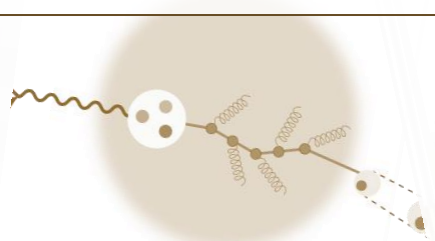
Cold QCD at RHIC
Recent Results and Prospects



Oleg Eyser

QCD Evolution

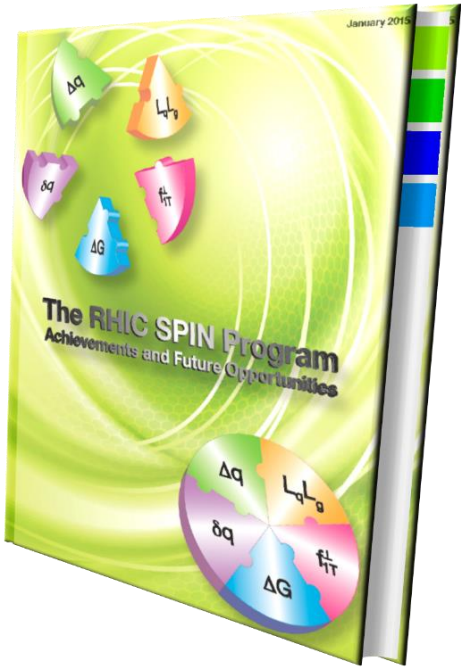
May 20-24, 2018

Santa Fe, NM

BROOKHAVEN
NATIONAL LABORATORY

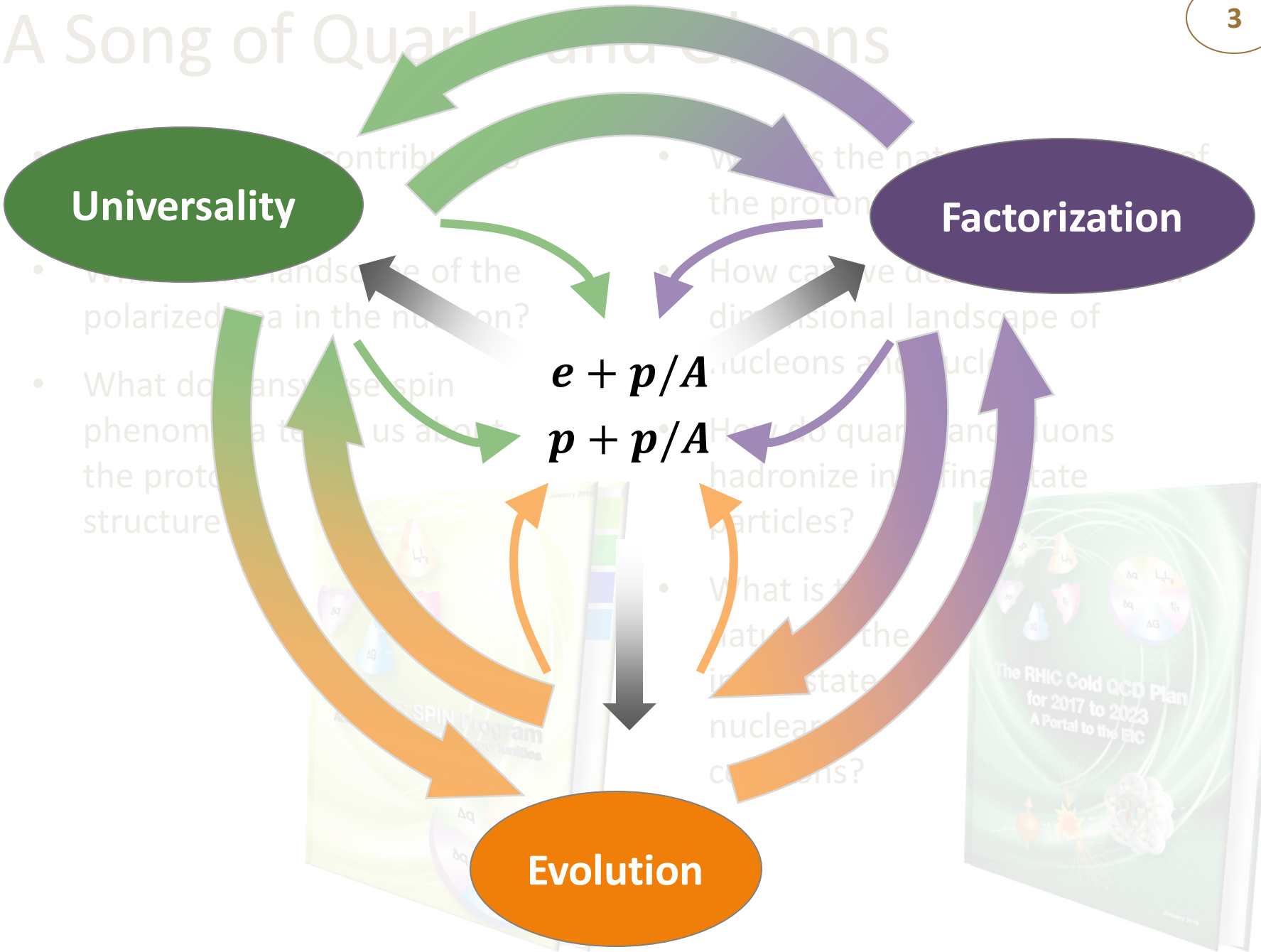
A Song of Quarks and Gluons

- 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?

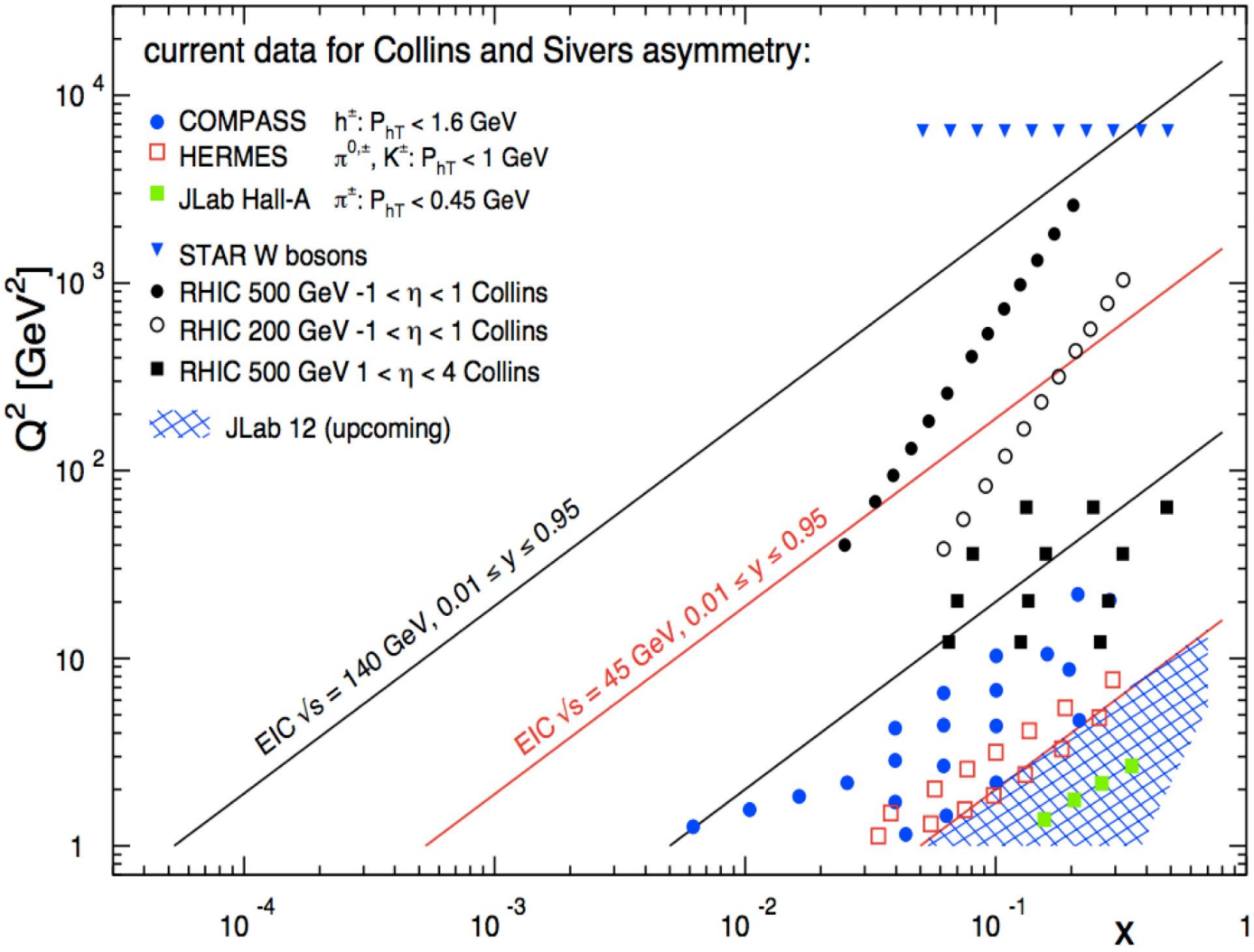


- What is the nature of the spin of the proton?
- How can we describe the multi-dimensional landscape of nucleons and nuclei?
- How do quarks and gluons hadronize into final state particles?
- What is the nature of the initial state in nuclear collisions?

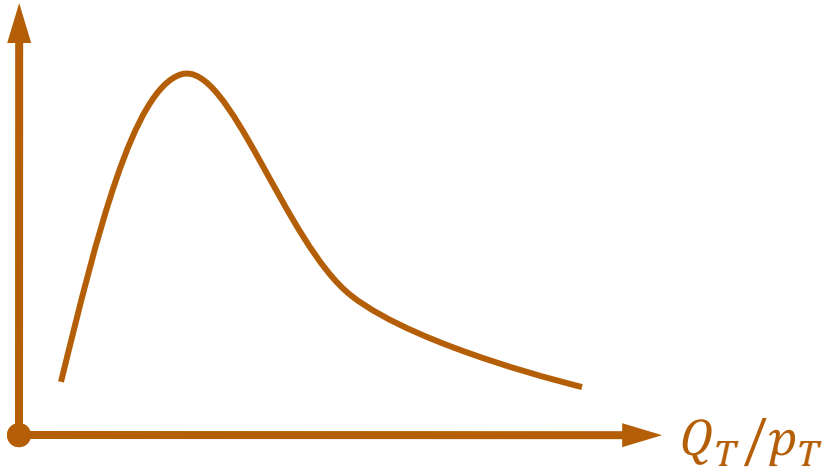
A Song of Quarks and Gluons



World Data Landscape



Factorization and Scale



Initial / final state effects

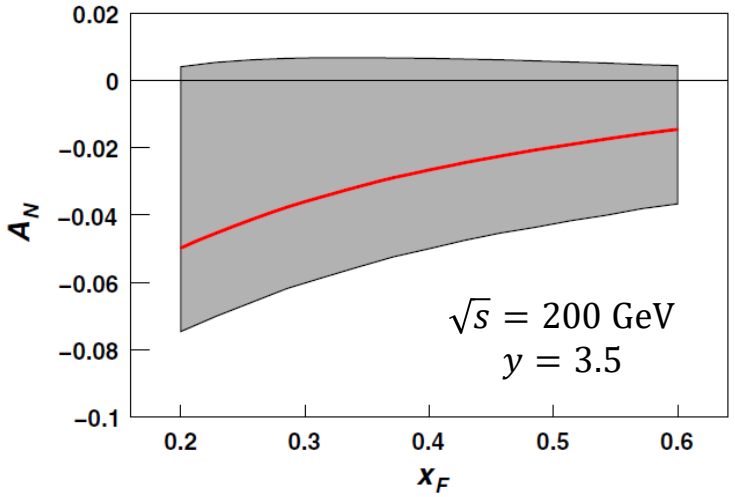
- TMD factorization: two characteristic scales Q^2 and Q_T^2
- Collinear factorization: twist-3 with one hard scale
- Both are closely related

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

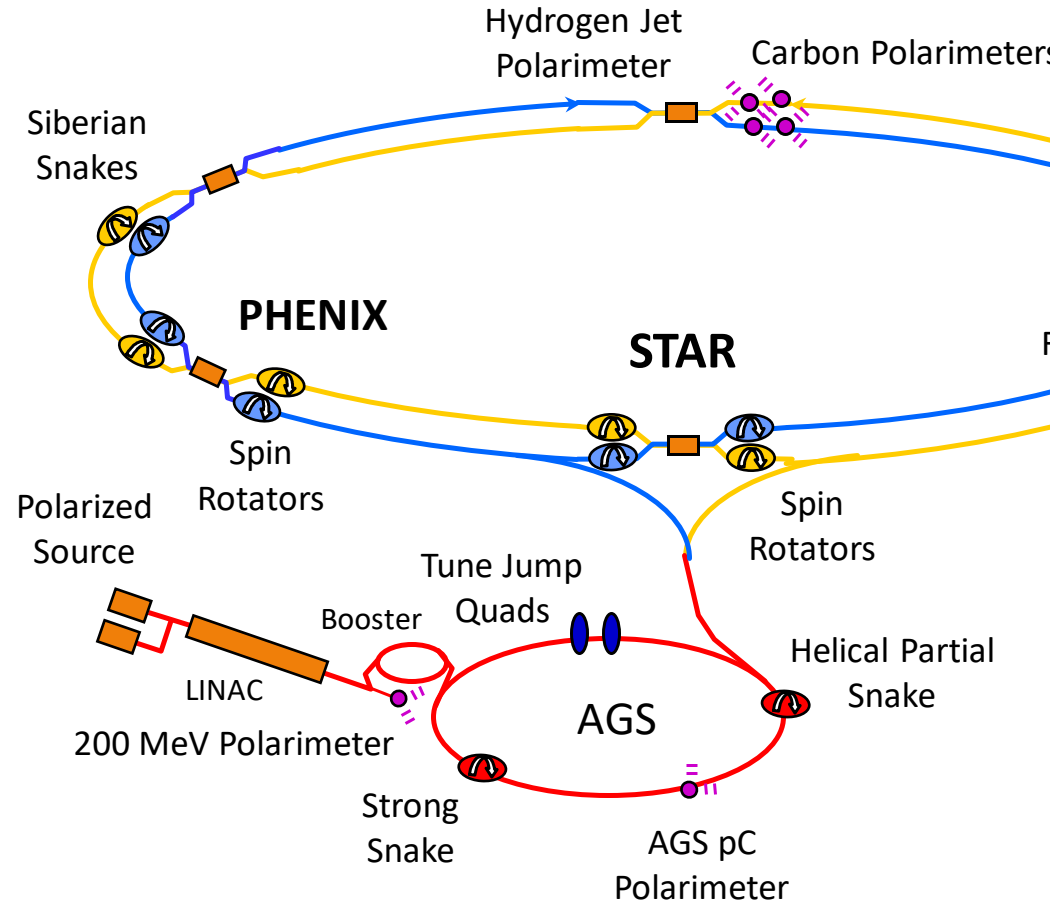
$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x, x)$$

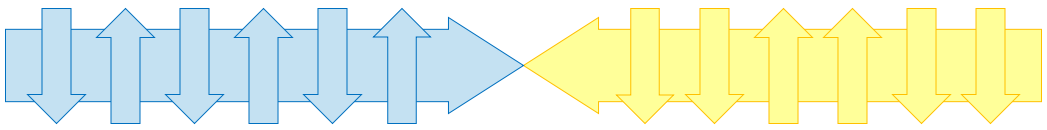
$f_{1T}^{\perp q}$: Sivers TMD function
$T_{q,F}$: Efremov-Teryaev-Qiu-Sterman correlator

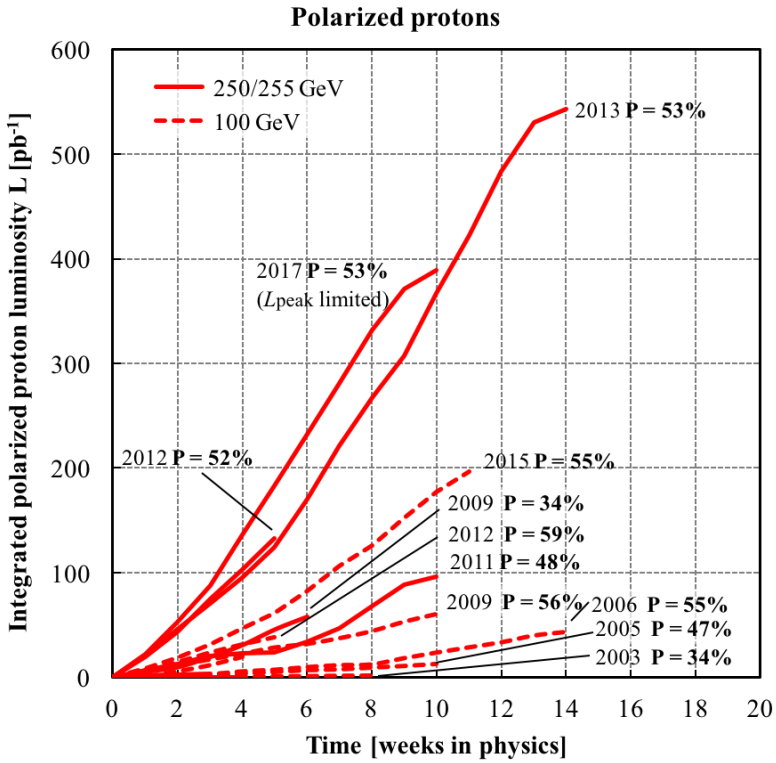
Direct photons, PRL 110, 232301

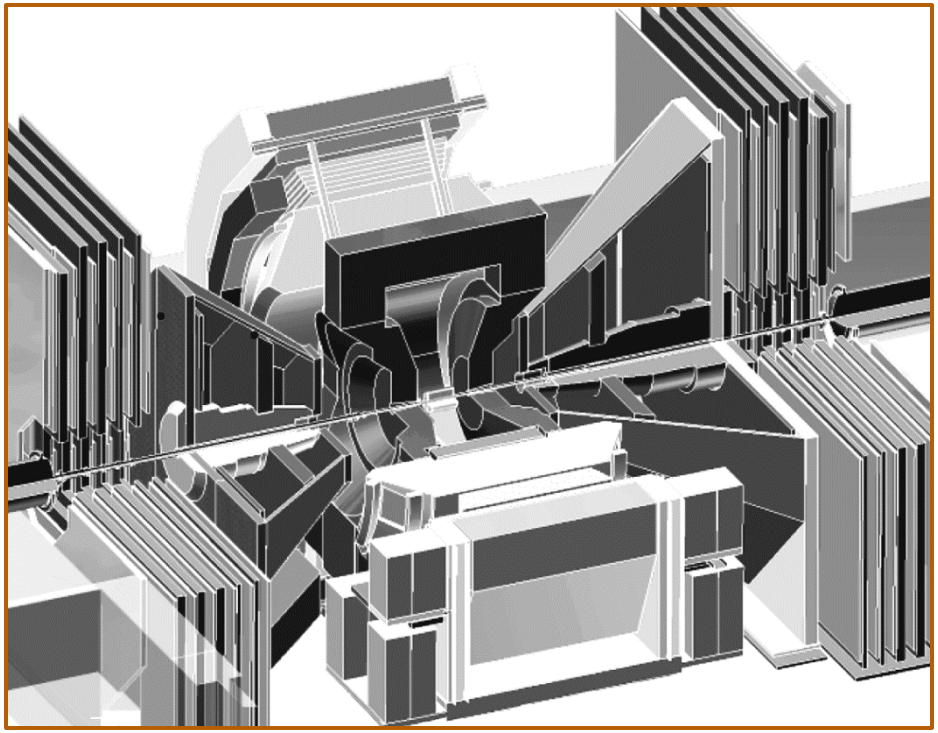


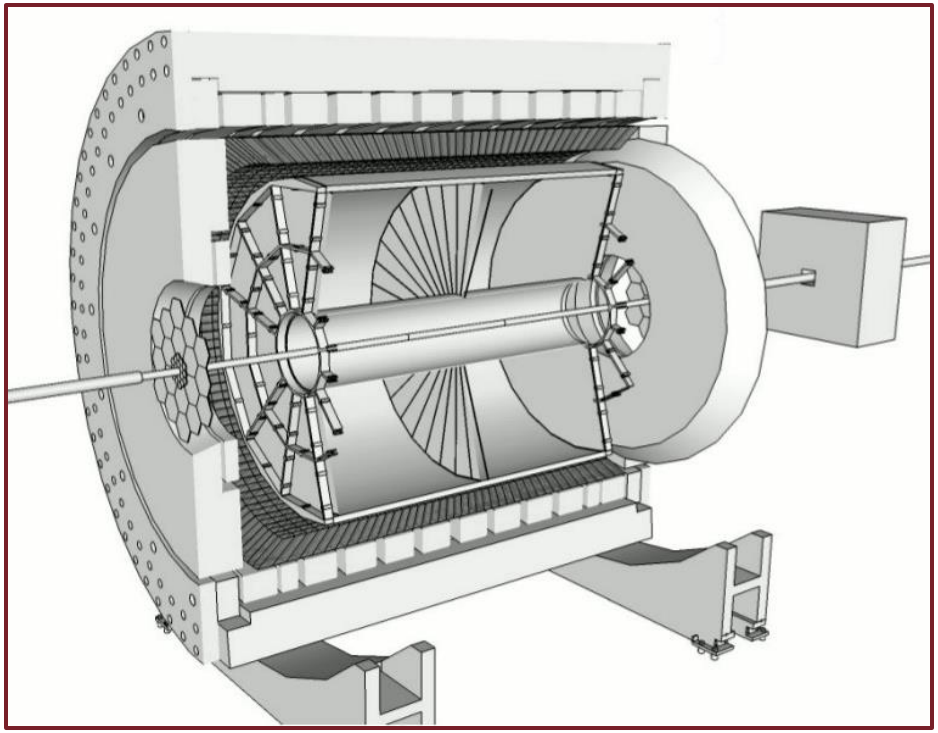
RHIC as a Polarized Proton Collider











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

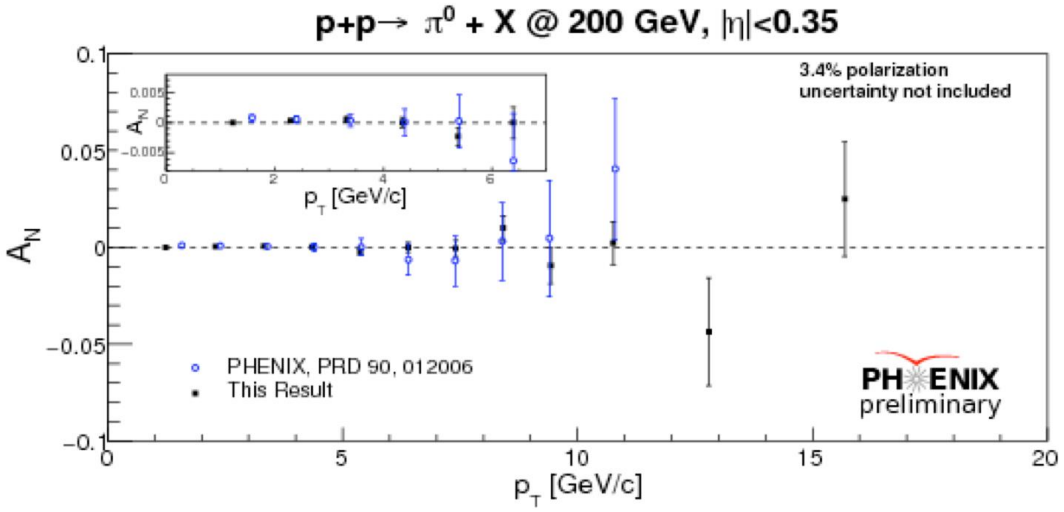
Forward EMCal, $2.5 < \eta < 4$

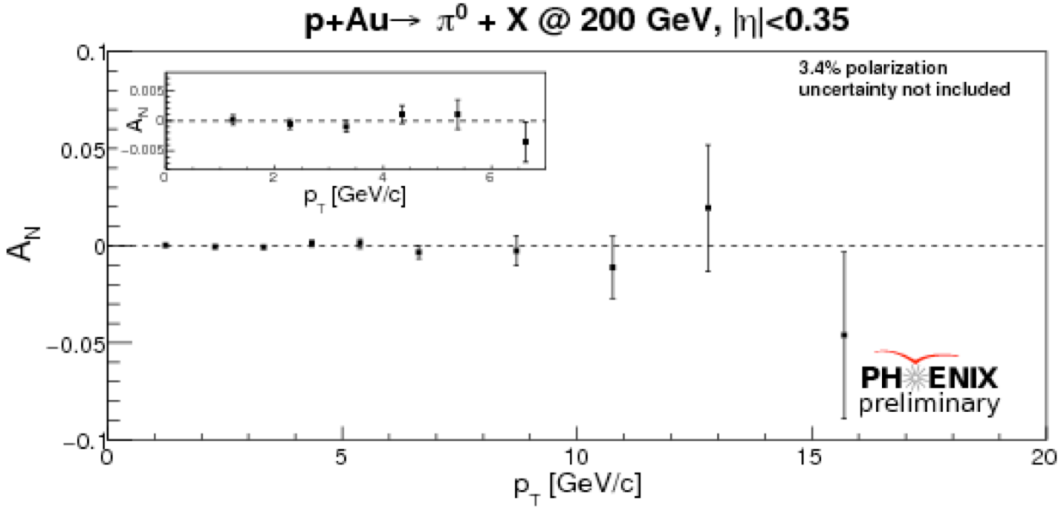
TMD Functions in $p + p$

Sivers function $f_{1T}^{\perp}$	$\cos\phi_S$	$W^{\pm}, Z^0, \gamma^*_{DY}$
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 $T_{q,F}$	$\cos\phi_S$	γ_{direct} hadrons, jets
gluon-gluon correlator T_G	$\cos\phi_S$	heavy flavor

Inclusive Hadrons (Midrapidity)

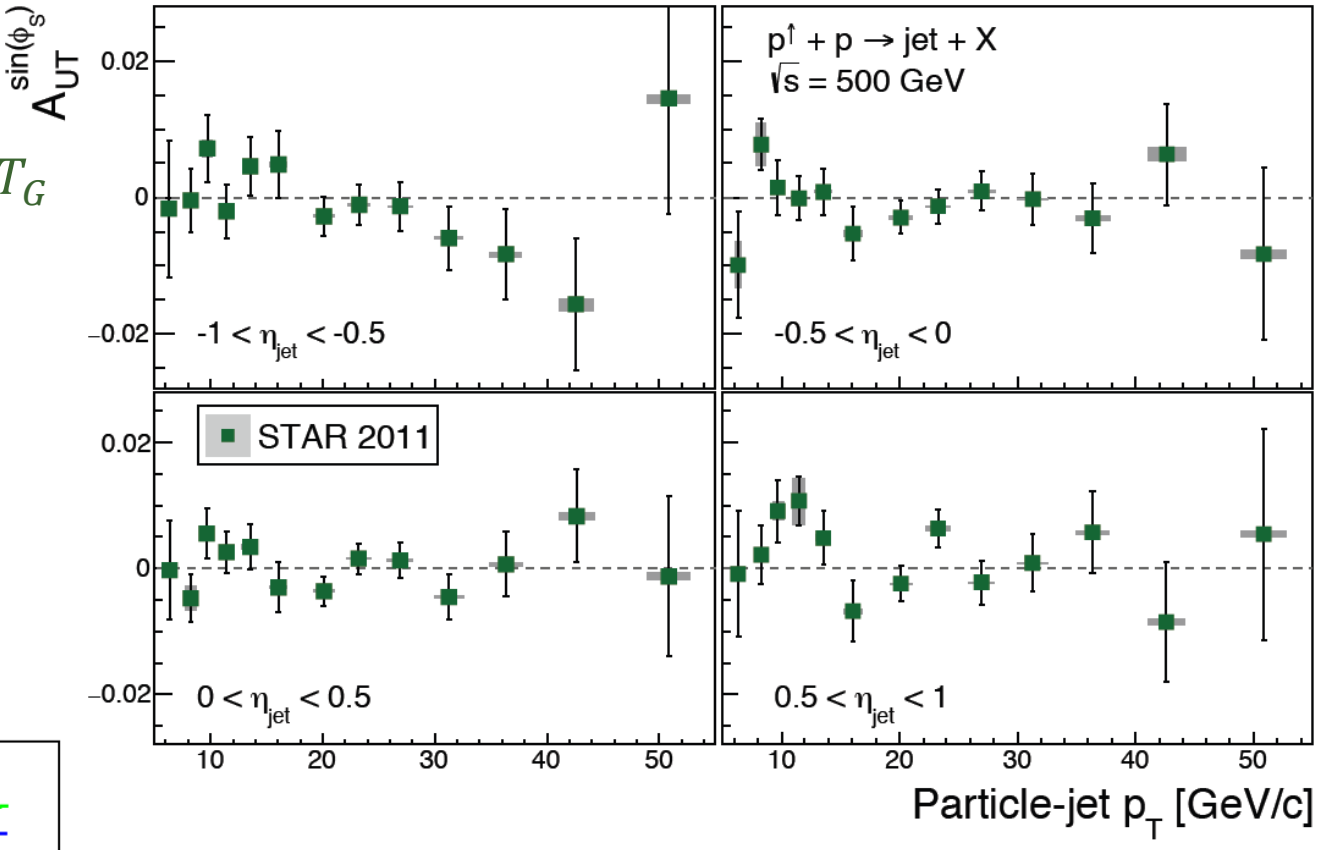
- Sensitive to T_G
- Neutral pions
- $\sqrt{s_{NN}} = 200$ GeV
- $|\eta| < 0.35$
- Very high precision
- First look at nuclear effects
- $p + Al$ not shown



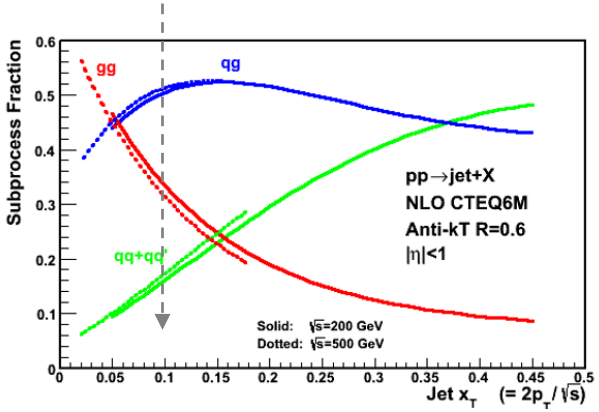


Inclusive Jets (Midrapidity)

- Sensitive to gluon T_G
- $\sqrt{s} = 500$ GeV
- Different rapidity regions
- Additional data on disk ($350\ \mathrm{pb}^{-1}$)



$p_T = 25\ \mathrm{GeV}/c$

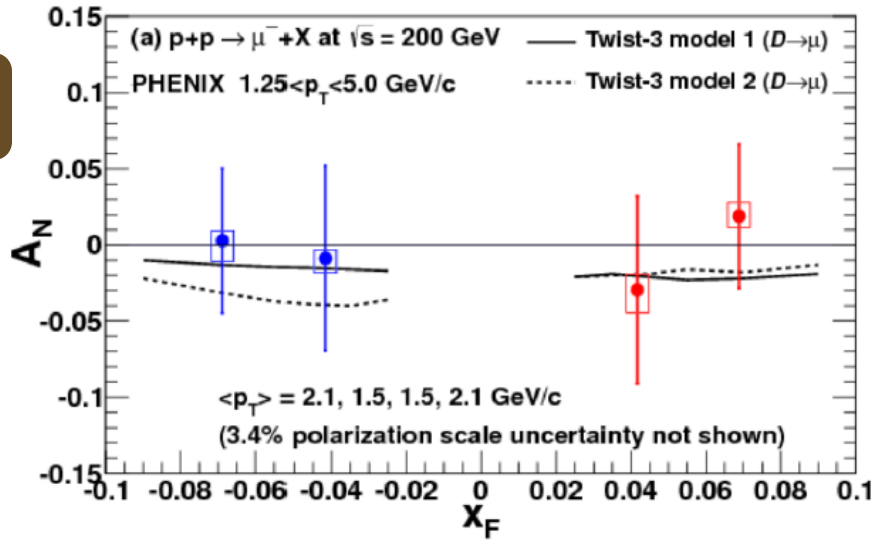


Phys.Rev. D97, 032004 (2018)

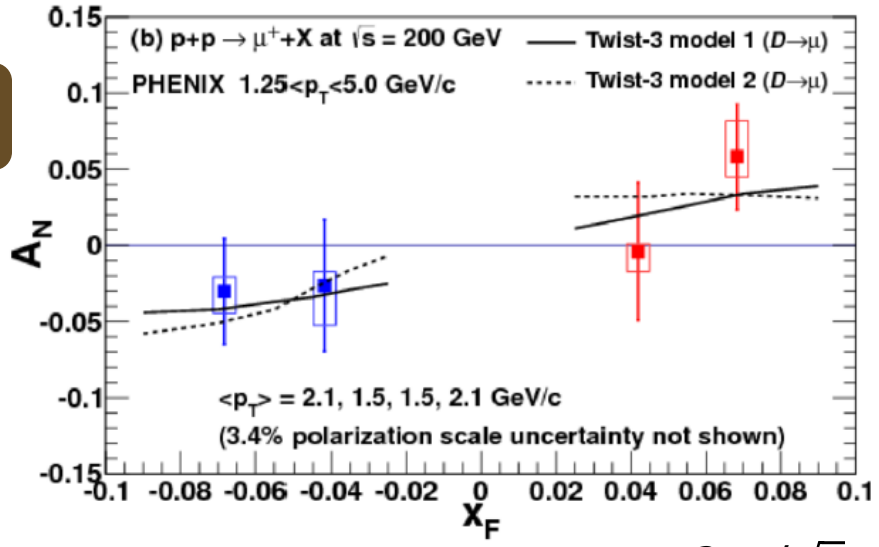
Heavy Flavor (Forward)

- Sensitive to gluon T_G
- $\sqrt{s} = 200$ GeV
- Single muons mostly from heavy flavor meson decay
- $1.2 < |\eta| < 2.2$
- Additional data on disk (40 pb^{-1}) w/ improved instrumentation

μ^-



μ^+



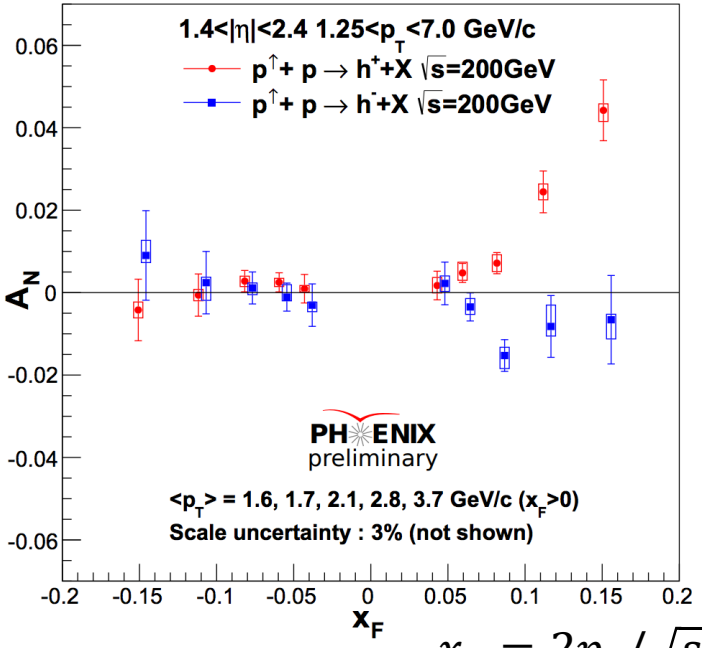
Phys.Rev. D95, 112001 (2017)

Theory curves from
Phys. Rev. D84, 014026 (2011)

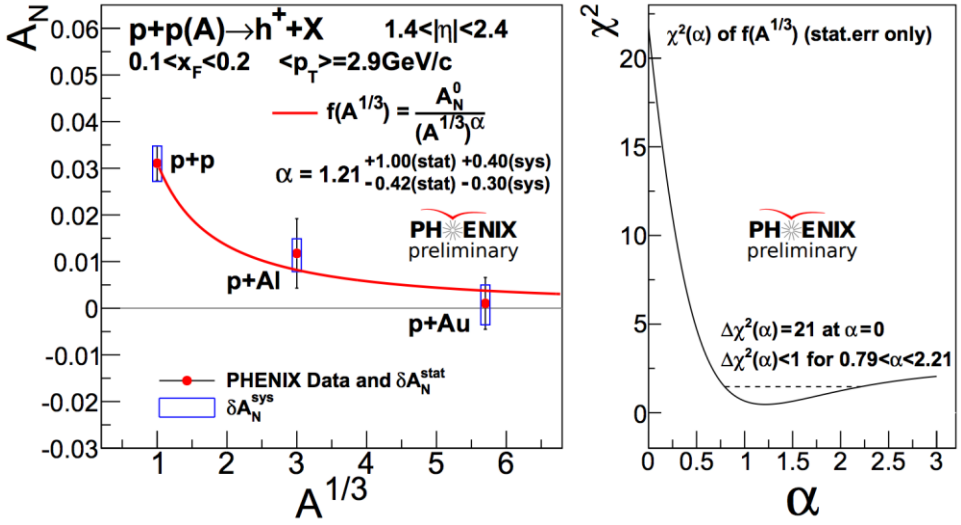
$x_F = 2p_L/\sqrt{s}$

Charged Hadrons (Forward)

- Hadrons are main background for muon measurement
- Mixture of mostly pions and Kaons
- x_F dependence very similar to BRAHMS ($\pi^{\pm}$) and other neutral mesons
- Shown at DIS 2018 (J. Bok)



$$x_F = 2p_L/\sqrt{s}$$



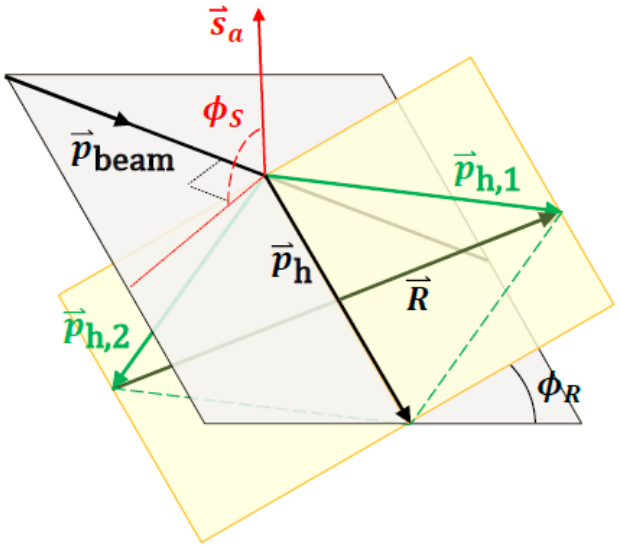
- A dependence observed for $0.1 < x_F < 0.2$

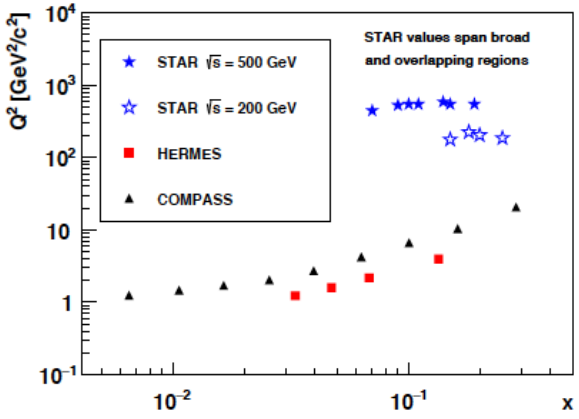
$$A_N(A) = A_N^{p+p} \cdot \left(A^{1/3}\right)^{\alpha}$$

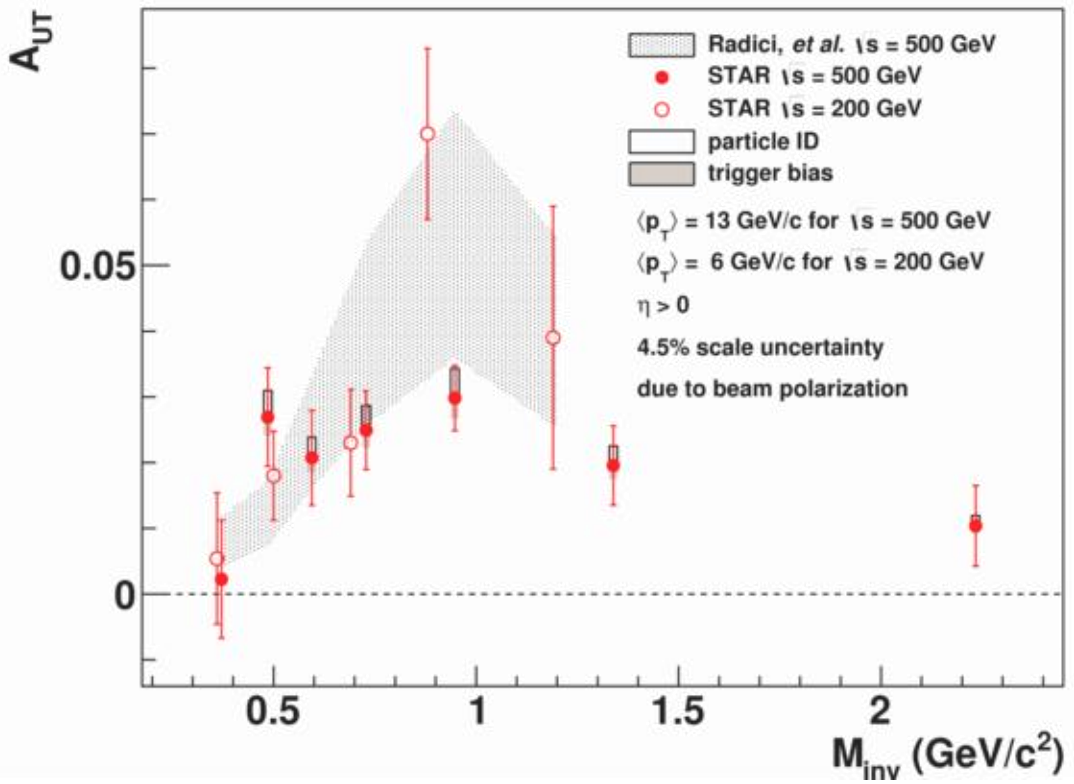
$$\alpha = 1.21^{+1.00+0.40}_{-0.42-0.30}$$

- More detailed in N_{coll}^{avg}

Interference Fragmentation





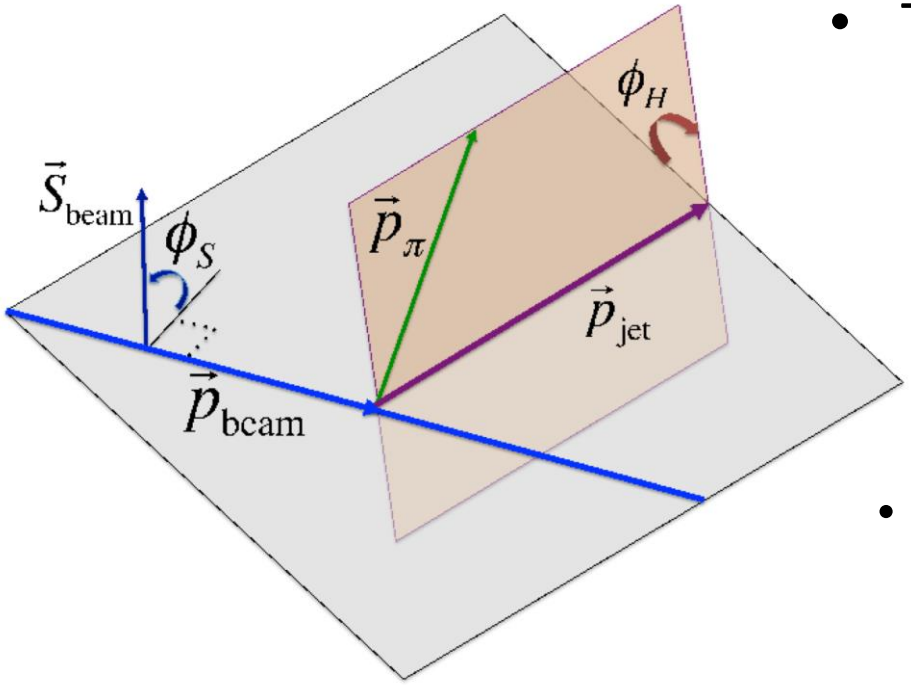


Phys. Lett. B 780, 332 (2018)

M. Radici et al., Phys. Rev. D94, 034012 (2016)

First observation of non-zero transversity in $p + p$ collisions!

Hadrons in Jets



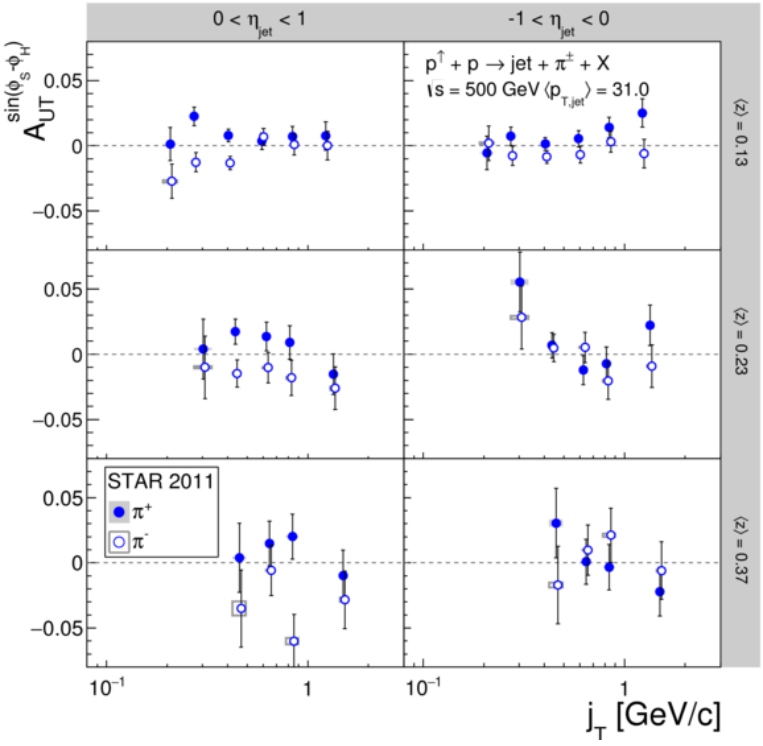
- Two scales for TMD measurement
  - p_T of jet
  - j_T of hadron in jet

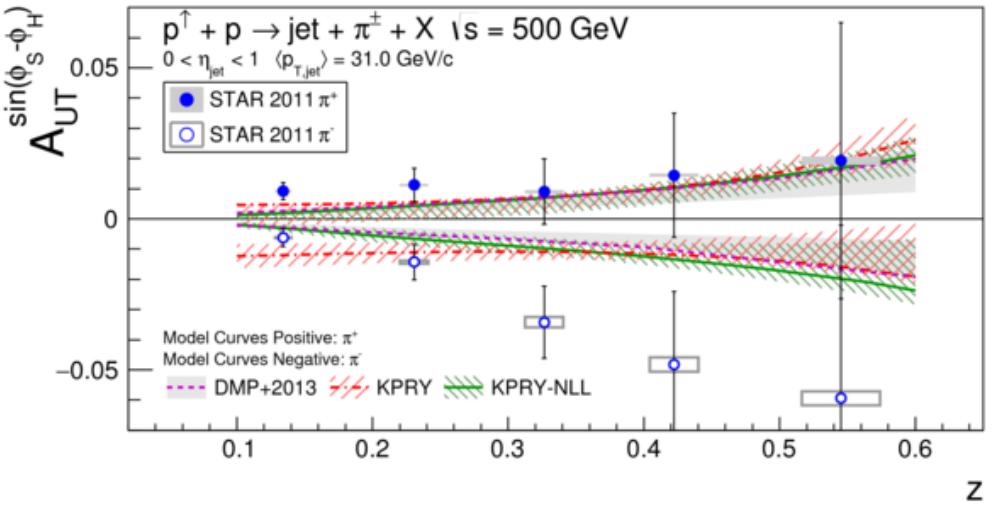
- Jet reconstruction (anti-k_T)
  - PYTHIA + GEANT
  - Kinematics corrected to particle level and parton level matching
  - Trigger bias
- Pion purities / hadron contamination
- Leak through from other asymmetries

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

Collins Effect in Jets (Mid-Rapidity)

- First measurement of Collins effect in p+p collisions
- $\sqrt{s} = 500$ GeV
- Multi-dimensional binning
  $p_T - z$





Phys.Rev. D97, 032004 (2018)

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

Comparison 200 / 500 GeV

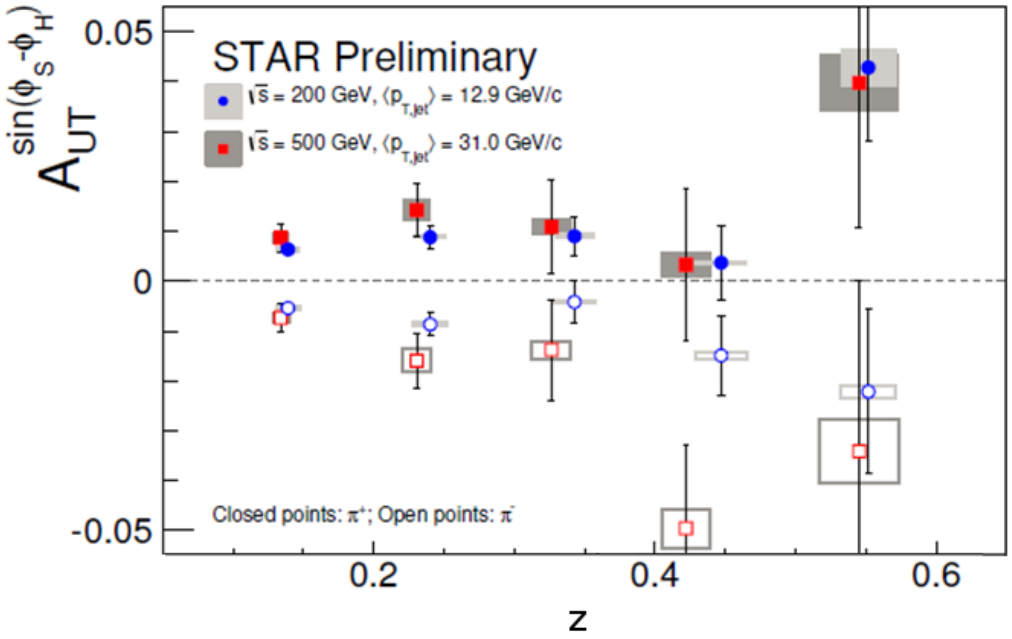
$\sqrt{s} = 200$ 500 GeV

$p + p \rightarrow jet + \pi^+ + X$

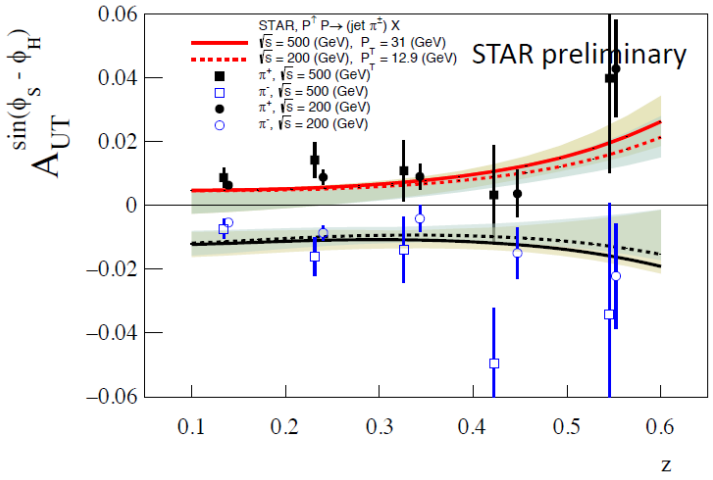
$p + p \rightarrow jet + \pi^- + X$

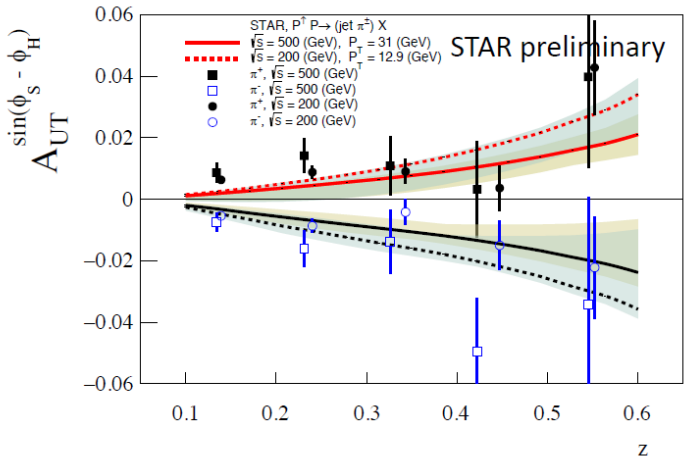
Phys.Rev. D97, 032004 (2018)

Publication in preparation



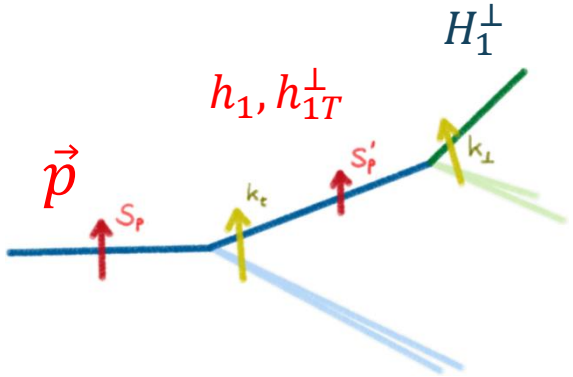
Comparison with / without TMD evolution
Phys. Lett. B773, 300-306 (2017)



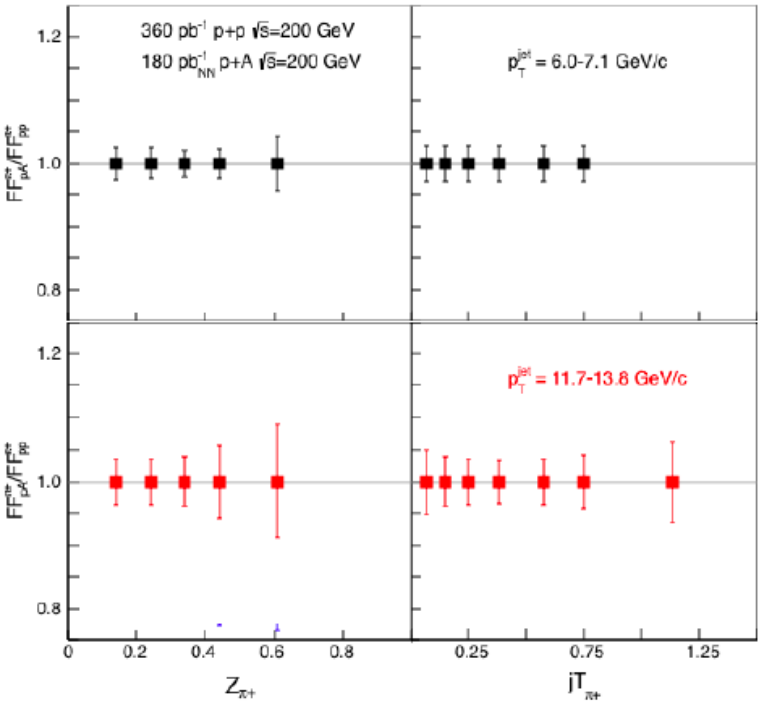


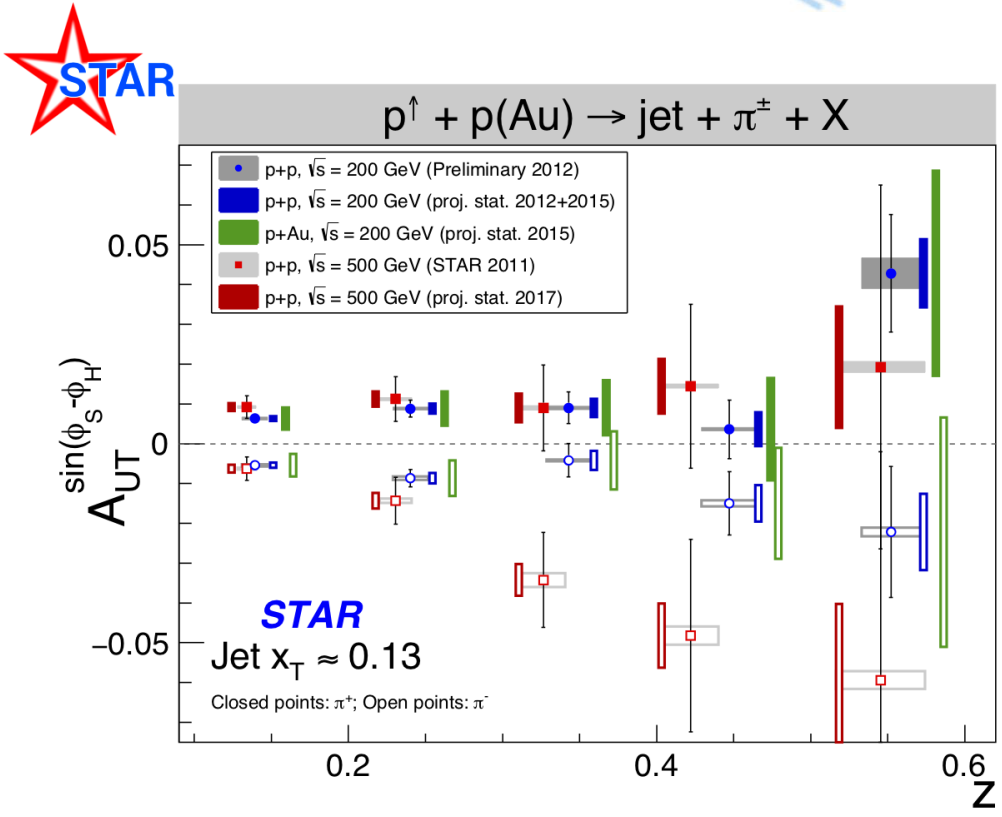
Nuclear Fragmentation Functions

- Identified hadron in jet ($|\eta| < 1$)
  - Transverse momentum dependent
  - Nuclear effects in hadronization
- Test universality
  - $e + A$ and $p + A$

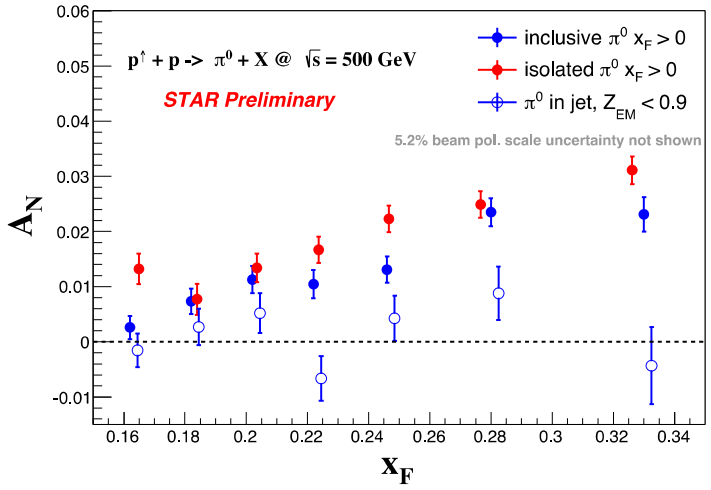


$FF_{pA}/FF_{pp}(\pi^+)$

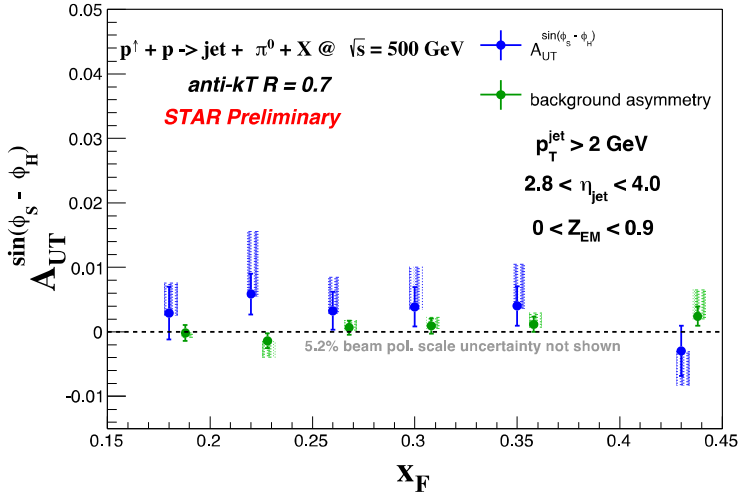


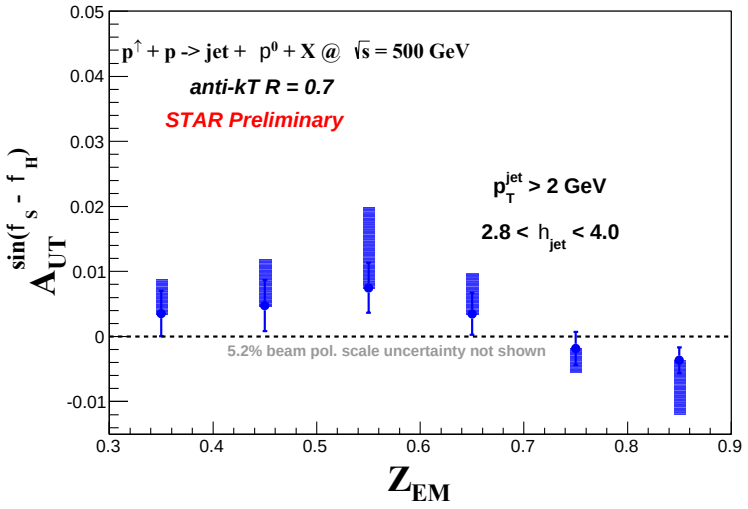


Jet Asymmetries (Forward)



- Electromagnetic jets with correlated π^0
- $2.5 < |\eta| < 4.0$
- $\sqrt{s} = 500$ GeV
- Background corrected asymmetries
  - Small asymmetries with π^0 tag
  - Small Collins effect
  - Publication in preparation



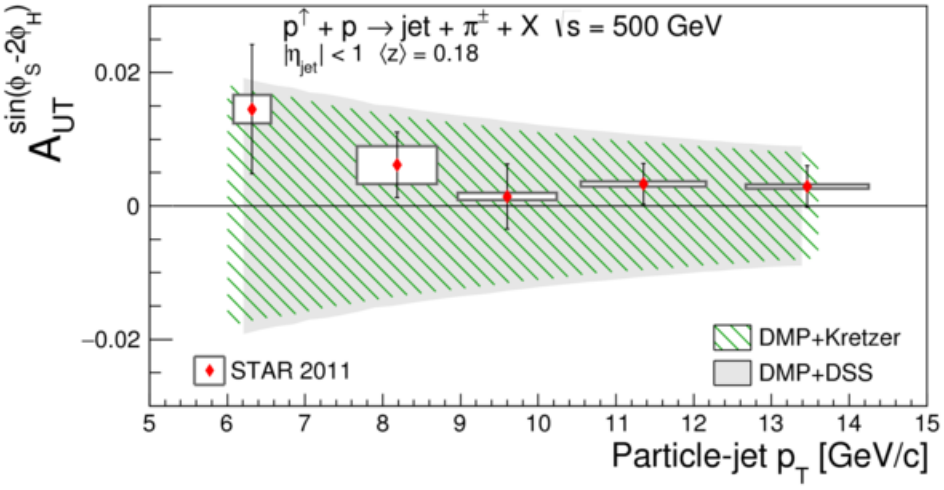


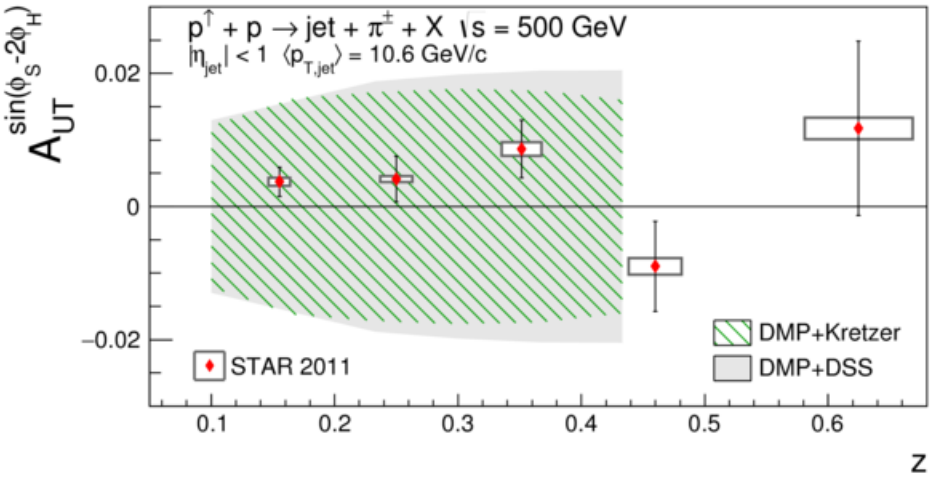
Gluon Linear Polarization

- Collins-like fragmentation

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto A_{UT} \cdot \cos(\phi_S - 2\phi_h)$$

- Expected to be small but completely unconstrained
- First measurement!



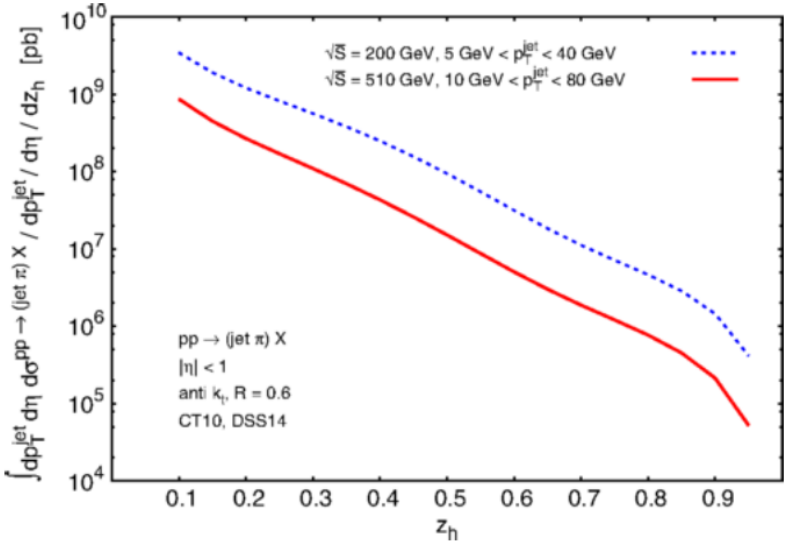


Phys. Rev. D97, 032004 (2018)

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

Gluon Fragmentation Functions

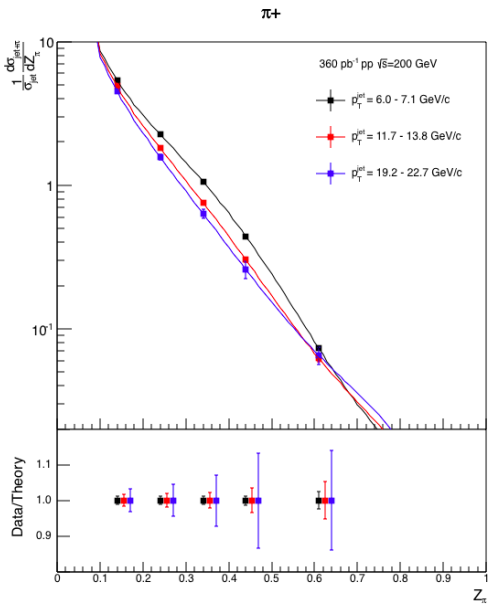
Phys. Rev. D92, 054015 (2015)

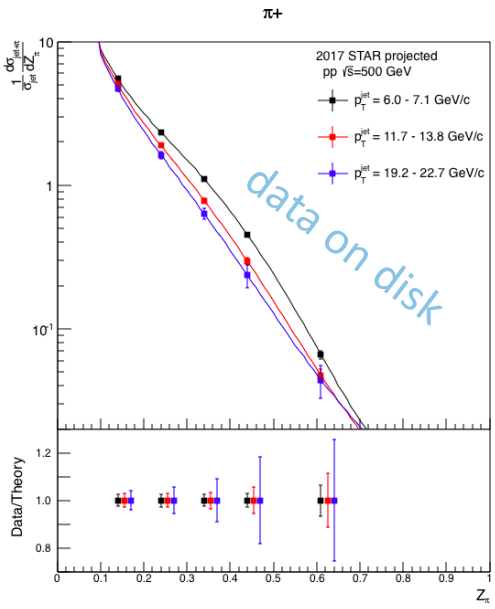


$$\frac{d\sigma^{pp\to jet+X}}{dp_{jet}\, d\eta\, dz_h}$$

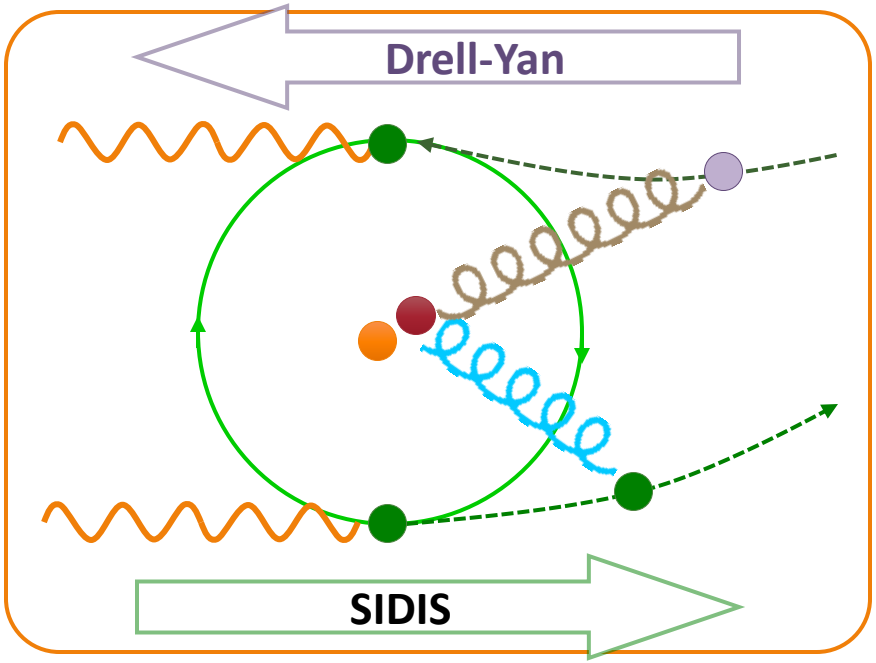
- Differential in hadron p_T-fraction, z_h, sensitive to gluon fragmentation (Kaufmann, Mukherjee, Vogelsang)
- Complementary to LHC

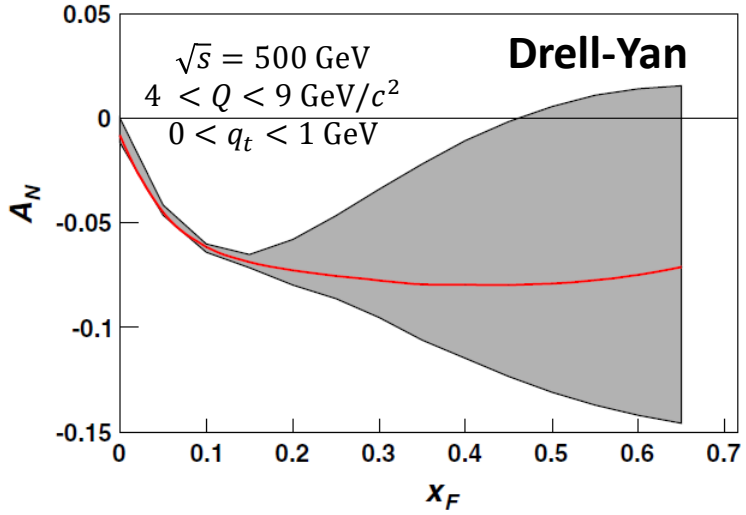
- Mid-Rapidity $|\eta| < 1.0$
- 200 / 500 GeV
- Charged pions π^+ / π^- in jet
- Projections 360 pb^{-1}
  Kaufmann, DSSV14 PDF+FF

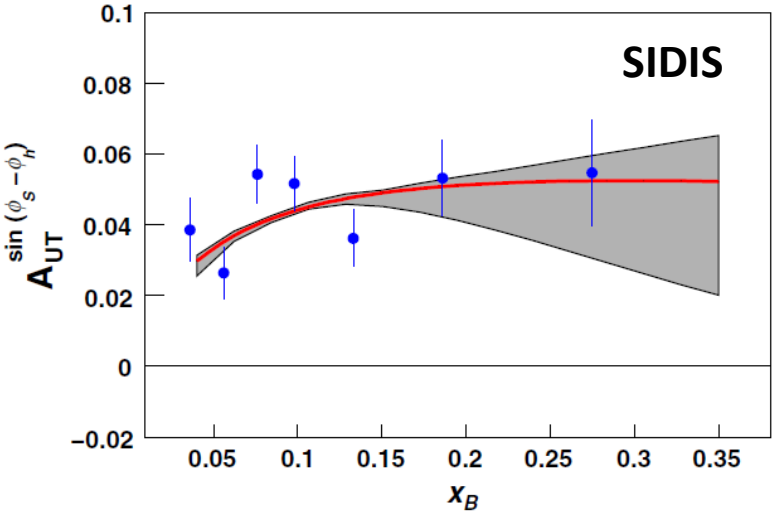




Non-Universality of Sivers Effect







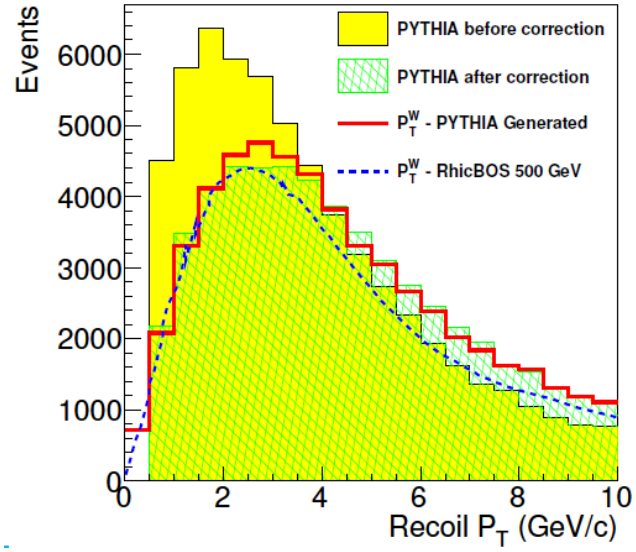
Gamberg, Kang, Prokudin
Phys. Rev. Lett. 110, 232301 (2013)
with HERMES data

W-Boson Production in $p + p$

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

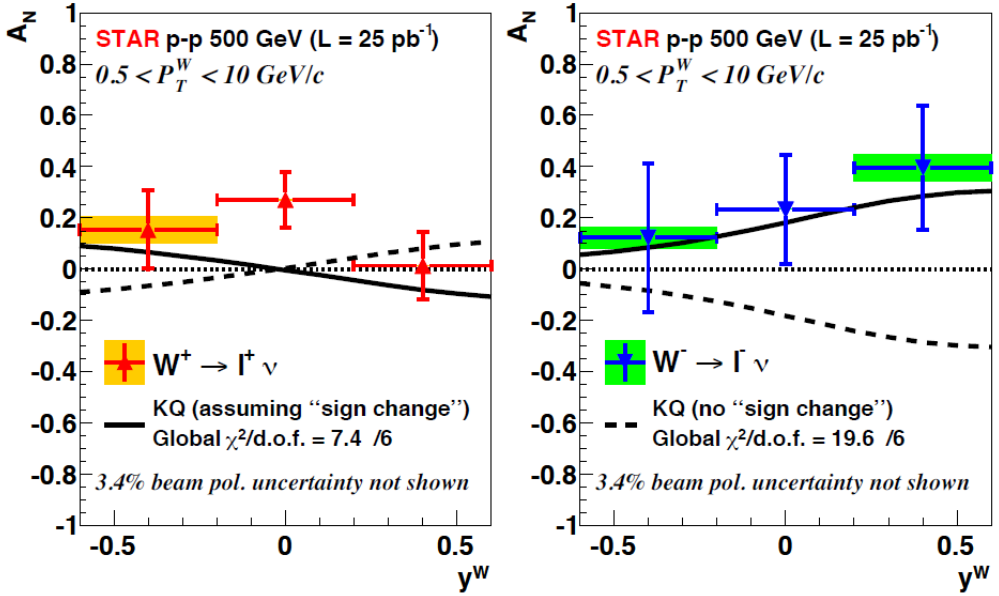
- Requires full reconstruction of $W^{\pm}$ kinematics
- Missing transverse momentum from recoil

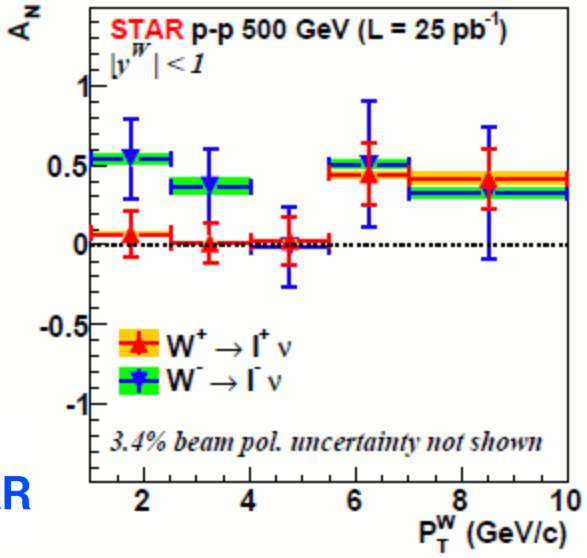
$$P_T^W = P_T^e + P_T^\nu = P_T^{recoil}$$



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

Comparison with Phys. Rev. Lett. 103, 172001



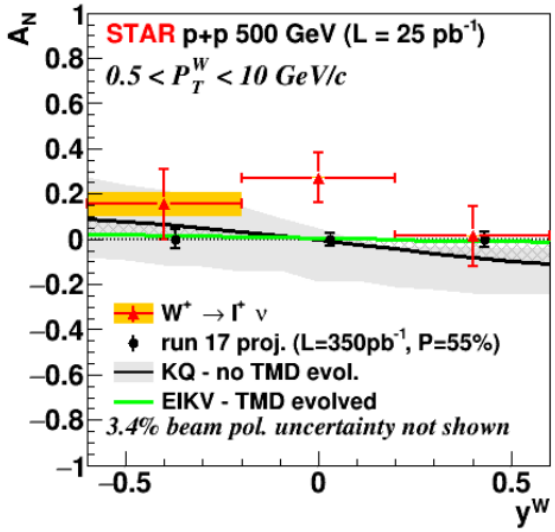


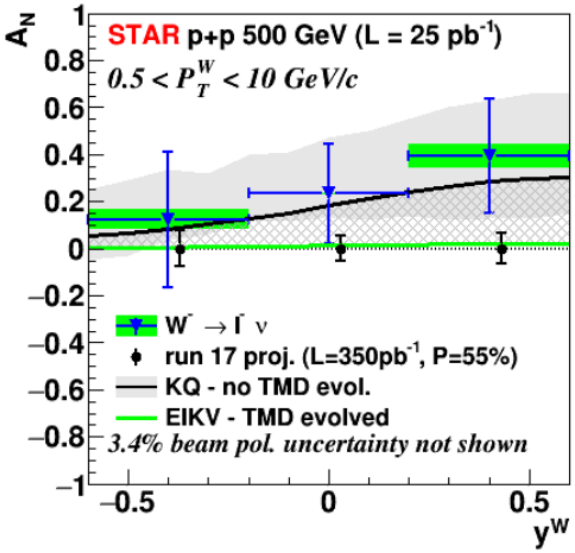
STAR

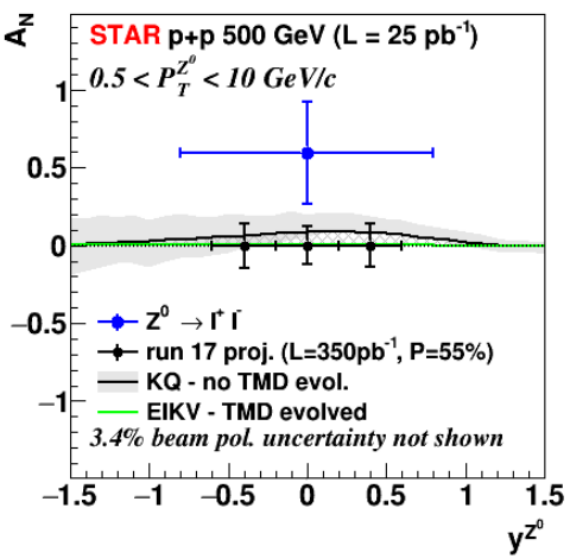
Next Steps

- Successful completion of run 2017
  - $\sqrt{s} = 510$ GeV
  - $\mathcal{L}_{int} = 350\ \mathrm{pb}^{-1}$
  - $P_p = 55\%$

$$W^+, W^-, Z^0$$



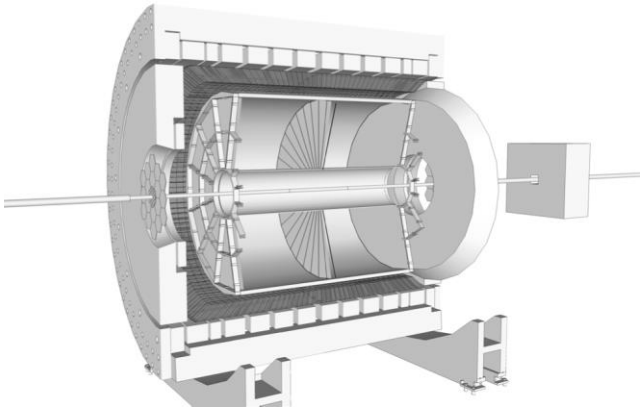




- Rigorous test of the universality of TMD spin-orbit effects
- Experimental constraint on strength of Q^2-evolution

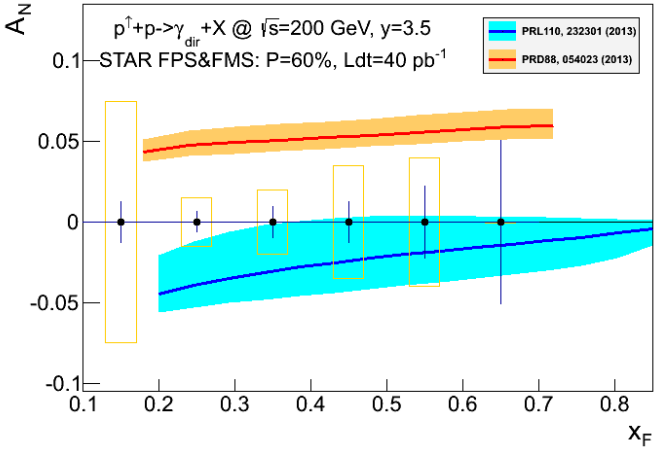
At the same time…

FMS equipped with pre/post-shower detectors 2015/2017

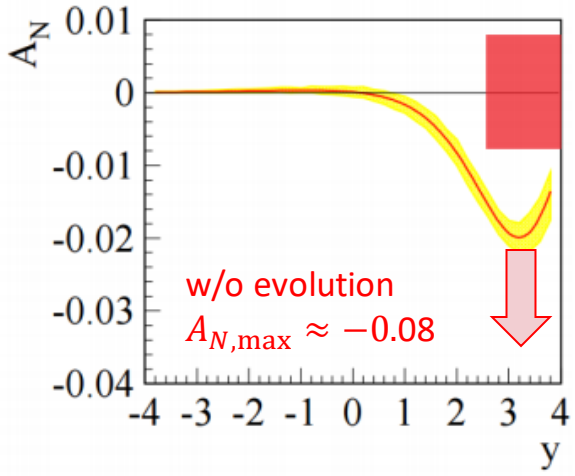


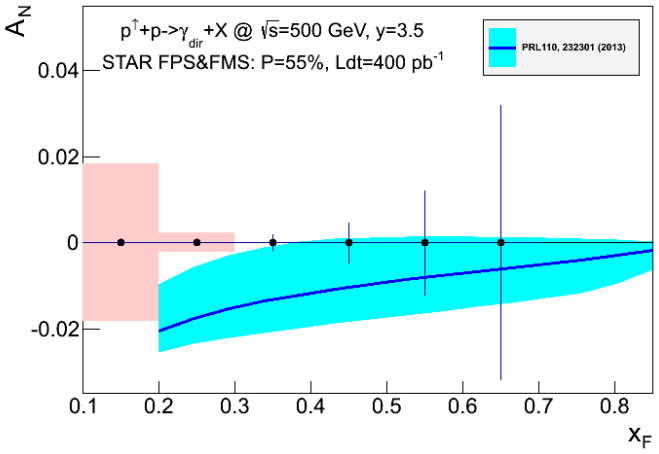
- $2.5 < \eta < 4.0$
- High p_T trigger
- Excellent background rejection required (10^6)
- Multi-variate analysis based on simulation with full detector response

Direct photon production
(projections, data on disk)



$4.0 < M_{DY} < 9.0$ GeV



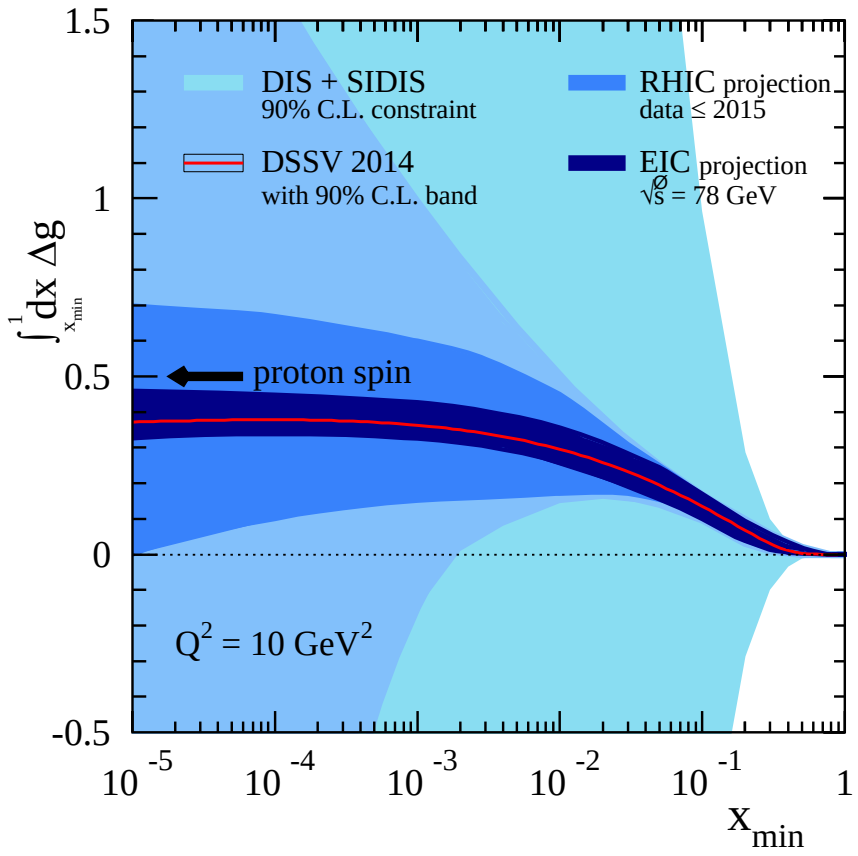


Gluon Polarization

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

- First evidence of non-zero gluon polarization
  Phys. Rev. Lett. 113, 012001 (2014)

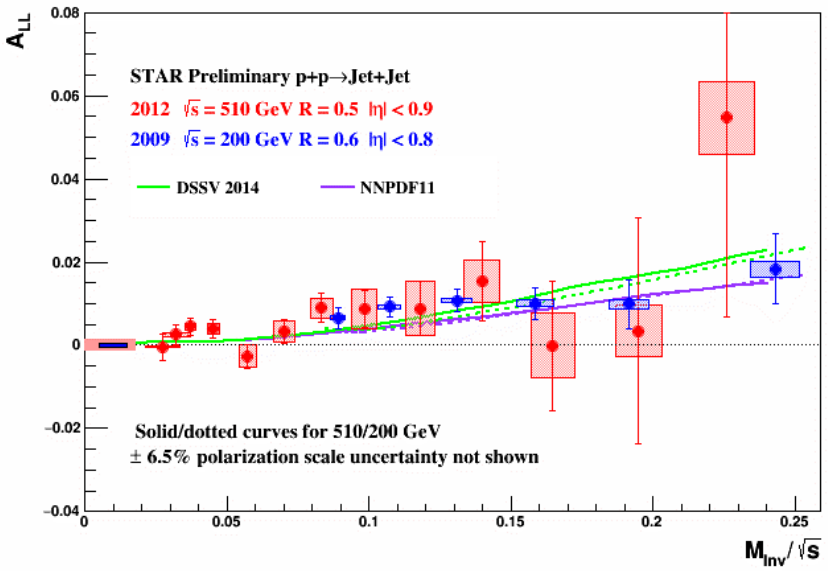
$$\int_{0.05}^{1} \Delta g(x, Q^2)dx = 0.2^{+0.06}_{-0.07}$$



- Small x largely unconstrained
- Forward rapidity → low x
- Correlated probes → functional form

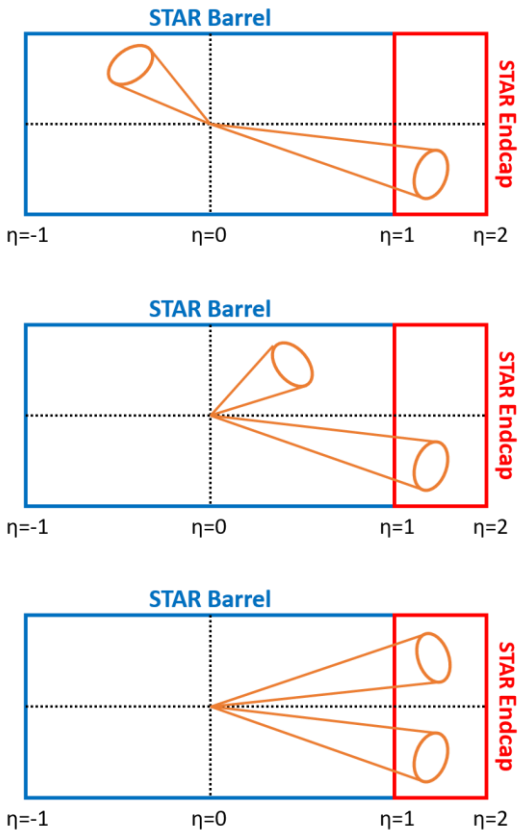
- First measurement of $A_{LL}(dijets)$
- $\sqrt{s} = 200$ GeV

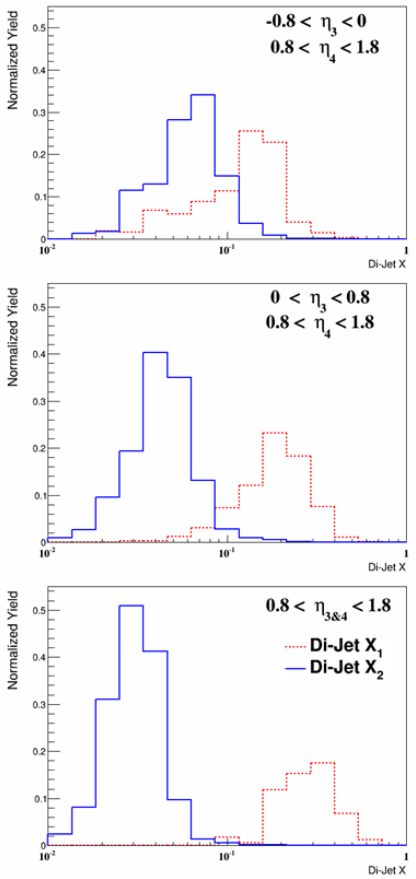
Phys. Rev. D**95** 71103 (2017)

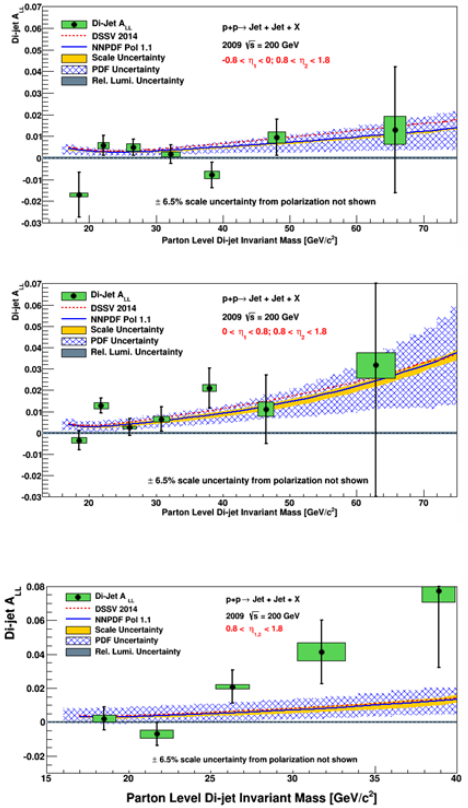


$$\sqrt{x_1} \cdot \sqrt{x_2} = M/\sqrt{s}$$

Different Dijet Topologies

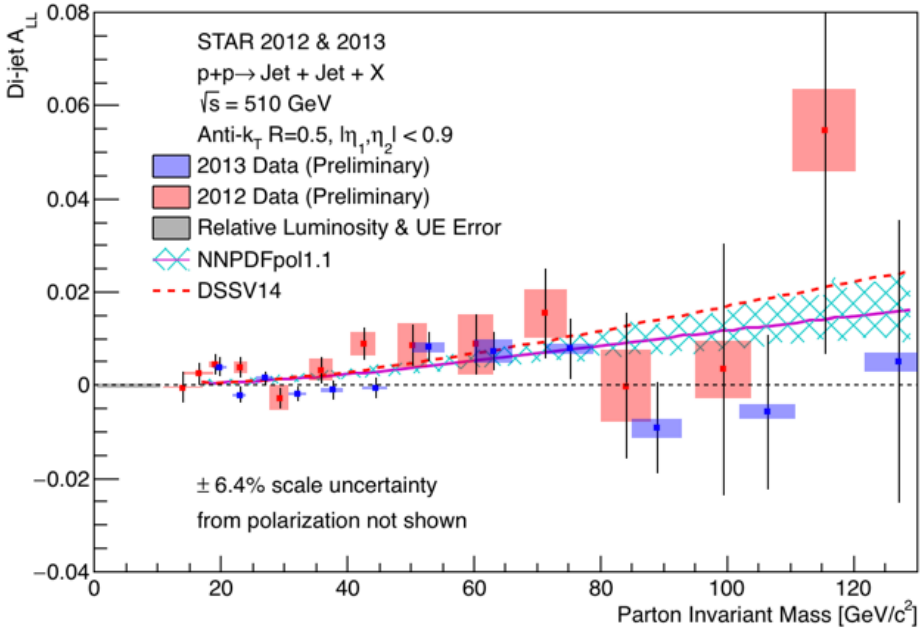


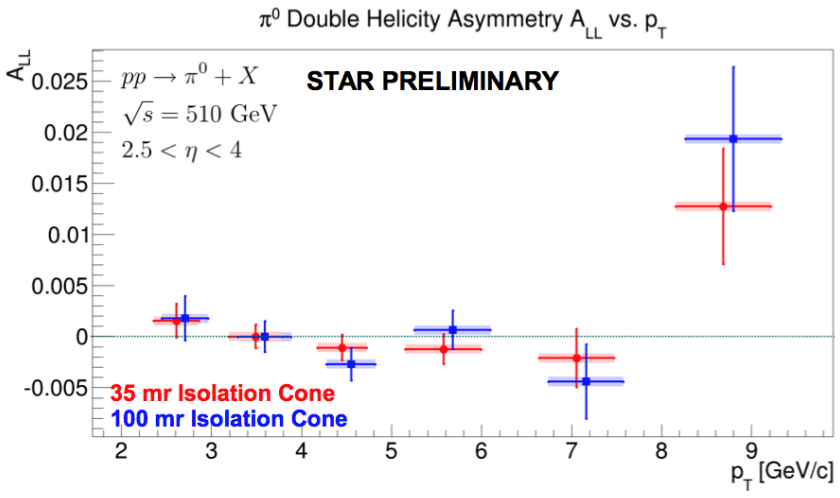




- $\sqrt{s} = 200$ GeV (2009)
- Publication in preparation

More Results Underway





- Jets and Dijets
- $\sqrt{s} = 510$ GeV, 2012 and 2013
- Final results (2012) will have three η-bins

$$-0.9 < \eta < -0.3$$
$$0.3 < \eta < 0.3$$
$$0.3 < \eta < 0.9$$

} 4 dijet topologies

- Underlying event correction

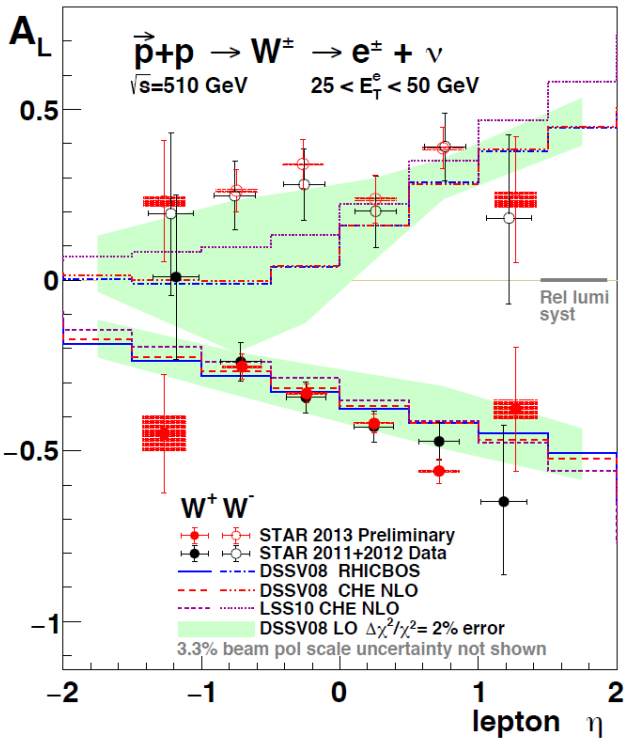
- π^0 at forward rapidity
- $2.5 < \eta < 4.0$
- $\sqrt{s} = 510$ GeV, 2012 + 2013
- Publication in preparation

Sea Quark Helicity

- Parity violating (single-spin) asymmetry

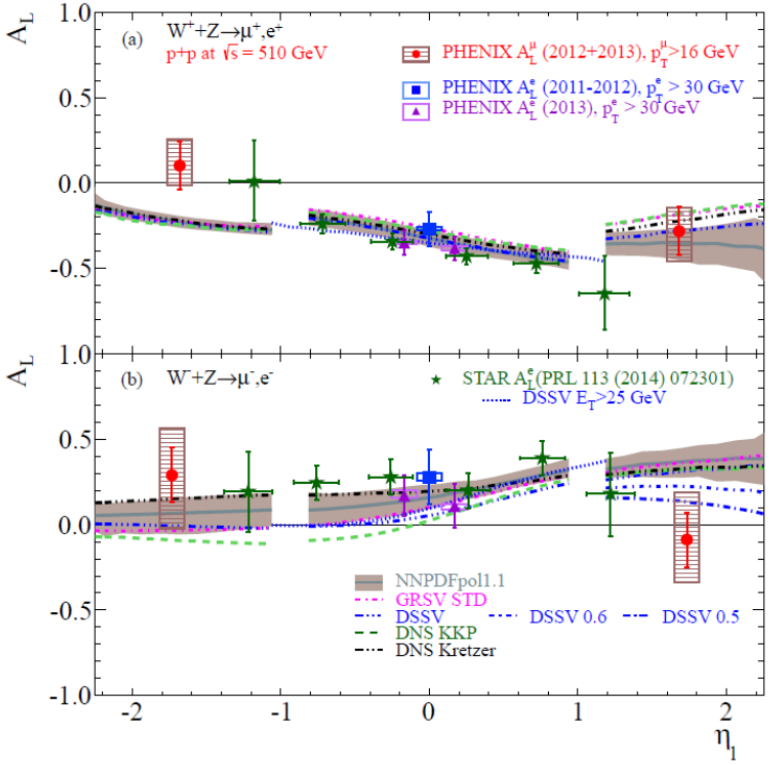
$$A_L(l^-) = \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

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



Impact shown in NNPDFpol1.1
arXiv:1702.05077

$p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm}\ (e^{\pm})$

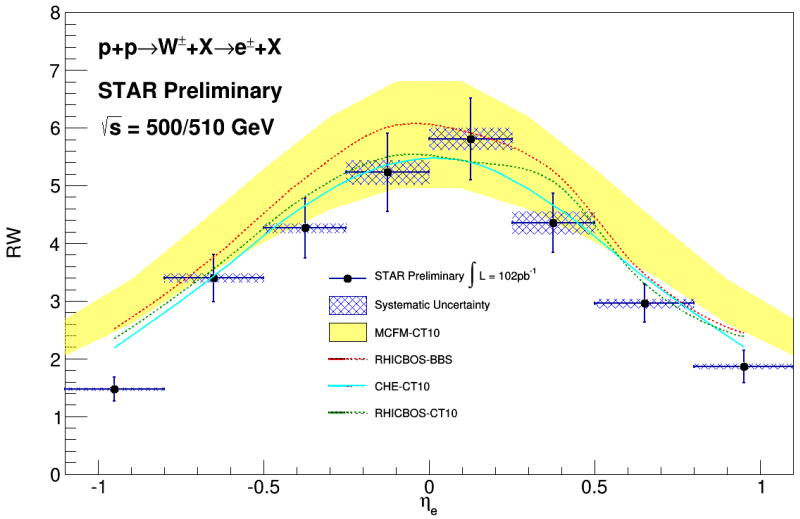


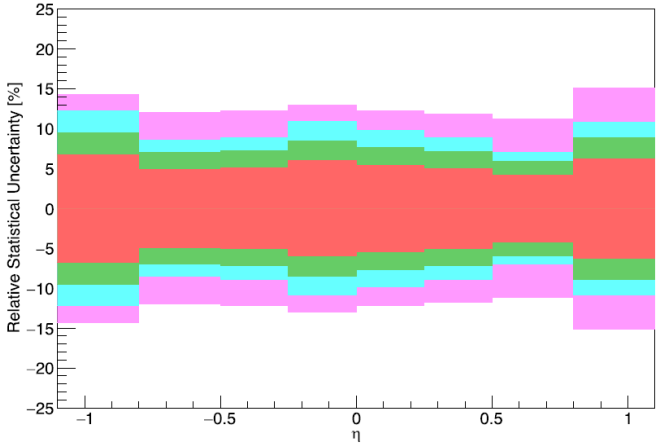
arXiv:1804.04181

Flavor Composition of the Sea

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

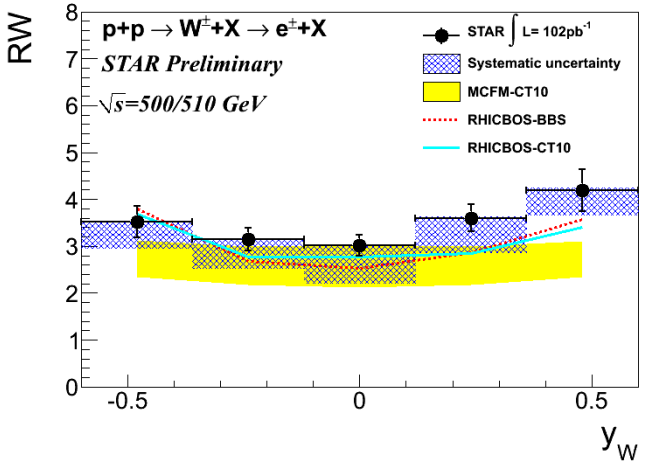
- Unpolarized (longitudinal+transverse)
- STAR coverage: $0.1 < x < 0.3$
- Final results will include Z^0 ratio
- Projected uncertainties





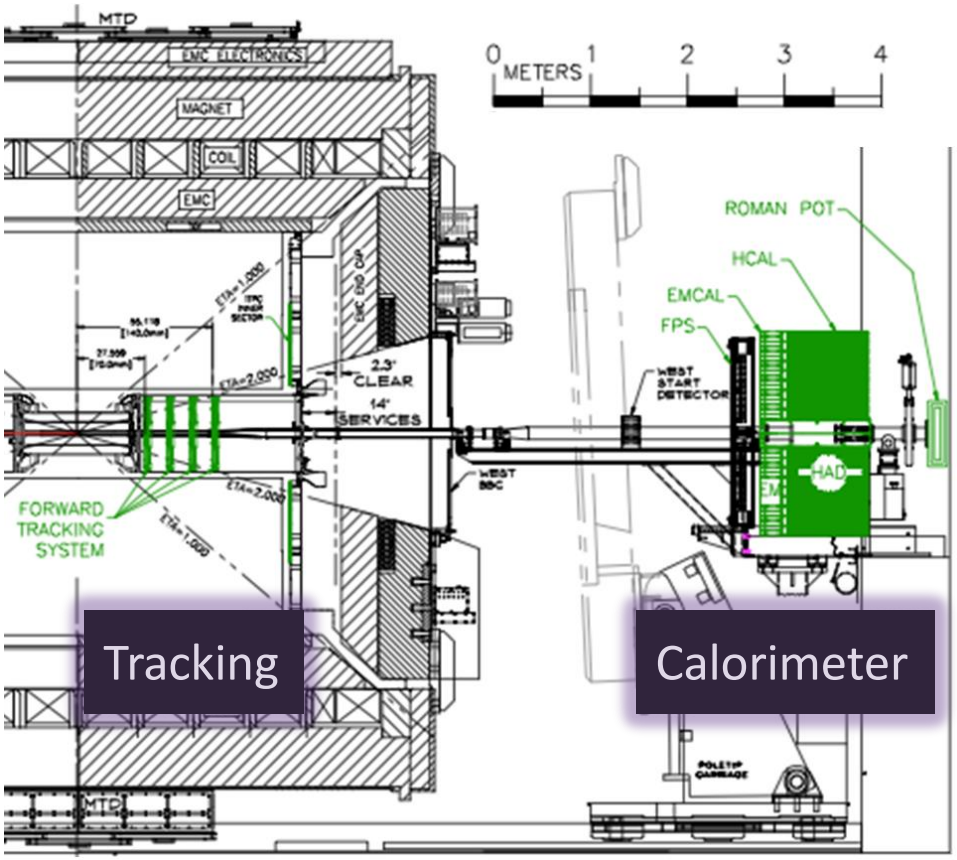
$2011 + 12, L_{int} \approx 100\ \text{pb}^{-1}$
$2013, L_{int} \approx 250\ \text{pb}^{-1}$
$2017, L_{int} \approx 350\ \text{pb}^{-1}$
combined

With fully reconstructed W kinematics



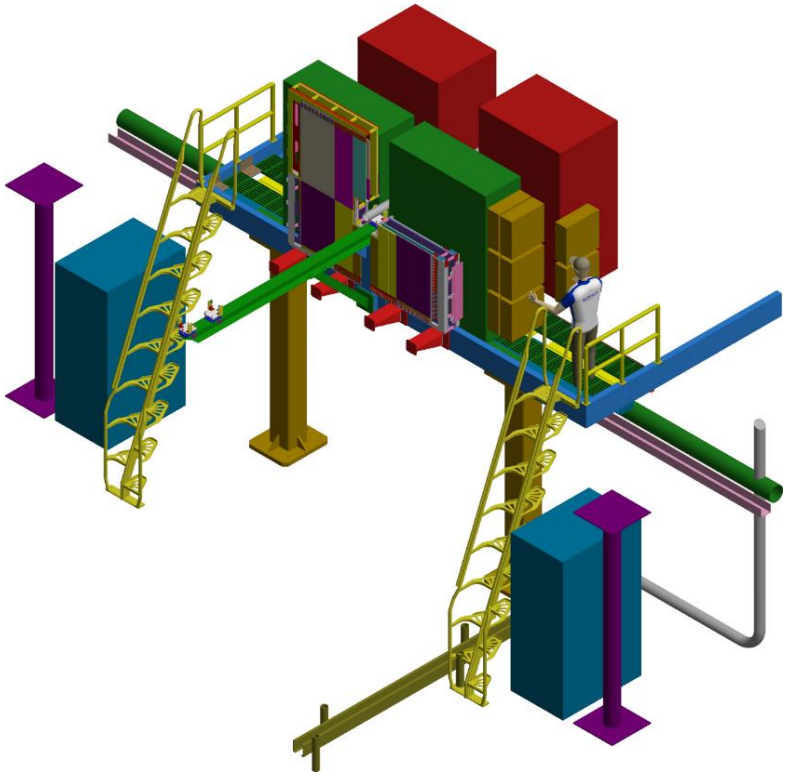
Forward Detector Upgrade

$2.5 < \eta < 4.0$



	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

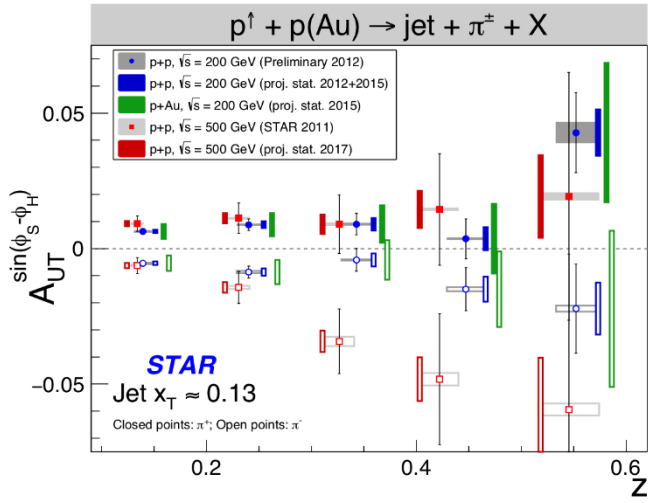


Spin Dependent Fragmentation

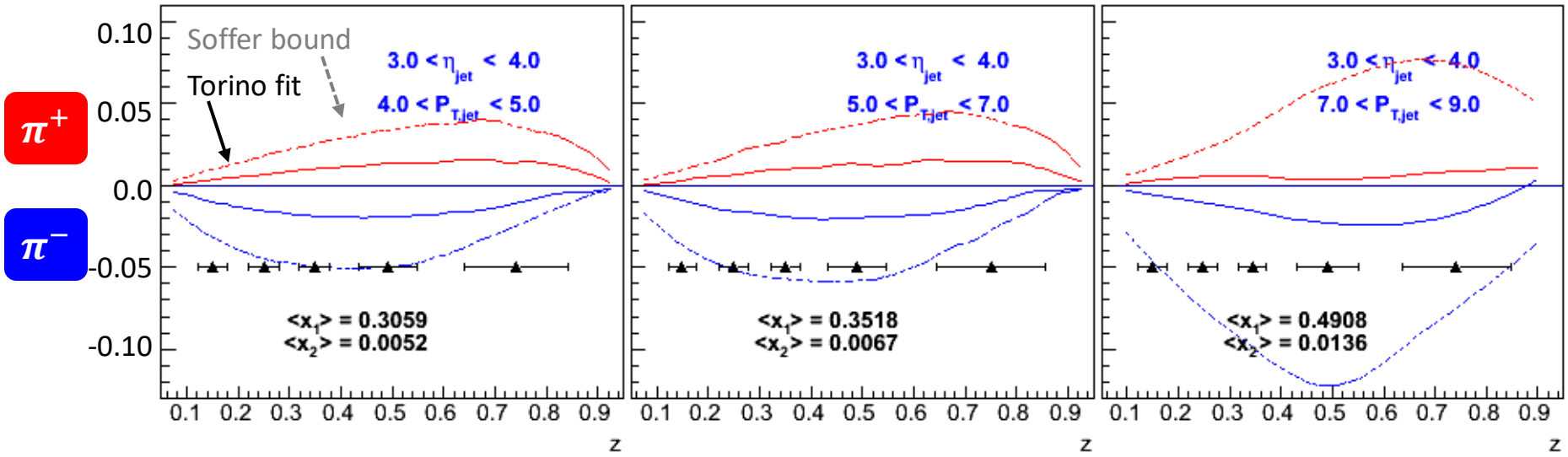
- Hadron in jet
  - STAR measured at midrapidity
  - Move to higher x

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

  - Multi-dimensional binning



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



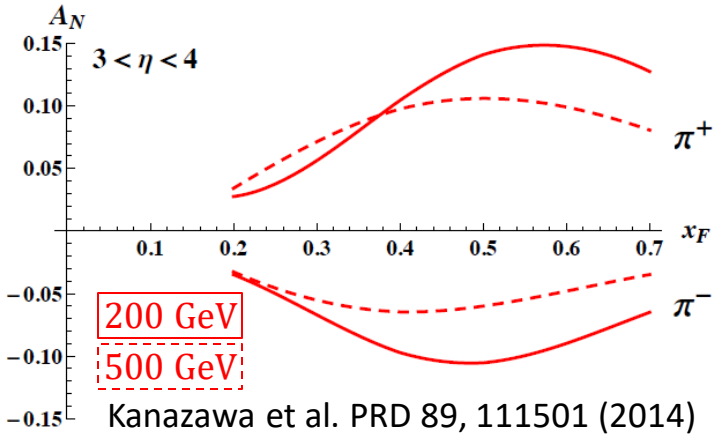
Torino: Phys. Rev. D87 (2013) 094019 Soffer bound&transversity: Phys. Rev. Lett. 74 (1995) 1292

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

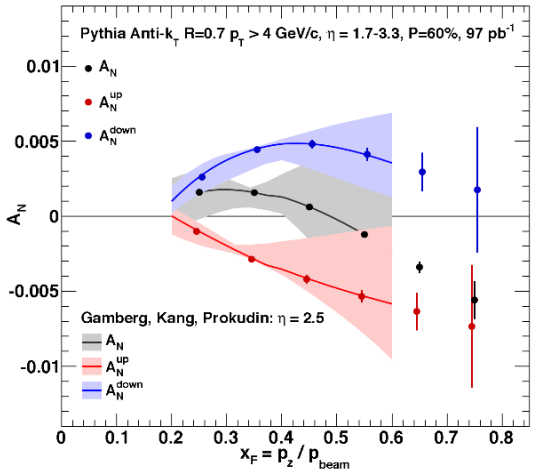


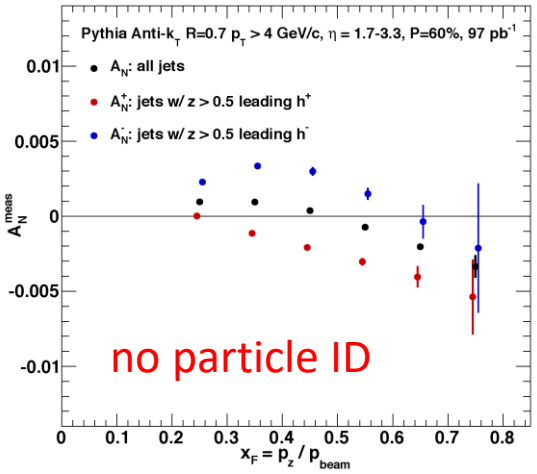
Kanazawa et al. PRD 89, 111501 (2014)

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

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

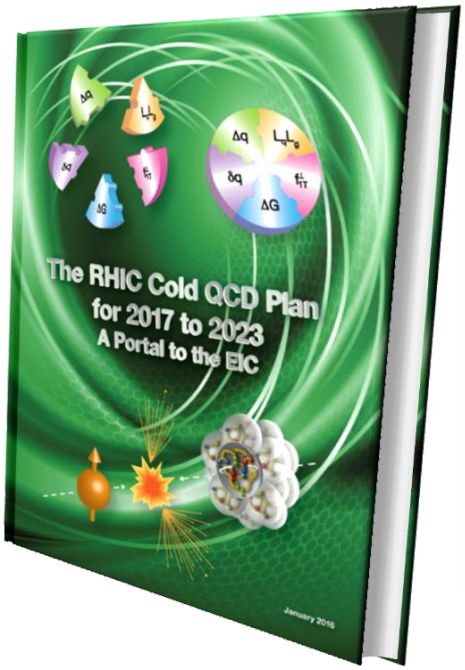
- Cancellation of u & d quark Sivers
- Bias from high-z charged pion

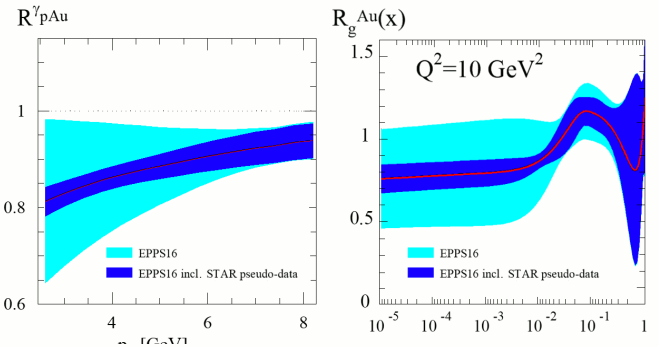


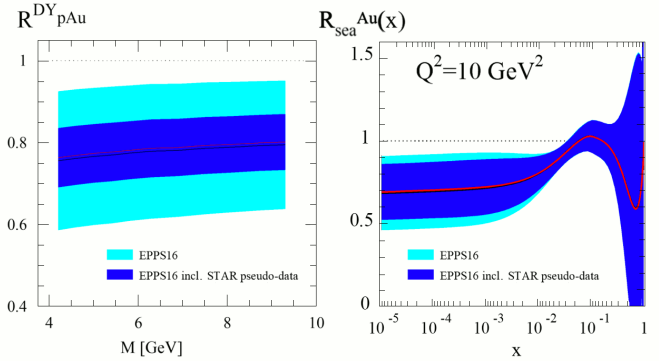


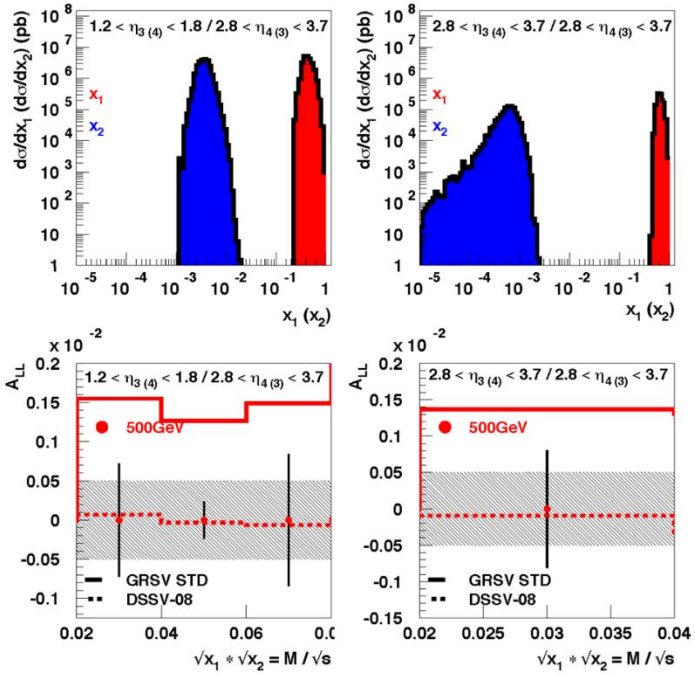
More Cold QCD at RHIC

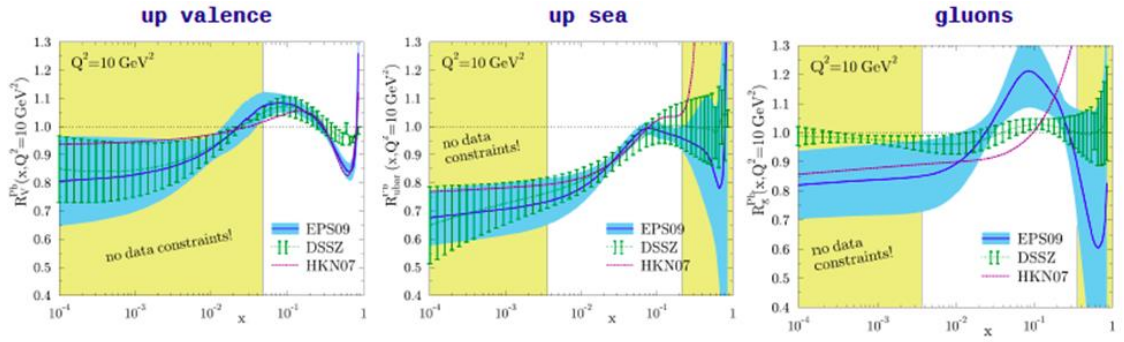
- Extend x-range for gluon helicity with dijets
- Nuclear parton distributions
- Nuclear suppression R_{pA}
  - Drell-Yan → sea quarks
  - Direct photons → gluons











Outlook

Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
2021	$p^{\uparrow}p$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal
2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking

BACK UP

Ideally…

Drell-Yan Production

$$p^{\uparrow} + p \rightarrow \gamma^{*} \rightarrow l^{+} + l^{-}$$

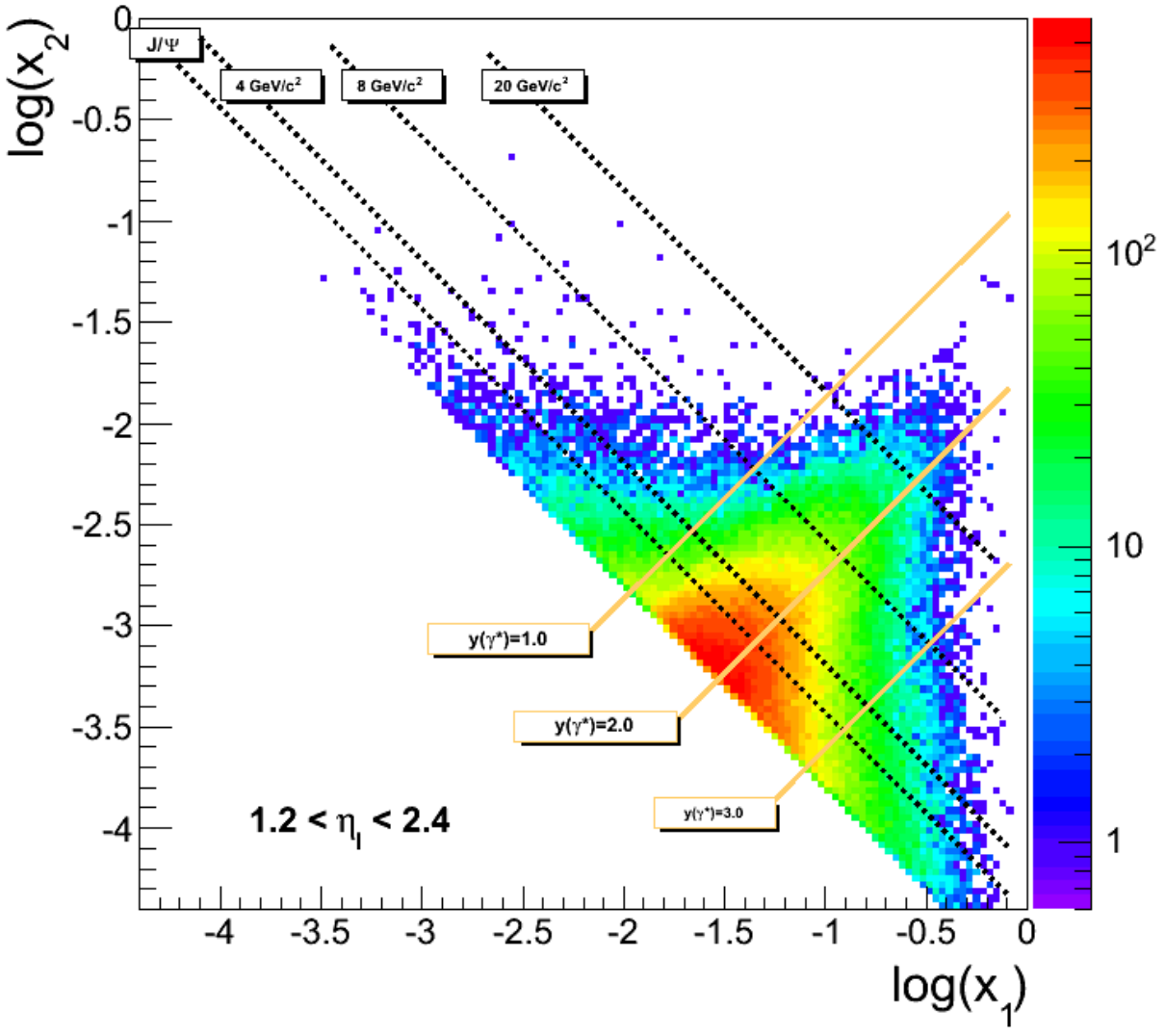
$$\sqrt{s} = 500\ \mathrm{GeV}$$

$$Q^2 = M^2 \gg p_T^2$$

Get rid of background

Scan x with rapidity

Accumulate a few fb^{-1}



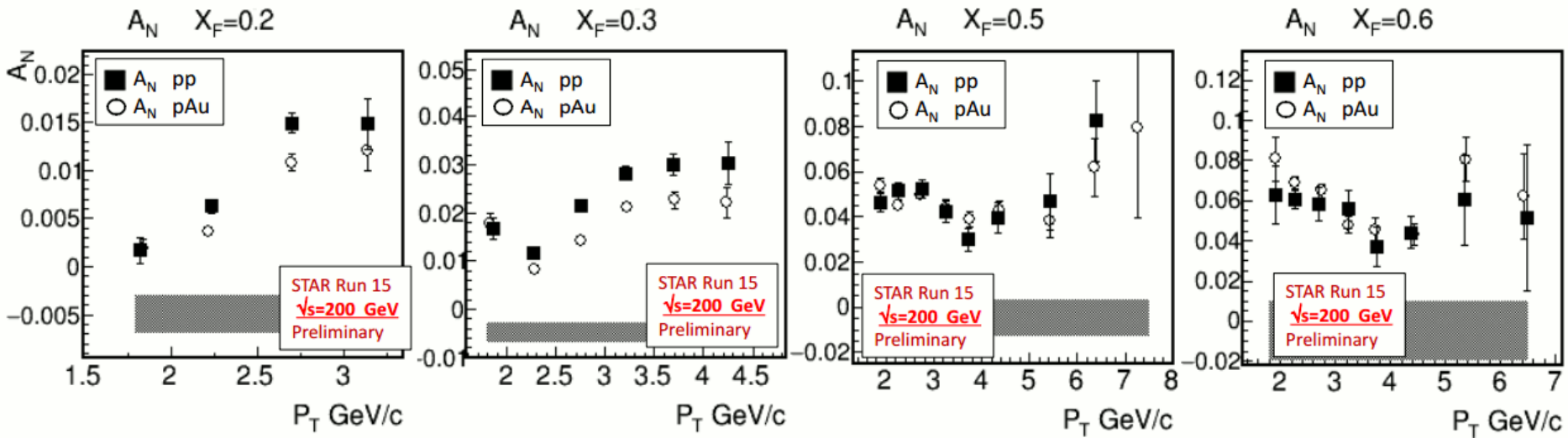
Nuclear Effects in $A_N(\pi^0)$

- Polarized: Transverse spin asymmetries of inclusive π^0 production
- Possibly gluon saturation effects (CGC)
- Nuclear effects on fragmentation process
- RHIC Run 2015
  - $\vec{p}+p$/ $\vec{p}+Al$ / $\vec{p}+Au$

STAR FMS

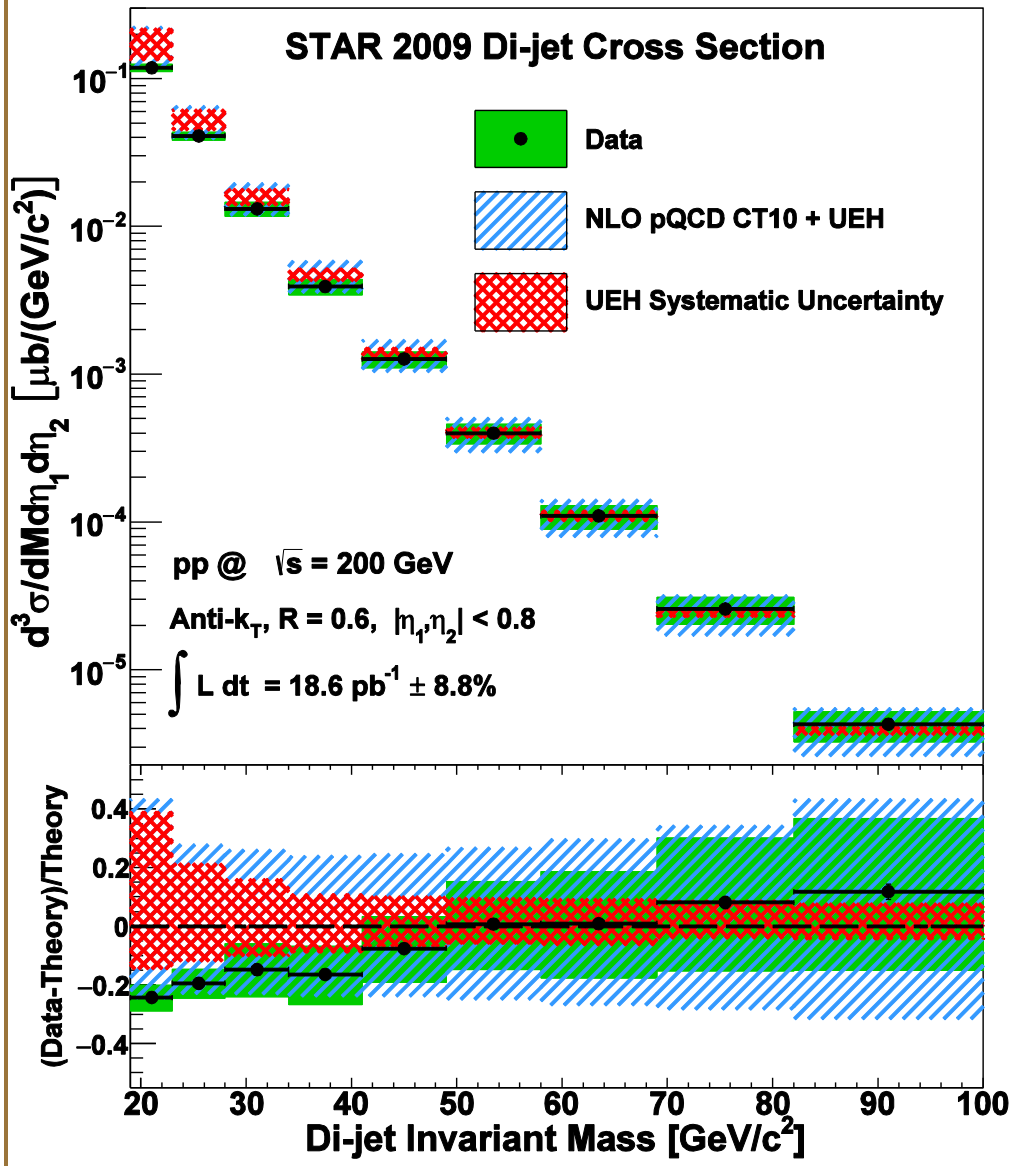
$2.5 < \eta_\gamma < 4.0$

$p+p$ @ $\sqrt{s} = 200$ GeV



No suppression can be observed so far.

2009 Dijet Cross Section



- Dijet cross section plotted as a function of dijet invariant mass corrected back to particle level
- Experimental systematic uncertainties include detector effects and uncertainties from unfolding
- Theory predictions corrected for underlying event effects
- Uncertainty on underlying event correction and theory prediction take into account scale variation and PDF uncertainties

Helicity Asymmetry of Dijets

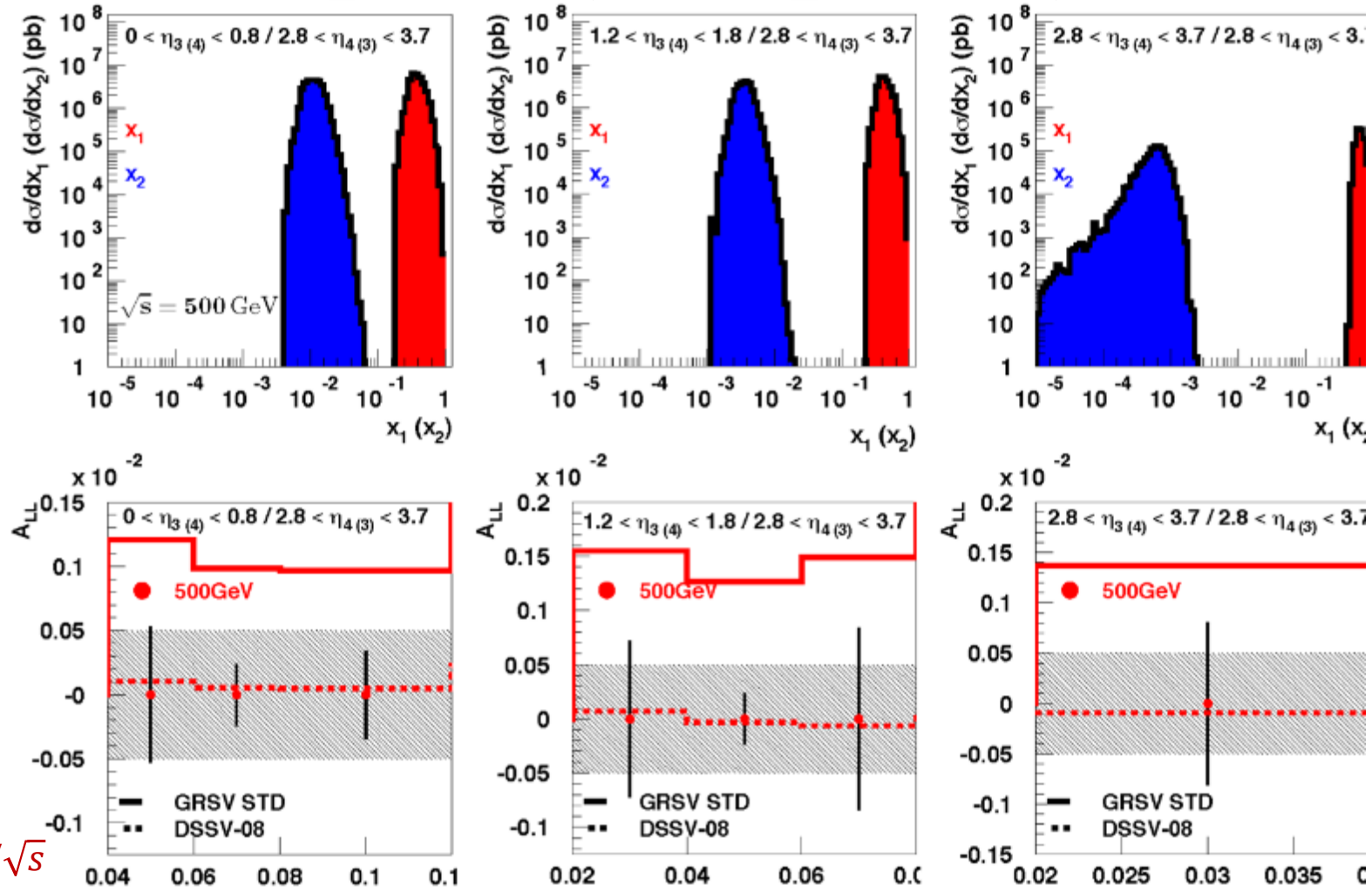
$\sqrt{s} = 500$ GeV

Jet cone $R < 0.7$

$E_{T3} > 5$ GeV

$E_{T4} > 8$ GeV

more forward correlation

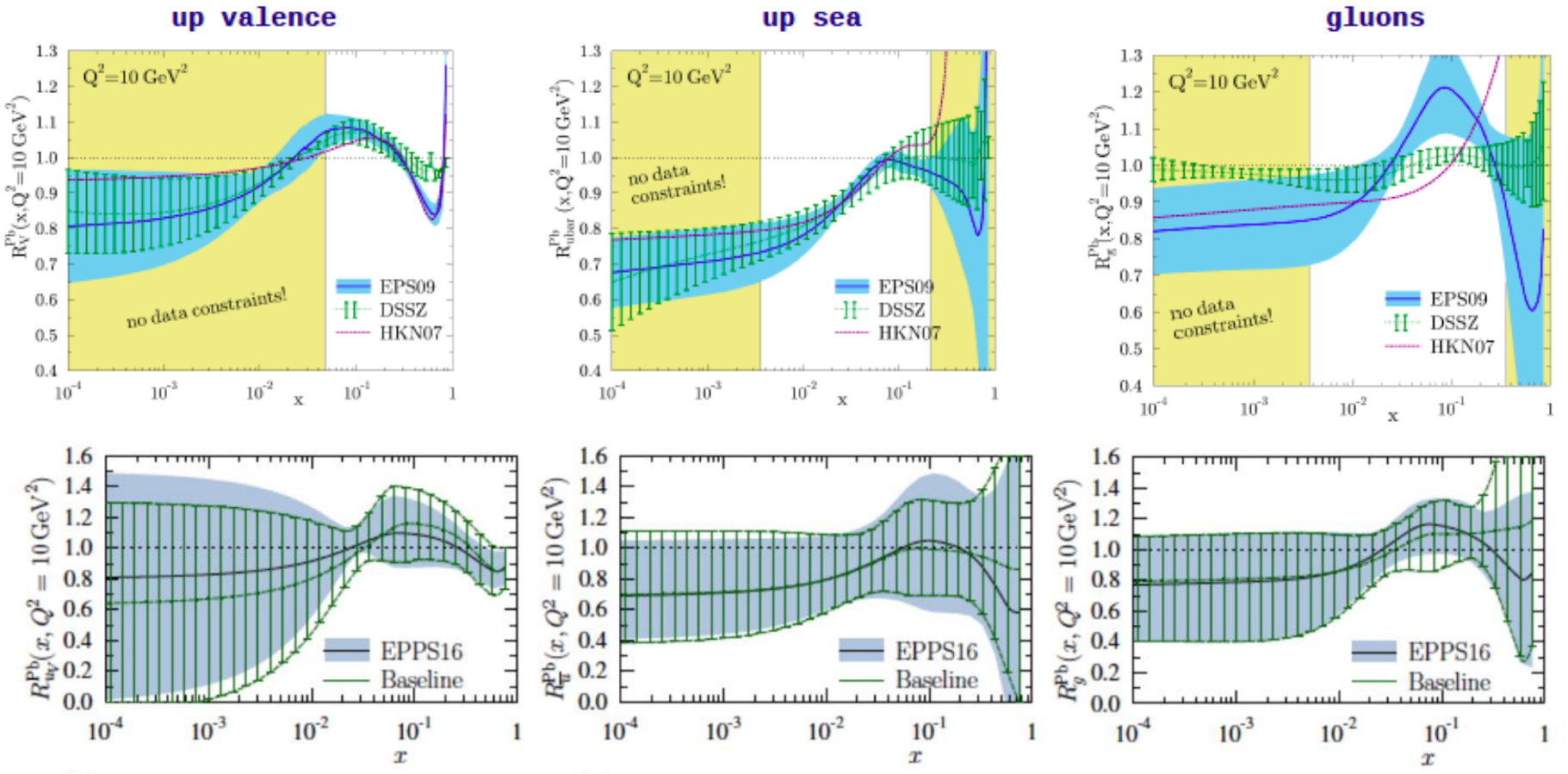


$\sqrt{x_1} \cdot \sqrt{x_2} = M/\sqrt{s}$

Nuclear Parton Distributions

- Initial conditions for heavy ion collisions (here Pb)
  - Largely unconstrained
  - LHC Run I $p + Pb$ data at very high Q^2

H. Paukkunen, DIS (2014)
K.J. Eskola et al. EPJ C77, 163 (2017)



Nuclear Modification: $R_{pA}(\gamma_{dir})$

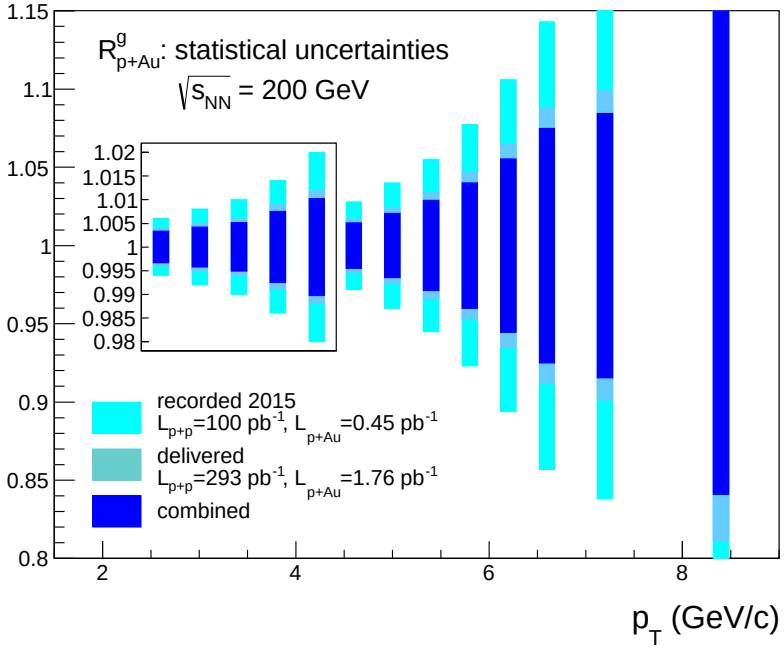
Direct photons

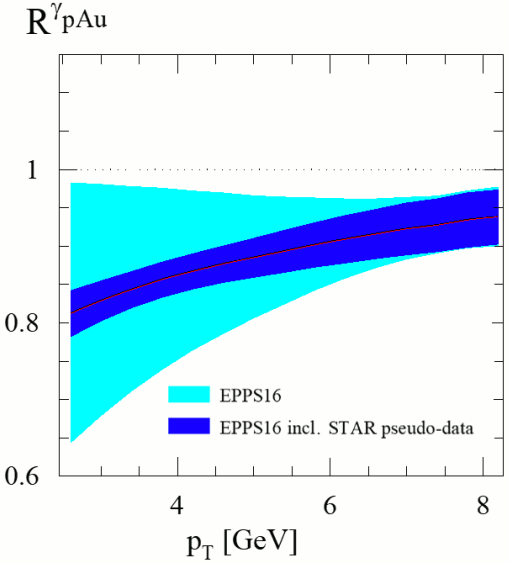
- $2.5 < \eta_\gamma < 4.0$
- Moderate Q^2
- Medium to low x

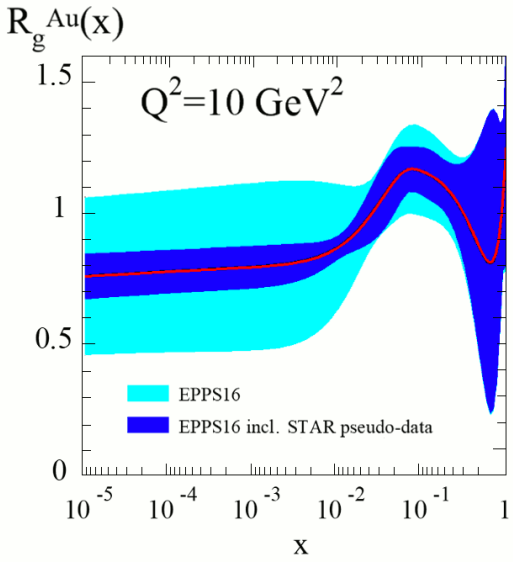
$$R_{pA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{pA}}{dN^{pp}}$$

RHIC 2015

- $p + Al, L_{\text{int}} = 1.0\ \text{pb}^{-1}$
- $p + Au, L_{\text{int}} = 0.45\ \text{pb}^{-1}$







Nuclear Modification: $R_{pA}(\gamma^*_{DY})$

Drell-Yan production

- $2.5 < \eta_{\gamma^*} < 4.5$
- Moderate-high $Q^2 = M^2_{\gamma^*}$
- Medium x

- Drell-Yan at forward η
- 2017: $p + p$ @ $\sqrt{s} = 500$ GeV
- 2023: $p + p/Al/Au$ @ $\sqrt{s_{NN}} = 200$ GeV