10th International Workshop on Charm Physics (CHARM 2020)

Open charm experimental overview

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GAČR CZECH SCIENCE FOUNDATION

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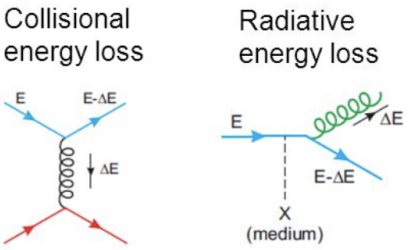
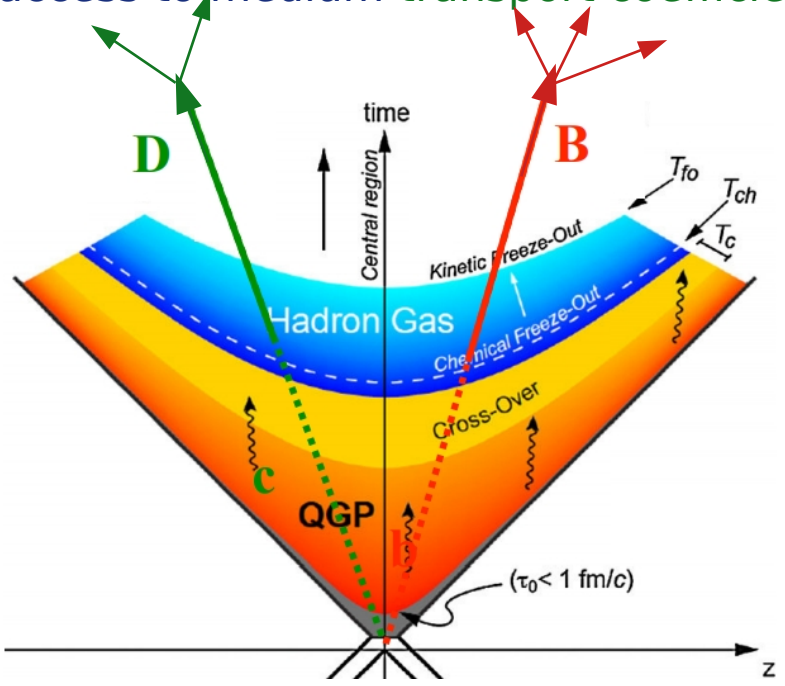
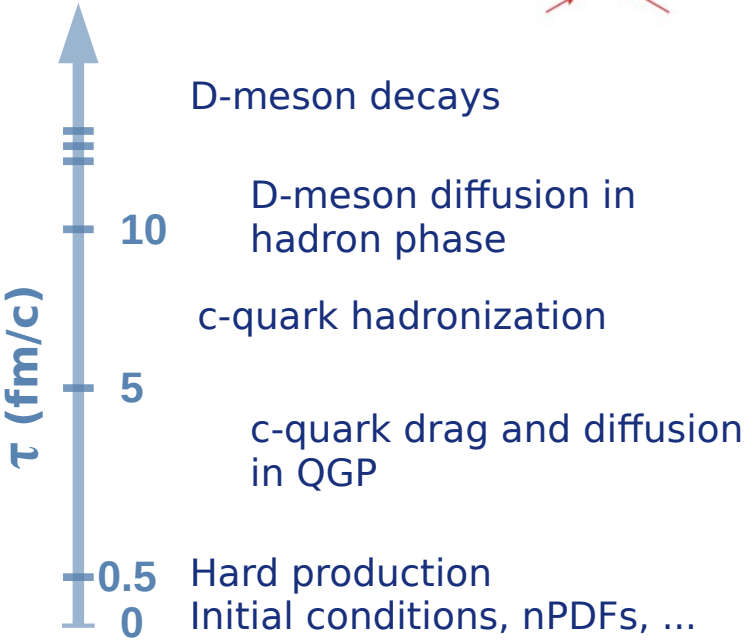
FJFI
CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Heavy flavour in HI collisions

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







Hadronization

$$\frac{\mathrm{d}\sigma^{\mathrm{H_c}}}{\mathrm{d}p_{\mathrm{T}}} = PDF(x_1\mu_{\mathrm{F}})PDF(x_2\mu_{\mathrm{F}}) \otimes \frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(x_1, x_2, \mu_{\mathrm{R}}, \mu_{\mathrm{F}}) \otimes D_{\mathrm{c}\to\mathrm{H_c}}(z = p_{\mathrm{H_c}}/p_{\mathrm{c}}, \mu_{\mathrm{F}})$$

- Fragmentation

  $c \to D^0, D^*, D_s, \Lambda_c$

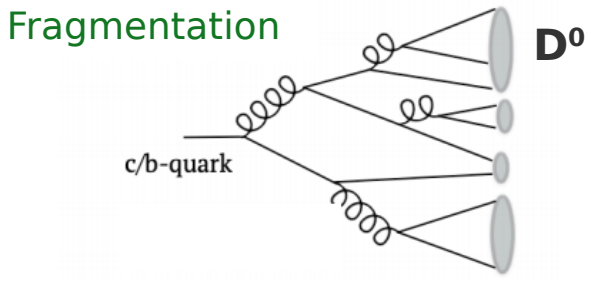
  assumed universal across coll. systems and en., from vacuum e^+e^-, ep data

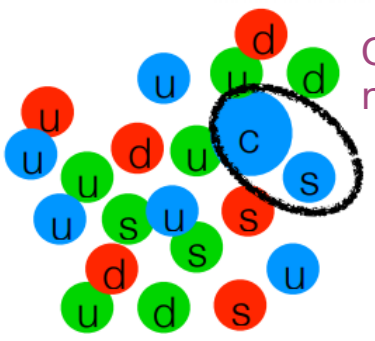
- Coalescence

  $c + q(s) \to D\ (D_s), D^*, \ldots$

  $c + q + q(s) \to \Lambda_c (\Xi_c), \ldots$

  depends on phase-space of surrounding q(s) quarks in medium

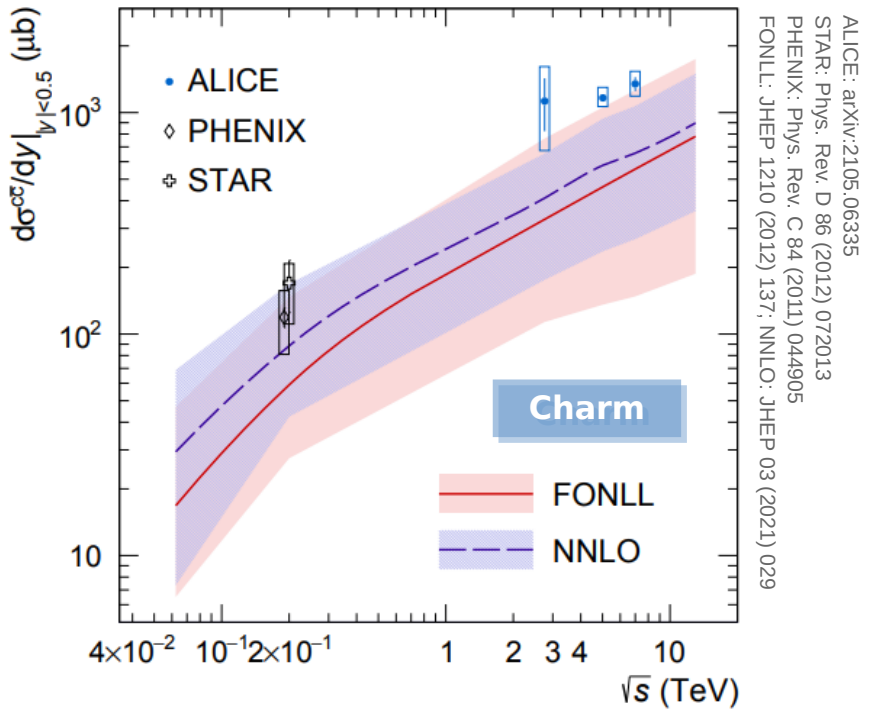




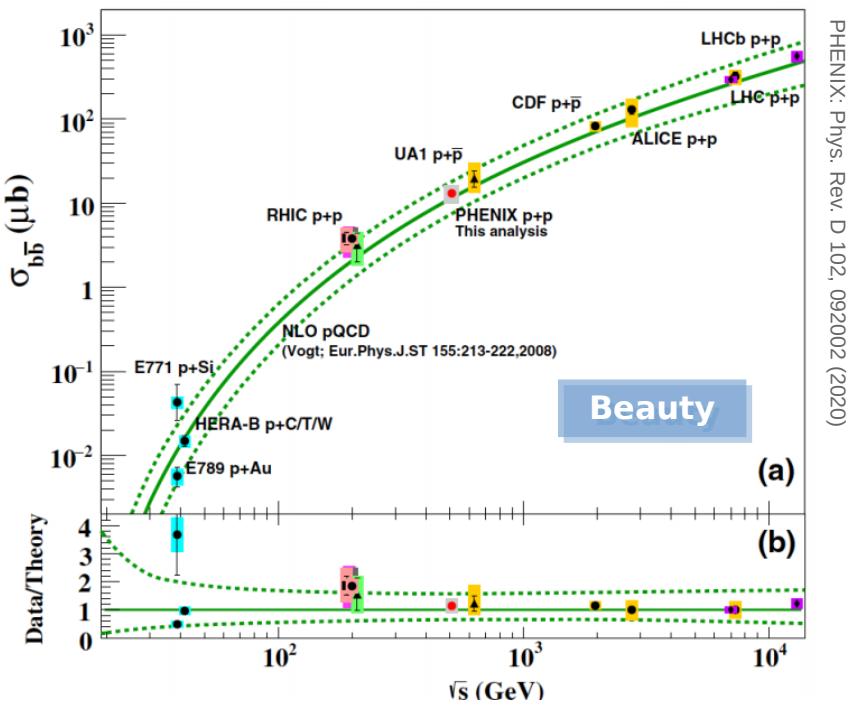
➔ D_s, B_s, Λ_c, ... : good probes of in-medium hadronization

Charm and beauty in pp

- Reference for modificaitons in HI collisions, test of pQCD
- FONLL and NNLO pQCD calculations:
  - Charm cross section on the upper edge
  - Beauty cross section well described



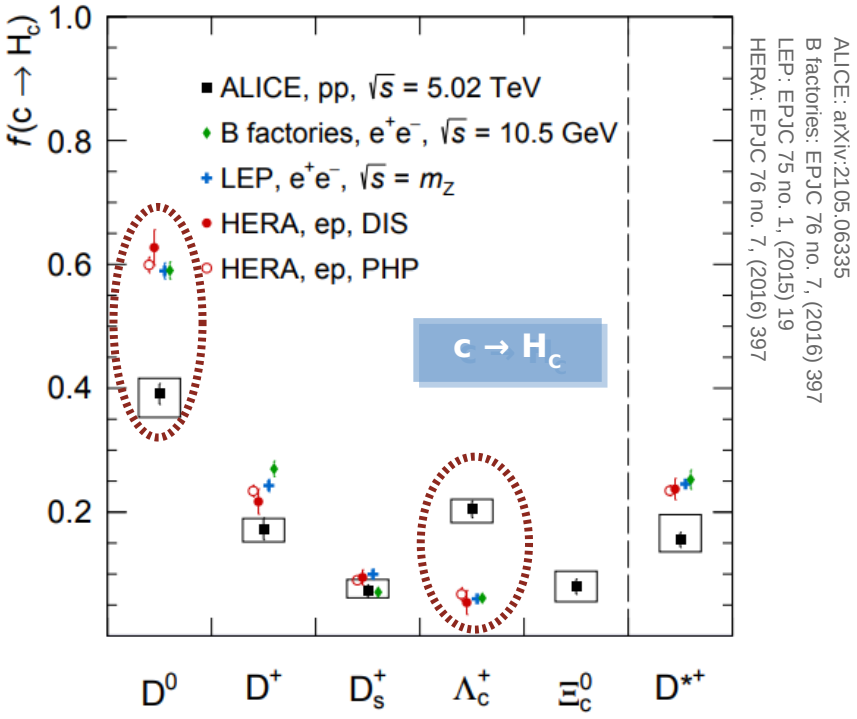
ALICE: arXiv:2105.06335
STAR: Phys. Rev. D 86 (2012) 072013
PHENIX: Phys. Rev. C 84 (2011) 044905
FONLL: JHEP 1210 (2012) 137; NNLO: JHEP 03 (2021) 029

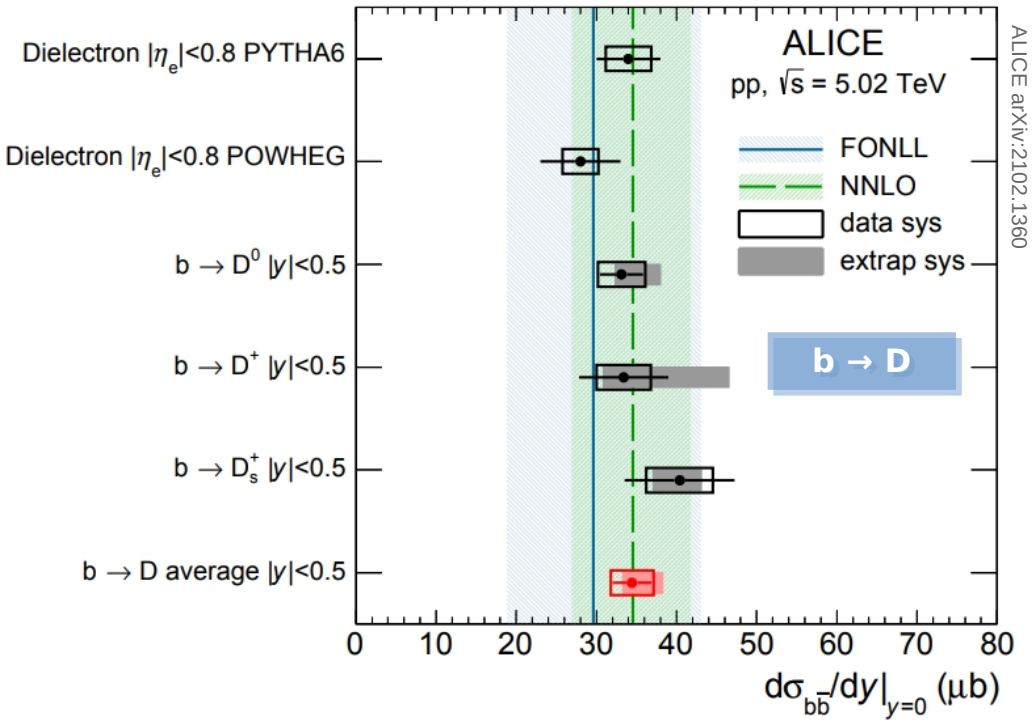


PHENIX: Phys. Rev. D 102, 092002 (2020)

Fragmentation fractions in pp

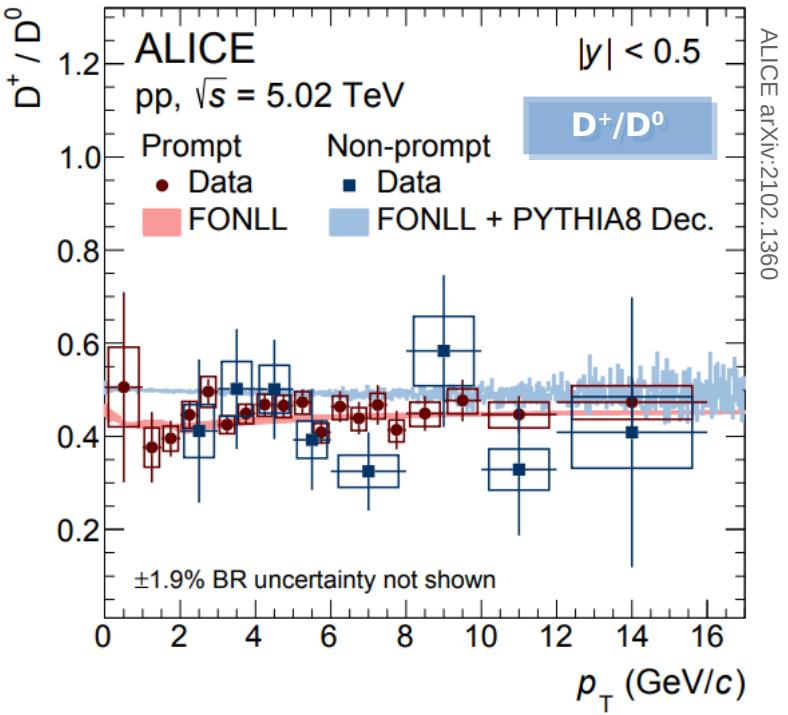
- **Charm fragmentation not universal**
- b → D consistent with FONLL and NNLO

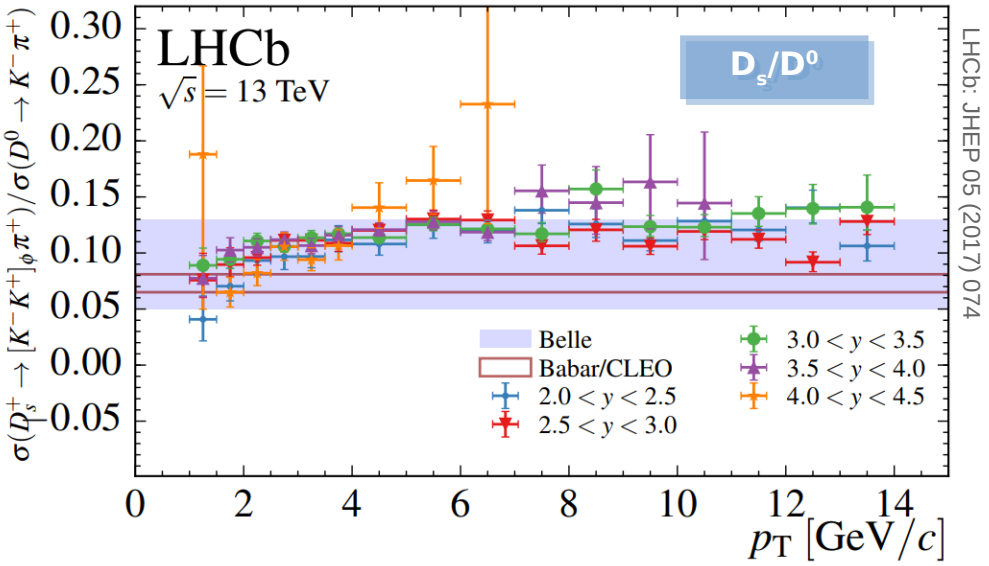




Meson-to-meson yield ratios in pp

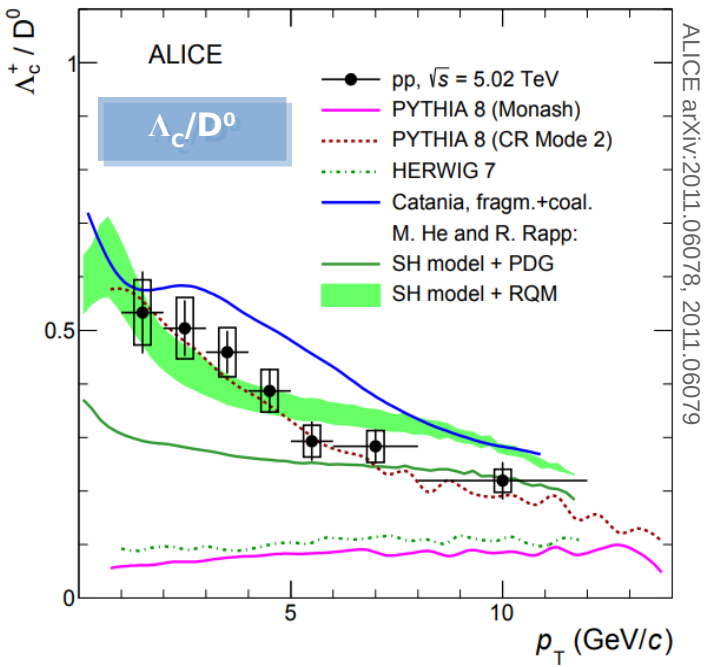
- Meson-to-meson yield ratios described well by models and e^+e^- measurements
  - Both prompt and non-prompt
  - ~ Flat p_T dependence
  - No evidence of strangeness modification

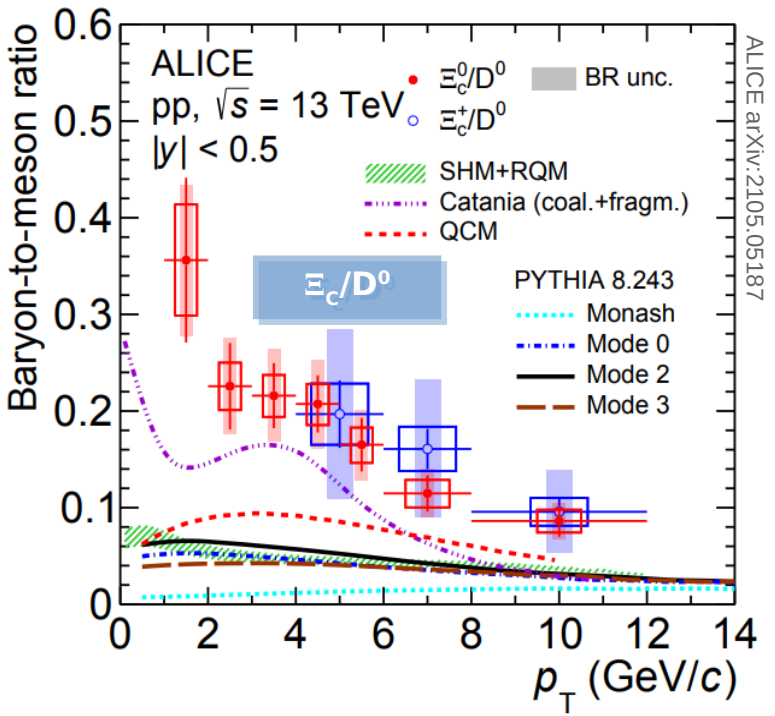




Baryon-to-meson yield ratios in pp

- **Enhancement of baryon-to-meson yield ratios – disagreement with models using e^+e^- fragmentations**. Better agreement with data:
  - PYTHIA 8 with Colour Reconnection modes – does not describe Ξ_c (Ω^0_c)/D^0
  - Statistical hadronization + RQM model - does not describe Ξ_c(Ω^0_c)/D^0
  - **Fragmentation + coalescence production in pp – Catania model** (underestimates Ω^0_c/D^0)



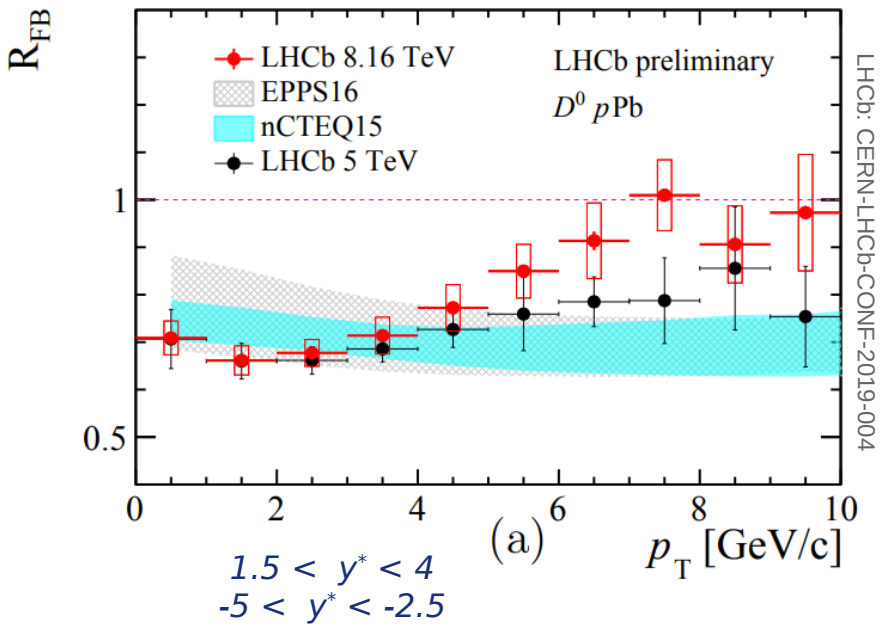


PYTHIA 8 Monash: Eur. Phys. J. C 74 (2014) 3024
PYTHIA 8 Mode2: JHEP 08 (2015) 003
HERWIG 7: Eur. Phys. J. C58 (2008) 639–707
POWHEG: JHEP 09 (2007) 126
GM-VFNS: Phys. Rev. D 101 (2020) 114021
M. He and R. Rapp: PLB 795 (2019) 117-121
RQM: Phys. Rev. D 84 (2011) 014025
Catania: arXiv:2012.12001, EPJC 78 no. 4, (2018) 348

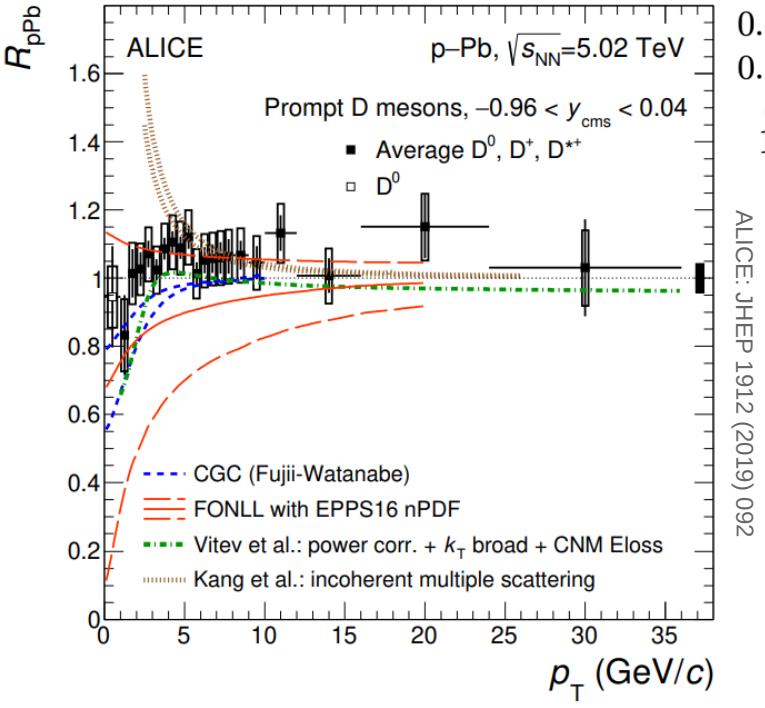
Charm in pA

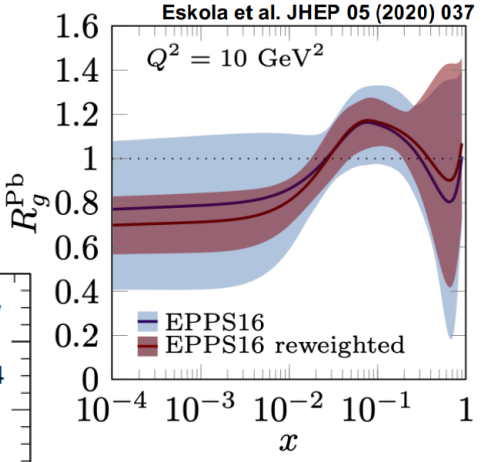
- Control experiment for cold nuclear matter effects
  - Constraints on nPDF
- **nPDFs with shadowing describe low p_T D-meson data**

Forward/ Backward y



Mid-y



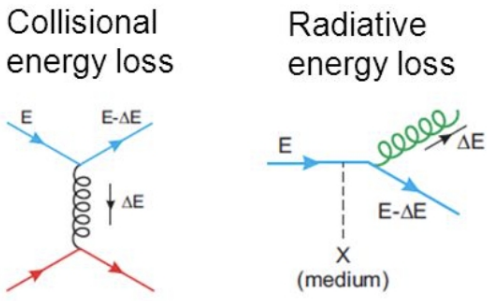


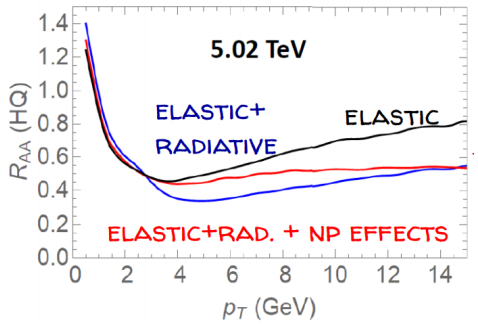
Heavy Ion Collisions

Heavy-flavour suppression in HI

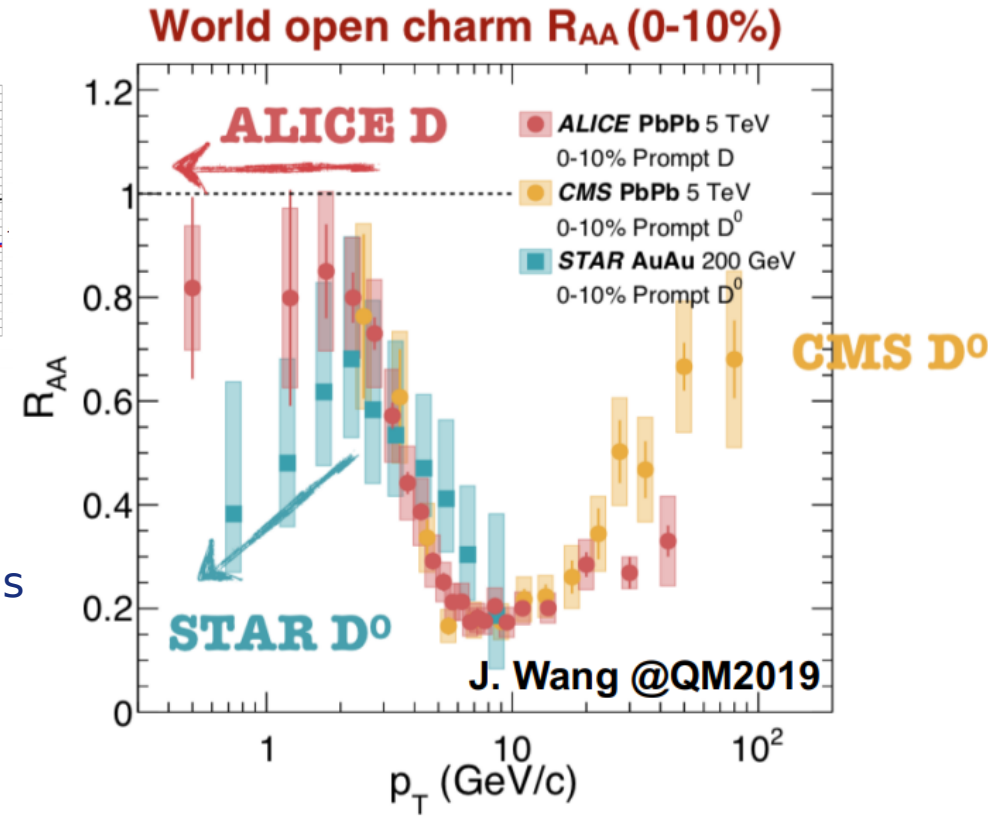
- Interplay between collisional and radiative processes
  - Low p_T: elastic interactions dominate
  - High p_T: radiative en. loss

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$





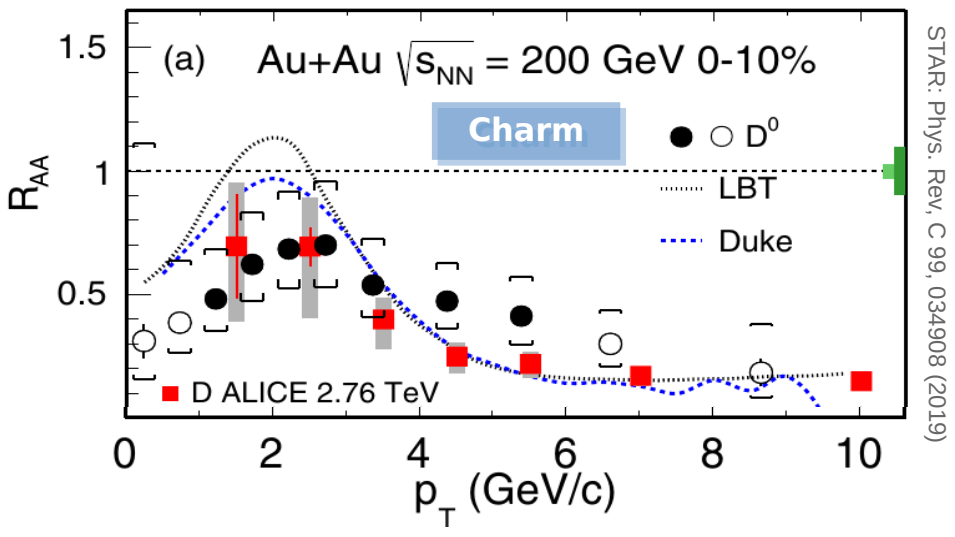
arXiv:2003.12536

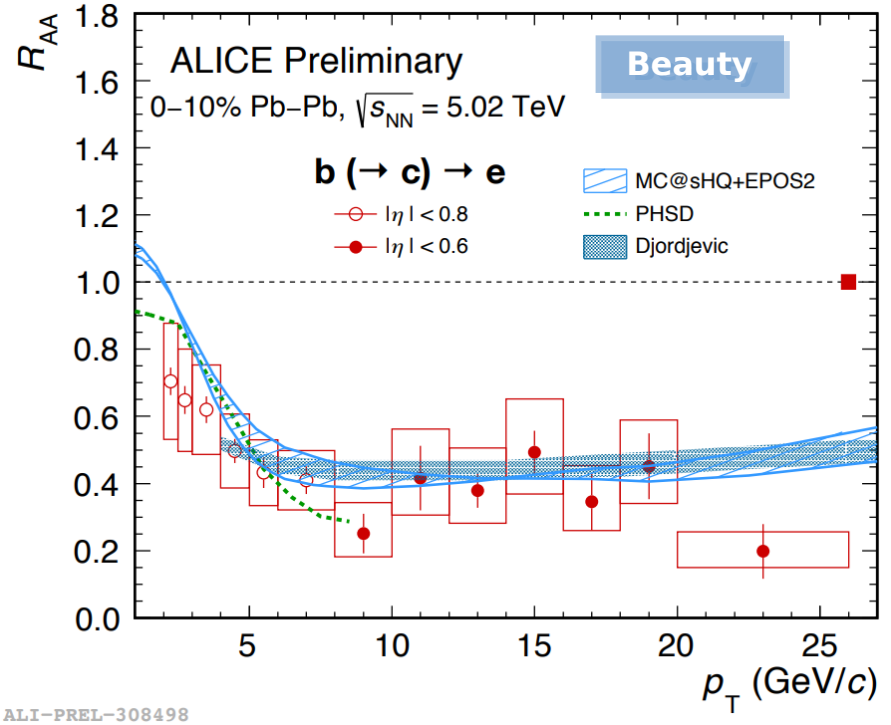


- R_{AA}: different regimes can be identified
- Strong charm suppression in central AA collisions
- Low-p_T R_{AA} bump
  - Flow effect
  - Recombination with light quarks

Charm and beauty R_{AA} vs models

- Interplay between collisional and radiative energy processes
- **Charm and beauty suppression described by models with collisional and radiative en. loss**



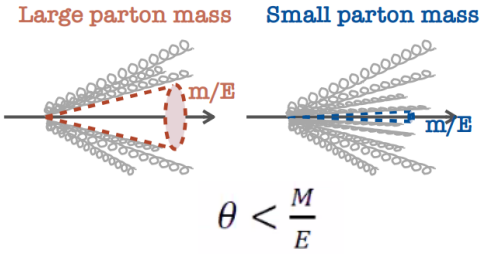


Flavour dependence

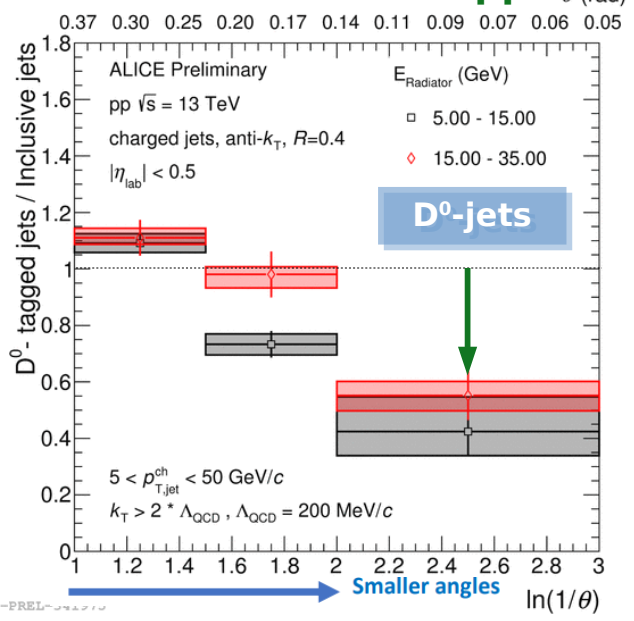
- Radiative en. loss
  - Dead cone effect: suppression of small-angle gluon radiation

$$\Delta E_{gluons} > \Delta E_{light\text{-}quarks} > \Delta E_{heavy\text{-}quarks}$$

$$\Delta E_{c\text{-}quarks} > \Delta E_{b\text{-}quarks}$$



First direct observation of dead-cone effect in pp

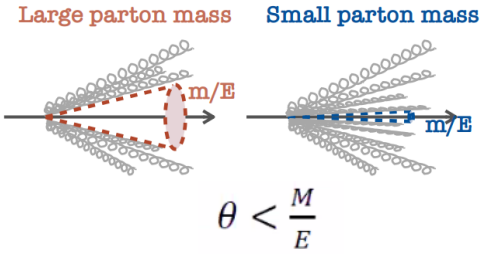


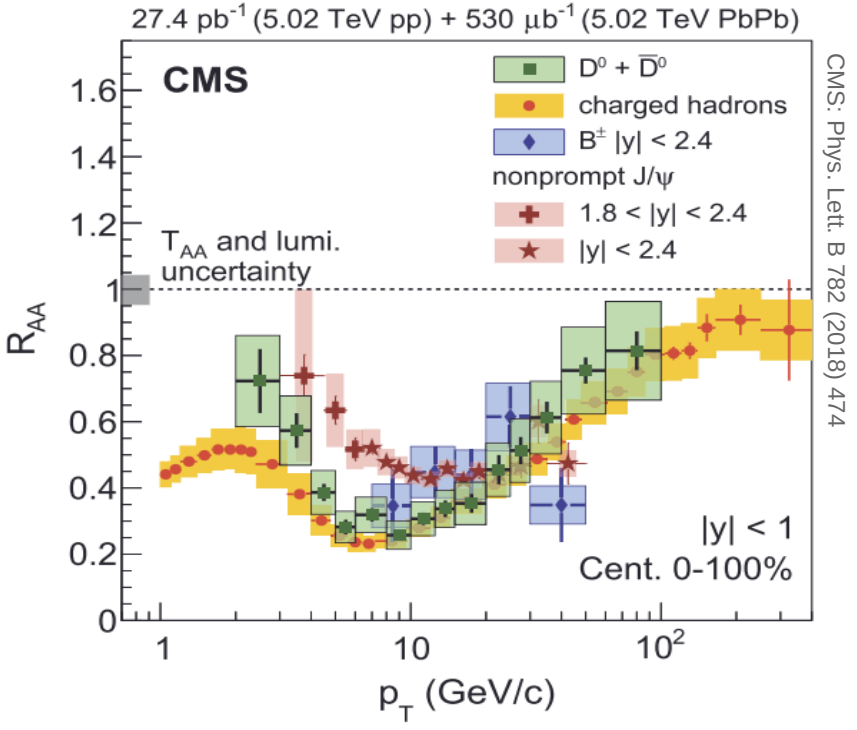
Flavour dependence

- Radiative en. loss
  - Dead cone effect: suppression of small-angle gluon radiation

$\Delta E_{gluons} > \Delta E_{light\text{-}quarks} > \Delta E_{heavy\text{-}quarks}$

$\Delta E_{c\text{-}quarks} > \Delta E_{b\text{-}quarks}$ → $R_{AA}^{c\text{-}hadron} > R_{AA,}^{b\text{-}hadron}$





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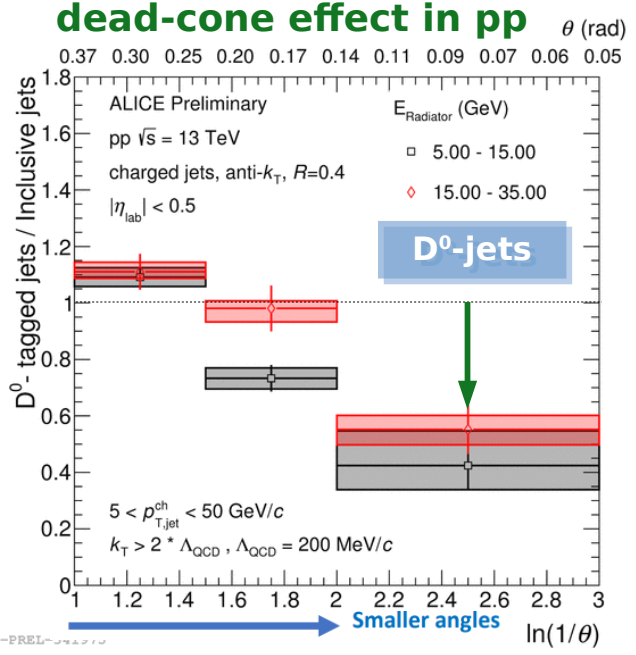
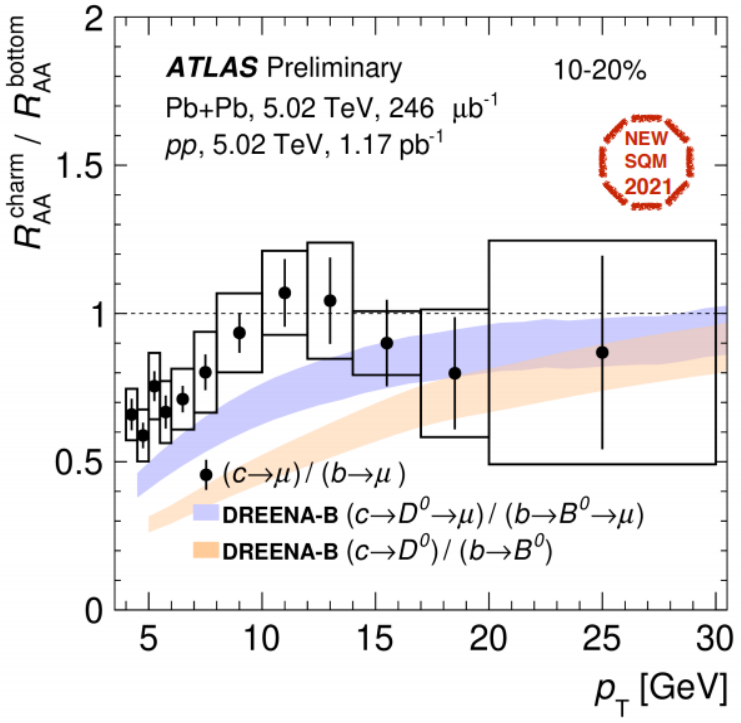
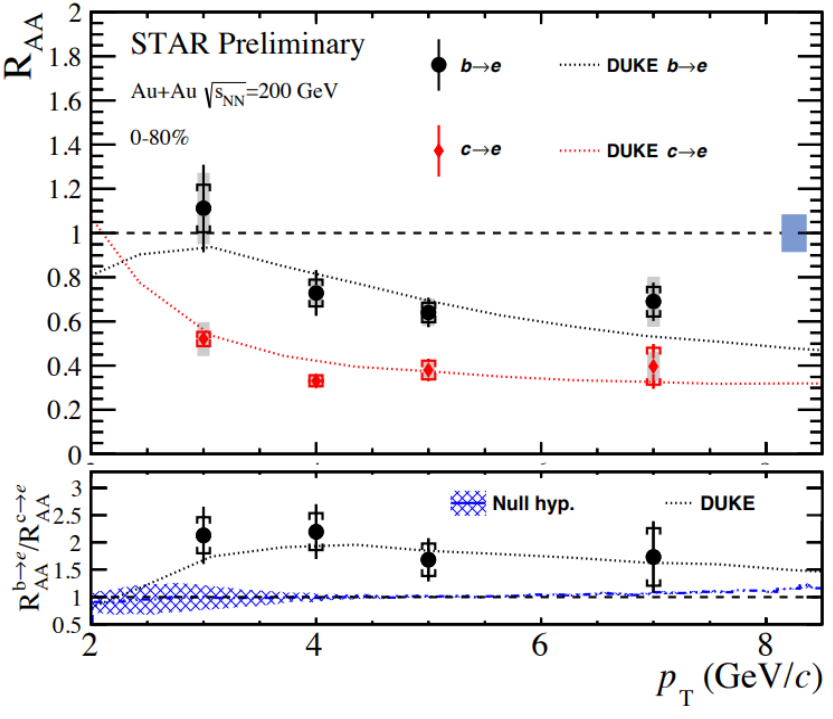


Charm vs beauty R_{AA}

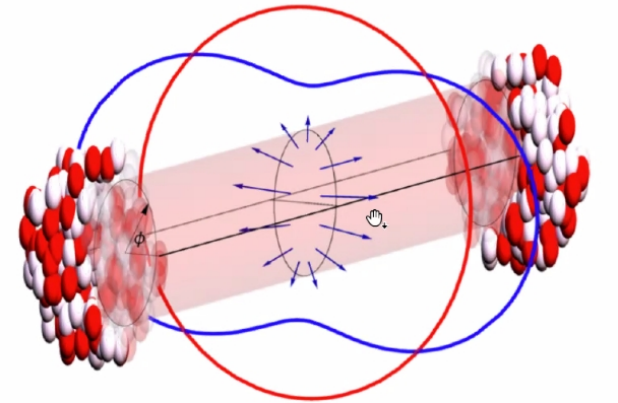
- **Beauty R_{AA} > charm R_{AA}** at intermediate p_T → suggesting larger en. loss for charm quarks
- Beauty R_{AA} ~ charm R_{AA} at higher p_T
- **Described by models including dead-cone effect**



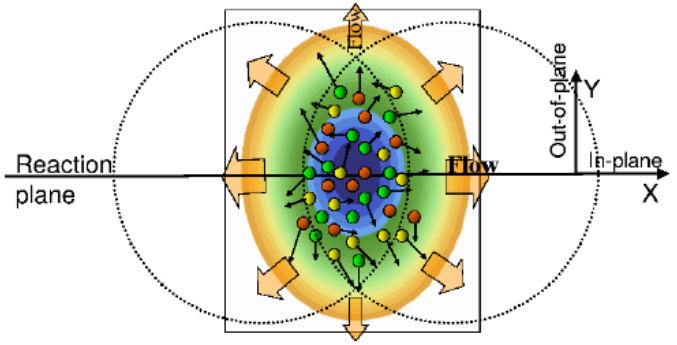


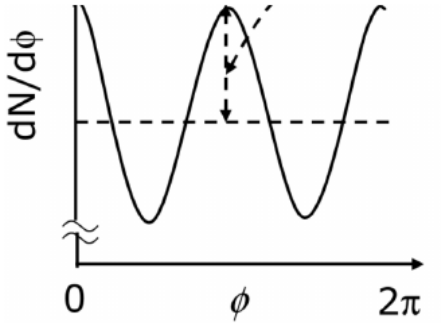
Anisotropic Flow in HI

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

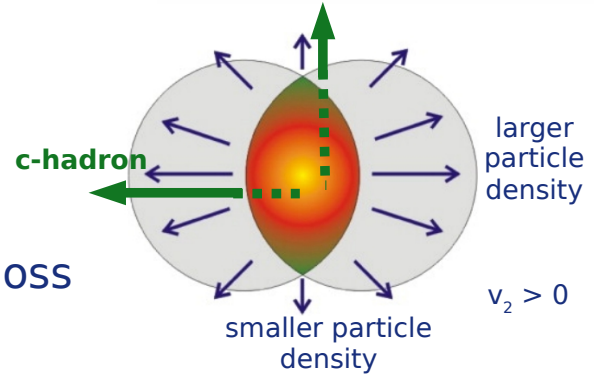


$$\frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^2N}{2\pi p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_{EP})\right)\right] \qquad v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$



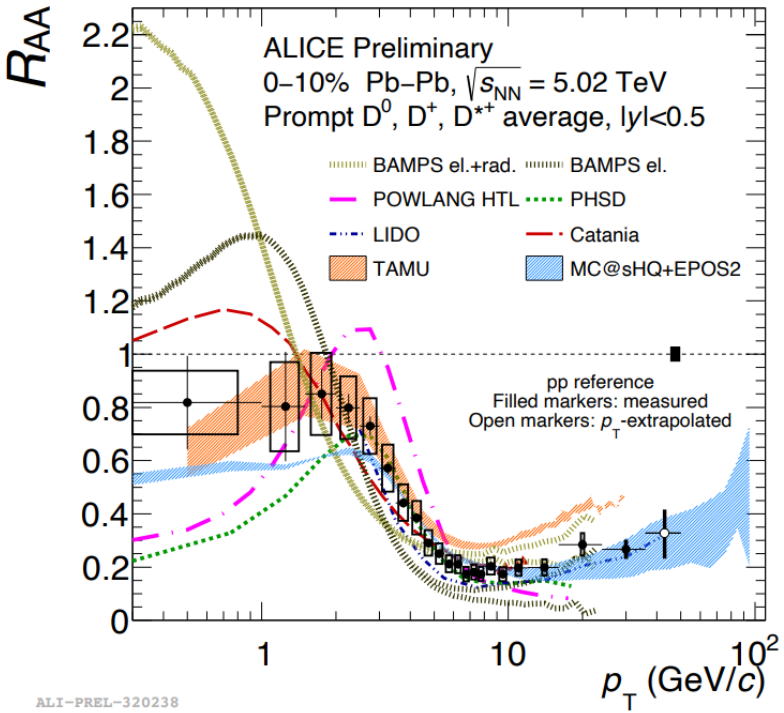


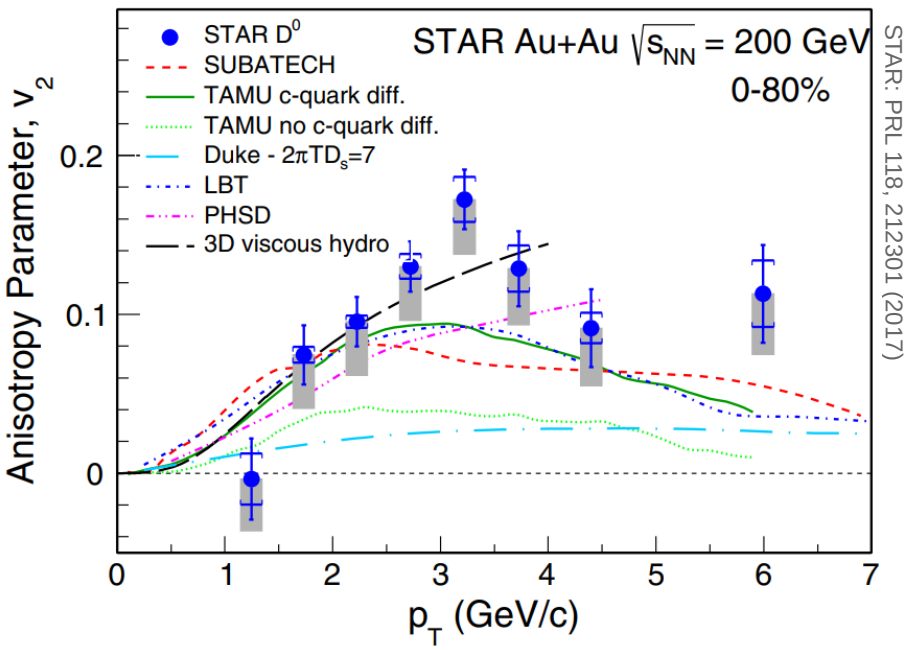
- Heavy-flavour elliptic flow, v_2
  - Low p_T: Collective motion of the system, hq thermalization ?
  - High p_T: Path-length dependent parton energy loss



HF Anisotropic Flow in HI

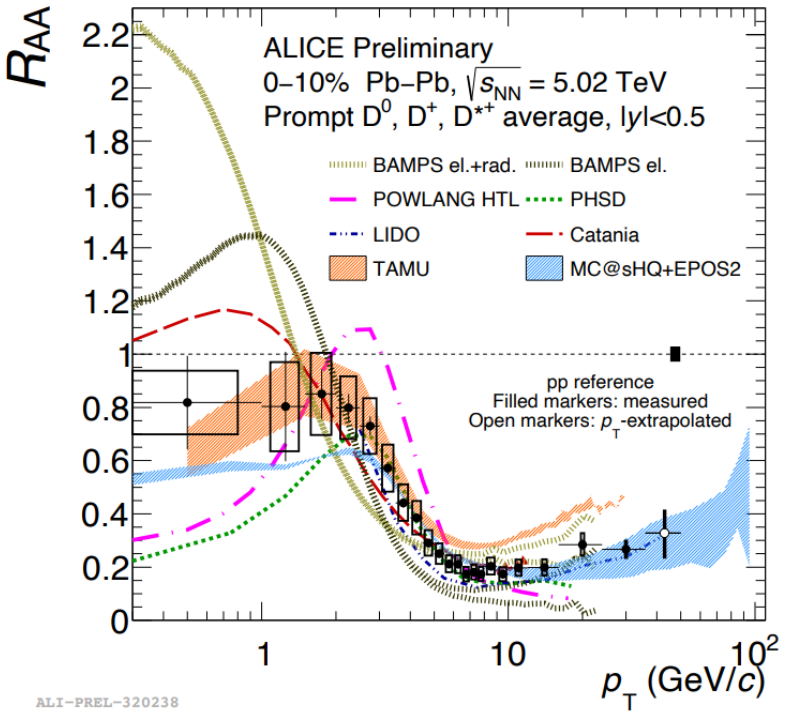
- Further constraints on energy loss mechanism and discriminate between different models
  - Models describe the main data features but differ in details ($2\pi TD_s \sim$ 2-5 at T_c)
- Additional powerful constraints on D_s diffusion coefficient

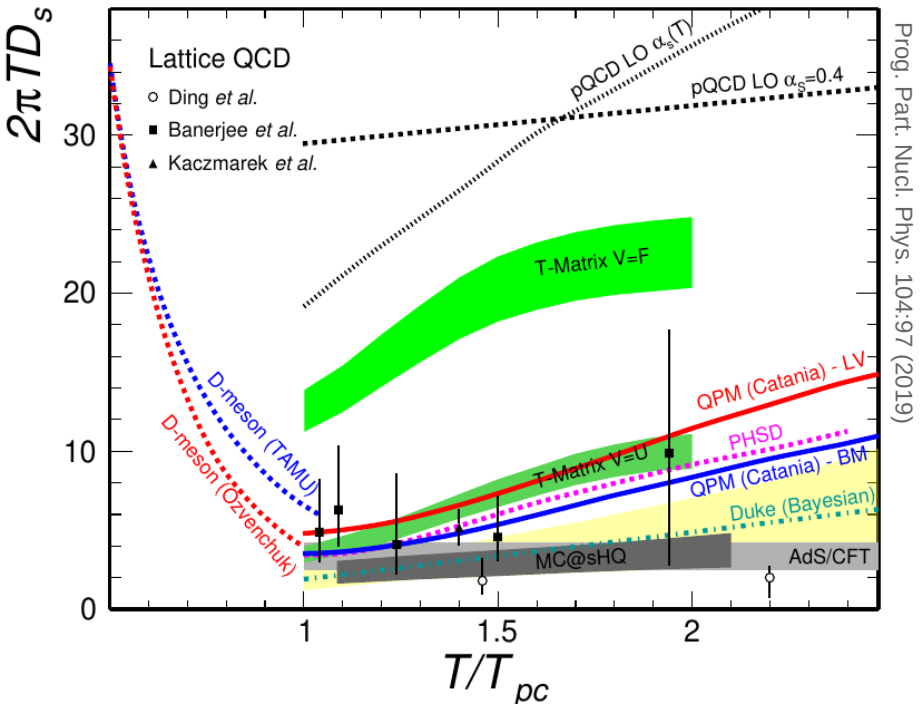




HF Anisotropic Flow in HI

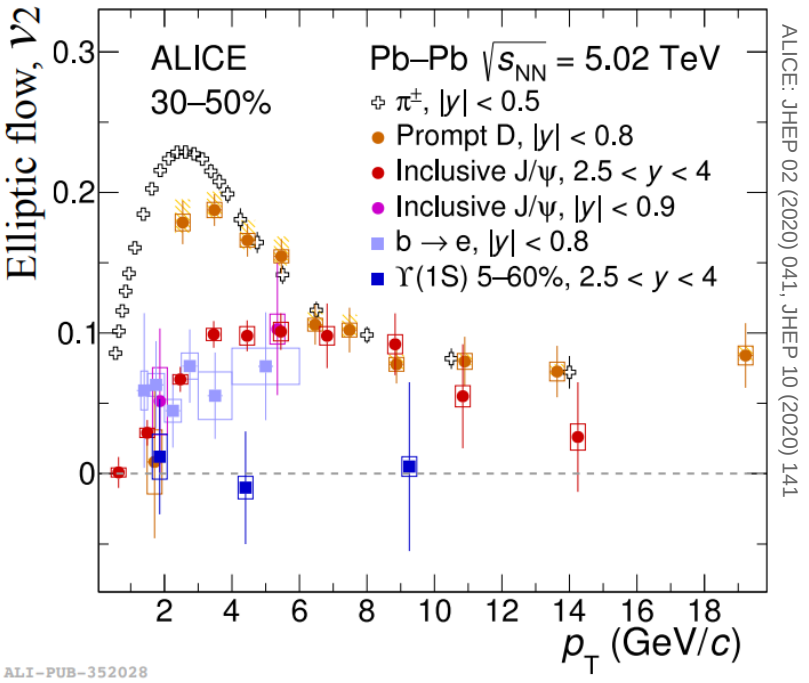
- Further constraints on energy loss mechanism and discriminate between different models
- Additional powerful constraints on D_s diffusion coefficient
- v_2 vs coll. energy → temperature dependence of D_s



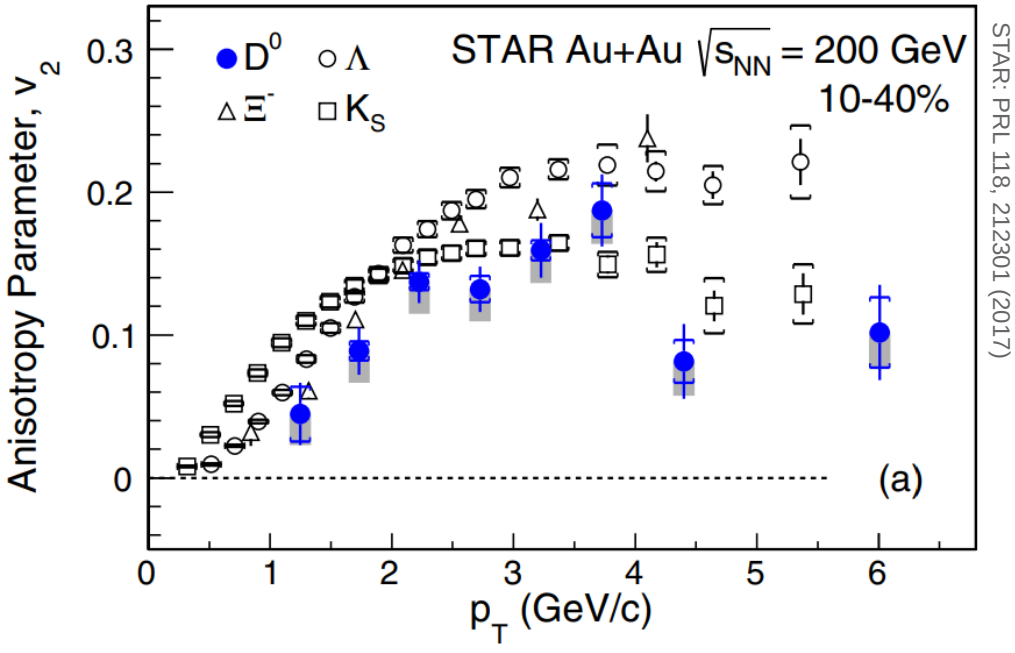


D meson v_2

- **D meson v_2 > 0**, mass ordering at lower p_T
- **Strong charm quark coupling with the medium**



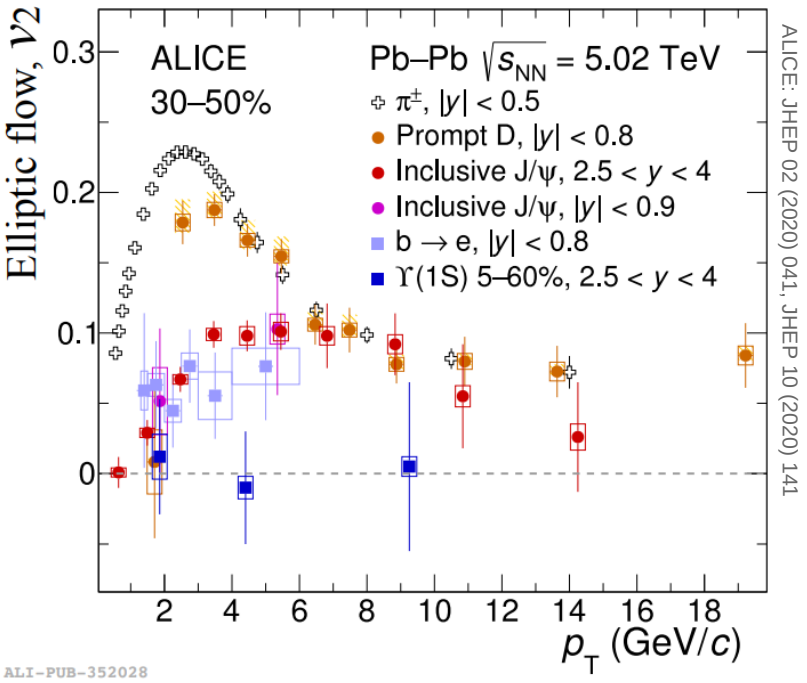
ALICE: JHEP 02 (2020) 041, JHEP 10 (2020) 141

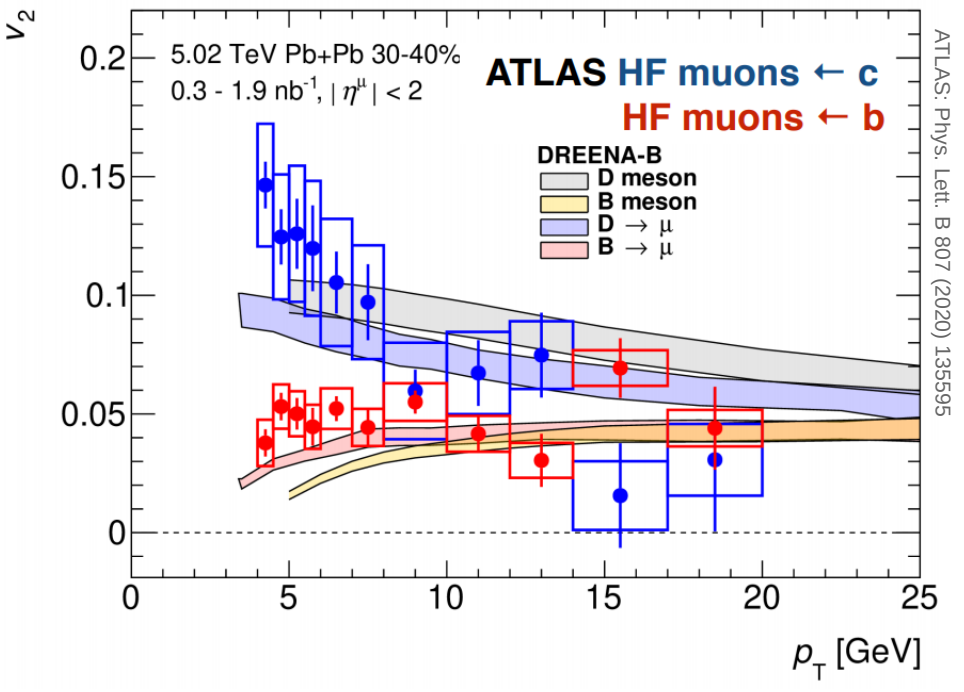


STAR: PRL 118, 212301 (2017)

Charm and beuaty v_2 at LHC

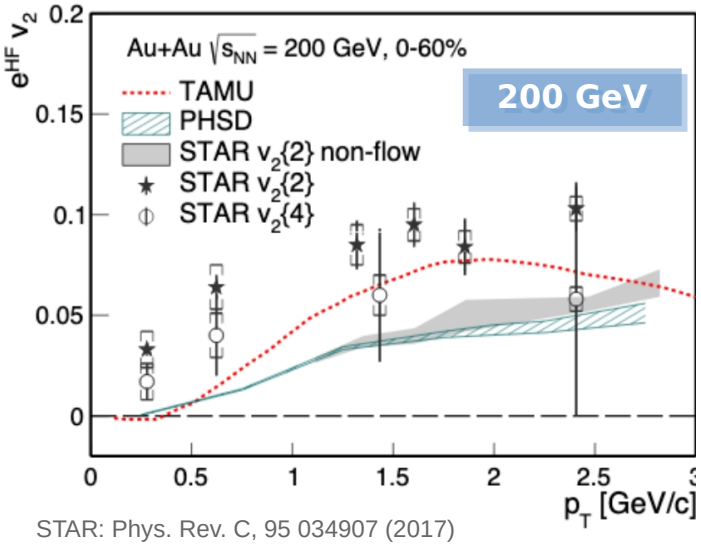
- **D meson $v_2 > 0$, b → e,μ $v_2 > 0$**
- **Strong charm and beauty quark coupling with the medium**
  - low/intermediate p_T: $v_2^b < v_2^c$ – collectivity
  - high p_T: $v_2^b \sim v_2^c$ – parton en. loss



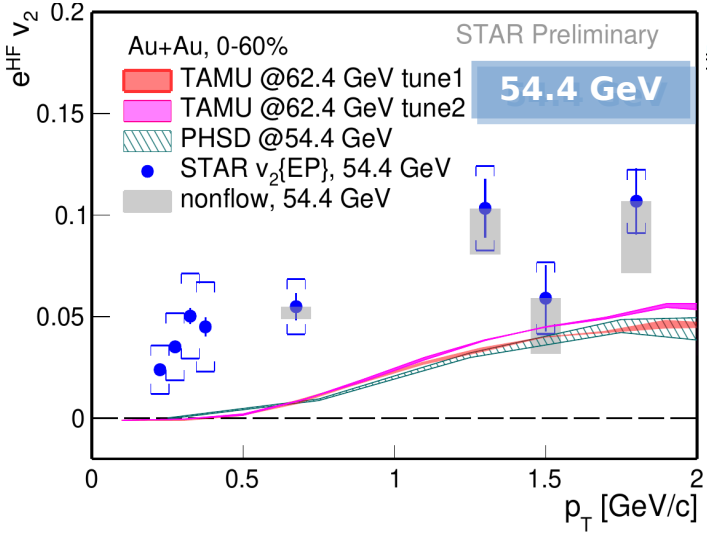


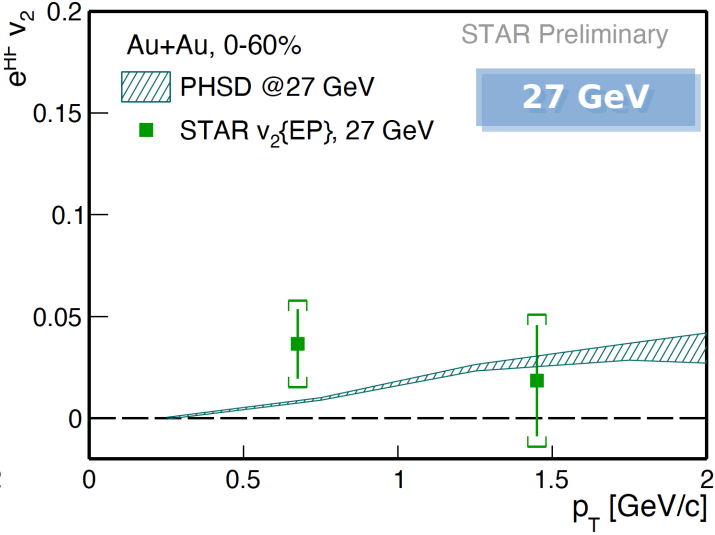
HF v_2 vs energy

- **Significant non-zero v_2 at 54.4 GeV** of c,b → e, similar to v_2 at 200 GeV
- Hint of smaller v_2 at 27 GeV
- **HF(c) quarks interact strongly with the medium in 54.4 GeV Au+Au collisions**
- At low p_T models lower than data



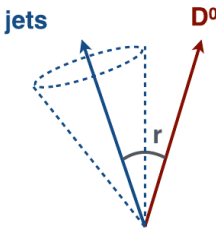
STAR: Phys. Rev. C, 95 034907 (2017)

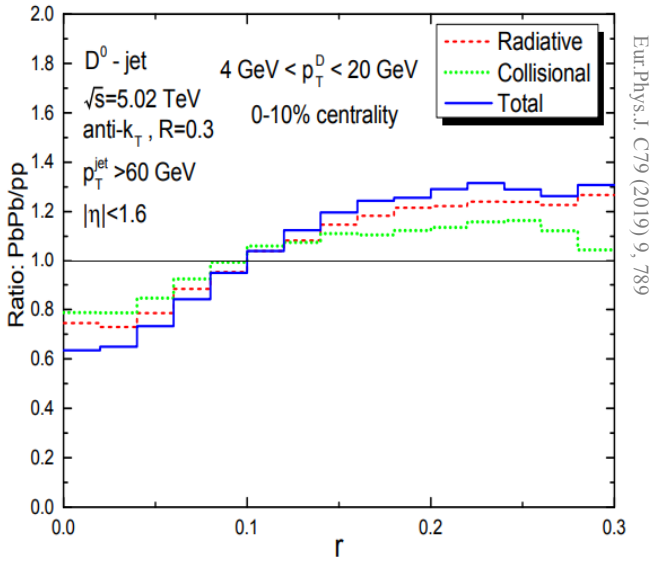




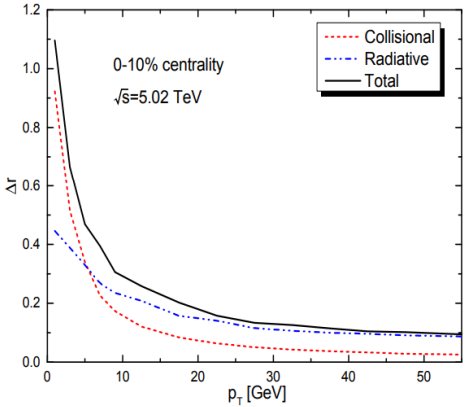
D-jets in HI

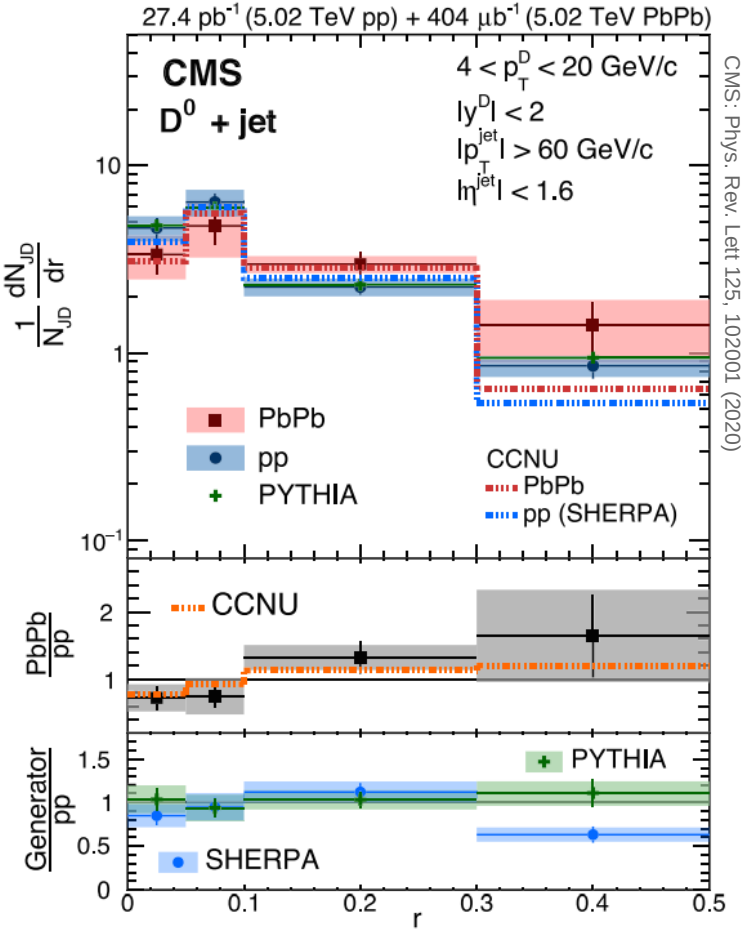
- Radial profile of D^0 mesons in jets
- Diffusion of charm w.r.t jet axis → interaction mechanisms between hq and medium, coll. vs rad. en. loss
  Sensitivity to D_S





Eur.Phys.J. C79 (2019) 9, 789





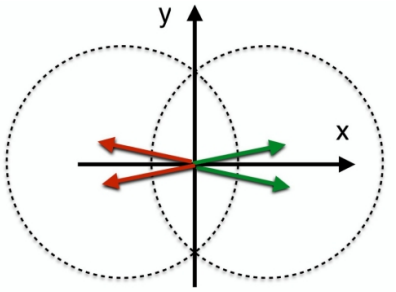
CMS: Phys. Rev. Lett 125, 102001 (2020)

- **Hint of broader radial distribution in PbPb w.r.t. pp for $4 < p_T^D < 20$ GeV/c**

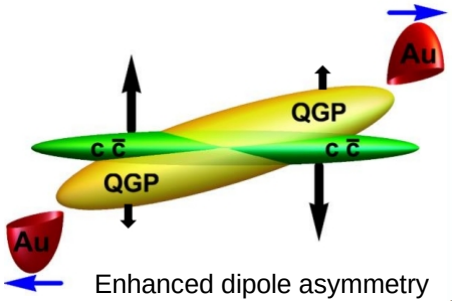
Directed flow, v_1

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

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

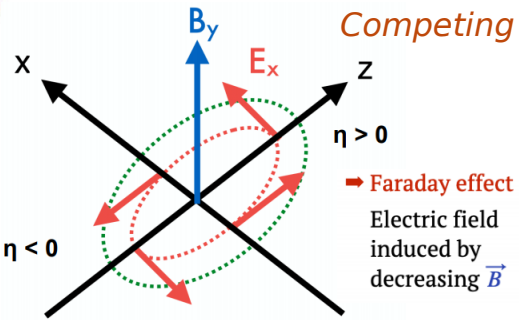


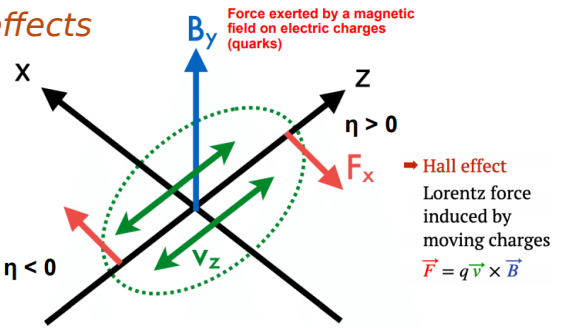
Tilt



Enhanced dipole asymmetry

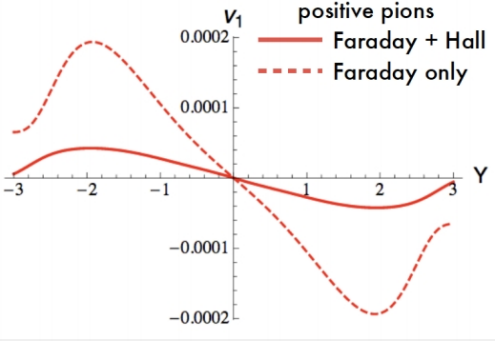
EM field
Charged-dependent v_1,
Sensitive to QGP conductivity





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

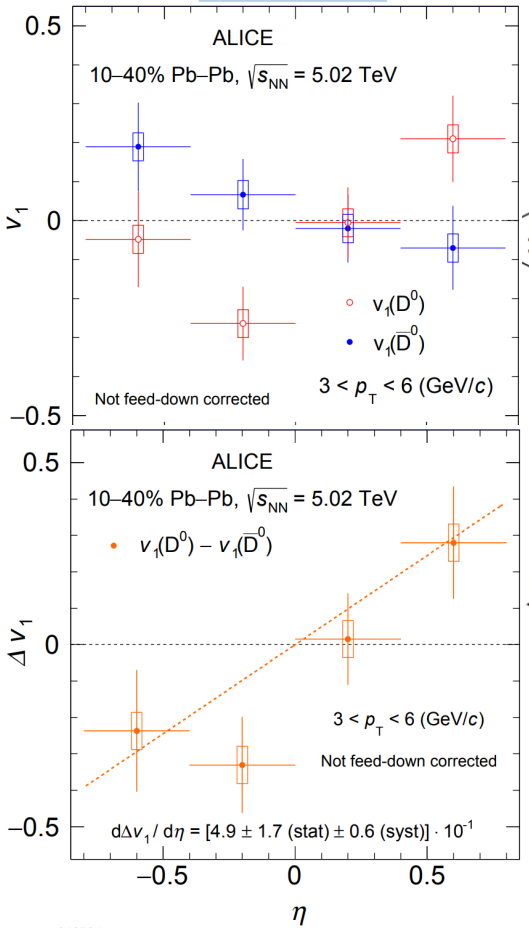
- Heavy-quarks:
  - produced early, shifted from the bulk
  - formation time comparable to when B is maximum



D^0 directed flow, v_1

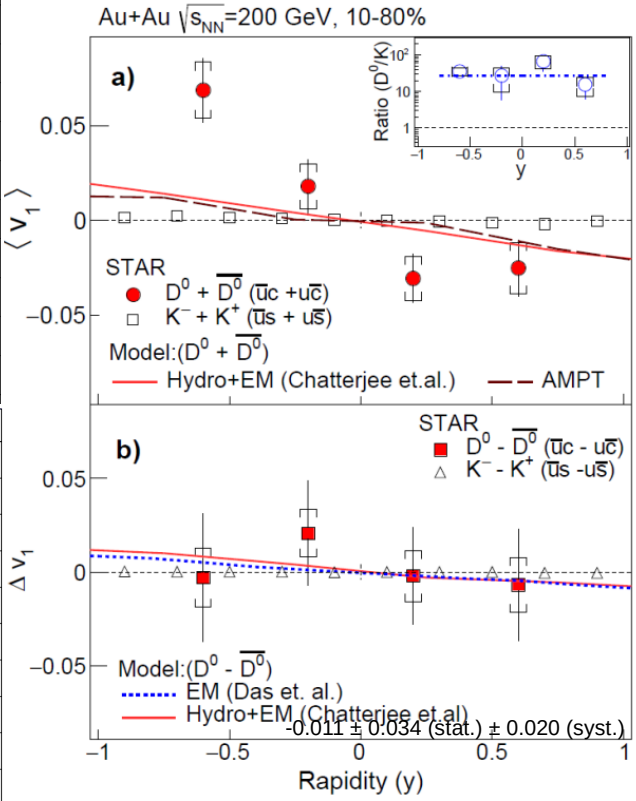
- **Large D^0 directed flow v_1 vs y**
- dv_1/dy slope:
  - RHIC: Negative, similar for D^0 and D^{0bar}
  - LHC: Positive for D^0 and negative for D^{0bar}
- **$d\Delta v_1/dy(D^0\text{-}D^{0bar})$ slope:** negative at RHIC, positive and larger at LHC
- Larger B than the induced E at LHC ?
- Tilt dominance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

LHC



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

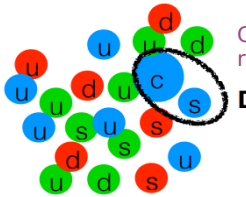
RHIC



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

D_s production in AA

- Probes of hadronization: fragmentation vs coalescence
- Recombination: modification of p_T-dependent charm hadro-chemistry
- Recombination: s quarks abundant in the QGP → $D_s(B_S)/D(B)$ enhancement



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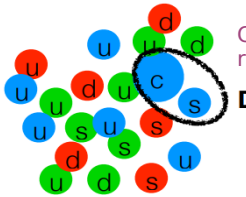
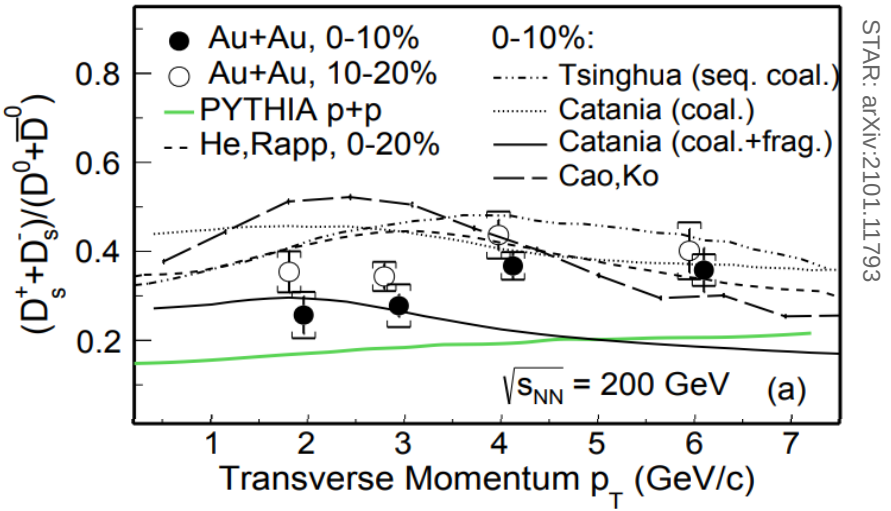
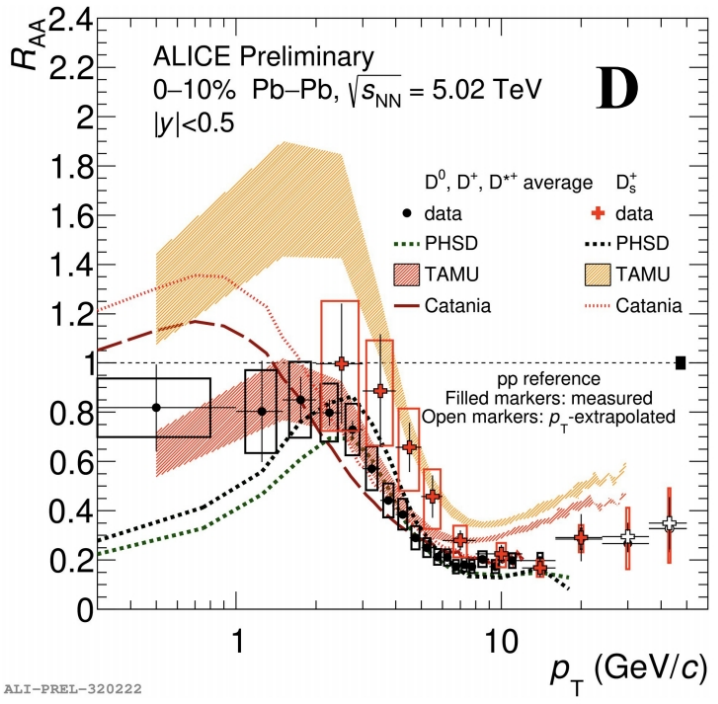


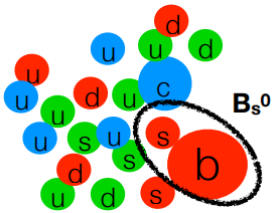


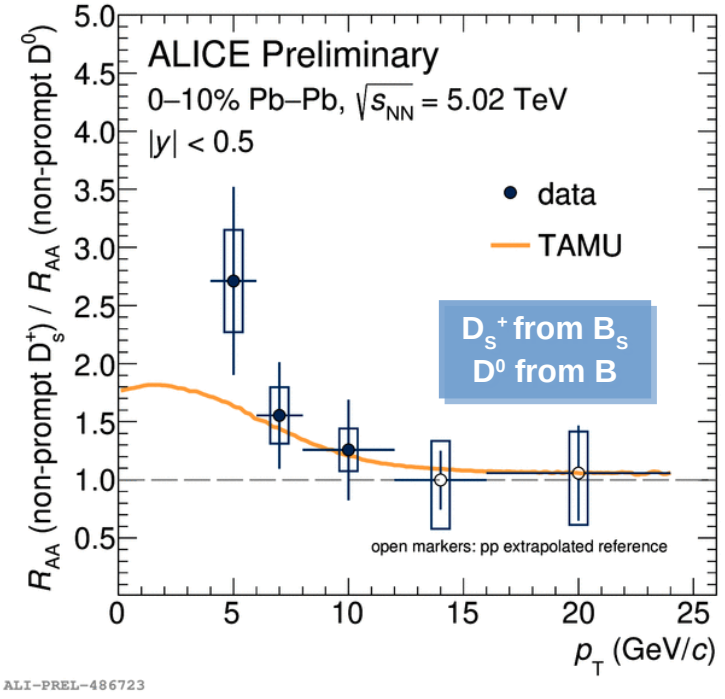


- **Enhancement in D_s^+/D^0 ratio** compared to PYTHIA
- Smaller suppression of D_s^+ than D^0 at p_T < 10 GeV
- Consistent with models including **strangeness enhancement and charm quark coalescence + frag.**

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

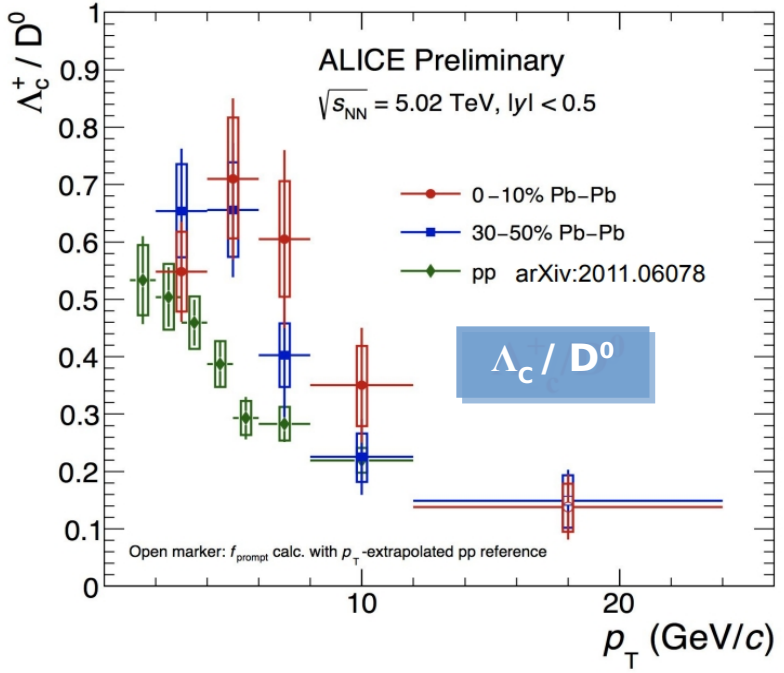


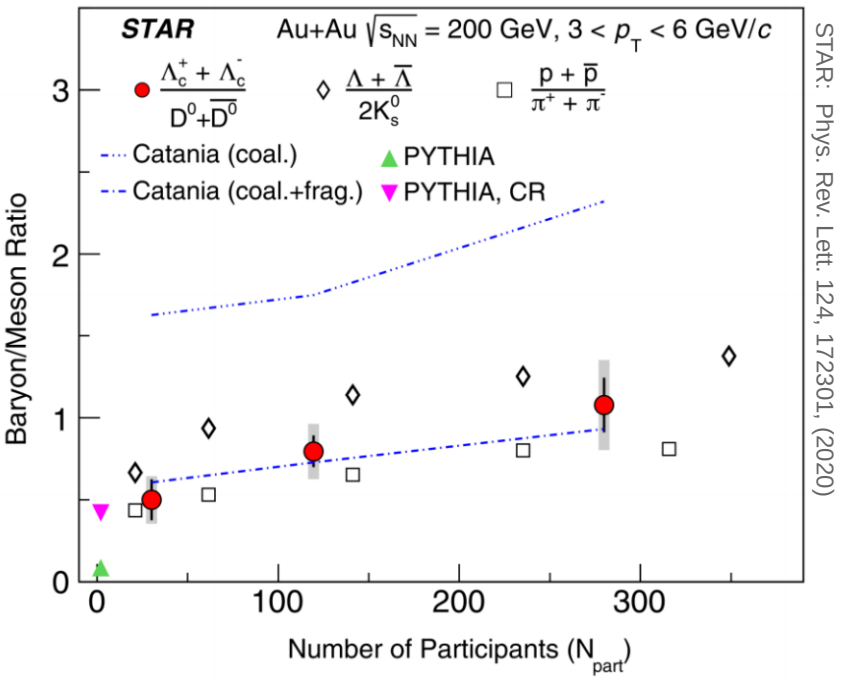


- Upcoming LHC Run3,4 will provide more information on beauty quark hadronization

Λ_c production in AA

- 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**





Summary

- Strong coupling of heavy-flavour quarks with the medium from 54.4 GeV up to 5.02 TeV
  - Large low p_T elliptic flow, R_{AA} flow bump
- Heavy-flavour energy loss, indications of flavour dependence at intermediate p_T
  - High p_T elliptic flow > 0, R_{AA} < 1
- Evidence of charm quark hadronization via coalescence at low p_T, fragmentation at high p_T
  - Strange/non-strange meson and baryon/meson enhancement
  - Hadronization in pp still an open question
- Measurements are getting more precise and differential → constraints on theoretical models and extraction of the medium properties
- More precise results still to be expected, especially in the beauty sector, with the upcoming LHC Run3,4

Thank you !

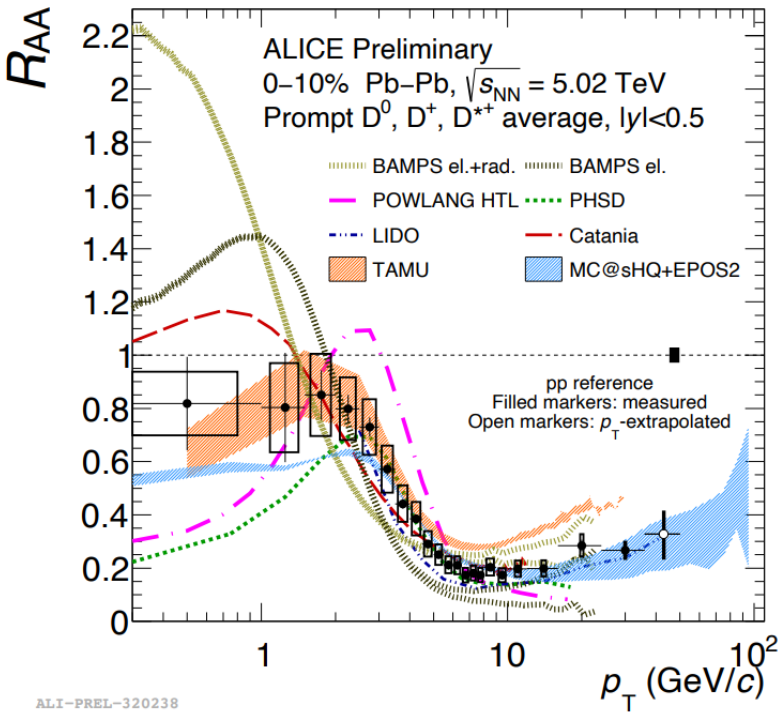
This work was supported by grant from The Czech Science Foundation, grant number: GJ20-16256Y

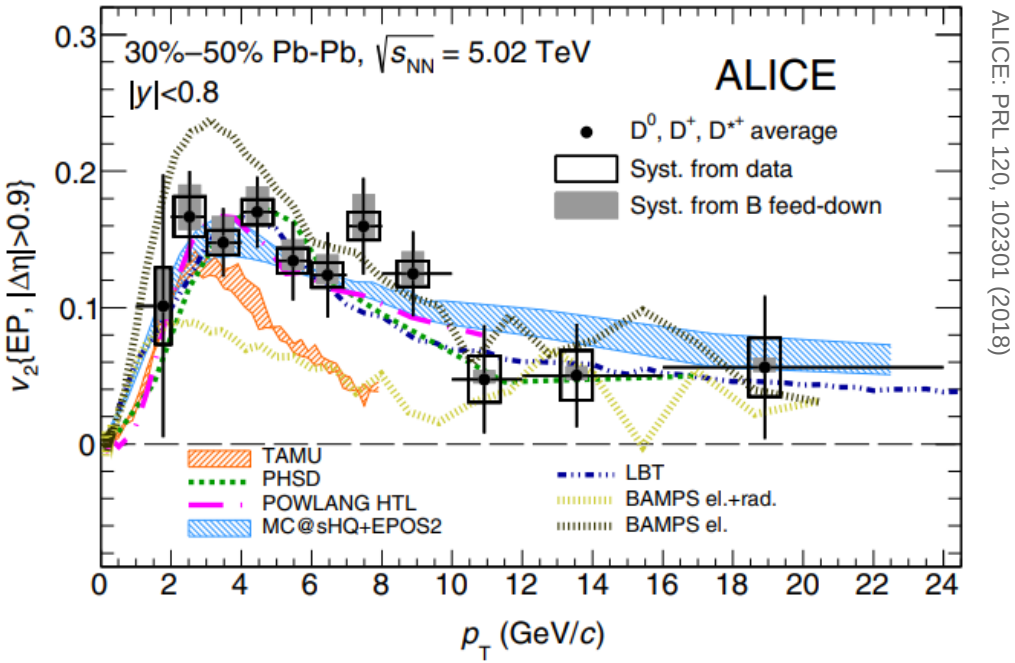
GAČR GRANTOVÁ AGENTURA ČESKÉ REPUBLIKY

Backup

HF Anisotropic Flow in HI

- Further constraints on energy loss mechanism
- Discriminate between different models

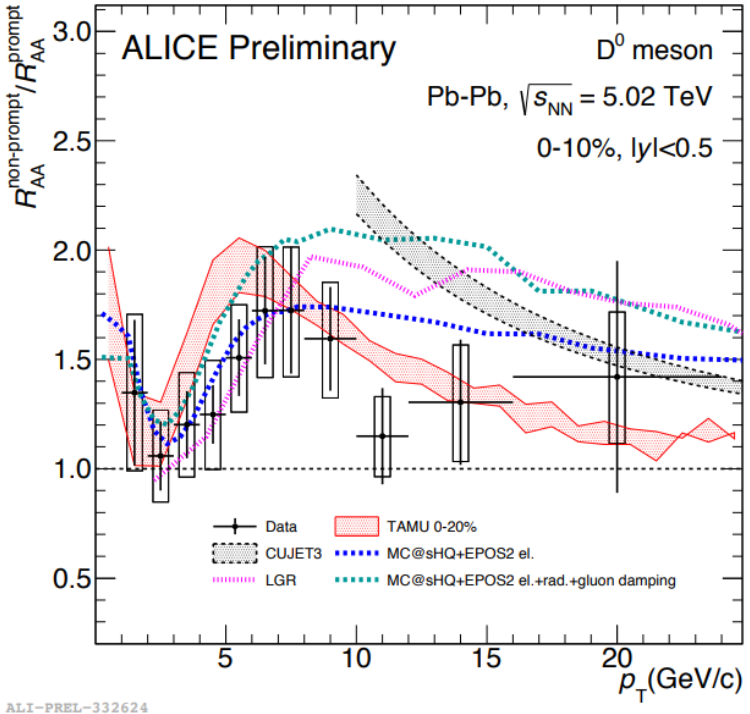


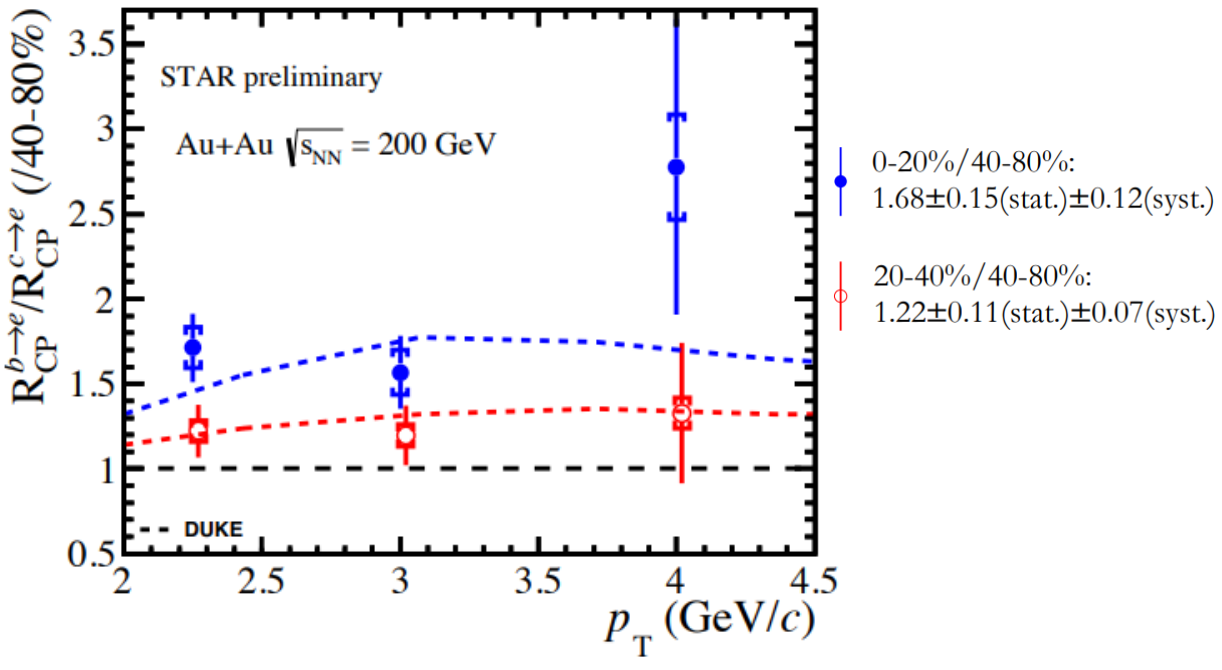


ALICE: PRL 120, 102301 (2018)

R_{AA} - Flavour dependence

- **Beauty R_{AA} > charm R_{AA}** → suggesting larger en. loss for charm quarks at intermediate p_T
- Beauty R_{AA} ~ charm R_{AA} at high p_T
- Described by models including dead-cone effect





B_s, B_c R_{AA} in AA

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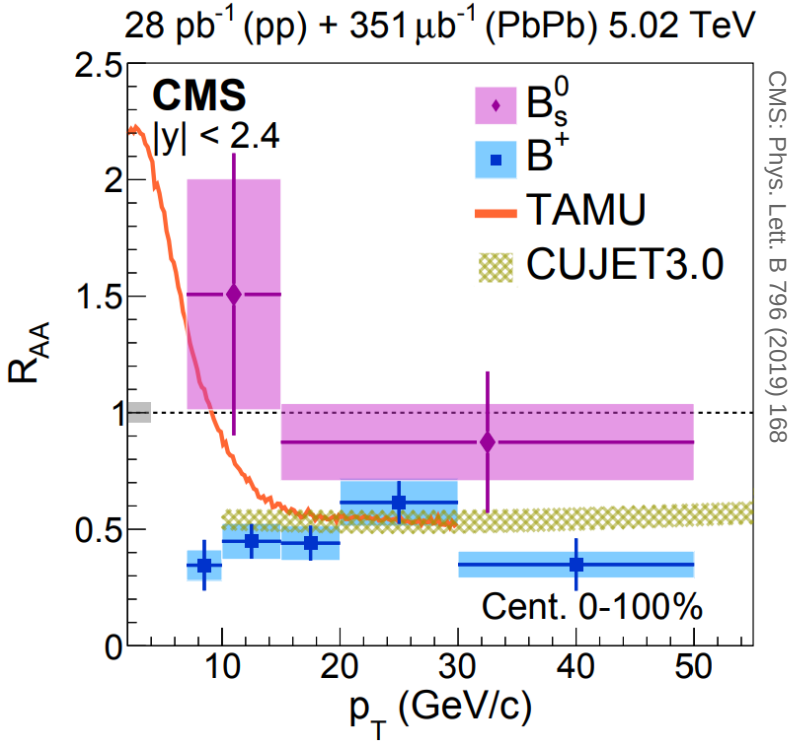

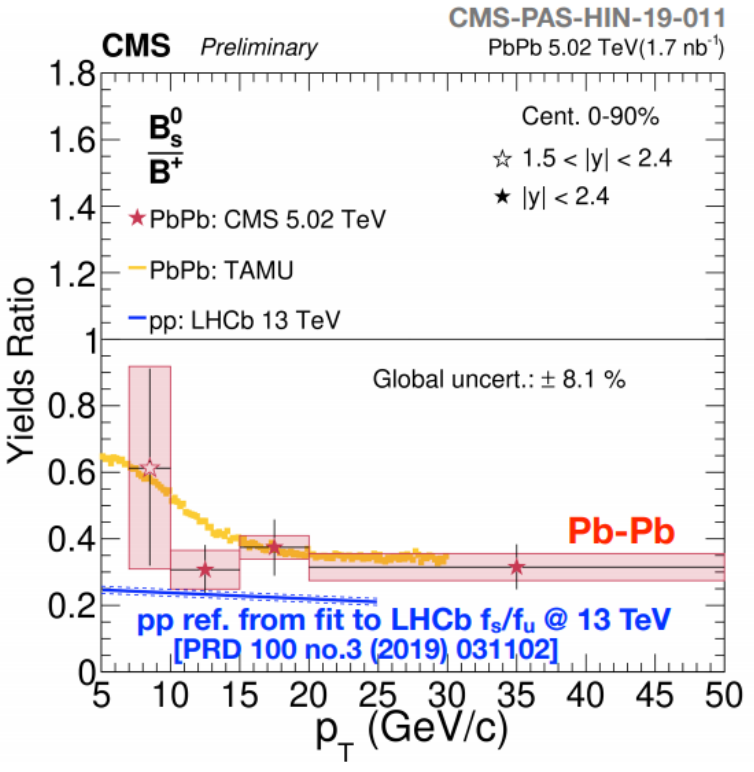

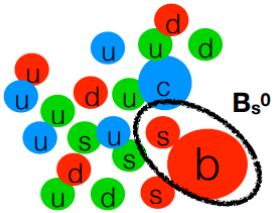

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