Recent Results from RHIC

Jim Drachenberg

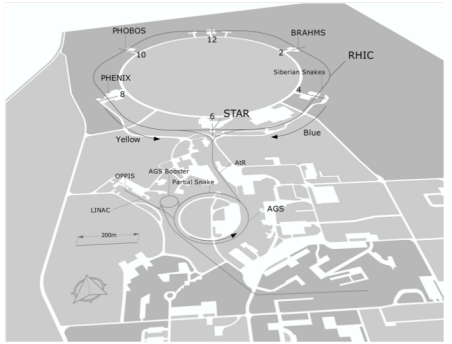
Workshop on Novel Probes of the Nucleon Structure in SIDIS, e^+e^-, and pp (FF2019)

March 14, 2019

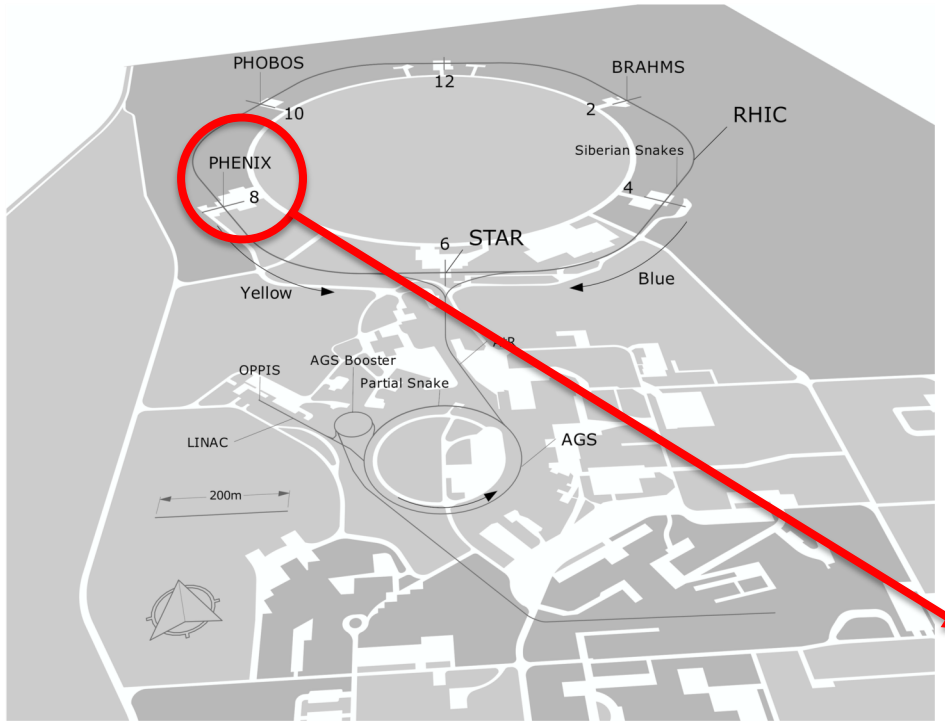
OUTLINE

- RHIC, PHENIX, and STAR
- Inclusive hadrons
- In-jet and dihadron
- Hyperons
- In progress
- Summary

ABILENE CHRISTIAN UNIVERSITY

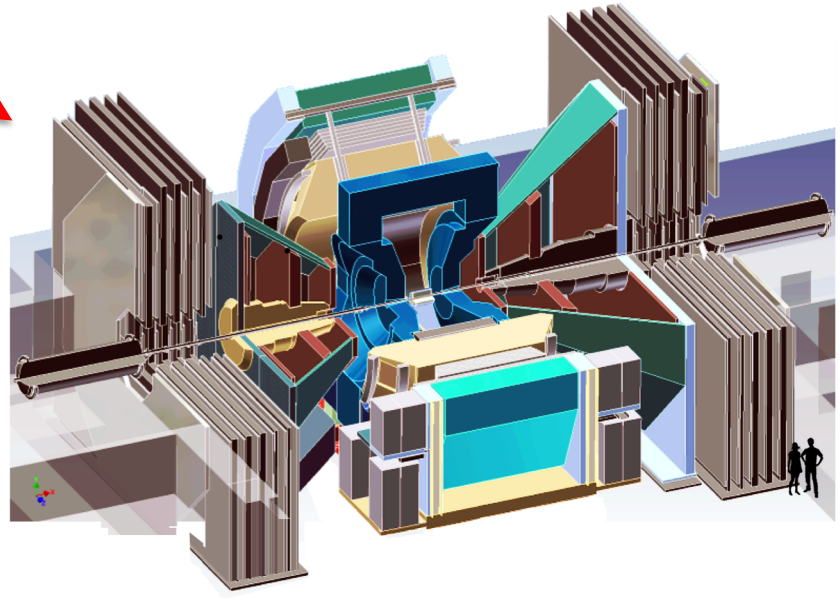


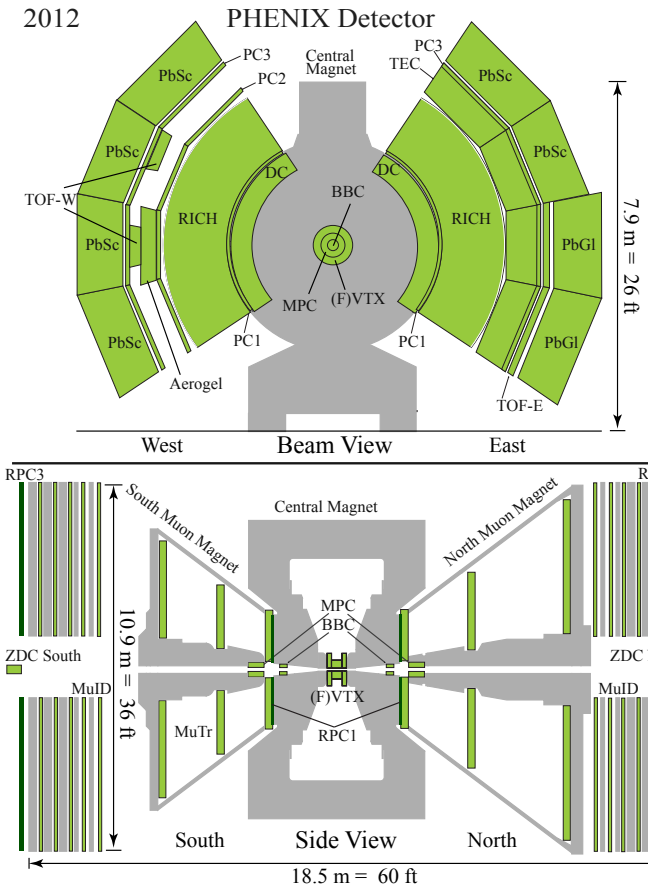
The Relativistic Heavy Ion Collider



RHIC as Polarized-proton Collider

- "Siberian Snakes" → mitigate depolarization resonances
- Choice of spin orientation → ***independent of experiment***
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill





Central Arms: $|\eta| < 0.35$

VTX + Tracking + PID + E/M Cal.

$e^{\pm}, \gamma, \pi^{\pm}, K$, and π^0

Muon Arms: $1.4 < |\eta| < 2.4$

VTX + Tracking + muon/hadron ID

$\mu^{\pm}, h^{\pm}\ (\pi, K), J/\psi, \Upsilon$

MPC: $3.1 < |\eta| < 3.9$

E/M cal.: π^0, η

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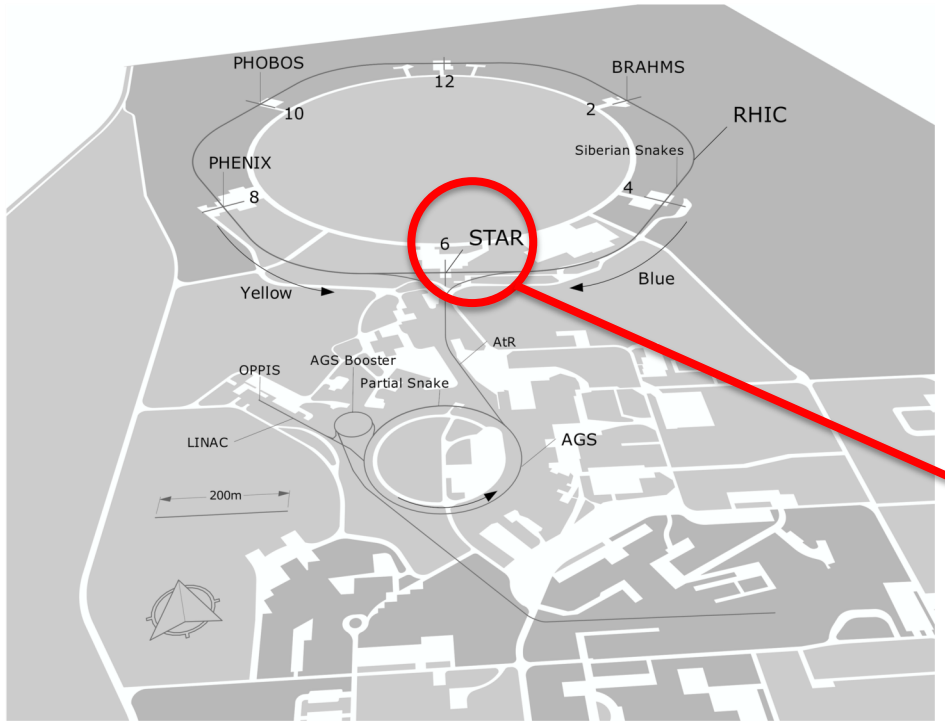

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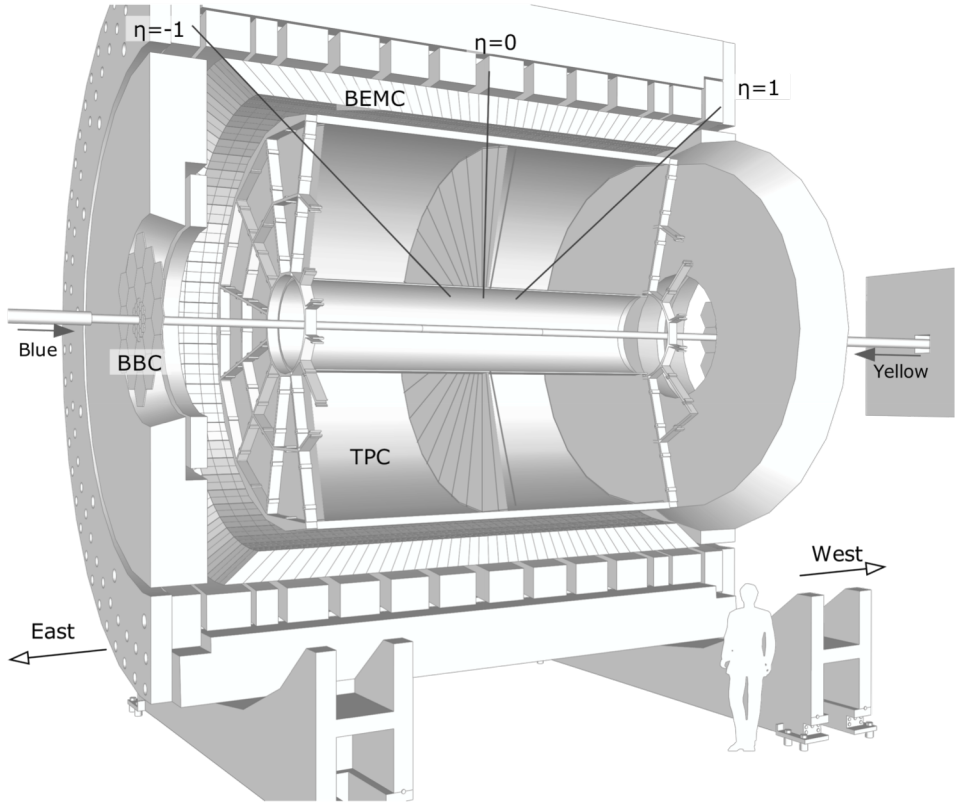

Central Detectors: $|\eta| < 1$

Tracking + PID + E/M Cal.

Jets, $\pi^{\pm}$, K, p, $e^{\pm}$, π^0, γ

Forward Detectors: $1 < \eta < 2$ and $2.5 < \eta < 4$

Tracking ($1 < \eta < 2$) + E/M Cal.

Jets ($1 < \eta < 2$), π^0, γ, $e^{\pm}$

What's New Since Last Time?

Some FF-relevant papers from STAR and PHENIX:

- Updates to dihadron and $\gamma - h^{\pm}$ correlations [PRD 98, 072004 (2018) & arXiv:1809.09045]
  - Implications for factorization-breaking in pp? [*See Joe's talk at 12:15 on Saturday!*]

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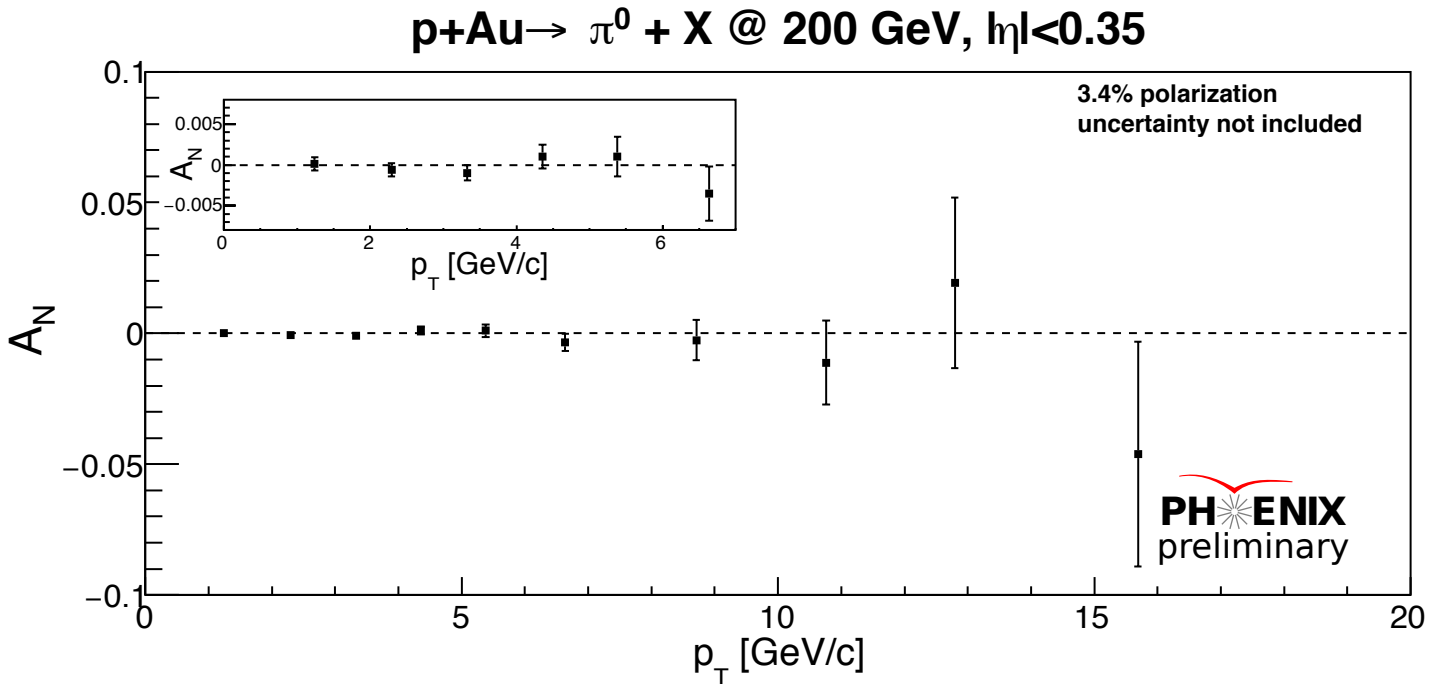
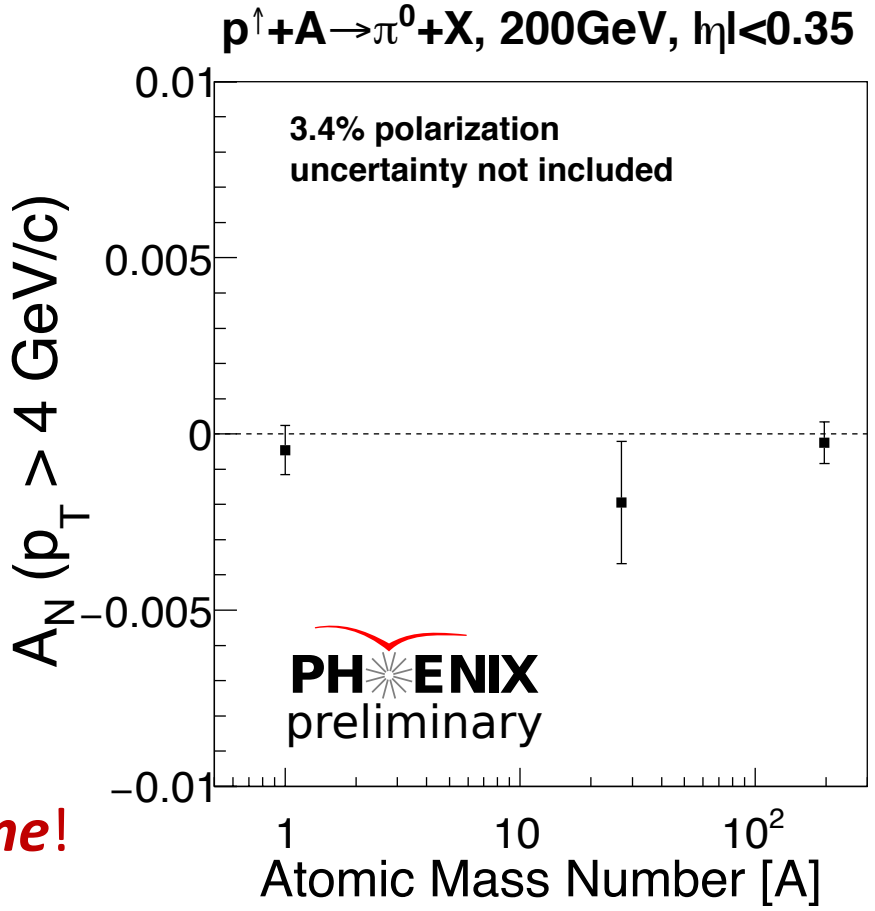
Inclusive Hadron: TSSA for pions in pp and pA





- STAR and PHENIX have shown no TSSA for inclusive jets and neutral pions/etas at midrapidity for a ***very long time***!
- *Anything change in pA?*
  - First look also shows a null asymmetry

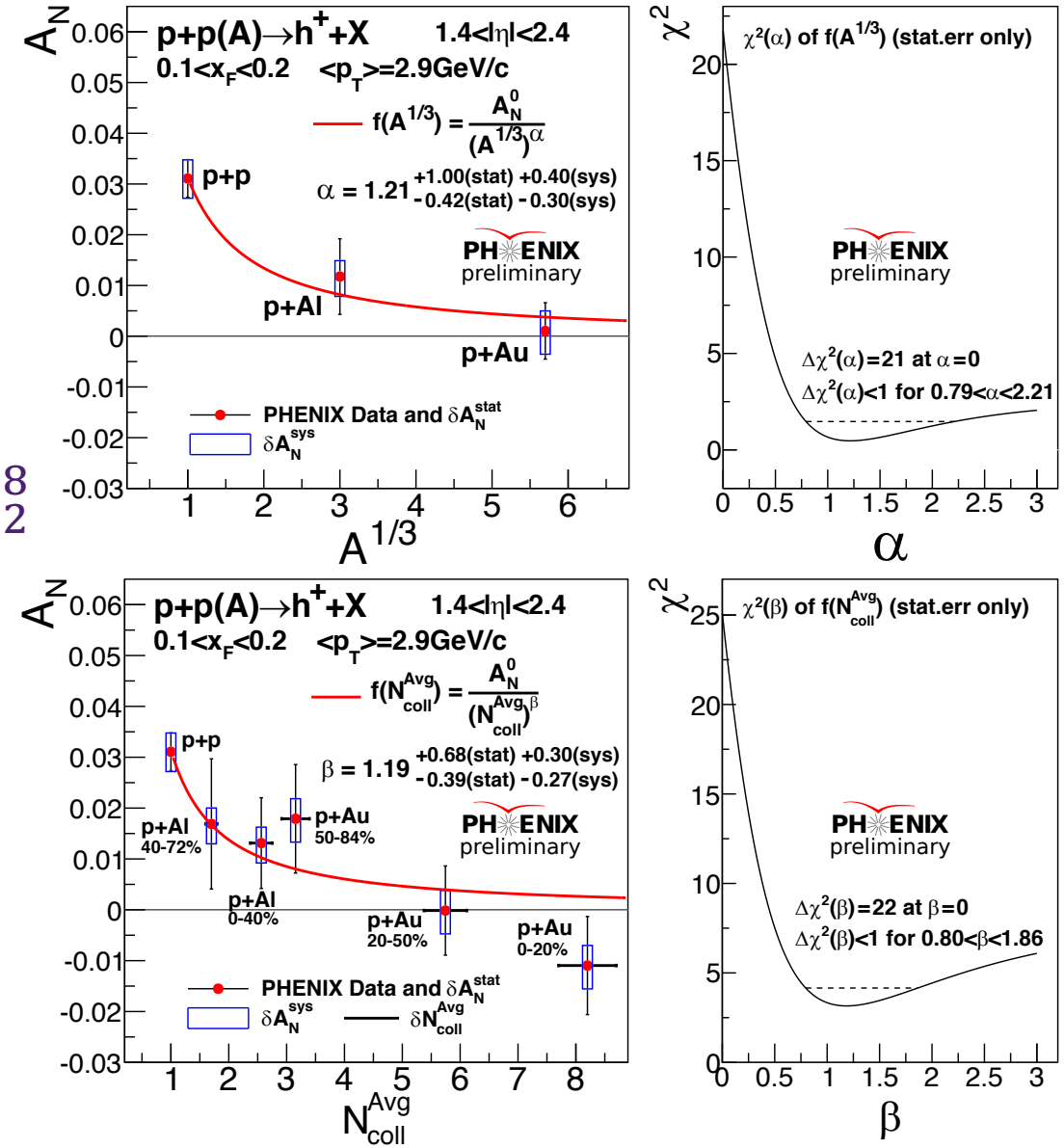
Inclusive Hadron: TSSA for pions in pp and pA

Different story at ***forward*** *pseudorapidity*

- Unidentified hadrons (π^+/K^+) in Muon Tracker ($1.4 \leq |\eta| \leq 2.4$)
- ***A-dependence*** in TSSA for $p^{\uparrow} + p(A) \rightarrow h^+ + X$
- Hatta et al. expect $A^{1/3}$ suppression to twist-3 FF from gluon saturation [PRD 95, 014008 (2017)]
  - Best fit from PHENIX data: $A^{-\alpha/3}$, $\alpha = 1.21^{+1.08}_{-0.52}$

What about impact parameter?

- Classify centrality with beam-beam counter
  - *Model calculation for # binary collisions*
- Asymmetry shows centrality dependence
  - Best fit from PHENIX data: $A^{-\beta}$, $\beta = 1.19^{+0.74}_{-0.47}$



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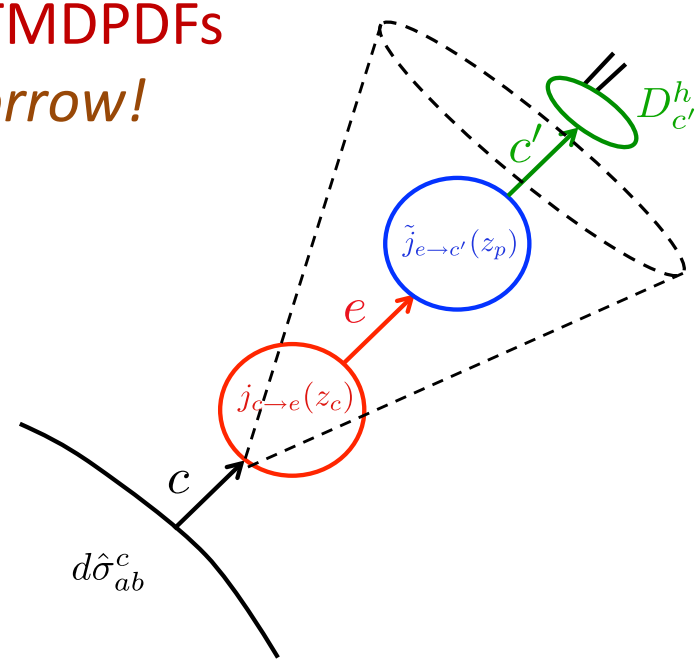
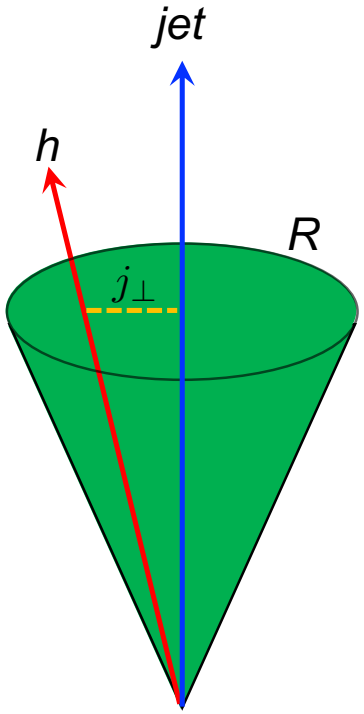
  - Implications for TMD factorization and universality?
  - More precise look at j_T structure of asymmetries

Hadrons Within Jets

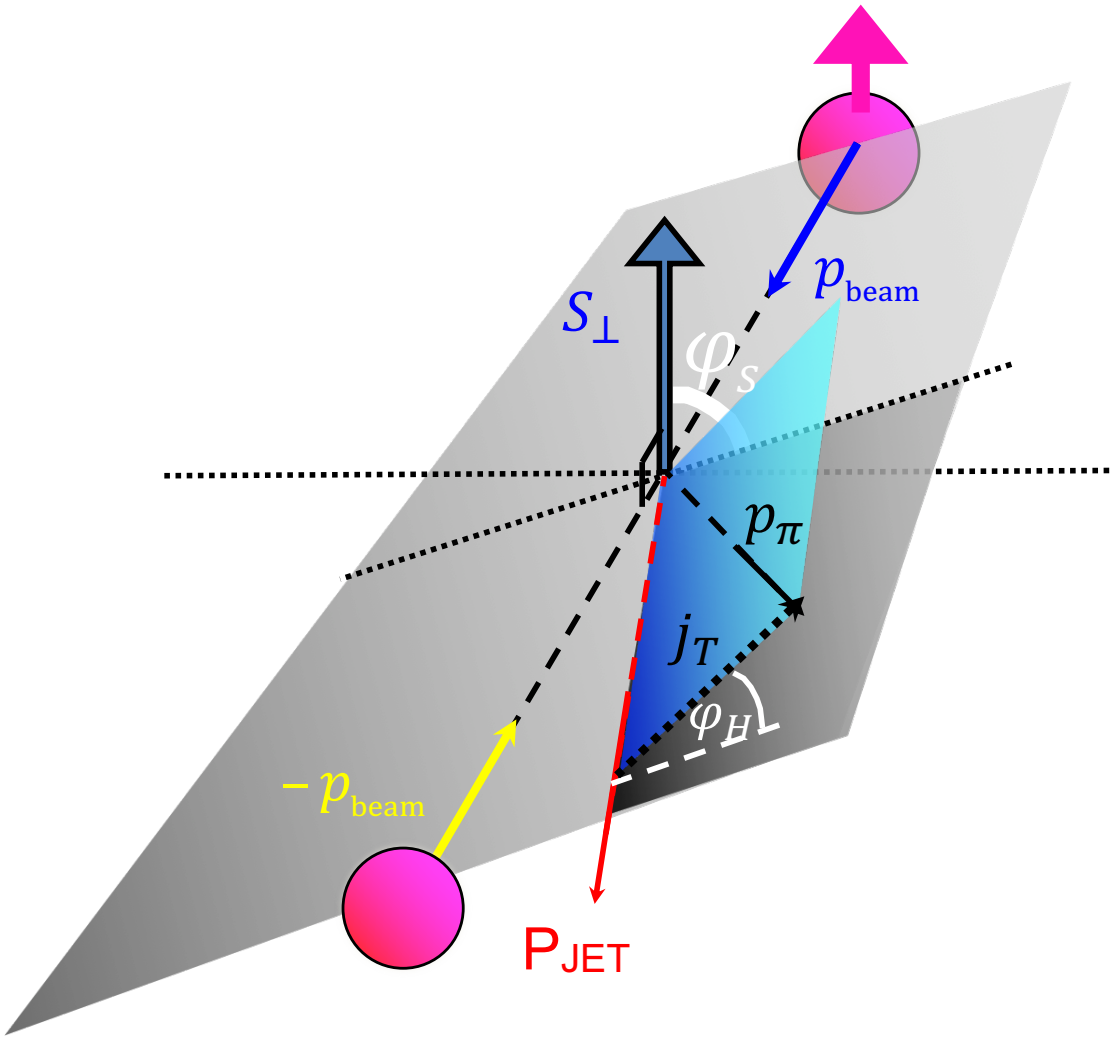
Following the approach of PRD 92, 054015 (2015) and JHEP11 (2017) 068

- Formulate NLO partonic cross-section in terms of *universal* jet functions
- Also define semi-inclusive transverse-momentum-dependent (TMD) jet functions
- Facilitate comparison with standard TMDFF from SIDIS and e^+e^- using inclusive jets with $j_\perp \ll p_{T,\mathrm{jet}} \times R$ calculated relative to *standard jet axis*
- Argue FFs universal to NLO, *including TMDFFs*
- No dependence on TMDPDFs
- *See Felix's talk, tomorrow!*





Polarized Hadrons Within Jets



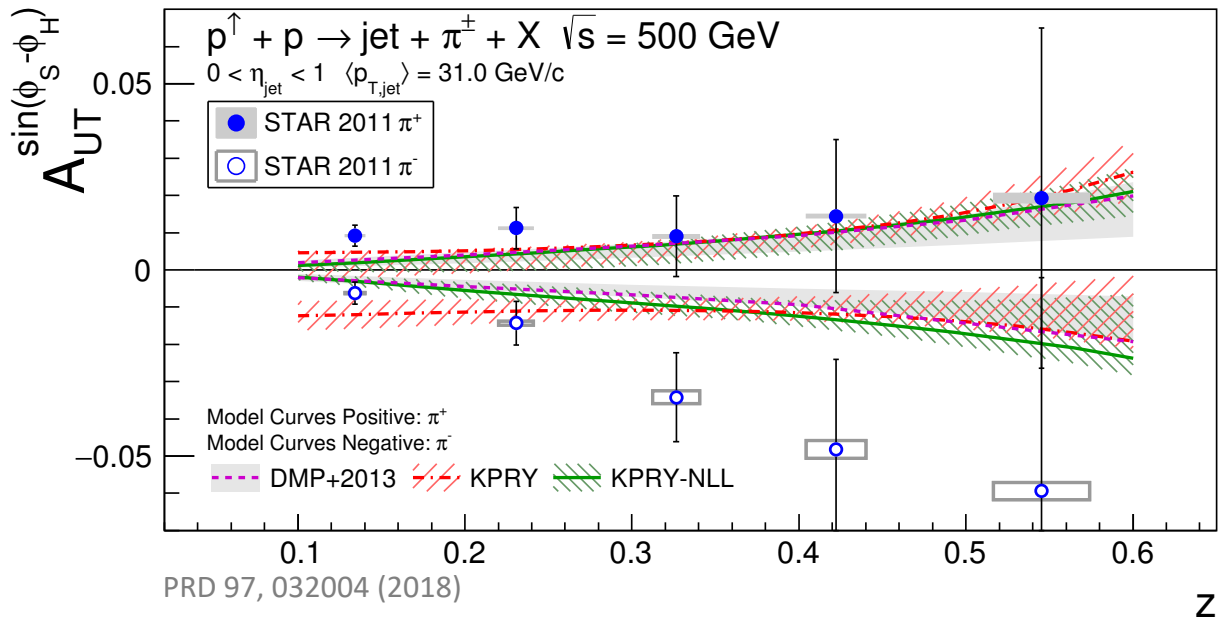
Anselmino et al., PRD 73, 014020 (2006)
F. Yuan, PRL 100, 032003 (2008)
D'Alesio et al., PRD 83, 034021 (2011)

Hadrons-in-jets have long been proposed as a means to probe the Collins effect

- Quarks inside proton have transverse polarization
- Quark polarization transfer during hard scatter
- Distribution of hadrons from fragmenting quark correlated to quark polarization
- Azimuthal asymmetry in distribution of hadrons within the jet
  - Requires non-zero quark transversity
  - Requires spin-dependent TMD FF

(*analogous effect for gluon linear polarization*)

Collins Effect: Universality and Evolution



PRD 97, 032004 (2018)

Models based on SIDIS/e^+e^-

- *Assume universality and robust factorization*
- **DMP&KPRY: no TMD evolution**
- **KPRY-NLL: TMD evolution up to NLL**

Consistency between models and STAR data at 95% confidence level

→ Suggests robust factorization and universality

To evolve or not to evolve?

$\chi^2/\nu = 14/10$ (w/o) vs. $17.6/10$ (with)

For now, "Beauty is in the eye of the beholder!"

(a.k.a. need more data!)

STAR Collaboration, PRD 97, 032004 (2018)
D'Alesio, Murgia, Pisano: PLB 773, 300 (2017)
Kang, Prokudin, Ringer, Yuan: PLB 774, 635 (2017)

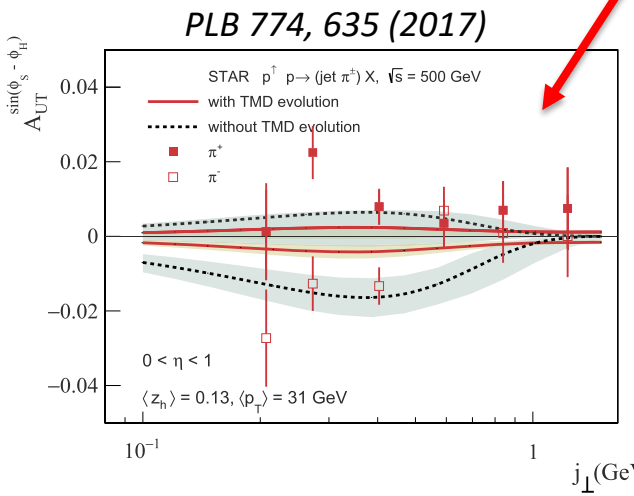
Collins Effect at RHIC

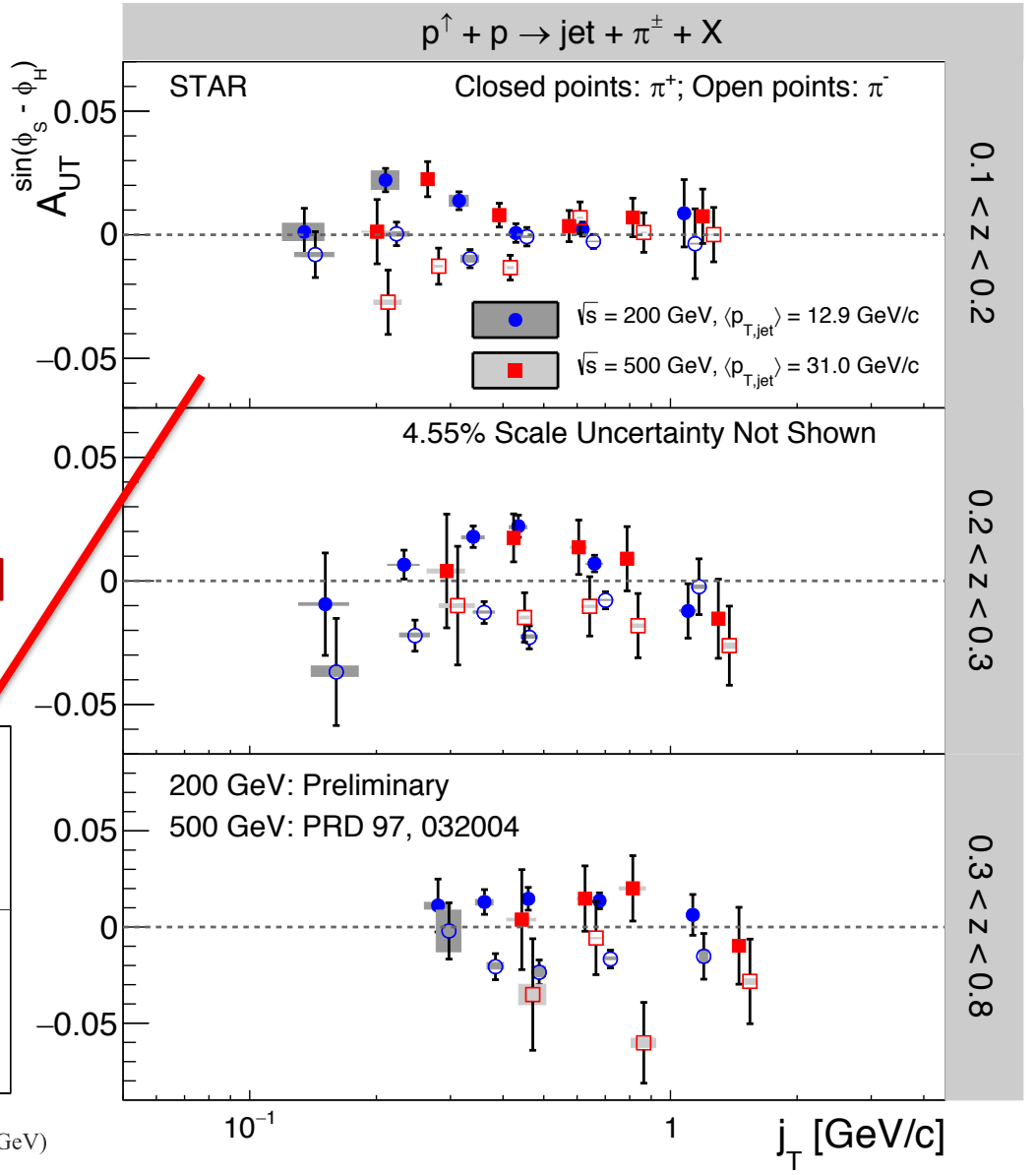
Evaluate the j_T dependence directly

- 200 and 500 GeV in ***complete agreement*** for common x_T
- Shape of asymmetries vs. j_T changes with z
  - Peak appears to shift to higher j_T for increasing z
  - Suggests asymmetry does not factorize as

$$A_{UT} \sim f(j_T) \times f(z)?!$$

- Models agree relatively well but more work needed
  - ***More unpolarized data!***
  - More thought at low j_T





500 GeV: STAR Collaboration, PRD 97, 032004 (2018)
200 GeV: Int. J. Mod. Phys. Conf. Ser. 40, 1660040

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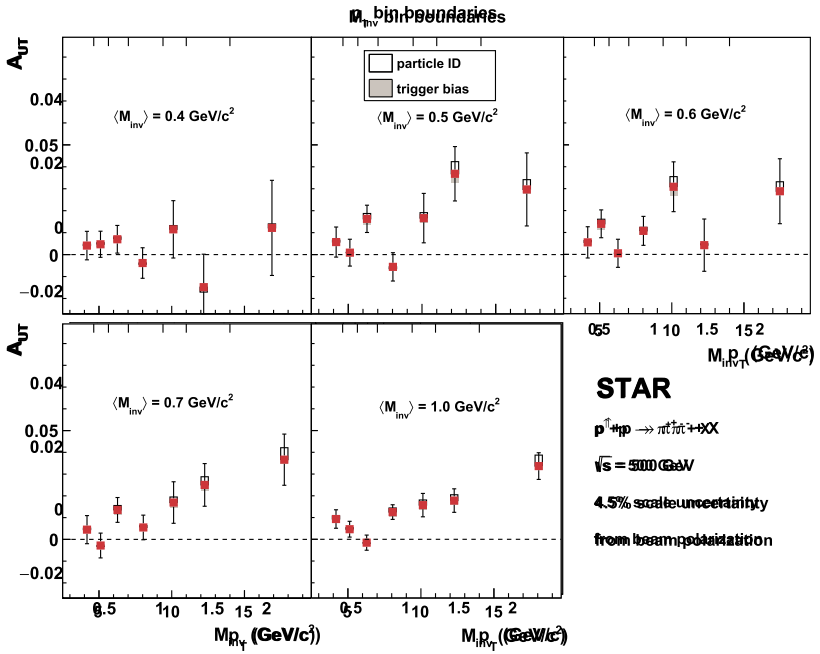
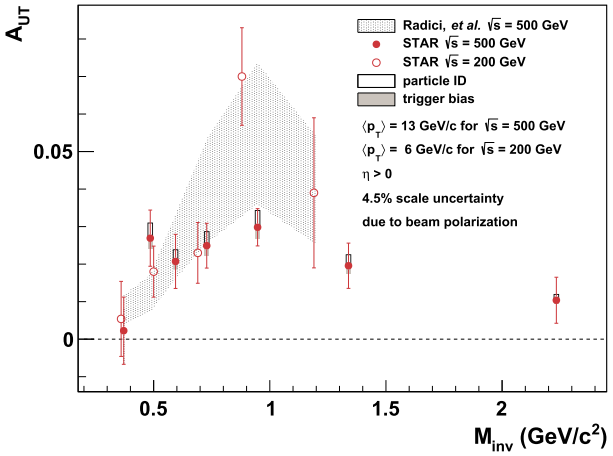
  - More precise look at j_T structure of asymmetries
- TSSA in dihadrons from $p + p$ at $\sqrt{s} = 500$ GeV [PLB 780, 332 (2018)]
  - Access to transversity in pp through collinear factorization framework
  - 200 GeV contributed to global analysis [*See Alessandro's talk at 11:50, tomorrow!*]

Dihadrons: TSSA for charged pions





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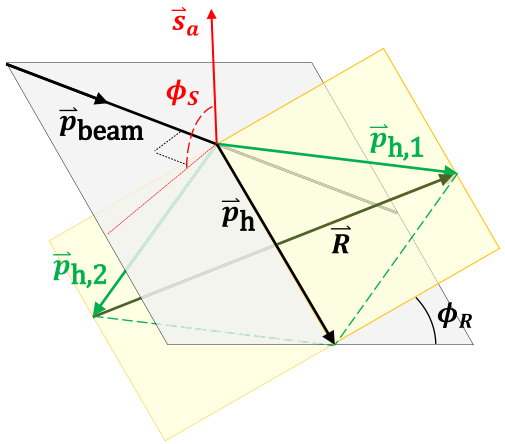

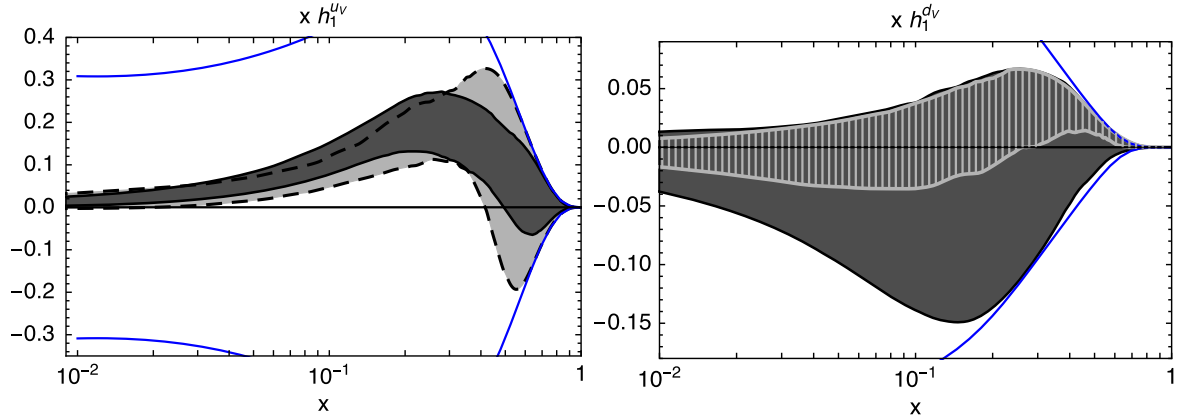

Radici and Bacchetta, PRL 120, 192001 (2018)

Significant dihadron asymmetries at RHIC (200 & 500 GeV)

- *Strong dependence on pair p_T*
- In terms of invariant mass, data are consistent with 68% of replicas based on SIDIS & e^+e^- data → Same as in SIDIS!
- More unpolarized data needed! [*we're working on it!*]
- 200 GeV: ***Significant impact*** on global transversity analysis!
  - *See Alessandro's talk at 11:50, tomorrow*

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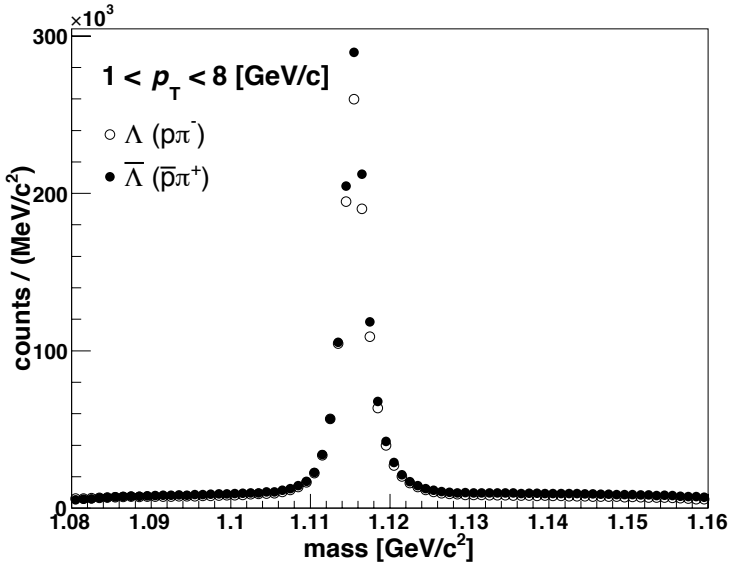
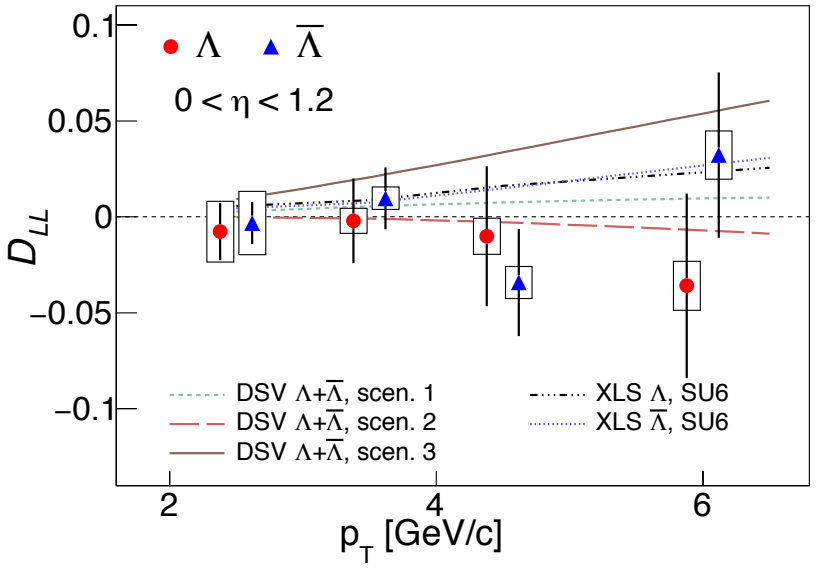
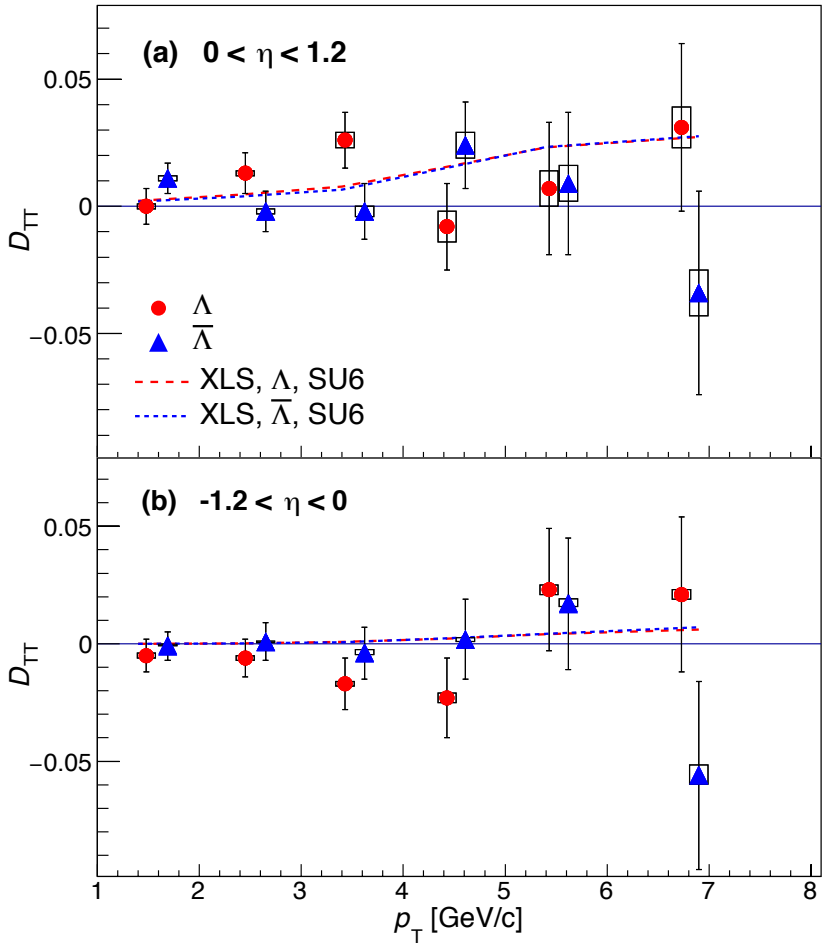
  - 200 GeV contributed to global analysis [*See Alessandro's talk at 11:50, tomorrow!*]
- Updates to spin-asymmetries in hyperon production [PRD 98, 91103 & 112009 (2018)]
  - Sensitive to polarized FF

Hyperons







First measurement of Λ D_{TT} at RHIC!

- Sensitive to transversity and transversely polarized FF
- Possible channel to constrain transversity of strange quarks
- Consistent with model calculation from PRD 70, 034015 (2004) and PRD 73, 077503 (2006)

Improved precision for Λ D_{LL}

- Sensitive to polarized PDF and polarized FF

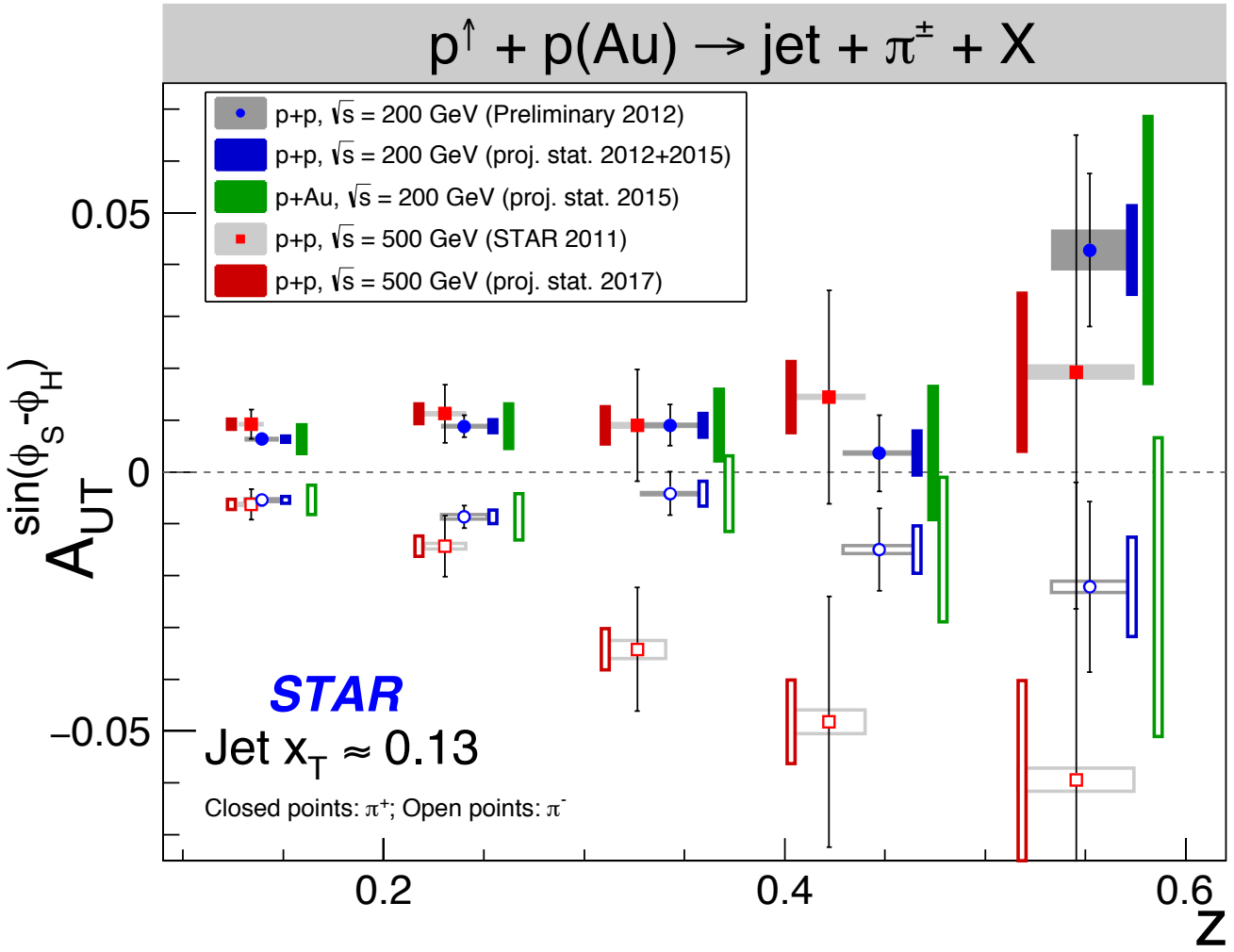
STAR Collaboration, PRD 98, 91103 (2018)
STAR Collaboration, PRD 98, 112009 (2018)

In Progress

Successful runs in 2015 and 2017

- Far more precise comparison of 200 and 500 GeV
- Possible extraction of kaon Collins
- First look at Collins in $p + A$

  → *Unique window into hadronization*



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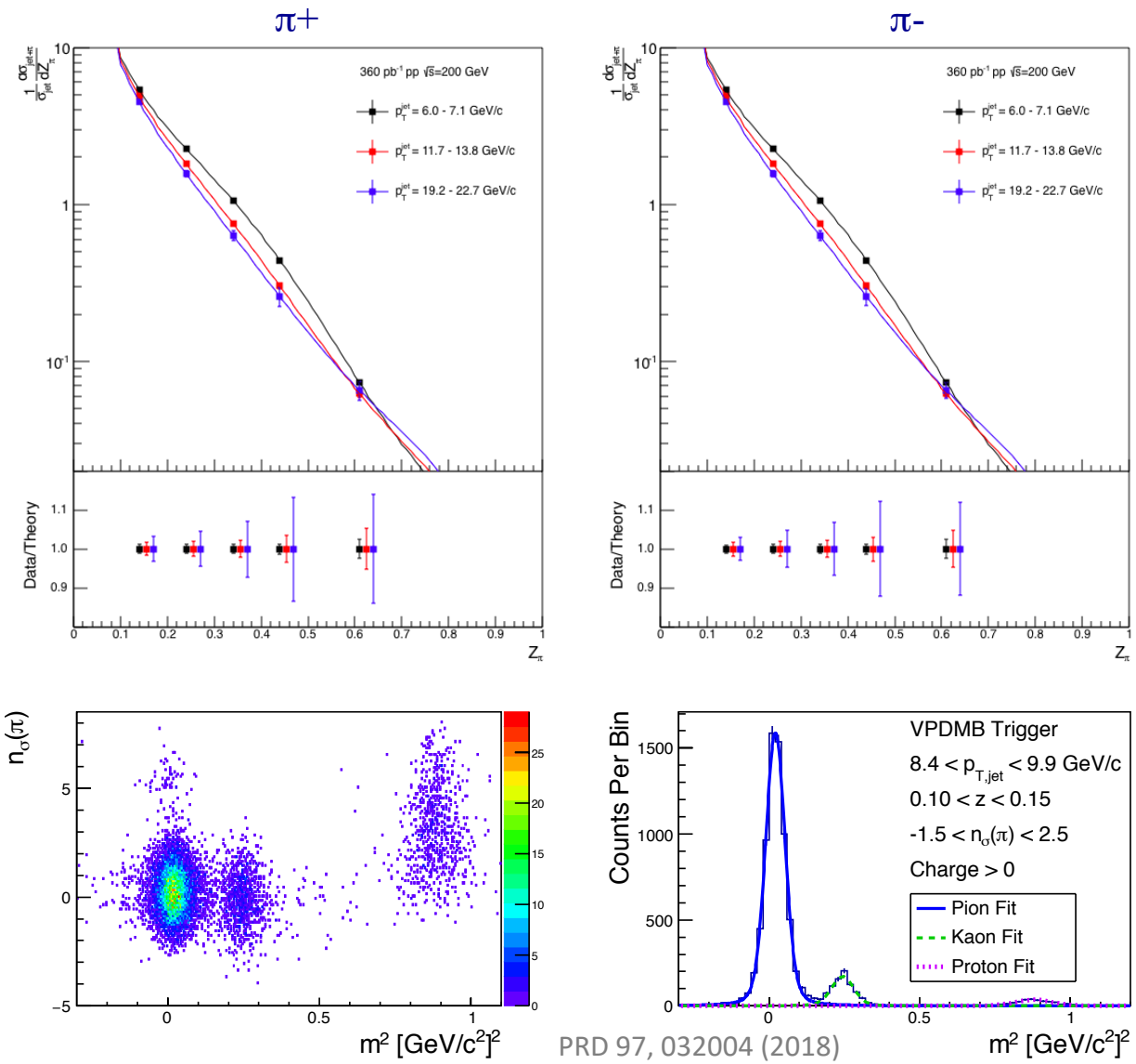
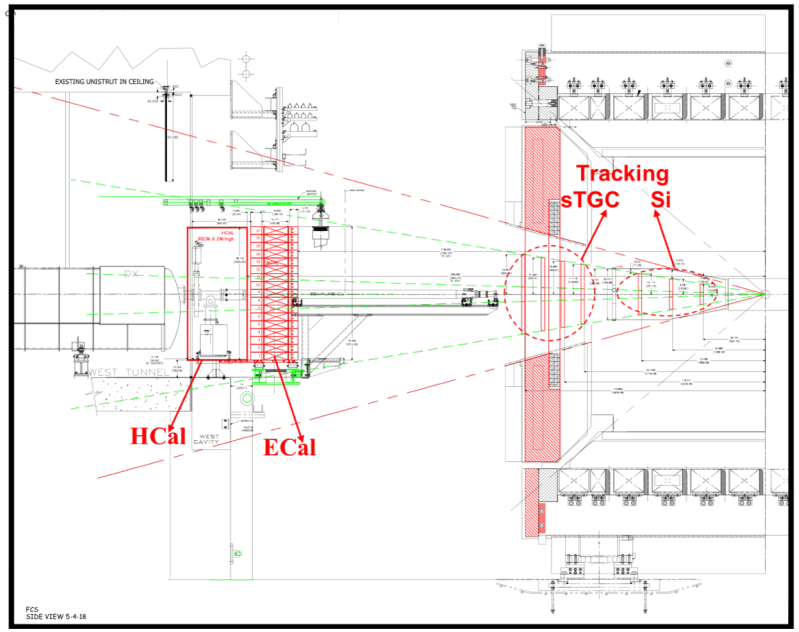


PRD 97, 032004 (2018)

The RHIC Spin Collaboration, arXiv:1602.03922

Unpolarized in-jet & dihadron studies ***ongoing***

- STAR equipped with ***particle ID***, e.g. time-of-flight (TOF) and energy-loss (dE/dx) in TPC
- Use PID to identify pion-in-jet, kaon-in-jet, etc.
  - *Enhance sensitivity to strangeness w/ K-tag*
- ***STAR forward upgrade!*** [*see Elke's talk!*]



Summary

- Improved precision for inclusive hadron asymmetries in pp and new data for pA
  - Midrapidity neutral pions and etas consistent with zero
  - Forward charged hadron asymmetries show dependences in A and centrality
- New look at j_T dependence of Collins asymmetries in pp
  - Consistency between 200 and 500 GeV
  - Appears that the asymmetry does not factorize as $A_{UT} \sim f(j_T) \times f(z)$
  - Analysis of unpolarized in-jet FF underway
- Finalized and published results from dihadron asymmetries
  - Already impacting global transversity analyses
  - Analysis of unpolarized dihadron FF underway
- Published results from lambda hyperons
  - First look at D_TT at RHIC
  - Improved precision of D_LL
- *Lots of new data and homework!*