Production of open-charm hadrons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV measured by the STAR experiment

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OUTLINE

INTRODUCTION

- Motivation for open-charm hadron measurements in heavy-ion collisions
- STAR detector
- Event and track selection
- Open-charm hadrons measurements with the HFT

OPEN CHARM MEASUREMENTS

- Energy loss in the QGP
  - $D^{\pm}$ and D^{0} nuclear modification factor
- Collectivity
  - D^{0} elliptic flow
  - D^{0} directed flow
- Charm quark hadronization
  - D_s/D^{0} ratio
  - Λ_c/D^{0} ratio

PHYSICS MOTIVATION

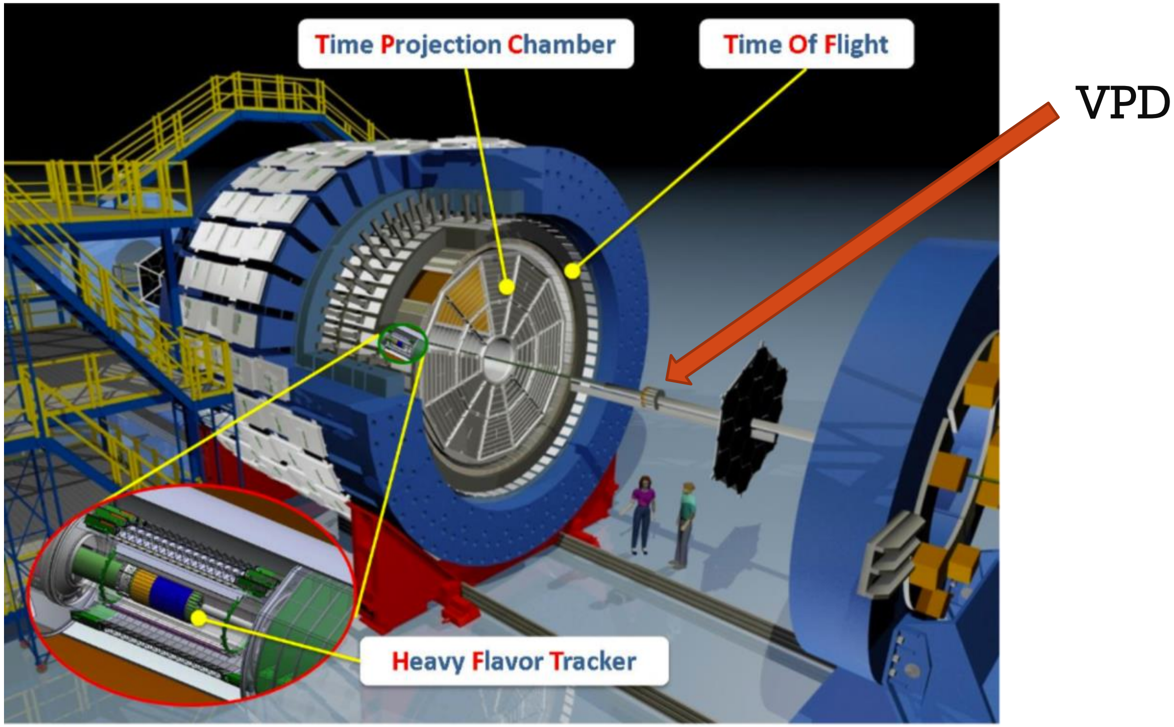
- At RHIC energies, charm and bottom quarks are produced predominantly through partonic hard scatterings at early stage of A+A collisions
  - They experience the whole evolution of the system which makes them an excellent probe of the QGP
  - Observed open-charm hadrons come primarily from initially produced charm quarks with small feedown from bottom decays
- Study of various open-charm hadron species in A+A collisions is essential for understanding the QGP properties as well as charm quark hadronization in the medium
  - **Energy loss in the medium**
    - **D^0, $D^\pm$ nuclear modification factor**
  - **Initial tilt of the bulk + initial electromagnetic field**
    - **D^0 directed flow**
  - **Heavy quark diffusion coefficient**
    - **D^0 elliptic flow**
  - **Hadronization**
    - **D_s, Λ_c production**

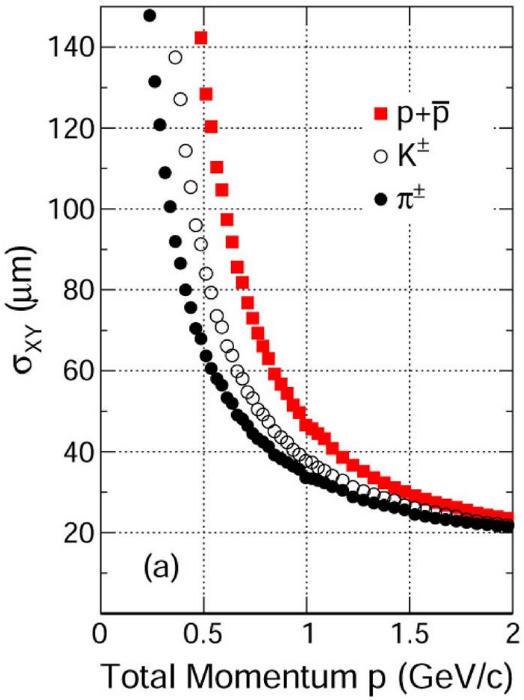
STAR DETECTOR

- **S**olenoidal **T**racker **A**t **R**HIC
- **Heavy Flavor Tracker** (HFT, 2014–2016) is a 4-layer silicon detector
  - MAPS – 2 innermost layers, Strip detectors – 2 outer layers
- **Time Projection Chamber** (TPC) and **Time Of Flight** (TOF)
  - Particle momentum (TPC) and identification (TPC and TOF), centrality (TPC)
- Vertex Position Detector (VPD)
  - Vertex position along the beam axis

Zero Degree Calorimeter

Centrality determination

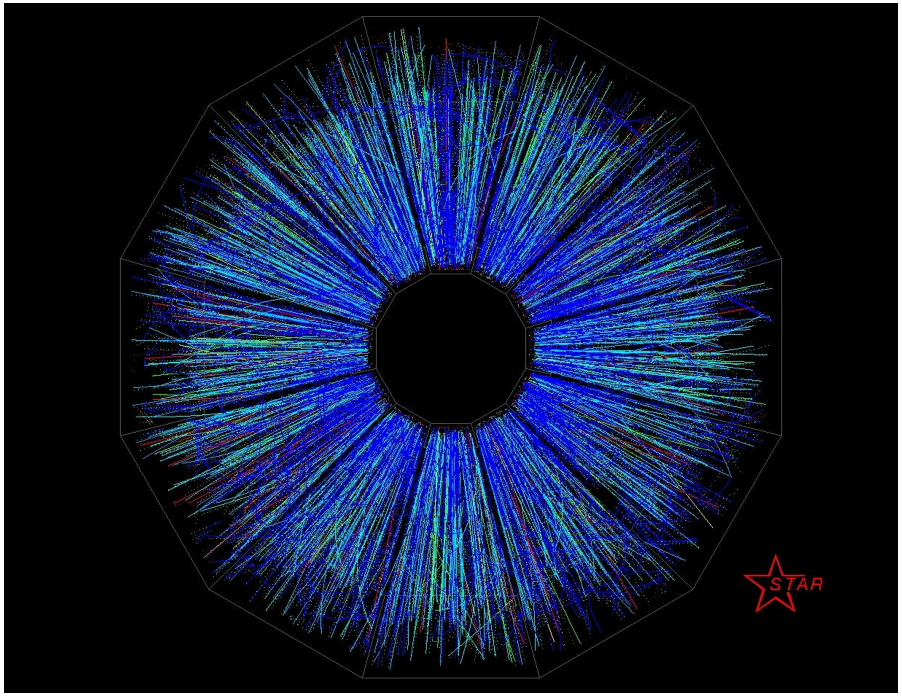




PRL 118 212301 (2017)

EVENT AND TRACK SELECTION

- Event selection cuts
  - Position of primary vertex along the beam axis (TPC, VPD)
- Track quality cuts
  - p_T – suppresses combinatorial background from low p_T particles
  - $|\eta| < 1$ – detector acceptance
  - Minimum number of hits in the TPC for each track – good track quality
- Particle identification (PID)
  - TPC – energy loss of charged particles in the TPC gas
  - TOF – velocity of the charged particles
- Topological cuts
  - Possible only with use of the HFT
  - Constrain topology of the reconstructed secondary vertex
  - Suppress combinatorial background



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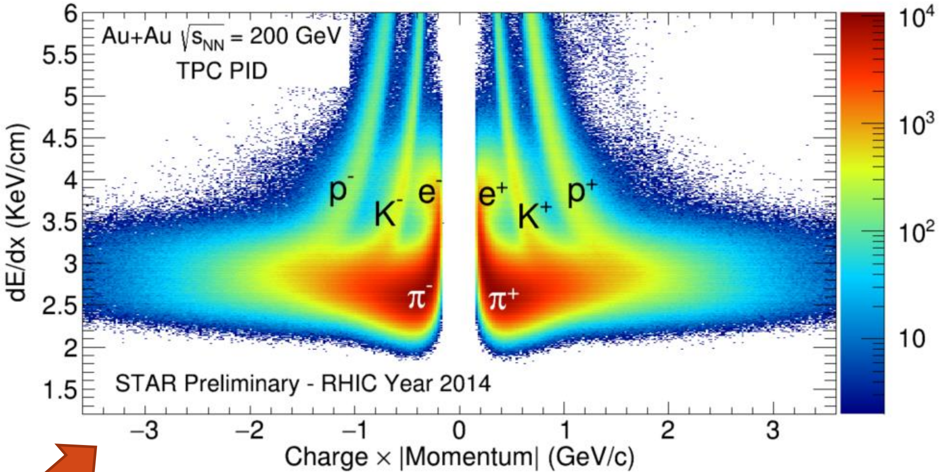

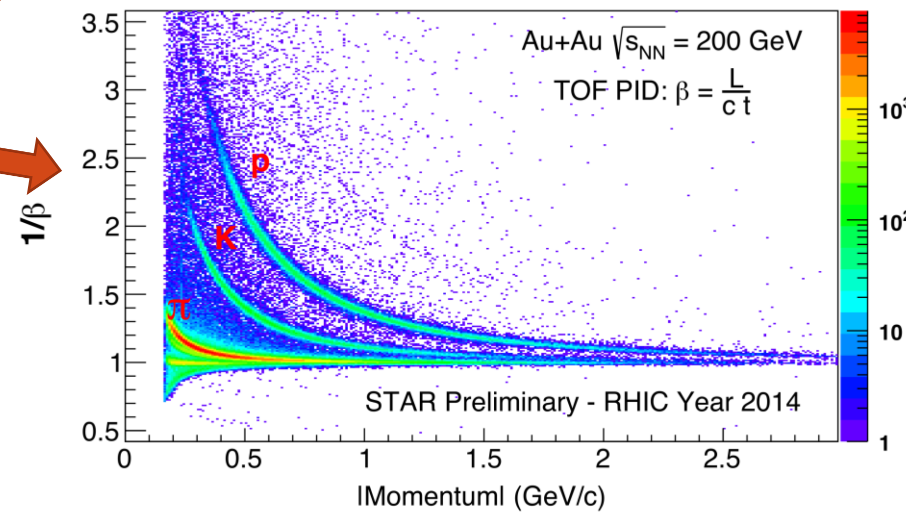

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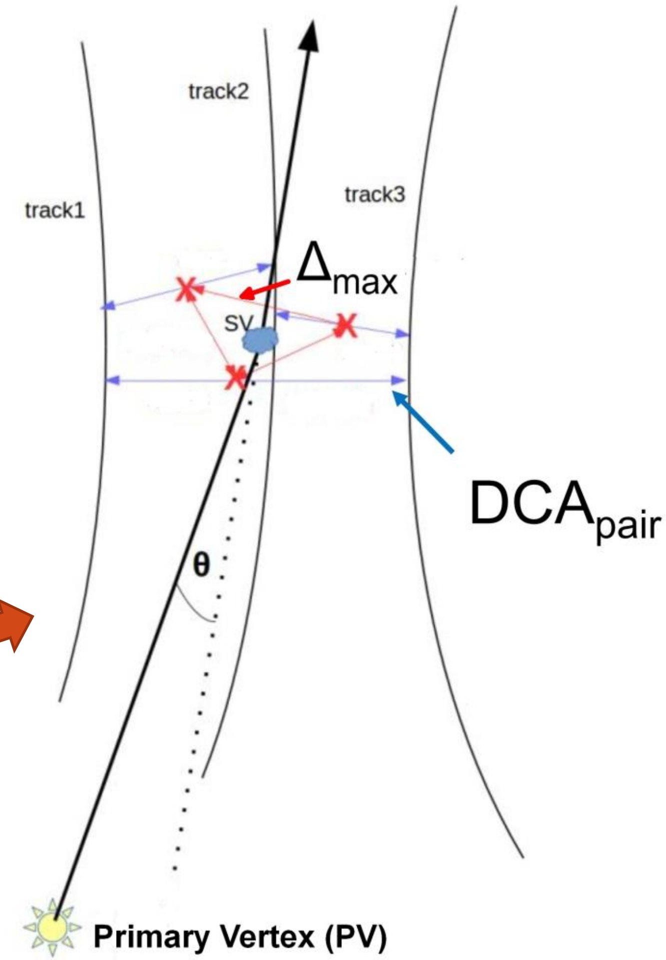


OPEN-CHARM MEASUREMENTS WITH THE HFT

- Decay channels used*:
  - $D^+ \rightarrow K^-\pi^+\pi^+$ $c\tau = (311.8 \pm 2.1)\ \mu m$ $BR = (8.98 \pm 0.28)\ \%$
  - $D^0 \rightarrow K^-\pi^+$ $c\tau = (122.9 \pm 0.4)\ \mu m$ $BR = (3.93 \pm 0.04)\ \%$
  - $D_s^+ \rightarrow \phi\pi^+,\ \phi \rightarrow K^-K^+$ $c\tau = (149.9 \pm 2.1)\ \mu m$ $BR = (2.27 \pm 0.08)\ \%$
  - $\Lambda_c^+ \rightarrow K^-\pi^+p$ $c\tau = (59.9 \pm 1.8)\ \mu m$ $BR = (6.35 \pm 0.33)\ \%$
  - *Charge conjugate particles are also measured

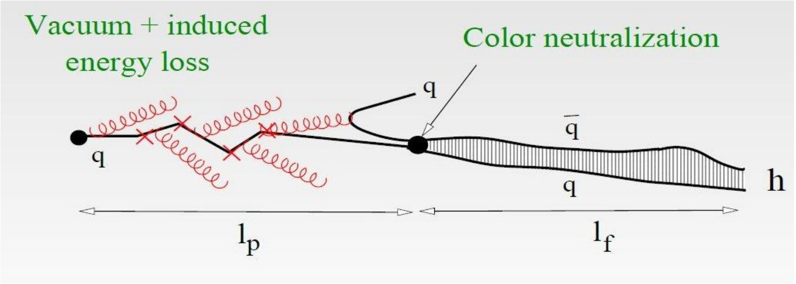
- The HFT allows direct topological reconstruction of open-charm hadrons through their hadronic decays

- STAR took data with the HFT in 2014 and 2016 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
  - 2014: ~900M minimum-bias events
  - 2016: ~1.3B minimum-bias events

HEAVY QUARK ENERGY LOSS IN THE QGP

- At RHIC, charm quarks are created predominantly during the hard scattering
  - They pass through the QGP where they loose energy
- The precise mechanism of open-charm suppression in A+A collisions is not known

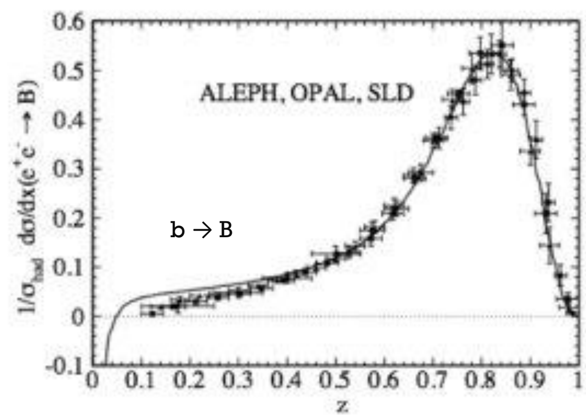
- **Quark propagation through the QGP**
  - Production phase
    - "Free" quark with large virtuality (does not have its gluon field)
    - Radiative energy loss
      - Vacuum – restoration of the gluon field
      - Medium induced
  - Formation phase
    - "Pre-hadron"
    - Momentum transfer between the quarks
- **Hadronization process**
  - Fragmentation, coalescence…

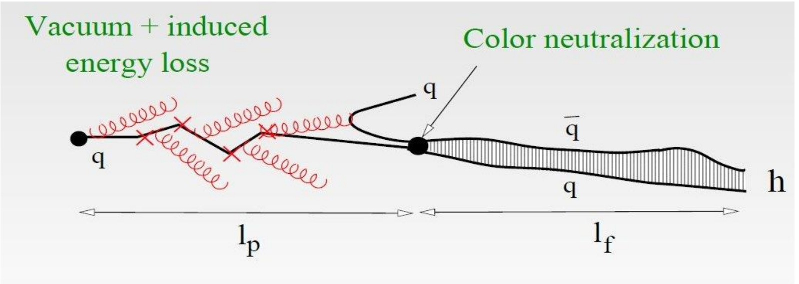


Kopeliovich, et al.: arXiv:1208.4951v1 [hep-ph]

HEAVY QUARK ENERGY LOSS IN THE QGP

- Example: Kopeliovich, et al.: arXiv:1208.4951v1
  - Any quark looses its gluon field after the hard scattering
  - Light flavor quarks:
    - Production time t_p is very short
      - Quark quickly restores its gluon field by vacuum radiation
    - Formation time t_f is long compared to t_p
      - Pre-hadron interacts with the QGP
        - **Collisional energy loss**
  - Heavy flavor quarks:
    - Production time t_p is also short
      - Vacuum radiation suppressed by the dead-cone effect
    - Formation phase
      - Large momentum transfer from the heavy to the light quark – can break the pre-hadron
      - The heavy quark will carry lower fraction of the final state hadron momentum
        - **Shift to lower value of the fragmentation function**





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$D^{\pm}$ and D^0 nuclear modification factor

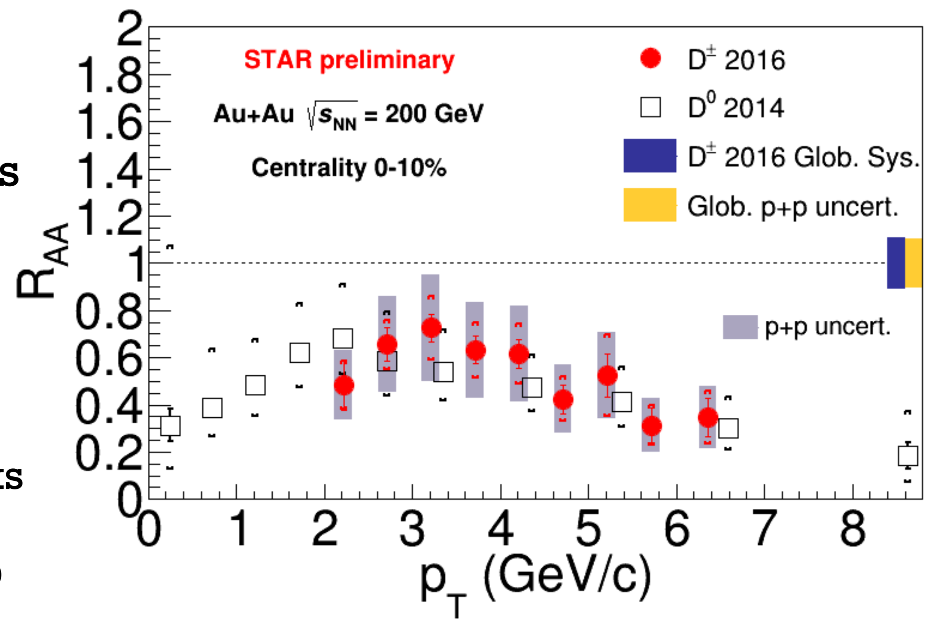
- Nuclear modification factor:

$$R_{AA}(p_T) = \frac{\mathrm{d}N_D^{AA}/\mathrm{d}p_T}{\langle N_{coll} \rangle \, \mathrm{d}N_D^{pp}/\mathrm{d}p_T}$$

- Reference: combined D^0 and D* measurement in 200 GeV p+p collisions using 2009 data

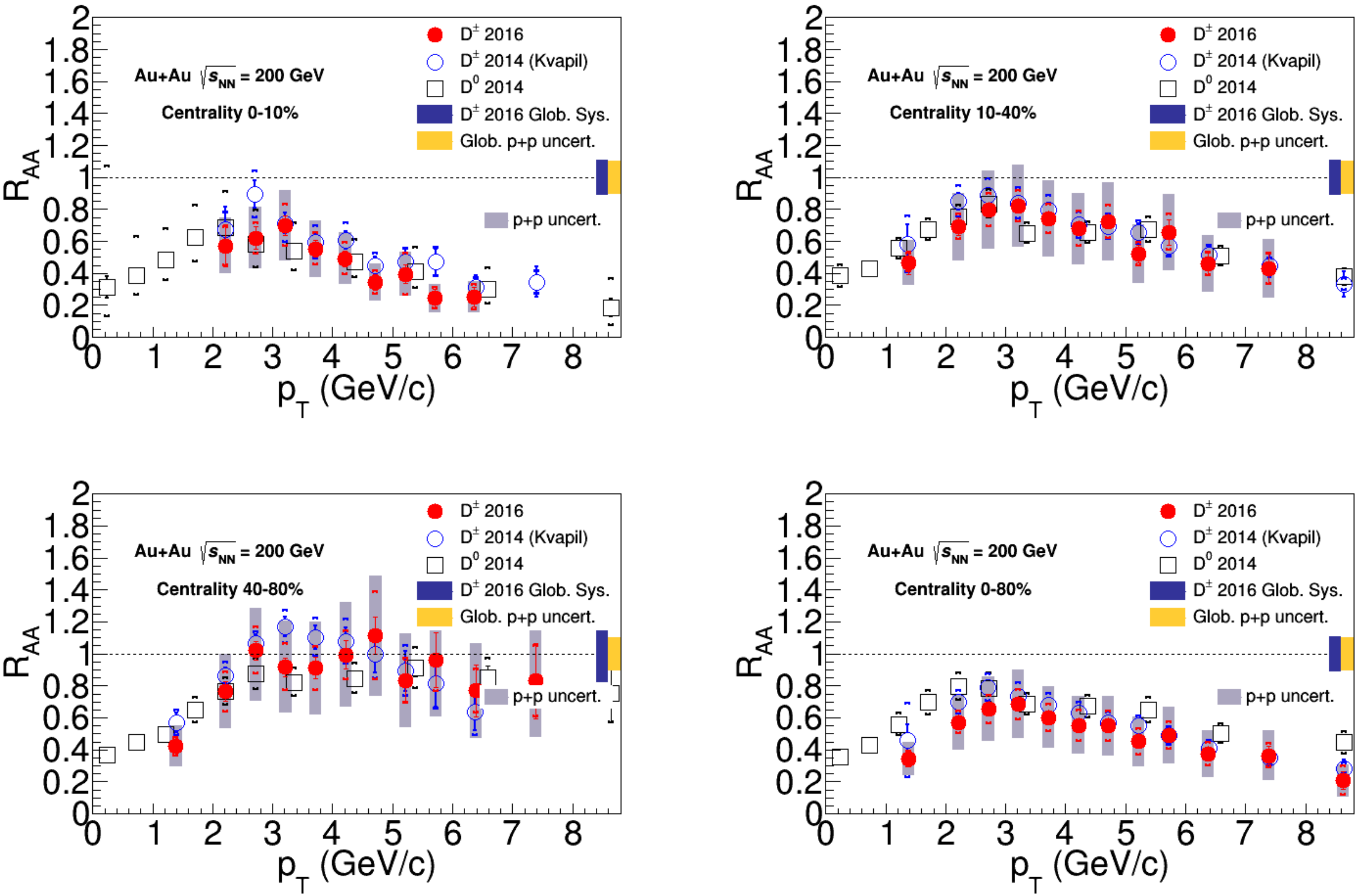
- **High p_T $D^{\pm}$ and D^0 suppressed in central Au+Au collisions**
  - Strong interactions between charm quarks and the medium
  - Similar level of suppression for $D^{\pm}$ and D^0

- **Low p_T D^0 suppressed as well**
  - Integrated RAA < 1



D^0 (STAR): arXiv:1812.10224v1

$D^{\pm}$ AND D^{0} R_{AA} CENTRALITY DEPENDENCE



COLLECTIVITY

- Shape of the QGP fireball has direct influence on particle production in A+A collisions
- The initial geometry of the bulk propagates to the azimuthal p_T distribution of final state hadrons
- We can expand this distribution into the Fourier series:

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

where φ is the azimuthal angle, Ψ_n is the n-th order event plane angle and **v_n is the n-th order harmonic coefficient**

  - **v_1 = directed flow**
  - **v_2 = elliptic flow**
  - **v_3 = triangular flow**
  - **…**

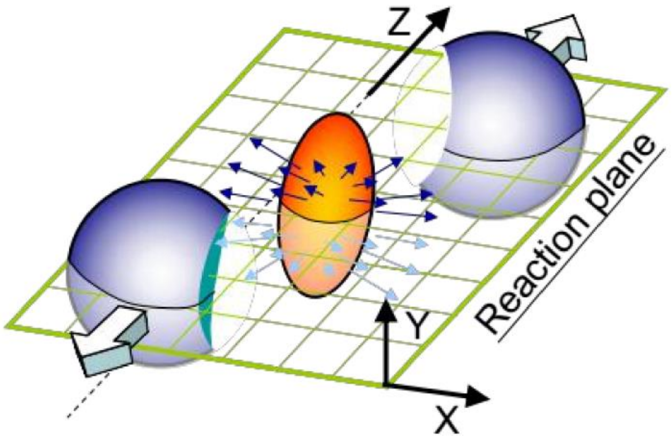


Figure by R. Vertesi

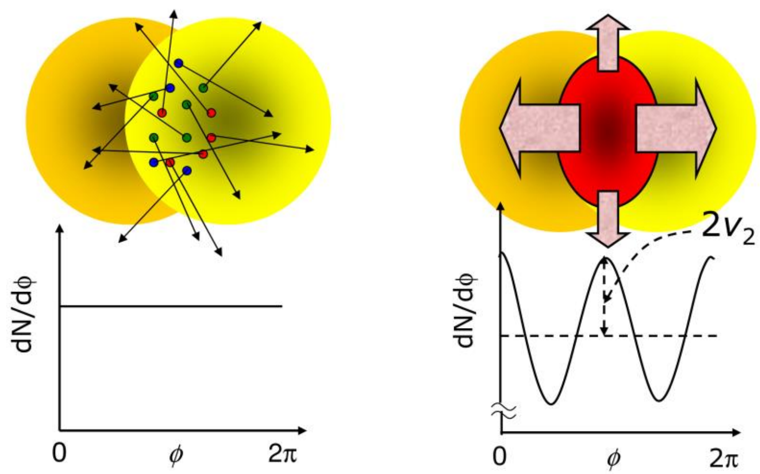
ELLIPTIC FLOW

Light flavor quarks:

- In semi-central A+A collisions the shape of the overlap region can be approximated by an ellipse
- High pressure in the center of the bulk and zero pressure at the surface (the bulk sits in the vacuum)
  - Works only if the mean free path of the particles in the bulk is (much) smaller than the size of the bulk itself
- Higher pressure gradient in the event plane
- Leads to elliptic asymmetry of the azimuthal p_T distribution

Heavy flavor quarks:

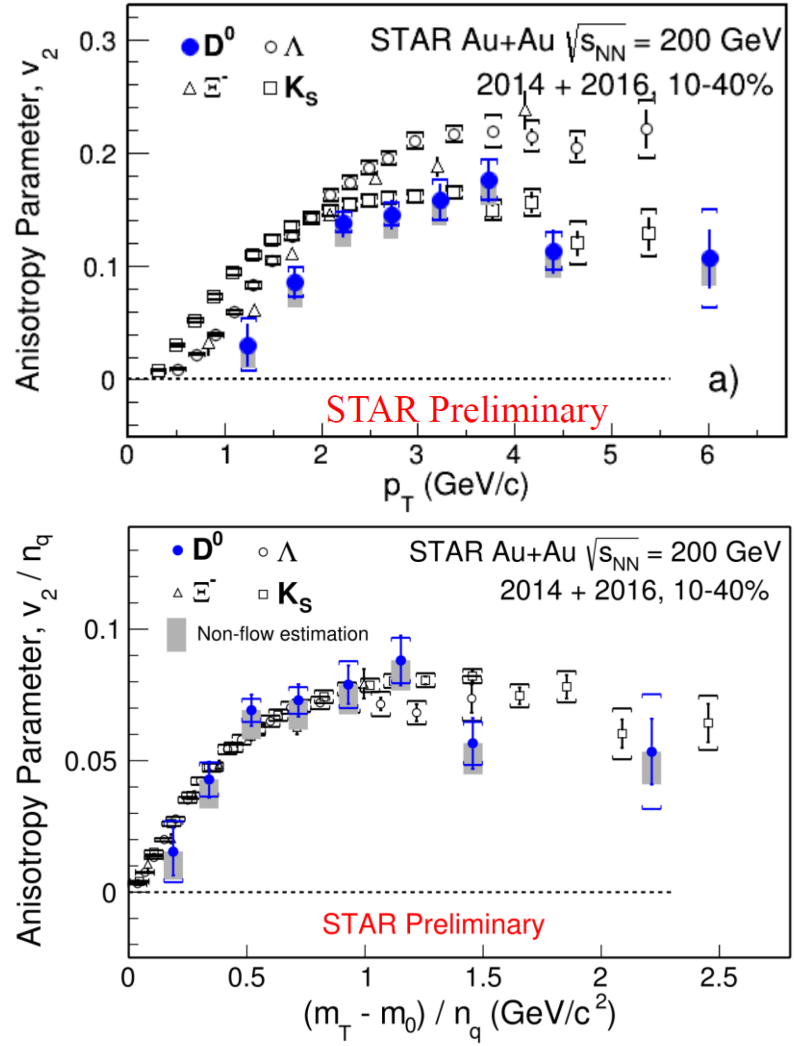
- Heavy quark interacts and thus thermalizes with the surrounding medium
- The more thermalized it gets, the more it will "flow" with the bulk



Hirano: arXiv:0808.2684v1

D^0 ELLIPTIC FLOW

- Non-zero elliptic flow (v_2) of D^0
  - Strong collective behavior of charm quarks
- As a function of p_T
  - Mass ordering for $p_T < 2$ GeV/c
  - Comparable to light mesons for $p_T > 2$ GeV/c
- As a function of $(m_T - m_0)/n_q$
  - Follows Number of Constituent Quarks (NCQ) scaling
- **Suggests that c quarks might have achieved thermal equilibrium with the QGP**

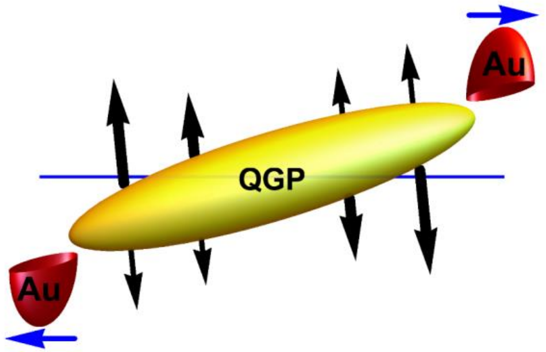


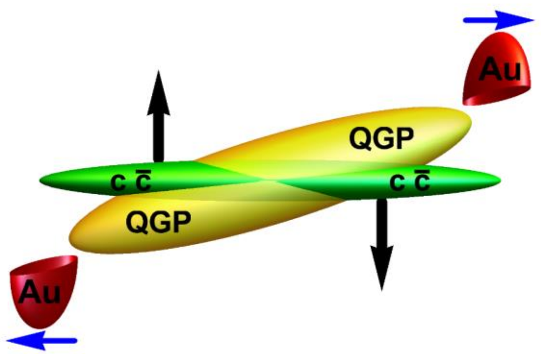
HEAVY-FLAVOR QUARKS DIRECTED FLOW

- **Hydrodynamics**

- Light-flavors
  - Tilted bulk
  - Transverse and longitudinal pressure
  - *Bozek, Wyskiel, Phys. Rev. C81, 054902 (2010)*

- Heavy-flavors
  - Difference between the tilt of the bulk and the density profile of HF production
  - Larger slope of HF than light flavors
  - *Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)*





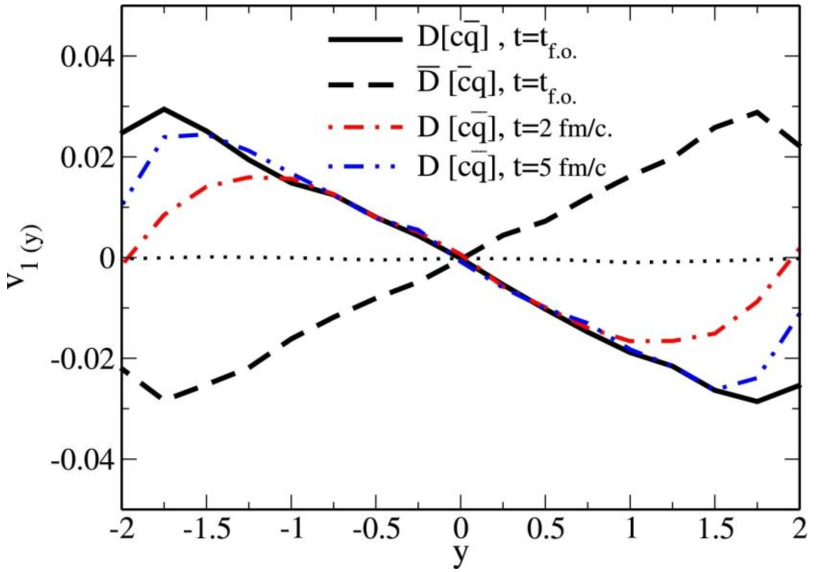
Figures by P. Bozek

HEAVY-FLAVOR QUARKS DIRECTED FLOW

- **Initial EM field from passing spectators**

- Light-flavors
  - Most light flavor quarks created late in the collision
  - Do not "feel" the initial EM field

- Heavy-flavors
  - Created early
  - Should experience the initial EM field
  - EM field "survives" long enough due to presence of the QGP
    - QGP is a conductor
    - *Gursoy et. al., Phys Rev C 89, 054905 (2014)*
  - Predicted opposite slope for D^0 and $\overline{D^0}$ due to opposite charge of c and $\bar{c}$ quarks
    - *Das et. al., Phys Lett B 768, 260 (2017)*



Das et. al., Phys Lett B 768, 260 (2017)

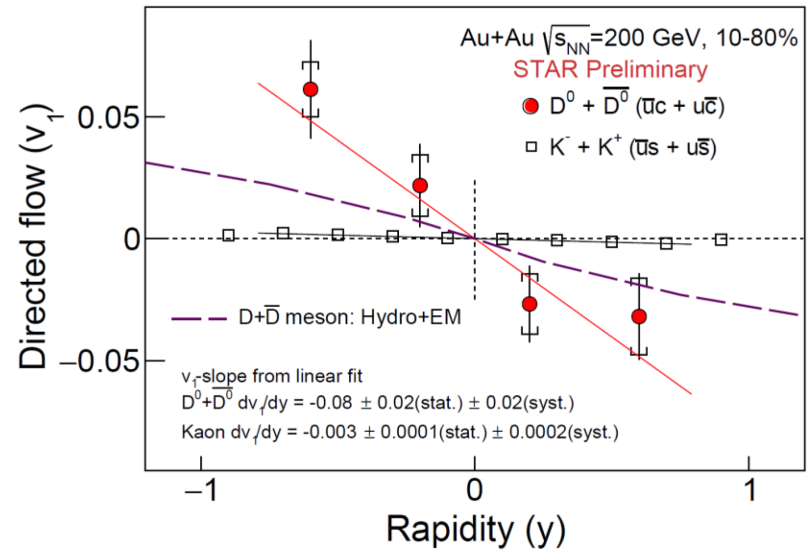
D^0 DIRECTED FLOW

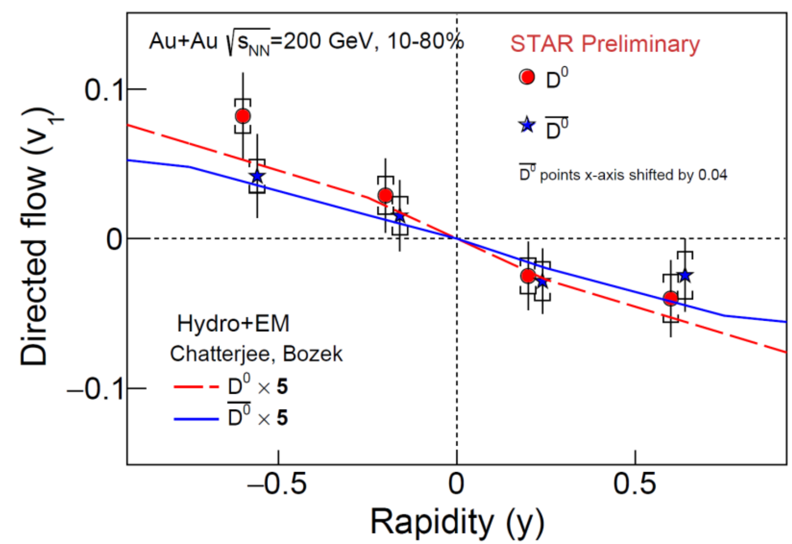
- First evidence of non-zero directed flow (v_1) of D^0 and $\overline{D^0}$ as a function of rapidity (y)

- Negative v_1 slope for combined D^0 and $\overline{D^0}$
- Model underpredicts the slope of D^0
- **Larger v_1 slope for D^0 than for kaons**

- Insufficient precision to conclude about the EM induced splitting
- **Negative v_1 slope for both D^0 and $\overline{D^0}$**

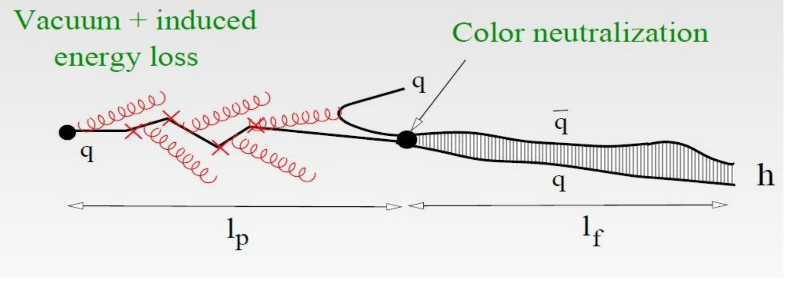
Kaons (STAR): PRL 120, 062301 (2018).





CHARM QUARK HADRONIZATION

- Fragmentation
  - Heavy quark radiates gluon which splits into quark anti-quark pair
  - The anti-quark is captured by the heavy quark
  - Present in the vacuum and the QGP
- Coalescence
  - The heavy quark passes through the QGP
  - It captures an anti-quark from the medium which is close in a kinematic phase-space
  - Present only in the QGP
- Statistical Hadronization Model (SHM)
  - Treats the QGP as a thermalized statistical source of particles



Kopeliovich, et al.: arXiv:1208.4951v1 [hep-ph]

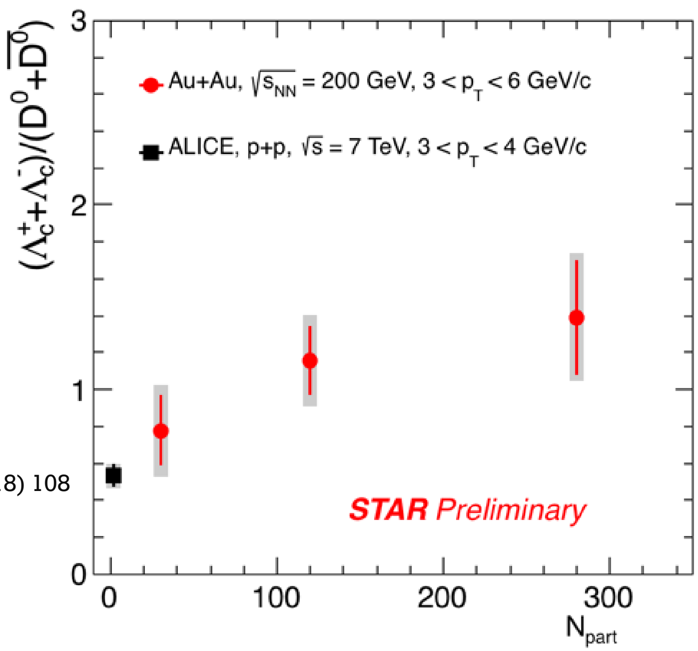
Λ_C/D^0 RATIO (STAR)

CENTRALITY DEPENDENCE

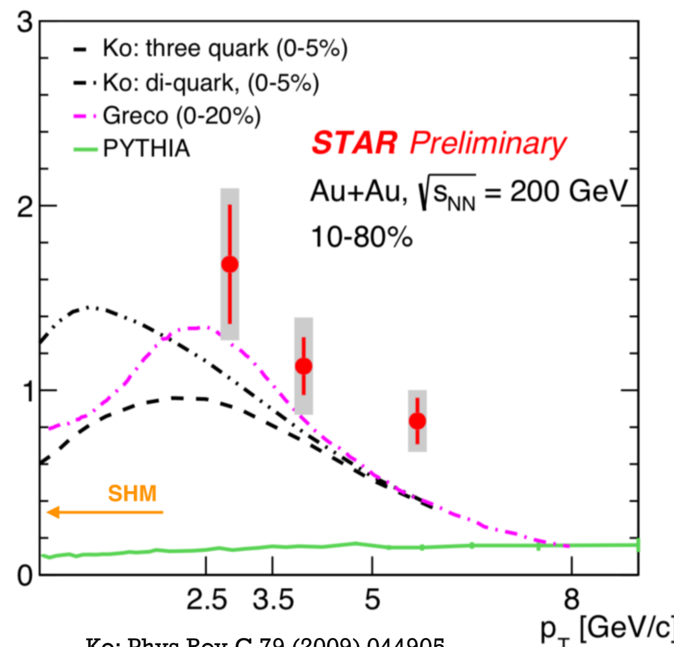
- The value in peripheral collisions is consistent with p+p measurement at $\sqrt{s} = 7$ TeV by ALICE
- **Enhancement of the ratio increases towards central collisions**

p_T DEPENDENCE

- Coalescence models closer to data than PYTHIA
- SHM underpredicts data
- **Strong enhancement towards low p_T**



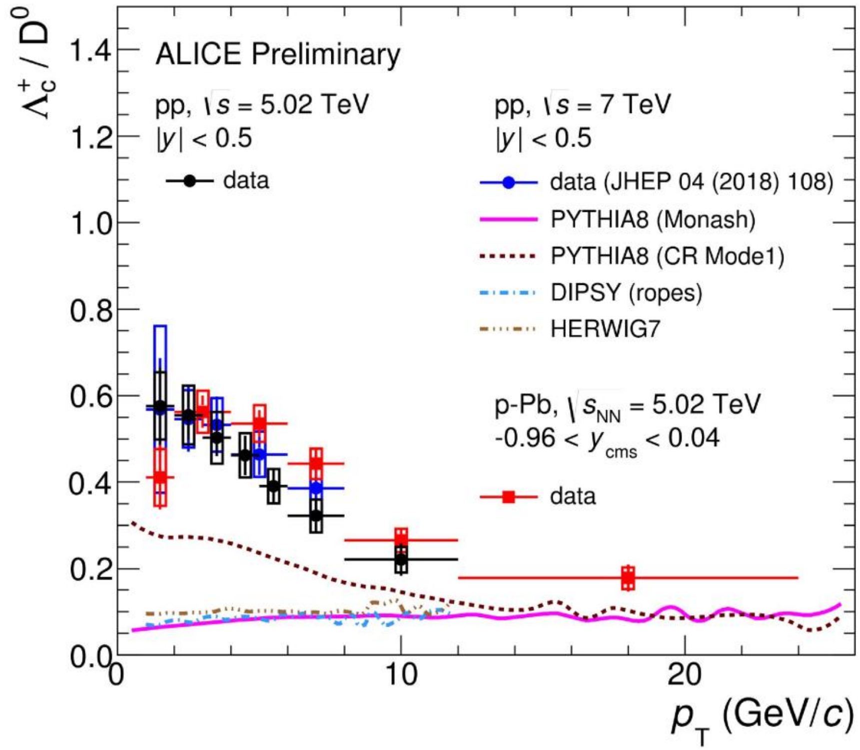
ALICE: JHEP 04 (2018) 108



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

Λ_c/D^0 RATIO (ALICE)

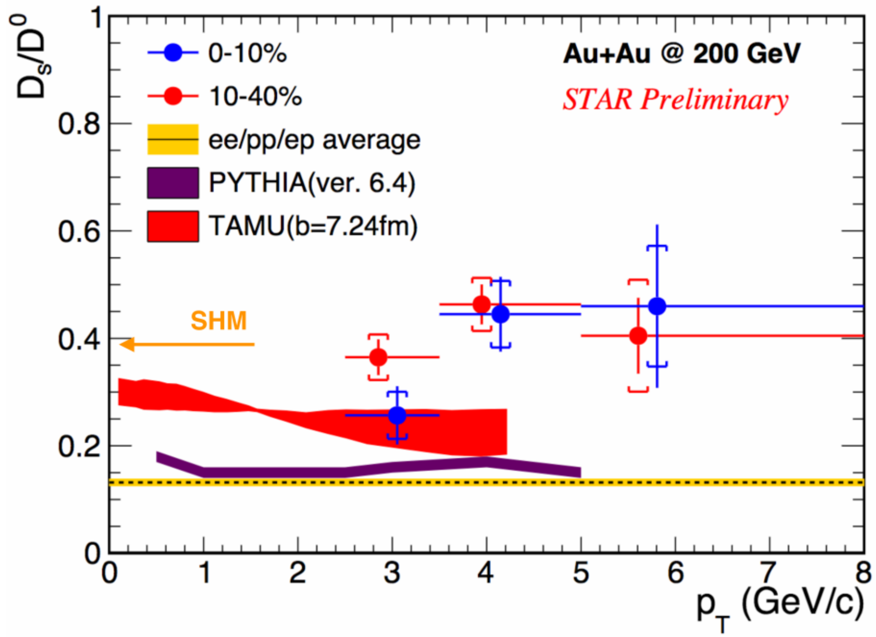
- ALICE measurements of Λ_c/D^0 ratio in p+p and p+Pb collisions
- Both colliding systems underpredicted by model calculations
- Possibly due to wrong fragmentation ratio of Λ_c from HERA?
- **We do not quite understand production of Λ_c**



ALICE: JHEP 04 (2018) 108

D_s/D^0 ENHANCEMENT

- D_s/D^0 ratio as a function of p_T
- Enhancement of D_s/D^0 ratio in Au+Au collisions with respect to PYTHIA and elementary collisions (ee/pp/ep)
  - TAMU underpredicts measurements
  - Reasonable agreement with SHM
- **D_s is enhanced in Au+Au collisions possibly due to strangeness enhancement and coalescence hadronization**



ep/pp/ep avg: EPJ C 76, 397 (2016)
TAMU: PRL 110, 112301 (2013)
SHM: Phys.Rev.C 79 (2009) 044905

CONCLUSION

- STAR has extensively studied production of open-charm hadrons in heavy-ion collisions
  - Outstanding spatial resolution of the STAR HFT allows precise measurements of open-charm hadrons
  - Presented results provide significant constraints on model calculations
- D^0 and $D^{\pm}$ mesons are significantly suppressed in central Au+Au collisions
  - Important for understanding charm quark energy loss in the QGP
- D^0 mesons have larger v_1 slope than light-flavor mesons
  - Can probe initial tilt of the bulk
- D^0 mesons have v_2 comparable to light-flavor hadrons
  - c quarks are possibly in thermal equilibrium with the medium
- Λ_c/D^0 and D_s/D^0 enhancements in Au+Au collisions with respect to p+p collisions
  - Important for understanding hadronization process
  - Importance of coalescence

THANK YOU FOR ATTENTION