New results on jets and heavy flavor in heavy-ion collisions with ALICE

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on behalf of the ALICE Collaboration

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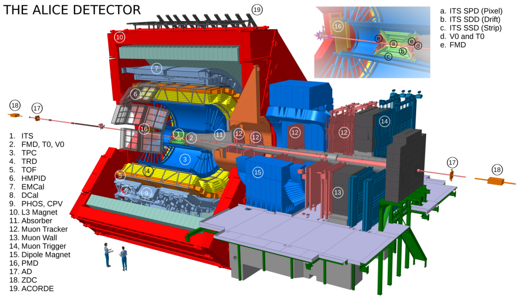
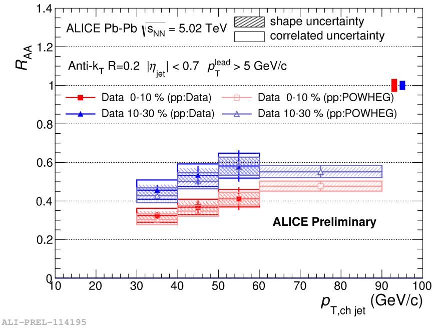
ALICE



- D mesons via hadronic decays (ITS, TPC, TOF)
  - PID, topological cuts
  - invariant mass analysis
- Semi-leptonic decays of heavy-flavor hadrons
  - $e^{\pm}$ (TPC, TOF, EMCal)
  - $\mu^{\pm}$ (muon arm)

- Jet reconstruction using anti-k_{T} algorithm
  - charged constituents (ITS, TPC) $\rightarrow$ *charged jets*
  - add neutral constituents (EMCal, DCal) $\rightarrow$ *full jets*

Jets as probe of the QGP



- Jets are strongly suppressed in Pb–Pb collisions compared to scaled pp collisions
- Quantified via nuclear modification factor:

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

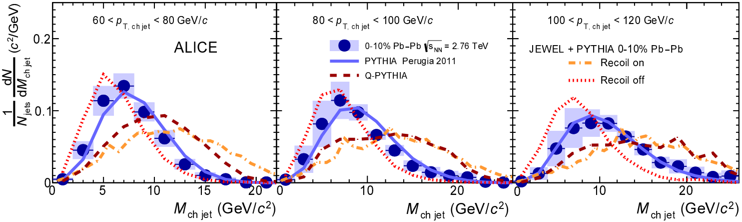
- Attributed to parton energy loss in the QGP

- What is the underlying energy loss mechanism?
- Is the internal structure of the jet modified?

Jet Mass

First jet mass measurement in heavy-ion collisions

arXiv:1702.00804, submitted to PLB



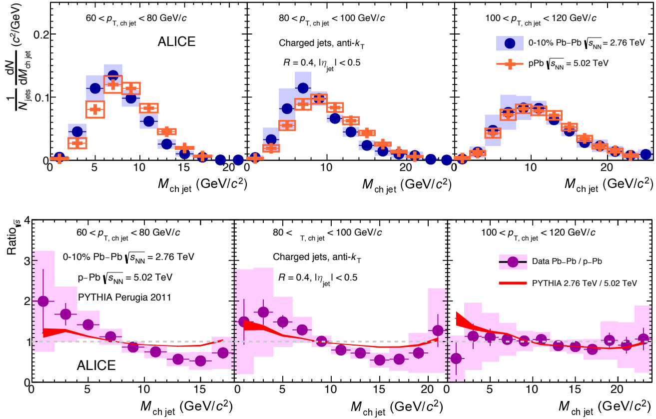
- Models predict **larger** jet mass due to softening of parton fragmentation in the medium → not observed
- Competing effects:
  - Softer fragmentation → jet mass increases
  - Out-of-cone radiation → jet mass decreases

Mass calculated from the 4-momentum of the jet

$$M = \sqrt{E^2 - p_T^2 - p_z^2}$$

Jet Mass (Pb–Pb and p–Pb collisions)

arXiv:1702.00804, submitted to PLB

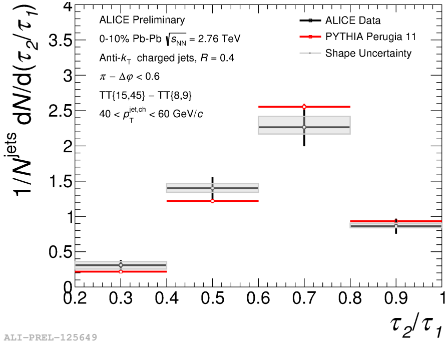


No significant difference observed between p–Pb and Pb–Pb collisions

Nsubjettiness

Nsubjettiness τ_N is a measure of how much N-cored a jet is

$$\tau_N = \frac{\sum_{i=1}^{N} p_{T,i} \min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1}^{N} p_{T,i}}$$



R_0 = jet resolution parameter
$\Delta R_{i,j}$ = distance in η, φ between track i and subjet j
$p_{T,i} = p_T$ of track i

$\tau_N \rightarrow 0$: the jet has N or fewer cores
$\tau_N \rightarrow 1$: the jet has more than N cores
$\tau_2/\tau_1 \rightarrow 0$: **the jet has two hard cores**

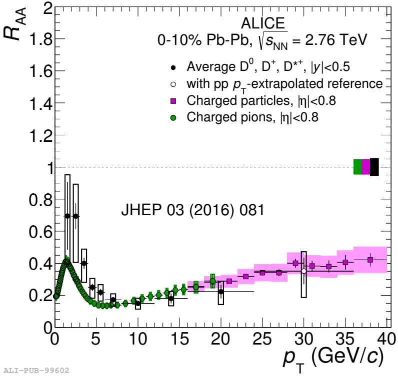
Coherent emission
$\rightarrow$ jet becomes more 2-pronged
(τ_2/τ_1 decreases)

Incoherent emission
$\rightarrow$ jet becomes less 2-pronged
(τ_2/τ_1 increases)

No modification observed compared to PYTHIA

Heavy-Flavor Production

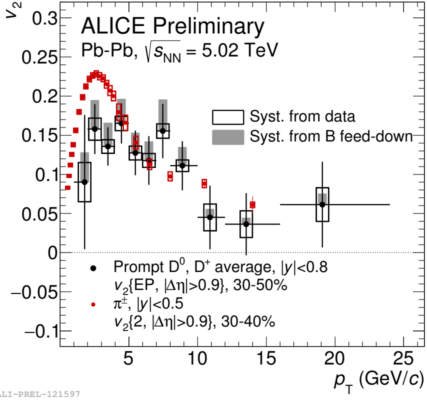
- Charm and beauty produced in high-Q^2 processes
- Produced early in the collision → experience medium evolution
- Negligible thermal production in the QGP ($m_{c,b} \gg T_{QGP}$)



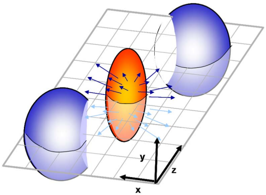
- Thermalization in the QGP (low p_T) → charm expected to flow with the medium
- Flavor-dependent energy loss in the QGP
  - Color charge (Casimir factor): $\Delta E_q < \Delta E_g$
  - Dead cone effect (radiative energy loss): $\Delta E_b < \Delta E_c < \Delta E_{u,d,s,g}$

See also plenary **Quarkonia and HF** by **A. Festanti**, Tuesday

D-Meson vs π Elliptic Flow

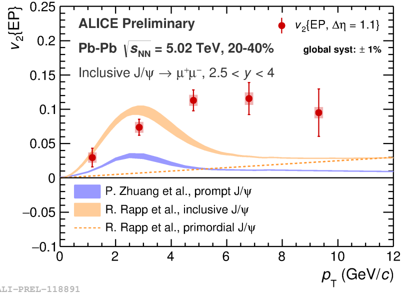


$$v_2(\mathrm{D}) \approx v_2(\pi)$$



- High-p_T: sensitive to path-length dependence of parton energy loss
- Low-p_T: charm can thermalize in the medium and flow

J/ψ Elliptic Flow



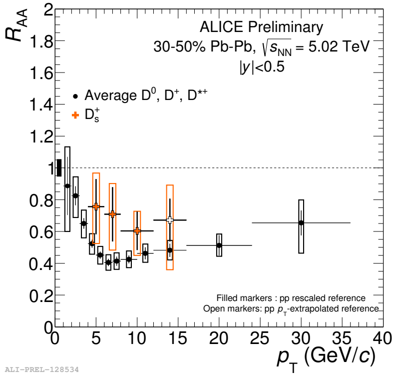
Regeneration models have difficulty reproducing the J/ψ v_2

- Interactions of charm quarks with the QGP should give rise to a positive v_2
- In particular, thermalized charm quarks should flow with the medium $\rightarrow$ (re)generated J/ψ

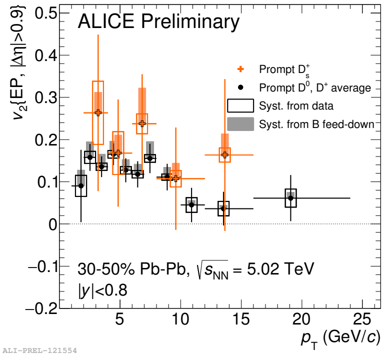
Strange and Non-Strange D Meson

Study possible coalescence with strange quarks, enhanced in the QGP

$\rightarrow$ expected $R_{AA}(D_s) > R_{AA}(D^0, D^+)$



R_{AA} of strange D meson slightly above the non-strange D, but compatible within uncertainties



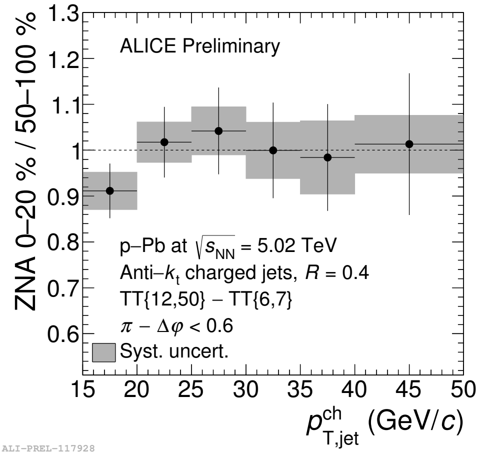
First measurement of $v_2(D_s^+)$ at the LHC

Similar v_2 of non-strange and strange D mesons

p–Pb collisions: QGP in small systems?

- p–Pb collisions used to disentangle cold nuclear matter effects from the QGP phenomenology in Pb–Pb collisions
- QGP-like effects in the soft sector observed in high-multiplicity p–Pb (and pp) collisions
  - Elliptic flow
  - Strangeness enhancement
- What about hard probes?
  - Jet quenching not observed (yet?)
  - Difficult to characterize the event activity classes ≈ centrality classes in Pb–Pb
    - Event multiplicity strongly affected by jets

Semi-Inclusive Hadron-Jet Cross Section



- Jets recoiled from high-p_T hadrons
- Self-normalized ratio of cross sections

$$\frac{1}{\sigma^{pPb\rightarrow h+X}} \frac{d\sigma^{pPb\rightarrow h+jet+X}}{dp^{ch}_{T,jet}} = \frac{1}{\cancel{T_{pPb}}\,\sigma^{pp\rightarrow h+X}} \frac{\cancel{T_{pPb}}\,d\sigma^{pp\rightarrow h+jet+X}}{dp^{ch}_{T,jet}}$$

$\rightarrow$ no T_{pPb} scaling needed

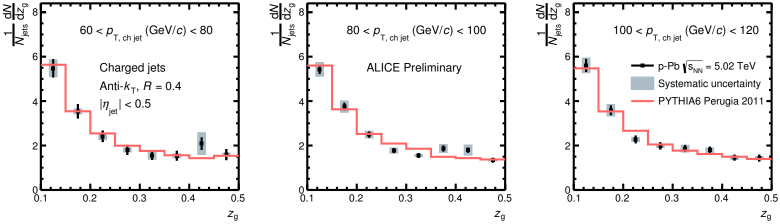
- No modification of the jet yield observed in high event activity p–Pb collisions

ZNA = energy deposited in forward neutron calorimeters (Pb-going direction)

Jet Hard Substructure

- Reclusterize anti-k_{T} jets with Cambridge/Aachen
- Undo last step of C/A until soft-drop condition $z_{\mathrm{g}} > 0.1$ on the two subjets in fullfilled

$$z_{\mathrm{g}} = \frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$



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- No modification in the jet hard substructure observed in minimum-bias p–Pb compared to PYTHIA
- Next: redo the analysis in multiplicity classes, measure a pp baseline

Summary

Pb–Pb collisions

- New observables to investigate modifications in the jet internal substructure
  - jet mass and nsubjettiness
  - first such measurements in heavy-ion collisions
  - no modification attributable to the QGP observed within a jet cone radius of $R < 0.4$
- More precise measurements of the heavy-flavor v_2 and R_{AA}
  - first measurement at the LHC of the v_2 of strange D mesons
  - v_2 of pions, open and hidden charm as well as strange D mesons are compatible within uncertainties

Summary

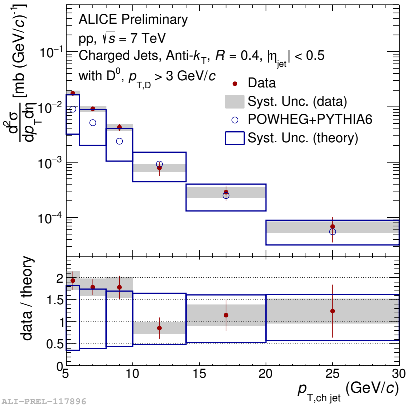
p–Pb collisions

- Self-normalized semi-inclusive hadron-jet cross sections used to compare jet production in high-multiplicity vs. low-multiplicity
- No suppression of the jet production observed in high-activity (“central”) p–Pb collisions
- No modification observed in the jet hard substructure (minimum-bias events)

Future plans

More analysis ongoing from ALICE:

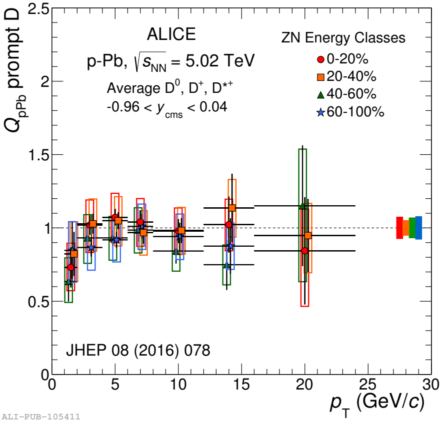
- Charm jets tagged with fully reconstructed D mesons
- D-h (pp and p–Pb) and e-h correlations
- b-jets (pp and p–Pb)
- Di-jet asymmetry
- γ-jet correlations
- Jet-h correlations
- More jet shape observables



Analysis ongoing in p–Pb and Pb–Pb

Extra Slides

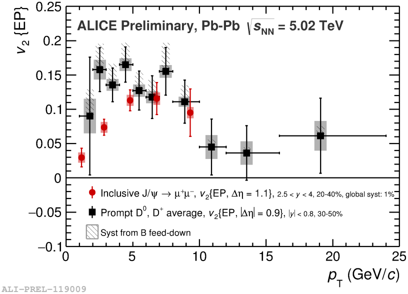
D-Meson Production vs. Multiplicity



- No suppression observed for D mesons in the measured p_T interval within uncertainties
- No ordering w.r.t. multiplicity classes

We use the expression Q_{pPb} instead of R_{pPb} to stress the possible presence of biases in the centrality selection

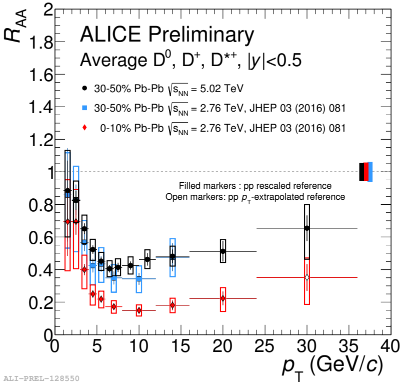
J/ψ Elliptic Flow

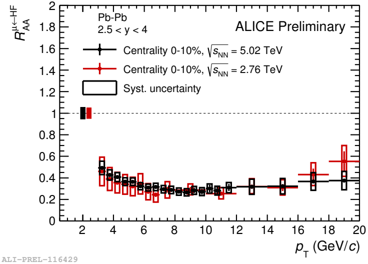


Similar v_2 for hidden (J/ψ) and open (D) charm

- Interactions of charm quarks with the QGP should give rise to a positive v_2
- In particular, thermalized charm quarks should flow with the medium $\rightarrow$ (re)generated J/ψ

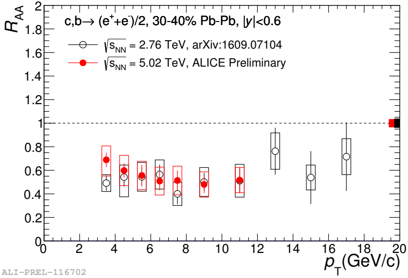
HF Nuclear Modification Factor

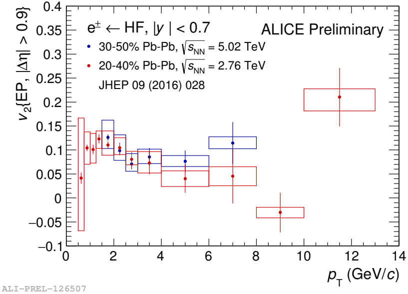




- R_{AA} measured in Run-2 with much greater precision
- No dependence on $\sqrt{s_{\mathrm{NN}}}$ observed
- Potential to be more constraining for the models

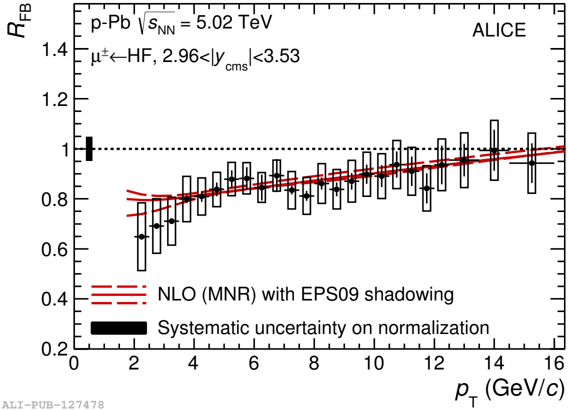
Heavy-Flavor Electrons





ALICE

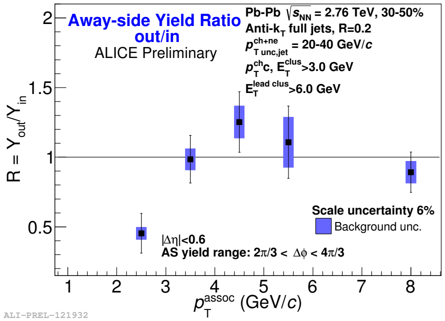
Heavy-Flavor Muon Forward/Backward Ratio

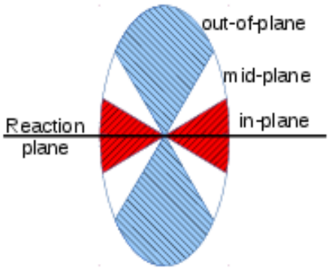


- Cold Nuclear Matter effects more pronounced at large rapidities
- Measurement in agreement with NLO calculations with nuclear shadowing

Crucial to disentangle from QGP phenomenology

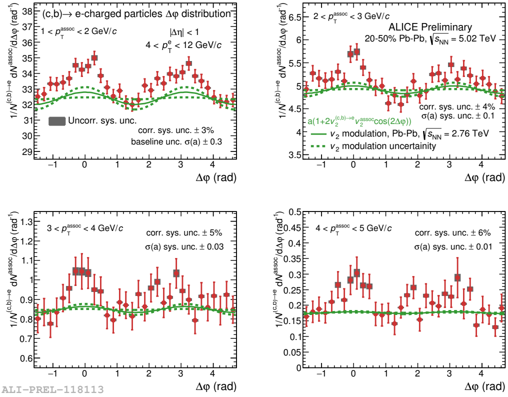
Jet-Hadron Correlations





- Partons expected to loose more energy when traversing more medium (out-of-plane)
- No difference observed between in- and out-of-plane jet-hadron yields

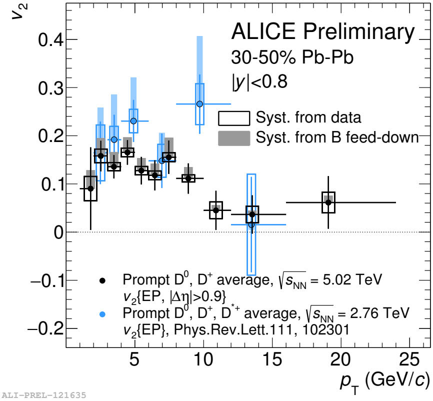
e-h Correlations

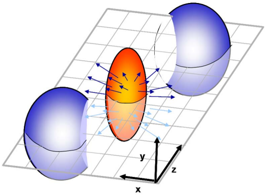


Trigger: heavy-flavor electron
Associated: charged hadron

- Near side → modification of the parton fragmentation in the QGP
- Away side → path-length dependence of in-medium energy loss
- $\Delta\varphi$ measured for $4 < p_T^e < 12$ GeV/c and in 4 bins of p_T^{assoc} from 1 to 5 GeV/c
- Next: measure I_{CP} and I_{AA}

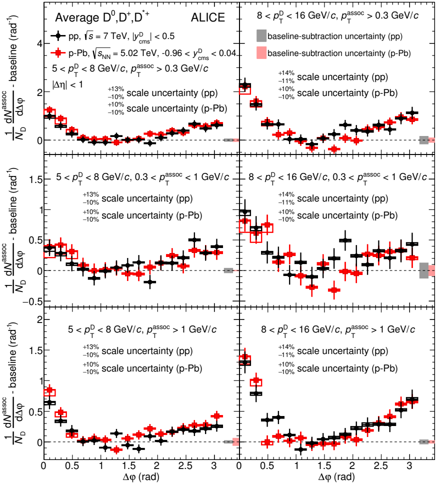
D-Meson Elliptic Flow at $\sqrt{s_{\rm NN}} = 5.02$ and 2.76 TeV





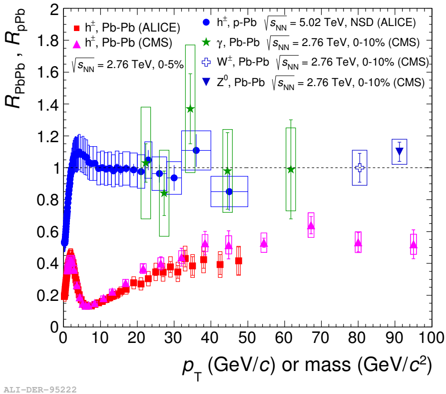
- Similar magnitude of D-meson v_2 at $\sqrt{s_{\rm NN}} = 5.02$ and 2.76 TeV
- Much smaller uncertainties in Run-2 $\rightarrow$ more powerful constraints for heavy-quark transport models

Azimuthal D-h correlations



- No modification observed in minimum-bias p–Pb ($\sqrt{s_{\rm NN}} = 5$ TeV) compared to a pp baseline ($\sqrt{s_{\rm NN}} = 7$ TeV)
- Powerful tool to study modification of the fragmentation of charm jets
- Near side: modification of parton fragmentation
- Away side: look for yield suppression, path-length dependence of energy loss

Jets in Heavy-Ion Collisions



Phys. Lett. B 720 (2013) 52
Eur. Phys. J. C 72 (2012) 1945
Phys. Lett. B 710 (2012) 256
Phys. Lett. B 715 (2012) 66
JHEP 03 (2015) 022

- Nuclear modification factor:

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- Strong suppression of high-p_{T} hadrons
- Binary scaling works for EW probes (γ, Z, W)
- **No suppression** observed in high-p_{T} hadrons in pA collisions