Transverse Single-Spin Asymmetries of $W^{\pm}$-Bosons in p+p Collisions at $\sqrt{s} = 510$ GeV

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for the STAR Collaboration

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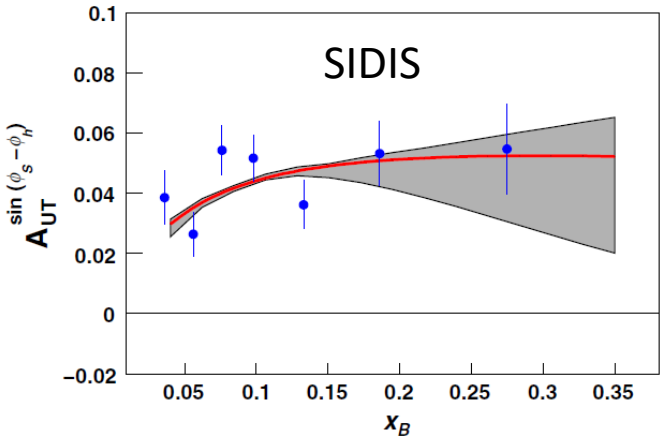
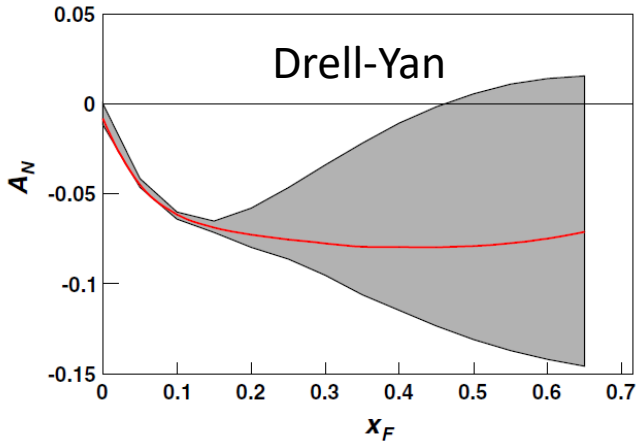
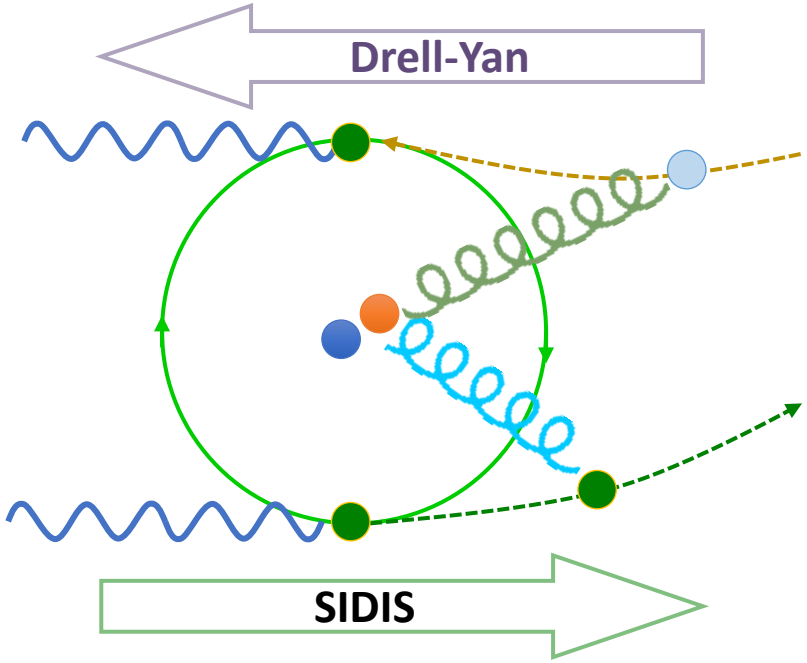
Supported by

QCD, Universality, and the Proton Structure

- Transverse spin asymmetries are an ideal tool to study the multidimensional structure of the nucleon.
  - Spin-orbit correlations
    Sivers effect: correlation between proton spin and transverse momentum of partons
  - Non-universality exhibits the process dependence
    Attractive color force in SIDIS turns into repulsive force in p+p







Gamberg, Kang, Prokudin
Phys. Rev. Lett. 110, 232301 (2013)
with HERMES data

Prospects for RHIC Run 2017

- Increased theoretical interest
- Significant uncertainty in sea-quark Sivers-TMD function
- Very different Q^2 range in SIDIS, Drell-Yan, and W-boson production
- TMD evolution not the same as DGLAP

from the STAR beam use request

www.bnl.gov/npp/pac.php

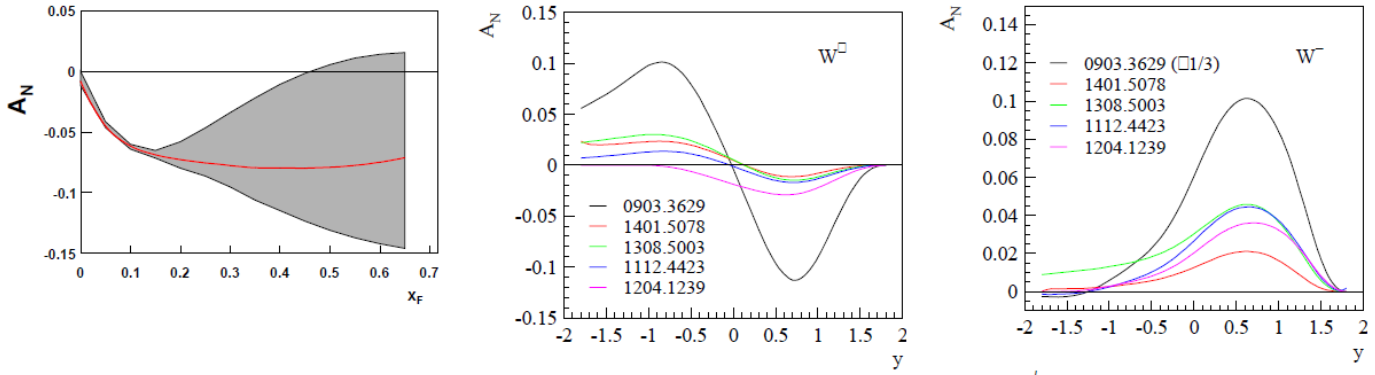
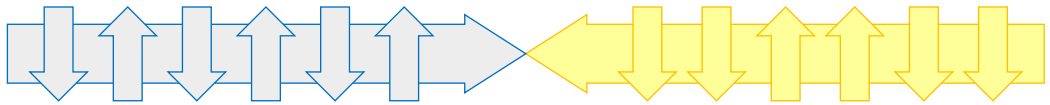


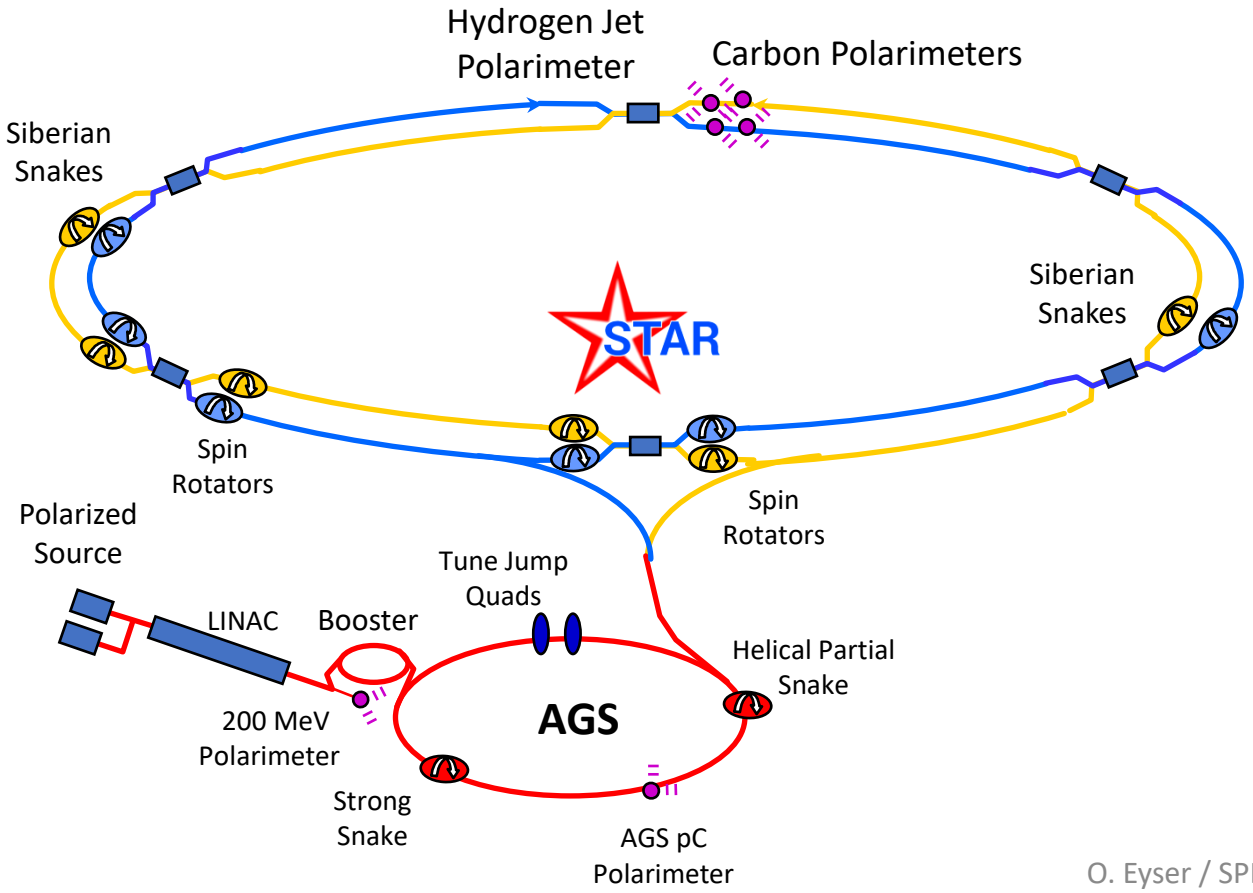
Figure 4–1: (left) Prediction for Sivers asymmetry A_N for DY lepton pair production at $\sqrt{s}$=500 GeV, for the invariant mass $4<Q<8$ GeV and transverse momenta $0 < q_T < 1$ GeV [19] **before any TMD evolution is applied**. (middle and right) A_N as a function of $W^{\pm}$ boson rapidity at $\sqrt{s}$=500 GeV, **both are before and after TMD evolution is applied.**

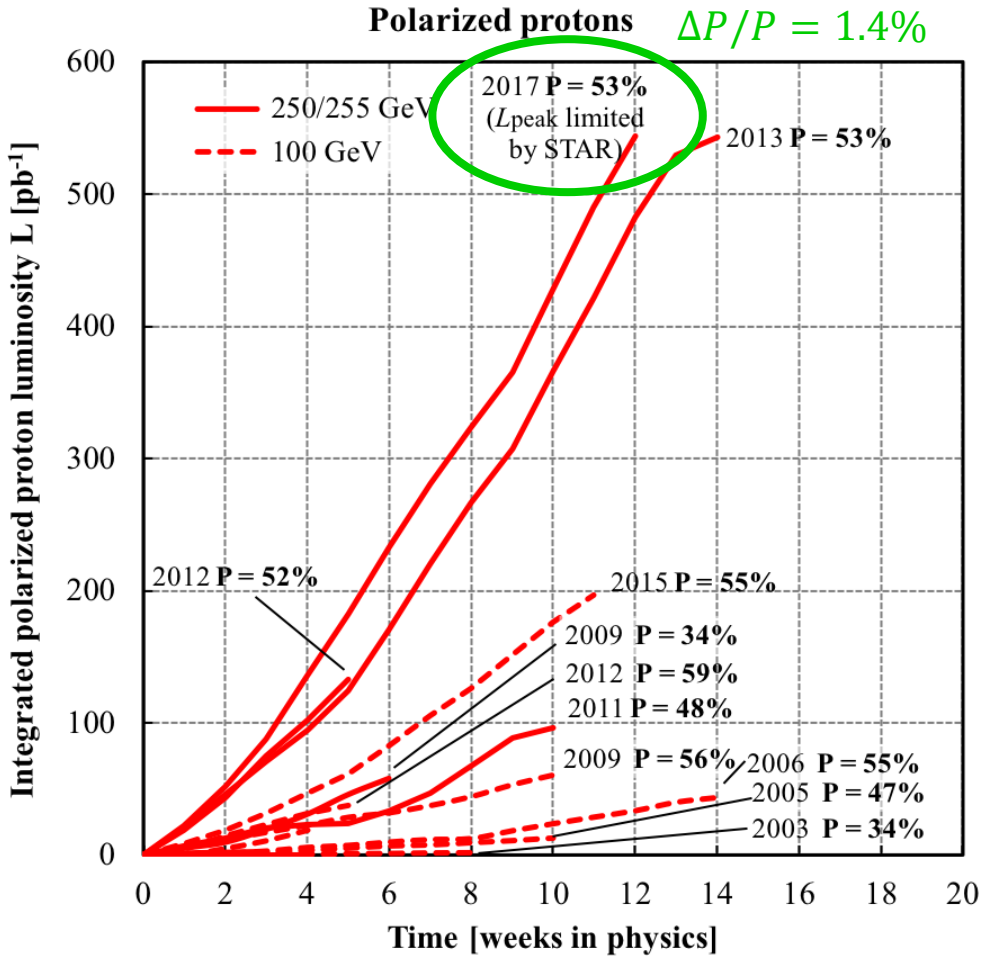
- Transverse asymmetries need the full reconstruction of the W-boson kinematics
  - Predicted asymmetries as function of rapidity and transverse momentum
  - Measurement of azimuthal modulation
  - Proof of principle measurement: PRL 116 (2016) 132301

RHIC as a Polarized Proton Collider

$\vec{p} + \vec{p}$ / $\vec{p} + A$ $\quad \sqrt{s_{NN}} = 200 - 510$ GeV







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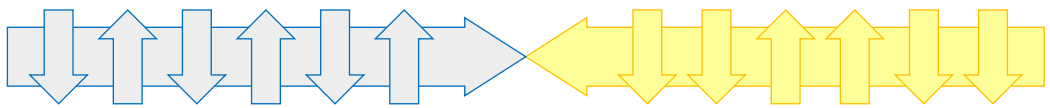
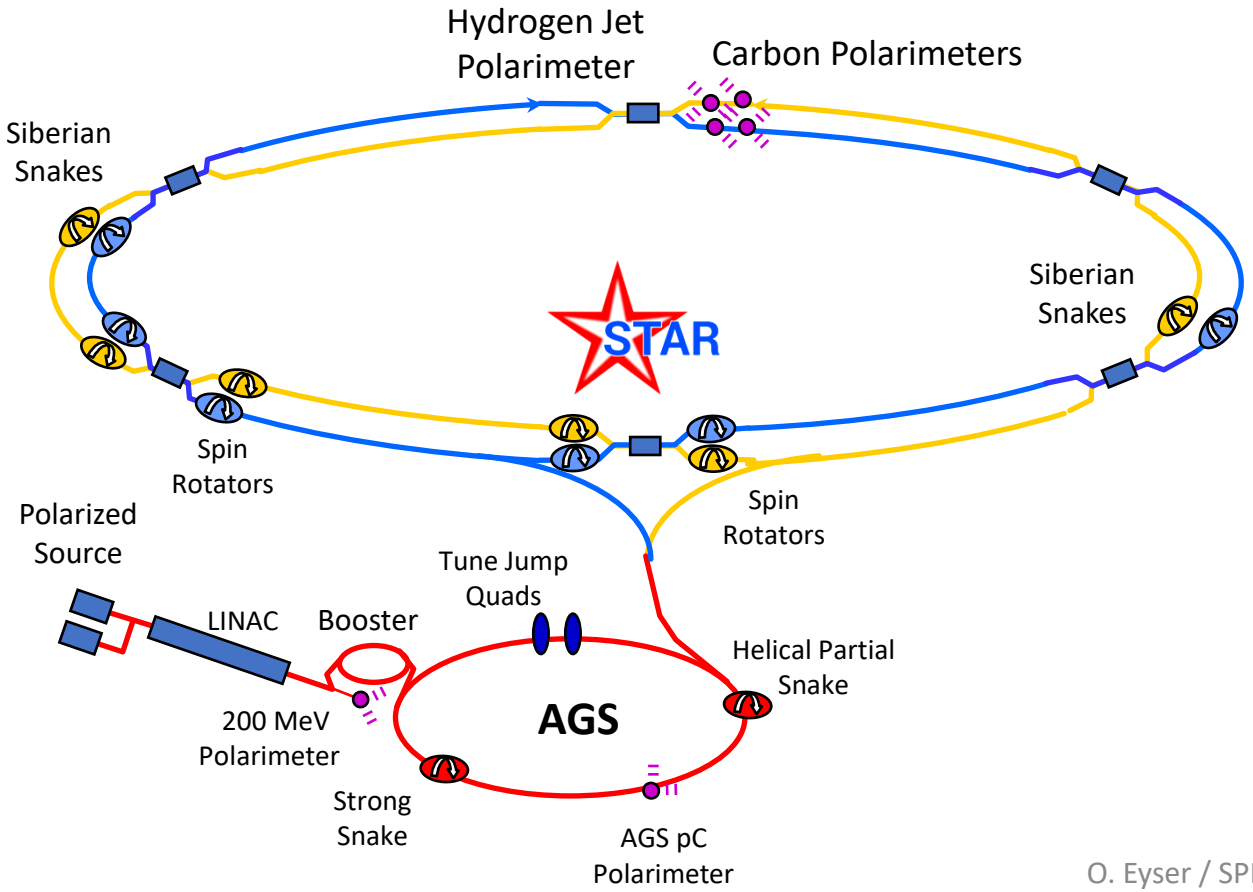
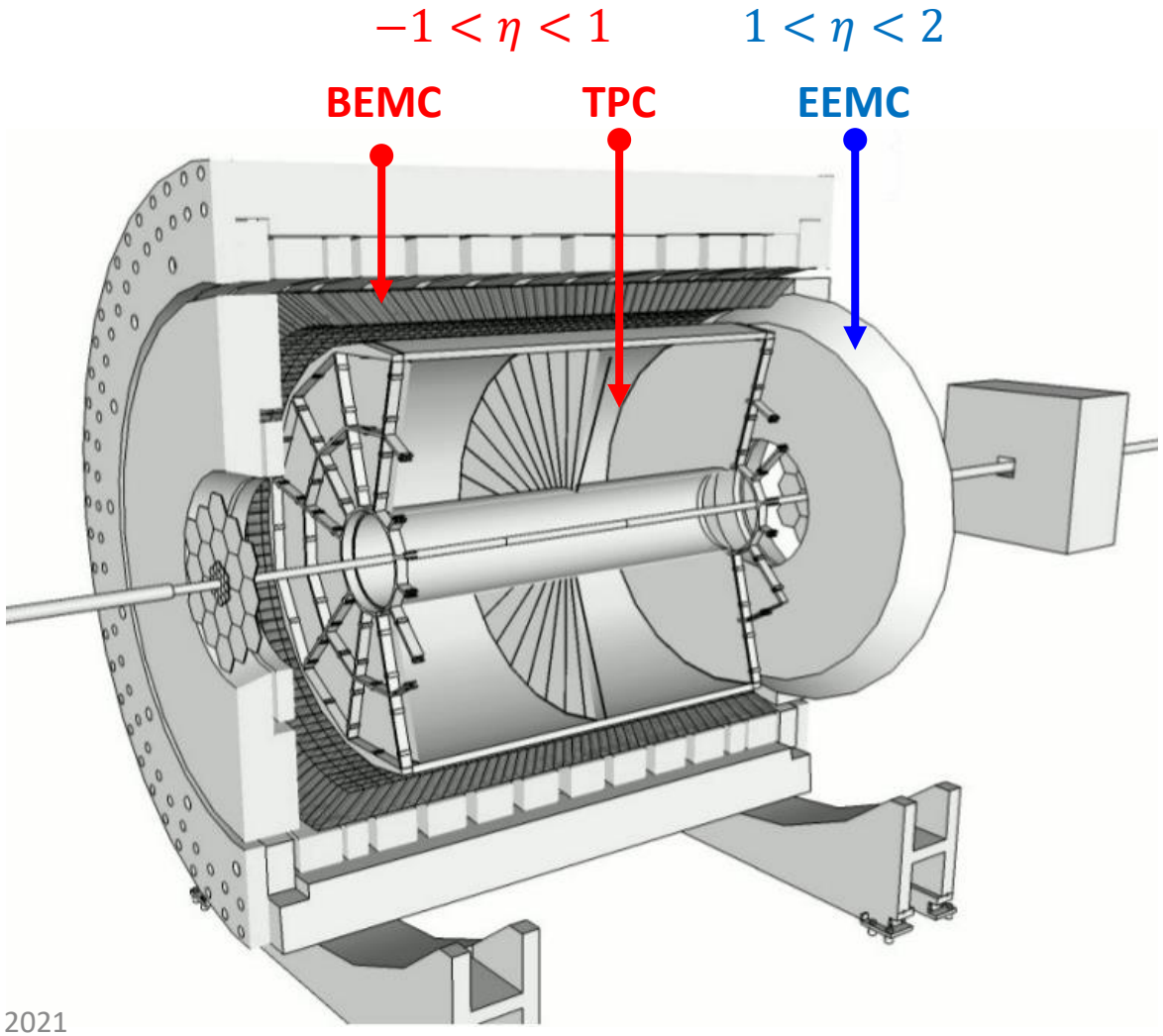
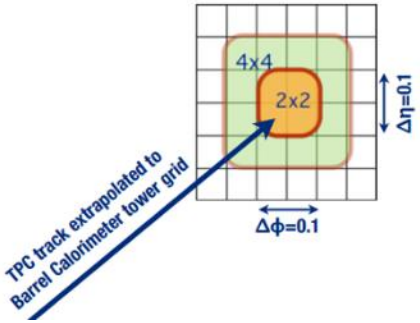


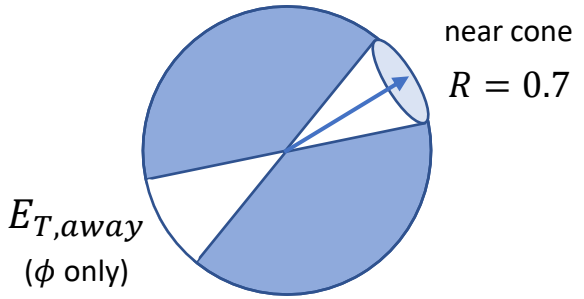




Lepton Candidate Selection

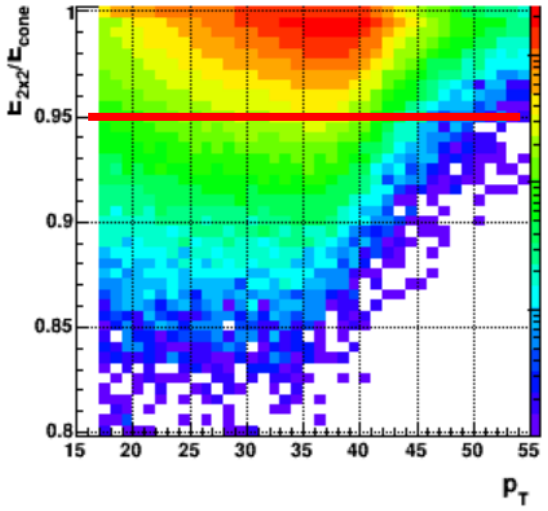
- 2017 data
  - Luminosity leveled (ZDC rate 330 kHz)
  - Barrel EMC high tower trigger
  - StiCA track reconstruction
- Electron candidate track with matched EMC hit:
  - TPC hits (≥15) and fit fraction (>51%)
  - EMC $E_{2\times2}/E_{4\times4} > 0.96$
  - $E_{2\times2}/E_{R=0.7} > 0.88$
  - $E_{T,away} < 10$ GeV
  - $p_{T,bal} > 0.8\, p_T$

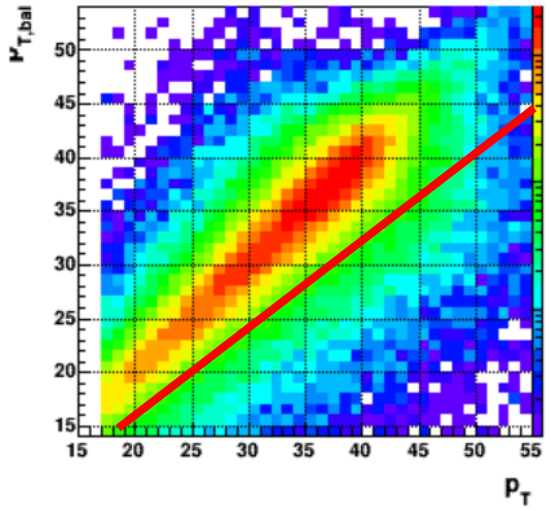


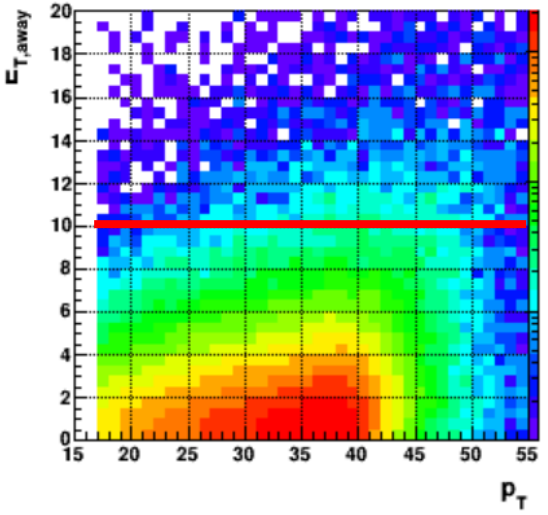


$$p_{T,bal} = \sum \vec{p}_{T,tracks} \cdot \vec{p}_{T,e} / |\vec{p}_{T,e}|$$

Embedded simulation:
- PYTHIA 6.4
- Tune: Perugia 12
- Zerobias data



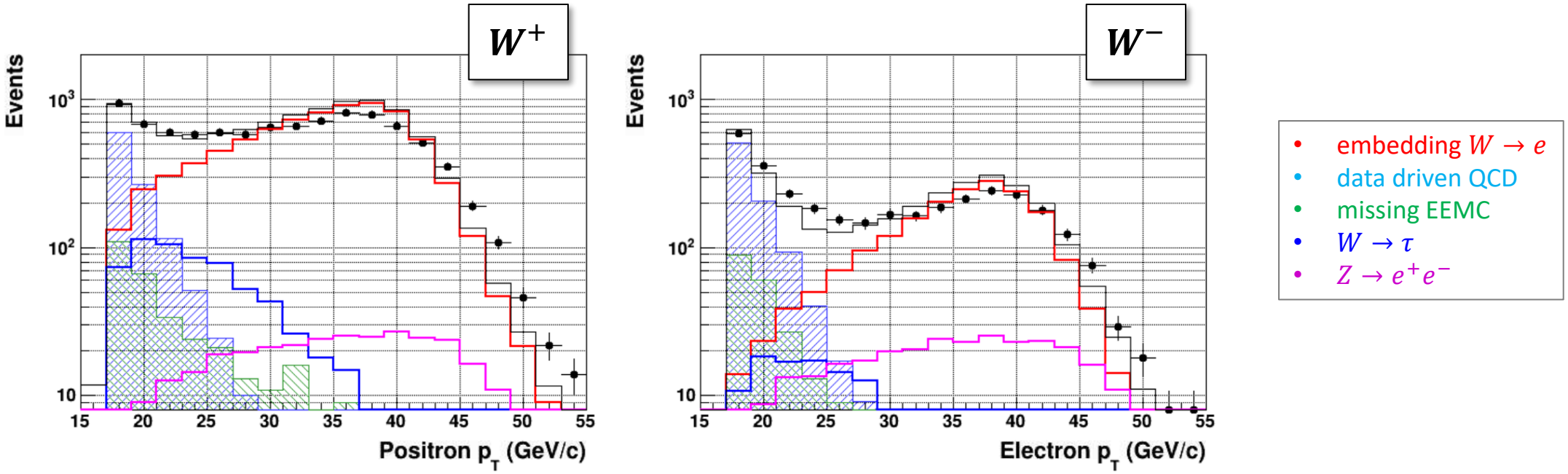




Lepton Candidate

- Well established method (helicity asymmetry and cross section ratio measurements)
  - Includes Z^0 and τ decays
  - Data driven QCD background normalized at low p_T-range
  - Missing EEMC estimated from cuts with / without EEMC
- Jacobian peak: Lepton candidate $p_T > 25$ GeV

Recent STAR W-boson results:
Phys. Rev. D 103 (2021) 012001
Phys. Rev. D 99 (2019) 051102



- embedding $W \rightarrow e$
- data driven QCD
- missing EEMC
- $W \rightarrow \tau$
- $Z \rightarrow e^+e^-$

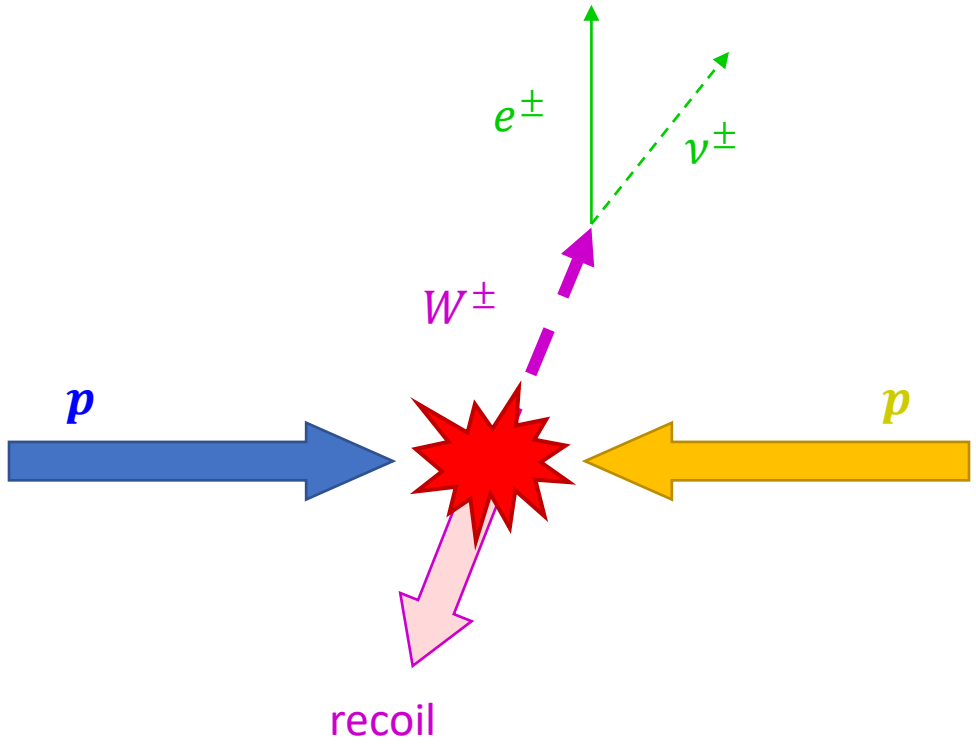
W-Boson Reconstruction

$$\boldsymbol{p} + \boldsymbol{p} \rightarrow \boldsymbol{W^{\pm}} \rightarrow \boldsymbol{e^{\pm}} + \boldsymbol{\nu}$$

- W-boson decay
  - $p_{T,W}$ is lost
  - Almost no azimuthal angle correlation
- Measure recoil from the collision (tracks and EMC)

$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$

$$p_{T,recoil} = \sum(p_{T,TPC} + E_{T,EMC})$$



W-Boson Reconstruction

$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

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- Limited barrel acceptance
  - Comparison with simulation
  - Recoil p_T correction
  - $p_{z,\nu}$ is more problematic

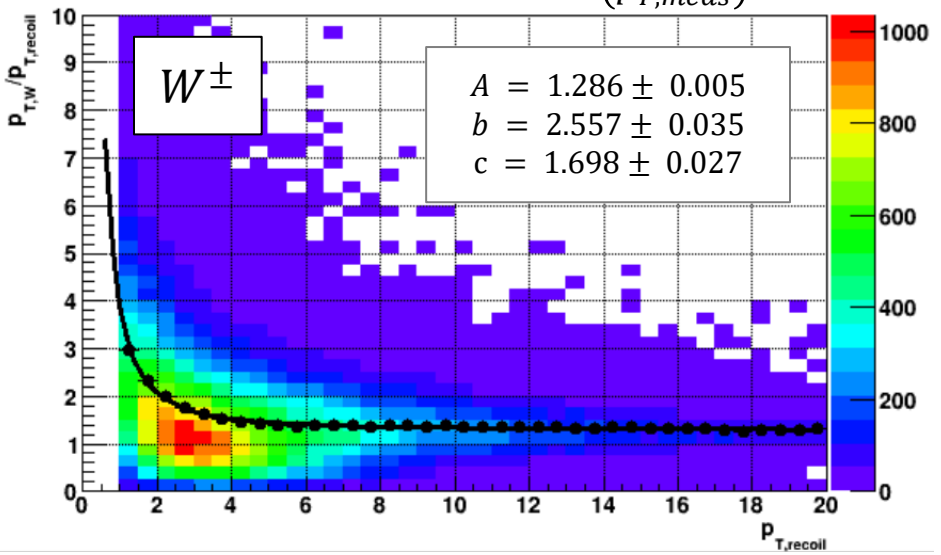
$$M_W^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2$$

$$p_{\nu,z} = \frac{A}{p_{e,T}^2}\left[p_{e,z} \pm p_e \cdot \sqrt{1 - \frac{p_{e,T}^2 \cdot p_{\nu,T}^2}{A^2}}\right]$$

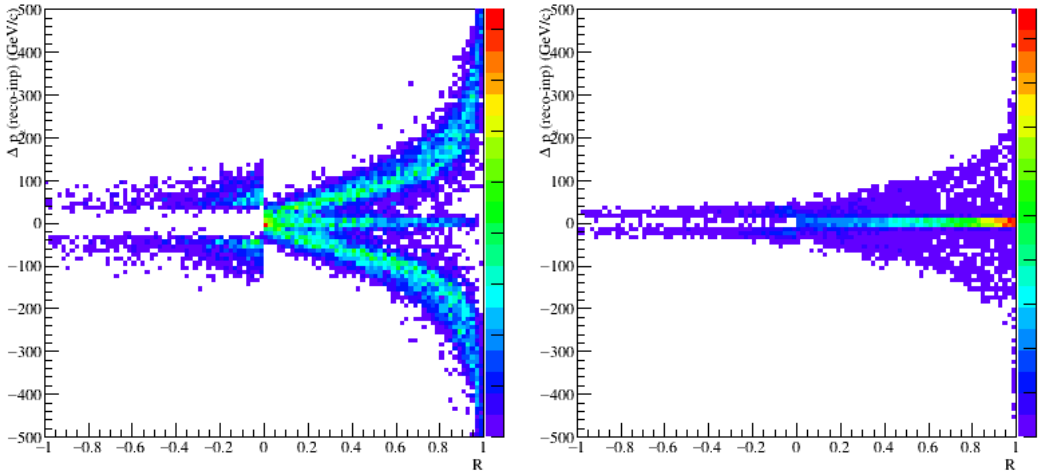
$$A = M_W^2 + \vec{p}_{e,T} \cdot \vec{p}_{\nu,T}$$

$$R = 1 - \frac{p_{e,T}^2 \cdot p_{\nu,T}^2}{A^2}$$

$$p_{T,W} = f(p_{T,meas}) = A + \frac{b}{(p_{T,meas})^c}$$



W^-



Azimuthal Angle Smearing

- Transverse spin asymmetries are measured through azimuthal modulations:

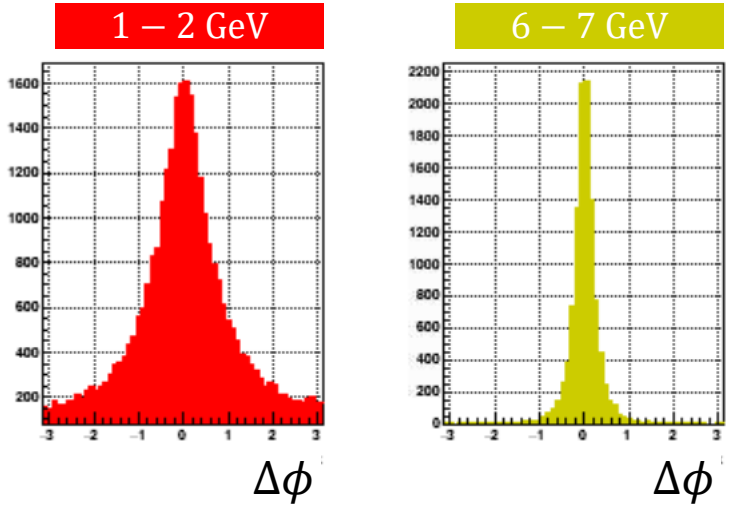
$$d\sigma(\phi) = \sigma_0[1 + P A_N \cos(\phi)]$$

$$A_N = \frac{d\sigma(\phi) - d\sigma(\phi+\pi)}{d\sigma(\phi) + d\sigma(\phi+\pi)} \qquad A_N = \frac{1}{P}\frac{N_\phi - N_{\phi+\pi}}{N_\phi + N_{\phi+\pi}}$$

- Toy Monte Carlo study → determine asymmetry dilution
  - 100k MC samples based on input distribution from embedding (per η-bin)

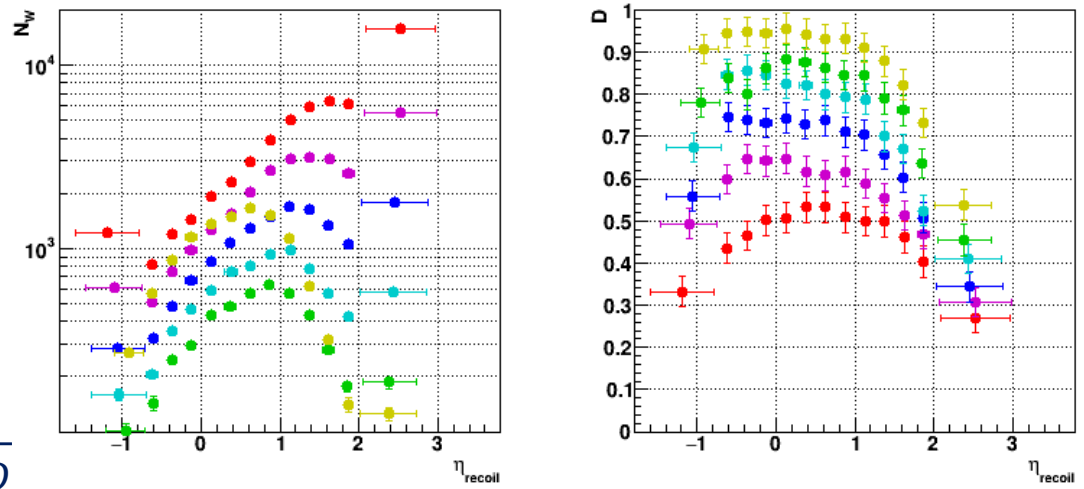
$$D = A_{N,meas}/A_{N,input}$$

$p_{T,recoil}$



$$\Delta\phi = \phi_W - \phi_{recoil}$$

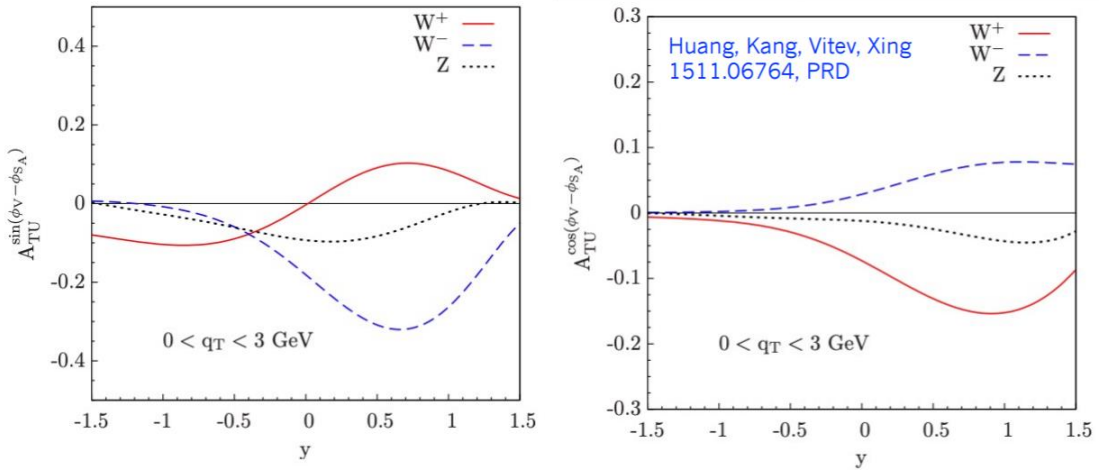
$$\sigma_{A_N} \propto \frac{1}{\sqrt{N}D}$$



Asymmetry correction: $A_N = A_{N,meas}/D$

Transversal Helicity Function g_{1T}

- Transversal helicity can also be measured in W-production
- χ^2 of fit is improved
- Uncertainties in A_S are similar to A_N
- Measured A_S consistent with 0
- Cross talk in A_N is very small
  - W^-: $\Delta A_N/\sigma_{A_N} < 20\%$
  - Included in $\sigma_{syst}(A_N)$



$$\phi_V - \phi_{S_A} = \phi - \pi/2$$

$$\boldsymbol{A_N}: \sin(\phi_V - \phi_{S_A}) = -\cos\phi$$

$$\boldsymbol{A_S}: \cos(\phi_V - \phi_{S_A}) = \sin\phi$$

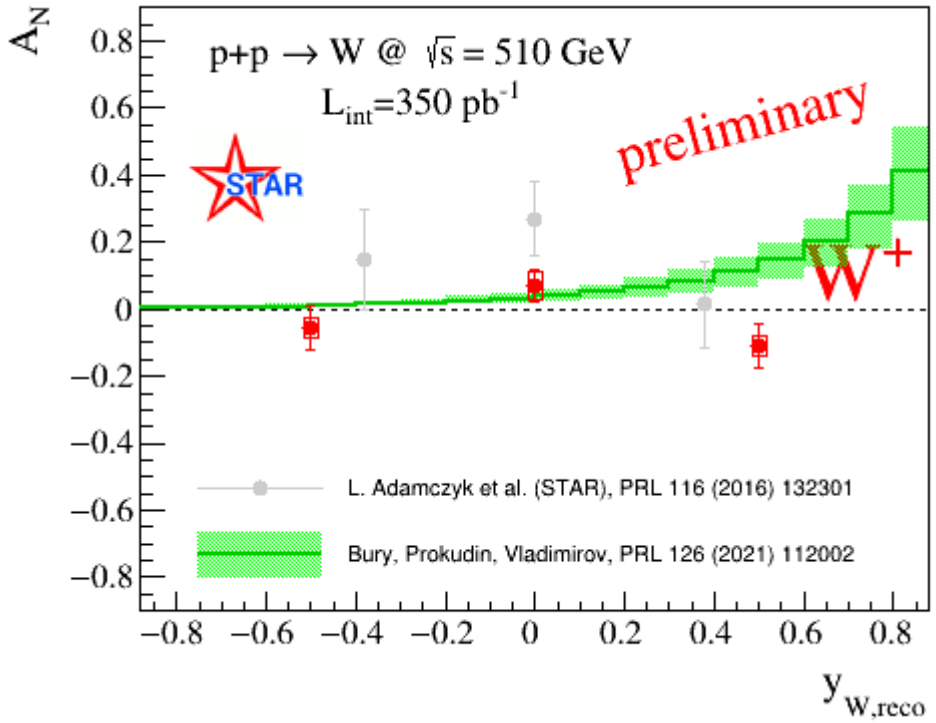
$$\begin{aligned}
\frac{d\sigma^W}{dyd^2\vec{q}_T} =& \sigma_0^W \Big\{ F_{UU} + S_{AL}F_{LU} + S_{BL}F_{UL} + S_{AL}S_{BL}F_{LL} \\
&+ |\vec{S}_{AT}| \left[\sin(\phi_V - \phi_{S_A})F_{TU}^{\sin(\phi_V-\phi_{S_A})} + \cos(\phi_V - \phi_{S_A})F_{TU}^{\cos(\phi_V-\phi_{S_A})}\right] \\
&+ |\vec{S}_{BT}|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

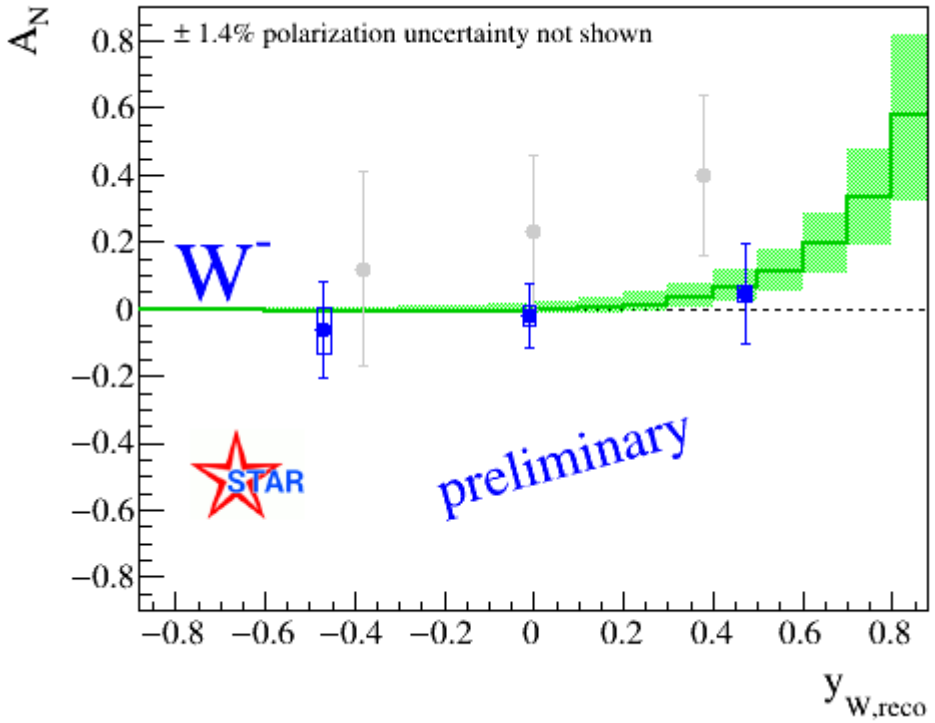
$$F_{TU}^{\sin(\phi_V-\phi_{S_A})} = \mathcal{C}^W \left[(v_q^2 + a_q^2)\frac{\hat{q}_T \cdot \vec{k}_{aT}}{M_A} f_{1T}^{\perp} \bar{f}_1\right],$$

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

Z. Kang, CFNS Workshop on RHIC physics for EIC, May 2021

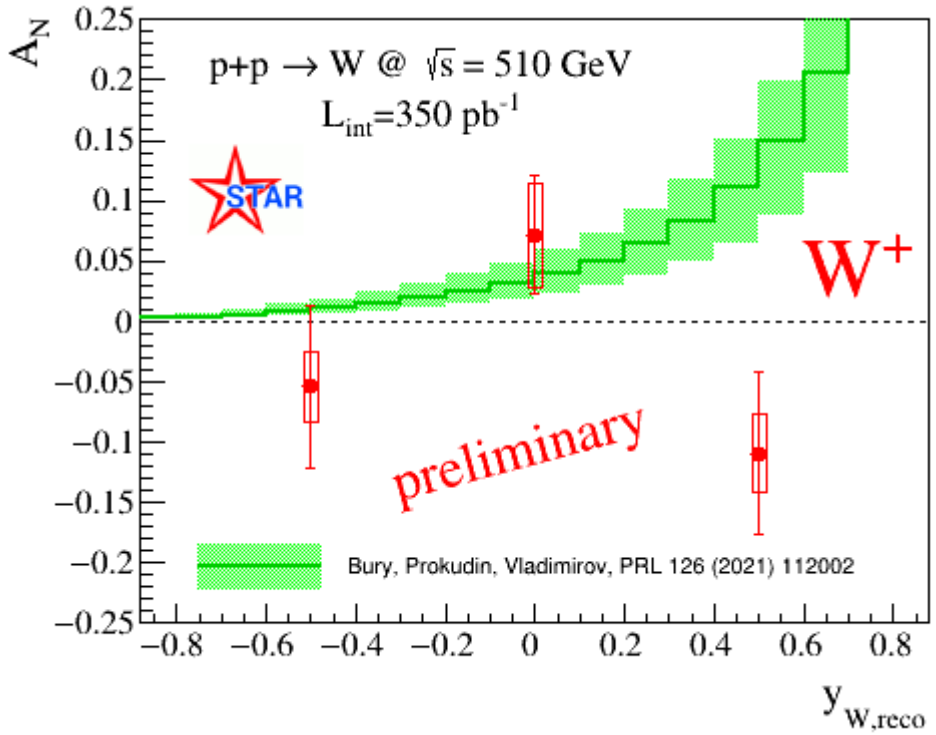
Results: $A_N(W^{\pm})$

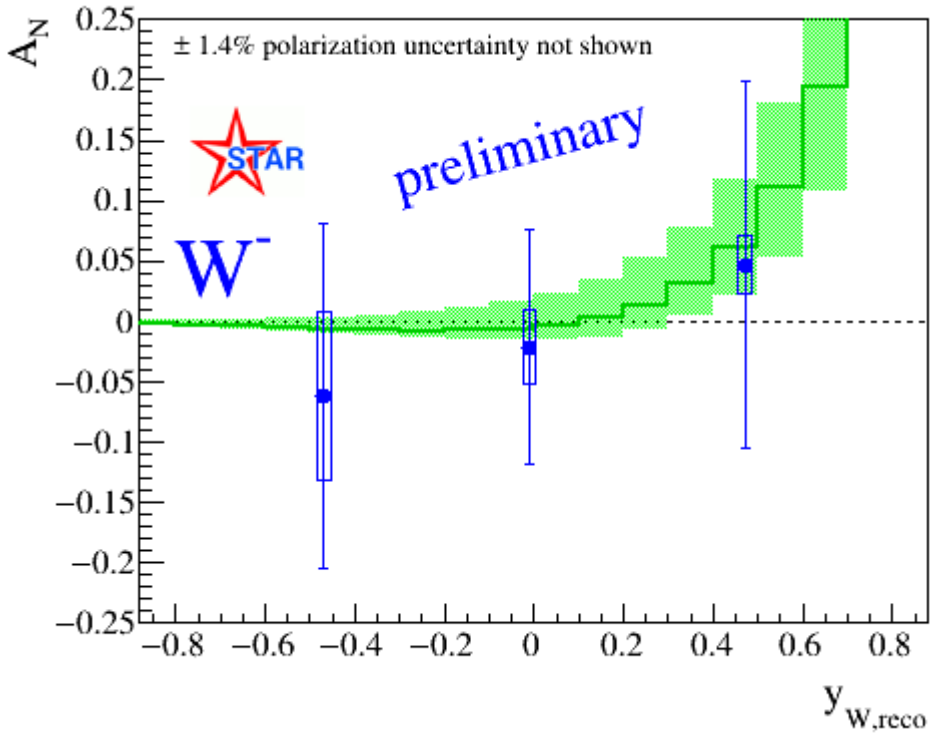




- Comparison with new theory prediction (N^{3}LO), PRL 126 (2021) 112002
  - Updated for STAR kinematics
  - Based on first global fit to world data, PRD 102 (2020) 054002

Results: $A_N(W^{\pm})$

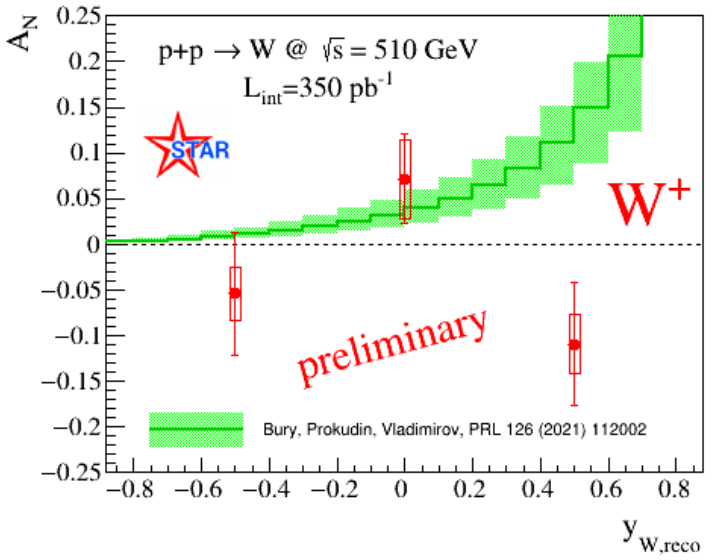


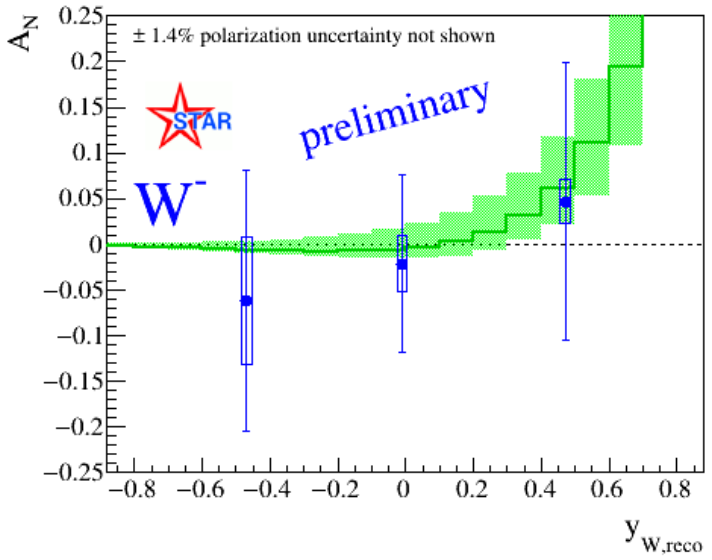


- Comparison with new theory prediction (N^{3}LO), PRL 126 (2021) 112002
  - New STAR data will have biggest impact on high-x region of quark Sivers function

Summary

- New results of transverse single-spin asymmetries of $W^{\pm}$-bosons
  - Much improved precision over PRL 116 (2016) 132301
  - Corrected for smeared reconstruction of the recoil
  - Expect big impact in Sivers function at high-x in next global TMD fit

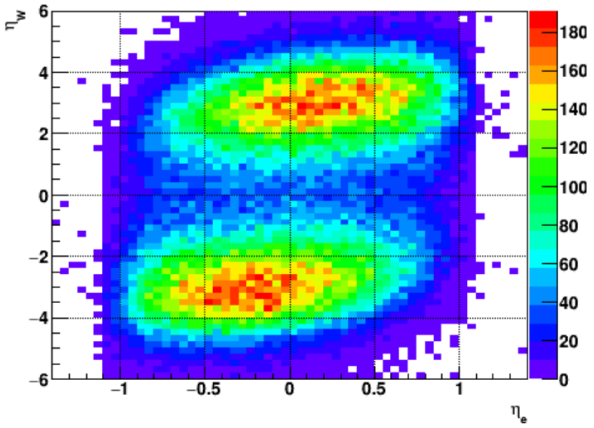


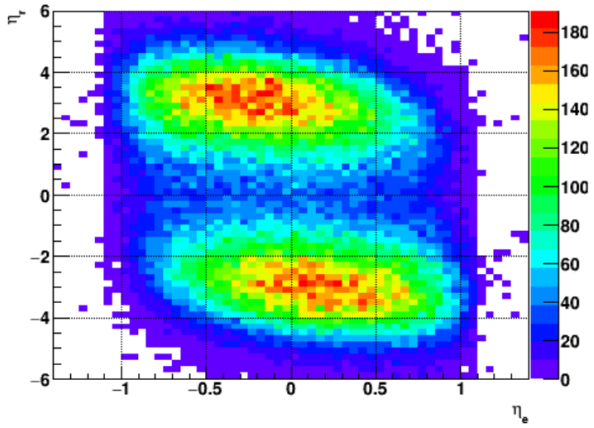


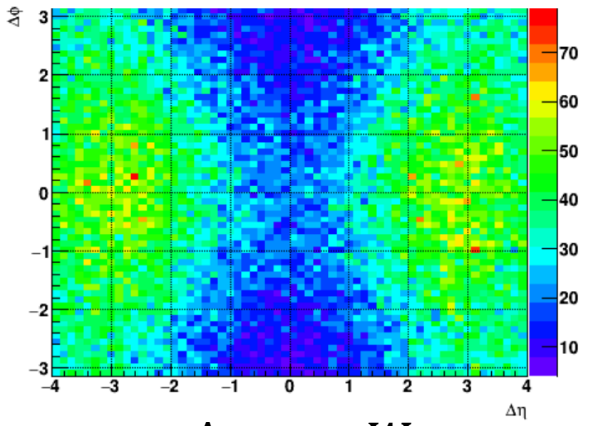
$$-\vec{p}_{rec} = \vec{p}_W = \vec{p}_e + \vec{p}_\nu$$

W^+

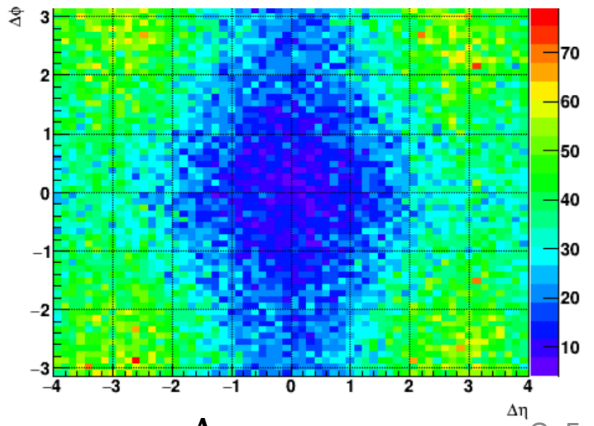
W-boson **MC true** **recoil**







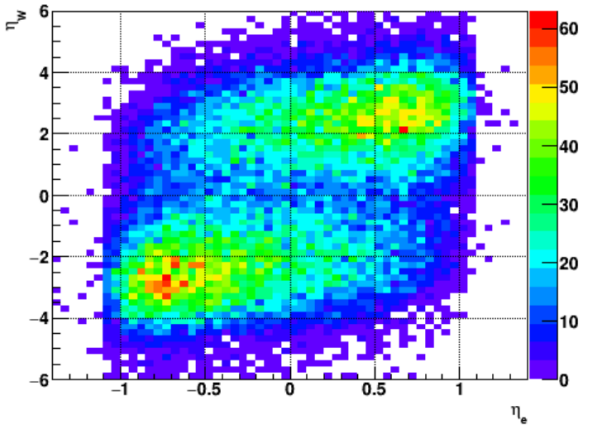
$\Delta = e - W$

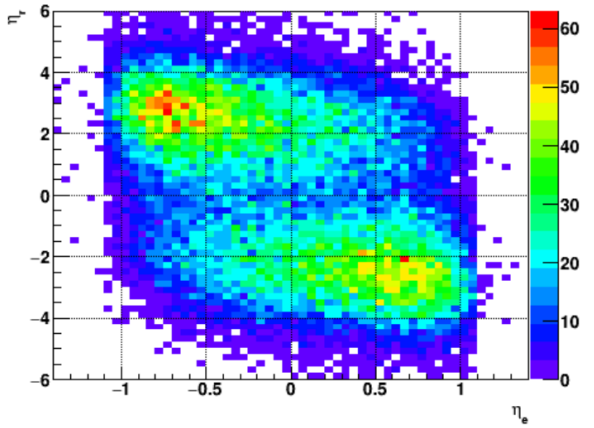


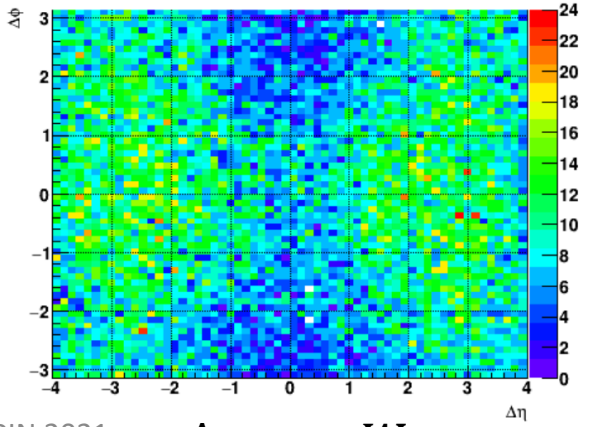
$\Delta = e - rec$

W^-

W-boson **MC true** **recoil**







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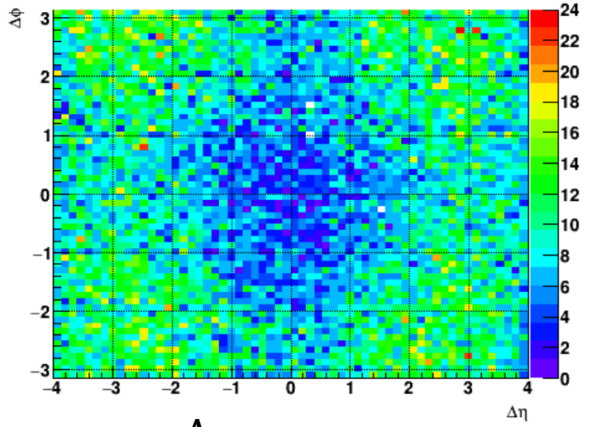


$\Delta = e - rec$

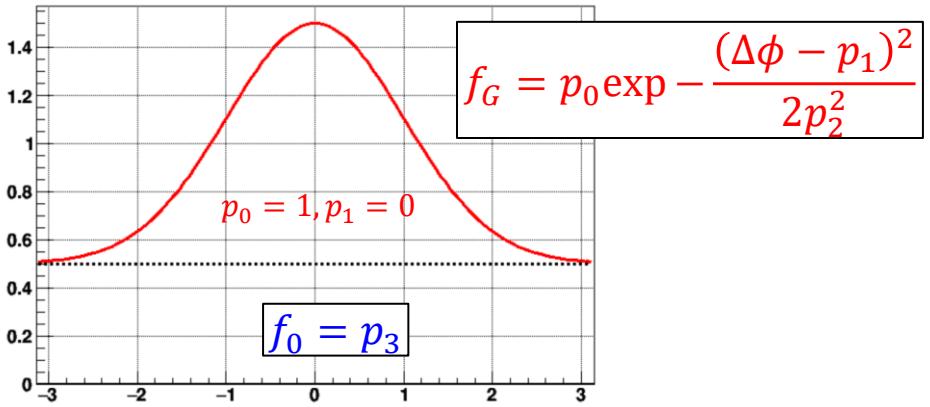
Azimuthal Angle Reconstruction

- Transverse spin asymmetries are measured through azimuthal modulations:

$$d\sigma(\phi) = \sigma_0[1 + PA_N \cos(\phi)]$$

$$A_N = \frac{d\sigma(\phi) - d\sigma(\phi+\pi)}{d\sigma(\phi) + d\sigma(\phi+\pi)} \qquad A_N = \frac{1}{P}\frac{N_\phi - N_{\phi+\pi}}{N_\phi + N_{\phi+\pi}}$$

- Toy Monte Carlo study → dilution factor $\mathrm{D} = A_{N,meas}/A_{N,input}$

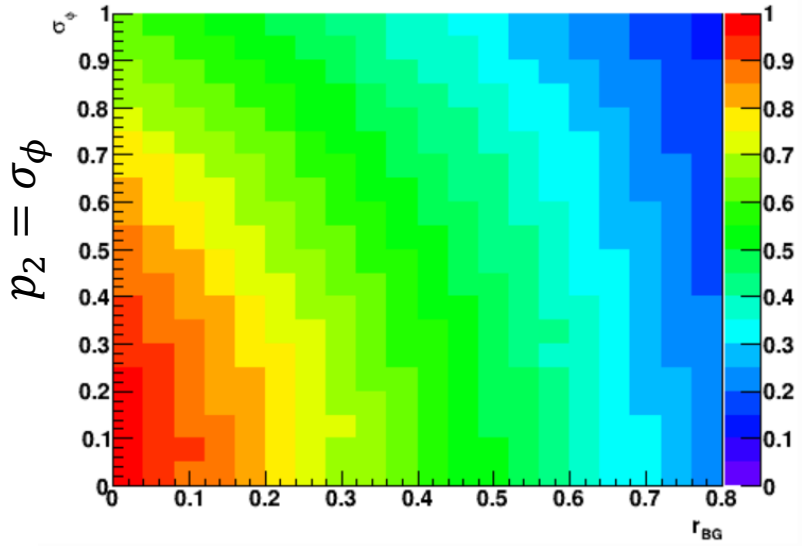


$$\boldsymbol{r_{BG} = \frac{BG}{S + BG}}$$

$$\boldsymbol{S = \int f(x)dx = \sqrt{2\pi} \cdot p_2}$$

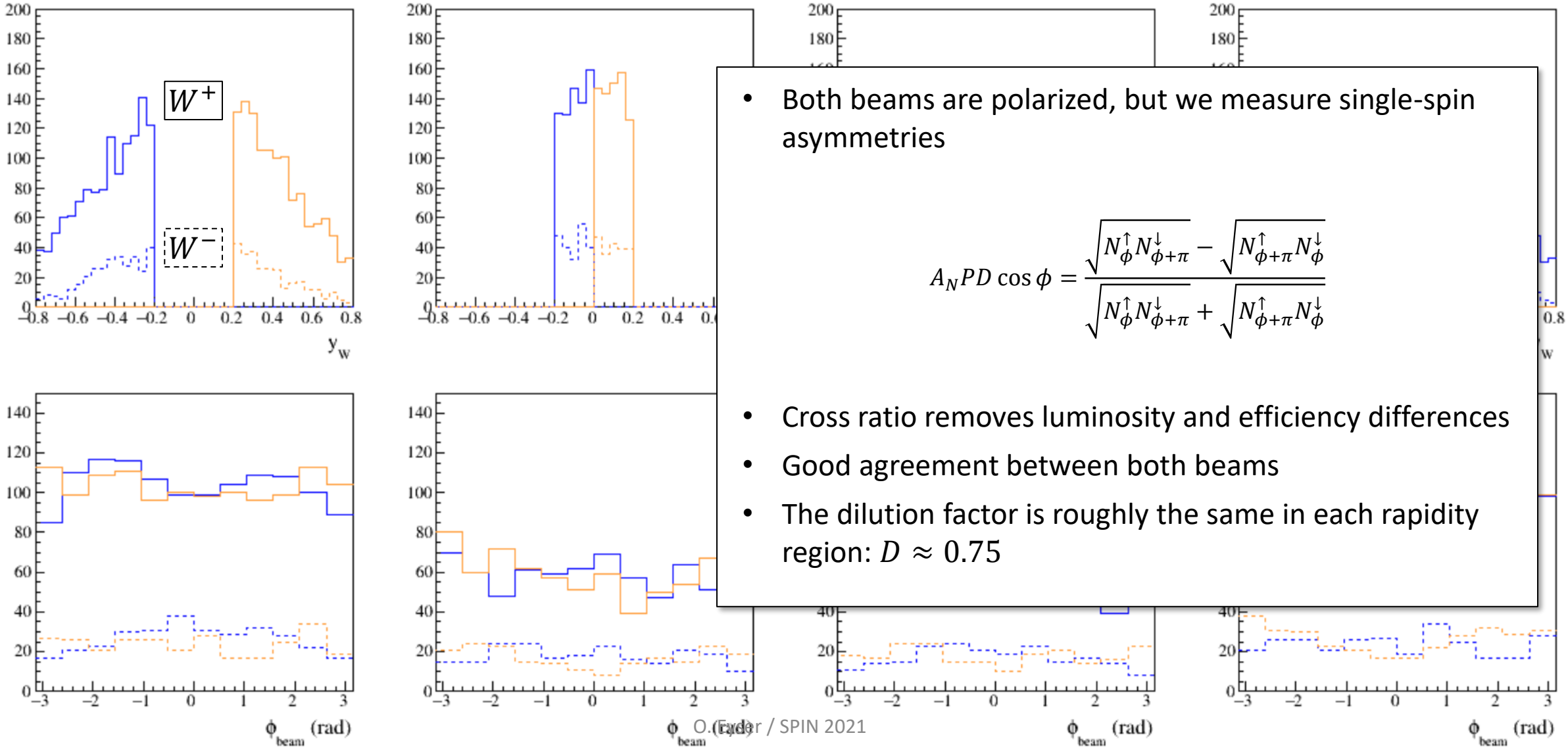
$$\boldsymbol{BG = 2\pi p_3}$$

$$A_{N,input} = A_{N,meas}/D$$



W-Bosons & Binning

$-0.8 < y_{beam} < -0.2$ | $-0.2 < y_{beam} < 0.0$ | $0.0 < y_{beam} < 0.2$ | $0.2 < y_{beam} < 0.8$



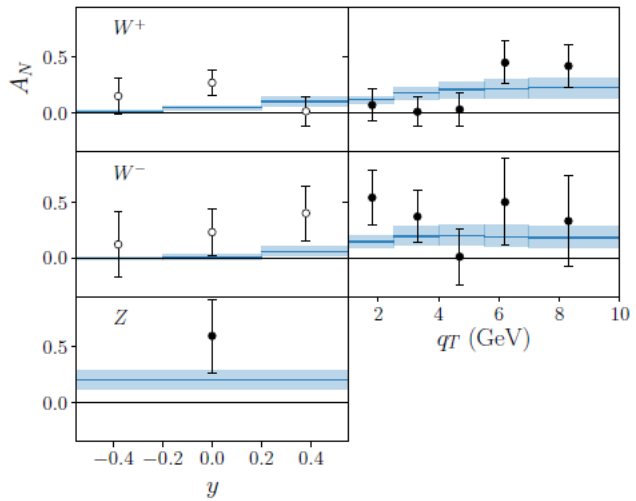
- Both beams are polarized, but we measure single-spin asymmetries

$$A_N P D \cos\phi = \frac{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} - \sqrt{N_{\phi+\pi}^\uparrow N_\phi^\downarrow}}{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} + \sqrt{N_{\phi+\pi}^\uparrow N_\phi^\downarrow}}$$

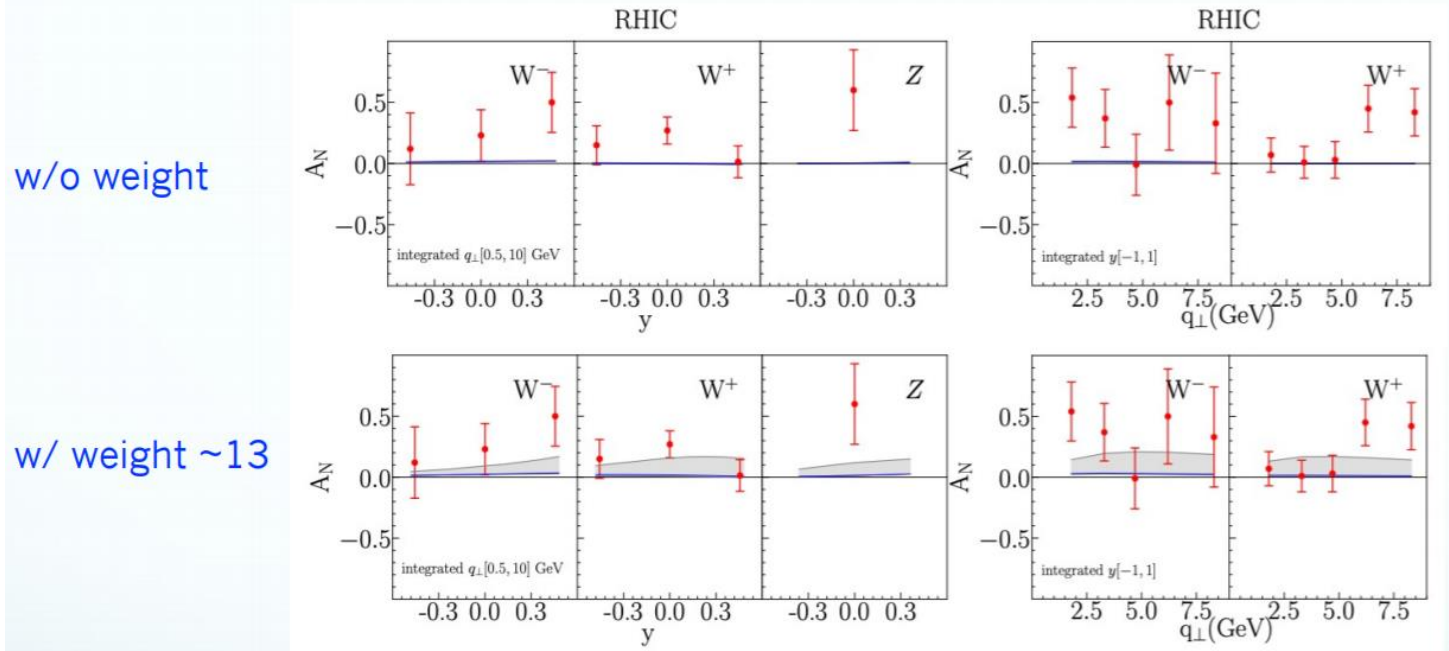
- Cross ratio removes luminosity and efficiency differences
- Good agreement between both beams
- The dilution factor is roughly the same in each rapidity region: $D \approx 0.75$

Global Fit

- Original release: 2002.08384, Cammarota et al.
- Phys Rev. D102, 054002 (2020)
  2009.10710, Echevarria et al.
- PRL 126, 112002 (2021)
  2012.05135, Bury et al.
- 2103.03270, Bury et al.



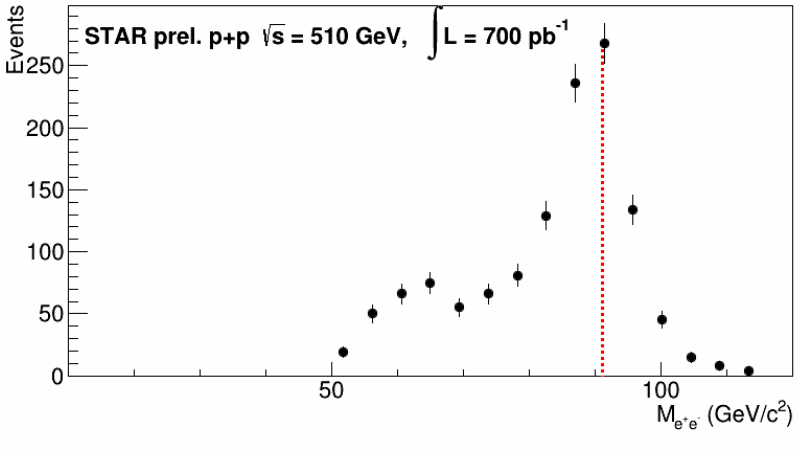
Z. Kang, RHIC→EIC workshop (CFNS, May 24)
https://indico.bnl.gov/event/10184

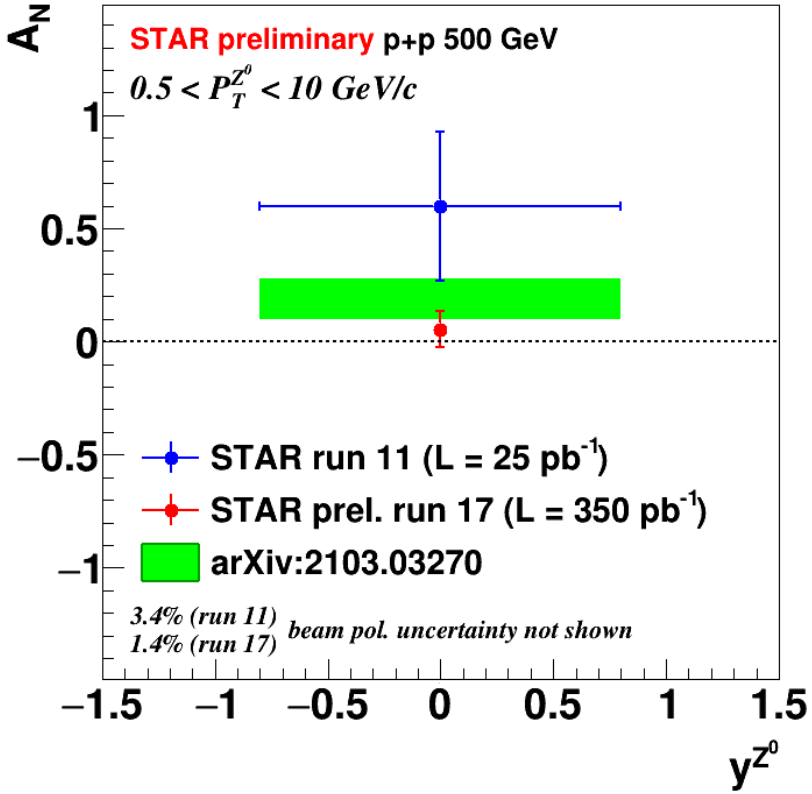


New Results for Z^0

$$p + p \rightarrow Z^0 \rightarrow e^+ + e^-$$

- Experimentally very clean
  - Two high-p_T electrons (e^+, e^-) from same vertex
- Leading systematic uncertainty from energy resolution
- Comparison with PRL 126 (2021) 112002
  (more details in arxiv:2103.03270)

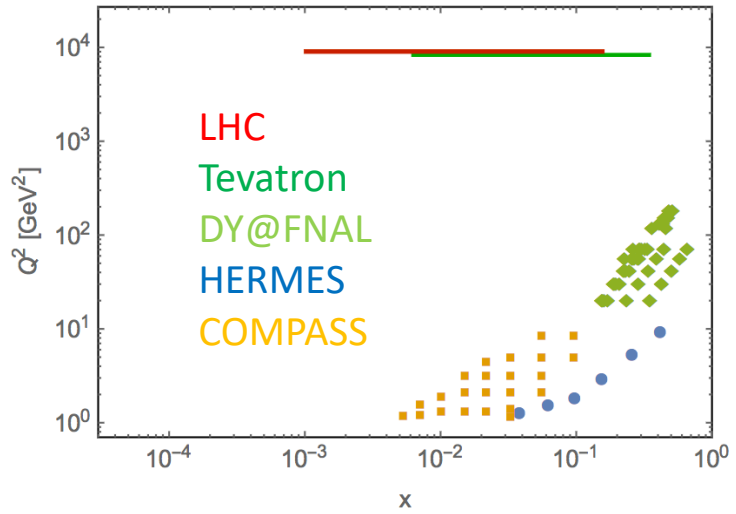


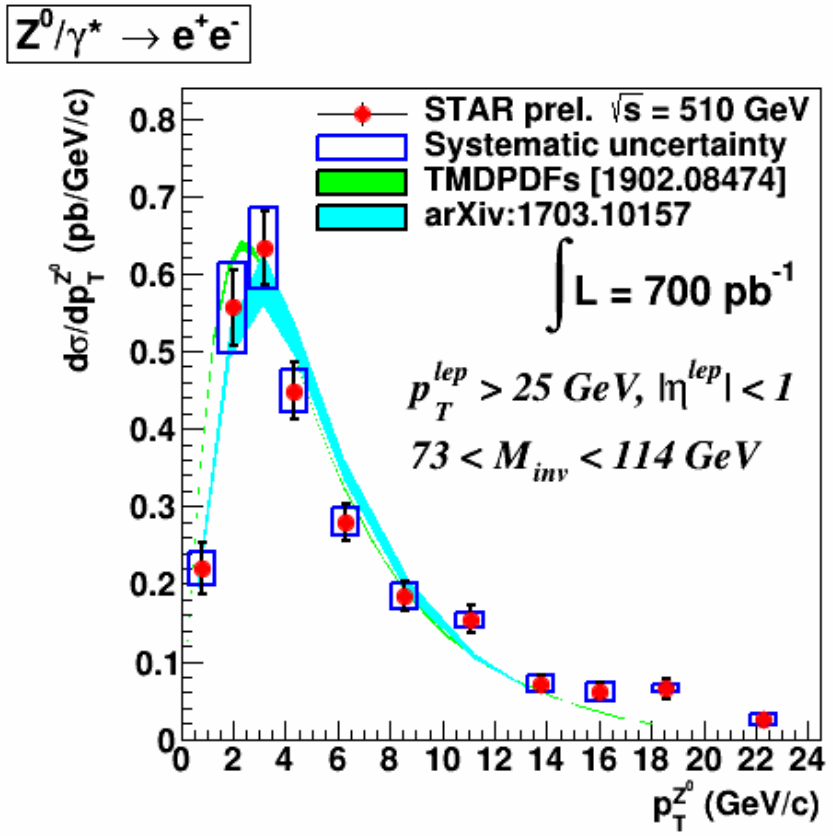


Unpolarized TMDs

$$p + p \rightarrow Z^0 \rightarrow e^+ + e^-$$

- Differential cross section of high interest for TMD-PDF fits
  - Pavia group, *JHEP* 07 (2020) 117





- 2017 data doubles the previous statistics
- Unfolded p_T spectrum
- Systematics from energy resolution and electron selection

Global luminosity uncertainty 8.5% not included in the plot