

PHENIX / STAR Nucleon Spin Highlights

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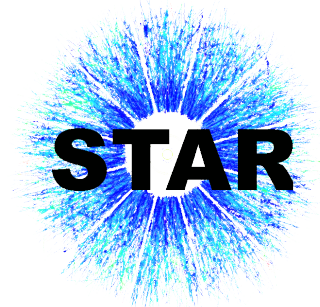
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For the PHENIX and STAR Collaborations



Outline

1. Introduction

- RHIC, PHENIX, and STAR

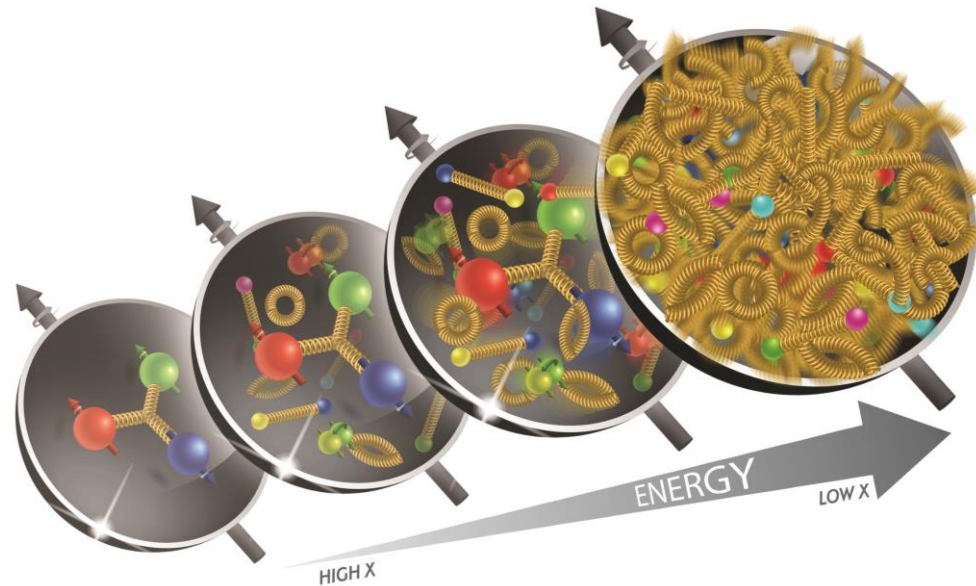
2. Nucleon helicity (Longitudinally polarized p + p)

- a. Sea quark polarization ($\Delta\bar{q}$)
- b. Gluon polarization (ΔG)

3. Transversely polarized p + p

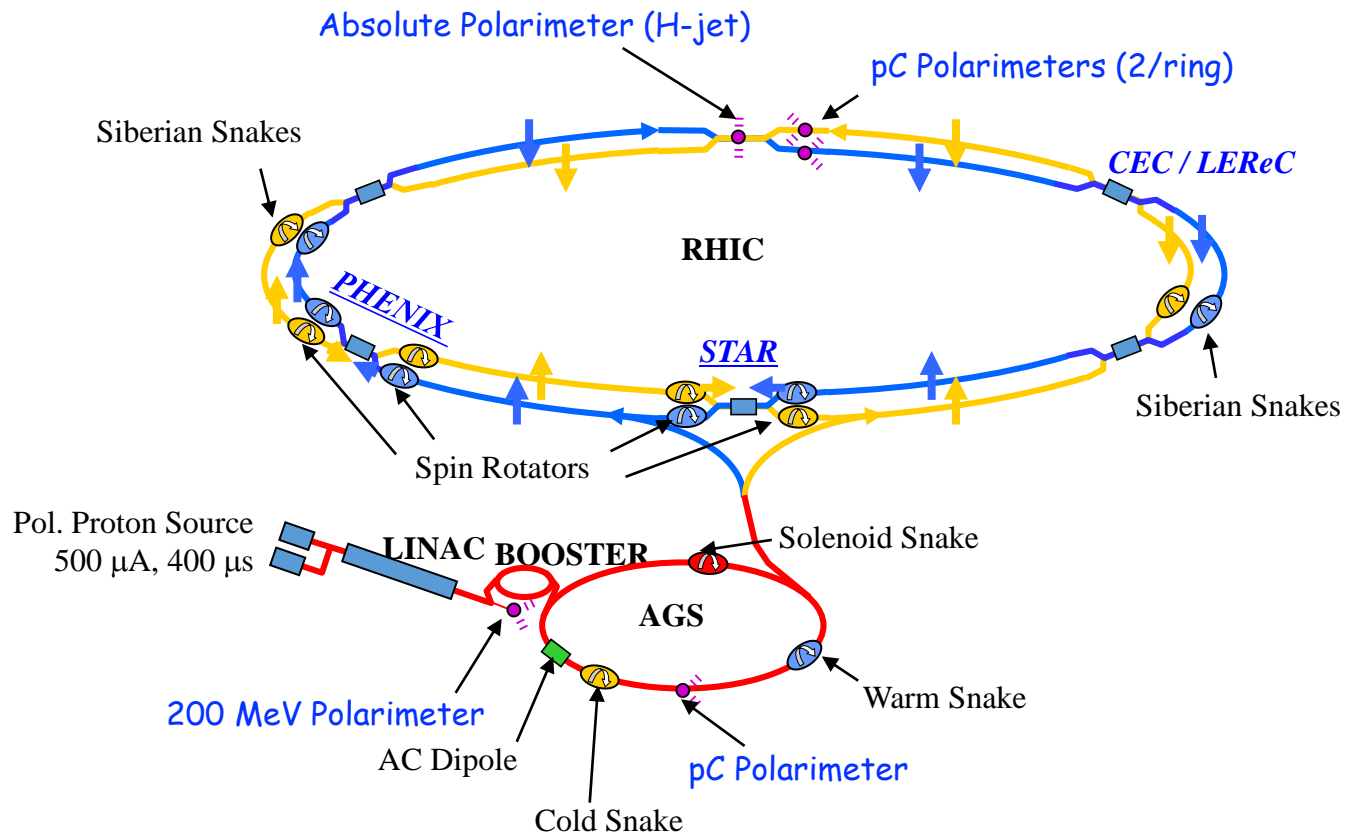
- Probes from PHENIX
- Probes from STAR

Introduction What $p + p$ can provide?



- **DIS** primarily probes via:
 - Electromagnetic interactions
 - a. Couple to charge
 - b. Insensitive to color
 - Weak interactions
 - a. Couple to weak charge
 - b. Insensitive to color
- **$p + p$** primarily probes via:
 - Strong interactions
 - a. Couple to color charge
 - b. Direct LO sensitivity to gluons
 - c. Insensitive to flavor

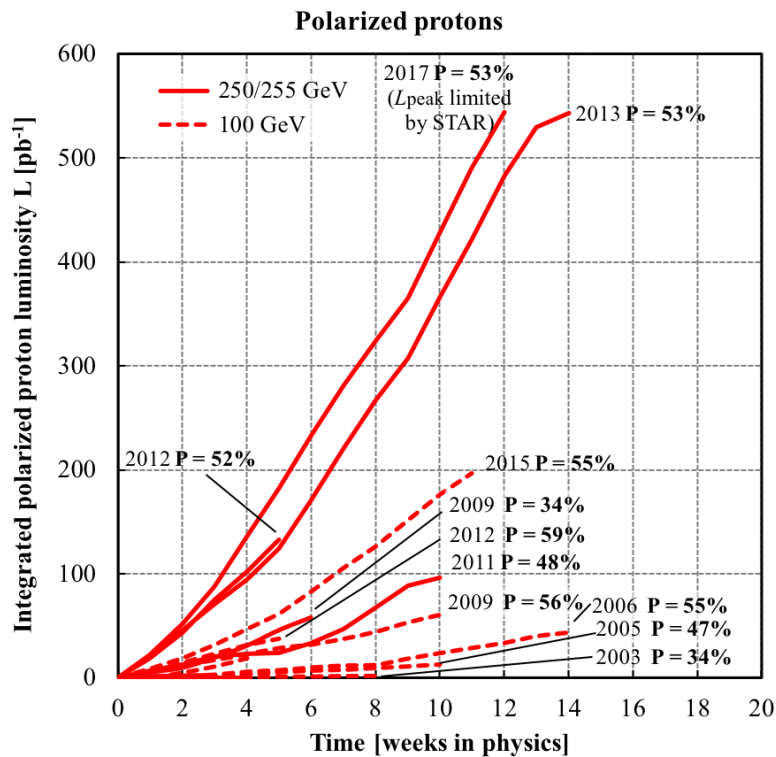
Introduction RHIC



• RHIC @ Brookhaven Lab., NY

- Polarized p + p (max. 120 bunches per ring) @ $\sqrt{s} = 62.5$ to 510 (GeV)
- Average beam polarization $\langle P \rangle \approx 60$ (%)
- Polarization direction (L or T) chosen by each experiment's decision

Introduction RHIC Spin Runs (2009 - 2017)



| Year | vs (GeV) | Type | $\langle P \rangle$ (%) | PHENIX | STAR |
|------|----------|------|-------------------------|-------------------------------|-------------------------------|
| | | | | Int. L (pb^{-1}) | int. L (pb^{-1}) |
| 09 | 200 | L | 56 / 57 | 16 | 25 |
| | 500 | L | 33 / 36 | 14 | 11 |
| 11 | 500 | L | 48 / 48 | 28 | 12 |
| 12 | 510 | L | 50 / 54 | 50 | 86 |
| 13 | 510 | L | 51 / 55 | 242 | 306 |
| 15 | 200 | L | 53 / 57 | x | 53 |
| 11 | 500 | T | 48 / 48 | x | 22 |
| 12 | 200 | T | 62 / 57 | 18 | 25 |
| 15 | 200 | T | 53 / 57 | 110 | 52 |
| 17 | 510 | T | 55 / 56 | x | 356 |

• Summary of RHIC Spin Runs

- CAVEAT: int. L can be different by the observable
(the values presented here was obtained by MB trigger or trigger without prescale)

Introduction PHENIX (2016)

- **Central Arms**

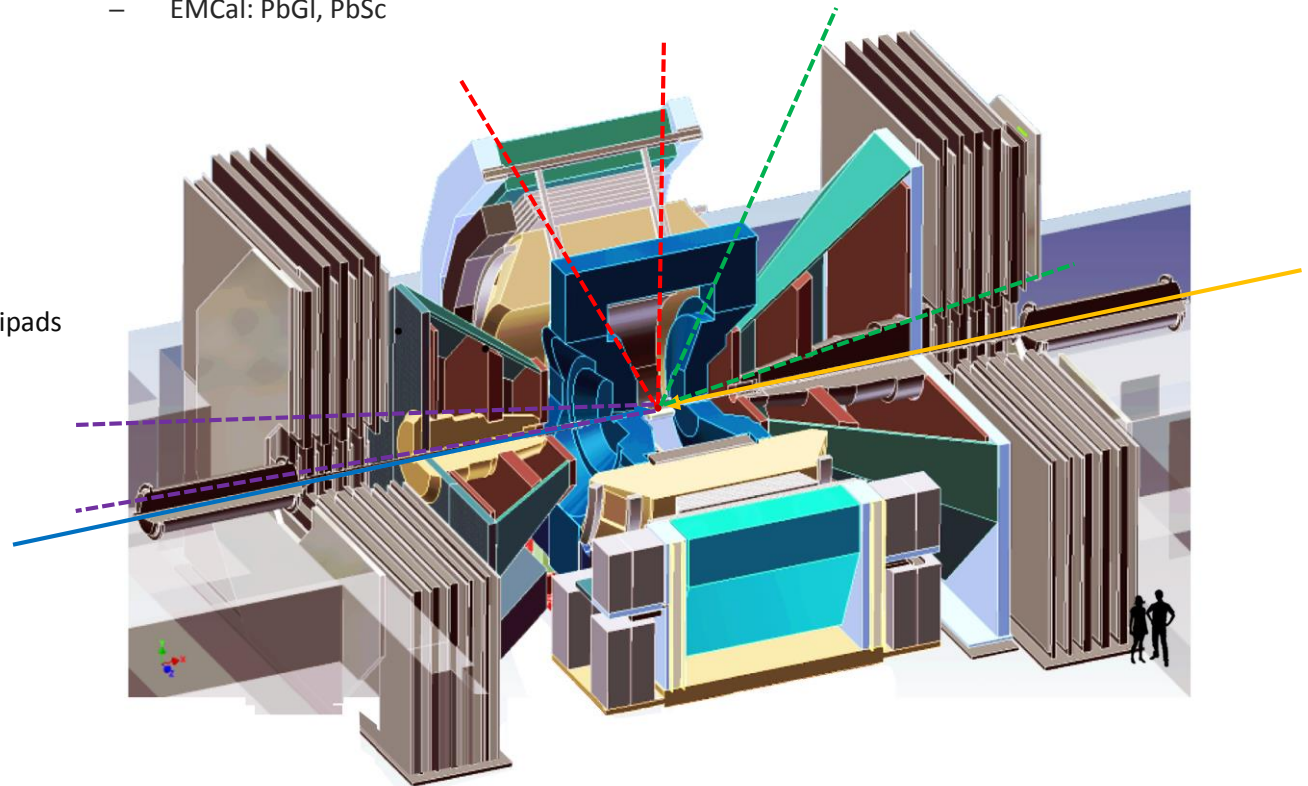
- $|\eta| < 0.35, \Delta\phi = \frac{\pi}{2} \times 2, 0.78 \text{ T}$
- VTX (Si pixel and strip, from 2011)
- Tracking: DC, PC
- pID: RICH, ToF
- EMCal: PbI, PbSc

- **Muon Arms**

- $1.2 < |\eta| < 2.2 (2.4), \Delta\phi = 2\pi, 0.72 \text{ T}$
- FVTX (Si strip, from 2012)
- Tracking: MuTr (CS chambers)
- pID: MuID, RPC

- **MPC / MPC-Ex**

- $3.1 < |\eta| < 3.8, \Delta\phi = 2\pi$
- MPC: PbWO_4 EMCal
- MPC-Ex: W absorber + Si minipads



Introduction STAR (2017)

- **TPC**

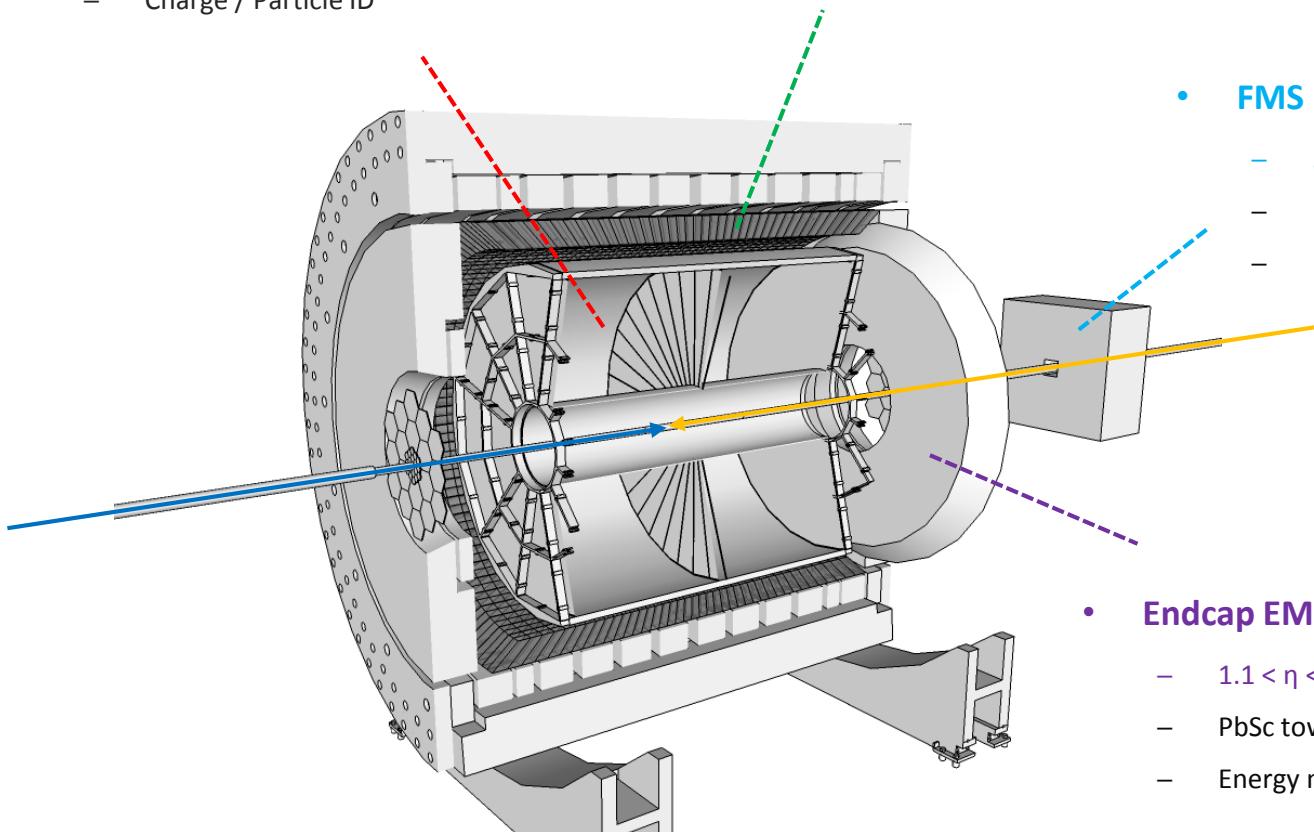
- $|\eta| < 1.3, \Delta\phi = 2\pi, 0.5 T$
- Charged track reconstruction
- Primary vertex measurement
- Charge / Particle ID

- **Barrel EMC**

- $|\eta| < 1.0, \Delta\phi = 2\pi$
- PbSc towers + SMD + preshower
- Energy measurement, Trigger

- **Also,**

- Barrel ToF ($|\eta| < 1.0, \Delta\phi = 2\pi$)
- VPD (Vertex Position Detector)
- ...



- **FMS**

- $2.5 < \eta < 4.0, \Delta\phi = 2\pi$
- PbGl towers + pre/postshower
- Energy measurement, Trigger

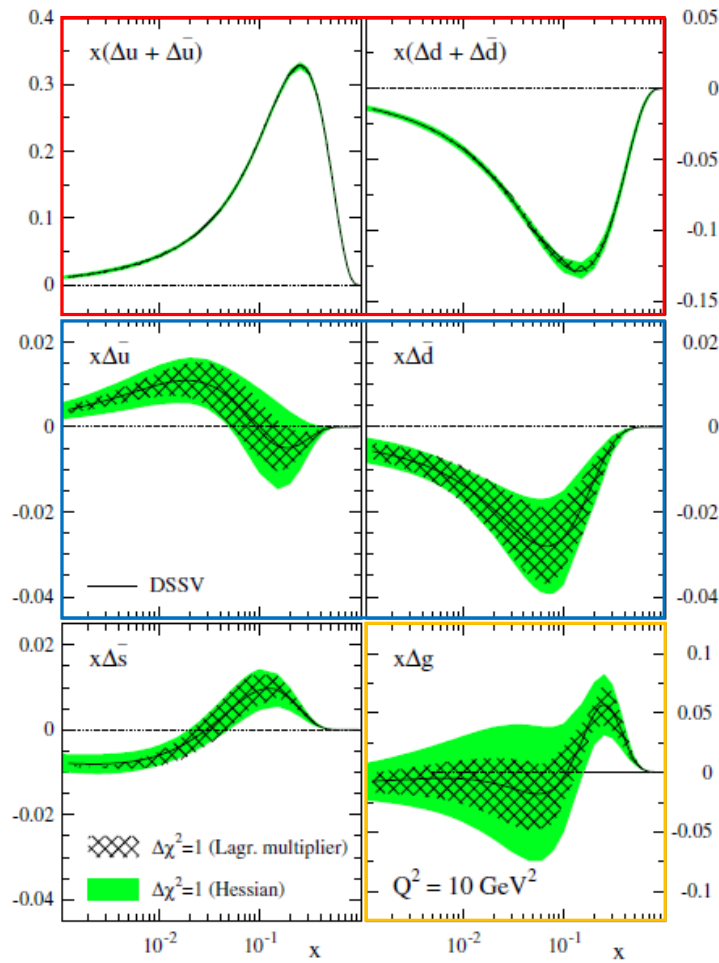
- **Endcap EMC**

- $1.1 < \eta < 2.0, \Delta\phi = 2\pi$
- PbSc towers + SMD + pre/postshower
- Energy measurement, Trigger

2. Nucleon helicity

(Longitudinally polarized p + p)

2. Nucleon helicity Motivation



- $S_p = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_z$

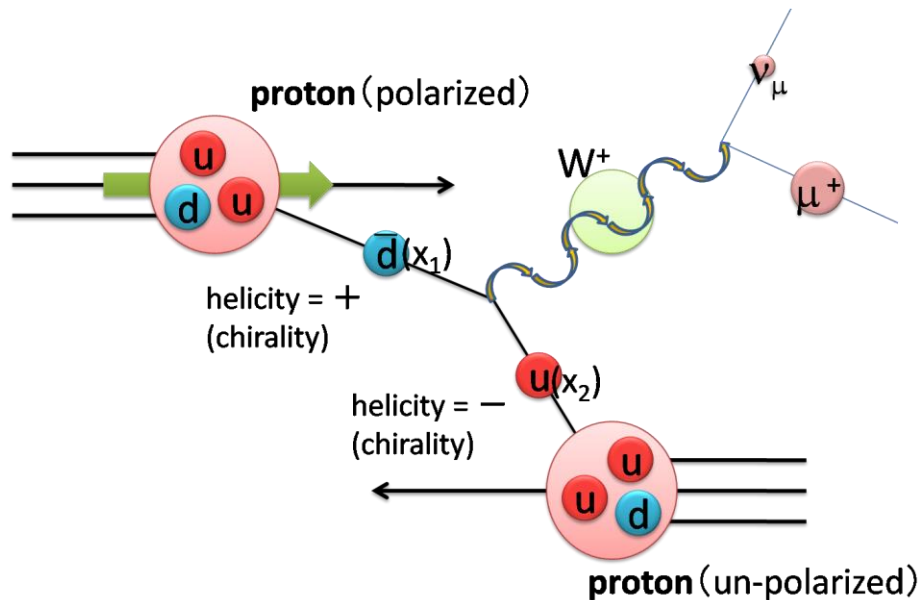
- $\Delta\Sigma?$

- $(\Delta q + \Delta \bar{q})$: well constrained down to $x \sim 10^{-3}$, thanks to DIS results
- $\Delta \bar{q}$: poorly constrained with large uncertainty, mainly originated from fragmentation functions
→ RHIC: fragmentation free W decay leptons

- $\Delta G?$

- Poorly constrained:
limited access in DIS via evolution effect
→ RHIC: gluon sensitive polarized $p + p$ collisions, various probes (π^0 , η , jet, ...)

2. Nucleon helicity – a. $\Delta\bar{q}$ RHIC W program



$$A_L = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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

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

technically,

$$A_L^W = \frac{1}{P} \frac{N_+ - RN_-}{N_+ + RN_-}$$

- P : avg. polarization of each beam
- N_+ (N_-): yields in same (opposite) helicity
- $R = \frac{L_+}{L_-}$: relative luminosity

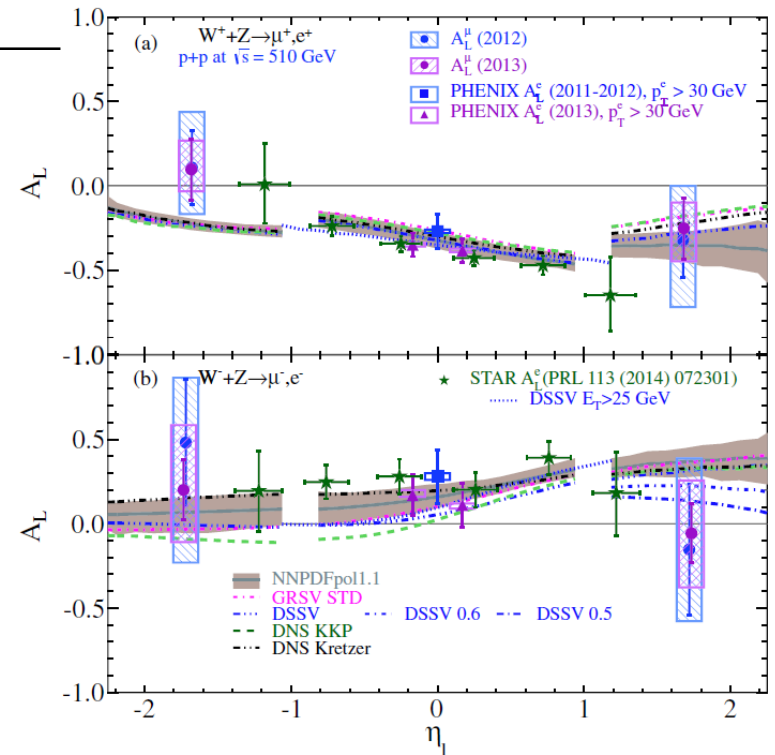
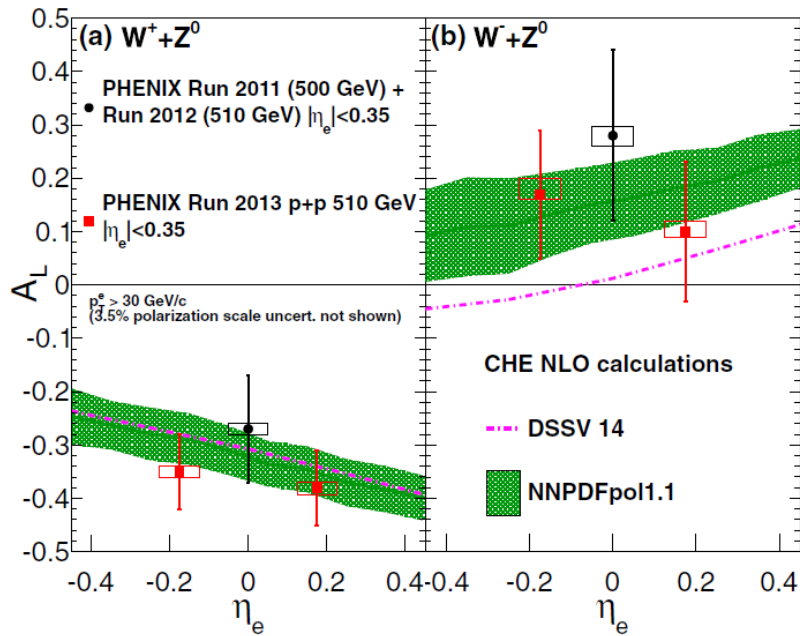
• $\Delta\bar{q}$ measurements at RHIC

- $W^\pm \rightarrow e^\pm$: PHENIX midrapidity ($|\eta| < 0.35$), STAR ($|\eta| < 1.3$)
- $W^\pm \rightarrow \mu^\pm$: PHENIX forward rapidity ($1.2 < |\eta| < 2.2 / 2.4$)

2. Nucleon helicity – a. $\Delta\bar{q}$ PHENIX, $W A_L$ (2011-2013)

PRD93, 051103 (2016)

PRD98, 032007 (2018)

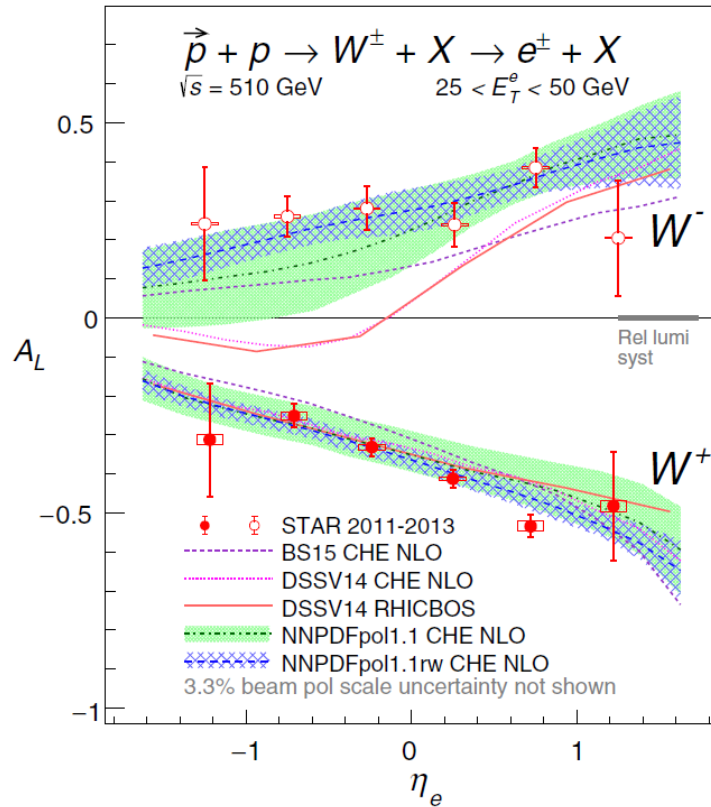


- **$W \rightarrow e A_L, |\eta| < 0.35$**
 - Int. $L = 240 \text{ pb}^{-1}$ (2011 - 2013)
 - Signal extraction by e^\pm isolation + Jacobian peak
 - x (partonic momentum fraction) ~ 0.16 (M_W / \sqrt{s})

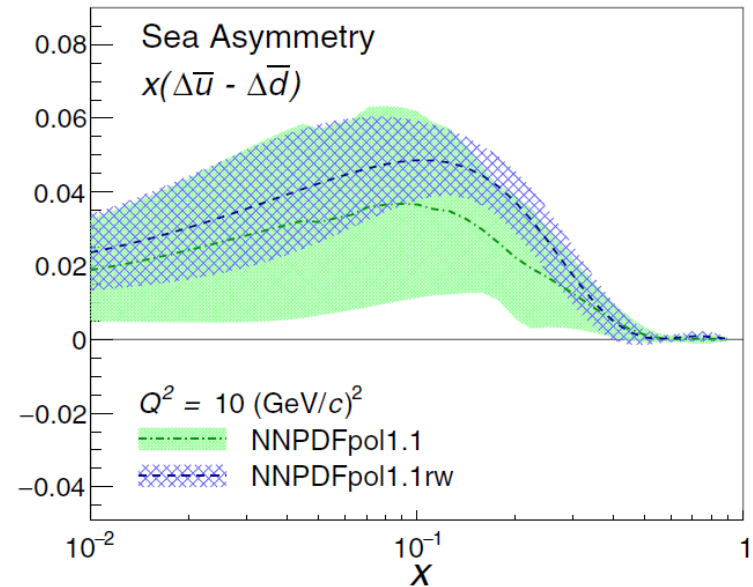
- **$W \rightarrow \mu A_L, 1.2 < |\eta| < 2.2 / 2.4$**
 - Int. $L = 53$ (2012) + 285 (2013) pb^{-1}
 - Signal extraction based on W likelihood
 - $x \sim 0.1$ (backward) / ~ 0.3 (forward)



2. Nucleon helicity – a. $\Delta\bar{q}$ STAR, $W A_L$ (2011-2013)



PRD99, 051102 (2019)

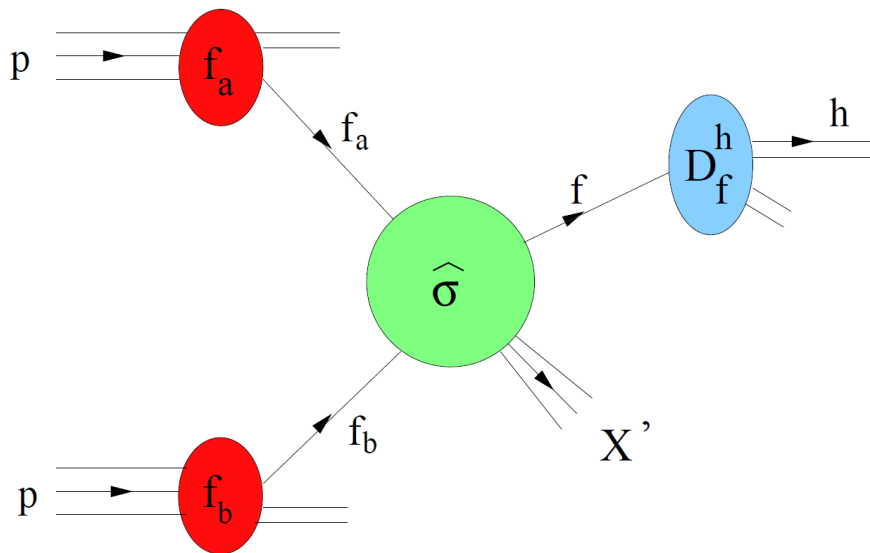


- $W \rightarrow e A_L, |\eta| < 1.3$**

- Int. $L = 86 \text{ (2011-2012)} + 250 \text{ (2013)} \text{ pb}^{-1}$
- Signal extraction by e^\pm isolation + missing energy detection + Jacobian peak
- $0.05 < x < 0.25$

- Sizable positive $\Delta\bar{u}$ / negative $\Delta\bar{d}$ observed
- Clear flavor asymmetry ($\Delta\bar{u} - \Delta\bar{d}$)

2. Nucleon helicity – b. ΔG Probe ΔG at RHIC



$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++-} - \sigma_{+-}}{\sigma_{+++} + \sigma_{+-}}$$

$$= \frac{\Sigma_{abf} (\Delta f_a \otimes \Delta f_b) \otimes \Delta \hat{\sigma}^{a+b \rightarrow h+X} \otimes D_f^h}{\Sigma_{abf} (f_a \otimes f_b) \otimes \hat{\sigma}^{a+b \rightarrow h+X} \otimes D_f^h}$$

- $f(\Delta f)$: unpol (pol) PDF
- $\hat{\sigma}(\Delta \hat{\sigma})$: unpol (pol) partonic cross section
- D_f^h : fragmentation function

technically,

$$A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

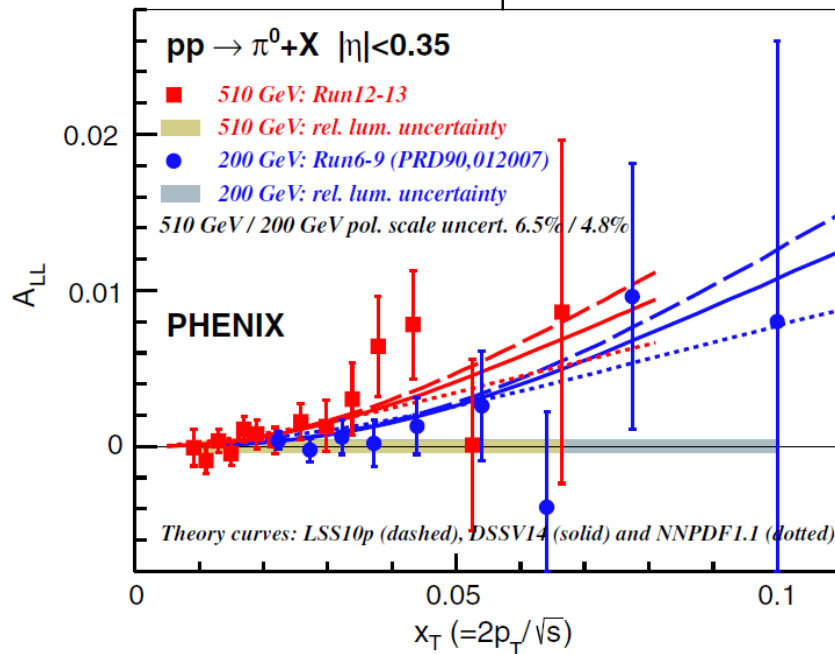
- P : avg. polarization of each beam
- N_{++} (N_{+-}) : yields in same (opposite) helicity
- $R = \frac{L_{++}}{L_{+-}}$: relative luminosity

• ΔG measurements at RHIC

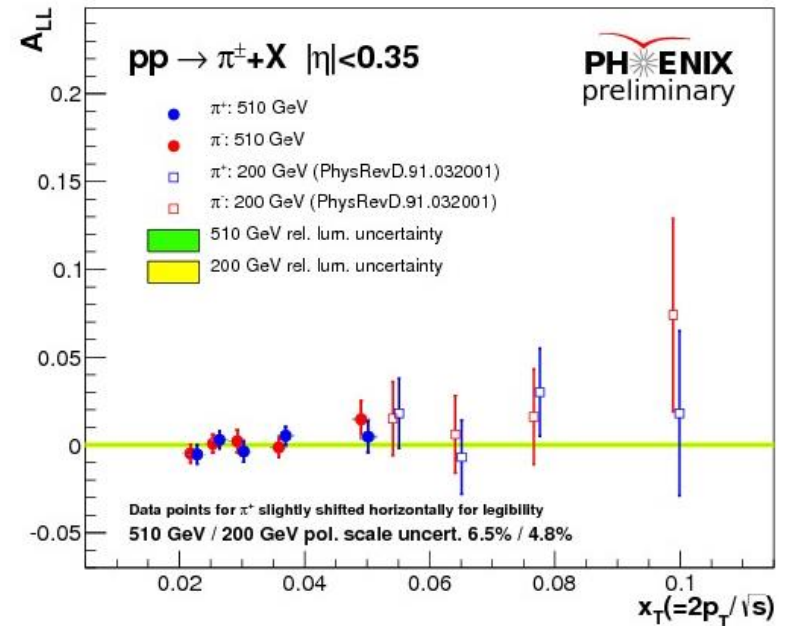
- Various probes: **jet**, direct γ , π^0 , π^\pm , η , heavy flavor decay electrons, etc
- Wide pseudorapidity (η) coverage

2. Nucleon helicity – ΔG PHENIX, $\pi^0 / \pi^\pm A_{LL}$

PRD93, 011501 (2016)



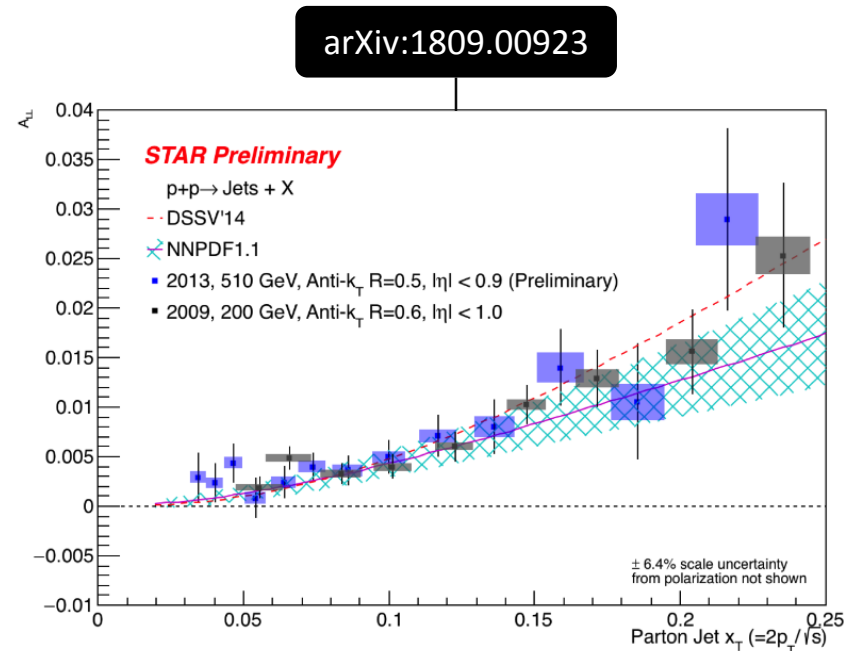
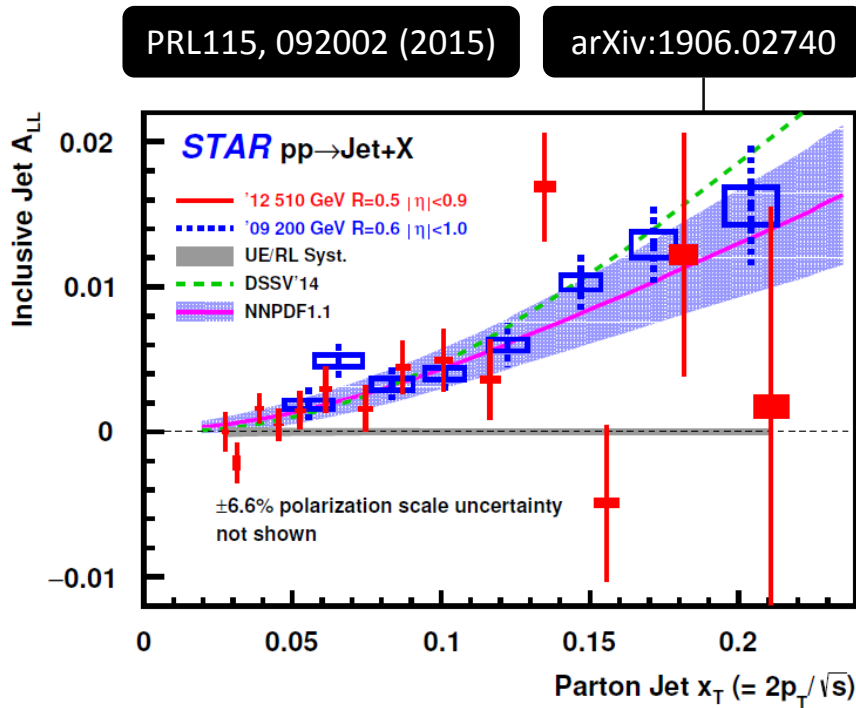
- Inclusive $\pi^0 A_{LL}$, $|\eta| < 0.35$
 - Int. $L = 20$ (2012) + 108 (2013) pb^{-1}
 - Confirm non-zero ΔG via hadron production
 - x down to ~ 0.01



- $\pi^\pm A_{LL}$, $|\eta| < 0.35$
 - Int. $L = 108$ pb^{-1} (2013)
 - Complementary probe to previous π^0 / π^\pm results



2. Nucleon helicity – $b. \Delta G$ STAR, inclusive jet A_{LL}



- **Inclusive jet A_{LL} , $|\eta| < 0.9$**

- First non-zero ΔG observed (2009):

- \rightarrow DSSV14: $\int_{0.05}^1 dx \Delta g(x) = 0.20^{+0.06}_{-0.07}$ (90 % C.L.)

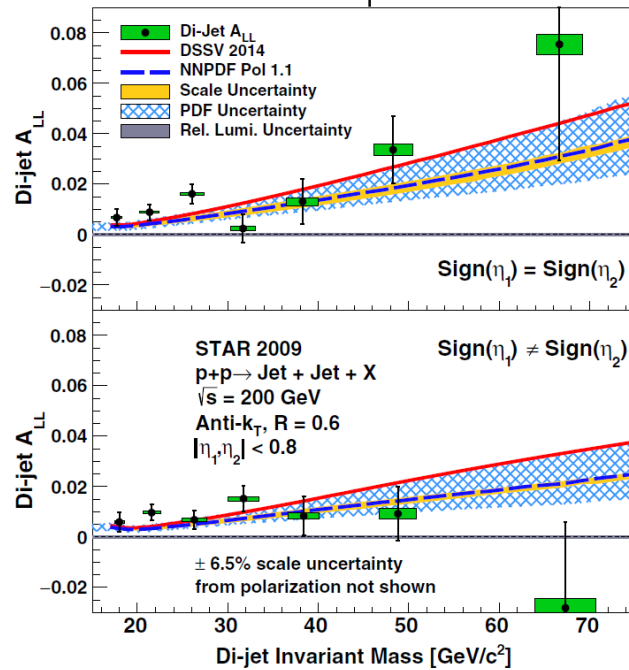
- \rightarrow NNPDF1.1: $\int_{0.05}^{0.20} dx \Delta g(x) = 0.17^{+0.06}_{-0.06}$

- 2009: $\sqrt{s} = 200$ GeV, int. $L = 21$ pb $^{-1}$, $x > 0.05$
- 2012: $\sqrt{s} = 510$ GeV, int. $L = 82$ pb $^{-1}$, $x \sim 0.015$
- 2013 results coming soon: embedding study is underway for systematic

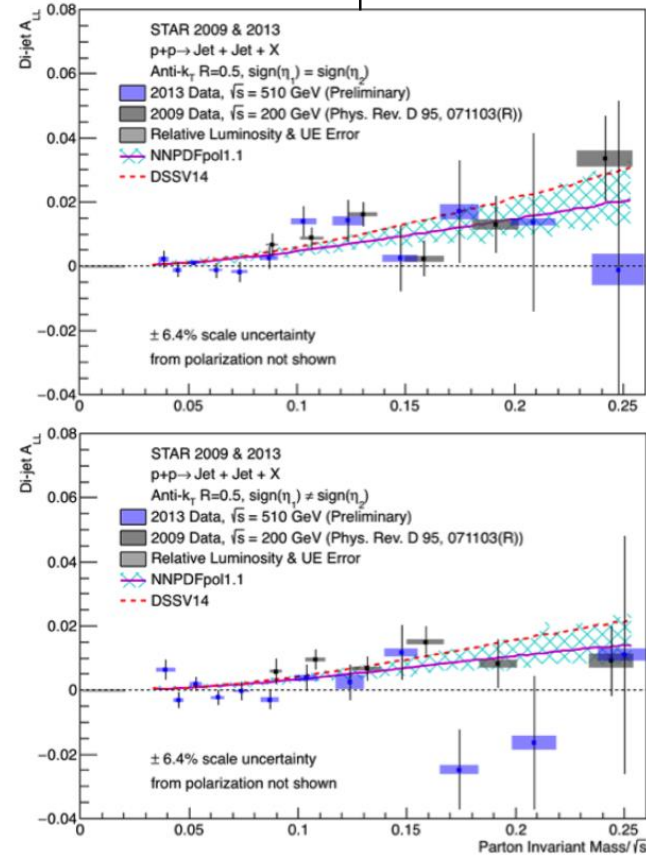


2. Nucleon helicity – $b. \Delta G$ STAR, dijet A_{LL}

PRD95, 071103 (2017)



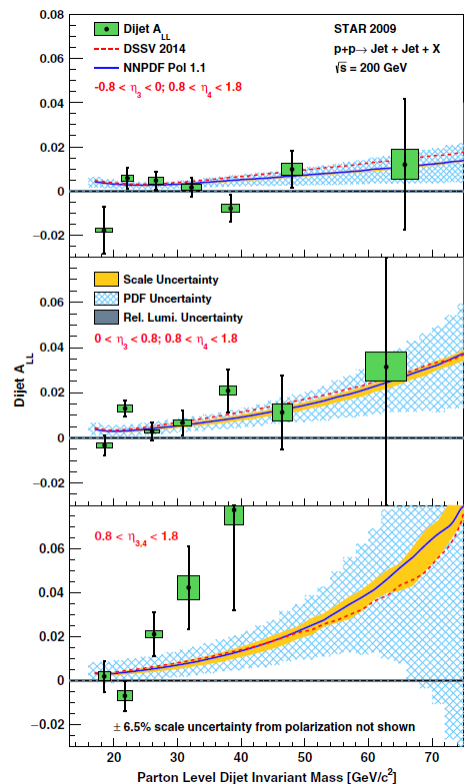
arXiv:1809.00923 (preliminary)



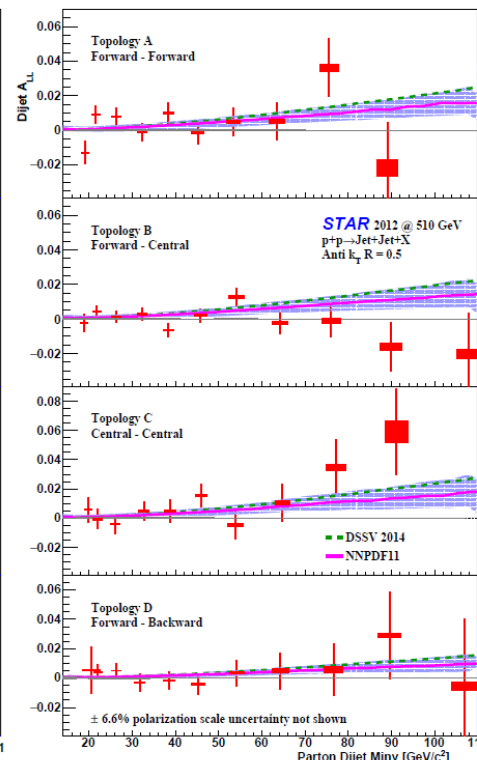
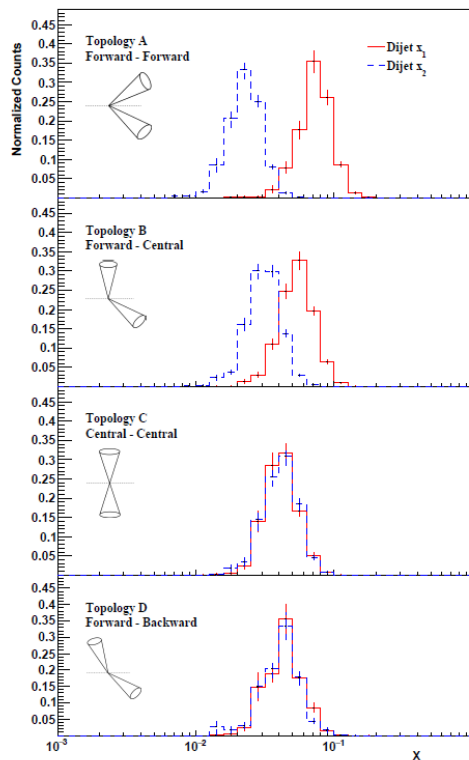
- **Midrapidity dijet A_{LL} , $|\eta| < 0.8$**
 - Dijet invariant mass $M = \sqrt{s} \sqrt{x_1 x_2}$
 - Check previous page for conditions (\sqrt{s} , etc)
 - 2012: [arXiv:1906.02740](https://arxiv.org/abs/1906.02740) / 2013: analysis near completion



2. Nucleon helicity – $b. \Delta G$ STAR, dijet A_{LL}



PRD98, 032011 (2018)



arXiv:1906.02740

- Top: $-0.8 < \eta_3 < 0; 0.8 < \eta_4 < 1.8$
- Middle: $0 < \eta_3 < 0.8; 0.8 < \eta_4 < 1.8$
- Bottom: $0.8 < \eta_{3,4} < 1.8$

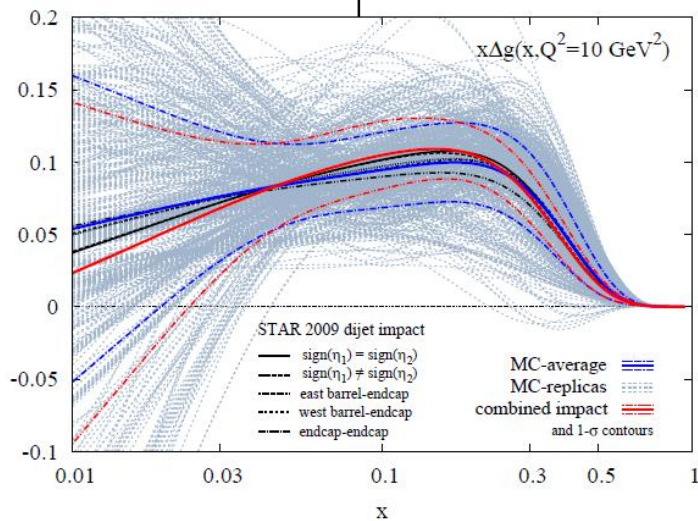
| Bin | η_3 and η_4 Regions | Physics Description |
|-----|---|---------------------|
| A | $0.3 < \eta_{3,4} < 0.9; \eta_3 \cdot \eta_4 > 0$ | Forward-Forward |
| B | $ \eta_{3,4} < 0.3; 0.3 < \eta_{4,3} < 0.9$ | Forward-Central |
| C | $ \eta_{3,4} < 0.3$ | Central-Central |
| D | $0.3 < \eta_{3,4} < 0.9; \eta_3 \cdot \eta_4 < 0$ | Forward-Backward |

- **Dijet A_{LL} by η topologies, $-0.8 < \eta < 1.8$**

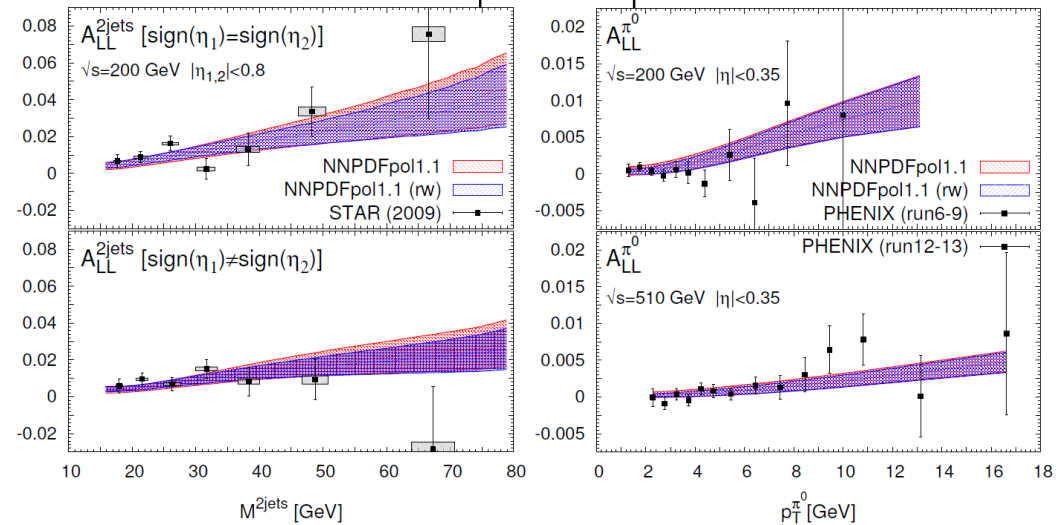
- Narrows down sampled x_g distribution and θ^* (scattering angle in partonic CoM frame)

2. Nucleon helicity Impact of RHIC data on ΔG constraint

arXiv:1902.10548



arXiv:1702.05077

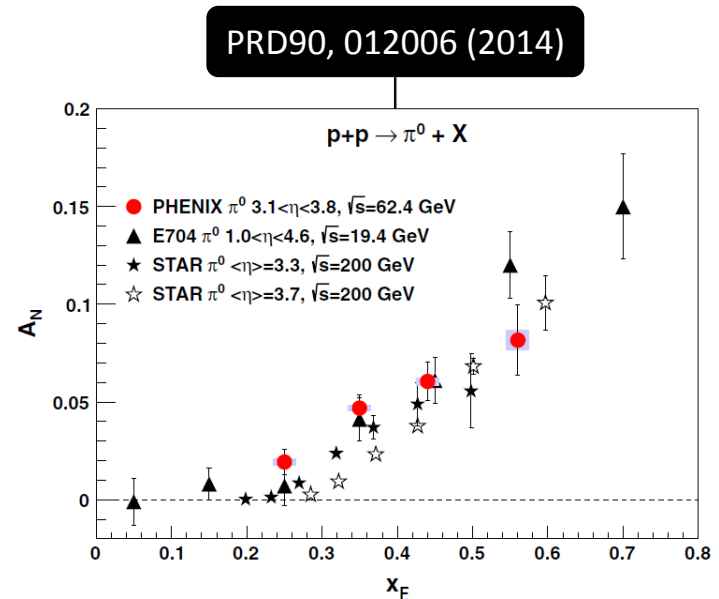
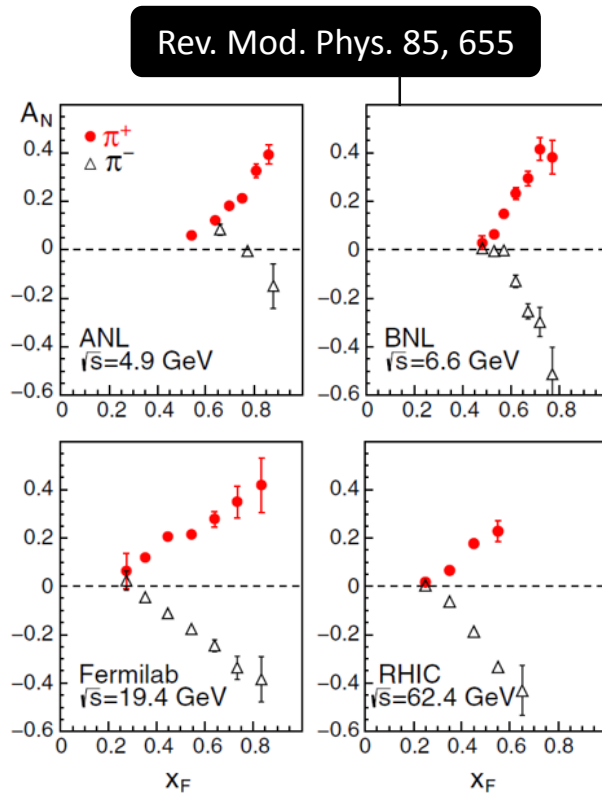


- **Impact of RHIC data on ΔG (2009-2013)**

- Left: MC sampling variant of DSSV14 (STAR 2009 dijet)
- Right: reweighted NNPDFpol1.1 (STAR 2009 dijet, and PHENIX 2009 + 2013 π^0)

3. Transversely polarized p + p

3. Transverse $p + p$ Motivation



$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{1}{P} \times \frac{N_L - N_R}{N_L + N_R}, \quad X_F = \frac{2p_z}{\sqrt{s}} \sim (x_1 - x_2)$$

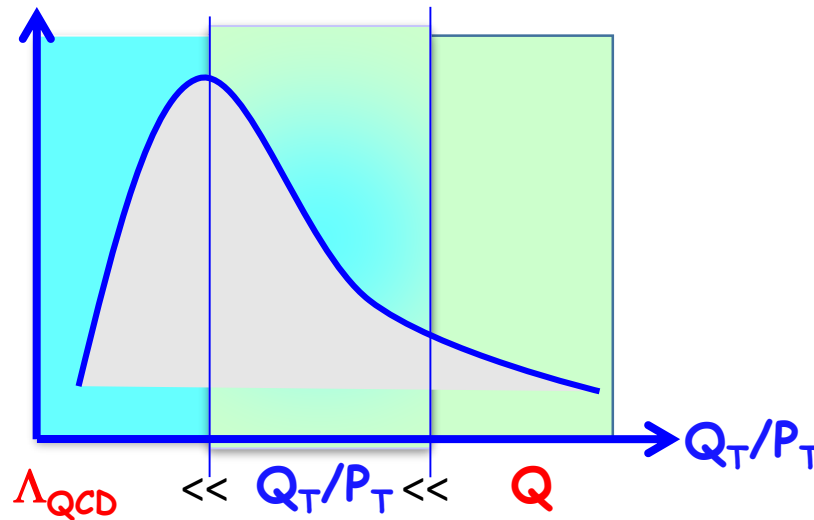
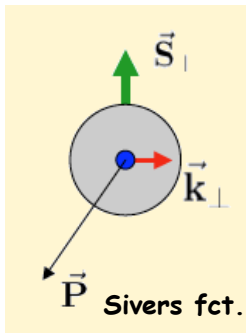
- **Transverse single spin asymmetry (A_N)**

- Large, increasing A_N : expected to be very small in conventional pQCD calculation
- TMD (transverse momentum dependent) / Collinear Twist 3

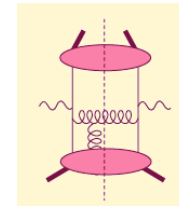
3. Transverse $p + p$ Motivation (continue)

* Quoted from Carl Gagliardi, SPIN2018

TMD



Twist-3



Efremov, Teryaev;
Qiu, Serman
or
Twist-3 FF

• **TMD**

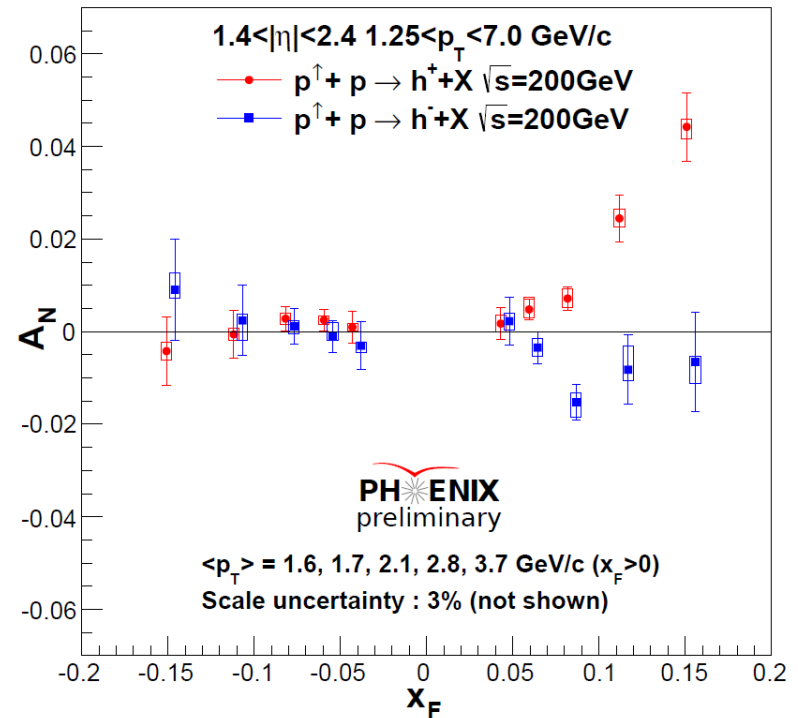
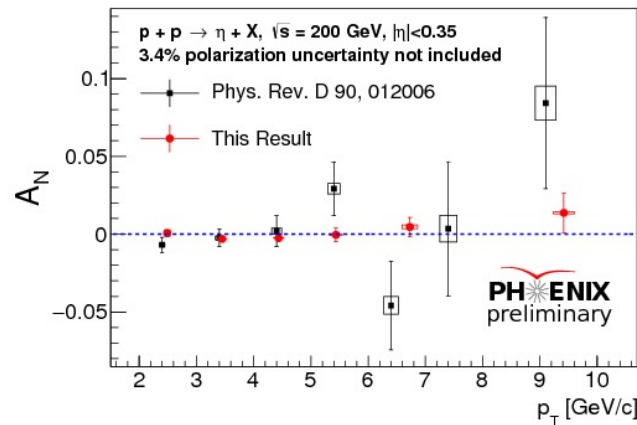
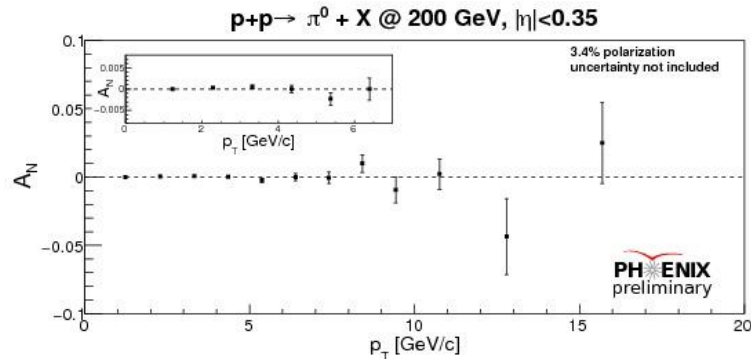
- Requires two scales: Q^2 (hard) and p_T (soft)
- SIDIS, Drell-Yan, W/Z , hadrons in jets...
- Access full transverse momentum k_T

• **Collinear Twist-3**

- Requires single hard scale: p_T
- Proper for inclusive A_N (π^0 , γ , jet)
- Access average transverse momentum $\langle k_T \rangle$

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

3. Transverse $p + p$ PHENIX, π^0 , η , and charged hadrons A_N



- π^0 and η A_N at $|\eta| < 0.35$

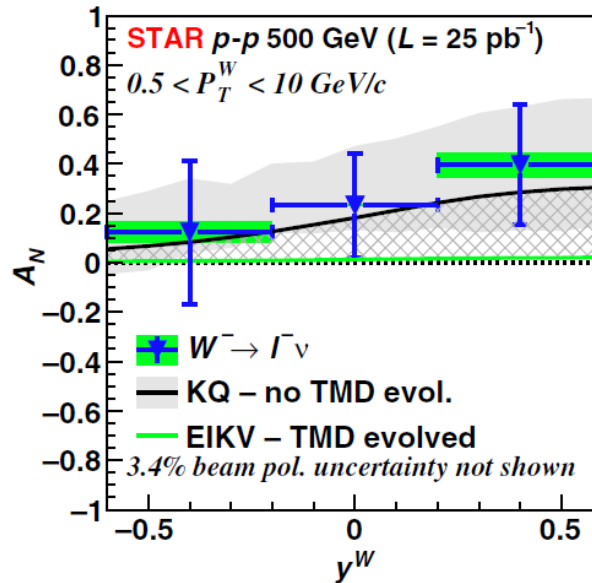
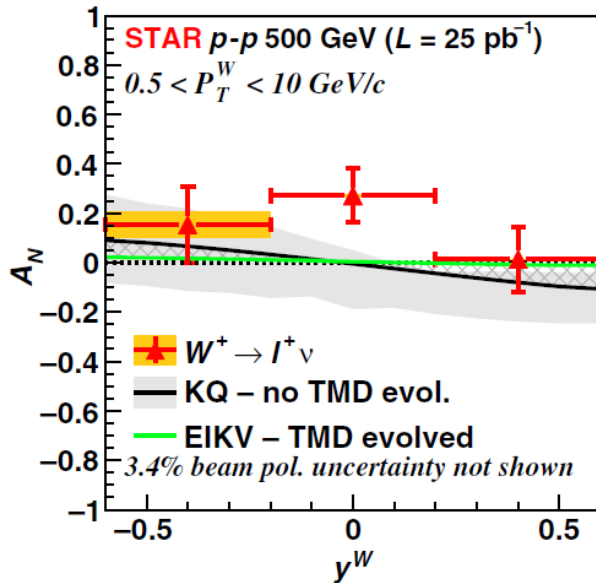
- $\sqrt{s} = 200$ GeV (2015)
- Sensitive to Twist-3 trigluon correlations
- Consistent with zero

- π^\pm and K^\pm A_N at $1.2 < |\eta| < 2.2$

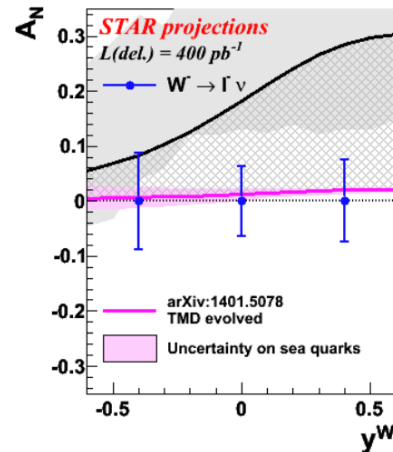
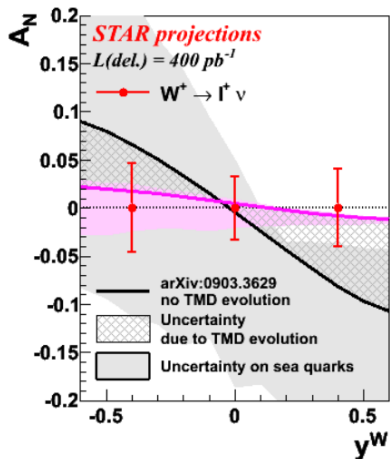
- $\sqrt{s} = 200$ GeV (2015)
- Increasing h^+ A_N for $x_F > 0$
- Comparable to BRAHMS results (PRL101, 042001 (2008))



3. Transverse $p + p$ STAR, $W A_N$



PRL116, 132301 (2016)



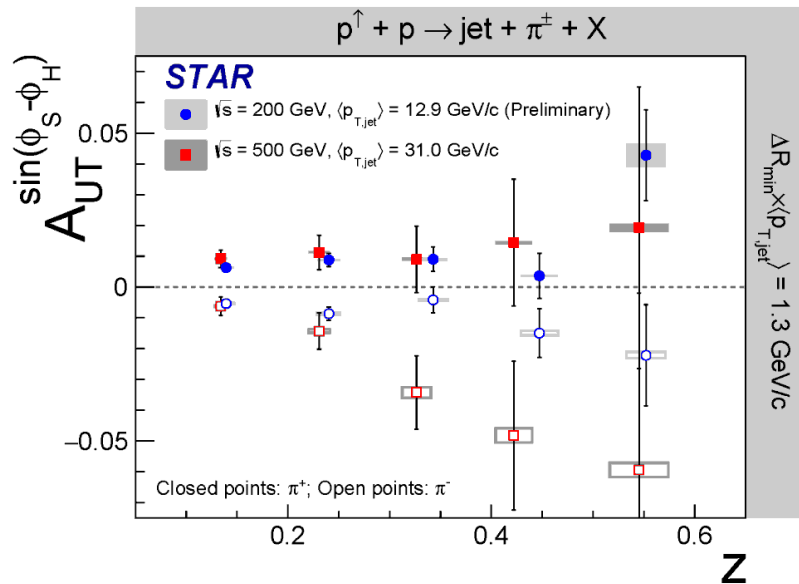
- $W A_N$ at $|\eta| < 1.0$

- $\sqrt{s} = 500$ GeV, int. $L = 25$ pb^{-1} (2011)
 - 1st anti-quark Sivers function measurement
 - 1st experimental evidence of Sivers-sign change
- 2017 analysis (int. $L \sim 350$ pb^{-1}) is underway
 - (\leftarrow projection: arXiv:1602.03922)

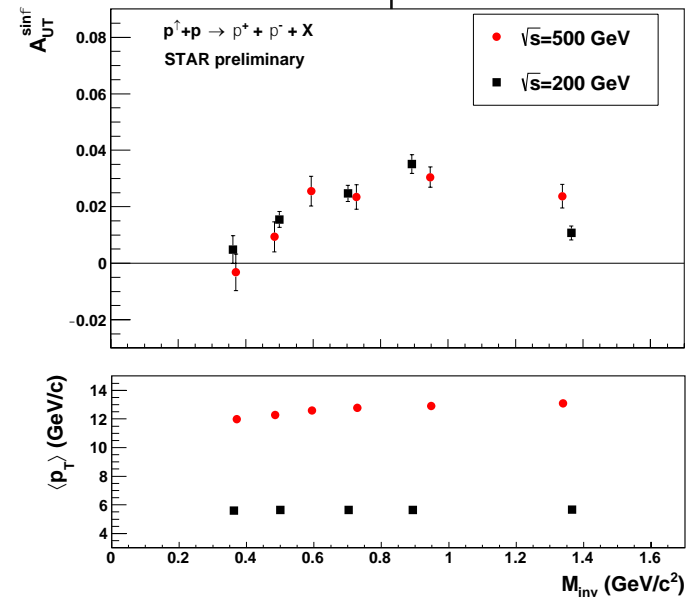


3. Transverse $p + p$ STAR, Transversity via $p + p$

PRD97, 032004 (2018)



PLB 780, 332 (2018)

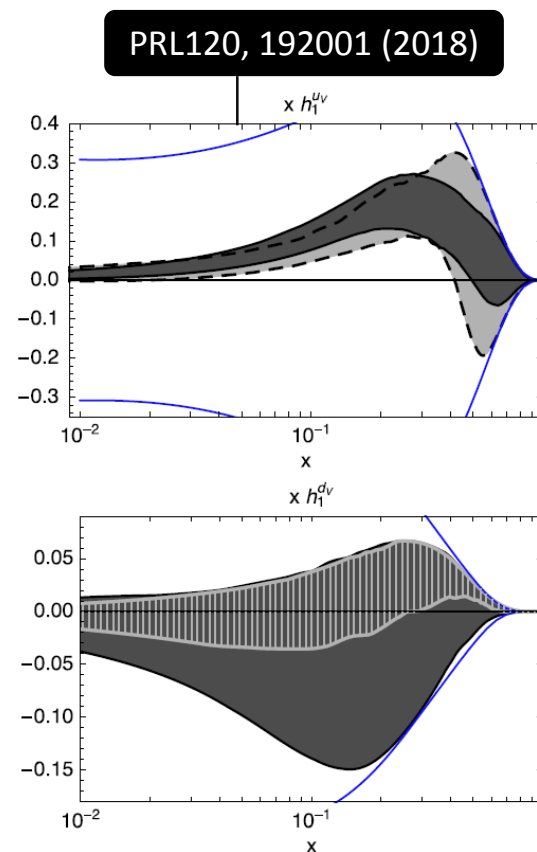
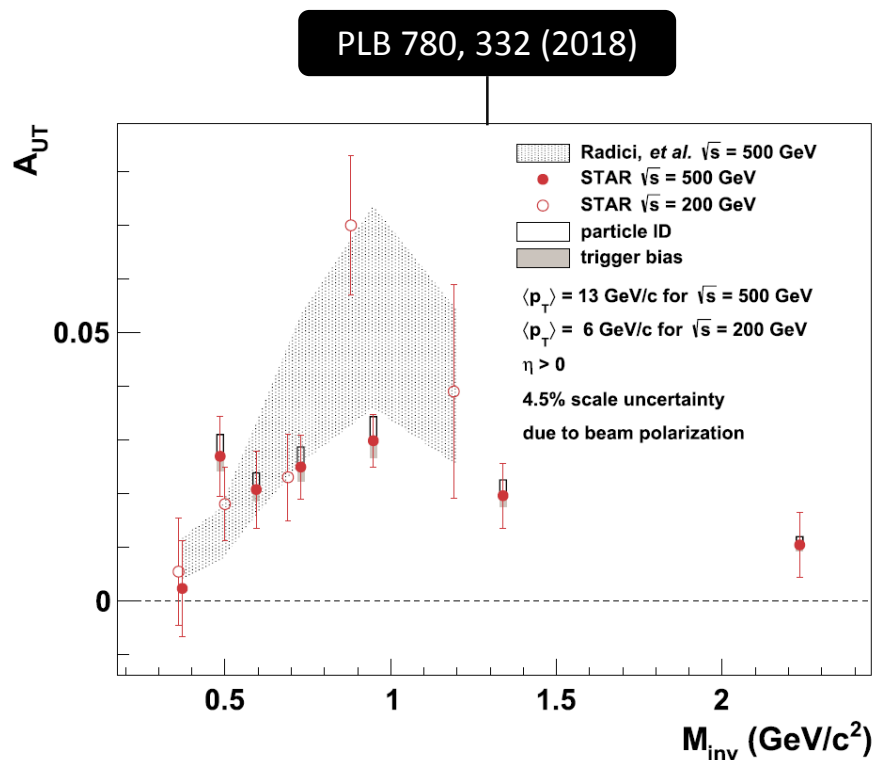


- **Transversity via SSA of the azimuthal asymmetry**

- $\sqrt{s} = 200 / 500 \text{ GeV}$, (2006, 2011, and 2012)
- 1st transversity measurement in $p + p$ convoluted with:
 - a. Collins fragmentation function (left)
 - b. Di-hadron IFF (interference fragmentation function) (right)
- Similar magnitude for different energy



3. Transverse $p + p$ STAR, IFF via π^\pm pairs and Global analysis

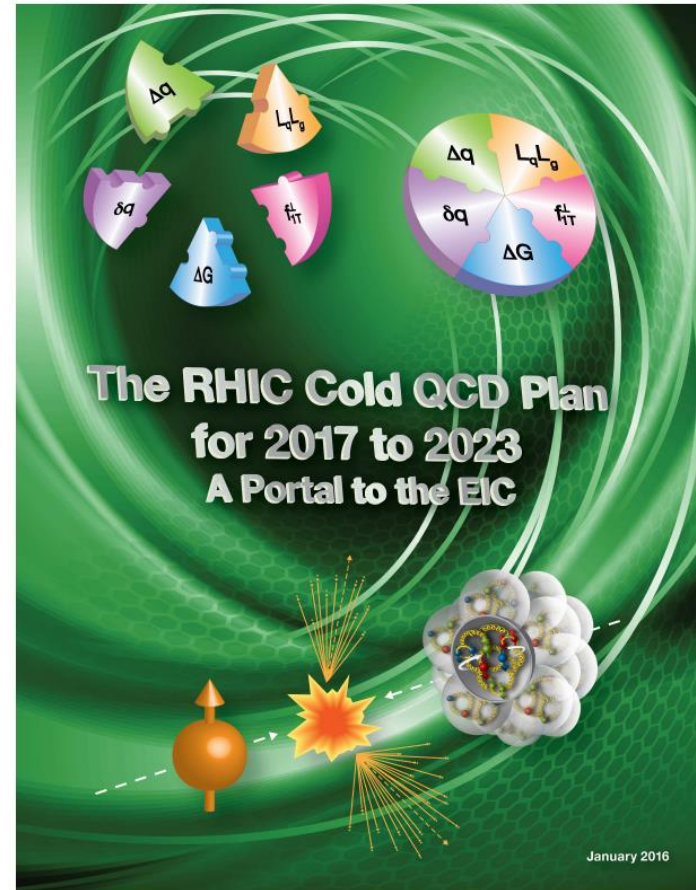


- IFF via π^\pm pair

- $\sqrt{s} = 200$ GeV, int. $L = 1.8$ pb $^{-1}$ (2006) / $\sqrt{s} = 500$ GeV, int. $L = 25$ pb $^{-1}$ (2011)
- Similar asymmetries even for different scale (200 vs. 500)
- Consistent with theoretical calculations + Significant uncertainty reduction in h_1^{u-val}

4. Summary

- **RHIC polarized p + p**
 - Provides invaluable complementary info to DIS for more consistent and complete picture
 - No additional p + p is planned until 2021, but both collaborations are now preparing upgrade:
 - a. sPHENIX (brand new barrel detector)
 - b. STAR forward upgrade
- **Nucleon helicity (Longitudinal p + p results)**
 - $\Delta\bar{q}$: RHIC W program concluded, clear physics impact
 - ΔG : observed and confirmed non-zero gluon polarization, via various probes
- **Transverse p + p results**
 - Many striking results including 1st transversity measurement in p + p
 - Not finished yet: STAR RUN15 ($\sim 50 \text{ pb}^{-1}$) and RUN17 ($\sim 350 \text{ pb}^{-1}$) results are yet to come



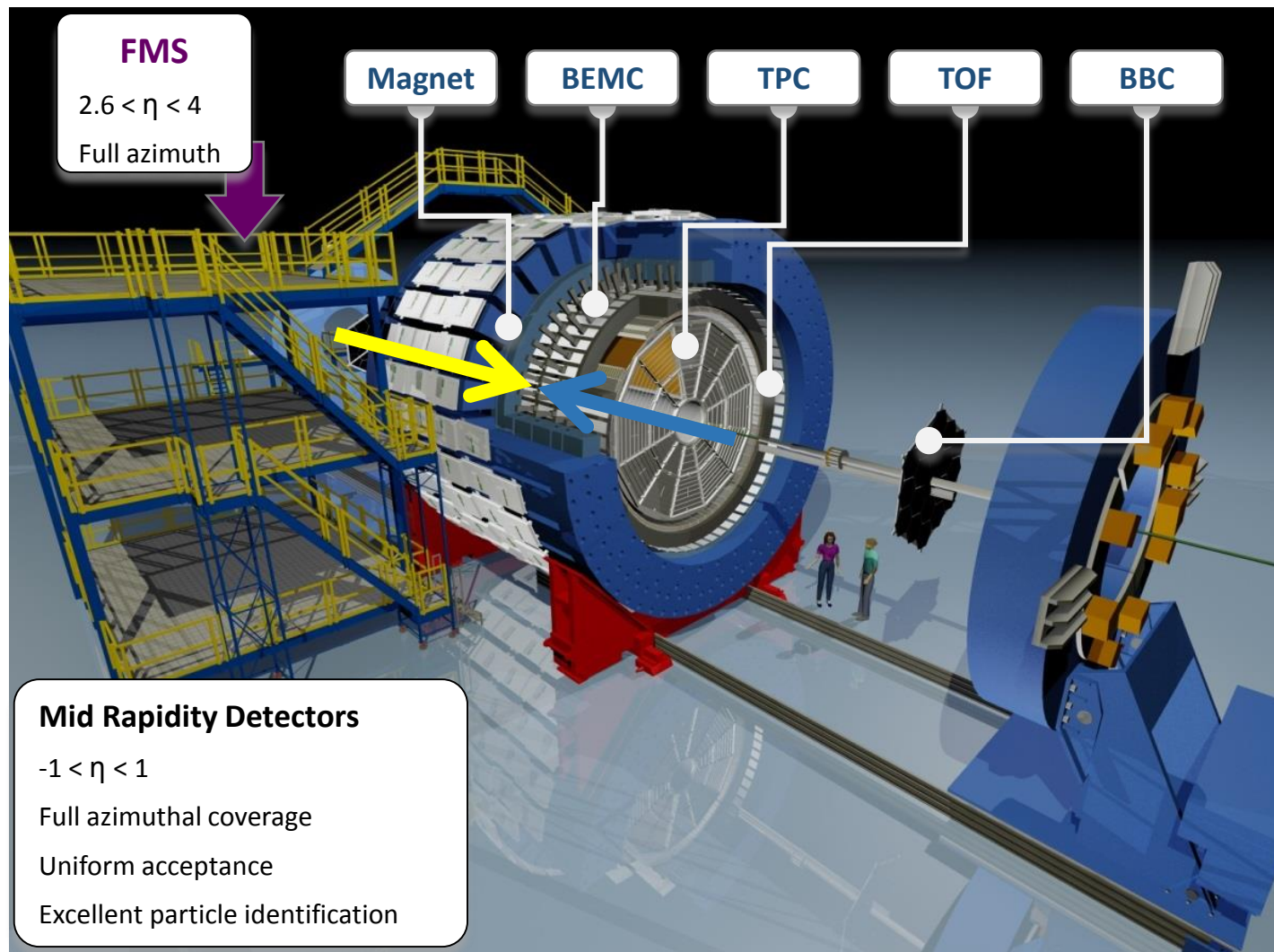
arXiv: 1501.01220

arXiv: 1602.03922

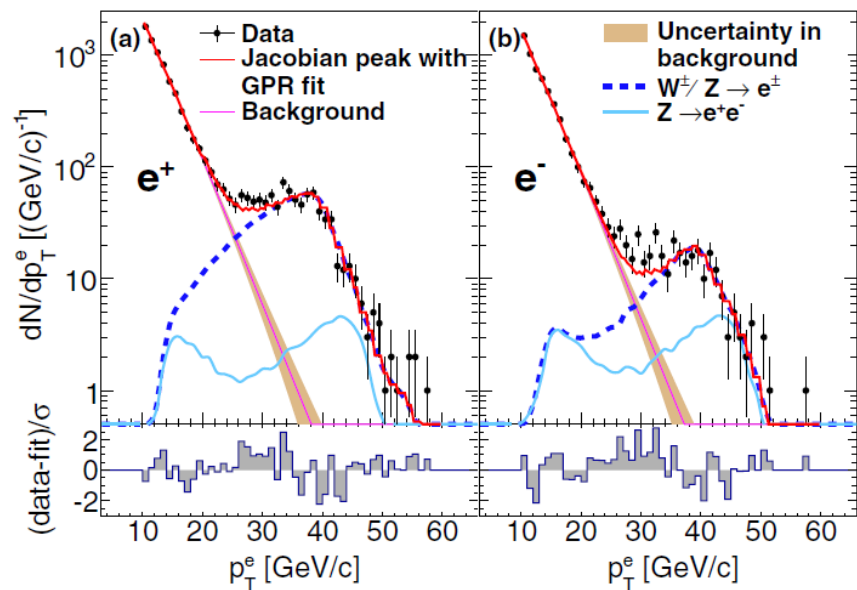
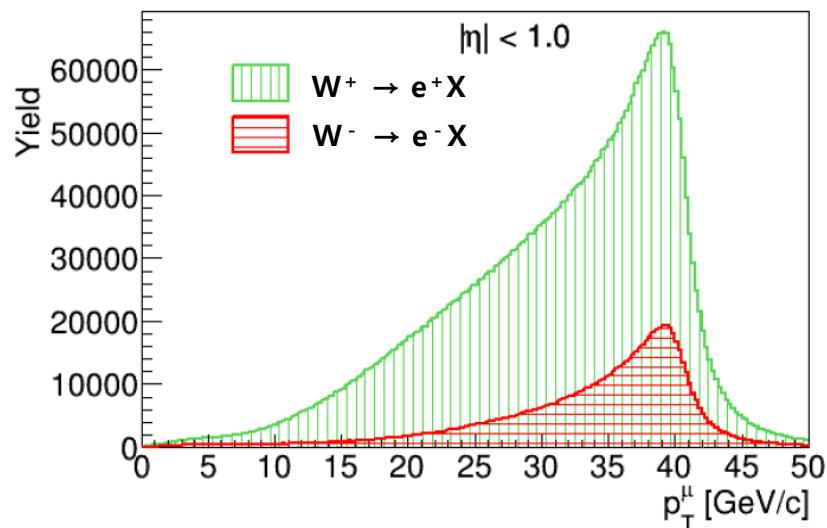
- RHIC/AGS Users Meeting 2019 (<https://www.bnl.gov/aum2019>)

Backup STAR detector

- This slide was shamelessly stolen from [Carl Gagliardi's SPIN2018 talk!](#)

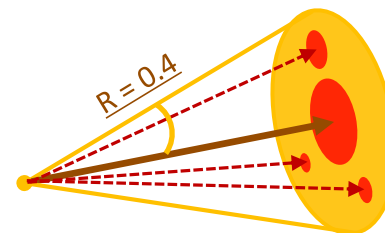


Backup PHENIX W, Central arms



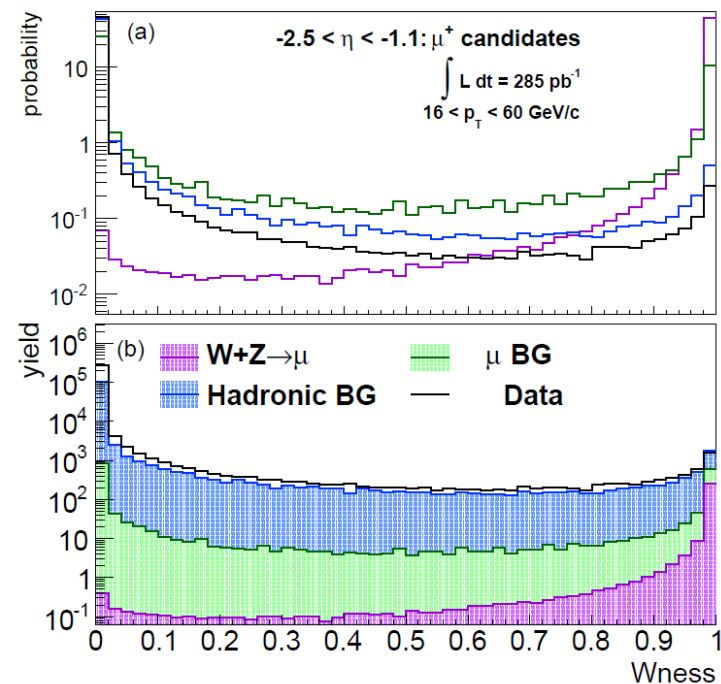
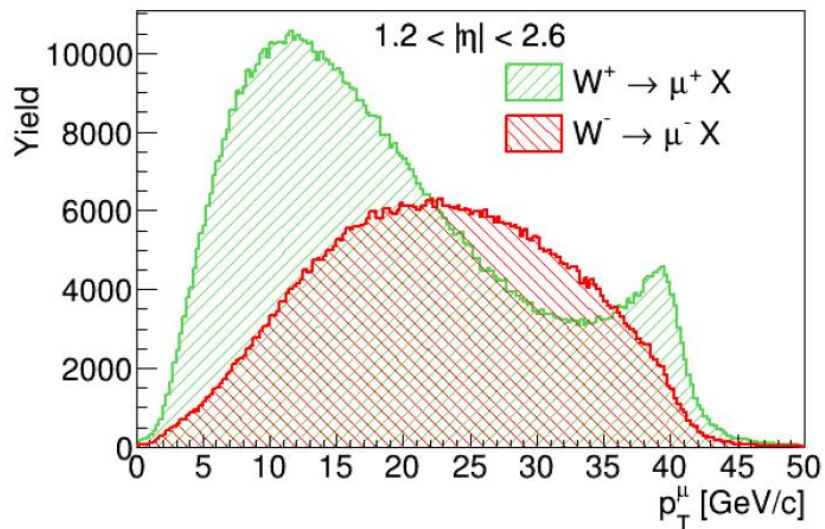
- $W^\pm \rightarrow e^\pm$ at $|\eta| < 0.35$

- Distinct Jacobian peak
- Triggered by energy
- Momentum measurement by energy
- Charge determination by tracking in B-field

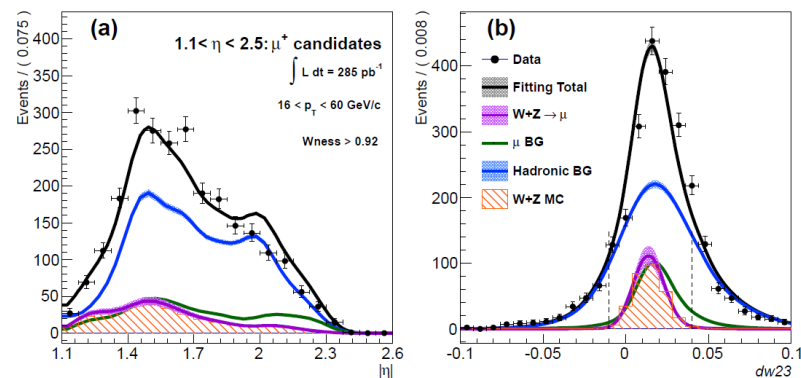


$$\frac{E_{\text{cone}} - E_{\text{candidate}}}{E_{\text{candidate}}} < 10 (\%)$$

Backup PHENIX W, Muon arms



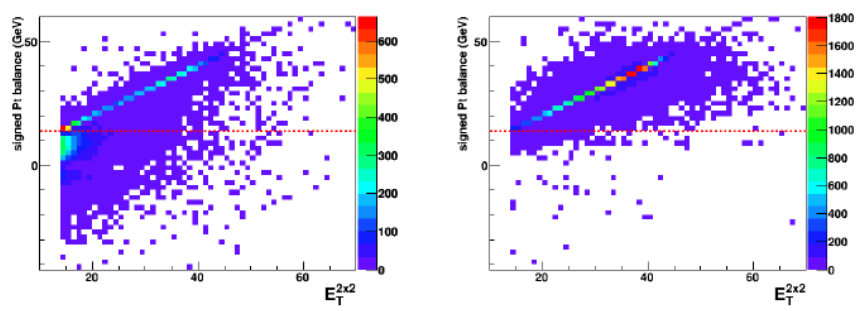
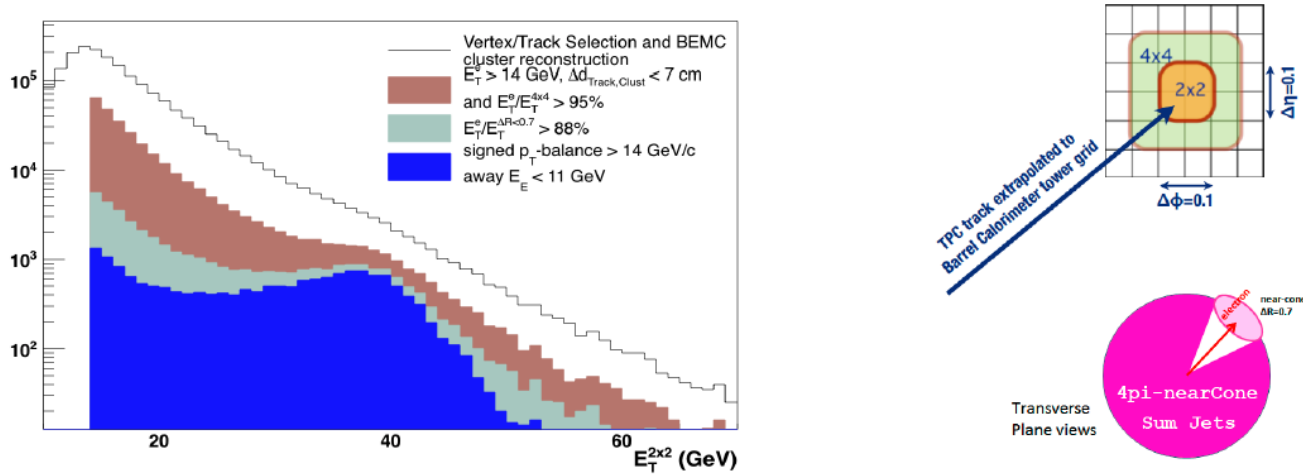
- $W^\pm \rightarrow \mu^\pm$ at $1.2 < |\eta| < 2.2 / 2.4$
 - Suppressed/No Jacobian peak
 - Triggered by momentum
 - Momentum measurement by tracking in B-field
 - Charge determination by tracking in B-field



Backup STAR W analysis

- This slide was shamelessly stolen from Jinlong Zhang's RHIC/AGS User Meeting 2019 talk!

W selection

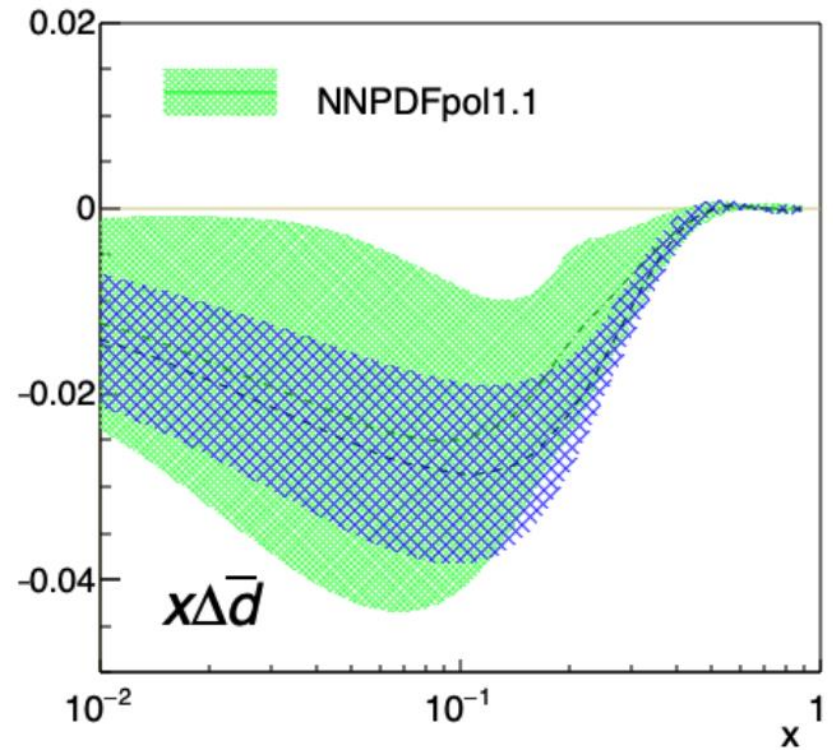
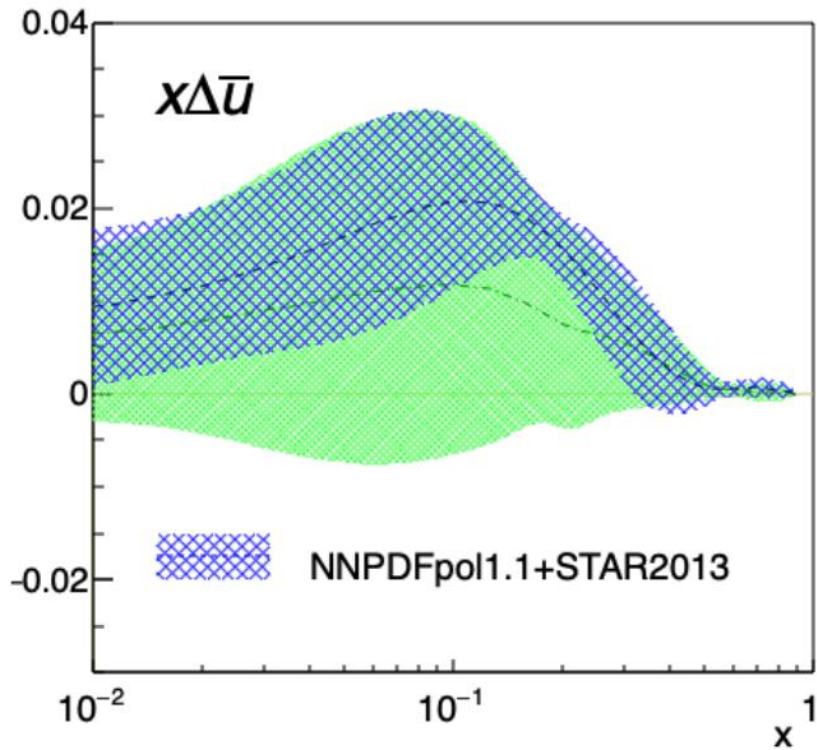


$$\vec{p}_T^{bal} = \vec{p}_T^e + \sum_{\Delta R < 0.7} \vec{p}_T^{jets}$$

Signed- p_T balance =

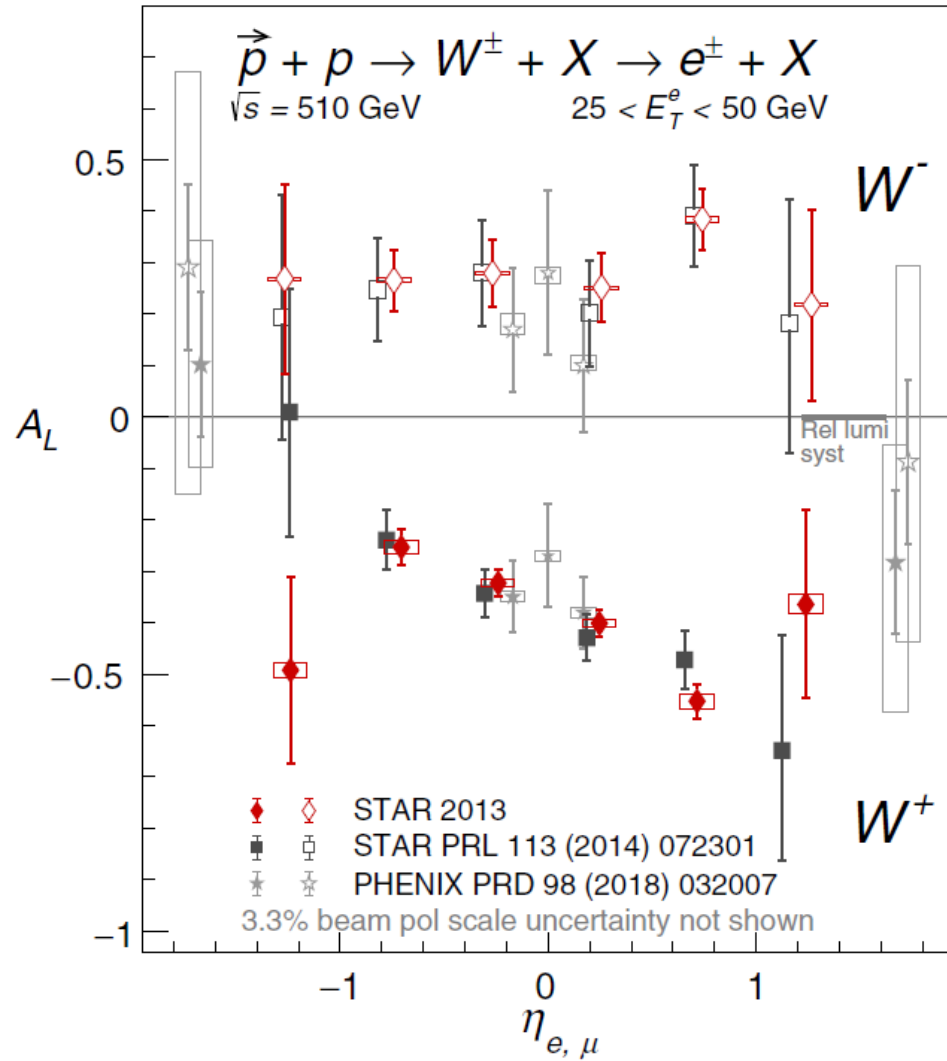
$$\frac{\vec{p}_T^e \cdot \vec{p}_T^{jets}}{|\vec{p}_T^e|}$$

Backup STAR W impact



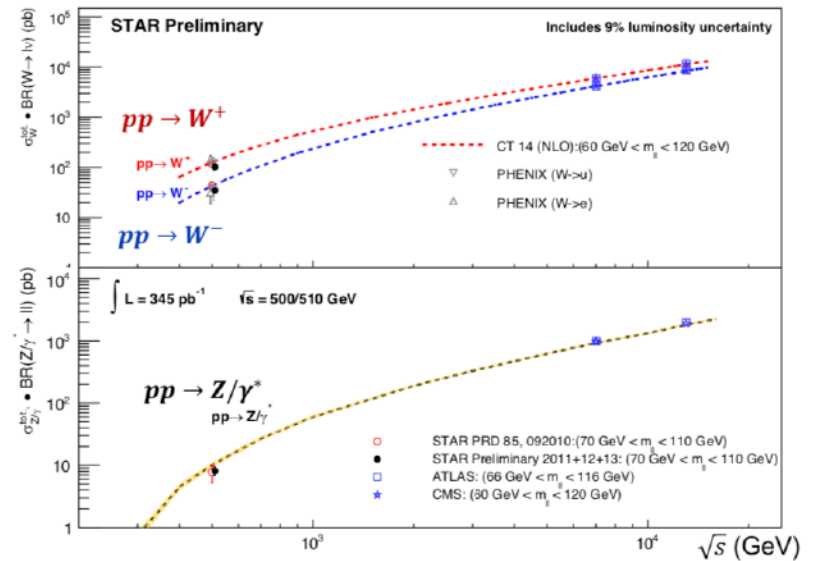
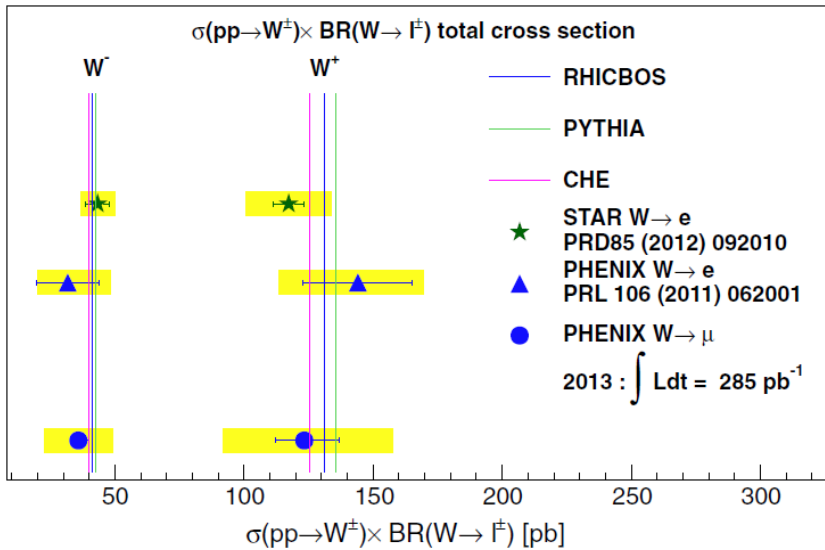
Backup RHIC W (all)

PRD99, 051102 (2019)



Backup W cross sections (PHENIX / STAR)

PRD98, 032007 (2018)

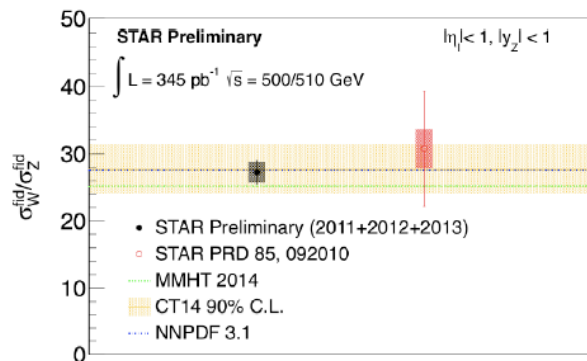
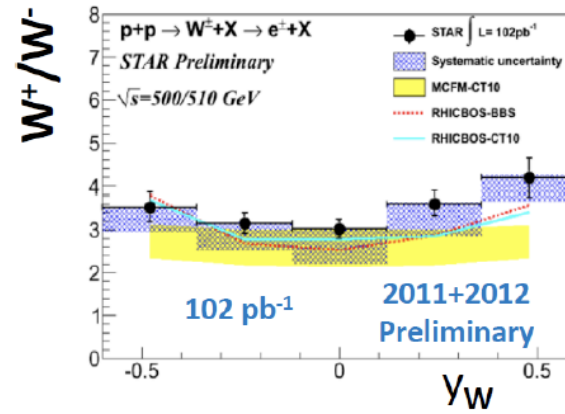
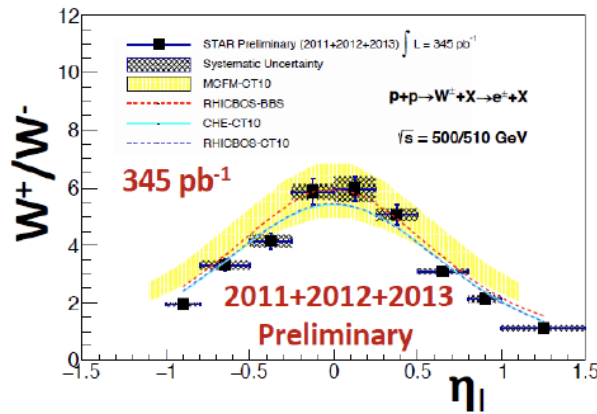


Backup STAR W/Z cross section ratio

- This slide was shamelessly stolen from Jinlong Zhang's RHIC/AGS User Meeting 2019 talk!

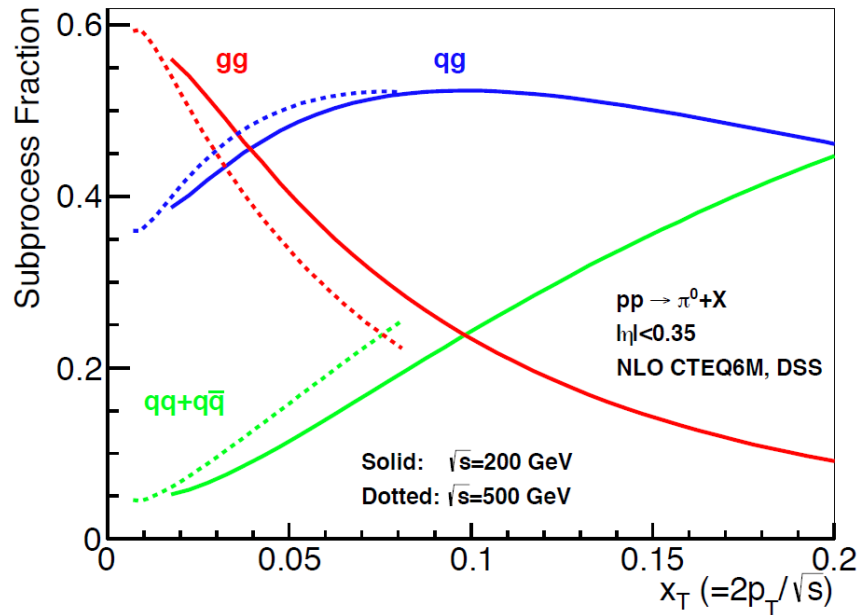
W/Z Cross Section Ratio

See Matt Posik's Poster



- Complementary measurement to SeaQuest and E-866, for $\sim 0.06 < x < \sim 0.4$, constraining unpolarized sea quark distributions.
- W kinematics determined from data and simulation; Cornerstone for $W A_N$ measurement

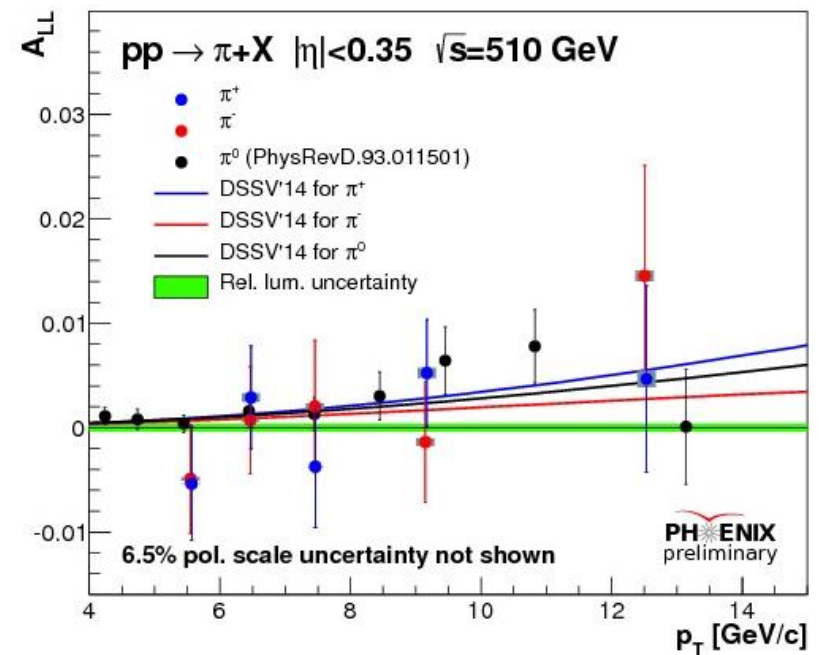
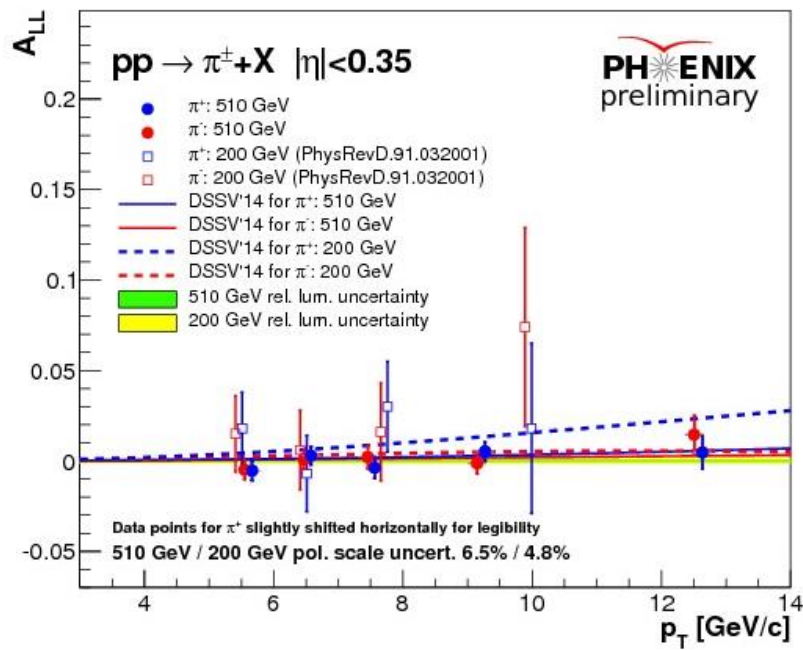
Backup Gluon polarization and π^0 ALL



arXiv: 1501.01220

- $\Delta\sigma (pp \rightarrow \pi^0 X) \approx \Delta q (x_1) \otimes \Delta g (x_2) \otimes \Delta\hat{\sigma}^{gq \rightarrow gq}(\hat{s}) \otimes D_q^{\pi^0}(z)$
 - $\Delta q (x_1)$: quark PDF (parton distribution functions), via DIS
 - $\Delta g (x_2)$: gluon PDF, ?
 - $\Delta\hat{\sigma}^{gq \rightarrow gq}(\hat{s})$: partonic hard scattering cross section, via pQCD calculation
 - $D_q^{\pi^0}(z)$: fragmentation functions, via e^+e^- collision

Backup PHENIX Central arm π^\pm , vs. p_T

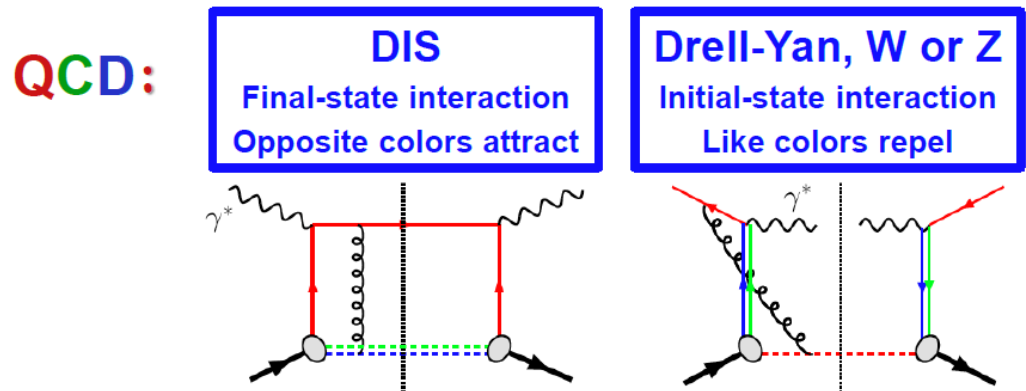


Backup Color interactions in QCD

- This slide was shamelessly stolen from Carl Gagliardi's SPIN2018 talk!

Color interactions in QCD

Controlled non-universality of the Sivers function



$$\text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{Drell-Yan}} \text{ or } \text{Sivers}_W \text{ or } \text{Sivers}_Z$$

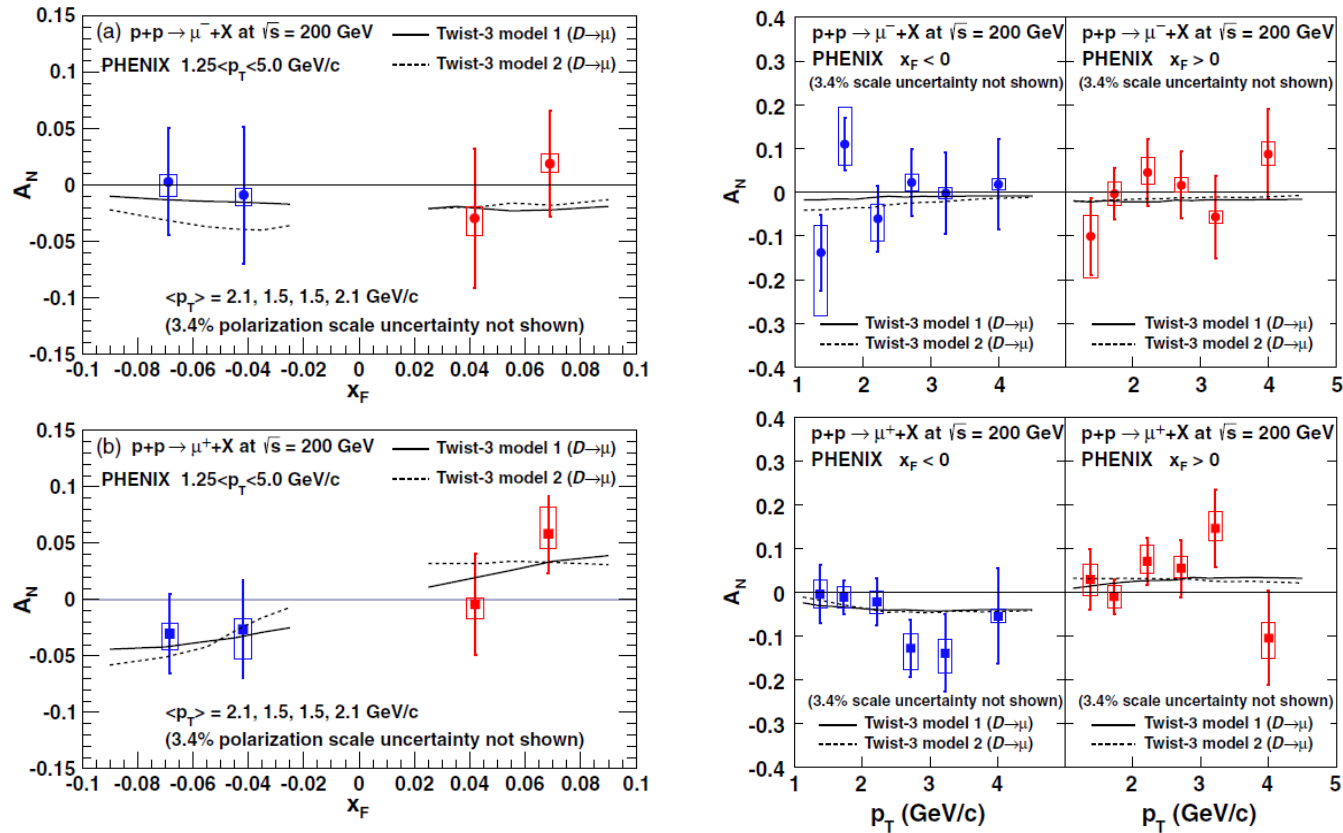
A_N for direct photon has related sign change in Twist-3

Critical test of factorization

**Opportunity to visualize the repulsive interaction
between like color charges**

**Can explore all of these observables
in 510 GeV pp collisions at RHIC**

Backup PHENIX Forward open heavy flavor

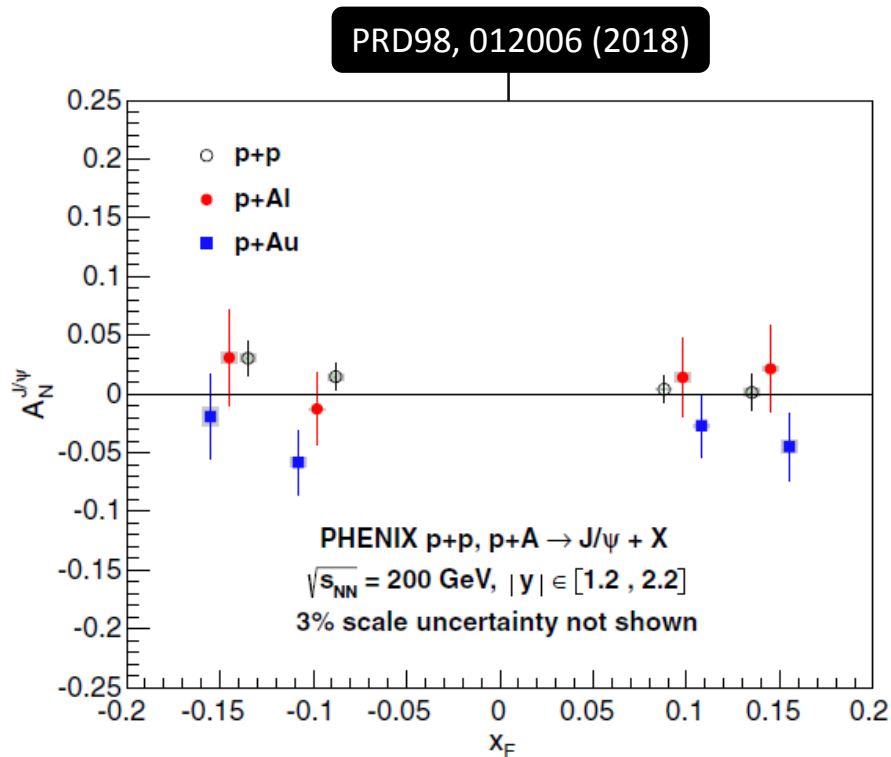


- **Open heavy decay μ A_N at $1.2 < |\eta| < 2.2$**

- $\sqrt{s} = 200$ GeV, int. $L = 9.2$ pb $^{-1}$ (2012)
- Sensitive to Twist-3 trigluon correlations
- Consistent with zero within uncertainties

PRD95, 112001 (2017)

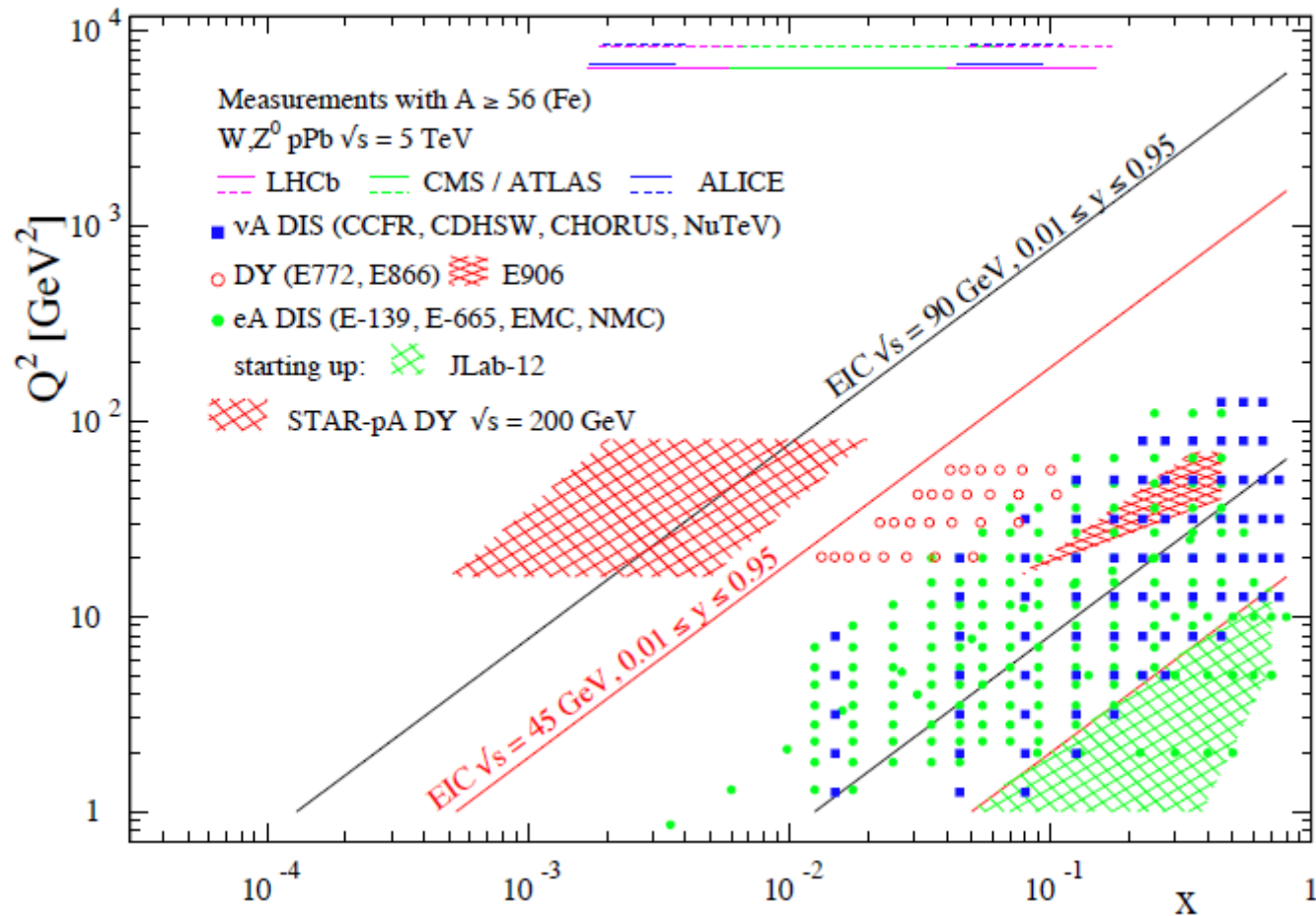
Backup PHENIX Forward J/ψ



- $J/\psi A_N$ at $1.2 < |\eta| < 2.2$
 - $\sqrt{s} = 200 \text{ GeV}$ (2015)
 - int. $L = 40 \text{ (pp)}, 6.0 \text{ (pAl)}, \text{ and } 6.6 \text{ (pAu)} \text{ pb}^{-1}$
 - Consistent with zero, No clear A dependence

Backup Q^2 vs. x kinematic coverage

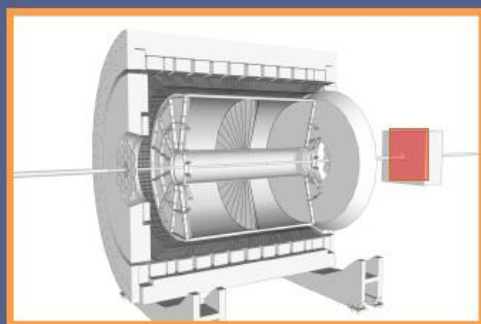
arXiv: 1602.03922



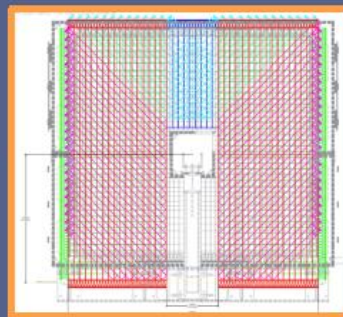
Backup STAR RUN17 DY

- This slide was shamelessly stolen from Renee Fatemi's RHIC/AGS user meeting 2019 talk!

DRELL-YAN A_N FROM 400 PB⁻¹ IN 2017



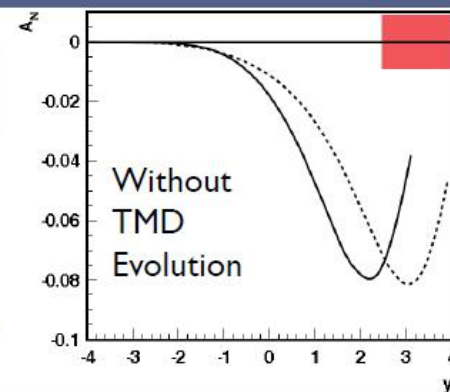
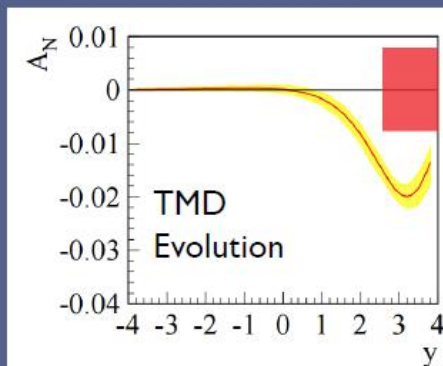
+



FMS post-shower detector added for 2017 run. Combining with pre-shower allows factor of 10^6 suppression in ratio of QCD background to signal!

DY e^+e^- in $2.5 < \eta < 4.0$
 $4.0 \text{ GeV} < M_{e^+e^-} < 9.0 \text{ GeV}$

Note: The orange square is the statistical uncertainty achievable with 400 pb⁻¹.

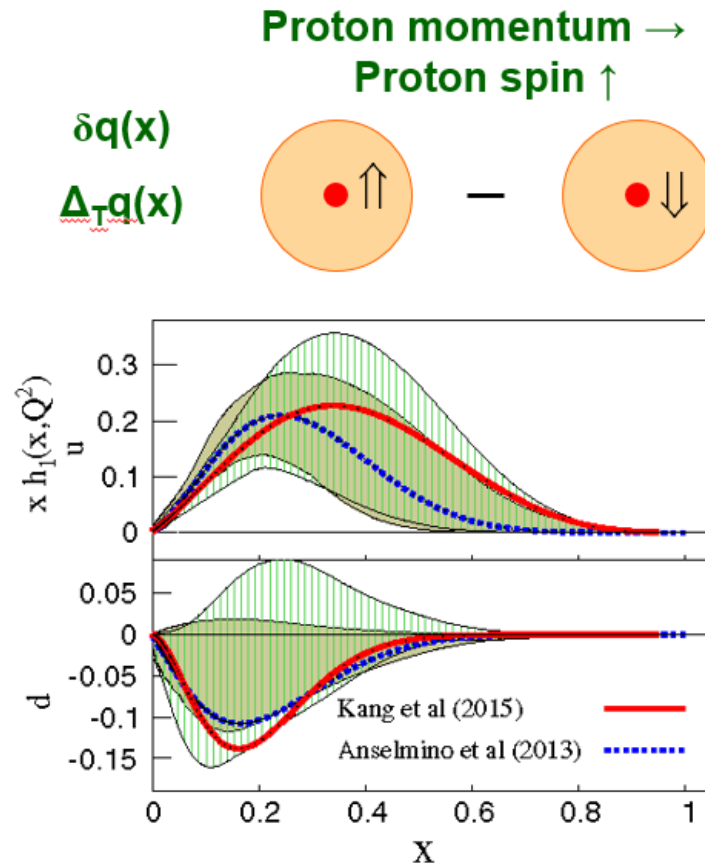


Phys.Rev.D 89, 074013 (2014)

Backup Transversity

- This slide was shamelessly stolen from Carl Gagliardi's SPIN2018 talk!

Transversity

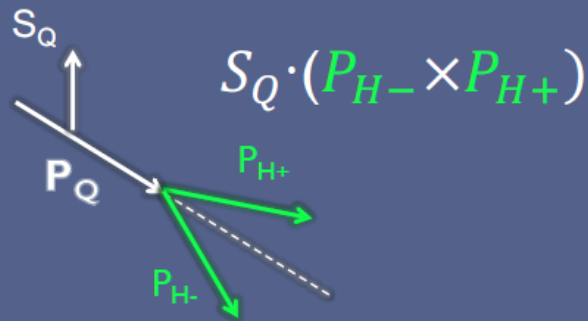


- Quark polarization along spin of a transversely polarized proton
 - Third collinear, leading twist distribution
 - Chiral odd
- Much less data than for helicity
- Before **STAR**, only observed in SIDIS combined with e^+e^-
- Several recent global analyses including:
 - Collins effect SIDIS input:
 - PRD 93, 014009 (2016)
 - PRD 92, 114023 (2015)
 - IFF SIDIS + **STAR** pp input:
 - PRL 120, 192001 (2018)
 - All show large uncertainties

Backup Transversity – IFF vs. Collins FF

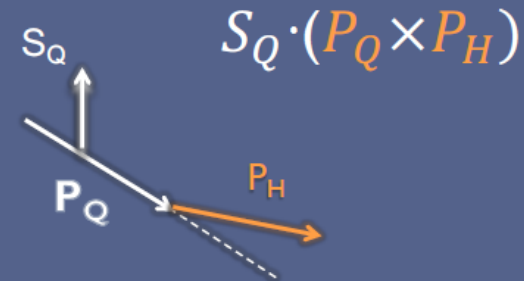
- This slide was shamelessly stolen from **Renee Fatemi's** RHIC/AGS user meeting 2019 talk!

TRANSVERSITY



Interference Fragmentation Functions

Correlation between spin of transversely polarized quark and momentum cross-product of dihadron pair.



Collins Fragmentation Functions

Correlation between spin of transversely polarized quark and transverse momentum kick given to fragmentation hadron.