STAR Results and Plans

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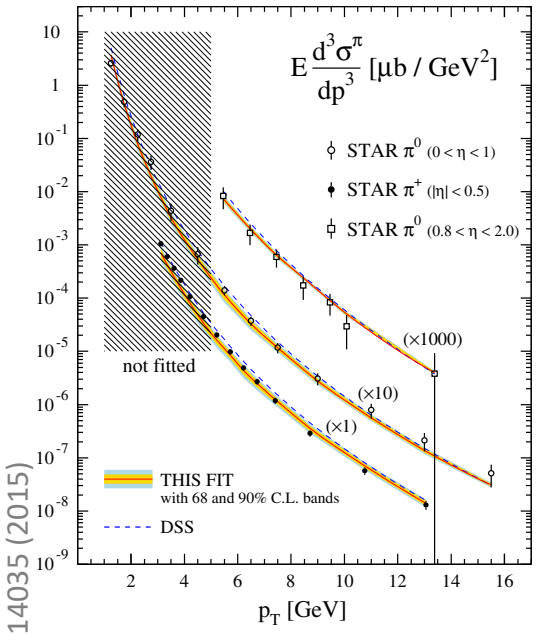
Fragmentation Functions 2018

February 20, 2018

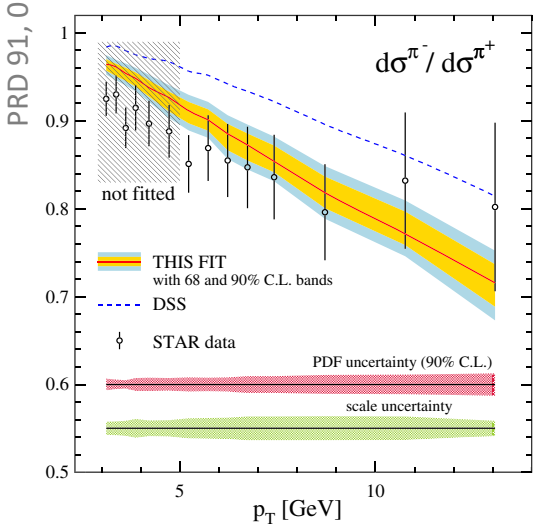
OUTLINE

- Inclusive hadrons
- Jet Reconstruction at STAR
- Collins Effect
- Di-hadrons
- Hyperons
- What's next

Inclusive Hadron Constraints on FFs

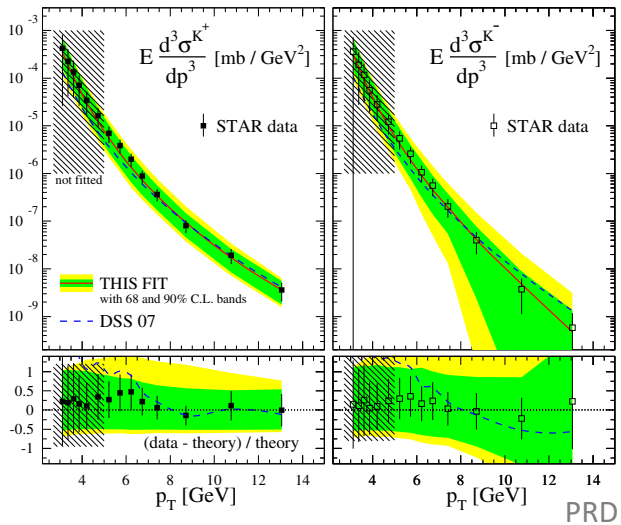


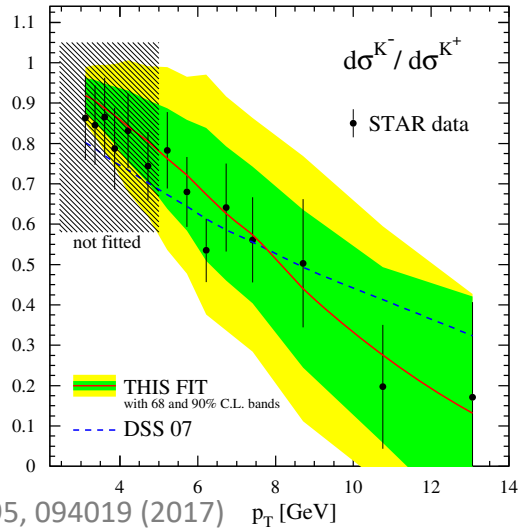
PRD 91, 014035 (2015)



STAR results included in "reloaded" DSS analysis

- $\pi^{\pm}$ and K at midrapidity
  - Fit to π^+, K^+ and π^-/π^+, K^-/K^+ ratios
- π^0 at mid and intermediate pseudorapidity
- Tension between RHIC & ALICE results?
  - *Excluding data with $p_T < 5$ GeV/c largely resolves*
  - *Remaining tension accounts for some degree of imprecision in $D_g^{\pi^+}$*
  - *Theoretical scale uncertainty remains large*
  - *STAR and ALICE agree relatively well below cutoff*

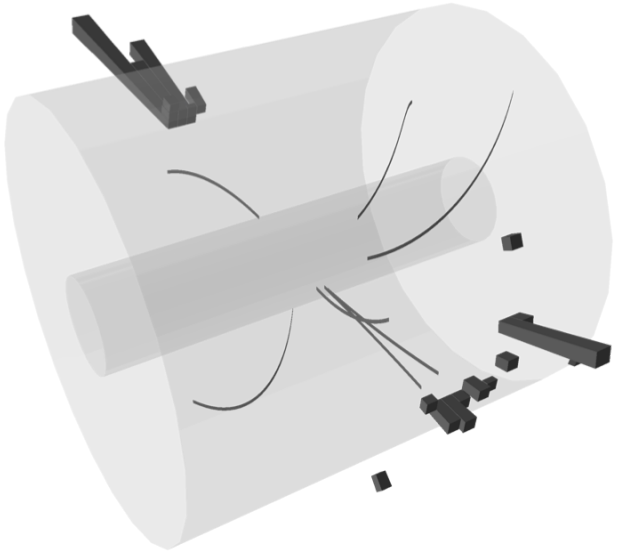




PRD 95, 094019 (2017)

Jet Reconstruction at STAR

STAR Di-jet event at detector level



e.g. Anti-k_T algorithm

JHEP 0804, 063 (2008)

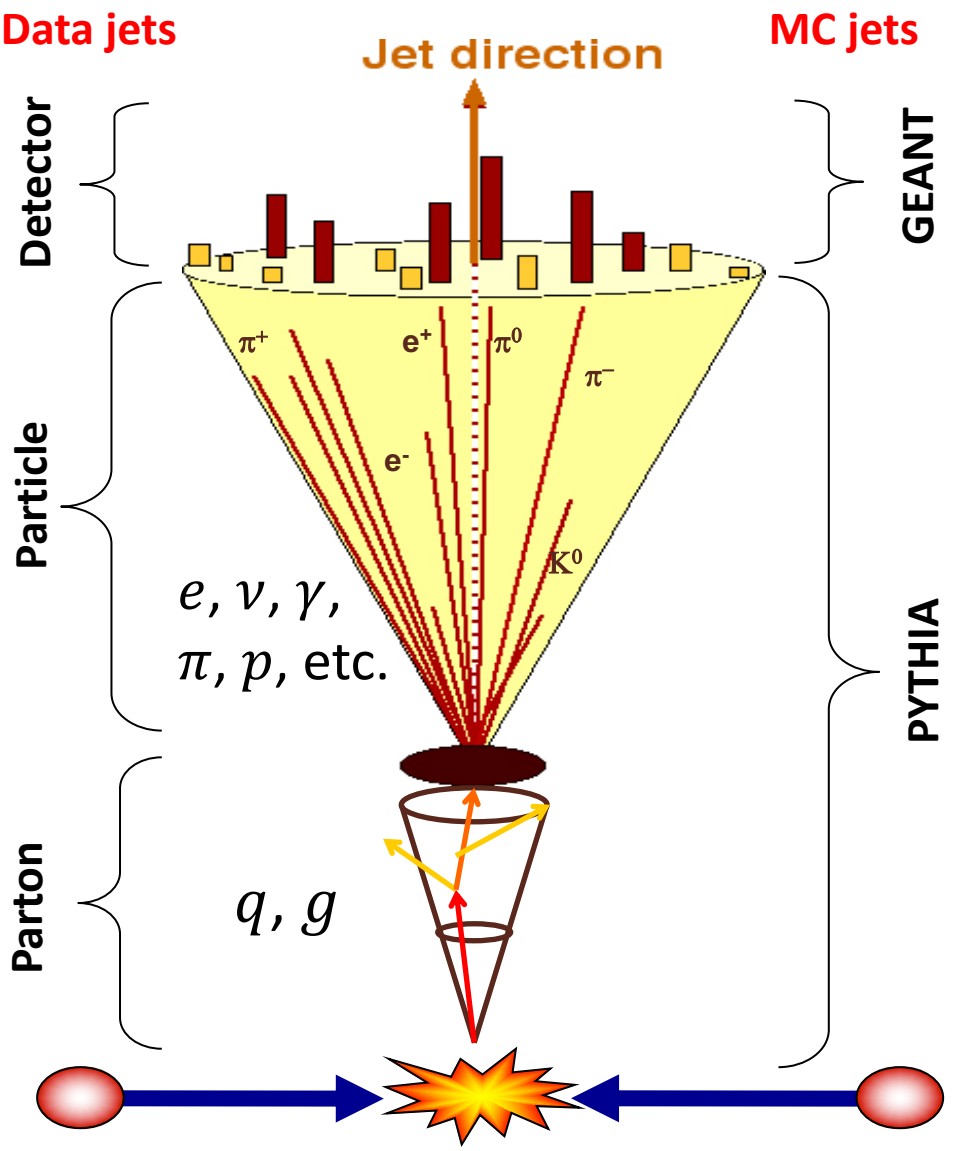
Radius parameter $R = 0.5$ or 0.6

Use **PYTHIA** + **GEANT** to quantify detector response

$\pi^{\pm}$ **Kinematic Variables**

$z - \pi$ momentum / jet momentum

$j_T - \pi\ p_T$ relative to jet axis



Jet Reconstruction at STAR

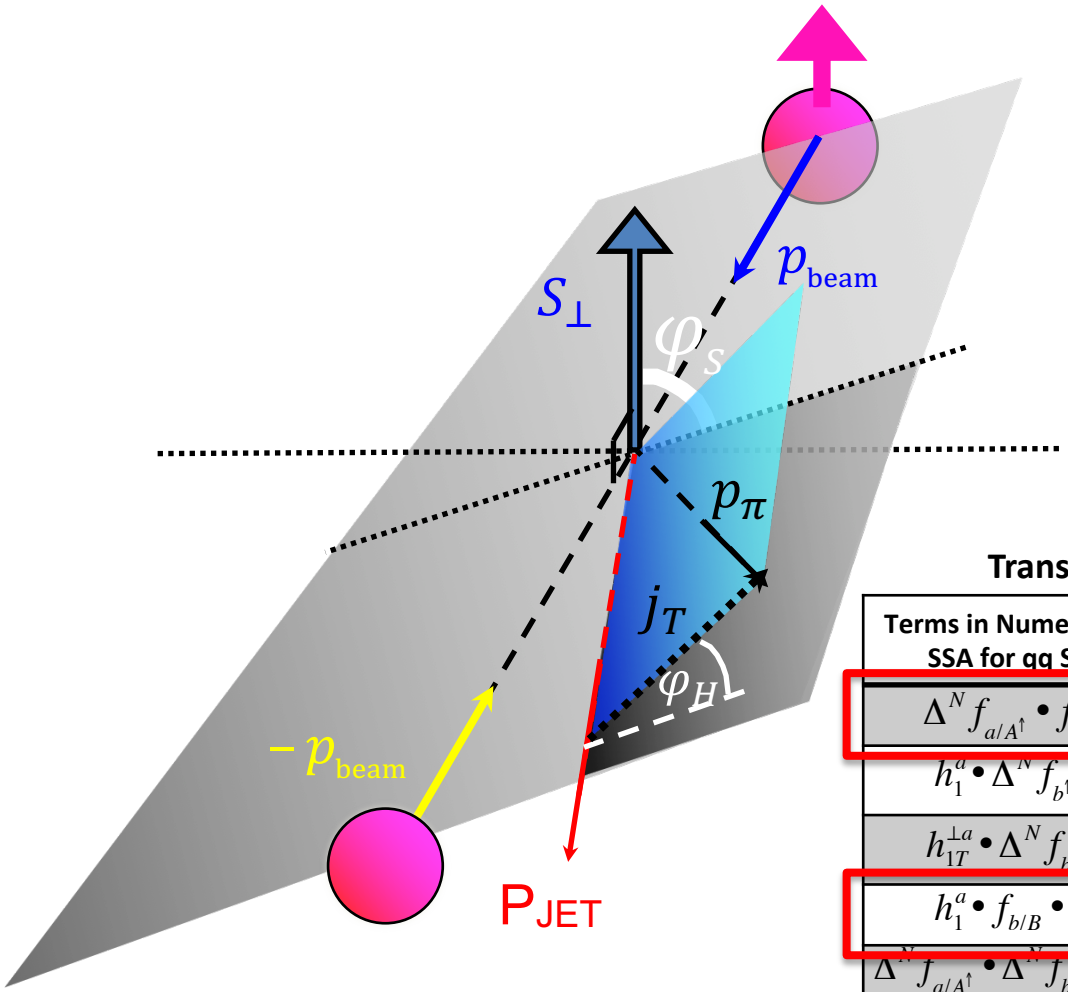
From the detector data

- Anti-k_T jet-finding algorithm with $R = 0.6$ (200 GeV) or $R = 0.5$ (500 GeV)
- Inputs
  - Charged-particle "track" momenta from TPC ($p_T \geq 0.2$ GeV/c) – assume m_π
  - E/M energy from calorimeter "towers" ($E_T \geq 0.2$ GeV) – assume $m = 0$
- Cuts/requirements
  - Tracks pointing to towers: $E_T' = E_T - p_T c$ (negative energy set to zero)
  - Tracks required to pass "quality" cuts and stem from collision vertex
  - $\geq 6\%$ of jet energy from charged particles w/ total $p_{T,\mathrm{chg}} \geq 0.5$ GeV/c

From the Monte Carlo simulation

- Simulate QCD events with PYTHIA (e.g. Perugia 0 or Perugia 2012)
- Simulate detector response with GEANT
- Embed simulated ADCs into randomly triggered real data events
- Run Anti-k_T algorithm (same R parameter as data) at three levels:
  - **"detector-jet":** simulated detector tracks/towers
  - **"particle-jet":** all stable, hadronized, final-state PYTHIA particles
  - **"parton-jet":** PYTHIA hard-scattered partons including intial/final-state radiation but excluding beam remnant and underlying event

STAR Jets and Transverse Spin Physics



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

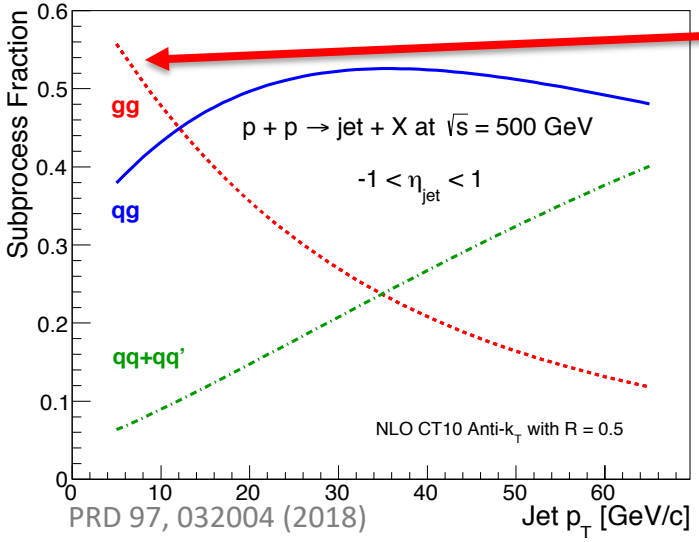
Asymmetry modulations sensitive to various contributions (often involving *transversely polarized quarks* or *linearly polarized gluons*)

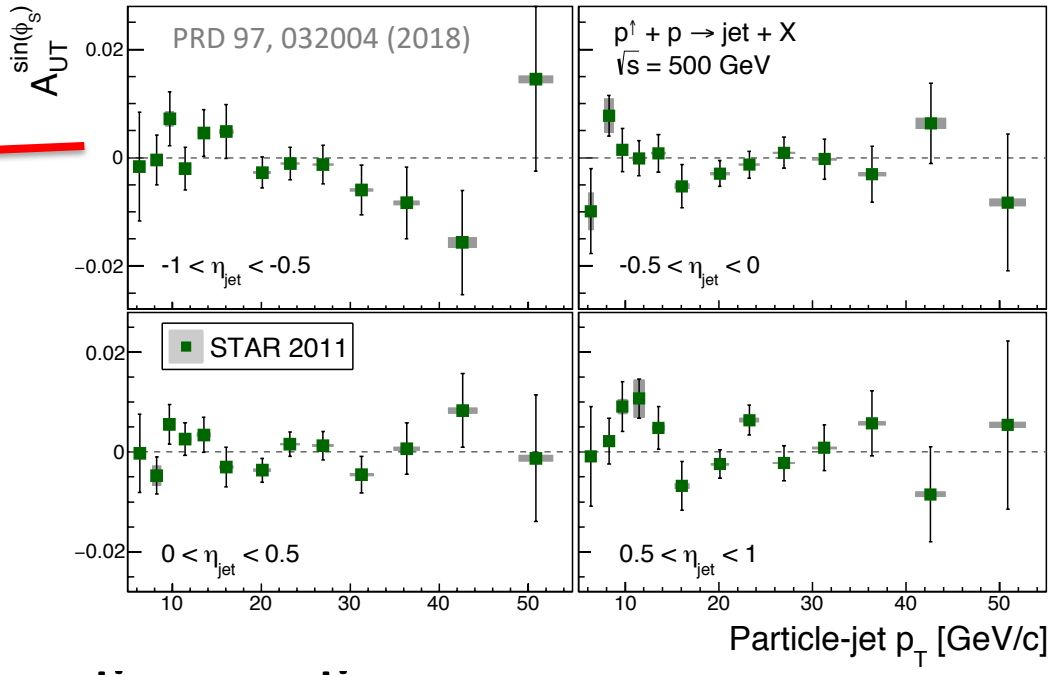
A_{UT} – Transverse single-spin asymmetry (also written A_N)

Transverse Momentum Dependent (TMD) Approach

Terms in Numerator of TMD SSA for qq Scattering	English Names	Modulation
$\Delta^N f_{a/A^\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers • PDF • FF	$\sin\left(\phi_{S_A}\right)$
$h_1^a \bullet \Delta^N f_{b^\uparrow/B} \bullet D_{\pi/q}$	Transversity • Boer-Mulders • FF	$\sin\left(\phi_{S_A}\right)$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b^\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity • Boer-Mulders • FF	$\sin\left(\phi_{S_A}\right)$
$h_1^a \bullet f_{b/B} \bullet \Delta^N D_{\pi/q^\uparrow}$	Transversity • PDF • Collins	$\sin\left(\phi_{S_A} - \phi_H\right)$
$\Delta^N f_{a/A^\uparrow} \bullet \Delta^N f_{b^\uparrow/B} \bullet \Delta^N D_{\pi/q^\uparrow}$	Sivers • Boer-Mulders • Collins	$\sin\left(\phi_{S_A} - \phi_H\right)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta^N D_{\pi/q^\uparrow}$	Pretzelocity • PDF • Collins	$\sin\left(\phi_{S_A} + \phi_H\right)$
$\Delta^N f_{a/A^\uparrow} \bullet \Delta^N f_{b^\uparrow/B} \bullet \Delta^N D_{\pi/q^\uparrow}$	Sivers • Boer-Mulders • Collins	$\sin\left(\phi_{S_A} + \phi_H\right)$

Inclusive Jet Constraints on Gluon Twist-3/TMDs





Data kinematics corrections:

- Find simulated jets matched across all three levels: ***detector, particle, parton***
- Evaluate shift between **detector-jet** and **particle-jet** kinematics
- Apply shift to kinematics of real data jets

Inclusive jets at RHIC dominated by gluonic subprocesses at lower jet p_T

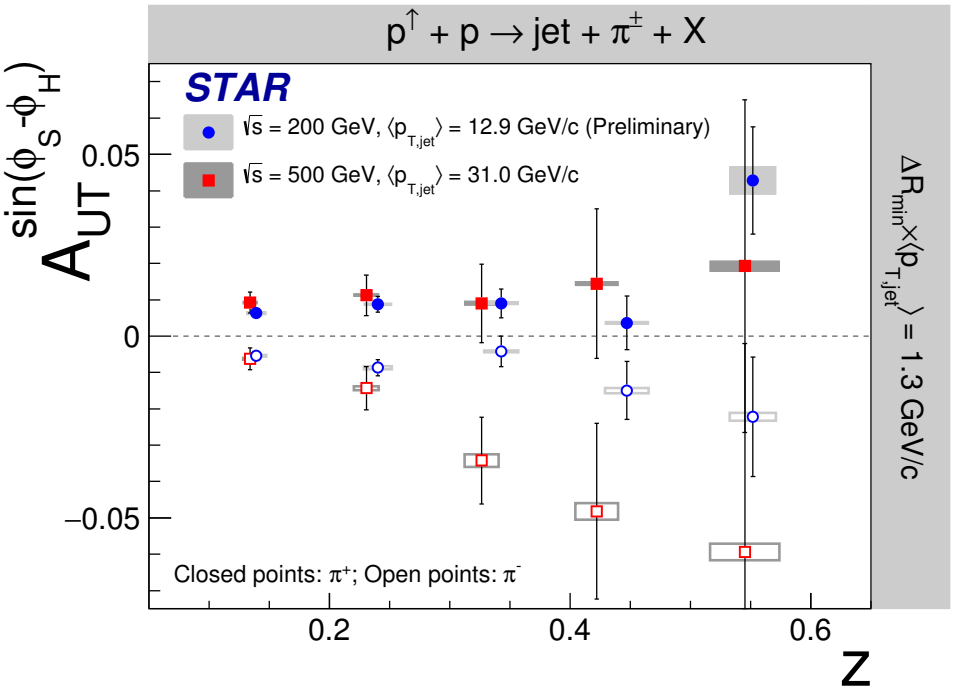
$A_{UT}^{\sin(\phi_S)}$ at $\sqrt{s} = 500$ GeV consistent with zero

Similar to the case of jets, dijets, and neutral pions at $\sqrt{s} = 200$ GeV

STAR Hadrons Within Jets: Collins Effect

New 500 GeV Paper: Phys. Rev. D 97, 032004 (2018)

200 GeV: Int. J. Mod. Phys. Conf. Ser. 40, 1660040



Calculate $A_{UT}^{\sin(\phi_S-\phi_H)}$ for all charged particles within jets

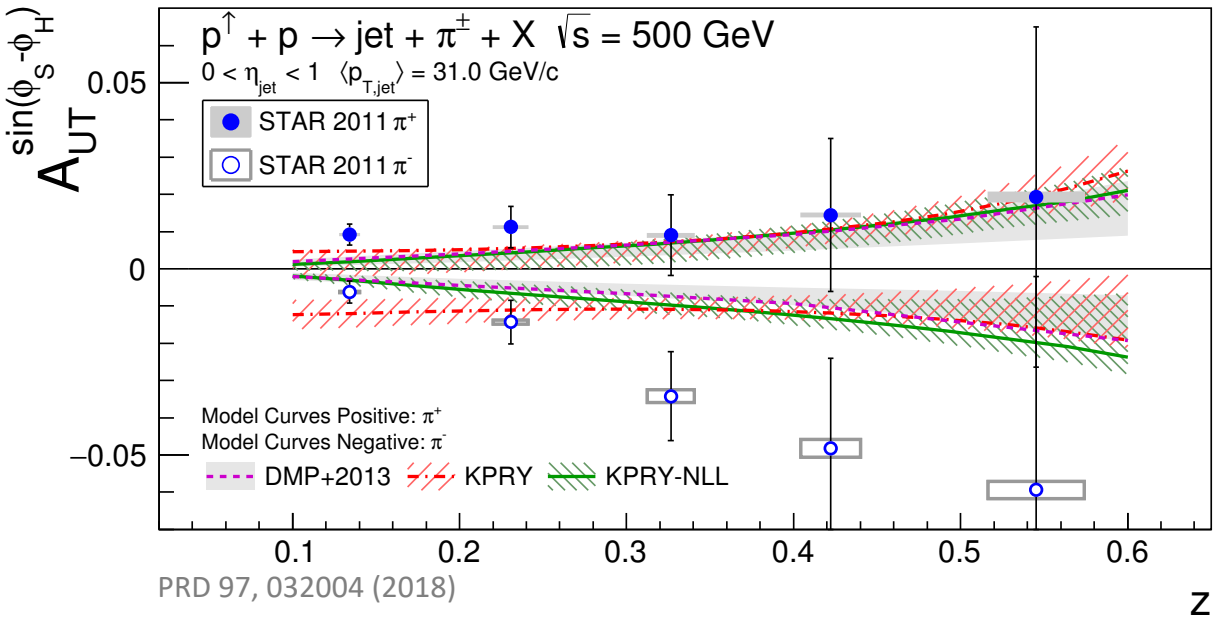
- Pass jet selection requirements
- Pass particle ID quality requirements
- Minimum angular separation between particle and jet axis:

$$\Delta R = \sqrt{\left(\eta_{\text{jet}} - \eta_{\pi}\right)^2 + \left(\phi_{\text{jet}} - \phi_{\pi}\right)^2} > 0.04$$

Kinematic Corrections

- Find simulated jets matched at all three levels: detector, particle, parton
- Find simulated particles w/in jets matched at **detector** and **particle** levels
- Evaluate shift between **detector-level** and **particle-level** kinematics
- Apply shift to kinematics of real data hadrons

STAR Hadrons Within Jets: Collins Effect



PRD 97, 032004 (2018)

Models based on SIDIS/e^+e^-

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

DMP: PLB 773, 300 (2017)
KPRY: PLB 774, 635 (2017)

Consistency between models and STAR data at 95% confidence level

→ Suggests robust factorization and universality

To evolve or not to evolve?

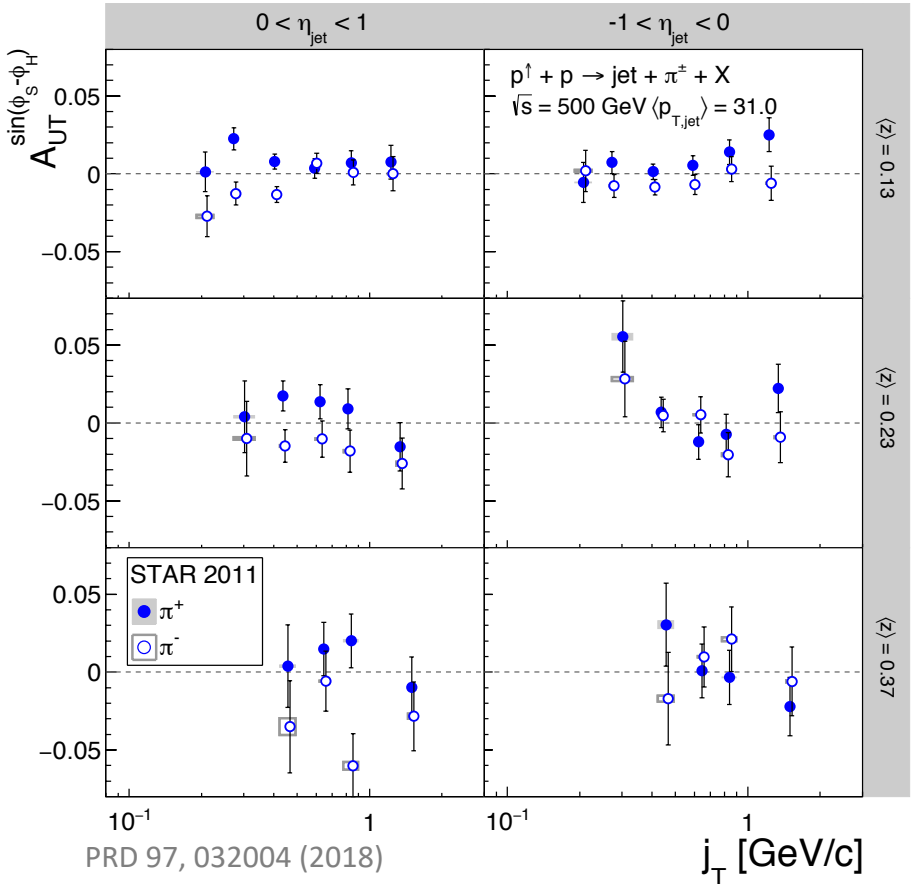
$\chi^2/\nu = 14/10$ (w/o) vs. $17.6/10$ (with)

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

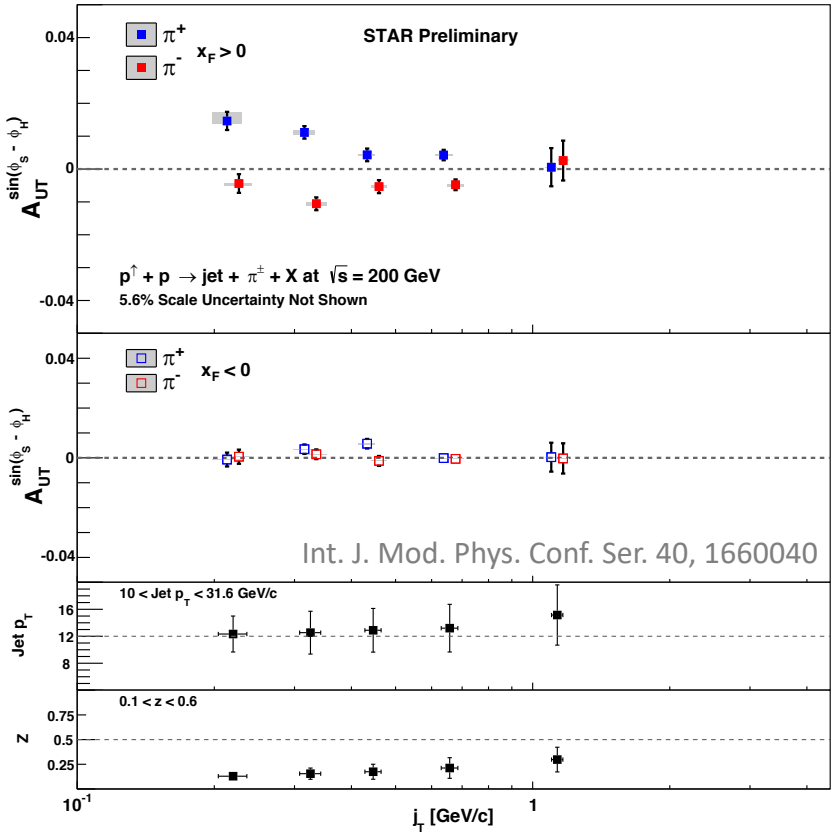
(a.k.a. need more data!)

STAR Hadrons Within Jets: Collins Effect

Dependence on j_T (momentum transverse to jet)



PRD 97, 032004 (2018)

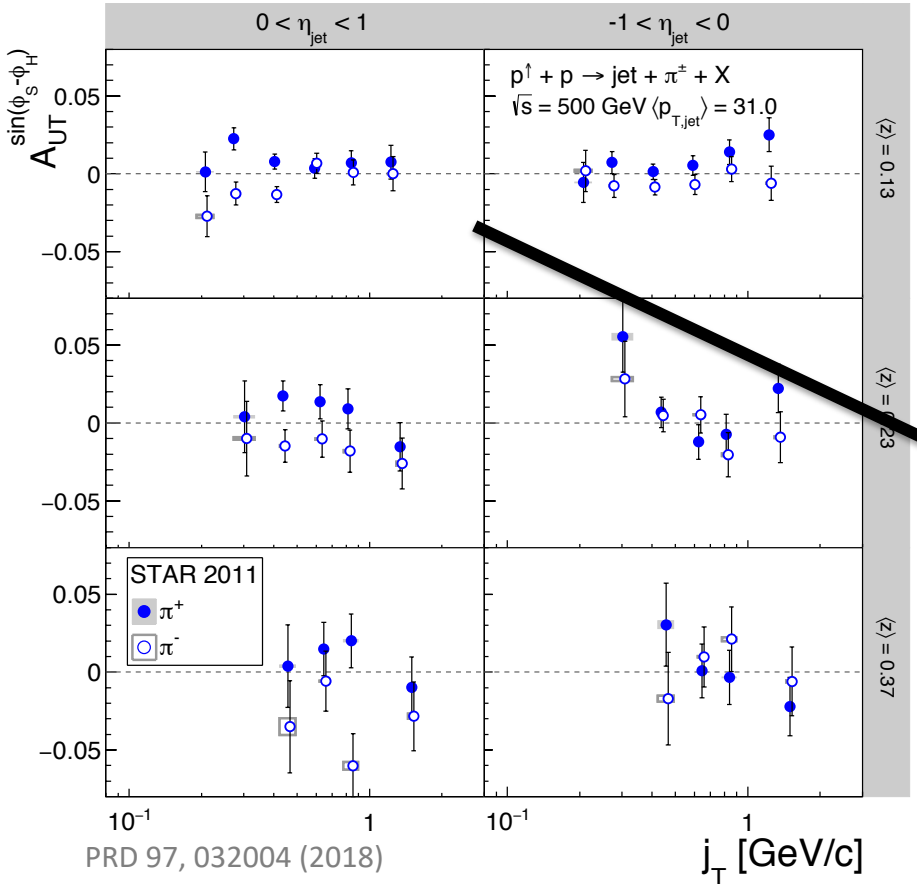


Int. J. Mod. Phys. Conf. Ser. 40, 1660040

Asymmetries appear to decrease with j_T
Consistent between energies?

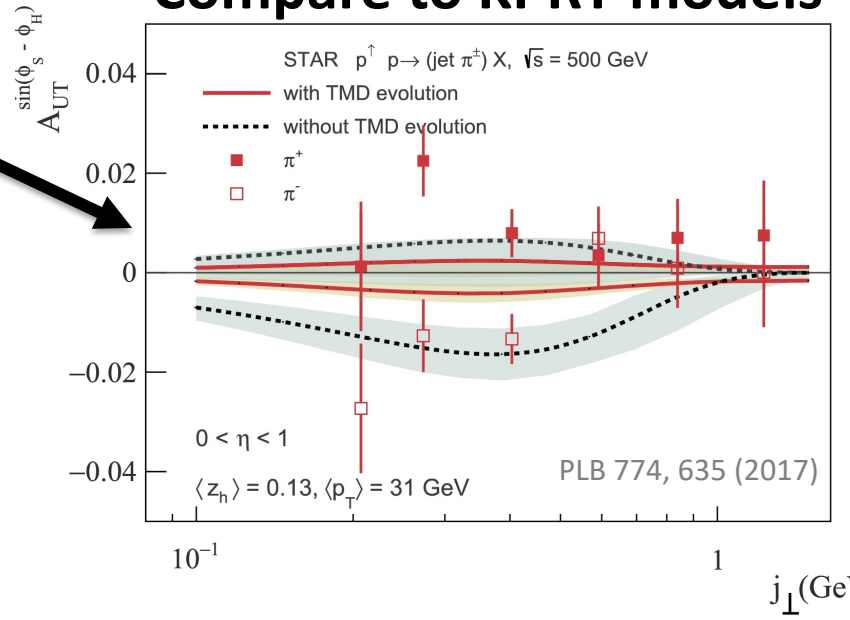
STAR Hadrons Within Jets: Collins Effect

Dependence on j_T (momentum transverse to jet)



PRD 97, 032004 (2018)

Compare to KPRY models



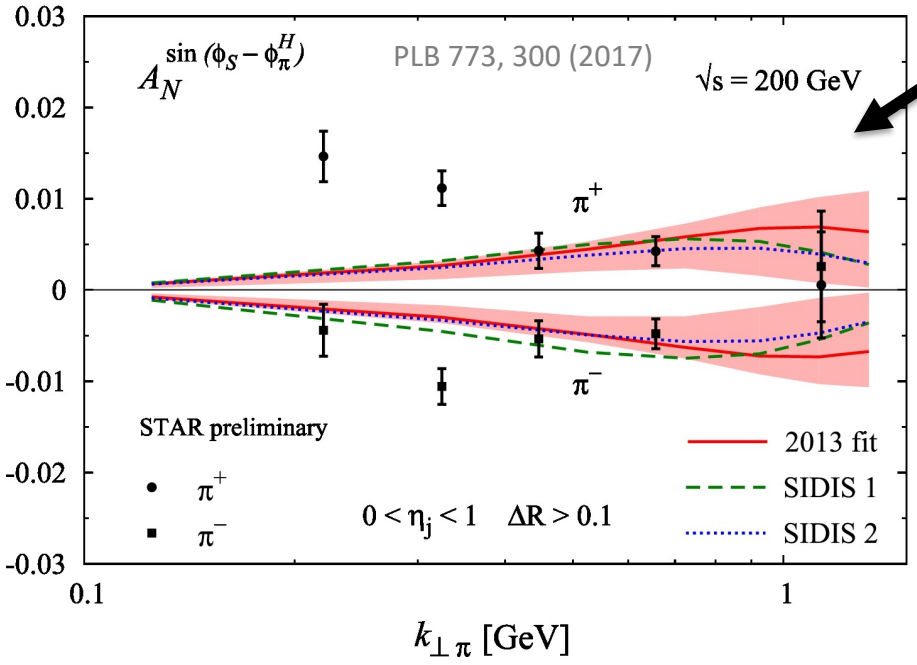
Decent agreement with either model

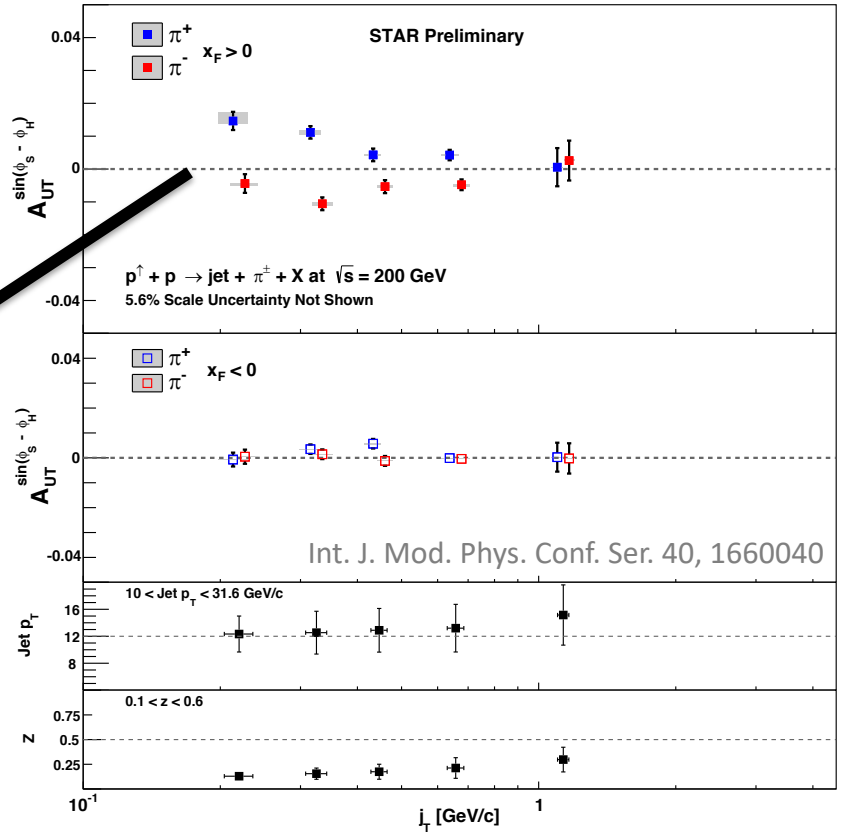
"Better" agreement with "no evolution"???

STAR Hadrons Within Jets: Collins Effect

Dependence on j_T (momentum transverse to jet)

Compare to DMP models

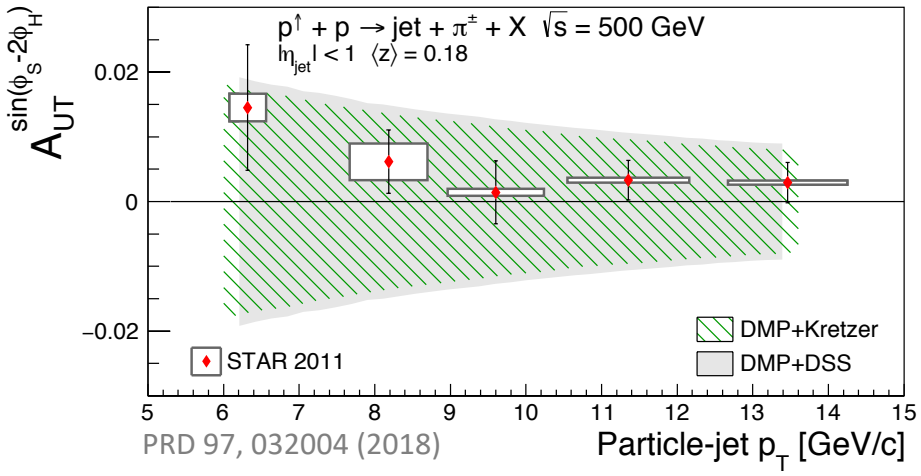




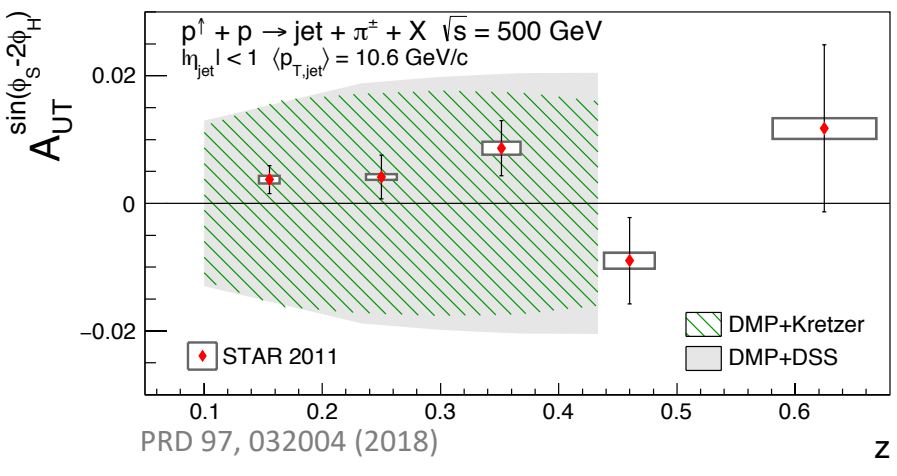
Further investigation of low j_T region needed
e.g. unpolarized TMD data, model parameterization, etc.

STAR Hadrons Within Jets: Collins-like Asymmetry

$A_{UT}^{\sin(\phi_S - 2\phi_H)}$ **sensitive to linearly polarized gluons in a polarized proton**



PRD 97, 032004 (2018)



PRD 97, 032004 (2018)

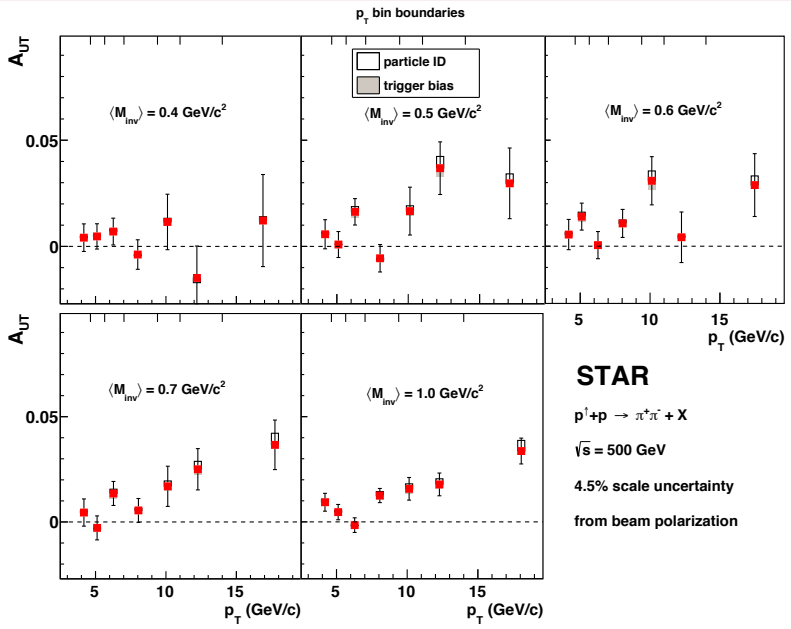
STAR 2011 data provide first measurement

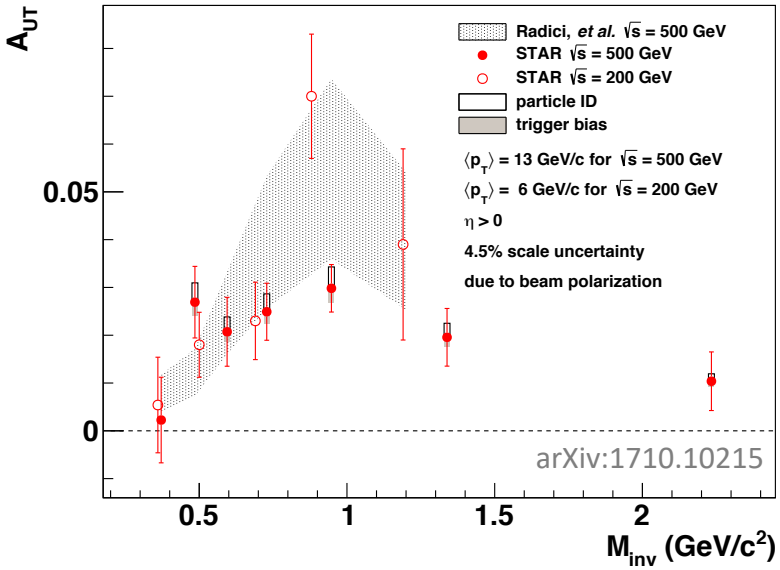
Model calculations based upon maximized scenarios for two unpolarized FF sets (Kretzer & DSS)

2011 asymmetries "small" but ~2σ from zero

Recent STAR datasets (2015 & 2017) should tell us if "non-zero" asymmetry is real or statistics

STAR Di-hadron Constraints on Transversity





Significant di-hadron asymmetries at STAR

- Apparent in both 200 and 500 GeV
- *Strong dependence on pair* p_T

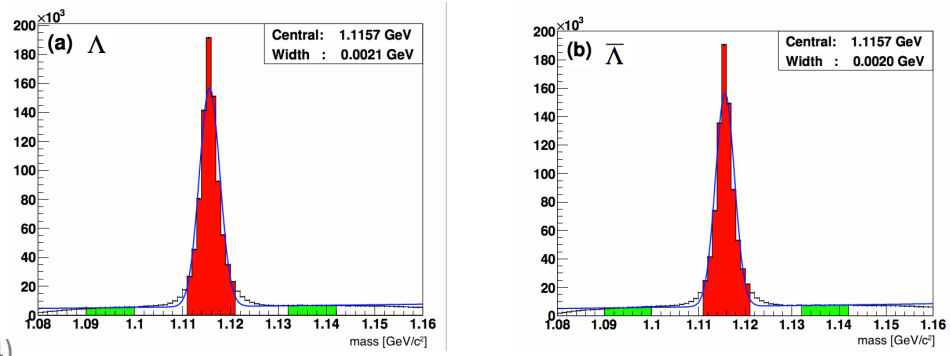
In terms of invariant mass data are consistent with 68% of replicas based on SIDIS & e^+e^- data

→ ***Same mechanism as in SIDIS!***

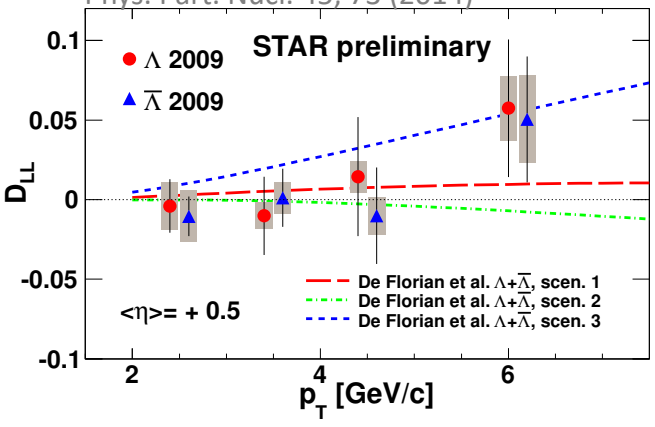
Tension at ***forward*** scattering?

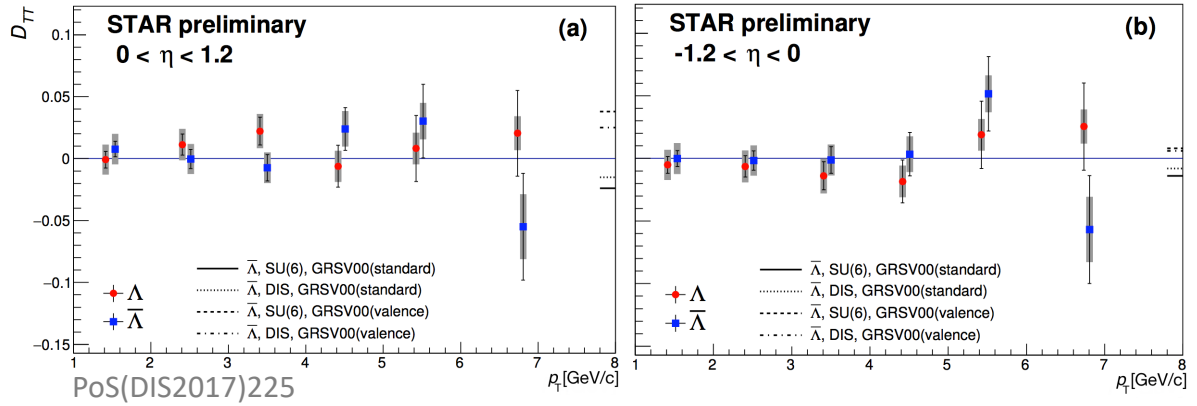
→ ***More information needed on*** D_g^1***?***

STAR Hyperon Spin Transfer



Phys. Part. Nucl. 45, 73 (2014)



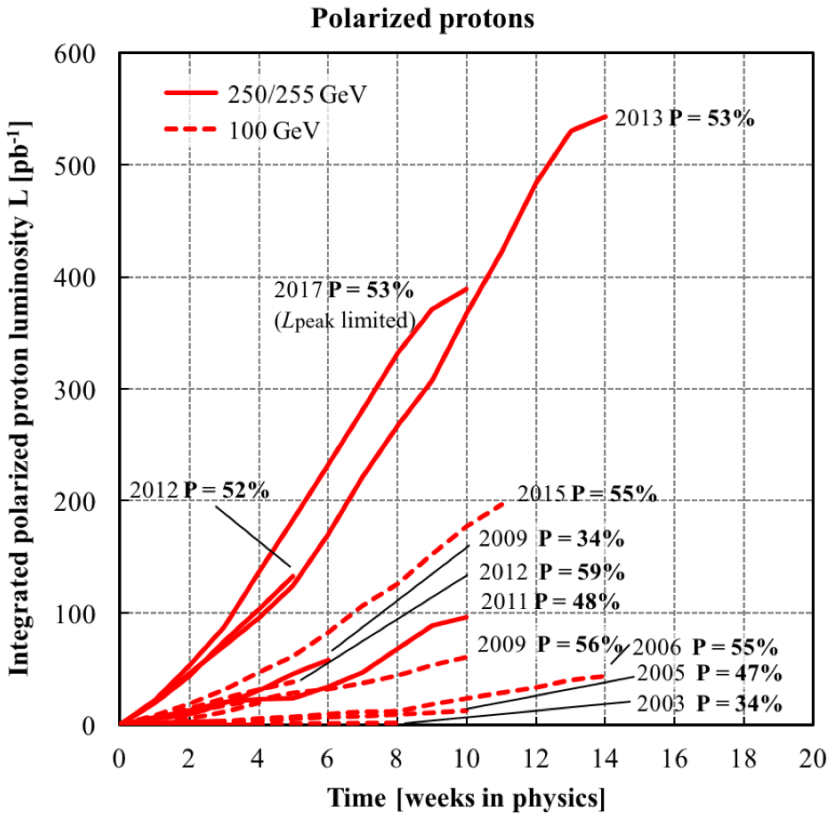


PoS(DIS2017)225

- Λ D_{LL} sensitive to polarized PDF and polarized FF
- Λ D_{TT} sensitive to transversity and transversely polarized FF
- *Substantial improvement in precision of D_{LL} over previous measurement (PRD 80, 111102 (2009))*
- *First measurement of D_{TT} from data taken in 2012*
- Both papers currently in STAR internal review

Future Measurements

Recent datasets promise unique opportunities!

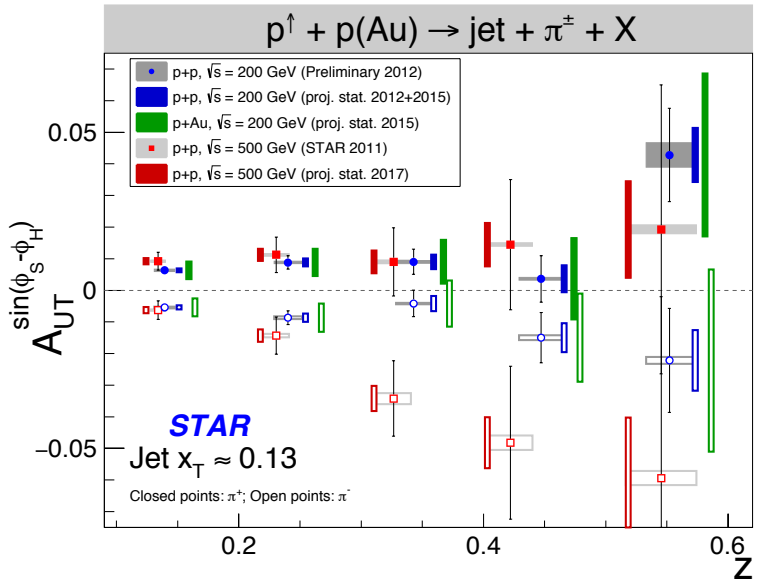


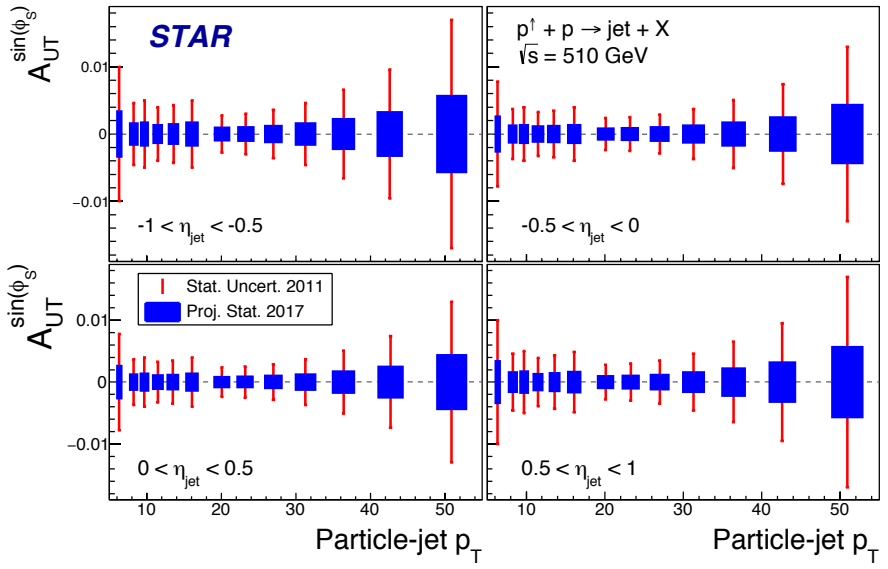
Transverse Luminosity Recorded

Year	$\sqrt{s}$ [GeV]	STAR	PHENIX	$\langle P \rangle$ [%]
2006	62.4	0.2 pb^{-1}	0.02 pb^{-1}	48
2006	200	8.5 pb^{-1}	2.7 pb^{-1}	57
2008	200	7.8 pb^{-1}	5.2 pb^{-1}	45
2011	500	25 pb^{-1}	--	48
2012	200	22 pb^{-1}	9.7 pb^{-1}	56
2015	200	53 pb^{-1}	52 pb^{-1}	57
2015	200 pAu	0.42 pb^{-1}	0.20 pb^{-1}	60
2015	200 pAl	1.0 pb^{-1}	--	54
2017	510	320 pb^{-1}	--	56

Dramatically increased figure of merit in recent years

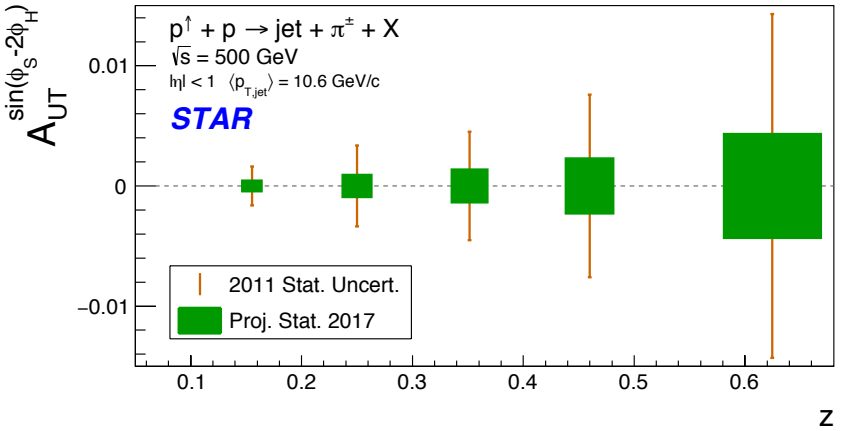
Future Measurements: Runs 2015 and 2017





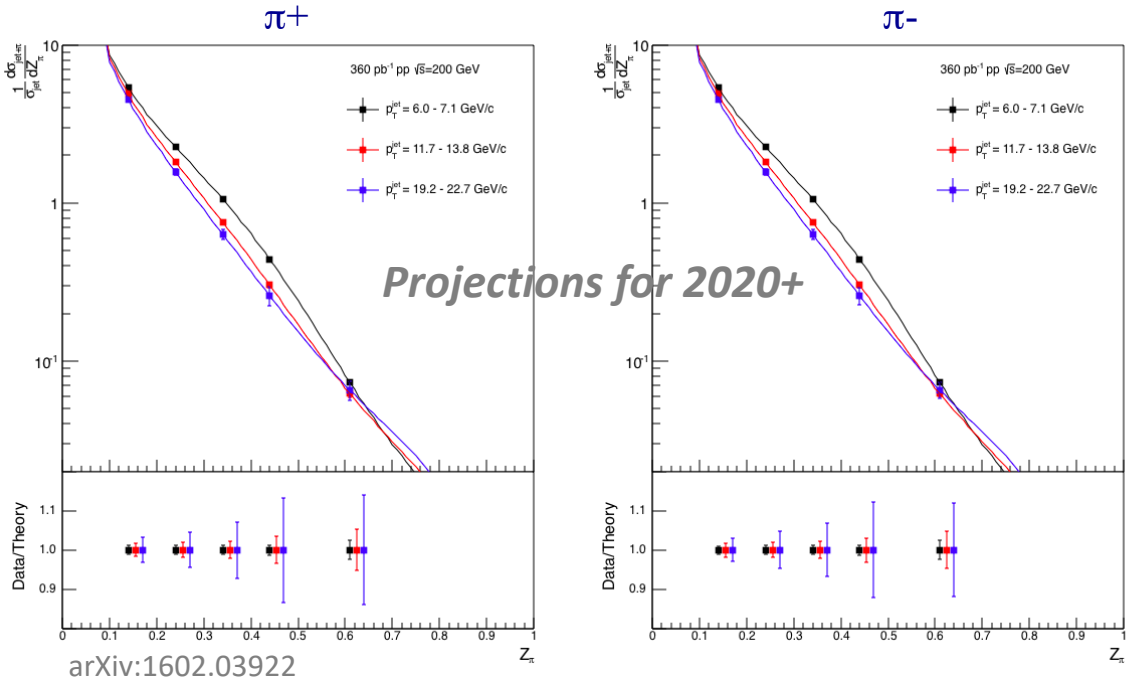
Successful runs in 2015 and 2017

- More precise evaluation of TMD evolution in Collins FF
- Better constraints on ETQS/gluon Sivers
- More precise constraints on gluon linear polarization effects
- Extraction of K and p Collins
- First look at Collins in p+A



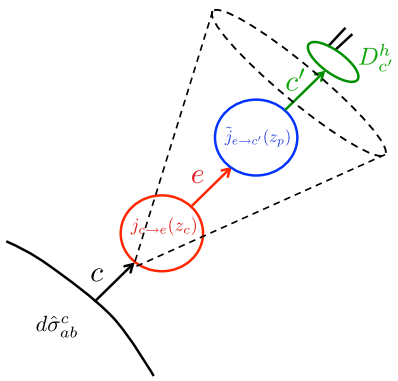
Plots from arXiv:1602.03922

Future Measurements: Gluon FFs

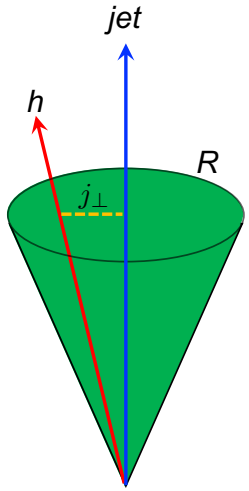


Projections for 2020+

arXiv:1602.03922



PRD 92, 054015 (2015)



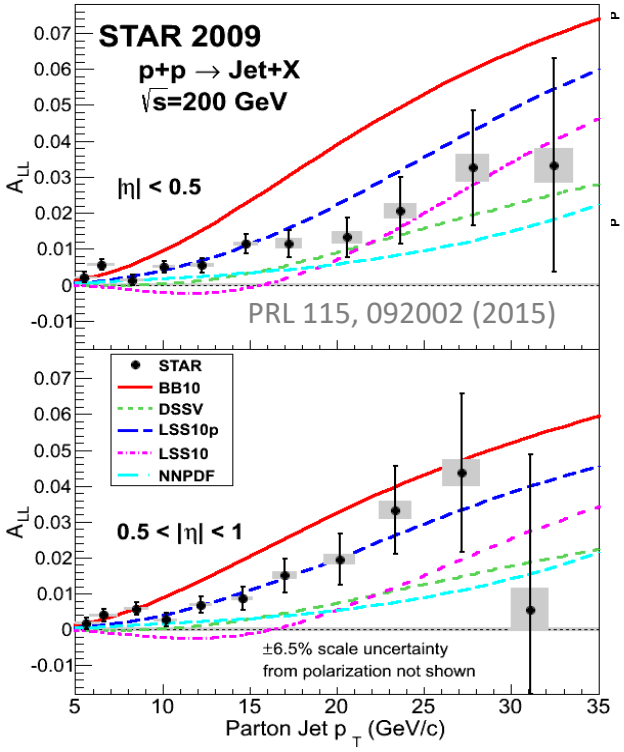
JHEP11(2017)068

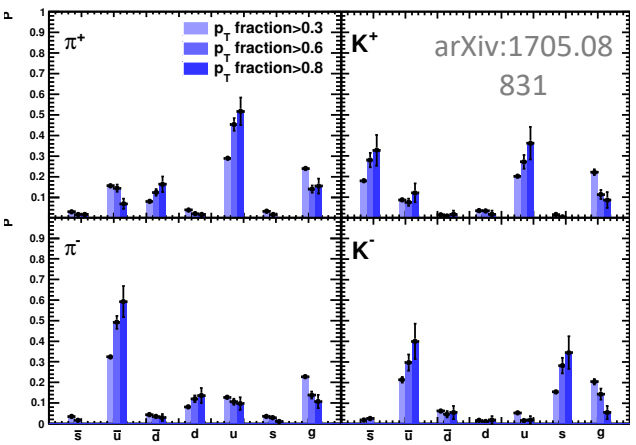
Multiplicities of hadrons within jets:

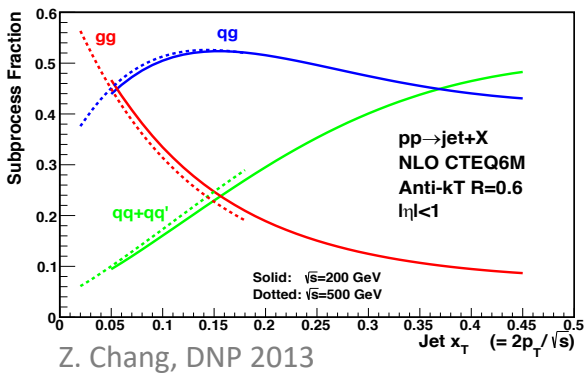
sensitivity to collinear and TMD FFs

- Data in-hand for both 200 and 500 GeV pilot measurements
- Requires a more careful handling of kinematics and U.E. corrections than with spin asymmetries, e.g. Collins
- STAR PID capability enables measurement of multiplicities for $\pi^{\pm}$, K, and p

Future Measurements: Tagged A_{LL}

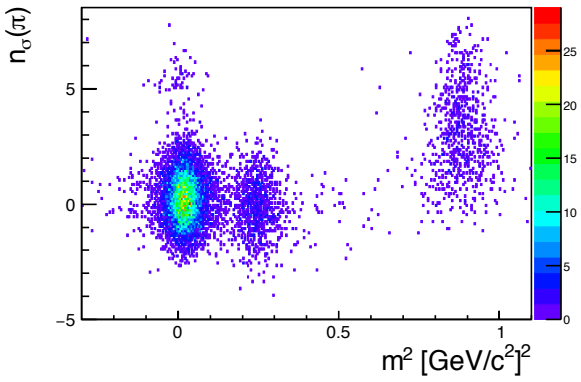


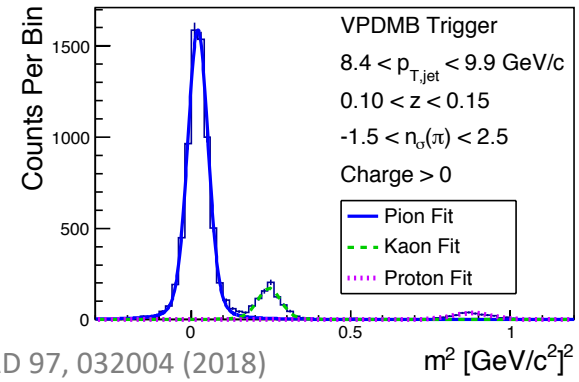




Z. Chang, DNP 2013

Enhance sensitivity, e.g. to strange PDF and FF, by tagging jet with kaon





PRD 97, 032004 (2018)

Utilize same particle ID infrastructure as used for Collins analysis

Future Measurements

RHIC Cold QCD physics after BES-II at Mid- & Forward Rapidities:

The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC (arXiv:1602.03922)

STAR:

Midrapidity:

https://drupal.star.bnl.gov/STAR/system/files/STAR_Midrapidity_Beyond_BESII.pdf

Forward-rapidity Proposal:

https://drupal.star.bnl.gov/STAR/system/files/ForwardUpgrade.v20.pdf

sPHENIX:

Midrapidity:

https://www.sphenix.bnl.gov/web/sph-cqcd-2017-002

Forward-rapidity LOI:

https://www.sphenix.bnl.gov/web/node/450

Strong endorsement by RHIC PAC:

- As the physics program that is foreseen for forward physics is substantial, full utilization of future polarized proton beam time must be made to realize the proposed forward physics program.
- RHIC management is encouraged to find a way to enhance and include a forward physics program at RHIC.

Summary

- **Inclusive hadron results included in "reloaded" DSS FFs**
- **First publications of hadrons-within-jets from STAR**
- STAR 200 GeV di-hadrons included in global IFF analyses
- STAR 500 GeV di-hadrons finalized and almost in journal
- Updated hyperon finalized
- **On the horizon**
  - Precision measurements from 2015-2017
  - First $p + A$ Collins
  - In-jet FFs for π, K, and p
  - Flavor tagged A_{LL}, e.g. for strange PDF and FF
- **What's on your wish list?**

Stay tuned!