TRANSVERSE SINGLE SPIN ASYMMETRIES FOR GAUGE BOSON PRODUCTION AT RHIC

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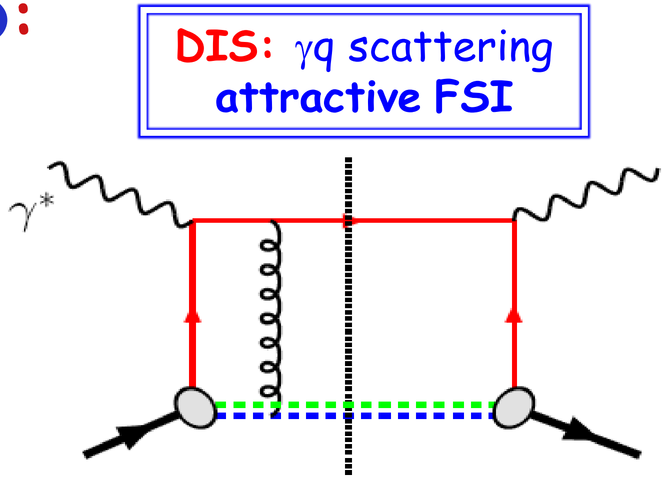
Spin2016 @ University of Illinois

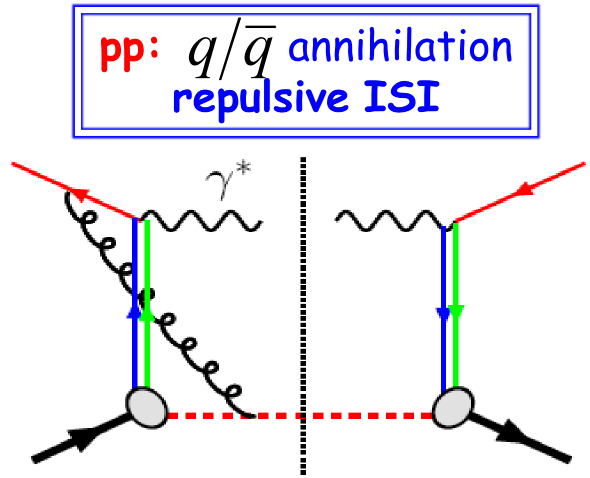
Contents

- Gauge boson production at RHIC
  - W,DY and Direct Photons
- W/Z production (Run11 results, Run17 expectation)
- Direct Photons (Run15 – no result, yet)
- Drell-Yan (Run17 – no result)
- Future plans
- Summary

Sivers Function and DIS vs DY (incl. W)

QCD:





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

The none-universality of the Sivers function

a fundamental prediction from the gauge invariance of QCD

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

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

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

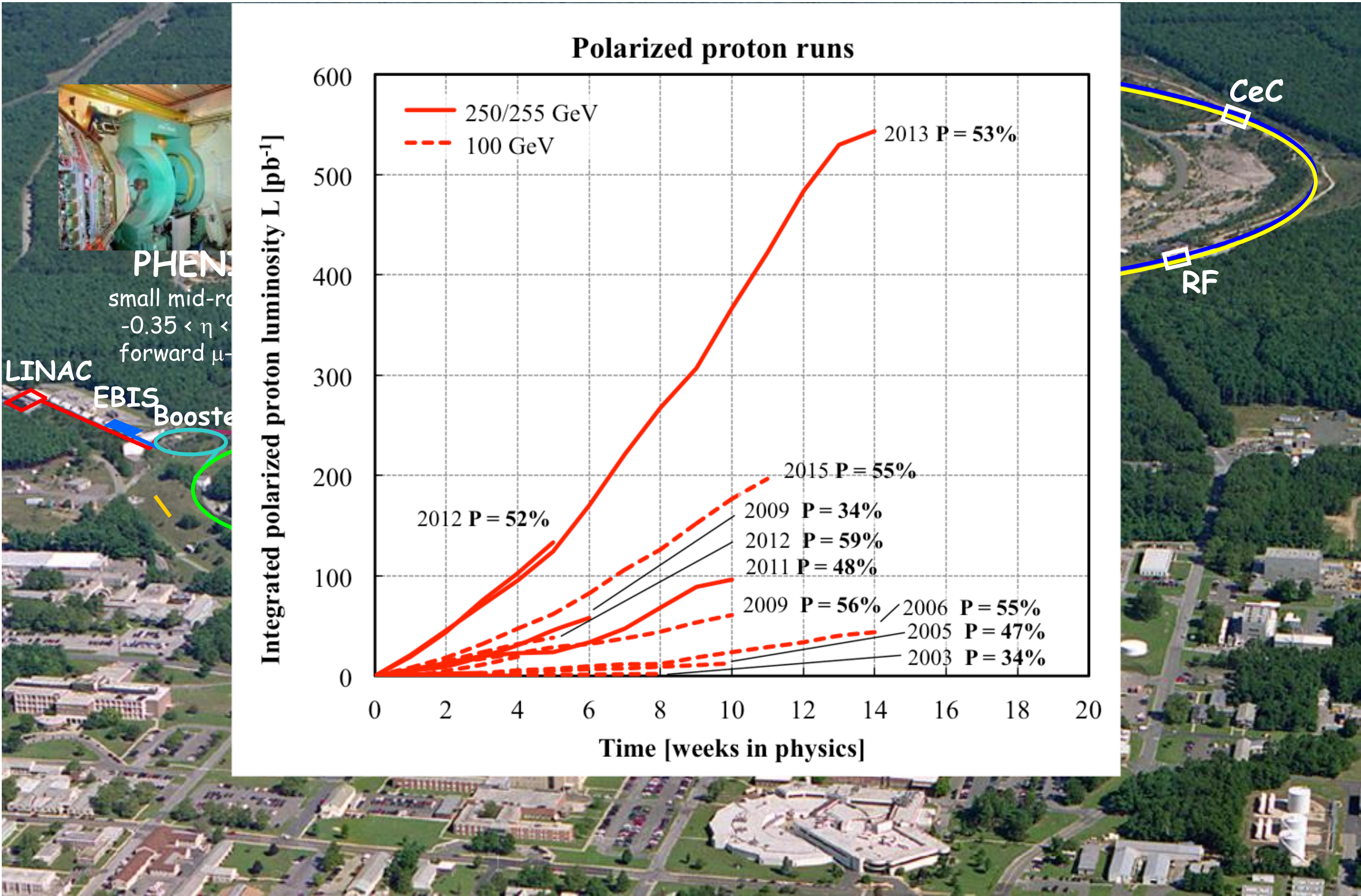
Polar. weak boson production (only at RHIC)

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

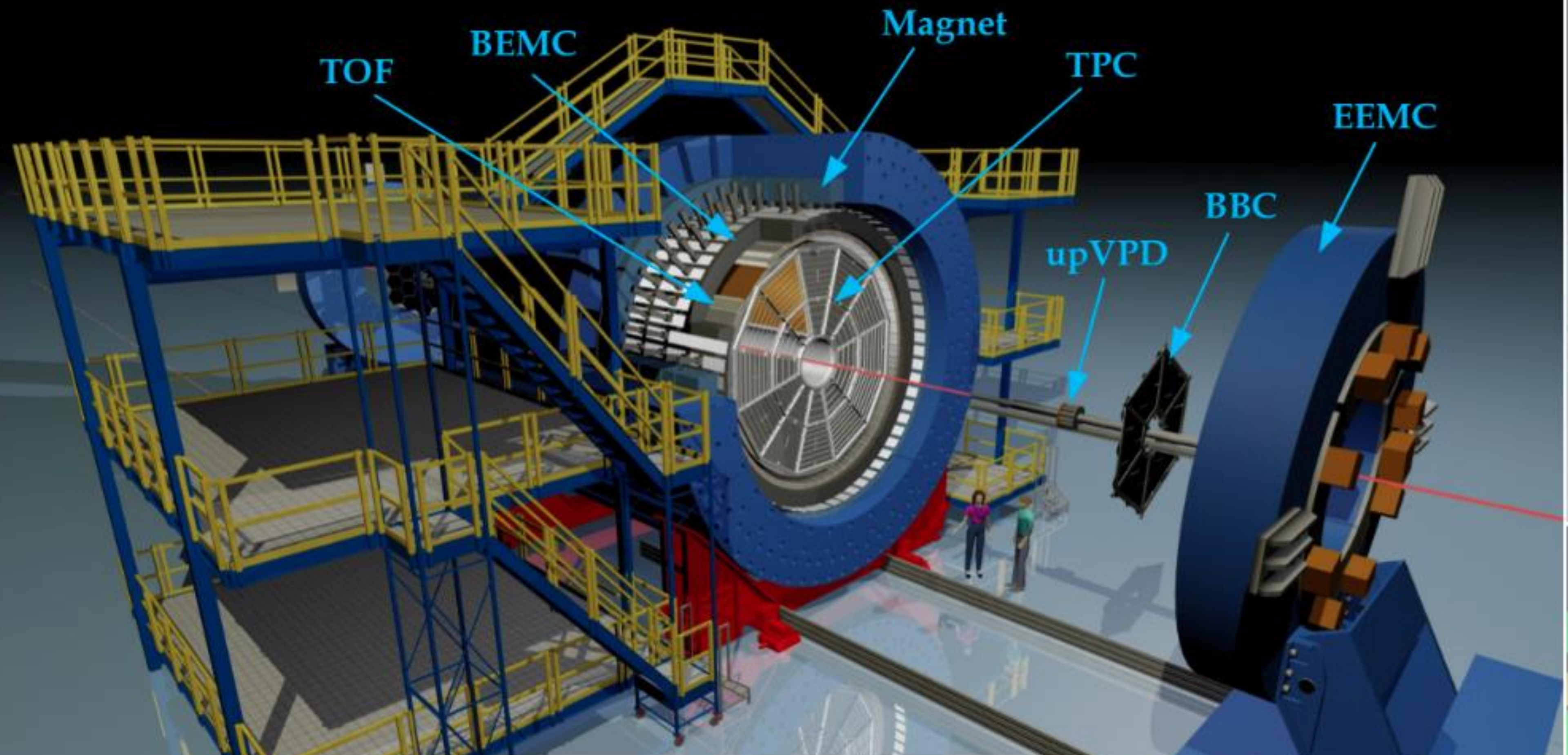
Sivers Function and DY, W and direct photons

	$A_N(W^{+/-}, Z^0)$	$A_N(DY)$	$A_N(\gamma)$
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

RHIC@BNL in 2016



The Solenoid Tracker At RHIC (STAR)



- Full azimuthal coverage
- $-1 < \eta < 1$ coverage
- Uniform acceptance for all beam energies
- Excellent PID

Measurement of TSSA for weak bosons @ STAR

PRL 116, 132301 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

Measurement of the Transverse Single-Spin Asymmetry in $p^\uparrow + p \rightarrow W^\pm/Z^0$ at RHIC

L. Adamczyk,[1] J. K. Adkins,[20] G. Agakishiev,[18] M. M. Aggarwal,[31] Z. Ahammed,[49] I. Alekseev,[16] A. Aparin,[18] D. Arkhipkin,[3] E. C. Aschenauer,[3] A. Attri,[31] G. S. Averichev,[18] X. Bai,[7] V. Bairathi,[27] A. Banerjee,[49] R. Bellwied,[45] A. Bhasin,[17] A. K. Bhati,[31] P. Bhattarai,[44] J. Bielcik,[10] J. Bielcikova,[11] L. C. Bland,[3] I. G. Bordyuzhin,[16] J. Bouchet,[19] J. D. Brandenburg,[37] A. V. Brandin,[26] I. Bunzarov,[18] J. Butterworth,[37] H. Caines,[53] M. Calderón de la Barca Sánchez,[5] J. M. Campbell,[29] D. Cebra,[5] I. Chakaberia,[3] P. Chaloupka,[10] Z. Chang,[43] S. Chattopadhyay,[49] X. Chen,[22] J. H. Chen,[40] J. Cheng,[46] M. Cherney,[9] W. Christie,[3] G. Contin,[23] H. J. Crawford,[4] S. Das,[13] L. C. De Silva,[9] R. R. Debbe,[3] T. G. Dedovich,[18] J. Deng,[39] A. A. Derevschikov,[33] B. di Ruzza,[3] L. Didenko,[3] C. Dilks,[32] X. Dong,[23] J. L. Drachenberg,[48] J. E. Draper,[5] C. M. Du,[22] L. E. Dunkelberger,[6] J. C. Dunlop,[3] L. G. Efimov,[18] J. Engelage,[4] G. Eppley,[37] R. Esha,[6] O. Evdokimov,[8] O. Eyser,[3] R. Fatemi,[20] S. Fazio,[3] P. Federic,[11] J. Fedorisin,[18] Z. Feng,[7] P. Filip,[18] Y. Fisyak,[3] C. E. Flores,[5] L. Fulek,[1] C. A. Gagliardi,[43] D. Garand,[34] F. Geurts,[37] A. Gibson,[48] M. Girard,[50] L. Greiner,[23] D. Grosnick,[48] D. S. Gunarathne,[42] Y. Guo,[38] A. Gupta,[17] S. Gupta,[17] W. Guryn,[3] A. Hamad,[19] A. Hamed,[43] R. Haque,[27] J. W. Harris,[53] L. He,[34] S. Heppelmann,[32] S. Heppelmann,[5] A. Hirsch,[34] G. W. Hoffmann,[44] D. J. Hofman,[8] S. Horvat,[53] X. Huang,[46] H. Z. Huang,[6] B. Huang,[8] T. Huang,[28] P. Huck,[7] T. J. Humanic,[29] G. Igo,[6] W. W. Jacobs,[15] H. Jang,[21] A. Jentsch,[44] J. Jia,[3] K. Jiang,[38] E. G. Judd,[4] S. Kabana,[19] D. Kalinkin,[15] K. Kang,[46] K. Kauder,[51] H. W. Ke,[3] D. Keane,[19] A. Kechechyan,[18] Z. H. Khan,[8] D. P. Kikoła,[50] I. Kisel,[12] A. Kisiel,[50] L. Kochenda,[26] D. D. Koetke,[48] L. K. Kosarzewski,[50] A. F. 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Pile,[3] J. Pluta,[50] K. Poniatowska,[50] J. Porter,[23] M. Posik,[42] A. M. Poskanzer,[23] N. K. Pruthi,[31] J. Putschke,[51] H. Qiu,[23] A. Quintero,[19] S. Ramachandran,[20] R. Raniwala,[36] S. Raniwala,[36] R. L. Ray,[44] H. G. Ritter,[23] J. B. Roberts,[37] O. V. Rogachevskiy,[18] J. L. Romero,[5] A. Roy,[49] L. Ruan,[3] J. Rusnak,[11] O. Rusnakova,[10] N. R. Sahoo,[43] P. K. Sahu,[13] I. Sakrejda,[23] S. Salur,[23] J. Sandweiss,[53] A. Sarkar,[14] J. Schambach,[44] R. P. Scharenberg,[34] A. M. Schmah,[23] W. B. Schmidke,[3] N. Schmitz,[24] J. Seger,[9] P. Seyboth,[24] N. Shah,[40] E. Shahaliev,[18] P. V. Shanmuganathan,[19] M. Shao,[38] M. K. Sharma,[17] B. Sharma,[31] W. Q. Shen,[40] Z. Shi,[23] S. S. Shi,[7] Q. Y. Shou,[40] E. P. Sichtermann,[23] R. Sikora,[1] M. Simko,[11] S. Singha,[19] M. J. Skoby,[15] D. Smirnov,[3] N. Smirnov,[53] W. Solyst,[15] L. Song,[45] P. Sorensen,[3] H. M. Spinka,[2] B. Srivastava,[34] T. D. S. Stanislaus,[48] M. Stepanov,[34] R. Stock,[12] M. 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(STAR Collaboration)

New paper from STAR

Phys. Rev. Lett. 116, 132301 (2016)

Editor's suggestion

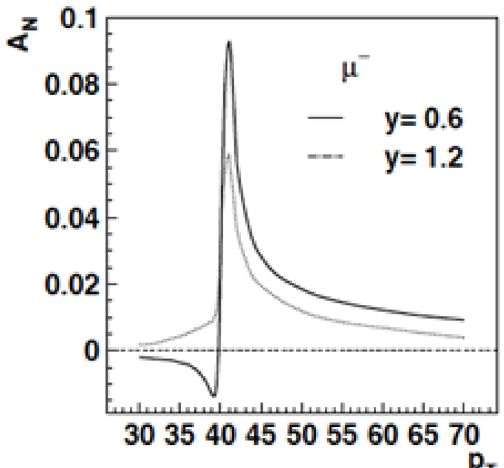
[arXiv:1511.06003]

World's first direct experimental test of the sign change in the Sivers function

- **RHIC is the only polarized p+p collider.** Its top energy is enough to produce weak bosons
- **Selection of weak bosons well established at STAR**
  - **Long. spin asymmetries:**
    Phys. Rev. Lett. 113, 072301 (2014)
    Phys. Rev. Lett. 106, 062002 (2011)
  - **unpolarized xsec:**
    Phys. Rev. D 85, 092010 (2012)
- **This measurement is STAR's first attempt to reconstruct the produced boson's kinematics**

W RECONSTRUCTION WITH RECOIL

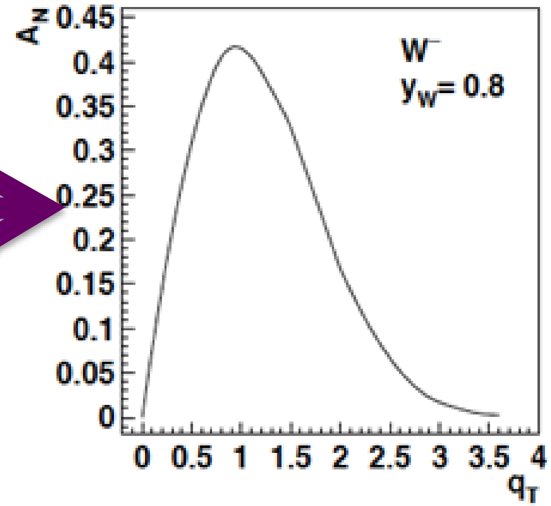
Decay Lepton Asymmetries



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

Dec

W Asymmetries



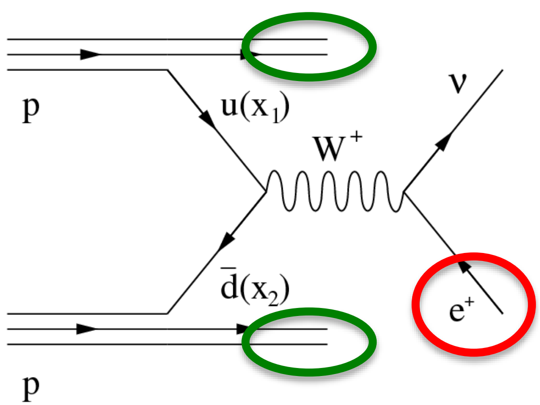
l to measure

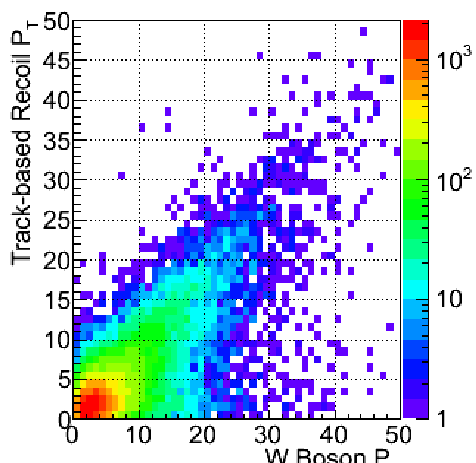
rom W decay

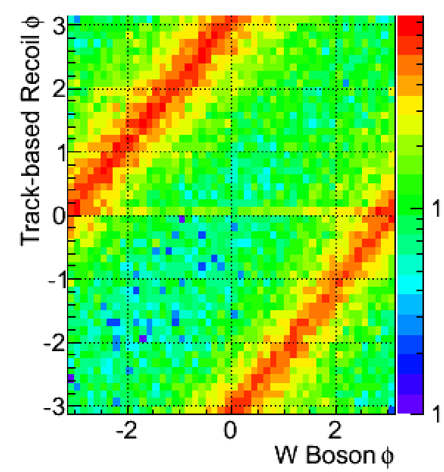
recoil

W momentum reconstruction well tested at FermiLab and LHC

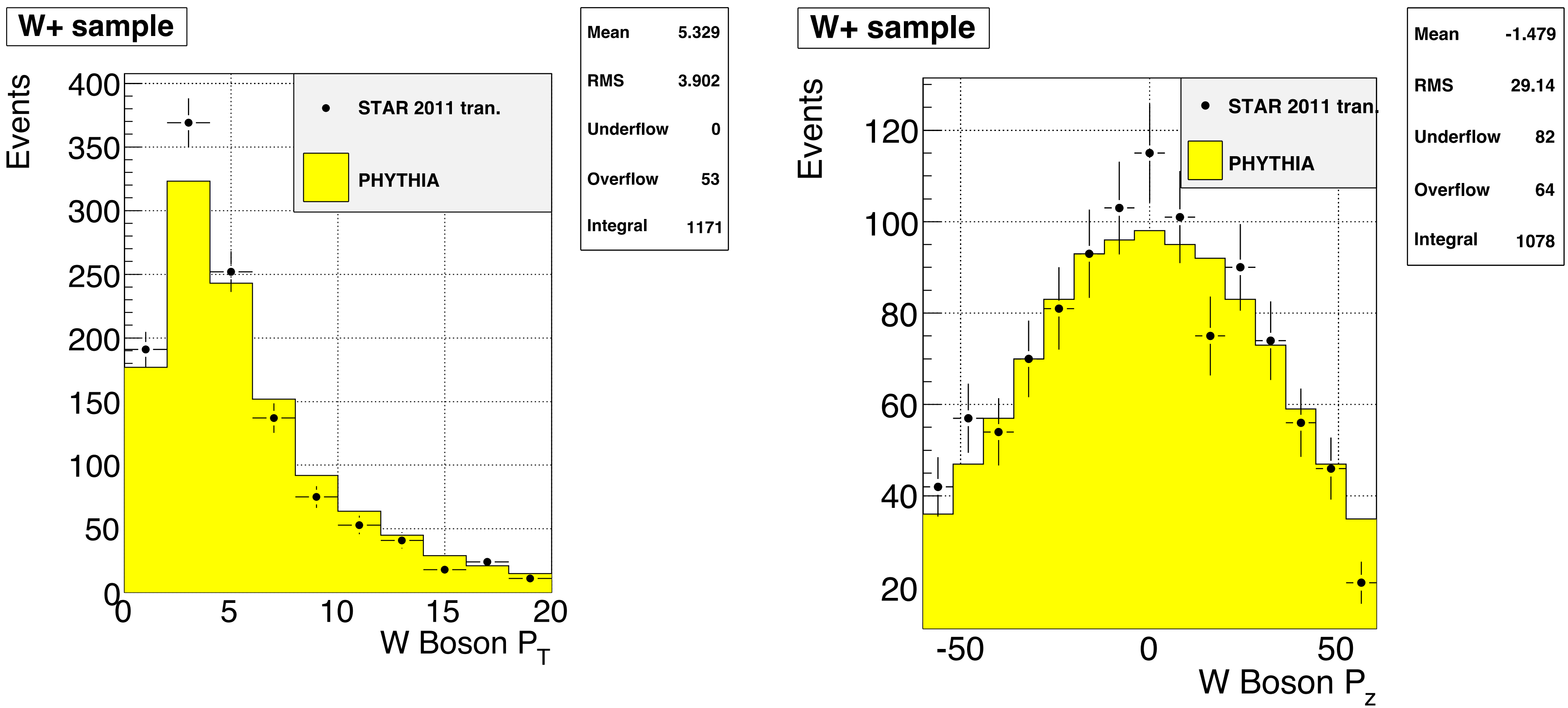
[CDF: PRD 70, 032004 (2004); ATLAS: JHEP 1012 (2010) 060]







W RECONSTRUCTION DATA VS MC



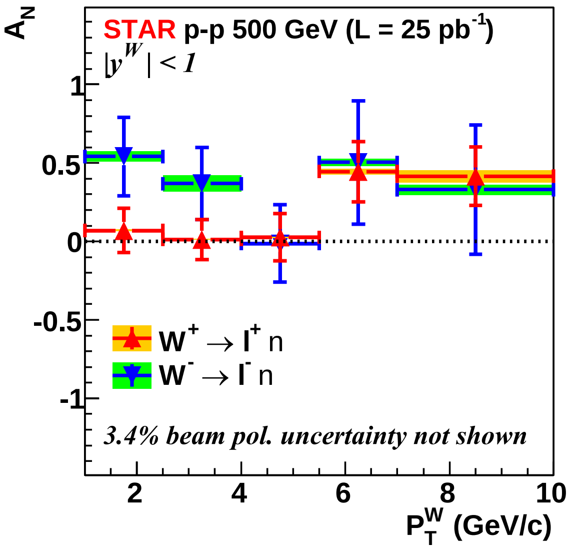
GOOD data/MC agreement

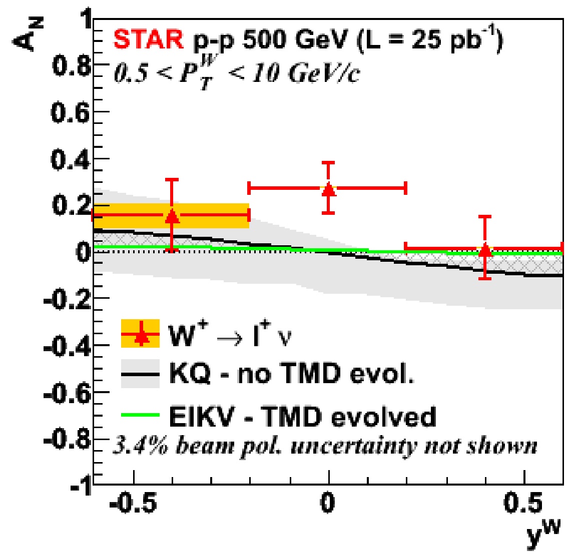
A_N FOR W PRODUCTION

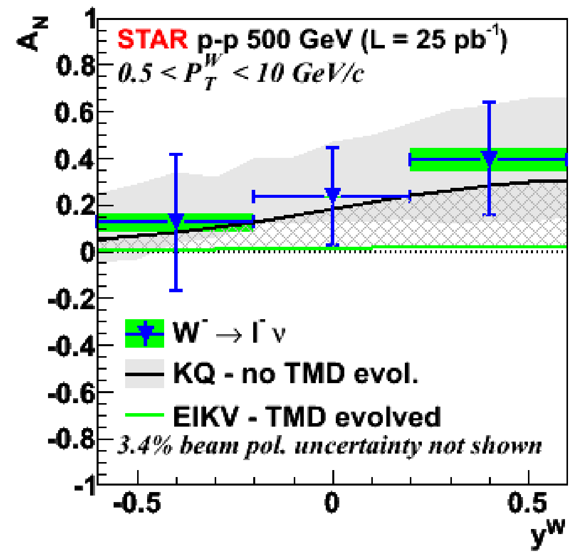
We use the "left-right" formula to cancel dependencies on geometry and luminosity

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

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





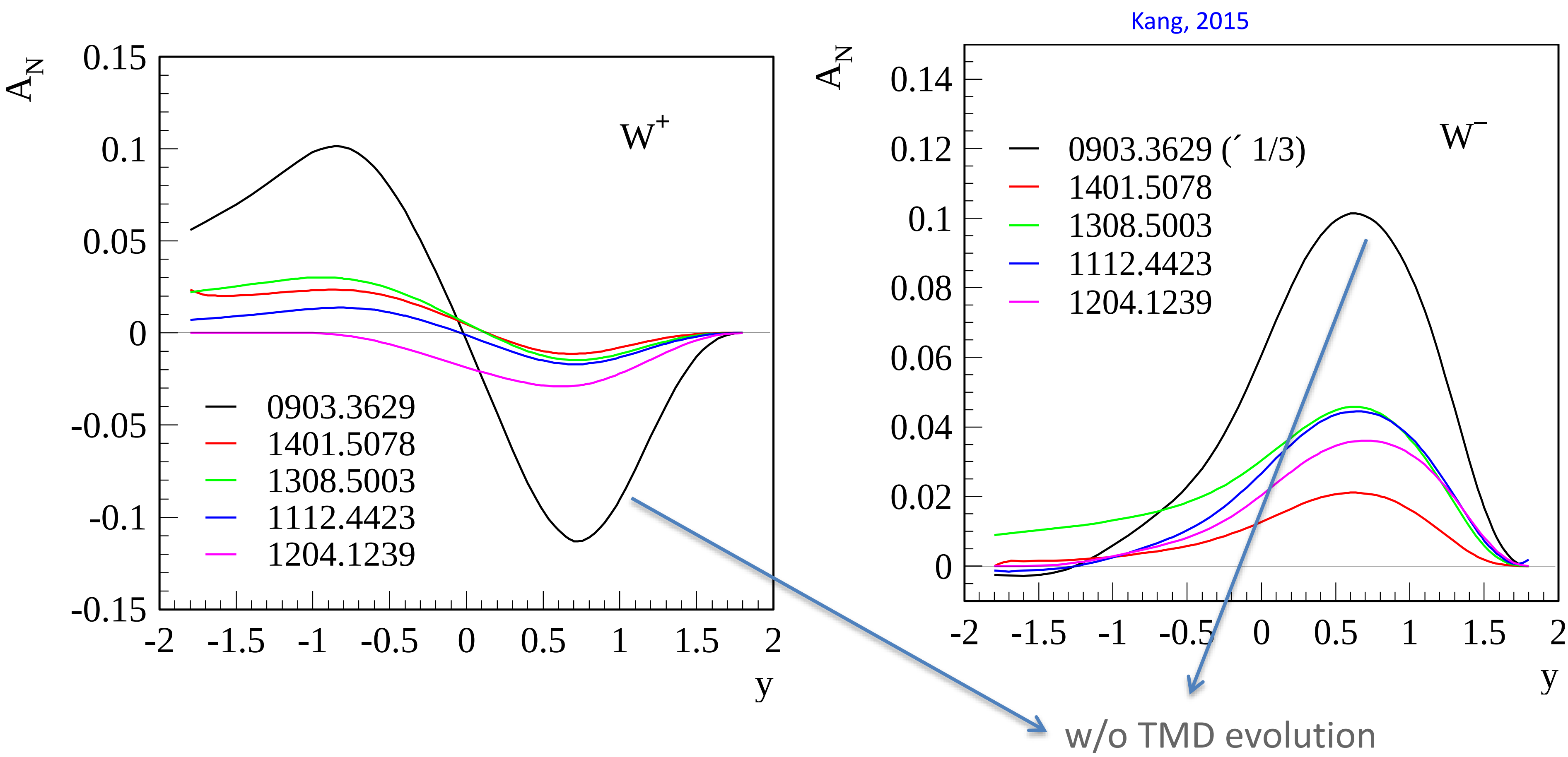


Results versus rapidity are compared with:

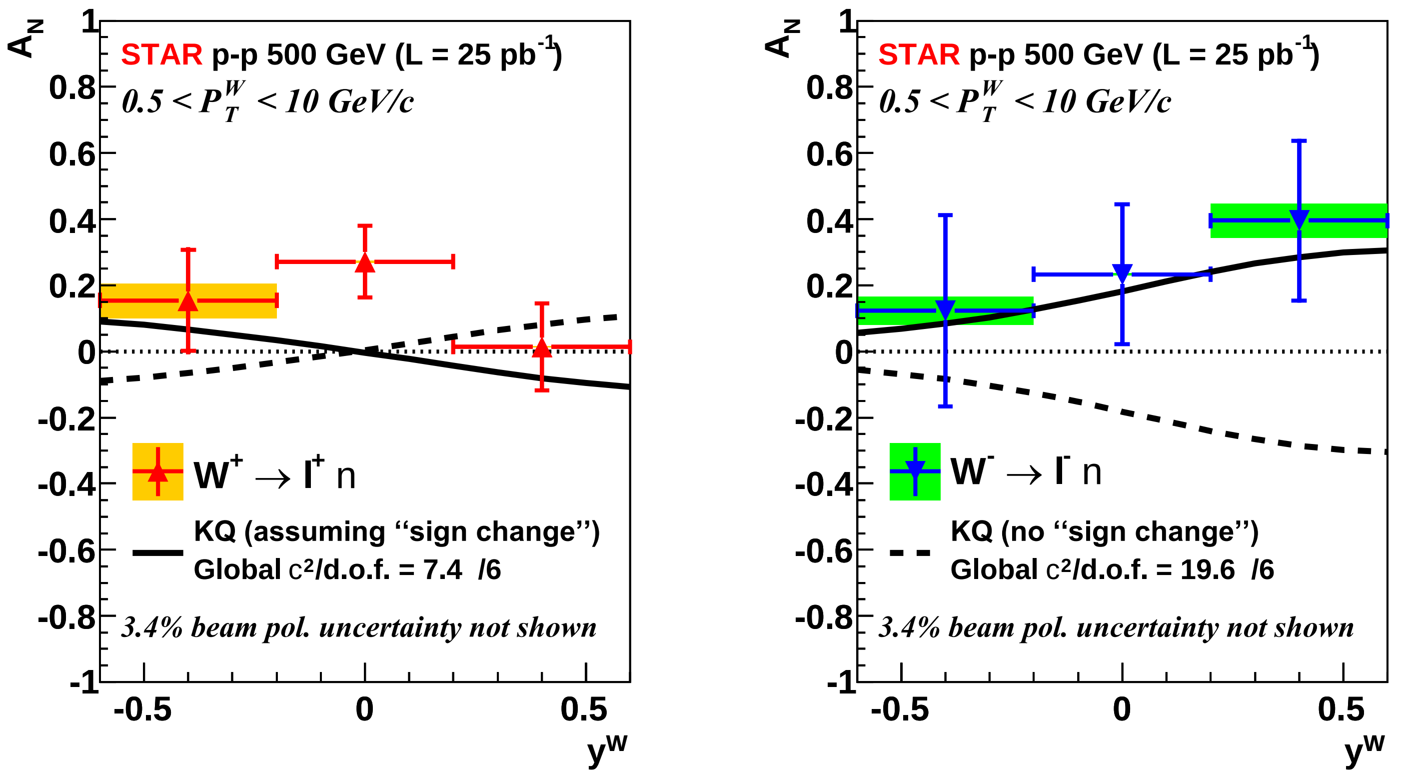
- **KQ model** [Z.-B. Kang and J. -W. Qiu, Phys. Rev. Lett. 103, 172001 (2009)]
  - It does not include TMD evolution
  - **Grey band** is the theory uncertainty
- **EIKV model** [M. G. Echevarria, A. Idilbi, Z.-B. Kang, I. Vitev, Phys. Rev. D89, 074013 (2014)]
  - Includes the largest prediction for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

TMD Q^2 EVOLUTION

- Even the evolution formalism itself has large room to improve
- Non-perturbative Sudakov needs further improvement
- Large Q^2 coverage from SIDIS to DY to W/Z



SIVER'S SIGN CHANGE, IF NO TMD EVOLUTION



A global fit to the (unevolved) KQ prediction was performed:

- **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**

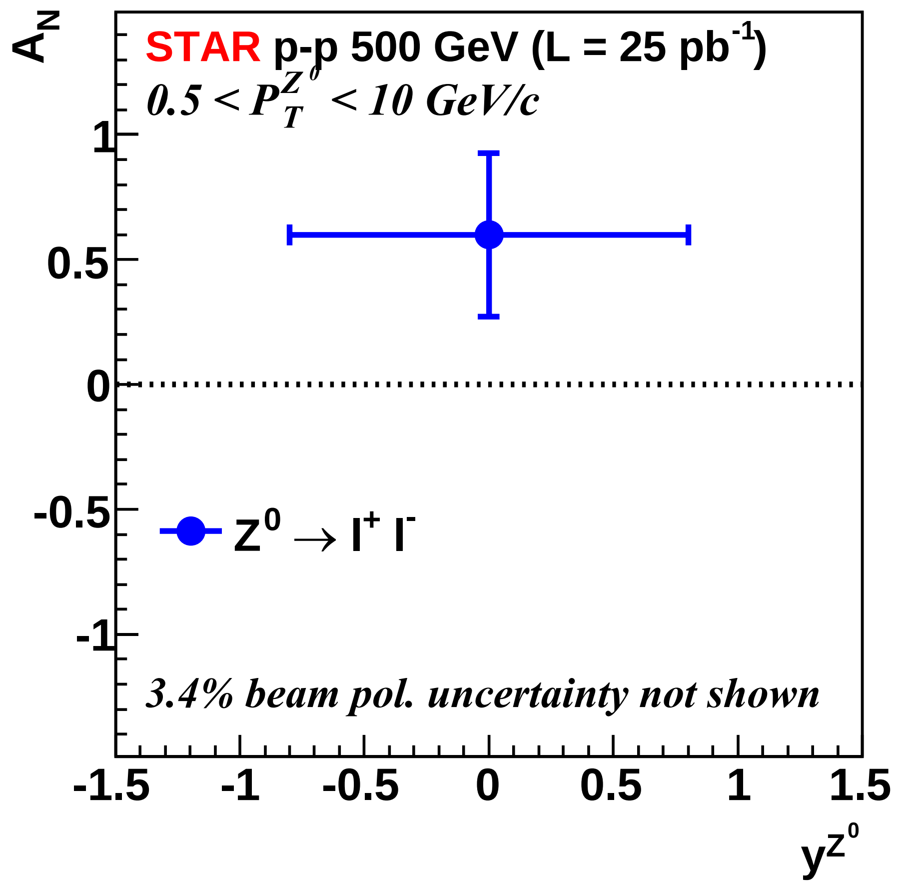
If there are no evolution effects,
our data favor the hypothesis of Sivers sign change

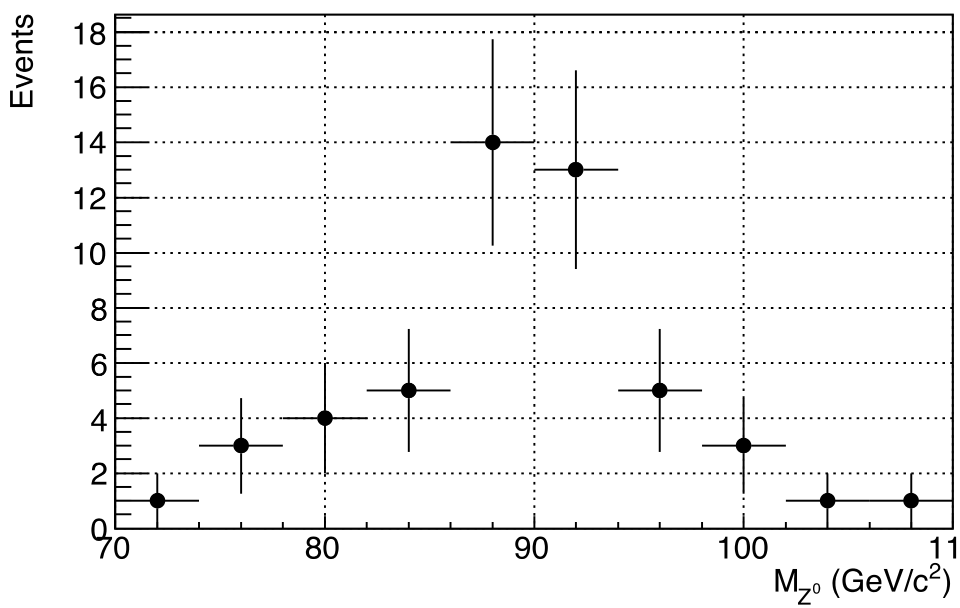
A_N FOR Z^0 PRODUCTION

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

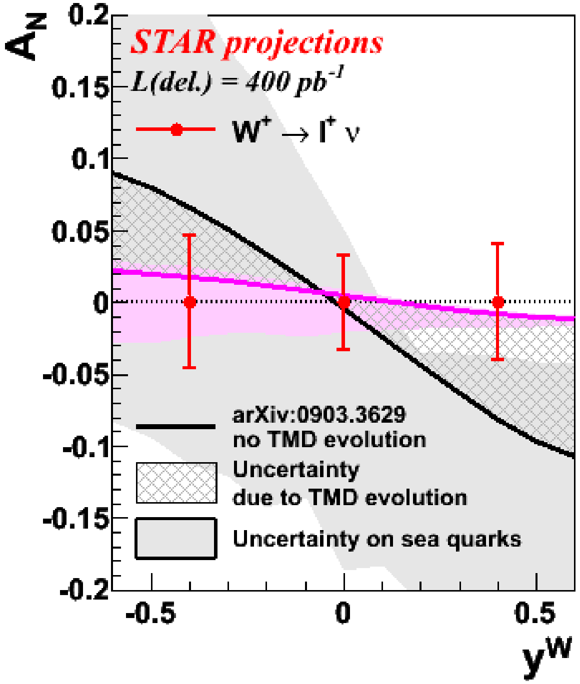
$$pp \rightarrow Z^0 \rightarrow e^+e^-$$

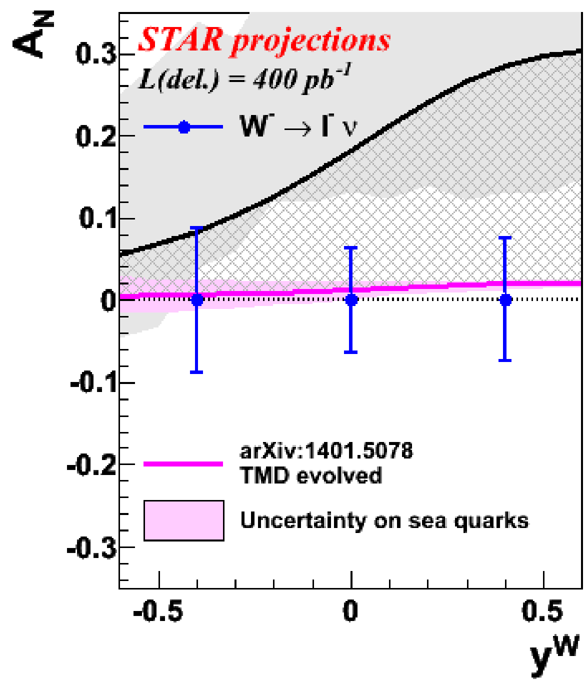
A_N measured in a single y, P_T bin

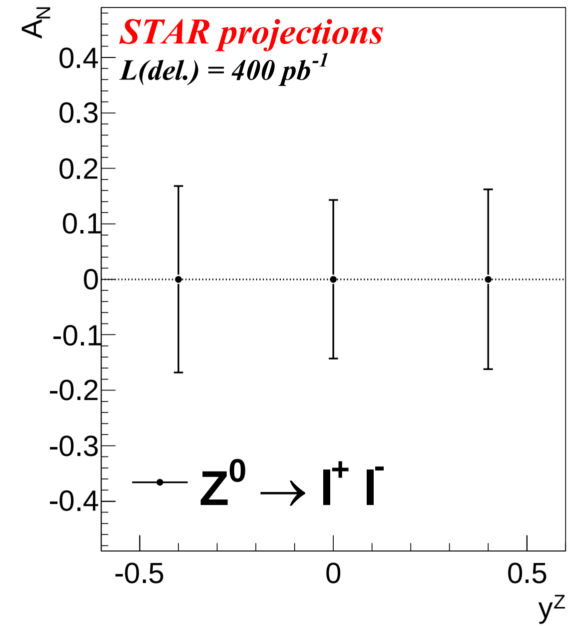




RUN17 W/Z EXPECTATION







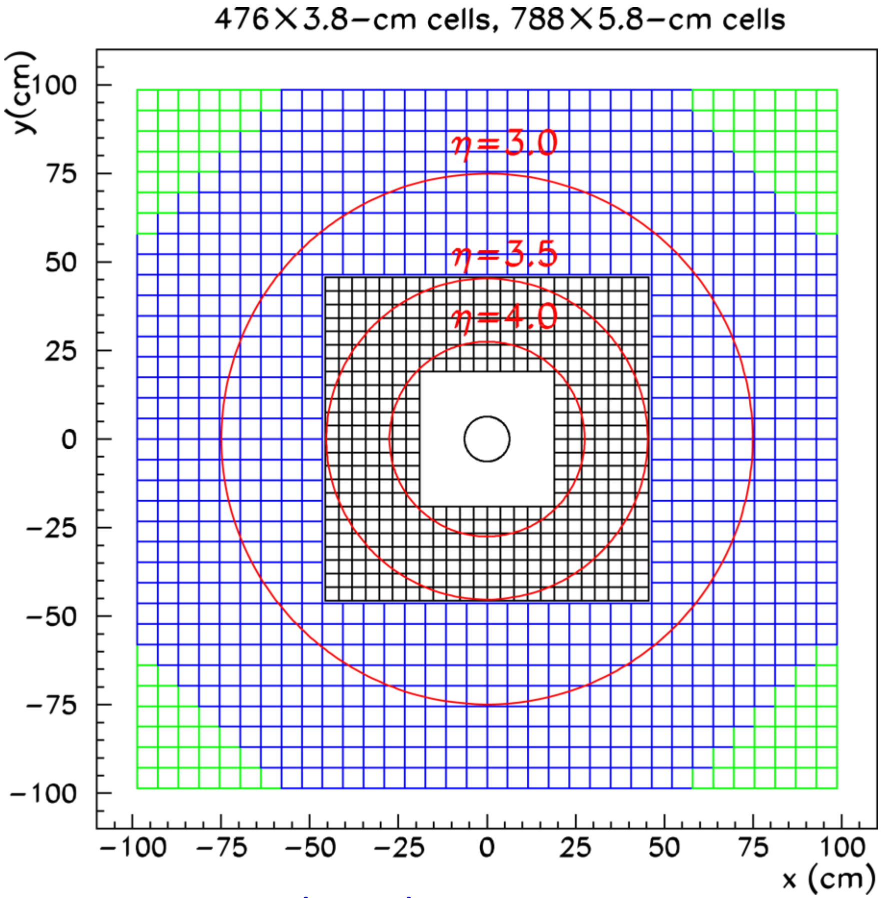
Large statistics will allow us to

- **Precisely measure A_N for Ws within a few %** in several P_T, y bins.
- Measure the very clean **Z^0 channel**.
- Test sign change if evolution is less than factor ~5

Run11 had 25pb^{-1}

Run17 expectation is 400 pb^{-1}

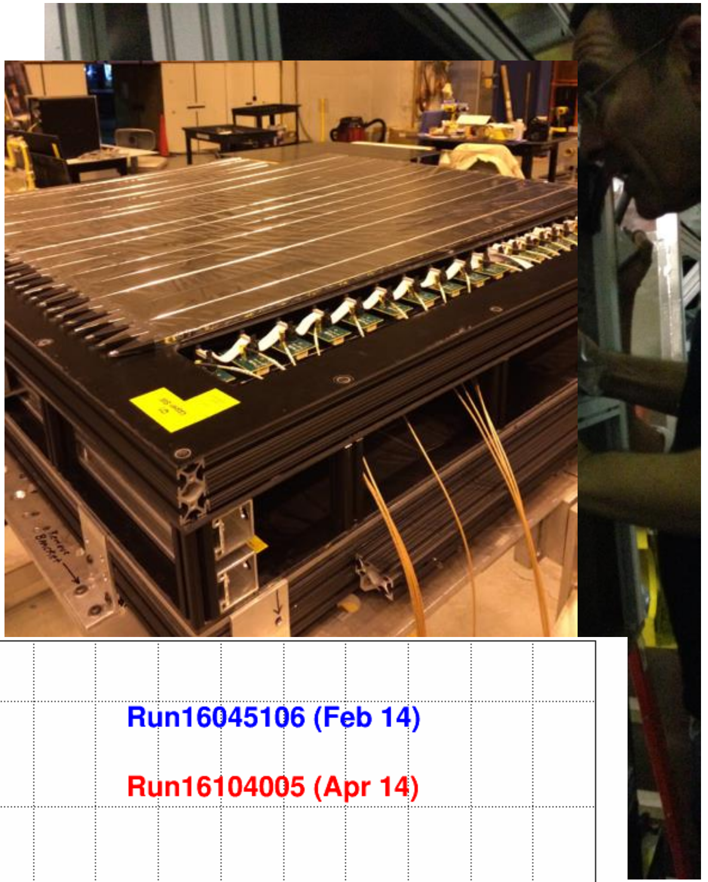
STAR FORWARD CALORIMETER (FMS)

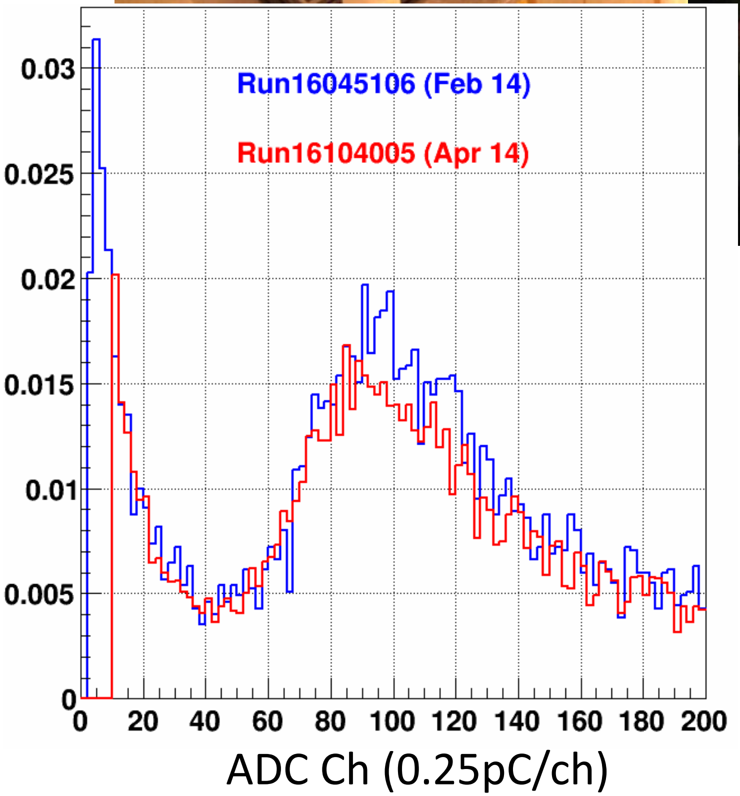


- A_N for pi0 / eta / EM-jet
- A_N for direct photon (FPS)
- A_N with diffractive tag (roman pot)
- A_N in pAu & pAl
- (unpol) Gluon Saturation
- DY and J/Psi (Run 17)

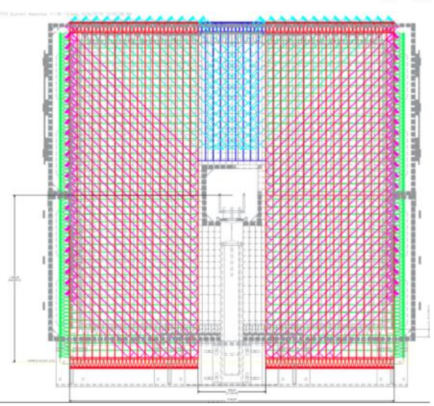
RUN 15

- FMS refurbishment
  - Annealing PbG with sun light and re-stack
  - Replaced unstable PMT-bases
  - Trigger upgrade
- FPS for photon/electron/hadron PID
  - SiPM (Hamamatsu S12572) readout
  - 3 layer scinti. with Pb conveter in front of FMS



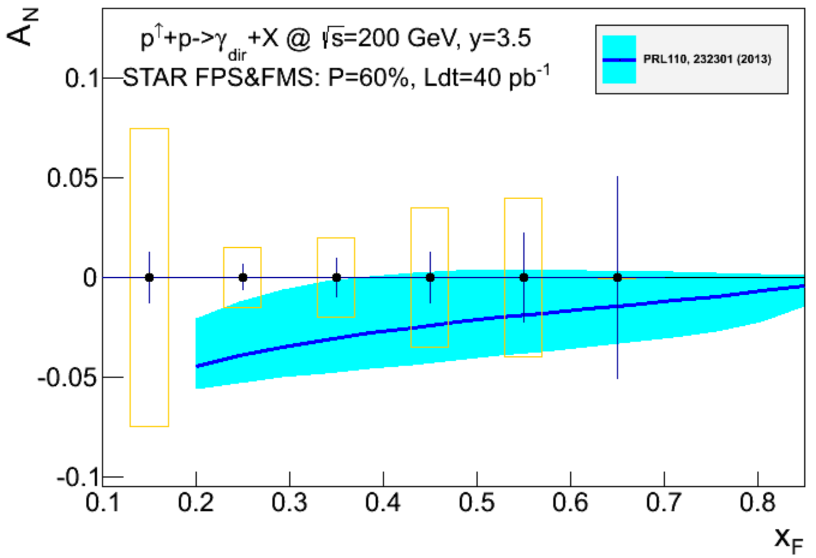


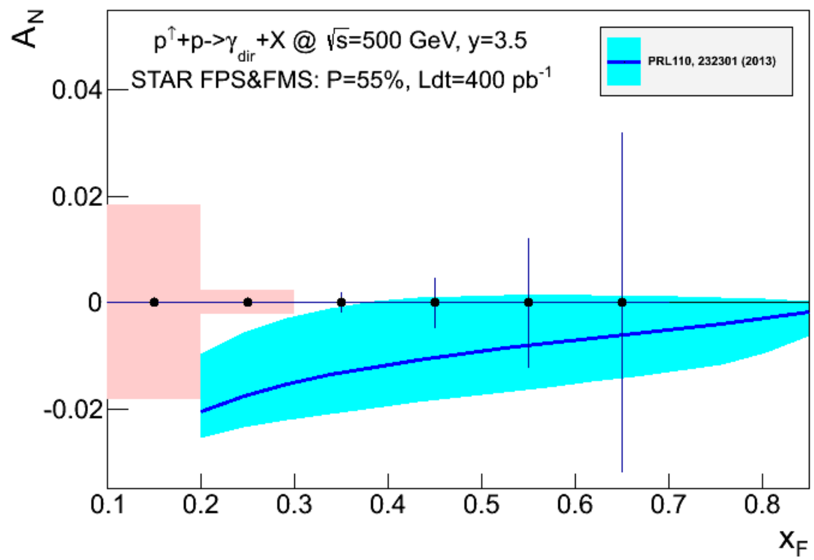
RUN 17



Post Shower Detector
Design follows successful
Preshower design
→ 3 layers of u, x, y with
SiPM readout

RUN15 DIRECT PHOTON A_N





A_N for direct photon production:

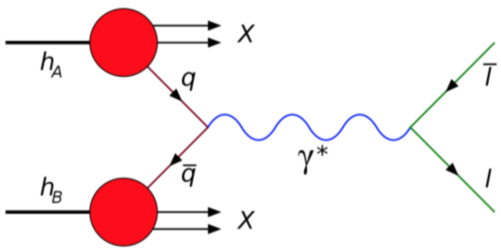
- sensitive to sign change, but in TWIST-3 formalism
- indirect constraints on Sivers fct
- no sensitivity to sea-quarks; mainly u_v and d_v at high x
- collinear objects but more complicated evolutions than simple DGLAP

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

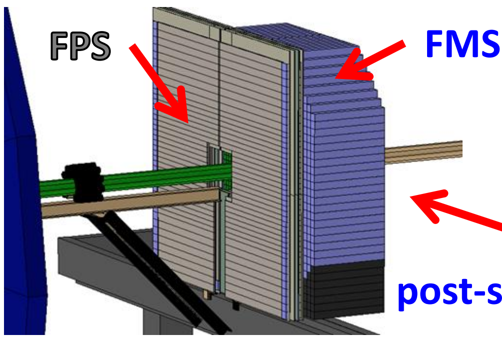
Not a replacement for a $A_N(W^{+/-}, Z^0, DY)$ measurement
but an important complementary piece in the puzzle

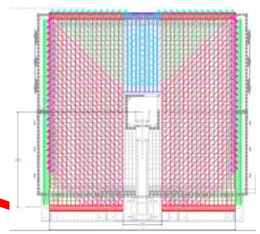
Analysis is on-going….

RUN17 DY A_N



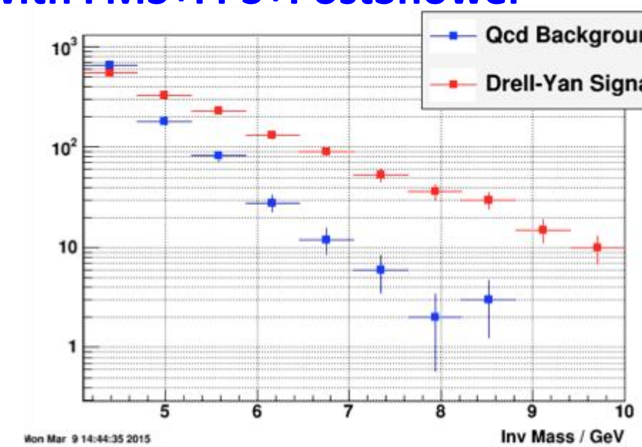
- **Very Challenging (RHIC QCD WP arXiv:1602.03922)**
- QCD background ~10^5-10^6 larger than DY cross-section
- Need to reduce hadron background by ~10^3 per particle
- PID and background rejection is the key



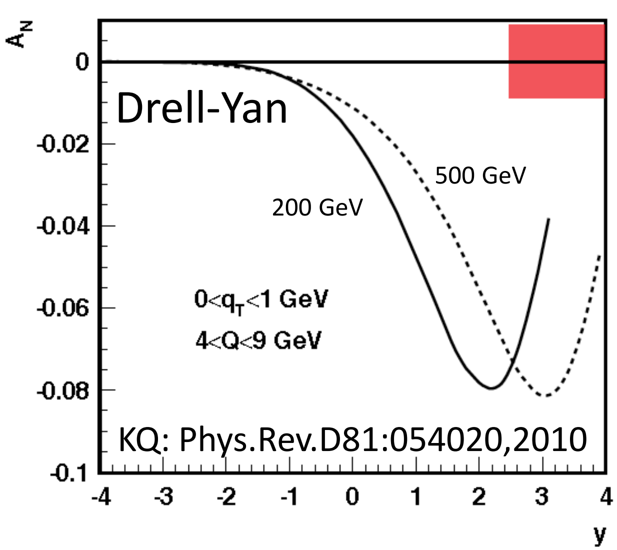


post-shower upgrade

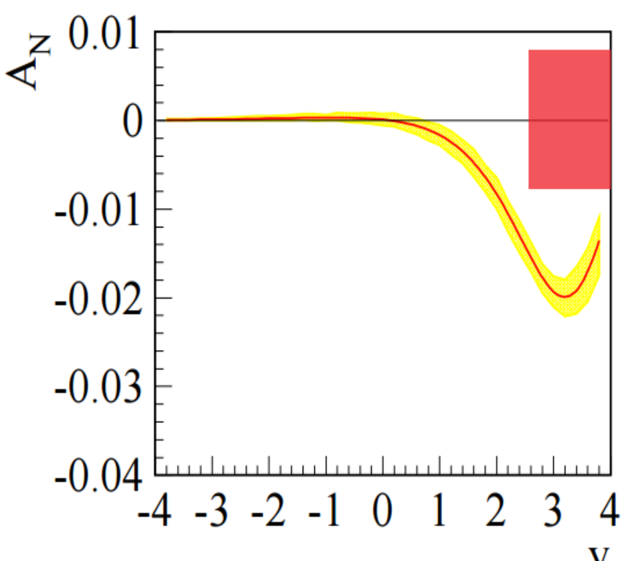
The expected yields of DY and QCD background with FMS+FPS+PostShower



No TMD Evolution



With TMD Evolution



Run-17 $\int L_{del}$=400 pb^{-1}
→ A_N for DY to +/- 0.008

RHIC polarized p+p & p+A Timeline

2015 — 2017 — ≧2021 — ≧ 2025

Upgrades:
- FMS-Preshower
- MPCEX
- RP Phase-II*

Run:
- p+p 200 GeV longitudinal & transverse
- p↑+Au/Al 200 GeV transverse

Goal:
- $\Delta g(x,Q^2)$
- transverse sp…
  stru…
- …
- …
- S…

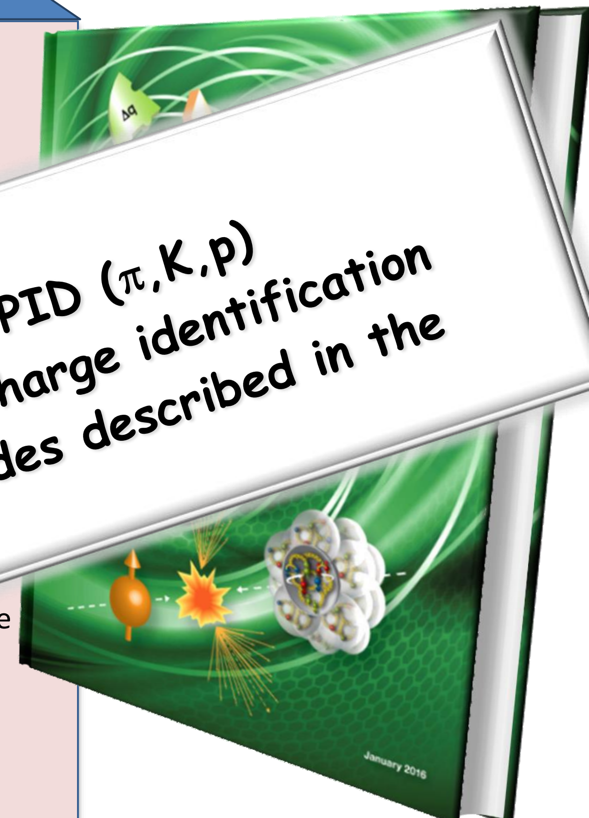
Upgrades:
- FMS-Postshower

Run:
- p+p 510 GeV transverse

Goal:
- A_N for $W^{\pm}$, Z^0, DY, γ
  → Sea-quark Sivers f…
  → sign change Si…
  → TMD…

Upgrades:
- Forward Ecal+Hcal
- Forward tracker
- RP full Phase II

Run:
- p+p 510 …
  …
- …ture of the
  …w and high x
- …MDs & Twist-3
- Spin effects in diffraction
- (un)pol FF
- nPDF: $g(x,Q^2)$, $q(x,Q^2)$
- Saturation
- (un)pol nFF



Needed Hardware:
- ➤ wide acceptance mid-rapidity detector with good PID (π,K,p)
- ➤ forward rapidities ($4.5 > \eta > 1$) Ecal + HCal + charge identification
- → both STAR and sPHENIX have dedicated upgrades described in the RHIC Cold QCD Plan

RHIC polarized p+p & p+A Timeline

2015 — 2017 — ≧2021 — ≧ 2025

2015

Upgrades:
- ❑ FMS-Preshower
- ❑ MPCEX
- ❑ RP Phase-II*

Run:
- ❑ p+p 200 GeV longitudinal & transverse
- ❑ p↑+Au/Al 200 GeV transverse

Goal:
- ❑ $\Delta g(x,Q^2)$
- ❑ transverse spin structure of the p
- ❑ Search for exotics

- ❑ Spin effects in diffraction
- ❑ J/Ψ in UPC → GPD E_g

- ❑ nPDF: $g(x,Q^2)$
- ❑ Saturation

2017

Upgrades:
- ❑ FMS-Postshower

Run:
- ❑ p+p 510 GeV transverse

Goal:
- ❑ A_N for $W^{\pm}$, Z^0, DY, γ
- → Sea-quark Sivers fct.
- → sign change Sivers fct.
- → TMD evolution

- ❑ transverse spin structure of the p
- ❑ Search for exotics

- ❑ Spin effects in diffraction
- ❑ J/Ψ in UPC → GPD E_g

≧2021

Upgrades:
- ❑ Forward Ecal+Hcal
- ❑ Forward tracker
- ❑ RP full Phase II

Run:
- ❑ p+p 510 GeV longitudinal & transverse

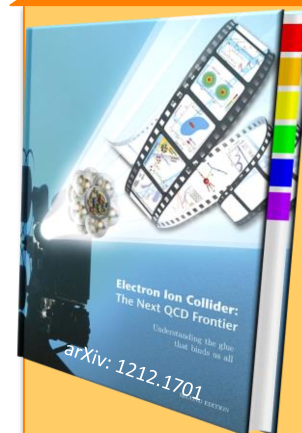
In parallel to sPHENIX:
- ❑ transverse pp 200 GeV
- ❑ p↑+A (C, Cu, Au) 200 GeV transverse

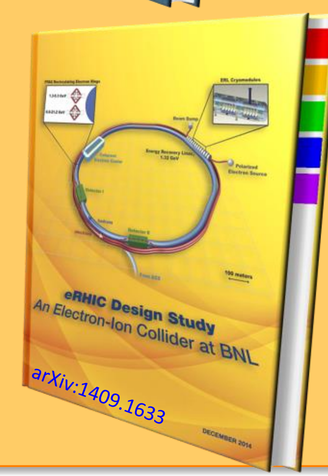
Goal:
- ❑ $\Delta g(x,Q^2)$ @ low x
- ❑ transverse spin structure of the proton at low and high x
  - → TMDs & Twist-3
- ❑ Spin effects in diffraction
- ❑ (un)pol FF

- ❑ nPDF: $g(x,Q^2)$, $q(x,Q^2)$
- ❑ Saturation
- ❑ (un)pol nFF

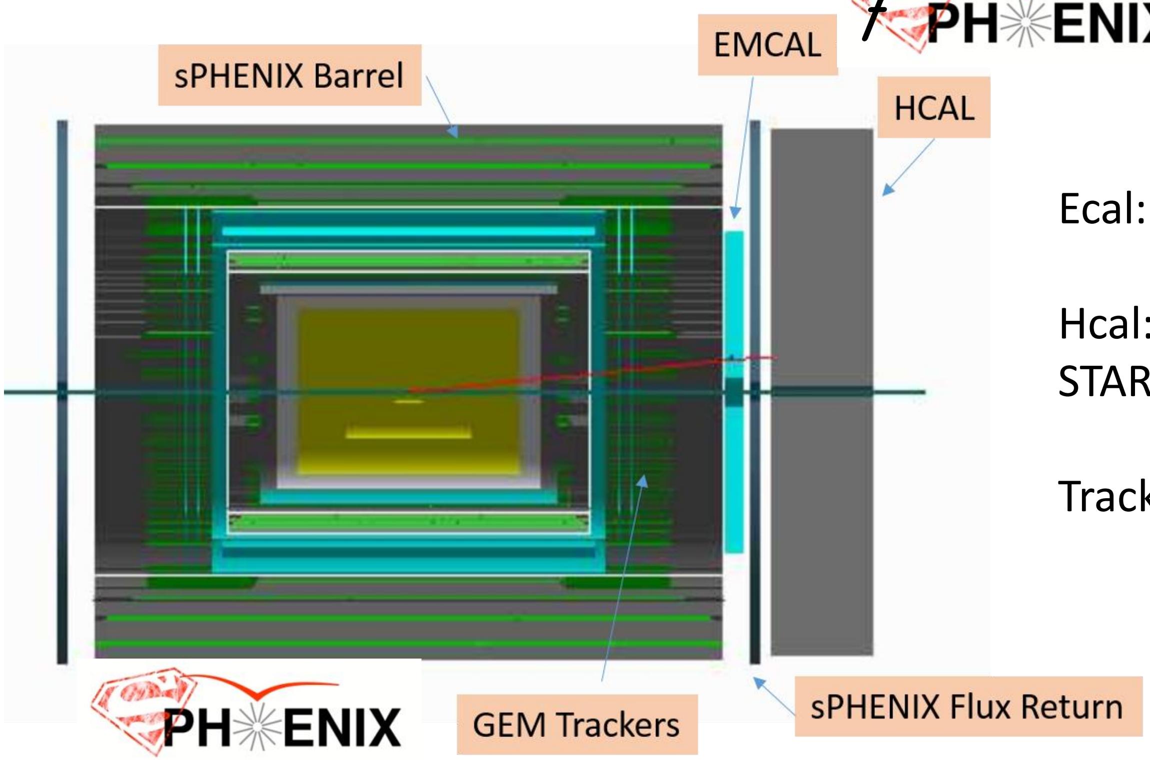
≧ 2025

eRHIC





fsPHENIX Upgrade Plans

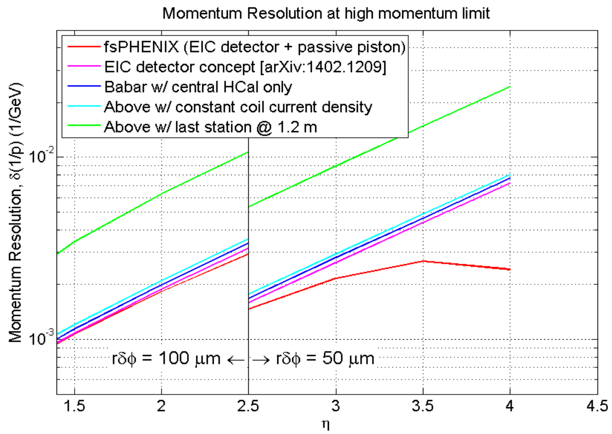


Ecal: reuse PHENIX Ecal

Hcal: follow design ideas from STAR fHCal and EIC fHCal

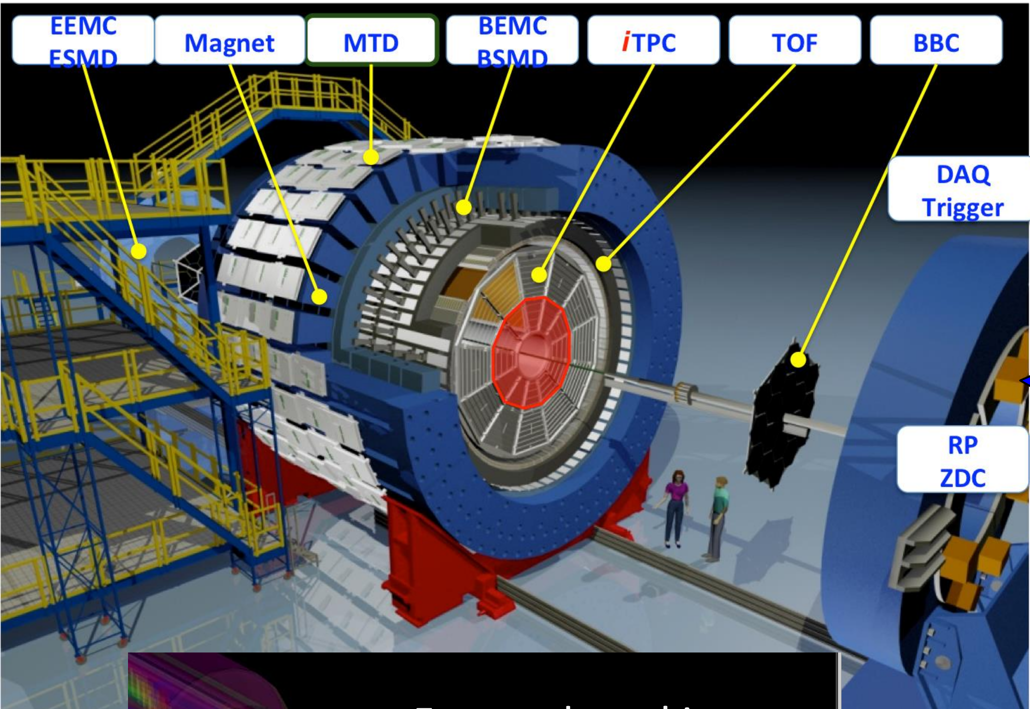
Tracking: 3 stations of GEM Trackers

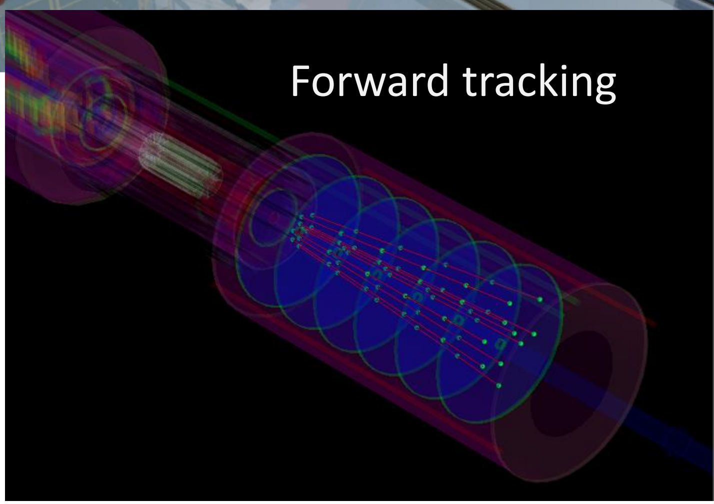
In addition to the central detector upgrade, sPHENIX has a plan for a forward arm 1 < η < 4.5



STAR forward Upgrade plans

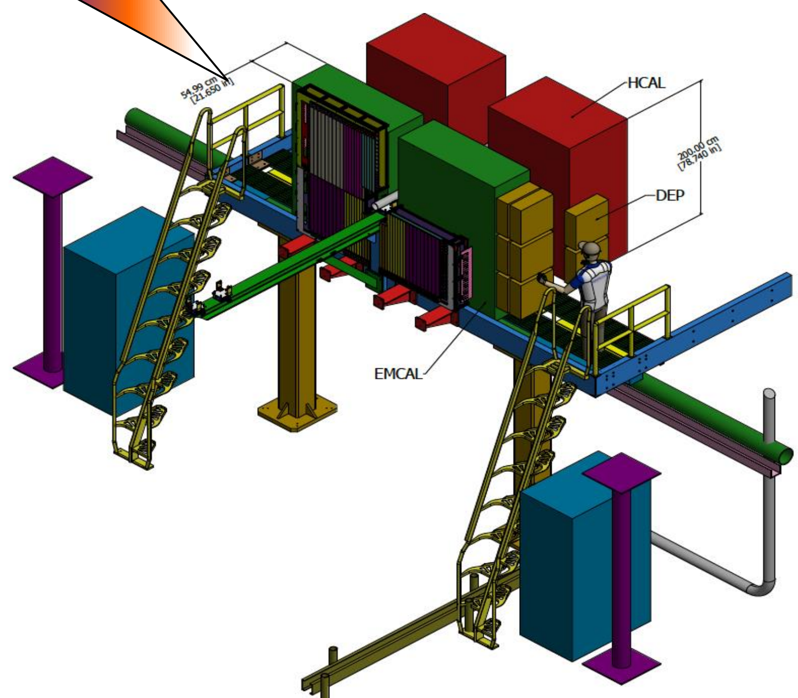
Add to existing STAR at rapidity $2.5 < \eta < 4.5$





Ecal: reuse PHENIX Ecal
Hcal: design ala STAR fHCal and EIC fHCal
Tracking: 4-6 Si strip-disks

Preshower &
ECal & HCal

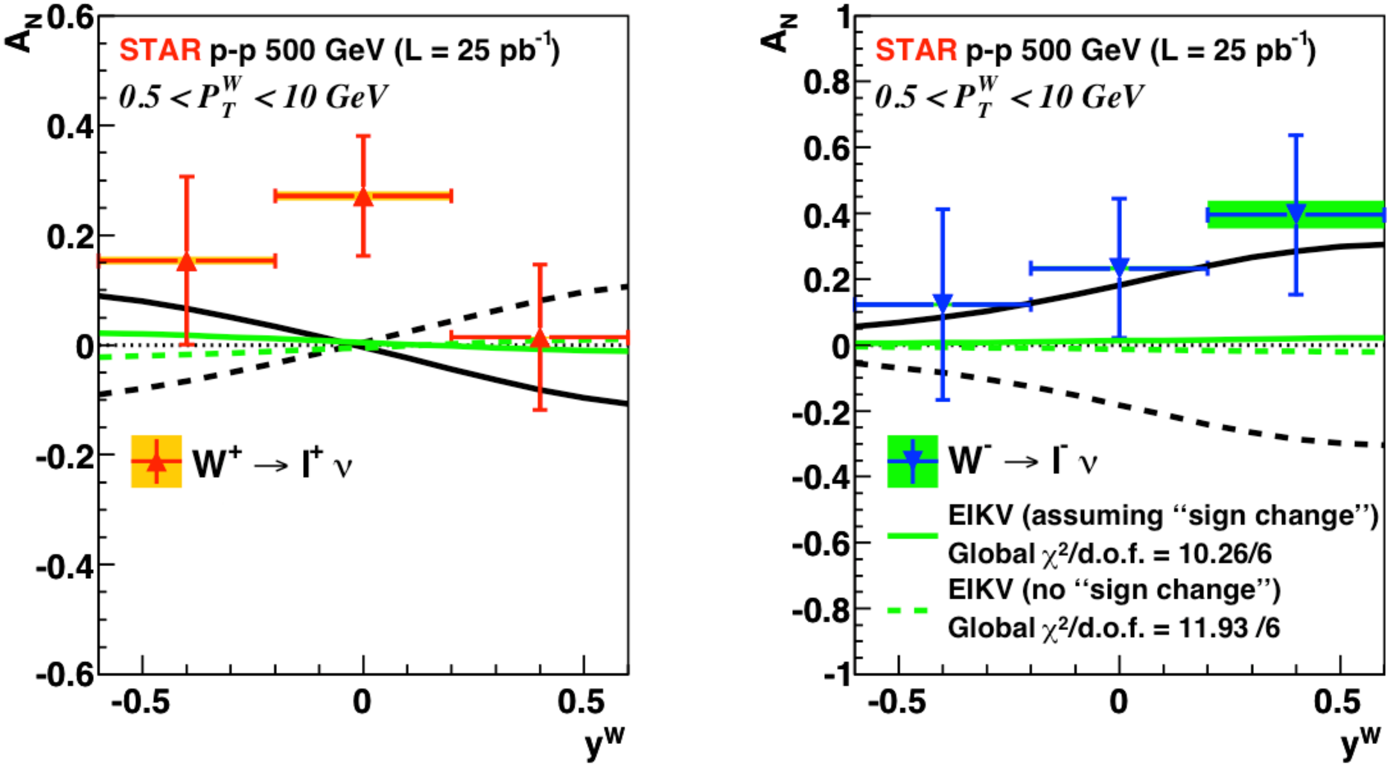


SUMMARY

- Gauge Boson (W,γ^*, γ) productions at RHIC are very unique and capable probe to study proton at RHIC
- Run11 (510GeV) first measurement of A_N for $W^\pm$ and Z^0
  - First indication of Siver's sign change, if one assumes no (small) TMD Q^2 evolution
- Run15 (200GeV) was successful with improved FMS with addition of FPS
  - Direct photon analysis is underway
  - Many other physics (A_N for pAu/pAl, A_N with diffractive tag, gluon saturation…)
- Run17 (510GeV) expected to deliver ~400/pb with transverse polarization
  - W, Z, DY, Photon
  - Large Q^2 range from DY to W/Z to see TMD Q^2 evolution
  - Sign change and flavor separation
- Future upgrades are being discussed for both STAR and sPhenix

BACKUP

The Sivers' sign change (strong TMD evol.)



Size of the TMD evolution still uncertain

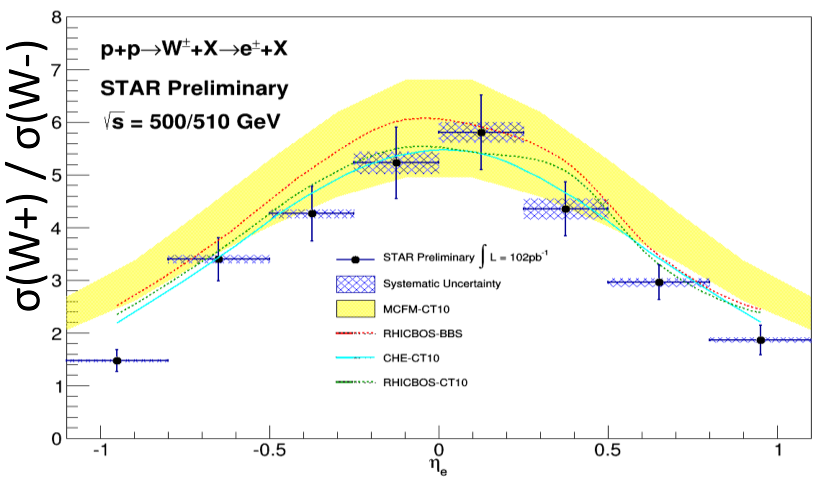
-> terms calculable from QCD + non-perturbative terms (need data)

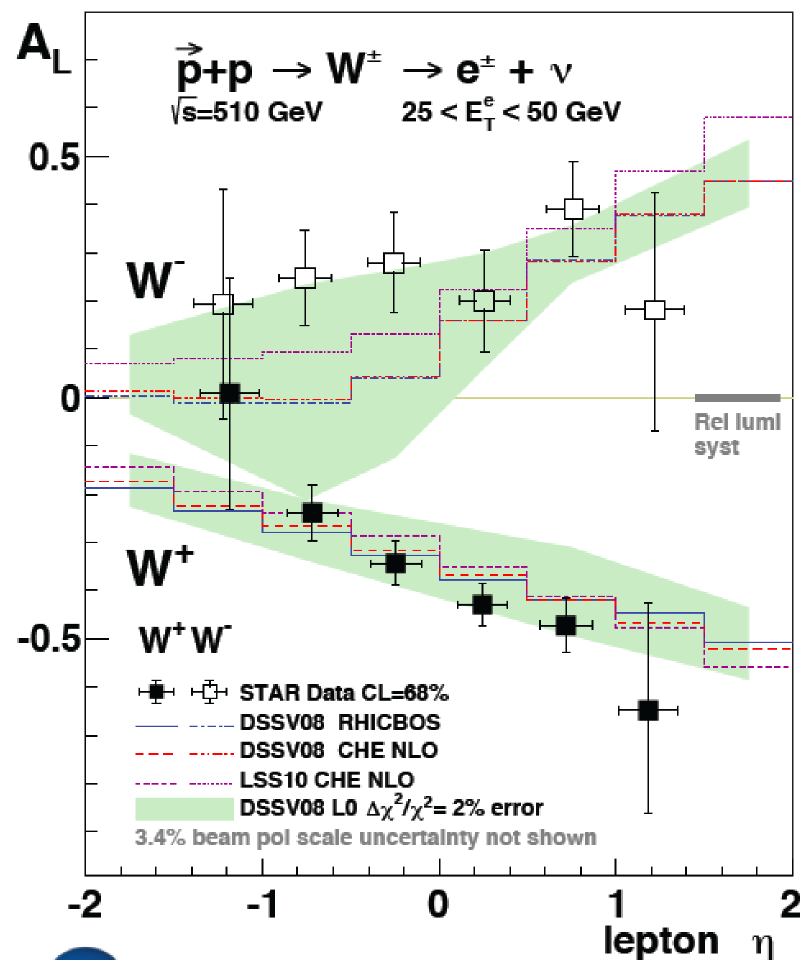
A global fit to the EIKV prediction (largest predicted evolution effect):

- **solid line:** assumption of a sign change in the Sivers function → **Chi2/d.o.f. = 10.26/6**
- **dashed line:** assumption of no sign change in the Sivers function → **Chi2/d.o.f. = 11.93/6**

Our uncertainties are still too high to compare with predictions

SEA QUARK FLAVOR SEPARATION



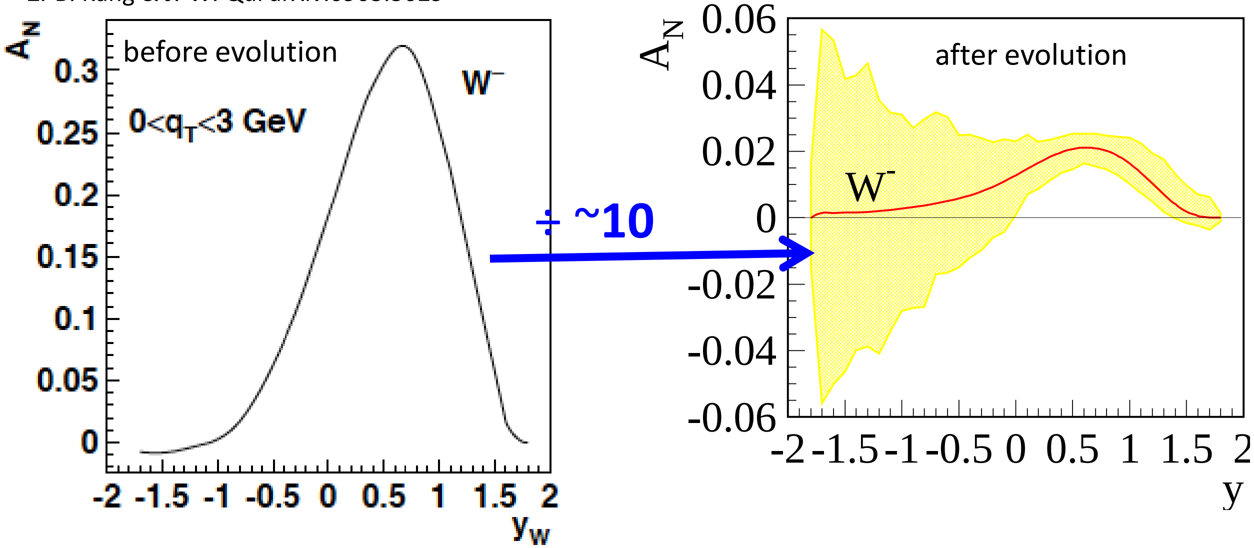


NEW arXiv:1404.6880

Motivations – The TMD evolution

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

Z. Kang: original paper arXiv:1401.5078



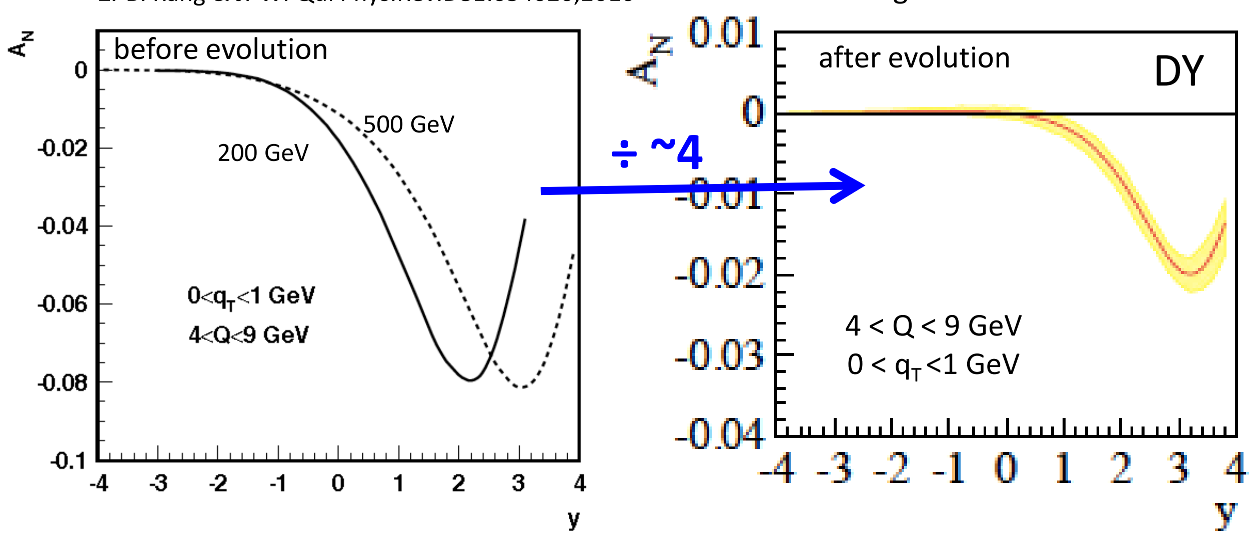
Very strong evolution effects

size of the effect still under discussion in theory community

For details see Talk by J. Collins in this session and **J. Collins, T. Rogers, Phys.Rev. D91 (2015) 7, 074020**

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

Z. Kang et al. arXiv:1401.5078



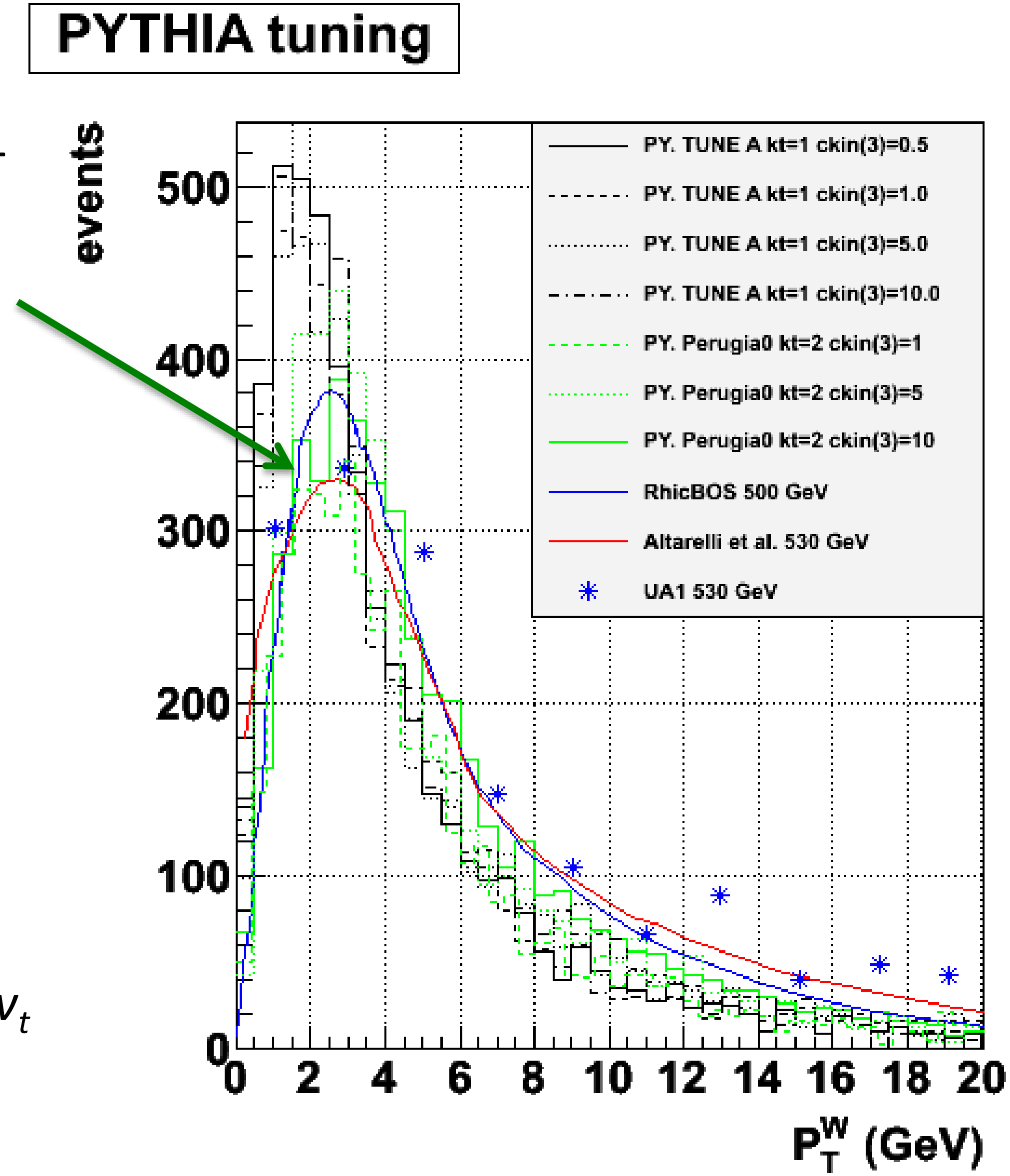
Data & MC

Monte Carlo

→ **PYTHIA** reconstructed trough GEANT simulated STAR detector

→ **Perugia tune** with hard P_T > 10 GeV

→ PYTHIA **embedded** into real zero-bias pp events



Data sample

- **pp – transverse** (collected in 2011) @ √500 GeV
- Integrated luminosity: **~ 25 pb^{-1}**
- Events triggered in Barrel EMCAL

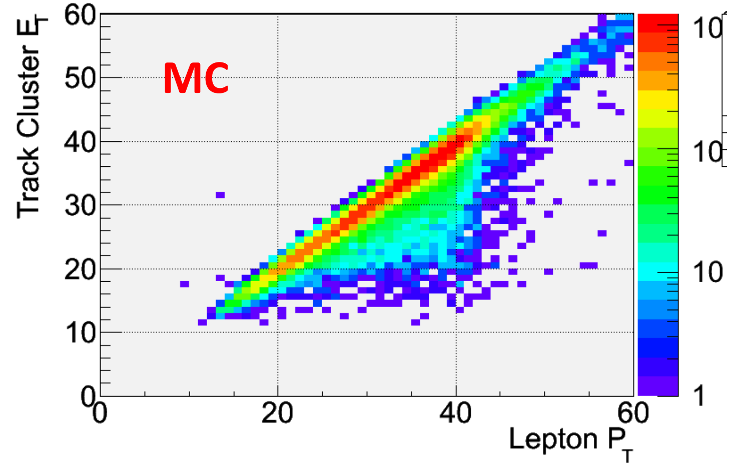
Signal	Background
$W \rightarrow e\nu_e$	$W \rightarrow \tau\nu_\tau \rightarrow e\nu_e\nu_\tau$
	$Z \rightarrow ee$
	QCD events

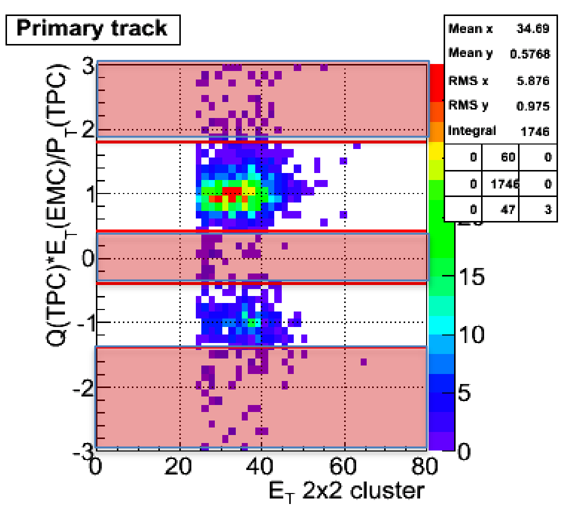
Electron identification

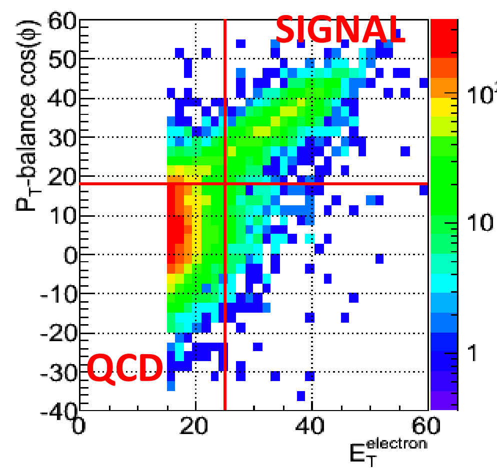
- **Isolation:** $(P^{track}+E^{cluster}) / \Sigma[P^{tracks}$ in R=0.7 cone] > 0.8
- **Imbalance:** no energy in opposite cone (E<20 GeV)
- **E_T > 25 GeV**
- Track |η| < 1
- |Z-vertex|<100 cm
- **Charge separation** (avoids charge misidentification):

  0.4 < |Charge (TPC) x E_T (EMC) / P_T (TPC)| < 1.8
- Signed P_T balance > 18 GeV/c (**rejects QCD Background**)
- 0.5 GeV/c < P_T^W < 10 GeV /c

We calculate energy from the cluster







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

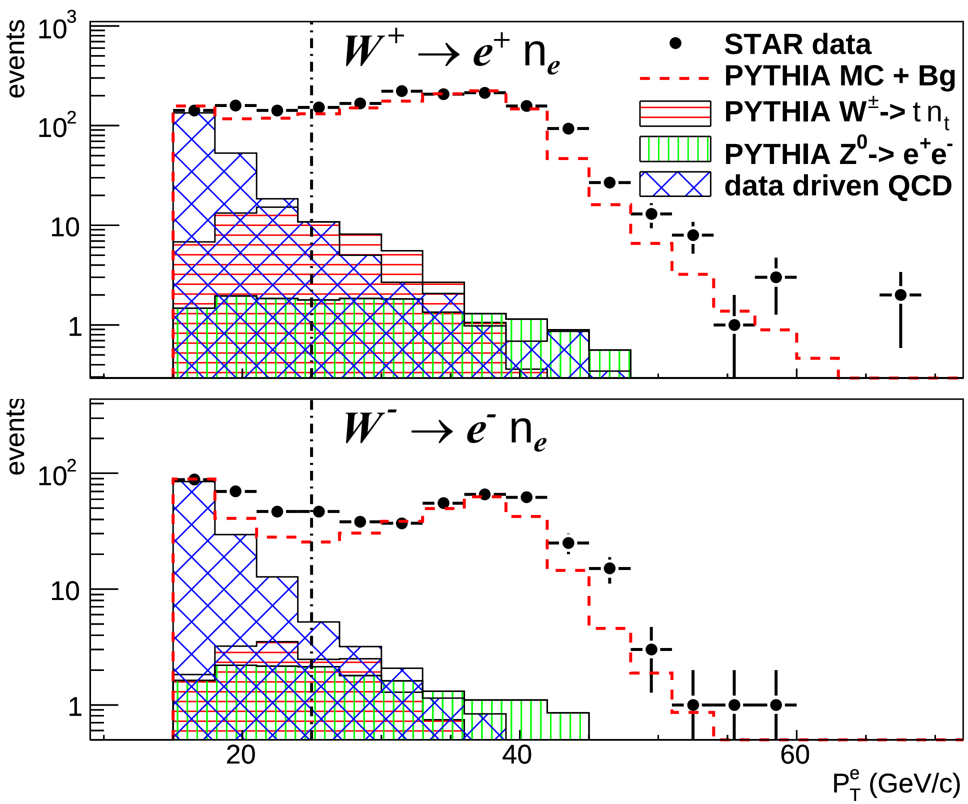
Background estimation

Background from W and Z boson decays estimated via Monte Carlo

- **PYTHIA 6.4 with Perugia 0 tune**
- **normalized to recorded data luminosity**

Data-driven QCD background estimation

- **Reverse of P_T-balance cut [PT-balance < 15 GeV] → Selects QCD events**
- **Plot lepton-P_T > 15 GeV**
- **QCD sample normalized to the first P_T-bin [15-19 GeV]**



- Positive-charge signal **1016 events**
- $Z^0 \rightarrow ee$ **[B/S = 0.79% ± 0.03%]**
- $W^+ \rightarrow tv_t$ **[B/S = 1.89% ± 0.04%]**
- ***QCD*** **[B/S = 1.6% ± 0.09%]**

- Negative-charge signal **275 events**
- $Z^0 \rightarrow ee$ **[B/S = 2.67% ± 0.1%]**
- $W^- \rightarrow tv_t$ **[B/S = 1.77% ± 0.1%]**
- ***QCD*** **[B/S = 3.39% ± 0.23%]**

Backgrounds under control!

STAR: A_N^W

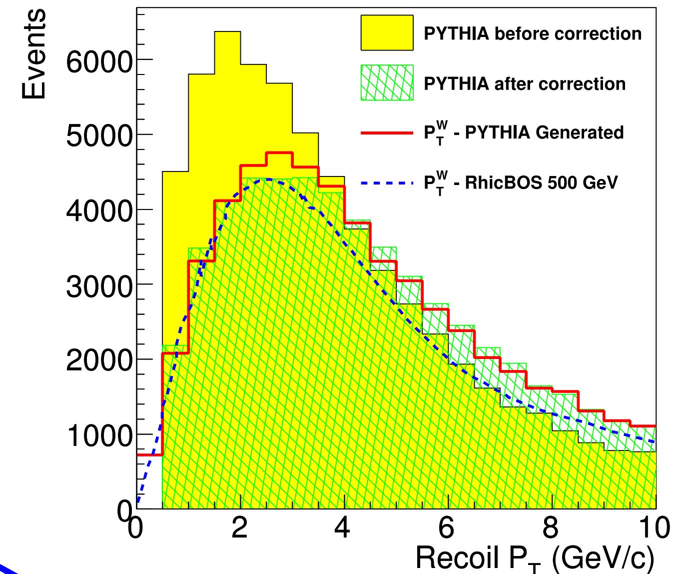
Analysis Strategy to fully reconstruct Ws:

Follow the analysis steps of the A_L

→ W candidate selection via high p_t lepton

Data set 2011 transverse 500 GeV data set (25 pb^{-1})

- ✓ In transverse plane: $$\vec{P}_T^W = \vec{P}_T^e + \vec{P}_T^n = \vec{P}_T^{recoil}$$
- ✓ Recoil reconstructed using tracks and towers: $$\sum_{i=tracks+trackless-\ clusters} \vec{P}_T^i$$
- ✓ Part of the recoil not within STAR acceptance
  - → correction through MC (Pythia)



W Rapidity reconstruction:

- ✓ W longitudinal momentum (along z) can be calculated from the invariant mass: $$M_w^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2$$
- ✓ Neutrino longitudinal momentum component from quadratic equation $$\left|\vec{p}_T^e\right|^2 (p_z^\nu)^2 - 2Ap_z^e p_z^\nu + \left|\vec{p}_T^\nu\right|^2 \left|\vec{p}^e\right|^2 - A^2 = 0 \quad A = \frac{M_W^2}{2} + \vec{p}_T^e \vec{p}_T^\nu$$

GOOD data/MC agreement after P_T correction