ALICE Highlights

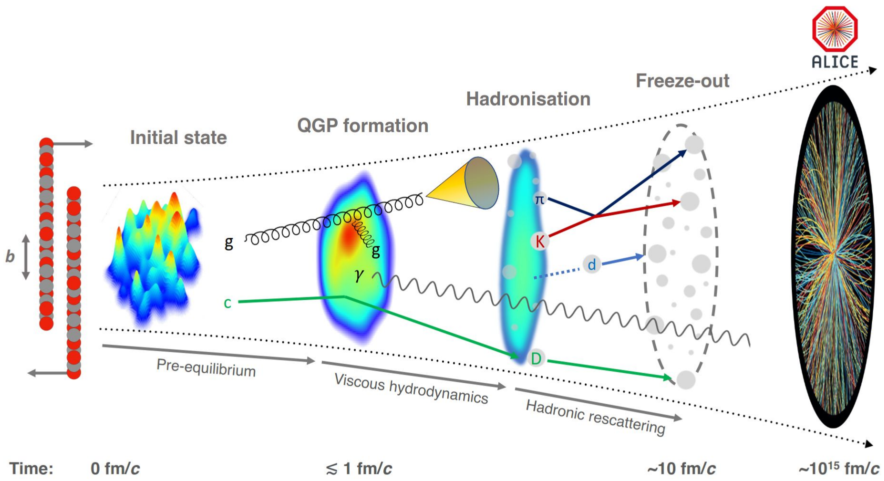
Light Ion Workshop, CERN, 11-15 Nov 2024

C.Cheshkov, IP2I Lyon
for the ALICE Collaboration

Outline

- Parton energy loss
- Flow & collectivity
- Strangeness production
- Heavy flavour
- Other measurements
- Conclusions

Quark-Gluon Plasma (QGP) studies in HI collisions



Hard probes:

- Collisional and radiative parton energy loss ➔ jet-quenching phenomena
  - Shift of jet and high-pT hadron spectra, azimuthal anisotropy, jet-axis smearing, energy transfer outside of jet cone, modification of jet substructure
- Thermalization of heavy quark
  - Modification of charm hadron spectra, azimuthal anisotropy
- Suppression of quarkonia via screening inside hot medium, (re)generation of charmonia at LHC via recombination of thermalized charm quarks

Soft probes:

- Thermal equilibrium ➔ statistical hadronization
  - Hadron chemistry
- Strongly-coupled system ➔ almost perfect liquid
  - Radial and anisotropic particle flow

Many of these QGP signatures present also in small systems, many but not all…

Study small systems in order to answer:

- Are QGP droplets formed in small systems?
- If yes, which are the limits for QGP formation? Which is the role of the initial state? Which are the mechanisms allowing fast equilibration? Which are the relevant hadronization mechanisms? Which are the consequences for our understanding of QGP in large systems?

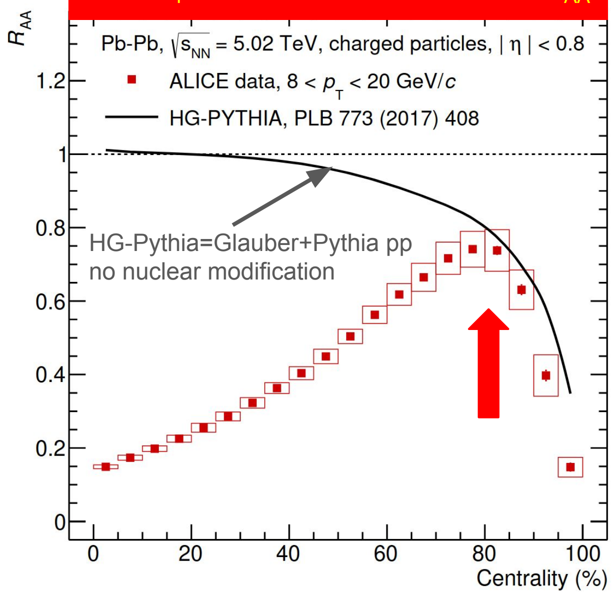
Light-ion data are essential to answer these questions!

Parton energy loss

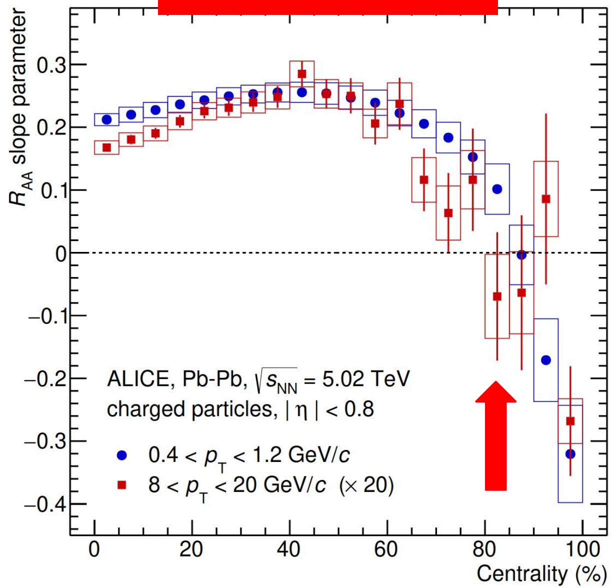
Absence of (visible) parton E_{loss} in peripheral Pb-Pb

High-p_T nuclear modification factor R_{AA}

Phys.Lett. B793 (2019) 420-432



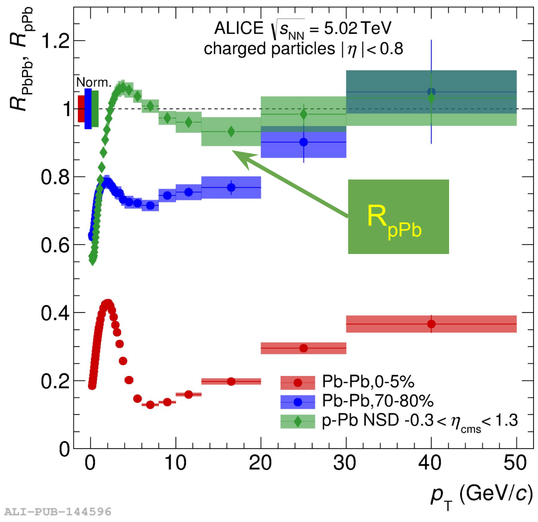
Slope of high-p_T R_{AA}



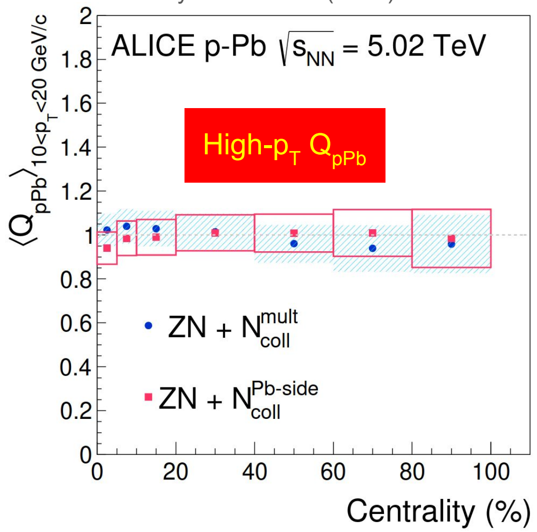
- High-p_T R_{AA} ➜ HG-PYTHIA at 80+% centrality
  - R_{AA} < 1 due to selection bias -> no evidence of suppression
- Slope of high-p_T R_{AA} vs p_T ➜ 0 at 80+% centrality
  - Slope > 0 - typical sign of spectra shift due to E_{loss}
  - Observed slope < 0 at very periph collisions likely due to ‘jet-veto’ bias

Absence of (visible) parton E_{loss} in p-Pb

JHEP 1811 (2018) 013



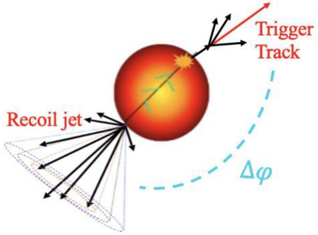
Phys. Rev. C 91 (2015) 064905

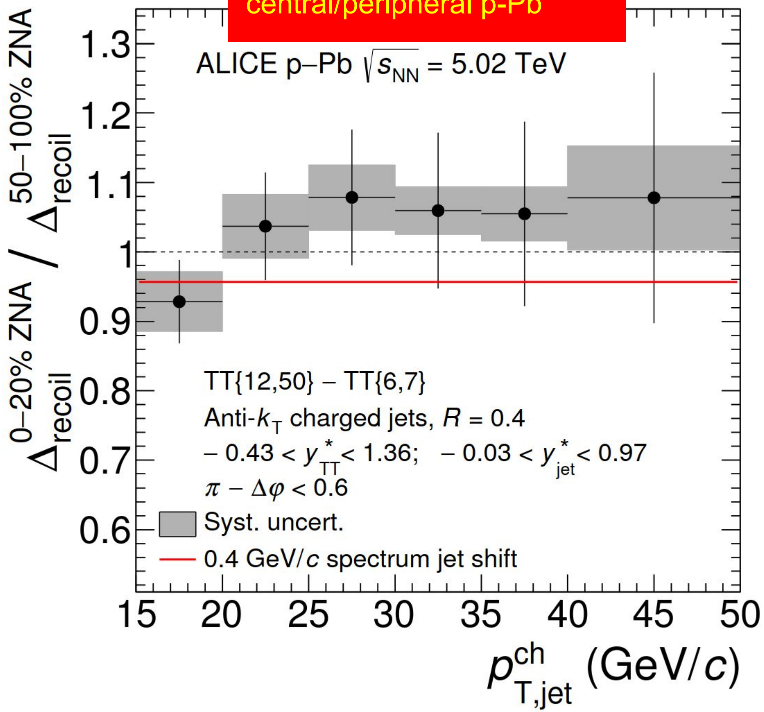


- R_{pPb} (0-100%) compatible with 1 at high p_T
- R_{pPb} vs centrality (Q_{pPb}) should be more sensitive, but significant centrality selection biases
  ➜ Hybrid approach based on energy in neutron Zero-Degree Calorimeter in Pb-going direction
  - N_{coll} - via data-driven approach based on wounded nucleon model ➜ up to 10% uncertainty
  - High-p_T Q_{pPb} compatible with 1 up to most central collisions

Absence of (visible) parton E_{loss} in p-Pb

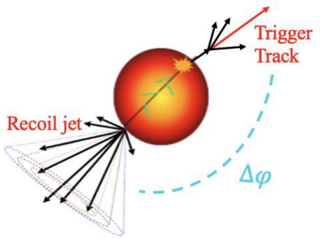
Phys. Lett. B 783 (2018) 95



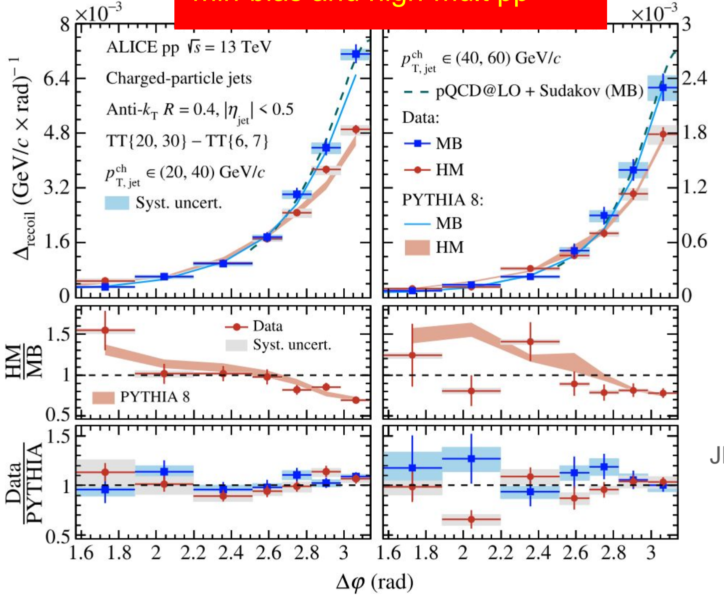


- No sign of sizable E_{loss} in hadron-jet correlations
- Energy transfer out-of-cone
  < 0.4 GeV/c (90% CL)

Hadron-jet correlations in pp



Azimuthal h-jet correlations in min-bias and high-mult pp

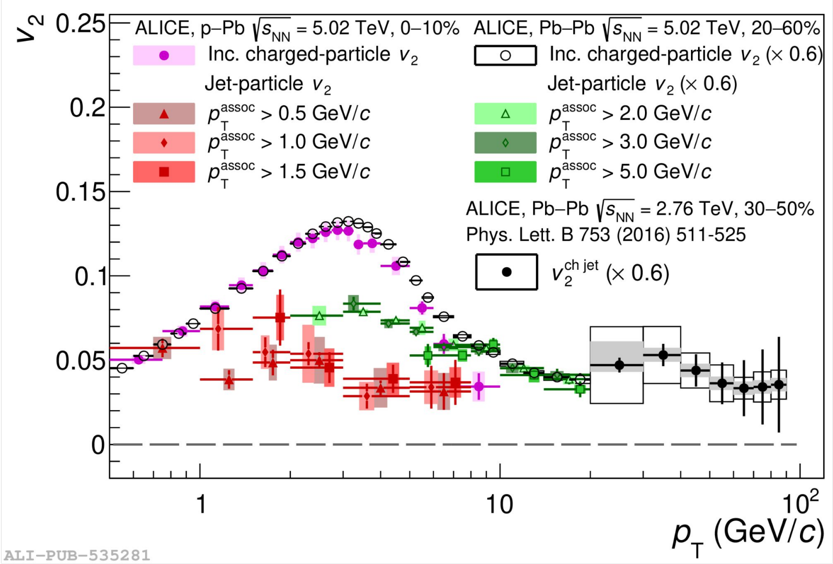


JHEP 05 (2024) 229

- Significant azimuthal broadening between trigger hadron and recoil jet in high-mult collisions ➜ jet quenching? No!
  - Reproduced by PYTHIA
  - Multiplicity-selection bias, forward mult-selection favors high-mult events with jets in forward direction
  - Fundamental problem in pp ➜ limits the searches for parton energy loss effects

(Mini)jet azimuthal anisotropy in p-Pb

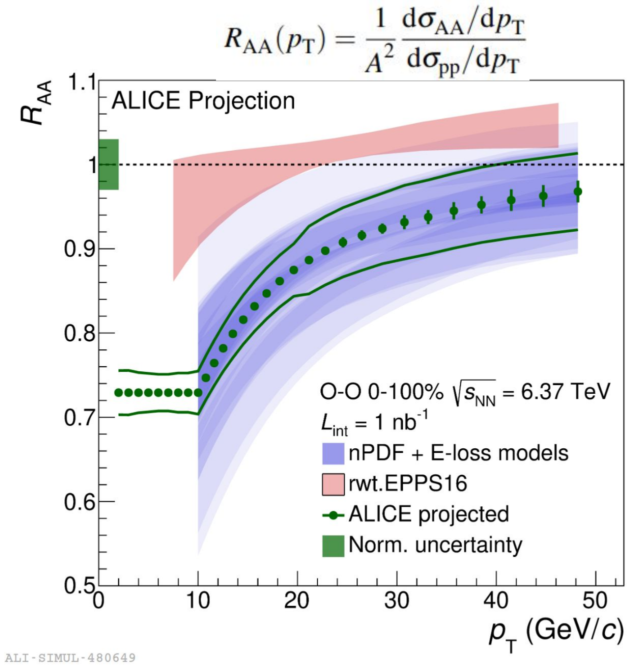
JHEP 08 (2024) 234

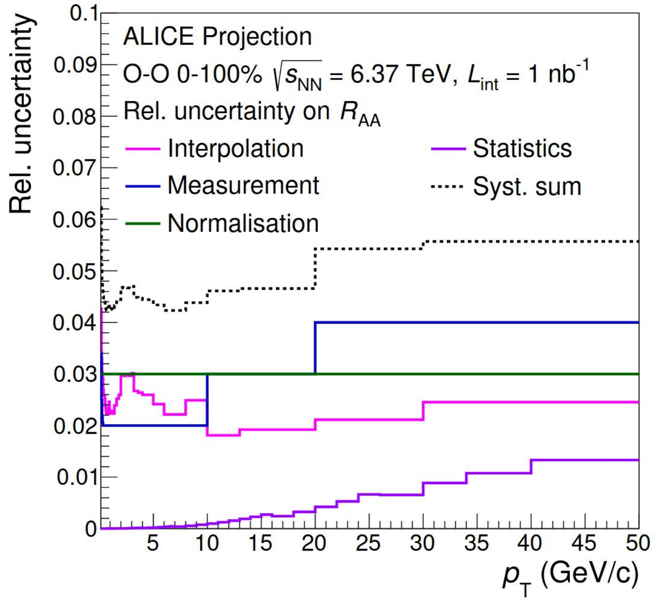


Jet-particles v_2>0, compatible with measurement at high p_T (ATLAS - Eur. Phys. J. C 80 (2020) 73)

- Significant asymmetry despite absence of sizable E_{loss} effects in spectra!
- Absence of significant slope of v_2 vs p_T, unlike AA
  ➜ related to absence of spectra shift? In AA, power-law high-pT spectrum + path-length Eloss ➜ v2 ~ $1/p_T$
- v_2>0 and Q_{pPb}~1 qualitatively described by transport model (AMPT) via parton escape

Parton energy loss (O-O projections)





- Quasi zero-bias in 0-100% due to triggerless continuous readout in Run 3
- pp reference via interpolation of measured spectra at 2.76, 5.02 and 7 TeV
- **R_{AA} measurement with 5% precision**, main uncertainties from O-O measurement itself (syst) and luminosity

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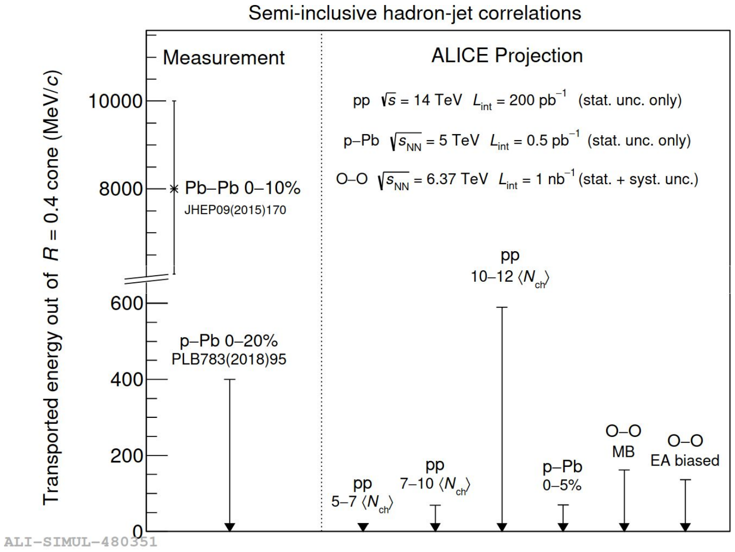
Parton energy loss (O-O projections)

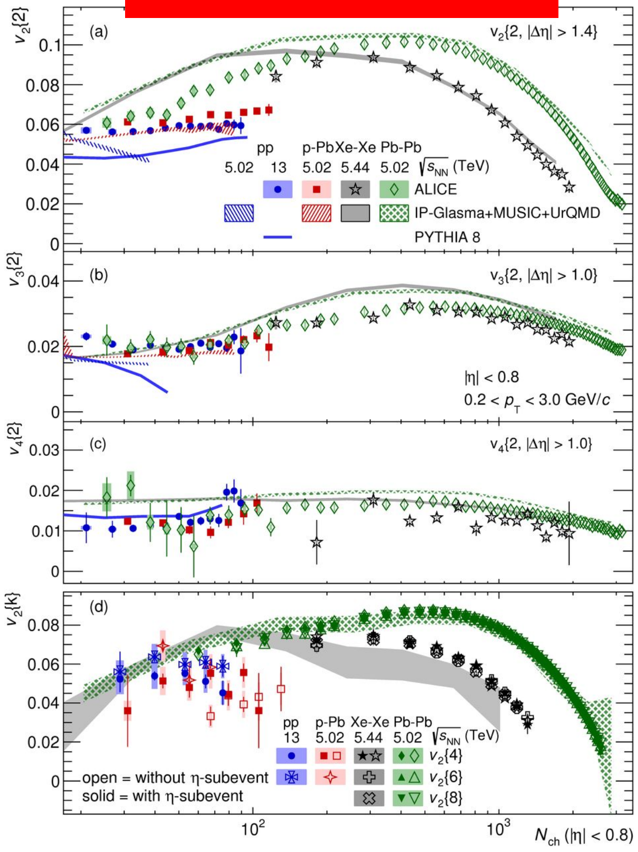


- As low as **150 MeV (at 90% CL)** reachable in 0-100% and centrality/event-activity based measurements of hadron-jet correlations
- Possibly the most precise measurement in the search of onset of parton E_{loss}

Collectivity, particle flow

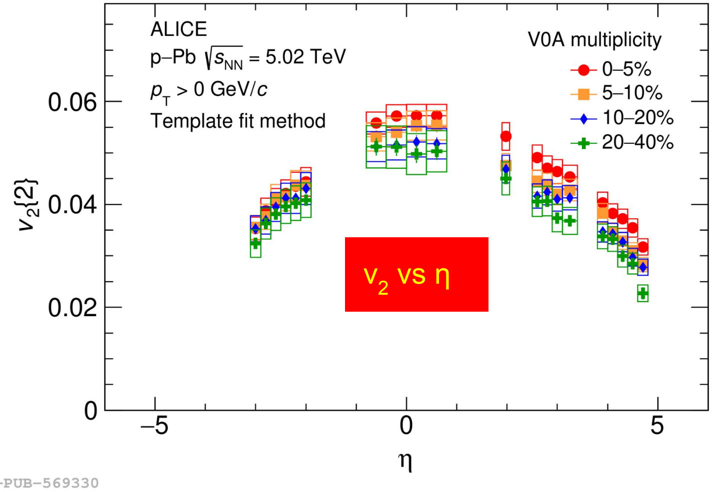
Anisotropic flow in pp and p-Pb

Flow harmonics vs multiplicity



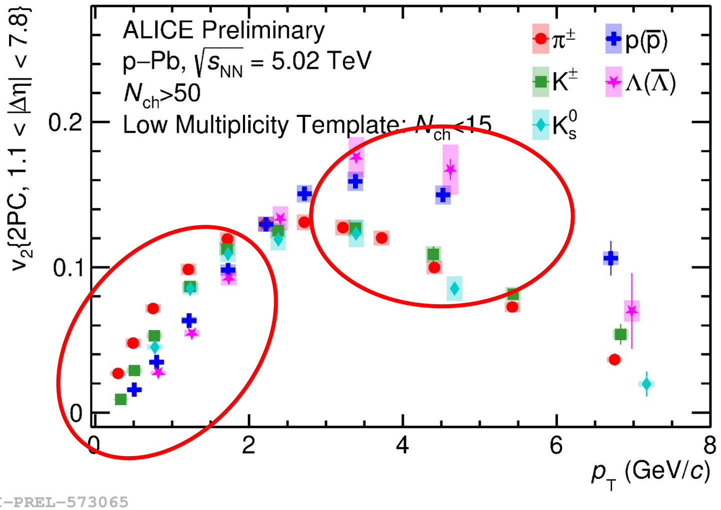
Phys. Rev. Lett. 123, 142301 (2019)

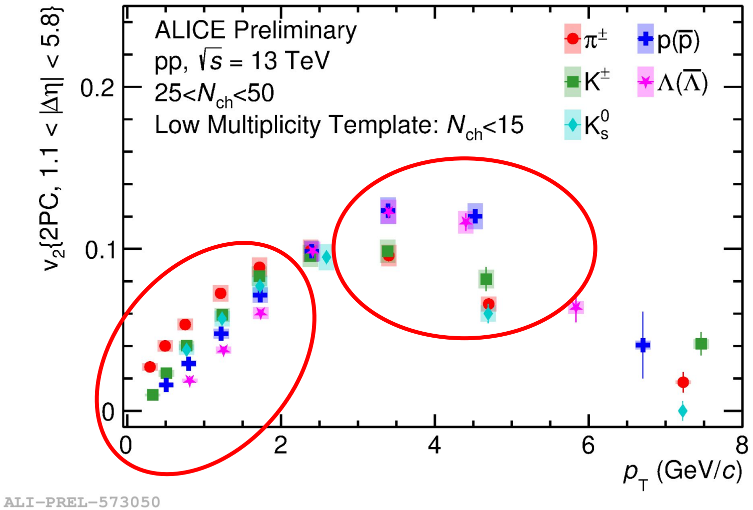
JHEP 01 (2024) 199



- Anisotropic flow present in p-Pb and pp
- Long-range correlations in p-Pb observed up to Δη~8

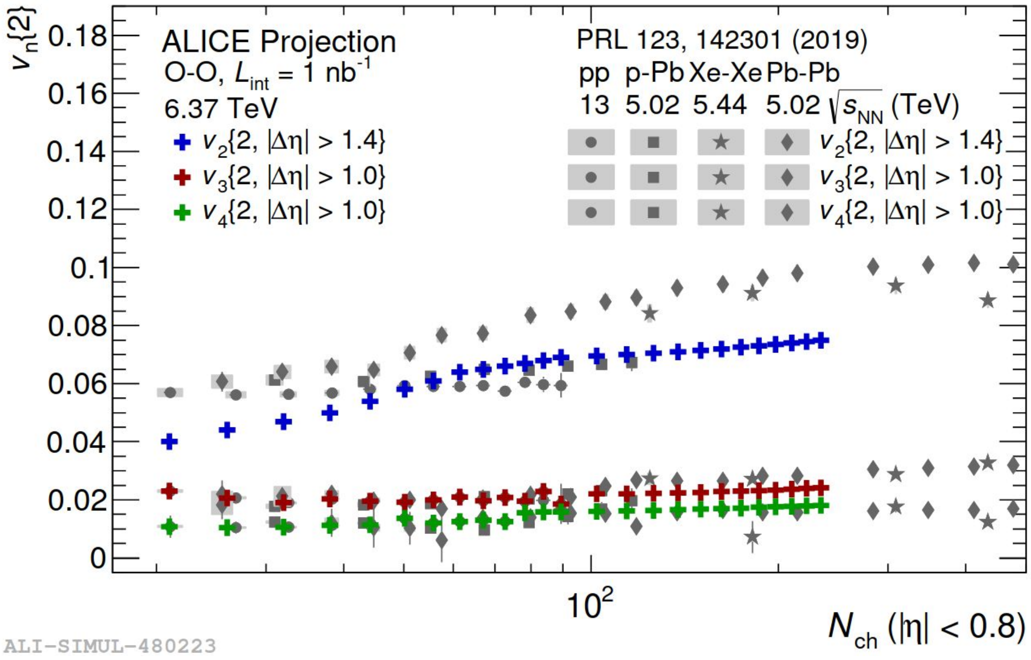
Identified particle flow in p-Pb and pp

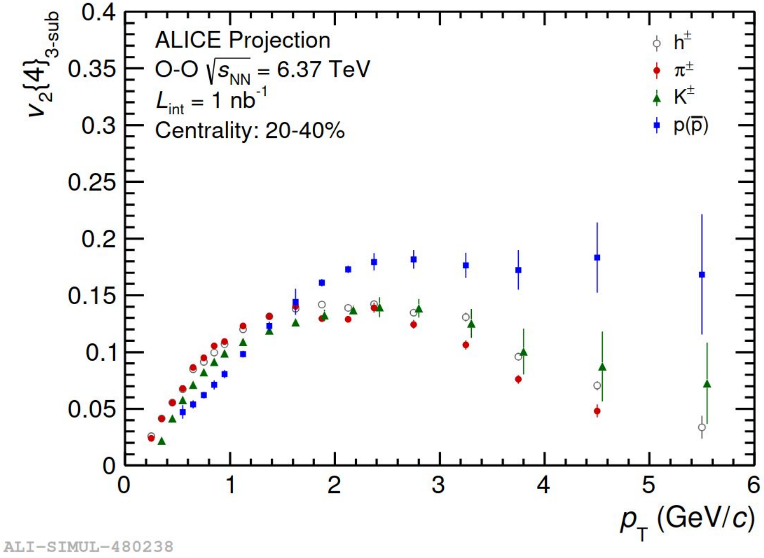




- **Mass ordering at low p_T**
  ➜ in AA interpreted as interplay of radial and anisotropic flow
- **Baryon-meson grouping at intermediate p_T**
  ➜ in AA interpreted as result from coalescence of flowing partons

Flow measurements in O-O (projections)



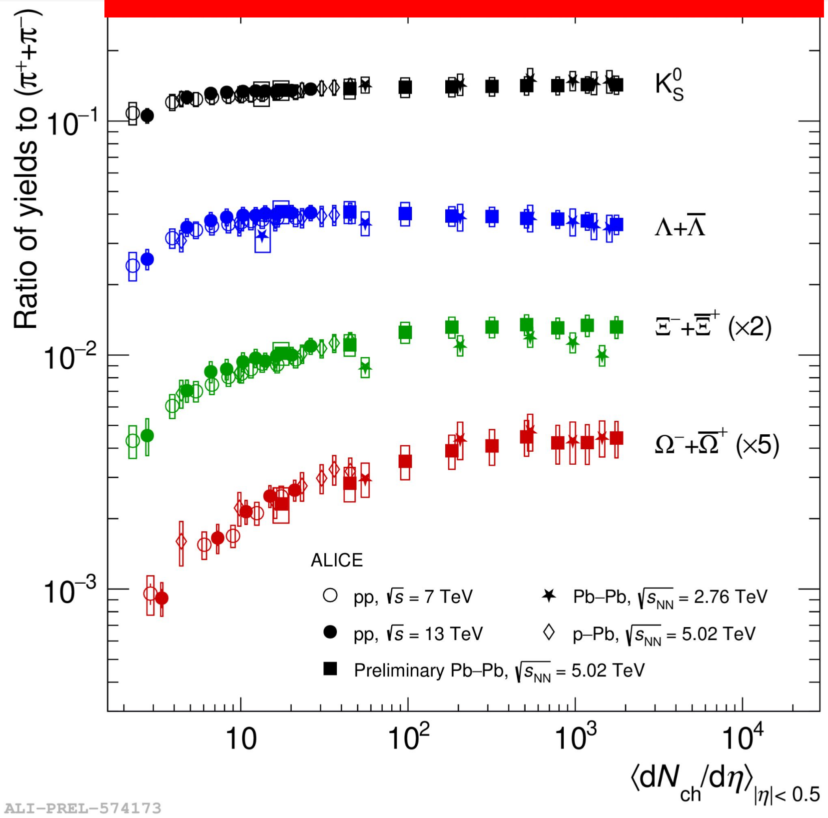


- Cover multiplicity range from low-mult pp to semi-peripheral Pb-Pb
- Advantage wrt pp and p-Pb ➜ **better defined initial-state spatial anisotropy**

Strangeness production

Strangeness production vs multiplicity

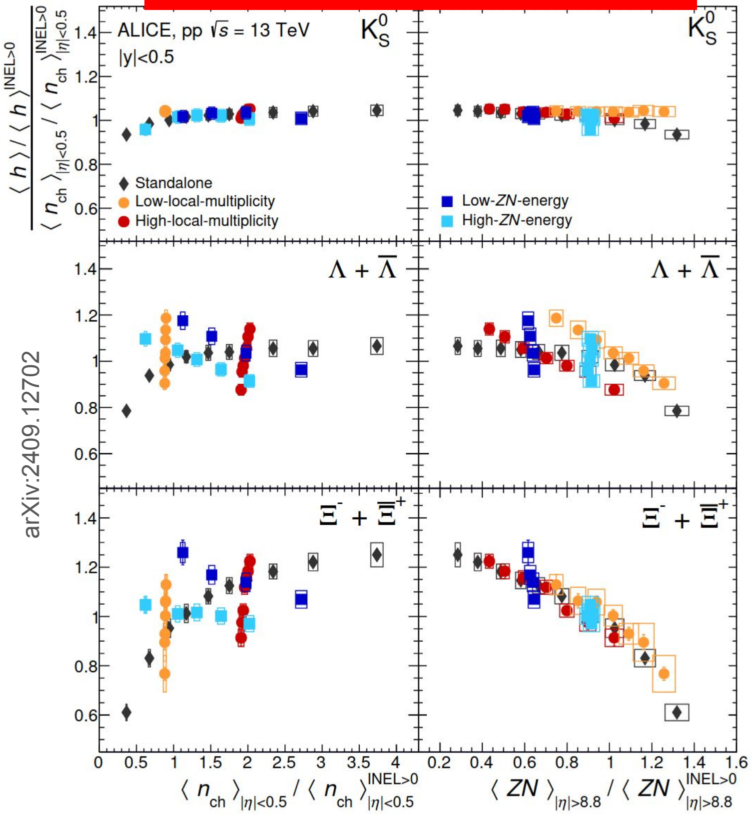
Ratio of strange particles/pions yields vs multiplicity



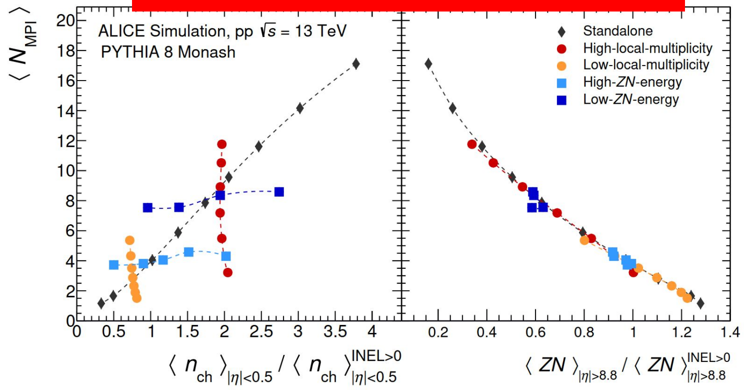
- **Smooth increase S/π vs multiplicity**, independent of √s & collision system
- **Larger strangeness content ➜ stronger increase**
- S/π values reached in Pb-Pb compatible with hadronization of system in thermal equilibrium, described by statistical hadronization models
- S/π at low multiplicity pp described for example by PYTHIA tuned to ee collisions
- ALICE performed numerous analyses related to various aspects of strangeness production

Strangeness vs effective energy in pp

Strange particles/pions yields vs local multiplicity and ZN energy



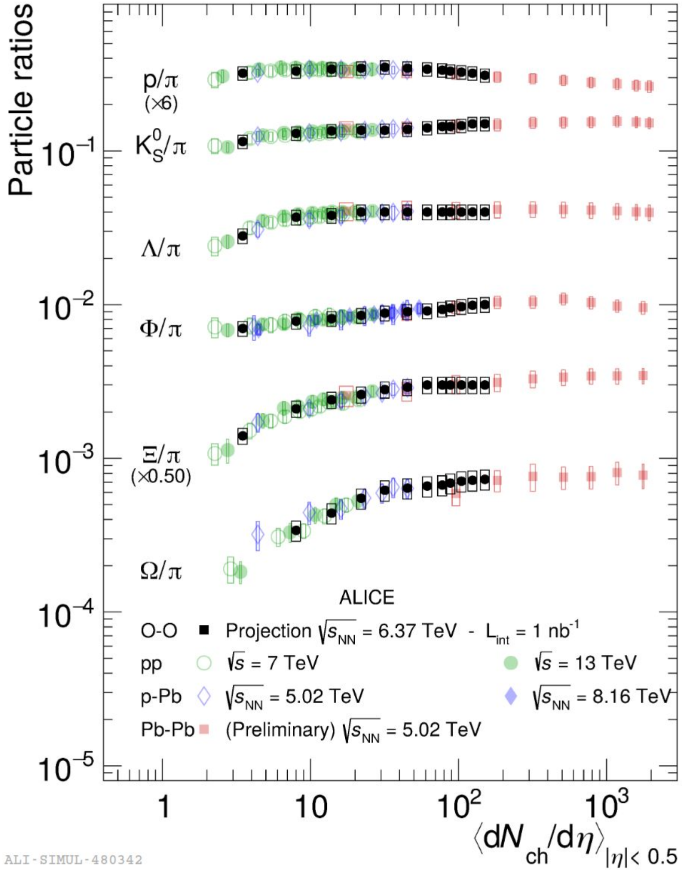
N_{MPI} vs local multiplicity and ZN energy



- **Effective energy = $\sqrt{s} - E_{leading}$**
  $E_{leading}$ - leading (very forward) baryon energy
  Energy in neutron Zero-Degree Calorimeters (ZN) - proxy for $E_{leading}$
- Effective energy as measure of energy available for particle production, **in PYTHIA strongly correlated to N_{MPi}**

- Multi-differential analysis vs local multiplicity and ZN energy:
  - **Fixed ZN energy ➜ no enhancement of strange baryons vs multiplicity**
  - **Fixed local multiplicity ➜ enhancement of strange baryons vs leading energy**

Strangeness production (O-O run projections)



- Cover multiplicity range from low-mult pp to semi-peripheral Pb-Pb
- Assess S/π ratio at same multiplicity as pp and p-Pb, but with completely different initial-state geometry
  - **Same mult in pp and O-O ➜ high N_{MPI} in pp vs several N-N collisions in O-O**

Heavy-flavour

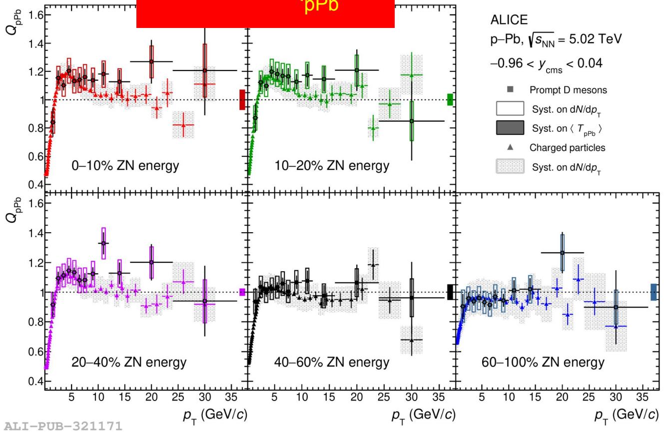
HQ transport in large and small systems

- HQ produced in initial hard scatterings, no thermal production
- Interaction with QGP ➜ thermalization and energy loss
- Large HQ mass ➜ "Brownian motion" inside QGP
  - Incomplete thermalization
  - Encoded in diffusion coefficient D_s

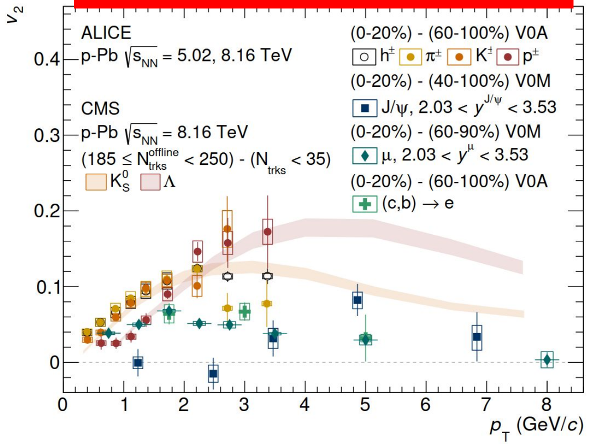
- Simultaneous measure of open-HF R_{AA} and v_2 ➜ constrain D_s

D-meson Q_{pPb}

JHEP 12 (2019) 092



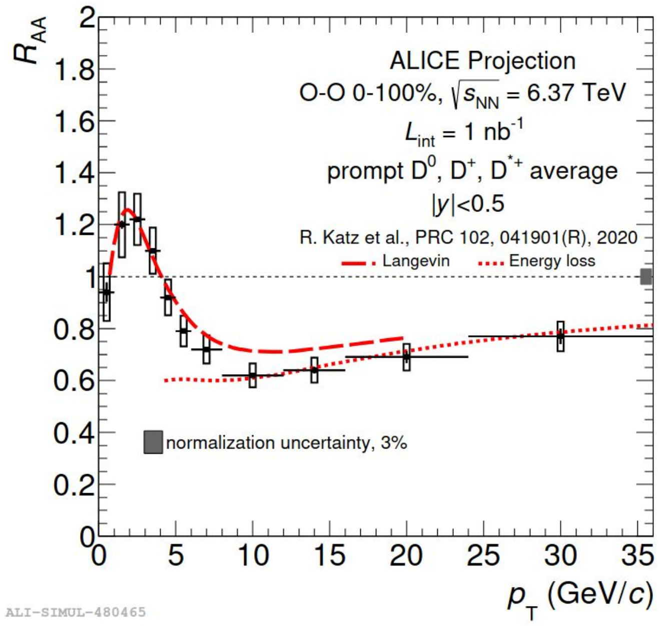
Hadron, HF e and μ, J/ψ v_2 in p-Pb

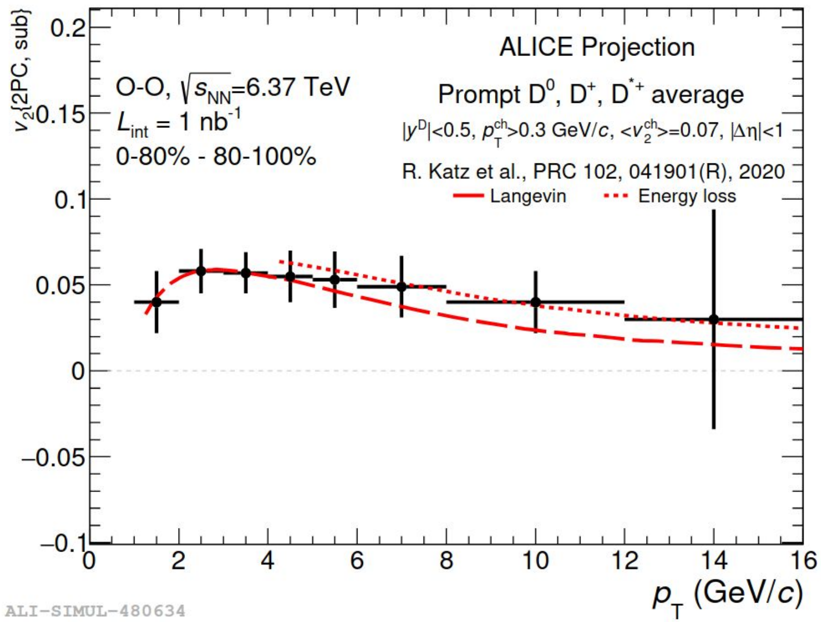


Eur. Phys. J. C 84 (2024) 813

- HQ (charm) farther away from equilibrium in small systems
- **No strong D-meson spectra modification in p-Pb** except possible mild shadowing at low p_T and hint of enhancement at intermediate p_T
- However, **significant charm v_2 also in p-Pb (and pp)**, ratio wrt LF particles similar to Pb-Pb

Charm R_{AA} and v_2 (O-O projections)





- O-O collisions will allow to search for onset of charm thermalization and energy-loss effects
- Improved background rejections thanks to new ITS2 and significantly better track pointing resolution in Run 3
- pp reference obtained via extrapolation of measured lower energy spectra using FONLL

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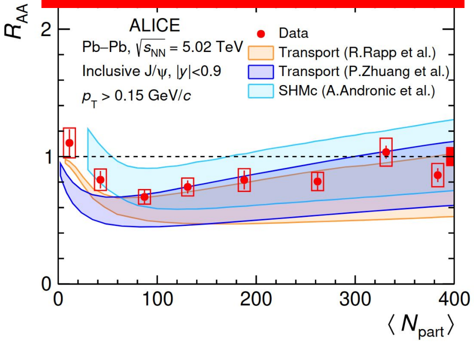
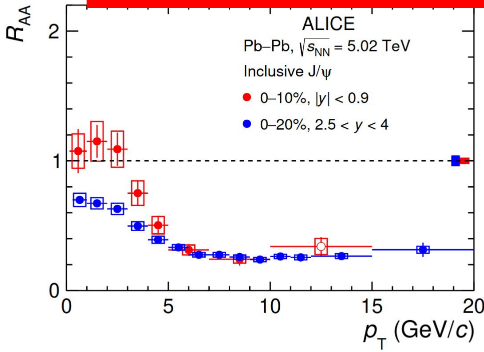
Charmonia in large and small systems

J/ψ R_{AA} vs centrality in Pb-Pb

Phys. Lett. B 849 (2024) 138451

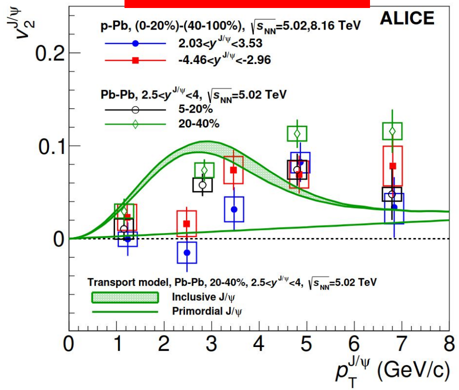


J/ψ R_{AA} vs p_T in central Pb-Pb



- In Pb-Pb at LHC, (re)generation of charmonia via recombination of thermalized charm quarks
  - Enhanced production, at low p_T
  - Flow inherited from charm quarks
  - Azimuthal anisotropy at high p_T from path-length dependent dissociation

J/ψ v2 in p-Pb



Phys. Lett. B 780 (2018) 7-20

- **Surprisingly, significant J/ψ v_2 in p-Pb, despite**
  - **Expected negligible (re)generation and dissociation in p-Pb**
  - **No sign of spectra modification apart from mild shadowing**

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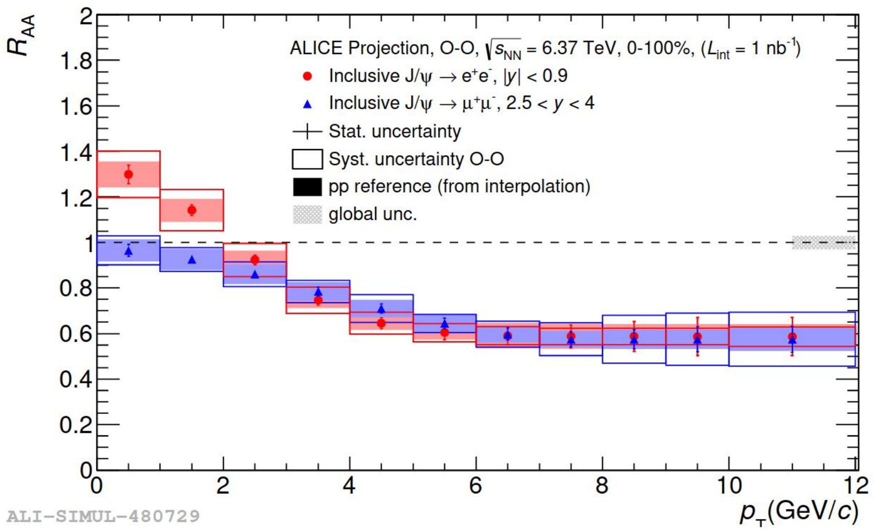
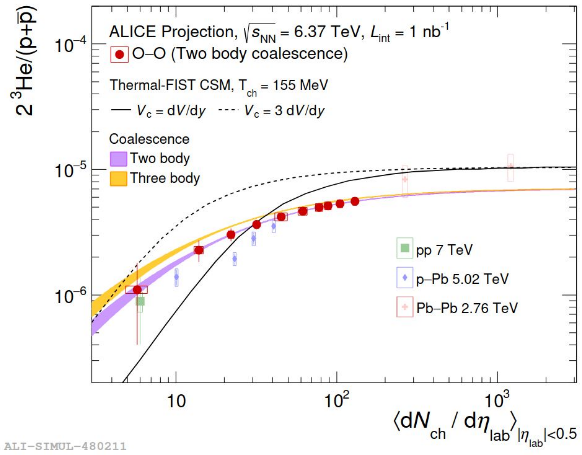
Chamonia measurement (O-O projections)

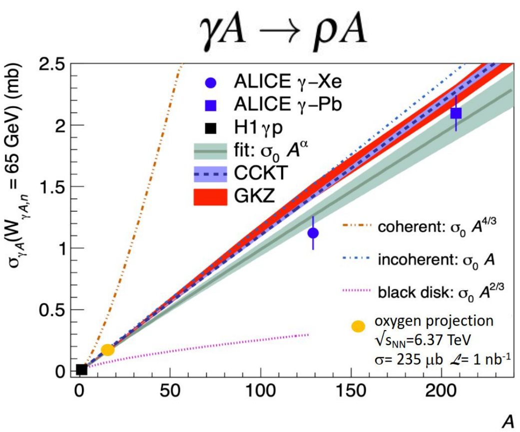


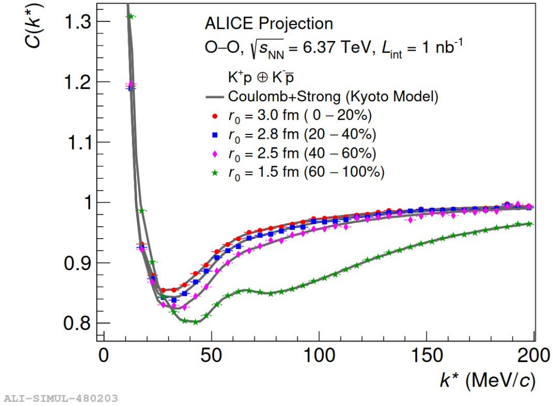
- Search for onset of formation of deconfined medium in small systems
- Midrapidity vs forward rapidity R_{AA} -> disentangle (re)generation and dissociation effects
- Data could be insufficient for precise enough measurement of J/ψ flow

Other interesting measurements in O-O

- Production light nuclei
  - Cover multiplicity range which is most sensitive to distinguish coalescence from thermal models
- Hadron-hadron interactions via femtoscopy
  - Source size between 1.5 and 3 fm
- Photoproduction of vector mesons in UPC
  - Fill the gap between proton and Xe/Pb







Conclusions

- ALICE has prepared rich light-ion physics program
- The mains goals are
  - Search for onset of parton energy loss in small systems
  - Measurement of bulk particle flow, bridging pp, p-Pb and peripheral Pb-Pb
  - Study of strangeness enhancement
  - Search for HQ thermalization and origins of HF flow in small systems

- Projections for O-O run (L_{int}=1nb^{-1}) can be found in: http://cds.cern.ch/record/2765973

- Each new collision system ➜ leap in our studies of QGP, particularly true for p-Pb, but also for Xe-Xe:
  - About 20 published papers

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Conclusions

- Many light-ion measurements will profit from upgraded ALICE apparatus in Run 3
- Completing Run 3 Pb-Pb sample remains priority for ALICE
  - About 1.5 nb^{-1} collected in 2023
  - pp reference data at 5.36 TeV have been just collected
  - 2024 Pb-Pb run is ongoing
- In 2026, ALICE will take Pb-Pb or p-Pb data, with a preference for p-Pb in case of successful Pb-Pb data taking
- ALICE is interested in further ion species (for example Ne-20) if it is in addition and at no cost for planned Pb-Pb and p-Pb data taking

Thank you for your attention!