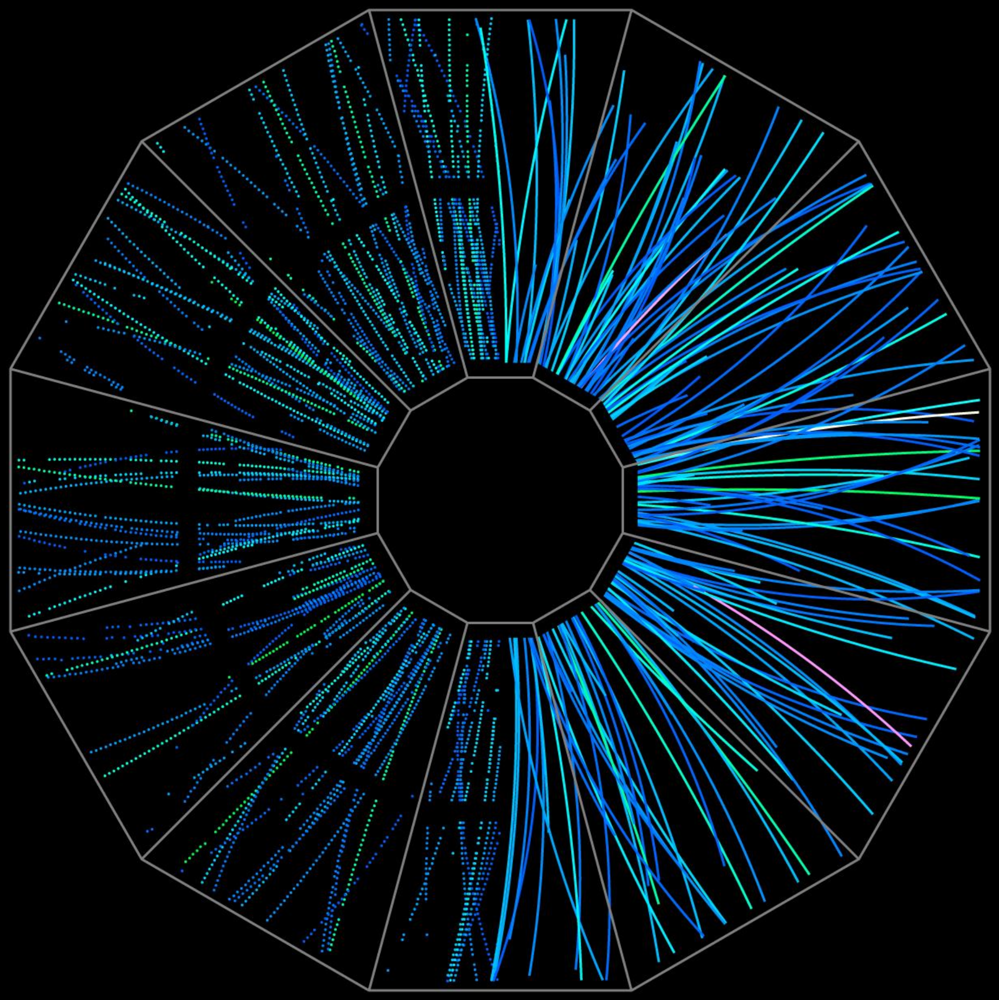


Measurements of open heavy-flavor hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR experiment

Lukáš Kramárik, for the STAR collaboration
Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague

30 July 2020

40th International Conference on High Energy Physics (ICHEP)
28 July – 6 August 2020
virtual conference

STAR

FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING CTU IN PRAGUE

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

20 years | STAR COLLABORATION

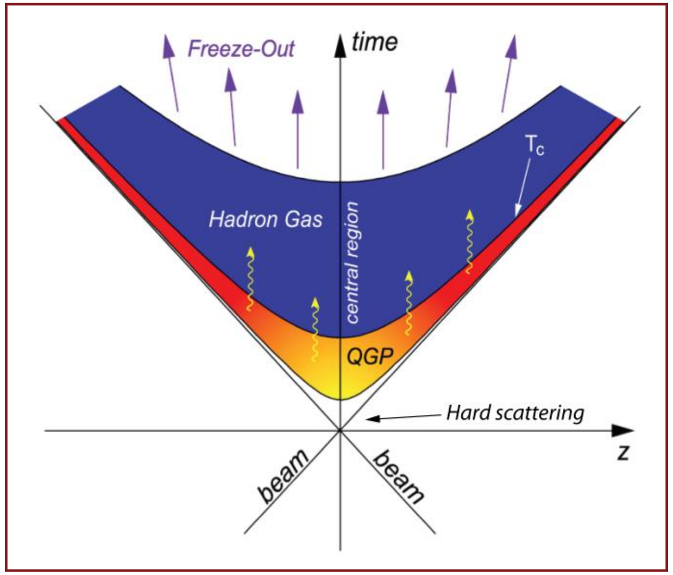
Acknowledgement
The work was also supported from European Regional Development Fund-Project "Center of Advanced Applied Science" No. CZ.02.1.01/0.0/0.0/16-019/0000778 and by the grant LTT18002 of Ministry of Education, Youth and Sports of the Czech Republic.

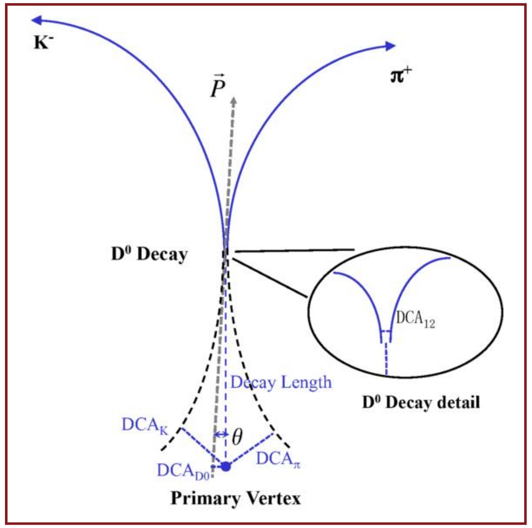
Outline

- Motivation – probing quark-gluon plasma
- The Solenoid Tracker At RHIC
- Heavy flavor energy loss in Au+Au collisions
- Directed and elliptic flow of charm quarks in Au+Au collisions
- Hadronization of charm quarks in Au+Au collisions

Heavy-flavor quarks as a probe of quark-gluon plasma (QGP)

- QGP is hot and dense medium produced in **heavy-ion collisions**
- HF quarks possess **large masses**
  - → they are produced primarily at the **early stages of nuclear collisions**
  - → they experience the **whole evolution of the system including the QGP phase**
- HF hadrons allow to probe **the quark mass dependence of energy loss** in the QGP
- **Collective behavior** of heavy-flavor quarks
  - → sensitive to the degree of thermalization in the QGP
  - → constrain the heavy-flavor quark diffusion coefficient



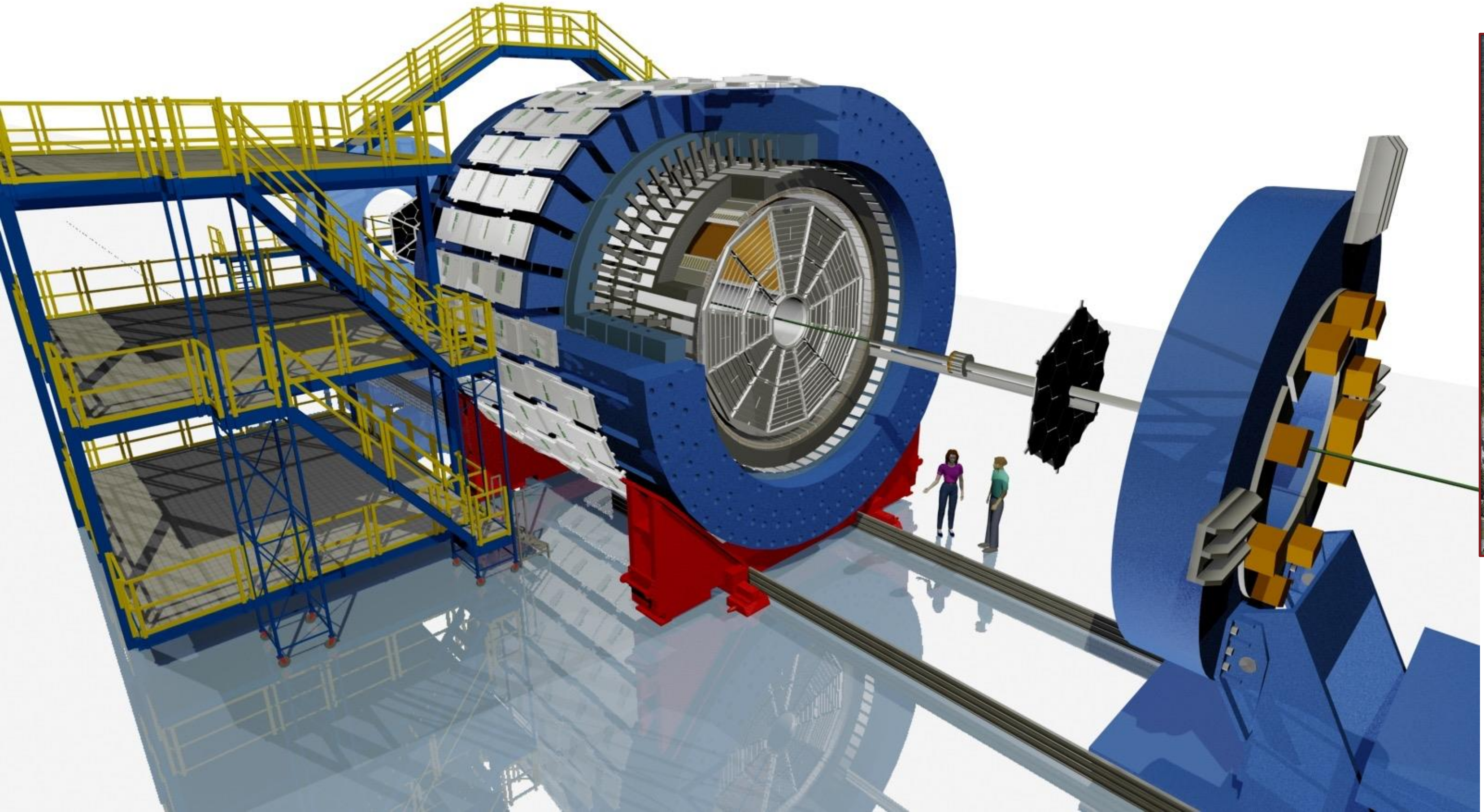


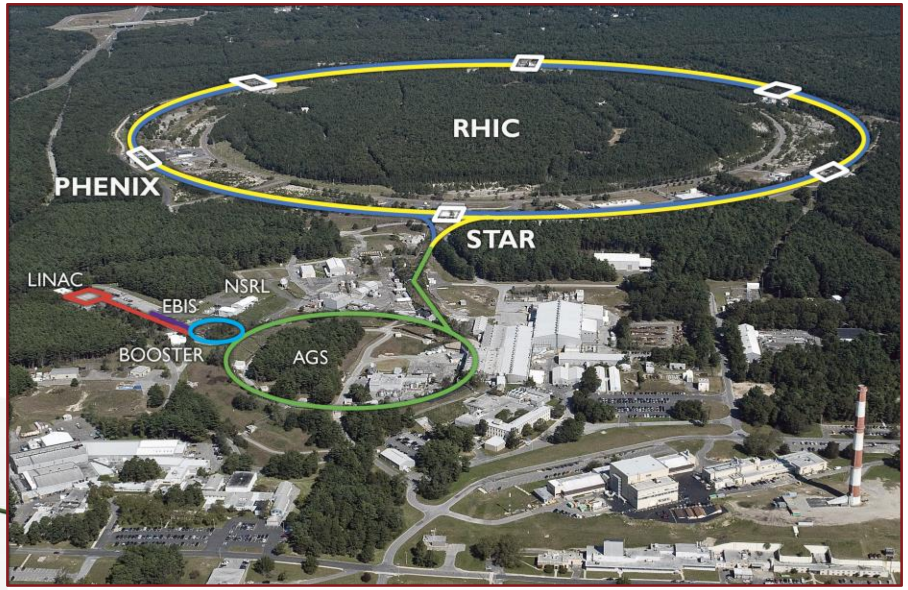
Open charm hadrons are studied via hadronic decays:

- $\mathbf{D^+(c\bar{d}) \rightarrow K^- \pi^+ \pi^+}$, *branching ratio (BR) = (8.98 ± 0.28) %*
- $\mathbf{D^0(c\bar{u}) \rightarrow K^- \pi^+}$, *BR = (3.93 ± 0.04) %*
- $\mathbf{D_s^+(c\bar{s}) \rightarrow \Phi \pi^+, \Phi \rightarrow K^- K^+}$, *BR = (2.27 ± 0.08) %*
- $\mathbf{\Lambda_c^+(udc) \rightarrow K^- \pi^+ p}$, *BR = (6.35 ± 0.33) %*

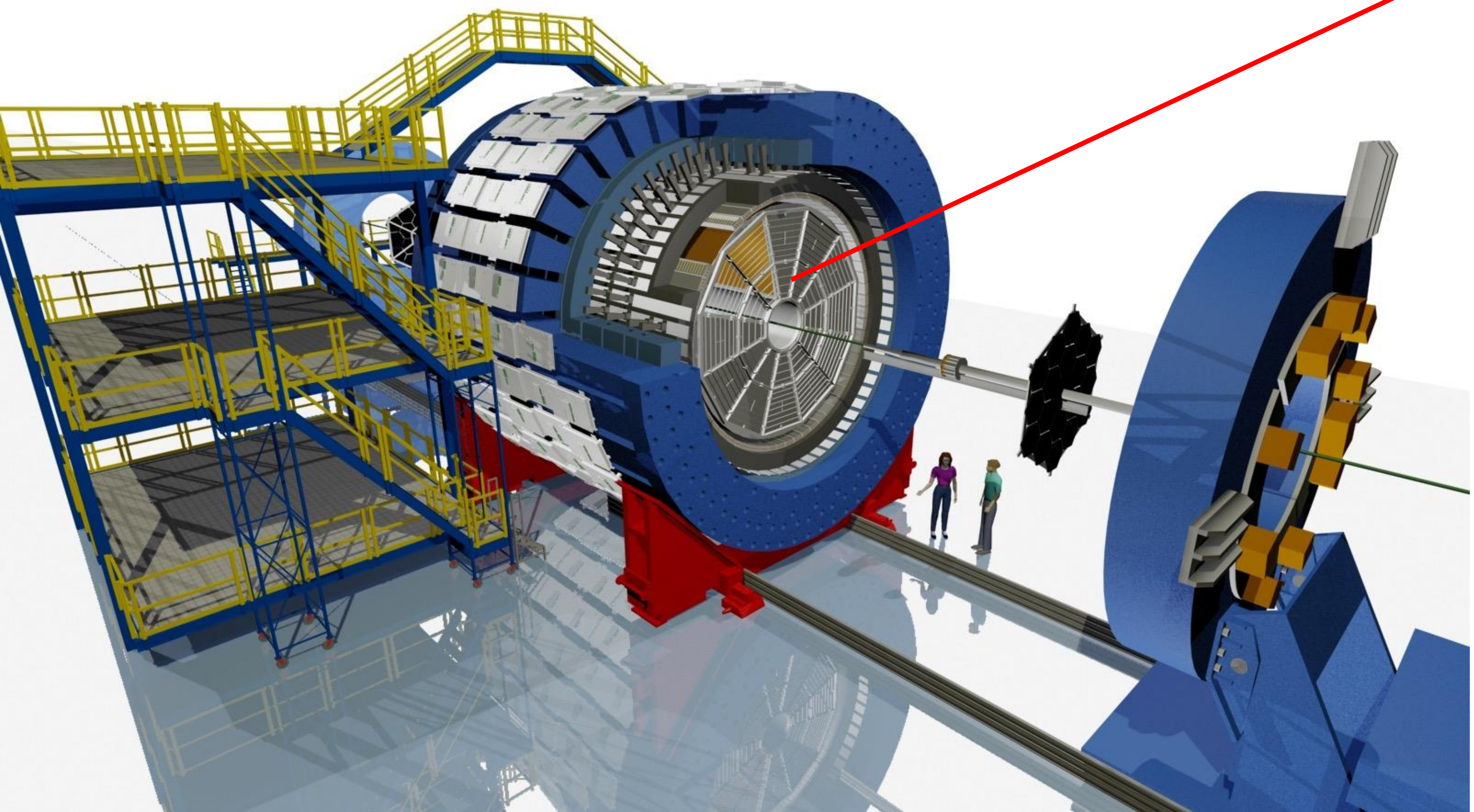
The Solenoid Tracker At RHIC

- Situated at **Relativistic Heavy-Ion Collider at Brookhaven National Laboratory (BNL) in the USA**
- Designed to study the strongly interacting matter
- Excels in **tracking and identification of charged particles** at mid-rapidity with full azimuthal coverage
- Most of the subsystems are immersed in 0.5 T solenoidal magnetic field



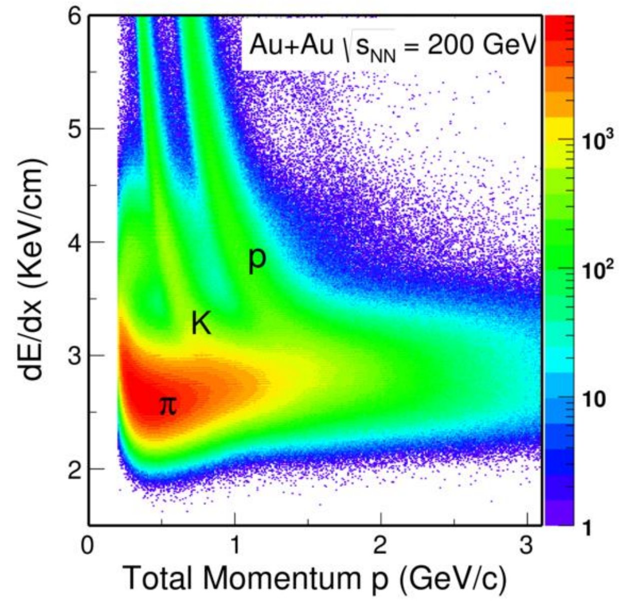


The Solenoid Tracker At RHIC



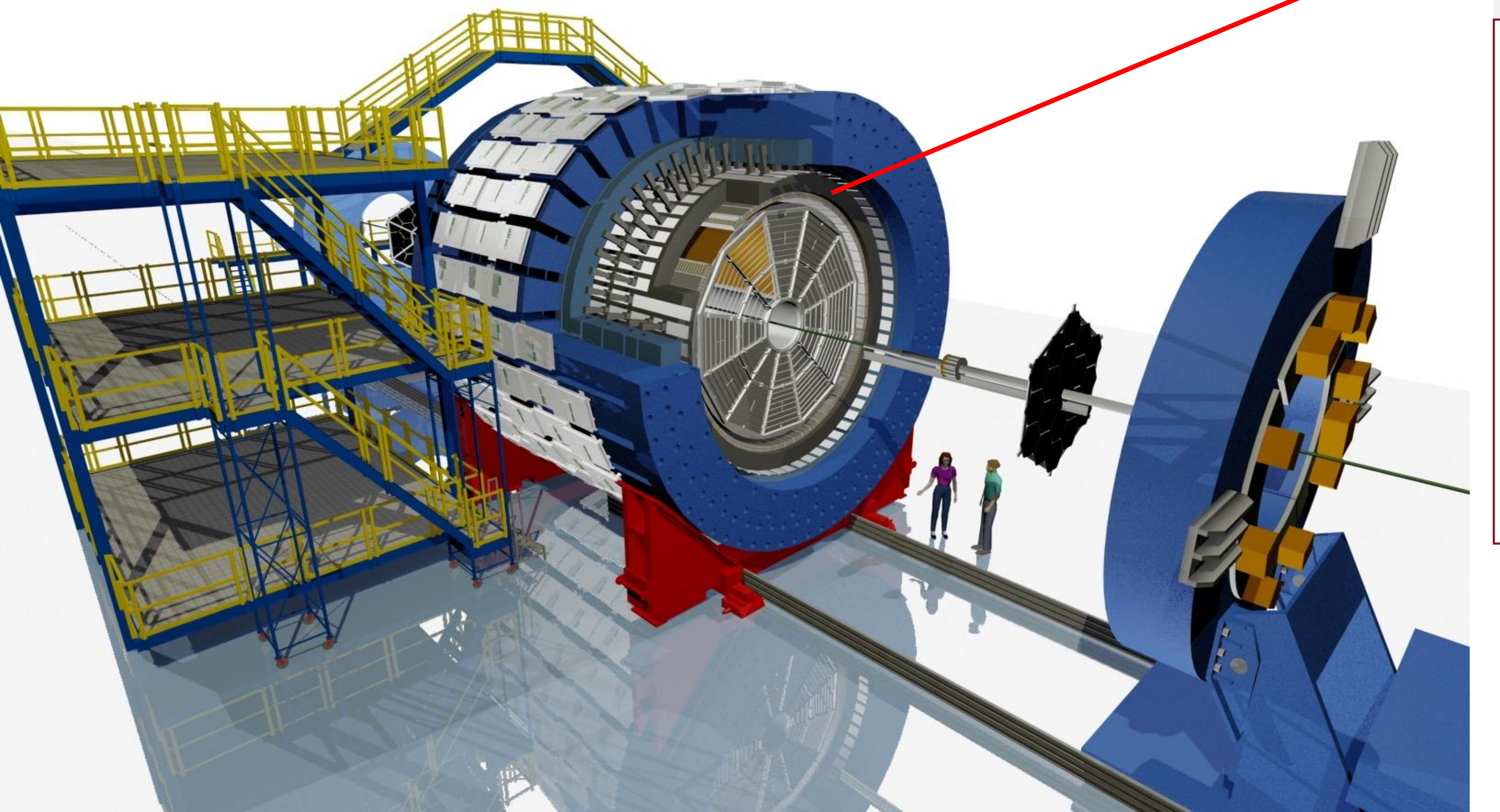
Time Projection Chamber (TPC)

- Main tracking device; momentum determination
- Particle identification via specific energy loss d*E*/dx



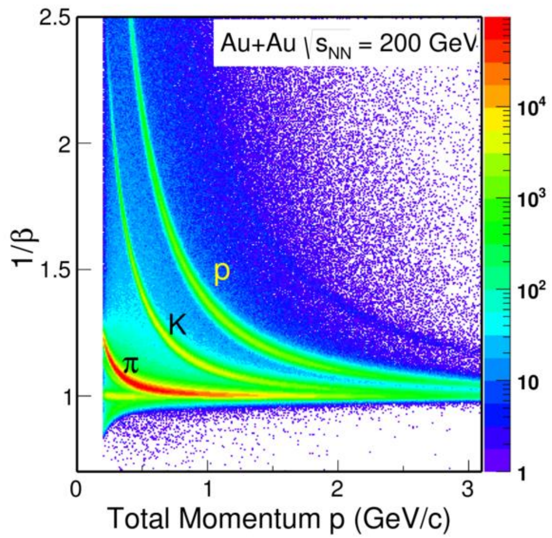
PRL 118, 212301, (2017)

The Solenoid Tracker At RHIC



Time Of Flight (TOF)

- Measures particle velocity β
- Improves particle identification in the momentum range of 0.6–3 GeV/c



PRL 118, 212301, (2017)

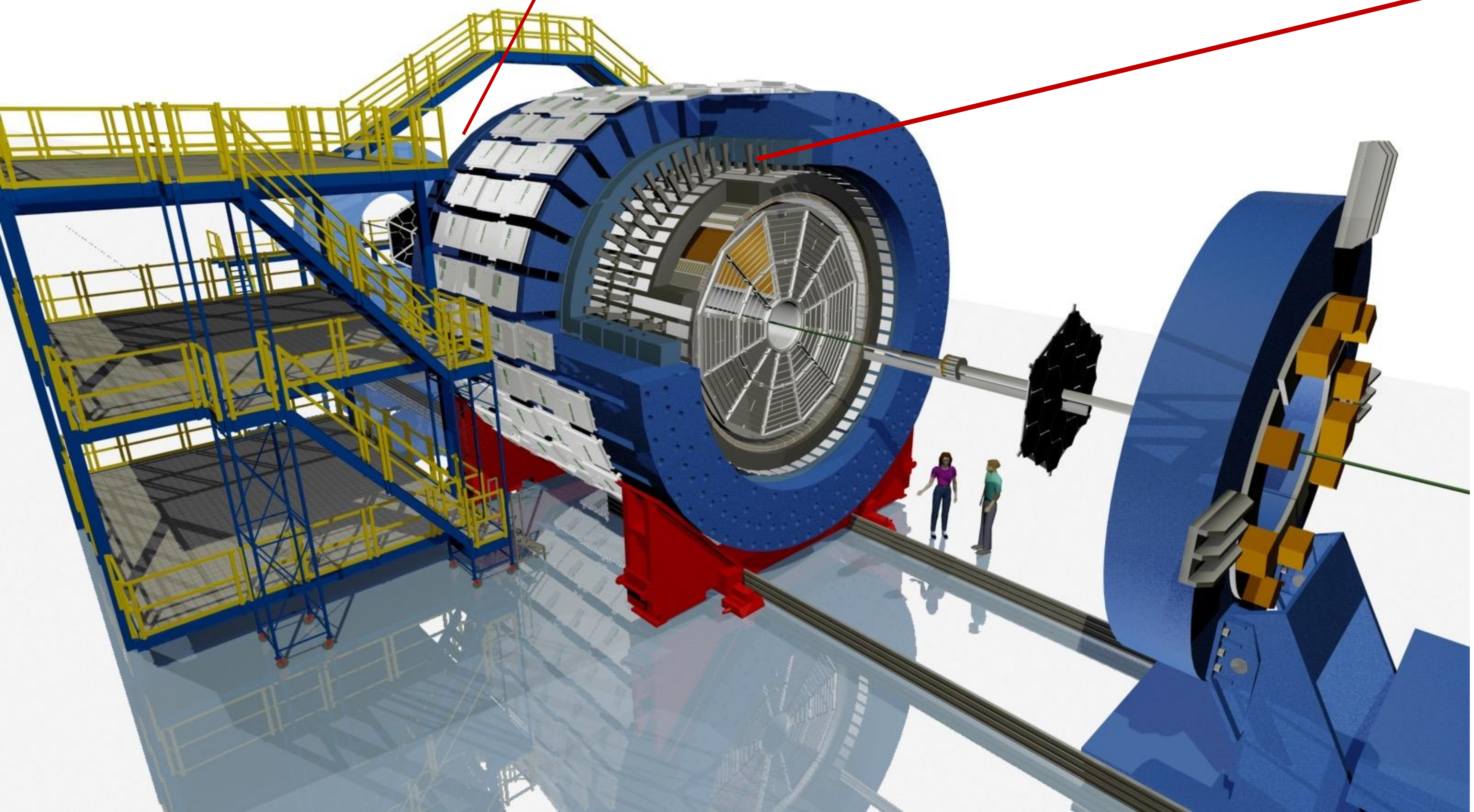
The Solenoid Tracker At RHIC

Forward Meson Spectrometer

- $2.5 < \eta < 4$
- Event plane measurements for flow studies

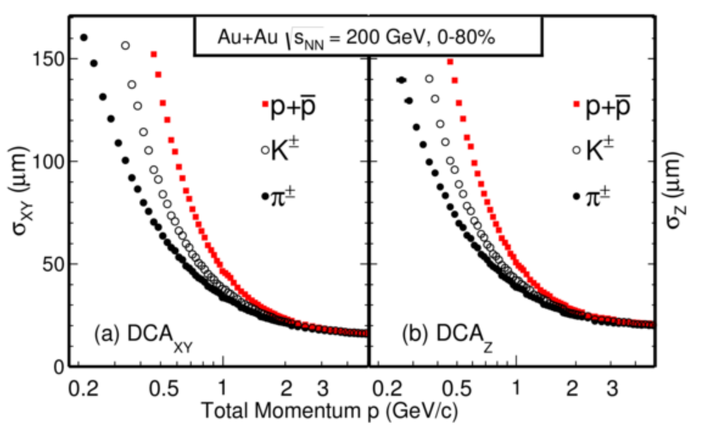
Barrel ElectroMagnetic Calorimeter

- Trigger on and identify high transverse momentum (p_T) electrons

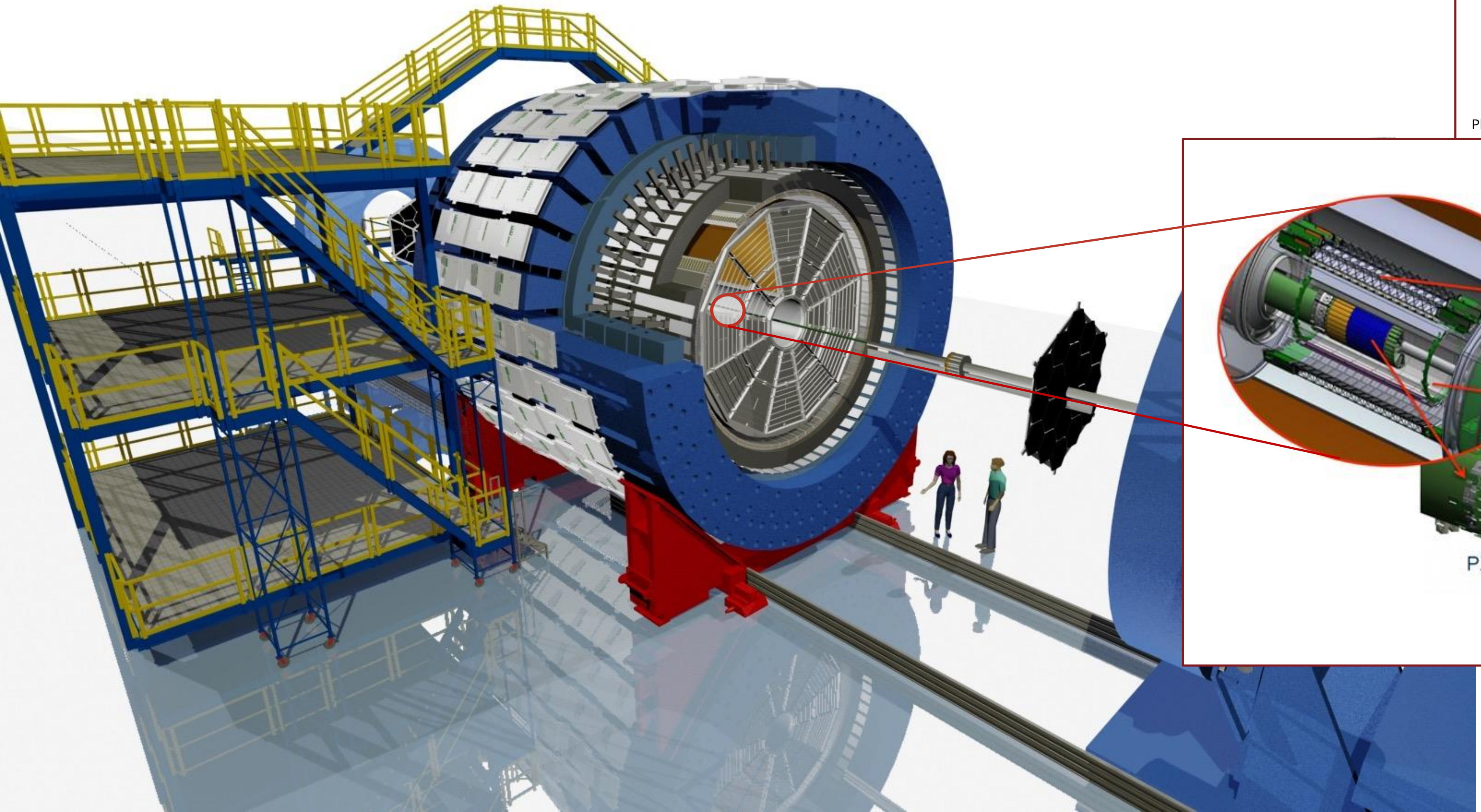


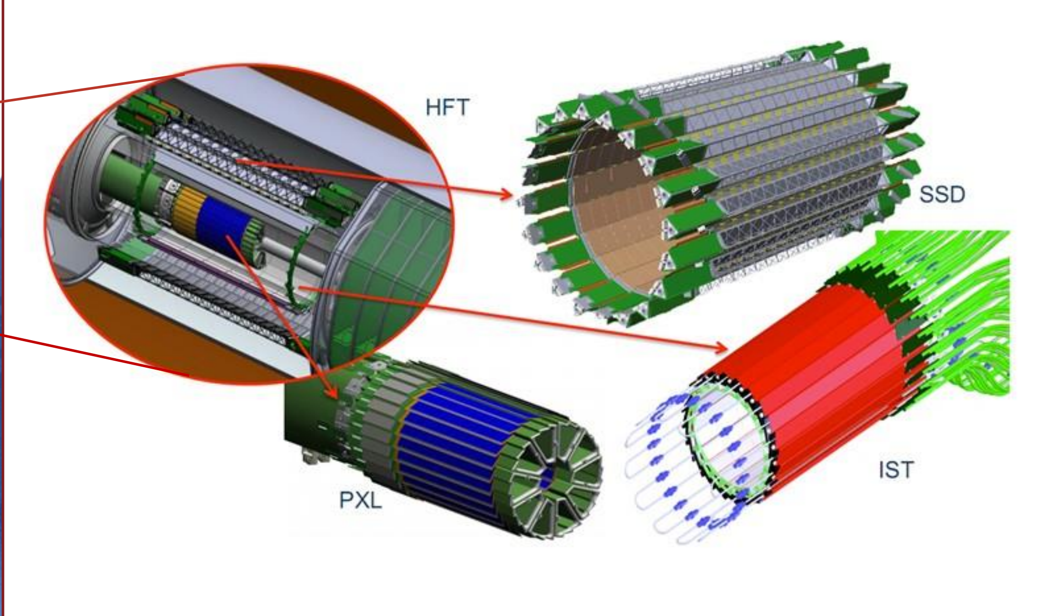
The Solenoid Tracker At RHIC

Heavy Flavor Tracker (HFT)
- Inner tracking system
- First application of MAPS in collider experiments
- Excellent **DCA_{xy} and DCA_z resolution: ~50 μm** for kaons at p_T = 750 MeV/c
- Significantly improves the signal/background for open HF reconstruction



Phys Rev C.99.034908 (2019)





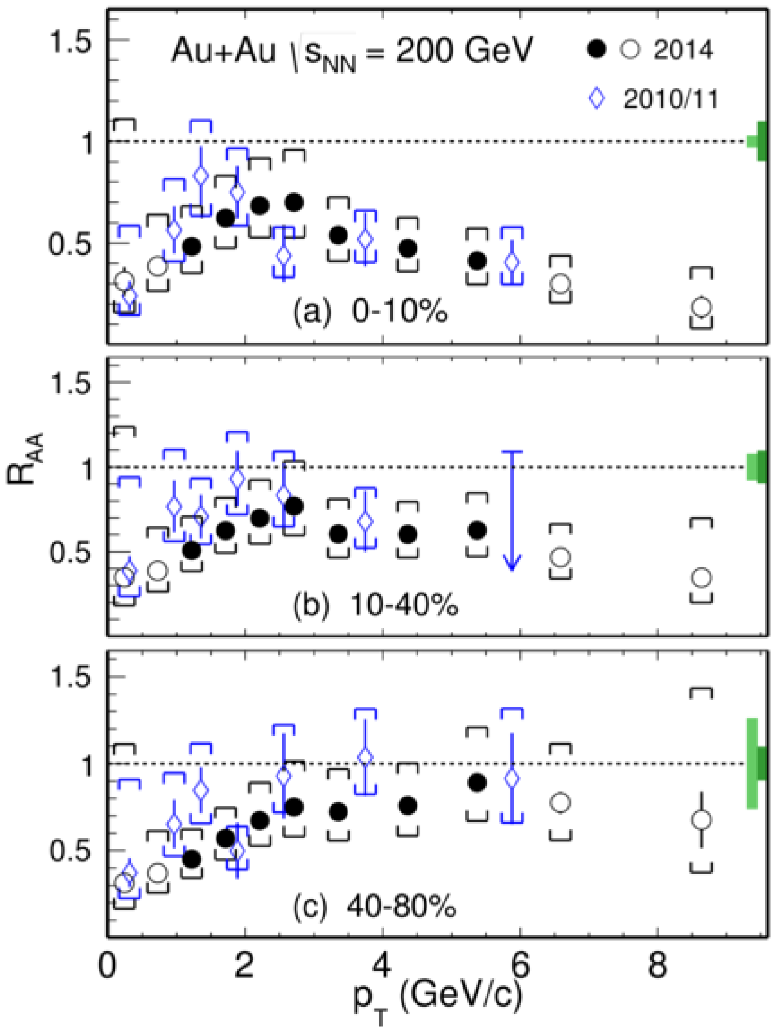
Energy loss in Au+Au collisions: D^0

- Nuclear modification factor R_{AA}:

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}$$

- Yields at high p_T are **greatly suppressed** in central collisions
- Suppression at high p_T decreases towards more peripheral collisions
- No significant centrality dependence for D^0 suppression at low p_T

STAR D^0: Phys Rev C.99.034908 (2019)



Energy loss in Au+Au collisions: D^0

- Nuclear modification factor R_{AA}:

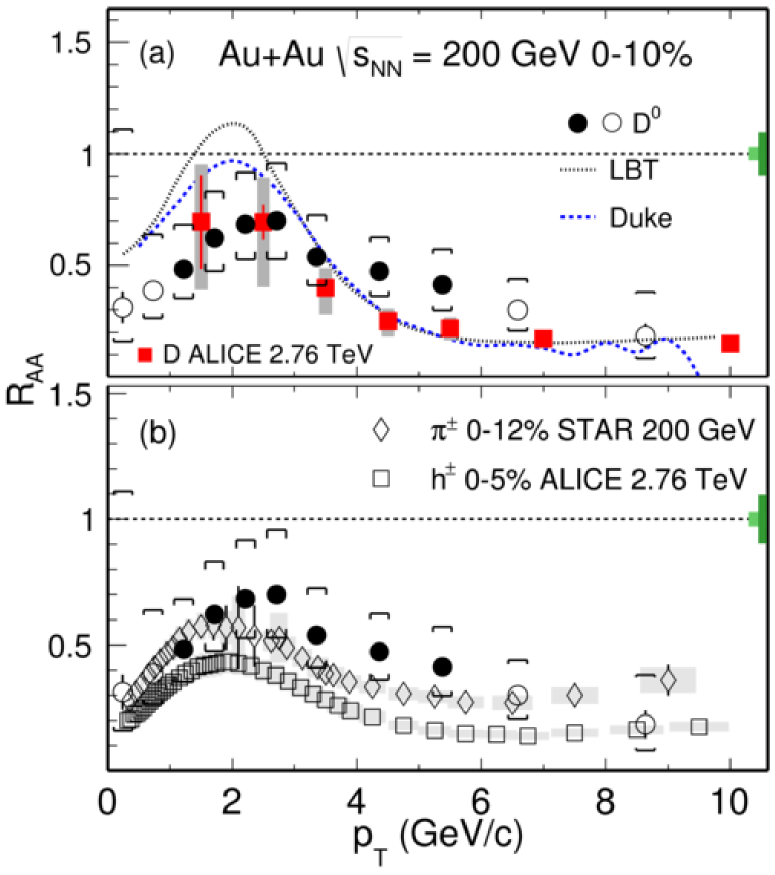
$$R_{AA} = \frac{dN_{AA} / dp_T}{\langle T_{AA} \rangle d\sigma_{pp} / dp_T}$$

- Yields at high p_T are **greatly suppressed** in central collisions
- Suppression at high p_T decreases towards more peripheral collisions
- No significant centrality dependence for D^0 suppression at low p_T

- D^0 shows **similar suppression to light mesons** at high p_T
- D^0 R_{AA} is **comparable to that from the LHC** measurements in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- Models that include both collisional and radiative losses are consistent with data at p_T > 3 GeV/c

- **Charm quarks lose significant amount of energy when traversing through the QGP**

STAR D^0: Phys Rev C.99.034908 (2019)



Energy loss in Au+Au collisions: D^0

- Nuclear modification factor R_{AA}:

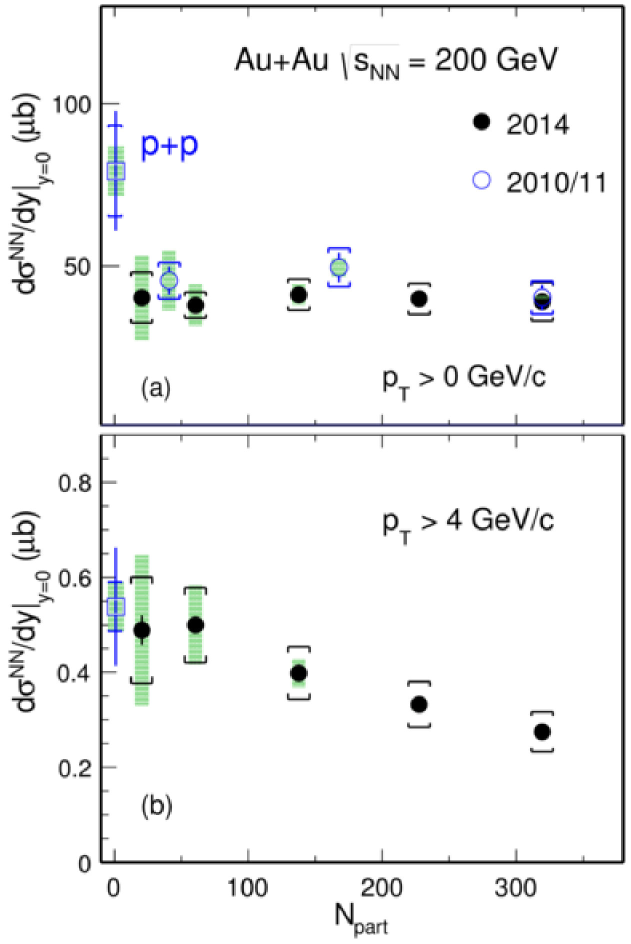
$$R_{AA} = \frac{dN_{AA} / dp_T}{\langle T_{AA} \rangle d\sigma_{pp} / dp_T}$$

- Yields at high p_T are **greatly suppressed** in central collisions
- Suppression at high p_T decreases towards more peripheral collisions
- No significant centrality dependence for D^0 suppression at low p_T

- D^0 shows **similar suppression to light mesons** at high p_T
- D^0 R_{AA} is **comparable to that from the LHC** measurements in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- Models that include both collisional and radiative losses are consistent with data at $p_T > 3$ GeV/c

- **Charm quarks lose significant amount of energy when traversing through the QGP**
- p_T-integrated D^0 cross-section is independent of centrality, and smaller than that in p+p collisions

STAR D^0: Phys Rev C.99.034908 (2019)

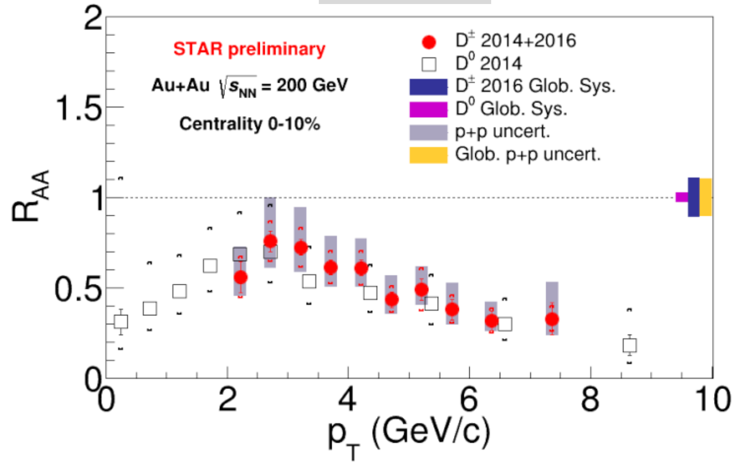


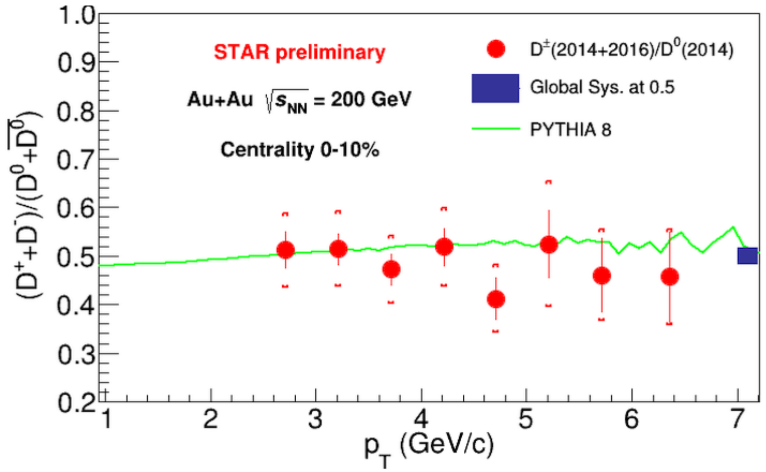
Energy loss in Au+Au collisions: D±

- **Similar level of suppression and centrality dependence** for D± and D⁰ mesons
- D±/ D⁰ yield ratios **are compatible with PYTHIA**

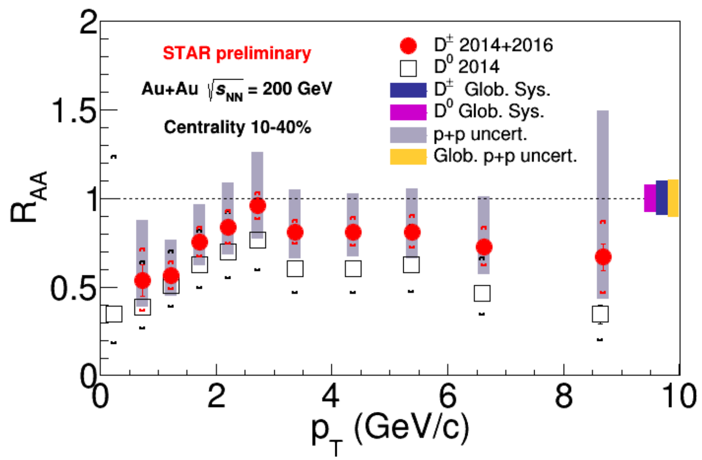
Poster by J. Vaněk – Thursday 13:39

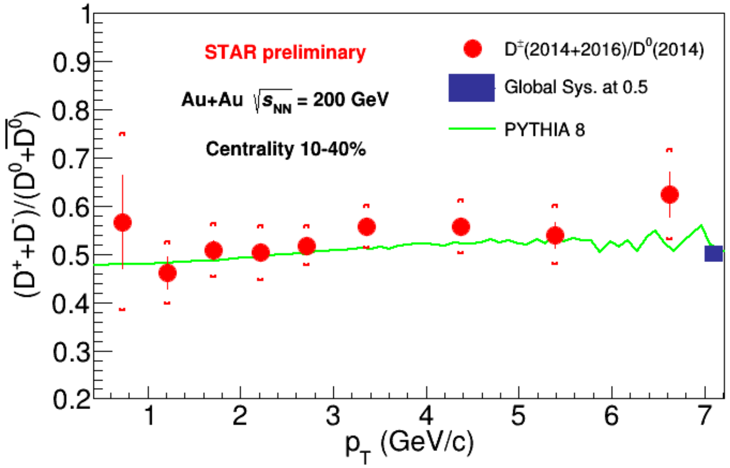
0–10%



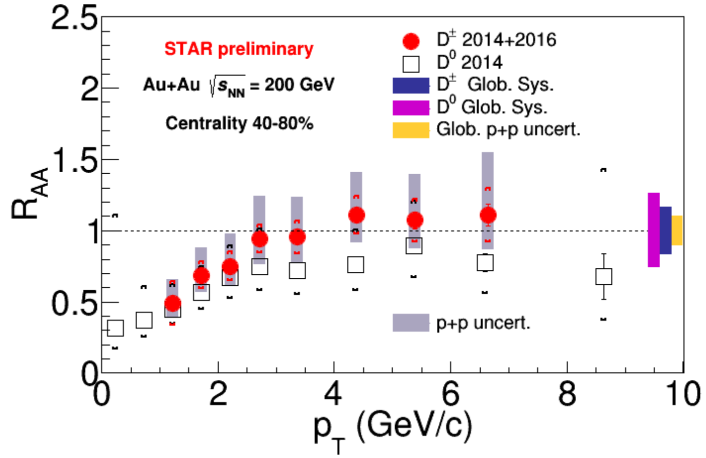


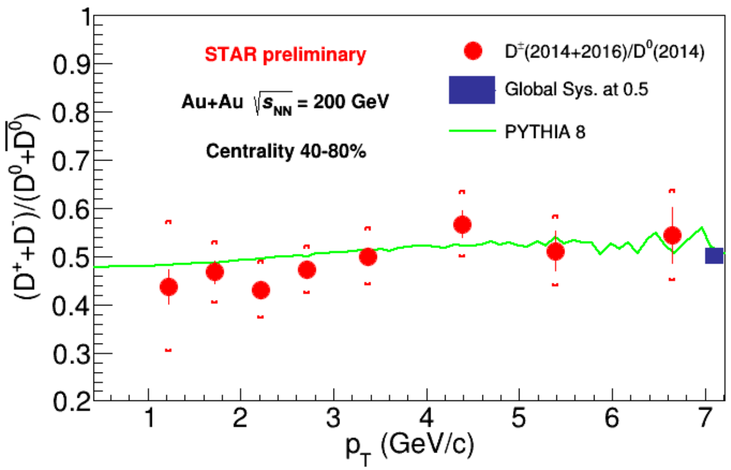
10–40%





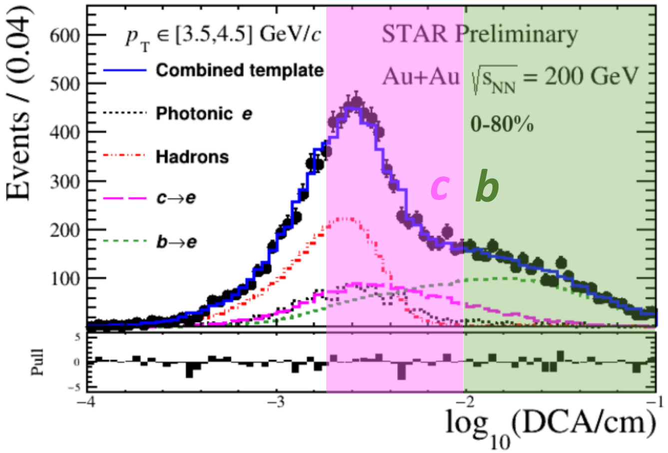
40–80%





STAR D^0: Phys Rev C.99.034908 (2019)

Energy loss in Au+Au collisions: heavy-flavor decayed electrons

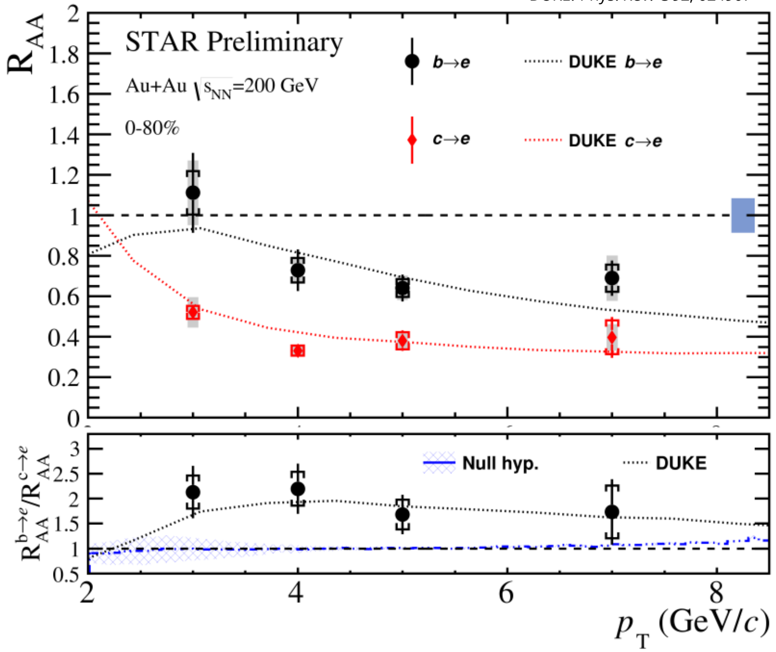


- Measurement of electrons from **charm and beauty** hadron decays
- Extract charm and bottom decayed **electron fractions**
  - background from photonic electrons and hadrons

  → template fitting to Distance of Closest Approach (DCA) distribution (enabled thanks to HFT)

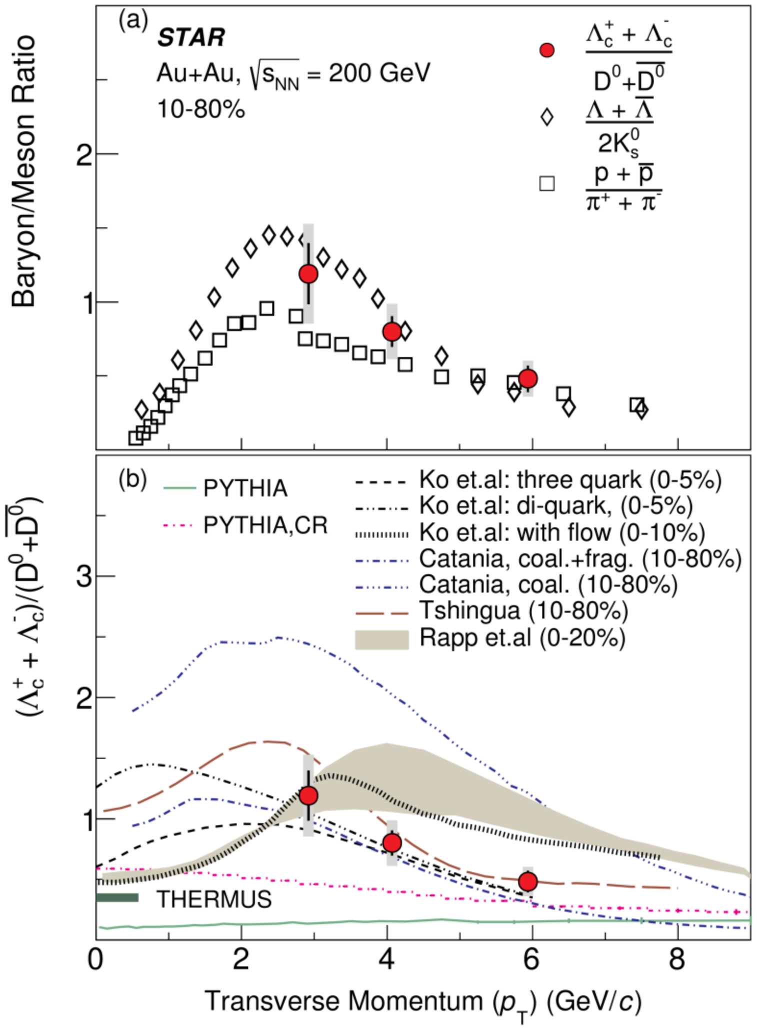
- Charm-decayed electrons show suppression at high-p_T of R_{AA} ~ 0.4
- Data consistent with DUKE model prediction
- Beauty-decayed electrons suppression is smaller than charm-decayed electrons with ≥ 3σ significance
  - **Evidence of mass dependence of energy loss**

DUKE: Phys. Rev. C 92, 024907



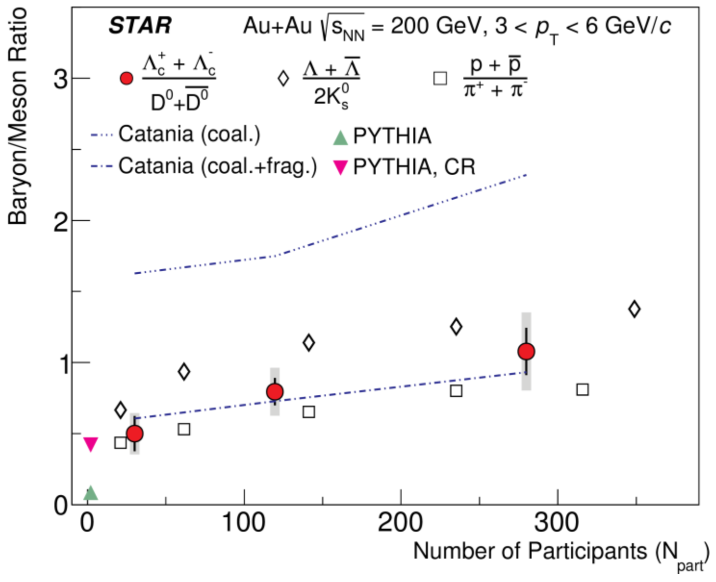
Λ_c/D_0 yield ratio in Au+Au collisions

Phys. Rev. Lett. 124 (2020) 172301



- Helps to understand charm quark hadronization
- Λ_c/D_0 is **comparable with baryon-to-meson** ratios for light and strange flavor hadrons
- Data can be used to **constrain model calculations**

Phys. Rev. Lett. 124 (2020) 172301



- **Increase towards more central collisions:**
  - Similar to those for light and strange-flavor hadrons
  - Consistent with the Catania model calculation including both **coalescence and fragmentation hadronization**

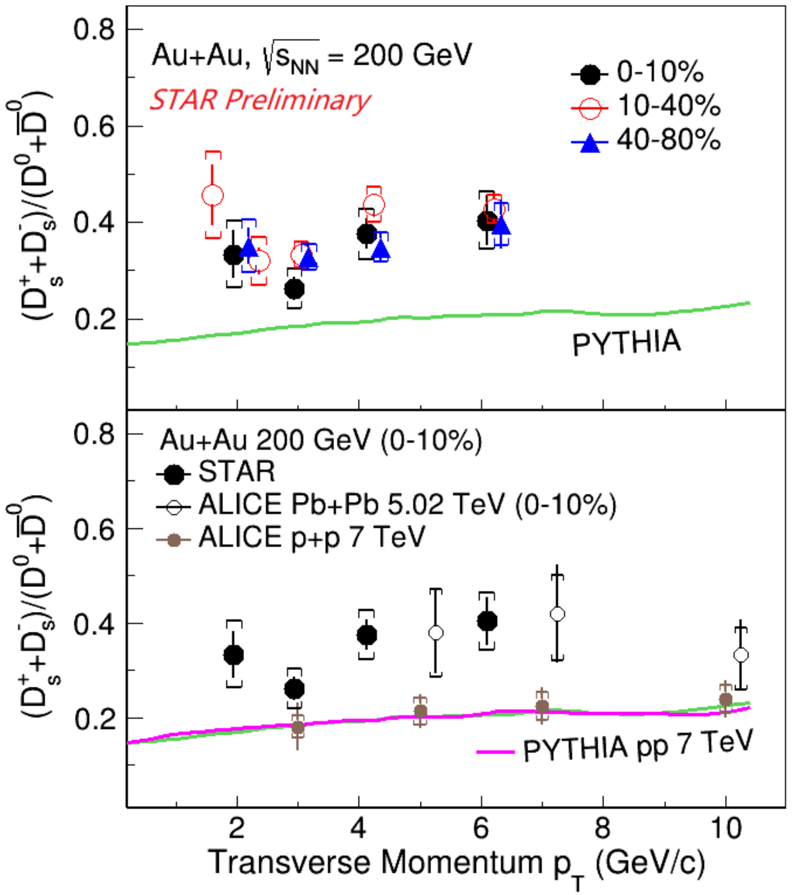
D_s/D_0 yield ratio in Au+Au collisions

- D_s/D_0 yield ratio probes **strangeness enhancement** and **coalescence of charm** quarks with strange quarks in QGP

- Significantly larger than fragmentation baseline (PYTHIA p+p)
- No significant centrality dependence

- PYTHIA calculation consistent with ALICE p+p results at $\sqrt{s}$ = 7 TeV
- STAR measurements at high p_T are consistent with ALICE Pb+Pb results at $\sqrt{s_{NN}}$ = 5.02 TeV

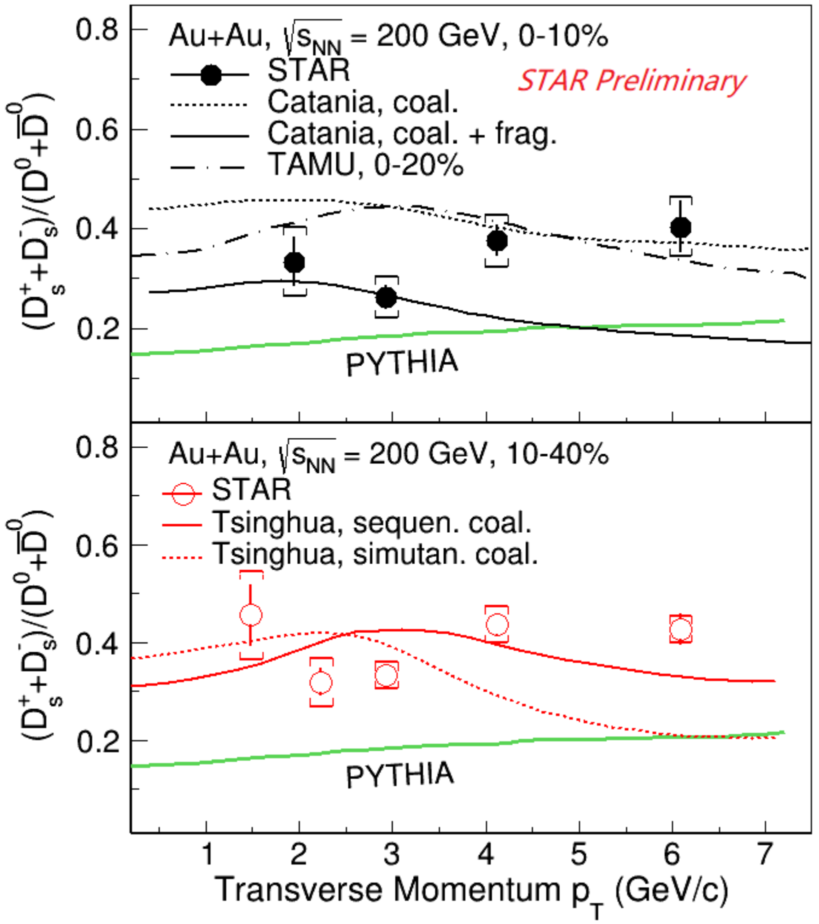
ALICE p+p: ALICE Collaboration, Eur. Phys. J. C (2017) 77: 550.
ALICE Pb+Pb: ALICE Collaboration, J. High Energ. Phys. (2018) 2018: 174.



D_s/D_0 yield ratio in Au+Au collisions

- D_s/D_0 yield ratio probes **strangeness enhancement** and **coalescence of charm** quarks with strange quarks in QGP
- Significantly larger than fragmentation baseline (PYTHIA p+p)
- No significant centrality dependence
- Catania model calculation with only coalescence hadronization describes data for $p_T > 4$ GeV/c
- Catania model calculation with both coalescence and fragmentation hadronization describes data for lower p_T
- **Tsinghua model with sequential coalescence hadronization** qualitatively describes data
- Enhancement of D_s meson in Au+Au collisions suggests that **charm quarks also participate in coalescence hadronization** in the QGP

Catania: Plumari S, Minissale V, Das S K, et al., Eur. Phys. J. C (2018) 78: 348.
TAMU: He M, Ralf R., In preparation.
Tsinghua: Zhao J, Shi S, Xu N, Zhuang P., arXiv (2018):1805.10858.



Total charm cross section

Coll. system	Hadron	dσ/dy [μb]
Au+Au at 200 GeV (10-40% central)	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 at 200 GeV	**Total**	**130 ± 30 ± 26**

STAR p+p: Phys Rev Lett.121.229901

D^0:

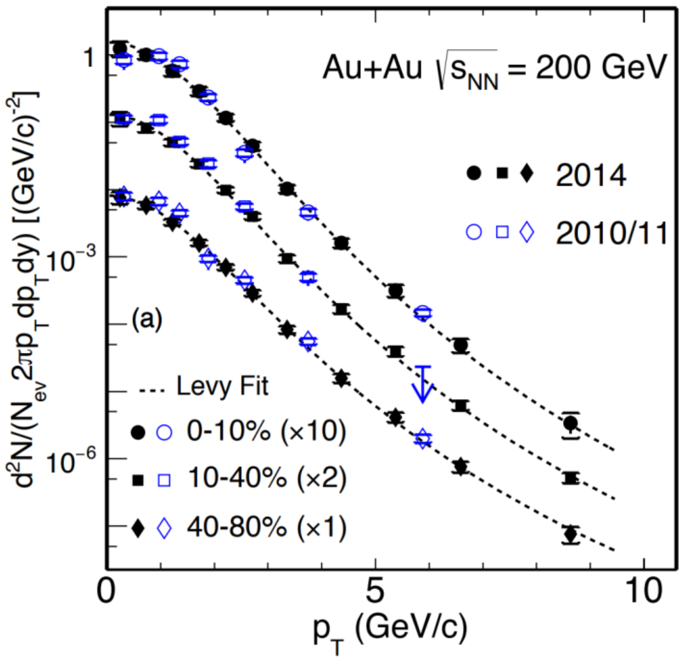
- measured down to zero p_T

D^+ and D_s :

- Levy (power law) fits to measured spectra and extrapolate down to zero p_T

Λ_c :

- using Λ_c/D^0 in 10-80% central collisions
- three model calculations fit to data and extrapolate down to zero p_T, differences are included in systematics

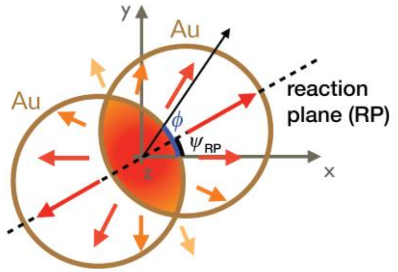


- The charm quark cross-section in **Au+Au collisions**, scaled by the number of binary nucleon-nucleon collisions, is **consistent with that measured in p+p collisions** within the uncertainties
- **Redistribution of charm quarks** among open-charm hadron species

Elliptic flow v_2 of D^0

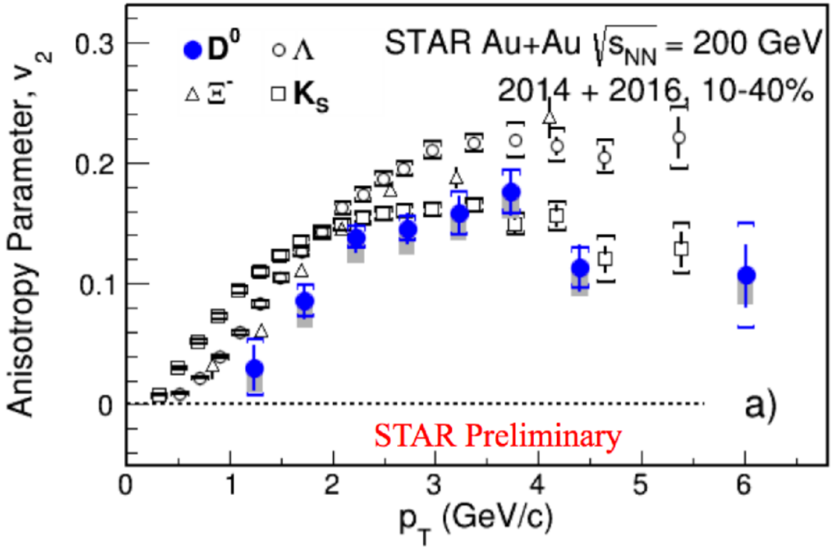
- Fourier expansion of the **particle yield** with respect to the event plane:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi-\psi_{RP}\right)\right]\right)$$

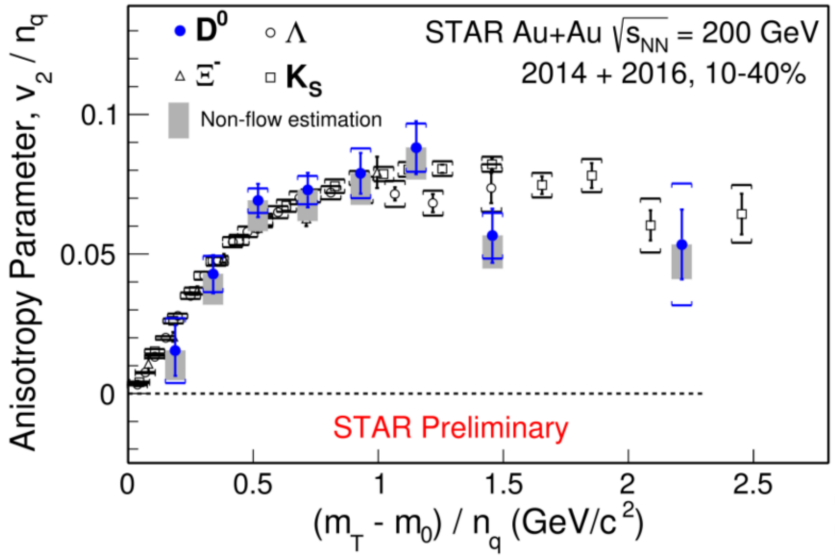


- Light flavor v_2 suggests **hydrodynamic behavior** of a strongly interacting matter

STAR D^0 v_2 2014: Phys. Rev. Lett. 118 (2017) 212301



STAR D^0 v_2 2014: Phys. Rev. Lett. 118 (2017) 212301



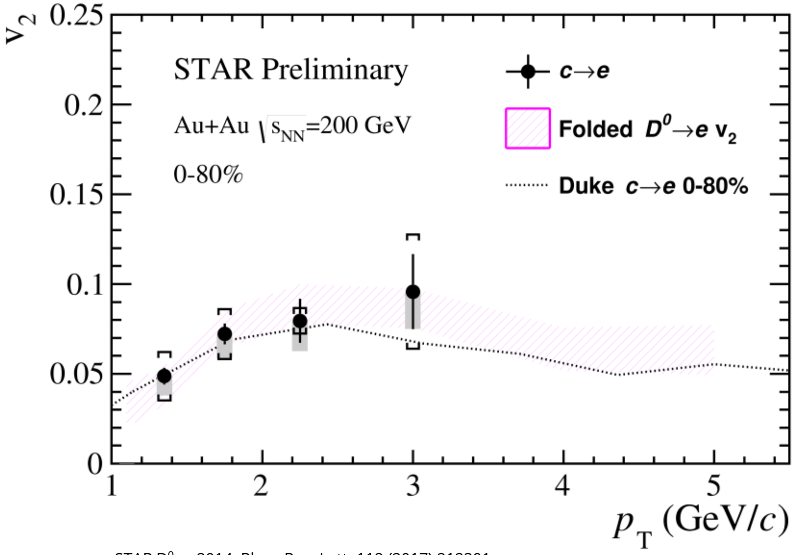
- $p_T < 2$ GeV/c: clear mass ordering of v_2
- $p_T > 2$ GeV/c: D^0 v_2 consistent with light mesons

- D^0 v_2 follows number of constituent quarks scaling
  → suggesting that **charm quarks flow with the QGP**

Elliptic flow v_2 of heavy-flavor decayed electrons

Charm-decayed electrons

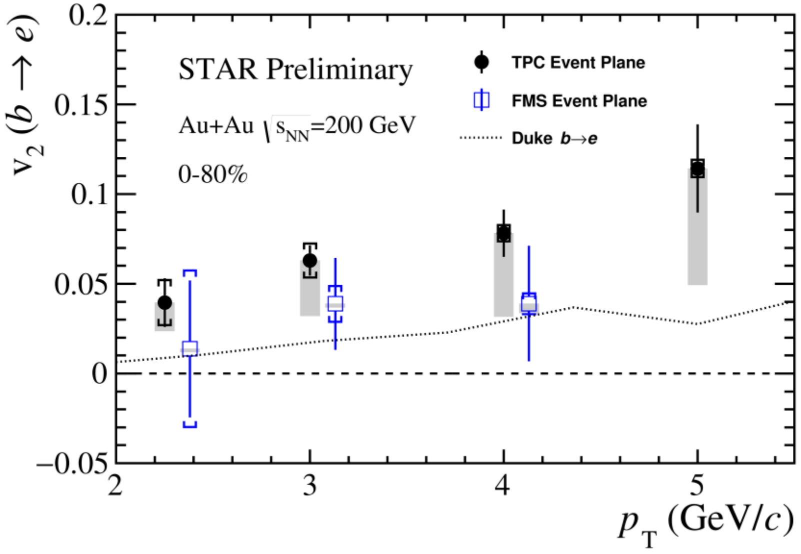
- Measured D^0 v_2 folded to decayed electron v_2 with semi-leptonic decays simulated in EvtGen
- **Charm electron v_2 consistent with folded D^0 v_2** and DUKE model



STAR D^0 v_2 2014: Phys. Rev. Lett. 118 (2017) 212301
DUKE: Phys. Rev. C 92, 024907

Beauty-decayed electrons

- First observation of **non-zero bottom electron v_2**
  - TPC event plane measurement with full non-flow subtraction **significant at 3.4σ**
- Forward Meson Spectrometer ($2.5 < \eta < 4$) as event plane detector reduces non-flow to 0.5%

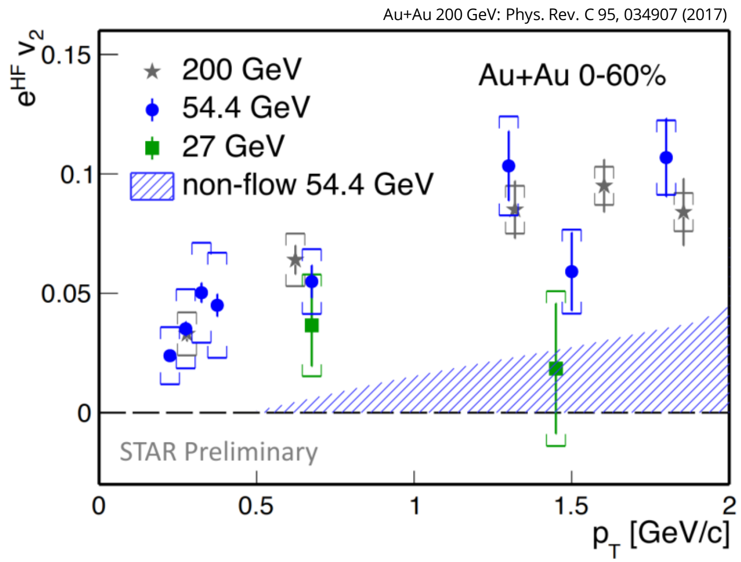


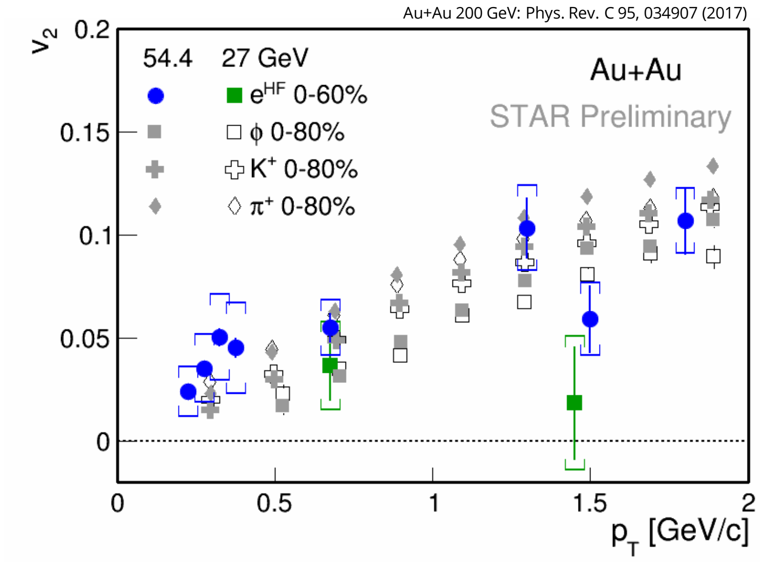
Elliptic flow v_2 of heavy-flavor decayed electron

Comparison of HF decayed electron v_2 in Au+Au collisions at $\sqrt{s_{NN}}$ = 27, 54.4 and 200 GeV

- Results in **54.4** GeV Au+Au collisions show v_2 comparable to that in **200** GeV
- Hint for lower v_2 in Au+Au collisions at **27** GeV than those at **54.4** and **200** GeV

- Comparable to light flavor meson v_2 at **54.4 GeV**

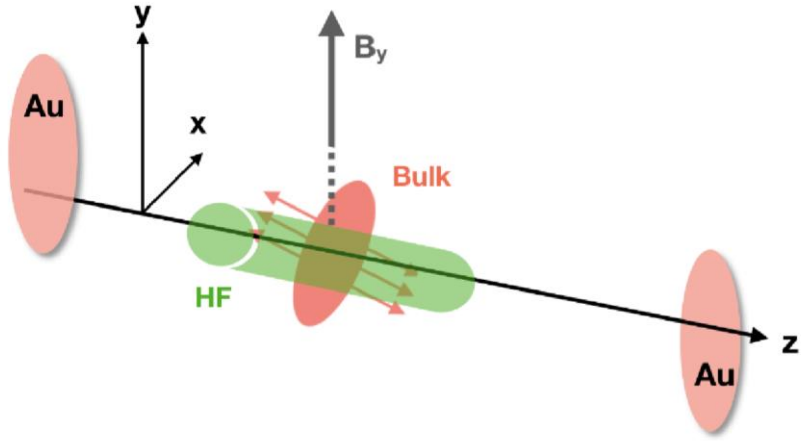




- **HF quarks interact strongly with the medium in 54.4 GeV Au+Au collisions**

Charm quark directed flow v_1

- Important to study **initial conditions** of heavy-ion collisions
- **Hydro models:**
  - v_1 magnitude depends on viscous drag on charm quarks and initial **tilt of QGP bulk**
- **Initial electromagnetic field:**
  - **opposite effects for c and $\bar{c}$**
  - induce larger v_1 for charm quarks than for light flavor quarks, due to the early production of charm quarks



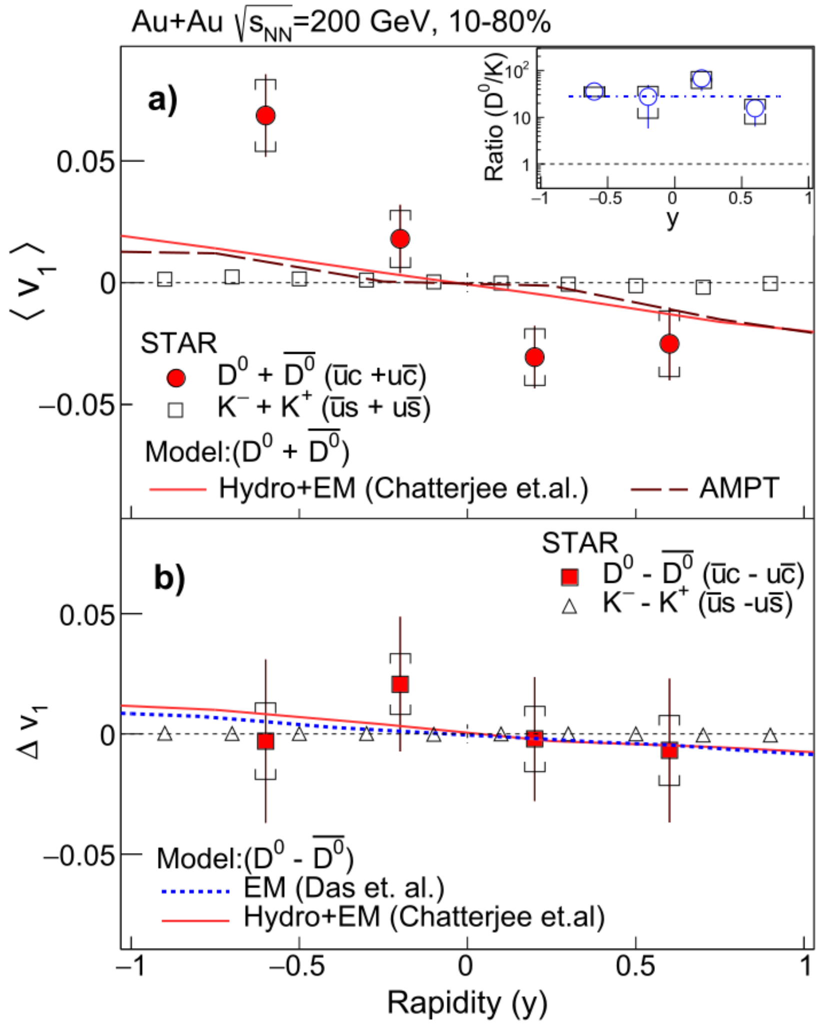
Charm quark directed flow v_1

- Important to study **initial conditions** of heavy-ion collisions
- **Hydro models:**
  - v_1 magnitude depends on viscous drag on charm quarks and initial **tilt of QGP bulk**
- **Initial electromagnetic field:**
  - **opposite effects for c and $\bar{c}$**
  - induce larger v_1 for charm quarks than for light flavor quarks, due to the early production of charm quarks

---

- Measured D^0 v_1 slope is ~5-20 times larger than that for kaons
- Tilted source models **predict the correct sign** of dv_1/dy, but the v_1 magnitudes are lower than data
  - → **Help to constrain initial conditions**

STAR D^0 v_1: Phys. Rev. Lett. 123 (2019) 162301



Charm quark directed flow v_1

- Important to study **initial conditions** of heavy-ion collisions
- **Hydro models:**
  - v_1 magnitude depends on viscous drag on charm quarks and initial **tilt of QGP bulk**
- **Initial electromagnetic field:**
  - **opposite effects for c and $\bar{c}$**
  - induce larger v_1 for charm quarks than for light flavor quarks, due to the early production of charm quarks

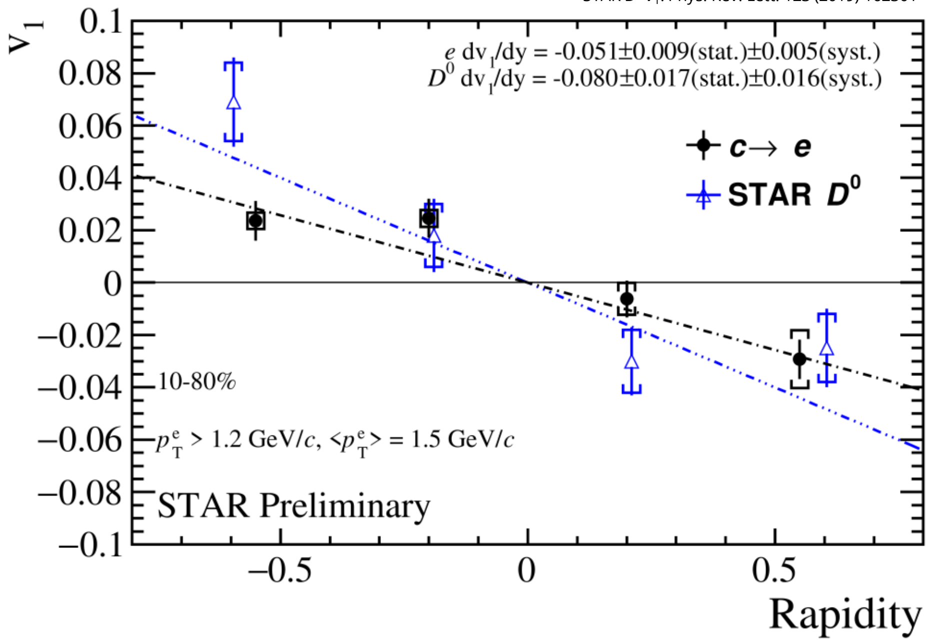
---

- Measured D^0 v_1 slope is ~5-20 times larger than that for kaons
- Tilted source models **predict the correct sign** of dv_1/dy, but the v_1 magnitudes are lower than data

  → **Help to constrain initial conditions**

- v_1 magnitude of **charm-decayed electrons is consistent with D^0 mesons**

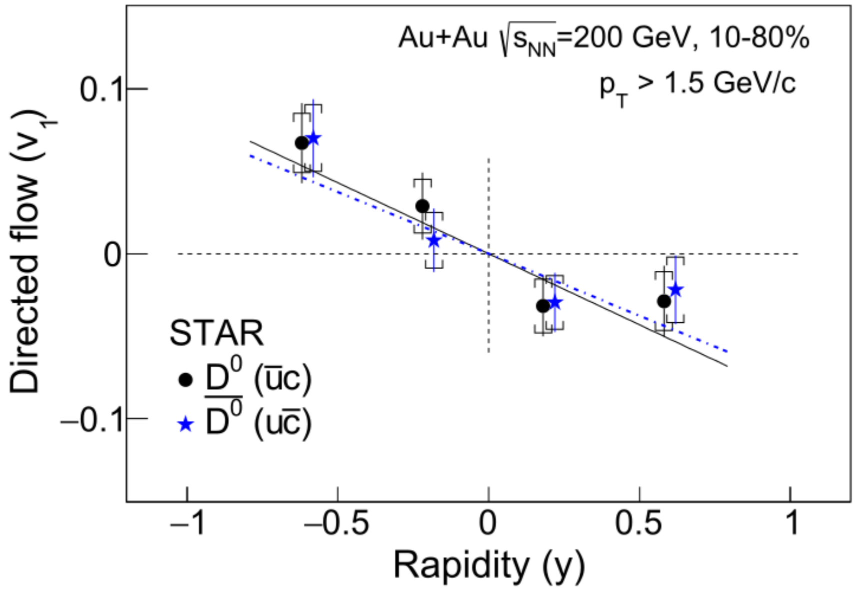
STAR D^0 v_1: Phys. Rev. Lett. 123 (2019) 162301

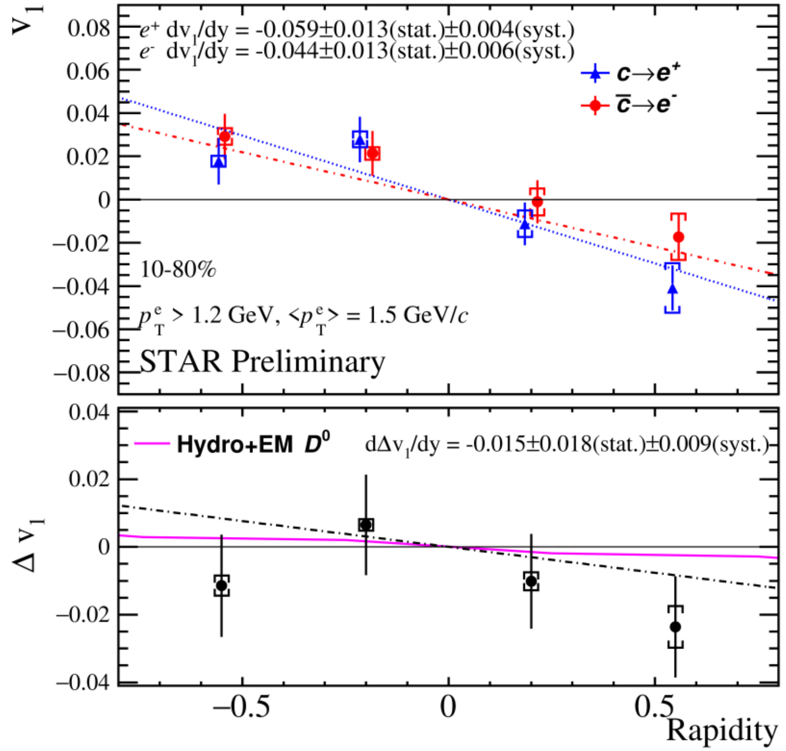


Charm quark directed flow v_1

- c and c̄ v_1 magnitude probed by both charmed-decayed electrons and D^0 mesons
  - Within the uncertainties, **no splitting due to electromagnetic field**

STAR D^0 v_1: Phys. Rev. Lett. 123 (2019) 162301





Conclusions

- D meson production is **strongly suppressed** in central Au+Au collisions compared to that in p+p collisions
  - → strong charm-medium interactions
  - → less suppression of beauty-decayed electrons compared to charm-decayed ones
- D^0 meson and charm-decayed electrons exhibit similar v_2 as light flavor in Au+Au collisions
  - → charm quarks **have gained significant flow** in the QGP
  - → charm quarks may have **achieved local thermal equilibrium**
- Directed **flow v_1 of D^0 is significantly larger** than that for light hadrons
  - → constraints for the geometric and transport parameters of the hot QCD medium
  - → observed no c and $\bar{c}$ splitting due to electromagnetic field within uncertainties
- Charm quarks participate in **coalescence hadronization** in the QGP
  - → Total per-NN charm quark cross section consistent with p+p, but **charm hadrochemistry significantly modified**

Thank you for your attention

STAR at ICHEP 2020:

- **Measurements of *J/ψ* photoproduction in ultra-peripheral collisions at RHIC**
  - Jaroslav Adam, 29 July 2020 (Wednesday), 19:18
- **Overview of upsilon production studies performed with the STAR experiment**
  - Leszek Kosarzewski, 30 July 2020 (Thursday), 09:12
- **Measurement of the central exclusive production of charged particle pairs in proton-proton collisions at $\sqrt{s}$ = 200 GeV with the STAR detector at RHIC**
  - Rafal Sikora, 30 July 2020 (Thursday), 10:25
- **Production of D^{+-} mesons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at the STAR experiment**
  - Jan Vaněk (poster), 30 July 2020 (Thursday), 13:39
- **Study of the central exclusive production of $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ pairs in proton-proton collisions at $\sqrt{s_{NN}}$ = 510 GeV with the STAR detector at RHIC**
  - Tomáš Truhlář (poster), 31 July 2020 (Friday), 13:30

Acknowledgement

The work was supported from European Regional Development Fund-Project "Center of Advanced Applied Science" No. CZ.02.1.01/0.0/0.0/16-019/0000778 and by the grant LTT18002 of Ministry of Education, Youth and Sports of the Czech Republic.

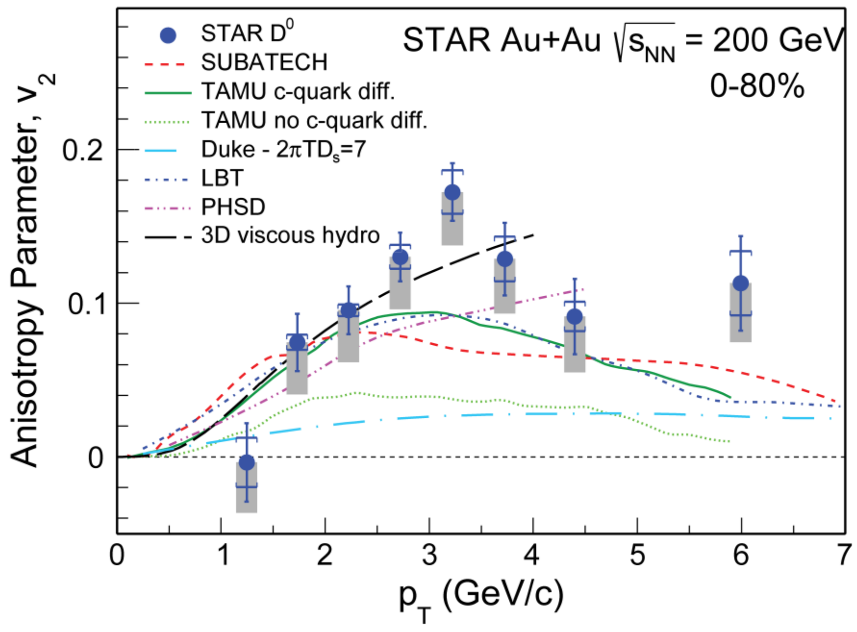
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

BACKUP

D^0 elliptic anisotropy compared to theory

STAR

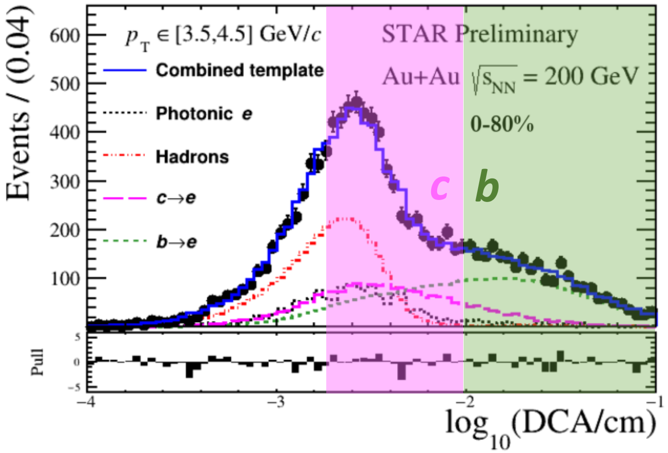


- TAMU model with no charm quark diffusion and Duke model are inconsistent with data
- 3D viscous hydro calculation agrees with data, suggesting that charm quarks may have achieved thermal equilibrium
- Charm quark diffusion coefficient:

$$(2\pi T)D_s \approx 2 - 12$$

- SUBATECH: pQCD + hard thermal loops
  H. Berrehrah et al., PRC 91 054902 (2015)
- TAMU: non-perturbative T-matrix approach
  M. He et al., EPJ C (2016) 76: 107
- Linearized Boltzmann Transport (LBT): Jet transport model extended to heavy quarks
  S. Cao et al., PRC 94 014909 (2016)
- Duke: transport properties tuned to LHC data
  S. Cao et al., PRC 92 024907 (2015)
- Parton-Hadron-String Dynamics (PHSD): Effective potential of c-quarks
  H. Berrehrah et al., PRC 90 051901 (2014)
- 3D viscous hydro: tuned to light hadrons
  L.-G. Pang et al., PRD 91 074027 (2015)

Energy loss in Au+Au collisions: heavy-flavor decayed electrons



- Measurement of electrons from **charm and beauty** hadron decays
- Goal is to extract beauty and charm-decayed electron from the background of photonic electrons and hadrons

  → template fitting to Distance of Closest Approach (DCA) distribution (enabled thanks to HFT)