Nucleon Spin Highlights of PHENIX and STAR

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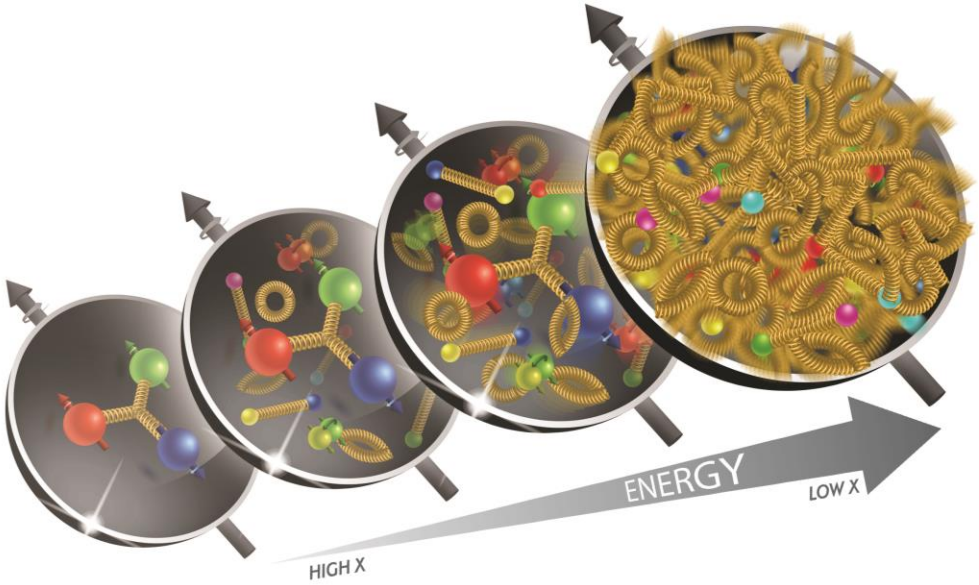
A **PERSONAL** study of RHIC spin results

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

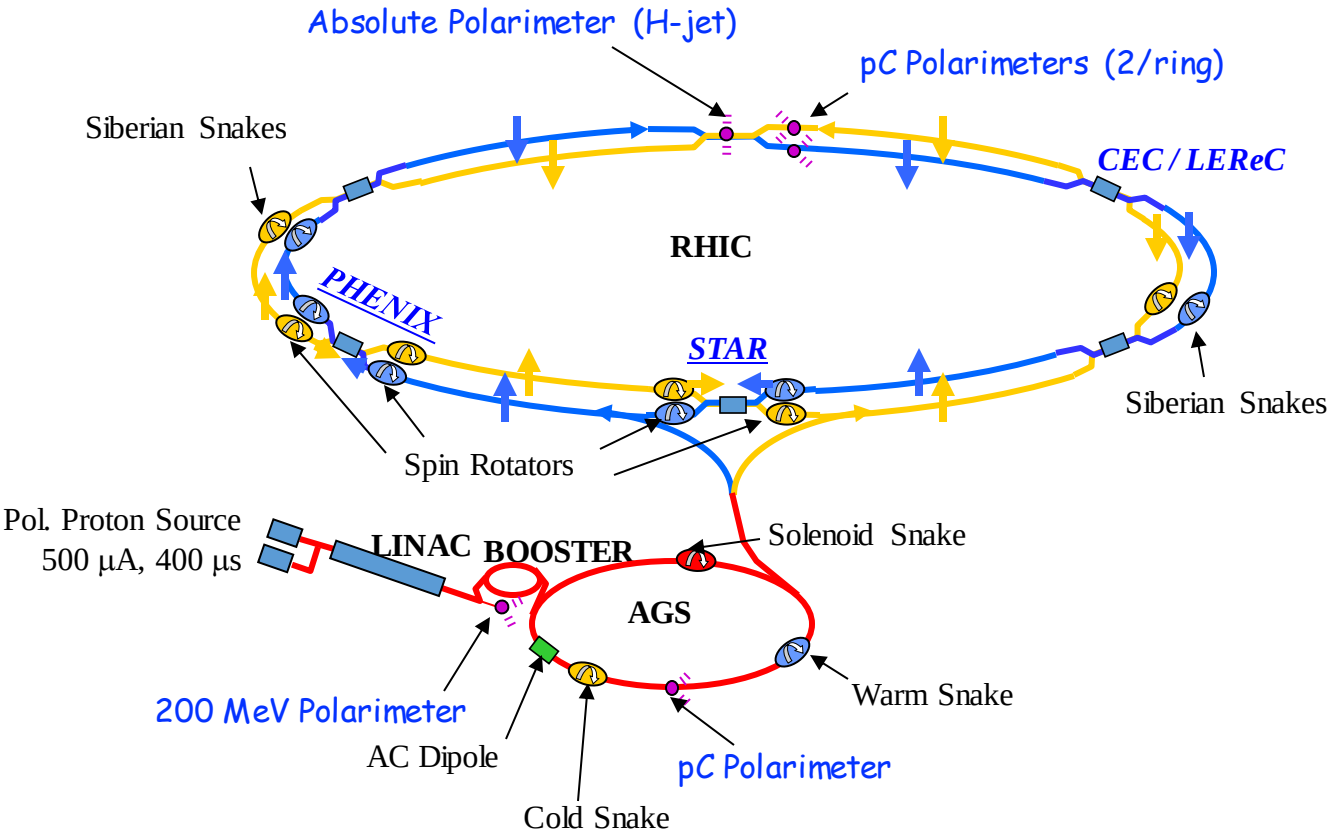
Introduction What p + p can provide?



- **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

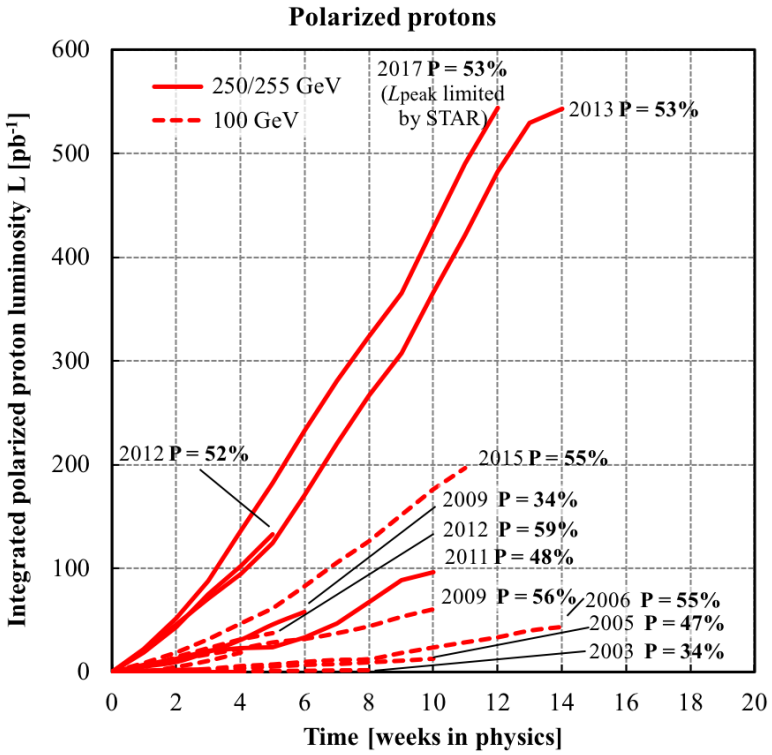
- **p + p** primarily probes via:
  - Strong interactions
    a. Couple to color charge
    b. Direct LO sensitivity to gluons
    c. Insensitive to flavor

Introduction RHIC



- **RHIC @ Brookhaven Lab., NY**
  - Polarized p + p (max. 120 bunches per ring) @ √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)



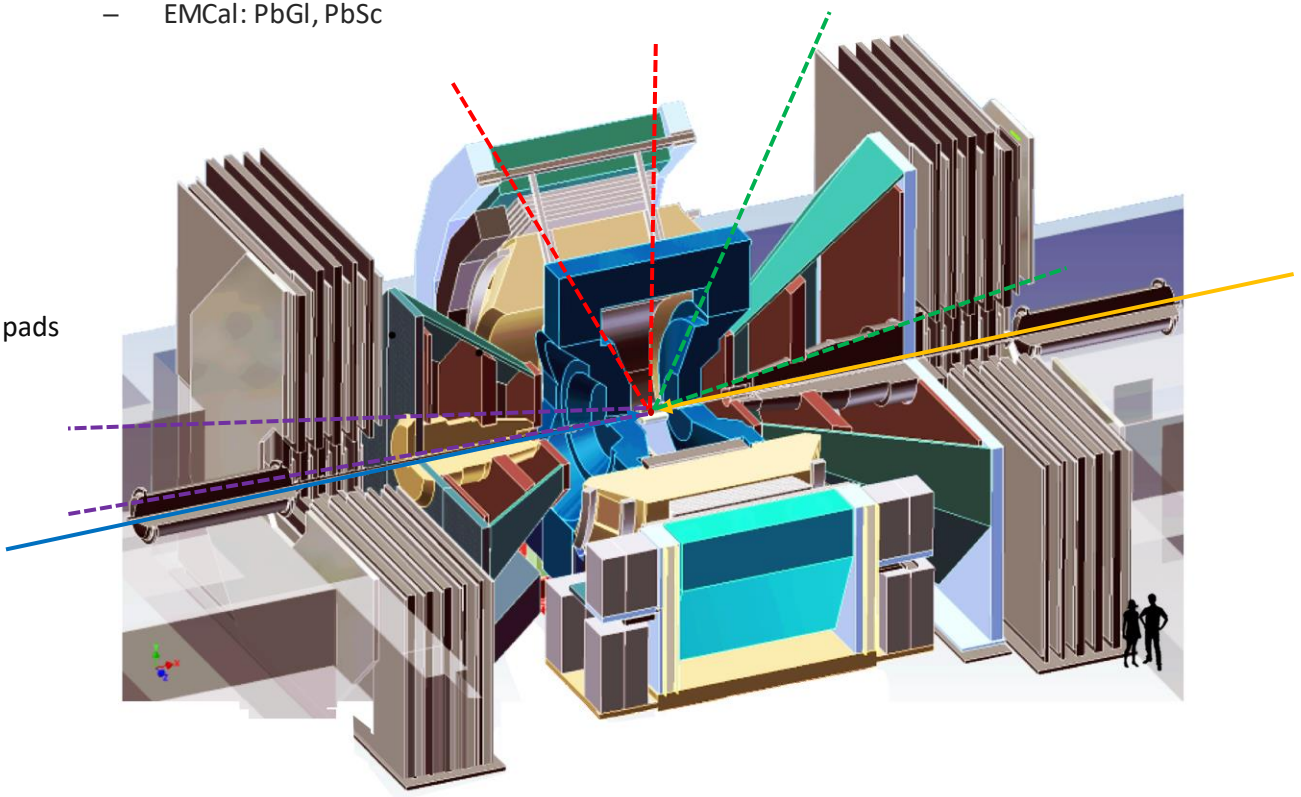
				PHENIX	STAR
Year	√s (GeV)	Type	⟨P⟩ (%)	Int. *L* (pb^{-1})	int. *L* (pb^{-1})
09	200	L	56 / 57	16	25
	500	L	33 / 36	14	11
11	500	L	48 / 48	28	12
12	510	L	50 / 54	50	86
13	510	L	51 / 55	242	306
15	200	L	53 / 57	x	53
11	500	T	48 / 48	x	22
12	200	T	62 / 57	18	25
15	200	T	53 / 57	110	52
17	510	T	55 / 56	x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

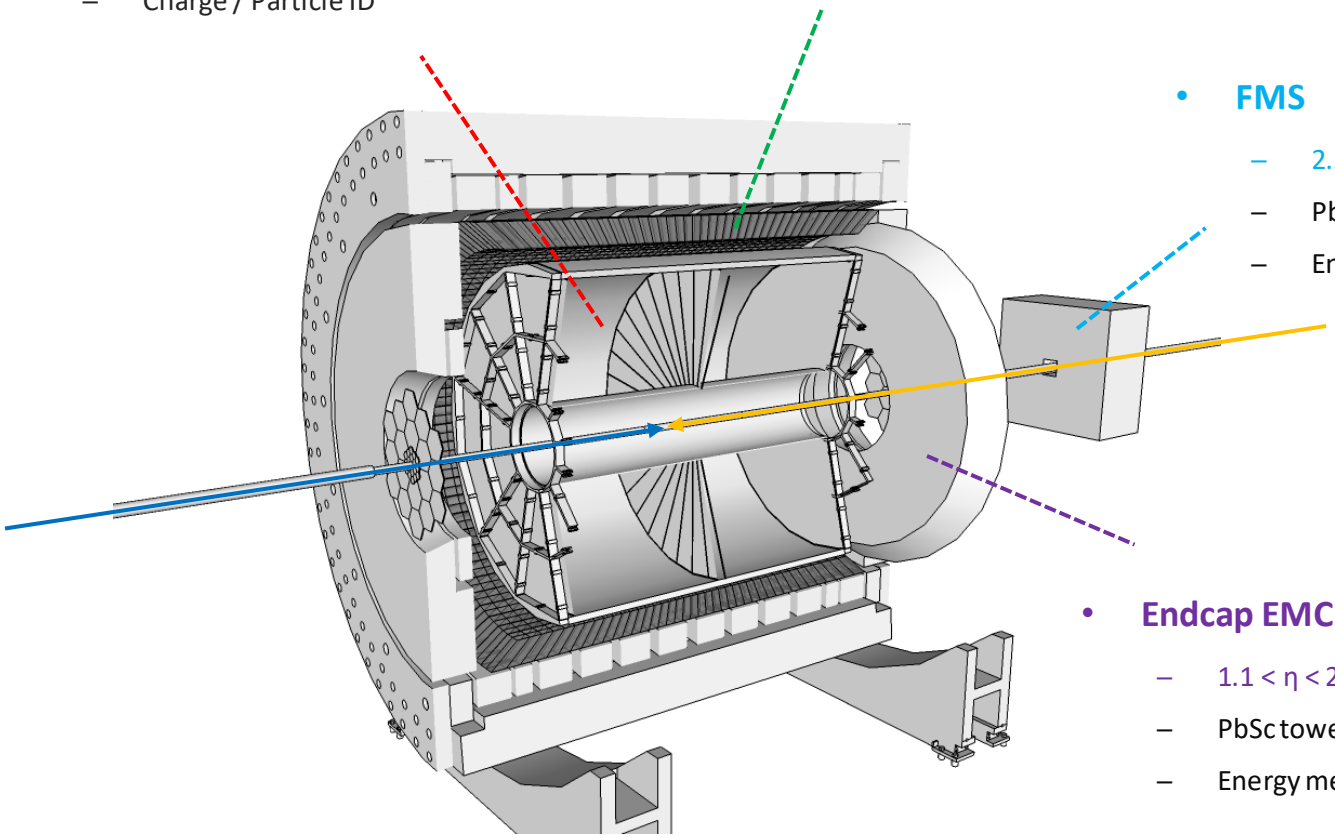
Introduction PHENIX (2016)

- **Central Arms**
  - $|\eta| < 0.35$, $\Delta\phi = \frac{\pi}{2} \times 2$, 0.78 T
  - VTX (Si pixel and strip, from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc
- **Muon Arms**
  - $1.2 < |\eta| < 2.2$ (2.4), $\Delta\phi = 2\pi$, 0.72 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)
  - …

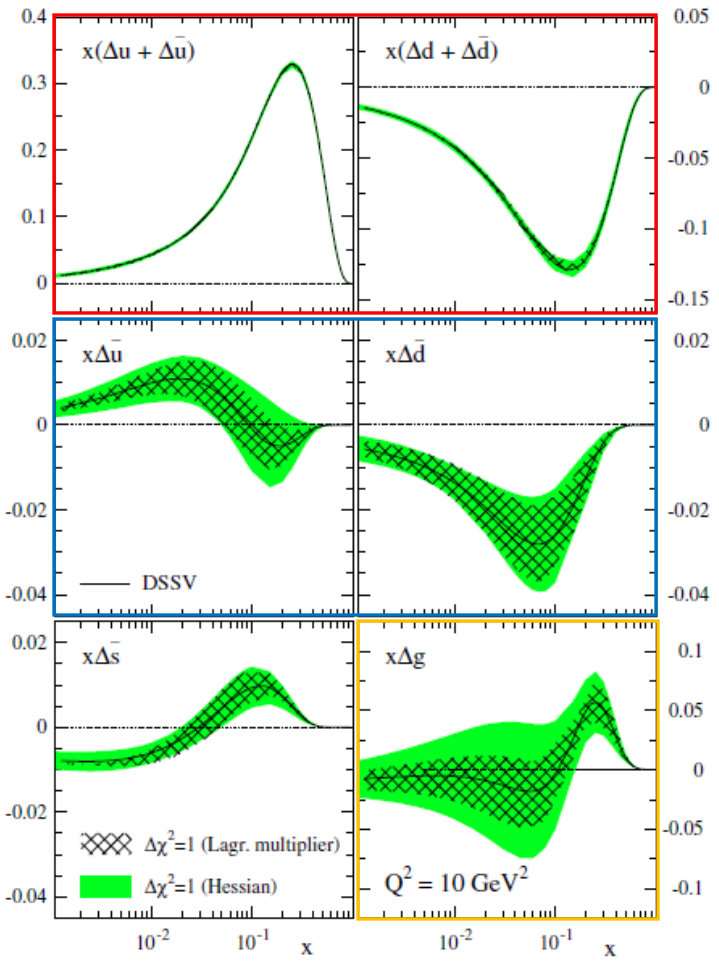


- **FMS**
  - $2.5 < \eta < 4.0$, $\Delta\phi = 2\pi$
  - PbGl towers + pre/postshower
  - Energy measurement, Trigger
- **Endcap EMC**
  - $1.1 < \eta < 2.0$, $\Delta\phi = 2\pi$
  - PbSc towers + SMD + pre/postshower
  - Energy measurement, Trigger

2. Nucleon helicity

(Longitudinally polarized p + p)

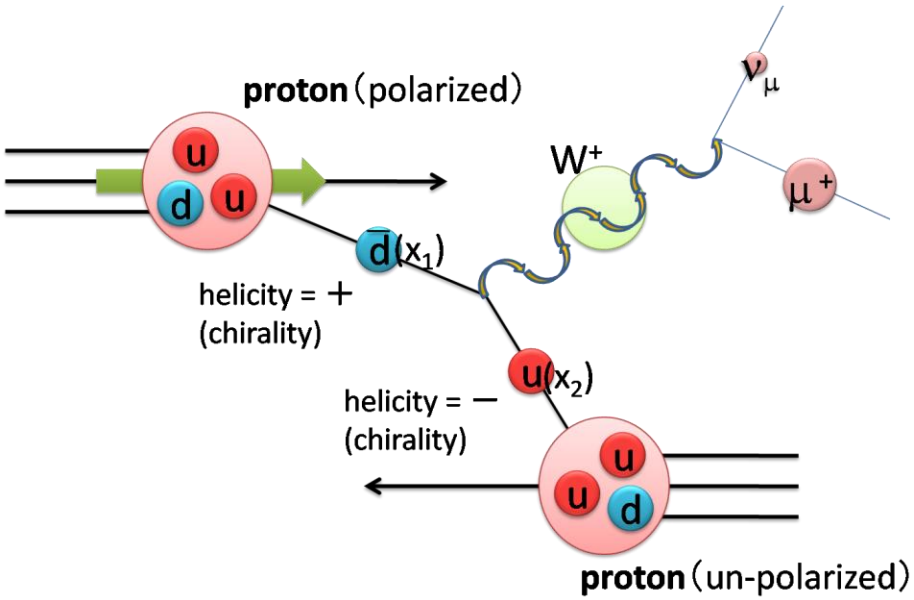
2. Nucleon helicity Motivation



PRD80. 034030 (2009)

- $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
- ΔΣ?
  - $(\Delta q + \Delta\bar{q})$: well constrained down to x ~ 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
- ΔG?
  - Poorly constrained: limited access in DIS
    → 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,

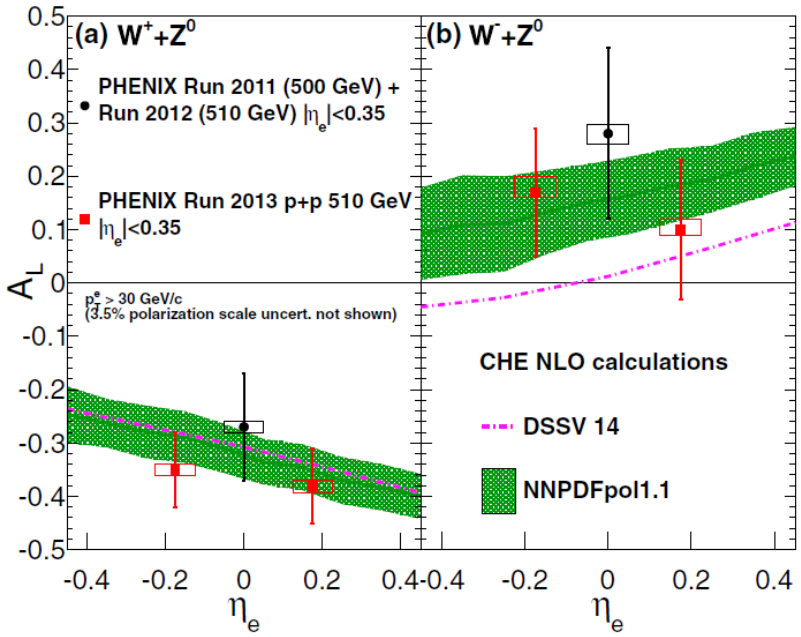
$$A_L^{W} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

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

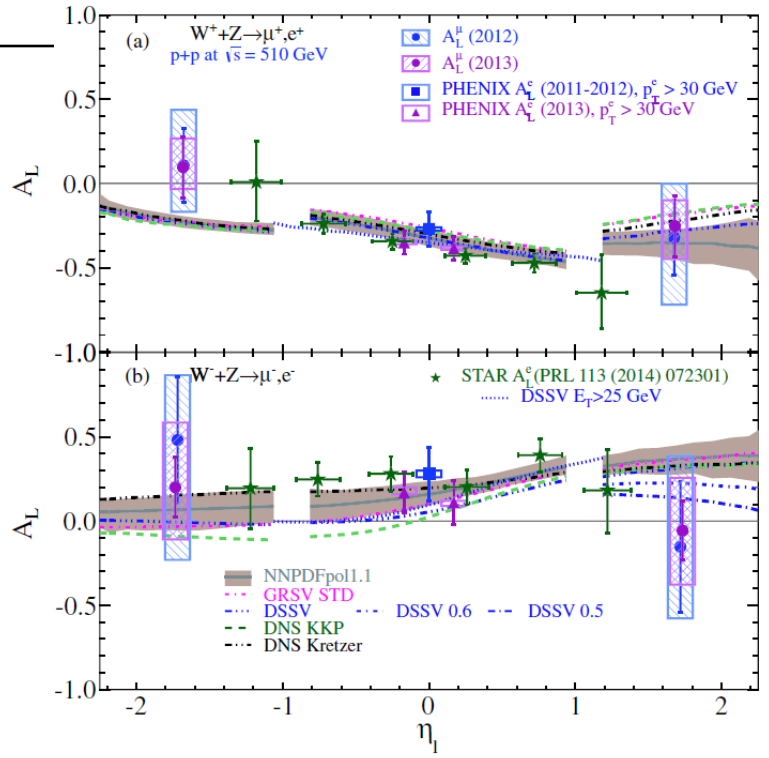
- **$\Delta\bar{q}$ measurements at RHIC**
  - $W^\pm \rightarrow e^\pm$: PHENIX midrapidity ($|\eta| < 0.35$), STAR ($|\eta| < 1.3$)
  - $W^\pm \rightarrow \mu^\pm$: PHENIX forward rapidity ($1.2 < |\eta| < 2.2 / 2.4$)

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

PRD93, 051103 (2016)

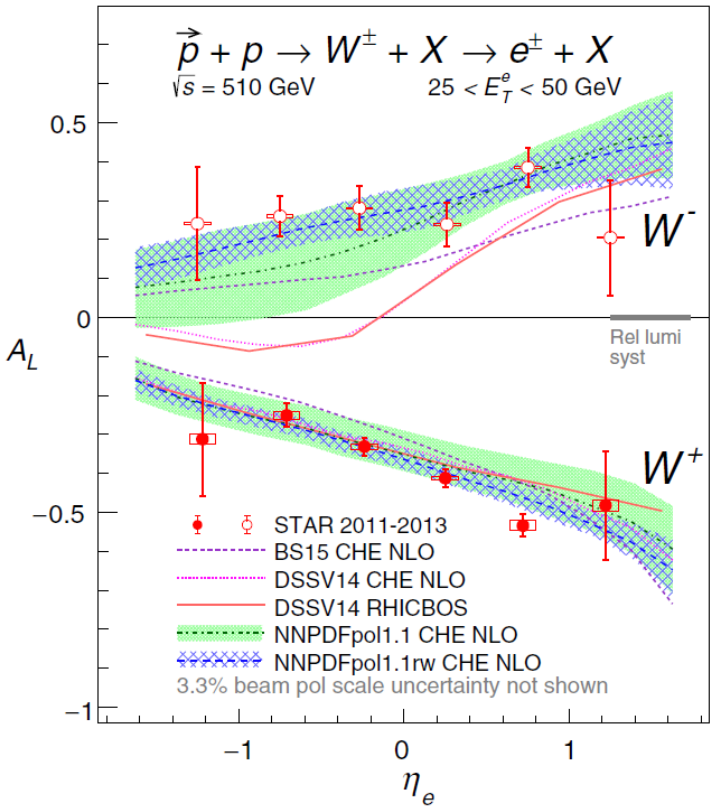


PRD98, 032007 (2018)

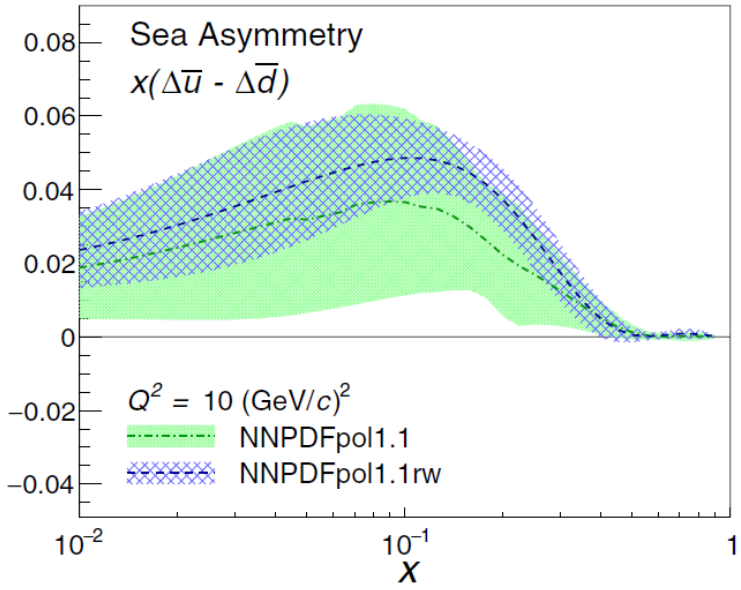


- **W → e A_L, $|\eta| < 0.35$**
  - Int. L = 240 pb^{-1} (2011 - 2013)
  - Signal extraction by e$^{\pm}$ isolation + Jacobian peak
  - x (partonic momentum fraction) ~ 0.16 (M_W/ √s)
- **W → μ A_L, $1.2 < |\eta| < 2.2 / 2.4$**
  - Int. L = 53 (2012) + 285 (2013) pb^{-1}
  - Signal extraction based on W likelihood
  - x ~ 0.1 (backward) / ~ 0.3 (forward)

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

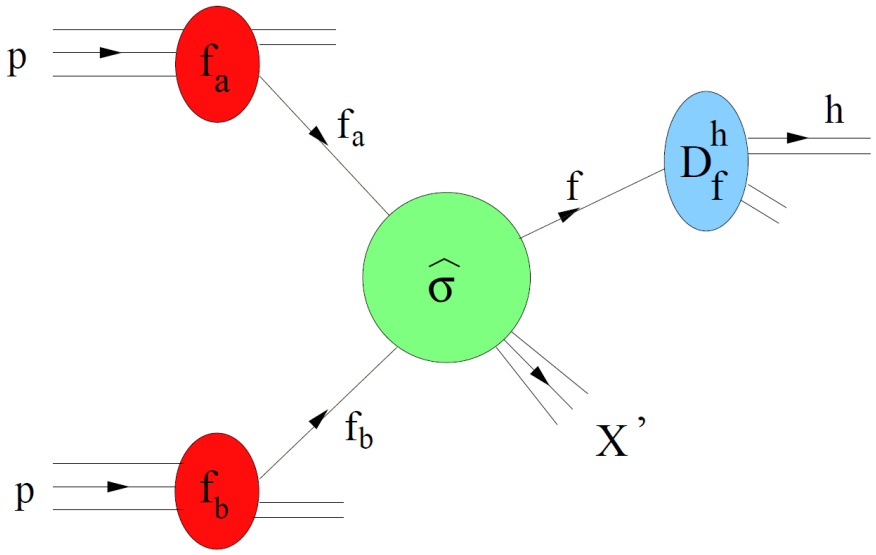


PRD99, 051102 (2019)



- **W → e A_L , |η| < 1.3**
  - Int. L = 86 (2011-2012) + 250 (2013) 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



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

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

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

technically,

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

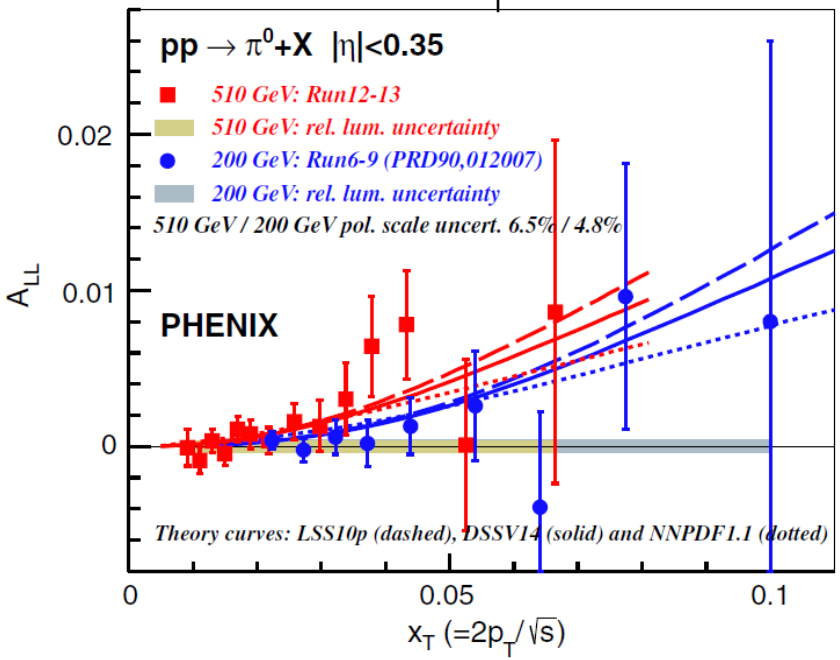
- P : avg. polarization of each beam
- N++ (N+-) : yields in same (opposite) helicity
- $R = \frac{L++}{L+-}$: relative luminosity

- **ΔG measurements at RHIC**
  - Various probes: **jet**, direct γ, **π⁰**, **π±**, η, heavy flavor decay electrons, etc
  - Wide pseudorapidity (η) coverage

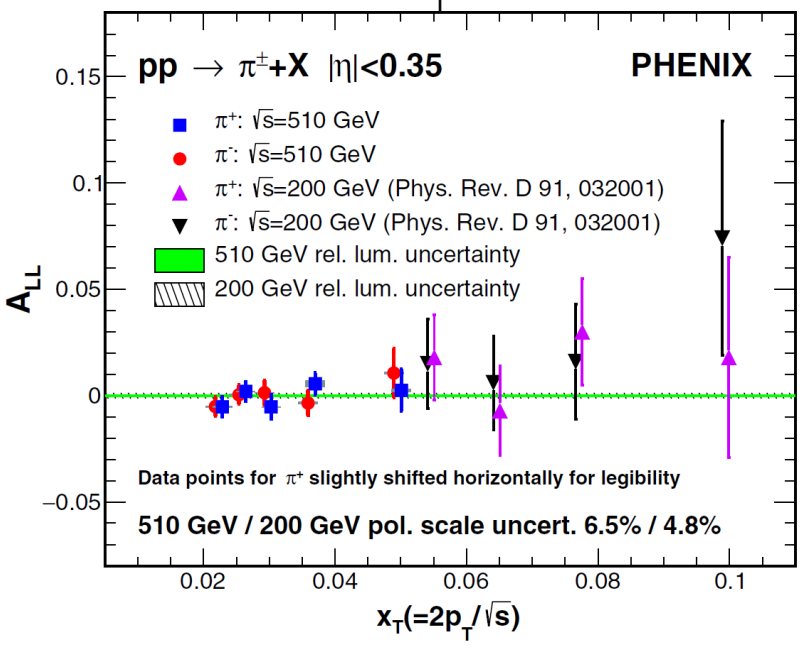
PHENIX

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

PRD93, 011501 (2016)



PRD102, 032001 (2020)

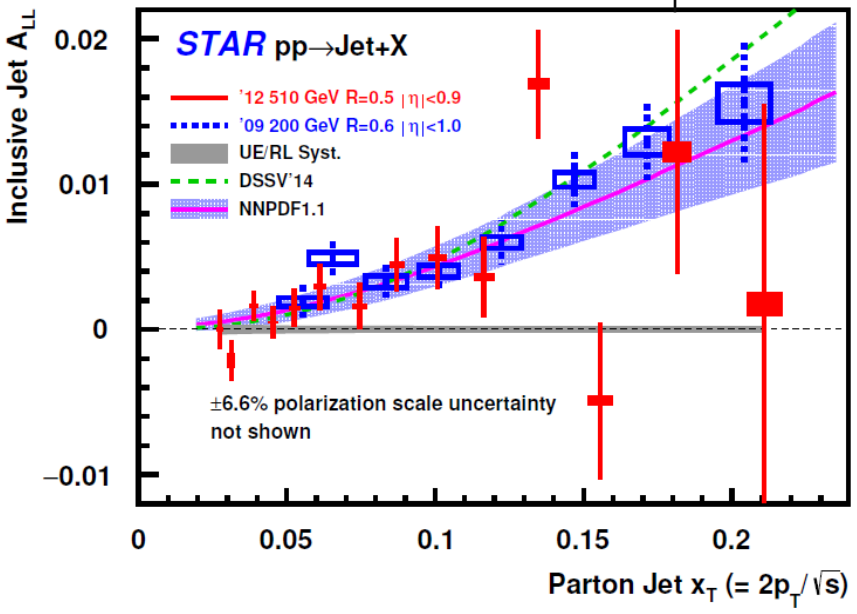


- **Inclusive π^0 A_{LL}, $|\eta| < 0.35$**
  - Int. L = 20 (2012) + 108 (2013) pb^{-1}
  - Confirm non-zero ΔG via hadron production
  - x down to ~ 0.01

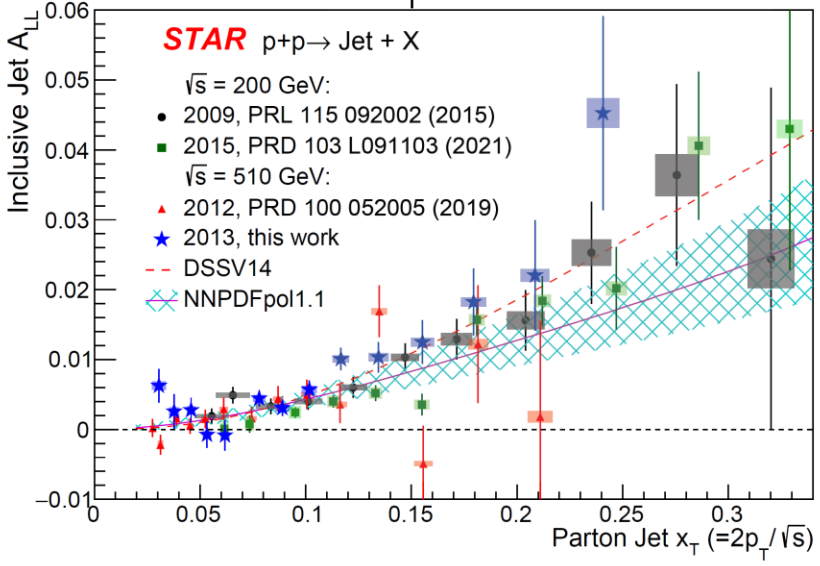
- **$\pi^\pm$ A_{LL}, $|\eta| < 0.35$**
  - Int. L = 108 pb^{-1} (2013)
  - Complementary probe to previous π^0 / $\pi^\pm$ results

2. Nucleon helicity – b. ΔG STAR, inclusive jet A_{LL}

PRL115, 092002 (2015) PRD100, 052005 (2019)



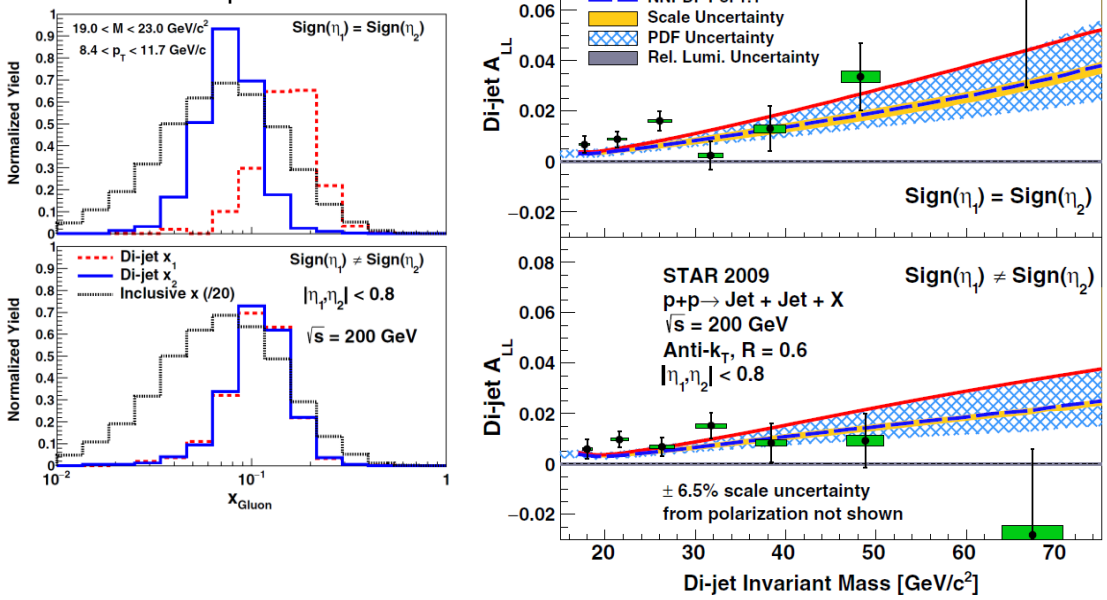
arXiv:2110.11020

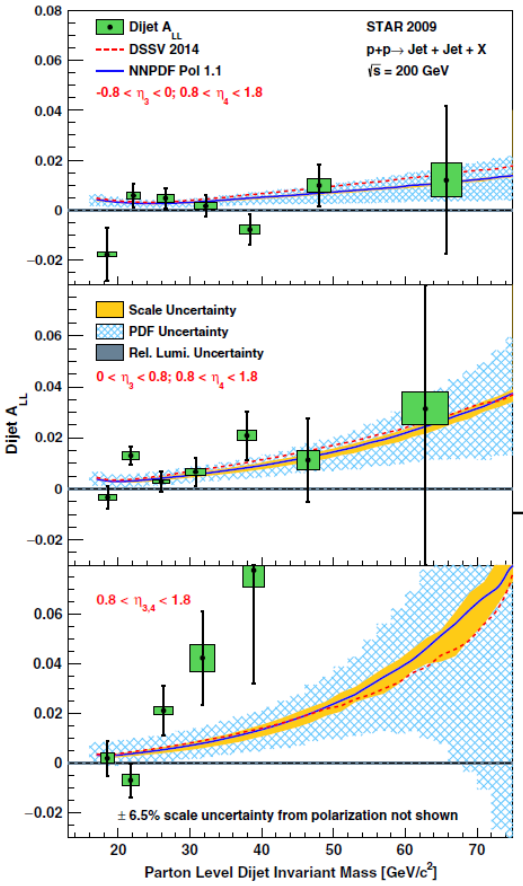


- **Inclusive jet A_{LL}, $|\eta| < 0.9$**
  - First non-zero ΔG observed (2009):
    → DSSV14: $\int_{0.05}^{1} dx\, \Delta g(x) = 0.20\ ^{+0.06}_{-0.07}$ (90 % C.L.)
    → NNPDF1.1: $\int_{0.05}^{0.20} dx\, \Delta g(x) = 0.17\ ^{+0.06}_{-0.06}$
  - 2009: √s = 200 GeV, int. L = 21 pb^{-1}, x > 0.05
  - 2012: √s = 510 GeV, int. L = 82 pb^{-1}, x ~ 0.015
  - 2013: √s = 510 GeV, int. L = ~250 pb^{-1}, 0.015 ≤ x ≤ 0.25
  - 2015: √s = 200 GeV, int. L = pb^{-1}, 0.05 ≤ x ≤ 0.5

2. Nucleon helicity – b. ΔG STAR, dijet A_{LL}

PRD95, 071103 (2017)

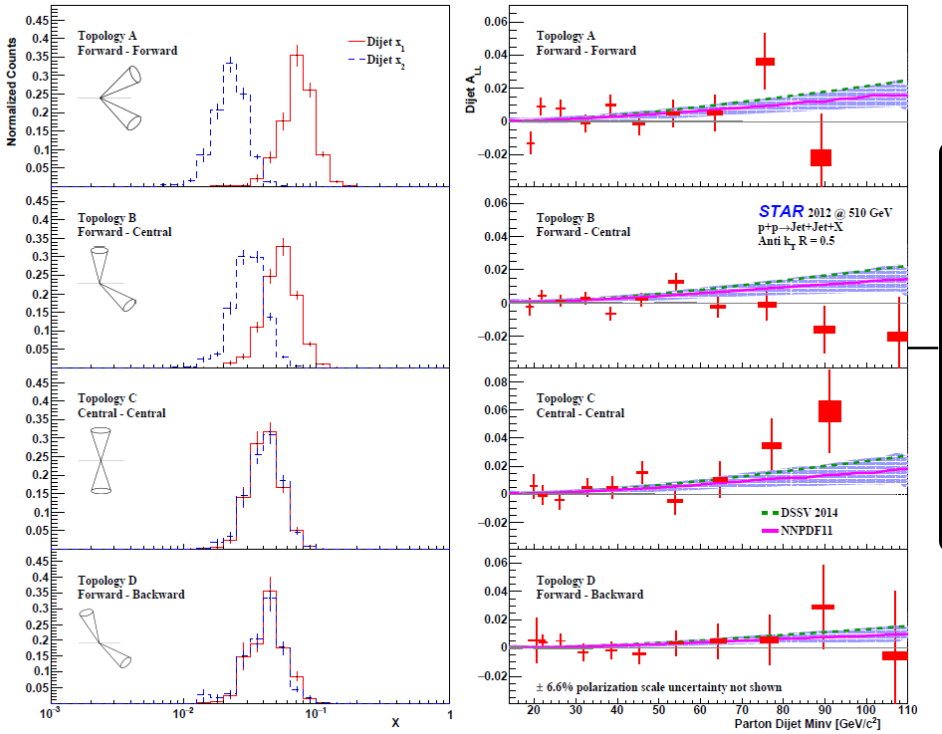




PRD98, 032011 (2018)

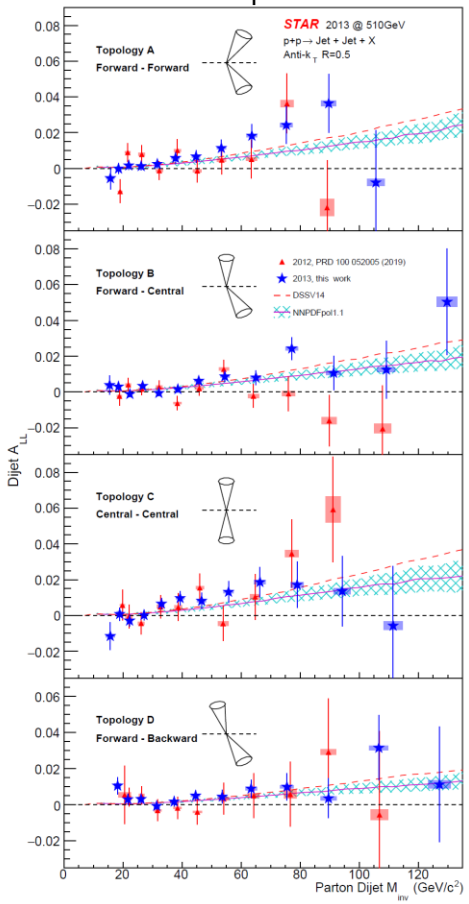
- **Midrapidity dijet A_{LL}, by η topologies, $|\eta| < 0.8$**
  - Dijet invariant mass M = √s √($x_1 x_2$)
  - Dijet $\eta_1 + \eta_2 = \log(x_1/x_2)$
  - Top: $-0.8 < \eta_3 < 0$; $0.8 < \eta_4 < 1.8$
  - Middle: $0 < \eta_3 < 0.8$; $0.8 < \eta_4 < 1.8$
  - Bottom: $0.8 < \eta_{3,4} < 1.8$

2. Nucleon helicity – b. ΔG STAR, dijet A_{LL}



PRD100, 052005 (2019)

arXiv:2110.11020

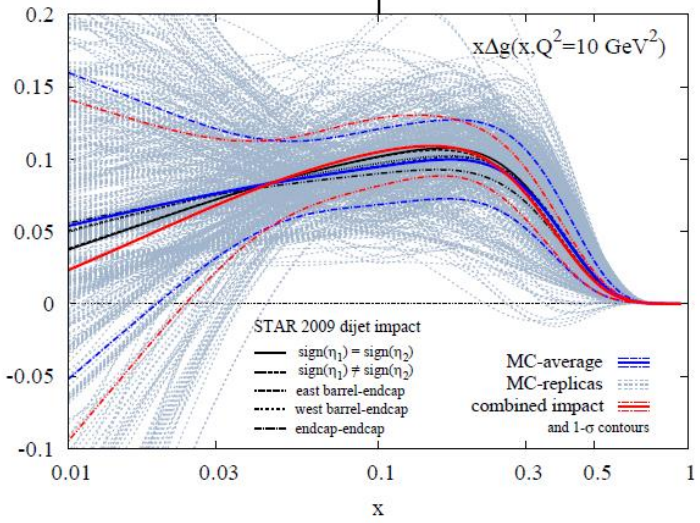


Bin	η_3 and η_4 Regions	Physics Description
A	$0.3 < \lvert\eta_{3,4}\rvert < 0.9;\ \eta_3 \cdot \eta_4 > 0$	Forward-Forward
B	$\lvert\eta_{3,4}\rvert < 0.3;\ 0.3 < \lvert\eta_{4,3}\rvert < 0.9$	Forward-Central
C	$\lvert\eta_{3,4}\rvert < 0.3$	Central-Central
D	$0.3 < \lvert\eta_{3,4}\rvert < 0.9;\ \eta_3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

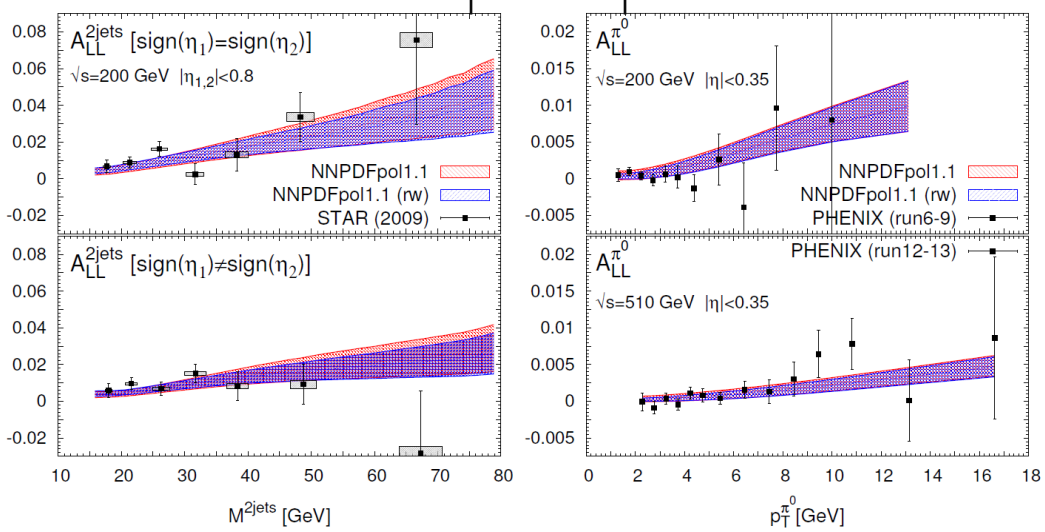
- **Dijet A_{LL} by η topologies, -0.8 < η < 1.8**
  - Narrows down sampled x_g distribution and θ* (scattering angle in partonic CoM frame)

2. Nucleon helicity Impact of RHIC data on ΔG constraint

PRD100, 114027



arXiv:1702.05077

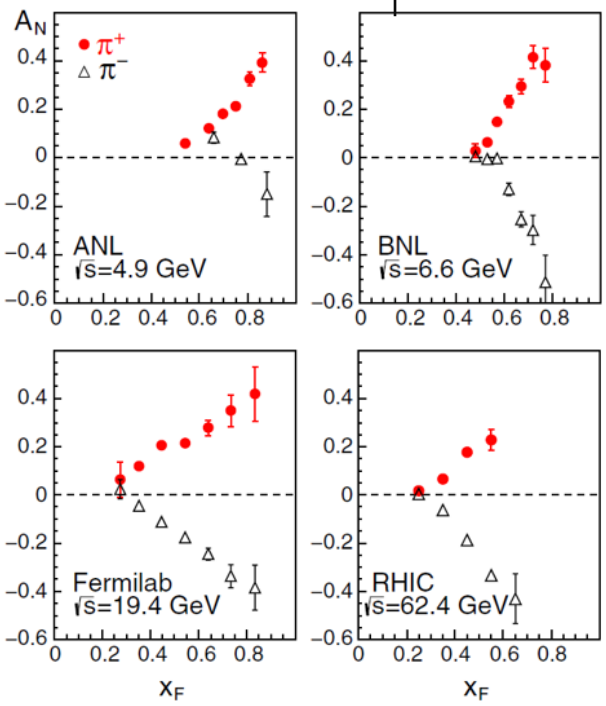


- **Impact of RHIC data on ΔG (2009-2013)**
  - Left: MC sampling variant of DSSV14 (STAR 2009 dijet)
  - Right: reweighted NNPDFpol1.1 (STAR 2009 dijet, and PHENIX 2009 + 2013 π^0)

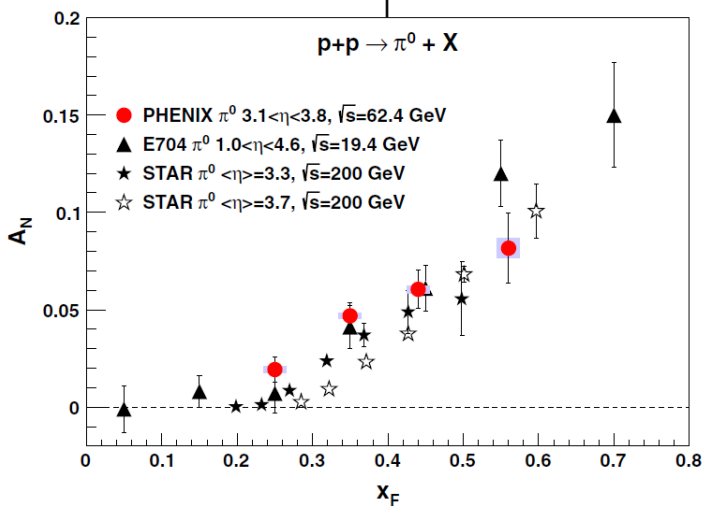
3. Transvesely polarized p + p

3. Transverse p + p Motivation

Rev. Mod. Phys. 85, 655



PRD90, 012006 (2014)

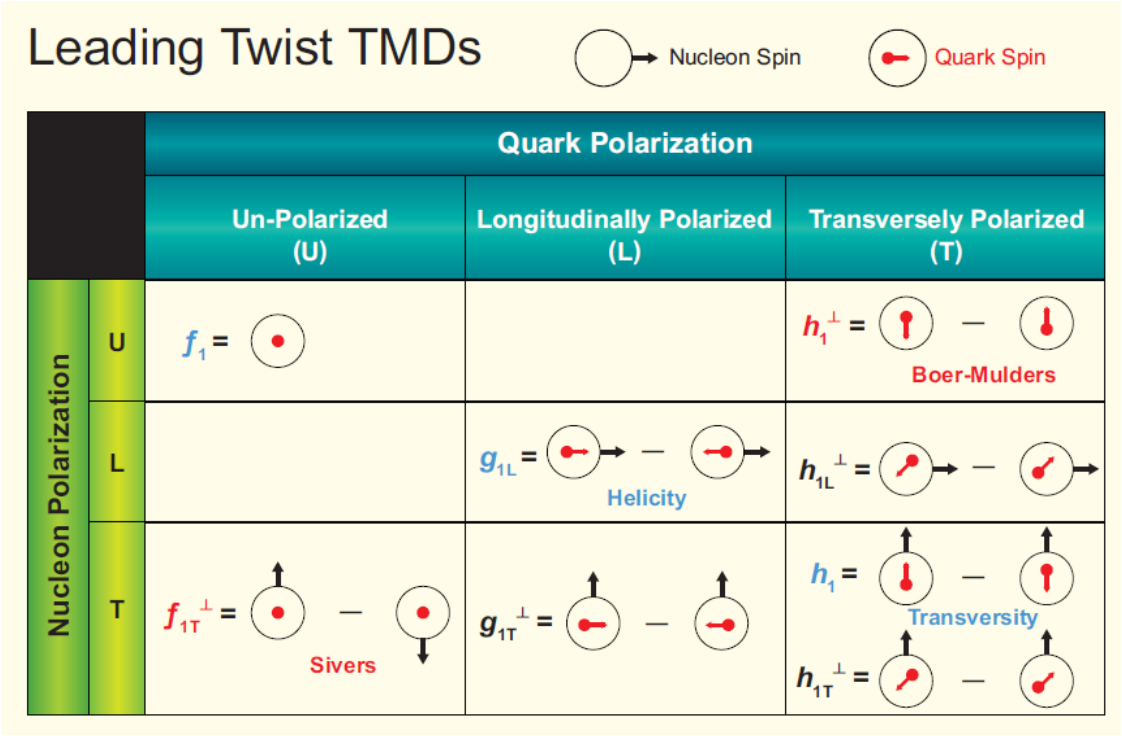


$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{1}{P} \times \frac{N_L - N_R}{N_L + N_R}, \quad X_F = \frac{2p_z}{\sqrt{s}} \sim (x_1 - x_2)$$

- **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)

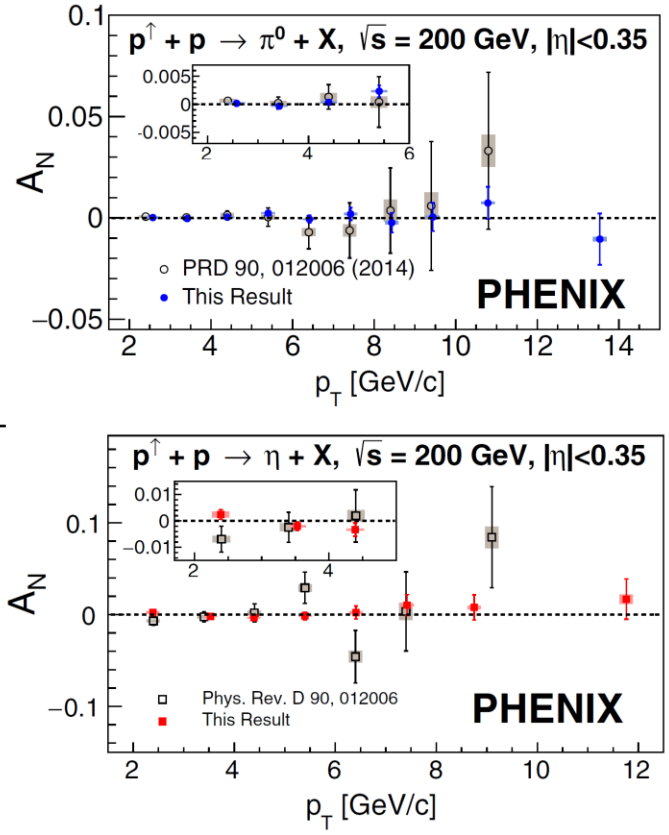


- **TMD**
  - Requires two scales: Q^2 (hard) and p_T (soft)
  - SIDIS, Drell-Yan, W/Z, hadrons in jets…
  - Access full transverse momentum k_T
- **Collinear Twist-3**
  - Requires single hard scale: p_T
  - Proper for inclusive A_N (π^0, γ, jet)
  - Access average transverse momentum $\langle k_T \rangle$

3. Transverse p + p

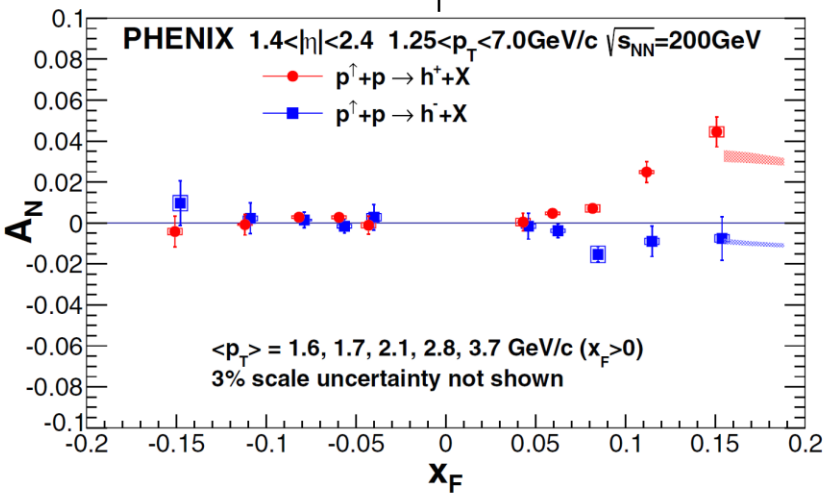
PHENIX, π^0, η, and charged hadrons A_N

PRD103, 052009 (2021)



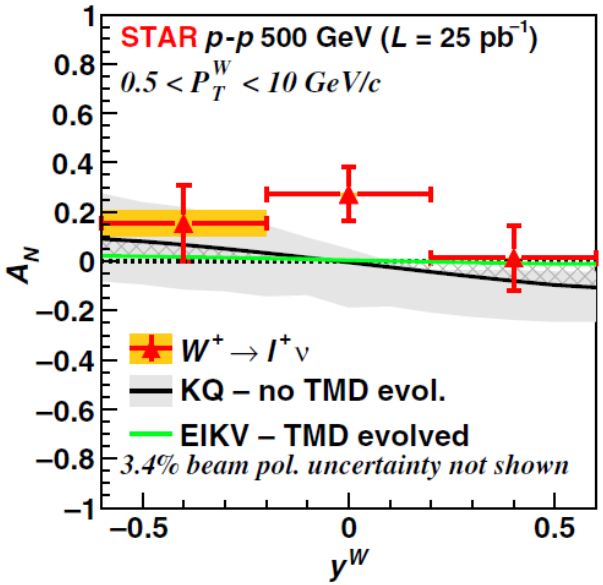
- **π^0 and η A_N at $|\eta| < 0.35$**
  - $\sqrt{s}$ = 200 GeV (2015)
  - Sensitive to Twist-3 trigluon correlations
  - Consistent with zero

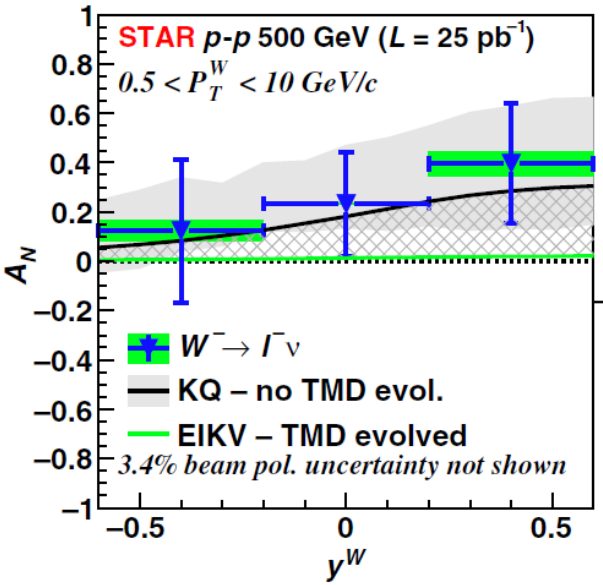
PRD108, 072016 (2023)



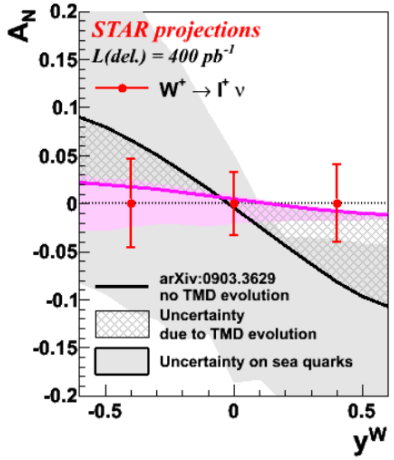
- **$\pi^{\pm}$ and $K^{\pm}$ A_N at $1.2 < |\eta| < 2.2$**
  - $\sqrt{s}$ = 200 GeV (2015)
  - Increasing h^+ A_N for $x_F > 0$
  - Comparable to BRAHMS results (**PRL101, 042001 (2008)**)

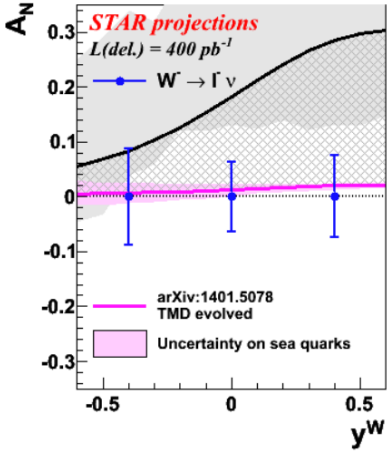
3. Transverse p + p STAR, W A_N





PRL116, 132301 (2016)





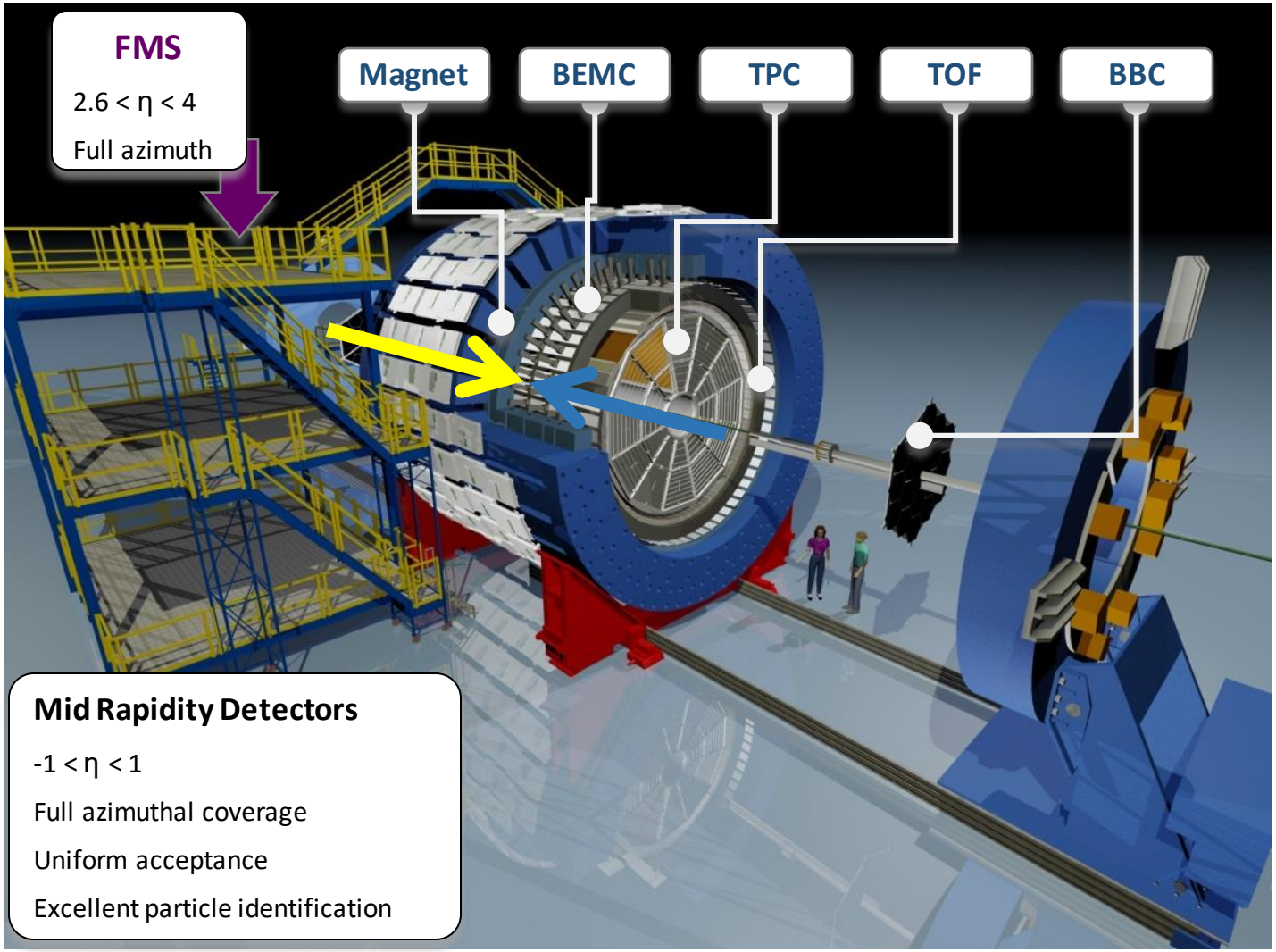
- **W A_N at $|\eta| < 1.0$**
  - $\sqrt{s}$ = 500 GeV, int. L = 25 pb^{-1} (2011)
    - a. 1st anti-quark Sivers function measurement
    - b. 1st experimental evidence of Sivers-sign change
  - 2017 analysis (int. L ~ 350 pb^{-1}) is underway
    (← projection: **arXiv:1602.03922**)

4. Summary

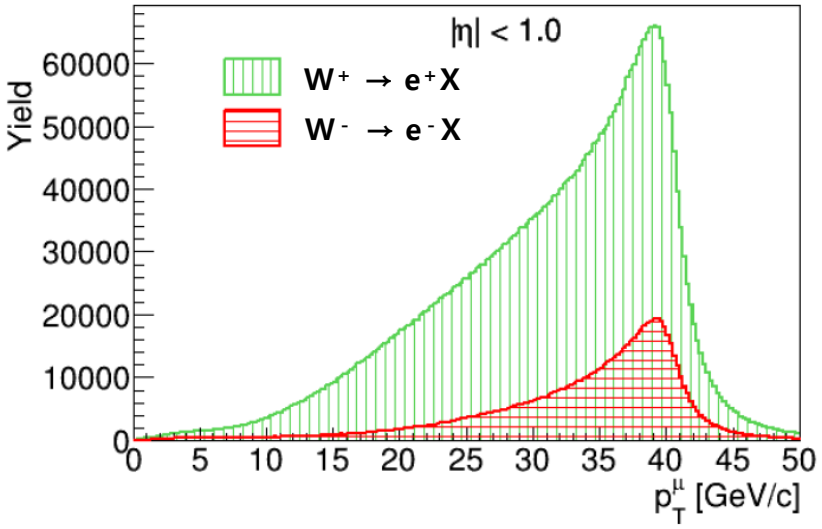
- **RHIC polarized p + p**
  - Provides invaluable complementary info to DIS for more consistent and complete picture
- **Nucleon helicity (Longitudinal p + p results)**
  - $\Delta\bar{q}$: RHIC W program concluded, clear physics impact
  - ΔG: observed and confirmed non-zero gluon polarization, via various probes
- **Transverse p + p results**
  - Many striking results including 1st transversity measurement in p + p

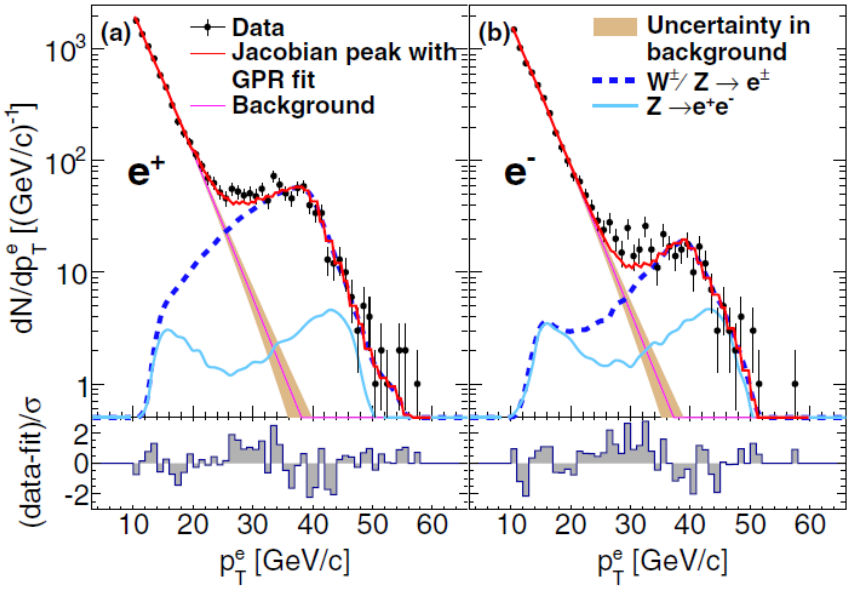
Backup STAR detector

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

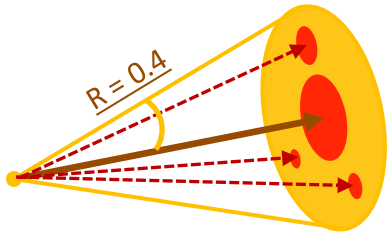


Backup PHENIX W, Central arms



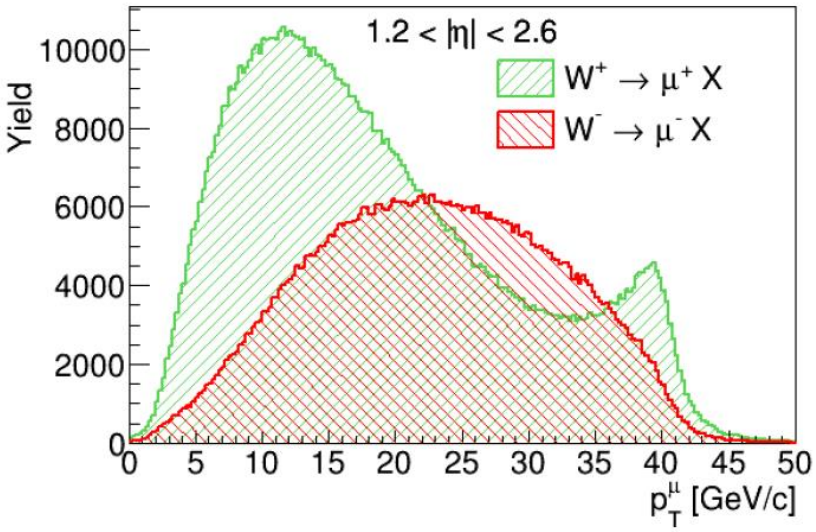


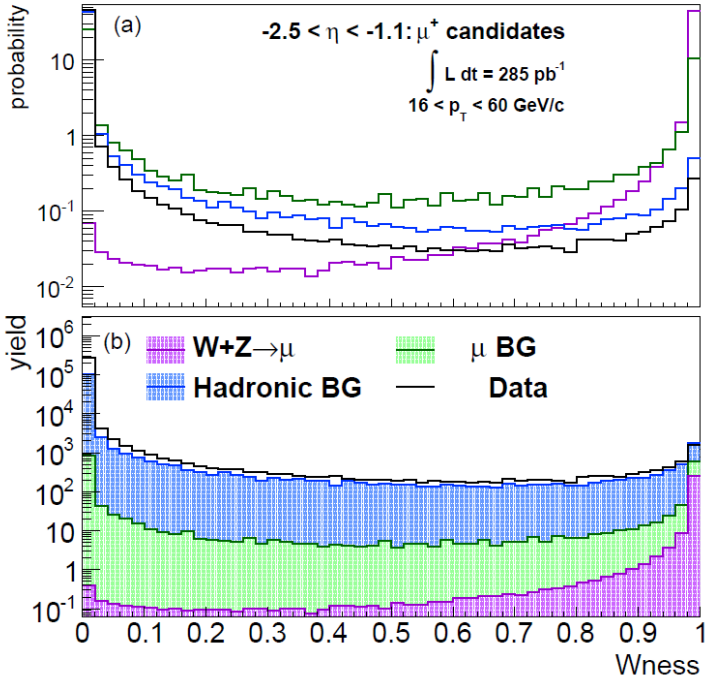
- ***W*$^{\pm}$ → e$^{\pm}$ at |η| < 0.35**
  - Distinct Jacobian peak
  - Triggered by energy
  - Momentum measurement by energy
  - Charge determination by tracking in B-field



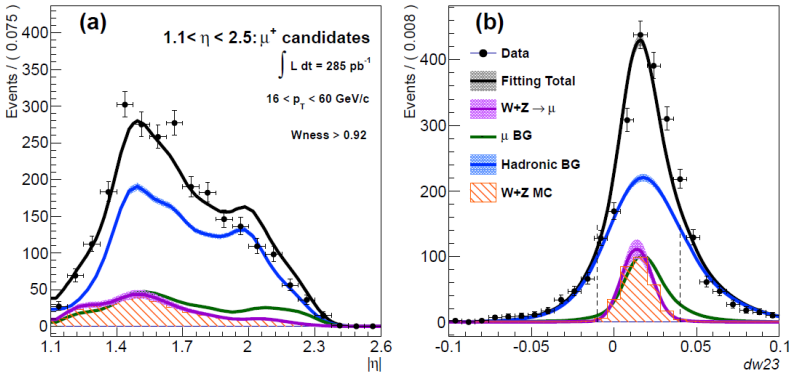
$$\frac{E_{cone} - E_{candiate}}{E_{candiate}} < 10\ (\%)$$

Backup PHENIX W, Muon arms





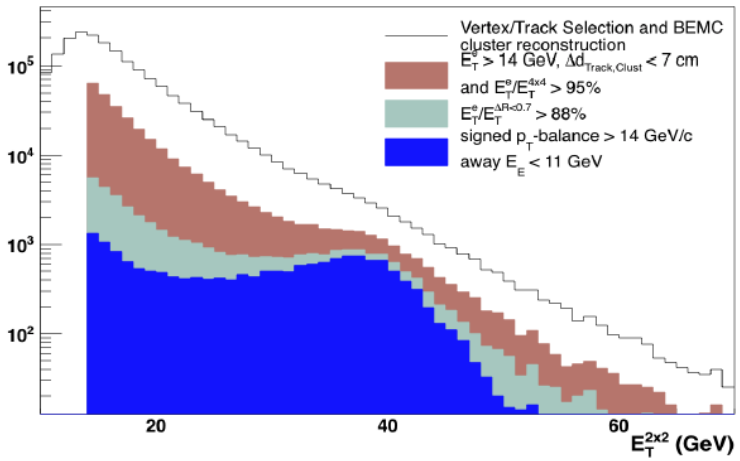
- ***W*$^{\pm}$ → μ$^{\pm}$ at 1.2 < |η| < 2.2 / 2.4**
  - Suppressed/No Jacobian peak
  - Triggered by momentum
  - Momentum measurement by tracking in B-field
  - Charge determination by tracking in B-field

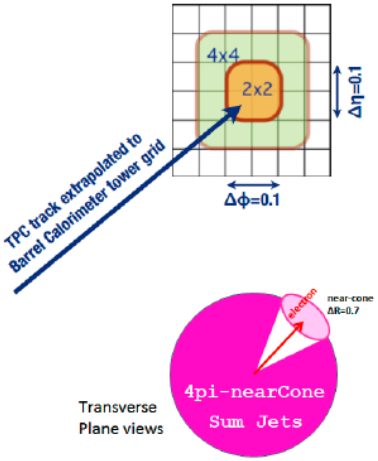


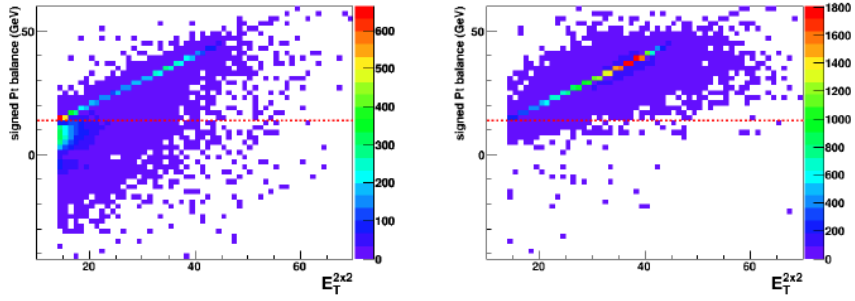
Backup STAR W analysis

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

W selection



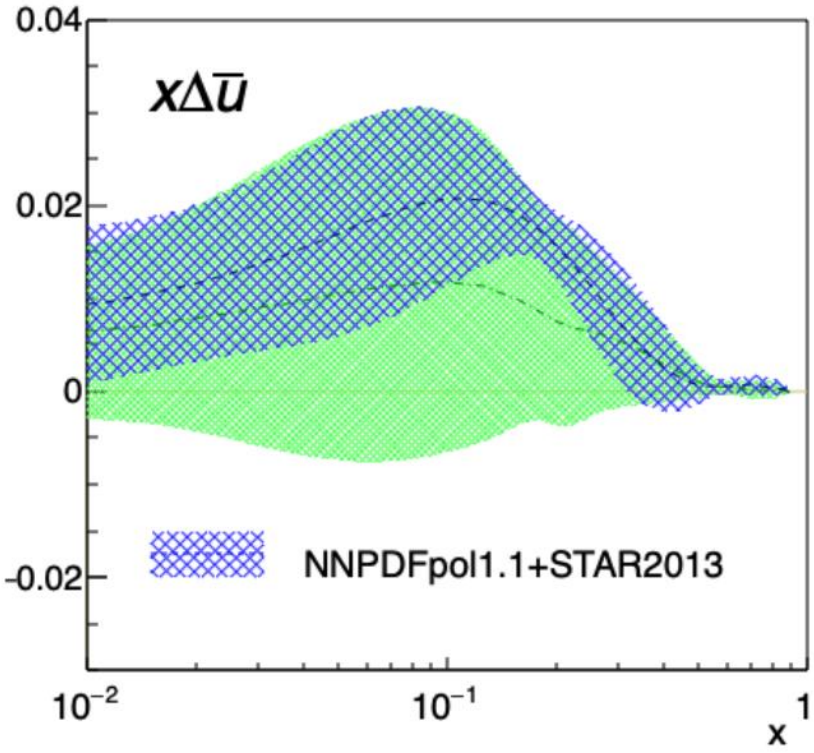


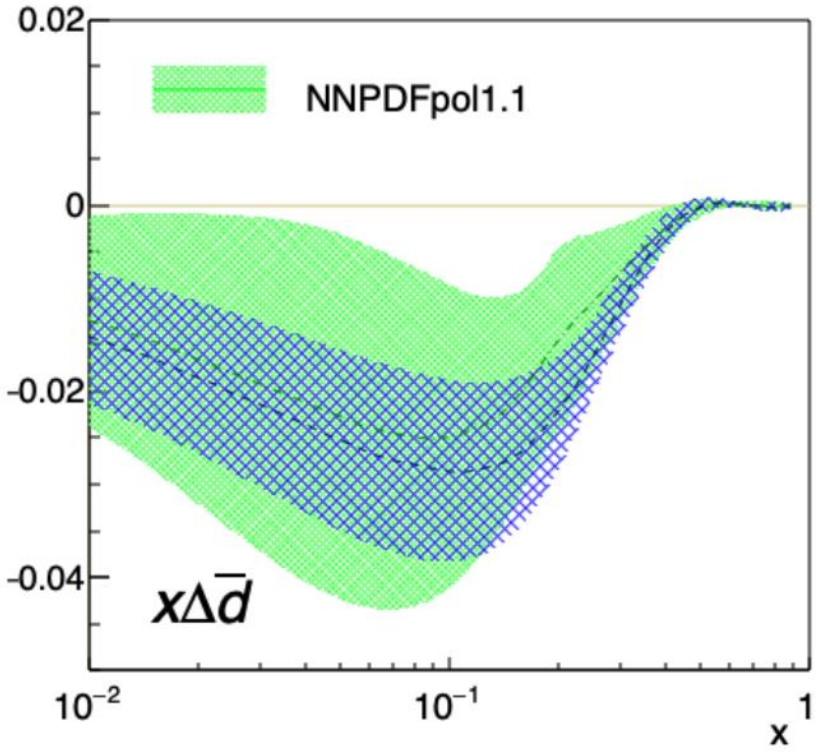


$$\vec{p}_T^{\,bal} = \vec{p}_T^{\,e} + \Sigma_{\Delta R<0.7}\, \vec{p}_T^{\,jets}$$

Signed-p_T balance $= \dfrac{\vec{p}_T^{\,e} \cdot \vec{p}_T^{\,jets}}{|\vec{p}_T^{\,e}|}$

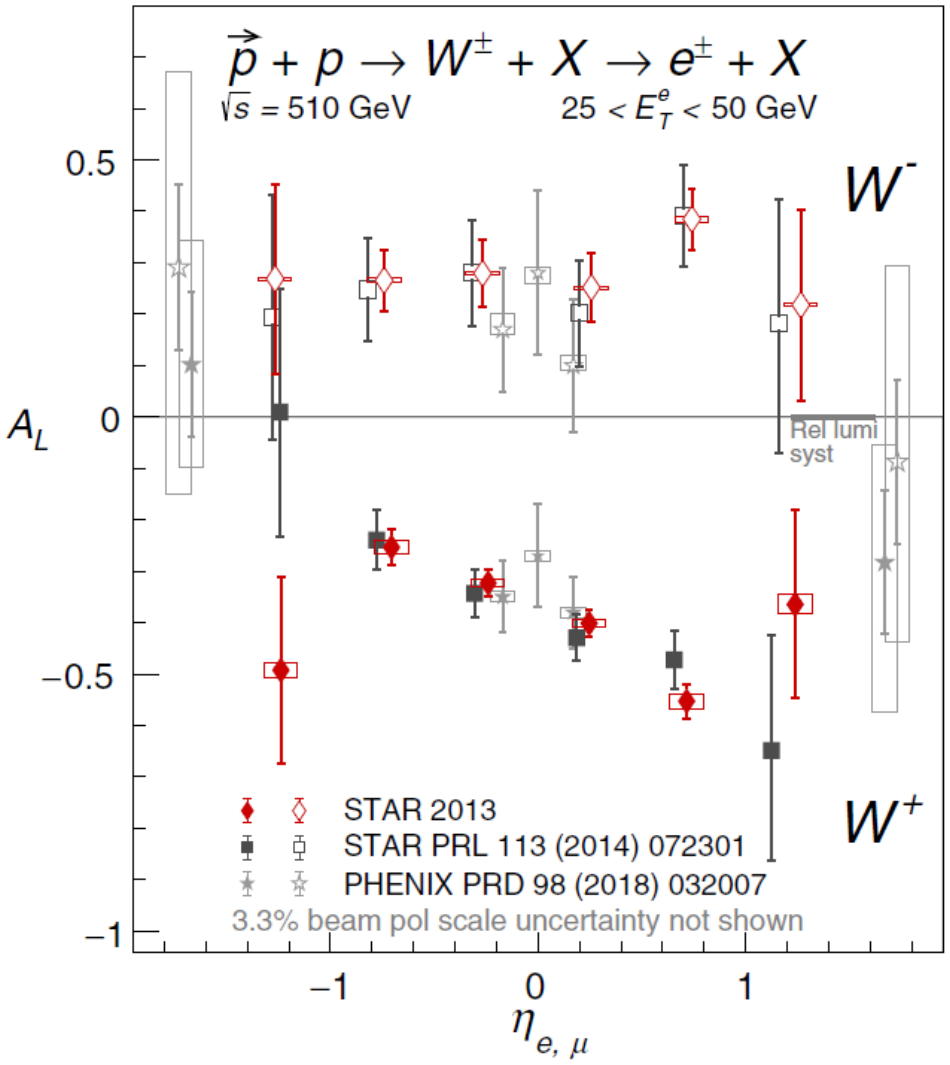
Backup STAR W impact





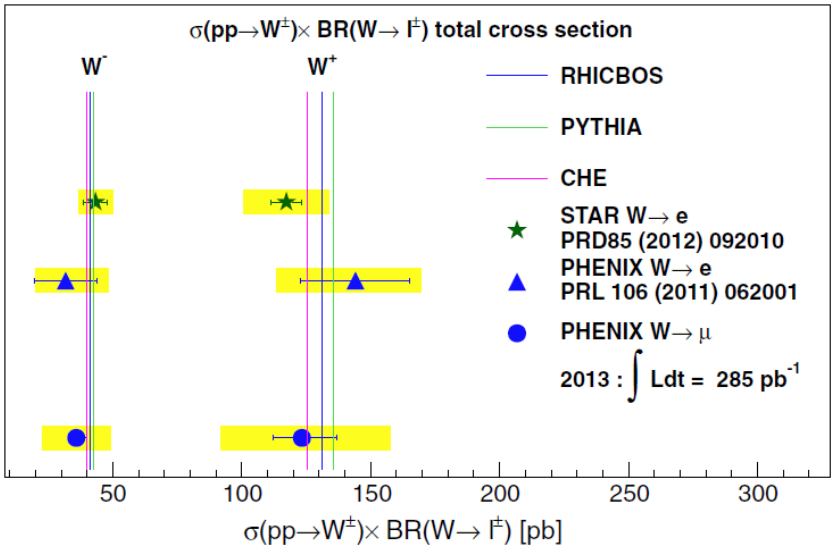
Backup RHIC W (all)

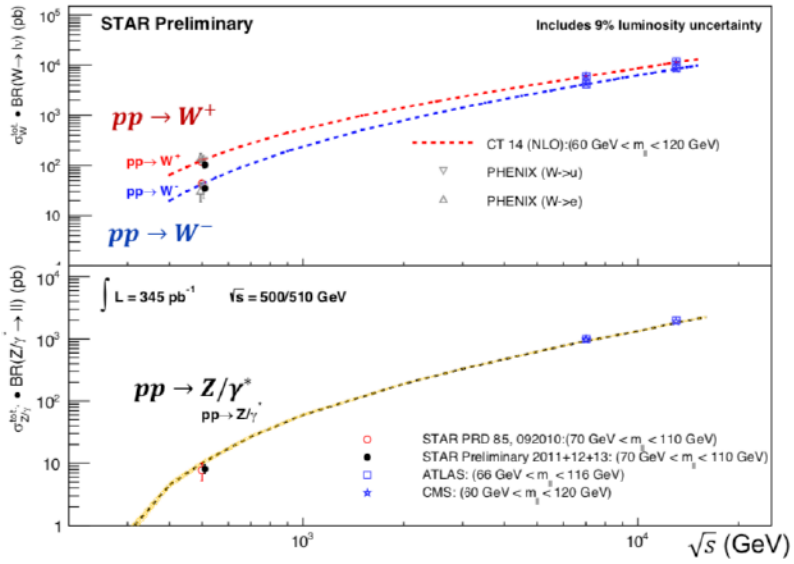
PRD99, 051102 (2019)



Backup W cross sections (PHENIX / STAR)

PRD98, 032007 (2018)



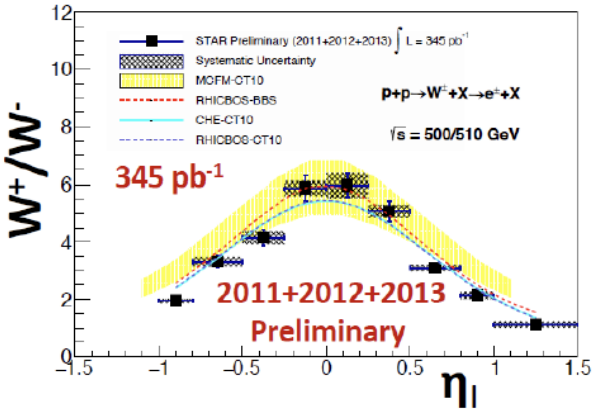


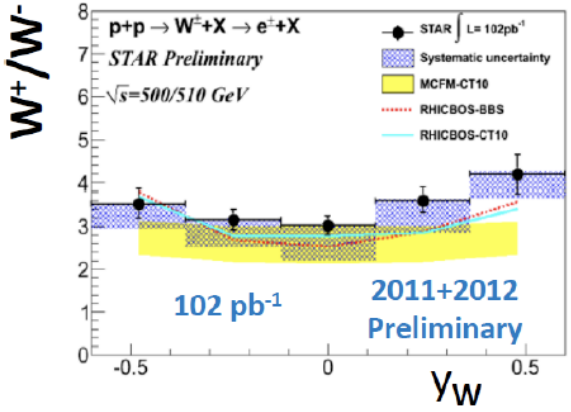
Backup STAR W/Z cross section ratio

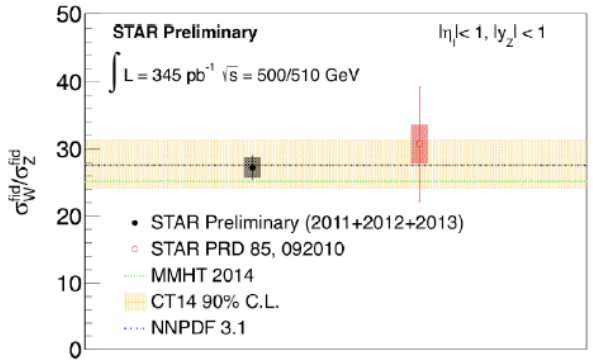
- This slide was shamelessly stolen from **Jinlong Zhang**'s RHIC/AGS User Meeting 2019 talk**!**

W/Z Cross Section Ratio

See Matt Posik's Poster

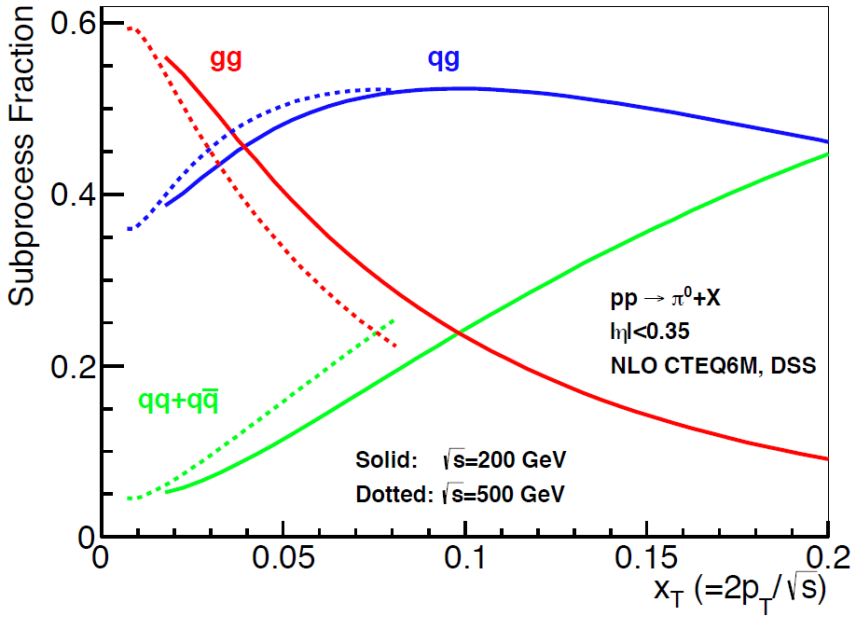






- Complementary measurement to SeaQuest and E-866, for ~0.06 < x < ~0.4 , constraining unpolarized sea quark distributions.
- W kinematics determined from data and simulation; Cornerstone for W A_N measurement

Backup Gluon polarization and π^0 A_{LL}



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 Color interactions in QCD

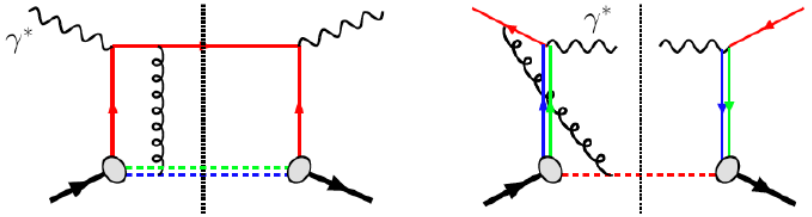
- This slide was shamelessly stolen from **Carl Gagliardi**'s SPIN2018 talk**!**

Color interactions in QCD

Controlled non-universality of the Sivers function

QCD:

DIS	Drell-Yan, W or Z
Final-state interaction	Initial-state interaction
Opposite colors attract	Like colors repel



$Sivers_{DIS} = -Sivers_{Drell\text{-}Yan}$ or $Sivers_W$ or $Sivers_Z$

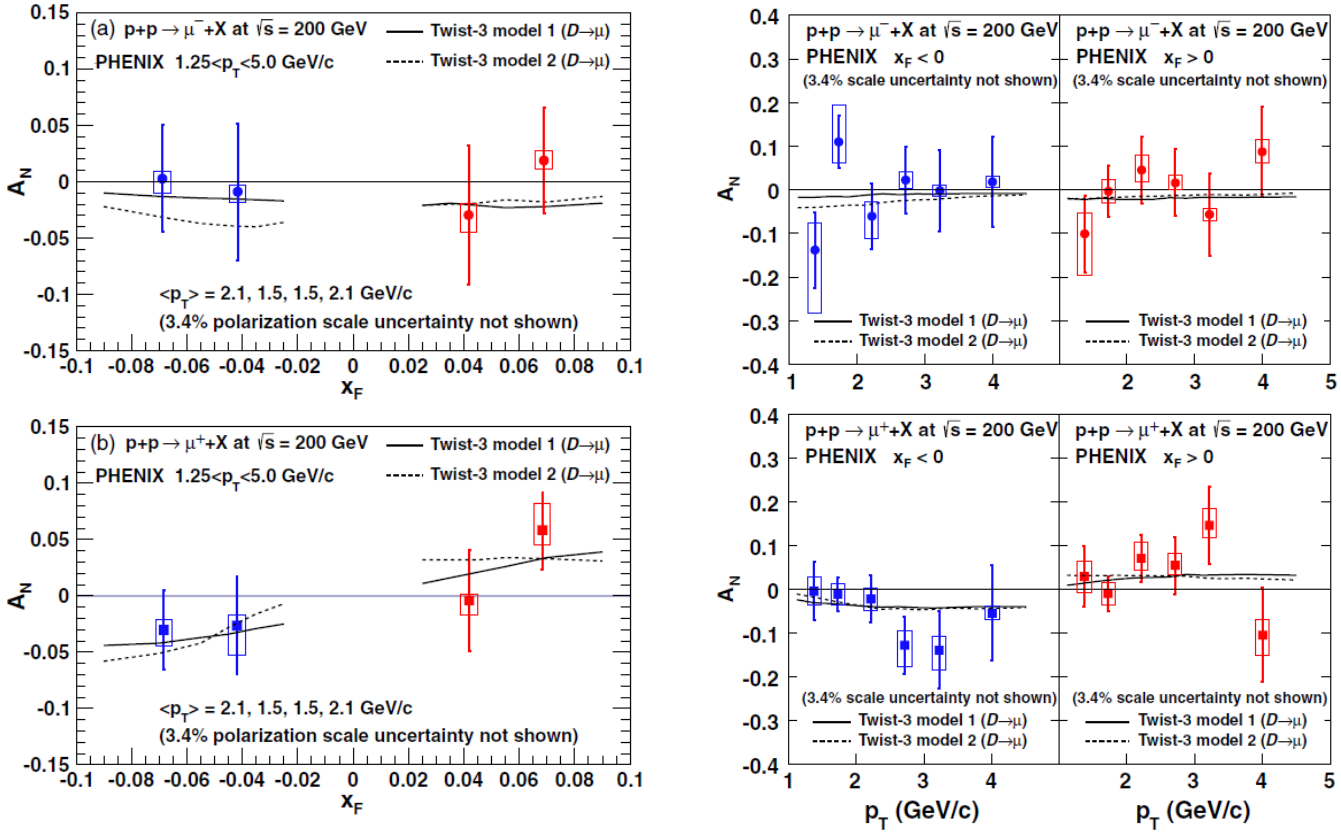
A_N for direct photon has related sign change in Twist-3

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

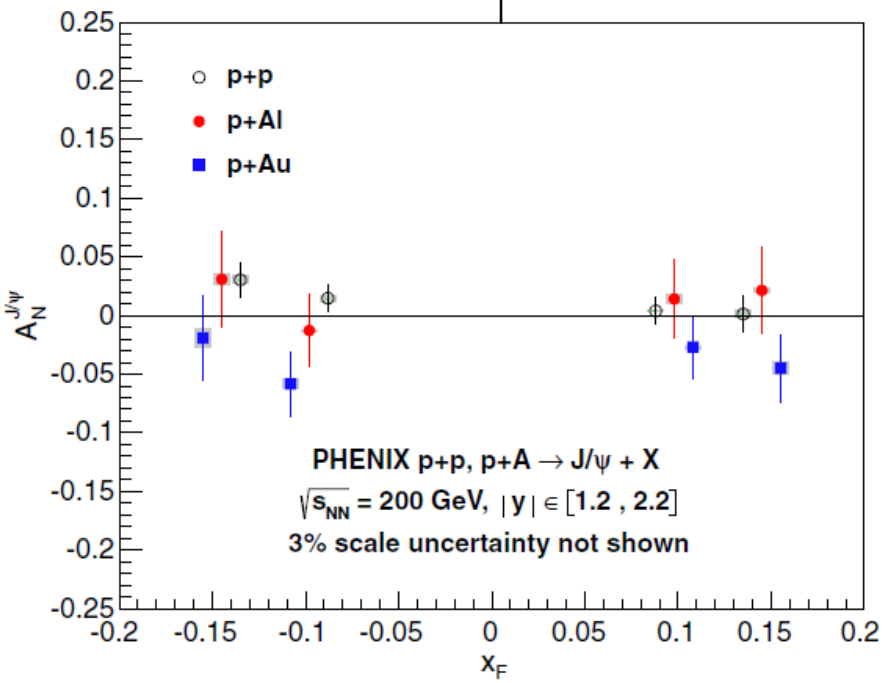


- **Open heavy decay μ A_N at 1.2 <|η| < 2.2**
  - √s = 200 GeV, int. L = 9.2 pb^{-1} (2012)
  - Sensitive to Twist-3 trigluon correlations
  - Consistent with zero within uncertainties

PRD95, 112001 (2017)

Backup PHENIX Forward J/ψ

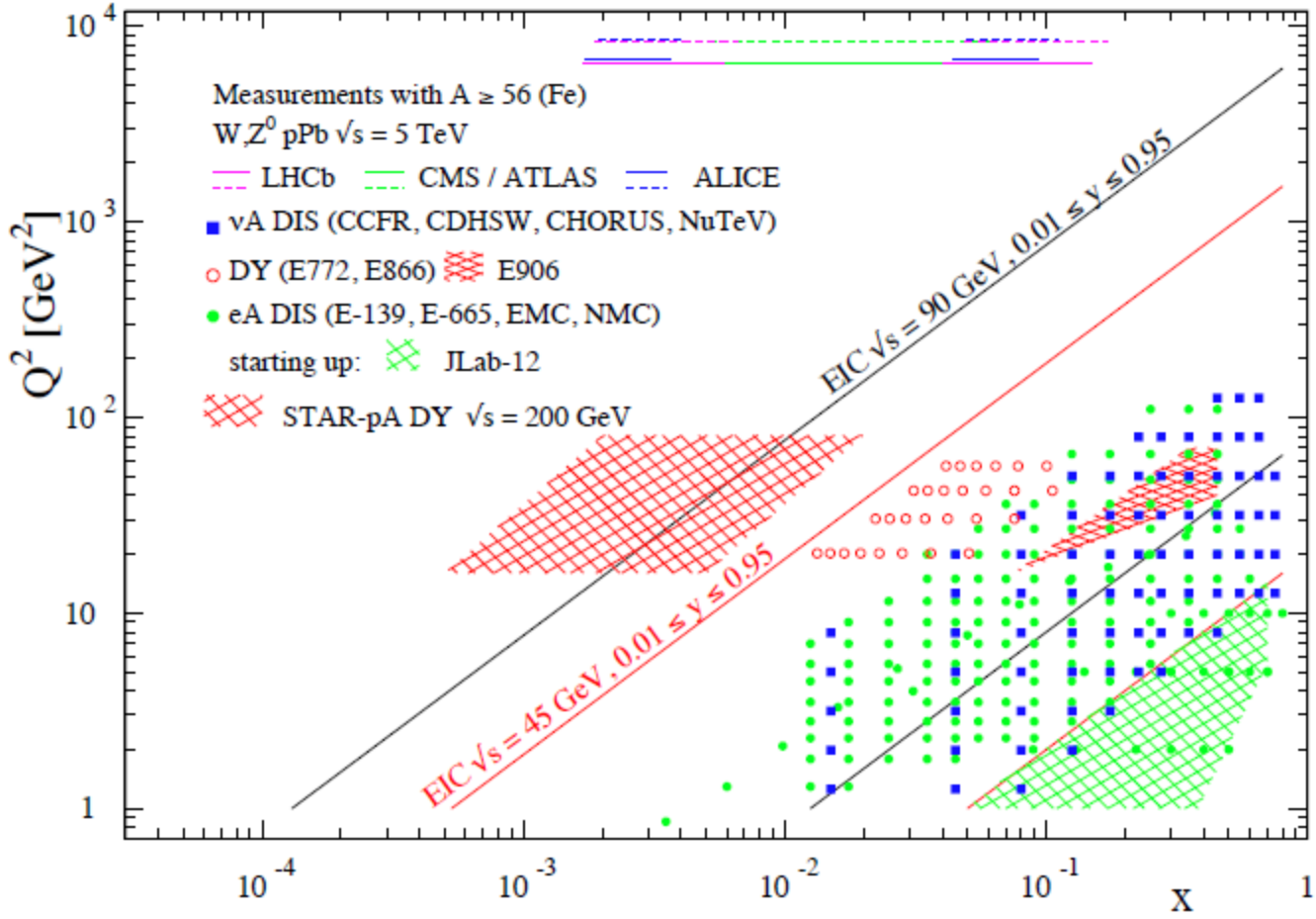
PRD98, 012006 (2018)



- **J/ψ A_N at 1.2 <|η| < 2.2**
  - √s = 200 GeV (2015)
  - int. *L* = 40 (pp), 6.0 (pAl), and 6.6 (pAu) pb^{-1}
  - Consistent with zero, No clear A dependence

Backup Q^2 vs. x kinematic coverage

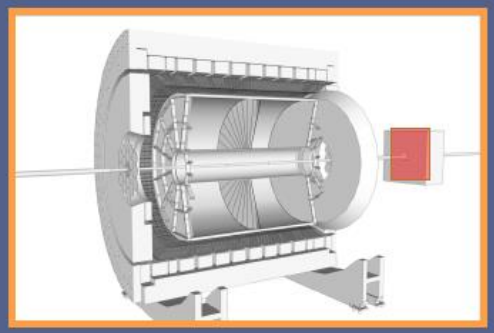
arXiv: 1602.03922



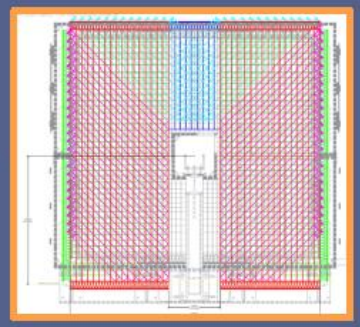
Backup STAR RUN17 DY

- 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



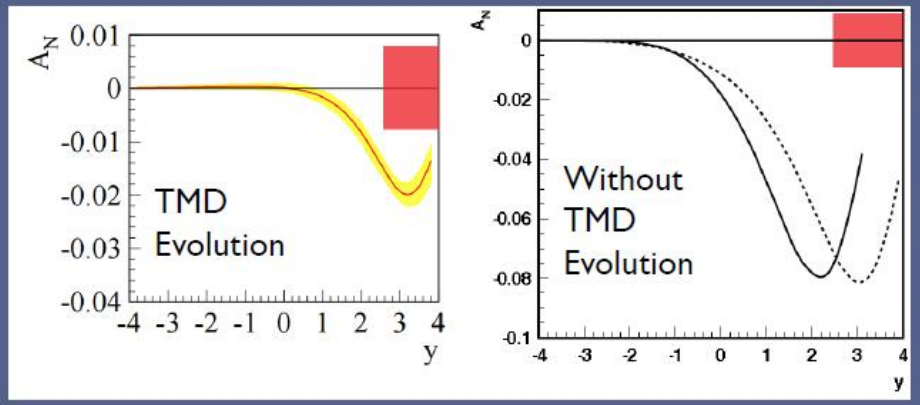
+



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} .

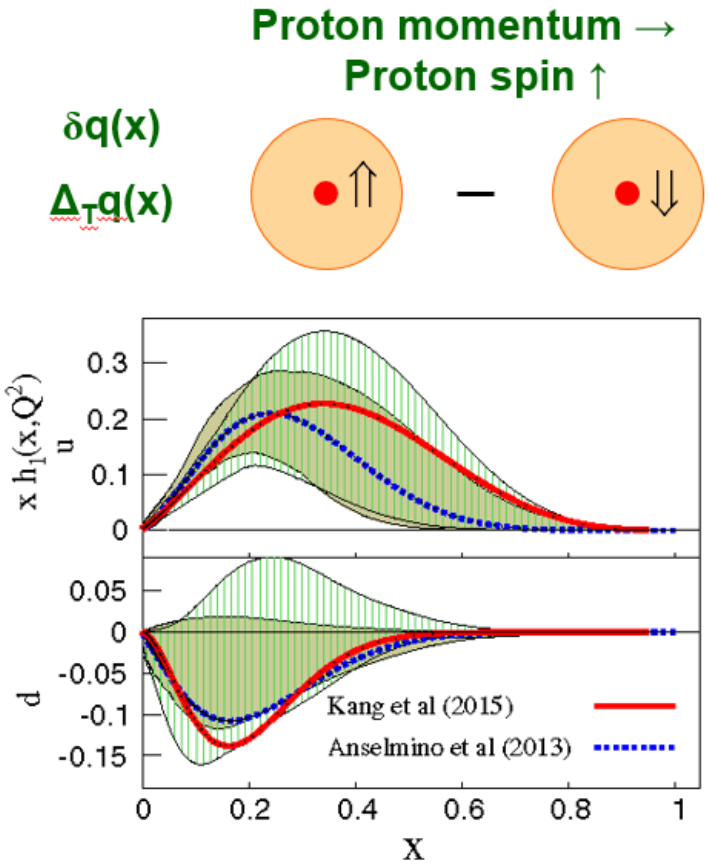


Phys.Rev.D 89, 074013 (2014)

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

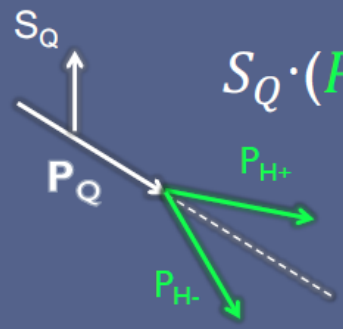
Backup Leading-twist TMD PDFs

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	$f_1 =$ 	*	$h_1^\perp =$ 
L	*	$g_1 =$ 	$h_{1L}^\perp =$ 
T	$f_{1T}^\perp =$ 	$g_{1T} =$ 	$h_1 =$  $h_{1T}^\perp =$ 

Backup Transversity – IFF vs. Collins FF

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

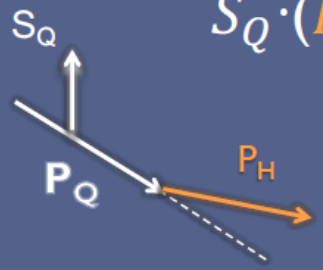
TRANSVERSITY



$S_Q \cdot (P_{H-} \times P_{H+})$

Interference Fragmentation Functions

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



$S_Q \cdot (P_Q \times P_H)$

Collins Fragmentation Functions

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