Heavy Flavor Measurements from STAR

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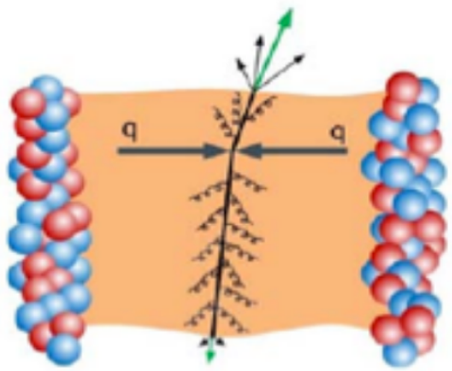
STAR

Heavy quarks as probes of QGP

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

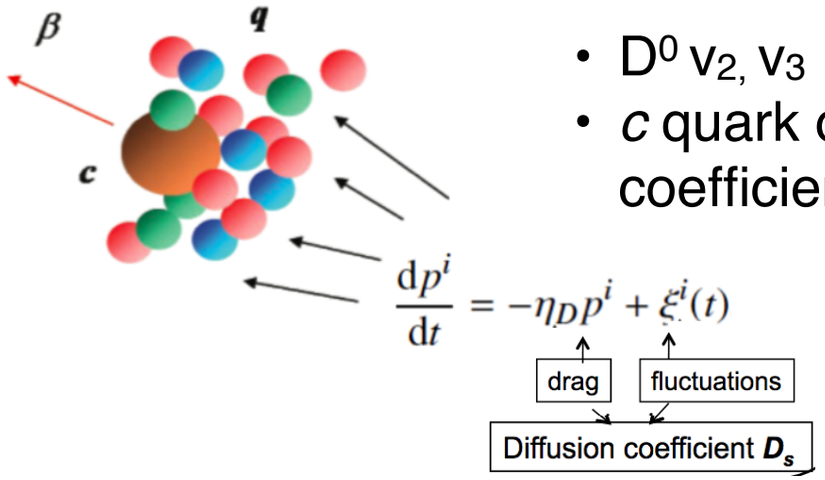
  ⟶ Ideal probes of the QGP

Energy Loss



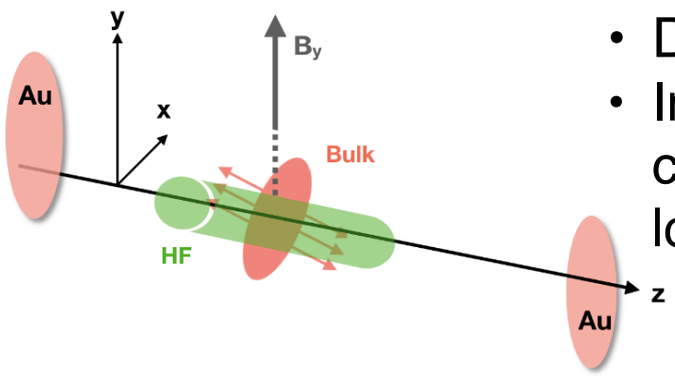
- D, B meson R_{AA} and R_{CP}
- Collisional and radiative energy loss

Transport



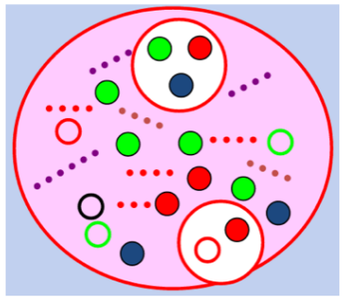
- D^0 v_2, v_3
- *c* quark diffusion coefficient in QGP

Initial conditions



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

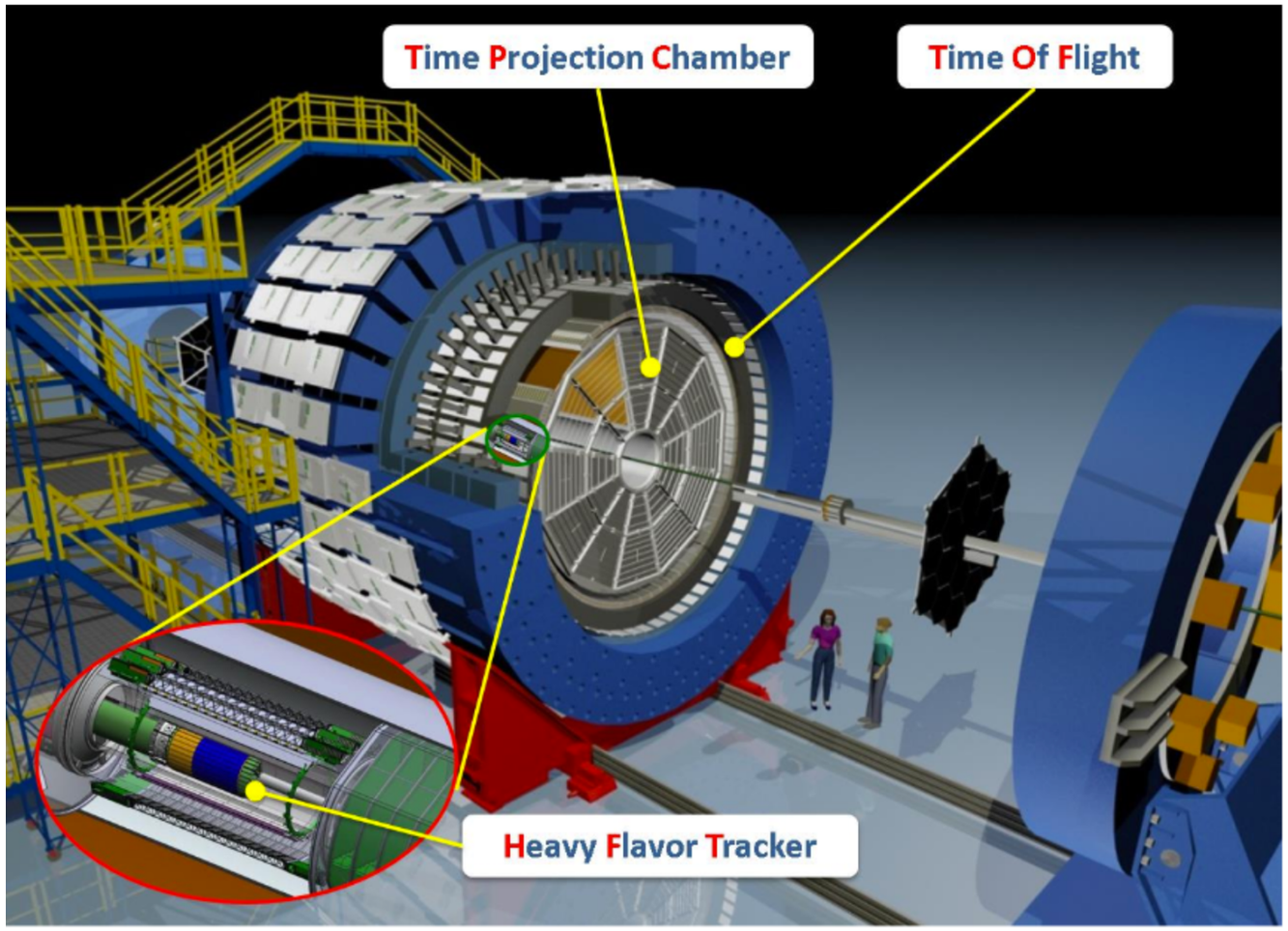
Hadronization



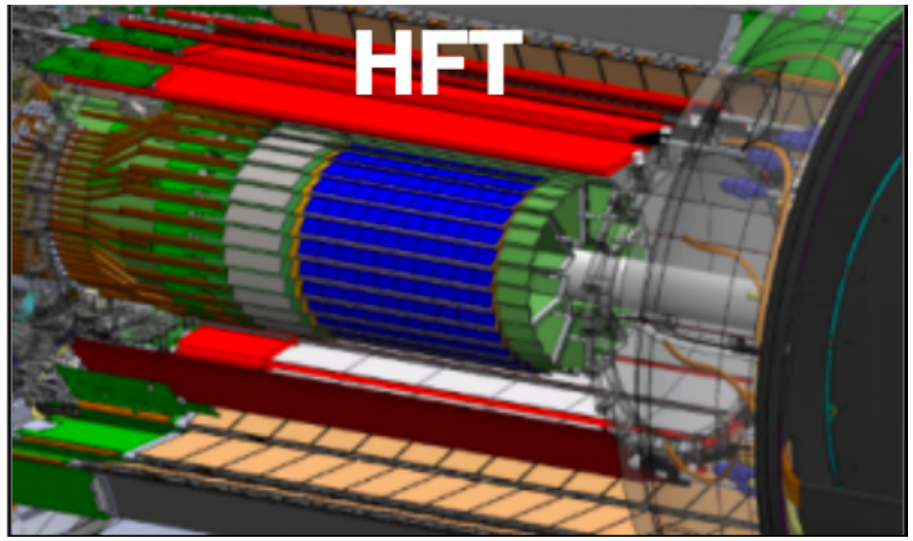
?

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

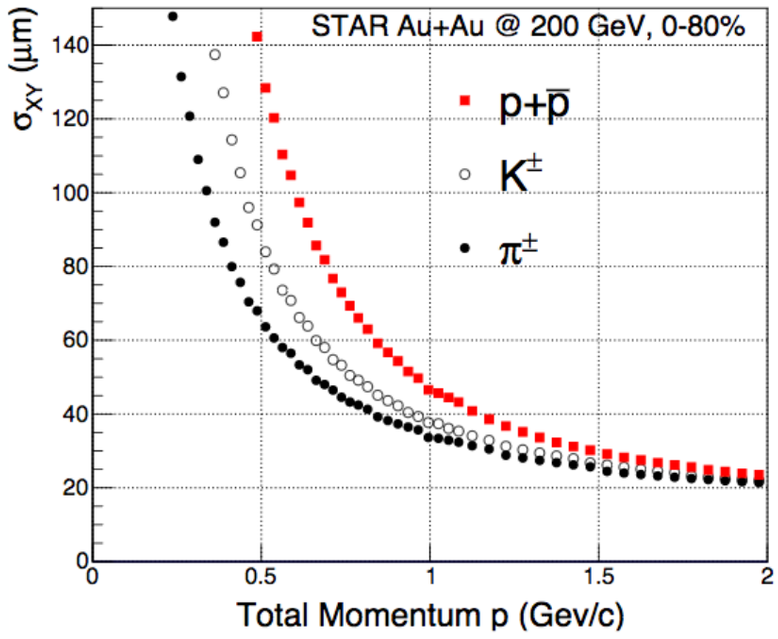
STAR Heavy Flavor Tracker



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

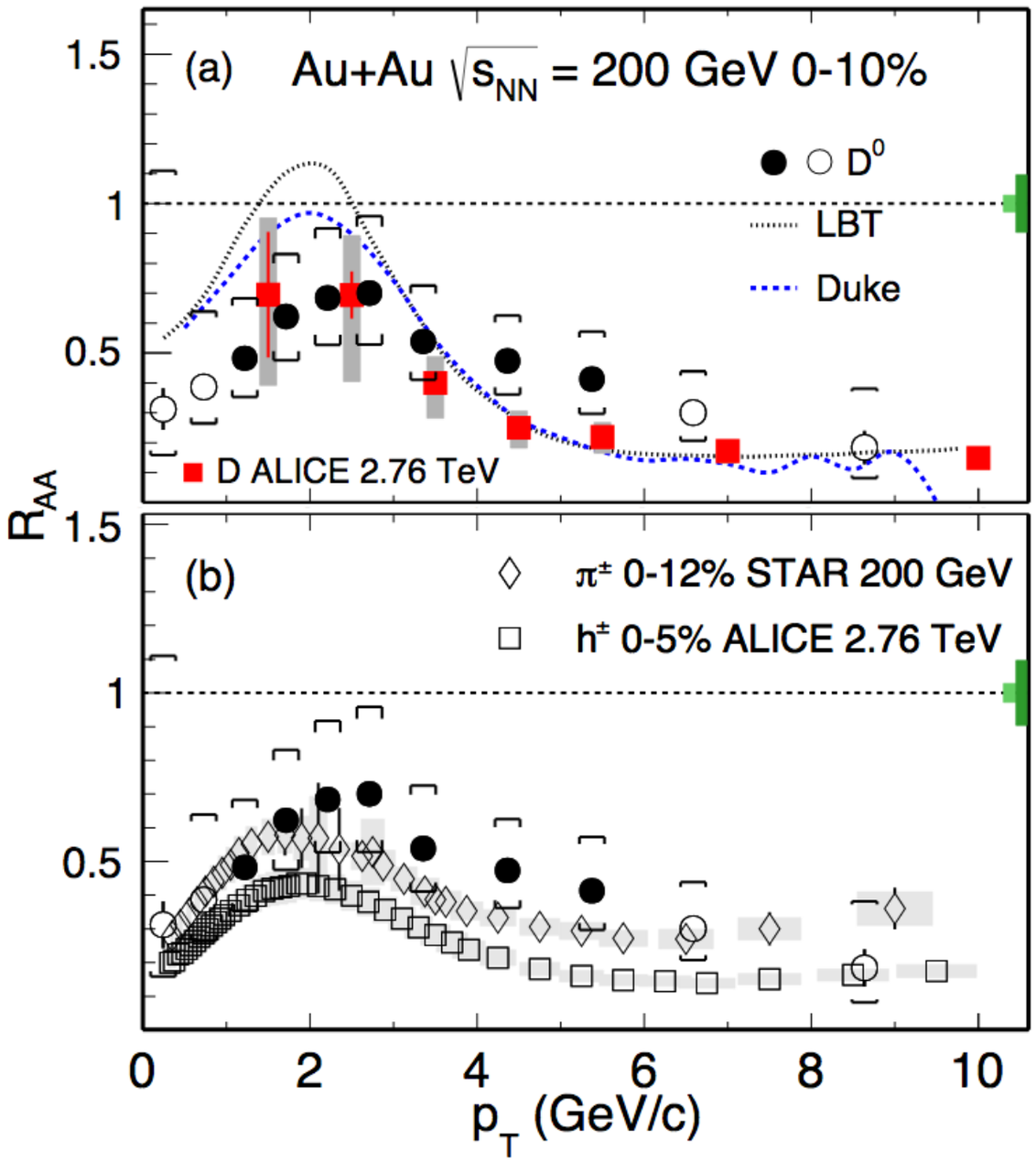


- Excellent track pointing resolution
- Topological reconstruction of charm hadron decays
- Vastly improved signal significances (eg: by factor of 15 for D^0)



Phys. Rev. Lett. 118 (2017) 212301

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

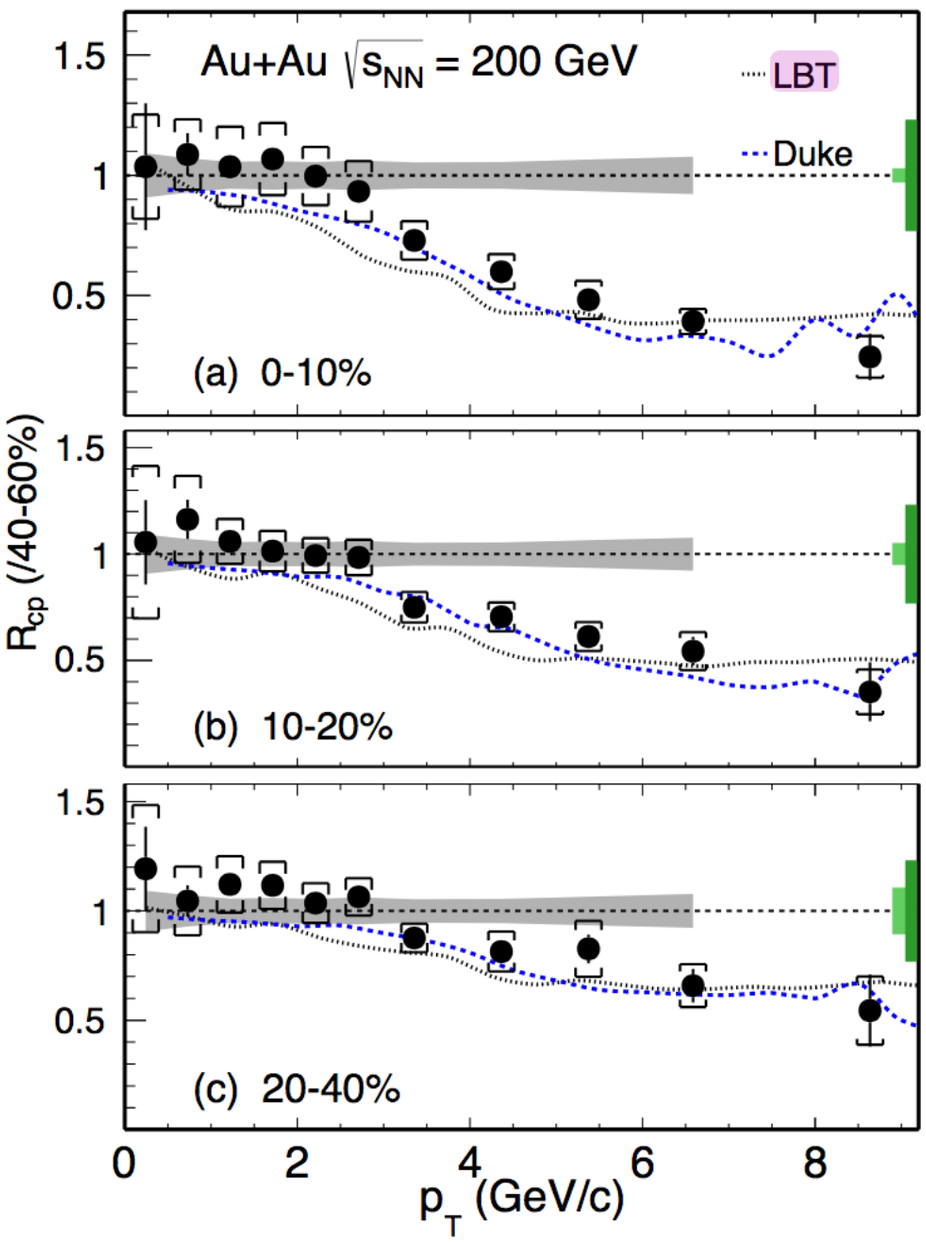


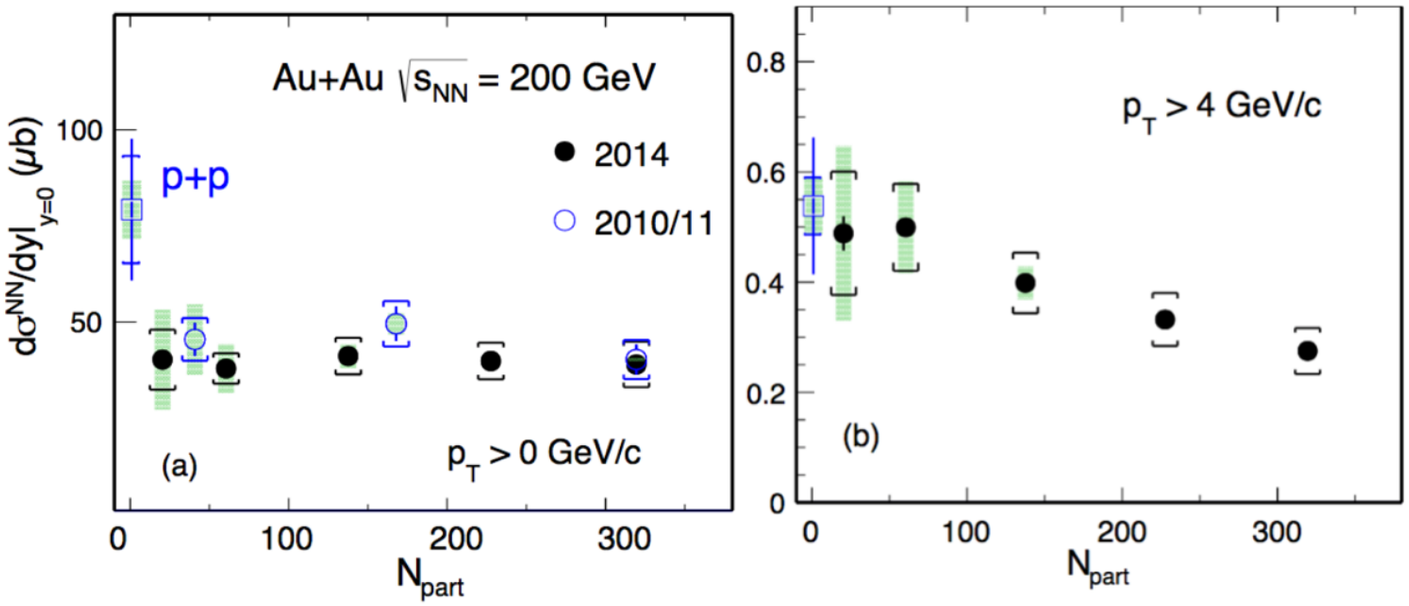
- Strong suppression of high p_T D^0 in central Au+Au collisions
  - Strong interactions and energy loss of *c* quarks with QGP
- Comparable to that seen for light flavor hadrons at high p_T, less at intermediate p_T (3-6 GeV/c)
- Model calculations can reproduce large suppression at high p_T
  - Include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

STAR: Phys Rev C.99.034908 (2019)

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

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



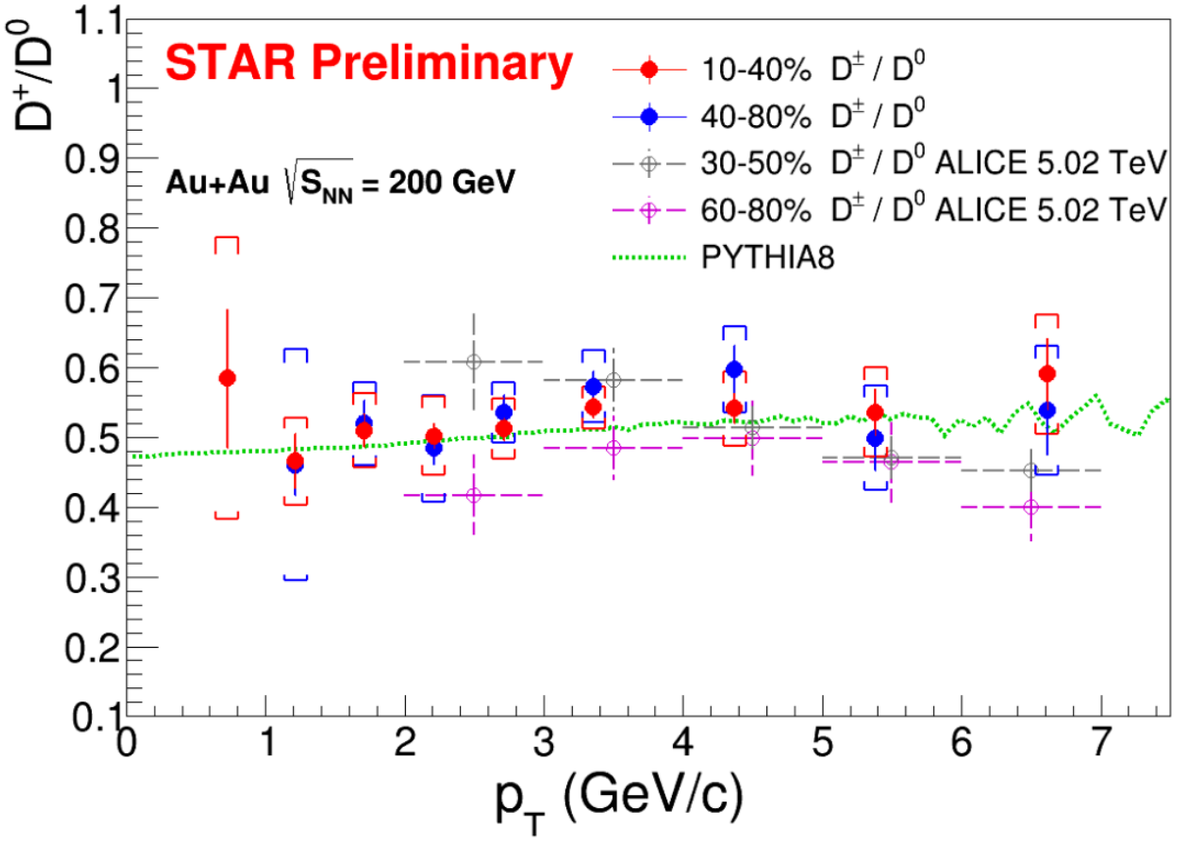


- High p_T suppression increase towards central events
- No strong centrality dependence at low p_T

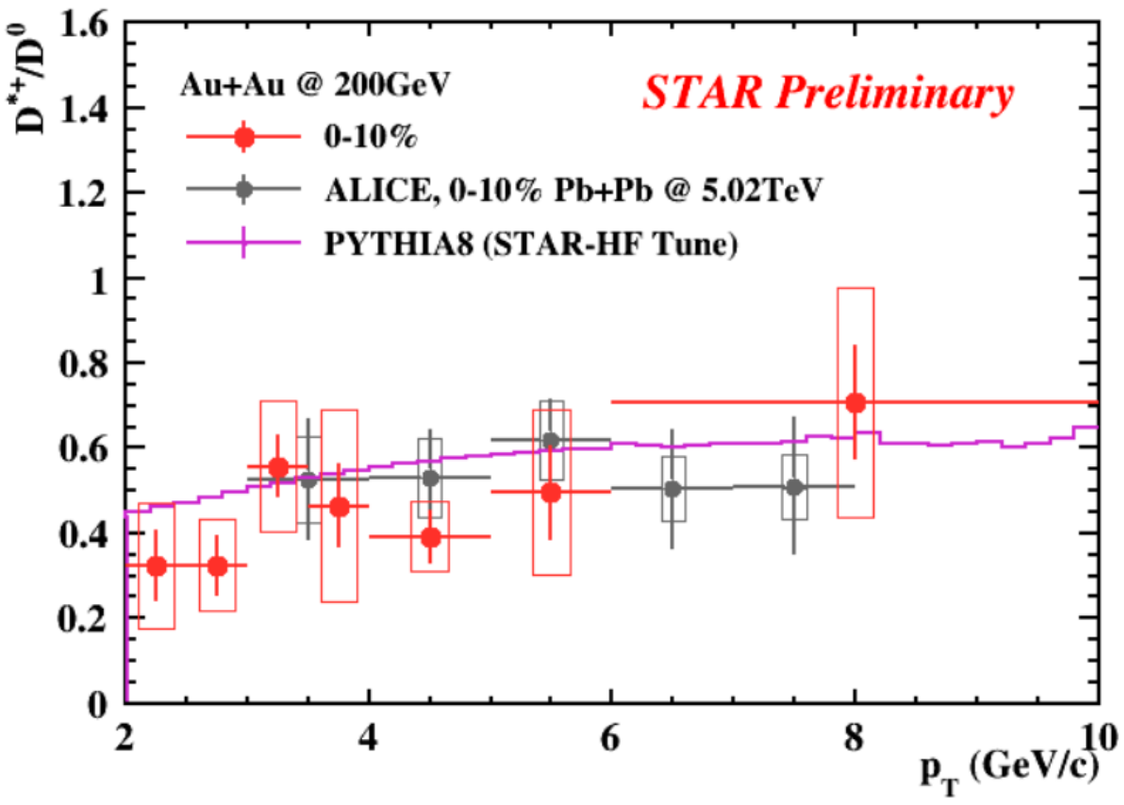
- Also seen from cross-section plots
- Total D^0 cross-section is lower than in p+p collisions

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

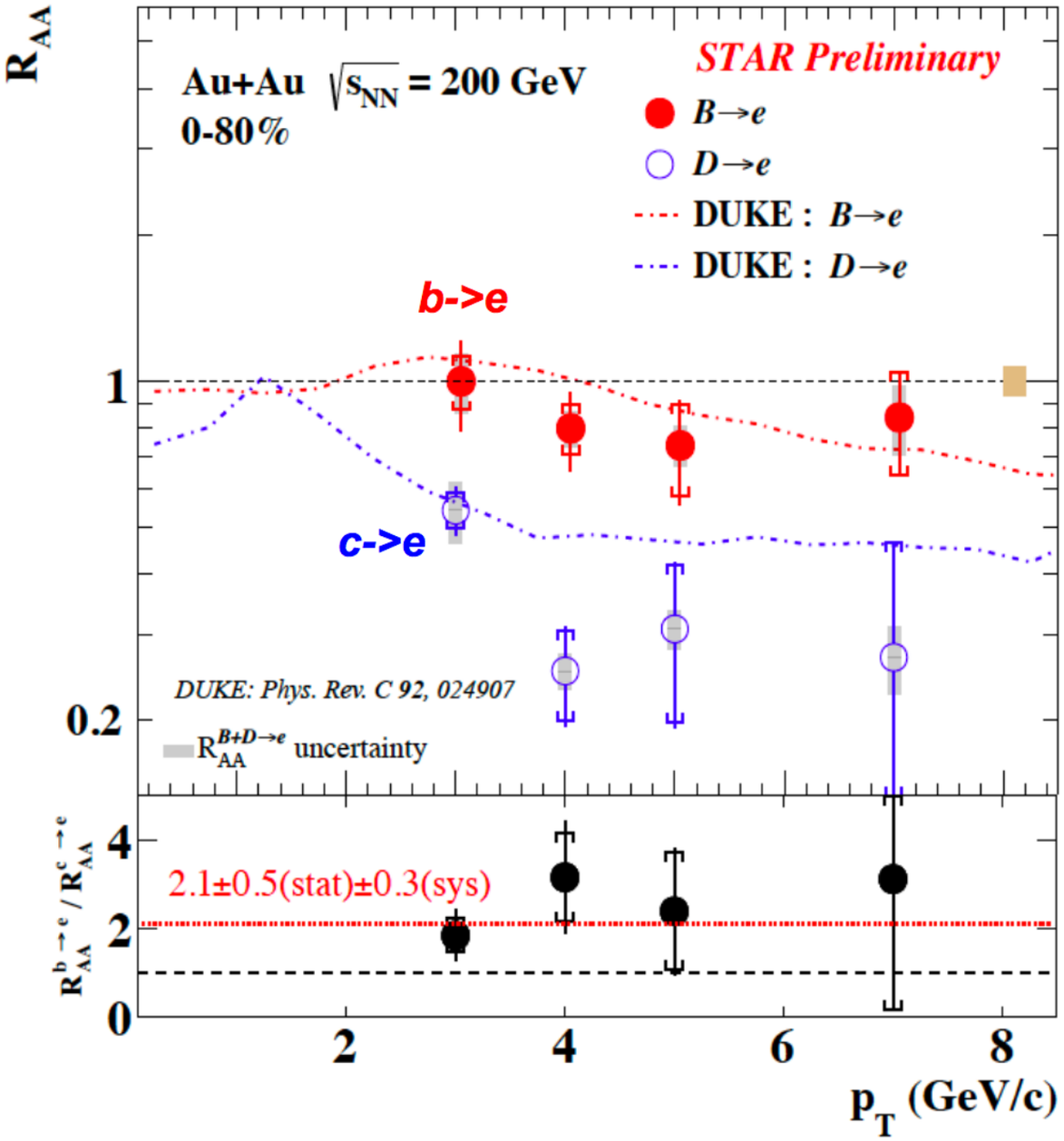
- Complementary to D^0 measurements

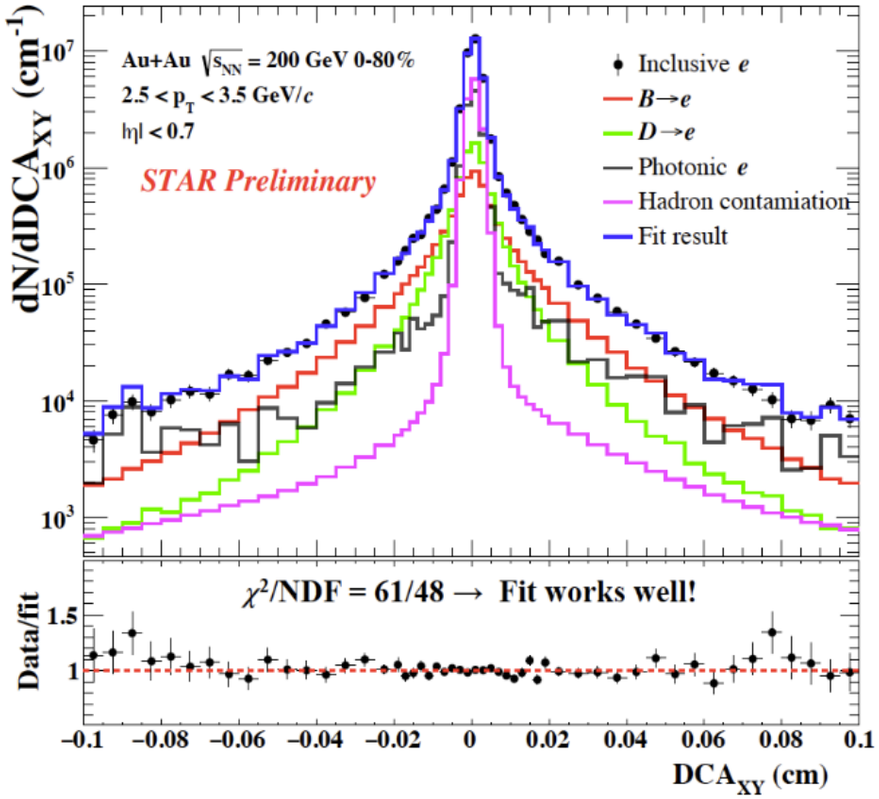
- No modification to $D^{+/-}/D^0$ and D^*/D^0 yield ratios compared to PYTHIA
- Indicates similar R_{AA} as for D^0

- 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

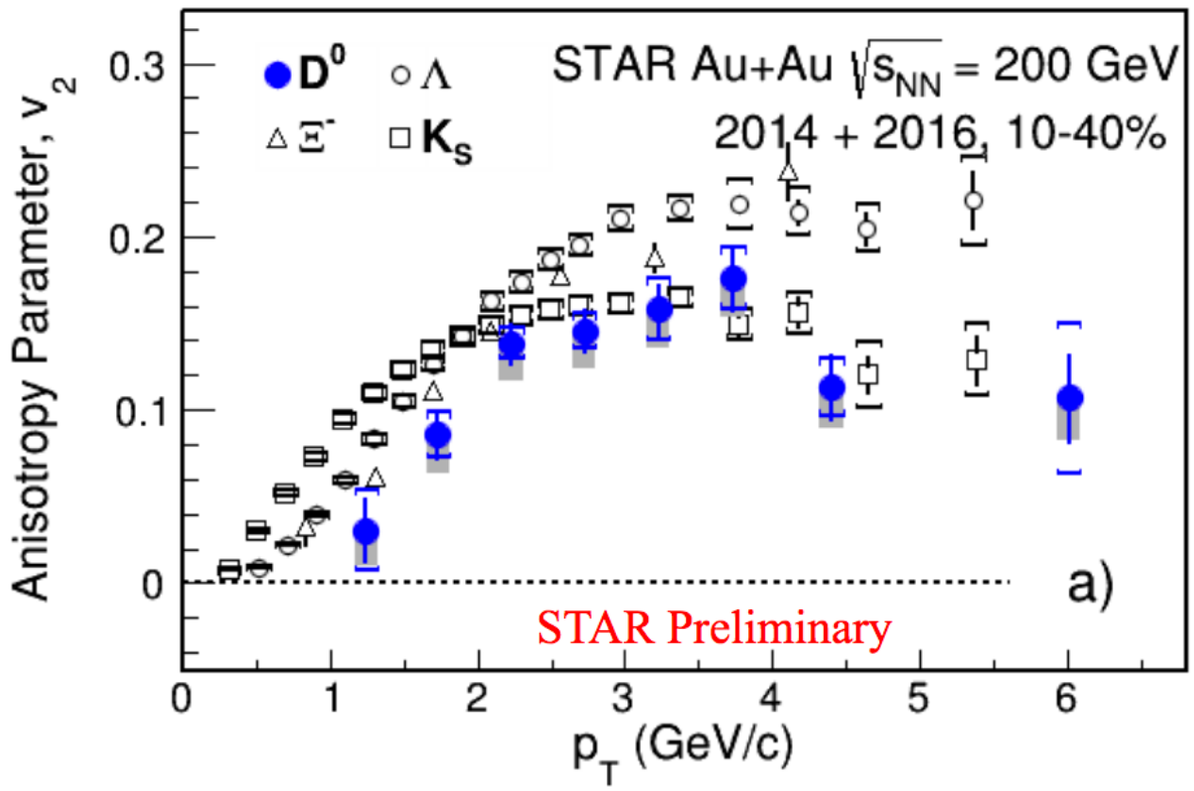


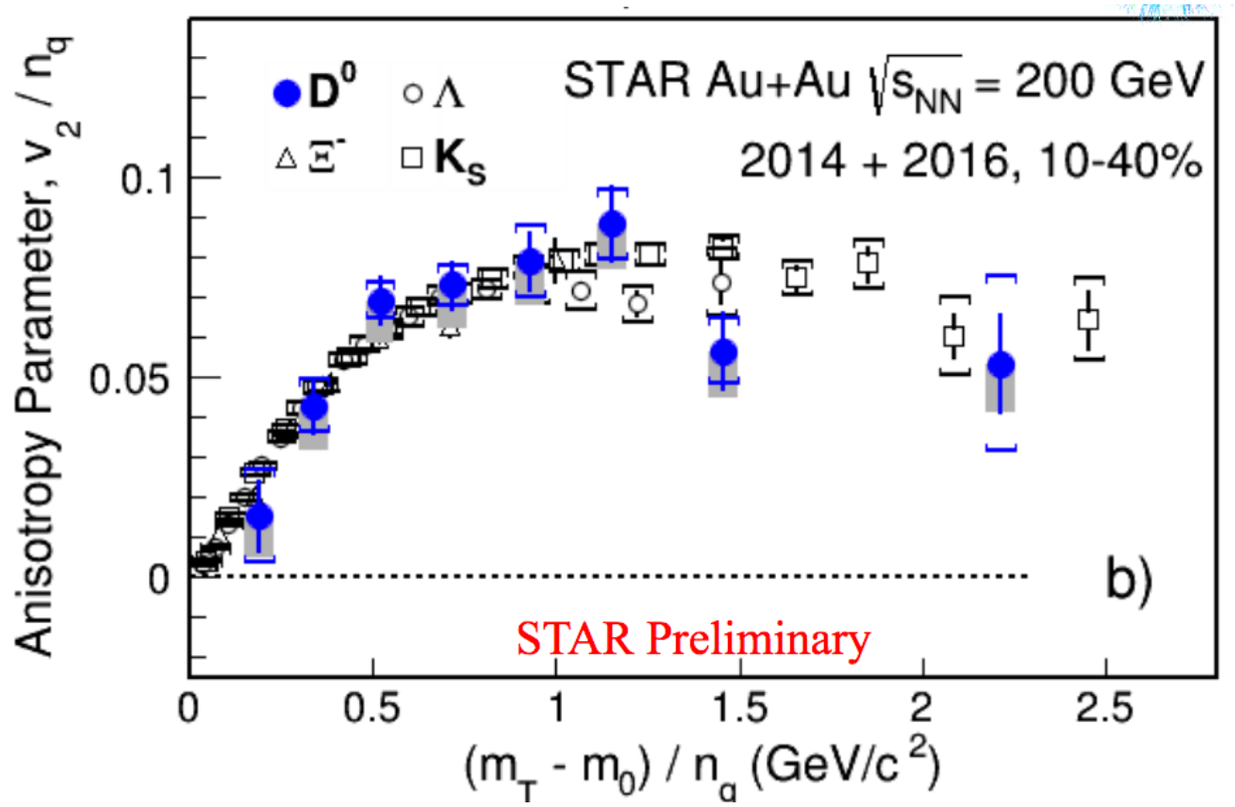


- Template fits to single electron DCA to extract e_D and e_B fractions
- Indication of higher R_{AA} for B —> e, compared to D —> e (~2 sigma effect)

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

Transport: D^0 elliptic low



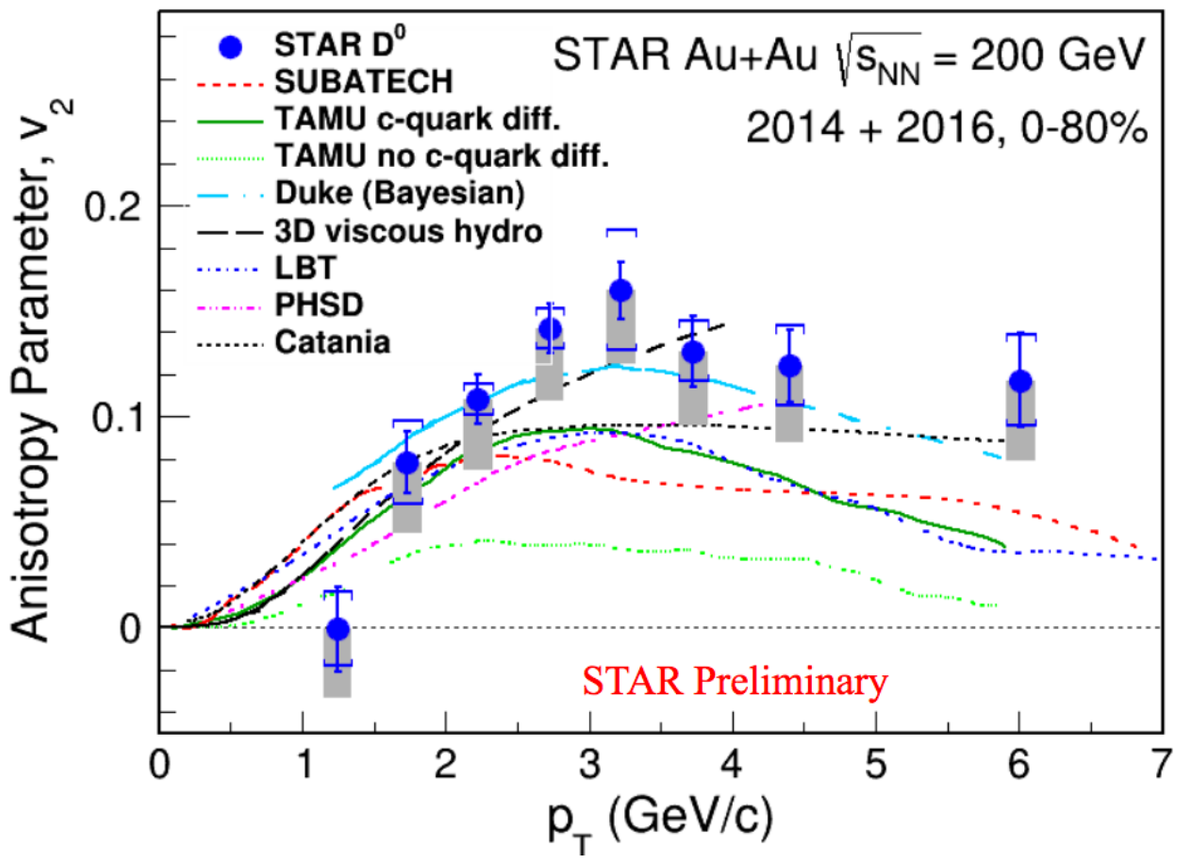


STAR Published results from 2014: Phys. Rev. Lett. 118 (2017) 212301

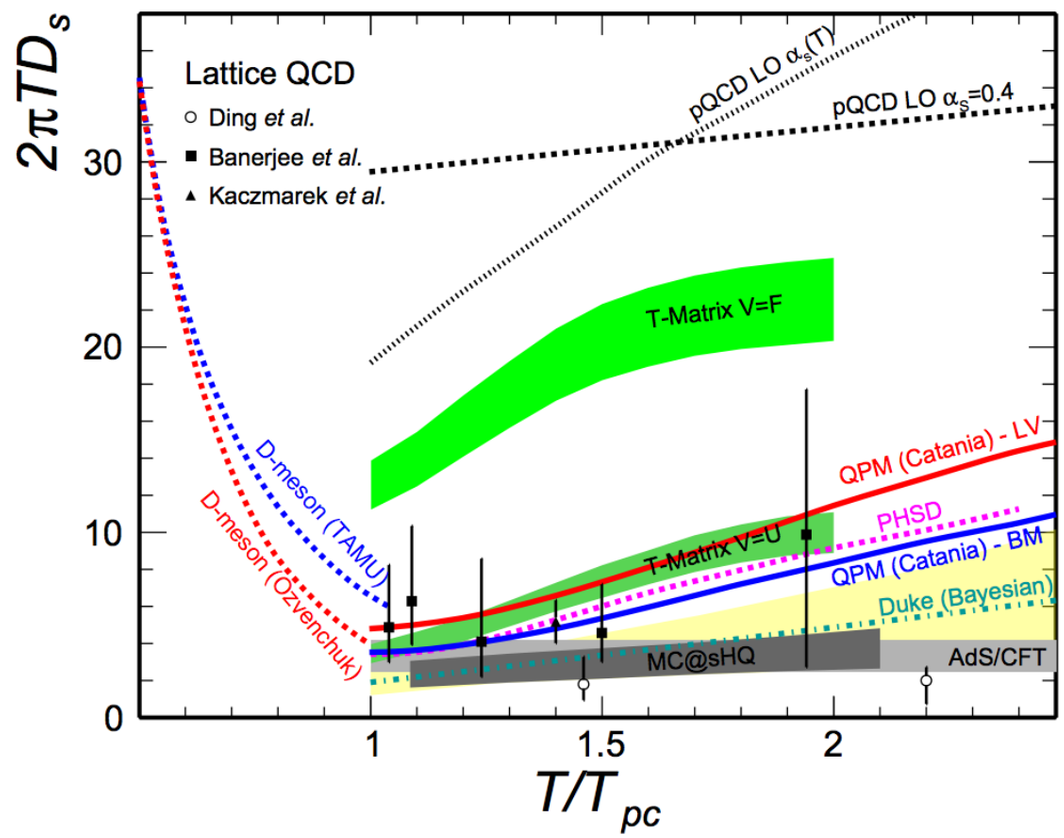
- Combined results from 2014+2016 data, improved precision

- 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



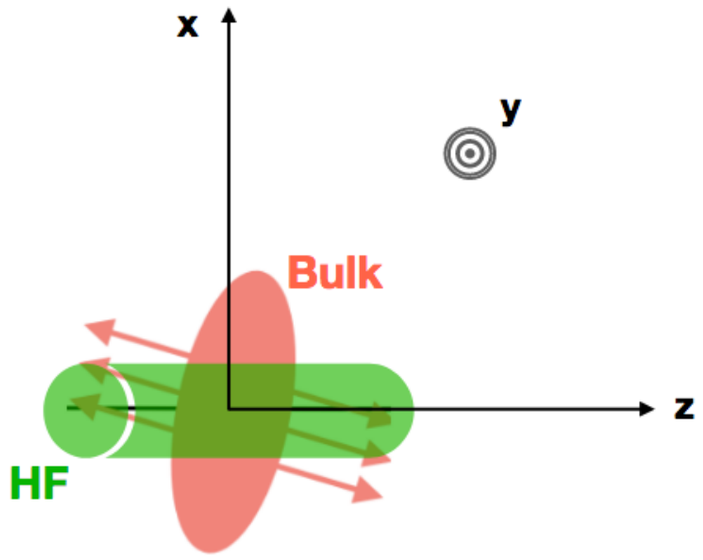
SUBATECH: PhysRevC 90, 054909 (2014), PhysRevC 92, 014910 (2015)
TAMU: PhysRevC 86, 014903 (2012), PhysRevLett110, 112301 (2013)
Duke: PhysRevC 92, 024907 (2015)
3D viscoushydro: PhysRevC 86, 024911 (2012)

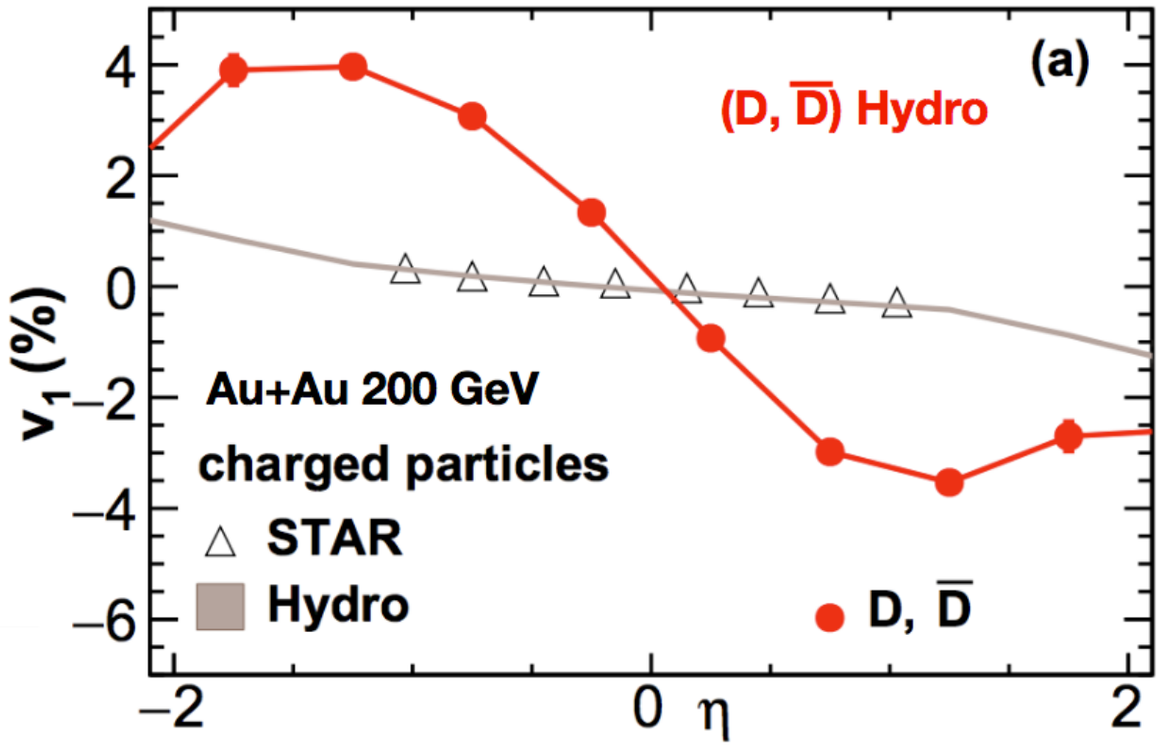


LBT: PhysRevC 94, 014909 (2016)
PHSD: PhysReV90, 051901 (2014), PhysReV90, 051901 (2014)
Catania: PhysReV96, 044905 (2017)

- 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





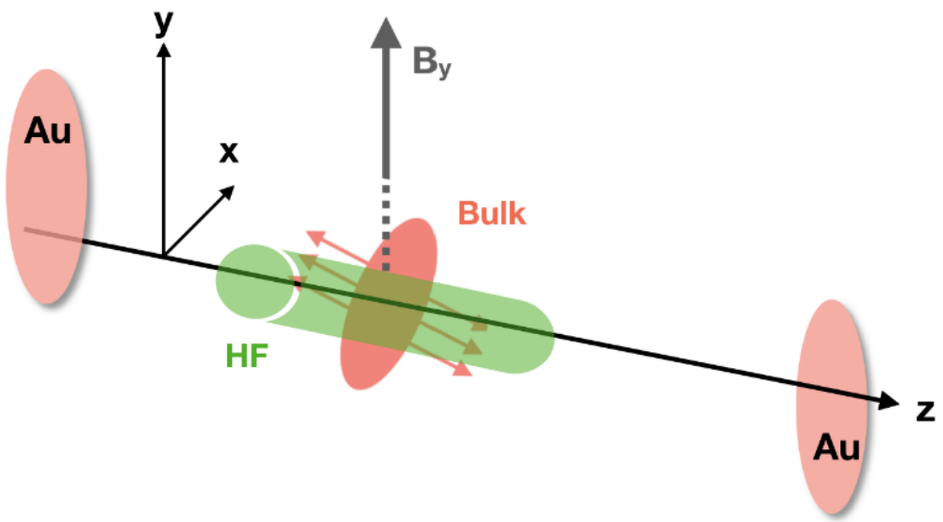
Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)

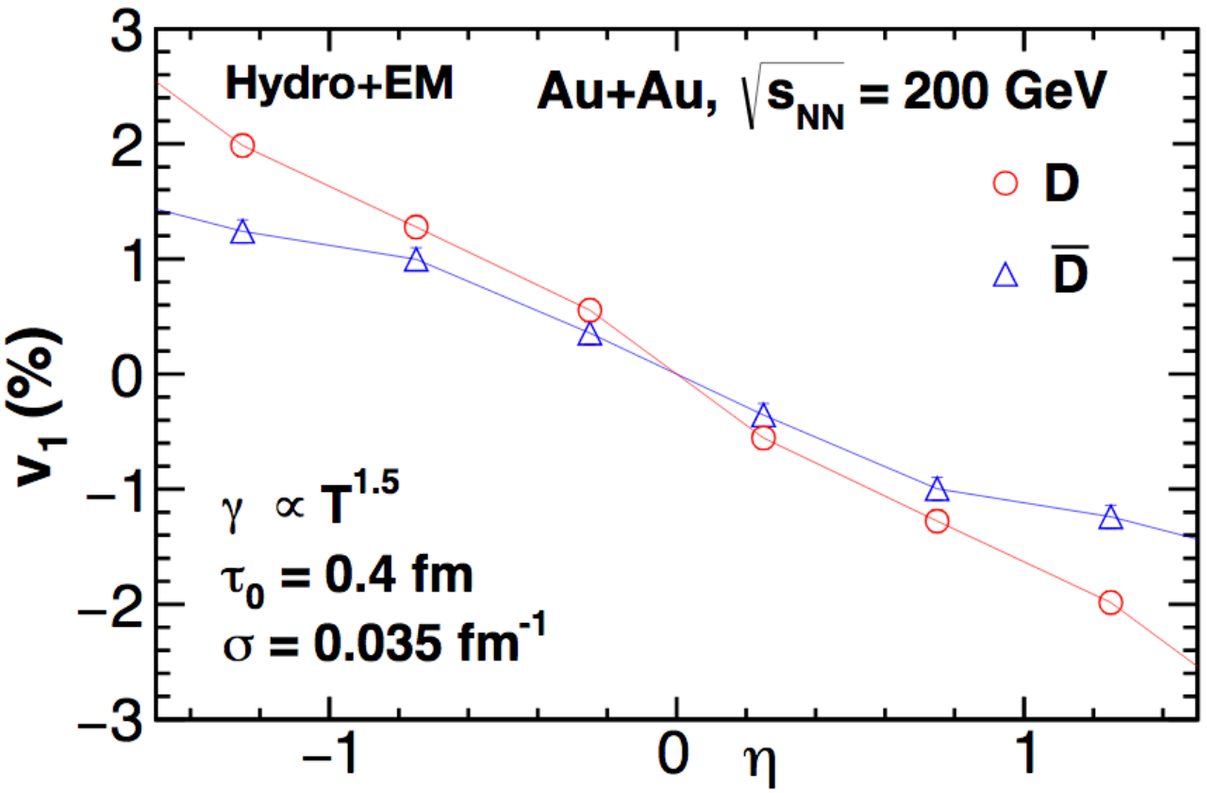
- Initial conditions in longitudinal direction: important for accurate modeling of HIC

- 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



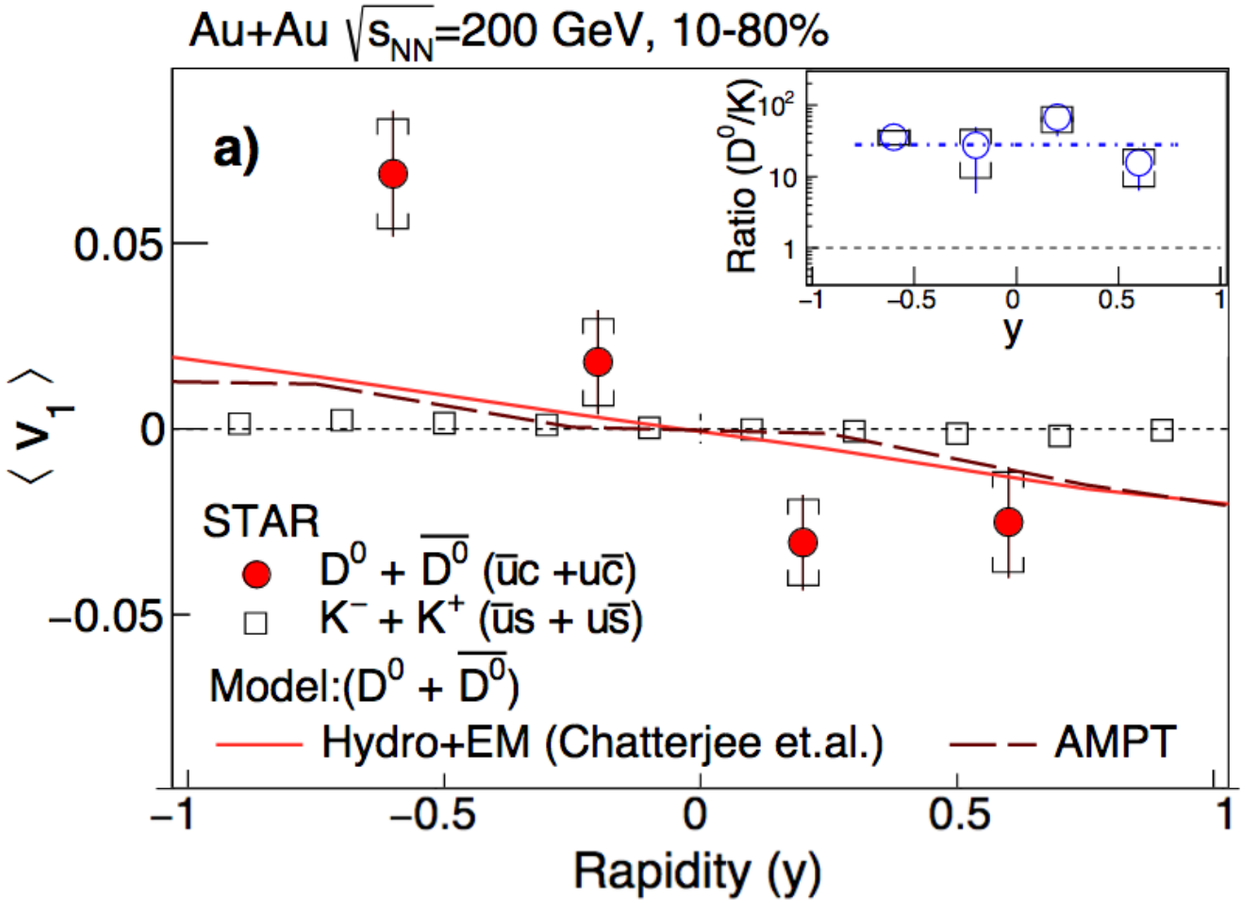


Das et. al., Phys Lett B 768, 260 (2017), Chatterjee, Bojek: arXiv1804.04893v1

- 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

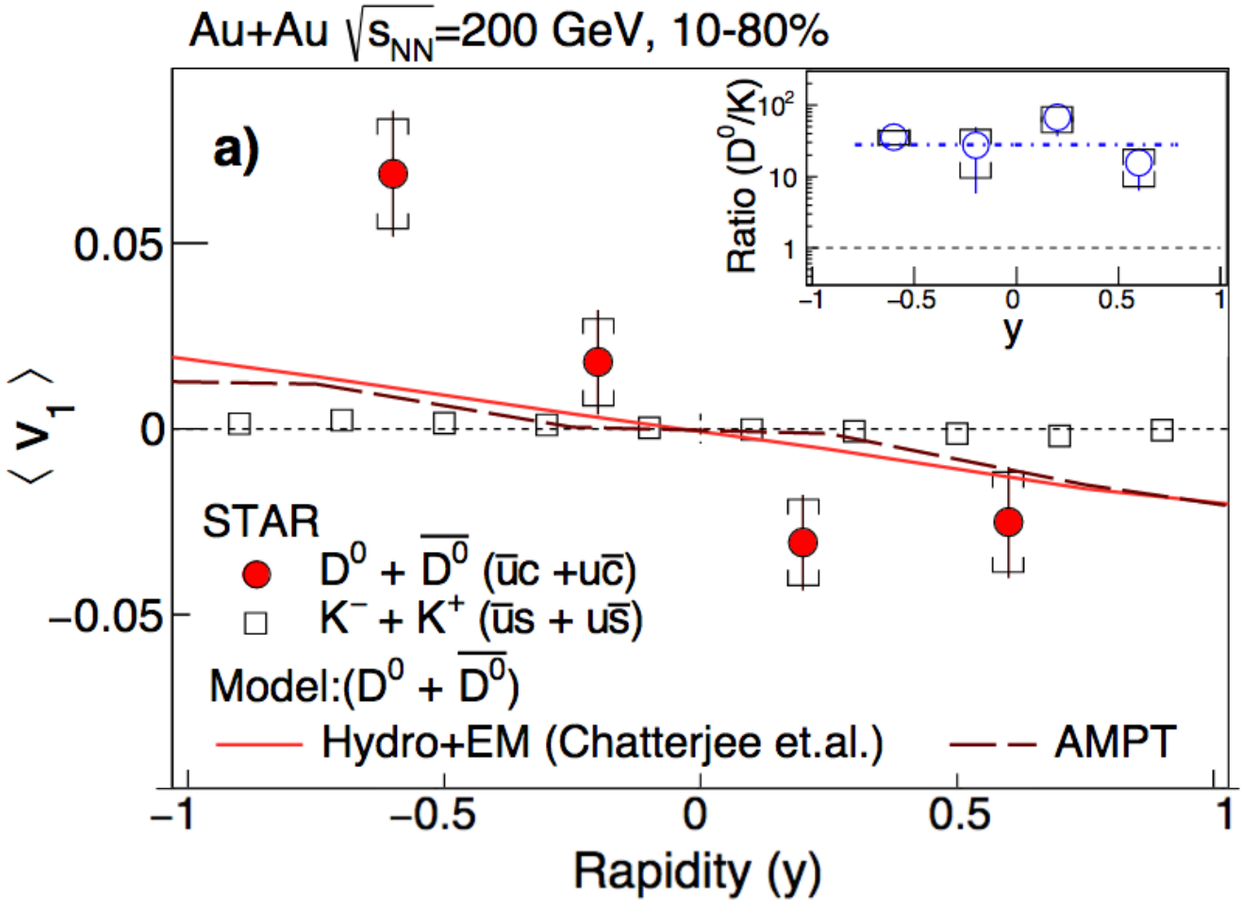


- Measured D^0 v_1 slope, ~5-20 times larger than that for kaons

- Hydro models show correct sign and large magnitude, but under-predicts the data
- AMPT also predicts large magnitude

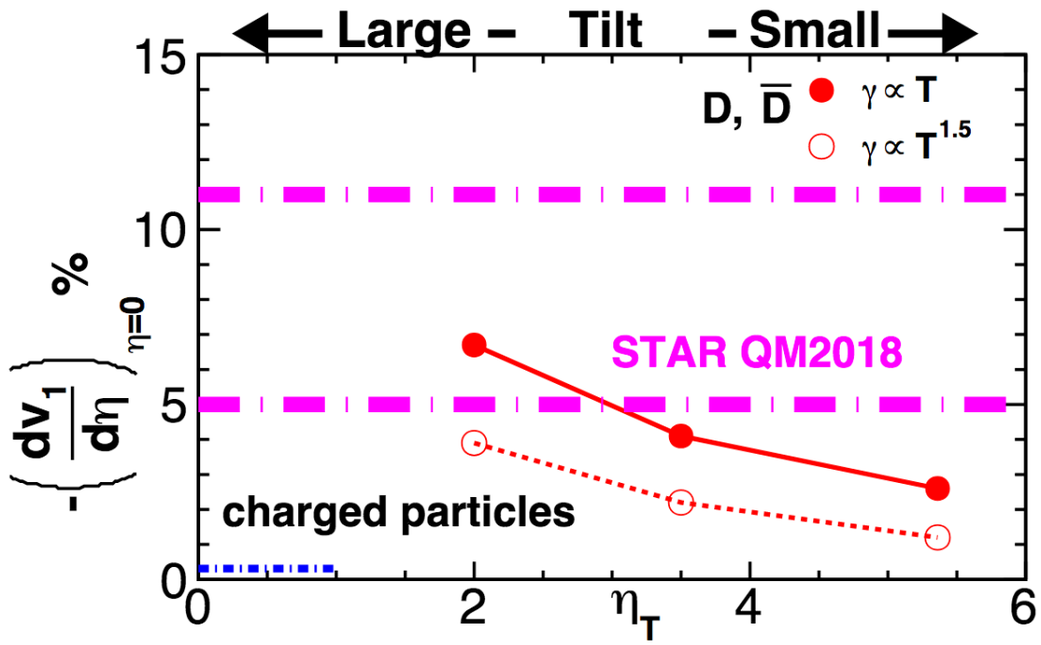
STAR: arXiv:1905.02052, Submitted to PRL

Directed flow of D^0 mesons



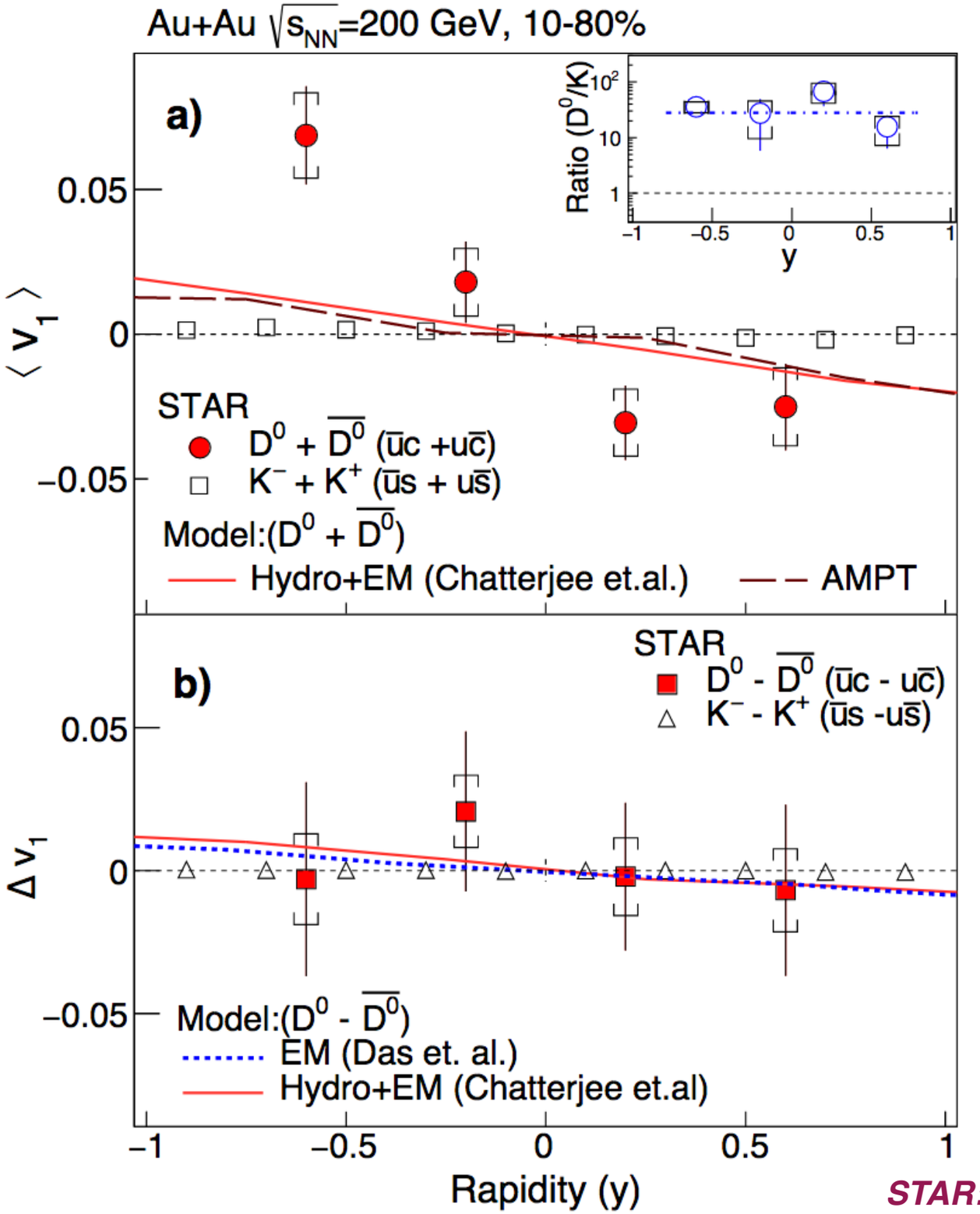
STAR: arXiv:1905.02052, Submitted to PRL

- 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

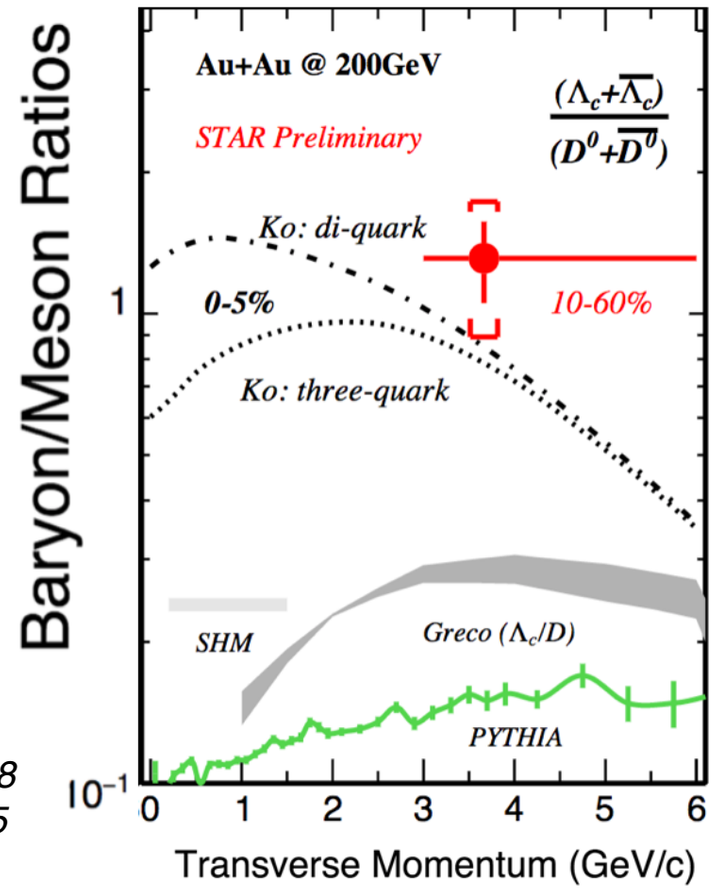
STAR: arXiv:1905.02052, Submitted to PRL

Λ_c production in HIC

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

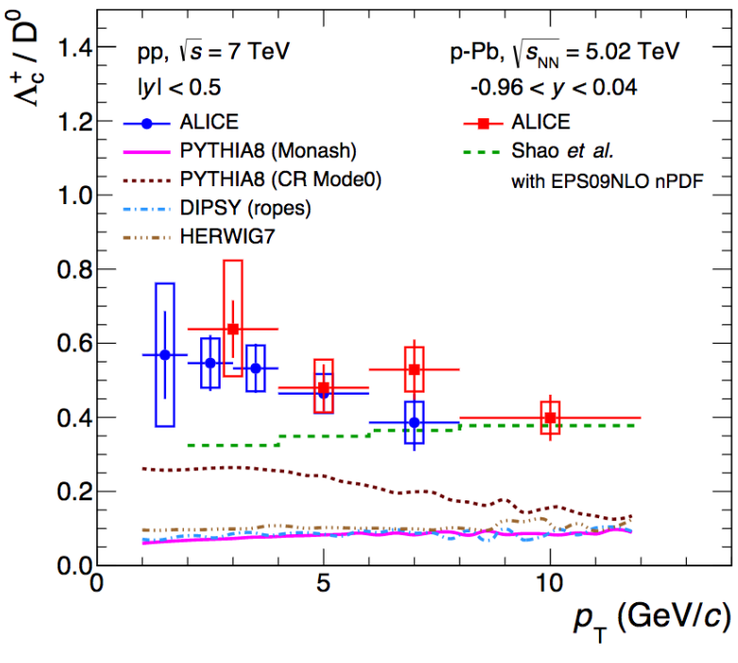
- Also important towards the understanding of charm quark energy loss in the QGP

STAR: QM17



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

ALICE: JHEP04(2018)108

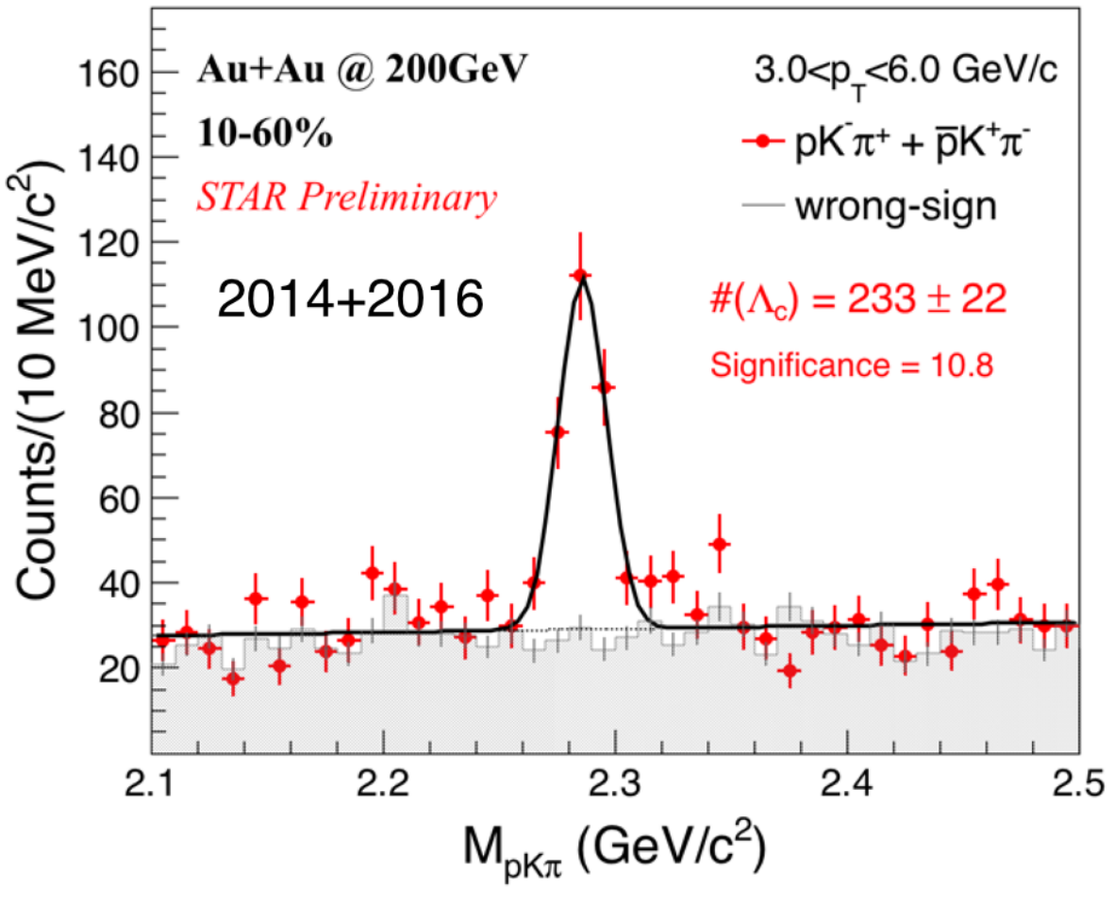


- Enhancement relative to PYTHIA seen in p+p and p+Pb collisions at LHC
- MPI with CR also under-predict
- What is the centrality dependence in HIC?

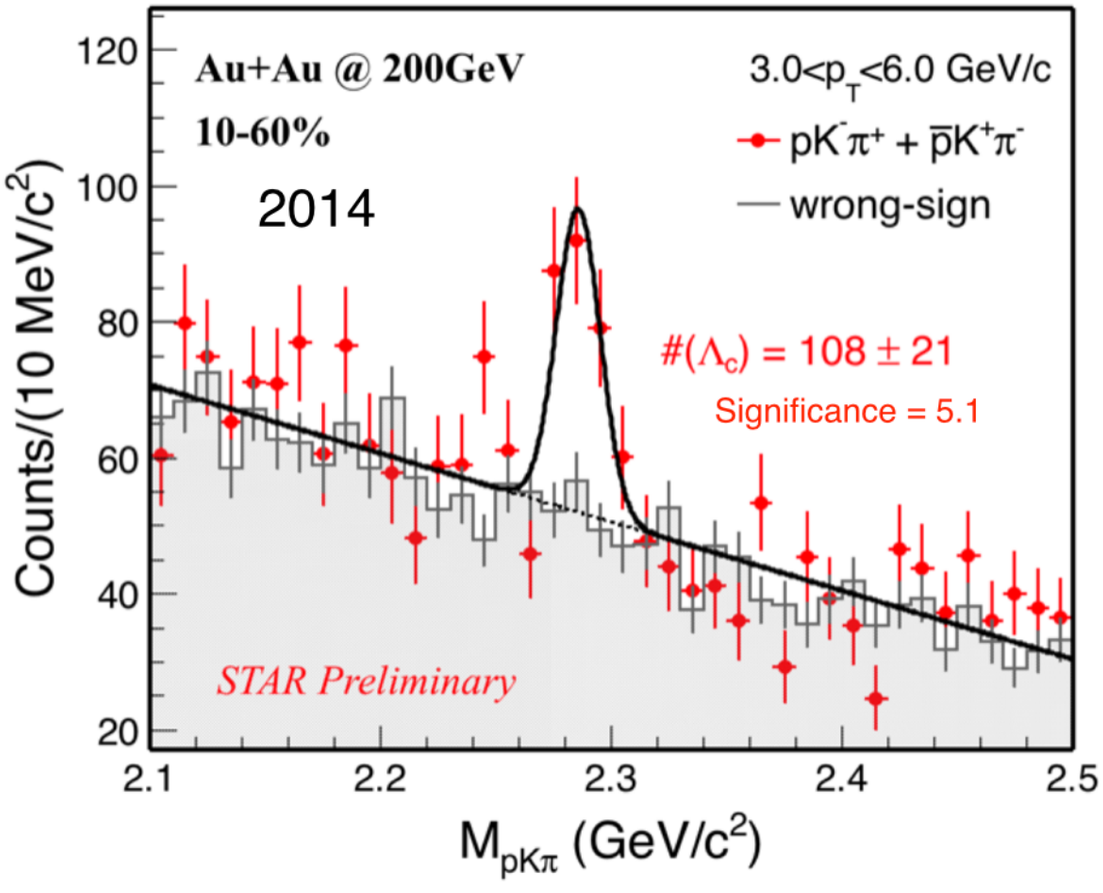
Λ_c signal reconstruction

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

QM18

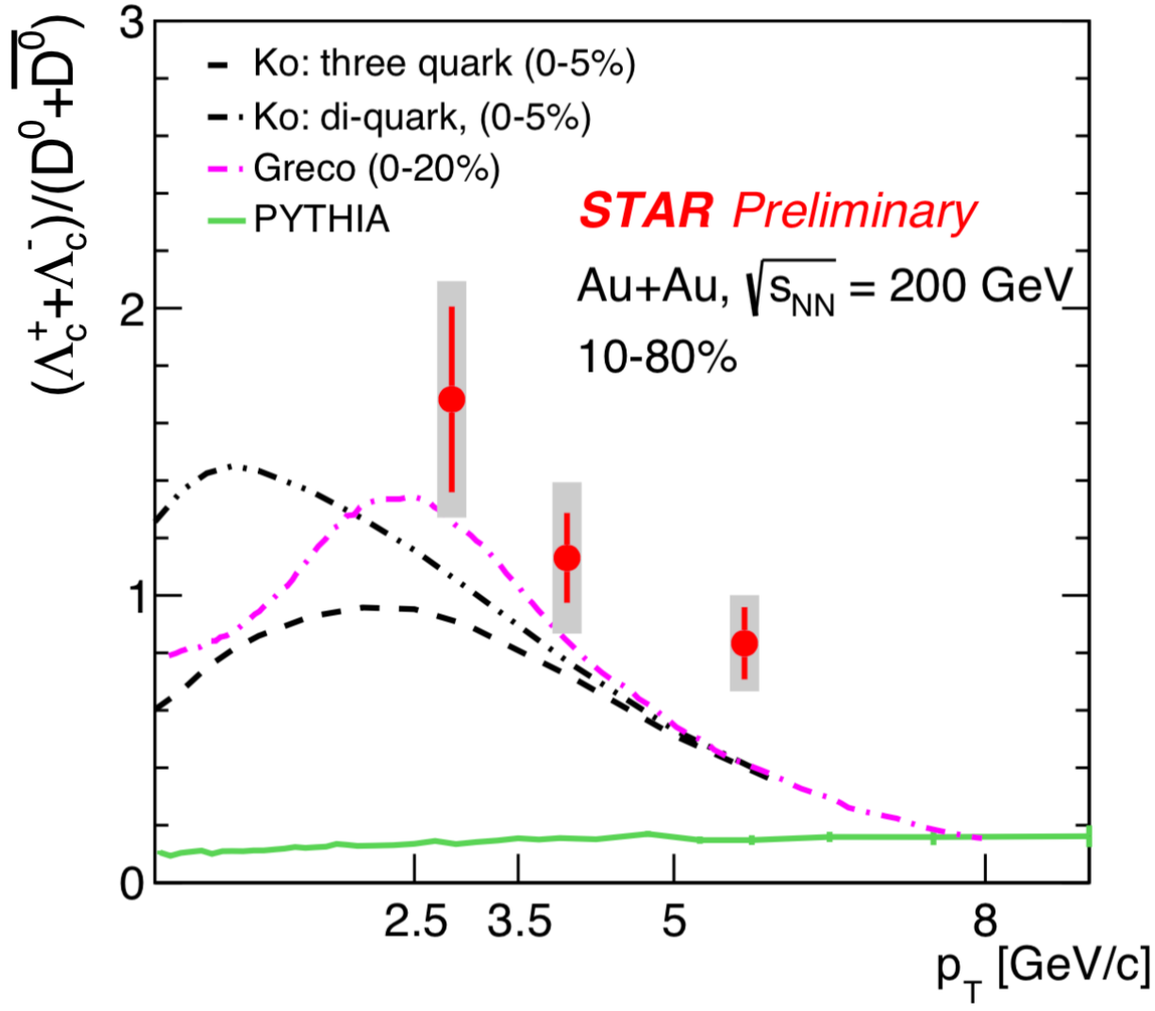


QM17

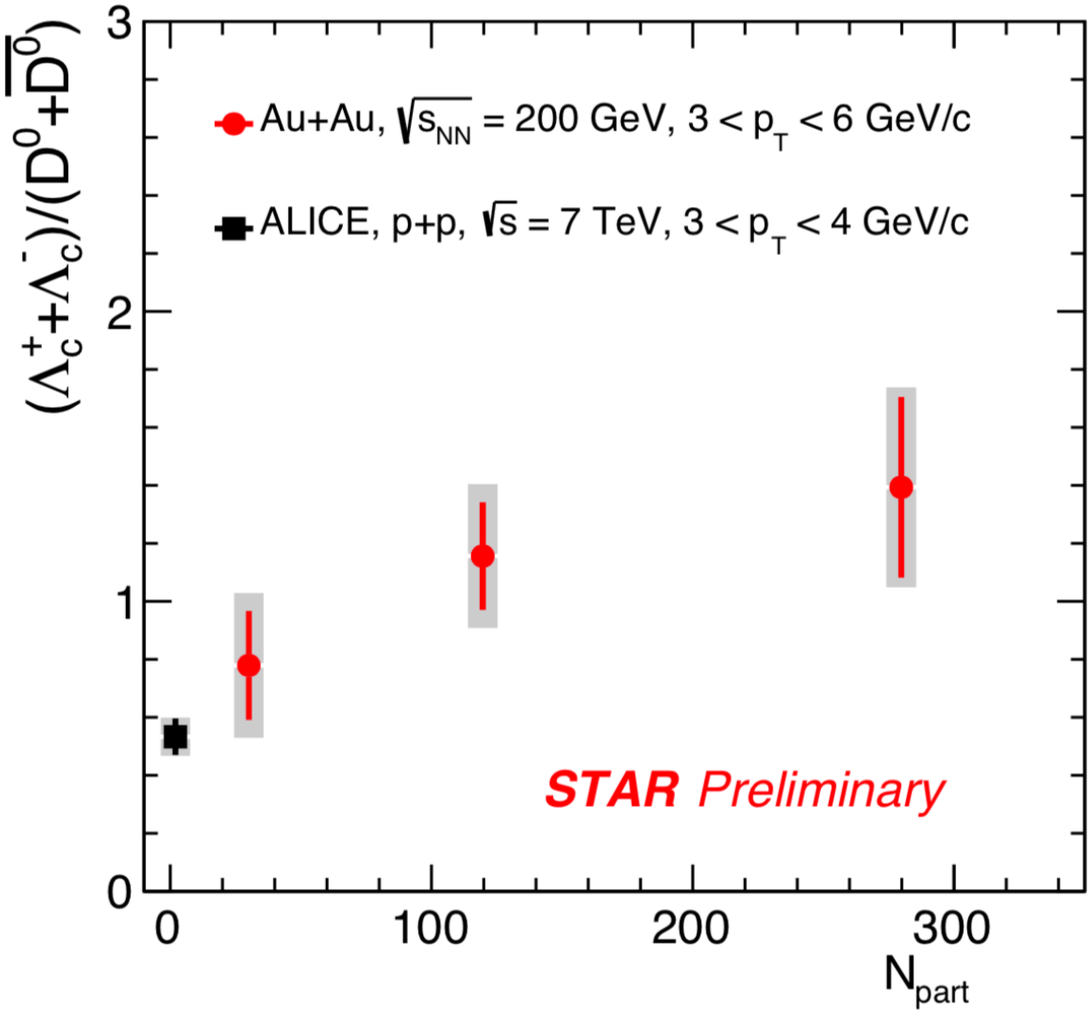


- More than 50% improvement in signal significance with TMVA BDT.
- Also new data from 2016 —> Effectively 4x more data compared to QM17

Λ_c/D^0 ratio: p_T dependence



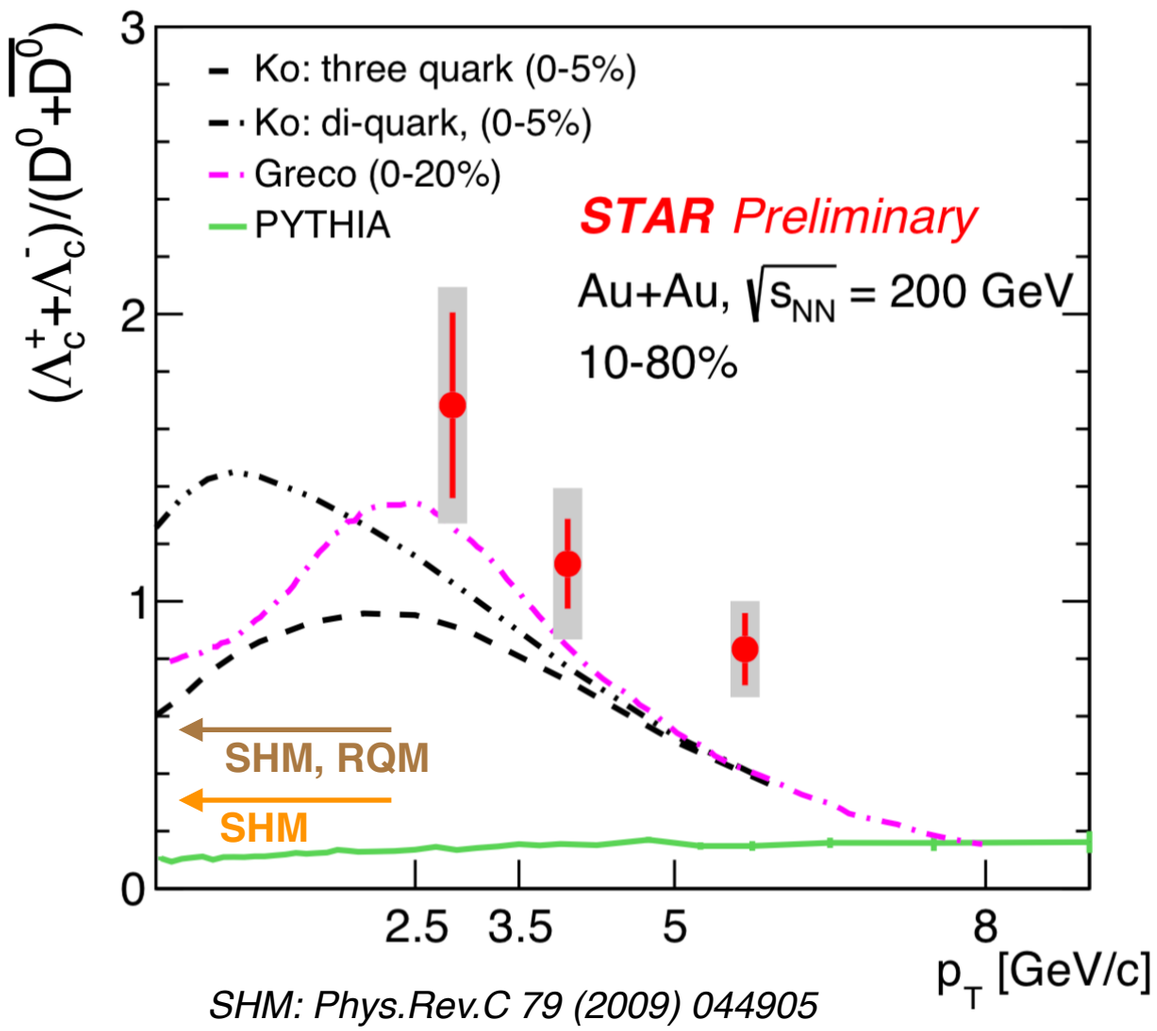
Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348

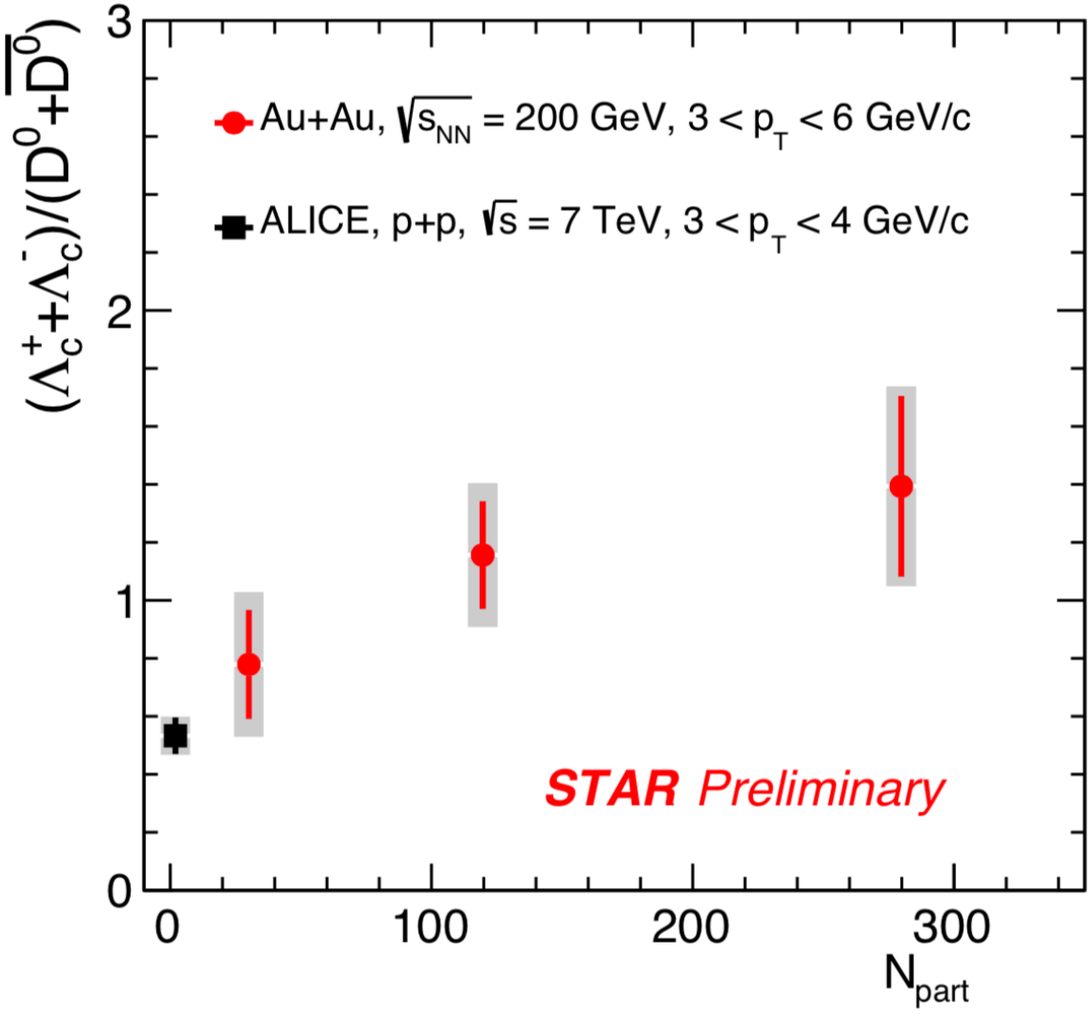


ALICE p+p: JHEP 04 (2018) 108

- Strong enhancement of Λ_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

Λ_c/D^0 ratio: p_T and centrality dependence



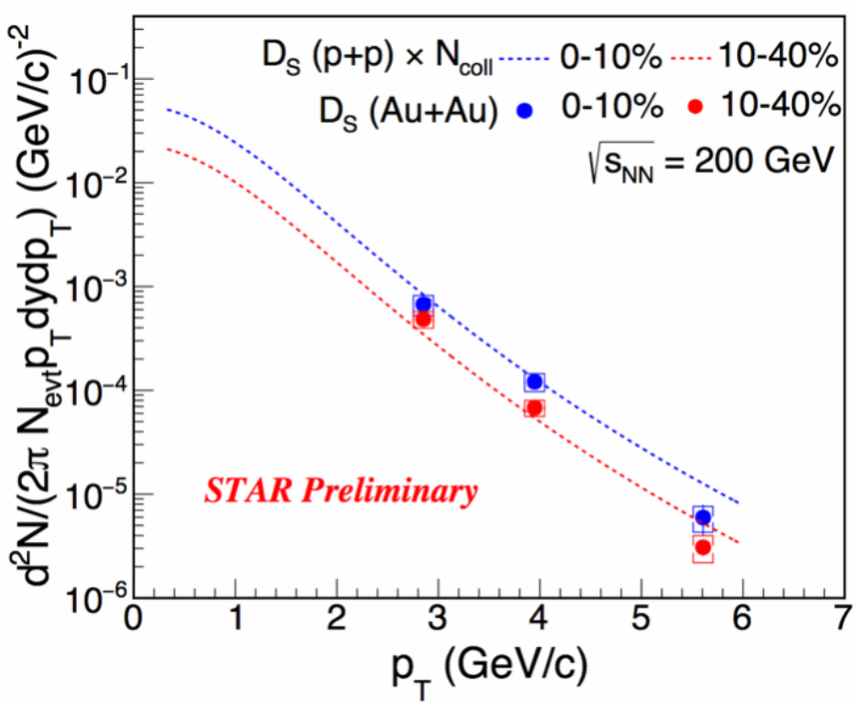


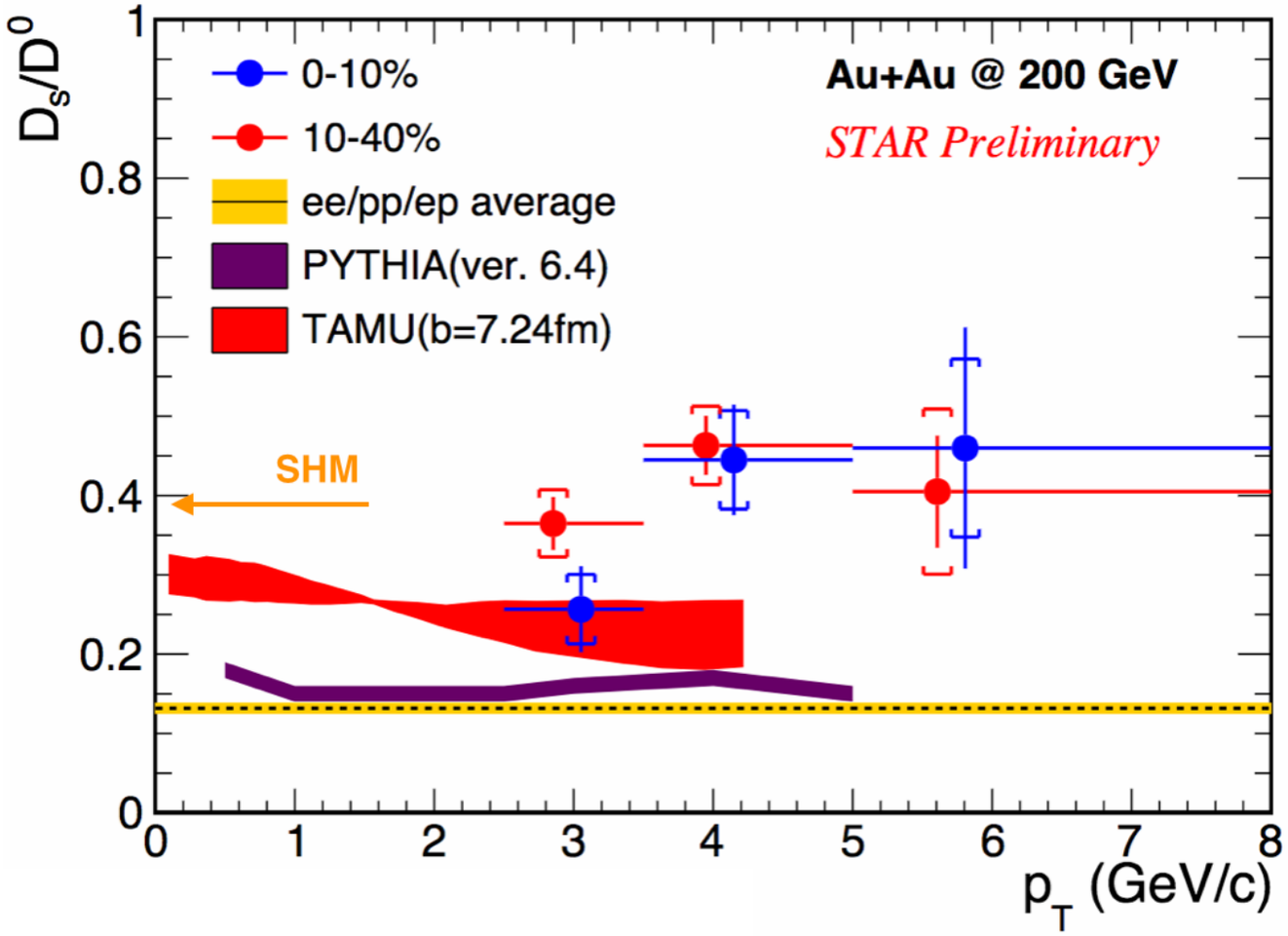
SHM: Phys.Rev.C 79 (2009) 044905
SHM, RQM: arXiv:1902.08889

- Strong enhancement of Λ_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 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%**

p+p: Phys Rev Lett.121.229901

- Total per-nucleon charm cross-section 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 per-nucleon charm cross section consistent with p+p, but hadrochemistry significantly modified

Back Up