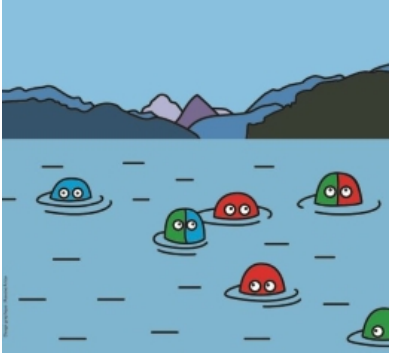

HF2022: Heavy Flavours from small to large systems

Experimental review of open heavy flavour in heavy ion collisions

Barbara Trzeciak

Czech Technical University in Prague

HF2022
Oct 18th, 2022

GAČR
CZECH SCIENCE FOUNDATION

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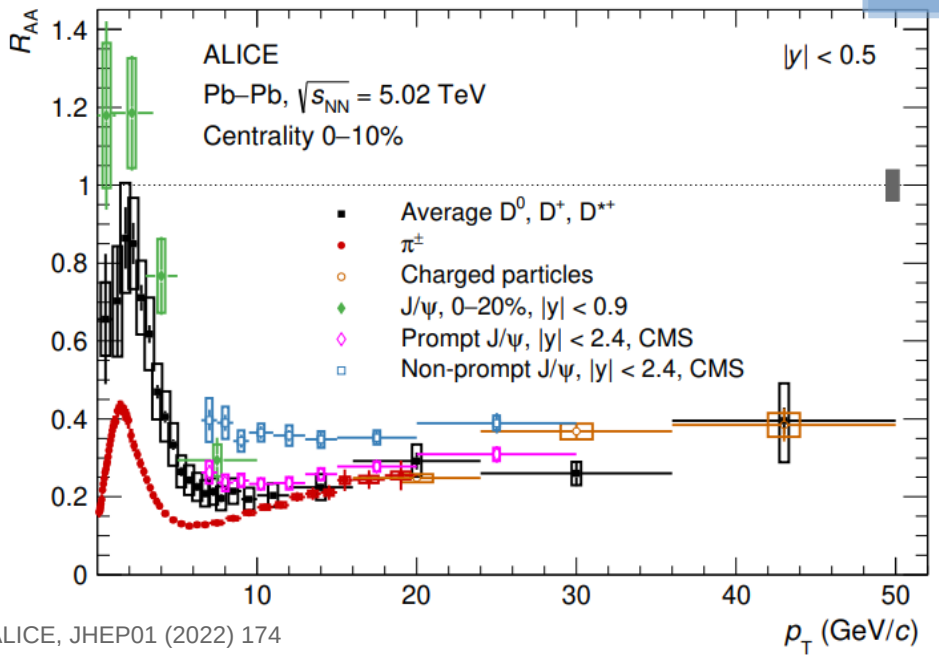
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Introduction: R_{AA}

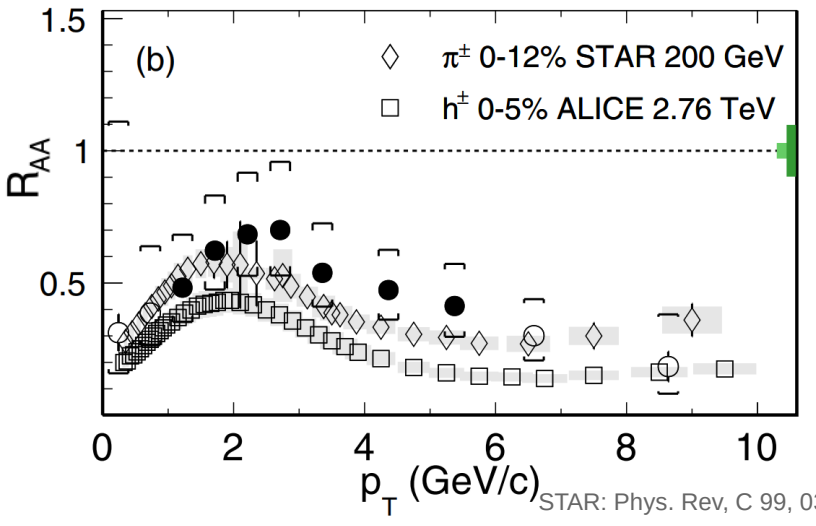
- **D meson yields strongly suppressed** in central HI collisions
- Different nuclear modification factor of HF mesons and light-flavour particles at low and intermediate p_T
  - Interplay of several effects

LHC



ALICE, JHEP01 (2022) 174

RHIC

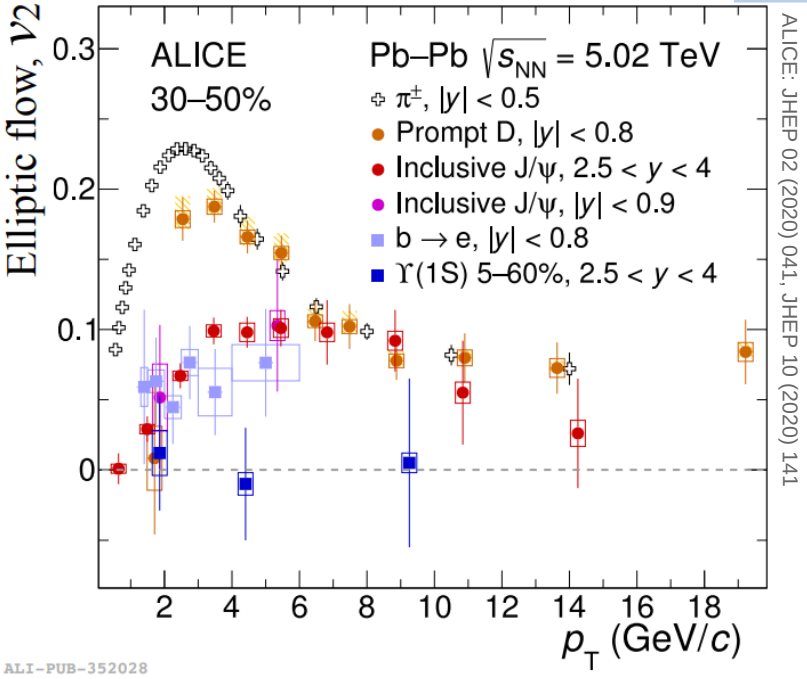


STAR: Phys. Rev, C 99, 034908 (2019)

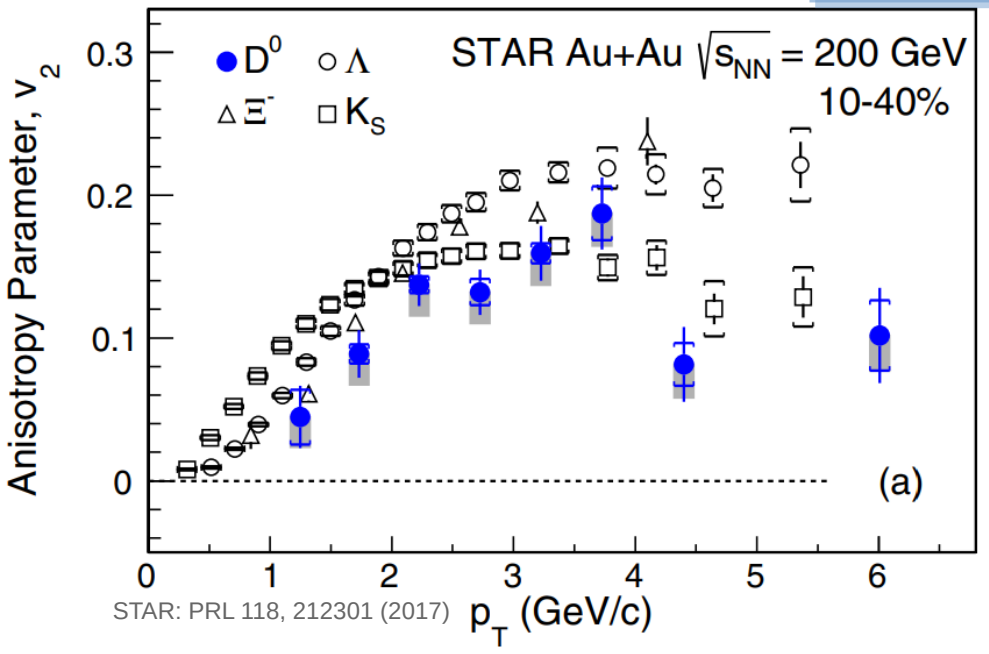
Introduction: v_2

- **D meson, b → e $v_2 > 0$**, mass ordering at lower p_T
- **Strong HF quark coupling with the medium**

LHC



RHIC

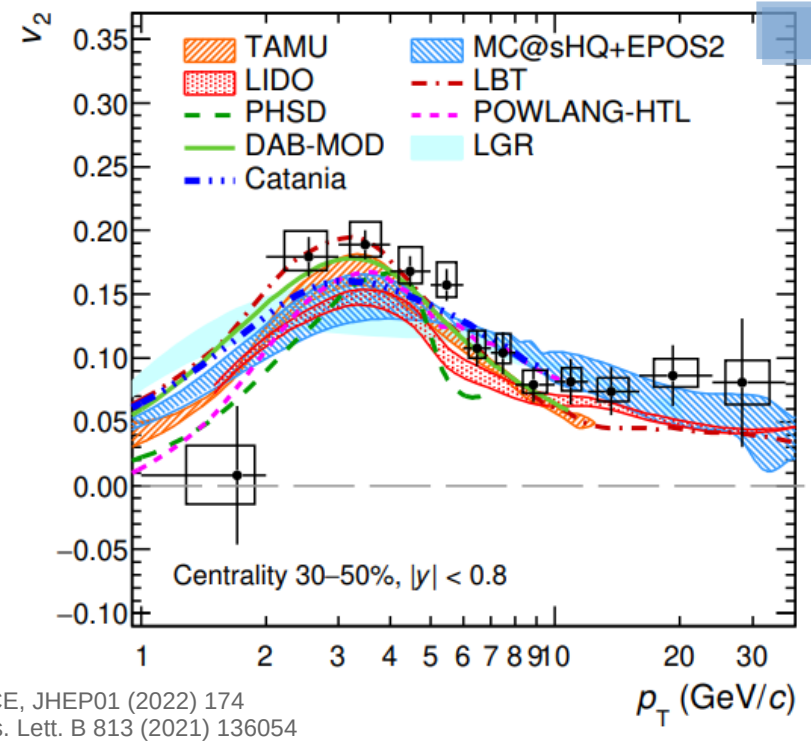


Quantitative understanding: comparisons with model calculations

Open charm v_2 vs models

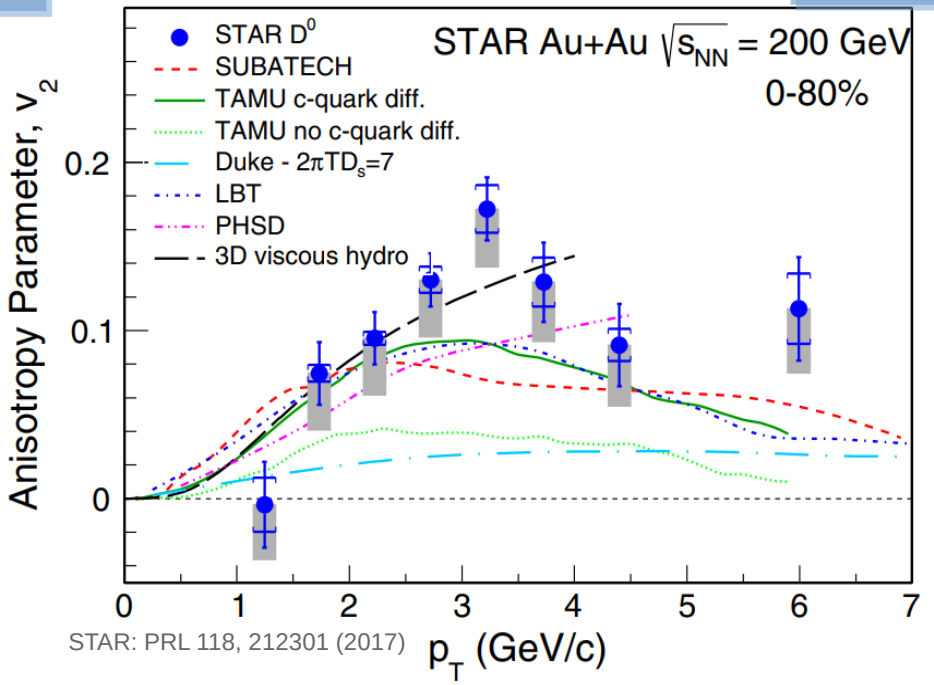
- Models tend to underestimate v_2 data in mid-central collisions at p_T 2-6 GeV/c
- Better description for the most central collisions

LHC



ALICE, JHEP01 (2022) 174
Phys. Lett. B 813 (2021) 136054

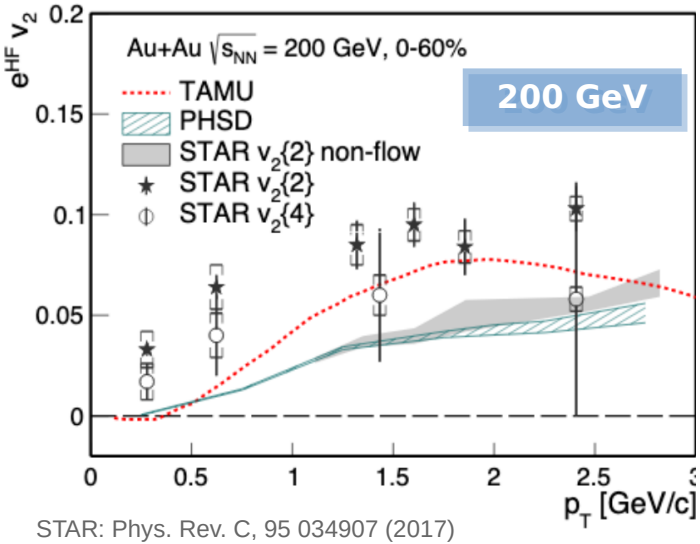
RHIC



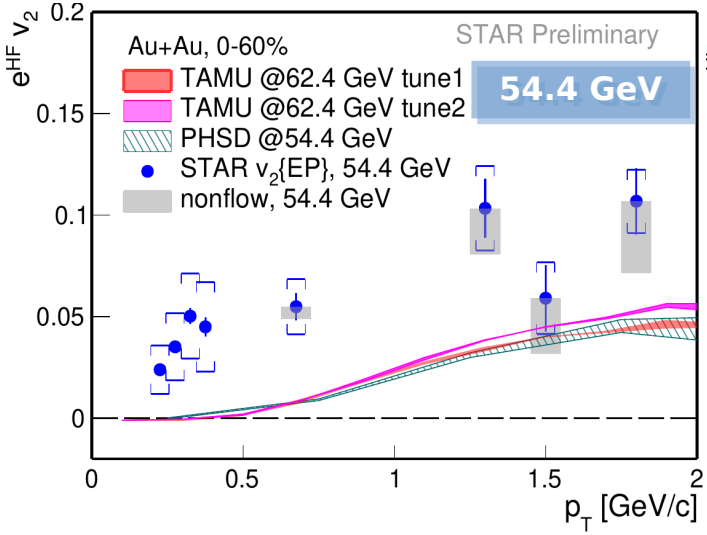
STAR: PRL 118, 212301 (2017)

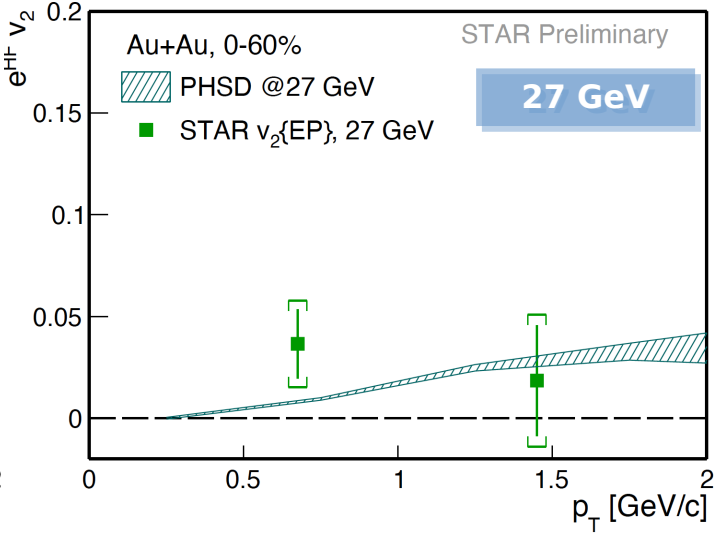
HFE v_2 vs energy

- **Significant non-zero v_2 at 54.4 GeV** of c,b → e, similar to v_2 at 200 GeV
- **HF(c) quarks interact strongly with the medium in 54.4 GeV Au+Au collisions**
- At low p_T models lower than data



STAR: Phys. Rev. C, 95 034907 (2017)

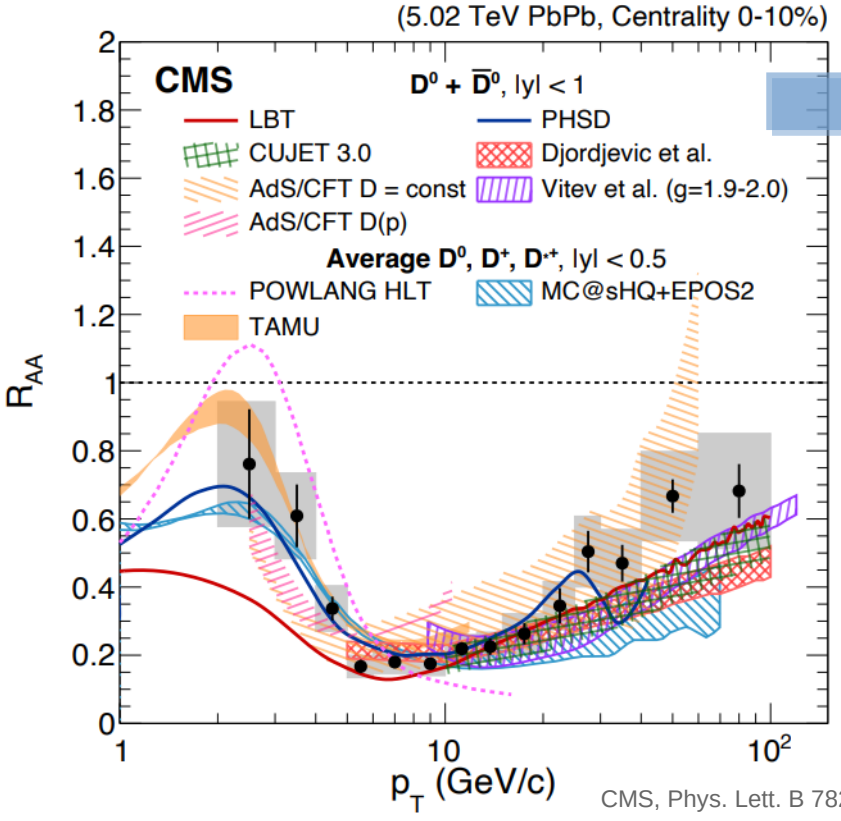




Open charm R_{AA} vs models

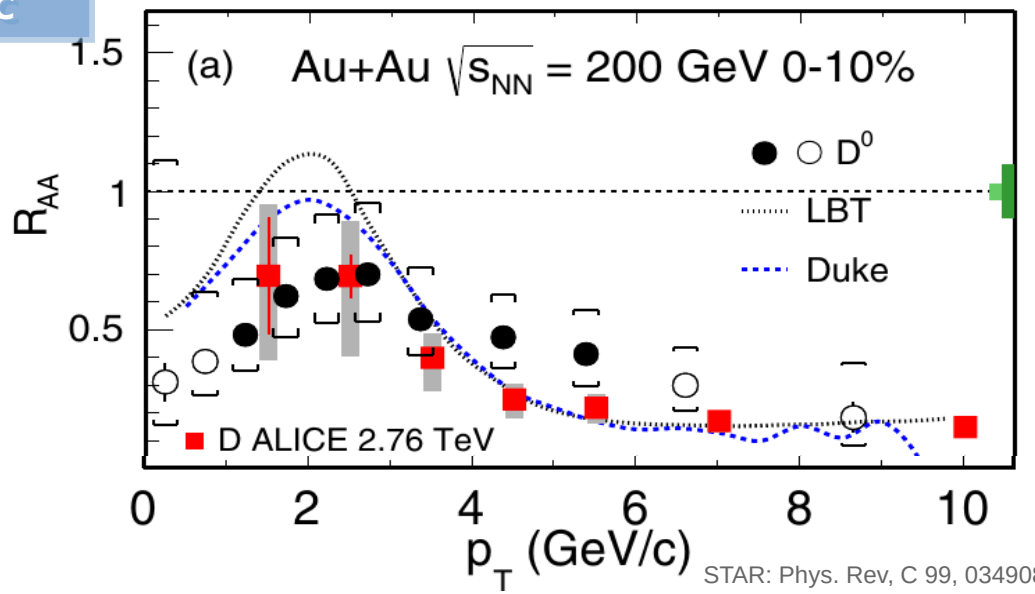
- Reasonable agreement with many models, especially at intermediate p_T
- Simultaneous description of R_{AA} and v_2 is challenging for the models

LHC



CMS, Phys. Lett. B 782 (2018) 474–496

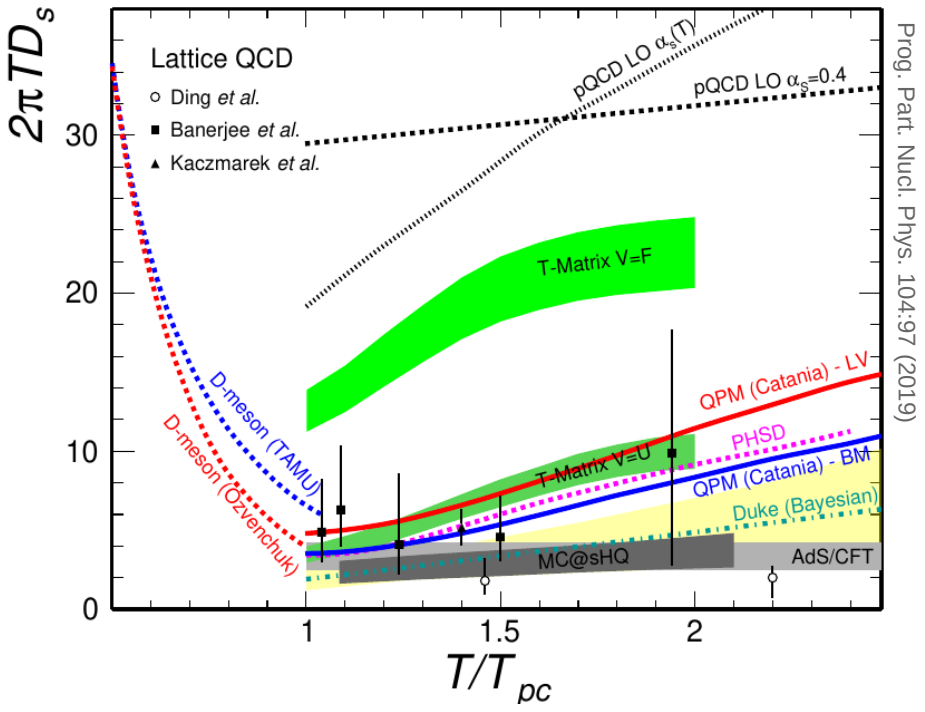
RHIC

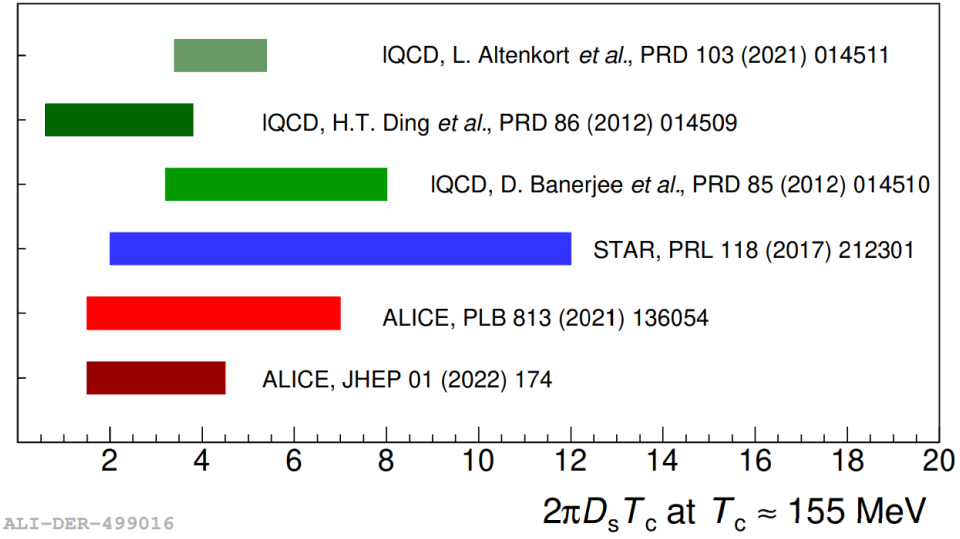


STAR: Phys. Rev, C 99, 034908 (2019)

Spatial diffusion coefficient

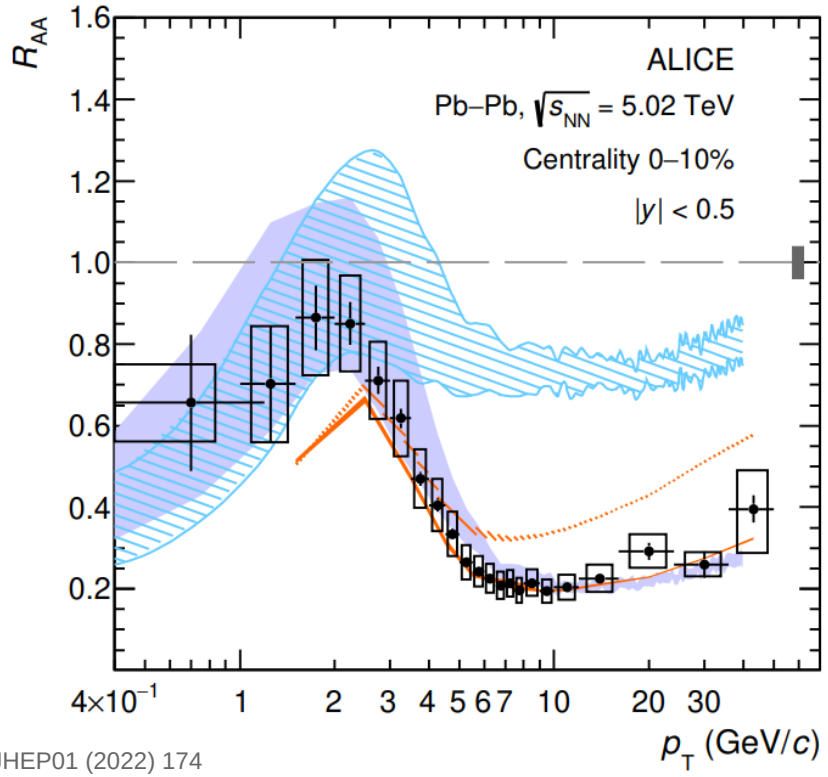
- D_s extraction: data-to-model comparison
- Data prefer strong coupling
- ALICE new constraints: $1.5 < 2\pi D_s T_c < 4.5$ (models that reasonably describe R_{AA} and $v_{2,}$ v_3)

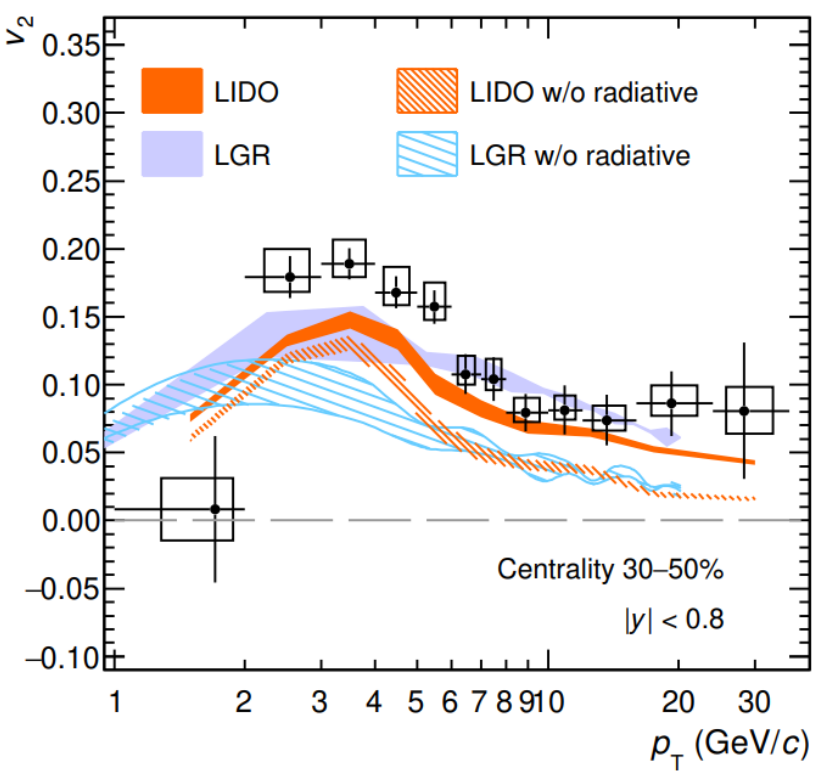




Open charm R_{AA} vs models (2)

- **Radiative energy loss important to describe intermediate and high p_T**

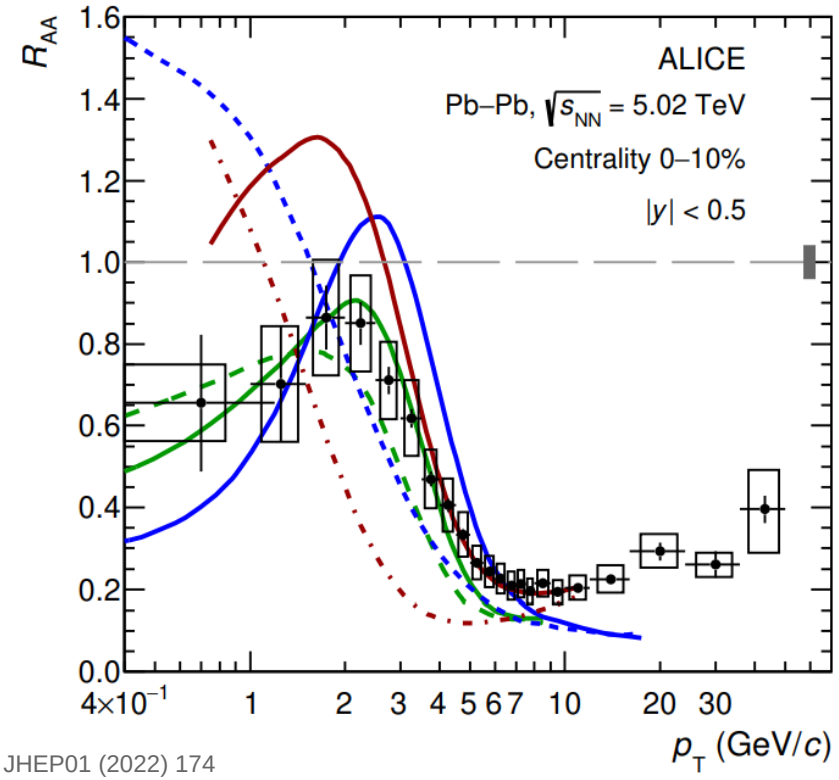




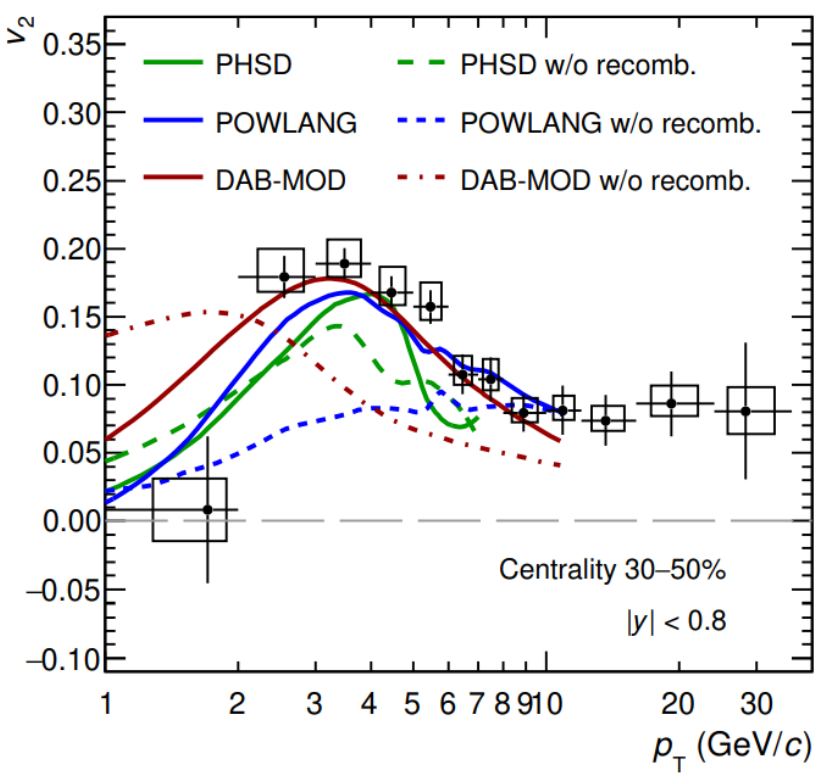
ALICE, JHEP01 (2022) 174

Open charm R_{AA} vs models (3)

- **Hadronisation via recombination important to describe low and intermediate p_T**



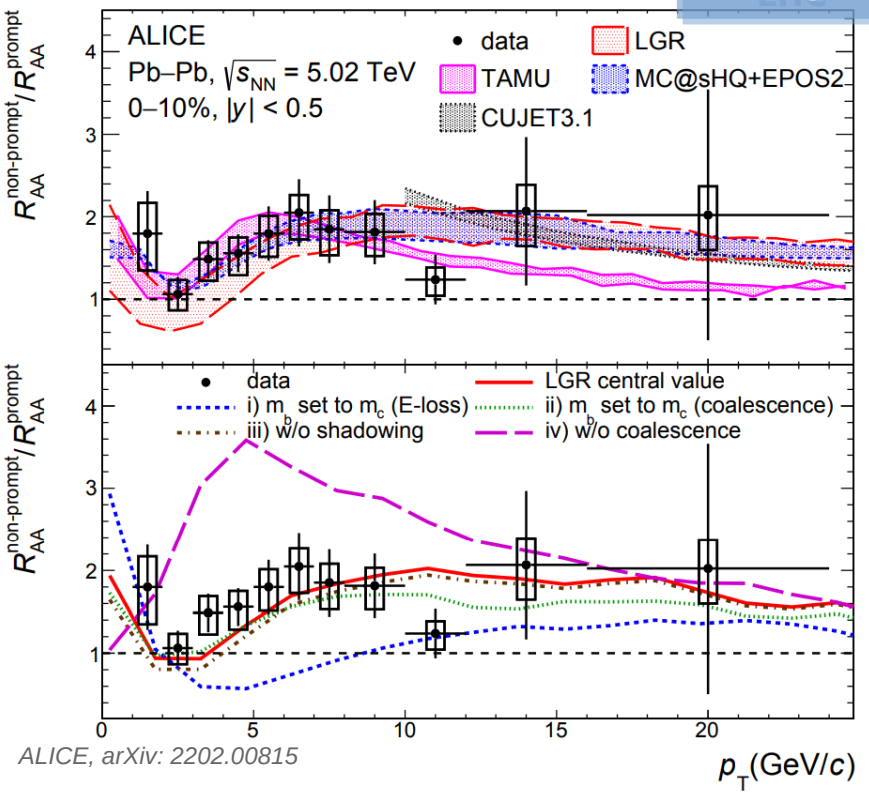
ALICE, JHEP01 (2022) 174



Separation of charm and beuty

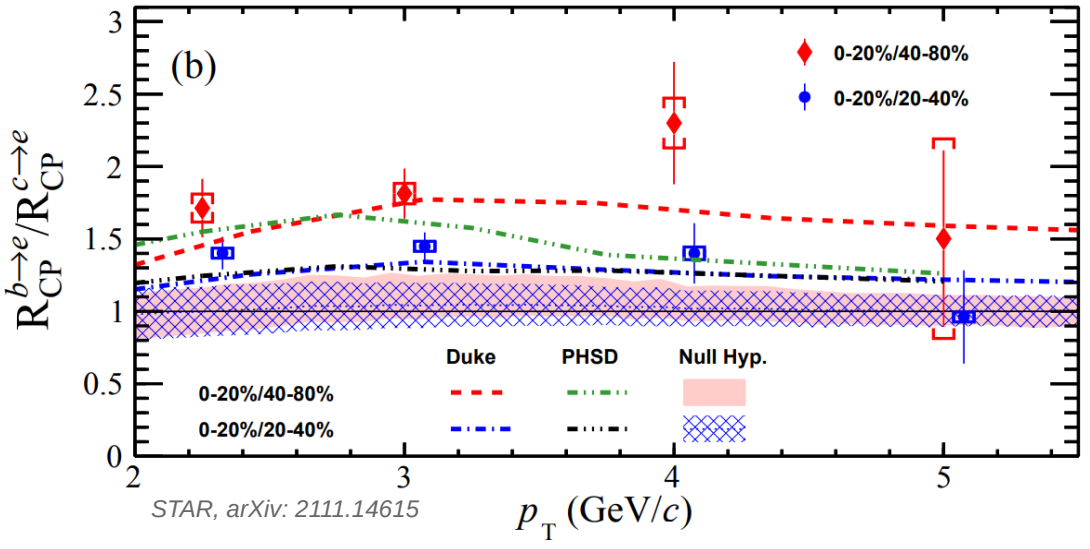
- **Beauty R_{AA} > charm R_{AA}** at intermediate p_T → suggesting larger en. loss for charm quarks
- **Consistent with quark-mass dependent energy loss and coalescence**

LHC



ALICE, arXiv: 2202.00815

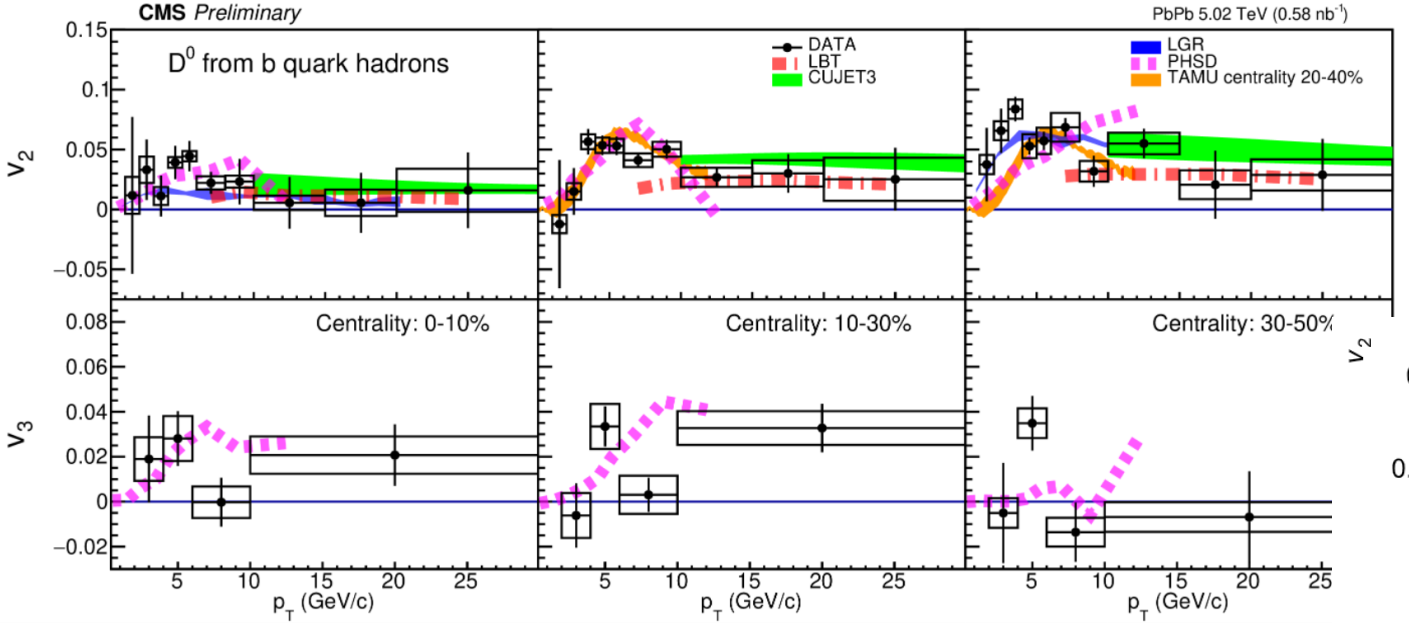
RHIC

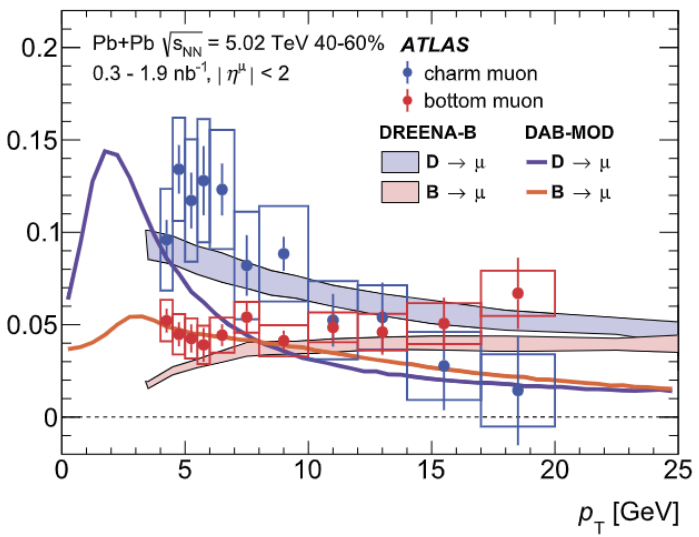


STAR, arXiv: 2111.14615

Open beauty v_2,v_3

- **beauty v_2 > 0 –** consistent with model predictions
- Non-zero v_3 with weak centrality dependence



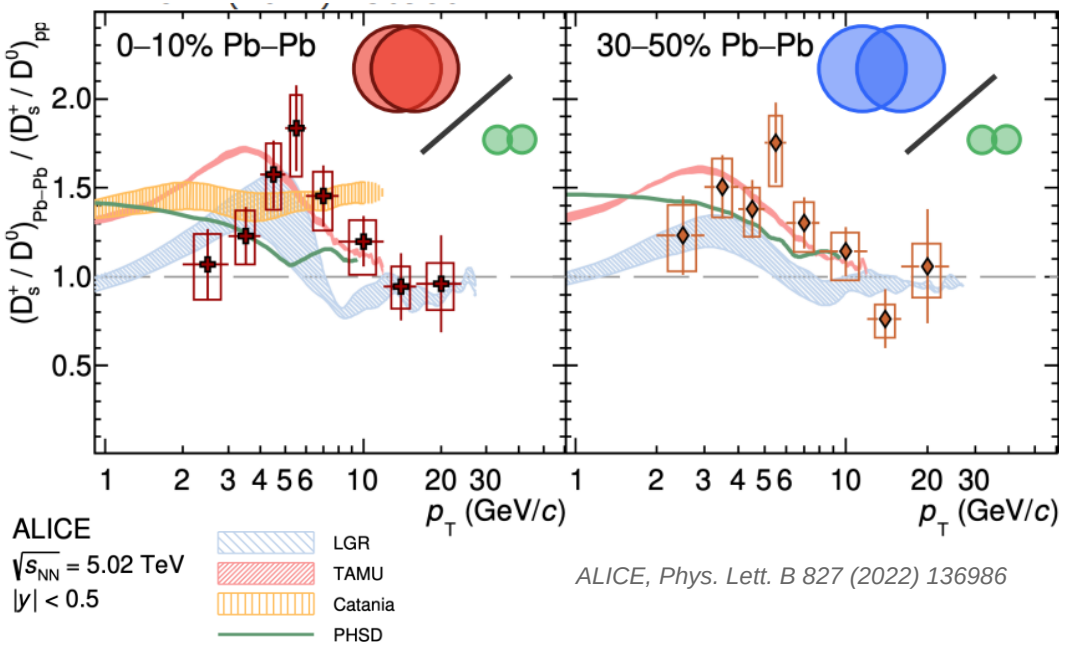


ATLAS: Phys. Lett. B 807 (2020) 135595

Charm hadrochemistry: D_s

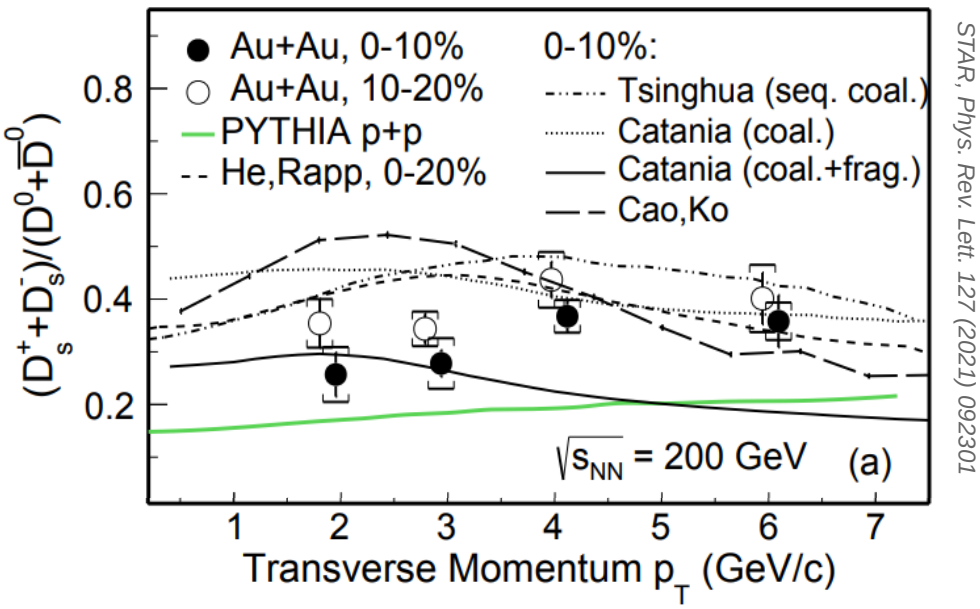
- **Enhancement in D_s^+/D^0 ratio** compared to pp
- Consistent with models including strangeness enhancement and **charm quark coalescence + fragmentation**

LHC



ALICE, Phys. Lett. B 827 (2022) 136986

RHIC

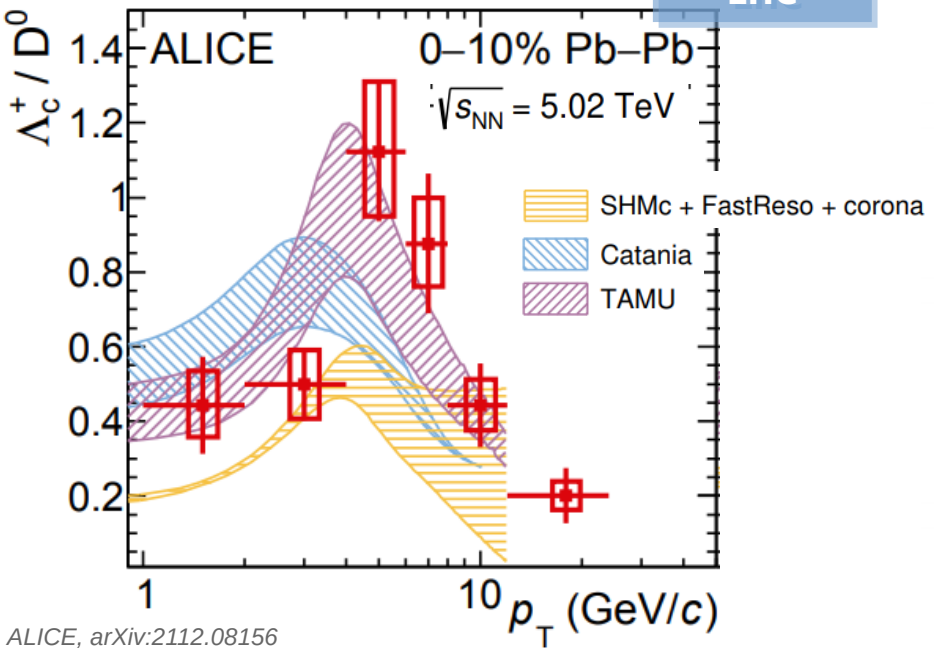


STAR, Phys. Rev. Lett. 127 (2021) 092301

Charm hadrochemistry: Λ_c

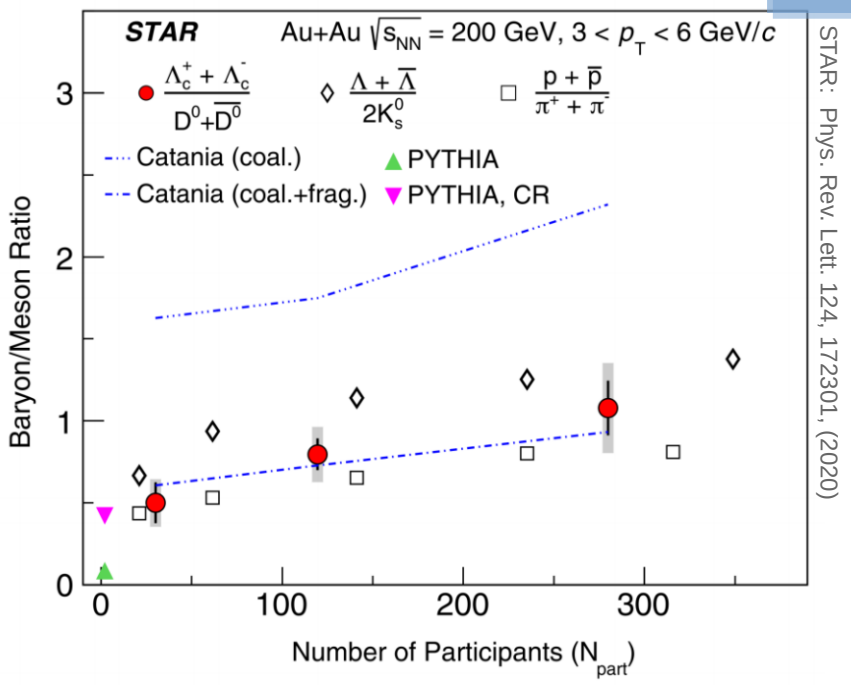
- Recombination: enhanced production of baryon w.r.t. mesons
- **Enhancement of Λ_c/D^0** w.r.t. pp collisions → recombination with light quarks, radial flow push ?
- Centrality dependence described by model with **fragmentation and coalescence**

LHC



ALICE, arXiv:2112.08156

RHIC



Total charm production cross section

- Total charm production cross section per binary collision in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.
  - **Consistent with p+p collisions.**

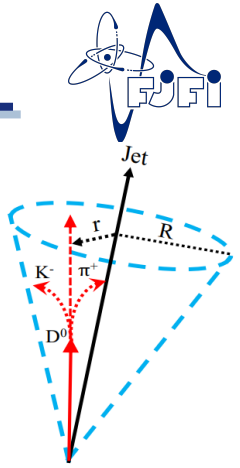
Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3*
	D_s [2]	15 ± 2 ± 4
	Λ_c [3]	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV [4]	**Total**	130 ± 30 ± 26

** Preliminary $D^{+/-}$ results*
*** Λ_c cross section derived from Λ_c/D^0 yield ratio*

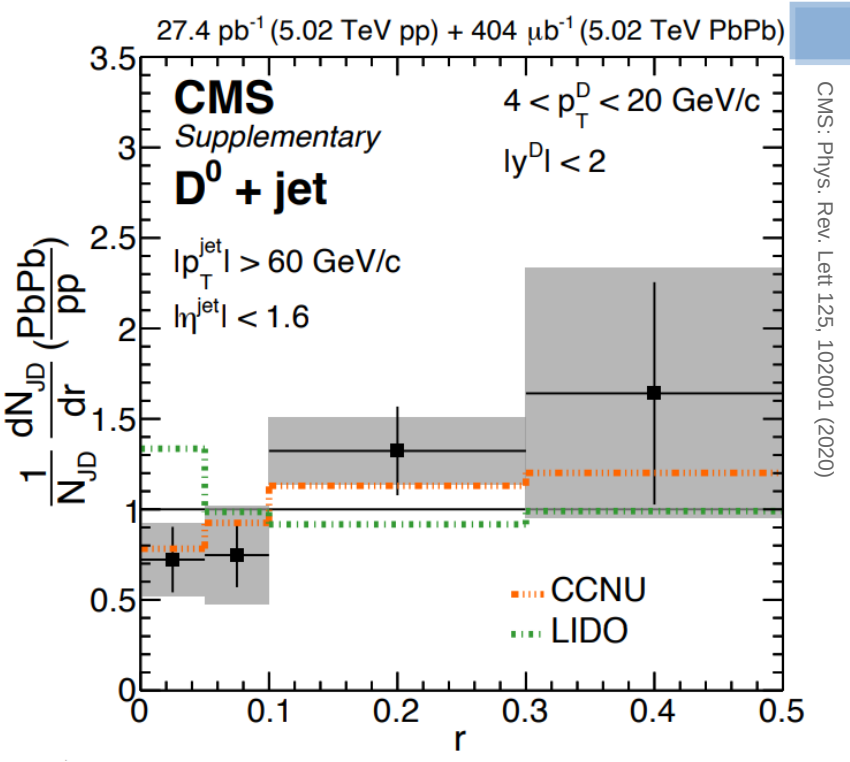
D^0 [1] STAR, Phys. Rev. C 99 (2019) 034908
D_s [2] STAR, Phys. Rev. Lett. 127 (2021) 092301
Λ_c [3]STAR, Phys. Rev. Lett. 124 (2020) 172301
p+p [4] STAR, Phys. Rev. D 86 (2012) 072013

Radial profile of D in jets

- Diffusion of charm w.r.t jet axis → interaction mechanisms between hq and medium, coll. vs rad. en. loss, sensitivity to D_s
- Hint of broader radial distribution in AA w.r.t. pp

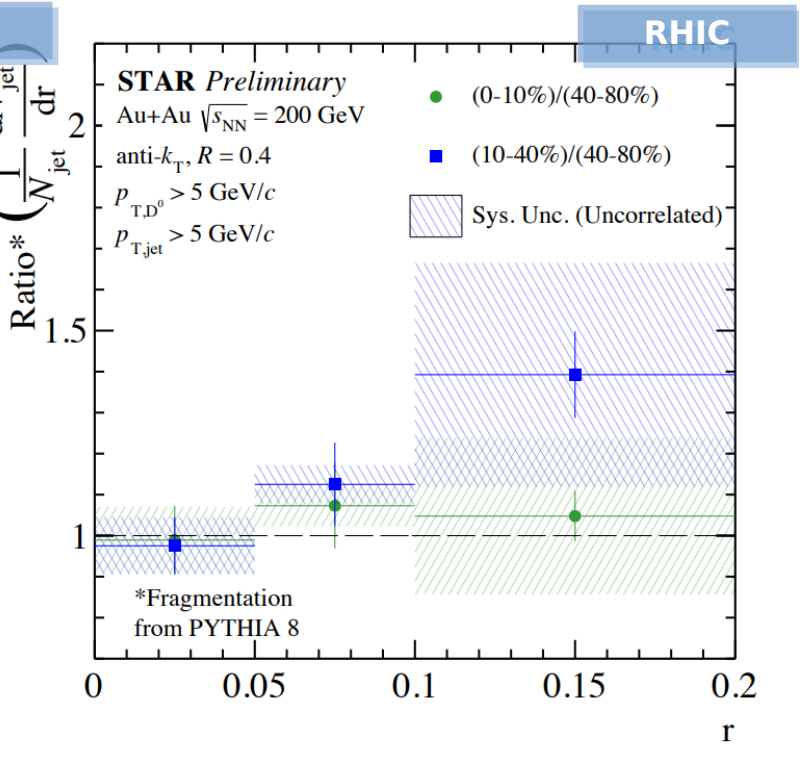


LHC



CMS: Phys. Rev. Lett 125, 102001 (2020)

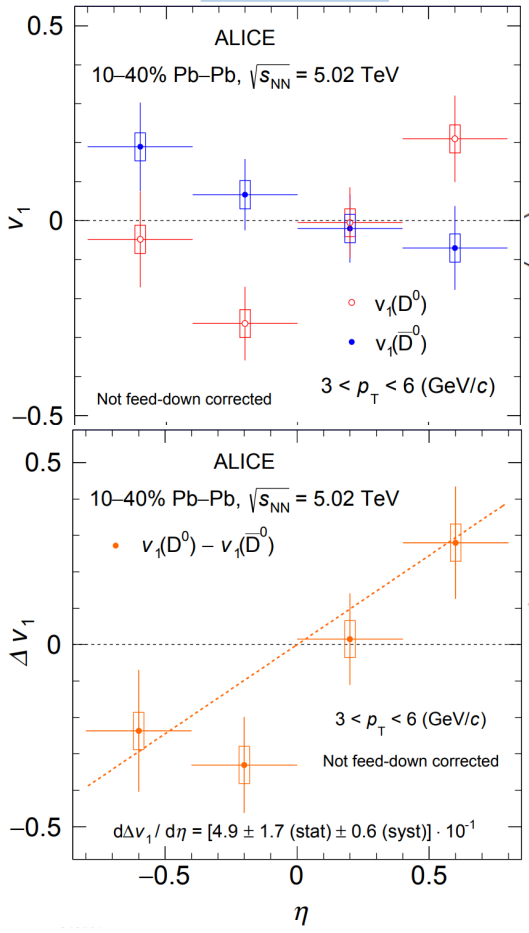
RHIC



D^0 directed flow, v_1

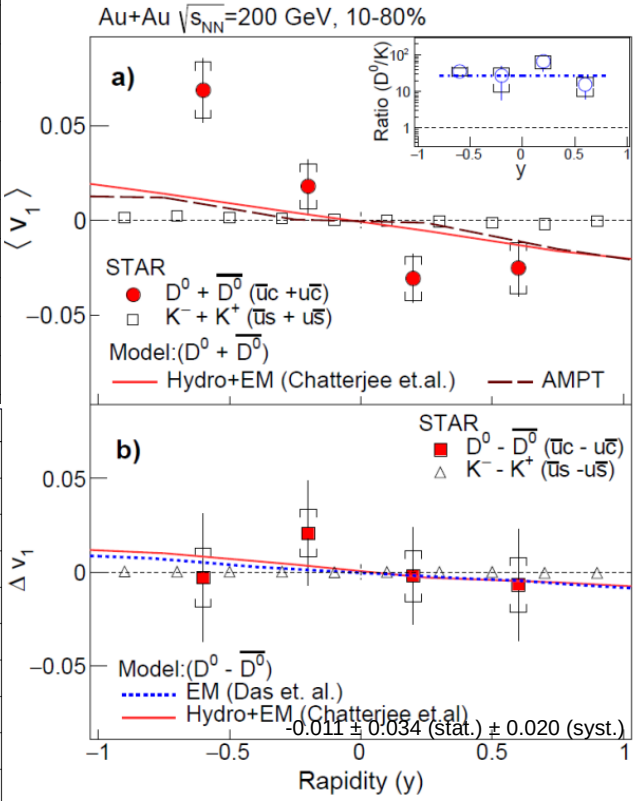
- **Large D^0 directed flow v_1 vs y**
- **Interplay between effects of the rapidly decreasing magnetic field and the initial tilt of the source**
- dv_1/dy slope:
  - RHIC: Negative, similar for D^0 and D^{0bar}
  - LHC: Positive for D^0 and negative for D^{0bar}
- **$d\Delta v_1/dy(D^0\text{-}D^{0bar})$ slope:** negative at RHIC, positive and larger at LHC
- Tilt dominance at RHIC ?
- Trend compatible with hydrodynamic model with EM, but larger v_1 magnitude

LHC



ALICE: Phys. Rev. Lett. 125, 022301 (2020)

RHIC



STAR: Phys. Rev. Lett. 123, 162301 (2019)

Summary

- Heavy quarks interact with the medium via collisional and radiative processes
- Indications of mass dependent energy loss
- Strong coupling of heavy-flavour quarks with the medium from 54.4 GeV up to 5.02 TeV, HF quarks participate in the collective motion
- Evidence of charm quark hadronization via coalescence

- Measurements are getting more precise and differential → constraints on theoretical models and extraction of the medium properties

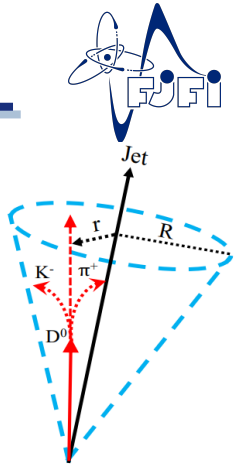
Thank you !

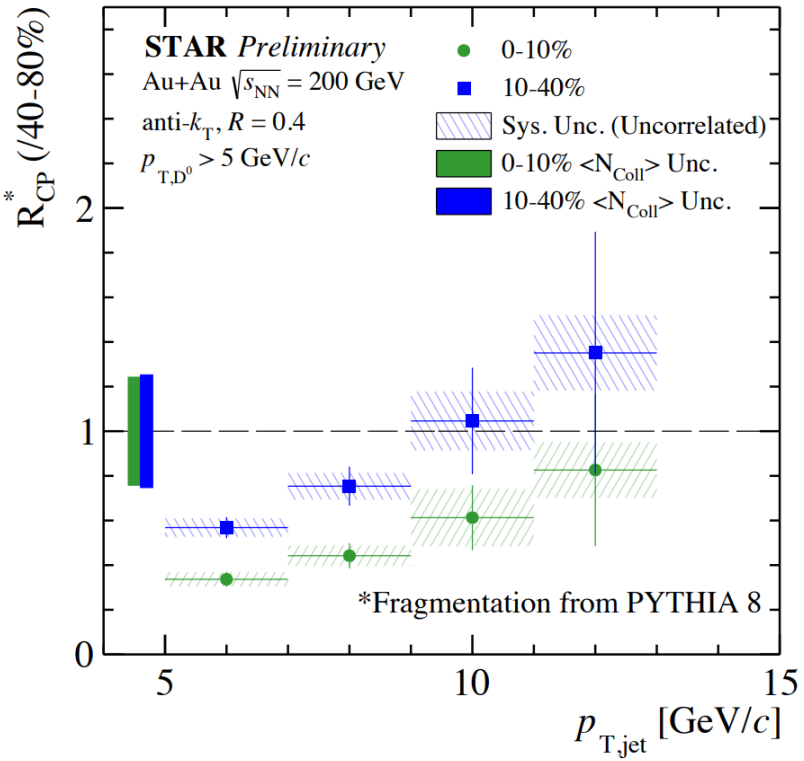
This work was supported by grant from The Czech Science Foundation, grant number: GJ20-16256Y

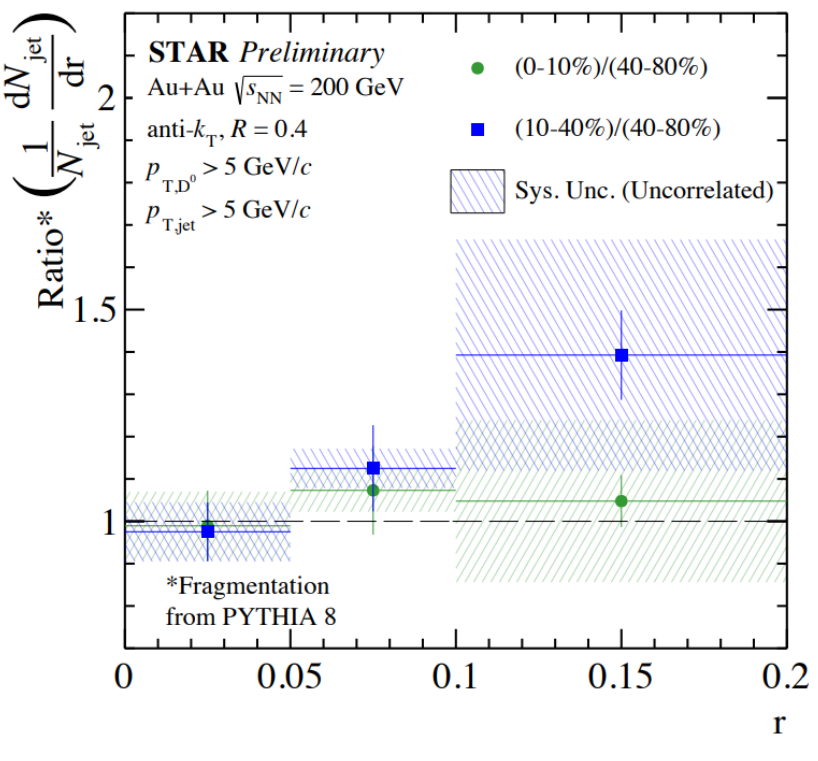
Backup

D^0-meson tagged jets

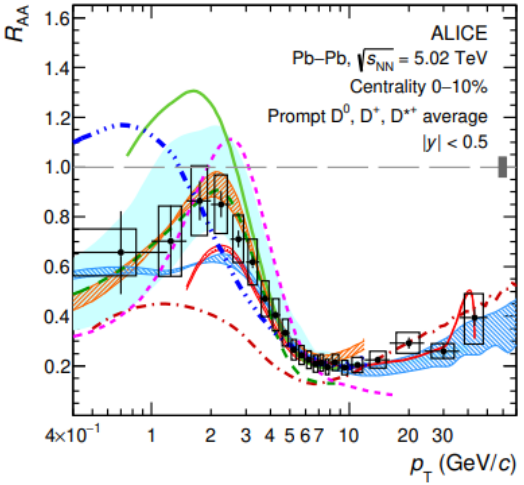
- R_{CP}: **strong suppression at low jet p_T**, hint of increasing trend.
- Ratio of radial distributions consistent with unity – hint of broader distribution. Potential to go to lower D^0 p_T.

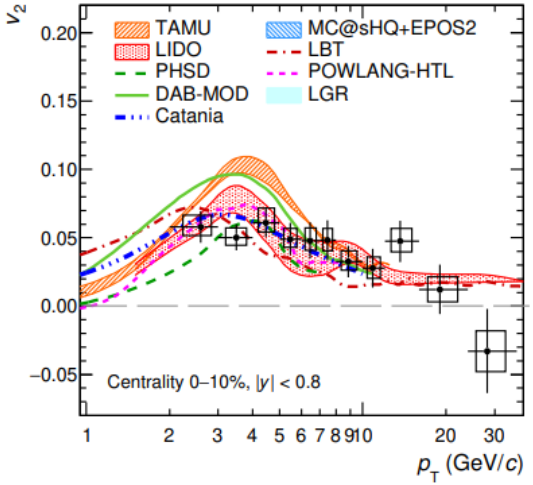


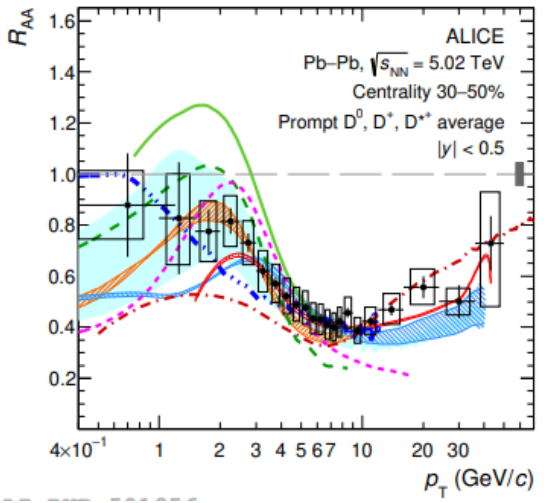


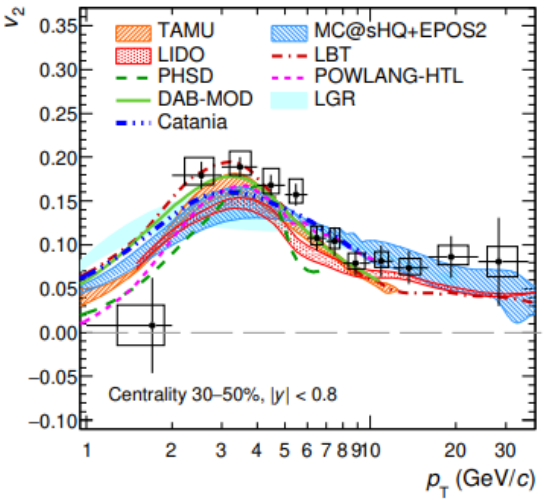


Constraining D_s



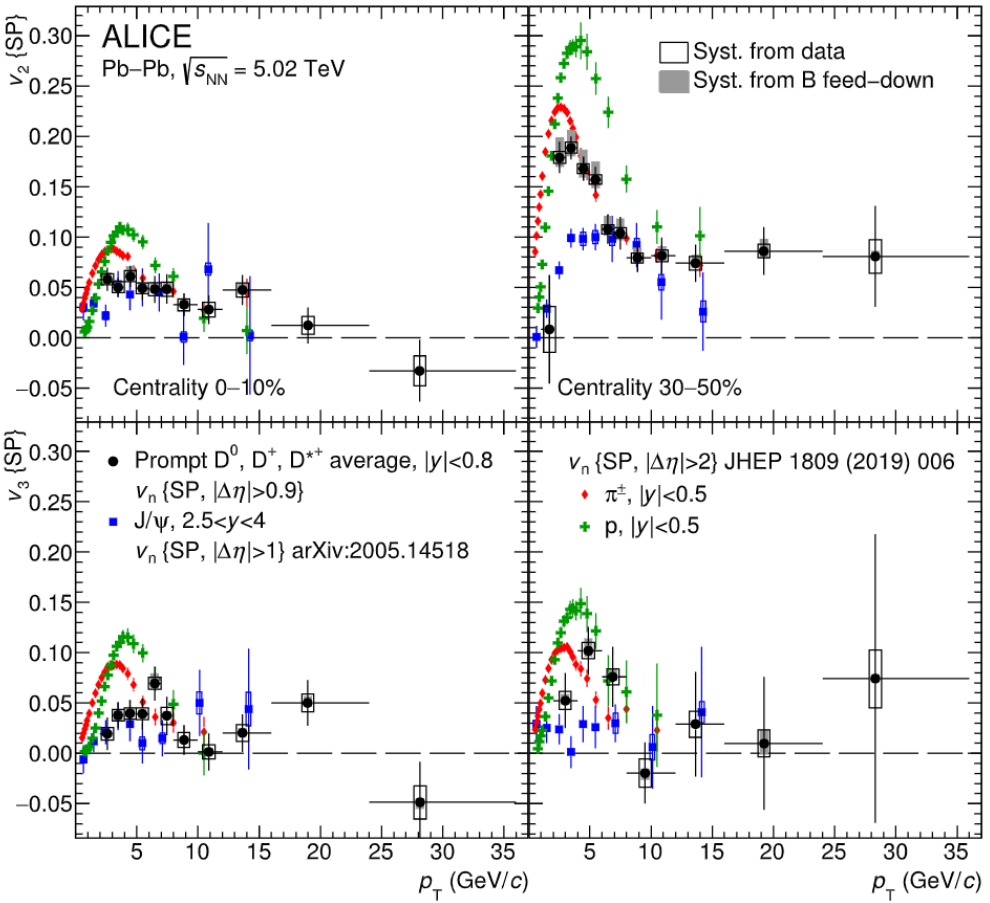


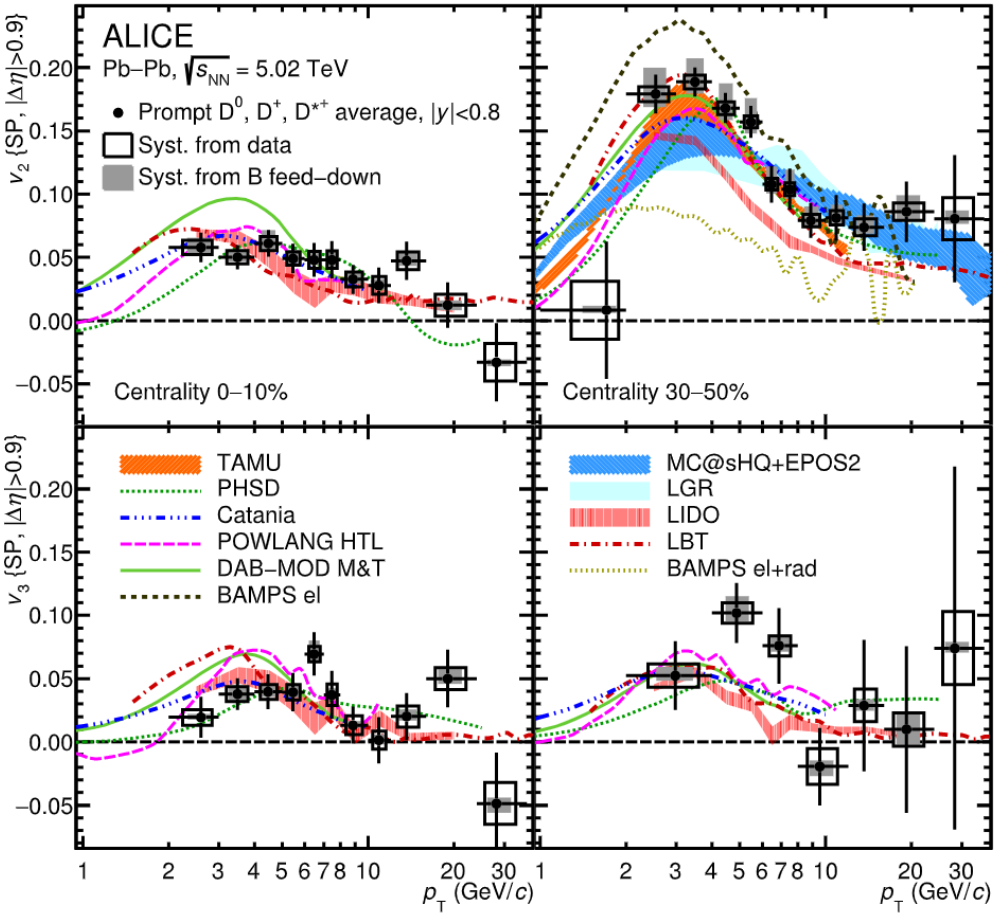




ALICE, JHEP01 (2022) 174

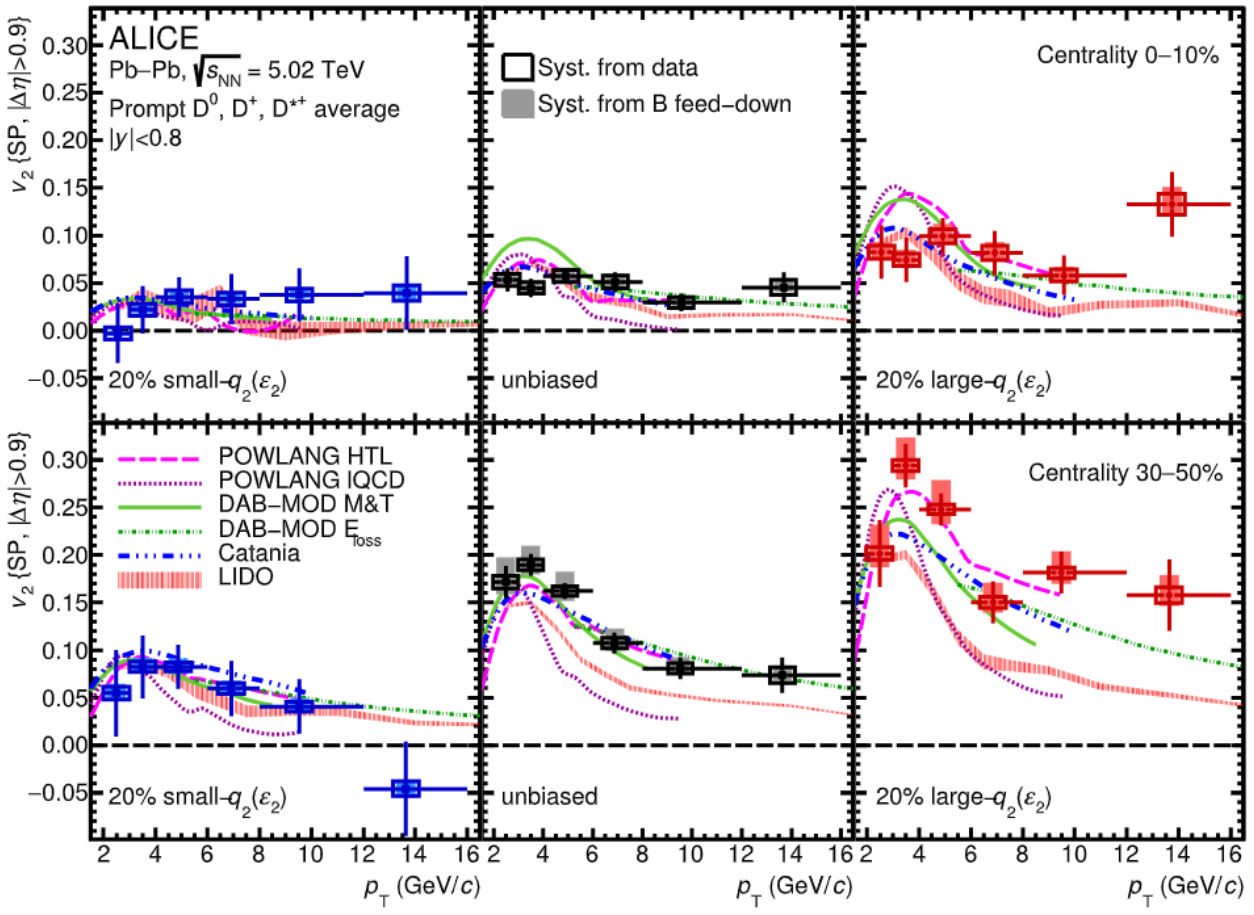
D v_2 and v_3





ALICE, Phys. Lett. B 813 (2021) 136054

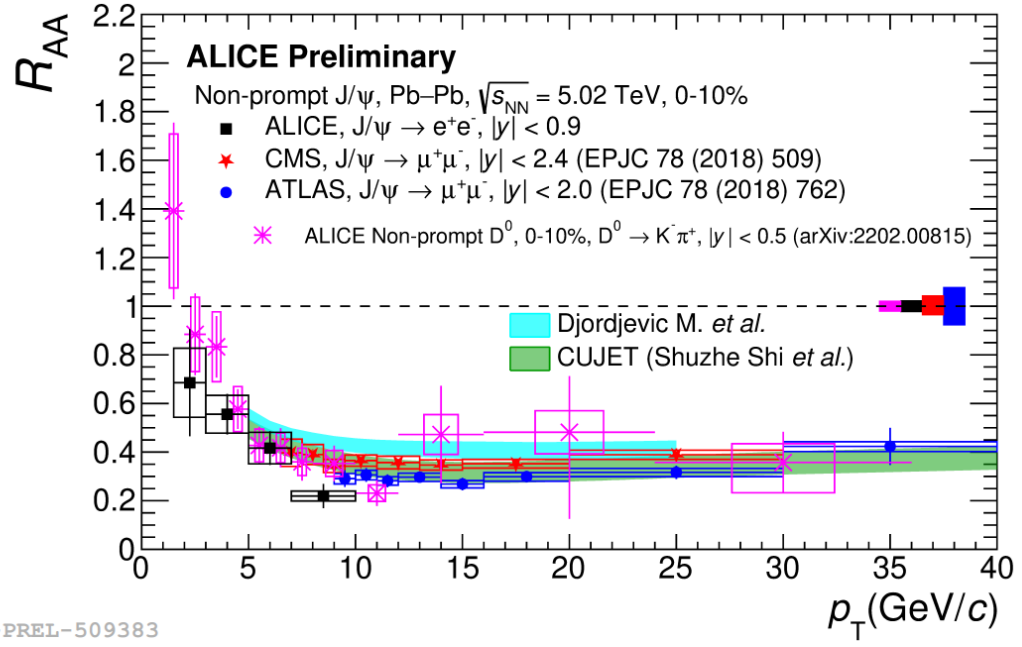
D v_2 EsE

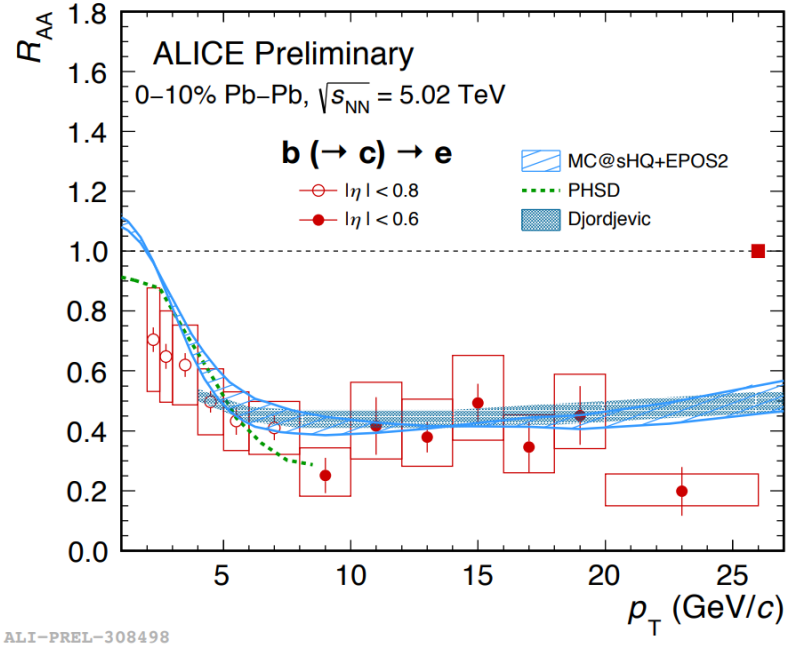


ALICE, Phys. Lett. B 813 (2021)

Open beauty R_{AA}

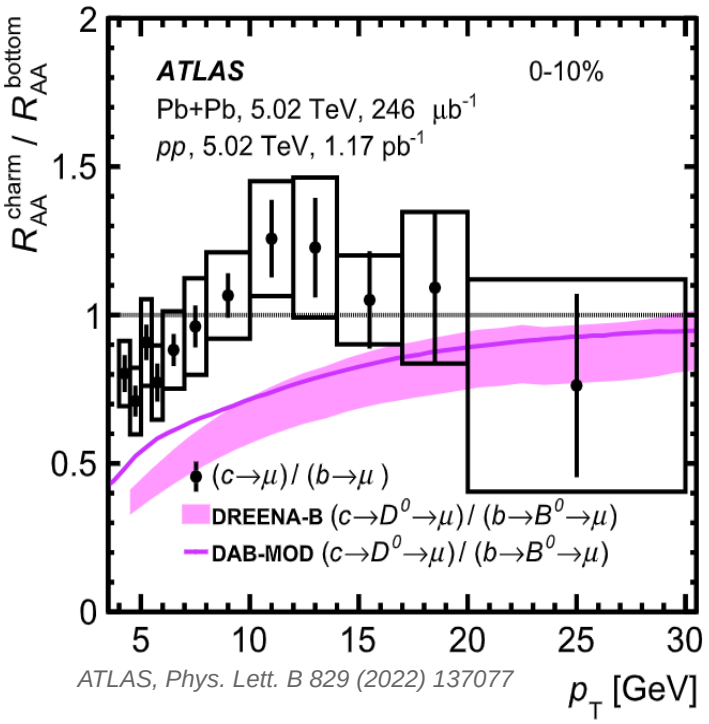
- Access to low p_T beauty hadron R_{AA}



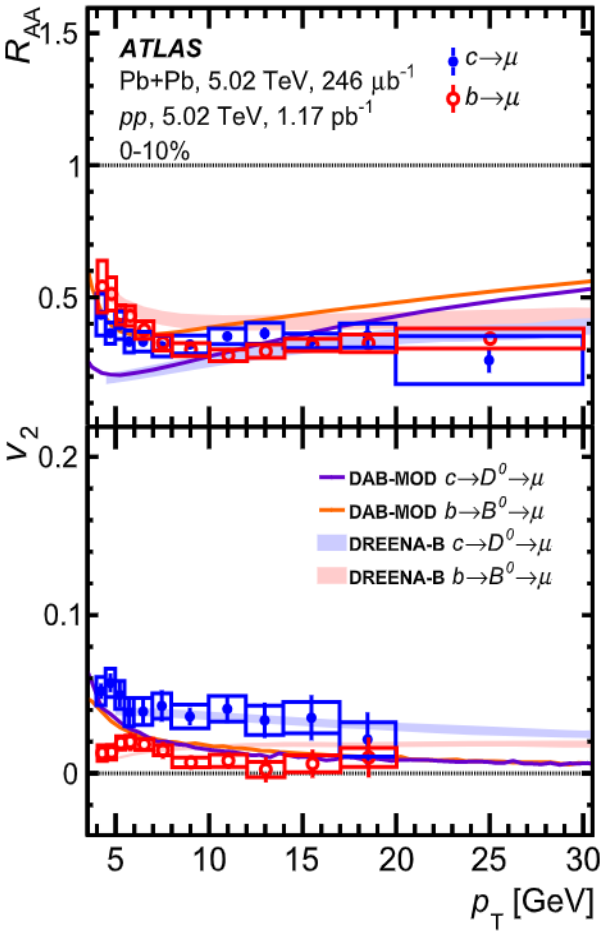


Charm vs beauty R_{AA} at LHC

- **Beauty R_{AA} > charm R_{AA}** at intermediate p_T → suggesting larger en. loss for charm quarks
- Tension between models and ATLAS muon data

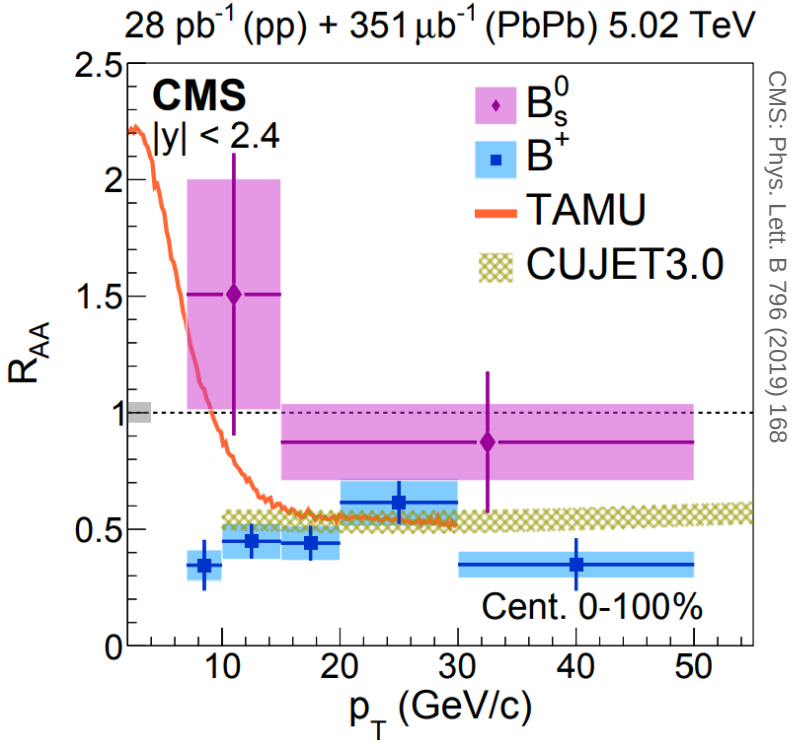


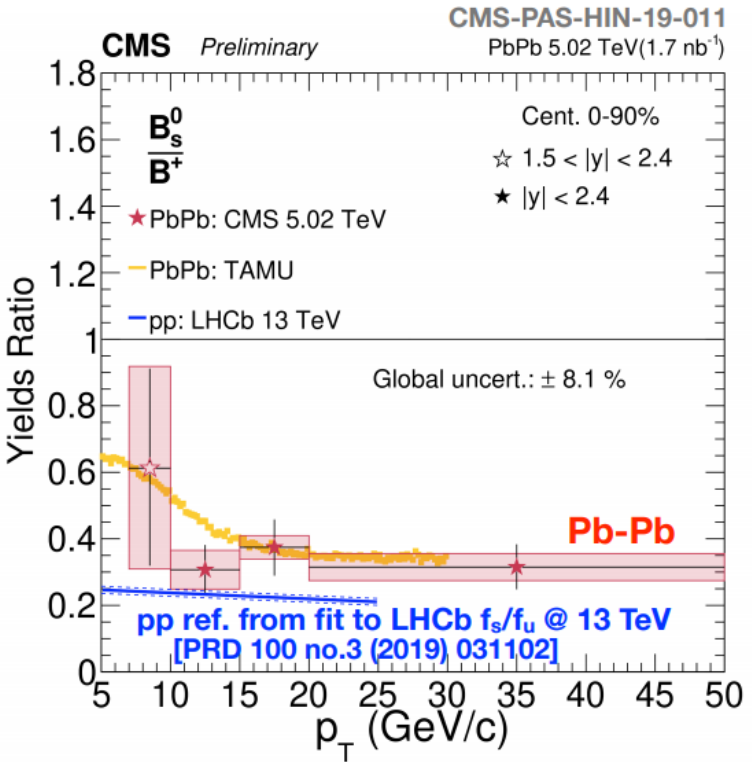
ATLAS, Phys. Lett. B 829 (2022) 137077

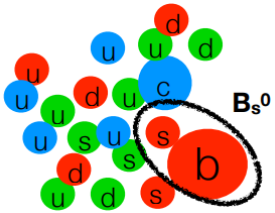


B_s, B_c R_{AA} in AA

- Hint of an enhancement of the B_s^0/B^+ ratio in PbPb w.r.t pp



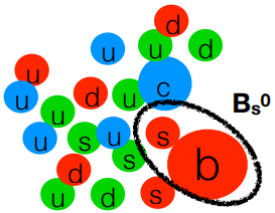


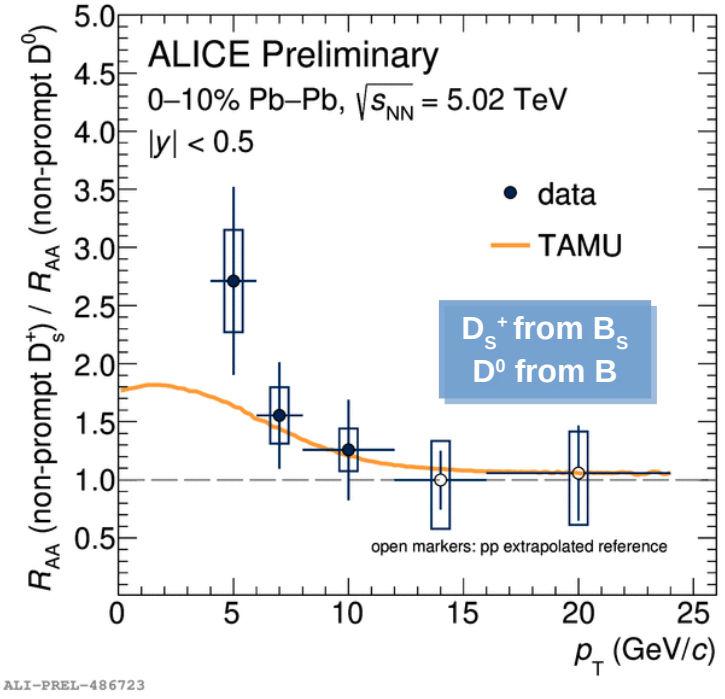


- Upcoming LHC Run3,4 will provide more information on beauty quark hadronization

B_s R_{AA} in AA

- Hint of enhancement of the B_s^0 in PbPb w.r.t pp at low p_T → beauty-quark hadronisation via coalescence

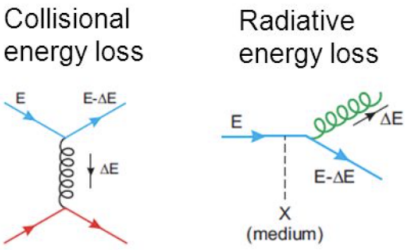


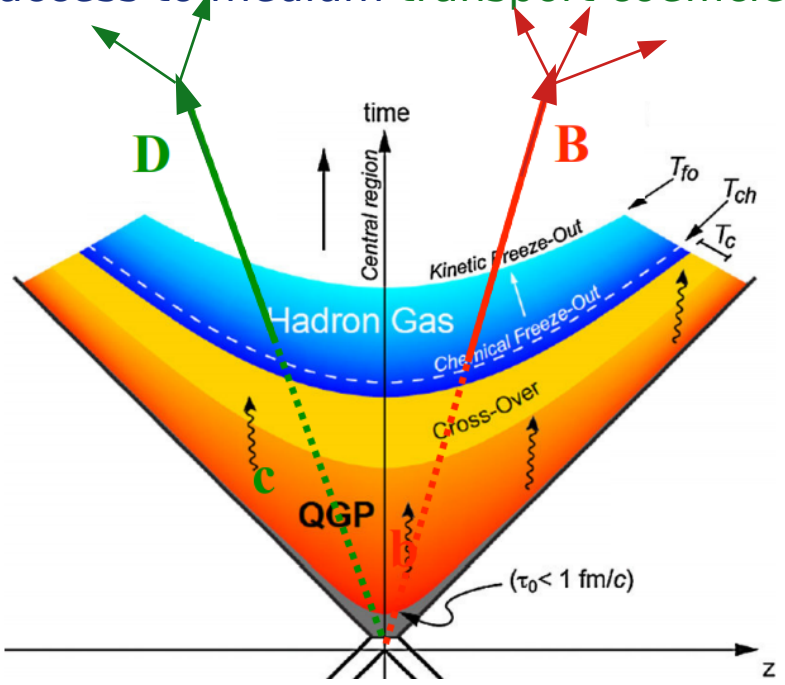


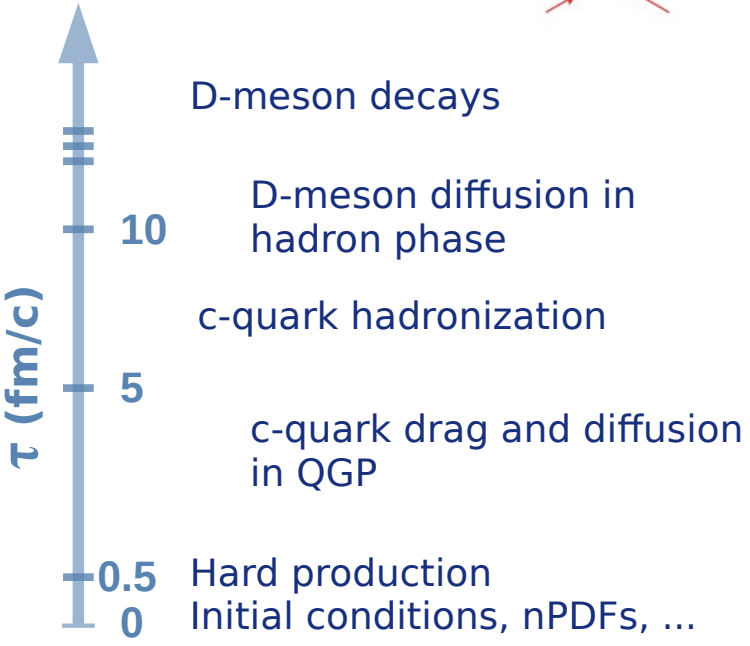
- Upcoming LHC Run3,4 will provide more information on beauty quark hadronization

Heavy flavour in HI collisions

- Heavy-flavour quarks (c,b), $m_Q >> \Lambda_{QCD}, T_{QGP}$: produced in initial hard scatterings, no thermal production
- Interactions with the medium → parton energy loss, flow
  - ➔ Constraints on energy loss mechanisms (collisional/radiative process)
  - ➔ Direct access to medium transport coefficient: $D_s(2\pi T)$

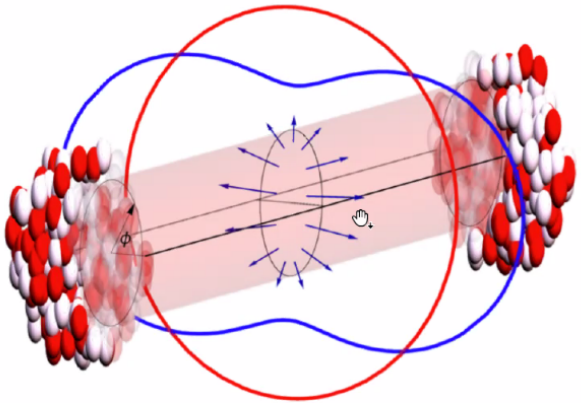




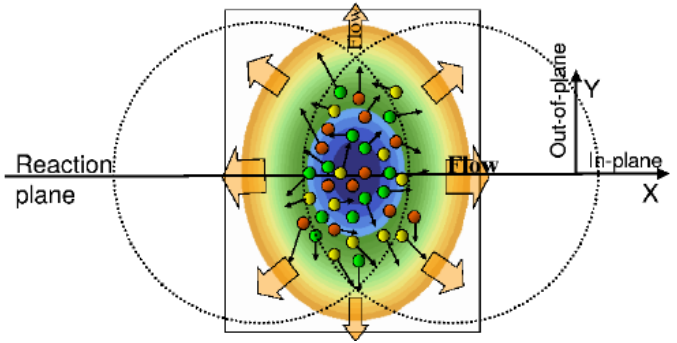


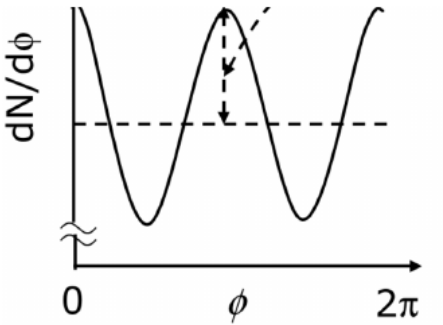
Anisotropic Flow in HI

- Collision geometry: initial spacial anisotropy
- Multiple interactions between the constituents of the medium → azimuthal momentum space anisotropy of particle emission, flow

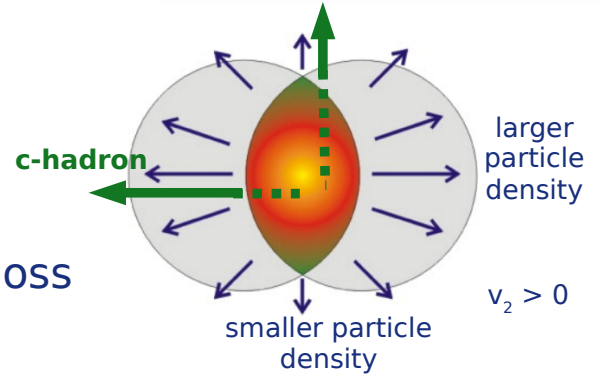


$$\frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^2N}{2\pi p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_{EP})\right)\right] \qquad v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$





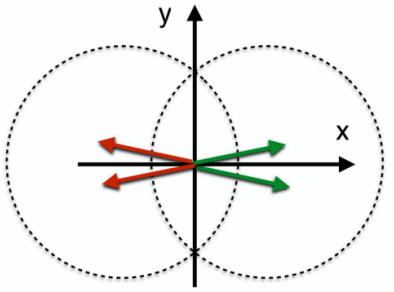
- Heavy-flavour elliptic flow, v_2
  - Low p_T: Collective motion of the system, hq thermalization ?
  - High p_T: Path-length dependent parton energy loss



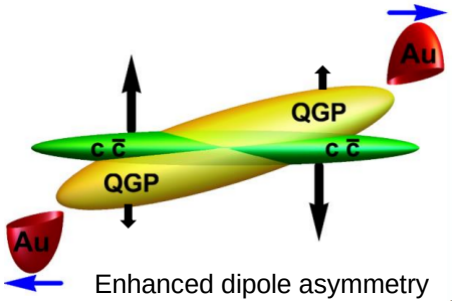
Directed flow, v_1

- Insights into initial tilt of matter and strong EM field in non-central HI collisions

$$v_1 = \langle cos(\phi_p) \rangle = \langle p_x / p_T \rangle$$

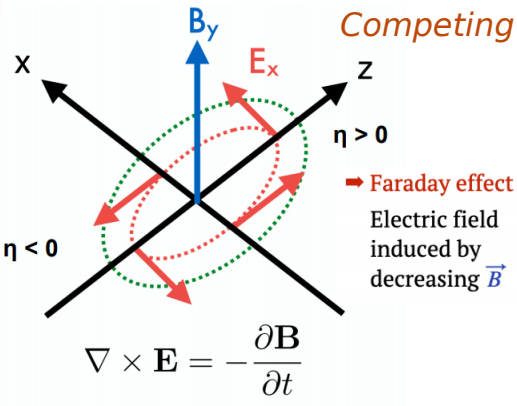


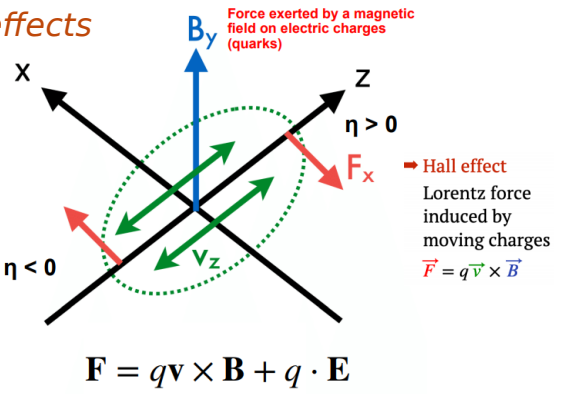
Tilt



Enhanced dipole asymmetry

EM field
Charged-dependent v_1,
Sensitive to QGP conductivity





- v_1: sensitivity to the three-dimensional spatial profile of initial conditions and pre-equilibrium early time dynamics in the evolution

- Heavy-quarks:
  - produced early, shifted from the bulk
  - formation time comparable to when B is maximum