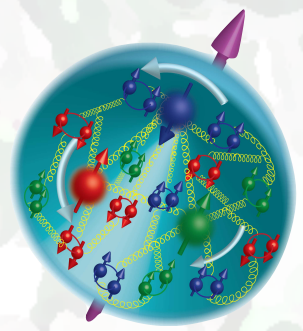
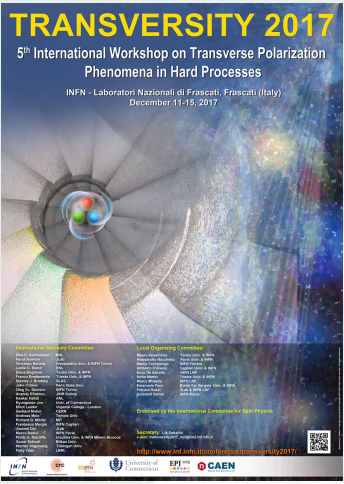


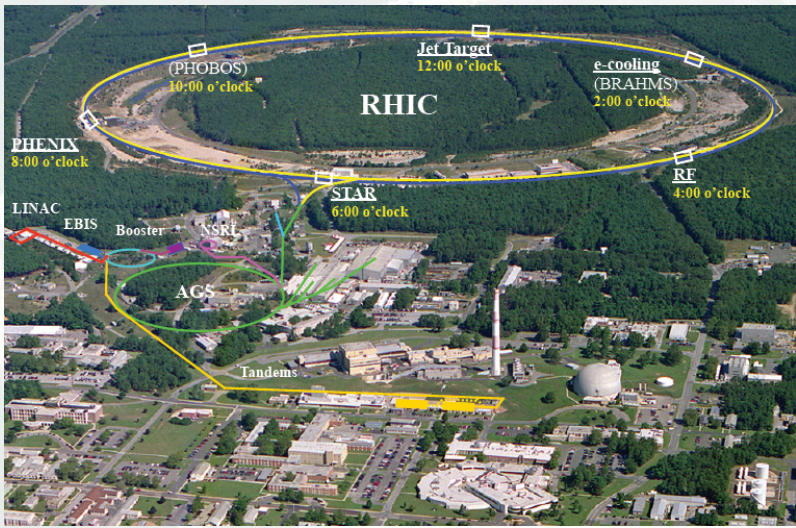


# New and future transverse spin results at STAR

Bernd Surrow

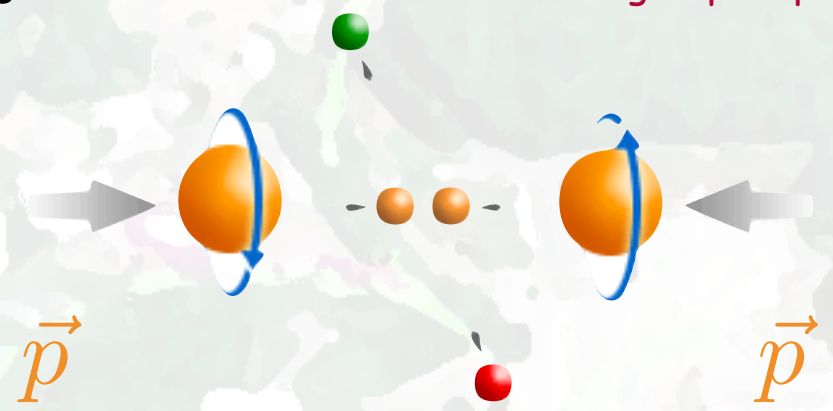


# Outline



- Recent Results and Prospects:
  - Reminder of unpolarized yield: Jets / Hadrons
  - Transversity-related measurements:
    - TMD Collins FFs: Azimuthal single-spin asymmetries of charged pions in jets
    - Di-hadron FFs: Azimuthal correlations of charged pion pairs

- Experimental aspects:  
RHIC / STAR



- Theoretical foundation

- Summary and Outlook

# Theoretical foundation

## □ Probe transverse proton spin structure using high-energy polarized p+p collisions

- Important new insight into the **transverse proton spin structure** at STAR in **polarized p+p collisions at high energies** using **well established processes** both theoretically and experimentally **involving jets / hadrons**

- **Transversity-related measurements**: Important insight into transverse spin structure - **Need coupling of transversity ( $h_1$ ) to chiral-odd transverse spin dependent fragmentation function (FF)**:

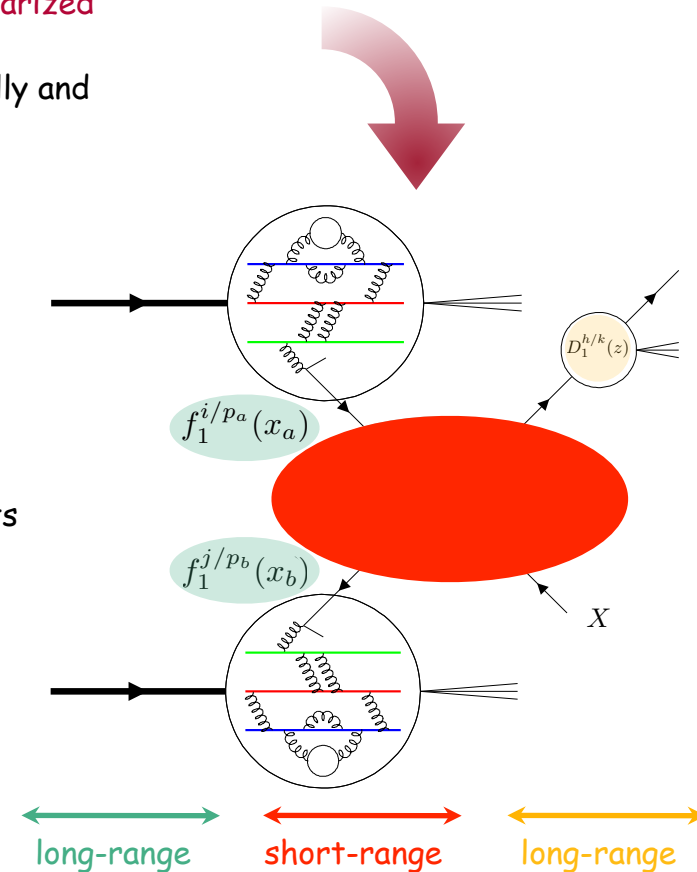
- **Collins TMD FFs**: Azimuthal single-spin asymmetries of charged pions in jets

$$\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^{\perp h/k}(z, k_T)$$

- **Di-hadron FFs**: Azimuthal correlations of charged pion pairs

$$\sum_{i,j,k} h_1^{i/p_a}(x_a) \otimes f_1^{j/p_b}(x_b) \otimes H_1^{\triangleleft h_1 h_2/k}(z, M_h)$$

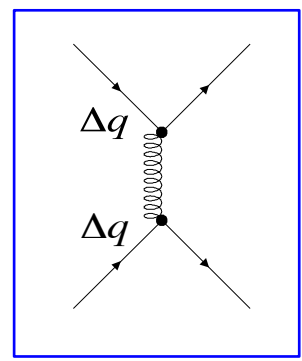
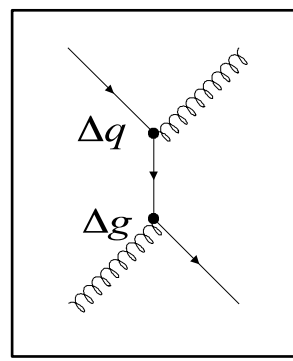
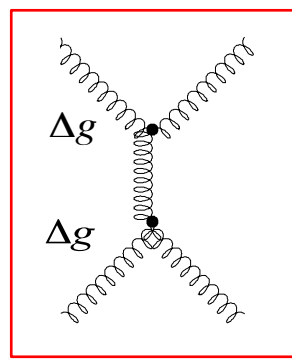
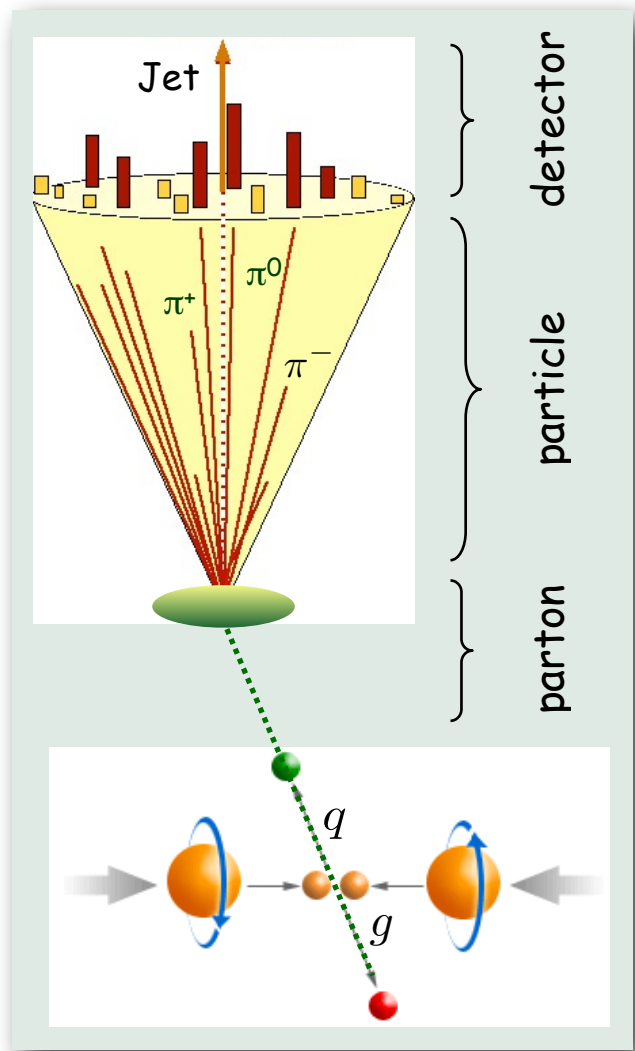
- Deepen our understanding concerning universality, factorization and evolution!



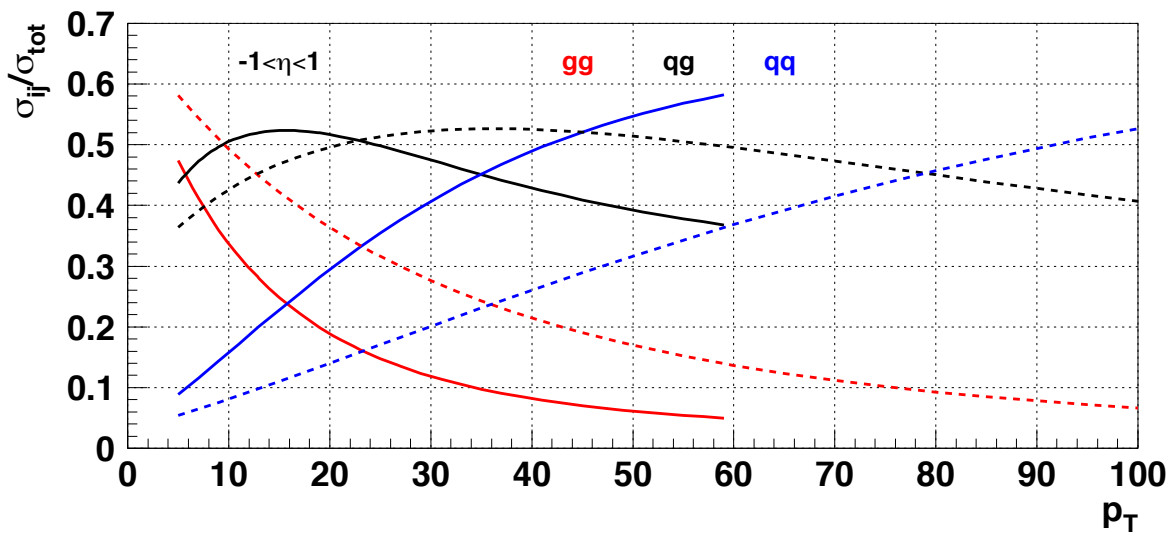
FF Review: A. Metz and A. Vossen, Prog. Part. Nucl. Phys. 91 (2016) 136.

# Theoretical foundation

□ Transversity studies involving jets / hadrons (1)



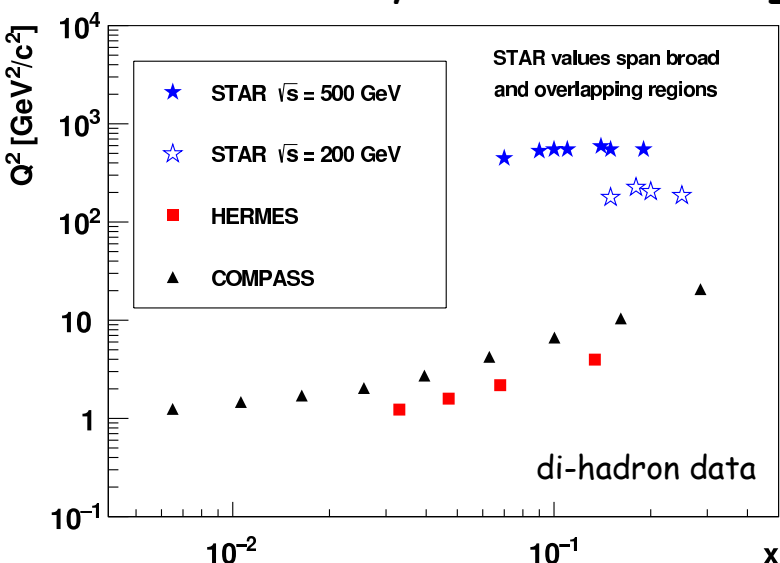
Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)





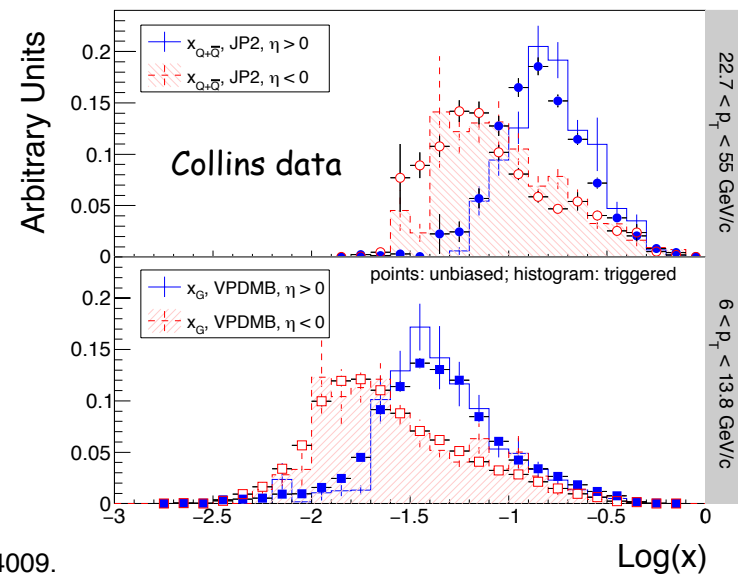
# Theoretical foundation

## Transversity studies involving jets / hadrons (2)



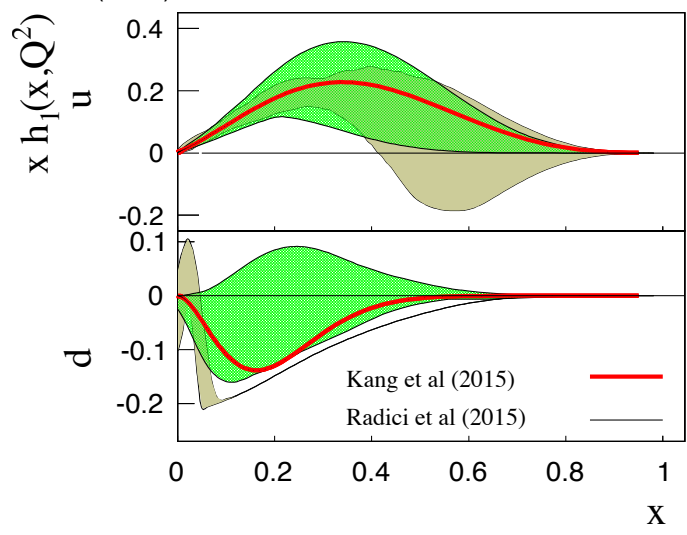
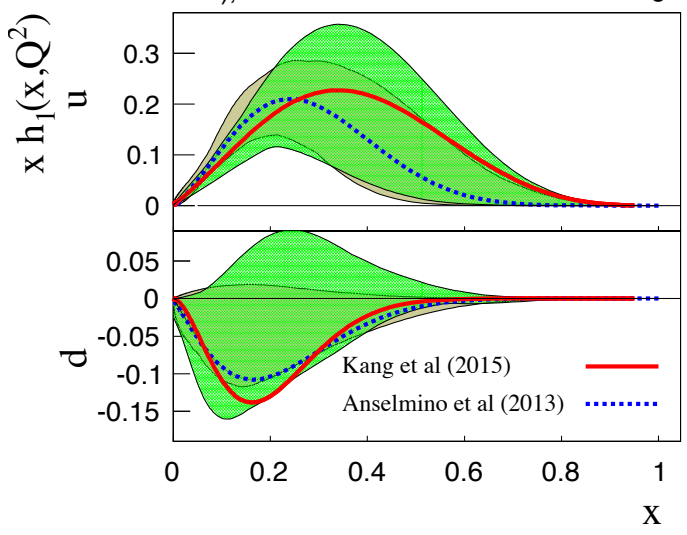
- Probe transversity  $h_1$  in Di-hadronFFs and TMD Collins FFs type measurements in  $x$  region where  $h_1$  uncertainties are large
- Clear impact of STAR data in new global fit based on di-hadron measurements

L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.



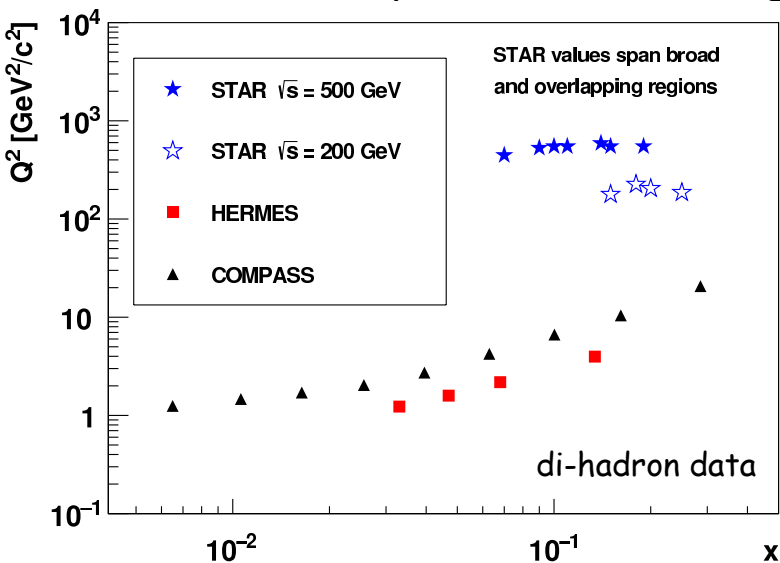
L. Adamczyk et al. (STAR Collaboration), arXiv:1710.10215.

Z. Kang et al., Phys. Rev. D93 (2016) 014009.



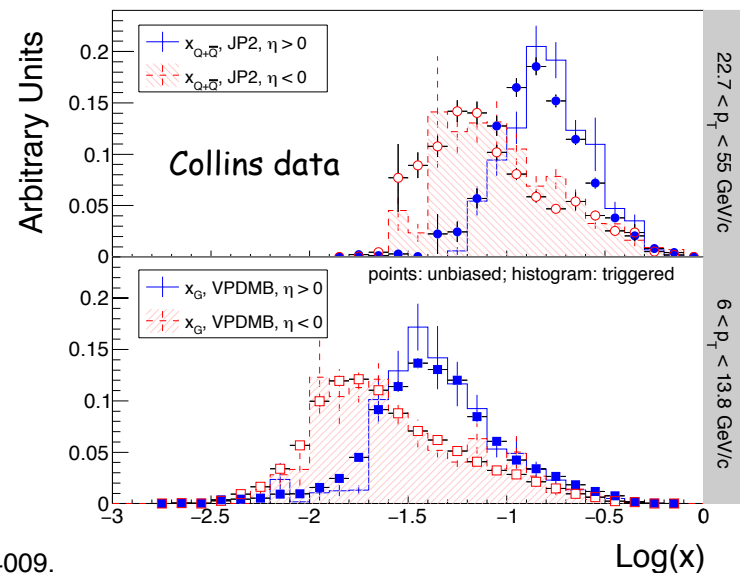
# Theoretical foundation

## Transversity studies involving jets / hadrons (2)



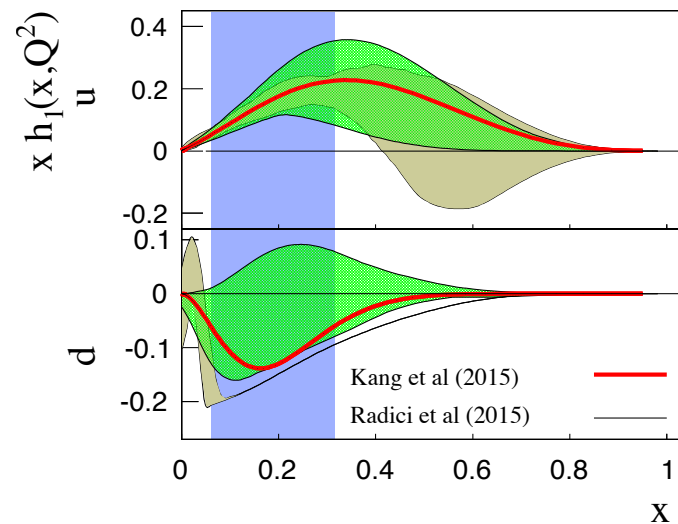
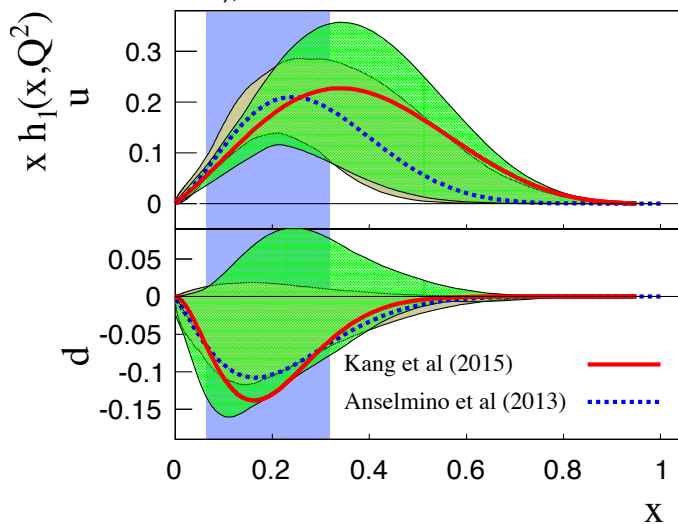
- Probe transversity  $h_1$  in **Di-hadronFFs** and **TMD Collins FFs** type measurements in  $x$  region where  $h_1$  uncertainties are large
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L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.



Z. Kang et al., Phys. Rev. D93 (2016) 014009.

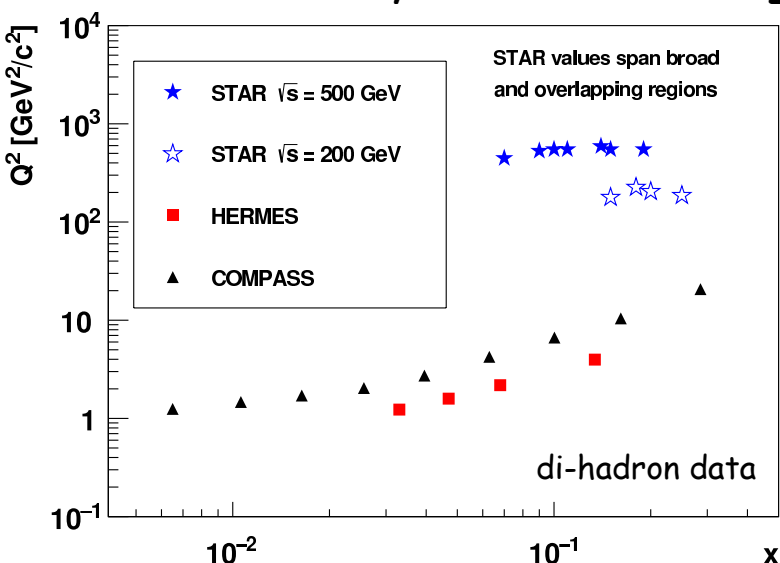
L. Adamczyk et al. (STAR Collaboration), arXiv:1710.10215.





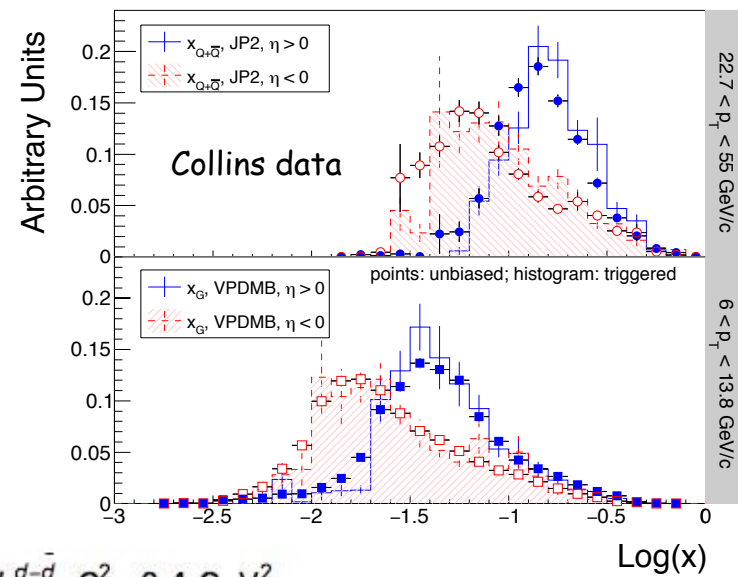
# Theoretical foundation

## Transversity studies involving jets / hadrons (2)



- Probe transversity  $h_1$  in Di-hadronFFs and TMD Collins FFs type measurements in  $x$  region where  $h_1$  uncertainties are large
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L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.

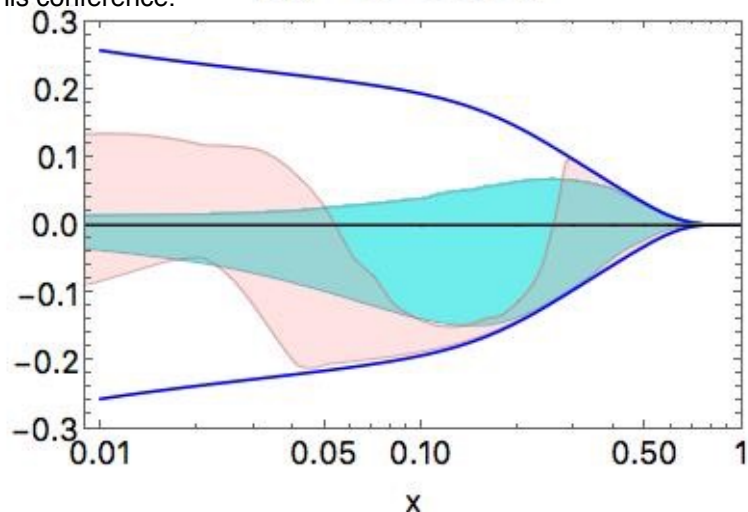
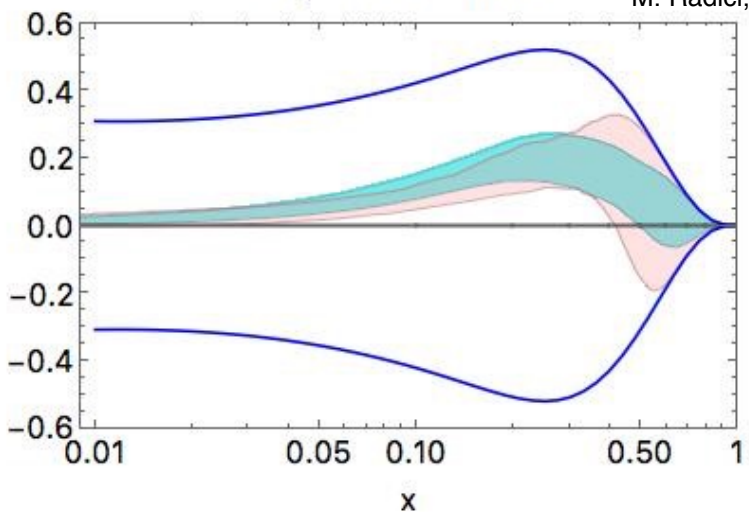


L. Adamczyk et al. (STAR Collaboration), arXiv:1710.10215.

$x h_1^{u-\bar{u}} Q^2 = 2.4 \text{ GeV}^2$

M. Radici, this conference.

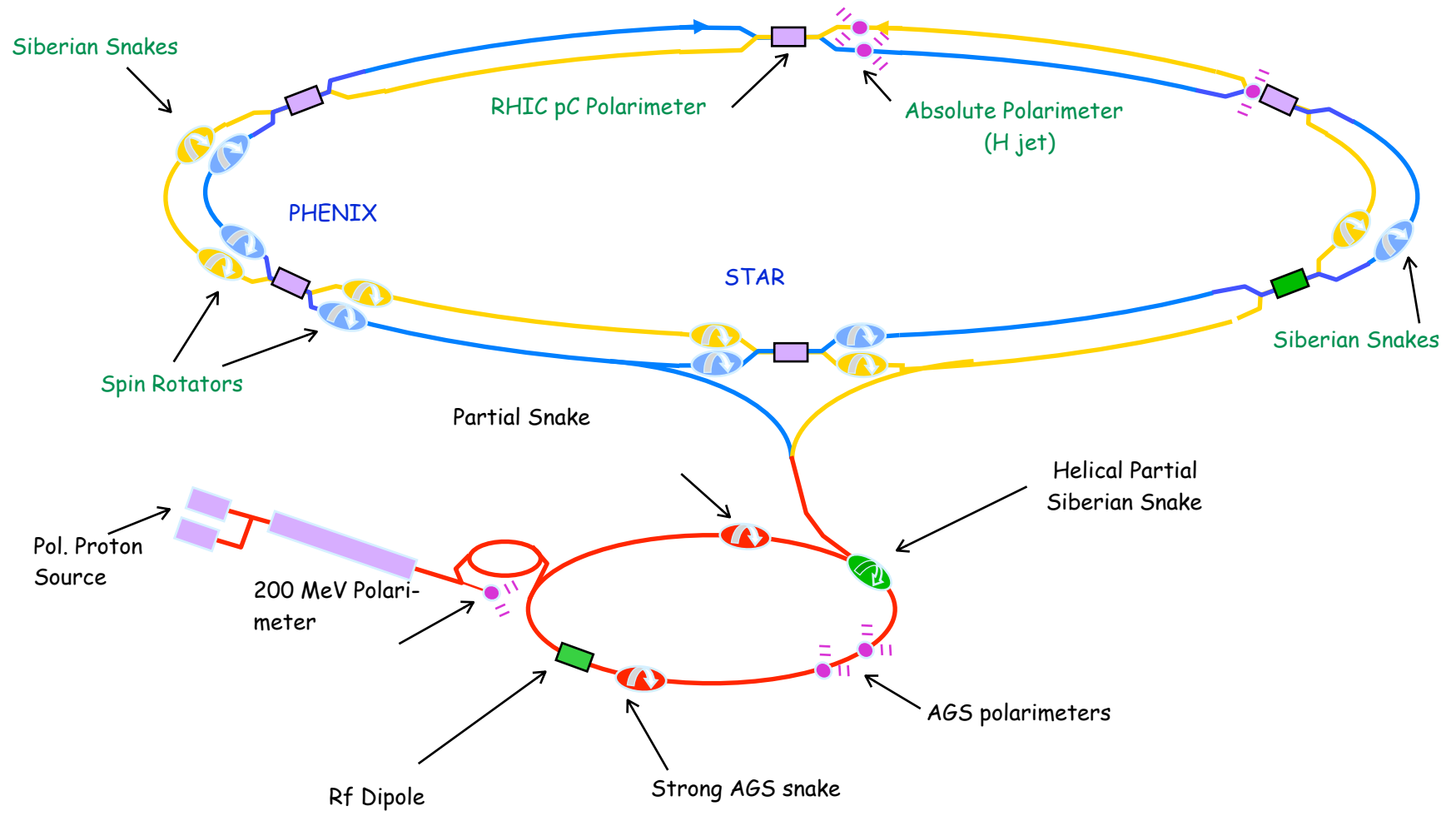
$x h_1^{d-\bar{d}} Q^2 = 2.4 \text{ GeV}^2$





# Experimental aspects - RHIC

- The world's first polarized proton+proton collider







# Experimental aspects - RHIC

## □ Polarized p+p collisions

- Di-hadronFFs (2006 at 200GeV and 2011

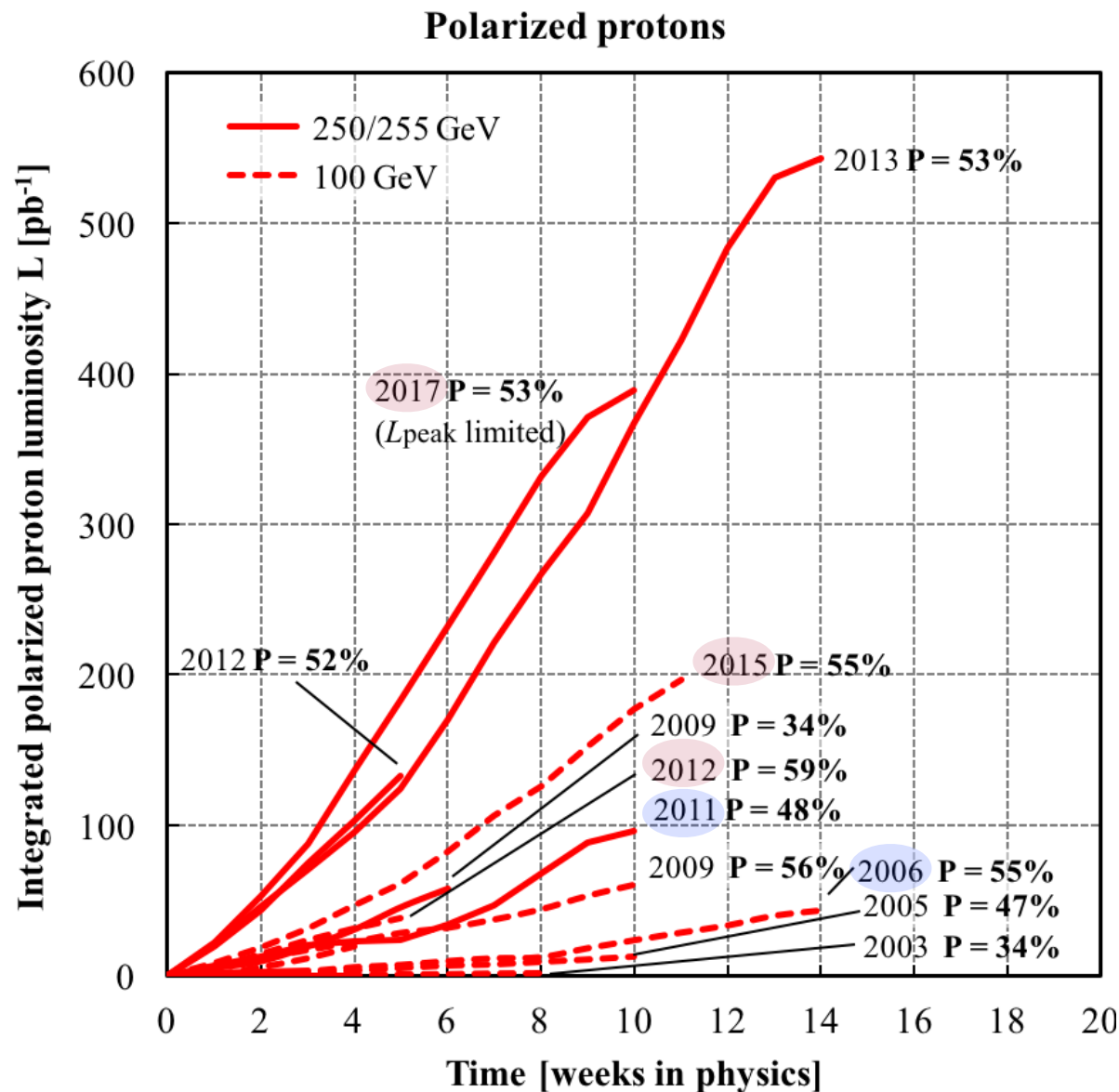
at 500GeV) and TMD Collins FFs (2006 /

2012 at 200GeV and 2011 at 500GeV)

type measurements

- Large data samples in 2015 / 2017!

Year	CME	$L_{rec}$ (pb <sup>-1</sup> )	$\langle P \rangle$ (B/Y) (%)
2006	200	8.5 pb <sup>-1</sup>	57
2006	62.4	0.2 pb <sup>-1</sup>	48
2008	200	7.8 pb <sup>-1</sup>	45
2011	500	25 pb <sup>-1</sup>	53/54
2012	200	22 pb <sup>-1</sup>	61/58
2015	200	53 pb <sup>-1</sup>	53/57
2015	200 pAu	0.42 pb <sup>-1</sup>	60
2015	200 pAl	1.0 pb <sup>-1</sup>	54
2017	510	320 pb <sup>-1</sup>	56/56



# Experimental aspects - STAR

## □ Overview

- Calorimetry system with  $2\pi$  coverage:

BEMC ( $-1 < \eta < 1$ ) and EEMC ( $1 < \eta < 2$ )

- TPC: Tracking and particle ID

( $|\eta| < 1.3$ )

- ZDC: Relative

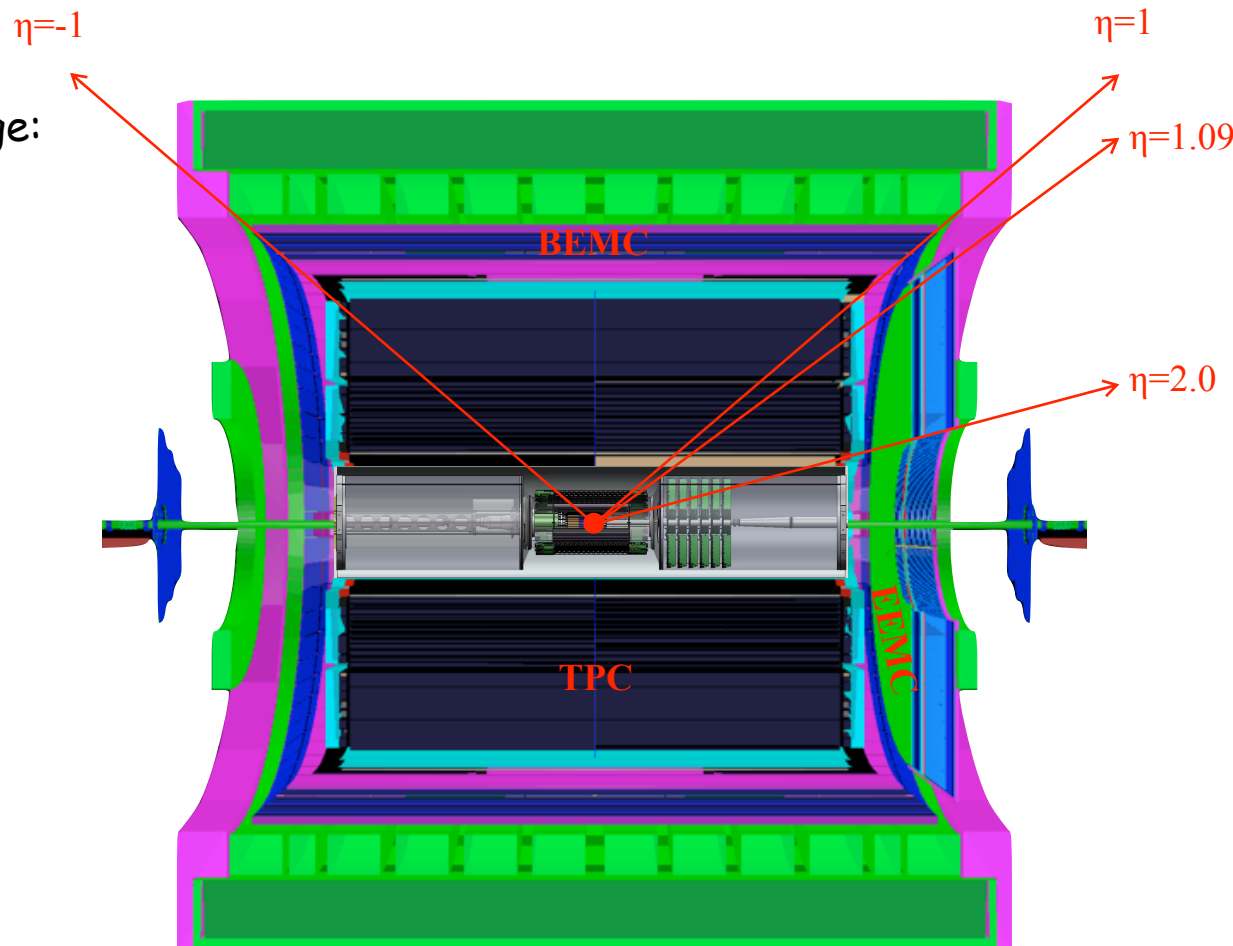
luminosity and local

polarimetry

- BBC: Relative

luminosity and

Minimum bias trigger

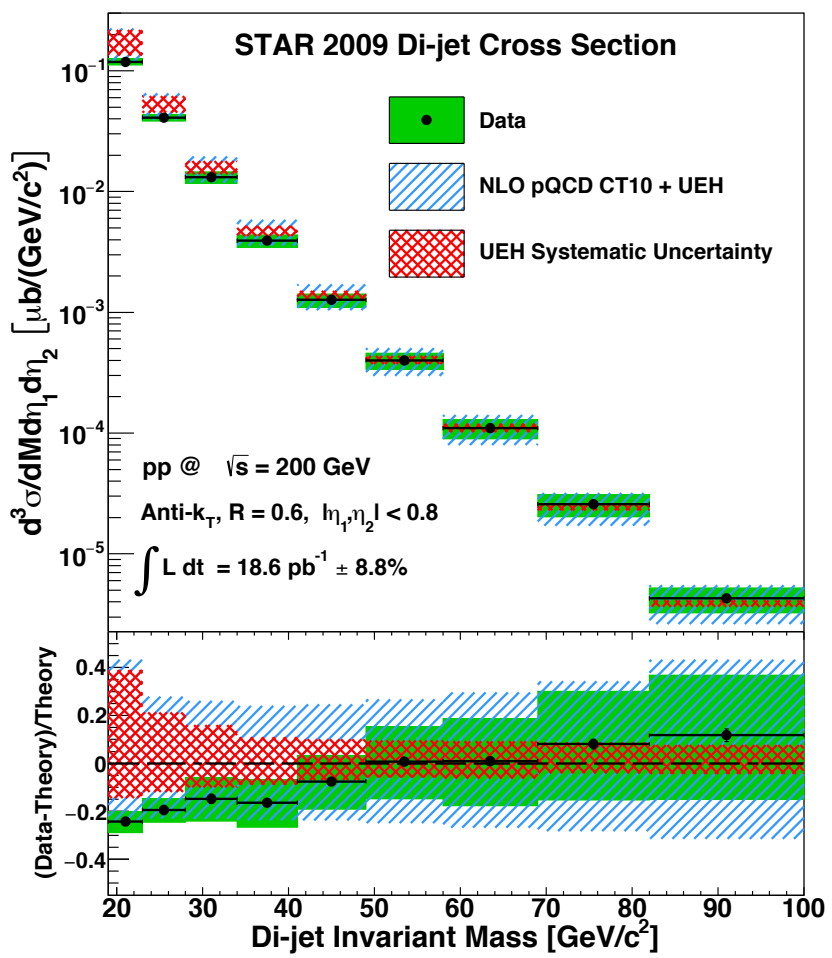


(STAR 2013 configuration)

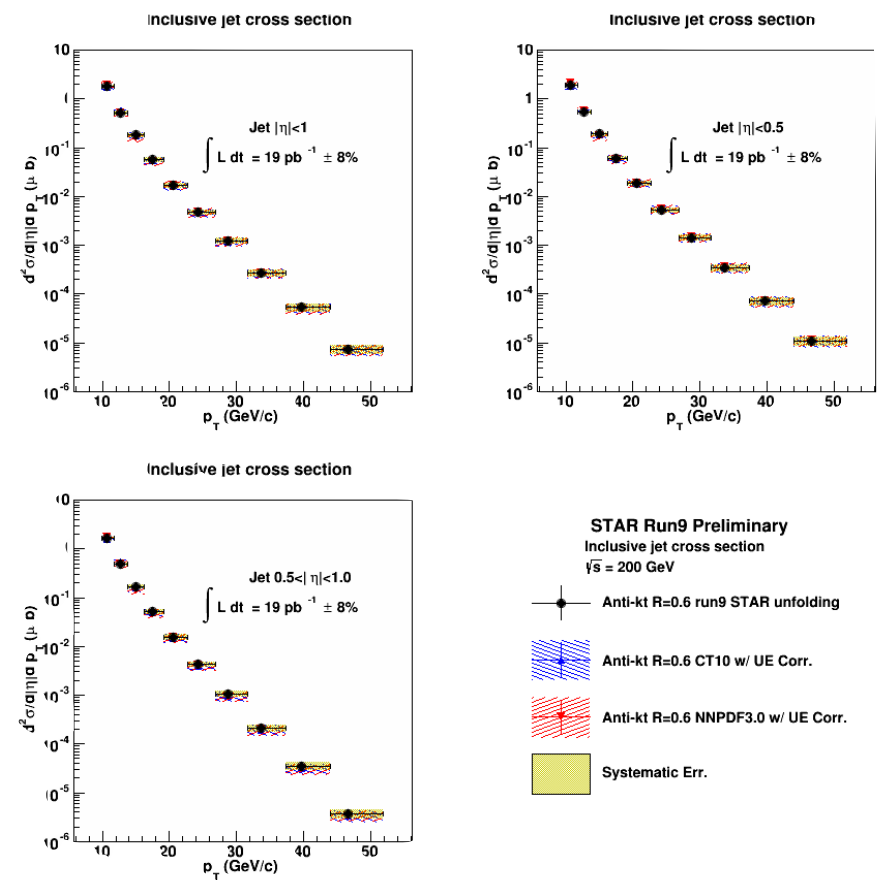
$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)$$

# Results / Status - Jet / Di-Jet Cross-Section

□ STAR: Inclusive Jet / Di-Jet cross-section measurements at 200GeV



○ Data are well described by NLO pQCD plus hadronization and underlying event corrections

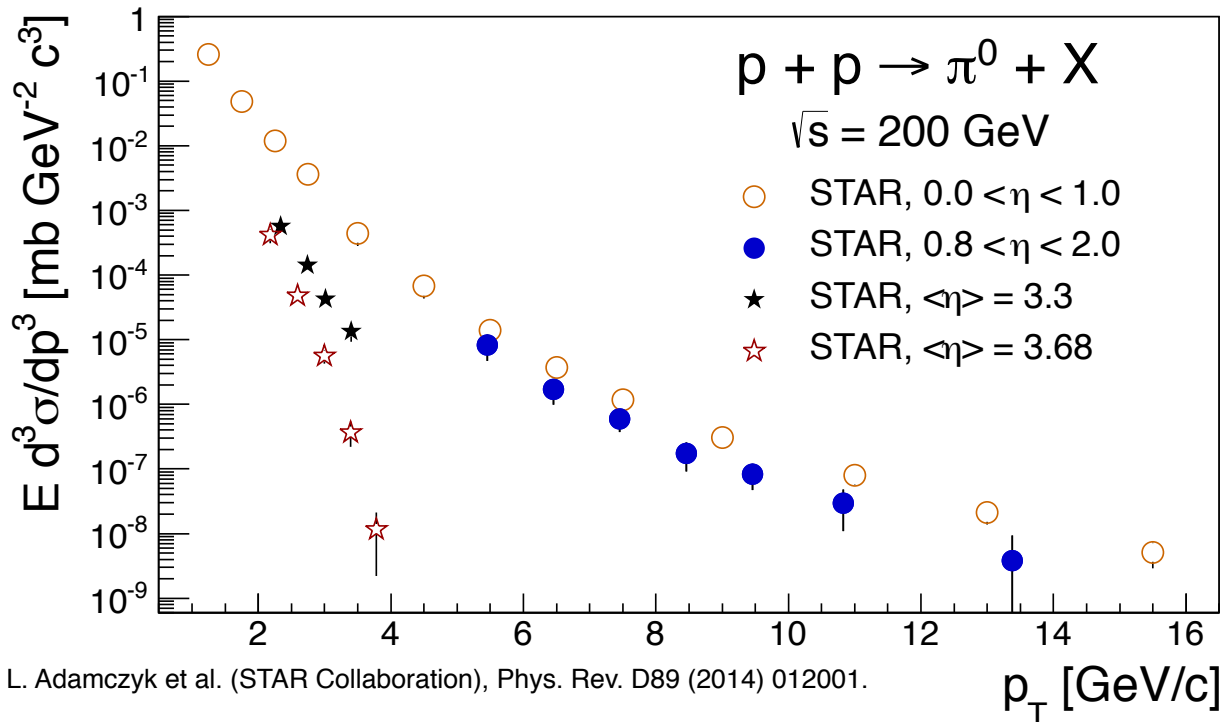


X. Li et al. (STAR Collaboration), DIS 2015.

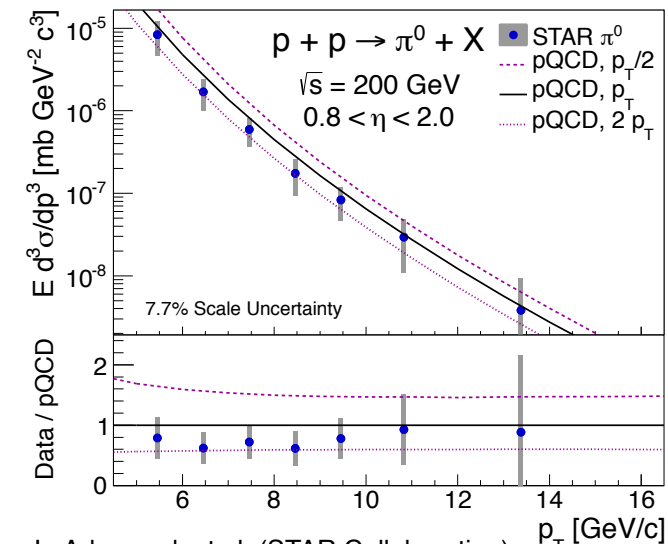
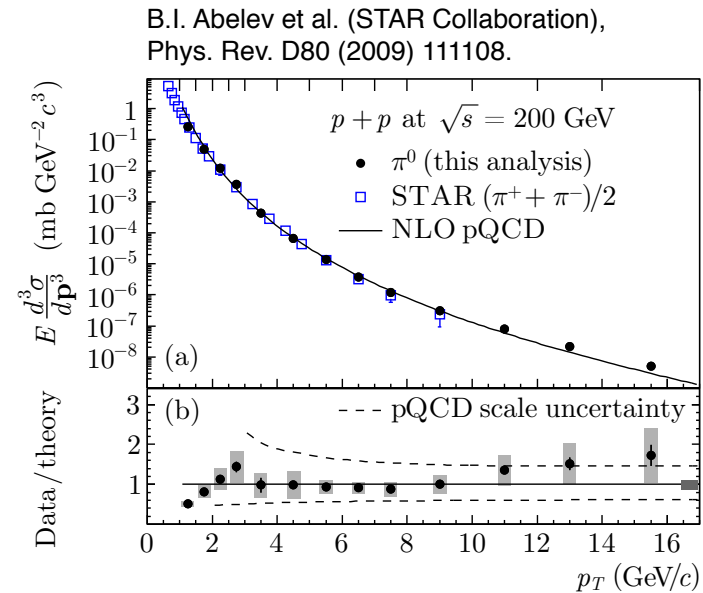
L. Adamczyk et al. (STAR Collaboration), Phys. Rev. D95 (2017) 71103.

# Results / Status - Pion Cross-Section

## STAR: Pion cross-section measurements at 200 GeV



- Compilation of neutral pion final state cross-section measurements at varying  $\eta$  and charged pion sum cross-section measurement
- Data are well described by NLO pQCD

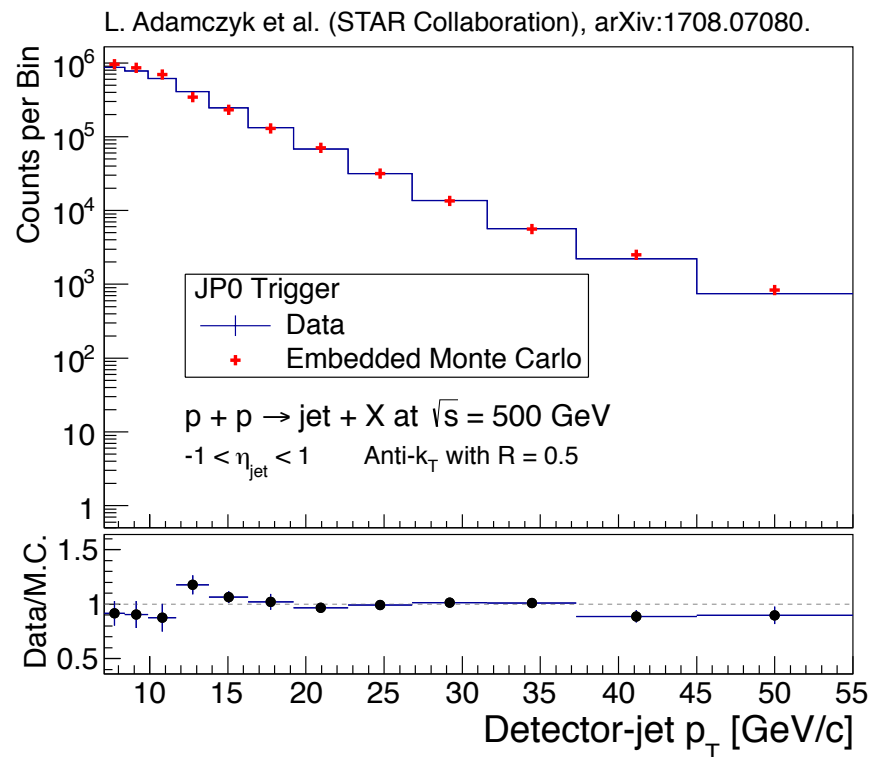
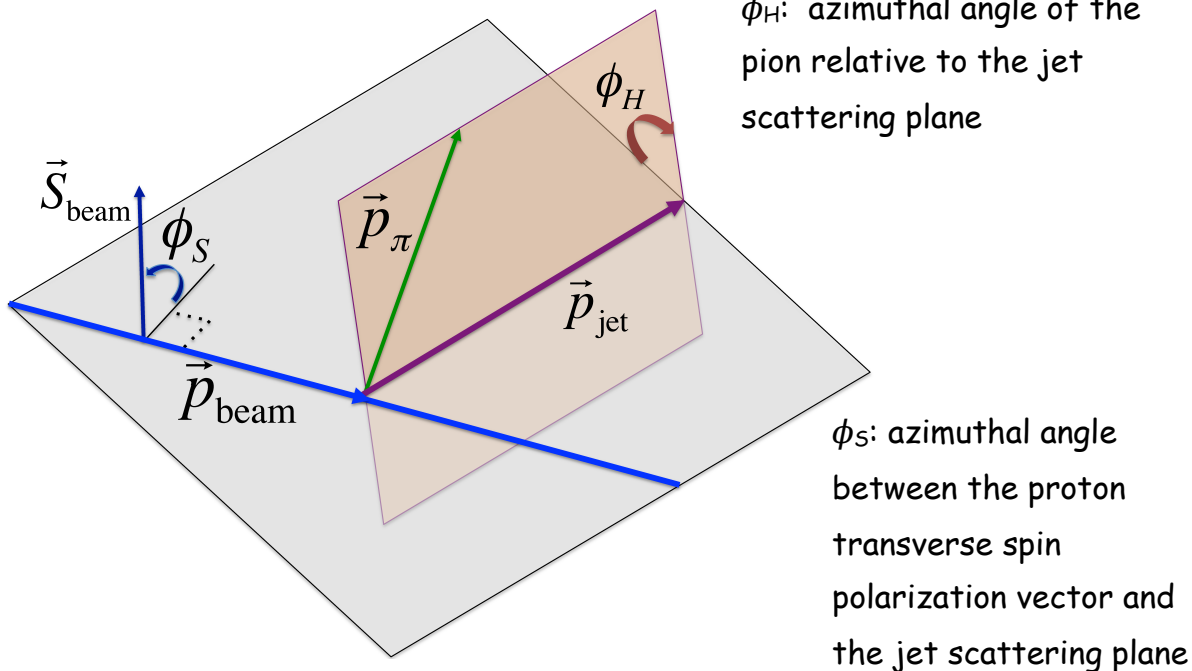


L. Adamczyk et al. (STAR Collaboration), Phys. Rev. D89 (2014) 012001.

Bernd Surrow

# Results / Status - Collins Asymmetry measurements (1)

## □ STAR: Azimuthal single-spin asymmetry measurement of charged pions in jets

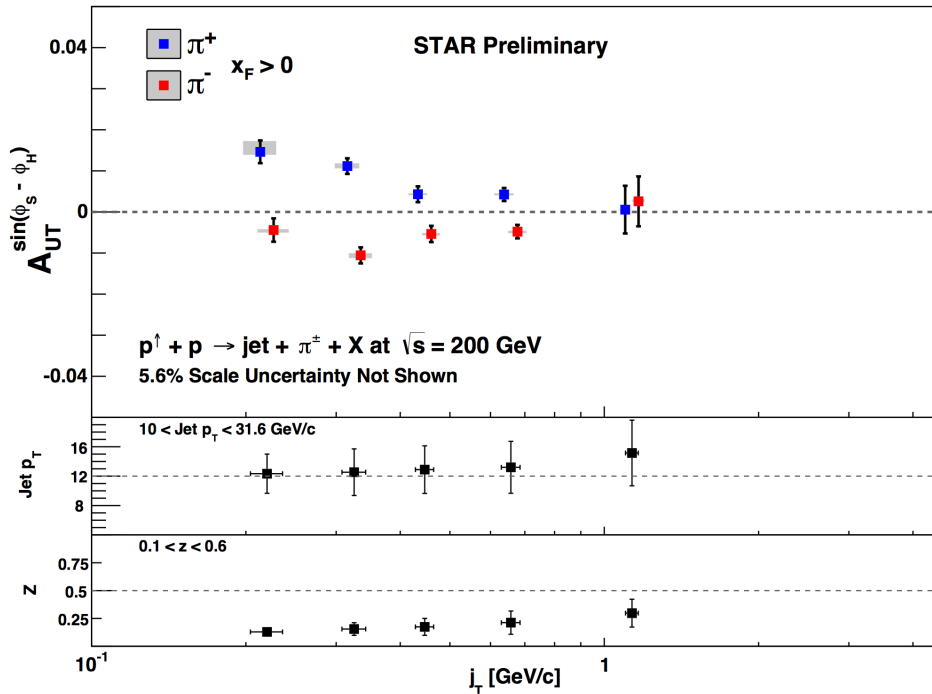


- Spin-dependent term of  $\sin(\phi_S - \phi_H)$  modulation of  $A_{UT}$  yields sensitivity to  $h_1$  coupled to Collins fragmentation function
- Event selection: Jet-patch trigger / Jet finding using anti- $k_T$  algorithm ( $R=0,5, 500\text{GeV}$ ) followed by charged pion selection within jet requiring  $0.1 < z < 0.8$  and  $dE/dx$  particle ID of TPC
- Embedded MC sample (PYTHIA 6.426 / Perugia 0 tune) for evaluation of systematic uncertainties / Good data-MC comparison

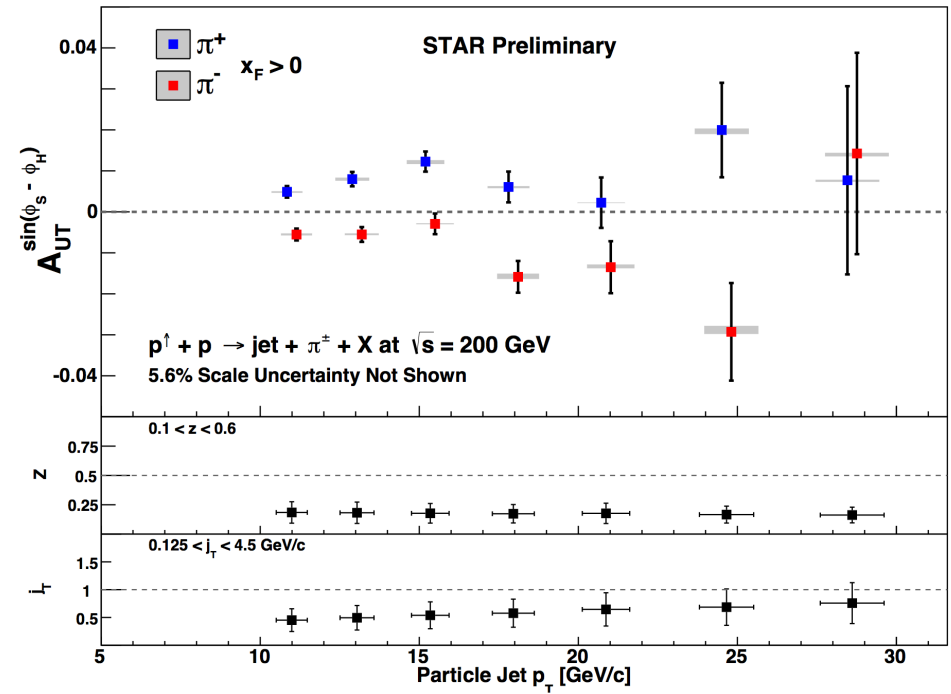
# Results / Status - Collins Asymmetry measurements (2)

## STAR: Collins asymmetry $A_{UT}$ at 200GeV

J. K. Adkins and J. Drachenberg, Spin 2014.



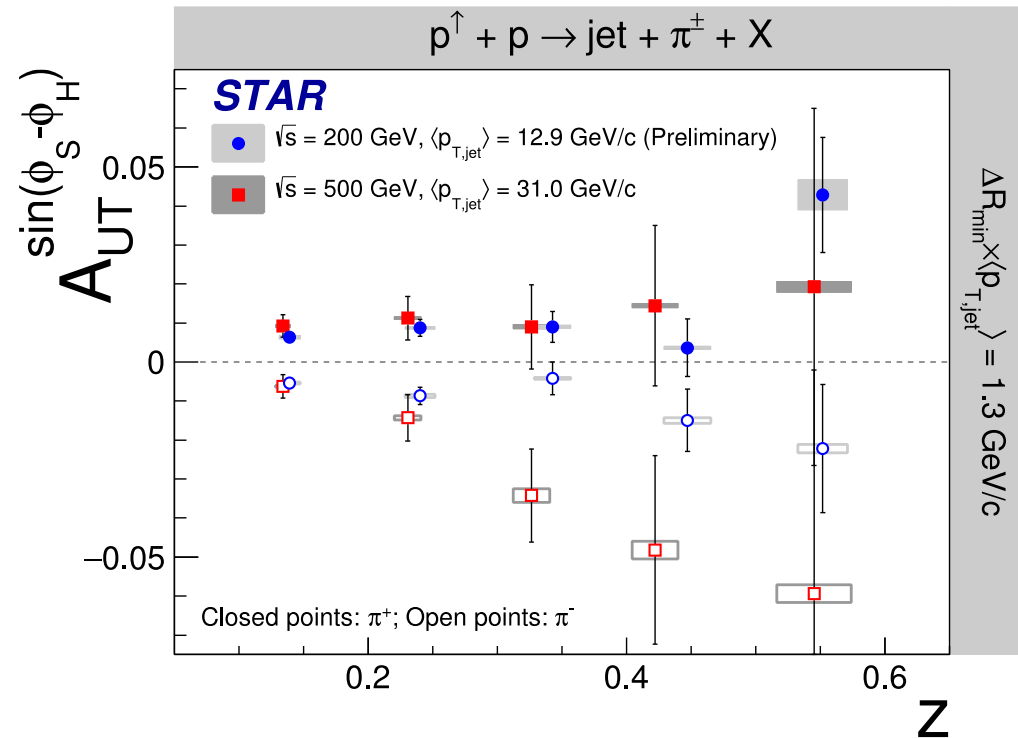
J. K. Adkins and J. Drachenberg, Spin 2014.



- Clear first observation of Collins asymmetry ( $\sin(\phi_S - \phi_H)$  modulation) at 200GeV based on 2012 data shown for  $x_F > 0$
- Strong dependence on  $j_T$
- Statistical uncertainty shown as solid lines / Systematic uncertainties shown as shaded bands dominated at low  $p_T$  by parton-jet matching and high- $p_T$  by trigger bias / Generally, measurement dominated by statistical uncertainties at medium and high  $p_T$ !

# Results / Status - Collins Asymmetry measurements (3)

- STAR: Collins asymmetry  $A_{UT}$  at 200GeV and 500GeV



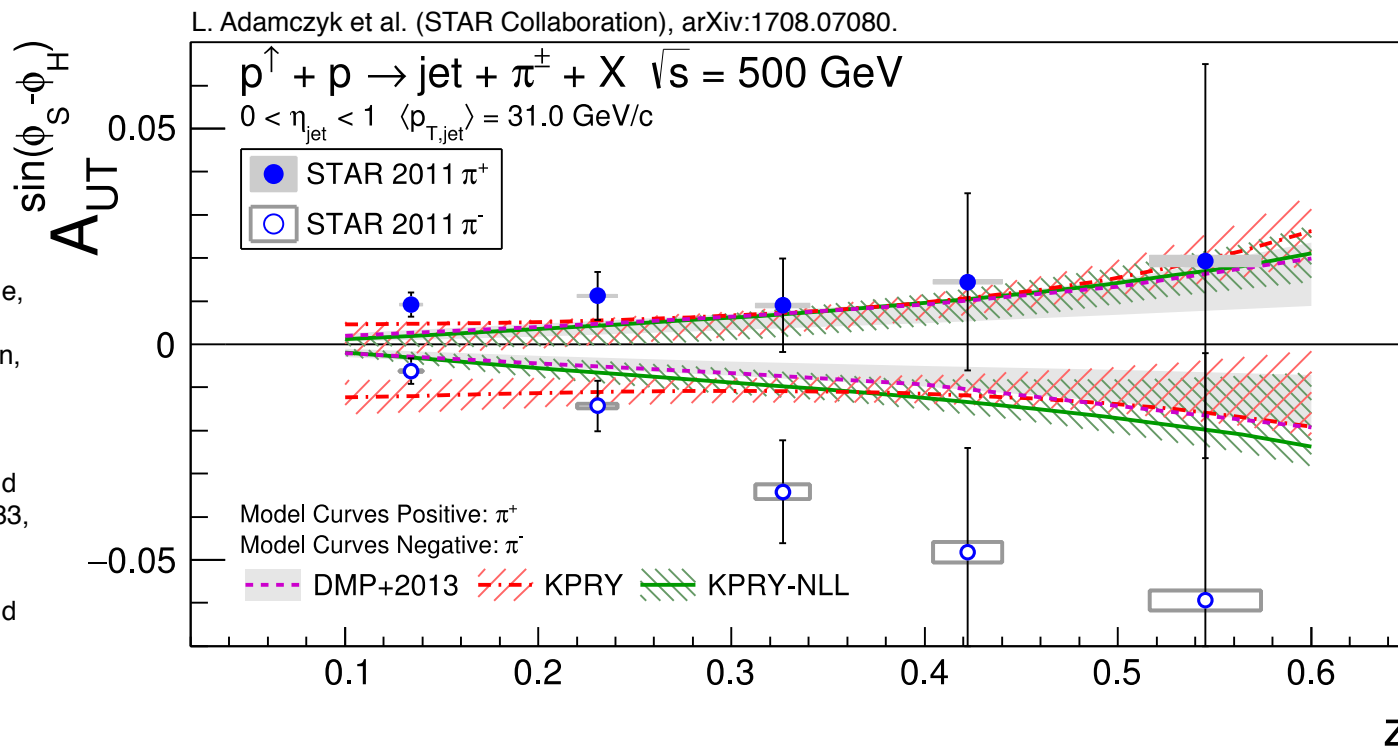
200GeV: J. K. Adkins and J. Drachenberg, Spin 2014.

500GeV: L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.

- Non-zero Collins asymmetry ( $\sin(\phi_S - \phi_H)$  modulation) observed at 500GeV based on 2011 data shown as a function of  $z$
- Asymmetries are found to be consistent with 200GeV preliminary results for consistent cuts and  $x_T$
- Statistical uncertainty shown as solid lines / Systematic uncertainties shown as shaded bands dominated at low  $p_T$  by parton-jet matching and high- $p_T$  by trigger bias / Generally, measurement dominated by statistical uncertainties at medium and high  $p_T$ !

# Results / Status - Collins Asymmetry measurements (4)

- STAR: Collins asymmetry  $A_{UT}$  at 500 GeV compared to model calculations



KPRY / KPRY-NLL:

Z.-B. Kang, A. Prokudin,  
F. Ringer, and F. Yuan,  
arXiv:1707.00913.

DMP+2013:

M. Anselmino, M. Boglione,  
U. D'Alesio, S. Melis,  
F. Murgia, and A. Prokudin,  
Phys. Rev. D 87, 094019  
(2013).

U. D'Alesio, F. Murgia, and  
C. Pisano, Phys. Rev. D 83,  
034021 (2011).

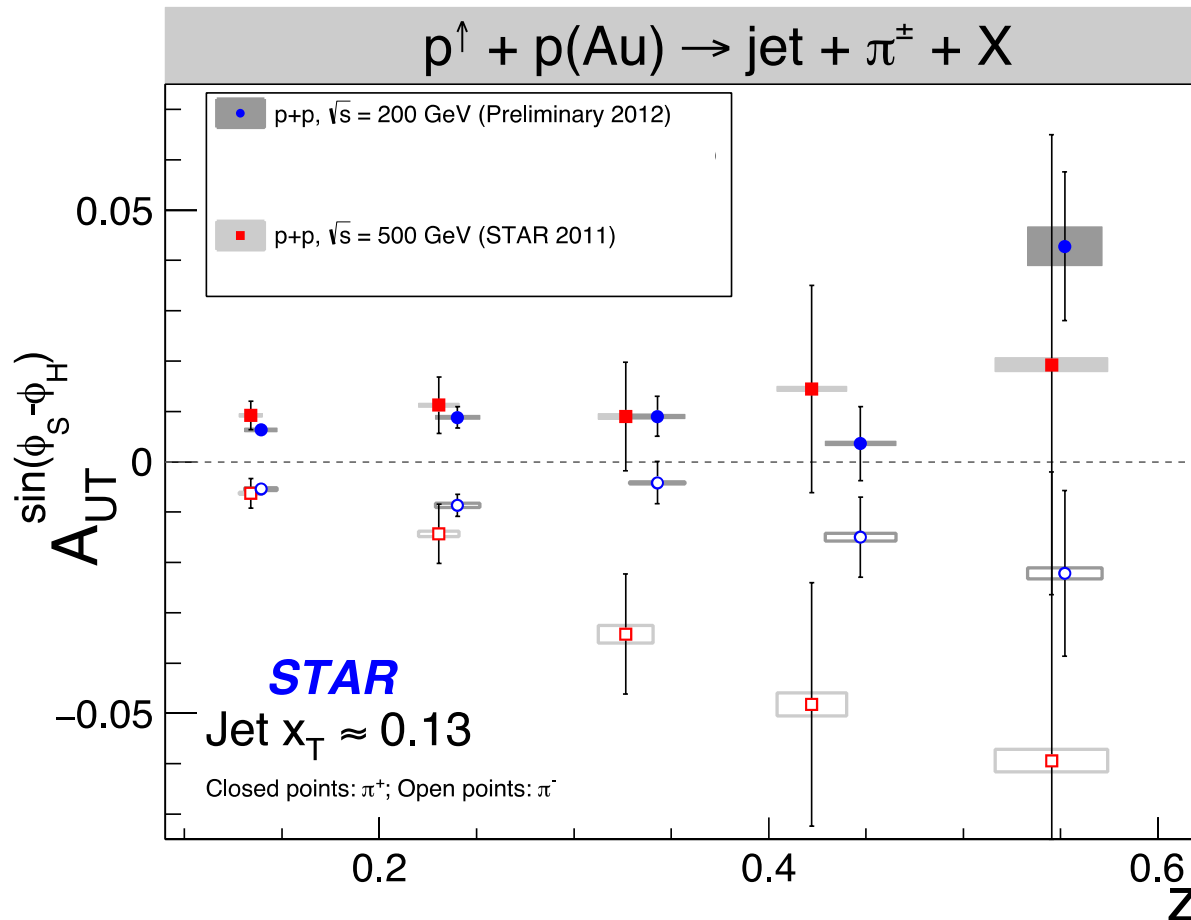
U. D'Alesio, F. Murgia, and  
C. Pisano, arXiv:  
1707.00914.

- Models based on SDIS and  $e^+/e^-$  assuming robust factorization and universality of the Collins function
- DMP / KPRY: No TMD evolution
- KPRY-NLL: TMD evolution up to NLLG
- General agreement between data and model calculations is consistent with assumptions of robust TMD-factorization and universality of the Collins function



# Results / Status - Collins Asymmetry measurements (4)

- STAR: Collins asymmetry  $A_{UT}$  at 200GeV and 500GeV and projections

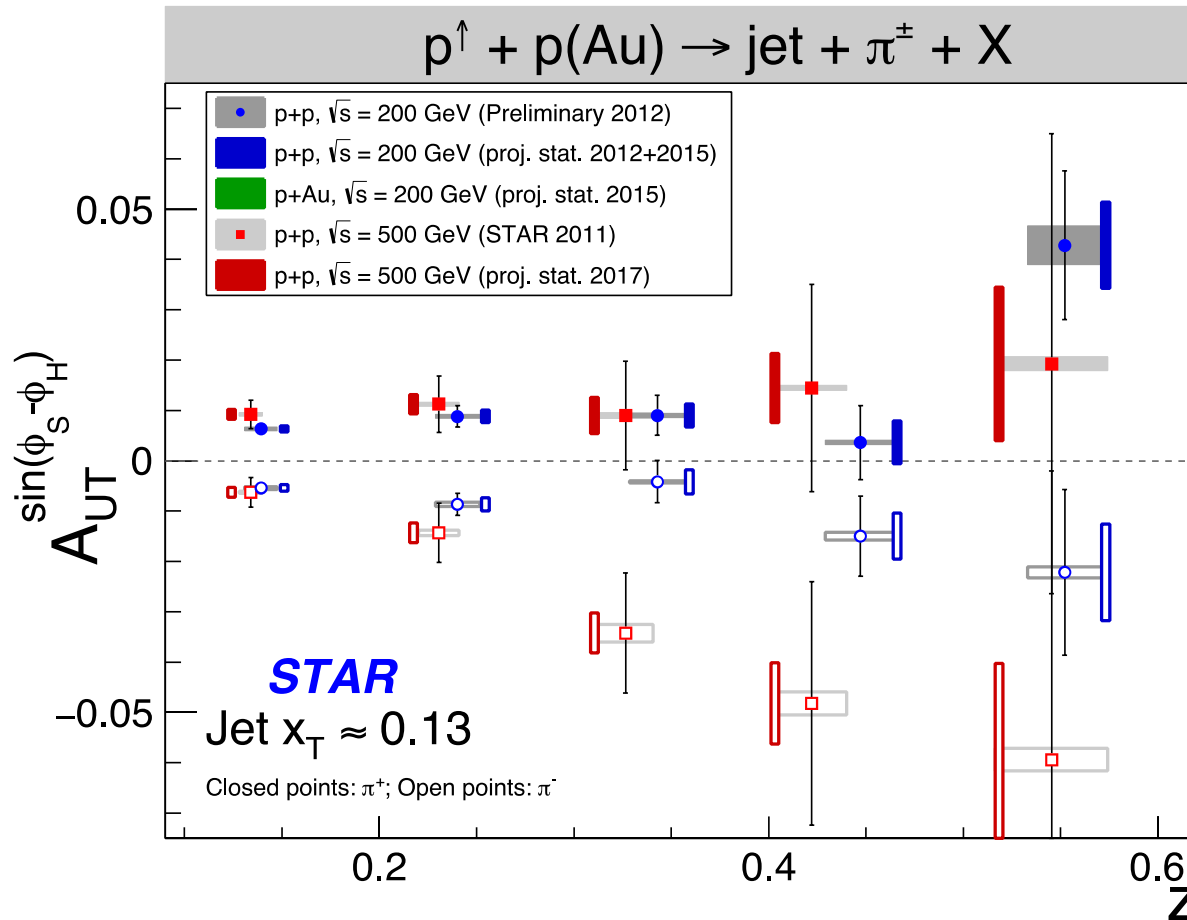


200GeV: J. K. Adkins and J. Drachenberg, Spin 2014.

500GeV: L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.

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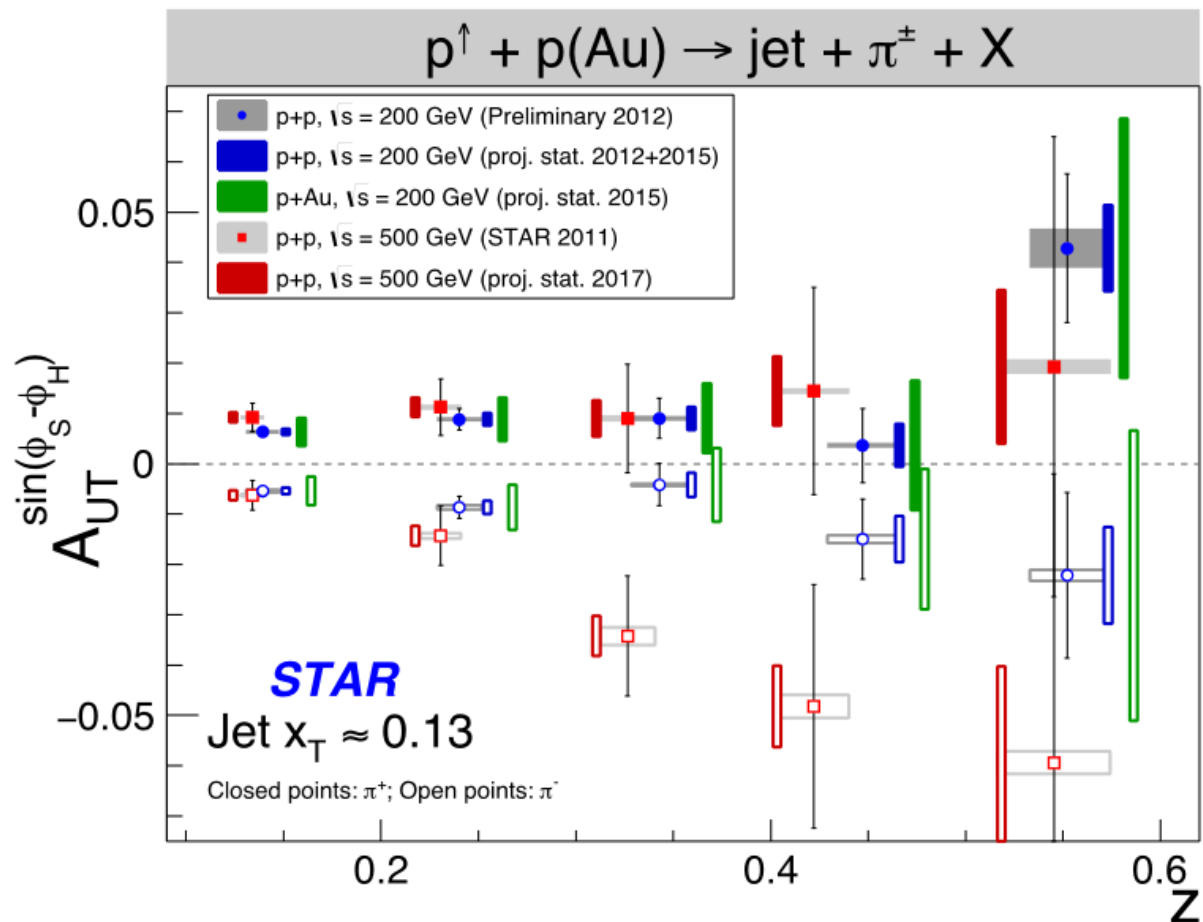


200GeV: J. K. Adkins and J. Drachenberg, Spin 2014.

500GeV: L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.

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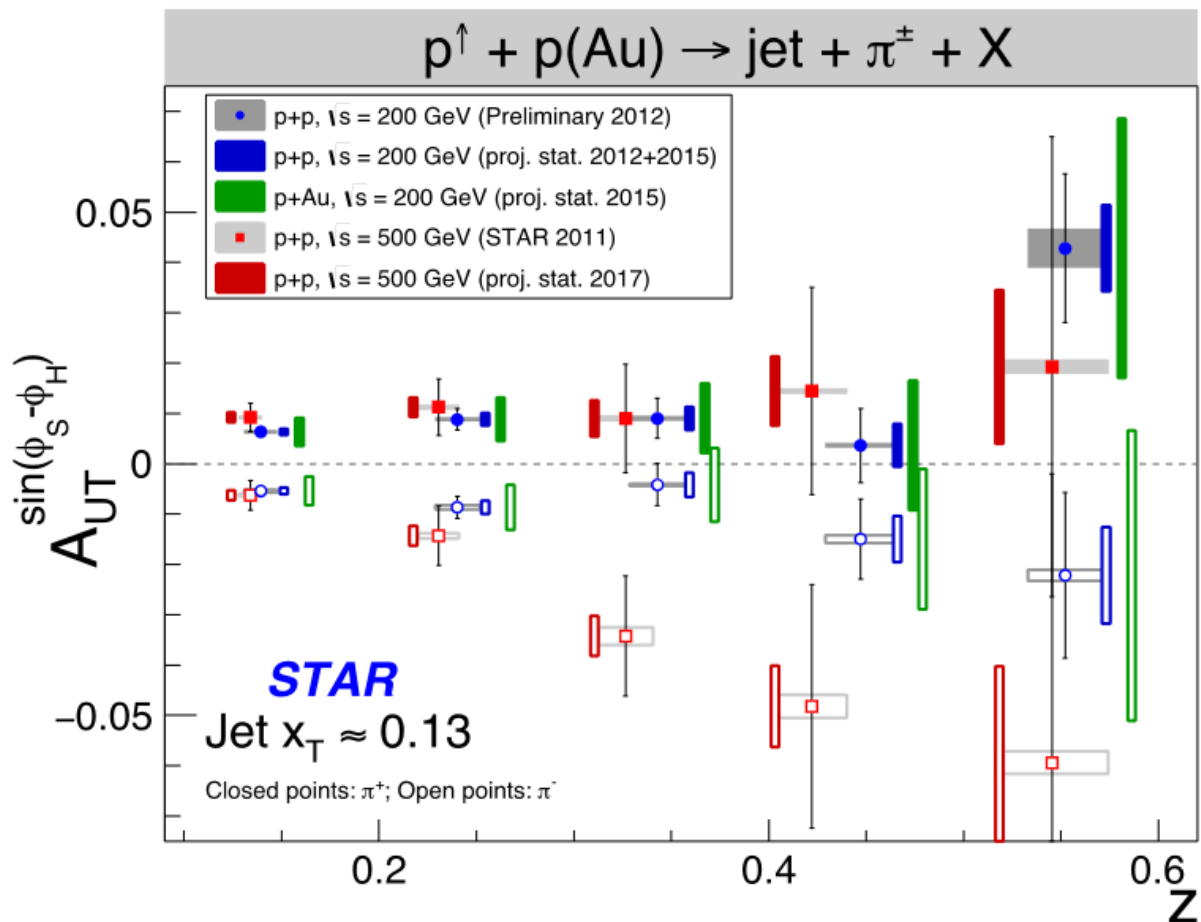


200GeV: J. K. Adkins and J. Drachenberg, Spin 2014.

500GeV: L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.

# Results / Status - Collins Asymmetry measurements (4)

- STAR: Collins asymmetry  $A_{UT}$  at 200GeV and 500GeV and projections



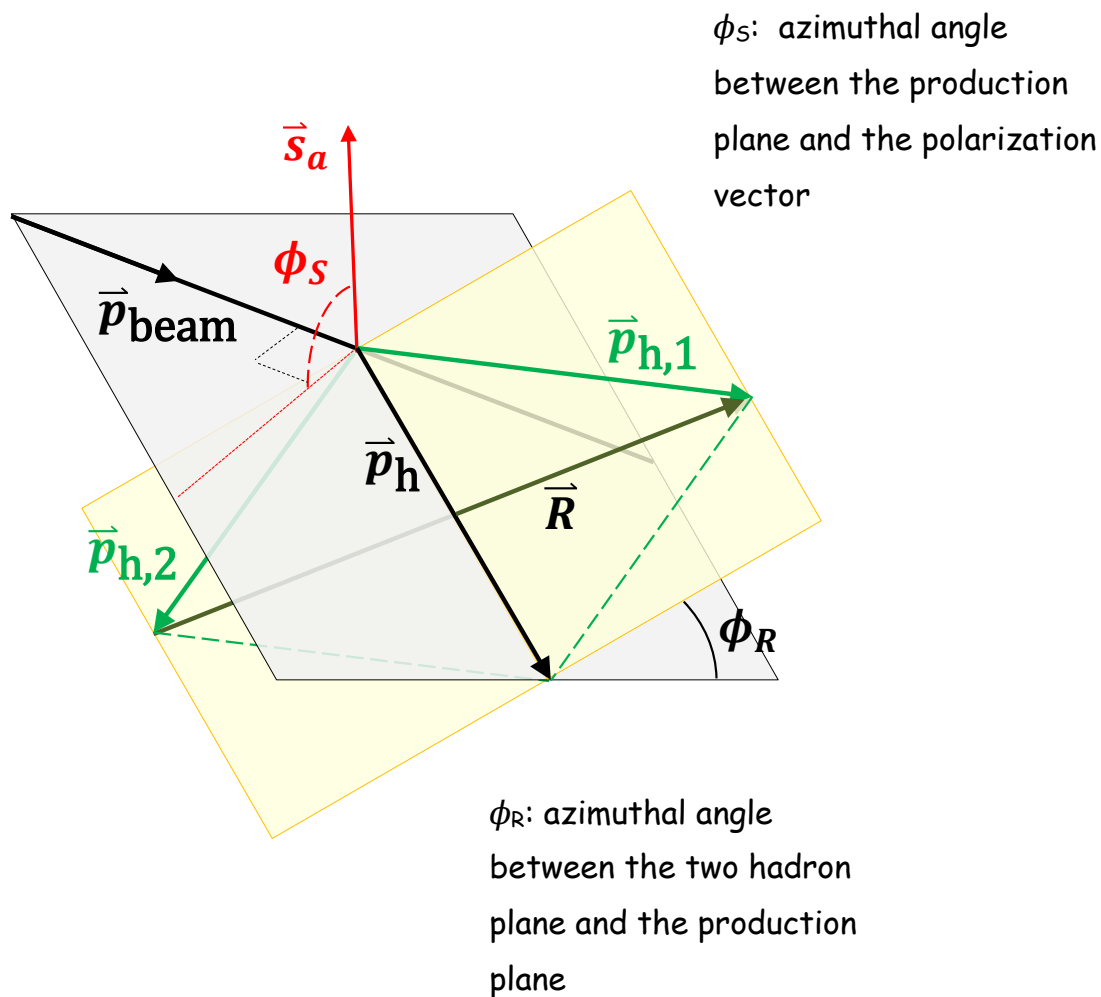
200GeV: J. K. Adkins and J. Drachenberg, Spin 2014.

500GeV: L. Adamczyk et al. (STAR Collaboration), arXiv:1708.07080.

- Higher precision in 2015 and 2017 will allow more precise comparison!
- First polarized p + A run should allow for first glimpse in p+A!

# Results / Status - IFF Asymmetry measurements (1)

## □ STAR: Azimuthal correlations of charged pion pairs



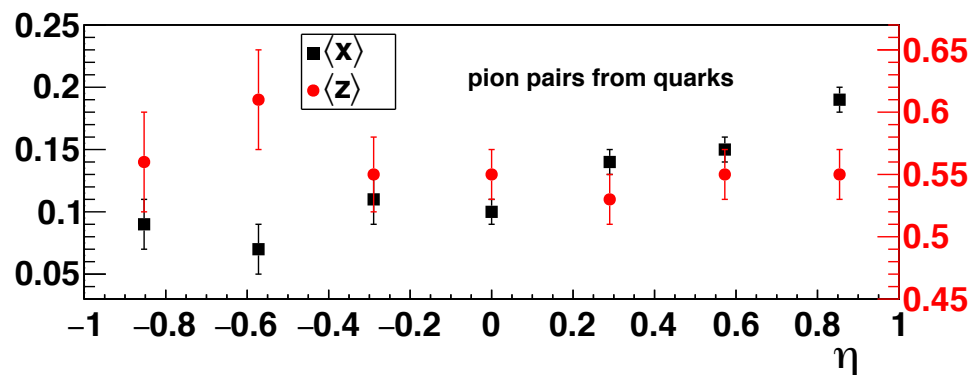
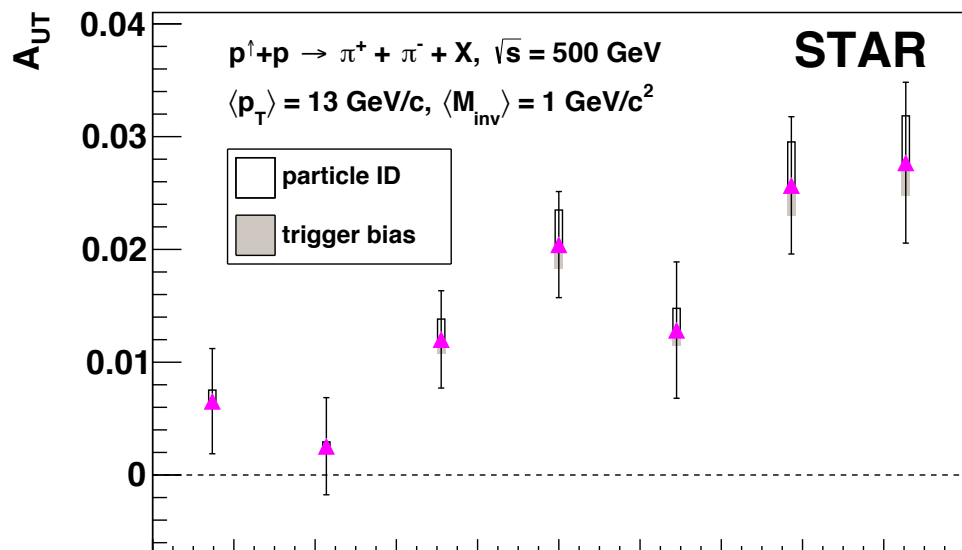
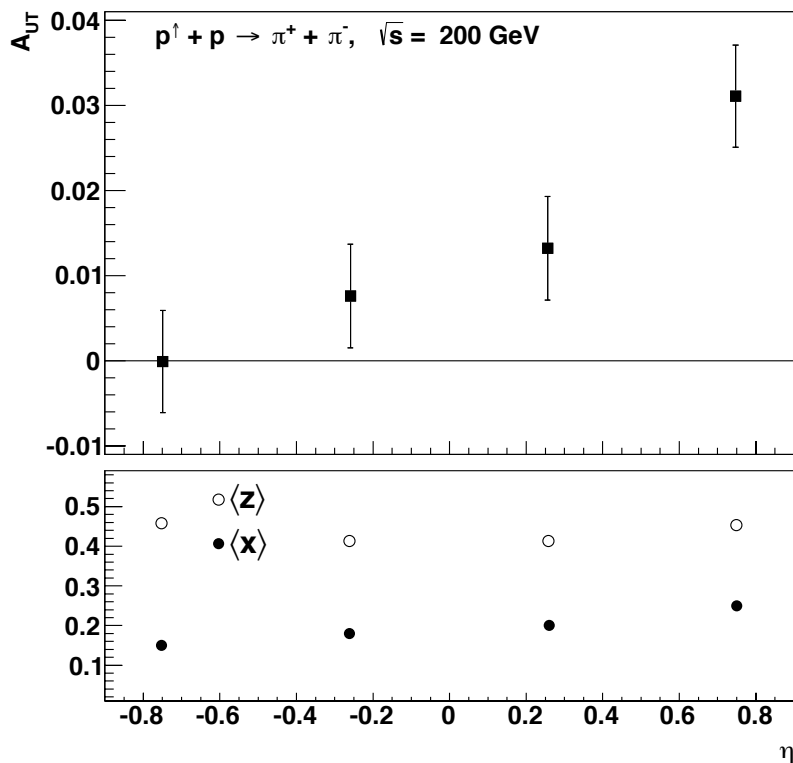
- Amplitude  $A_{UT}$  of  $\sin(\phi_S - \phi_H)$  is extracted by a fit to data **sensitive to  $h_1$  coupled to di-hadron fragmentation function**
- Event selection: **High-Tower trigger and Jet-patch trigger / Charged pion selection with  $dE/dx$  particle ID of TPC - 98% purity**
- **MC sample (PYTHIA)** passed through STAR detector simulation is used for parton kinematic determination / **Good data-MC comparison**
- Systematic uncertainties are very small compared to the statistical precision of the measurement, and they are not shown in the final result figures!

# Results / Status - IFF Asymmetry measurements (3)

- STAR: Azimuthal correlations of charged pion pairs at 200GeV and 500GeV

L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 115 (2015) 242501.

J. Adams et al. (STAR Collaboration), arXiv:1710.10215.

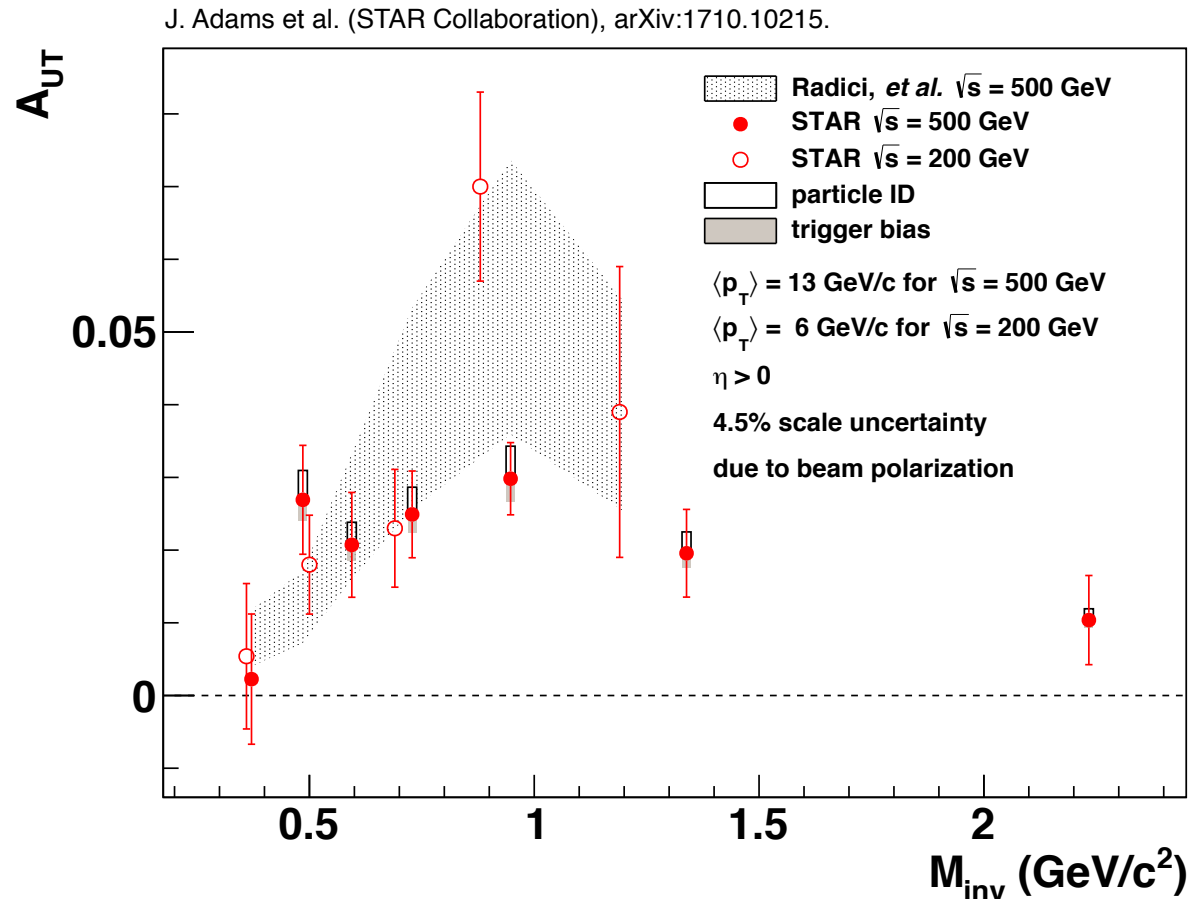


- Significant charged pion pair asymmetries at 200GeV and 500GeV

- Measurement is dominated by statistical uncertainties!

# Results / Status - IFF Asymmetry measurements (4)

- STAR: Azimuthal correlations of charged pion pairs compared to model calculations



- Overall good agreement with models based on SDIS and  $e^+/e^-$  and data at 200 GeV and 500 GeV in terms of

$M_h$

# Summary / Outlook

- TMD Collins FFs: Azimuthal single-spin asymmetries of charged pions in jets
  - First observations of Collins effect in polarized p+p collisions at 200GeV (2006) and 500GeV (2011)
  - General agreement between data and model calculations is consistent with assumptions of robust TMD-factorization and universality of the Collins function
  - Evolution effects seem to be slow - more precise data needed!
  
- Di-hadron FFs: Azimuthal correlations of charged pion pairs
  - Significant charged pion pair asymmetries at 200GeV (2006 / 2012) and 500GeV (2011) observed!
  - Overall good agreement with models based on SDIS and  $e^+/e^-$  and data at 200GeV and 500GeV
  
- Future
  - Higher precision results expected from large data samples in 2015 at 200GeV and 2017 at 510GeV
  - New studies in polarized p+A collisions in 2015
  - Great for potential for additional studies as documented in coldQCD plan at RHIC beyond 2020!

E. Aschenauer et al., arXiv:1602.03922.



Thank you!

Jim Drachenberg (Lamar University)

and

Andreas Metz (Temple University)