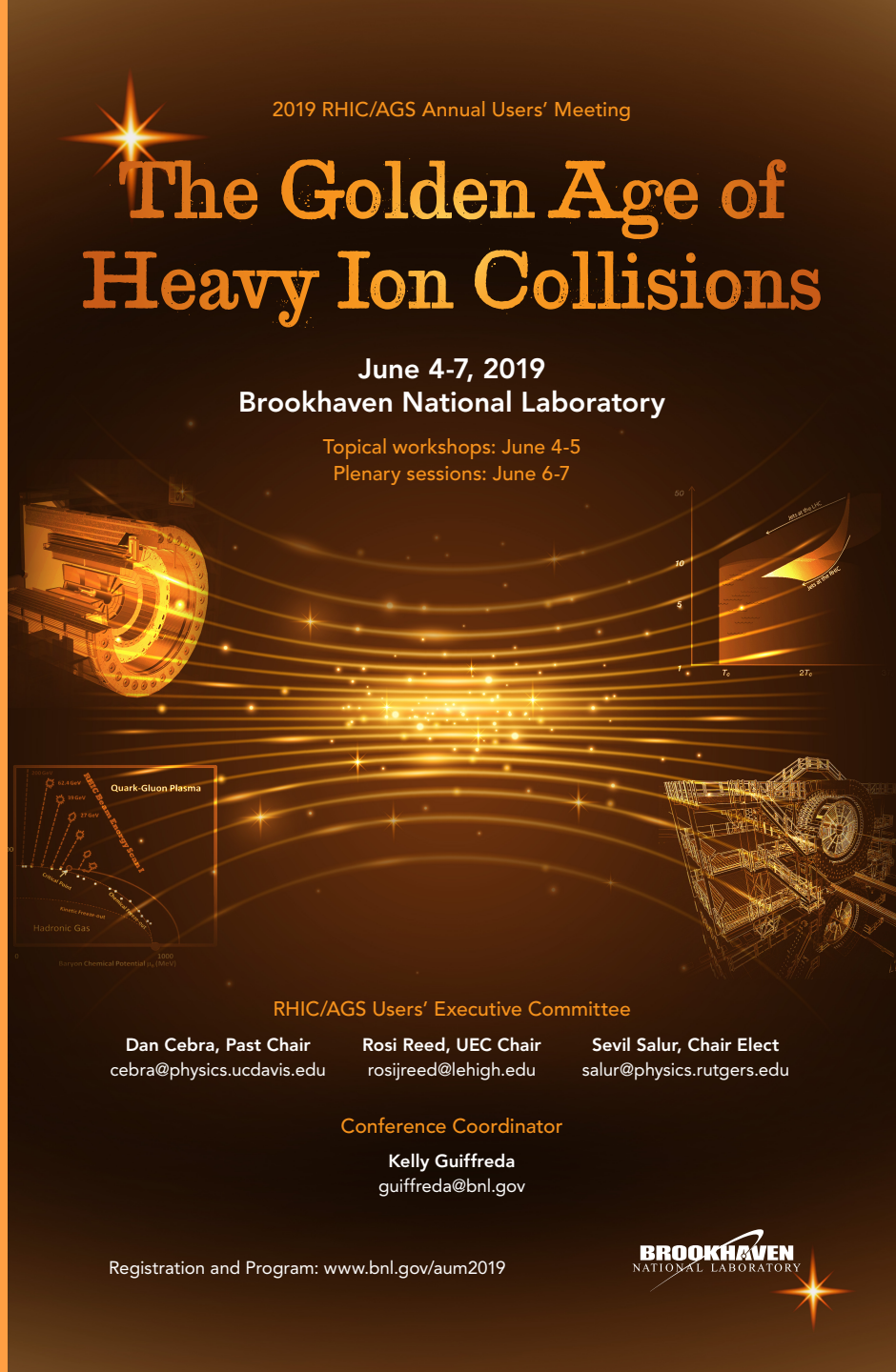
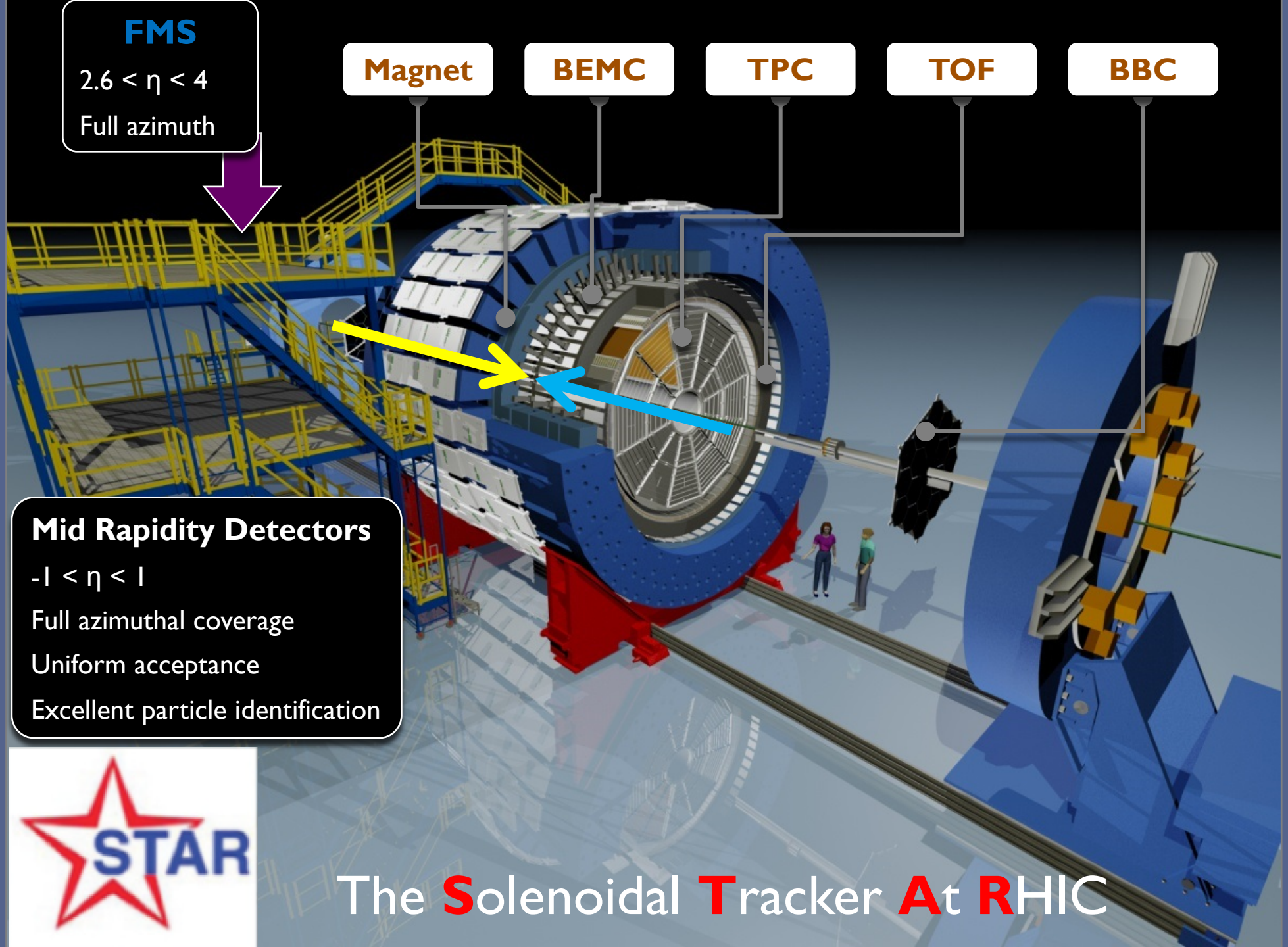
TRANSVERSE SPIN RESULTS FROM STAR

Renee Fatemi

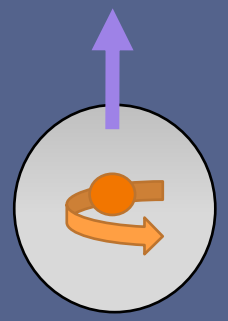
University of Kentucky




FMS
2.6 < η < 4
Full azimuth
Magnet
BEMC
TPC
TOF
BBC
Mid Rapidity Detectors
-1 < η < 1
Full azimuthal coverage
Uniform acceptance
Excellent particle identification
STAR
The Solenoidal Tracker At RHIC

TRANSVERSE SPIN → QCD CORRELATIONS

SPIN - MOMENTUM



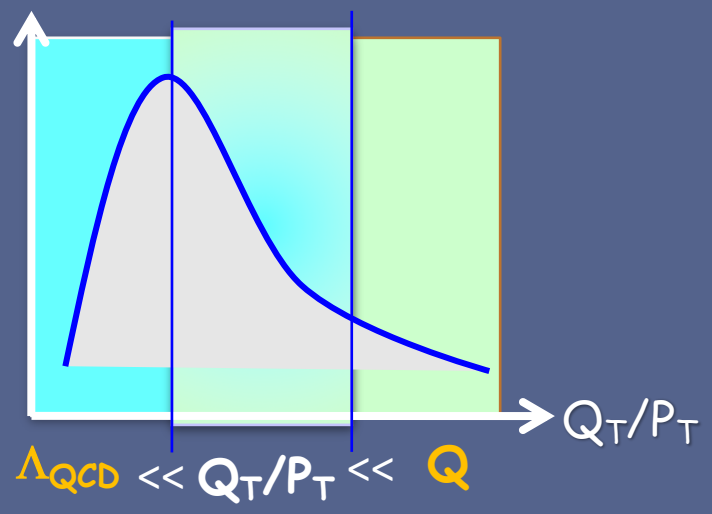
Sivers TMD and Twist-3 Correlators

- $W^{+/-}$ & Z A_N
- Drell-Yan
- Direct Photon
- Inclusive Jet

TMD

Requires two scales:
Hard scale Q^2
Soft scale : p_T

Appropriate for SIDIS, DY, $W^{+/-}$ & Z, hadrons in jets

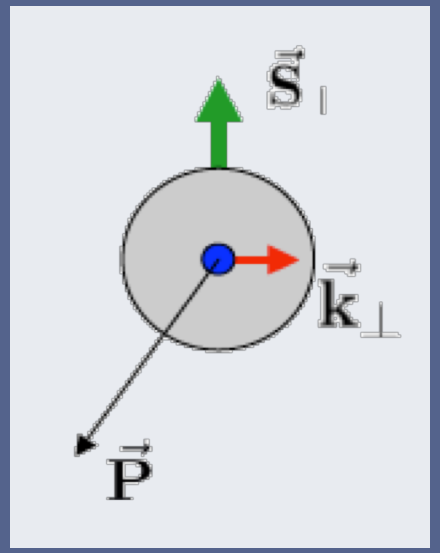


Collinear Twist-3

Single hard scale : p_T

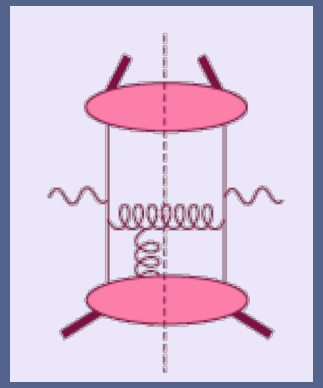
Appropriate for inclusive π^0, jet, γ

Sensitive to $<k_T>$



ETQS correlators connected to TMD_S via:

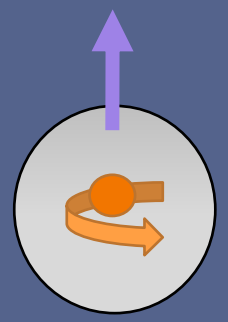
$$-\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$



Efremov, Teryaev; Qiu, Sterman

TRANSVERSE SPIN → QCD CORRELATIONS

SPIN - MOMENTUM



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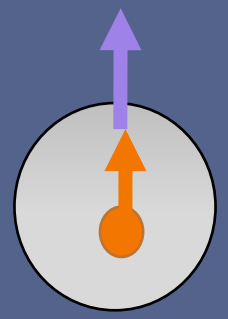
SPIN – SPIN

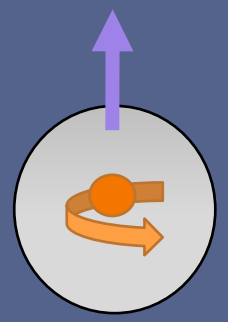


Collinear/TMD Transversity ⊗ Fragmentation Function

- Lambda D_{TT}
- Interference Fragmentation Function
- Hadrons in Jets

TRANSVERSE SPIN → QCD CORRELATIONS

SPIN - MOMENTUM



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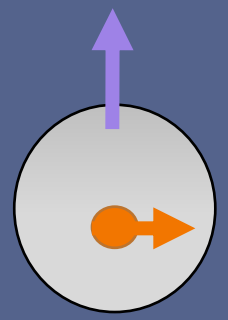
SPIN – SPIN

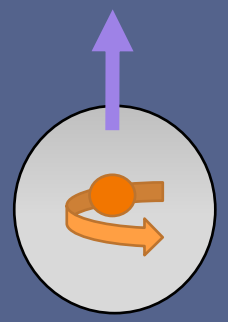


Collinear/TMD Transversity $\otimes$ Fragmentation Function
- Lambda D_{TT}
- Interference Fragmentation Function
- Hadrons in Jets

Gluon Linear Polarization
- Hadrons in Jets

TRANSVERSE SPIN → QCD CORRELATIONS

SPIN - MOMENTUM



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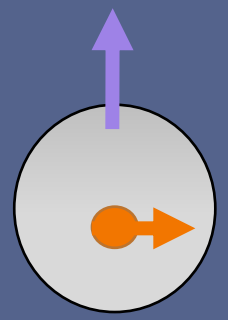

Collinear/TMD Transversity ⊗ Fragmentation Function
- Lambda D_{TT}
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- Hadrons in Jets

Gluon Linear Polarization
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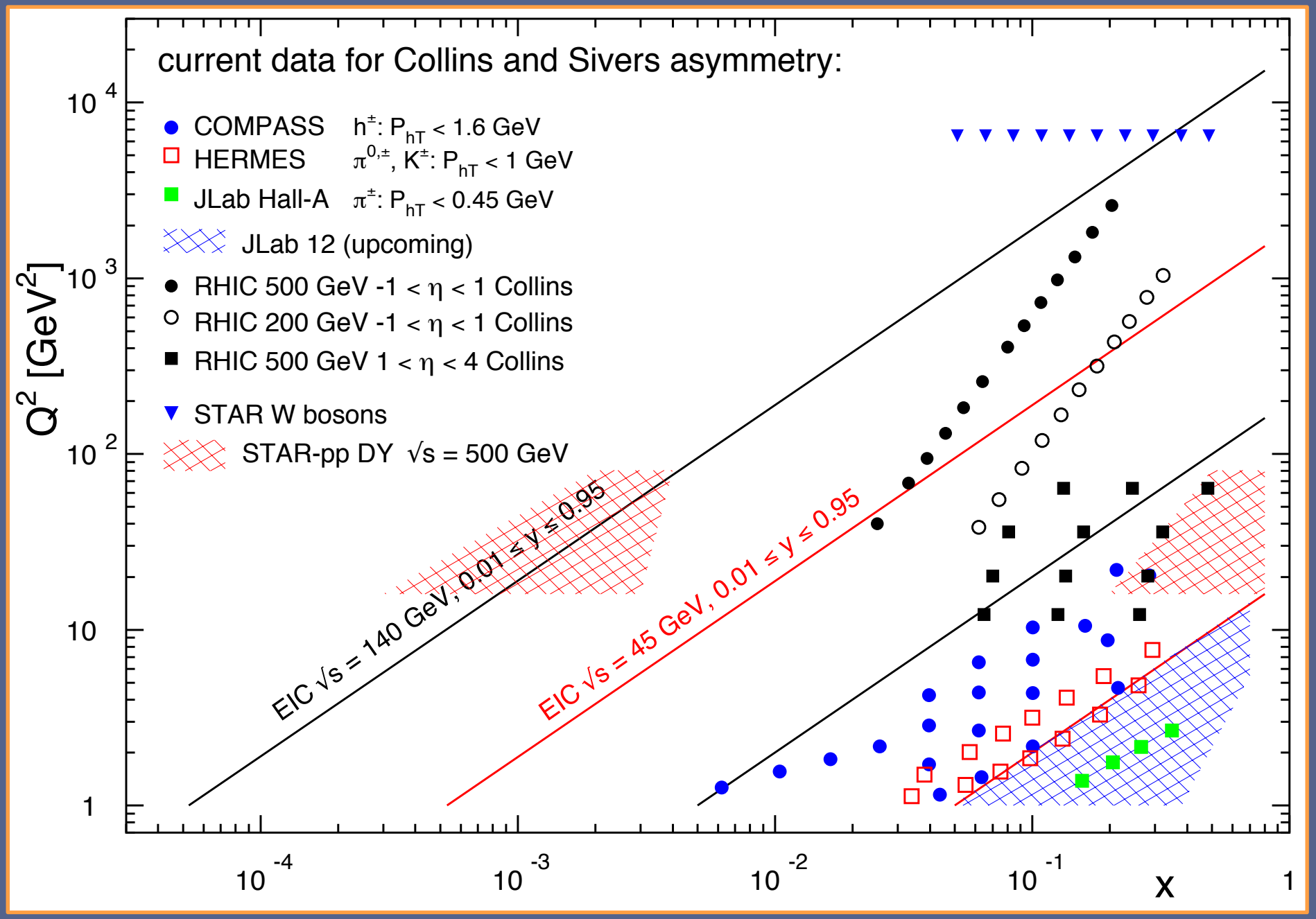
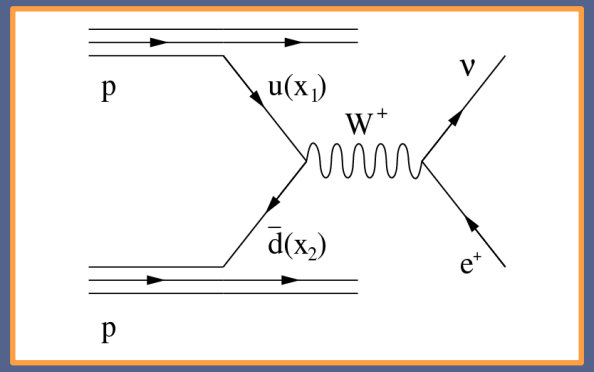
DIFFRACTIVE-SPIN

?

Origin of FORWARD SSA
- $p^{\uparrow} + p \rightarrow p + \pi^0 + X$


current data for Collins and Sivers asymmetry:
COMPASS $h^{\pm}$: P_{hT} < 1.6 GeV
HERMES $\pi^{0,\pm}$, $K^{\pm}$: P_{hT} < 1 GeV
JLab Hall-A $\pi^{\pm}$: P_{hT} < 0.45 GeV
JLab 12 (upcoming)
RHIC 500 GeV -1 < η < 1 Collins
RHIC 200 GeV -1 < η < 1 Collins
RHIC 500 GeV 1 < η < 4 Collins
STAR W bosons
STAR-pp DY √s = 500 GeV
EIC √s = 140 GeV, 0.01 ≤ y ≤ 0.95
EIC √s = 45 GeV, 0.01 ≤ y ≤ 0.95
Q^2 [GeV^2]
10^4
10^3
10^2
10
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
1

$W^{+/-} + Z^0$ A_N



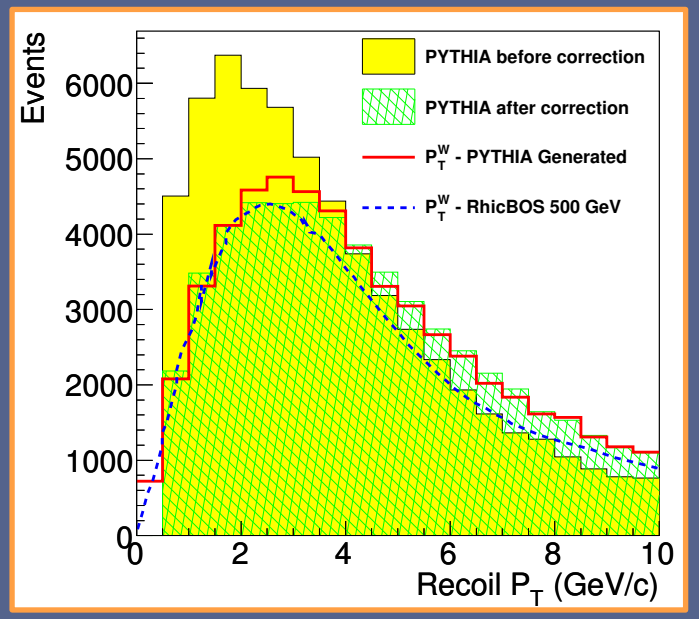
Single Spin Asymmetry of W/Z production in transversely polarized p+p :

- Sensitive to the q/qbar Sivers' functions
- Hard scale set by $M_{W/Z}$ - Soft scale set by $P_T^{W/Z}$
- Maximal signal in full reconstruction of W/Z

- Reconstruction relies on measurement of the hadronic recoil:

$$\vec{P}_T^W = \vec{P}_T^e + \vec{P}_T^\nu = -\vec{P}_T^{recoil}$$

- Uncorrected P_T^{recoil} is sum over towers and tracks excluding $e^{+/-}$ of W/Z candidate
- PYTHIA embedded into data used to correct for efficiency and fiducial losses.
- Method used at LHC and Fermilab and now at STAR!

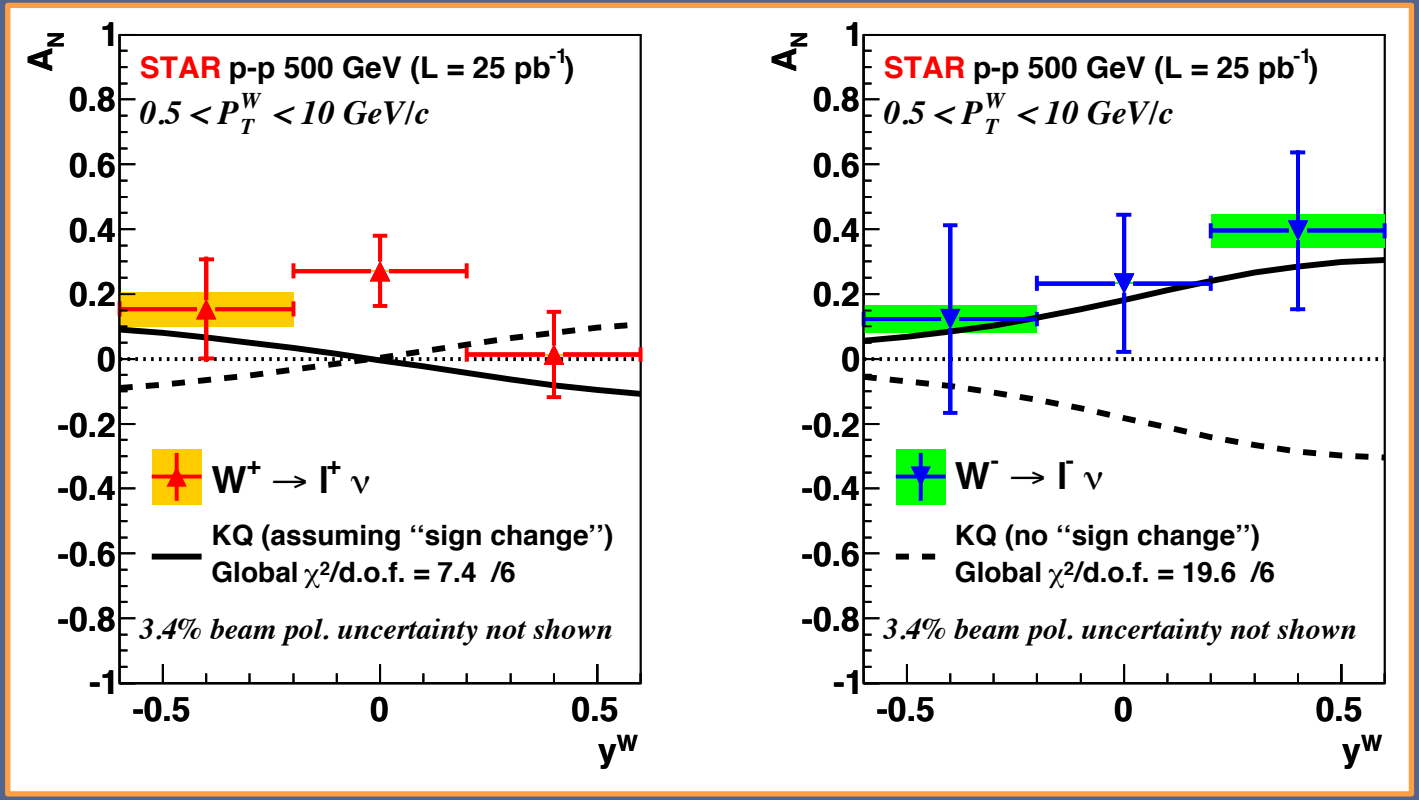


$W^{+/-}$ A_N FROM 25PB^{-1} IN 2011

Theoretical curves include no evolution effects. Z.-B. Kang and J. -W. Qiu, Phys. Rev. Lett. 103, 172001.

Data favor Sivers Function sign change.

TMD evolution has non-perturbative component that must be measured!



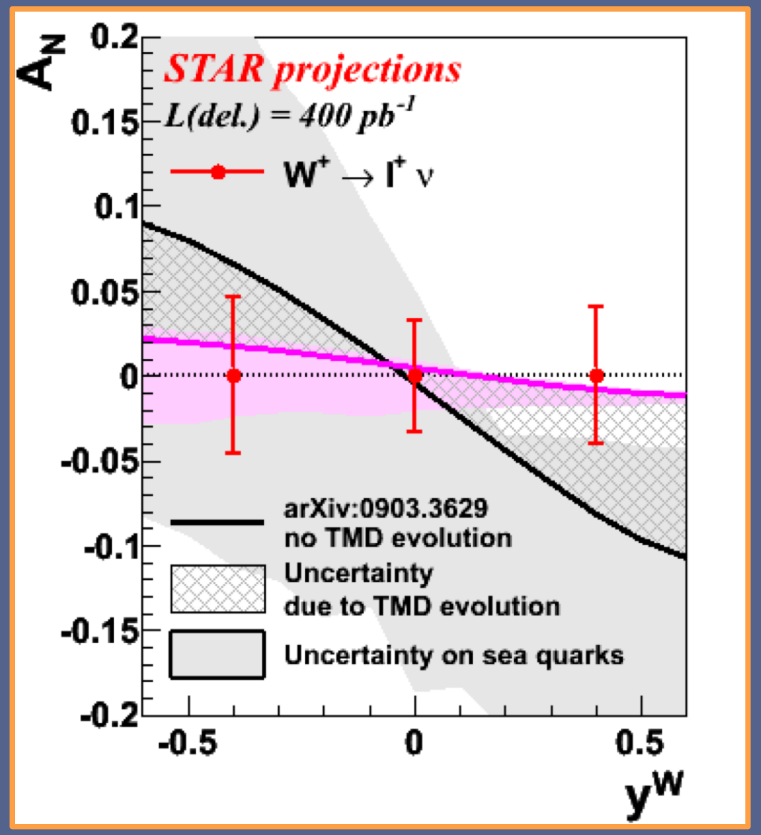
Phys. Rev. Lett. **116** (2016) 132301

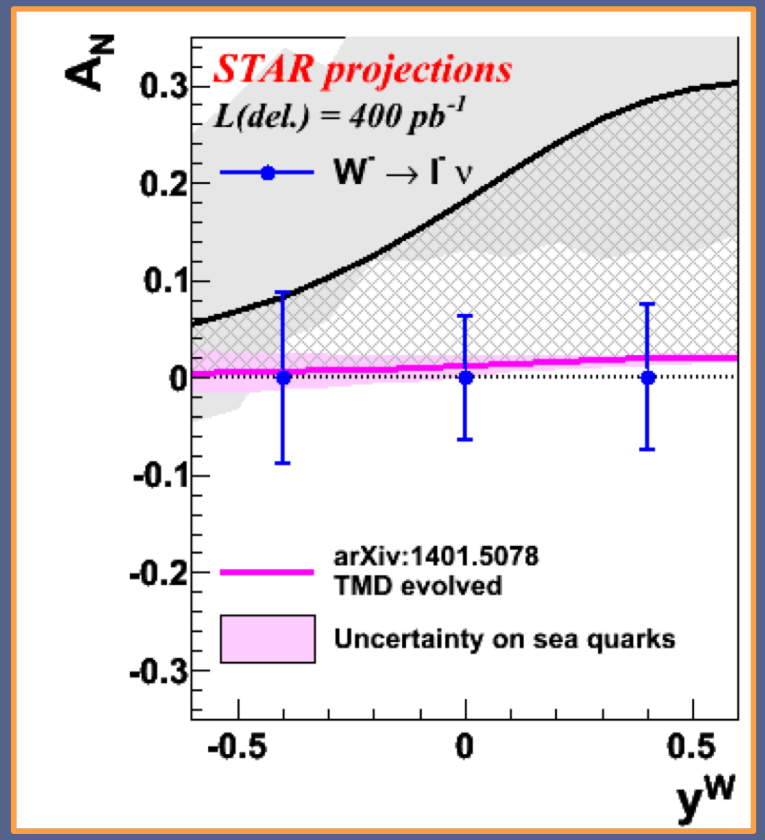
$W^{+/-}$ A_N FROM 400 PB^{-1} IN 2017

Data will provide:

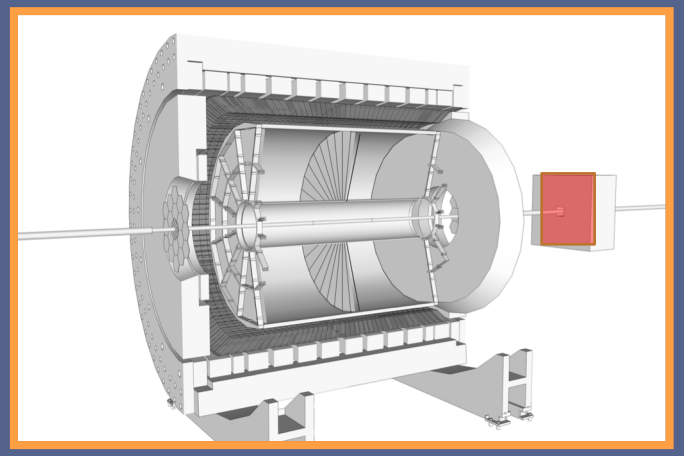
1. Rigorous test of Sivers sign-change.
2. Constraints on sea quark Sivers function
3. Experimental input into TMD evolution

Analysis ongoing – will be released when EMC calibration is finalized.





DRELL-YAN A_N FROM 400 PB^{-1} IN 2017



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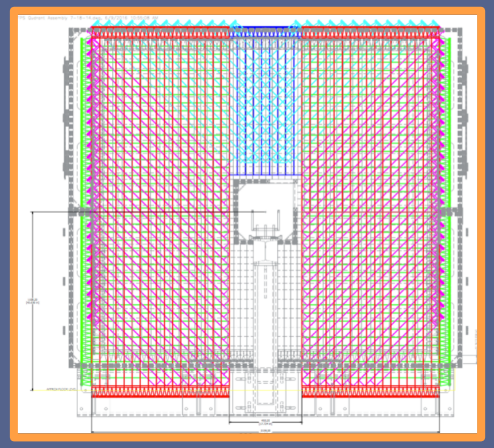
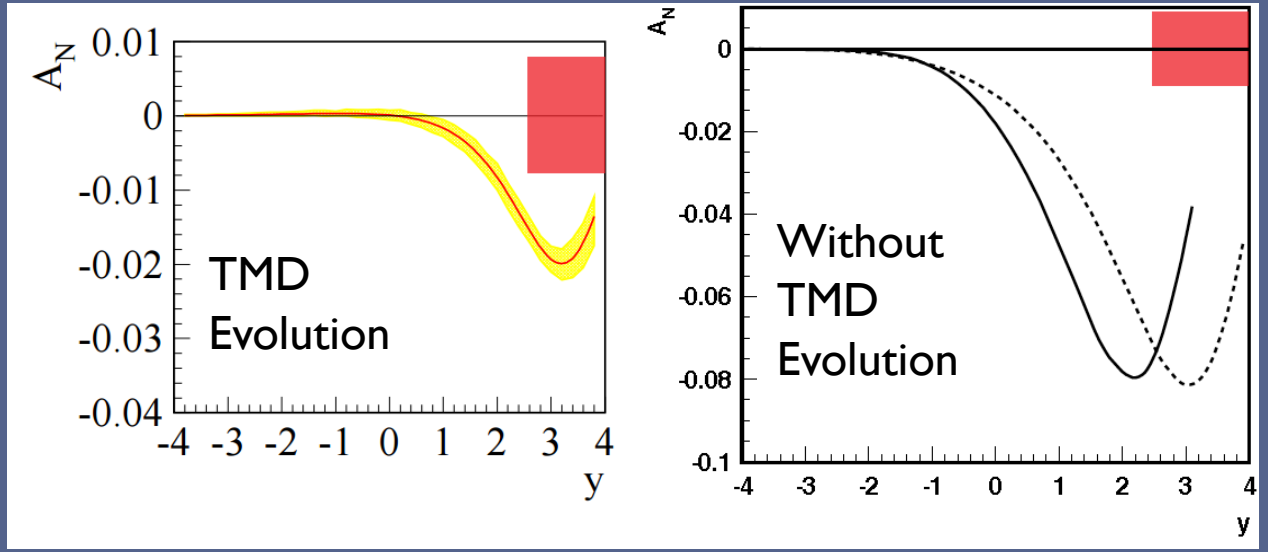


FMS post-shower detector added for 2017 run. Combining with pre-shower allows factor of 10^6 suppression in ratio of QCD background to signal!

DY e+e- in $2.5 < \eta < 4.0$
$4.0\ GeV < M_{e+e-} < 9.0\ GeV$

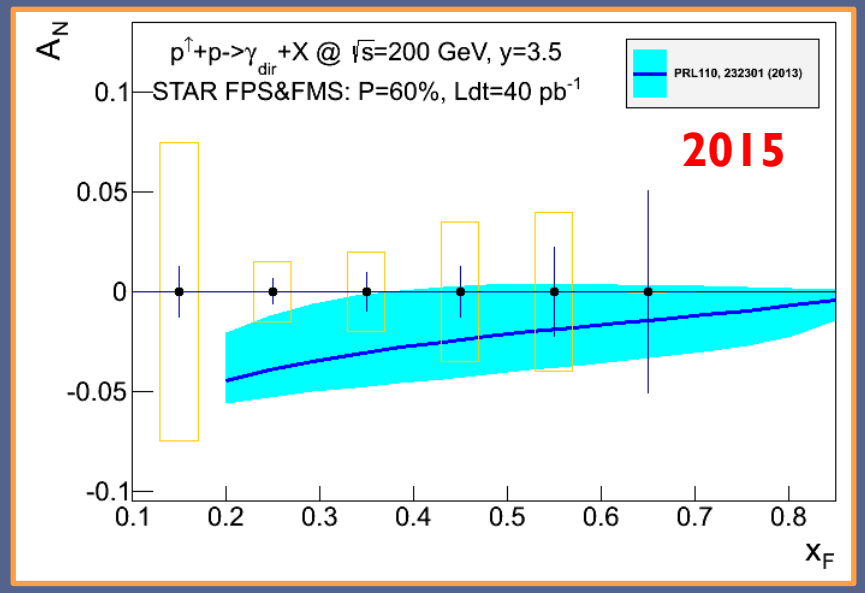
Note: The orange square is the statistical uncertainty achievable with 400 pb^{-1} .

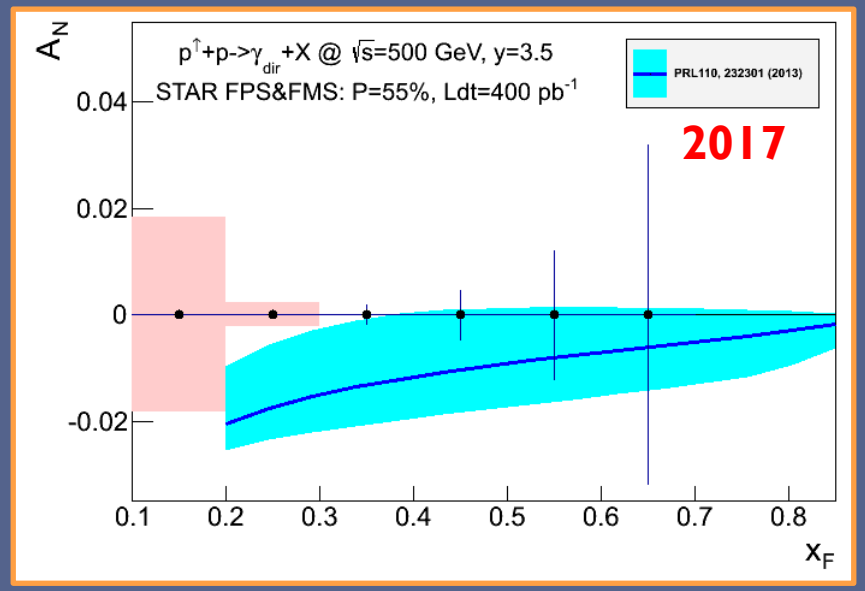


Phys.Rev.D 89, 074013 (2014)

DIRECT-γ A_N

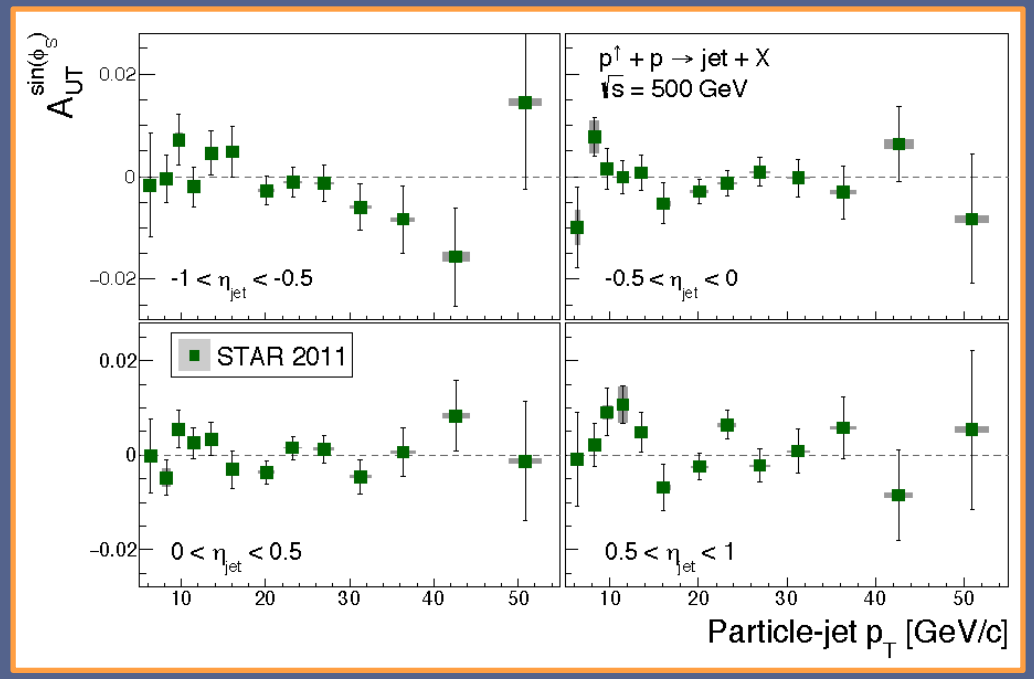
- Sensitive to Sivers twist-3 correlators and sign change within twist-3 framework.
- Constrains Sivers TMD functions via ETQS Equation.
- Comparison of 200 and 500 GeV data will provide information on $T_{q,F}$ (x_1,x_2) evolution.
- Blue curves are theoretical predictions based on fits to existing SIDIS data.
- Complementary to $W^{+/-}$ & Z A_N



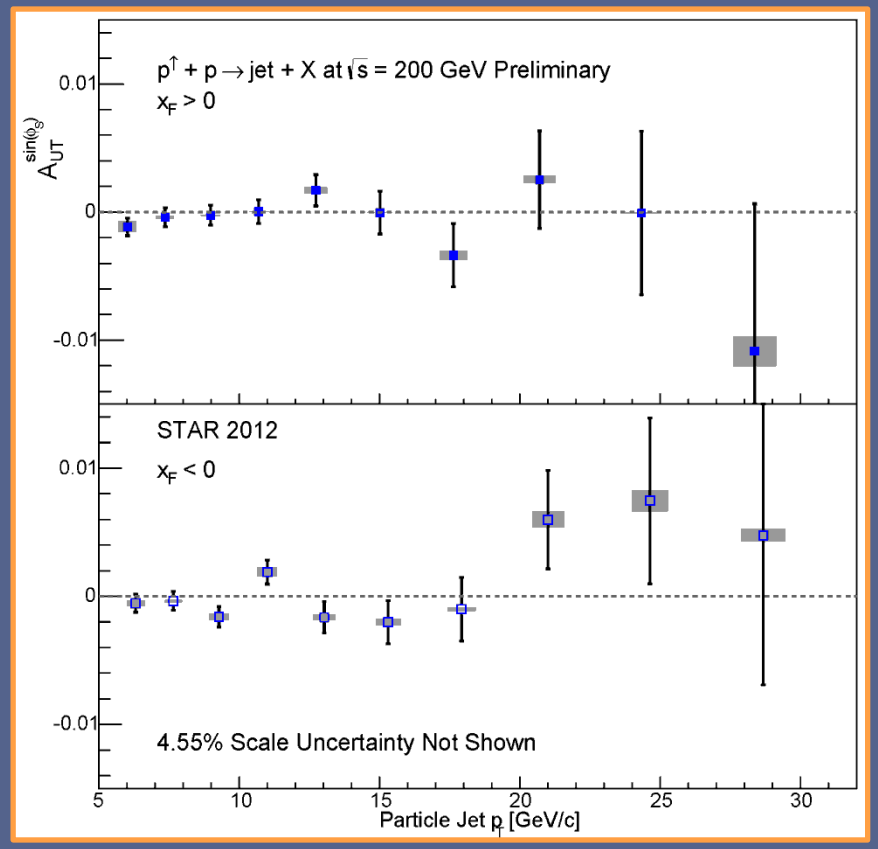


GLUON TWIST-3 CORRELATORS: INCLUSIVE JET A_N

500 GeV: PRD 97, 032004 (2018)



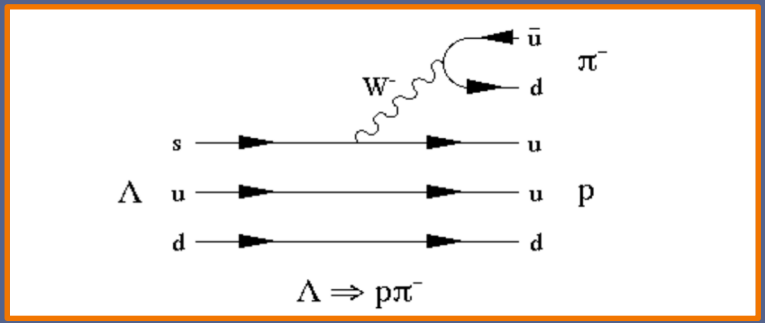
200 GeV: Preliminary



Sensitive to the gluon Sivers function via the Twist-3 relationship

FIRST MEASUREMENT OF THE LAMBDA TRANSVESE SPIN TRANSFER D_{TT} AT RHIC

$$D_{TT} = \frac{d\sigma^{p\uparrow p\to\Lambda\uparrow X} - d\sigma^{p\uparrow p\to\Lambda\downarrow X}}{d\sigma^{p\uparrow p\to\Lambda\uparrow X} + d\sigma^{p\uparrow p\to\Lambda\downarrow X}}$$



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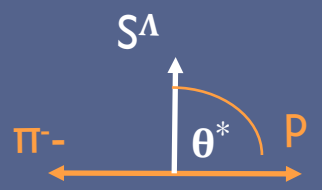
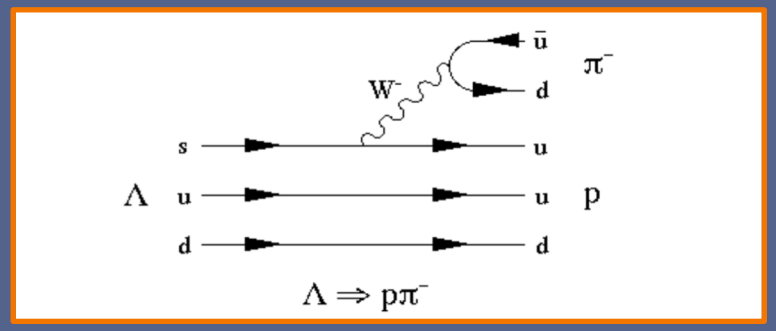


$$d\sigma \propto 1 + \alpha P_\Lambda \cos\theta^*$$



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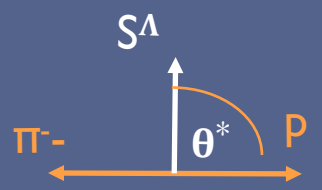
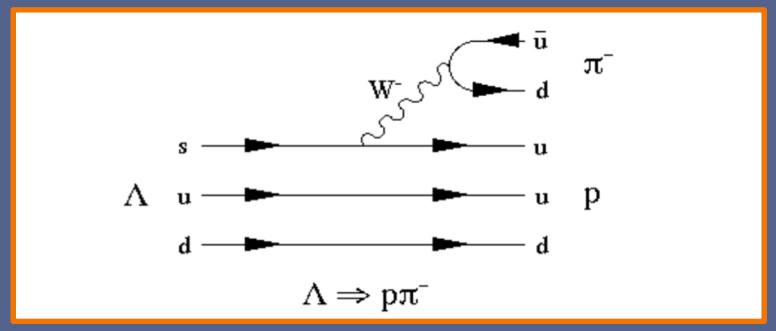


$$d\sigma \propto 1 + \alpha P_\Lambda \cos\theta^*$$

Proton momentum prefers direction of *Λ* polarization.



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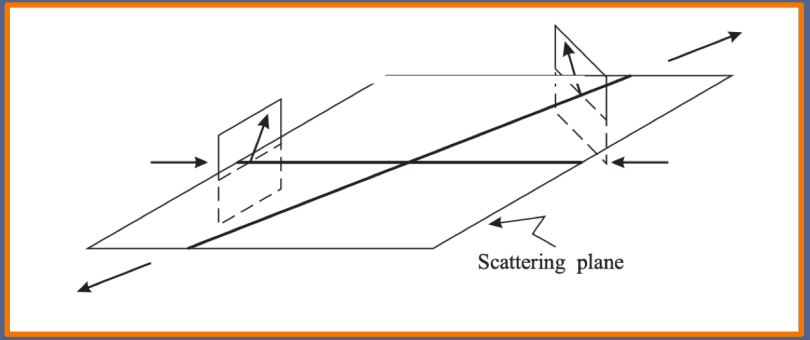
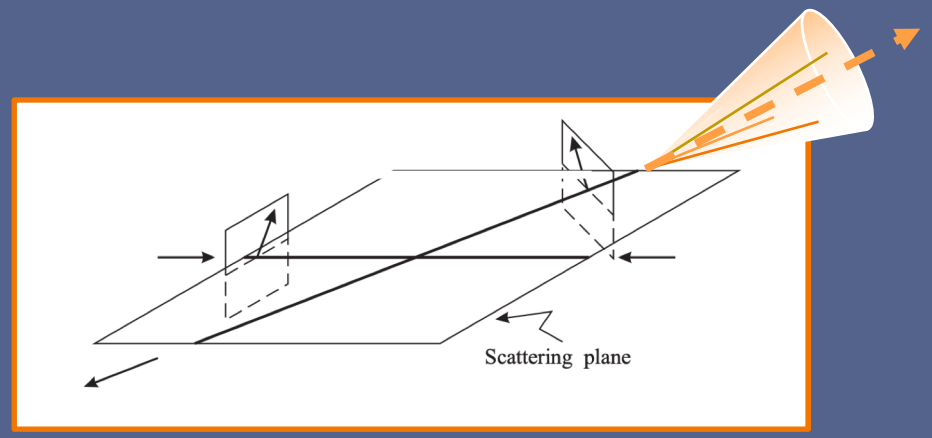


Experimentally θ^* is determined from transverse spin orientation of the outgoing fragmenting parton.

FIRST MEASUREMENT OF THE LAMBDA TRANSVESE SPIN TRANSFER D_{TT} AT RHIC

$$D_{TT} = \frac{d\sigma^{p\uparrow p\to\Lambda\uparrow X} - d\sigma^{p\uparrow p\to\Lambda\downarrow X}}{d\sigma^{p\uparrow p\to\Lambda\uparrow X} + d\sigma^{p\uparrow p\to\Lambda\downarrow X}}$$



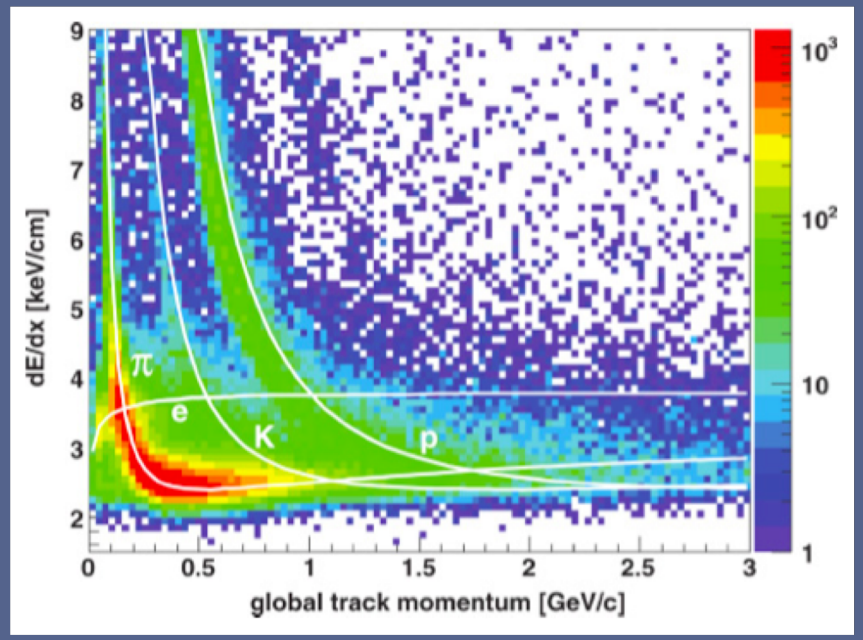
Experimentally θ^* is determined from transverse spin orientation of the outgoing fragmenting parton. Jet associated with Λ used as parton proxy.

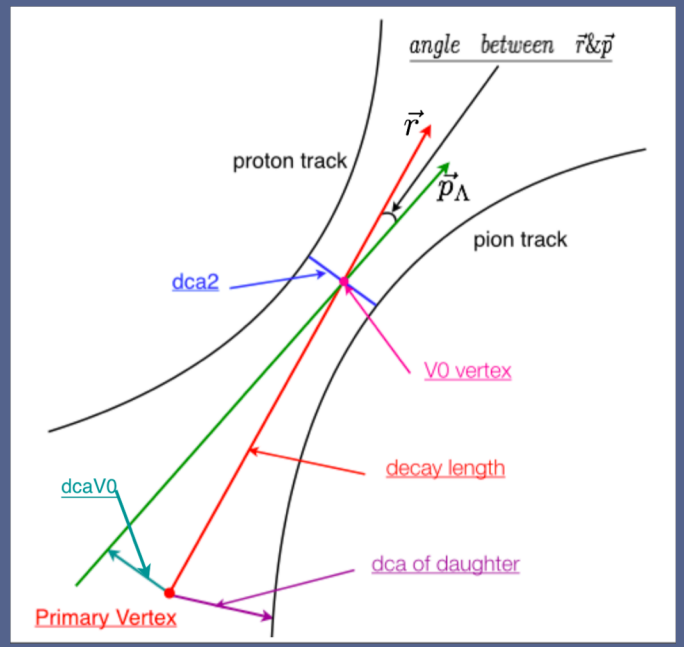
FIRST MEASUREMENT OF THE LAMBDA TRANSVESE SPIN TRANSFER D_{TT} AT RHIC

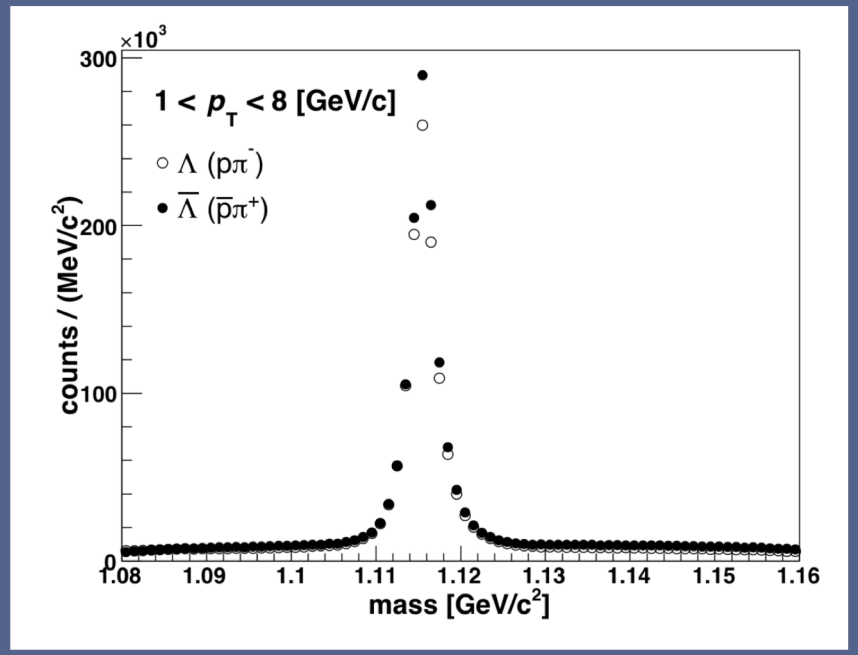
$$D_{TT} = \frac{d\sigma^{p\uparrow p\to\Lambda\uparrow X} - d\sigma^{p\uparrow p\to\Lambda\downarrow X}}{d\sigma^{p\uparrow p\to\Lambda\uparrow X} + d\sigma^{p\uparrow p\to\Lambda\downarrow X}} = \frac{d\Delta_T\sigma}{d\sigma}$$

If the Λ spin direction is highly correlated with the strange constituent quark spin orientation, $|\Lambda\rangle = (ud)_{00}s^{\uparrow}$, then D_{TT} is sensitive to both the strange transversity PDF and the transversely polarized Λ FF.

LAMBDA RECONSTRUCTION



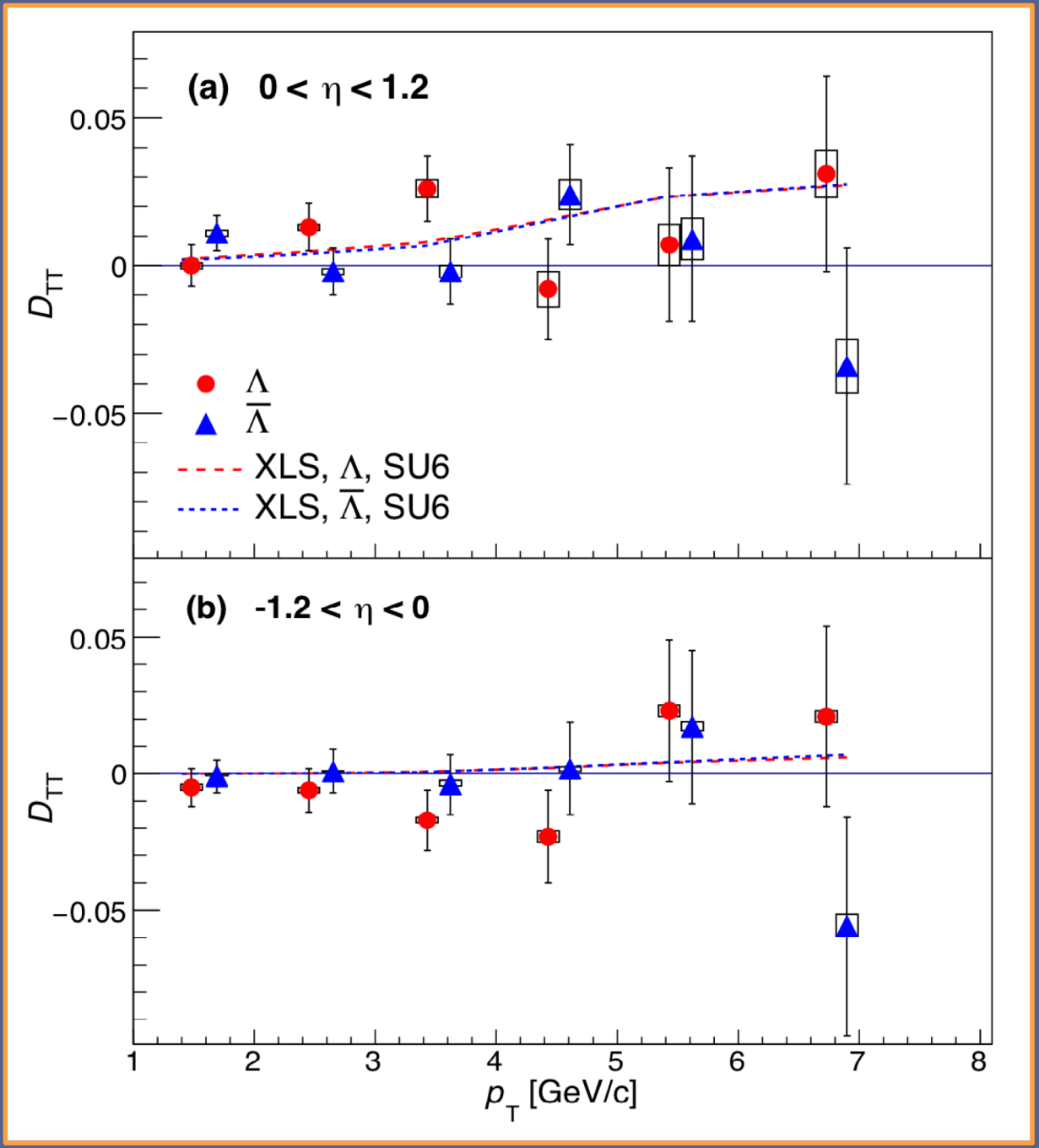




- TPC dE/dx and topological cuts are used to reconstruct decay proton and pion.
- Require Lambda to be associated with a jet reconstructed using the anti-k_T method with R = 0.6.

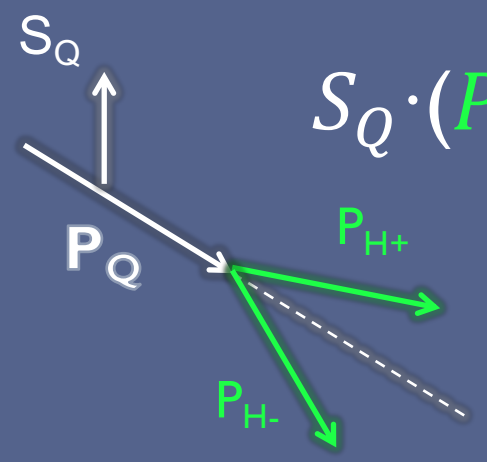
LAMBDA D_{TT}

- First extraction of D_{TT} from18 pb^{-1} in $\sqrt{s}$ = 200 GeV p+p collisions.
- Lambda asymmetries are consistent with model predictions by Xu, Liang and Sichtermann, PRD 73 (2006) 077503
- Lambda asymmetries are also consistent with zero.



Phys.Rev. D98, 091103 (2018)

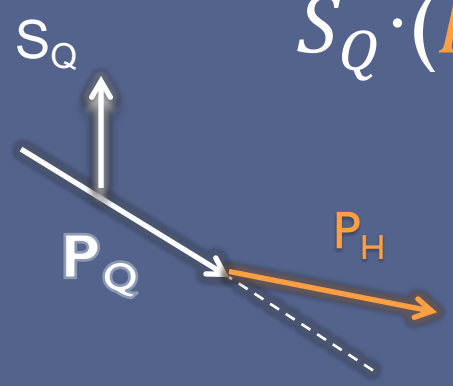
TRANSVERSITY



$$S_Q \cdot (P_{H-} \times P_{H+})$$

Interference Fragmentation Functions

Correlation between spin of transversely polarized quark and momentum cross-product of dihadron pair.



$$S_Q \cdot (P_Q \times P_H)$$

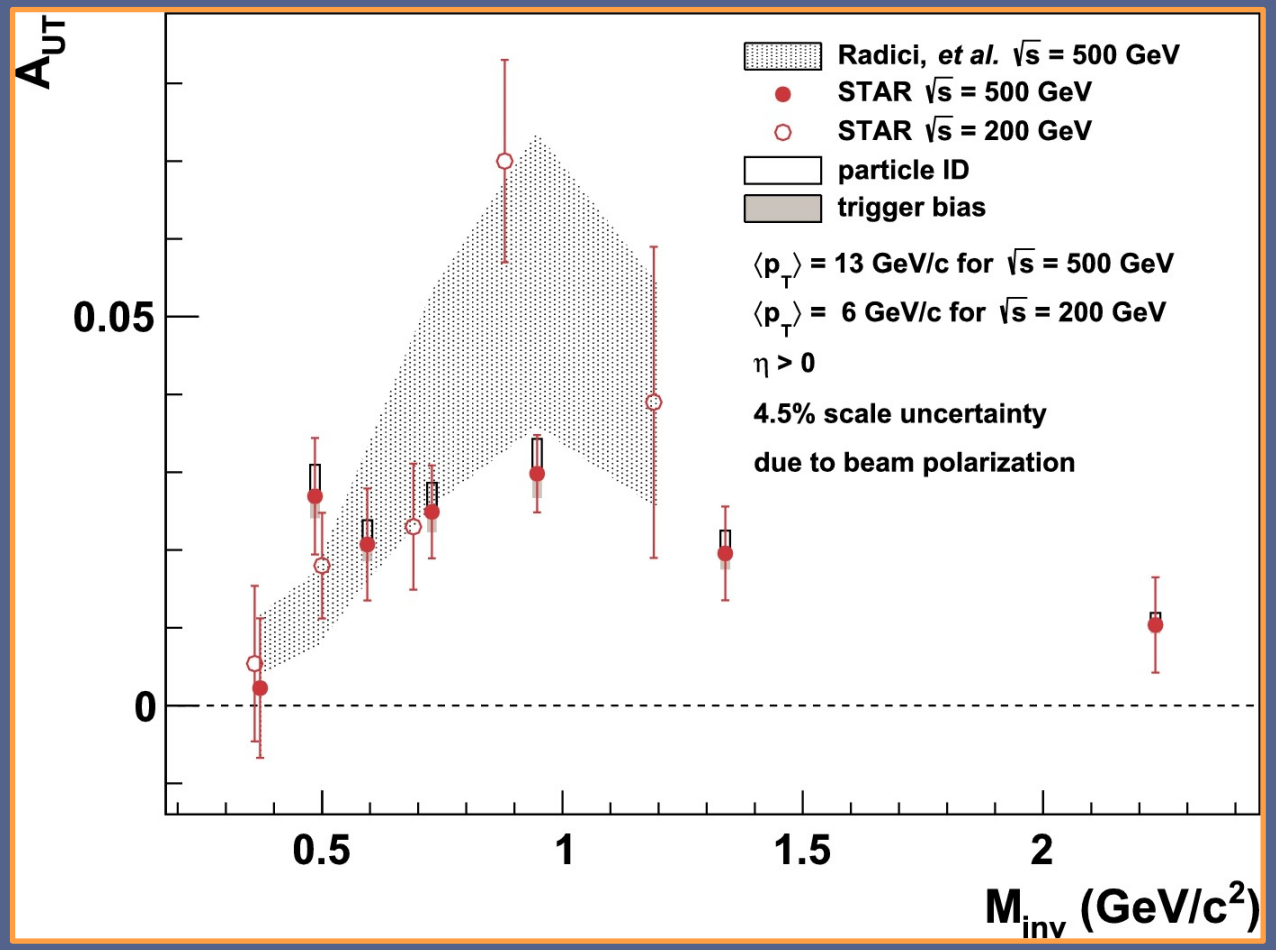
Collins Fragmentation Functions

Correlation between spin of transversely polarized quark and transverse momentum kick given to fragmentation hadron.

TRANSVERSITY ⊗ IFF

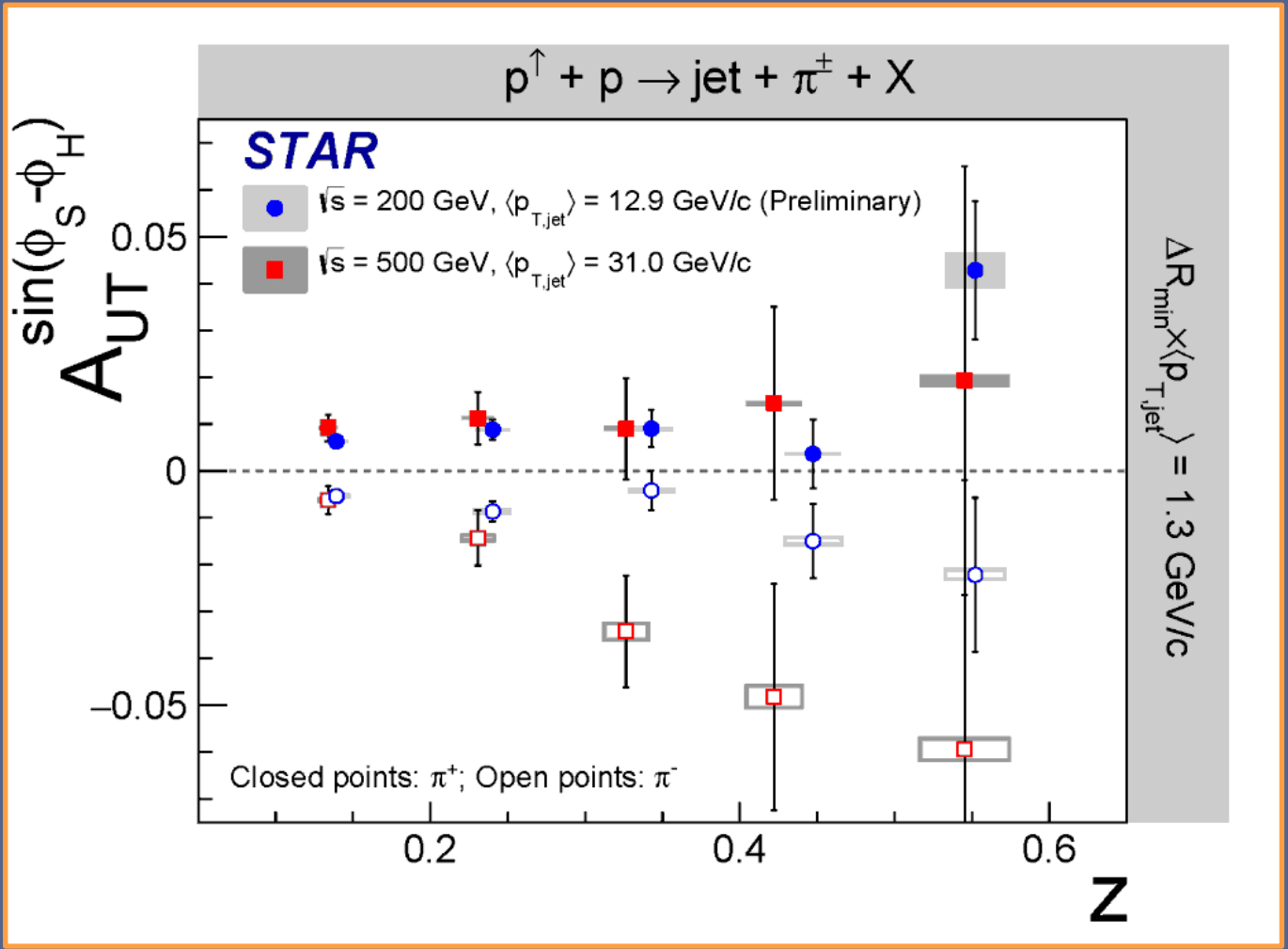
Phys.Lett. B780 (2018) 332

- First significant transversity signal measured in proton-proton collisions.
- Despite different scales asymmetries are very similar in 200 and 500 GeV when $<x_T>$ is similar.
- STAR data are well described by IFF theoretical calculations incorporating SIDIS and e+e- data.
- Recent global analysis by Radici and Bacchetta (PRL 120, 192001) shows significant reduction in uncertainty for u quark transversity distributions from STAR data.



TRANSVERSITY ⊗ COLLINS FF

- Complementary TMD channel to the collinear dihadron channel.
- Again asymmetries are very similar in 200 and 500 GeV.
- Additional statistics for both 200 and 500 GeV are on tape!
- Provides input on TMD evolution, which cannot be calculated fully from first principles.



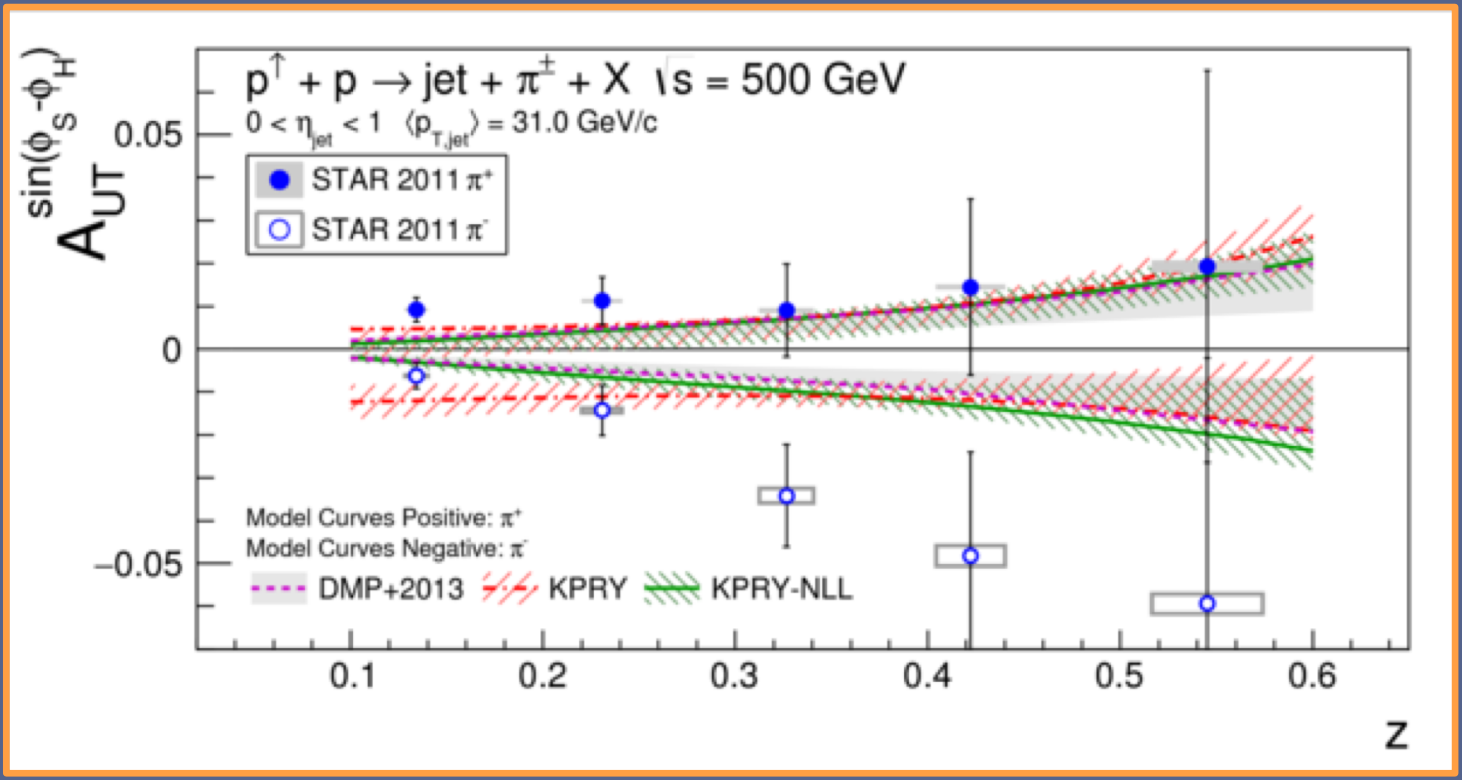
Phys. Rev. **D 97** (2018) 32004

500 GEV $A_{UT}^{\sin(\phi_S-\phi_H)}$ VS Z

STAR data compared to calculations by

1. D'Alesio, Murgia & Pisano, Phys. Lett. **B773**, 300 (2017)

2. Kang, Prokudin, Ringer, & Yuan, Phys.Lett. **B774** 635-642 (2017) without and with evolution.



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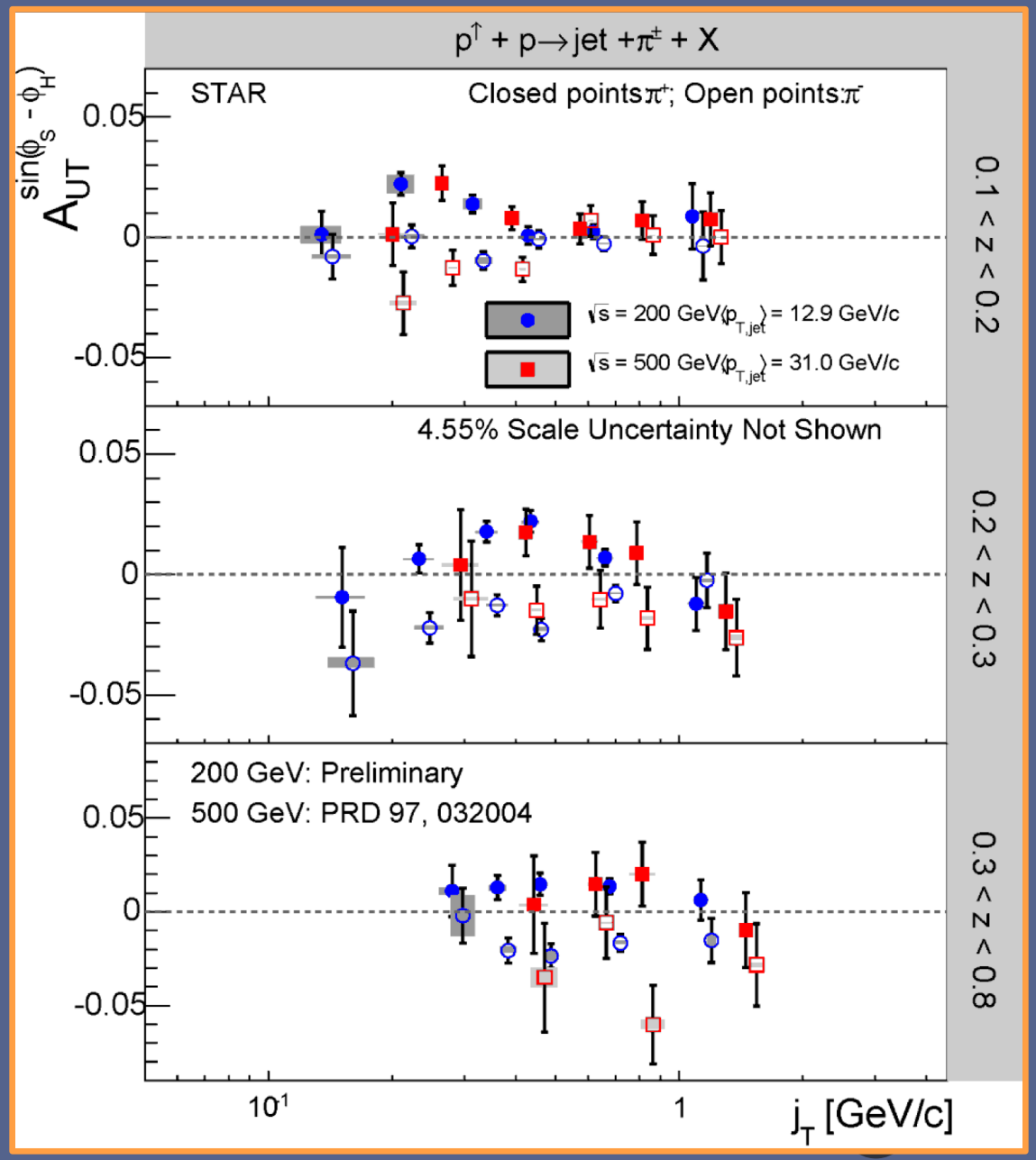
Data and theory agree - **TMD Evolution effects appear to be small.** At the current level of precision the data supports theoretical work by by Kang, Liu, Ringer and Xing JHEP 1711 (2017) 068 , ie **universality holds for Collins TMDs in p+p collisions.** Need more data!

$A_{UT}^{\mathrm{SIN}(\phi_S-\phi_H)}$ VS J_T IN BINS OF Z

- 200 and 500 GeV tell the same story.
- Shape of j_T changes with z.
- Peak of distribution moves towards higher $\langle j_T \rangle$ as z increases.
- Hadron j_T is independent of initial state transverse momentum.



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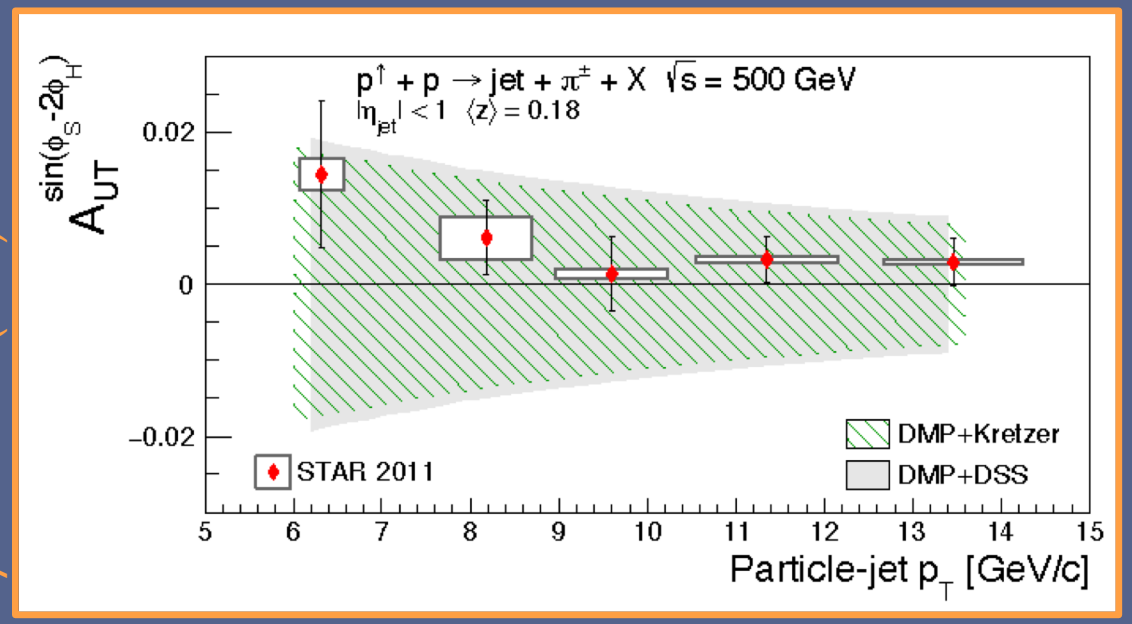
GLUON TMDS @ 200 AND 500 GEV

- **$\sin(\phi_s\text{-}2\phi_H)$ moment** Gluon Linear Polarization $\otimes$ Collins-Like FF
- First limit on linearly polarized gluons in a polarized proton!



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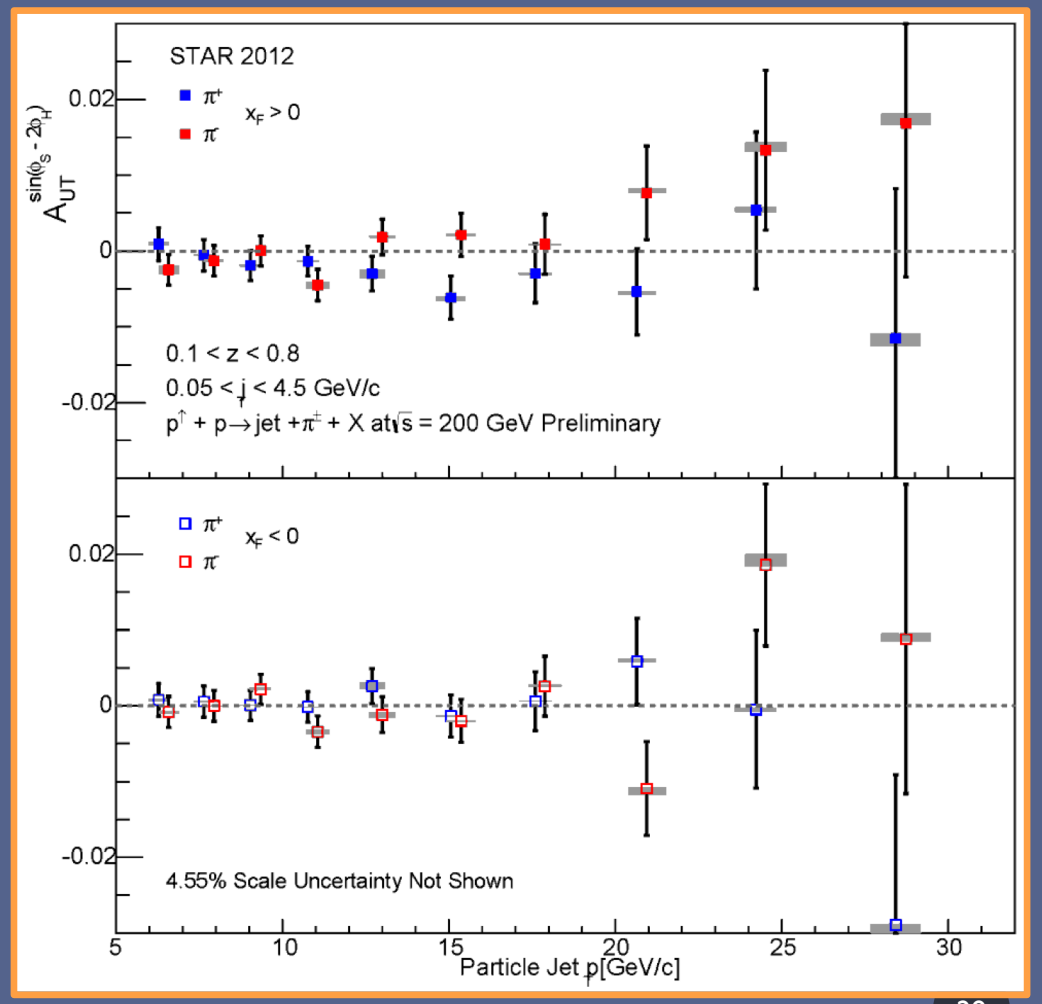
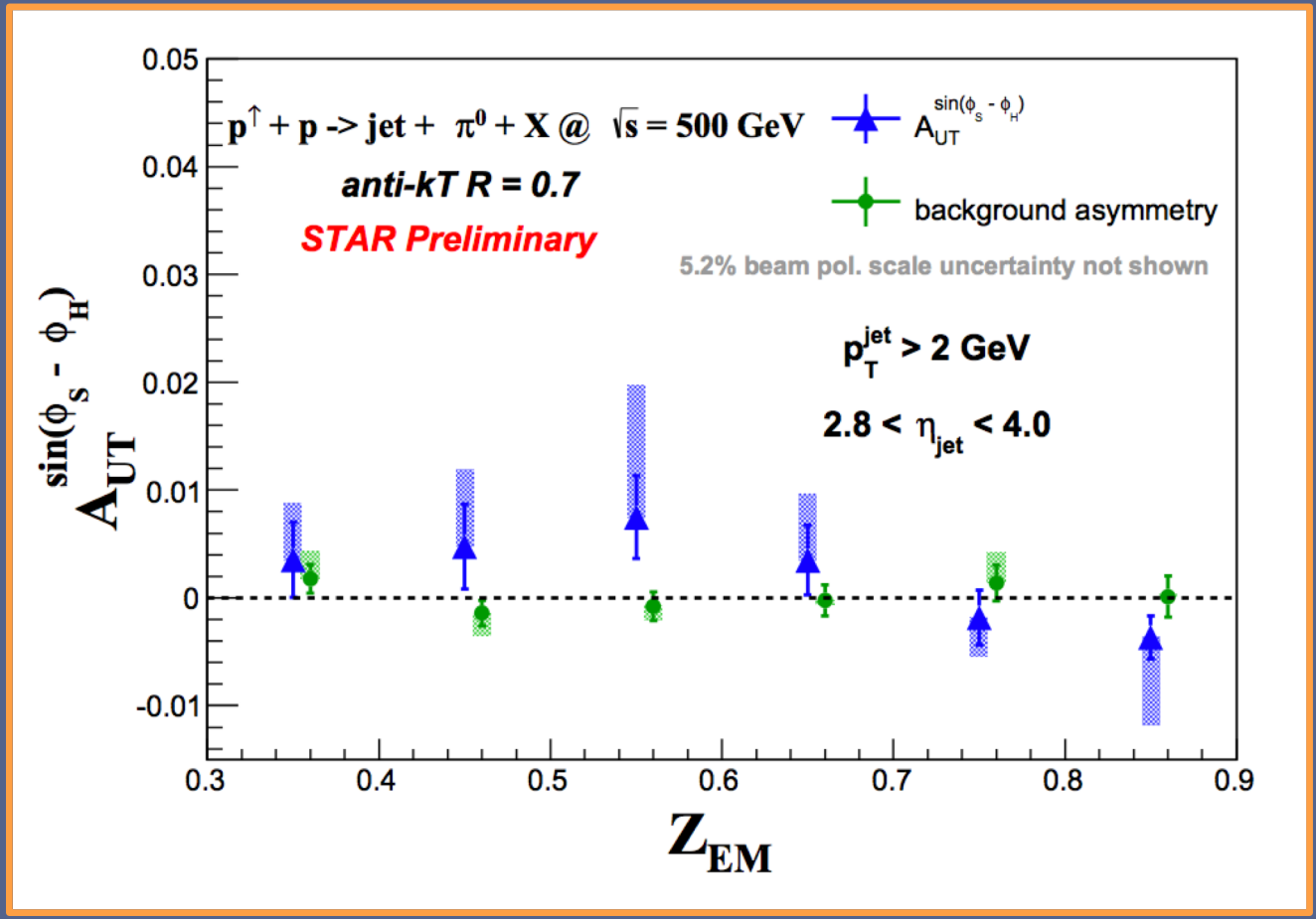
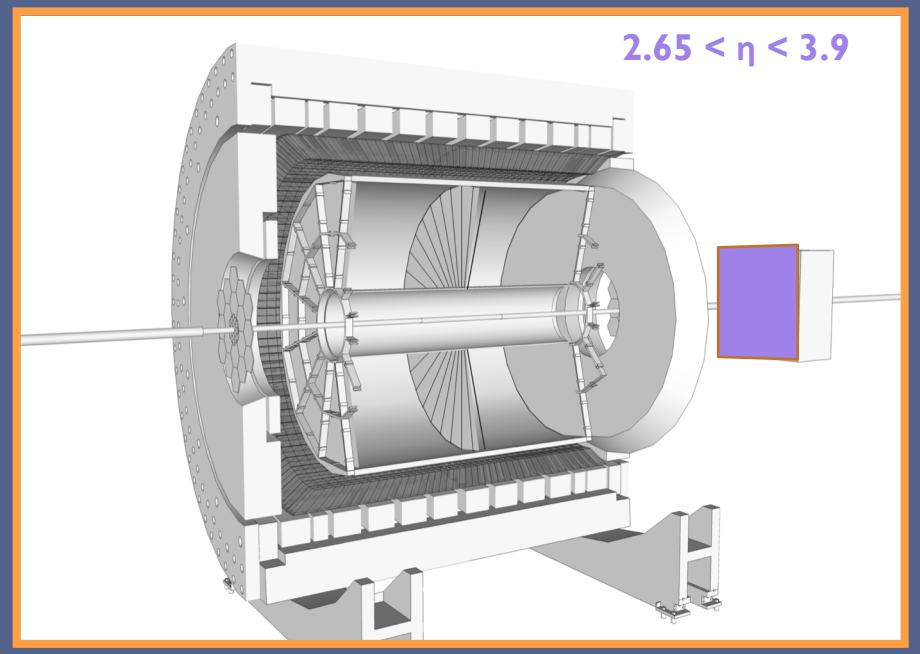


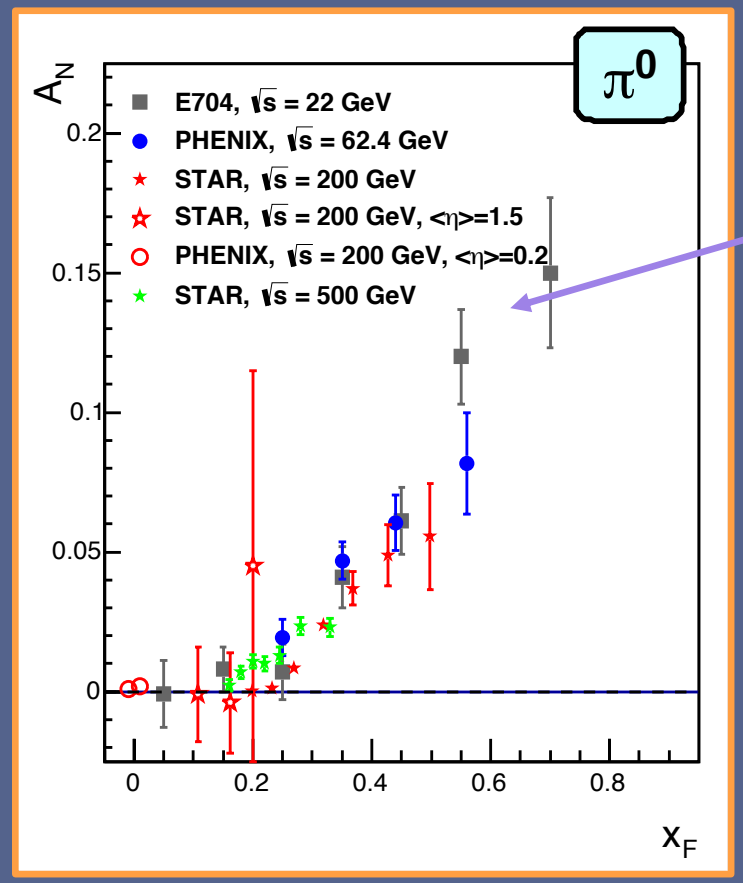
Far-Forward Collins TMD FF

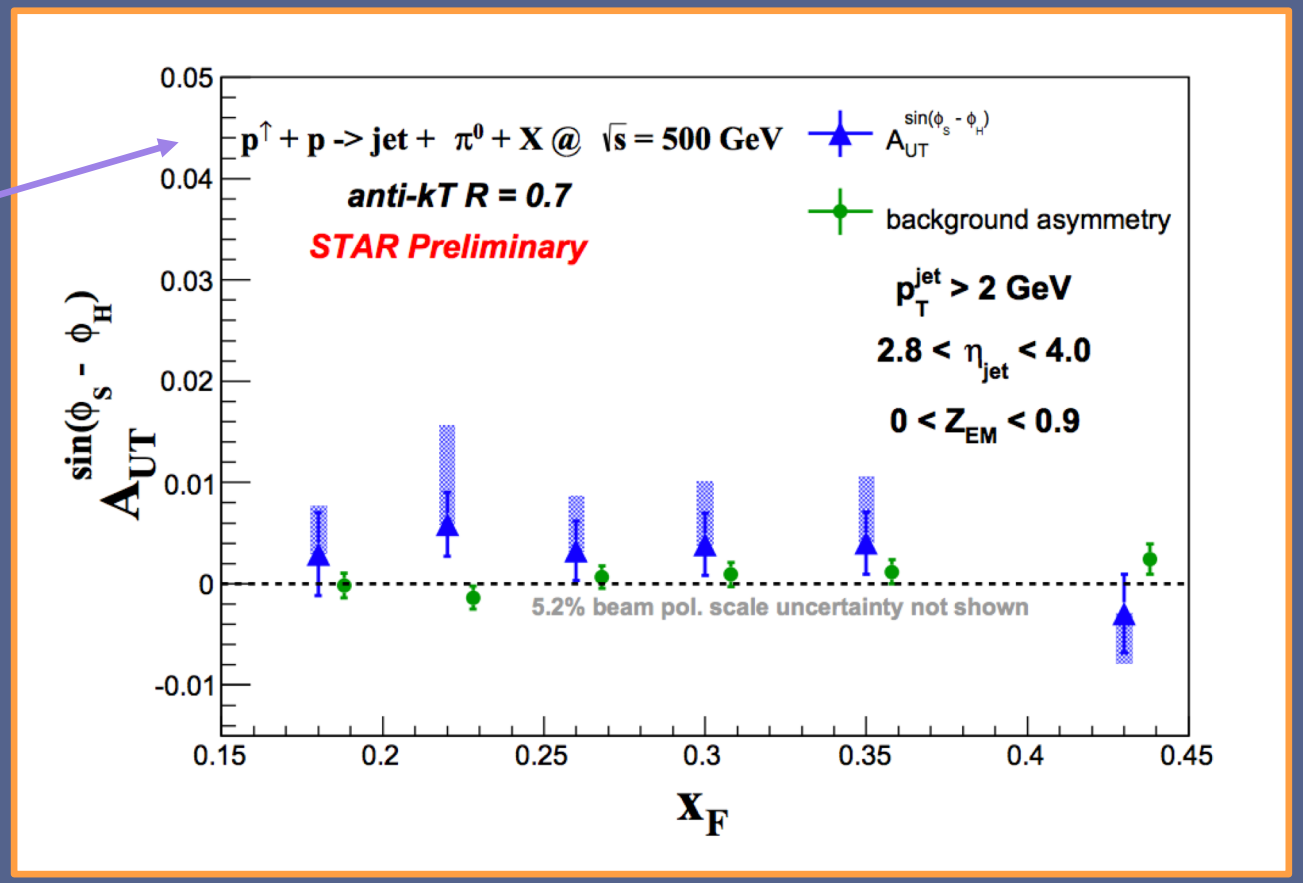




- No charged tracks – EM jets only. Leads to large systematic error on reconstruction of the Collins angle.
- π^0 reconstruction
- Size and shape of asymmetries very similar to mid-rapidity.

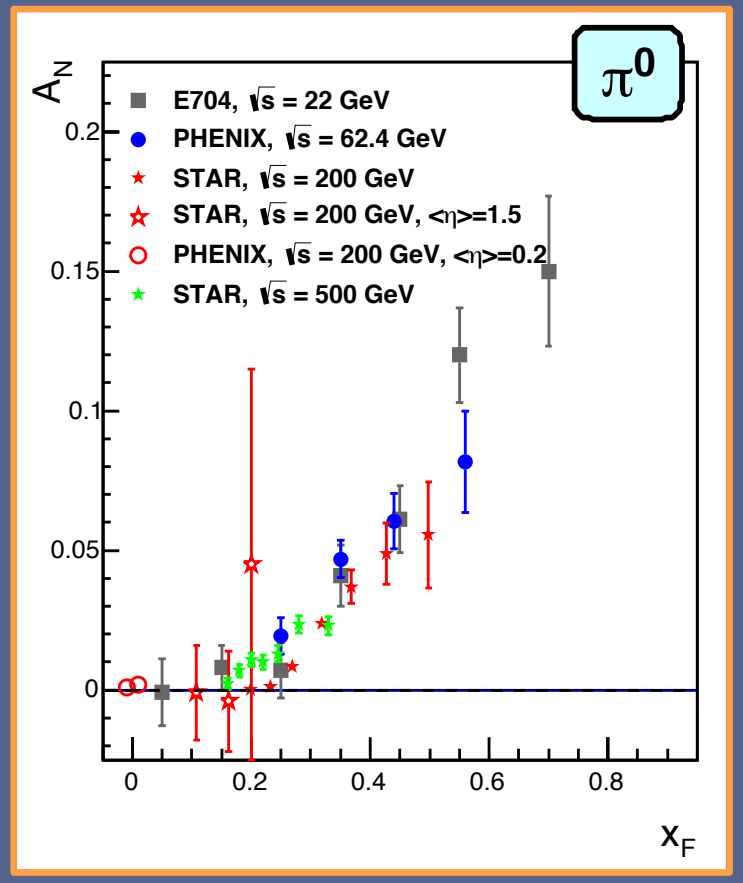
DOESN'T EXPLAIN LARGE FORWARD SSA

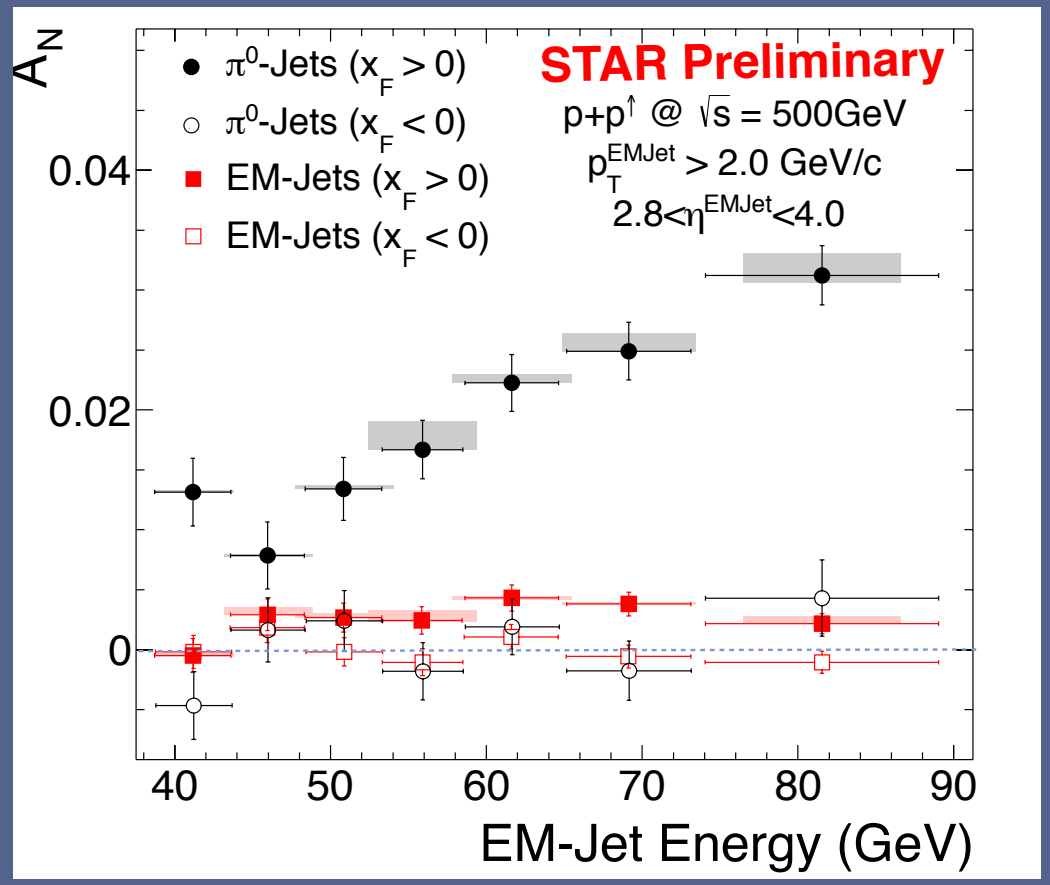




Jet asymmetries don't represent size or shape of inclusive π^0 SSA!

DOESN'T EXPLAIN LARGE FORWARD SSA

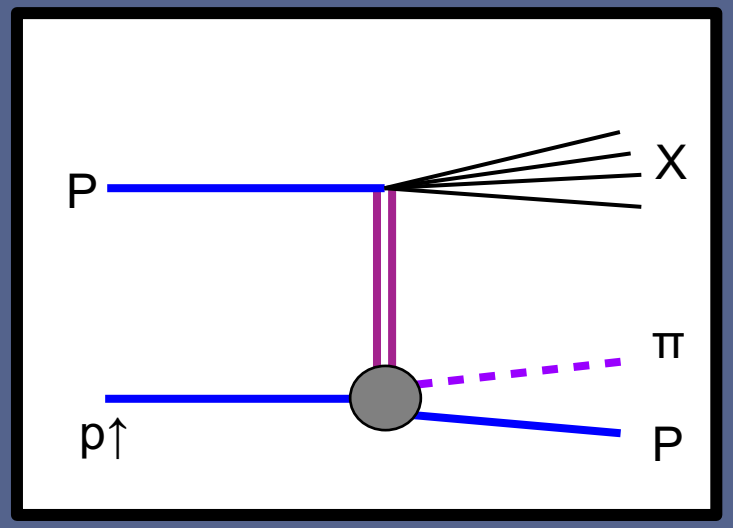




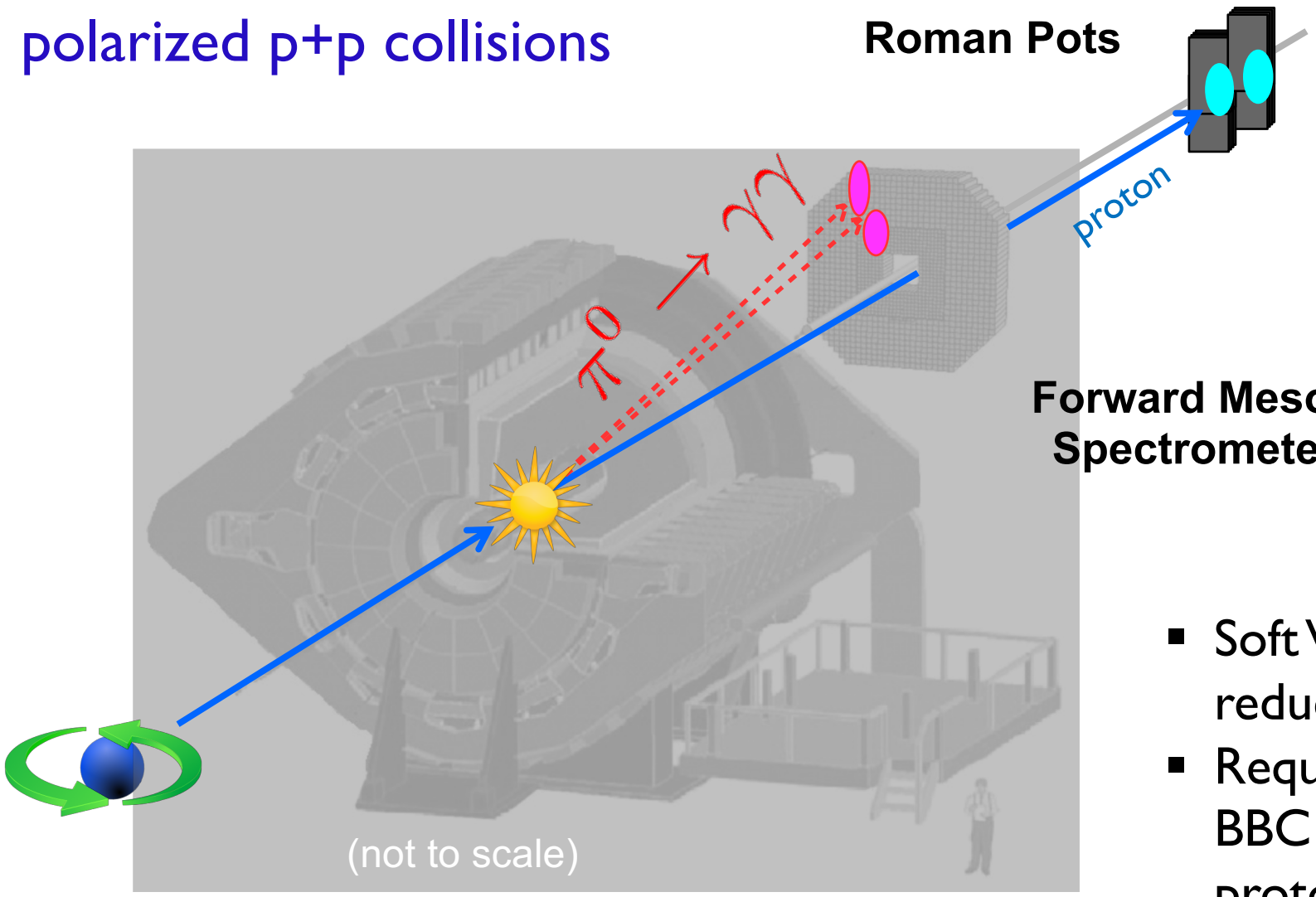
"Recover" asymmetries if "jet" is composed largely of a single pion.

Possible SSA channel : $p^{\uparrow}p \rightarrow p\pi^{0}X$

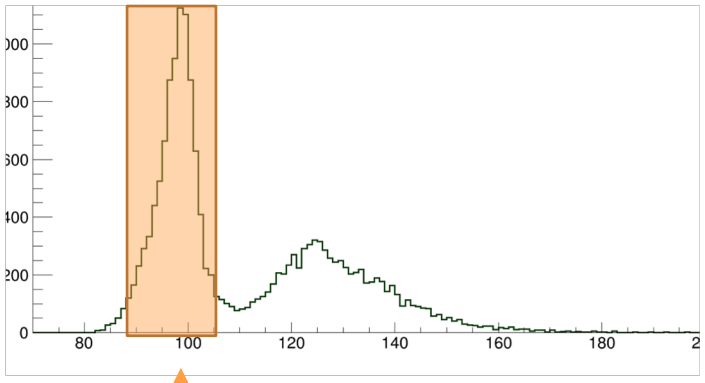
- Signature is an isolated neutral pion and proton scattered in the far forward region
- **Possible Model: Incident polarized proton may fluctuate into a proton + pion pair, which then interacts with the opposing proton**
- **Incident proton transverse spin may be correlated with proton + pion angular momentum**
- **Goal: study asymmetries modulated by proton and pion azimuthal angles**



200 GeV transversely polarized p+p collisions



$E_{sum} = E_{proton} + E_{pion}$ Distribution



$$p^{\uparrow} + p \rightarrow p + \pi^0 + X$$

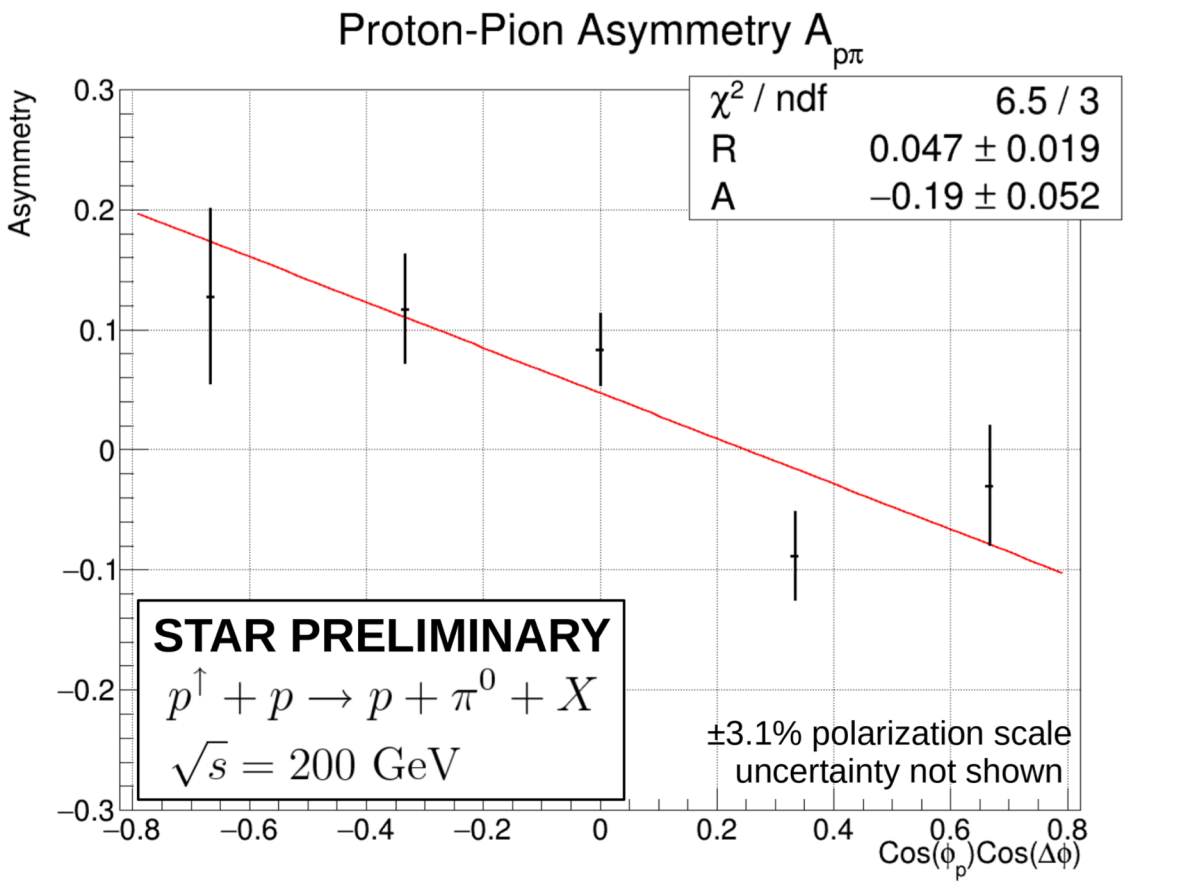
- Soft Veto on forward BBC to reduce accidental coincidences
- Require energy in backward BBC + TOF to ensure 2nd proton breaks up

C. Dilks

$\mathrm{Cos}(\Phi_P)\mathrm{Cos}(\Delta\Phi)$ Asymmetry

$$\frac{1}{\langle P\rangle}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}} = R + A\cos\phi_p\cos\Delta\phi$$

- Several asymmetries investigated. The largest is the pion asymmetry in the scattering plane of the proton with a 19% asymmetry ~4σ!
- Vertical error bars are statistical uncertainties
- Horizontal error bars are propagated from FMS and RP position uncertainties
- 5% background under π^0 mass peak
- 3.1% scale uncertainty from polarization



$\underbrace{\text{Cos}(\Phi_P)}$Cos(ΔΦ) Asymmetry

Spin UP/DOWN proton scatters L/R

$$\frac{1}{\langle P \rangle}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}} = R + A\cos\phi_p\cos\Delta\phi$$

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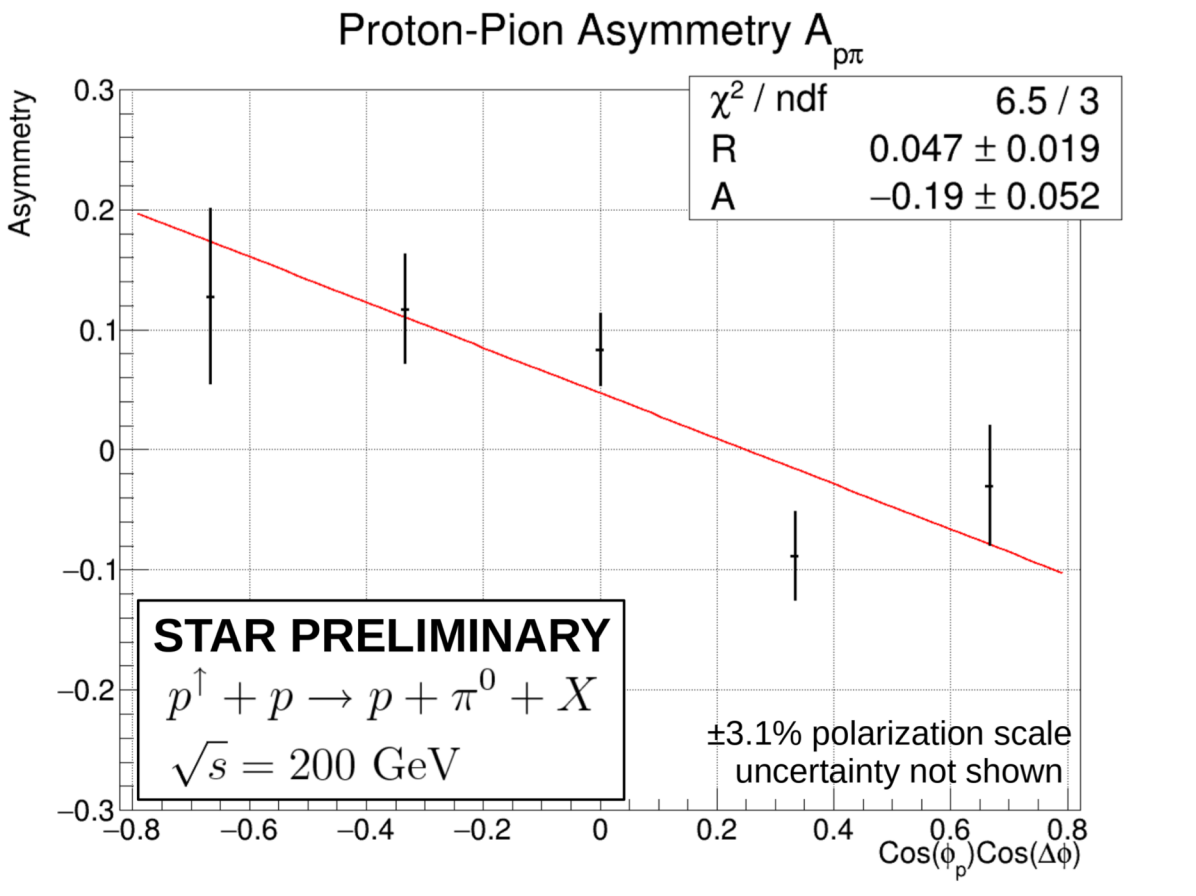

$\mathrm{Cos}(\Phi_p)\underbrace{\mathrm{Cos}(\Delta\Phi)}$ Asymmetry

Pion is within the scattering plane of detected proton

$$\frac{1}{\langle P\rangle}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}} = R + A\cos\phi_p\cos\Delta\phi$$

- Several asymmetries investigated. The largest is the pion asymmetry in the scattering plane of the proton with a 19% asymmetry ~4σ!
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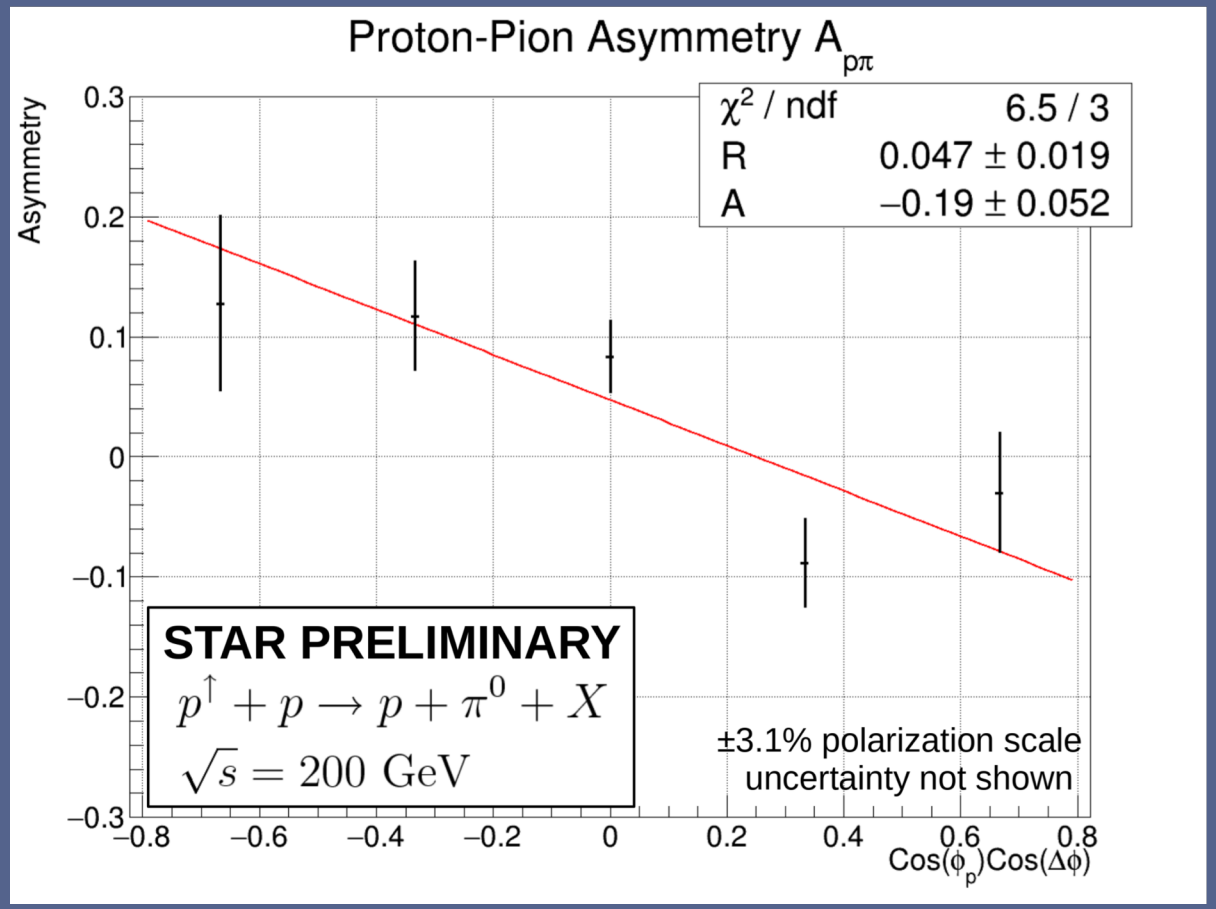
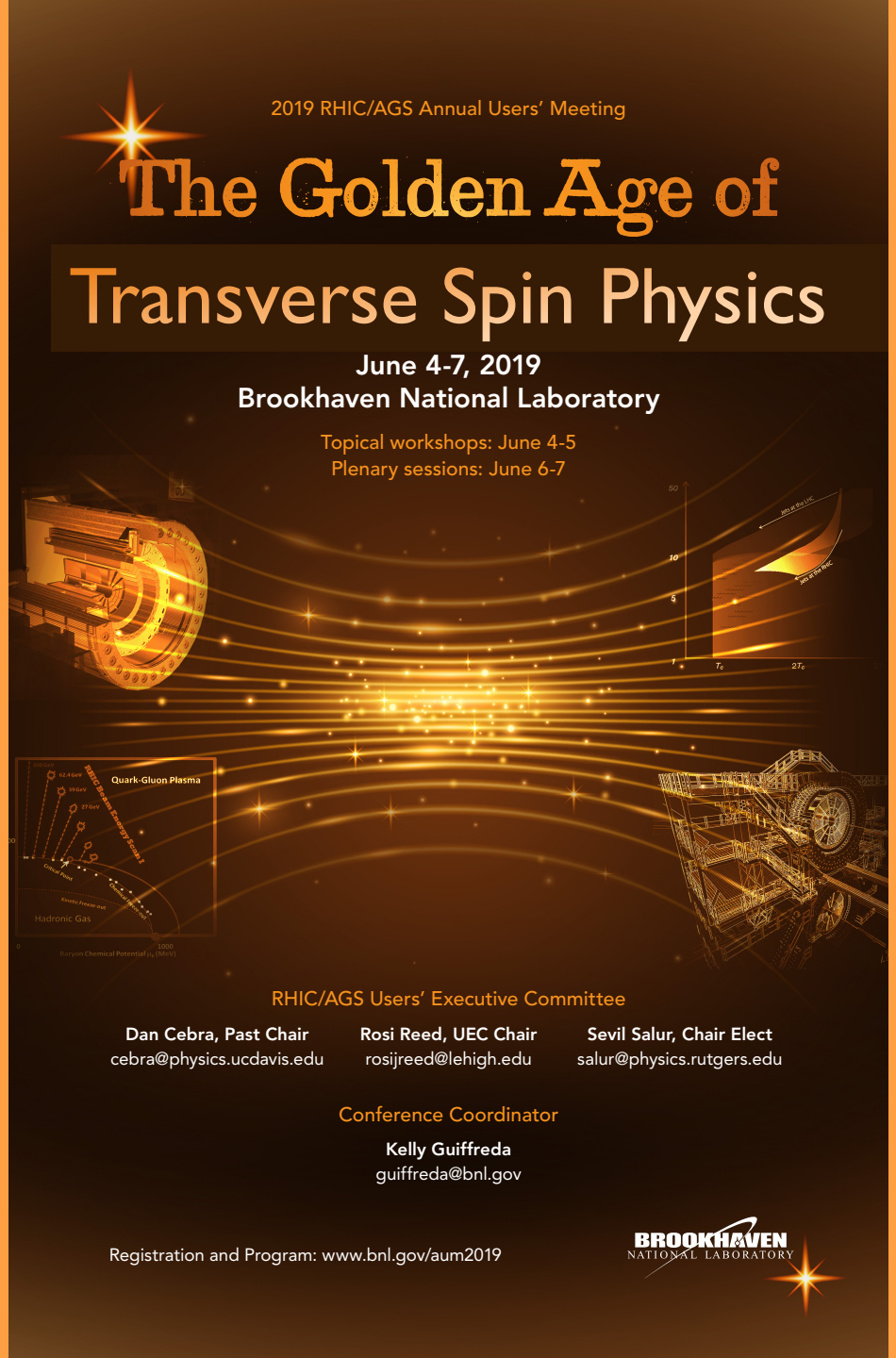


NEW PUBLICATIONS

- Lambda D_{TT}
  Phys.Rev. D98, 091103
- Transversity and Interference Fragmentation Function via di-hadron A_{UT} at $\sqrt{s}$ = 500 GeV
  Phys.Lett. B780 (2018) 332
- Collins Function, Gluon Linear Polariztion and Twist-3 Sivers Function via charged pion in jet A_{UT} at $\sqrt{s}$ = 500 GeV .
  Phys. Rev. D 97 32004



NEW PRELIMINARY RELEASES

- Inclusive Jet twist-3 Sivers Function at $\sqrt{s}$ = 200 GeV
- Collins Function via charge pion in jet A_{UT} differential in z and jT at $\sqrt{s}$ = 200 GeV.
- Forwqard diffractive pion spin SSA at $\sqrt{s}$ = 200 GeV .