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

Sooraj Radhakrishnan for the STAR Collaboration
Lawrence Berkeley National Laboratory

BERKELEY LAB

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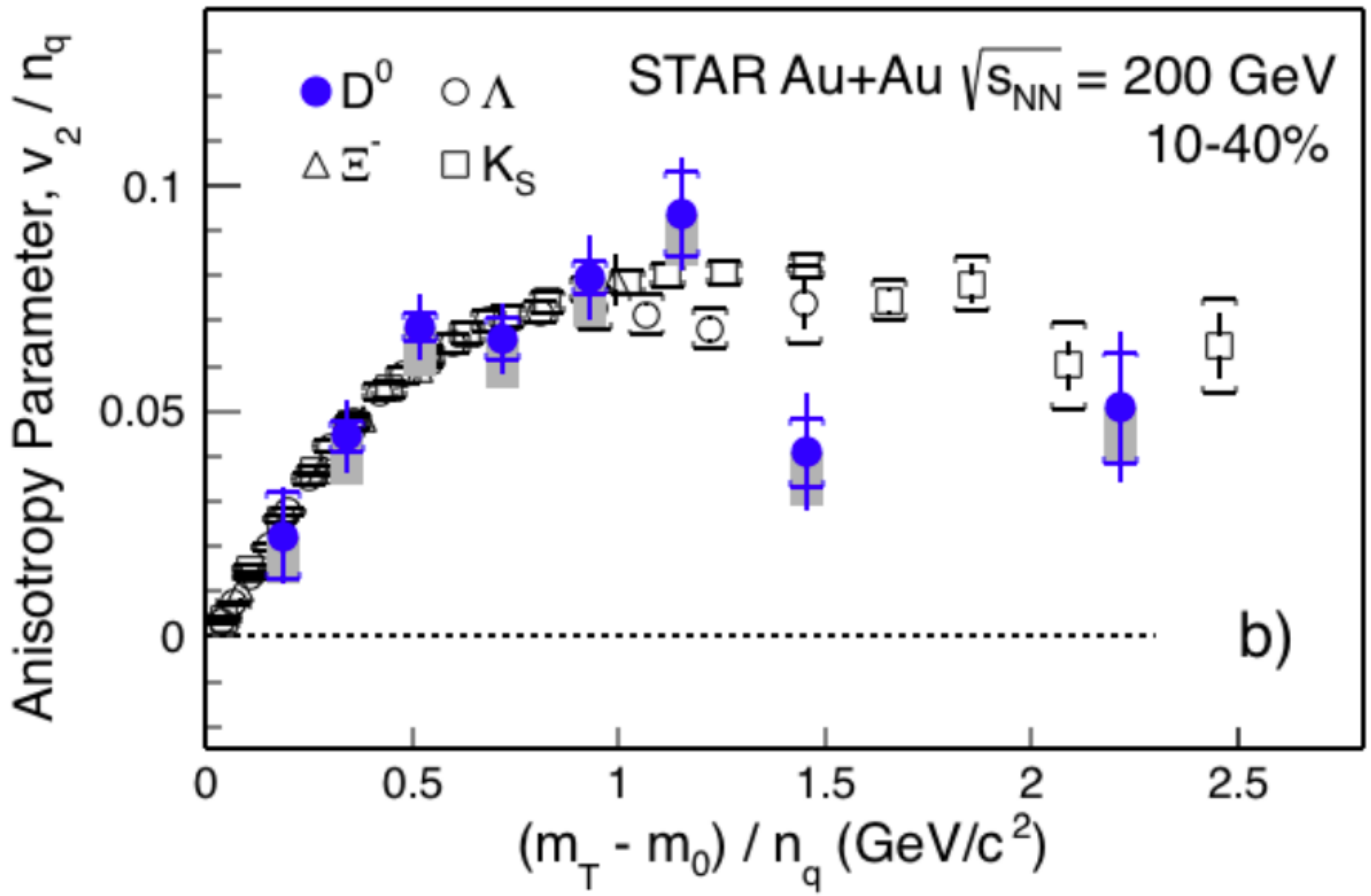
STAR

Phys. Rev. Lett. 118 (2017) 212301

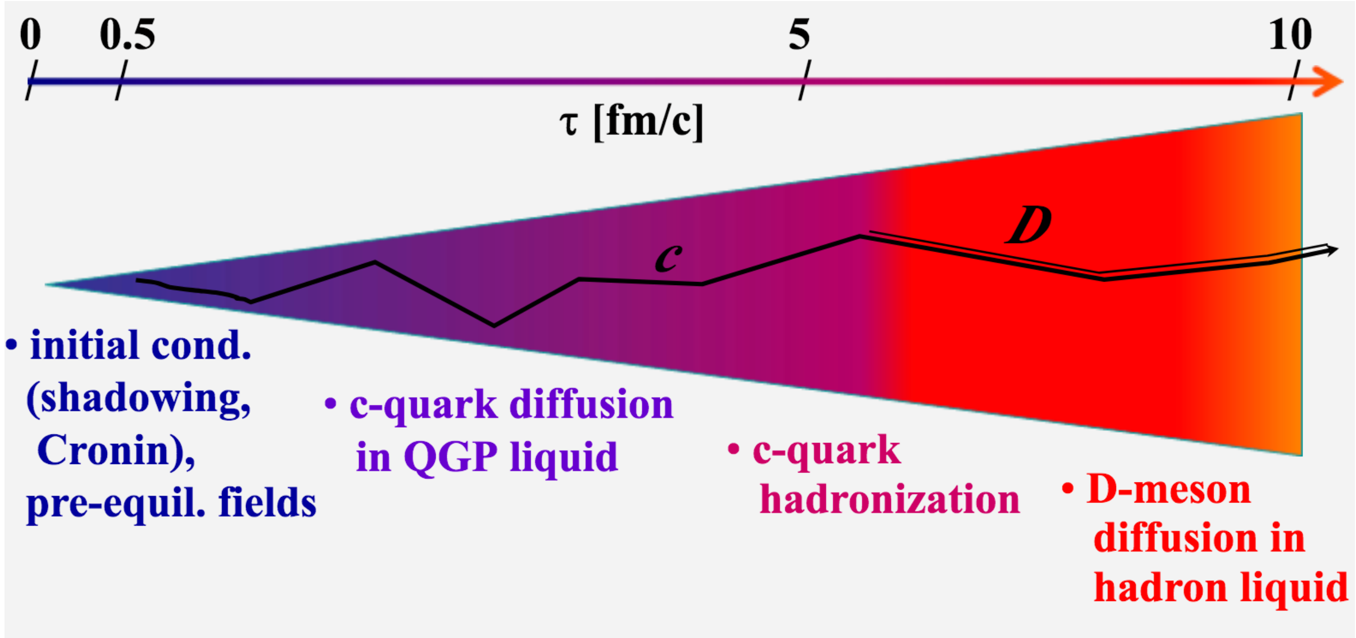


Charm quarks seem to acquire the same flow as light quarks!

Introduction

Large collective flow and modification of yields for charm hadrons in A+A collisions!!!

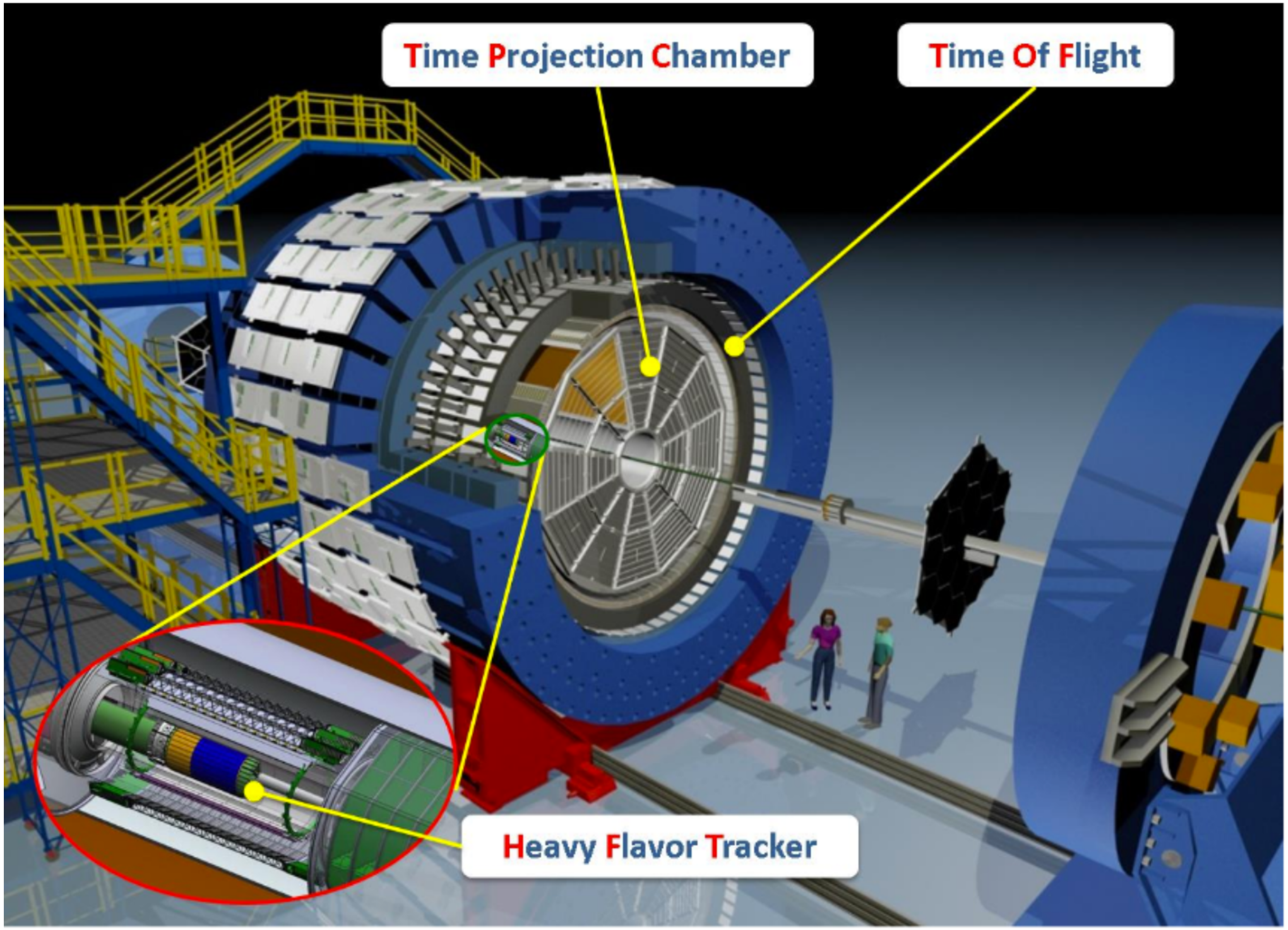
Understand heavy quark production, transport and hadronization in the presence of QGP



- Hadronization
  Λ_c, D_s
- In medium energy loss
  D^0
- Medium modifications to yields
  $D^{*+/-}$
- Total charm cross-section
- Mass dependence of energy loss
  B (from non-prompt D^0)

New extensive measurements by STAR! →

The STAR Detector



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

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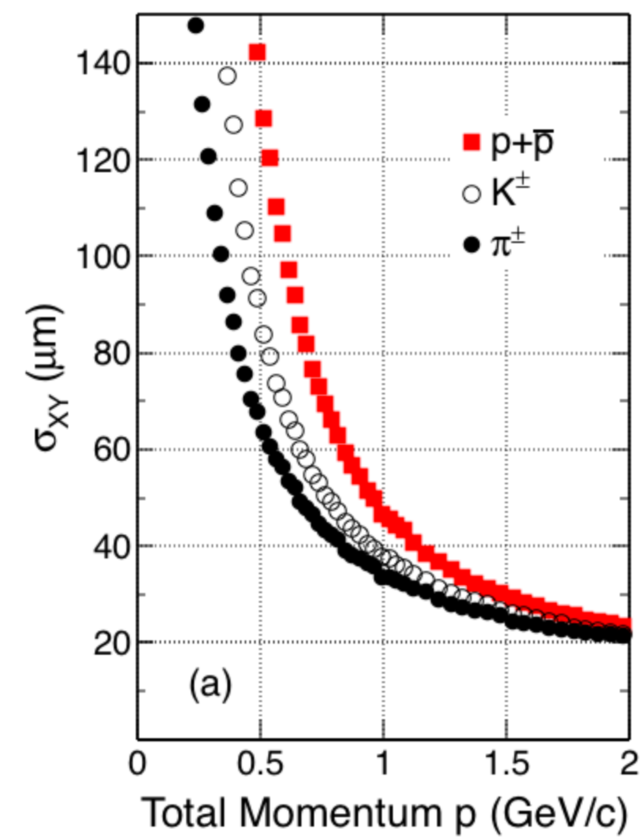
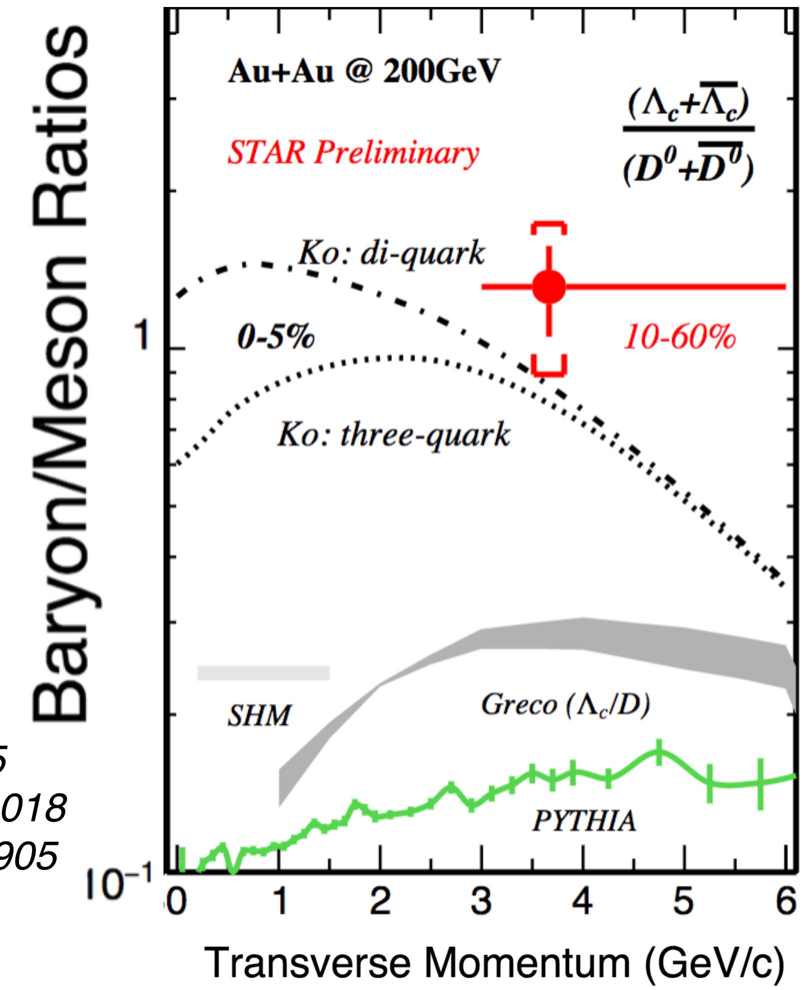


STAR Heavy Flavor Tracker (HFT) provides excellent vertex resolution and allows reconstruction of charm hadron decays

Λ_c and Heavy Flavor Hadronization

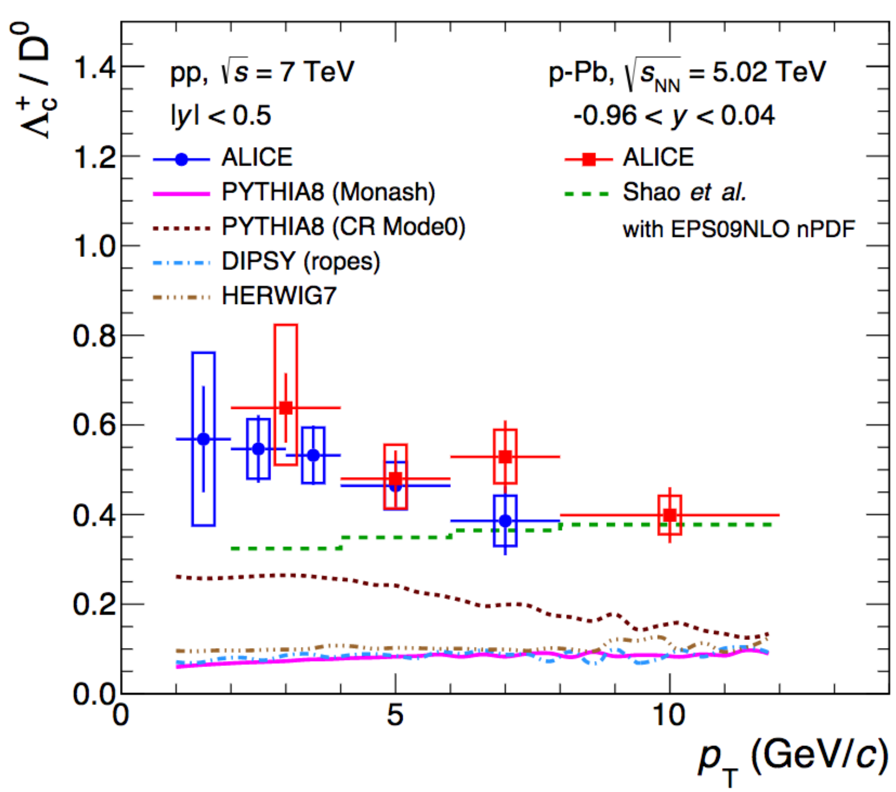
- Strong enhancement of Λ_c/D^0 ratio seen in Au+Au collisions by STAR
  - Enhancement predicted from coalescence hadronization
- An enhancement relative to PYTHIA also seen in p+p and p+Pb collisions at LHC

STAR: QM17



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

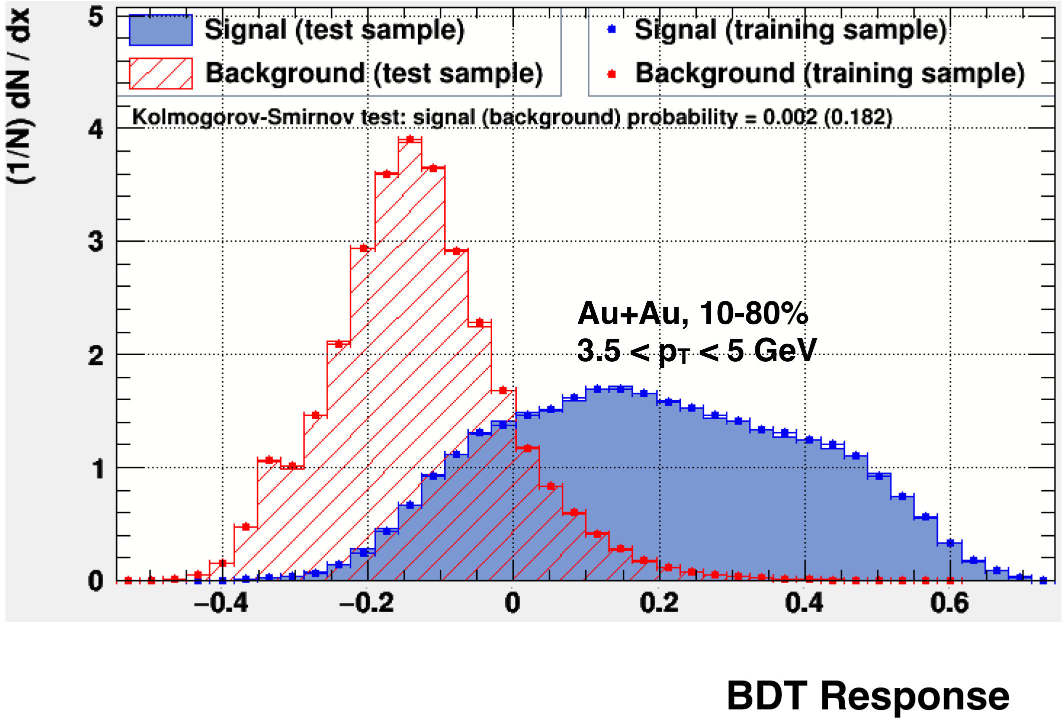
ALICE: arXiv:1712.09581



- 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?

Boosted Decision Trees (BDT) for Λ_c Signal Extraction

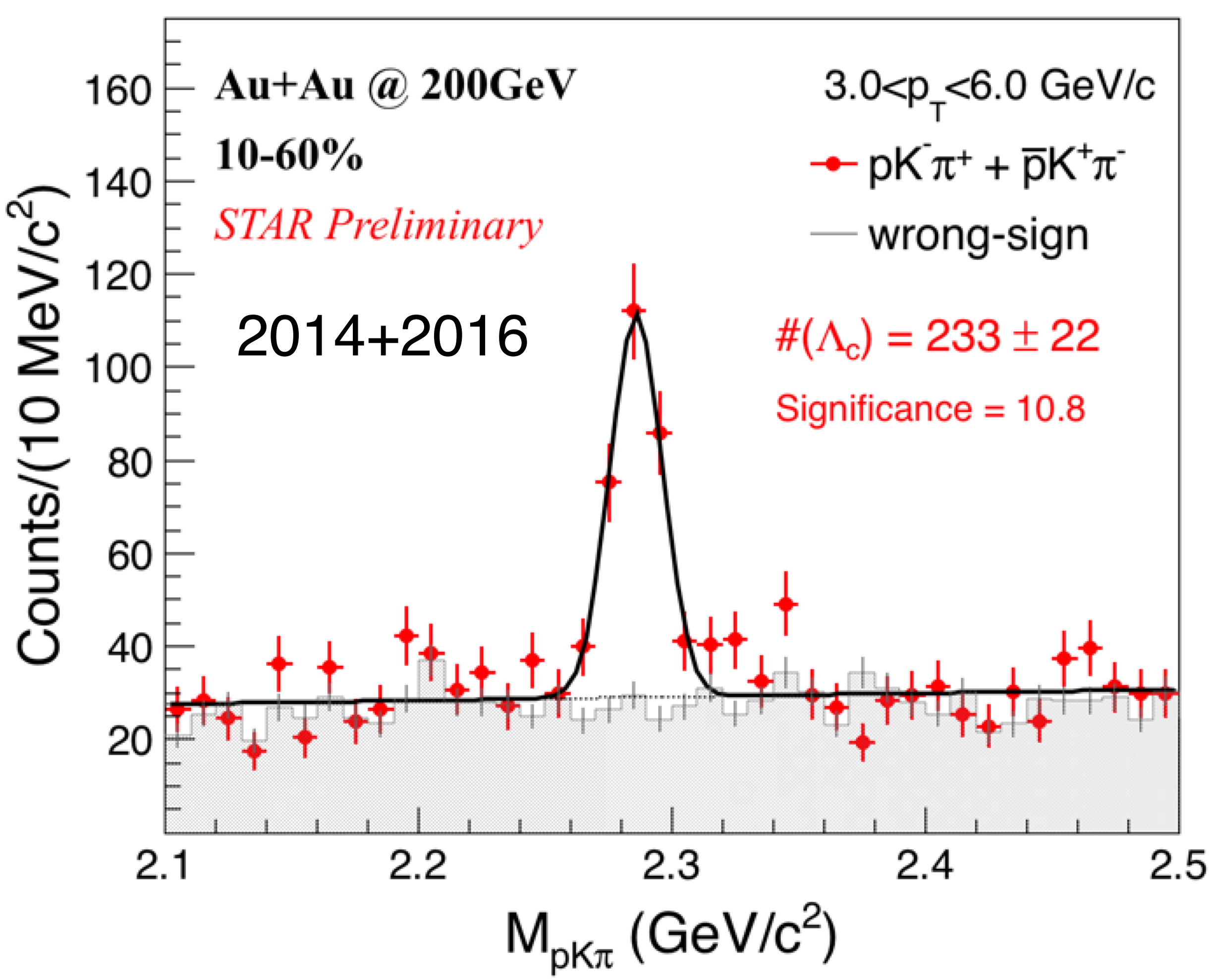
- Simple cuts on variables have limitations on signal-background separation
- Supervised learning algorithms can do better!
  - Boosted Decision Trees: successive binary cuts on attributes
  - Good performance for classification problems
  - 7 topological variables as input
  - For training: signal from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



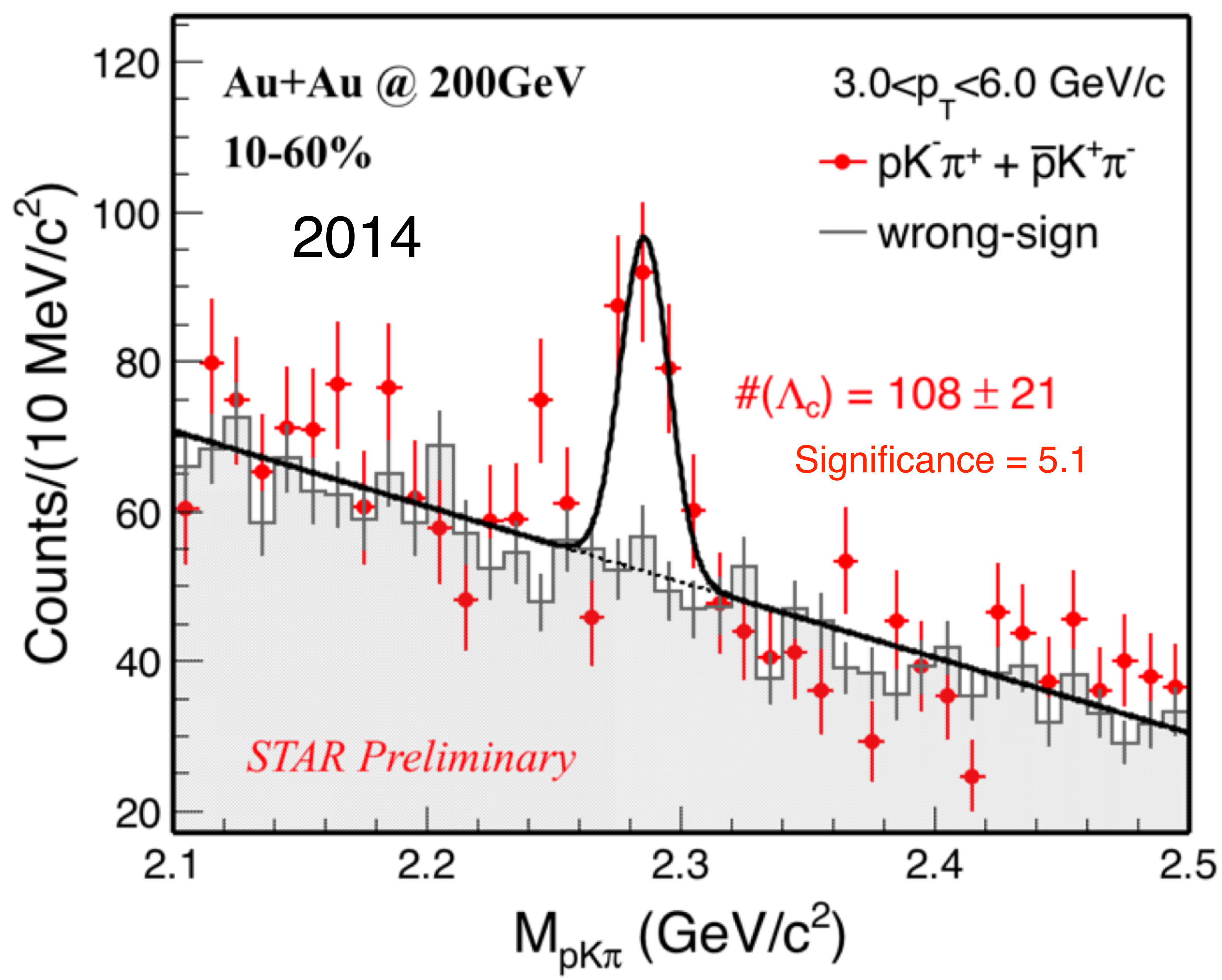
Boosted Decision Trees (BDT) for Λ_c Signal Extraction

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

QM18



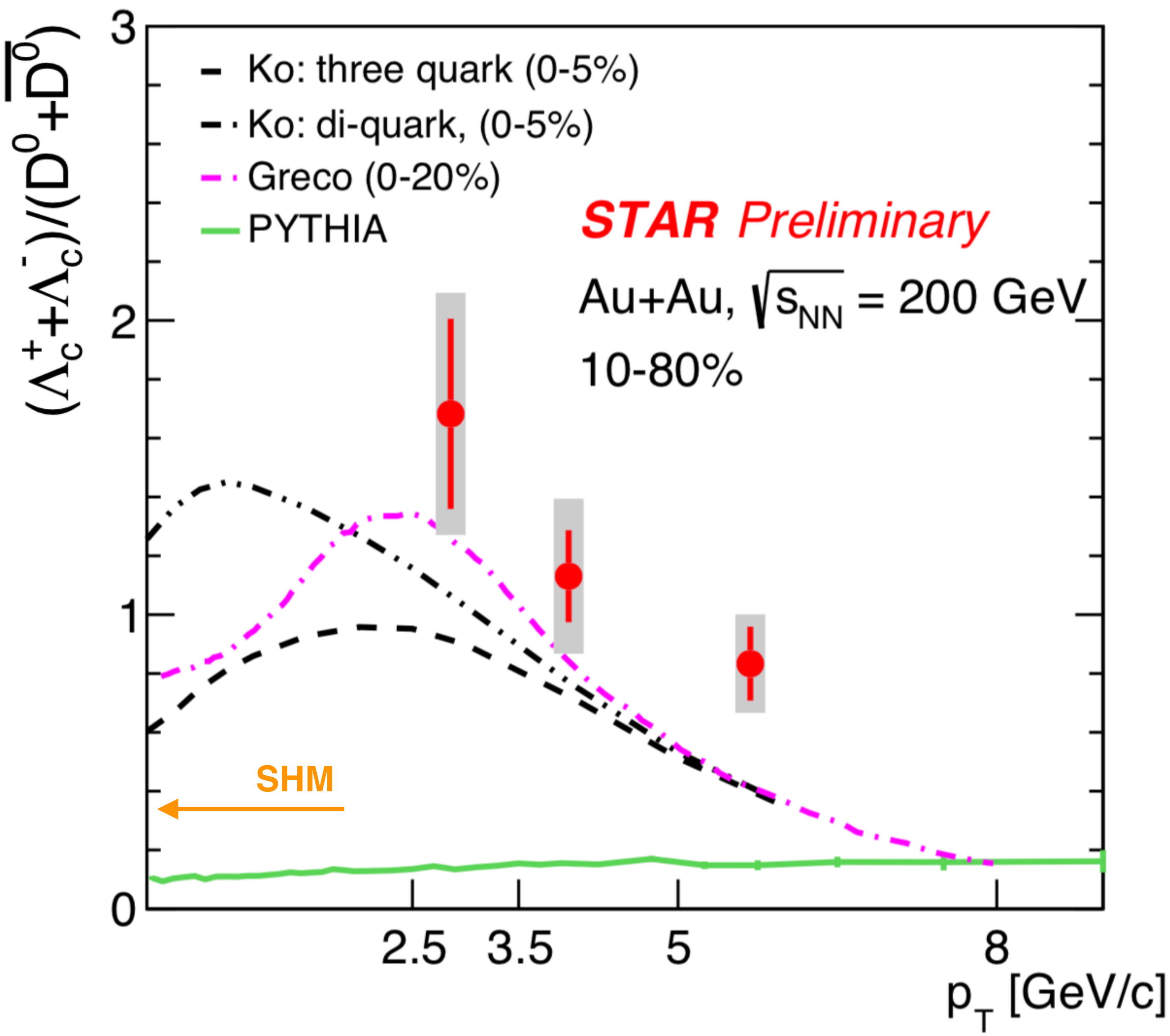
QM17



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

See also: Poster #83 (Fu, Chuan)

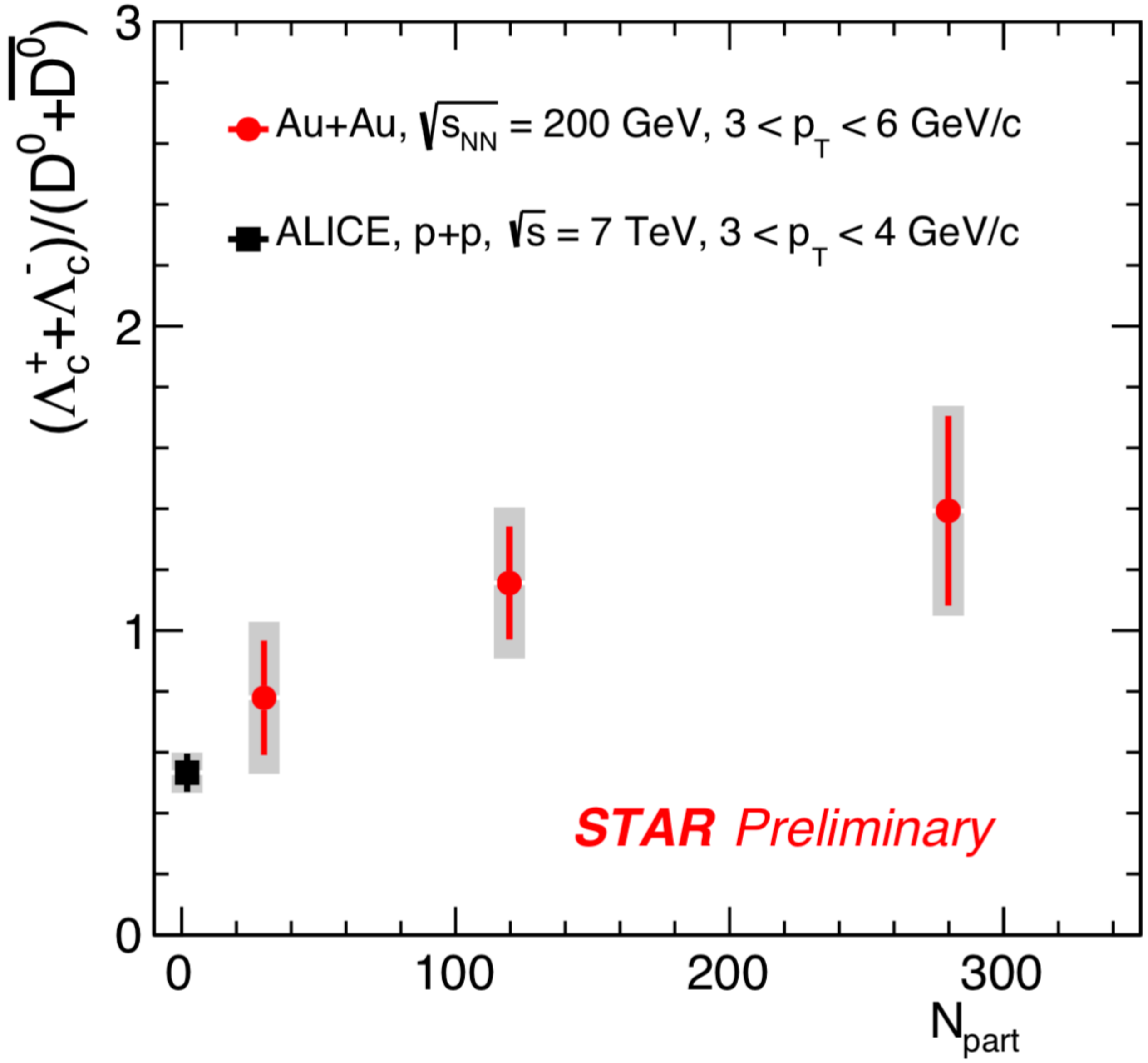
p_T Dependence of Λ_c/D^0 Ratio



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 Statistical Hadronization Models

Centrality Dependence of Λc Production

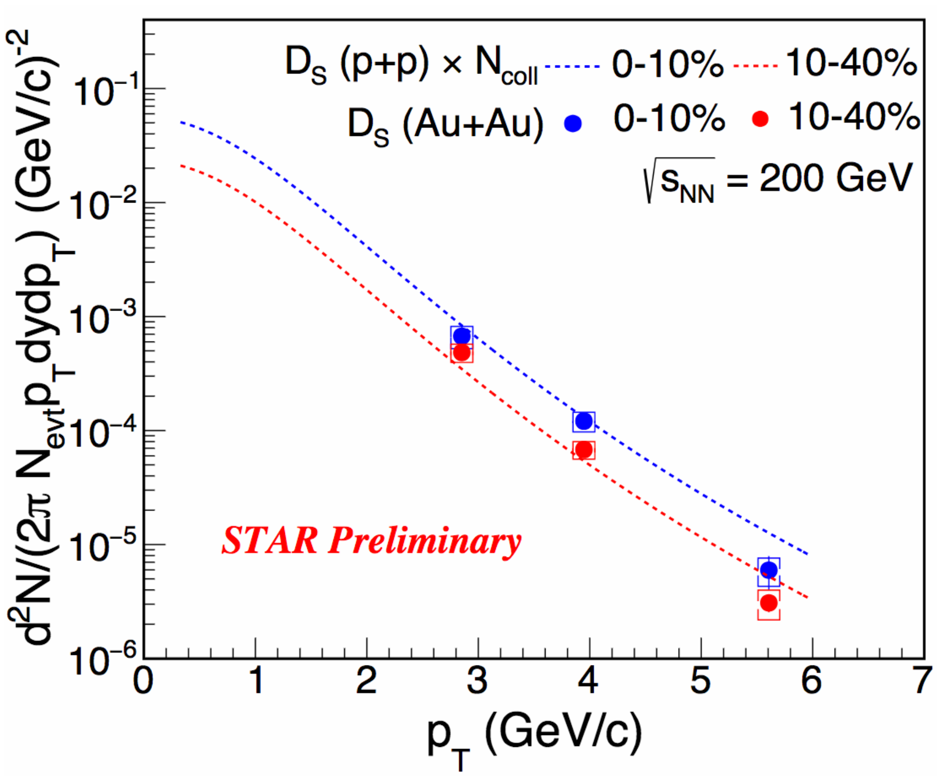


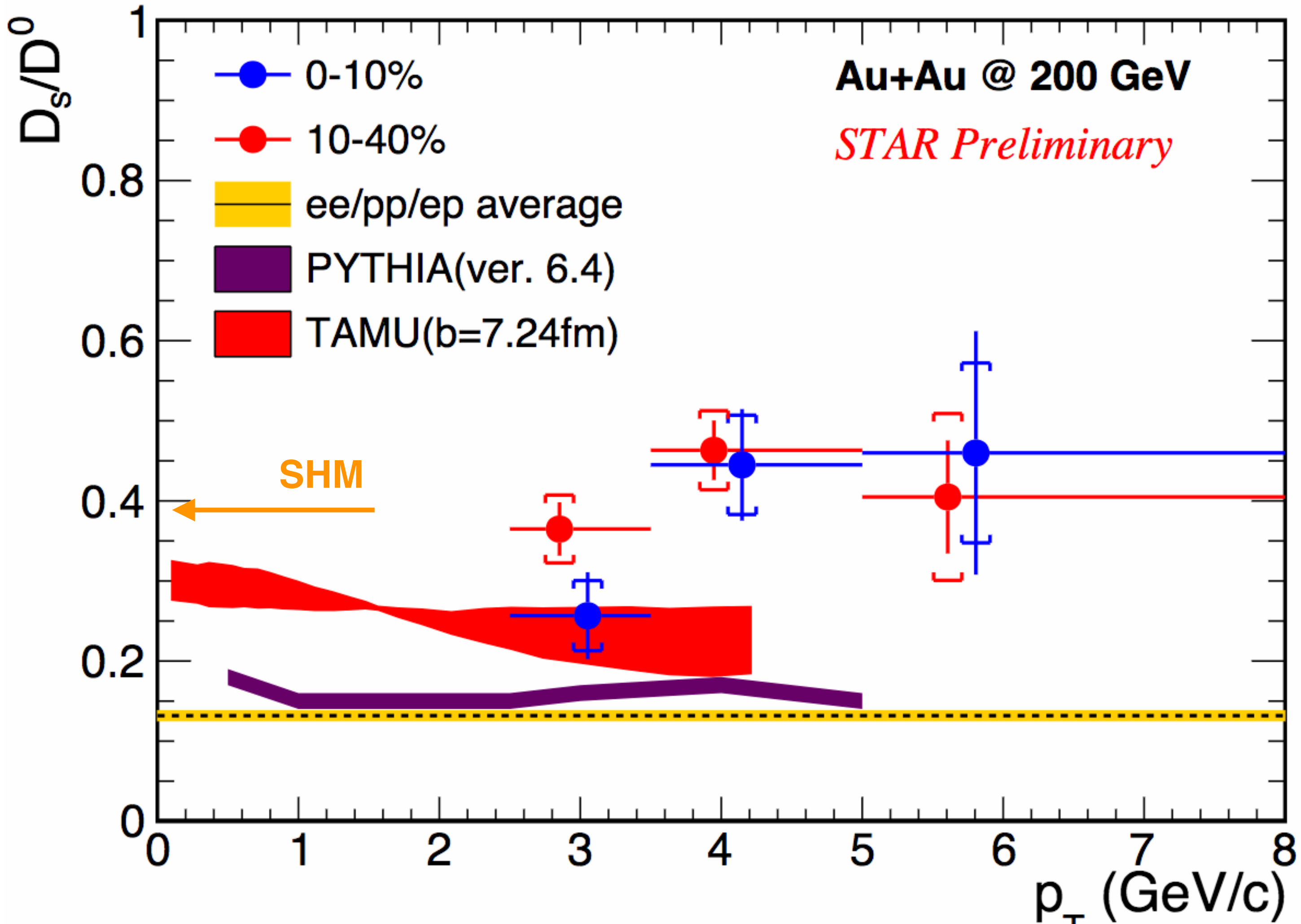
ALICE: arXiv:1712.09581

- First measurement of centrality dependence of Λc 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 p+p values at 7 TeV

D_s Production

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



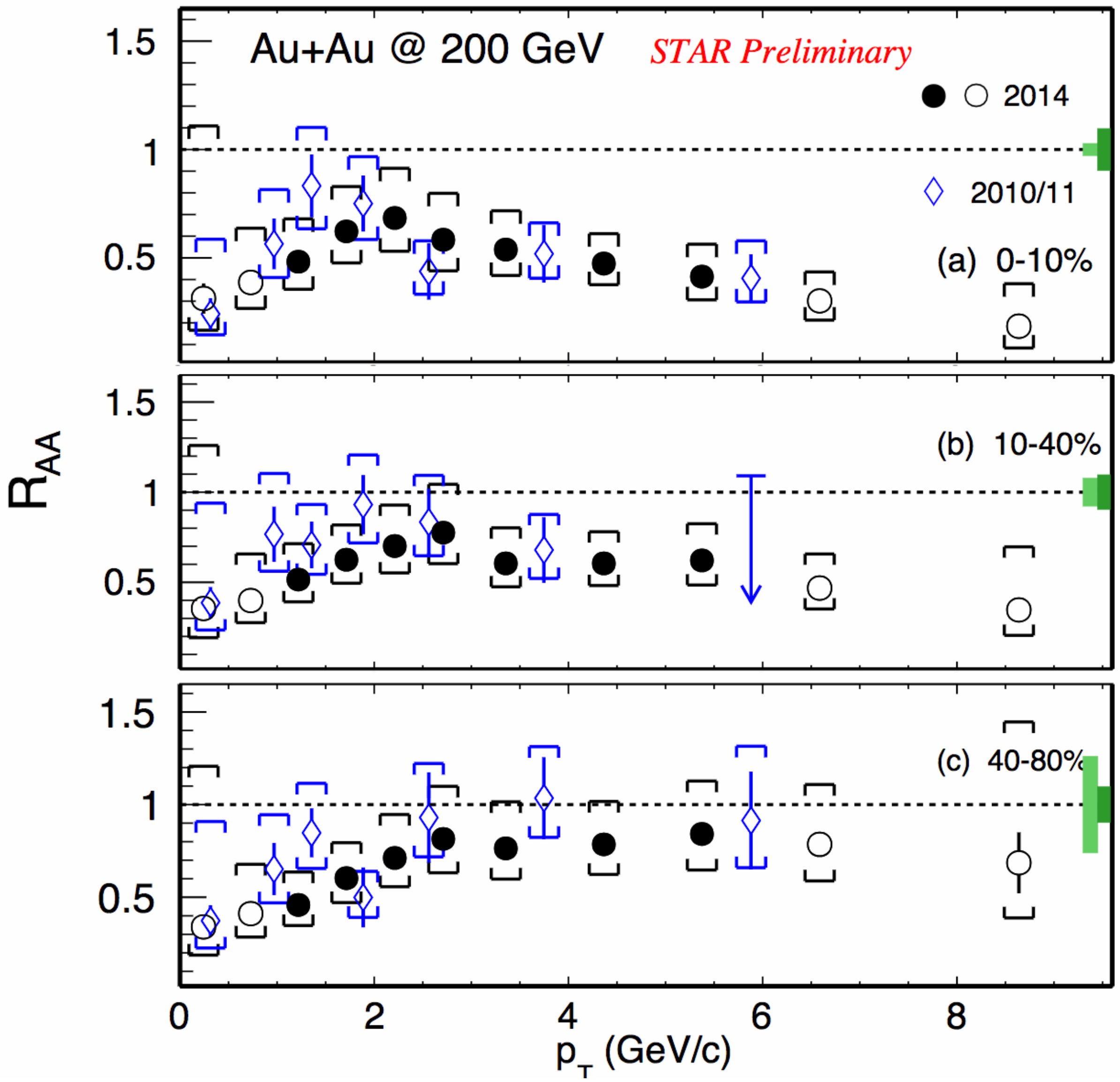


- D_s yield (relative to D^0) is enhanced in A+A collisions
- Enhancement is larger than model predictions, particularly at higher p_T
- Ratio close to SHM predictions

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}

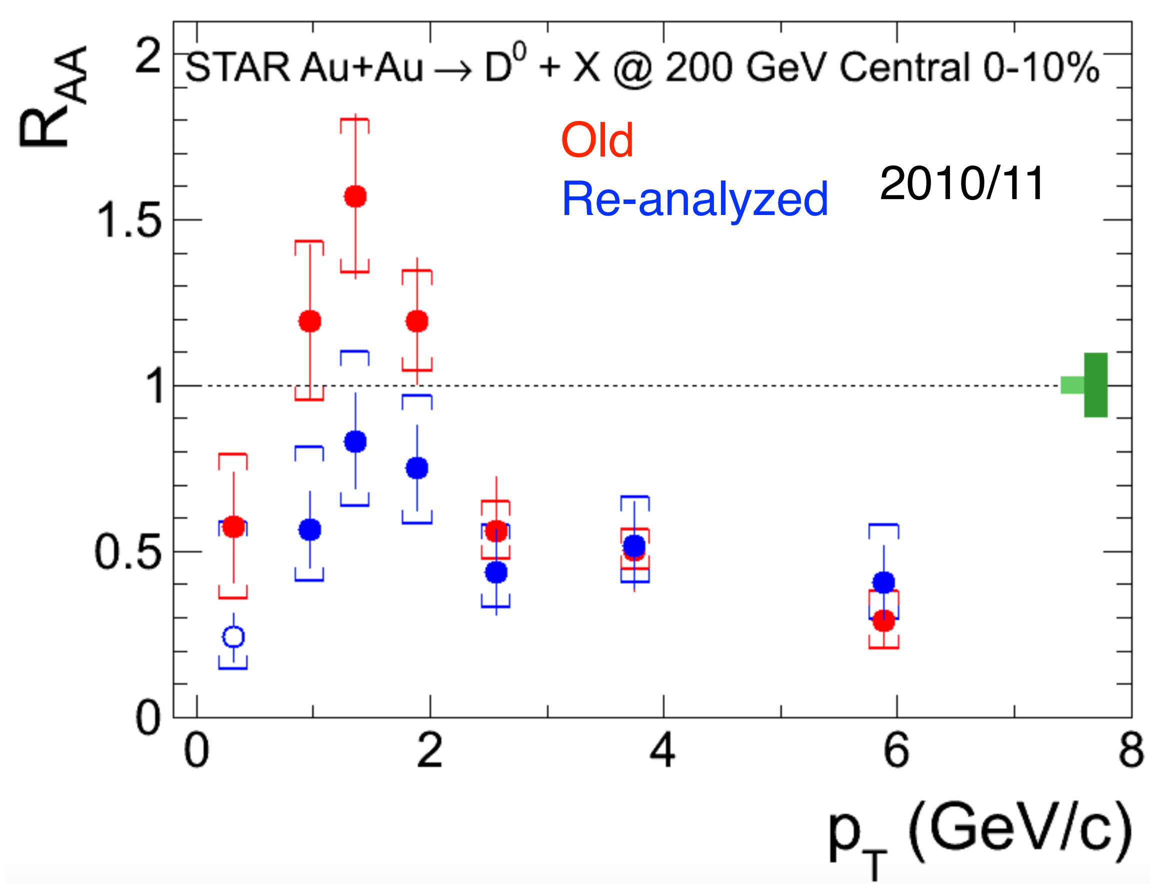
- Updated results from STAR for D^0 extending to low p_T and non-central collisions



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

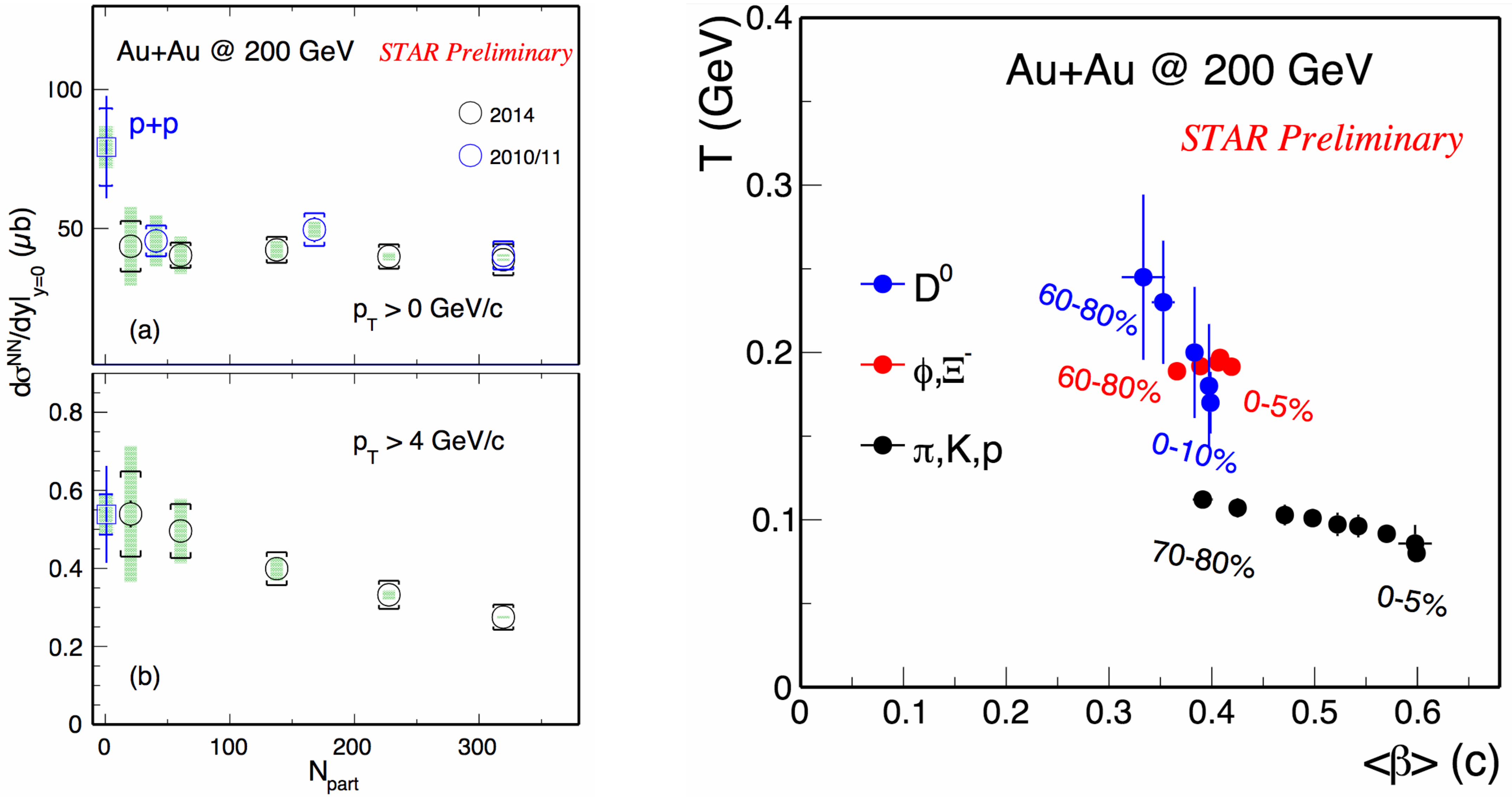
See: Poster #81 (Xie, Guannan)

- Mistake found in efficiency correction for 2010/11 TPC analysis
- Affected low p_T values mainly
- Will publish erratum



- Re-analyzed results are consistent with HFT measurements.

D^0 Cross-section and BW Fits to Spectra

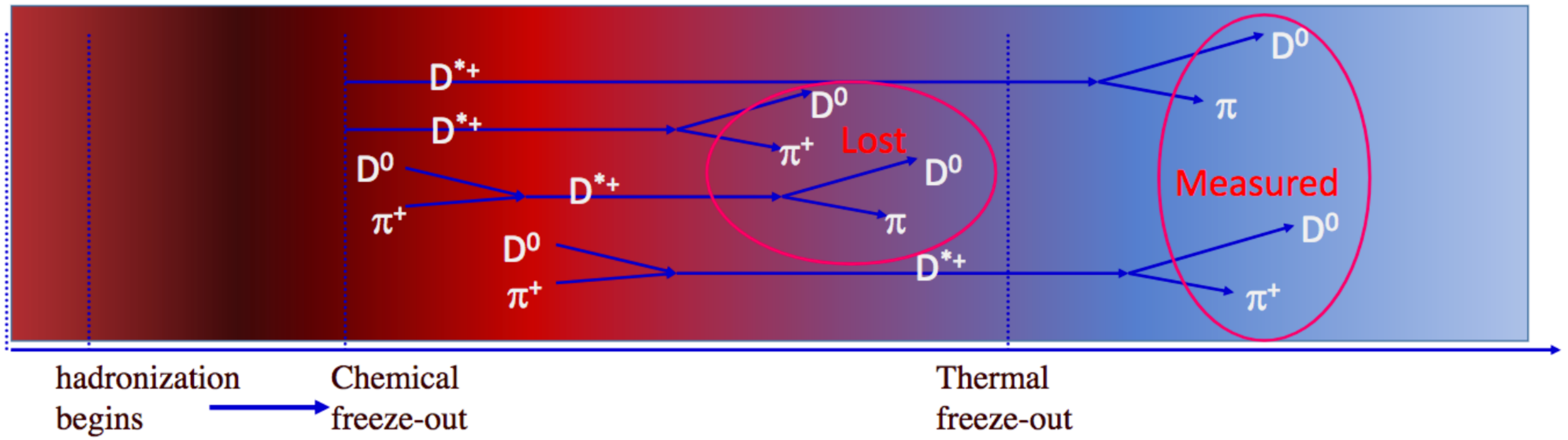


- Total D^0 cross-section is nearly independent of centrality, and smaller than in p+p. However, decreases towards central collisions for $p_T > 4$ GeV/c
- Blast Wave fits to D^0 spectra:
  - BW fits to $p_T < 5$ GeV/c. Both standard and Tsallis BW fits tried

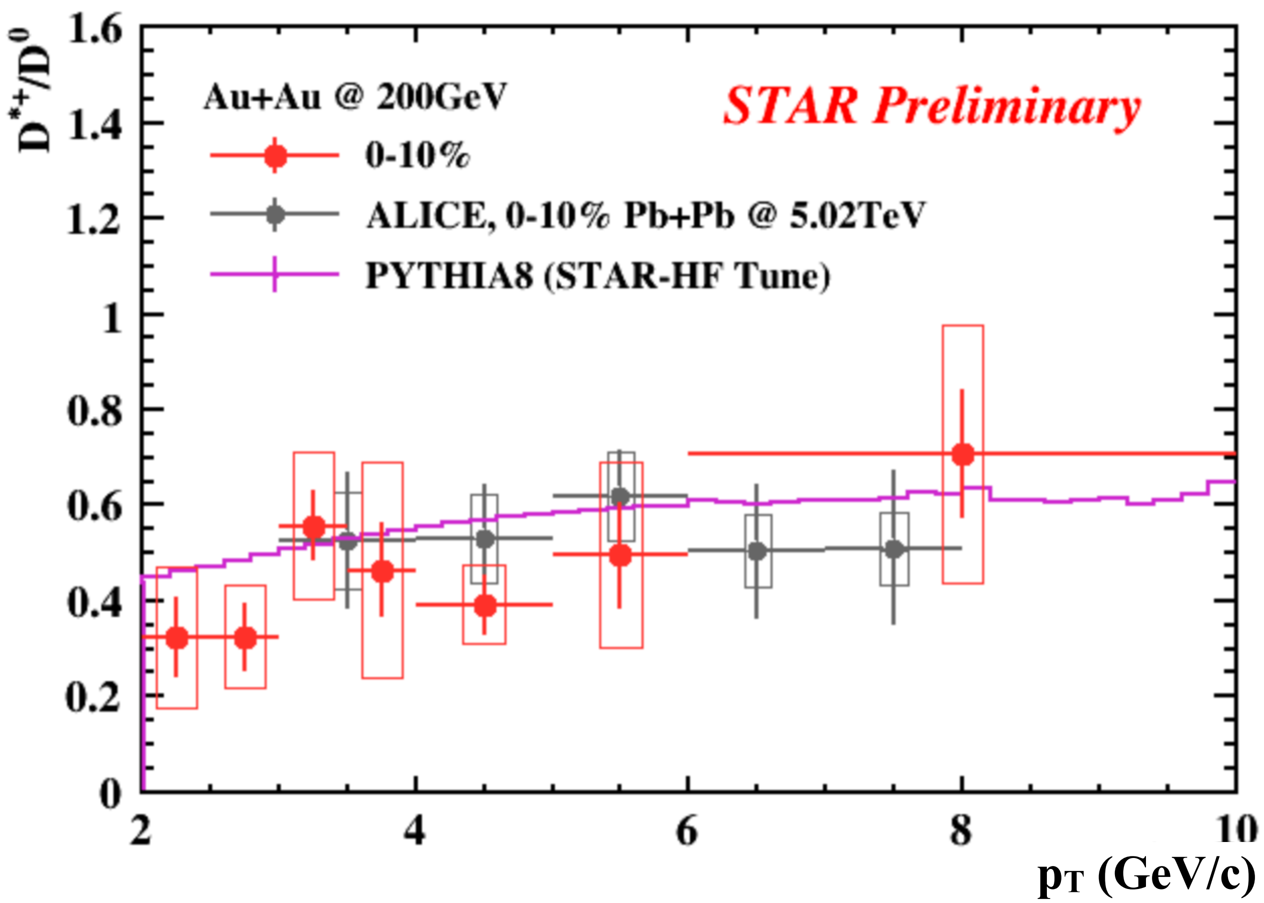
See: Poster #81 (Xie, Guannan)

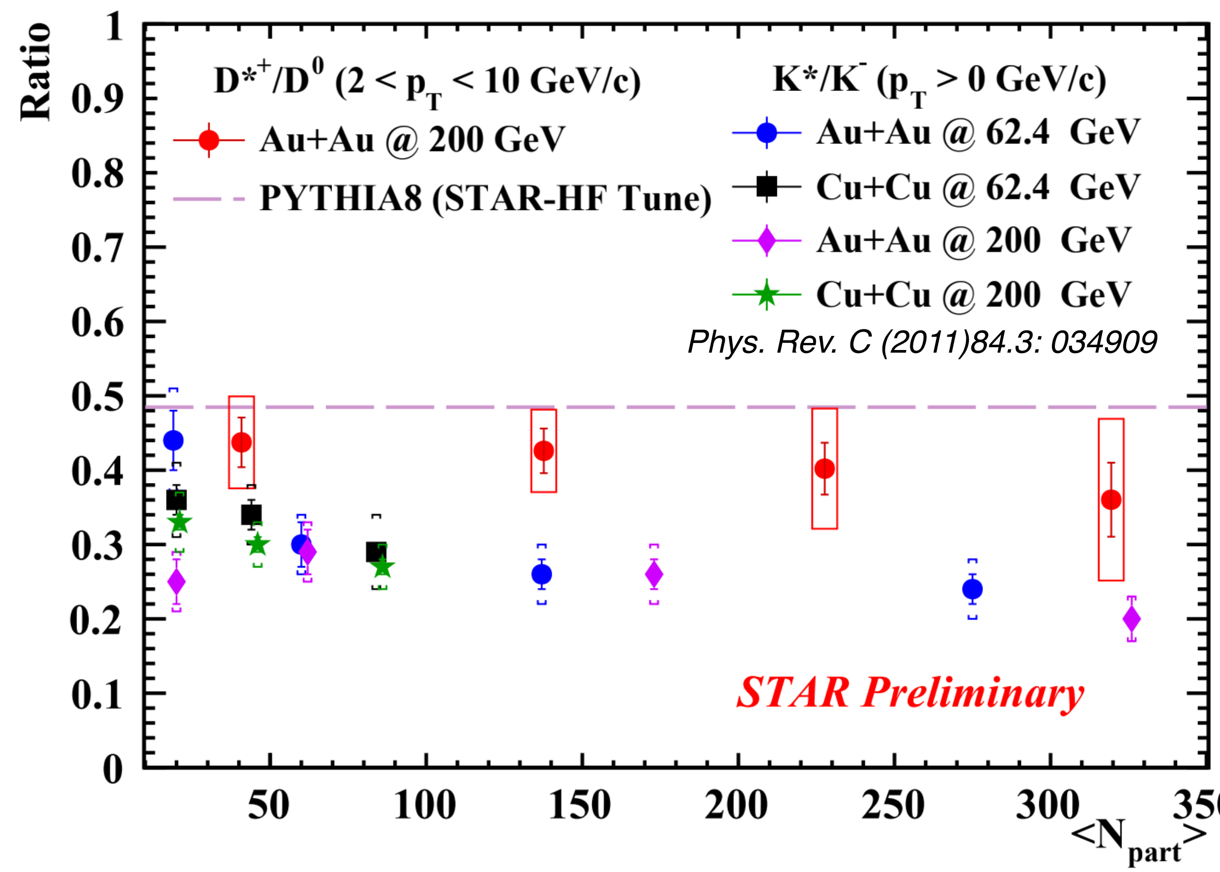
D^* Production in Au+Au Collisions

- Measure D^{*+}/D^0 ratio
  - D^{*+} feed-down contribution to D^0 yields ($D^{*+} \rightarrow D^0\pi^+_{soft}$)
  - Hot medium effects:
    - Shorter life time in medium (?). Lifetime in vacuum is ~2000 fm/c, but spectral functions 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 at higher p_T.
- Ratio of the integrated yields shows no strong centrality dependence.

See: Poster #87 (Ji, Yuanjing)

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

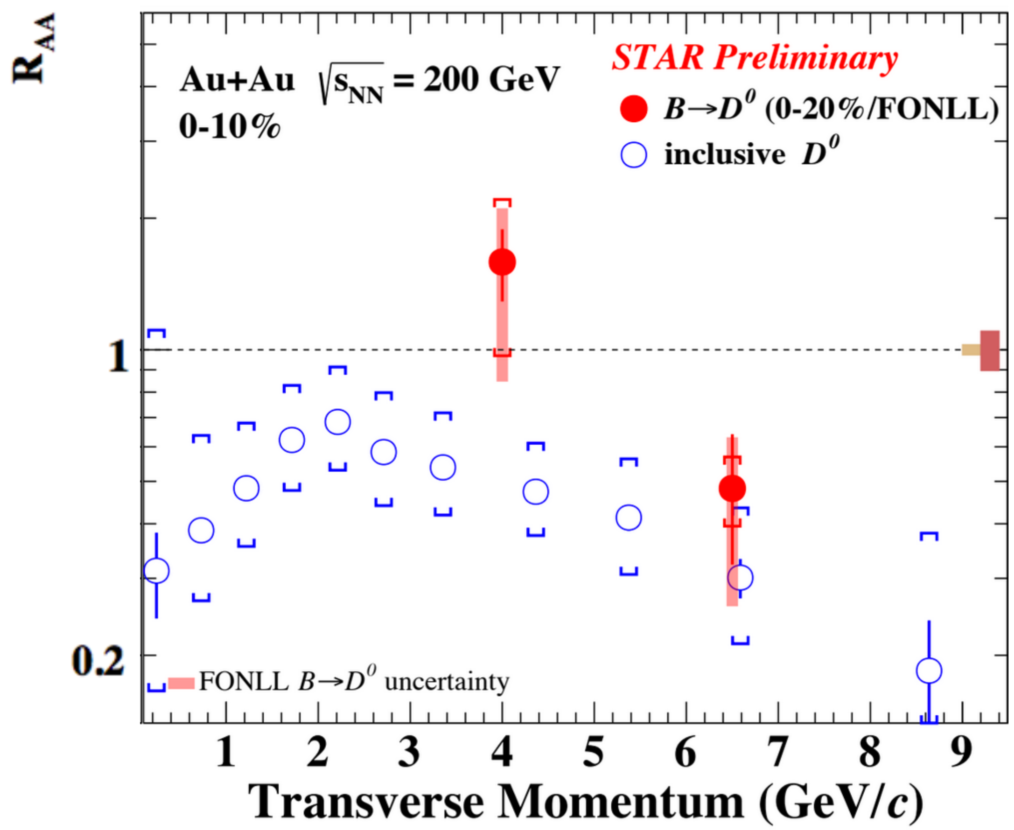
Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28 *
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

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

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

Non-prompt D^0

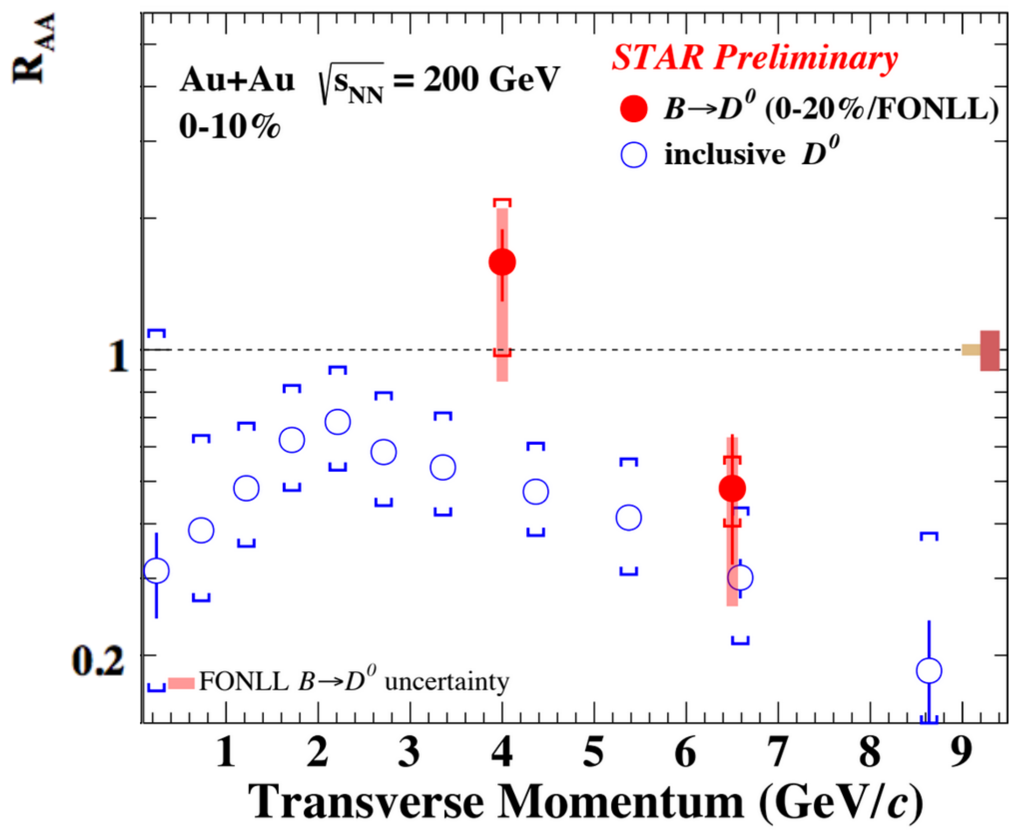
- Charm quarks interact strongly with the medium. How about bottom?
- Is there mass hierarchy for energy loss? Is $\Delta E_c > \Delta E_b$?



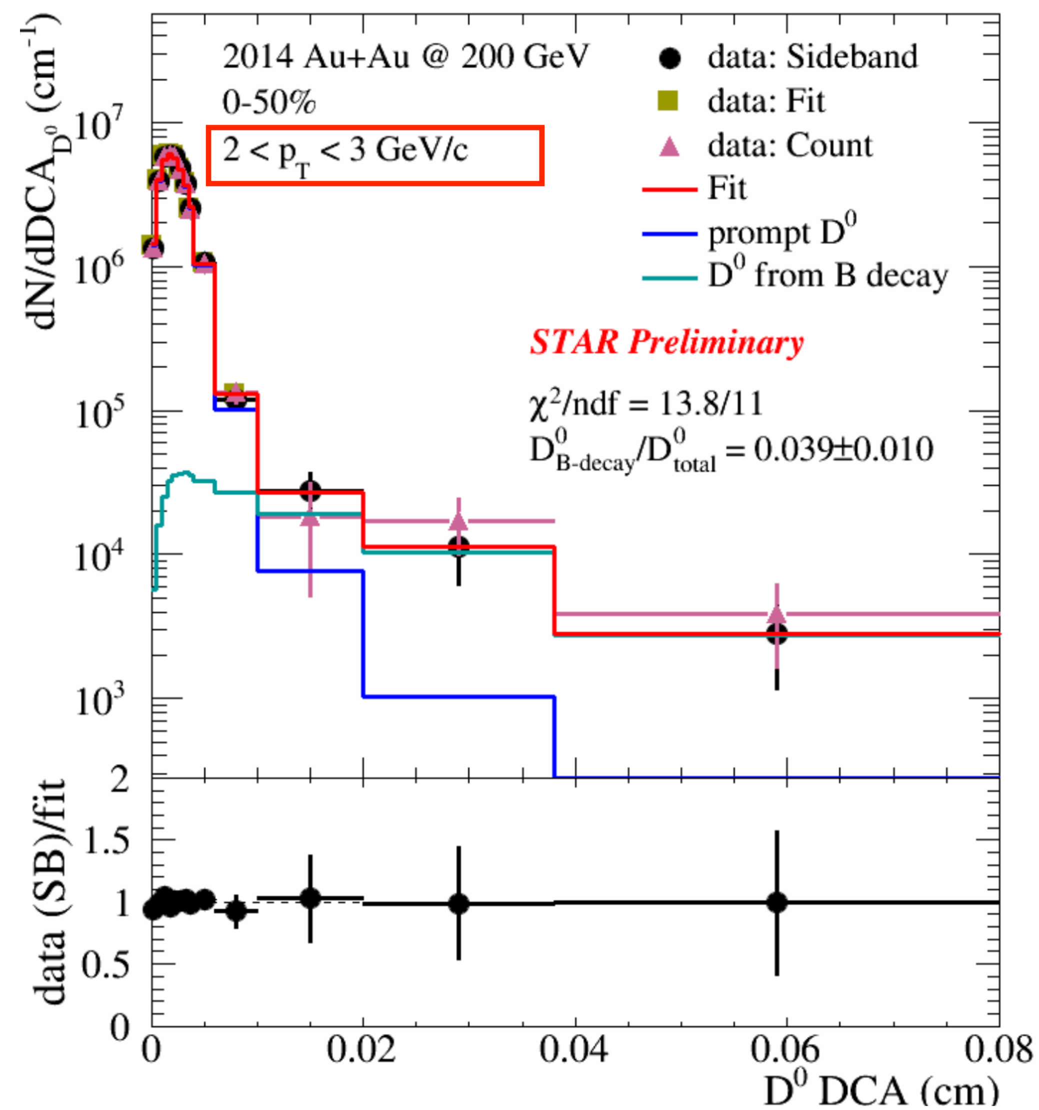
- R_{AA} of B mesons estimated from the measured non-prompt D^0 fraction
- Need better statistics and improved precision to understand mass dependence of energy loss.

Non-prompt D⁰

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



- Improved signal significance for non-prompt D⁰ fraction using BDT
- New results with 2014+2016 data on the way



- R_{AA} of B mesons estimated from the measured non-prompt D⁰ fraction
- Need better statistics and improved precision to understand mass dependence of energy loss.

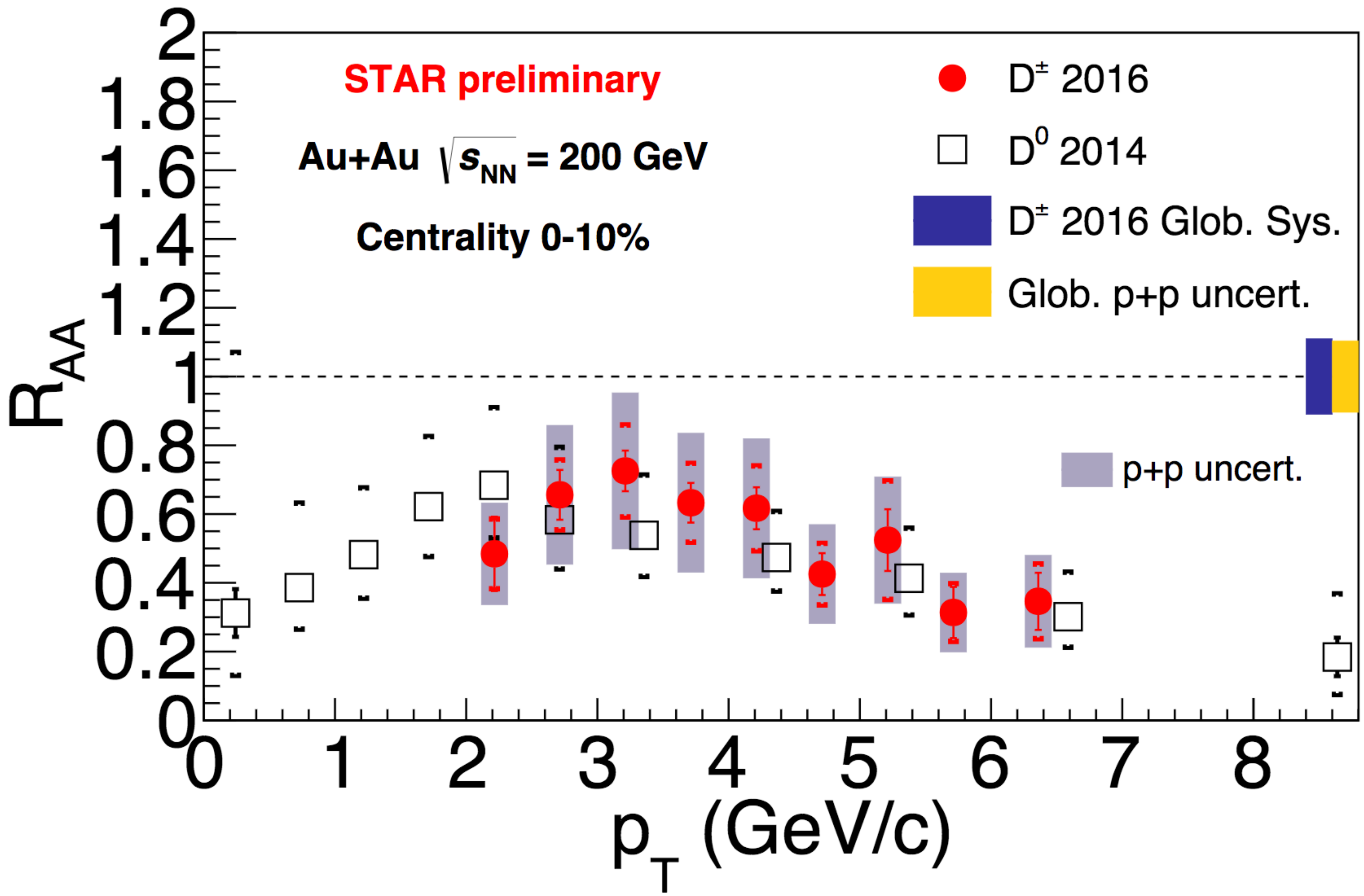
See: Poster #541 (Chen, Xiaolong)

Summary

- Extensive measurements of charm hadron yields in heavy-ion collisions by STAR
  - Combined 2014+2016 data
  - Improved significance from supervised machine-learning algorithms
- Strong modification of charm hadron spectra and hadrochemistry in A+A collisions!
  - Total charm cross-section consistent with p+p within systematic uncertainties.
  - Strong enhancement seen for Λ_c/D^0 ratio 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
- Non-prompt D^0 R_{AA} study has been performed, need better precision measurements to understand mass dependence of energy loss

Back Up

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



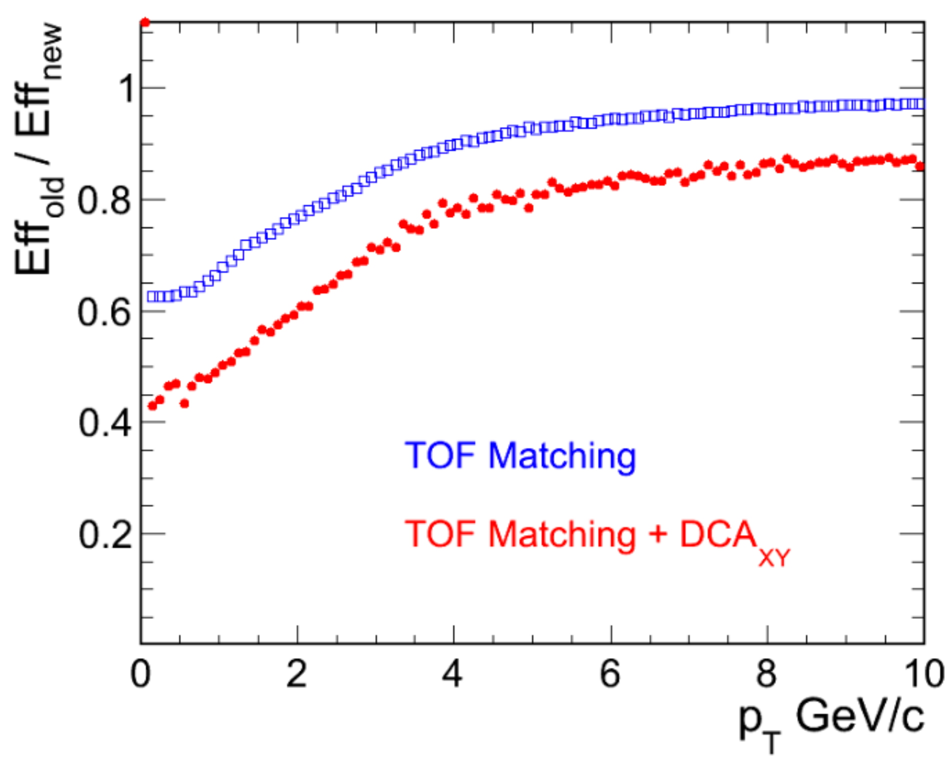
- Similar suppression for D^0 and $D^{+/-}$
- Spectra measurements important for total charm cross-section

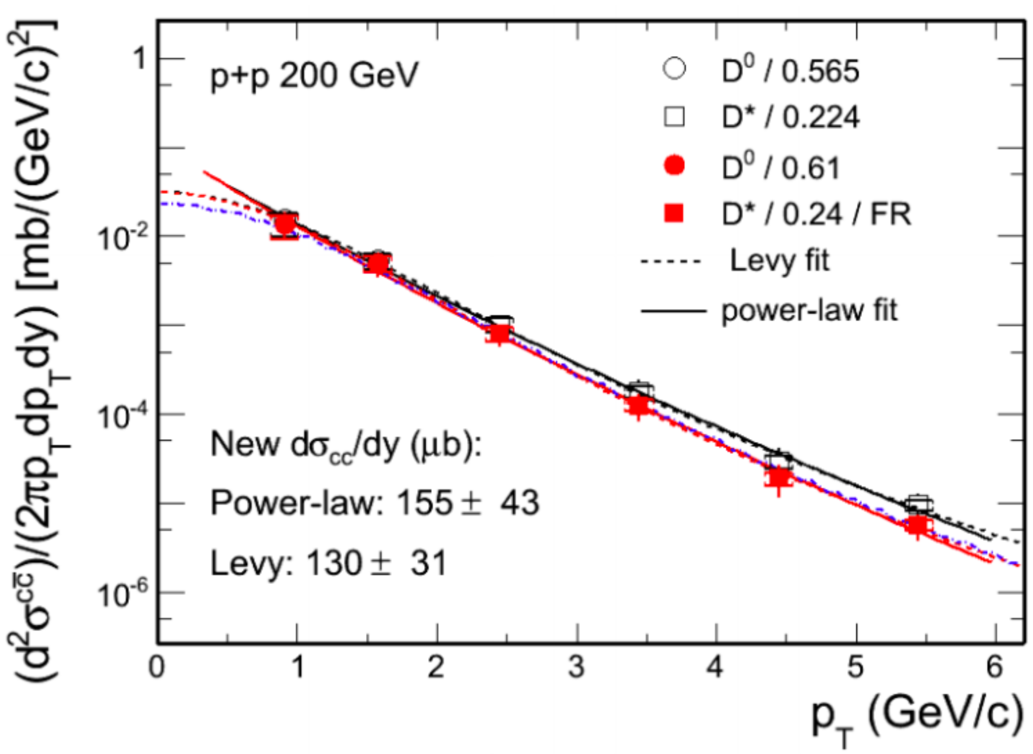
See: Poster #84 (Vanek, Jan)

Erratum details

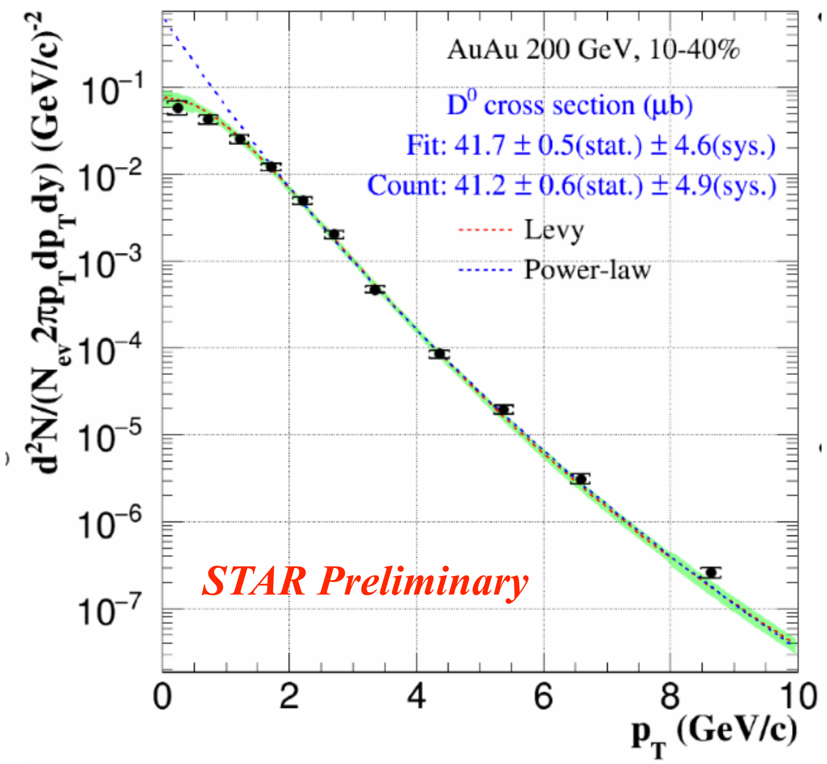
Erratum: D^0 in AuAu (2010/2011 TPC Analysis) - I
PRL 113 (2014) 142301

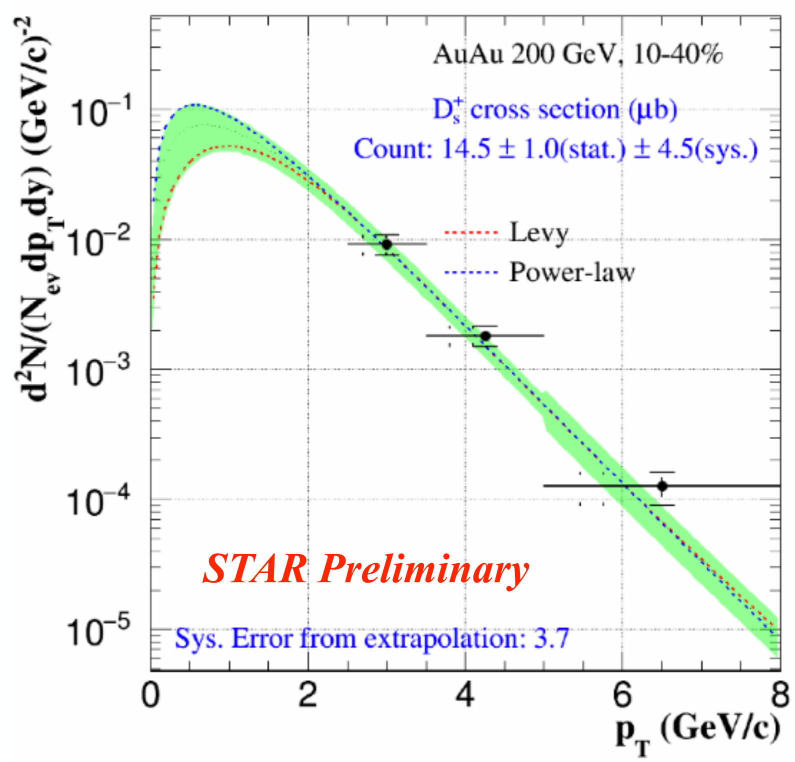
1. Two mistakes were discovered in calculating TOF related efficiency corrections
   - **Hybrid PID: algorithm inconsistently implemented in data analysis vs efficiency calculation**
   - **a transverse distance of closest approach cut efficiency was included in the correction two times**
2. p+p measurement: 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**

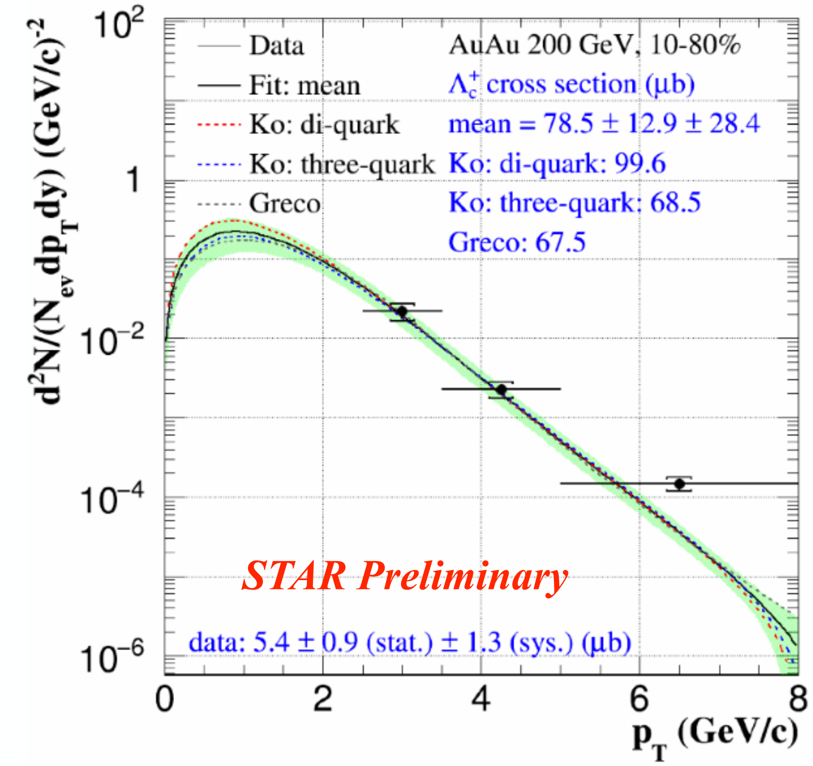




Total charm cross-section: procedure





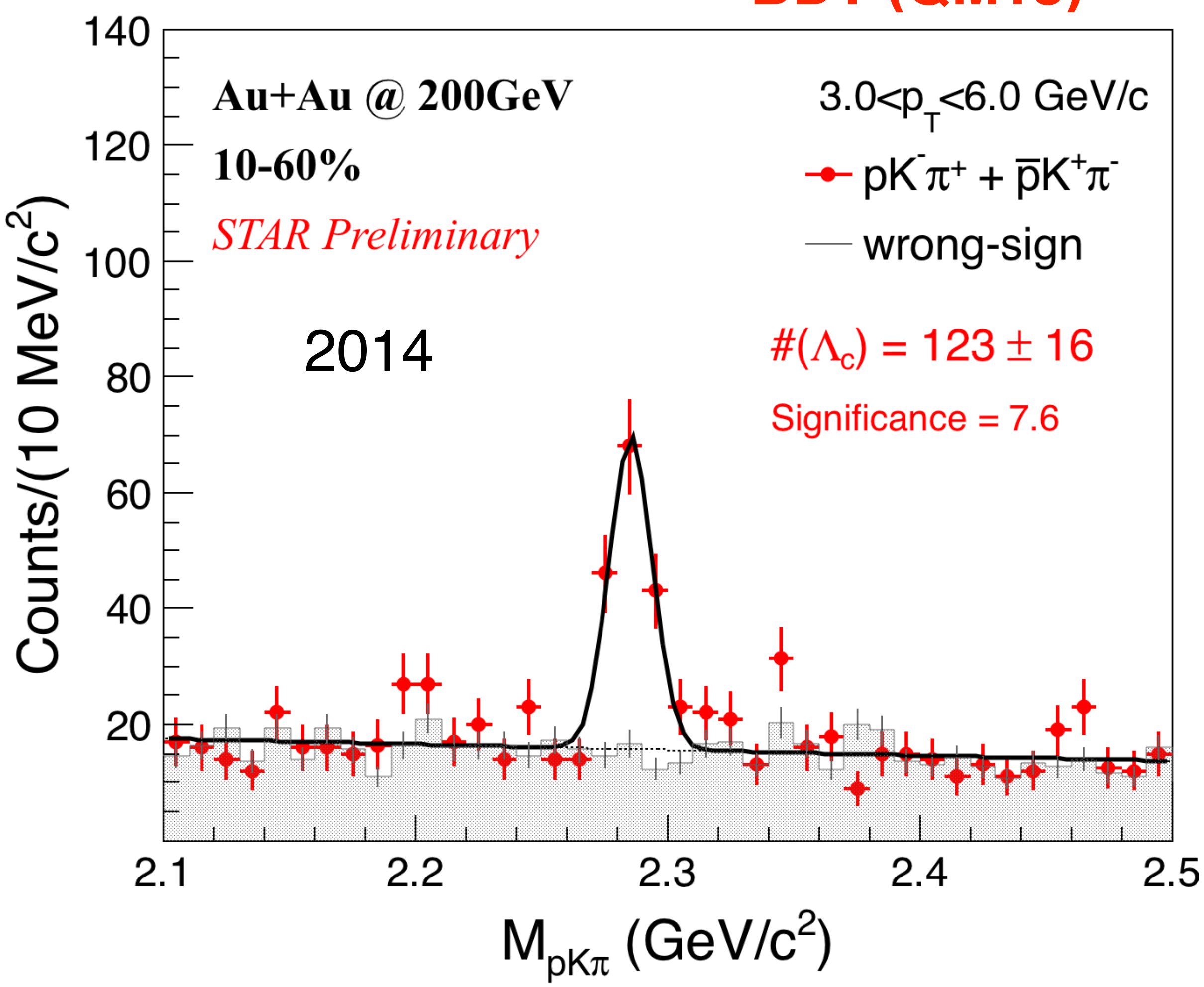


- Extracted for 10-40% centrality.
- Yields for $D^{+/-}$ and Λ_c are scaled to 10-40% centrality using measured ratio to D^0.
- Uncertainty evaluation and propagation:
  - In the p_T range with data points:
    - point by point statistical error propagated
    - point by point systematic error propagated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

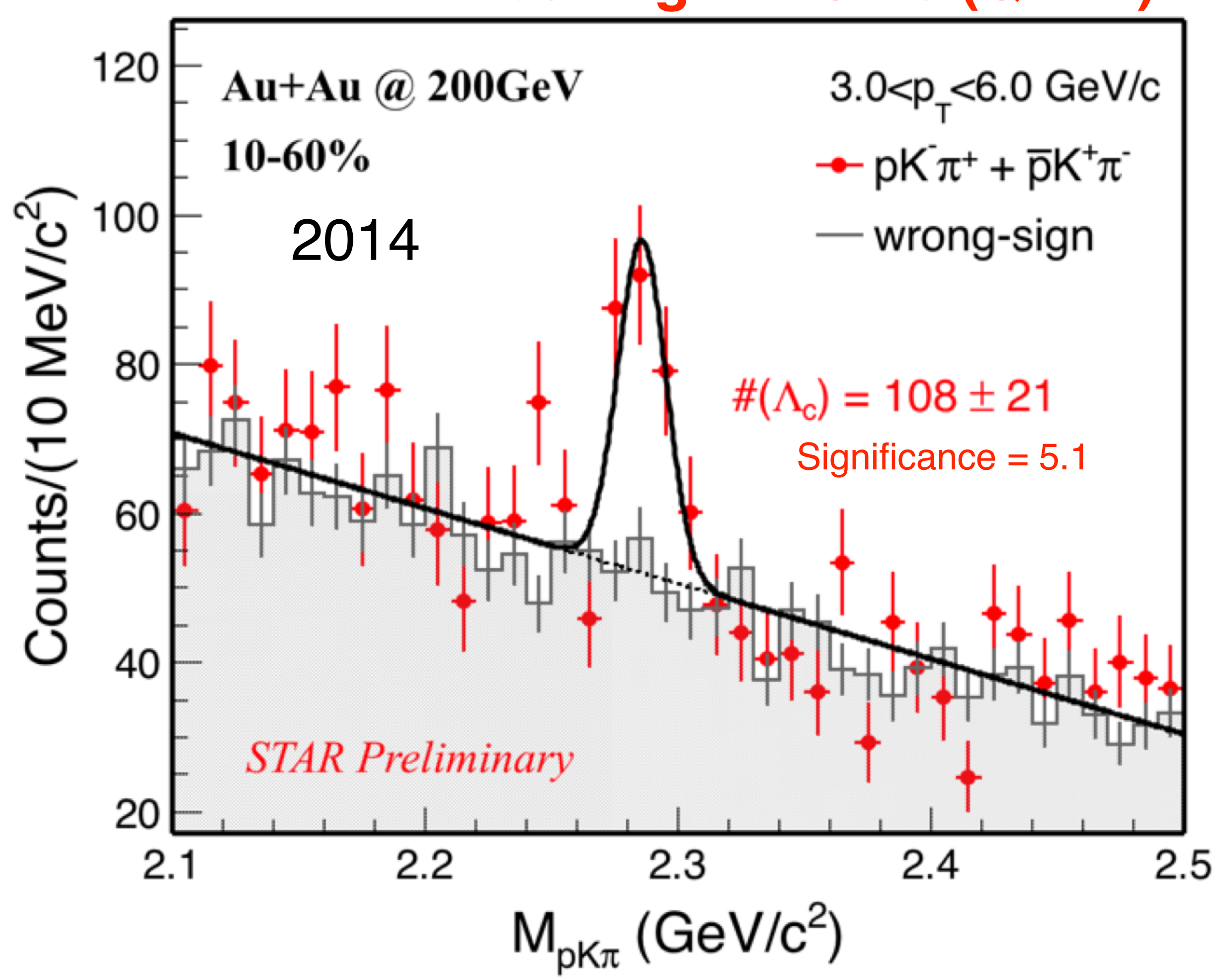
BDT vs Rectangular Cuts Comparison

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

BDT (QM18)



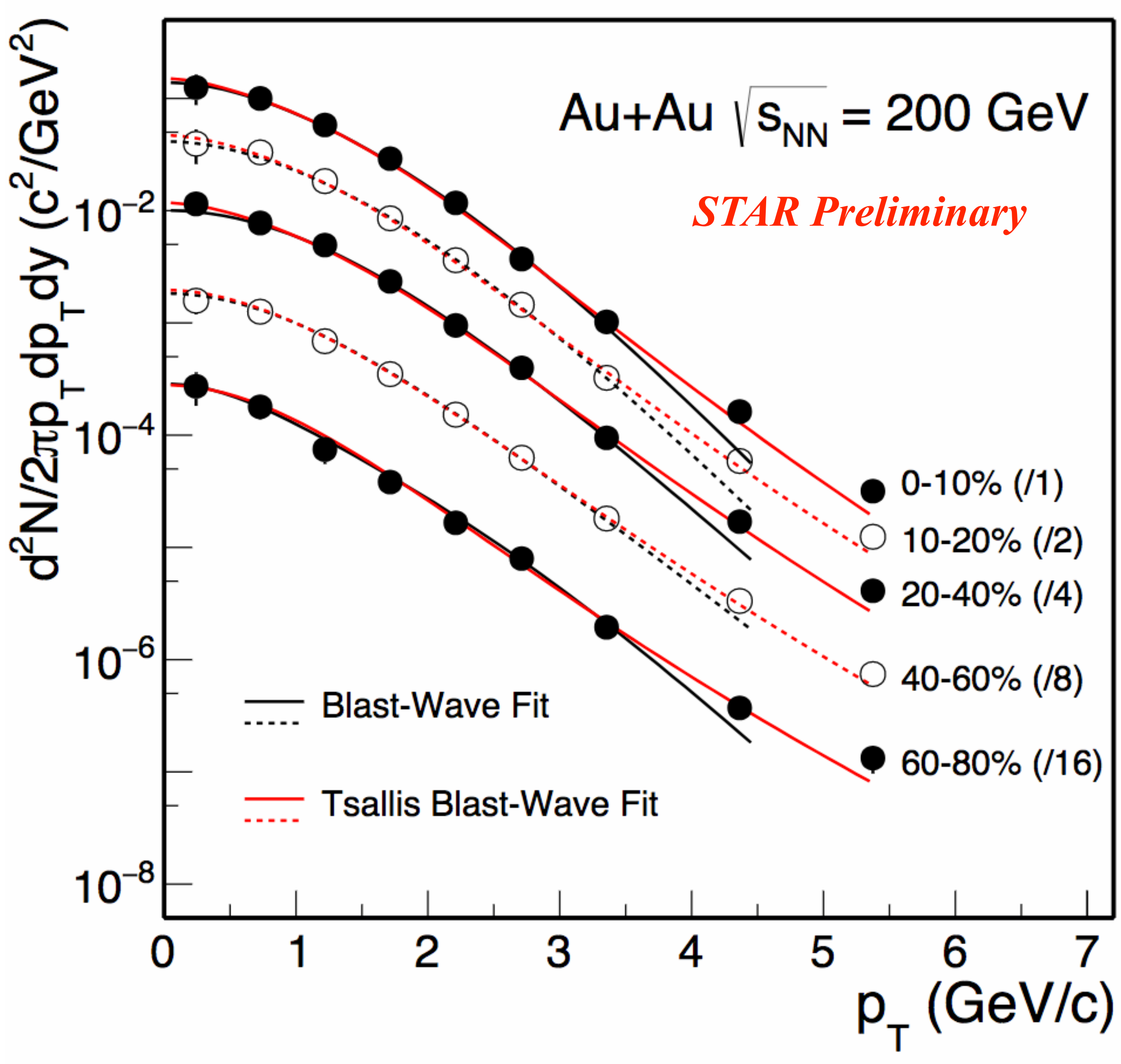
Rectangular Cuts (QM17)



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

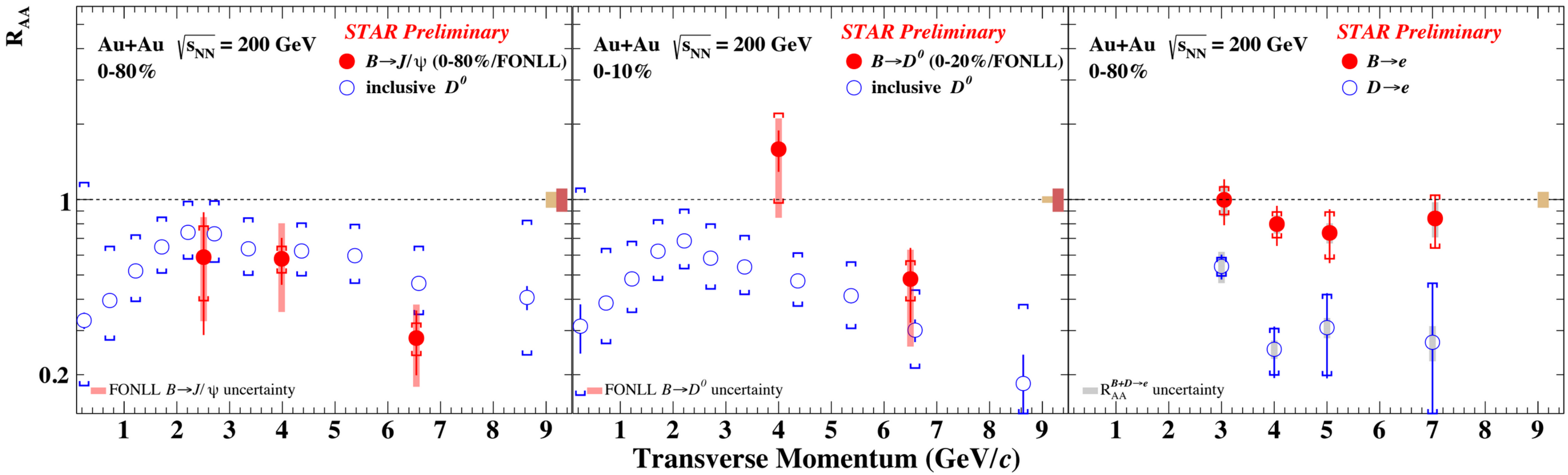
See also: Poster #83 (Fu, Chuan)

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.