Transverse Spin Results from STAR

J. Kevin Adkins for the STAR Collaboration
University of Kentucky
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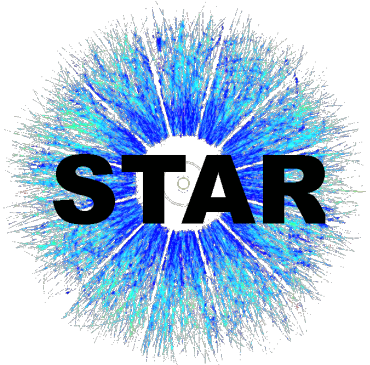
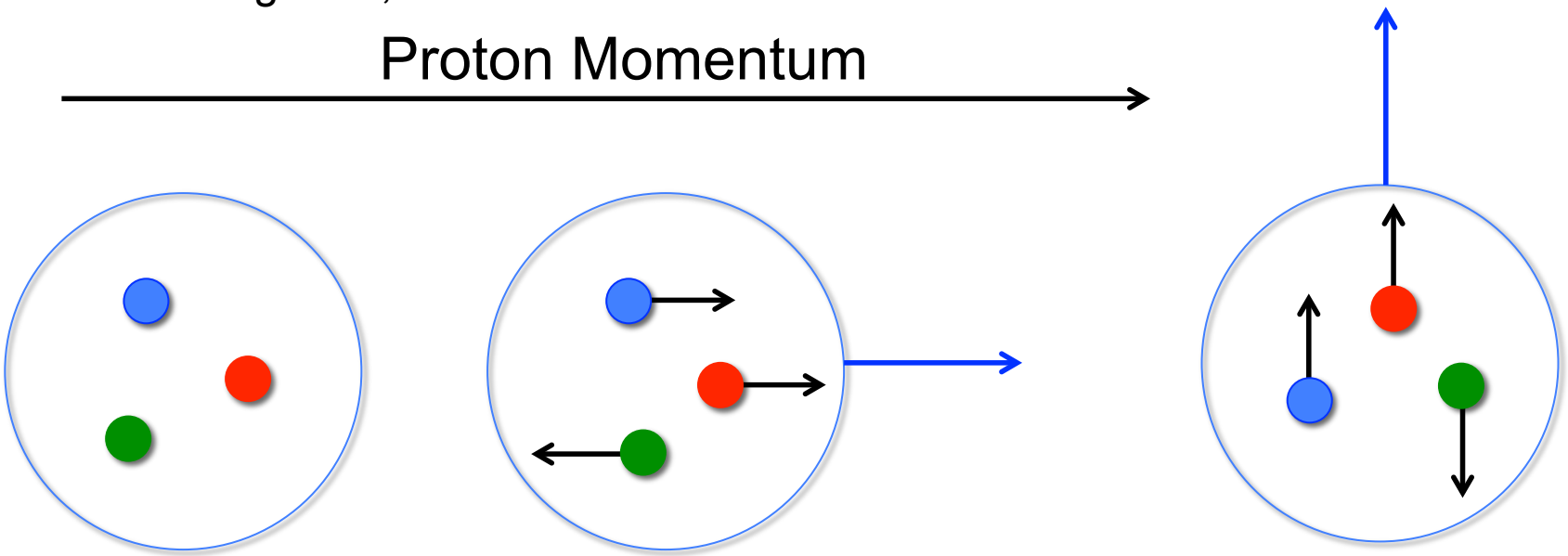
UNIVERSITY OF KENTUCKY



Describing the Proton's Spin Structure

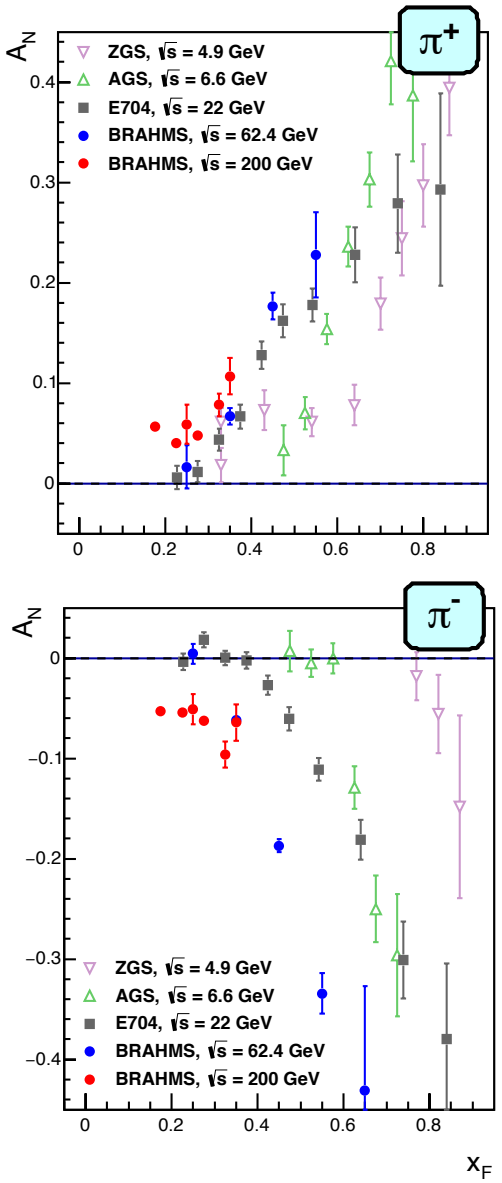
Distribution	Partons	Name	Proton Polarization
f(x)	q, G	Momentum	Unpolarized
Δf(x)	q, G	Helicity	Longitudinal
$h_1(x)$	q	Transversity	Transverse

*At leading twist, and in the collinear factorization



Factorization Schemes

- Leading twist collinear factorization fails to accurately reproduce large inclusive pion single-spin asymmetries (SSA)
  - It predicts these results should be nearly zero!
- SSA allow for detailed study of the proton's transverse spin structure
- TMD factorization used when there are two momentum scales: $\Lambda_{QCD} \leq p_T << Q$
  - Hadrons in jets, W/Z boson, etc.
- Twist-3 collinear correlators are used to describe results where there is a single momentum scale: $\Lambda_{QCD} << Q$
  - Inclusive jet, direct-γ



arXiv:1602.03922

What Can We Learn Using SSA in $p^{\uparrow}p$?

Inclusive jet asymmetry
A_N for reconstructed $W^{\pm}$ and Z^0
Direct γ
Drell-Yan

Twist-3 quark-gluon correlators
Sivers TMD
Sivers function sign change

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Hadrons in jets Dihadron (IFF) asymmetry	→	Transversity Collins fragmentation function

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Hadrons in jets
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→ Transversity
Collins fragmentation function

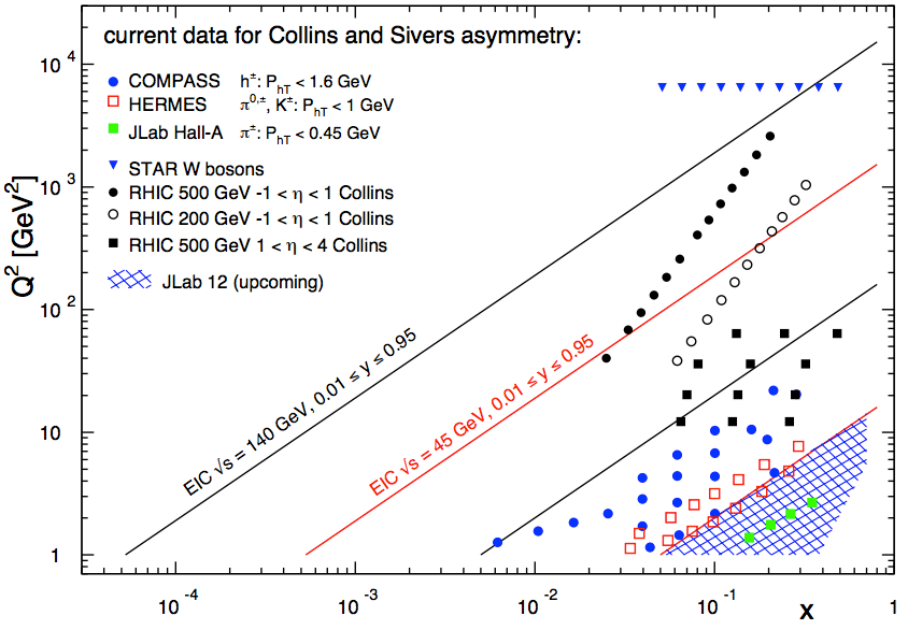
TMD Q^2 evolution
Universality
Factorization breaking effects

Why Look to p+p? Kinematic Coverage!

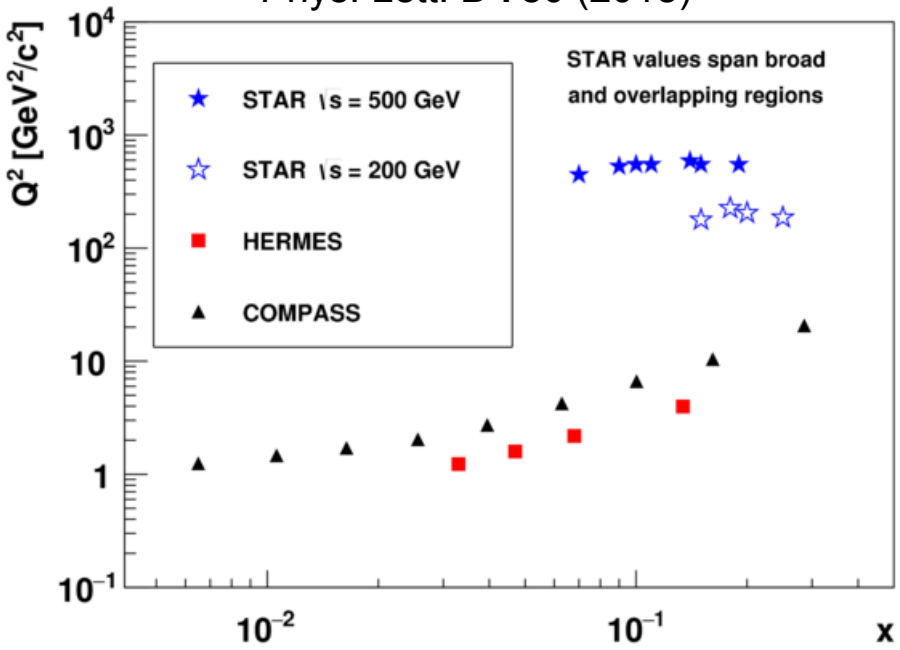
- STAR covers a similar range in *x* to that of SIDIS results
  - Important for studies of TMD universality

- Much higher in Q^2
  - We can learn something about the evolution of TMDs

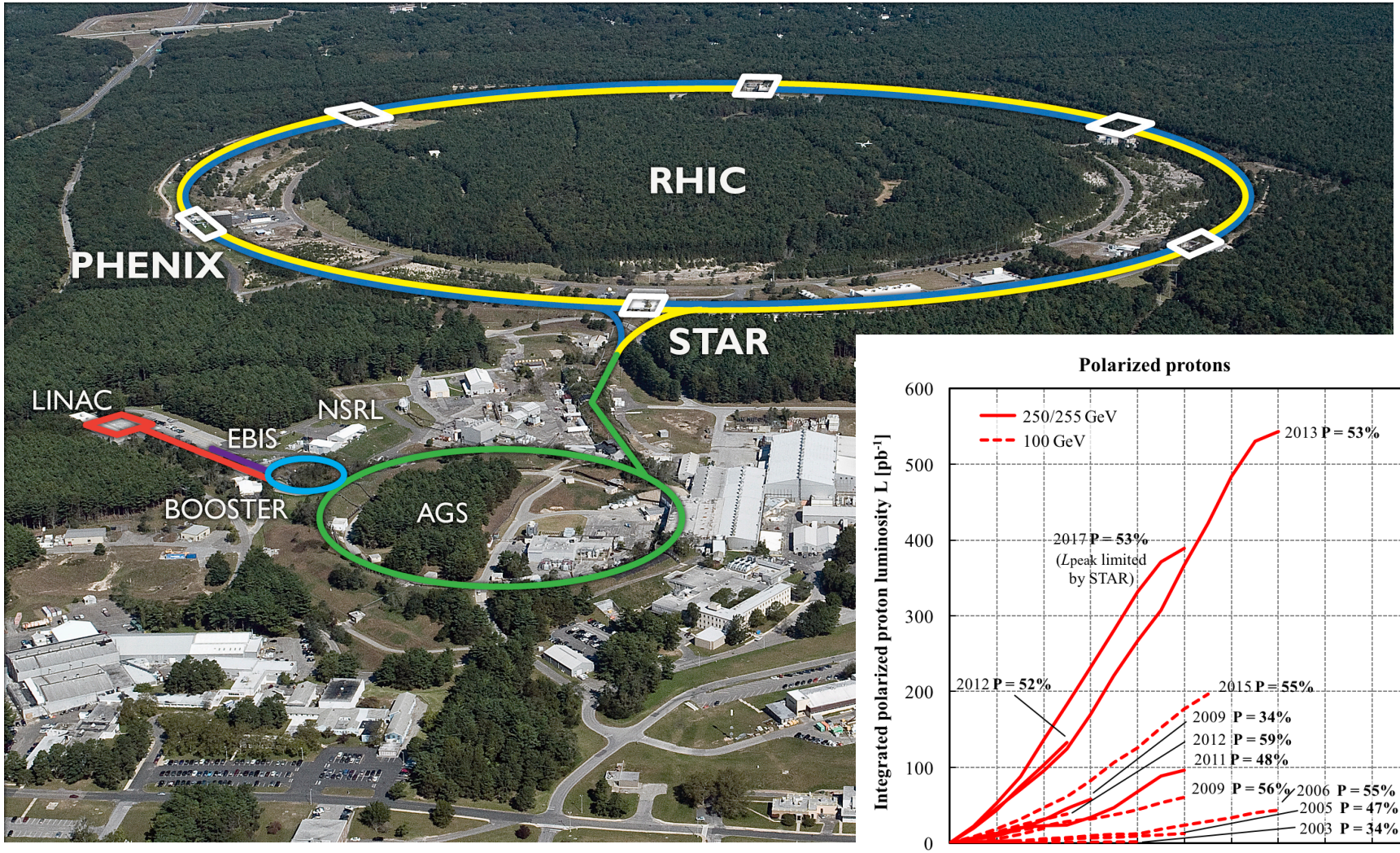
arXiv:1602.03922



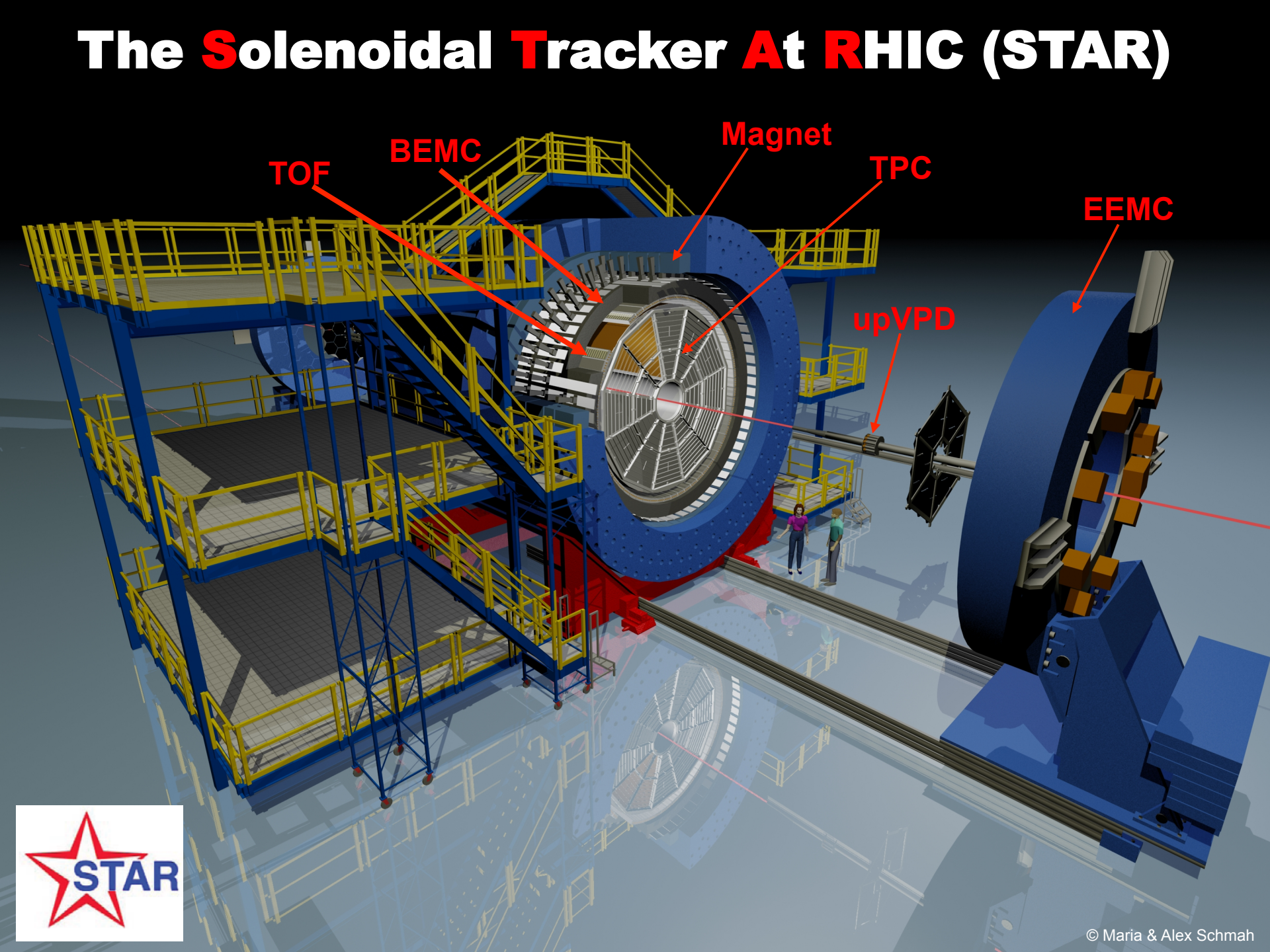
Phys. Lett. B **780** (2018)



Relativistic Heavy Ion Collider



The Solenoidal Tracker At RHIC (STAR)



Inclusive jet asymmetry
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Direct γ
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Twist-3 quark-gluon correlators
Sivers TMD
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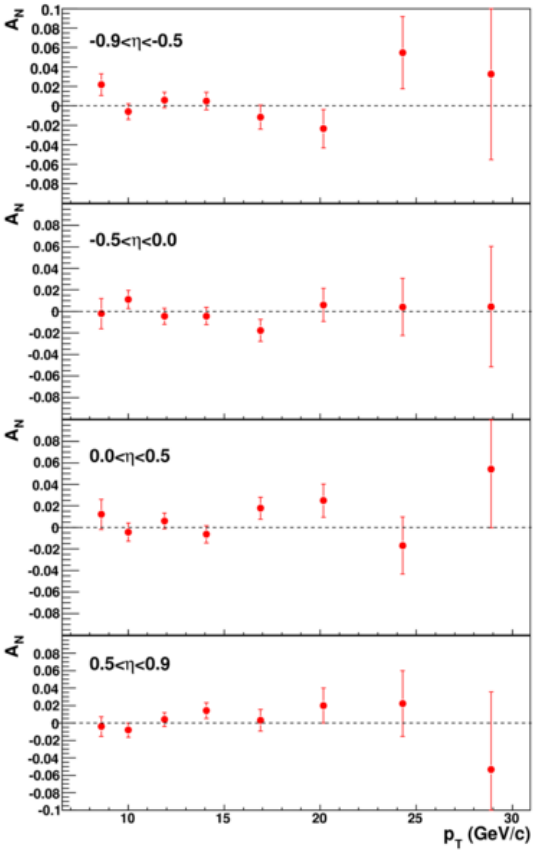
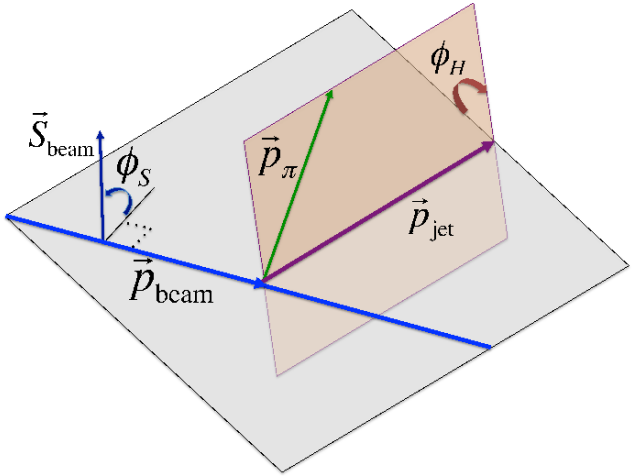
Inclusive Jet Asymmetry (A_N)

- In p+p, A_N is sensitive to the initial state quark-gluon twist-3 correlators
  - Correlators described by the Efremov-Teryaev-Qiu-Sterman (ETQS) function
  - ETQS function related to leading twist Sivers TMD by k_T integration
- A_N has been measured by STAR previously at $\sqrt{s}$ = 200 GeV



Phys. Rev. D **86** (2012)



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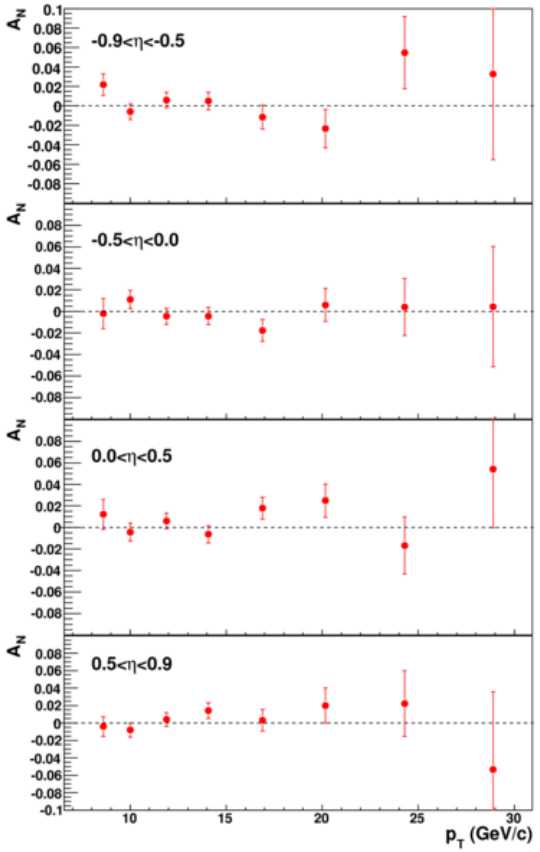

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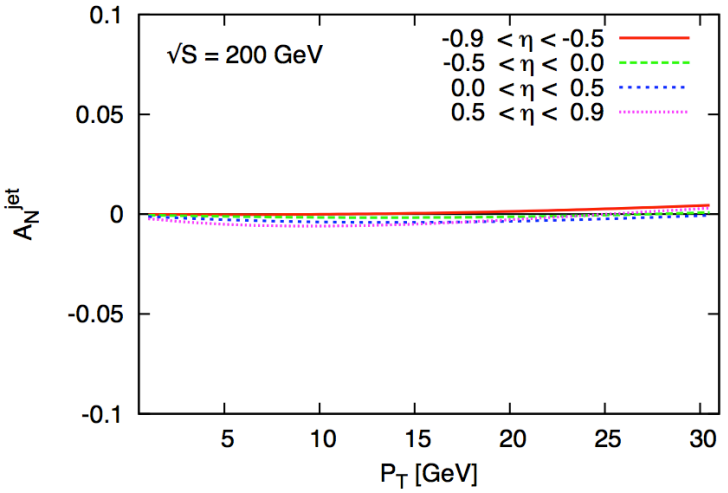

Phys. Lett. B **720** 2013

Inclusive Jet Asymmetry (A_N)

$\sqrt{s}$ = 500 GeV

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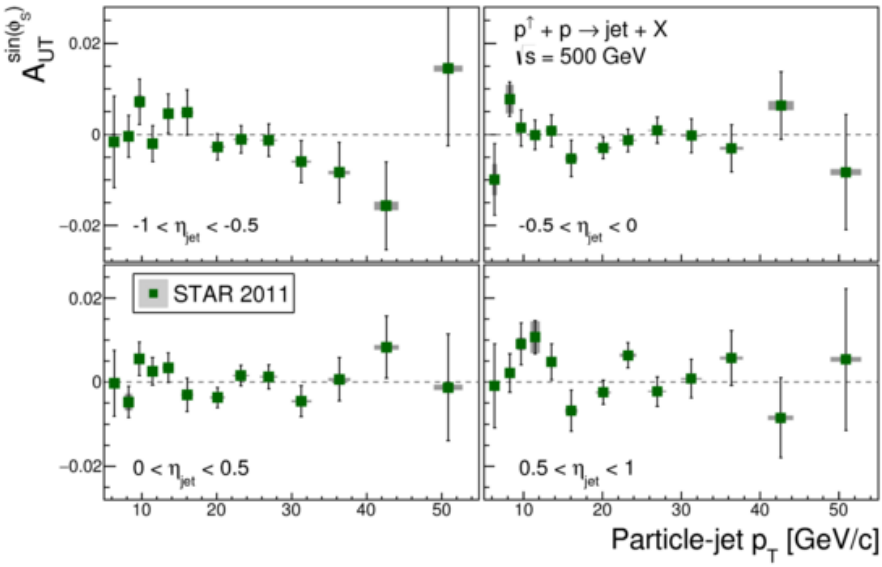
  - ETQS function related to leading twist Sivers TMD by k_T integration
- A_N has been measured by STAR previously at $\sqrt{s}$ = 200 GeV
- Twist-3 theory curves of A_N predict an asymmetry close to zero
- Recent $\sqrt{s}$ = 500 GeV inclusive jet A_N also consistent with zero
  - Enhanced gluon input!



Phys. Rev. D **97** (2018)

$$d\sigma_{UT} \approx d\sigma_{UU}\left[1 + A_N \sin\left(\phi_S\right)\right]$$

A_N for $W^{\pm}$ and Z^0

- Single-spin asymmetries using fully reconstructed $W^{\pm}$ and Z^0 bosons sensitive to quark/antiquark Sivers function
  - Described by TMD factorization ($M^{W/Z}$ sets hard scale, and $p_T^{W/Z}$ sets soft scale)

- Provides laboratory to test sign change
  - Sivers function measured in DY/$W^{\pm}$/Z^0 asymmetries predicted to be opposite in sign from that measured in SIDIS

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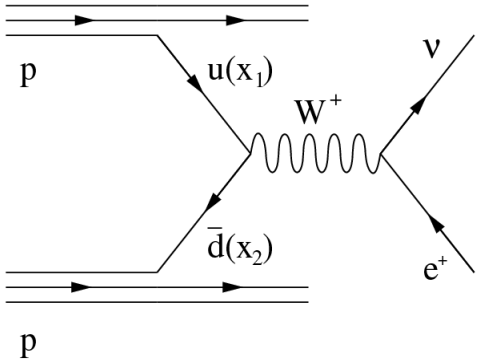
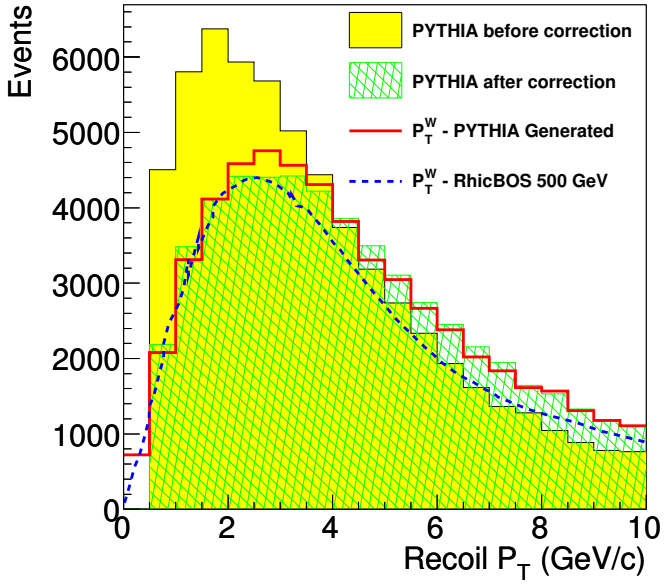
- Kinematics of W fully reconstructed:

$$\vec{p}_T^{\,W} = \vec{p}_T^{\,e} + \vec{p}_T^{\,\nu}$$

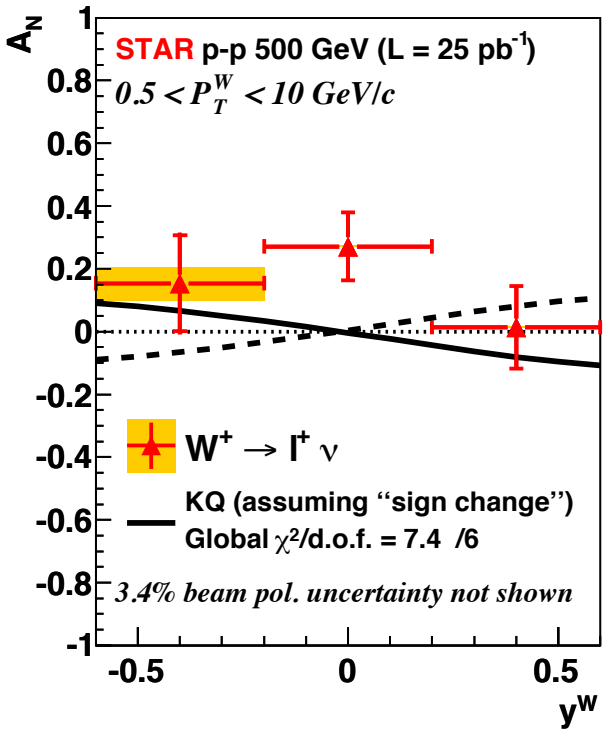
  - Efficiency and fiducial losses accounted for with Pythia MC embedded into data

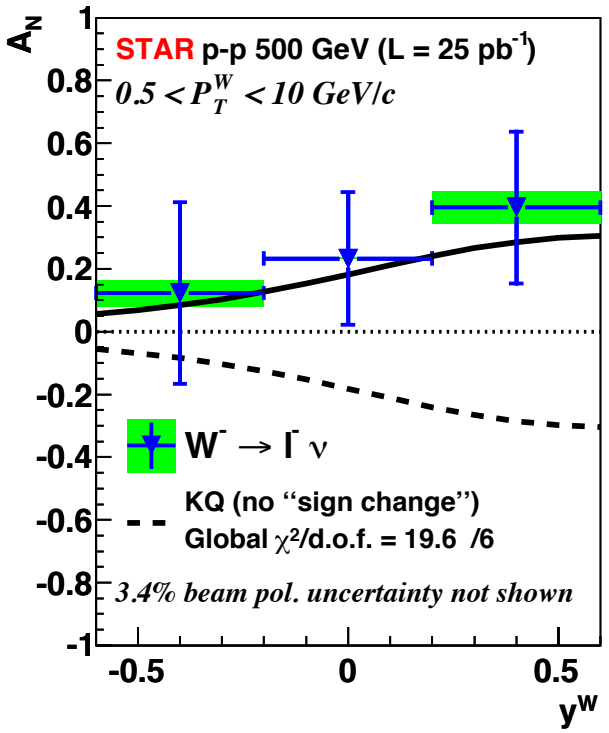




A_N for $W^{\pm}$ and Z^0

$\sqrt{s}$ = 500 GeV

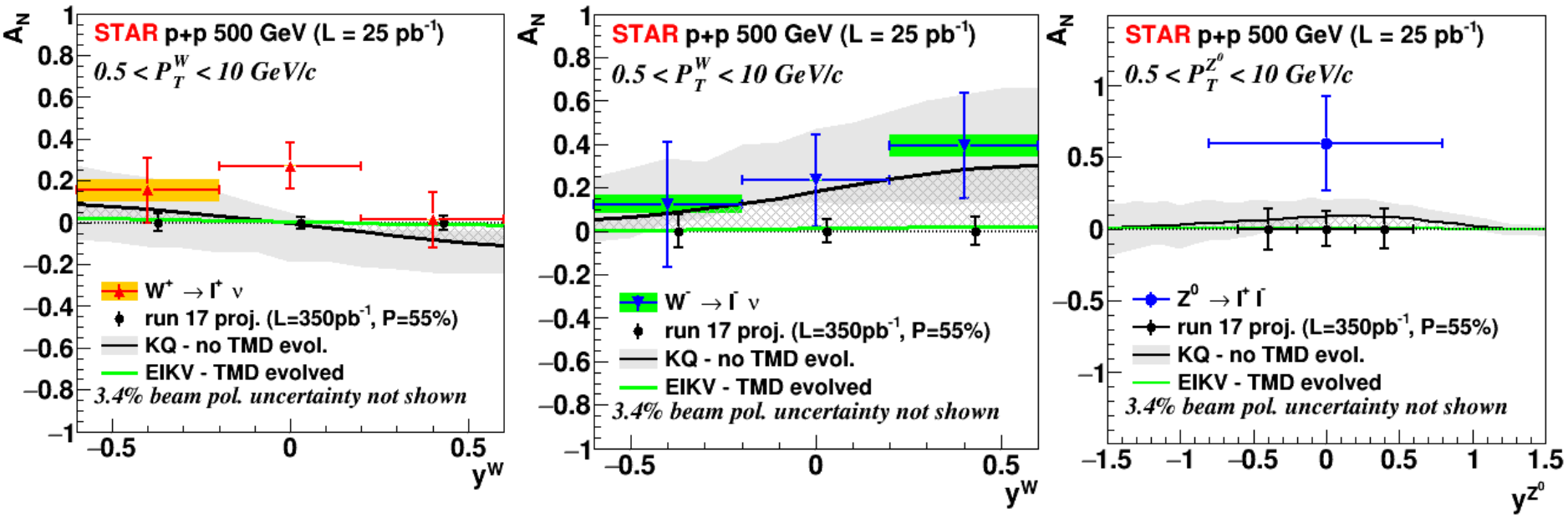




Phys. Rev. Lett. **116** (2016)

- A_N results for both W^+ and W^- favor theory curves which DO assume a Sivers sign change
- KQ theory curves: Phys. Rev. Lett. 103, 172001
  - Assume no TMD evolution
  - Evolution effects seem rather small!

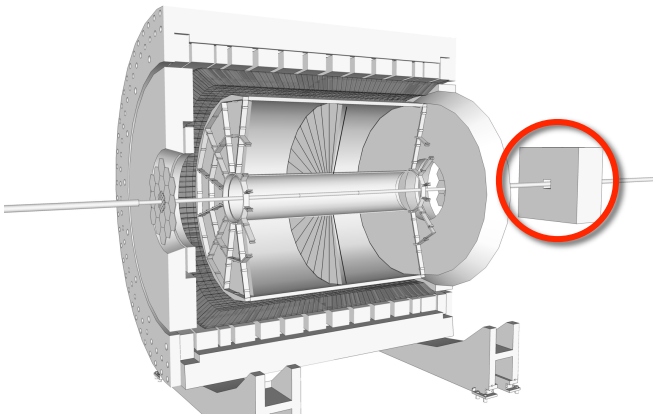
Coming soon: A_N for $W^{\pm}$ and Z^0 from 2017!

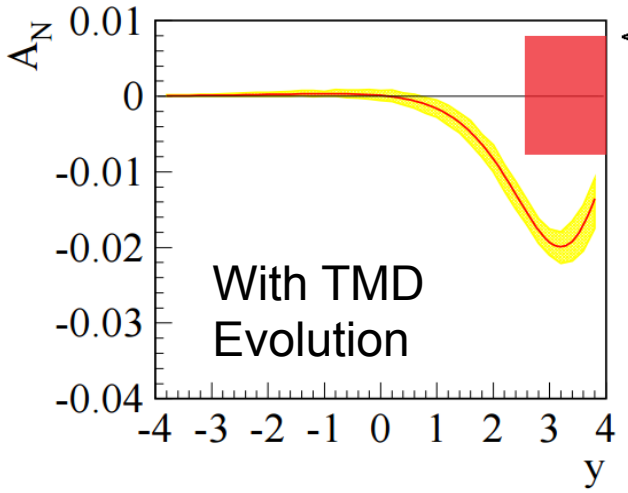


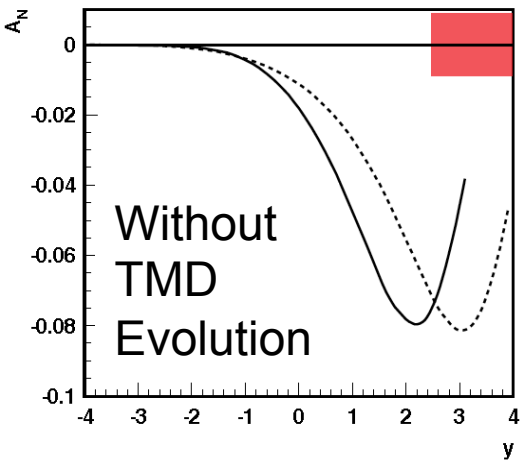
- 2017 transverse p+p run collected 350 pb^{-1} integrated luminosity
- This increase in statistical power will provide:
  - An enhanced look at the Sivers sign change
  - Input on sea quark Sivers function
  - Additional input on TMD evolution
- EIKV theory curves: Phys. Rev. D **89**, 074013 (2014)

Coming soon: Drell-Yan from 2017!

- FMS outfitted with postshower for 2017 run
  - Combined with preshower detector allows for factor of 10^6 suppression of QCD background to signal ratio
- FMS allows for forward e^+e^- DY coverage:
  - $2.5 < \eta < 4.0$ and $4.0\ \text{GeV}/c^2 < M_{e^+e^-} < 9.0\ \text{GeV}/c^2$
- Red square: statistical precision using 400 pb^{-1}







Phys.Rev.D 89, 074013 (2014)

Coming soon: Direct γ A_N from 2015 and 2017!

- Also sensitive to twist-3 quark-gluon correlators
  - Related to Sivers TMD via ETQS function
- Can give input on sign change in twist-3 factorization
- Measurements at both $\sqrt{s}$ = 200 and 500 GeV give input on evolution of quark-gluon correlators

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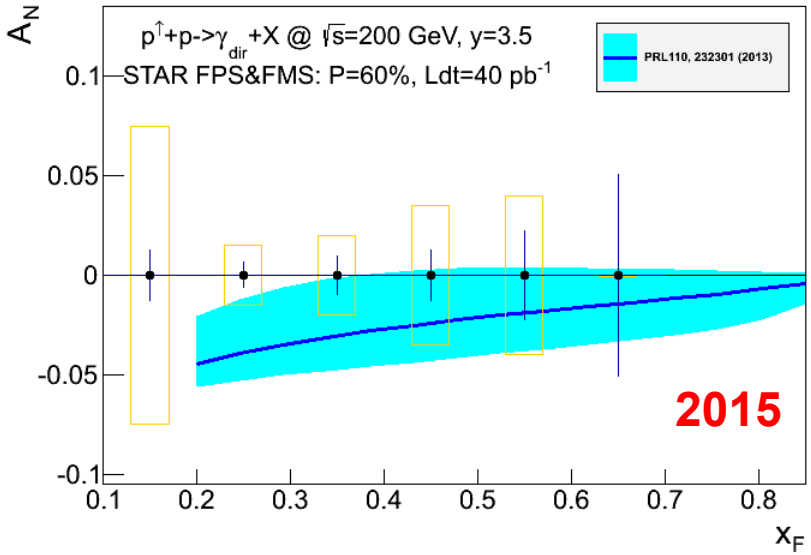
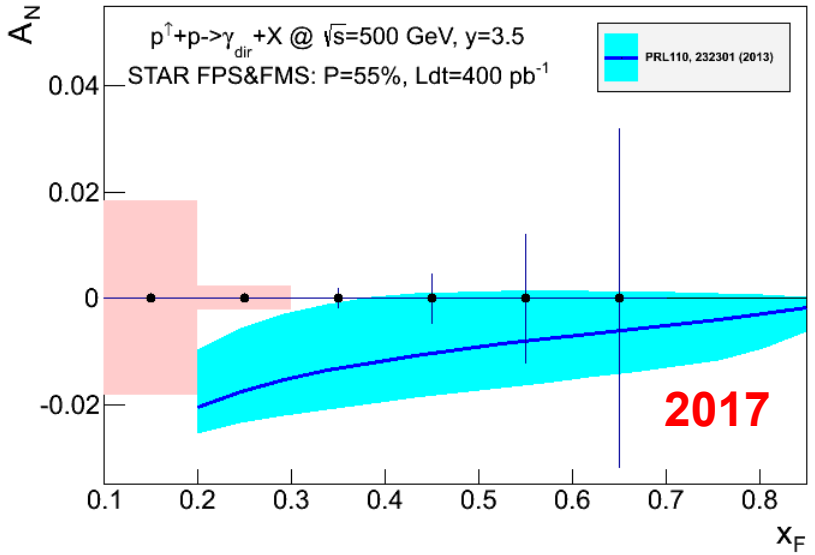
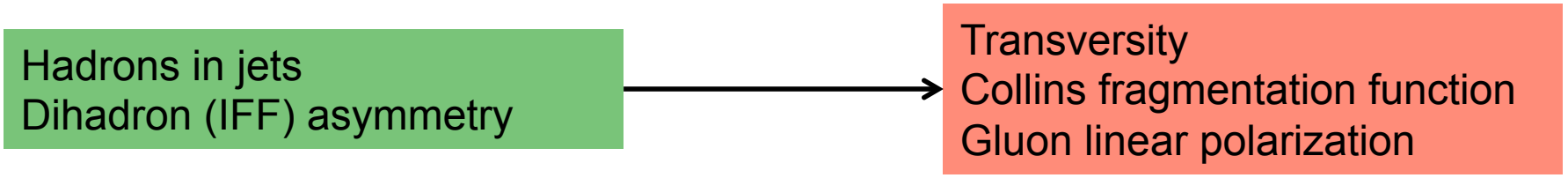
- Statistical projections (lines) with systematic error estimates (boxes) given below
  - Blue curves are predictions based on SIDIS results

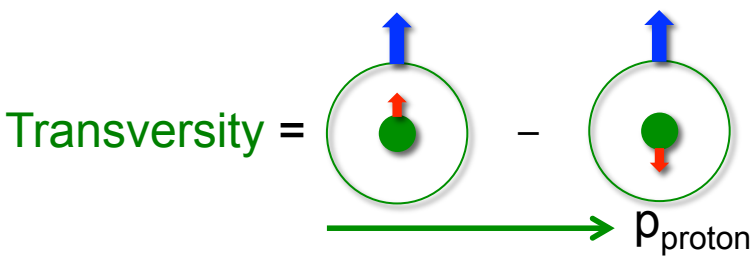


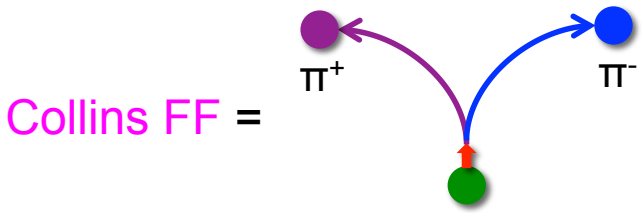


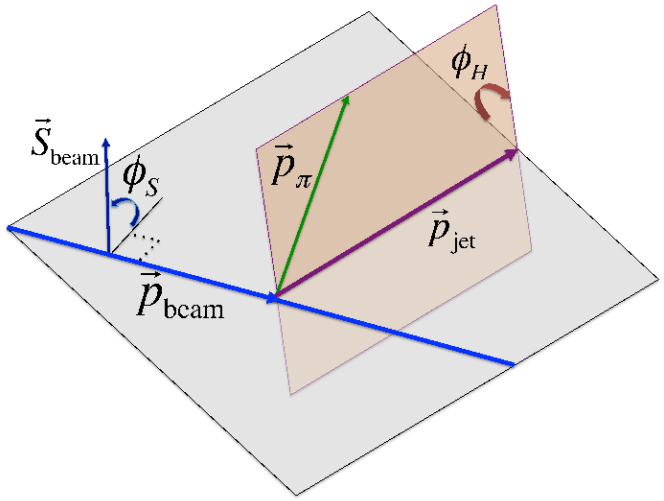

Hadrons in jets
Dihadron (IFF) asymmetry
Transversity
Collins fragmentation function
Gluon linear polarization

Collins Asymmetry

- Connects the initial state quark spin (transversity) to the final state pion distribution within the jet (Collins FF)
- Hadronized pions within jets are asymmetrically distributed
  - Looking at the difference between spin states will allow access to transversity distribution and Collins FF via asymmetry measurements







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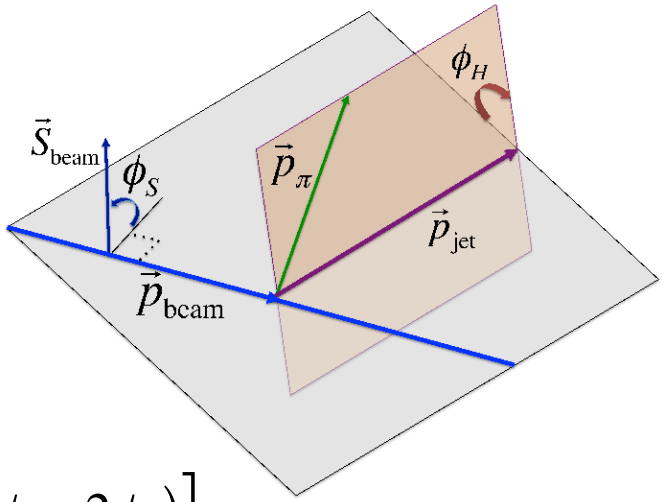

$$d\sigma_{UT} \approx d\sigma_{UU}\left[1 + A_{UT}^{\sin(\phi_s-\phi_h)} \sin\left(\phi_s - \phi_h\right) + A_{UT}^{\sin(\phi_s-2\phi_h)} \sin\left(\phi_s - 2\phi_h\right)\right]$$

Transversity × Collins

Collins-like Asymmetry

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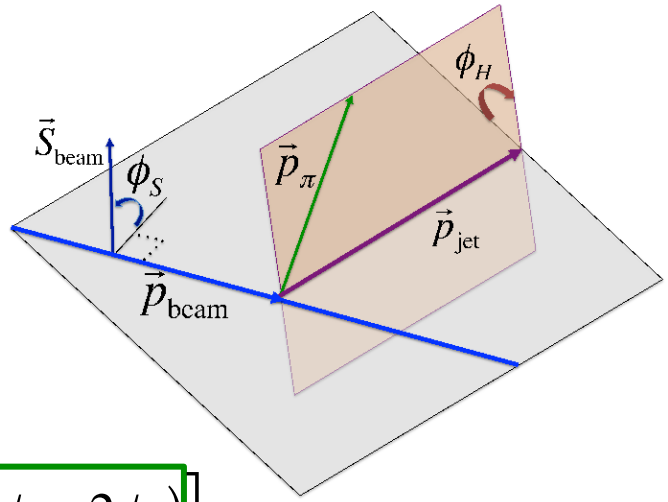
- Collins-like: Same as Collins but for *linearly* polarized gluons



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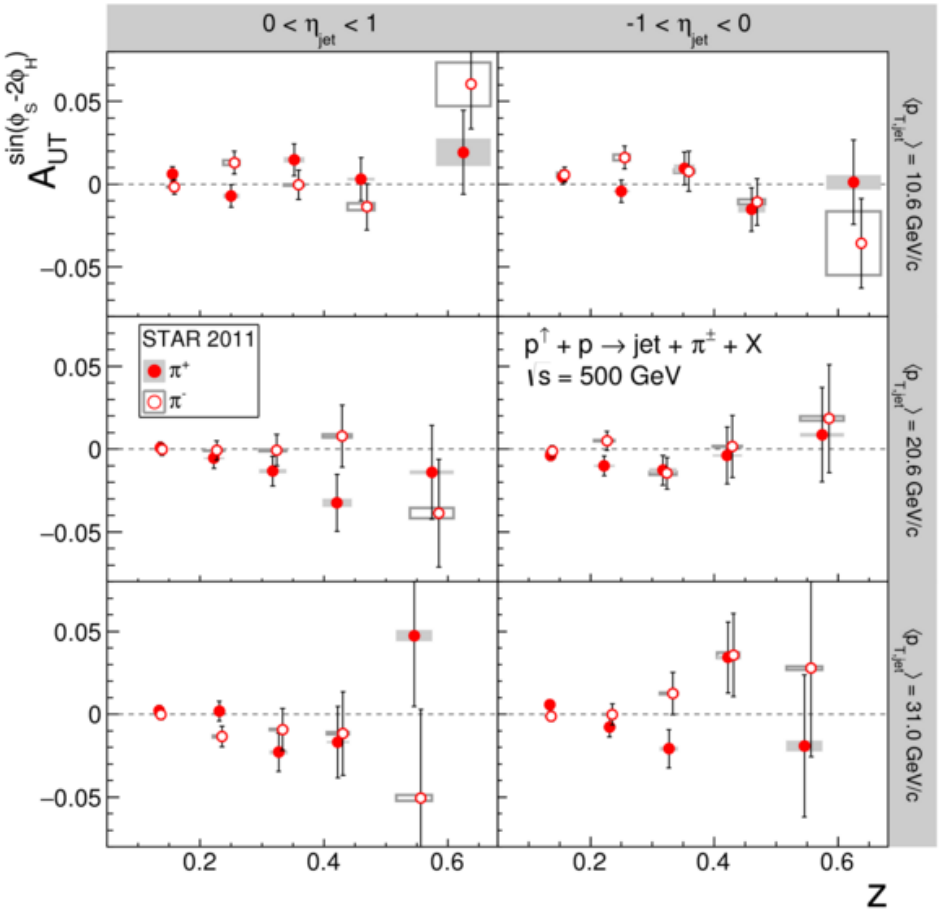
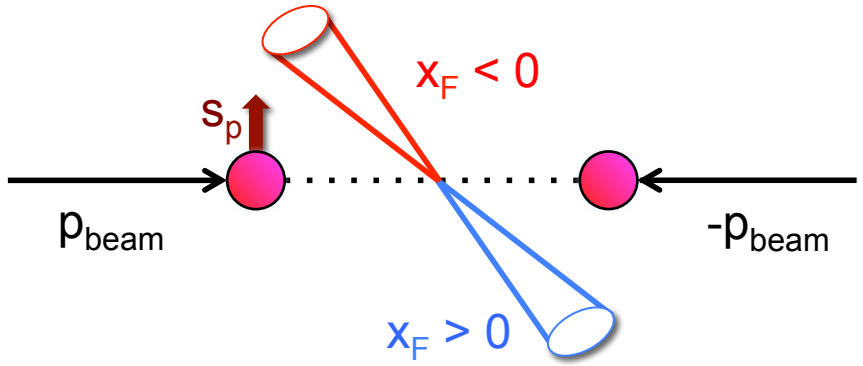
Linearly Polarized Gluons × Collins-like

Collins-like vs. p_T and z

$\sqrt{s}$ = 500 GeV



Phys. Rev. D **97** (2018)



- First ever measurement of Collins-like asymmetry!
- No statistically significant asymmetry observed, even when both charge states statistics combined

Collins-like vs. p_T and z

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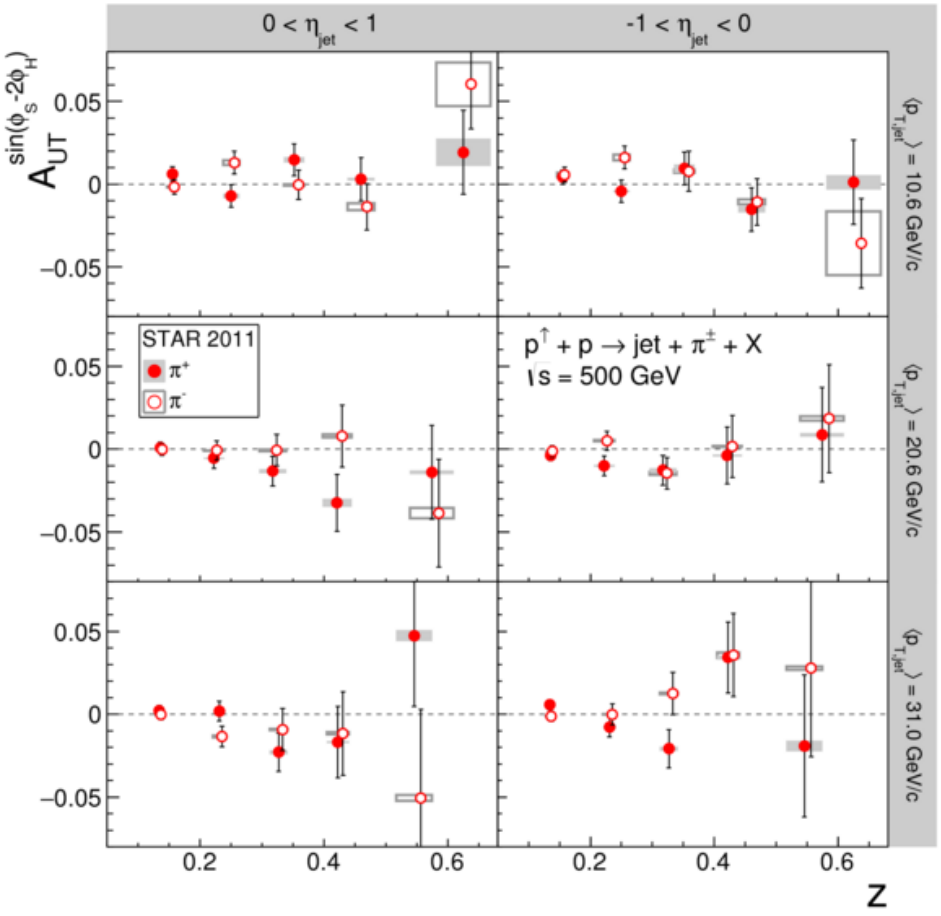

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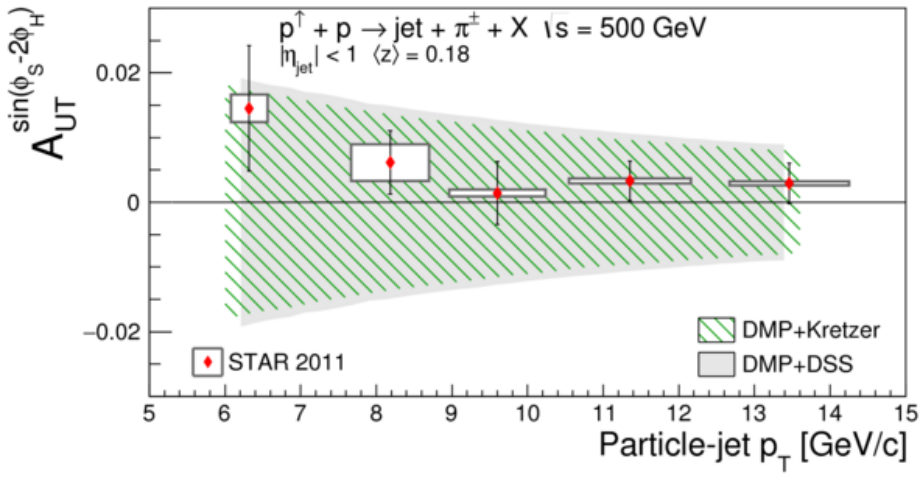
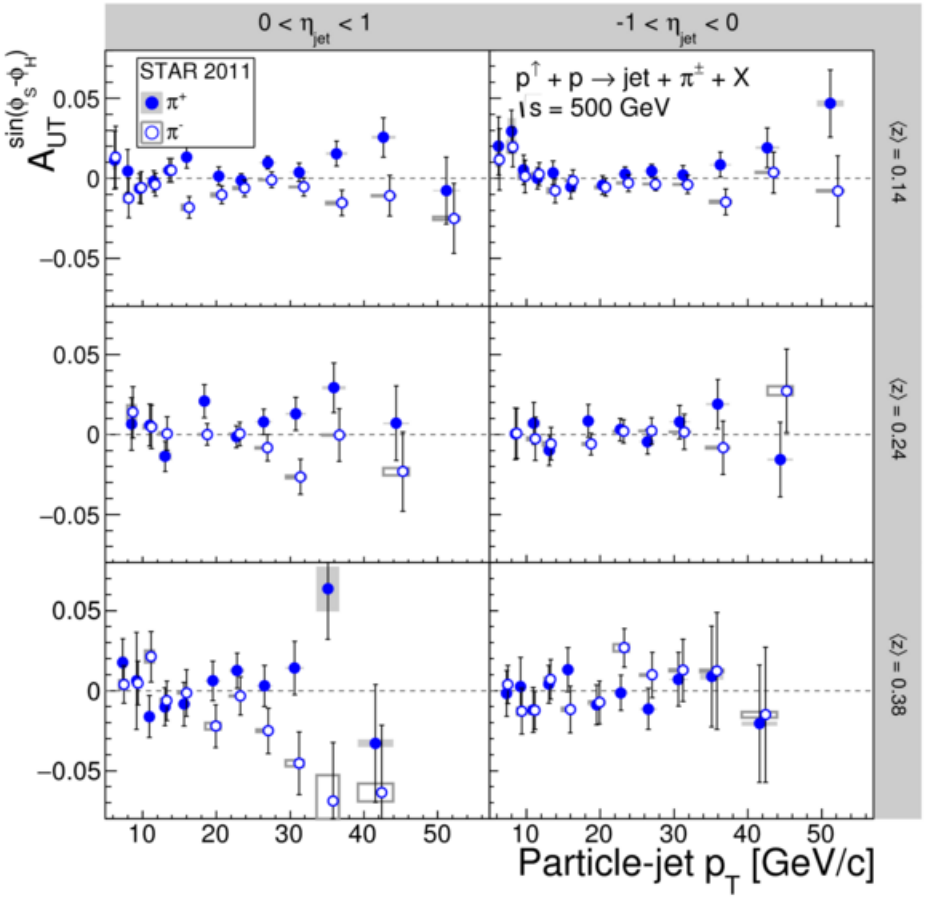
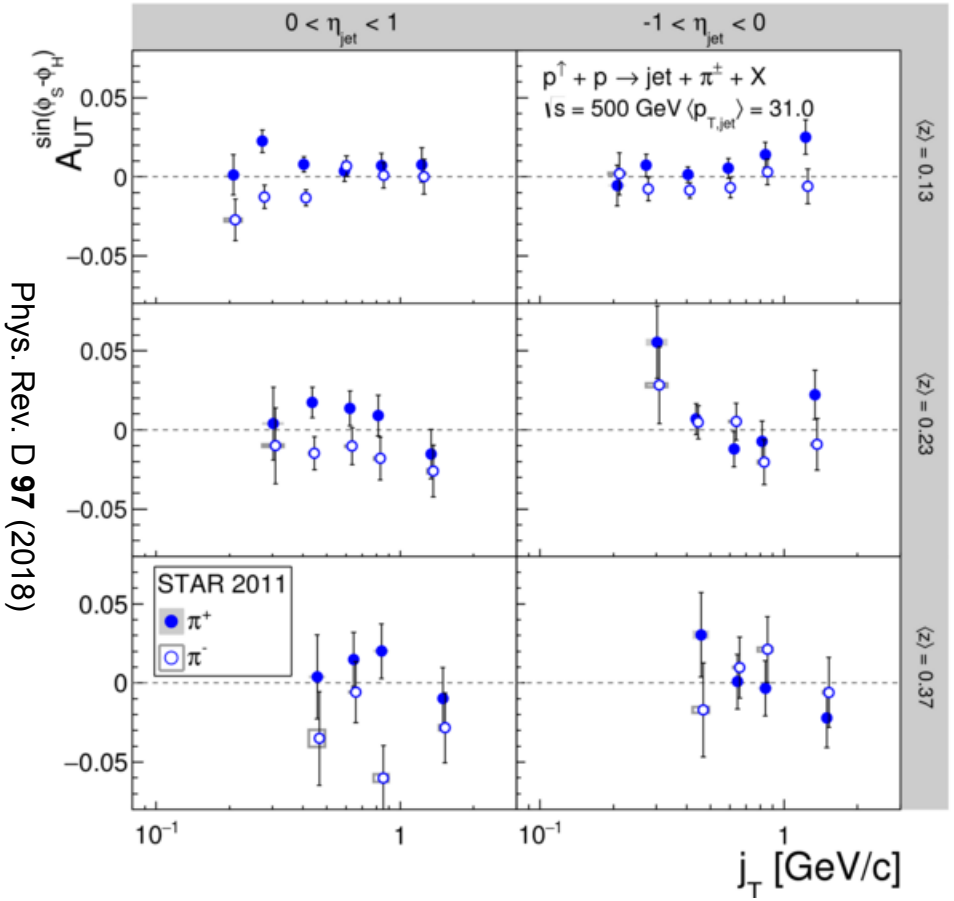


- First ever measurement of Collins-like asymmetry!
- No statistically significant asymmetry observed, even when both charge states statistics combined
- Will give first ever input to constrain theoretical models

Collins vs. p_T and j_T

$\sqrt{s}$ = 500 GeV



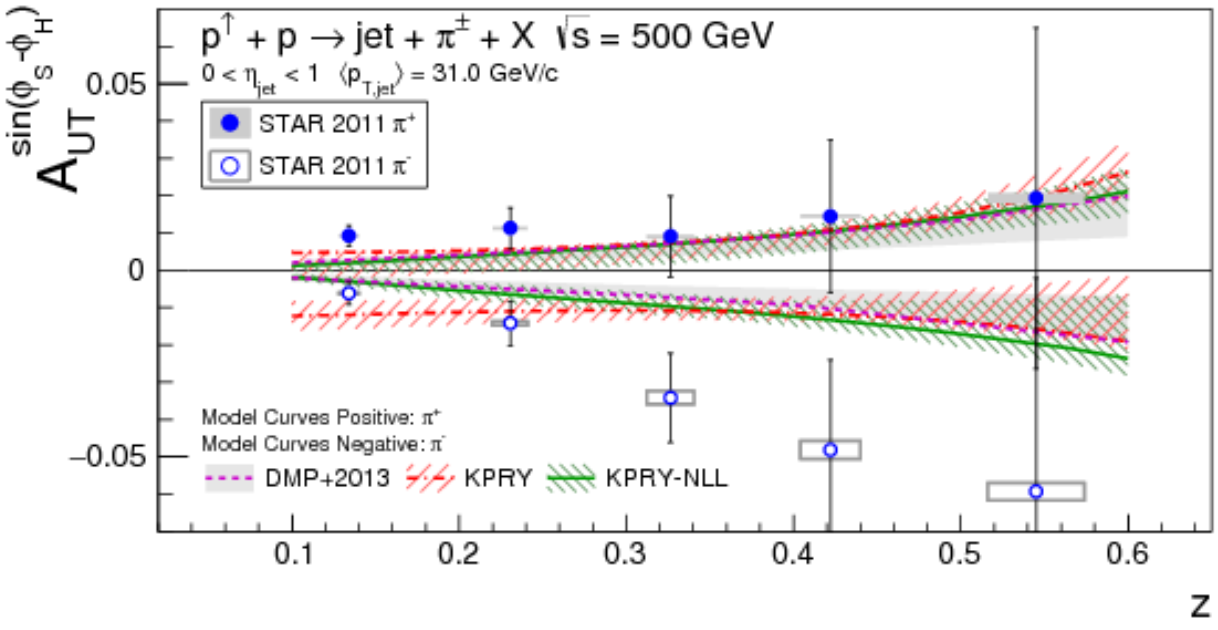


Phys. Rev. D **97** (2018)

- Multi-dimensional binning scheme provides the fine details that could be lost if integrated over
- (p_T,η) related to (Q^2,x) dependence of transversity

Collins vs. z

$\sqrt{s}$ = 500 GeV



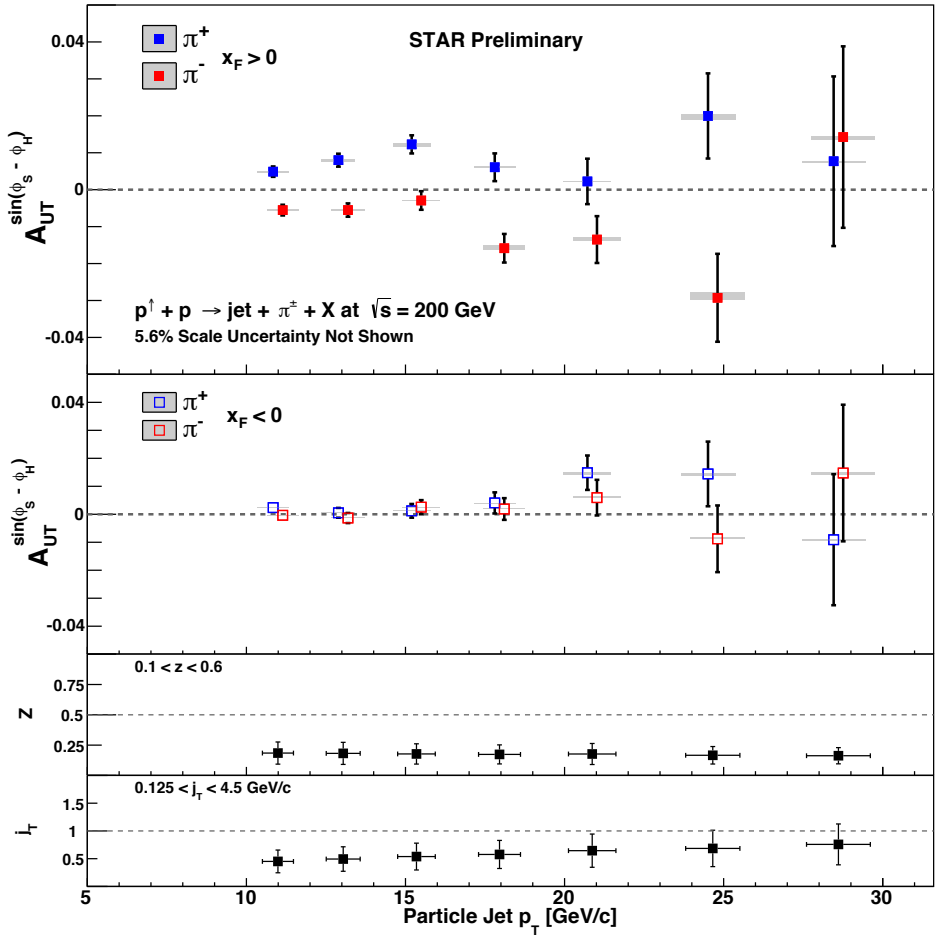
- ★ Theory curves use transversity and Collins FFs extracted from SIDIS and e^+e^-
- ★ STAR results agree quite well with these curves
- ★ Points to universality of Collins function and small factorization breaking effects!

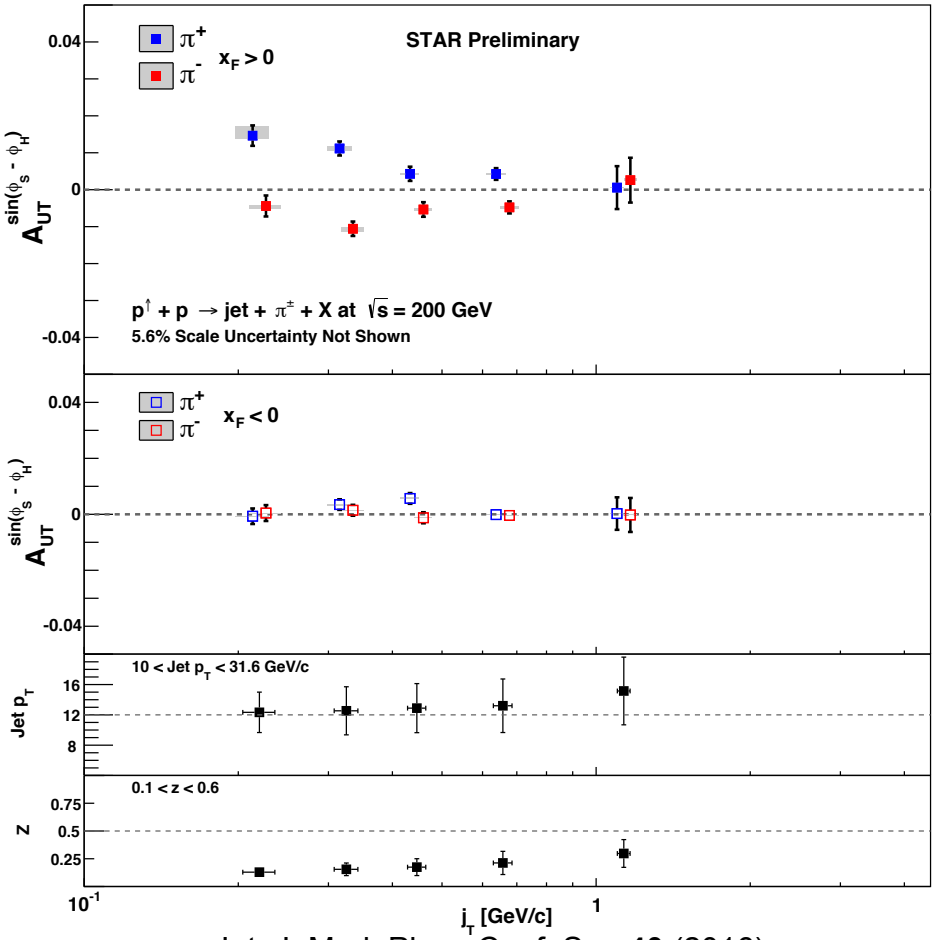
Data:
Phys. Rev. D **97** (2018)

Theory curves:
Phys. Lett. B773 (2017) 300-306
Phys. Lett. B774 (2017), 635-642

Collins vs. p_T and j_T

$\sqrt{s}$ = 200 GeV



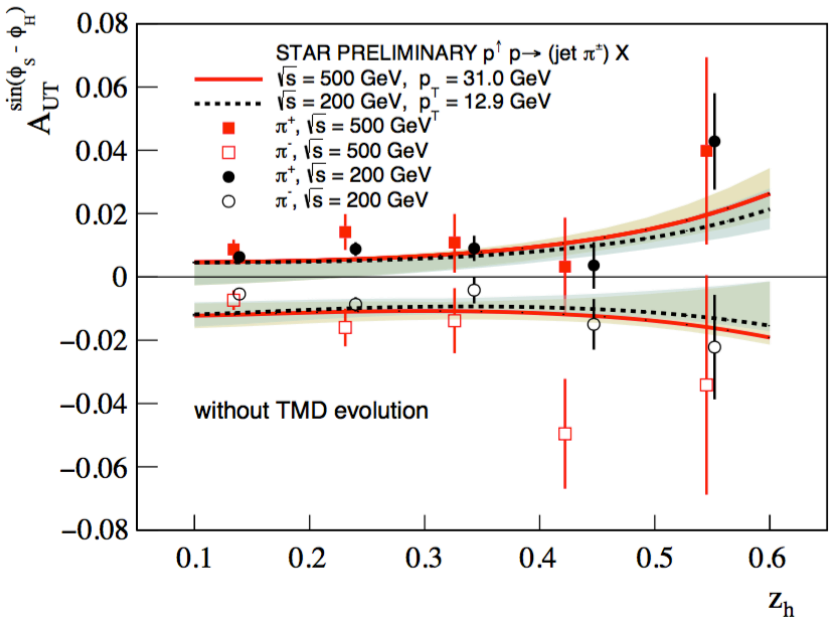


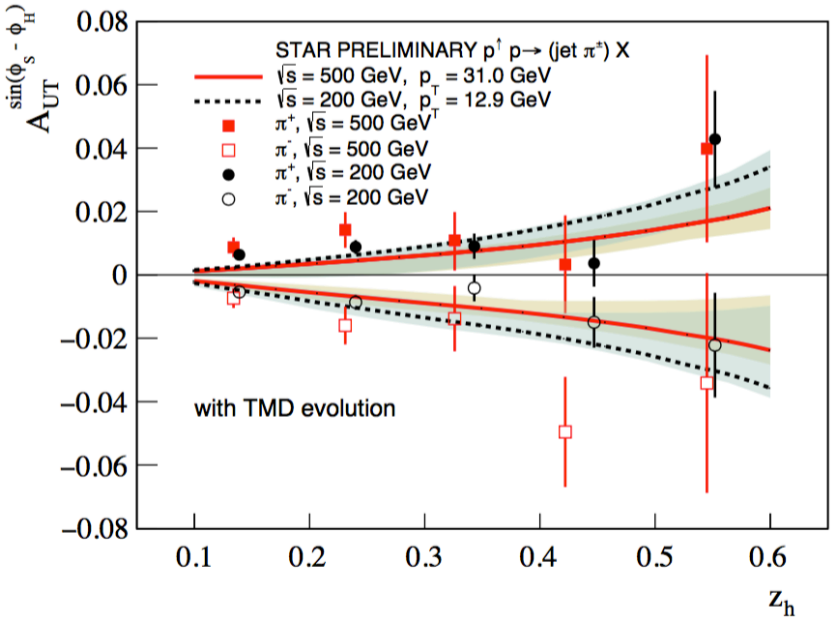
Int. J. Mod. Phys. Conf. Ser. **40** (2016)

- This will very soon be replaced by final results, with binning similar to 500 GeV!
- Combined with results from 500 GeV analysis gives good look at Q^2 evolution

Theory Comparisons

- Recent theory investigations used transversity and Collins FF extracted from SIDIS and e^+e^- results
  - Compared to STAR preliminary results from $\sqrt{s}$ = 200 and 500 GeV at same kinematics
- Theory results plotted without (top) and with (bottom) evolution applied to the TMDs
  - Both sets match STAR data well, pointing to slow evolution with Q^2
- Within error budget, we see no effects of factorization breaking for Collins asymmetry measured in jets

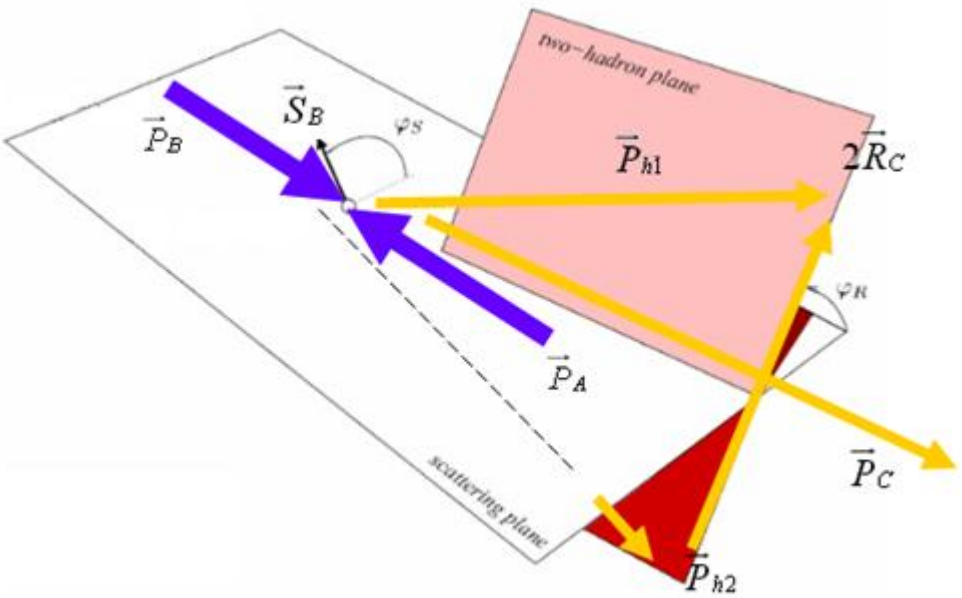




Phys. Lett. B **744** (2017)

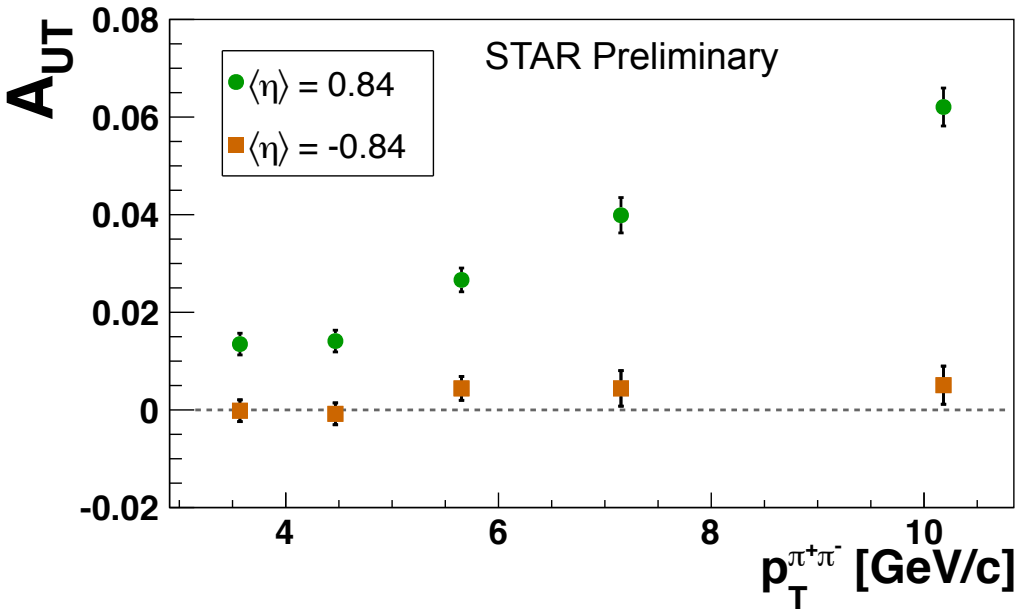
Di-hadron or Interference Fragmentation Function (IFF) Asymmetry

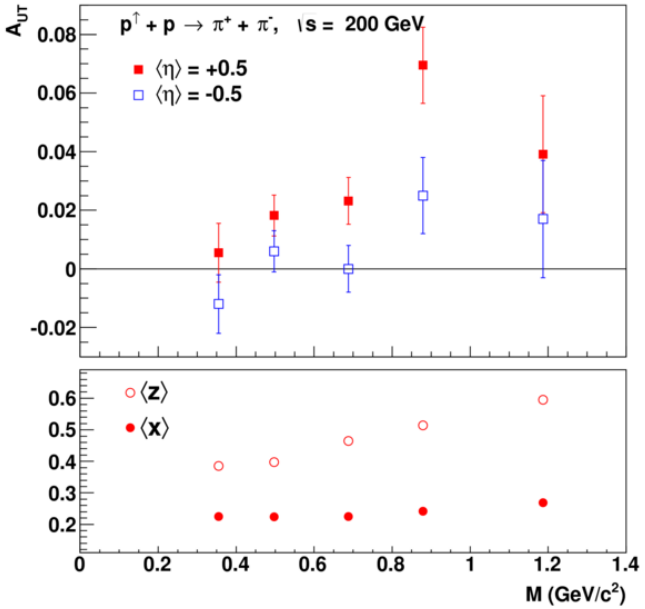
- Correlates quark polarization to azimuthal distribution of final state hadron pairs
- IFF process is collinear, where Collins is dependent upon transverse momentum
- Survives integration over transverse momentum, leading to simpler extraction of transversity
- $\phi_{SR} = \phi_S - \phi_R$ is angle between spin vector and hadron scattering plane
- Experimentally: $d\sigma_{UT} \approx d\sigma_{UU}\left[1 + A_{UT}^{\sin(\phi_{SR})} \sin\left(\phi_S - \phi_R\right)\right]$



STAR Di-hadron

$\sqrt{s}$ = 200 GeV





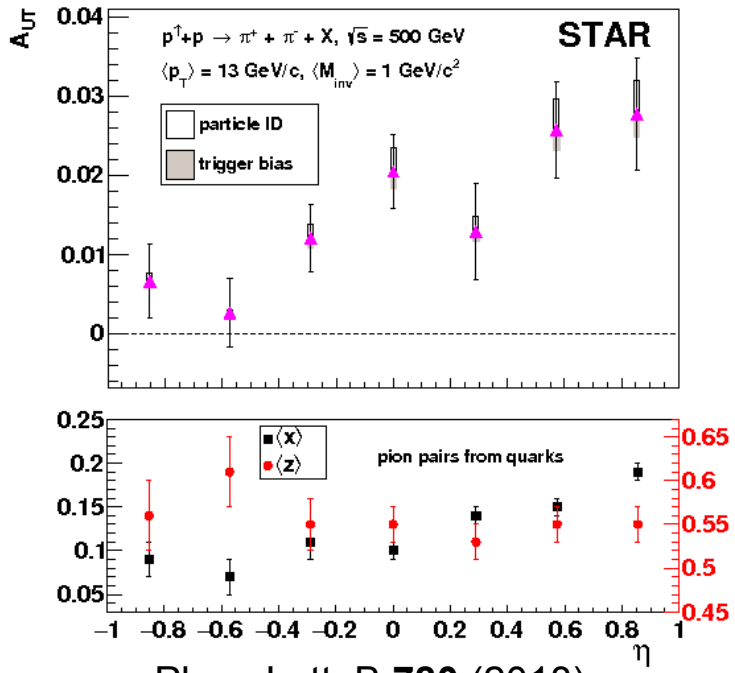
Phys. Rev. Lett. **115** 242501 (2015)

★ 2012 data reinforces the message from the previous 2006 result (right side), but with much higher statistical precision!

★ Asymmetry increases with η, which is directly related to increasing momentum fraction

STAR Di-hadron

$\sqrt{s}$ = 500 GeV



Phys. Lett. B **780** (2018)

- ★ 500 GeV results again show significant asymmetries
- ★ Higher COM energy probes an x-range on the upper end of SIDIS results, but with a higher effective Q^2
- ★ Offers great chance to compare with 200 GeV IFF, and learn something about Q^2 evolution of transversity

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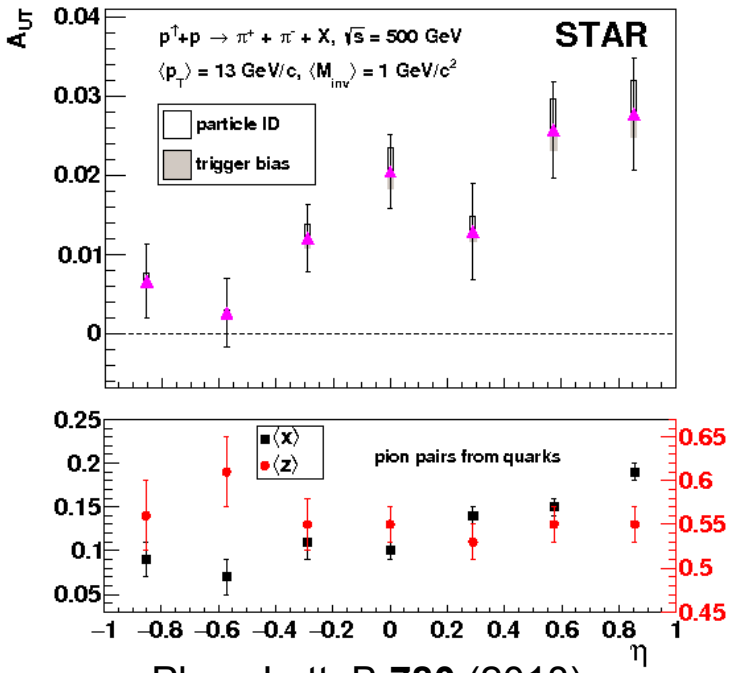
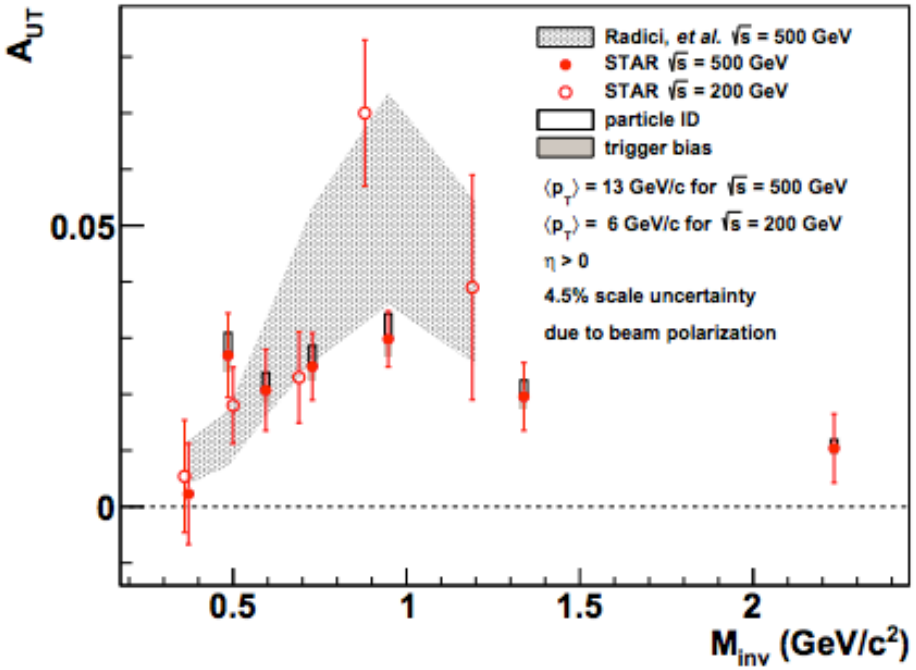


Phys. Lett. B **780** (2018)



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- ★ Higher COM energy probes an x-range on the upper end of SIDIS results, but with a higher effective Q^2
- ★ Offers great chance to compare with 200 GeV IFF, and learn something about Q^2 evolution of transversity
- ★ Decent agreement for similar kinematics, and when compared to theory that is fit to SIDIS and e^+e^- experiments

Conclusions

- STAR has the ability to access many observables that are sensitive to lots of different transverse spin related phenomena:
  - Sivers function
  - Twist-3 quark-gluon correlation functions
  - Transversity and linearly polarized gluons
  - Collins(-like) and interference fragmentation functions

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- When compared to results from SIDIS and e^+e^-, we can start to develop a deeper understanding of factorization breaking effects and universality of TMDs
- Many more results will be coming soon from higher statistics proton-proton datasets and also from p+A collisions

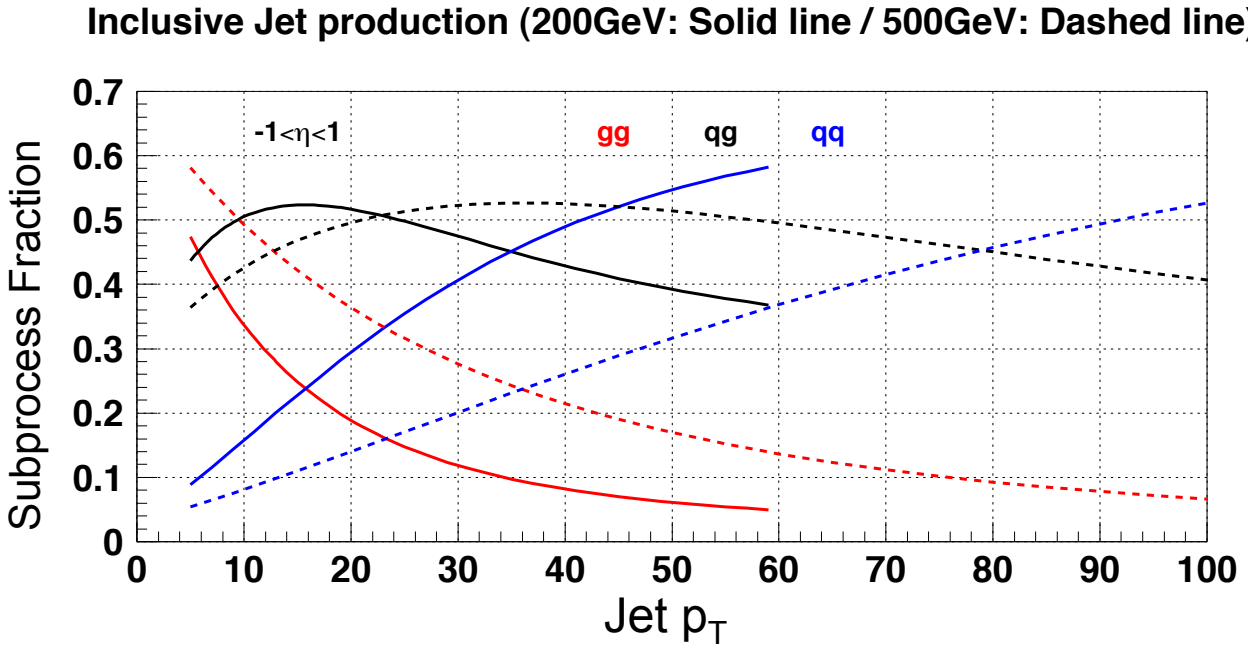
Looking to the Future

Year	Species	L_{int}	Physics	Observable
2017	$p^{\uparrow}p$ (500 GeV)	350 pb^{-1}	Sea quark Sivers Transversity & Collins Gluon linear polarization Gluon + quark twist-3 Gluon FF	W/Z A_N and DY A_{UT} in jets A_{UT} in jets Inclusive jet A_N Hadrons in jets
2021	$p^{\uparrow}p$ (500 GeV)	1.1 fb^{-1}	Sea quark Sivers Transversity & Collins Gluon linear polarization Gluon + quark twist-3 Gluon FF	W/Z A_N and DY A_{UT} in jets A_{UT} in jets Inclusive jet A_N Hadrons in jets
2023	$p^{\uparrow}p$ (200 GeV)	300 pb^{-1}	Transversity & Collins Gluon linear polarization Gluon + quark twist-3 Gluon FF	A_{UT} in jets A_{UT} in jets Inclusive jet A_N Hadrons in jets
2023	$p^{\uparrow}Au$ (200 GeV) $p^{\uparrow}Al$ (200 GeV)	1.8 pb^{-1} 12.6 pb^{-1}	A-dependence of TMDs	A_{UT} & hadrons in jets

Backup

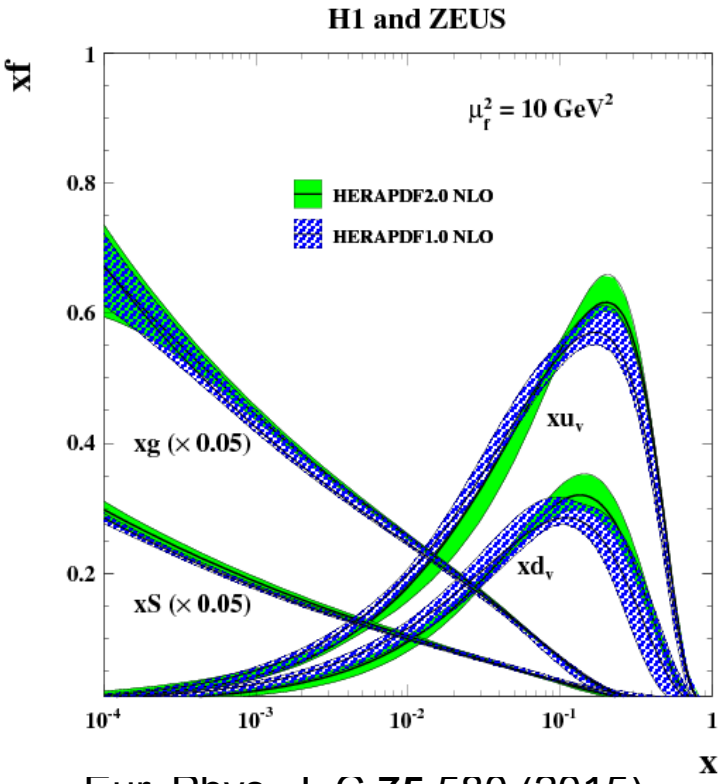
Capabilites at RHIC/STAR

- Proton collisions $\sqrt{s}$ = 200 GeV and $\sqrt{s}$ = 500 GeV
- 500 GeV accesses higher jet p_T than 200 GeV
  - $p_T \approx Q$, so 500 GeV accesses lower *x* with higher gluon content
  - Expect smaller asymmetries for 500 GeV

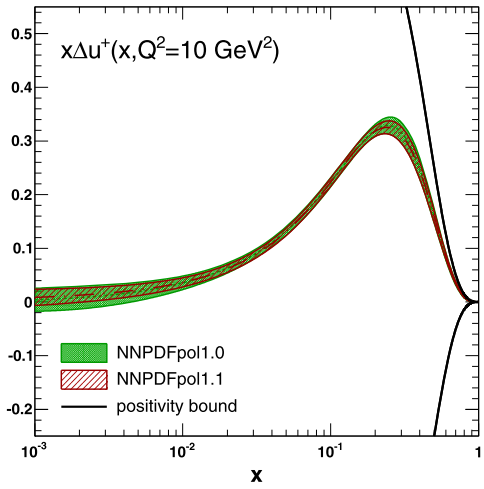


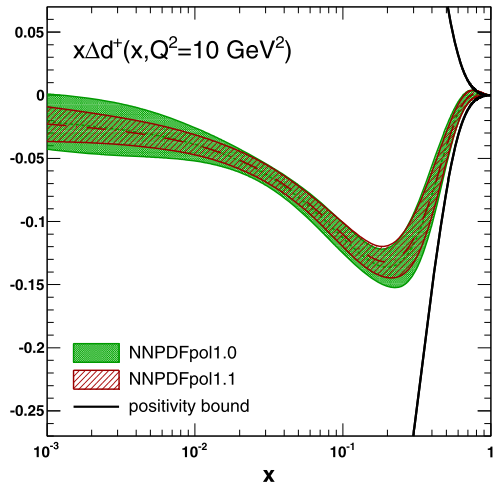
Current PDF Knowledge

- Valence momentum and helicity PDFs are well constrained



Eur. Phys. J. C **75** 580 (2015)

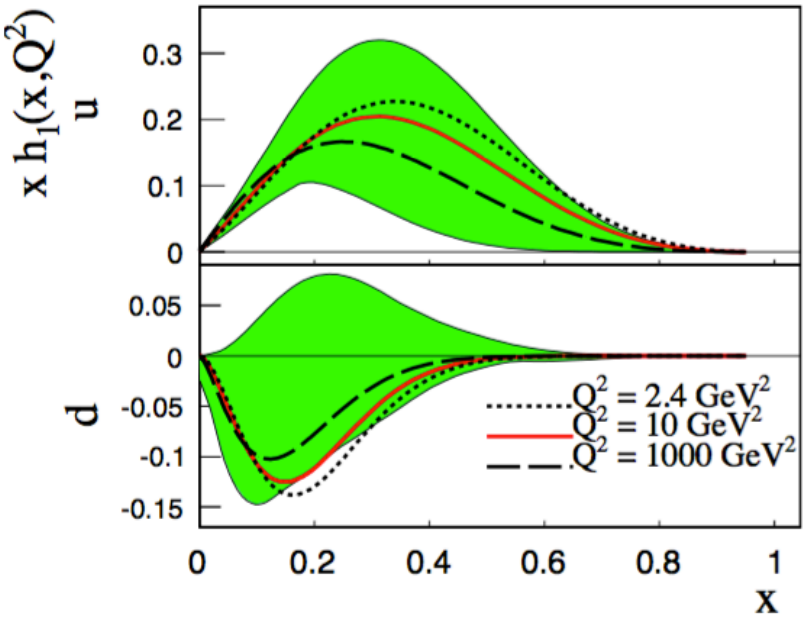




Nuclear Physics B, Vol 887 (2014)

(Limited) Knowledge of Transversity

- Transversity remains wildly unconstrained, even in valence contributions!
- One contributing factor to limited knowledge is because transversity is chiral odd
  - Accessibility highly suppressed in inclusive lepton scattering
- To constrain transversity as well as helicity we need more data across a broad range in *x*
- Can be accessed if paired with another appropriate chiral odd function
  - Single spin asymmetries!



Phys. Rev. D **93** 014009 (2016)