

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

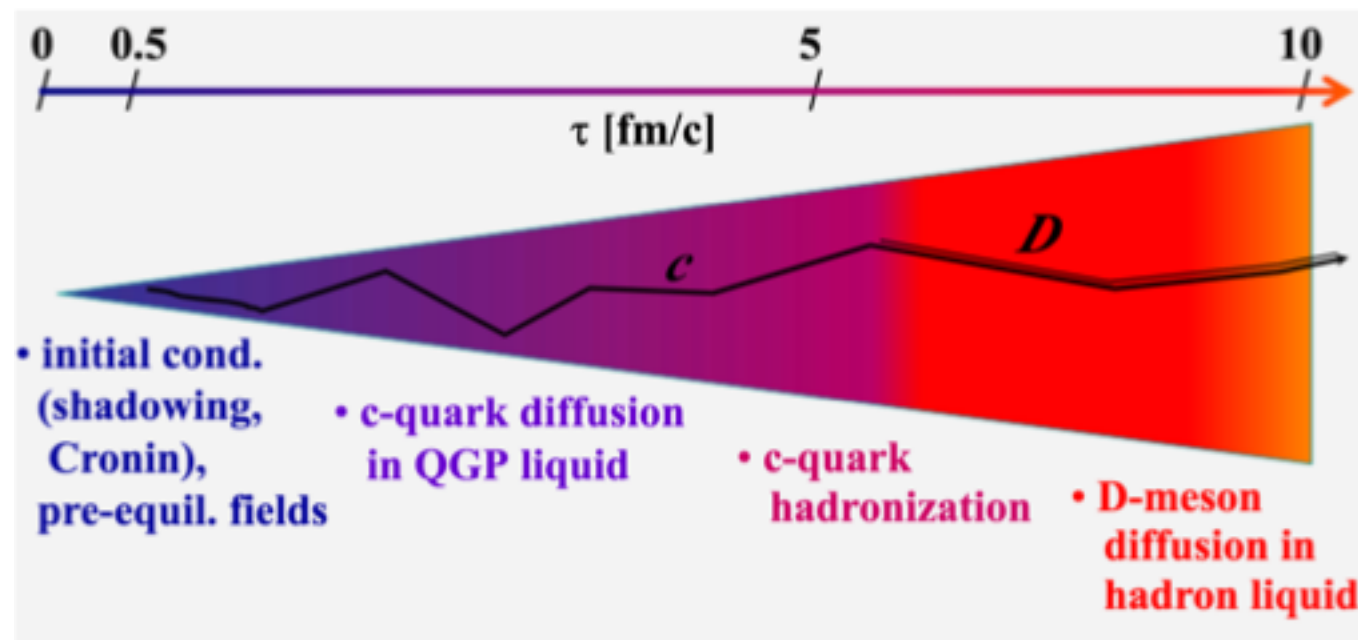
*Spiros Margetis for the STAR Collaboration
Kent State University*



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

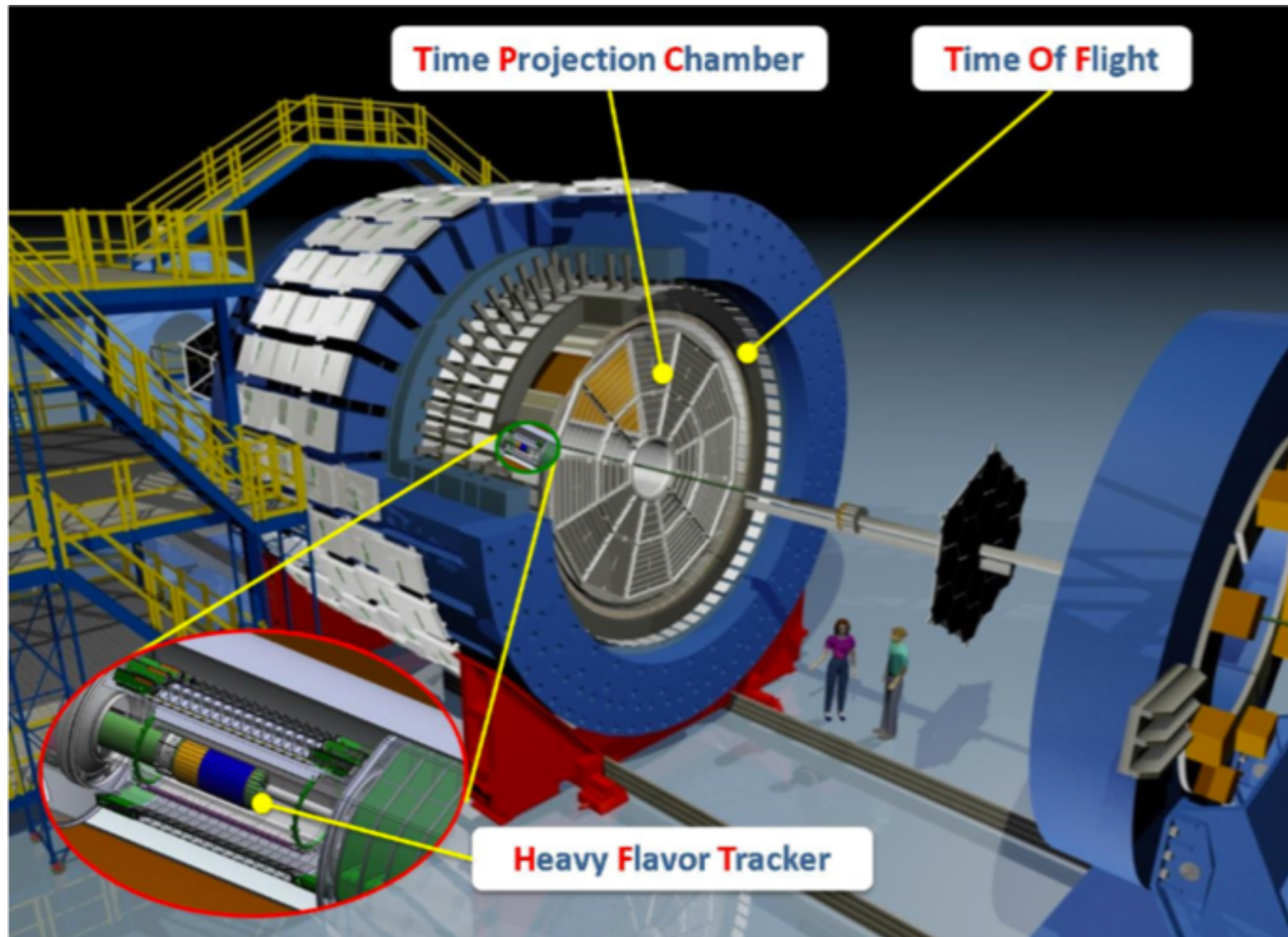


New [high statistics/optimized] extensive measurements by STAR!

- 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**

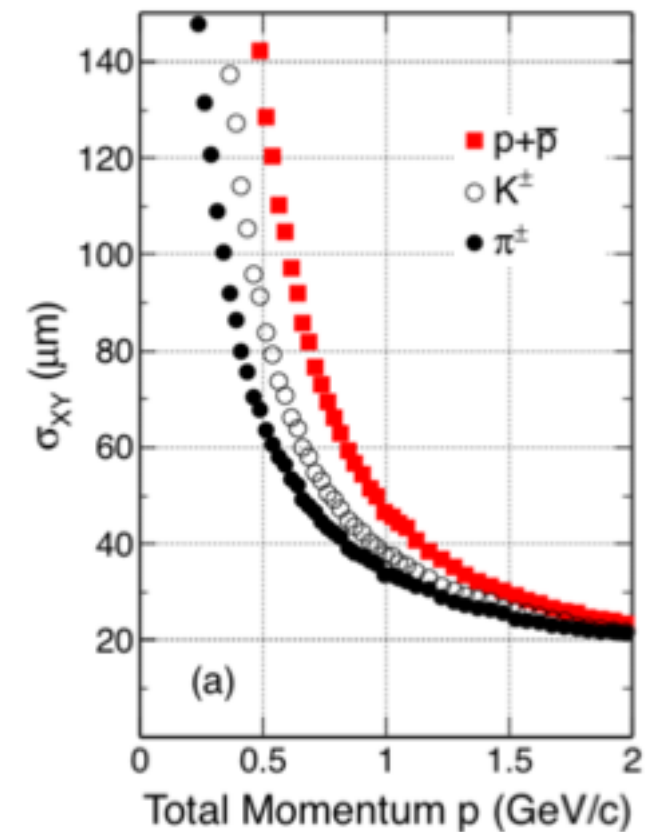
* Not reported here. See QM2018 talks of S. Sinha and S. Radhakrishnan

The STAR Detector



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

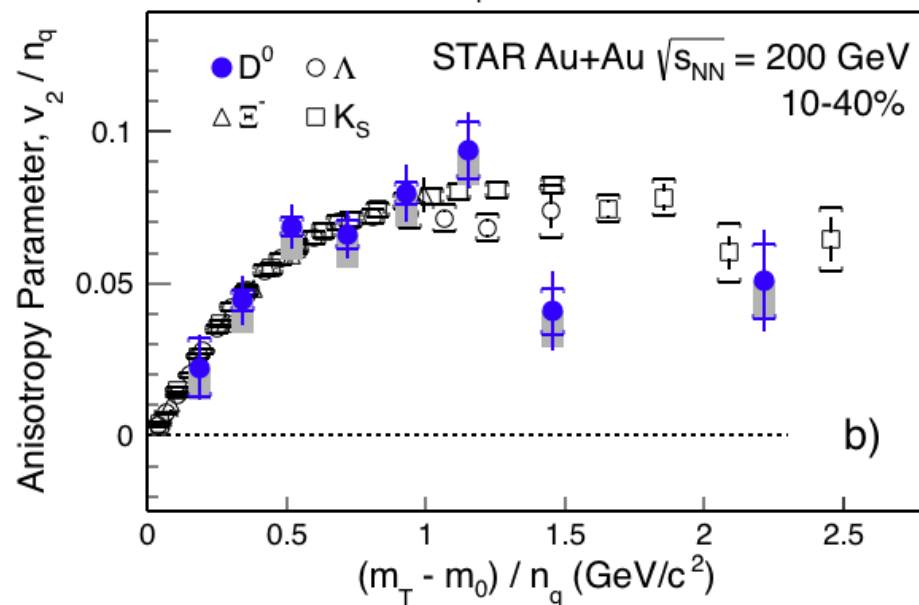
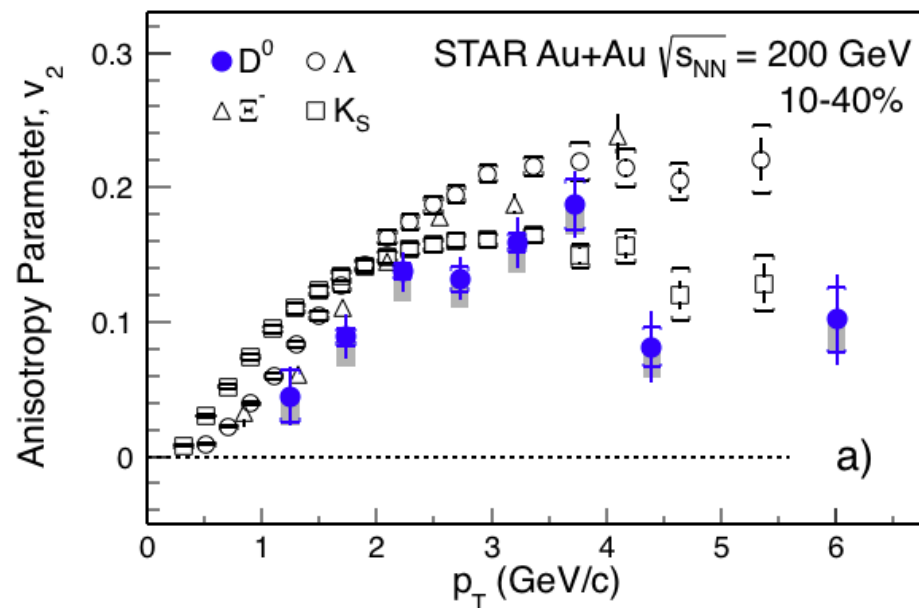
Phys. Rev. Lett. 118 (2017) 212301



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 flow magnitude consistent with NCQ scaling in minimum bias and 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

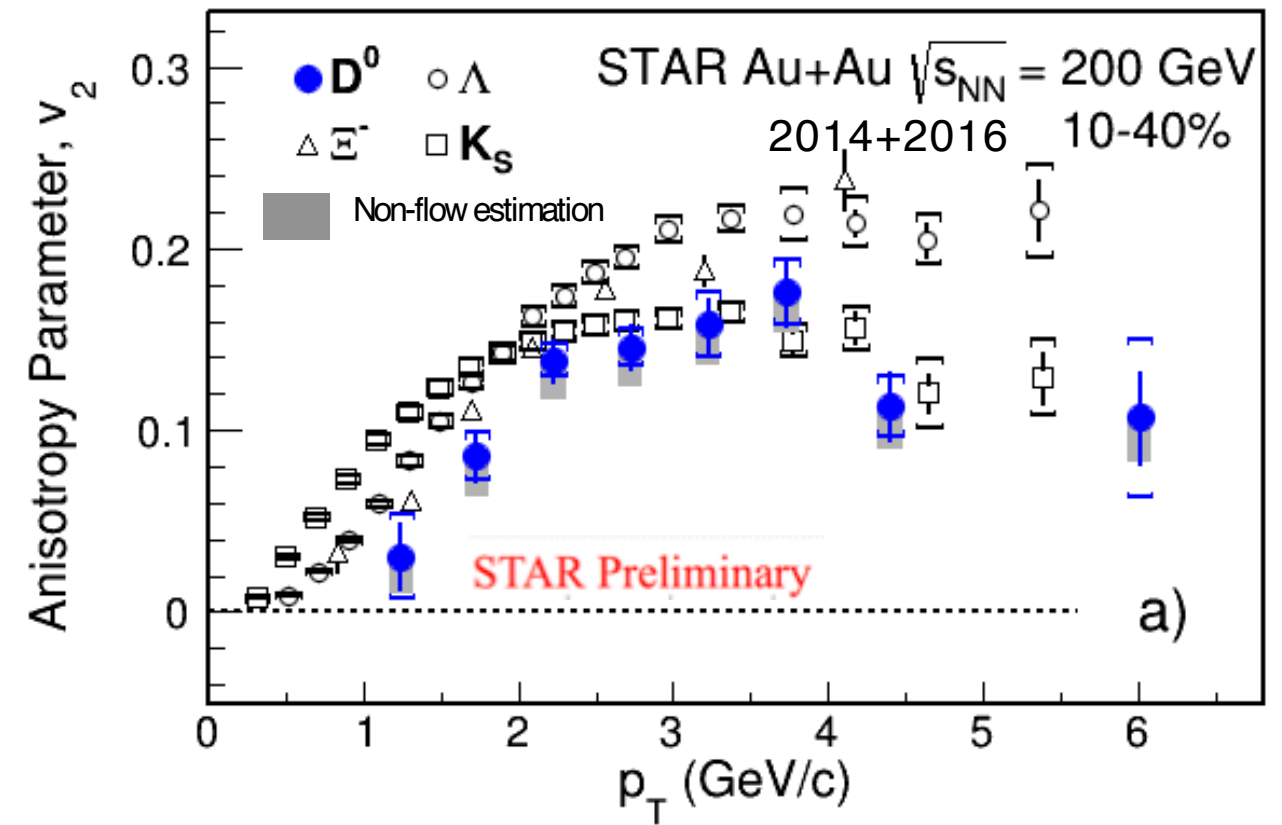
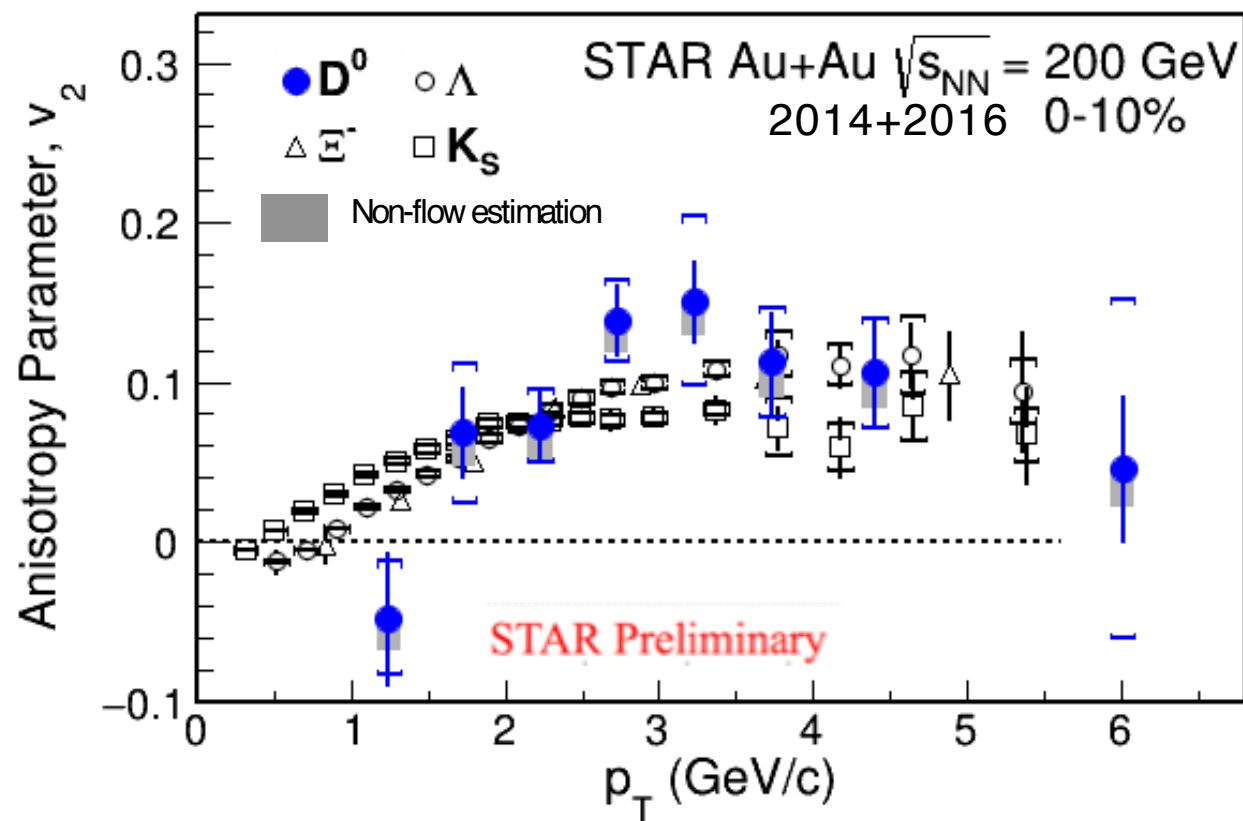
Precise D^0 v_2 measurement can allow:

→ Quantitative studies of QGP properties (transport coefficients)



D⁰ v₂ Comparison to Light Hadrons

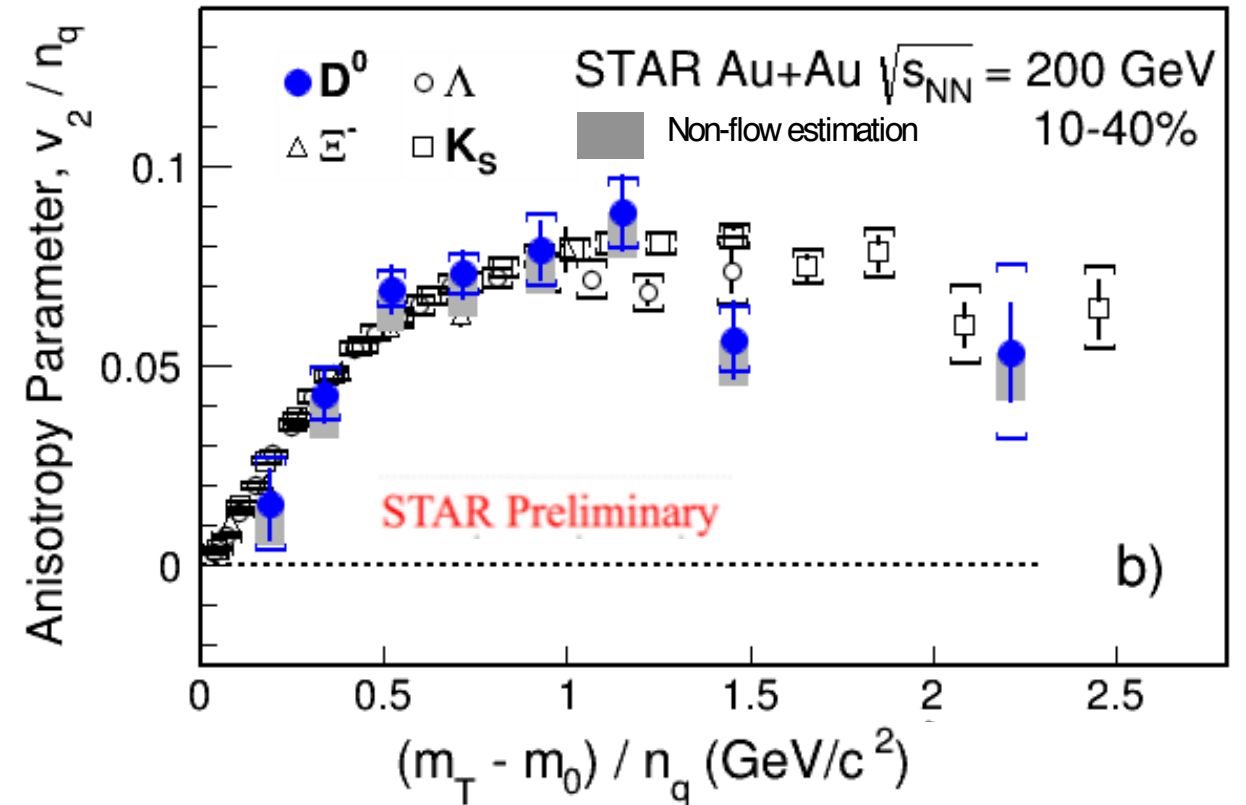
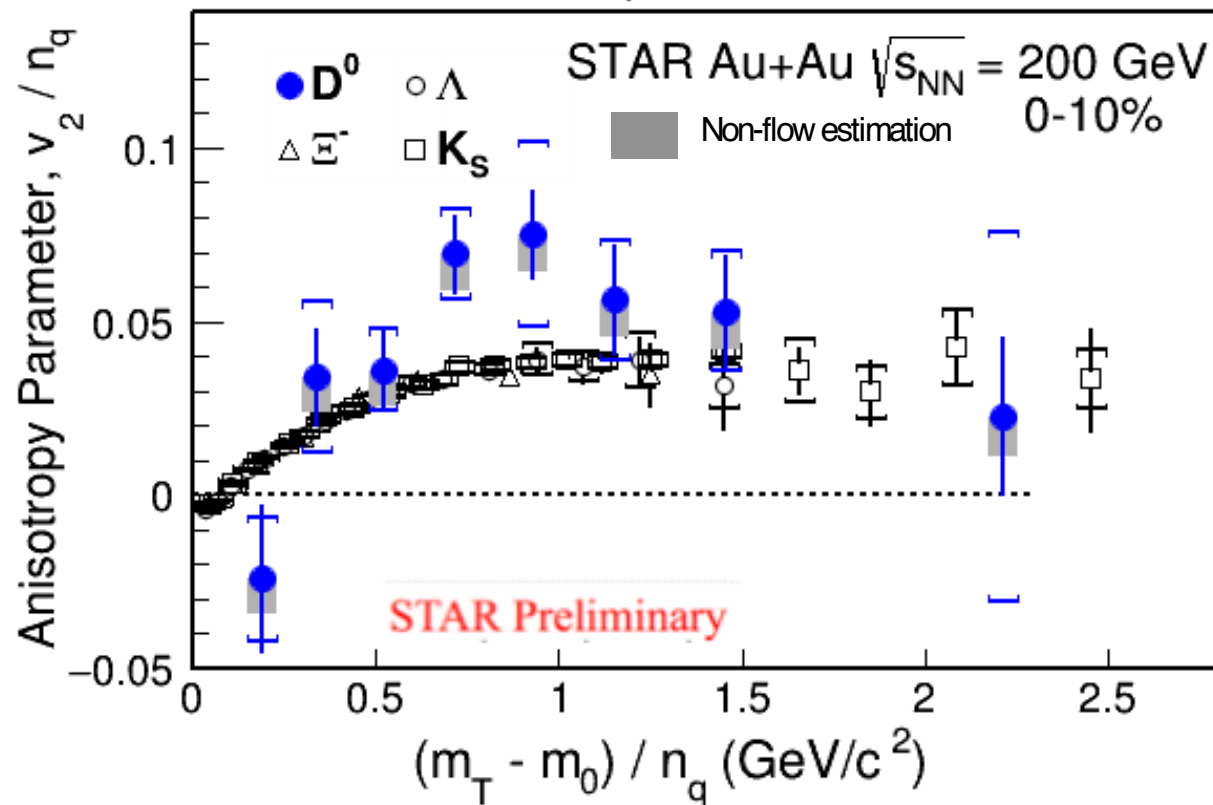
Phys. Rev. C 77, 054901 (2008)



- D⁰ v₂ results from combined 2014 + 2016 data
- D⁰ v₂ measurement extended to 0-10% centrality
- Clear mass ordering for $p_T < 2$ GeV/c in 10-40% centrality
- D⁰ v₂ for $p_T > 2$ GeV/c in 10-40% centrality follows the mesons



NCQ Scaling Test

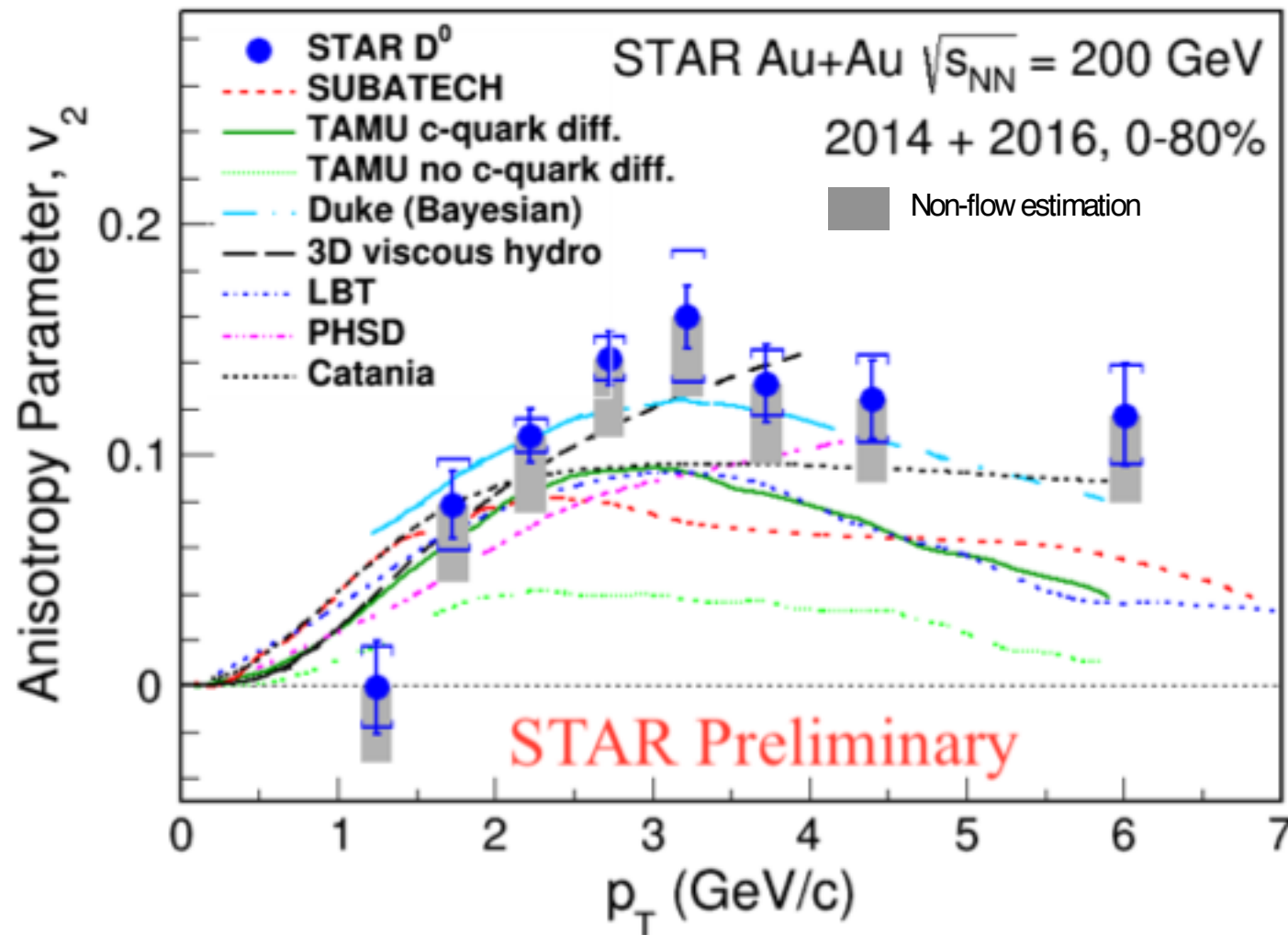


- NCQ scaling test with improved precision in D^0 v_2 measurement
- NCQ-scaled D^0 v_2 consistent with light hadrons for $(m_T - m_0)/n_q < 2.5$ GeV/c² in 10-40%
- Evidence of charm quarks flowing with the medium

Charm quark appear to have achieved thermal equilibrium with the medium



D⁰ v₂: Data vs. Models



Compared Models	x ² /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 x 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* 92, 024907 (2015)
 [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)

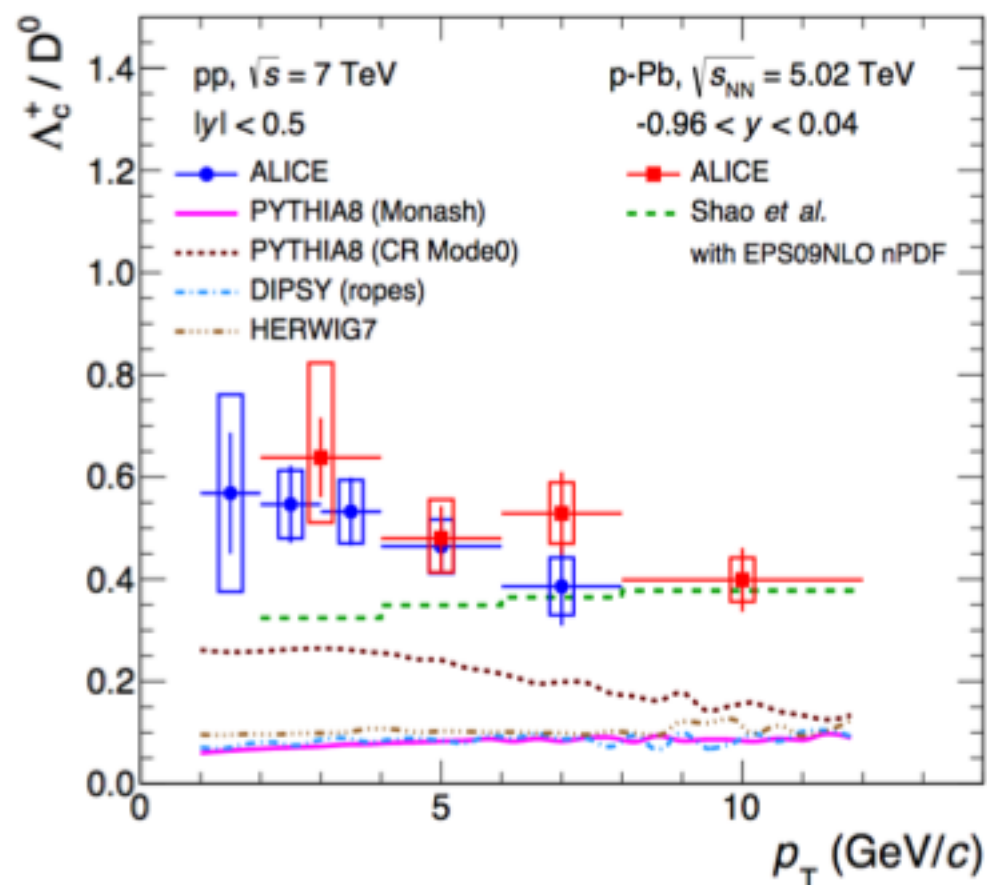
- D⁰ v₂ results from combined 2014 + 2016 data
- Improved precision to constrain the models



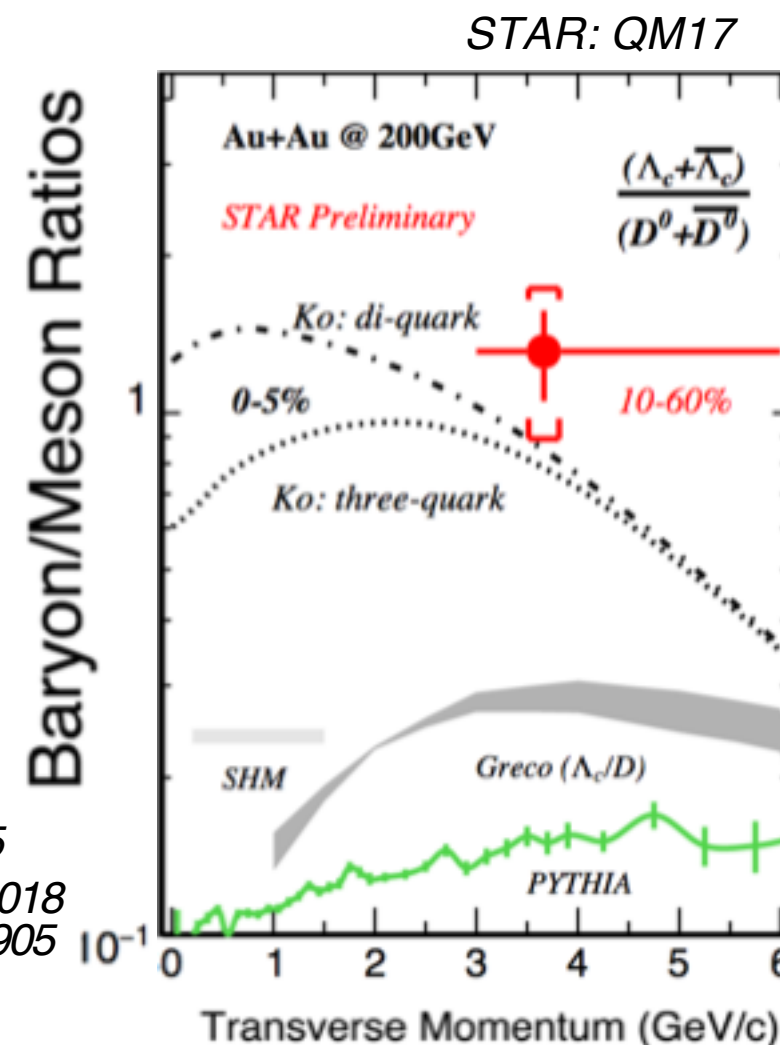
Λ_c and Heavy Flavor Hadronization

- 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

ALICE: arXiv:1712.09581



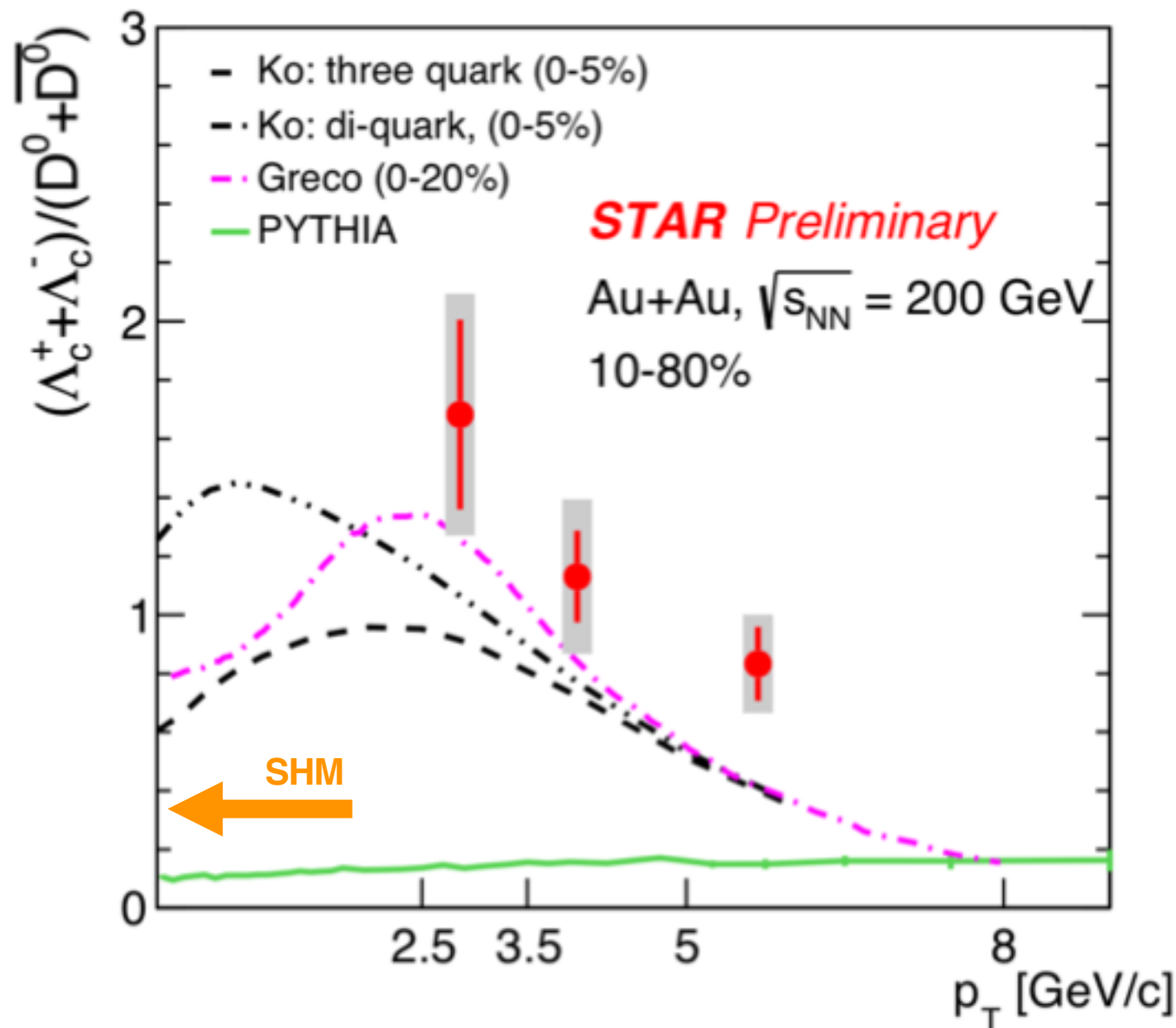
Ko: PRC 79 (2009) 044905
 Greco: PRD 90 (2014) 054018
 SHM: PRC 79 (2009) 044905



- 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

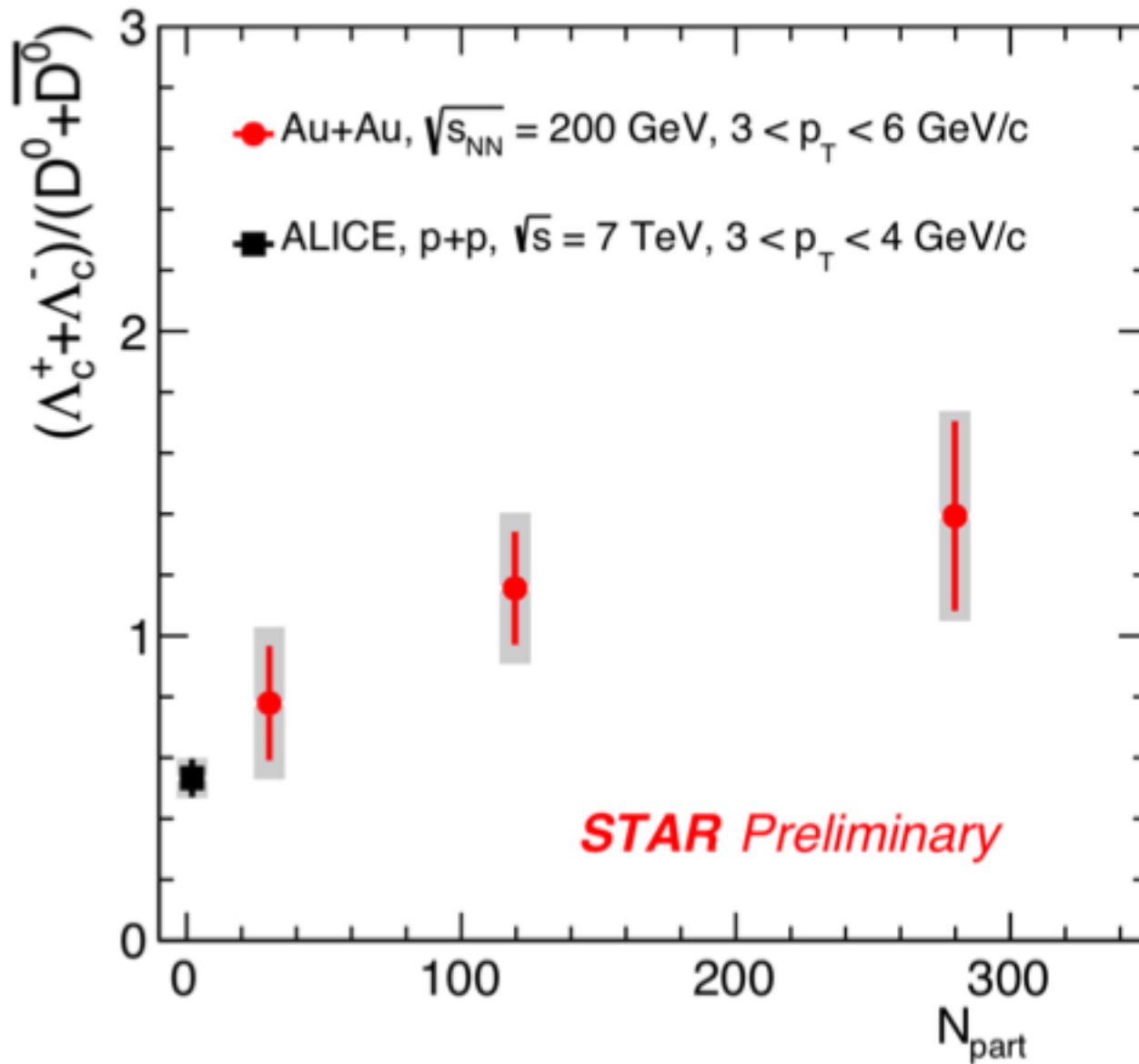


Ko: *Phys.Rev.C* 79 (2009) 044905
 Greco: *Eur.Phys.J.C* (2018) 78:348
 SHM: *Phys.Rev.C* 79 (2009) 044905

- 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



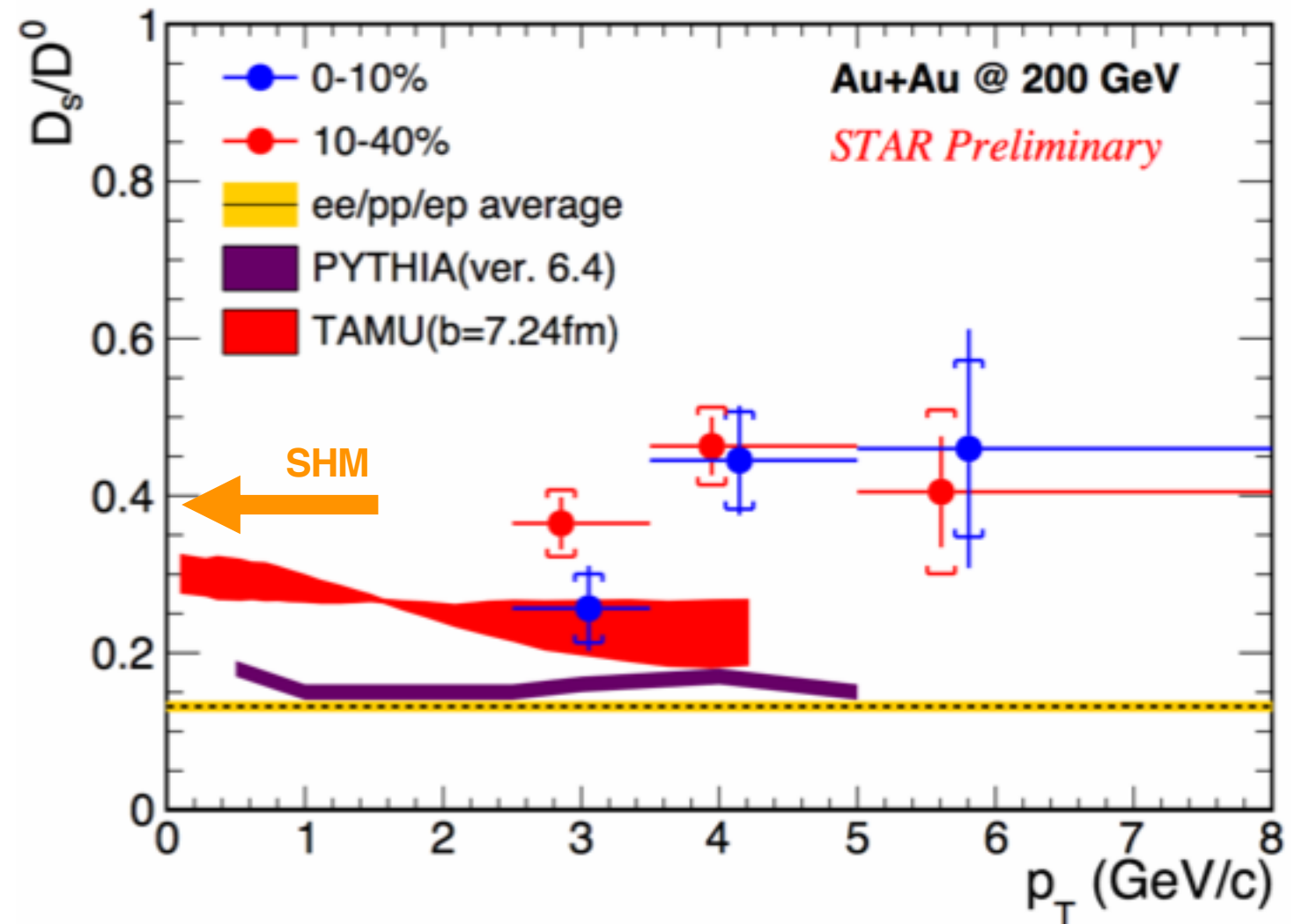
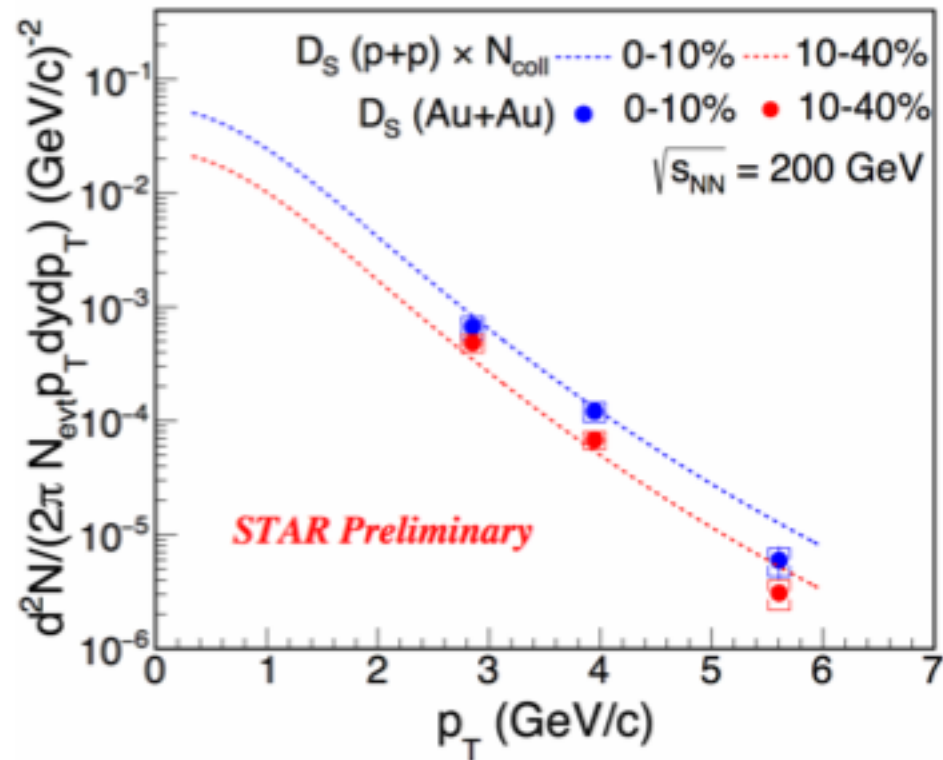
ALICE: arXiv:1712.09581

- 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 p+p values at 7 TeV



D_s Production

- D_s/D⁰ enhancement expected in central A+A collisions, from strangeness enhancement and coalescence hadronization



- D_s yield (relative to D⁰) 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 Lisovsky, et. al. EPJ C 76, 397 (2016)

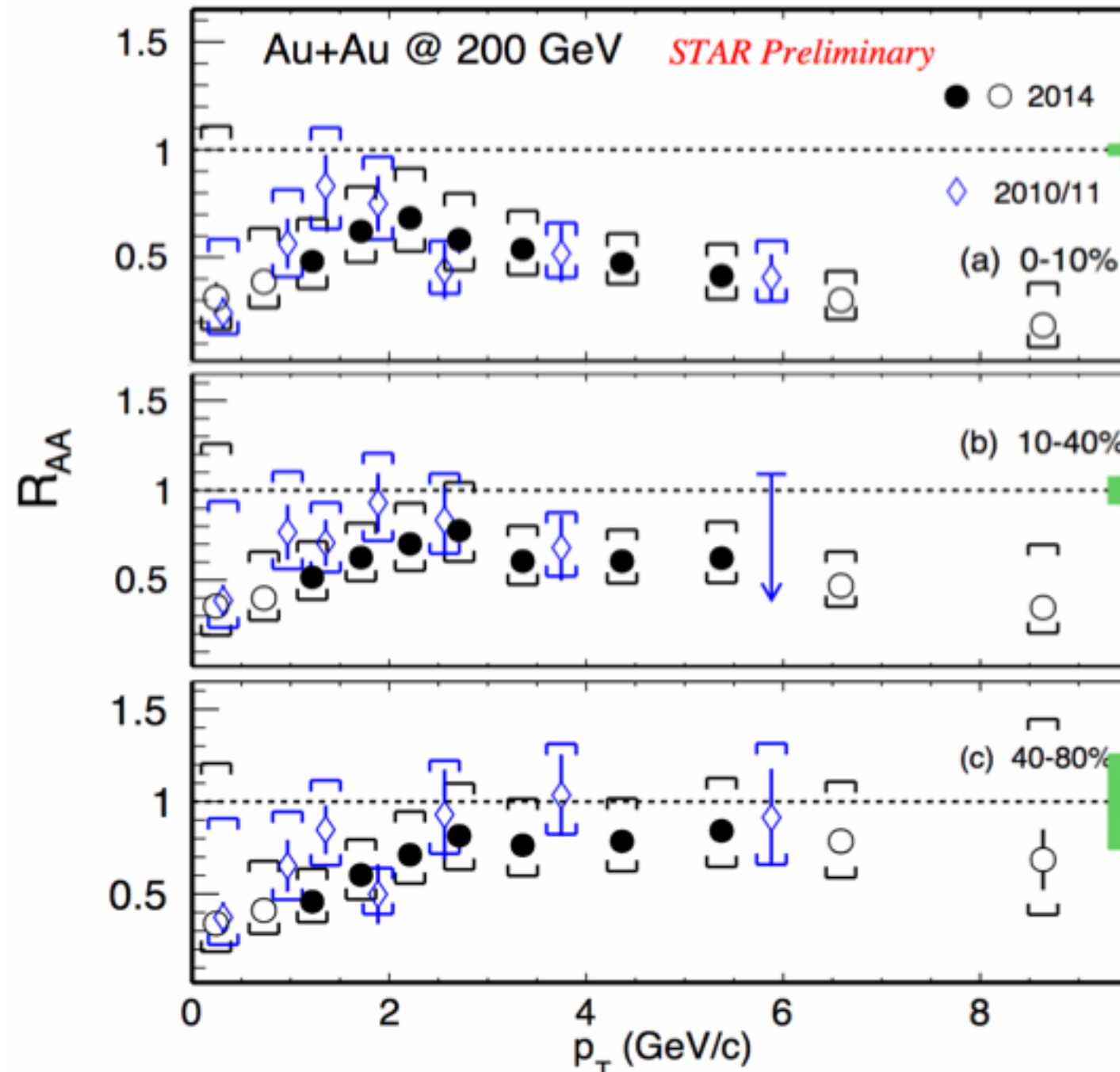
TAMU: H. Min et al. PRL 110, 112301 (2013)

SHM: A. Andronic et al., PLB 571 (2003) 36



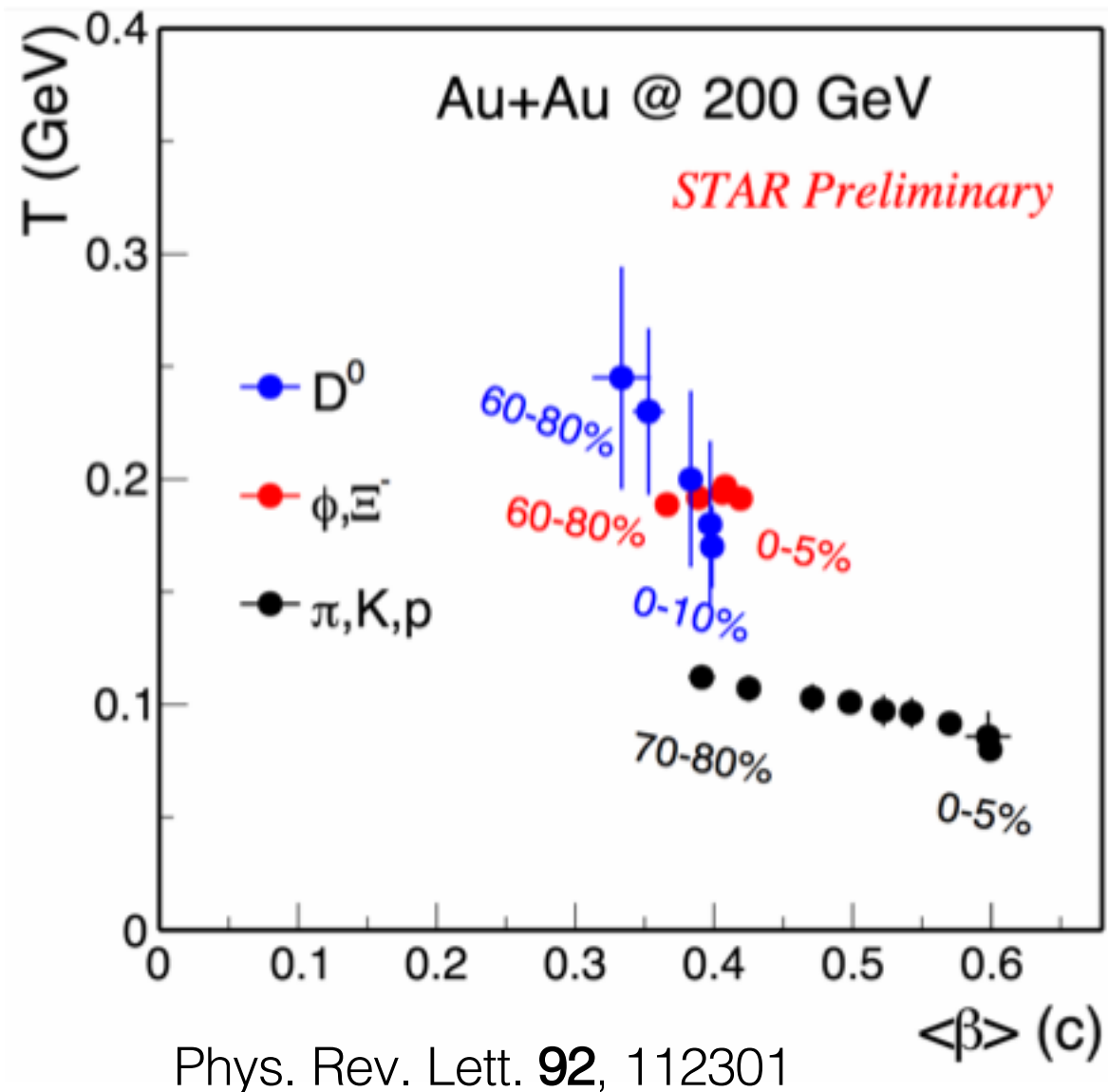
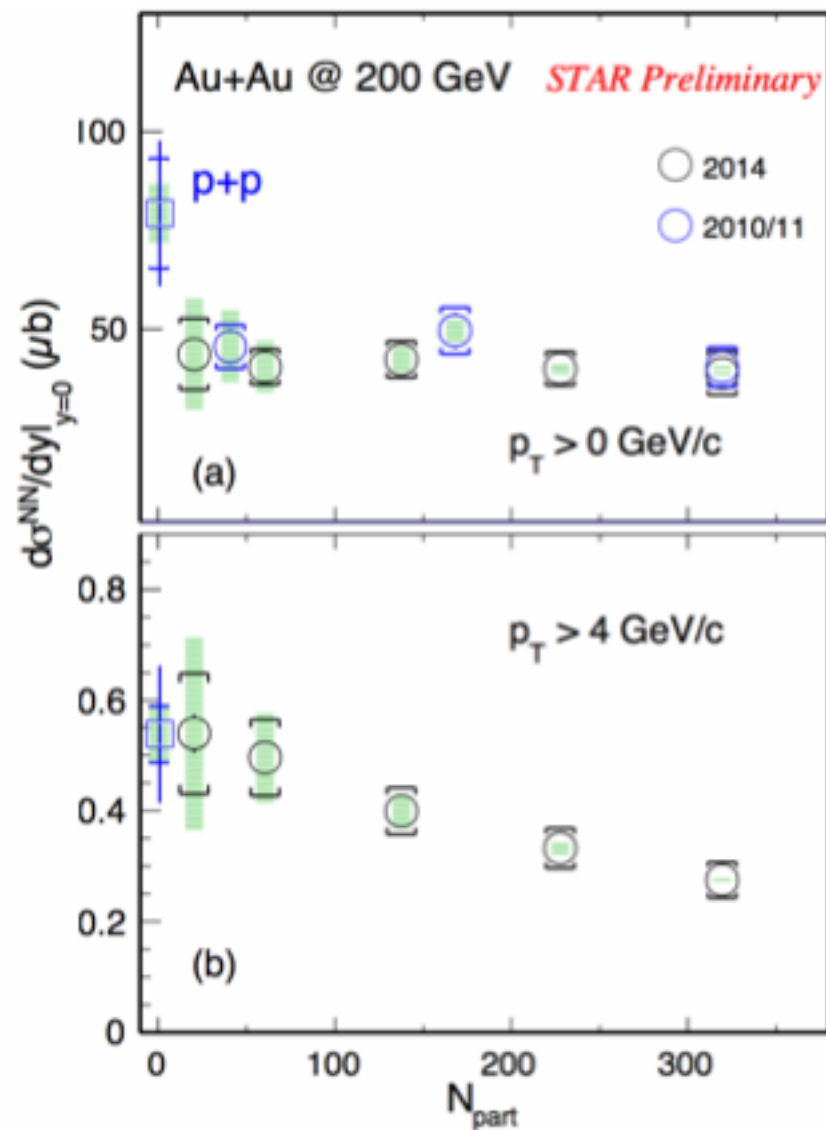
D⁰ Spectra and R_{AA}

- Updated results from STAR for D⁰ 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

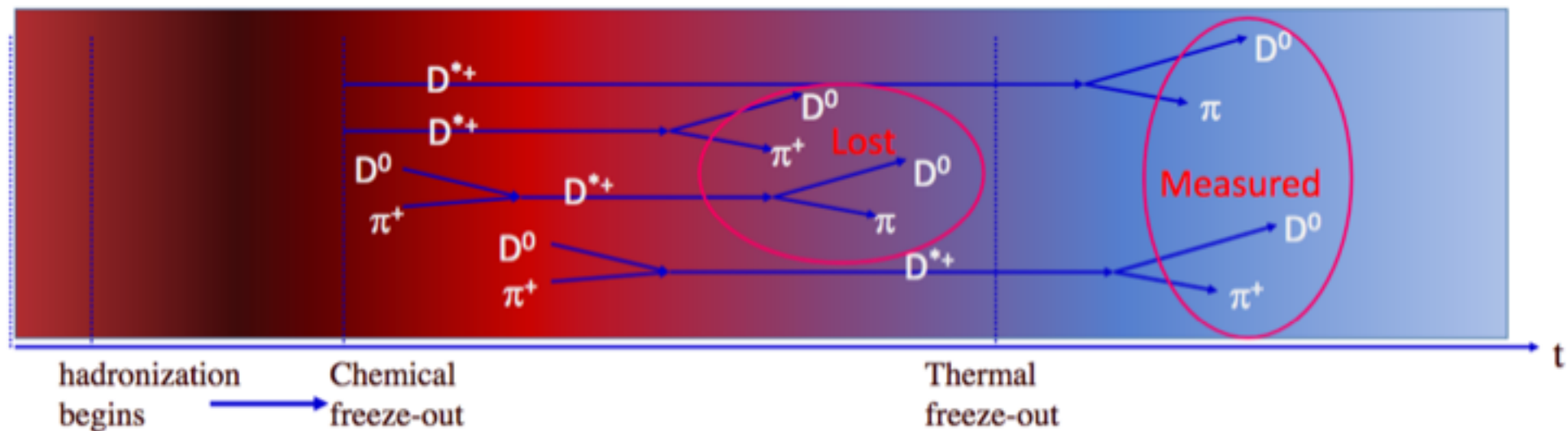
D⁰ Cross-section and BW Fits to Spectra



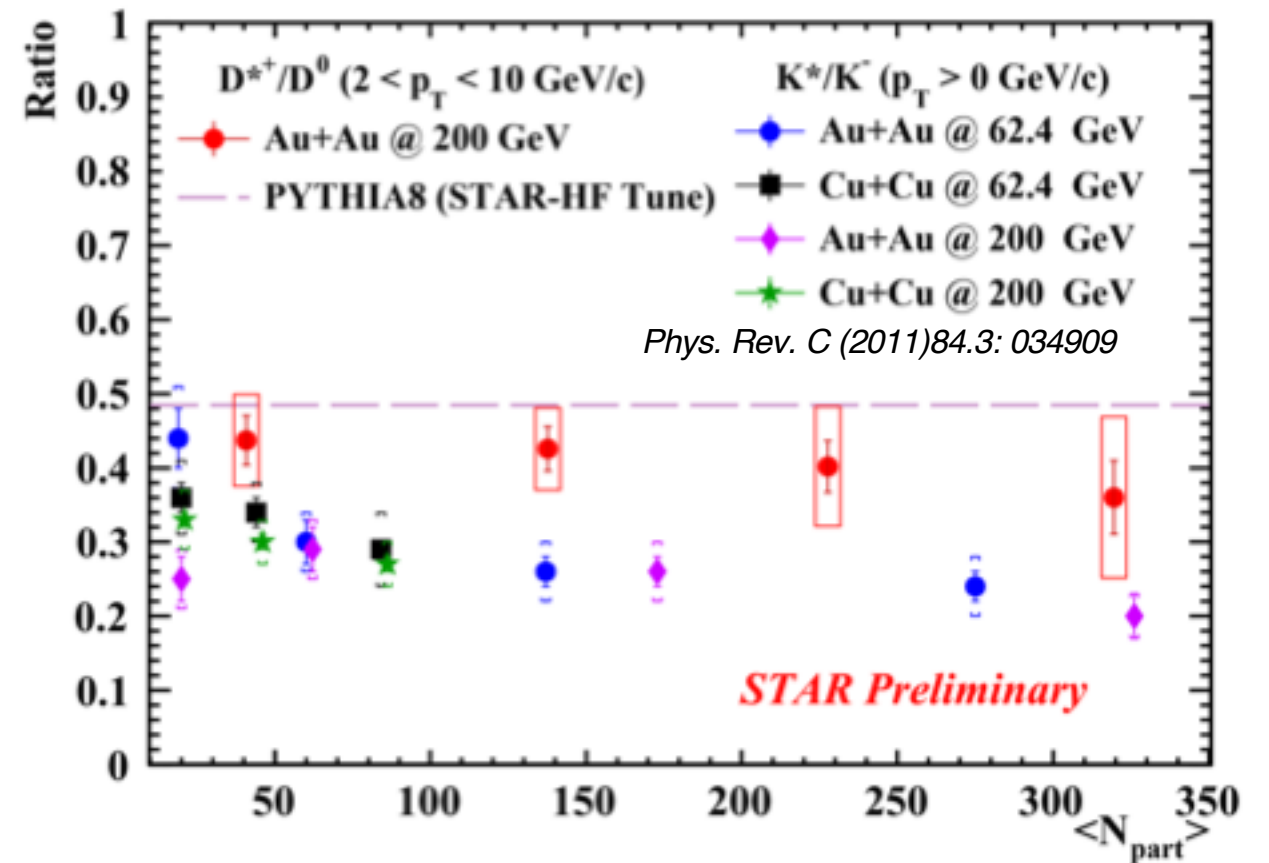
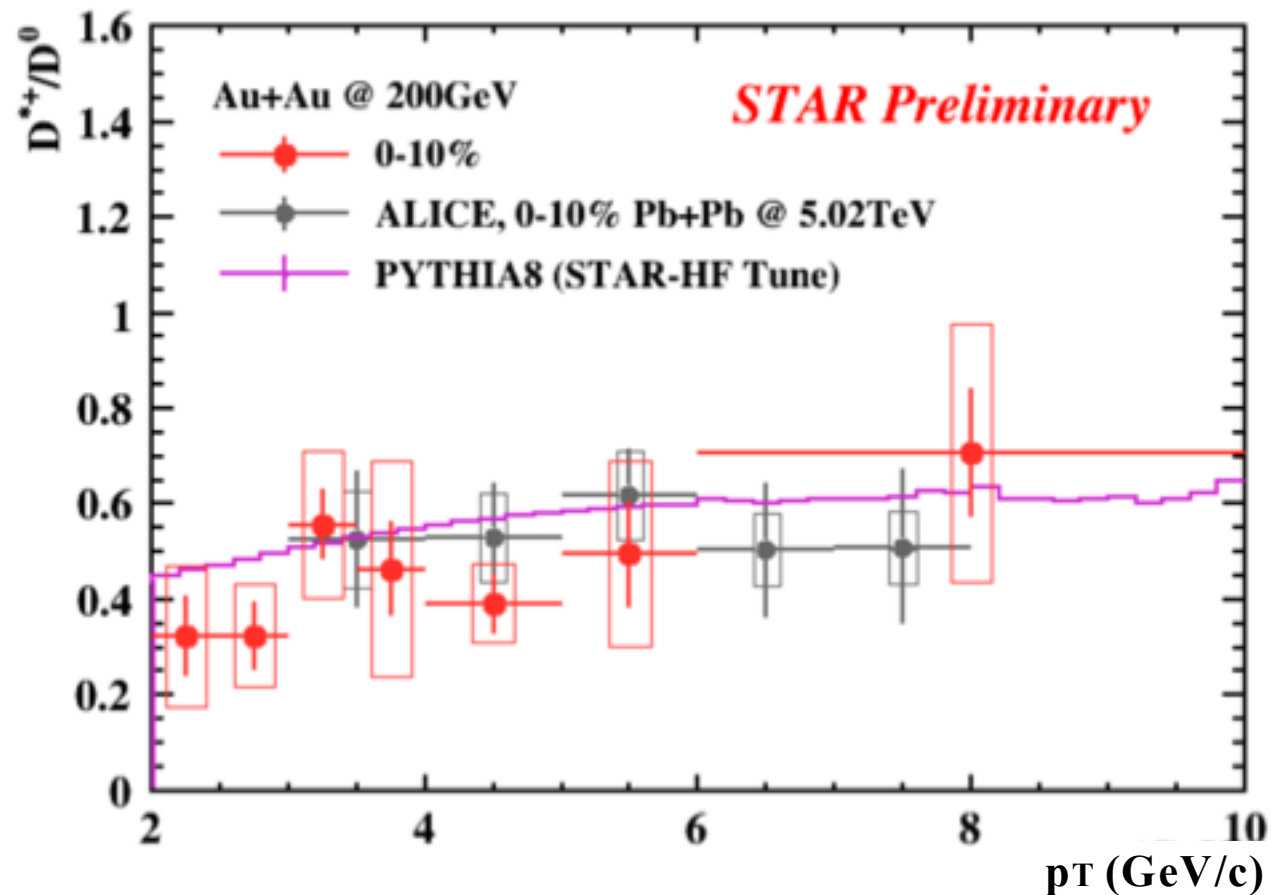
- Total D⁰ cross-section is nearly independent of centrality, and smaller than in p+p. However, decreases towards central collisions for $p_T > 4$ GeV/c
- Blast Wave fits to D⁰ spectra:
 - BW fits to $p_T < 5$ GeV/c. Both standard and Tsallis BW fits tried
 - Result suggest an earlier freeze-out for D⁰ than light 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*⁺/D⁰ 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 $d\sigma/dy$ (μb)
Au+Au 200 GeV (10-40%)	D^0	$41 \pm 1 \pm 5$
	D^+	$18 \pm 1 \pm 3$
	D_s^+	$15 \pm 1 \pm 5$
	Λ_c^+	$78 \pm 13 \pm 28^*$
	Total	$152 \pm 13 \pm 29$
p+p 200 GeV	Total	$130 \pm 30 \pm 26$

* 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 STAR**
 - 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 systematic 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

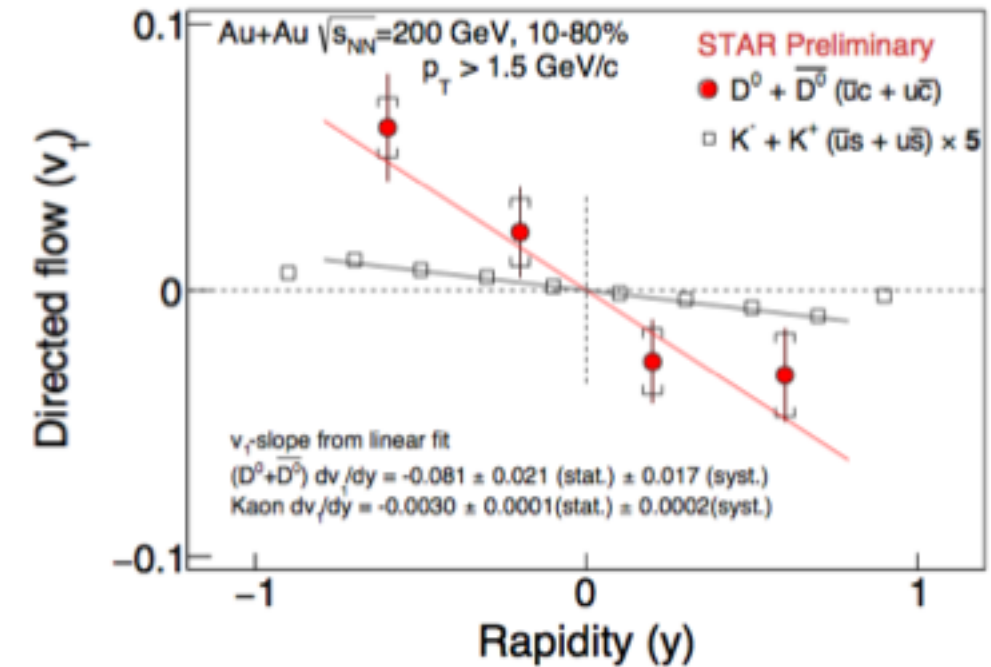




Summary

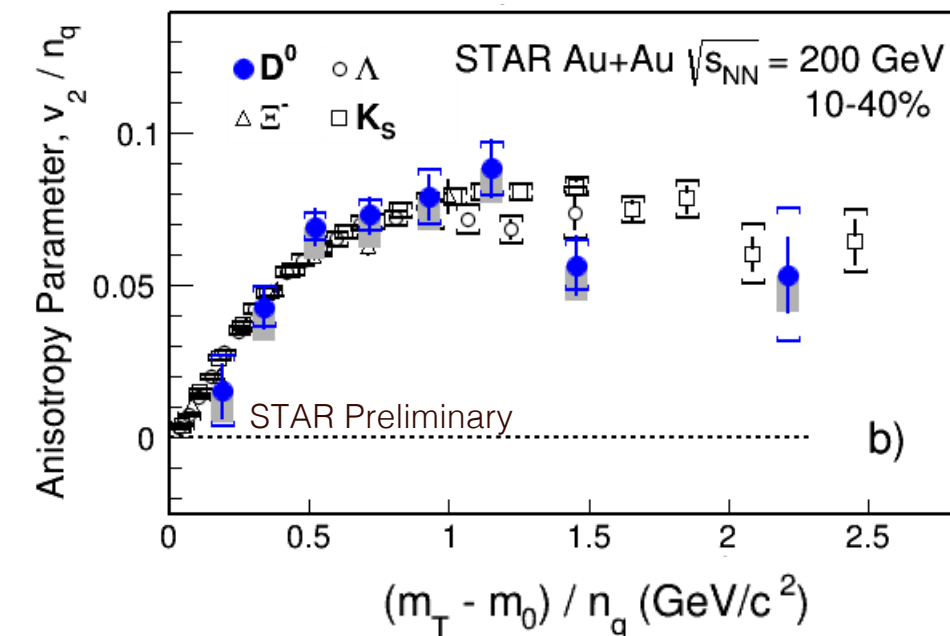
Directed flow

- First evidence of non-zero directed flow for heavy flavor
- Both D^0 and \bar{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



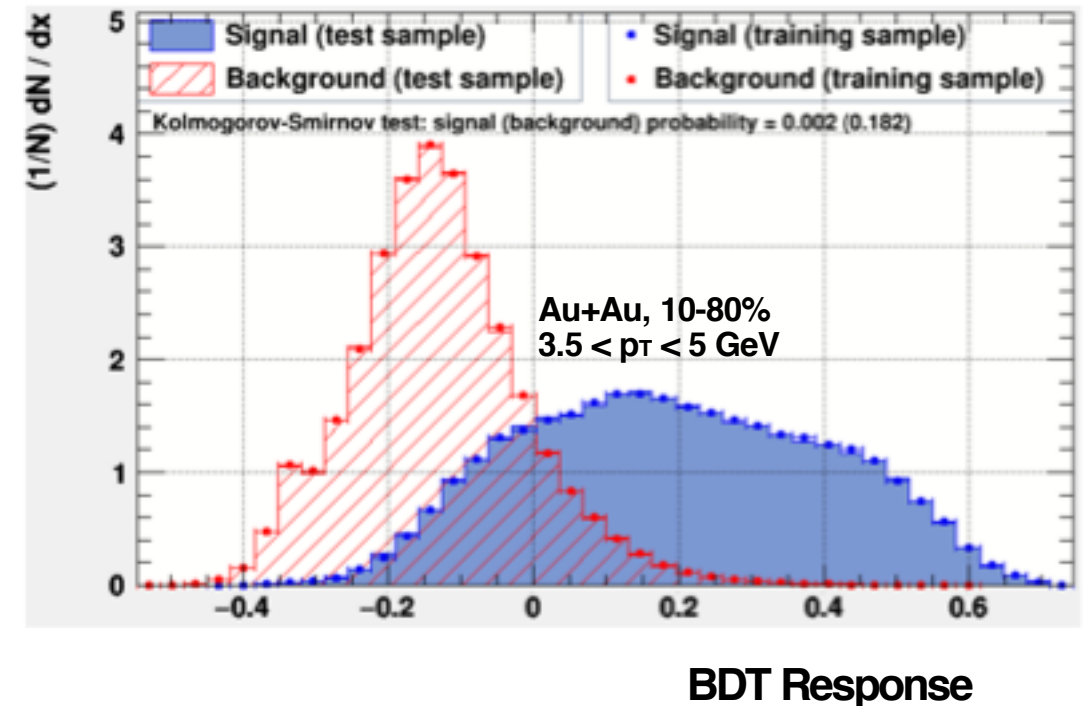
Elliptic flow

- 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

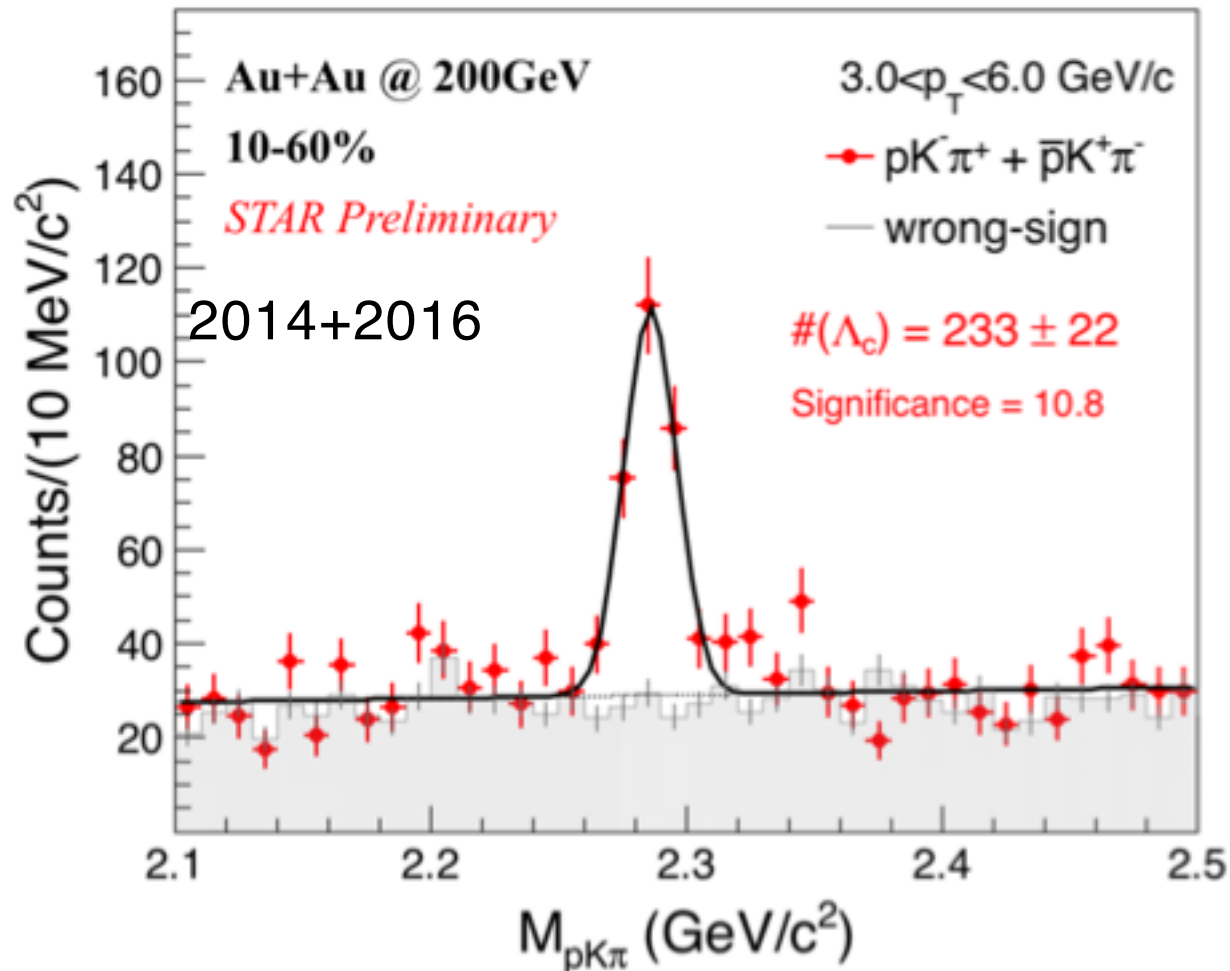
- Simple cuts on variables have limitations on signal-background separation
- Supervised learning algorithms can do better!
 - Boosted Decision Trees: successive binary cuts on attributes
 - Good performance for classification problems
 - 7 topological variables as input
 - For training: signal from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



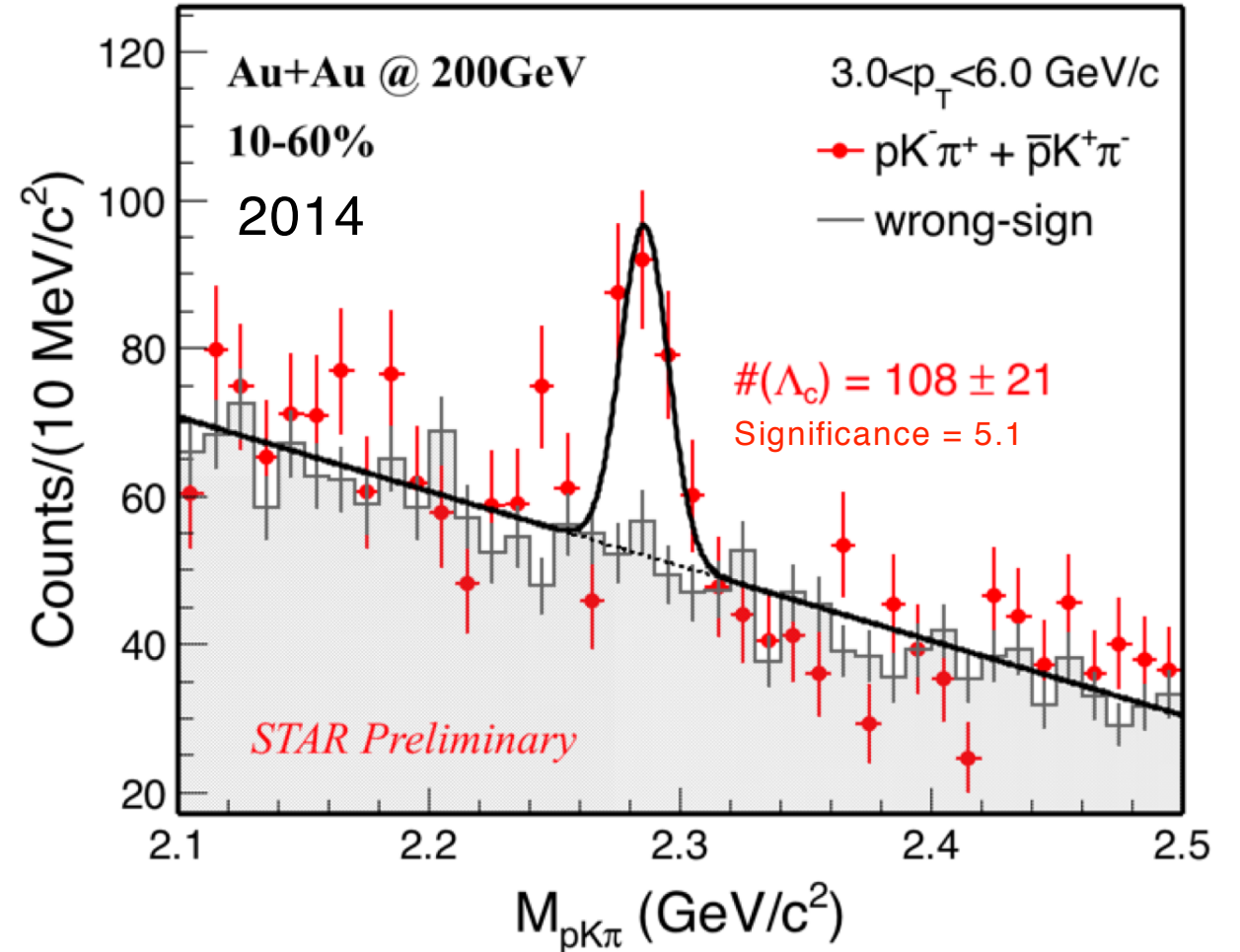
Boosted Decision Trees (BDT) for Λ_c Signal Extraction

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

QM18



QM17

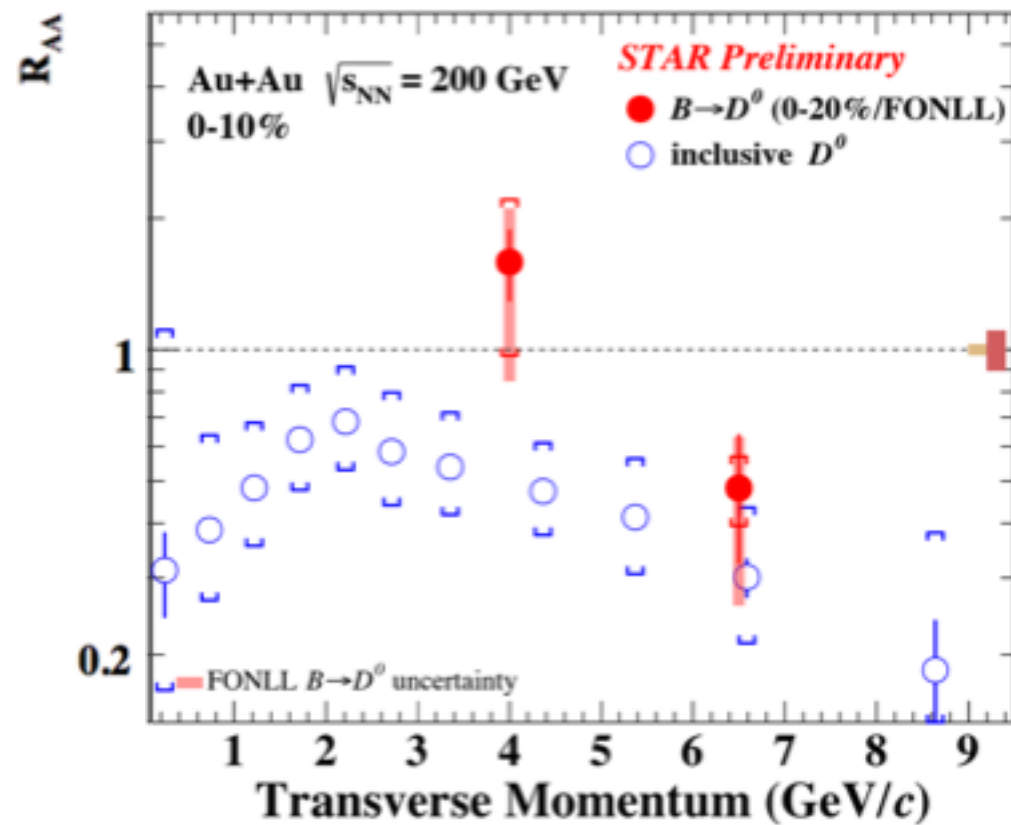


- More than 50% improvement in signal significance with TMVA BDT.
- Also new data from 2016 \rightarrow Effectively 4x more data compared to QM17



Non-prompt D^0

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

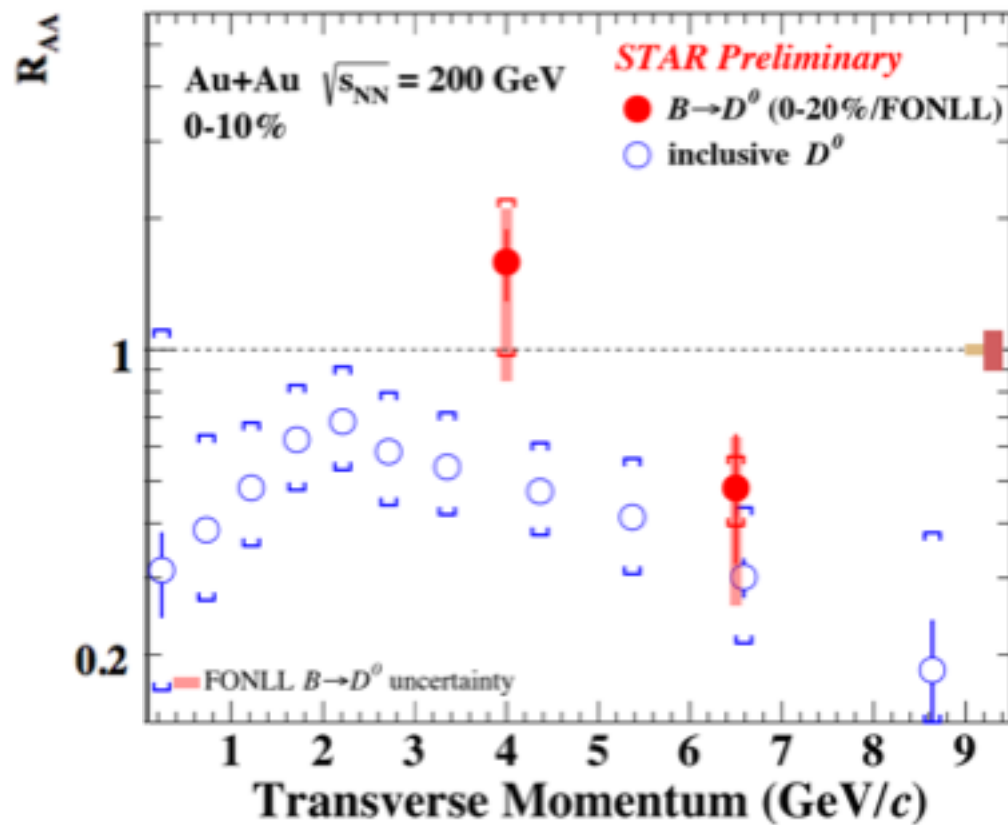


- R_{AA} of B mesons estimated from the measured non-prompt D^0 fraction
- Need better statistics and improved precision to understand mass dependence of energy loss.

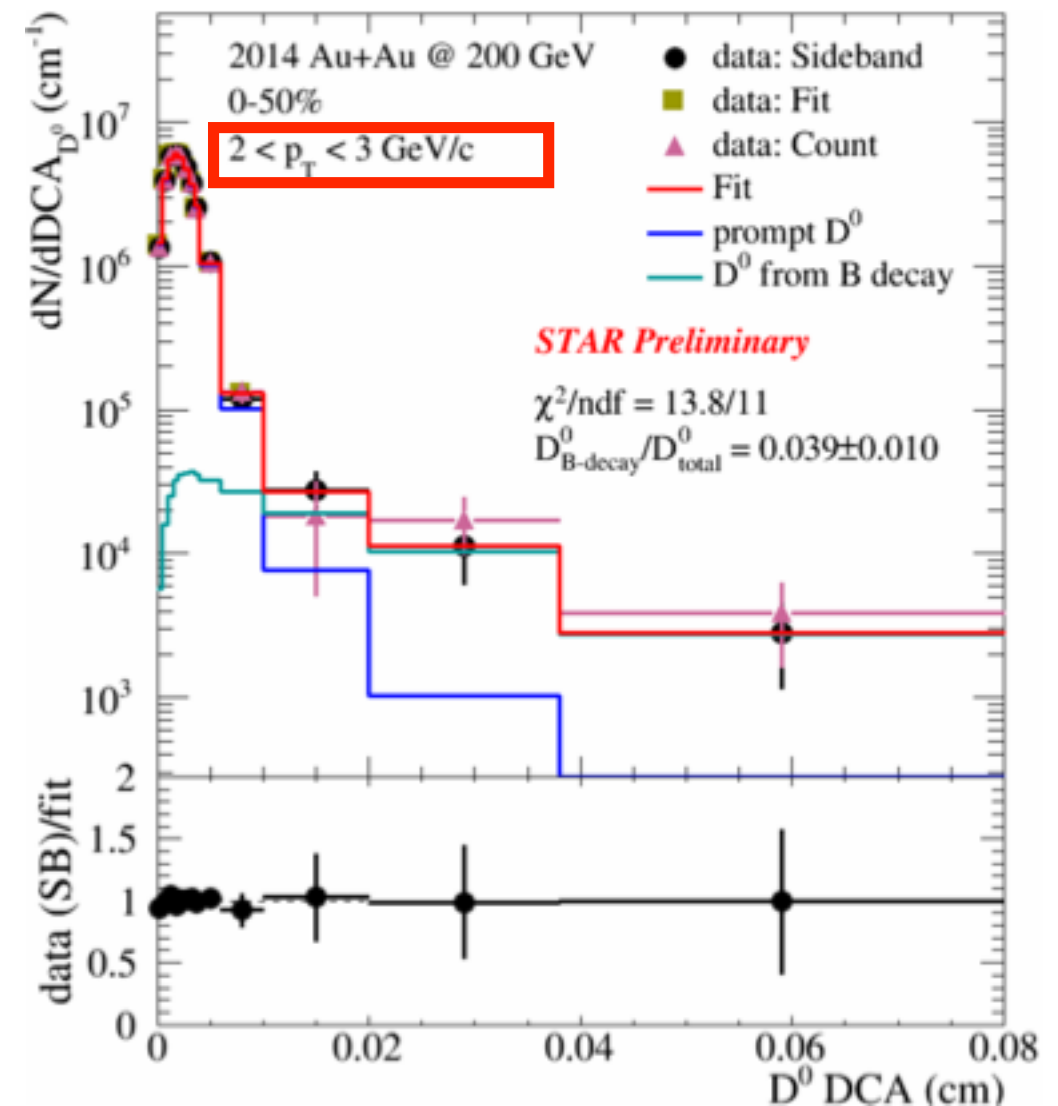
Non-prompt D^0

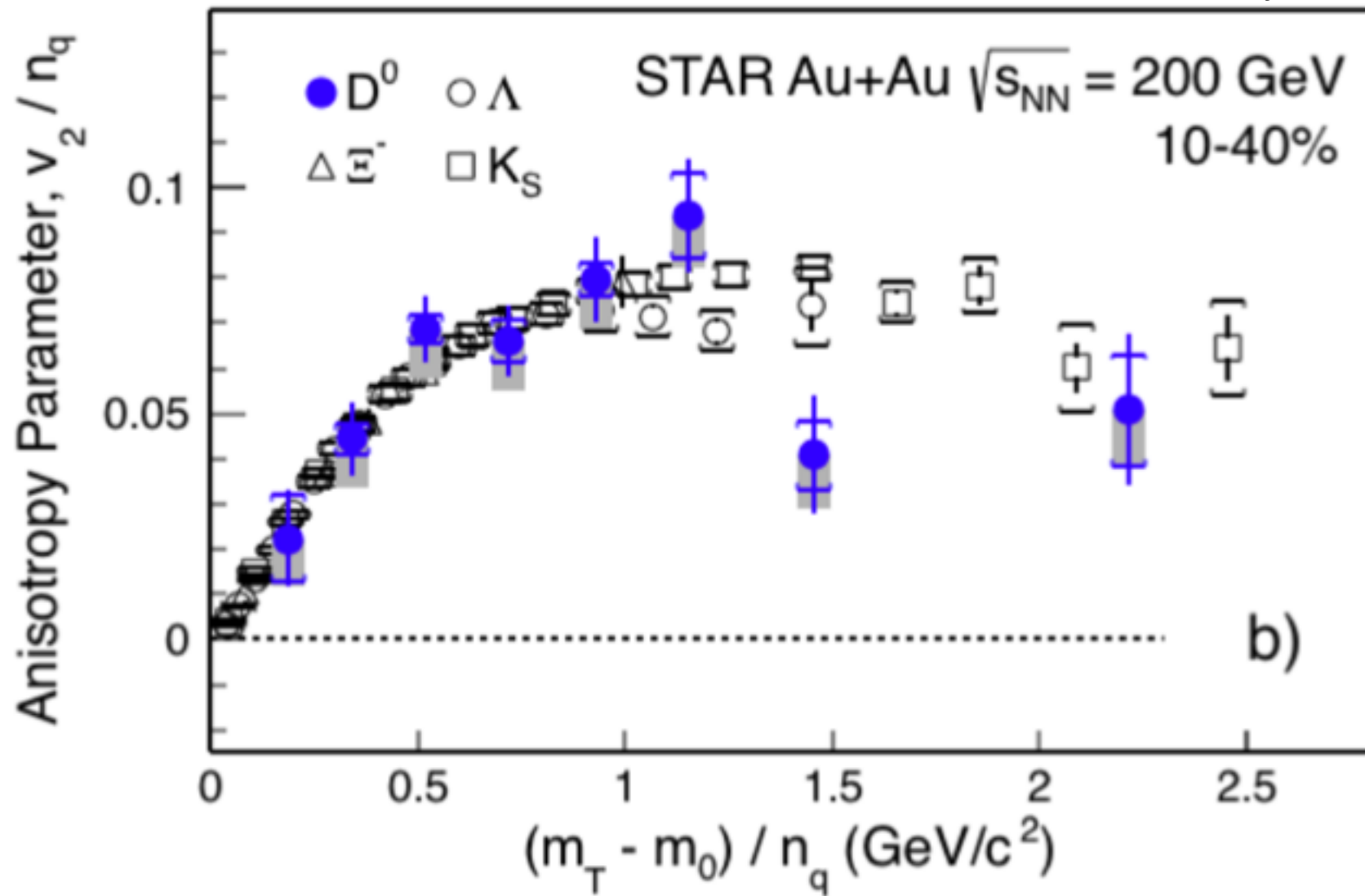
- Charm quarks interact strongly with the medium. How about bottom?
- Is there mass hierarchy for energy loss? Is $\Delta E_c > \Delta E_b$?

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



- 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.





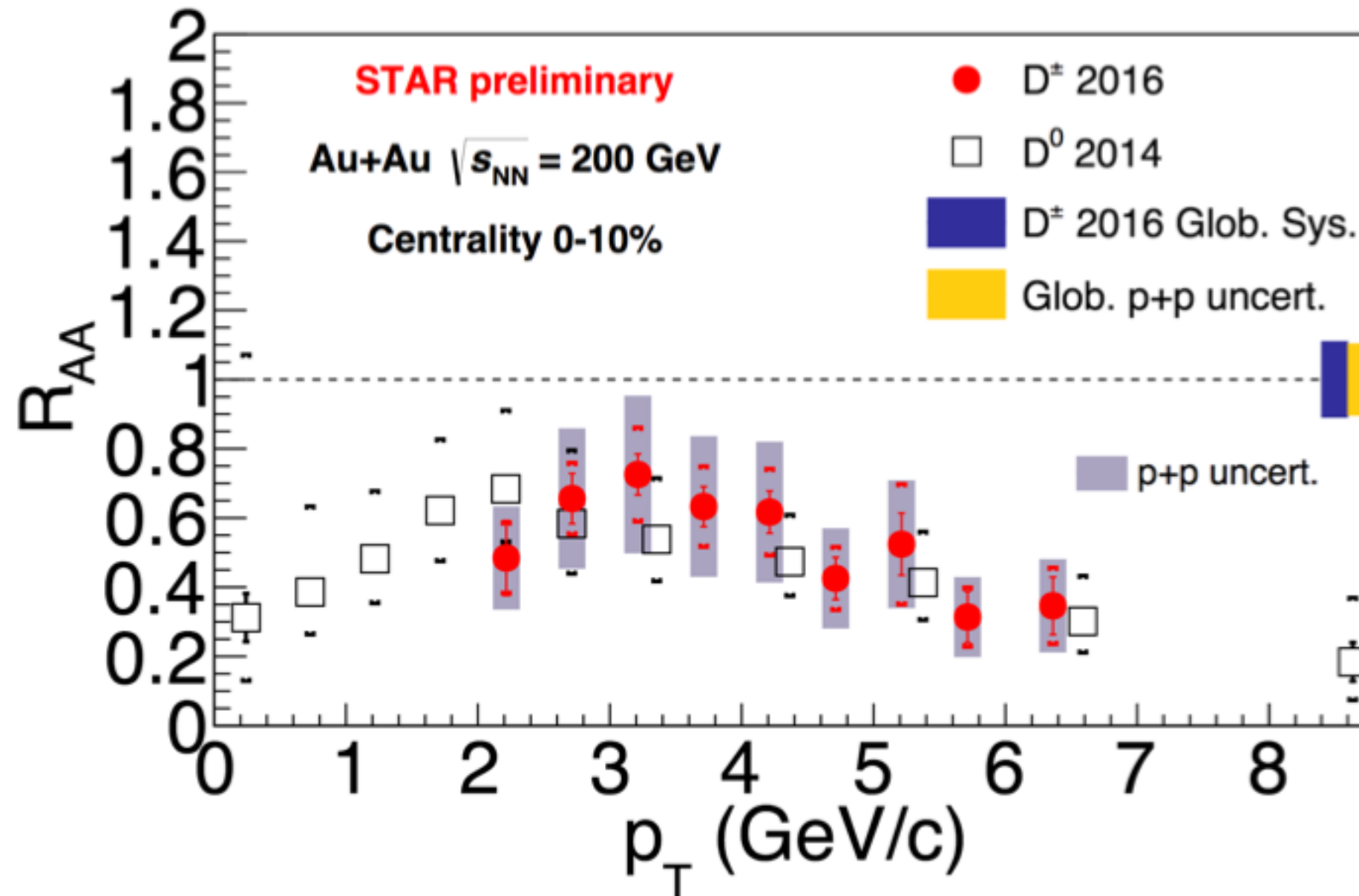
Charm quarks seem to acquire the same flow as light quarks!



Back Up II



D^{+/-} R_{AA}



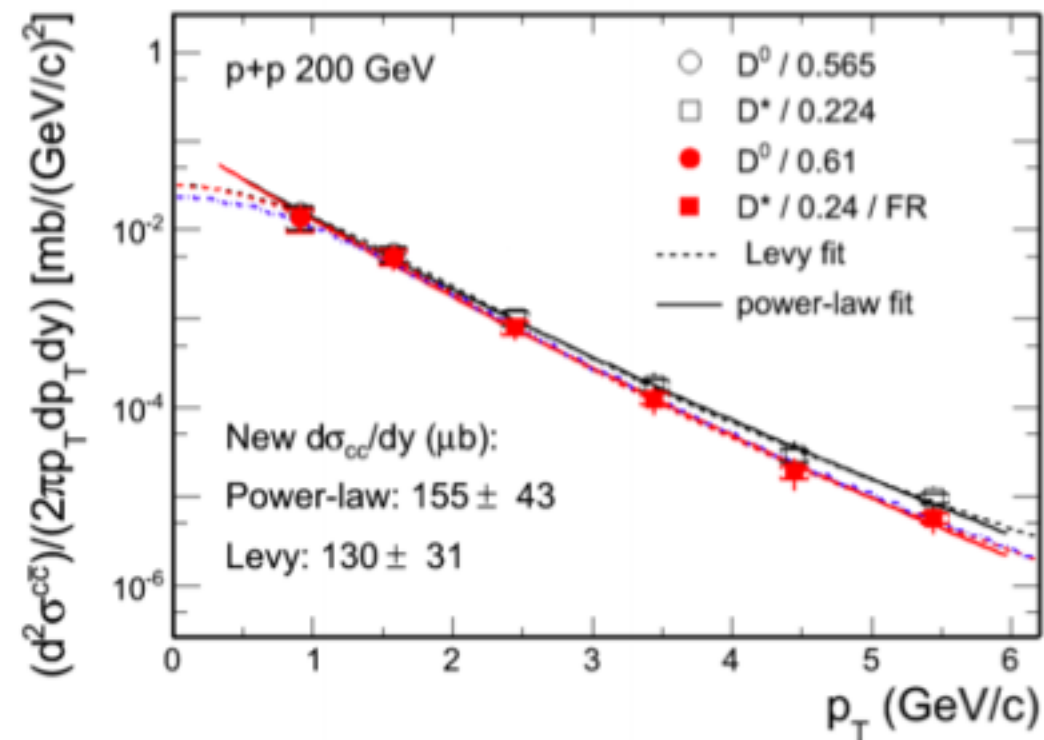
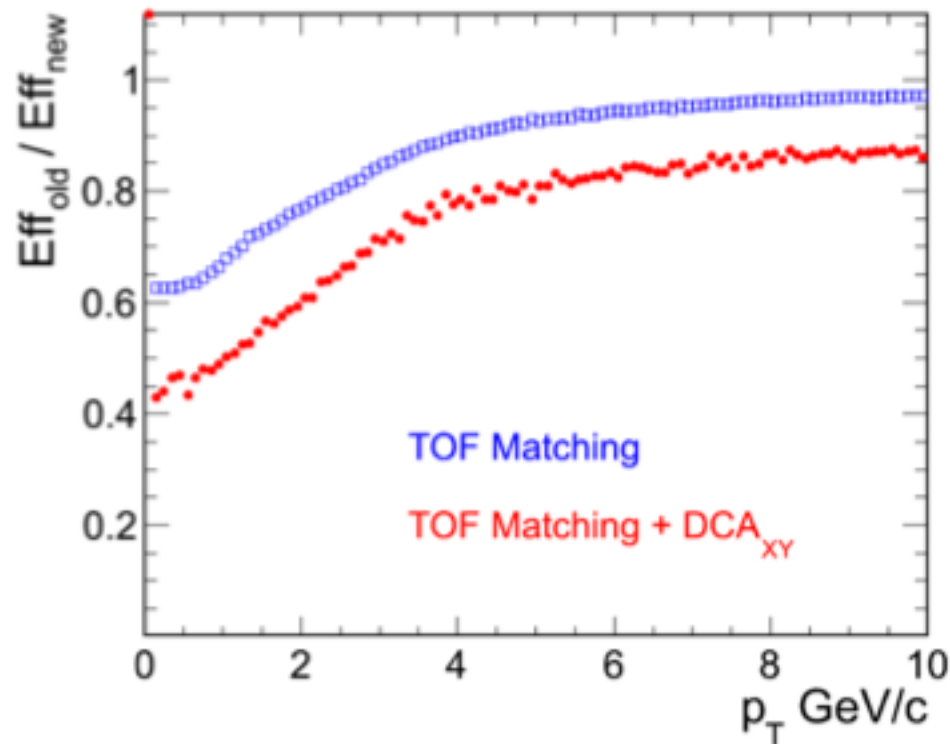
- Similar suppression for D⁰ and D^{+/-}
- Spectra measurements important for total charm cross-section



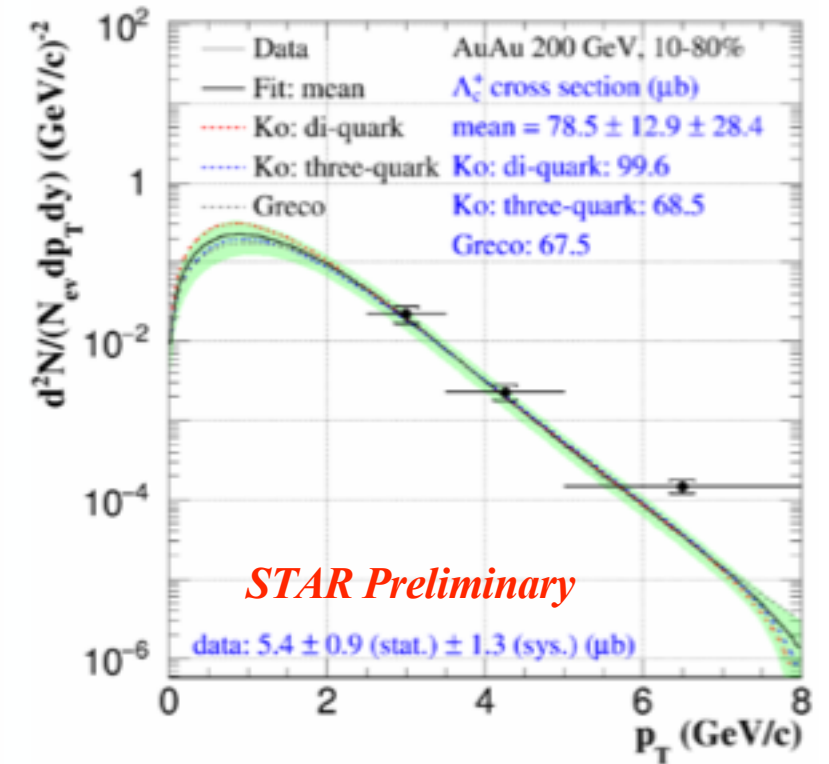
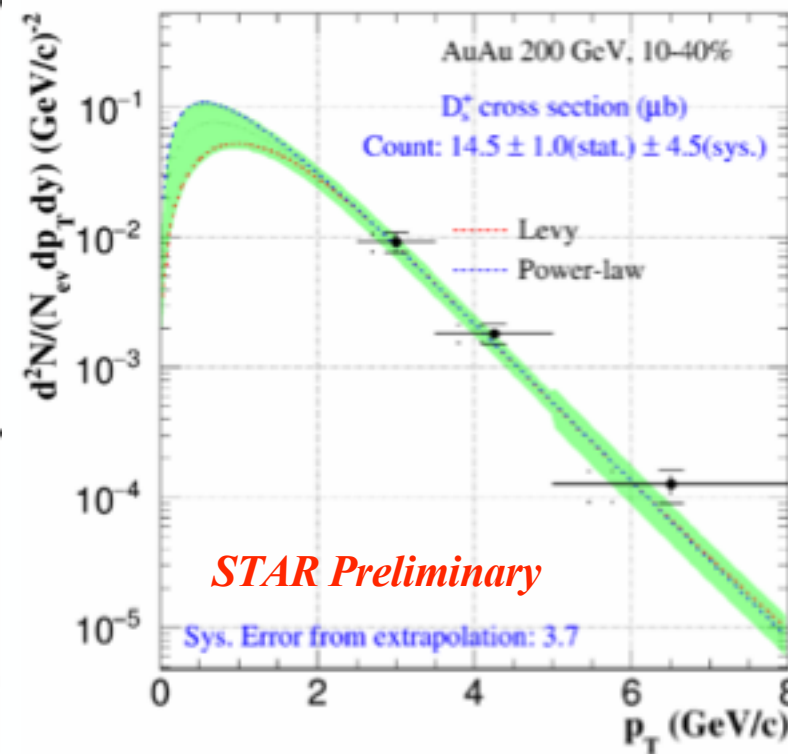
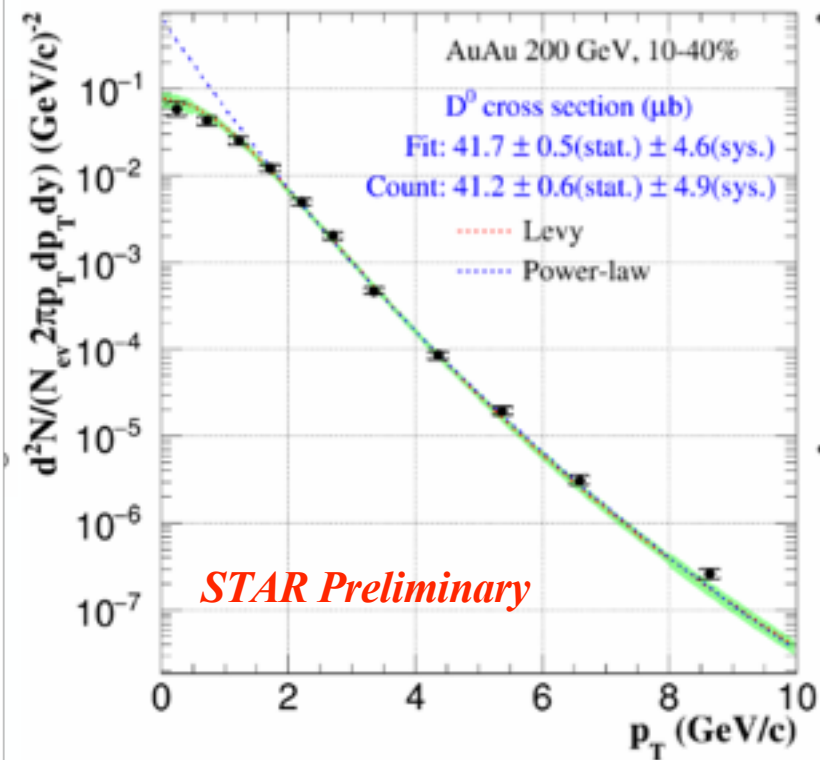
Erratum details

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

- 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
- 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 $c \rightarrow D^0$ and $c \rightarrow D^*$ frag. ratios



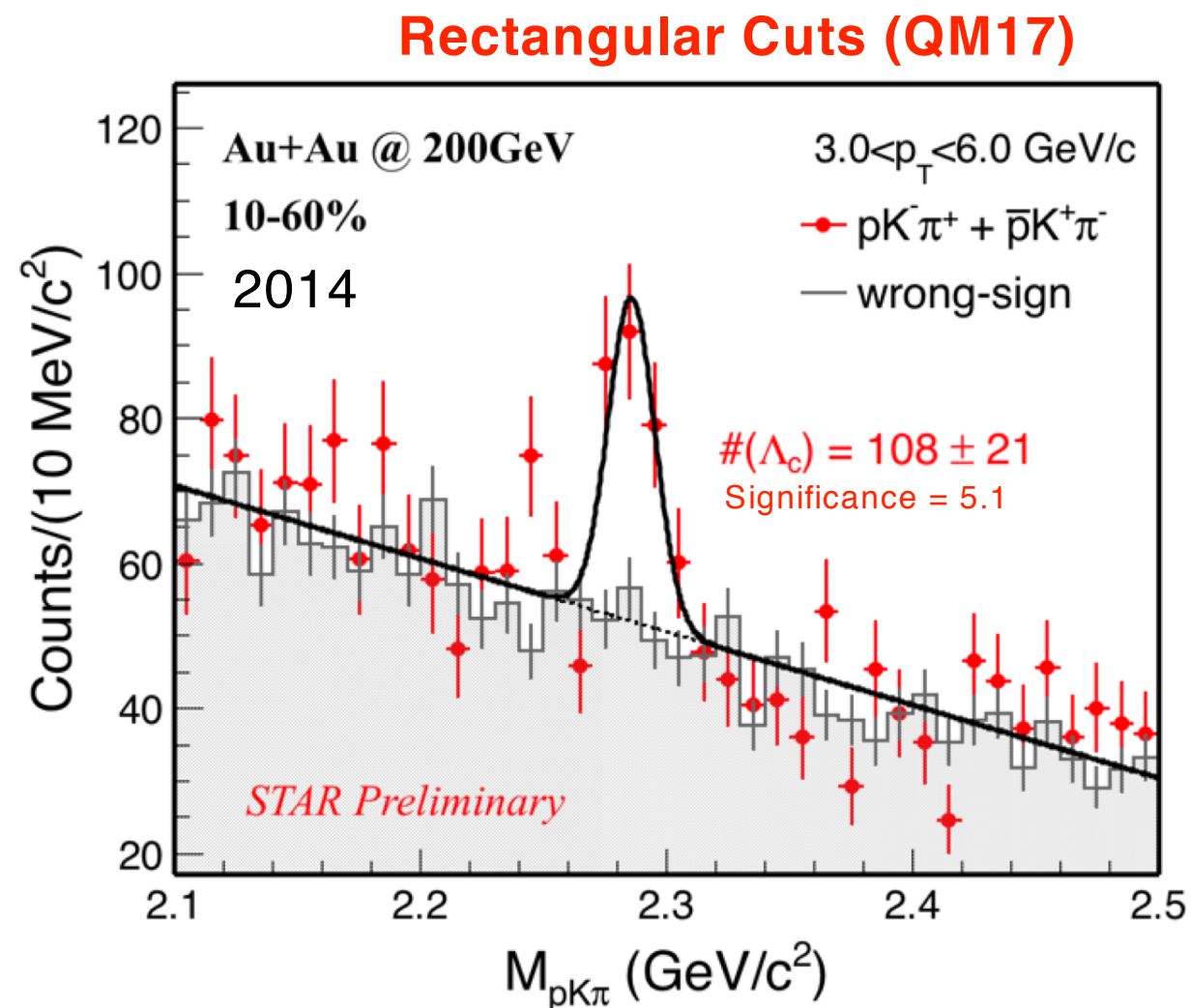
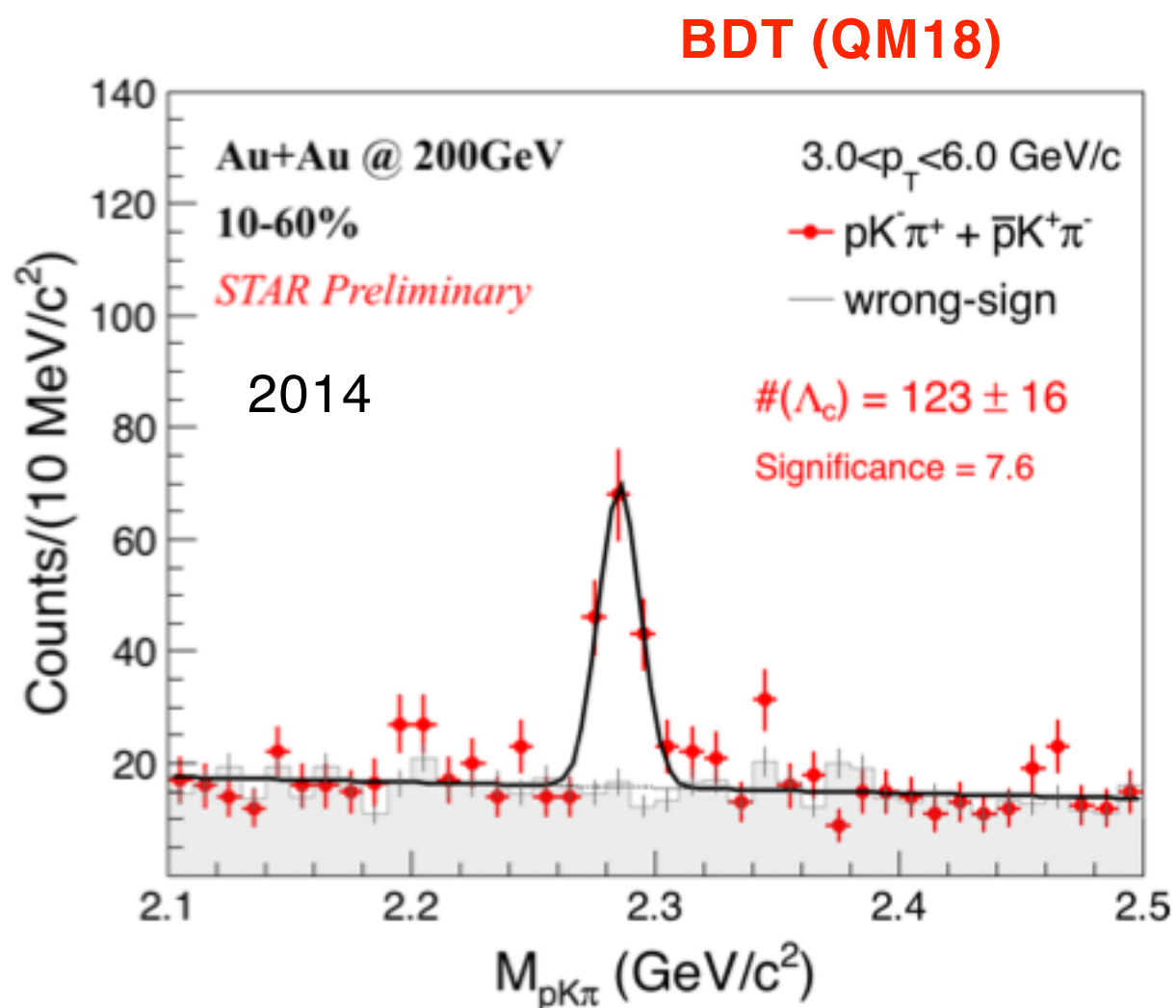
Total charm cross-section: procedure



- 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

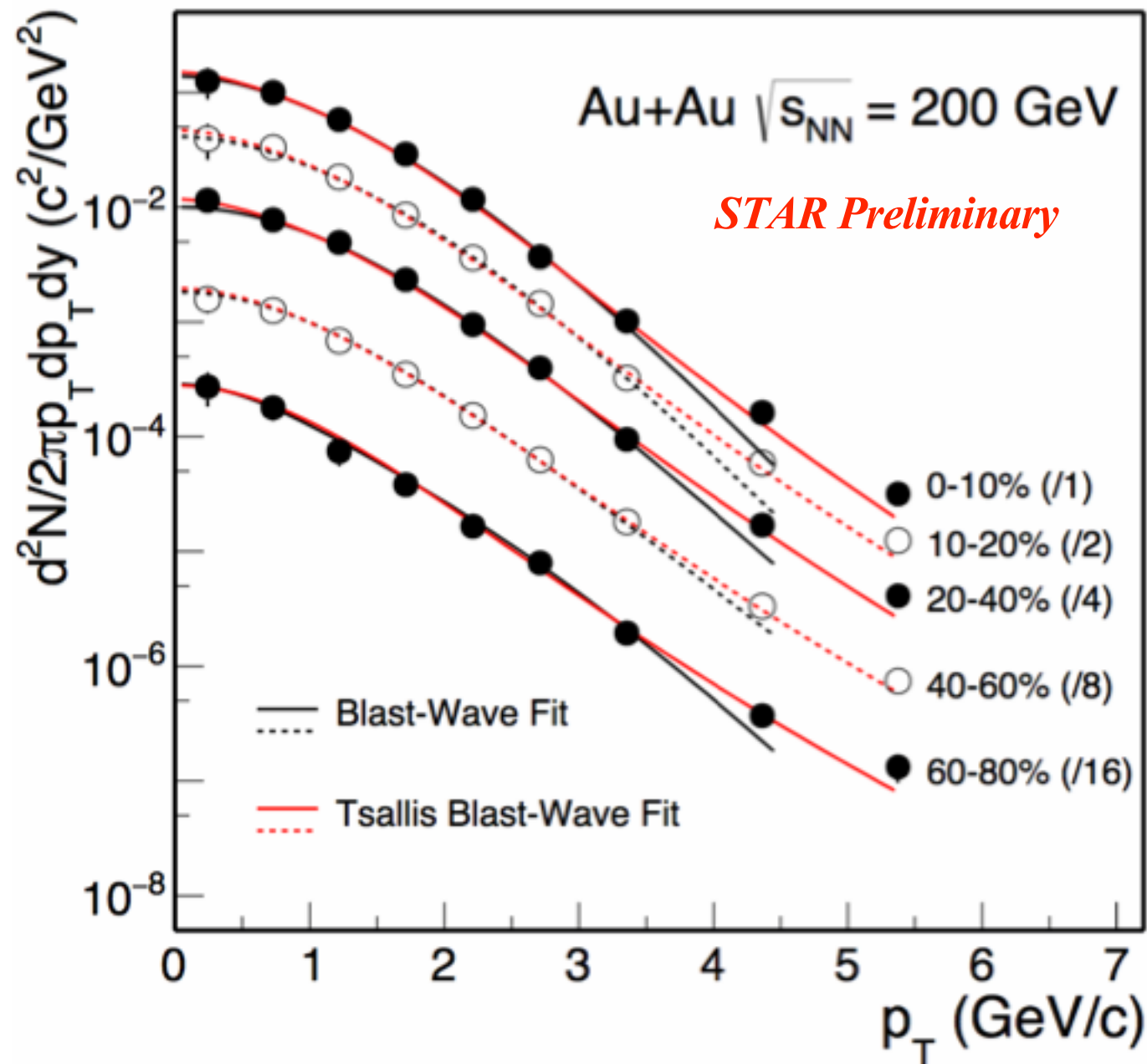
- Simple cuts on variables have limitations on signal-background separation
- Supervised learning algorithms can do better!



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



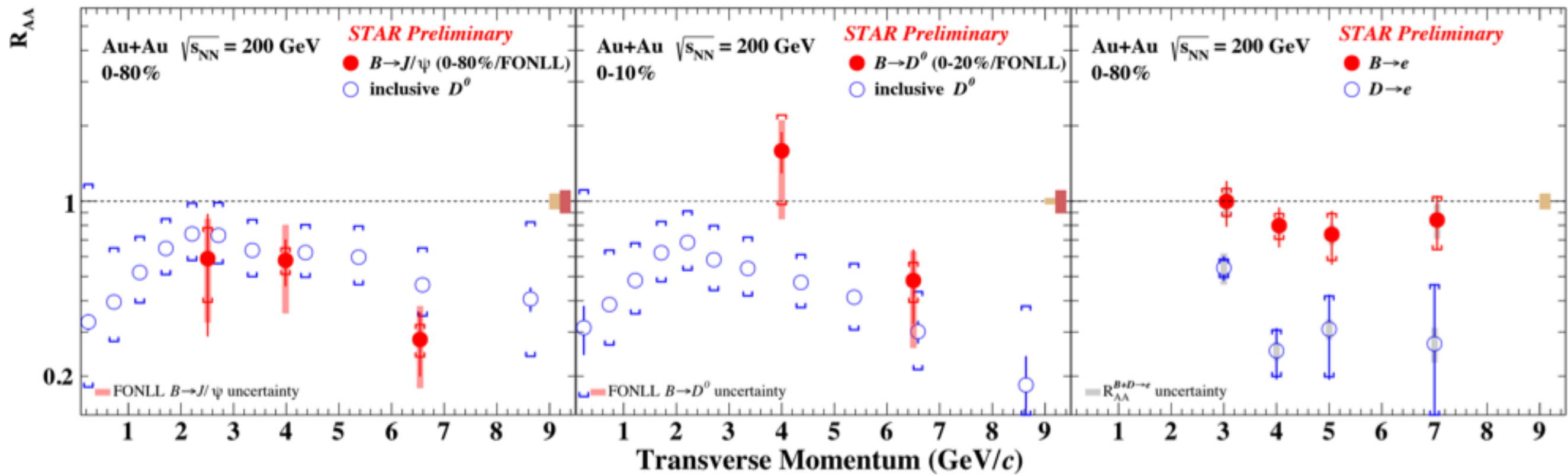
BW fits to D^0 spectra



- 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.

