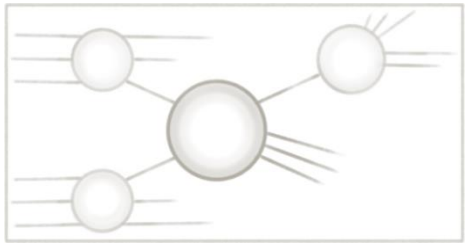
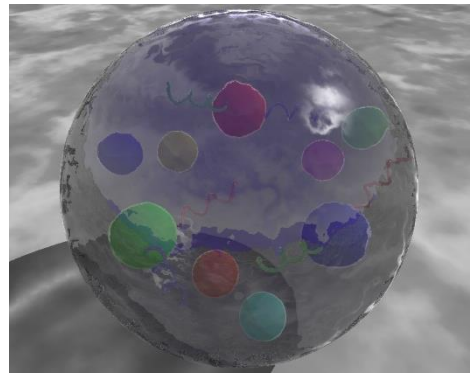
The RHIC Cold QCD Program

Recent Results & Future Prospects



Oleg Eyser

International Workshop on Hadron Structure and Spectroscopy



November 16-18, 2020

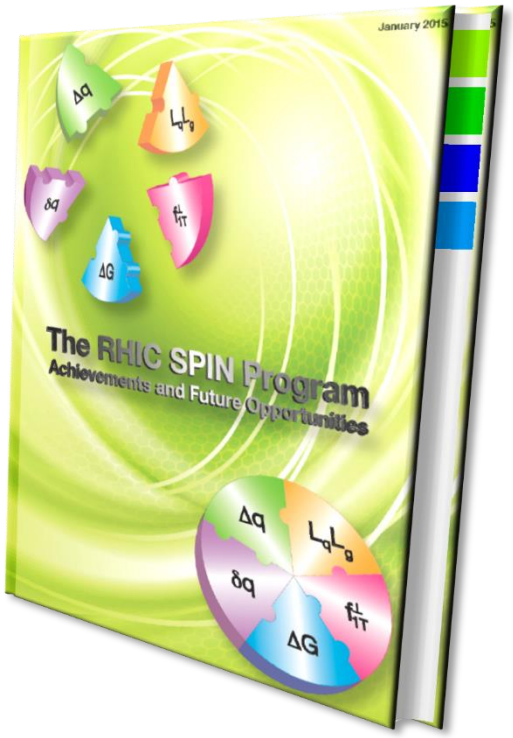
INFN Trieste (virtual)

BROOKHAVEN NATIONAL LABORATORY

The RHIC Cold QCD Program

- Gluon polarization
- Sea quark polarization
- Transverse spin effects

- What is the nature of the spin of the proton?
- How do gluons contribute to the proton spin?
- What is the landscape of the polarized sea in the nucleon?
- 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?
- What is the nature of the initial state in nuclear collisions?

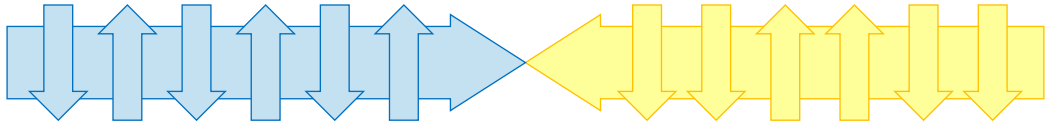


arxiv:1501.01220

arxiv:1602.03922

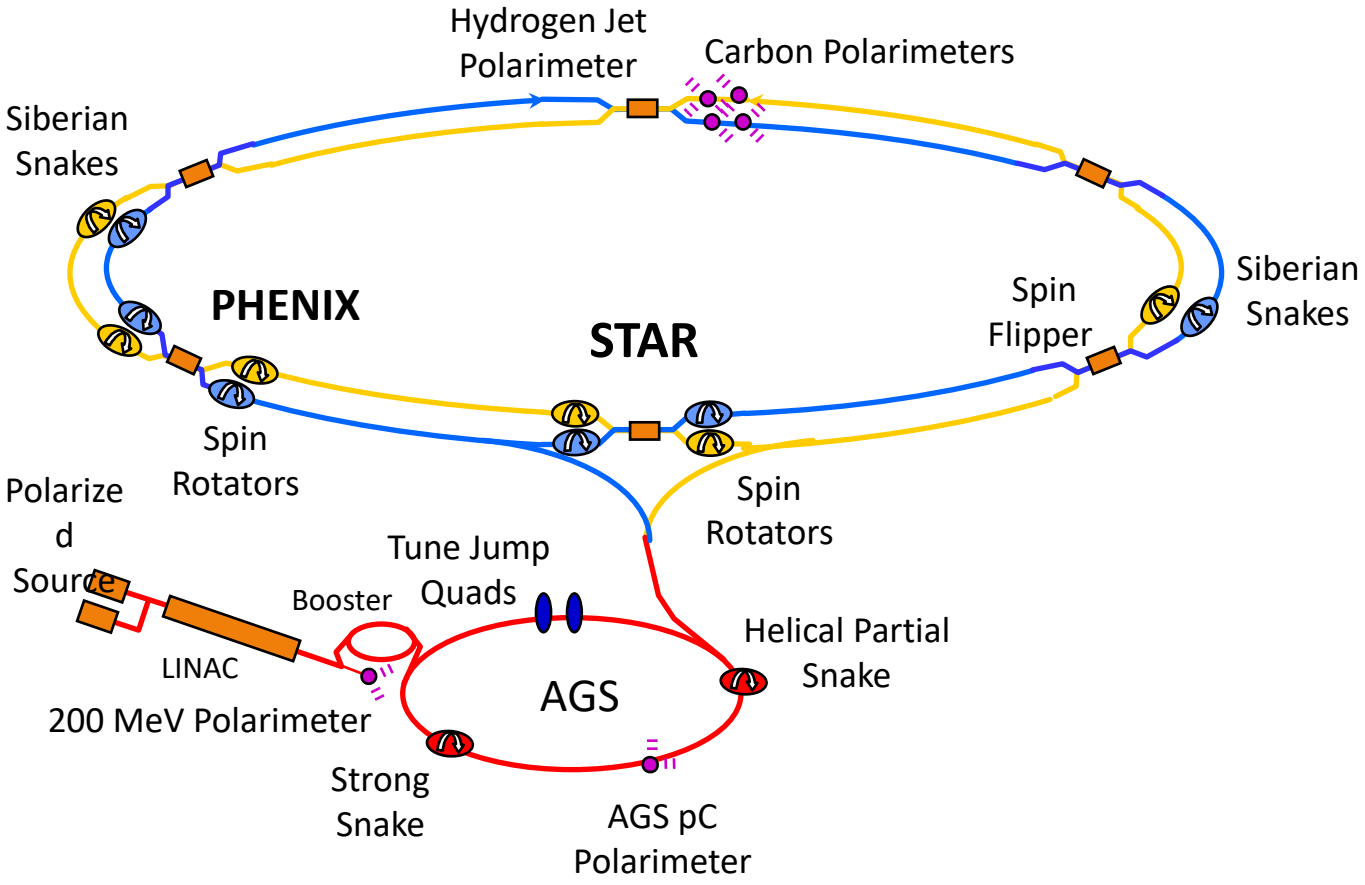

The Relativistic Heavy Ion Collider
at Brookhaven National Laboratory

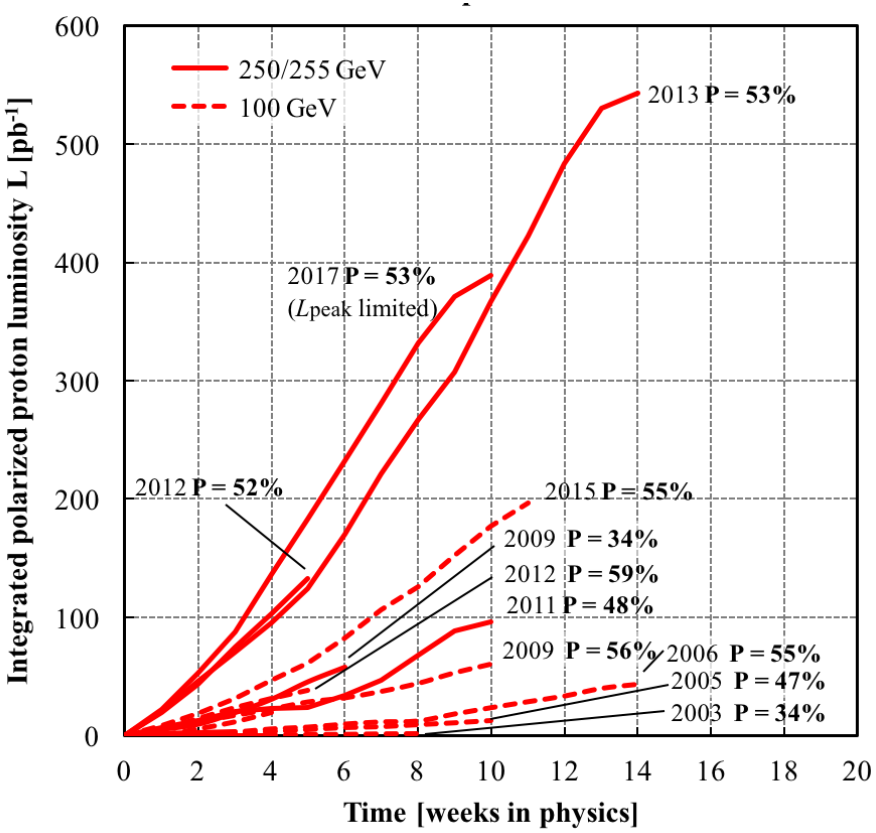
RHIC as a Polarized Proton Collider

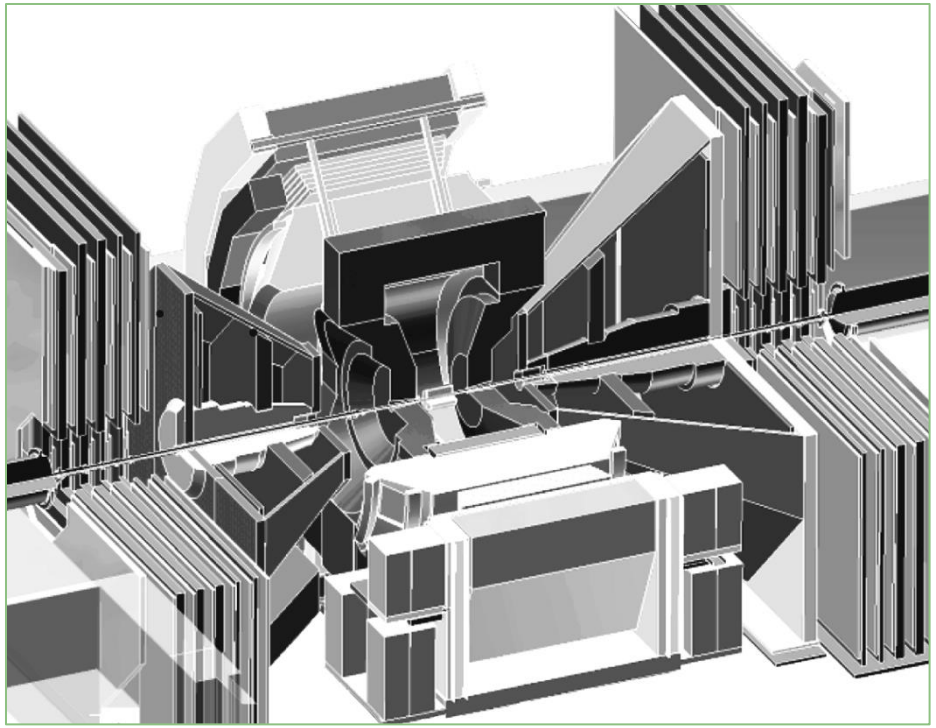


$\vec{p} + \vec{p}$ / $\vec{p} + A$

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







PHENIX

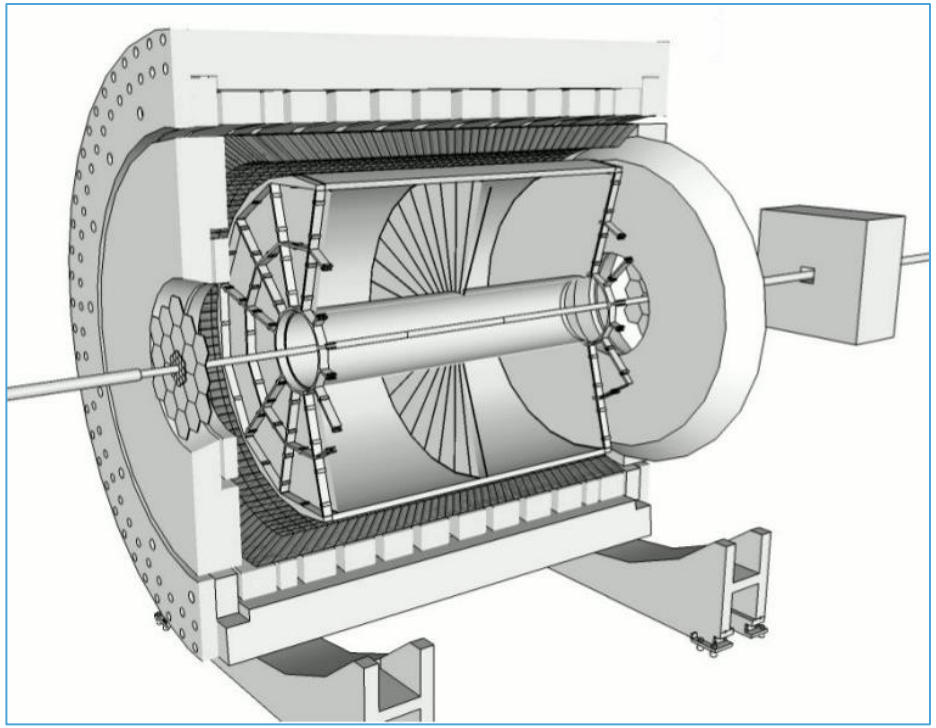
High resolution

High rate

DC / Pad Chambers / Muon Arms

EMCal

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



STAR

Large acceptance

$-1 < \eta < 2$

TPC+TOF

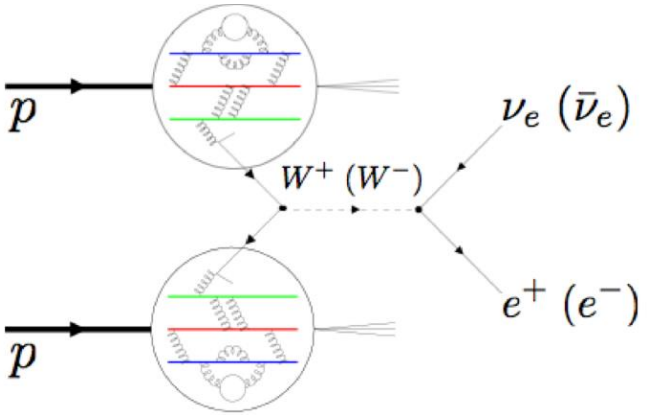
EMCal

Forward EMCal, $2.5 < \eta < 4$

Sea Quark Polarization

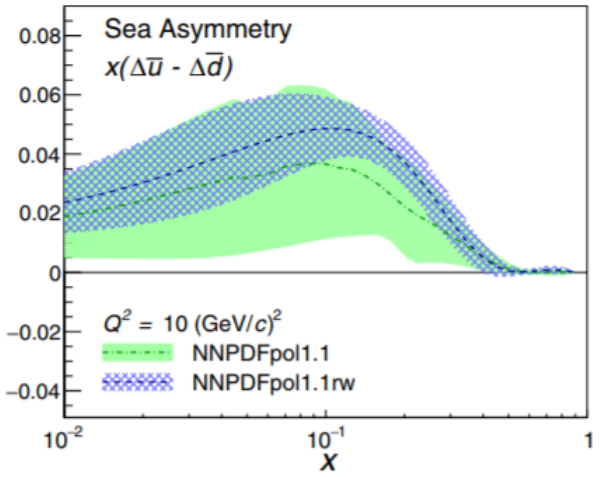
- Parity violating (single-spin) asymmetry

$$A_L(l^-) = \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$



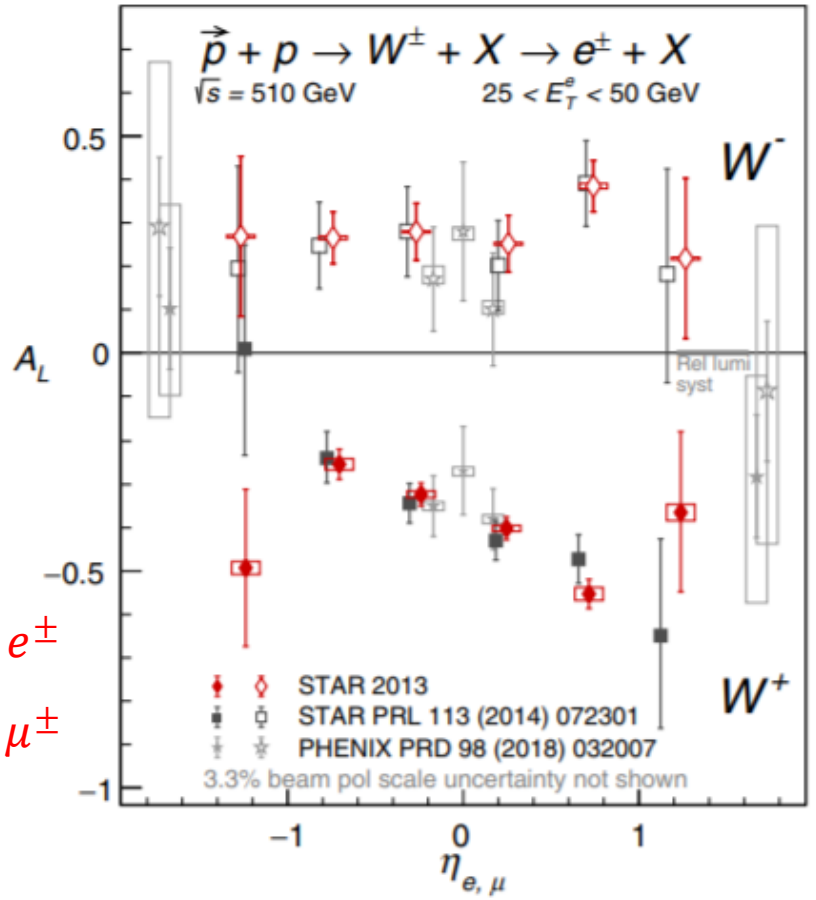
- Final results from the RHIC W-program (2009-2013)
  - PRD 99 (2019) 051102R
  - PRD 98 (2018) 032007

- Impact study in NNPDFpol1.1
  - arXiv:1702.05077



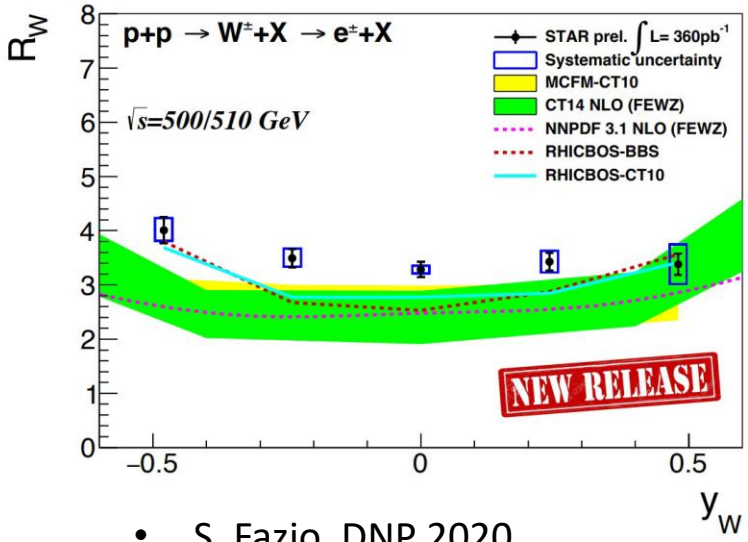
$p + p \rightarrow W^{\pm} \rightarrow e^{\pm}$

$p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm}$



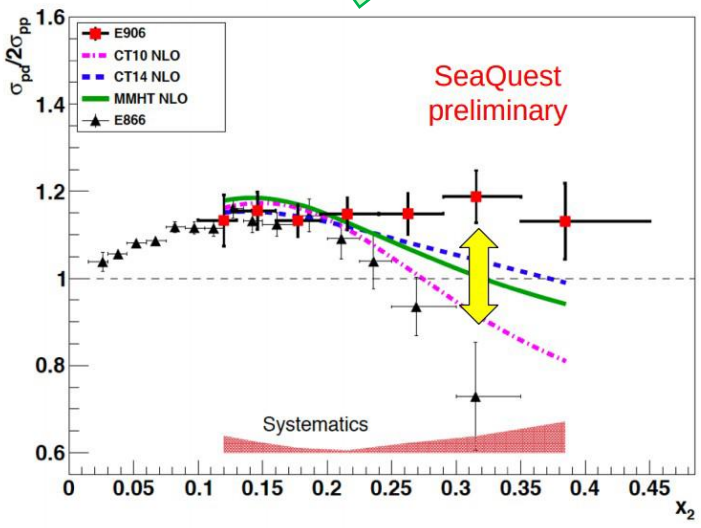
Flavor Composition of the Sea

$$R(x_F) = \frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

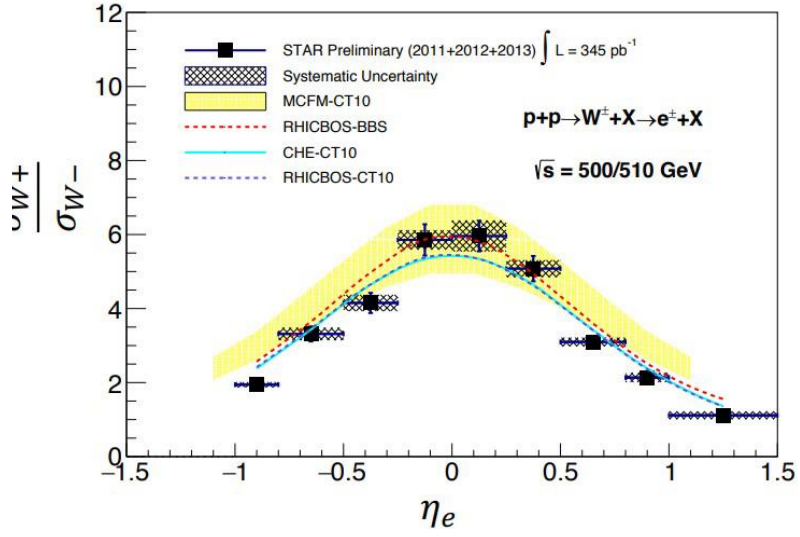


- S. Fazio, DNP 2020

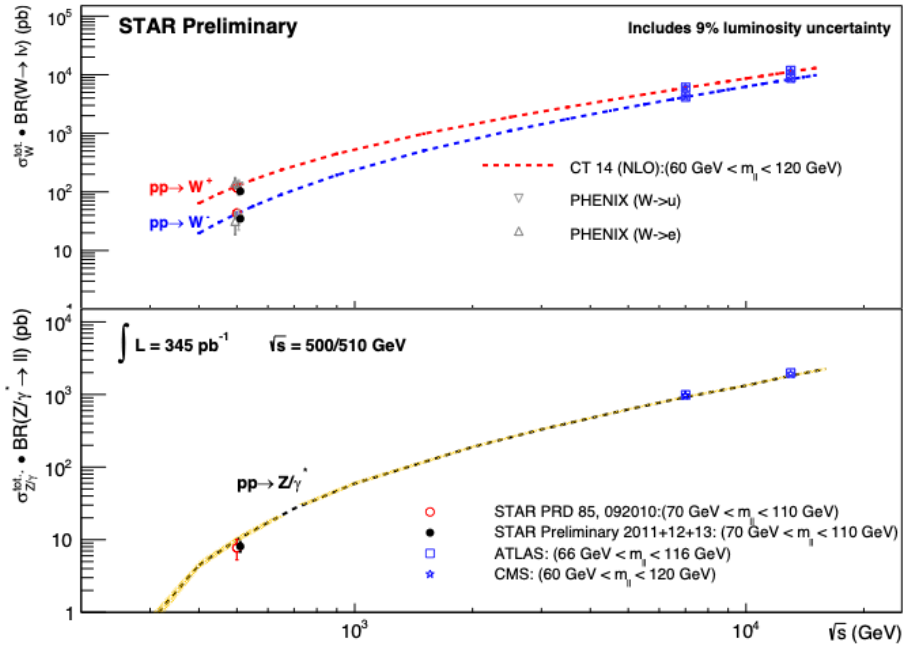
$0.1 < x < 0.3$



- W. Lorenzon, Hadron 2019



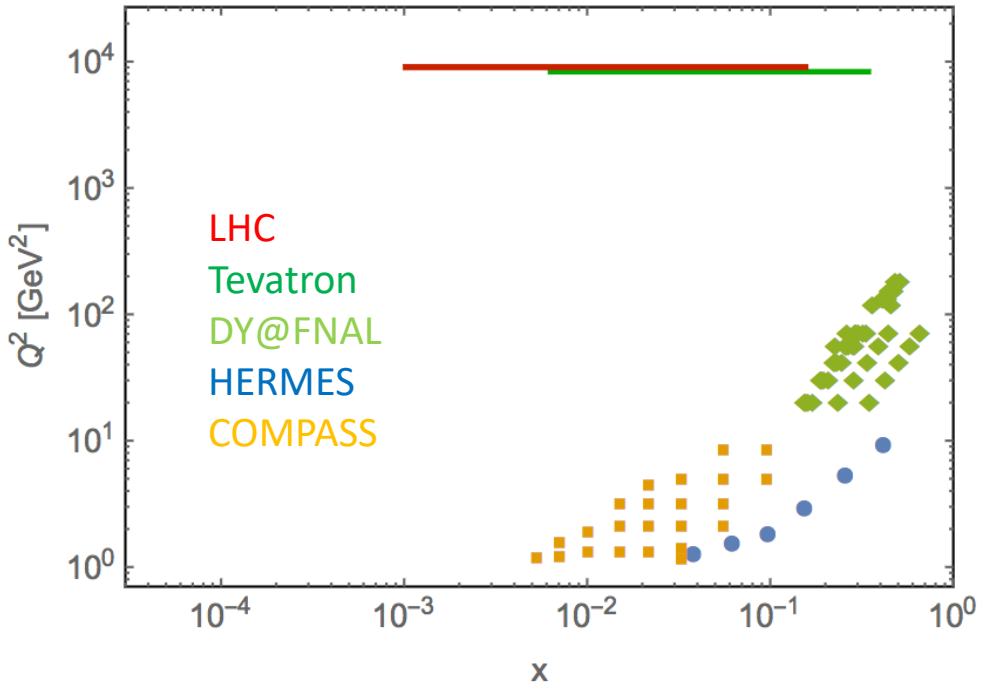
- Publication in preparation
- Additional data × 2

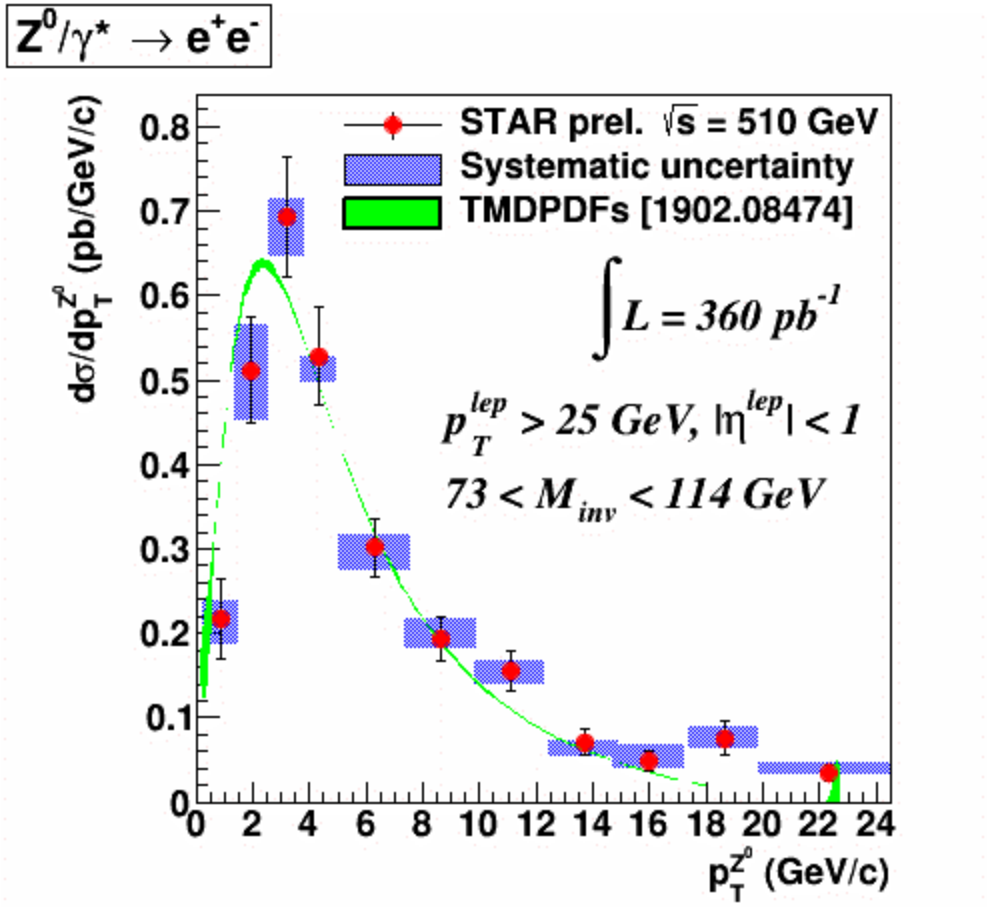


Unpolarized TMDs

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

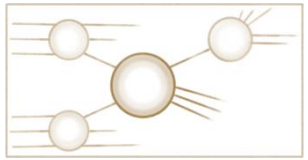
- Experimentally very clean
- Differential cross section input for global analyses
- STAR: $0.1 < x < 0.3$





- Unfolded p_T spectrum
- Systematics from energy resolution and electron selection
- 2017 data: 350 pb^{-1}

Accessing the Gluon Polarization

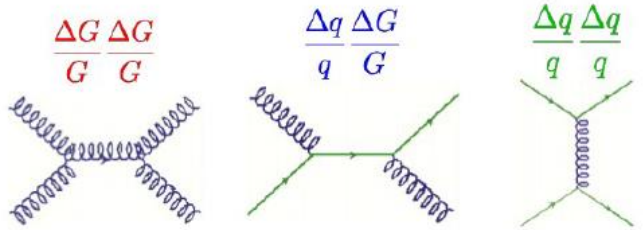


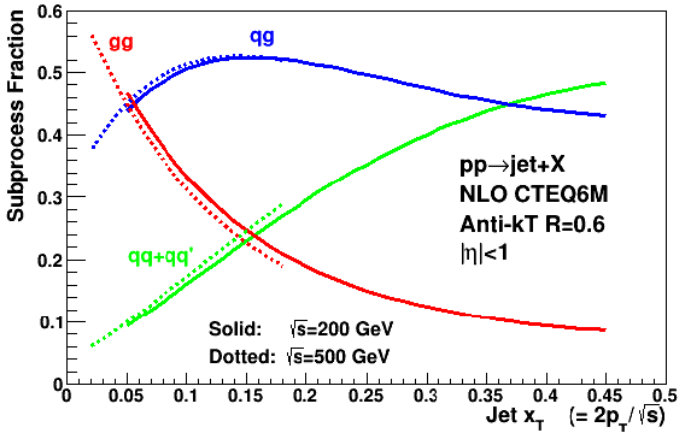
Double helicity asymmetries in proton collisions:

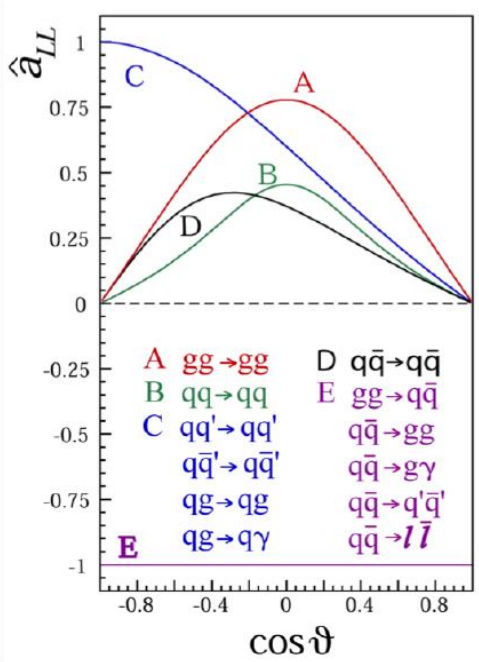
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

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

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



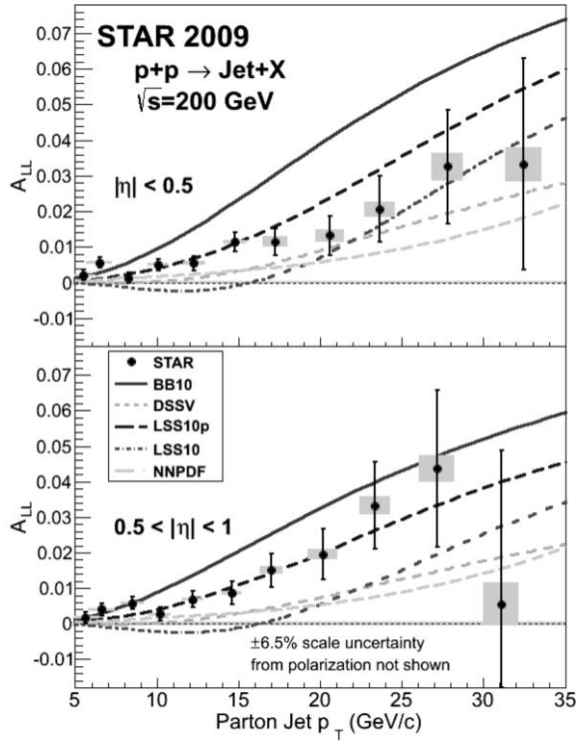




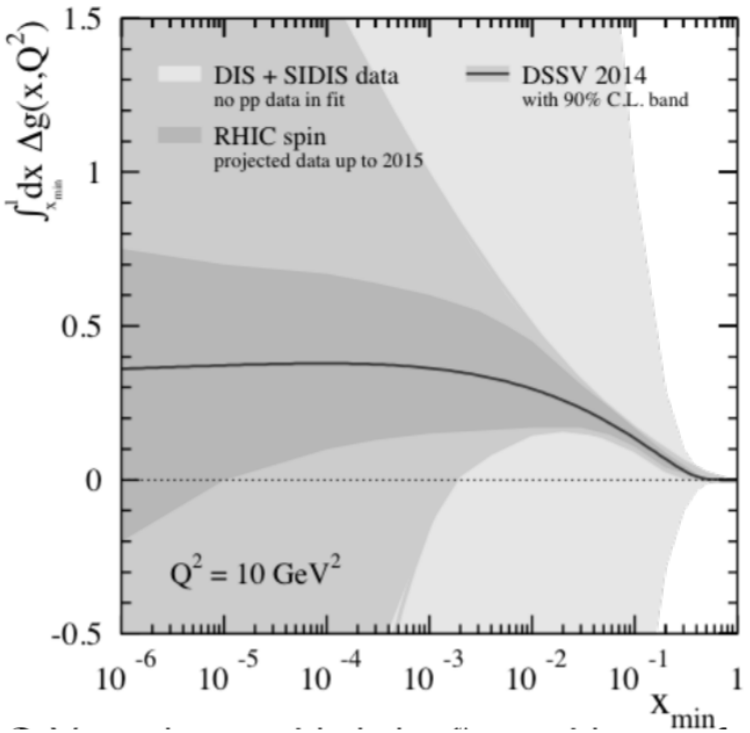
- Beam polarizations
  - $P_{1,2} \approx 55 - 60\%$
  - $\delta P/P \approx 3.5\%$
  - $\delta(P_1 P_2)/(P_1 P_2) \approx 6\%$
  - Residual transverse polarization
- Relative luminosity
  - Fill-by-fill $\Delta R \approx 4\%$
  - Overall $\Delta R < 5 \cdot 10^{-4}$
  - From rates in different detectors (BBC/VPD/ZDC)

Gluons are polarized in the proton!

PRL 115 (2014) 092002



Inclusive jet asymmetries at $\sqrt{s} = 200$ GeV (midrapidity) point to evidence of non-zero gluon polarization.



DSSV

PRL 113 (2014) 012001

$$\int_{0.05}^{1} \Delta g(x)dx = 0.2^{+0.06}_{-0.07}$$

A different global analysis finds similar result.

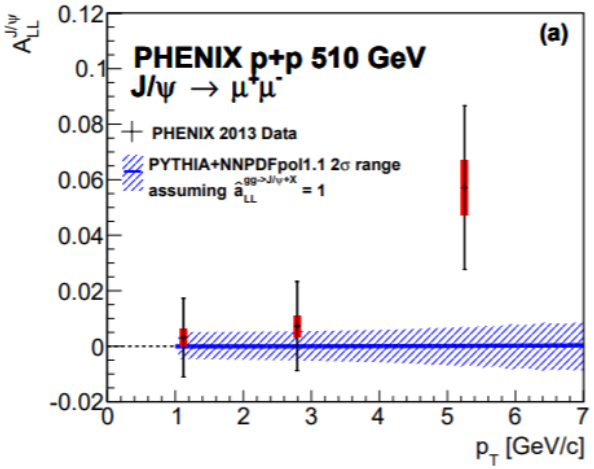
NNPDF

NPB 887 (2015) 276

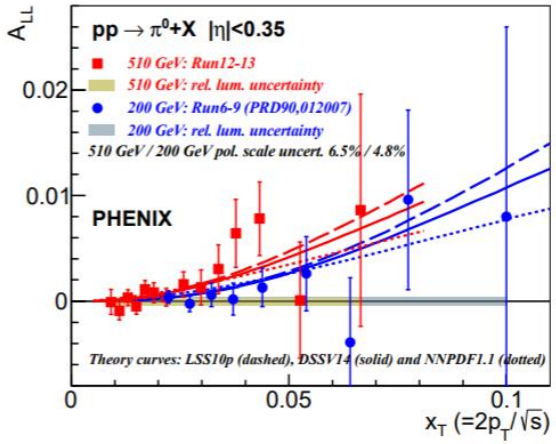
$$\int_{0.05}^{0.5} \Delta g(x)dx = 0.23 \pm 0.07$$

Inclusive Meson Measurements

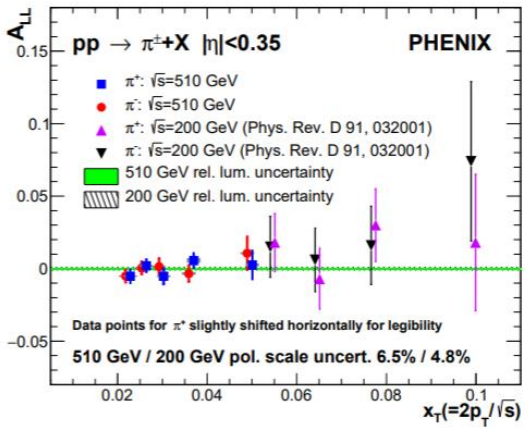
PRD 94 (2016) 112008



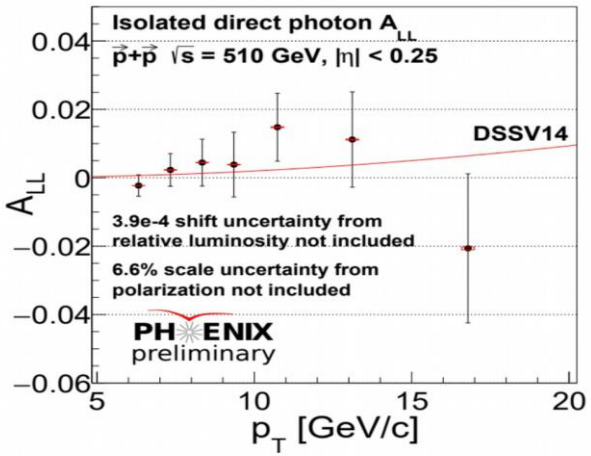
PRD 93 (2016) 011501



PRD 102 (2020) 032001



Patel, RAUM 2020



- PHENIX has measured a wide variety of probes at 200 & 510 GeV
- Very precise data
- Asymmetries are small
- Limited sensitivity to non-zero gluon polarization

Jet Asymmetries at 500 GeV

- Inclusive jets

$$x \approx x_T e^{\pm\eta}$$

$$x_T = 2p_T/\sqrt{s}$$

increase energy

- Dijets

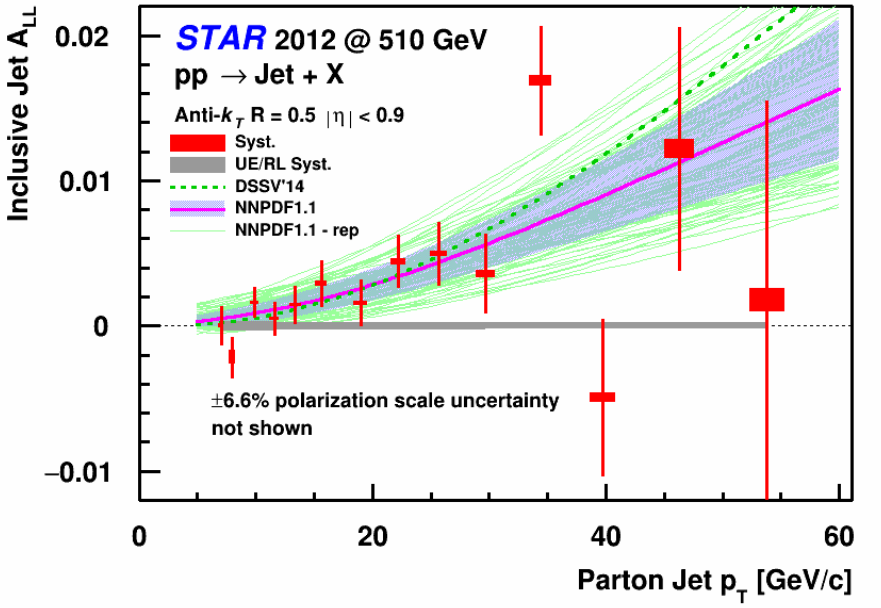
$$x_1 = (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})/\sqrt{s}$$

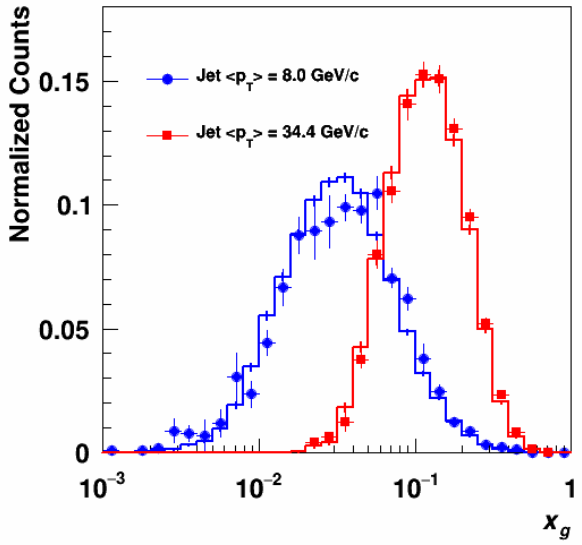
$$x_2 = (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})/\sqrt{s}$$

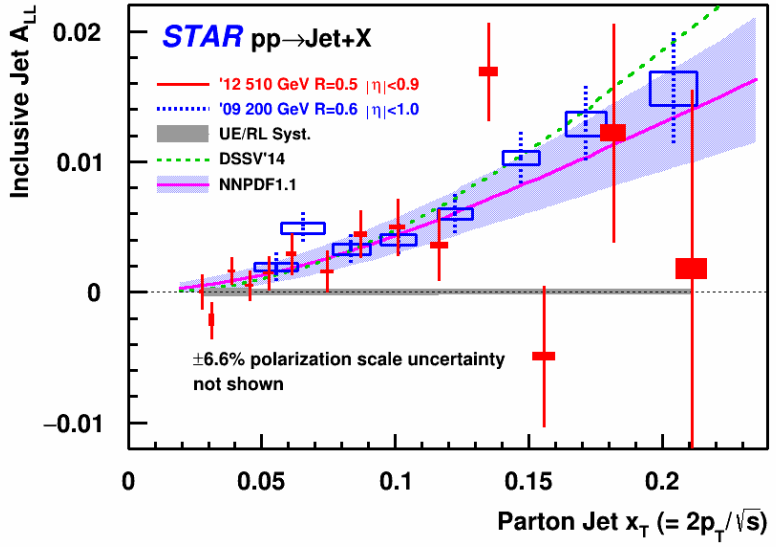
$$M = \sqrt{x_1 x_2 s}$$

$$|\cos\theta^*| = \tanh(|\eta_3 - \eta_4|/2)$$

Phys. Rev. D**100** (2019) 052005







Dijet Asymmetries

- Inclusive jets

$$x \approx x_T e^{\pm\eta}$$

$$x_T = 2p_T/\sqrt{s}$$

- Dijets

$$x_1 = (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})/\sqrt{s}$$

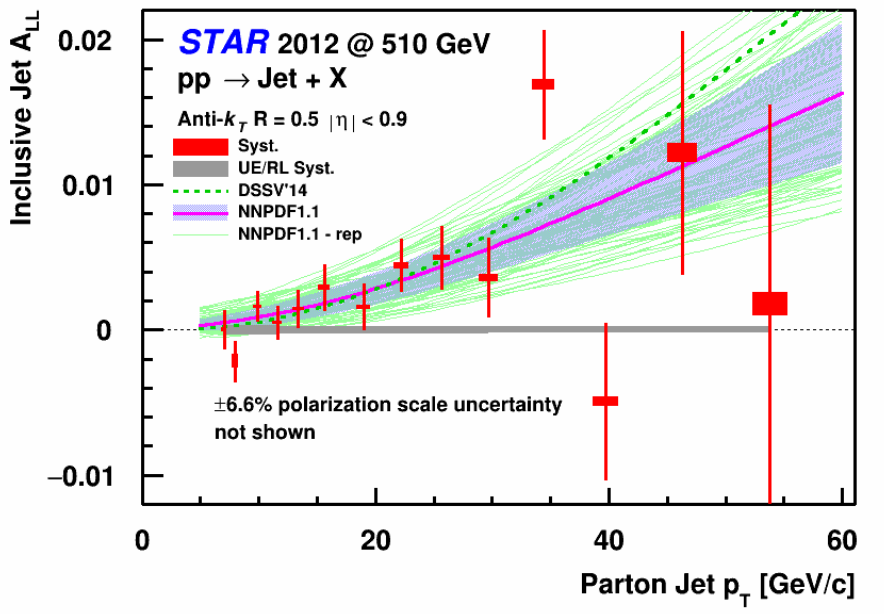
$$x_2 = (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})/\sqrt{s}$$

$$M = \sqrt{x_1 x_2 s}$$

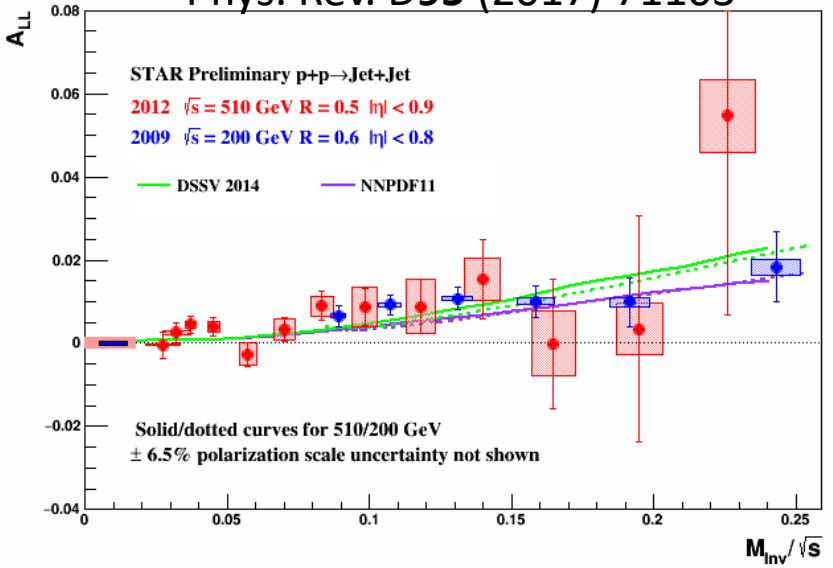
$$|\cos\theta^*| = \tanh(|\eta_3 - \eta_4|/2)$$

dijet correlations

Phys. Rev. D**100** (2019) 052005



Phys. Rev. D**95** (2017) 71103



Dijets at Moderate Forward Rapidity

Phys. Rev. D**98** (2018) 032011

- Inclusive jets

$$x \approx x_T e^{\pm\eta}$$

$$x_T = 2p_T/\sqrt{s}$$

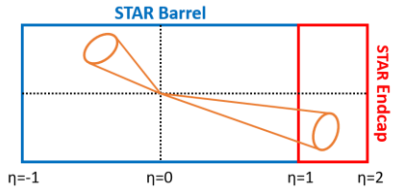
- Dijets

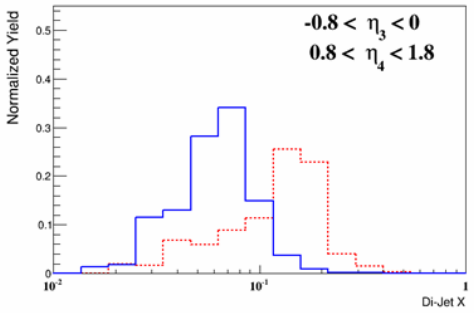
$$x_1 = (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})/\sqrt{s}$$

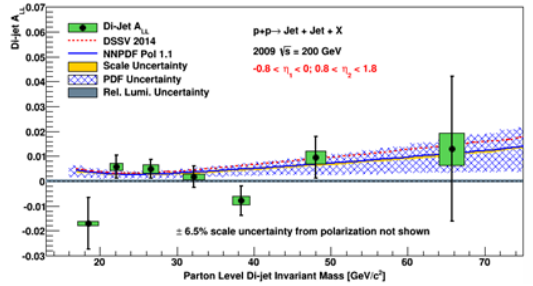
$$x_2 = (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})/\sqrt{s}$$

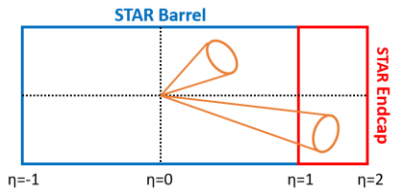
$$M = \sqrt{x_1 x_2 s}$$

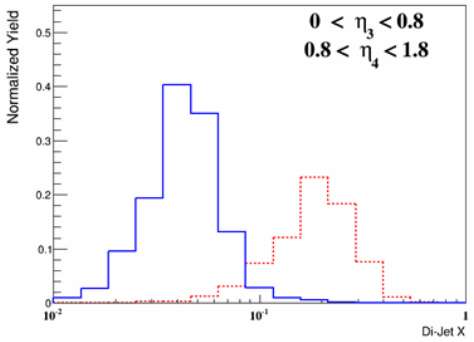
$$|\cos\theta^*| = \tanh(|\eta_3 - \eta_4|/2)$$

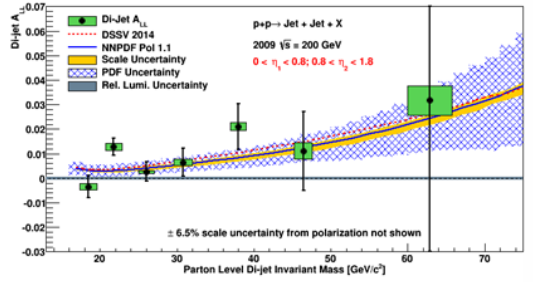


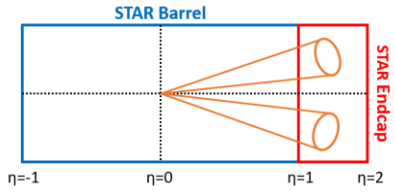


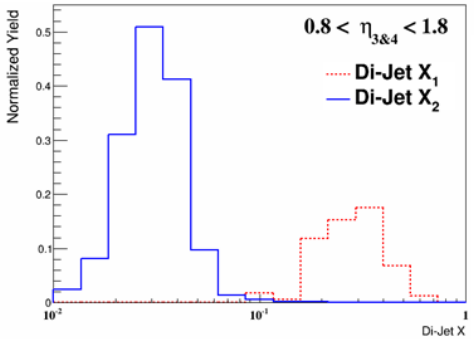


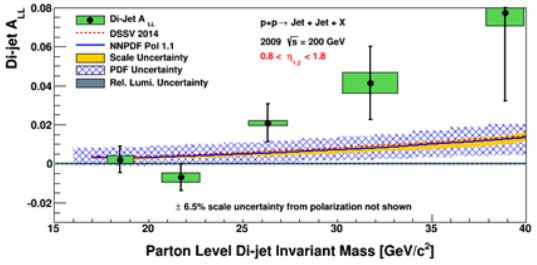












Dijets at 500 GeV

- Inclusive jets

$$x \approx x_T e^{\pm\eta}$$

$$x_T = 2p_T/\sqrt{s}$$

- Dijets

$$x_1 = (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})/\sqrt{s}$$

$$x_2 = (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})/\sqrt{s}$$

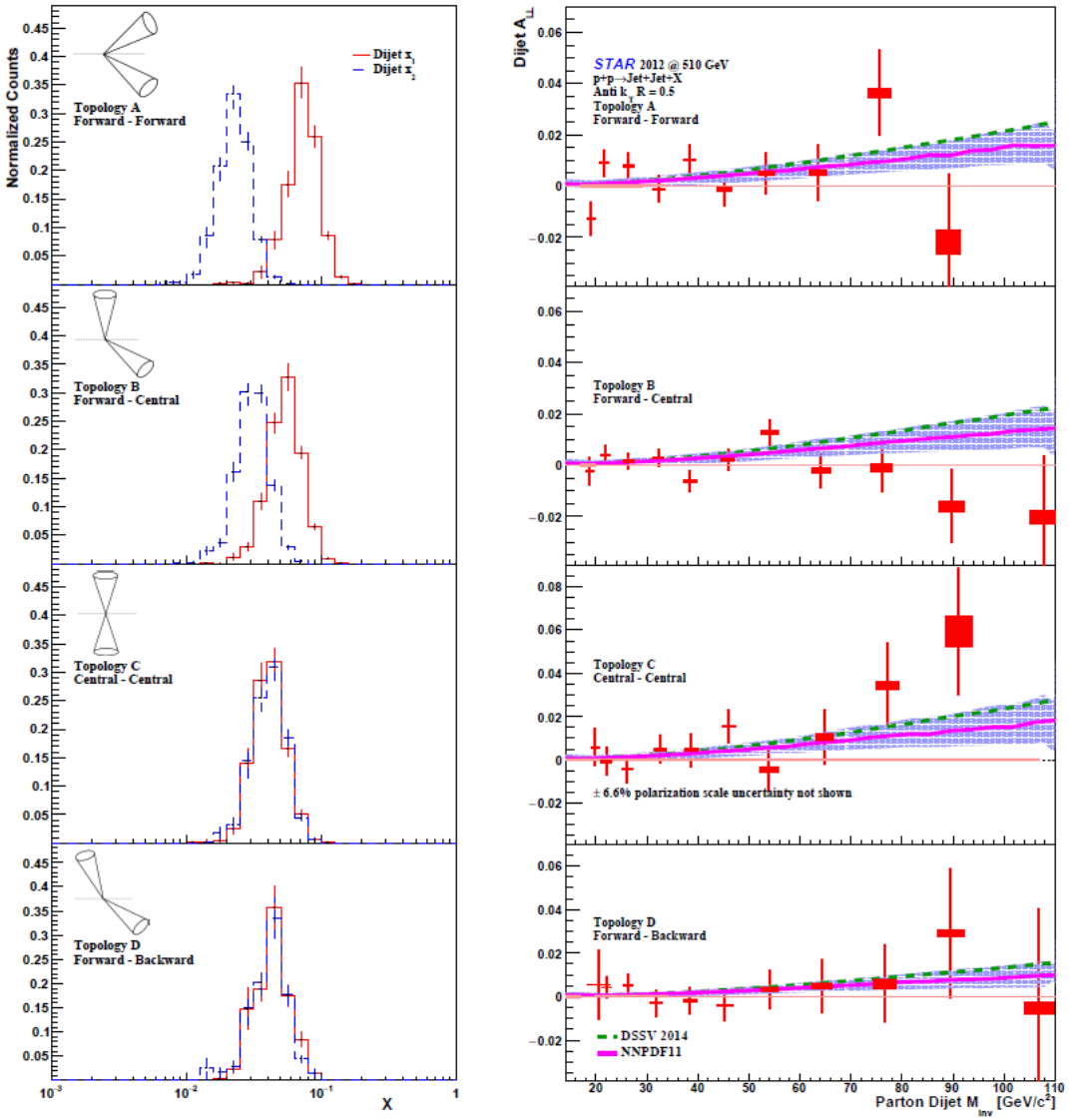
$$M = \sqrt{x_1 x_2 s}$$

$$|\cos\theta^*| = \tanh(|\eta_3 - \eta_4|/2)$$

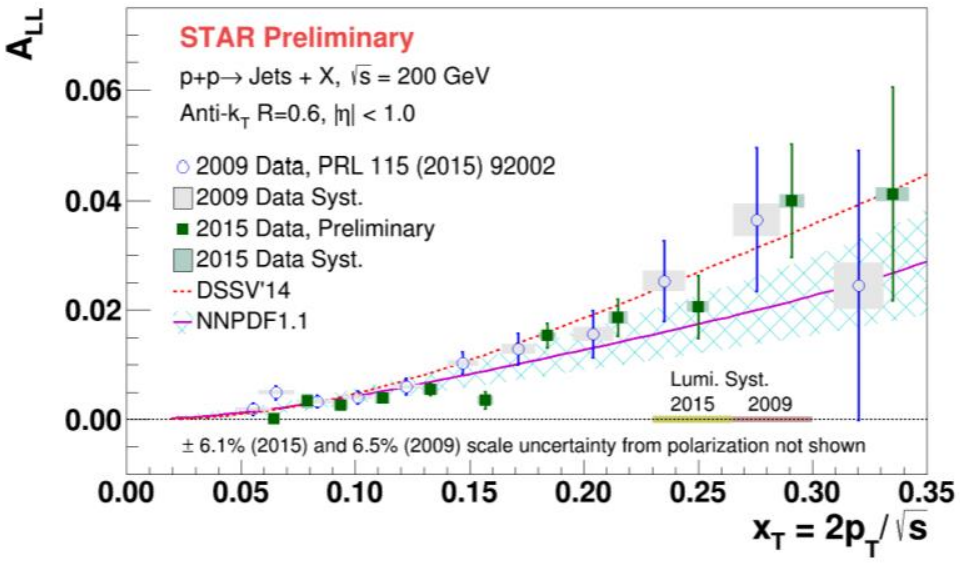
- Full correction for underlying event
- $\int_{x=0.01}^{1} \delta g(x, Q^2 = 10\ \mathrm{GeV}^2) = 0.296 \pm 0.108$

[arxiv:1902.10548]

Phys. Rev. D**100** (2019) 052005

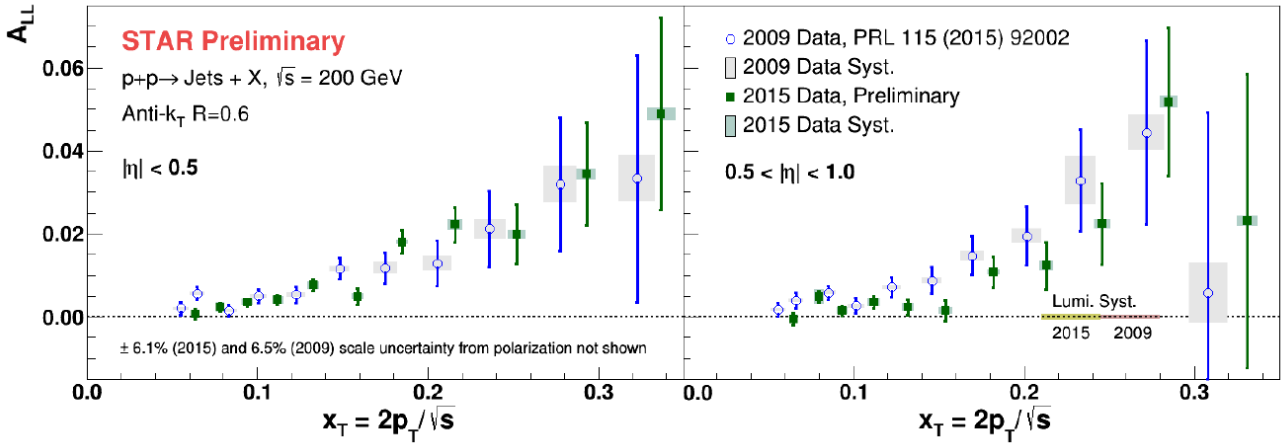


Recent Results

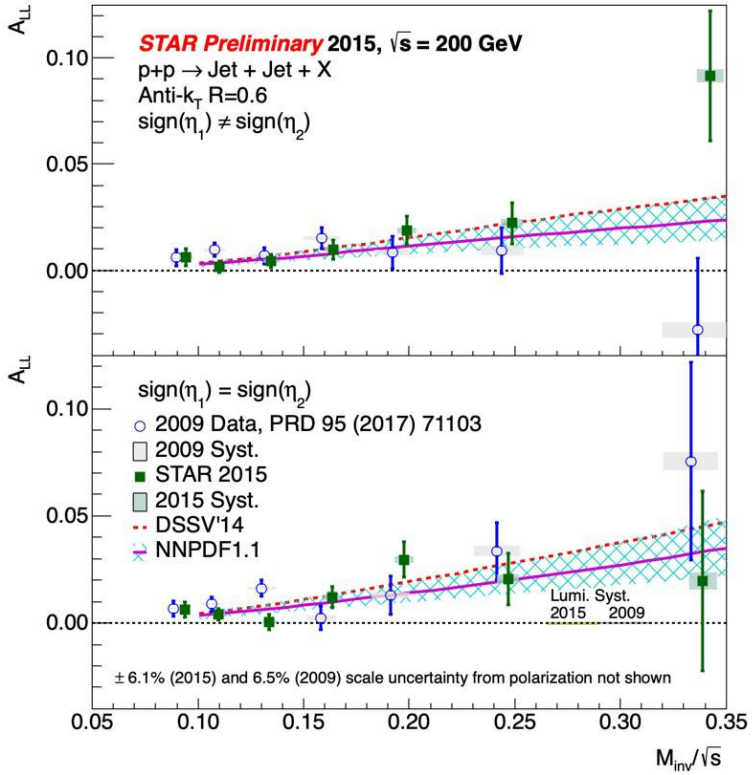


- New preliminary results for inclusive jets and dijets
  - $\sqrt{s} = 200$ GeV
  - Improved figure-of-merit
  - Improved systematics
- Publications in preparation
  - $\sqrt{s} = 200$ GeV
  - $\sqrt{s} = 510$ GeV

$|\eta| < 0.5$ $\quad$ $0.5 < |\eta| < 1.0$

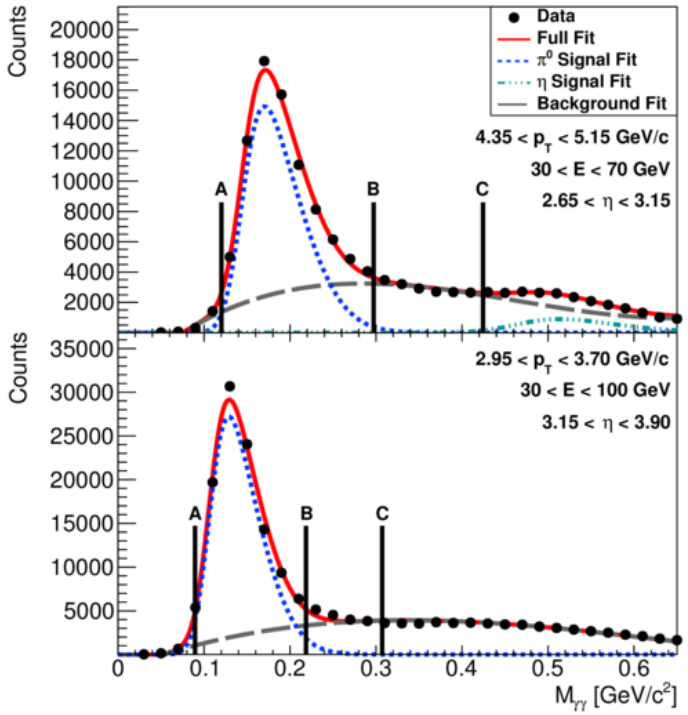


N. Lukow et al. (STAR), RAUM 2020

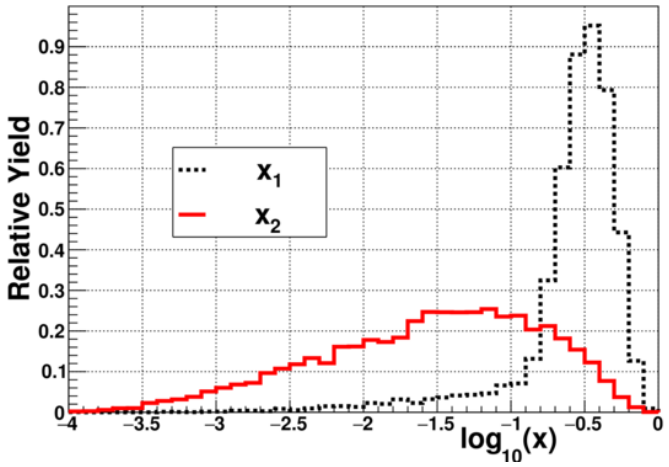


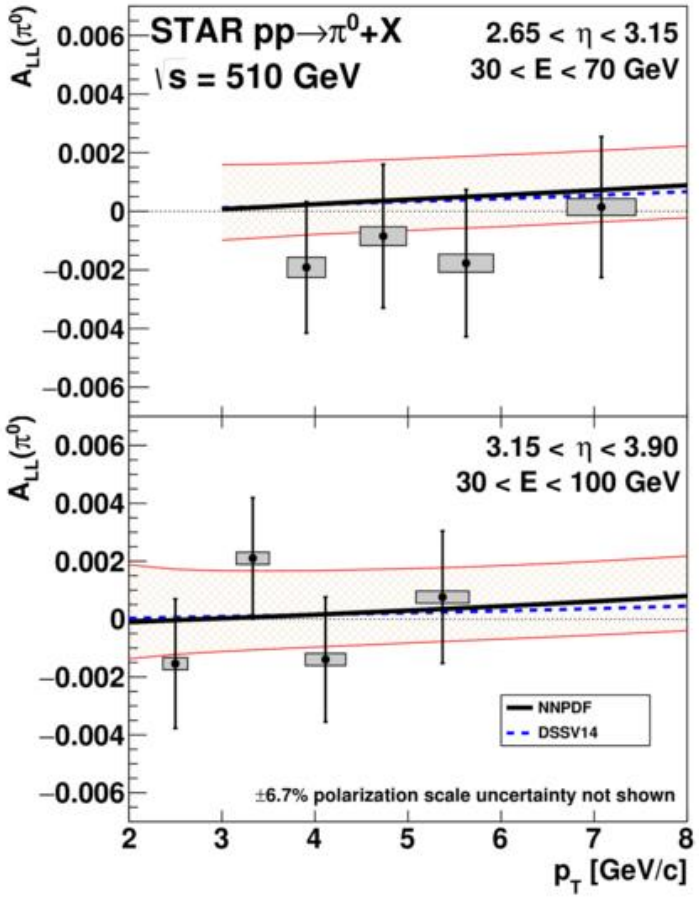
Pion Asymmetries at Forward Rapidity

- Forward rapidity $2.6 < \eta < 4.0$
- $\sqrt{s} = 510$ GeV
- Asymmetries are small, $A_{LL} \approx 10^{-4}$ (expected)
- Phys. Rev. D98, 032013 (2018)



Sensitive to $x \approx 10^{-3}$

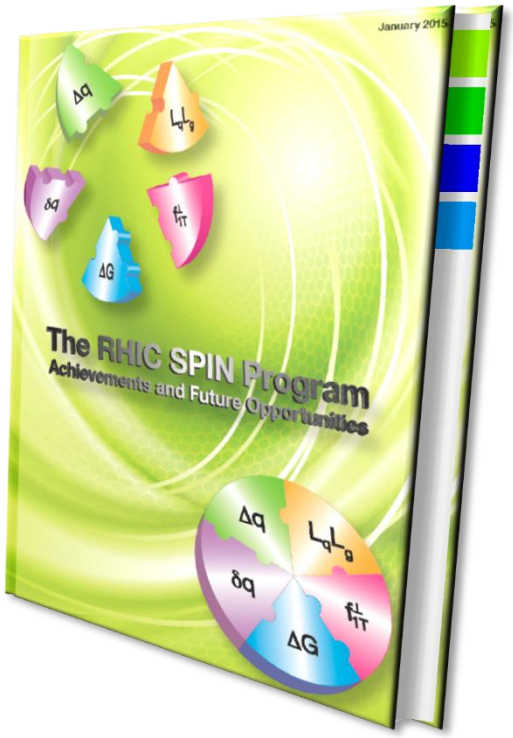




The RHIC Cold QCD Program

- Gluon polarization
- Sea quark polarization
- Transverse spin effects

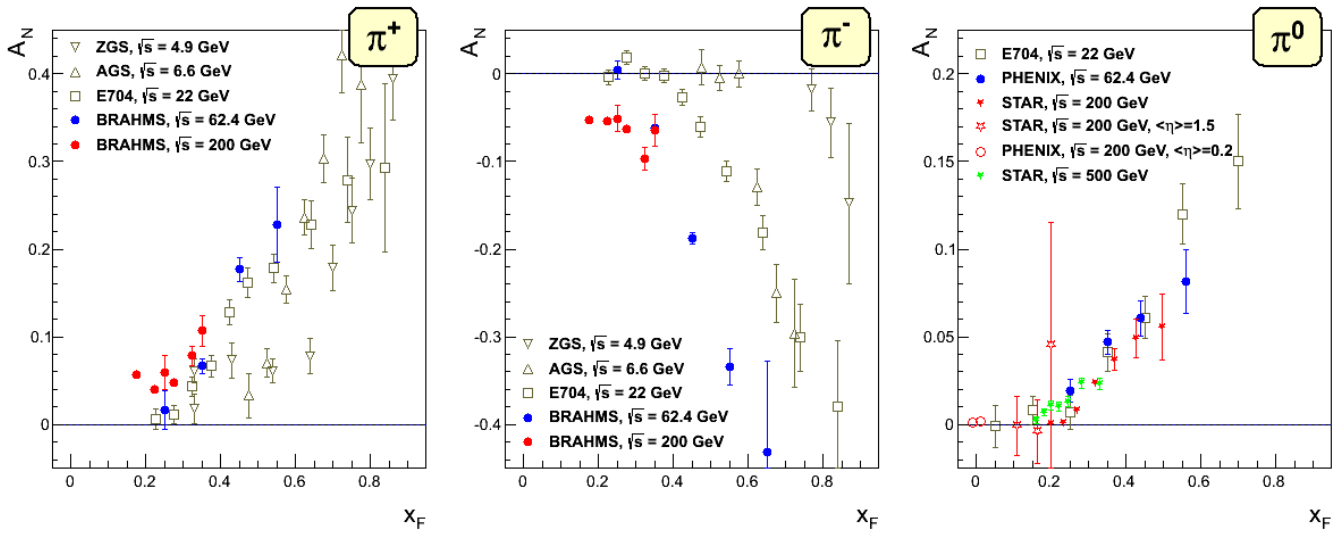
- What is the nature of the spin of the proton?
- How do gluons contribute to the proton spin?
- What is the landscape of the polarized sea in the nucleon?
- What do transverse spin phenomena teach us about the proton structure?
- How can we describe the multi-dimensional landscape of nucleons and nuclei?
- How do quarks and gluons hadronize into final state particles?
- What is the nature of the initial state in nuclear collisions?



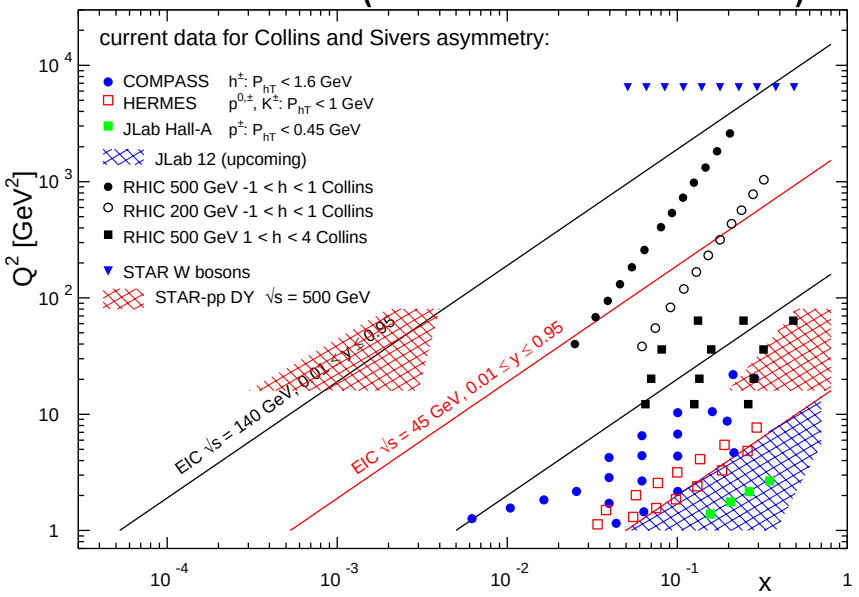
arxiv:1501.01220

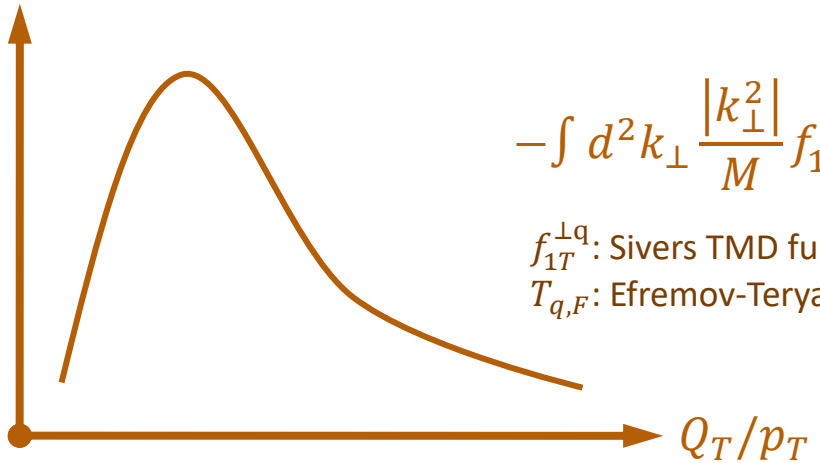
arxiv:1602.03922

Transverse Spin Effects



World Data (Collins & Sivers TMDs)





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

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

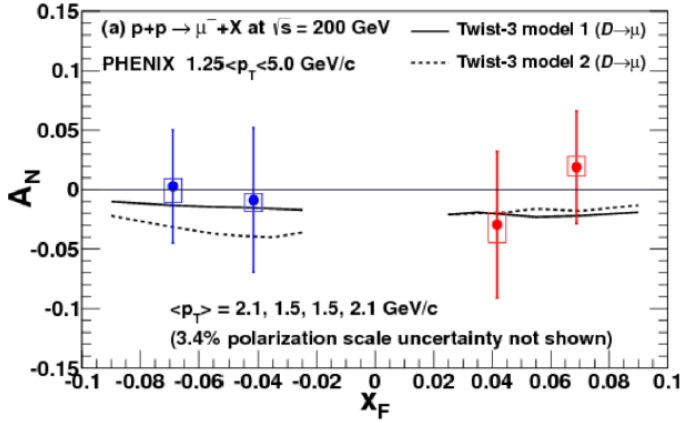
$Q^2 \gg Q_T^2 \gtrsim \Lambda_{QCD}^2$ $\quad$ $Q^2, Q_T^2 \gg \Lambda_{QCD}^2$

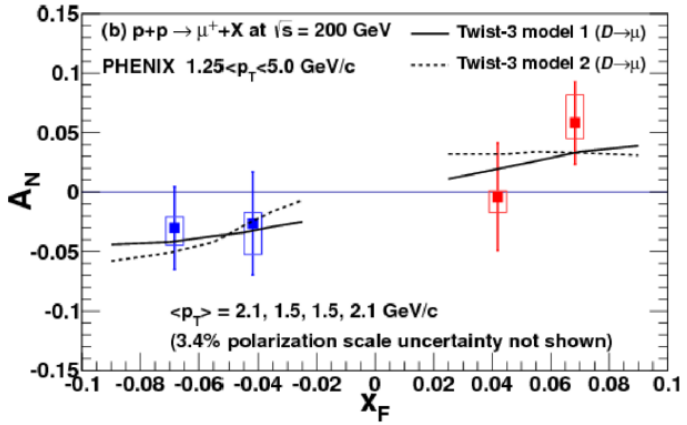
Factorization and scale!

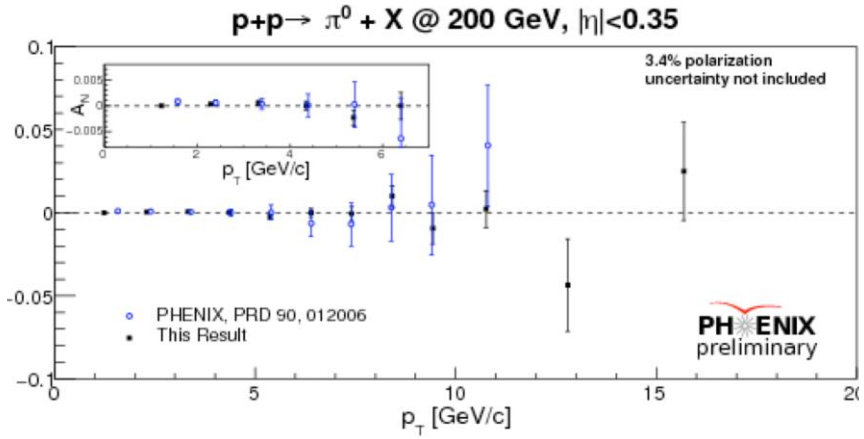
- TMD factorization: two characteristic scales Q^2 and Q_T^2
- Collinear factorization: twist-3 with one hard scale
- Both are closely related

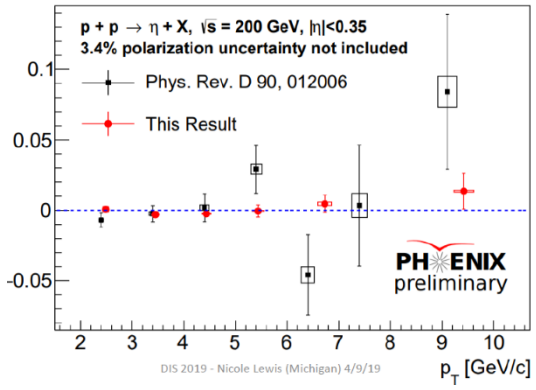
Inclusive Measurements

Phys.Rev. D95 (2017) 112001

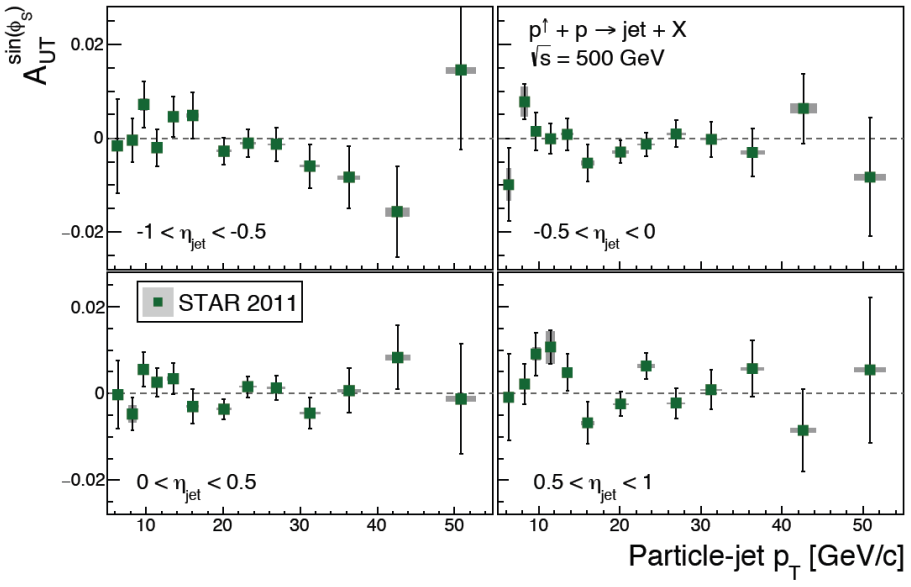








Phys.Rev. D97 (2018) 032004

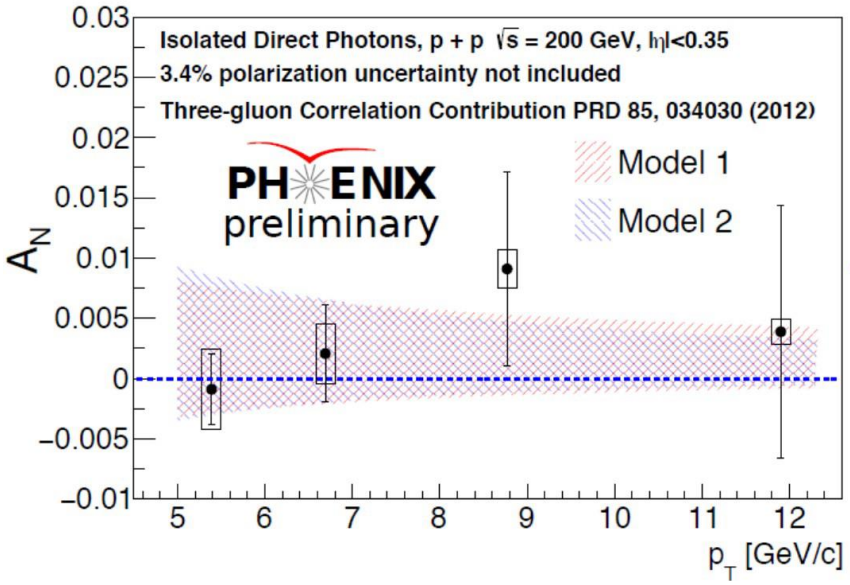


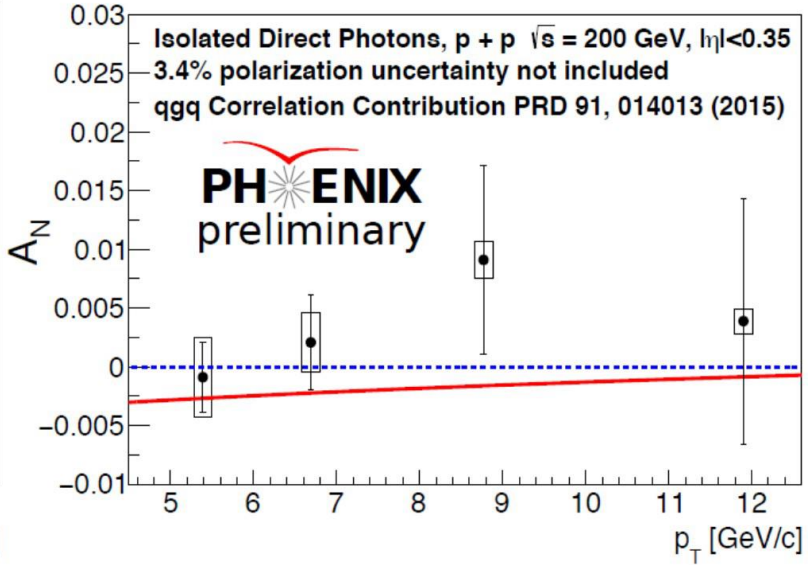
- $\vec{p} + p, \vec{p} + Al, \vec{p} + Au$
- Different probes (π^0, η, $\mu^{\pm}$, jets)
- $\sqrt{s_{NN}} = 200 / 500$ GeV
- Sensitive to gluon T_G
- Very high precision, consistent with zero

Direct Photons

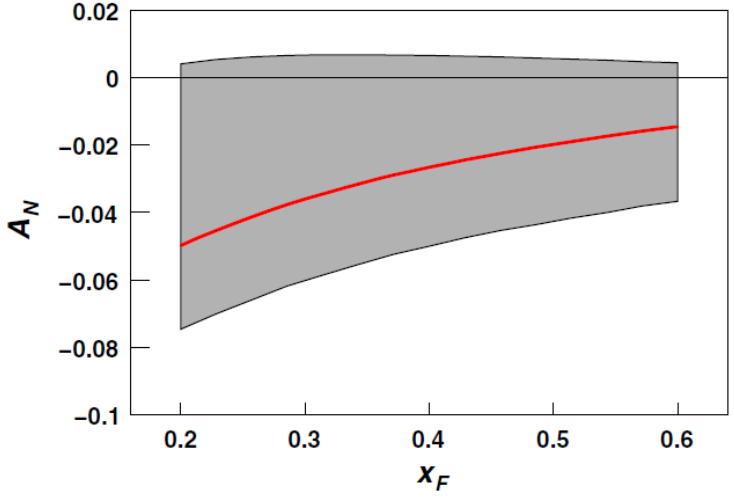
- First measurement from PHENIX
- Constrains twist-3 ETQS function
  - Related to Sivers-TMD
- Larger asymmetries expected at forward rapidity

M. Patel et al. (PHENIX), RAUM 2020





Gamberg, Kang, Prokudin
PRL 110, 232301 (2013)

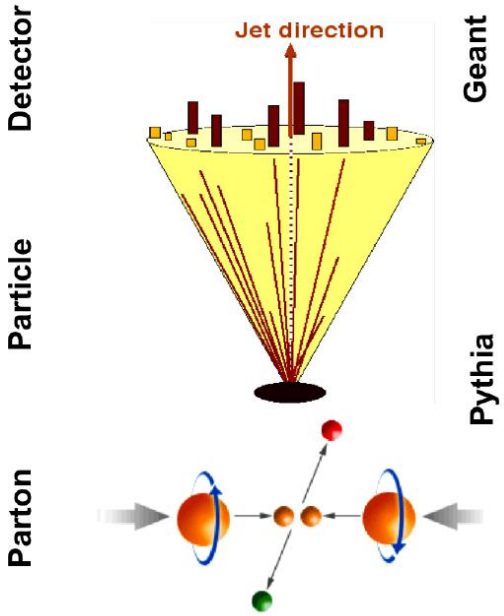


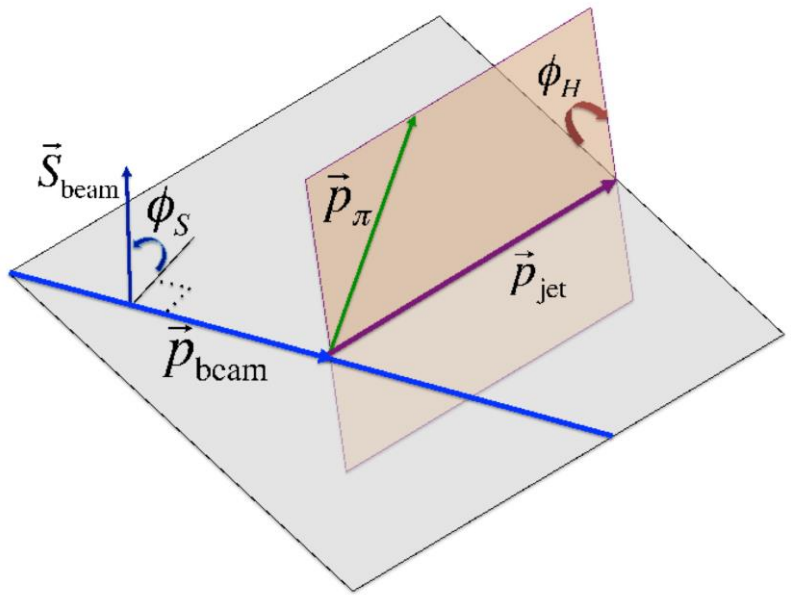
$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2) = T_{q,F}(x,x)$$

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

Hadrons in Jets

- Two scales for TMD measurement
  - p_T of jet
  - j_T of hadron in jet
- Jet reconstruction (anti-k_T)
  - PYTHIA + GEANT
  - Kinematics corrected to particle level and parton level matching
  - Trigger bias
- Pion purities / hadron contamination
- Leak through from other asymmetries





$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

Collins TMD & transversity

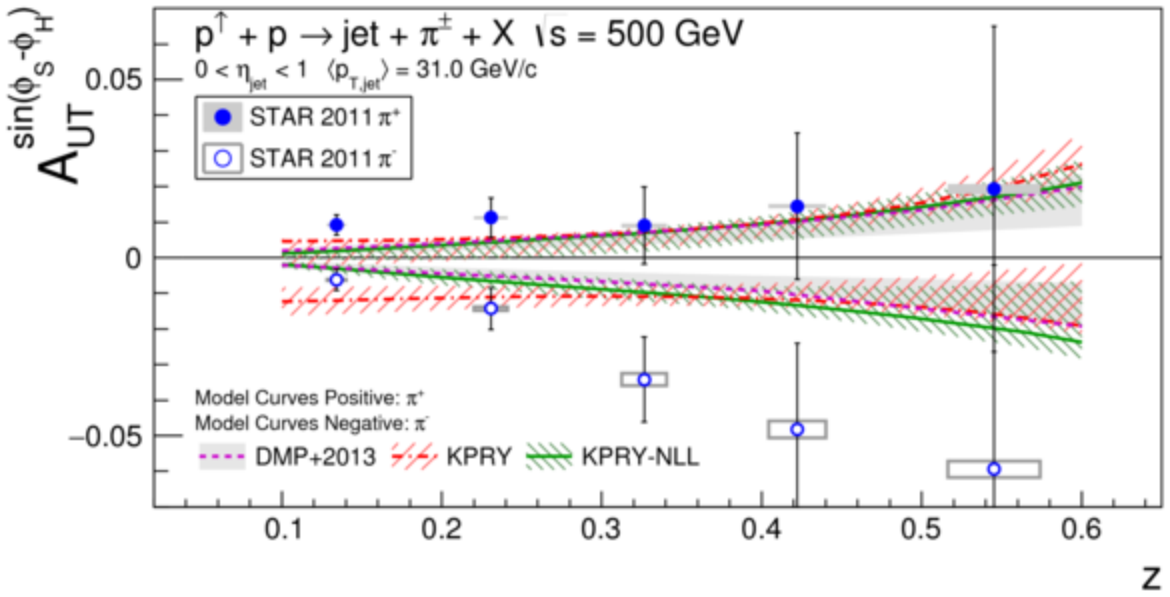
Collins-like (linear gluon polarization)

Collins Asymmetries

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

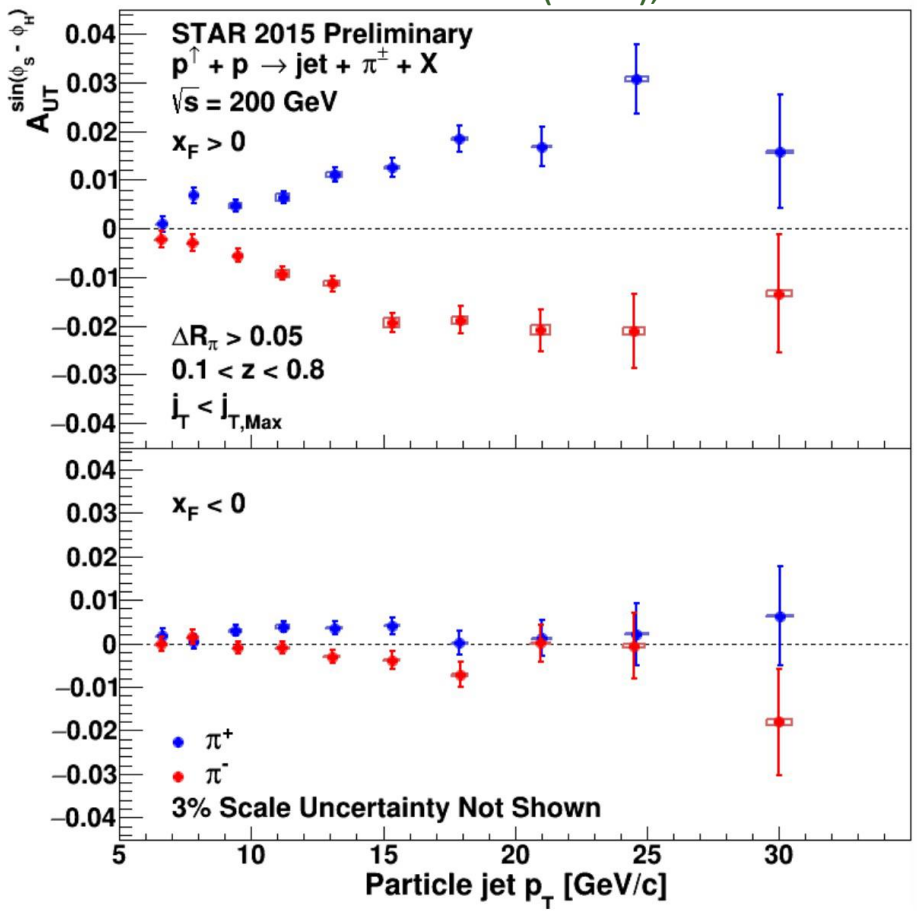
- New data at $\sqrt{s} = 200$ GeV
- Multidimensional binning p_T, j_T, z
- Separate asymmetries for $\pi^{\pm}, K^{\pm}$
- Publication in preparation

Phys. Rev. D97 (2018) 032004



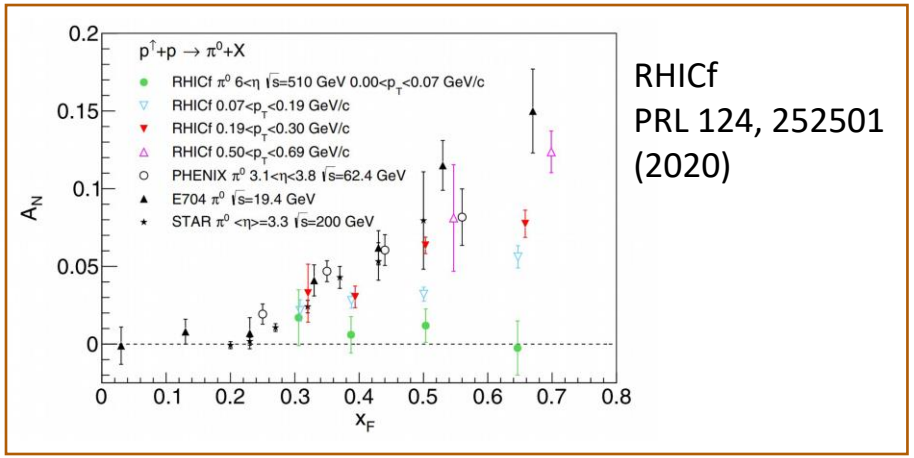
Comparison with
Phys. Lett. B773, 300-306 (2017)
arXiv:1707.00913

T. Lin et al. (STAR), RAUM 2020



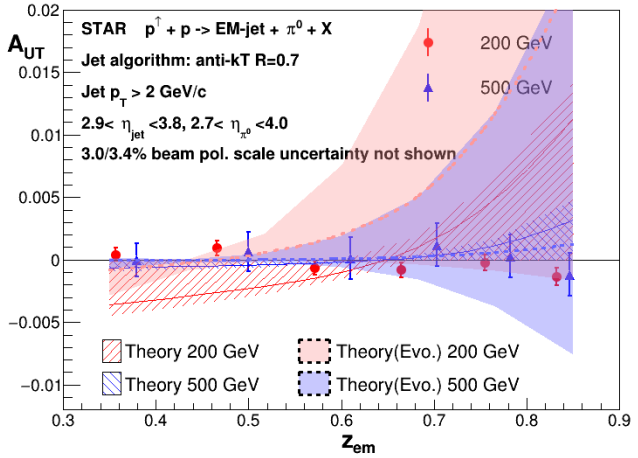
Going Forward

- Electromagnetic jets with forward calorimeter
  - π^0 in jet
- $2.8 < \eta < 4.0$



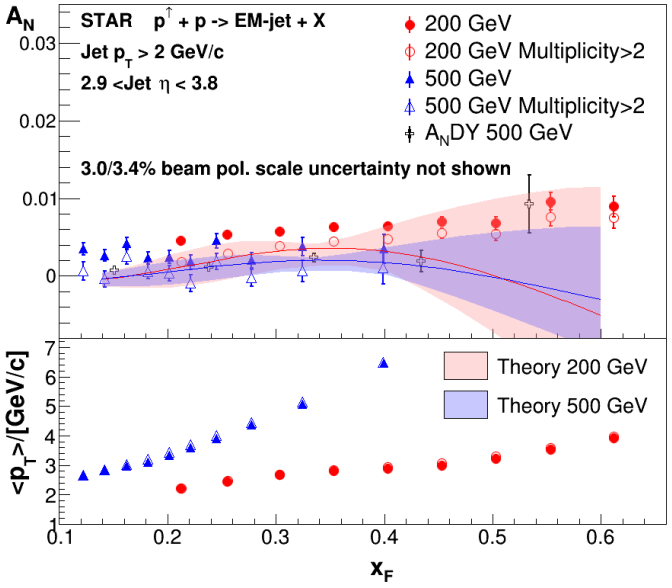
RHICf
PRL 124, 252501 (2020)

- Collins asymmetries are small.

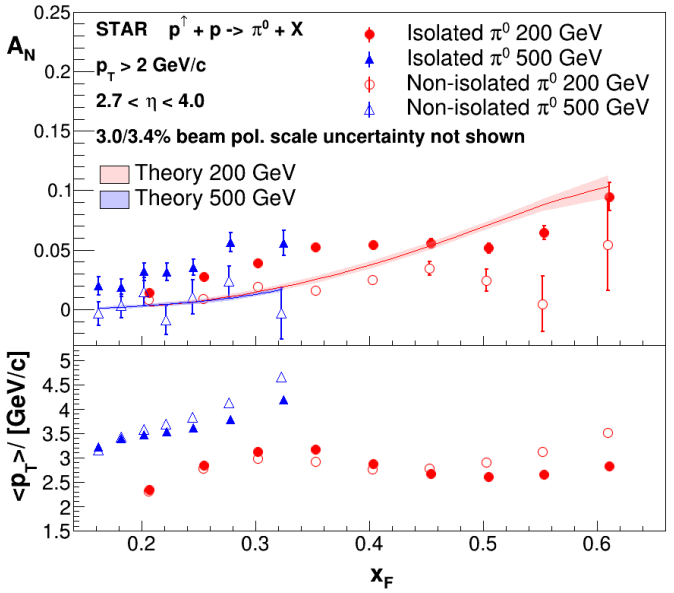


Comparison with
Z. Kang et al., PLB 774, 635 (2017)
L. Gamberg et al., PRL 110, 232301 (2013)
J. Cammarota et al., arxiv:2002.08384

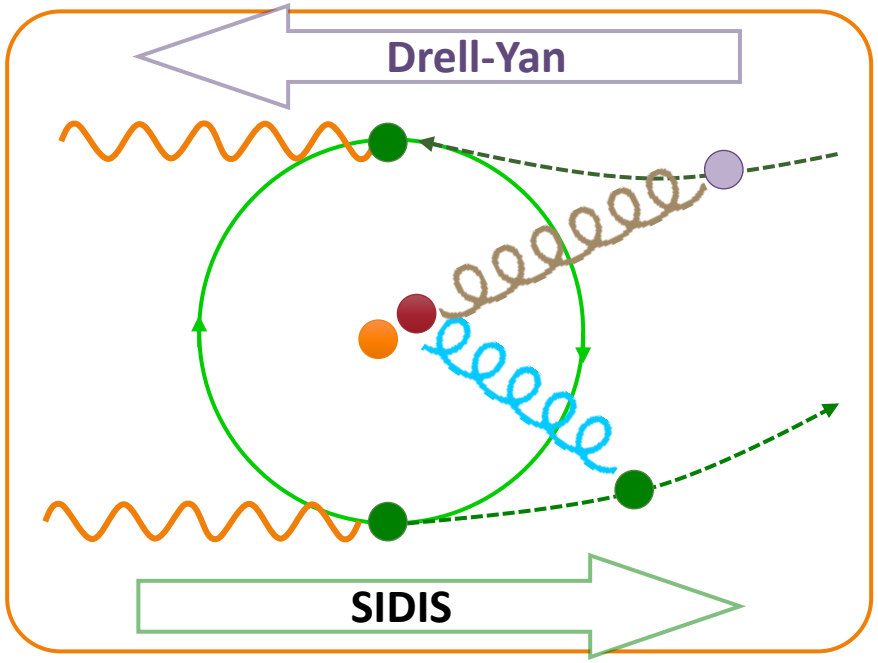
- Jet asymmetries are consistent with previous results.

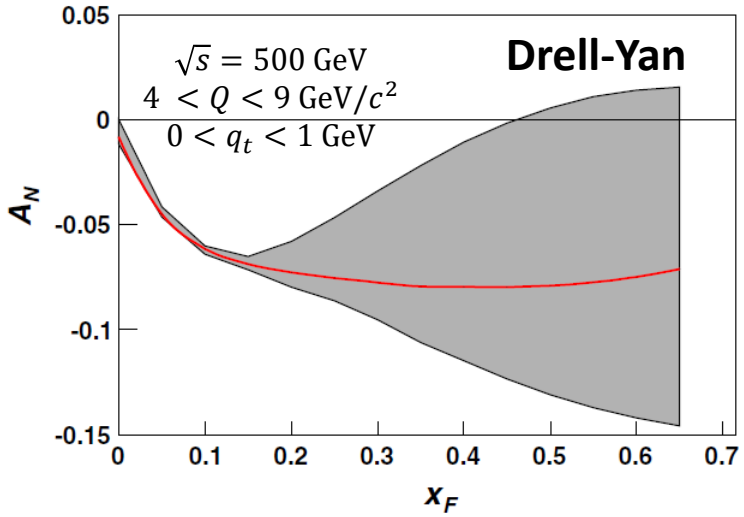


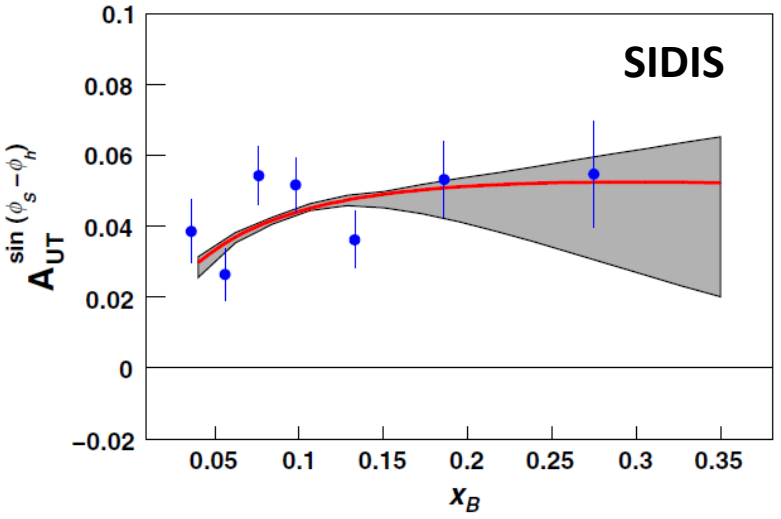
- Pion asymmetries increase with isolation.



Non-Universality of Spin-Orbit Correlations







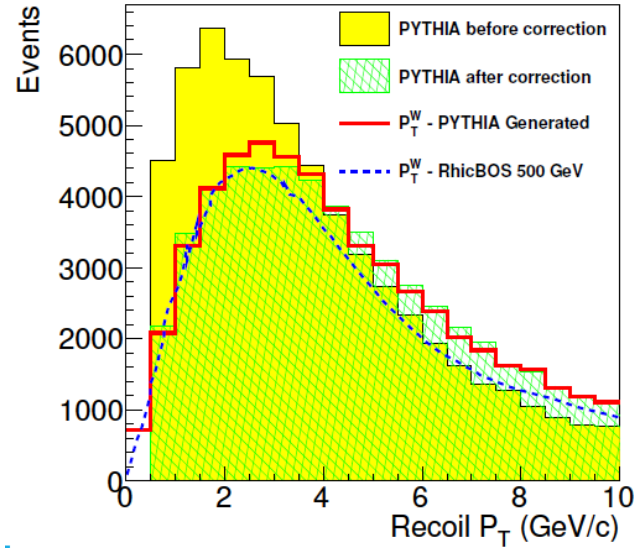
Gamberg, Kang, Prokudin
Phys. Rev. Lett. 110, 232301 (2013) with HERMES data

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

$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

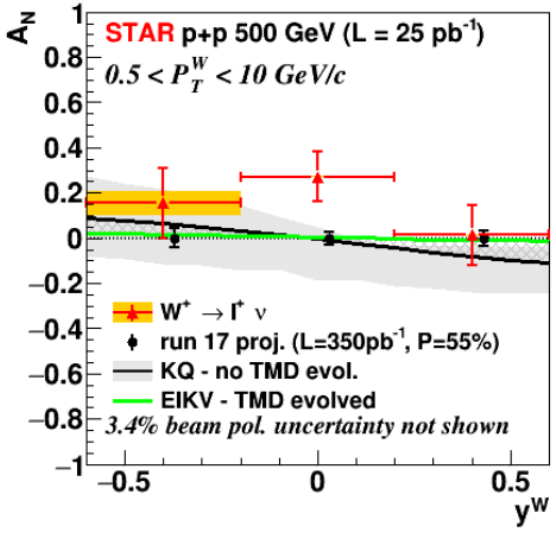
- Requires full reconstruction of $W^{\pm}$ kinematics
- Missing transverse momentum from recoil

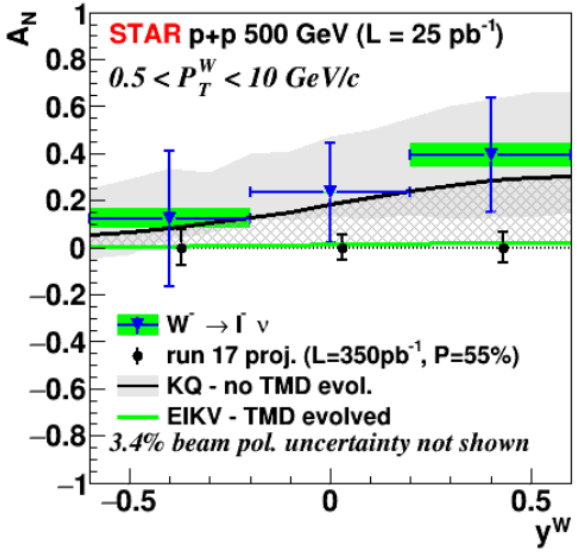
$$P_T^W = P_T^e + P_T^{\nu} = P_T^{recoil}$$

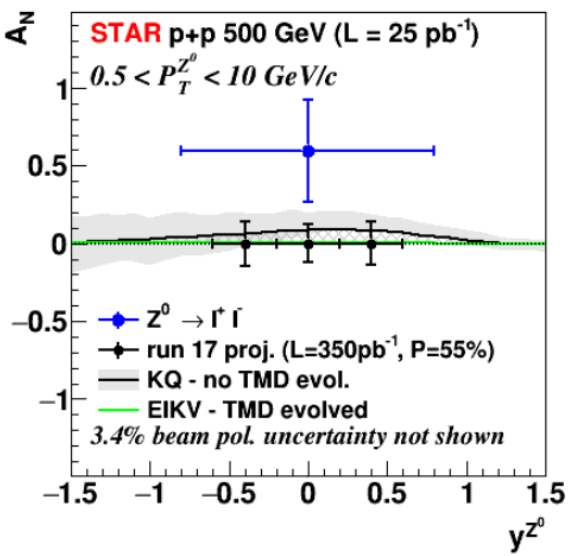


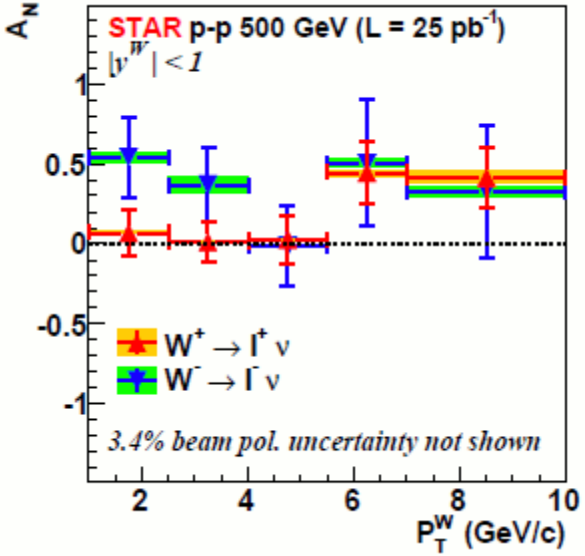
Phys. Rev. Lett. 116, 132301 (2016)

Comparison with Phys. Rev. Lett. 103, 172001







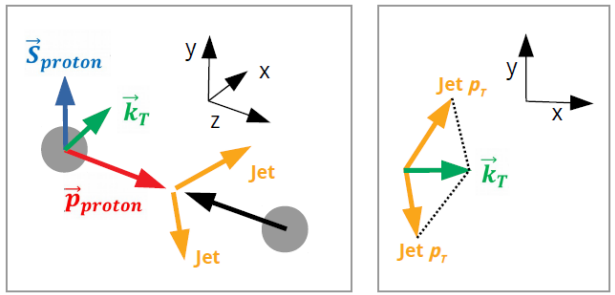


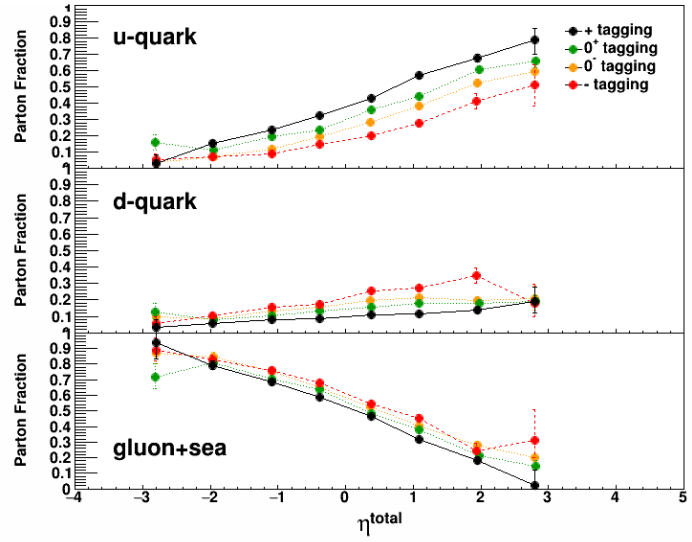
Sivers Asymmetries in Dijets

- Correlation between proton spin and parton k_T

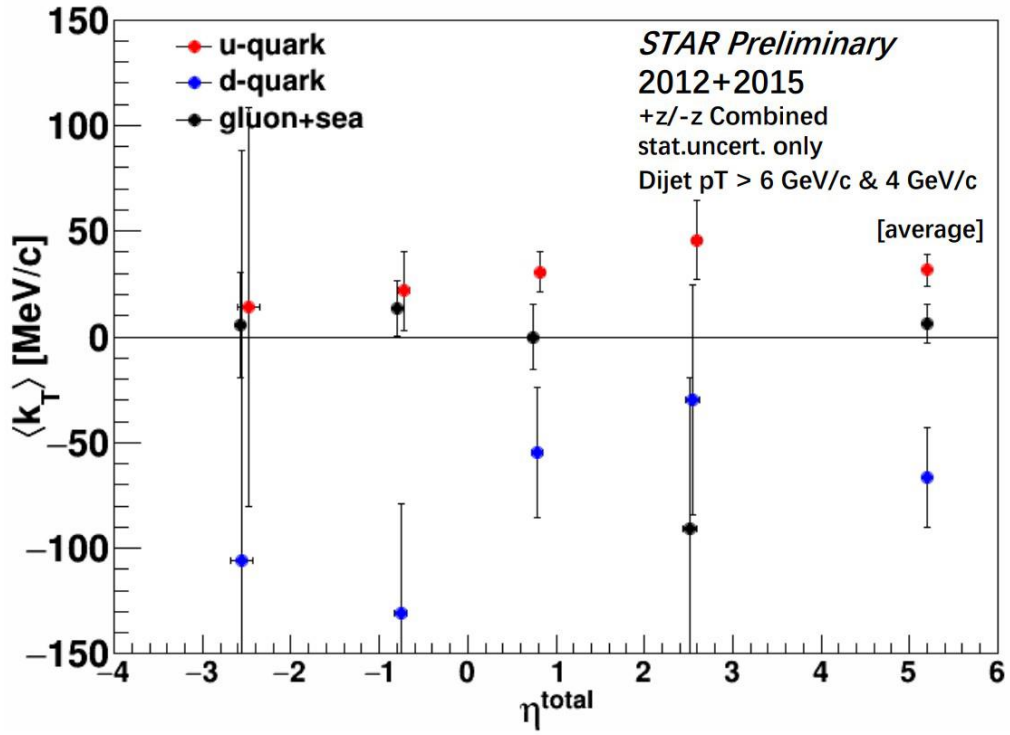
$$\left\langle \vec{S} \cdot (\vec{p} \times \vec{k}_T) \right\rangle \neq 0$$

- Enhance quark flavor with charge tagging
  - Track p_T weighted charge
  - $\eta_{total} = \eta_1 + \eta_2$
  - Unfolded to parton $\langle k_T \rangle$
- More data on disk, $\sqrt{s} = 510$ GeV





$\sqrt{s} = 200$ GeV

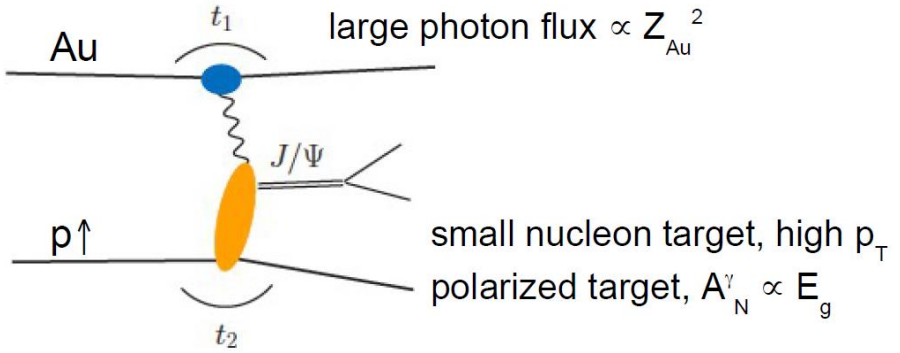


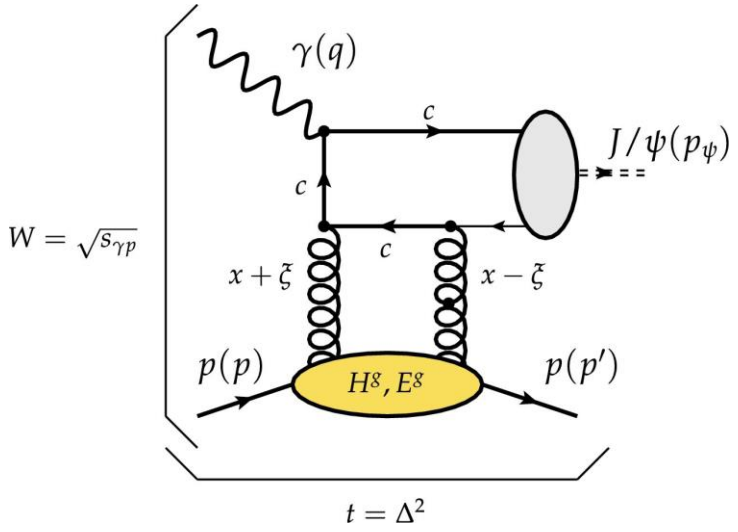
J/psi Production in UPC

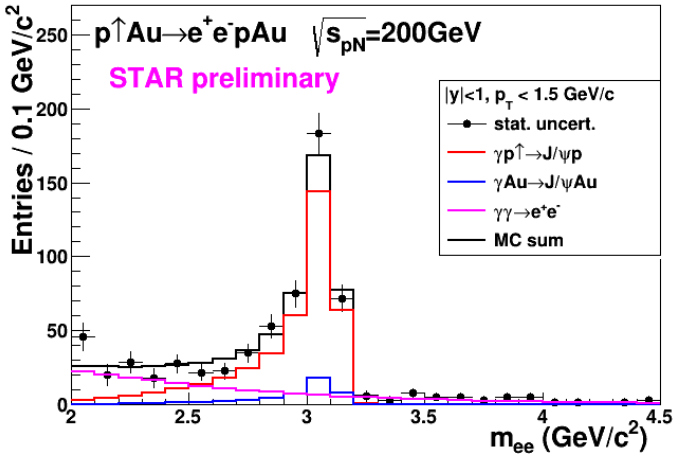
- Photoproduction with polarized protons

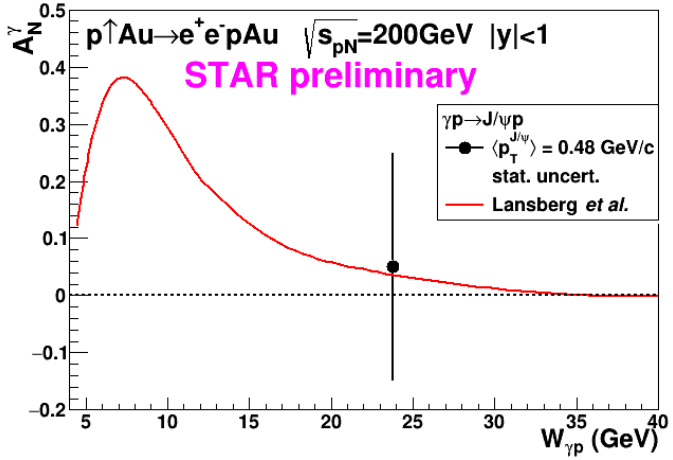
$$d\sigma/d\phi \propto 1 + A_N^{\gamma} \cos\phi$$

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









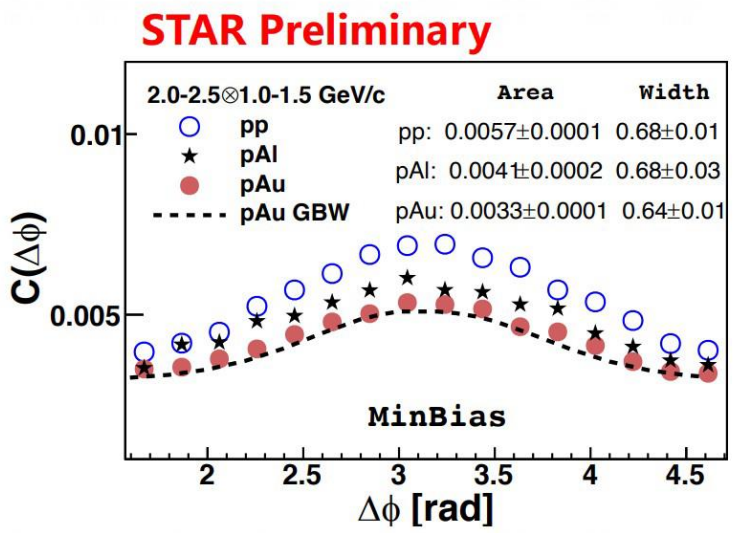
Phys.Lett. B793 (2019) 33-40

- Expect larger asymmetry at low $W_{\gamma p}$
- Statistical uncertainty is still large

Non-linear Gluon Dynamics

- Dihadron correlations in p+p / p+Au collisions at forward rapidity
  - High-p_T pion (trigger) high-x parton (quark / p)
  - Associated pion low-x parton (gluon / Au)
- Extract from fit: area / width / pedestal
  - Area suppressed for p+Au / p+Al
  - No suppression at high-p_T
  - Dependence on event activity

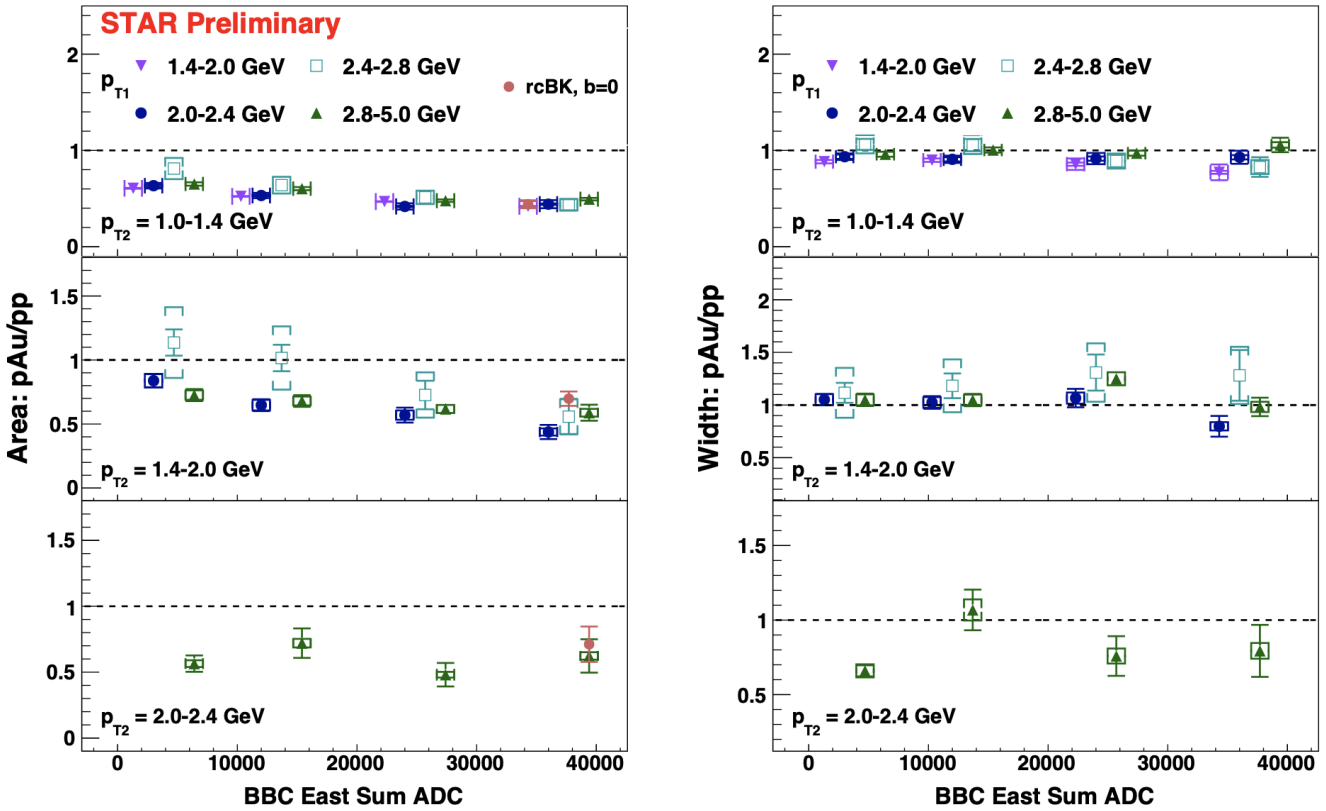
$$C(\Delta\phi) = N_{pair}(\Delta\phi)/N_{trig}$$



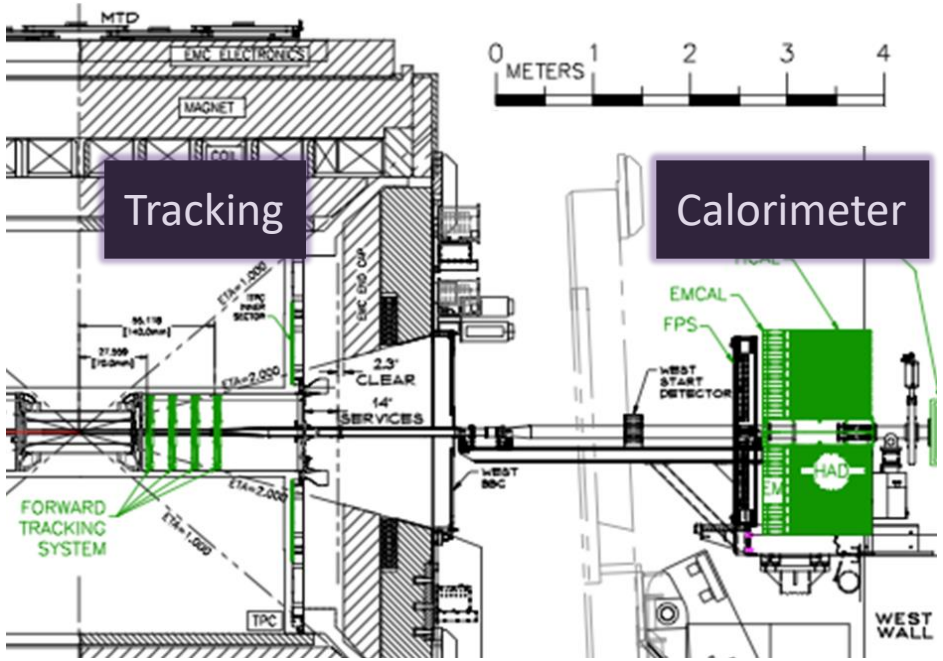
MinBias = no selection on event activity

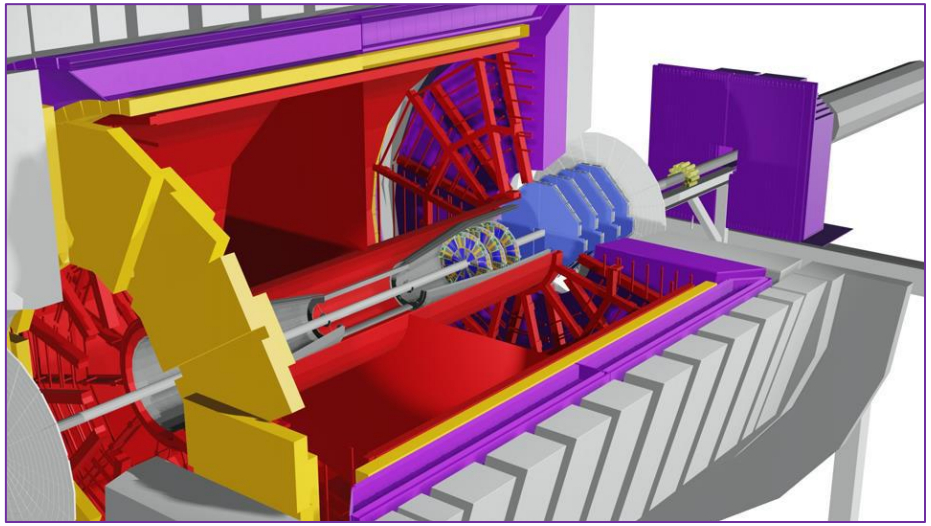
GBW: A. Stasto et al., PLB 716, 430 (2012)

X. Chu et al. (STAR), DNP 2020



STAR Forward Detector Upgrade





- Tracking and calorimetry at forward pseudorapidities $2.5 < \eta < 4.0$

- Si-Tracker
- sTGC disks
- Preshower detector
- EMCAl
- HCAL

- Prototype tests in 2019/20
- Calorimeters installed through 2020
- Ready for data taking in late 2021

	p+p / p+A	A+A
Tracking	charge separation photon suppression	$\frac{\delta p}{p} \approx 20 - 30\%$ at $0.2 < p_T < 2.0$ GeV/c

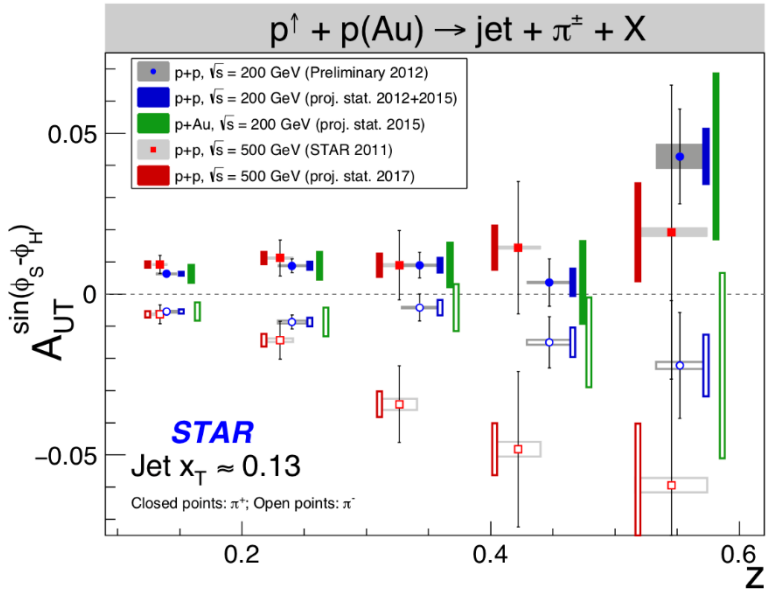
	p+p / p+A	A+A
ECAL	$\approx 10\%/\sqrt{E}$	$\approx 20\%/\sqrt{E}$
HCAL	$\approx 60\%/\sqrt{E}$	n/a

Spin Dependent Fragmentation

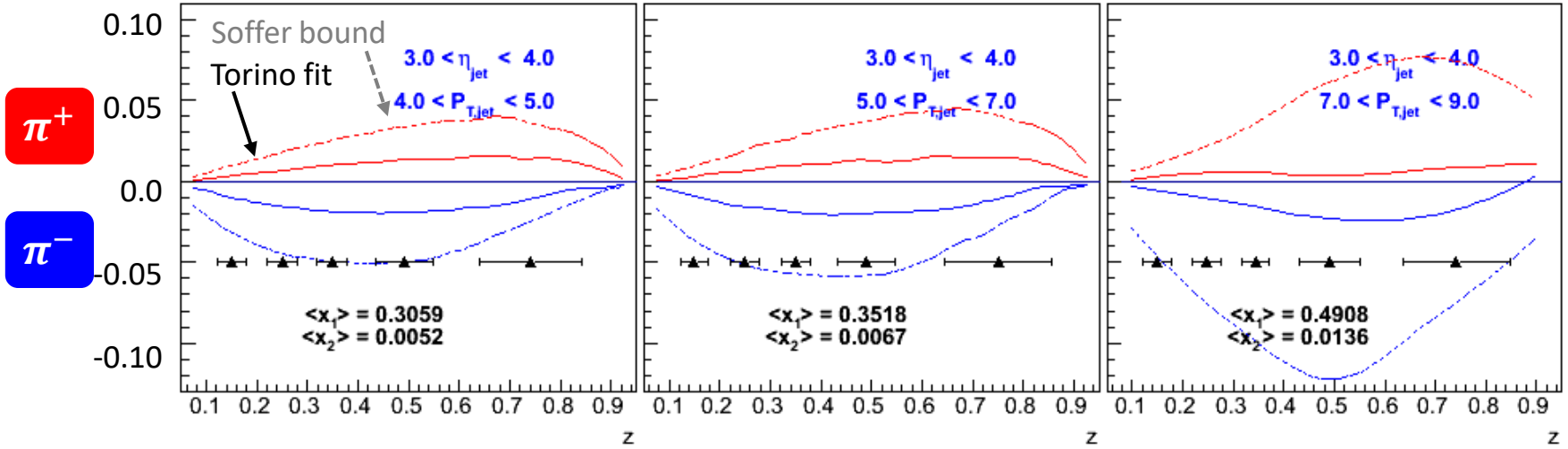
- Hadron in jet
  - STAR measured at midrapidity, 200 – 500 GeV
  - Move to higher x

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

  - 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

Other Hadron / Jet Observables

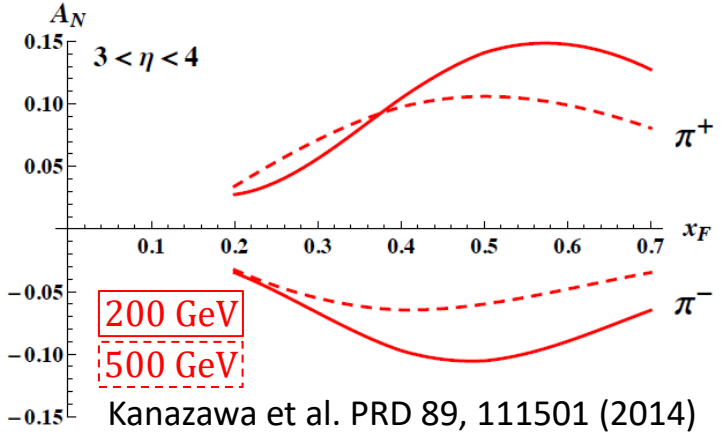
- Suggested large spin dependent effects in quark fragmentation
  - Collinear quark-gluon-quark correlators

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

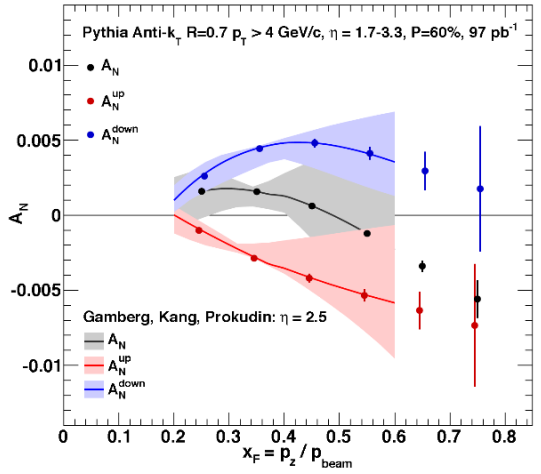
  - Flavor dependence
  - Evolution effects of ETQS distribution functions
- Test origin of large transverse asymmetries
  - Compare direct photons and jets

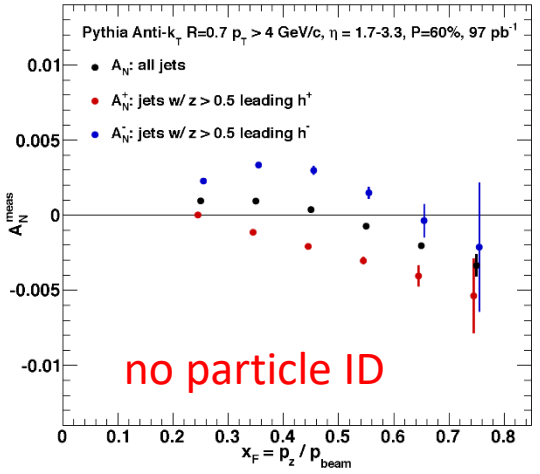
$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x, x)$$

  - 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.
- Upgrades to existing facilities are important: RHIC run 2022, transversely polarized p+p collisions at $\sqrt{s} = 510$ GeV.
- Measurements are complementary to and will inform experimental requirements for the future electron-ion collider.