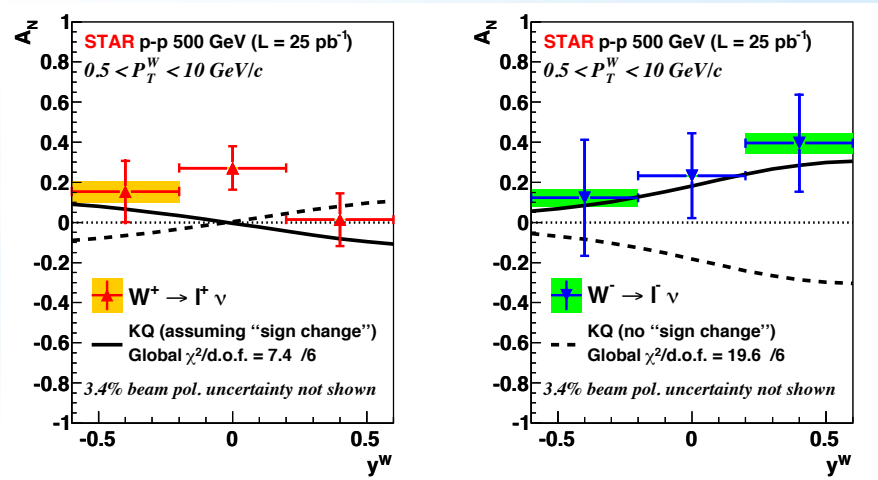




- Single transverse spin asymmetry



Kang, Qiu(2009)



STAR (2015)

W-boson production in TMD

- Differential cross section for W-boson production

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

  - Hadronic tensor

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

  - Quark-quark correlator

$$\Phi^q(x_a, \vec{k}_{aT}, S_A) = \int \frac{dz^- d^2\vec{z}_T}{(2\pi)^3} e^{ik_a^+ z^- - i\vec{k}_{aT}\cdot\vec{z}_T}\langle P_A, S_A|\bar{\psi}_j^q(0)\psi_i^q(z)|P_A, S_A\rangle,$$

$$\bar{\Phi}^q(x_b, \vec{k}_{bT}, S_B) = \int \frac{dz^+ d^2\vec{z}_T}{(2\pi)^3} e^{ik_b^- z^+ - i\vec{k}_{bT}\cdot\vec{z}_T}\langle P_B, S_B|\psi_i^q(0)\bar{\psi}_j^q(z)|P_B, S_B\rangle$$

  - Expansion $\Phi^q(x_a, \vec{k}_{aT}, S_A) = \Phi^{q[\gamma^+]}\frac{\gamma^-}{2} + \Phi^{q[\gamma^+\gamma^5]}\frac{\gamma^5\gamma^-}{2} + \Phi^{q[i\sigma^{\alpha+}\gamma^5]}\frac{-i\sigma^{\alpha-}\gamma^5}{2}$

- Leading twist TMDs

Sivers function

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

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

helicity function

Transversal helicity function

- Final result

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

Phenomenology for TMDs

- Without TMD evolution
- Gaussian model for quark TMDs

➢ Unpolarized quark TMD

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

↓

CTEQ6

➢ Helicity TMD

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

↓

DSSV

➢ Sivers function

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

Anselmino et al, 2009

$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}},$$

$$h(k_T) = \sqrt{2e}\,\frac{k_T}{M_1}e^{-k_T^2/M_1^2}$$

➢ Transversal helicity distribution

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

Kotzinian et al, 2006

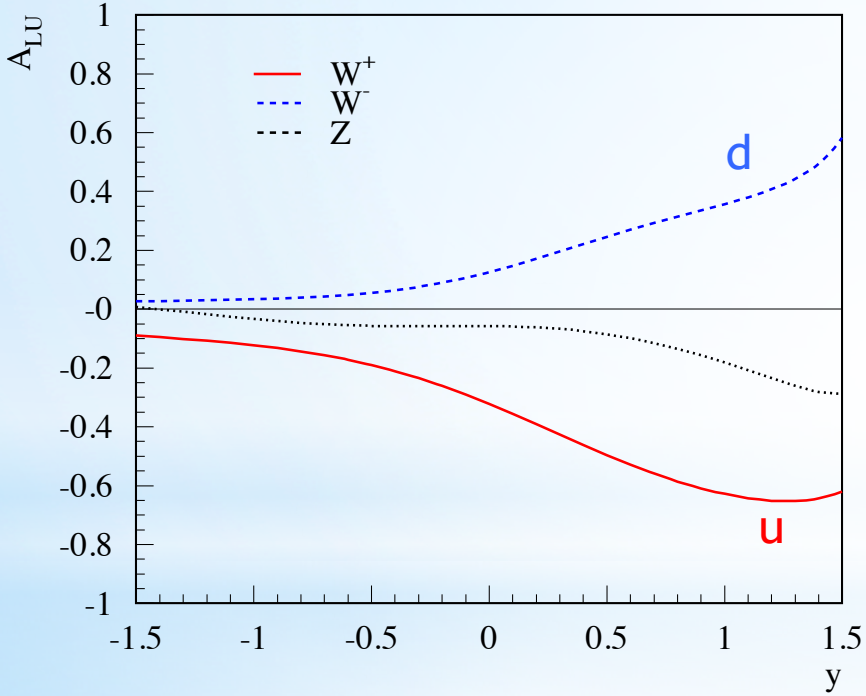
$$g_{1T}^{q(1)}(x) \approx x\int_x^1 \frac{dz}{z}g_{1L}^q(z)$$

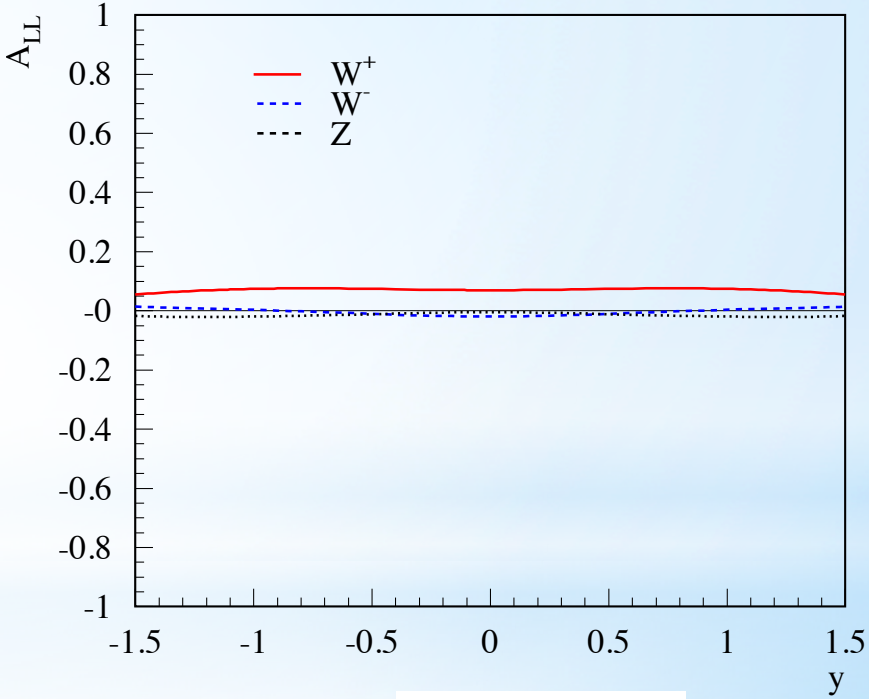
Wandzura-Wilczek approximation

Single/double longitudinal spin asymmetry

$$A_{LU} = \frac{F_{LU}}{F_{UU}}$$
$$F_{LU} = -\mathcal{C}^W \left[2 v_q a_q \, g_{1L} \, \bar{f}_1\right]$$
$$F_{UU} = \mathcal{C}^W \left[(v_q^2 + a_q^2) \, f_1 \, \bar{f}_1\right]$$

$$A_{LL} = \frac{F_{LL}}{F_{UU}}$$
$$F_{LL} = -\mathcal{C}^W \left[(v_q^2 + a_q^2) \, g_{1L} \, \bar{g}_{1L}\right]$$





Flavor separation of quark helicity distribution

$$u + \bar{d} \to W^+$$
$$d + \bar{u} \to W^-$$

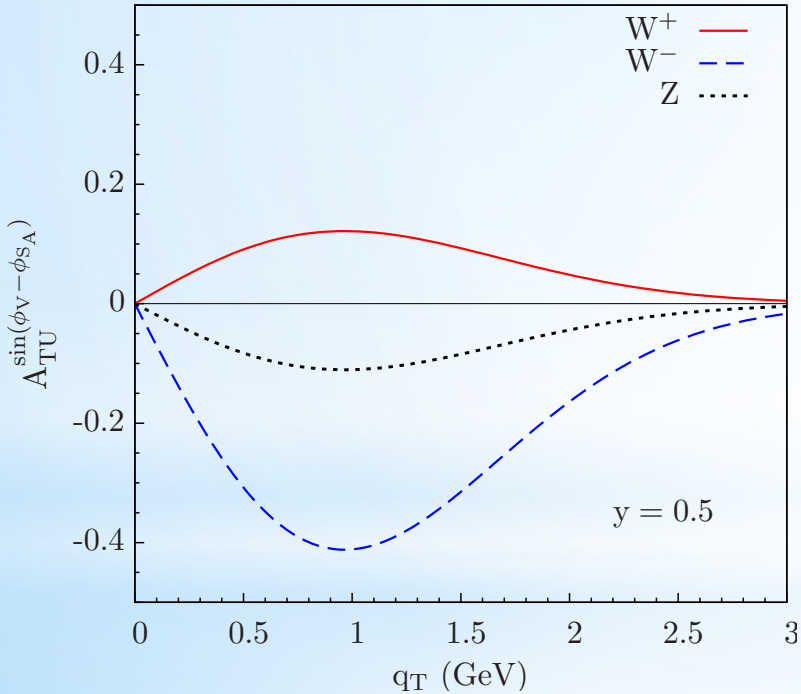
Single transverse spin asymmetry I

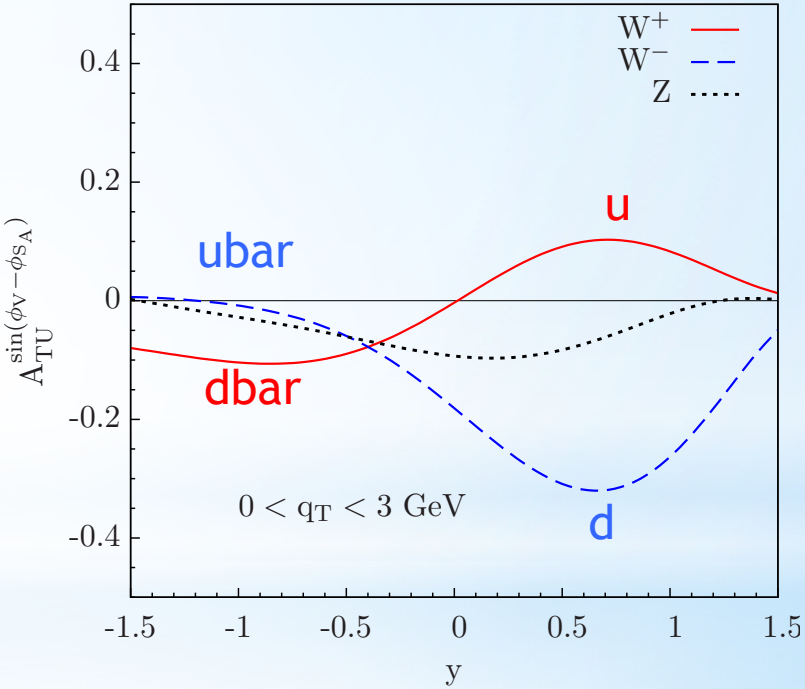
$$A_{TU}^{\sin(\phi_V-\phi_{S_A})} = \frac{F_{TU}^{\sin(\phi_V-\phi_{S_A})}}{F_{UU}}$$

$$A_{TU}^{\sin(\phi_V-\phi_{S_A})} = -A_N$$

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

One of the main goals of W spin program





- Flavor separation of quark Sivers function
- Constrain sea quark Sivers function

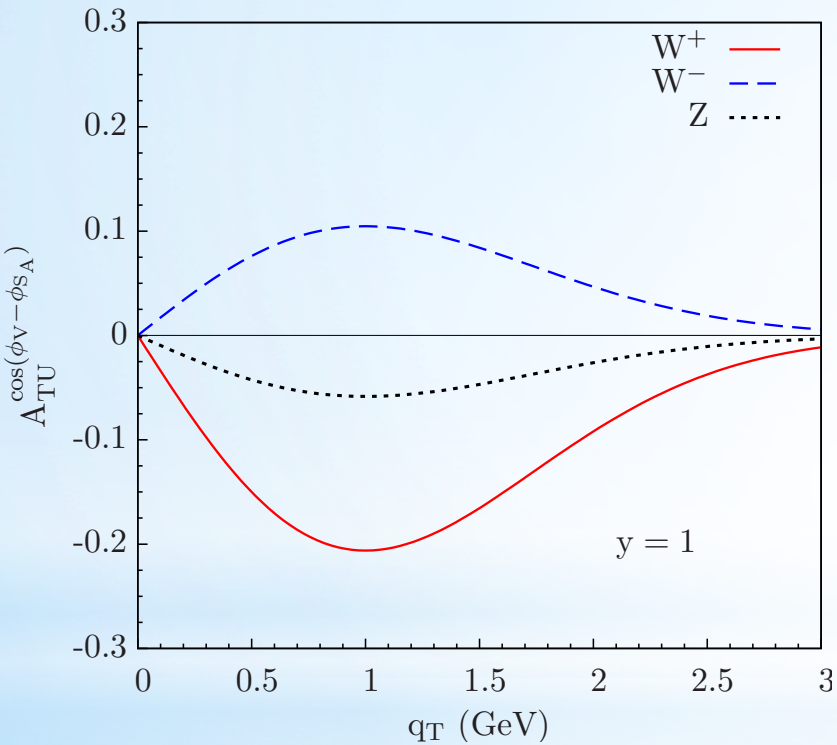
$$u + \bar{d} \to W^+$$

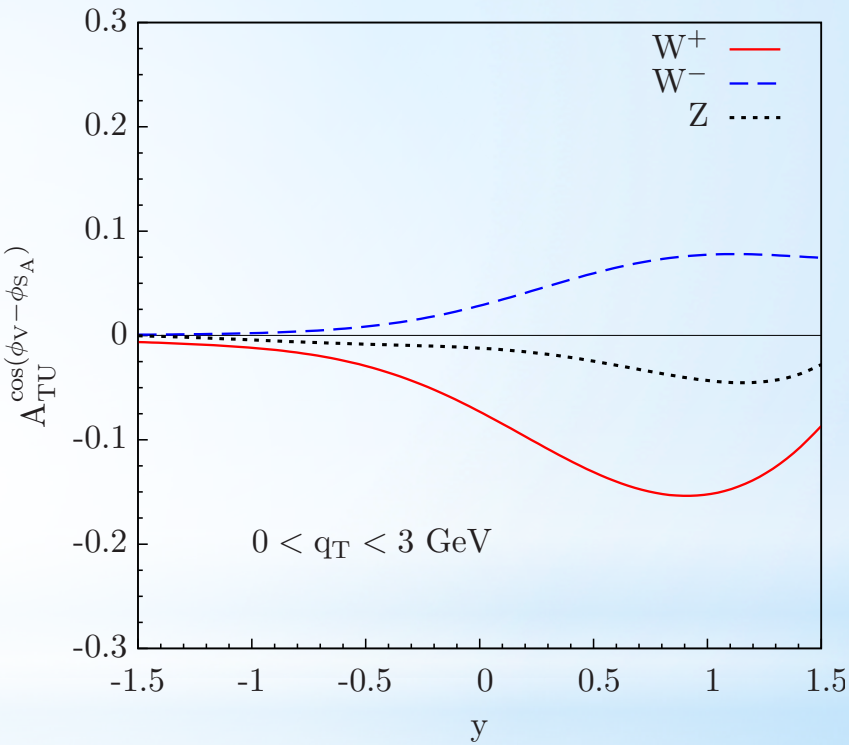
$$d + \bar{u} \to W^-$$

Single transverse spin asymmetry II

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

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



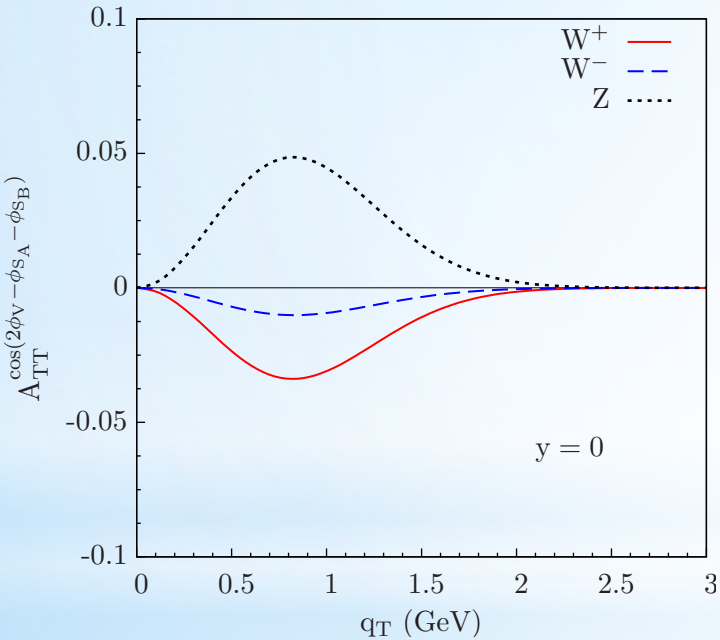


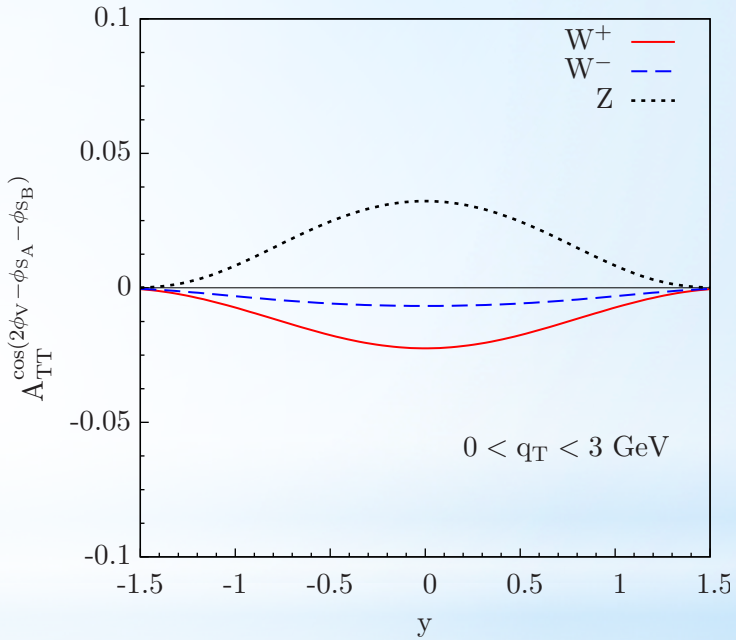
- Constrain transversal-helicity distribution
- Test the universality of g_1T

Double transverse spin asymmetry I

$$A_{TT}^{\cos(2\phi_V-\phi_{S_A}-\phi_{S_B})} = \frac{F_{TT}^{\cos(2\phi_V-\phi_{S_A}-\phi_{S_B})}}{F_{UU}}$$

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





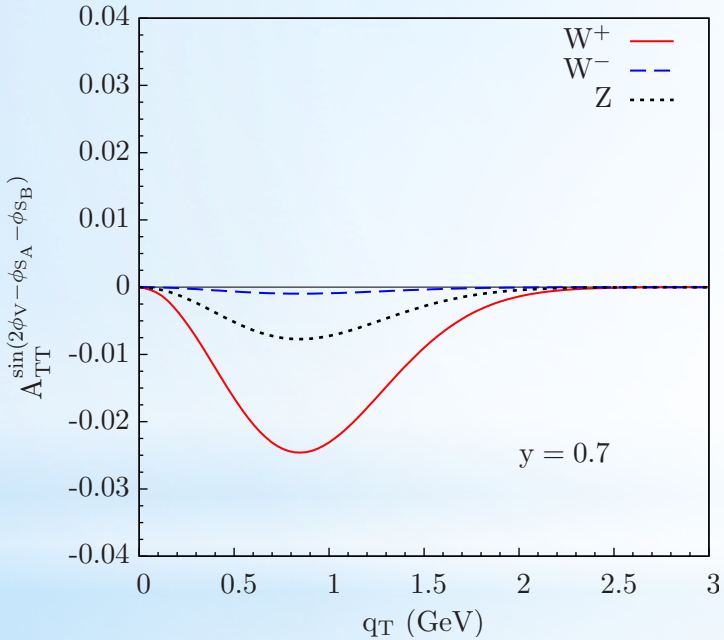
$$u + \bar{d} \to W^+$$

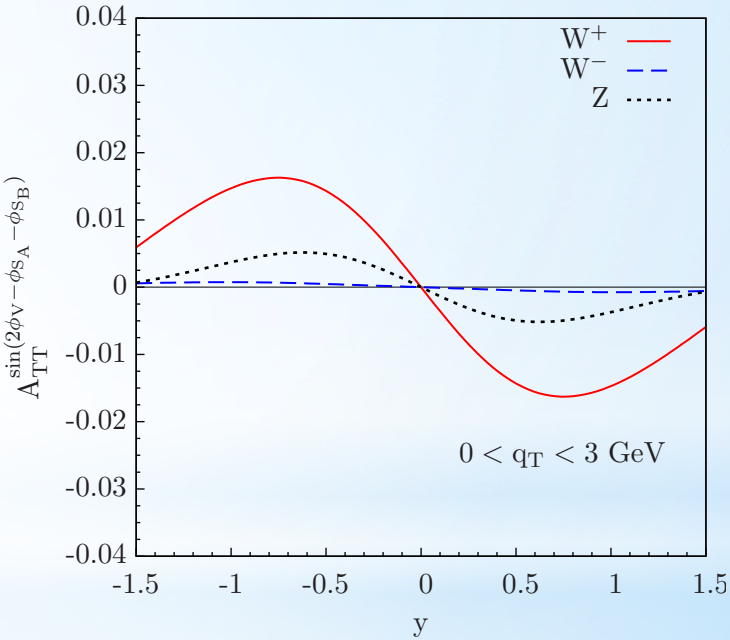
$$d + \bar{u} \to W^-$$

Double transverse spin asymmetry II

$$A_{TT}^{\sin(2\phi_V-\phi_{S_A}-\phi_{S_B})} = \frac{F_{TT}^{\sin(2\phi_V-\phi_{S_A}-\phi_{S_B})}}{F_{UU}}$$

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

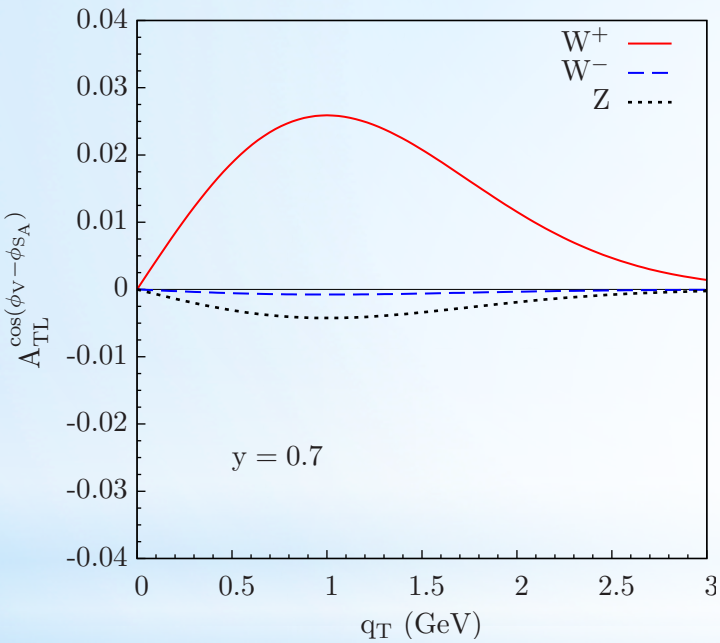


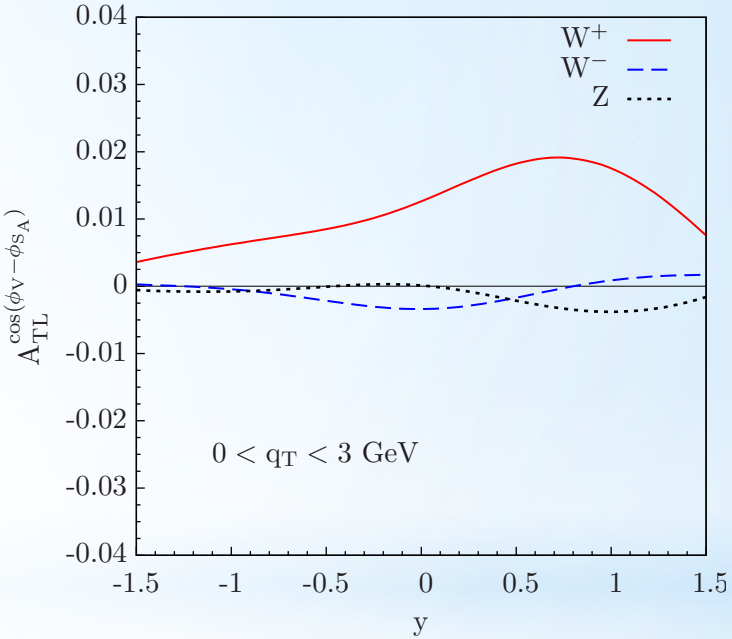


Transverse-longitudinal double spin asymmetry I

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

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

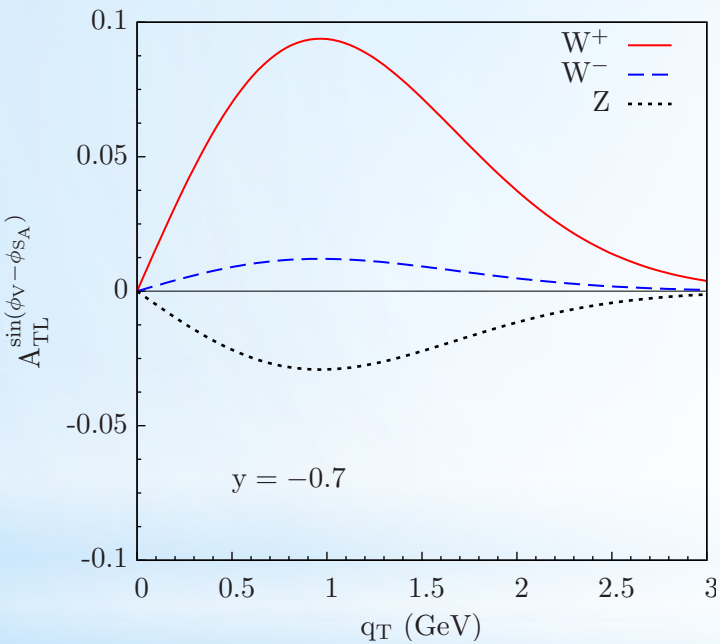


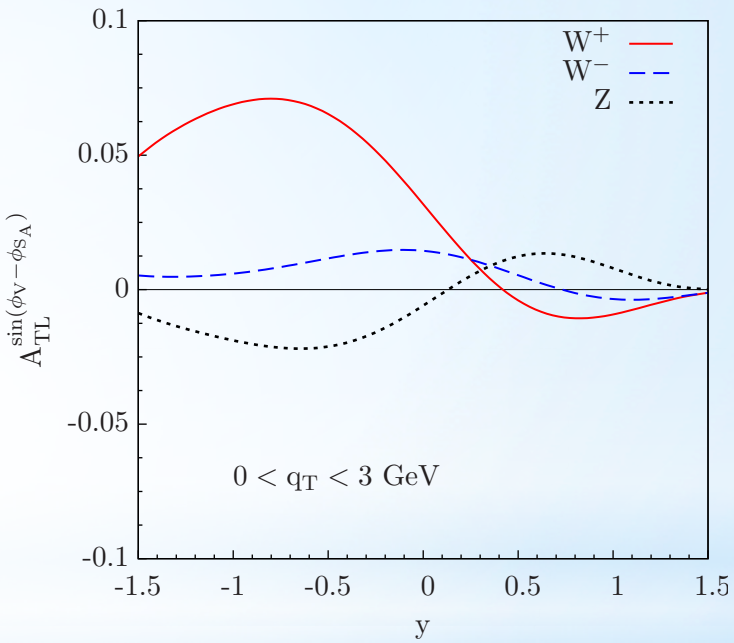


Transverse-longitudinal double spin asymmetry II

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

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





Summary

- Within TMD factorization formalism, we presented the cross sections for weak boson production in polarized pp collisions.

- To assess the feasibility of experimental measurements, we estimated the spin asymmetries at the top RHIC energy.

- 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.