Heavy Ion Physics with ALICE

– recent results –

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Les Rencontres de Physique de la Vallée d'Aoste

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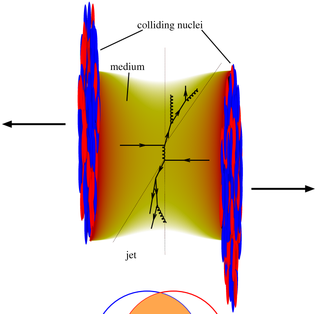
motivation

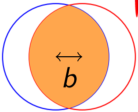
- heavy-ion collisions allow us to study **strongly interacting matter**
- quantitative understanding of medium behaviour, e.g.
  - expansion
  - ultimately aiming for thermodynamic properties: temperature dependence of η/s (viscosity / entropy density)
- study interaction of hard probes with medium, e.g.
  - energy loss mechanisms
- address evolution from small to large systems, e.g.
  - multiplicity dependence of particle production

$\rightsquigarrow$ heavy-ion collisions to do **precision measurements**

heavy-ion collisions

$\sigma_{\mathrm{PbPb}} \simeq 8$ b





- geometric description of collision
  $\rightsquigarrow$ impact parameter *b*
  $\rightsquigarrow$ centrality (fraction of σ_{geom})
- high energy density in overlap region, non-trivial shape
- soft production of "**bulk matter**"
  - thermalization and hydrodynamic evolution
  - freeze-out and hadronization
- **hard probes**

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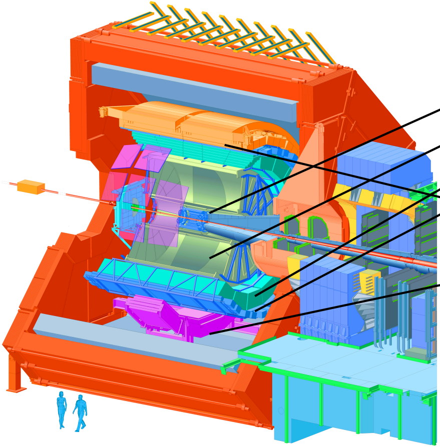
understand evolution of bulk matter
and interaction of hard probes

ALICE detector



- central barrel tracking, solenoidal $|\mathbf{B}| = 0.5\ \mathrm{T}$:
  - Inner Tracking System
  - Time Projection Chamber
  - Transition Radiation Det.
  - Time-of-Flight detector
- central barrel calorimetry:
  - EMCAL + DCAL
  - PHOS
- trigger and event classification:
  - V0
  - SPD
  - ZDC
- muon spectrometer

$\rightsquigarrow$ **excellent particle identification over wide $p_\perp$ range**, also in high-multiplicity environment of Pb–Pb

datasets

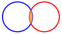
- data collected
  - with different collision systems
  - at different energies

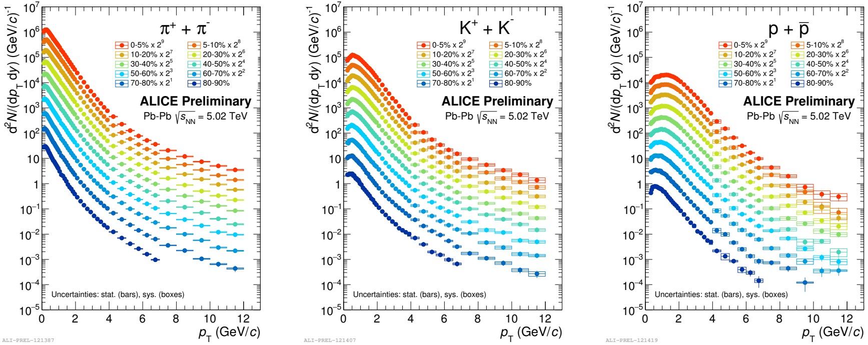
	Run 1 (2009 – 2013)	**Run 2** (2015 – now)
pp	0.9, 2.76, 7, 8 TeV	5, 13 TeV
p–Pb	5.02 TeV	5.02, 8.16 TeV
Pb–Pb	2.76 TeV	5.02 TeV

- in the following focus on new results, i.e.
  - new type of analysis on run 1 data
  - precision measurement on run 2 data

$\rightsquigarrow$ systematic study of
system and energy dependence

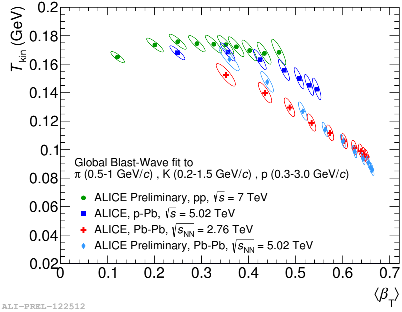
particle production

- $p_\perp$ spectra for π, K, p (identified by ITS, TPC, TOF, HMPID)
- exponential (low $p_\perp$) + power law (high $p_\perp$)
- evolution from central  to peripheral  events



$\rightsquigarrow$ **precision measurements** of particle production

collective expansion



- assume collective expansion with:
  - fluid velocity β_T
  - kinetic freeze-out temperature T_kin

  $\rightsquigarrow$ **radial flow**
  (Boltzmann-Gibbs blast-wave model)
  [Schnedermann et al., PRC 48, 2462]
- simultaneous fit to π, K, p spectra
- system expanding with nearly $\frac{2}{3}c$

$\rightsquigarrow$ spectra consistent with collective expansion

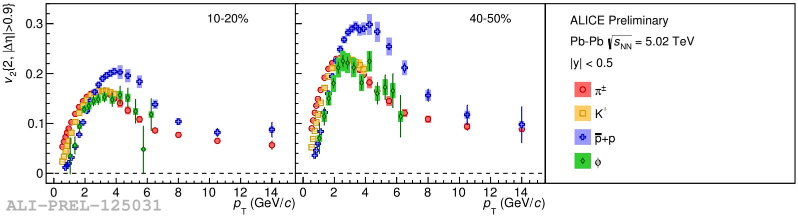
confirmed by more detailed modelling by
relativistic hydrodynamics

azimuthal anisotropy

- eccentricity and fluctuations of initial state + interaction
  $\rightsquigarrow$ azimuthal modulation
- decomposition into Fourier components:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} = \frac{\mathrm{d}^2N}{2\pi\, p_\perp \mathrm{d}p_\perp \mathrm{d}y}\left(1 + \sum_{n=1}^{\infty} 2\, v_n \cos(n(\varphi - \psi_n))\right)$$

exploiting particle identification



$\rightsquigarrow$ **elliptic flow** v_2

$\rightsquigarrow$ **mass ordering** as expected from hydrodynamic evolution

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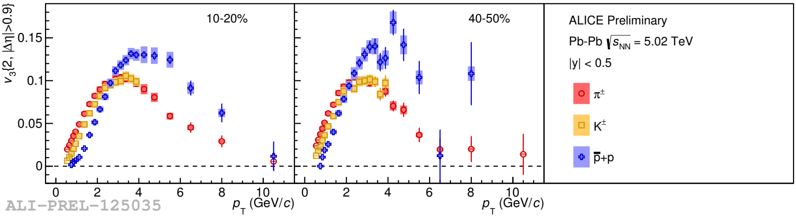


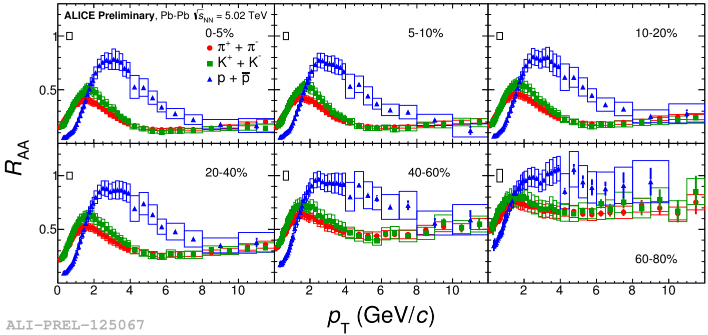
$\rightsquigarrow$ **triangular flow** v_3

$\rightsquigarrow$ **mass ordering** as expected from hydrodynamic evolution

nuclear modification factor

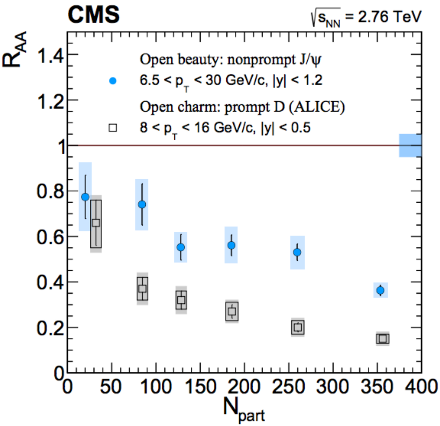
- compare Pb–Pb collision with incoherent pp superposition, here for $p_\perp$ spectra:

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N^{\mathsf{AA}}/\mathrm{d}p_\perp}{\langle N_{\mathrm{coll}}\rangle \; \mathrm{d}N^{\mathsf{pp}}/\mathrm{d}p_\perp}$$



suppression of particle yields ⇝ **energy loss**

heavy-flavour production

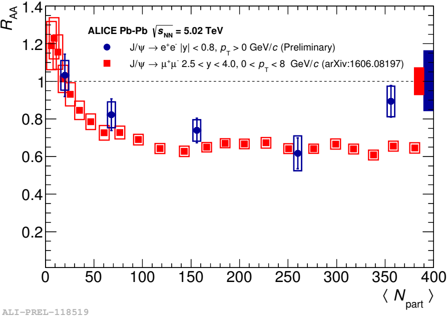


[CMS-HIN-14-005, arXiv:1610.00613]

- heavy-flavour quarks produced early in the collision
- smaller energy loss expected for heavier particles
- D mesons as probes for open charm
- non-prompt J/ψ as proxy for open beauty

⇝ **strong suppression**
also in the heavy-flavour sector

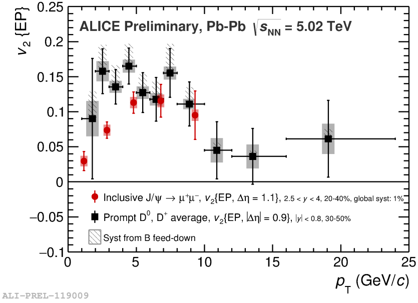
charmonium



- production of $c\bar{c}$ pairs
- charmonium states $(J/\psi, \psi(2S), \ldots)$ take double role
  - dissociation
  - recombination
- consider J/ψ
  - nuclear modification factor
  - elliptic flow

⇝ consistent with recombination, strong interaction with the medium

charmonium



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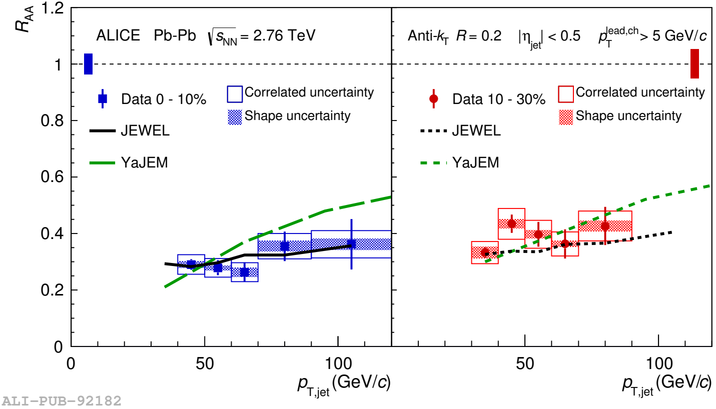
jet suppression

- measure nuclear modification factor for jets (anti-kt, $R = 0.2$)



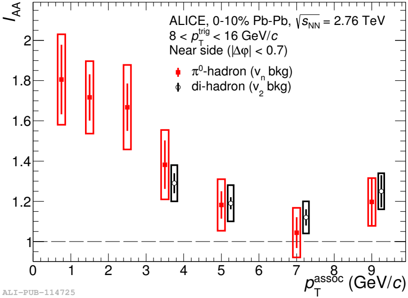
also jets are strongly suppressed

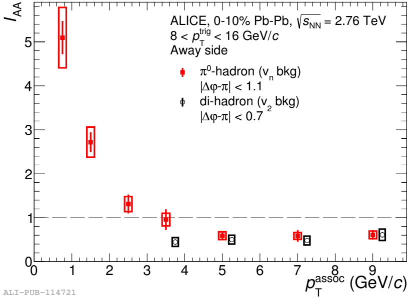
⇒ interesting to **further characterize jets**

jet production

- use two-particle correlations to measure jet-induced yields
- compare Pb–Pb and pp

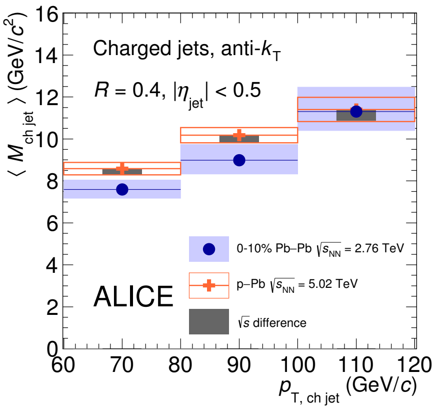
$$I_{AA} = \frac{Y_{\mathrm{Pb-Pb}}}{Y_{\mathrm{pp}}}$$





⇝ **enhancement of low-$p_\perp$ fragments** around jet

jet mass



[arXiv:1703.00804]

- charged anti-kt jets, $R = 0.4$, E-scheme
- reconstruct invariant mass:

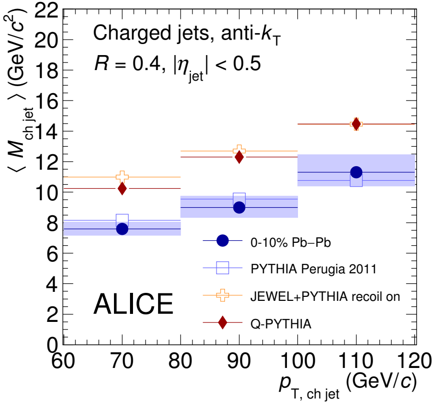
$$M = \sqrt{E^2 - {p_\perp}^2 - p_z^2}$$

- sensitive to jet quenching
  - compare with p–Pb
  - compare with models
- models implementing quenching deviate from data

first measurement of jet mass in Pb–Pb

⇝ important constraint for improvement of models

jet mass



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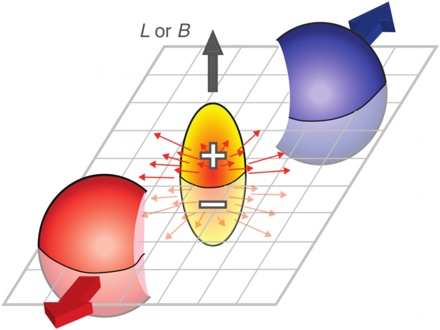
chiral magnetic effect

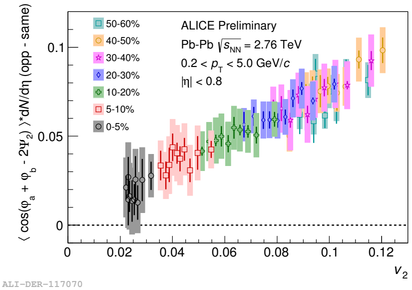


- strong magnetic field
  generated because of chiral anomaly
  ⇝ charge separation
- measure by using correlations
  in events of different v_2
  (event shape engineering)
- extract CME fraction

⇝ testing fundamental QCD:
upper limit for CME fraction: $\sim 20\%$

chiral magnetic effect

ALICE



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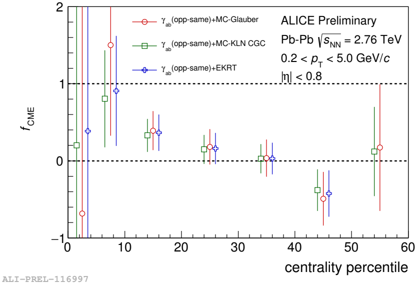

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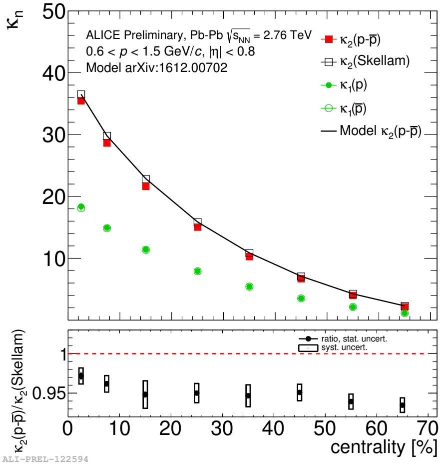
particle moments



- net particle production:

$$x := N_p - N_{\bar{p}}$$
$$\kappa_2(x) := \langle x^2 \rangle - \langle x \rangle^2$$

- fluctuations linked to thermodynamic properties
- participant fluctuations vanish for κ_2
- baryon number conservation $\rightsquigarrow$ deviation from Skellam

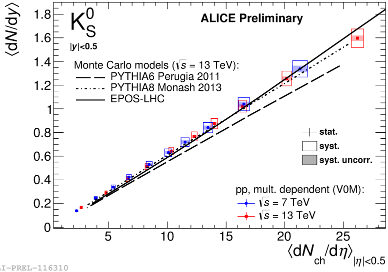
[P. Braun-Munzinger et al., arXiv:1612.00702, NPA in print]

$\rightsquigarrow$ **agreement with lattice QCD calculations**

strangeness production

now moving to small systems

- reconstruct strange particles, here K^0_s and Λ as function of the event multiplicity
- compare scaling at different energies



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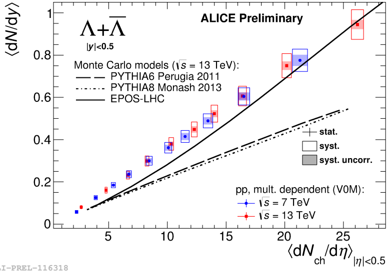
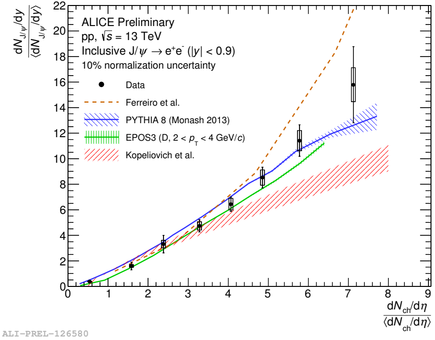


ALI-PREL-116318

⇝ **strangeness production scales** with $\mathrm{d}N/\mathrm{d}\eta$ (across energies)

J/ψ production



- measure J/ψ yield as function of multiplicity
- expressed as self-normalized yields

⇝ **multiplicity dependence** reasonably well modelled

future plans

- **Pb–Pb runs**
  - Pb–Pb run 2018
  - Pb–Pb runs during run 3
    target: 10 nb^{-1}
- run 3 to do **high-precision measurements** of
  - heavy flavour and quarkonia
  - jets
  - low mass dileptons
  - heavy nuclear states
- **upgrades during long shutdown 2** (2019 - 2020)
  - Time Projection Chamber:
    replace MWPCs with GEMs
    $\rightarrow$ continuous read-out to benefit from 50 kHz of Pb–Pb collisions
  - Inner Tracking System:
    complete replacement by MAPS-based detector

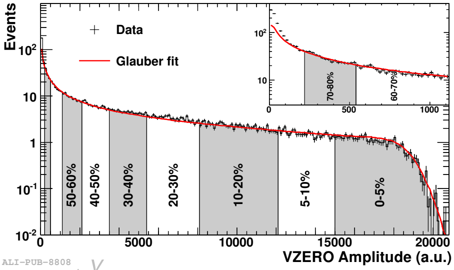
conclusions

- **many new results**, both
  - new types of analysis on run 1 data
  - precision measurements from run 2 data
- **small systems** interesting and useful
  to study evolution to large (Pb–Pb) systems
- moving towards **precision measurements**
  of heavy-ion collisions

Thank you!

Backup

Global event characteristics



here: forward multiplicities

- impact parameter $\rightsquigarrow$ geometry
  BUT: not directly measurable
  translates to multiplicity
- classify events
  - by centrality:

$$C = \frac{\sigma(b \leq b_0)}{\sigma_{\text{had}}}$$

  - by reaction plane
    measured from anisotropic
    particle emission

high multiplicities, e.g. for 10 % most central events:
$\sim 140\ \mathrm{GeV}$ **per unit area in** η-φ