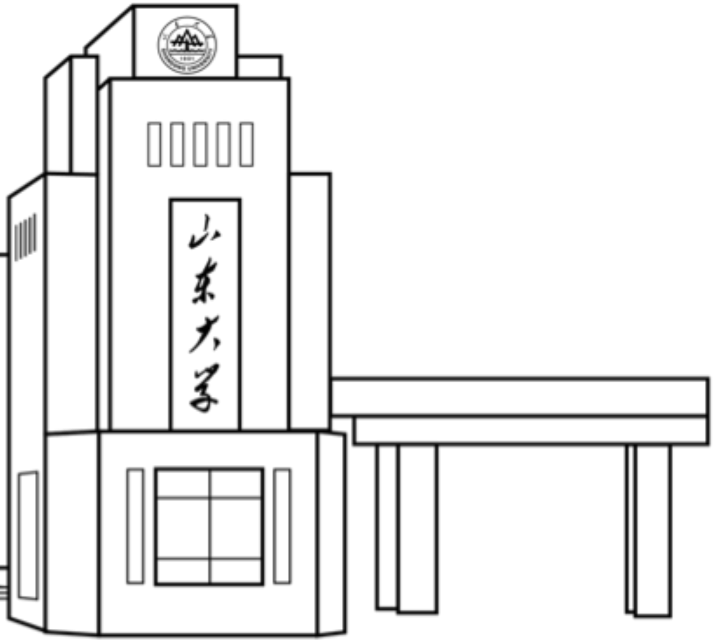
Measurement of the transverse momentum dependent (TMD) *W* boson A_L at RHIC-STAR

26th International Symposium on Spin Physics
A Century of Spin



Chao Wang (Shandong University),
For the STAR collaboration

2025.09.24

Supported in part by
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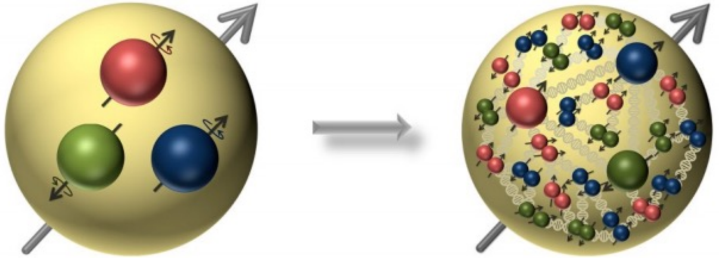
Leading twist TMD PDFs

- Proton spin structure



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$g_1(x) \longrightarrow g_1(x, k_T)$$

TMDs		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally polarized (L)	Quark polarization: Transversely polarized (T)
Nucleon polarization	U	f_1 Unpolarized		$h_1^{\perp}$ Boer–Mulders
	L		g_{1L} Helicity	$h_{1L}^{\perp}$ Longi-transversity
	T	$f_{1T}^{\perp}$ Sivers	g_{1T} Trans-helicity	h_1 Transversity; $h_{1T}^{\perp}$ Pretzelosity

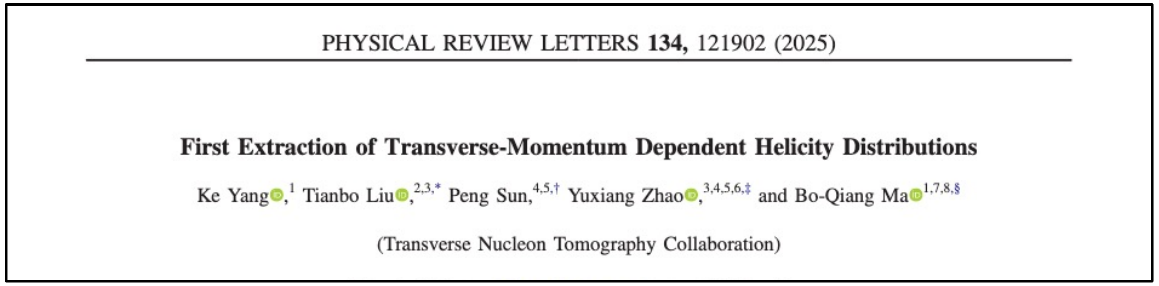
Nucleon spin — Quark spin

- The helicity distribution is defined as the difference in probabilities for a parton's helicity to be aligned or anti-aligned with the proton's helicity.

First global analysis of TMD helicity distributions

K.Yang, T.B.Liu, P.Sun, Y.X.Zhao and B.Q.Ma, PRL 134, 121902 (2025)

- With limited SIDIS data: HERMES(PRD 2019) CLAS(PLB 2018).
- Beyond x, the k_T dependence is extracted: for different x regions, the k_T dependence is different.

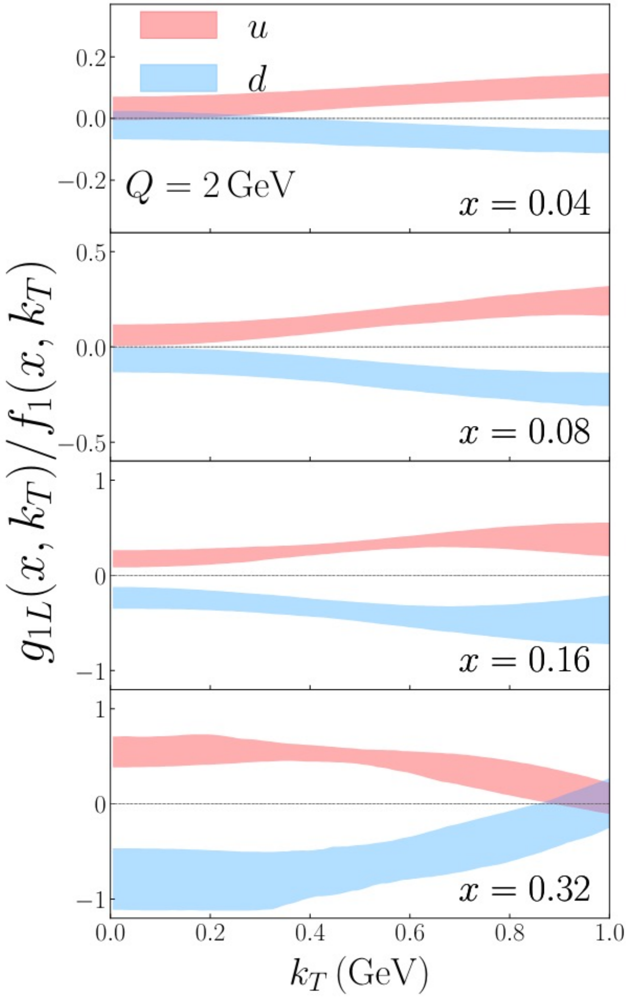


PHYSICAL REVIEW LETTERS **134,** 121902 (2025)

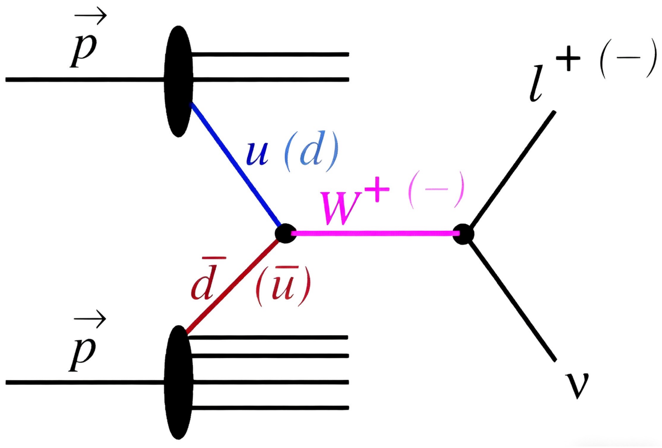
First Extraction of Transverse-Momentum Dependent Helicity Distributions

Ke Yang,[1] Tianbo Liu,[2,3,*] Peng Sun,[4,5,†] Yuxiang Zhao,[3,4,5,6,‡] and Bo-Qiang Ma[1,7,8,§]

(Transverse Nucleon Tomography Collaboration)



Probing sea quarks via *W* production



Unique way to study proton spin-flavor structure:

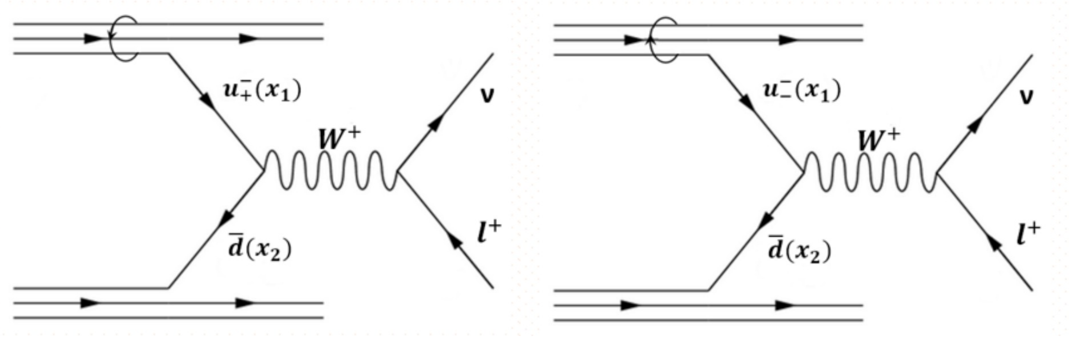
- RHIC provides polarized proton beam.
- STAR measures *W* boson via its leptonic decay.
- *W* boson selects quark/antiquarks with specific helicity.

Longitudinal single-spin asymmetry

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

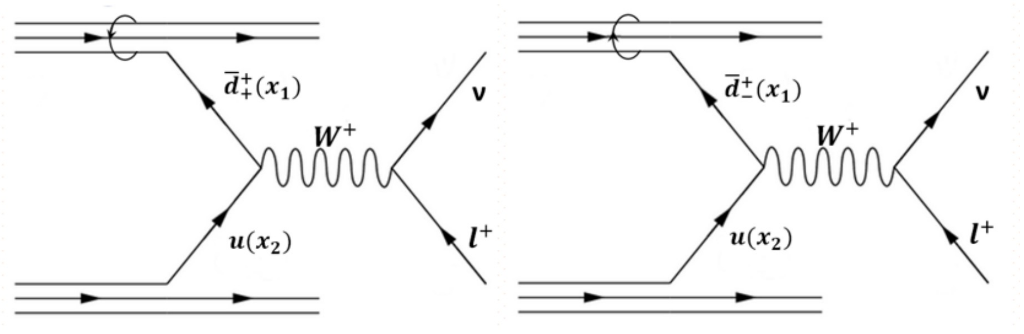
From W A_L to helicity distributions

- For W^+, if polarized proton provide u



Proton helicity = "+"　　Proton helicity = "-"

- if polarized proton provide $\bar{d}$



Proton helicity = "+"　　Proton helicity = "-"

$$A_L^{W^+} \propto \frac{u_+^-(x_1)\,\bar{d}(x_2) - u_-^-(x_1)\,\bar{d}(x_2)}{u_+^-(x_1)\,\bar{d}(x_2) + u_-^-(x_1)\,\bar{d}(x_2)} = -\frac{\Delta u(x_1)}{u(x_1)},$$

$$A_L^{W^+} \propto \frac{\bar{d}_+^+(x_1)\,u(x_2) - \bar{d}_-^+(x_1)\,u(x_2)}{\bar{d}_+^+(x_1)\,u(x_2) + \bar{d}_-^+(x_1)\,u(x_2)} = \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$$

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\,\bar{d}(x_2) + \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)} \simeq \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & x_1 \gg x_2,\ forward, \\[2ex] \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & x_1 \ll x_2,\ backward. \end{cases}$$

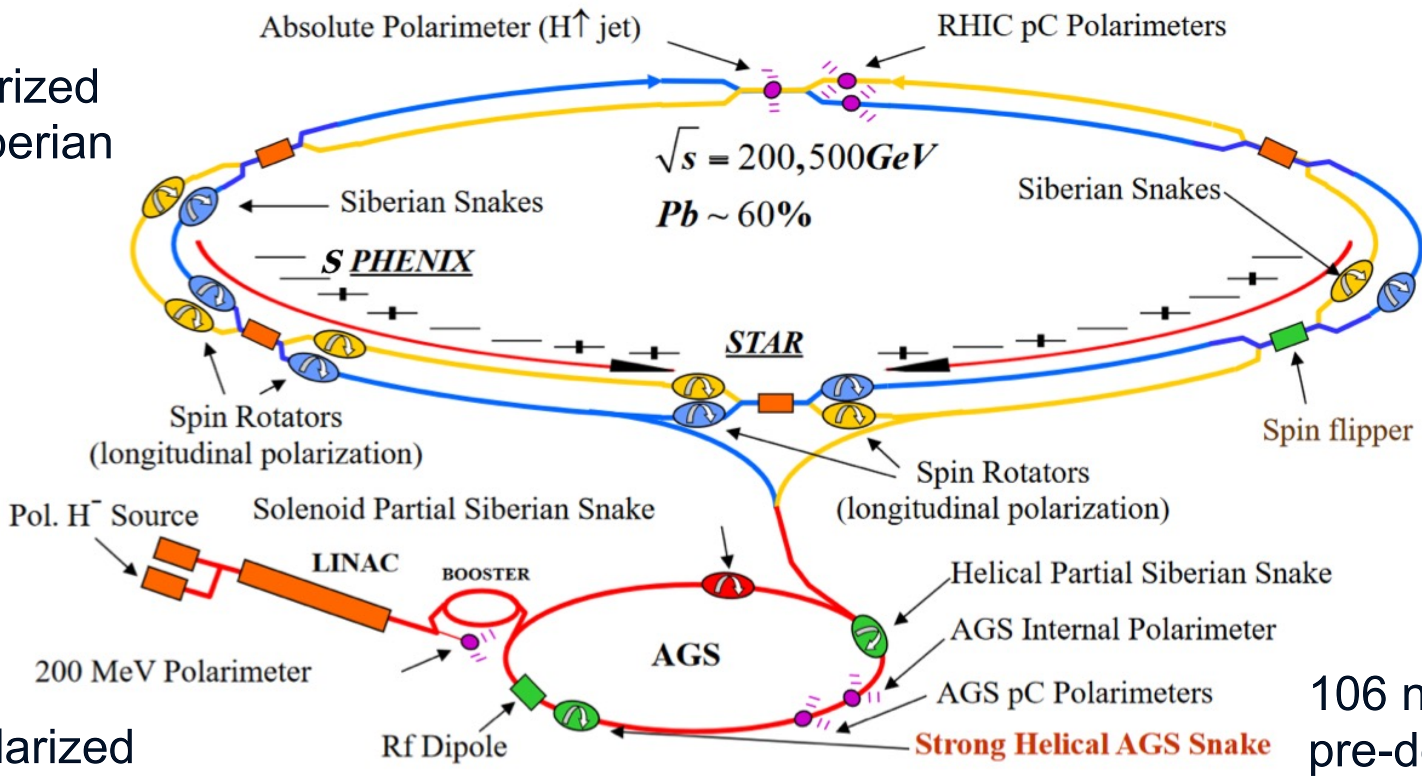
- Analogous for W^- .

Relativistic Heavy Ion Collider-RHIC

- RHIC is the first polarized proton–proton collider.

Accelerate polarized protons with Siberian Snakes

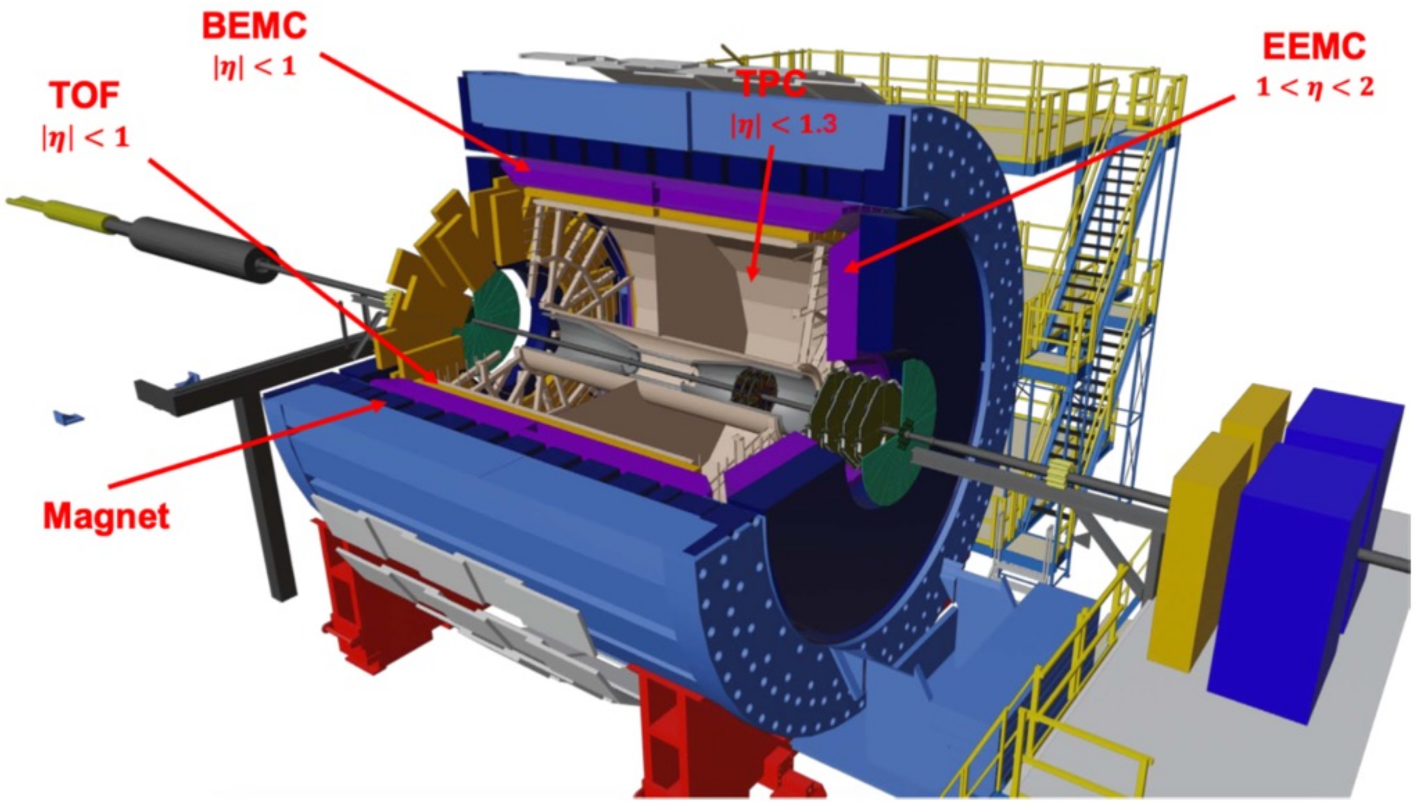
Manipulate spin directions with spin rotators



High current polarized proton source

106 ns bunch crossing with pre-determined spin directions

The Solenoidal Tracker At RHIC - STAR



Time Projection Chamber

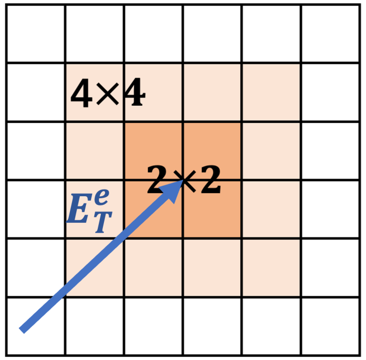
- main detector for tracking
- particle identification via dE/dx
- vertex reconstruction
- $|\eta| \lesssim 1.3$

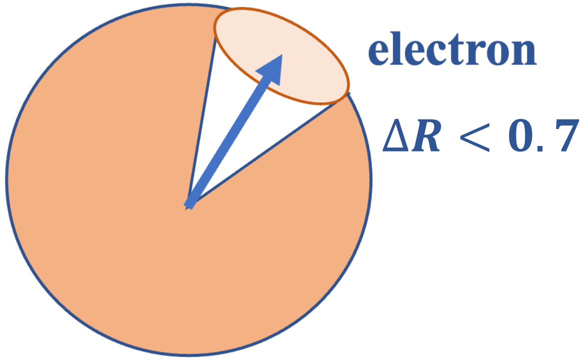
Barrel and Endcap E.M. Cal.

- neutral EM energy measurement
- triggering (towers, patches of towers)
- $|\eta|$ < 1 and 1< η < 2

W selection

Used data collected in 2013 with longitudinally polarized proton-proton collisions at $\sqrt{s} = 510$ GeV.





E_T^e: transverse energy of electron

$E_T^{4\times4}$: transverse energy deposit in 4×4 cluster

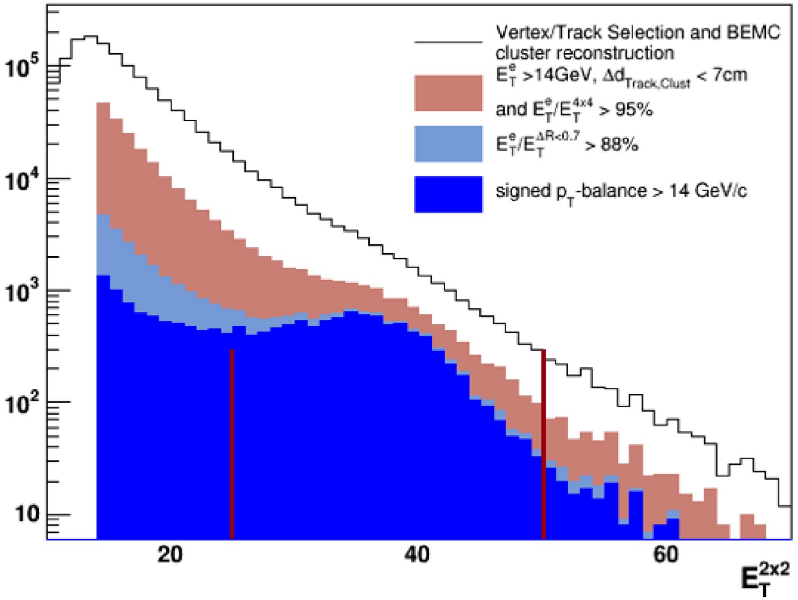
$E_T^{\Delta R<0.7}$: sum of transverse energy in nearside cone ($\Delta R < 0.7$)

$$\vec{p}_T^{\text{ balance}} = \vec{p}_T^{\ e} + \sum_{\Delta R>0.7} \vec{p}_T^{\text{ jets}}$$

$$\text{signed } p_T\text{-balance} = \frac{\vec{p}_T^{\ e} \cdot \vec{p}_T^{\text{ balance}}}{|\vec{p}_T^{\ e}|}$$

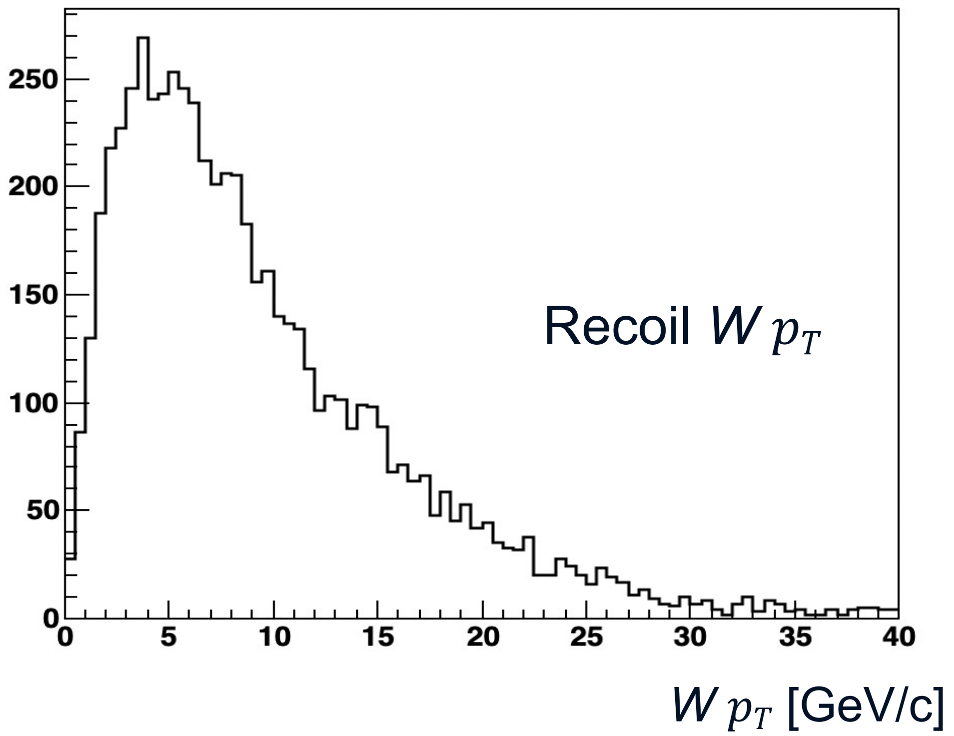
Isolated lepton and large missing p_T

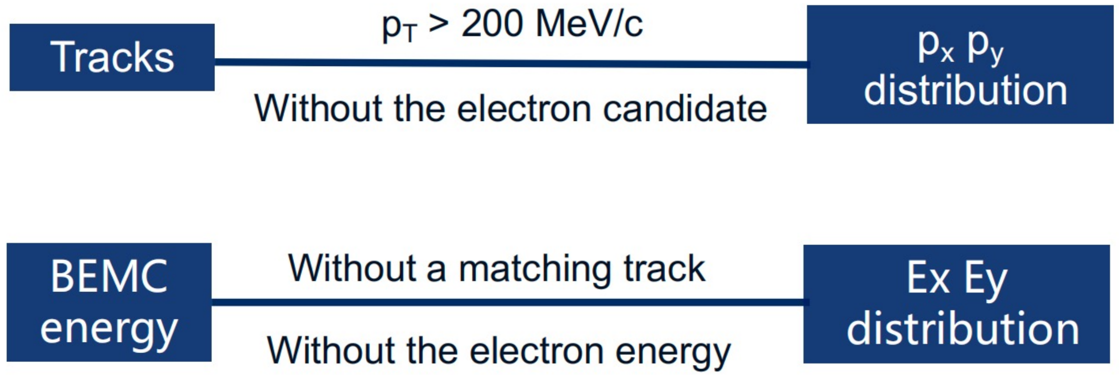
- $E_T^e / E_T^{4\times4}$ > 95%
- $E_T^e / E_T^{\Delta R<0.7}$ > 88%
- Signed p_T-balance > 14 GeV/c



Full $W\ p_T$ reconstruction

- The full reconstruction of $W\ p_T$ has been accomplished in the $W\ A_N$ analysis with the hadronic recoil. *Refer to: STAR, Phys.Rev.Lett. 116, 132301(2016)*



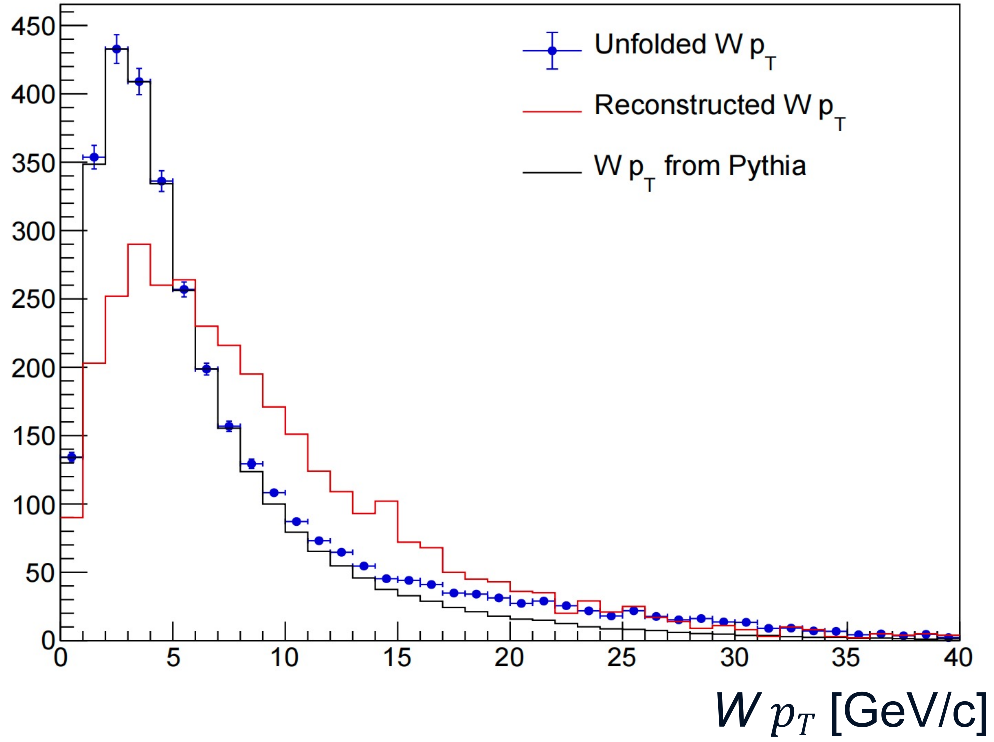


$$\vec{p}_T^{\,\mathrm{recoil}} = \sum_{\substack{i\in\mathrm{track} \\ i\neq e}} \vec{p}_{T,i} + \sum_{\substack{j\in\mathrm{cluster} \\ \mathrm{no\ track\ match}}} \vec{E}_{T,j}/c$$

The unfolding process

- The response matrix is built on the embedding $W\,p_T$ and the Pythia level.
- Embedding: Pythia + Geant + zero-bias data

- Unfold the recoil $W\,p_T$ *from data* with the response matrix to obtain the unfolded $W\,p_T$ distribution.

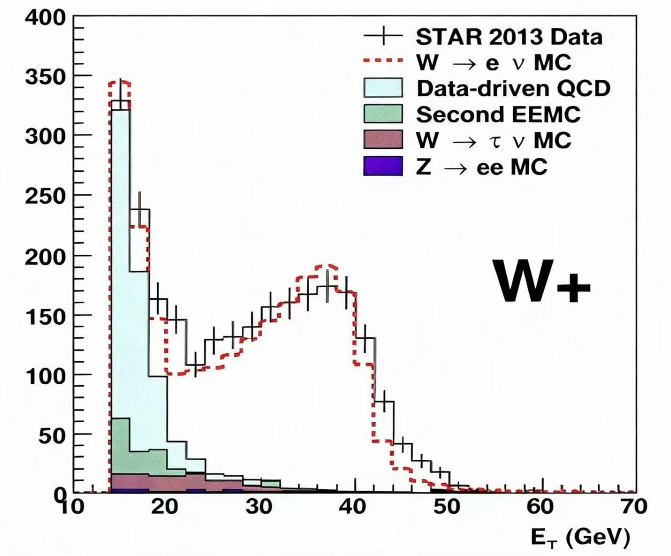


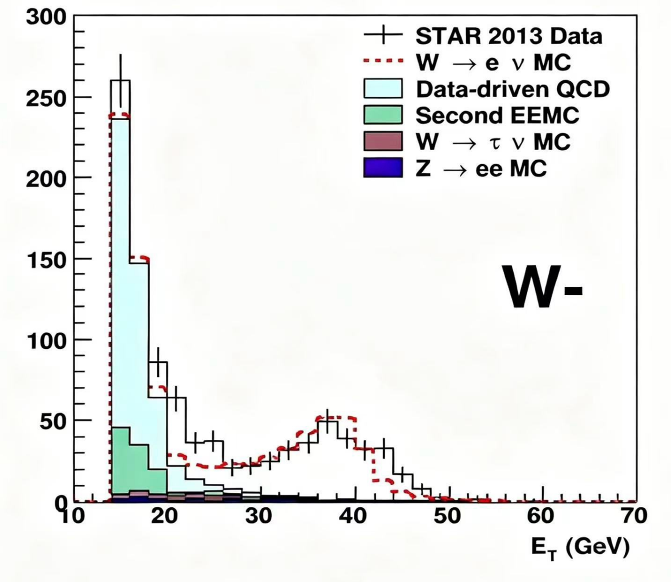
Backgrounds and signal purity

- **Electroweak backgrounds:** estimated from MC embedding.
- **"Second EEMC" background:** compare distributions with and without EEMC and take their difference as the background.
- **Data-Driven QCD background:** use events that pass the *W* selection but fail the p_T balance cut, then normalize to data in a low-E_T window.

$$\beta = 1 - f_Z - f_{\text{EEMC}} - f_{\text{QCD}}$$

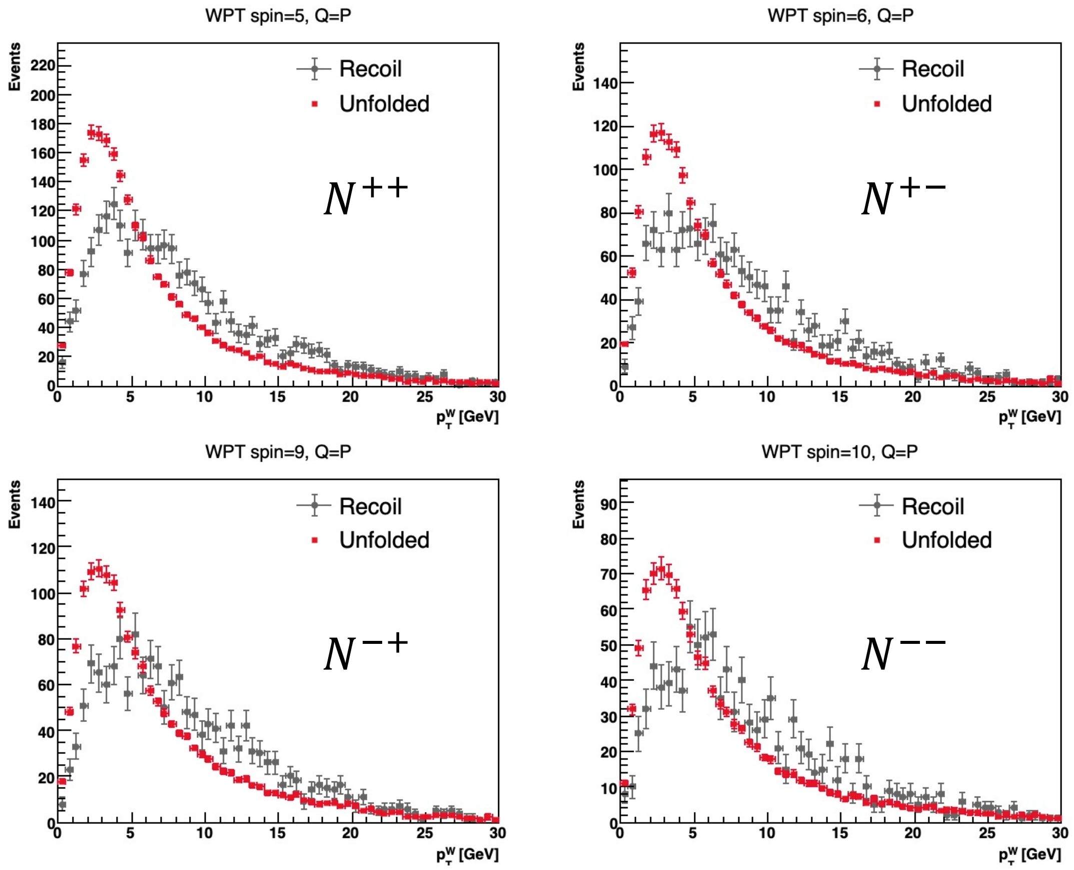
$W\ p_T \in [5,8]$

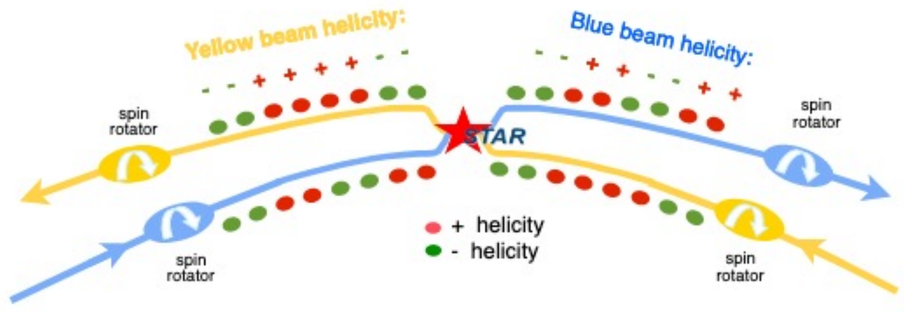




Spin asymmetry extraction from spin-sorted yield

Spin-sorted W p_T distributions:





$$A_L^{\text{Blue}} = \frac{1}{\beta P_B} \frac{M^{++} + M^{+-} - M^{-+} - M^{--}}{\sum_i M^i},$$

$$A_L^{\text{Yellow}} = \frac{1}{\beta P_Y} \frac{M^{++} - M^{+-} + M^{-+} - M^{--}}{\sum_i M^i}$$

$$R^i = \frac{\langle L \rangle}{L^i}, \qquad M^i = R^i N^i \quad (i = ++, +-, -+, --)$$

N^i: raw yield, R^i: relative luminosity

$$\beta = 1 - f_Z - f_{\text{EEMC}} - f_{\text{QCD}}$$

Systematic uncertainties

Refer to: STAR, Phys.Rev.D 99, 051102 (2019)

BEMC calibration uncertainties

Uncertainty due to p_T dependence of background function

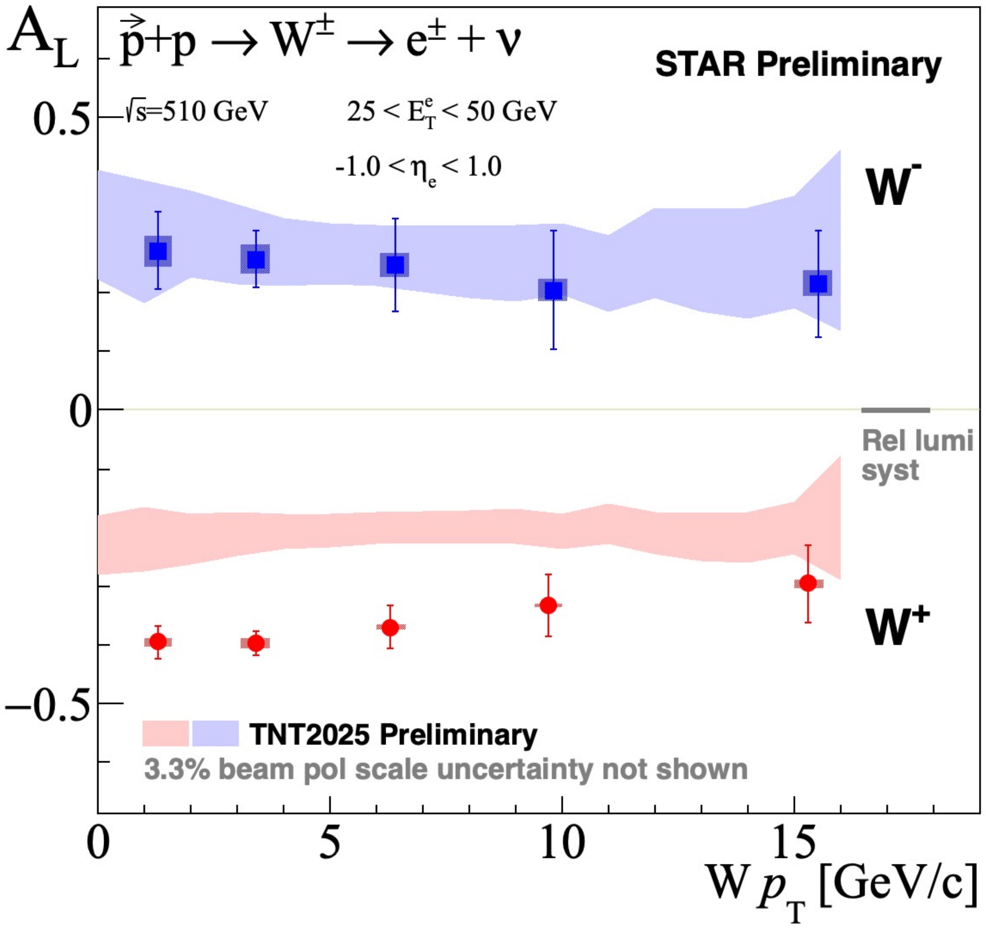
Relative luminosity uncertainty:

- Estimated from a high-p_T [25,50] GeV, QCD sample

Beam polarization uncertainty:

- Correlated scale 3.3%

Results: TMD W A_L



- The p_T averaged A_L value is consistent with the published $A_L(\eta)$ in 2019;
- As $W^{\pm}$ p_T increases, magnitude of A_L for $W^{\pm}$ decreases slightly;
- Theory curves taken from TNT group;

  K.Yang, T.B.Liu, P.Sun, Y.X.Zhao and B.Q.Ma, PRL 134, 121902 (2025)
- Significant difference between data and TNT2025 predictions, especially for W^{+}.

Summary

- ✓ First measurement of TMD $W^{\pm}$ A_L in *pp* collisions at $\sqrt{s} = 510$ GeV, expected to provide unique constraints for TMD helicity distributions.
- ✓ A_L has been extracted as the function of $W^{\pm}$ p_T.
  - As $W^{\pm}$ p_T increases, magnitude of A_L for $W^{\pm}$ decreases slightly.
  - Significant difference between data and TNT2025 predictions, especially for W^{+}.

Thank you for your attention !

Backup

A_L vs. electron eta