Highlights from the Cold QCD Program at RHIC

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Brookhaven National Laboratory

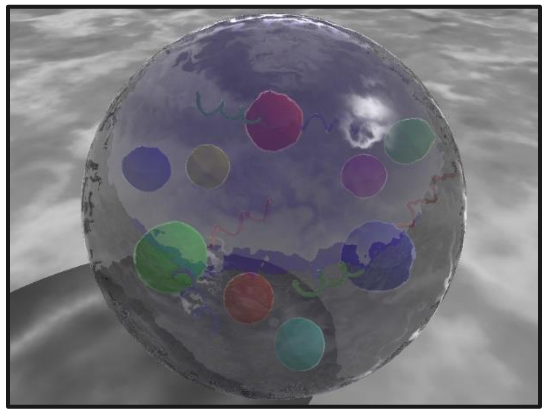
Joint 20th International Workshop on Hadron Structure and Spectroscopy
and
5th Workshop on Correlations in Partonic and Hadronic Interactions

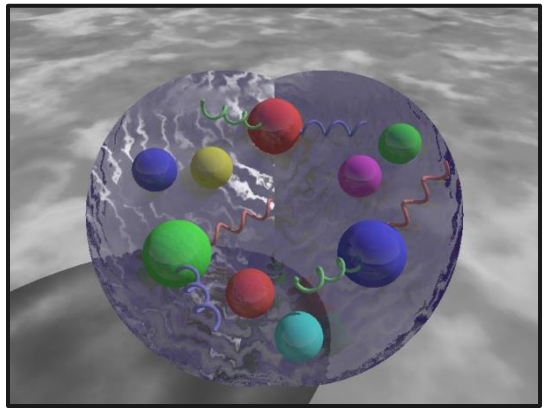
September 30, 2024

Yerevan, Armenia

Brookhaven National Laboratory

Cold QCD at RHIC





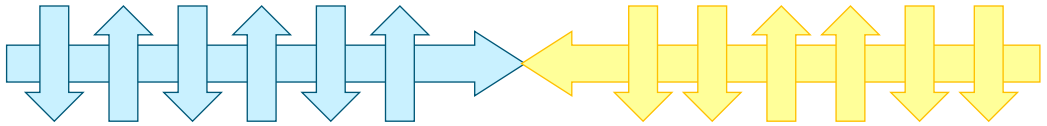
- What is the nature of the spin of the proton?
  - Gluon polarization
  - Sea quark polarization
- What do transverse spin phenomena teach us about the proton structure?
- How can we describe the multi-dimensional landscape of nucleons and nuclei?
- How do quarks and gluons hadronize into final state particles?

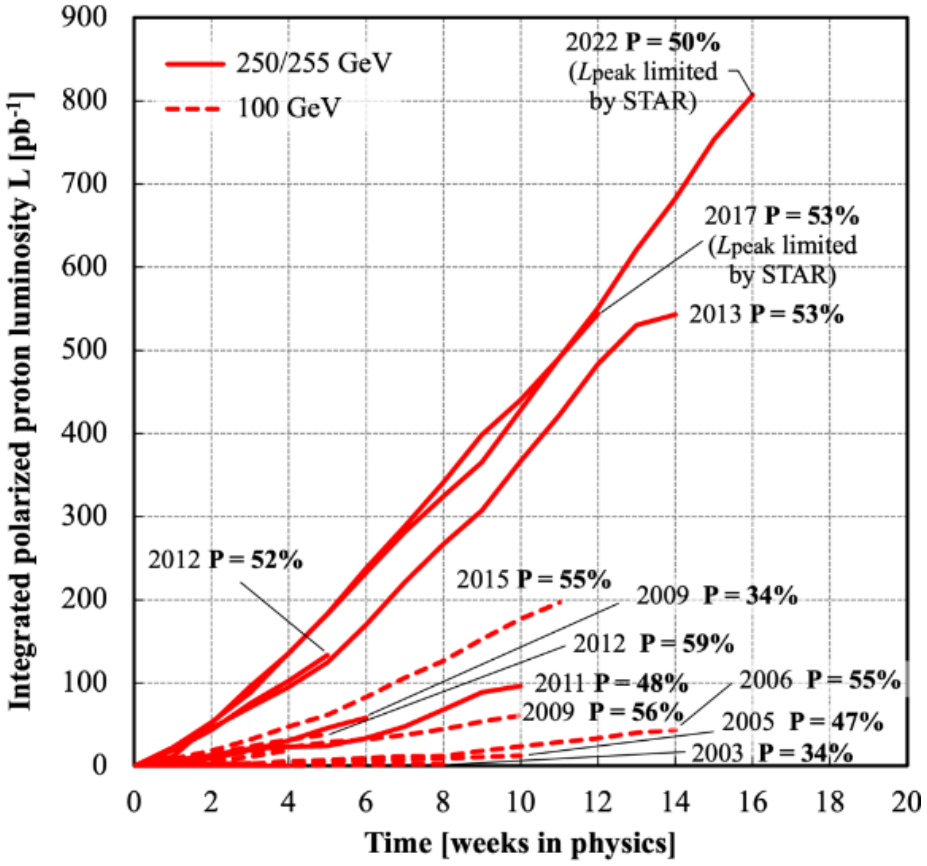
RHIC Spin Plan for 2024 to 2028: Completing the RHIC Science Mission

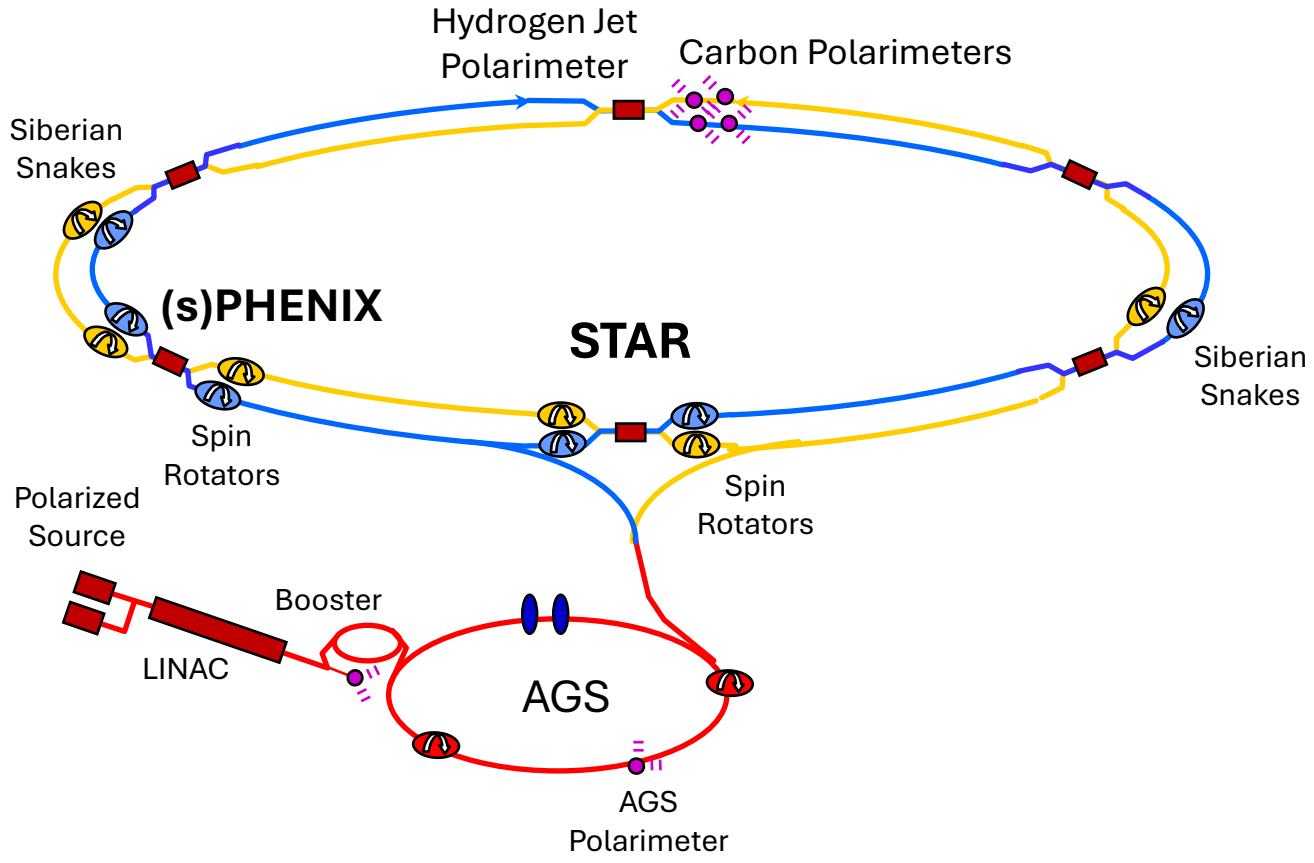
The Relativistic Heavy Ion Collider

$\vec{p} + \vec{p}$ / $\vec{p} + A$

$\sqrt{s_{NN}} = 200 - 510$ GeV







The Relativistic Heavy Ion Collider

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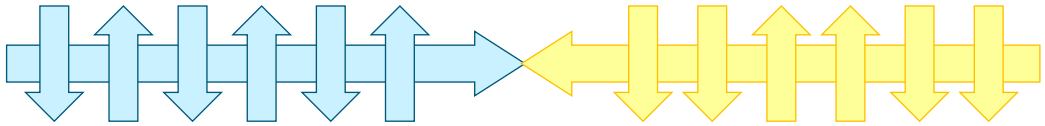
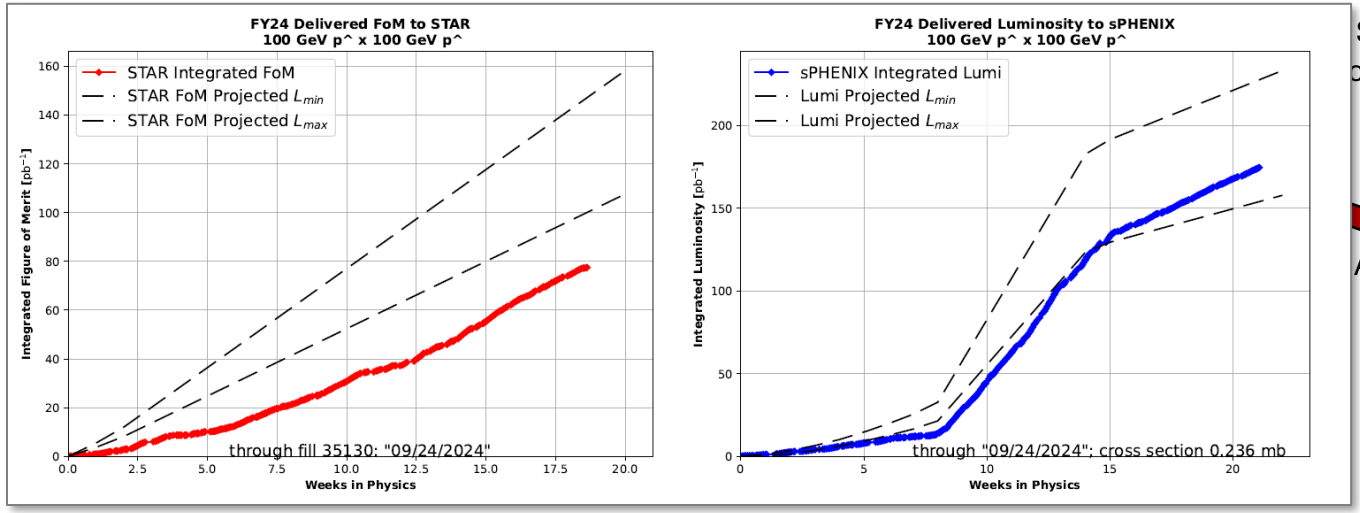
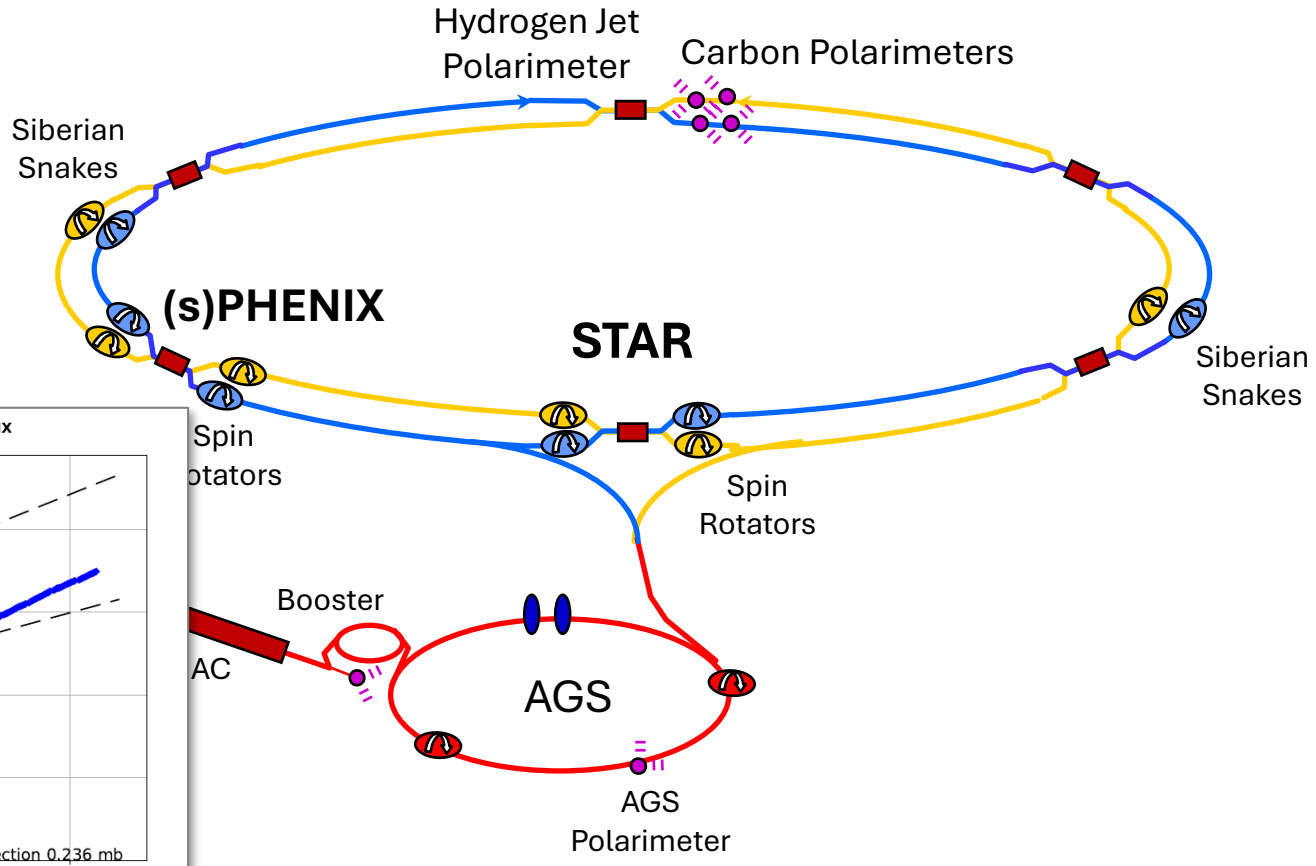


- September 30:
  RHIC Run 24 is concluding as we speak
- Delivered luminosities as per last Tuesday
  (RHIC Run Coordinator Kiel Hock)





PHENIX

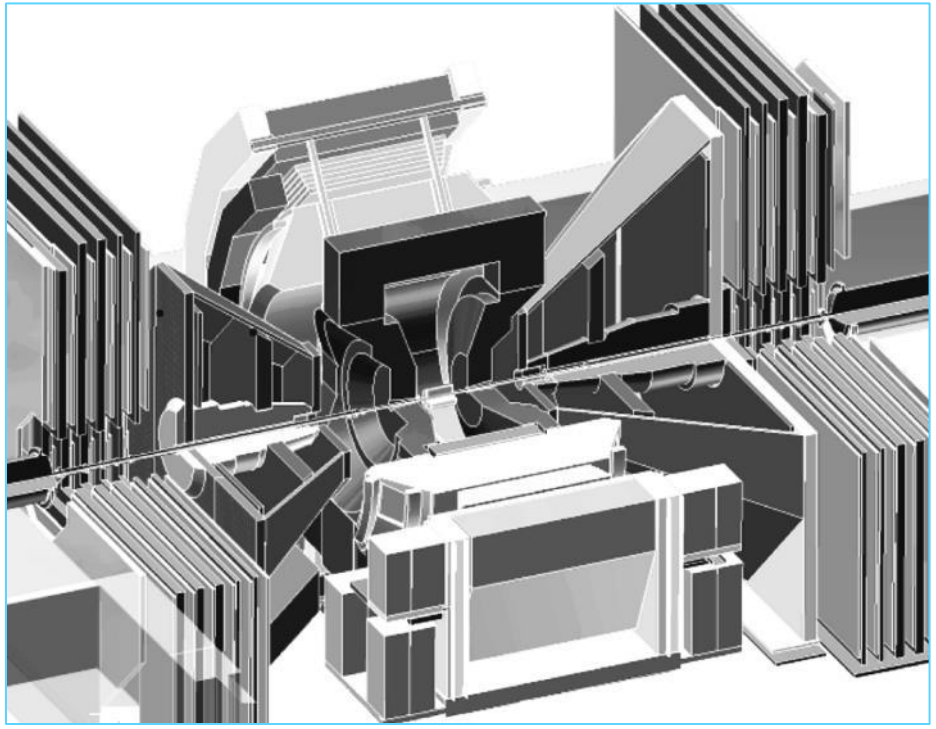
High resolution

High rate

DC / Pad Chambers / Muon Arms

EMCal

Forward EMCal, $3 < |\eta| < 4$



STAR

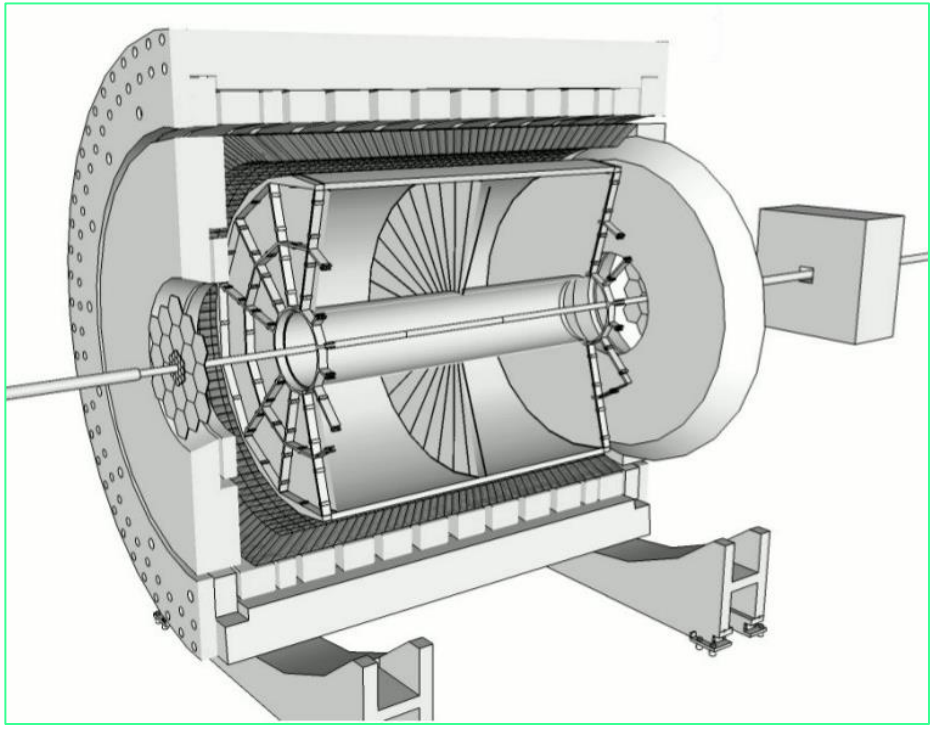
Large acceptance

$-1 < \eta < 2$

TPC+TOF

EMCal

Forward EMCal, $2.5 < \eta < 4$

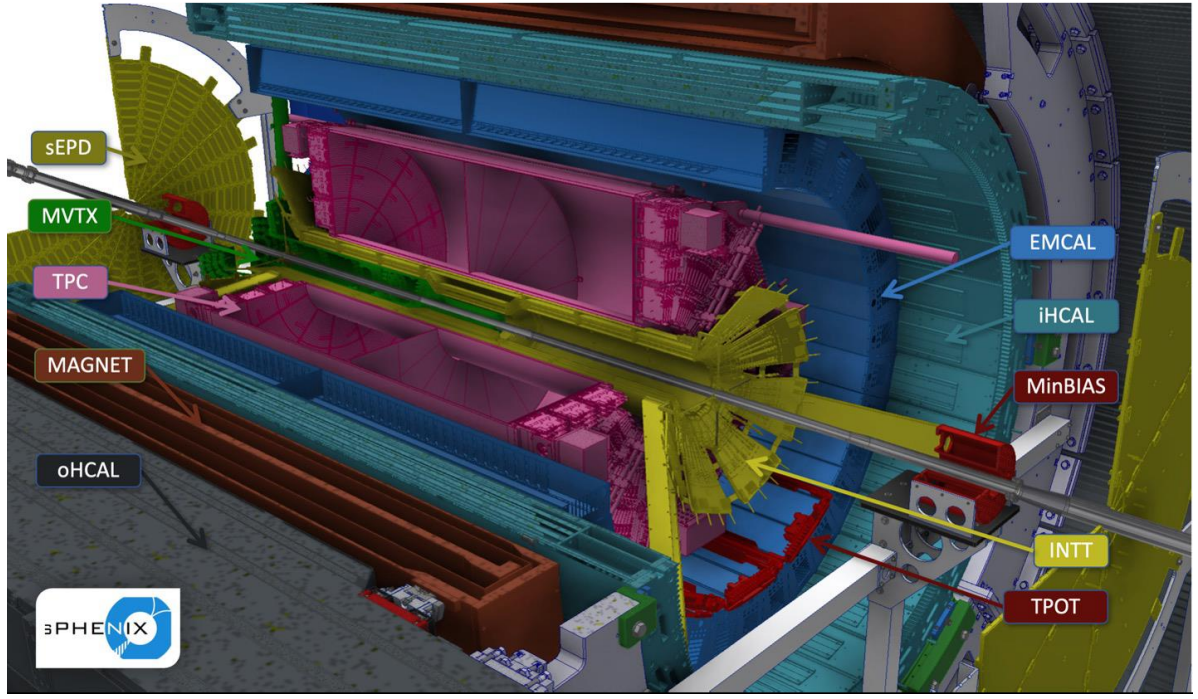


sPHENIX

$-1.1 < \eta < 1.1$

Precision tracking

Ecal + Hcal



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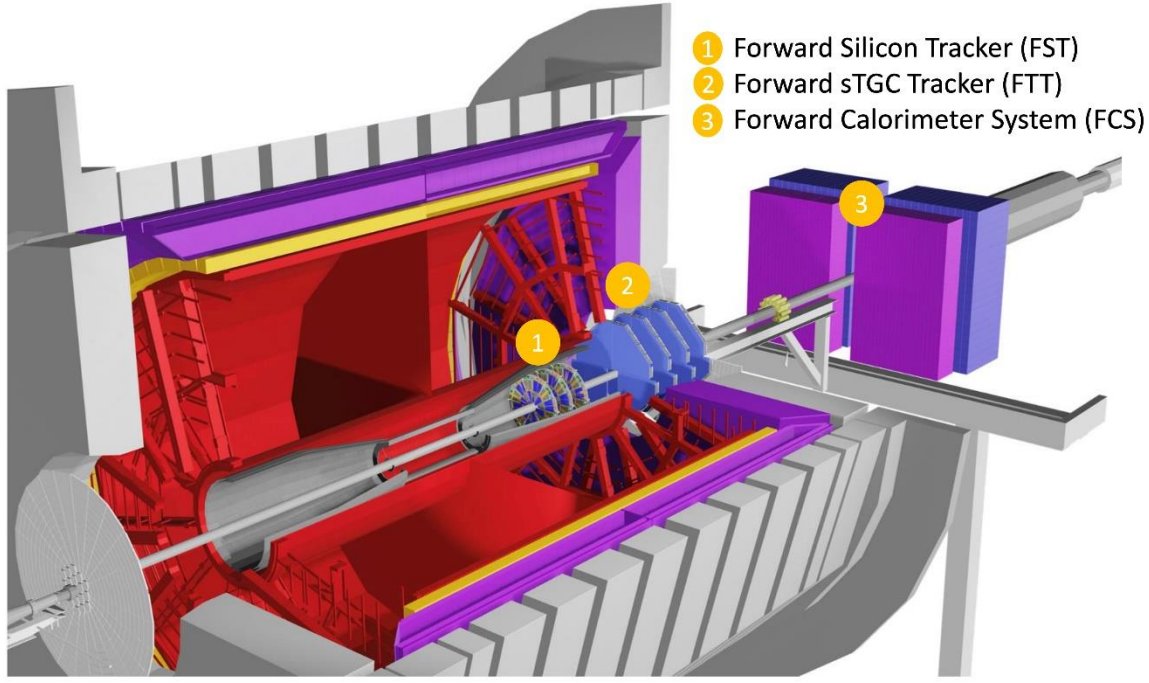
Forward detectors

$2.5 < \eta < 4$

Si & sTGC trackers

Ecal & Hcal

with EPD (preshower)



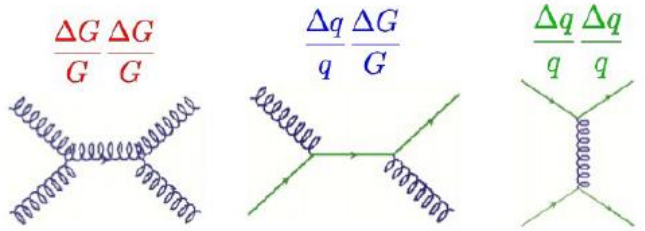
Helicity Measurements

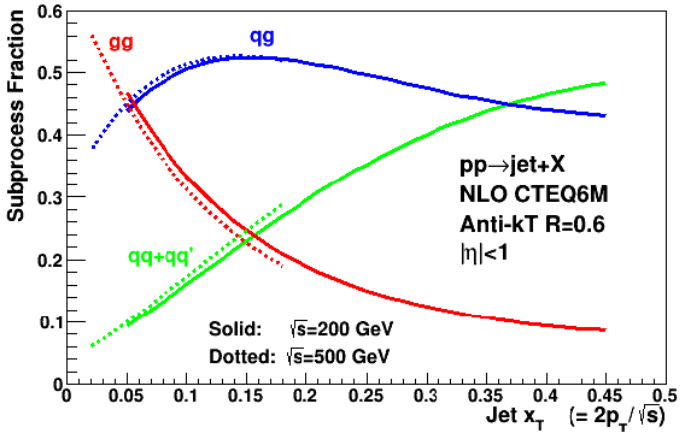
- Double helicity asymmetries in proton collisions

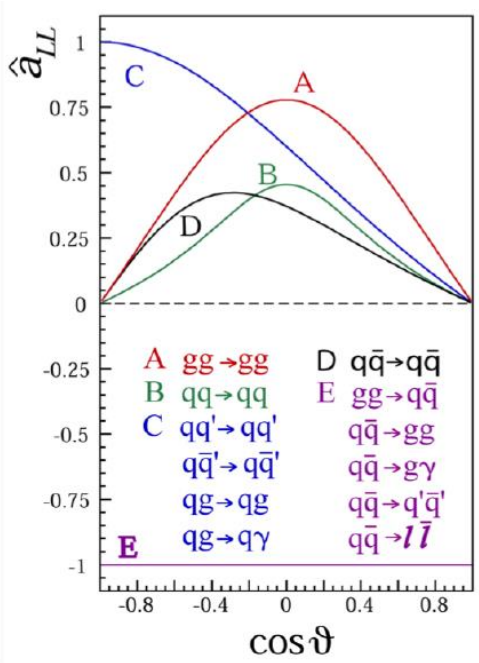
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

$$A_{LL} = \frac{1}{P_1 P_2} \frac{N^{++} - R_3 N^{+-}}{N^{++} + R_3 N^{+-}}$$

$$R_3 = \frac{L_{++} + L_{--}}{L_{+-} + L_{-+}}$$

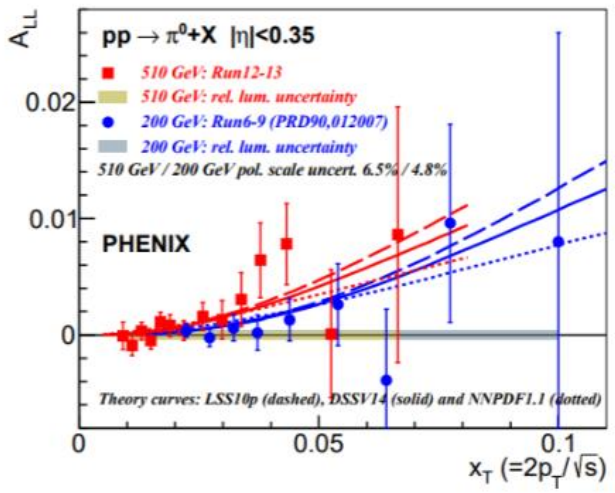


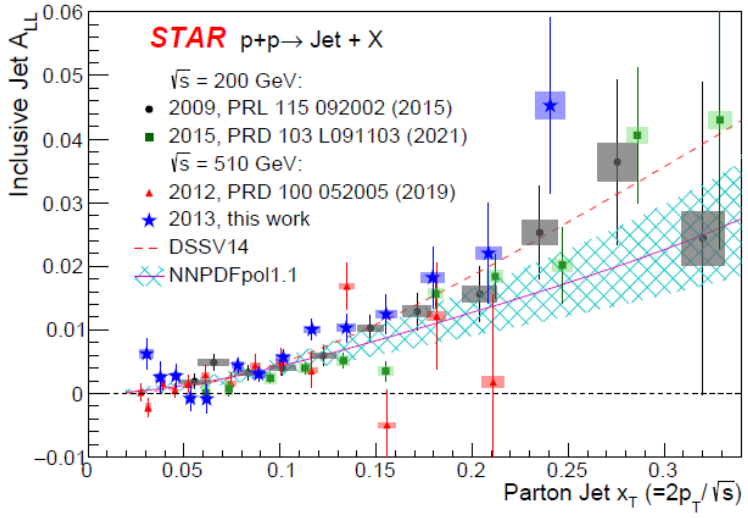




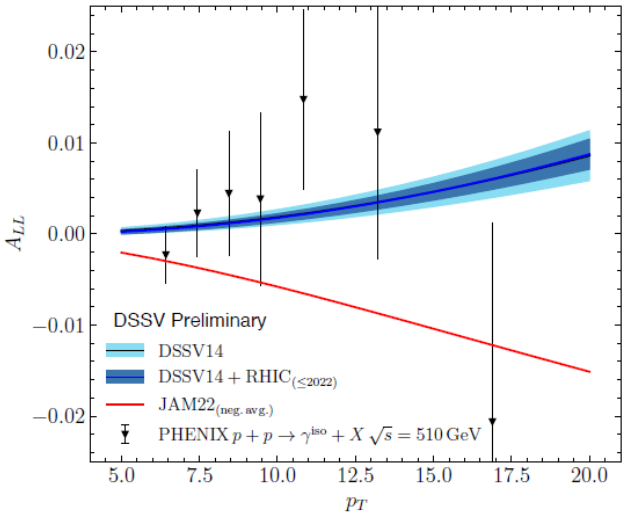
- Beam polarizations
  - $P_{1,2} \approx 55 - 60\%$
  - $\delta P/P \approx 3.5\%$
  - $\delta(P_1P_2)/(P_1P_2) \approx 6\%$
  - Residual transverse polarization
- Relative luminosity
  - Fill-by-fill $\Delta R \approx 4\%$
  - Overall $\Delta R < 5 \cdot 10^{-4}$
  - From rates in different detectors (BBC/VPD/ZDC)

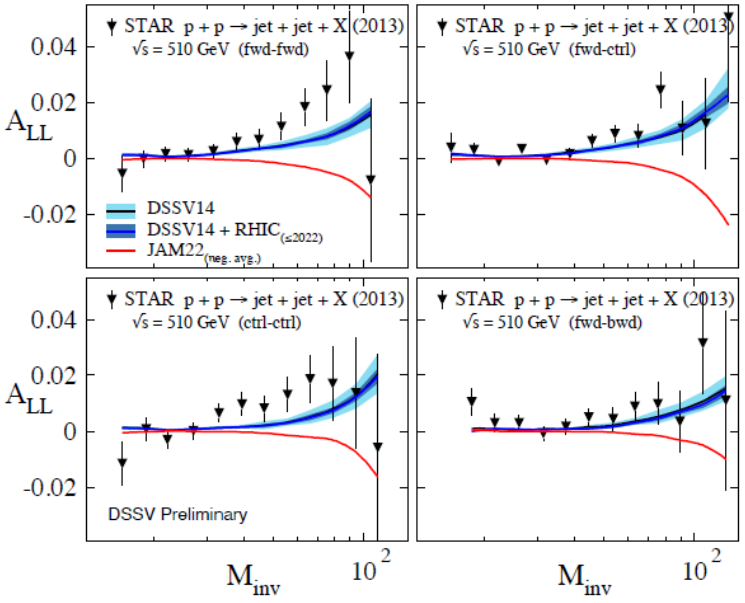
Polarized Gluons in the Proton

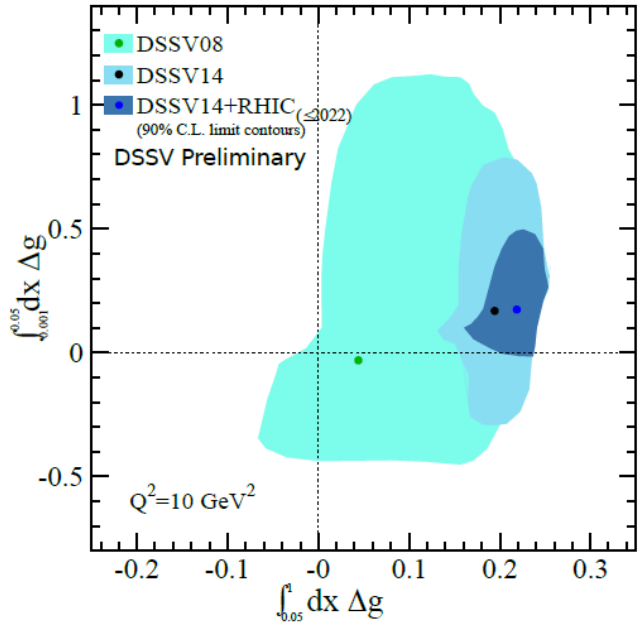




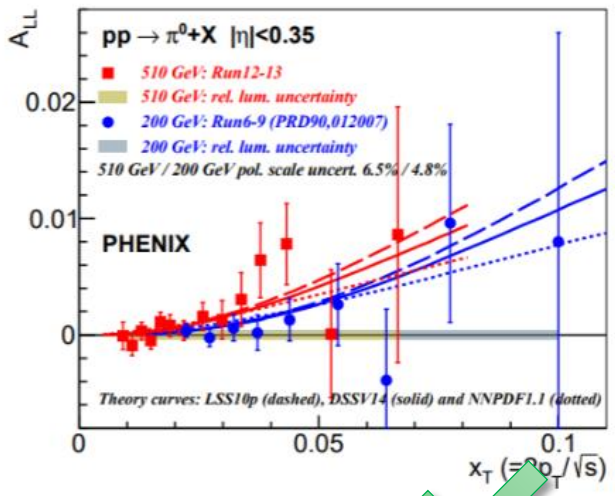
- Phys. Rev. D**94** (2016) 112008
- Phys. Rev. D**93** (2016) 011501
- Phys. Rev. D**102** (2020) 032001
- Phys. Rev. Lett. 130 (2023) 251901
- Phys. Rev. Lett. 115 (2014) 092002
- Phys. Rev. D**95** (2017) 71103
- Phys. Rev. D**98** (2018) 032011
- Phys. Rev. D**100** (2019) 052005

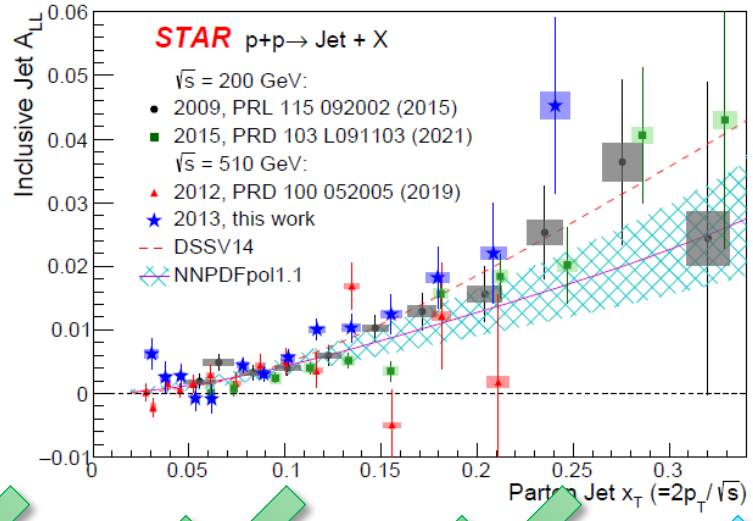






Polarized Gluons in the Proton





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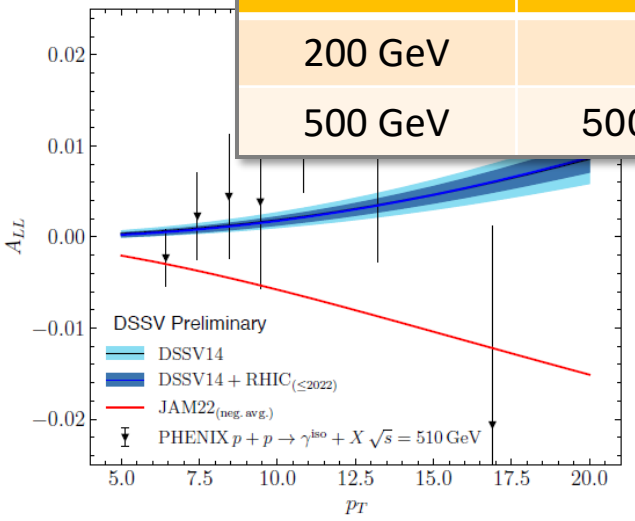
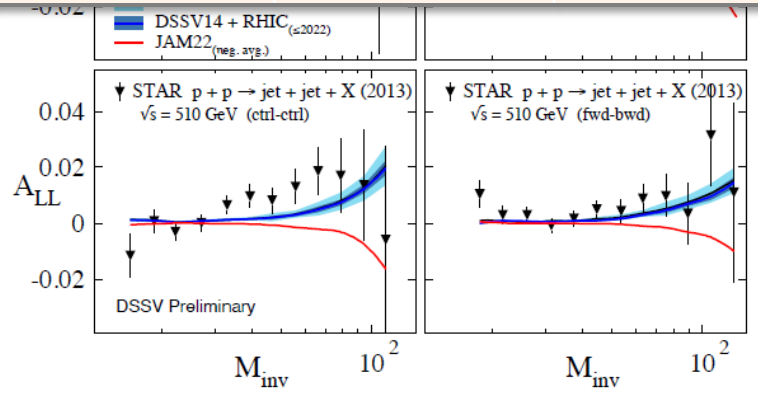
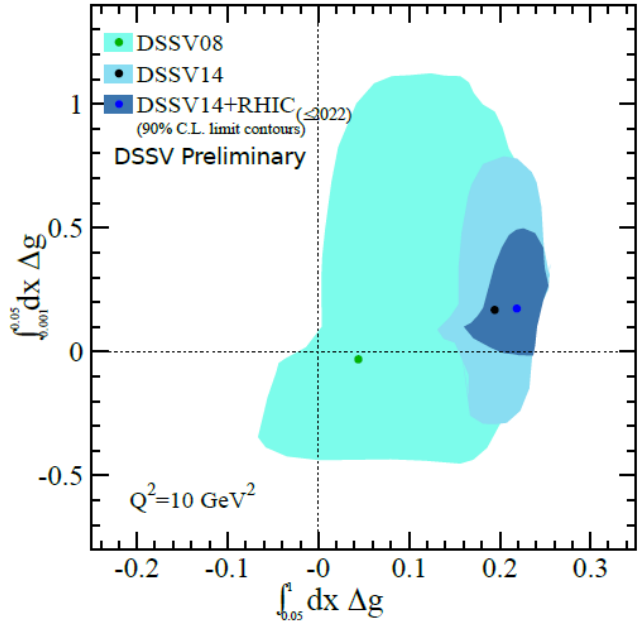
- Phys. Rev. D**95** (2017) 71103
- Phys. Rev. D**98** (2018) 032011
- Phys. Rev. D**100** (2019) 052005

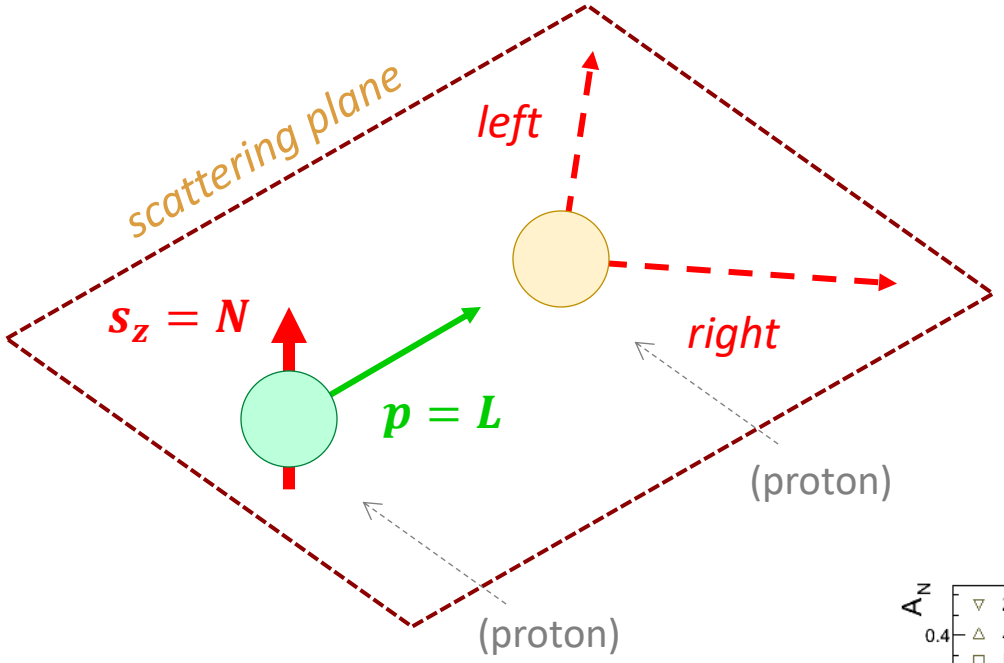
2009	2011	2012	2013	2015
200 GeV				200 GeV
500 GeV	500 GeV	510 GeV	510 GeV	







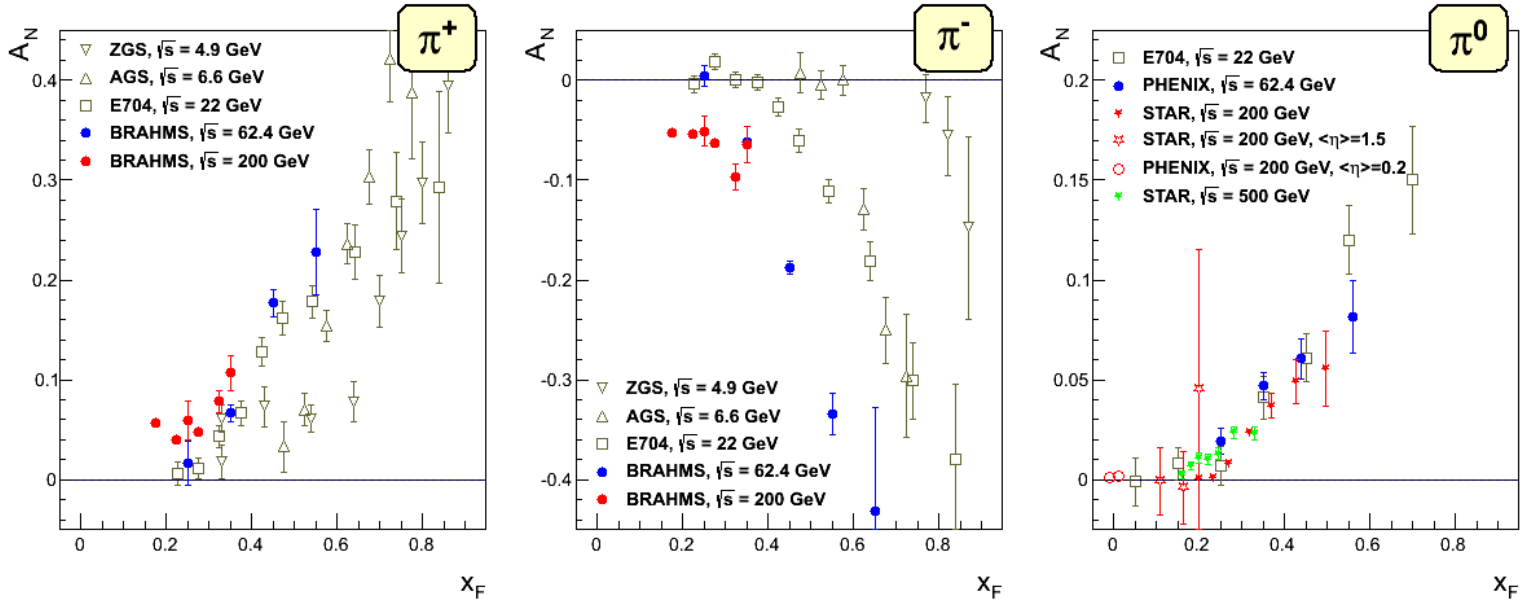
Transverse Spin Effects



$$s_z = \pm\frac{1}{2}\hbar \Rightarrow P = \frac{n^{\uparrow} - n^{\downarrow}}{n^{\uparrow} + n^{\downarrow}}$$

$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$

$$\varepsilon = A_N \cdot P = \frac{N_L - N_R}{N_L + N_R}$$



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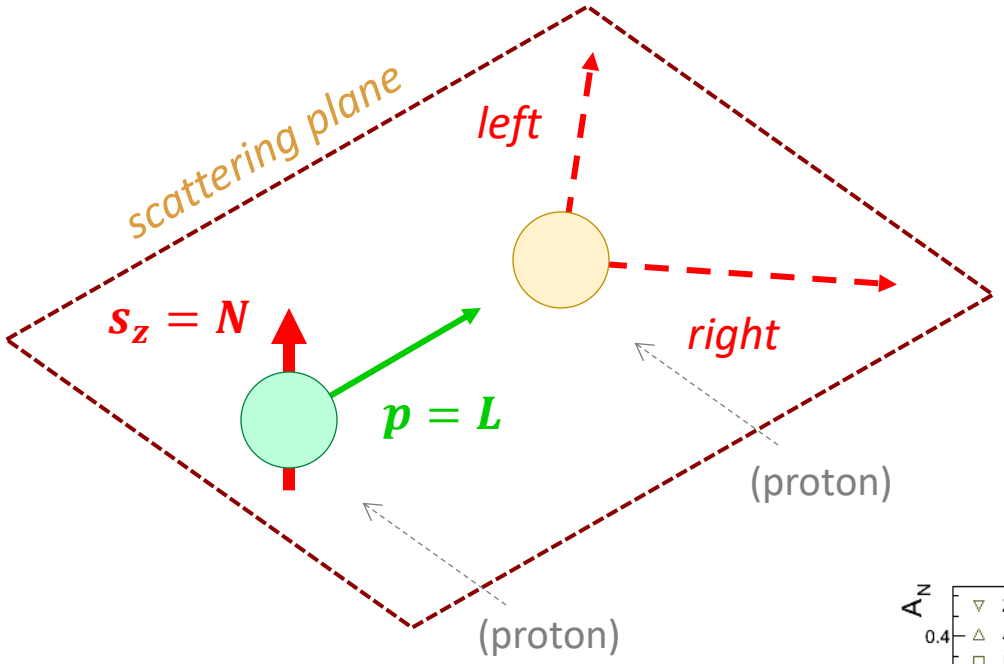
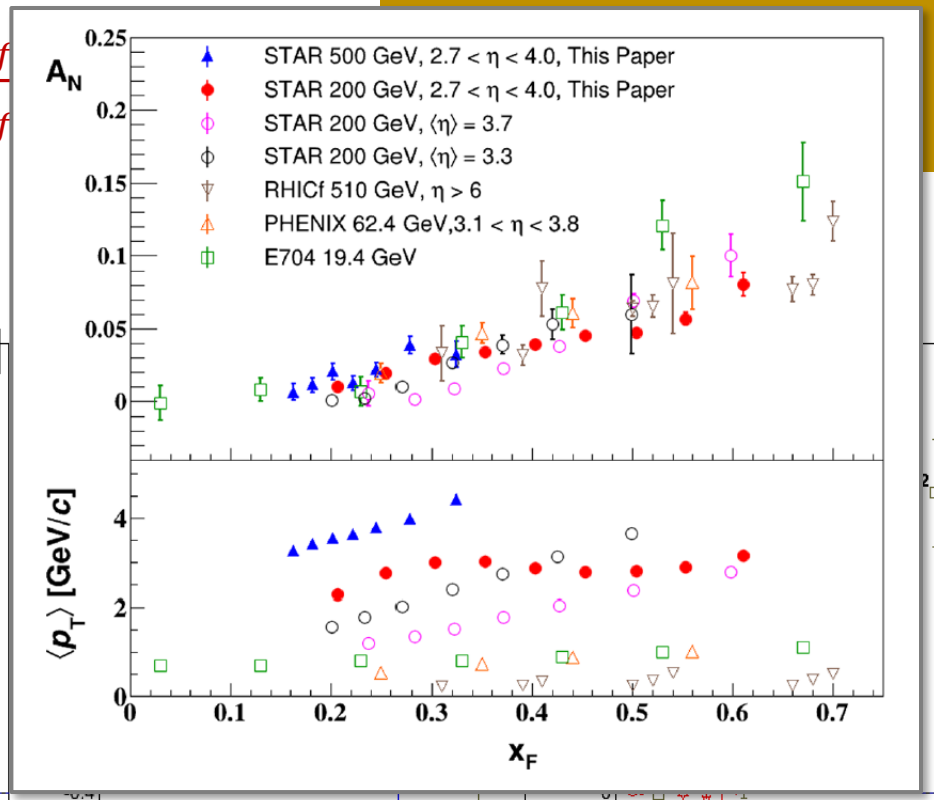


$$s_z = \pm\frac{1}{2}\hbar \Rightarrow P = \frac{n^{\uparrow} - n^{\downarrow}}{n^{\uparrow} + n^{\downarrow}}$$

$$A_N = \frac{d\sigma_{lef}}{d\sigma_{lef}}$$

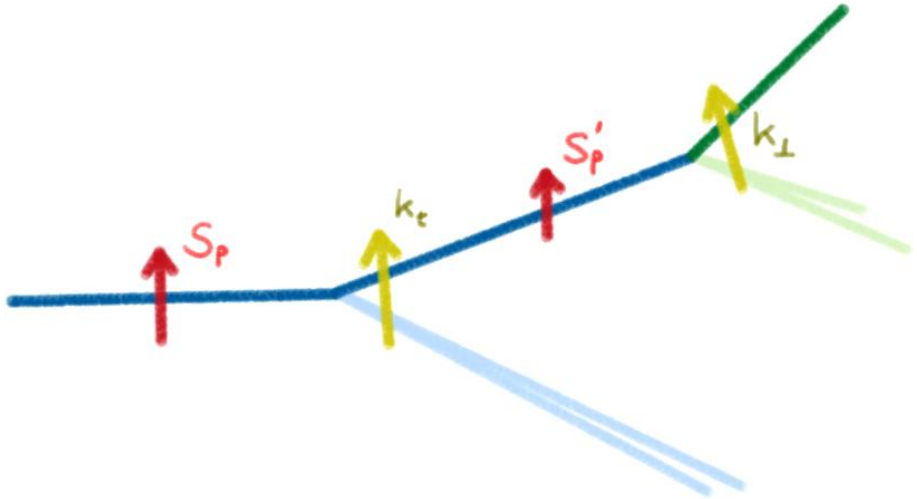


Polarization Effects in Nucleons / Partons

- Leading twist **transverse momentum dependent (TMD)** parton distribution functions

nucleon	quark: U	quark: L	quark: T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

hadron	quark: U	quark: L	quark: T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$H_{1T}^\perp$	G_{1T}	$H_1, H_{1T}^\perp$



$f_{1T}^\perp \otimes f_1 \otimes D_1$

$h_1 \otimes h_1^\perp \otimes D_1$

$h_{1T}^\perp \otimes h_1^\perp \otimes D_1$

$h_1 \otimes f_1 \otimes H_1^\perp$

$f_{1T}^\perp \otimes h_1^\perp \otimes H_1^\perp$

$h_{1T}^\perp \otimes f_1 \otimes H_1^\perp$

polarized initial state

polarized final state

Initial and Final State Effects

Sivers function $f_{1T}^{\perp}$	$\cos\phi_S$	$W^{\pm}$, Z^0, Drell-Yan γ^*
quark transversity h_1		
$\otimes$ Collins fragmentation function $H_1^{\perp}$	$\cos(\phi_S - \phi_h)$	hadrons in jets
$\otimes$ interference fragmentation $H_1^{\sphericalangle}$	$\cos\phi_R$	hadron pairs
gluon linear polarization h_1^g		
$\otimes$ Collins-like fragmentation $H_1^{\perp,g}$	$\cos(\phi_S - 2\phi_h)$	hadrons in jets
quark-gluon correlator $T_{q,F}$	$\cos\phi_S$	jets, hadrons, γ_{direct}
gluon-gluon correlator T_G	$\cos\phi_S$	heavy flavor

Initial and Final State Effects

Sivers function $f_{1T}^{\perp}$

quark transversity h

⊗ Collins fragme

⊗ interference f

gluon linear polariz

⊗ Collins-like fra

quark-gluon correla

gluon-gluon correla

-Yan γ^*

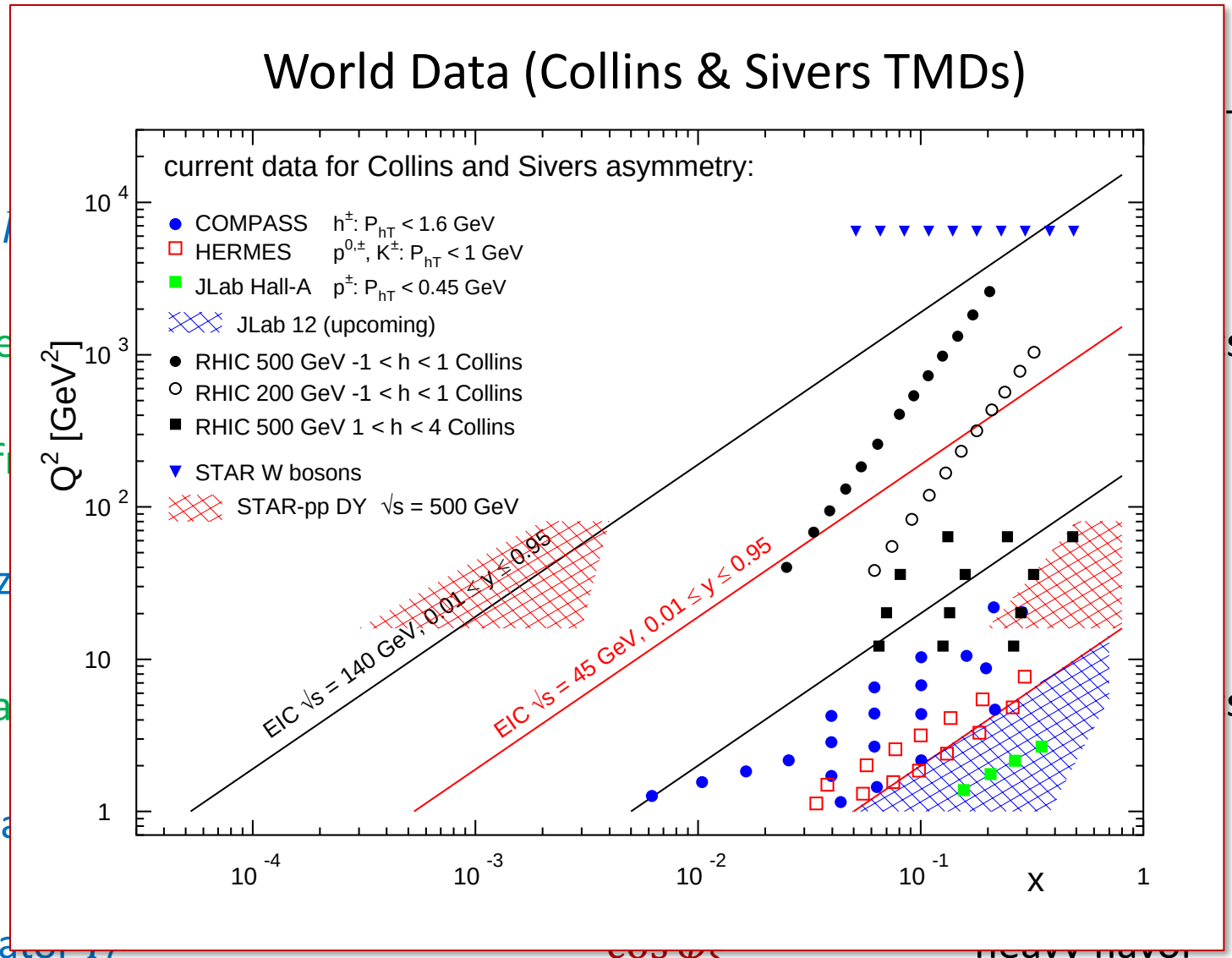
s

s

γ_{direct}

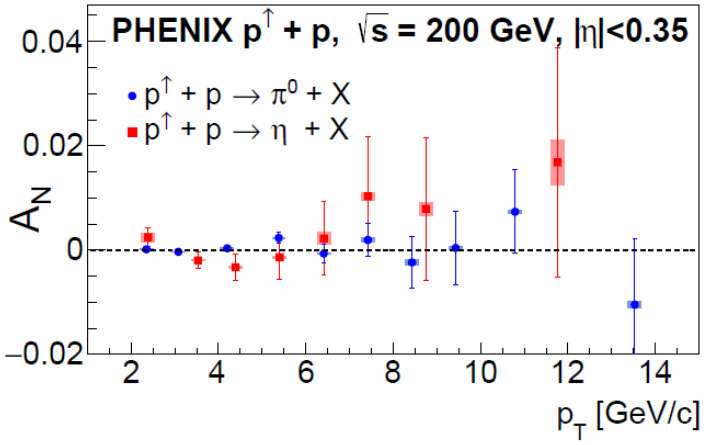
$\cos\phi_S$

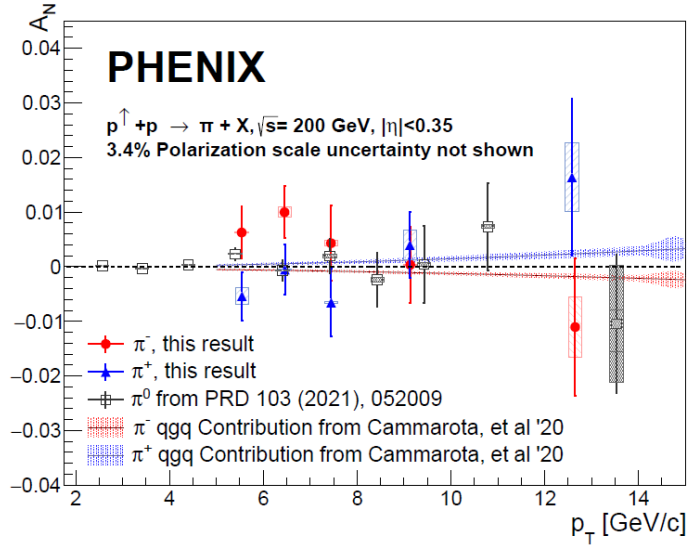
heavy flavor

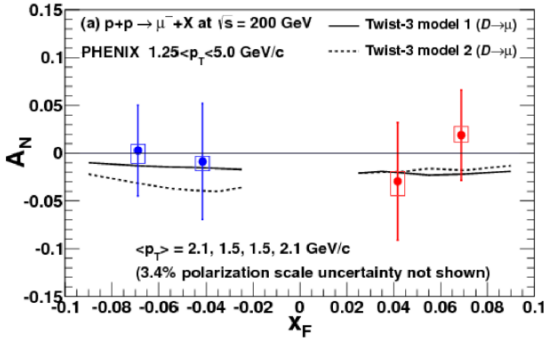


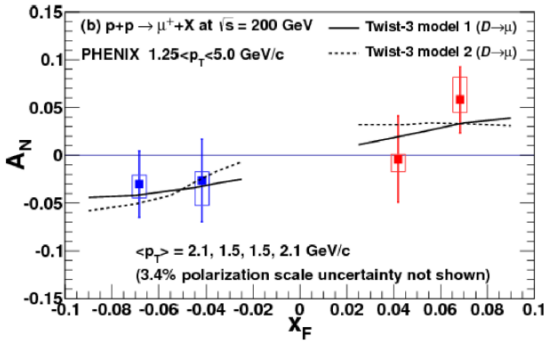
Inclusive Measurements

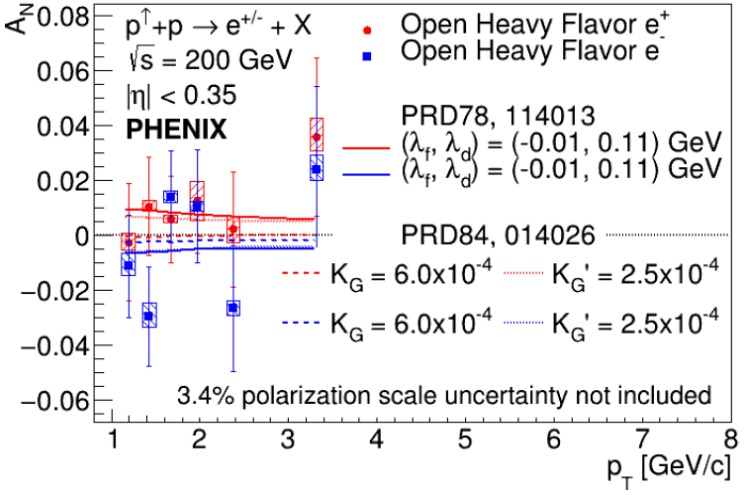
- $\vec{p}+p, \vec{p}+Al, \vec{p}+Au$ - $\sqrt{s_{NN}} = 200$ GeV
- Sensitive to gluon $T_G^{(f,d)}$
- Midrapidity pions:
  - very high precision, consistent with zero
  - charged pions limited by trigger efficiency
  - Phys. Rev. D103 (2018) 052009
  - Phys. Rev. D103 (2021) 052009
  - Phys. Rev. D105 (2022) 032003
  - Indication of charge dependence
- Heavy flavor
  - inclusive muons, $1.2 < \eta < 2.2$
  - midrapidity electrons
  - Phys. Rev. D95 (2017)112001
  - arxiv:2204.12899





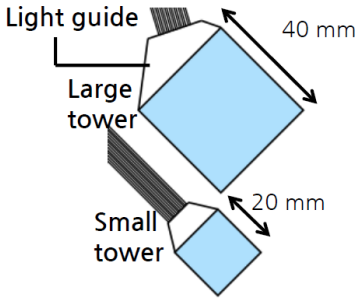


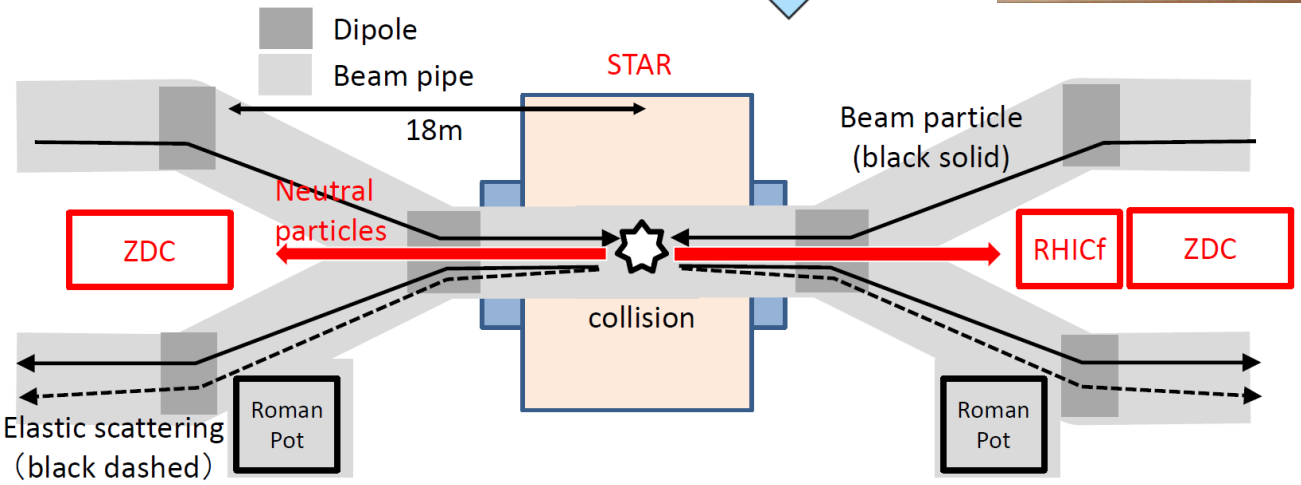




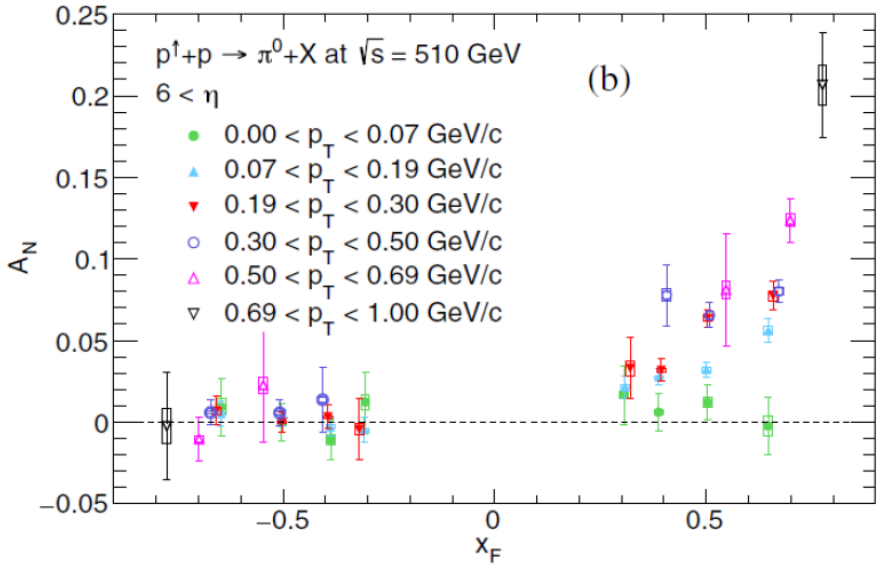
RHICf Experiment

- Longitudinally segmented calorimeter for n, γ, and π^0 reconstruction
- $\eta > 6.0$, $\sqrt{s} = 510$ GeV
- Low luminosity with radial polarization
- On-going analysis in combination with other STAR detectors

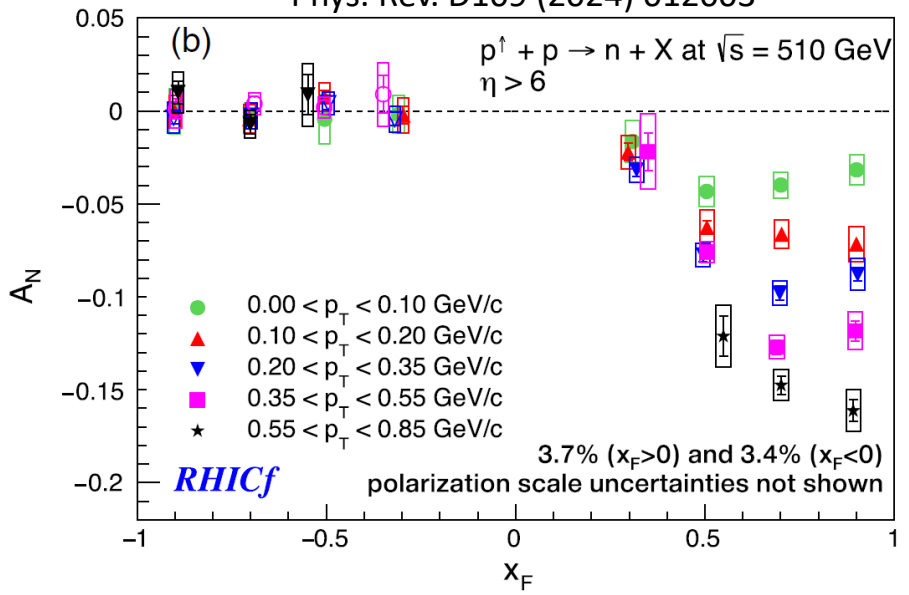




Phys. Rev. Lett. 124 (2020) 252501



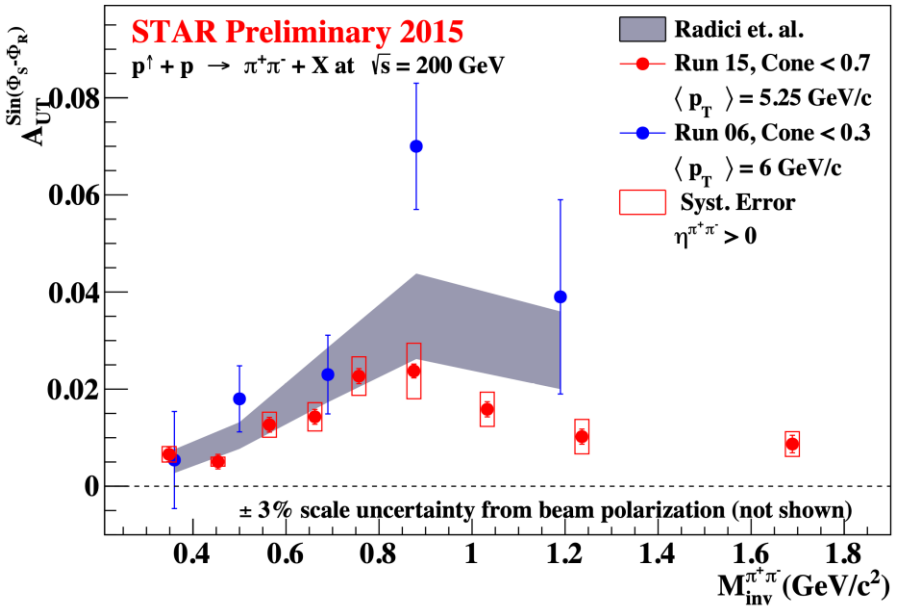
Phys. Rev. D109 (2024) 012003

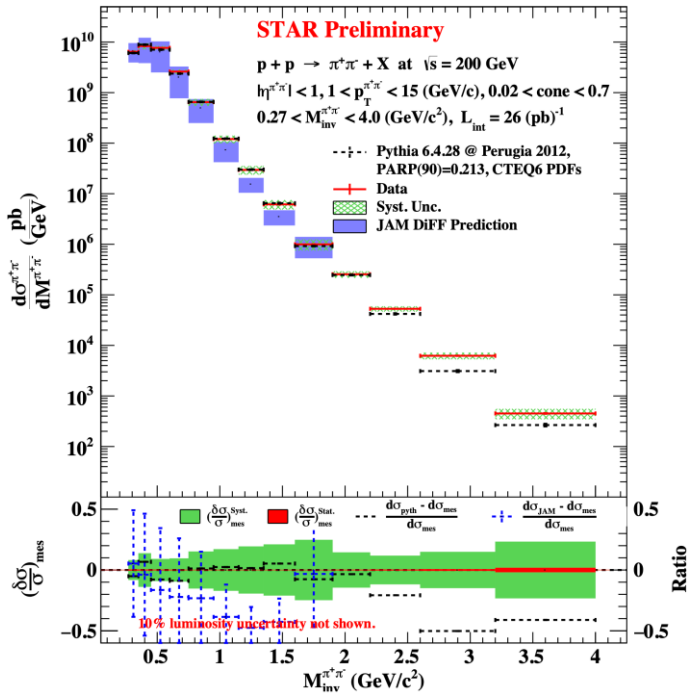


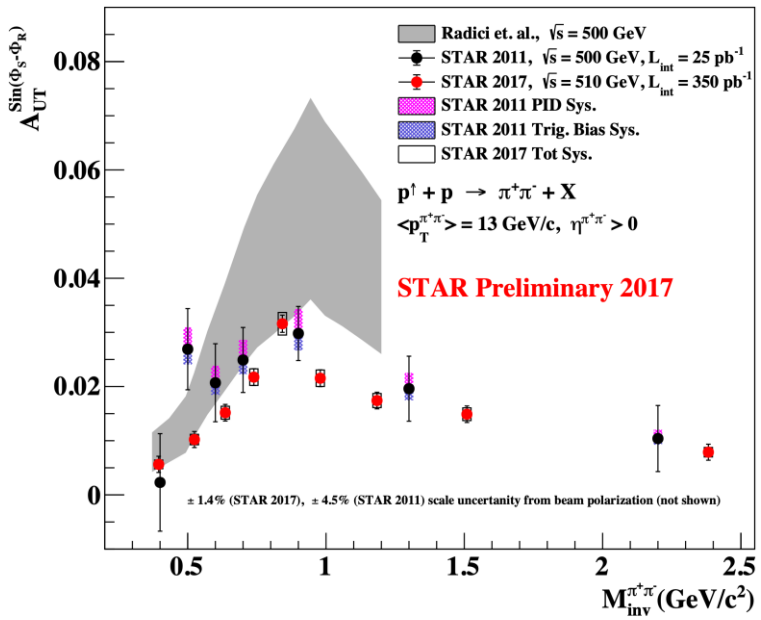
Interference Fragmentation Functions

- Dipion correlation at mid-rapidity
- Improved statistics at 200 and 510 GeV
- Measurement of cross section (200 GeV) for model-independent extraction of transversity

$$A_{UT} \propto \frac{h_1^a(x) \otimes H_1^{\sphericalangle}(z, M_h^2)}{f_1^a \otimes D_1}$$







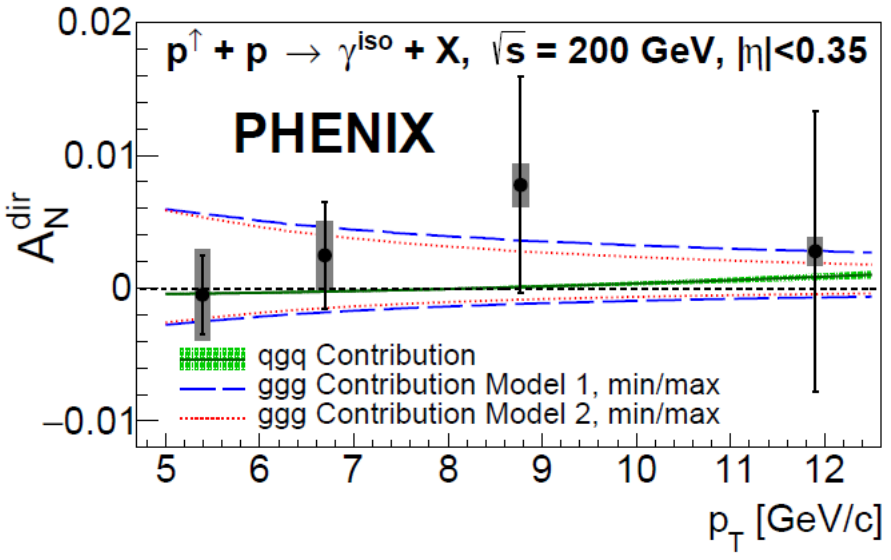
Direct Photons

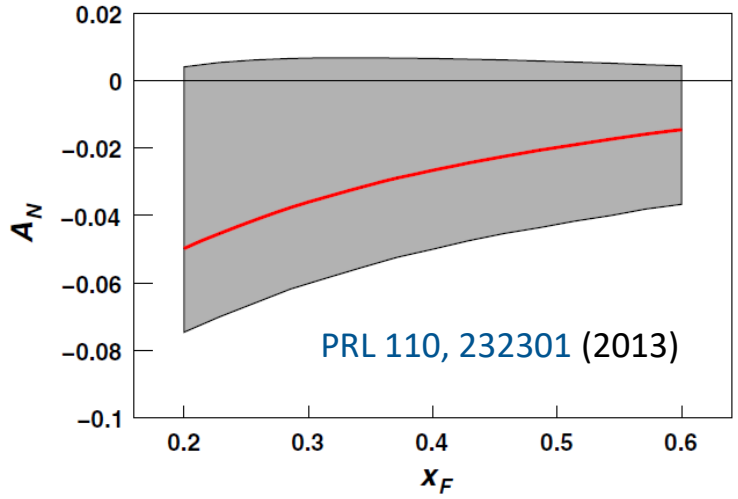
- First measurement from PHENIX
- Constrains twist-3 ETQS function
  - Dominated by ggg correlator
  - Small contribution from qgq correlators
  - Related to Sivers-TMD
- Larger asymmetries expected at forward rapidity

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

$f_{1T}^{\perp q}$: Sivers TMD function
$T_{q,F}$: Efremov-Teryaev-Qiu-Sterman correlator

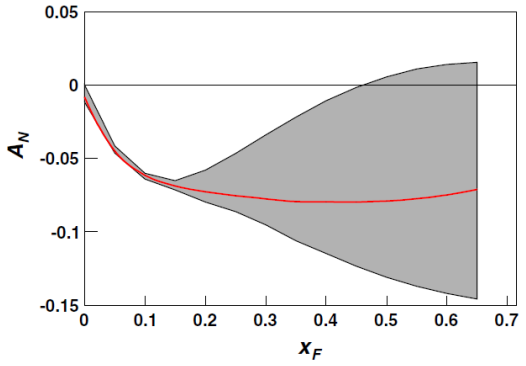
Phys. Rev. Lett. 127 (2021) 162001

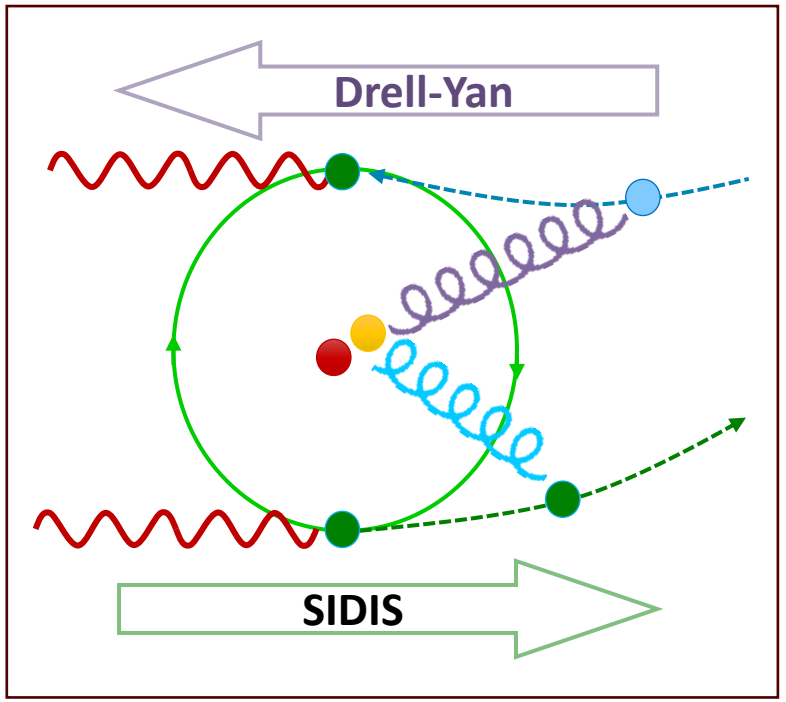




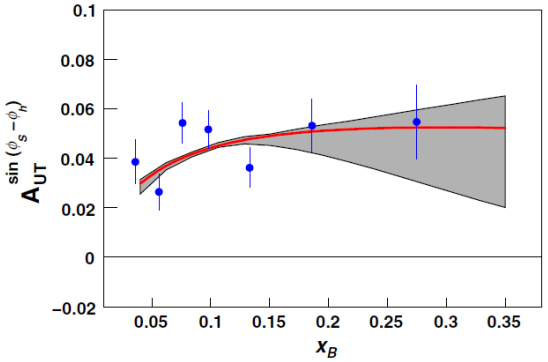
Fundamental Test of QCD Framework

- Test universality of Sivers effect
- SIDIS vs. Drell-Yan

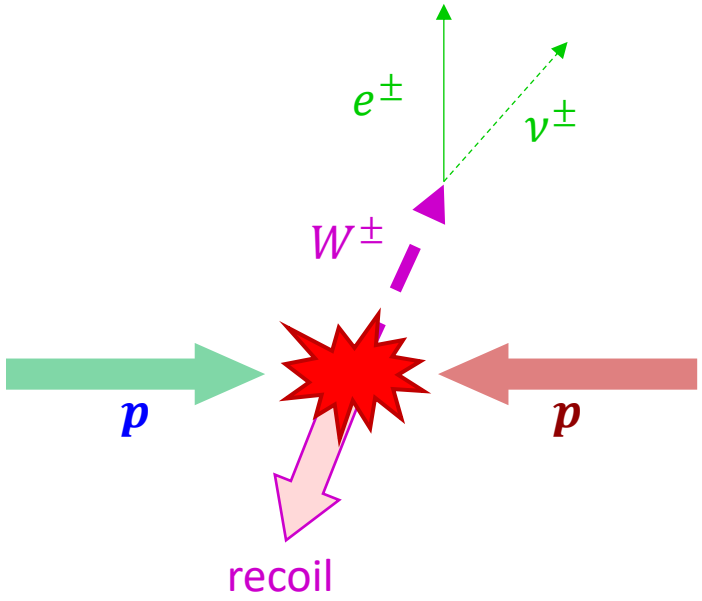


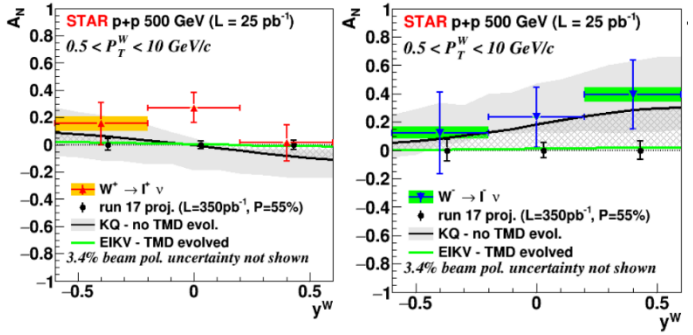


Gamberg, Kang, Prokudin
PRL 110, 232301 (2013)
with HERMES data



- Proof-of-principle of W-boson reconstruction at STAR



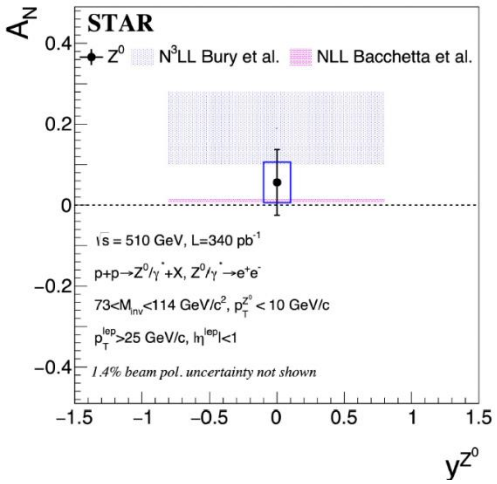


W-Boson Production in $p^{\uparrow} + p$

- Test of universality of Sivers effect
- W-boson decay
  - $p_{T,W}$ is lost
  - Almost no azimuthal angle correlation
- Measure recoil from the collision (tracks and EMC)

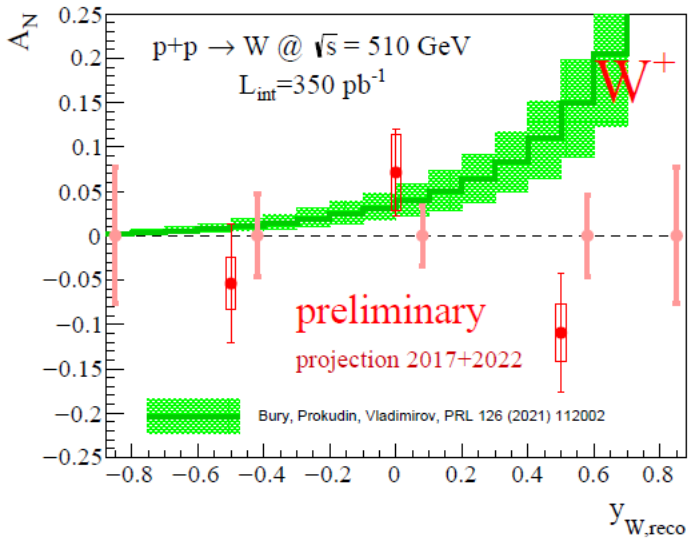
$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$

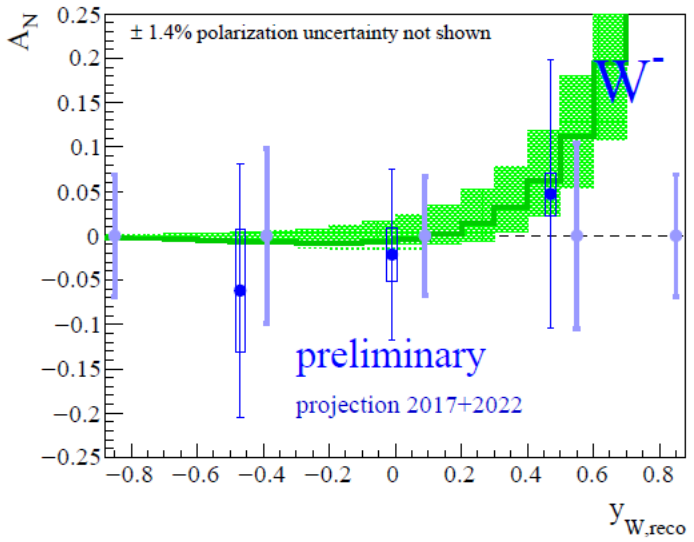
$$p_{T,recoil} = \sum(p_{T,TPC} + E_{T,EMC})$$

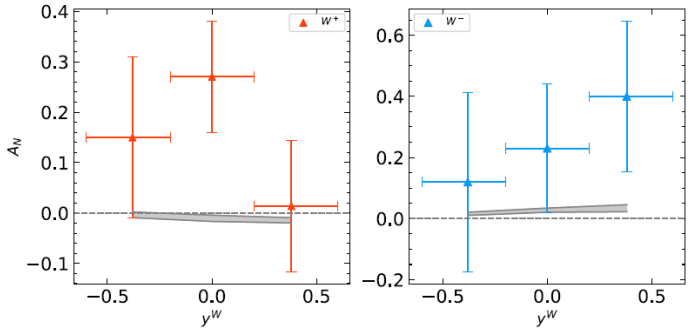


Z^0-boson

Phys. Lett. B854 (2024) 138715





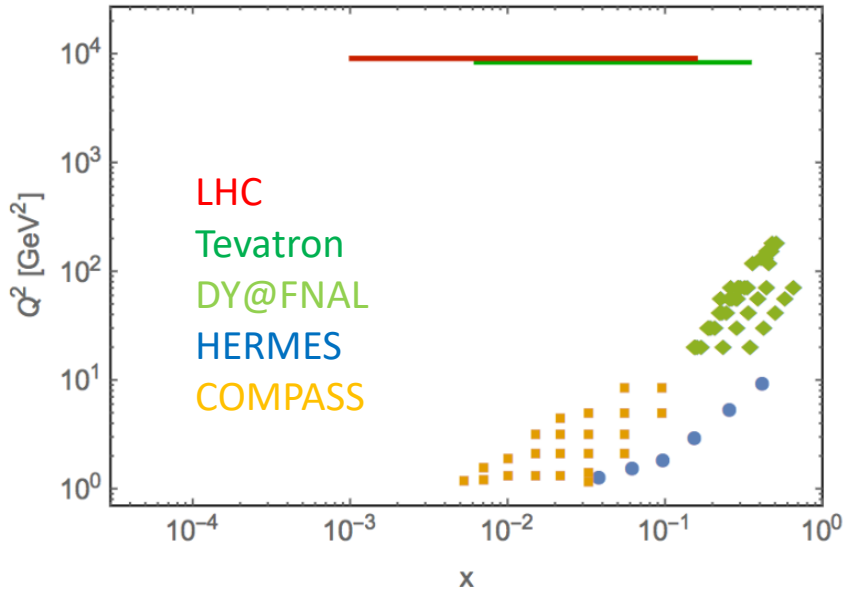


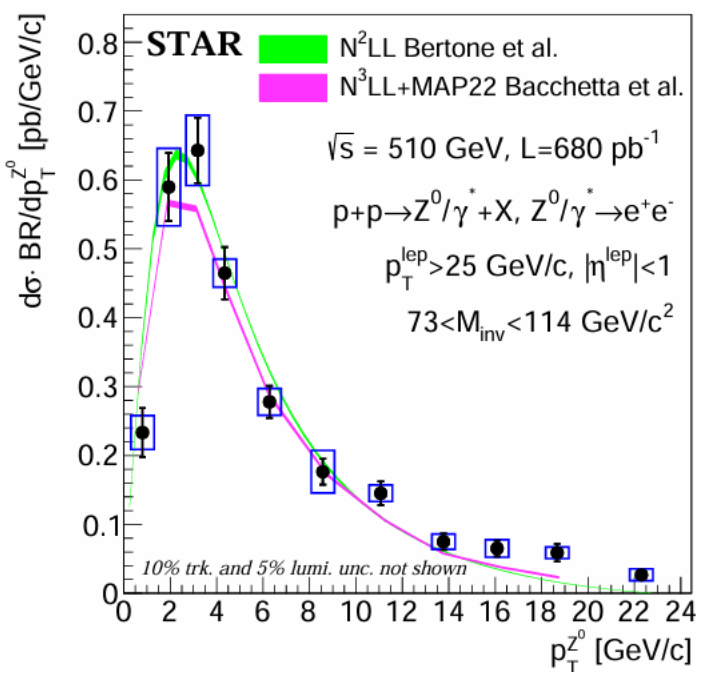
Bacchetta et al.,
Phys. Lett. B 827 (2022) 136961
Comparison with PRL 116 (2016) 13201

Unpolarized TMDs

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

- Experimentally very clean
- Differential cross section input for global analyses
- STAR: $0.1 < x < 0.3$





JHEP 06 (2019) 028
JHEP 10 (2022) 127

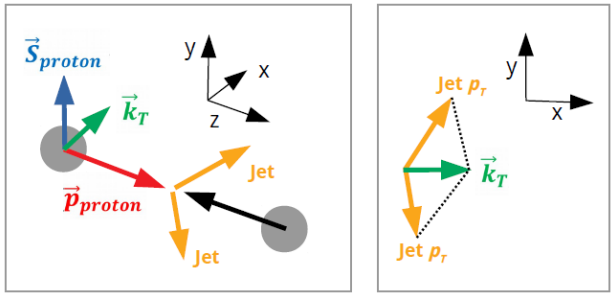
- Data from 2011-2017
- Unfolded p_T spectrum
- Systematics from energy resolution and electron selection
- Accepted for publication in PLB

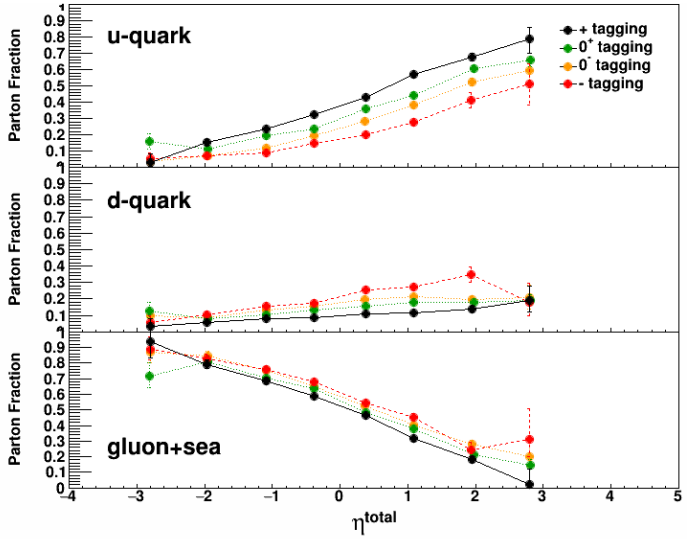
Sivers Asymmetries in Dijets

- Correlation between proton spin and parton k_T

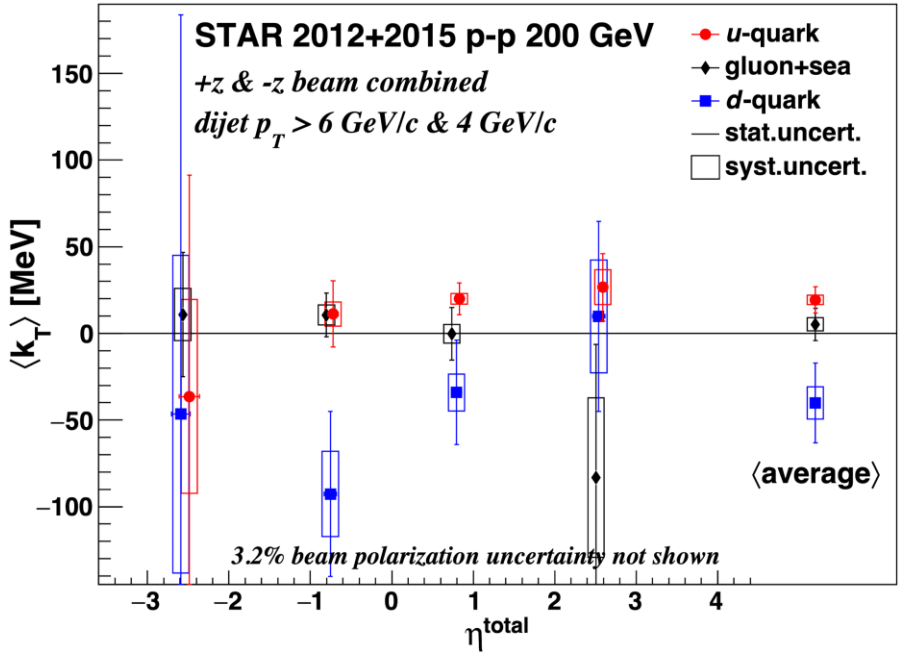
$$\left\langle \vec{S} \cdot (\vec{p} \times \vec{k}_T) \right\rangle \neq 0$$

- Enhance quark flavor with charge tagging
  - Track p_T weighted charge
  - Unfolded to parton $\langle k_T \rangle$
- More data on disk, $\sqrt{s} = 510$ GeV





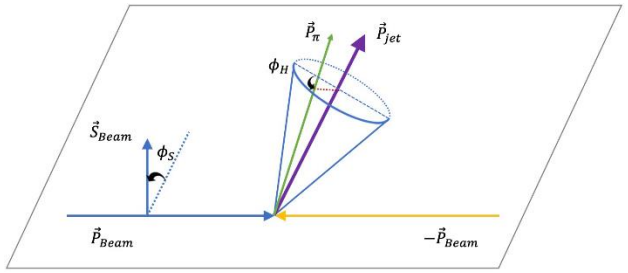
$\sqrt{s} = 200$ GeV, arxiv:2305.10359

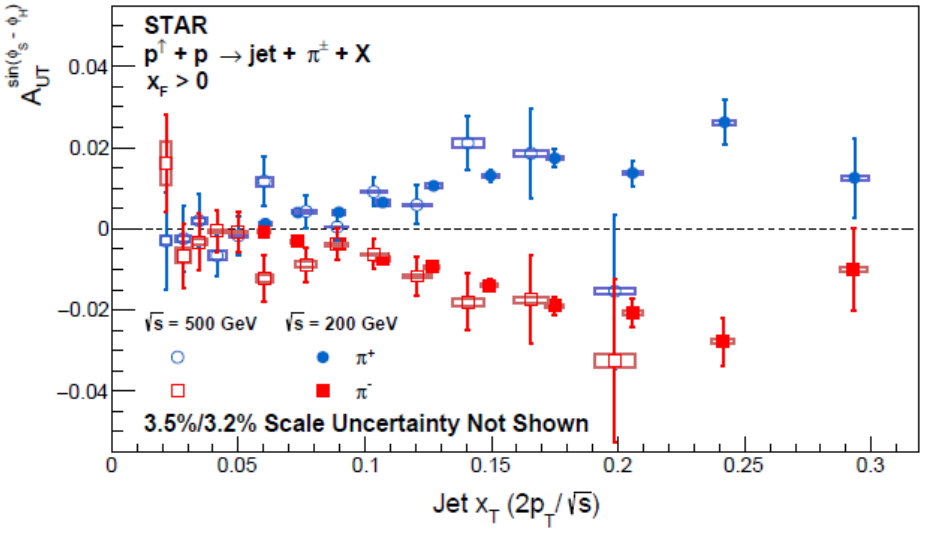


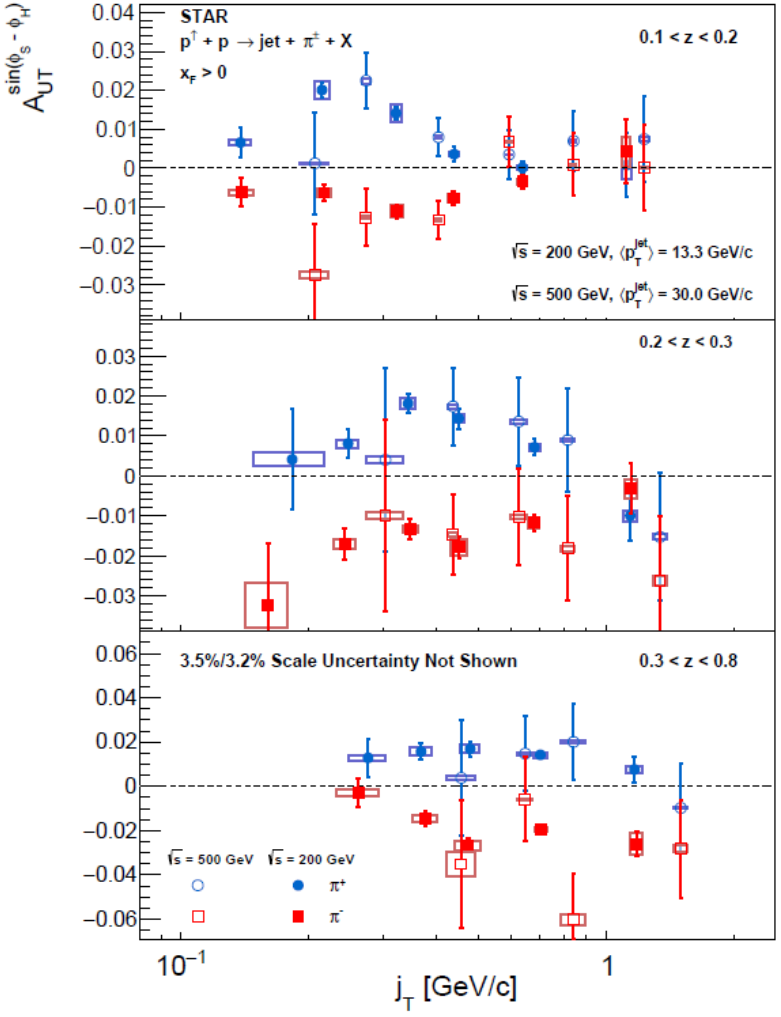
Hadrons in Jets

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

- Two scales for TMD measurement
  - p_T of jet
  - j_T of hadron in jet
- Phys. Rev. D **106**, 072010 (2022)
- Multidimensional binning
  p_T, j_T, z
- Separate asymmetries for
  $\pi^{\pm}, K^{\pm}, p/\bar{p}$
- More data on disk
  $\vec{p} + p, \vec{p} + A$

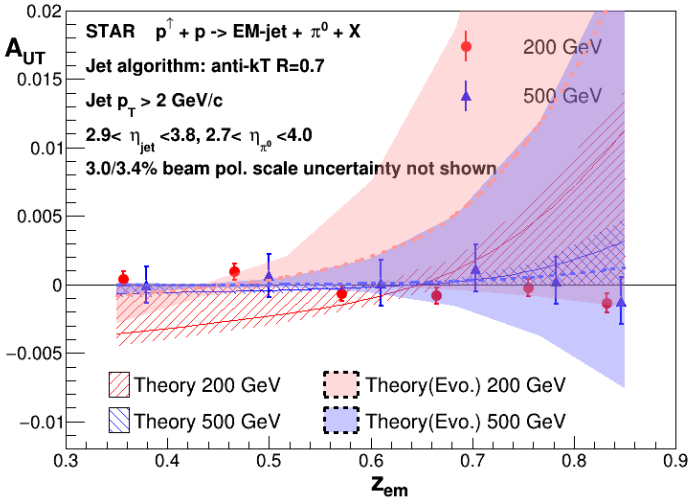




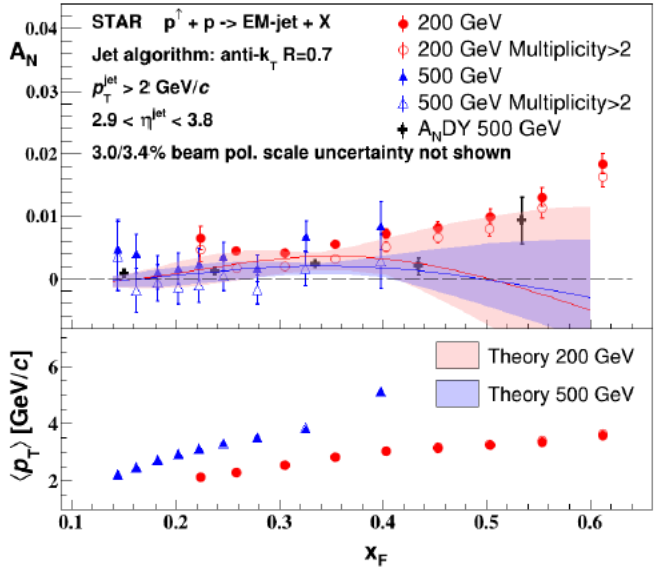


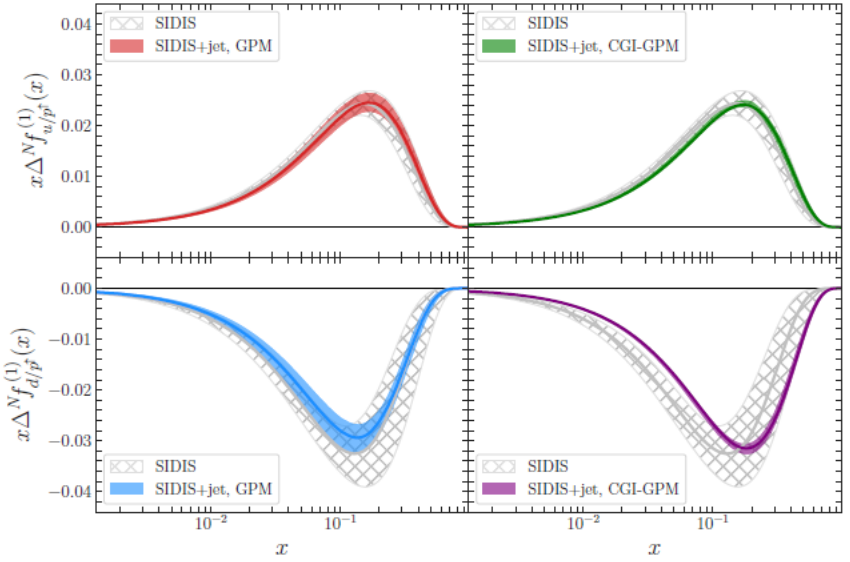
Transverse Spin at Forward Rapidities

- Electromagnetic jets with forward calorimeter
  - π^0 in jet
- $2.8 < \eta < 4.0$
- Phys. Rev. D103 (2021) 92009
- Collins asymmetries are very small.
- Jet asymmetries are small and consistent with previous results
- Significant impact on Sivers function in global fit:
  Phys. Lett. B 815, 136135 (2021)
- Studies of possible diffractive contributions to transverse spin asymmetries



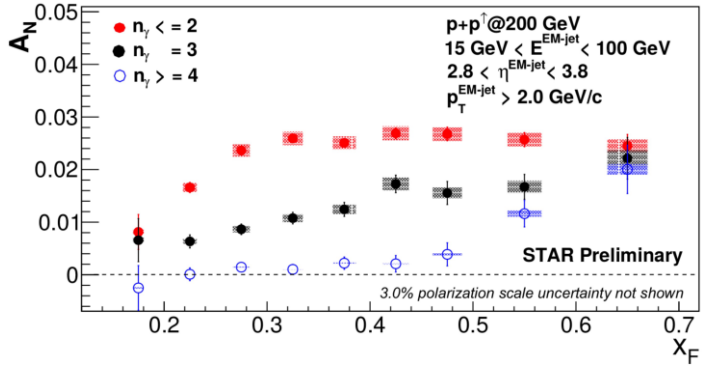
Comparison with
Z. Kang et al., PLB 774, 635 (2017)
L. Gamberg et al., PRL 110, 232301 (2013)
J. Cammarota et al., arxiv:2002.08384



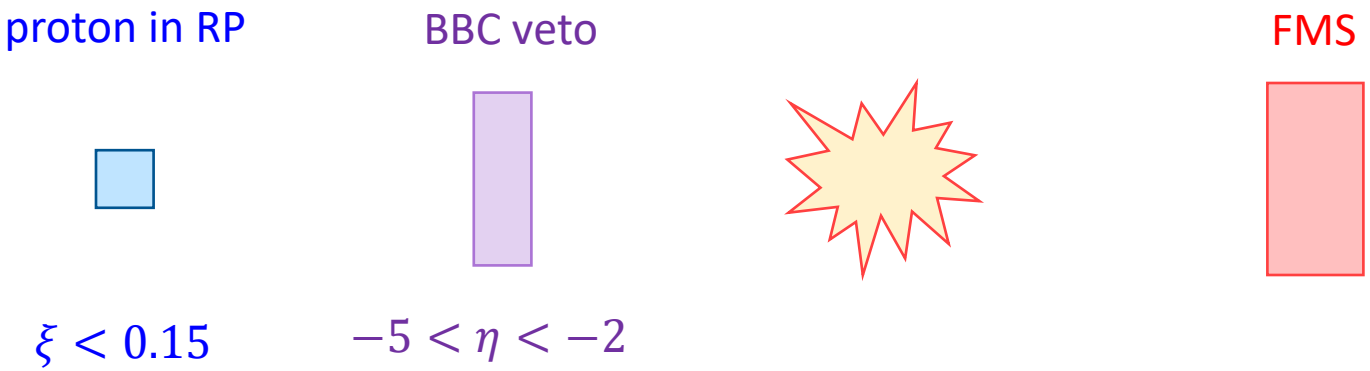


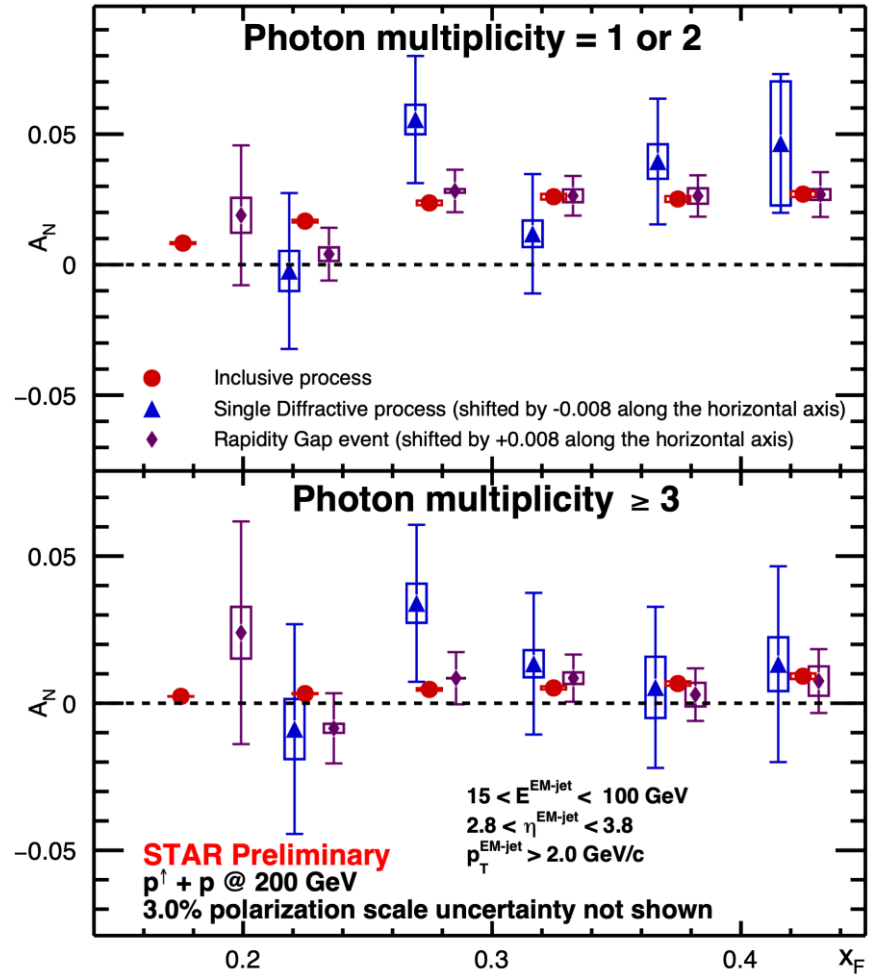
Transverse Spin in Diffractive Processes

- Strong multiplicity dependence of transverse spin asymmetry of em-jets at forward rapidities



- Can rapidity gap events provide more insight?
- STAR with Roman Pots in 2015 and 2017, $\sqrt{s} = 200$ GeV, 510 GeV





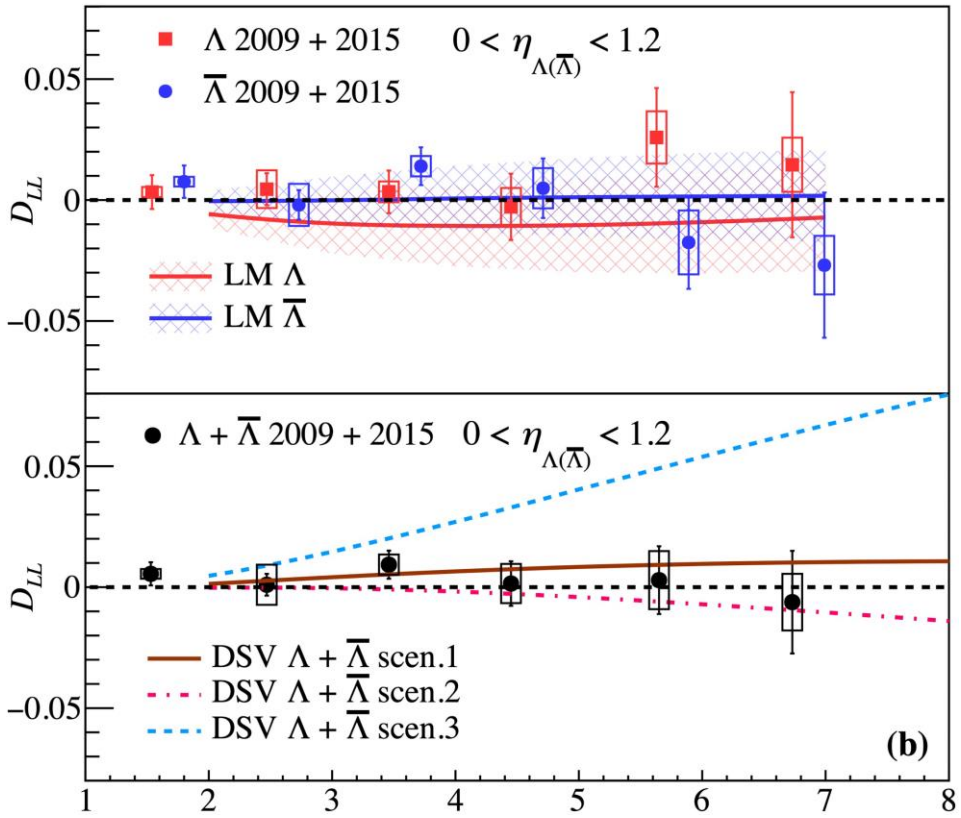
Λ Transverse Spin Transfer

$$D_{TT}^{\Lambda} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\delta\sigma^{\Lambda} = \sum\int dx_a dx_b dz \delta f_a(x_a) f_b(x_b) \delta\sigma(ab \to cd) \delta D^{\Lambda}(z)$$

- Access to s-quark transversity
- So far consistent with zero
- More data on disk

Phys. Rev. D109 (2024) 012004

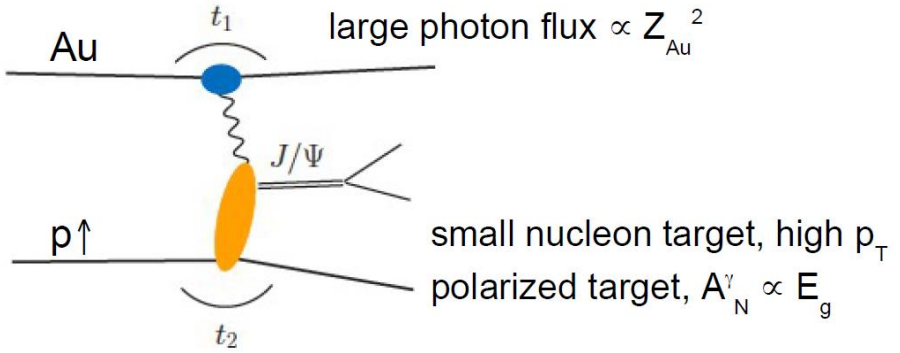


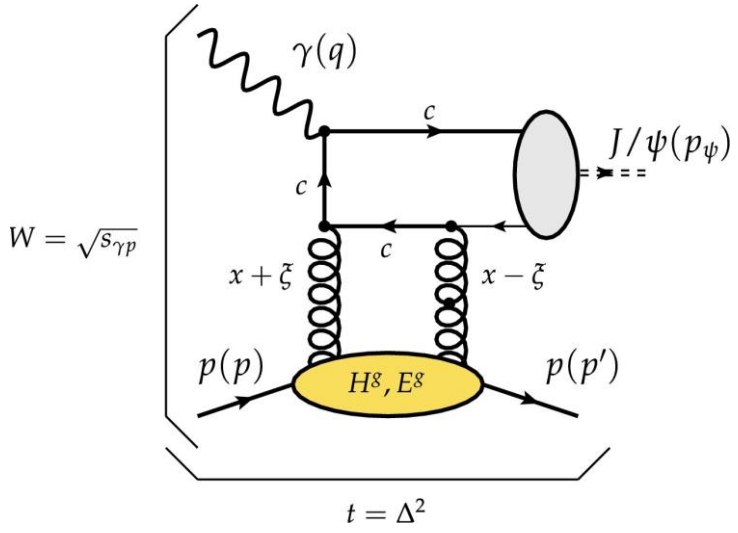
J/psi Production in UPC

- Photoproduction with polarized protons

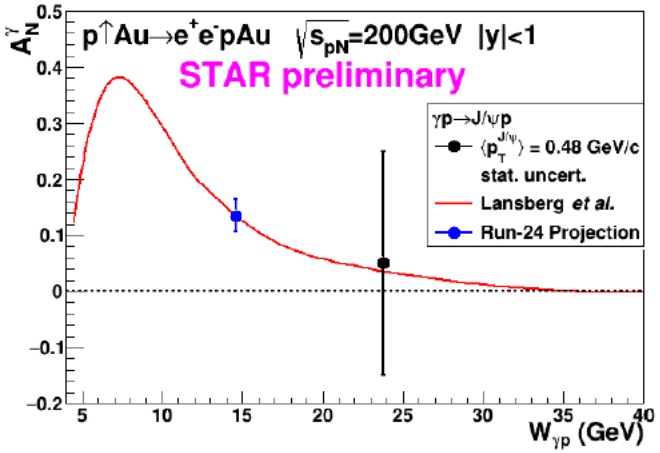
$$d\sigma/d\phi \propto 1 + A_N^{\gamma} \cos\phi$$

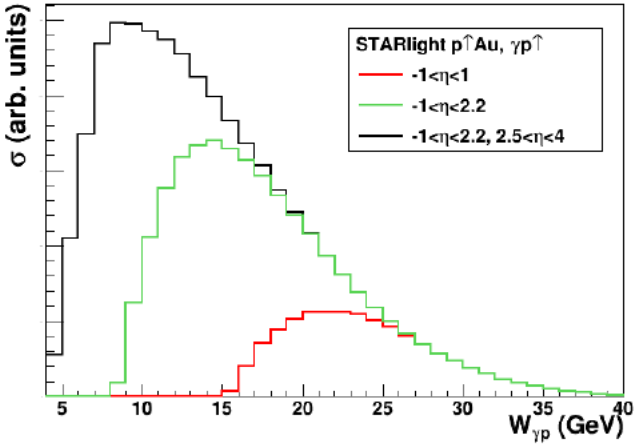
$$A_N^{\gamma} \propto p_T \frac{\mathrm{Im} H^g E^{g*}}{|H^g|^2}$$





Phys.Lett. B793 (2019) 33-40





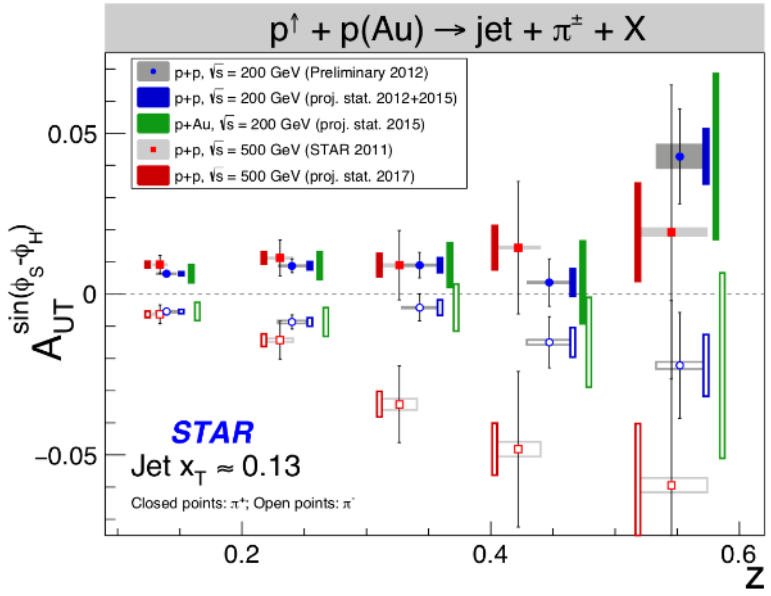
- Expect larger asymmetry at low $W_{\gamma p}$
- → higher $\sqrt{s}$ or forward rapidity

Future Measurements

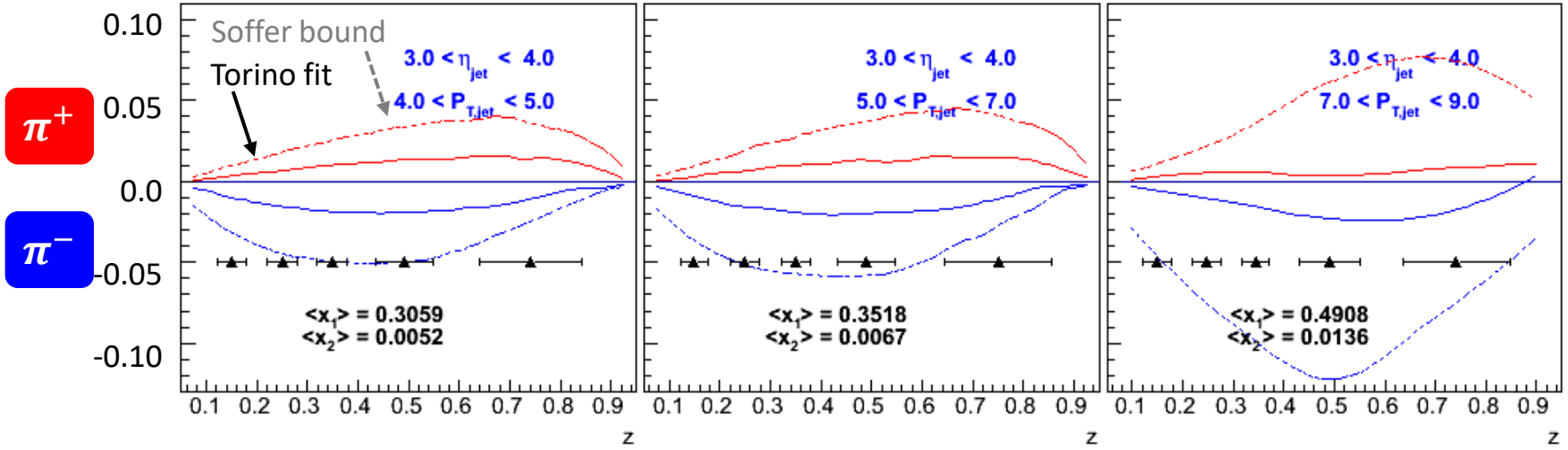
- Hadron in jet
  - STAR measured at midrapidity, 200 – 500 GeV
  - Move to higher x

$$\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$$

  - Multi-dimensional binning



$\sqrt{s} = 500$ GeV, 268 pb^{-1}sampled



Torino: Phys. Rev. D87 (2013) 094019 Soffer bound&transversity: Phys. Rev. Lett. 74 (1995) 1292

Future Measurements

- Suggested large spin dependent effects in quark fragmentation
  - Collinear quark-gluon-quark correlators

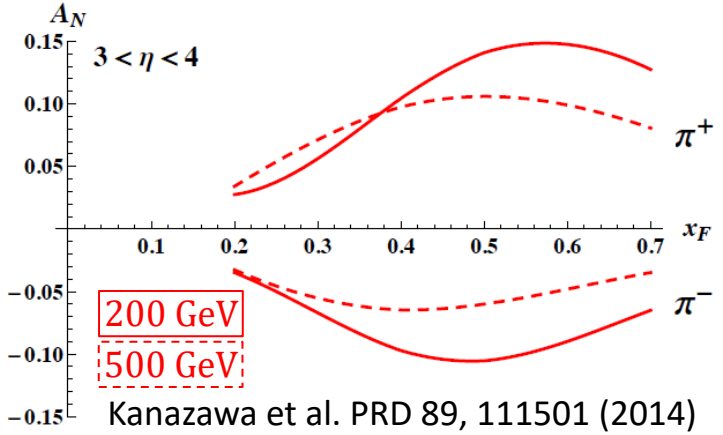
$$\widehat{H}_{FU}^{\Im}(z, z_z)$$

  - Flavor dependence
  - Evolution effects of ETQS distribution functions

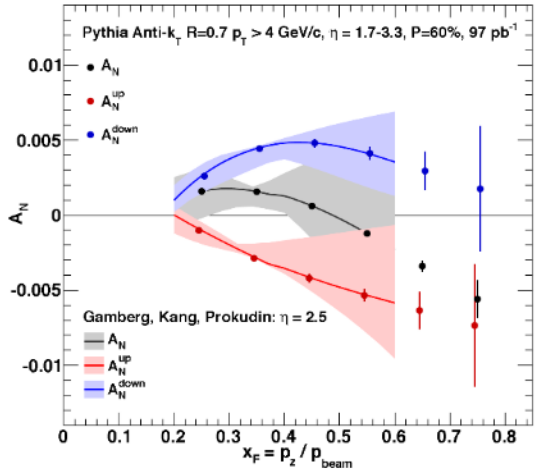
- Test origin of large transverse asymmetries
  - Compare direct photons and jets

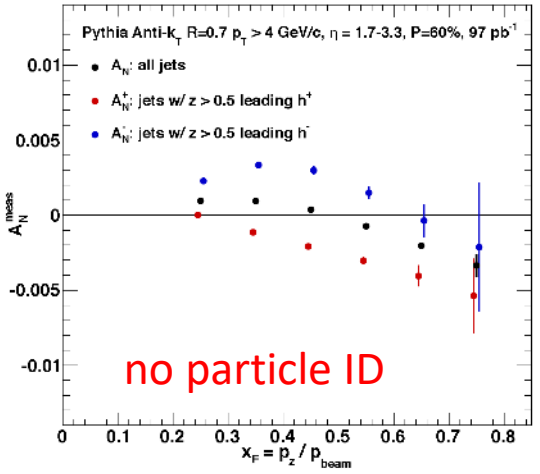
$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x, x)$$

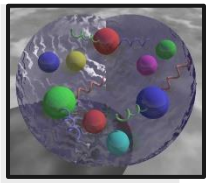
  - Cancellation of u & d quark Sivers
  - Bias from high-z charged pion



Kanazawa et al. PRD 89, 111501 (2014)

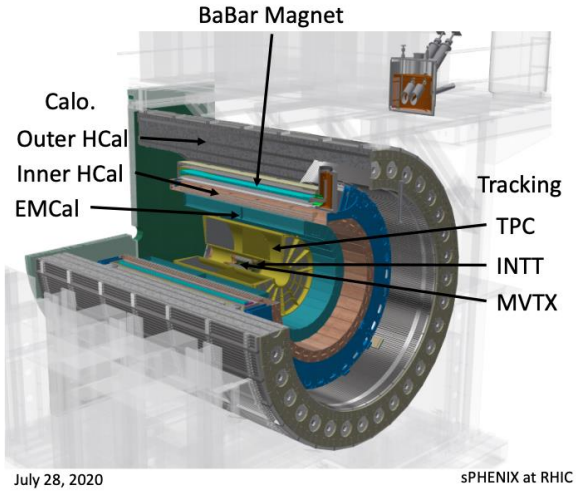


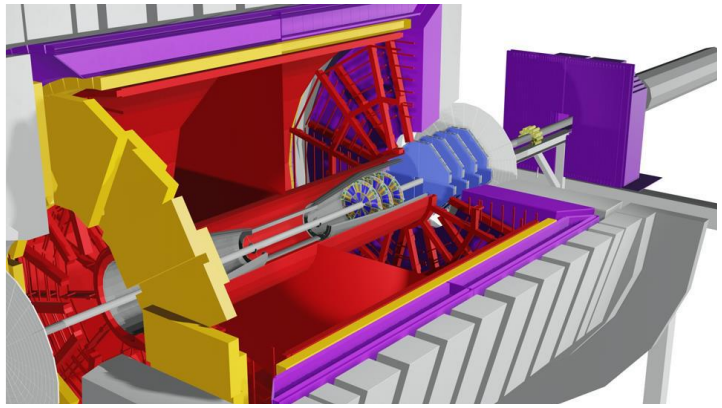




Summary

- RHIC data at mid- and forward rapidity has made significant impact on our understanding of
  - the gluon polarization,
  - the sea quark polarization, and
  - transverse spin effects.
- Many exciting results are expected to come from data already on disk (200 GeV, 508 GeV).
- Measurements are complementary to and will inform experimental requirements for the future EIC.





Շնորհակալություն