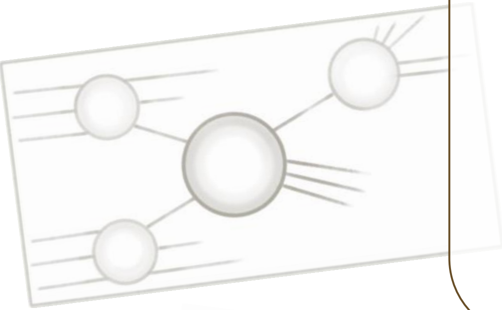
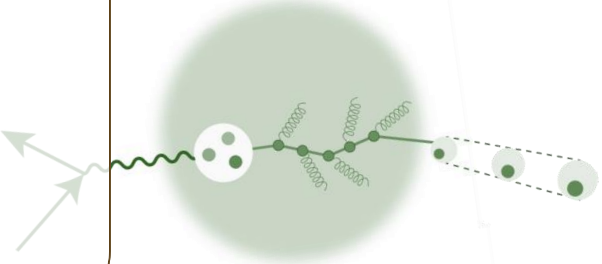


Recent Results from RHIC
Cold QCD and Spin



Oleg Eyser

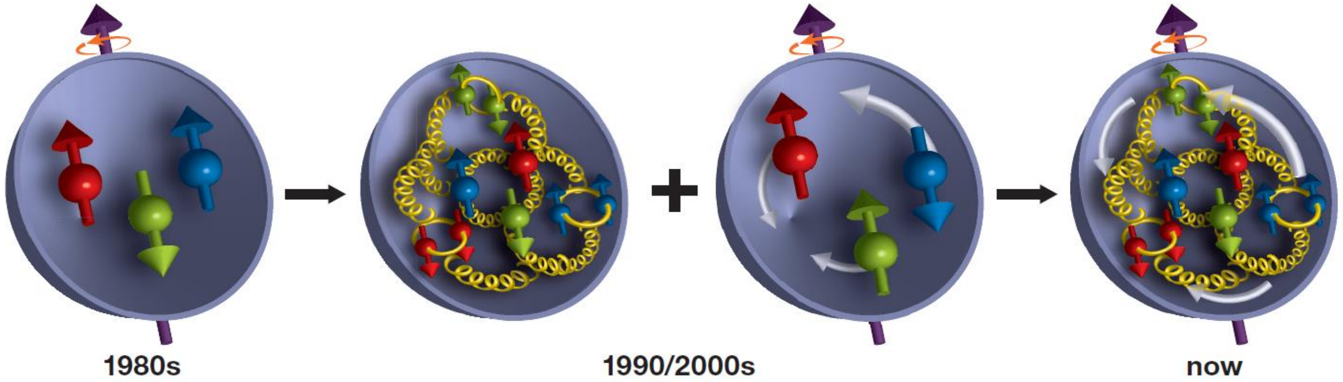
Correlations in Partonic and Hadronic Interactions

February 3 – 7, 2020

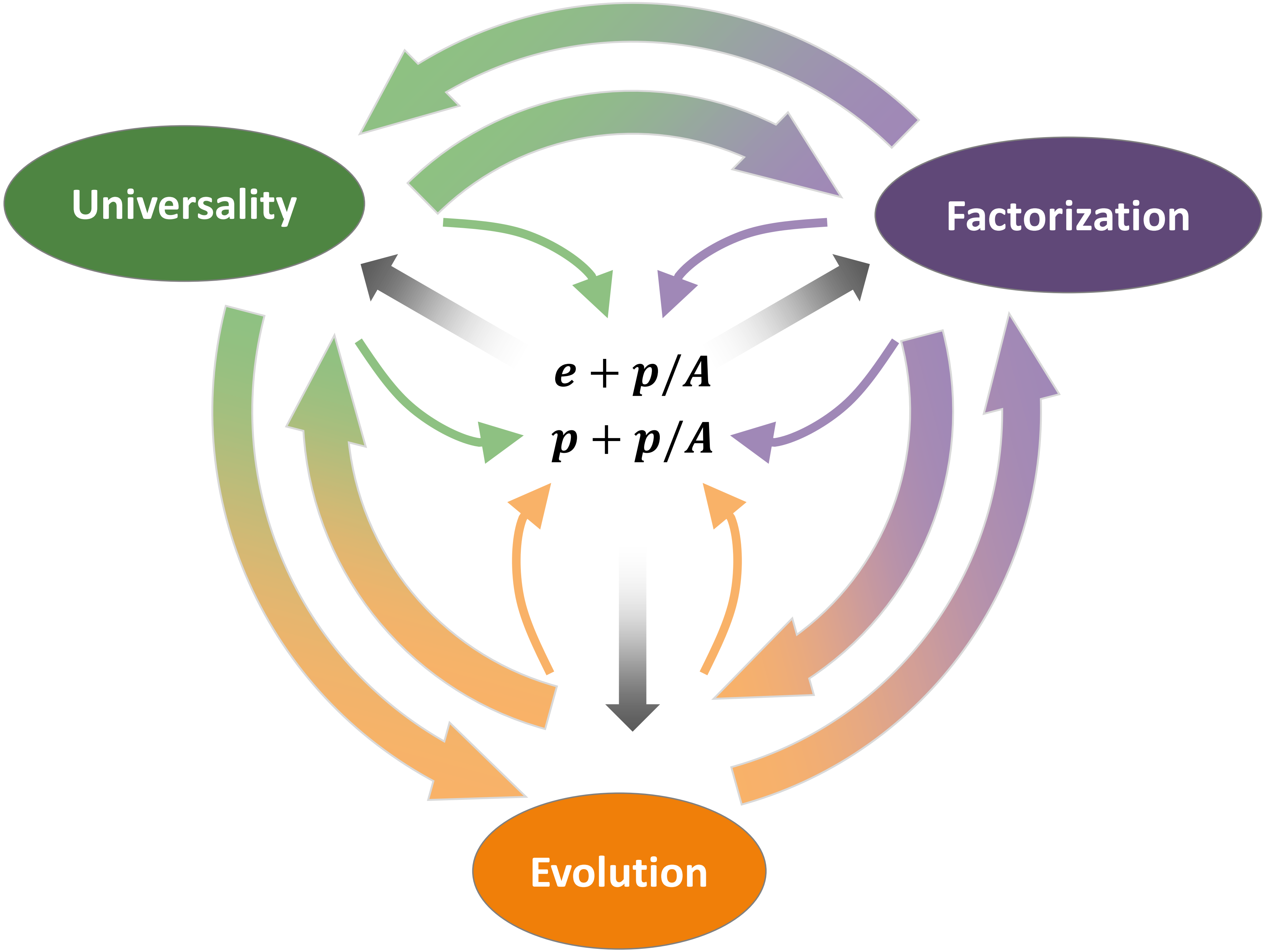
CERN

BROOKHAVEN
NATIONAL LABORATORY

Nucleons & Nuclei

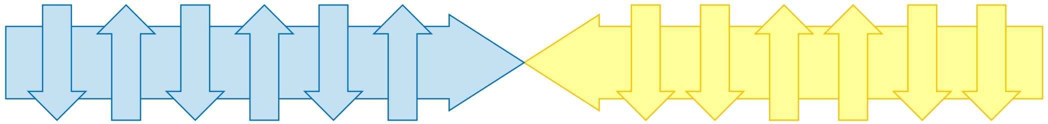


- What is the nature of the spin of the proton?
- How do gluons contribute to the proton spin?
- How polarized are the sea quarks in the nucleon?
- What do transverse spin phenomena teach us about the proton structure?
- How can we describe the multi-dimensional landscape of nucleons and nuclei?
- How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



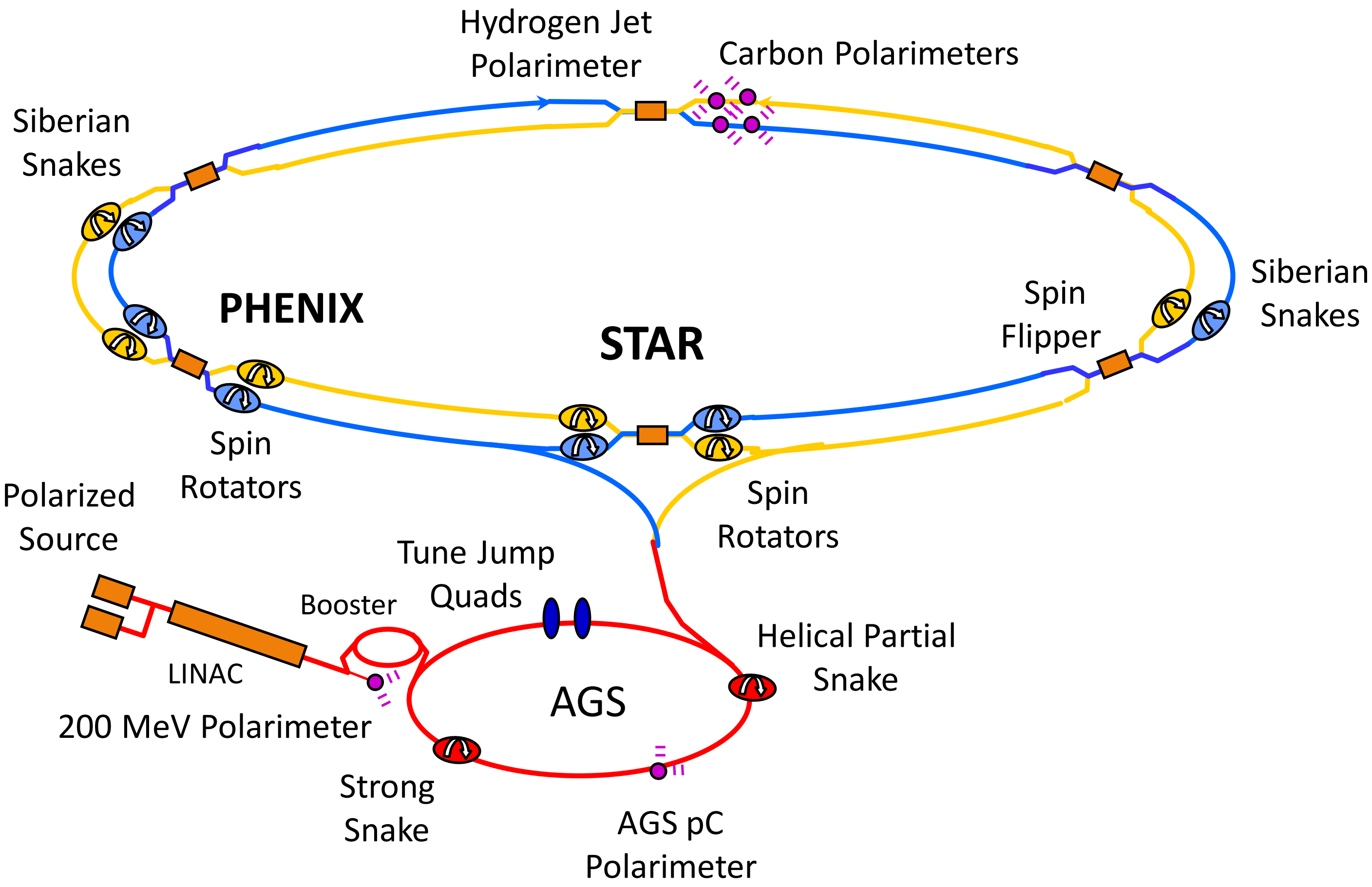
Universality
Factorization
$e + p/A$
$p + p/A$
Evolution

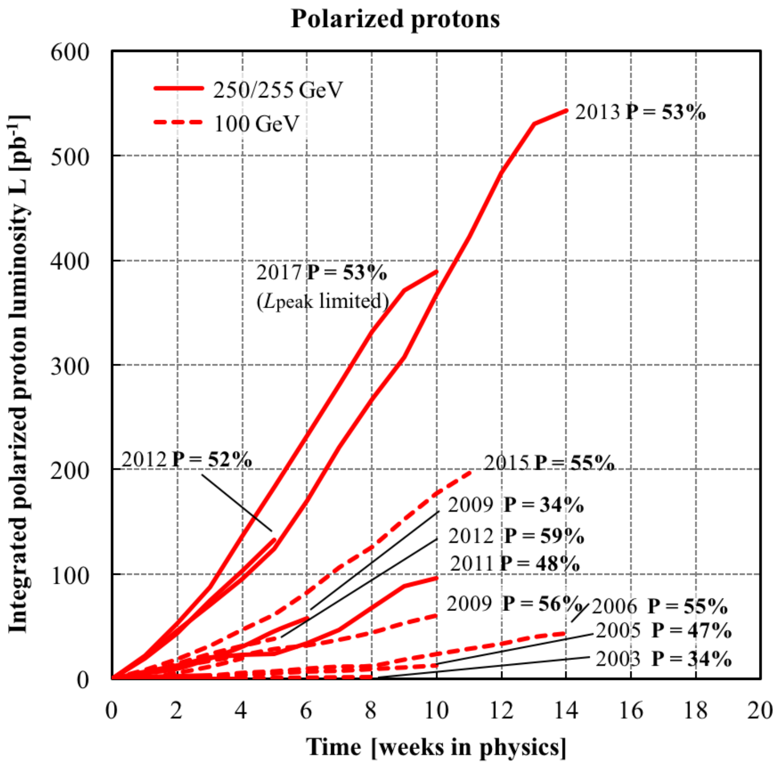
RHIC as a Polarized Proton Collider

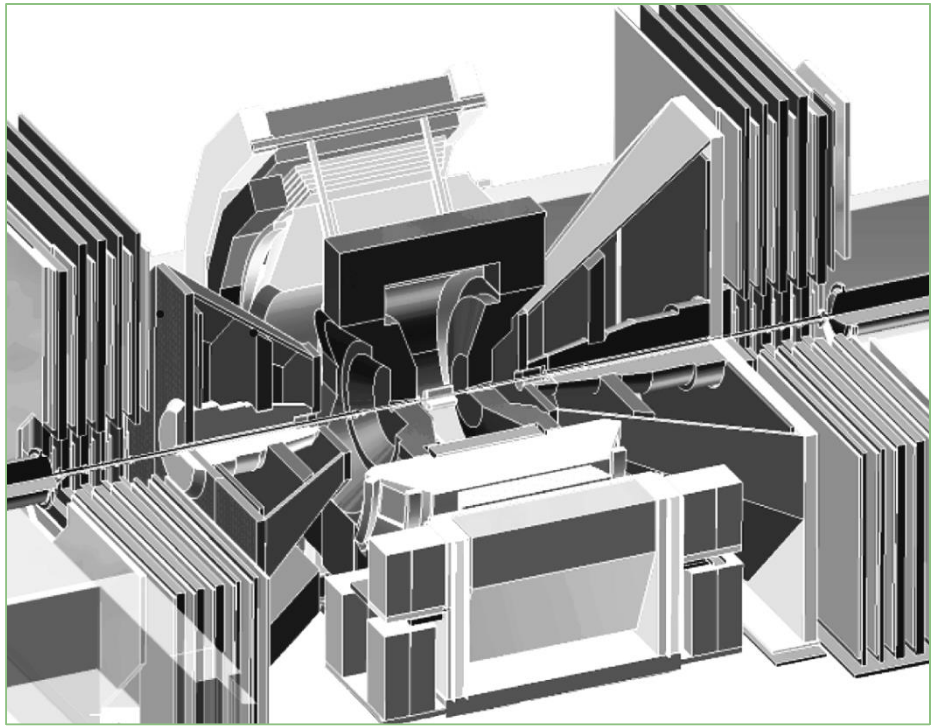


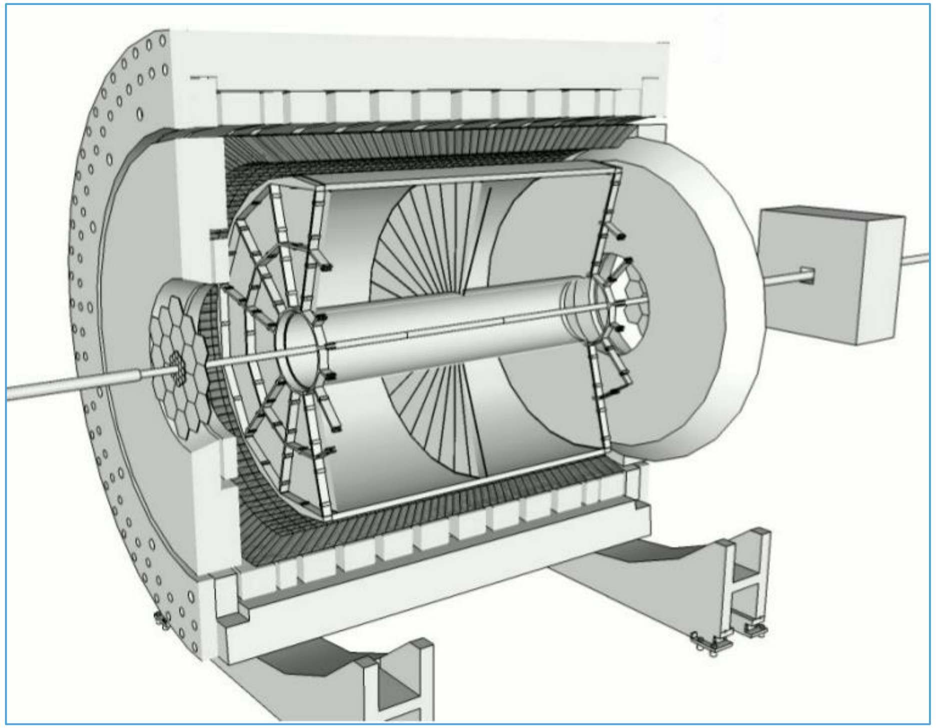
$\vec{p} + \vec{p} \,/\, \vec{p} + A$

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









PHENIX

High resolution

High rate

DC / Pad Chambers / Muon Arms

EMCal

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

STAR

Large acceptance

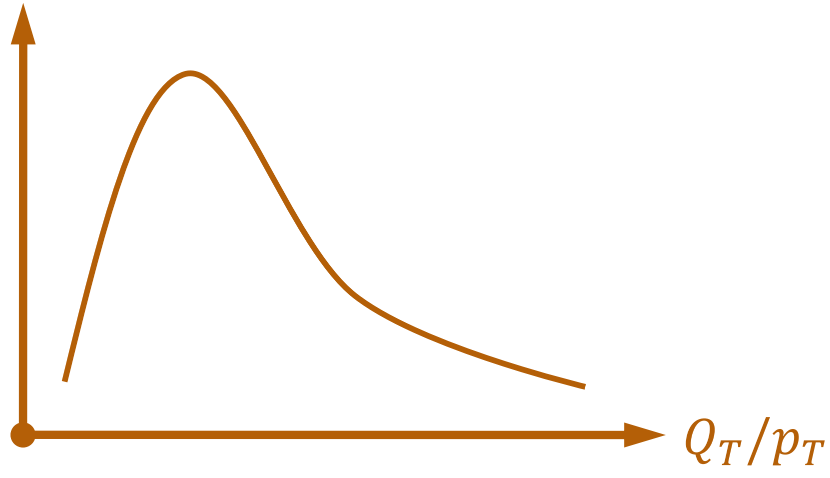
$-1 < \eta < 2$

TPC+TOF

EMCal

Forward EMCal, $2.5 < \eta < 4$

Transverse Spin Effects



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

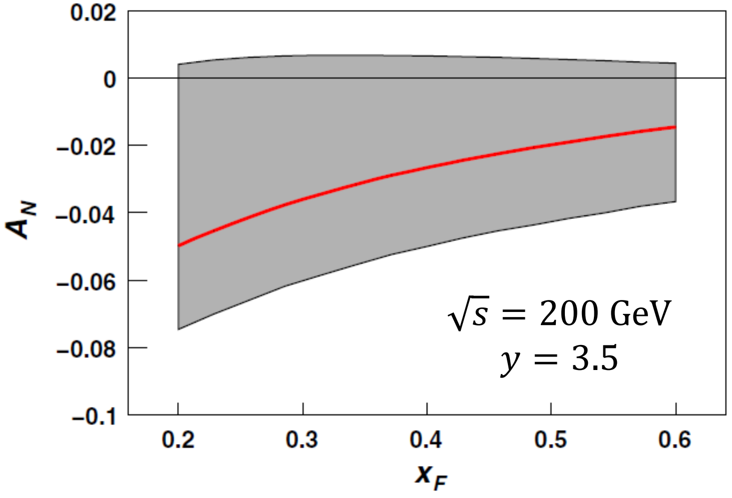
$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x,x)$$

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

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

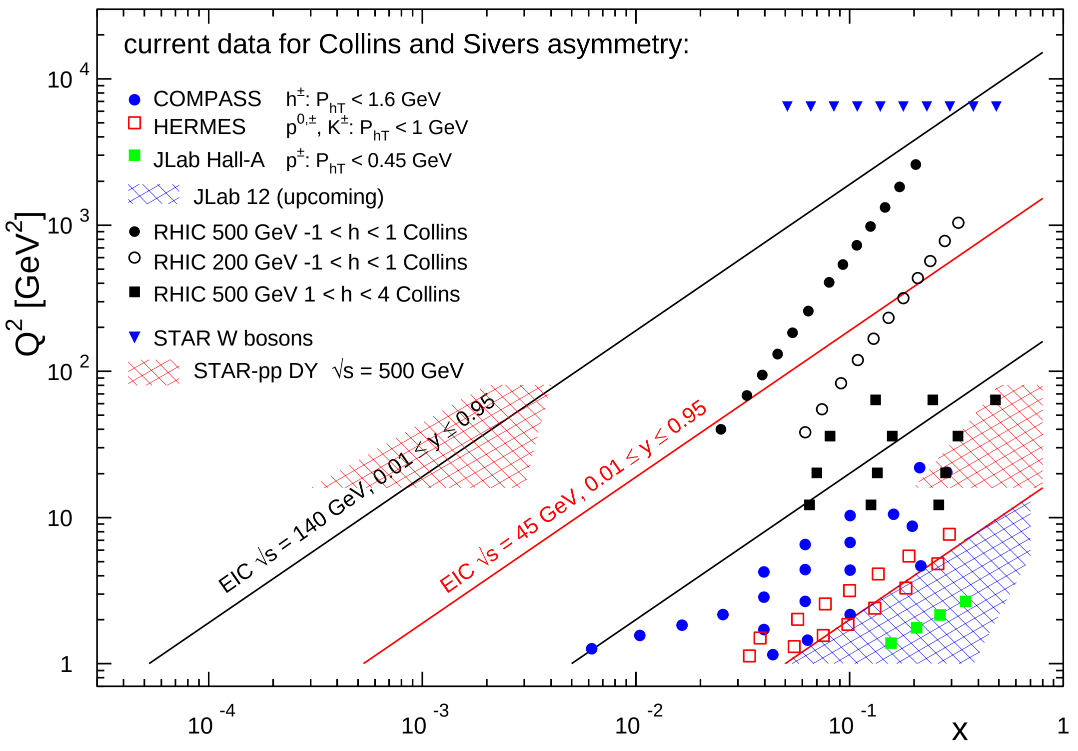
Direct photons, PRL 110, 232301



Initial and Final State Effects

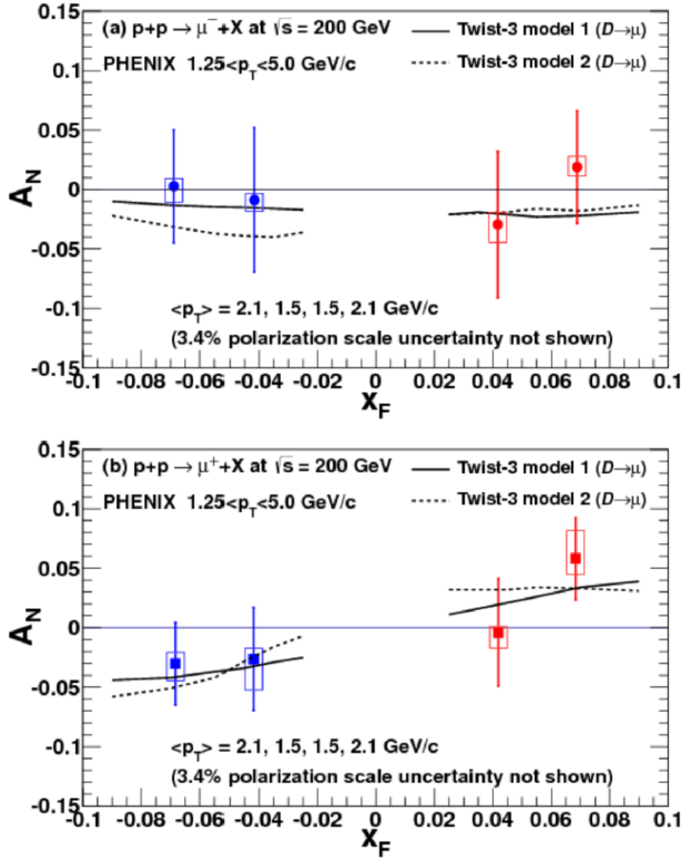
Sivers function $f_{1T}^{\perp}$	$W^{\pm}, Z^0$, Drell-Yan γ^* $\cos\phi_S$
quark transversity h_1	
$\otimes$ Collins fragmentation function $H_1^{\perp}$	hadrons in jets $\cos(\phi_S - \phi_h)$
$\otimes$ interference fragmentation $H_1^{\angle}$	hadron pairs $\cos\phi_R$
gluon linear polarization h_1^g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

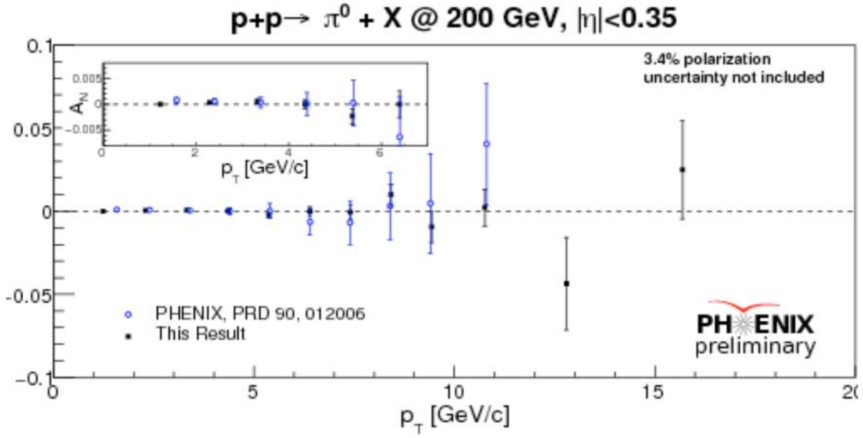
World Data (Collins & Sivers TMDs)

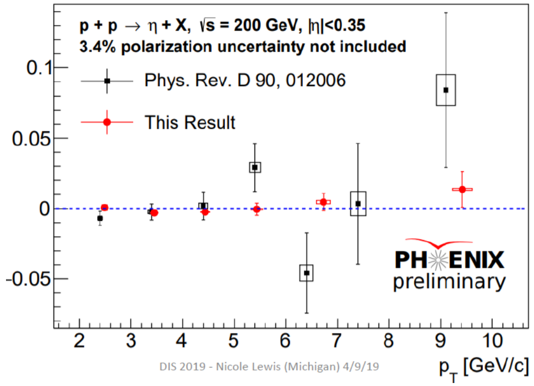


Inclusive Measurements

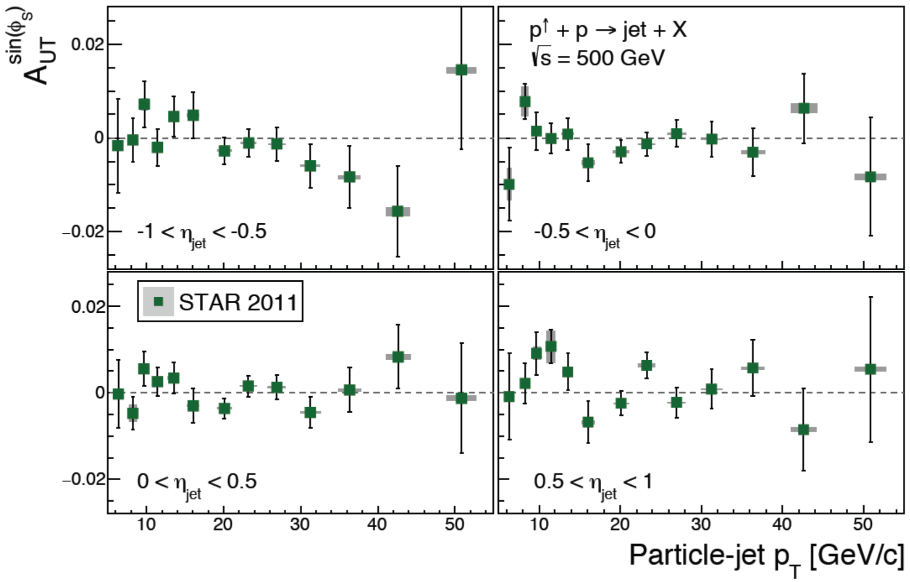
Phys.Rev. D95 (2017) 112001







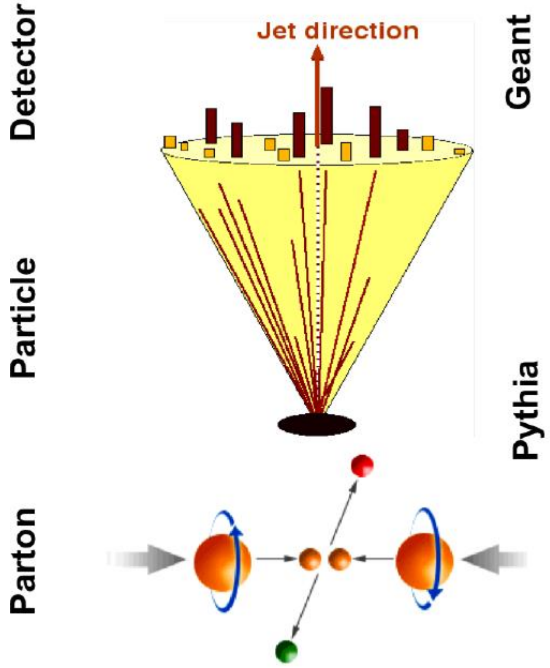
Phys.Rev. D97 (2018) 032004

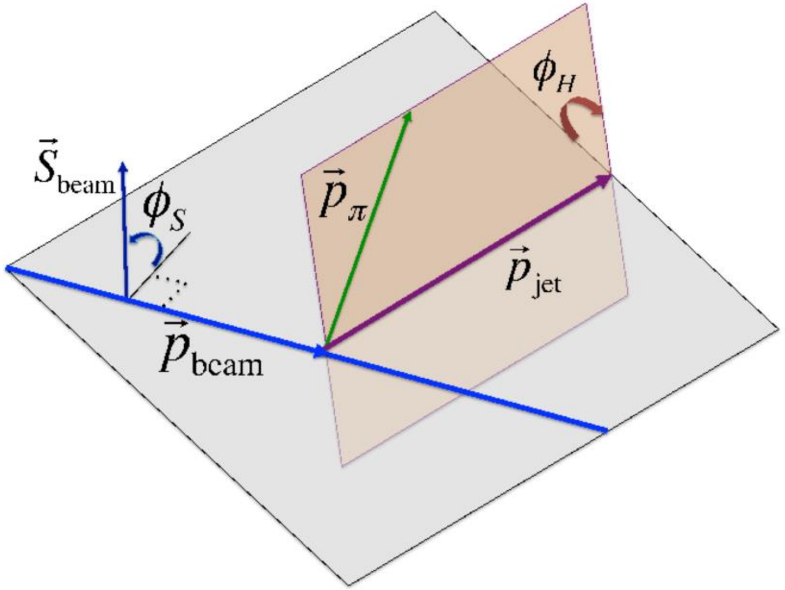


- $\vec{p} + p, \vec{p} + Al, \vec{p} + Au$
- Different probes (π^0, η, $\mu^\pm$, jets)
- $\sqrt{s_{NN}} = 200$ / 500 GeV
- Sensitive to gluon T_G
- Very high precision, consistent with zero

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

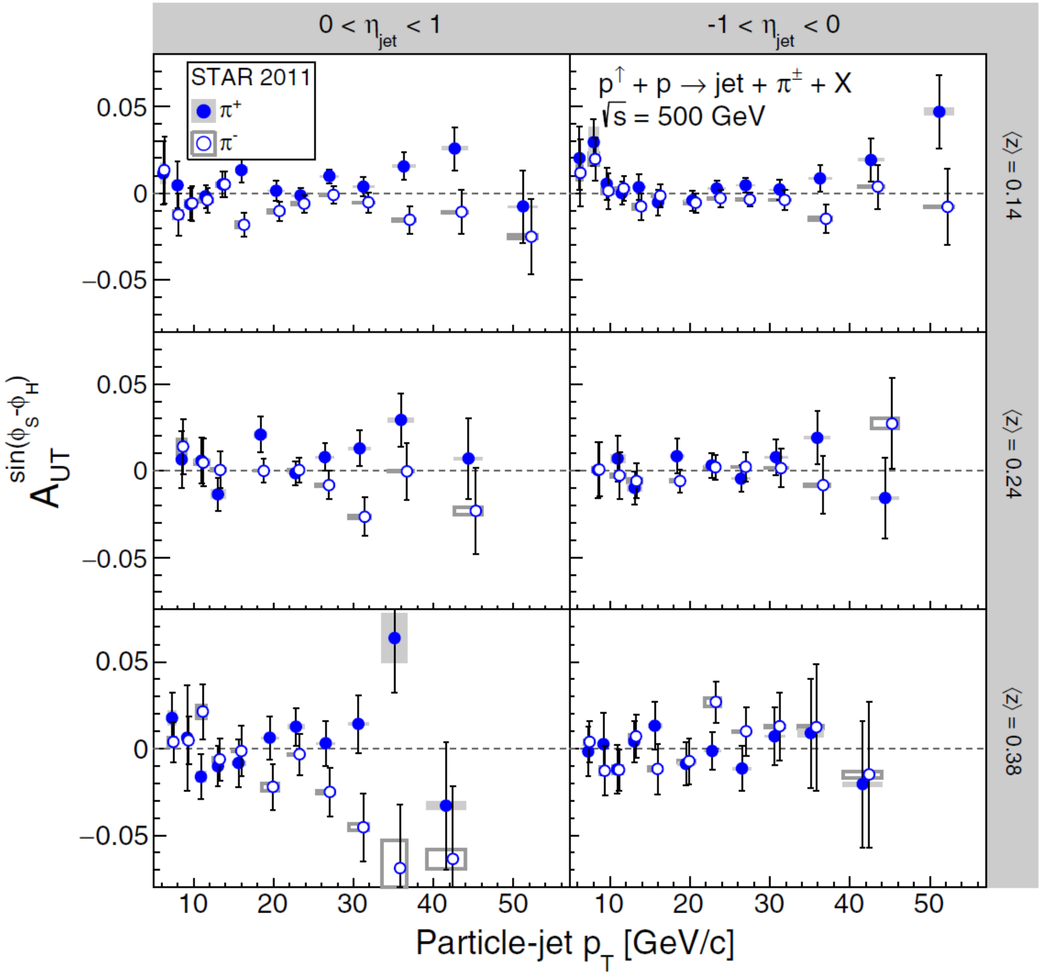


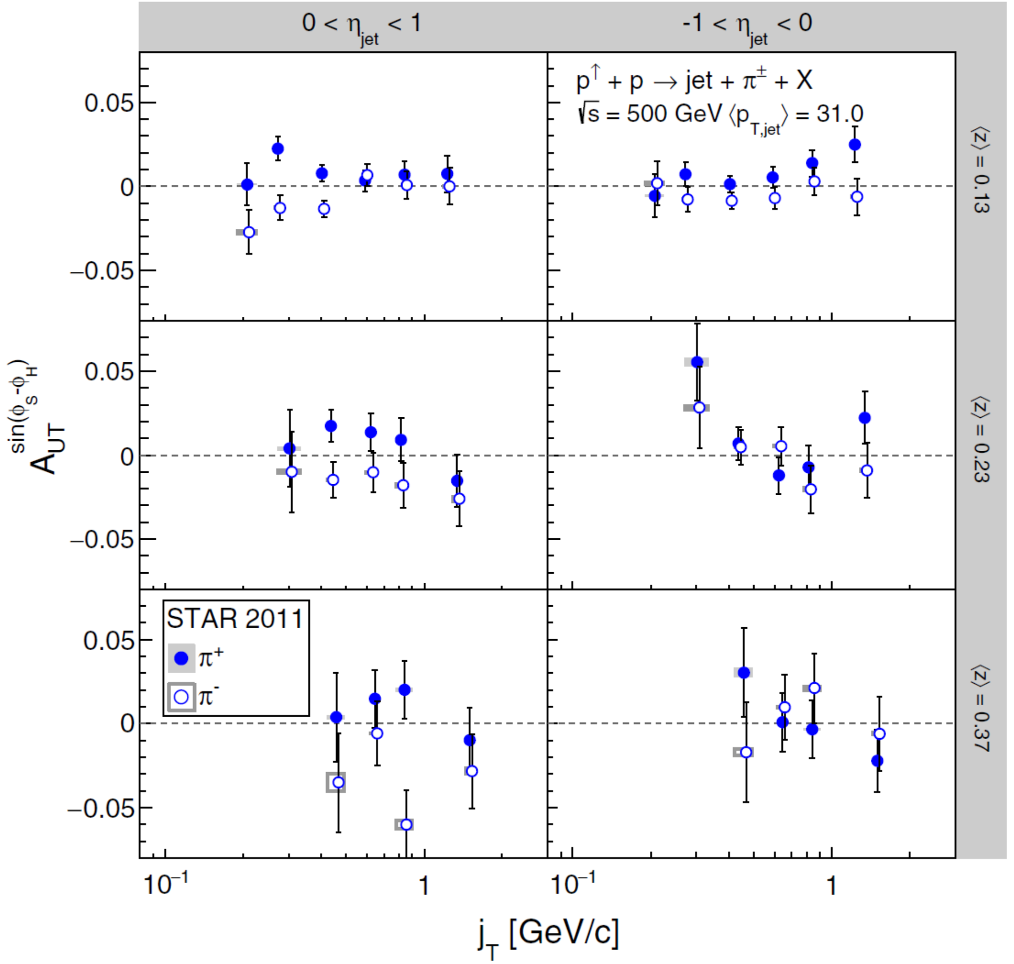


$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H)$$

Collins Asymmetries

Phys. Rev. D97 (2018) 032004

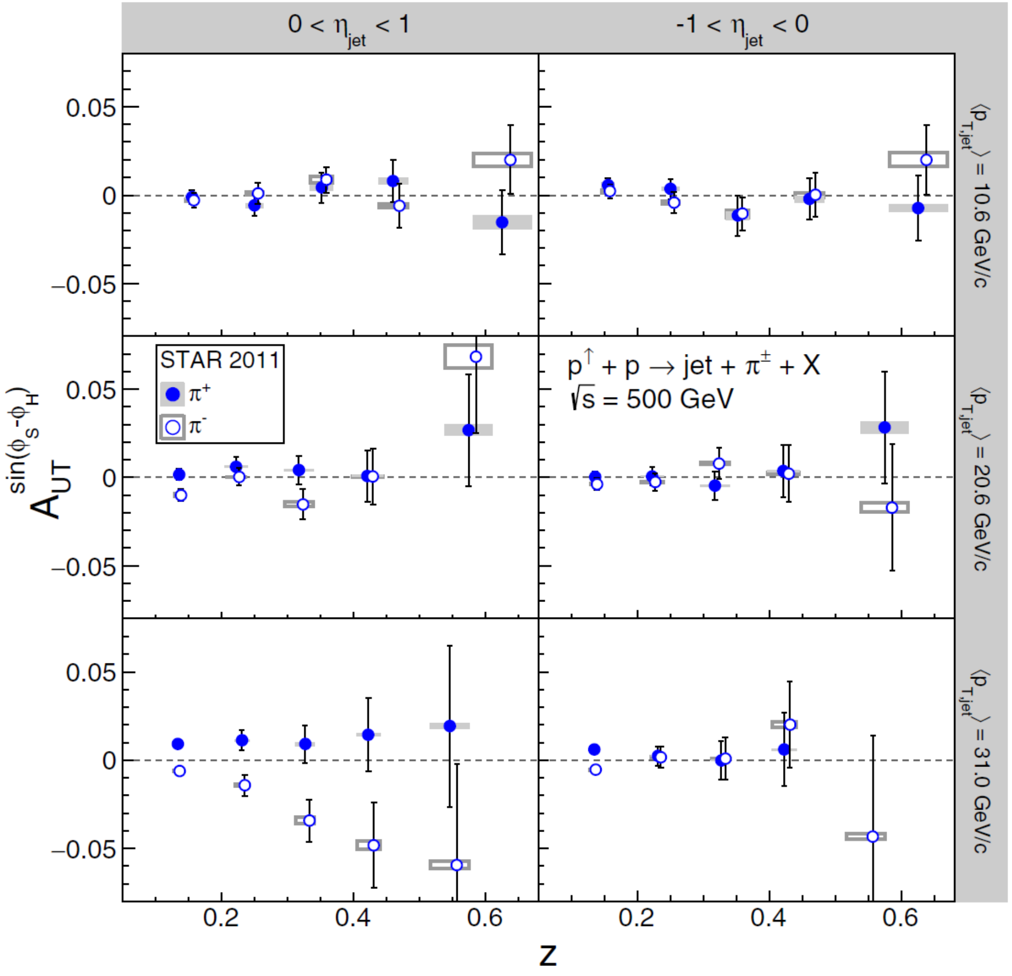


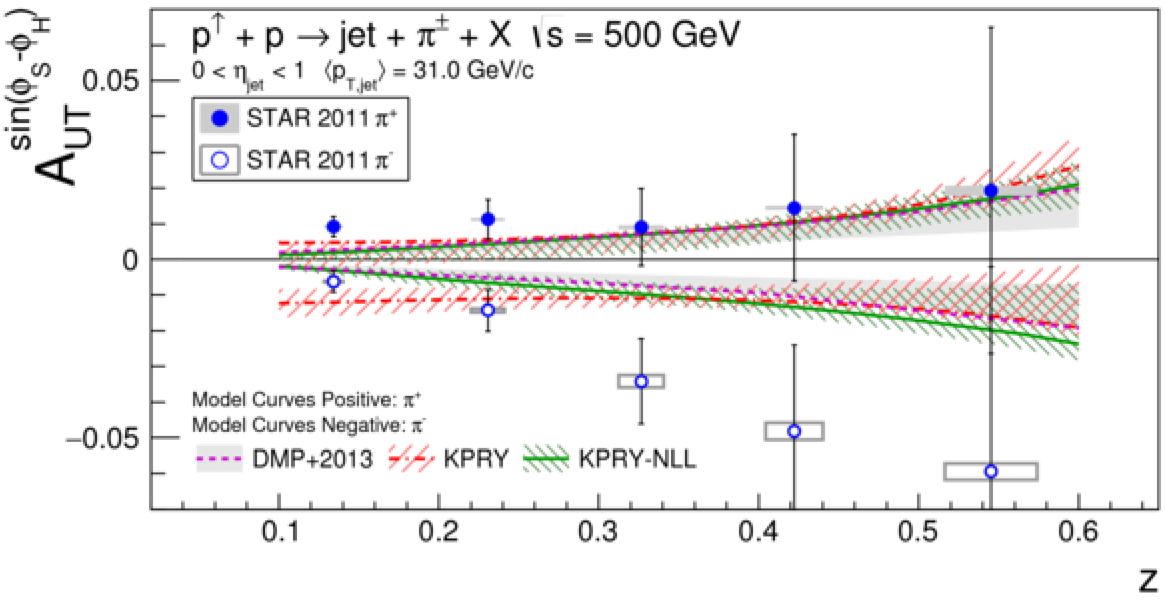


$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

Collins Asymmetries

Phys. Rev. D97 (2018) 032004



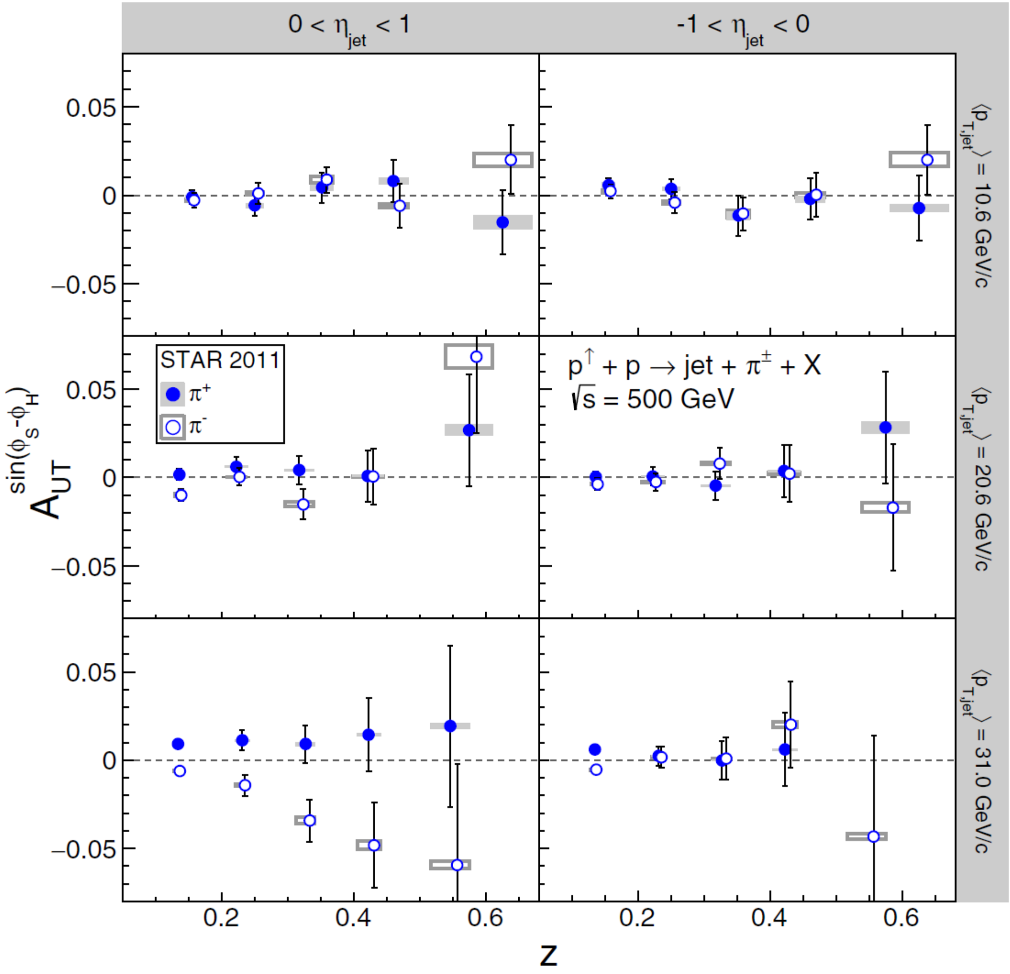


Comparison with
Phys. Lett. B773, 300-306 (2017)
arXiv:1707.00913

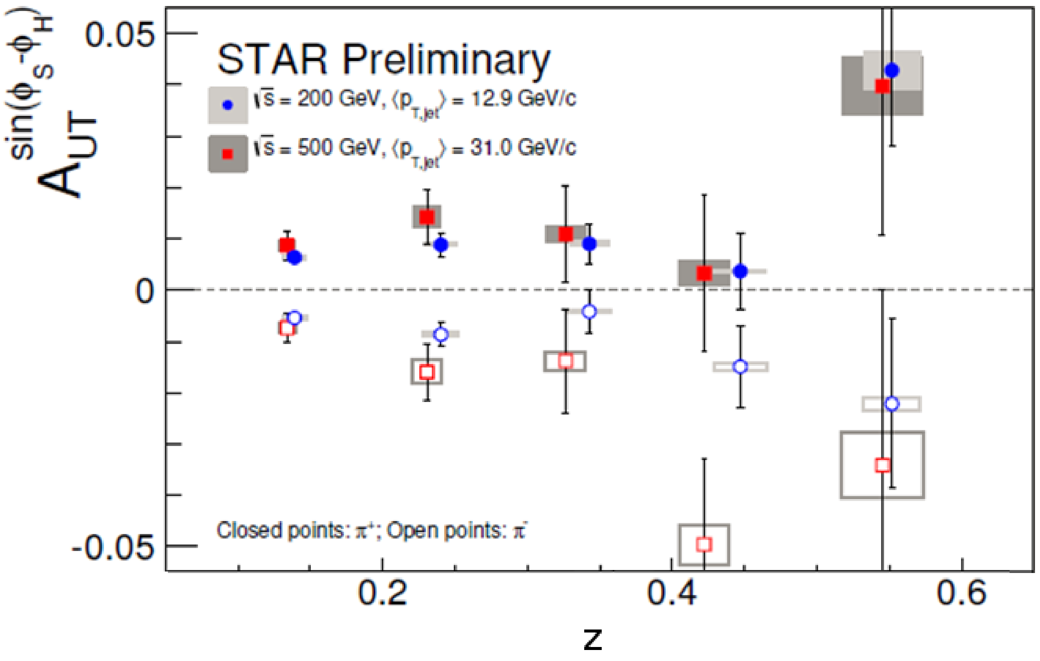
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

Collins Asymmetries

Phys. Rev. D97 (2018) 032004



Comparison with preliminary data at 200 GeV

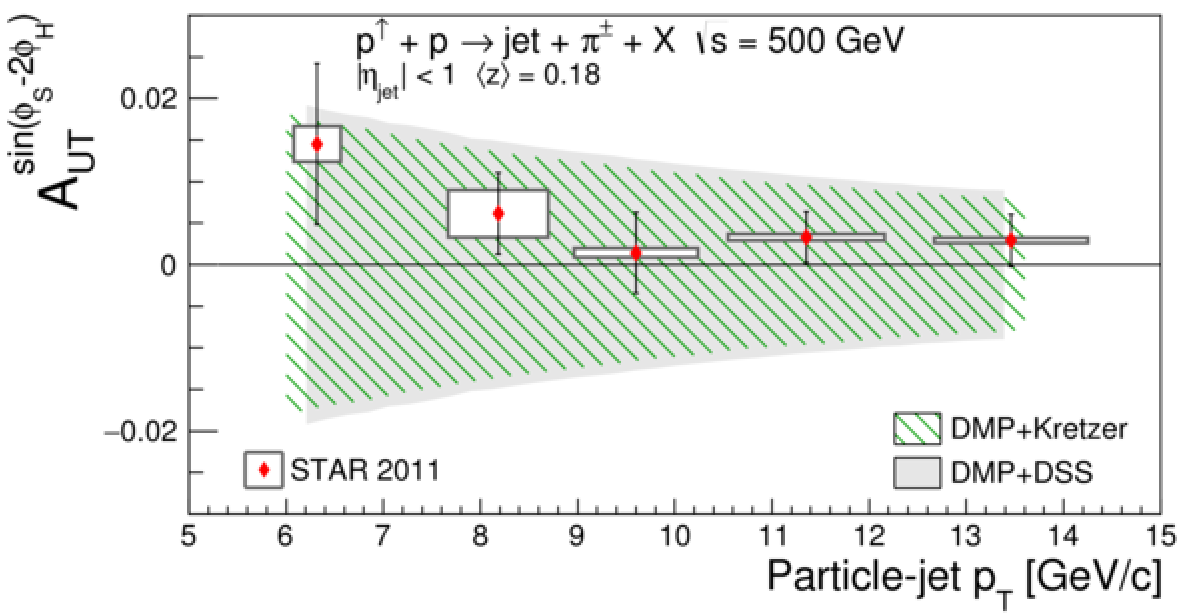


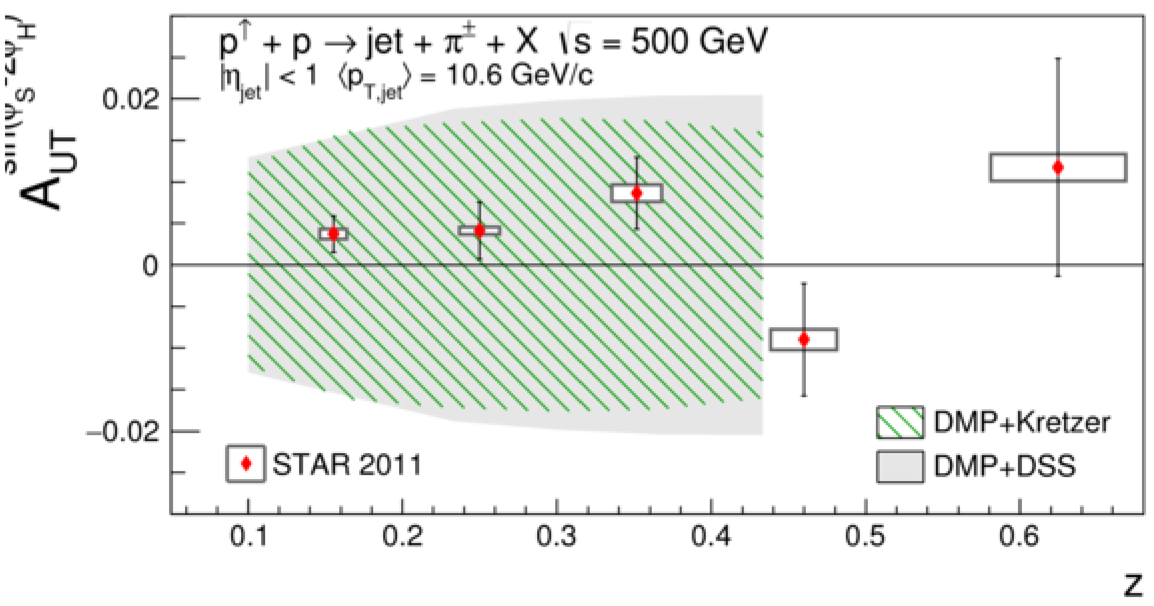
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

Collins-Like Asymmetries

Phys. Rev. D97 (2018) 032004

- Linear gluon polarization
- Upper limits from Phys. Lett. B773 (2017) 300-306
- First data!

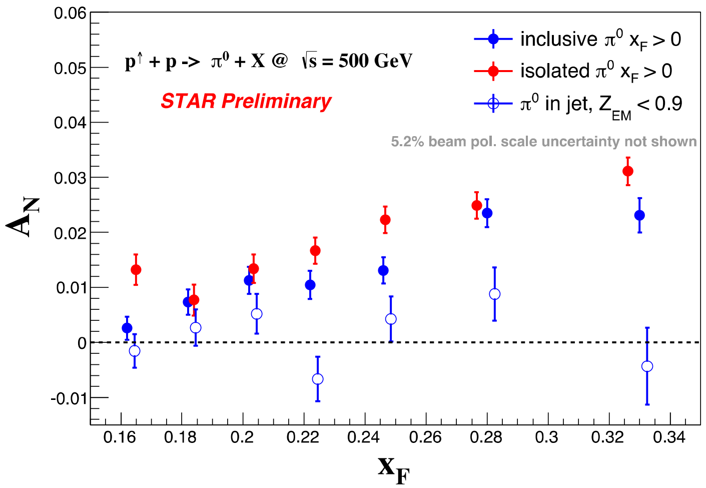


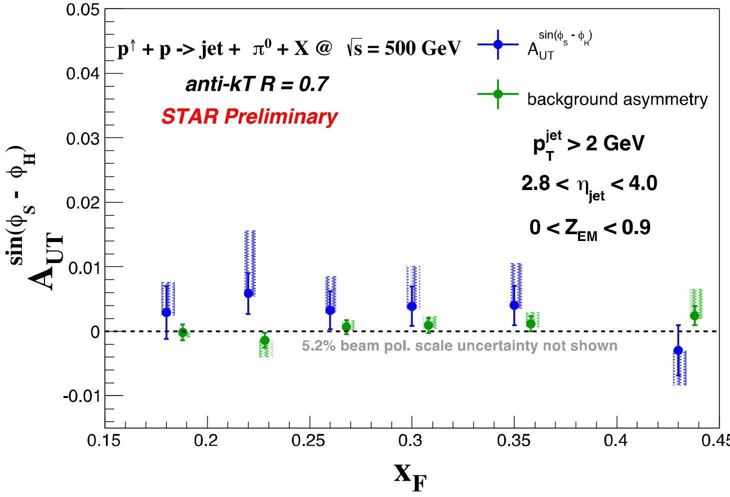


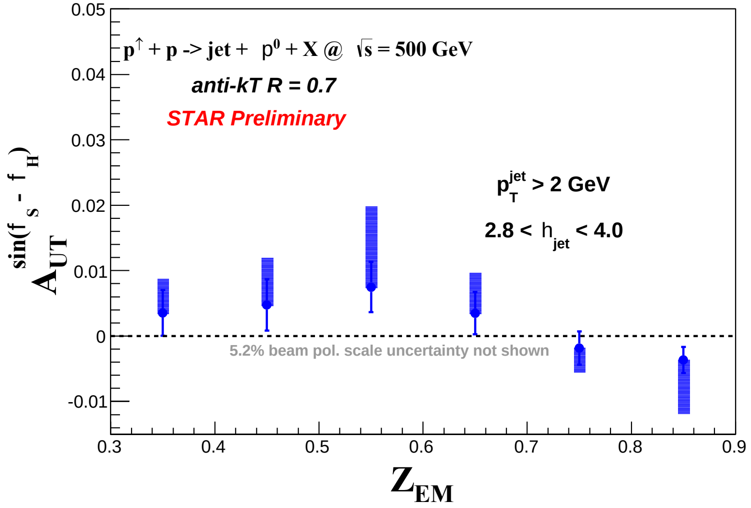
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

Hadrons in Jets (Forward)

- Electromagnetic jets with forward calorimeter
  - π^0 in jet
- $2.8 < \eta < 4.0$
- Additional data on disk
  - $\sqrt{s} = 200$ & 500 GeV

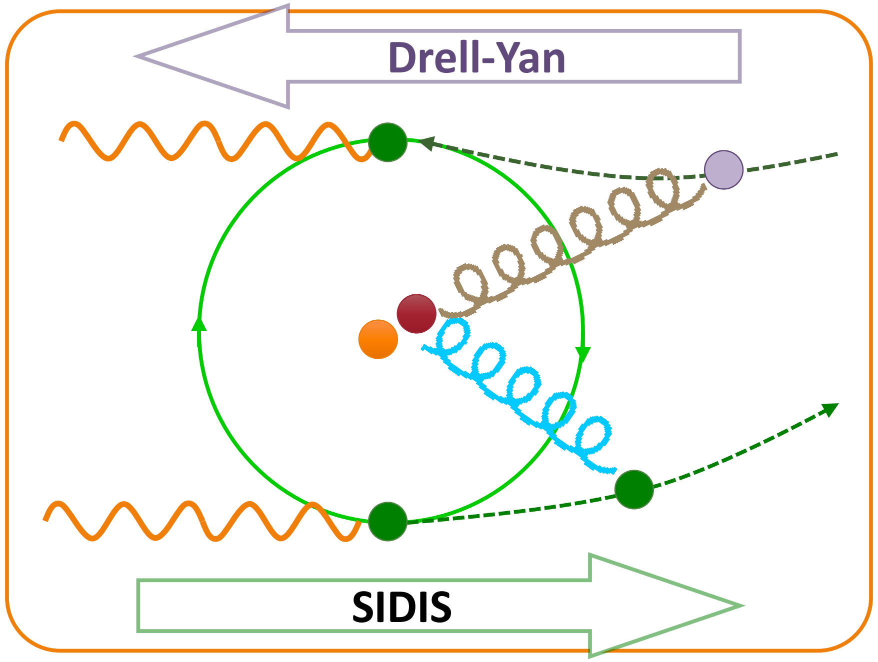


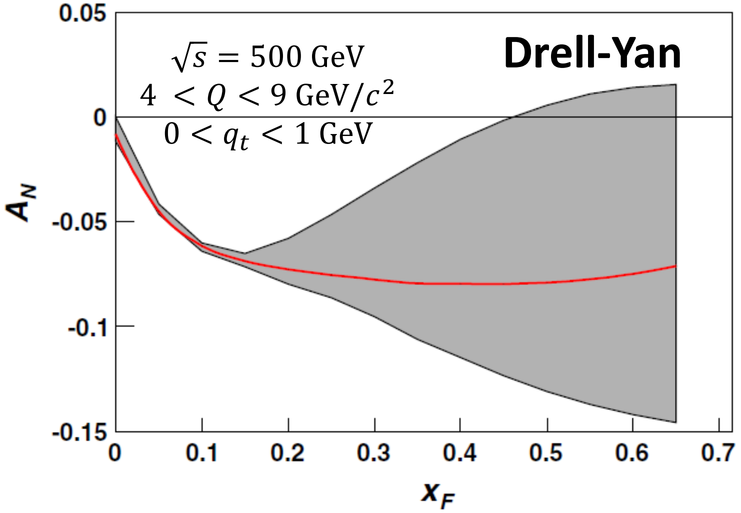


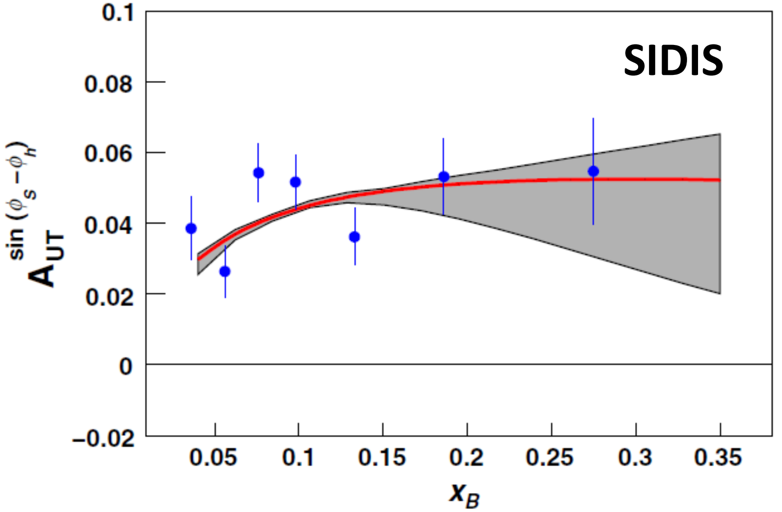


$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

Non-Universality of Spin-Orbit Correlations







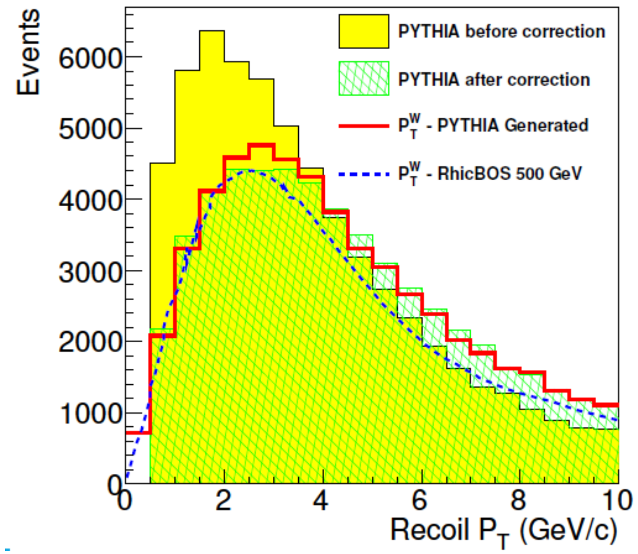
Gamberg, Kang, Prokudin
Phys. Rev. Lett. 110, 232301 (2013) with HERMES data

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

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

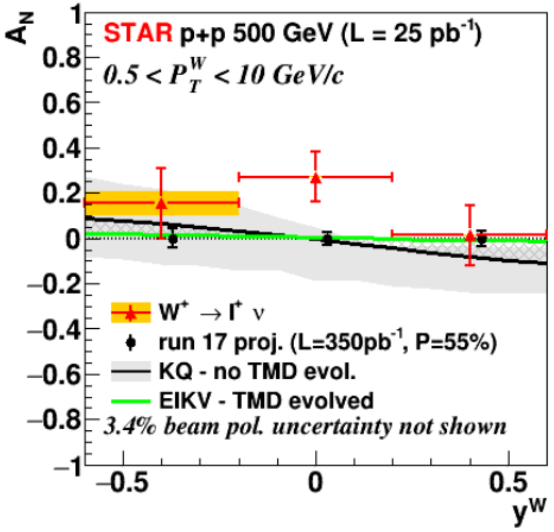
- Requires full reconstruction of $W^{\pm}$ kinematics
- Missing transverse momentum from recoil

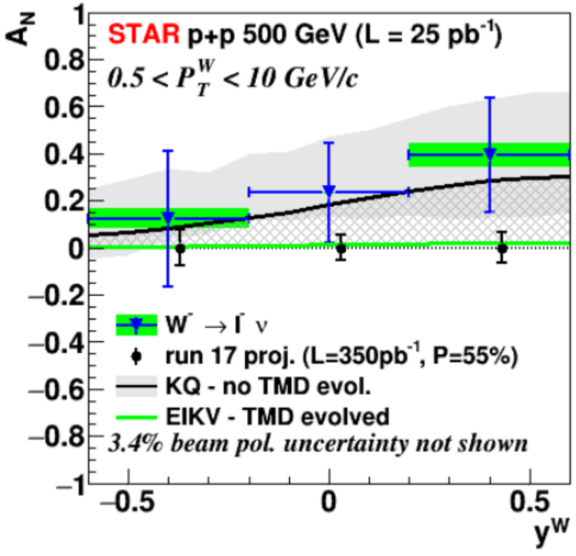
$$P_T^W = P_T^e + P_T^\nu = P_T^{recoil}$$

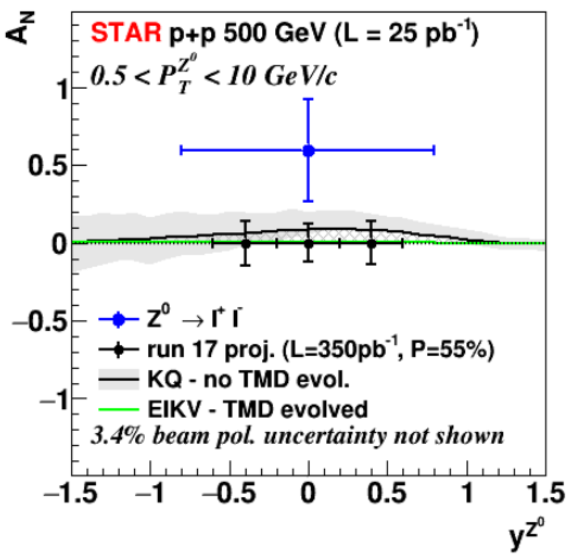


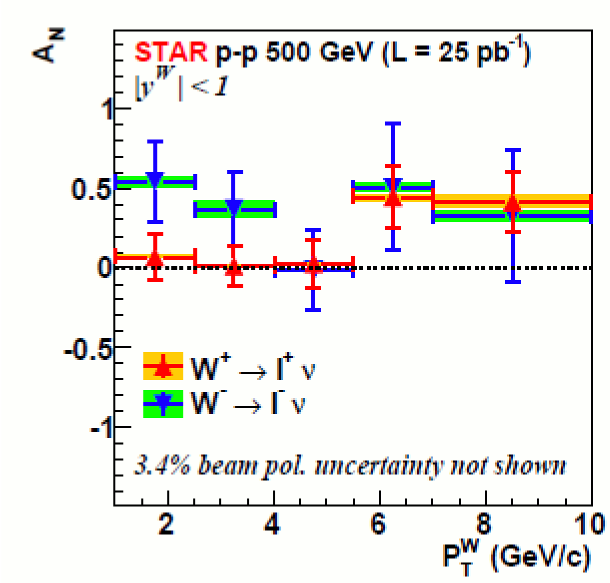
Phys. Rev. Lett. 116, 132301 (2016)

Comparison with Phys. Rev. Lett. 103, 172001





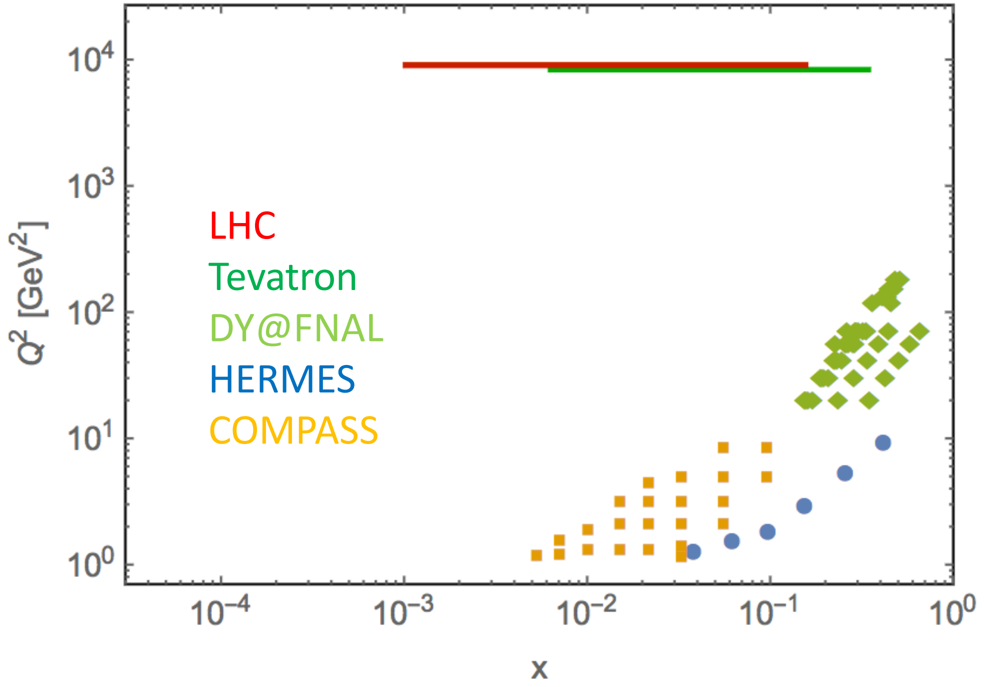


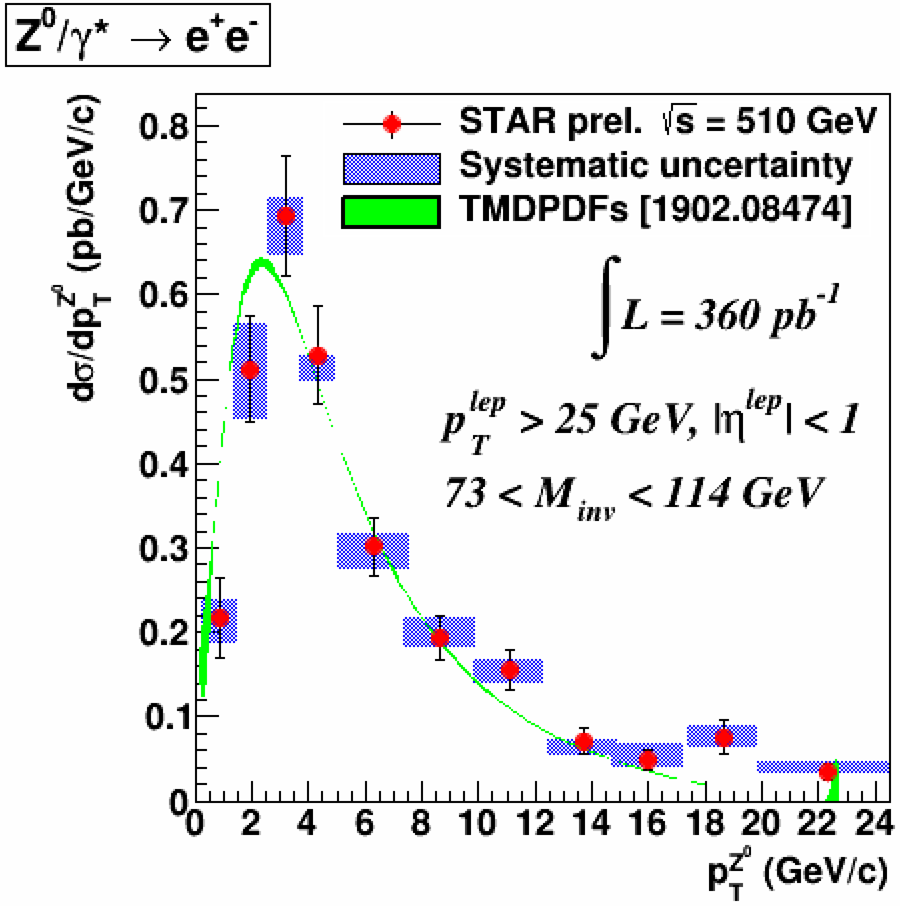


Unpolarized TMDs

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

- 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: $350\ \mathrm{pb}^{-1}$

Gluon Polarization

$$\frac{1}{2} = \Delta\Sigma + \Delta G + L_q + L_G$$

Double helicity asymmetries:

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

$$A_{LL} = \frac{1}{P_1 P_2} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}} \qquad R = L_{++}/L_{+-}$$

- Inclusive jets

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

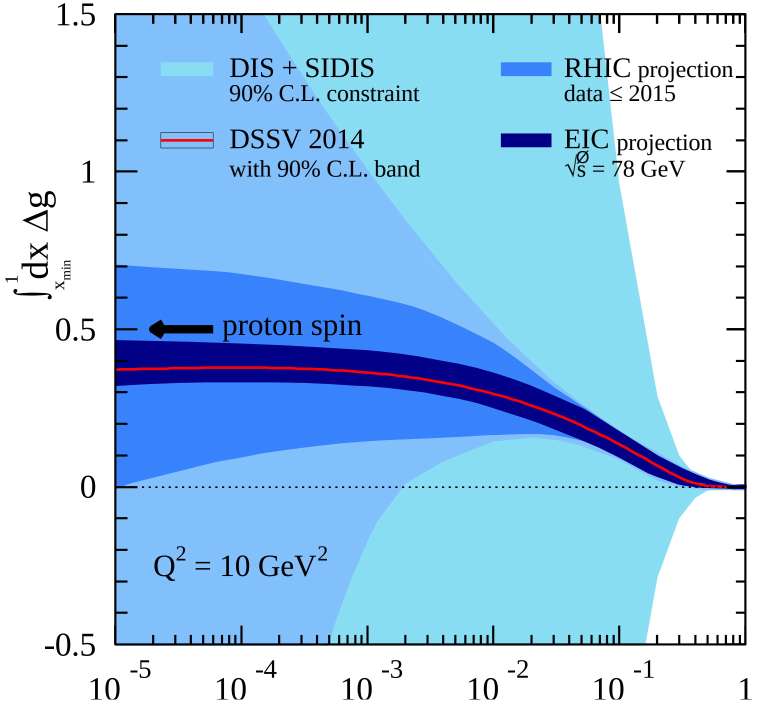
$$x_T = 2p_T/\sqrt{s}$$

- Dijets

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

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

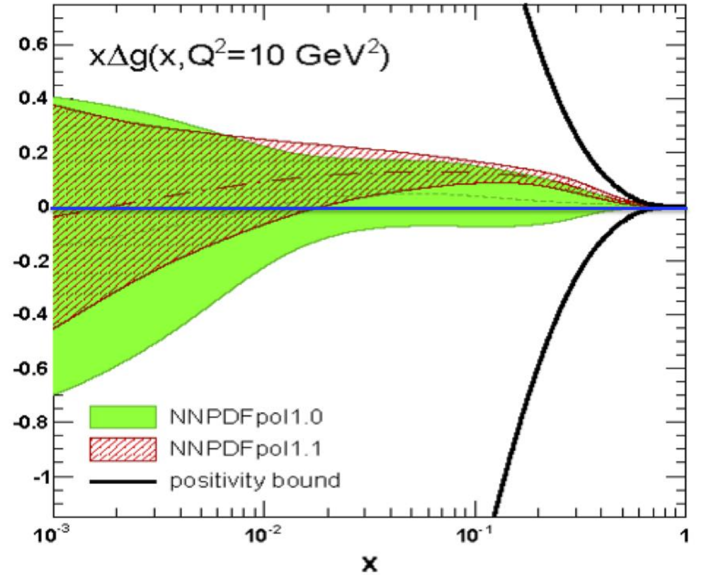
$$M = \sqrt{x_1 x_2 s}$$



DSSV

PRL 113 (2014) 012001

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

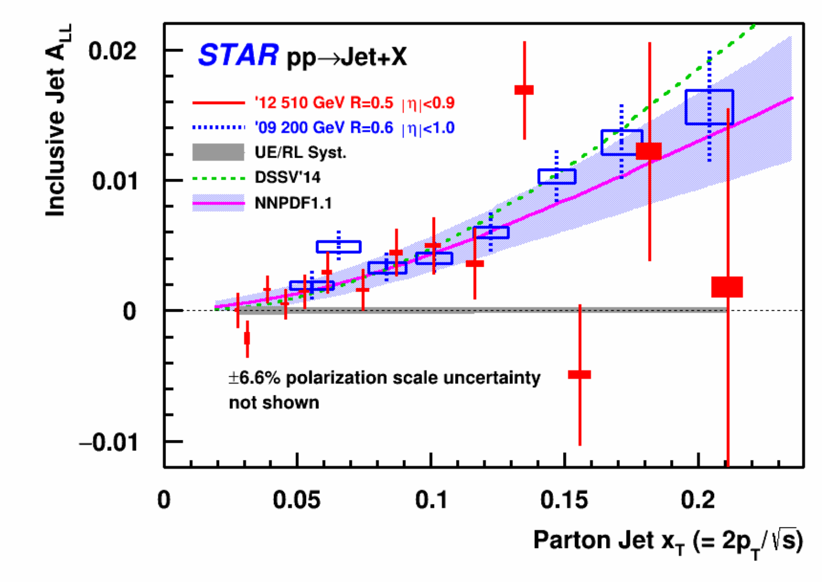


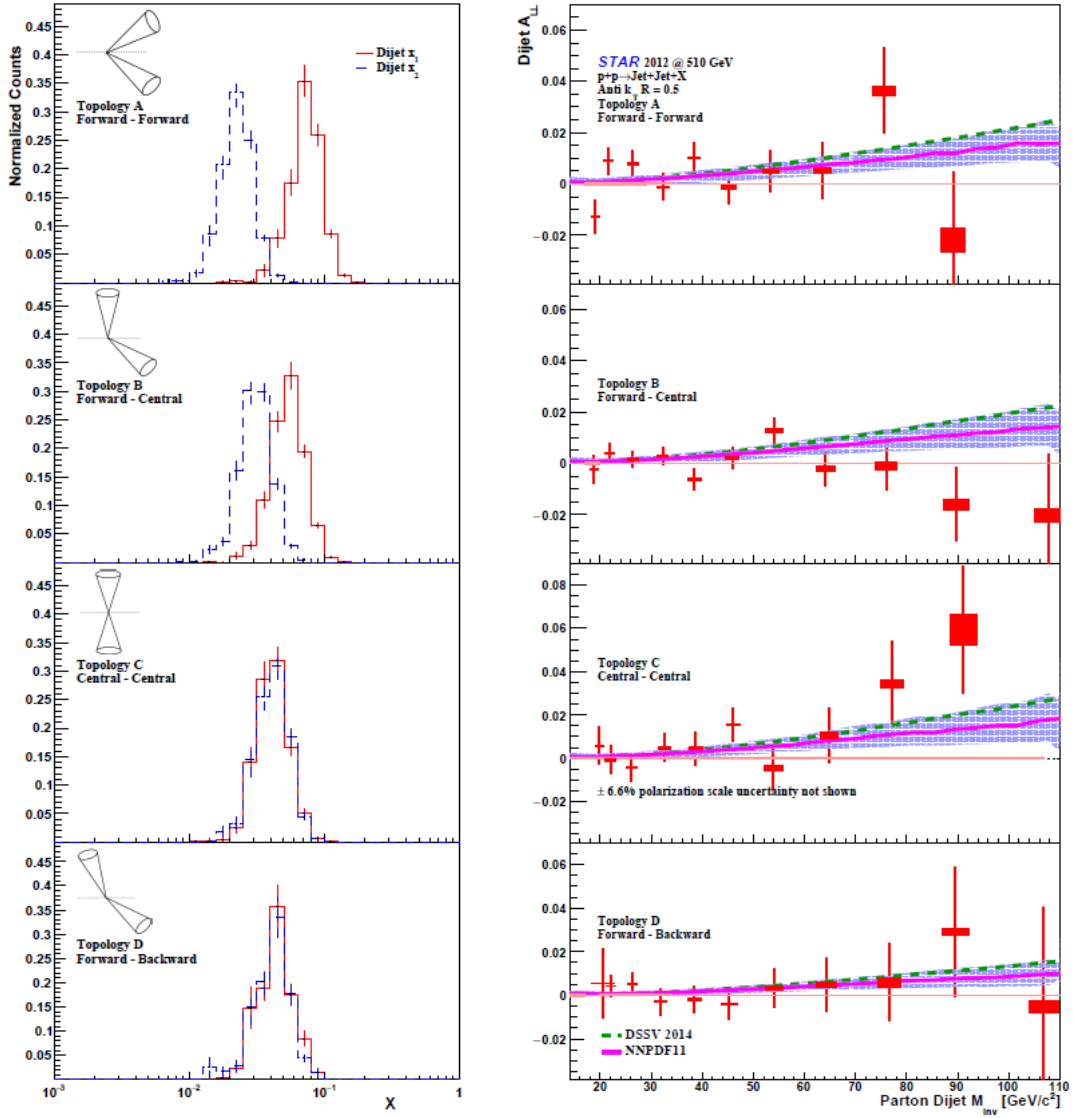
NNPDF

NPB 887 (2015) 276

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

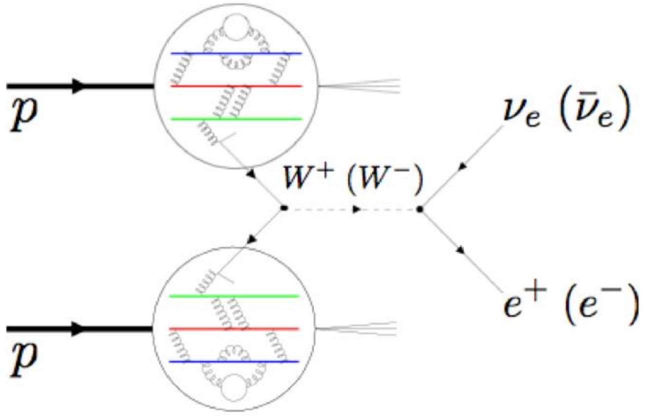
Gluon Polarization





- Published results at 200 and 510 GeV
- Full correction for underlying event
- Phys. Rev. D**98** (2018) 032011
- Phys. Rev. D**100** (2019) 052005
- More data on disk

Sea Quark Polarization

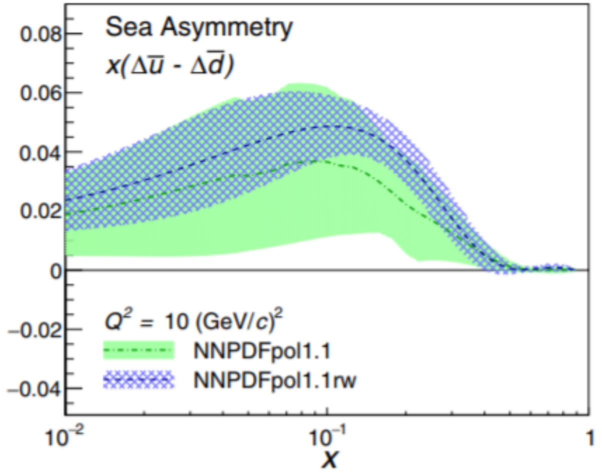


- Parity violating (single-spin) asymmetry

$$A_L(l^-) = \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta\mathrm{d}(\mathrm{x}_1)\bar{\mathrm{u}}(x_2)(1+\cos\theta)^2}{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + \Delta\mathrm{d}(\mathrm{x}_1)\bar{\mathrm{u}}(x_2)(1+\cos\theta)^2}$$

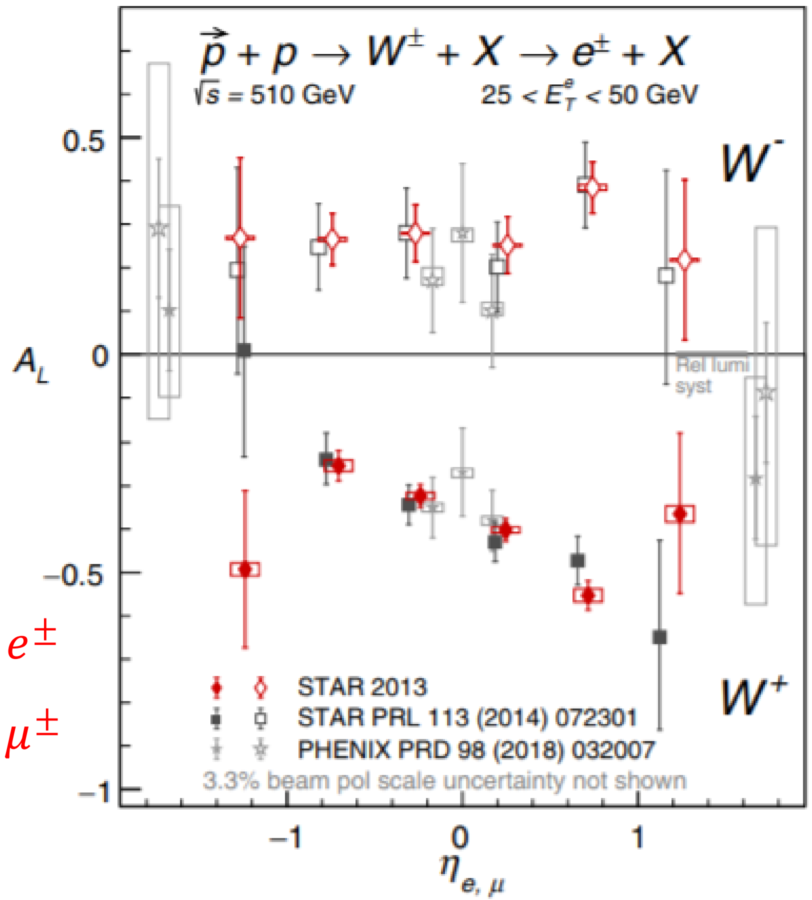
- Final results from the RHIC W-program (2009-2013)
  - PRD 99 (2019) 051102R
  - PRD 98 (2018) 032007

- Impact study in NNPDFpol1.1
  - arXiv:1702.05077

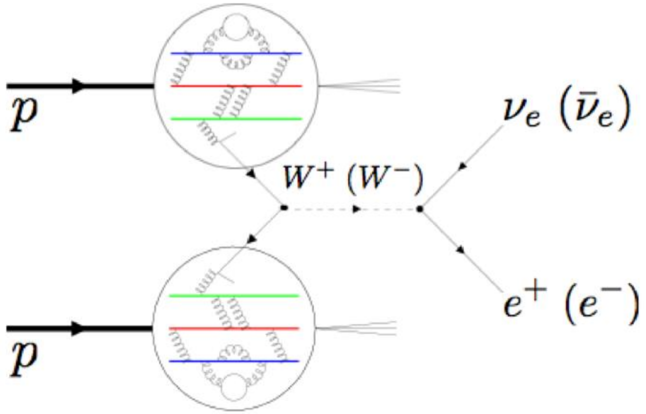


$p + p \rightarrow W^{\pm} \rightarrow e^{\pm}$

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

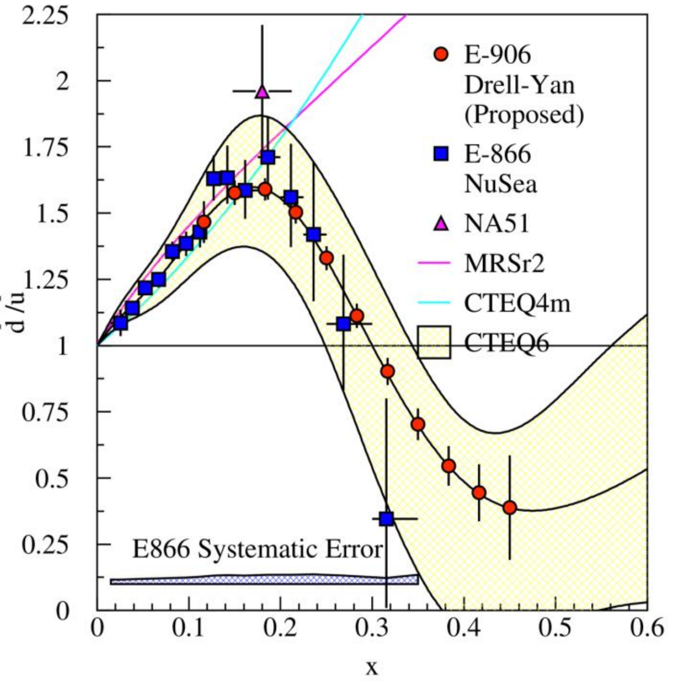


Flavor Composition of the Sea

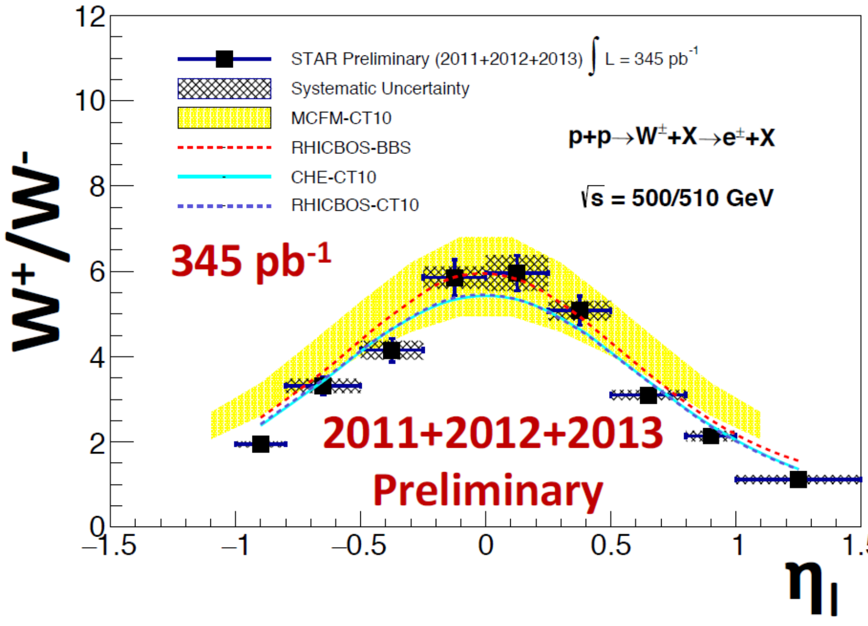


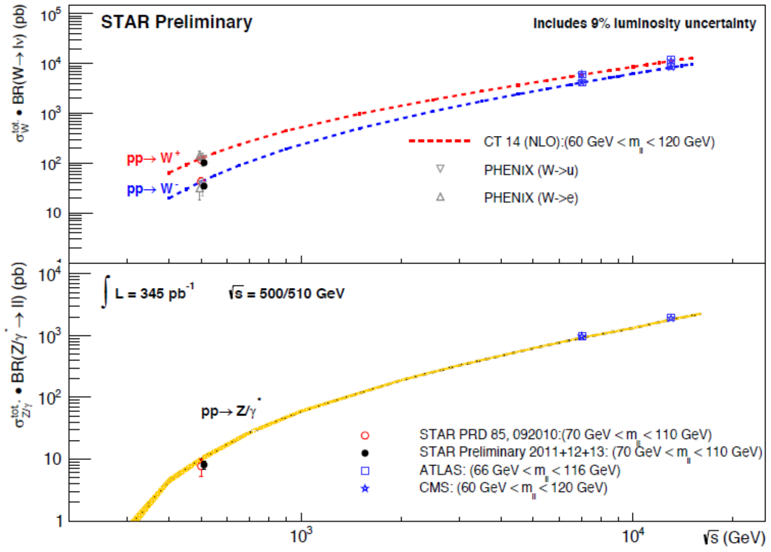
$$R(x_F) = \frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

$0.1 < x < 0.3$



J. Phys. Conf. Ser. 295 (2011) 012163



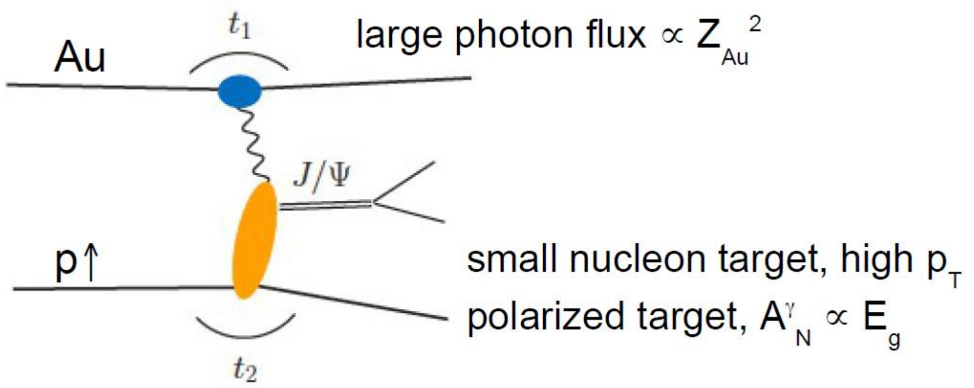


J/psi Production in UPC

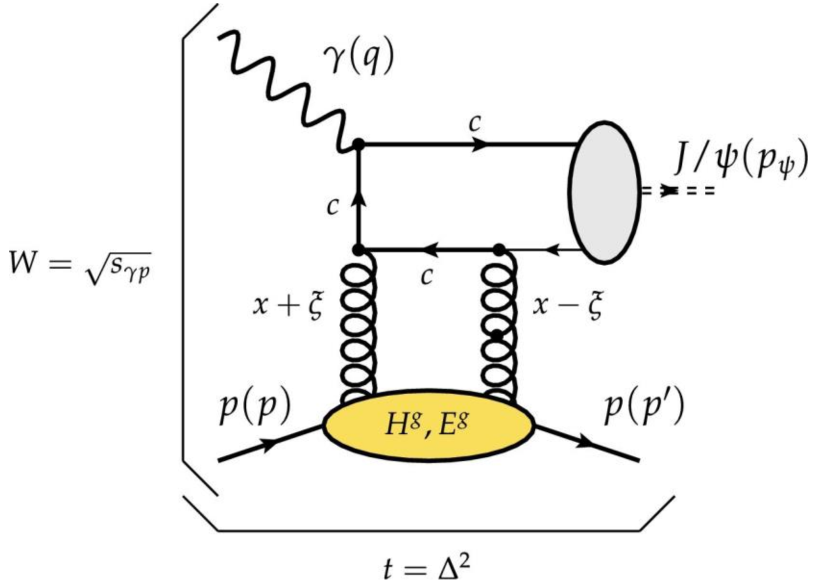
- Photoproduction with polarized protons

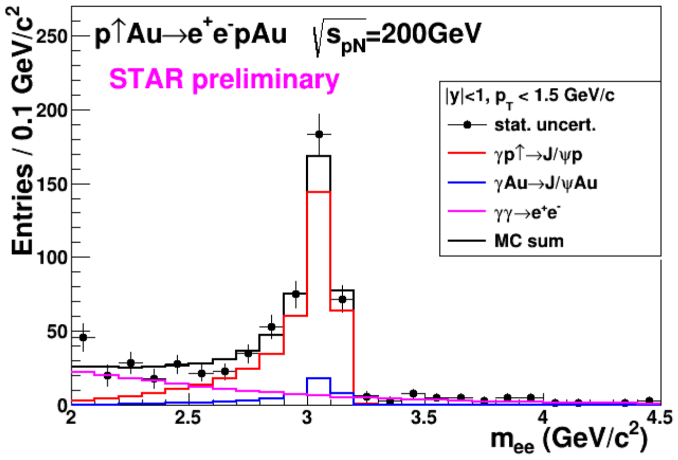
$$d\sigma/d\phi \ \propto 1 + A_N^{\gamma}\cos\phi$$

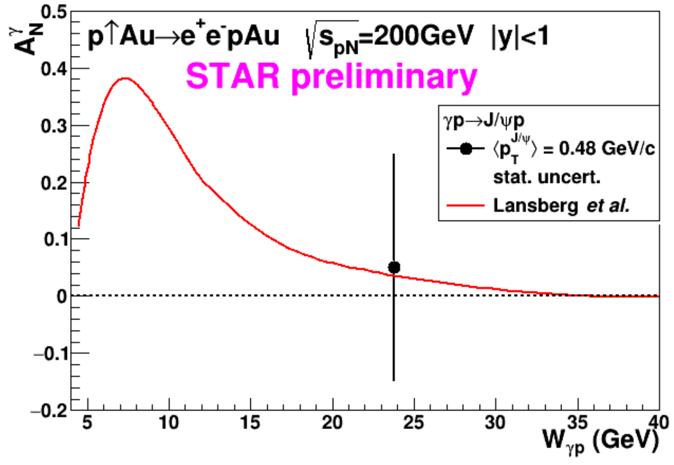
$$A_N^{\gamma} \propto p_T \frac{\mathrm{Im} H^g E^{g*}}{|H^g|^2}$$



Phys.Lett. B793 (2019) 33-40







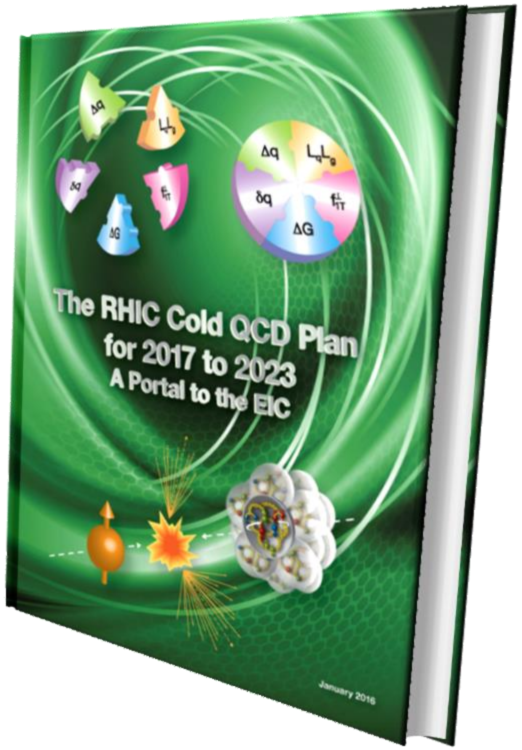
Need more statistics, lower $W_{\gamma p}$

STAR Forward Detector Upgrade

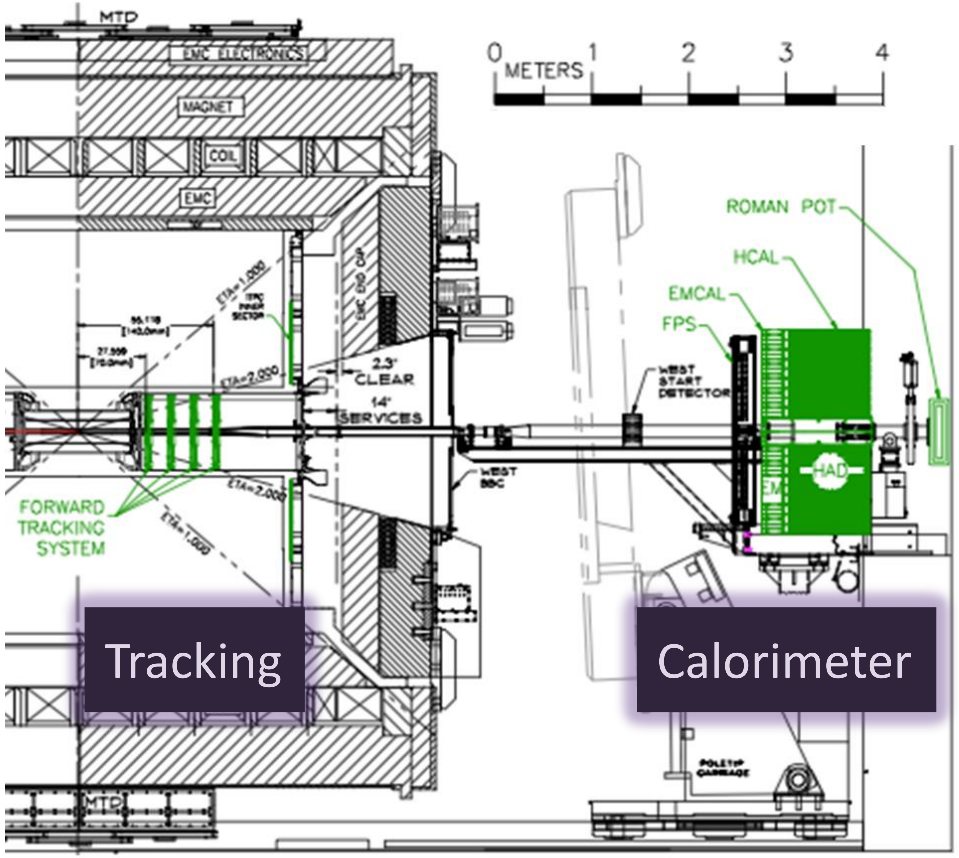
- Tracking and calorimetry at forward pseudorapidities

$$2.5 < \eta < 4.0$$

arxiv:1602.03922



- Si-Tracker
- sTGC disks
- Preshower detector
- EMCAl
- HCAL
- Prototype tests in 2019/20
- 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

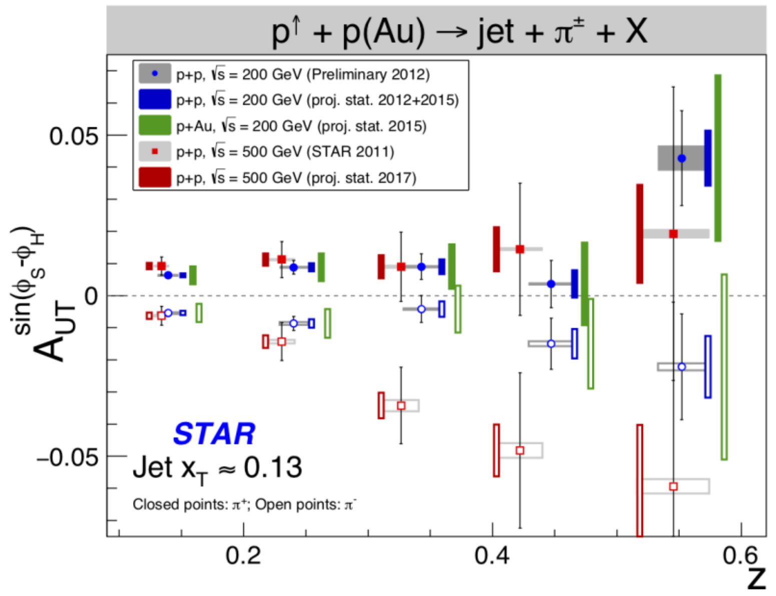
	p+p / p+A	A+A
ECAL	$\approx 10\%/\sqrt{E}$	$\approx 20\%/\sqrt{E}$
HCAL	$\approx 60\%/\sqrt{E}$	n/a

Spin Dependent Fragmentation

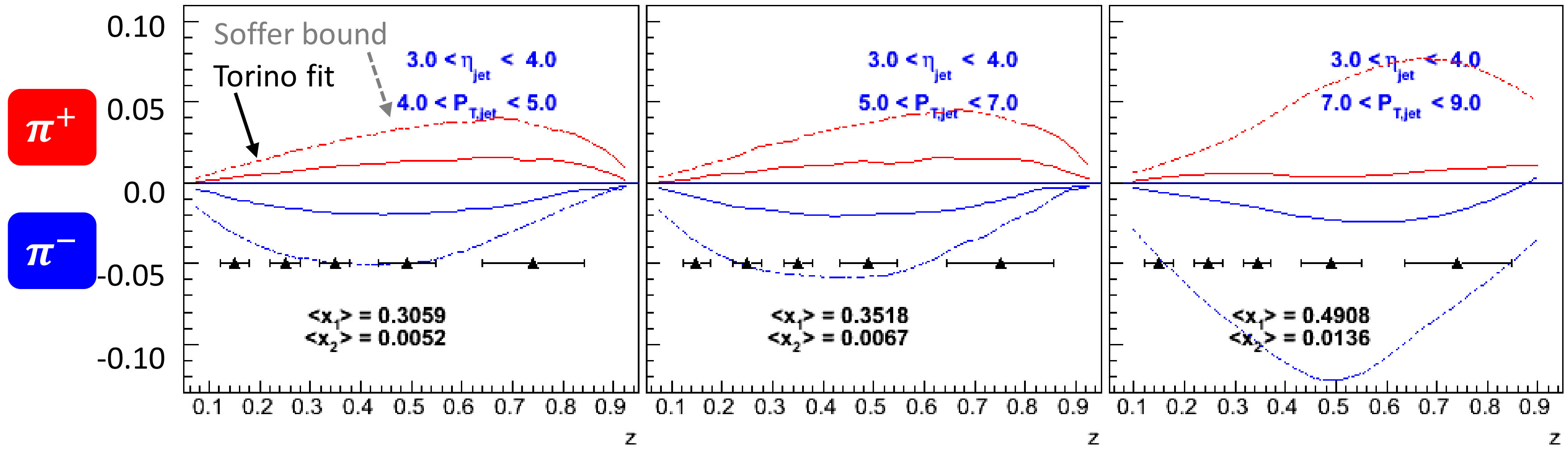
- Hadron in jet
  - STAR measured at midrapidity, 200 – 500 GeV
  - Move to higher x

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

  - Multi-dimensional binning



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



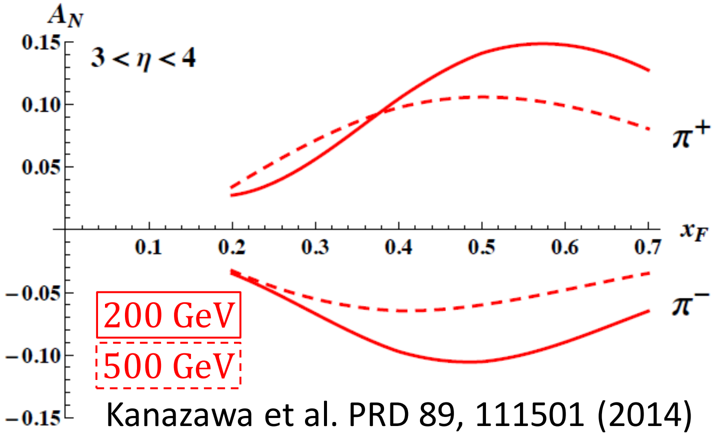
Torino: Phys. Rev. D87 (2013) 094019 Soffer bound&transversity: Phys. Rev. Lett. 74 (1995) 1292

Other Hadron / Jet Observables

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

$$\hat{H}_{FU}^{\Im}(z, z_Z)$$

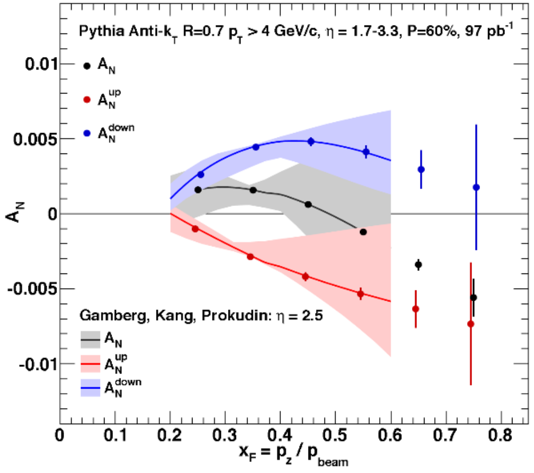
  - Flavor dependence
  - Evolution effects of ETQS distribution functions

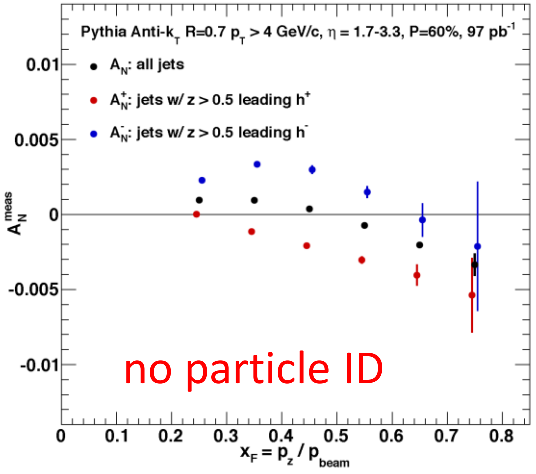


- Test origin of large transverse asymmetries
  - Compare direct photons and jets

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

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





Summary

- RHIC has made significant impact on our understanding of
  - the gluon polarization,
  - the sea quark polarization, and
  - transverse spin effects.
- More data is already on disk and are being analyzed.
- **Upgrades to existing facilities are important.**
- Measurements will be highly relevant and complementary to the future electron-ion collider.