Measurements of open charm production and flow in 200 GeV Au+Au collisions with the STAR experiment at RHIC

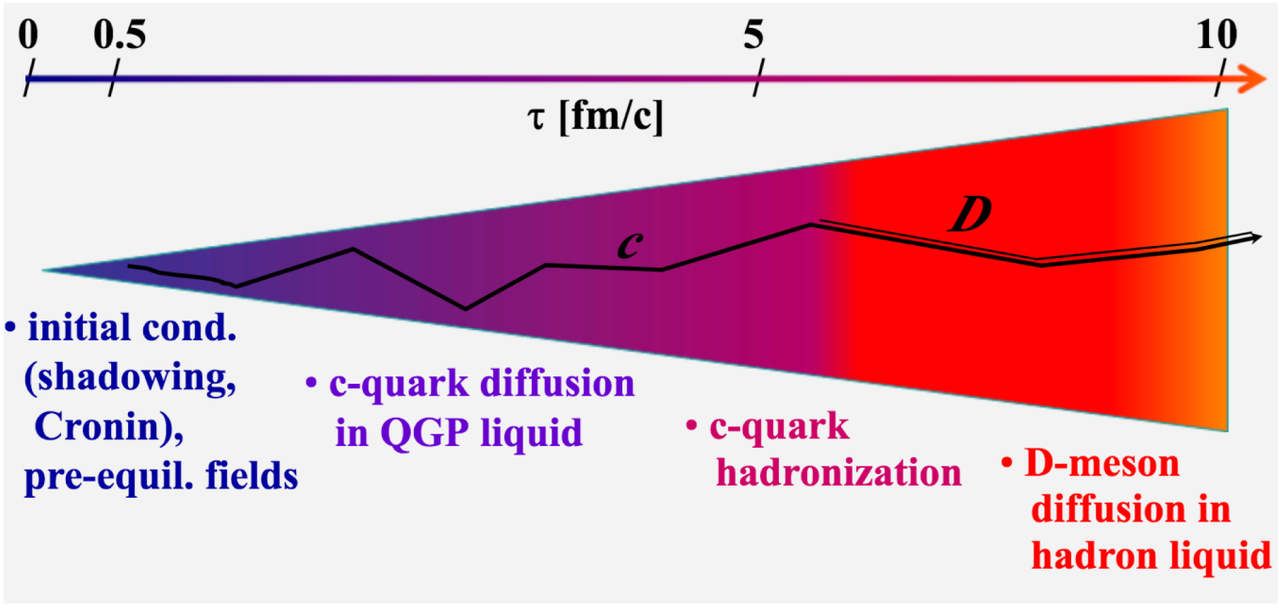
Spiros Margetis for the STAR Collaboration
Kent State University

ICNFP 2018, 10 July 2018, Crete, Greece

Introduction

Large collective flow and suppression of yields for charm hadrons in 200 GeV A+A collisions have been already reported by STAR

New data: Understand better heavy quark production, transport and hadronization in the presence of QGP

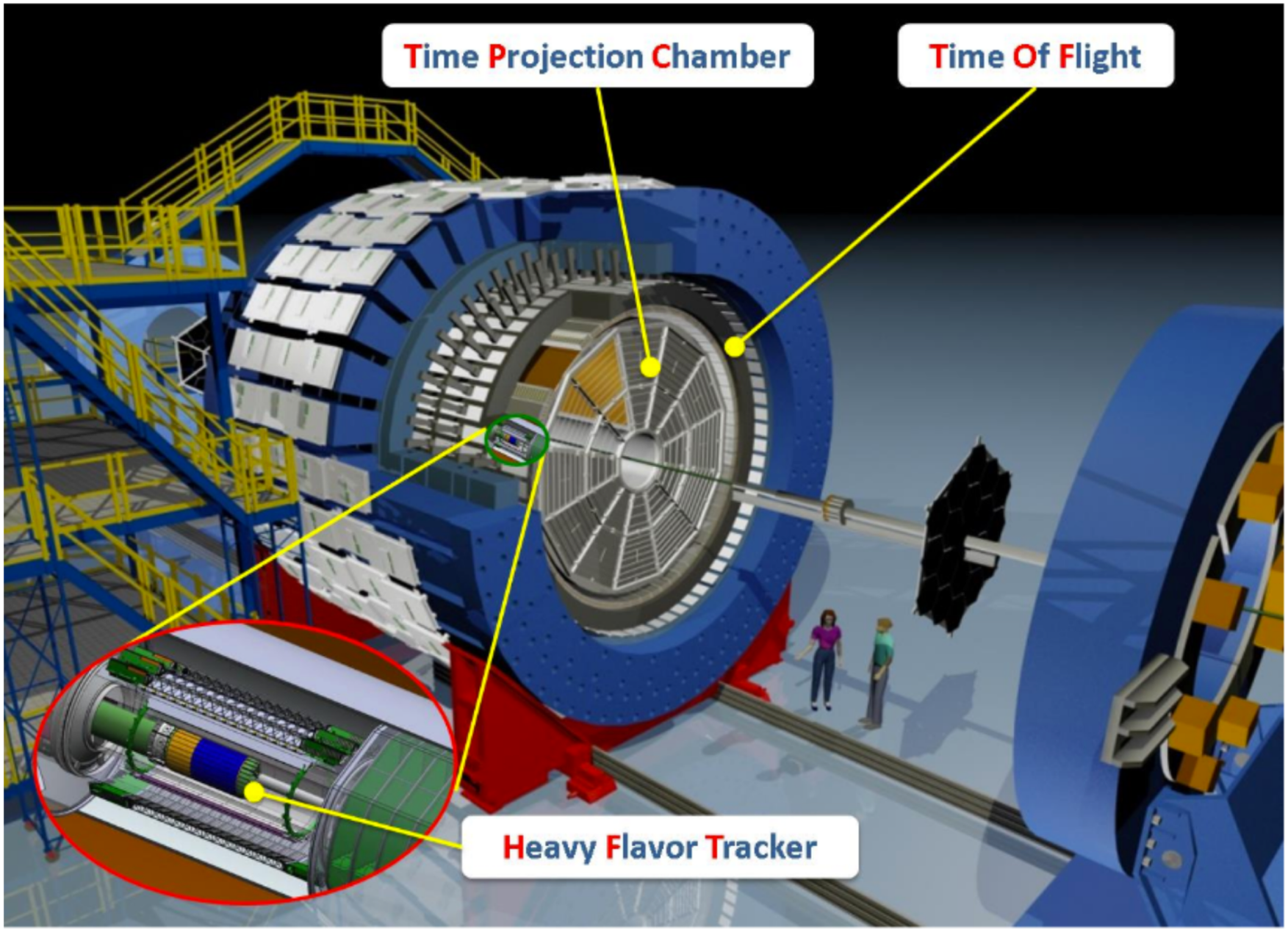


New [high statistics/optimized] extensive measurements by STAR!

- Large directed* (v_1) and **elliptic (v_2) flow of D^0**
- Hadronization: Λ_c, D_s
- **In medium energy loss: D^0,** B-mesons*
- Medium modifications to yields/life-time: $D^{*+/-}$
- **Total charm cross-section**

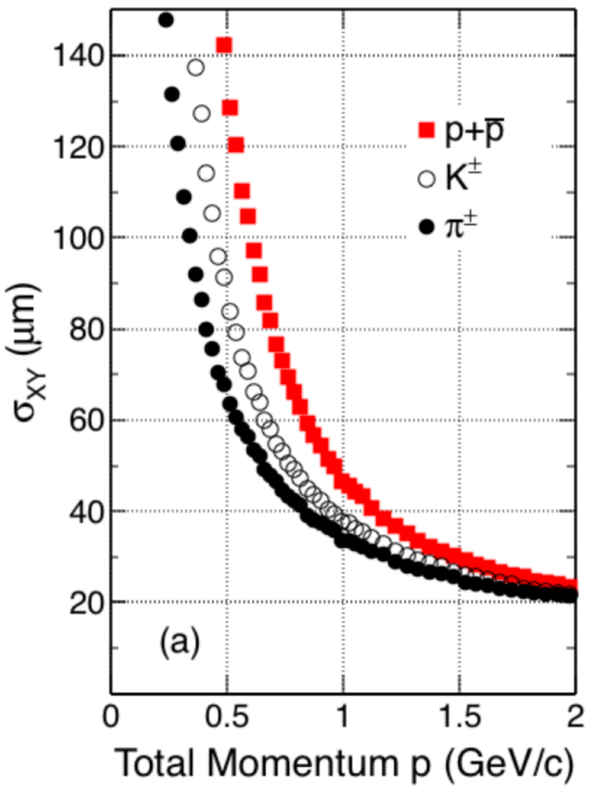
* Not reported here. See QM2018 talks of S. Sinha and S. Radhakrishnan

The STAR Detector



- 2 layers of Si pixels with MAPS and 2 layers of Si strips
- Full azimuthal coverage

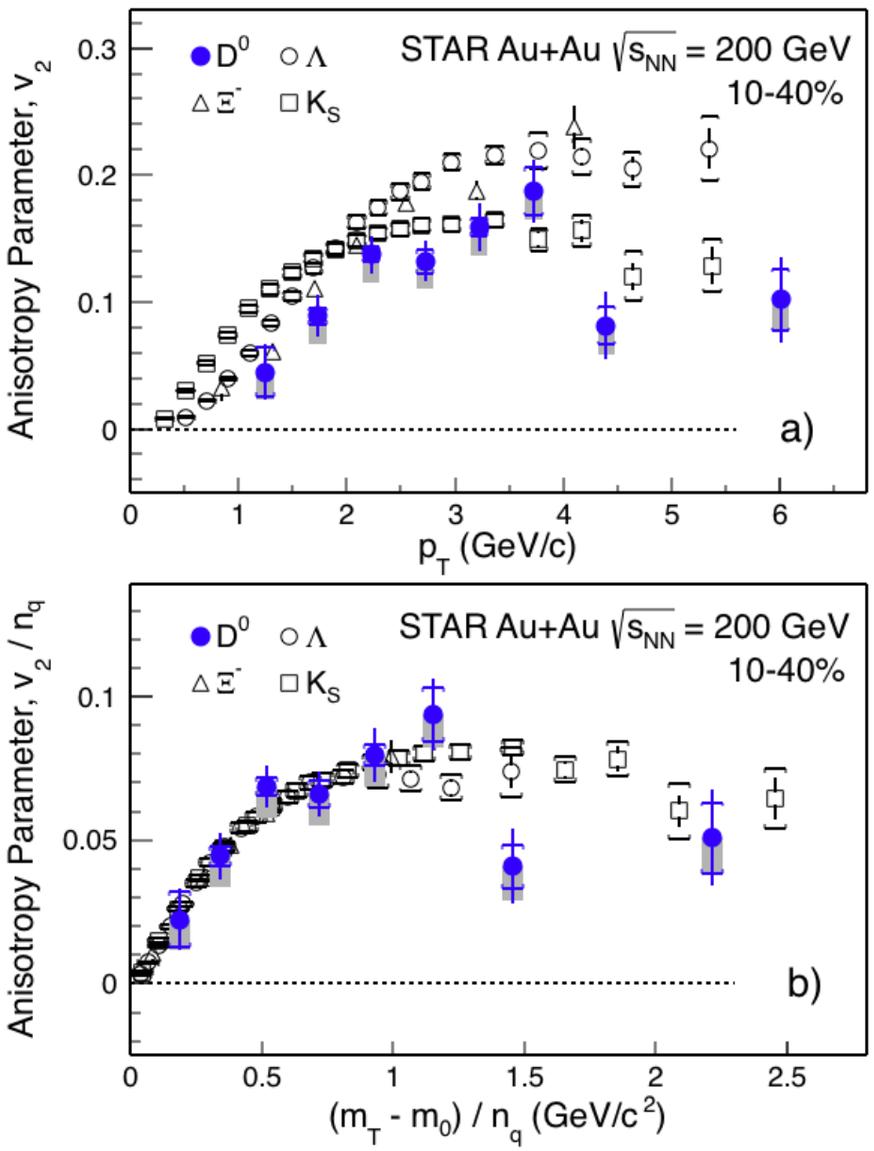
Phys. Rev. Lett. 118 (2017) 212301



STAR Heavy Flavor Tracker (HFT) provides excellent vertex/track-dca resolution and allows reconstruction of charm hadron decays

Recent D^0 Elliptic Flow (v_2) Results from STAR

L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 118, 212301 (2017)



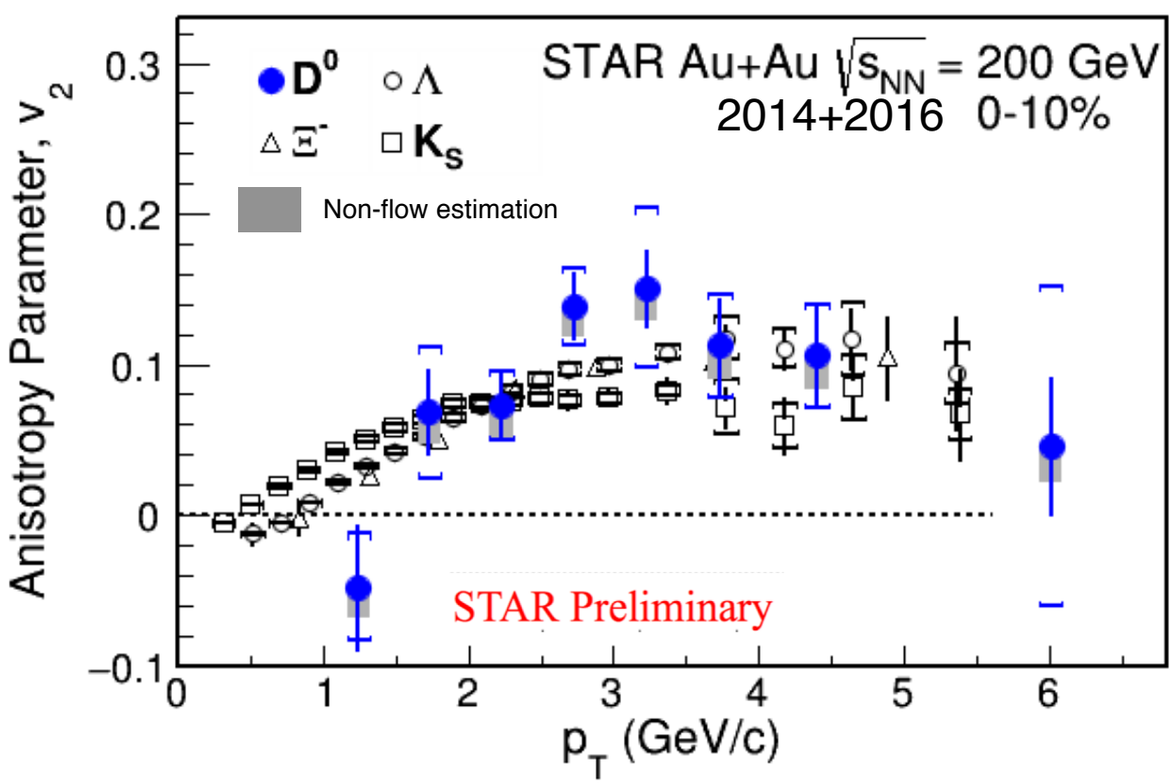
- STAR published D^0 v_2 from data taken during 2014 run
- D^0 elliptic flow magnitude consistent with NCQ scaling in mid-central collisions.
- High statistics 2016 run data allow to improve precision of the charm flow measurements at RHIC energy
- The 2016 data also allow us to extend NCQ scaling test to finer centrality bins

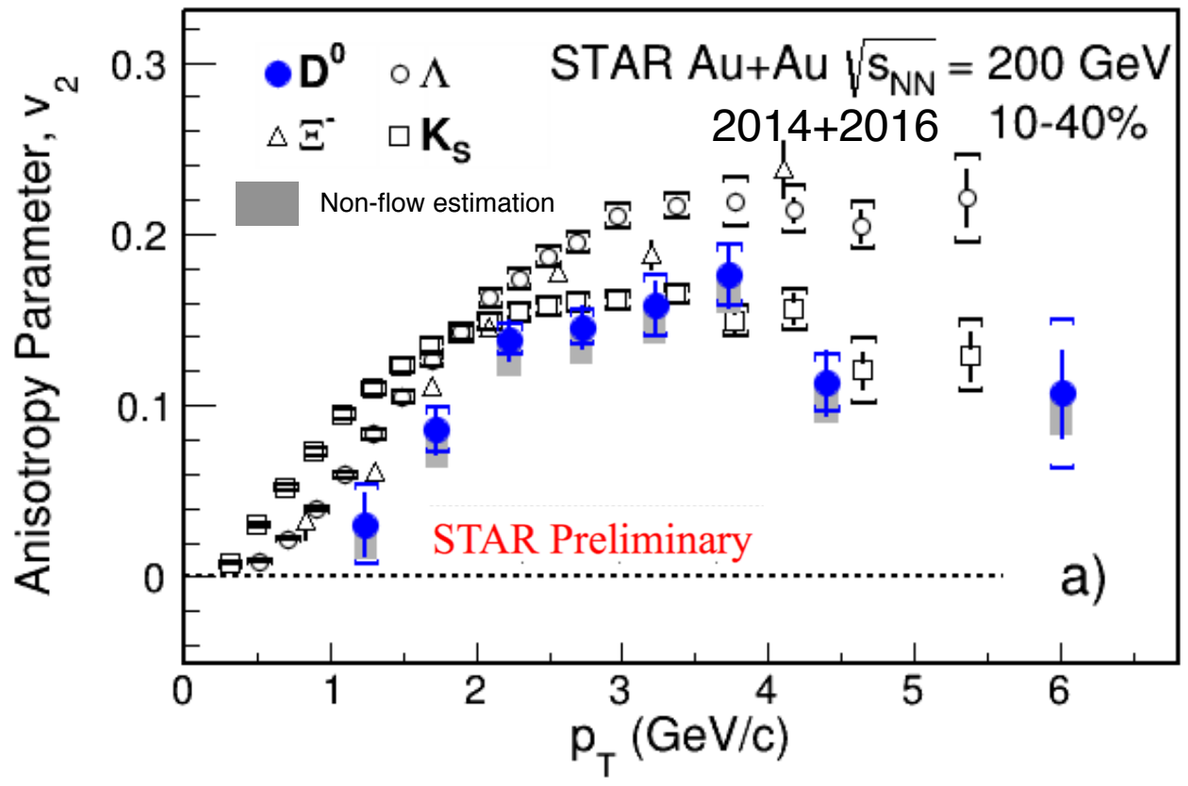
Precise D^0 v_2 measurement can allow:

→ Quantitative studies of QGP properties (transport coefficients)

D^0 v_2 Comparison to Light Hadrons

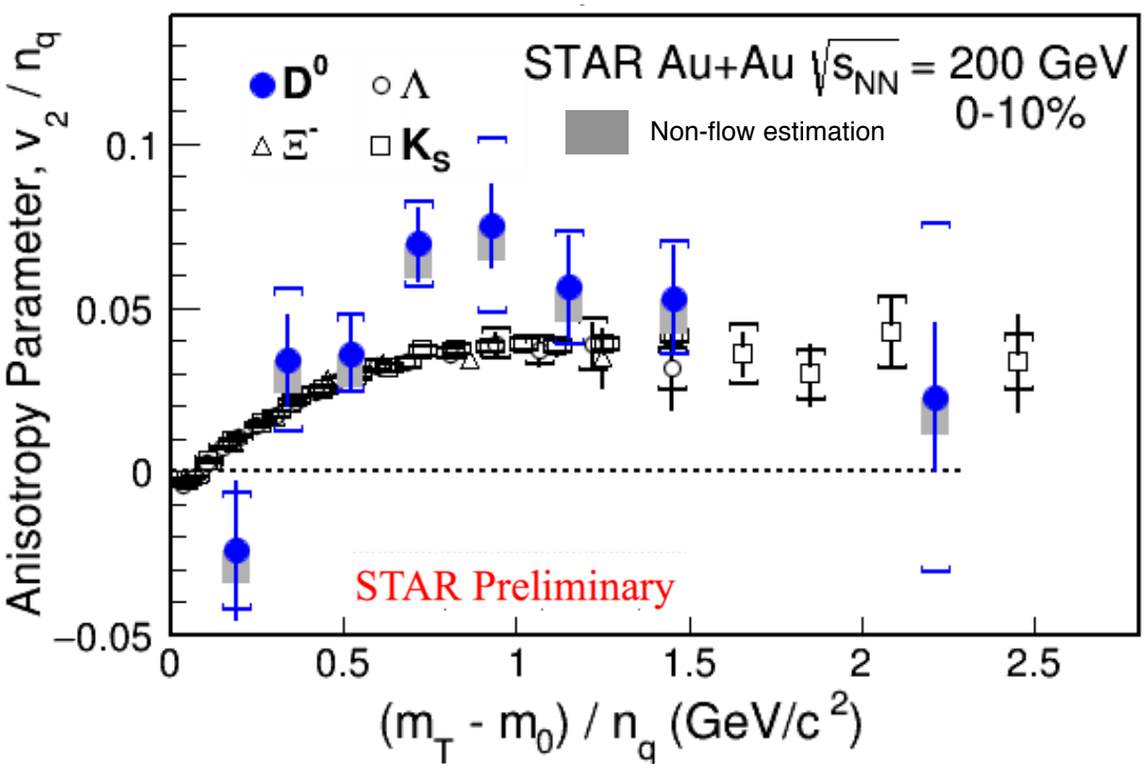
Phys. Rev. C 77, 054901 (2008)

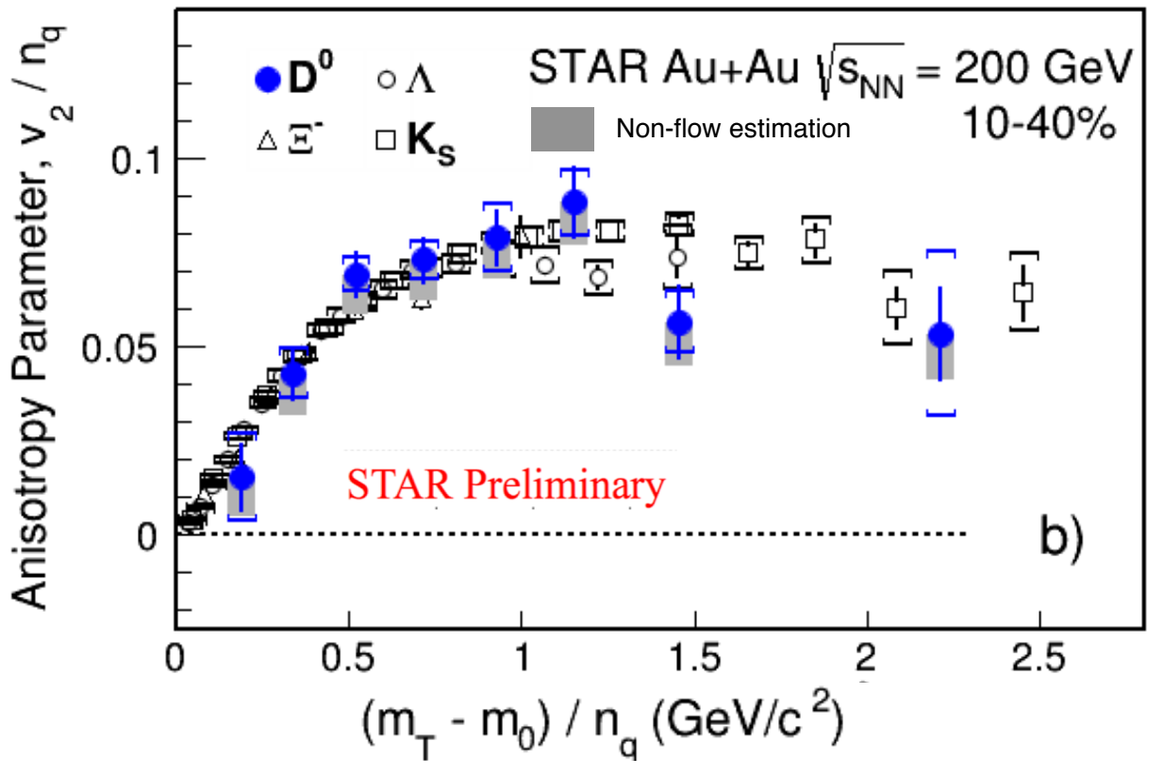




- D^0 v_2 results from combined 2014 + 2016 data
- D^0 v_2 measurement extended to 0-10% centrality
- Clear mass ordering for $p_T < 2$ GeV/c in 10-40% centrality
- D^0 v_2 for $p_T > 2$ GeV/c in 10-40% centrality follows the mesons

NCQ Scaling Test

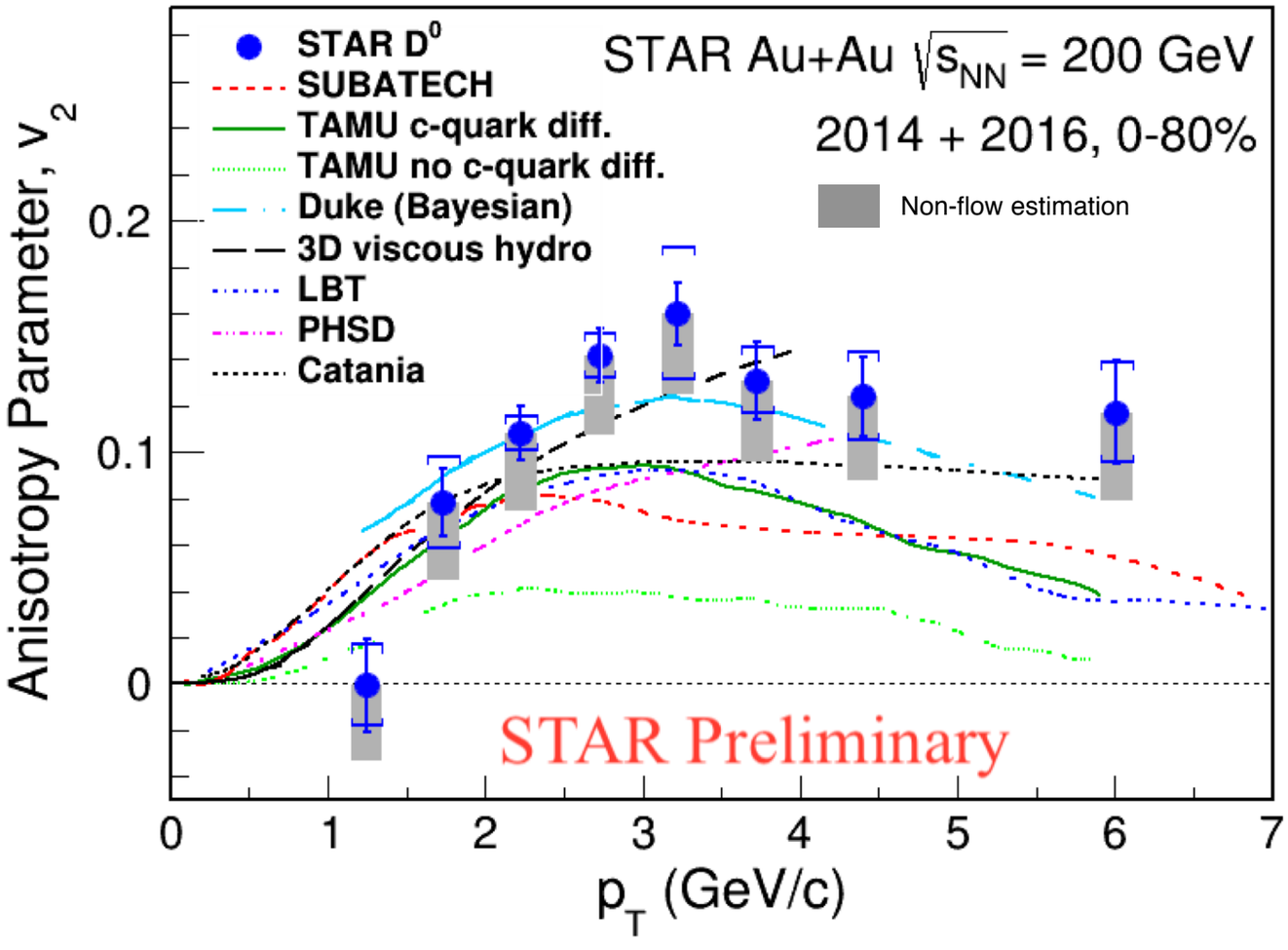




- NCQ scaling test with improved precision in D^0 v_2 measurement
- NCQ-scaled D^0 v_2 consistent with light flavor hadrons for $(m_T - m_0)/n_q < 2.5$ GeV/c^2 in 10-40%
- Evidence of charm quarks flowing with the medium

Charm quarks appear to have achieved thermal equilibrium with the medium

D^0 v_2: Data vs. Models



Compared Models	x2/NDF	p-value
SUBATECH [1]	17.3/8	0.026
TAMU c quark diff. [2]	12.0/8	0.15
TAMU no c quark diff. [2]	33.7/8	4.5×10^{-5}
Duke (Bayesian) [3]	8.5/8	0.39
3D viscous hydro [4]	3.7/6	0.71
LBT [5]	13.3/8	0.10
PHSD [6]	8.7/7	0.27
Catania [7]	9.7/8	0.29

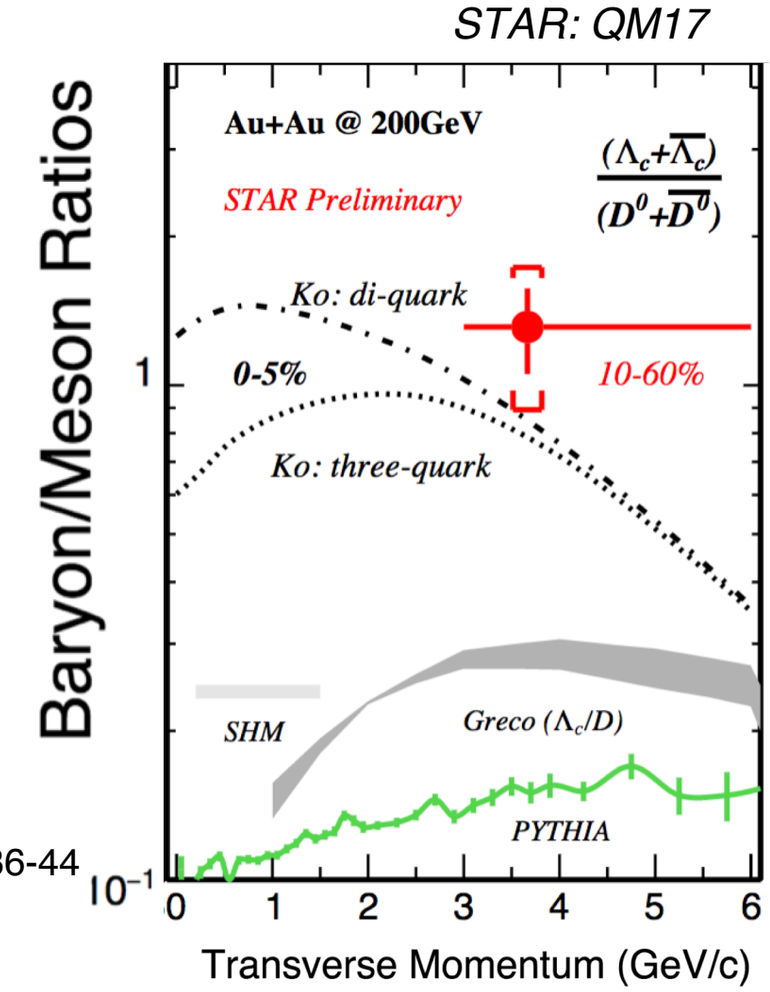
[1] SUBATECH: *Phys Rev C 90, 054909 (2014), Phys Rev C 92, 014910 (2015)*
[2] TAMU: *Phys Rev C 86, 014903 (2012), Phys Rev Lett 110, 112301 (2013)*
[3] Duke: *Phys. Rev. C 97, 014907 (2018)*
[4] 3D viscous hydro: *Phys Rev C 86, 024911 (2012)*
[5] LBT: *Phys Rev C 94, 014909 (2016)*
[6] PHSD: *Phys ReV 90, 051901 (2014), Phys ReV 90, 051901 (2014)*
[7] Catania: *Phys ReV 96, 044905 (2017)*

- D^0 v_2 results from combined 2014 + 2016 data
- Improved precision to constrain the models

Λ_c and Heavy Flavor Hadronization

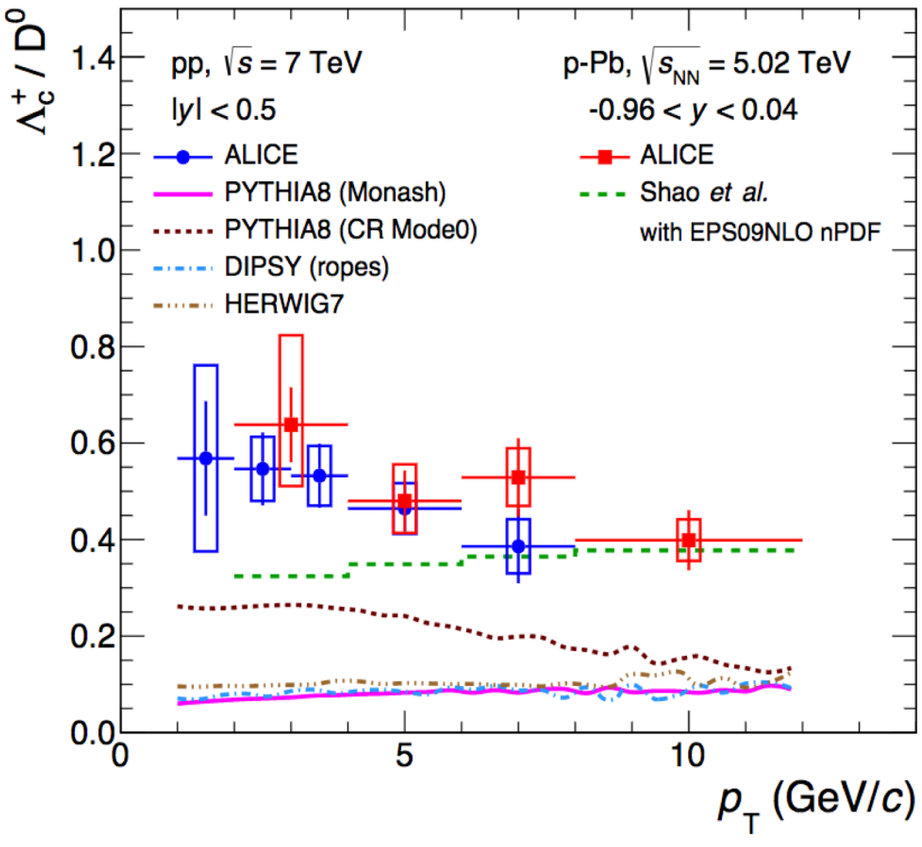
- Strong enhancement of Λ_c/D^0 ratio seen in Au+Au collisions by STAR
  - Enhancement predicted from coalescence hadronization
- An enhancement relative to PYTHIA also seen in p+p and p+Pb collisions at LHC

STAR: QM17



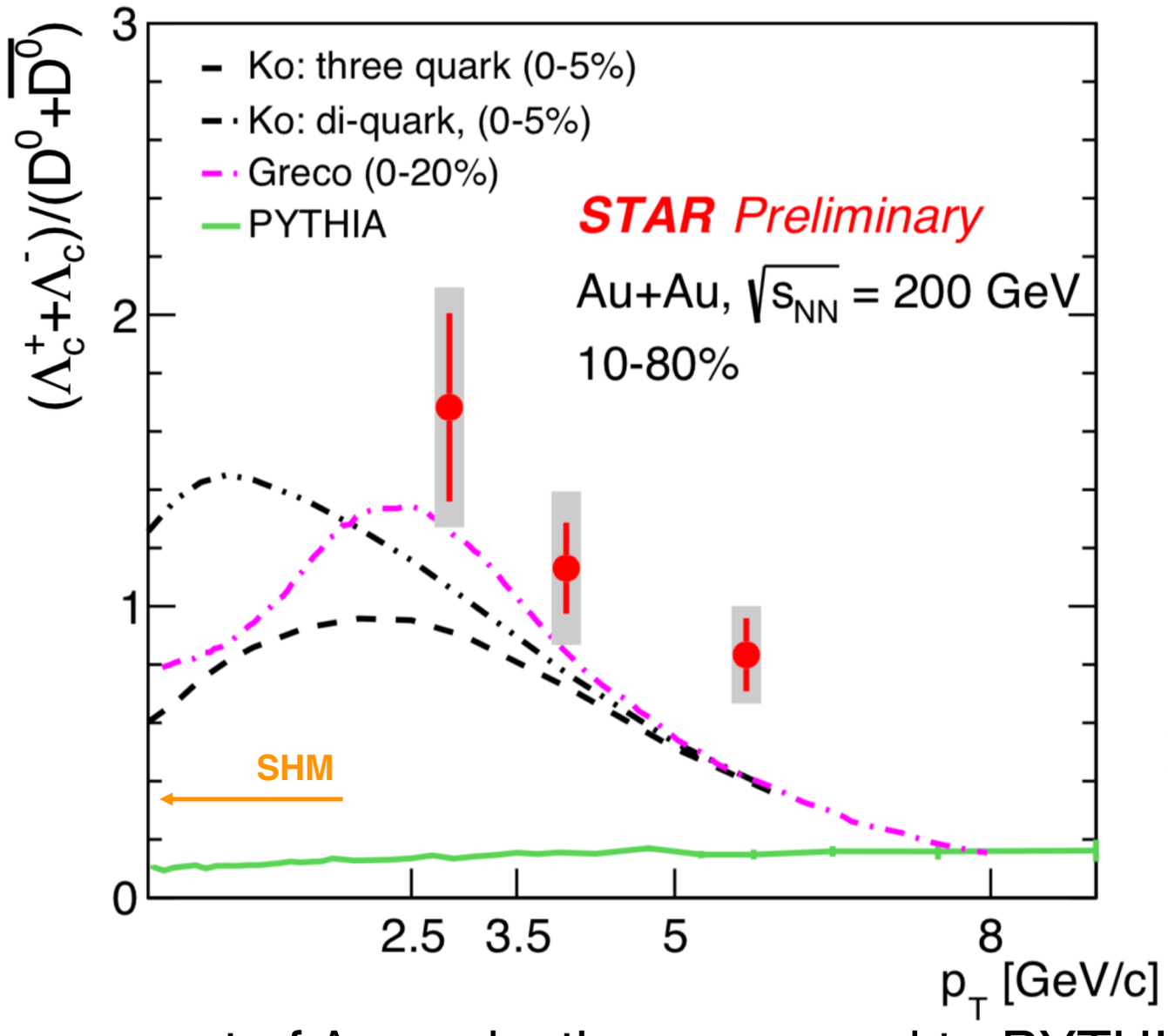
Ko: PRC 79 (2009) 044905
Greco: PRD 90 (2014) 054018
SHM: Phys.Lett. B571 (2003) 36-44

ALICE: arXiv:1712.09581



- How does Λ_c production change from peripheral to central A+A collisions?
- What is the p_T dependence of Λ_c production in A+A collisions?

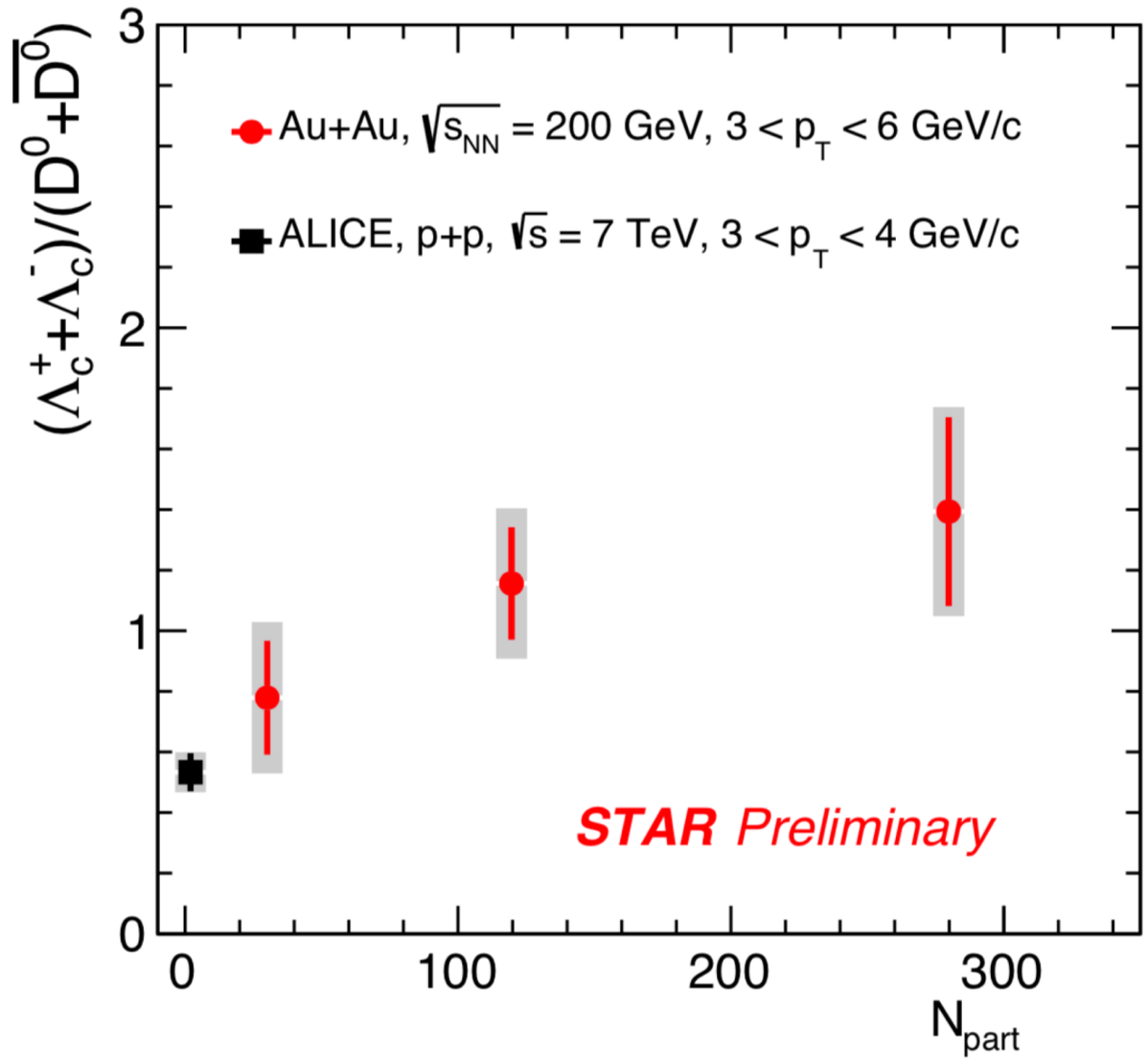
p_T Dependence of Λ_c/D^0 Ratio



Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Lett. B571 (2003) 36-44

- Strong enhancement of Λ_c production compared to PYTHIA calculations
- Enhancement increases towards low p_T
- Coalescence model predictions are closer to data, but the observed enhancement is larger than that predicted by models, particularly at higher p_T
- Ratio not described by the Statistical Hadronization Model

Centrality Dependence of Λ_c Production

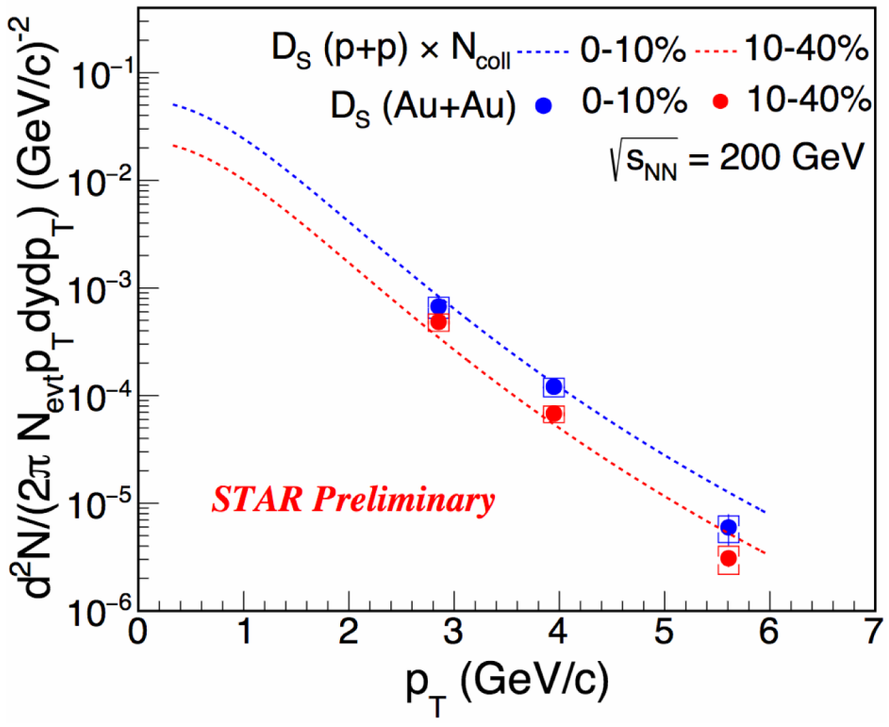


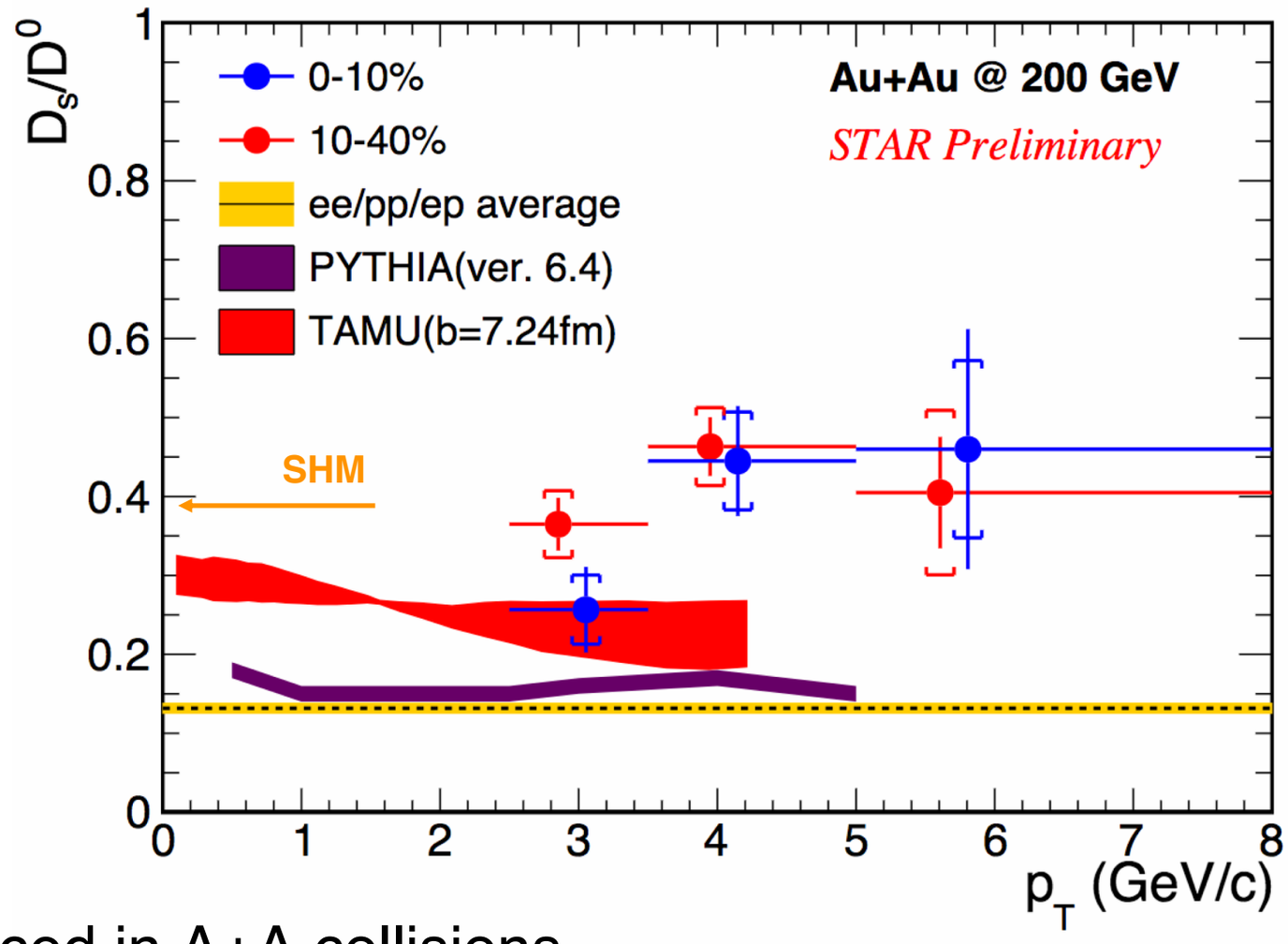
ALICE: arXiv:1712.09581

- First measurement of centrality dependence of Λ_c production in heavy-ion collisions
- Λ_c/D^0 ratio increases from peripheral to central, indicative of hot medium effects
- Ratio for peripheral Au+Au consistent with the p+p value at 7 TeV

D_s Production

- D_s/D^0 enhancement expected in central A+A collisions, from strangeness enhancement and coalescence hadronization



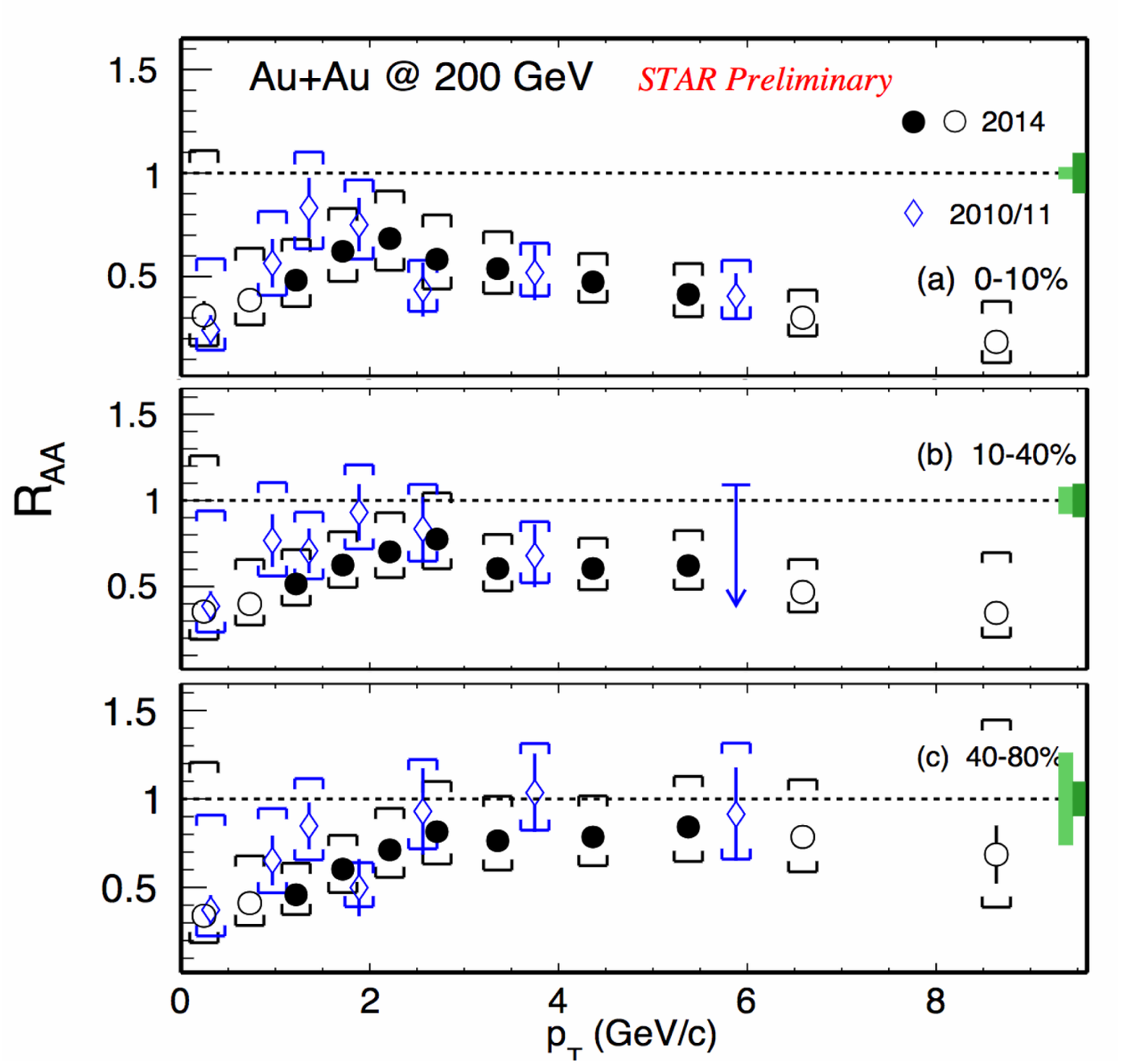


- D_s yield (relative to D^0) is enhanced in A+A collisions
- Enhancement is larger than model predictions, particularly at higher p_T
- Ratio close to SHM predictions

ep/pp/ep avg: M Lisovyi, et. al. EPJ C 76, 397 (2016)
TAMU: H. Min et al. PRL 110, 112301 (2013)
SHM: A. Andronic et al., PLB 571 (2003) 36

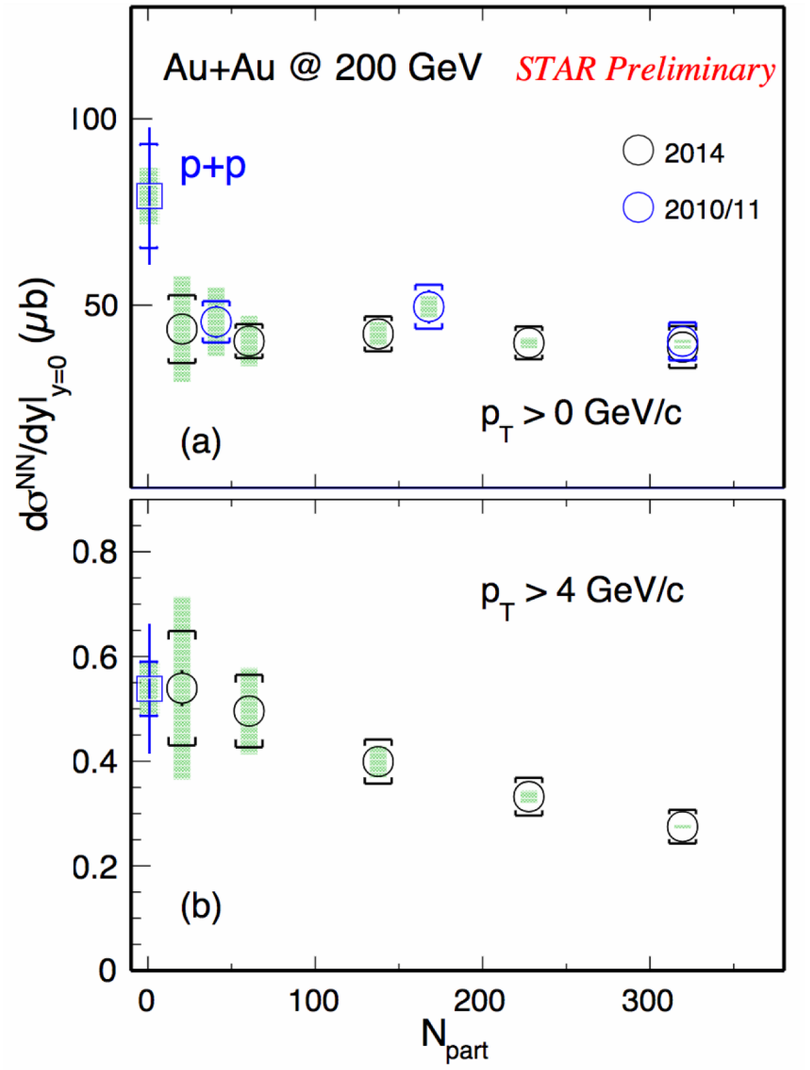
D^0 Spectra and R_{AA}

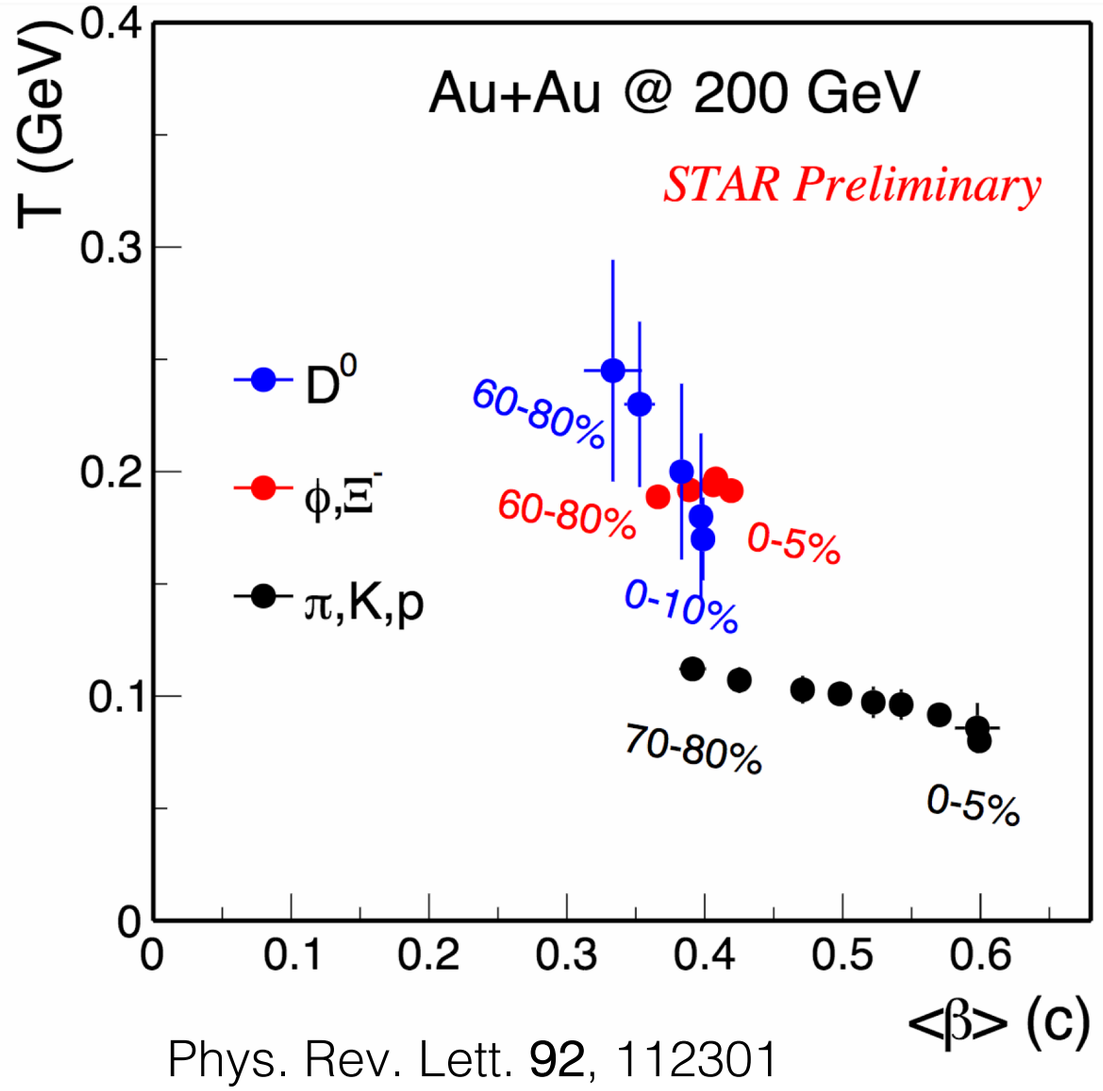
- Updated results from STAR for D^0 extending to low p_T and non-central collisions



- R_{AA} in central events < 1 at all p_T
- Suppression at high p_T increases towards central collisions

D^0 Cross-section and BW Fits to Spectra



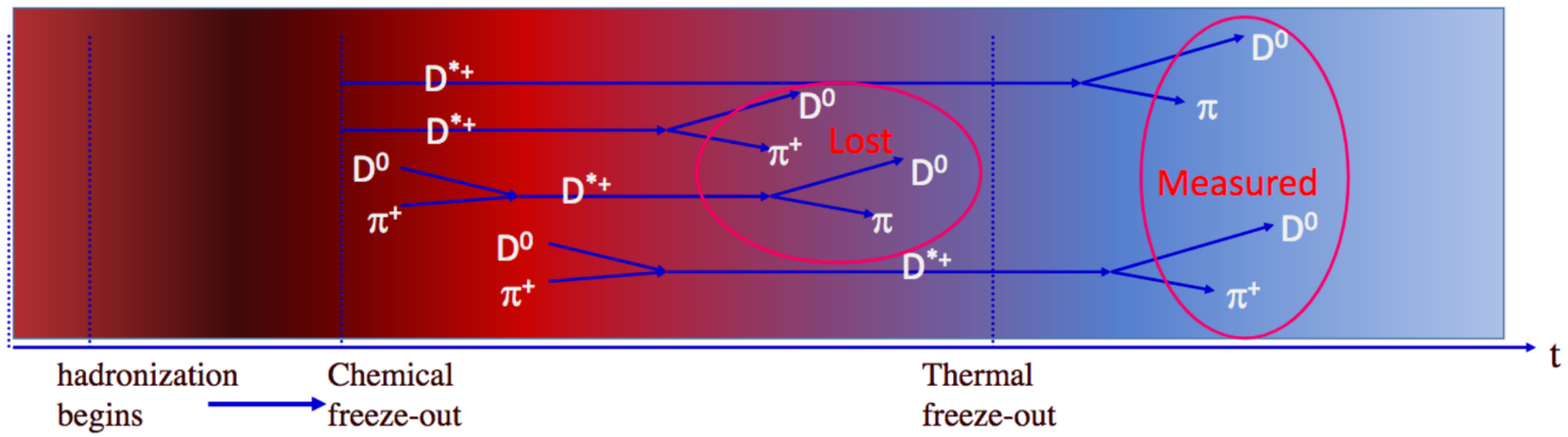


Phys. Rev. Lett. **92**, 112301

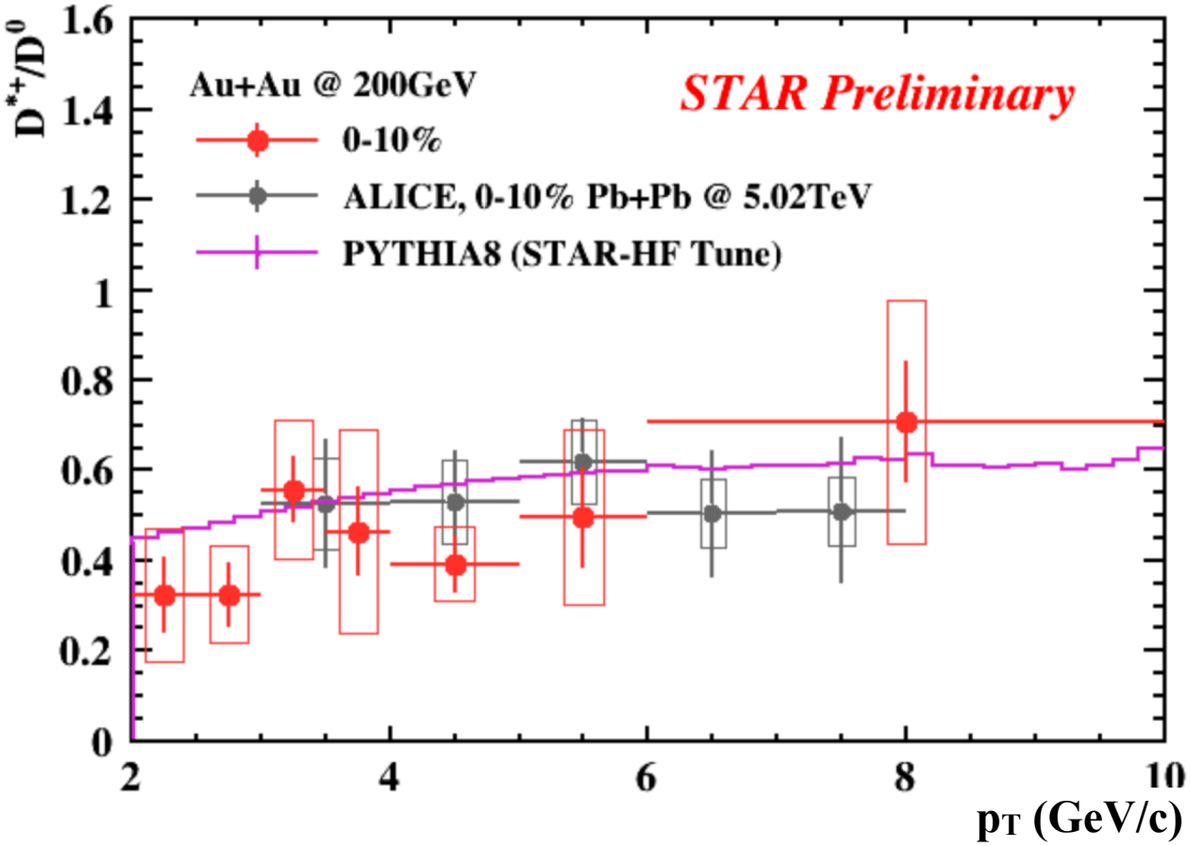
- Total D^0 cross-section is nearly independent of centrality, and smaller than in p+p. However, decreases towards central collisions for $p_T > 4$ GeV/c
- Blast Wave fits to D^0 spectra:
  - BW fits to $p_T < 5$ GeV/c. Both standard and Tsallis BW fits tried
  - Results suggest an earlier freeze-out for D^0 than light flavor hadrons

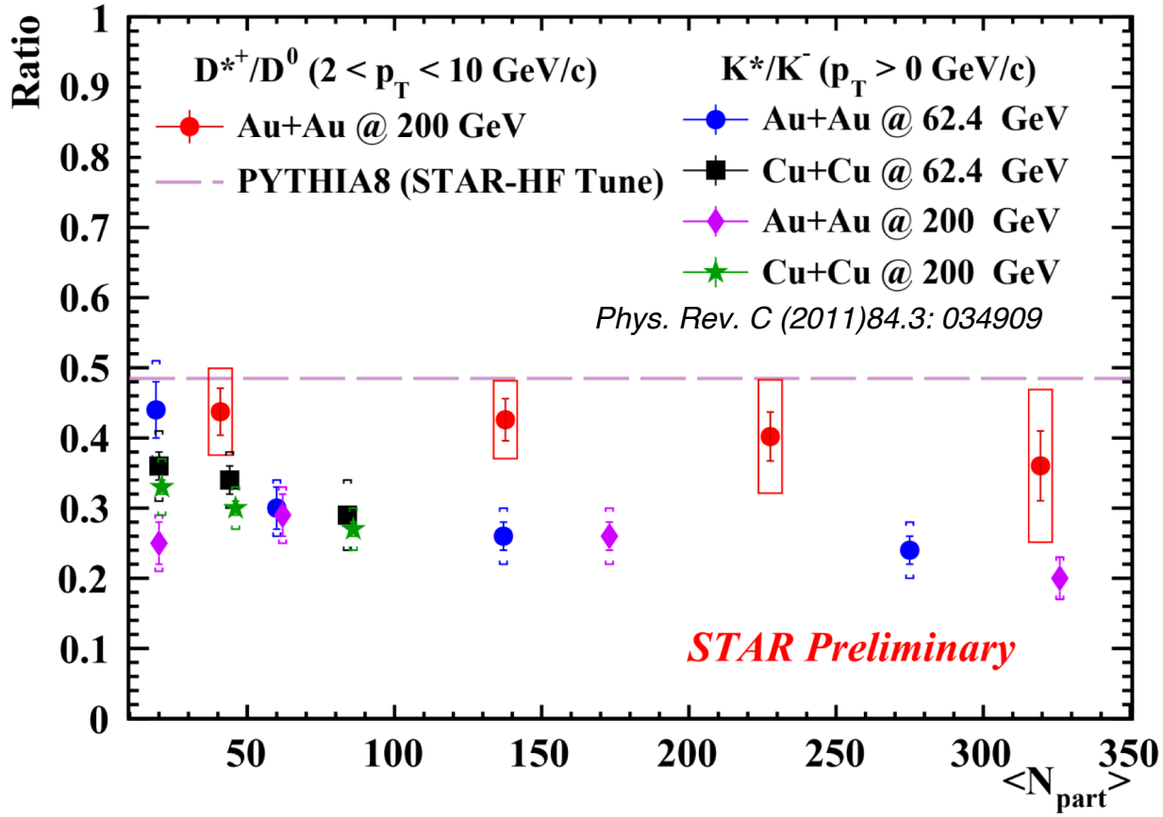
D^* Production in Au+Au Collisions

- Measure D^{*+}/D^0 ratio
  - D^{*+} feed-down contribution to D^0 yields ($D^{*+} \rightarrow D^0 \pi^+_{soft}$)
  - In-medium effects:
    - Shorter life time in medium (?). Lifetime in vacuum is ~2000 fm/c, but spectral function predicted to broaden in medium *(R.Rapp et.al Phys. Rev. C (2018)97, 034918)*
    - Rescattering can lead to loss of yield which was already seen for K^* *(STAR, Phys. Rev. C (2011)84, 034909)*



D* Production in Au+Au Collisions





- D^{*+}/D^0 ratio consistent with PYTHIA and with ALICE data [arXiv:1804.09083] at higher p_T
- Ratio of the integrated yields shows no strong centrality dependence

Total Charm Cross-section

- Total charm cross-section is estimated from the various charm hadron measurements

  - D^0 yields are measured down to zero p_T
  - For $D^{+/-}$ and D_s, Levy (power law) fits to measured spectra are used for extrapolation (systematics).
  - For Λ_c, three model fits to data are used and differences are included in systematics

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28 *
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%**

- Total charm cross-section is consistent with p+p value within uncertainties.

Summary

- Extensive measurements of charm hadron yields in heavy-ion collisions by STAR
  - Combined 2014+2016 data
  - Improved significance from supervised machine-learning algorithms

- Large D^0 elliptic flow
  - Improved precision of D^0 v_2 results with combined 2014 and 2016 data
  - D^0 v_2 result suggests charm quarks achieve a thermal equilibrium with the medium
  - Precise D^0 v_2 measurements can further constrain model calculations

- Strong modification of charm hadron spectra and hadrochemistry in A+A collisions!
  - Total charm cross-section consistent with p+p within uncertainties.
  - Strong enhancement seen for Λ_c/D^0 ratio in Au+Au. Suggests coalescence hadronization of deconfined charm quarks in the medium
  - Strong suppression of D^0 yields at higher p_T in most central collisions

THANK YOU

Back Up

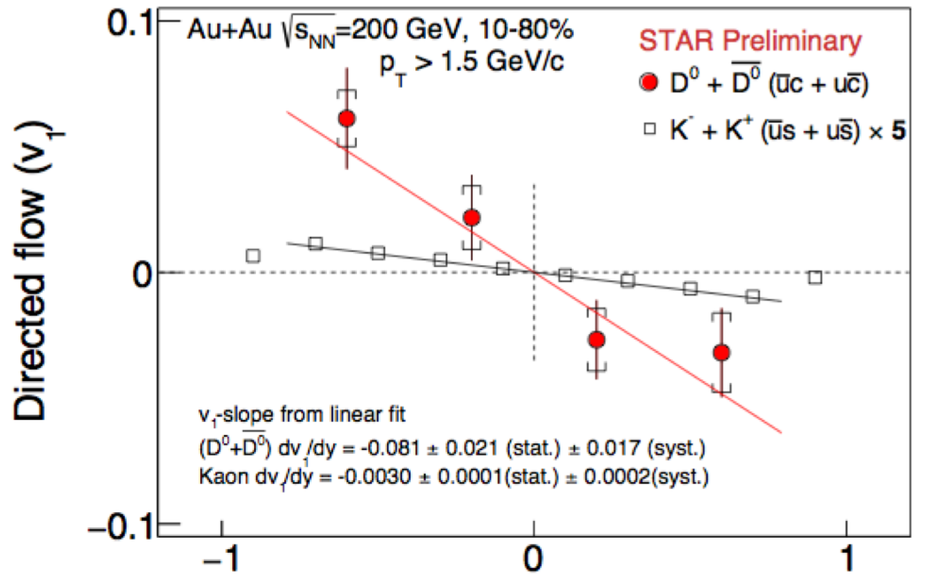
2
0

Summary

Directed flow

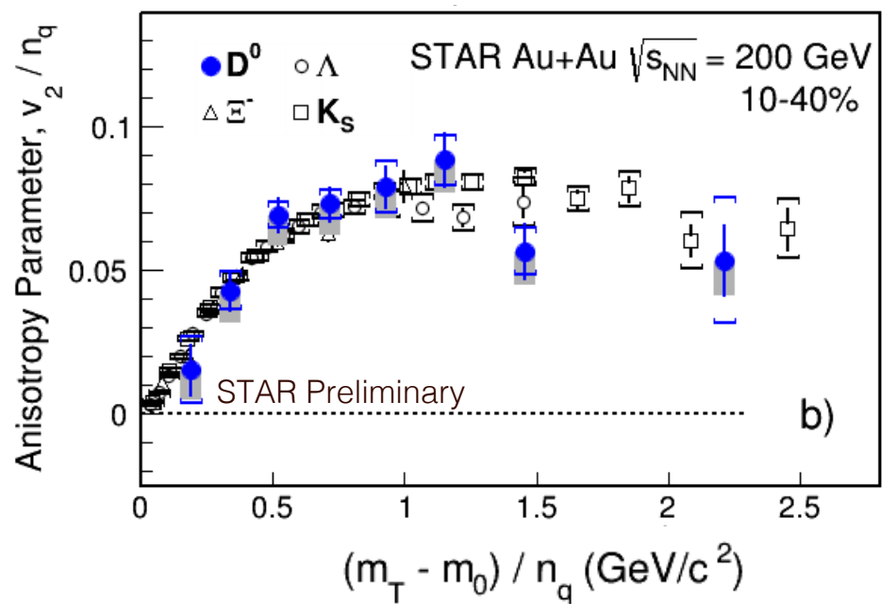
- First evidence of non-zero directed flow for heavy flavor
- Both D^0 and $\overline{D}^0$ show negative v_1-slope near mid-rapidity
- Heavy flavor v_1 > light flavor v_1

  Data can be used to probe initial matter distribution
- Current precision is not sufficient to draw conclusion on magnetic field induced charge separation of heavy quarks



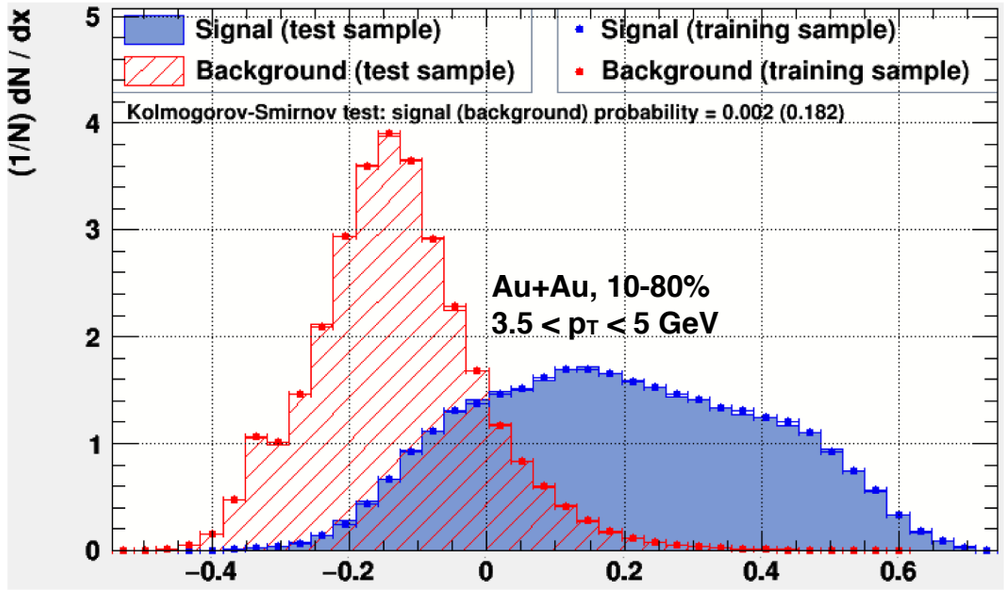
Elliptic flow

- Improved precision of D^0 v_2 results with combined 2014 and 2016 data
- D^0 v_2 result suggests charm quarks achieve a thermal equilibrium with the medium
- Precise D^0 v_2 measurements can further constrain model calculations



Boosted Decision Trees (BDT) for Λ_c Signal Extraction

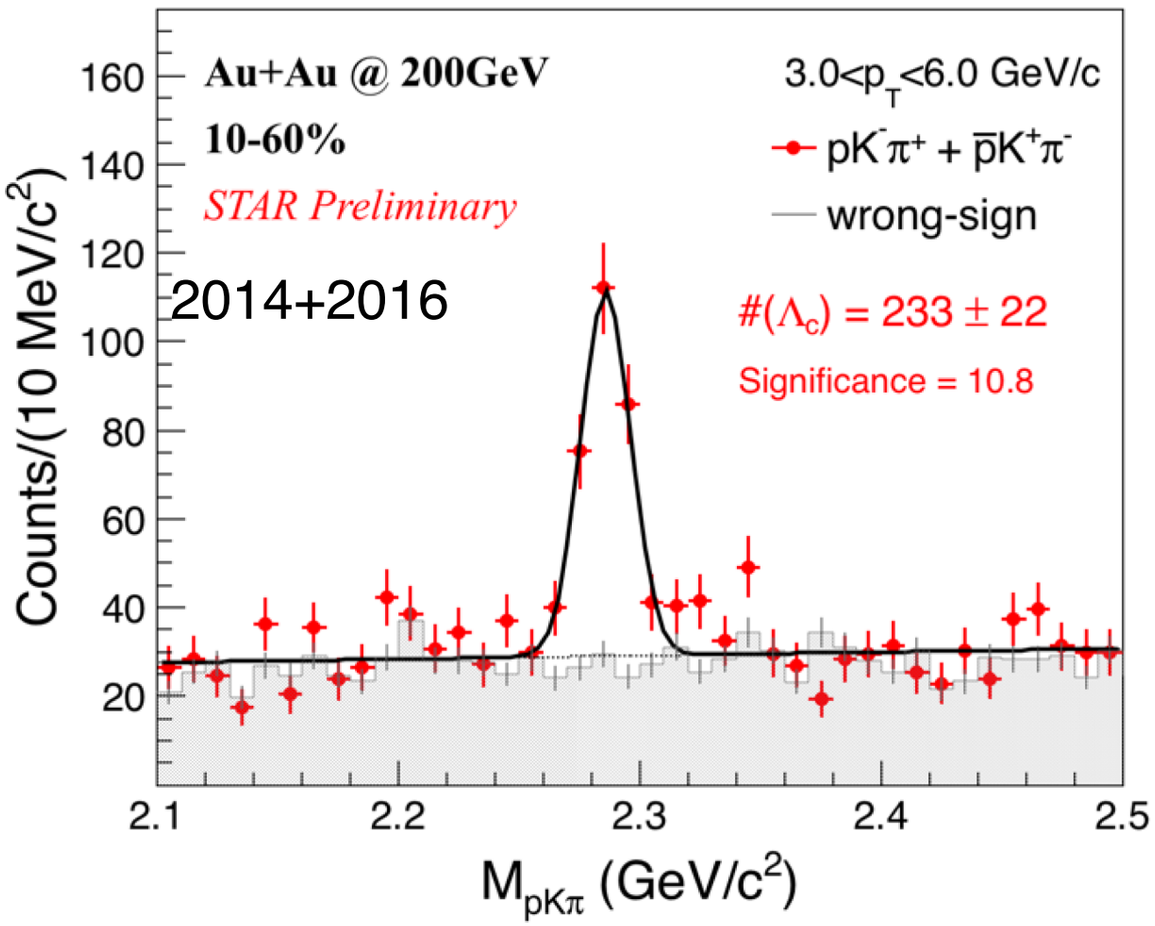
- Simple cuts on variables have limitations on signal-background separation
- Supervised learning algorithms can do better!
  - Boosted Decision Trees: successive binary cuts on attributes
  - Good performance for classification problems
  - 7 topological variables as input
  - For training: signal from MC (with detector effects), background from data



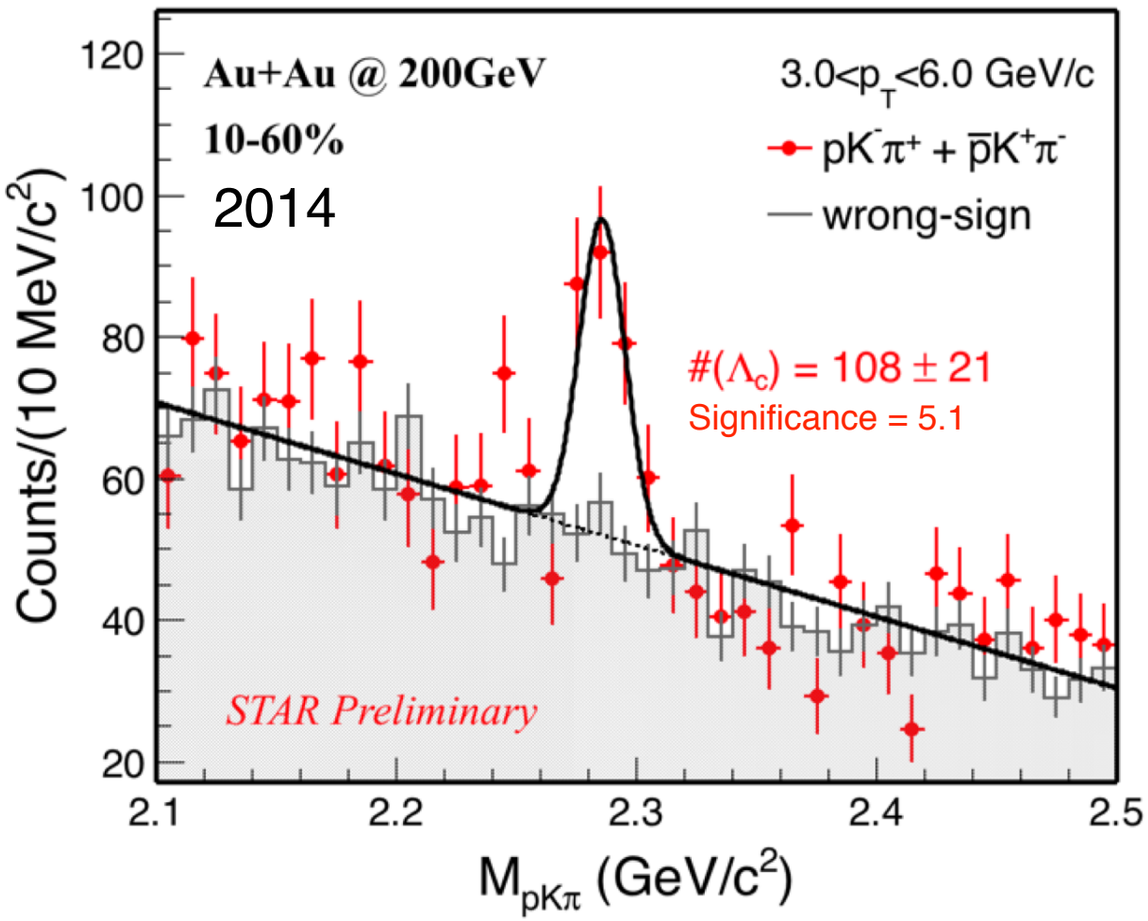
Boosted Decision Trees (BDT) for Λ_c Signal Extraction

- Simple cuts on variables have limitations on signal-background separation
- Supervised learning algorithms can do better!

QM18



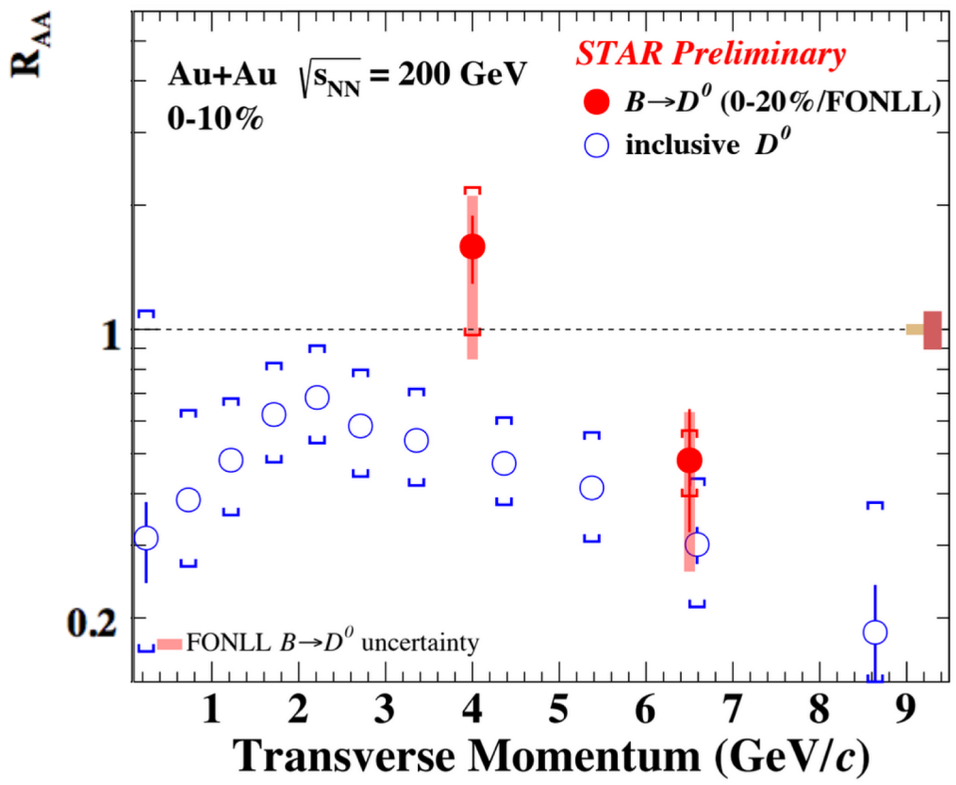
QM17



- More than 50% improvement in signal significance with TMVA BDT.
- Also new data from 2016 —> Effectively 4x more data compared to QM17

Non-prompt D^0

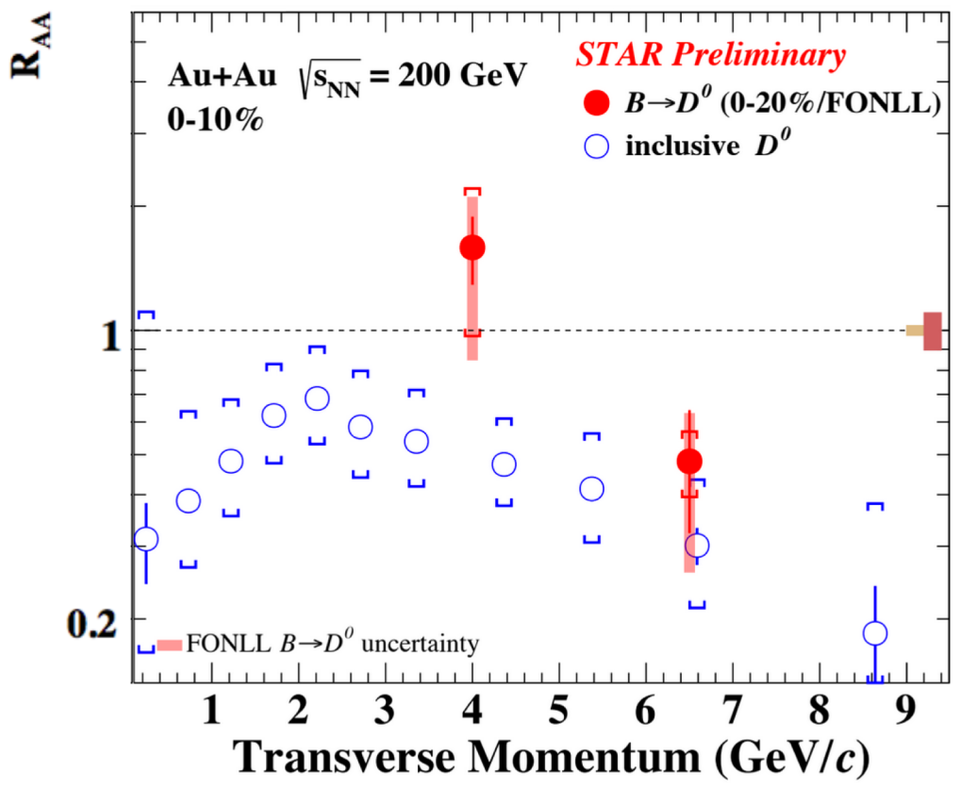
- Charm quarks interact strongly with the medium. How about bottom?
- Is there mass hierarchy for energy loss? Is $\Delta E_c > \Delta E_b$?



- R_{AA} of B mesons estimated from the measured non-prompt D^0 fraction
- Need better statistics and improved precision to understand mass dependence of energy loss.

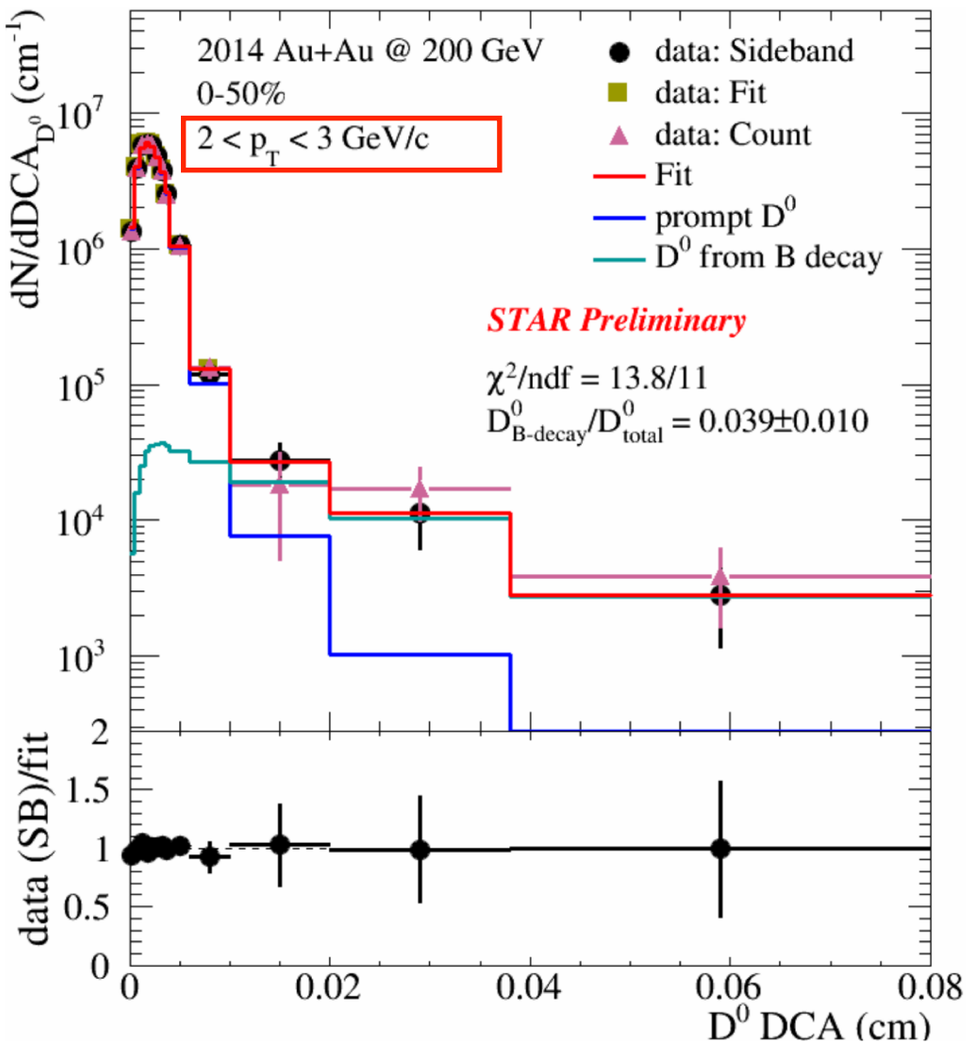
Non-prompt D^0

- Charm quarks interact strongly with the medium. How about bottom?
- Is there mass hierarchy for energy loss? Is $\Delta E_c > \Delta E_b$?

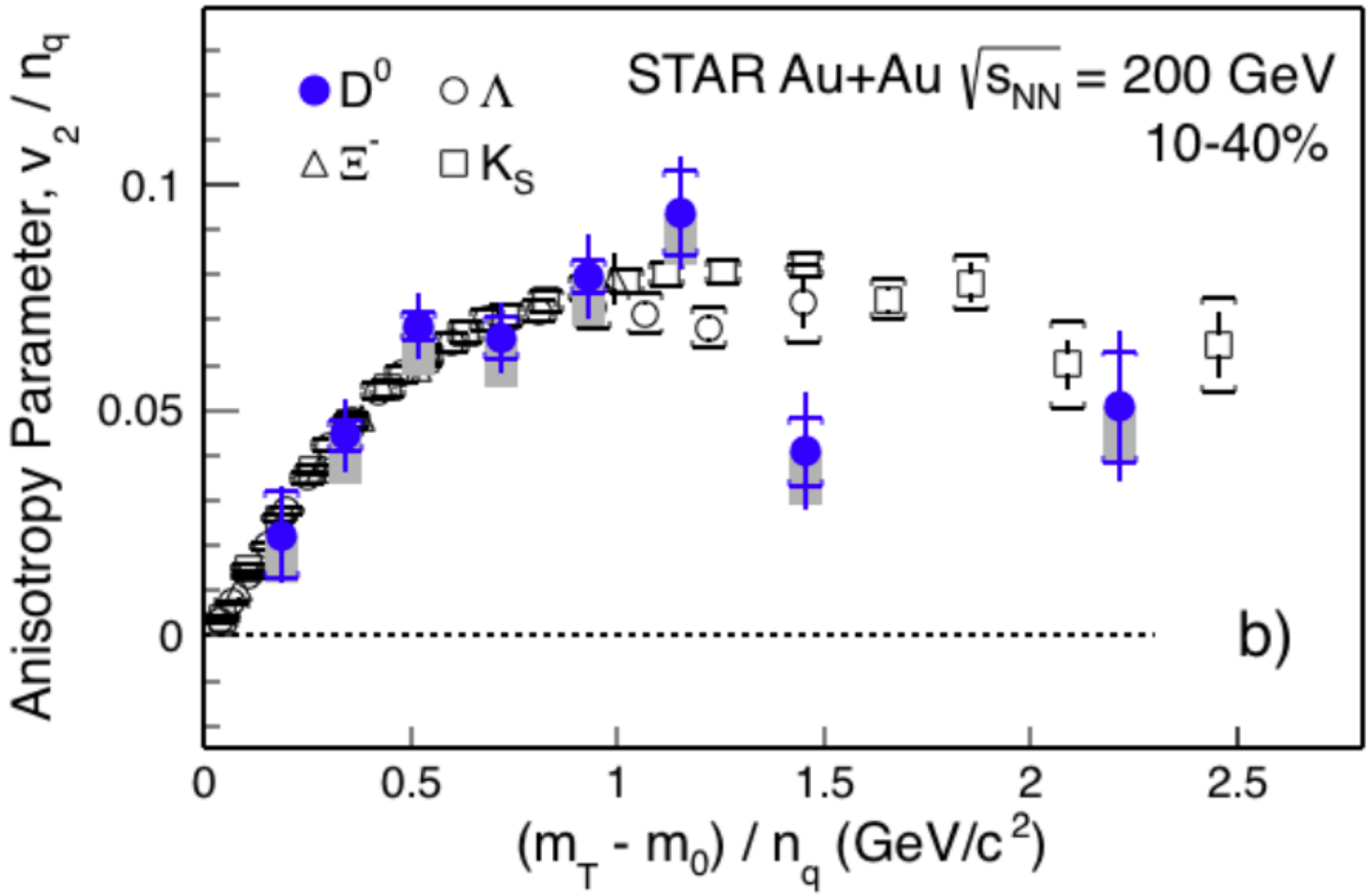


- R_{AA} of B mesons estimated from the measured non-prompt D^0 fraction
- Need better statistics and improved precision to understand mass dependence of energy loss.

- Improved signal significance for non-prompt D^0 fraction using BDT
- New results with 2014+2016 data on the way



Phys. Rev. Lett. 118 (2017) 212301



Charm quarks seem to acquire the same flow as light quarks!

Duke: *Phys. Rev. C 97, 014907 (2018)*

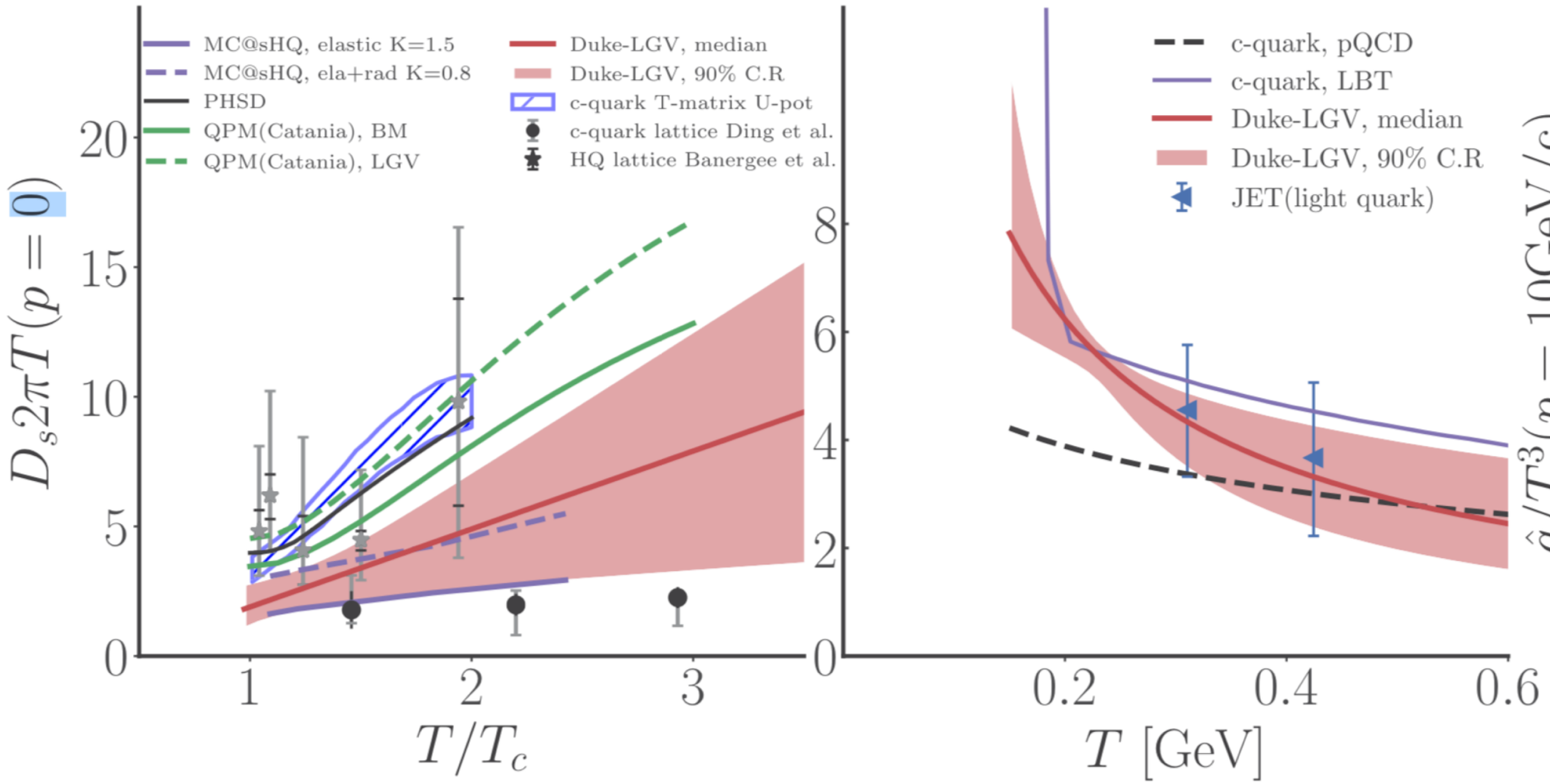
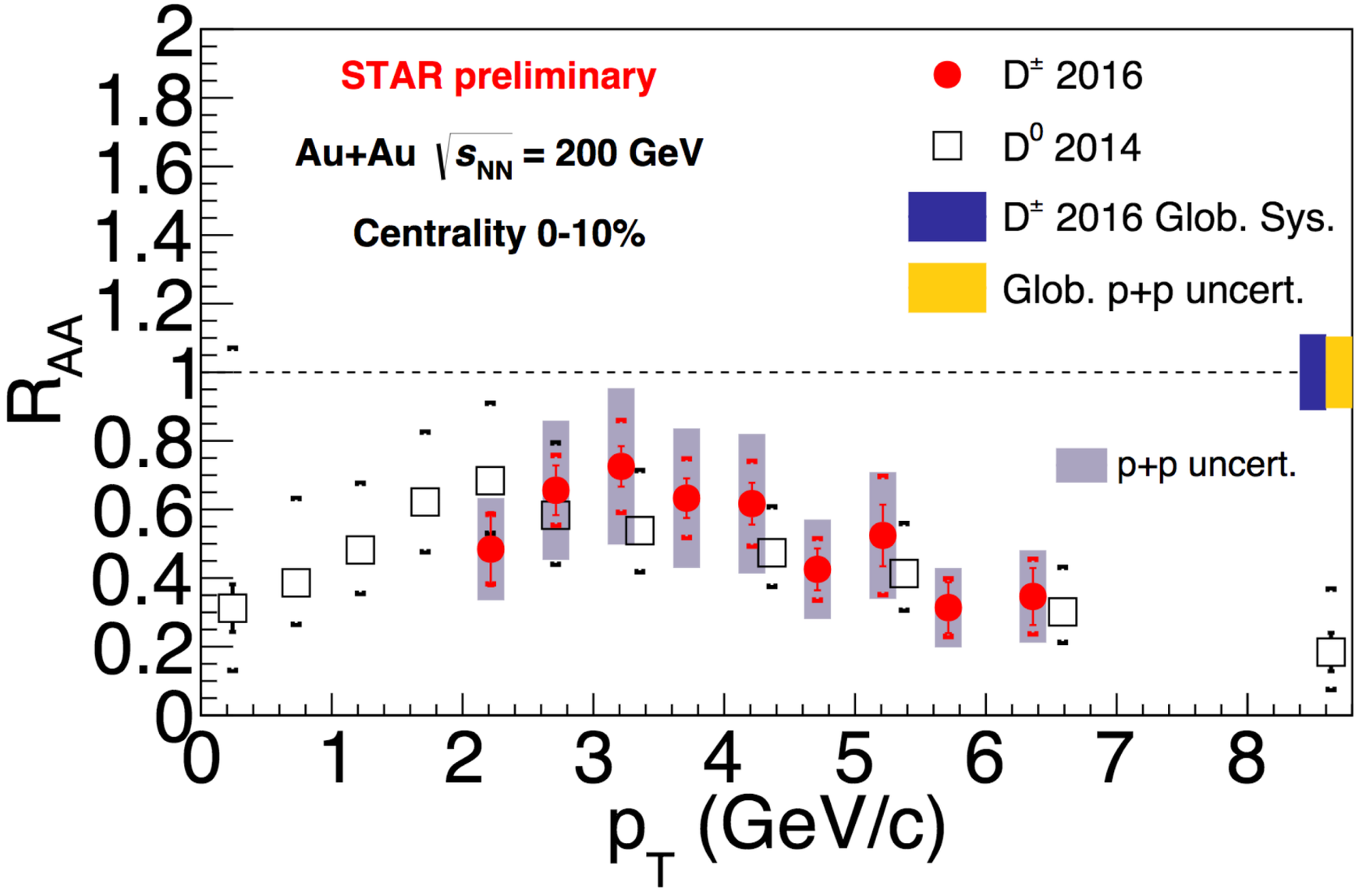


FIG. 12. Comparison of the heavy quark diffusion coefficients across multiple approaches available in the literature. (Left) Spatial diffusion coefficient at zero momentum $D_s 2\pi T(p=0)$. (Right) Momentum diffusion coefficient $\hat{q}/T^3$ at $p = 10$ GeV.

Back Up II

$D^{+/-}$ R_{AA}



- Similar suppression for D^0 and $D^{+/-}$
- Spectra measurements important for total charm cross-section

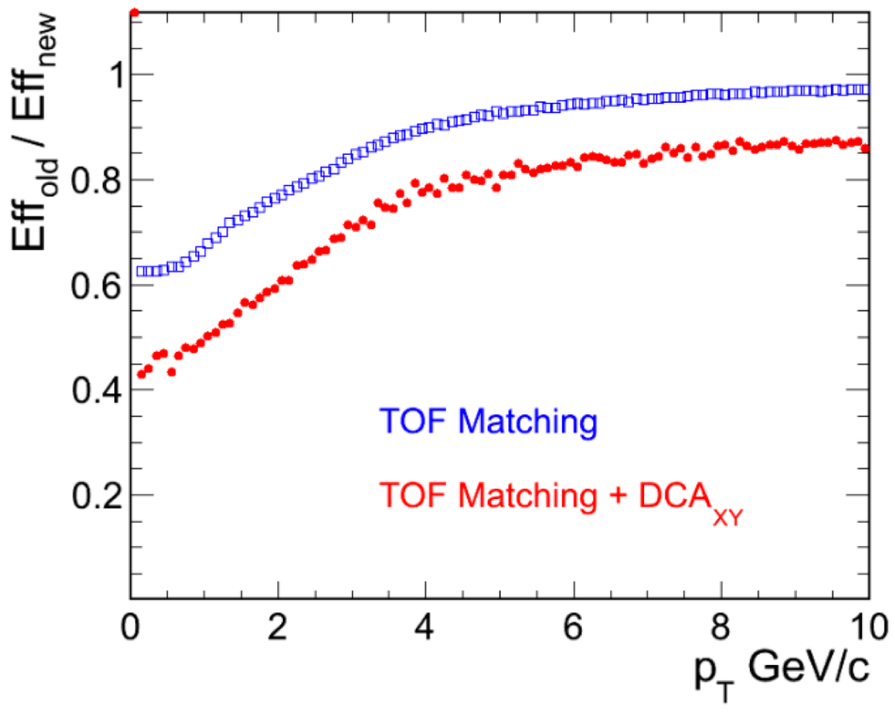
Erratum details

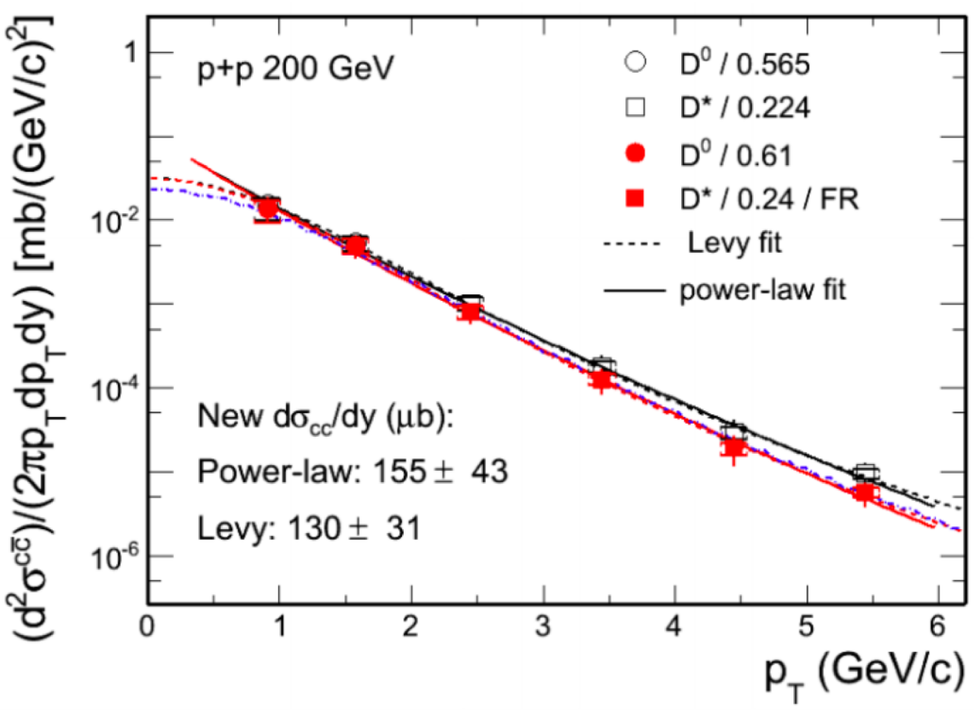
Erratum: D^0 in AuAu (2010/2011 TPC Analysis) - I

PRL 113 (2014) 142301

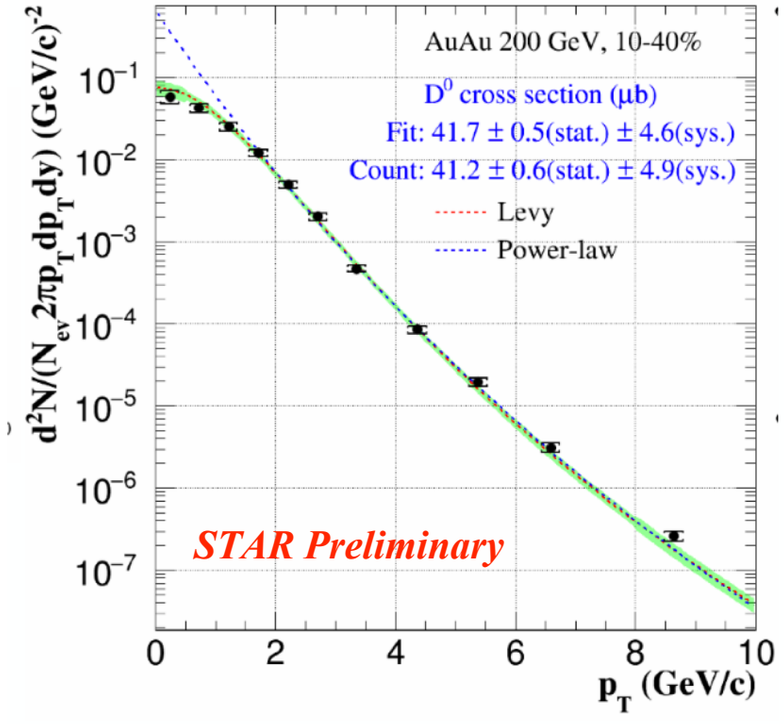
1. Two mistakes were discovered in calculating TOF related efficiency corrections
   - **Hybrid PID: algorithm inconsistently implemented in data analysis vs efficiency calculation**
   - **a transverse distance of closest approach cut efficiency was included in the correction two times**
2. p+p measurement: no issue (D^0 at p_T<2 GeV/c + D^* at 2-6 GeV/c, *PRD 86 (2012) 072012*), but the p+p D^0 baseline used for R_{AA} is updated with latest knowledge of charm frag. ratios
   - **considering the p_T dependence of D^*/D^0 frag. ratio**
   - **latest world average of c —> D^0 and c —> D^* frag. ratios**

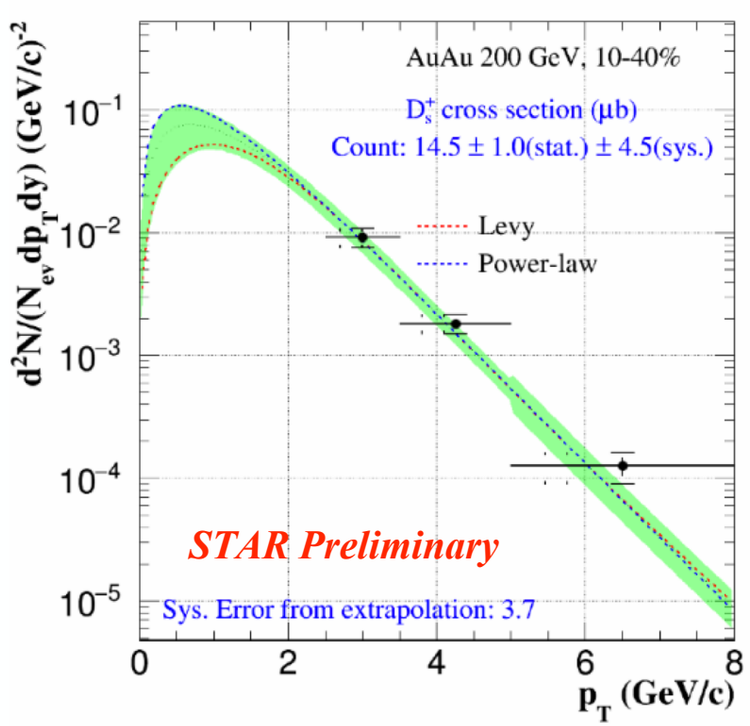
-
-
-

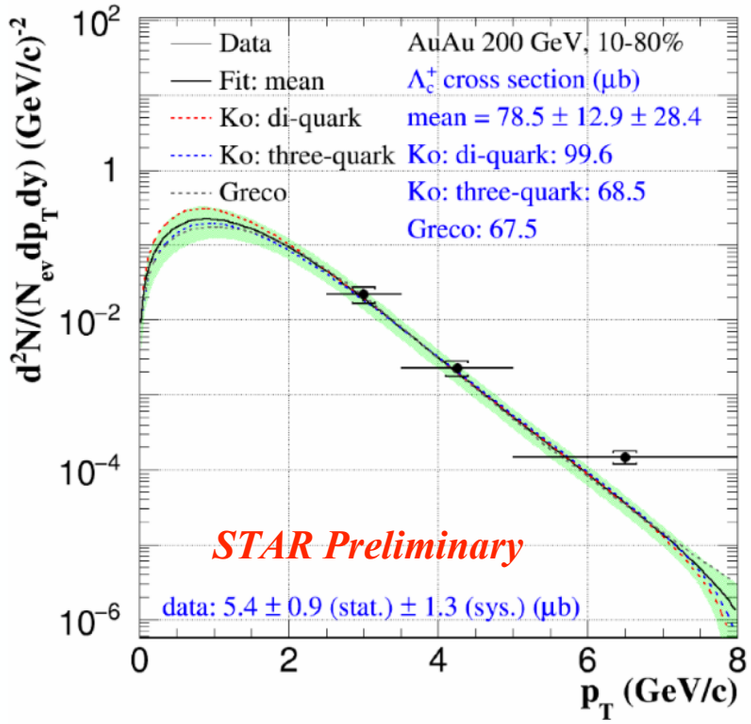




Total charm cross-section: procedure





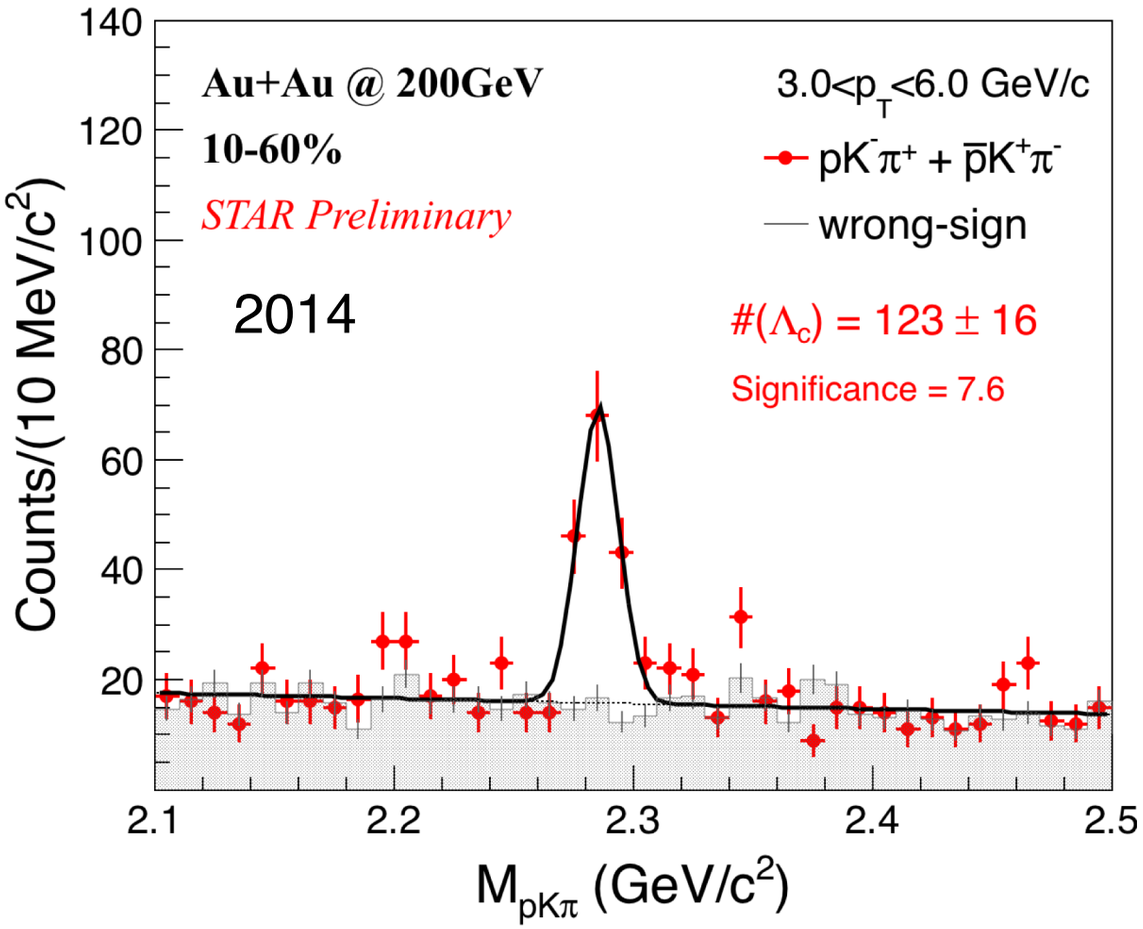


- Extracted for 10-40% centrality.
- Yields for $D^{+/-}$ and Λ_c are scaled to 10-40% centrality using measured ratio to D^0.
- Uncertainty evaluation and propagation:
  - In the p_T range with data points:
    - point by point statistical error propagated
    - point by point systematic error propagated
  - In the p_T range without data points
    - uncertainties from fit to points with statistical + systematic error
    - extrapolation uncertainty from variation of fit function

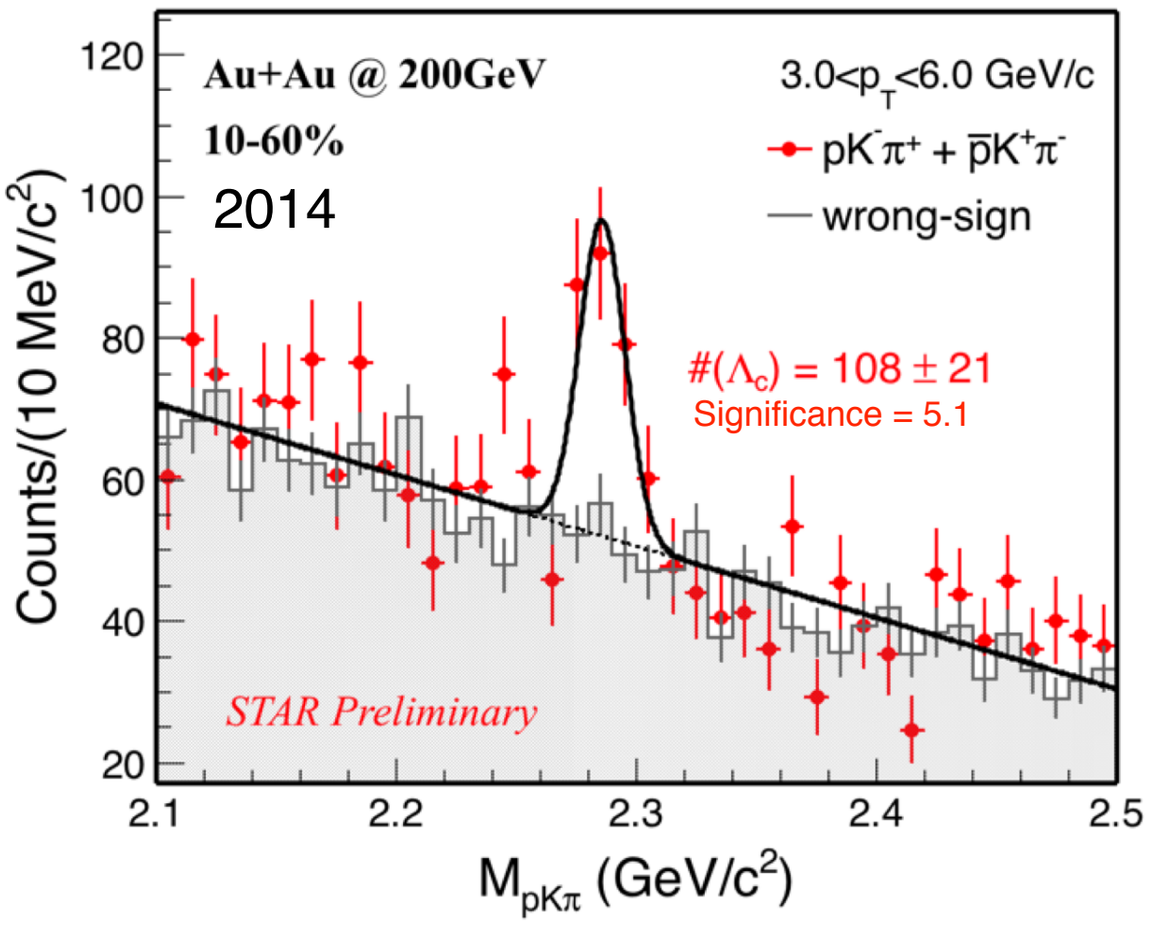
BDT vs Rectangular Cuts Comparison

- Simple cuts on variables have limitations on signal-background separation
- Supervised learning algorithms can do better!

BDT (QM18)

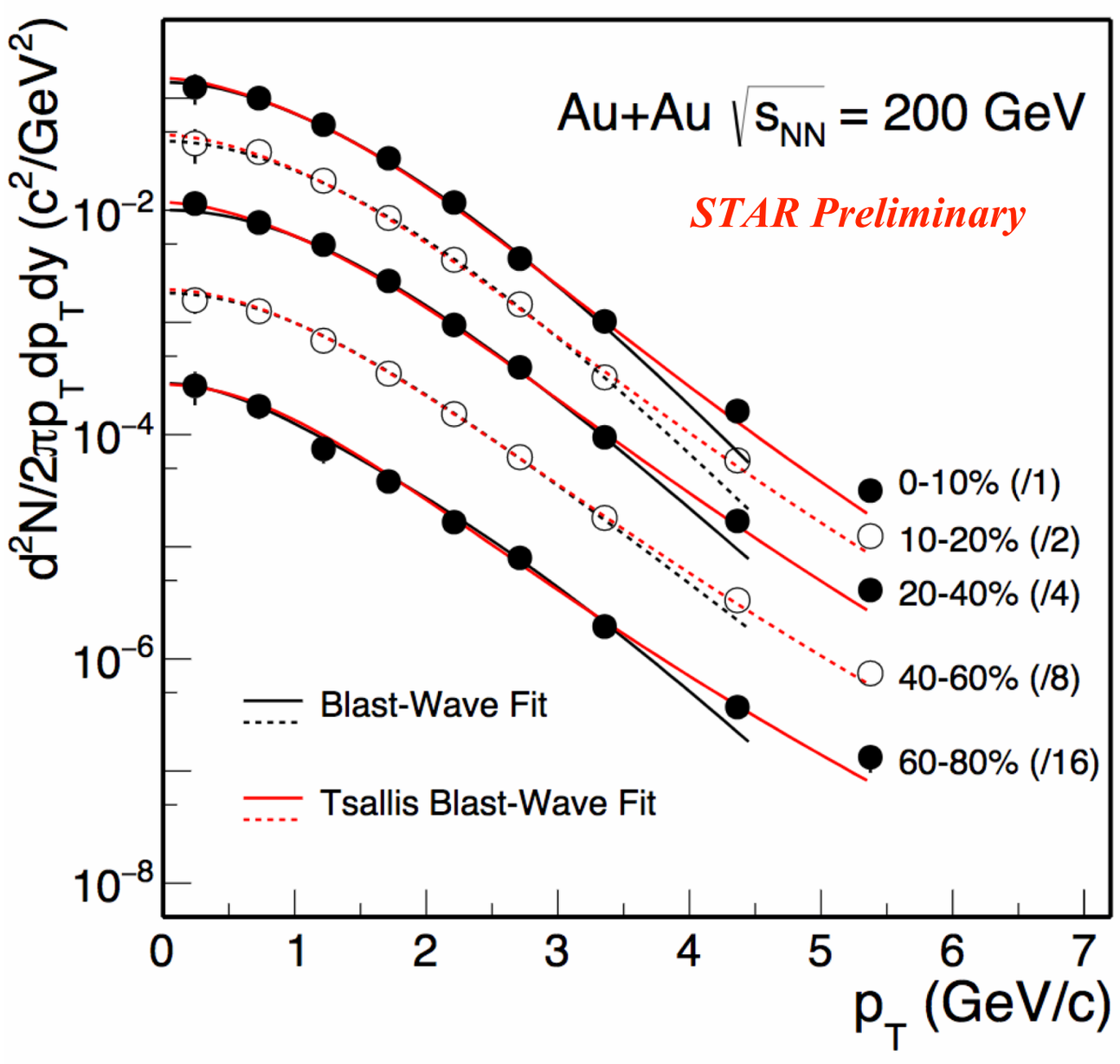


Rectangular Cuts (QM17)



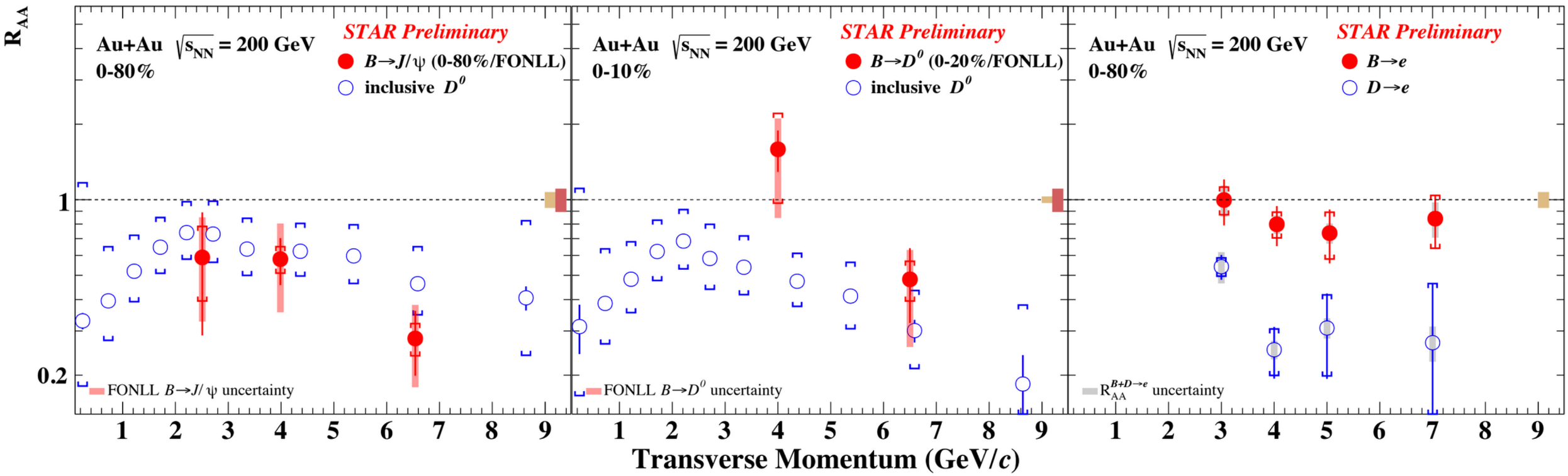
- More than 50% improvement in signal significance with TMVA BDT.

BW fits to D^0 spectra



- Fit values shown were from BW fits
- TBW gives lower temperatures for all particles, but similar radial flow

R_{AA} of B through different channels



- The decay kinematics need to be unfolded for a fair comparison among different channels.