Highlights from heavy-flavour measurements in heavy-ion collisions with ALICE at the LHC

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ALICE

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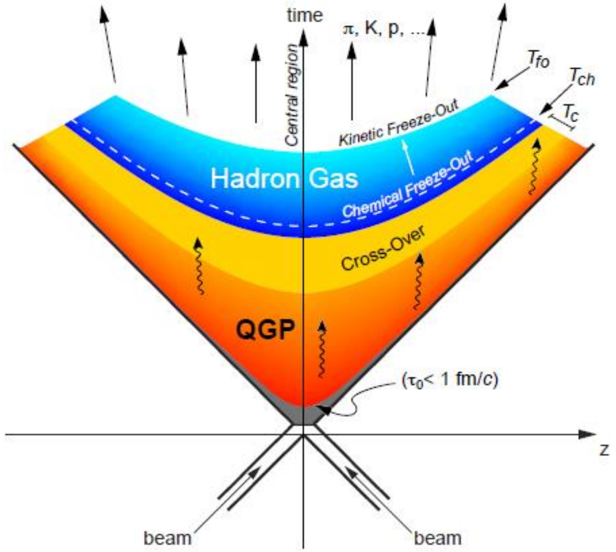
Why study heavy flavours?

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 $< \tau_{QGP}$ (~0.3 fm/c)
- Flavour conserved by the strong interaction
- Experience the full collision history
  - ➢ Excellent probes to characterise 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

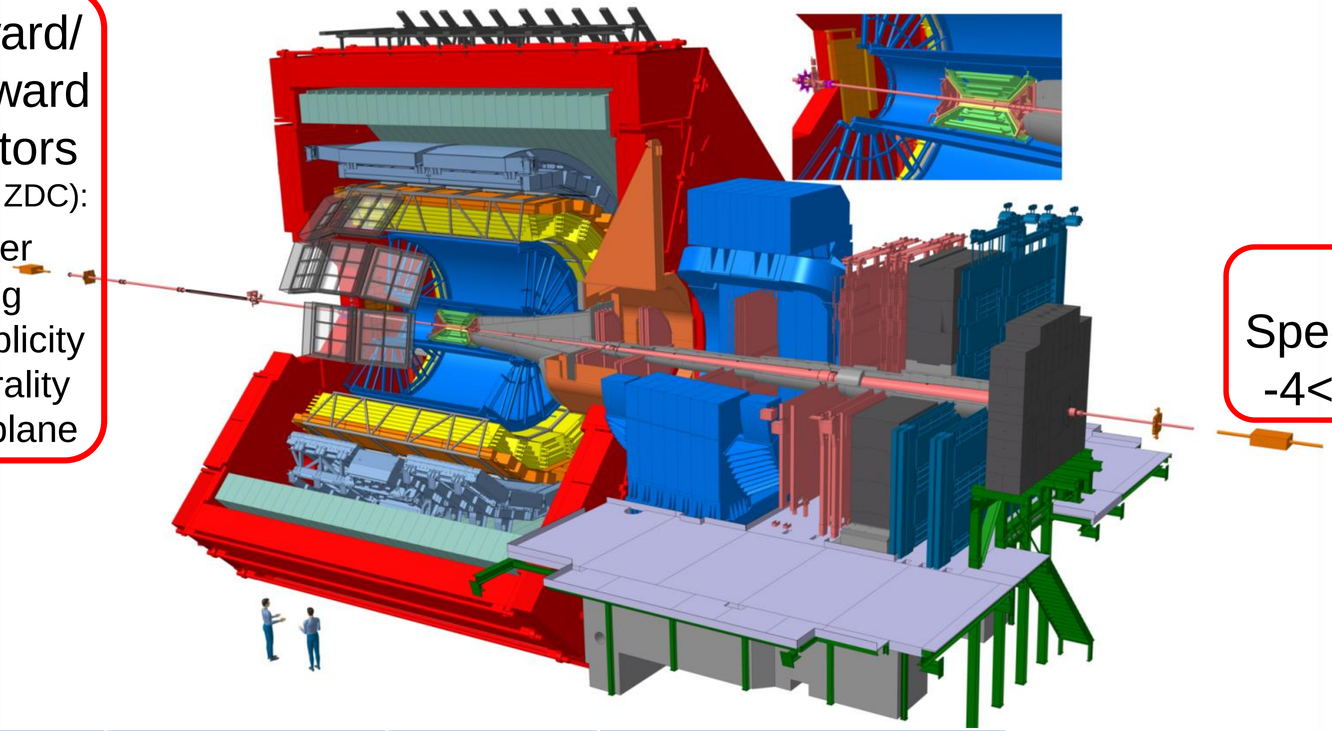
❖ p–Pb collisions: control experiment, cold nuclear matter effects, QGP formation in high-multiplicity events?

❖ pp collisions: reference, tests of pQCD-based predictions, production mechanisms

ALICE layout

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

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



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

System	year	$\sqrt{s_{NN}}$ (TeV)	L_{int} (μb^{-1}) μ triggers
Pb–Pb	2010-2011	2.76	~75
Pb–Pb	2015 + 2018	5.02	~225 + 750
Xe–Xe	2017	5.44	~0.3

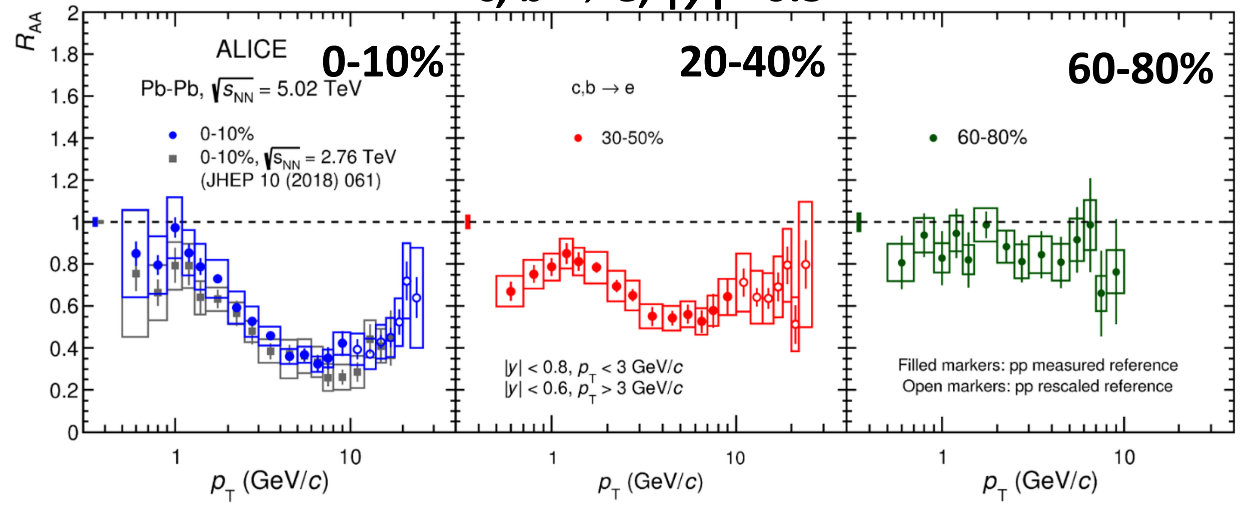
Heavy-flavour channels

- $D^0 \to K^-\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D^{*+} \to D^0 (\to K^-\pi^+)\ \pi^+$
- $D^+_s \to \phi\ (\to K^-K^+)\pi^+$
- D, B → eX
- D, B → μX
- B → eX via impact parameter
- $J/\psi \to e^-e^+$
- $J/\psi,\ \psi\ (2S) \to \mu^-\mu^+$
- Υ (1S, 2S, 3S) $\to \mu^-\mu^+$

- $\Lambda_c^+ \to pK^0_s,\ \Lambda_c^+ \to pK^-\pi^+$
- $\Lambda_c^+ \to e^+\Lambda\nu_e$
- $\Xi_c^0 \to e^+\Xi^-\nu_e,\ \Xi_c^0 \to \pi^+\Xi^-$
- $\Xi_c^+ \to \pi^+\pi^+\Xi^-$
- $\Omega_c^0 \to \Omega^-\pi^+$
- $\Sigma_c^0 \to \Lambda_c^+\pi^-$
- $\Sigma_c^{++} \to \Lambda_c^+\pi^+$

Heavy-flavour lepton R_{AA} in Pb–Pb collisions at 5.02 TeV

c, b → e, |*y*|< 0.5

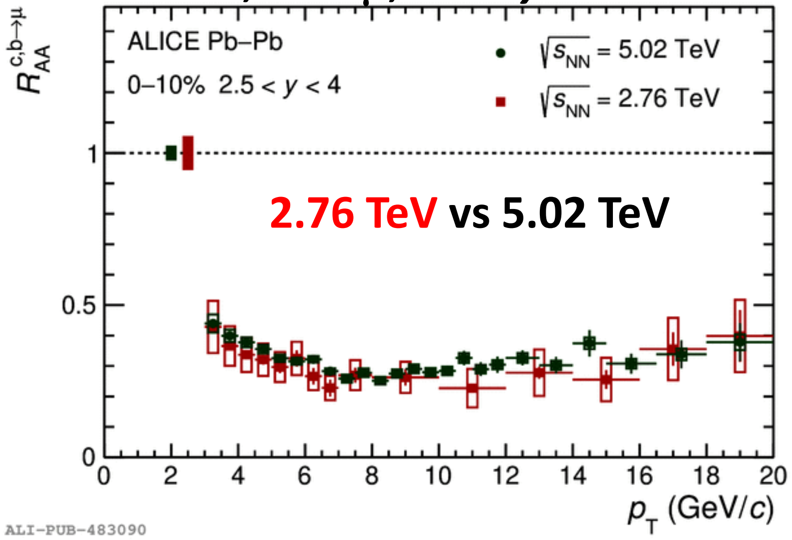


ALICE, PLB 804 (2020) 135377

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

- ❑ Measurement over a wide p_T interval from central to peripheral collisions
- ❑ Strong suppression, increasing with centrality: reaching a factor ~ 3 for 5 < p_T < 10 GeV/*c* in the 10% most central collisions

c, b → μ, 2.5 < *y* < 4

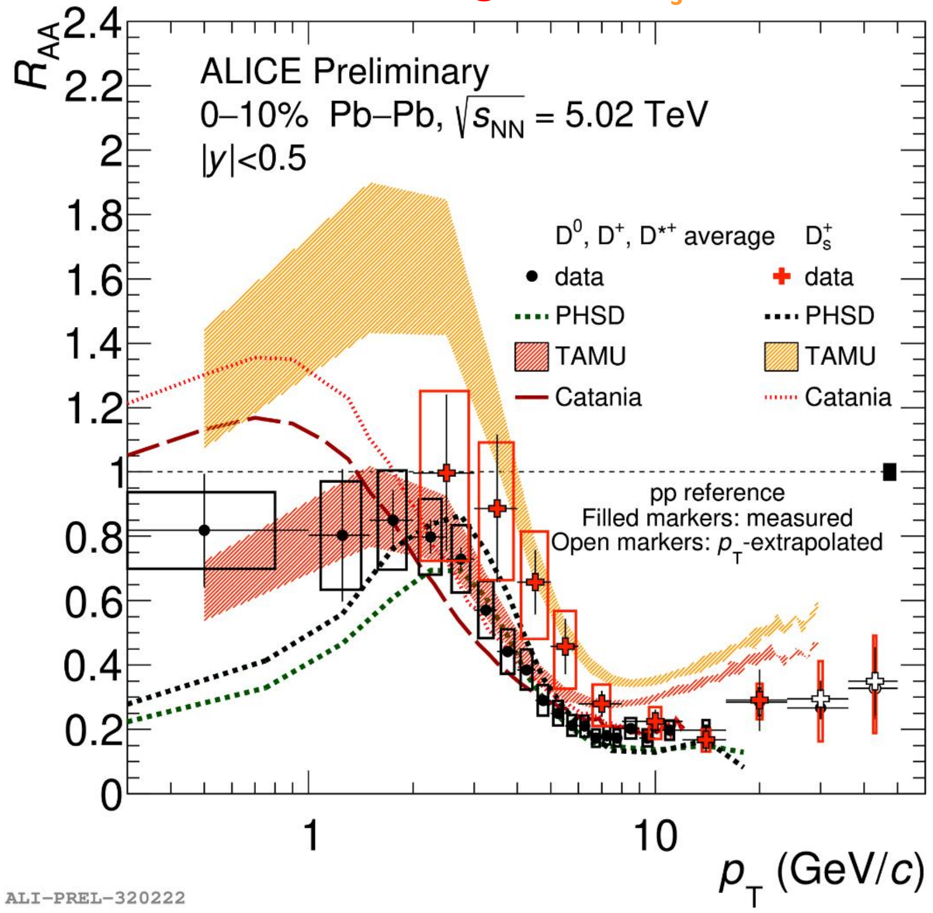


ALICE, PLB 820 (2021) 136558

- ❑ Similar suppression of heavy-flavour decay leptons at mid and forward *y*
  - ➢ Heavy quarks experience in-medium energy loss over a wide *y* interval
- ❑ Similar suppression of heavy-flavour decay muons at 2.76 and 5.02 TeV

Non-strange and strange D-meson R_{AA} in Pb–Pb collisions

non-strange D vs D^+_s

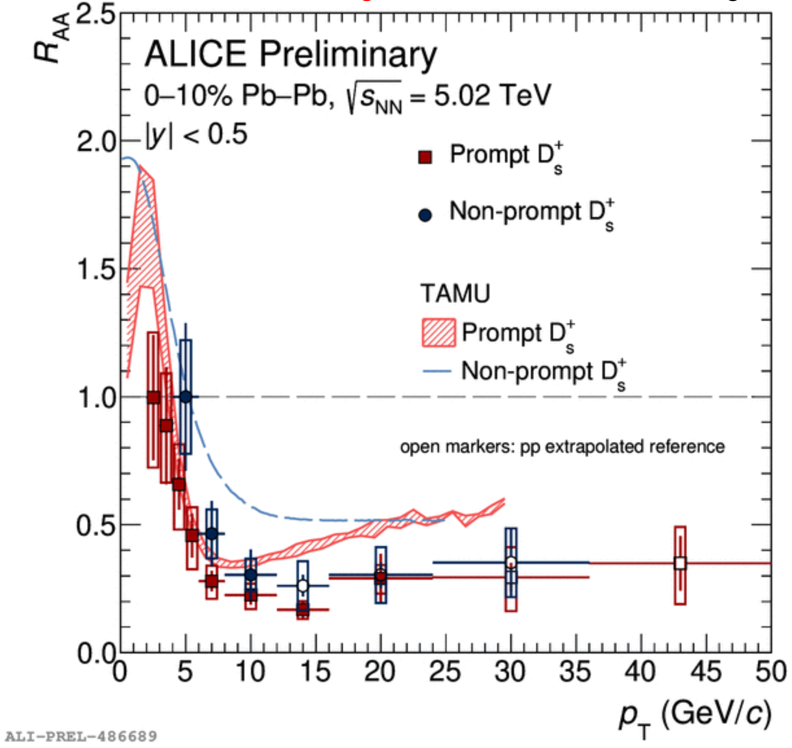


- First time D^0 mesons are measured down to $p_T = 0$
- Hint of a smaller suppression for D_s^+ compared to non-strange D mesons at $p_T < 8$ GeV/c
  - Expected from strangeness enhancement in the QGP and charm-quark hadronisation via coalescence
- Similar suppression for D_s^+ and non-strange at $p_T > 8$ GeV/c where fragmentation is the dominant mechanism
- R_{AA} hierarchy described within uncertainties by transport models including hadronisation via coalescence

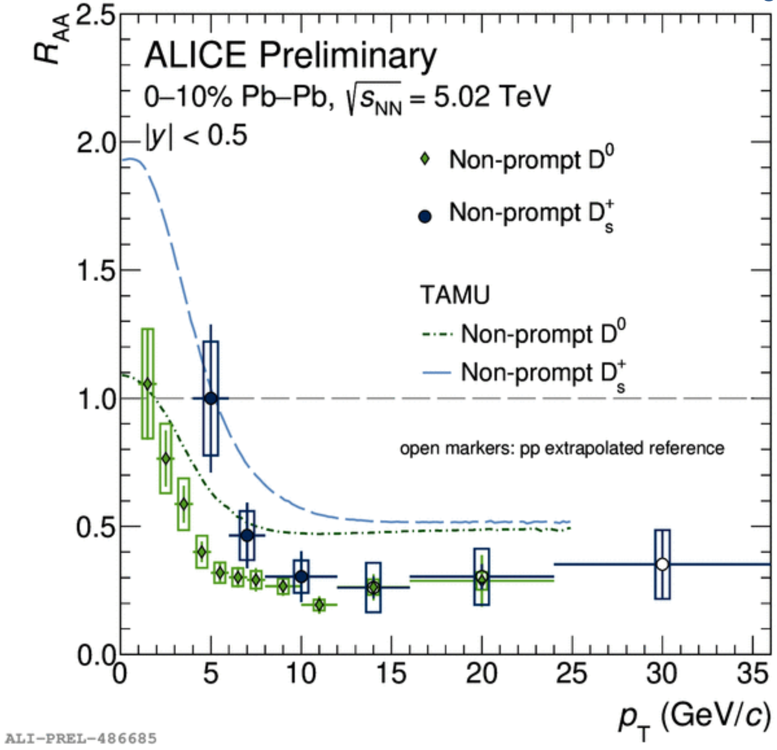
PHSD: PRC 93 (2016) 034906
TAMU: PRL 124 (2020) 042301
PRC 96 (2017) 054901
Catania: EPJC 78 (2018) 348

Non-prompt D^0 and D_s^+ R_{AA} in Pb–Pb collisions

prompt D^+_s & non-prompt D^+_s



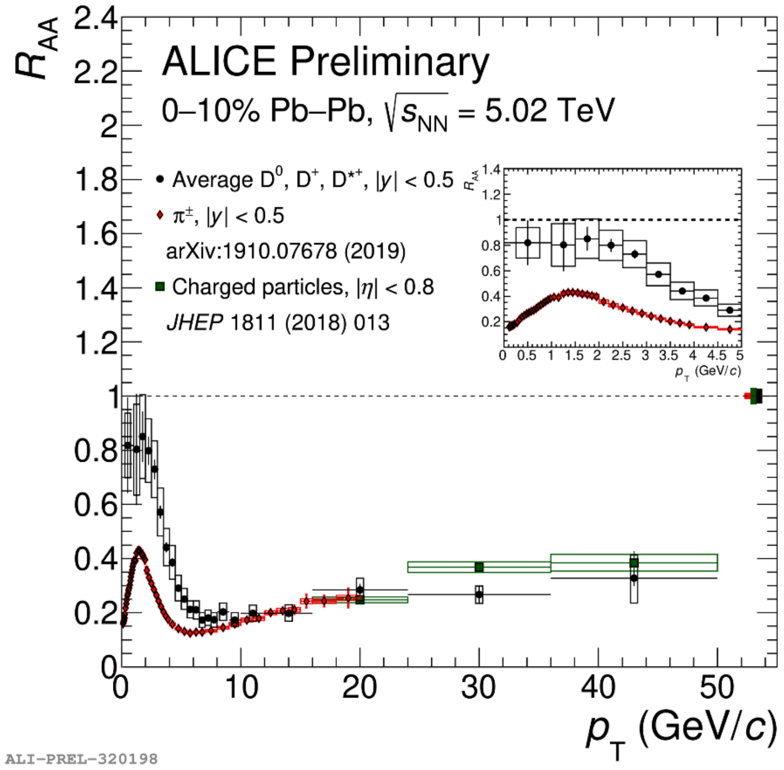
non-prompt D^0 & non-prompt D^+_s

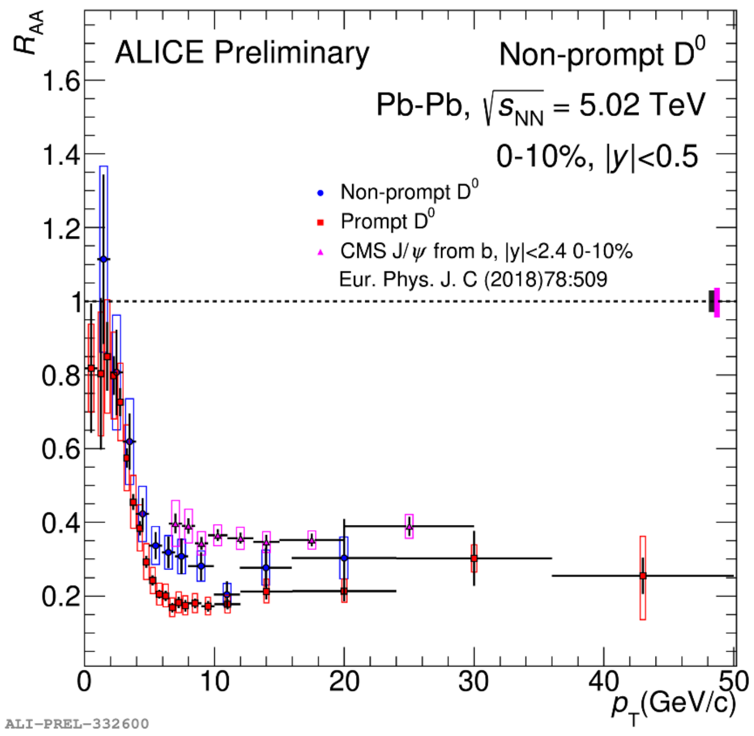


TAMU: PRL 124 (2020) 042301
PRC 96 (2017) 054901

- First measurement of non-prompt D_s^+ in central Pb–Pb collisions
- Hint for a larger R_{AA} for non-prompt D_s^+ (from beauty decays) compared to prompt D_s^+, as expected from mass dependent energy loss and beauty-quark coalescence
- Hint for R_{AA} (non-prompt D_s^+) > R_{AA} (non-prompt D^0) at low/intermediate p_T
  - Interplay of beauty-quark hadronisation via coalescence and strangeness enhancement
- TAMU model predicts the difference in R_{AA} while overestimating the R_{AA} values

Open heavy-flavour R_{AA} hierarchy





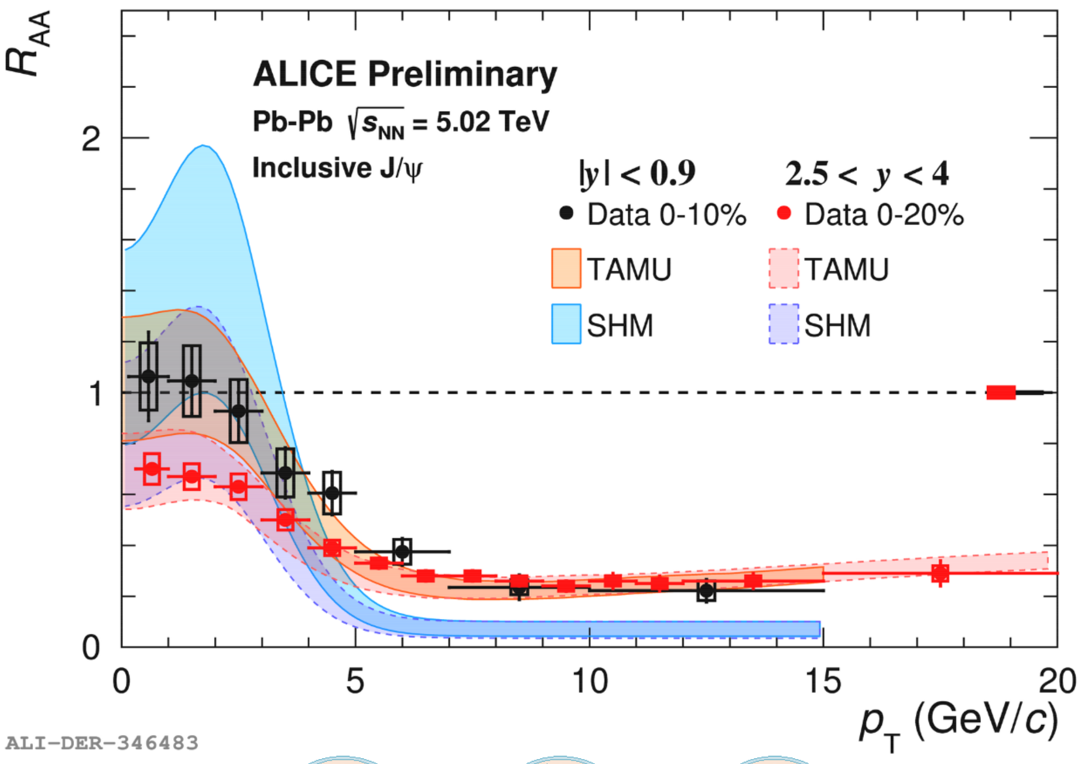
$\pi^{\pm}$: ALICE, PRC 101 (2020) 044907

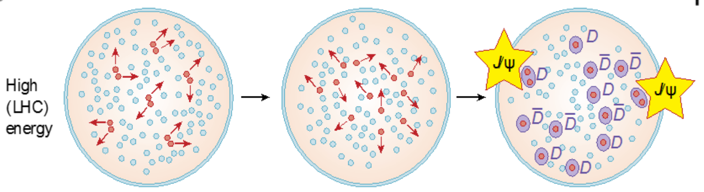
$\Delta E(g) > \Delta E(c) > \Delta E(b) \rightarrow \Delta E(\pi^{\pm}) > \Delta E(D) > \Delta E(B) \overset{?}{\rightarrow} R_{AA}(\pi^{\pm}) < R_{AA}(D) < R_{AA}(B)$

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

- Comparable D-meson, charged-particle and $\pi^{\pm}$ R_{AA} for p_T > 10 GeV/c
- D-meson R_{AA} larger than that of $\pi^{\pm}$ at low/intermediate 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]*
- R_{AA} (prompt D^0) < R_{AA} (non-prompt D^0) ~ R_{AA} (J/ψ ← b)

Charmonia: J/ψ R_{AA} in Pb–Pb collisions



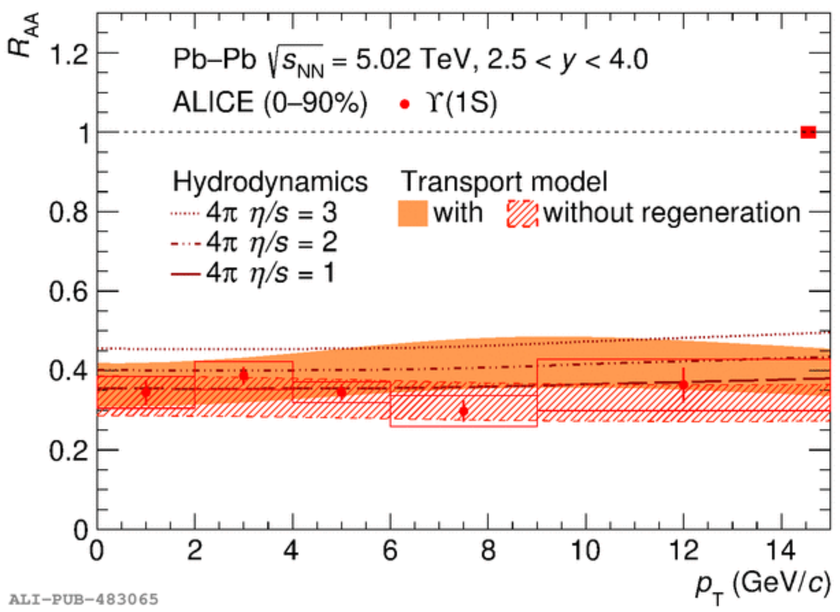


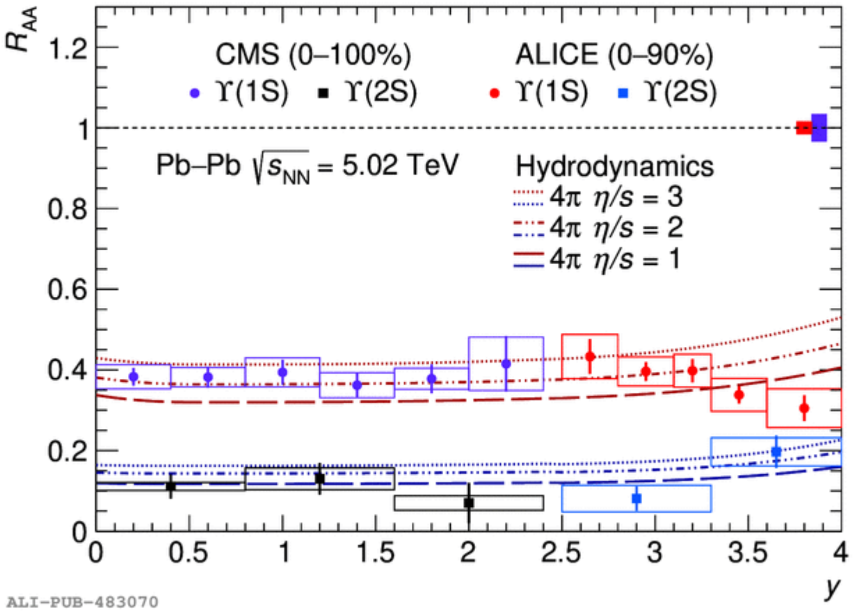
- **Significant suppression** at both midrapidity and forward rapidity in central Pb–Pb collisions
- **Less suppression at low p_T and midrapidity** compared to forward rapidity
  - Interplay between **suppression** mechanism and **regeneration** from charm quarks

- R_{AA} (inclusive J/ψ) well described by the TAMU transport model over the whole p_T interval and the SHM statistical hadronisation model up to p_T ~ 5 GeV/c at both midrapidity and forward rapidity

SHM: JHEP 07 (2021) 035
TAMU: PRL 124 (2020) 042301
PRC 96 (2017) 054901

Bottomonia: Υ(1S) and Υ(2S) R_{AA} in Pb–Pb collisions





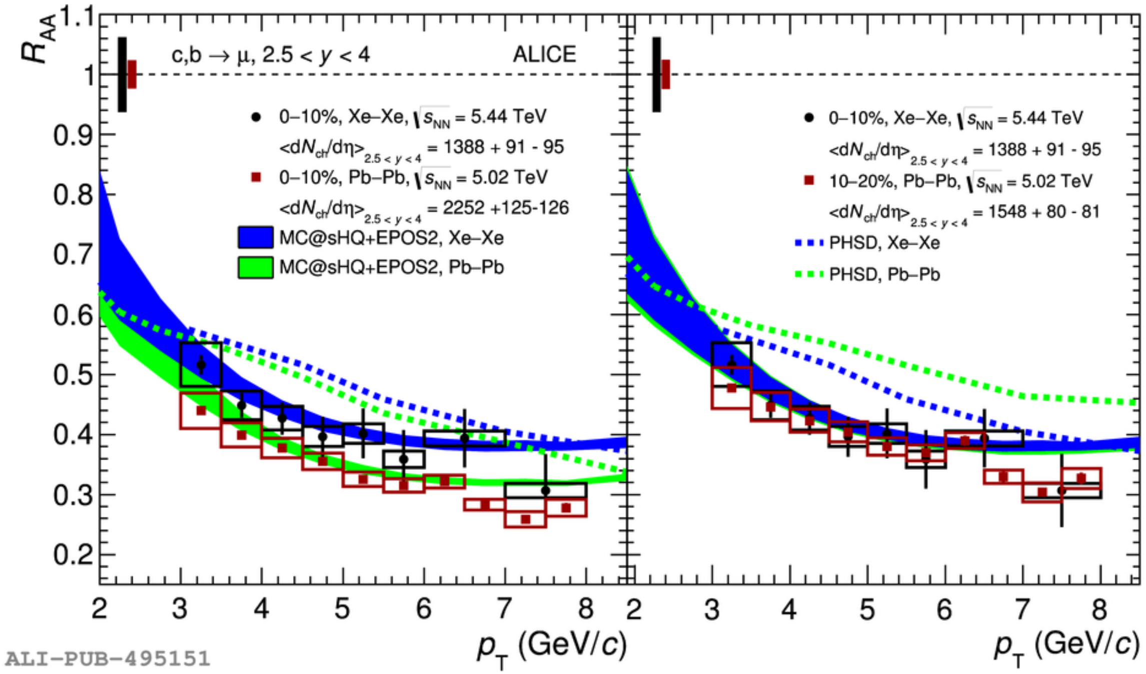
ALICE, PLB 822 (2021) 136579

TM: PRC 96 (2017) 054901
Hydro: Universe 2 (2016) 16

- Clear suppression of Υ(1S) production at forward rapidity: a factor ~3, independently of p_T
  - Regeneration effects small
- Dependence of Υ(1S) suppression on *y* in the ALICE acceptance
- Sequential suppression of bottomonia: Υ(2S) suppression stronger by a factor 2-3 compared to Υ(1S)

- Υ(1S) suppression described by transport models with and without regeneration
- Some tension with the hydrodynamical model to describe the Υ(1S) R_{AA} at large *y*, large η/s values disfavoured

Heavy-flavour decay muons R_{AA}: Xe–Xe vs Pb–Pb collisions



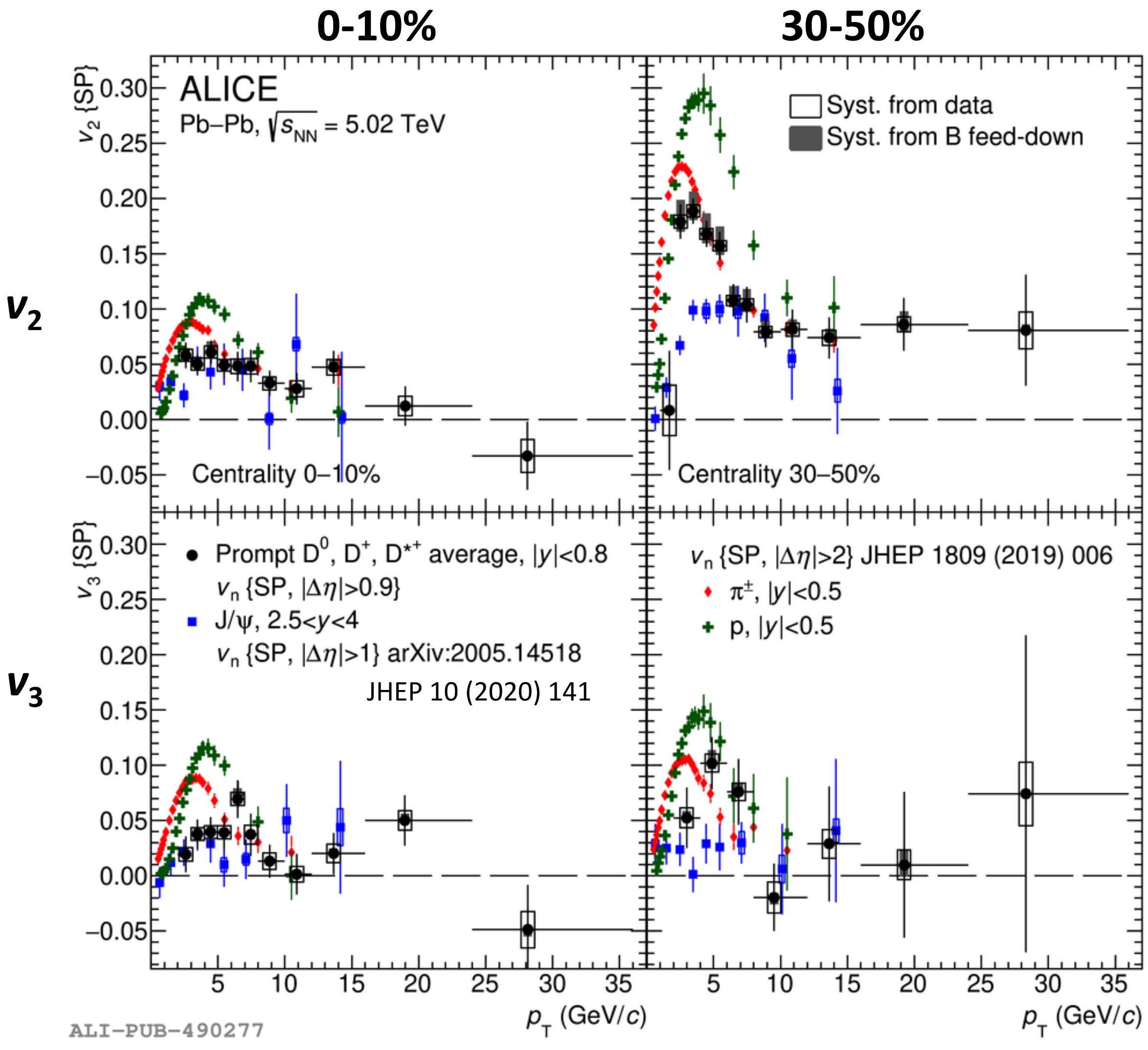
ALICE, PLB 821 (2021) 136637

PSHD: PRC 93 (2016) 034906
MC@sHQ: PRC 89 (2014) 014905

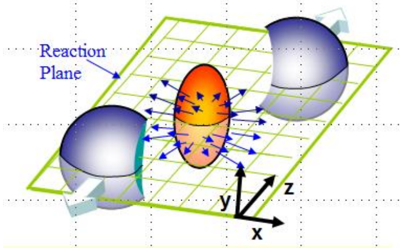
- Comparison of R_{AA} in different collision systems: sensitivity to path-length dependence of in-medium energy loss
- Smaller suppression in Xe–Xe than Pb–Pb collisions for same centrality classes
- Similar R_{AA} in Xe–Xe and Pb–Pb collisions for centrality classes with similar charged-particle multiplicity

- MC@sHQ+EPOS2: in fair agreement with the measured R_{AA} of c,b → μ for both Pb–Pb and Xe–Xe collisions
- PSHD: difficulties to describe R_{AA} of c,b → μ in both Xe–Xe and Pb–Pb collisions
  - New constraints to transport model calculations

Heavy-flavour azimuthal anisotropy in Pb–Pb collisions



ALICE, PLB 813 (2021) 136054



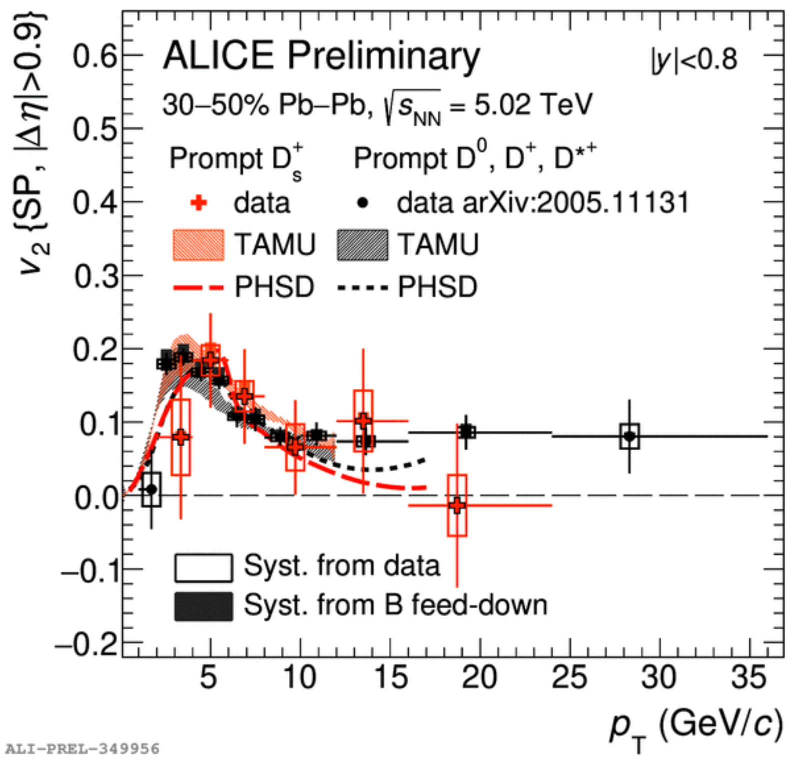
$$\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$

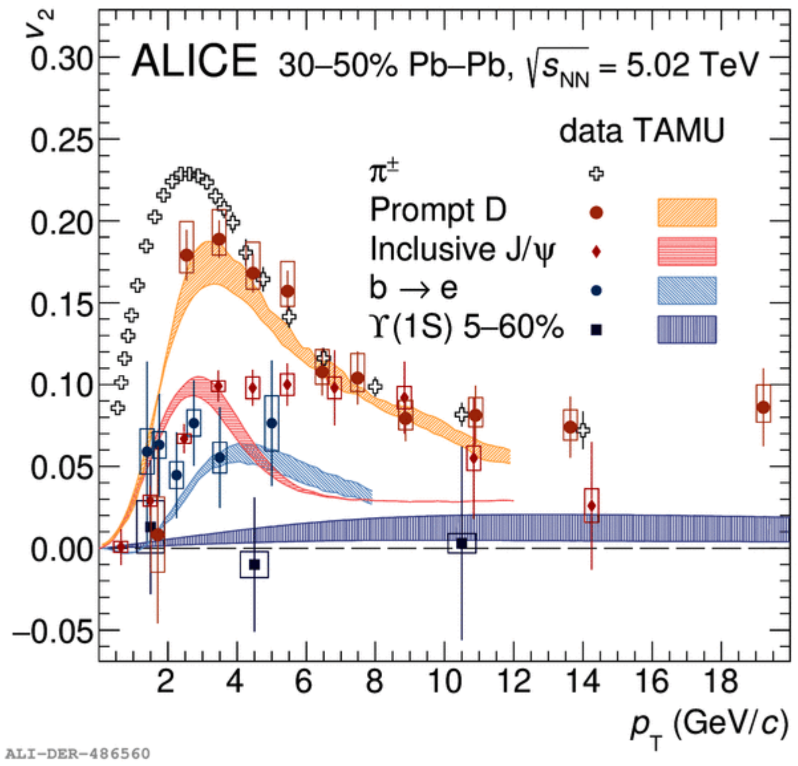
- v_2: test participation in the collective expansion at low p_T
  path-length dependence of parton in-medium energy loss at high p_T
- v_3: initial-state event-by-event fluctuations

- ❑ Significant positive v_2, v_3 measured for D and J/ψ

- ❑ p_T < 3-4 GeV/c: mass hierarchy observed
  - ➢ v_n(Jψ) < v_n(D) < v_n(p) < $v_n(\pi^{\pm})$
- ❑ 3-4 < p_T < 6-8 GeV/c: n-quark scaling and coalescence
  - ➢ v_n(J/ψ) < v_n (D) ~$v_n(\pi^{\pm})$ < v_n(p)
- ❑ p_T > 8 GeV/c: similar path-length dependence of in-medium energy loss for quarks and gluons
  - ➢ v_n(J/ψ) ~ v_n (D) ~ $v_n(\pi^{\pm})$ ~ v_n(p)

Heavy-flavour collectivity in Pb–Pb collisions





ALICE, PLB 813 (2021) 136054
ALICE, PRL 126 (2021) 162001
ALICE, JHEP 10 (2020) 141
ALICE, JHEP 09 (2018) 006

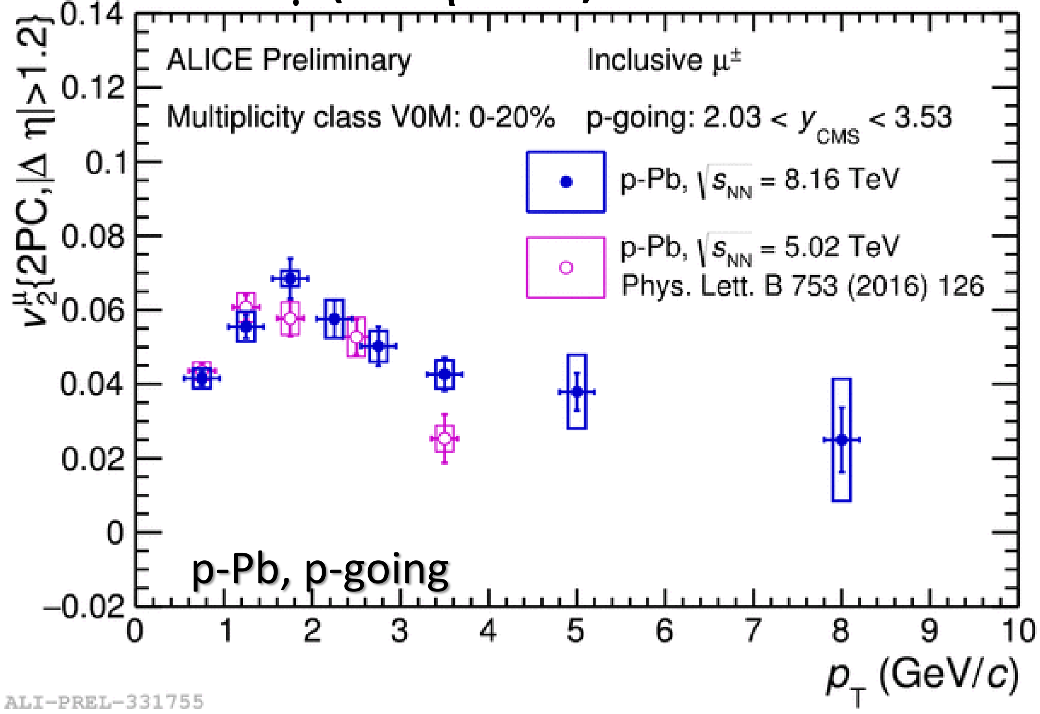
TAMU: PRL 124 (2020) 042301
PRC 96 (2017) 054901
PHSD: PLB 735 (2015) 014910
PRC 93 (2016) 0434906

- Similar v_2 for strange and non-strange D mesons
- Positive v_2 for electrons from beauty-hadron decays and no elliptic flow signal for ϒ(1S)
- TAMU model describes well the v_2 data except for J/ψ for p_T > 4 GeV/c
- PHSD model reproduces well the measured v_2 of strange and non-strange D mesons
  - Both TAMU and PHSH include charm and strange quark coalescence
- Precise measurements → constraints to models for charm spatial diffusion coefficient:

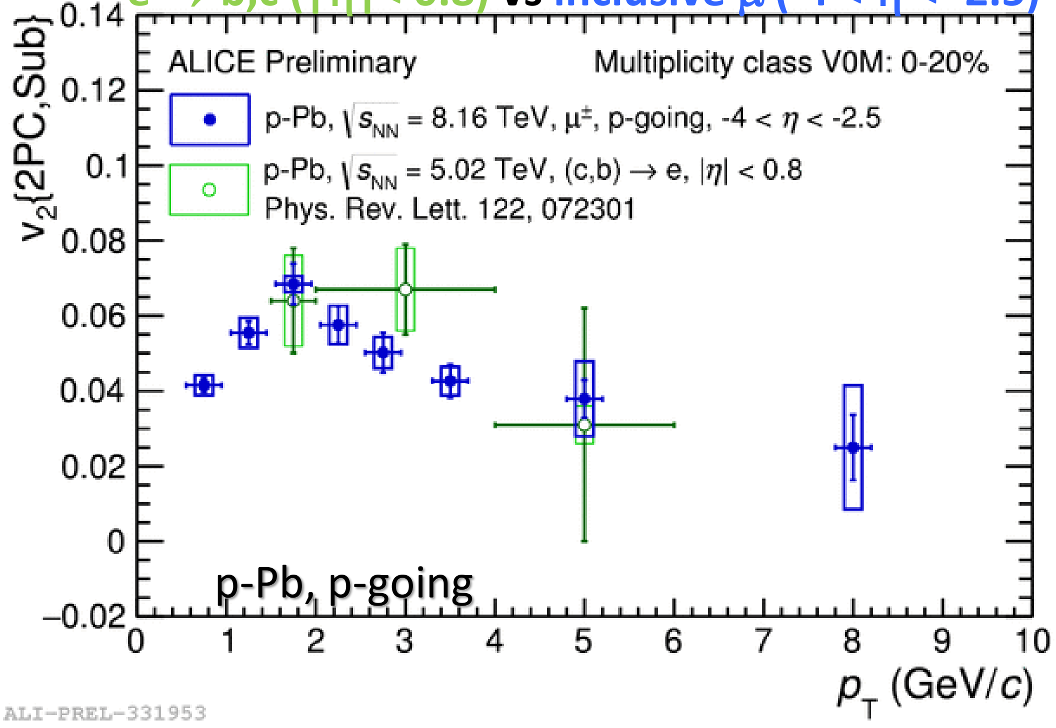
$$1.5 < 2\pi T_c D_s < 4.5 \quad (T_c \sim 155\text{ MeV})$$

Collectivity in small collision systems at high multiplicity

inclusive μ (-4 < η < -2.5): 5.02 TeV vs 8.16 TeV



e → b,c (|η|< 0.8) vs inclusive μ (-4 < η < -2.5)



- ❑ Inclusive μ dominated by open-heavy flavor hadron decays at p_T > 2 GeV/*c*

- ❑ Significant positive v_2 observed in the heavy-flavor sector in 0-20% p–Pb collisions
- ❑ No significant $\sqrt{s_{NN}}$ dependence and rapidity dependence
- ❑ Similar behaviour observed in Pb–Pb collisions

- ❑ New constraints to understand the origin of collectivity in small collision systems

Conclusion

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

- Open heavy flavours
  - Strong suppression of heavy-flavour yields: colour-charge and quark-mass dependence of in-medium parton energy loss and heavy-quark hadronisation via coalescence
  - Anisotropic flow measurements: participation of heavy quarks to the QGP collective motion and sensitivity of charm to initial-state event-by-event fluctuations
  - Comparisons Xe–Xe and Pb–Pb collisions: geometry and path-length dependence of in-medium energy loss
  - Collectivity observed in high-multiplicity p–Pb collisions

- Quarkonia
  - J/ψ suppression: interplay of suppression and recombination mechanisms
  - Significant J/ψ v_2 at low/intermediate p_T from thermalisation of charm quarks
  - Sequential suppression of Υ states and no azimuthal anisotropy for Υ(1S)

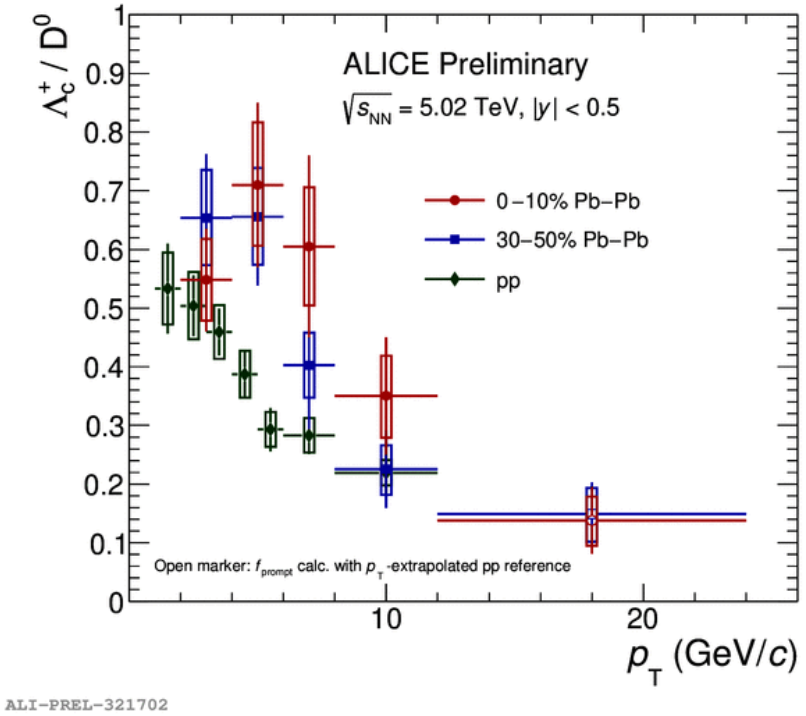
- LHC Run 3 crucial for heavy-flavour measurements
  - Improved precision on current measurements and access to new set of observables to characterize the QGP properties

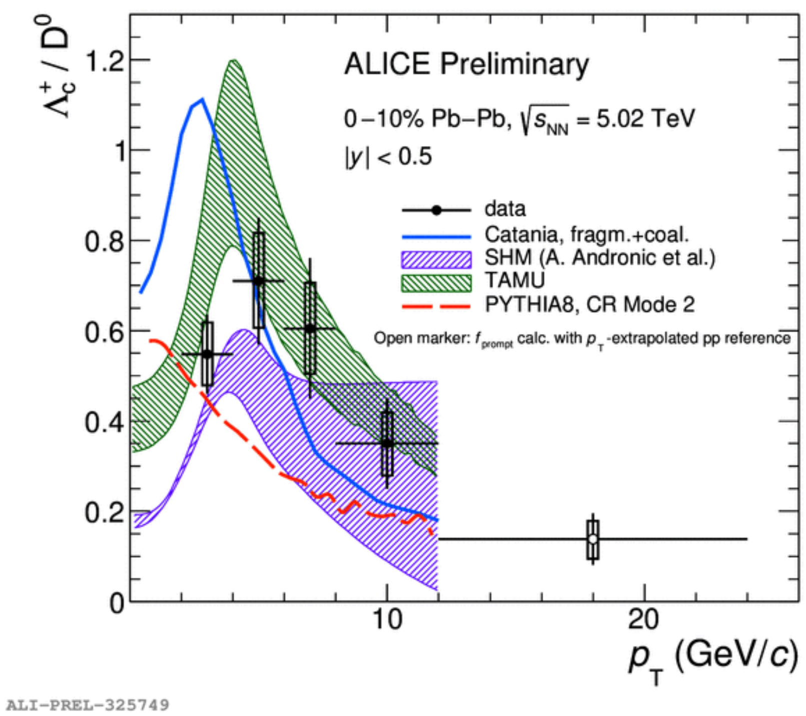
$\rightarrow$ Stay tuned!

Thank you for your attention

Backup slides

Differential yield ratios in Pb-Pb collisions

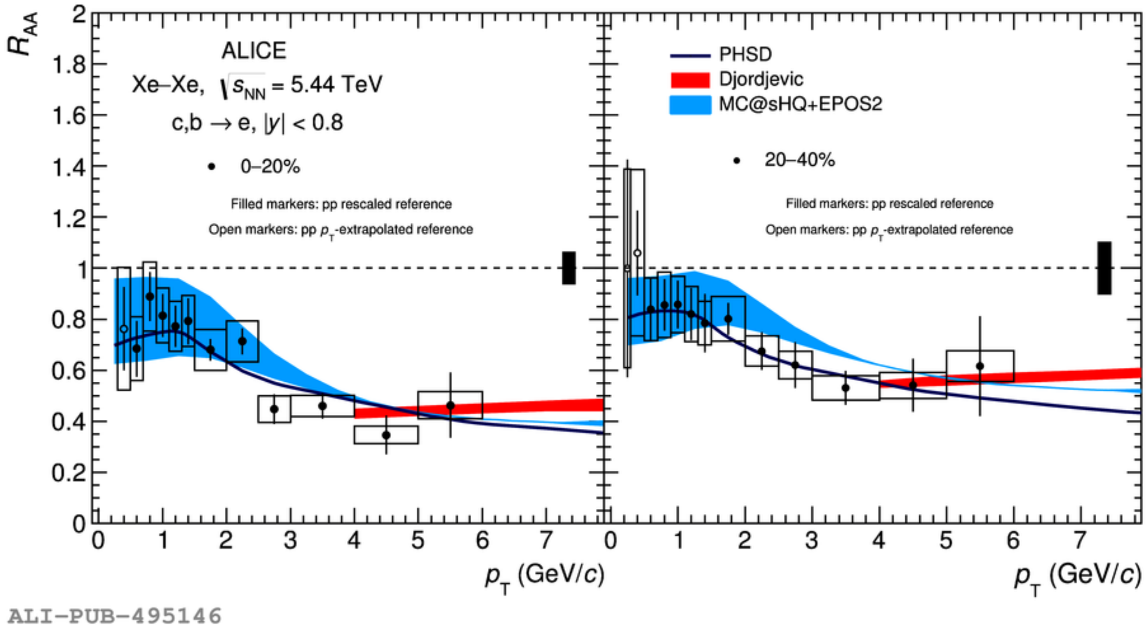




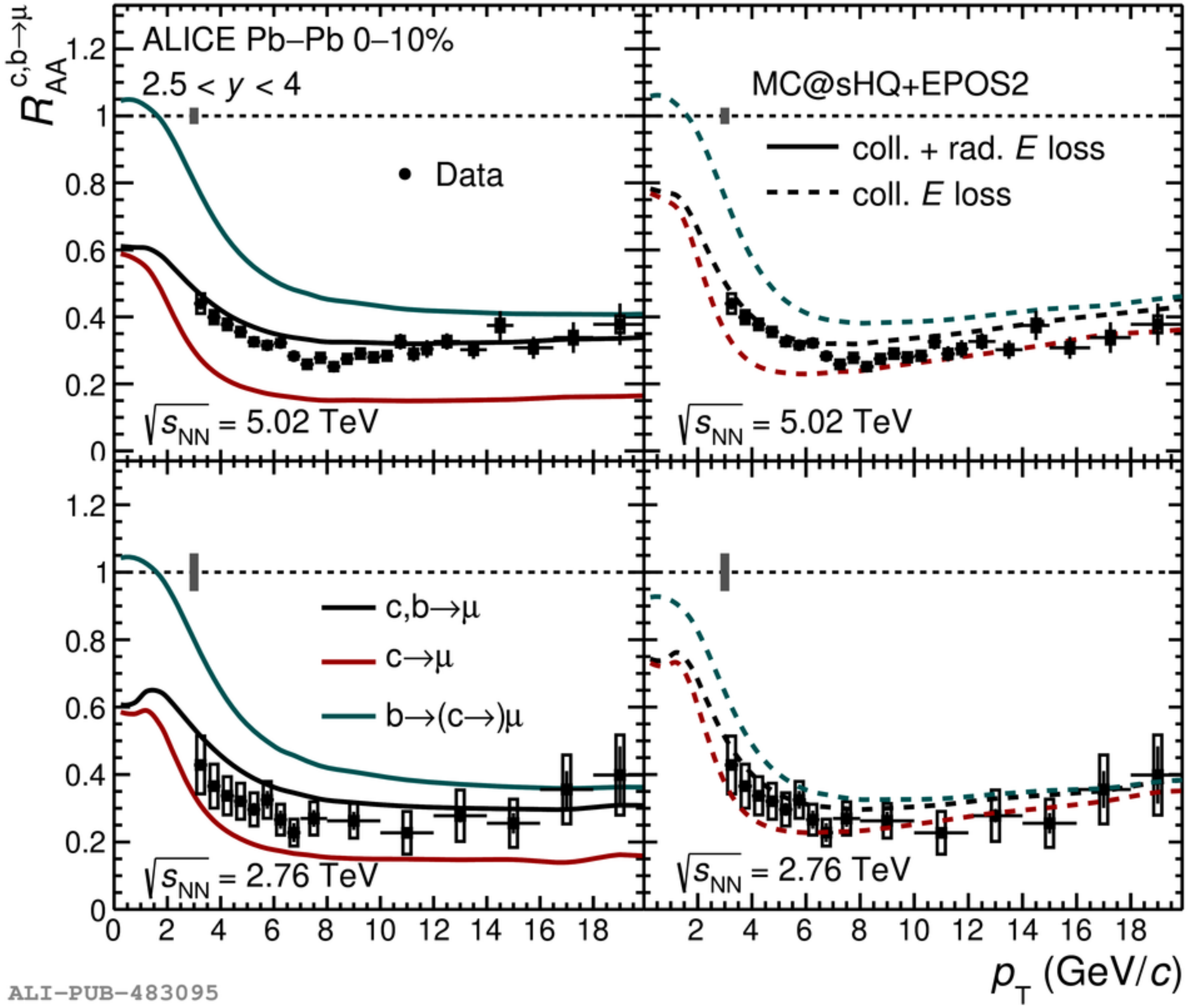
SHM: JHEP 07 (2021) 035
TAMU: PRL 124 (2020) 042301
PRC 96 (2017) 054901
Catania: EPJC 78 (2018) 348

- Λ_c^+/D^0 ratio: hint of enhanced Λ_c^+ production in Pb-Pb collisions compared to pp collisions via quark recombination and radial flow
- Models including hadronisation via coalescence (TAMU, Catania) and based on statistical hadronisation (SHM) describe within uncertainties the measured Λ_c^+/D^0 ratio in 0-10% Pb-Pb collisions

Heavy-flavour decay muons R_{AA}: Pb-Pb vs Xe-Xe collisions

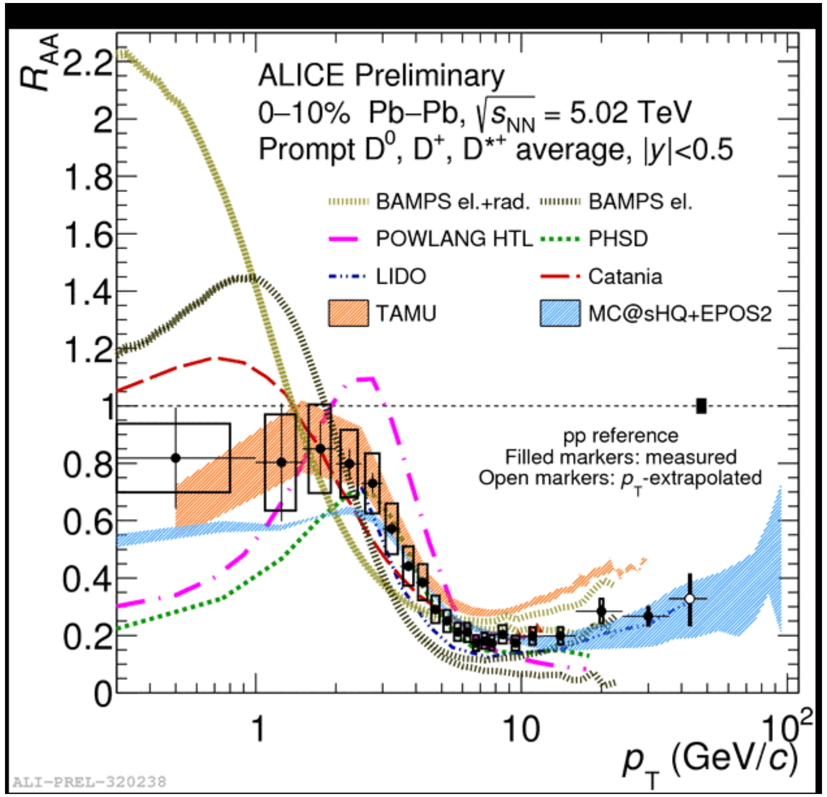


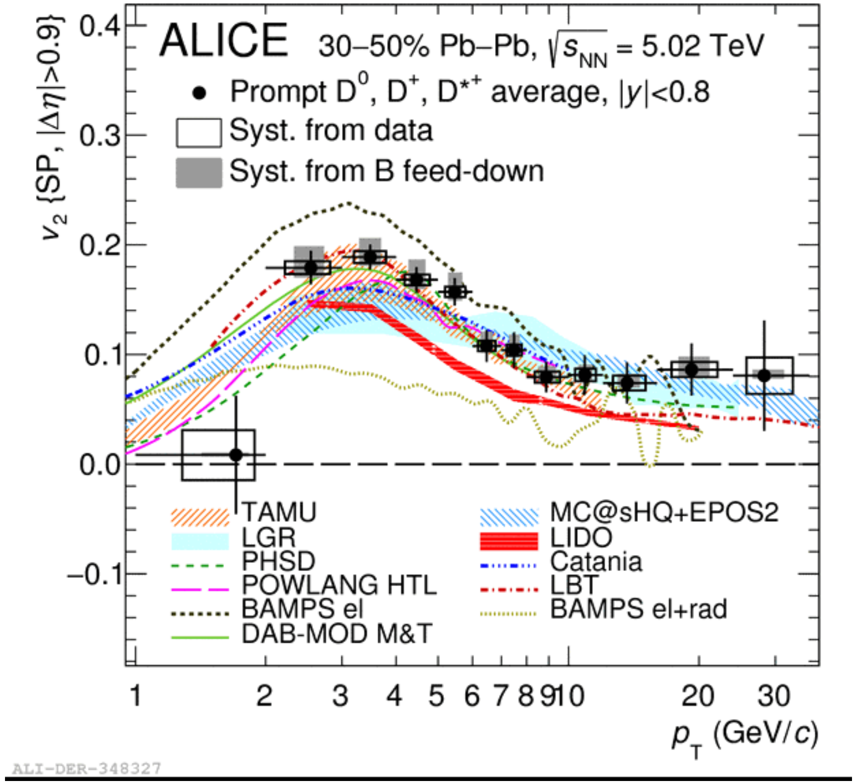
Heavy-flavour hadron decay muons in Pb-Pb: charm vs beauty



- ❑ Mass-depend in-medium energy loss → different in-medium energy loss expected for charm and beauty
- ❑ MC@sHQ+EPOS2 predictions with different energy loss scenarios in fair agreement with the measured R_{AA} of muons from both charm- and beauty-hadron decays
- ❑ Muons from beauty-hadron decays: dominant source at high p_T

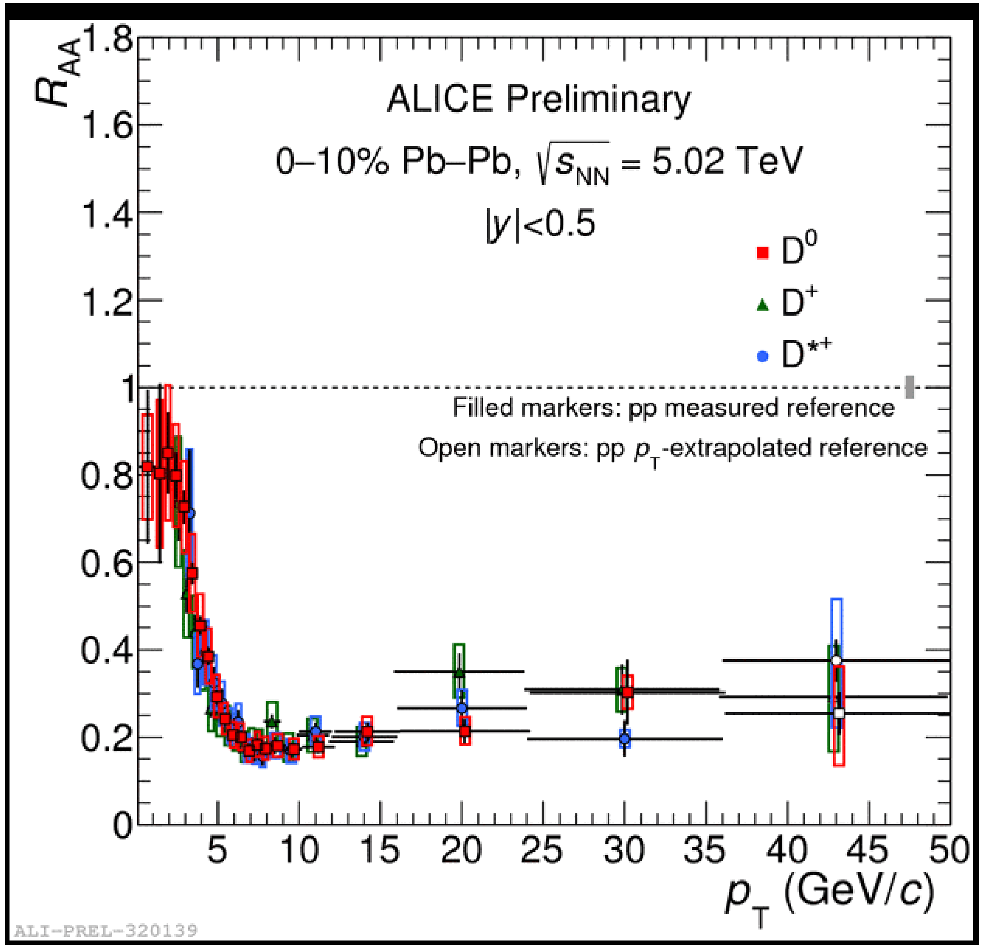
Model comparisons

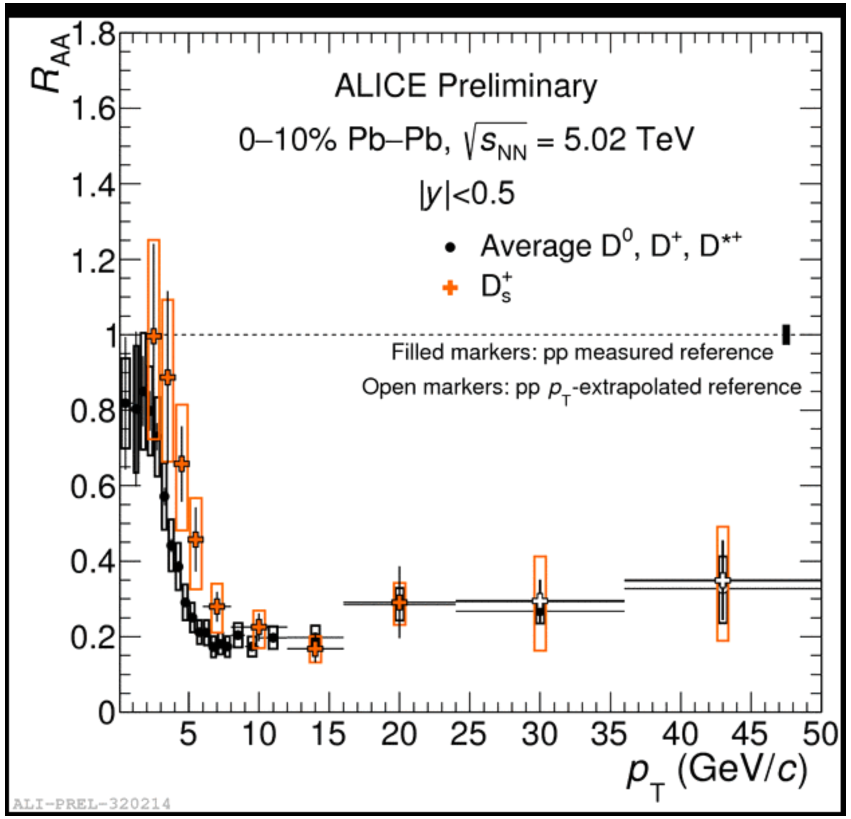




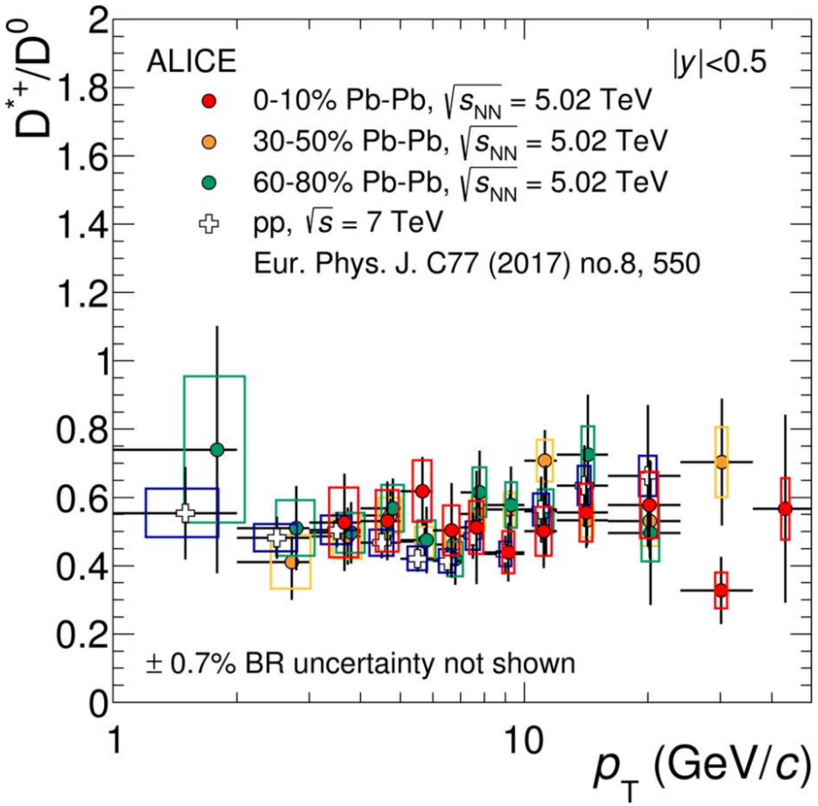
- Simultaneous description of R_{AA} and v_2 over a wide p_T interval is challenging: improved precision of the measurements can allow us to set important constraints to model calculations

D-meson R_{AA} in Pb-Pb collisions





Yield ratios



Bottomonia: Υ(1S) and Υ(2S) R_{AA} in Pb-Pb collisions

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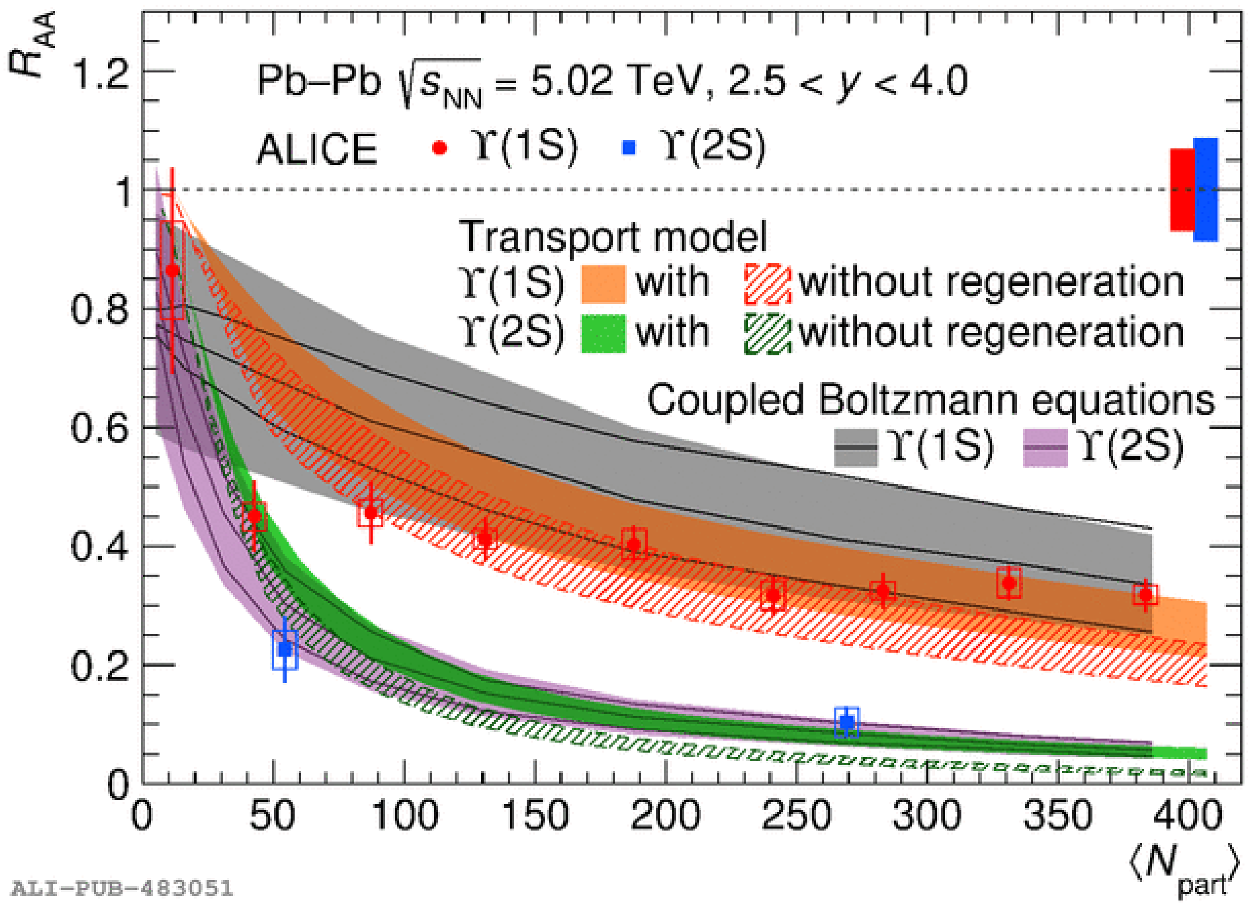
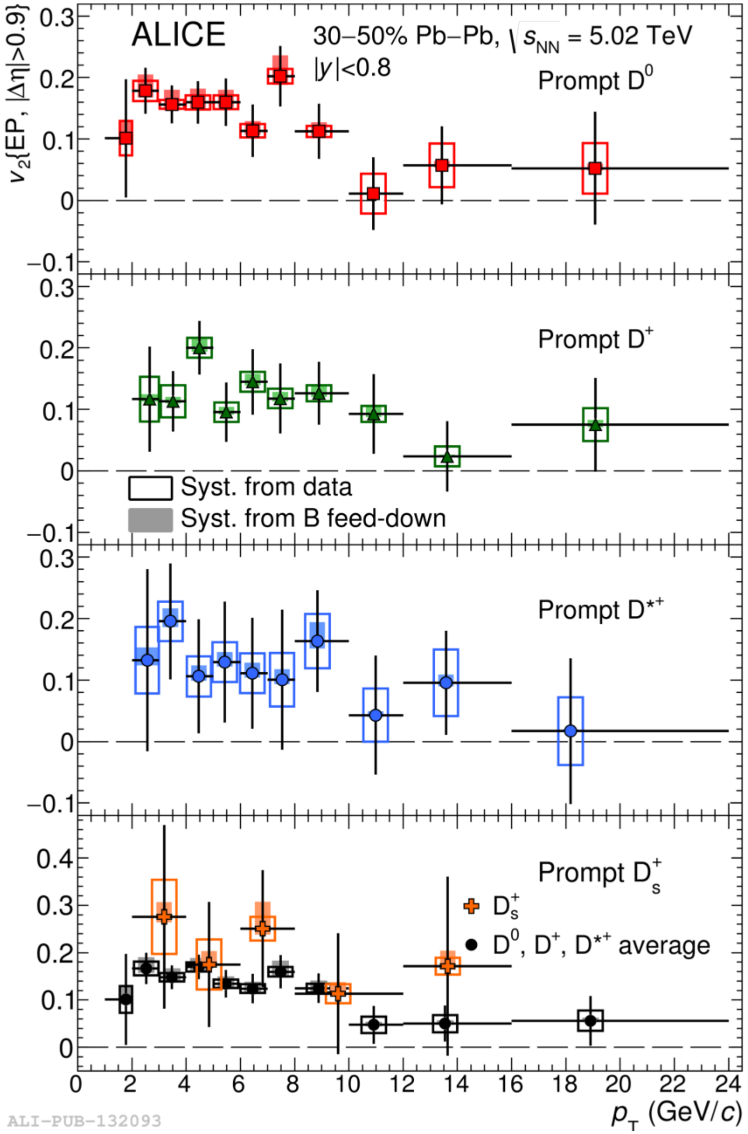
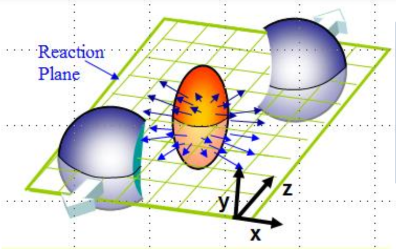


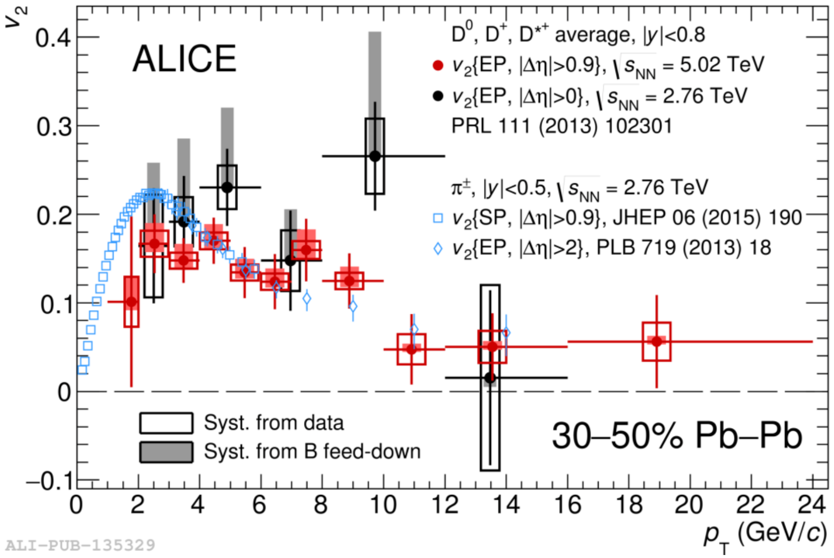
Elliptic flow (v_2) in Pb-Pb collisions



ALICE, PRL 120 (2018) 102301

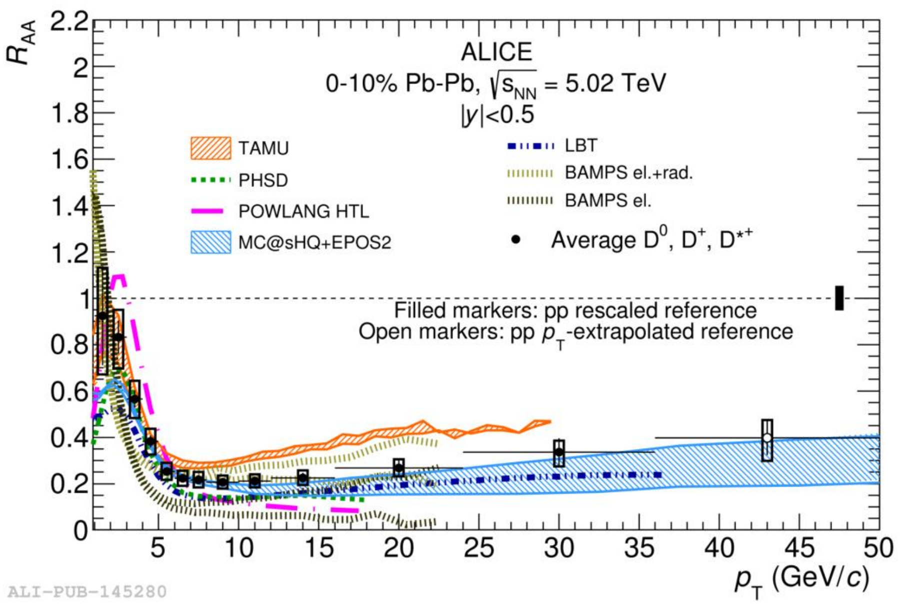


$$\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$

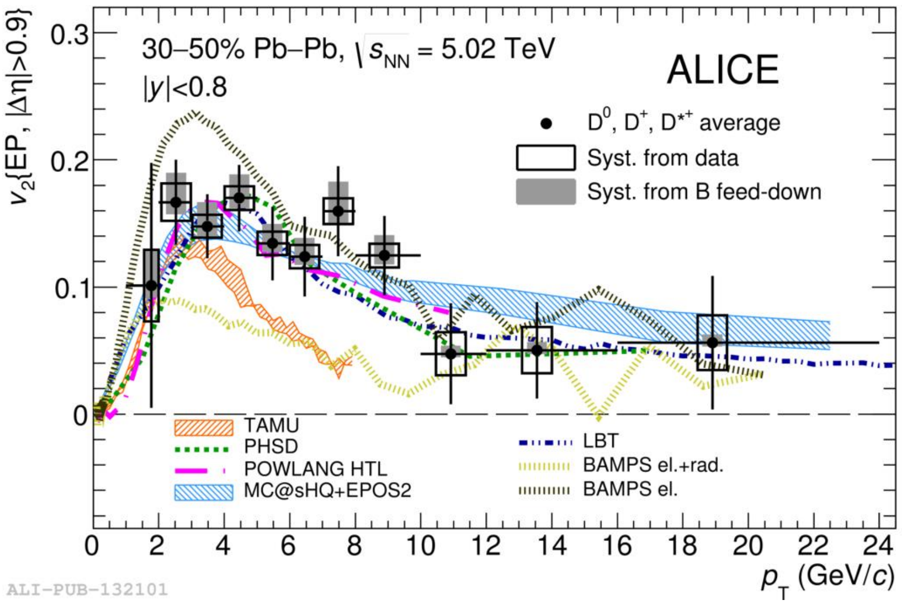


- First D_s^+ v_2 measurement, similar as non-strange D v_2
- Positive D-meson v_2 in $2 < p_T < 10$ GeV/c (hint of a larger charged-pion v_2 for $p_T < 4$ GeV/c)
  - Participation of charm quarks in the collective expansion of the system

Comparison with models



ALICE, arXiv:1804:09083

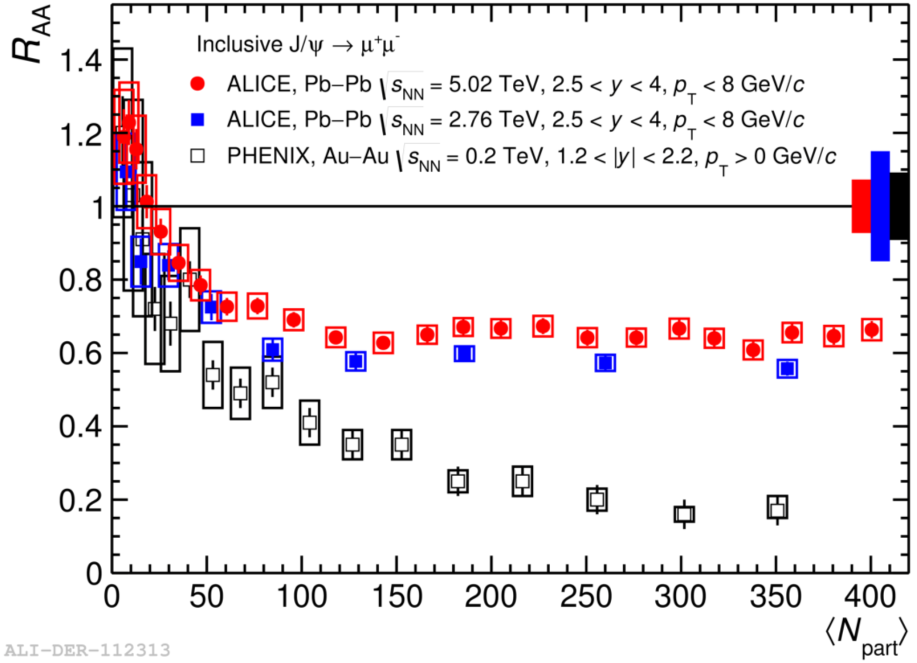


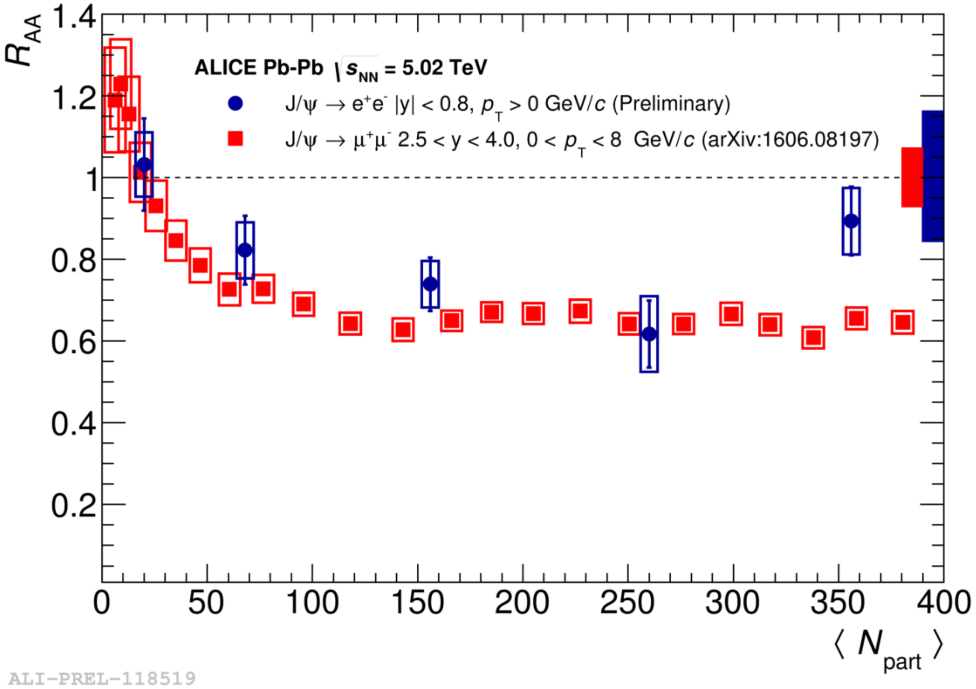
ALICE, PRL 120 (2018) 102301

- 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

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



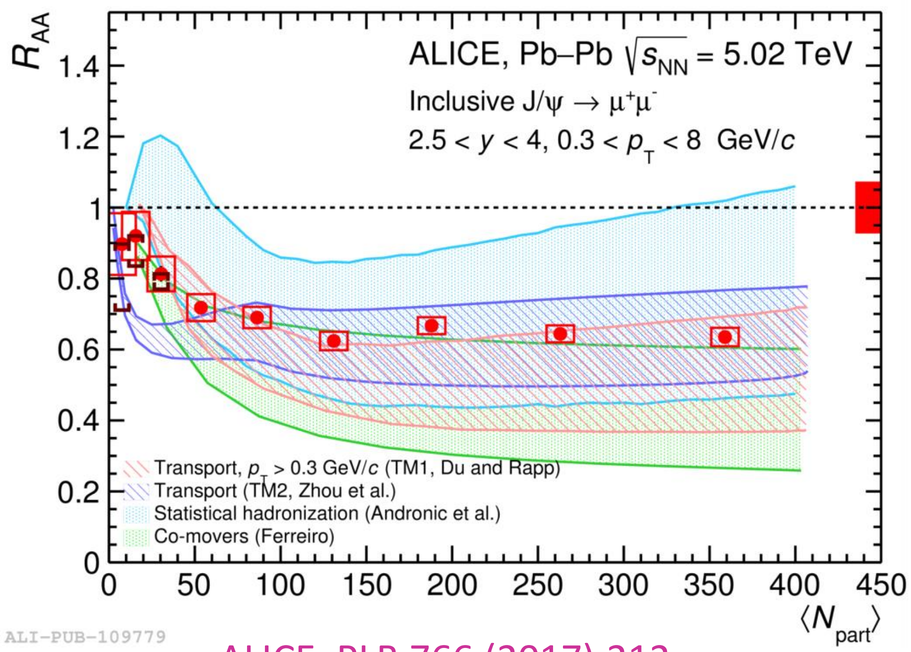


ALICE, PLB 766 (2017) 212, PHENIX, PRL 98 (2007) 232301

- Significant J/ψ suppression at $\sqrt{s_{NN}}$ = 2.76 TeV with a saturation for ⟨N_{part}⟩ > 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



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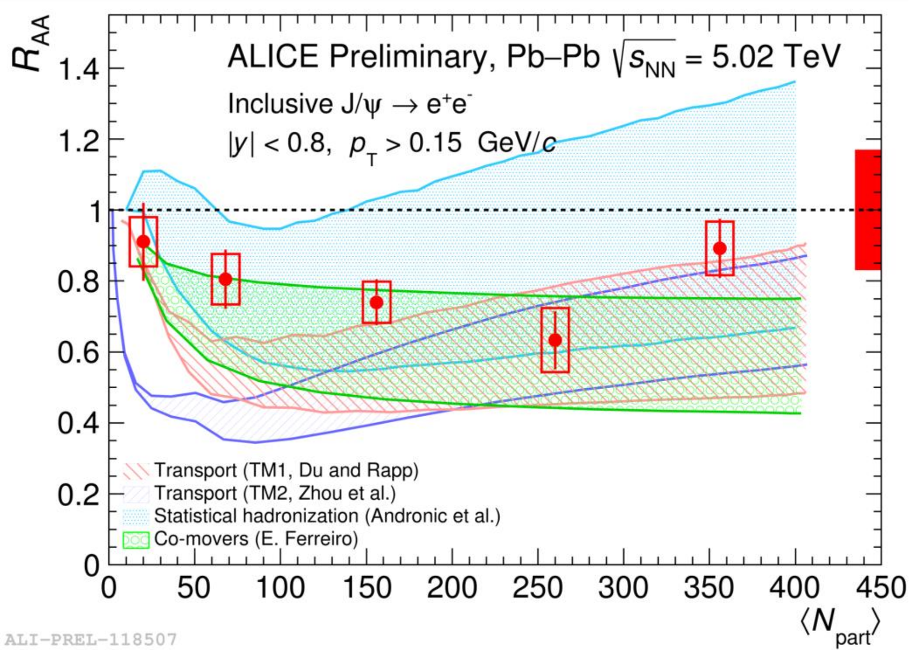
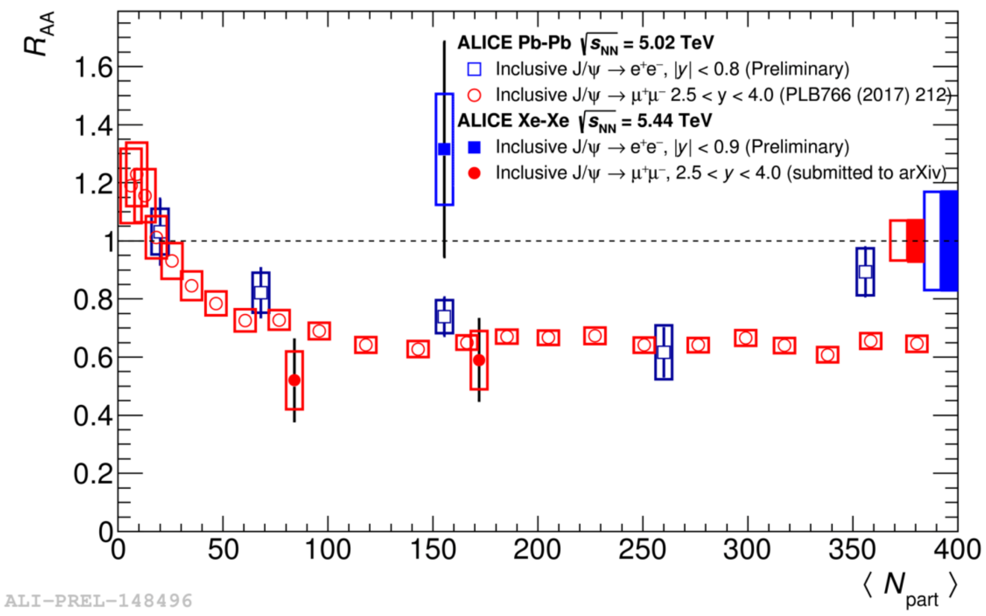
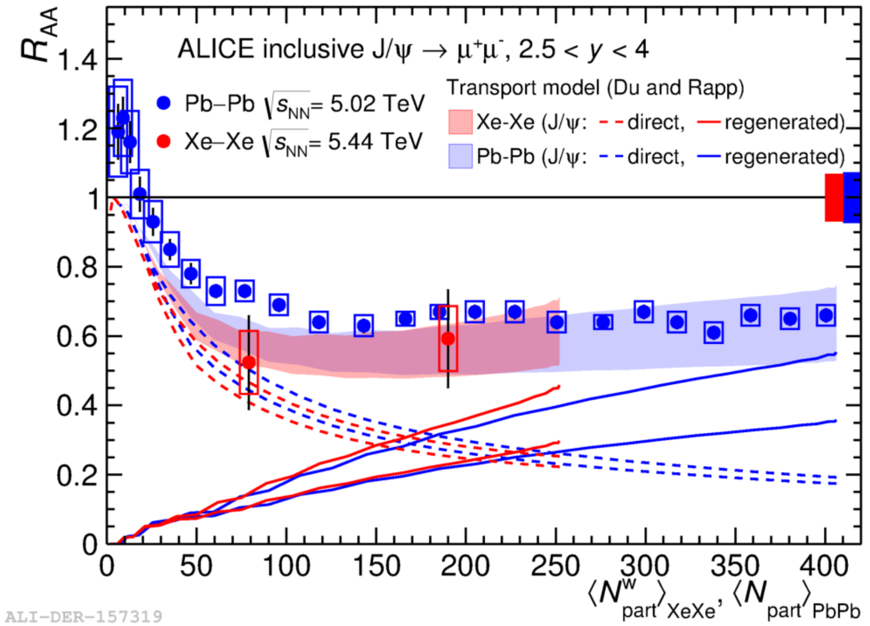
-0.8 < *y* < 0.8



- 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)

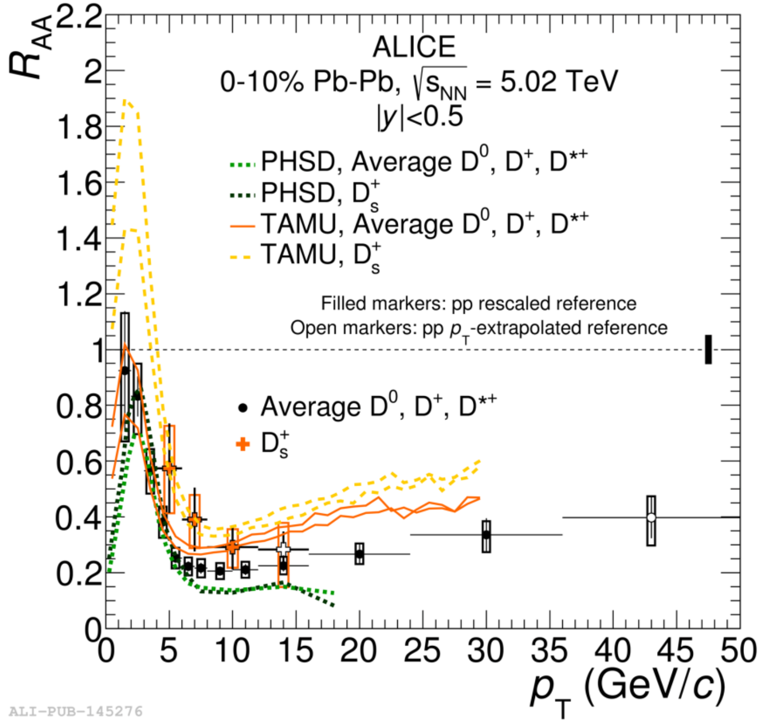
Forward rapidity

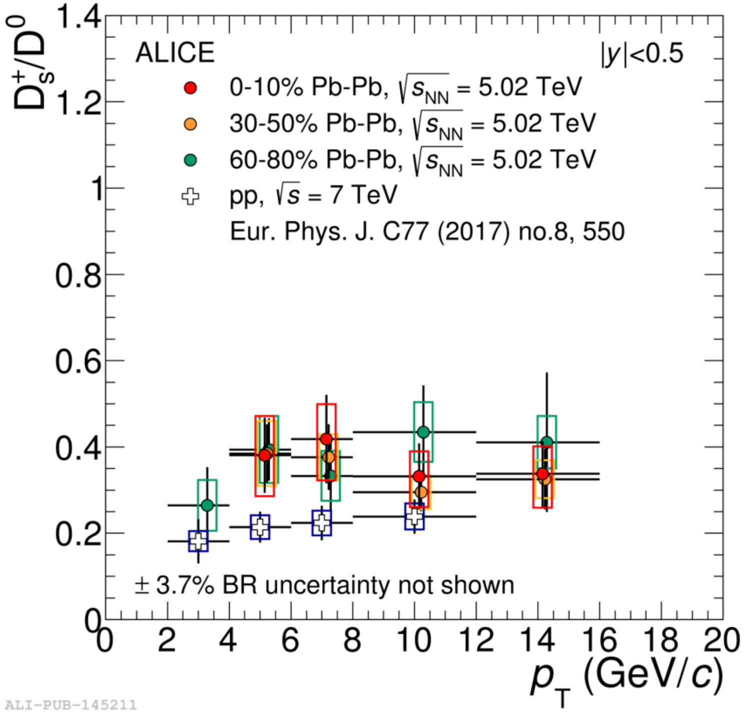
- ❑ R_{AA} in Xe-Xe collisions in agreement, within large uncertainties, with the Pb-Pb results and described by a transport model
- ❑ Similar relative contribution of suppression and regeneration processes at similar ⟨ N_{part} ⟩

Mid rapidity

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

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

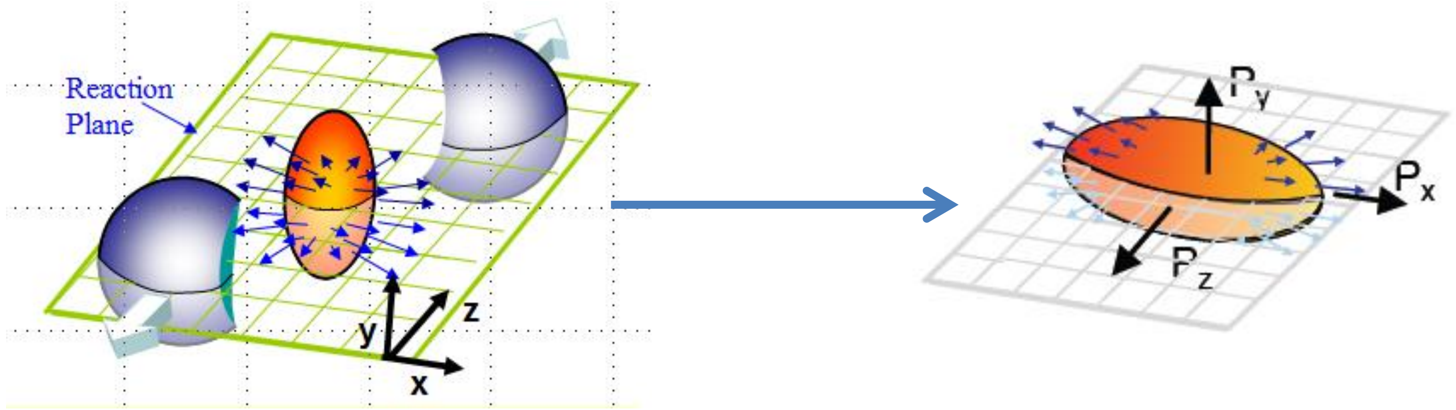
- Hint of enhanced D^+_s production compared to non-strange D mesons in central Pb-Pb collisions at 5.02 TeV as expected from models
  - Hadronisation via coalescence in a strangeness-rich environment?
- No significant dependence of D^+_s/D^0 ratio on collision centrality within uncertainties
  - Expected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

Observables

- Nuclear modification factor R_{AA}

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

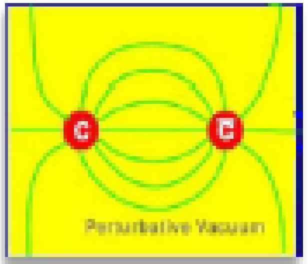
- Elliptic flow v_2

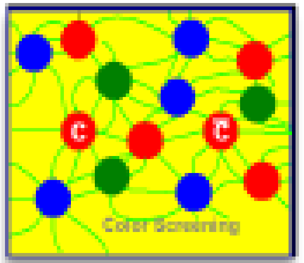


$$\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)] \qquad v_n = < \cos[n(\varphi - \Psi_n)] >$$

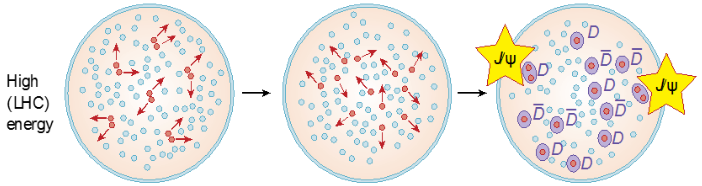
Quarkonium production

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





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



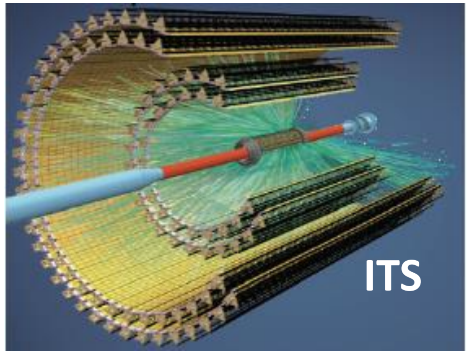
- Abundant production of $c\bar{c}$ at the LHC may lead to a recombination mechanism at hadronization (statistical approach) or in the QGP (kinetic approach) which enhances charmonium production
  [P. Braun-Munzinger & J. Stachel, PLB 490 (2000) 196, B. Thews et al., PRC 63 (2001) 054905]

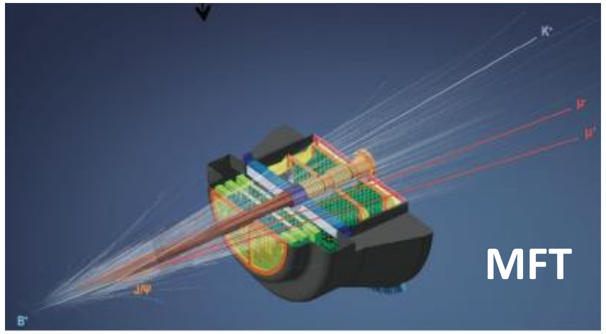
ALICE upgrade

- 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

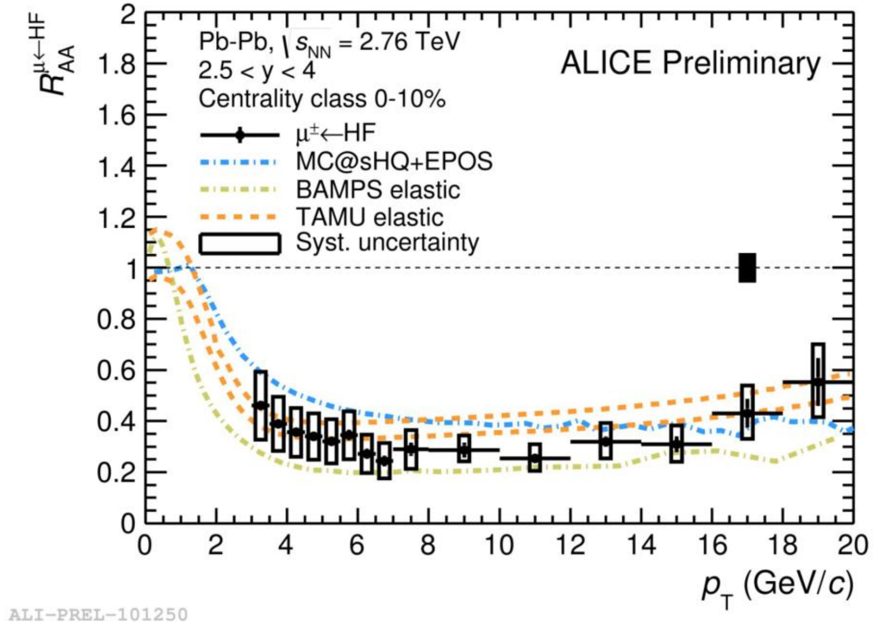
- **New Inner Tracking System (ITS)**
  - Improved pointing resolution,
    reduced material budget, faster readout
- **New Forward Muon Tracker (MFT)**
  - New Silicon tracker,
    heavy-flavour vertices also at forward rapidity
- **New TPC readout chambers based on GEM**
- **Upgraded readout for many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

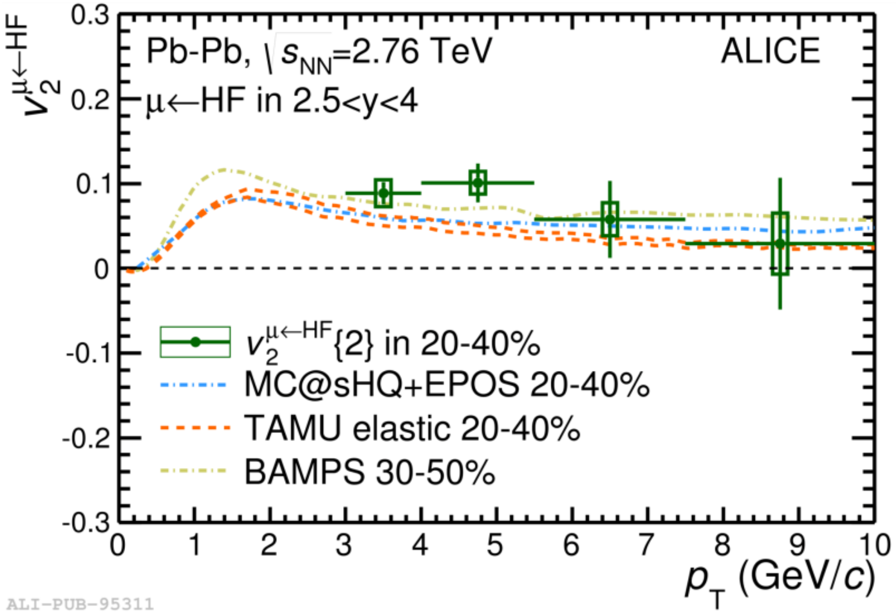




Muons from heavy-flavour hadron decays at $\sqrt{s_{NN}}$ = 2.76 TeV: comparison with models

ALICE, PLB 753 (2016) 41

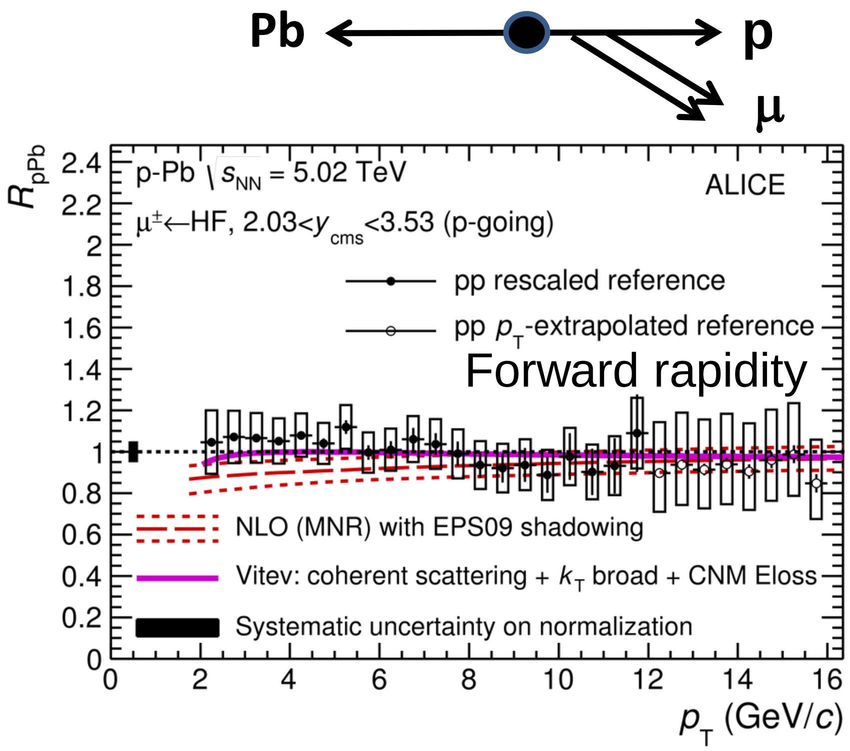




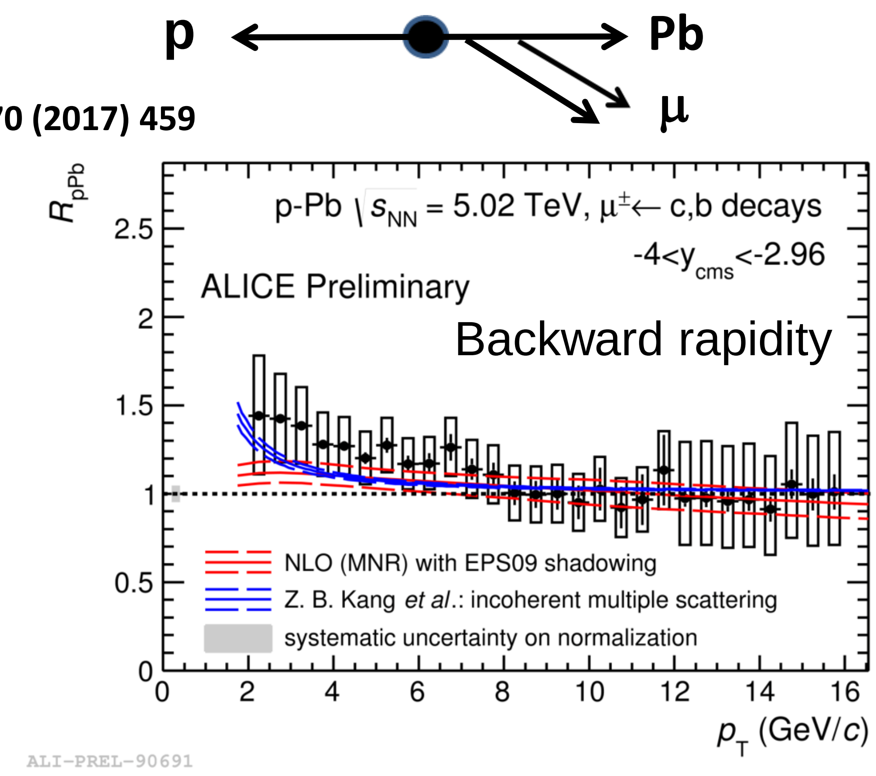
- R_{AA} in central collisions and v_2 in semi-central collisions reasonably described by models including energy loss in the QGP but not in details
  - Further constraints to models: comparison with Run 2 measurements

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



ALICE, PLB 770 (2017) 459



- 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