Heavy-flavor production at RHIC

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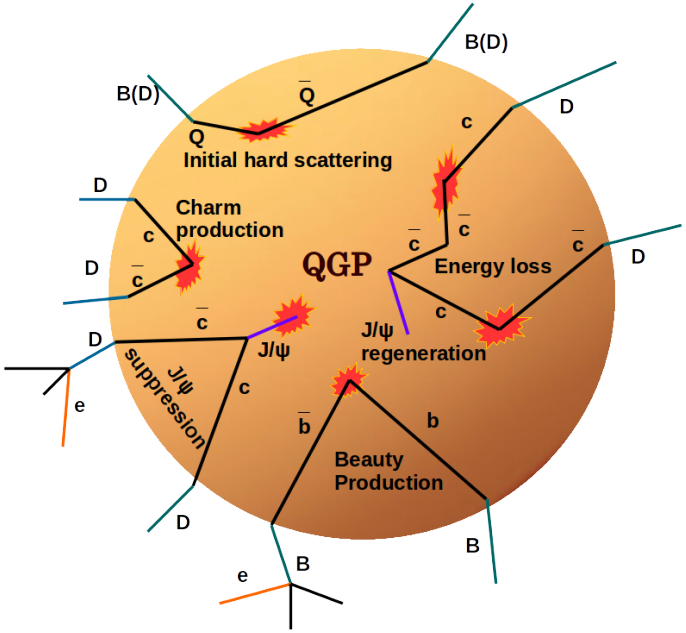
Outline

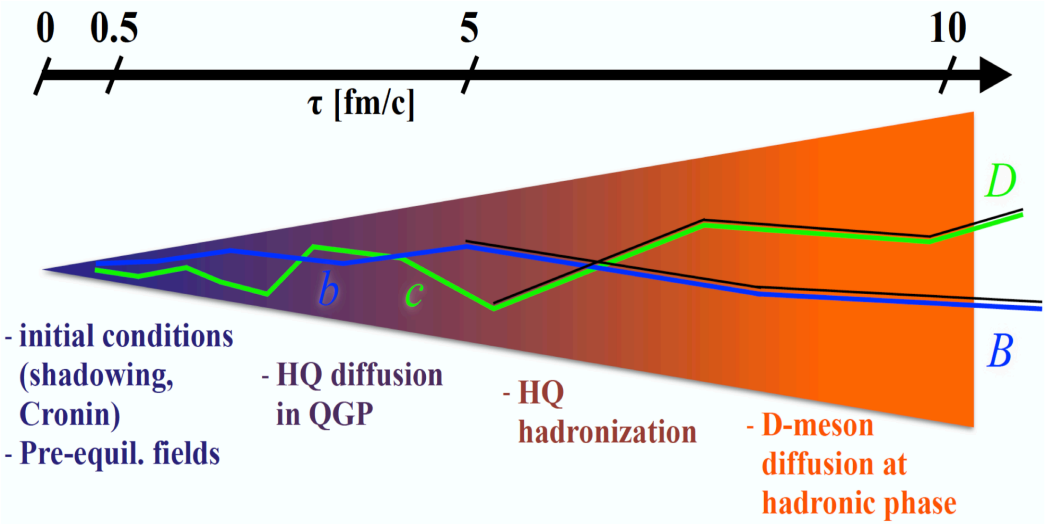
- Introduction
- STAR Experiment
- Open charm hadron measurements
- Quarkonium measurements
- Summary

Heavy Quarks

Heavy quarks: $m_{c/b} >> \Lambda_{QCD}$

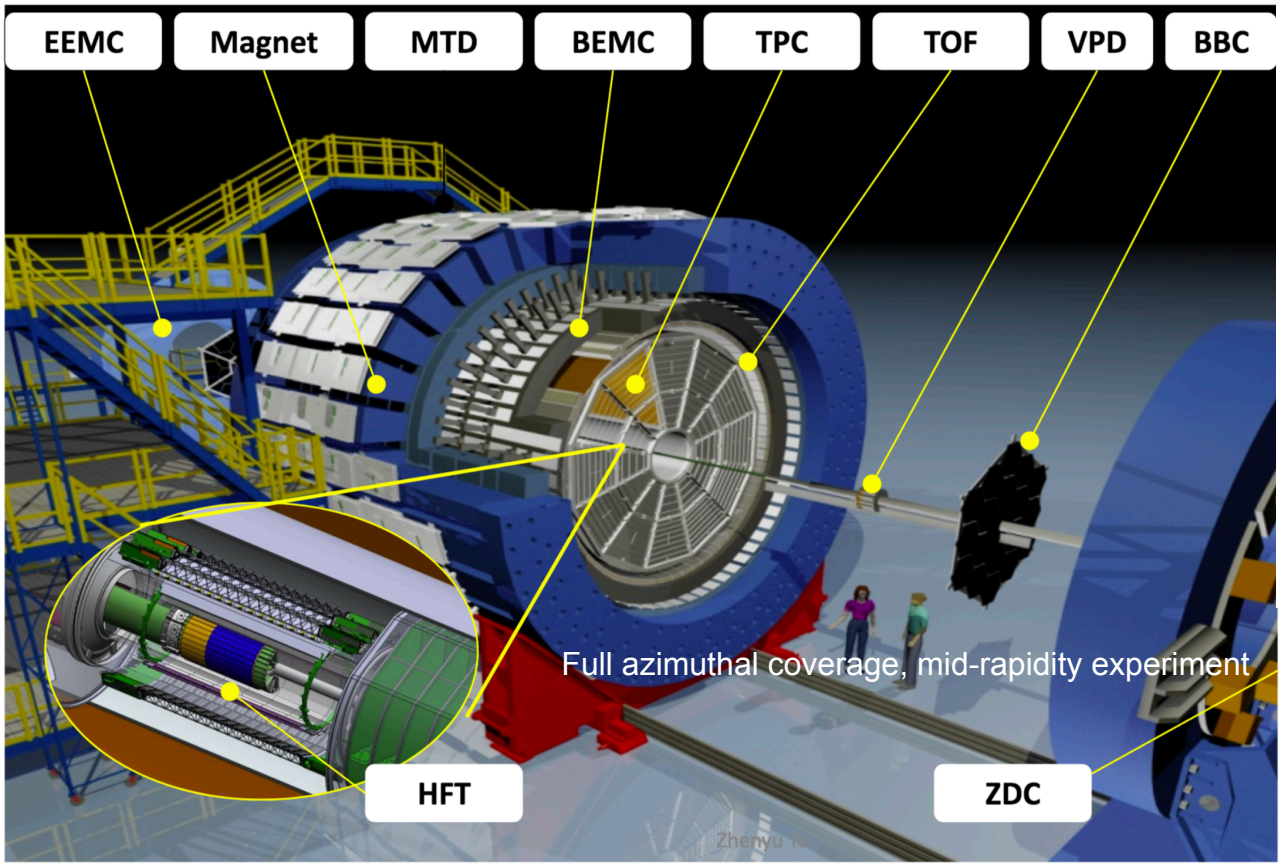
- Produced early through hard scatterings
- Experience the whole evolution of the system
- Thermal relaxation time is comparable to the life-time of the system.

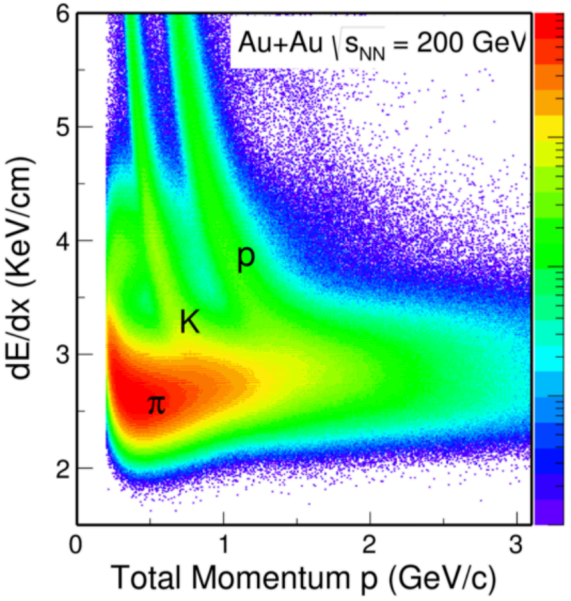


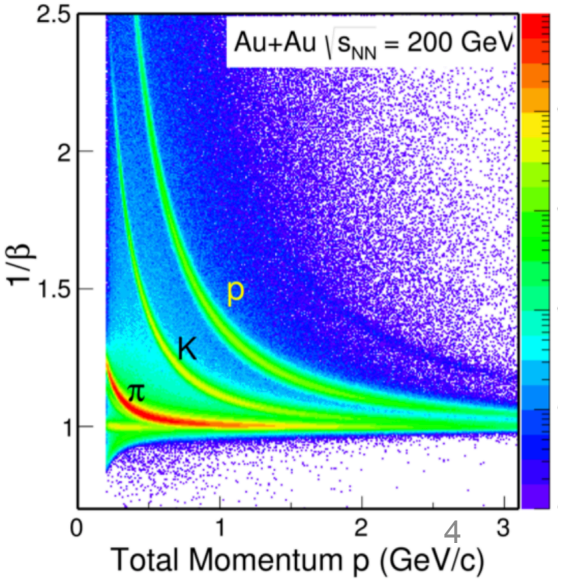


Excellent probes for the medium produced in heavy-ion collisions

Solenoidal Tracker At RHIC



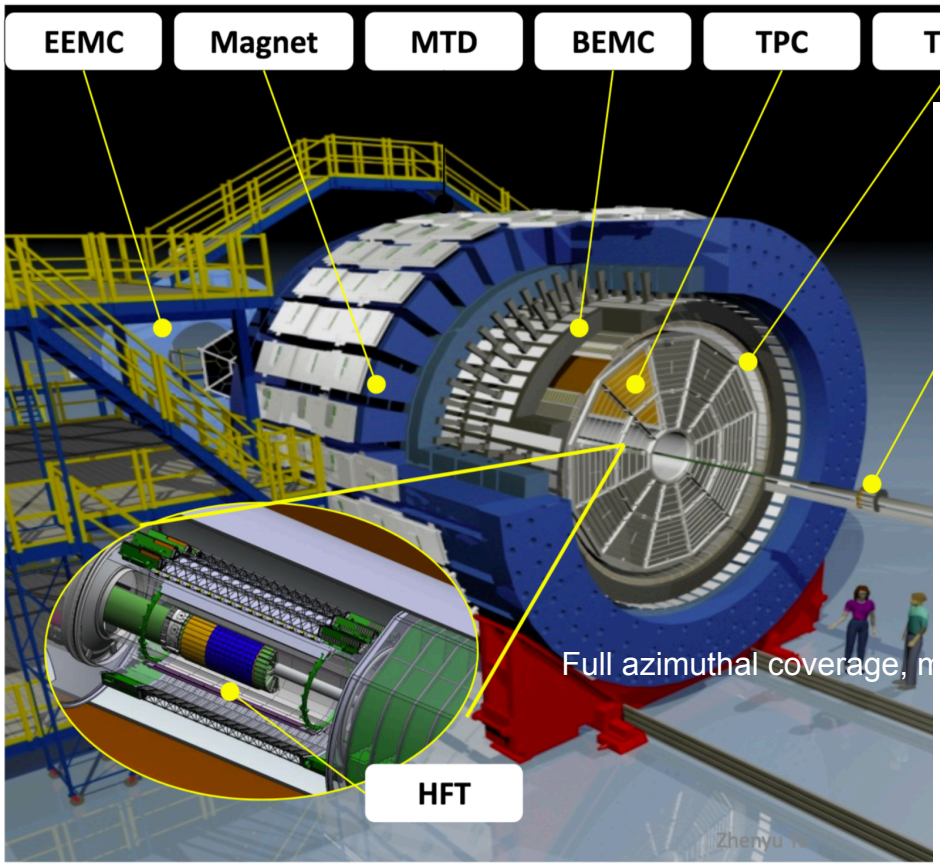


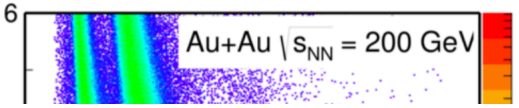


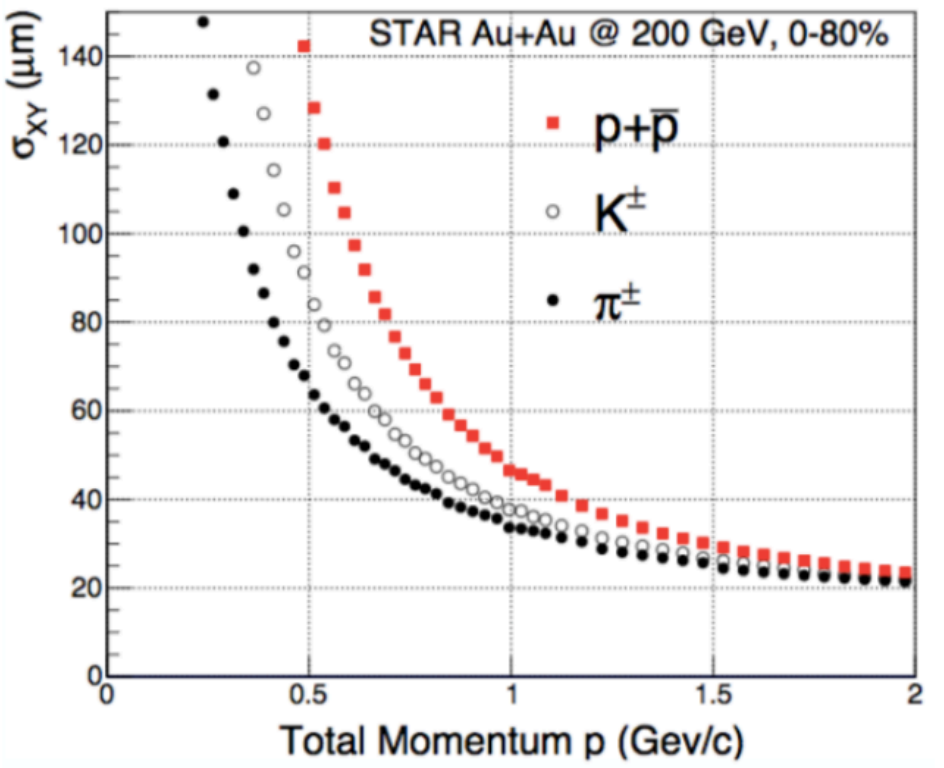
Charged particle tracking:
Time Projection Chamber (TPC) + Heavy Flavor Tracker (HFT, 2014-16)

Particle identification:
TPC, Time Of Flight detector (TOF), Muon Telescope Detector (MTD), Electromagnetic calorimeters (BEMC, EEMC)

Solenoidal Tracker At RHIC







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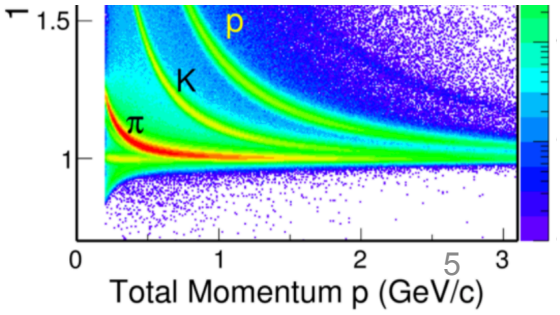
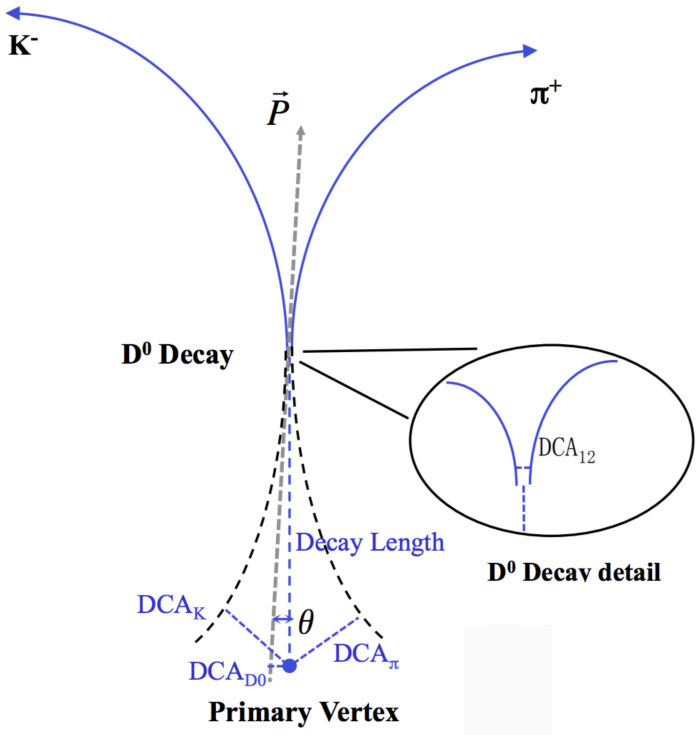
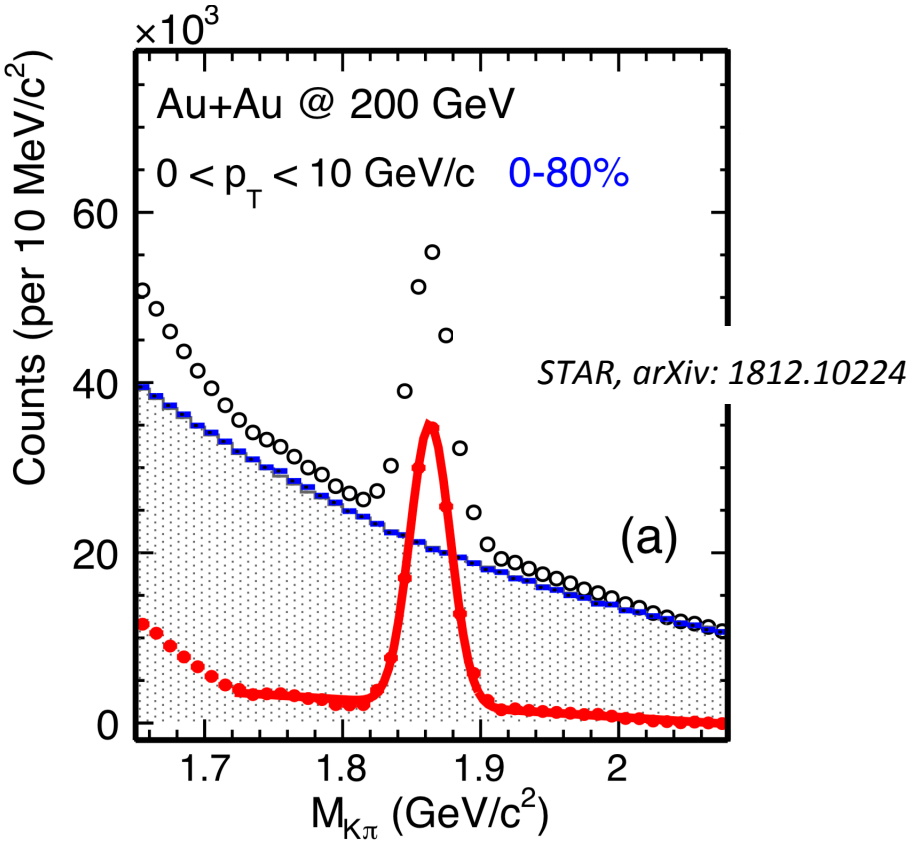


Open Charm (D^0) Identification

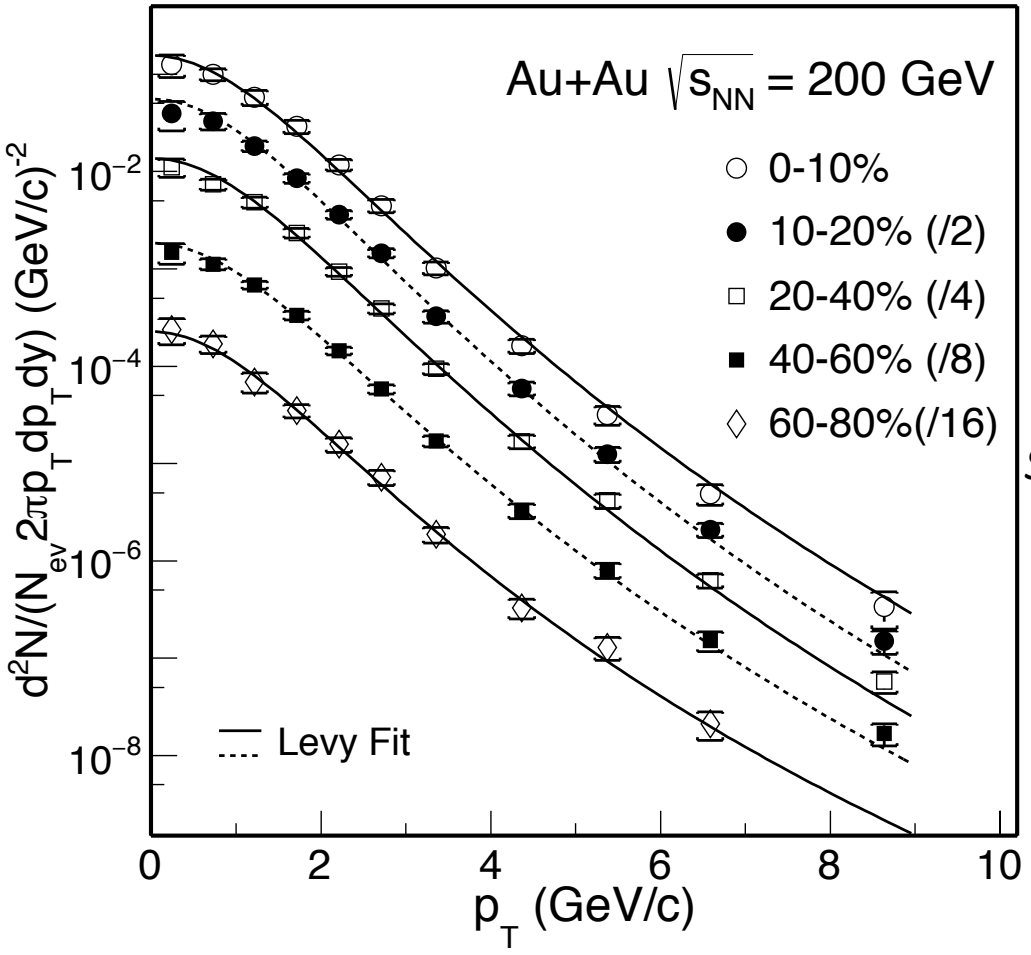


Topological reconstruction of D^0 meson using HFT



Significance improved by a factor of 15 for D^0, compared to reconstruction without HFT (PRL 113, 142301 (2014))

D^0 meson Production



STAR, arXiv: 1812.10224

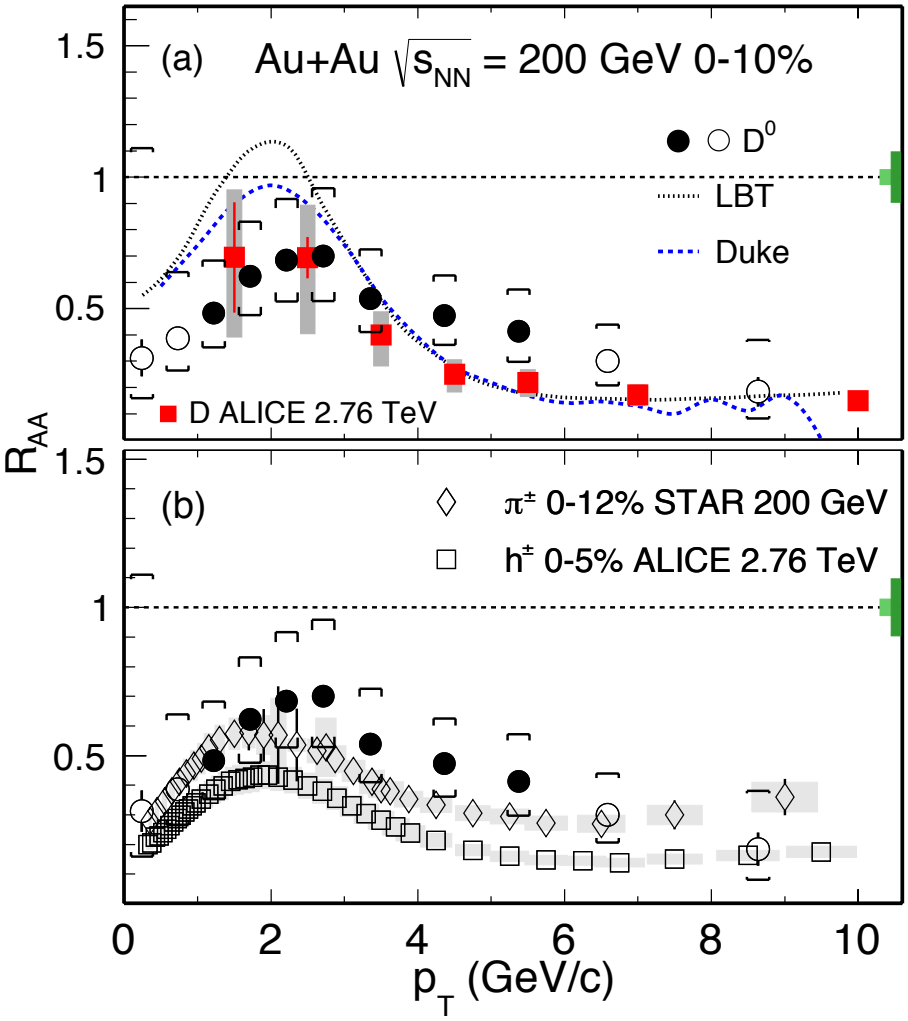
Precise measurements of D^0 spectra from low p_T up to p_T~9 GeV/c for multiple centrality classes.

D^0 meson Production

STAR, arXiv: 1812.10224
ALICE: JHEP 03 (2016) 081

Nuclear Modification Factor (R_{AA}):

- D^0 R_{AA} is less than unity in all p_T
- D^0 mesons show similar suppression as light flavor hadrons at high p_T in central Au+Au collisions.
- Similar level of suppression as at LHC.



Model comparison:

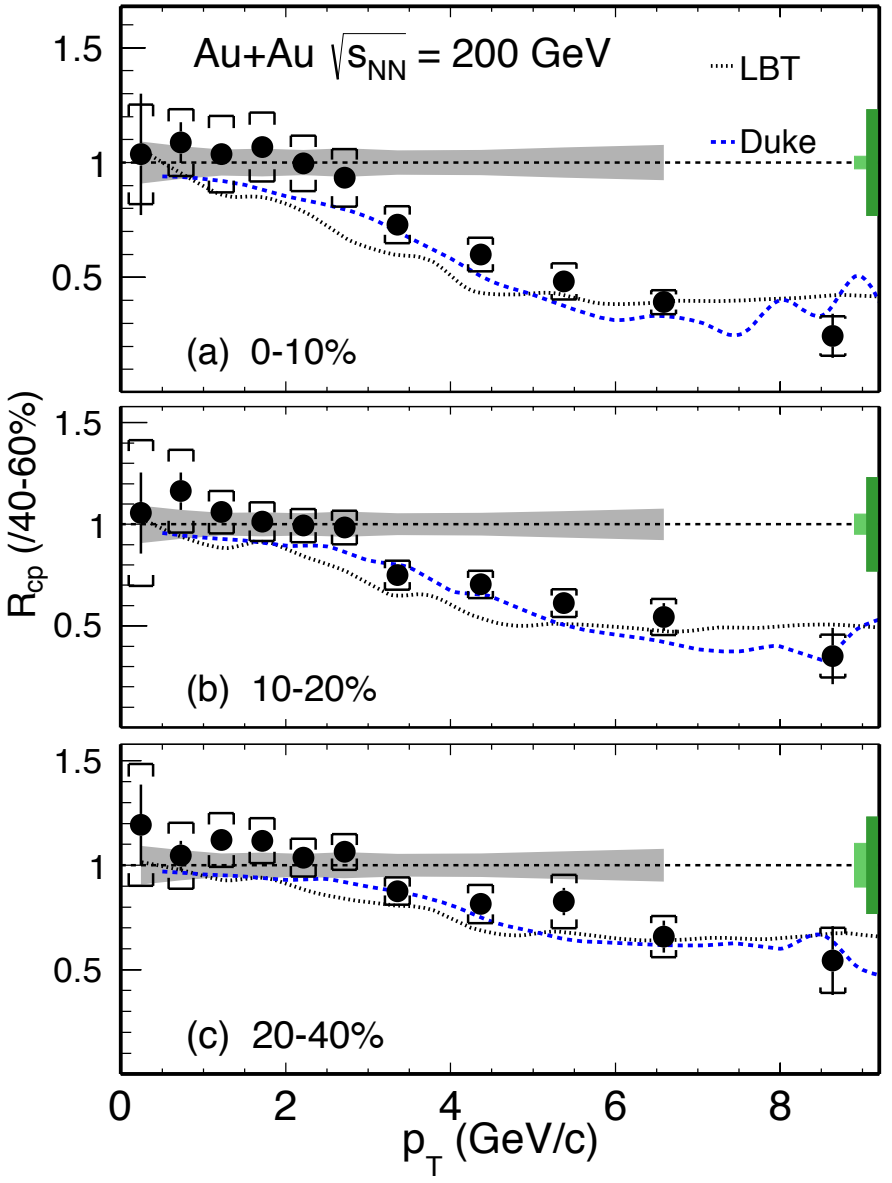
- Transport models with charm quark energy loss can describe the data.

LBT: Cao, Luo, Qin, Wang,
Phys. Rev. C 94 (2016) 014909
DUKE: Cao, Qin, Zhong, Bass, PRC 92 (2015) 024907

D^0 meson Production

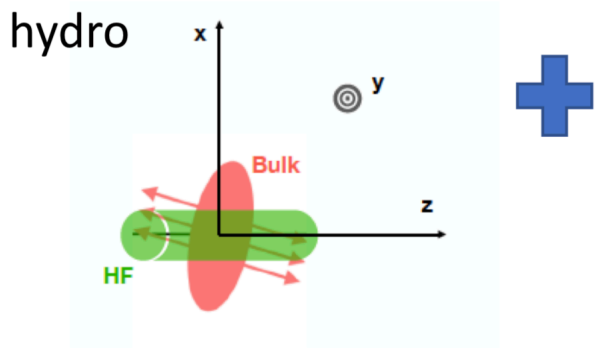
Nuclear Modification Factor (R_{CP})
For Different Centrality :

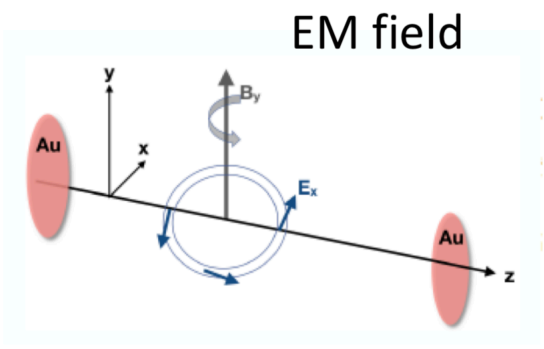
D^0 mesons shows more suppression at high p_T in central collisions than that of peripheral collisions

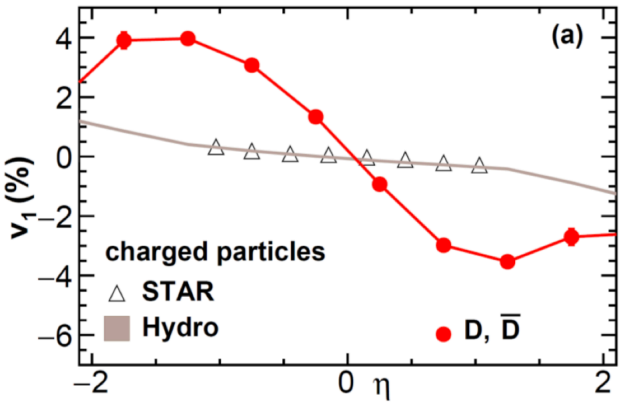


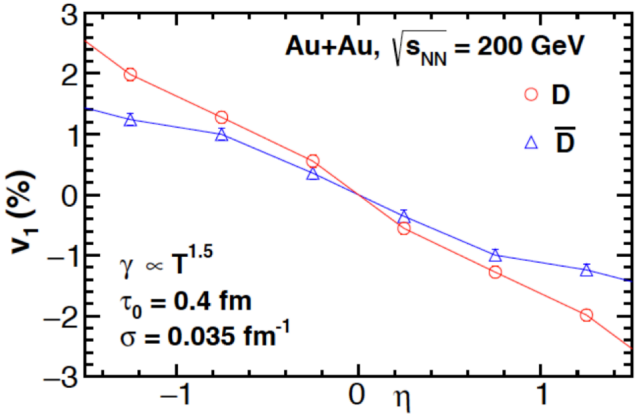
STAR, arXiv: 1812.10224

Directed flow (v_1) of D^0 mesons









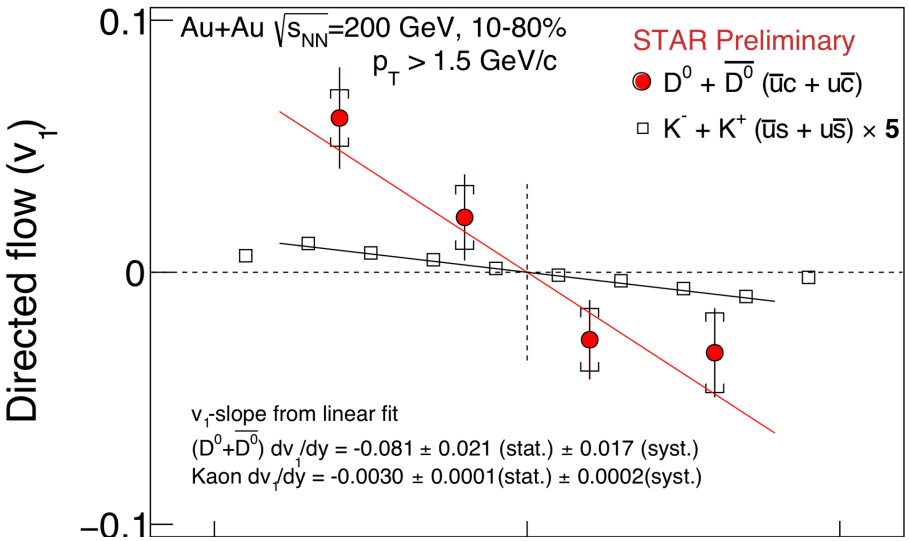
Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018), *arXiv: 1804.04893*

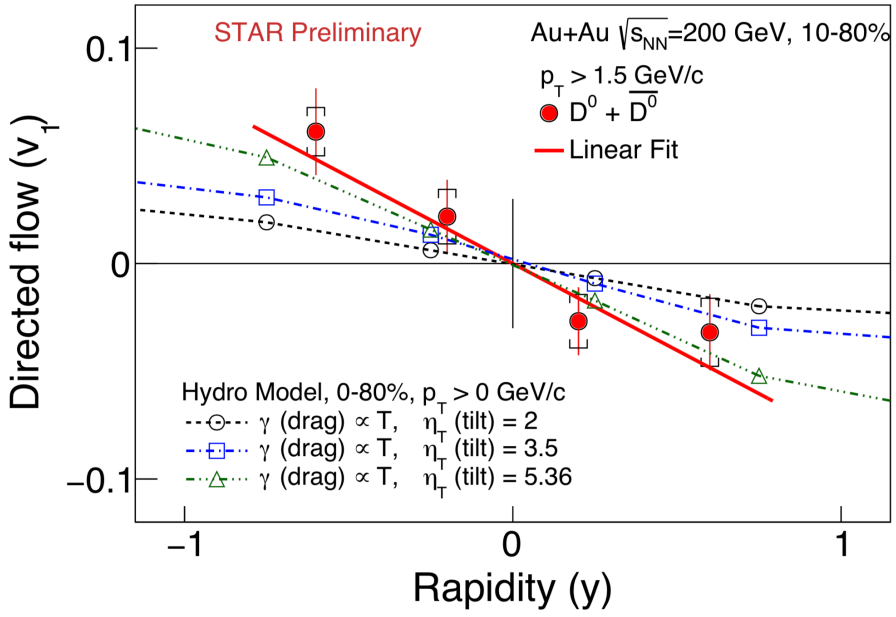
- Sensitive to initial tilt of fireball and viscous drag on charm quarks in QGP.

  - D^0 v_1 can probe initial longitudinal distribution of matter.

- Strong initial EM fields from spectators may induce additional v_1 with opposite sign for charm and anti-charm quarks

Directed flow (v_1) of D^0 mesons





- First evidence of non-zero D^0 v_1
- D^0 mesons exhibit much larger v_1 than light flavor hadrons
- In hydro model, D^0 v_1 is sensitive to the initially tilted source
- the data will help to constrain model parameters

Current precision does not allow to draw conclusion on magnetic field induced v_1 splitting.

Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018), *arXiv: 1804.04893*

Elliptic flow (v_2) of D^0 mesons

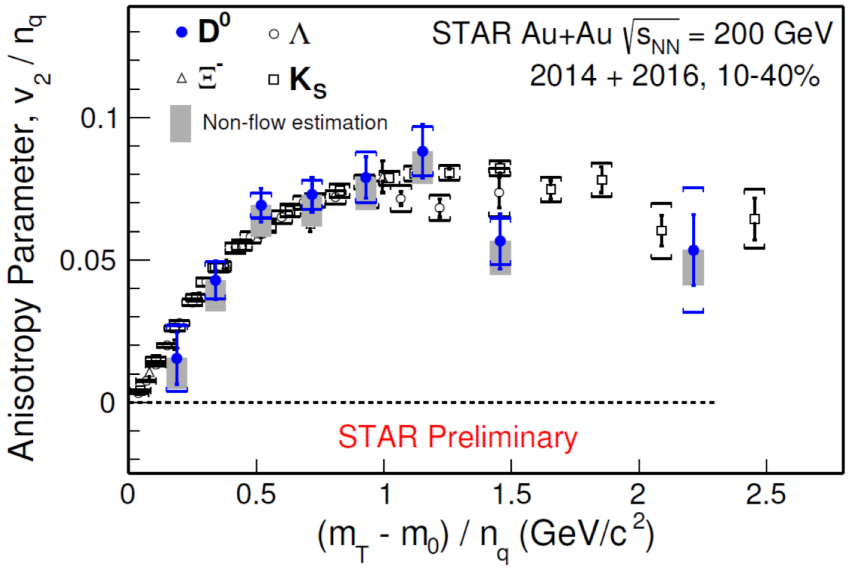
Improved precision from combined data from 2014 and 2016 runs:

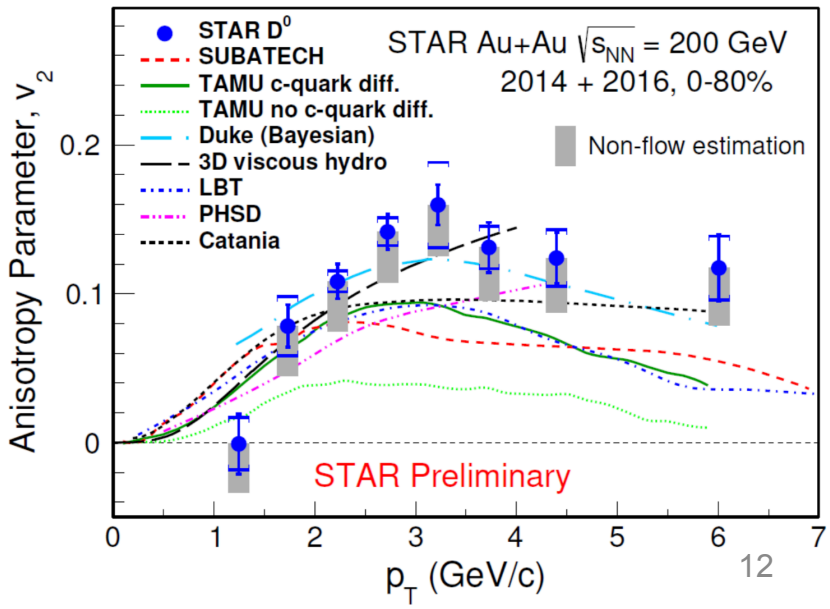
- Evidence of charm quarks attaining significant flow

- NCQ-scaling of D^0 v_2 consistent with light flavor hadrons in 10-40%

- Suggest strong interaction of charm quarks with QGP

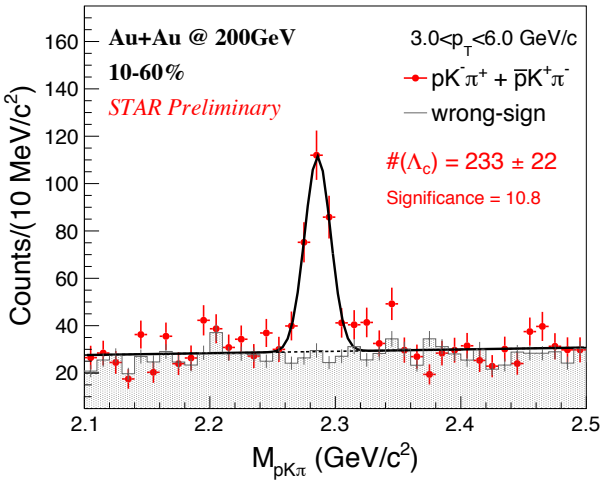
Data described by models with temperature-dependent charm diffusion coefficient $2\pi TD_s$ in the range of 2–12.

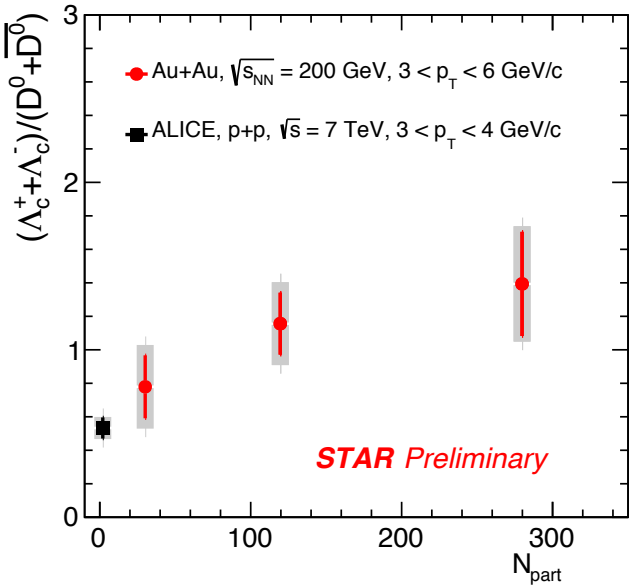


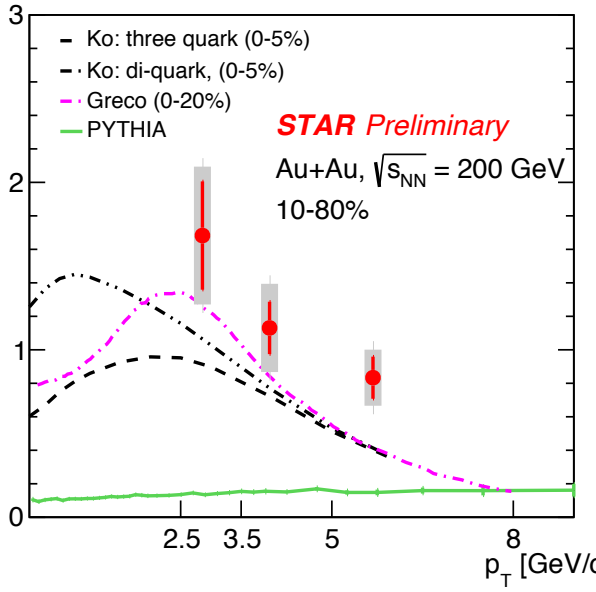


STAR, PRL **118** (2017) 212301

Λ_c/D^0 enhancement







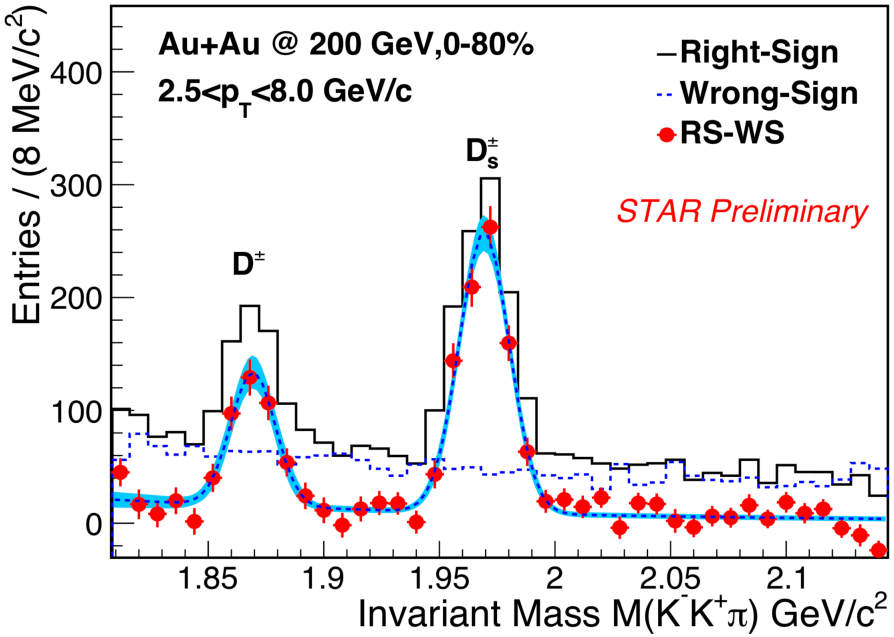
- Strong enhancement of Λ_c production in Au+Au collisions compared to PYTHIA (p+p) calculations.

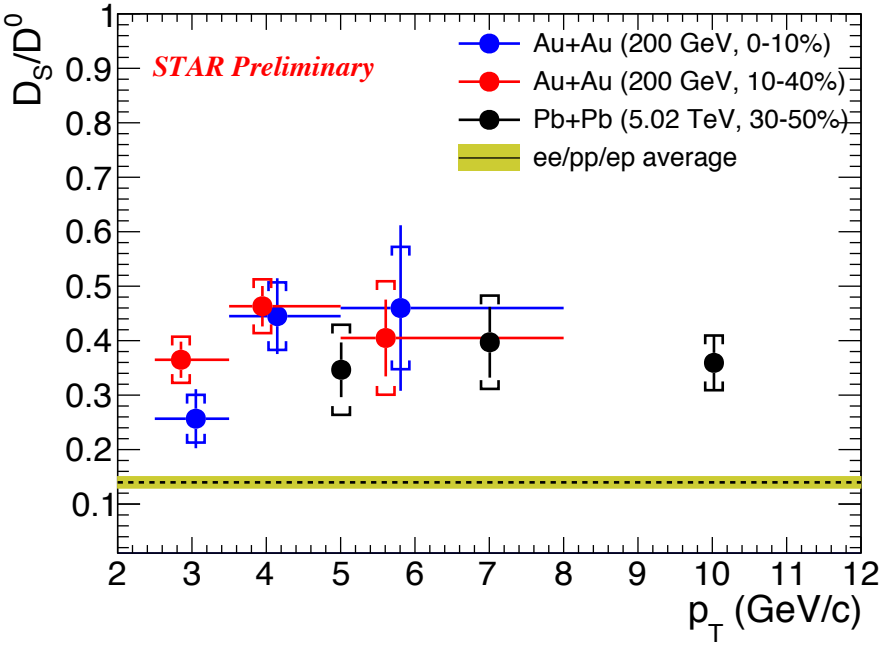
- Data suggest coalescence hadronization of charm quarks in QGP at intermediate p_T (2.5-8 GeV/c)

Model calculations: Ko: Phys. Rev. C79 (2009) 044905 Greco: Eur. Phys. J.C78 (2018) 348

D_S/D^0 enhancement

ALICE: NPA 967, 612 (2017)

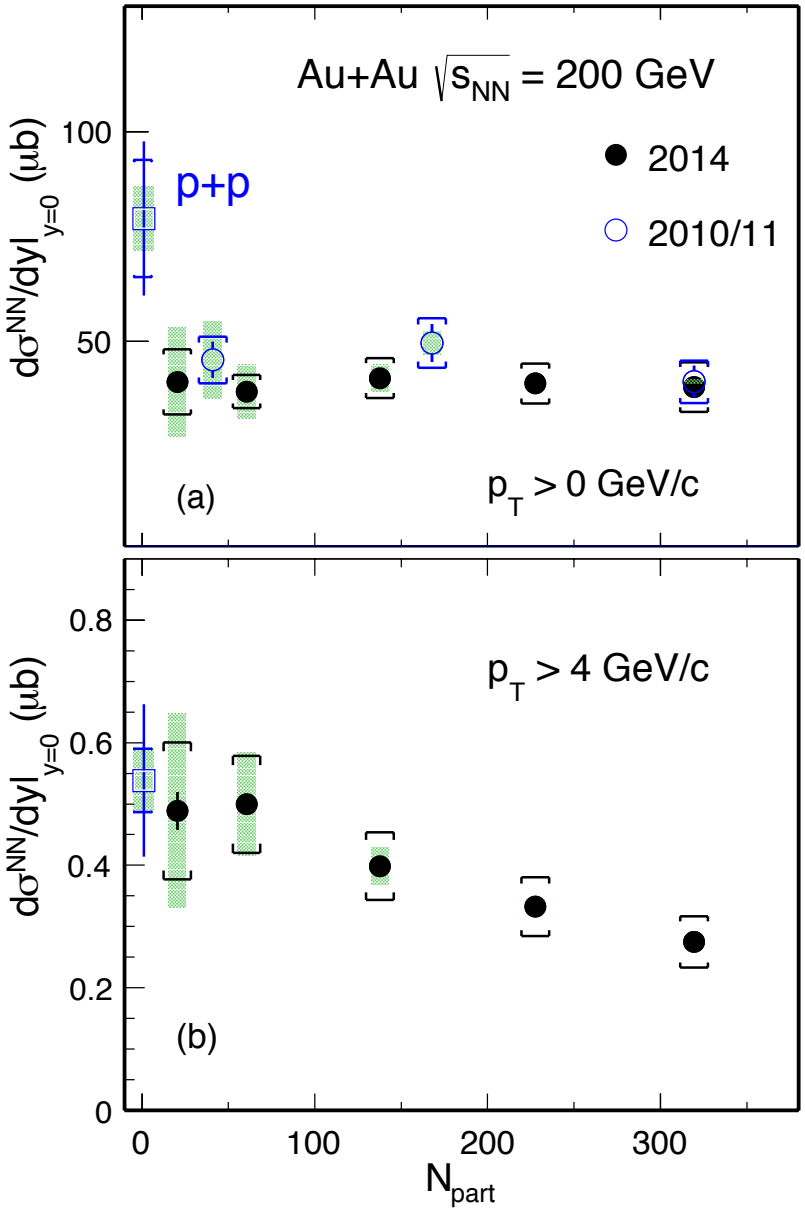




- Data suggests enhanced production of strange quarks and coalescence hadronization of charm quarks in heavy-ion collisions
- Strong D_S/D^0 enhancement observed in central Au+Au collisions relative to fragmentation baseline

D^0 cross section at RHIC

- Cross section (σ_{NN}) of D^0 production in Au+Au collisions at 200 GeV at midrapidity is lower than in pp collisions.
- Enhancement of Λ_c and D_S production compensates the suppression of D^0 cross section
- Total charm cross-section is consistent with p+p within uncertaneities



STAR, arXiv: 1812.10224

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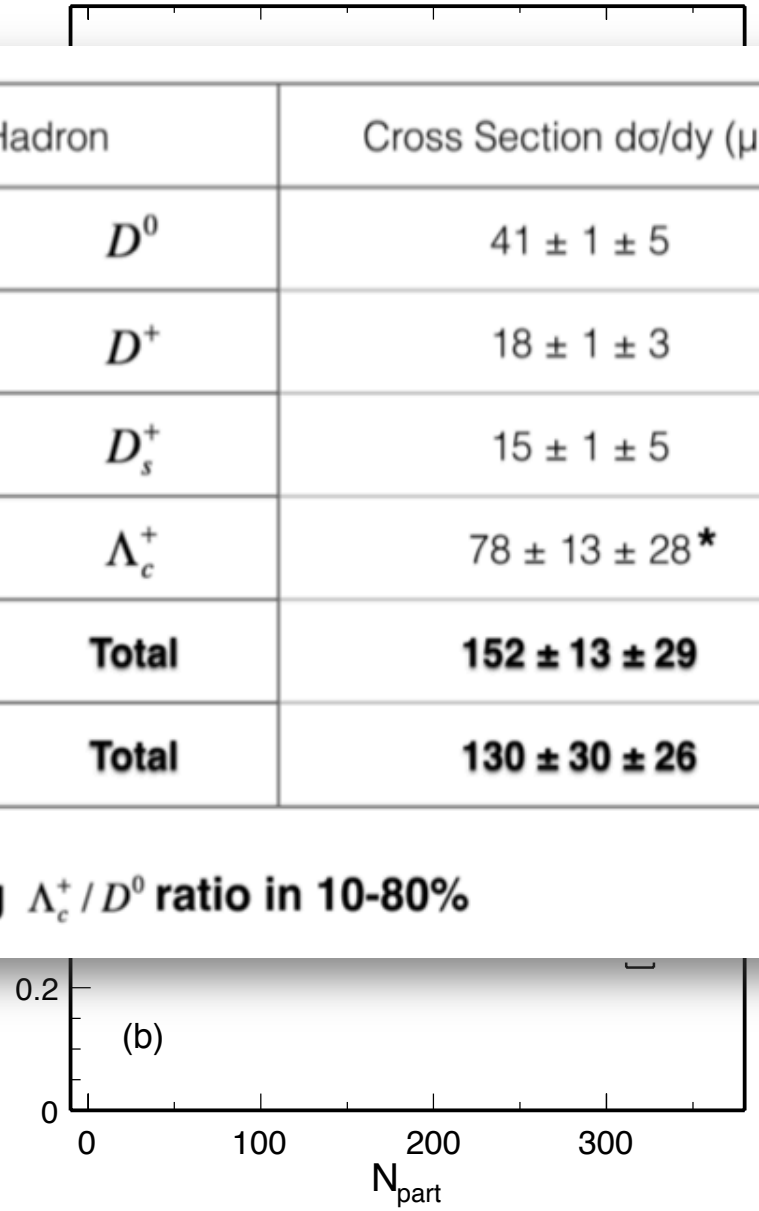
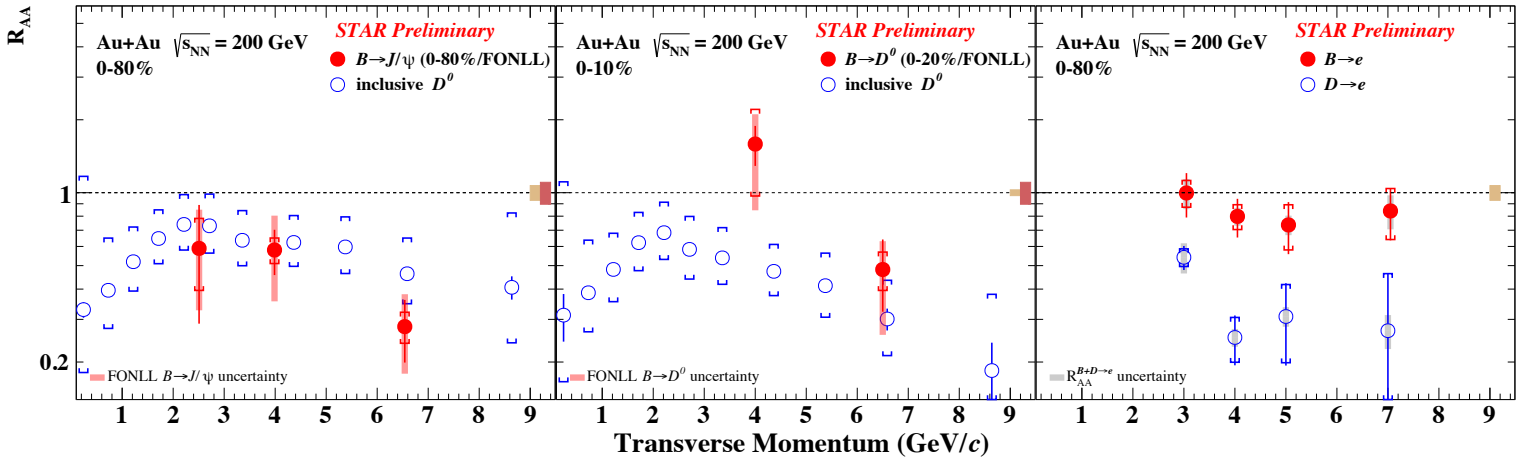
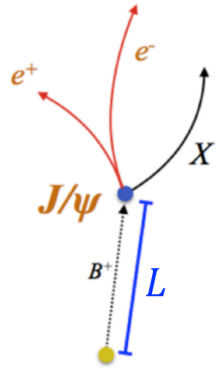
Charm Hadron		Cross Section dσ/dy (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28 *
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

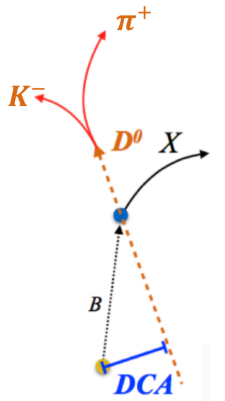
*** derived using Λ_c^+ / D^0 ratio in 10-80%**



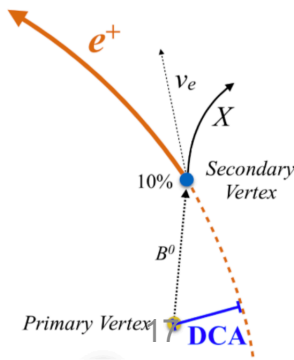
Bottom Measurements







- **Strong suppression** is observed for non-prompt J/ψ at high p_T
- **Strong suppression** of non-prompt D^0 is observed at high p_T
- Indication of **less suppression** for B → e than D → e (~2σ); consistent with $\Delta E_c > \Delta E_b$

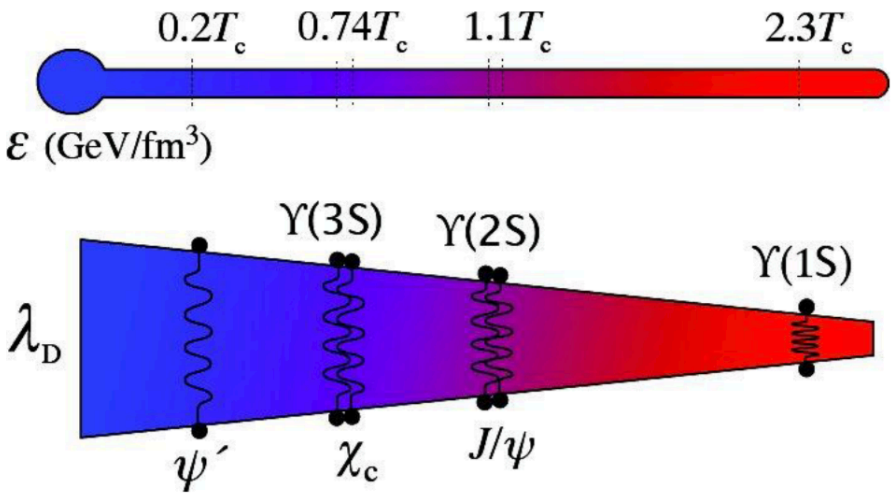


Quarkonium Measurements

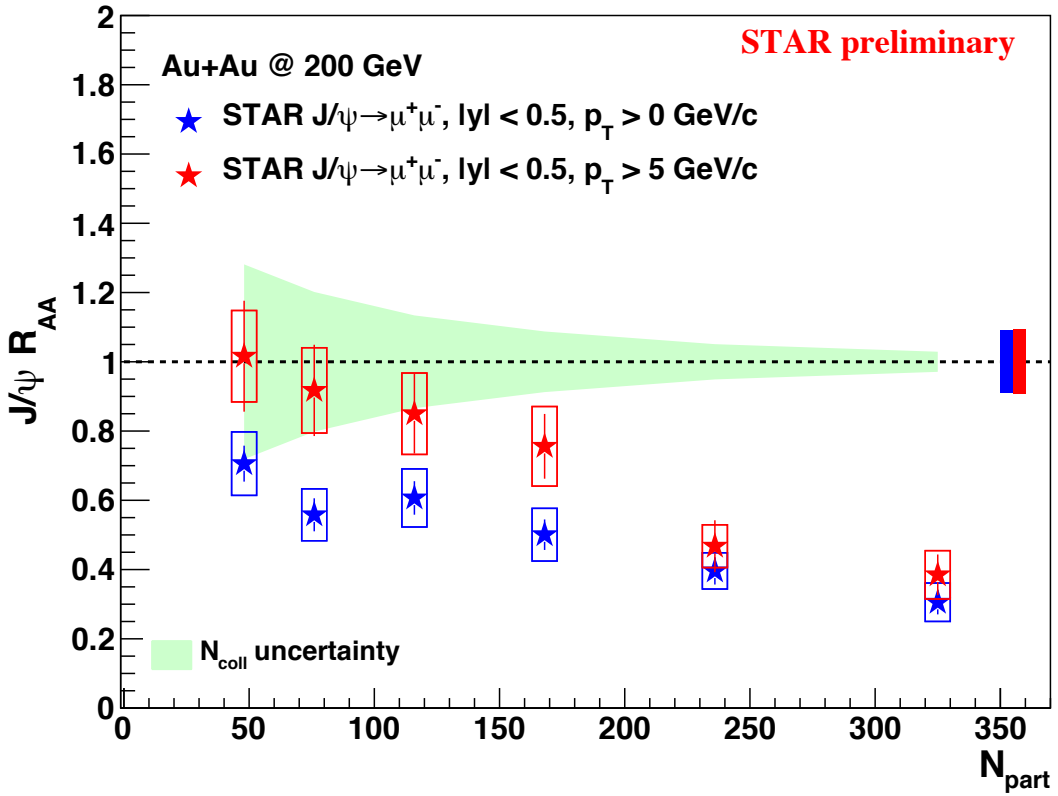
Quarkonia are bound states of a heavy quark and an anti-quark of the same flavor:

charmonia: J/ψ
bottomonia: ϒ(1s), ϒ(2s) and ϒ(3s)

Quarkonia dissociate in QGP due to color screening of potential between heavy quarks.



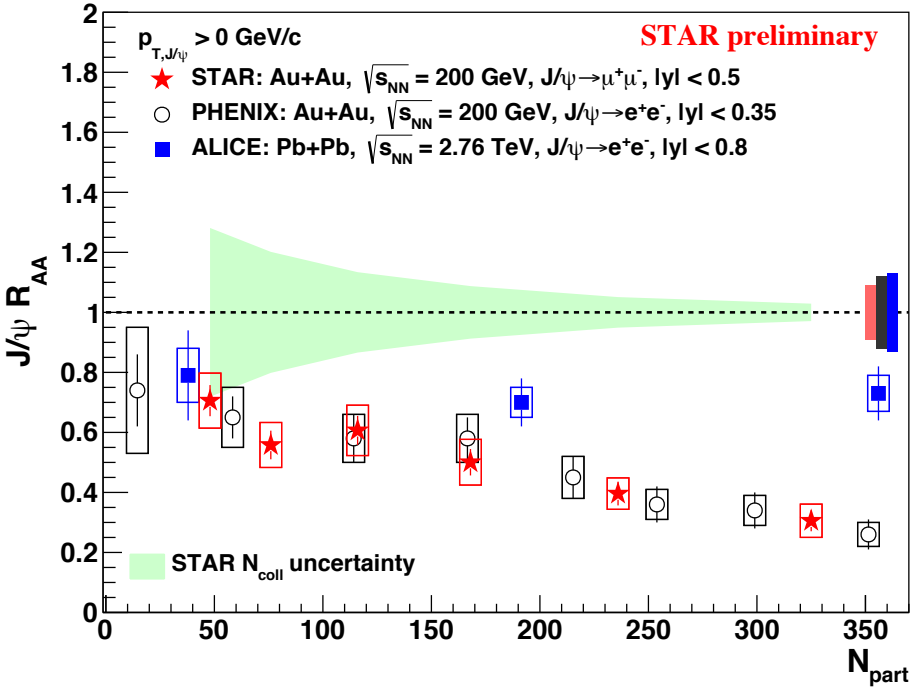
J/ψ suppression in heavy-ion collisions

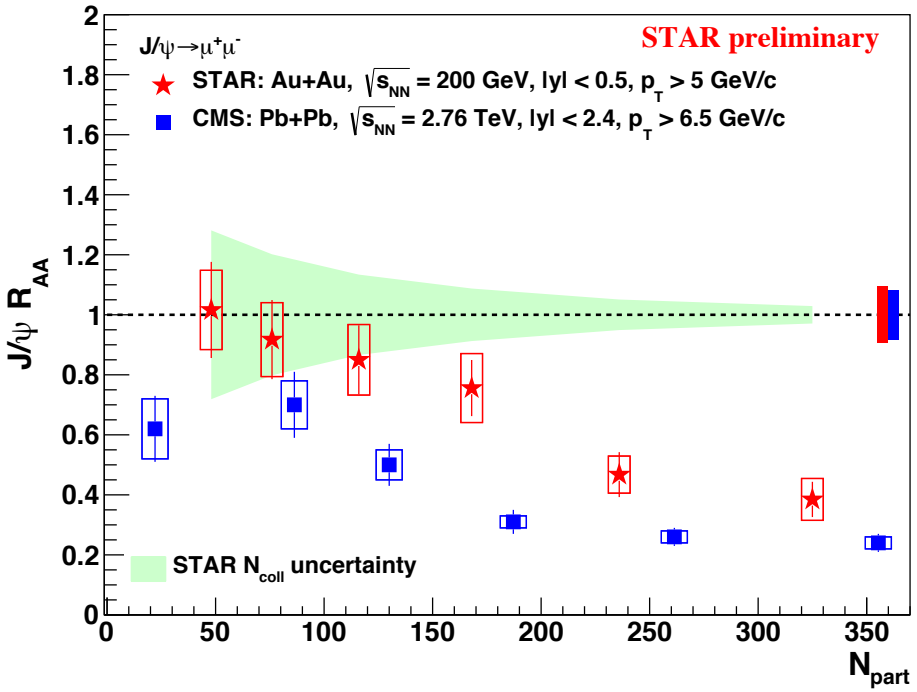


Central collisions: significant suppression is observed for both low p_T and high p_T (> 5 GeV/c) J/ψ

Peripheral collisions: R_{AA} of J/ψ for p > 0 GeV/c is smaller than that for p_T > 5 GeV/c

J/ψ suppression in heavy-ion collisions





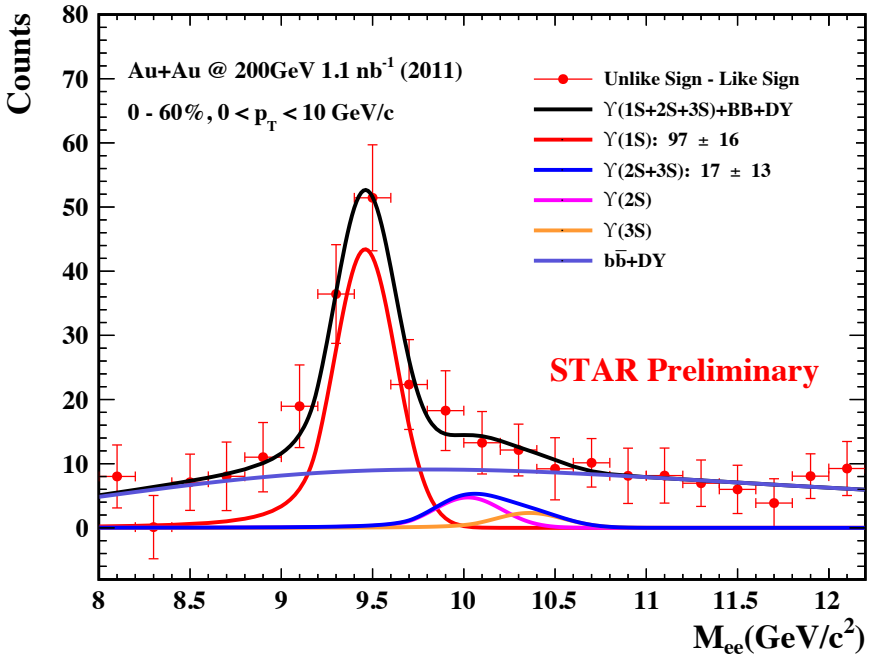
p_T > 0 GeV/c: less suppressed at the LHC in central events
- larger regeneration contribution due to higher charm cross-section

p_T> 5 GeV/c: more suppressed at the LHC in all centralities
- higher dissociation rate due to higher temperature

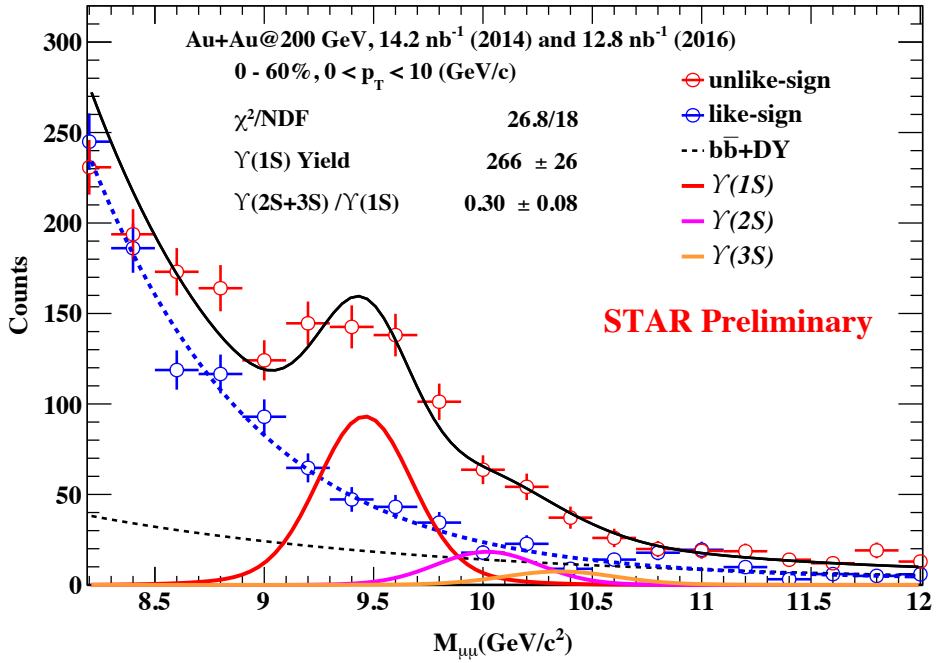
ALICE: PLB 734,314 (2014); PHENIX: PRL 98, 232301 (2007); CMS: JHEP 05, 063, (2012)

Upsilon (ϒ) in heavy-ion collisions

ϒ -> e^+e^-



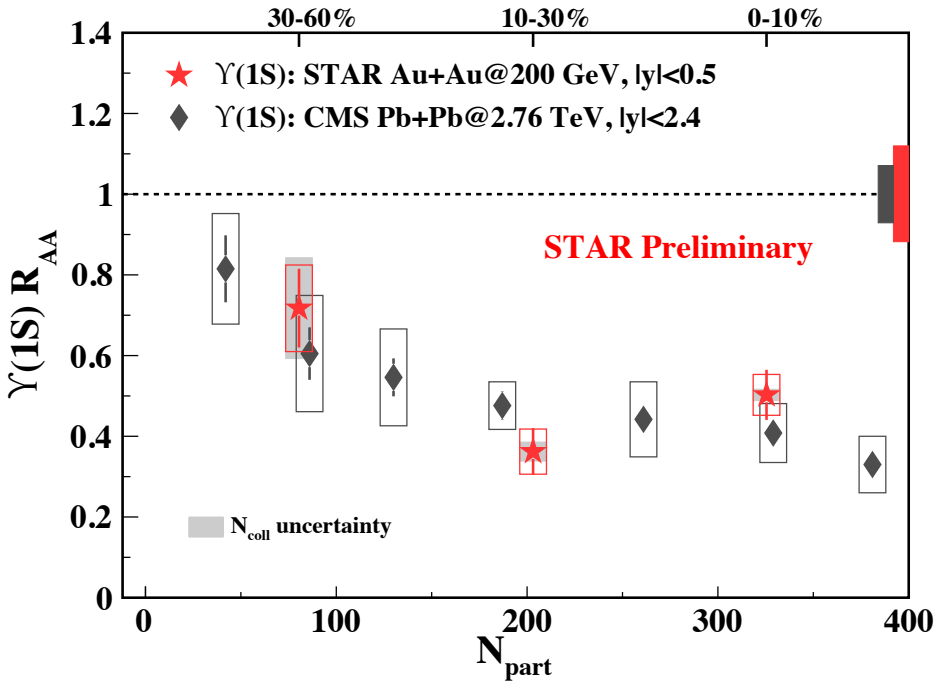
ϒ -> $\mu^+\mu^-$

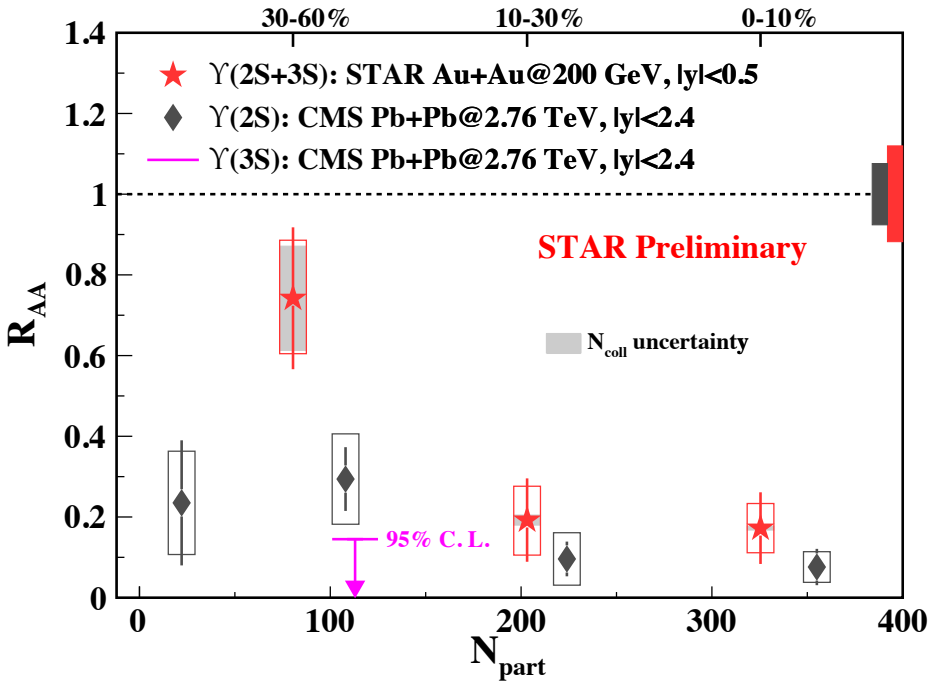


3 Crystal Ball fits for ϒ → e^+e^-
3 Gaussian fits for ϒ → $\mu^+\mu^-$ because of less bremsstrahlung

We combine results from the two channels and multiple runs to measure suppression of ϒ

ϒ suppression in heavy-ion collisions





- ϒ suppression increases from peripheral to central Au+Au collisions.
- ϒ(1S): suppression consistent with that measured by CMS at 2.76 TeV.
- ϒ(2S+3S): indication of less suppression at RHIC than LHC in peripheral collisions.

CMS: PLB 770, 357 (2017)

Summary

Open-Charm Measurements:

- **Suppression of D^0 yields in central collisions similar to that of light-flavor hadrons**
  -strong interaction of charm quarks with the QGP

- **Significant D^0 v_2**
  - data suggests charm quarks acquire similar flow as light flavor quarks

- **First evidence of large non-zero directed flow for heavy flavor**
  - sensitive probe of initial matter distribution in the longitudinal direction

- **Coalescence hadronization of charm quarks in QGP at intermediate p_T**

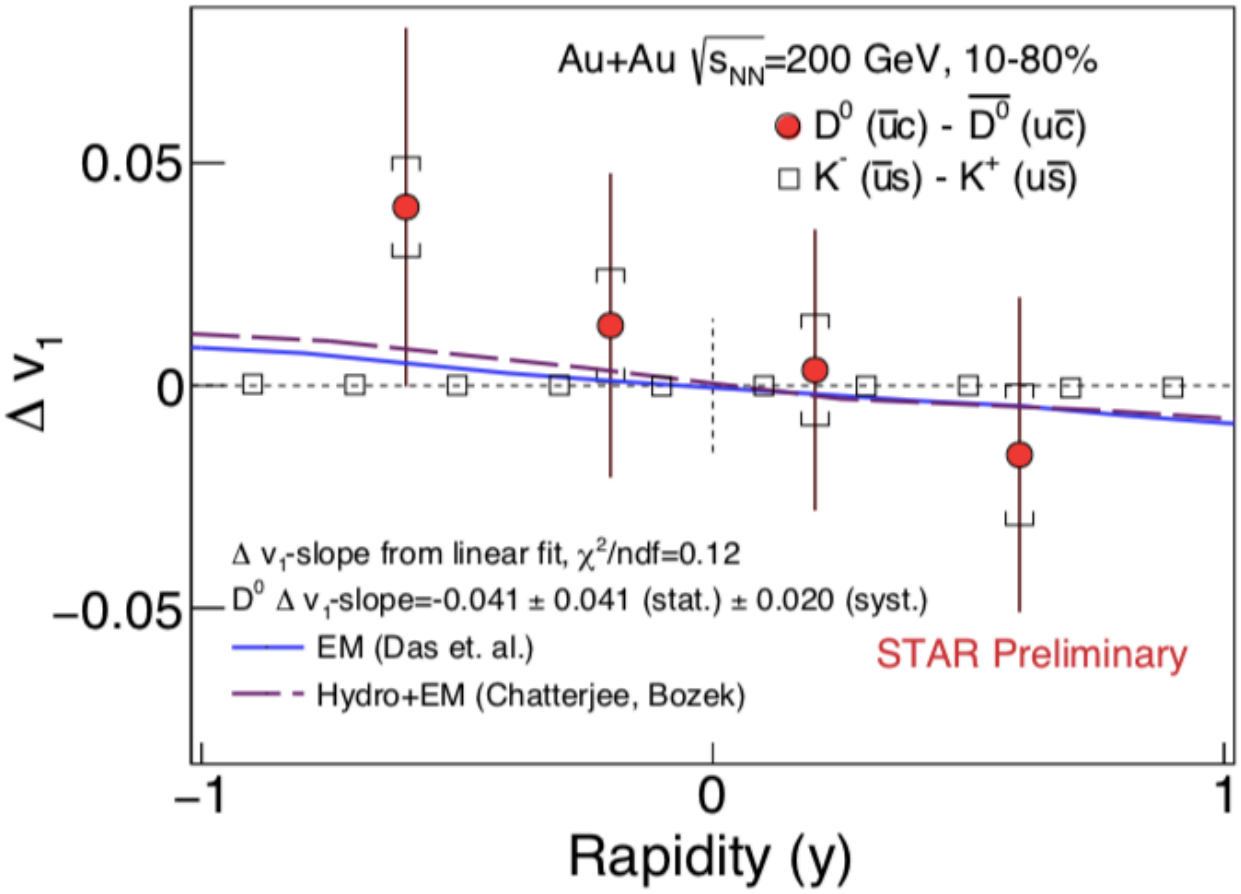
Quarkonium Measurements:

- **Significant suppression is observed for J/ψ in central Au+Au collision**
  - dissociation

- **Stronger suppression of Υ (2S+3S) than Υ (1S) in central Au+Au collisions observed**. Consistent with sequential melting scenario

Back-Up

Difference between D0 v1 and D0-bar v1:



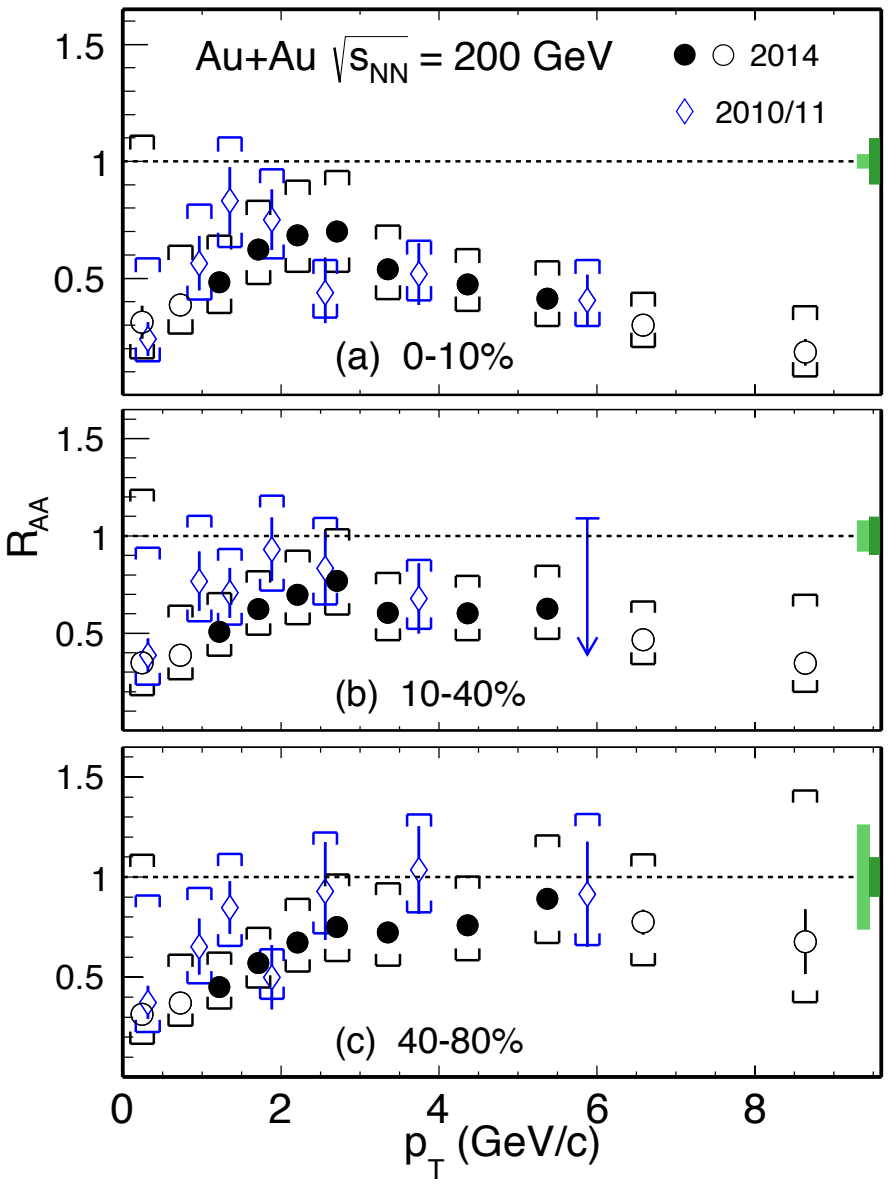
Current precision does not allow to draw firm conclusion on magnetic field induced v1 splitting

D^0 meson Production

Nuclear Modification Factor For Different Centrality :

D^0 mesons shows more suppression at high p_T in central collisions than that of peripheral collisions

Results are consistent with the re-analyzed 2010/11 TPC-only analysis



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