Exploring Quark Transversity in Polarized Proton-Proton Collisions at STAR

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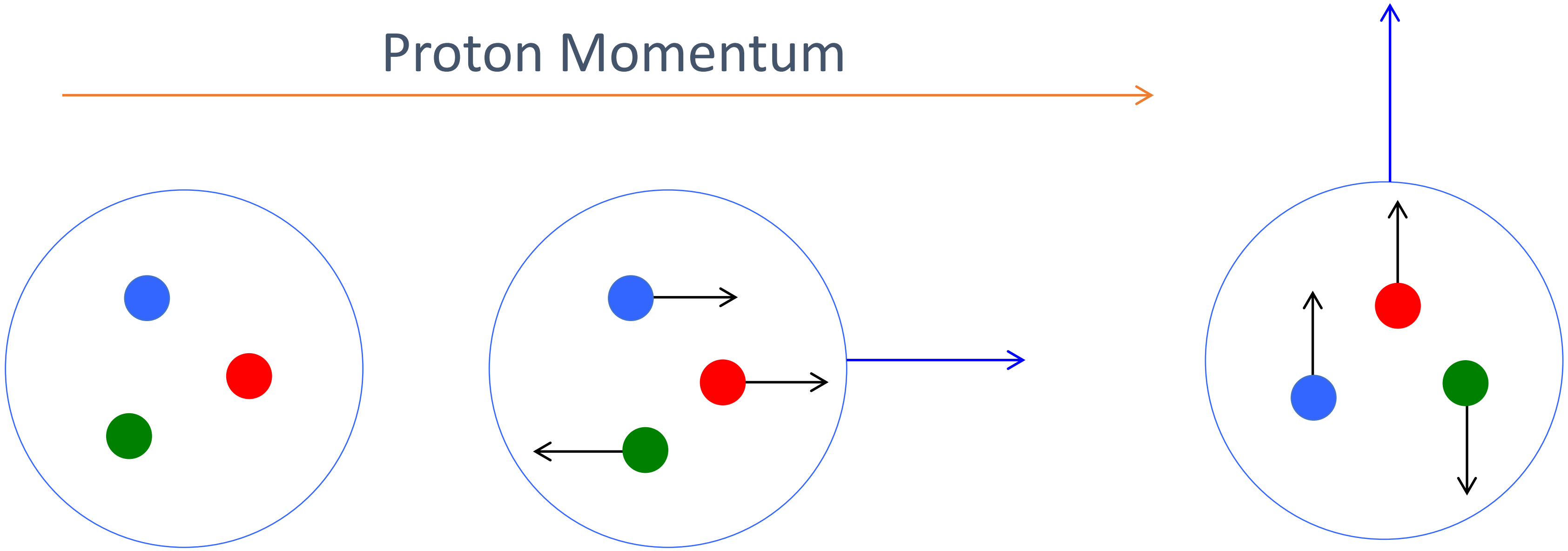
Describing the Proton's Spin Structure

Distribution	Partons	Name of Distribution	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



Blue arrow: proton spin
Black arrow: quark spin

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Least constrained of the three!

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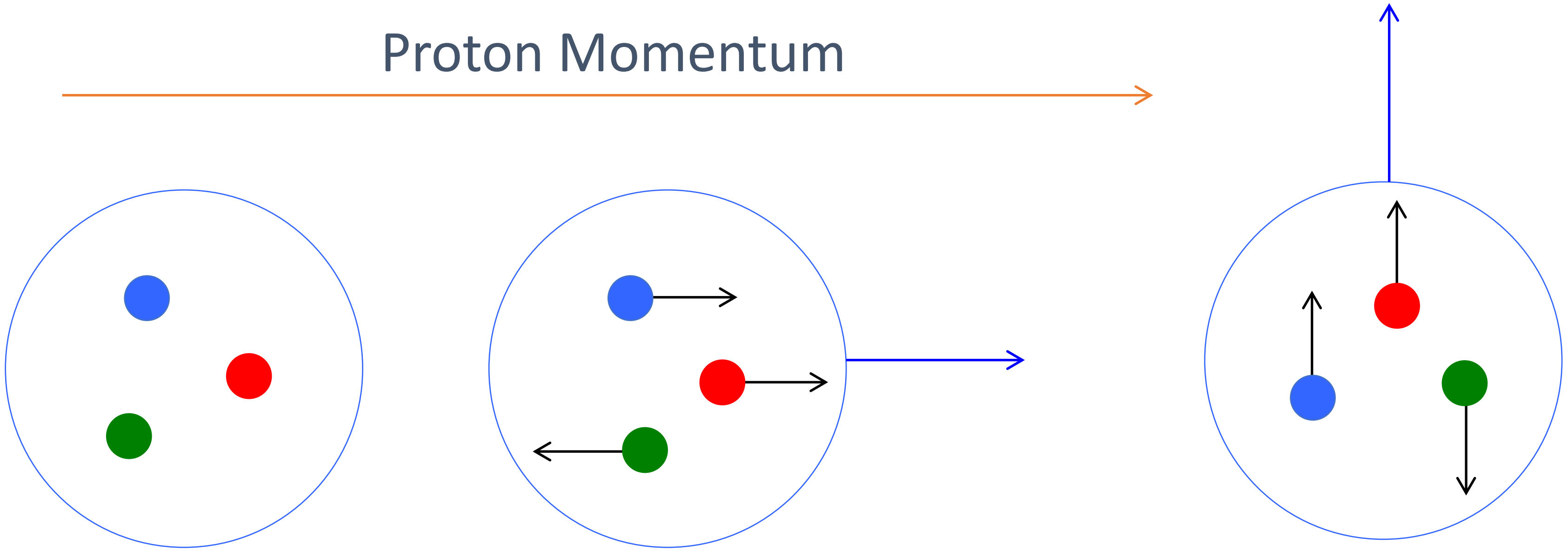

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Opportunities in p+p Collisions: Hadron-in-Jet Collins Effect

- Transverse single spin asymmetries (TSSA) in p+p collisions are a unique avenue for a detailed study of the proton's transverse spin structure
  - Collins effect in jets
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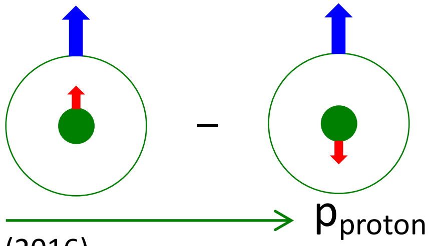
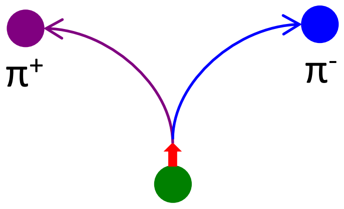
- Pions within jets are asymmetrically distributed
  - Looking at the difference between spin states will allow access to transversity distribution and Collins FF via asymmetry measurements

Transversity = (Collinear)



Collins FF = (TMD)



Phys. Rev. D 93, 014009 (2016)

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$$d\sigma_{UT} \approx d\sigma_{UU}\left[1 + \boxed{A_{UT}^{\sin(\phi_S-\phi_H)}\sin\left(\phi_S-\phi_H\right)} + \ldots\right]$$

Transversity x Collins

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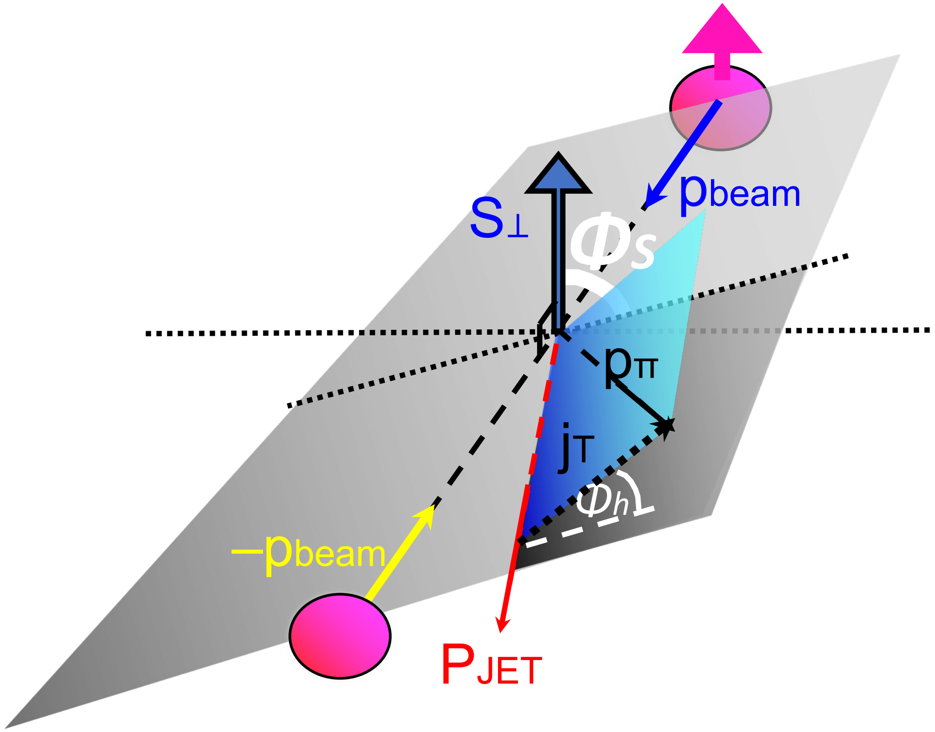

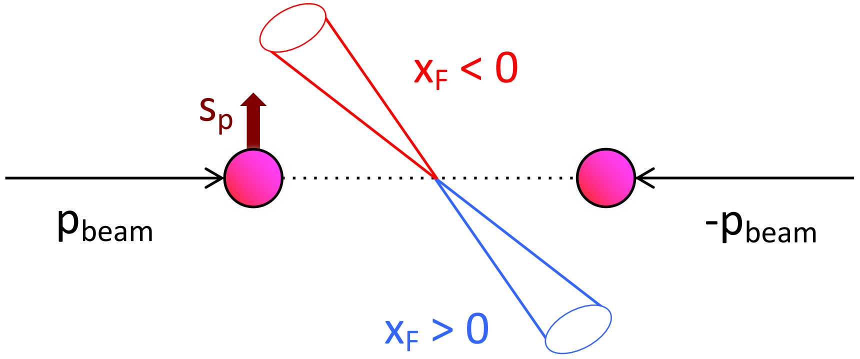

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- Correlates quark polarization to azimuthal distribution of final state hadron pairs
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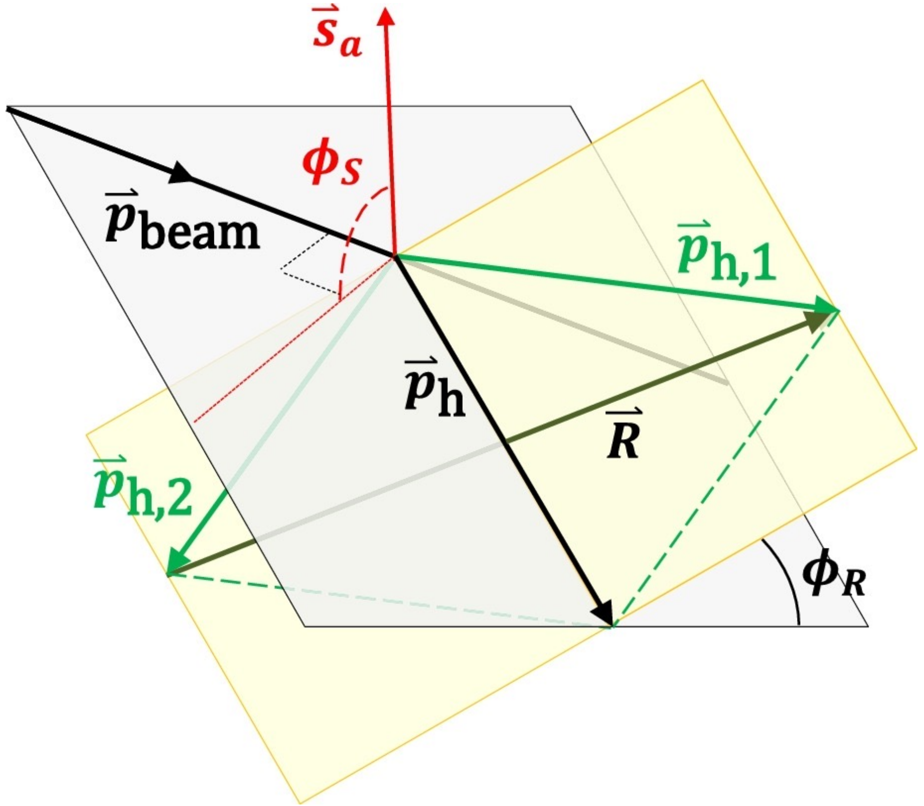
- IFF process is collinear, where Collins is dependent upon transverse momentum
- Modulated by a sine term similarly to the hadron-in-jet Collins asymmetry:



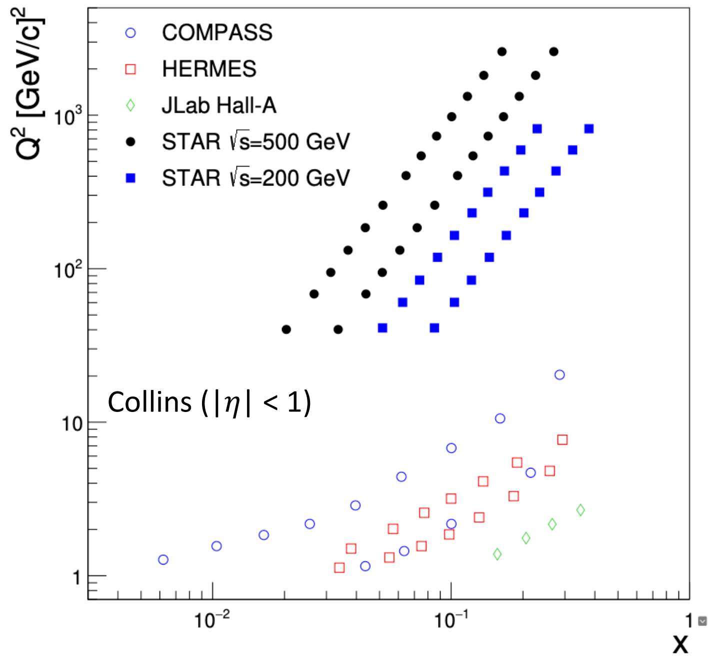
$$d\sigma_{UT} \approx d\sigma_{UU}\left[1 + A_{UT}^{\sin(\phi_{RS})}\sin\left(\phi_R - \phi_S\right) + \ldots\right]$$

Transversity x IFF

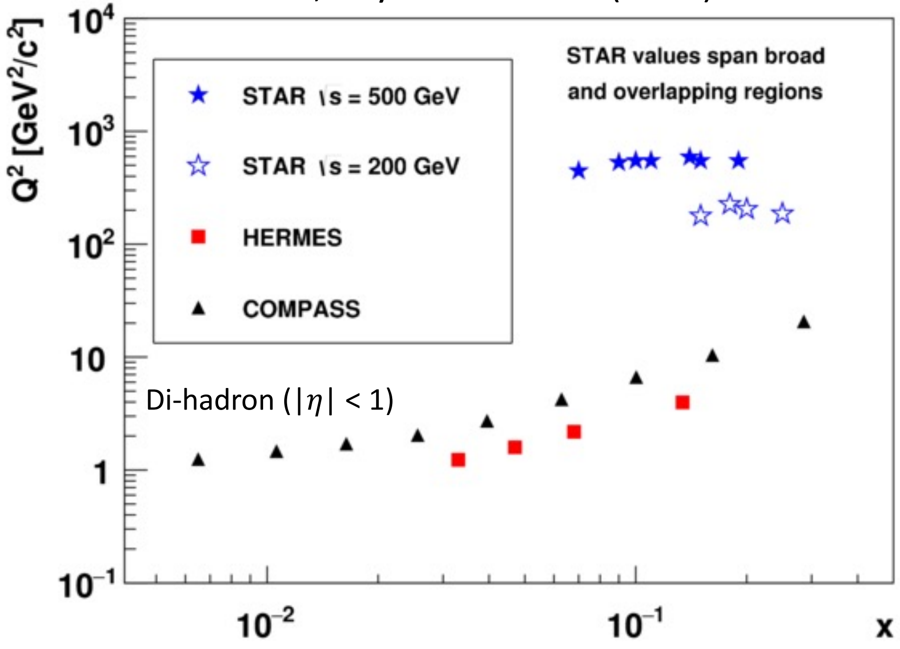
Why Look to p+p? Kinematic Coverage!

- STAR covers a similar range in *x* to that of SIDIS experiments but much higher in Q^2
  - Important for studies of TMD universality
  - We can learn about the evolution of TMDs and factorization breaking
- Collins and di-hadron at different energies allow for self-contained studies of these effects as well

STAR, arXiv:2205.11800



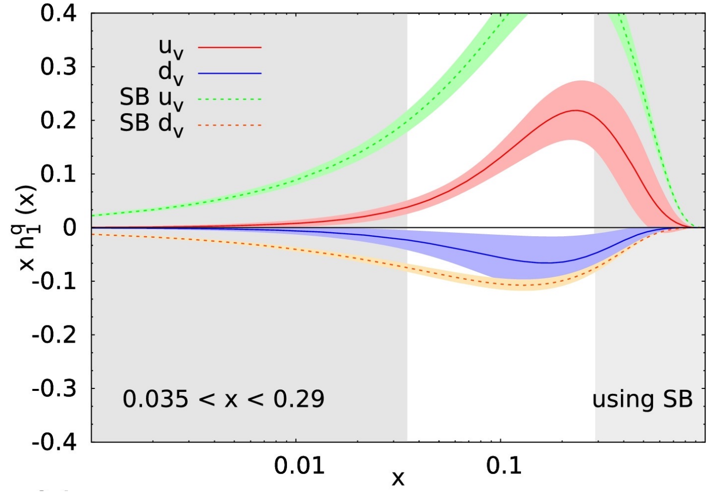
STAR, Phys. Lett. B **780** (2018)



Kinematic Coverage: STAR’s Impact

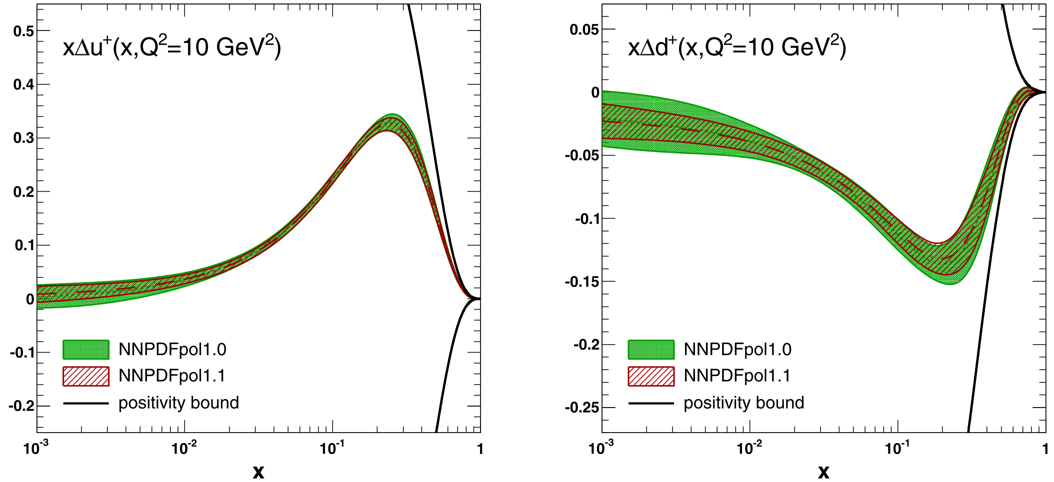
- Transversity is quite unconstrained, even in valence region
  - Unpolarized and helicity distributions quite well known!
- STAR’s kinematic coverage will help constrain transversity where uncertainties are the largest

Transversity Distribution



D’Alesio, et. al., PLB **803** 135347 (2020)

Helicity Distribution



NNPDF, Nuclear Physics B, Vol 887 (2014)

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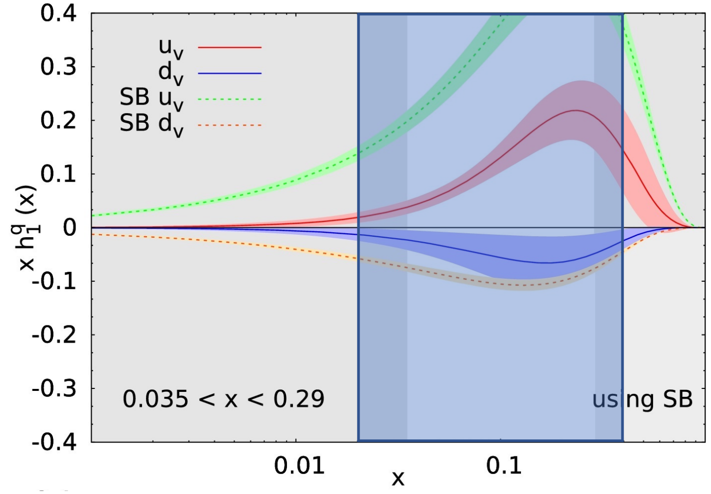

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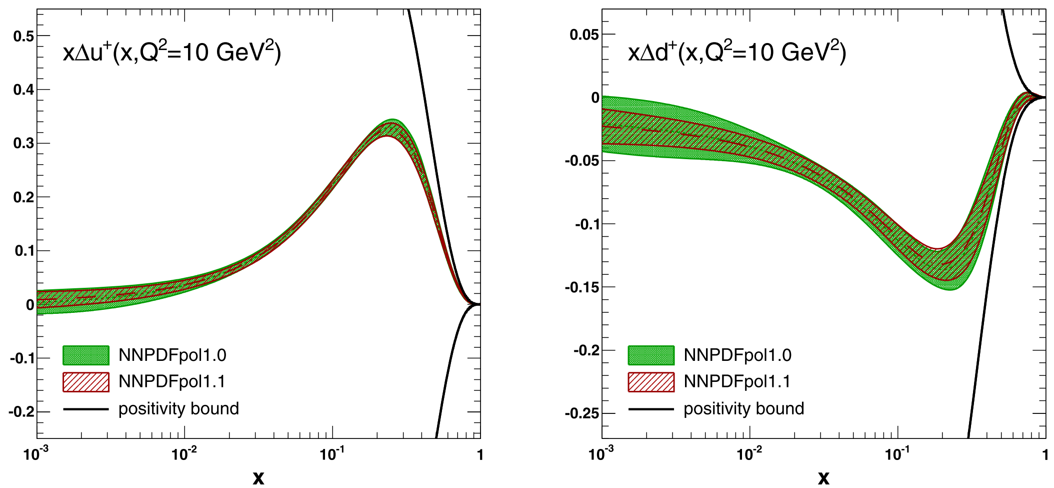

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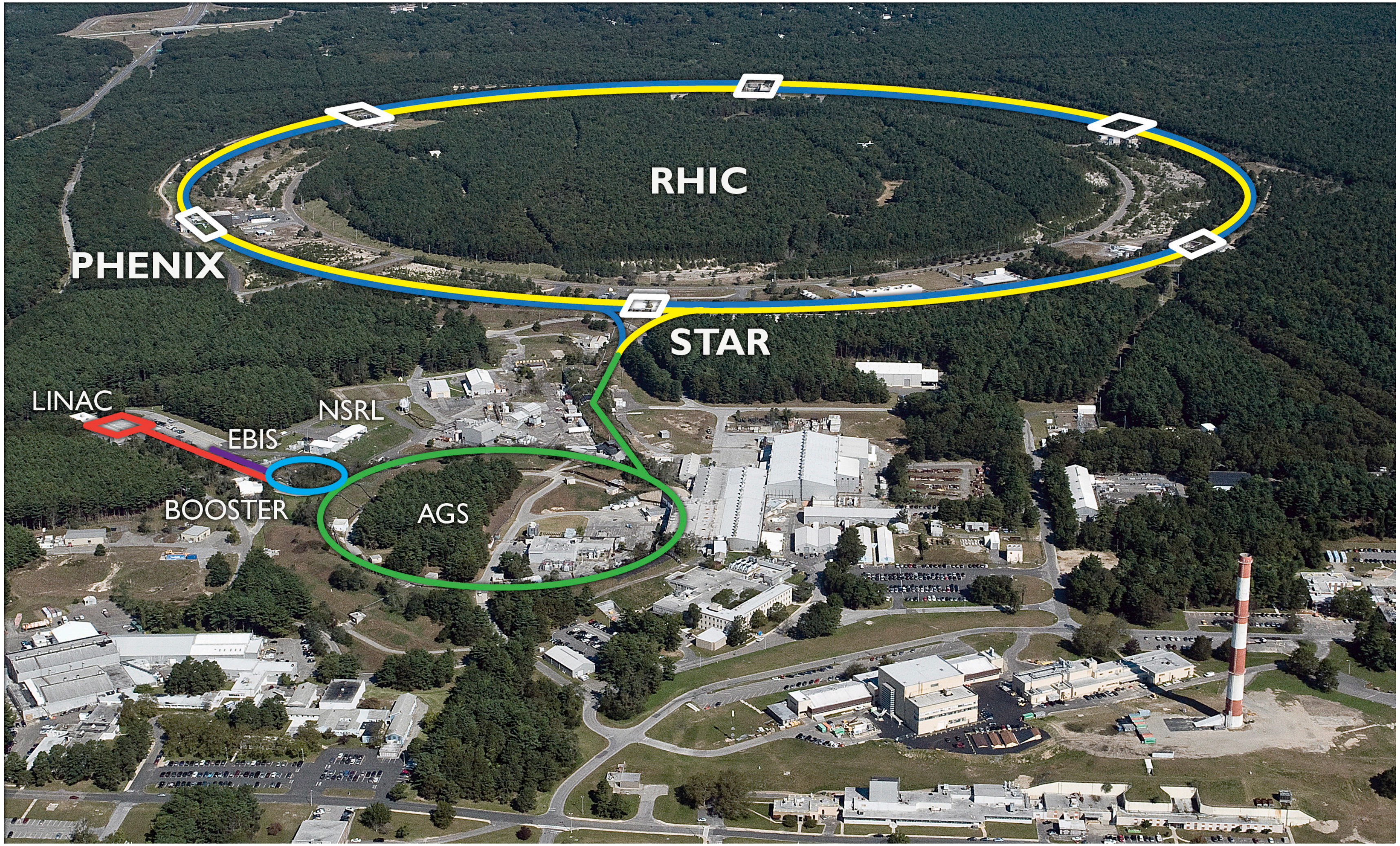
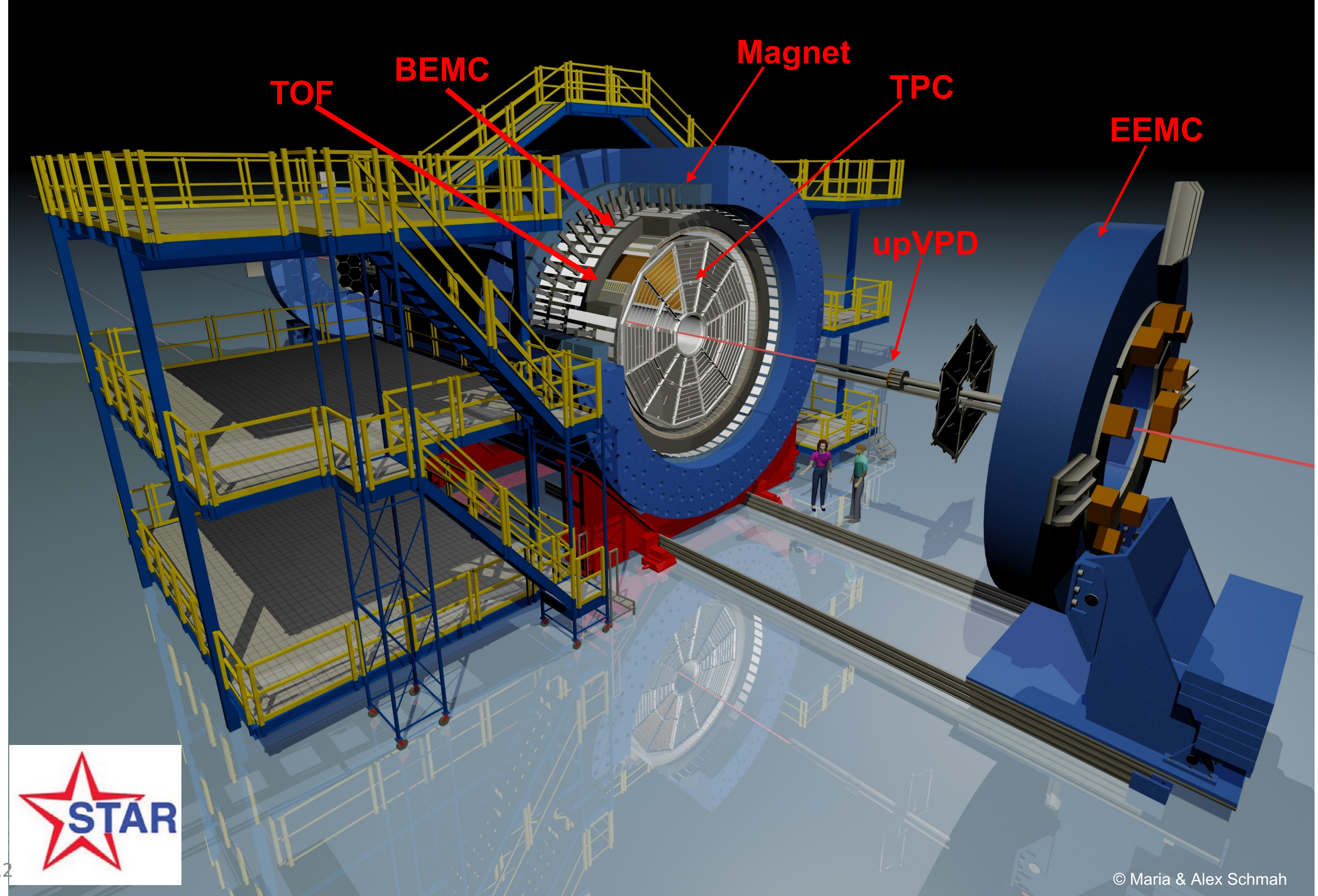
Relativistic Heavy Ion Collider



The Solenoidal Tracker At RHIC (STAR)



Data from Recent RHIC Runs

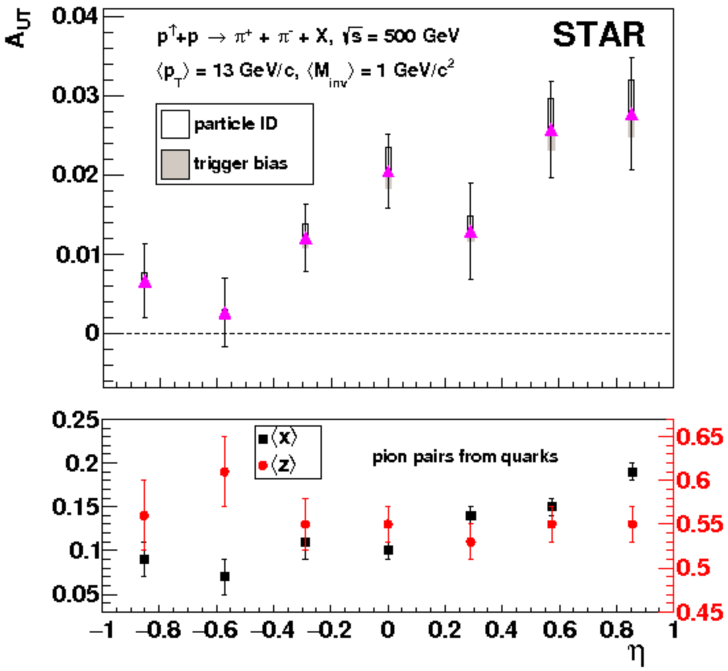
Year	2011	2012	2015	2017	2022
$\sqrt{s}$ (GeV)	500	200	200	510	508
L_{int} (pb^{-1})	25	22	52	350	400
Polarization	53%	57%	57%	58%	~52%

- For this talk, the 200 GeV data has better statistical precision than the 500 GeV data
- 500 GeV data probes lower momentum fraction than that of the 200 GeV data
- Analysis of forward and backward scattered jets with respect to the polarized proton beam gives access to a broad range of momentum fractions
- Note: Collins results from 2012 and 2015 data have been combined!

√s = 500 GeV

Previous STAR Result: Di-hadron Asymmetry

- 2011 500 GeV data
- 500 GeV results show significant asymmetries comparable to those from the previous 200 GeV measurement
- Higher COM energy probes an x-range on the upper end of SIDIS results, but with a higher effective Q^2
- Decent agreement with theory that is fit to SIDIS and e^+e^- experiments



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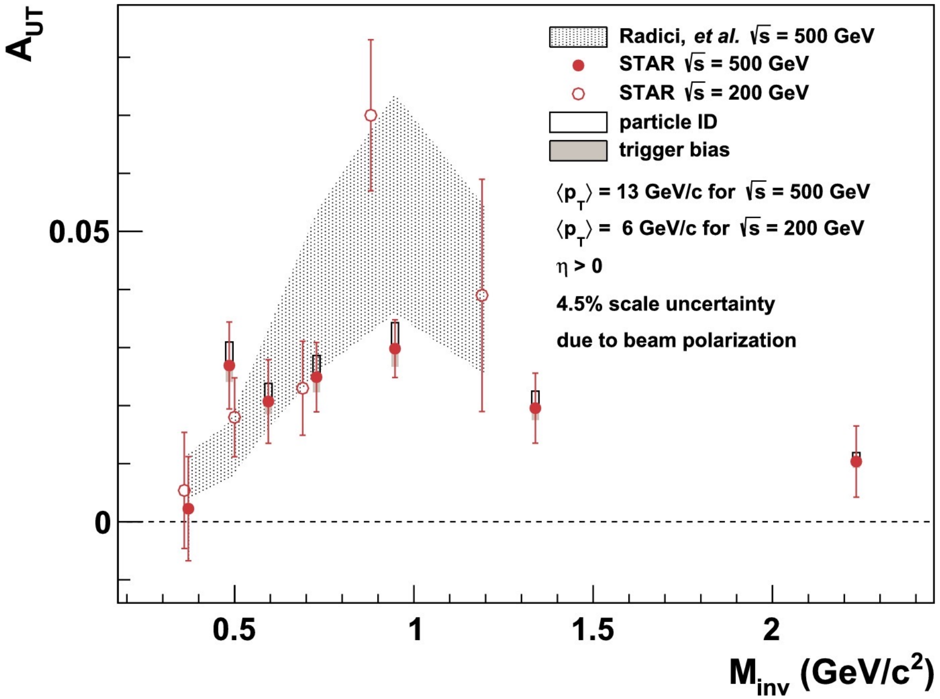
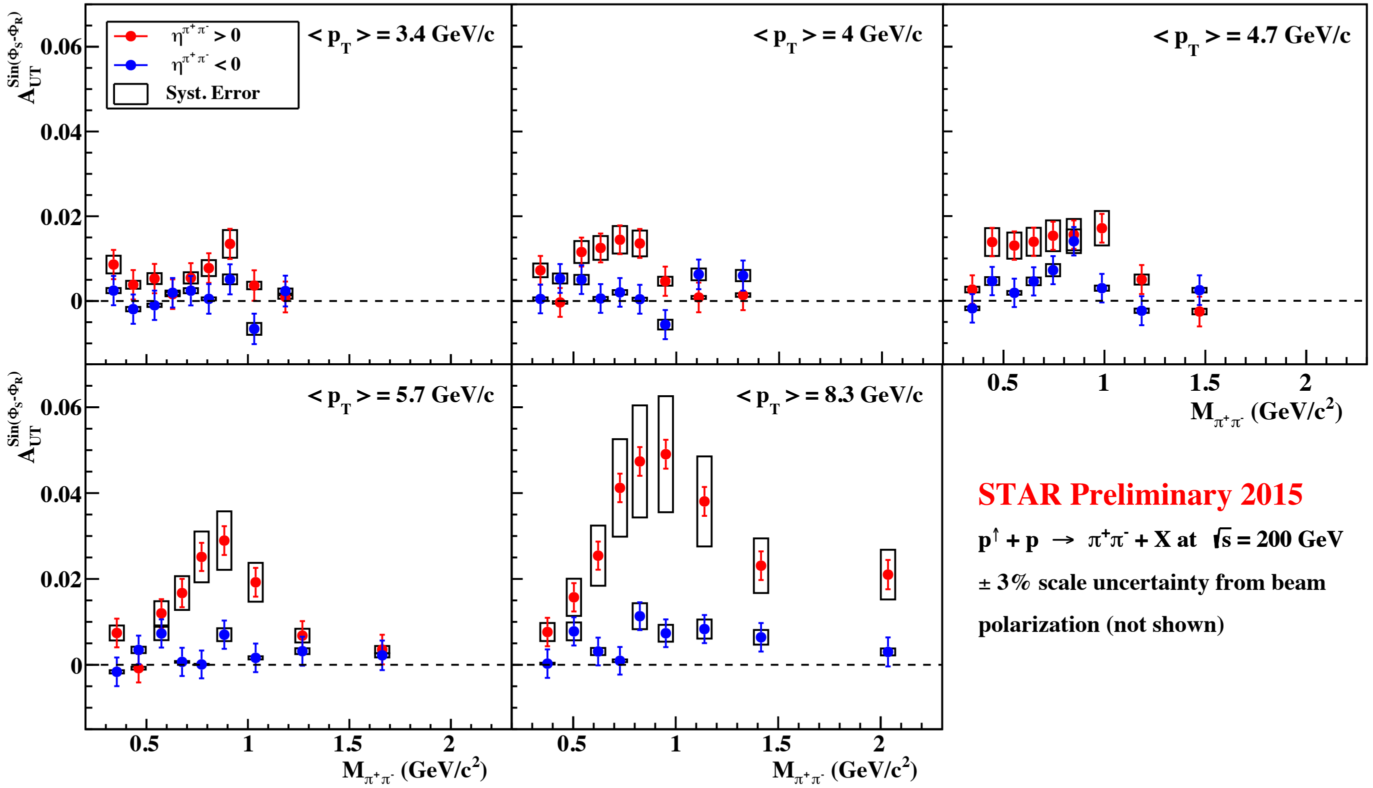


√s = 200 GeV

Recent Preliminary Result: Di-hadron Asymmetry



- Much higher statistical precision than any previous di-hadron asymmetry result
- Multidimensional binning probes transversity in fine details
- Enhancement of the asymmetry in the vicinity of the ρ mass (M ≈ 0.78 GeV/c^2)

√s = 200 GeV

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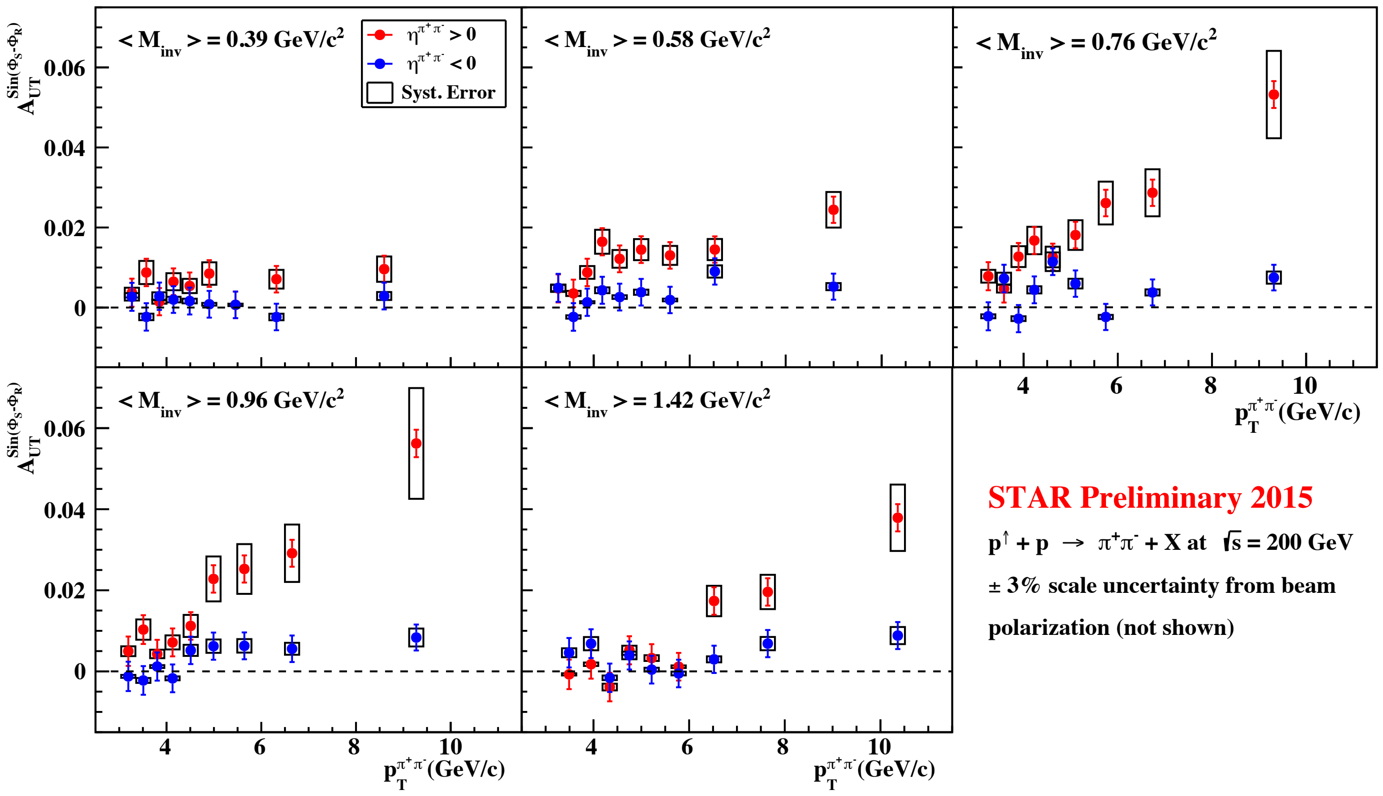

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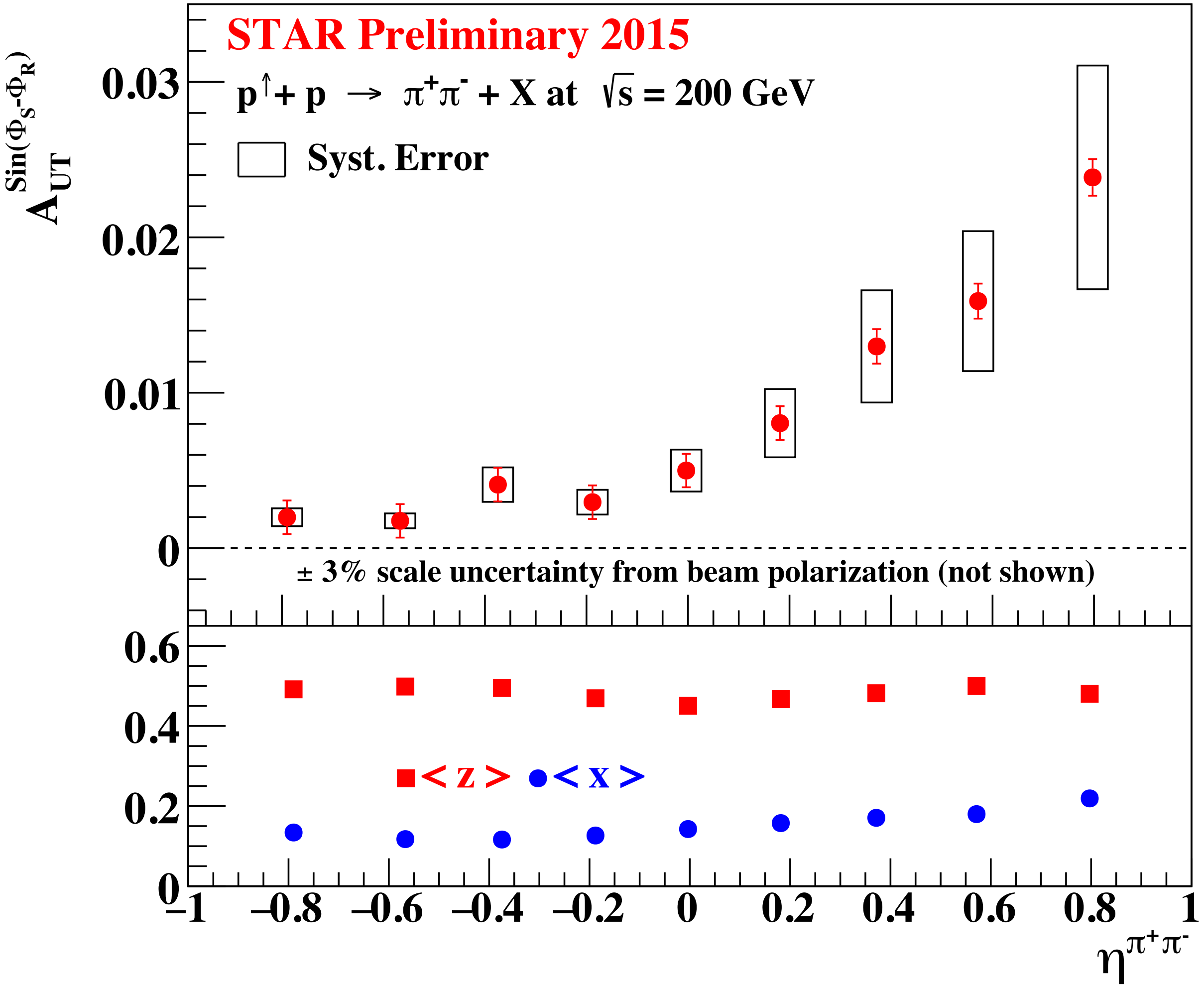
$\sqrt{s}$ = 200 GeV

Recent Preliminary Result: Di-hadron Asymmetry

- Integrated over all p_T and M_{inv} ranges
- $\eta > 0$ region gives a larger asymmetry
  - Samples larger *x* region than $\eta < 0$
  - Parton in this region comes from the polarized proton
- Sampled kinematics from simulation given on the bottom

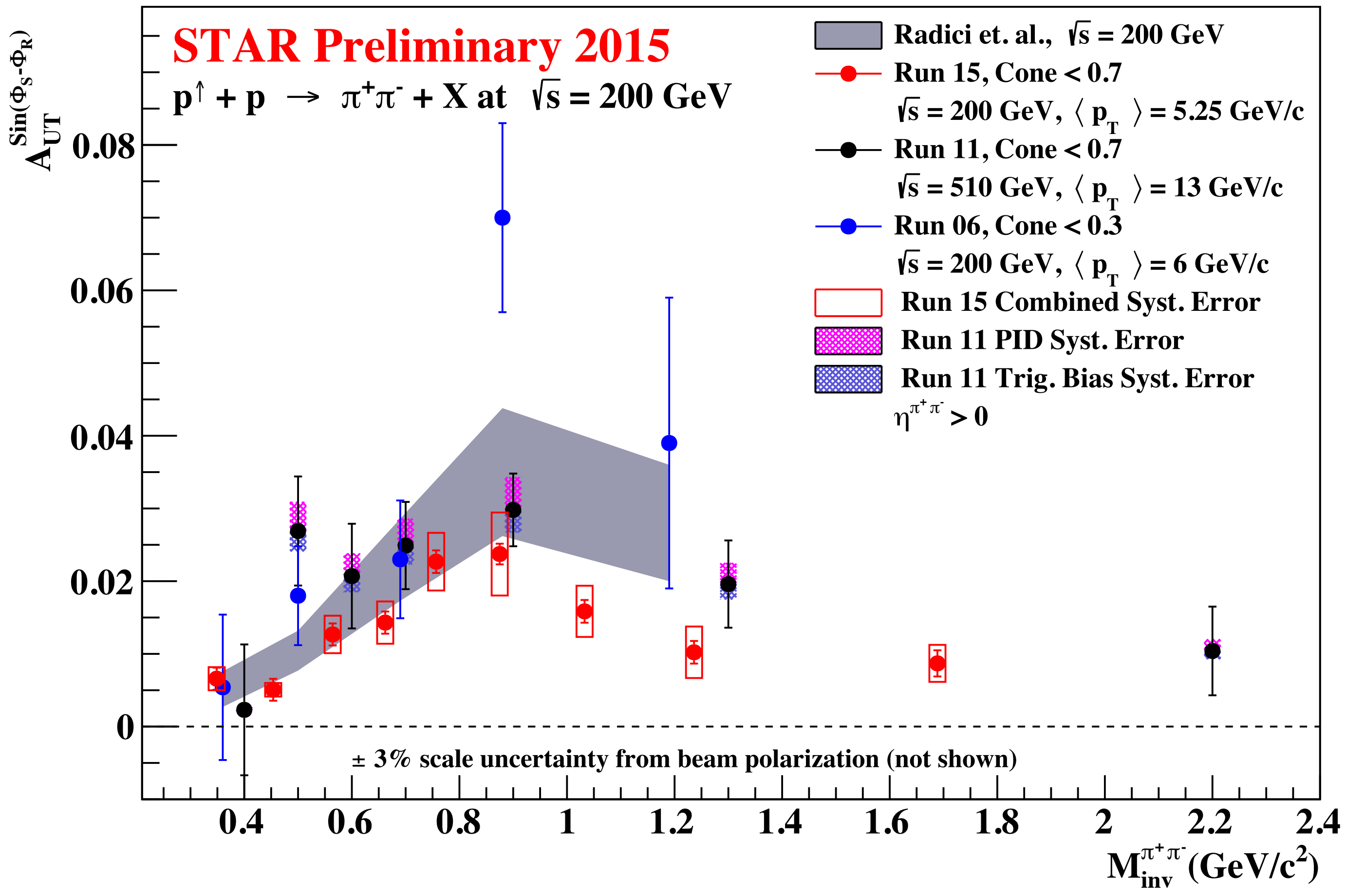
$$z = \frac{E_{\text{pair}}}{E_{\text{quark}}}$$



√s = 200 GeV

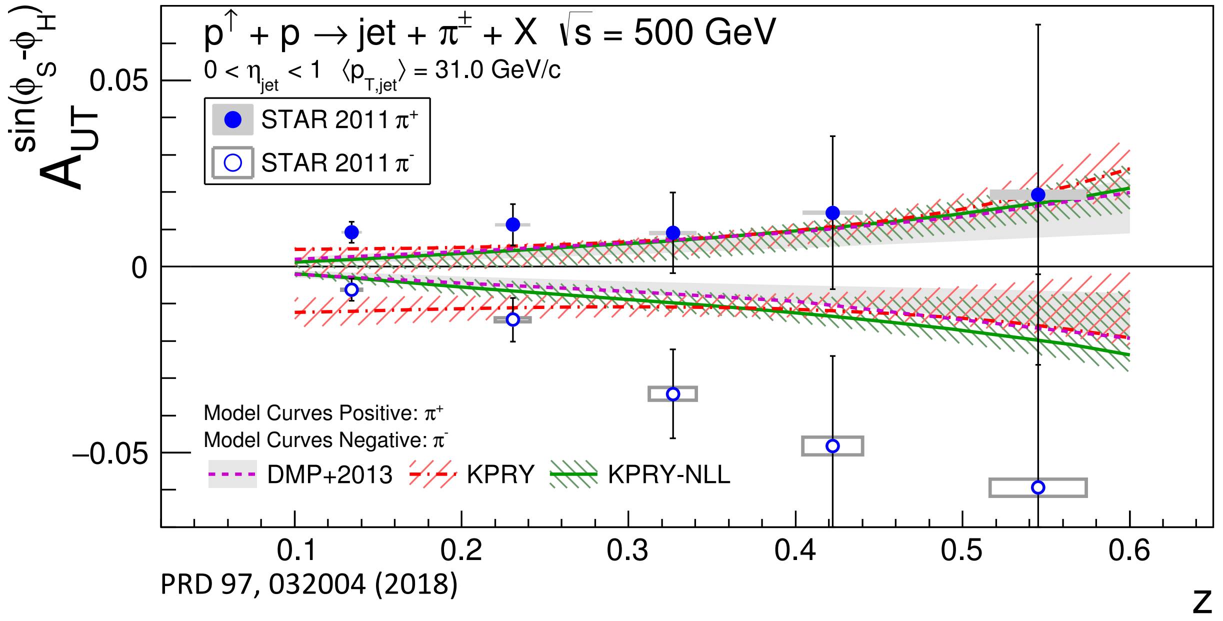
Recent Preliminary Result: Di-hadron Asymmetry

- Asymmetry integrates over all values of p_T for $\eta > 0$
- Good agreement with the previous 200 GeV result (shown earlier) with much better statistical precision
- 200 GeV theory curve agrees well, but overshoots at large M_{inv}
  - Predicts larger enhancement in the vicinity of M_ρ
  - Opportunity for model improvement with these new results



√s = 500 GeV

Previous STAR Result: Collins Asymmetry



PRD 97, 032004 (2018)

Theory curves:
D, Alesio, et. al. Phys. Lett. B773 (2017)
Kang, et. al. Phys. Lett. B774 (2017)

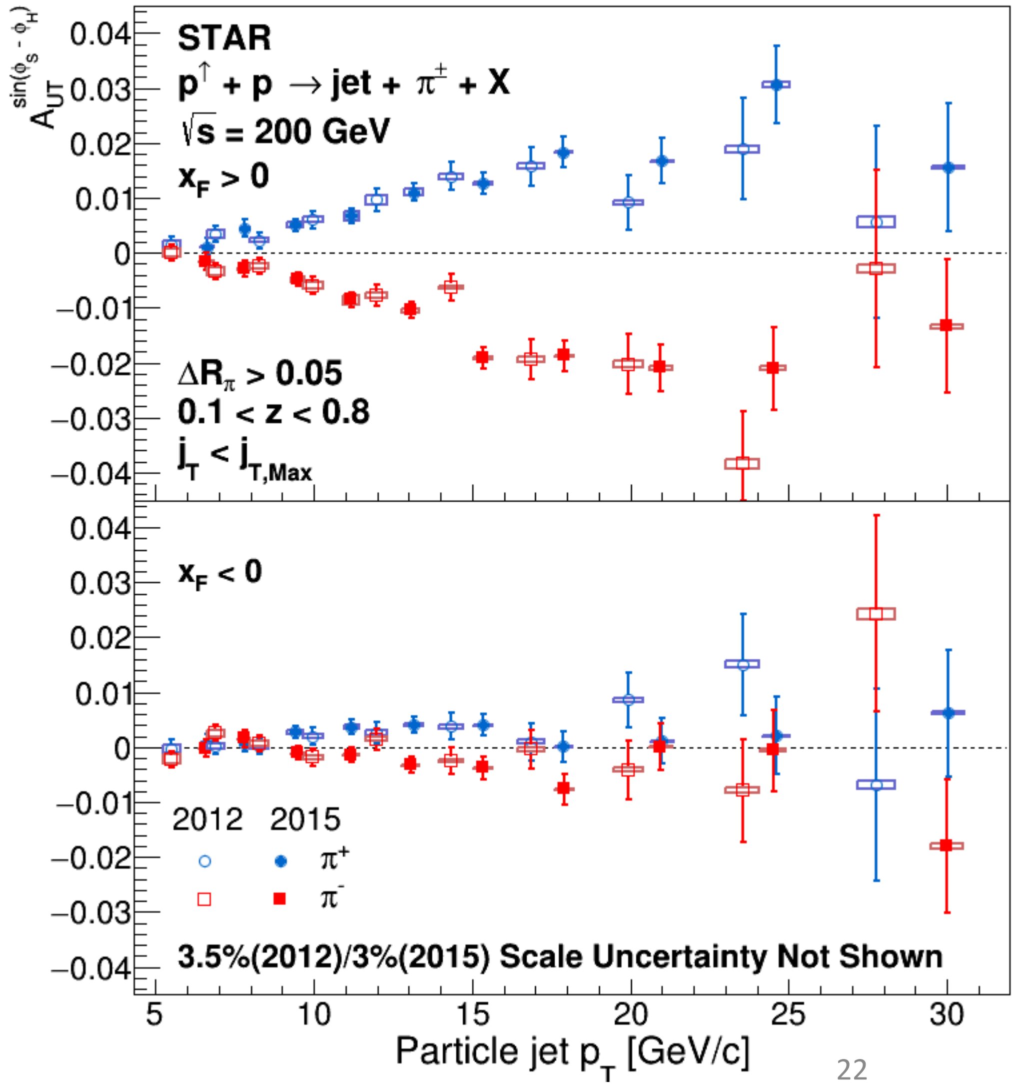
- 2011 500 GeV data
- First published Collins asymmetry in p+p collisions!
- Models based on SIDIS/e^+e^- data
  - DMP&KPRY: No TMD evolution
  - KPRY-NLL: TMD evolution up to NLL
- Consistency with models suggests universality and that factorization isn't broken in p+p

√s = 200 GeV

New STAR Result: Collins Asymmetry

- Paper submitted to PRD and now on the arXiv!
- 2012 and 2015 analyses finished simultaneously
  - Asymmetries are in excellent agreement!
- Results from both years combined into a single set of asymmetries for publication
- These are the most statistically precise and significant Collins asymmetries in p+p to date

STAR, arXiv:2205.11800



√s = 200 GeV

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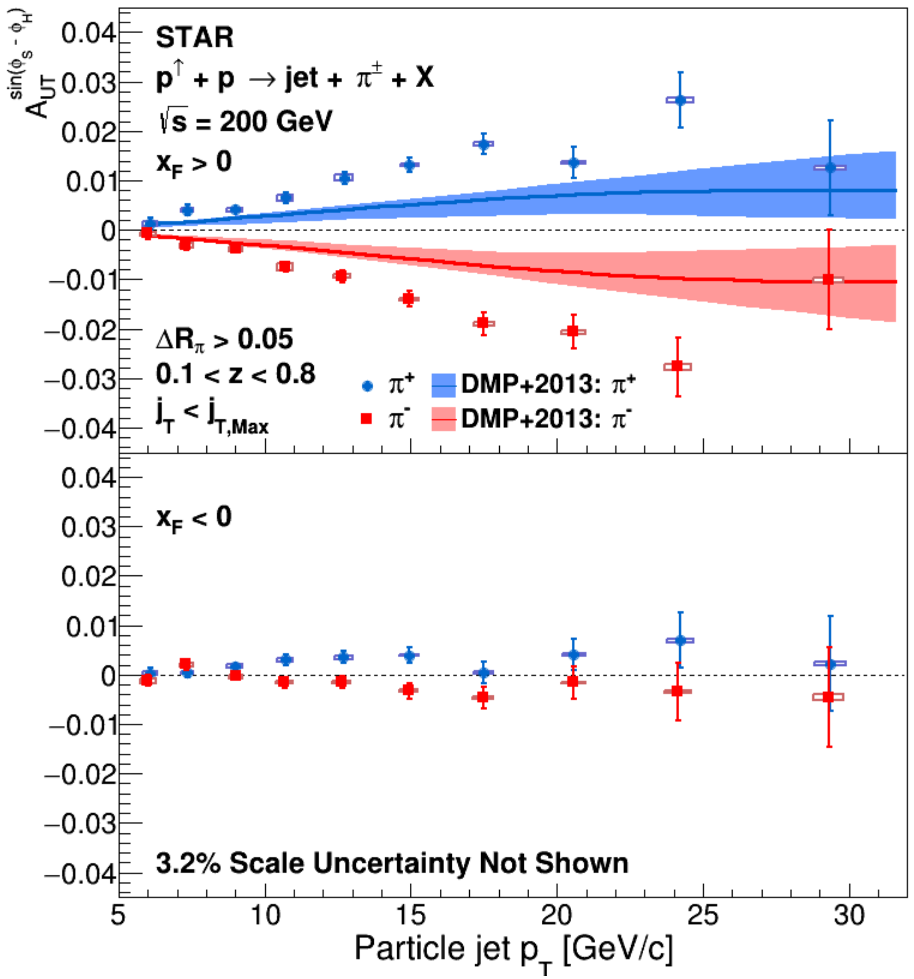


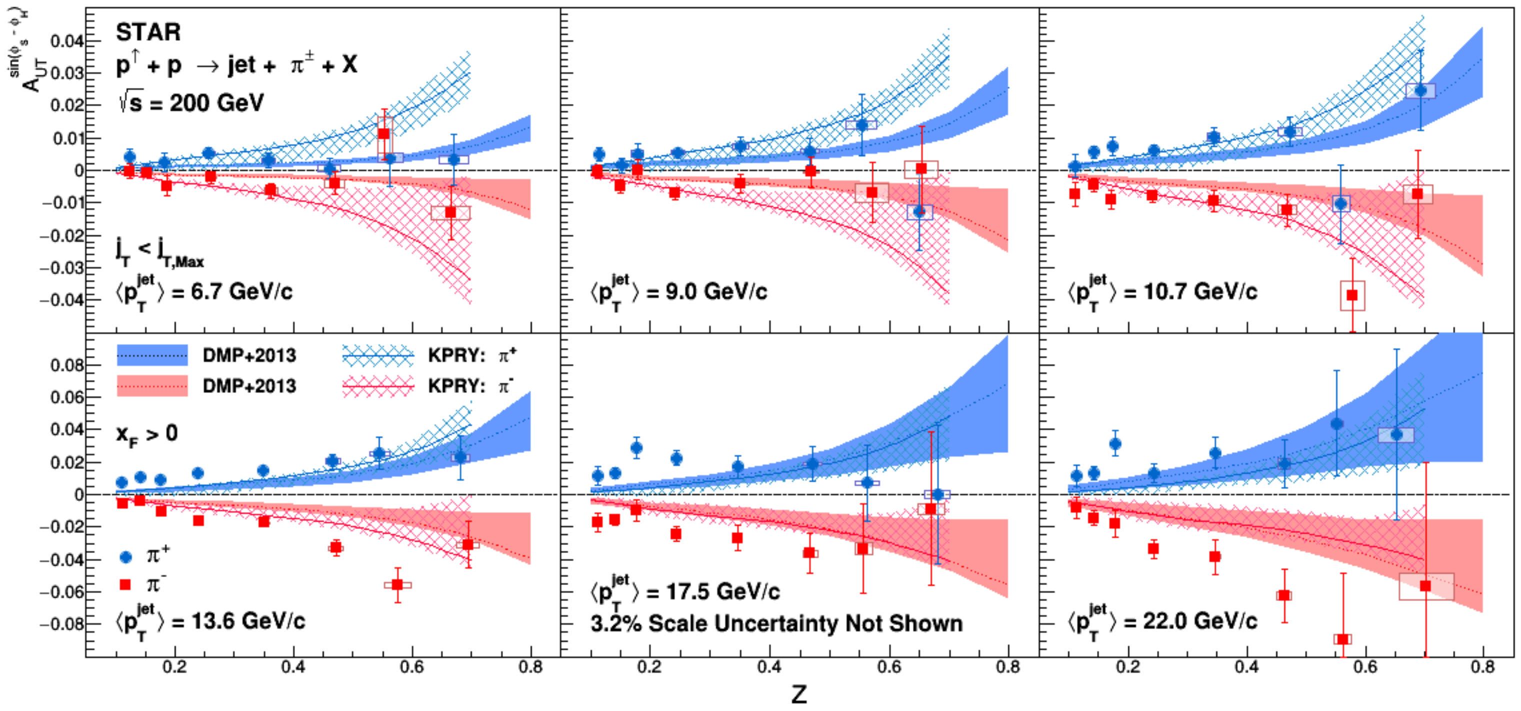
- DMP+2013 model uses transversity distribution from SIDIS and the Collins FF from e^+e^-
  - D'Alesio, et. al. PLB 773, 300 (2017)
  - Undershoots the amplitude, but follows the shape well
- $x_F > 0$ jets access larger values of *x* than $x_F < 0$ jets and the parton from the polarized proton
- x-axis values have been corrected to the particle level in simulation

√s = 200 GeV

$$z = \frac{p_{\text{hadron}}}{p_{\text{jet}}}$$

New STAR Result: Collins Asymmetry

STAR, arXiv:2205.11800



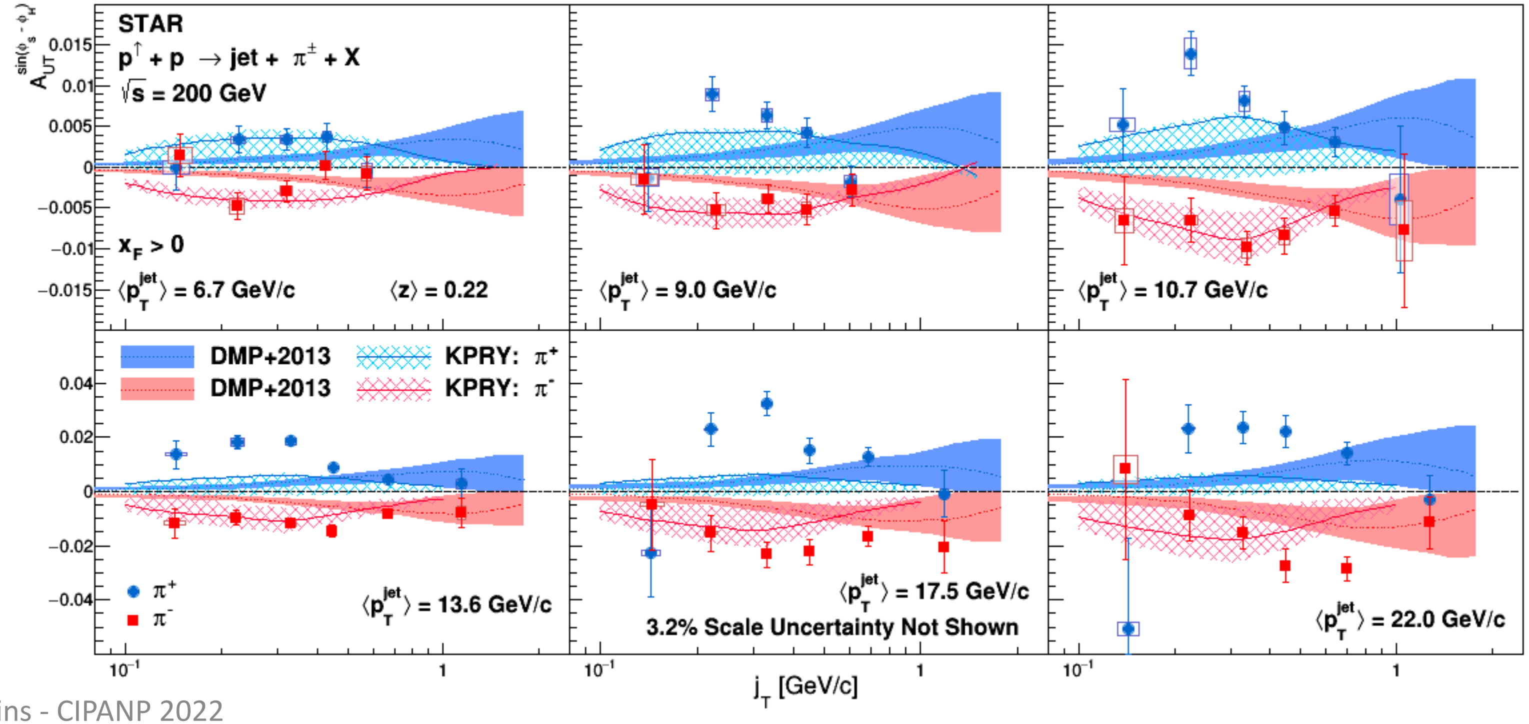
DMP+2013: D'Alesio, et. al. PLB 773, 300 (2017)
KPRY: Kang *et. al.*,PLB 774, 635 (2017);

- Both models assume factorization and universality
- Models do a reasonable job at lower jet p_T
- Models underestimate the size at high jet p_T
  - For all z for π^-
  - Low z for π^+

√s = 200 GeV

New STAR Result: Collins Asymmetry

- In both cases there are large differences between data and model calculations
  - KPRY does a better job of predicting the correct shape
- z and j_T dependences are important for understanding the Collins FF



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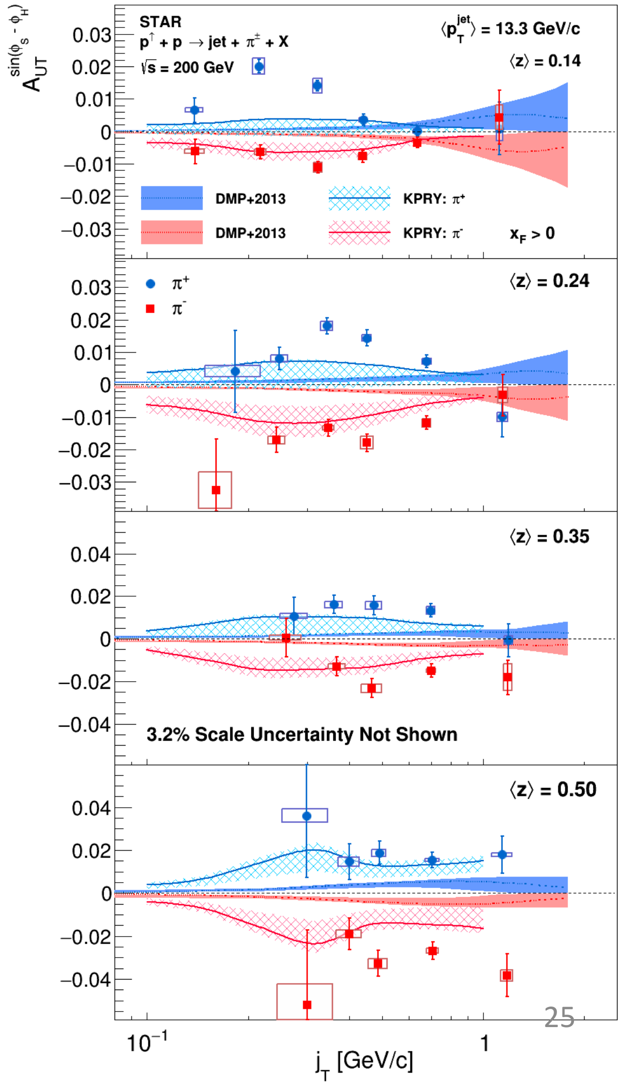
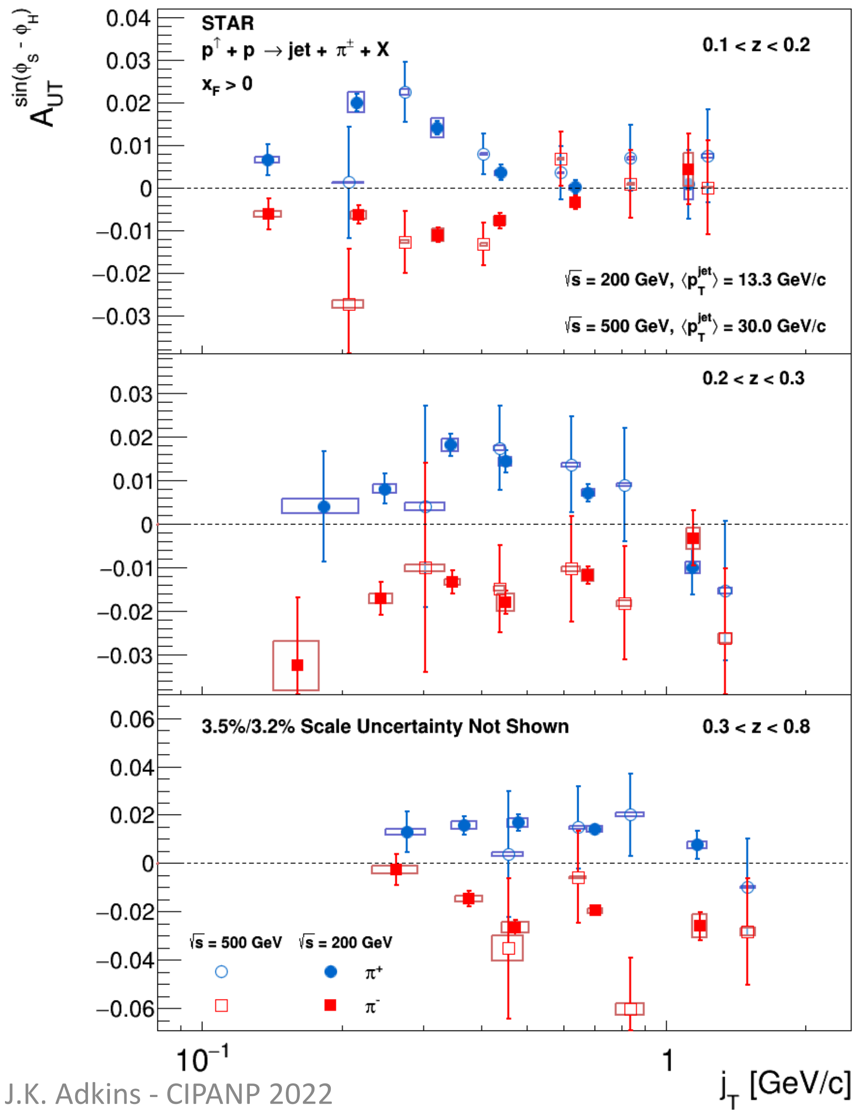
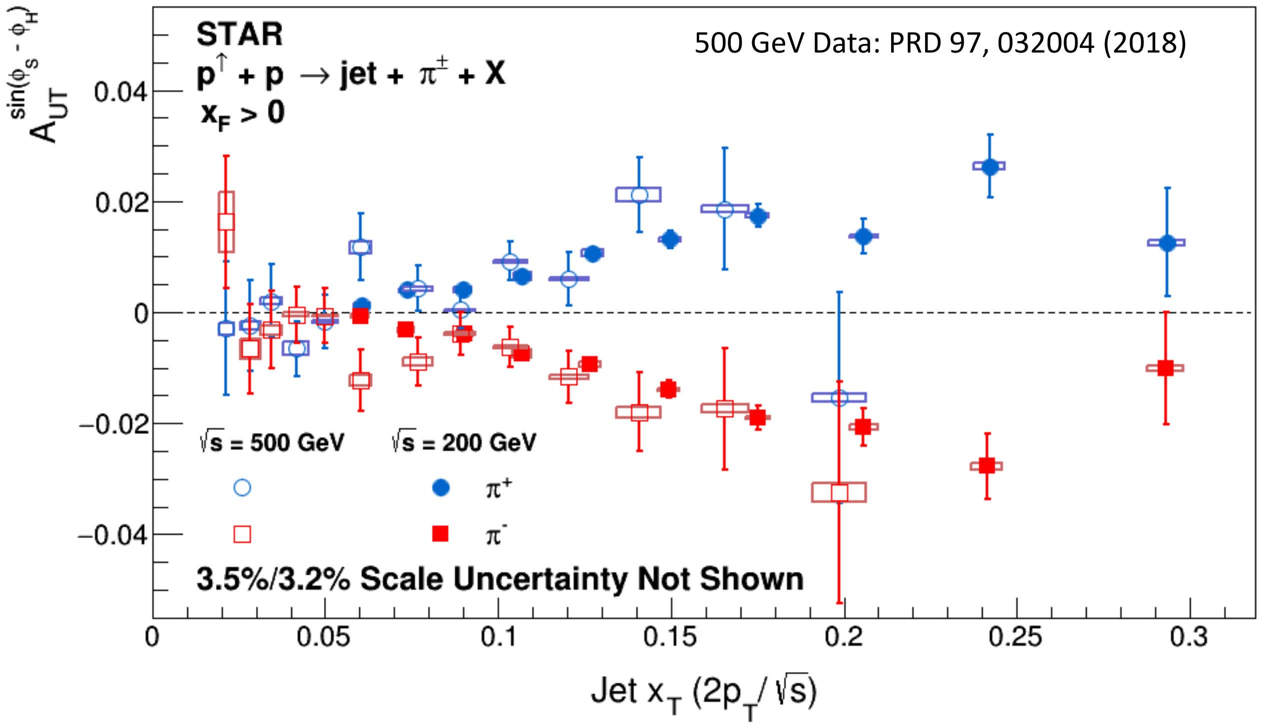


√s = 200 GeV | √s = 500 GeV

Collins Asymmetry: 200 GeV vs. 500 GeV

STAR, arXiv:2205.11800



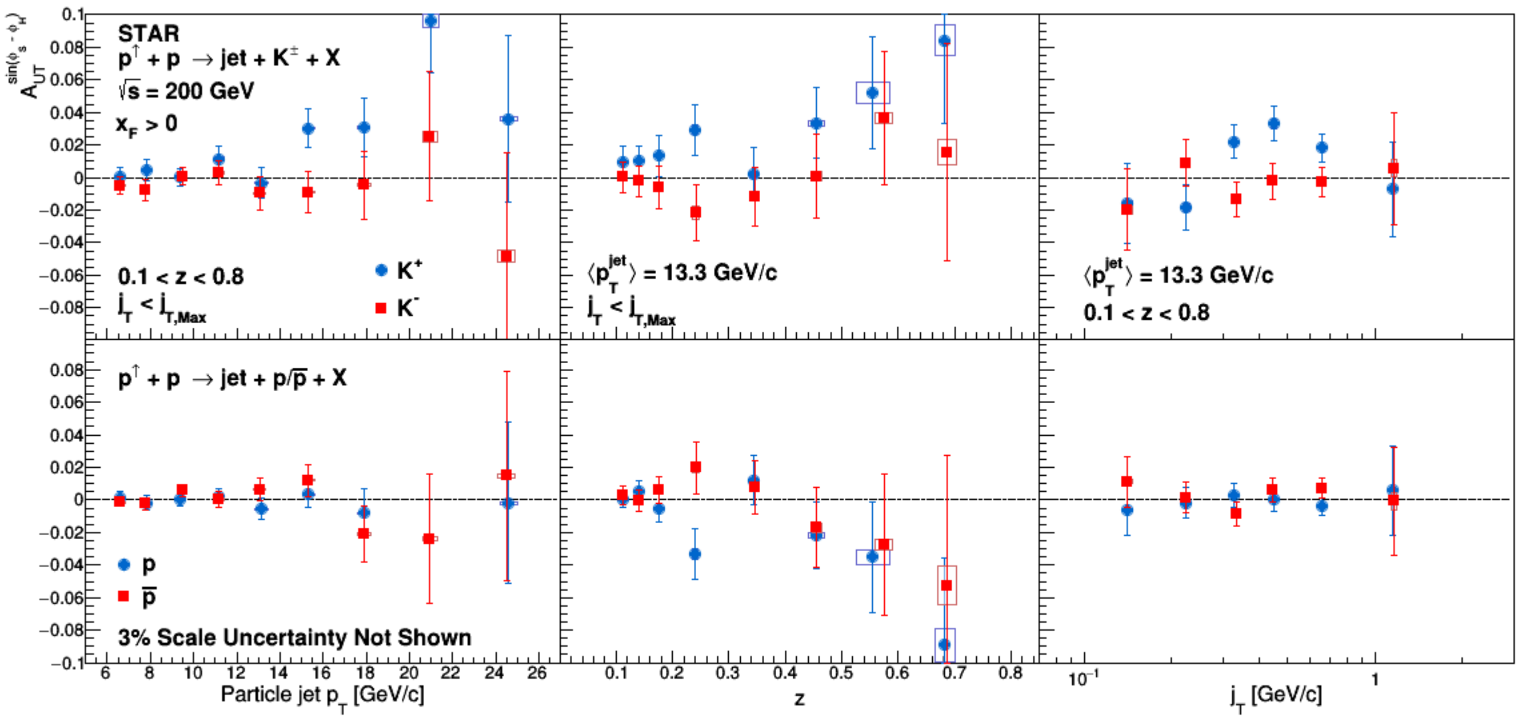


- Asymmetries agree well in both shape and amplitude for jet $x_T \geq 0.07$
- Slow evolution with Q^2

√s = 200 GeV

New STAR Result: Collins Asymmetry

STAR, arXiv:2205.11800



- First measurement of kaon and proton Collins asymmetries inside of jets (2015 data only)
- K^+ shows asymmetry similar to π^+ (favored fragmentation) but K^- is consistent with zero (unfavored fragmentation) within statistical precision
- Proton asymmetries consistent with zero within statistical precision

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- Di-hadron and Collins measurements using the 2017 510 GeV dataset are ongoing
- Additional transverse single-spin jet asymmetries in p+p from STAR:
    - Inclusive jet asymmetry (200 and 500 GeV; sensitive to twist-3 analogy of gluon Sivers)
    - Hadron-tagged jet asymmetries (200 GeV; sensitive to twist-3 analogy of quark Sivers)
    - Collins-like asymmetries (200 and 500 GeV; sensitive to linearly polarized gluons in transversely polarized protons)
    - All are zero within current statistical precision

Backup

Sources of Systematic Uncertainty

- Implement simulation to estimate systematic uncertainties
  - Use PYTHIA and GEANT with embedded zero bias events tosimulate detector response to QCD processes
  - Recreate the analysis in simulation framework with and without detector effects
- The hadron-in-jet and di-hadron analyses have several sources of systematic error in common:
  - Kinematic shifts (i.e., x-axis value shifts)
  - Trigger bias
  - Particle identification
  - Azimuthal smearing
- The Collins analysis receives additional errors due to the effect of one moment “leaking” into another (e.g., leak through of Collins-like to Collins, etc.)

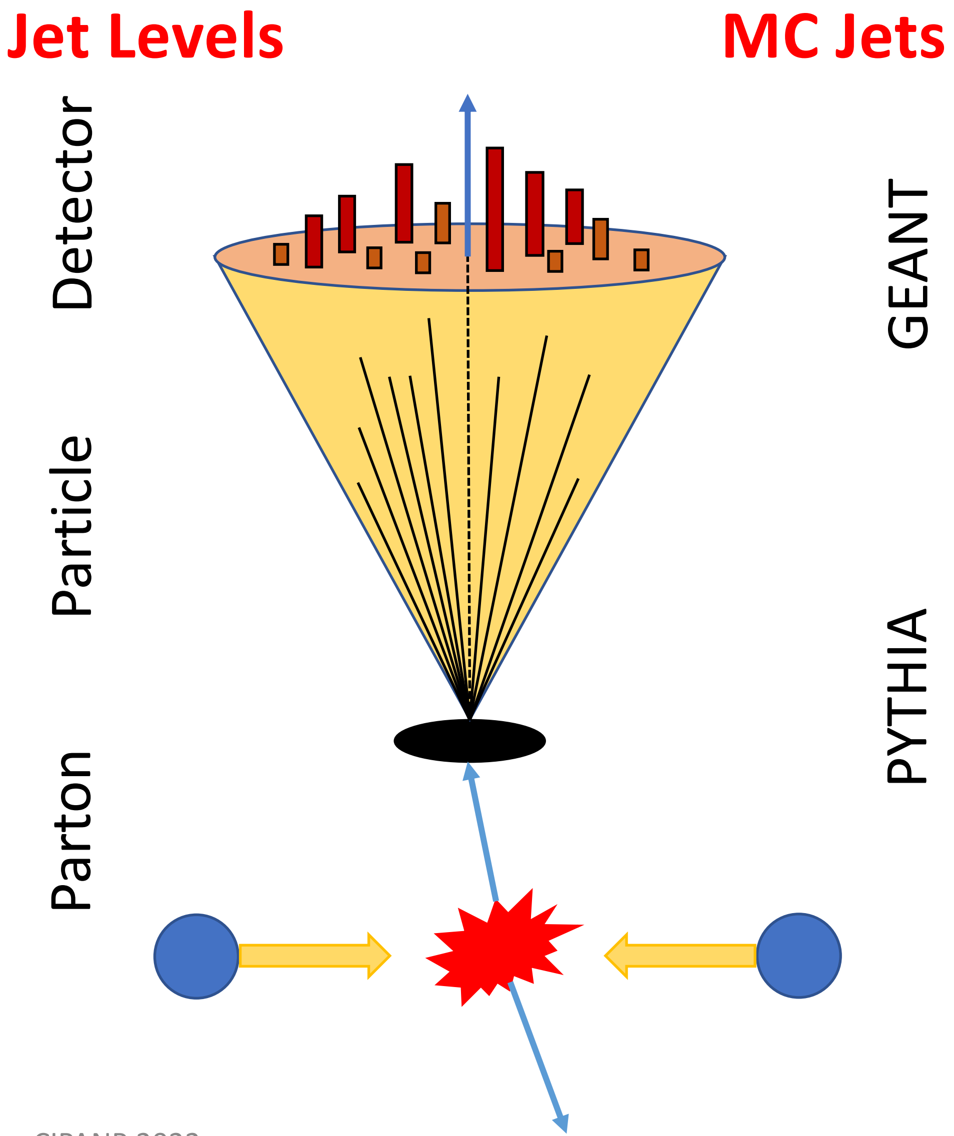
Jet Reconstruction: Collins Asymmetry

- Anti-k_T reconstruction algorithm
- Radius R = 0.6
- Jet level cuts:
  - $|z_{vertex}| < 60$ cm
  - $6 < p_{T,jet} < 31.6$ GeV/c
  - $R_{T,jet} < 0.95$
  - No tracks with $p_{T,track} > 20$ GeV/c
  - Sum of track $p_T > 0.5$
  - $-0.9 < \eta_{jet} < 0.9$
  - $-0.8 < \eta_{detector} < 0.9$
- Hadron cuts
  - $0.05 < j_T < 4.5$ GeV/c
  - $0.1 < z < 0.8$
  - $-1 < n_\sigma(\pi) < 2$
  - $\Delta R > 0.05$ (between track and jet)

Pion Pair Selection: Di-hadron Asymmetry

- Jet reconstruction is not required
- Look at all possible $\pi^+\pi^-$ pairs are formed and examined
  - $|z_{vertex}| < 60$ cm
  - Track DCA < 1 cm
  - $p_{T,track} > 1.5$ GeV/c
  - Track hits > 15
  - $-1 < n_\sigma(\pi) < 2$
  - $-1 < \eta_{track} < 1$
  - Cone size (η-φ space) < 0.7
  - $0.2 < M_{inv} < 4$ GeV/c
  - $2.5 < p_{T,pair} < 15$ GeV/c
  - $-1 < \eta_{pair} < 1$

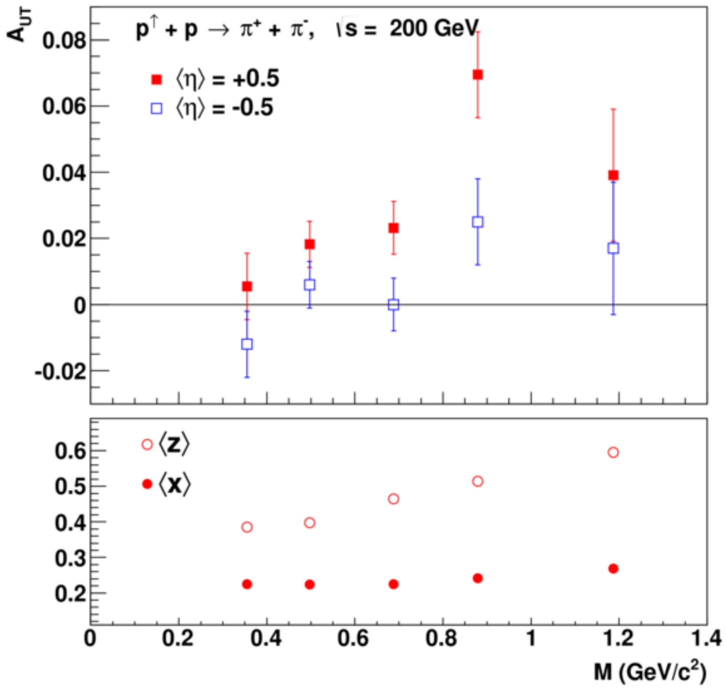
Simulation Framework



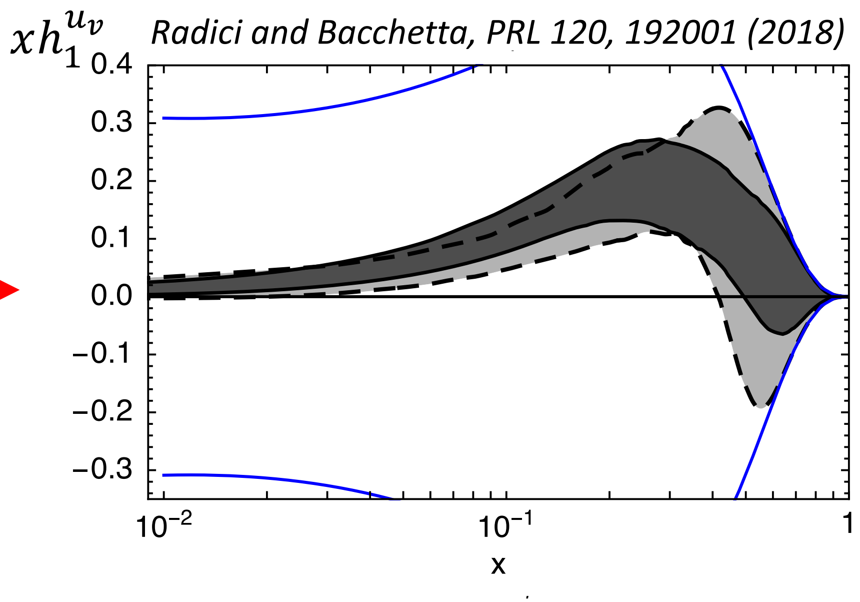
- **Simulation:** PYTHIA 6.4 Perugia 2012 with additional tuning to STAR data;
- **Three Simulation Levels :**
- Parton – hard scattered partons involved in 2->2 hard scatterings from PYTHIA
- Particle – partons propagate and hadronize into stable and color-neutral particles
- Detector – detector response to the stable particles

√s = 200 GeV

Previous STAR Result: Di-hadron Asymmetry



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

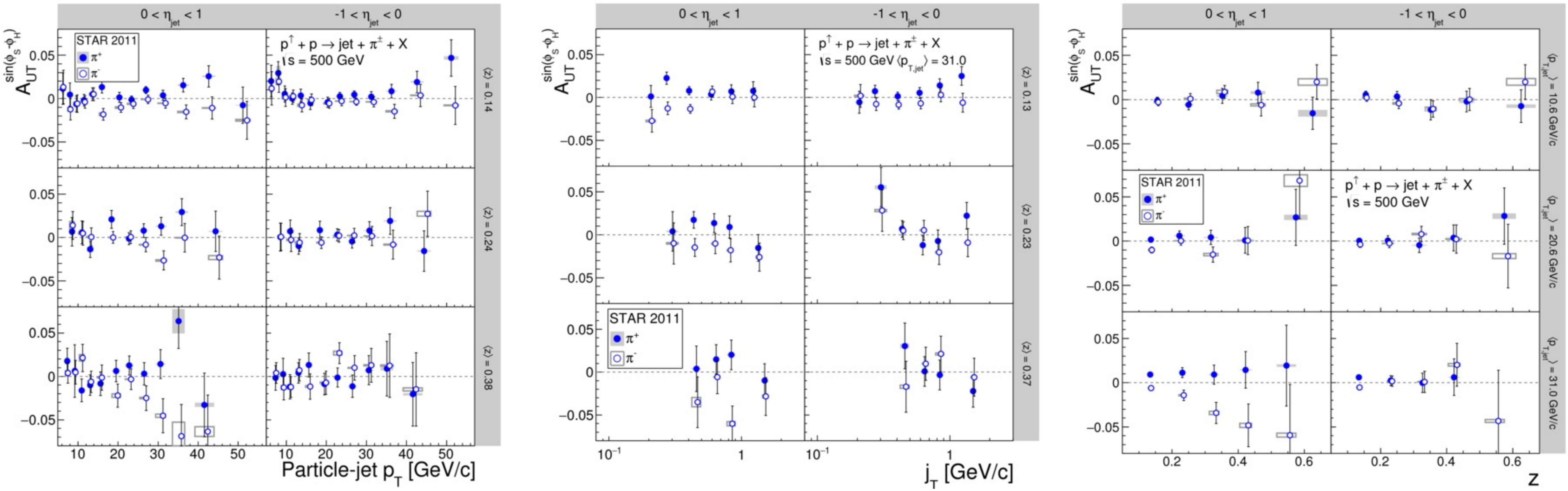


- 2006 200 GeV data
- First observation of transversity in p+p collisions!
- Data significantly improved the valence up quark transversity distribution
  - STAR can make an impact on transversity!

√s = 500 GeV

Previous STAR Result: Collins Asymmetry

$$z = \frac{p_{\mathrm{hadron}}}{p_{\mathrm{jet}}}$$



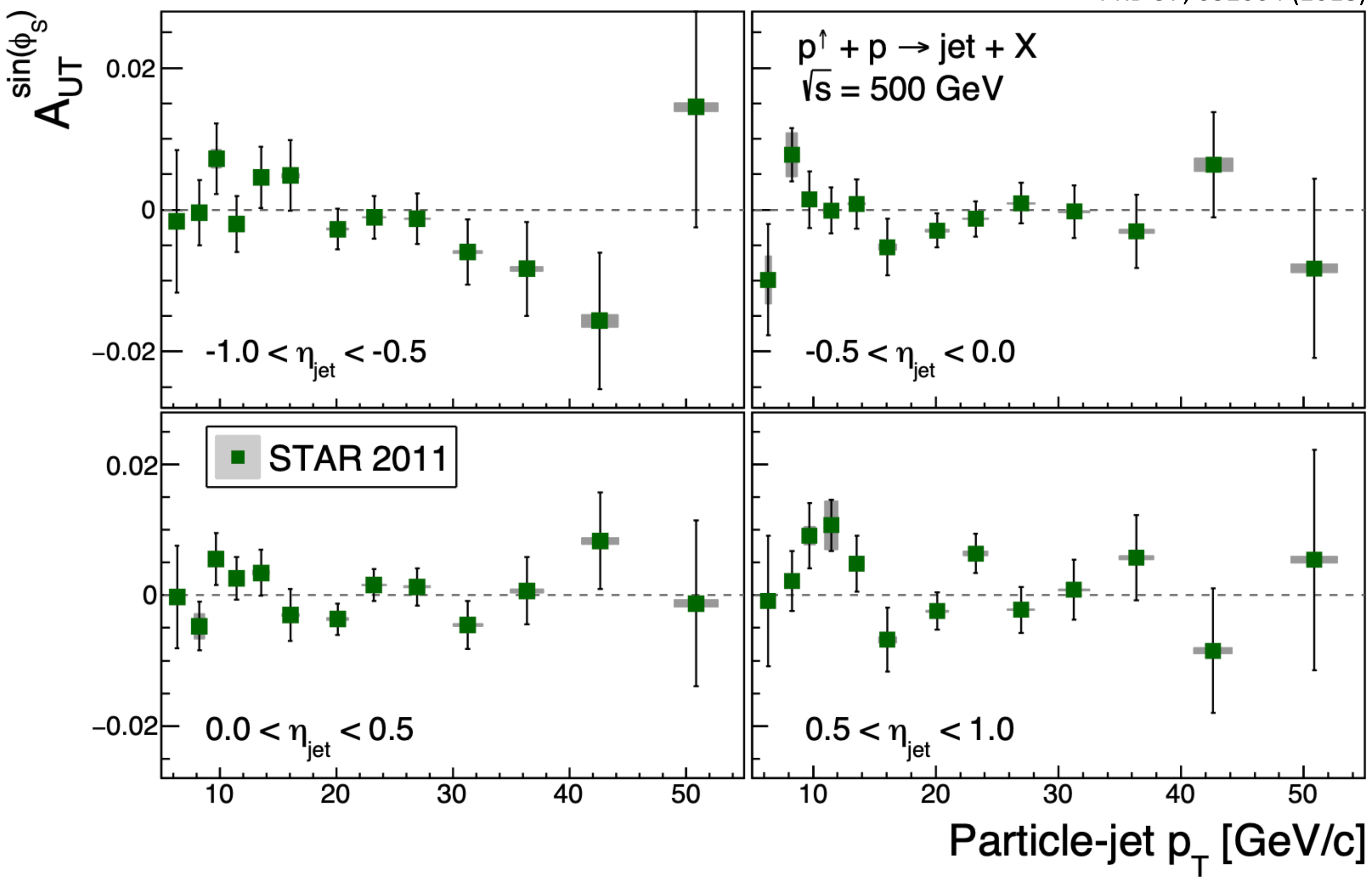
PRD 97, 032004 (2018)

- Multi-dimensional binning scheme gives insight into how the kinematic variables depend upon each other
  - z and j_T show up in FF, p_T ~ Q shows up in transversity

√s = 500 GeV

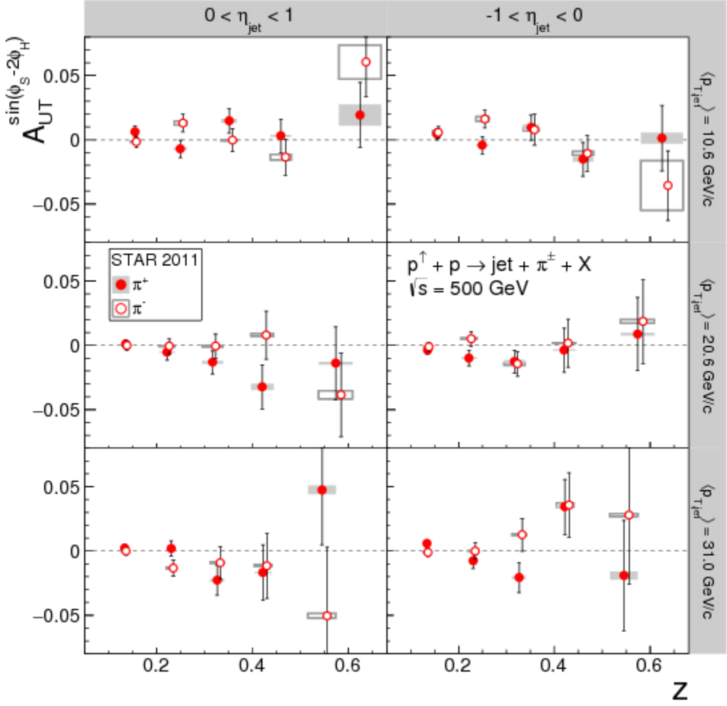
Previous STAR Result: Inclusive Jet Asymmetry

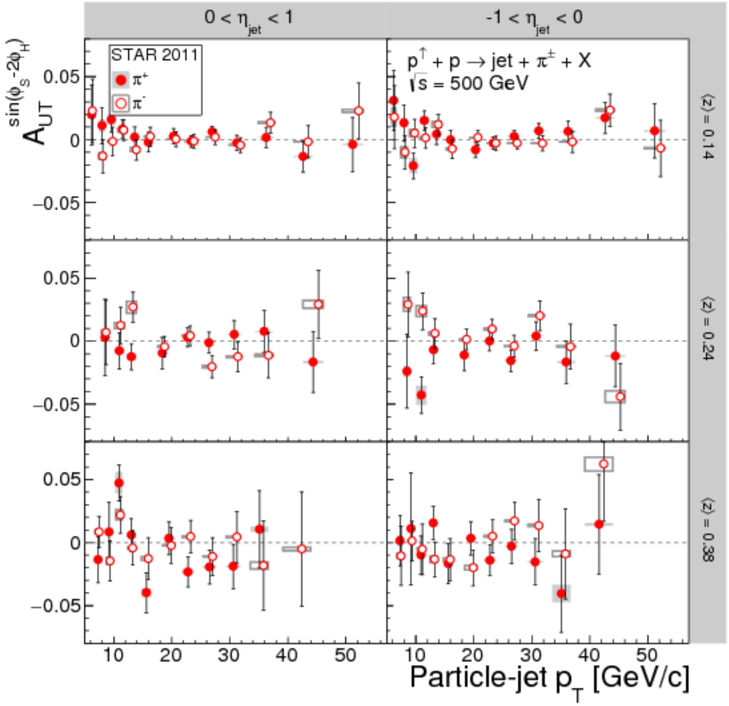
PRD 97, 032004 (2018)



√s = 500 GeV

Previous STAR Result: Collins-like Asymmetry

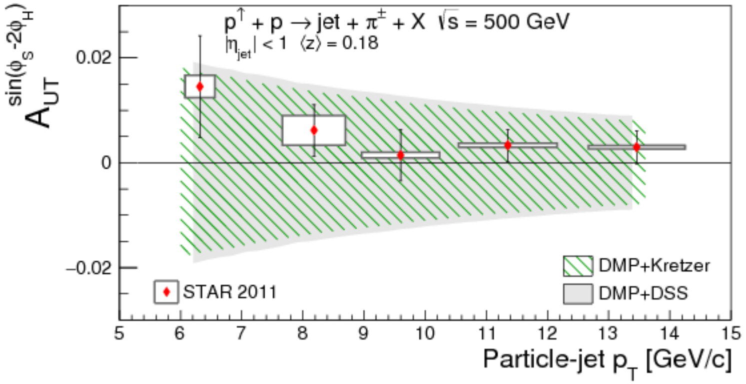


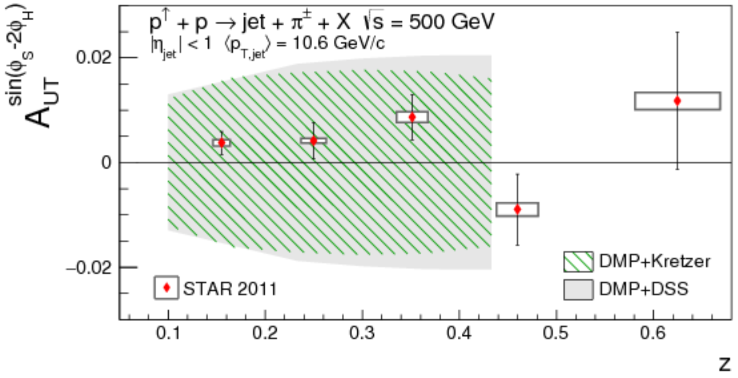


PRD 97, 032004 (2018)

√s = 500 GeV

Previous STAR Result: Collins-like Asymmetry





PRD 97, 032004 (2018)

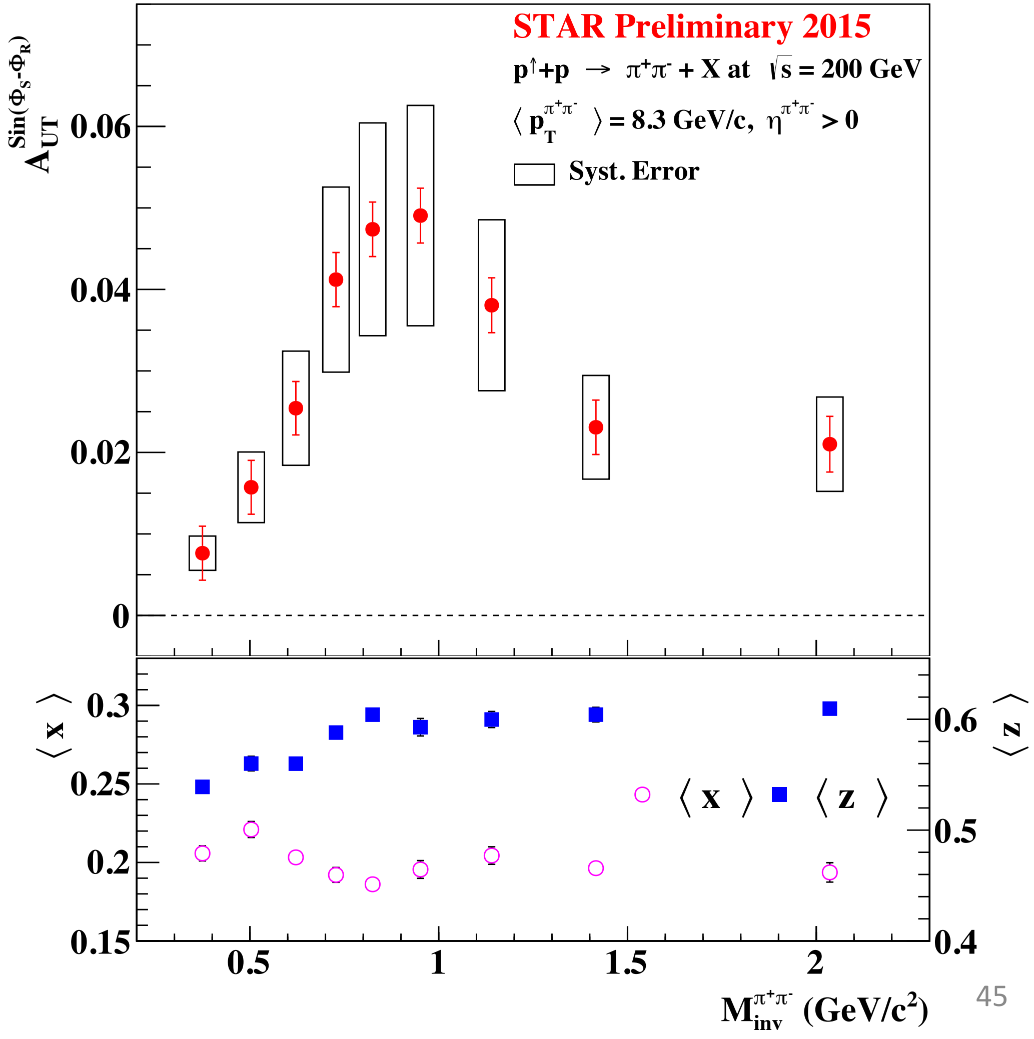
- Statistics combines both charge states to maximize precision
  - Still consistent with zero and within model predictions

New Preliminary Result: Di-hadron Asymmetry

- Asymmetry for the highest <p_T> bin shows the largest asymmetry

- Average sampled kinematics given on the bottom panel

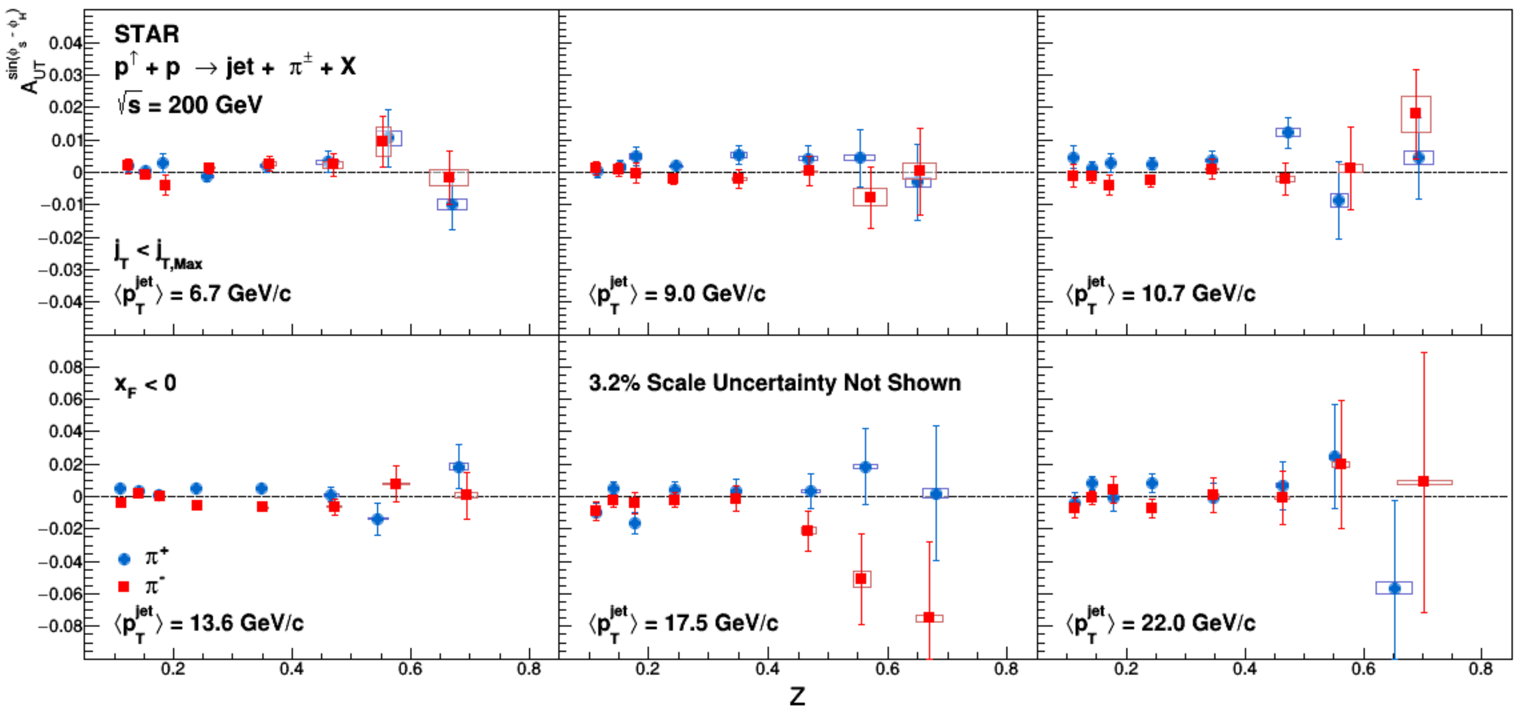
$$z = \frac{E_{\text{pair}}}{E_{\text{quark}}}$$



√s = 200 GeV

New STAR Result: Collins Asymmetry ($x_F < 0$)

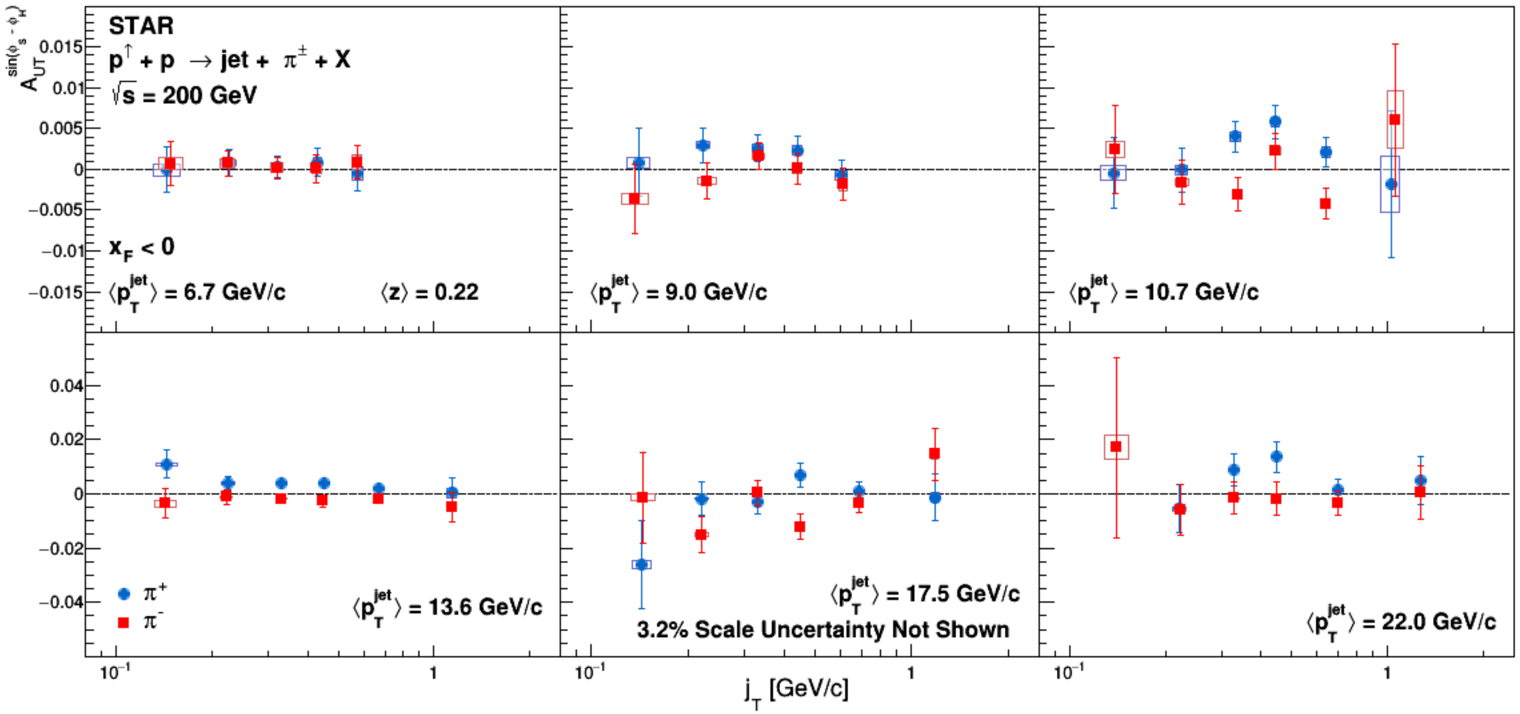
STAR, arXiv:2205.11800



√s = 200 GeV

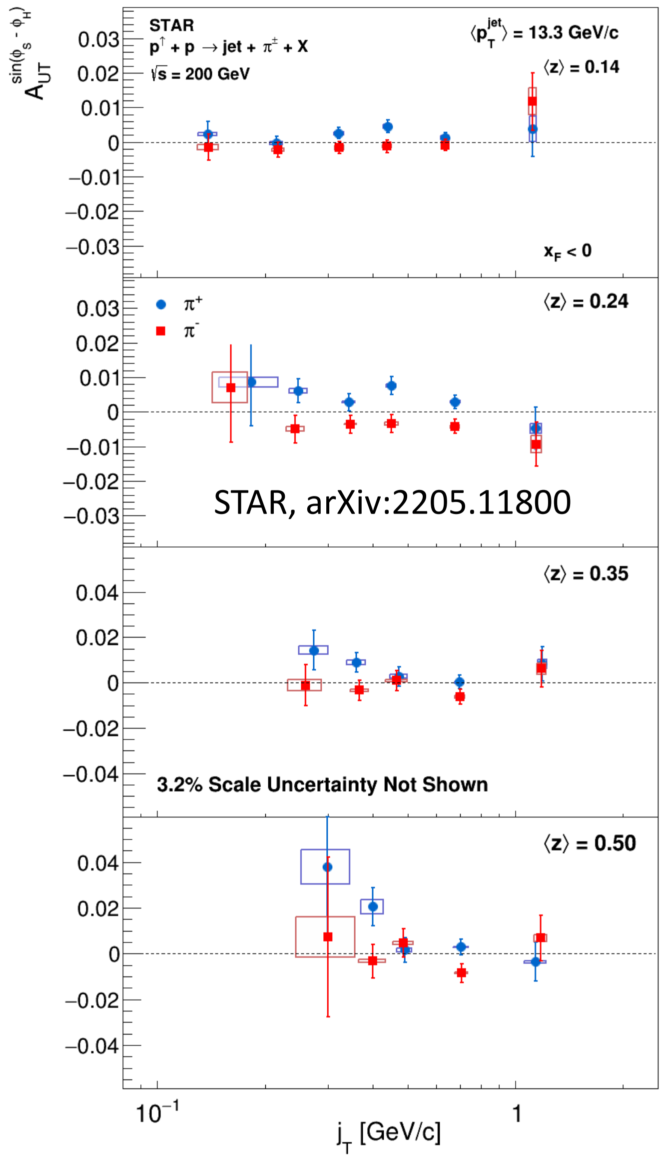
New STAR Result: Collins Asymmetry ($x_F < 0$)

STAR, arXiv:2205.11800



√s = 200 GeV

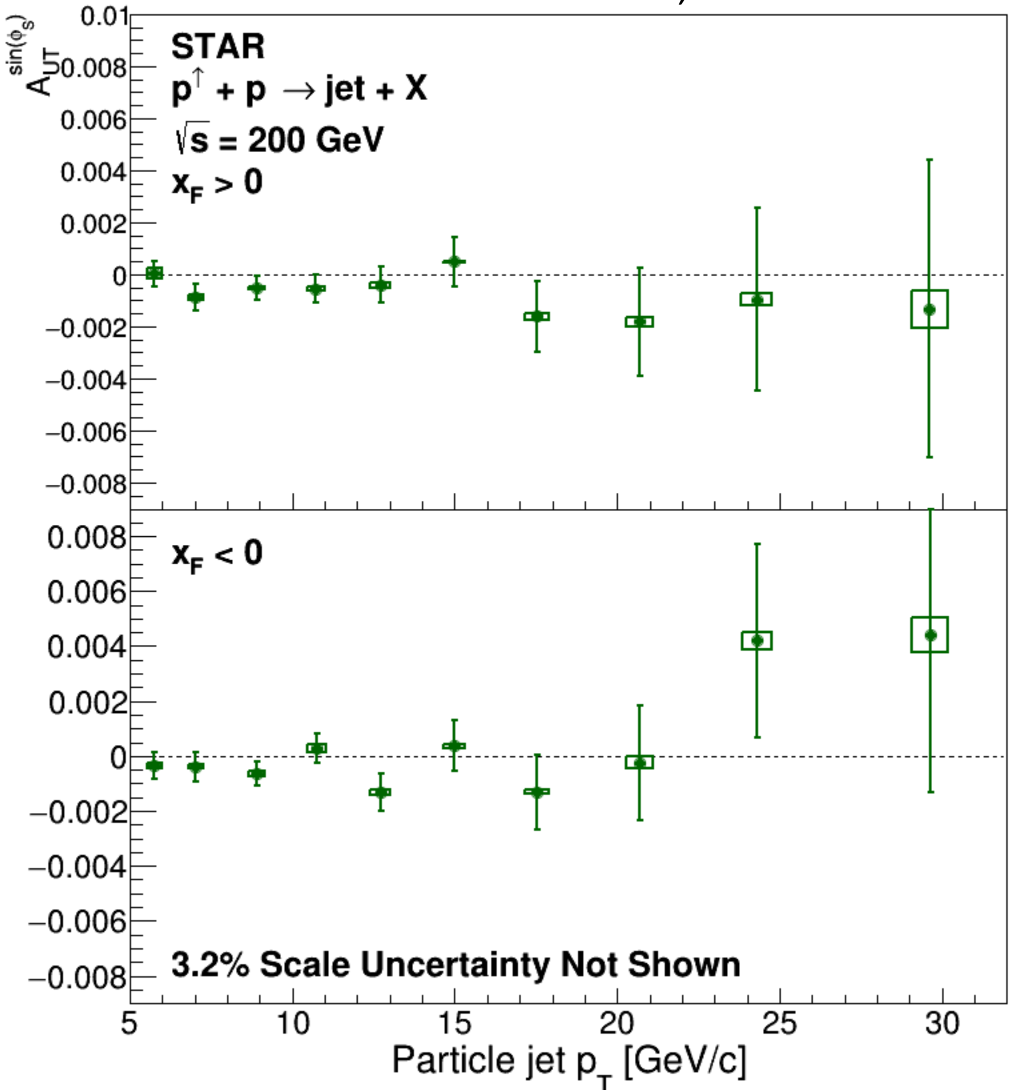
New STAR Result: Collins Asymmetry ($x_F < 0$)



√s = 200 GeV

New STAR Result: Inclusive Jet Asymmetry

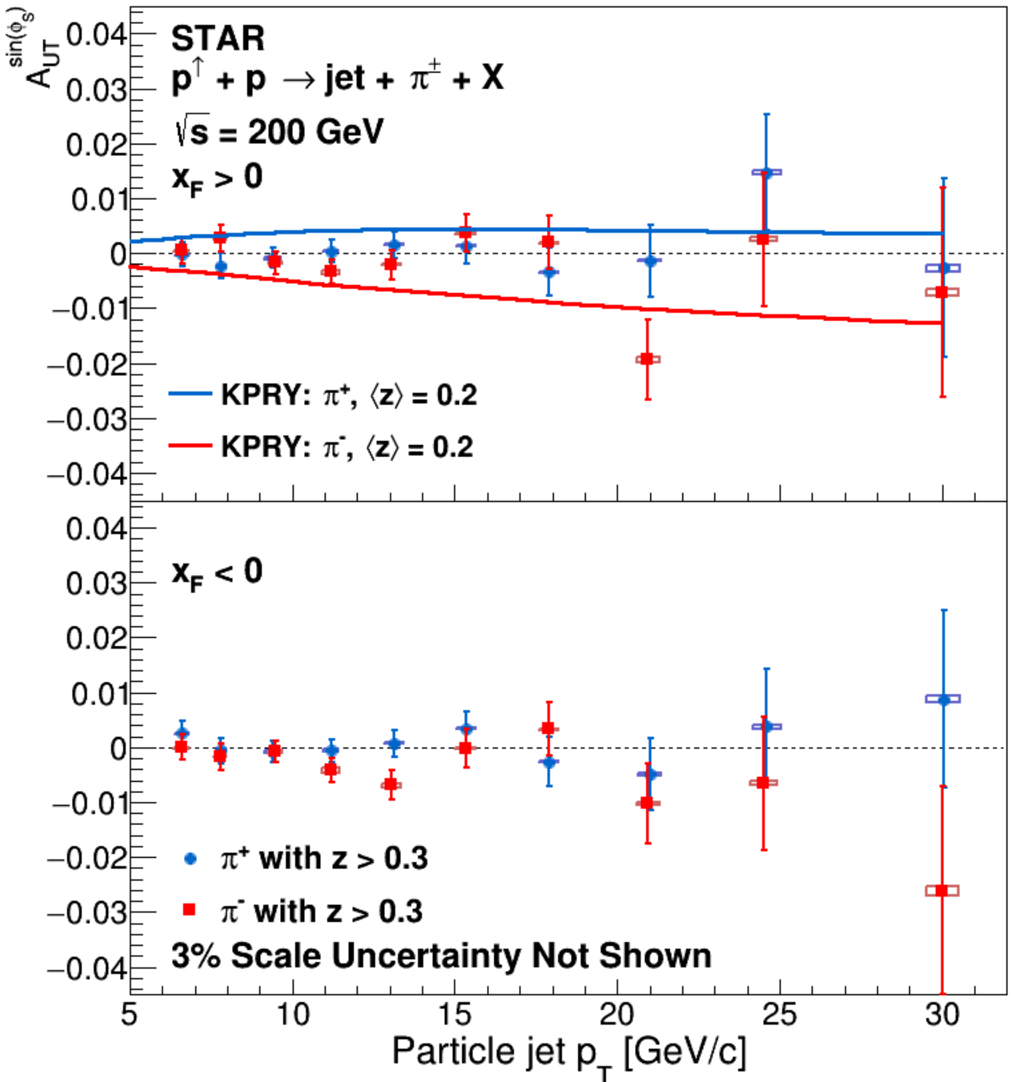
STAR, arXiv:2205.11800



√s = 200 GeV

New STAR Result: Hadron-Tagged Jet Asymm.

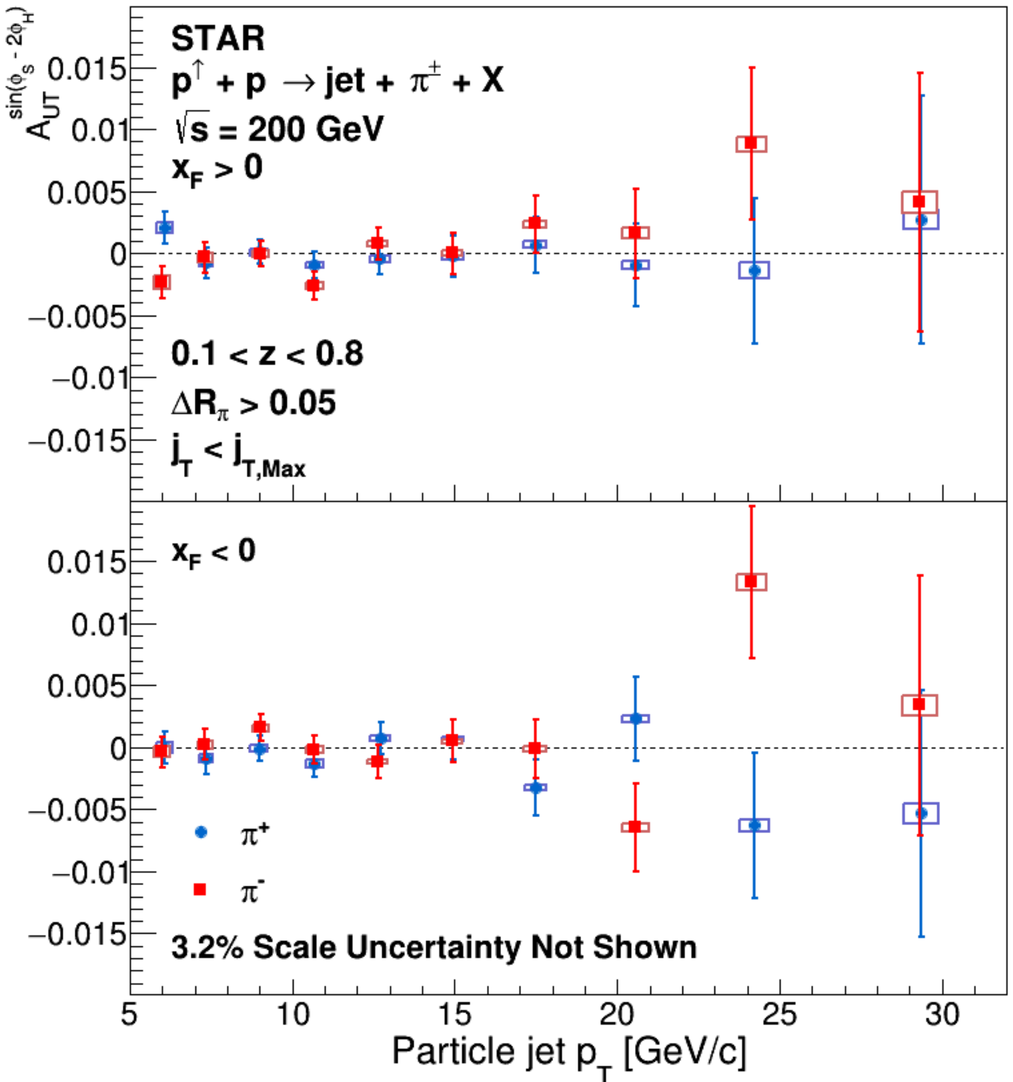
STAR, arXiv:2205.11800



√s = 200 GeV

New STAR Result: Collins-like Asymmetry

STAR, arXiv:2205.11800



√s = 200 GeV

New STAR Result: Collins-like Asymmetry

STAR, arXiv:2205.11800