Overview of the PHENIX Spin Program

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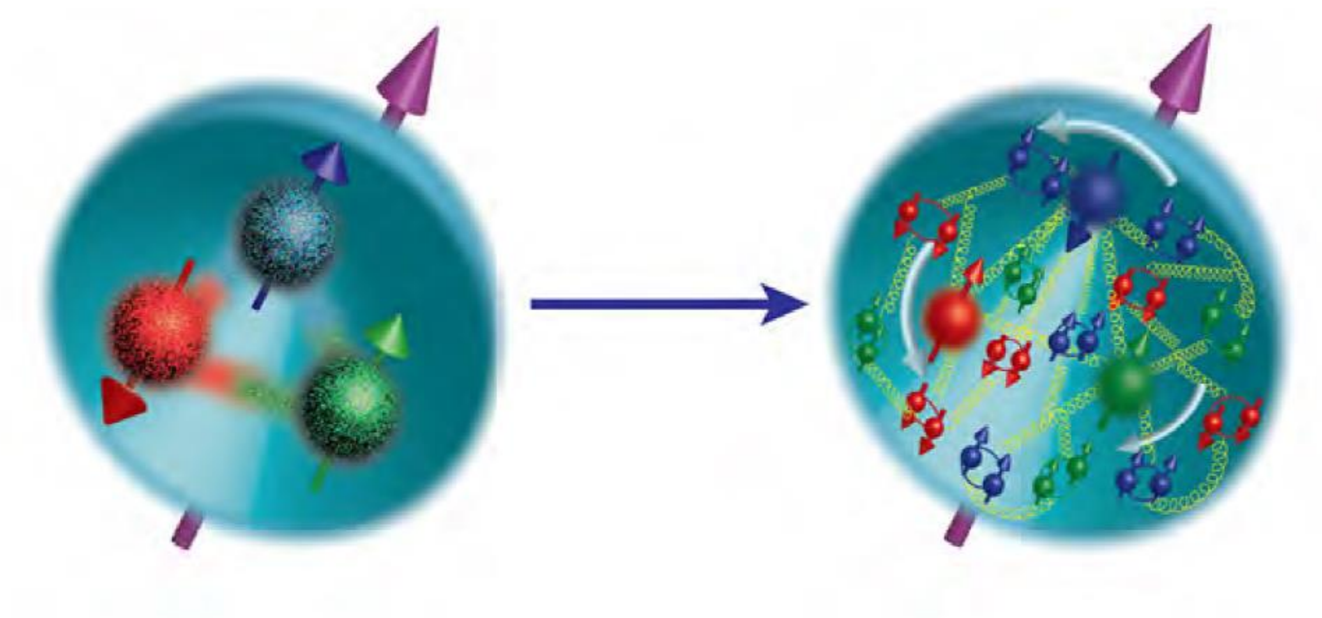
Outline

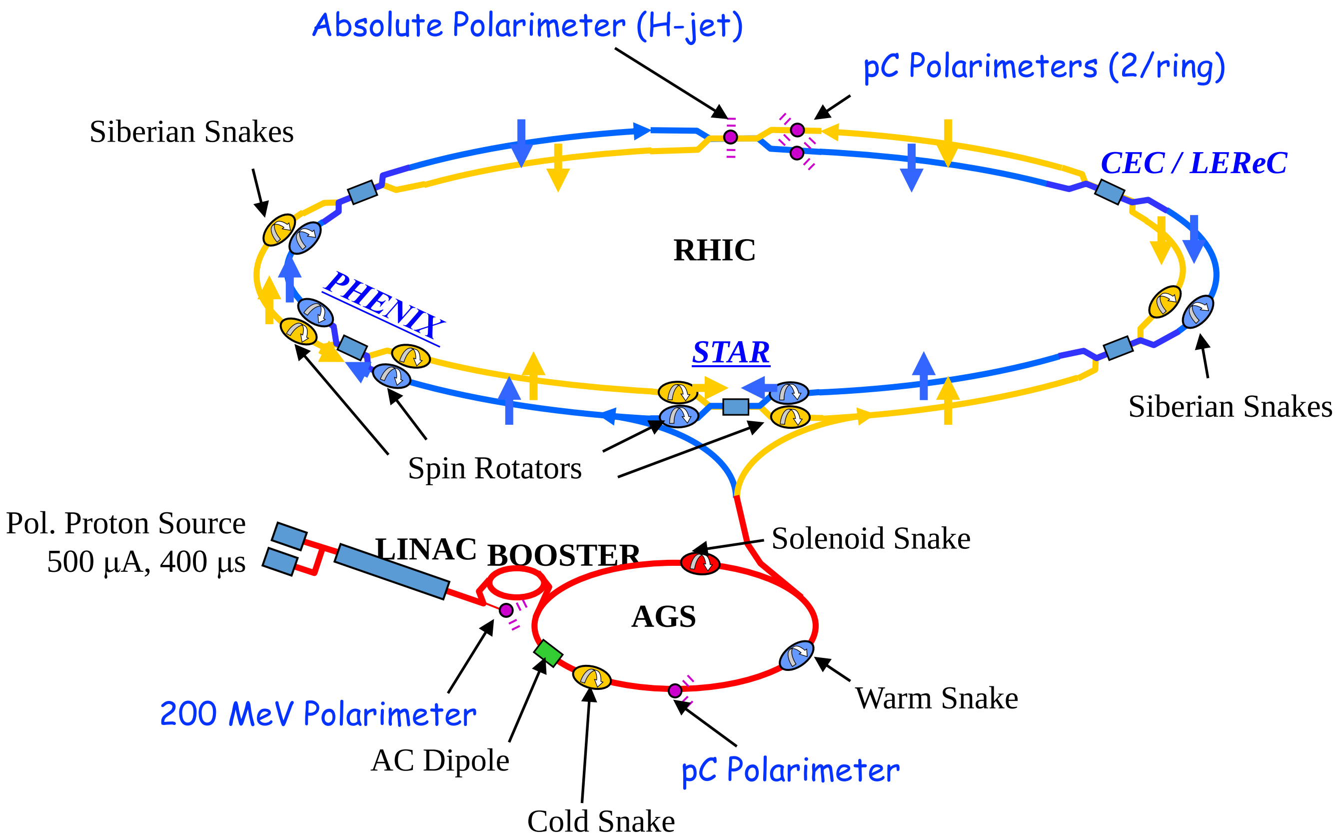
- **Introduction**
  - RHIC and PHENIX
- **Longitudinal spin highlights**
  - Polarized light sea quarks ($\Delta\bar{q}$)
  - Polarized gluons (ΔG)
- **Transverse spin highlights**
  - $p^{\uparrow} + p$ vs. $p^{\uparrow} + A$ in various probes

Introduction Motivation



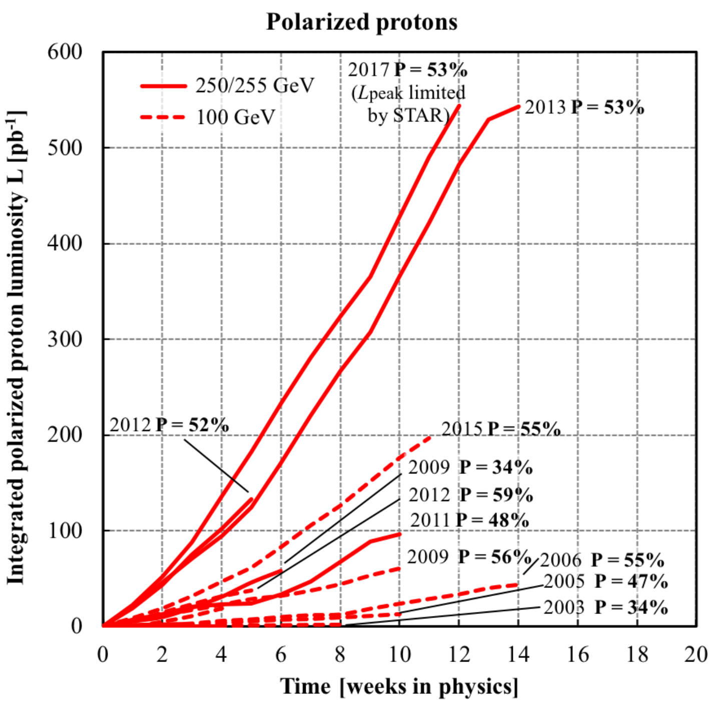
- **It's not a simple sum of big 3 chunks**
  - Jaffe-Manohar spin sum rule: $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
  - Unexpectedly large, increasing A_N vs. p_T which can't be explained by conventional pQCD
  - PHENIX (RHIC) aims both longitudinal spin structure and transverse spin phenomena

Introduction RHIC



- **RHIC @ Brookhaven Lab., NY**
  - Polarized p + p @ √s = 62.5 to 510 (GeV)
  - Maximum 120 bunches per ring, bunch by bunch polarization
  - Average beam polarization ($\langle P \rangle$) ≈ 60 (%)

Introduction RHIC spin runs (2009 - 2015)

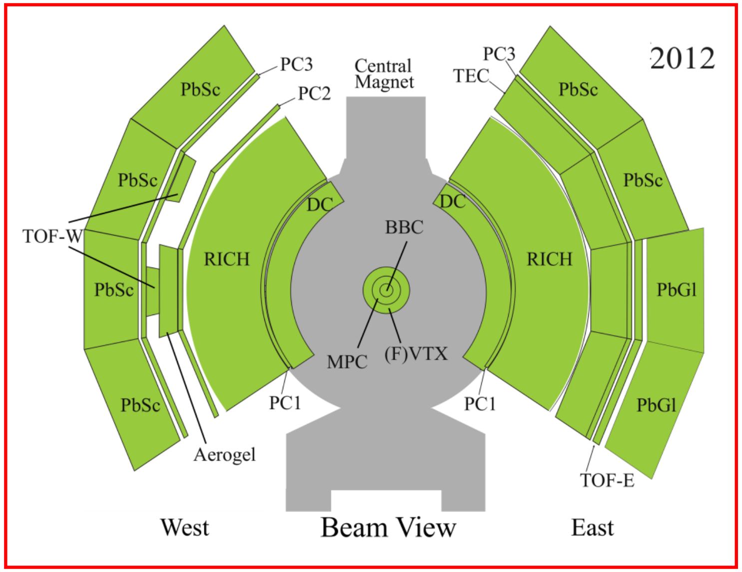


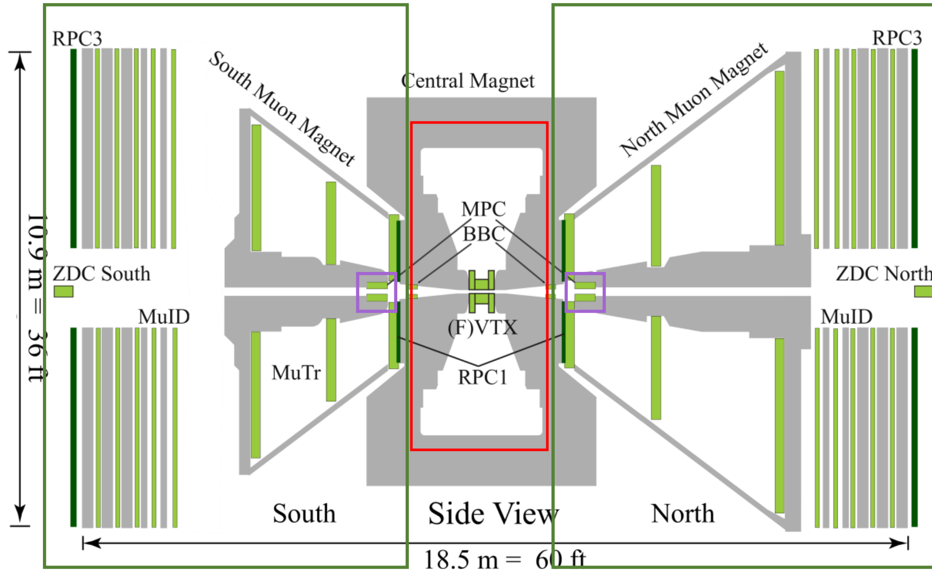
Year	√s (GeV)	Type	⟨P⟩ (Blue/Yellow) (%)	Int. L (pb^{-1})
09	200	L, p + p	56 / 57	15.6
	500	L, p + p	33 / 36	14
11	500	L, p + p	48 / 48	27.6
12	510	L, p + p	50.3 / 53.5	49.6
13	510	L, p + p	50.5 / 55.4	242.1
15	200	L, p + p	53.0 / 57.4	x
11	500	T, p + p	48 / 48	x
12	200	T, p + p	61.8 / 56.6	17.6
15	200	T, p + p	53.0 / 57.4	110.4
		T, p + Al	53.8	1233.5 (nb^{-1})
		T, p + Au	59.6	403.4 (nb^{-1})

- **Summary of RHIC spin runs**
  - PHENIX decommissioned in 2016
  - CAVEAT: int. *L* can be different by the observable

    (the values presented here was obtained by MB trigger)

Introduction PHENIX detectors (2016)

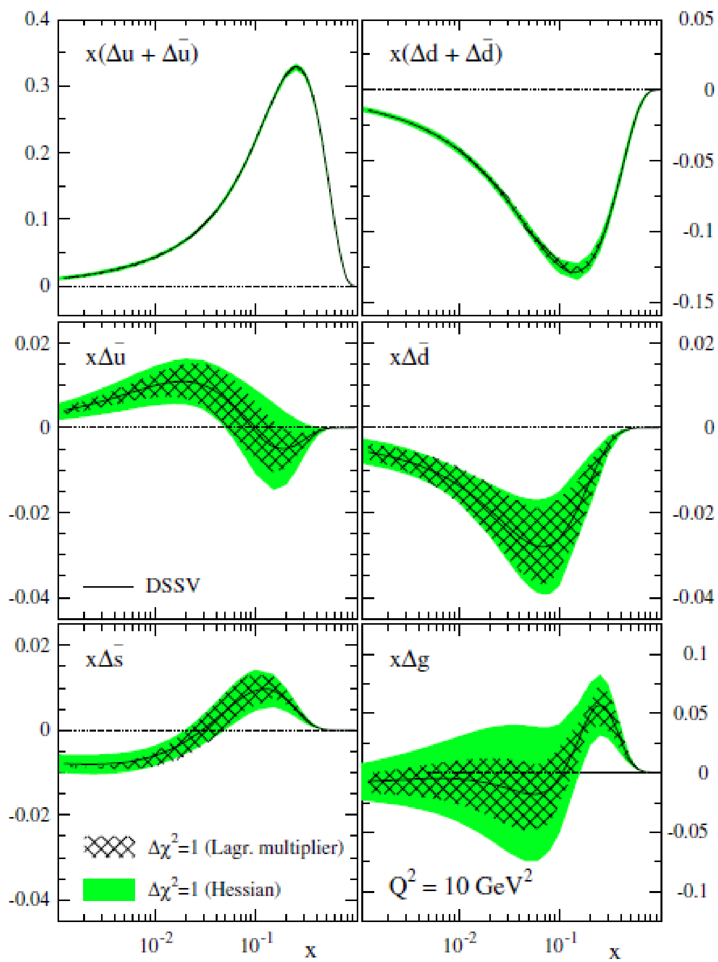




- **Central Arms** ($|\eta| < 0.35$, $\Delta\phi = \frac{\pi}{2} \times 2$)
  - VTX (Si pixel and strip, from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc
- **Muon Arms** ($1.2 < |\eta| < 2.2$ (S) or 2.4 (N), $\Delta\phi = 2\pi$)
  - FVTX (Si strip, from 2012)
  - Tracking: MuTr (CS chambers)
  - pID: MuID (steel interleaved Iarocci tubes), RPCs
- **MPC/MPC-Ex** ($3.1 < |\eta| < 3.8$, $\Delta\phi = 2\pi$)
  - EMCal ($PbWO_4$) / Preshower by W + Si minipads

Longitudinal Spin Highlights

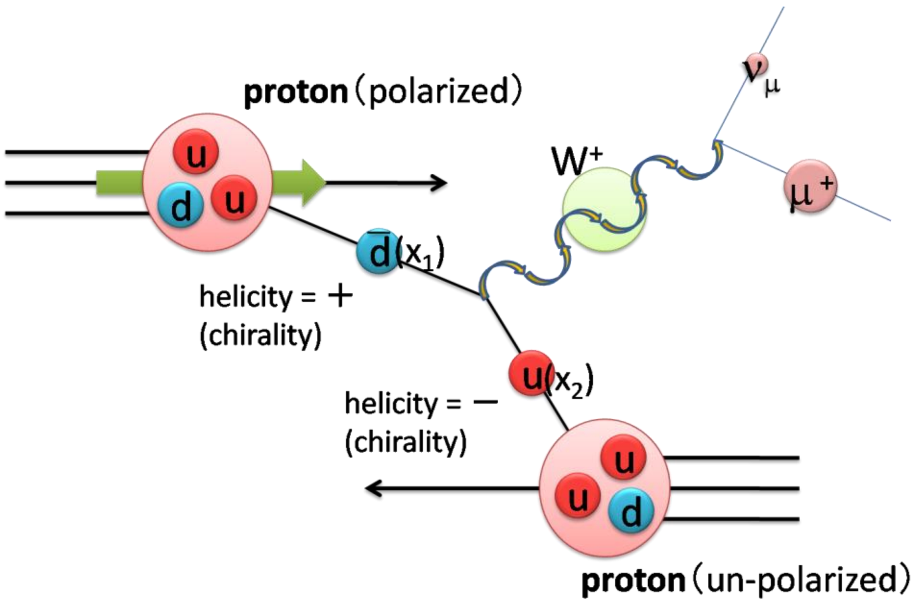
Longitudinal Spin Motivation



PRD80. 034030 (2009)

- $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
- $\Delta\Sigma$?
  - $(\Delta q + \Delta\bar{q})$: well constrained down to x ~ 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 via evolution effect → RHIC: gluon sensitive polarized p + p collisions, various probes (π^0, η, jet, …)

Longitudinal Spin $\Delta\bar{q}$ access by $W^{\pm} \rightarrow l^{\pm}$



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

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

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

technically,

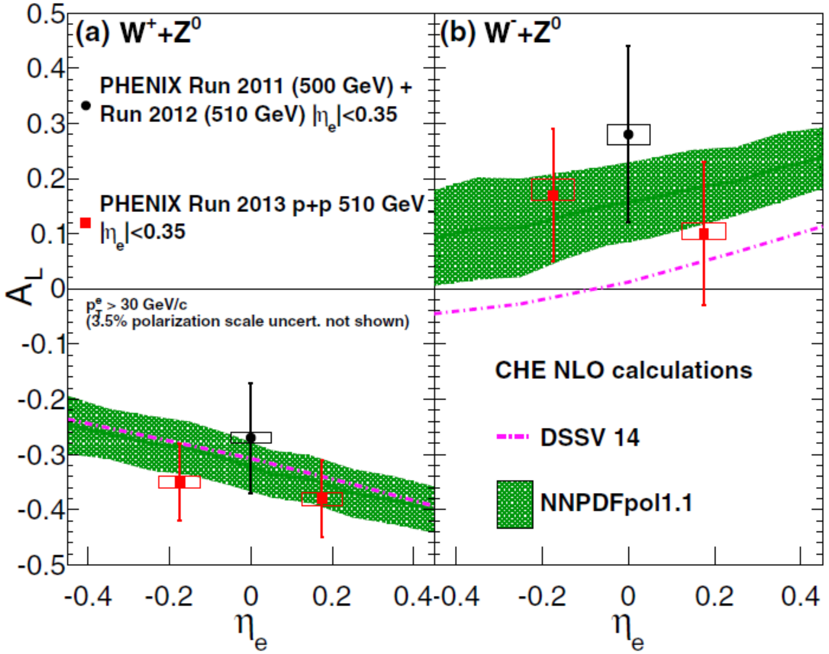
$$A_L^{W} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

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

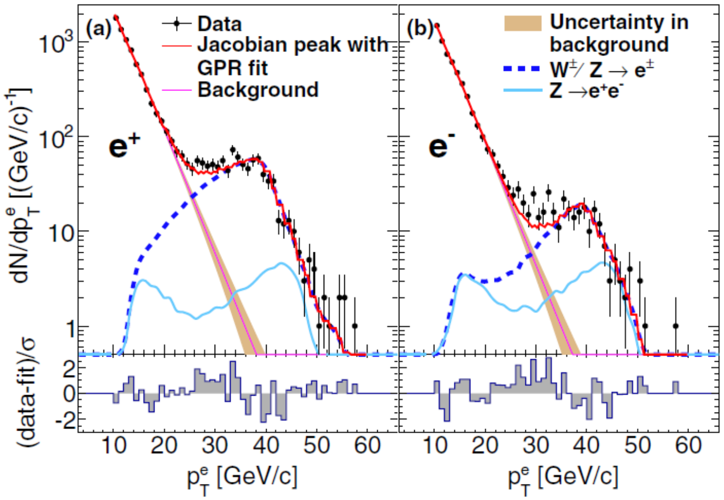
- **$\Delta\bar{q}$ measurements at PHENIX**
  - Midrapidity ($|\eta| < 0.35$): $W^{\pm} \rightarrow e^{\pm}$
  - Forward rapidity ($1.2 < |\eta| < 2.2 / 2.4$): $W^{\pm} \rightarrow \mu^{\pm}$

Longitudinal Spin

$\Delta\bar{q}$ access by $W^{\pm} \rightarrow e^{\pm}$



PRD93, 051103 (2016)

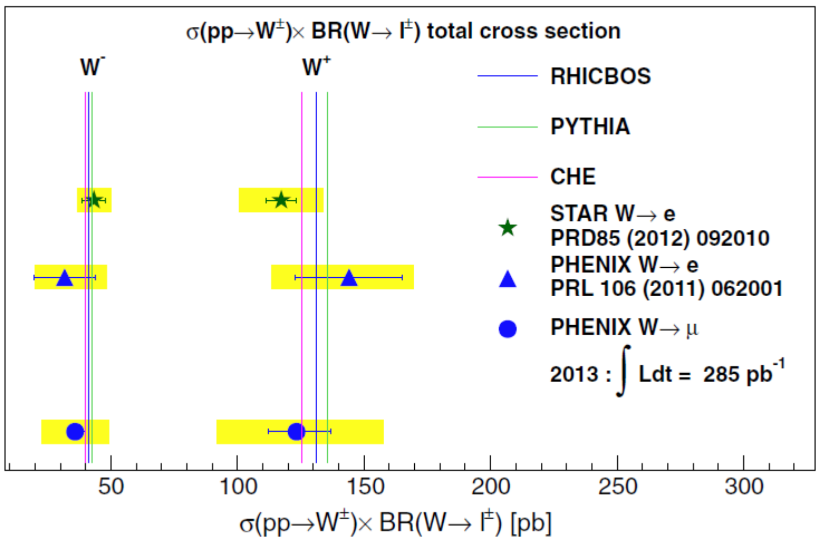


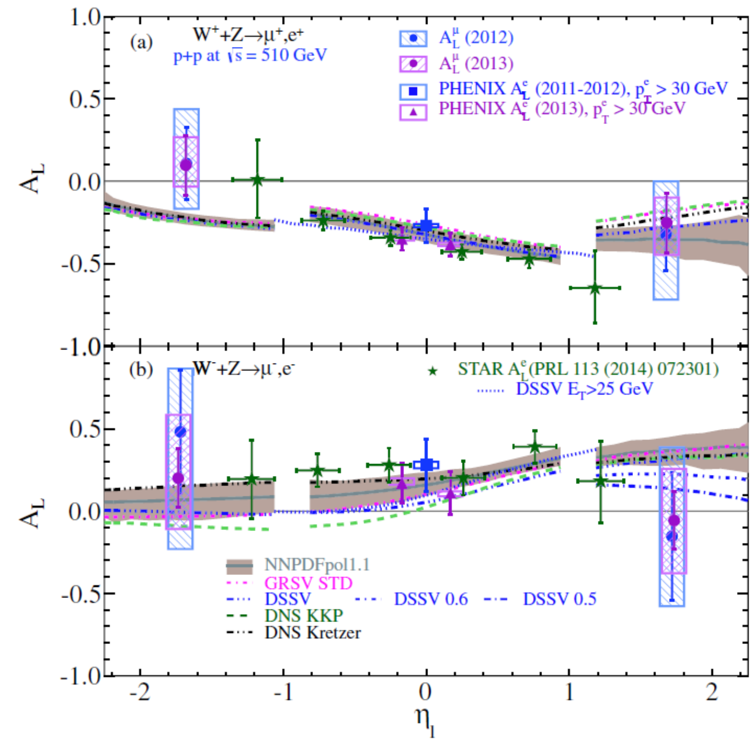
- ***W***$^{\pm}$**/Z**^{0} **→ e**$^{\pm}$**, A**$_{L}$ **, |η| < 0.35, with integrated Run11-13 data**
  - √s = 500 (11) / 510 (12, 13) GeV, Int. *L* = 240 pb^{-1}
  - Signal extraction via charge isolation + backgrounds estimation by Gaussian Process Regression
  - Probed x (parton momentum fraction) of ~ 0.16 (M_W / √s)

Longitudinal Spin

$\Delta\bar{q}$ access by $W^\pm \rightarrow \mu^\pm$

PRD98, 032007 (2018)

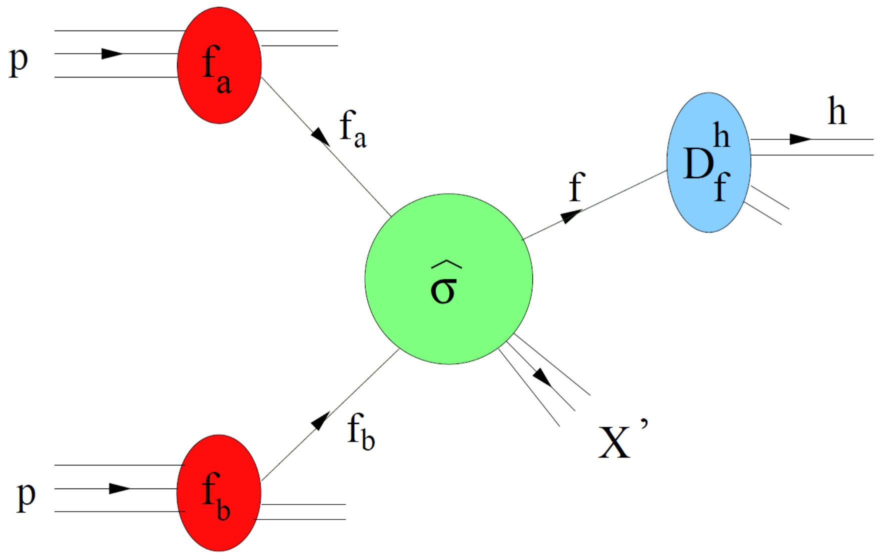




- **$W^\pm/Z^0 \rightarrow \mu^\pm$, A_L, , 1.2 < |η| < 2.2 / 2.4, with integrated RUN12-13 data**
  - √s = 510 GeV, Int. L = 53 (2012) + 285 (2013) pb^{-1}
  - <u>**First**</u> $W^\pm \rightarrow \mu^\pm$ measurement at |η| > 1, probed x of ~ 0.1 (backward) / ~ 0.3 (forward)
  - Consistent cross sections to existing RHIC $W^\pm \rightarrow e^\pm$ within uncertainties
  - Discrepancy to the theory curves at backward W^+ and forward W^-

Longitudinal Spin

ΔG access by various probes



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

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

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

technically,

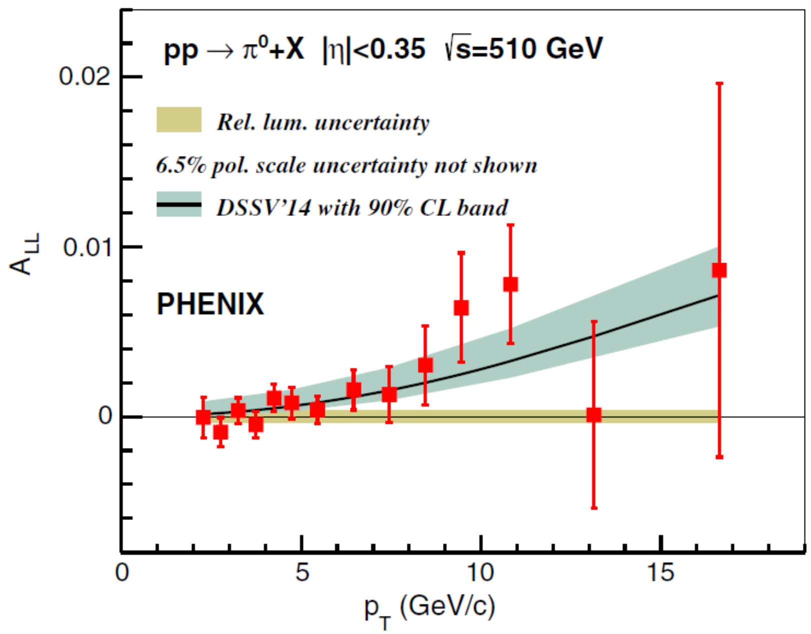
$$A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

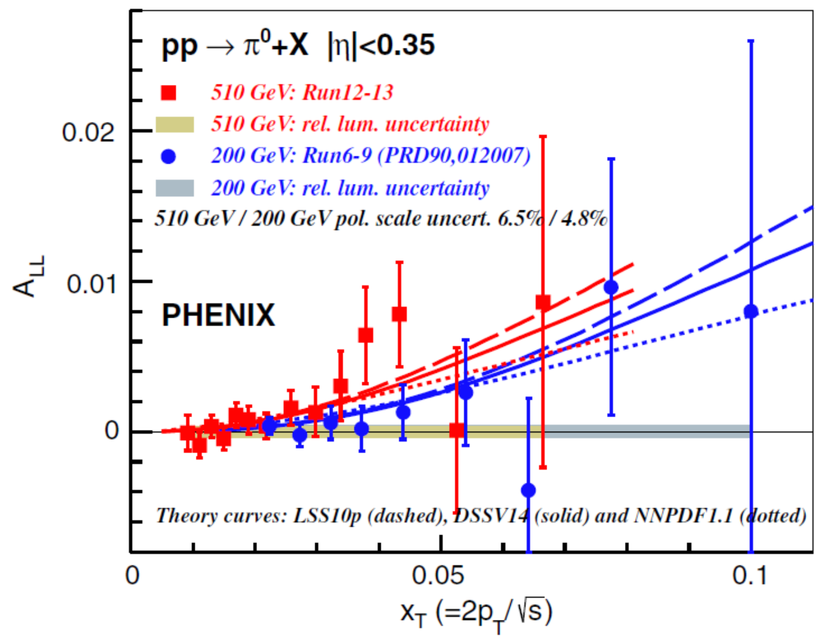
- P : avg. polarization of each beam
- N++ (N+-) : yields in same (opposite) helicity
- $R = \frac{L++}{L+-}$: relative luminosity

- **ΔG measurements at PHENIX**
  - Midrapidity ($|\eta| < 0.35$): direct γ, π^0, $\pi^{\pm}$, η, heavy flavor decay electrons
  - Forward ($1.2 < |\eta| < 2.2$ / 2.4, $3.1 < |\eta| < 3.8$): heavy flavor decay muons, π^0, η, π^0 rich EM clusters

Longitudinal Spin

ΔG access by π^0



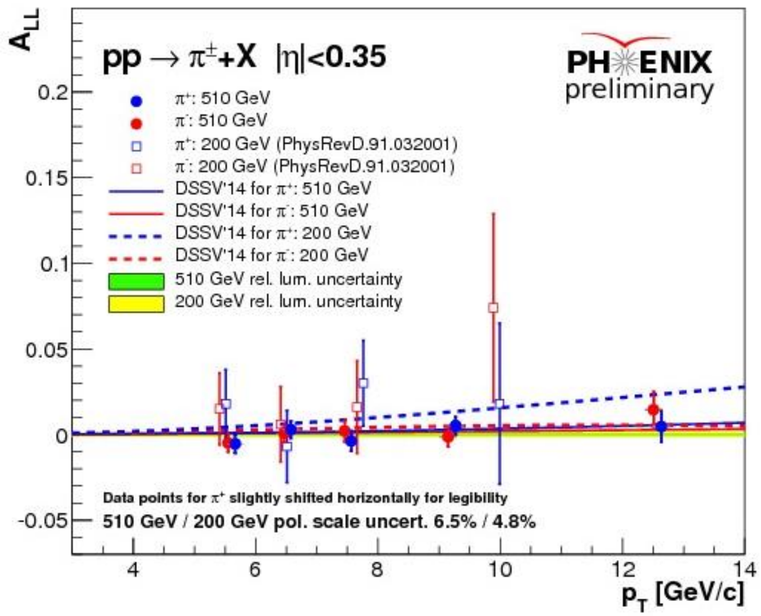


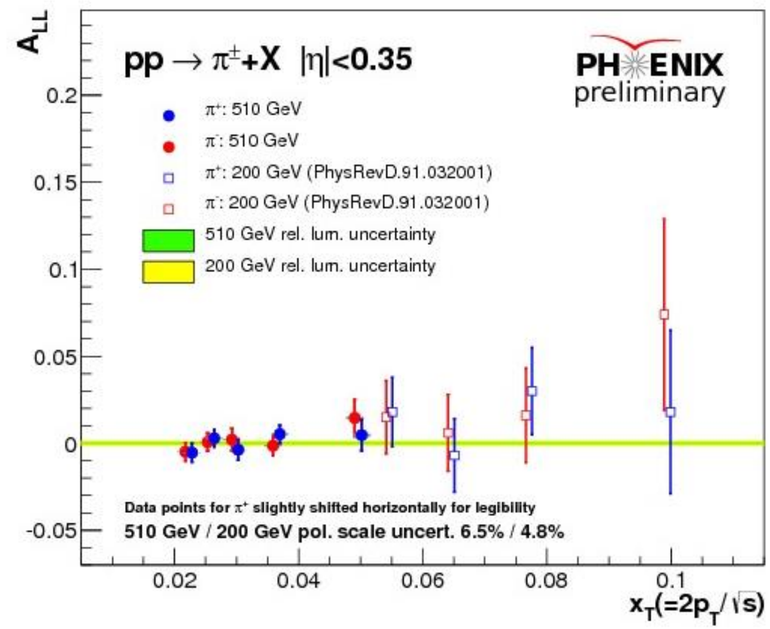
- **Inclusive π^0, A_{LL}, |η| < 0.35, with Run12-13 data**

PRD93, 011501 (2016)

  - √s = 510 GeV, Int. *L* = 20 (2012) + 108 (2013) pb^{-1}
  - Confirms non-zero gluon polarization via hadron production (first observed by 2009 STAR jet)
  - Extended x coverage down to ~ 0.01

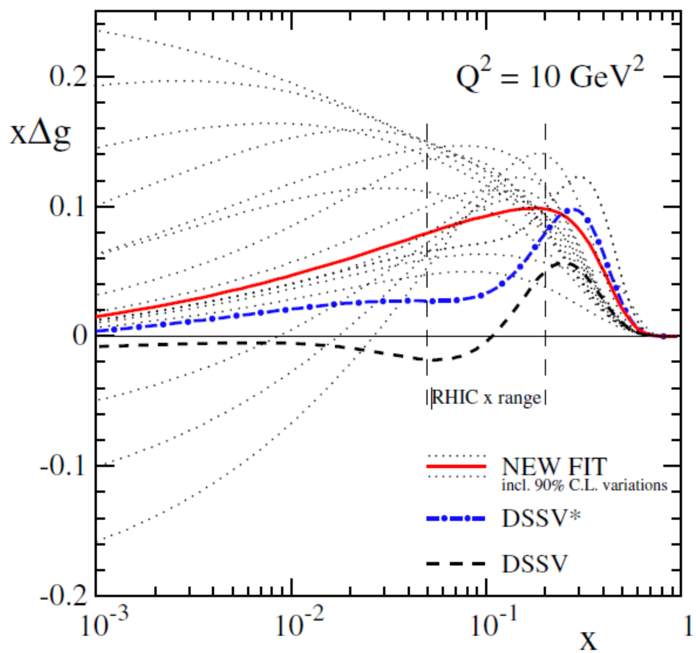
Longitudinal Spin ΔG access by $\pi^{\pm}$



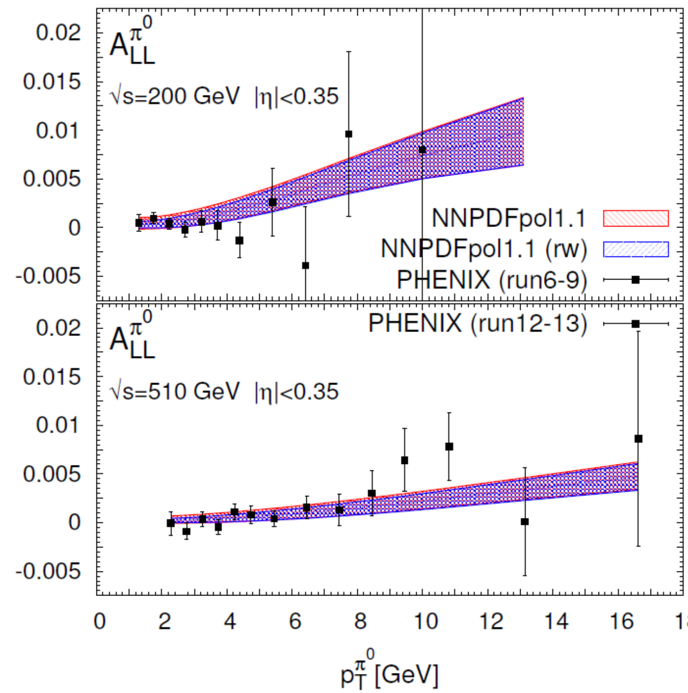


- **$\pi^{\pm}$, A_{LL}, |η| < 0.35, with Run13 data**
  - $\sqrt{s}$ = 510 GeV, Int. L = 108 pb^{-1}
  - Improved statistical precision + Matches to theory within uncertainty
  - Complementary probe: hardens previous π^0 / $\pi^{\pm}$ results

Longitudinal Spin Impact of RHIC ΔG measurement



PRL113, 012001 (2014)



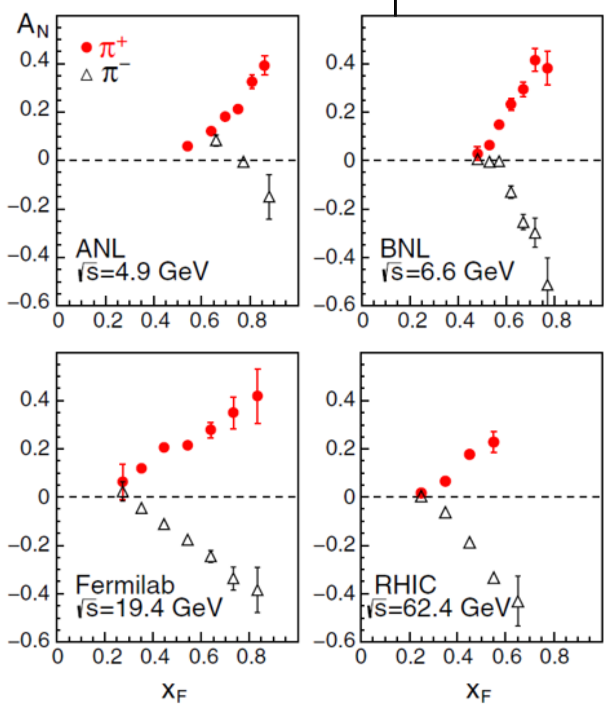
arXiv:1702.05077

- **Impact of RHIC data**
  - Left: DSSV new fit, w/ RHIC RUN9 data → $\int_{0.05}^{1} dx\, \Delta g\,(x) = 0.20\ ^{+0.06}_{-0.07}$ (90 % C.L.)
  - Right: reweighted NNPDFpol1.1, PHENIX 2009 + 2013 π^0

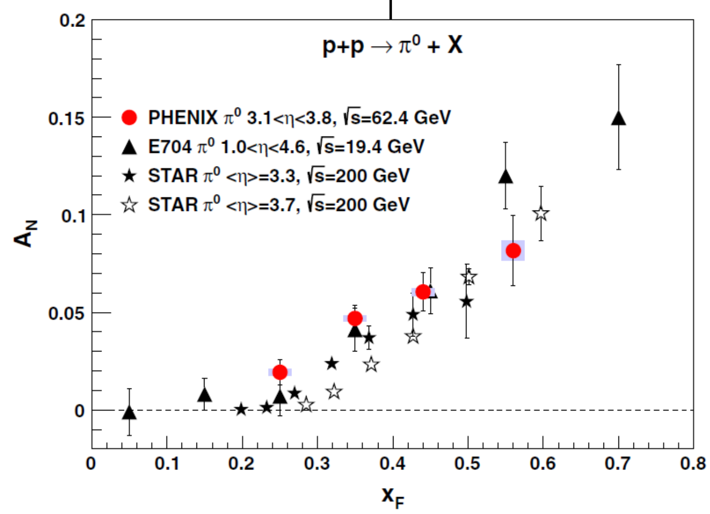
Transverse Spin Highlights

Transverse Spin Motivation

Rev. Mod. Phys. 85, 655



PRD90, 012006 (2014)



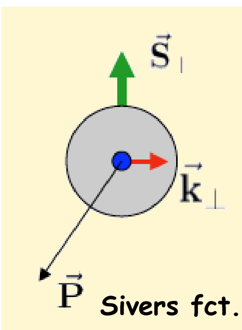
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{1}{P} \times \frac{N_L - N_R}{N_L + N_R}, \quad X_F = \frac{2p_z}{\sqrt{s}} \sim (x_1 - x_2)$$

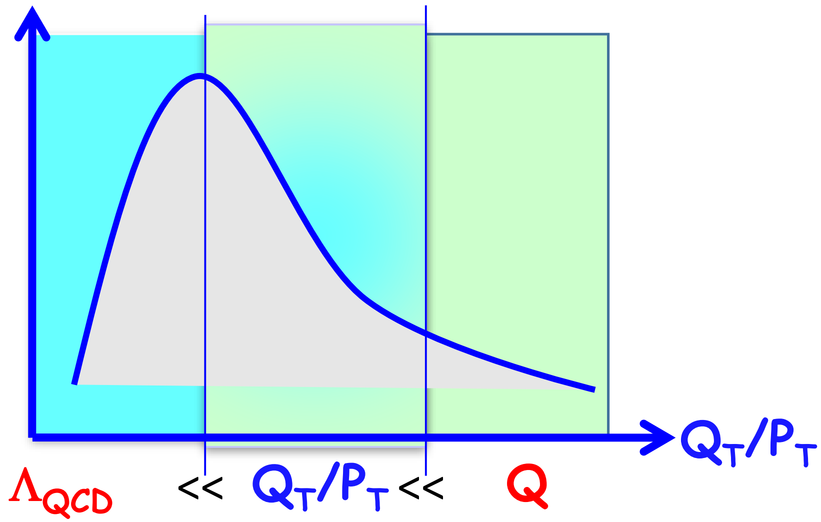
- **Transverse single spin asymmetry (A_N)**
  - Large, increasing A_N : expected to be very small in conventional pQCD calculation
    → TMD (transverse momentum dependent) / Collinear Twist 3

Transverse Spin   Motivation - TMD and Twist 3

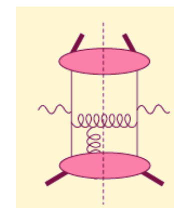
* Quoted from Carl Gagliardi, SPIN2018

TMD





Twist-3



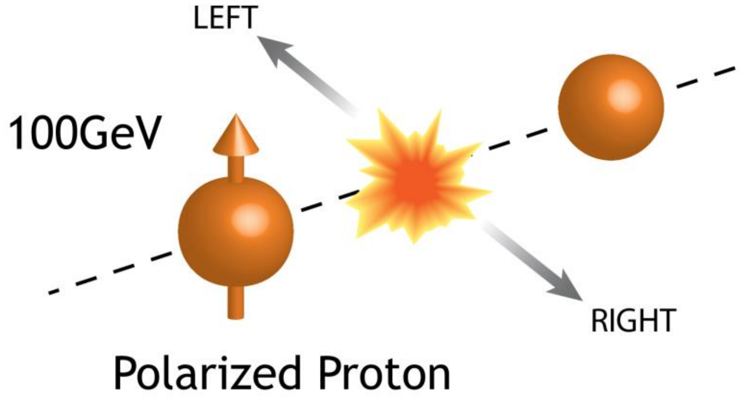
Efremov, Teryaev;
Qiu, Sterman
or
Twist-3 FF

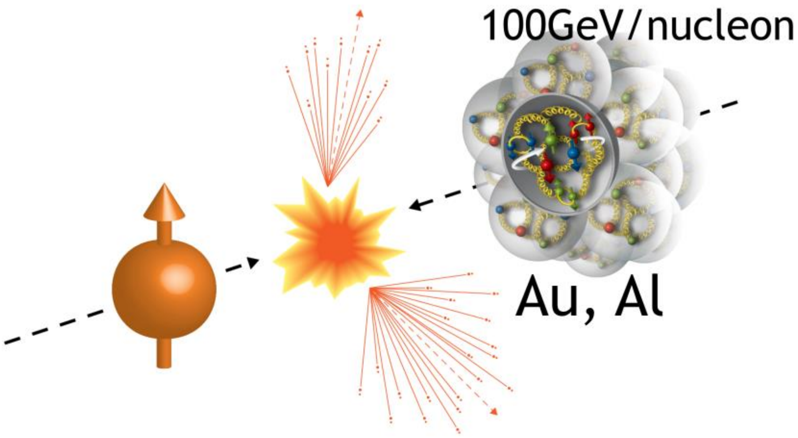
- **TMD**
  - Requires two scales: Q^2 (hard) and p_T (soft)
  - SIDIS, Drell-Yan, W/Z, hadrons in jets…
  - Access full transverse momentum k_T
- **Collinear Twist-3**
  - Requires single hard scale: p_T
  - Proper for inclusive A_N (π^0, γ, jet)
  - Access average transverse momentum $\langle k_T \rangle$

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

Transverse Spin

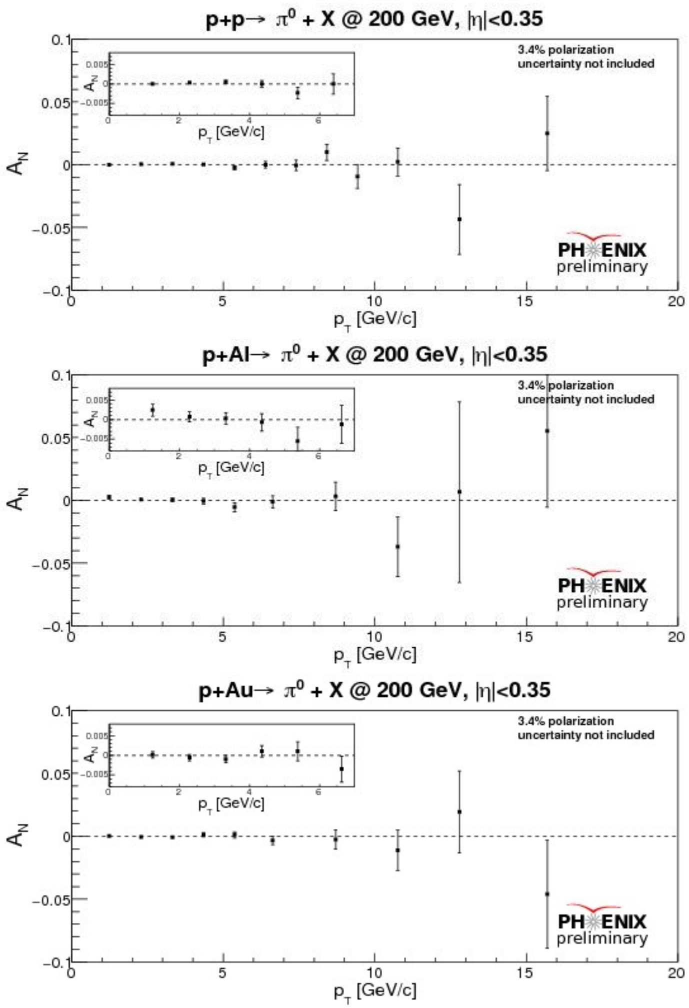
Motivation - $p^{\uparrow} + p$ vs. $p^{\uparrow} + A$

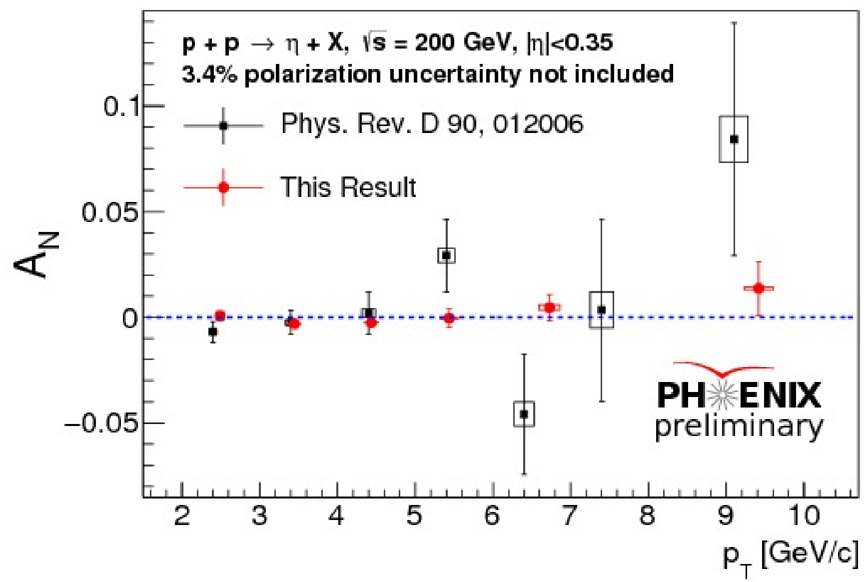




- **A_N in $p^{\uparrow} + p$**
  - Initial or Final state effect
  - Spin - Momentum correlation
  - Spin - Spin correlation
- **A_N in $p^{\uparrow} + A$**
  - Nuclear modification on PDFs (EMC effect, Nuclear shadowing)
  - Gluon saturation effect (CGC)
  - Multiple scatterings

Transverse Spin   Midrapidity π^0 and η



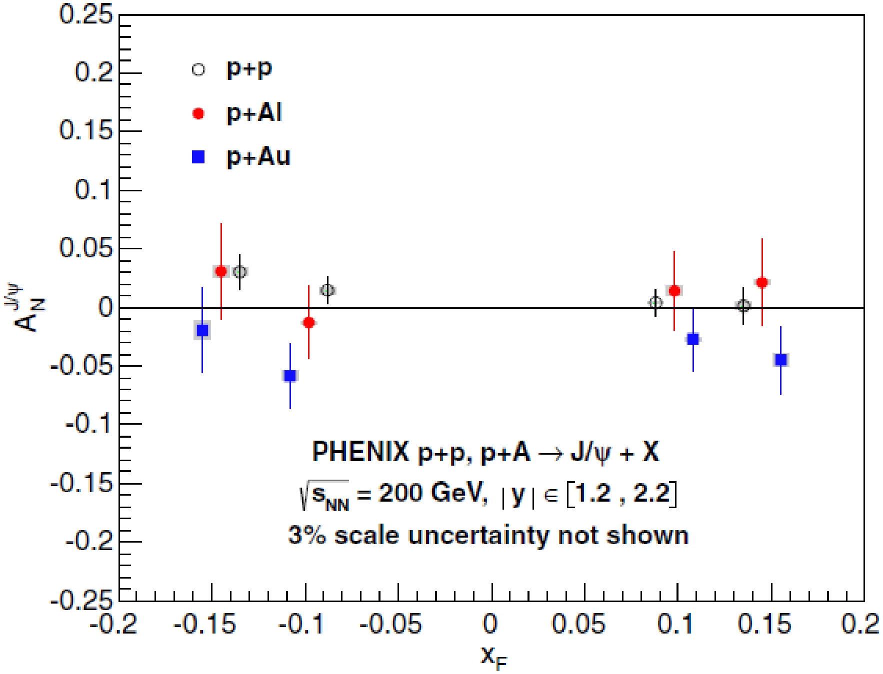


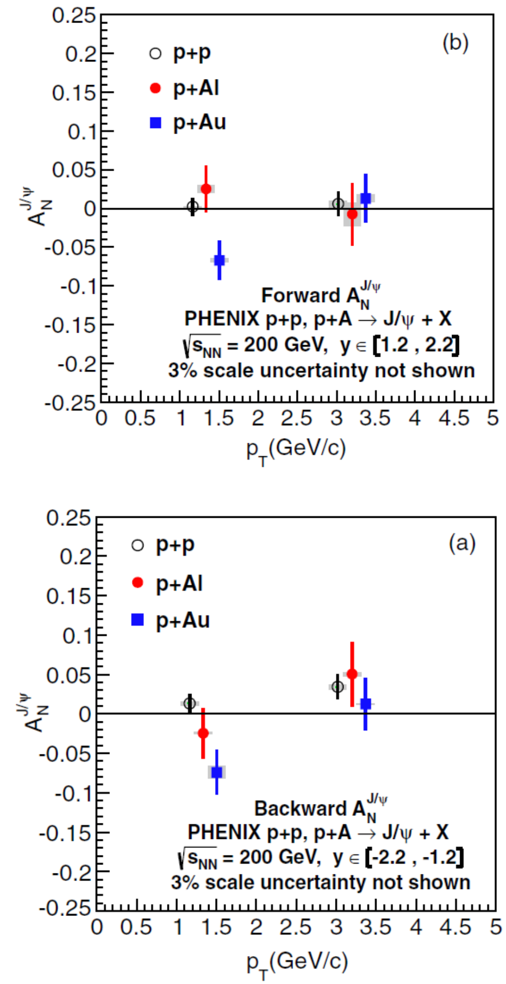
- **π^0 and η A_N at |η| < 0.35**
  - √s = 200 GeV (2015)
  - Sensitive to Twist-3 trigluon correlations
  - Consistent with zero
  - No A dependence observed

Transverse Spin

Forward J/ψ

PRD98, 012006 (2018)

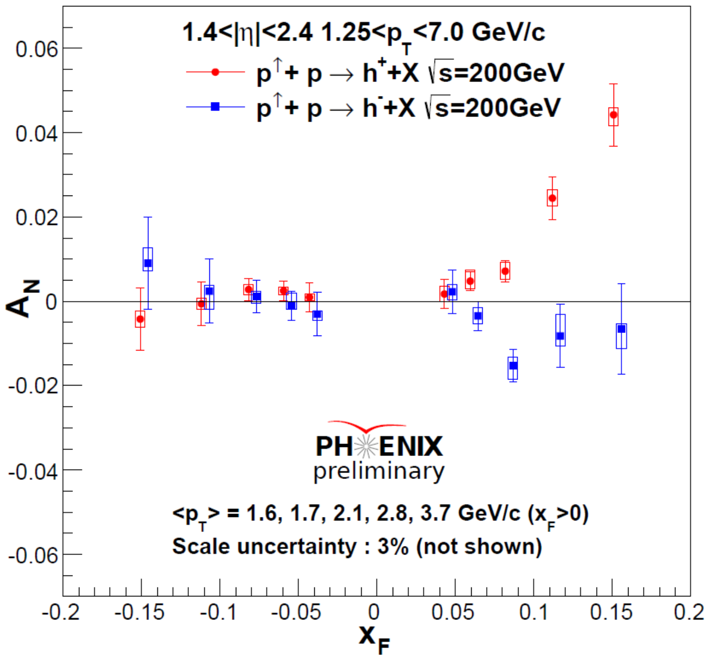




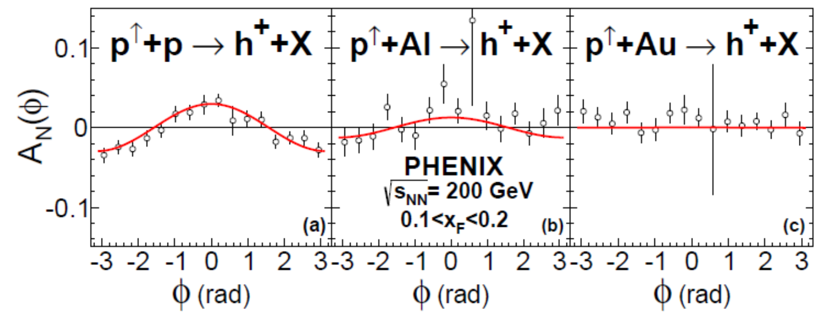
- **J/ψ A_N at 1.2 < |η| < 2.2**
  - √s = 200 GeV (2015)
  - int. L = 40 (pp), 6.0 (pAl), and 6.6 (pAu) pb^{-1}
  - p + p and p + Al are consistent with zero, but p + Au favors negative A_N

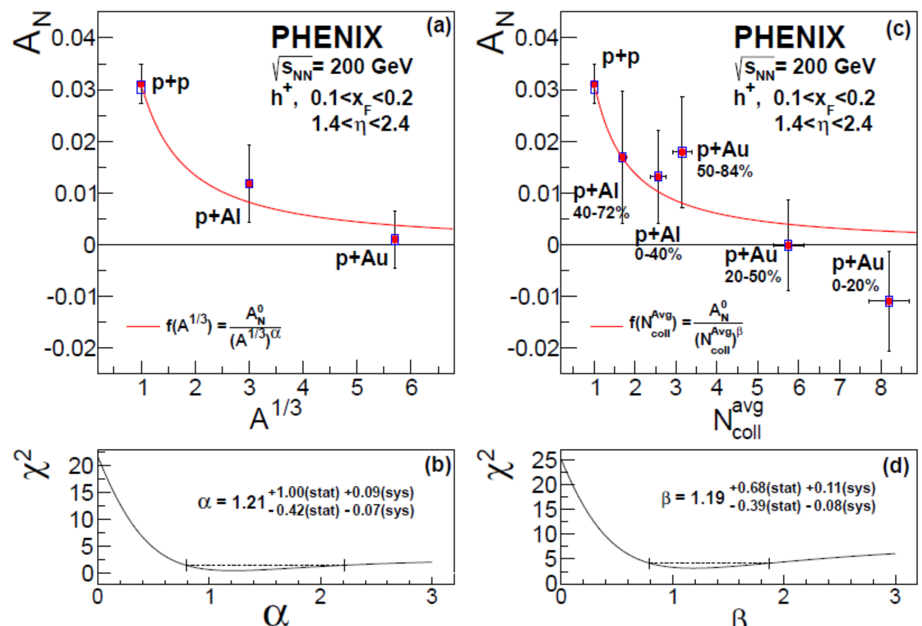
Transverse Spin

Forward charged hadron



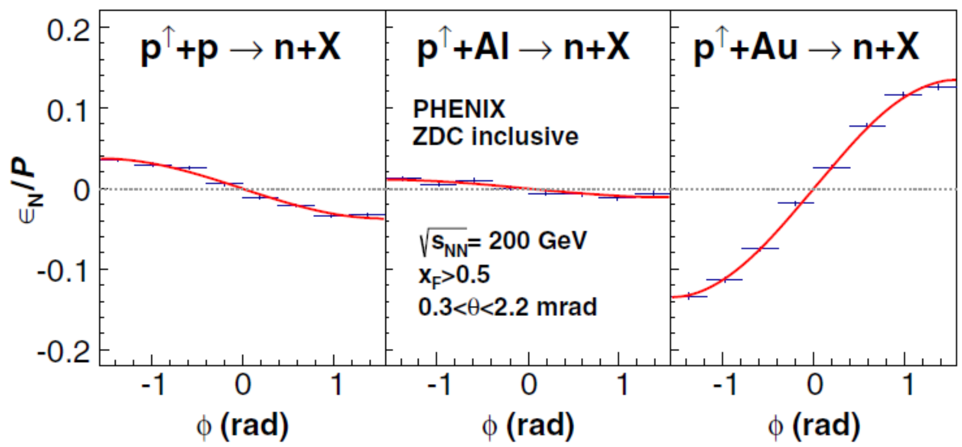
arXiv:1903.07422 (2018)

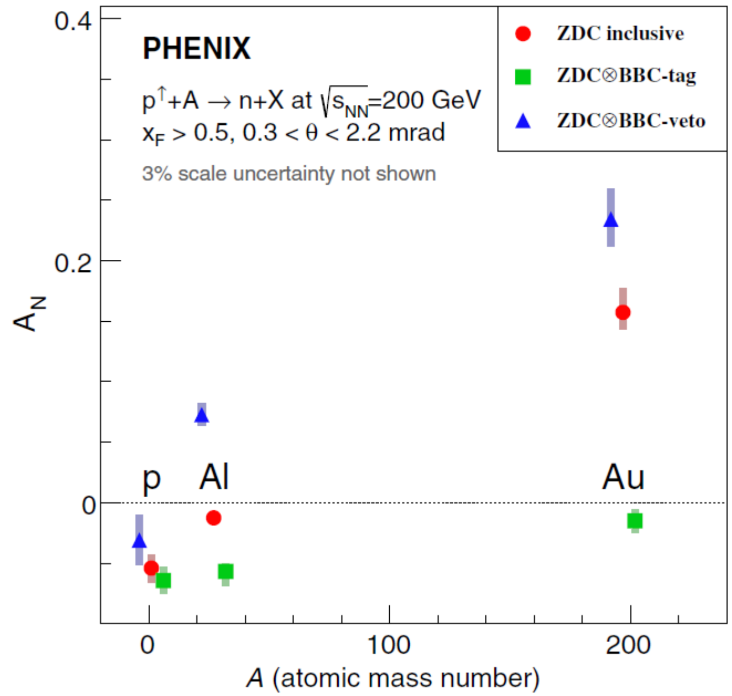




- $\pi^{\pm}$ and $K^{\pm}$ A_N at $1.2 < |\eta| < 2.2$
  - $\sqrt{s}$ = 200 GeV (2015)
  - Increasing h^{+} A_N for $x_F > 0$ in p + p
  - Clear $A^{1/3}$ dependence

Transverse Spin Very forward neutron





PRL120, 022001 (2018)

- **Neutron A_N at 0.3 < θ (mrad) < 2.2**
  - √s = 200 GeV (2015), $x_F > 0.5$
  - Left: ZDC inclusive trigger only
  - Right:
    - a. ZDC inclusive: deposited energy in ZDC > 15 GeV
    - b. ZDC ⊗ BBC-tag: ZDC inclusive + require a hit in each BBC
    - c. ZDC ⊗ BBC-veto: ZDC inclusive + require NO hit in both BBCs
  - Collisions with small impact parameter (BBC-tag) show negative asymmetry
  - Collisions with large impact parameter (BBC-veto) show strong A dependence

Summary

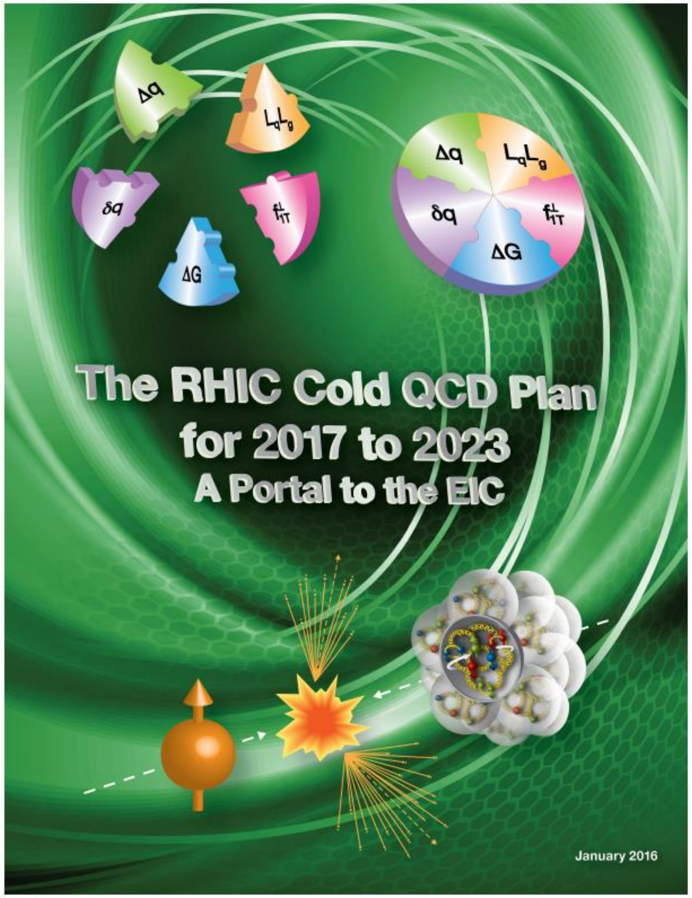
- **Longitudinal spin**
  - Polarized light sea quarks ($\Delta\bar{q}$):

    a. Midrapidity W → e: well matches with STAR data and new theoretical curves

    b. Forward W → μ: 1st measurement of W A_L at $|\eta| > 1$
  - Polarized gluons (ΔG)

    a. Confirms non-zero gluon polarization via hadron (π^0, J/ψ) production

    b. Extended x coverage
- **Transverse spin**
  - Consistent zero A_N in midrapidity, no A dependence
  - Noticeably large A_N for certain observable in forward rapidity, strong A dependence



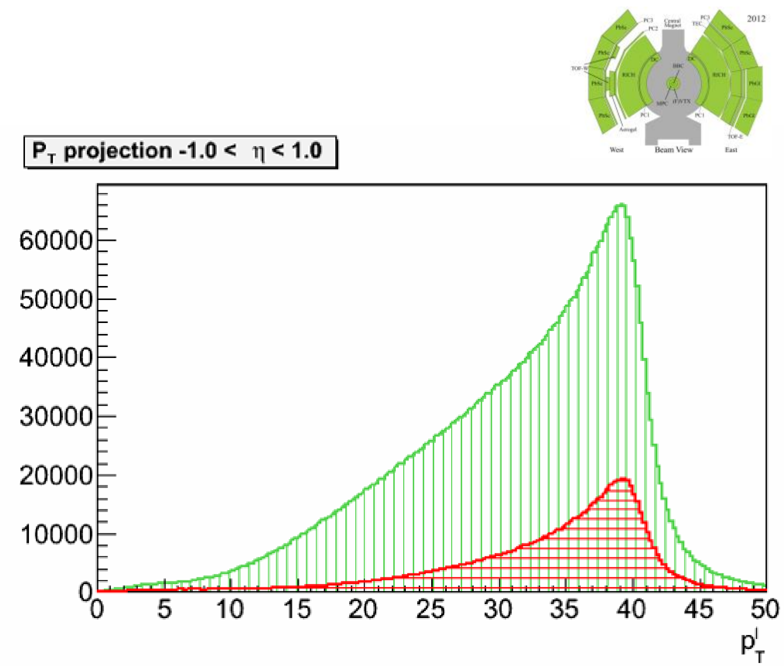
arXiv: 1501.01220

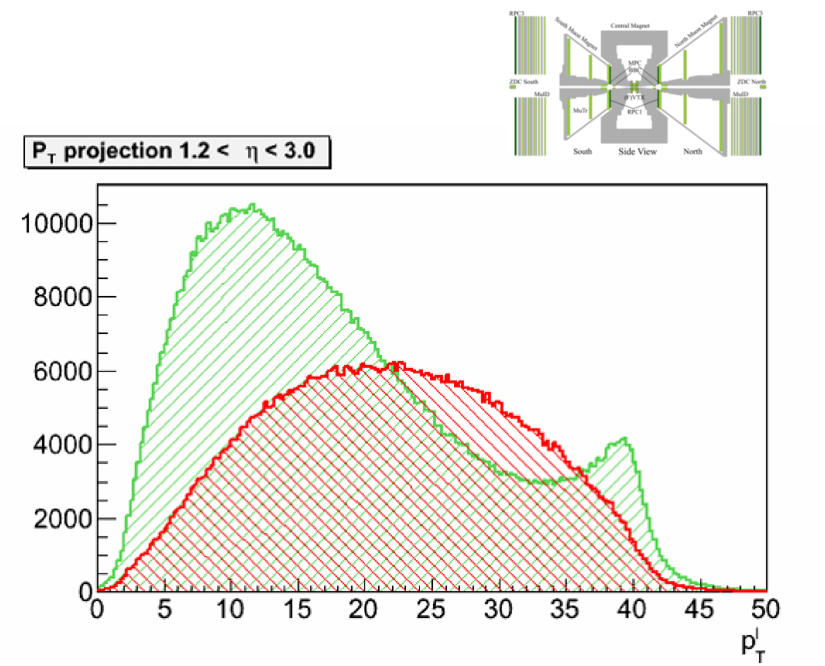
arXiv: 1602.03922

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

Backup

$\Delta\bar{q}$ access by $W^{\pm} \rightarrow e^{\pm}$ / $W^{\pm} \rightarrow \mu^{\pm}$





- ***W*** $^{\pm}$ **→ e** $^{\pm}$ at |η| < 0.35
  - Distinct Jacobian peak

    Triggered by energy

    Momentum by energy

    Charge by tracking in B-field

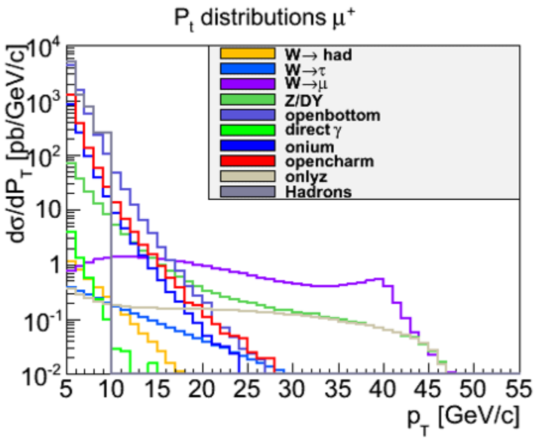
- ***W*** $^{\pm}$ **→ μ** $^{\pm}$ **at** 1.2 < |η| < 2.2 / 2.4
  - Suppressed/No Jacobian peak

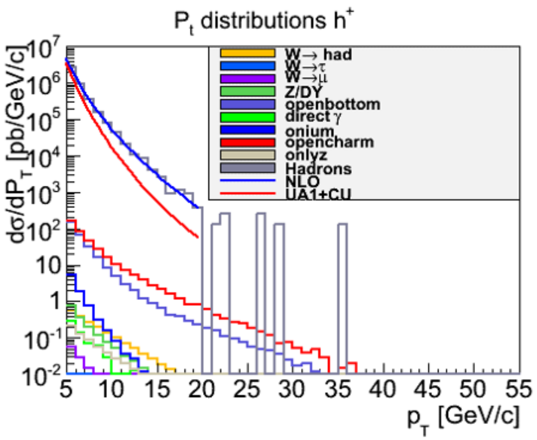
    Triggered by momentum

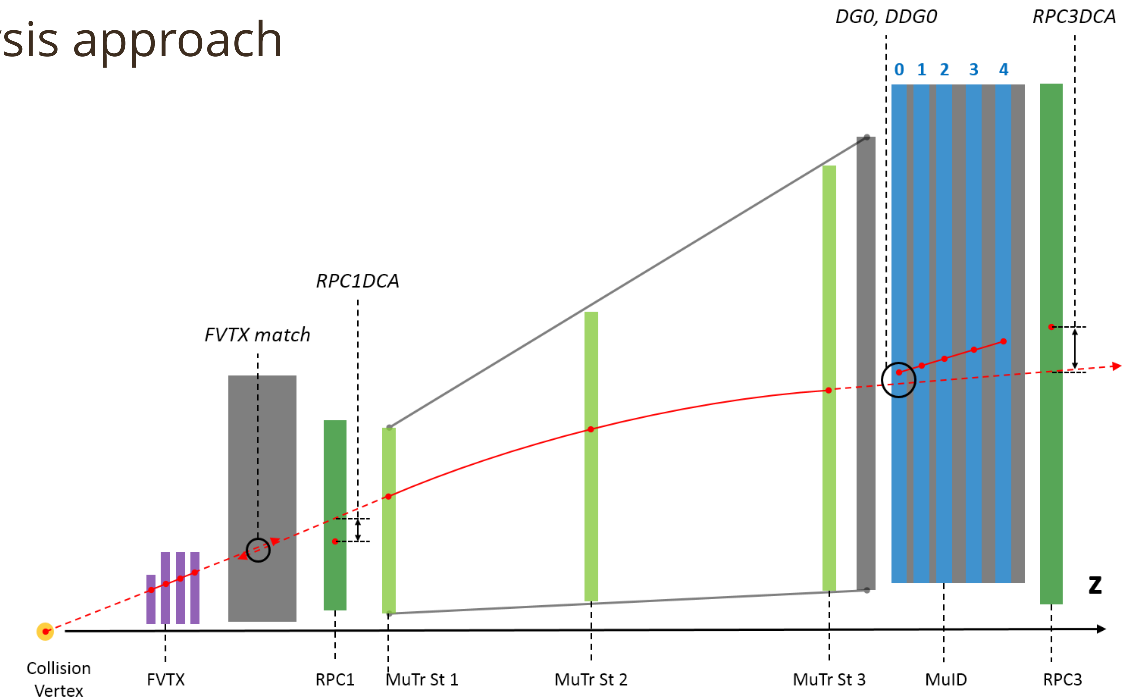
    Momentum by tracking in B-field

    Charge by tracking in B-field

Backup   W → μ analysis approach

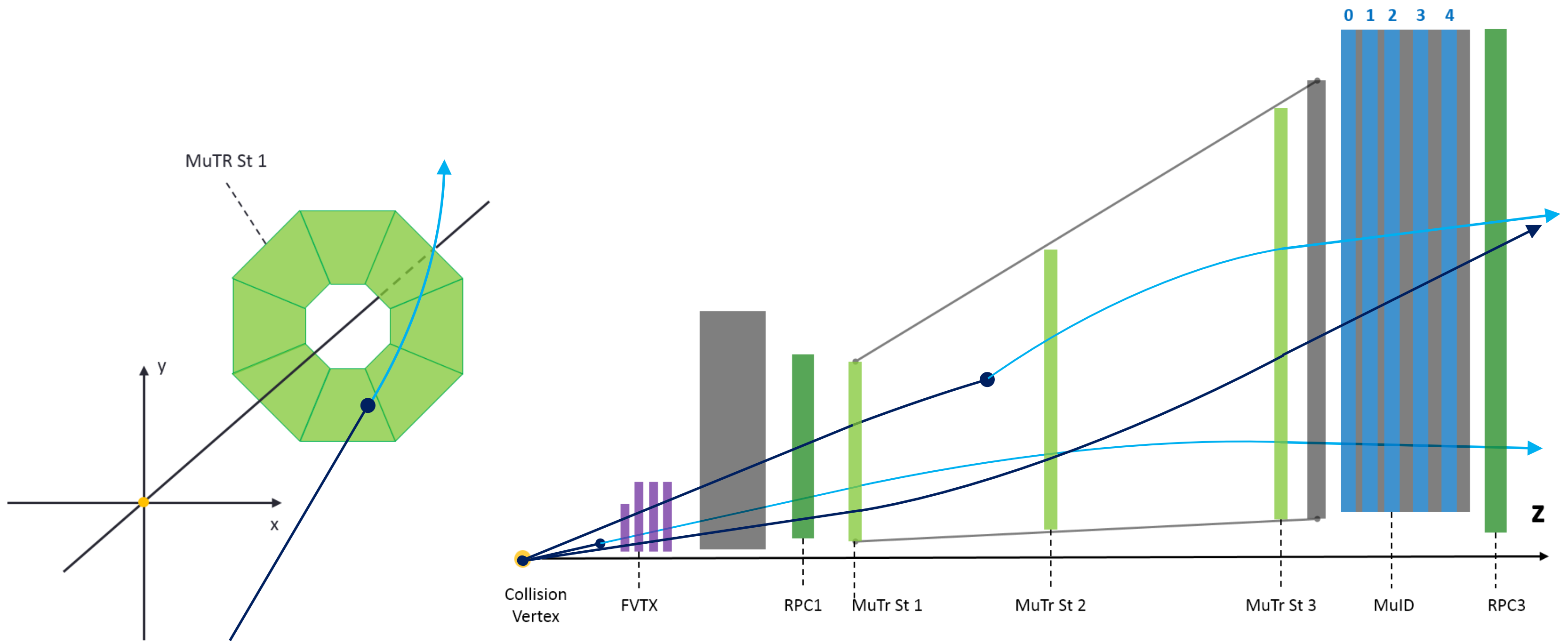






- **Challenges and Approach**
  - In addition to strongly suppressed Jacobian peak,
    a. Limited detector acceptance
    b. Abundant backgrounds (muonic and hadronic)
    c. Smearing in p_T reconstruction
  - No single variable can discriminate *W* signal from BG clearly, but each variable has advantage over certain type of BG

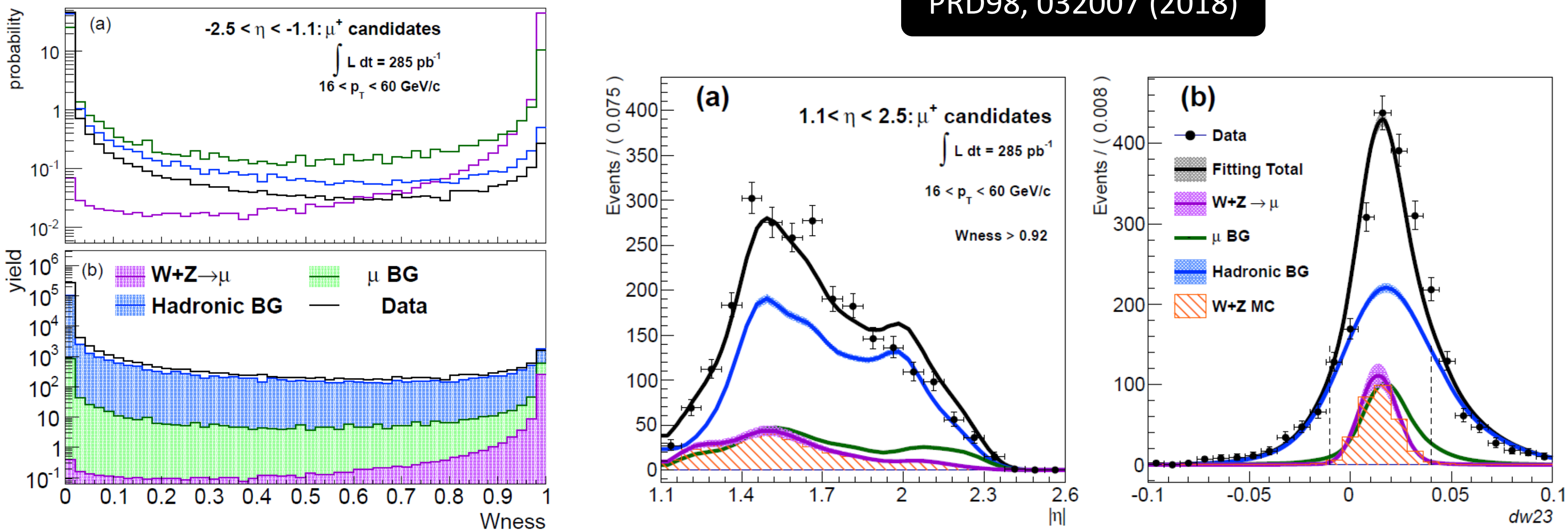
Backup W → μ analysis challenge: hadronic BG



- **Hadronic BG in Muon Arms**
  - Relatively low momentum charged hadrons (mainly $\pi^{\pm}$ and $K^{\pm}$, $p_T < 20$ (GeV))
  - Only small fraction of them penetrate through upstream absorber and reach MuTr, but enormous total cross section creates large backgrounds

Backup W → μ analysis signal extraction

PRD98, 032007 (2018)

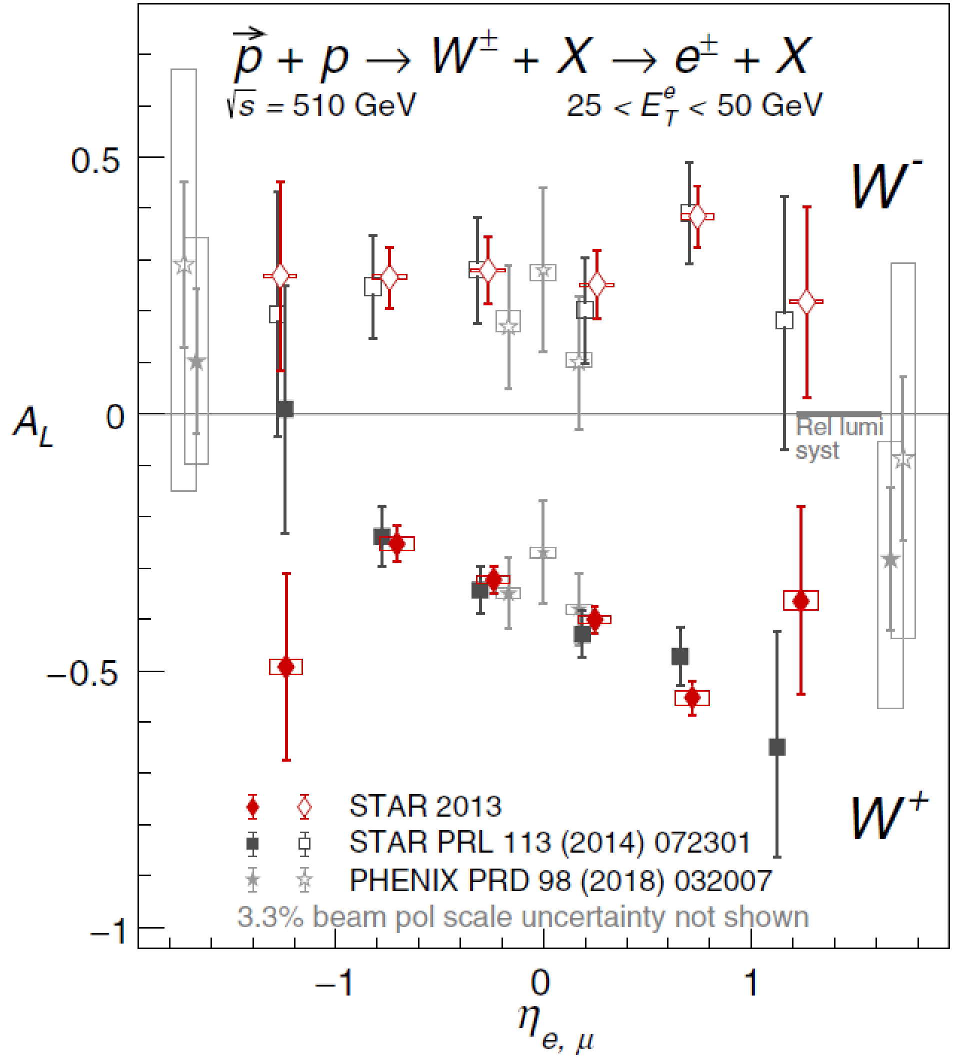


- **Multivariate analysis: *W* likelihood (Wness)**
  - Wness = $\frac{\lambda_{sig}}{\lambda_{sig} + \lambda_{BG}}$,

    where $\lambda_{sig} = (\lambda_{DG0,\,w} \cdot \lambda_{DDG0,\,w} \cdot \lambda_{DCA\_r,\,w} \ldots)$
  - Improve sample purity by applying high Wness filter on μ candidates
  - Signal estimation by unbinned max. likelihood fit

Backup RHIC W (all)

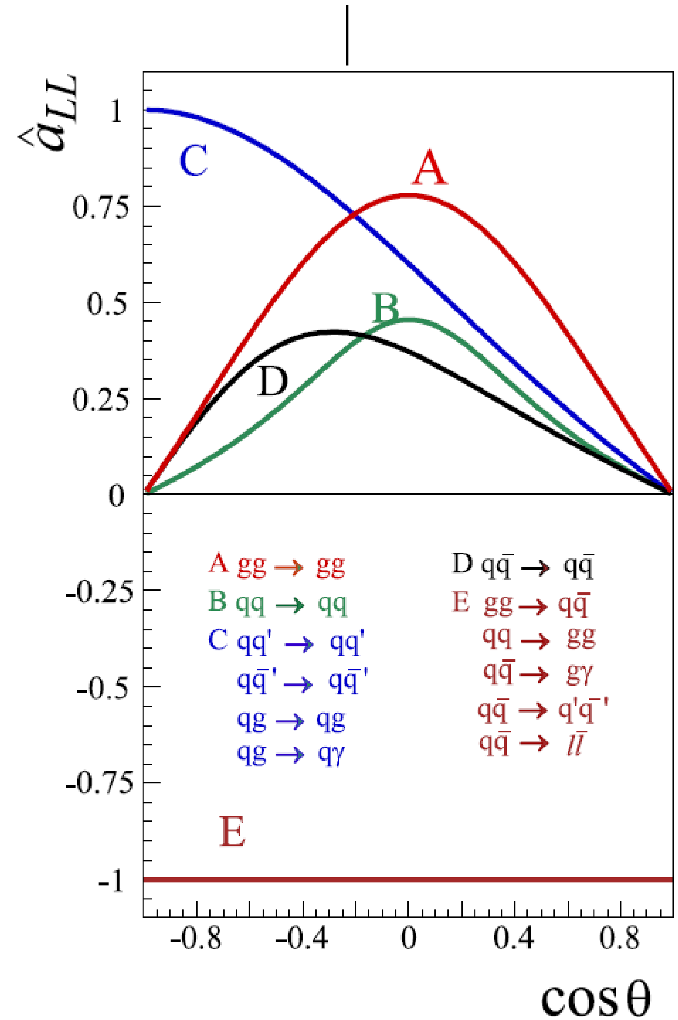
PRD99, 051102 (2019)



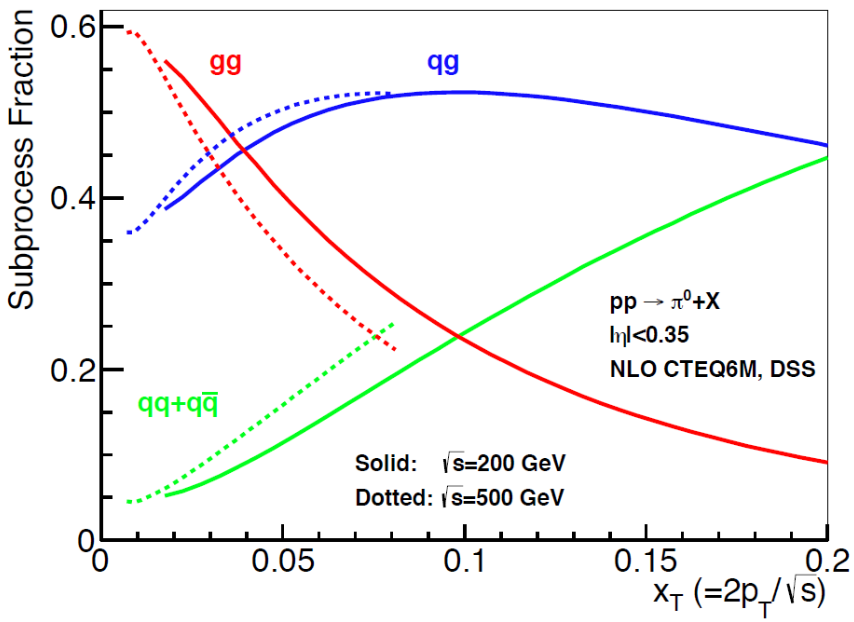
Backup LO dominant partonic processes

LO helicity dependent double spin asymmetries for partonic reactions at RHIC

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $\vec{p}p \to (Z^0, W^\pm)X$ [78]	$\vec{q}\vec{\bar{q}} \to Z^0$, $\vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm$, $q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	



Backup Gluon polarization and π^0 ALL

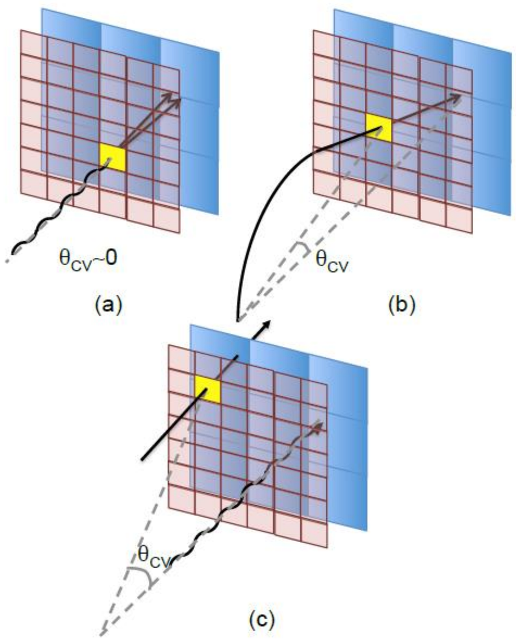


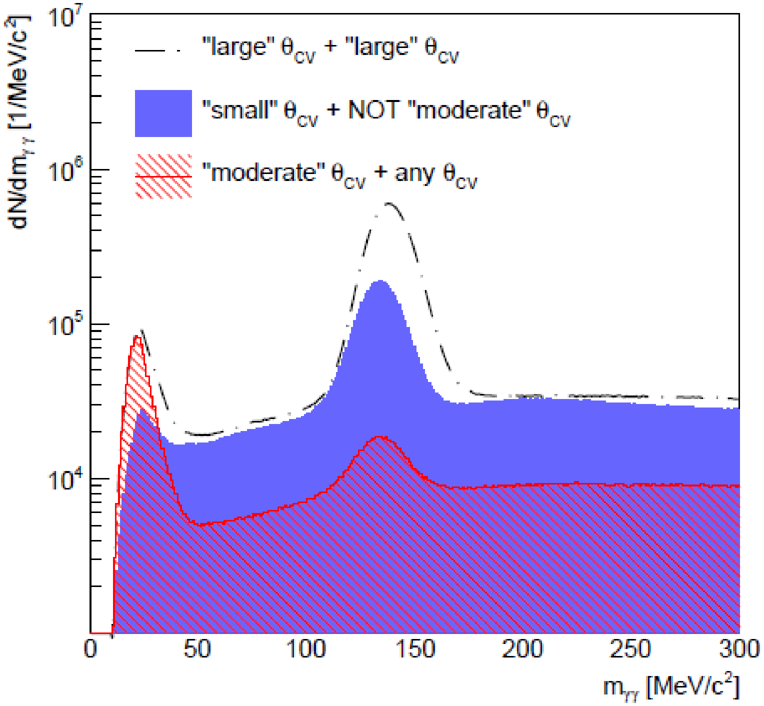
arXiv: 1501.01220

- $\Delta\sigma\,(pp \rightarrow \pi^0 X) \approx \Delta q\,(x_1) \otimes \Delta g\,(x_2) \otimes \Delta\hat{\sigma}^{gq \rightarrow gq}\,(\hat{s}) \otimes D_q^{\pi^0}(z)$
  - $\Delta q\,(x_1)$: 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](#) Central arm π^0 analysis

PRD90, 012007





- **Inclusive π^0 analysis**
  - Charge veto (θ_{cv}) + Time of flight + Relative Luminosity correction + Background asymmetry correction (by background sampling)

Backup Color interactions in QCD

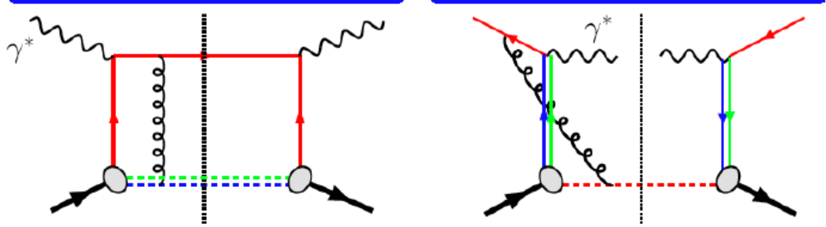
- This slide was shamelessly stolen from **Carl Gagliardi**'s SPIN2018 talk!

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



$\text{Sivers}_{\text{DIS}} = -\ \text{Sivers}_{\text{Drell-Yan}}$ or Sivers_{W} or Sivers_{Z}

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

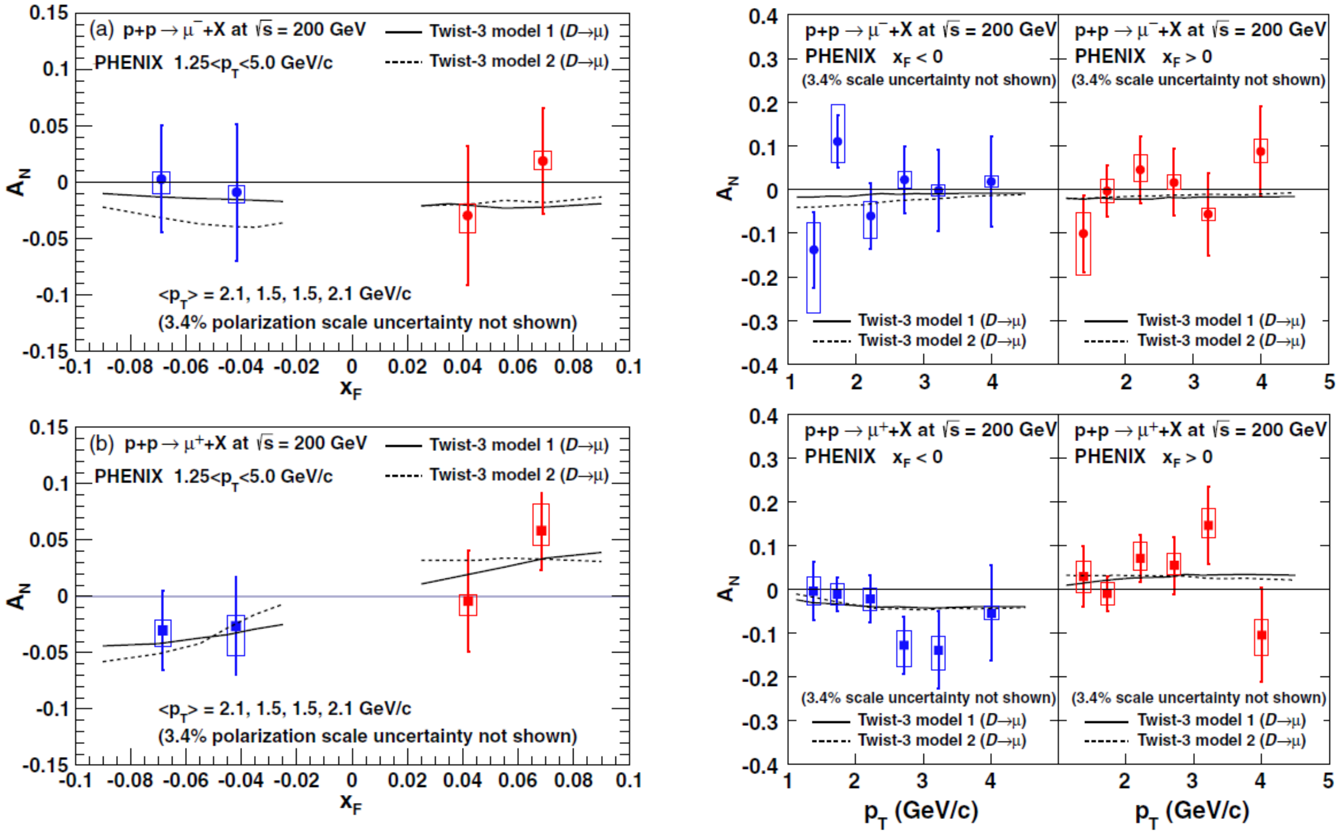
Critical test of factorization

Opportunity to visualize the repulsive interaction between like color charges

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

Backup

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

Midrapidity π^0 A_N, vs. A