# Heavy Flavor Measurements from STAR

***Sooraj Radhakrishnan (for the STAR Collaboration)***
*Lawrence Berkeley National Laboratory*

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

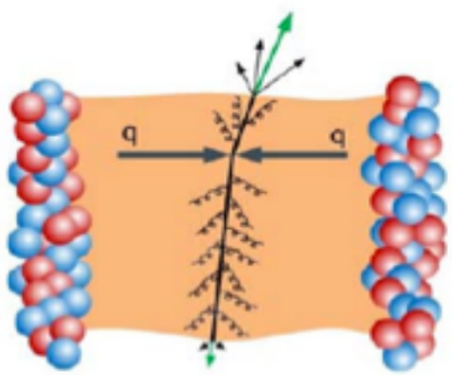
STAR

# Heavy quarks as probes of QGP

- Produced in initial hard scatterings, not thermally, in HIC at RHIC.
- Production cross-sections amenable to pQCD calculations

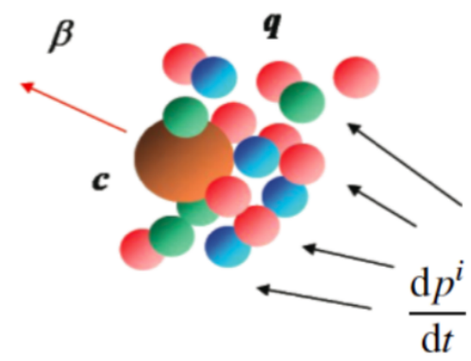
⟶ Ideal probes of the QGP

## Energy Loss




- D, B meson $R_{AA}$ and $R_{CP}$
- Collisional and radiative energy loss

## Transport



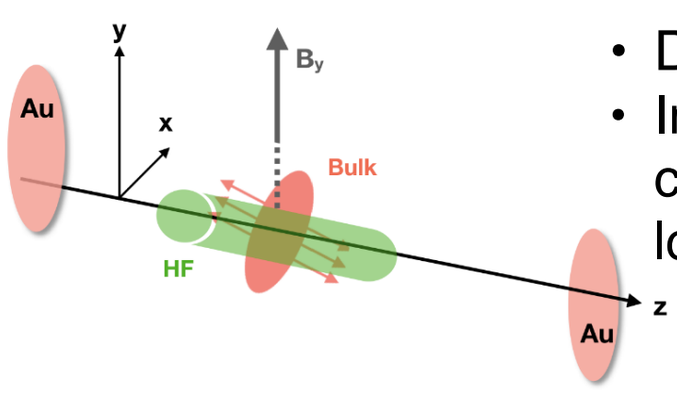

- $D^0$ $v_2$, $v_3$
- *c* quark diffusion coefficient in QGP

$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t)$$

drag → Diffusion coefficient $D_s$

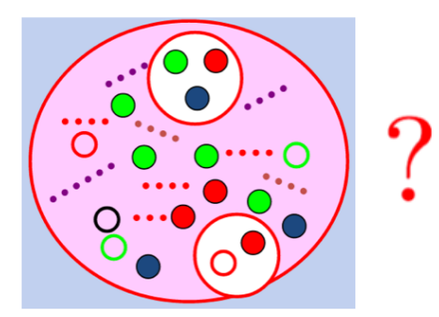
fluctuations → Diffusion coefficient $D_s$

## Initial conditions



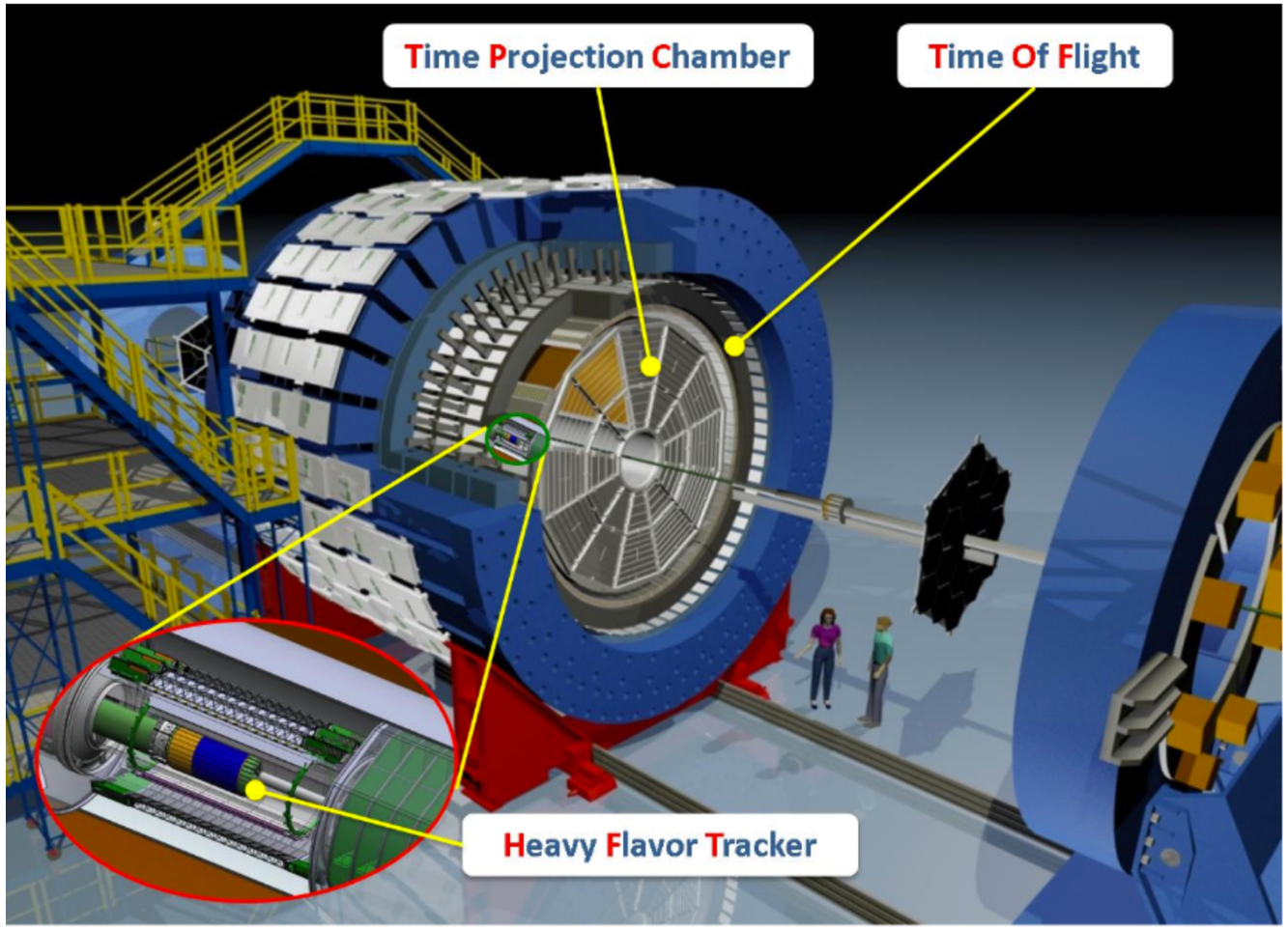

- $D^0$ directed flow
- Initial B-field, initial conditions in longitudinal direction

## Hadronization

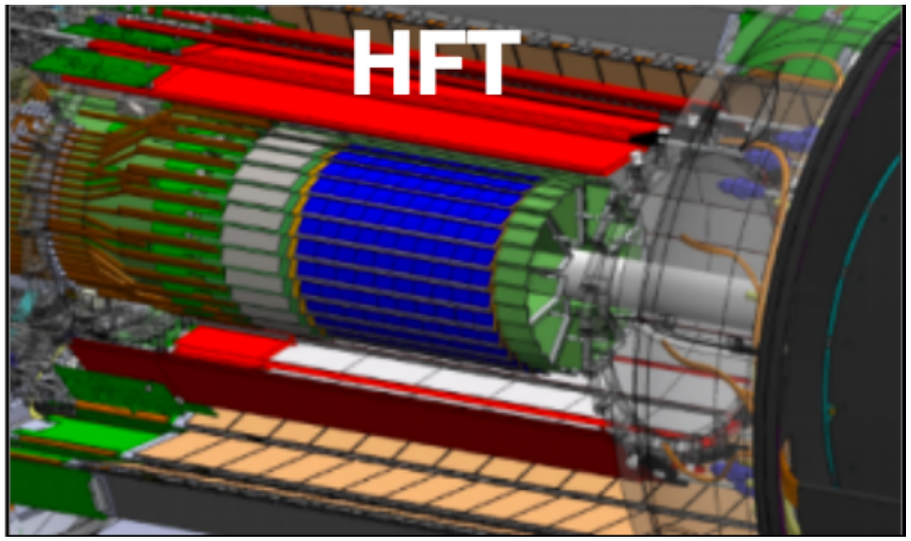


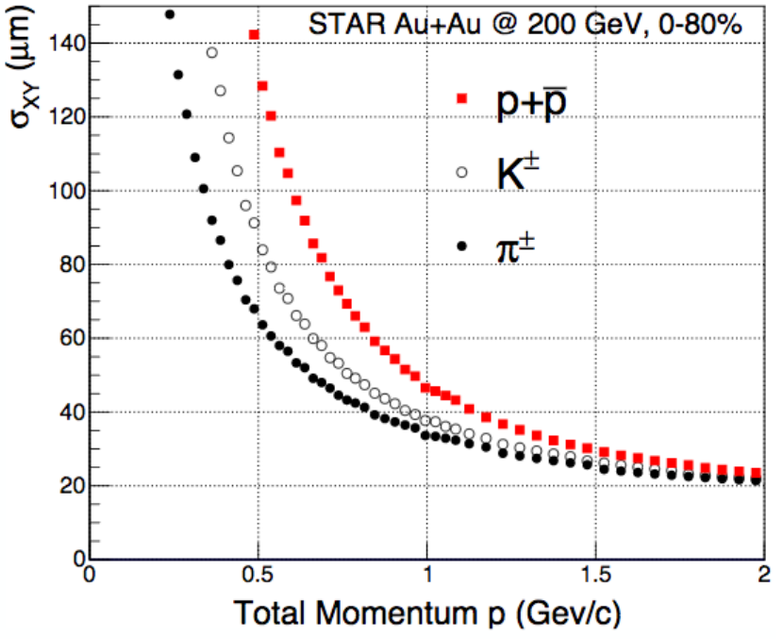

- $\Lambda_c$, $D_s$ production
- Coalescence?
- Ideal probes as total c quark is fixed at initial scatterings

# STAR Heavy Flavor Tracker




- 2 layers of Si pixels with MAPS and 2 layers of Si strips
- Full azimuthal coverage, $|\eta| < 1$

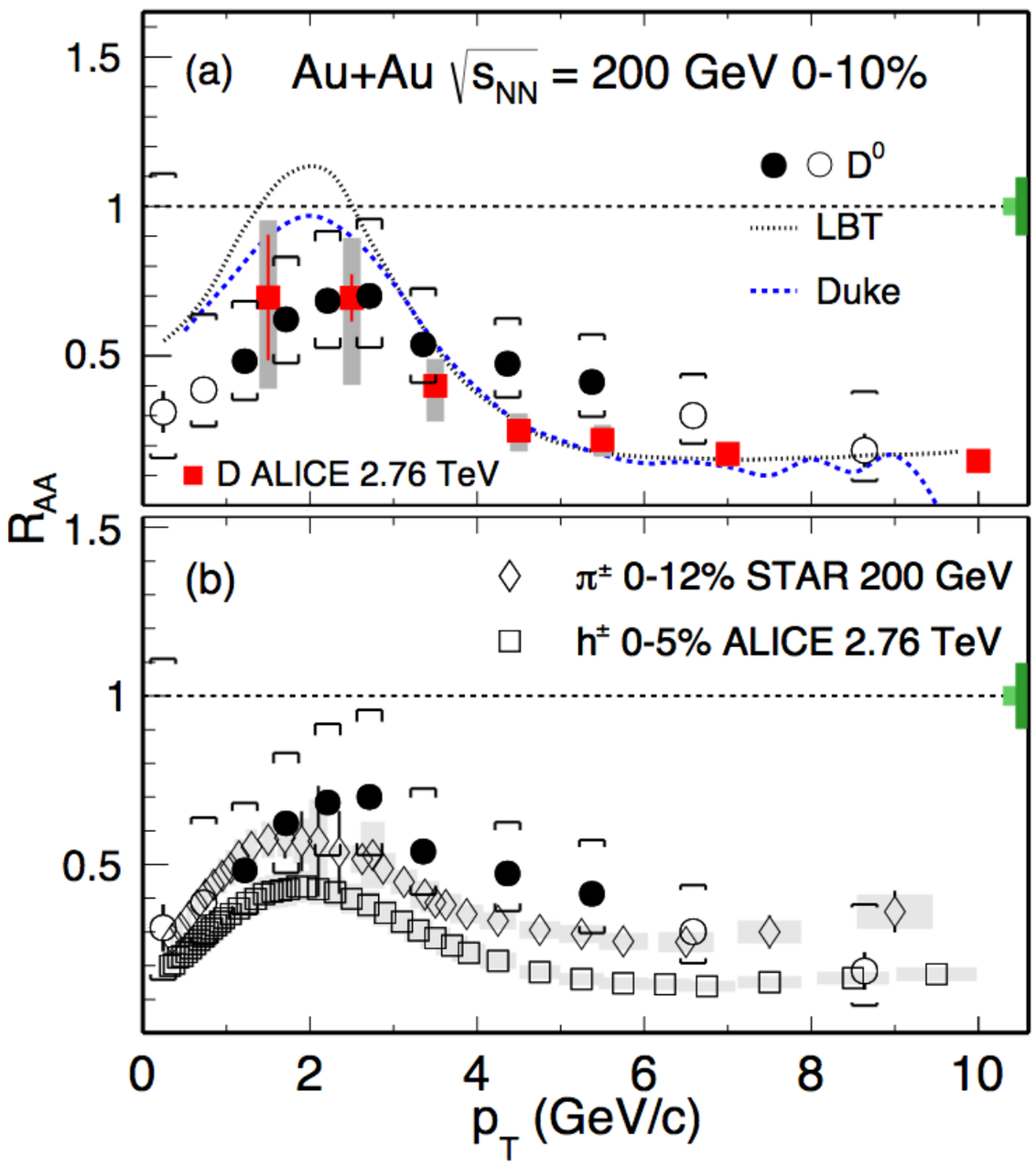



*Phys. Rev. Lett. 118 (2017) 212301*

- Excellent track pointing resolution
- Topological reconstruction of charm hadron decays
- Vastly improved signal significances (eg: by factor of 15 for $D^0$)

# Energy loss: $D^0$ $R_{AA}$ and $R_{CP}$

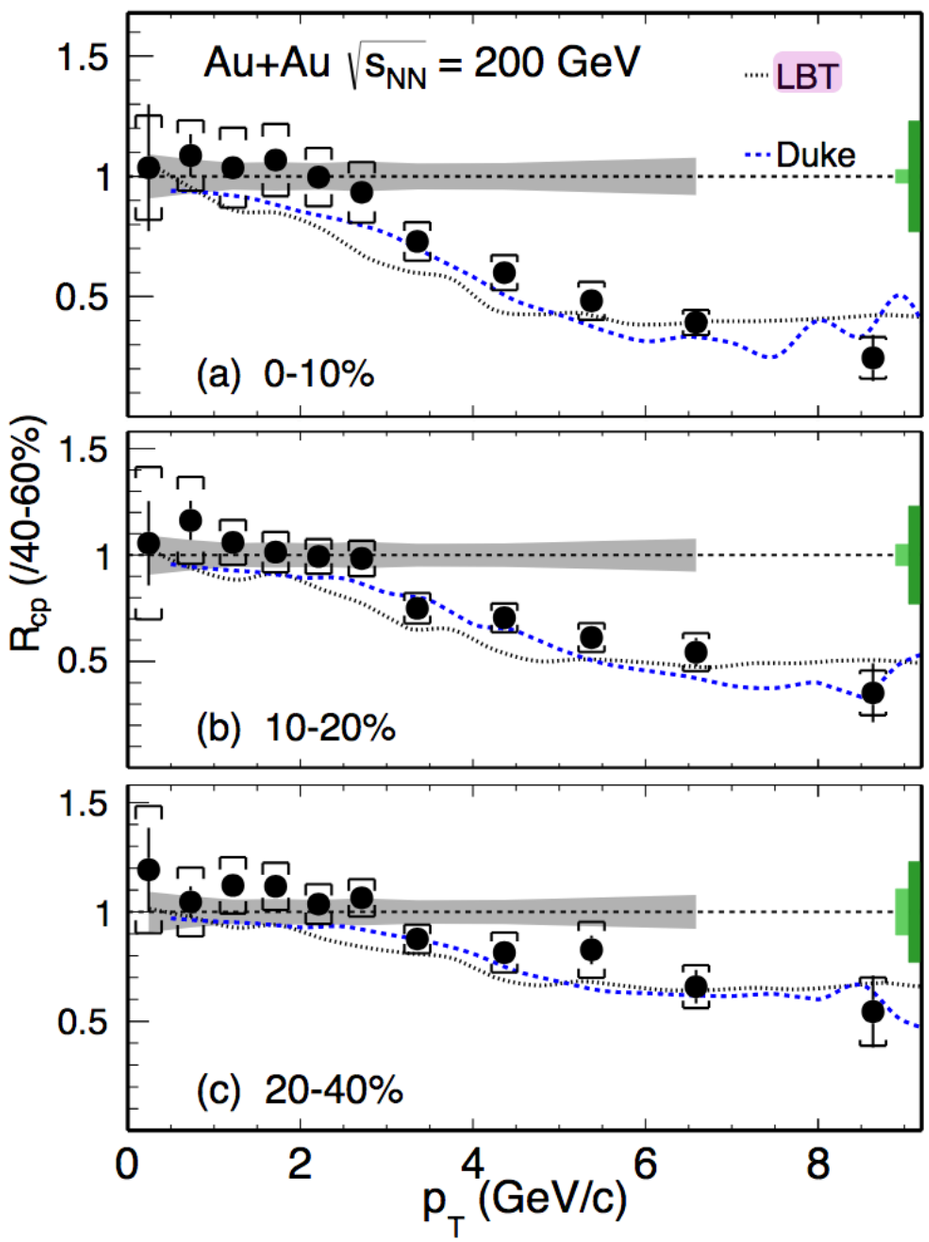


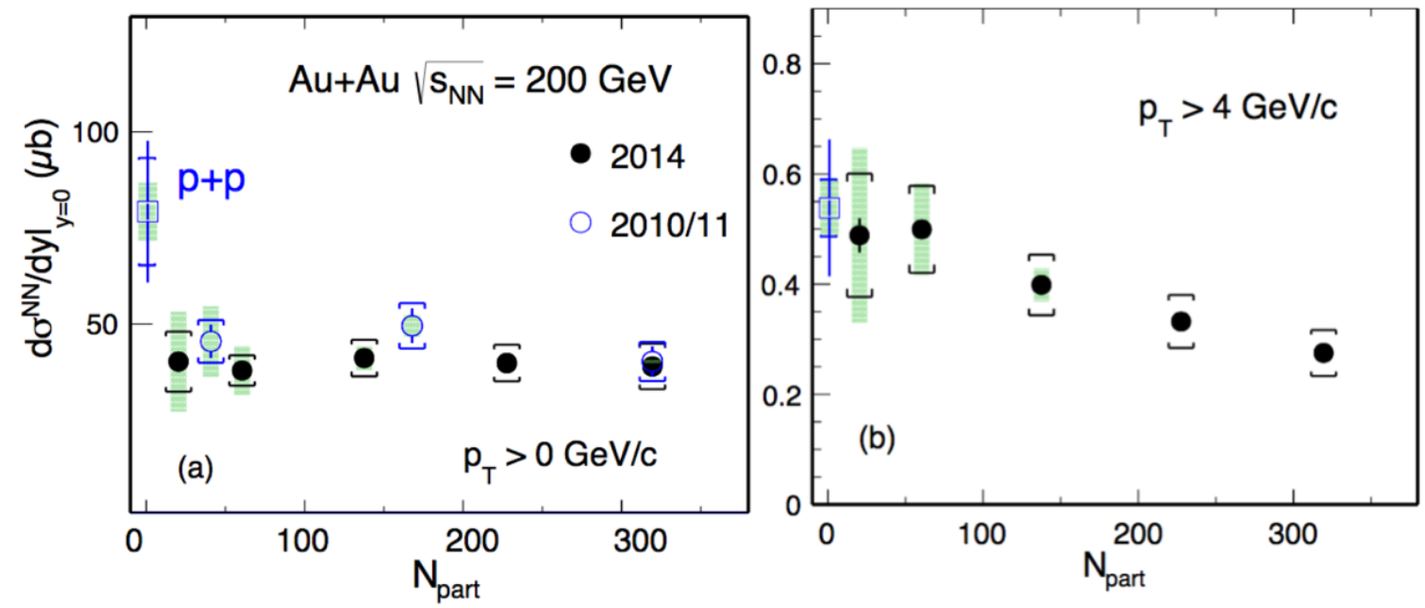

*STAR: Phys Rev C.99.034908 (2019)*

- Strong suppression of high $p_T$ $D^0$ in central Au+Au collisions
  - Strong interactions and energy loss of *c* quarks with QGP
- Comparable to that seen for light flavor hadrons at high $p_T$, less at intermediate $p_T$ (3-6 GeV/c)
- Model calculations can reproduce large suppression at high $p_T$
  - Include both collisional and radiative energy losses, both important in $p_T \sim 3$ - 10 GeV/c for *c* quarks

# Energy loss: $D^0$ $R_{AA}$ and $R_{CP}$

- Precision better for $R_{CP}$
- Better constraints on model calculations



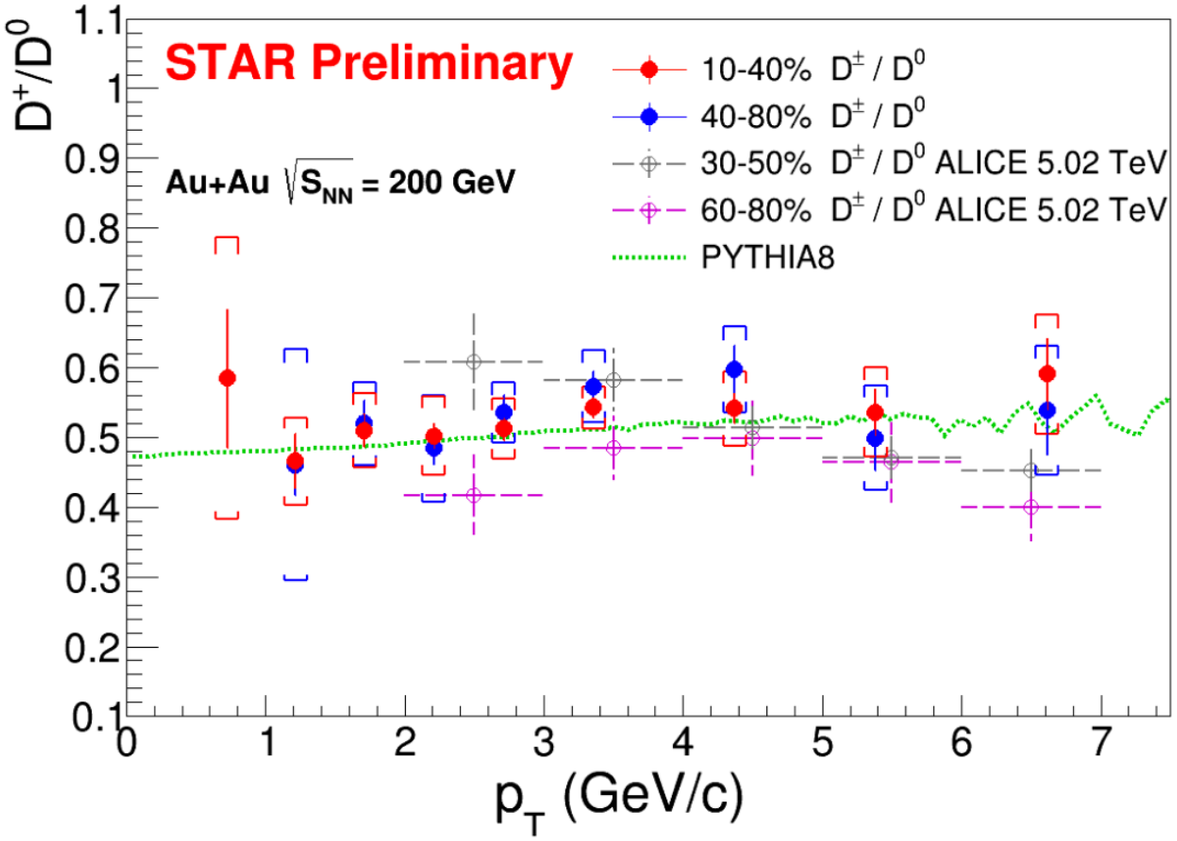




- High $p_T$ suppression increase towards central events
- No strong centrality dependence at low $p_T$

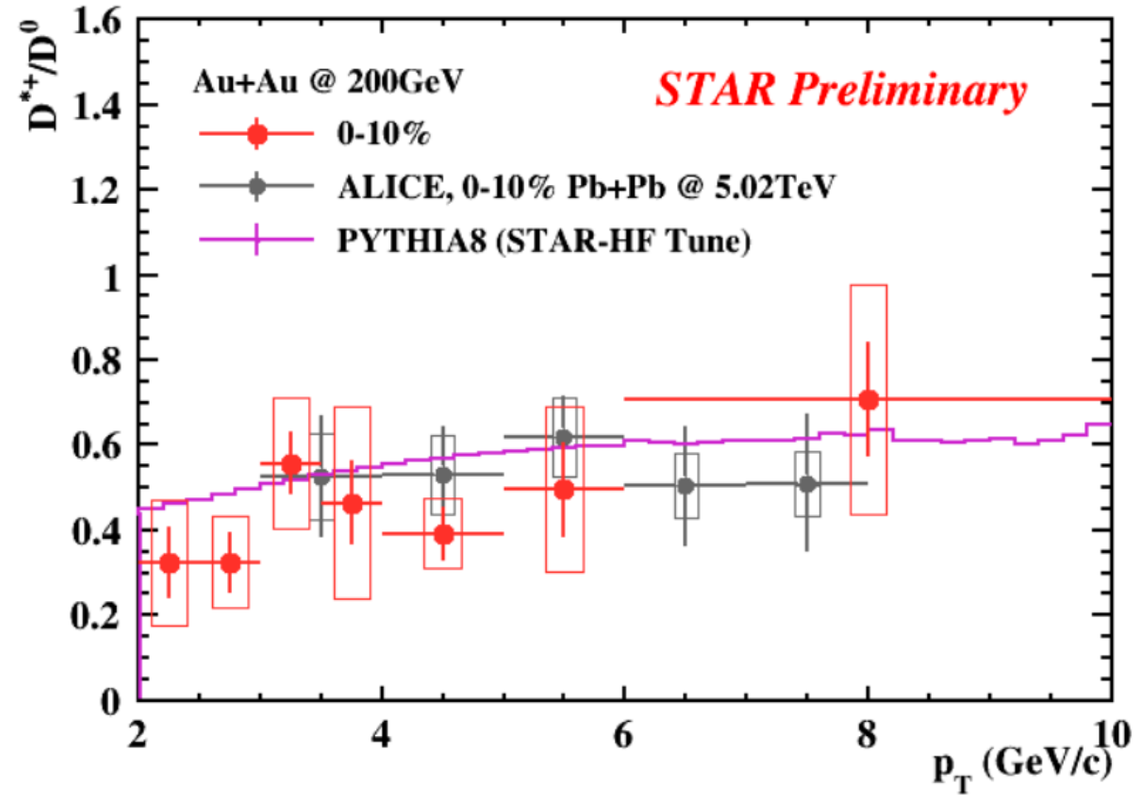
- Also seen from cross-section plots
- Total $D^0$ cross-section is lower than in p+p collisions

*STAR: Phys Rev C.99.034908 (2019)*

# Energy loss: $D^{+/-}$ and $D^*$ production




*ALICE Collaboration, JHEP 1810 (2018) 174*




*ALICE Collaboration, JHEP 1810 (2018) 174*

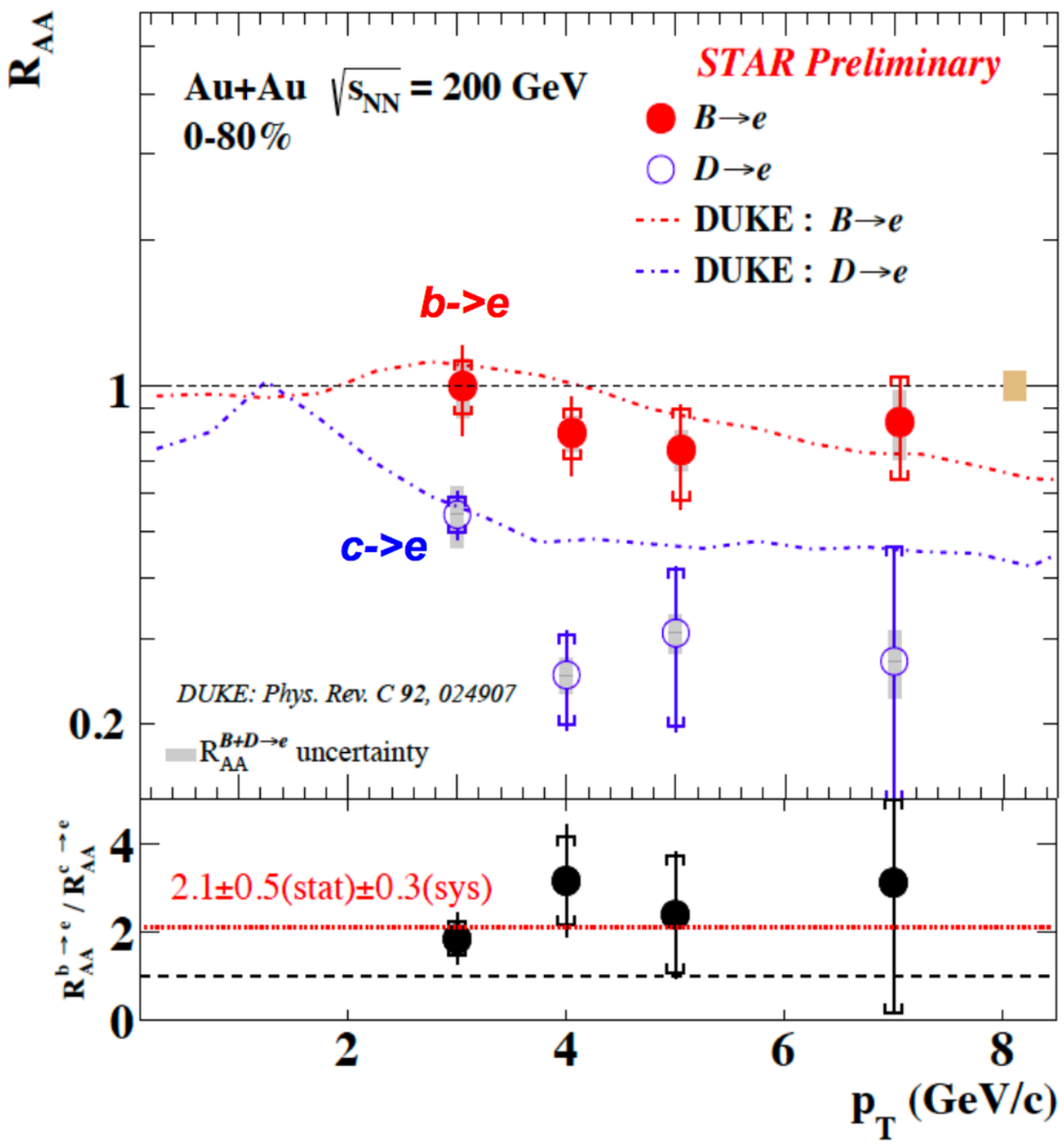
- Complementary to $D^0$ measurements

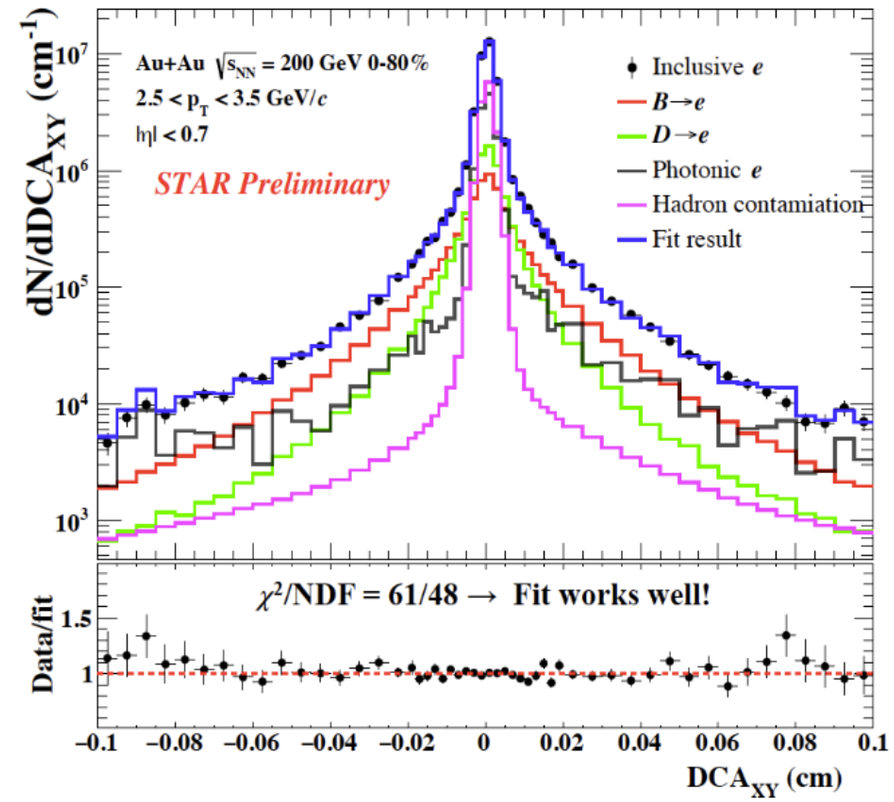
- No modification to $D^{+/-}/D^0$ and $D^*/D^0$ yield ratios compared to PYTHIA
- Indicates similar $R_{AA}$ as for $D^0$

- Similar observation from measurements at LHC

# Energy loss: electrons from B decays

- How about bottom?
- Mass hierarchy: radiative energy loss expected to be smaller for bottom

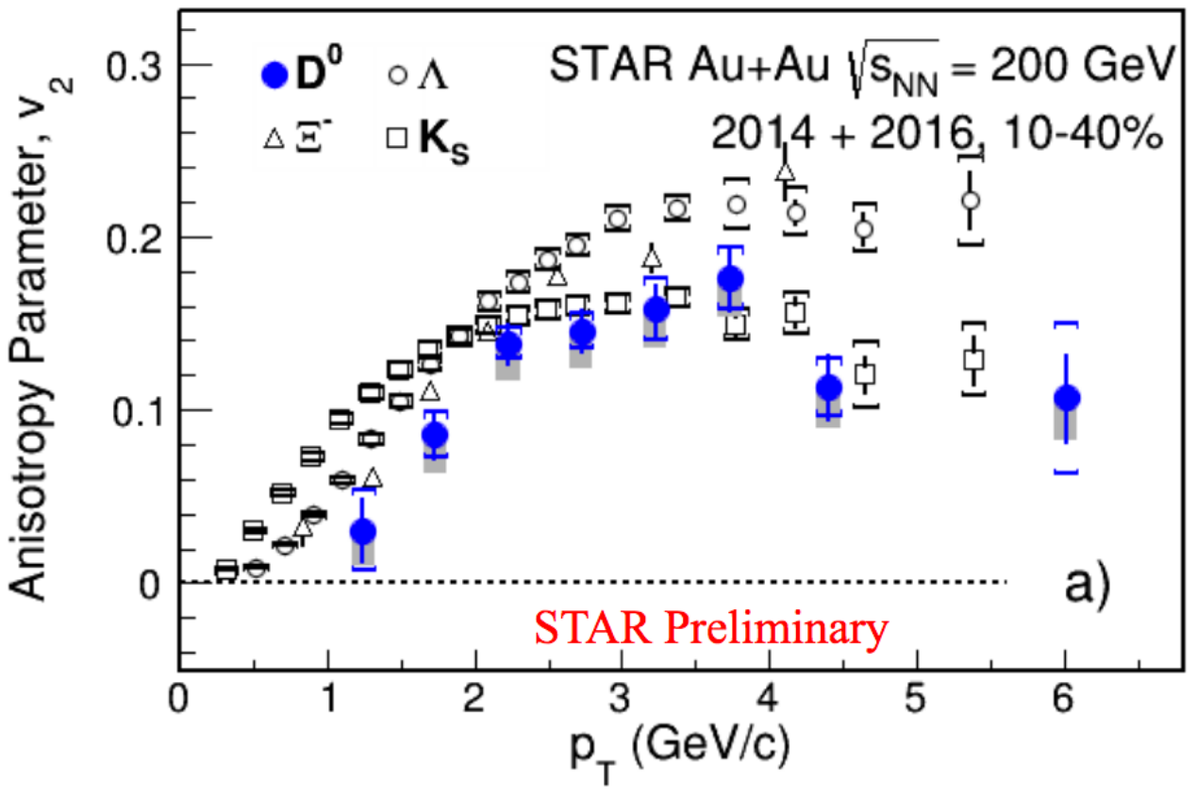


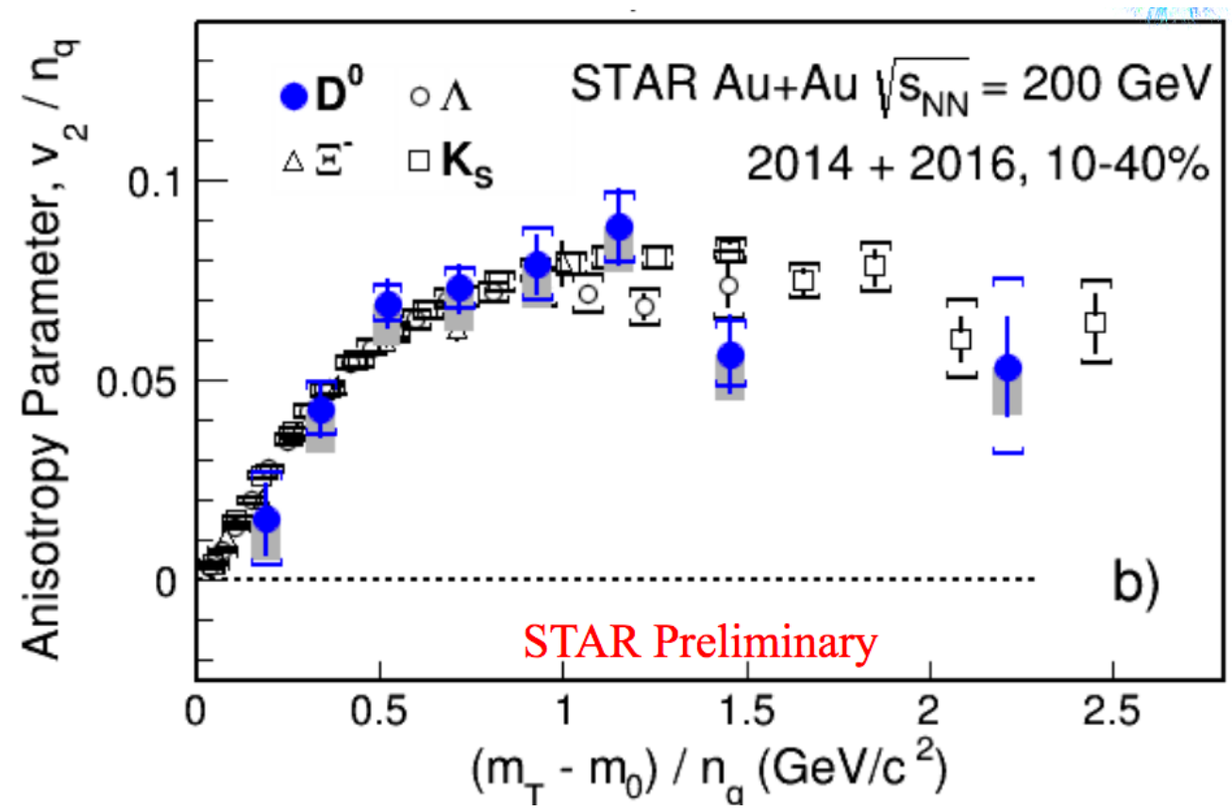




- Template fits to single electron DCA to extract $e_D$ and $e_B$ fractions
- Indication of higher $R_{AA}$ for B —> e, compared to D —> e (~2 sigma effect)

- Better precision measurements with full 2014+2016 data on the way!

# Transport: $D^0$ elliptic low



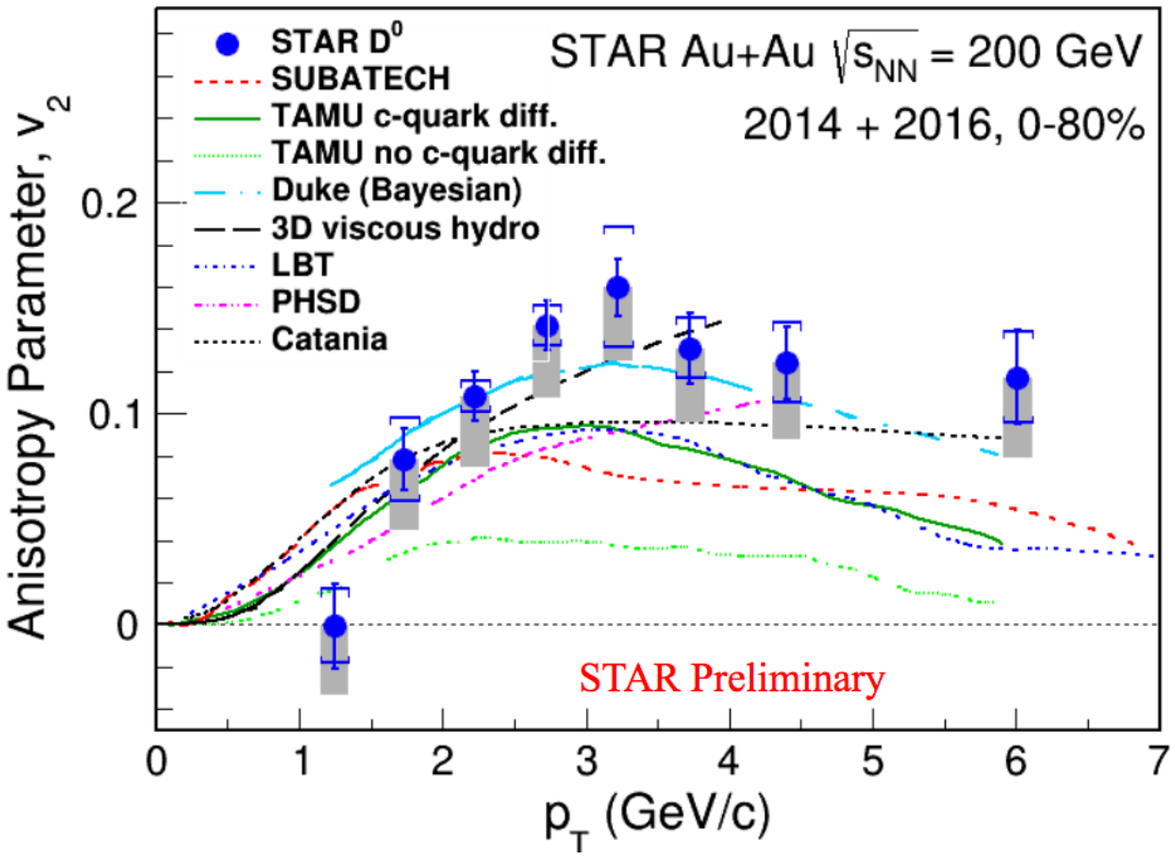



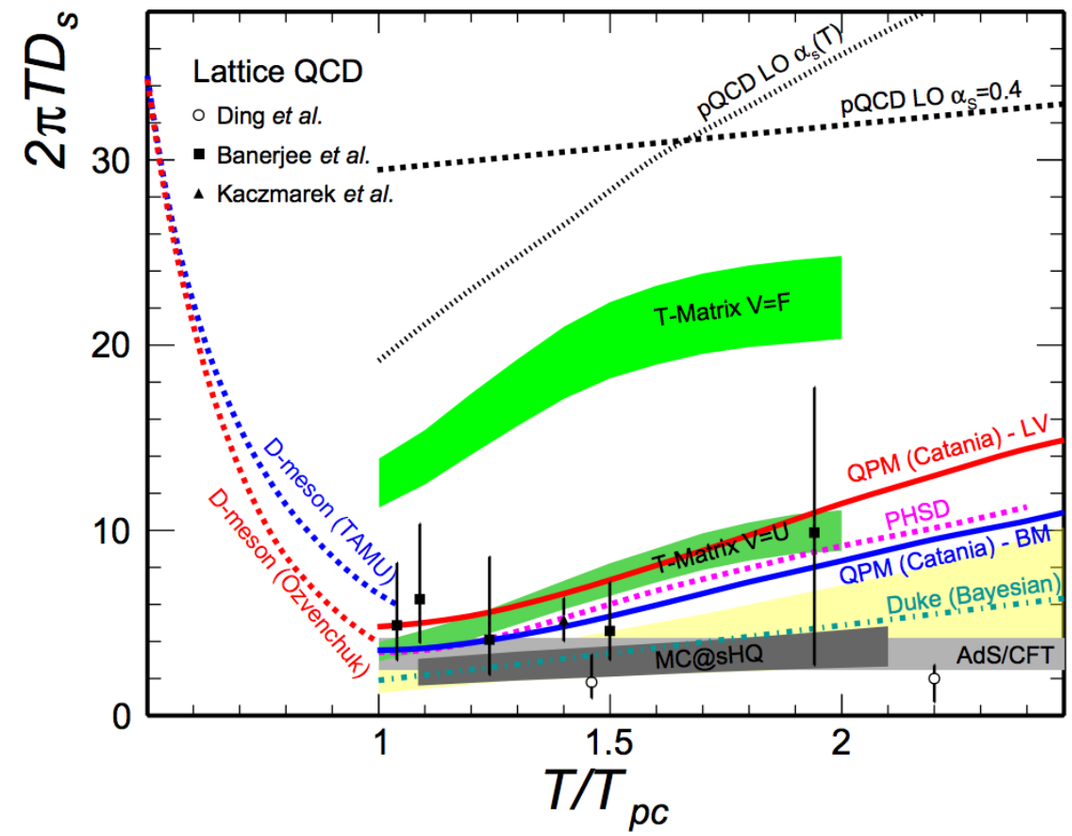

*STAR Published results from 2014: Phys. Rev. Lett. 118 (2017) 212301*

- Combined results from 2014+2016 data, improved precision

- Large magnitude of elliptic flow for $D^0$ mesons, comparable to that of light flavor hadrons
  - Shows NCQ scaling
  - Suggests charm quarks acquire similar flow as light flavor quarks

# Transport: $D^0$ $v_2$, model comparisons



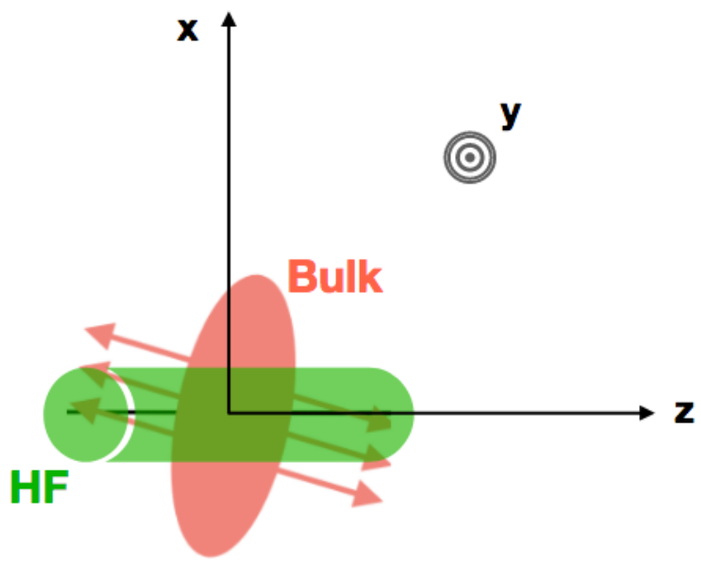



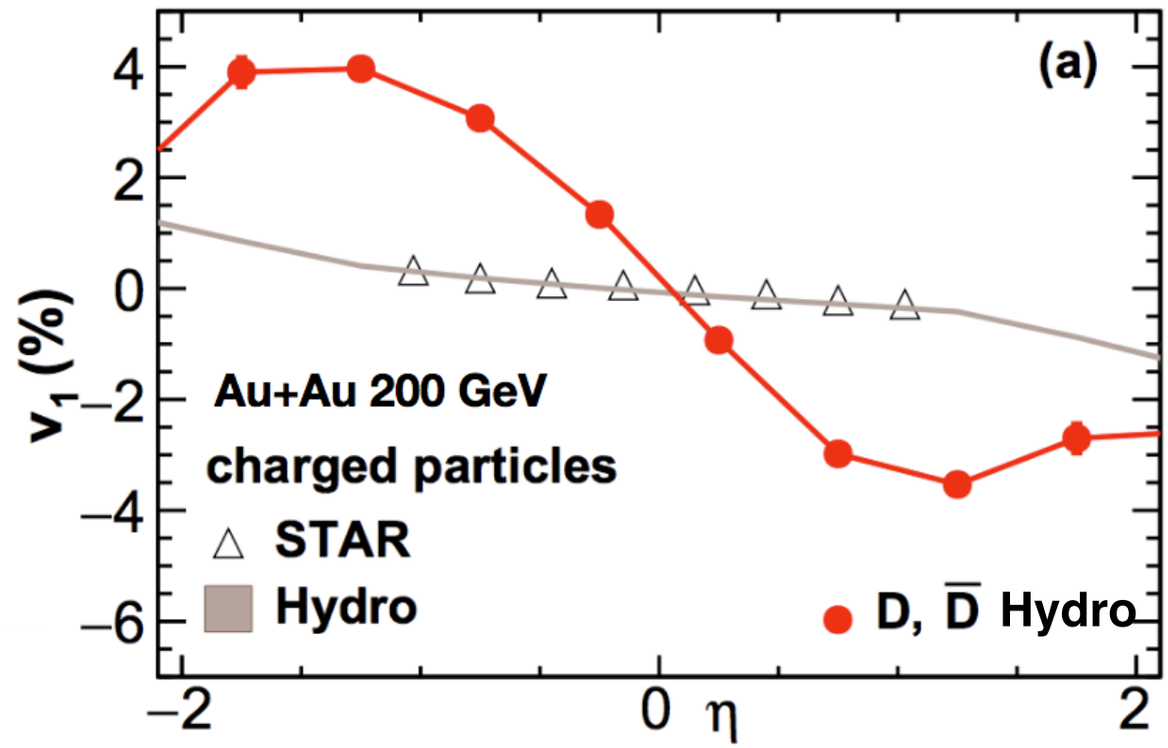

*SUBATECH: PhysRevC 90, 054909 (2014), PhysRevC 92, 014910 (2015)*
*TAMU: PhysRevC 86, 014903 (2012), PhysRevLett110, 112301 (2013)*
*Duke: PhysRevC 92, 024907 (2015)*
*3D viscoushydro: PhysRevC 86, 024911 (2012)*

*LBT: PhysRevC 94, 014909 (2016)*
*PHSD: PhysReV90, 051901 (2014), PhysReV90, 051901 (2014)*
*Catania: PhysReV96, 044905 (2017)*

- Transport models with charm quark diffusion in the medium can describe the data
- Value of diffusion coefficient well constrained by data around $T_c$

# Directed flow of $D^0$ mesons: Initial geometry



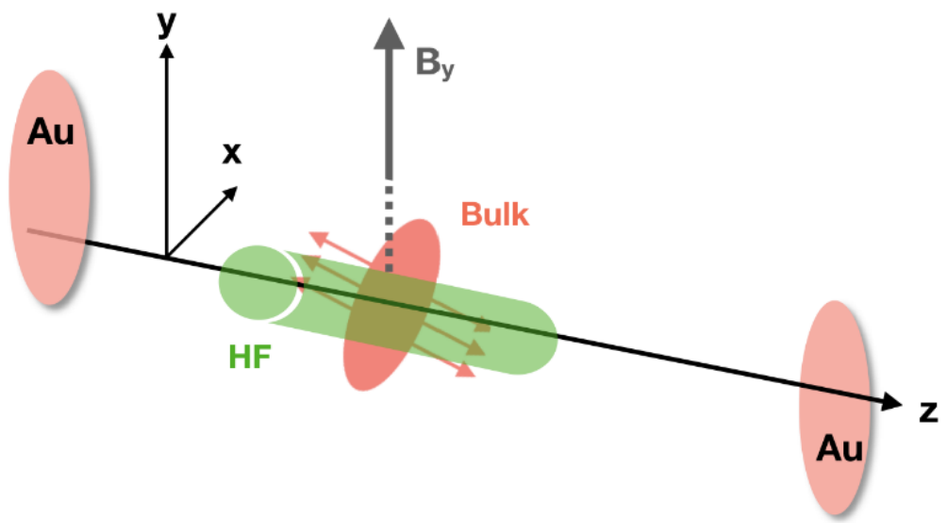

*Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)*

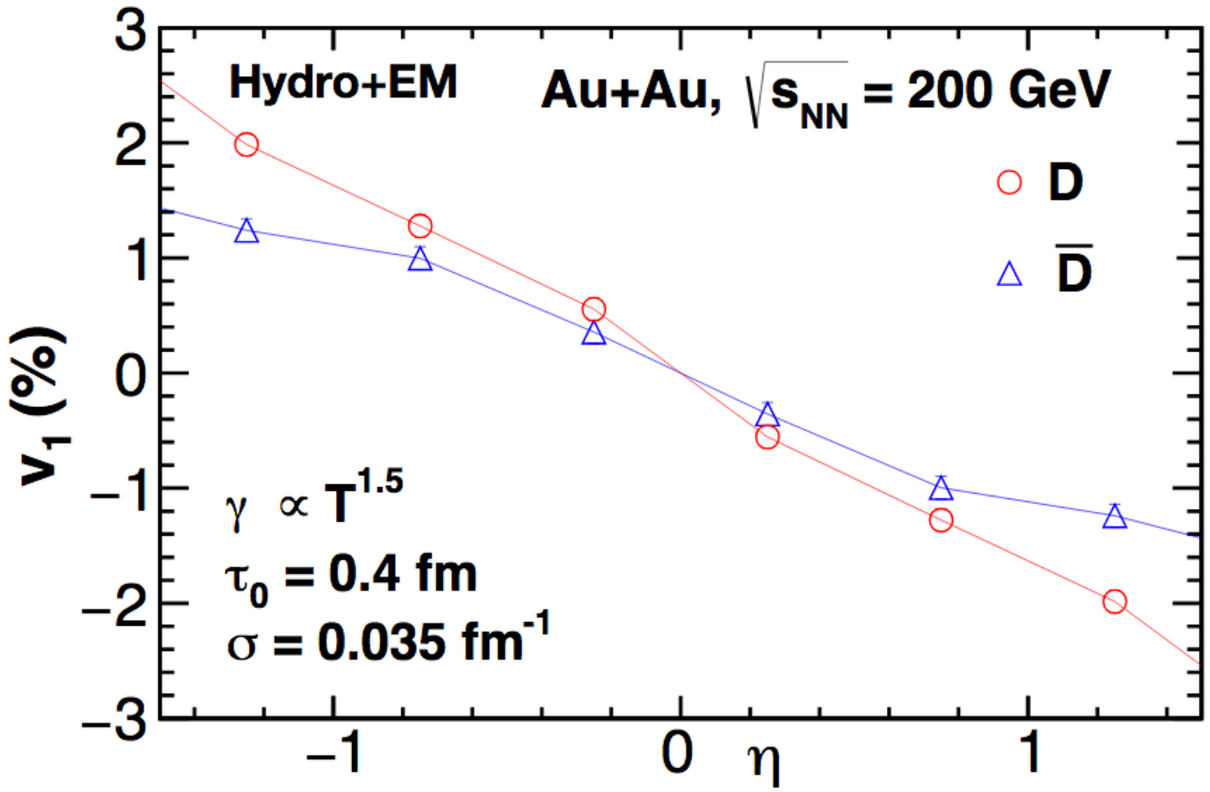
- Initial conditions in longitudinal direction: important for accurate modeling of HIC

- Tilted source for QGP bulk: explains light flavor $v_1$
- Charm quark production profile follows that of binary collisions, symmetric in rapidity
- Induces $v_1$ for charm quarks

- Magnitude depends on viscous drag on charm quarks and initial tilt of QGP bulk
- $D^0$ $v_1$ predicted to be order of magnitude larger than light flavor hadron $v_1$

# Directed flow of $D^0$ mesons: B field



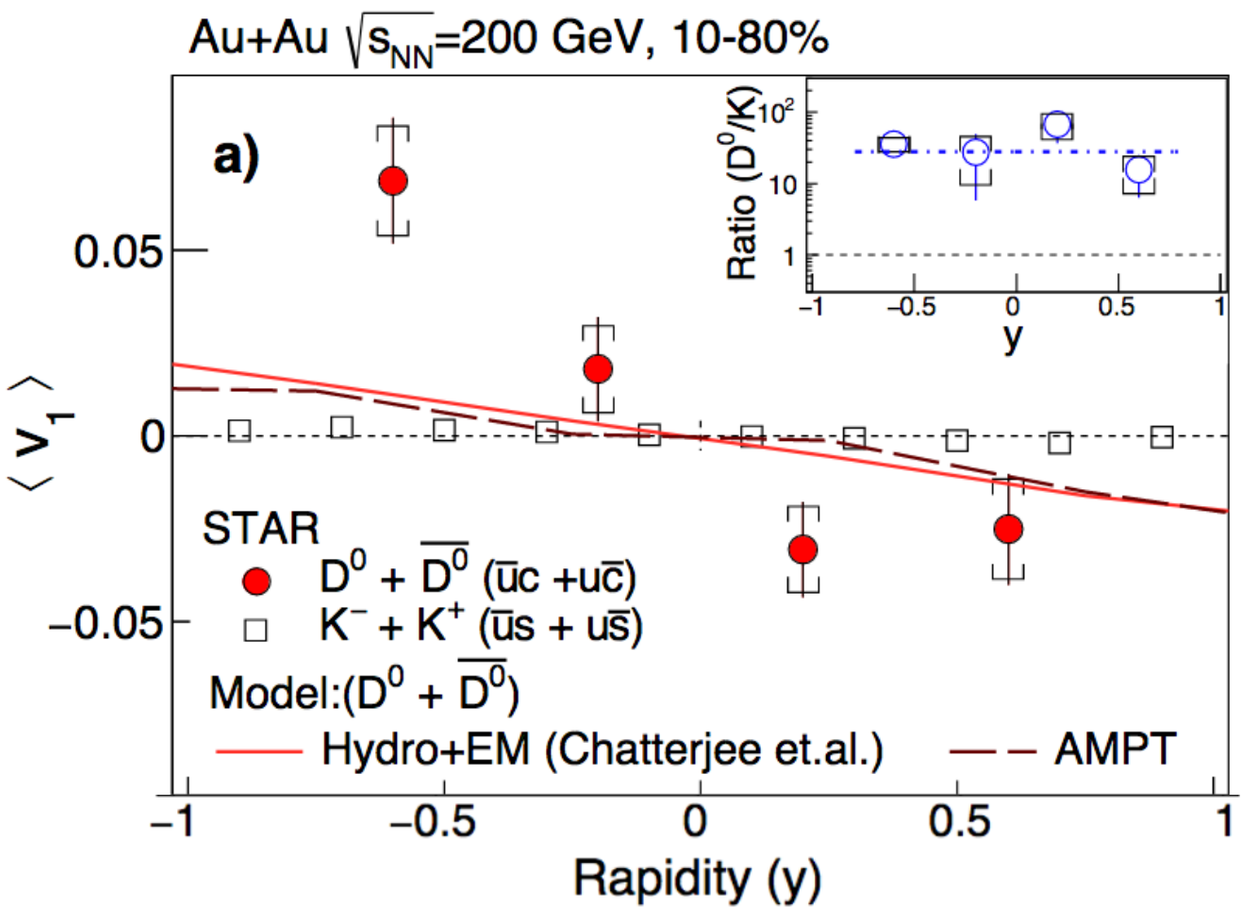




*Das et. al., Phys Lett B 768, 260 (2017), Chatterjee, Bojek: arXiv1804.04893v1*

- Also, strong magnetic fields during initial stages!
  - Induces opposite sign $v_1$ for *c* and *cbar* quarks
  - Model calculations predict a charge dependent split for $D^0$ and anti-$D^0$ v1

- Predicted difference is also order of magnitude larger than the effect for light flavor hadrons, as latter has large thermal production contribution during medium evolution

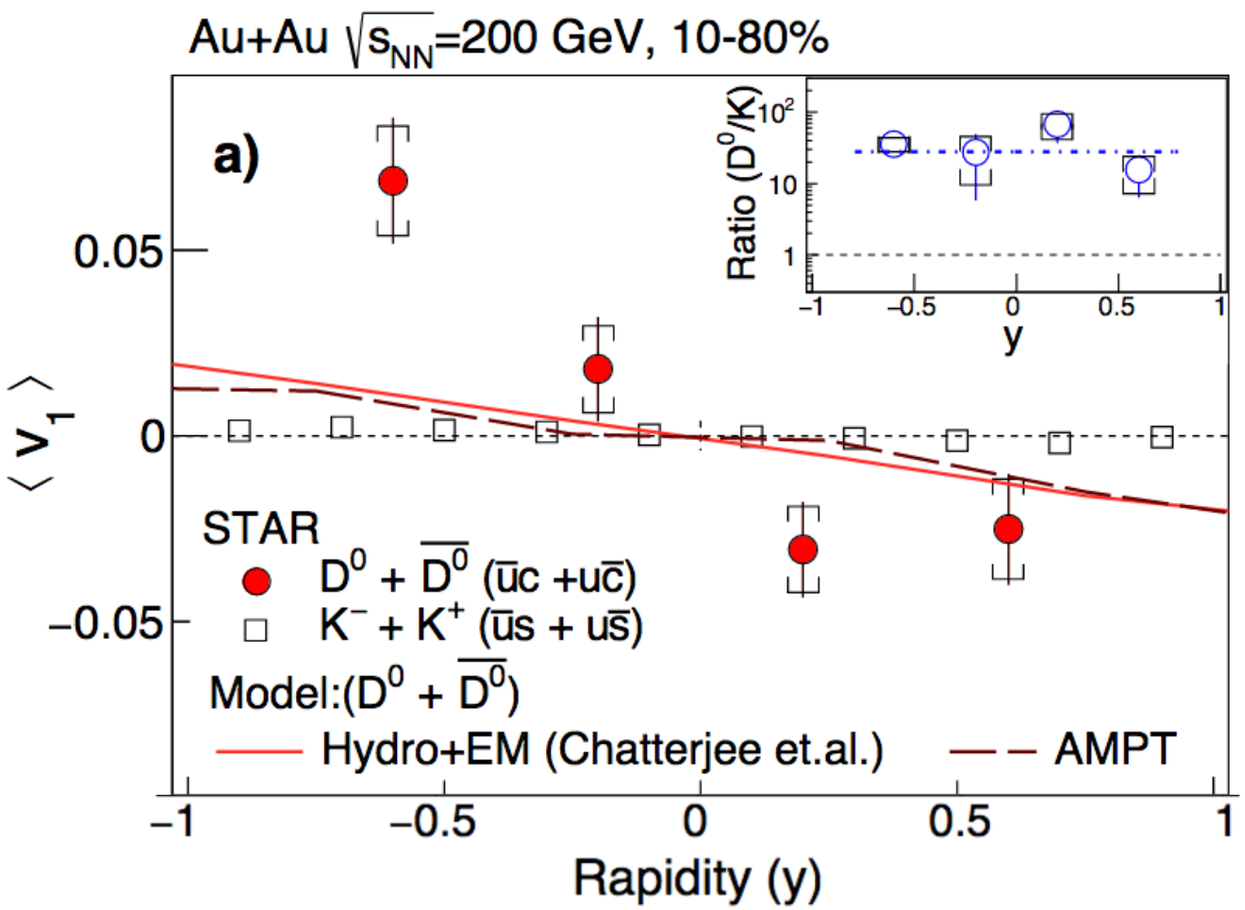
# Directed flow of $D^0$ mesons




- Measured $D^0$ $v_1$ slope, ~5-20 times larger than that for kaons
- Hydro models show correct sign and large magnitude, but under-predicts the data
- AMPT also predicts large magnitude

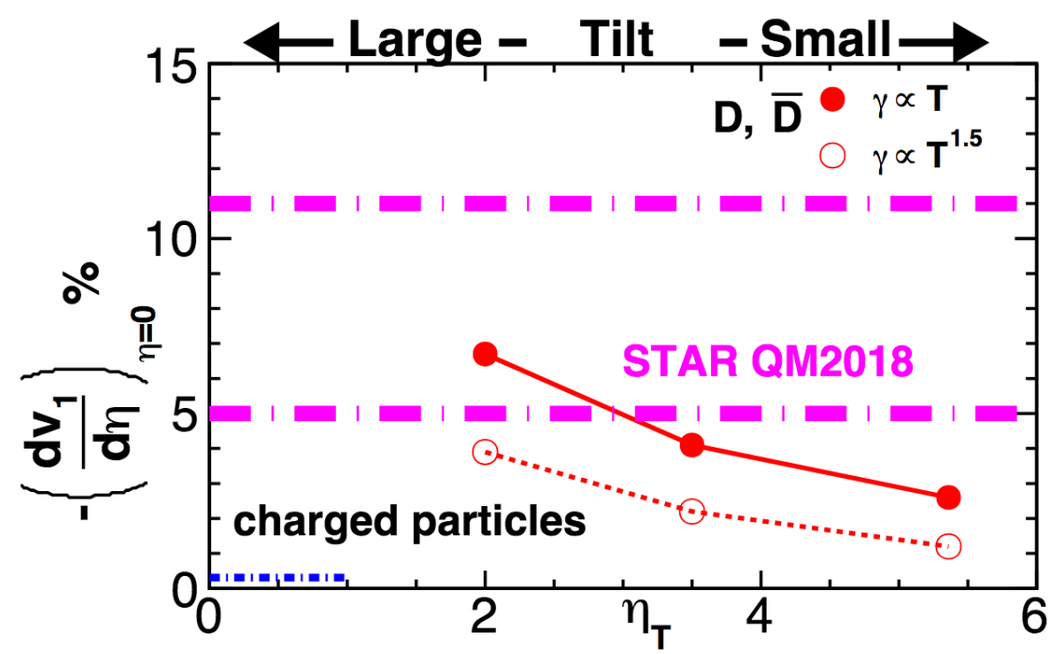
***STAR: arXiv:1905.02052, Submitted to PRL***

# Directed flow of $D^0$ mesons



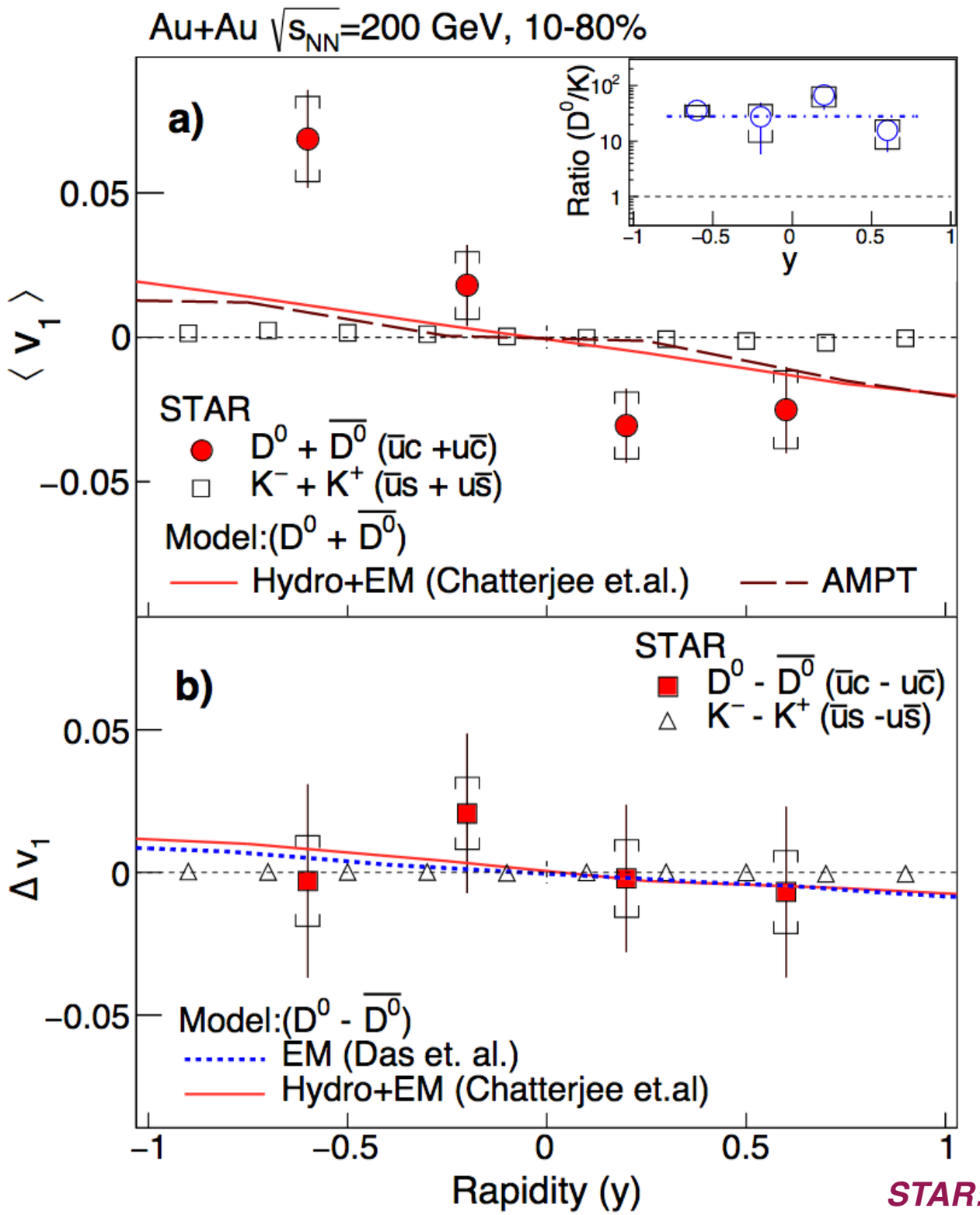

*STAR: arXiv:1905.02052, Submitted to PRL*

- Measured $D^0$ $v_1$ slope, ~5-20 times larger than that for kaons
- Hydro models show correct sign and large magnitude, but under-predicts the data
- Can help constrain model parameters




*Chatterjee, QM 2018, arXiv1804.04893v1*

# Directed flow of $D^0$ mesons




- Measured $D^0$ $v_1$ slope, ~5-20 times larger than that for kaons
- Models show correct sign and large magnitude, but under-predicts the data

- Consistent values for $D^0$ and anti-$D^0$
- Within the precision no EM field impact seen

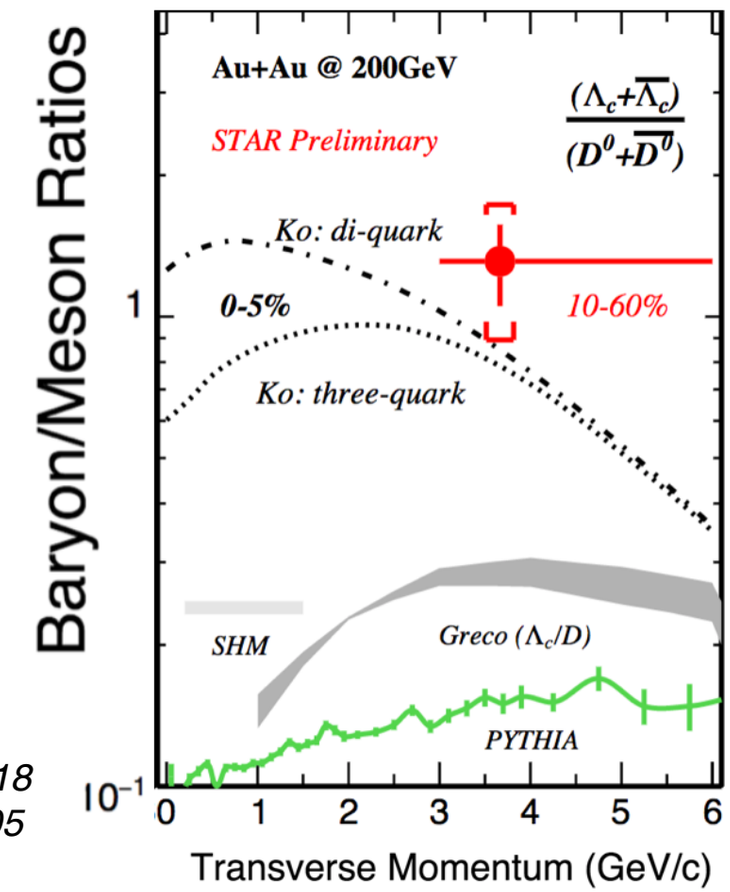
***STAR: arXiv:1905.02052, Submitted to PRL***

# $\Lambda_c$ production in HIC

- Help understand charm quark hadronization
  - Coalescence hadronization can become important for *c* quarks in presence of QGP
  - Significant enhancement of $\Lambda_c/D^0$ yield ratio relative to PYTHIA values predicted

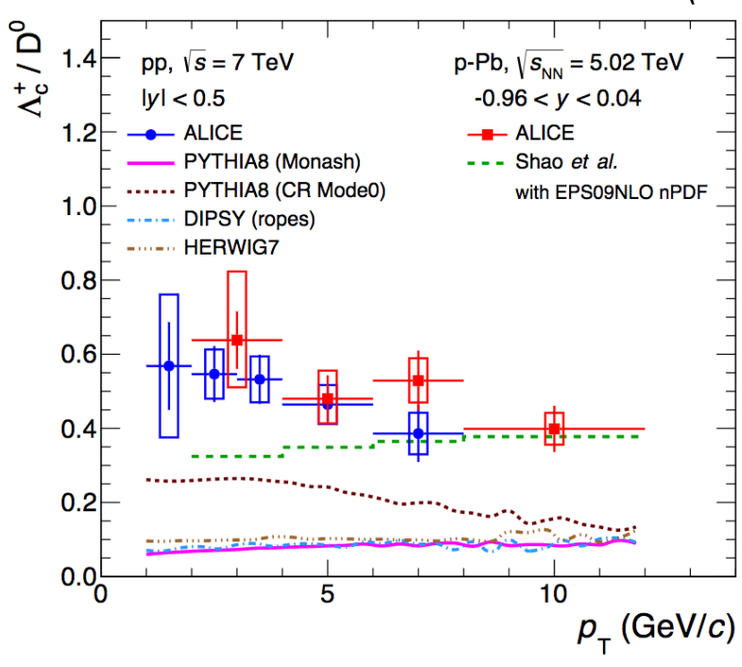
- Also important towards the understanding of charm quark energy loss in the QGP

STAR: QM17




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

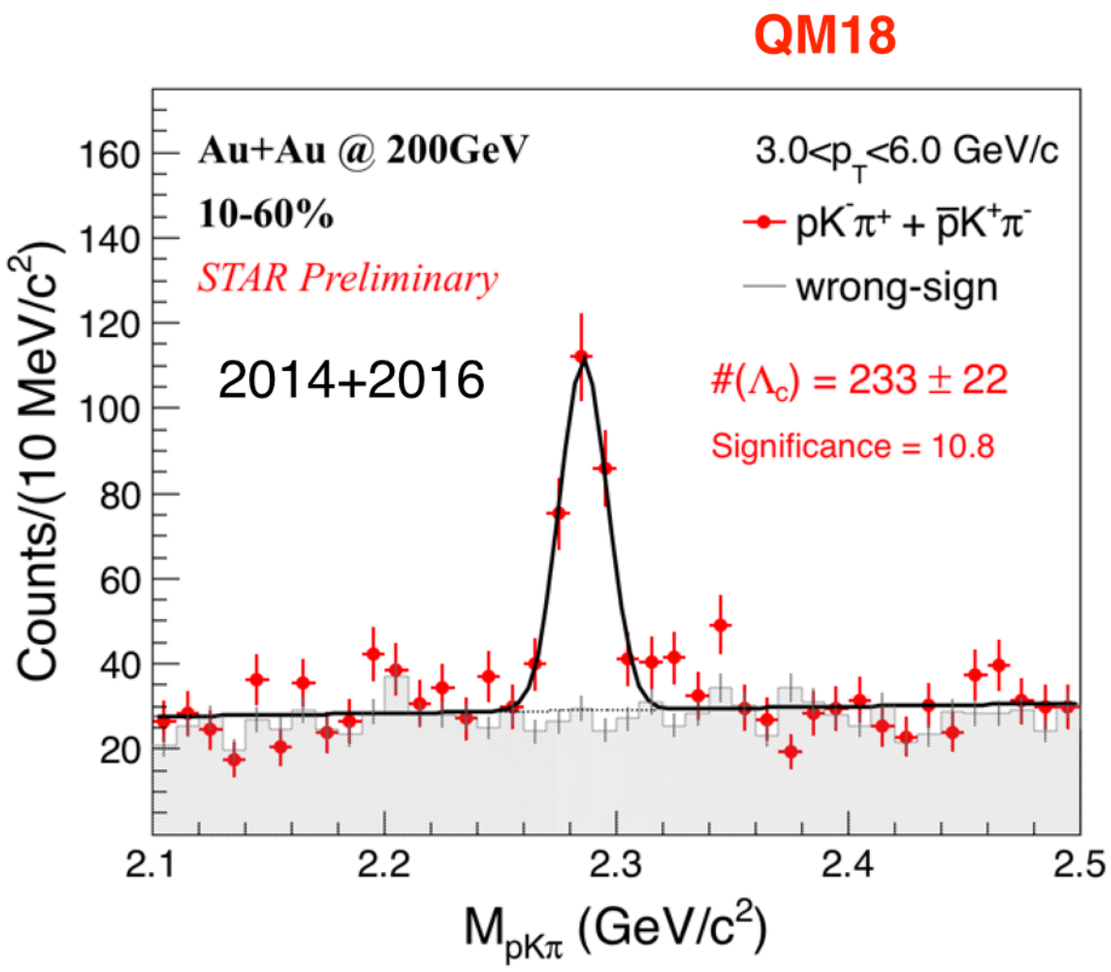
*ALICE: JHEP04(2018)108*

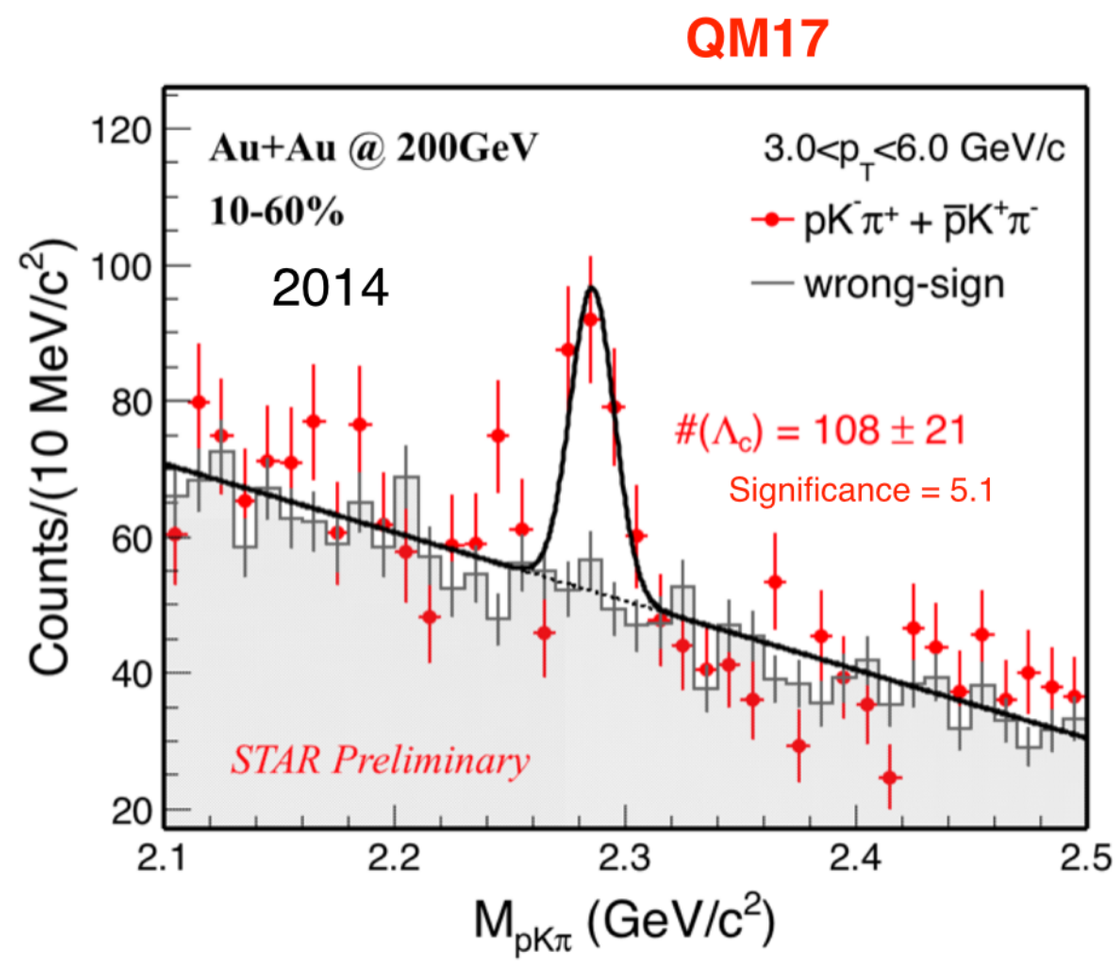



- Enhancement relative to PYTHIA seen in p+p and p+Pb collisions at LHC
- MPI with CR also under-predict
- What is the centrality dependence in HIC?

# $\Lambda_c$ signal reconstruction

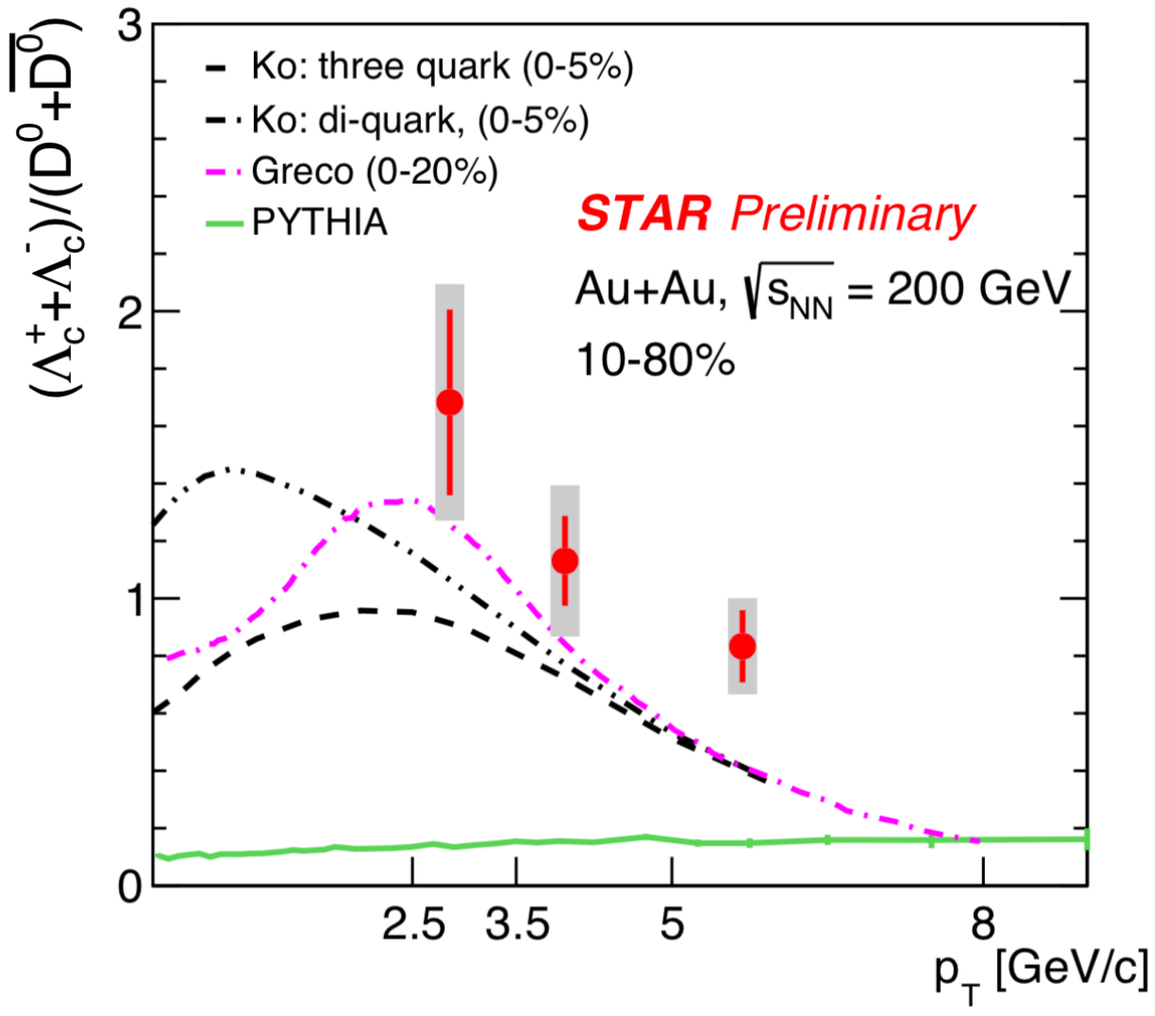
- Very short life time ($c\tau \sim 60$ μm), large combinatorial background
- Machine learning methods applied to further improve the signal significance for $\Lambda_c$ reconstruction

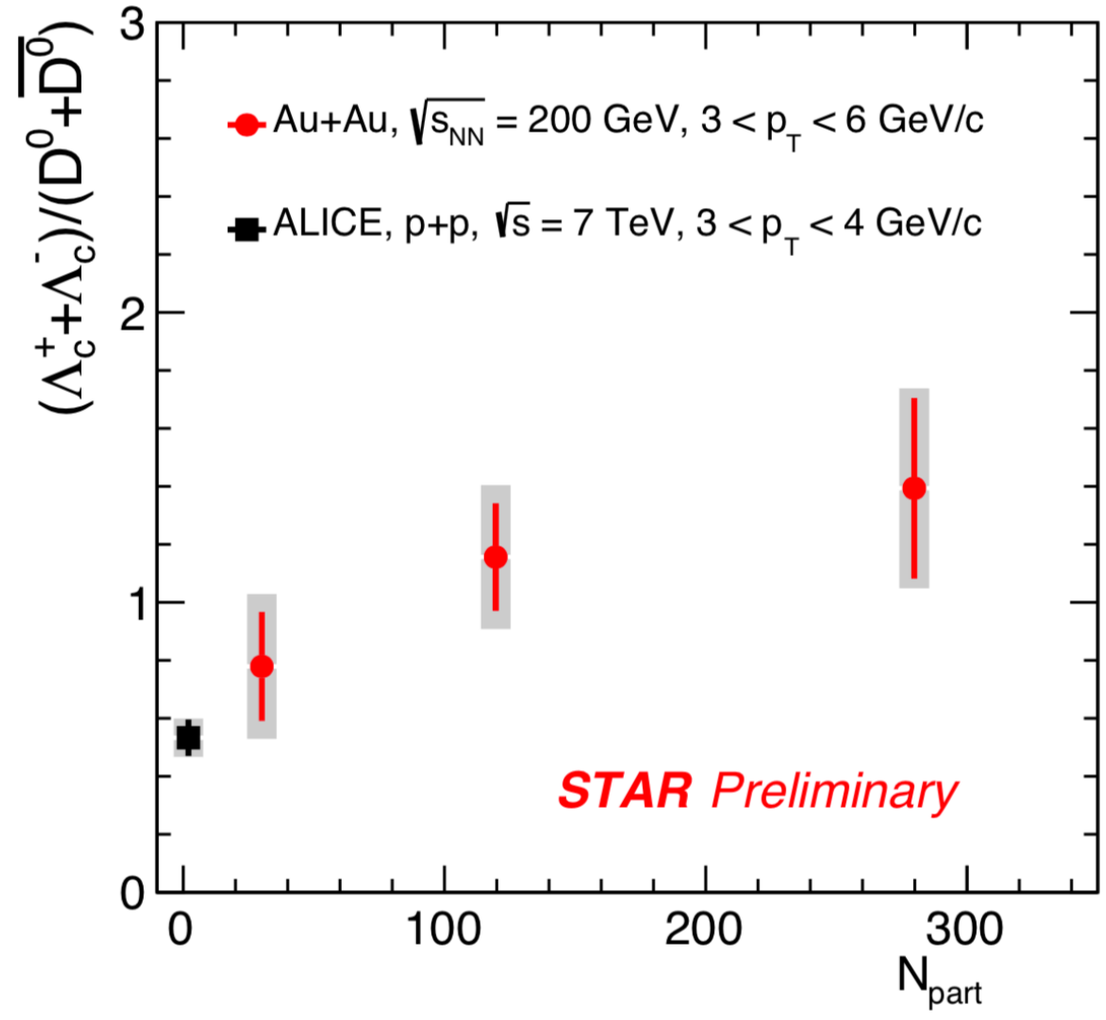



- More than 50% improvement in signal significance with TMVA BDT.
- Also new data from 2016 —> Effectively 4x more data compared to QM17

# $\Lambda_c/D^0$ ratio: $p_T$ dependence



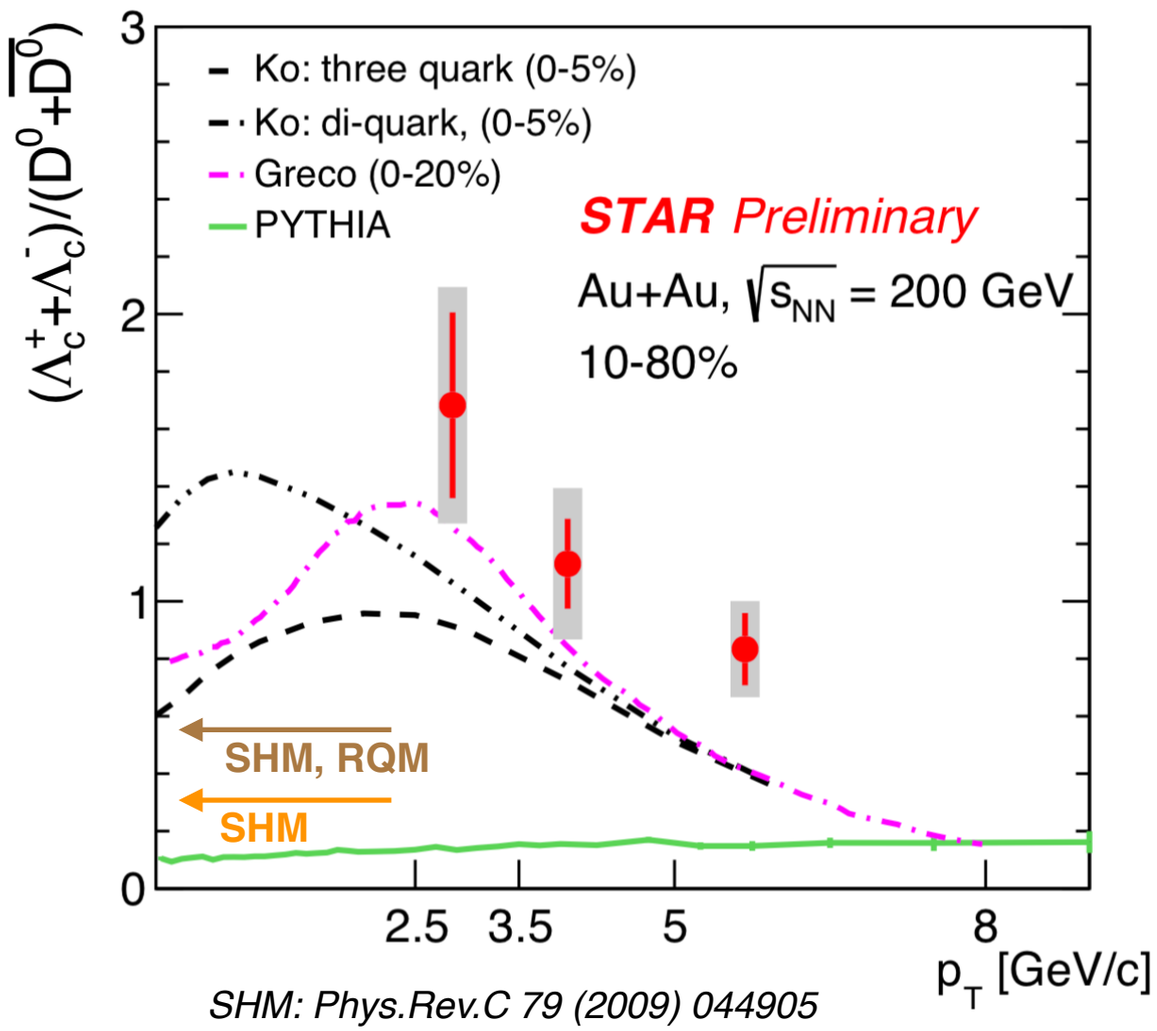



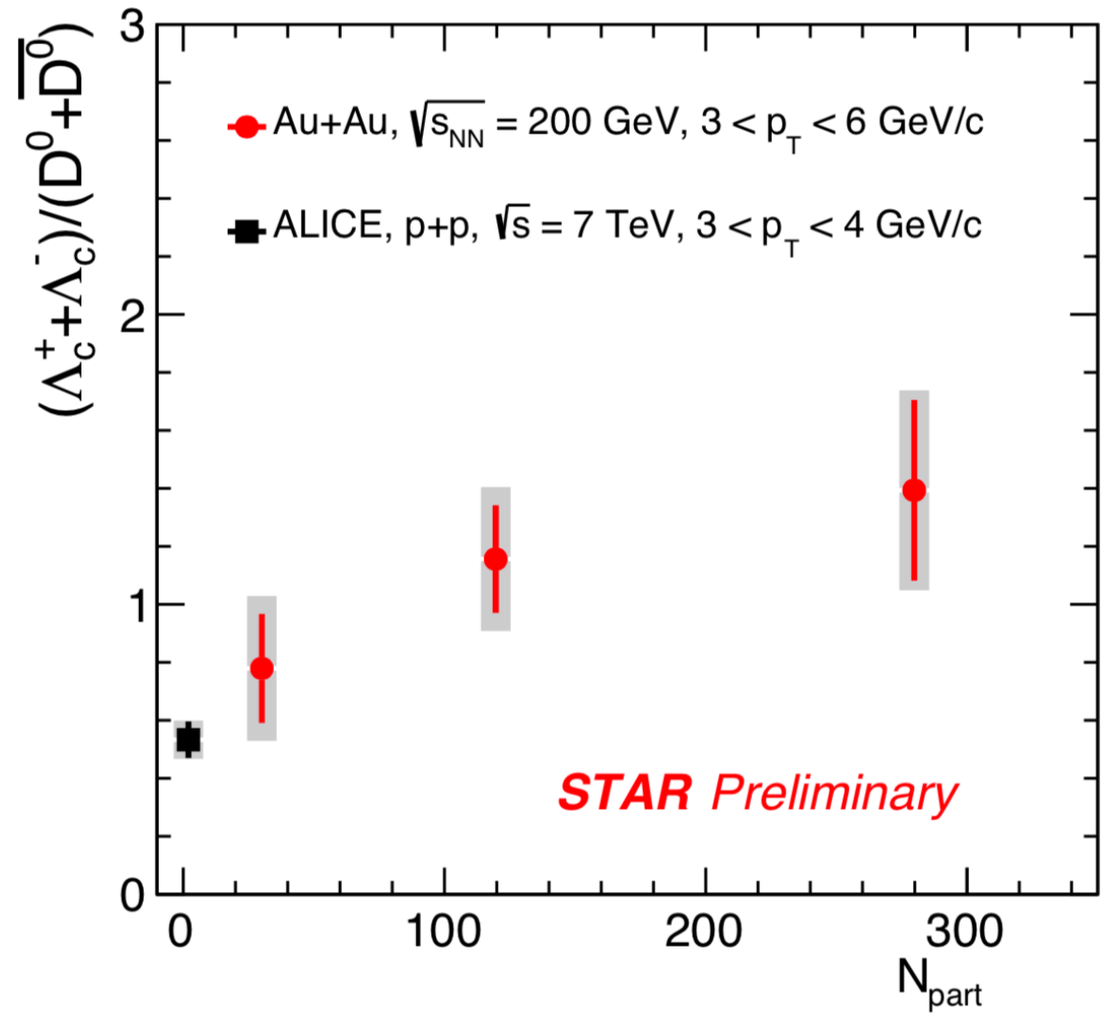

*Ko: Phys.Rev.C 79 (2009) 044905*
*Greco: Eur.Phys.J.C (2018) 78:348*

*ALICE p+p: JHEP 04 (2018) 108*

- Strong enhancement of $\Lambda_c/D^0$ yield ratio, compared to PYTHIA calculations in measured $p_T$ region
  - Enhancement increases towards more central events
  - Models with coalescence hadronization of *c* quarks qualitatively describe the enhancement and $p_T$ dependence

# $\Lambda_c/D^0$ ratio: $p_T$ and centrality dependence



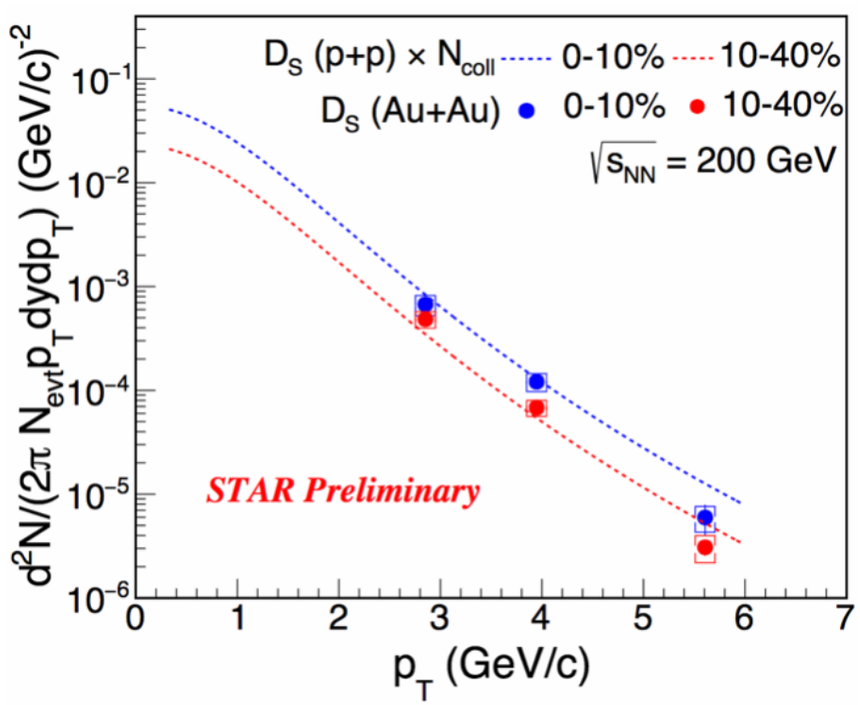



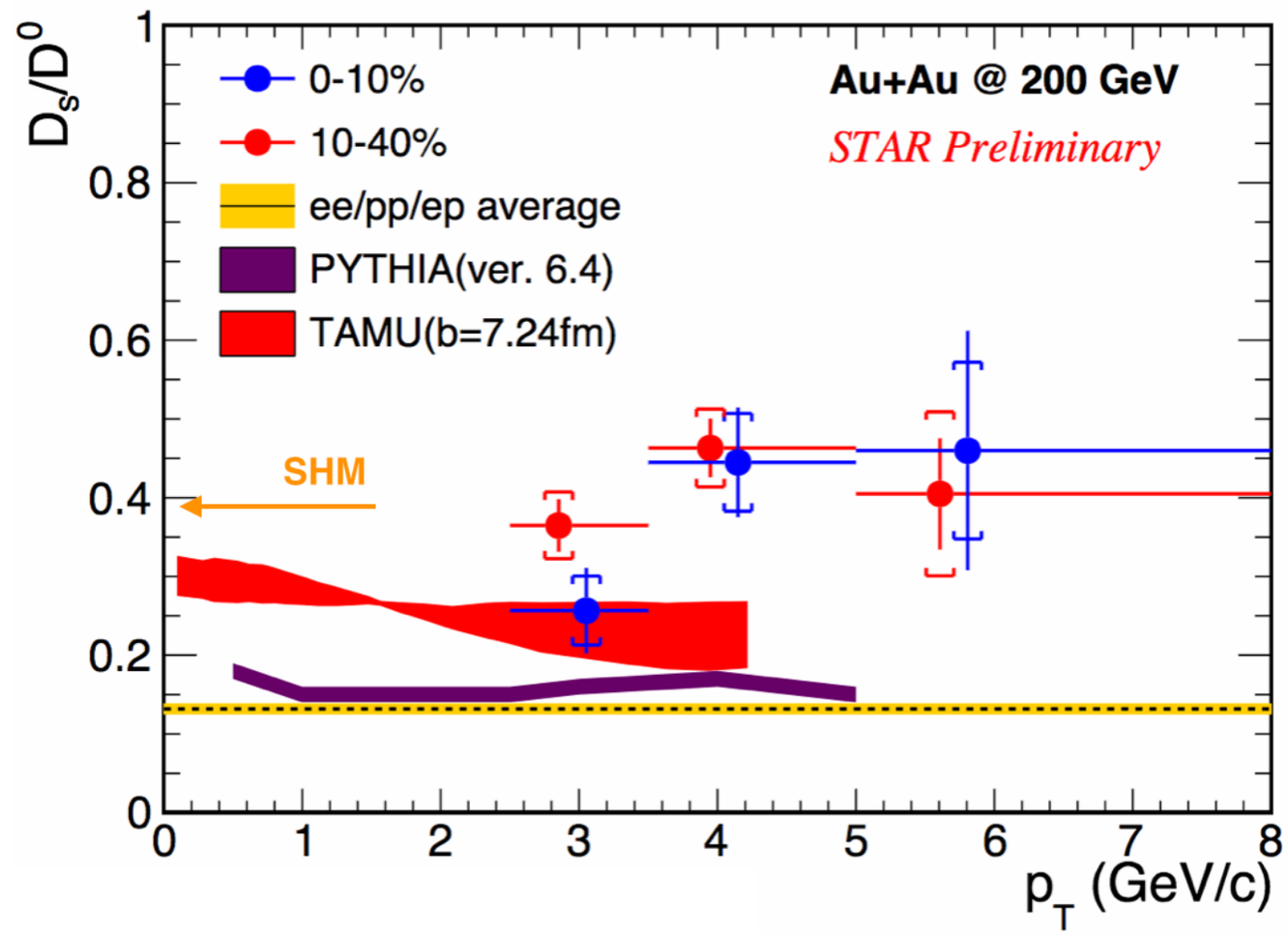

*SHM: Phys.Rev.C 79 (2009) 044905*
*SHM, RQM: arXiv:1902.08889*

- Strong enhancement of $\Lambda_c/D^0$ yield ratio, compared to PYTHIA calculations in measured $p_T$ region
  - $p_T$ integrated values (extrapolation with coalescence models) also larger than SHM calculations
  - Lower $p_T$ measurements can provide further understanding

# $D_s$ production in Au+Au

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




- Coalescence model calculations show enhancement, but under-predict the measured values

*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*

# Total charm cross section

- Total charm cross-section is extracted 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 $\Lambda_c$, 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 |
| | $\Lambda_c^+$ | 78 ± 13 ± 28* |
| | **Total** | **152 ± 13 ± 29** |
| p+p 200 GeV | **Total** | **130 ± 30 ± 26** |

*** derived using $\Lambda_c^+ / D^0$ ratio in 10-80%**

*p+p: Phys Rev Lett.121.229901*

- Total charm cross-section per binary nucleon-nucleon collision in A+A is consistent with p+p value within uncertainties.

# Summary

- **Energy loss:**
  - Strong suppression of D mesons at high $p_T$, comparable to that of light hadrons
  - Indication of less suppression of B —> e compared to that for D —> e
- **Transport:**
  - Charm quarks seem to acquire similar flow as light flavor quarks
  - Diffusion coefficient well constrained by data at $T=T_c$
- **Initial conditions:**
  - $D^0$ $v_1$ order of magnitude larger than $v_1$ of light flavor hadrons
  - Constraints for medium tilt and charm quark viscous drag
  - Consistent values for both $D^0$ and anti-$D^0$
- **Hadronization:**
  - Coalescence hadronization plays an important role at intermediate $p_T$ (2-8 GeV/c)
  - Total charm cross section per binary collision in Au+Au consistent with p+p, but hadrochemistry significantly modified

# Back Up