Transverse single-spin asymmetries in $p\,p \rightarrow W^{\pm}Z^{0}\,X$ at RHIC

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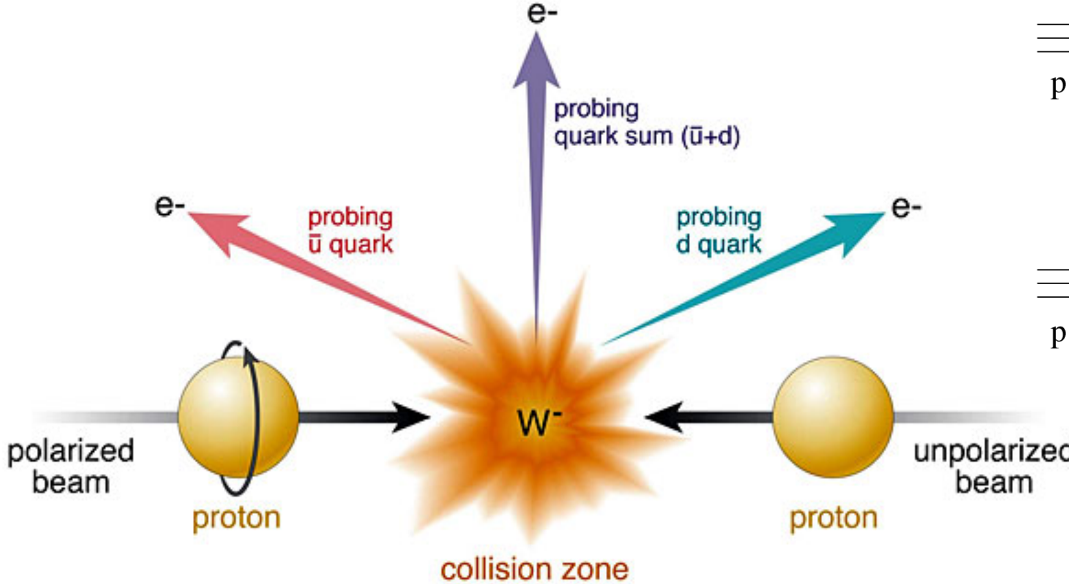
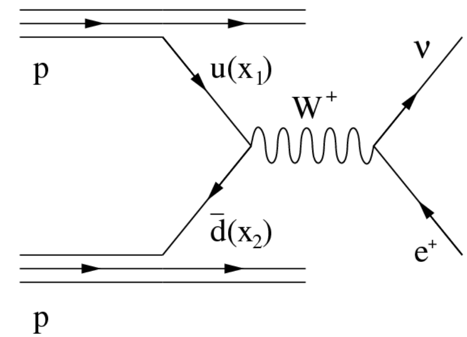
Fig. illustrates up/down transverse pol. directions

5th International Workshop on Transverse Polarization Phenomena in Hard Processes
TRANSVERSITY 2017
INFN – Frascati National Lab (Italy), December 11-15, 2017

W bosons: a golden probe!





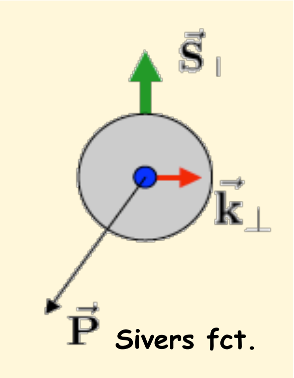
$u\bar{d} \rightarrow W^{+}$

$d\bar{u} \rightarrow W^{-}$

- **Ws naturally separate** quark flavors
  > rapidity: sea vs. valence quarks
- **Ws** are **maximally parity violating**
  > select only to one helicity of the couples (anti)quarks
- **Ws are theoretically clean**
  > no fragmentation function involved
- **Complementary to SIDIS**
  > high Q^2-scale (M^2 ~ 6400 GeV^2) tests the universality of PDFs

The Sivers function

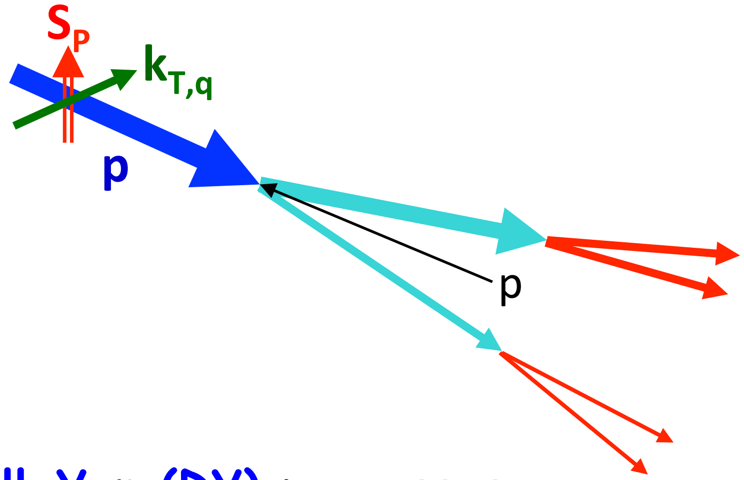
8 TMDs are allowed by gauge invariance



The TMD known as **Sivers function** is

- sensitive to **proton spin** – parton **transverse motion** correlations
- predicted not to be universal between SIDIS & pp

Tools to measure Sivers:



transverse single-spin asymmetry amplitude

$$A_N \approx \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Measure A_N for weak boson ($W^{+/-}$, Z^0) and Drell-Yan (DY) processes

Motivations – Transverse Single Spin Asymmetry (A_N)

QCD:

DIS: γq scattering
attractive FSI

pp: $q/\bar{q}$ annihilation
repulsive ISI

NSAC performance milestone (HP13)

$\text{Sivers}_{\text{DIS}}$ = - Sivers (DY or W or Z)

The sign change of the Sivers function
a fundamental prediction from QCD

Experimental test is critical test for our understanding of TMD's and TMD factorization

Test through Drell-Yan process: COMPASS (CERN), SeaQuest (FermiLab), STAR (BNL)

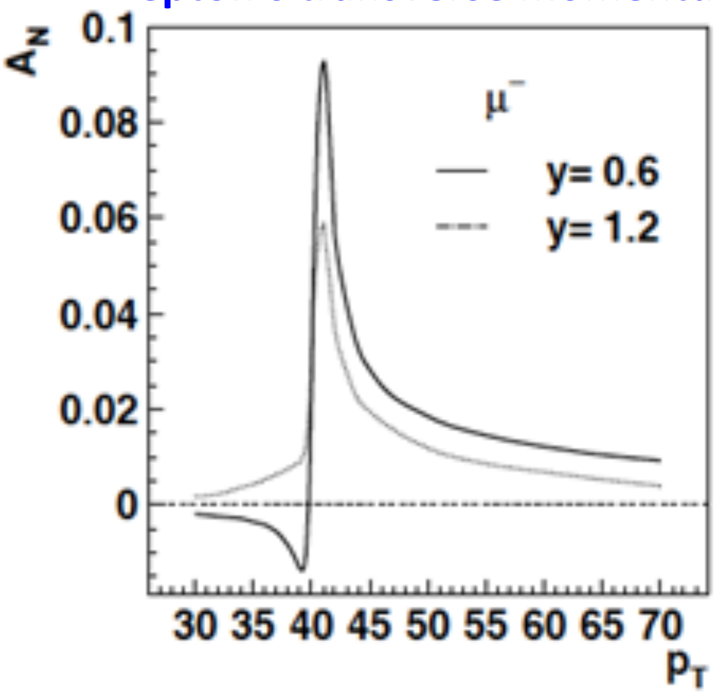
- Strong background suppression, high lumi
- @ STAR in run 2017(PostShower upgrade)

Polar. weak boson production (only at RHIC)

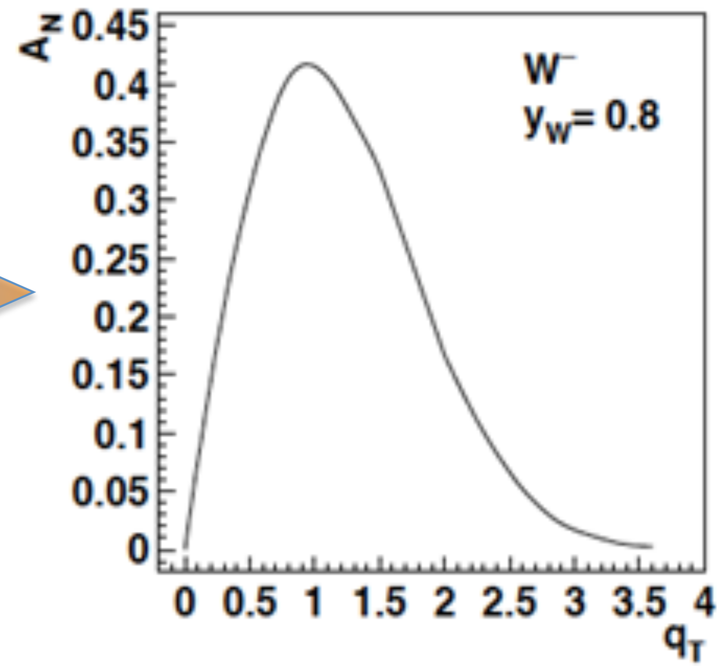
- Very low background
- Very high Q^2-scale (~ W/Z boson mass)

A_N for weak bosons

Lepton's transverse momentum



Boson's transverse momentum



- **Asymmetry from decay lepton sizeable in a very small p_T region**

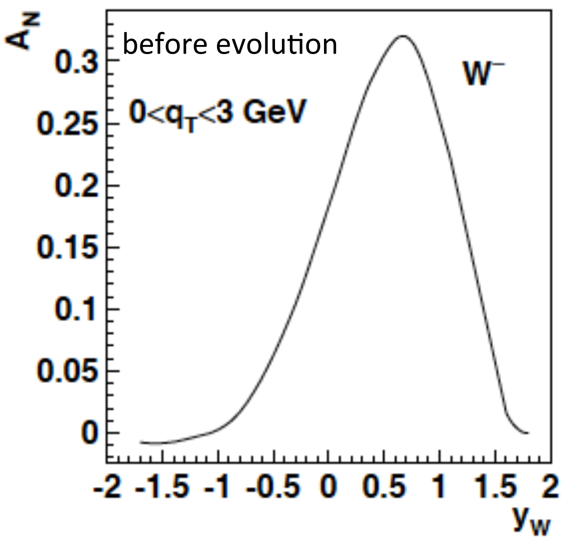
→ Full kinematical reconstruction of the produced boson is needed

> Z^0 easy to reconstruct (but small cross-section)

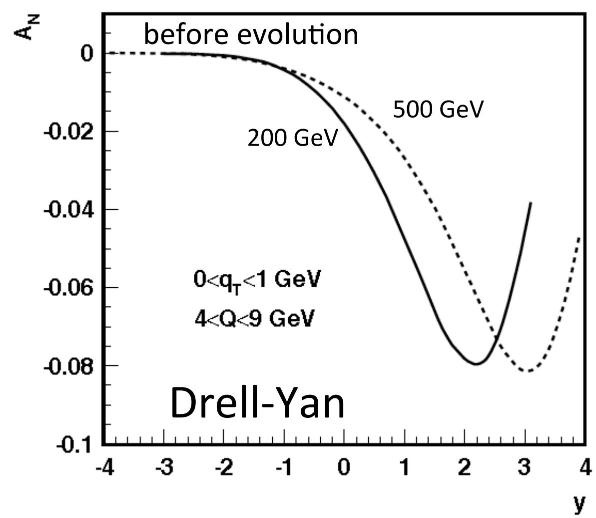
> W kin. can be reconstructed from the hadronic recoil

The TMD evolution & sea-quarks Sivers

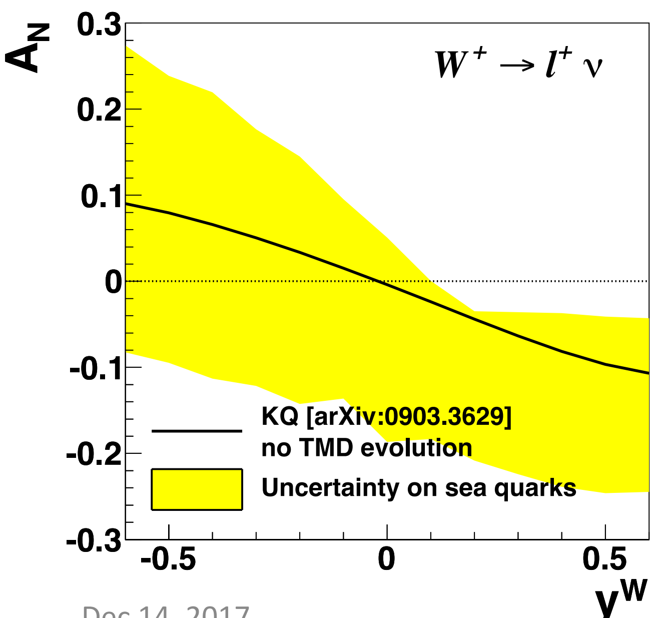
Z.-B. Kang & J.-W. Qui arXiv:0903.3629



Z.-B. Kang & J.-W. Qui Phys.Rev.D81:054020,2010



- **TMD evolution needs non-perturbatiove input**



- **What is the sea-quark Sivers fct.?**
  → ***Sea quarks are mostly unconstrained from existing SIDIS data... but*** **they can give a relevant contribution!**
  → W's ideal → rapidity dependence of A_N separates quarks from antiquarks

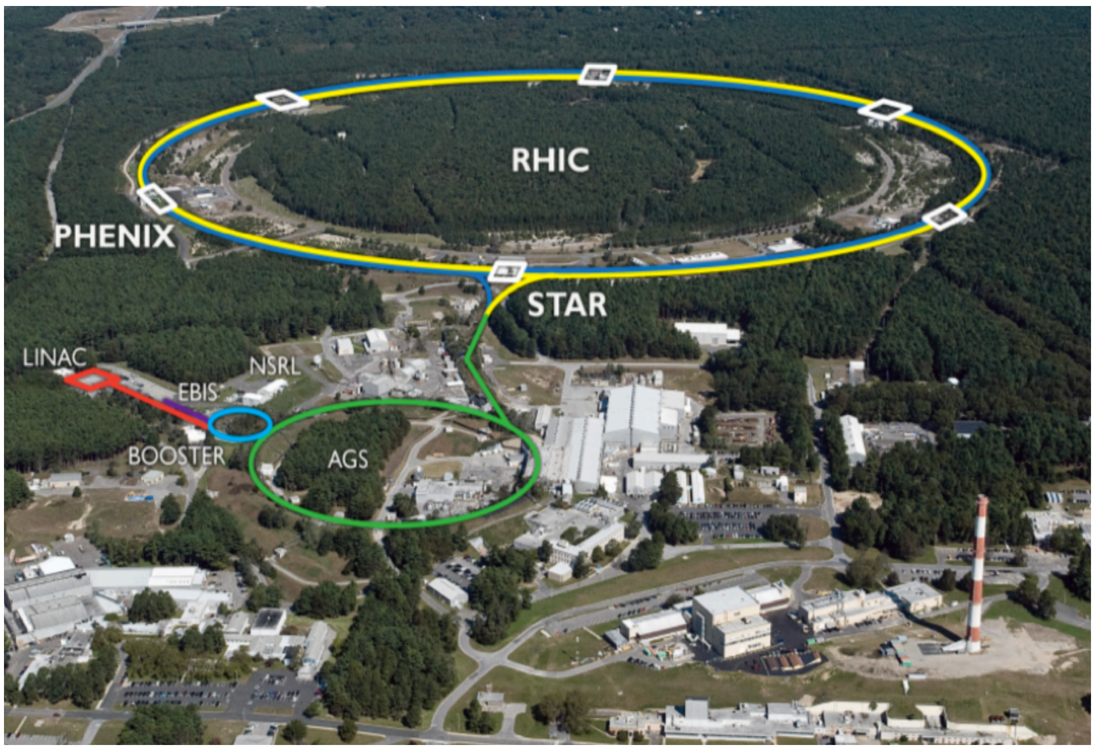
$W^{\pm}$ data can constrain the sea-quark Sivers function

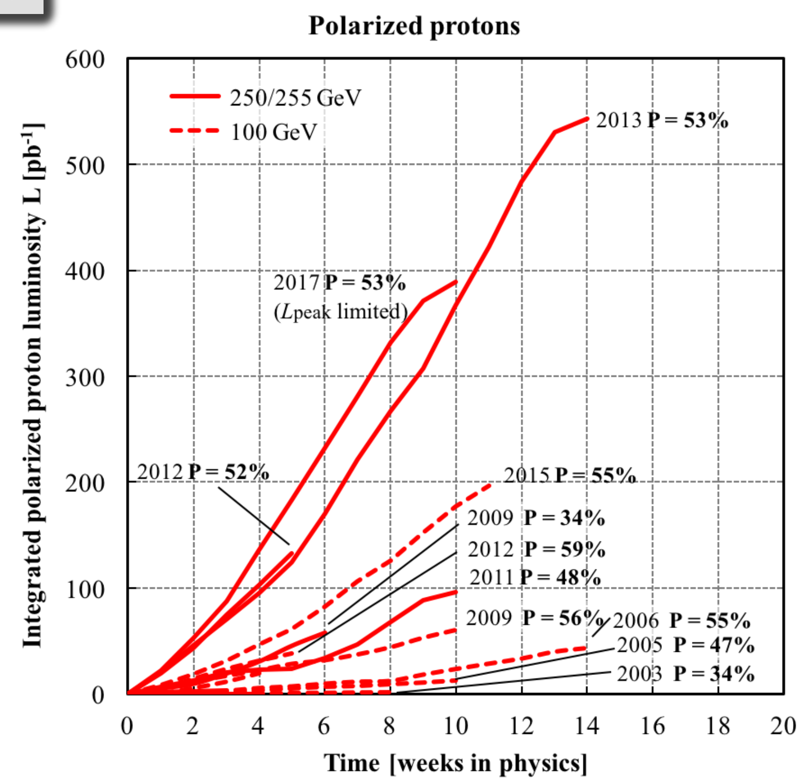
The Relativistic Heavy-Ion Collider

- **RHIC is the world's first and only polarized hadron collider**

Its top energy is enough to produce weak bosons

Beams: √s=<510 GeV pp; 50-60% polarization

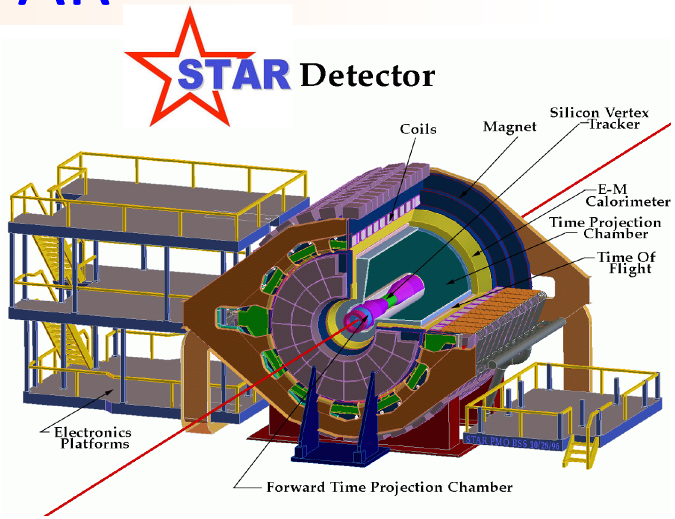




Weak bosons at STAR

Detector acceptance relevant to measurements of weak bosons

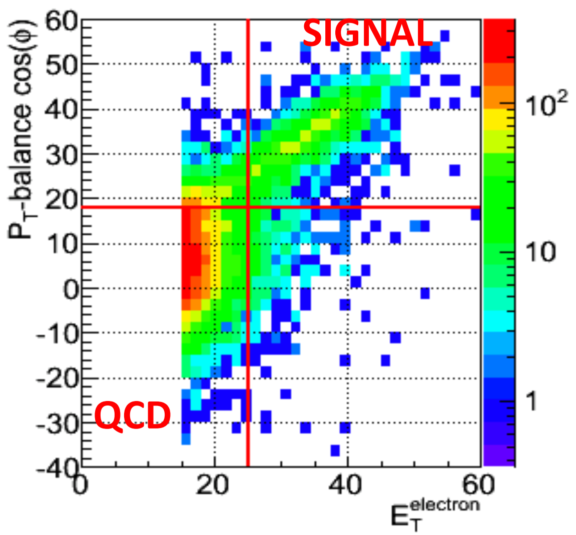
- **2π coverage Electromagnetic Calorimeter**
  - **Barrel: $-1 < \eta < 1$**
  - **End-cap: $1.1 < \eta < 2$**
- **Main tracker – Time projection chamber (TPC): $|\eta| < 1.3$**



Main selection Criteria

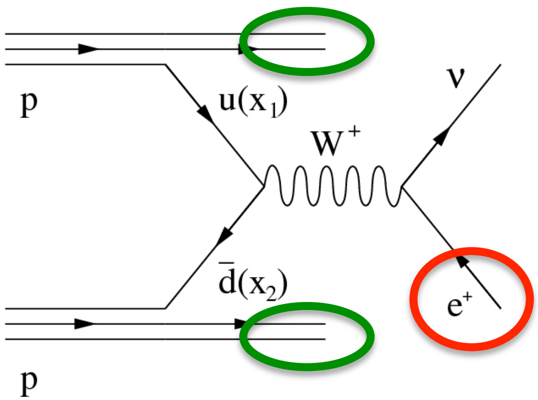
- **Isolation:** ($P^{track}+E^{cluster}$) / Σ[P^{tracks} in R=0.7 cone] > 0.8
- **Imbalance:** no energy in opposite cone (E<20 GeV)
- **$E_T > 25$ GeV**
- Track $|\eta| < 1$
- |Z-vertex|<100 cm
- **Charge separation** (avoids charge misidentification):

  $0.4 < |\text{Charge (TPC)} \times E_T \text{(EMC)} / P_T \text{(TPC)}| < 1.8$
- Signed P_T balance > 18 GeV/c (**rejects QCD Background**)
- 0.5 GeV/c $< P_T^W < 10$ GeV /c



$$\vec{P}_T^{\,bal} = \vec{P}_T^{\,e} + \sum \vec{P}_T^{\,recoil}$$

A_N of weak bosons @ STAR



Ingredients for the analysis

- Isolated electron
- neutrino (not measured directly)
- Hadronic recoil

W boson momentum reconstruction technique well tested at FermiLab and LHC

[CDF: PRD 70, 032004 (2004); ATLAS: JHEP 1012 (2010) 060]

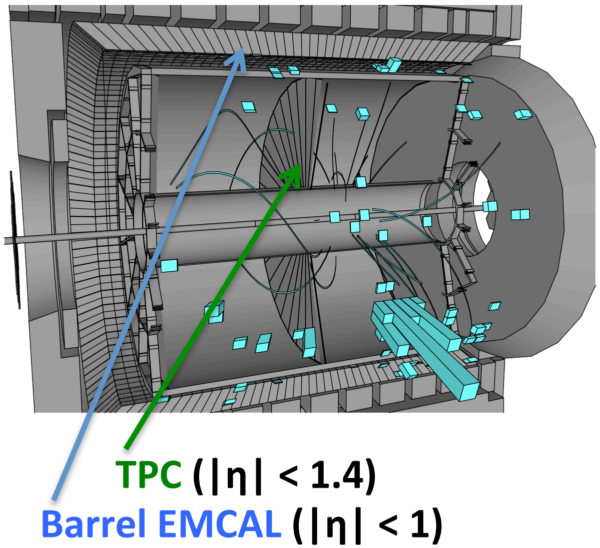
- ❑ **Select events with the W-signature (STEP 1)**
  - ➢ Isolated high P_T electron
- ❑ **Neutrino transverse momentum is reconstructed from missing P_T (Step 2)**

$$\vec{P}_T^{\nu} \approx - \sum_{i \in {tracks \atop clusters}} \vec{P}_T^{i}$$

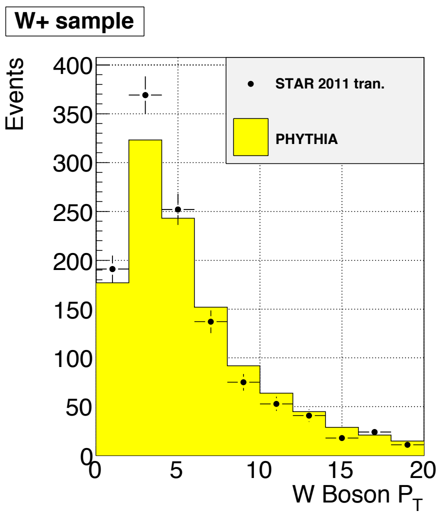
- ❑ **Neutrino's longitudinal momentum is reconstructed from the decay kinematics (Step 3)**

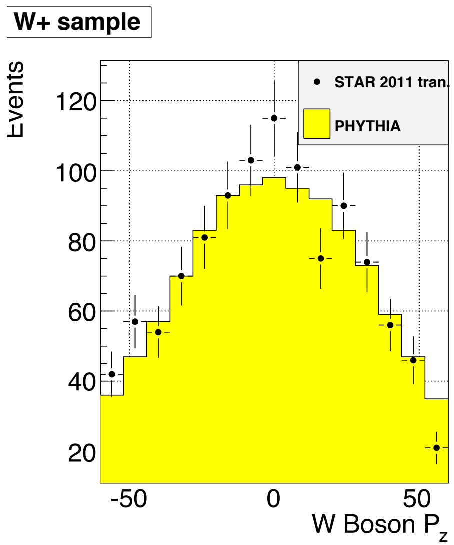
$$M_W^2 = \left(E_e + E_\nu\right)^2 - \left(\vec{p}_e + \vec{p}_\nu\right)^2$$

The STAR detector @ RHIC



A_N of weak bosons @ STAR



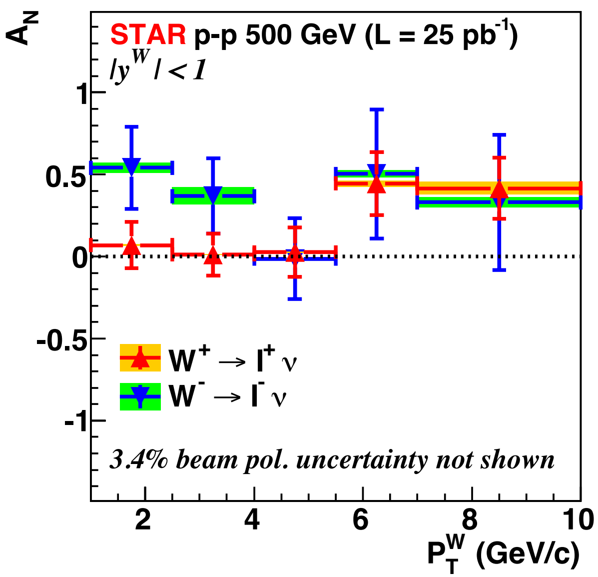


- This measurement is STAR's first time to reconstruct the produced W boson's kinematics

We use the "left-right" formula to cancel dependencies on geometry and luminosity

$$A_N \approx \frac{1}{P}\frac{\sqrt{N_R^{\uparrow}N_L^{\downarrow}} - \sqrt{N_L^{\uparrow}N_R^{\downarrow}}}{\sqrt{N_R^{\uparrow}N_L^{\downarrow}} + \sqrt{N_L^{\uparrow}N_R^{\downarrow}}}$$

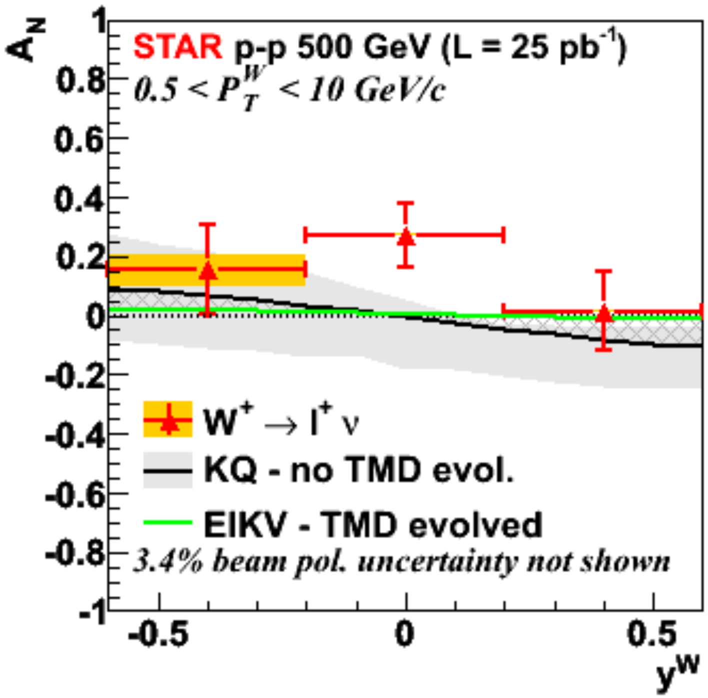
Average RHIC polarization
(p+p run 2011 tran.)
<P> = 53%

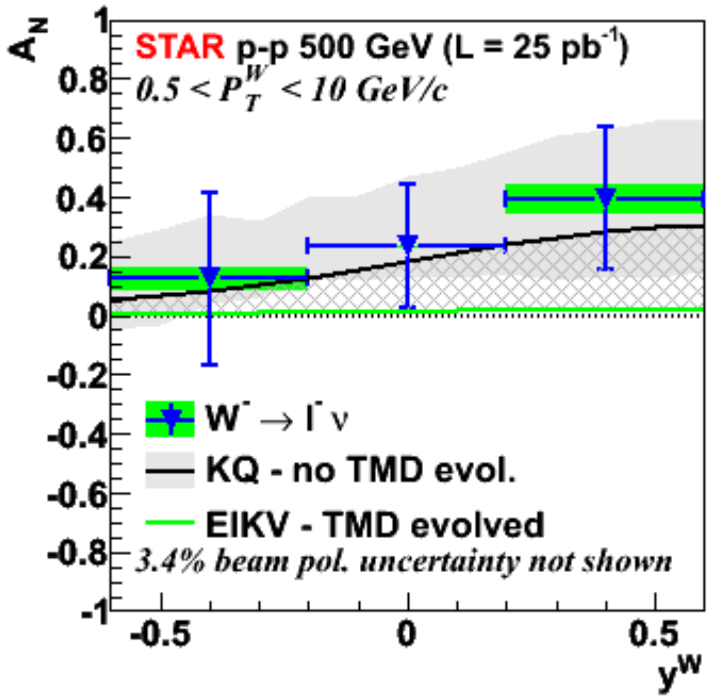


PRL 116, 132301 (2016)
Editor's suggestion

World's first direct experimental test of Sivers in p+p collisions

A_N vs W-rapidity

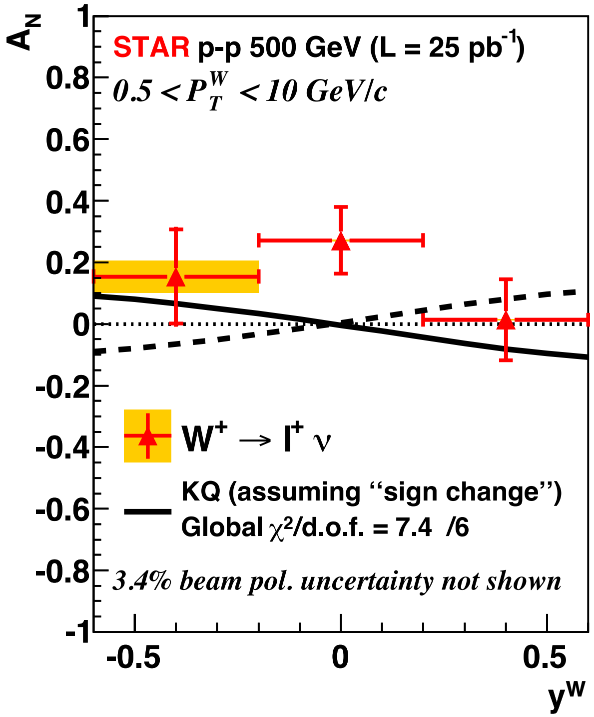


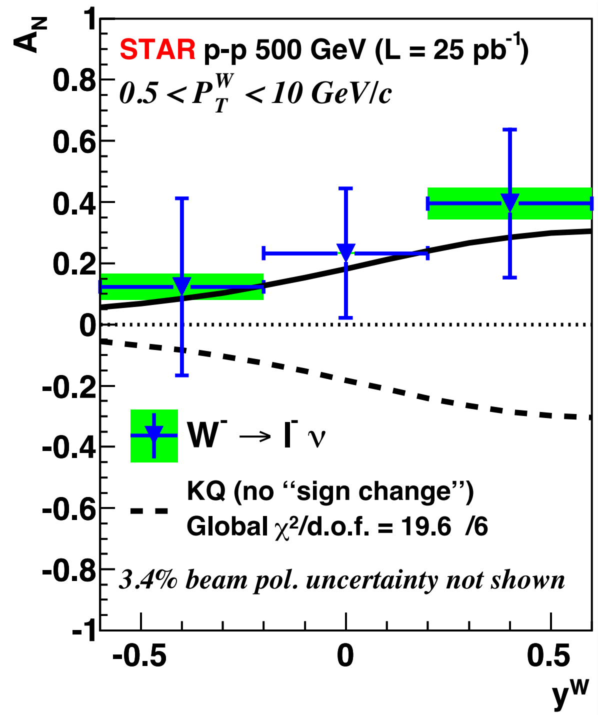


Results versus rapidity are compared with:

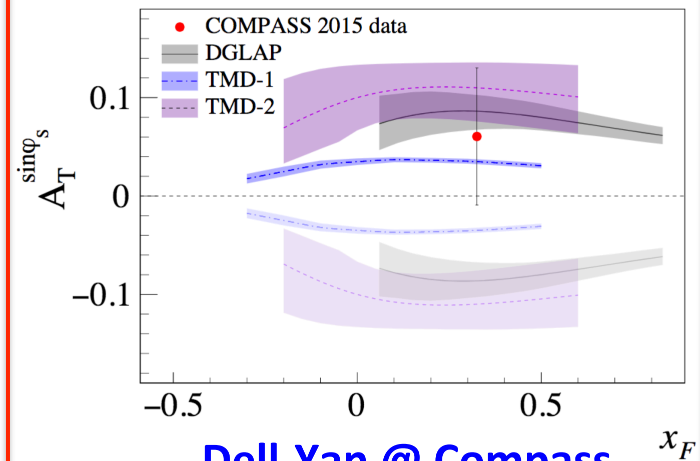
- **KQ model** [Z.-B. Kang and J. -W. Qiu, Phys. Rev. Lett. 103, 172001 (2009)]
    - It does not include TMD evolution
    - **Grey band** is the theory uncertainty
- **EIKV model** [M. G. Echevarria, A. Idilbi, Z.-B. Kang, I. Vitev, Phys. Rev. D89, 074013 (2014)]
    - Includes the largest prediction for TMD evolution
- **Grey hatched area** represents the current theoretical uncertainty on TMD evolution

The Sivers' sign change (no TMD evol.)





One more hint!



Dell-Yan @ Compass

[PRL 119,112002 (2017)]

light shades: No sign-change

A STAR global fit to the KQ prediction (Assumes NO evolution!)

- **solid line:** assumption of a sign change in the Sivers function → **Chi2/d.o.f. = 7.4/6**
- **dashed line:** assumption of no sign change in the Sivers function → **Chi2/d.o.f. = 19.6/6**

Current data show hint for small evolution effects in asymmetries and sign-change

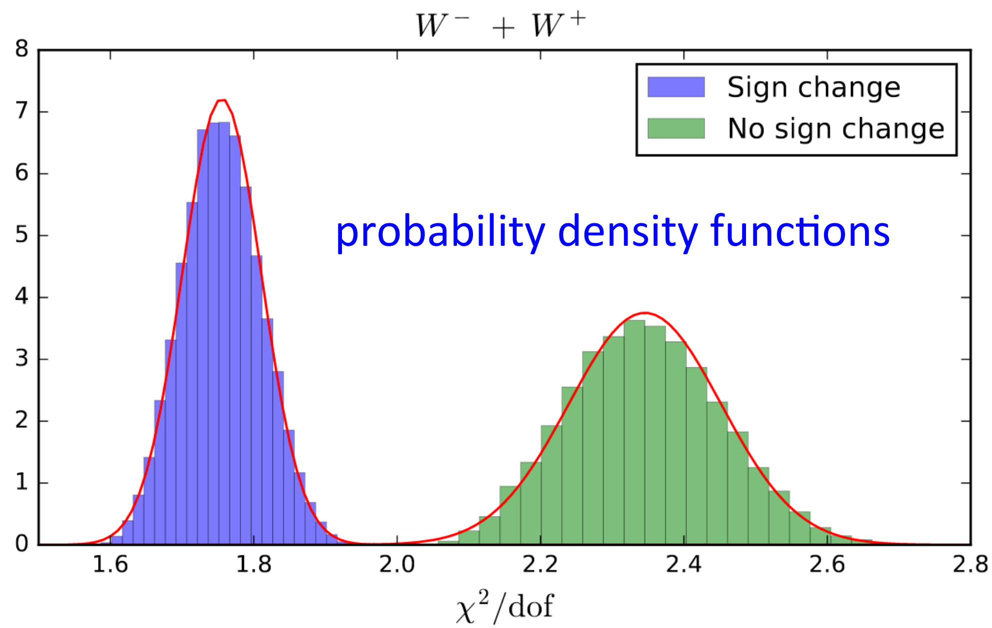
An independent test of sign-change

M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia, A. Prokudin
arXiv:1612.06413

- **Parameters trained on SIDIS data from:** COMPAS, HERMES, JLAB
  -> latest fit of Sivers
  -> different kine. region

- **No evolution effects** included in the predictions

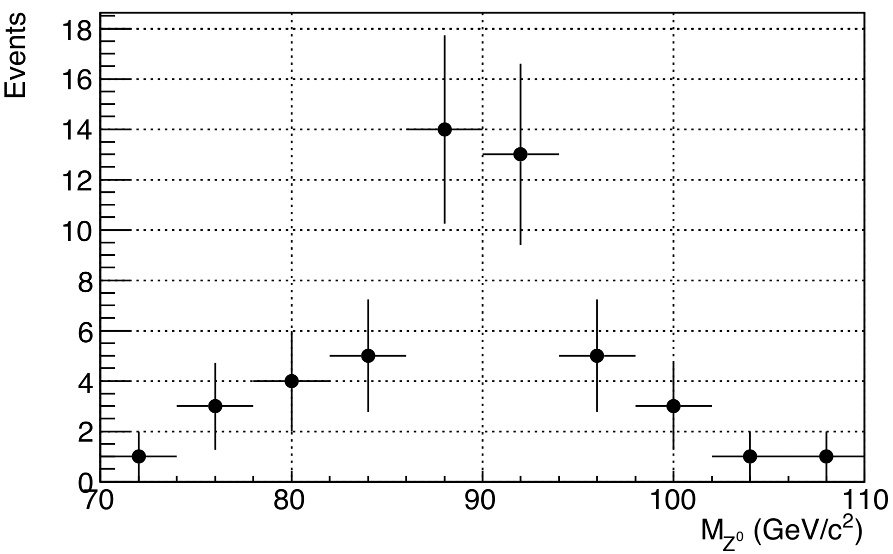
- **Global fit on our W^+ and W^- data**



- ➢ The model with sign change hypothesis gives a slightly better chi-square
- ➢ generally the agreement with the model is poor
- ➢ Authors conclude for the need of more precise data

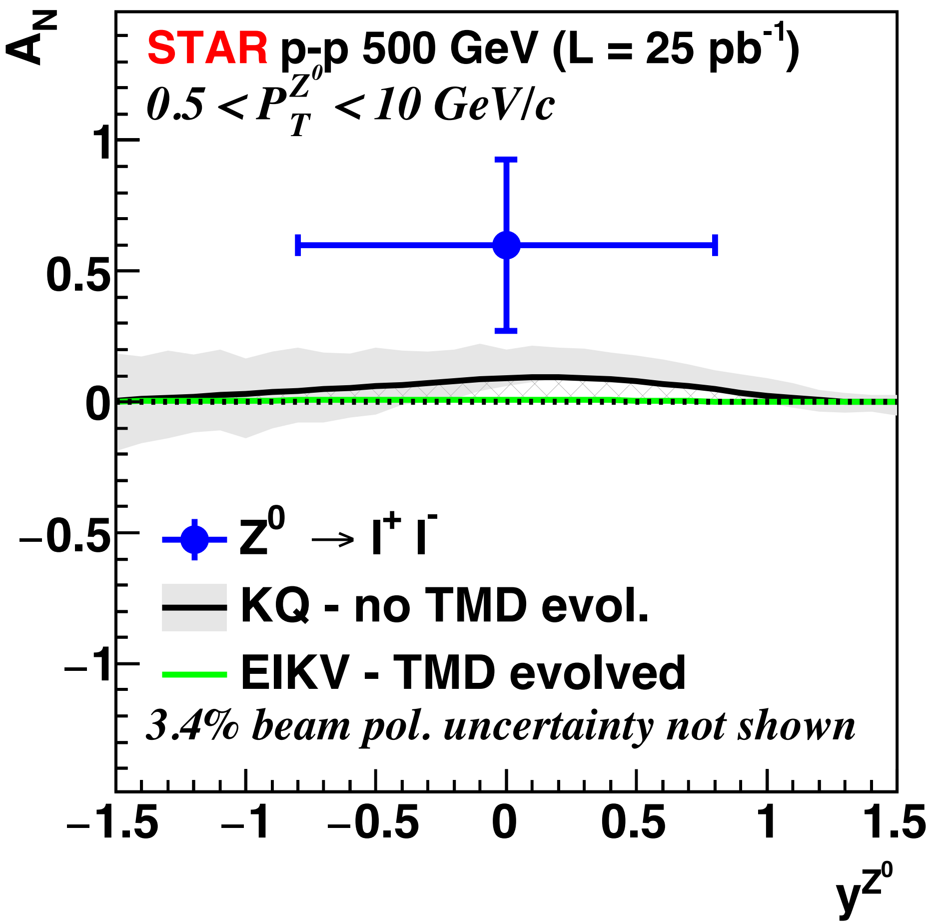
Z^0 Asymmetry $pp \rightarrow Z^0 \rightarrow e^+e^-$

- **Clean experimental momentum reconstruction**
- **Negligible background**
- **electrons rapidity peaks within tracker accept. (|η|< 1)**
- **Statistics limited**



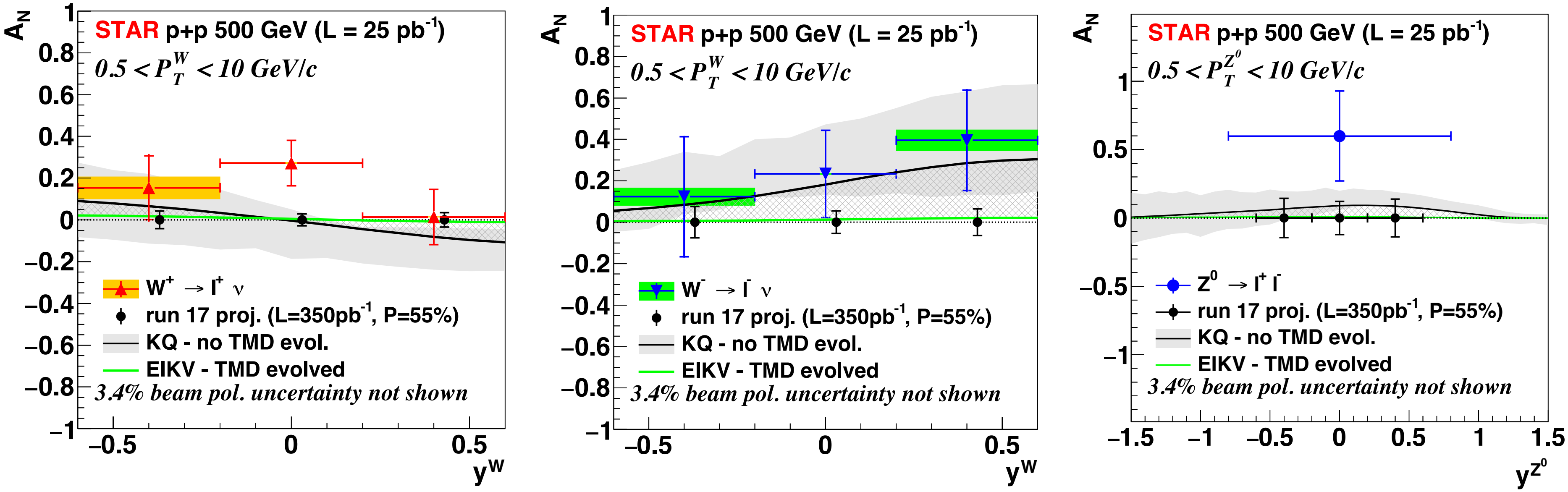
PRL 116, 132301 (2016)

A_N measured in a single y, P_T bin



STAR run 17 projections

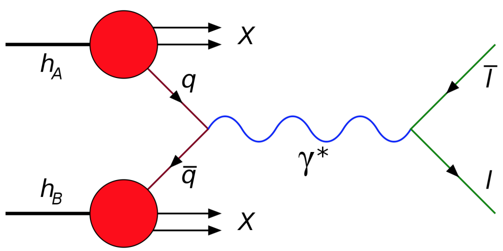
STAR collected 350 pb^{-1} transverse p+p in 2017



Large statistics will allow us to

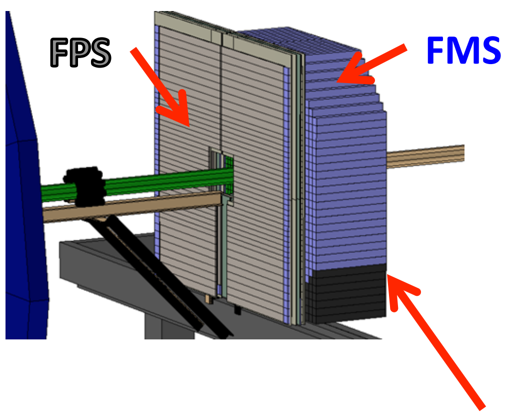
- **Precisely measure A_N for Ws within a few %** in several P_T, y bins.
- Measure the very clean **Z^0 channel**.
- Aim at a conclusive test of TMD evolution effects and sign change
- **Run 17 data production and calibration studies ongoing now**

A_N of Drell-Yan at STAR



- **Very Challenging: (RHIC QCD WP arXiv:1602.03922)**
  - QCD background ~10^5-10^6 larger than DY cross-section
  - Probability of wrongly identifying hadrons to be suppressed to ~0.01% while maintaining efficiency in identifying electrons

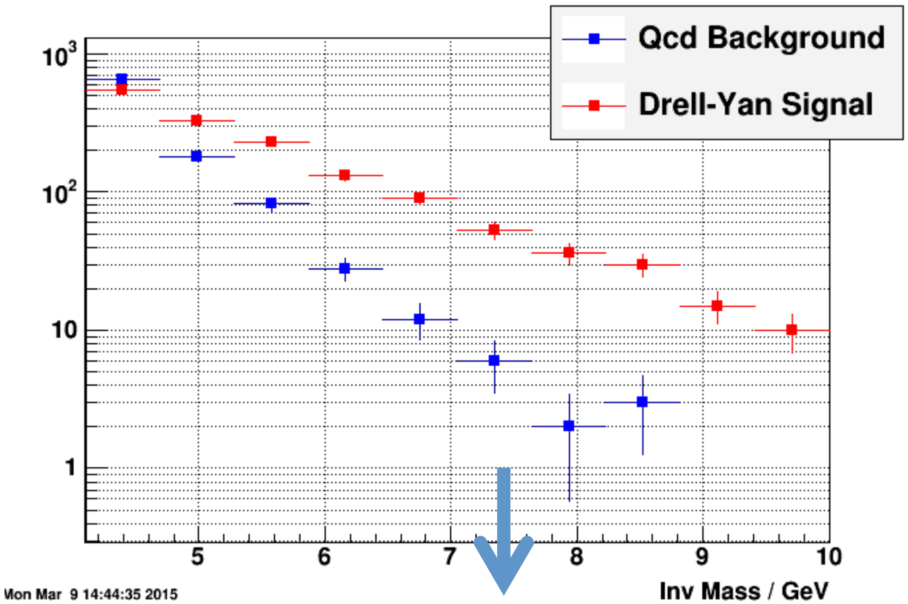
- **COMPASS (CERN) and proposed E-906/SeaQuest (FNAL)** pursue the investigation of TMD through this process
- **STAR can measure it...** with an upgrade
  - We installed for run-17 a forward Post-Shower detector behind the the FMS detector and its Pre-Shower



Preshower Detector (FPS): 3 layers of scintillator stripes with SiPMT-based read-out in front of the FMS,
→ distinguish photons and electrons/positrons
→ Installed for RUN-15

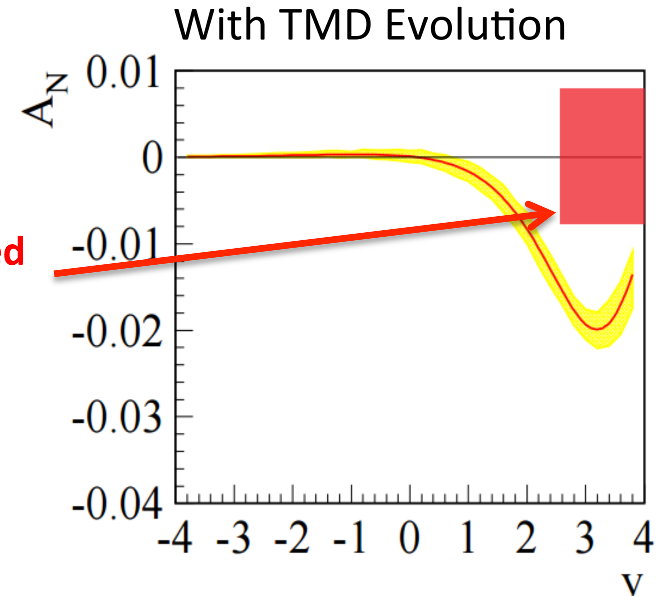
Postshower Detector (FPost): similar to the FPS but located behind the FMS,
→ distinguish electrons and hadrons
→ Installed for RUN-17

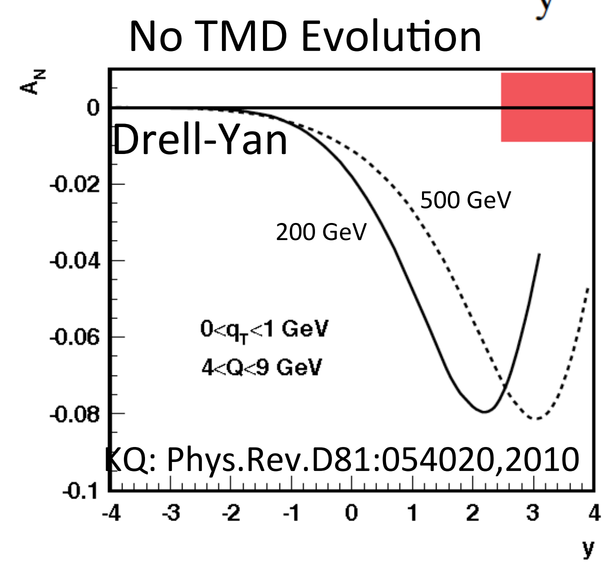
Drell-Yan at STAR – Background suppression



The expected yields of DY events and background <u>after the upgrade</u>

STAR projected uncertainty





The proposed forward-detector system (FPS + FMS + FPost) provides the needed rejection factor for measuring DY

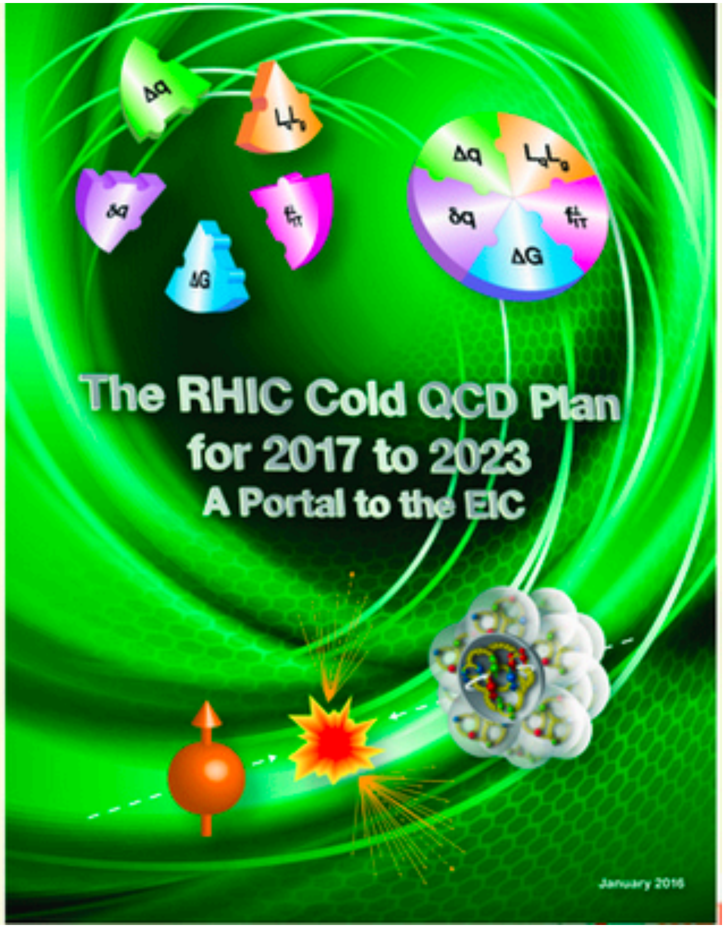
→ **STAR can measure DY to ± 0.008 in run-17 for $\int L_{del}$=400 pb^{-1}**

Conclusions

- **RHIC run 11:** STAR published the first measurement sensitive to the Sivers function in p+p collisions, based on 25 pb^{-1} of transversely polarized p+p data at $\sqrt{s}$= 500 GeV
  - Data hint for small TMD evolution effects and Sivers sign change
  - Large statistical uncertainties

- **RHIC run 17:** STAR collected 350 pb^{-1} of transversely polarized p+p data at $\sqrt{s}$= 510 GeV, which can give statistical significance to
  - Pin down TMD evolution
  - Investigate the contribution from sea-quarks to the Sivers fcn.
  - Ultimate test of the Sivers sign change measuring γ, $W^{\pm}$, Z^0, DY, all in one venue!

White Papers

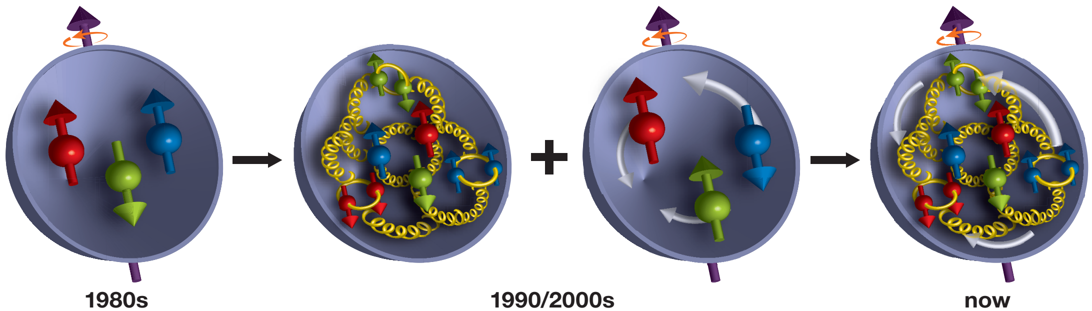


arXiv: 1501.01220

arXiv:1602.03922

BACKUP

The structure of a proton



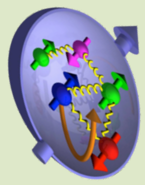
Today we know that a proton (nucleon) is a very complex object!

What is the dynamic structure of the nucleons?

Emerging questions:

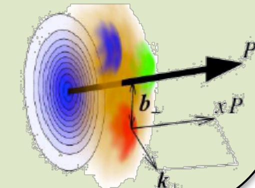
Proton Spin puzzle

What is the role of sea quarks and gluons in building the nucleon spin?



Visualize color interactions in QCD

understand deep aspects of gauge theories revealed by k_T dependent distributions

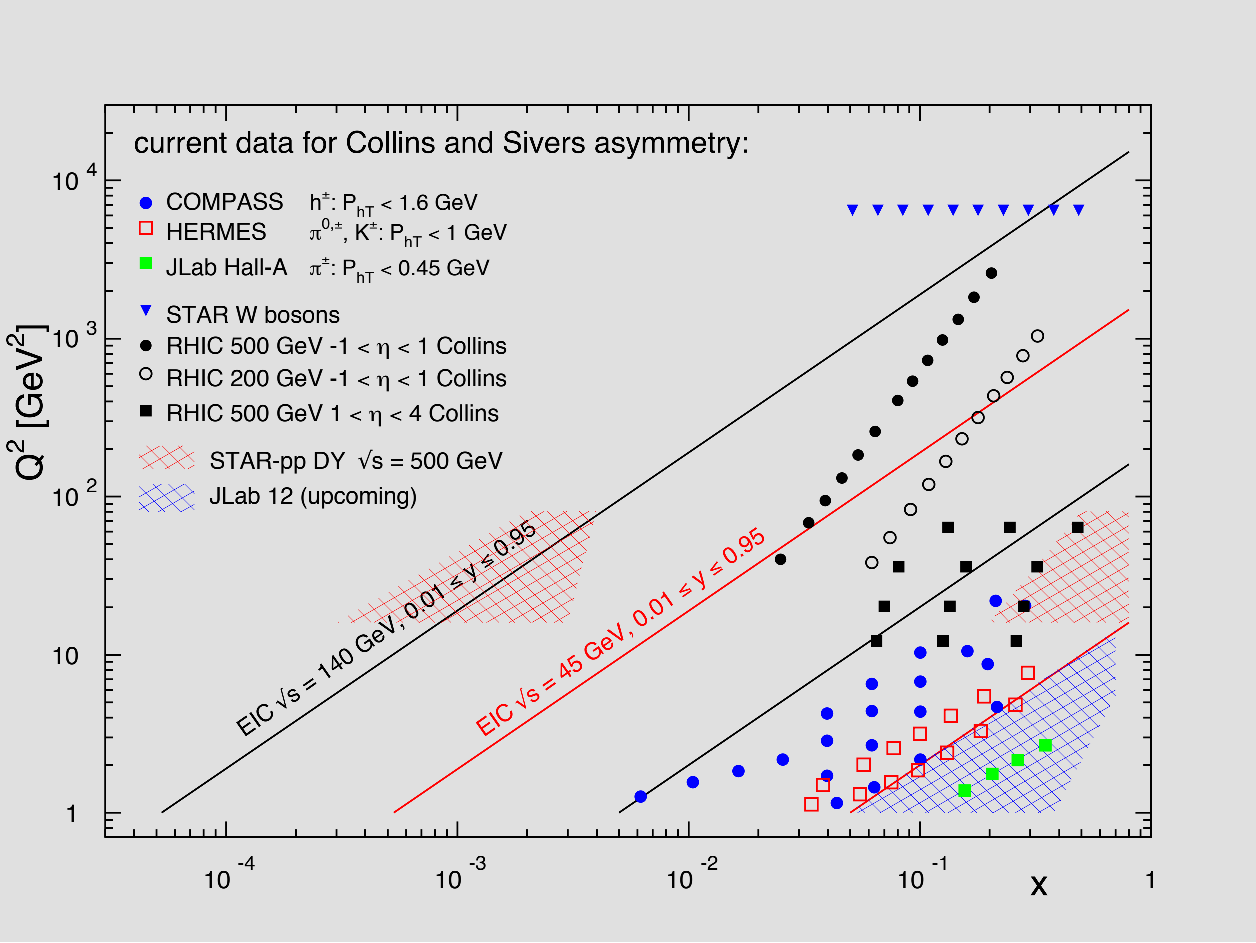


Summary table

	$A_N(W^{+/-},Z^0)$	$A_N(DY)$	$A_N(\gamma)$
sensitive to sign change through TMDs	yes	yes	no
sensitive to sign change through Twist-3 $T_{q,F}(x,x)$	no	no	yes
sensitive to TMD evolution	yes	yes	no
sensitive to sea-quark Sivers fct.	yes	yes	no
need detector upgrades	no	yes at minimum: FMS postshower	yes pre-showers installed for run-15
biggest experimental challenge	integrated luminosity	background suppression & integrated luminosity	need to still proof analysis on data

$A_N(W^{+/-},Z^0)$ clean probe sensitive to all questions without the need for upgrades

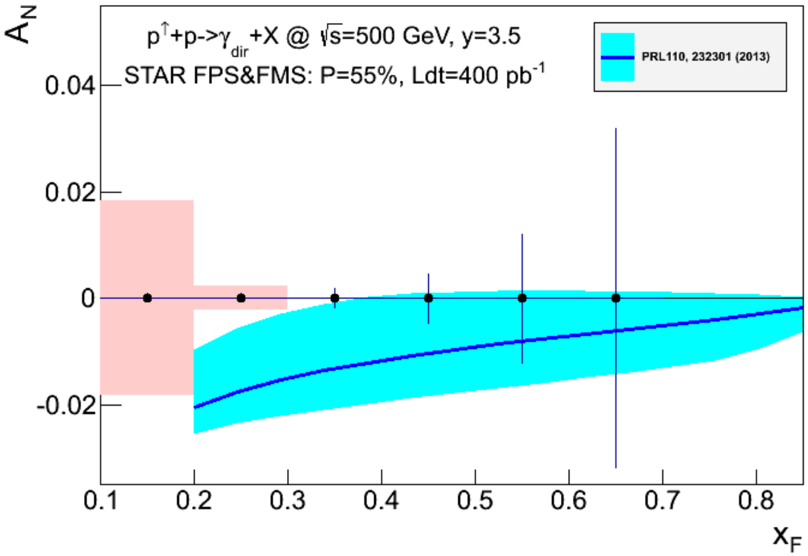
RHIC – a unique opportunity for TMDs!



Till today TMDs come only from fixed target low scale, high x measurements should establish concept at high √s and different x

→ polarised pp / pA at RHIC

A_N of direct-photons at STAR



A_N for direct photon production:

- sensitive to sign change, but in TWIST-3 formalism
- not sensitive to TMD evolution
- no sensitivity to sea-quarks; mainly u_v and d_v at high x
- collinear objects but more complicated evolutions than simple DGLAP
- indirect constraints on Sivers fct.

How do we access the sign change?

If the correlation due to different color interactions for initial and final state between the **Sivers fcn** and the **twist-3 correlation fcn** in the k_T integral would be violated, the asymmetry would be positive but the same magnitude

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

Not a replacement for a $A_N(W^{+/-}, Z^0, DY)$ measurement but an important complementary piece in the puzzle

Jets to access Transversity x Collins

$$A_{UT}^{\pi^\pm} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T) \hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u}) \Delta D_{q_1}^{\pi^\pm}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T) \hat{\sigma}_{UU} D_{q_1}^{\pi^\pm}(z,j_T)}$$

200 vs. 500 GeV Comparison:

- first observation of a TMD at low x and high Q^2
- Evolution: 200 GeV ←→ 500 GeV factor 3 in Q
- Test of factorization & Universality
  → compare with transversity from IFF
  → compare with SIDIS and e+e-
- Triggered a lot of theory work
  proof of factorization:
  Kang et al. arXiv:1705.08443
  asymmetry calculation:
  Kang et al. arXiv:1707.00913