Open heavy flavour production in heavy–ion collisions with ALICE

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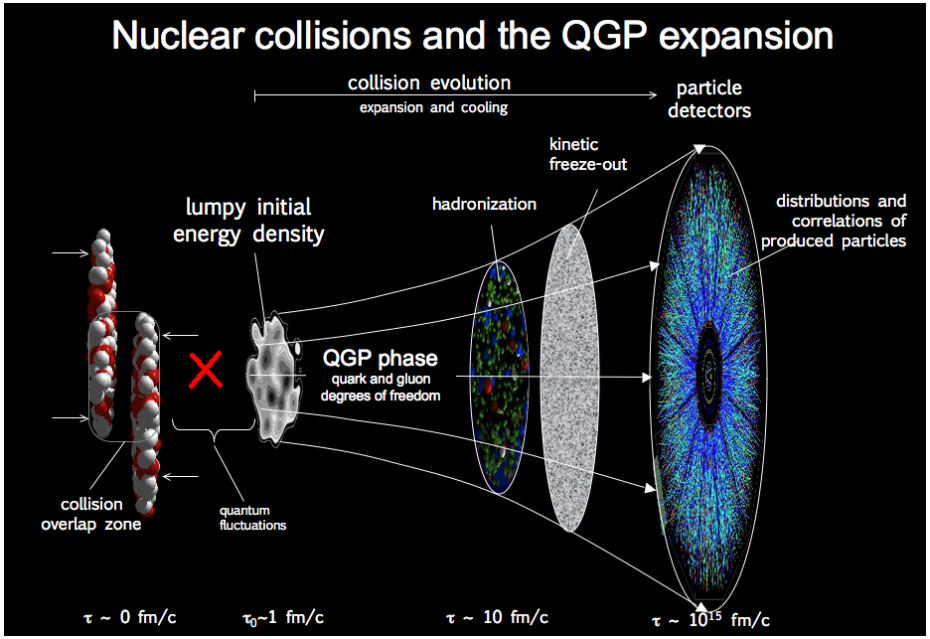
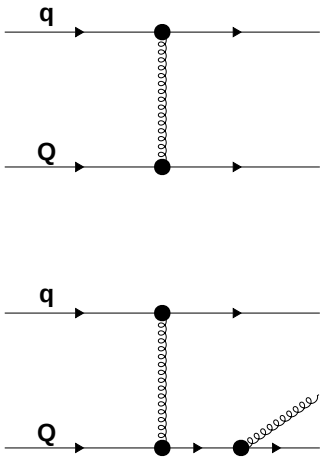
Heavy quark production

- Created in the initial hard scattering processes
- Experience evolution of system
- Hard scattering processes make pQCD calculations possible down to $p_{\mathrm{T}} = 0$ ($m_{\mathrm{c,b}} \gg \Lambda_{\mathrm{QCD}}$)
- Calibrated probes of quark matter



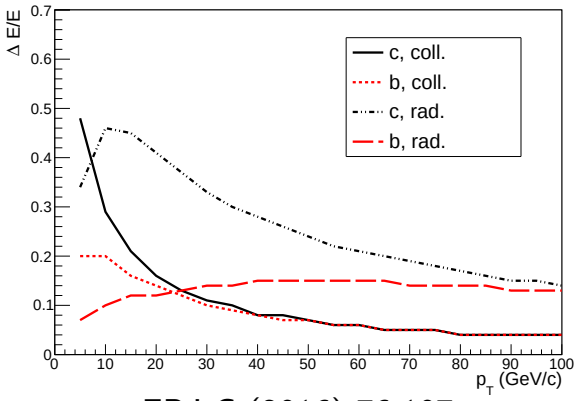
Heavy quarks in heavy–ion collisions

- Clear association of parton with measured hadron
- Learn about interaction with the quark-gluon plasma (QGP)



- In most models: Interaction of heavy quarks with constituent quarks and gluons of the medium
- Interactions can be radiative or collisional

- What are the transport properties of the medium?
- What is the contribution from collisional and radiative processes?
- Does energy loss depend on quark mass?
- Do heavy quarks hadronize differently in the medium?



EPJ C (2016) 76:107

Measurement of heavy quarks

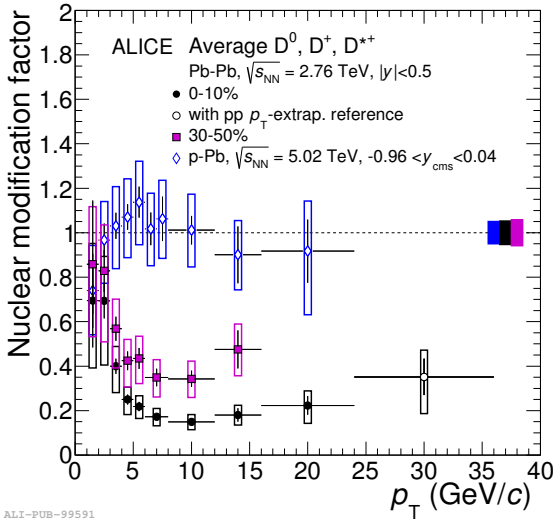
- Need to disentangle: production, interaction with medium and hadronization
- Nuclear modification factor quantifies changes with respect to binary–scaled pp collisions:

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- p–Pb collisions needed to constrain non–QGP effects
- Elliptic flow coefficient v_2 quantifies production relative to collision geometry:

$$v_2 = \langle \cos[2(\phi - \psi_2)] \rangle$$

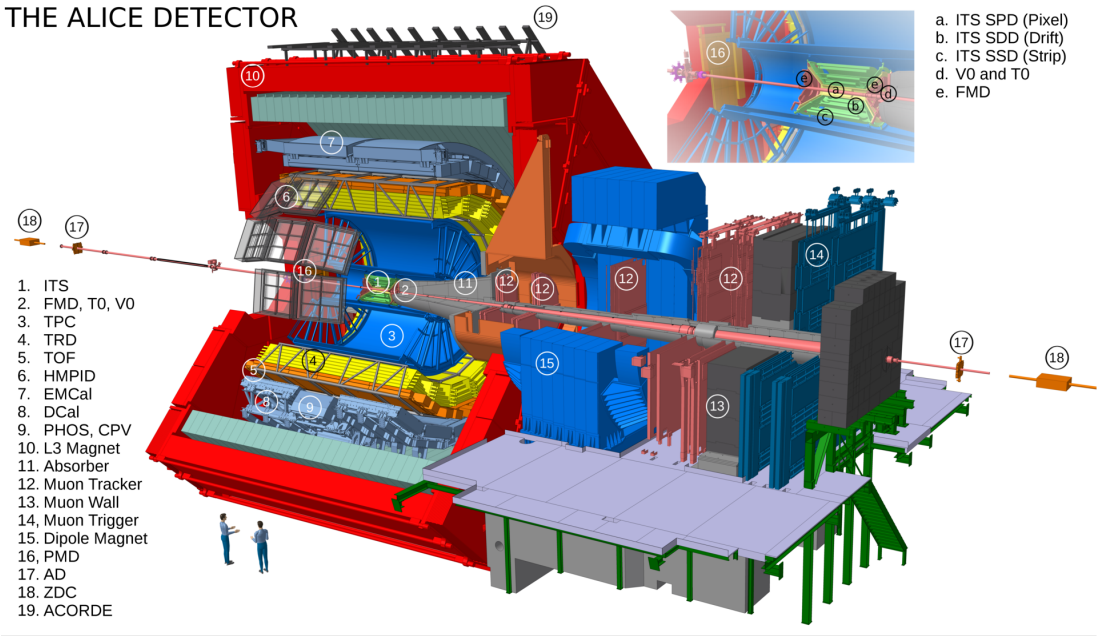
- Adresses heavy–quark thermalization and path–length dependence of energy loss



JHEP 1603 (2016) 081

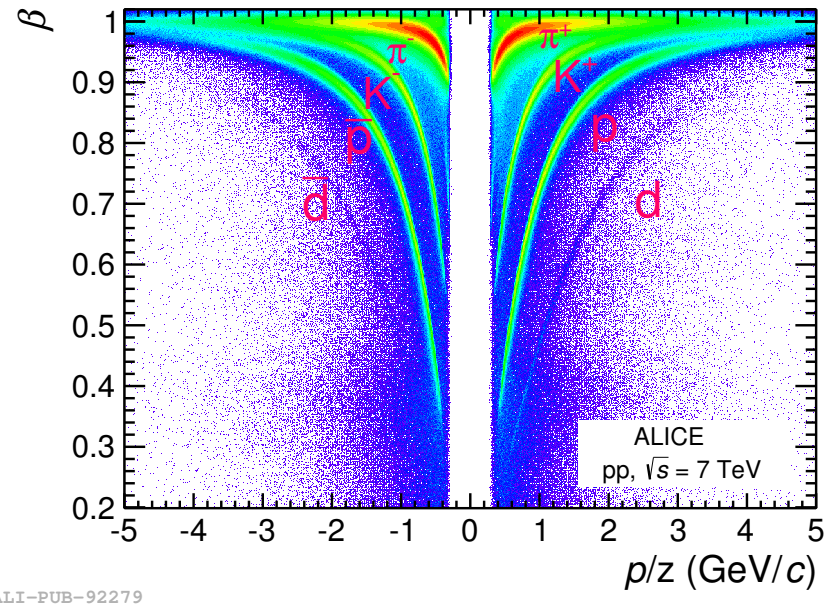
The ALICE detector

- **I**nner **T**racking **S**ystem: Tracking, reconstruction of primary and secondary vertices (track impact parameter resolution better than 50 $\mu\mathrm{m}$ for $p_{\mathrm{T}} > 1.5\ \mathrm{GeV}/c$)
- **T**ime **P**rojection **C**hamber: Tracking and particle identification via $\mathrm{d}E/\mathrm{d}x$
- **T**ime-**O**f-**F**light Detector: Particle Identification
- **Muon Spectrometer**: Absorber, tracking and trigger systems



Particle Identification with ALICE

TOF



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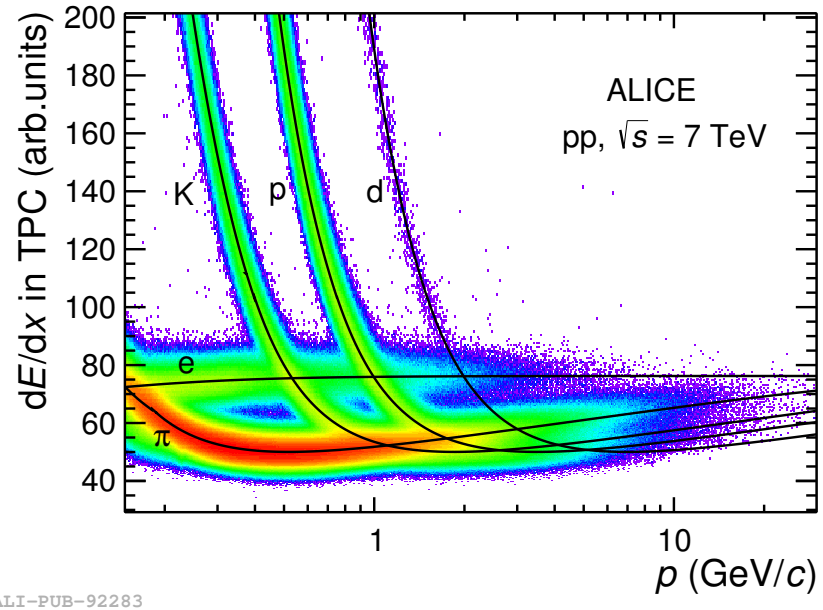
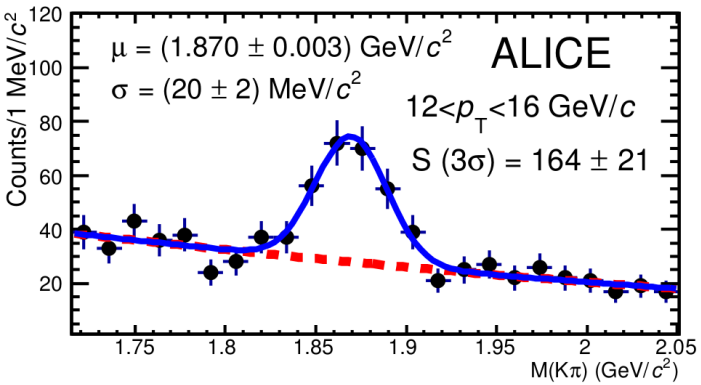
TPC



- Separation power of detectors is momentum dependent
- Combination of detectors improves particle identification

D mesons in pp

- Charmed hadrons measured with an invariant mass analysis
- Reduction of background via PID and topological selection
- Channels used (with branching ratios):
  - $D^0 \to K^-\pi^+$ $(3.93 \pm 0.04\%)$
  - $D^+ \to K^-\pi^+\pi^+$ $(9.46 \pm 0.24\%)$
  - $D^{*+} \to D^0\pi^+$ $(67.7 \pm 0.5\%)$
  - $D_s^+ \to \phi^-\pi^+$ $(2.27 \pm 0.08\%)$, $\phi \to K^+K^-$
- Data reproduced by FONLL over wide momentum range
- Measurement uncertainties much smaller than those from theory



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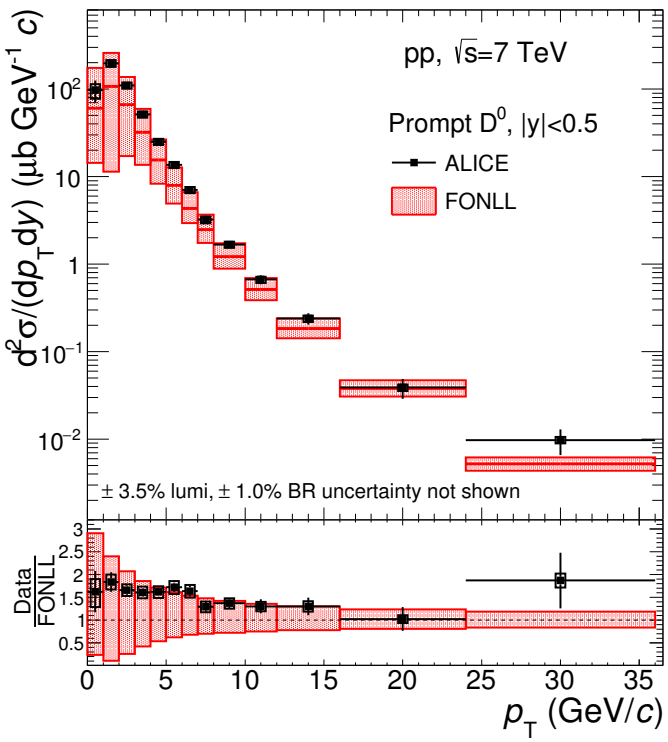
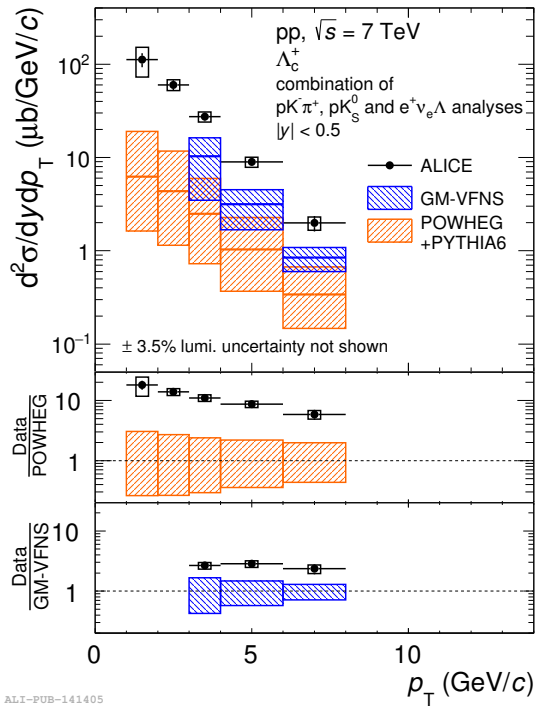
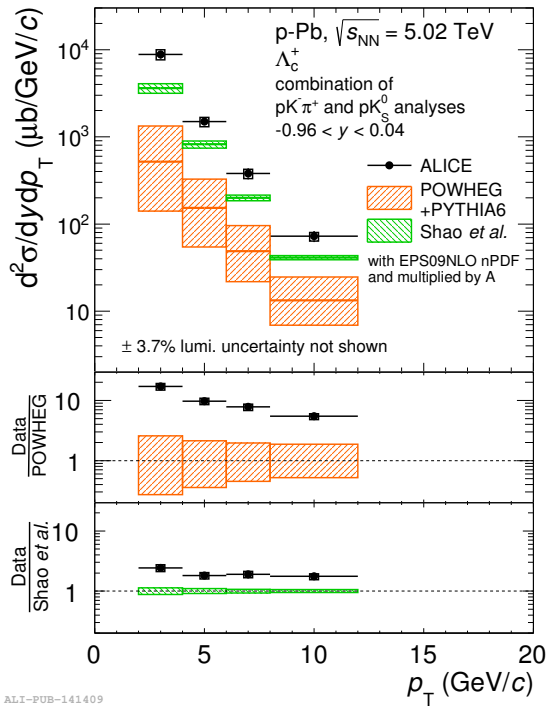
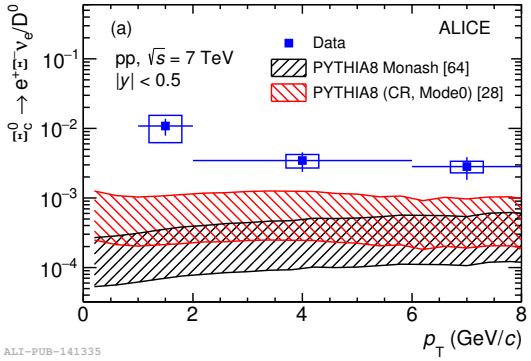


Charmed baryons







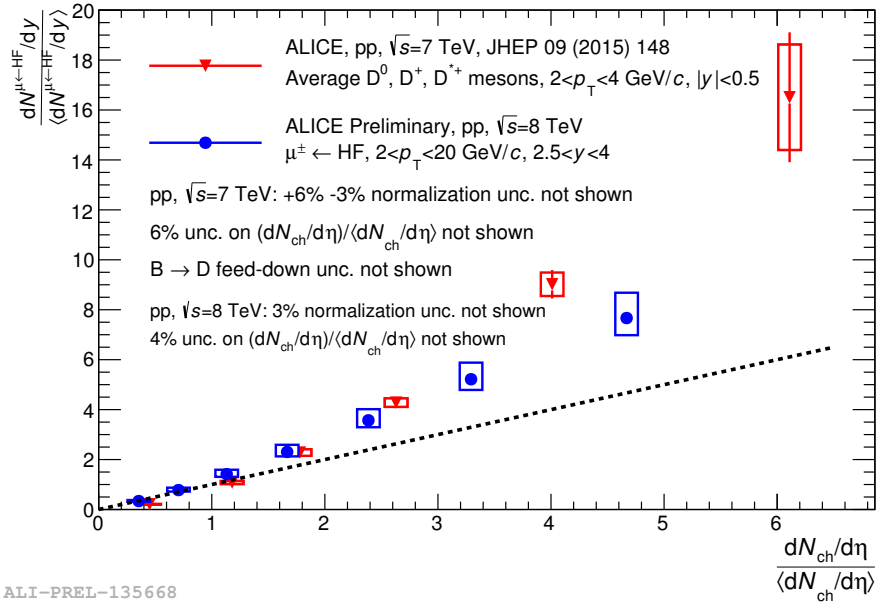
arXiv:1712.04242

arXiv:1712.09581

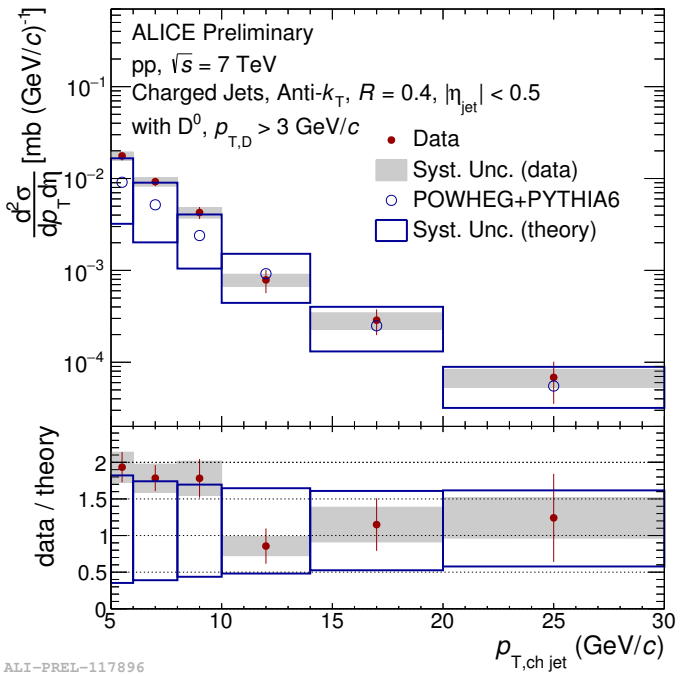
- Λ_c measured in pp and p–Pb collisions
- First mid–rapidity production measurement at the LHC
- First Ξ_c^0–production measurement in pp at the LHC
- Yields strongly underestimated by models

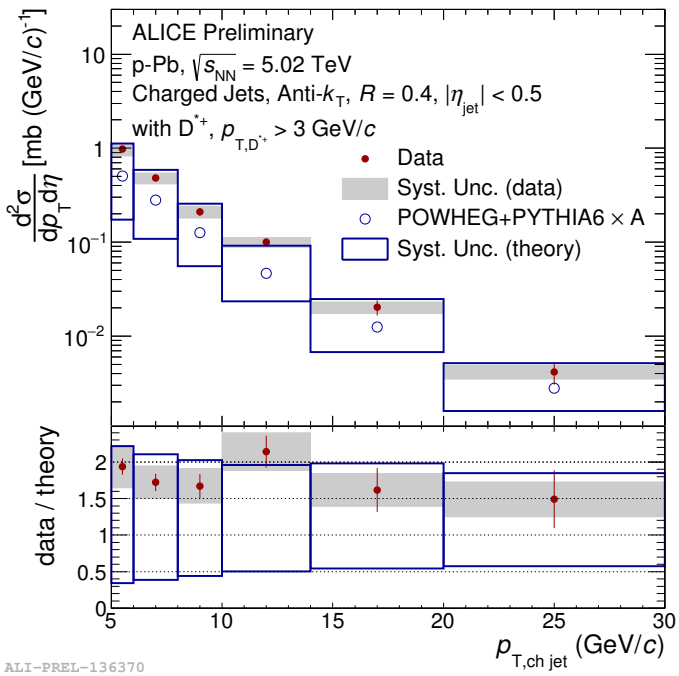
Heavy–flavour production as a function of multiplicity

- Heavy–flavour hadrons have significant branching ratio to final state with leptons → measure leptons and subtract background
- Both D mesons and heavy–flavour muons show a faster than proportional increase in production with event multiplicity
- Important to study role of multi–parton interactions and interplay of soft and hard processes in heavy–flavour production



D mesons in jets

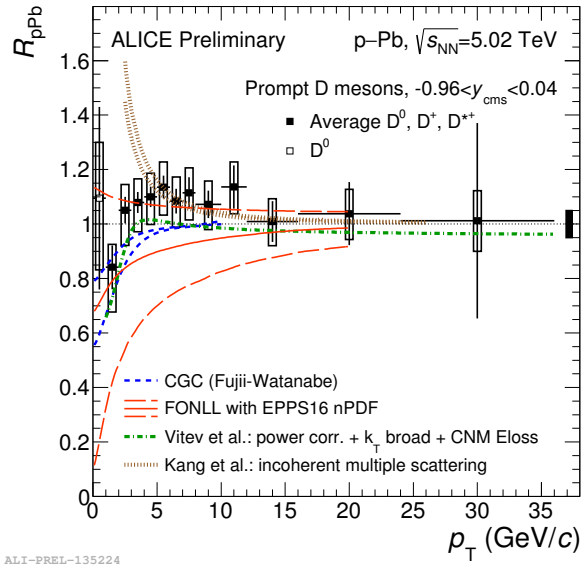


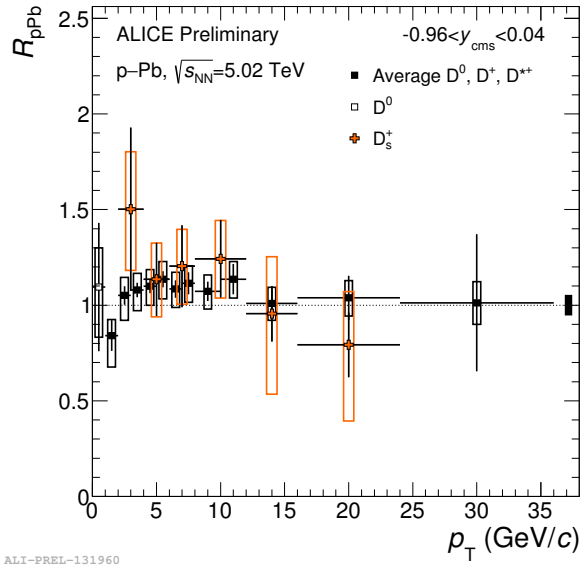


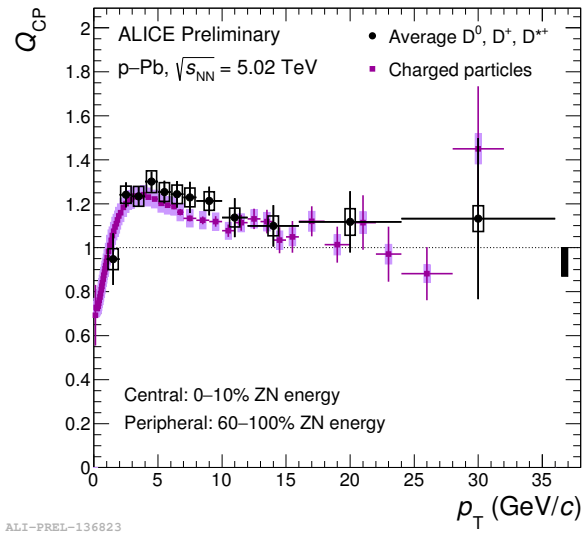
- D–jet measurements in pp and p–Pb collisions
- Closer access to parton kinematics

- Described by theory within uncertainties
- Future studies in Pb–Pb

D mesons in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV





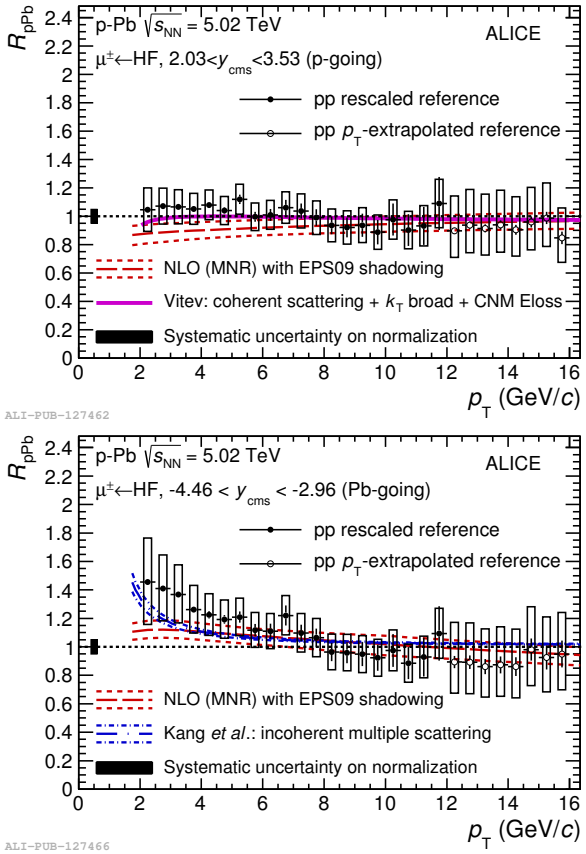


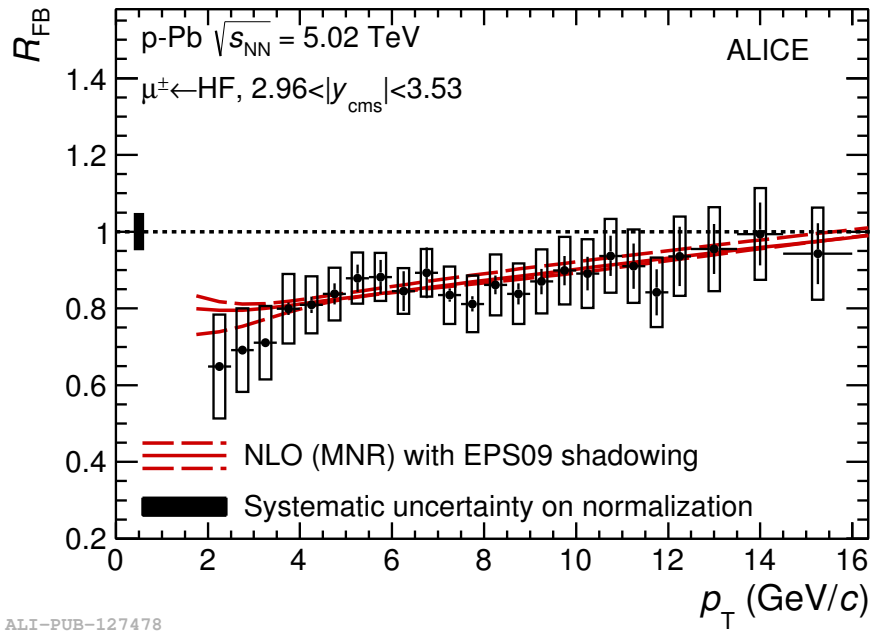
- R_{pA} constrains cold–nuclear matter effects
- Measured R_{pA} compatible with unity
- D_s measurement consistent with results for non–strange D mesons

$$Q_{\mathrm{CP}} = \frac{(\mathrm{d^2N^{promt\ D}/dp_T dy})^{0-10}_{\mathrm{pPb}} / \langle \mathrm{T_{pPb}} \rangle^{0-10}}{(\mathrm{d^2N^{promt\ D}/dp_T dy})^{60-100}_{\mathrm{pPb}} / \langle \mathrm{T_{pPb}} \rangle^{60-100}}$$

- Hint of $Q_{\mathrm{CP}} > 1$ for $2 < p_{\mathrm{T,D}} < 8\ \mathrm{GeV}/c$
- Requires model calculations for interpretation

Muons from heavy–flavour hadron decays in p–Pb collisions





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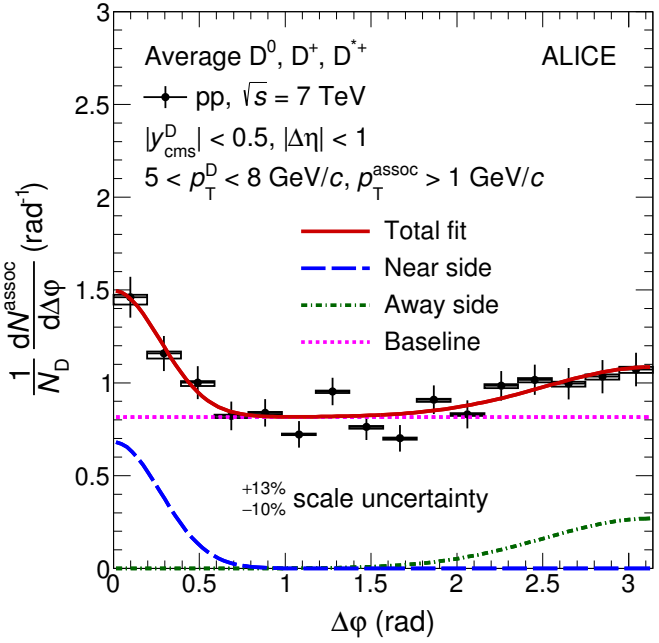
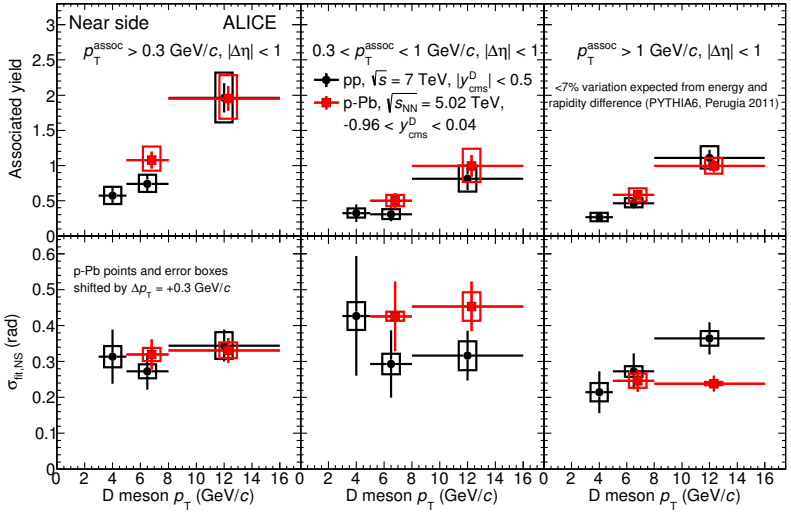
- Study of CNM effects at forward/backward rapidity with heavy-flavour decay muons
- Compare forward (p–going, low x in nucleus) and backward Pb–going, larger x in nucleus)

- Significant effects visible in the ratio (3.7 σ)
- Well described by pQCD calculation using EPS09 shadowing

Azimuthal correlations in p–Pb collisions

- Correlations of D mesons with charged particles
- Adress charm–jet properties
- The near– and away–side peaks agree between pp and p–Pb collisions within the uncertainties





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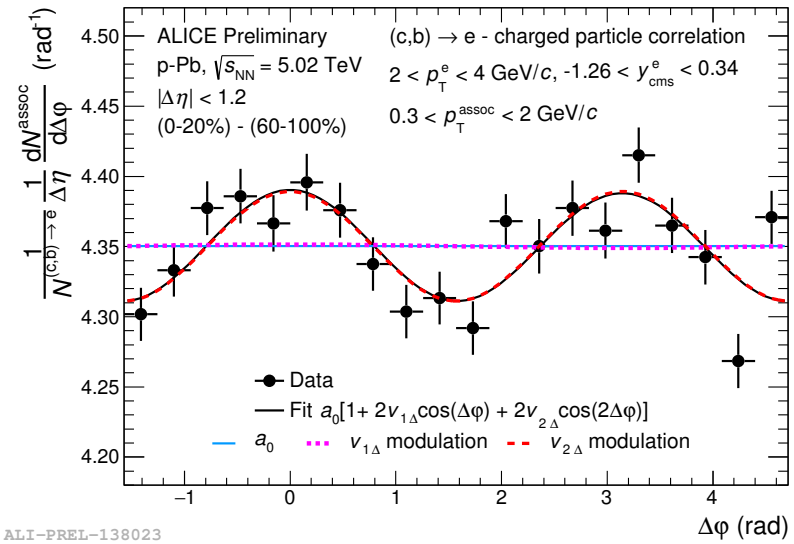
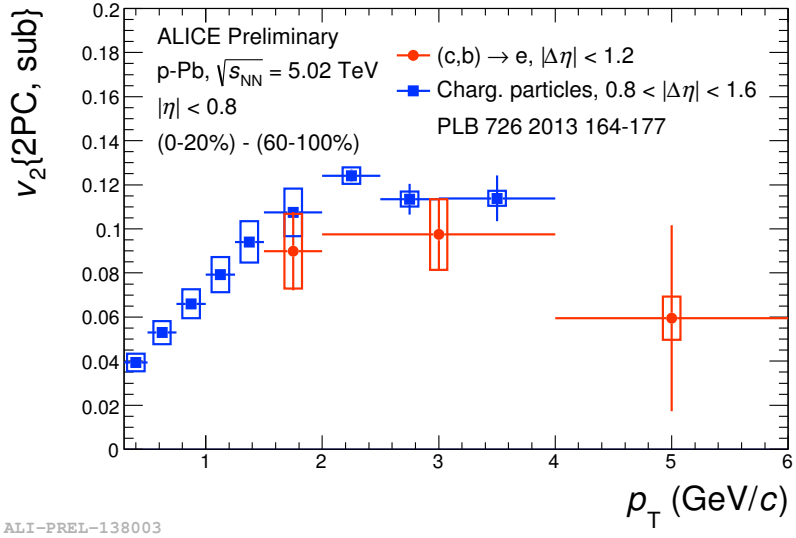
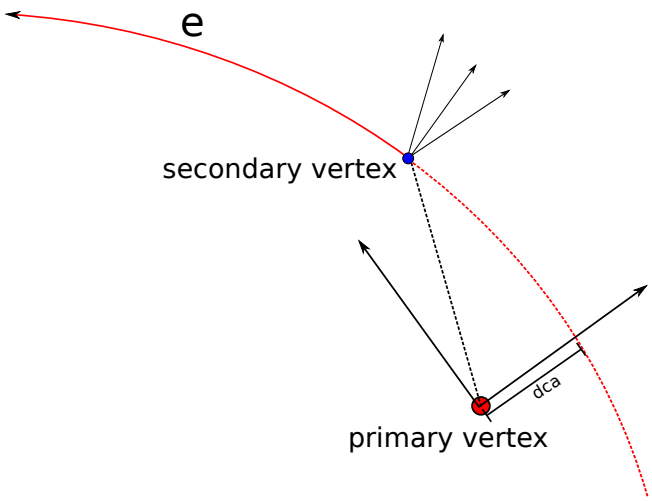
Azimuthal correlations in p–Pb collisions (2)

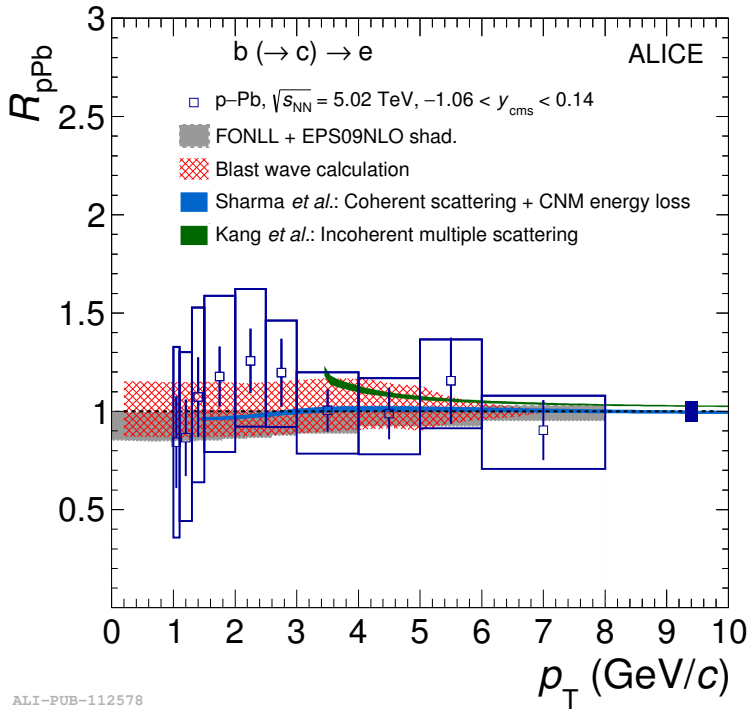
- Correlations of electrons from heavy–flavour hadron decays with charged particles
- Jet contribution removed by subtracting correlations in low–multiplicity collisions
- Positive v_2 measured vor heavy–flavour decay electrons in p–Pb collisions
- Similar effect size as for light hadrons
- Initial– or final–state effect?





Beauty–hadron decay electrons in p–Pb collisions





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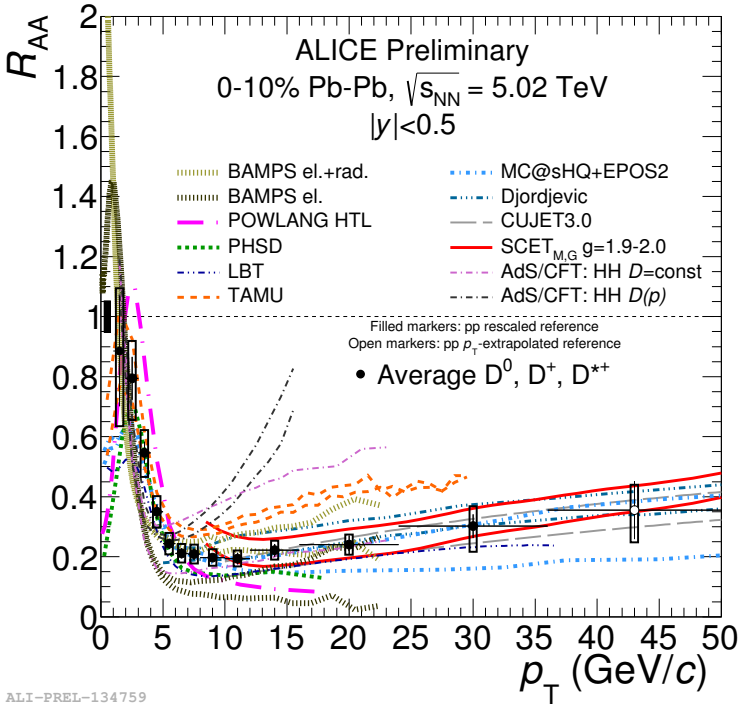
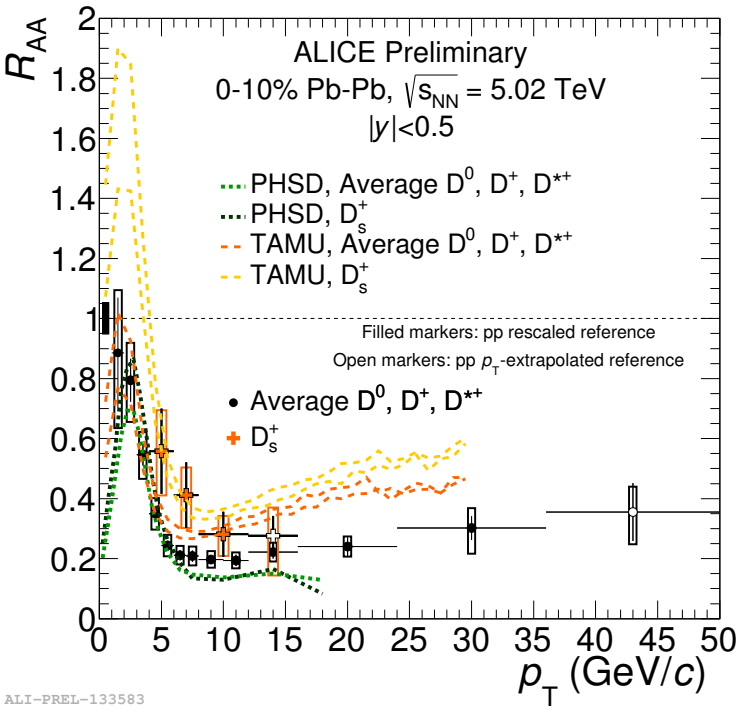
- Exploit large decay length for beauty hadrons ($c\tau \approx 500\ \mu\mathrm{m}$)
- Selection based on impact parameter reduces background
- Subtract non–beauty background contributions
- Resulting nuclear modification factor consistent with unity

D–meson R_{AA} in Pb–Pb collisions



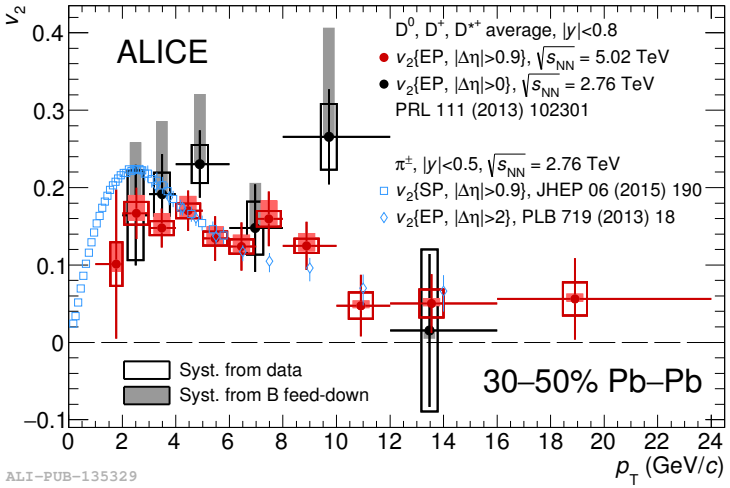


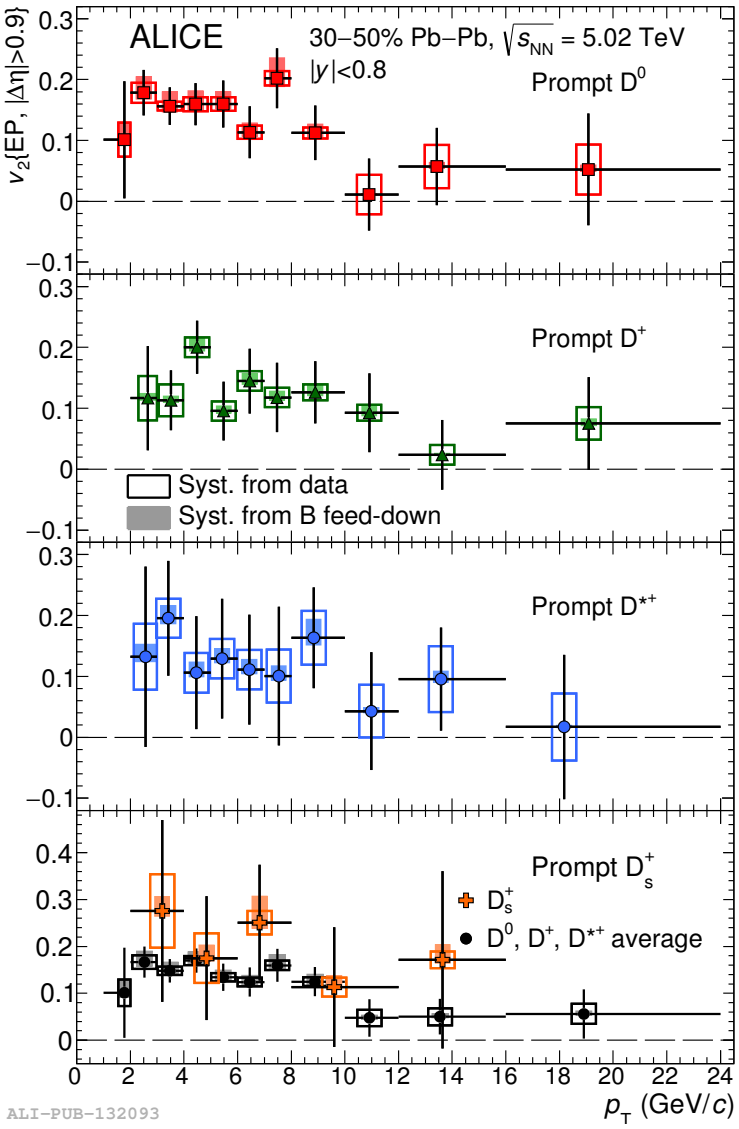
- Strong suppression of non–strange D–meson production at intermediate/high p_T in Pb–Pb collisions
- Data precision sufficient to set important constraints to models

- Hint of higher R_{AA} for D_s^+
- Increase consistent with models at low p_T; expected by models including hadronization via coalescence in strange–quark rich QGP environment

D–meson elliptic flow in Pb–Pb collisions

- Positive v_2 for D mesons up to 10 $\mathrm{GeV/c}$
- Similar effect for different charm–hadron species
- Similar v_2 for D mesons and charged pions, hint for lower D–meson v_2 at low p_{T}





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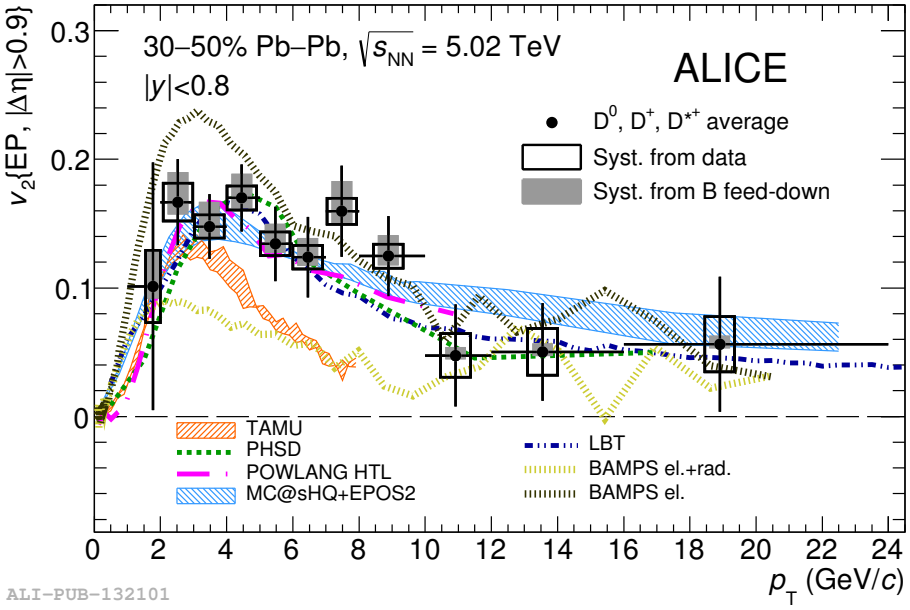
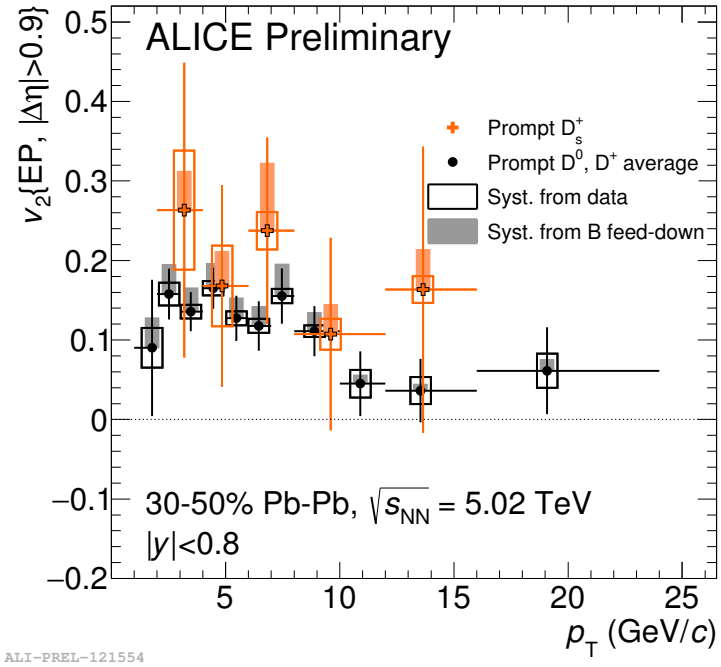
D meson elliptic flow in Pb–Pb collisions (2)

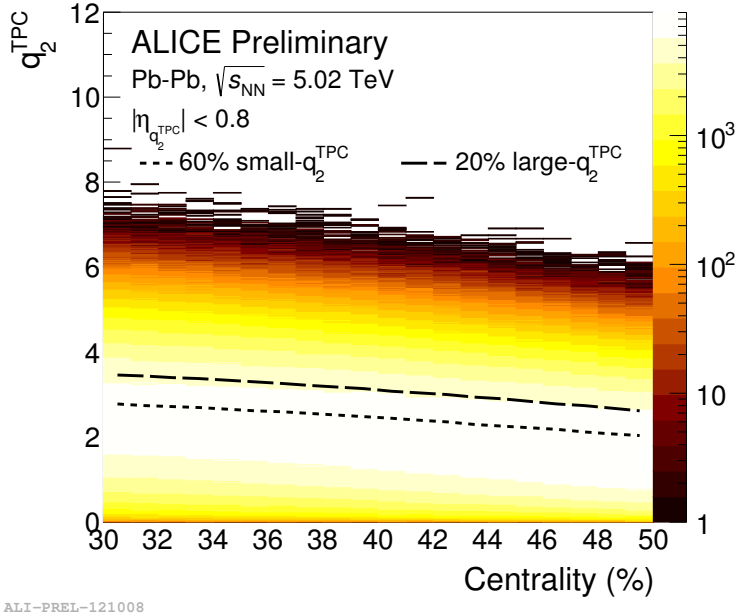


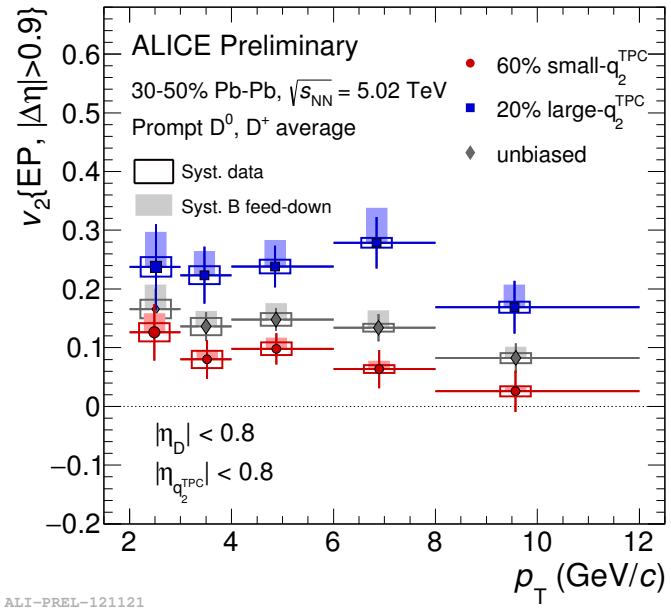


- Combination of D–meson species
- Models, which describe R_{AA} well, have different degrees of success for v_2

- The most successful models give $1.5 < 2\pi T D_s(T) < 7$
- This suggests a thermalization time $\tau_c = 3 - 14$ fm/c
- Hint of positive v_2 for D_s

D meson elliptic flow with event shape engineering



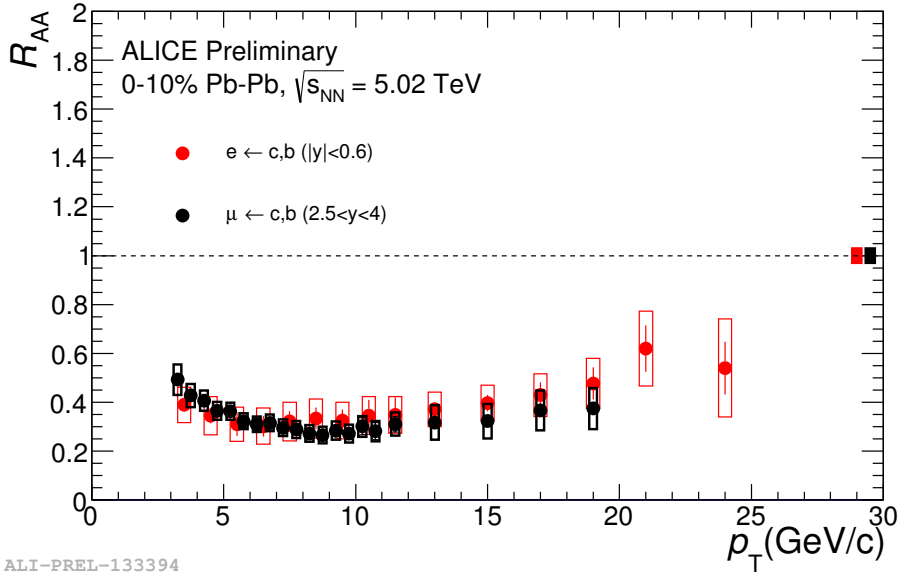


- Large event–by–event fluctuations of elliptic flow
- Quantified by reduced second order flow vector q_2^{TPC}
- q_2^{TPC} grows with multiplicity and strength of flow

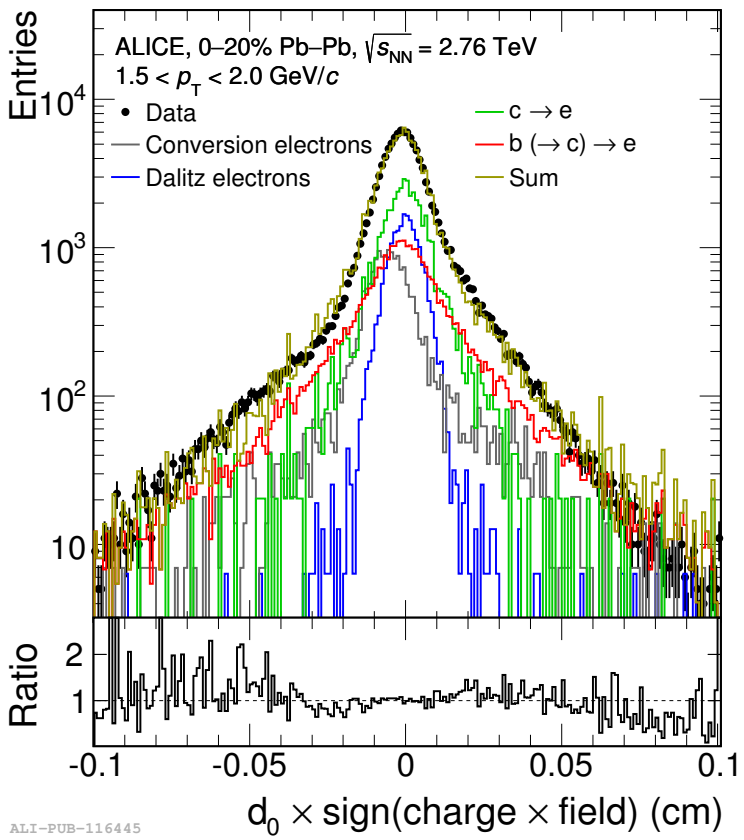
- Comparison of q_2^{TPC}–ranges shows significant effect
- Both D meson and q_2^{TPC} from mid–rapidity $\rightarrow$ some autocorrelation will be present

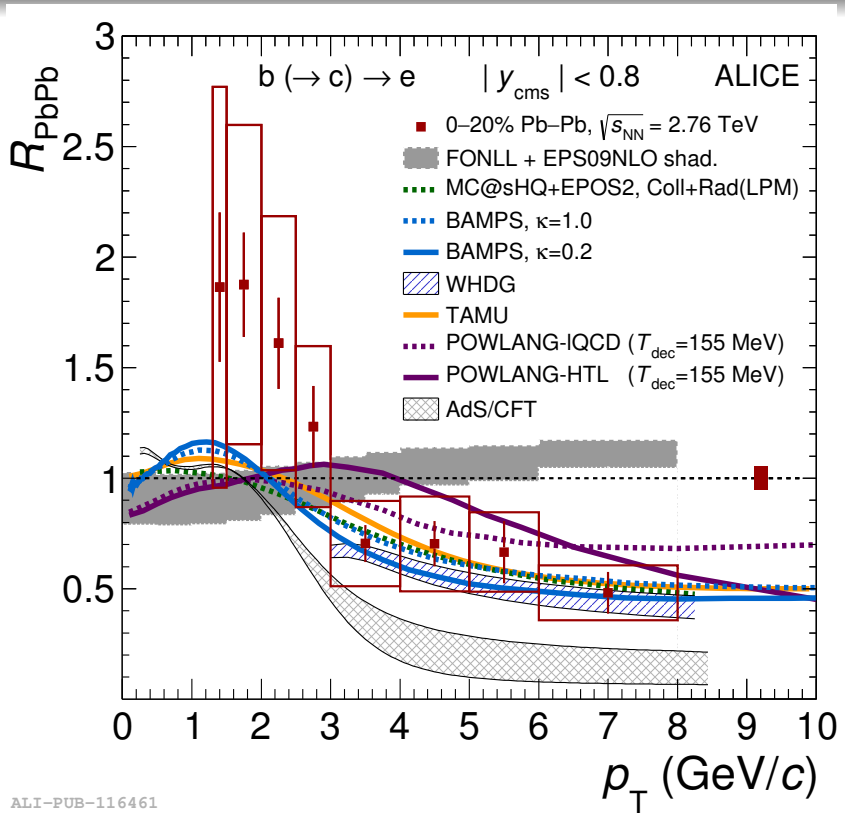
R_{AA} of muons and electrons from heavy–flavour hadron decays

- R_{AA} of muons from heavy–flavour hadron decays at forward rapidity
- R_{AA} of heavy–flavour electrons at mid–rapidity
- Similar suppression
- Charm contributes more at low p_{T}, beauty at higher p_{T} $(p_{\mathrm{T}} > 5\ GeV/\mathrm{c}) \rightarrow$ indication of beauty suppression at high p_{T}



Beauty–hadron decay electron R_{AA}





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- Impact parameter–based approach
- Information used in template fit to separate electron sources

- Indication of suppression of beauty–hadron decay electrons at high p_T
- R_{AA} described by models within uncertainties

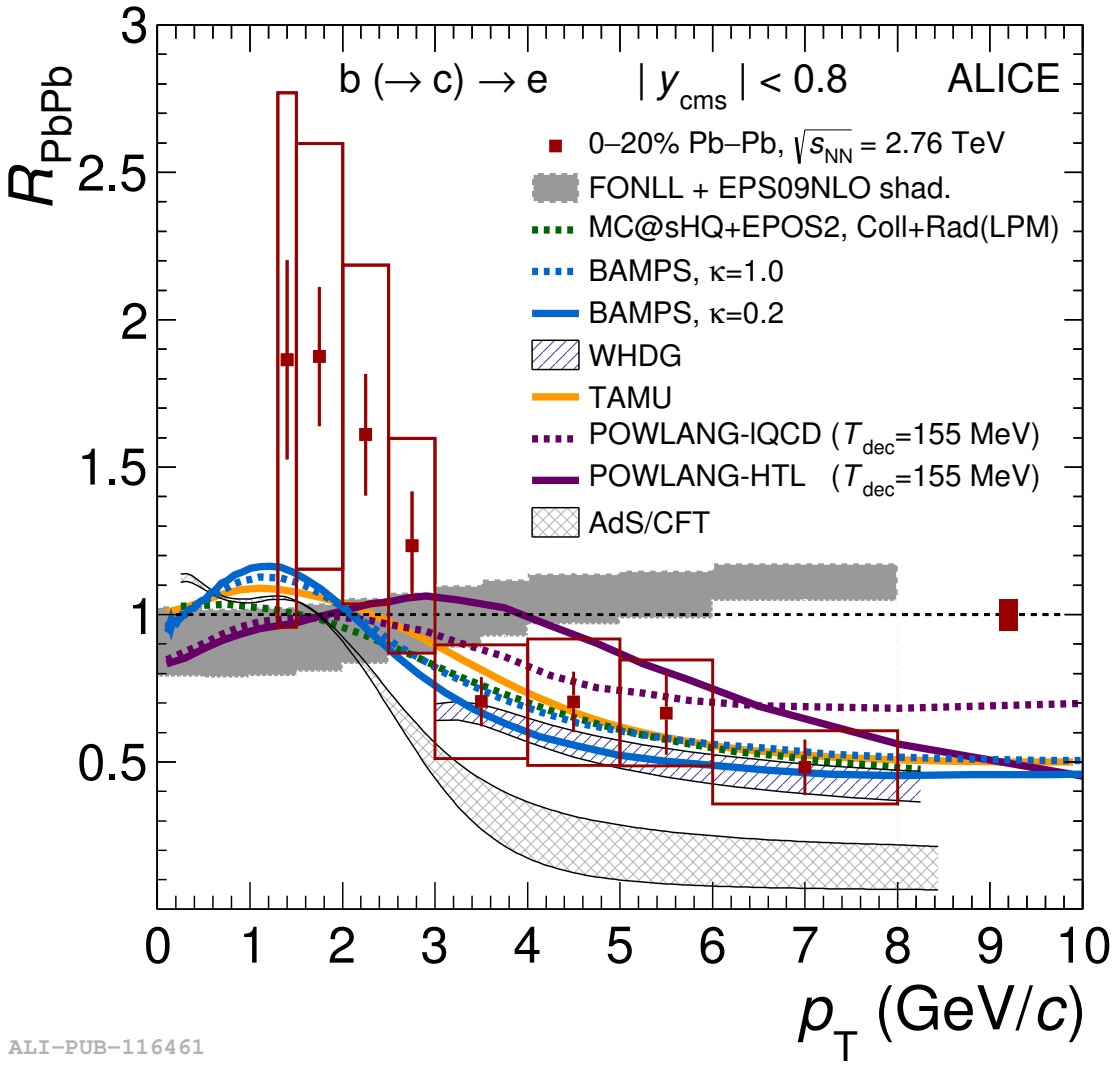
Conclusion and Summary

- Production of heavy flavours in pp collisions is described by pQDC–based calculations
- Significantly more charmed baryons are produced than expected from models

- R_{pPb} consistent with unity for D meson and beauty electron measurements at mid–rapidity
- Deviations from unity in D–meson Q_{CP} and in forward/backward comparison of muons from heavy flavour hadron decays

- D mesons show strong interactions with the medium in Pb–Pb collisions
- $\mathrm{D_s}$ meson suppression was also measured
- Indication of suppression for the beauty sector
- Analyses move towards higher accuracy and more complex observables

Appendix: v_2 of Electrons from heavy flavour hadron decays



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