Open heavy-flavour highlights with ALICE at the LHC

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Main focus:

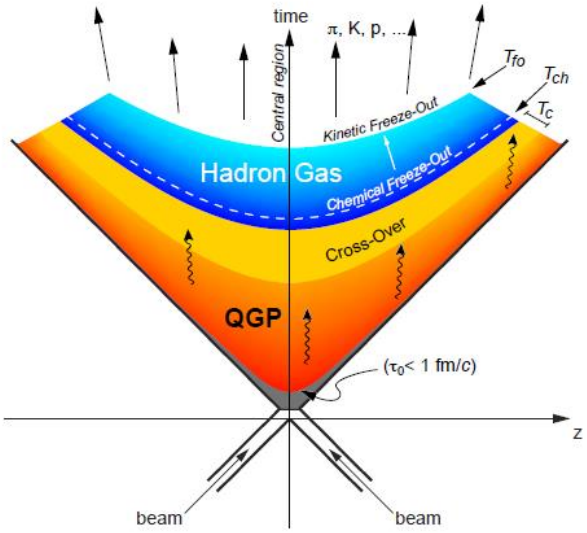
- Heavy-ion collisions:Pb-Pb, Xe-Xe
- Many recent results presented at SQM, IS, EPS-HEP conferences

Rencontres QGP-France 2019
Etretat, July 1-4, 2019

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)
  $\tau_{c/b}$ ~ 0.01-0.1 fm/c < τ_{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 radiative and collisional parton energy loss
    - Medium density and path-length dependence
    - Colour-charge dependence: $\Delta E_{gluons} > \Delta E_{quarks}$
    - Quark-mass dependence: $\Delta E_{gluons} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  - Heavy-quark participation in the collective expansion, thermalisation of the medium
  - Modification of hadronisation mechanisms in the medium

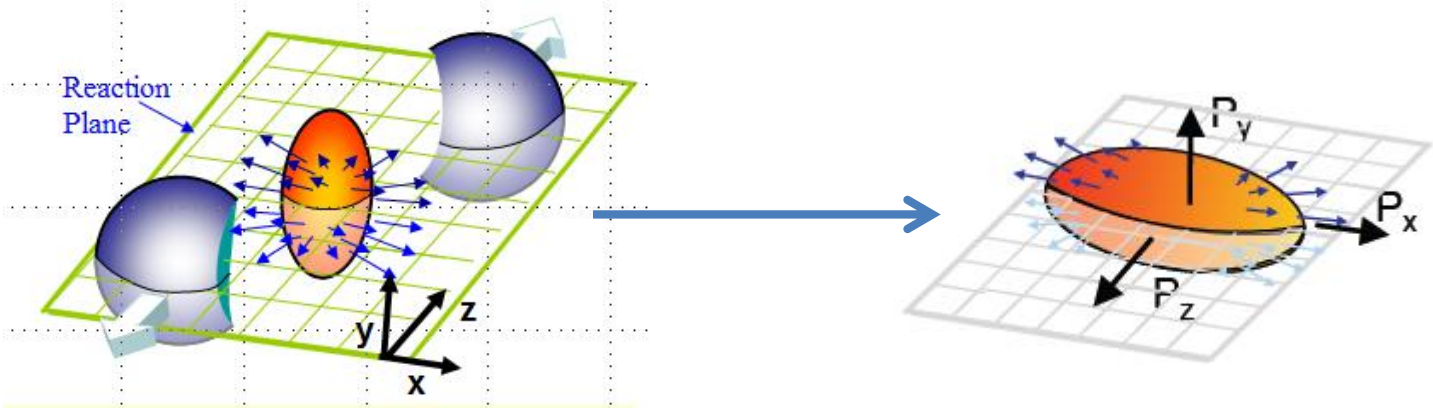
- pp collisions: reference, tests of pQCD-based predictions, production mechanisms
- p-Pb collisions: control experiment, cold nuclear matter effects

Key observables

- Nuclear modification factor R_{AA}

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

- Azimuthal anisotropy and Fourier coefficients



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

$v_n = < \cos[n(\varphi - \Psi_n)] >$

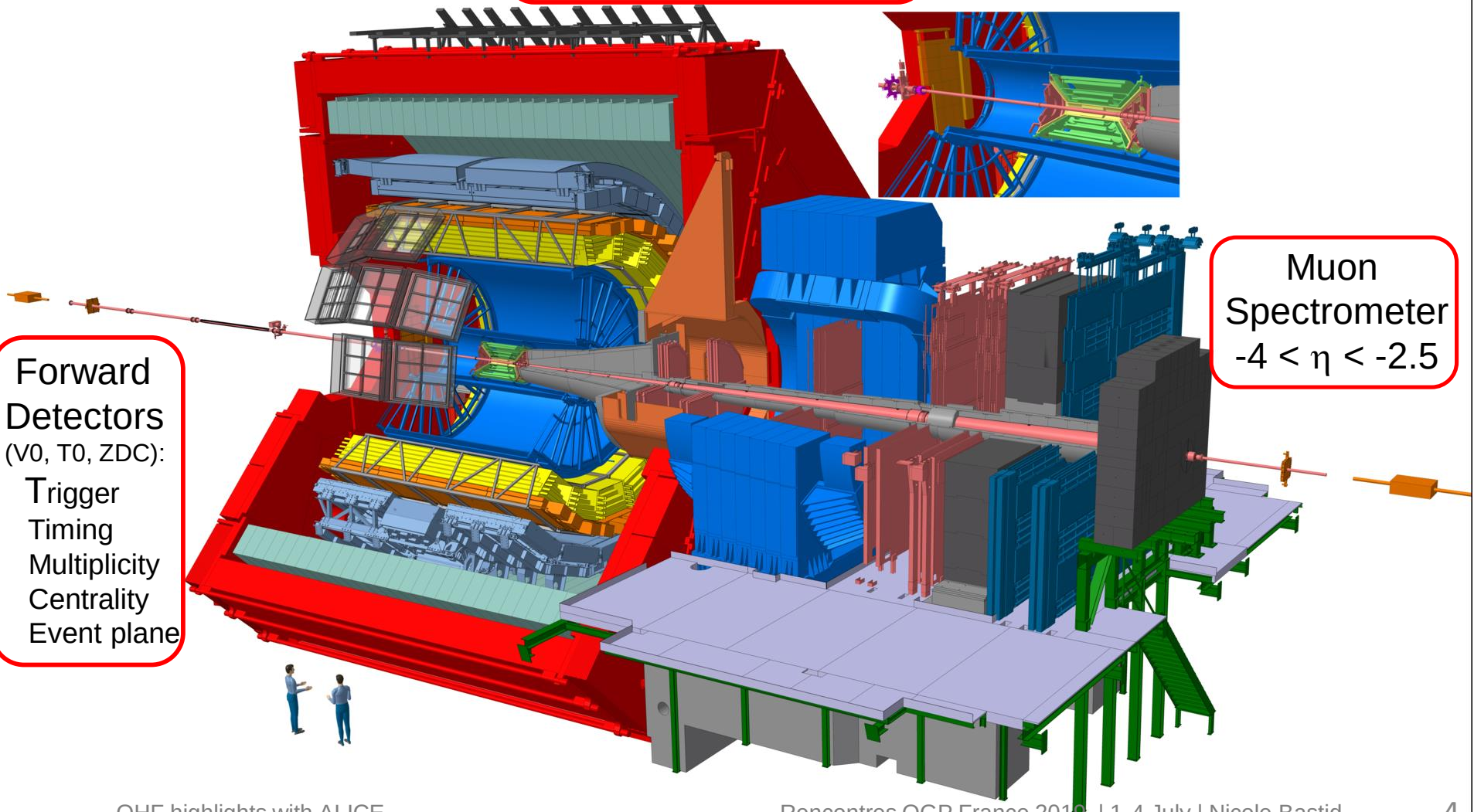
v_2 = elliptic flow

v_1 = directed flow

- Other interesting observables: particle ratios → hadronisation mechanisms
  production in jets

ALICE layout

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

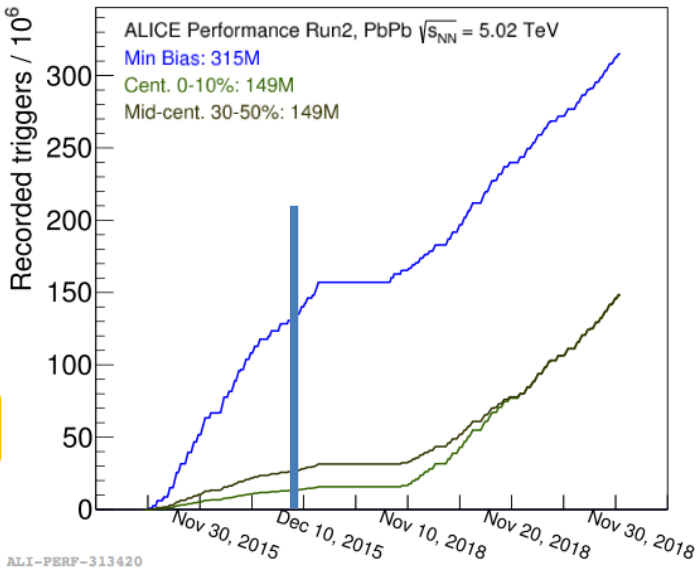


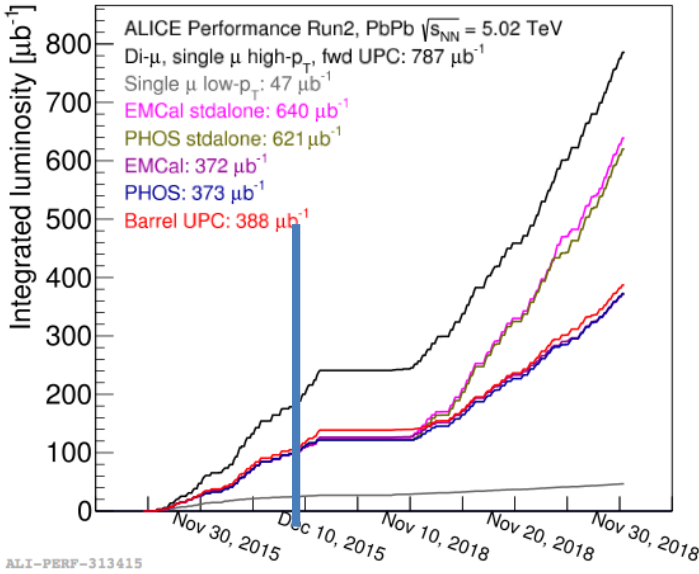
Muon Spectrometer
$-4 < \eta < -2.5$

Forward Detectors
(V0, T0, ZDC):
- Trigger
- Timing
- Multiplicity
- Centrality
- Event plane

Collected data samples with ALICE

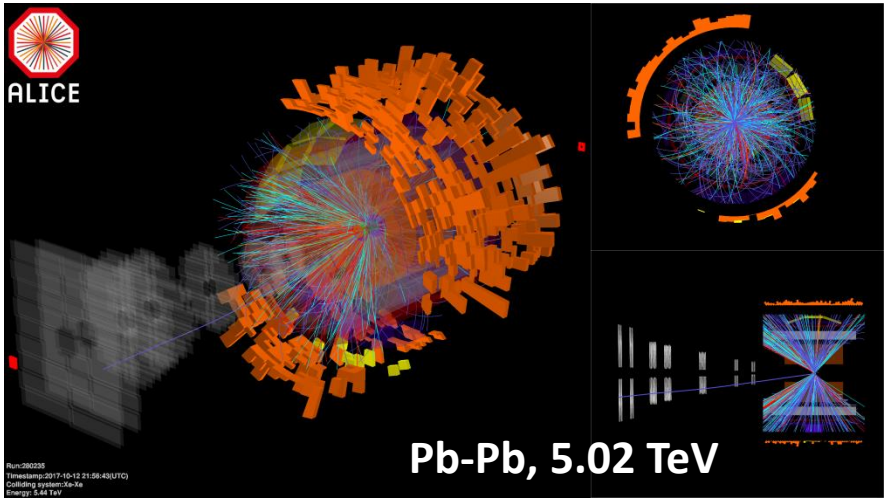
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 nb^{-1}, ~2.5 nb^{-1}
	2015,2017	5.02	~1.3 nb^{-1}
	2015-2018	13	~59 nb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
Pb-Pb	2010, 2011	2.76	~75 μb^{-1}
	2015, 2018	**5.02**	~250 μb^{-1},~0.9 nb^{-1}

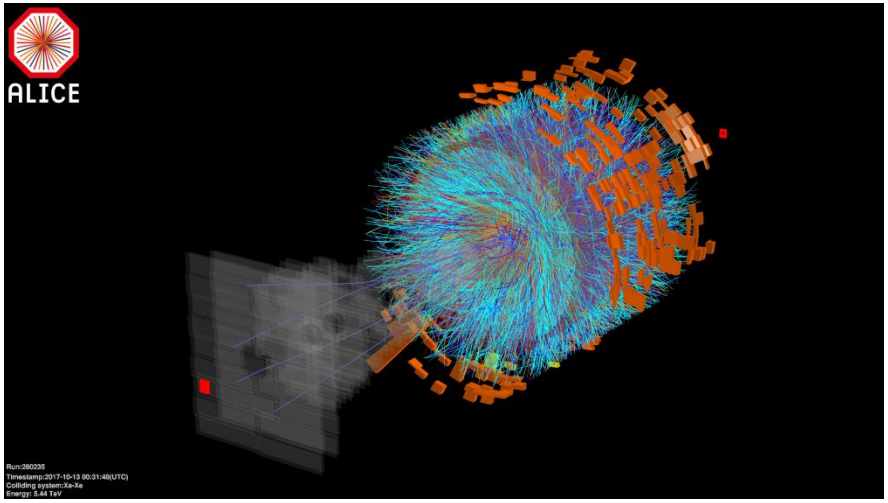




- LHC run 2 finished end of 2018 (December)
- Rich trigger menu
- Largest statistics collected for Pb-Pb in the 2018 run
  - Min. bias: ~1 x 2015
  - Central: ~9 x 2015
  - Mid-central: ~4 x 2015
  - μ high p_T: ~3 x 2015
- ➢ Significant increase of integrated luminosity: more precise measurements for hard probes

Open heavy-flavour channels studied in heavy-ion (Pb-Pb and Xe-Xe) collisions





Open heavy-flavour channels in ALICE

- Charmed hadrons ($|y| < 0.5$)
  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D^{*+} \rightarrow D^0 (K^-\pi^+)$
  - $D_s^+ \rightarrow \phi (K^-K^+)\pi^+$
  - $\Lambda_c^+ \rightarrow pK^0_s$

  } AA

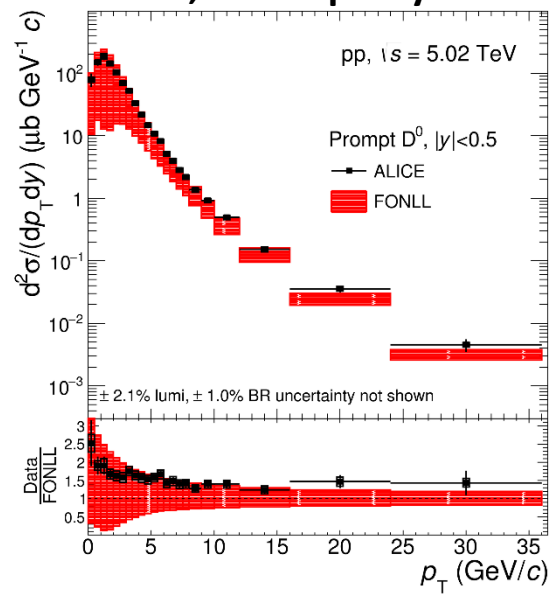
  - $^{b \rightarrow D^0}$
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - $\Lambda_c^+ \rightarrow e^+\Lambda\nu_e$
  - $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$

- Heavy-flavour hadron decay leptons
  - **eX ($|y| < 0.9$) ← c, b**
  - **μX ($2.5 < y < 4$) ← c, b**
  - **eX ← b via impact parameter**

} AA

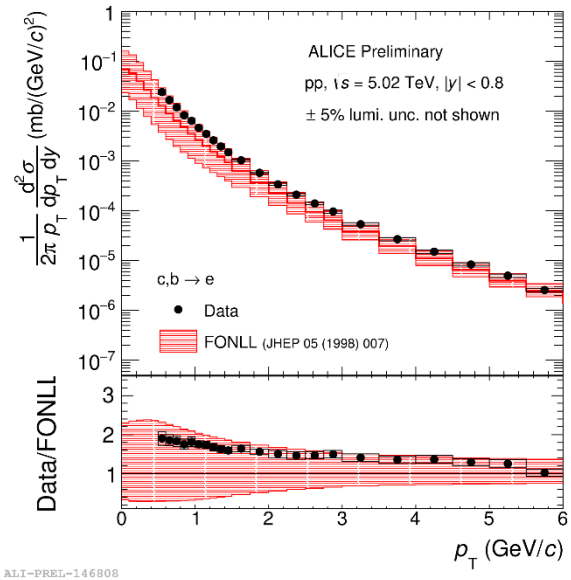
Open heavy-flavour production in pp collisions

D⁰, mid-rapidity



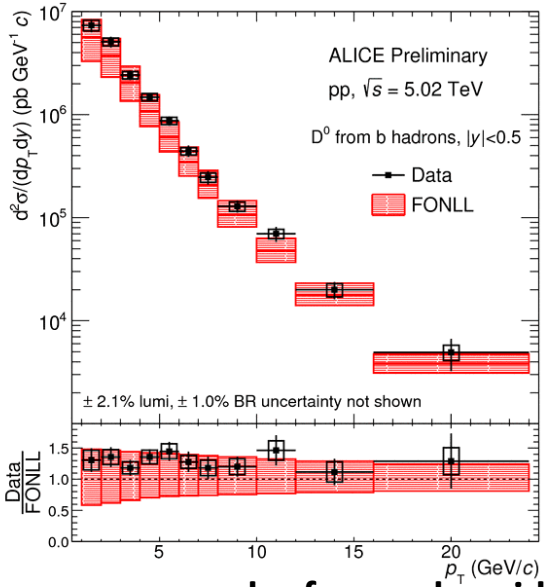
ALICE, Eur. Phys. J. C 79 (2019) 388

e ← c, b - mid-rapidity

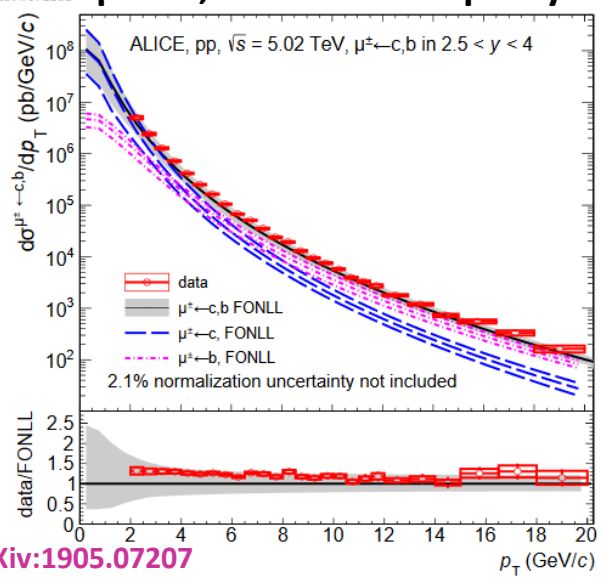


ALICE, Eur. Phys. J. C 79 (2019) 388

non-prompt D⁰ - mid-rapidity



μ ← c, b - forward rapidity

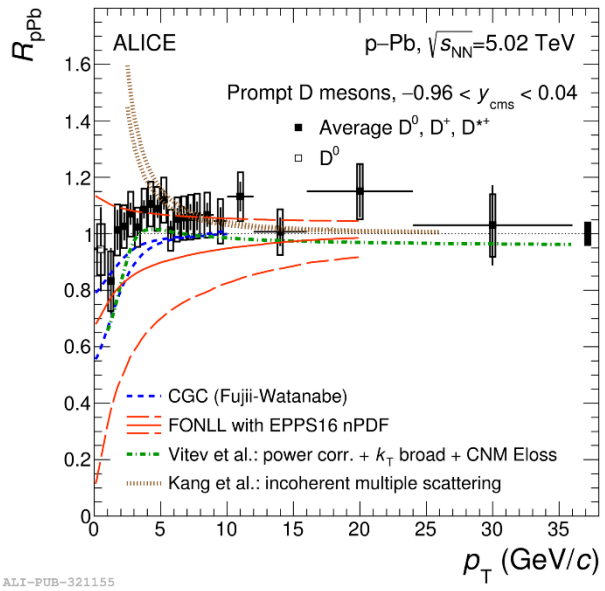


arXiv:1905.07207

- Precise measurements over a wide p_T interval
- Data well described by pQCD-based calculations at both central and forward rapidities
- Measured production cross sections at the upper edge of FONLL calculations
- Same trends at other $\sqrt{s}$ and for other channels
- Uncertainties smaller than theoretical ones
- Important reference for p-Pb and Pb-Pb/Xe-Xe collisions

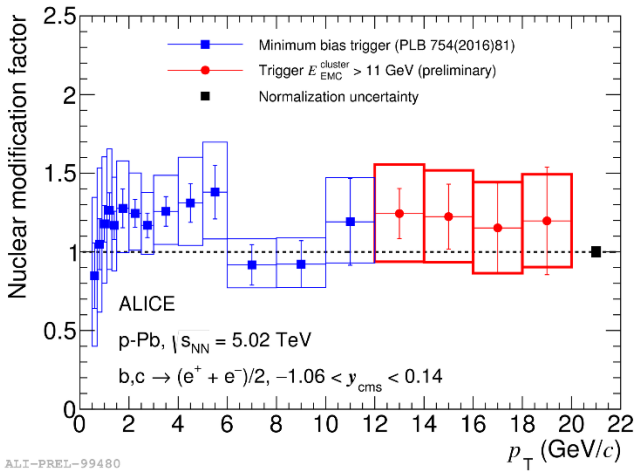
Open heavy-flavour production in p-Pb collisions

Prompt D, mid-rapidity



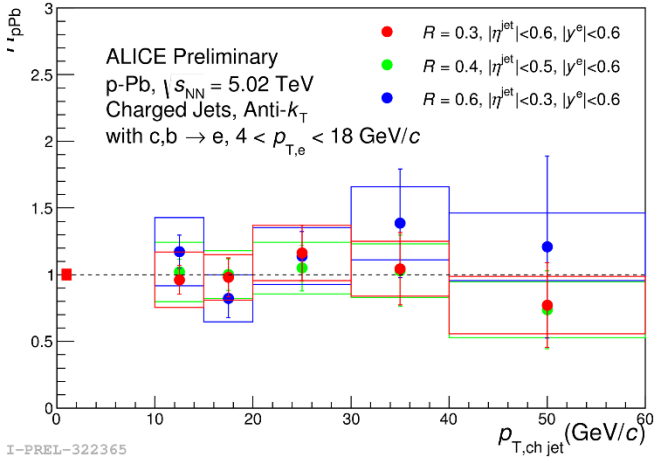
ALICE, Phys. Rev. C 94 (2016) 054908

e ← b+c, mid-rapidity

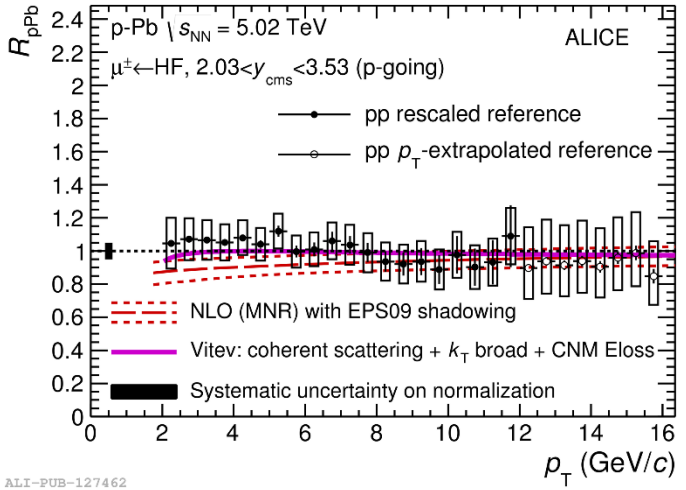


ALICE, Phys. Lett. B 754 (2016) 81

e ← b + c in jets, mid-rapidity



μ ← b+c, forward

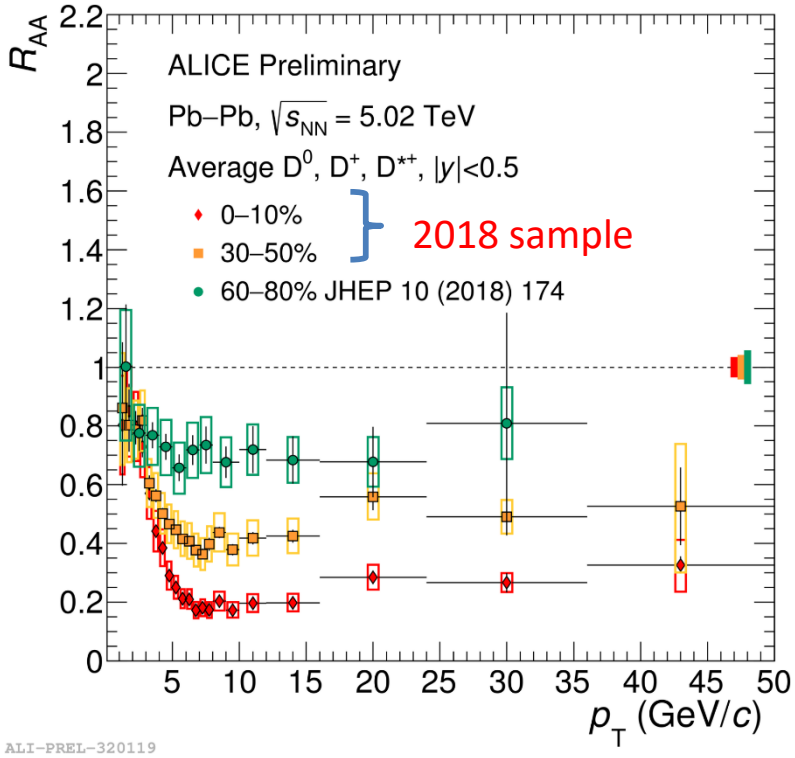


ALICE, Phys. Lett. B 770 (2017) 459

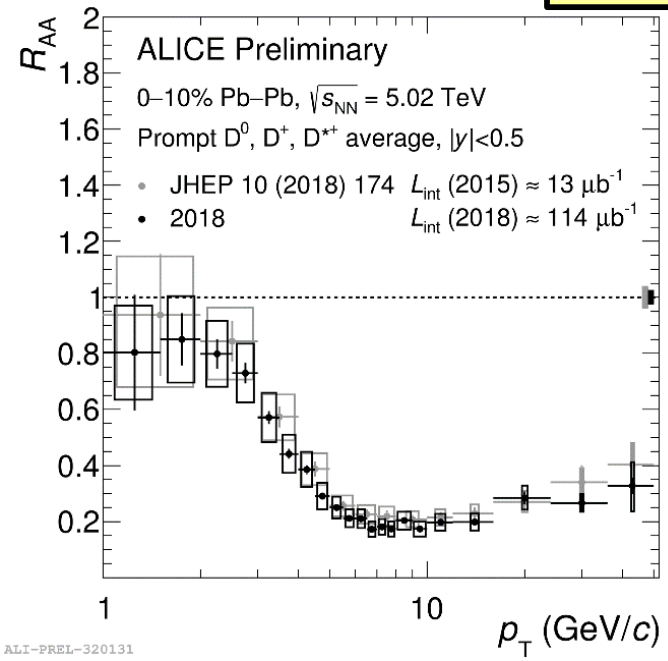
- R_{pPb} compatible with unity within uncertainties for all channels, at both mid-rapidity and forward rapidity at intermediate/high p_T
  - ➢ Cold nuclear matter effects are small
- R_{pPb} described by models including cold nuclear matter effects

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

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

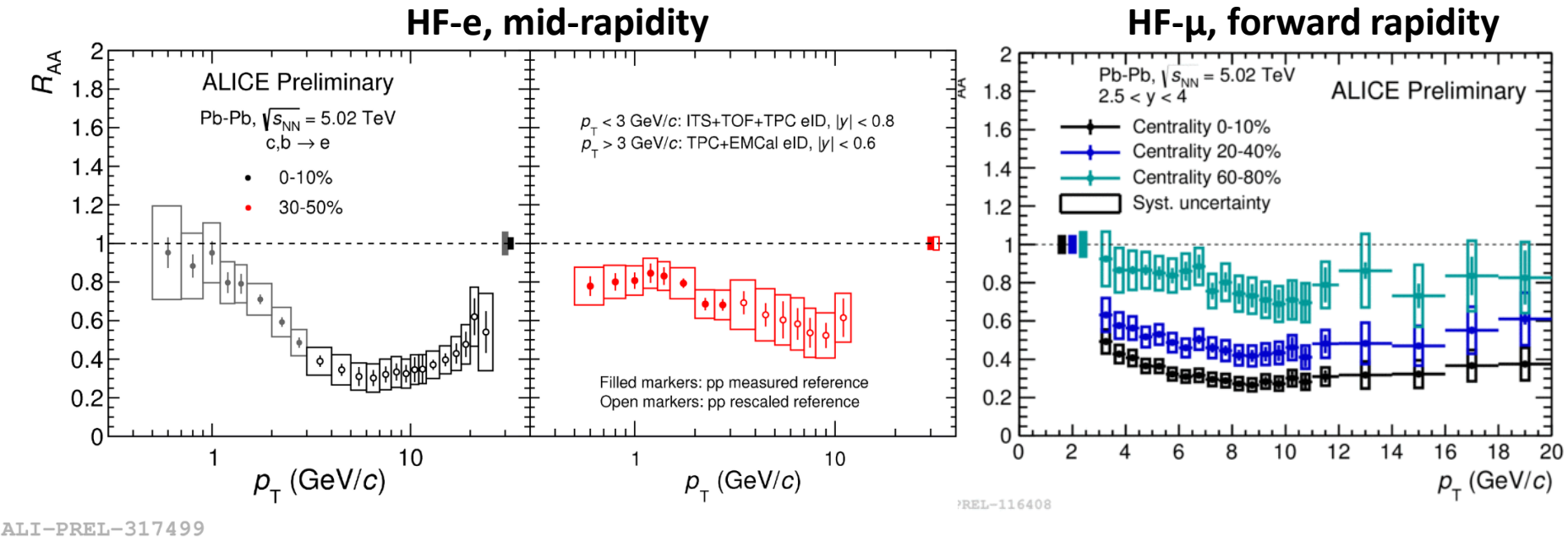


2018 vs. 2015



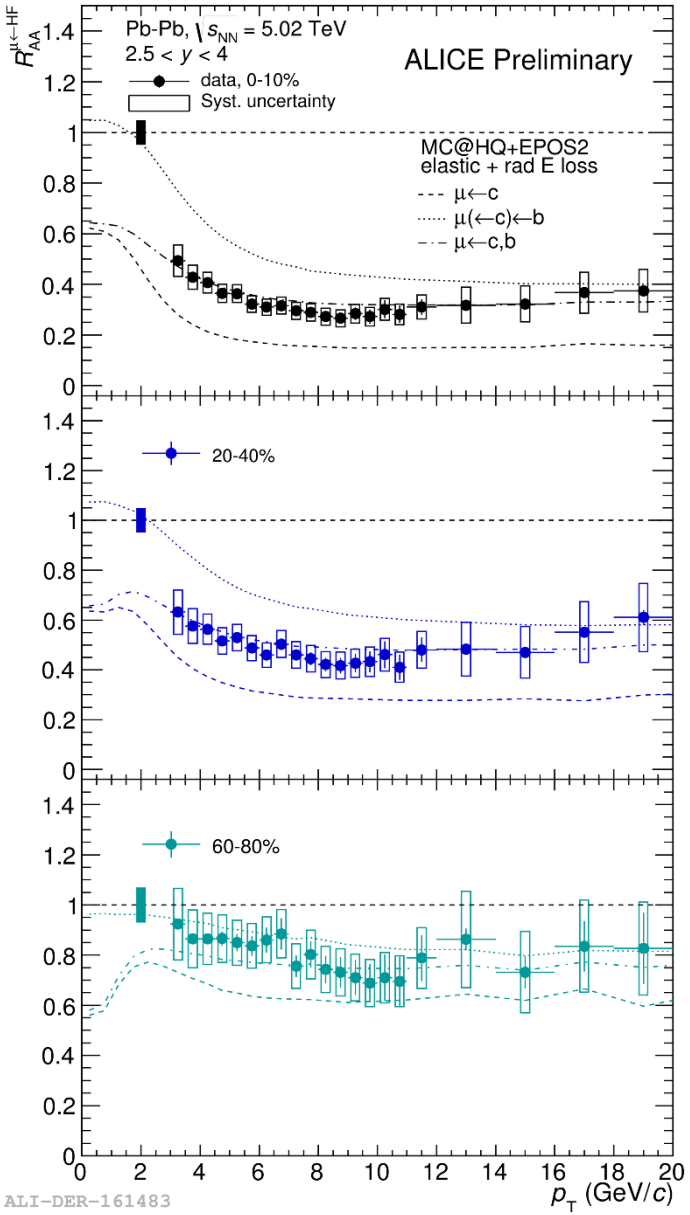
- More precise measurements with the 2018 Pb-Pb sample: better constrain at low p_T
  - Important for the measurement of the total charm cross section
- Increasing suppression from peripheral to central collisions
  - A factor of ~5 in the 0-10% centrality class at intermediate p_T ($6 < p_T < 8$ GeV/c)
- Decreasing suppression towards the low p_T region
  - Several competing effects: shadowing, flow, energy loss, …
- The measured suppression is due to final-state effects i.e effects related to the in-medium energy loss (R_{pPb} ~ 1)

Heavy-flavour lepton R_{AA} in Pb-Pb collisions



- Precise measurements over a wide p_T interval from central to peripheral collisions
- 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-flavour lepton yields suppressed by a factor of about 3 in the 10% most central collisions at intermediate p_T
  - ➢ Heavy quarks undergo strong interactions in the medium over a wide y region

Heavy-flavour decay muon R_{AA} vs. models

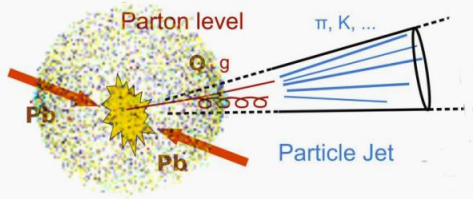


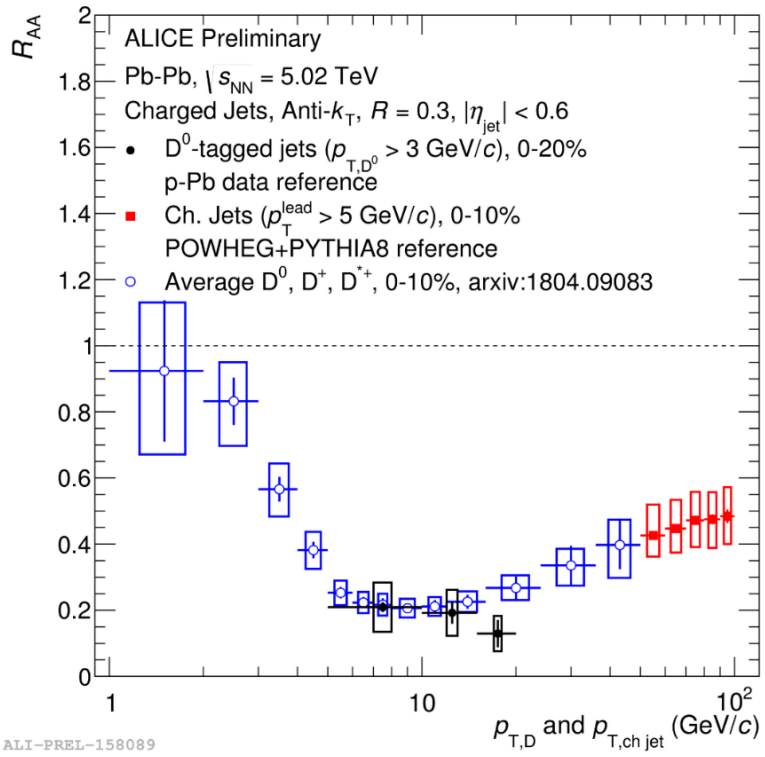
- MC@sHQ+EPOS2 describes well the measured R_{AA} over the whole p_T interval and all centralities from central to peripheral collisions
- TAMU (only elastic collisions) underestimates the suppression at high p_T and has difficulties to describe R_{AA} in peripheral collisions
- SCET describes well the measured R_{AA} in central collisions

➢ The improved precision of the R_{AA} measurement can allow us to set important constraints to models

D^0-tagged jet R_{AA} in Pb-Pb collisions

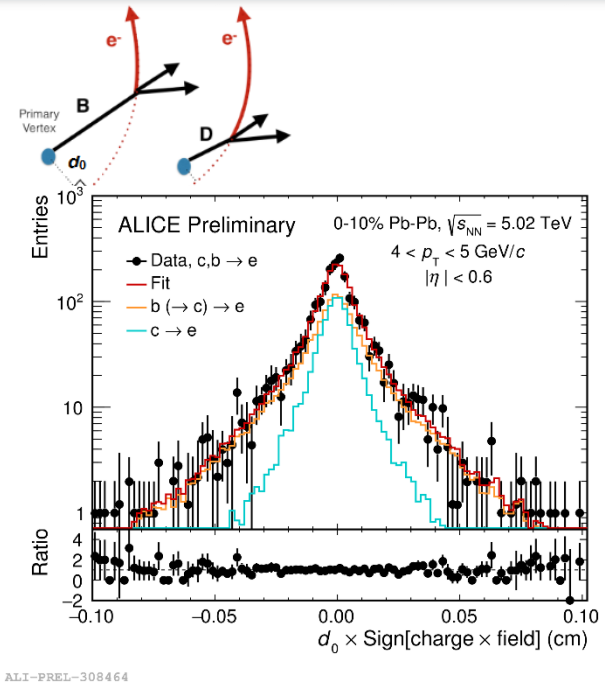
Charged jets containing a D^0 meson with $p_T > 3$ GeV/c

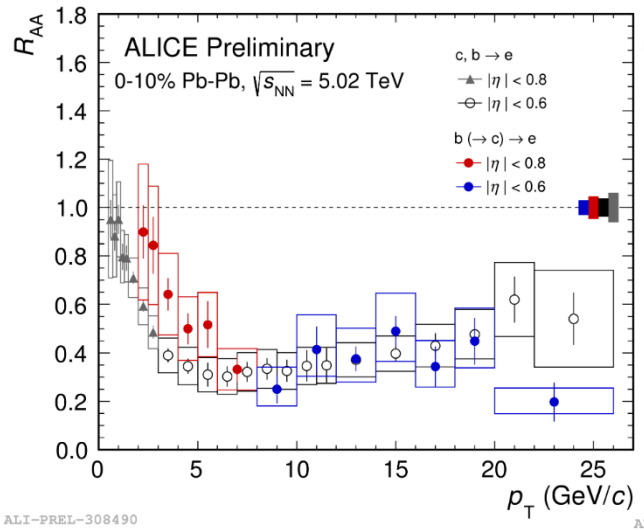


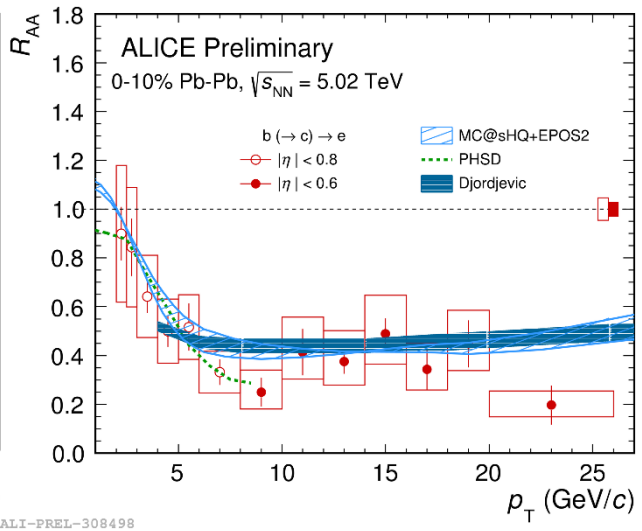


- D^0-tagged jet R_{AA} exhibits similar trends as D mesons vs p_T
  - Strong suppression (R_{AA} ~ 0.2) in $5 < p_{T,\ ch.\ jet} < 20$ GeV/c
- Hint of smaller suppression for charged jets with $p_T > 50$ GeV/c

Beauty-decay electron R_{AA} in Pb-Pb collisions







- Longer lifetime for beauty hadrons compared to other sources
  - Larger DCA (d_0) to the primary vertex
- MC templates fitted to data to separate the electron sources

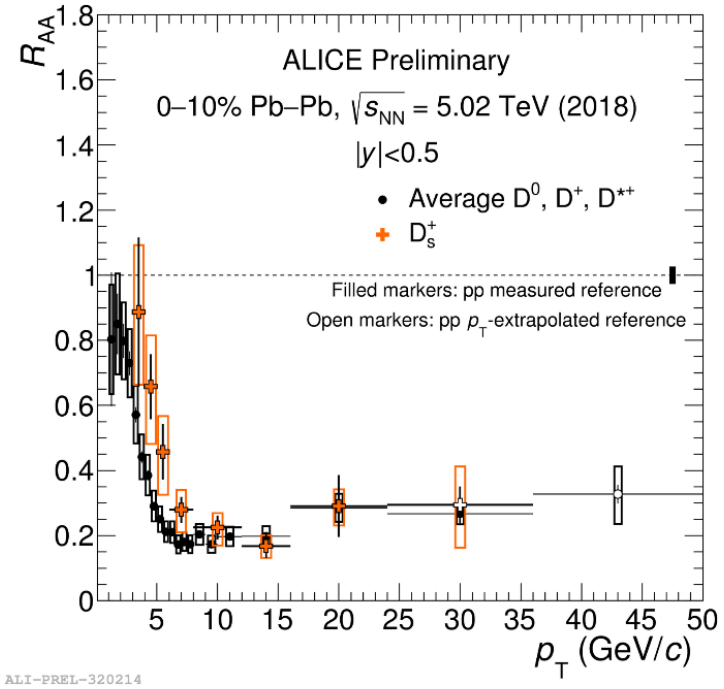
- Strong suppression of e ← b yields due to energy loss in the QGP
- Low p_T: hint for R_{AA} (e ← b) > R_{AA} (e ← c+ b)
- High p_T: similar R_{AA} as e ← c, b (e ← b dominates over e ← c in pp collisions)
- R_{AA} (e ← b) described by transport models

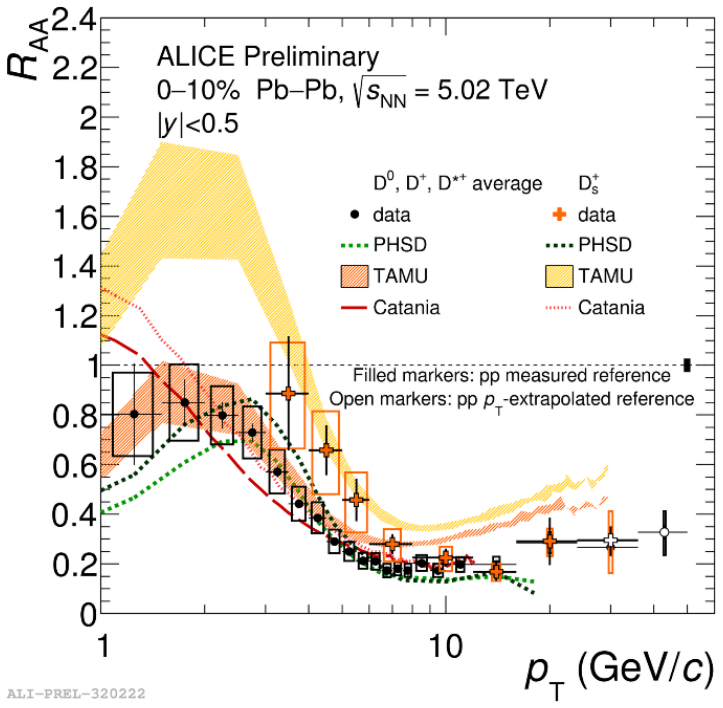
PHSD: Phys. Rev C 93 (2016) 034906; MC@sHQ+EPOS2: Phys. Rev. C 89 (2014) 014905; Djordjevic: Phys. Rev. C 92 (2015) 024918

Strange-D mesons in Pb-Pb collisions

$D^+_s \rightarrow \Phi\, \pi^+ \rightarrow K^+K^-\pi^+$

Study of hadronisation mechanisms and strangeness enhancement inside the QGP





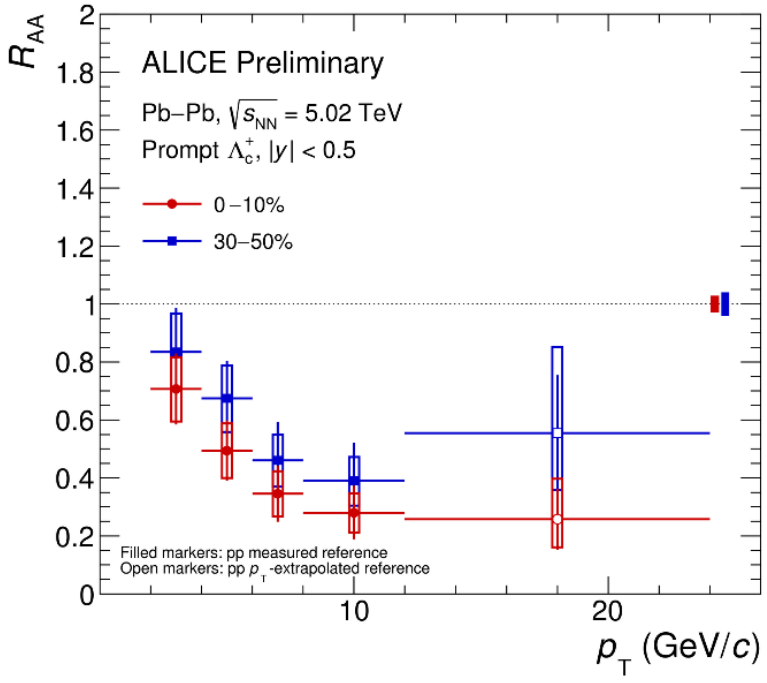
- Similar pattern for strange and non-strange D-meson R_{AA}
- Smaller suppression for strange D mesons than non-strange D mesons
  - Enhancement of strangeness in the QGP as expected
- Increase of the D^+_s R_{AA} w.r.t. non-strange D mesons predicted by three transport models

PHSD: Phys. Rev C 93 (2016) 034906; TAMU: Phys. Lett. B 735 (2014) 445; Catania: Eur. Phys. J. C (2018) 78

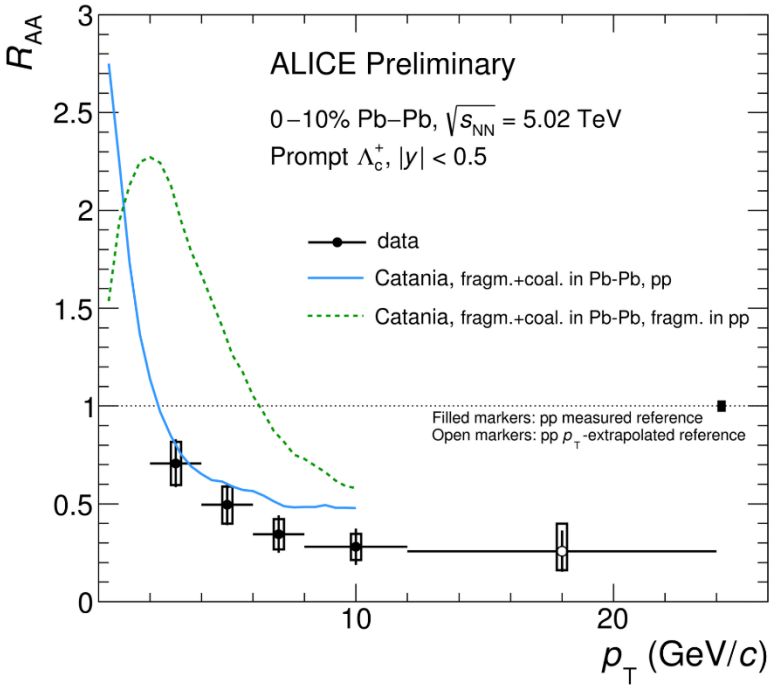
Charmed baryons in Pb-Pb collisions

$\Lambda^+_c \rightarrow K^0_s\, p \rightarrow \pi^+\, \pi^-\, p$

Important tool to study hadronisation mechanisms inside the QGP



ALI-PREL-321861



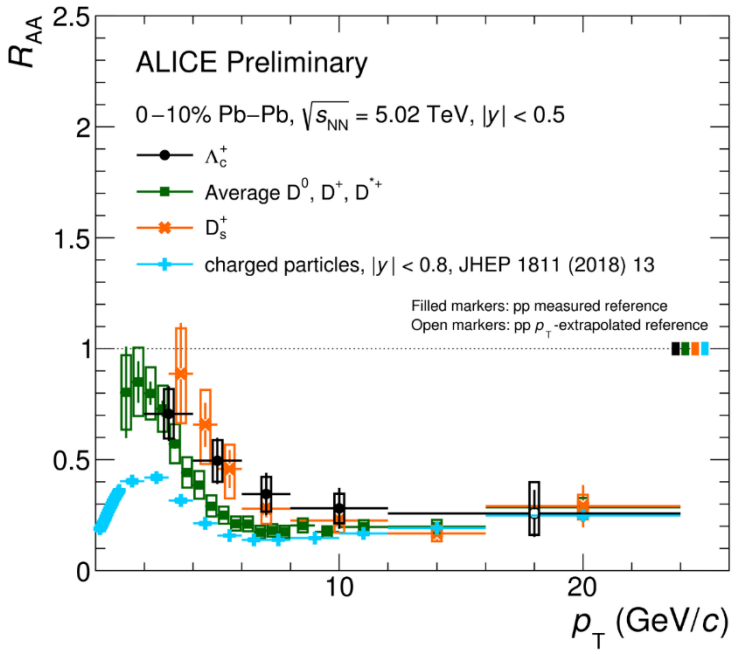
ALI-PREL-321835

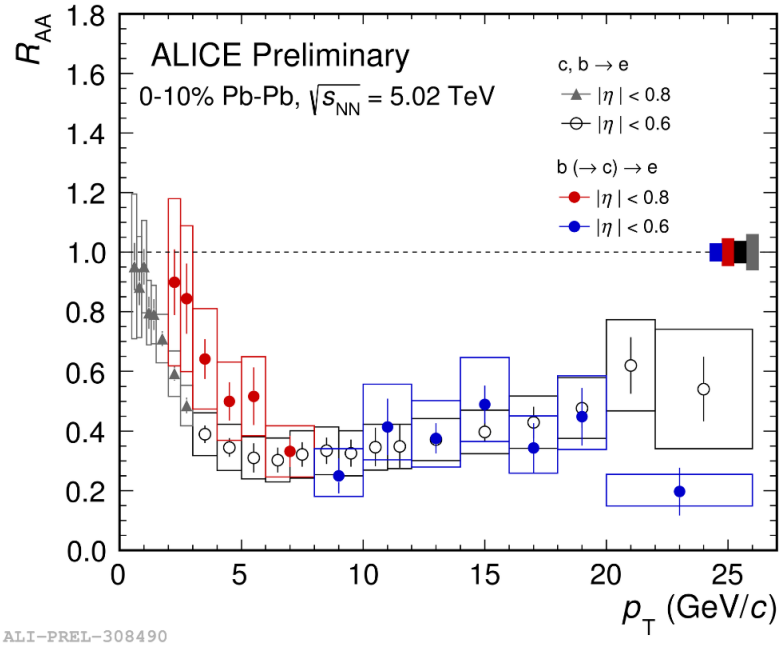
- Hint for a larger suppression (smaller R_{AA}) in central than in semi-central Pb-Pb collisions
- Good agreement with Catania model with a scenario where both coalescence and fragmentation are present in Pb-Pb and pp collisions

Catania: Eur. Phys. J. C (2018) 78; statitstical hadronisation model: arXiv:1901.09200

Where do we stand with R_{AA} hierarchy?

$\Delta E(\pi^{\pm}) > \Delta E(D) > \Delta E(B) \rightarrow R_{AA}(\pi^{\pm}) < R_{AA}(D) < R_{AA}(B)$?
as naively expected from colour-charge and quark-mass depend energy loss

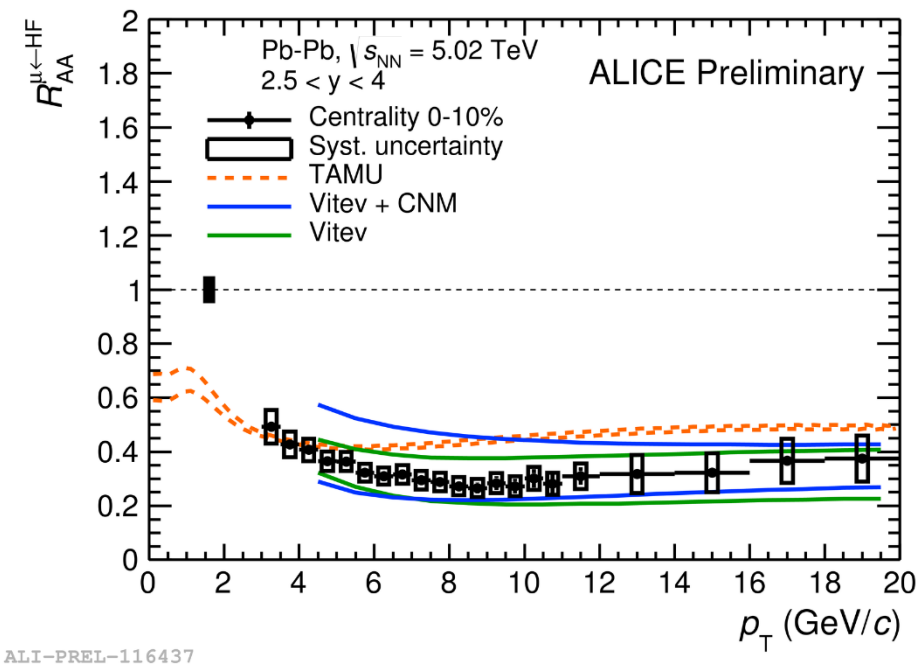




- D mesons less suppressed than charged particles at low p_T: interplay of different p_T shapes & fragmentation functions, flow, colour-charge dependence
- e ← b less suppressed than e ← b, c at low p_T: quark-mass ordering
- Hint for less suppression for D^+_s and Λ^+_c compared to D mesons, difficult to conclude for D^+_s
  - Hint of hierarchy observed at low p_T: $R_{AA}(\pi^{\pm}) < R_{AA}(D) < R_{AA}(B)$

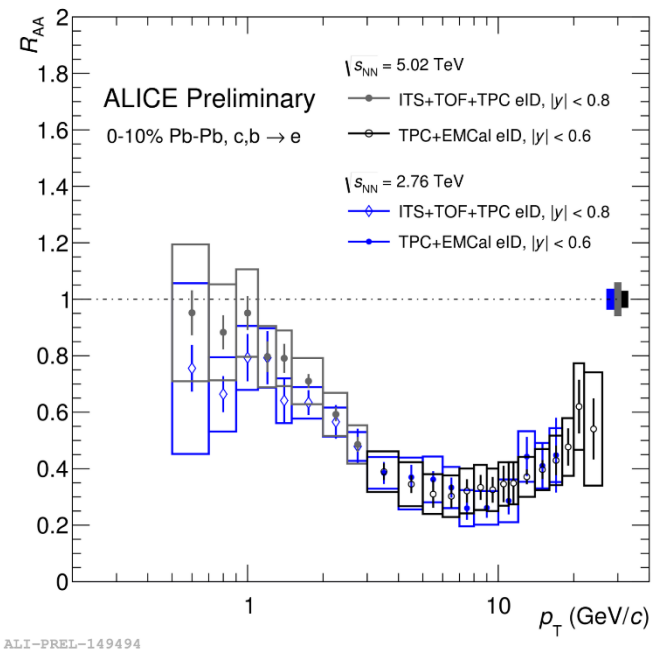
Open heavy-flavour R_{AA} *vs.* $\sqrt{s_{NN}}$

HF-μ, forward rapidity



ALI-PREL-116437

HF-e, mid-rapidity

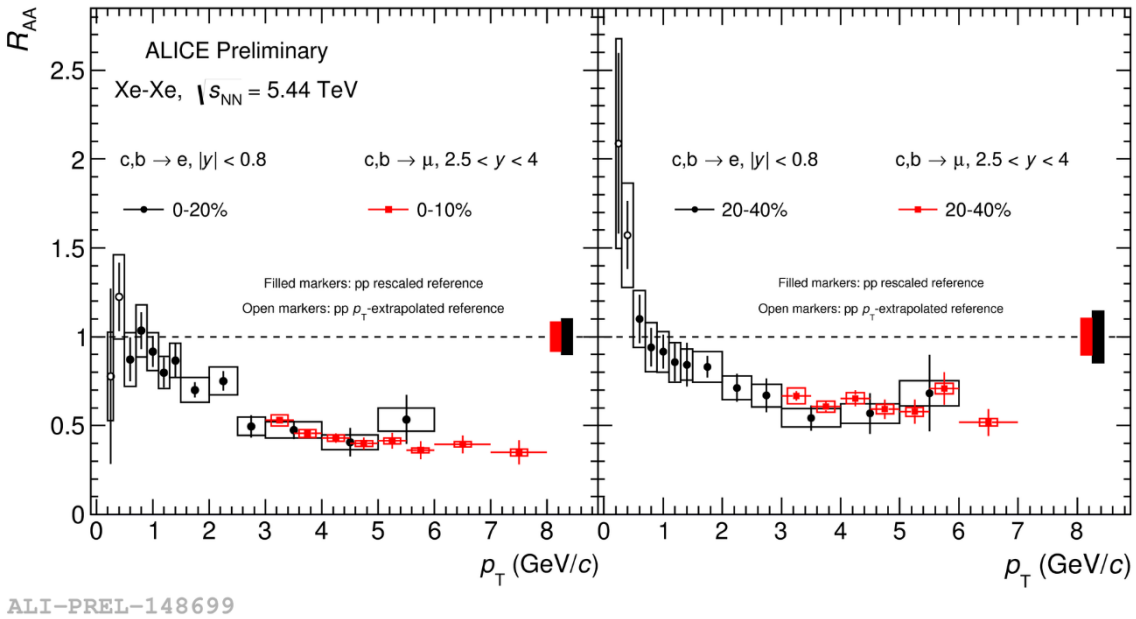


ALI-PREL-149494

- Similar R_{AA} at 5.02 TeV and at 2.76 TeV within uncertainties in central collisions for muons and electrons from heavy-flavour hadron decays at forward rapidity and mid-rapidity, respectively
  - Does not imply same energy loss at both energies:
    - interplay of energy loss and spectra shapes **[M. Djordjevic, arXiv: 1505.04316]**
    - possible different fractions of charm and beauty

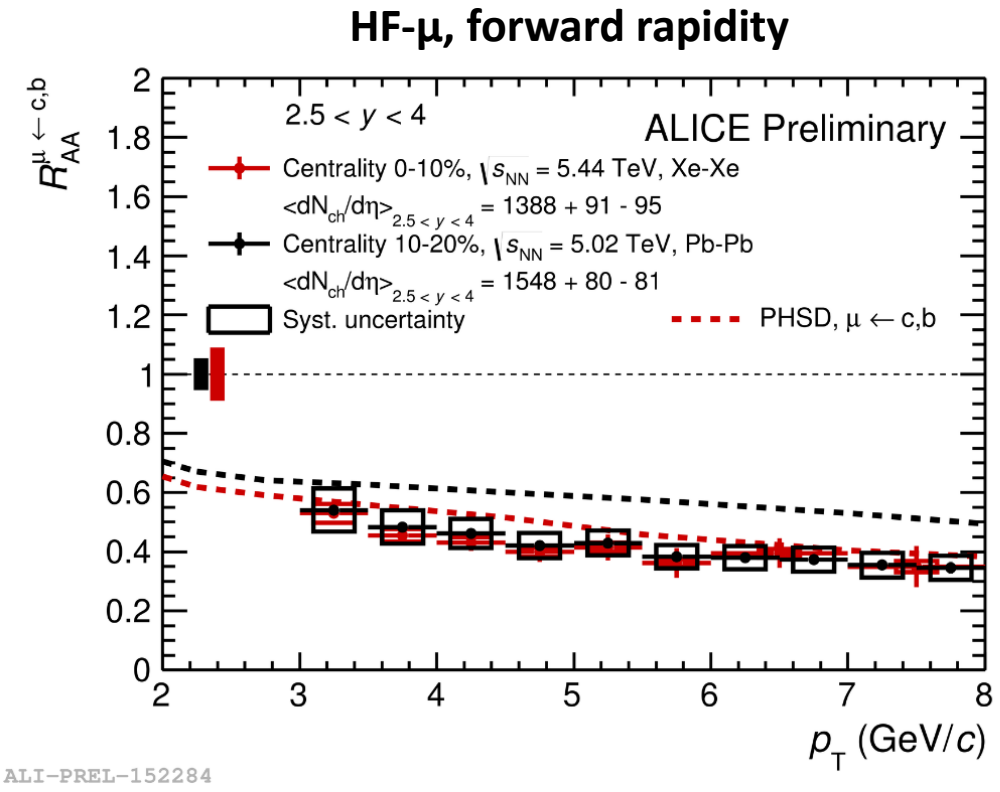
Open heavy-flavour R_{AA} in Xe-Xe collisions

- Investigate the system size dependence of heavy-quark in-medium energy loss
- Study initial-state effects on heavy-quark production
- Further characterize the hot and dense medium created in heavy-ion collisions and provide new constraints on model predictions



- Similar trends *vs.* p_T and centrality as in Pb-Pb collisions for leptons (muons at forward rapidity and electrons at mid-rapidity) from heavy-flavour hadron decays
  - Strong suppression of a factor of about 2 - 2.5 for $3 < p_T < 6$ GeV/*c* in central Xe-Xe collisions

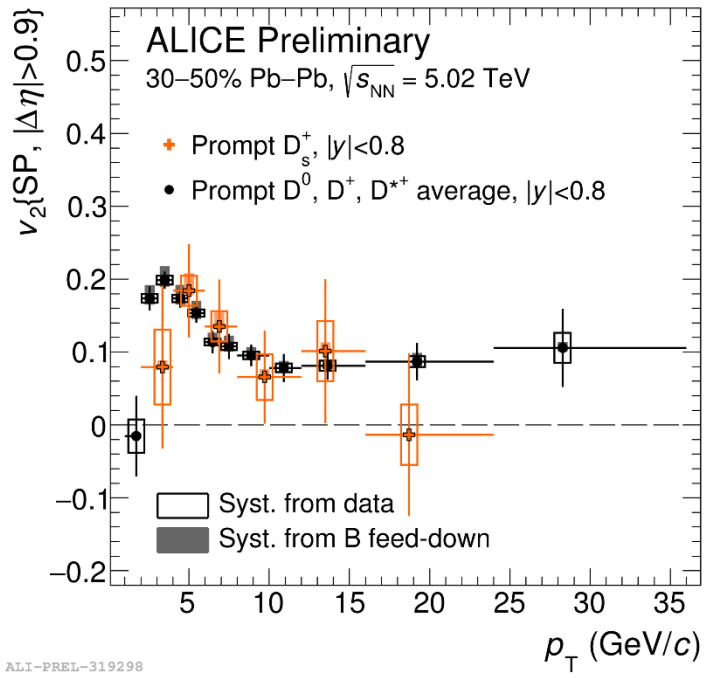
Open heavy-flavour R_{AA} in Xe-Xe and Pb-Pb



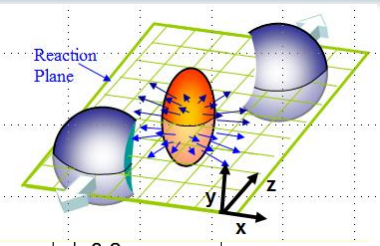
- Similar R_{AA} observed in Xe-Xe and Pb-Pb collisions for μ ← c, b when compared at similar average charged-particle multiplicity density <dN/dη>
- A bit of tension for PHSD model to reproduce the scaling observed at forward rapidity

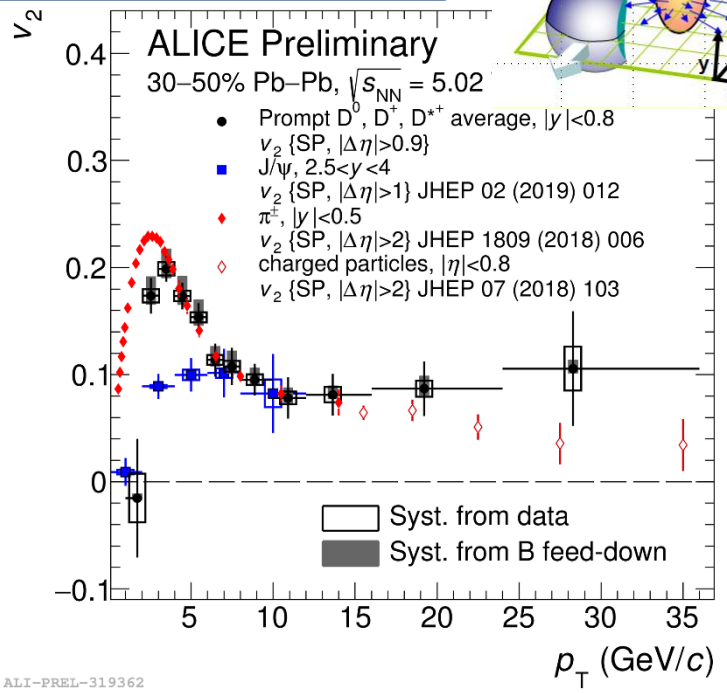
PHSD: Phys. Rev C 93 (2016) 034906

Strange and non-strange v_2 in Pb-Pb collisions



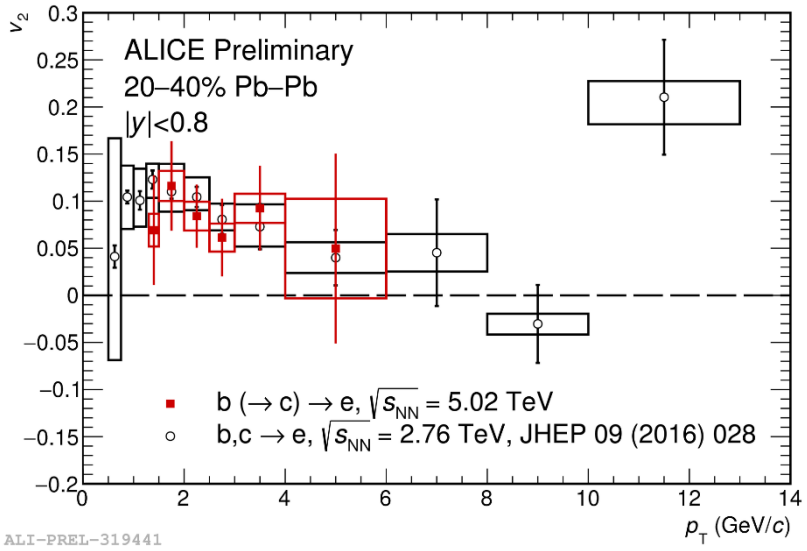
$$\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$

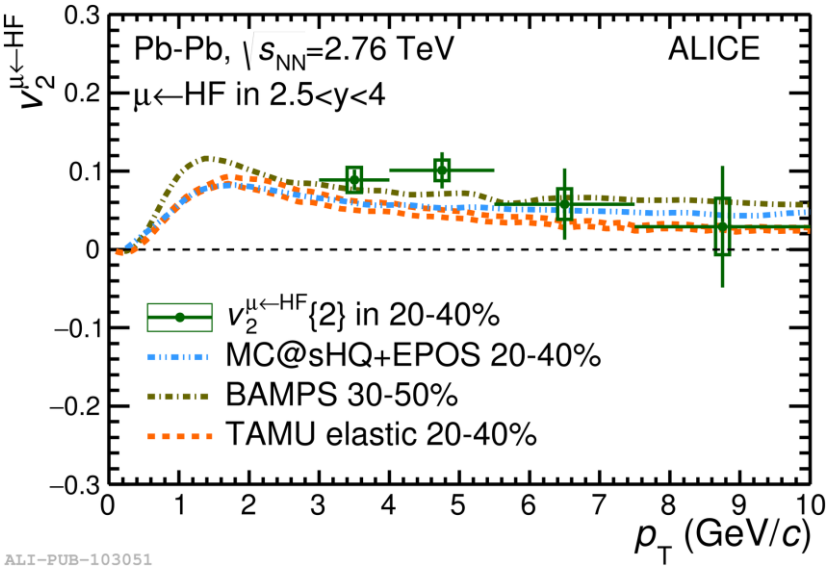




- Non-zero elliptic flow (v_2) for D mesons
  - Participation of charm quarks in the QGP collective expansion
- Non-strange D-meson v_2 compatible with $v_2(D^+_s)$ within uncertainties, down to p_T = 3 GeV/c
- Low p_T: $v_2(J/\psi) < v_2(D) < v_2(\pi^{\pm})$
  - Light quarks contribute to v_2 (D)
- High p_T: similar v_2 for different particles within uncertainties
  - In-medium path-length dependent energy loss effects

Beauty v_2 in Pb-Pb collisions



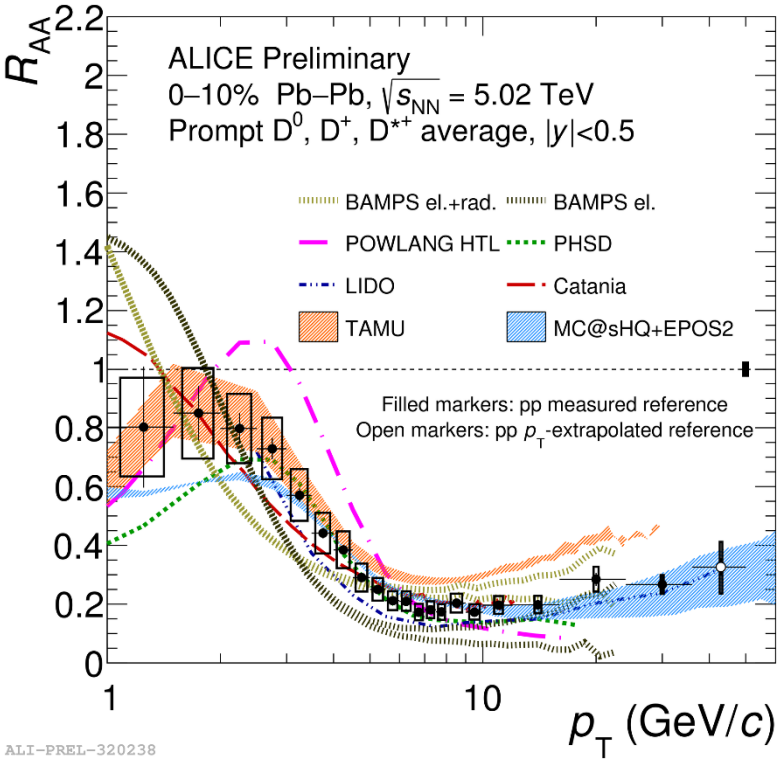


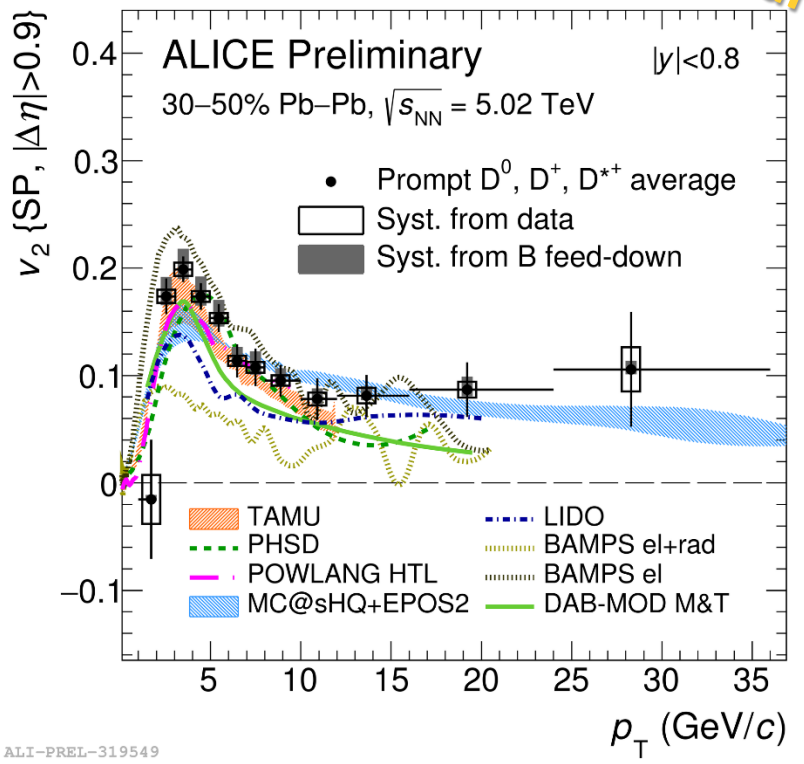
- Non-zero v_2 measured for beauty electrons, significance 3.49σ in $1.3 < p_T < 4$ GeV/c
  - Hint that b quarks participate in the collective expansion of the medium

- v_2 (e ← b) compatible with v2 (e ← b, c) within uncertainties
- Similar v_2 measured at forward rapidity for μ ← b, c
  - Participation of heavy quarks, mainly charm quarks, in the collective expansion of the system

D-meson R_{AA} and v_2 vs. models

2018 sample





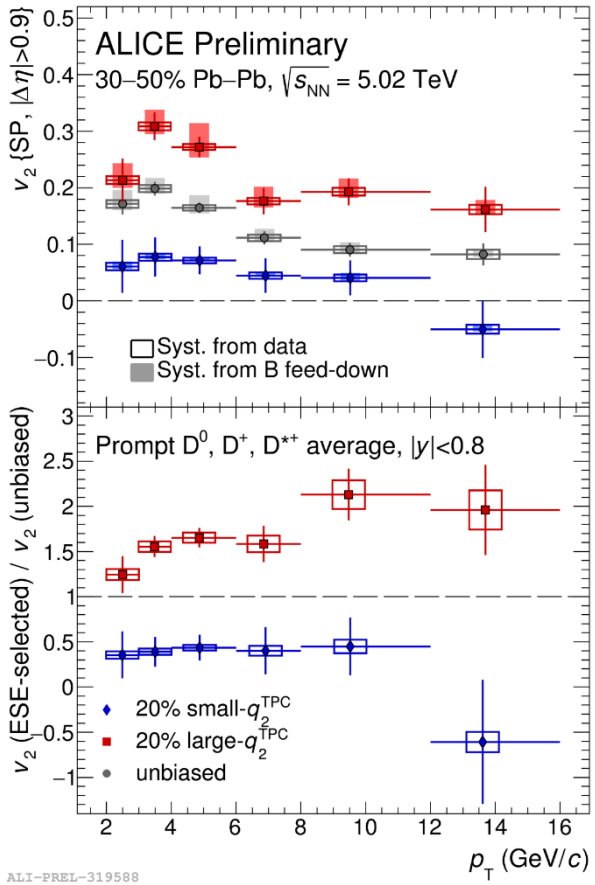
- Data precision constrains the description of charm interaction and diffusion in the medium at low p_T
- Interplay of CNM (shadowing), collisional and radiative energy loss, coalescence and realistic medium evolution required to describe data

D-meson v_2 with Event-Shape Engineering

- Fluctuations in the initial state and event eccentricity
  - Event-by-event variation of v_2 at a given centrality class
  - Studied by measuring v_2 for different 2nd order reduced q-vector (q_2) values

$$q_2 = \frac{|Q_2|}{\sqrt{M}} \qquad \langle {q_2}^2 \rangle = 1 + \langle M - 1 \rangle \langle {v_2}^2 - \delta_2 \rangle$$

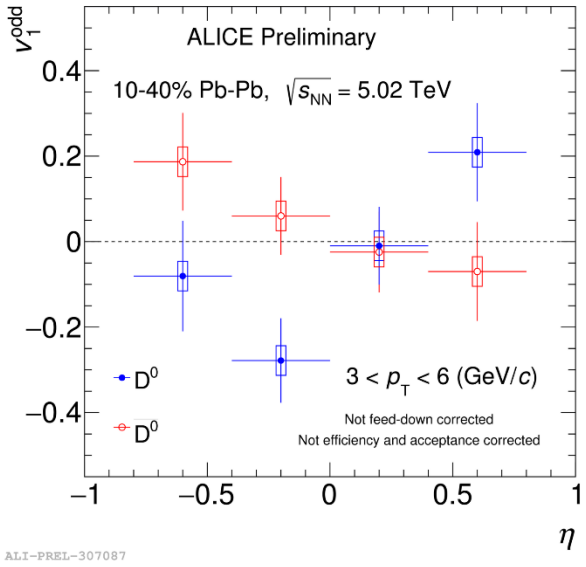
δ_2: non-flow effect

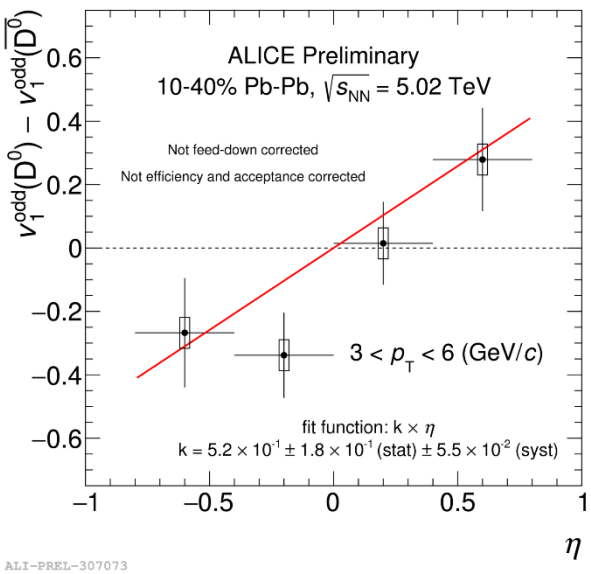


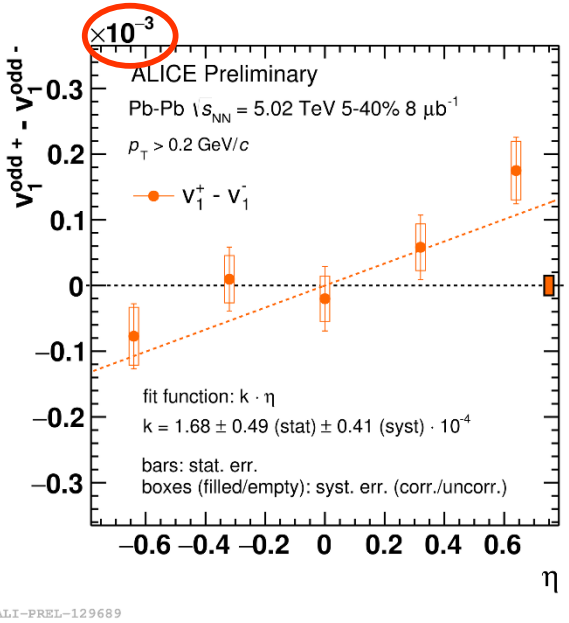
- D-meson v_2 with large q_2 > D-meson v_2 with small q_2
- Clear difference of D-meson v_2 in events (30-50% centrality class) with small and large q_2
  - Charm sensitive to collectivity of light-hadron bulk and even-by-event fluctuations in the initial state
- Hint of separation also with q_2^{V0A} (backup)

D-meson directed flow v_1 in Pb-Pb collisions

- Quantify the charge-dependent v_1 due to the presence of a strong electromagnetic field, generated by the movement of proton spectators
- Charm quarks produced when the magnetic field is maximum
  - Good probe to study the charge-dependent v_1



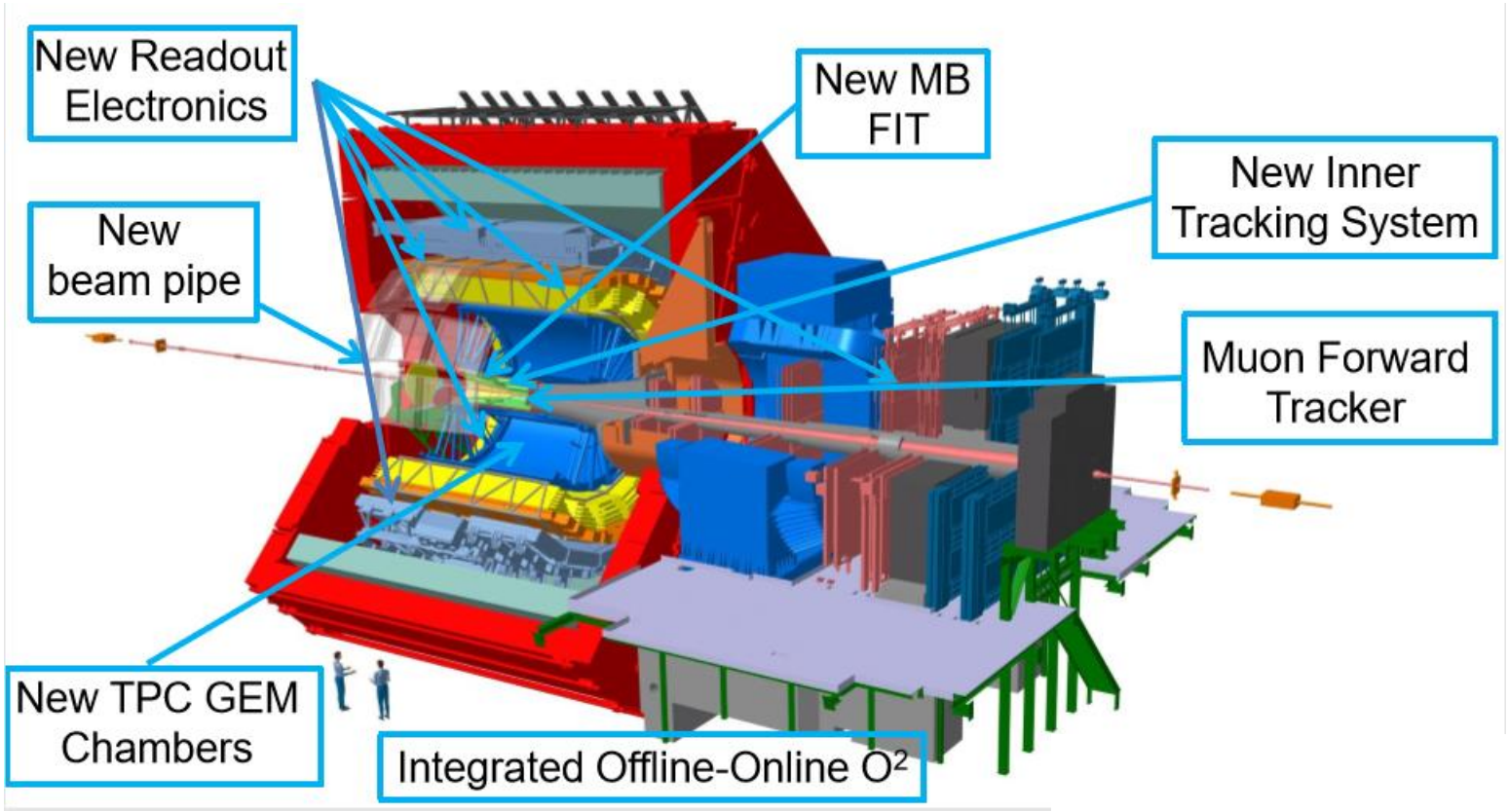




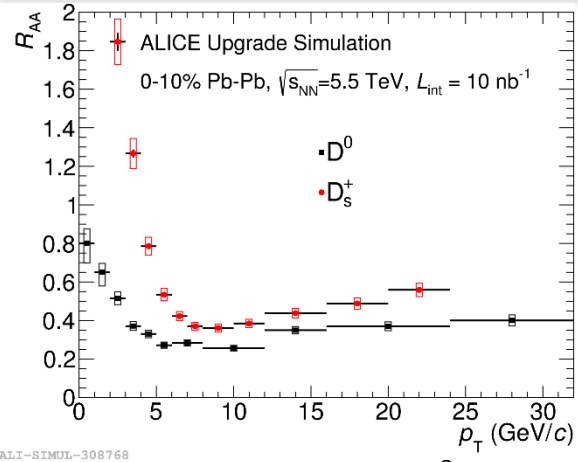
- Indication of opposite trend of v_1 as a function of η for D^0 and $\overline{D^0}$ mesons
- Positive slope for D^0 mesons with a 2.7σ significance
- Larger slope for D^0 mesons than charged particles [and than theoretical predictions, not shown]

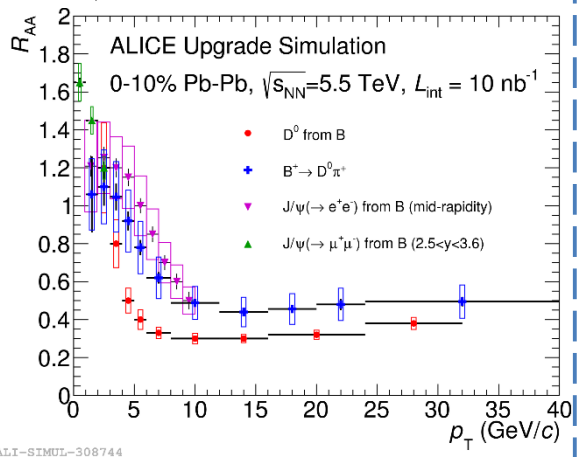
Open heavy-flavour prospects for run 3-4

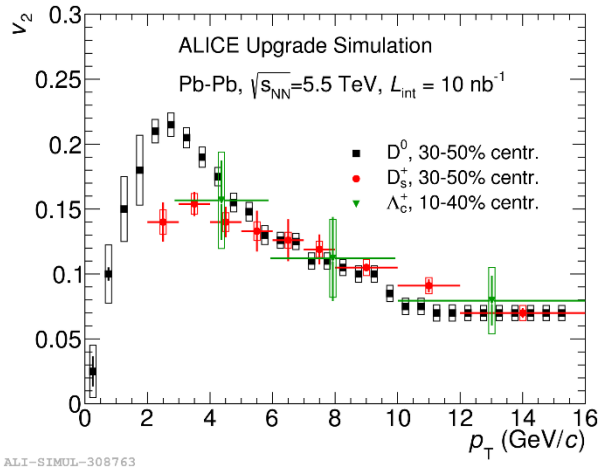
- High precision measurements of rare probes down to the low p_T region
  → x 100 larger minimum-bias sample (~10^{11} events) and x 10 larger sample for rare probes at forward rapidity compared to Run 2 (Pb-Pb: Lint > 10 nb^{-1})
- Increase readout rate to 50 kHz, presently limited to ~1 kHz
- Improvement of pointing resolution at mid-rapidity (UITS) and heavy-flavour vertices also forward rapidity (MUON + MFT)

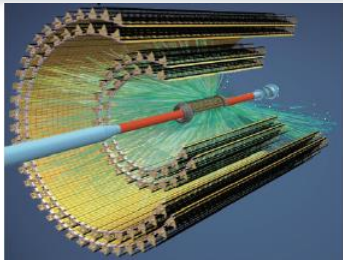


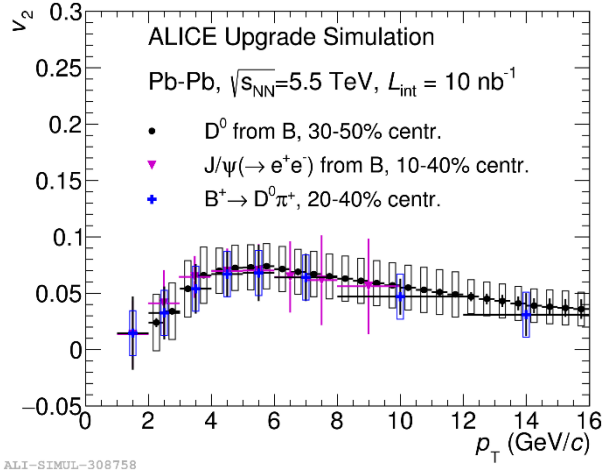
Selected performance studies with the new ITS







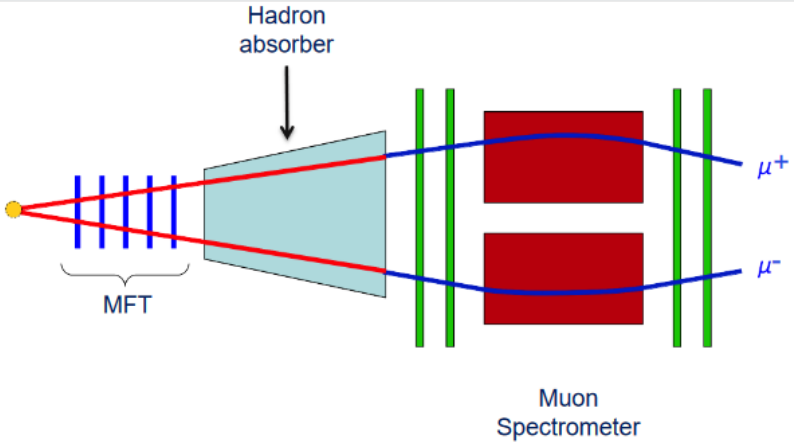




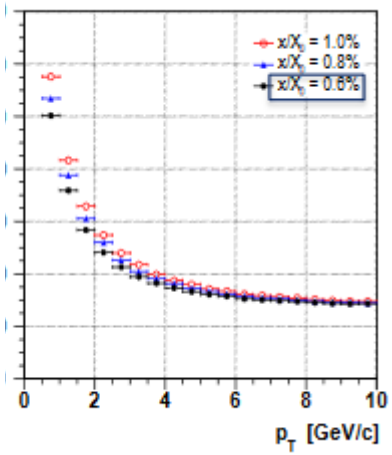
- D^0: uncertainties < 10%, down to p_T = 0
- D^+_s: can be measured down to low p_T with a good accuracy
- Beauty measurements via several channels at both mid and forward rapidity

- Elliptic flow measurements for charmed mesons and baryons (Λ^+_c), and beauty down to low p_T with high precision

Selected performance studies with MFT-MUON

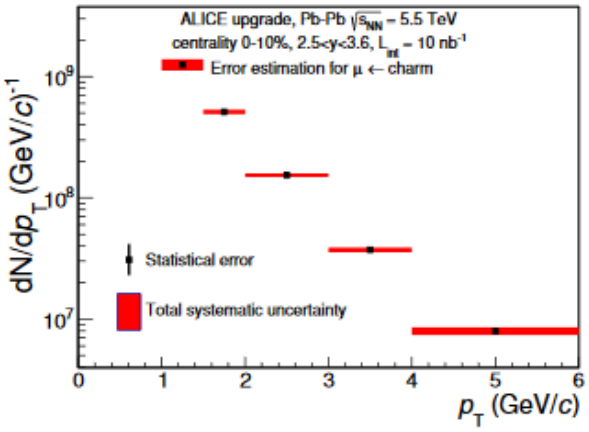


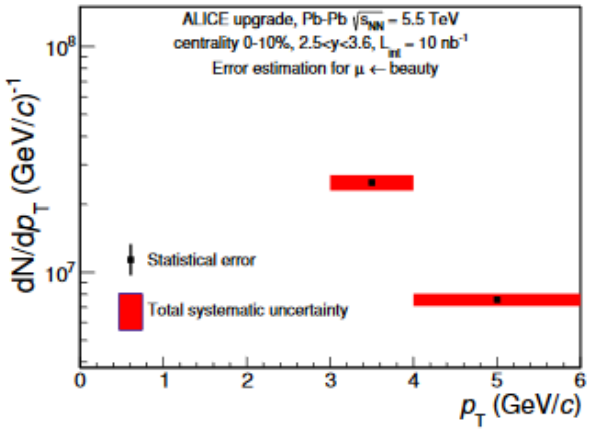
CERN-LHCC-2015-001

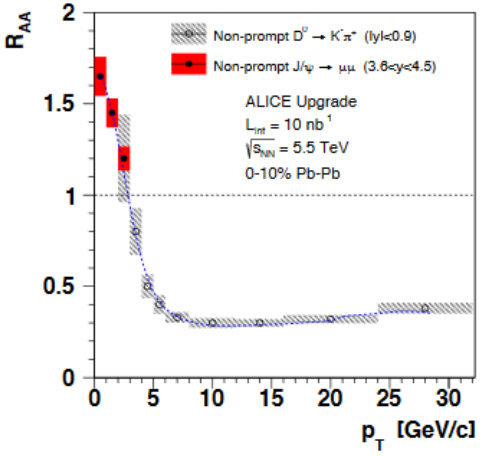


High pointing accuracy in the transverse plane after matching

CERN-LHCC-2015-001







❑ Charm and beauty measurements at forward rapidity ($2.5 < y < 3.6$) down to low p_T with high precision via single muons (c, b) and non-prompt J/ψ (b)

Conclusion

- Strong suppression of open heavy flavours over a wide rapidity interval
  - Heavy-quark energy loss
  - Indication of less suppression for beauty
  - Mass ordering?
- Charmed baryons and strange D mesons less suppressed than non-strange D mesons
  - Coalescence?
- Non-zero elliptic flow of open heavy flavours and also observed for beauty electrons
  - Participation of charm and beauty quarks in the collective expansion of the medium

More to come soon

- Ongoing analyses with the 2018 Pb-Pb sample
  - QM2019 in November

- ALICE upgrade
  - Fist data taking in 2021

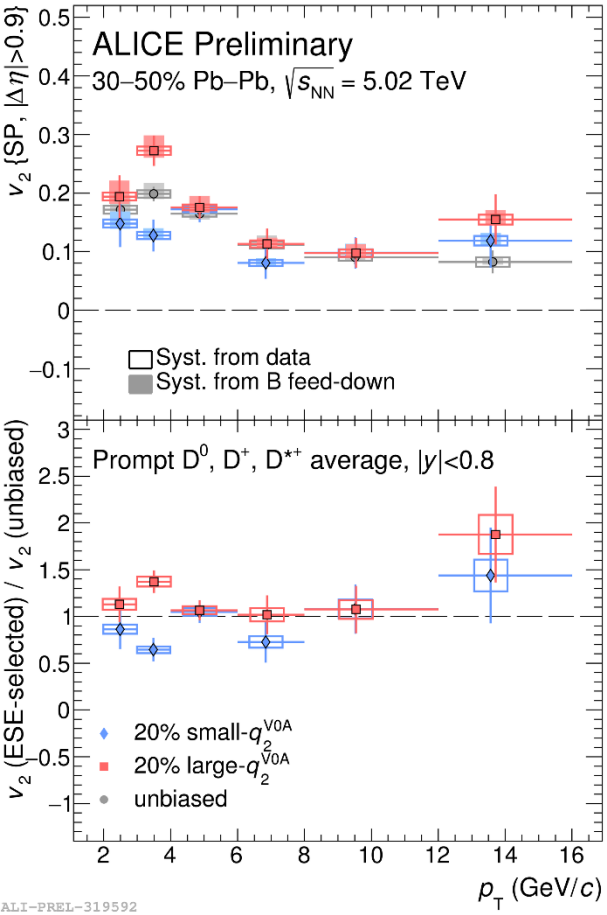

Thank you for
your attention

D-meson v_2 with Event-Shape Engineering

- Fluctuations in the initial state and event eccentricity
  - Event-by-event variation of v_2 at a given centrality class
  - Studied by measuring v_2 for different 2nd order reduced q-vector (q_2) values

$$q_2 = \frac{|Q_2|}{\sqrt{M}} \qquad \langle {q_2}^2 \rangle = 1 + \langle M - 1 \rangle \langle {v_2}^2 - \delta_2 \rangle$$

δ_2: non-flow effect

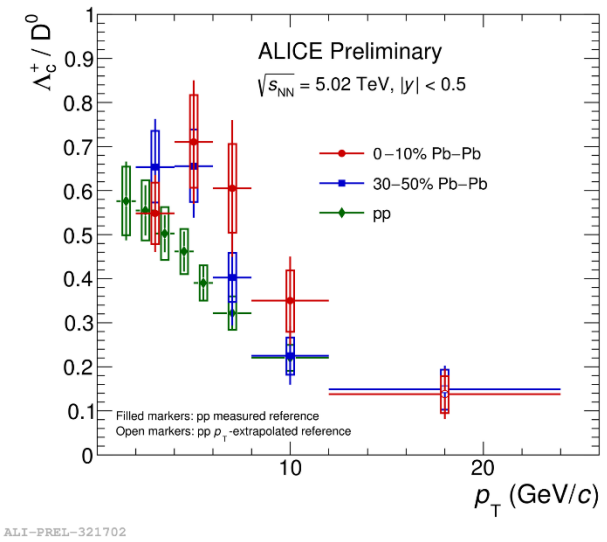


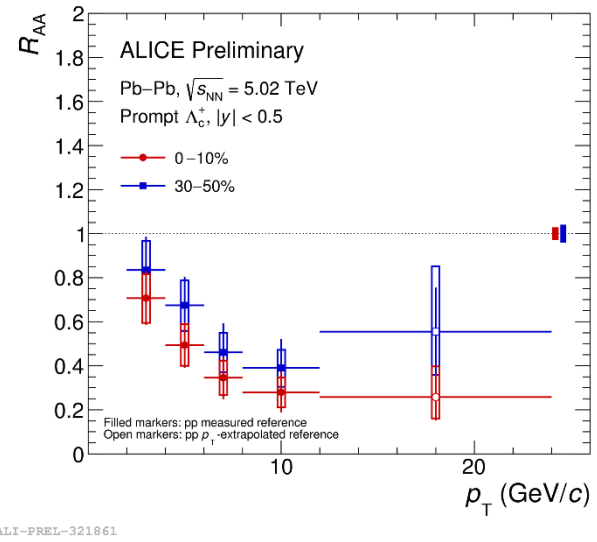
- D-meson v_2 with large q_2 > D-meson v_2 with small q_2
- Clear difference of D-meson v_2 in events (30-50% centrality class) with small and large q_2
  - Charm sensitive to collectivity of light-hadron bulk and even-by-event fluctuations in the initial state
- Hint of separation also with q_2^{V0A} (backup)

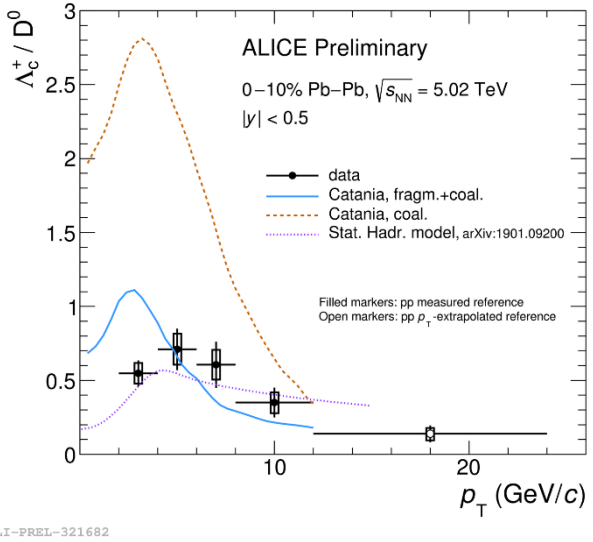
Charmed baryons in Pb-Pb collisions

$\Lambda^+_c \rightarrow K^0_s\, p \rightarrow \pi^+\, \pi^-\, p$

Important tool to study hadronisation mechanisms inside the QGP







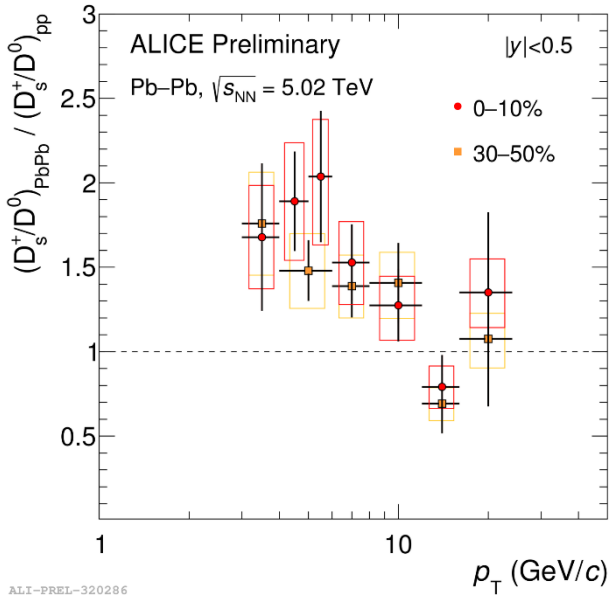
- Hint of a larger Λ^+_c/D^0 ratio in Pb-Pb collisions than in pp collisions at intermediate p_T, in particular
- Larger Λ^+_c/D^0 ratio in central than in semi-central Pb-Pb collisions
- Hint for a larger suppression (smaller R_{AA}) in central than in semi-central Pb-Pb collisions
- Good agreement of Λ^+_c/D^0 ratio with statistical hadronisation model and Catania model with a scenario where both coalescence and fragmentation are present

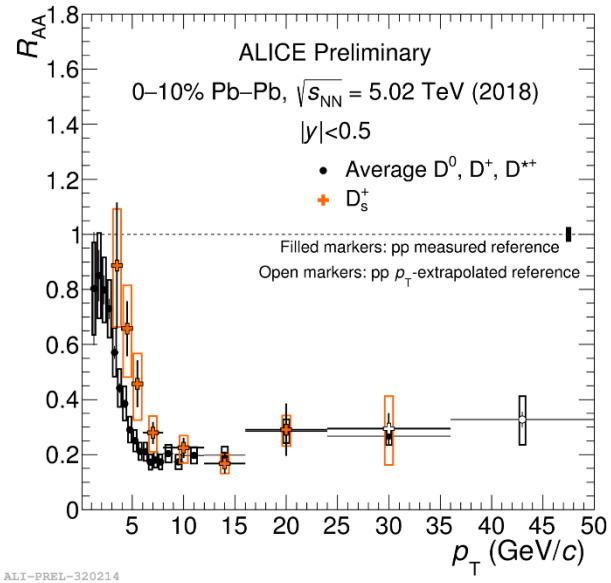
Catania: Eur. Phys. J. C (2018) 78; statitstical hadronisation model: arXiv:1901.09200

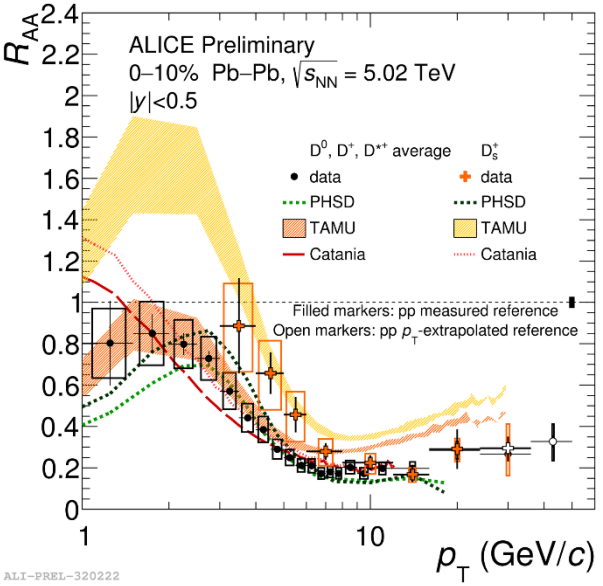
Strange-D mesons in Pb-Pb collisions

$D^+_s \rightarrow \Phi\, \pi^+ \rightarrow K^+K^-\pi^+$

Study of hadronisation mechanisms and strangeness enhancement inside the QGP



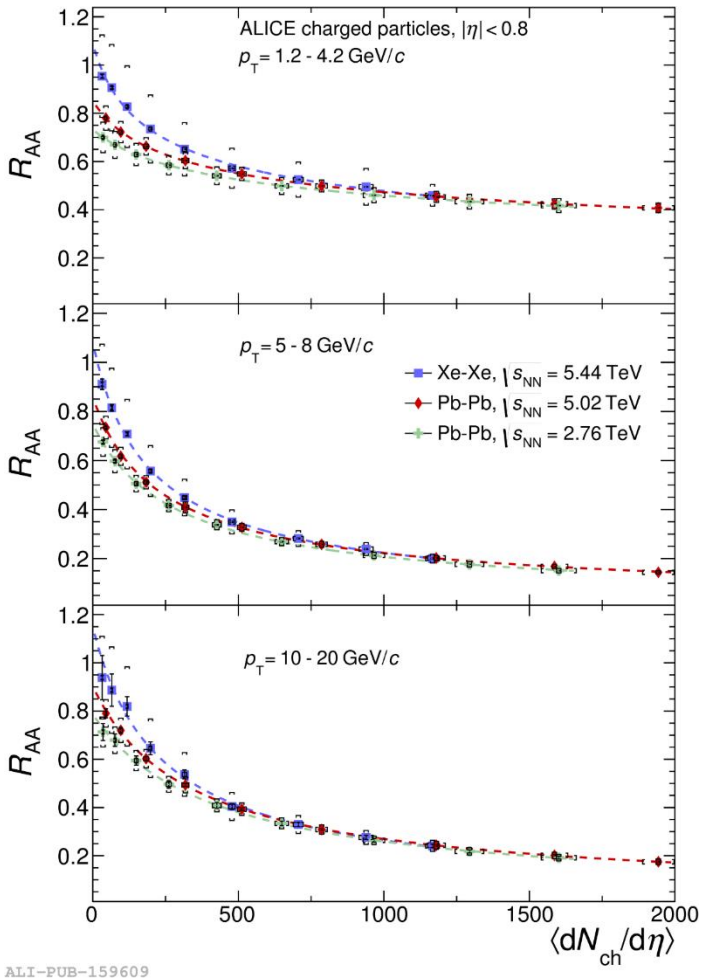


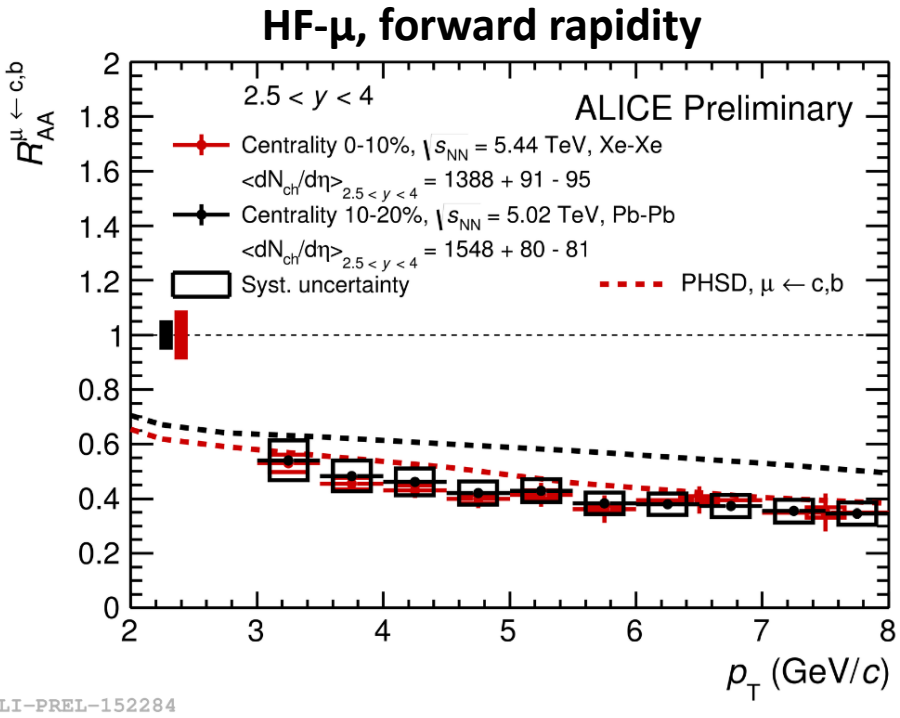


- Hint of enhancement of D^+_s/D^0 ratio in Pb-Pb collisions w.r.t. pp collisions
- Similar pattern for strange and non-strange D-meson R_{AA}
- Smaller suppression for strange D mesons than non-strange D mesons
  - Enhancement of strangeness in the QGP as expected
- Increase of the D^+_s R_{AA} w.r.t. non-strange D mesons predicted by three transport models

PHSD: Phys. Rev C 93 (2016) 034906; TAMU: Phys. Lett. B 735 (2014) 445; Catania: Eur. Phys. J. C (2018) 78

Open heavy-flavour R_{AA} in Xe-Xe and Pb-Pb





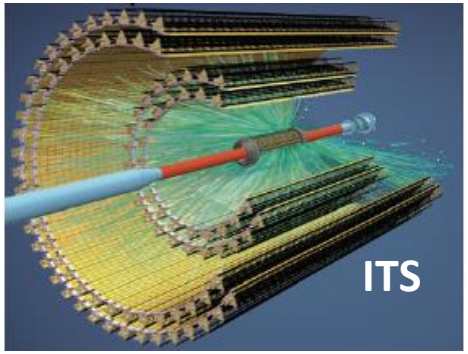
- Similar R_{AA} observed in Xe-Xe and Pb-Pb collisions for μ ← c, b when compared at similar average charged-particle multiplicity density $\langle dN/d\eta \rangle$
- A bit of tension for PHSD model to reproduce the scaling observed at forward rapidity

PHSD: Phys. Rev C 93 (2016) 034906

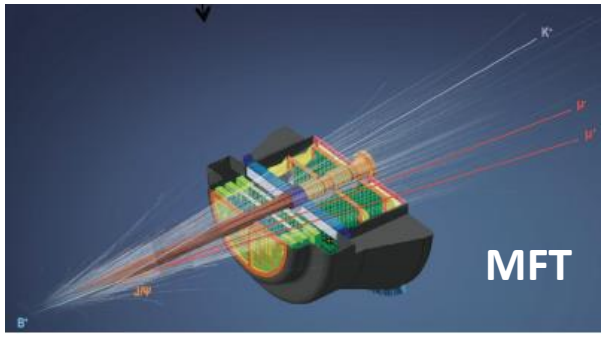
ALICE upgrade

- 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



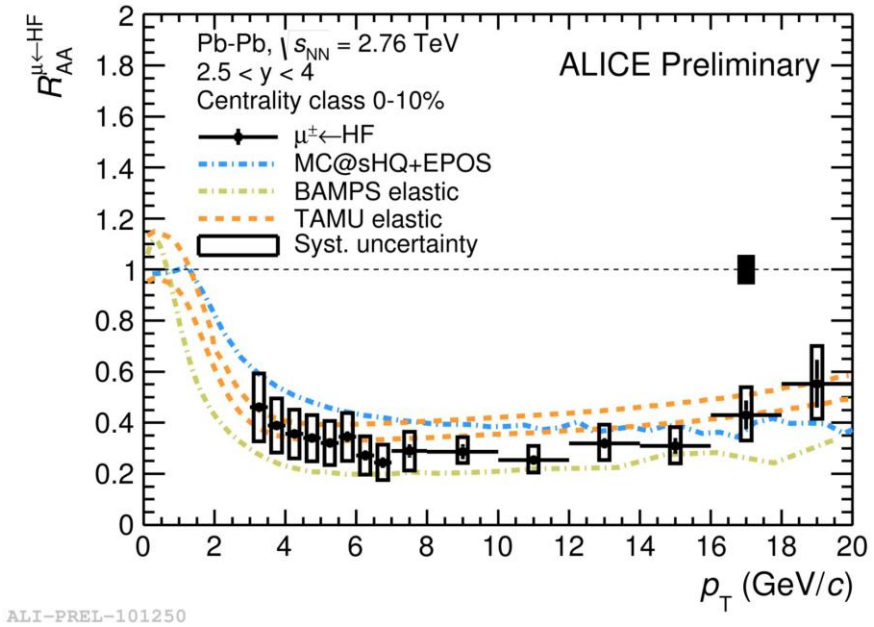
- **New Inner Tracking System (ITS)**
  - Improved pointing resolution,
    reduced material budget, faster readout
- **New Forward Muon Tracker (MFT)**
  - New Silicon tracker,
    heavy-flavour vertices also at forward rapidity
- **New TPC readout chambers based on GEM**
- **Upgraded readout for many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

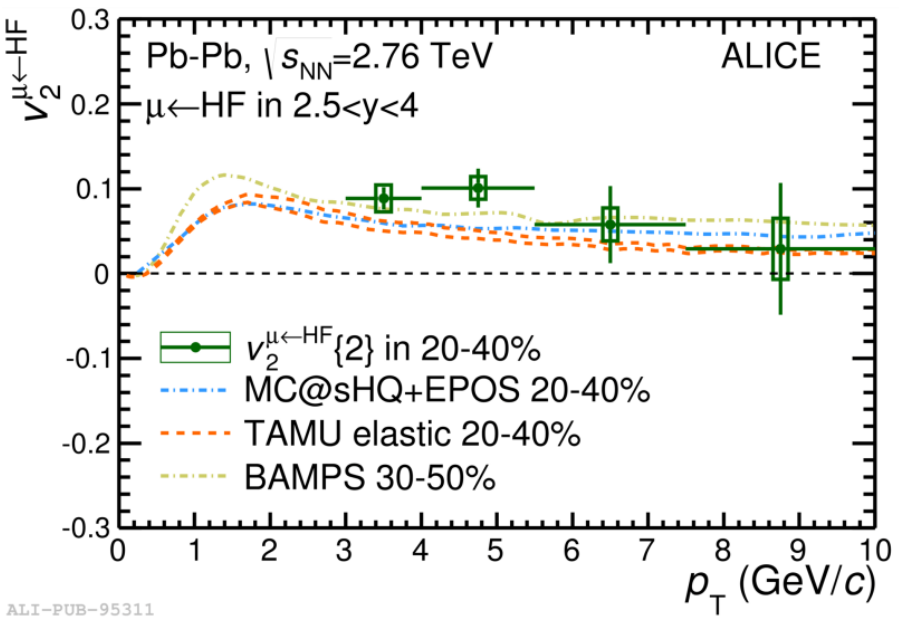


Technical Design Reports approved → moving to construction

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

ALICE, PLB 753 (2016) 41

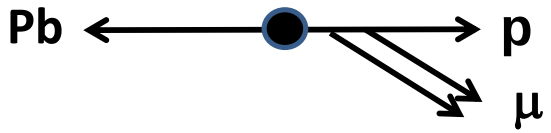


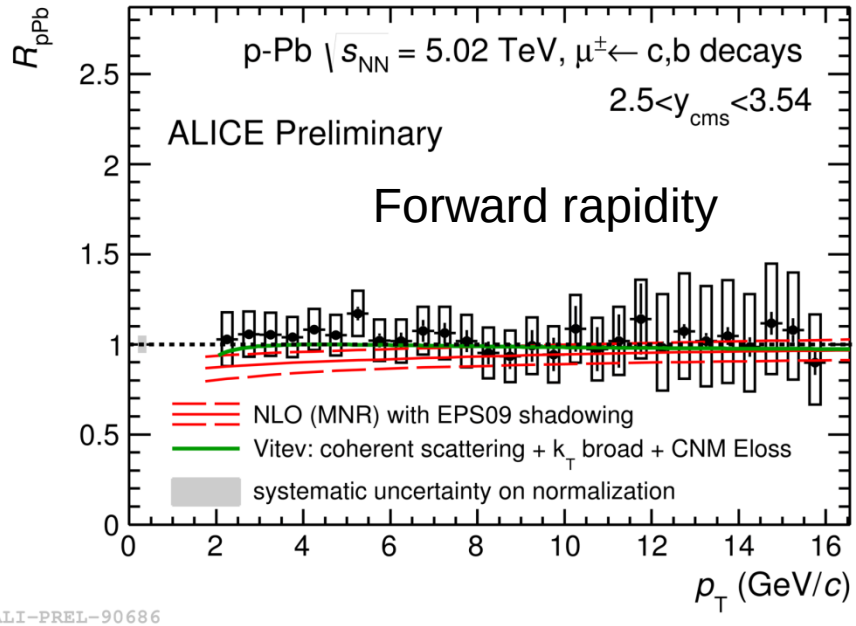


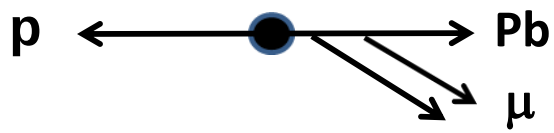
- R_{AA} in central collisions and v_2 in semi-central collisions reasonably described by models including energy loss in the QGP but not in details
  - Further constraints to models: comparison with Run 2 measurements

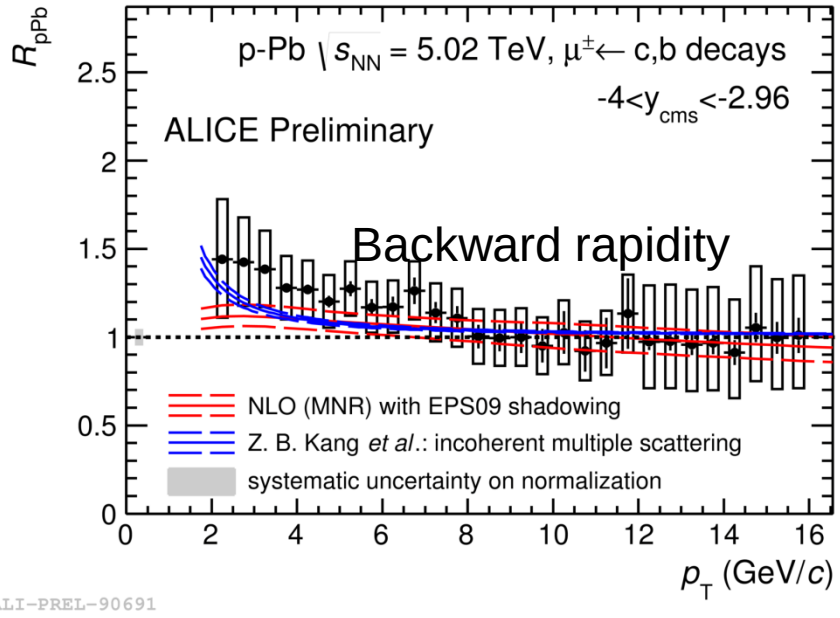
MC@ sHQ+EPOS, Coll + Rad (LPM): Phys. Rev. C 89 (2014) 014905;
BAMPS: Phys. Lett. B 717 (2012) 430;
TAMU: Phys. Lett. B 735 (2014) 445

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



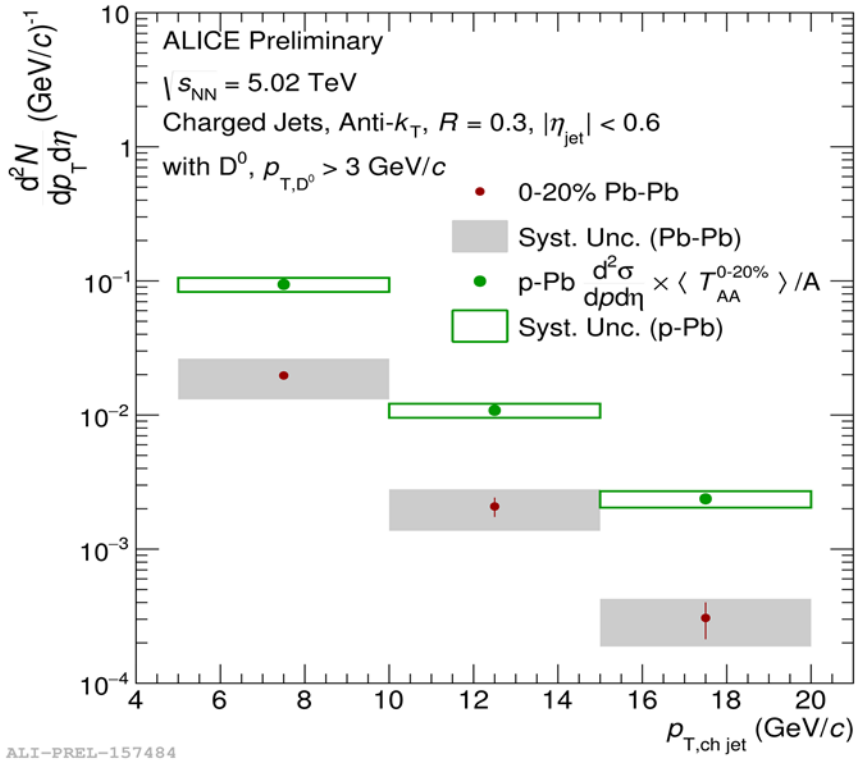






- R_{pPb} at forward rapidity is consistent with unity and, at backward rapidity is slightly larger than unity in $2 < p_T < 4$ GeV/c and close to unity at higher p_T
- Cold nuclear matter effects are small
- R_{pPb} described by perturbative QCD calculations implementing cold nuclear matter effects

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


ALICE Preliminary
√sNN = 5.02 TeV
Charged Jets, Anti-kT, R = 0.3, |ηjet| < 0.6
with D0, pT,D0 > 3 GeV/c
0-20% Pb-Pb
Syst. Unc. (Pb-Pb)
p-Pb d²σ/dpdη × ⟨ TAA0-20% ⟩ /A
Syst. Unc. (p-Pb)
d²N/dpT dη (GeV/c)⁻¹
pT,ch jet (GeV/c)
ALI-PREL-157484