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

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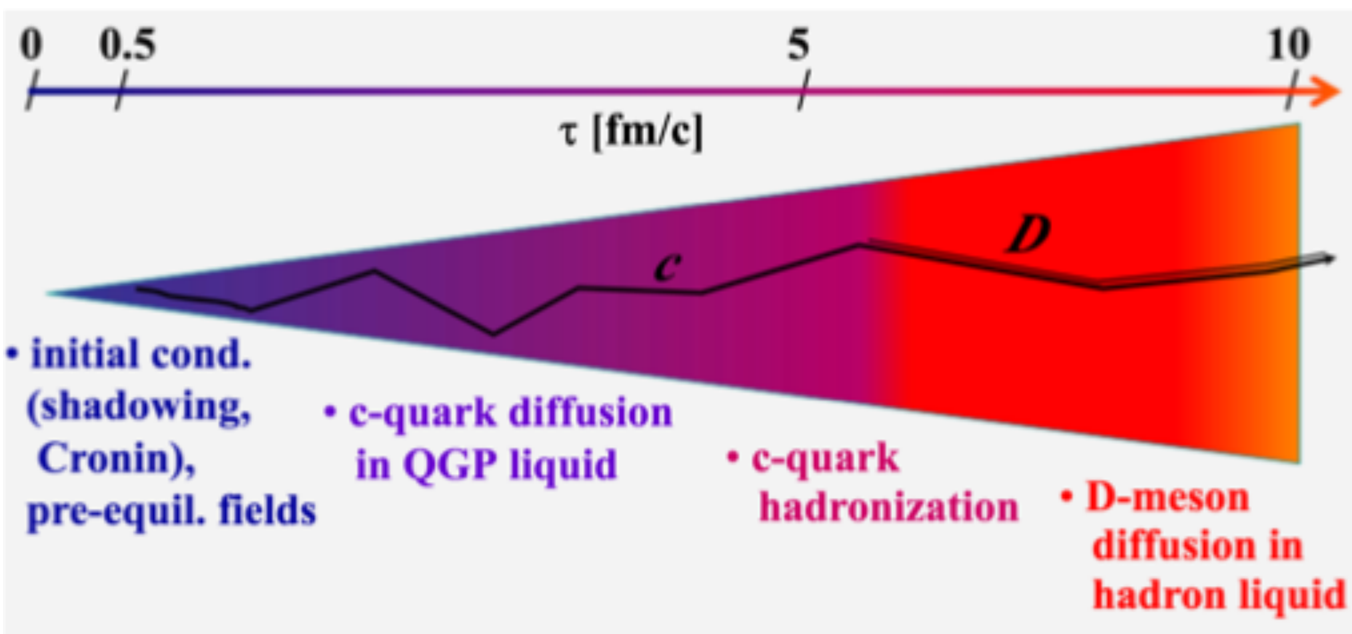
Introduction

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

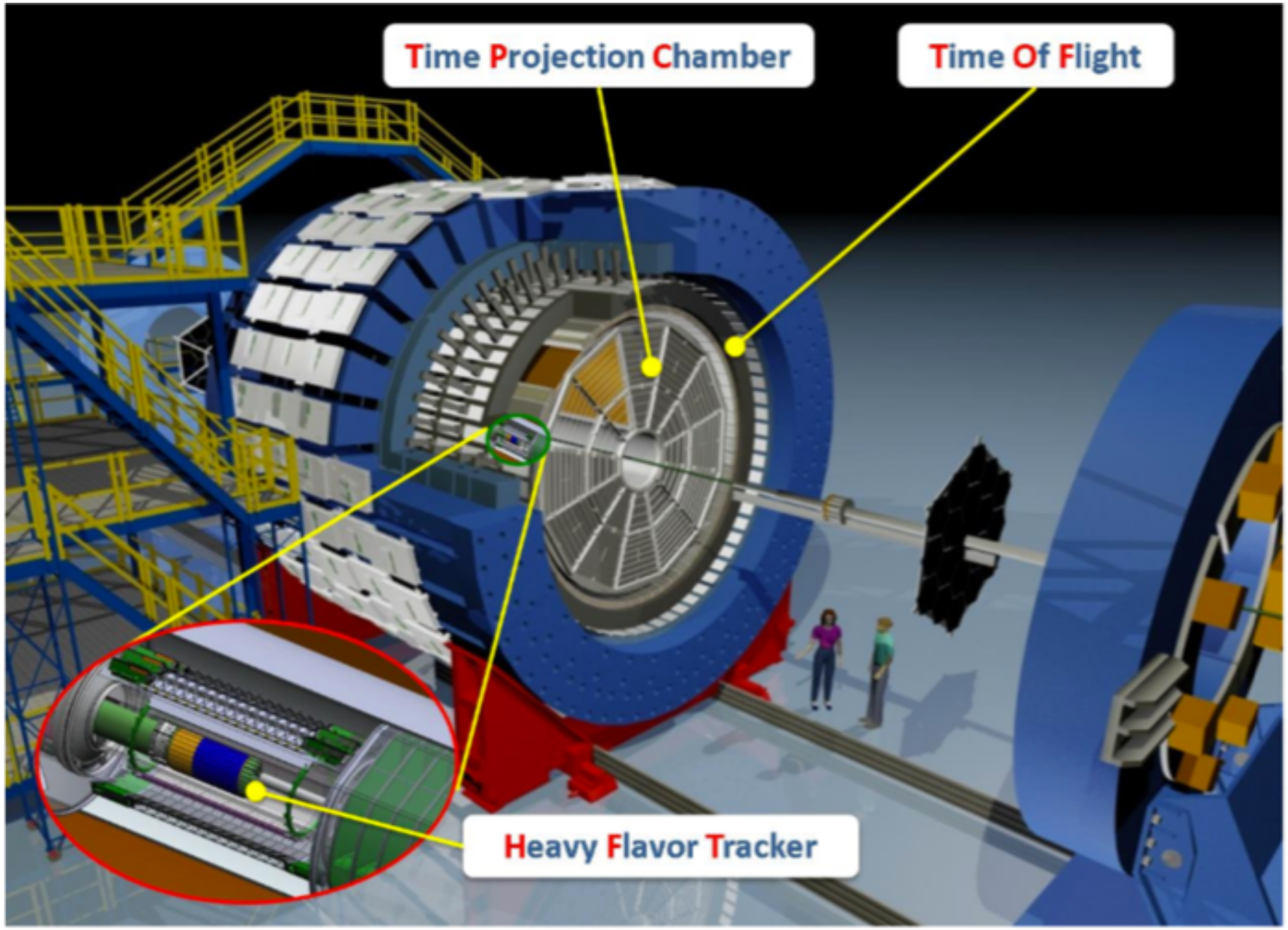


- Large directed* (v_1) and **elliptic (v_2) flow of D^0**
- Hadronization: Λ_c, D_s
- **In medium energy loss: D^0,** B-mesons*
- Medium modifications to yields/life-time: $D^{*+/-}$
- **Total charm cross-section**

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

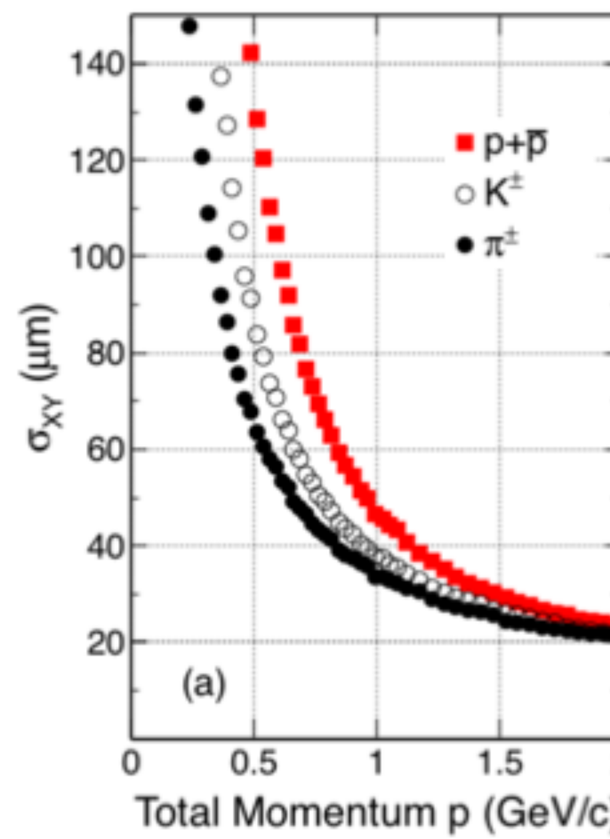
* Not reported here. See QM2018 talks of S. Sinha and S. Radhakrishnan

The STAR Detector



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

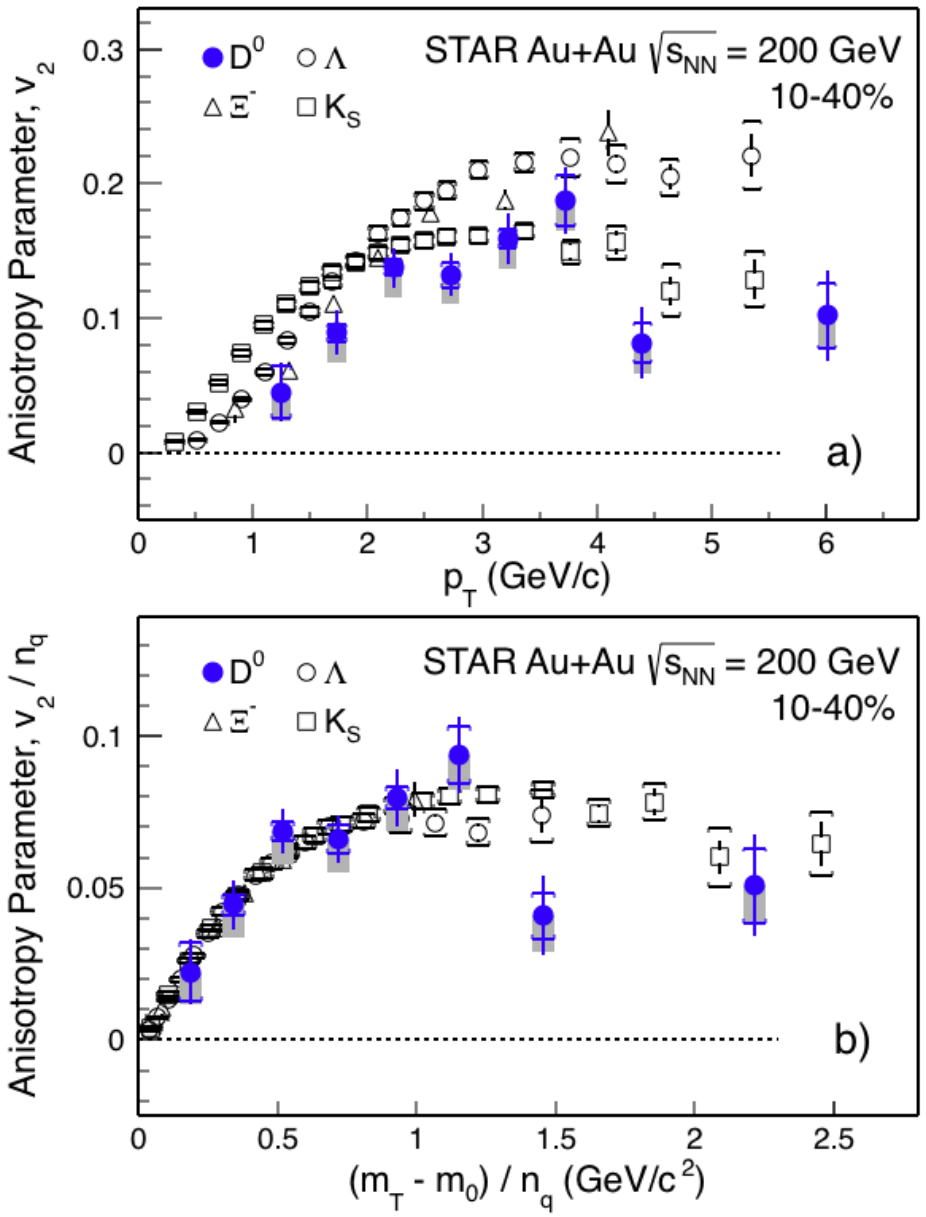
Phys. Rev. Lett. 118 (2017) 212301



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)

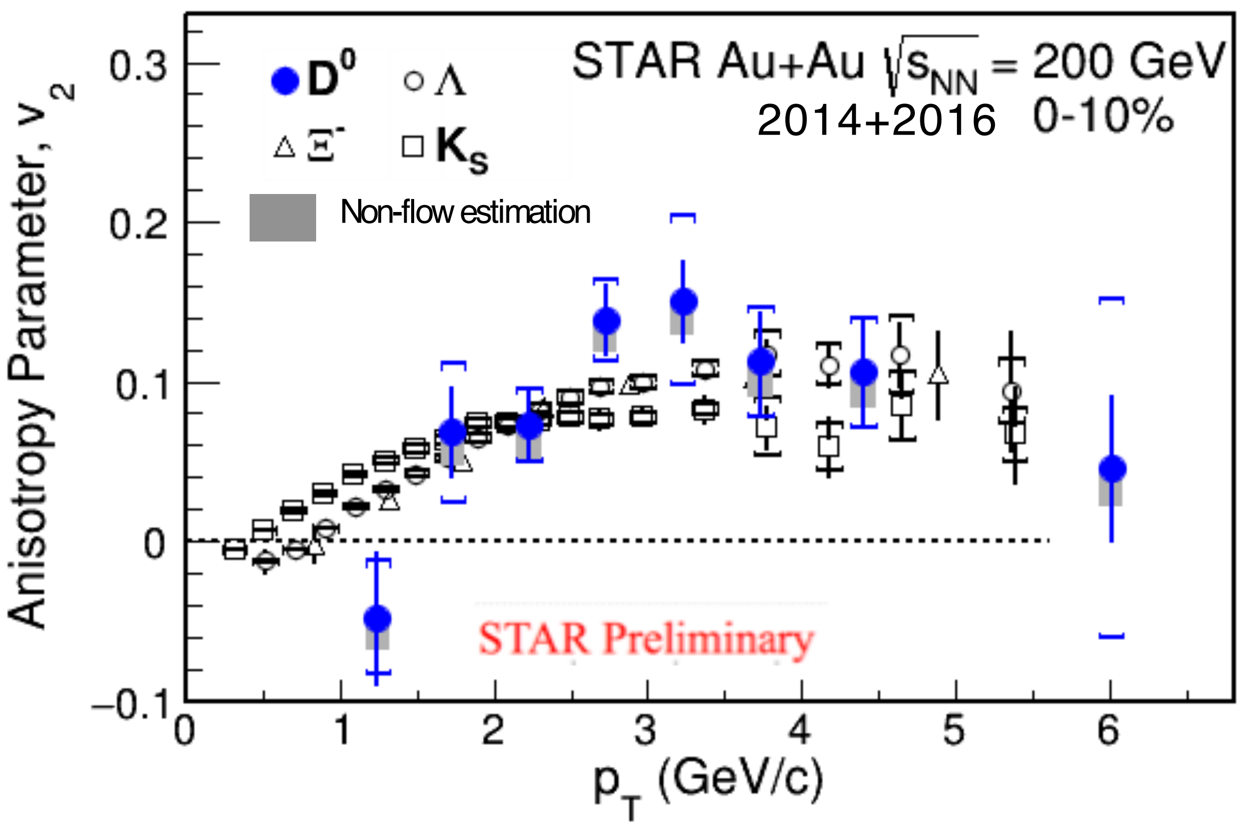


- STAR published D^0 v_2 from data taken during 2014 run
- D^0 elliptic flow magnitude consistent with NCQ scaling in mid-central collisions.
- High statistics 2016 run data allow to improve precision of the charm flow measurements at RHIC energy
- The 2016 data also allow us to extend NCQ scaling test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

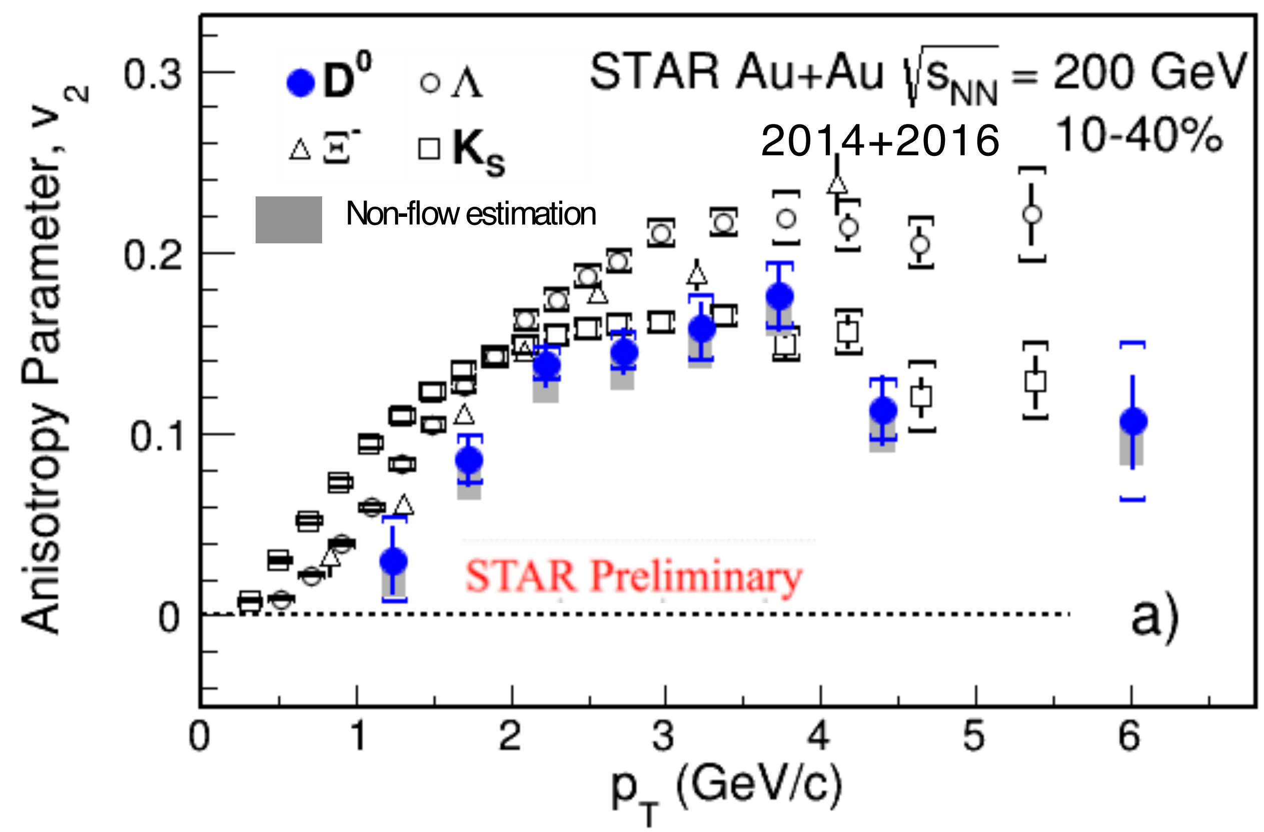
Precise D^0 v_2 measurement can allow:

→ Quantitative studies of QGP properties (transport coefficients)

D^0 v_2 Comparison to Light Hadrons

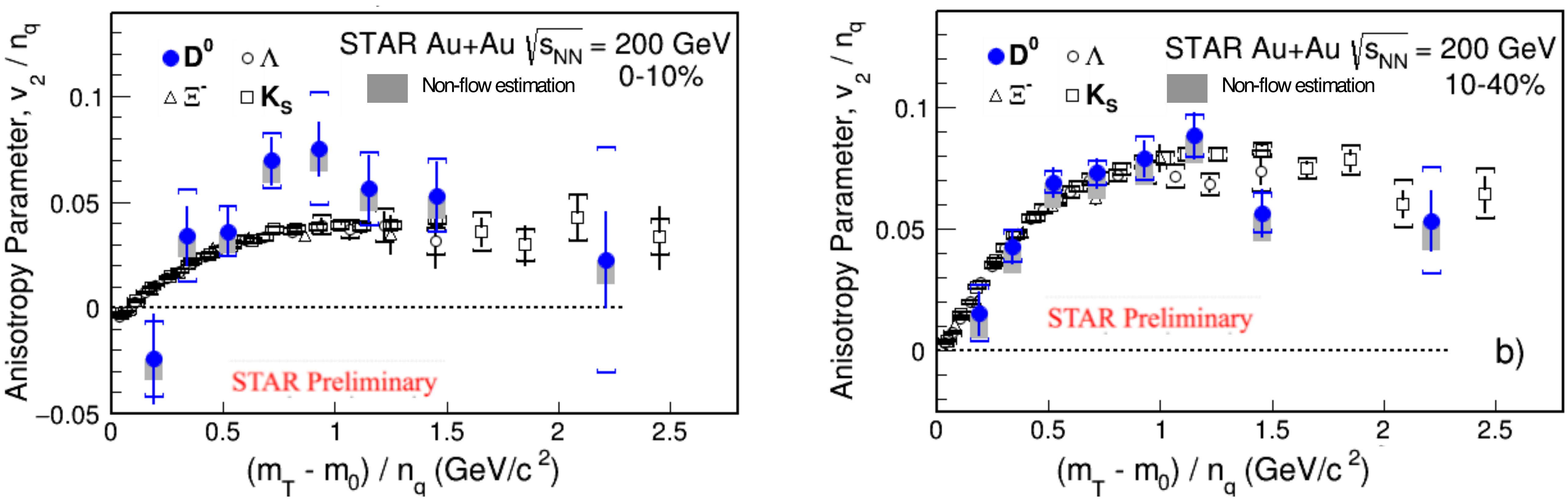


Phys. Rev. C 77, 054901 (2008)



- 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

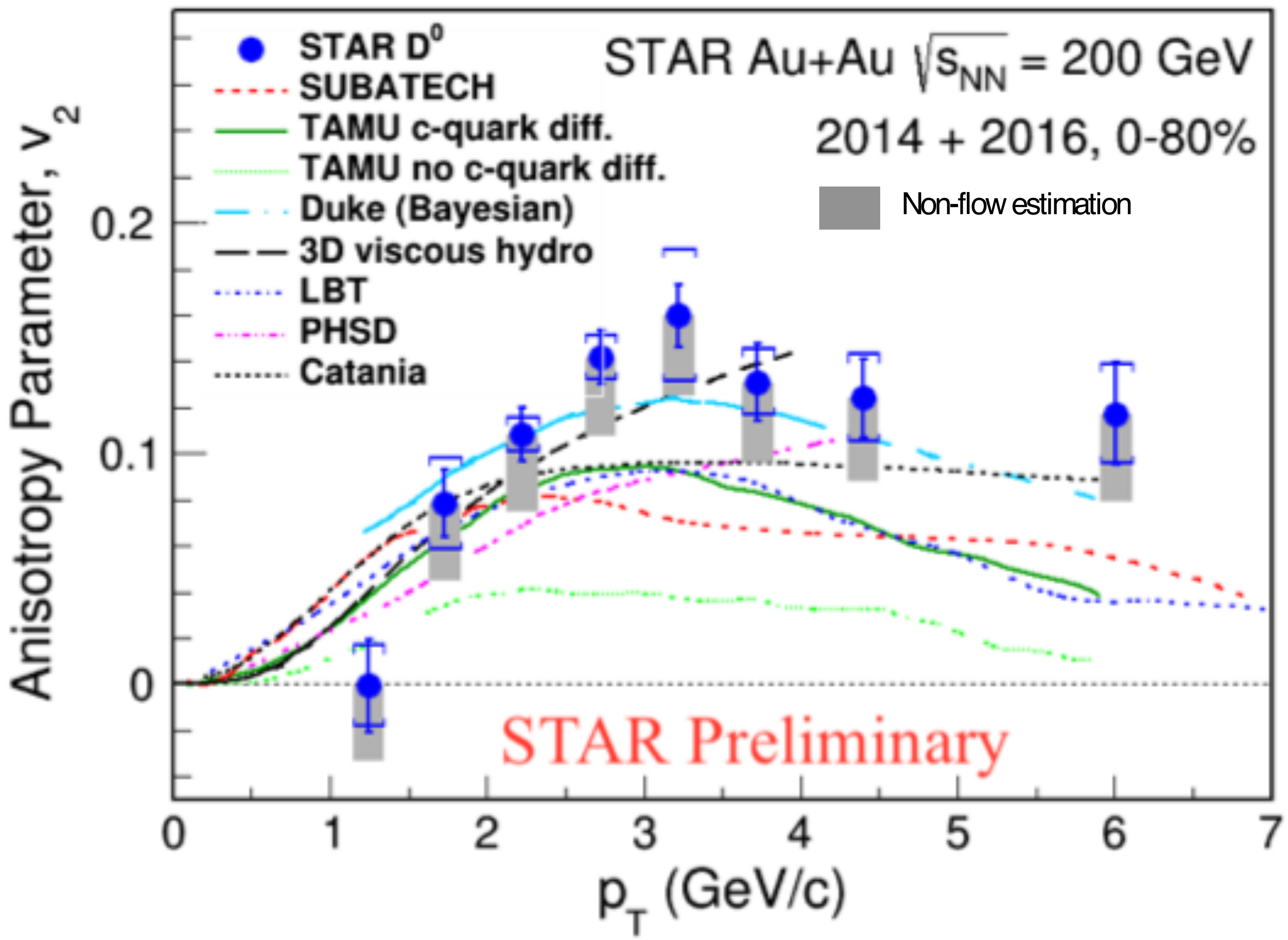
NCQ Scaling Test



- 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 $\times 10^{-5}$
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)*

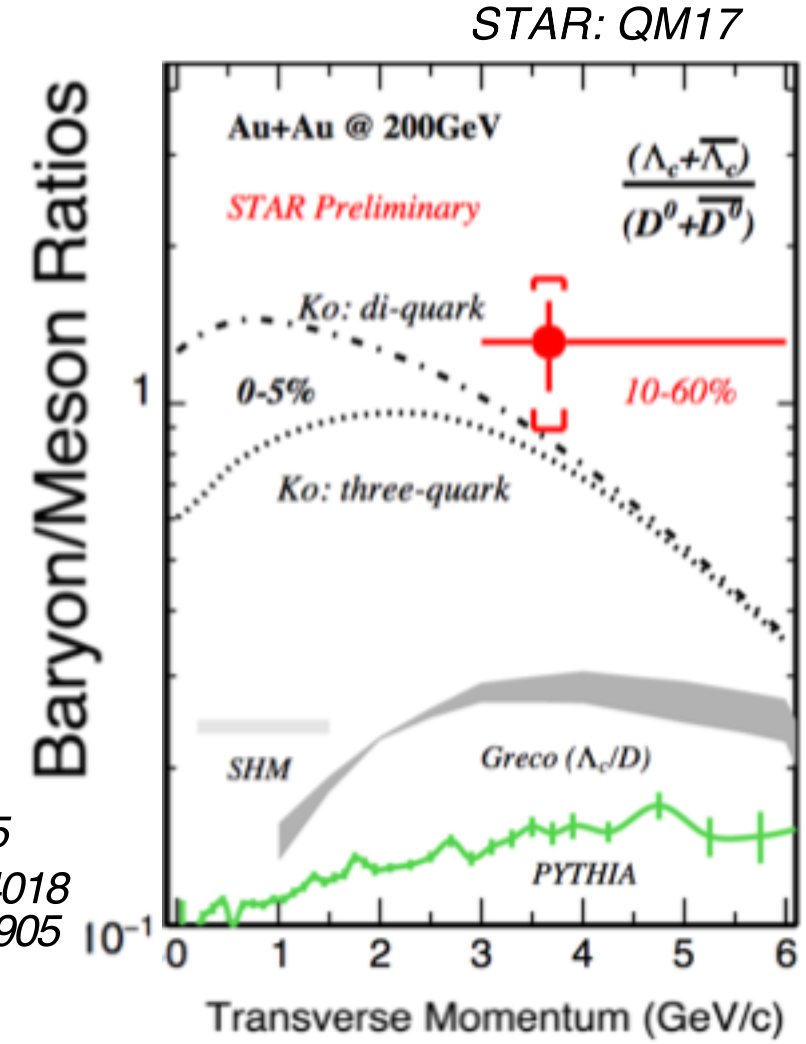
- D^0 v_2 results from combined 2014 + 2016 data
- Improved precision to constrain the models

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

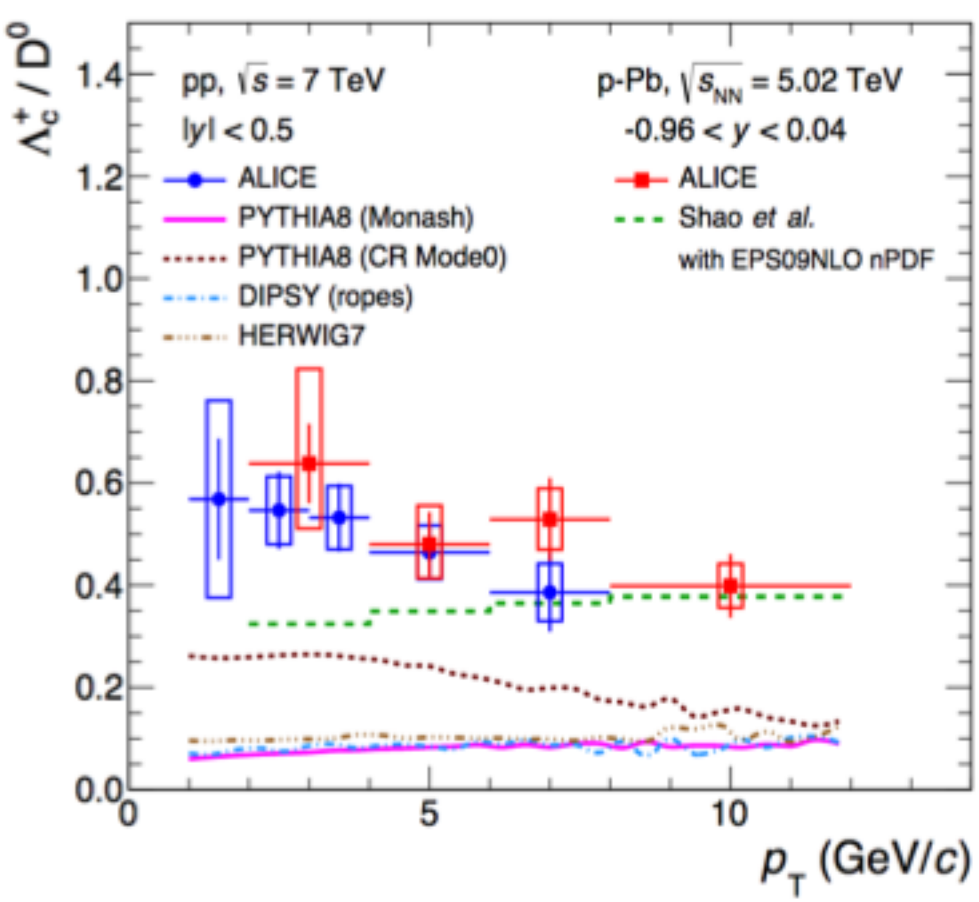
- An enhancement relative to PYTHIA also seen in p+p and p+Pb collisions at LHC

STAR: QM17



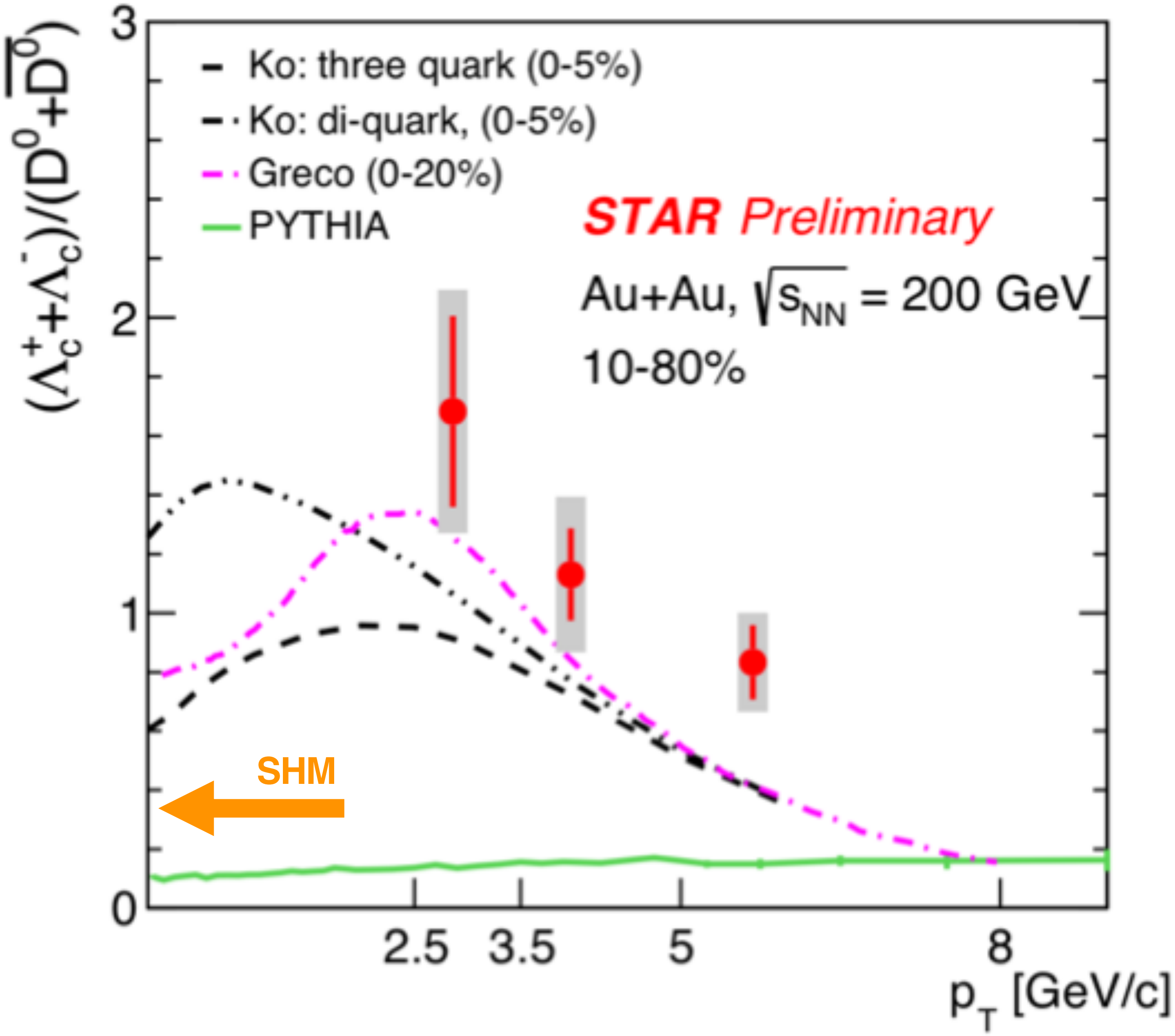
Ko: PRC 79 (2009) 044905
Greco: PRD 90 (2014) 054018
SHM: PRC 79 (2009) 044905

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?

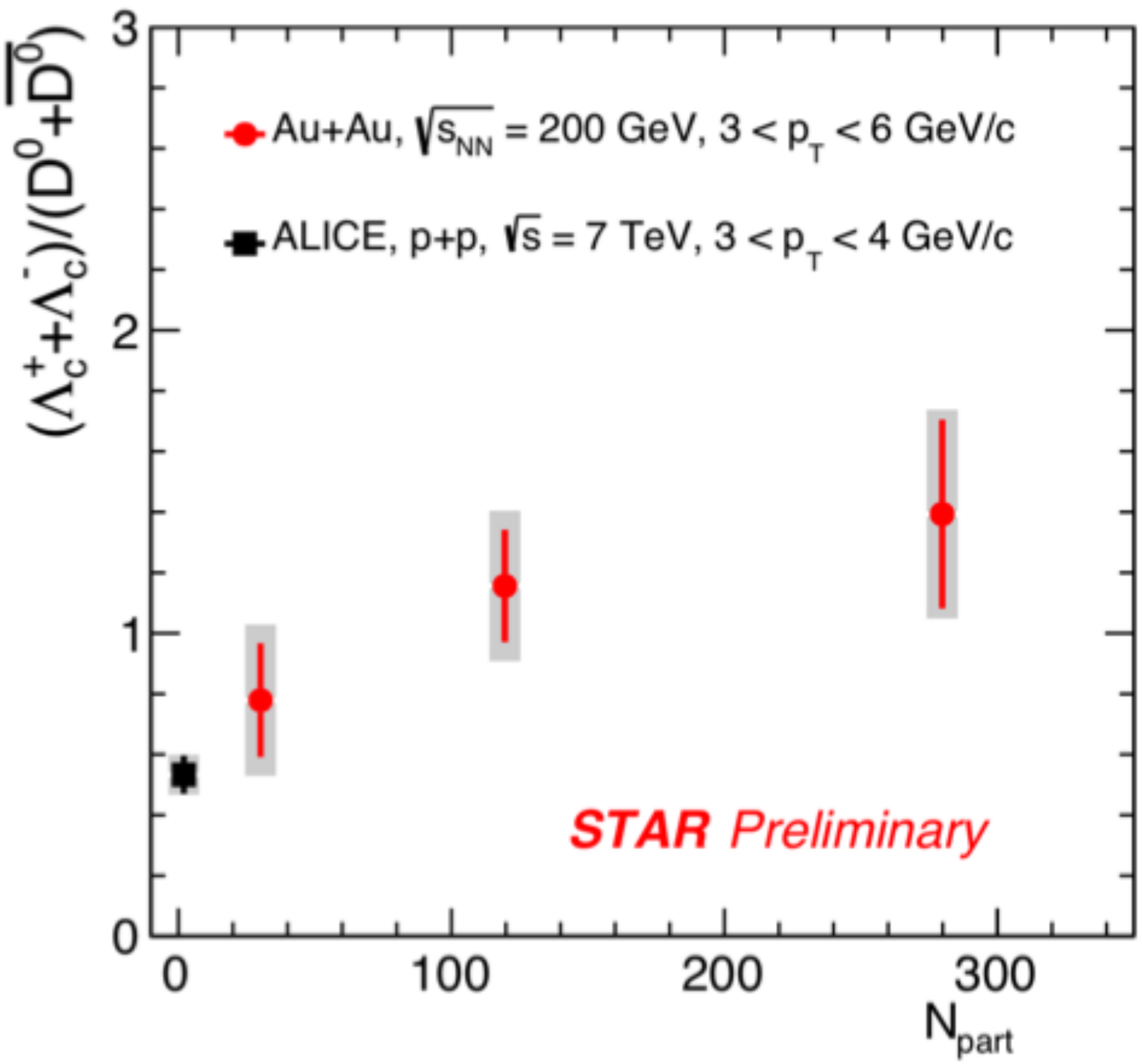
p_T Dependence of Λ_c/D^0 Ratio



Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905

- 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

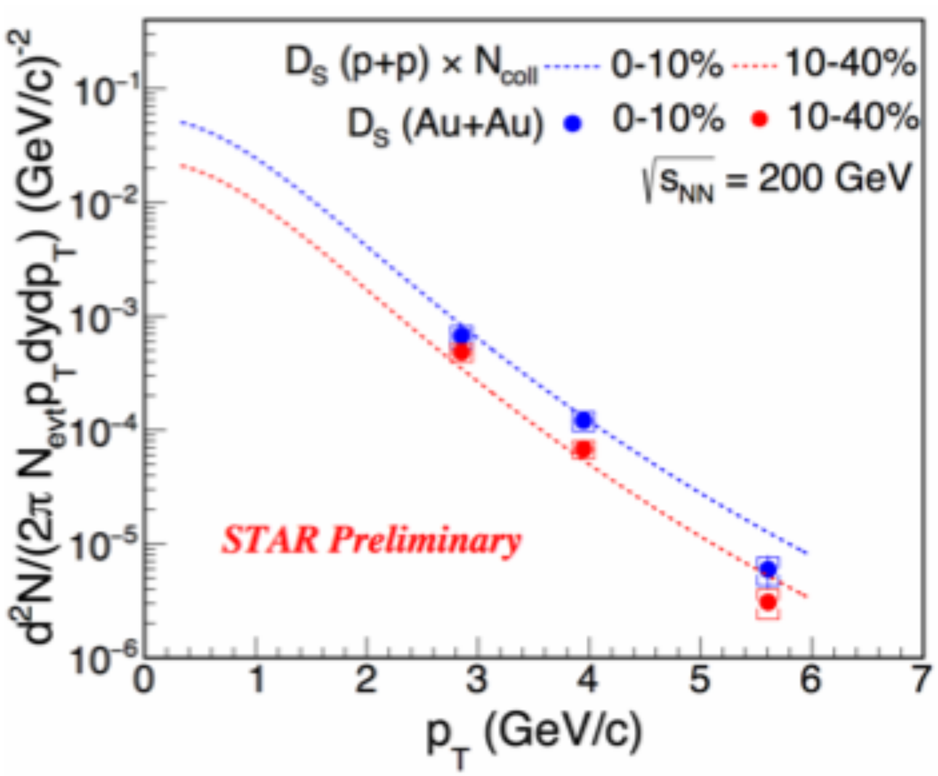


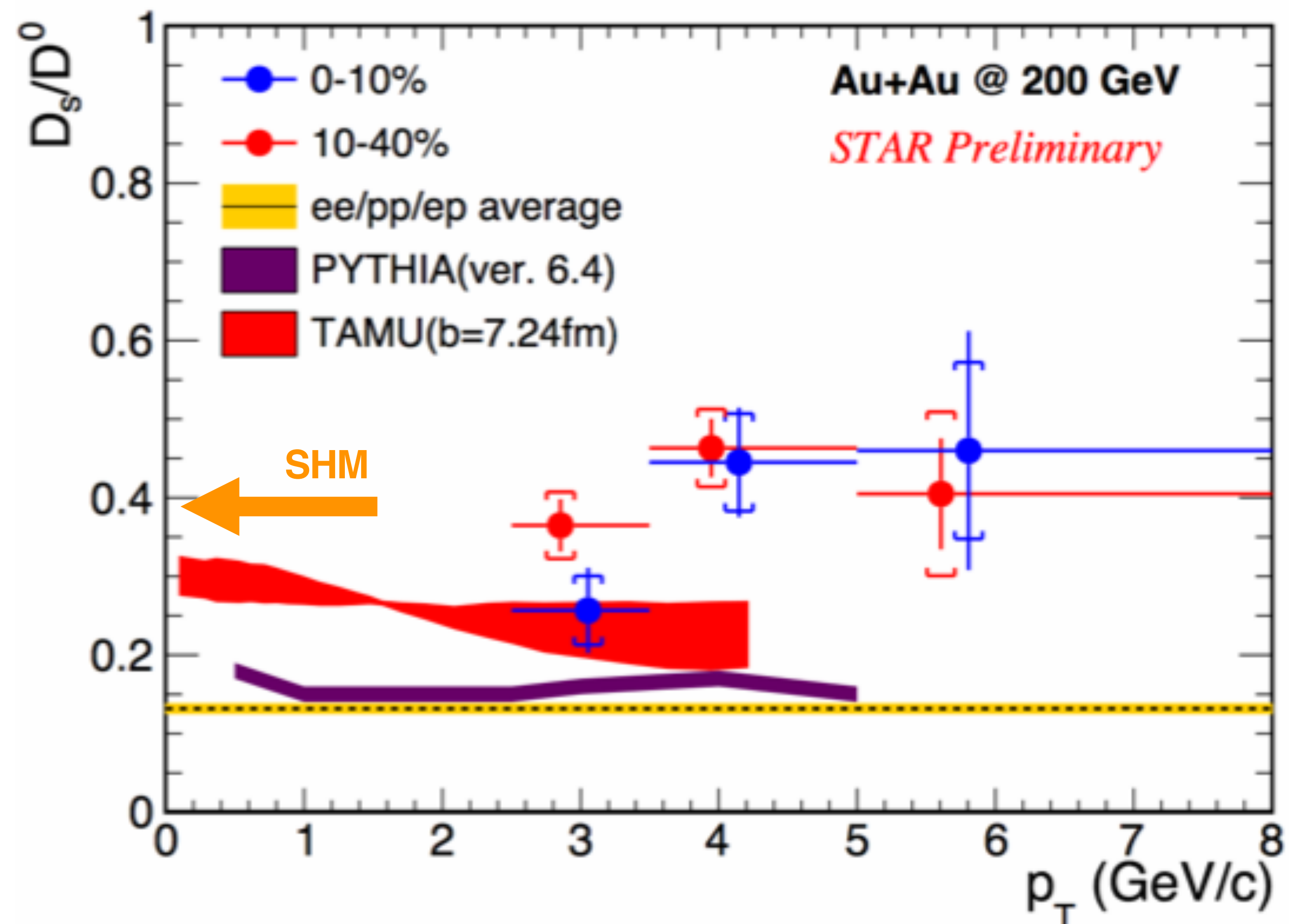
ALICE: arXiv:1712.09581

- 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



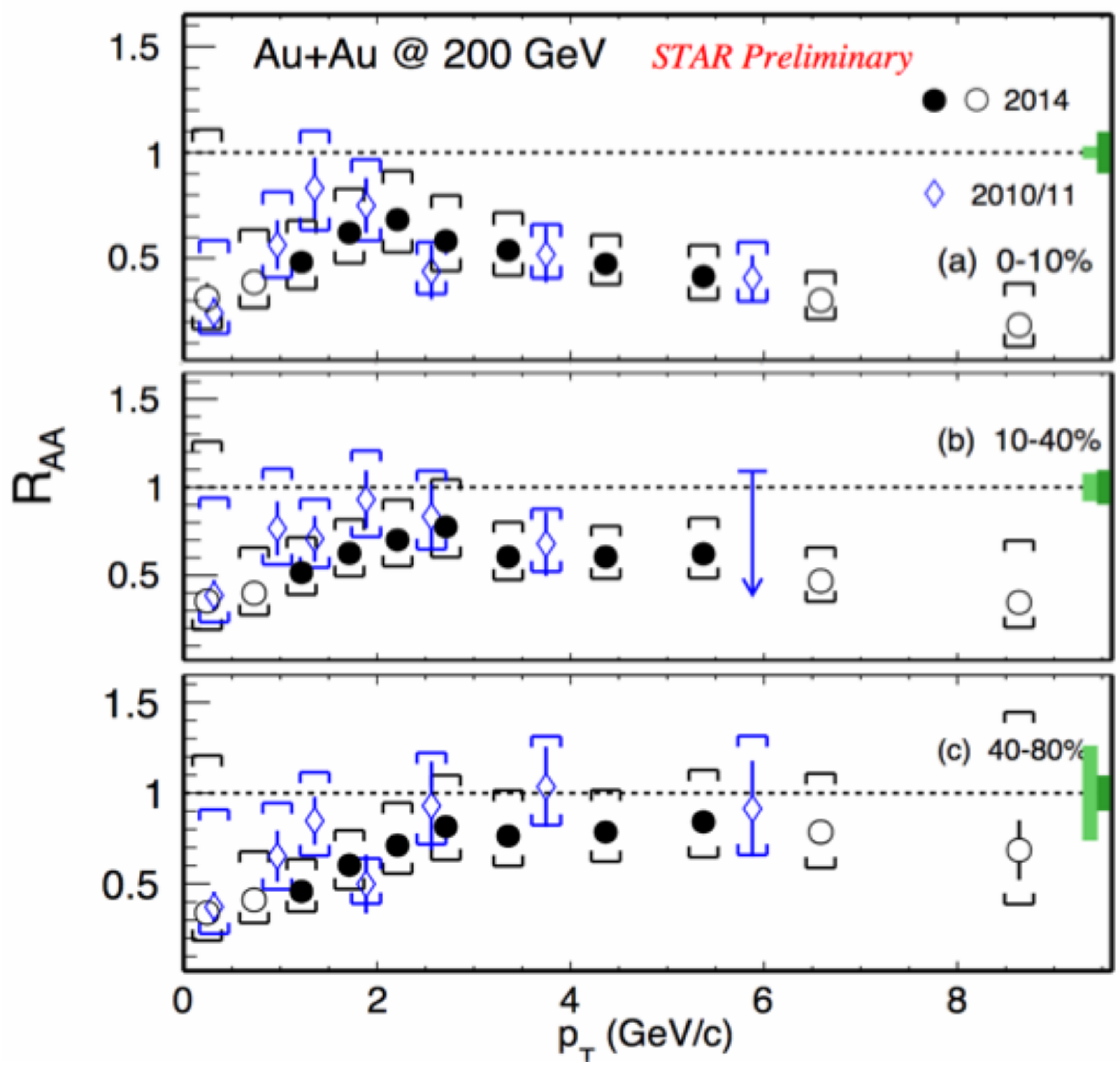


- D_s yield (relative to D^0) is enhanced in A+A collisions
- Enhancement is larger than model predictions, particularly at higher p_T
- Ratio close to SHM predictions

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

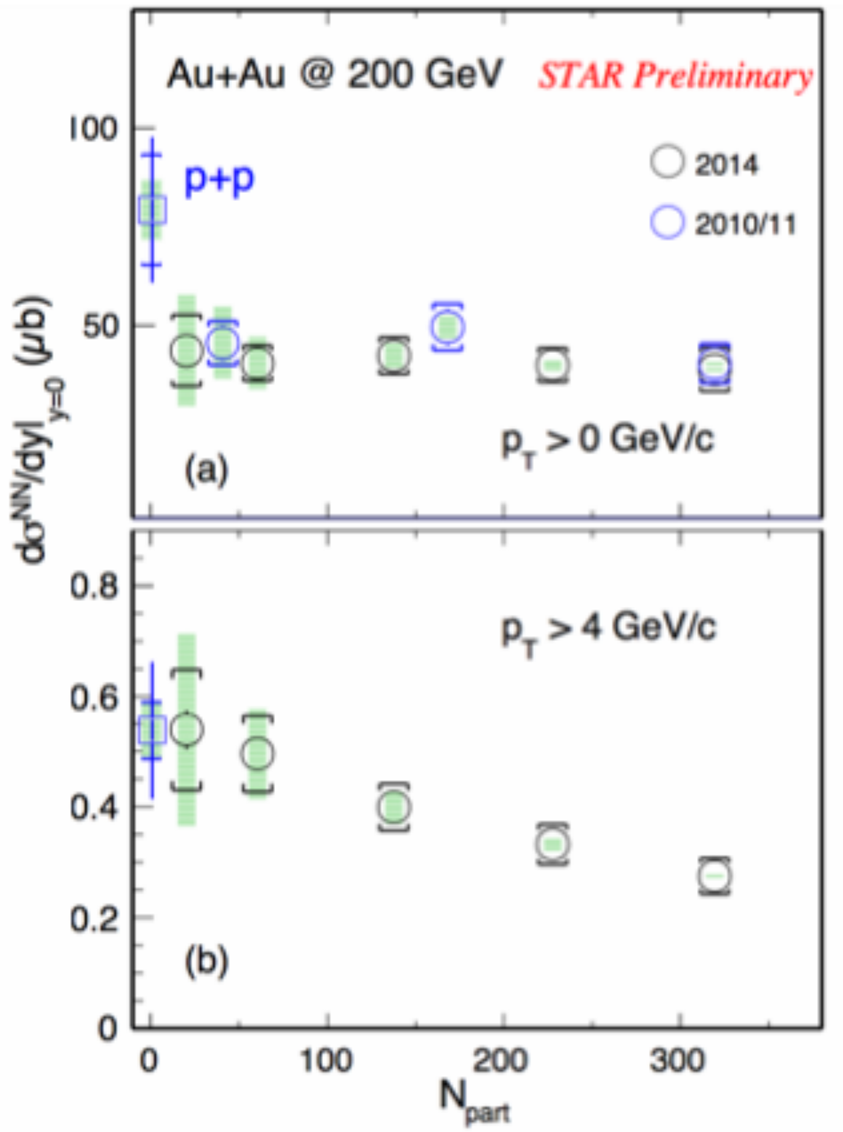
D^0 Spectra and R_{AA}

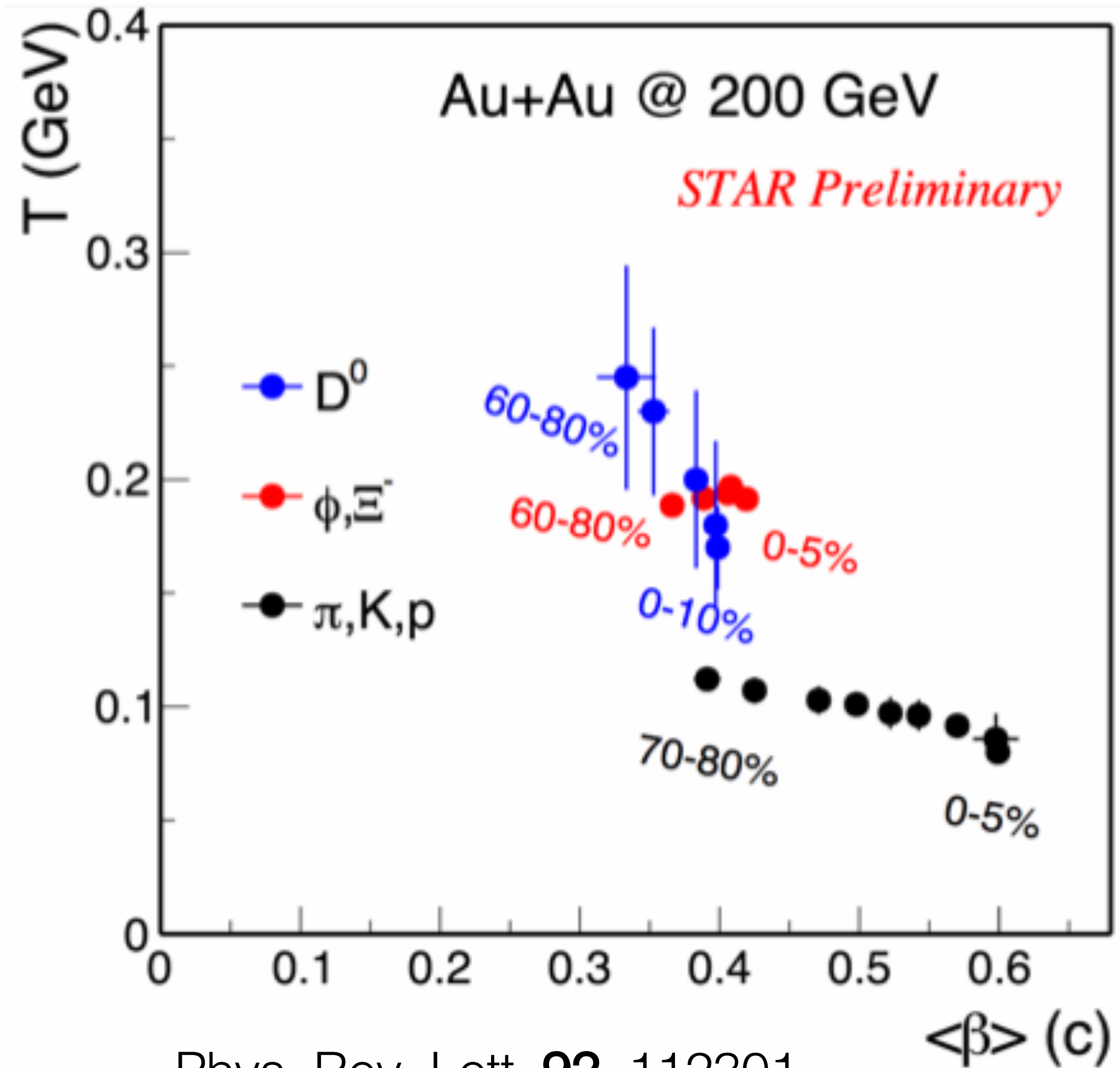
- Updated results from STAR for D^0 extending to low p_T and non-central collisions



- 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



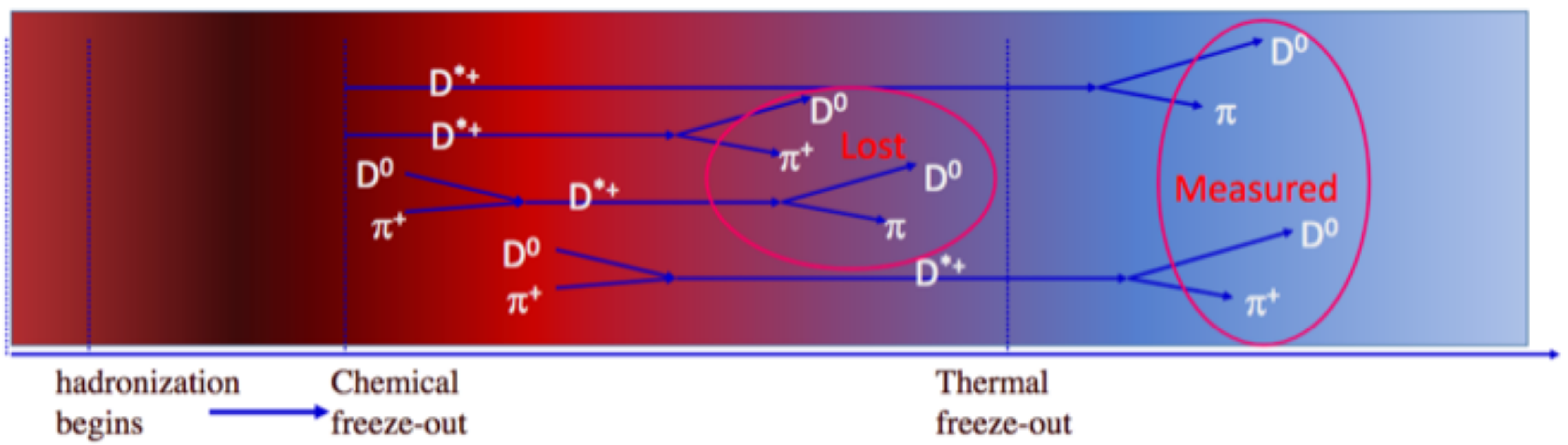


Phys. Rev. Lett. **92**, 112301

- 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)*



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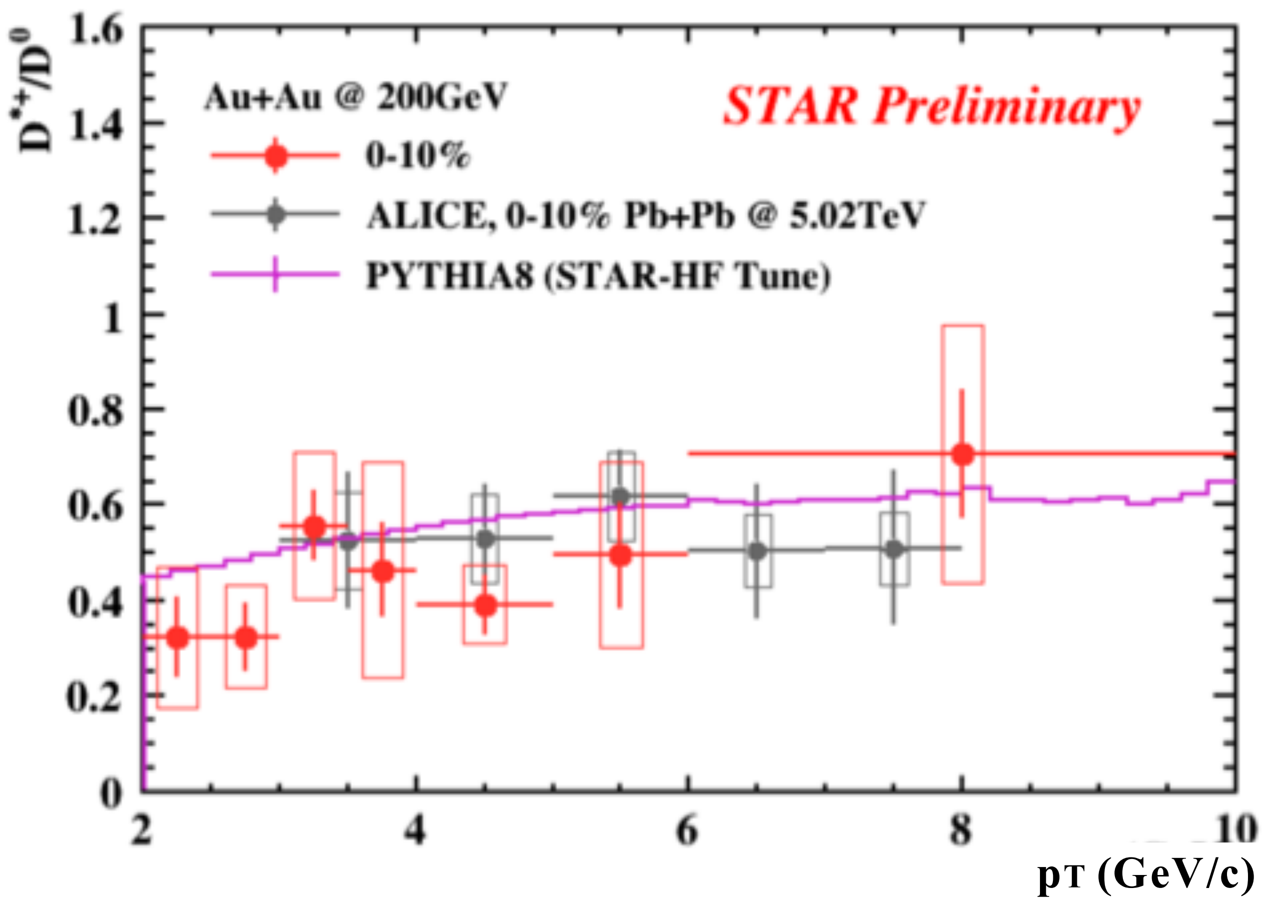
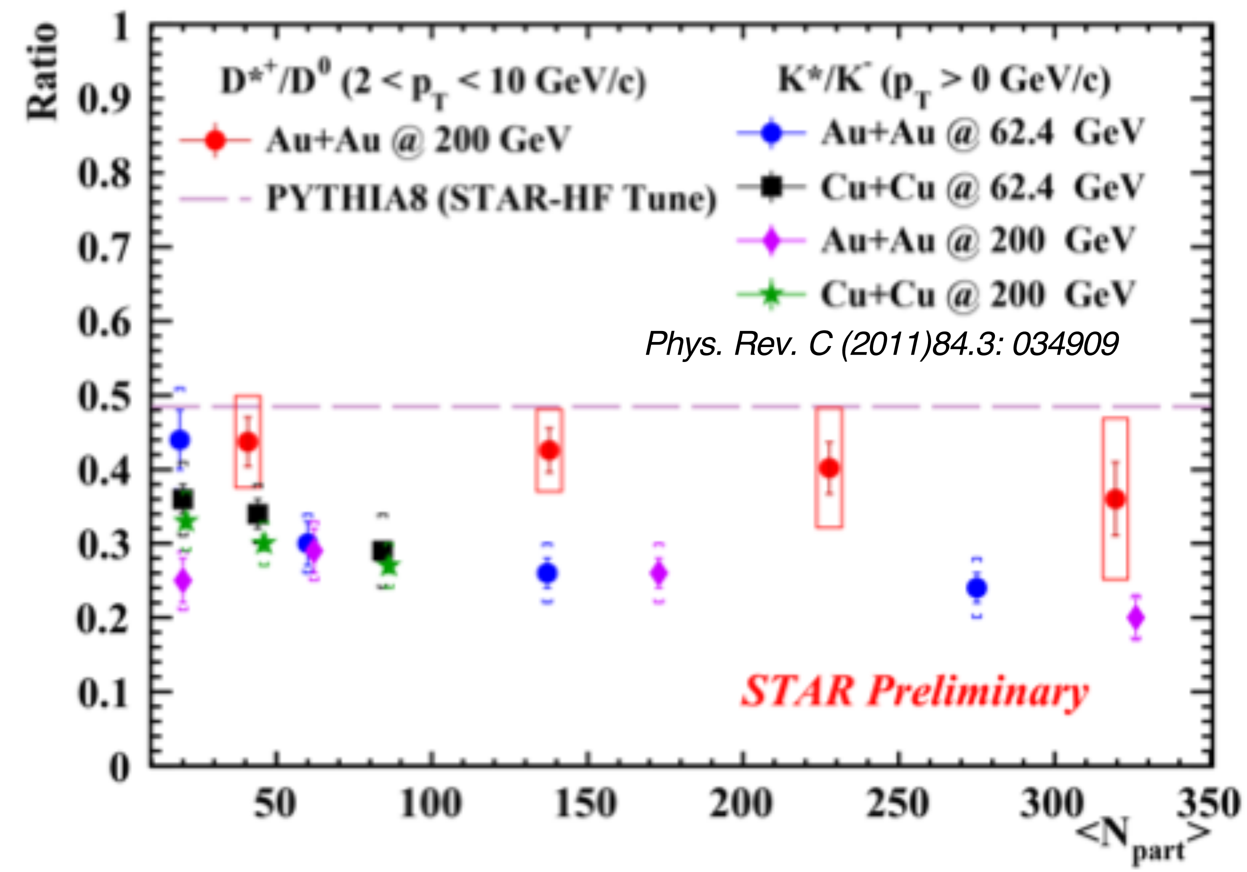




- D^{*+}/D^0 ratio consistent with PYTHIA and with ALICE data [arXiv:1804.09083] at higher p_T
- Ratio of the integrated yields shows no strong centrality dependence

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.

STAR

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

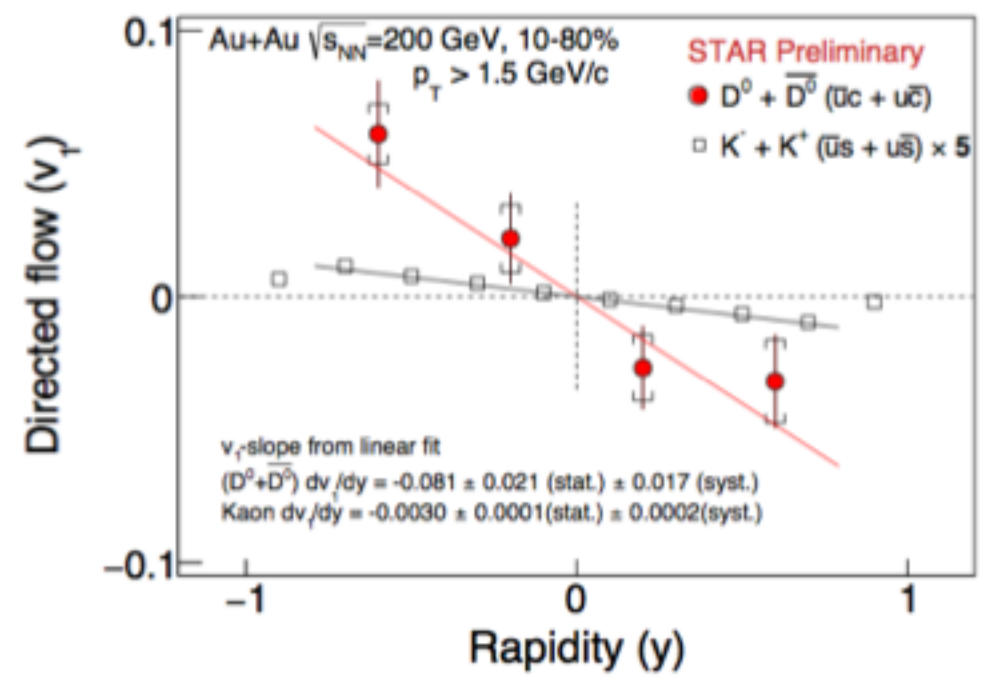
THANK YOU

Back Up

Summary

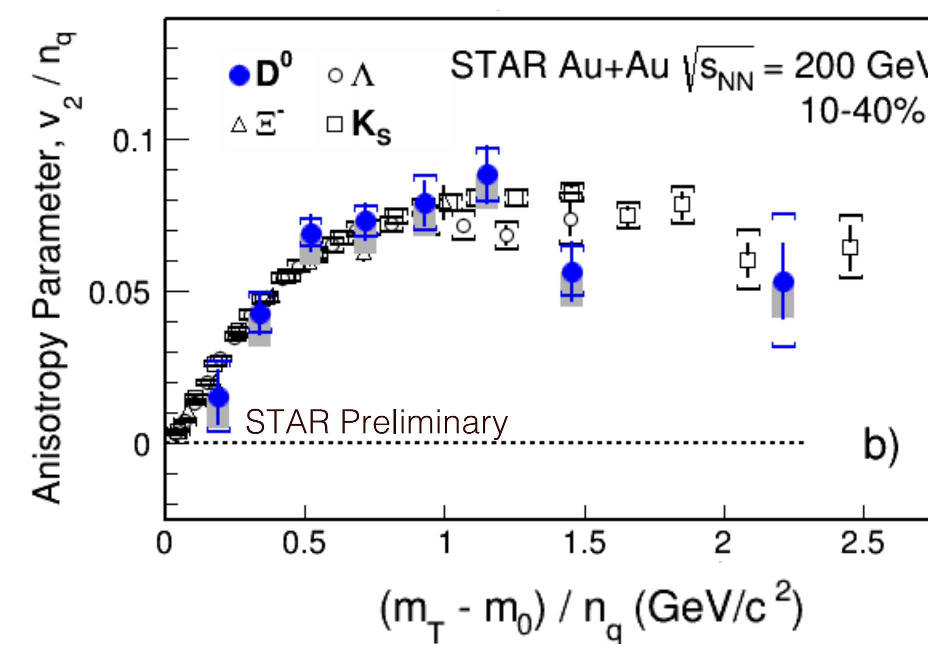
Directed flow

- 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



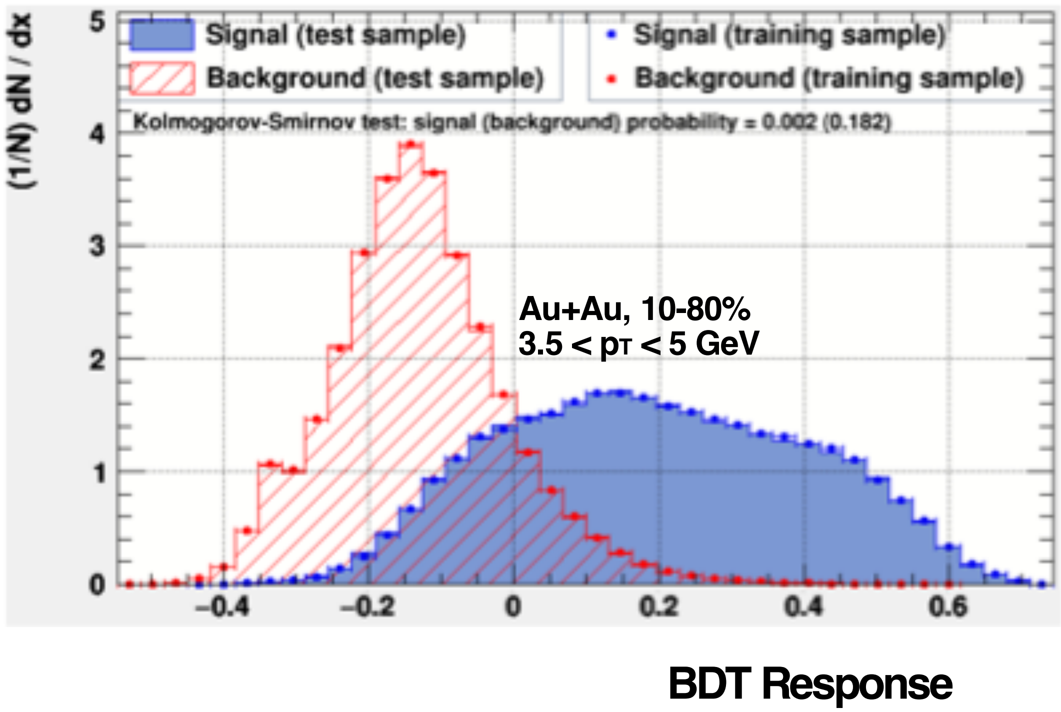
Elliptic flow

- 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



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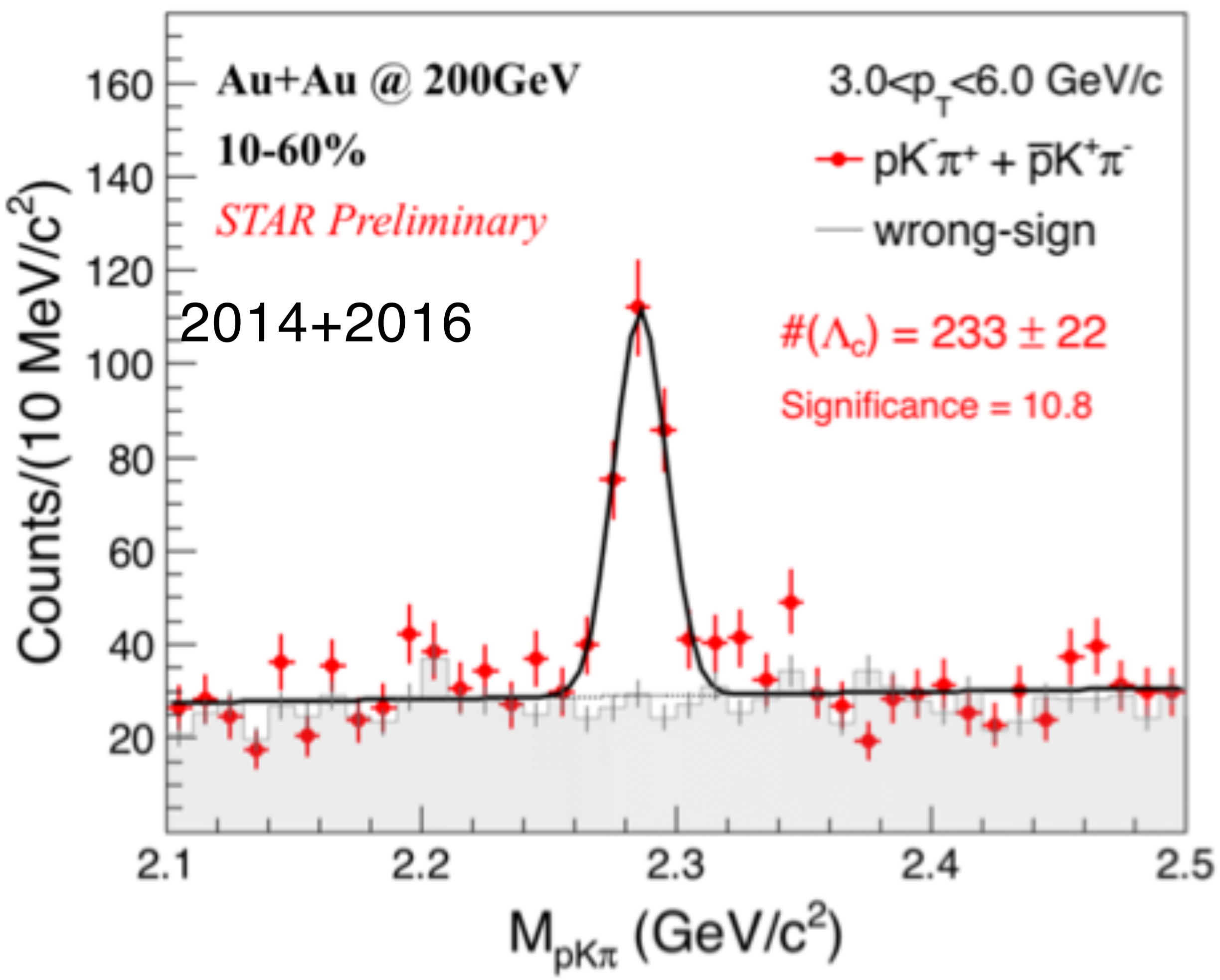
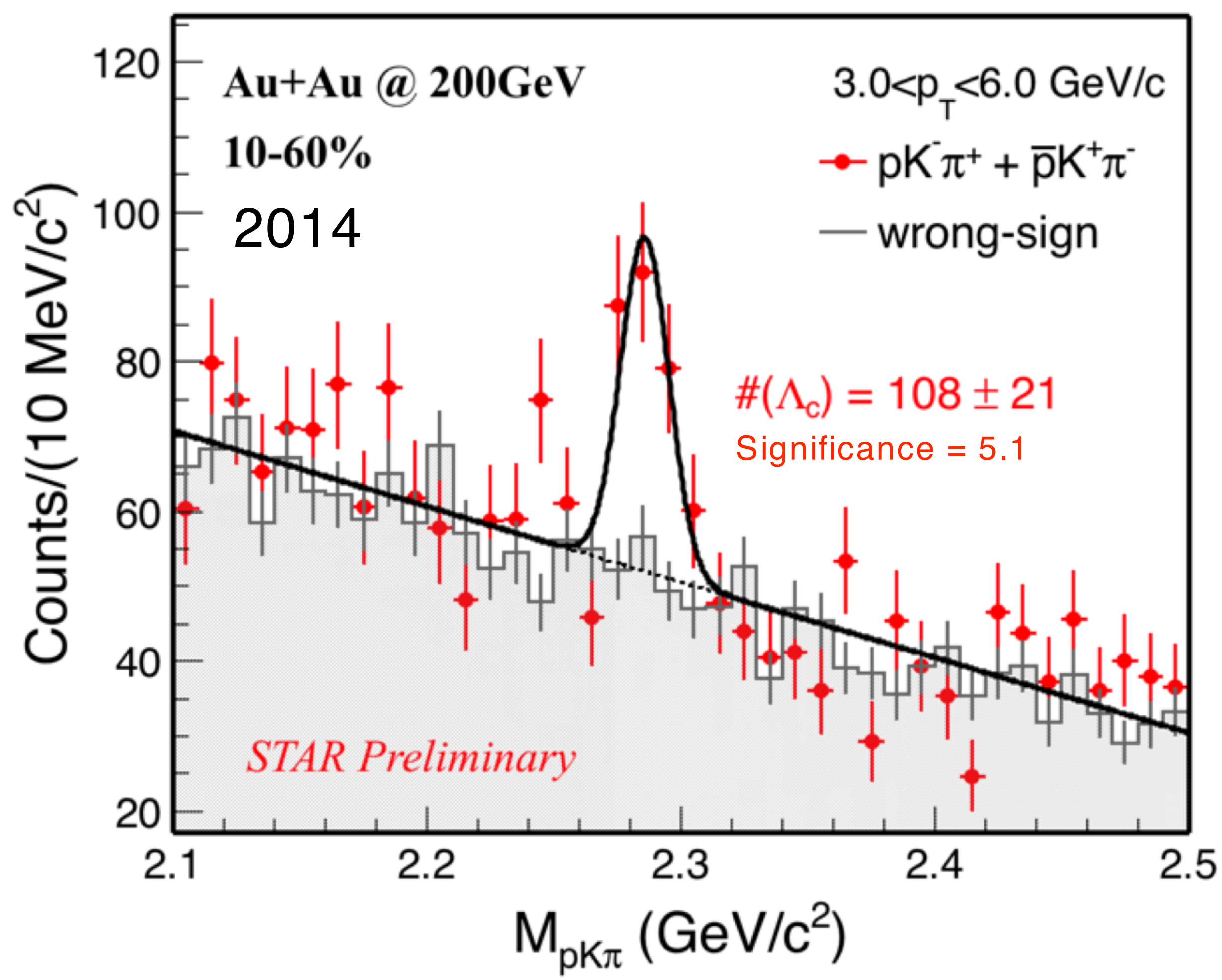
QM18



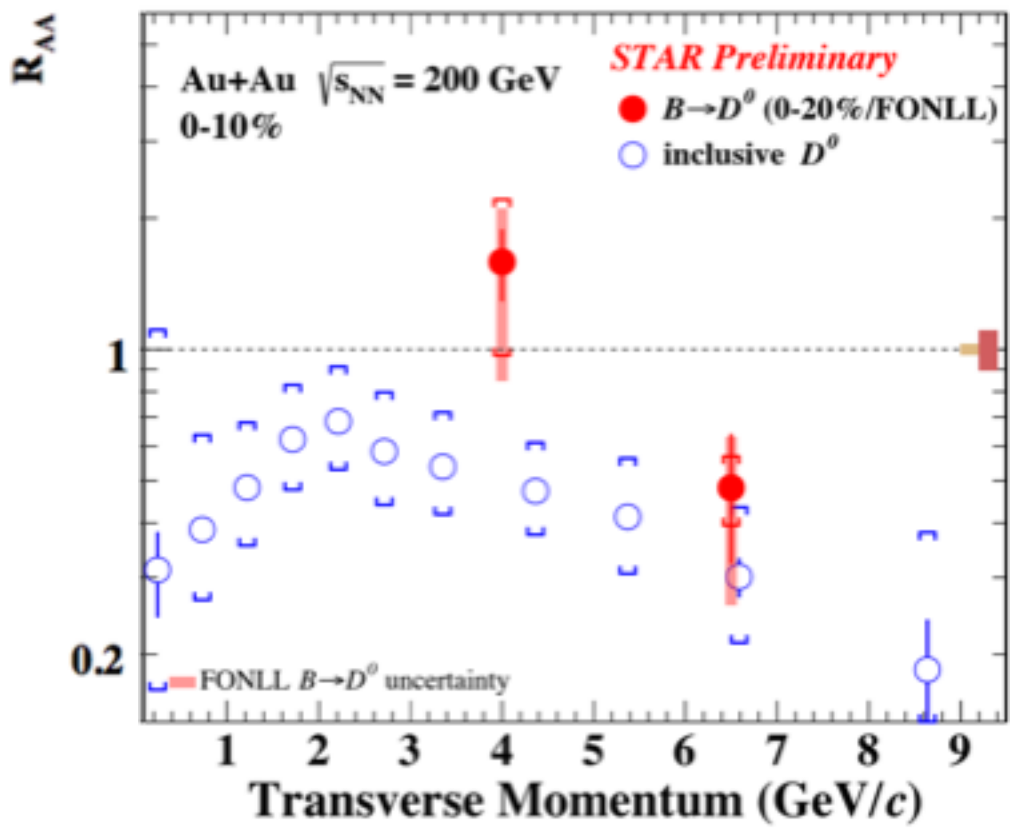
QM17



- 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

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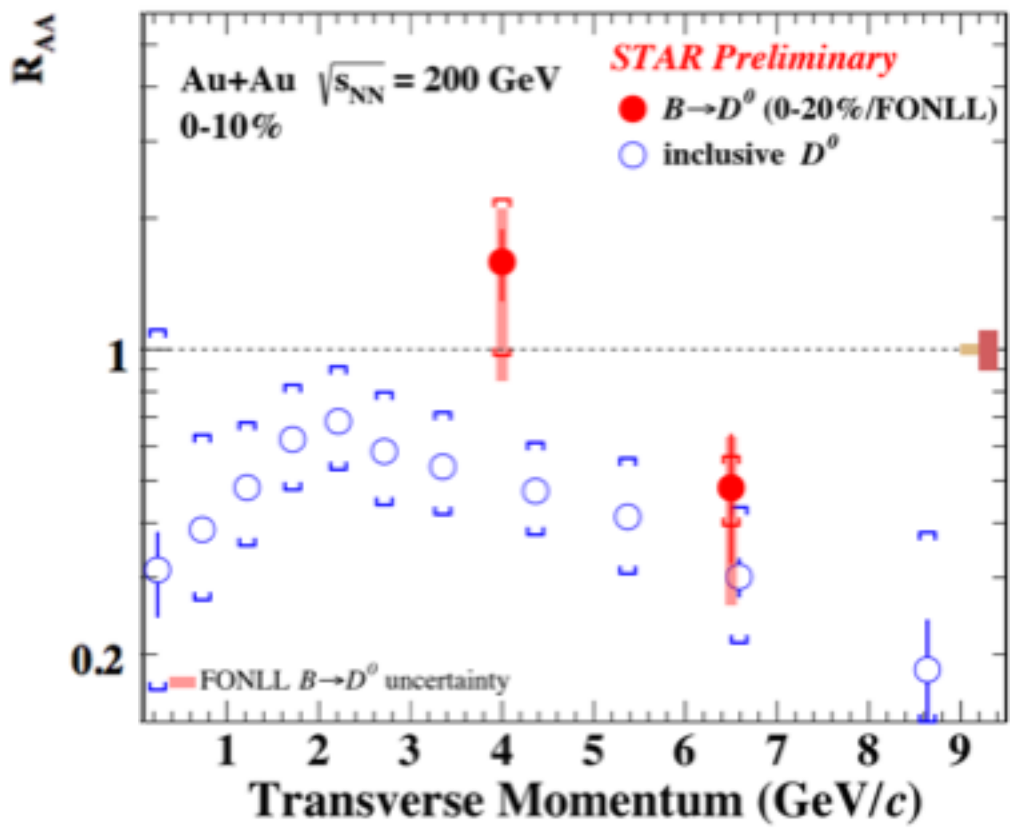
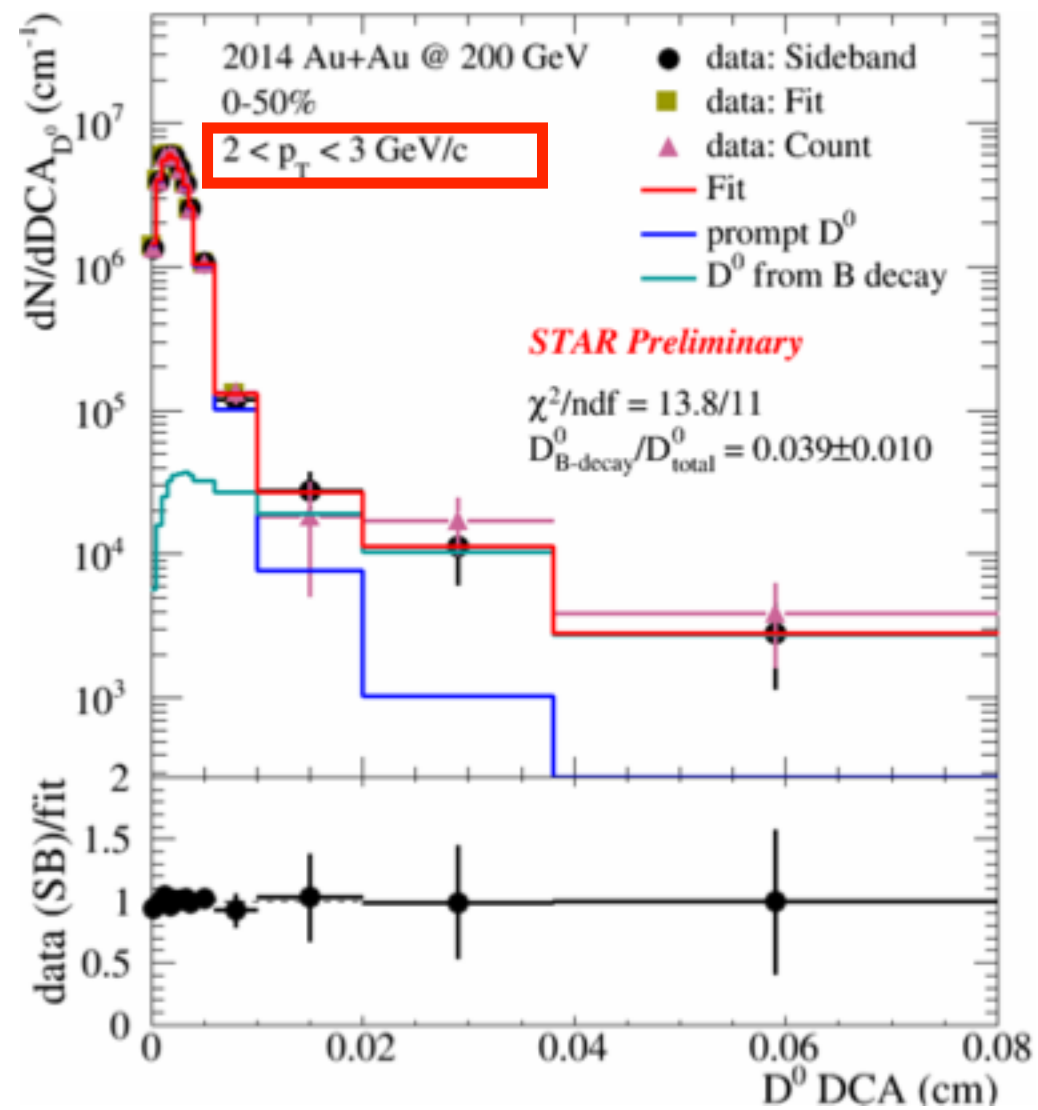


- Improved signal significance for non-prompt D^0 fraction using BDT
- New results with 2014+2016 data on the way



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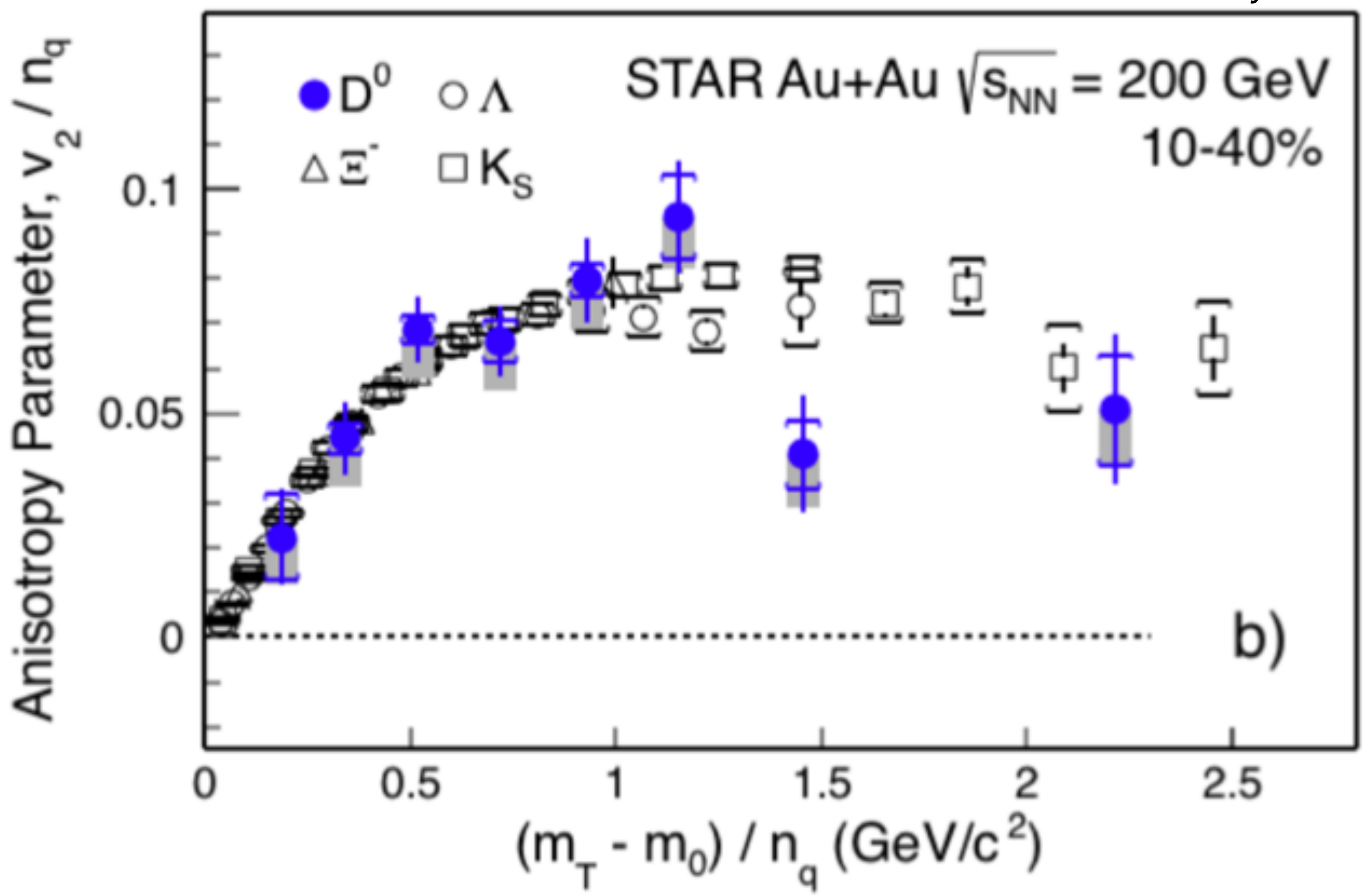


Charm quarks seem to acquire the same flow as light quarks!

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

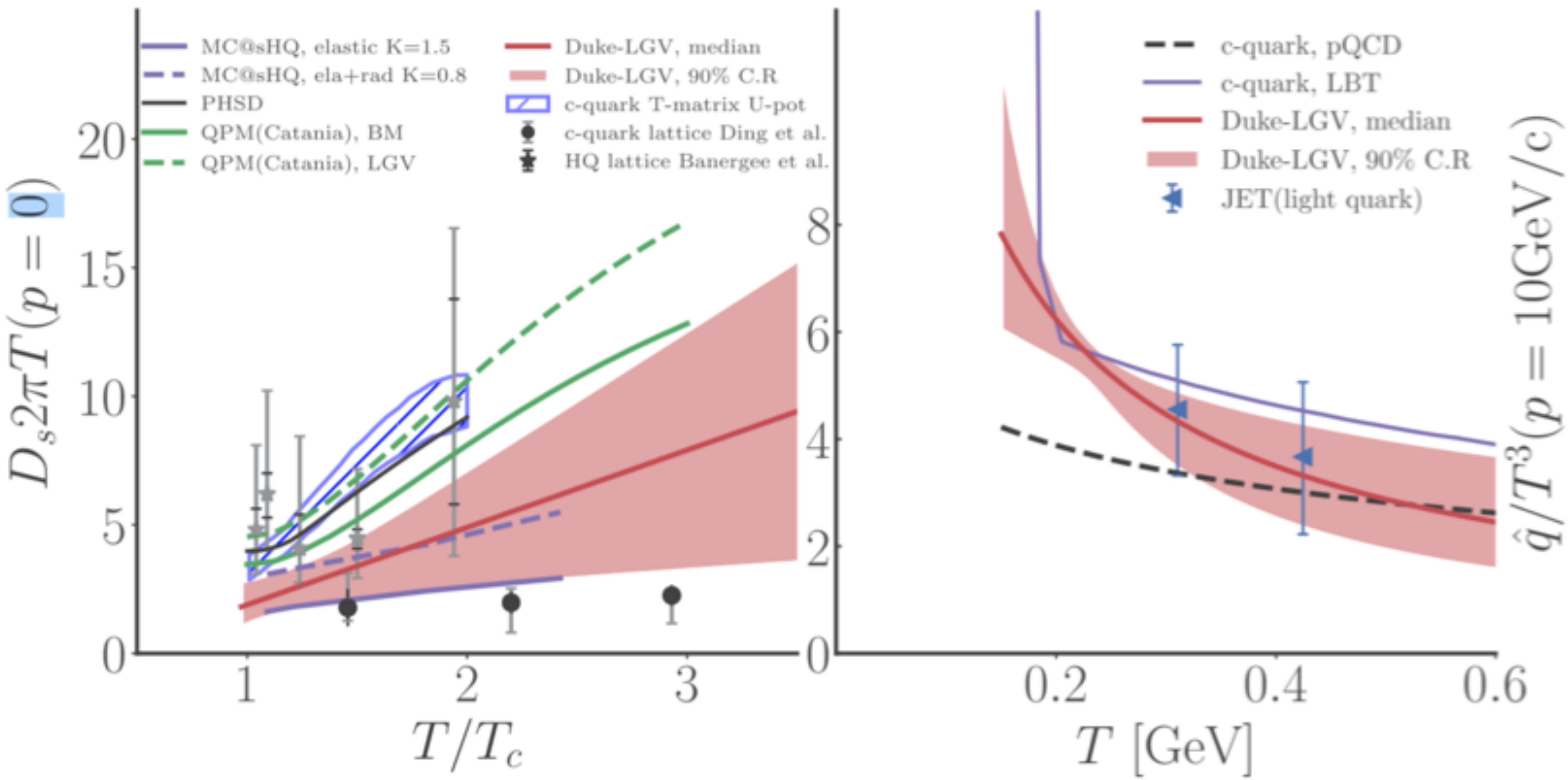
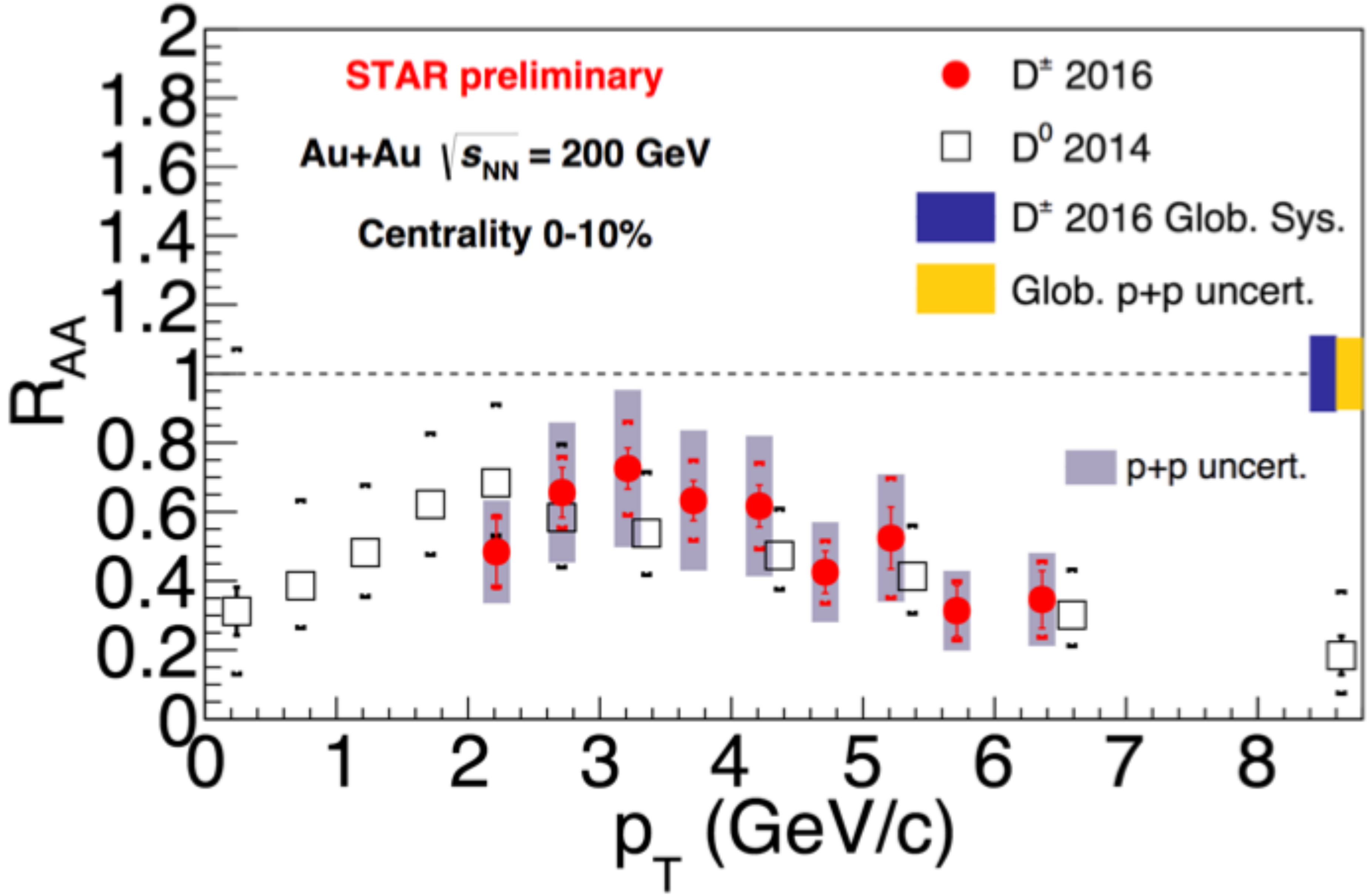


FIG. 12. Comparison of the heavy quark diffusion coefficients across multiple approaches available in the literature. (Left) Spatial diffusion coefficient at zero momentum $D_s 2\pi T(p=0)$. (Right) Momentum diffusion coefficient $\hat{q}/T^3$ at $p = 10$ GeV.

Back Up II

$D^{+/-}$ RAA

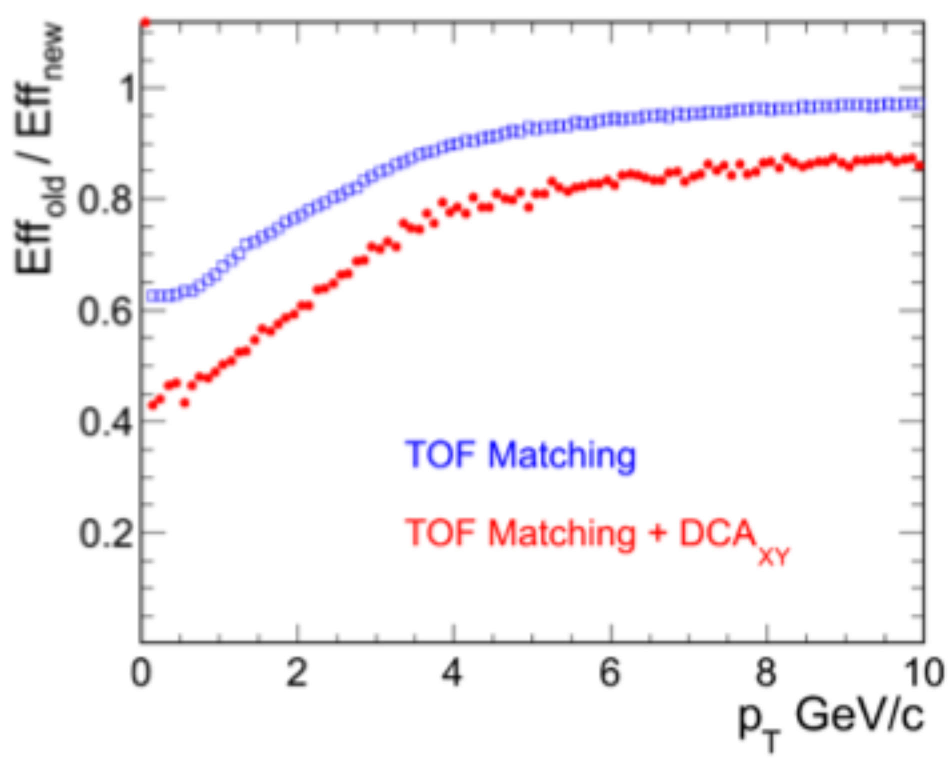


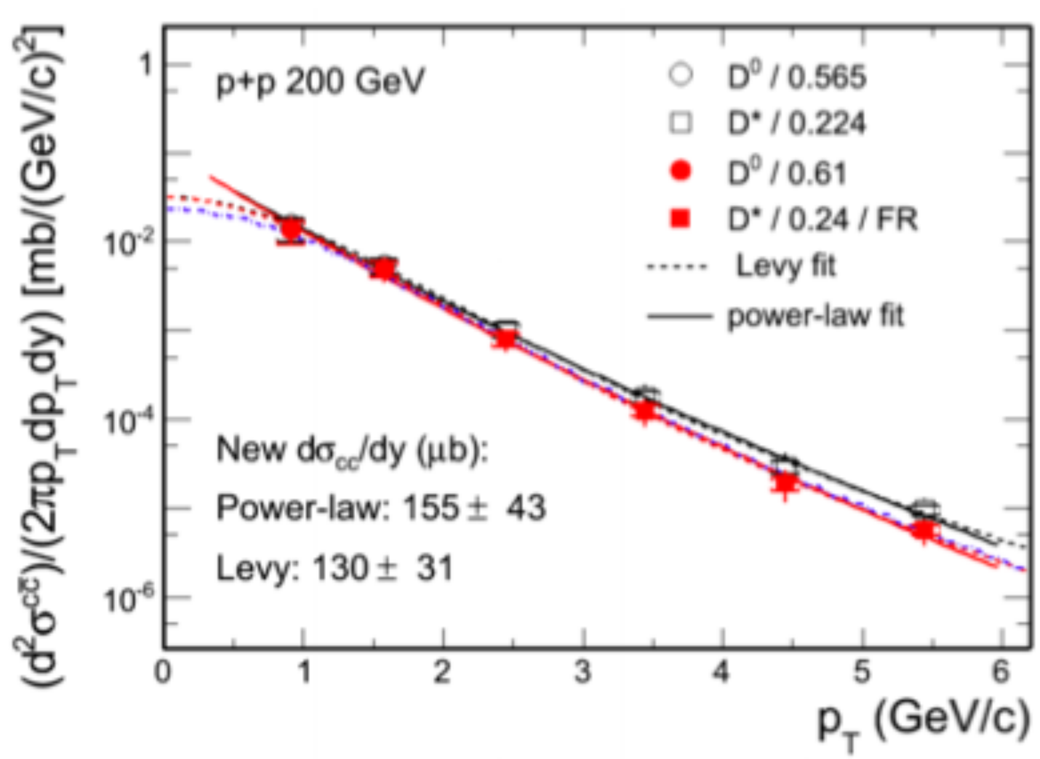
- Similar suppression for D^0 and $D^{+/-}$
- Spectra measurements important for total charm cross-section

Erratum details

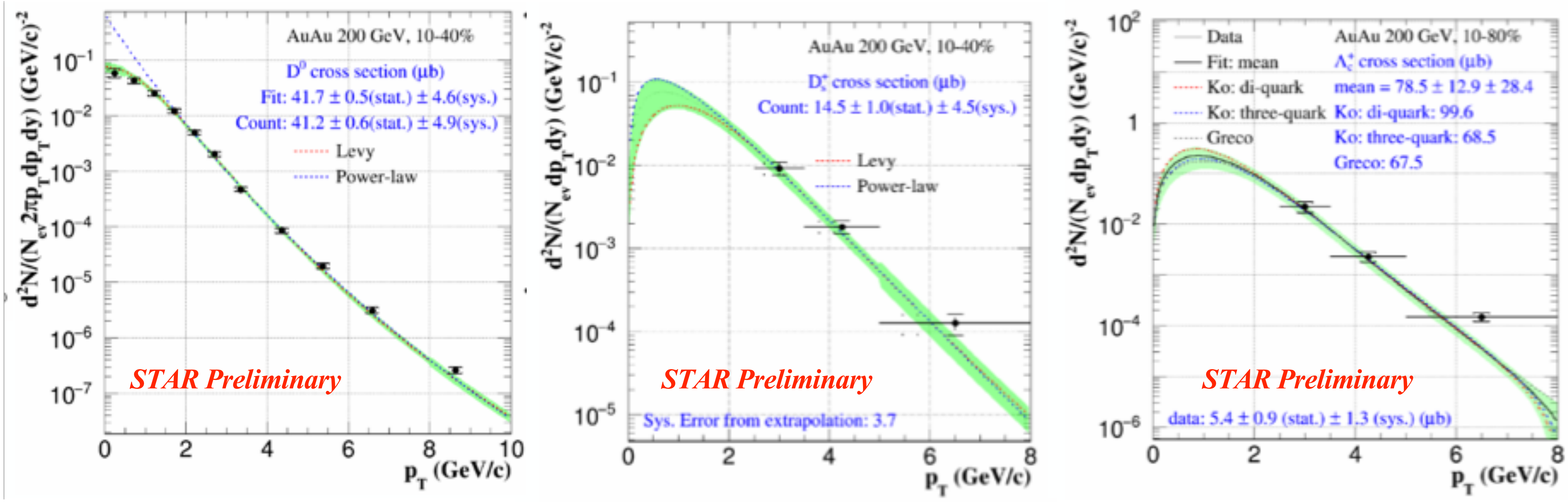
Erratum: D^0 in AuAu (2010/2011 TPC Analysis) - I
PRL 113 (2014) 142301

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

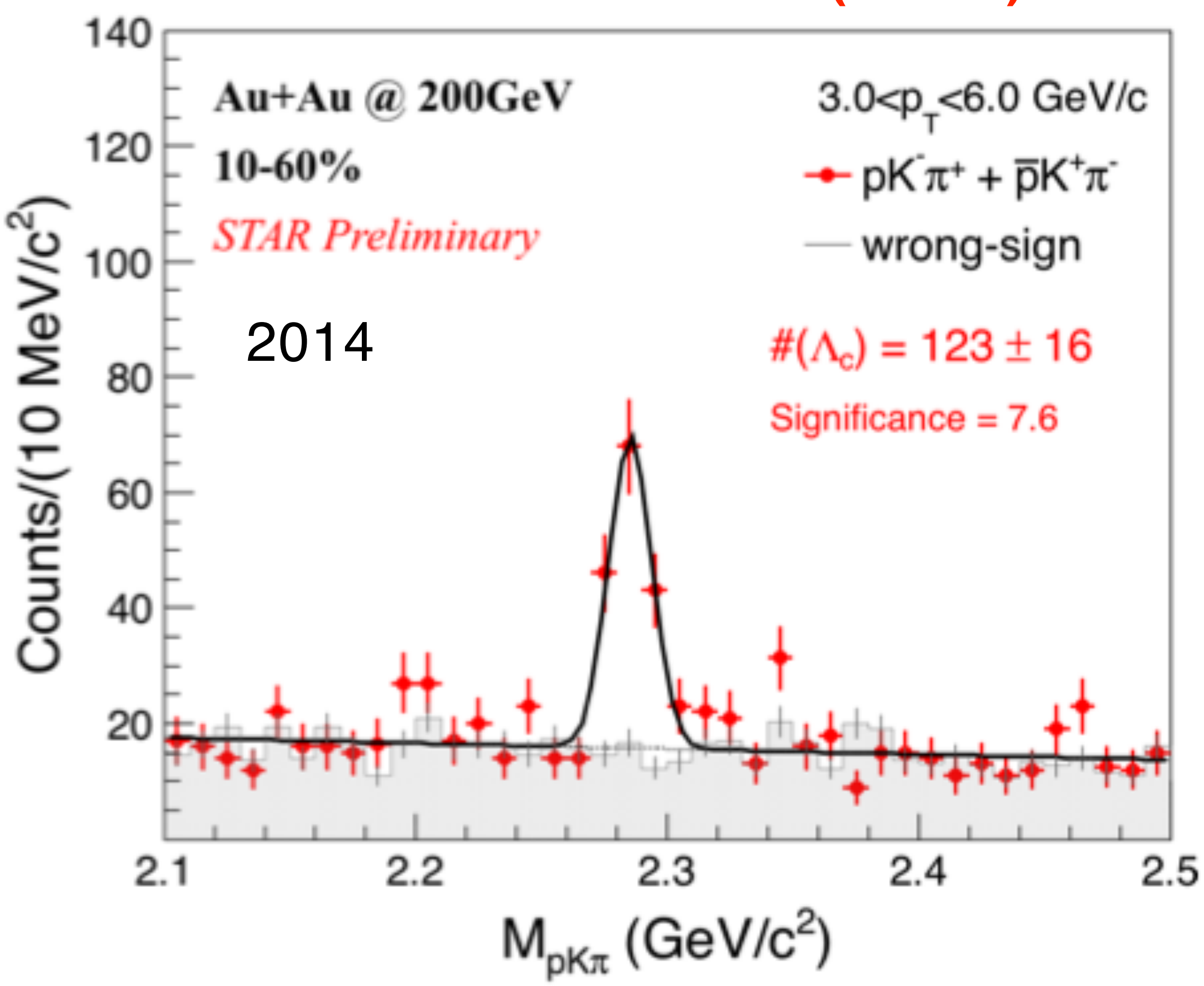


- Extracted for 10-40% centrality.
- Yields for $D^{+/-}$ and Λ_c are scaled to 10-40% centrality using measured ratio to D^0.
- Uncertainty evaluation and propagation:
  - In the p_T range with data points:
    - point by point statistical error propagated
    - point by point systematic error propagated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

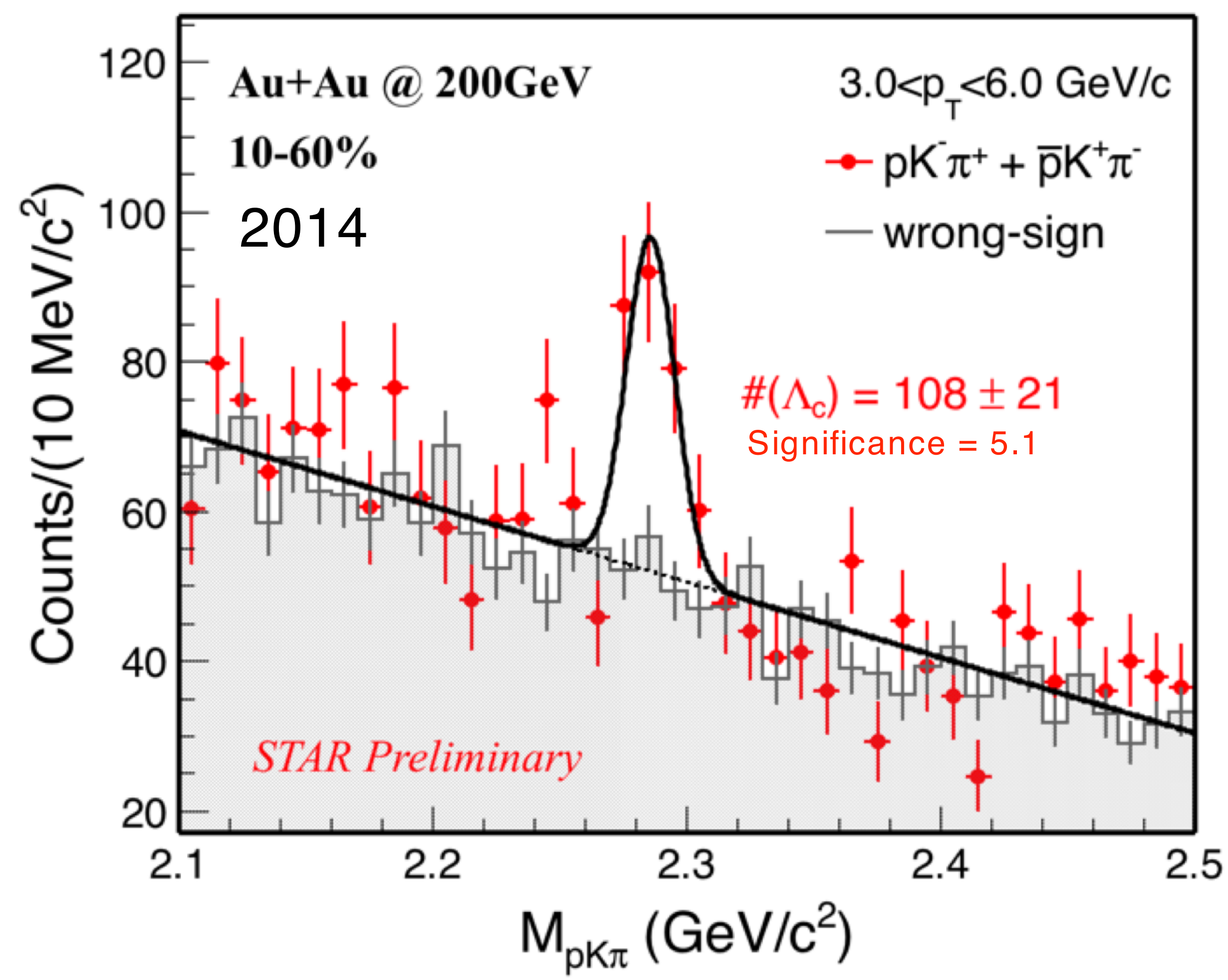
BDT vs Rectangular Cuts Comparison

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

BDT (QM18)

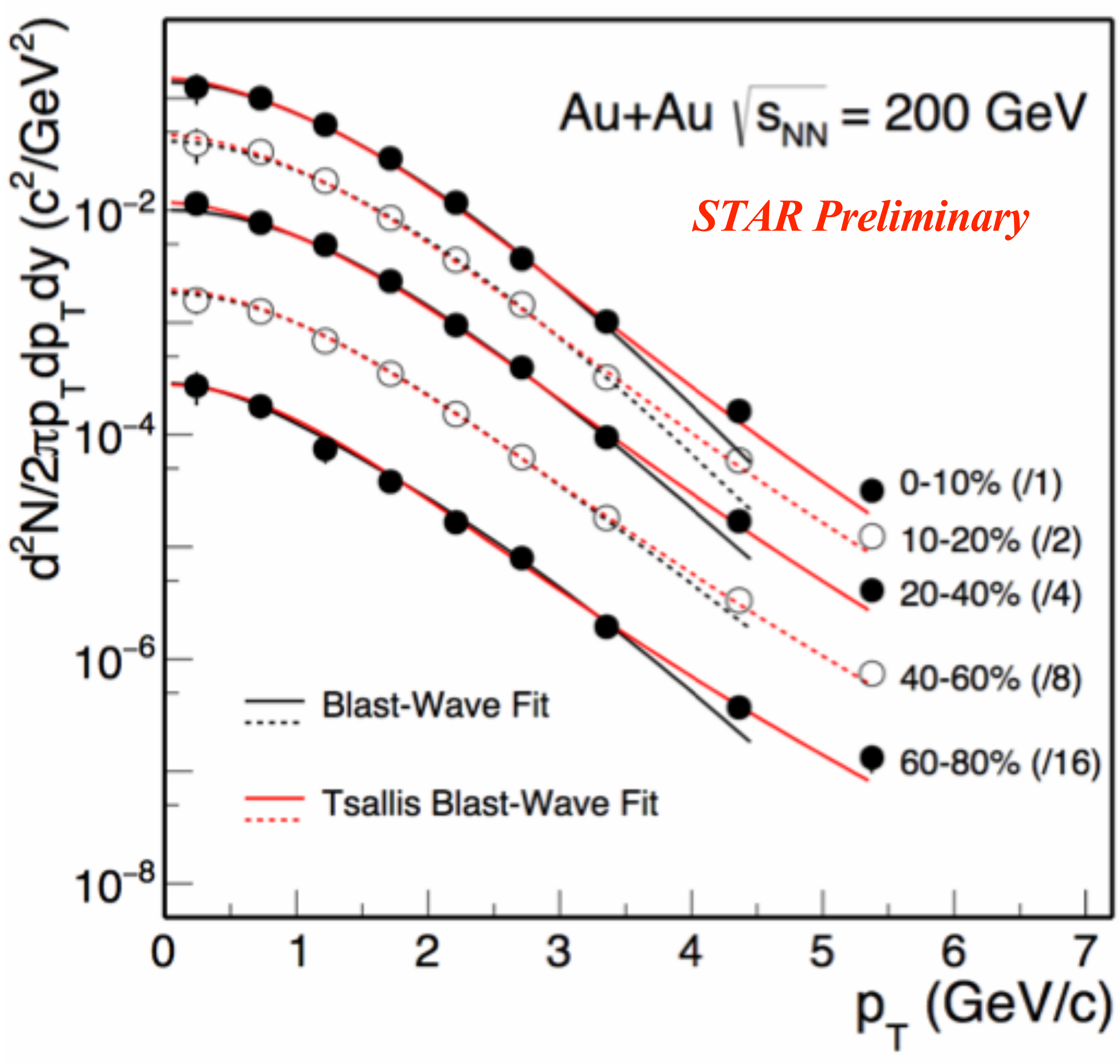


Rectangular Cuts (QM17)



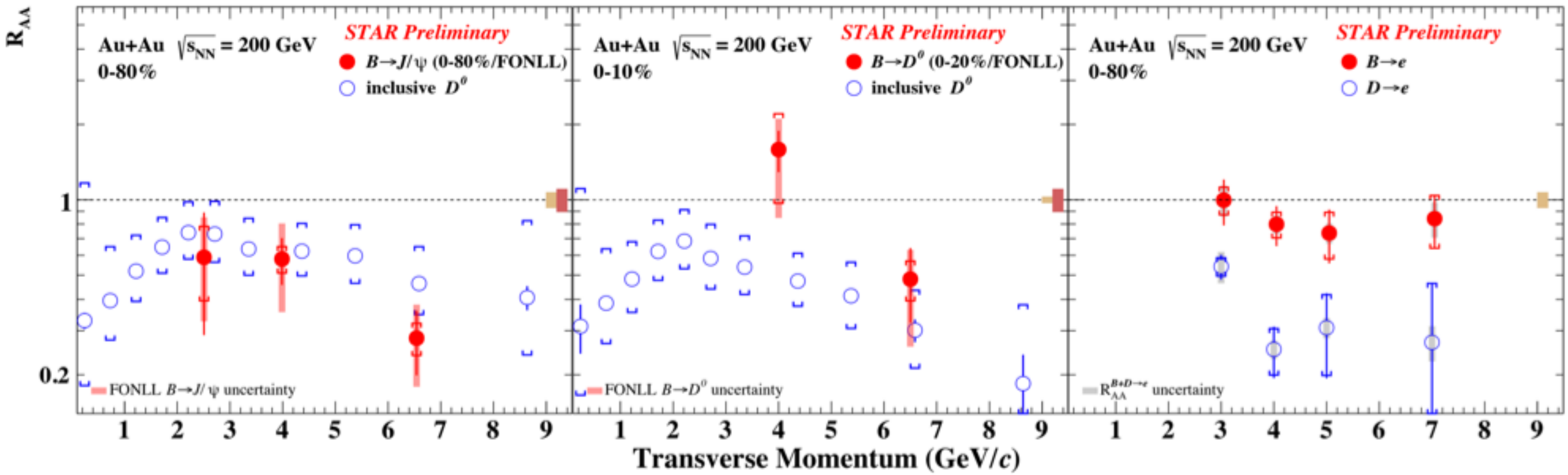
- More than 50% improvement in signal significance with TMVA BDT.

BW fits to D^0 spectra



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

RAA of B through different channels



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