Heavy-flavour highlights in heavy-ion collisions from ALICE at the LHC

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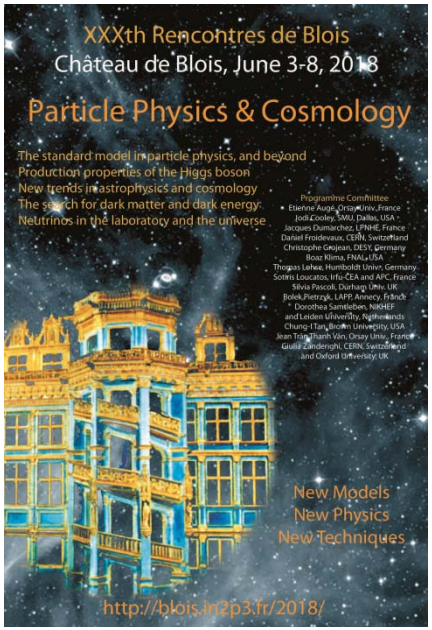
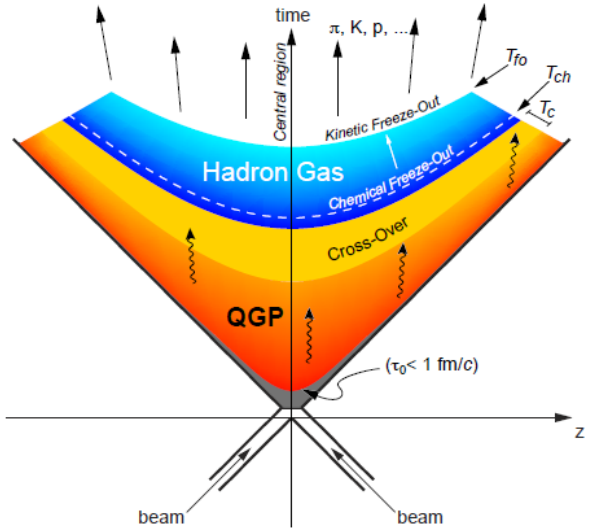
on behalf of the ALICE Collaboration



Why study heavy flavours?

Heavy-ion collisions

- Charm and beauty quarks produced in initial hard scatterings, prior to the formation of the Quark-Gluon Plasma (QGP)
  $\tau_{c/b} \sim 0.01\text{-}0.1$ fm/c $< \tau_{QGP}$ (0-1-1 fm/c)
- Flavour conserved by the strong interaction
- Experience the full collision history
  - ➢ Excellent probes to characterize the QGP

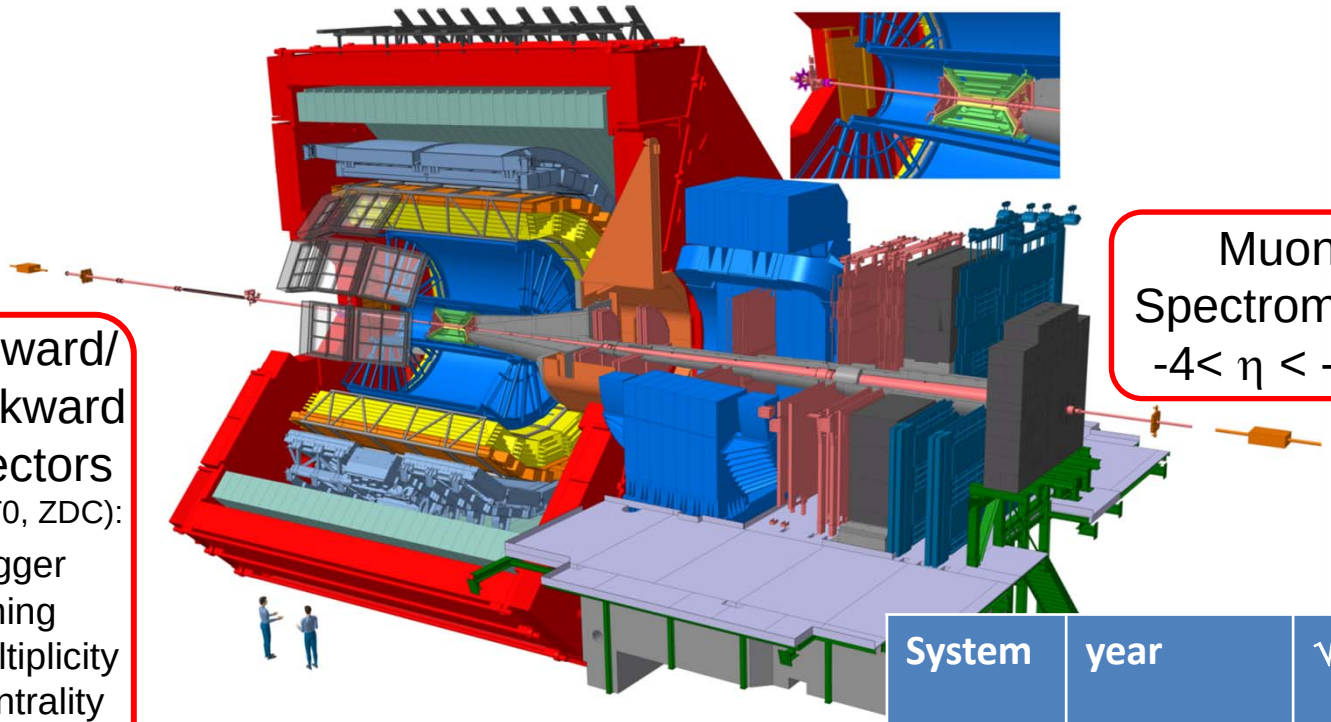


- Open heavy flavours:
  - In-medium parton energy loss → colour-charge and quark-mass dependence
  - Heavy-quark participation in the collective expansion, thermalisation of the medium
  - Modification of hadronisation mechanism in the medium
- Quarkonia:
  - Colour screening in the QGP → suppression
  - Charmonium regeneration

- pp collisions: reference, tests of pQCD-based predictions, production mechanisms
- p-Pb collisions: control experiment, cold nuclear matter effects

ALICE layout

Central Barrel, $|\eta| < 0.9$
vertexing (ITS),
tracking (ITS, TPC),
PID (ITS, TPC, TOF, TRD, HMPID, Calorimeters)

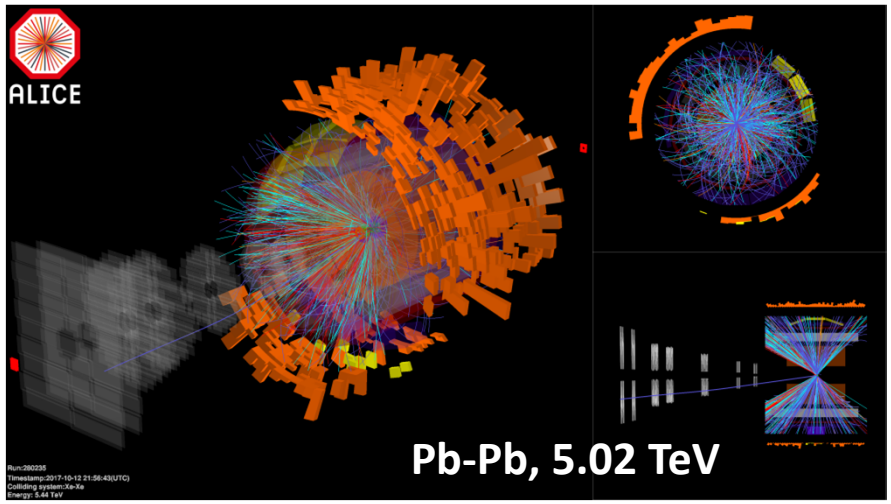


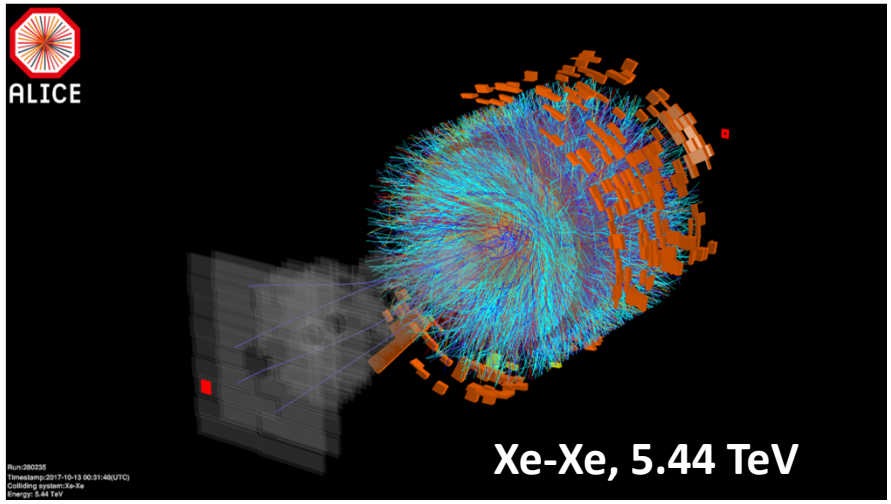
Muon Spectrometer
$-4 < \eta < -2.5$

Forward/ Backward detectors
(V0, T0, ZDC):
Trigger
Timing
Multiplicity
Centrality
Event plane

System	year	$\sqrt{s_{NN}}$ (TeV)	L_{int} (μb^{-1}) μ triggers
Pb-Pb	2010-2011	2.76	~75
Pb-Pb	2015	5.02	~225
Xe-Xe	2017	5.44	~0.3

Selected open heavy-flavour highlights in Pb-Pb and Xe-Xe collisions



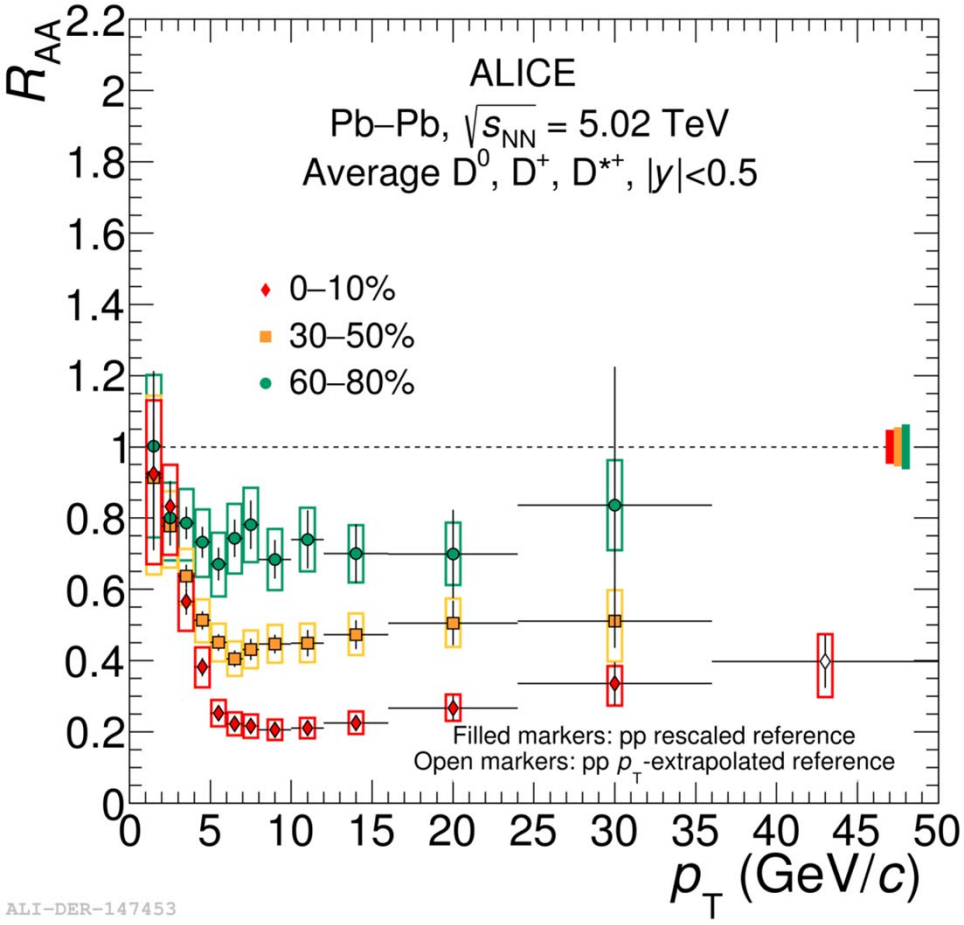


Open heavy-flavour channels in ALICE

- Charmed hadrons ($|y| < 0.5$)
  - $D^0 \rightarrow K^-\pi^+$
  - $D+ \rightarrow K^-\pi^+\pi^+$
  - $D^*_+ \rightarrow D^0 (K^-\pi^+)$
  - $D^+_s \rightarrow \phi (K^-K^+)\pi^+$
  - $\Lambda_c^+ \rightarrow pK^0_s$
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - $\Lambda_c+ \rightarrow e^+\Lambda\nu_e$
  - $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$

- Heavy-flavour hadron decay leptons
  - **c, b hadrons $\rightarrow$ eX ($|y| < 0.9$)**
  - **c, b hadrons $\rightarrow \mu$X ($2.5 < y < 4$)**
  - **b $\rightarrow$ eX via impact parameter**

D-meson R_{AA} in Pb-Pb collisions at 5.02 TeV



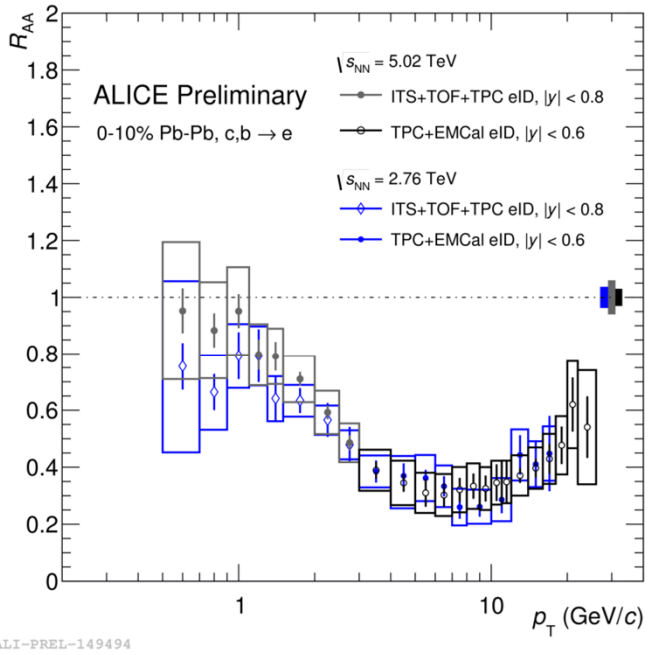
ALICE, arXiv:1804:09083

$$R_{AA}(p_T) = 1/< T_{AA} > \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

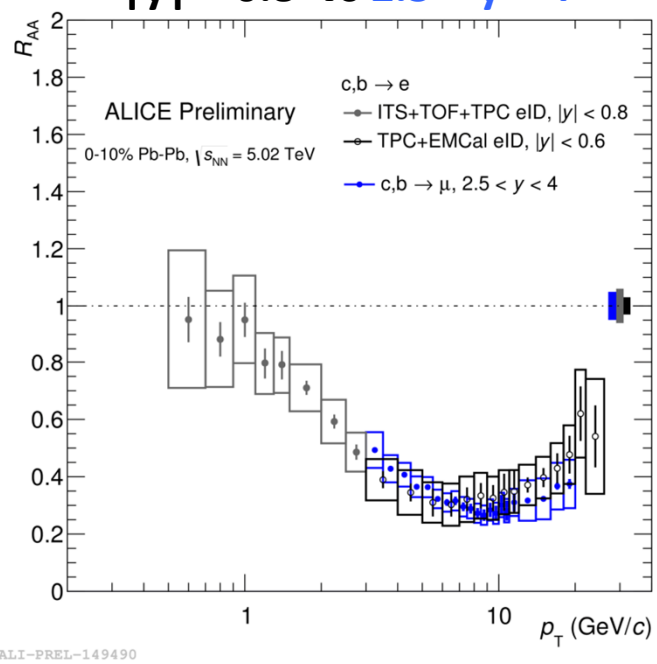
- Measurement over a wide p_T interval for 0-10%, 30-50% and 60-80% centrality classes
- Strong suppression of non-strange D mesons, increasing with centrality: a factor ~ 5 for $5 < p_T < 10$ GeV/c in the 10% most central collisions

Heavy-flavour hadron decay leptons R_{AA} in central Pb-Pb collisions at 5.02 TeV

5.02 TeV vs 2.76 TeV



|y| < 0.8 vs 2.5 < y < 4

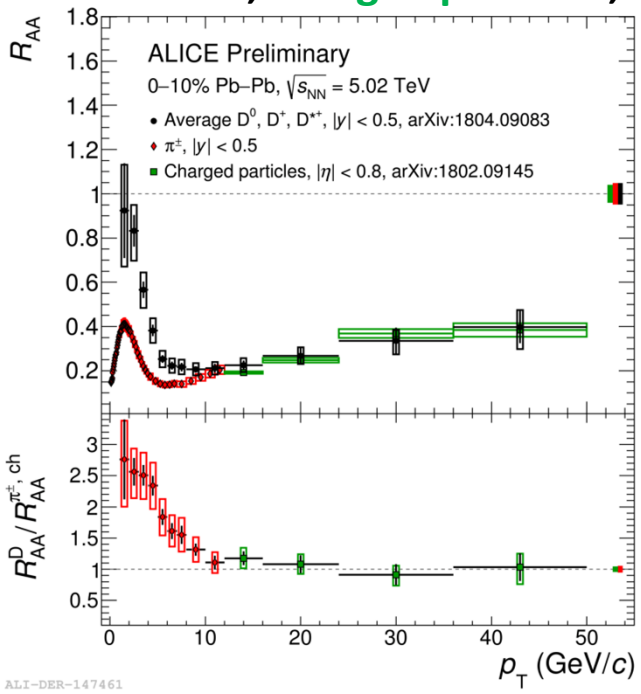


Electrons at 2.76 TeV: ALICE, arXiv:1805.04379

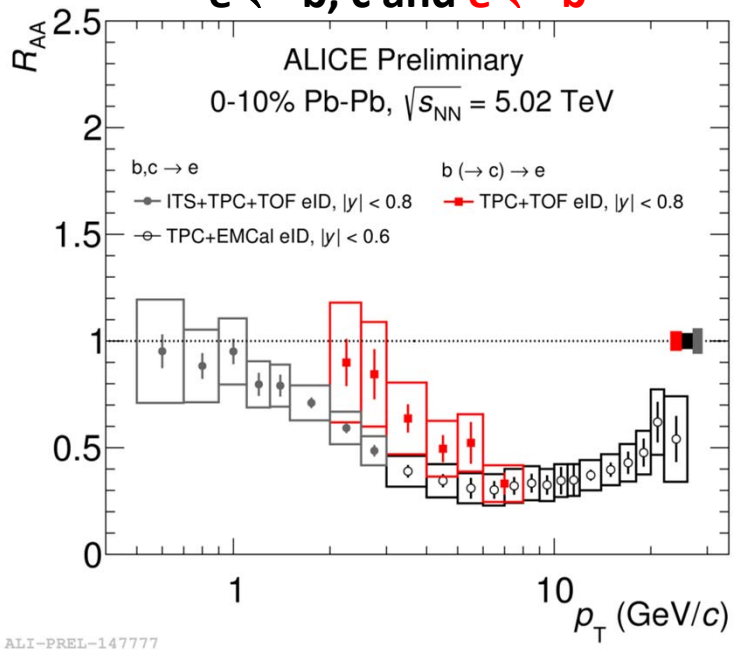
- Similar R_{AA} at 5.02 TeV and 2.76 TeV for heavy-flavour hadron decay electrons
  - Interplay between harder p_T spectra and stronger energy loss at 5.02 TeV w.r.t. 2.76 TeV [M. Djordjevic, PRC 92 (2015) 024918]
    Caveat: possible different fractions of charm and beauty
- Similar R_{AA} for heavy-flavour hadron decay muons at forward rapidity ($2.5 < y < 4$) and heavy-flavour hadron decay electrons at central rapidity ($|y| < 0.8$)
  - Heavy quarks undergo strong interactions in the medium over a wide y region

Open heavy-flavour R_{AA} hierarchy (I)

D mesons, charged particles, $\pi^{\pm}$



e ← b, c and e ← b

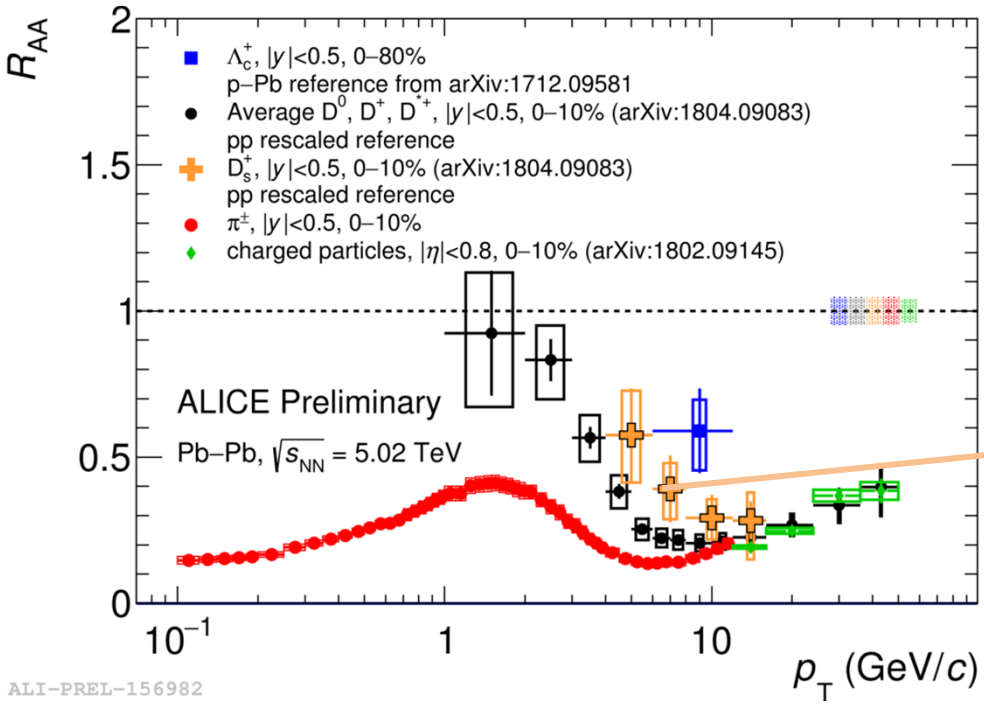


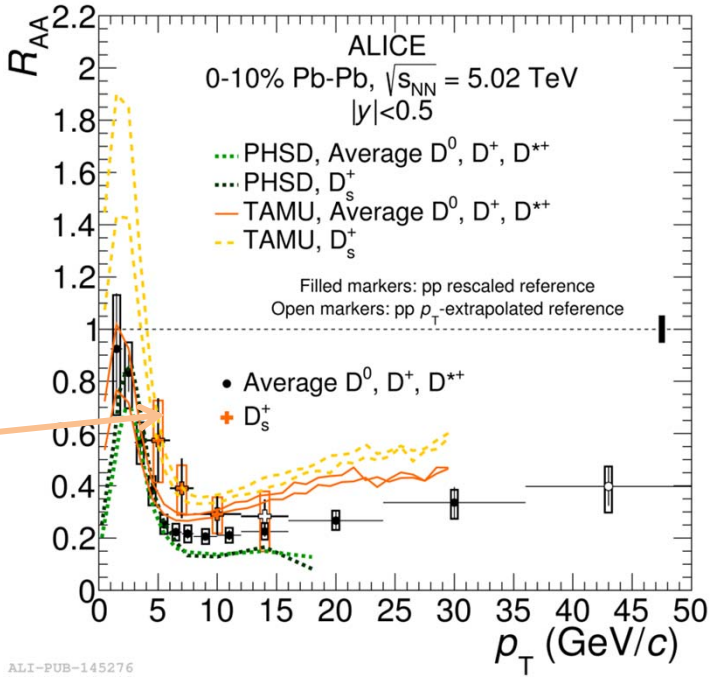
$\Delta E(\pi^{\pm}) > \Delta E(D) > \Delta E(B) \overset{?}{\rightarrow} R_{AA}(\pi^{\pm}) < R_{AA}(D) < R_{AA}(B)$

as naively expected from colour-charge and mass depend energy loss

- Comparable D-meson, charged particles and $\pi^{\pm}$ R_{AA} for $p_T > 10$ GeV/c
- D-meson R_{AA} larger than that of $\pi^{\pm}$ at low p_T
  - Interpretation not straightforward: possible mass and Casimir factor effects, different radial flow influence, different shapes of parton p_T distributions and different fragmentation functions [Djordjevic et al., PRL 112 (2014) 042302]
- Hint of larger R_{AA} of e ← b than that of e ← b, c

Open heavy-flavour R_{AA} hierarchy (II)



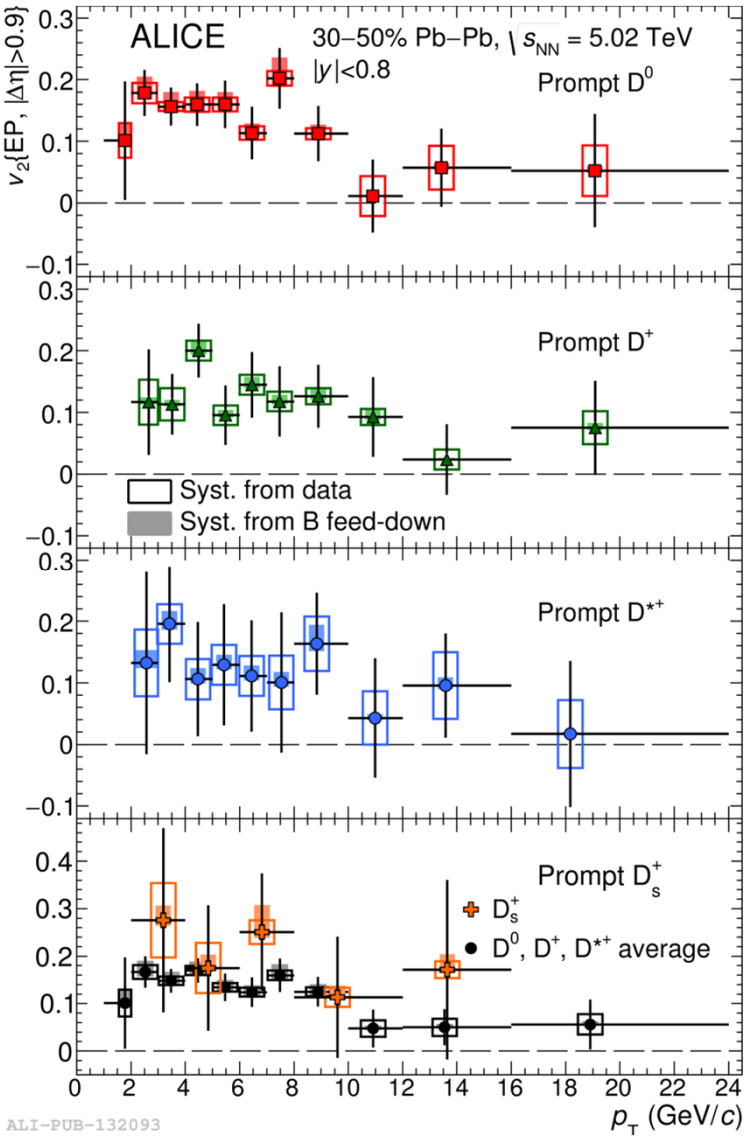


ALICE, arXiv:1804:09083

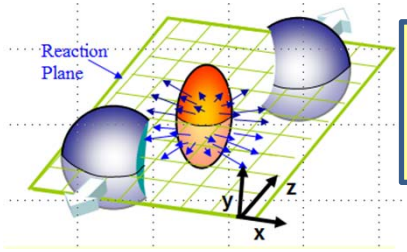
- Hint of enhanced D^+_s production compared to non-strange D mesons in central Pb-Pb collisions at 5.02 TeV as expected from models
  - Hadronisation via coalescence in a strangeness-rich environment?
- Hint of a larger R_{AA} for Λ_c^+ in 0-80% than for D mesons in 0-10%

- R_{AA} ordering consistent with recombination picture

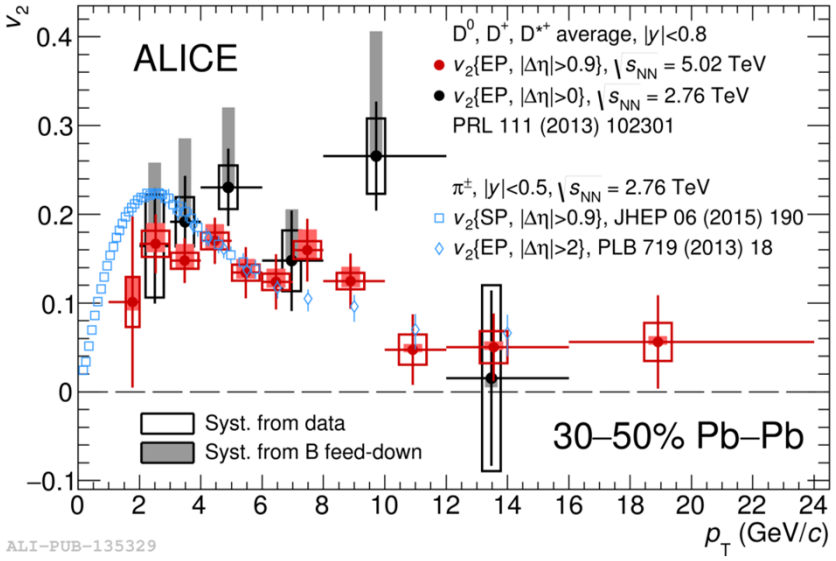
Elliptic flow (v_2) in Pb-Pb collisions



ALICE, PRL 120 (2018) 102301

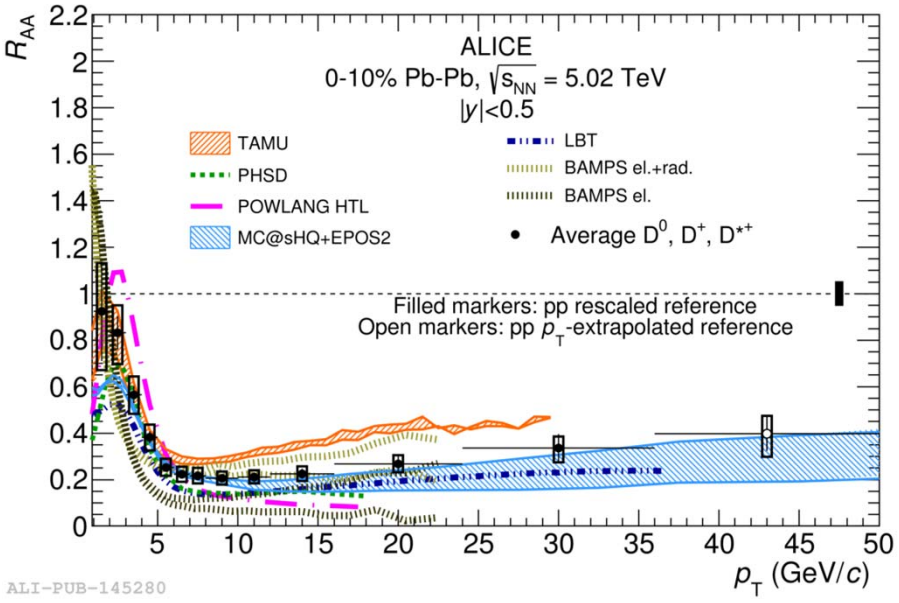


$$\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$

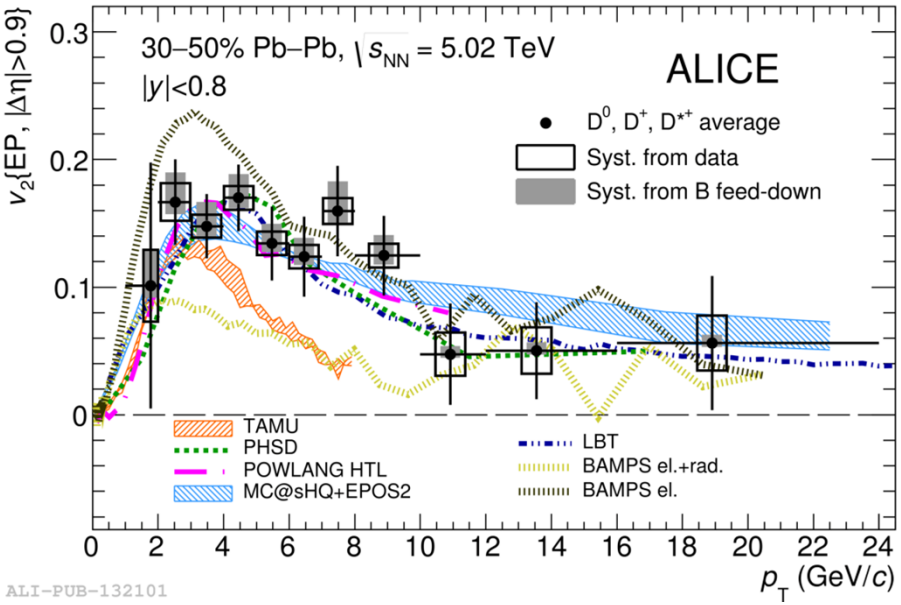


- First D^+_s v_2 measurement, similar as non-strange D v_2
- Positive D-meson v_2 in $2 < p_T < 10$ GeV/c (hint of a larger charged-pion v_2 for $p_T < 4$ GeV/c)
  - Participation of charm quarks in the collective expansion of the system

Comparison with models



ALICE, arXiv:1804:09083

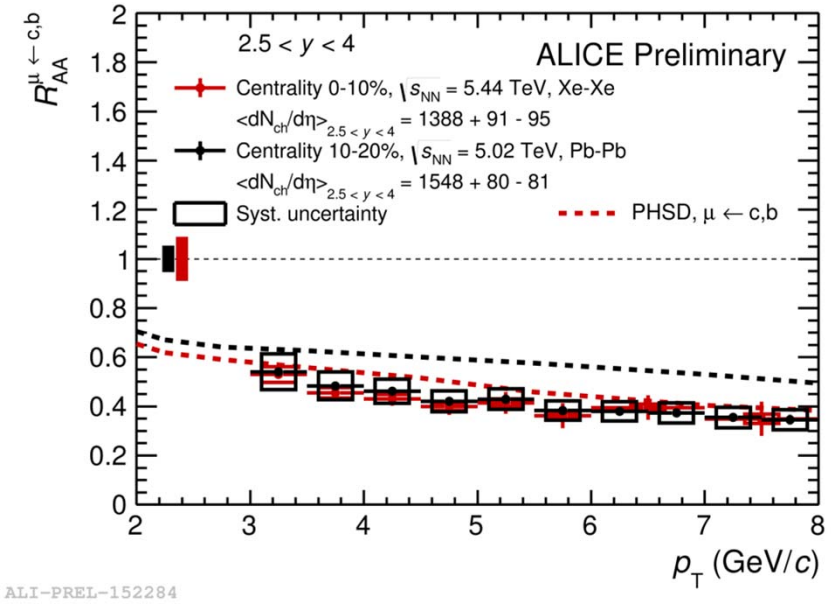


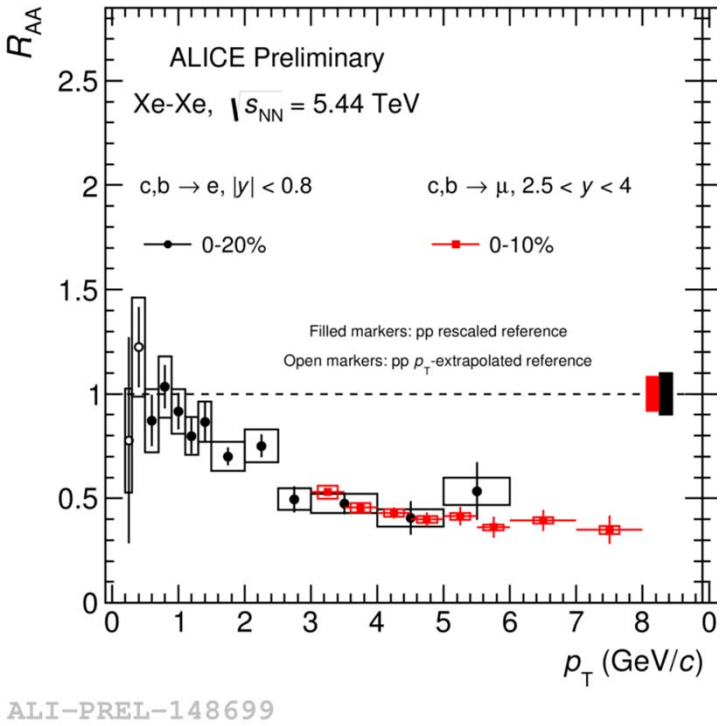
ALICE, PRL 120 (2018) 102301

- Models with diffusion coefficient $1.5 < 2\pi D_s(T) < 7$ at $T = T_c$ with a thermalisation time τ_{charm} = 3-14 fm/c describes better the v_2 measurement
- Simultaneous description of R_{AA} and v_2 over a wide p_T interval is challenging: improved precision of the measurements can allow us to set important constraints to models

POWLAND: Eur. Phys. J. C75 (2015) 121; MC@sHQ: PRC 89 (2014) 014905; LBT: PLB 777 (2018) 255; BAMPS: J. Phys. G 42 (2015) 115106; PHSD: PRC 93 (2016) 034906

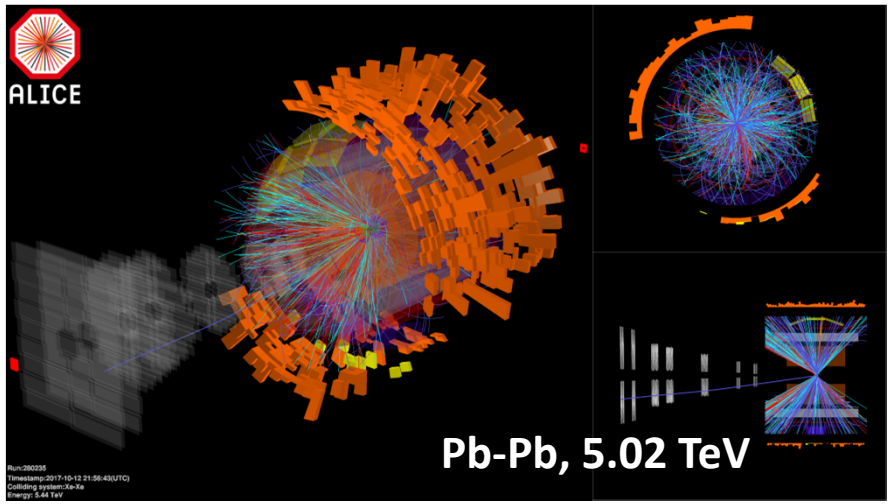
Heavy-flavour decay lepton R_{AA} in Xe-Xe collisions

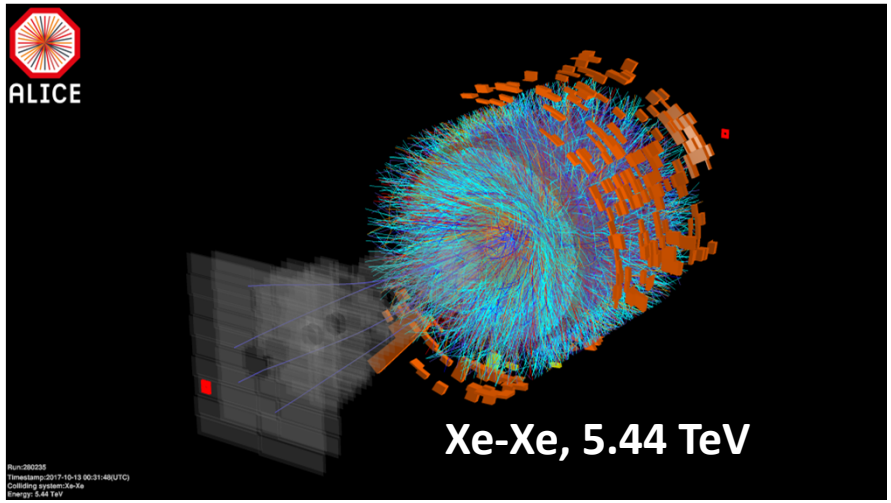




- Similar heavy-flavour hadron decay muon R_{AA} observed in central Xe-Xe and Pb-Pb collisions at similar charged-particle multiplicity
  - Possible interplay of geometry and path-length dependence of energy loss
  - Additional constraints to model calculations
- Similar suppression also observed for heavy-flavour hadron decay electrons at mid-rapidity

Selected quarkonium highlights in Pb-Pb and Xe-Xe collisions

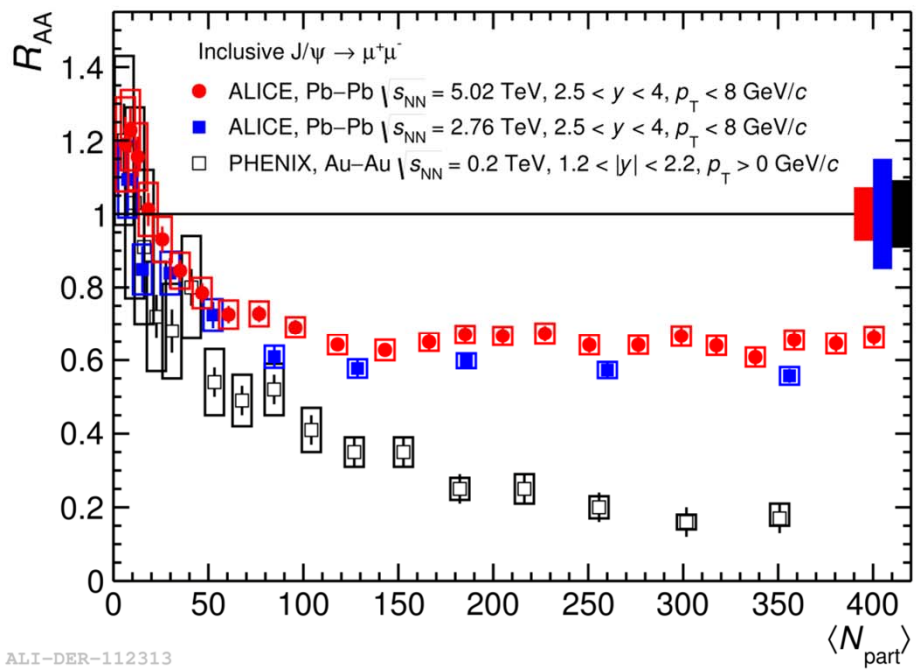


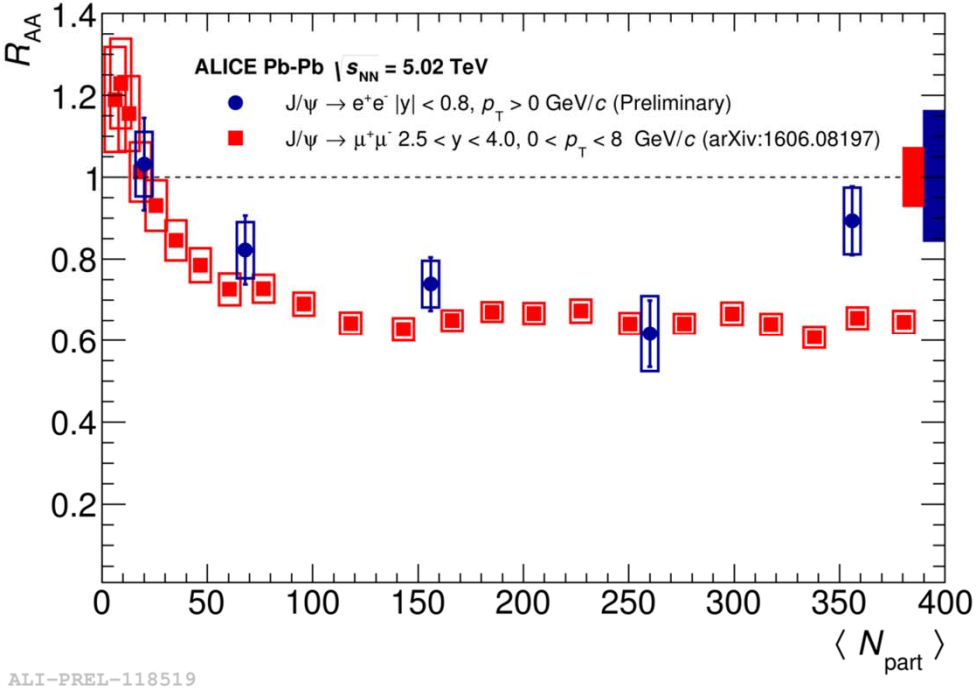


Quarkonium channels in ALICE

- Mid rapidity ($|y| < 0.9$)
  - $J/\psi \rightarrow e^+e^-$
- Forward rapidity ($2.5 < y < 4$)
  - $J/\psi \rightarrow \mu^+\mu^-$
  - $\psi(2S) \rightarrow \mu^+\mu^-$
  - $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S) \rightarrow \mu^+\mu^-$

J/ψ R_{AA} in Pb-Pb collisions at 5.02 TeV



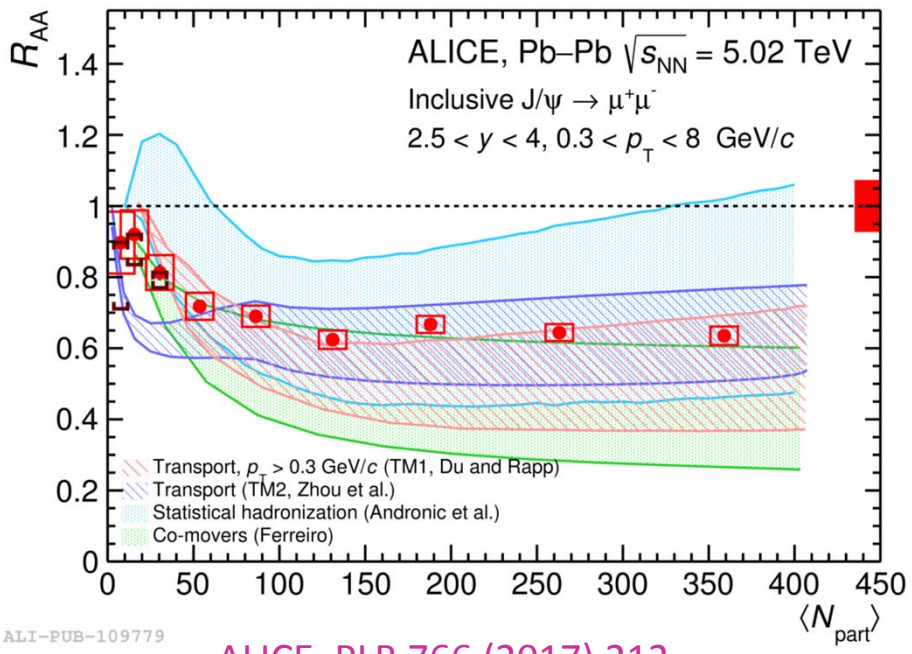


ALICE, PLB 766 (2017) 212, PHENIX, PRL 98 (2007) 232301

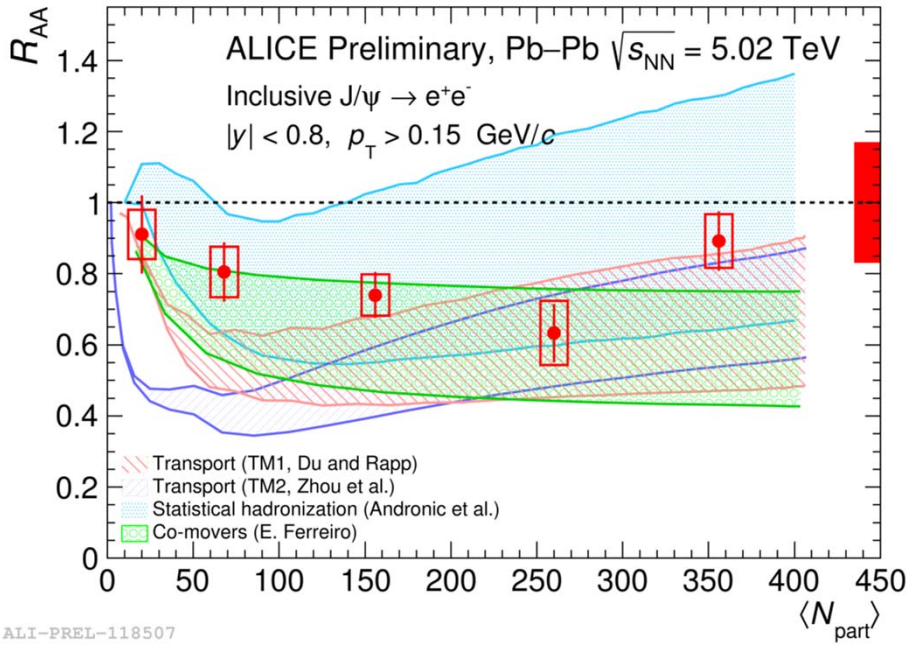
- Significant J/ψ suppression at $\sqrt{s_{NN}}$ = 2.76 TeV with a saturation for $\langle N_{part} \rangle$ > 50
- Different trends observed at RHIC
- Measured suppression at 5.02 TeV confirms the observations at 2.76 TeV with an increased precision
- Comparable J/ψ suppression at forward and mid rapidity with a hint of less suppression at mid rapidity in the most central collisions

J/ψ R_{AA} in Pb-Pb collisions at 5.02 TeV

2.5 < *y* < 4



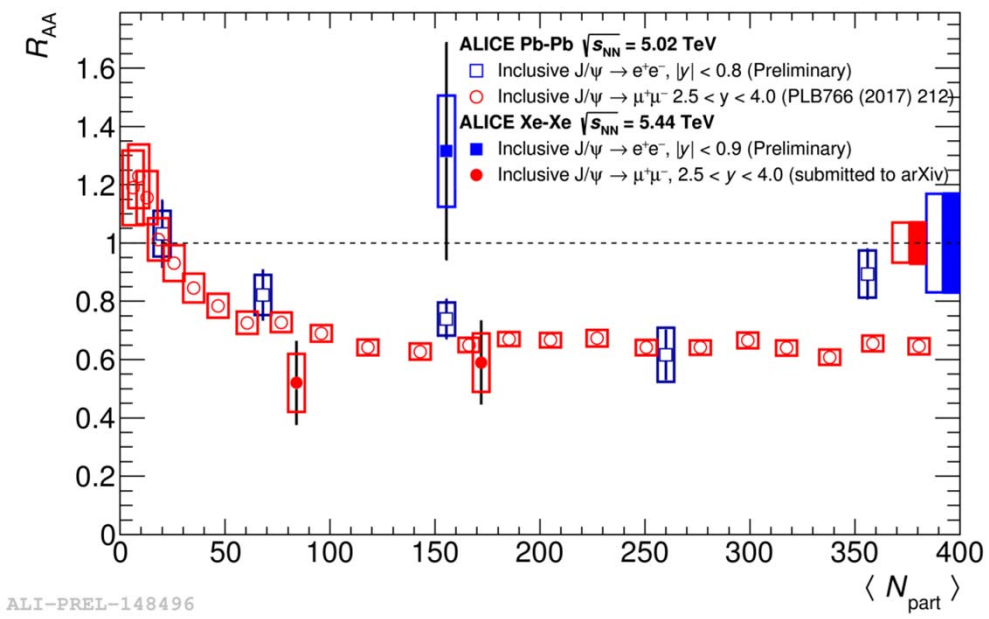
-0.8 < *y* < 0.8

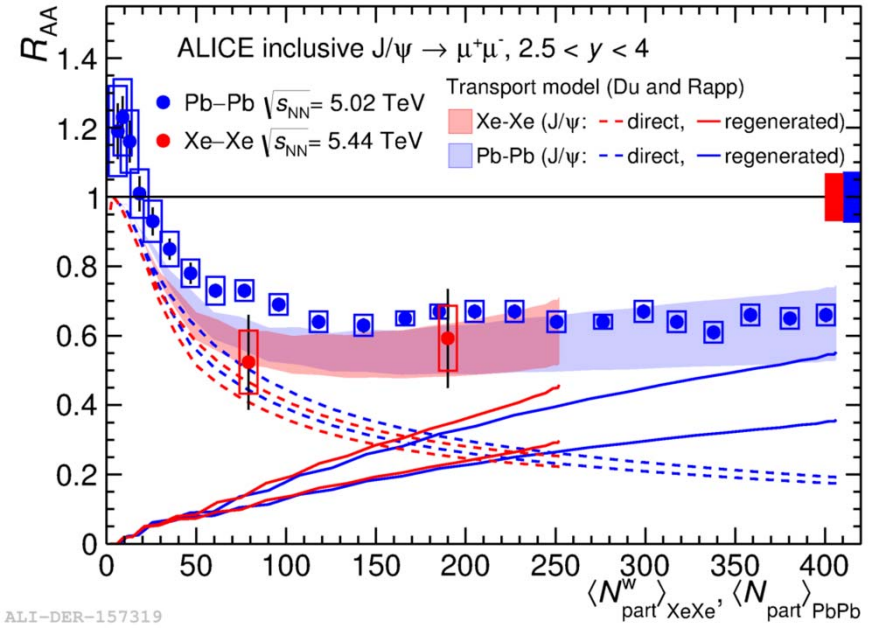


ALICE, PLB 766 (2017) 212

- Experimental observations interpreted as interplay between suppression and regeneration
- Data described by all models within their rather large uncertainties
  - Main uncertainty sources: charm cross section and cold nuclear matter effects on quarkonium production

J/ψ R_{AA} in Xe-Xe and Pb-Pb collisions





ALICE, PLB 766 (2017) 212 (Pb-Pb, 2.5 < y < 4), arXiv:1805.04383 (Xe-Xe, 2.5 < y < 4)

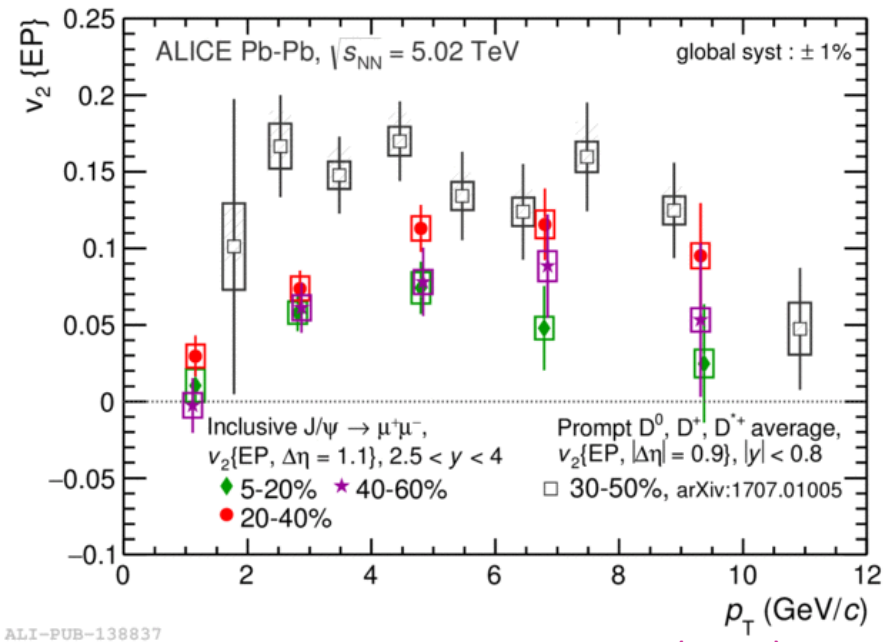
Forward rapidity

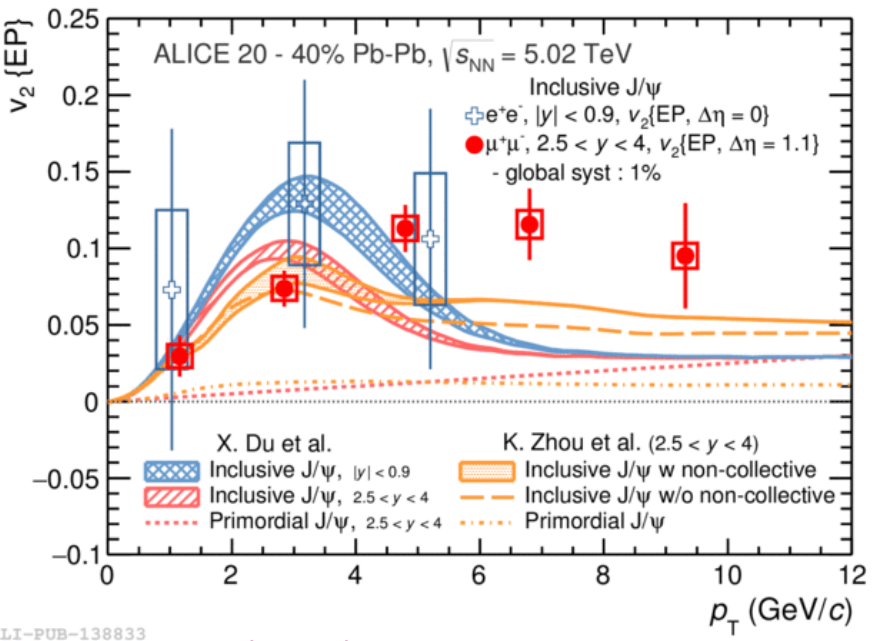
- R_{AA} in Xe-Xe collisions in agreement, within large uncertainties, with the Pb-Pb results and described by a transport model
- Similar relative contribution of suppression and regeneration processes at similar ⟨ N_{part} ⟩

Mid rapidity

- R_{AA} in Xe-Xe collisions consistent with unity within large uncertainties

J/ψ elliptic flow in Pb-Pb collisions at 5.02 TeV



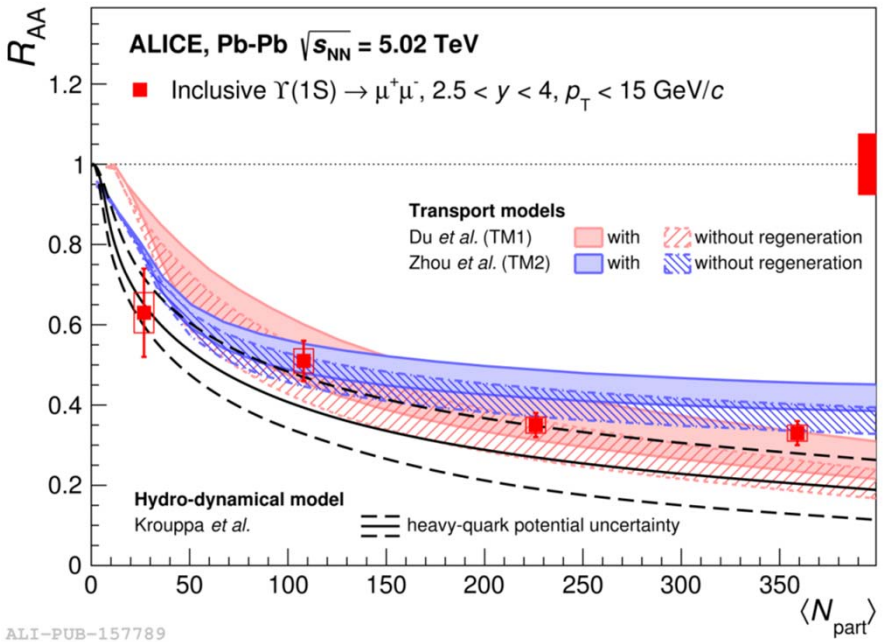


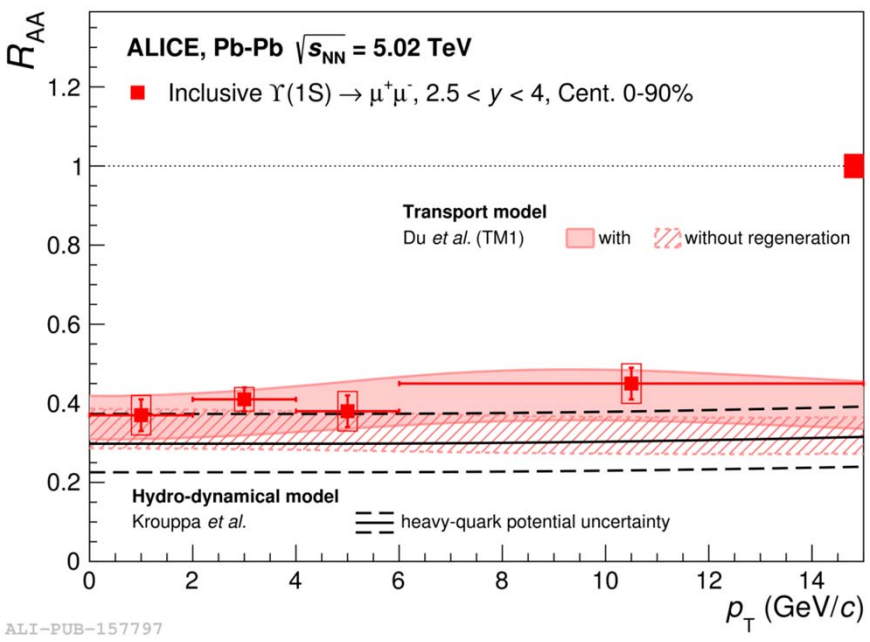
ALICE, PRL 120 (2018) 102301, ALICE, PRL 119 (2017) 242301

- Significant J/ψ v_2 signal observed at forward rapidity in 2 < p_T < 8 GeV/c
  - Highest significance: 6.6σ in 4 < p_T < 6 GeV/c for the 20-40% centrality class
- Compatible results at forward and mid rapidity
- At low p_T, transport models including regeneration reproduce the data
- At high p_T, the measured v_2 is underestimated by the models
- Larger D-meson v_2 at low p_T (but different kinematics)

→ Suggests that J/ψ mesons inheriting their flow from thermalized charm quarks

Υ(1S) and Υ(2S) R_{AA} in Pb-Pb collisions at 5.02 TeV





ALICE, arXiv:1805.04387

- Clear Υ(1S) suppression increasing with increasing centrality: a factor ~3 in the 0-10% centrality class
- No significant dependence of the Υ(1S) suppression on p_T
- Υ(1S) suppression described by transport models with and without regeneration
- Data on the upper edge of hydro-dynamical model for $\langle N_{part} \rangle > 70$

- R_{AA} (Υ(2S)) / R_{AA} (Υ(1S)) = 0.28 $\pm$ 0.12 (stat.) $\pm$ 0.06 (syst.) in 0-90% centrality class

Conclusion

- Large amount of results produced in heavy-ion collisions in the heavy-flavour sector during Run-1 and Run-2

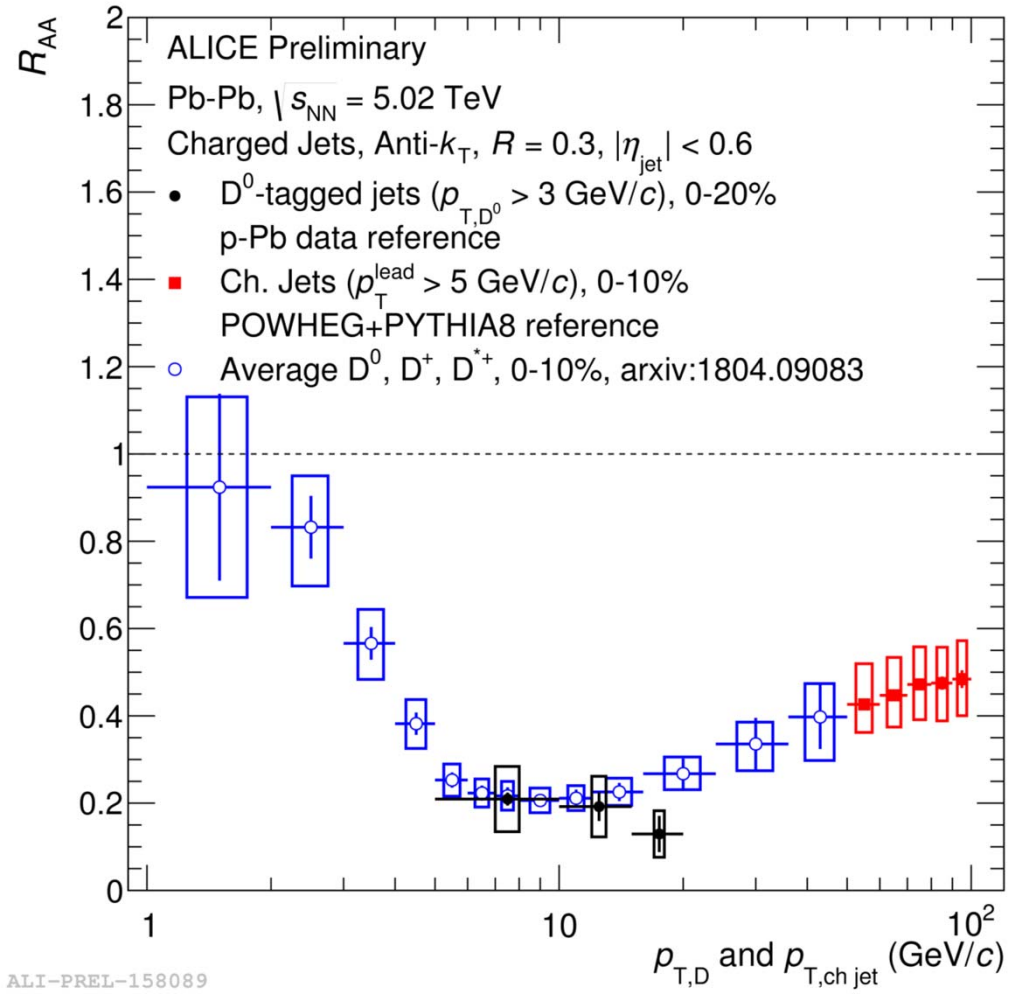
- Open heavy flavours
  - Strong suppression of heavy-flavour yields at high p_T
  - Hint of R_{AA} (D^+_s) > R_{AA} (D) and R_{AA} (Λ^+_c) > R_{AA} (D): R_{AA} ordering consistent with recombination picture
  - Significant D-meson v_2: strong coupling of charm quarks with the medium
  - Similar R_{AA} in central Xe-Xe and Pb-Pb collisions at similar $\langle dN/d\eta \rangle$
    - Geometry, path-length dependence of in-medium energy loss
- Quarkonia
  - J/ψ R_{AA} described by interplay of suppression and recombination mechanisms
  - Significant J/ψ v_2 at low/intermediate p_T from thermalization of charm quarks
  - Clear suppression of Υ production

- More to come soon: second Pb-Pb run scheduled at the end of 2018
- After the ALICE Upgrade, improved precision on current measurements and access to new set of observables to characterize the QGP properties
  - First measurement of D^0-tagged jet R_{AA} very promising

→ Stay tuned

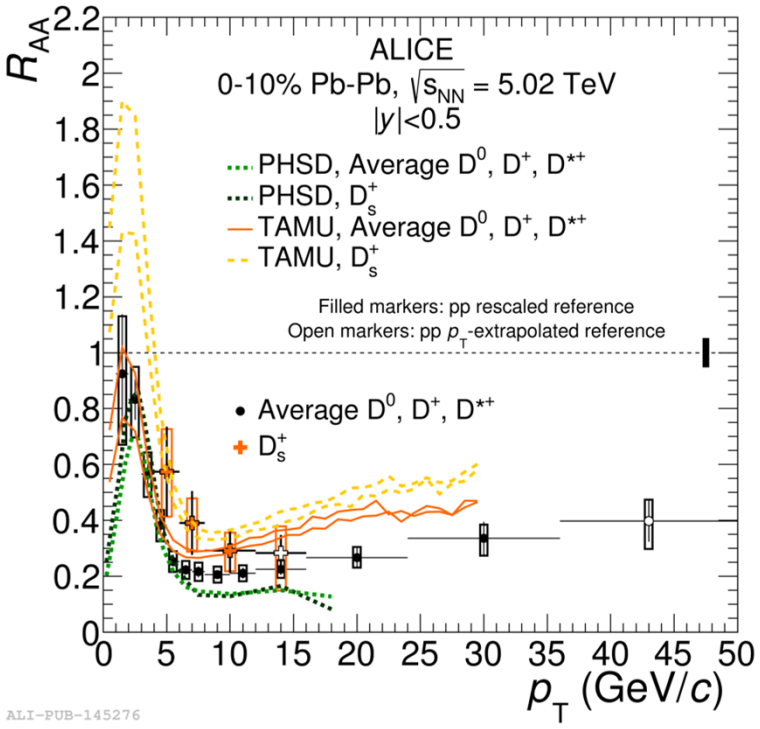

Thank you for
your attention

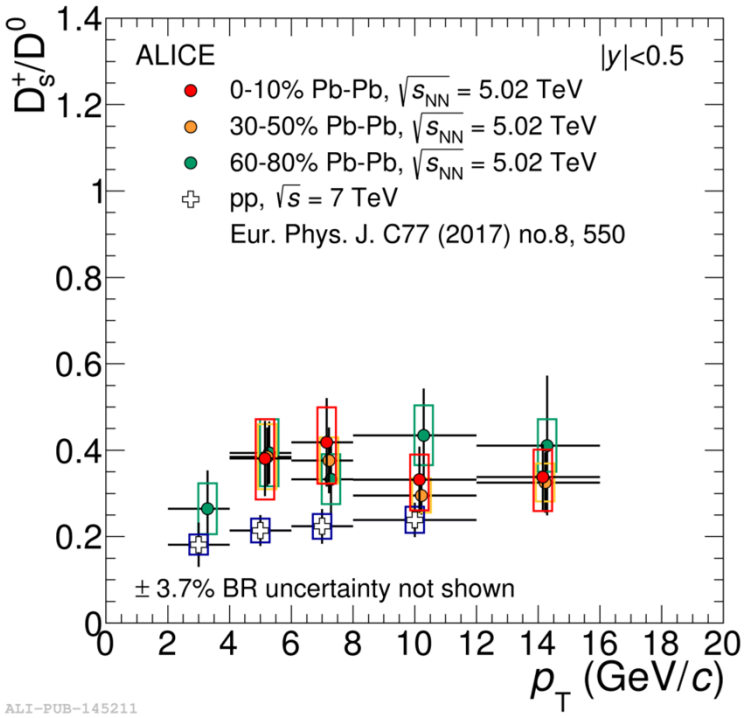
D-meson tagged jets



Similar suppression for D^0-tagged jets as for D^0 mesons

Strange and non-strange D-meson R_{AA} in Pb-Pb collisions at 5.02 TeV





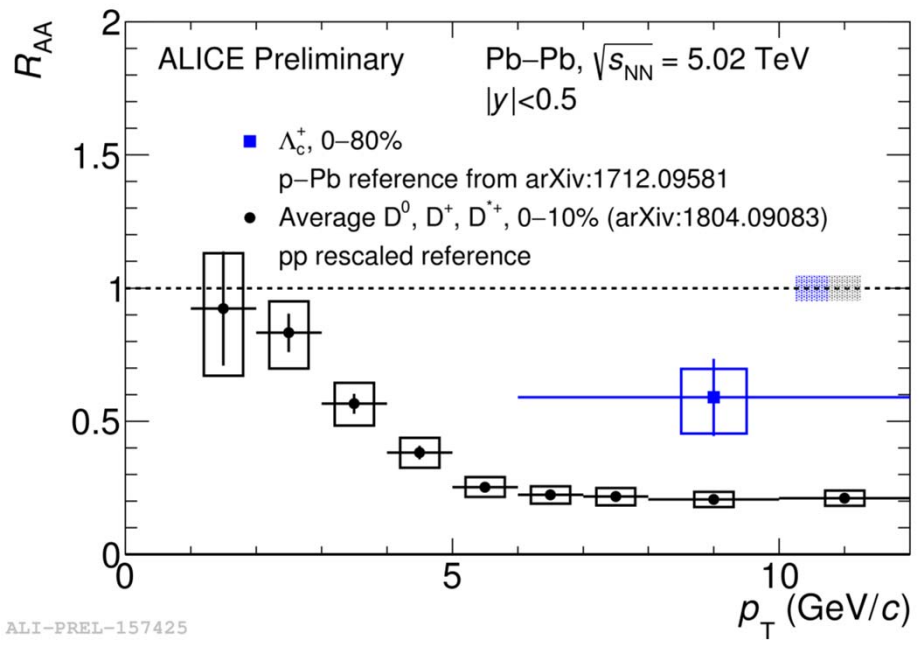
ALICE, arXiv:1804.09083

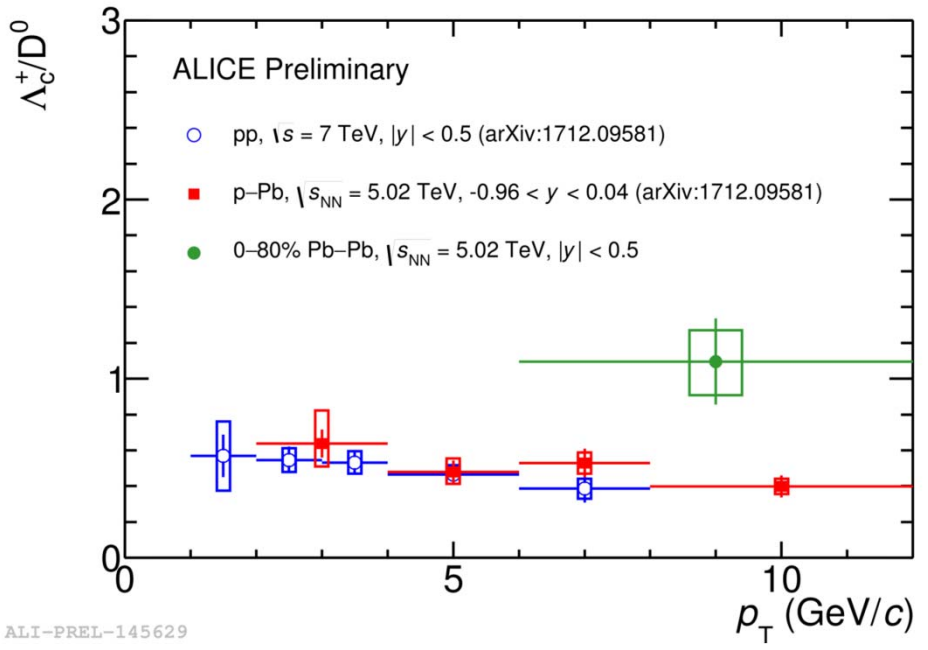
PHSD: PRC 93 (2016) 034906, TAMU: PLB 735 (2014) 445

- Hint of enhanced D^+_s production compared to non-strange D mesons in central Pb-Pb collisions at 5.02 TeV as expected from models
  - Hadronisation via coalescence in a strangeness-rich environment?
- No significant dependence of D^+_s/D^0 ratio on collision centrality within uncertainties
  - Expected within a pure coalescence scenario

Λ_c^+ measurements in Pb-Pb collisions at 5.02 TeV

$\Lambda_c^+ \rightarrow p\, K^0_s \rightarrow p\pi^+\pi^-$ **(BR ~ 1.58%)**

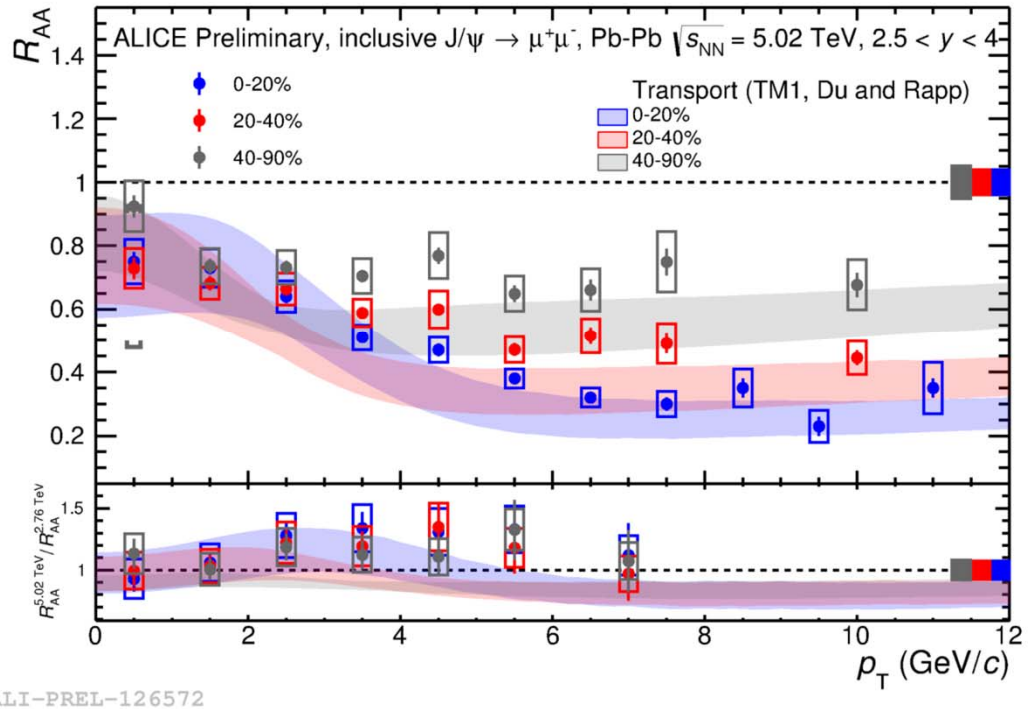




- Λ_c^+ measured in Pb-Pb colllisions at 5.02 TeV for 0-80%:
- Hint of a larger R_{AA} for Λ_c^+ in 0-80% than for D mesons in 0-10%
- Hint of an enhanced Λ_c^+/D^0 ratio in Pb-Pb compared to pp and p-Pb collisions
- Λ_c^+/D^0 ratio underestimated by models:
  - p_T = 9 GeV/*c:* **0.15-0.2** at LHC and RHIC (Ghost et al., PRD 90 (2014) 054018) and **~0.2** in Pb-Pb (0-20%) at 5.5 TeV (Das et al., PRD 94 (2016) 114039); p_T = 8 GeV/*c:* **0.1-0.2** in Pb-Pb (0-20%) at 2.76 TeV (Plumari et al., Eur. Phys. C 78 (2018) 348)

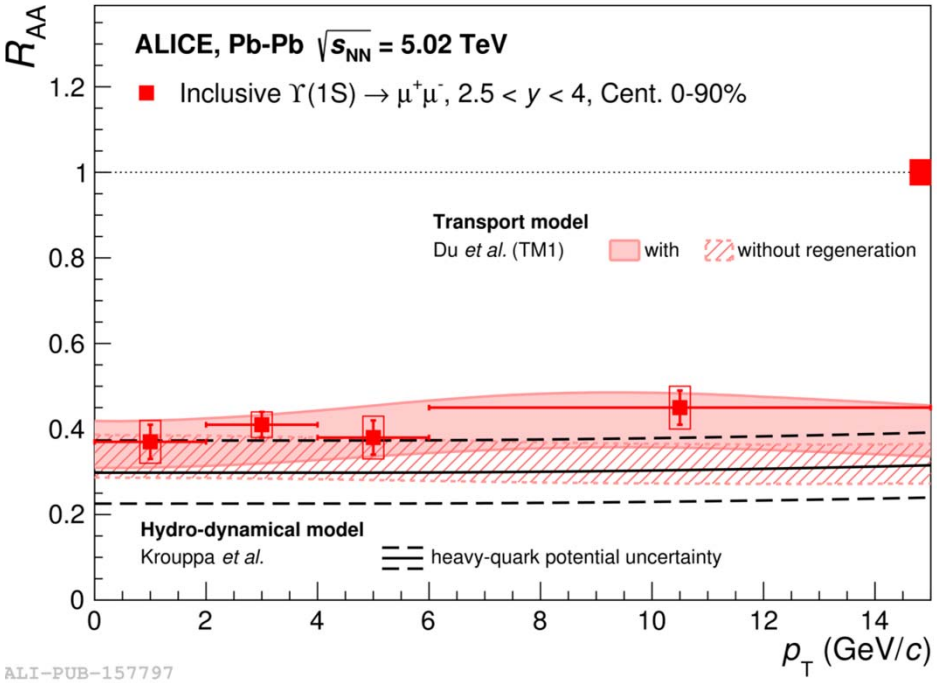
  → fragmentation not well understood

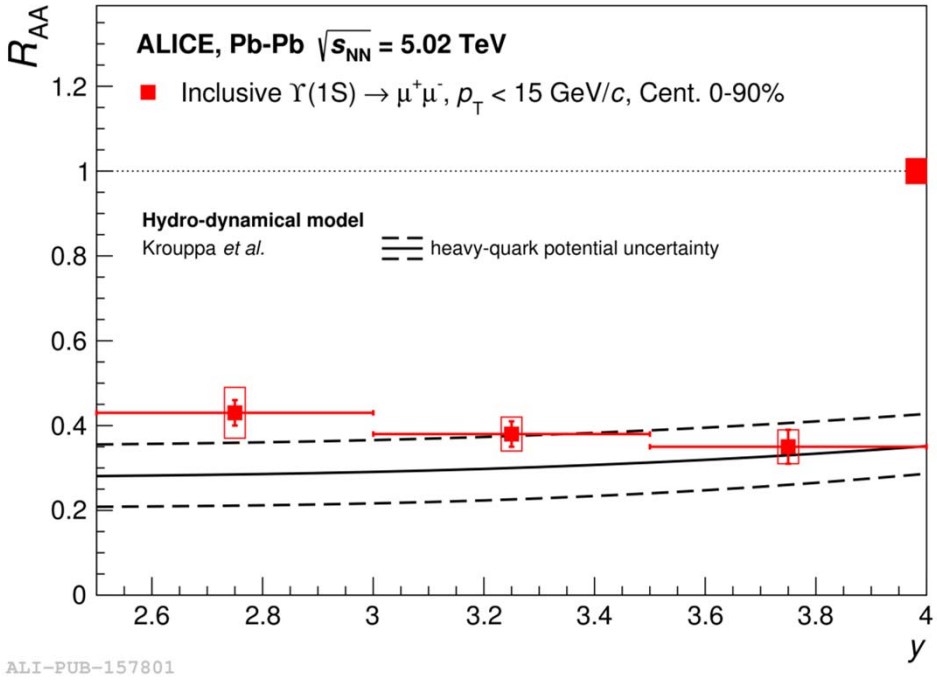
J/ψ R_{AA} in Pb-Pb collisions at 5.02 TeV



- Stronger p_T dependence in central collisions
- Suppression increases with increasing centrality at high p_T
- Experimental trends reproduced by transport model calculations

Υ(1S) and Υ(2S) R_{AA} in Pb-Pb collisions at 5.02 TeV





ALICE, arXiv:1805.04387

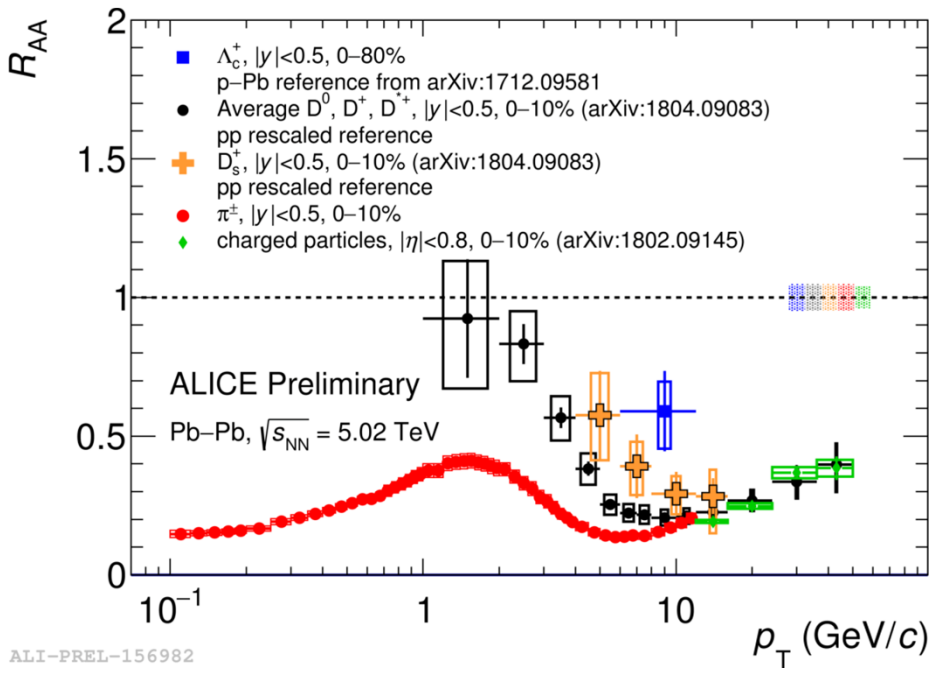
- No significant dependence of the Υ(1S) suppression on p_T and y
- In agreement with models within uncertainties

- R_{AA} (Υ(2S)) / R_{AA} (Υ(1S)) = 0.28 $\pm$ 0.12 (stat.) $\pm$ 0.06 (syst.) in 0-90% centrality class

Λ^+_c/D^0 ratio in Pb-Pb collisions

Oh et al. PRC 79 (2009) 044905	Au+Au (central) 0.2 TeV	~0.35 (p_T = 6 GeV/c)
Ghosh et al. PRD 90 (2014) 054018	RHIC, LHC	0.15 -0.2 (p_T = 9 GeV/c)
Das et al. PRD 94 (2016) 114039	Pb-Pb (0-20%) 5.5 TeV	~0.2 (p_T = 9 GeV/c)
Plumari et al. Eur. Phys. J. C78 (2018) 348	Pbb-Pb (0-20%) 2.76 TeV	0-1-0.5 (p_T = 8 GeV/c)

Open heavy-flavour R_{AA} hierarchy (II)



- Hint of enhanced D^+_s production compared to non-strange D mesons in central Pb-Pb collisions at 5.02 TeV as expected from models
  - Hadronisation via coalescence in a strangeness-rich environment?
- Hint of a larger R_{AA} for Λ_c^+ in 0-80% than for D mesons in 0-10%
- Λ_c^+/D^0 ratio underestimated by models:
  - p_T = 9 GeV/c: **0.15-0.2** at LHC and RHIC (Ghost et al., PRD 90 (2014) 054018) and **~0.2** in Pb-Pb (0-20%) at 5.5 TeV (Das et al., PRD 94 (2016) 114039); p_T = 8 GeV/c: **0.1-0.2** in Pb-Pb (0-20%) at 2.76 TeV (Plumari et al., Eur. Phys. C 78 (2018) 348)

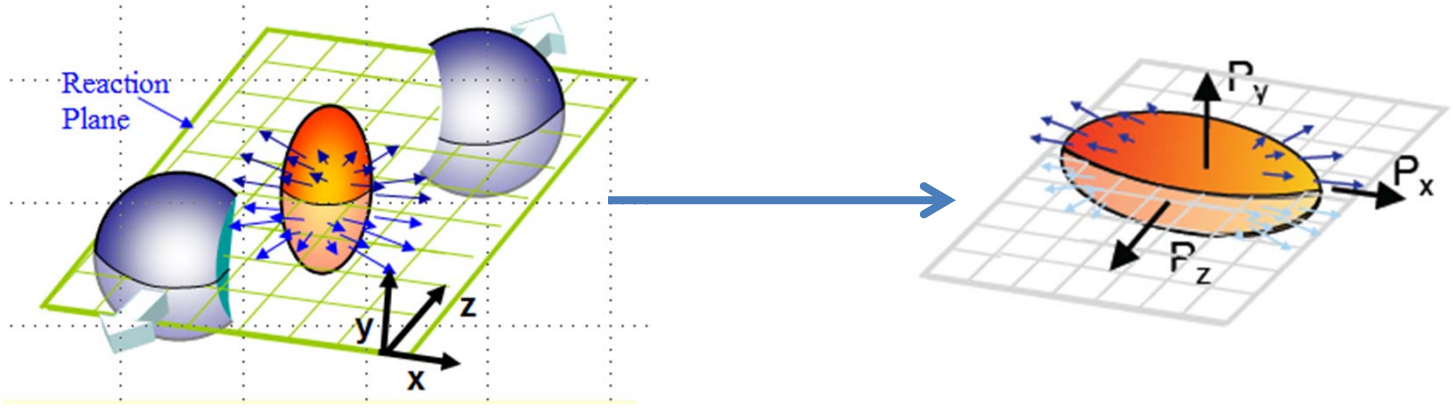
  → fragmentation not well understood

Observables

- Nuclear modification factor R_{AA}

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = 1/< T_{\mathrm{AA}} > \times \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

- Elliptic flow v_2

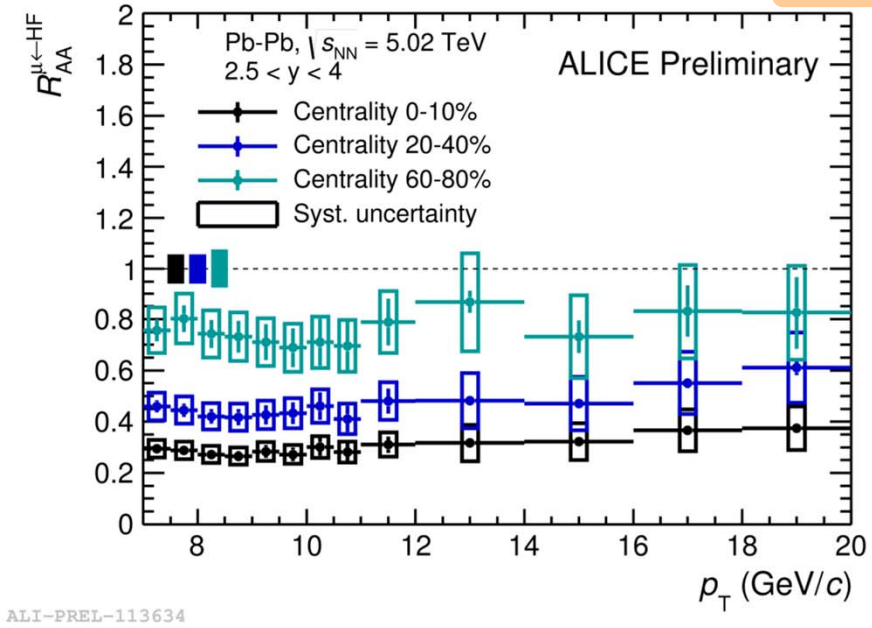


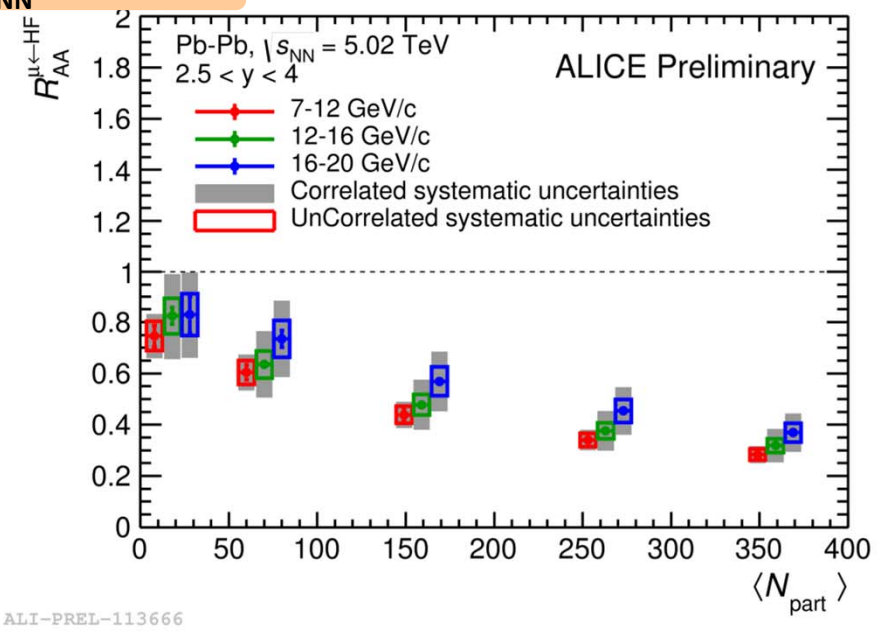
$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)] \qquad v_n = < \cos[n(\varphi - \Psi_n)] >$$

Production of muons from heavy-flavour hadron decays

First Run 2 results on open heavy flavours at forward rapidity (2.5 < y < 4) in the muon channel

Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

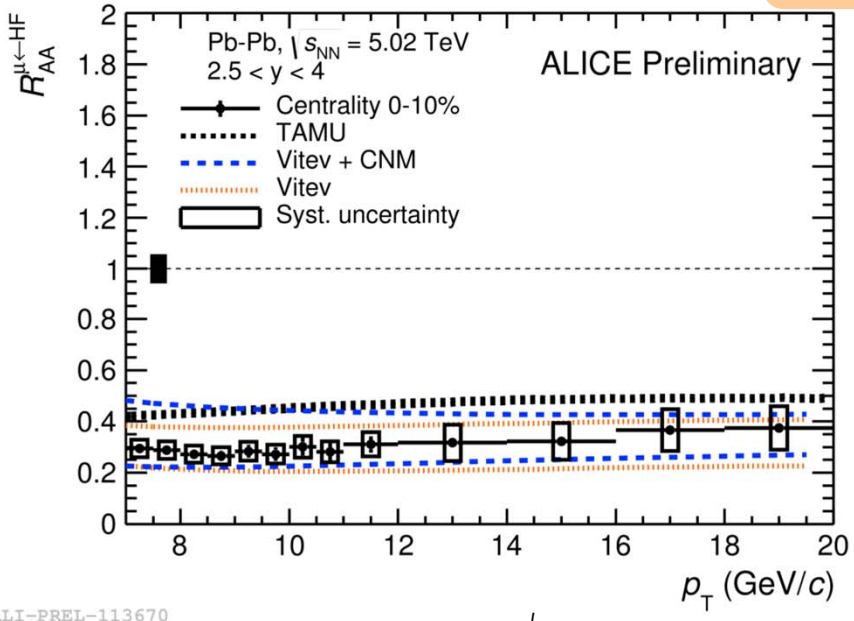


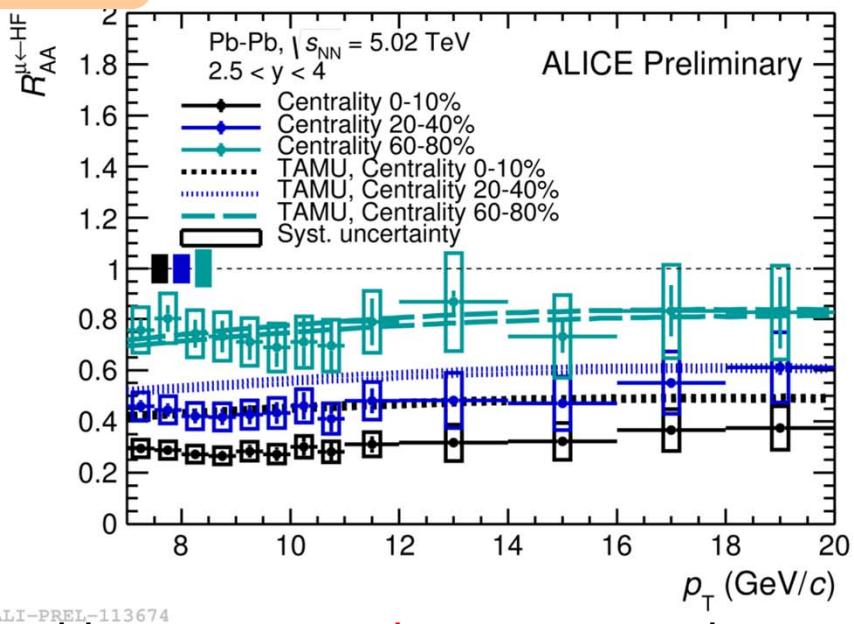


- Production of muons from heavy-flavour hadron decays measured in 5 centrality classes in 0-90% over a wide p_T range
- Strong suppression in the 10% most central collisions: factor ~3 for 7< p_T < 12 GeV/*c*
- No clear p_T dependence within uncertainties
- Clear increase of the suppression from peripheral to central collisions
- Beauty contribution larger than 50% for p_T > 5 GeV/c in pp collisions
  - Beauty suppression at intermediate/high p_T

Muons from heavy-flavour hadron decays at $\sqrt{s_{NN}}$ = 5.02 TeV: comparison with models

Pb-Pb
$\sqrt{s_{NN}}$ = 5.02 TeV



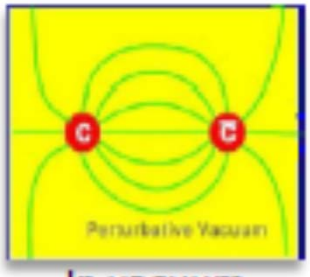


- R_{AA} measurements at $\sqrt{s_{NN}}$ = 5.02 TeV provide new constraints on energy loss models:
  - Vitev: describe the measured R_{AA} of $\mu \leftarrow$ HF in $2.5 < y < 4$ within uncertainties
  - TAMU: tends to overestimate the measured R_{AA} of $\mu \leftarrow$ HF in $2.5 < y < 4$ for central collisions (0-10%) and describe within uncertainties the measurement in semi-central and peripheral collisions (20-40%, 60-80%)

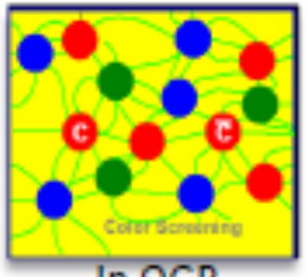
Vitev: Phys. Rev. C 80 (2009) 054902; TAMU: Phys. Lett. B 735 (2014) 445

Quarkonium production

- Colour screening in the QGP
  → quarkonium suppression
  [T. Matsui & H. Satz, PLB 178 (1986) 416]

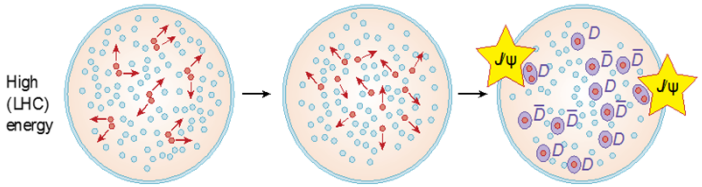


In vacuum



In QGP

Central A-A collisions	SPS 20 GeV	RHIC 0.2 TeV	LHC 2.76 TeV	LHC 5.02 TeV
N_{ccbar}/event	~0.2	~10	~85	~115

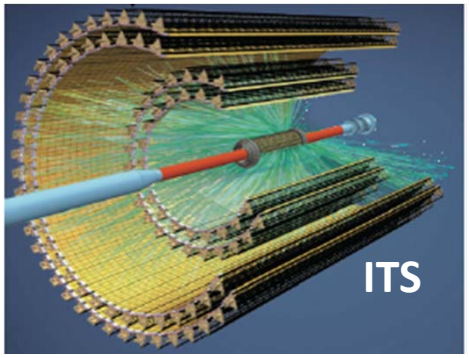


- Abundant production of $c\bar{c}$ at the LHC may lead to a recombination mechanism at hadronization (statistical approach) or in the QGP (kinetic approach) which enhances charmonium production
  [P. Braun-Munzinger & J. Stachel, PLB 490 (2000) 196, B. Thews et al., PRC 63 (2001) 054905]

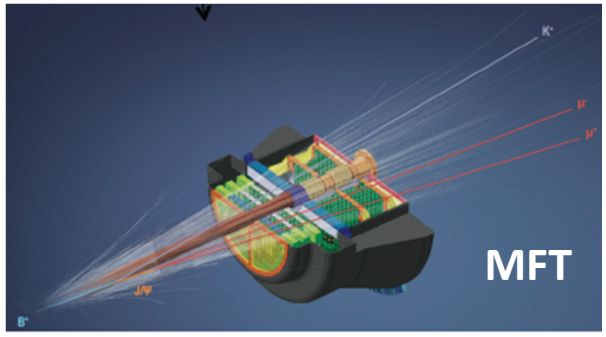
ALICE upgrade

- Major upgrade currently in preparation for LHC Run3 (2021-2023)
  - Ongoing R&D, construction and installation during the second Long Shutdown
  - New conditions with Run 3: Pb-Pb interaction may reach 50kHz (now ~ 8 kHz)

- Goals of ALICE Run 3:
  - High precision measurements of rare probes with main focus on the low p_T region
    → x 100 larger minimum-bias sample compared to Run 2 (~10^{11} events)
  - Increase readout rate to 50 kHz, presently limited to ~1 kHz
  - Improvement of pointing resolution at both central and forward rapidity



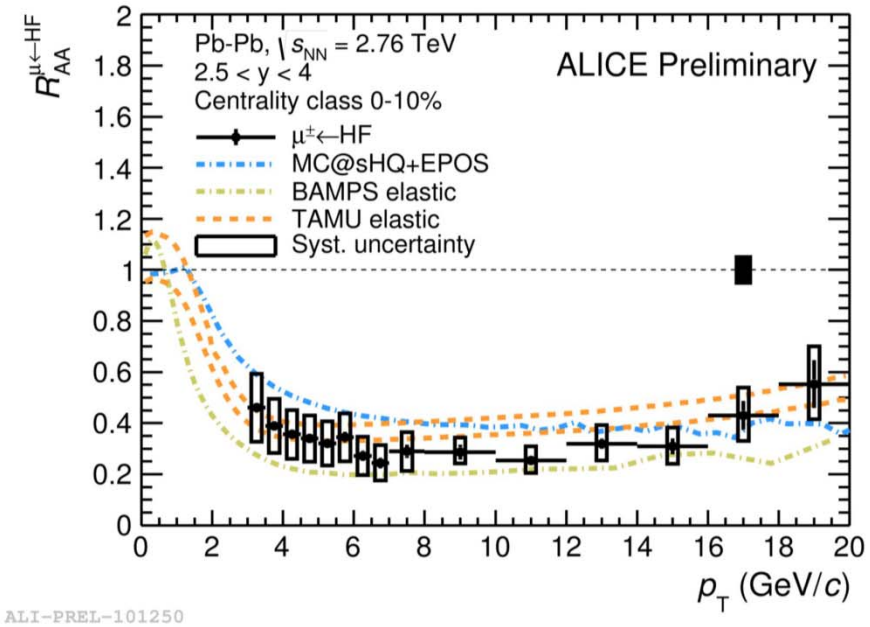
- **New Inner Tracking System (ITS)**
  - Improved pointing resolution,
    reduced material budget, faster readout
- **New Forward Muon Tracker (MFT)**
  - New Silicon tracker,
    heavy-flavour vertices also at forward rapidity
- **New TPC readout chambers based on GEM**
- **Upgraded readout for many detectors,**
  Integrated Online-Offline (O^2) system,
  New Fast Integration Trigger detector (FIT)

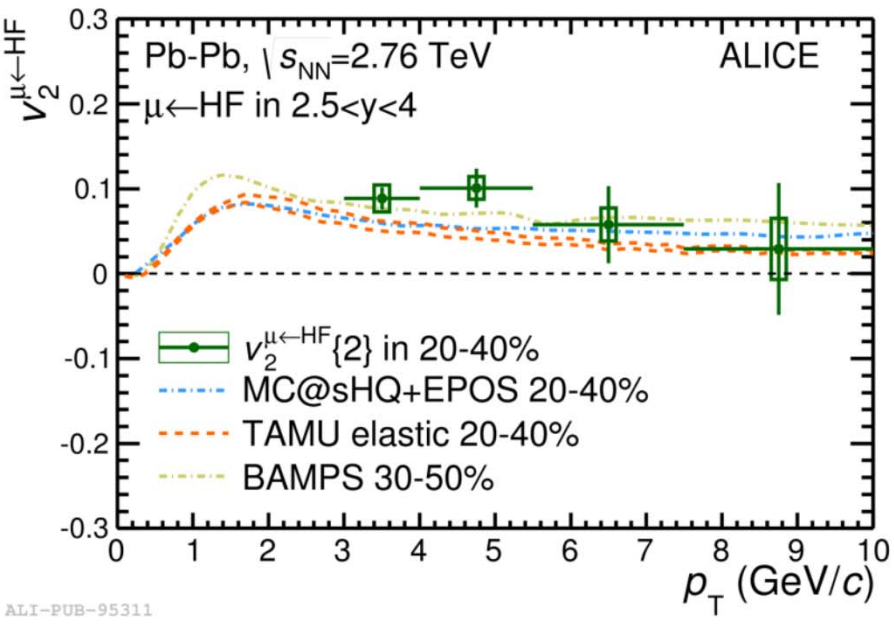


Technical Design Reports approved → moving to construction

Muons from heavy-flavour hadron decays at $\sqrt{s_{NN}}$ = 2.76 TeV: comparison with models

ALICE, PLB 753 (2016) 41

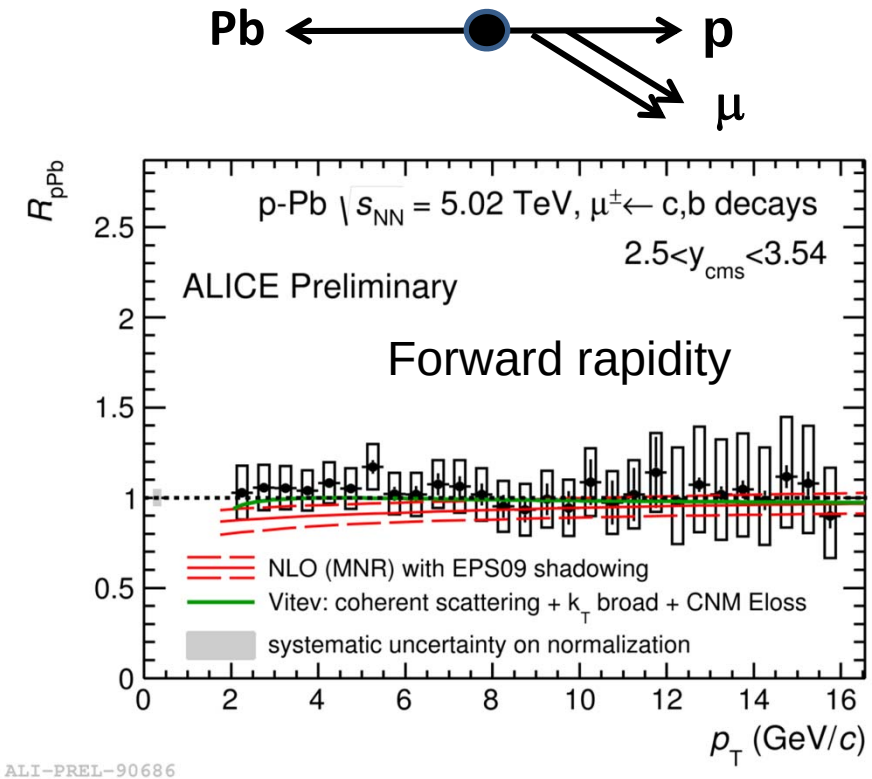


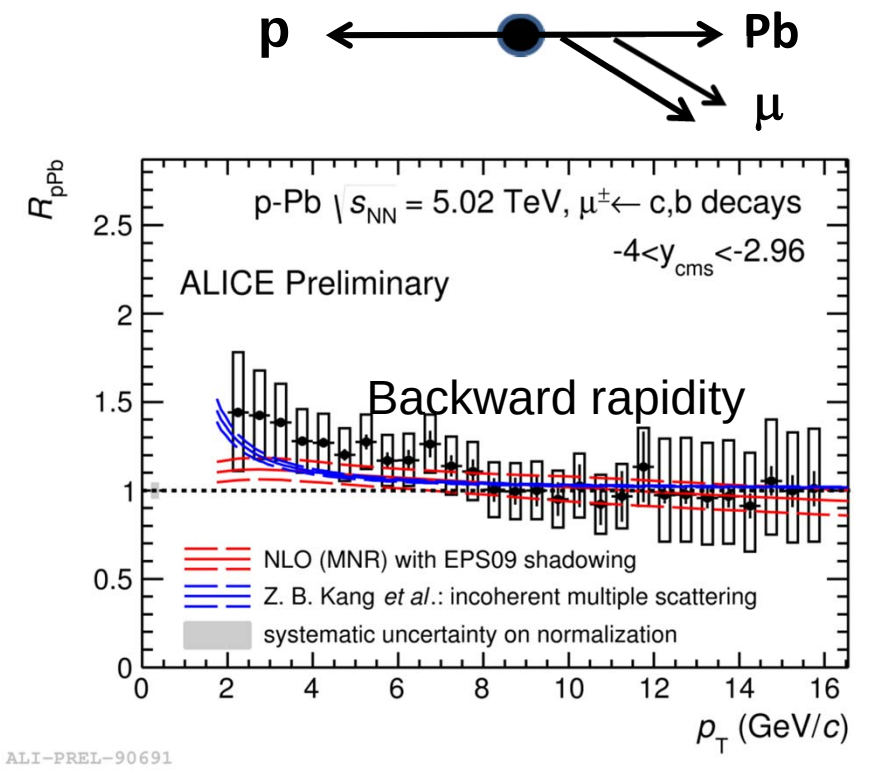


- R_{AA} in central collisions and v_2 in semi-central collisions reasonably described by models including energy loss in the QGP but not in details
  - Further constraints to models: comparison with Run 2 measurements

MC@ sHQ+EPOS, Coll + Rad (LPM): Phys. Rev. C 89 (2014) 014905;
BAMPS: Phys. Lett. B 717 (2012) 430;
TAMU: Phys. Lett. B 735 (2014) 445

Heavy-flavour decay muons: R_{pPb} *vs* p_T





- R_{pPb} at forward rapidity is consistent with unity and, at backward rapidity is slightly larger than unity in $2 < p_T < 4$ GeV/c and close to unity at higher p_T
- Cold nuclear matter effects are small
- R_{pPb} described by perturbative QCD calculations implementing cold nuclear matter effects

pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295, EPS09: K. J. Eskola et al., JHEP 04 (2009) 065
R. Sharma et al., Phys. Rev. C 80 (2009) 054902; Z.B. Kang et al., Phys. Lett. B 740 (2015) 23