Measurements of open heavy flavor hadrons at RHIC and the LHC

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OUTLINE

- Open heavy-flavor hadrons
- Physics motivation
- Reconstruction methods
- Charm and bottom quark production modification in heavy-ion collisions
- Collective flow of heavy quarks
- Open heavy-flavor hadrochemistry
- Open-charm mesons as a probe of initial state of heavy-ion collisions

OPEN HEAVY-FLAVOR HADRONS

- Open-charm hadrons
  - Mesons – one charm (anti-)quark and lighter antiquark (quark)
  - Baryons – one or more charm quarks

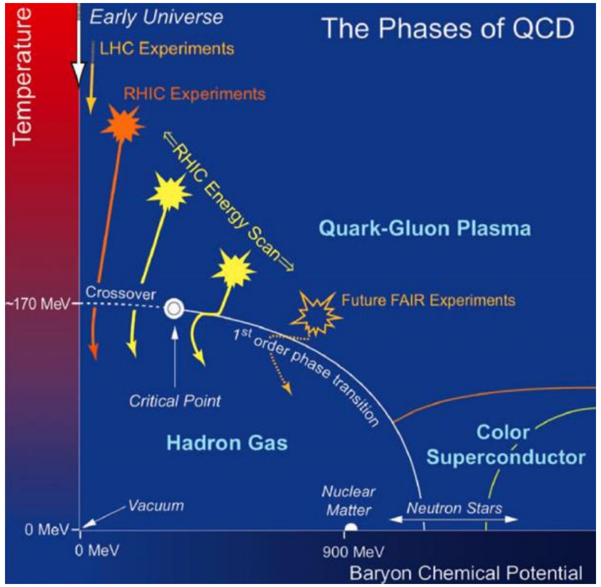
Hadron	M_{inv} [MeV/c^2]	$c\tau$ [μm]
D^+ $(c\bar{u})$	1869.66 ± 0.05	311.8 ± 2.1
D^0 $(c\bar{d})$	1864.84 ± 0.05	122.9 ± 0.4
D_s^+ $(c\bar{s})$	1968.35 ± 0.07	149.9 ± 2.1
Λ_c^+ (udc)	2286.46 ± 0.14	59.9 ± 1.8
Ξ_c^0 (dsc)	2470.44 ± 0.28	45.5 ± 0.7

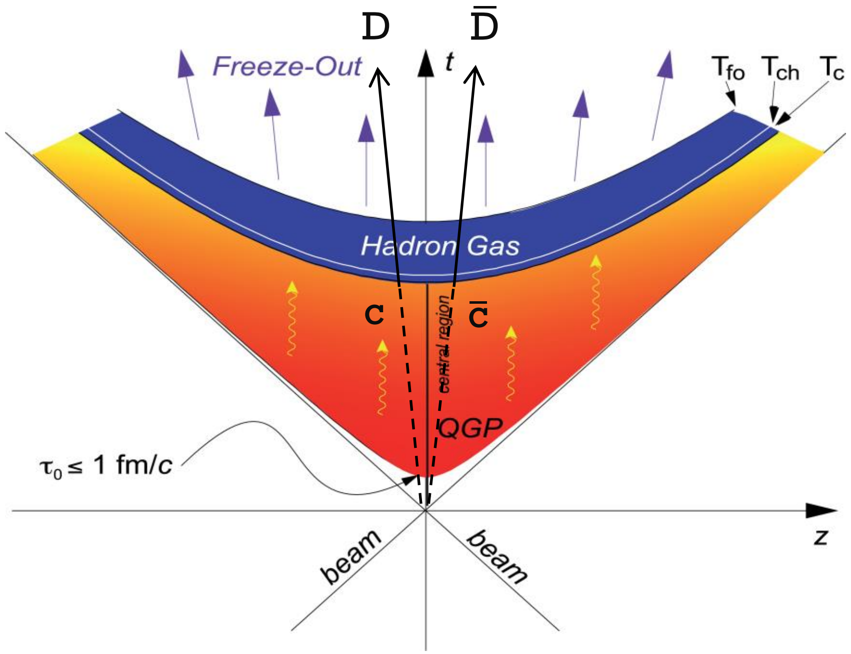
- Open-bottom hadrons
  - Mesons – one bottom (anti-)quark and lighter antiquark (quark)
  - Baryons – one or more bottom quarks

Hadron	M_{inv} [MeV/c^2]	$c\tau$ [μm]
B^+ $(u\bar{b})$	5279.34 ± 0.12	491.1 ± 1.2
B^0 $(d\bar{b})$	5279.66 ± 0.12	455.4 ± 1.2
B_s^0 $(s\bar{b})$	5366.92 ± 0.10	455.7 ± 1.5
Λ_b^0 (udb)	5619.60 ± 0.17	441.0 ± 2.7

PHYSICS MOTIVATION

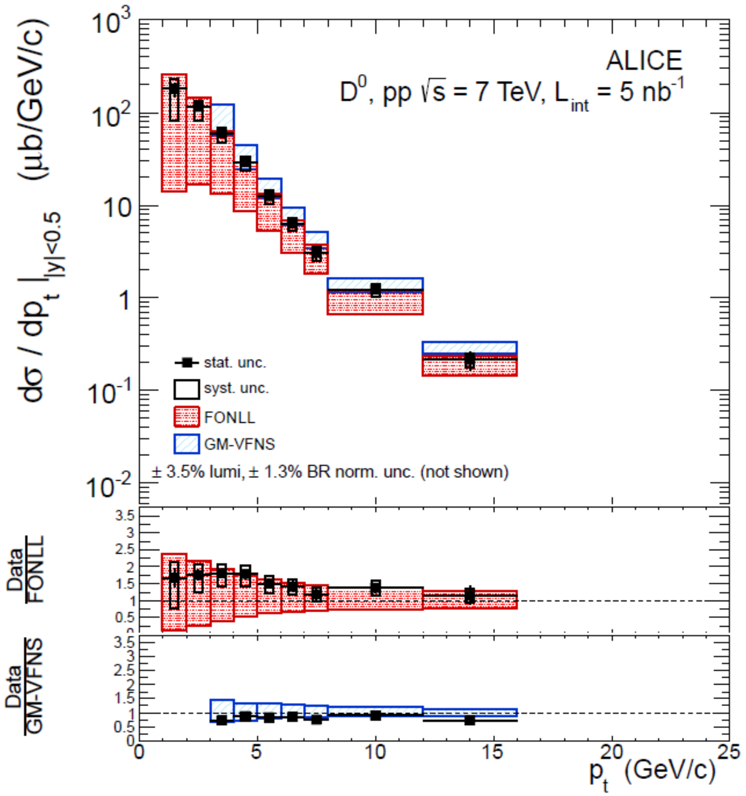
- **Quark-Gluon Plasma** (QGP) is an extreme state of matter where quarks and gluons are no longer trapped inside colorless hadrons
- QGP can be studied using relativistic heavy-ion collisions
- At RHIC energies, **charm and bottom quarks** are produced predominantly through hard partonic scatterings at **early stage** of Au+Au collisions
  - They experience **the whole evolution of the medium**

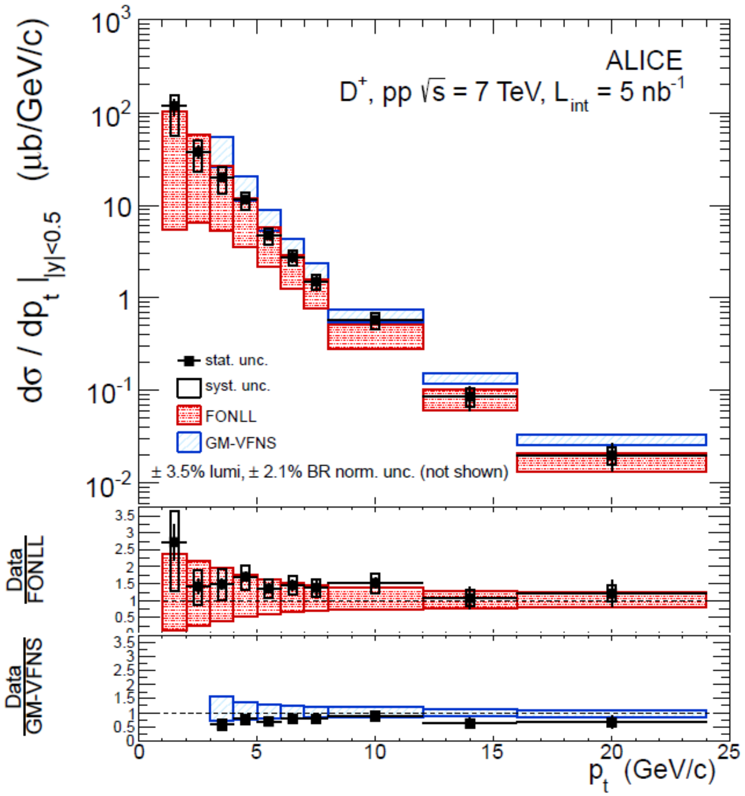




PHYSICS MOTIVATION

- Production of open-charm hadrons in p+p collisions is reasonably well understood
  - Spoiler alert – there will be a plot twist…
- Good agreement of models with open-charm spectra measured in p+p collisions

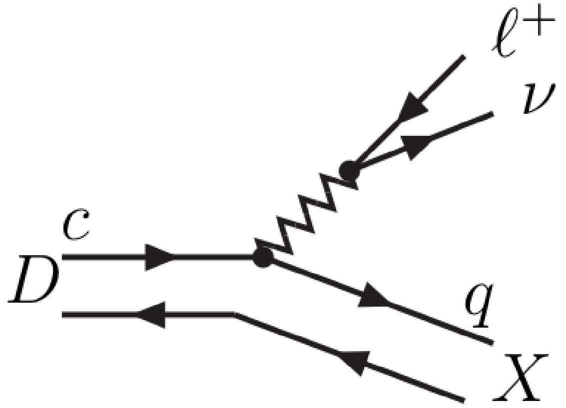




JHEP 01(2012)128

SEMI-LEPTONIC DECAYS OF OPEN HEAVY-FLAVOR HADRONS

- Weak decays to hadrons and l-ν_l pair
  - Heavy flavor (HF) electrons, non-photonic electrons (NPE)
- Method:
  - Identification of inclusive electrons
  - Fraction of electrons from other sources (decay of π^0, conversion electrons) estimated from simulation
- Pros:
  - Detection and identification of electrons relatively easy
  - Possible even without precise tracking
    - Only combined HF electrons from both *c* and *b*-hadrons
  - Reasonably high branching ratios
- Cons:
  - High background levels
  - Distinguishing decays of *c* and *b*-hadrons challenging
  - Does not provide full information about mother kinematics



Hadron*	Decay channel	*BR* [%]
D^+	e^+semileptonic	16.07 ± 0.30
D^0	e^+anything	6.49 ± 0.11
D_s^+	e^+semileptonic	6.33 ± 0.15
Λ_c^+	$\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$	3.6 ± 0.4
Ξ_c^0	$\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$	1.04 ± 0.24

*Charge conjugate particles are also measured

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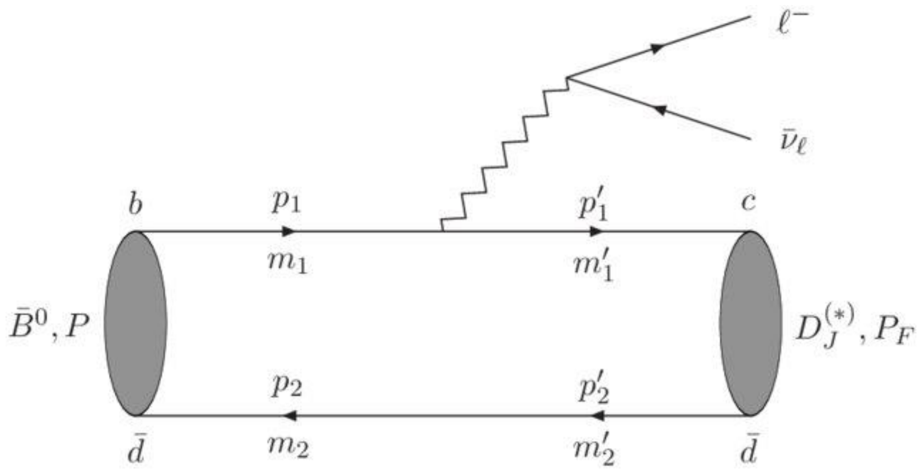

Hadron*	Decay channel	BR [%]
B^+	$B^+ \rightarrow e^+\nu_e X_c$	10.8 ± 0.4
B^0	$B^0 \rightarrow e^+\nu_e X_c$	10.1 ± 0.4
B_s^+	$B_s^+ \rightarrow e^+\nu_e X^-$	9.1 ± 0.8
Λ_b^0	$\Lambda_b^0 \rightarrow \Lambda_c^+ l^- \overline{\nu_l}$ anything	10.9 ± 2.2

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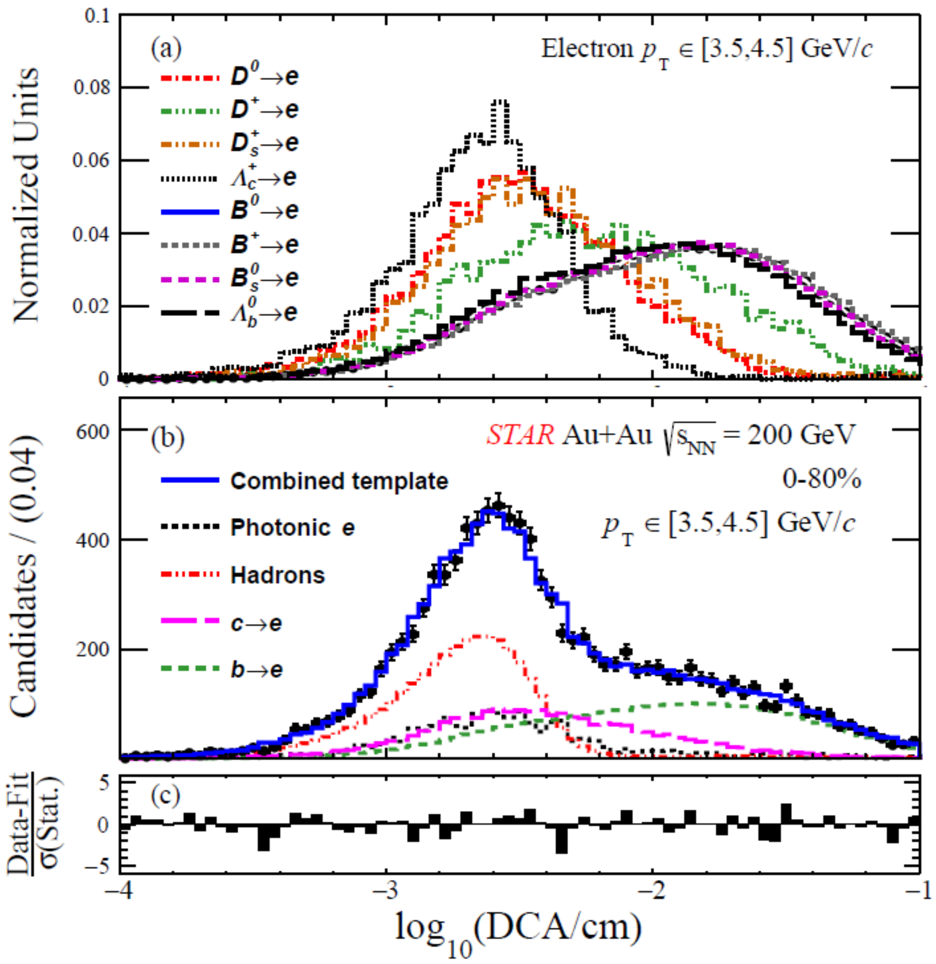


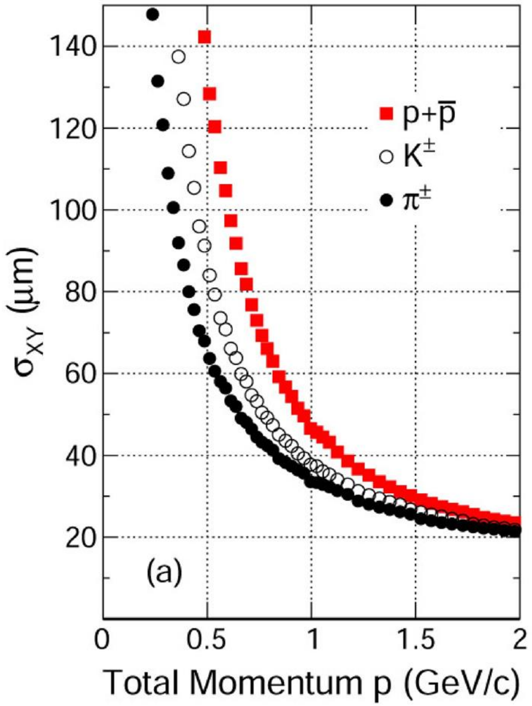
PhysRevC.95.034907

TOPOLOGICAL RECONSTRUCTION OF OPEN HEAVY-FLAVOR HADRONS

- Alternative approach is topological reconstruction of hadronic decays
- Pros:
  - Full information about mother kinematics for open-charm hadrons
- Cons:
  - Need very good spatial resolution
  - Small reconstruction efficiency
    - Need to use machine learning of multivariate analysis methods to optimize topological selection

Hadron*	Decay channel	*BR* [%]
D^+	$D^+ \to K^-\pi^+\pi^+$	8.98 ± 0.28
D^0	$D^0 \to K^-\pi^+$	3.93 ± 0.04
D_s^+	$D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$	2.27 ± 0.08
Λ_c^+	$\Lambda_c^+ \to K^-\pi^+p$	6.35 ± 0.33

- *Charge conjugate particles are also measured



PRL 118 212301 (2017)

DCA_{xy} resolution of STAR Heavy Flavor Tracker detector

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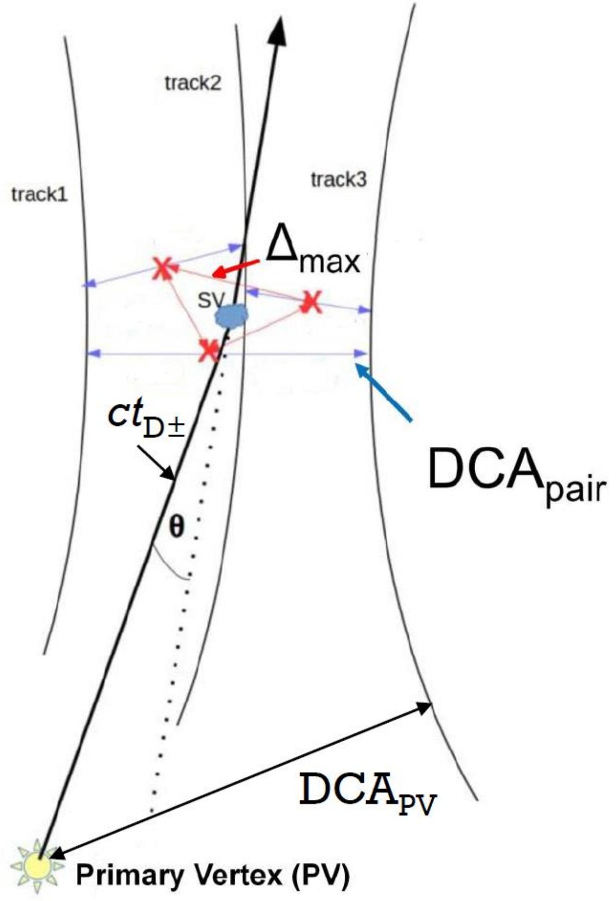


Cartoon of three-body decay topology

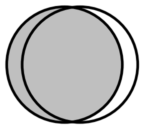
CHARM AND BOTTOM QUARK PRODUCTION MODIFICATION IN A+A COLLISIONS

D MESON NUCLEAR MODIFICATION FACTOR AT STAR

D⁰ (STAR): Phys. Rev. C 99, 034908, (2019).
π± (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
h± (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

- Nuclear modification factor:

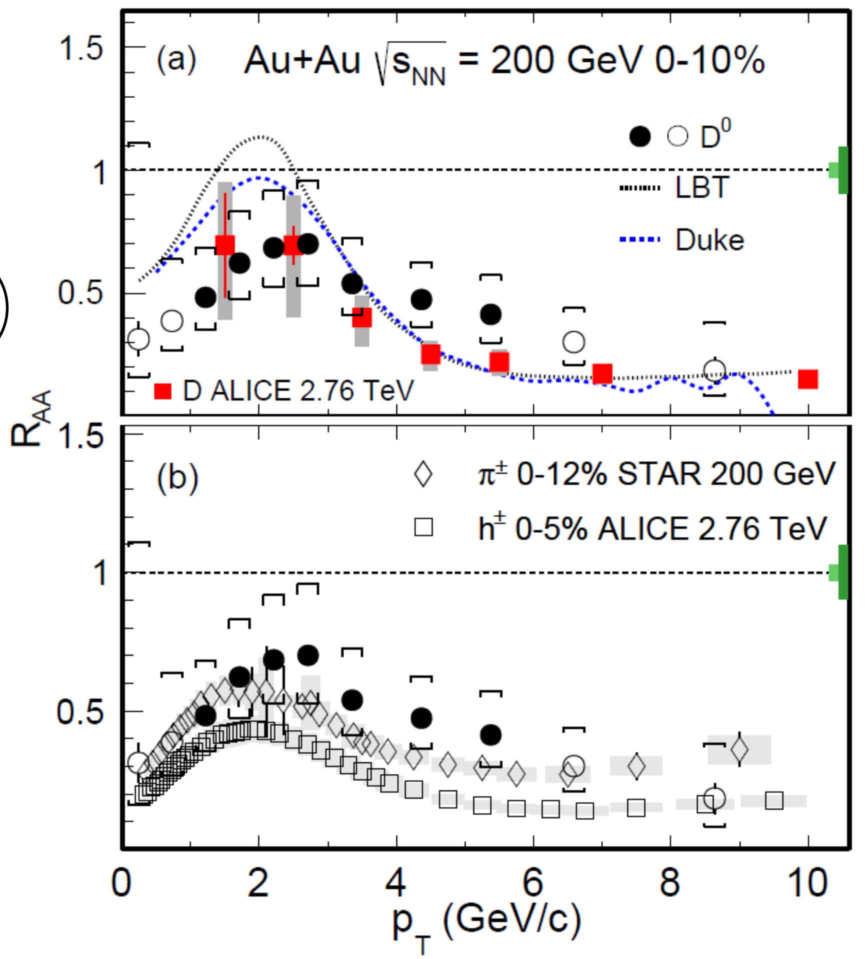
$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle\, dN^{pp}/dp_T}$$



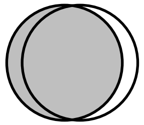
- Reference: combined D^0 and D* measurement in 200 GeV p+p collisions using 2009 STAR data

- D mesons suppressed in **central** Au+Au collisions
  - Suppression of D^0 mesons at high p_T comparable to light flavor hadrons at RHIC and D mesons at LHC
  - Reproduced by models incorporating both radiative and collisional energy losses

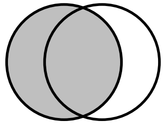
- **Strong interactions between charm quarks and the medium at RHIC energies**



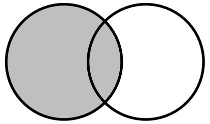
D MESON NUCLEAR MODIFICATION FACTOR AT STAR

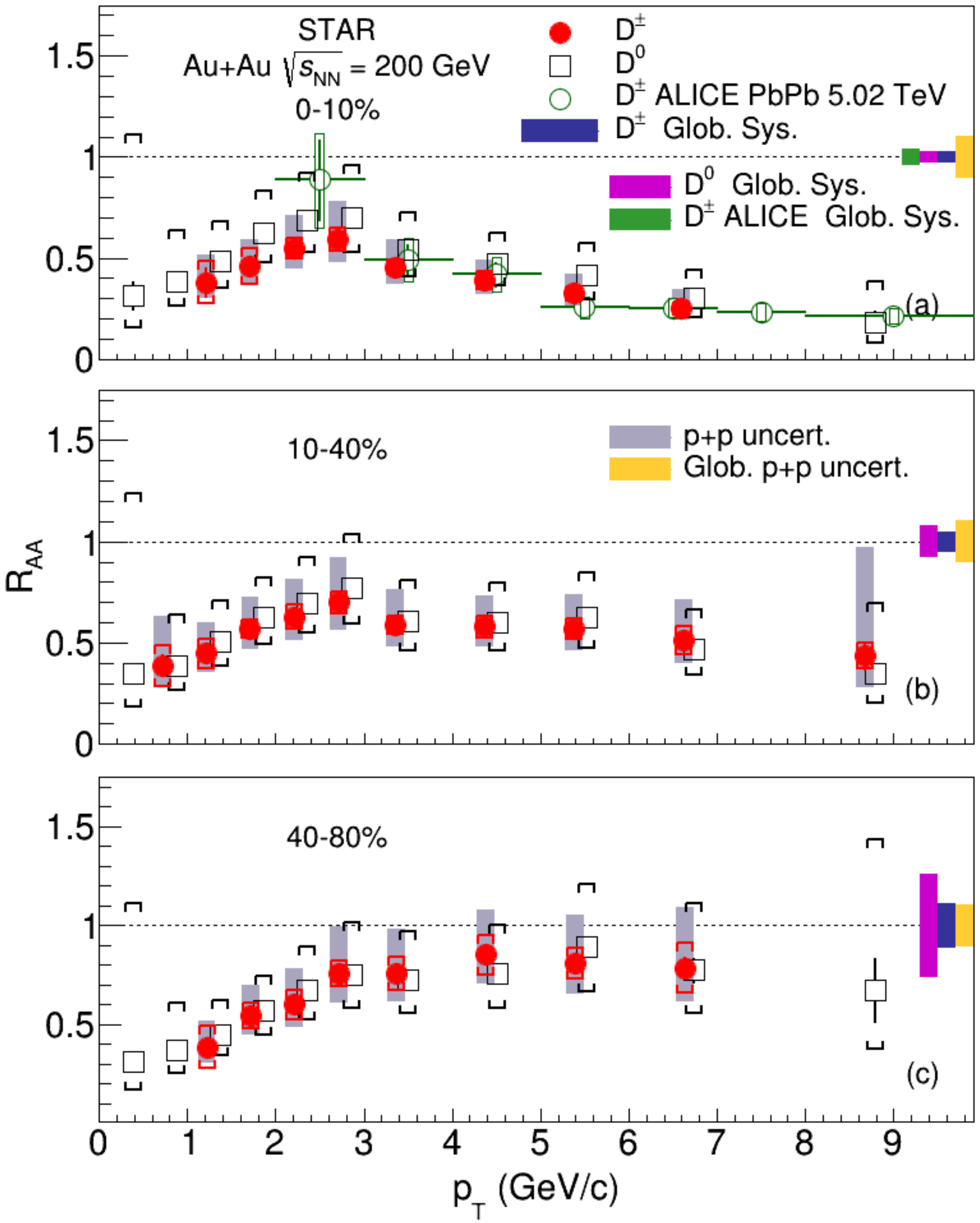


- Centrality dependence of D mesons R_{AA}
  - Suppression at high p_T increases towards more central collisions
  - Low-p_T D^0 suppressed for all studied centrality classes of Au+Au collisions



- **Integrated R_{AA} < 1 for D mesons from central to peripheral collisions**



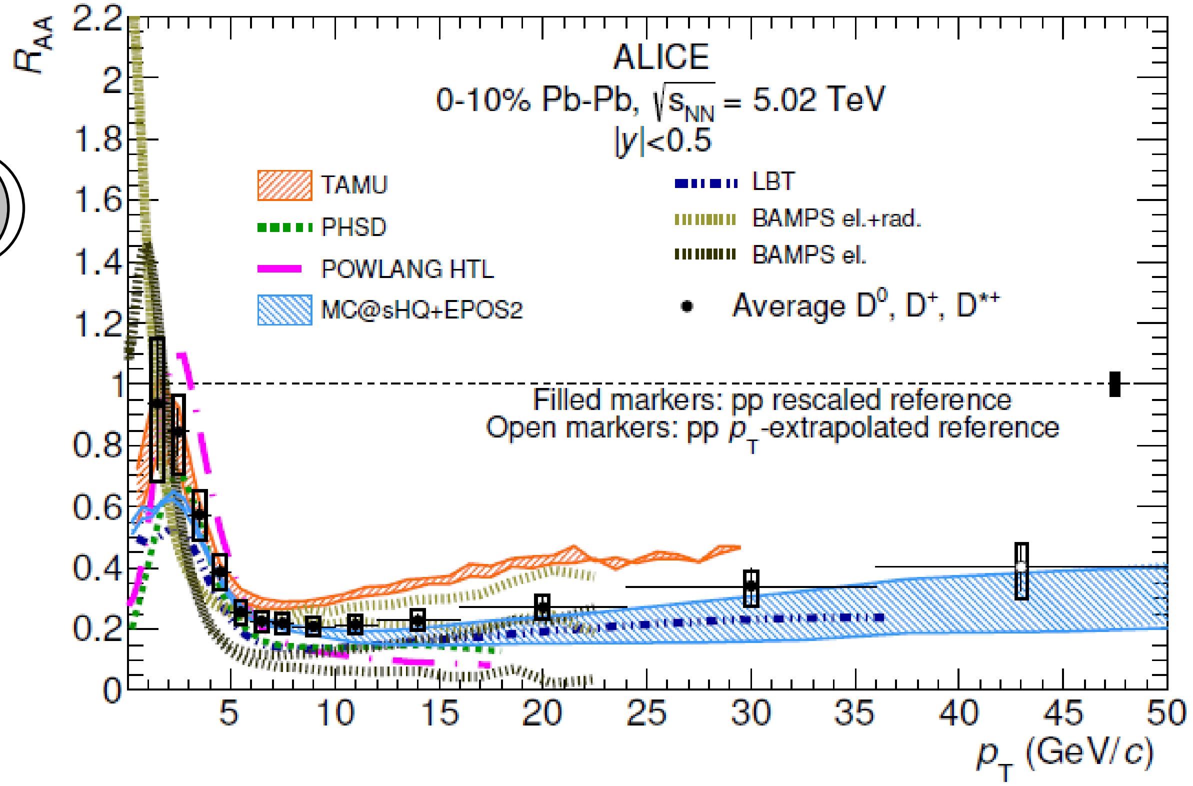


D[0] 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D (ALICE): JHEP10(2018)174

D MESON NUCLEAR MODIFICATION FACTOR AT ALICE

- Nuclear modification factor of prompt D mesons measured by ALICE in Pb+Pb collisions at 5.02 TeV

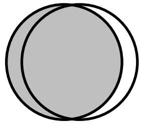
- **Similar level of suppression of D mesons in central heavy-ion collisions at the LHC and RHIC**
  - In overlapping p_T region

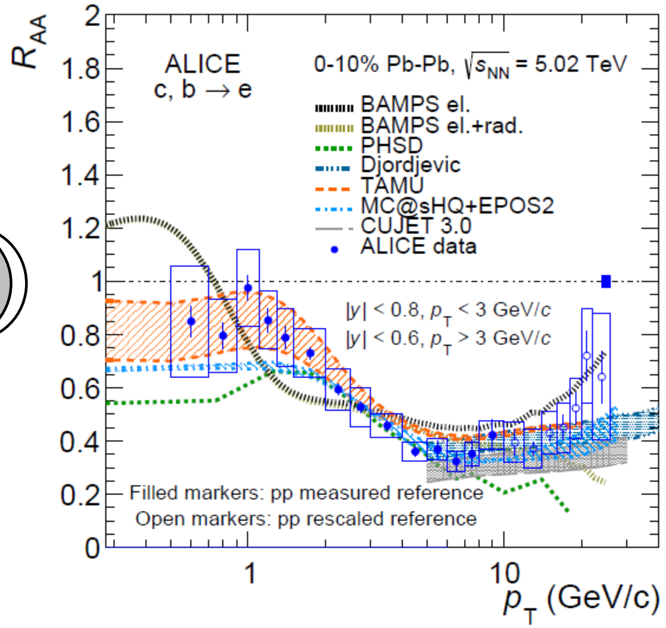


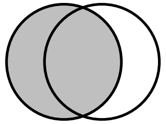
D (ALICE): JHEP10(2018)174

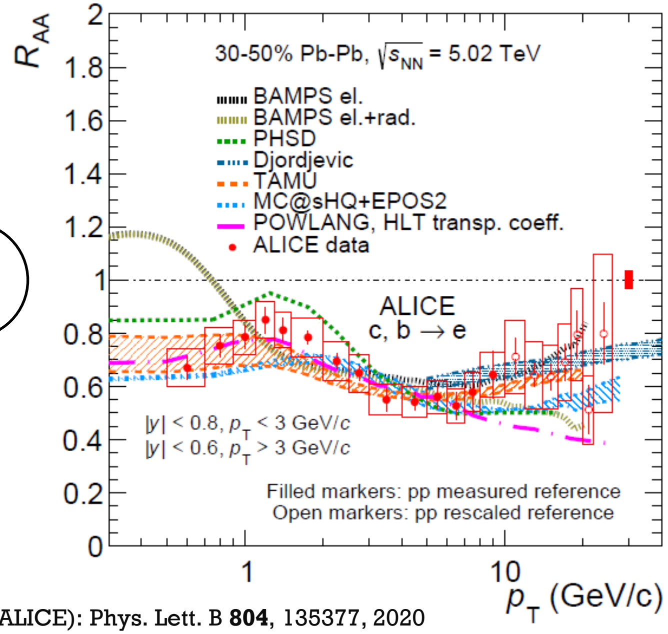
NON-PHOTONIC ELECTRONS MEASURED BY ALCIE

- Nuclear modification factor non-photonic electrons measured by ALICE in Pb+Pb collisions at 5.02 TeV
- Strong suppression of NPE in central and semi-central Pb+Pb collisions
- Many models able to describe data well







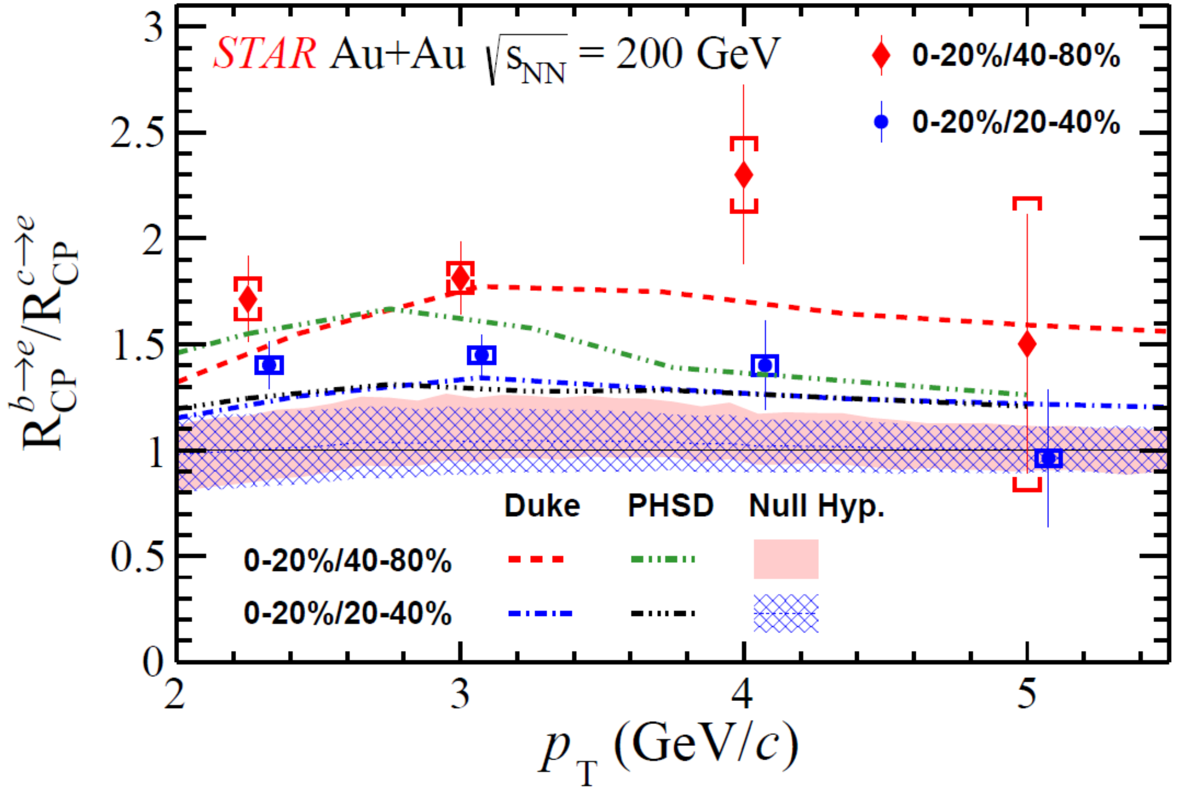


- **Supports energy loss of charm quarks in the QGP**
- But how is it with contribution of *c* quarks and *b* quarks?

NPE (ALICE): Phys. Lett. B **804**, 135377, 2020

NON-PHOTONIC ELECTRONS MEASURED BY STAR

- Ratio of R_{CP} of NPE from decays of open-bottom hadrons over R_{CP} of NPE from decays of open-charm hadrons Au+Au collisions
- Charm quarks are significantly more suppressed compared to bottom quarks in central Au+Au collisions
- **One of first strong evidences of mass ordering of heavy quark energy loss in the QGP**



NPE (STAR): arXiv:2111.14615 [nucl-ex]

COLLECTIVE FLOW OF HEAVY QUARKS

HARMONIC FLOW

- The initial geometry of the QGP bulk propagates to the azimuthal p_T distribution of final state hadrons
- Measured via harmonic flow coefficients (v_n) of the Fourier decomposition of azimuthal distribution of particles:

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

  where φ is the azimuthal angle, Ψ_n is the n-th order event plane angle

- Light flavor quarks:
  - Hadronization of asymmetrical QGP bulk
  - Various pressure gradients in different directions
- Heavy flavor quarks:
  - No harmonic flow without presence of QGP expected
  - Can acquire non-zero harmonic flow through interaction with the QGP

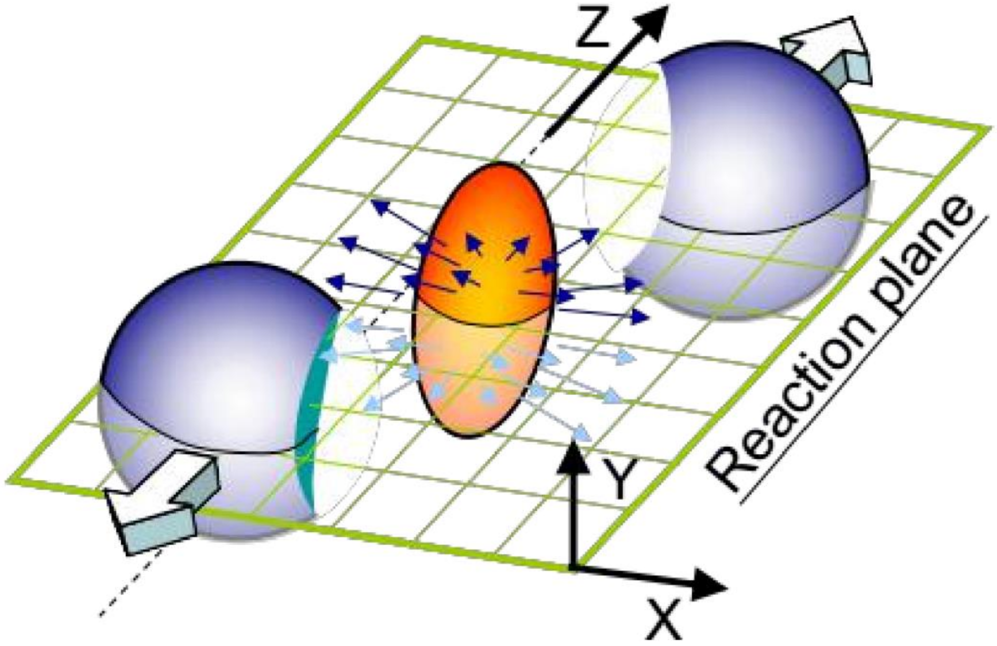
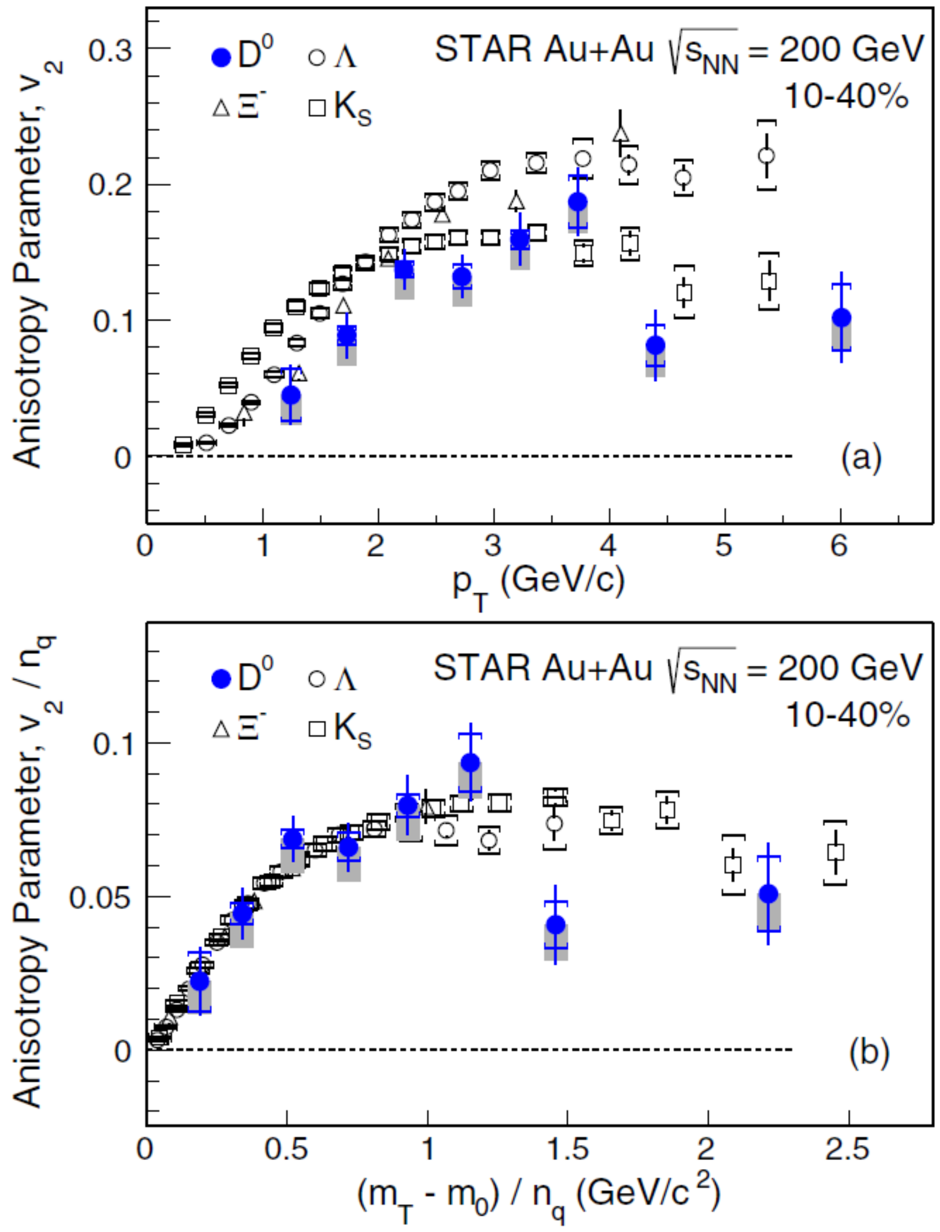


Figure by R. Vertesi

ELLIPTIC FLOW OF D^0 MESONS MEASURED BY STAR

- Elliptic flow of D^0 and light flavor hadrons measured by STAR in Au+Au collisions at 200 GeV
- Significant harmonic flow of D^0 mesons observed
- Elliptic flow of charm quarks follow the NCQ scaling

- **Charm quarks appear to be very close to local thermal equilibrium with the QGP at RHIC**

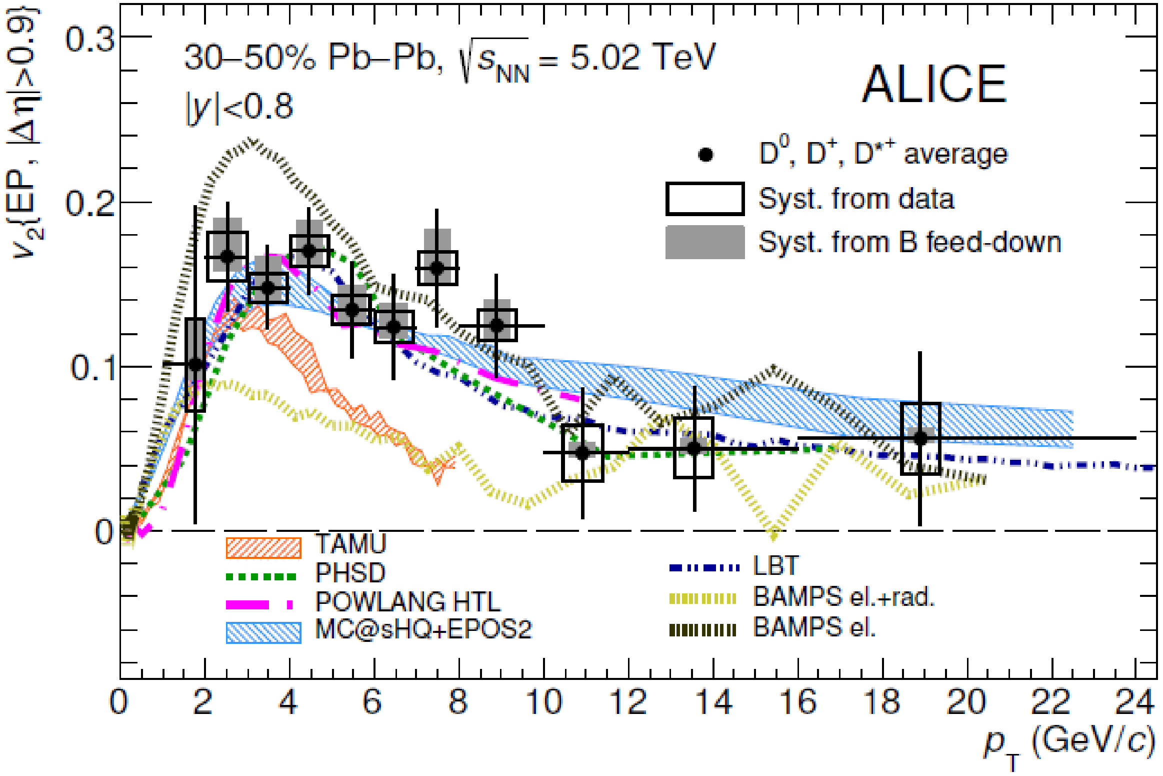


D^0 (STAR): Phys.Rev.Lett.118.212301

ELLIPTIC FLOW OF D MESONS MEASURED BY ALICE

- Elliptic flow of D mesons measured by ALICE in Pb+Pb collisions at 5.05 TeV
- Significant harmonic flow of D mesons observed
  - Comparable magnitude at in the overlapping p_T
- Several models able to reproduce both v_2 and R_{AA}
  - R_{AA} from slide 15

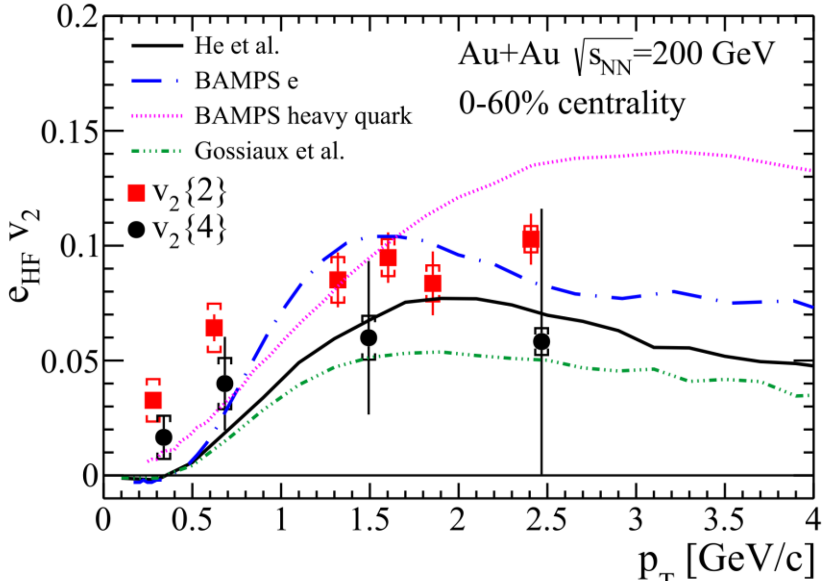
- **Further evidence of strong interactions of charm quarks with the QGP at the LHC**

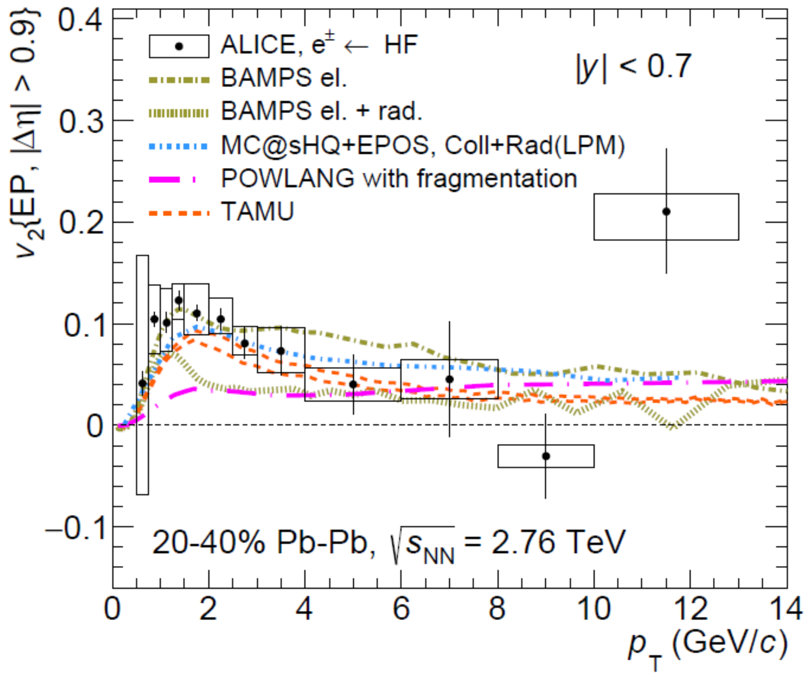


D (ALICE): JHEP10(2018)174

ELLIPTIC FLOW OF NPE MEASURED BY STAR AND ALICE

- Elliptic flow of NPE measured by STAR in Au+Au collisions at 200 GeV (top) and by ALICE in Pb+Pb collisions at 5.05 TeV (bottom)
- Significant elliptic flow of NPE observed at both RHIC and the LHC
  - Similar magnitude at RHIC and the LHC
- Models again suggest strong interactions of the charm quarks with the medium
- **Further evidence of strong interactions of charm quarks with the QGP at the LHC**





NPE v_2 (STAR): Phys. Rev. C 95, 034907
NPE v_2 (ALICE): JHEP 09 (2016) 028

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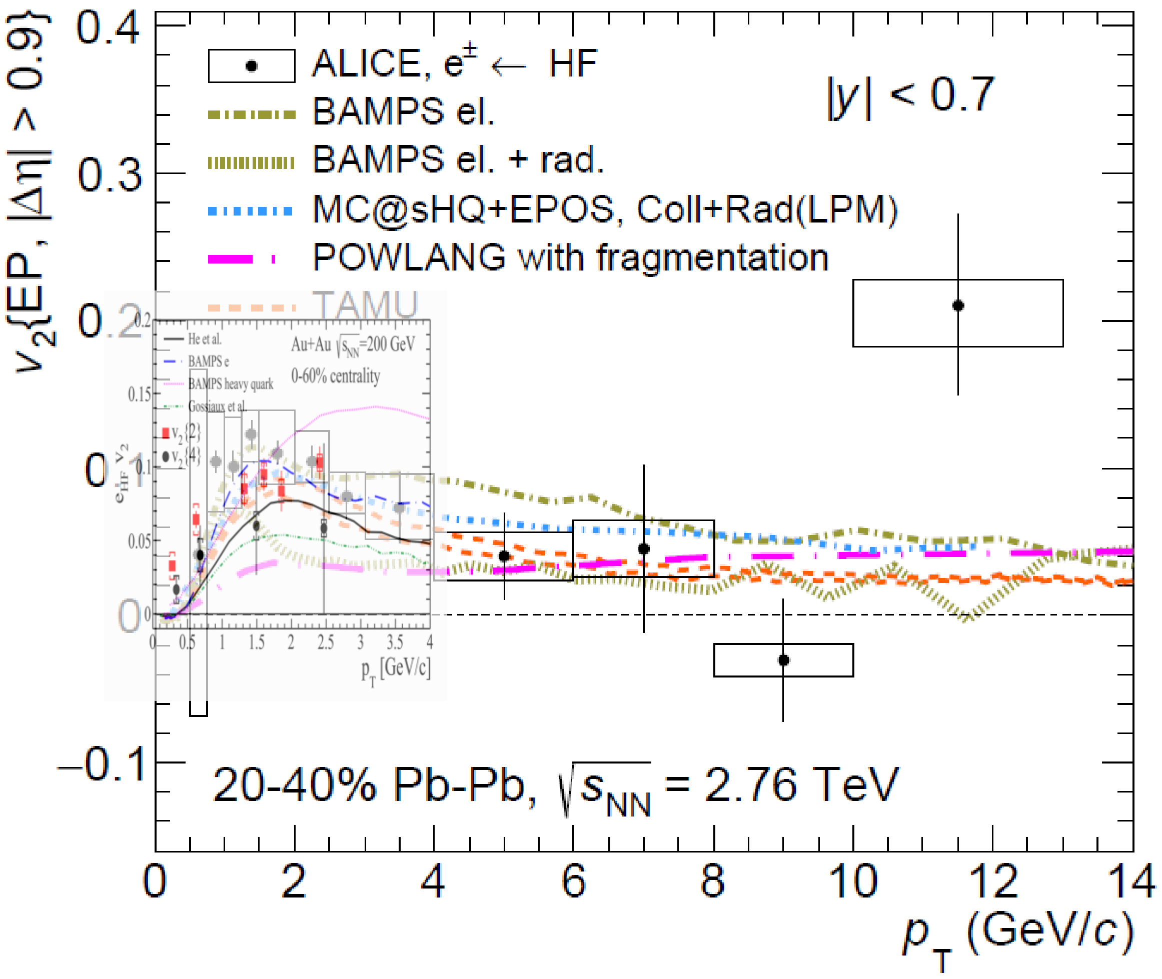

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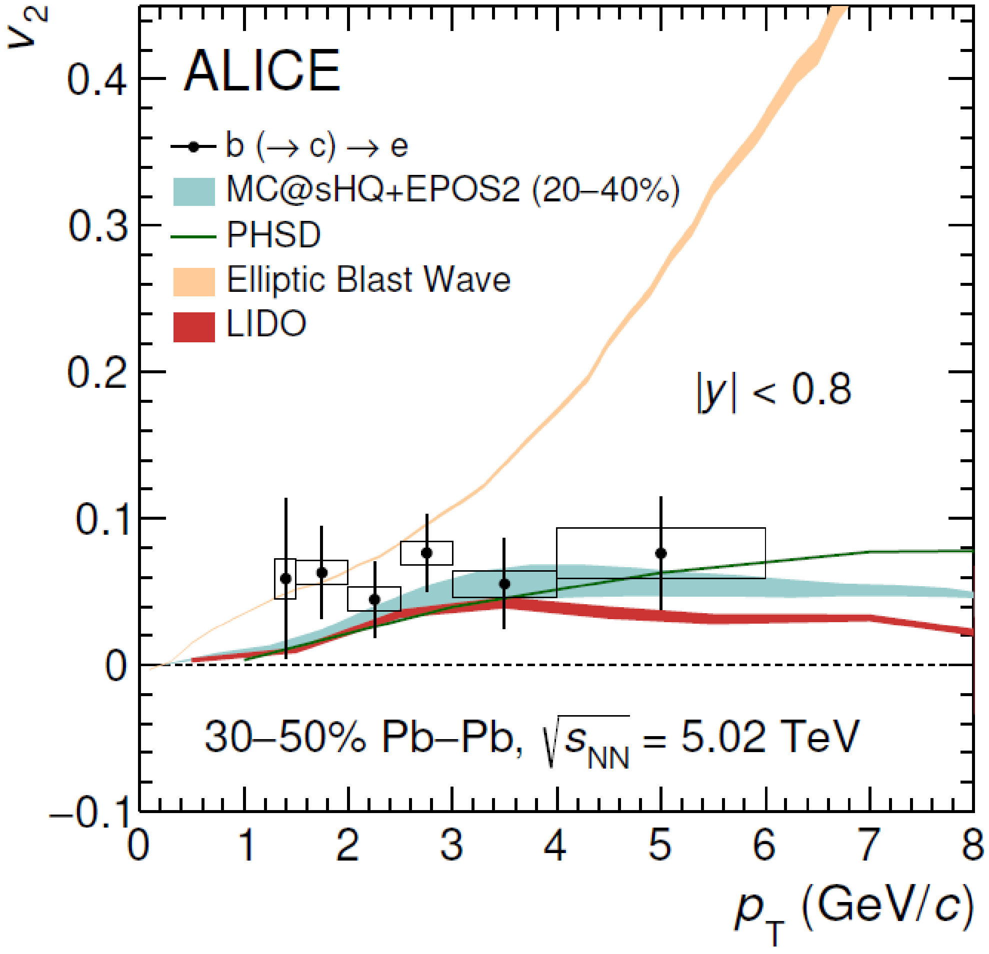
NPE v_2 (ALICE): JHEP 09 (2016) 028

ELLIPTIC FLOW OF NPE FROM DECAY OF OPEN-BOTTOM HADRONS BY ALICE

- Elliptic flow of NPE from decay of open-bottom hadrons measured ALICE in Pb+Pb collisions at 5.05 TeV (bottom)
- Significant elliptic flow observed
- Model incorporating full thermalization of bottom quarks does not describe the data at high p_T
- Models with substantial interactions of b-quarks with the QGP reproduce data
- **Even bottom quark experiences significant energy loss due to interaction with the QGP at the LHC energies**

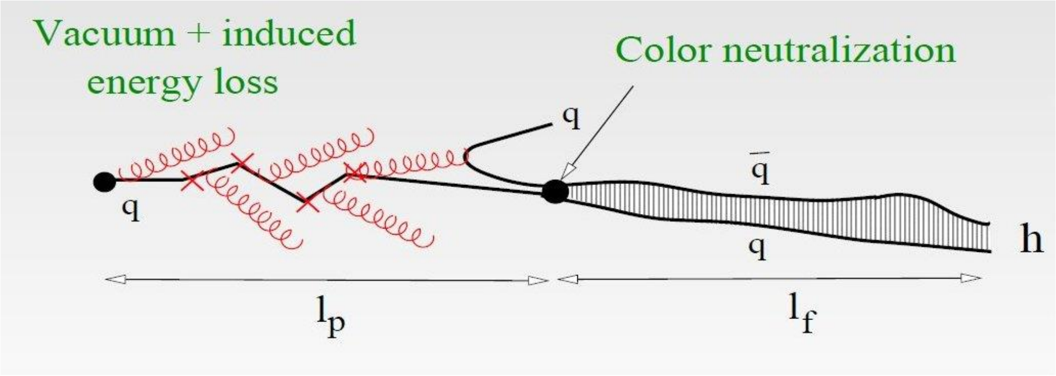


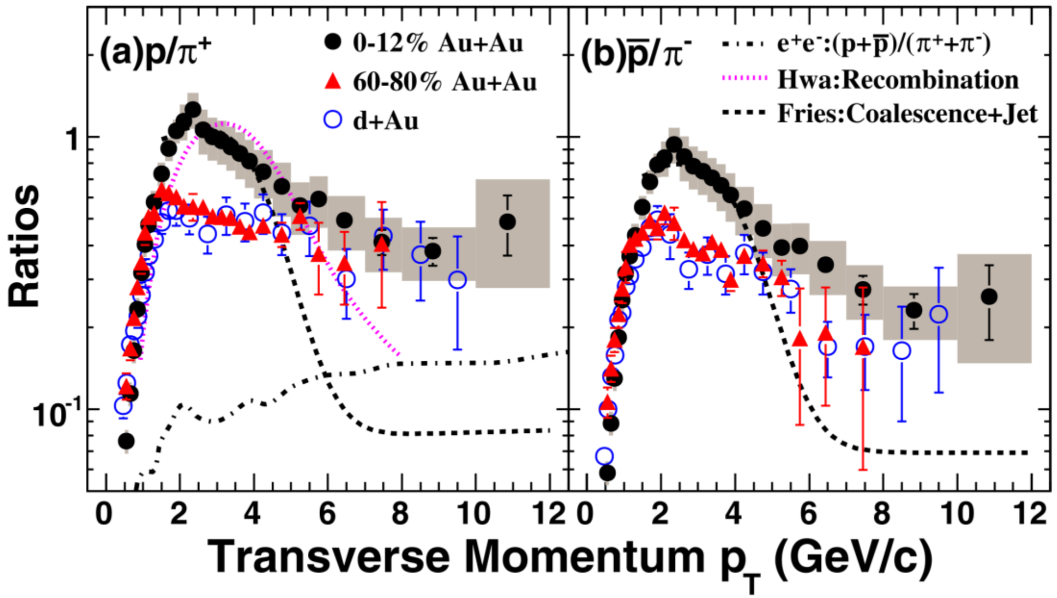
Phys. Rev. Lett. 126, 162001 (2021)

OPEN HEAVY-FLAVOR HADROCHEMISTRY

HADRONIZATION OF QUARKS IN A+A COLLISIONS

- **Fragmentation**
  - As a quark propagates through medium (or vacuum) it radiates gluons which then fragment into quark-antiquark pairs
  - Those pairs and the original quark then hadronize
- **Coalescence**
  - Quark propagating through medium hadronizes with surrounding (anti-)quarks
    - At intermediate hadron p_T ($2 < p_T < 8$ GeV/c)
    - Quarks need to be close in kinematic phase space
  - More likely to produce **light flavor** baryon (3 quarks) than meson (2 quarks) for given hadron p_T compared to vacuum case
    - Due to larger abundance of low p_T quarks in medium
- **How about heavy-flavor hadrons?**





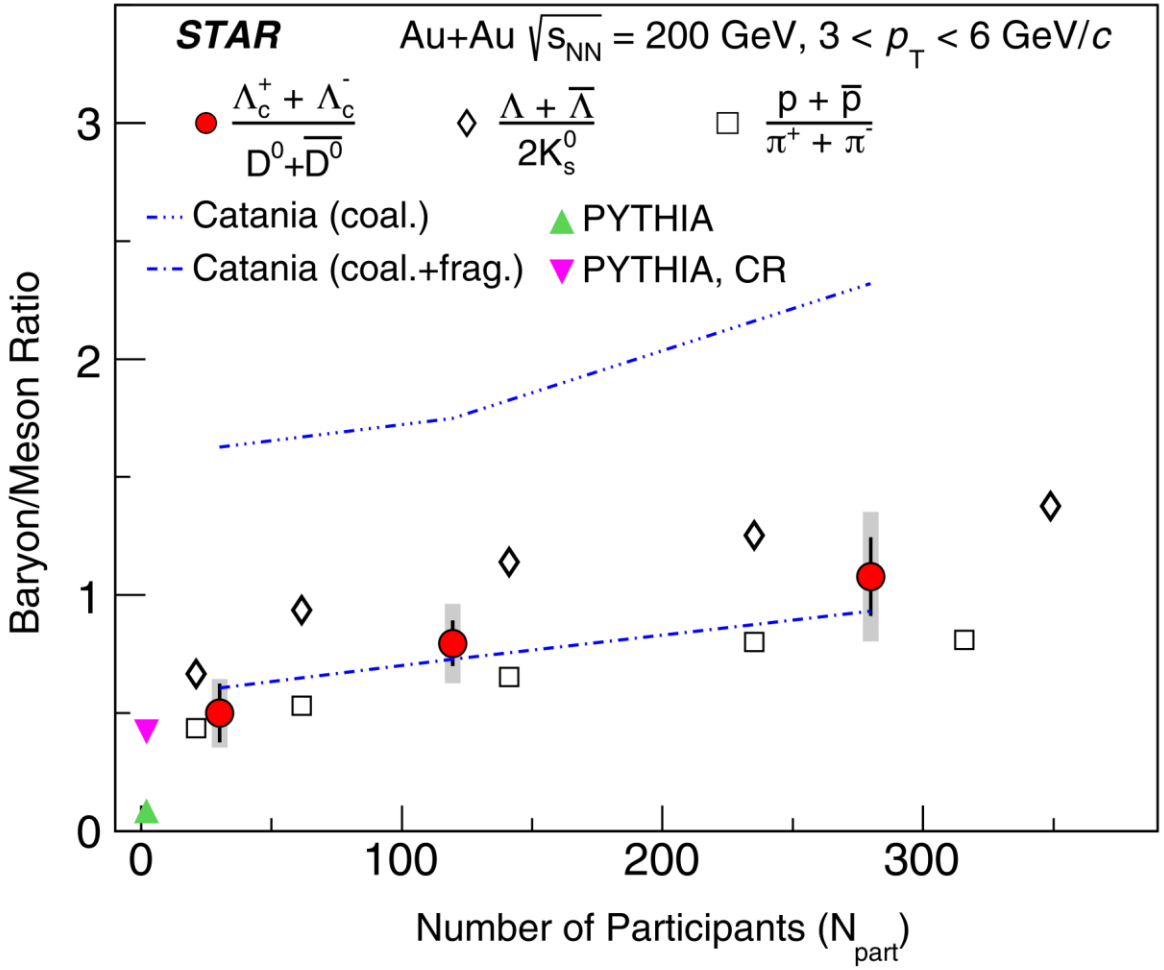
p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)

Λ_c/D^0 YIELD RATIO ENHANCEMENT AT STAR

- **Open-charm** baryon/meson yield ratio

CENTRALITY DEPENDENCE

- Enhancement of the ratio increases towards central collisions
- Data well described by Catania model with coalescence and fragmentation



Λ_c (STAR): Phys. Rev. Lett. 124, 172301, (2020)
p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)
Λ /K (STAR): Phys. Rev. Lett. 108, 072301 (2012)
Catania: Eur. Phys. J. C 78, 348, (2018)

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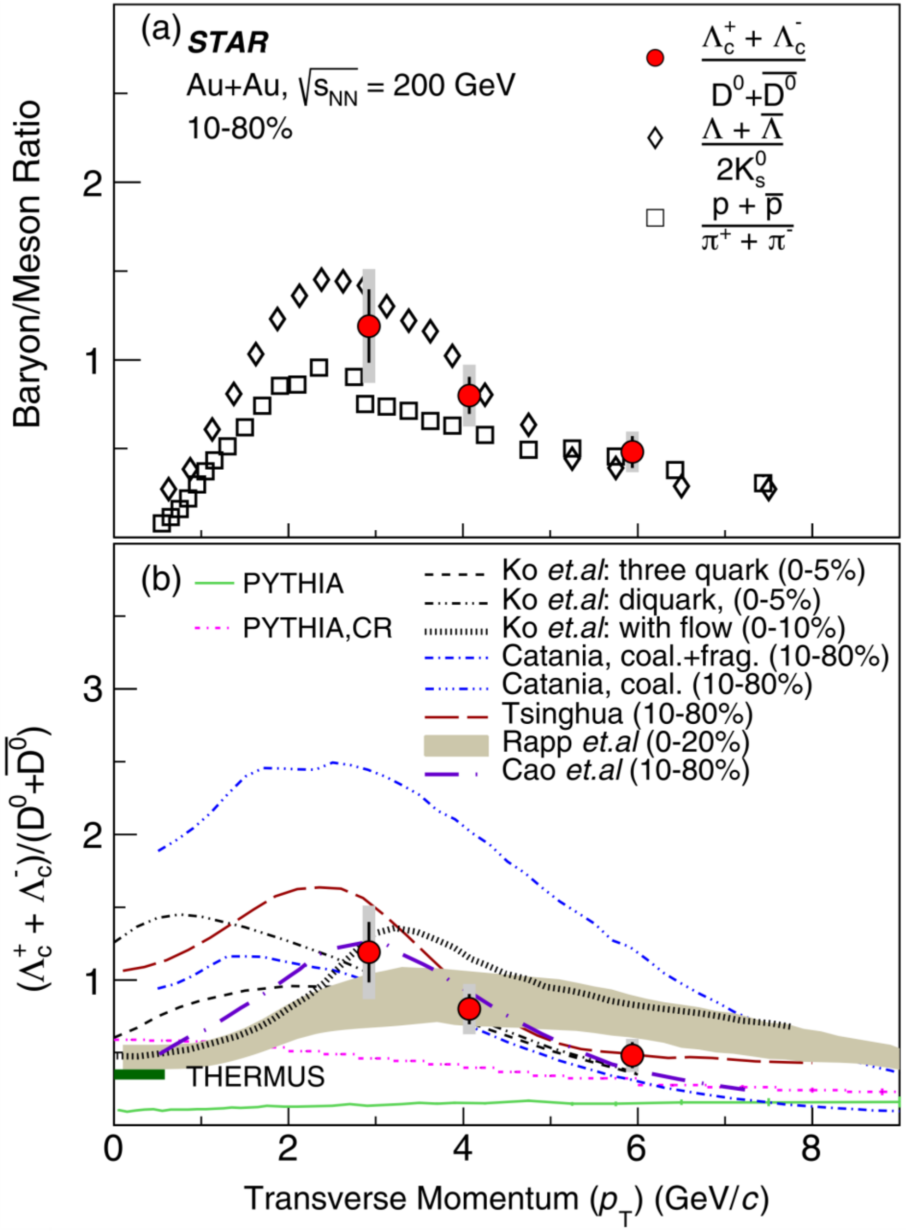
p_T DEPENDENCE

- Significant enhancement with respect to PYTHIA prediction
- Coalescence models closer to data than PYTHIA

- **Importance of coalescence and fragmentation hadronization of charm quarks**



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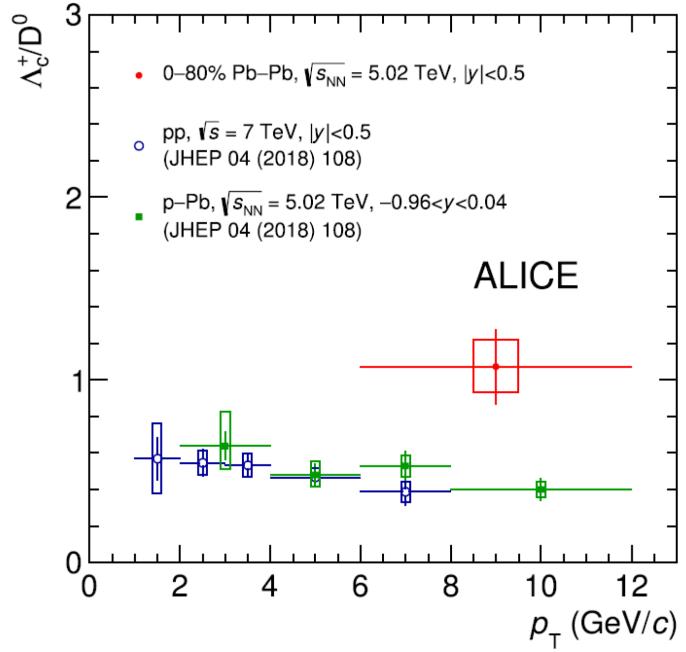
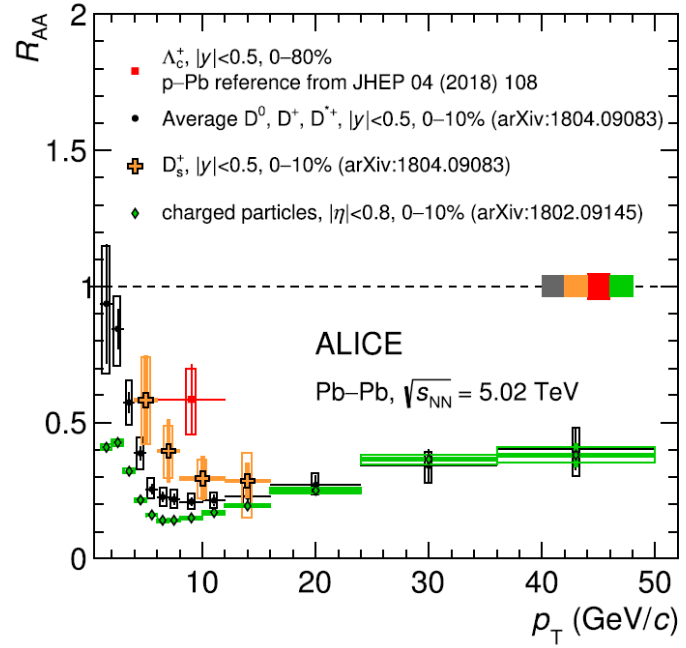
Λ/K (STAR): Phys. Rev. Lett. 108, 072301 (2012)
Ko *et al.*: Phys. Rev. C 101, 024909, (2020)

Catania: Eur. Phys. J. C 78, 348, (2018)
Tsinghua: arXiv:1805.10858, (2018)
Rapp *et al.*: Phys. Rev. Lett. 124, 042301 (2020)
Cao *et al.*: arXiv:1911.00456, (2019)

Λ_c/D^0 yield ratio enhancement by ALICE

- The enhancement is observed also by ALICE in Pb+Pb collisions at 5.02 TeV
- The measured R_{AA} suggests mass ordering of suppression of open-charm hadrons
- **Indicates importance of coalescence hadronization of charm quarks at the LHC**

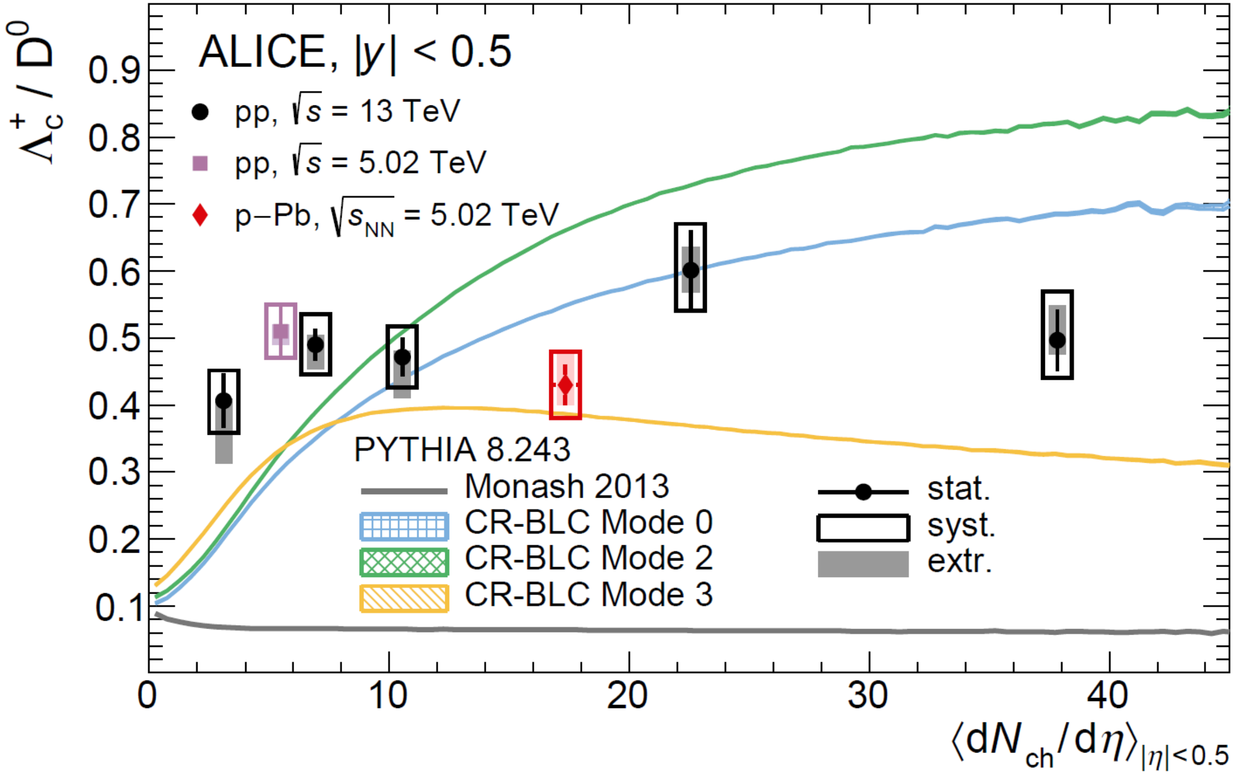




Physics Letters B 793 (2019) 212–223

Λ_c/D^0 yield ratio enhancement by ALICE in p+p

- Enhancement of the ratio in p+p collisions with respect to expected value, e.g. from PYTHIA
- The fragmentation ratios are typically taken from e^+e^- collisions
  - Very clear environment
- Proton-proton collisions are probably different
  - Color strings
- New approach to hadronization process in p+p collisions
  - "Color reconnection mechanism beyond leading color" JHEP 2015, 3 (2015)
- **Do we really understand charm hadronization in p+p collisions which are used as reference to A+A?**



Physics Letters B 829, 137065

Ξ_c/D^0 YIELD RATIO ENHANCEMENT BY ALICE IN p+p

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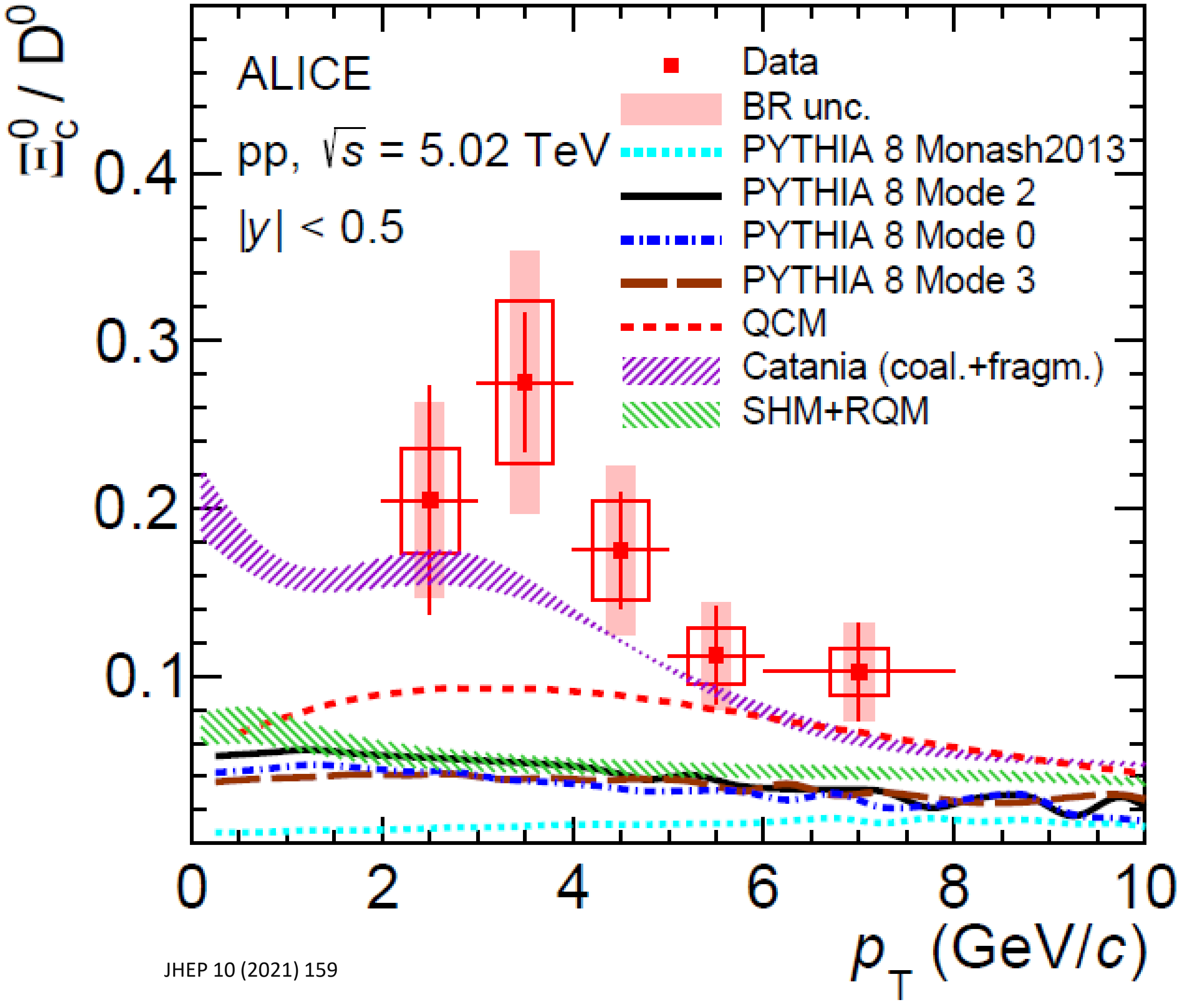
- The fragmentation ratios are typically taken from e^+e^- collisions
  - Very clear environment
- Proton-proton collisions are probably different
  - Color strings
- Reasonably re-produced by Catania model incorporating fragmentation and coalescence hadronization
  - Coalescence in p+p collisions?
- **Do we really understand charm hadronization in p+p collisions which are used as reference to A+A?**



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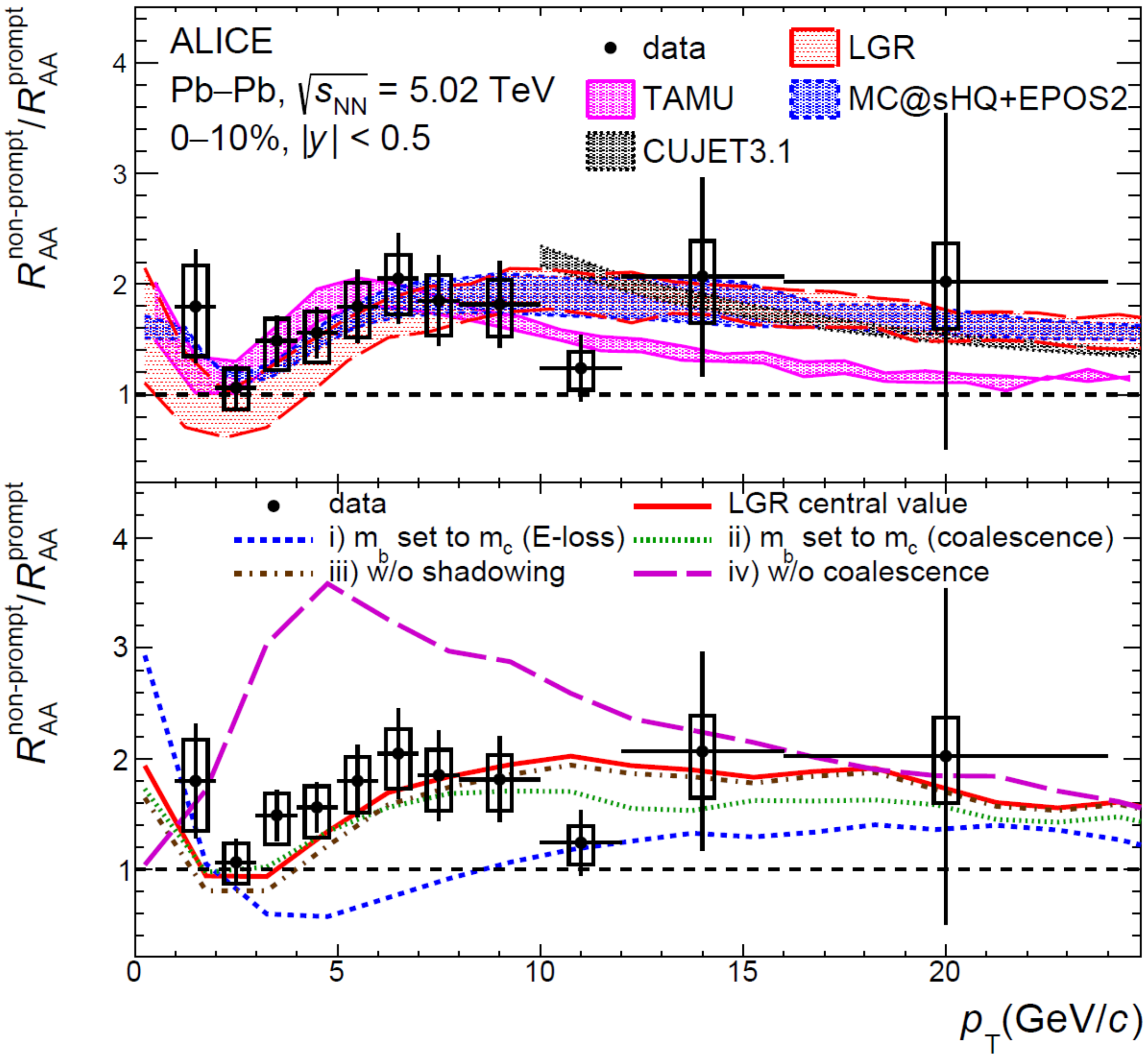
NON-PROMPT D^0 MESONS MEASURED BY ALICE

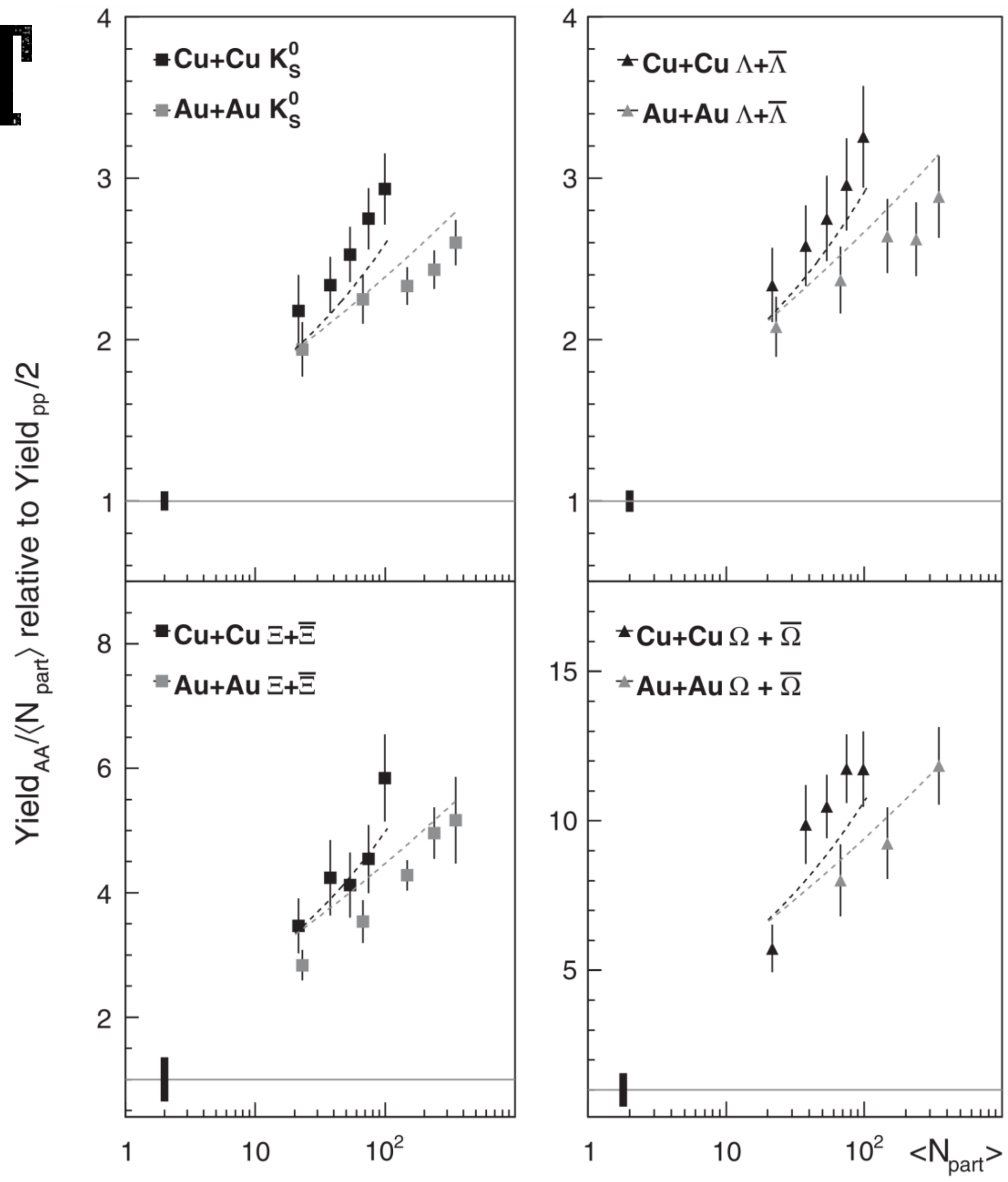
- Non-prompt D^0 mesons are used as tool to access information about open-bottom hadron production
- Selection of D^0 mesons which are far from primary vertex
  - Combined decay length of open-bottom hadrons (ca. 450 μm) and that of D^0 (122.9 ± 0.4 μm)
- LGR model provides good description of observed R_{AA} ratio
- **Coalescence hadronization is important for *c* and *b* quarks and the energy loss experienced by charm quarks is different from that of bottom quarks**



arXiv:2202.00815 [nucl-ex]

STRANGENESS ENHANCEMENT

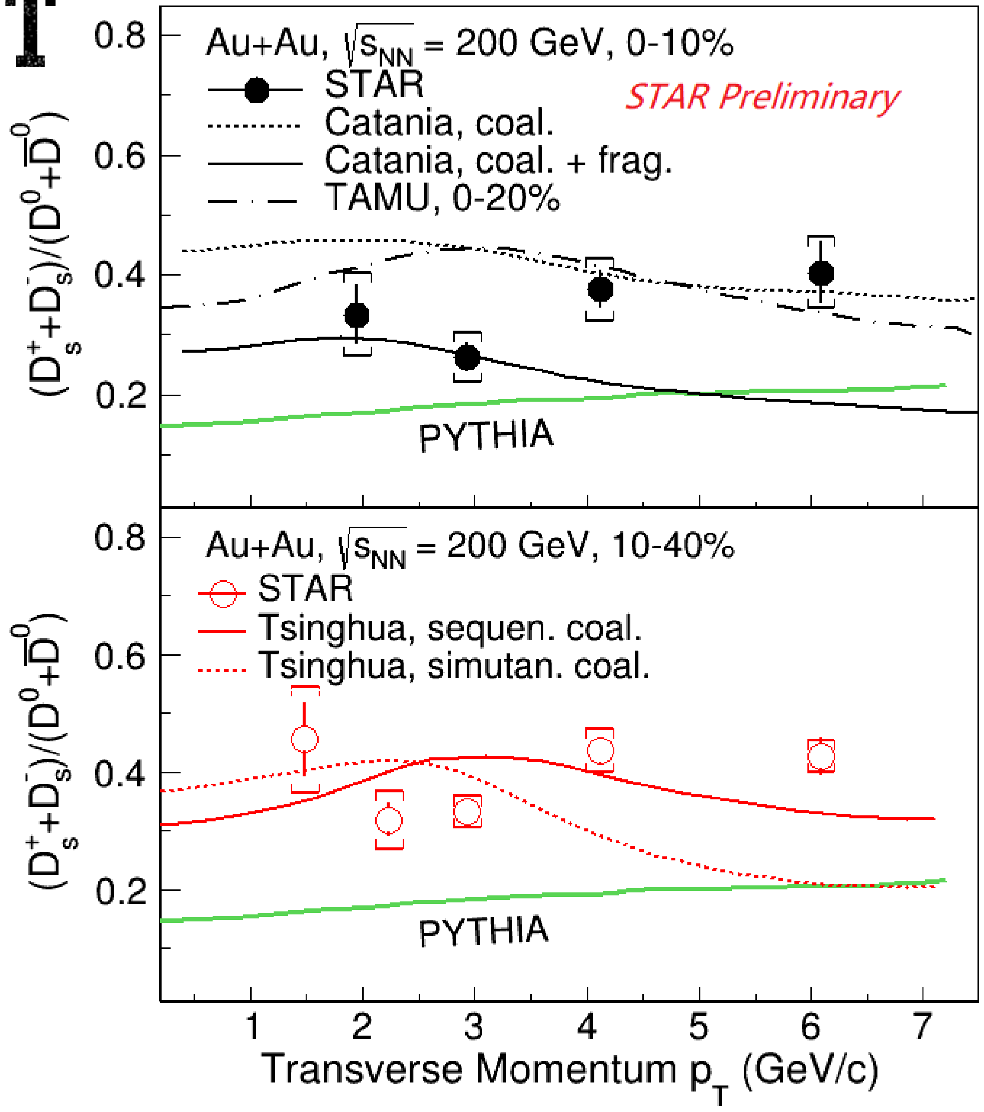
- Another very important phenomenon observed in heavy-ion collisions is **strangeness enhancement**
- Protons and neutrons do not contain any (valence) strange quarks
- Fragmentation of gluons
  - Present in both p+p and Au+Au
- Strange quark-antiquark pairs from QGP
  - Only in Au+Au
  - This additional mechanism leads to enhanced strangeness production per participant in Au+Au with respect to p+p for light hadrons
- **How about strange heavy-flavor hadrons?**



Strangeness enhancement (STAR): Phys. Rev. Lett. 108, 072301 (2012)

D_s/D^0 YIELD RATIO ENHANCEMENT

- D_s/D^0 yield ratio as a function of p_T
- Enhancement of D_s/D^0 ratio in Au+Au collisions with respect to PYTHIA baseline
- Comparison to models:
  - Catania model with only coalescence describes data for $p_T > 4$ GeV/c
  - Catania model with coalescence and fragmentation describes data for lower p_T
  - Tsinghua model with sequential coalescence hadronization is closer to data for both low and high p_T
- **Importance of coalescence hadronization of charm quarks with enhanced strangeness production**

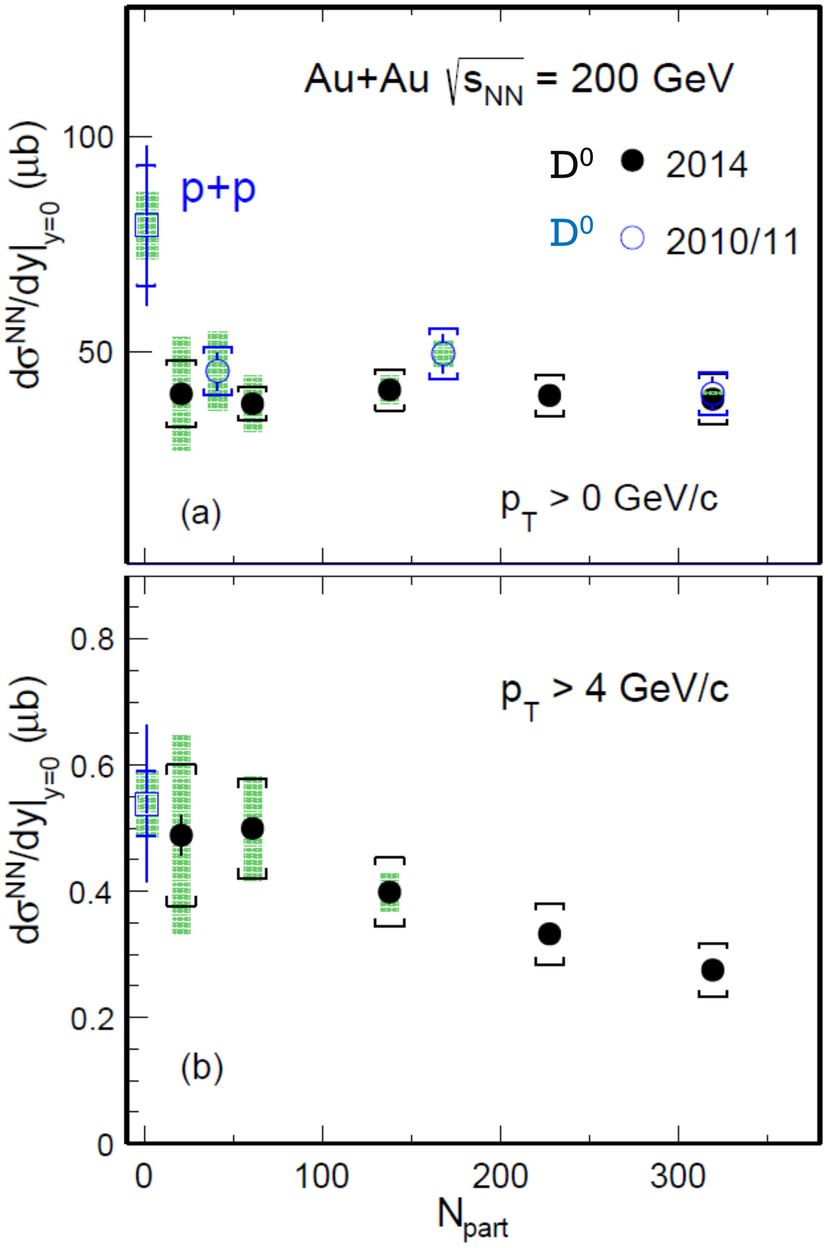


Catania: Eur. Phys. J. C 78, 348, (2018).
TAMU: Phys. Rev. Lett. 110, 112301 (2013)
Tsinghua: arXiv1805.10858, (2018).

TOTAL CHARM PRODUCTION CROSS SECTION

- Total charm production **cross section per binary collision** in Au+Au extracted from the measurements of open-charm hadrons
  - *The Λ_c cross-section is derived using the Λ_c/D^0 yield ratio
- The Au+Au result is consistent with that measured in p+p collisions within the uncertainties
- **Redistribution of charm quarks among open –charm hadron species**

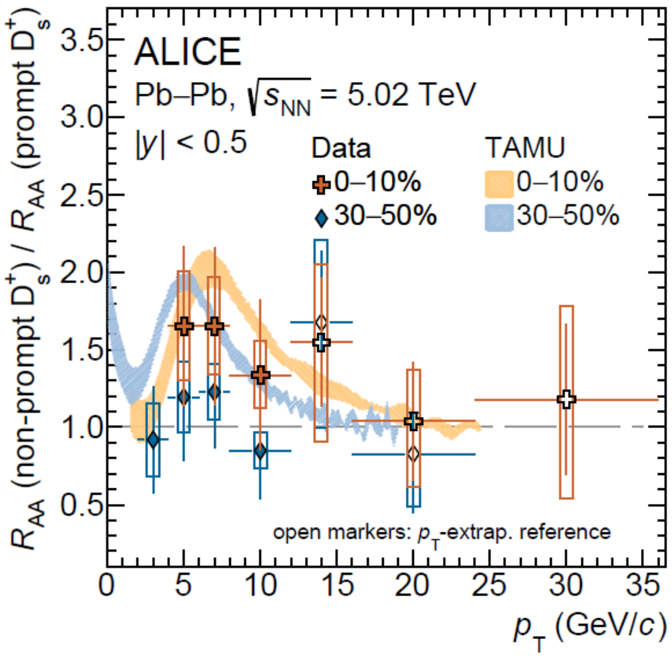
Coll. system	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40%	D^0	41 ± 1 ± 5
	$D^\pm$	18 ± 1 ± 3
	D_s	15 ± 1 ± 5
	Λ_c	78 ± 13 ± 28 *
	Total:	**152 ± 13 ± 29**
p+p at 200 GeV	**Total:**	**130 ± 30 ± 26**

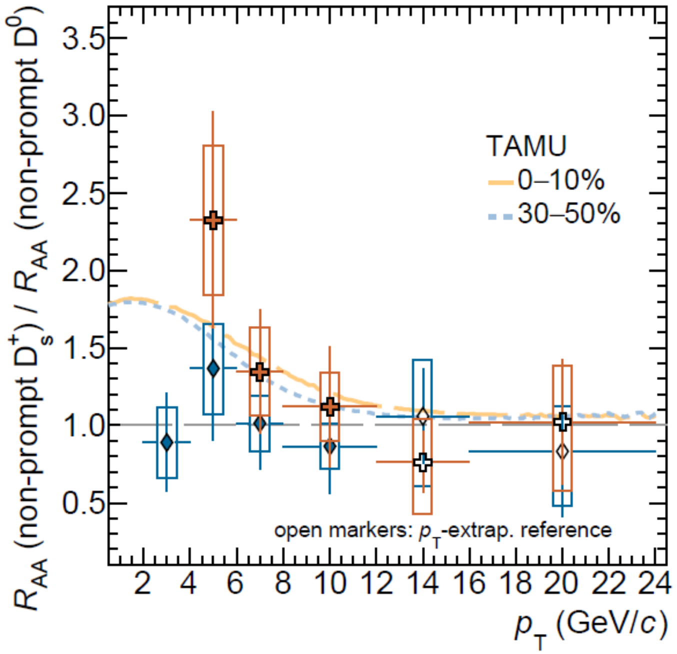


D[0] 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D[0] 2010/11 (STAR): Phys. Rev. Lett. 113, 142301 (2014), erratum: Phys. Rev. Lett. 121, 229901 (2018).
p+p (STAR): Phys. Rev. D 86 072013, (2012)

NON-PROMPT D_s MESONS MEASURED BY ALICE

- Access to information about strange open-bottom hadrons
- Same procedure as in case of non-prompt D^0 mesons
- Non-prompt D_s mesons are less suppressed compared to prompt D_s mesons
  - Lower energy loss of bottom quark compared to charm quark
- Low p_T non-prompt D_s are enhanced with respect to non-prompt D^0 mesons
  - Strangeness enhancement combined with coalescence hadronization of charm quarks
- **Charm quarks loose more energy in QGP than bottom quarks**
- **Non-prompt Ds mesons are enhanced due to strangeness enhancement and coalescence hadronization**



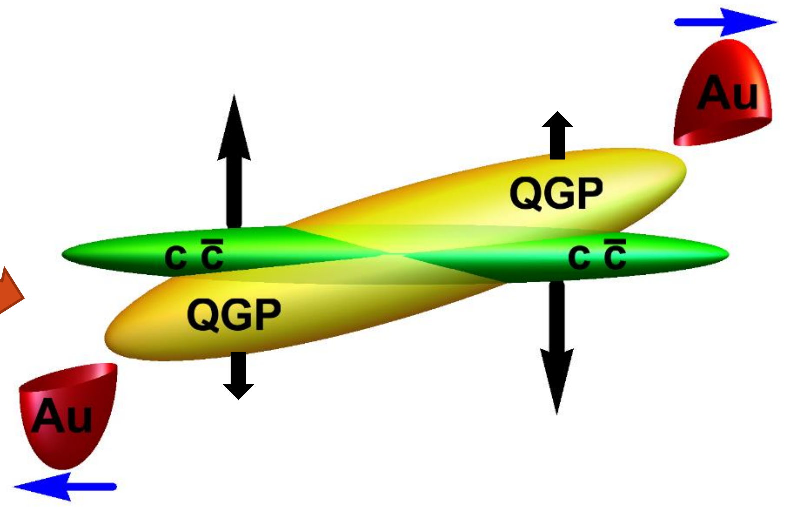


arXiv:2204.10386 [nucl-ex]

OPEN-CHARM MESONS AS A PROBE OF INITIAL STATE OF HEAVY-ION COLLISIONS

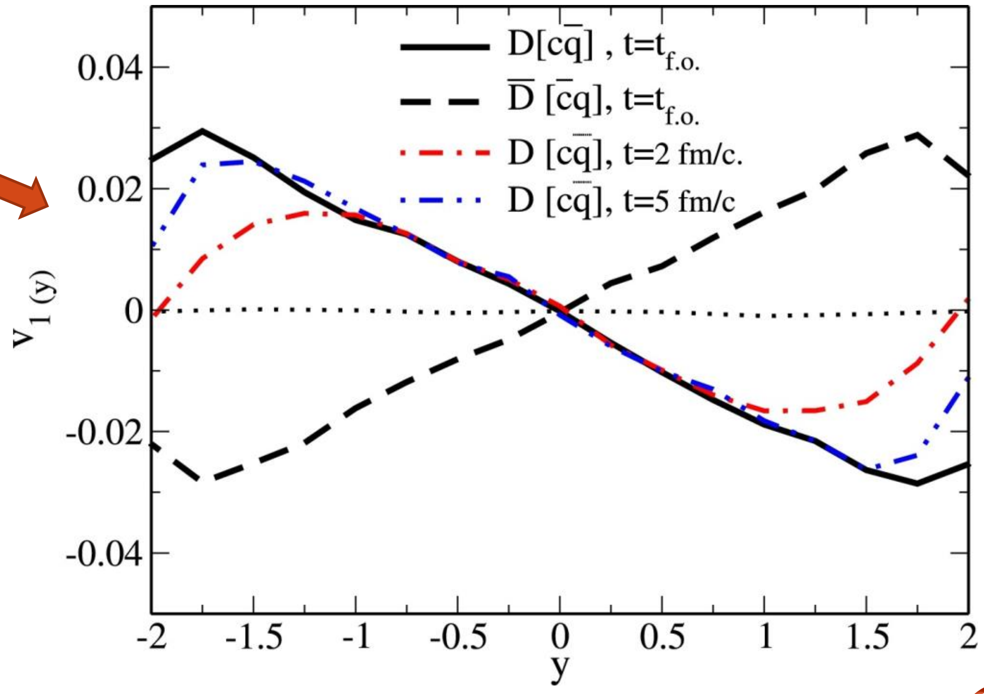
D^0 DIRECTED FLOW

- **Hydrodynamics** Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)
  - Difference between the tilt of the bulk and the longitudinal density profile of HF production
  - Larger slope dv_1/dy of charm quarks than light flavor quarks



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

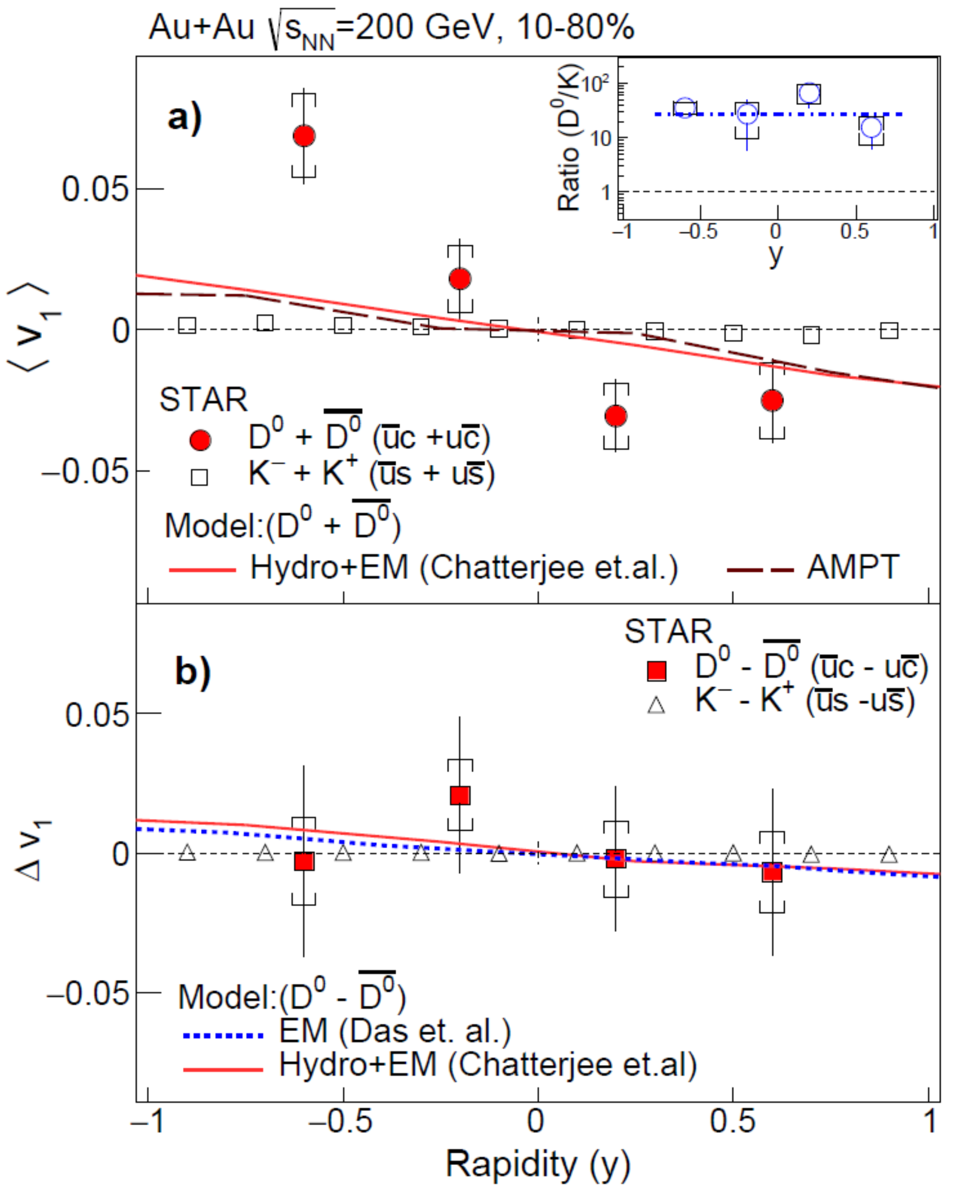
- **Initial EM field from passing spectators**
  - Predicted negative dv_1/dy slope for D^0 and positive one for $\overline{D^0}$



- **Hydrodynamics + EM field** Chatterjee, Bozek: Phys. Lett. B 798, 134955, (2019).
  - Negative dv_1/dy slope for both D^0 and $\overline{D^0}$
  - Larger magnitude of slope for D^0 than $\overline{D^0}$

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 dv_1/dy slope for both D^0 and $\overline{D^0}$
  - Larger slope than for kaons
- No EM induced splitting observed within the uncertainties
- **Measurement of D^0 directed flow can be used to constrain the difference between the tilt of the QGP bulk and the longitudinal density profile of HF production**



D^0 (STAR): Phys. Rev. Lett. 123, 162301 (2019).
Kaons (STAR): Phys. Rev. Lett. 120, 062301 (2018).

SUMMARY

- Charm quarks loose significant fraction of their energy in the QGP
  - Low values of R_{AA} of D mesons
  - Large collective flow of D mesons
- Charm quarks are close to thermal equilibrium with the medium
  - Large collective flow of D mesons
- Significant contribution of coalescence hadronization for charm quarks
  - Re-distribution of charm quarks among open-charm hadron species in A+A collisions with respect to p+p collisions
- Charm quarks can be used as a probe of initial EM field and initial tilt of the QGP bulk
  - Non-zero directed flow of D^0 mesons
- Bottom quarks loose less energy in QGP than charm quarks
  - Nuclear modification factors and yields of NPE from decays of open-bottom hadrons
  - Nuclear modification factors of non-prompt D mesons
- Bottom quarks loose some energy in the medium at the LHC
  - NPE from decays of open-bottom hadrons have significant elliptic flow

OUTLOOK

- sPHENIX experiment at RHIC
  - Expected to start taking data in 2023
  - Good spatial resolution will allow reconstruction of open heavy-flavor hadrons
  - E.g. possible to obtain high precision p+p reference for Au+Au data

- ALICE experiment
  - Recent upgrades to ALICE Inner Tracking System (ITS) will allow more precise measurements of open-heavy flavor hadrons
    - Baryons in Pb+Pb collisions as a function of both p_T and collision centrality
  - Planes to upgrade ALICE to giant silicon tracker utilizing Monolithic Active Pixel Sensors
    - Access to multi-charmed baryons, bottom-charmed hadrons and other exotic open-heavy flavor hadrons

THANK YOU FOR ATTENTION