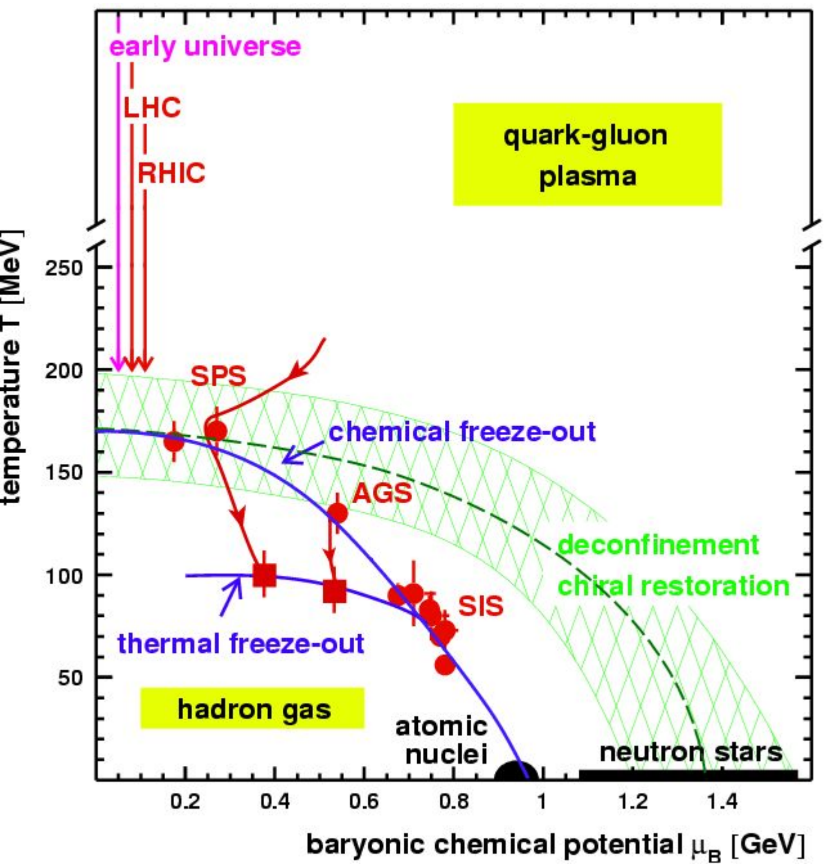
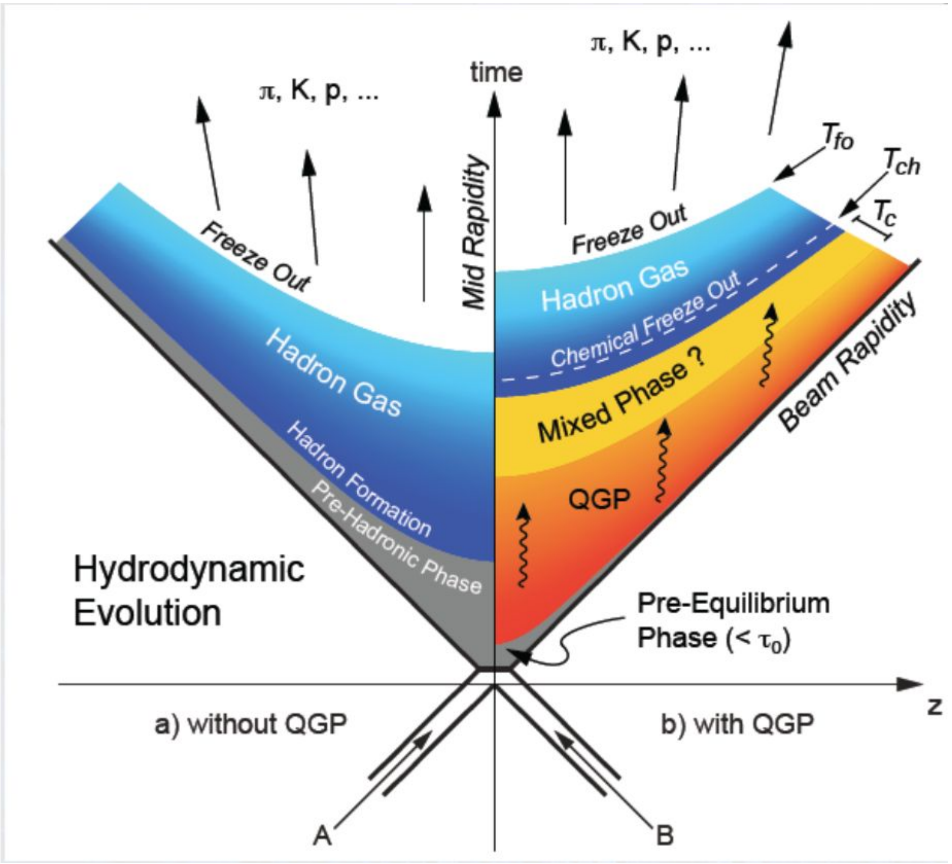
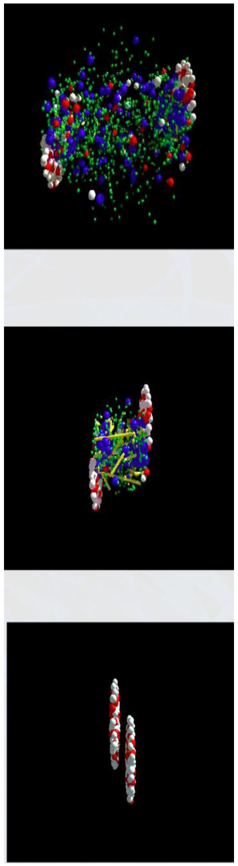
Recent results from the ALICE Experiment at LHC

Catalin Ristea* on behalf of the ALICE Collaboration
*Institute of Space Science, Romania

Relativistic Heavy-Ion Collisions and QGP







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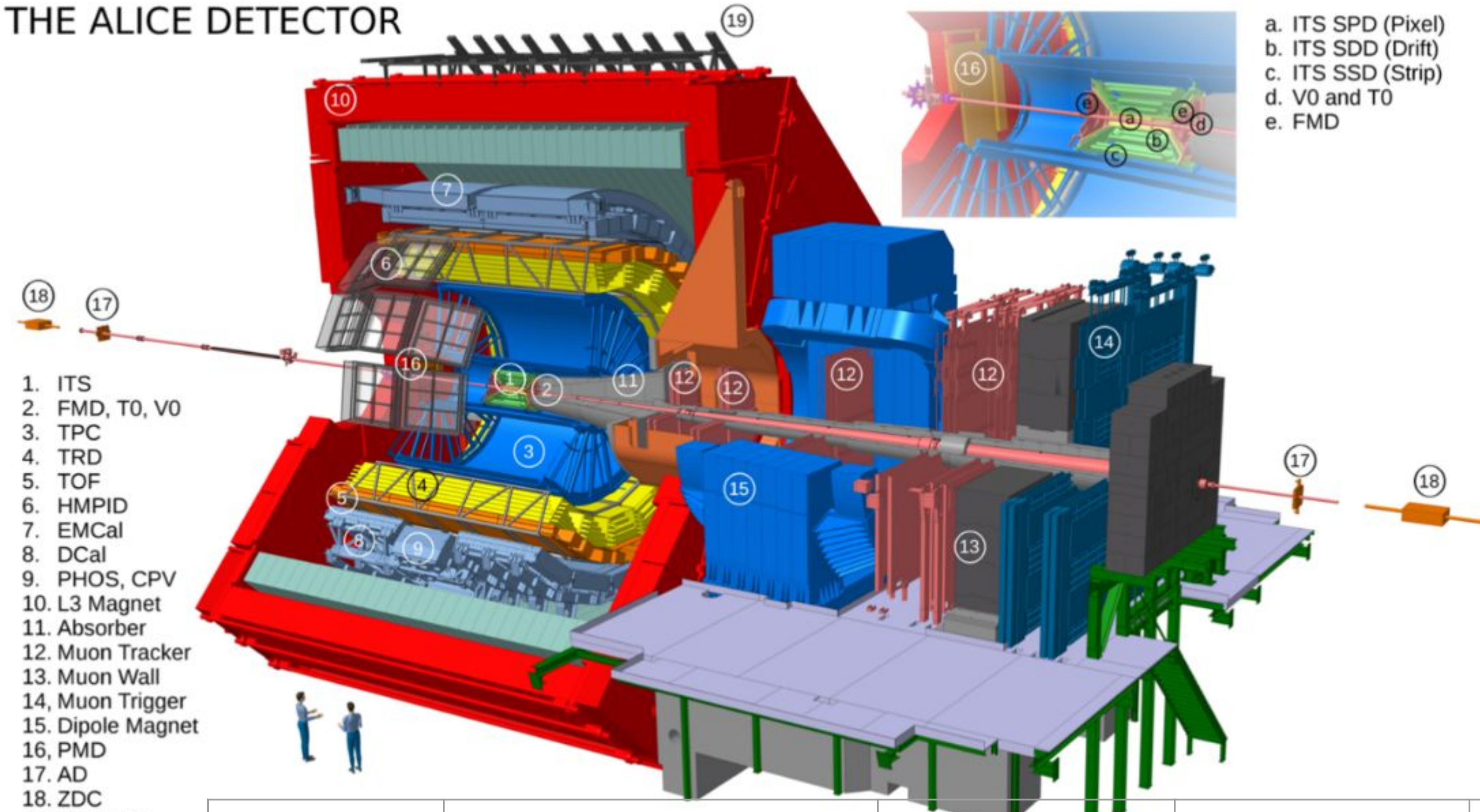
By changing the energy available in the collision and the projectile-target combinations, one can obtain systems characterized by various temperatures and baryon chemical potentials → different regions on the phase diagram can be investigated

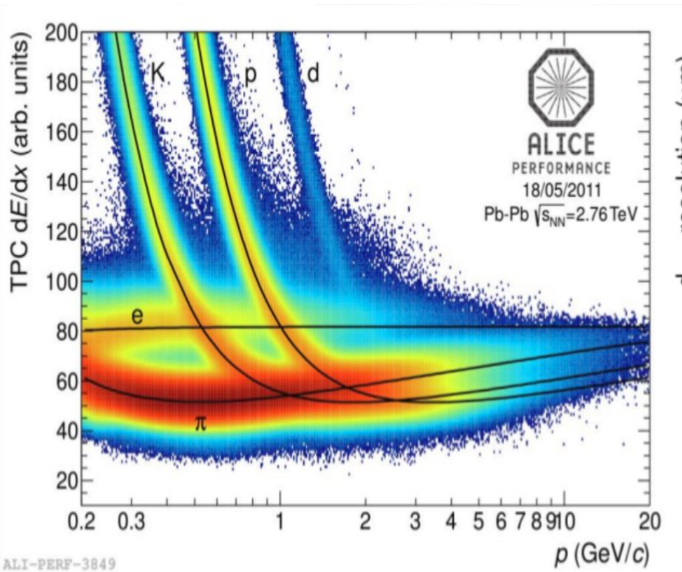


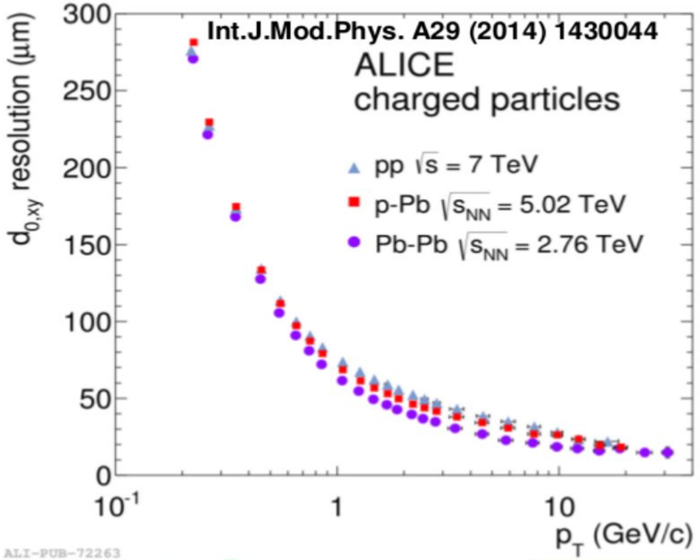
System	p-p	p-Pb / Pb-p	Xe-Xe	Pb-Pb
$\sqrt{s_{NN}}$ (TeV)	0.9, 2.76, 7, 8, 5.02, 13	5.02, 8.16	5.44	2.76, 5.02
L_{int}	200μb^{-1}, 100nb^{-1}, 1.5pb^{-1}, 2.5pb^{-1}, 1.3pb^{-1}, 25pb^{-1}	18 nb^{-1}, 25 nb^{-1}	30 μb^{-1}	75 μb^{-1}, 250 μb^{-1}

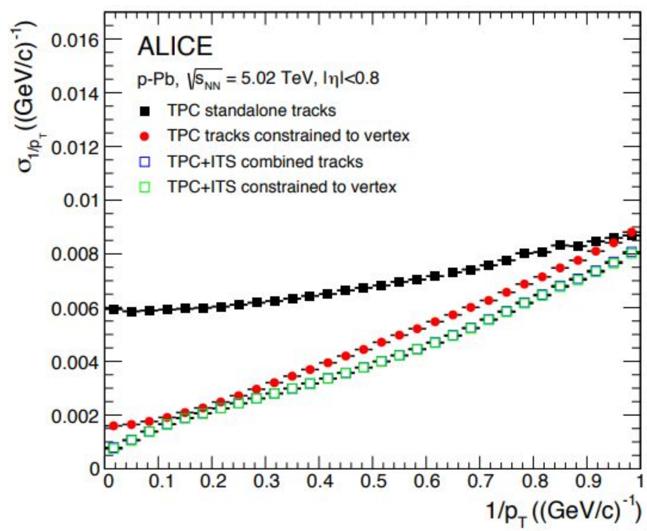
Dedicated detector to exploit the unique physics potential of nucleus-nucleus collisions at LHC
Study the physics of strongly interacting matter at the highest energy densities reached so far in laboratory
Comprehensive studies of hadrons, electrons, muons and photons to understand and describe QGP formation in heavy ion collisions

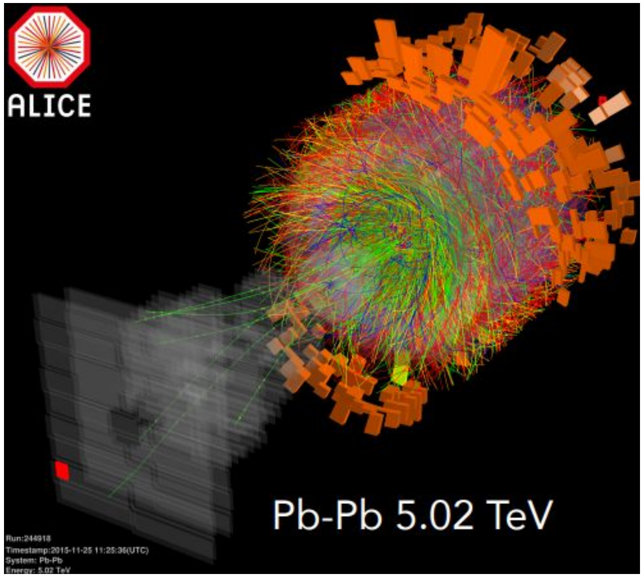
ALICE Performance

Int. J. Mod. Phys. A 29 (2014) 1430044









- Excellent PID for hadrons, leptons and photons
- Good tracking resolution in TPC & EmCal detectors to resolve the inner structure of (copiously produced) jets @ LHC
- Excellent vertex capability (HF, V^0s, cascades, conversions)
- Efficient low-momentum tracking down to 150 MeV/c

Charged particle production

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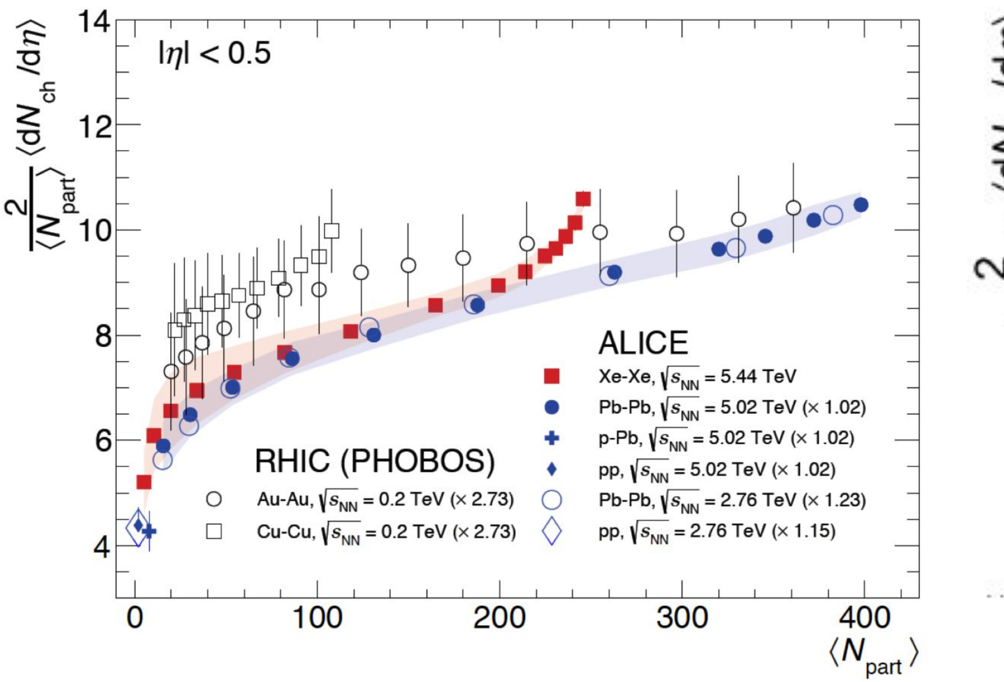
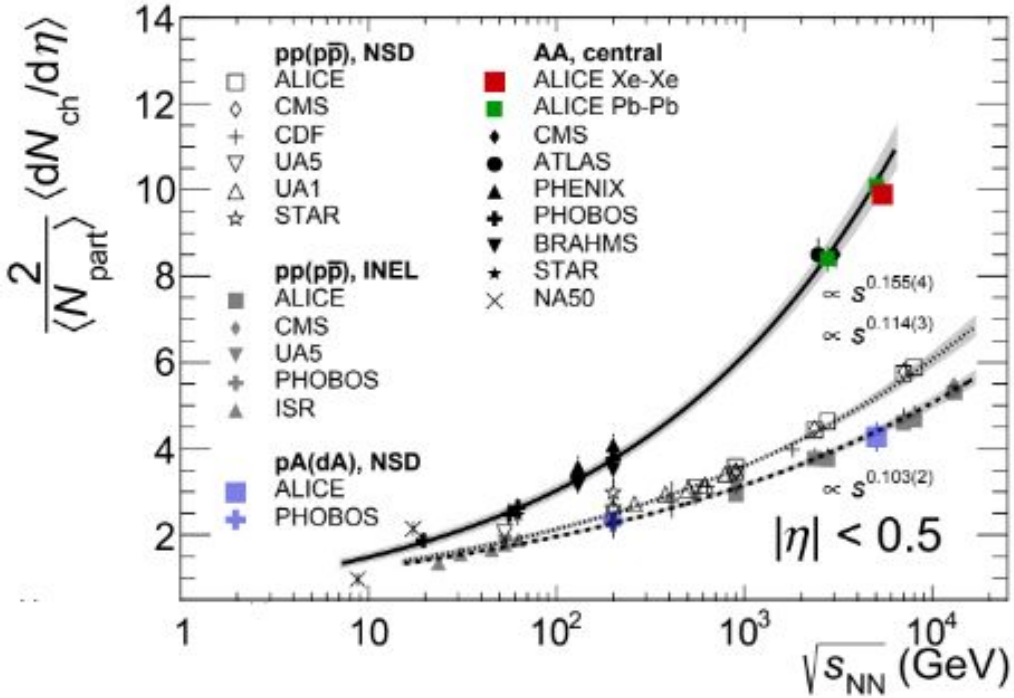




For most central collisions, Xe-Xe results are higher than Pb-Pb results at similar N_{part} → N_{part}- scaling violation for 0-5% Xe-Xe

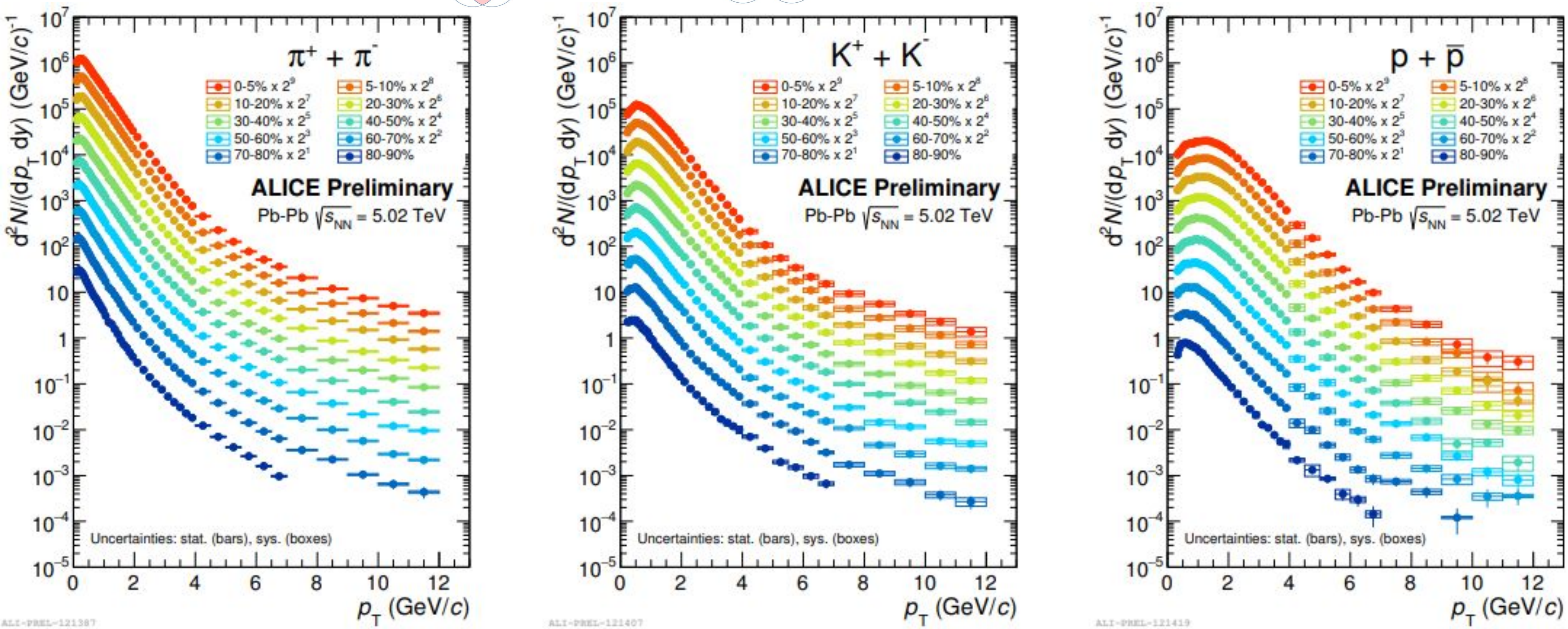
RHIC data showed the same behaviour (CuCu vs. AuAu)

- Xe–Xe result in agreement with the previous AA power-law trend

- a stronger rise with $\sqrt{s_{NN}}$ in AA than for pp and pA collisions

Particle production in Pb-Pb @ 5.02 TeV

Evolution from central to peripheral events

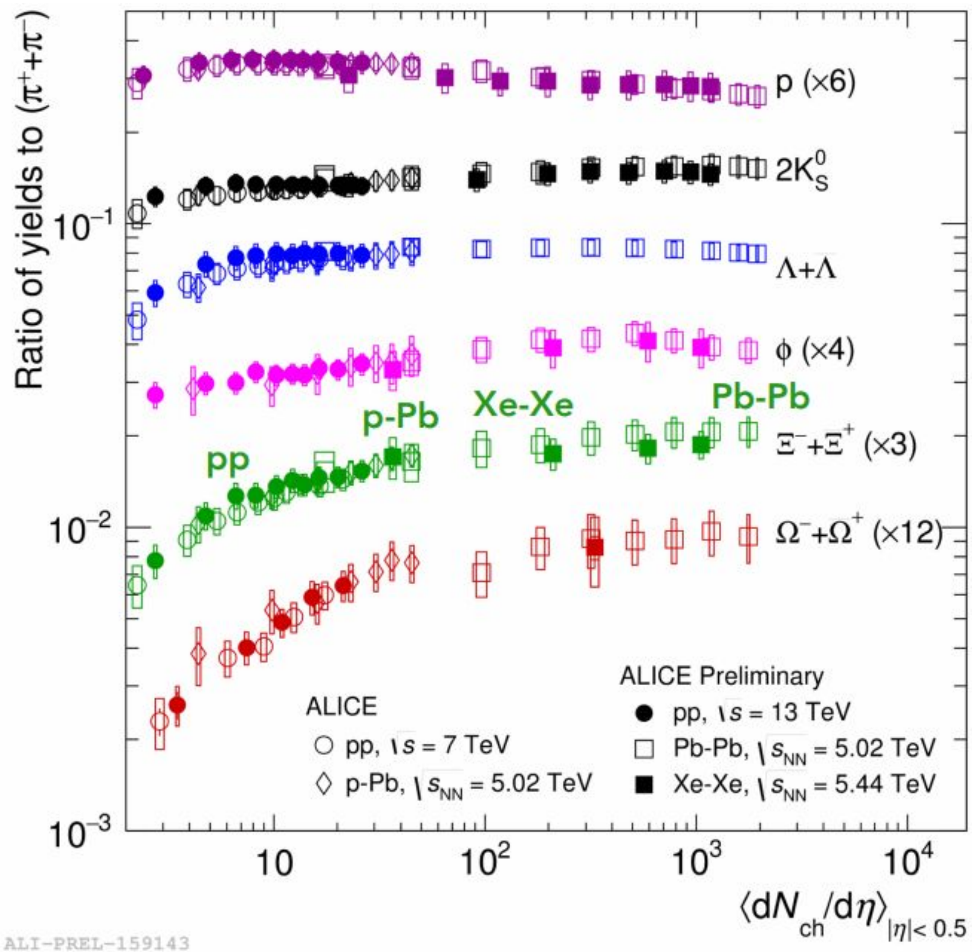


low	intermediate	high

90% of the particles are produced in low p_T and intermediate p_T regions
Exponential/Boltzmann behaviour at low p_T and power law shape at high p_T
Proton p_T spectra shape change from central → peripheral ⇒ radial flow

Strangeness production

Nature Physics 13 (2017) 535-539 + new analysis



New results from LHC-Run2

- pp 13 TeV
- Xe-Xe 5.44 TeV
- Pb-Pb 5.02 TeV

→ ***smooth increasing trend vs. multiplicity***

At similar multiplicity, no dependence on system nor energy

Pb-Pb ratios → good agreement with the statistical hadronization model, for a grand-canonical ensemble T_{ch} ~ 150-160 MeV

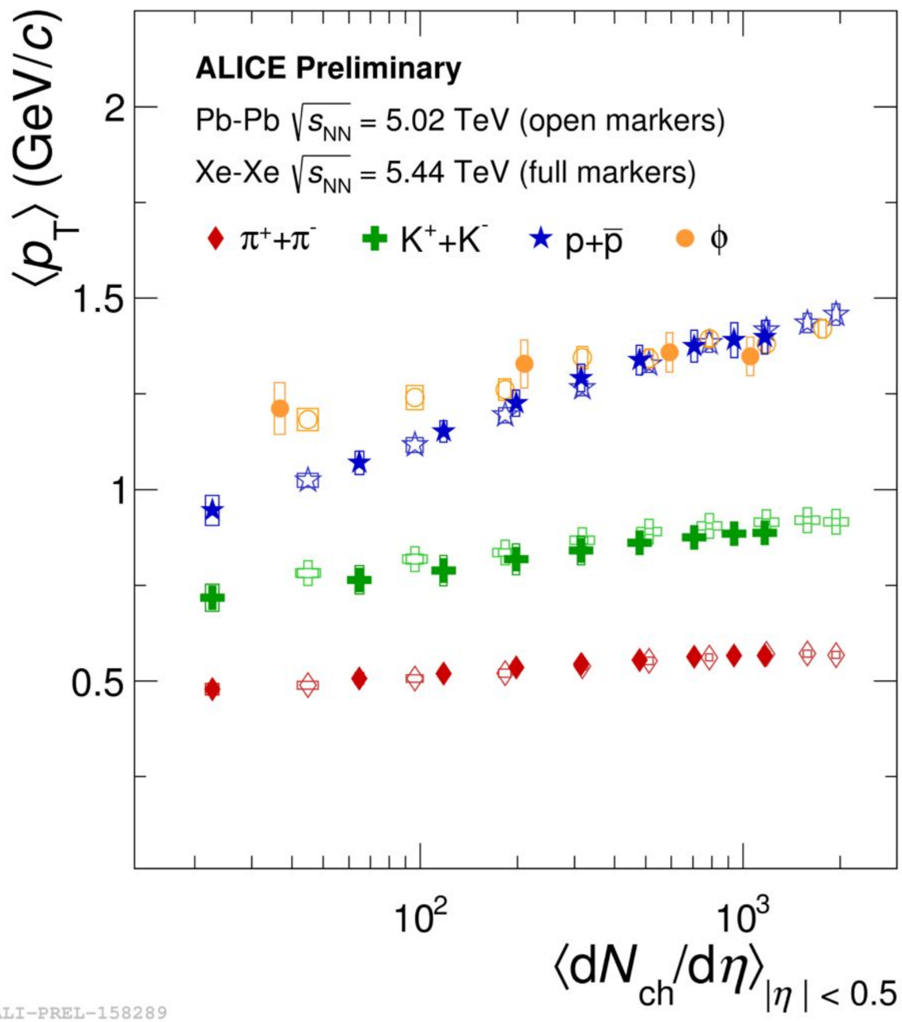
$\langle p_T \rangle$ for identified particles

→ the mass dependence of <p_T> reflects collective expansion in the radial direction

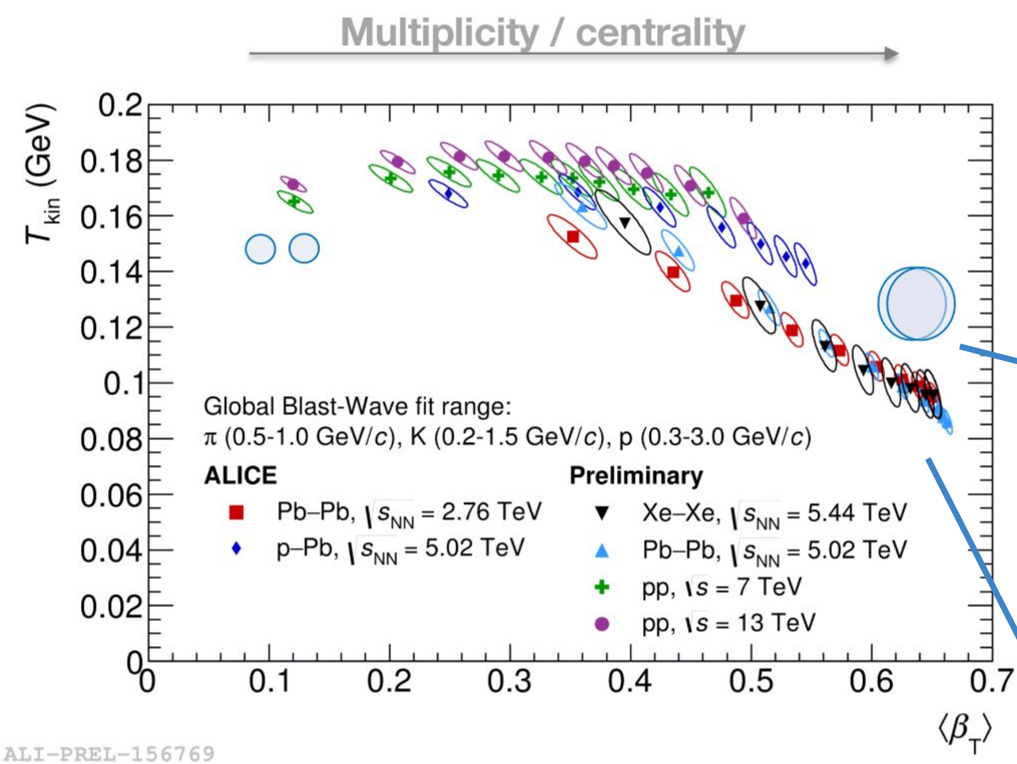
→ the differences in central values of <p_T> between protons and pions/kaons are smaller at lower multiplicities

→ smaller average collective velocity in the radial direction in peripheral collisions.

→ Φ meson behaviour is the same as the proton (similar mass) for higher multiplicities



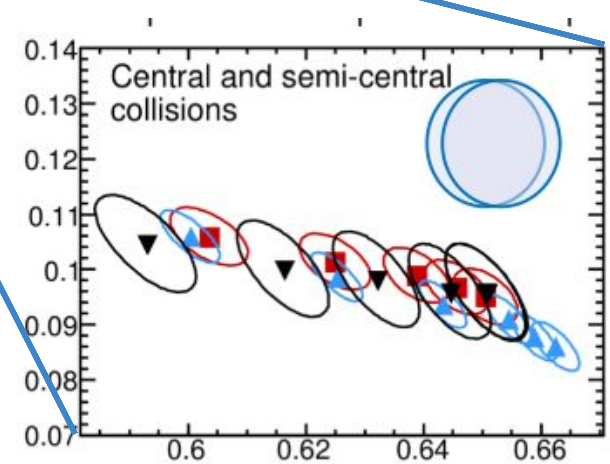
Blast-Wave fits to particle spectra



Simultaneous fit to the pi, K, p spectra:

$$\frac{dN}{p_\perp dp_\perp} \propto \int_0^R r dr\, m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{\rm kin}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{\rm kin}}\right)$$

T_{kin} – kinetic freeze-out temperature
β – transverse radial flow velocity



- β_T increases with centrality in AA collisions
  - Central Pb-Pb 5.02 TeV → largest β_T
- T_{kin} is lower in central collisions

- in p-p and p-Pb, similar evolution of the BW fit parameters towards high multiplicity

Baryon-to-meson ratio

Low to intermediate p_T < 7 GeV/c

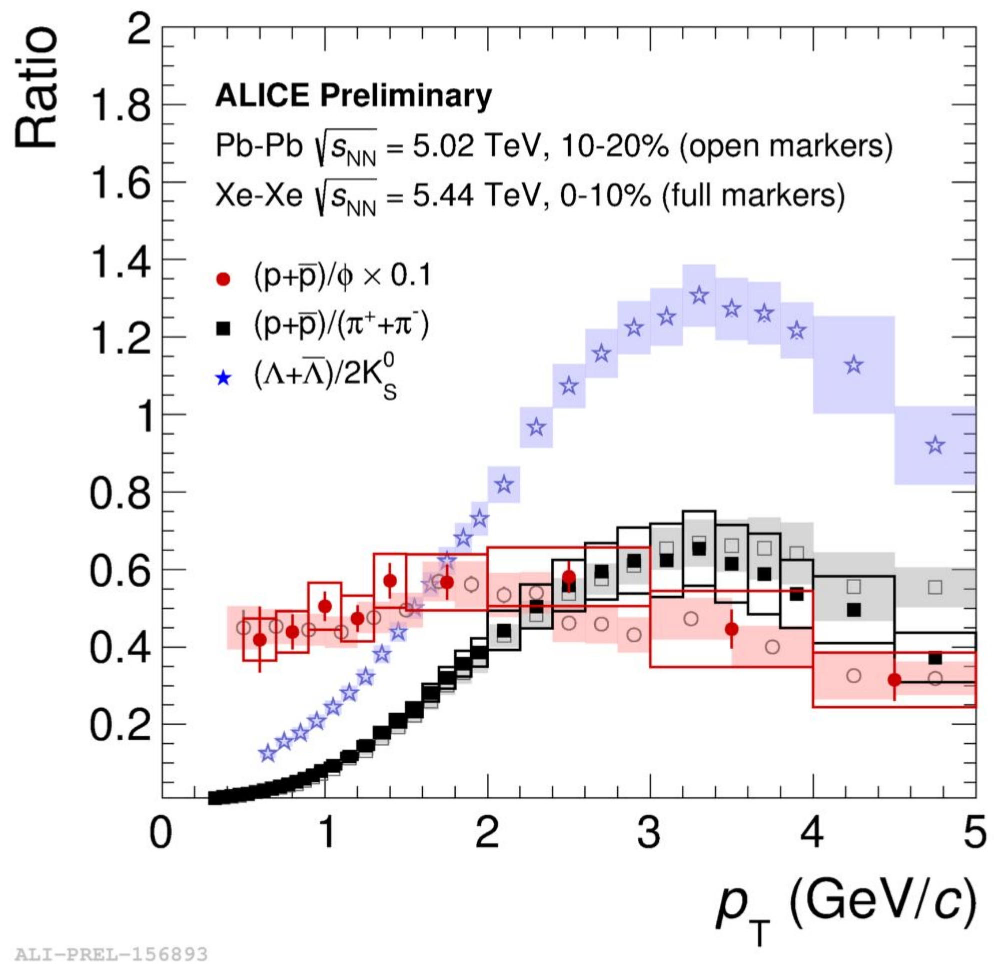
Baryon-to-meson ratios are important tools to study

- hydrodynamic behavior
- recombination/coalescence

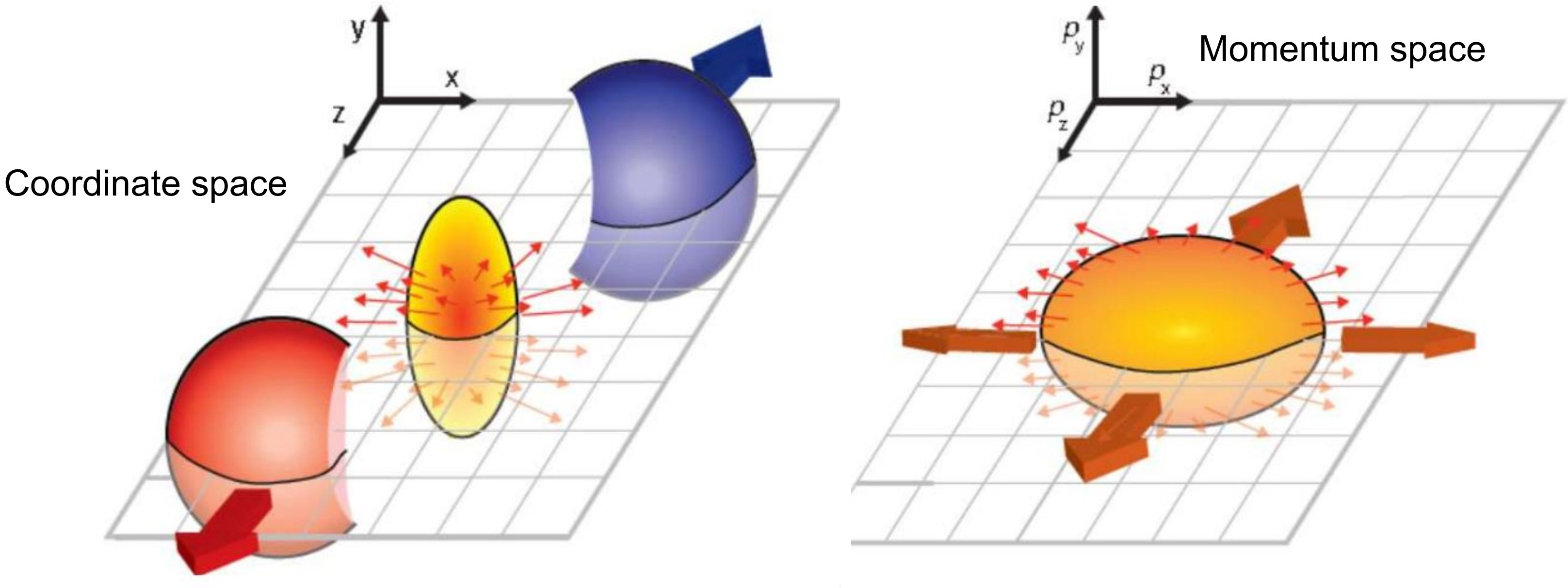
Different behaviour between p/Φ and p/π, Λ/K^0_S ratios

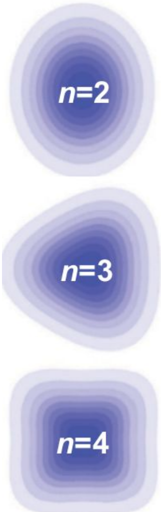
→ radial flow/expansion affects the particle ratios and p_T spectra ⇒ similar spectra for p/Φ
→ recombination role?

High p_T → constant ratios (due to jet fragmentation)



Anisotropic flow





Non-central collisions: overlap region is not symmetric in coordinate space

- spatial anisotropy → pressure gradients lead to momentum anisotropy

$$v_n = < \cos n(\varphi - \Psi_{\mathrm{RP}}) >$$

Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP}) — coefficients v_2 , v_3 , v_4, ... v_n

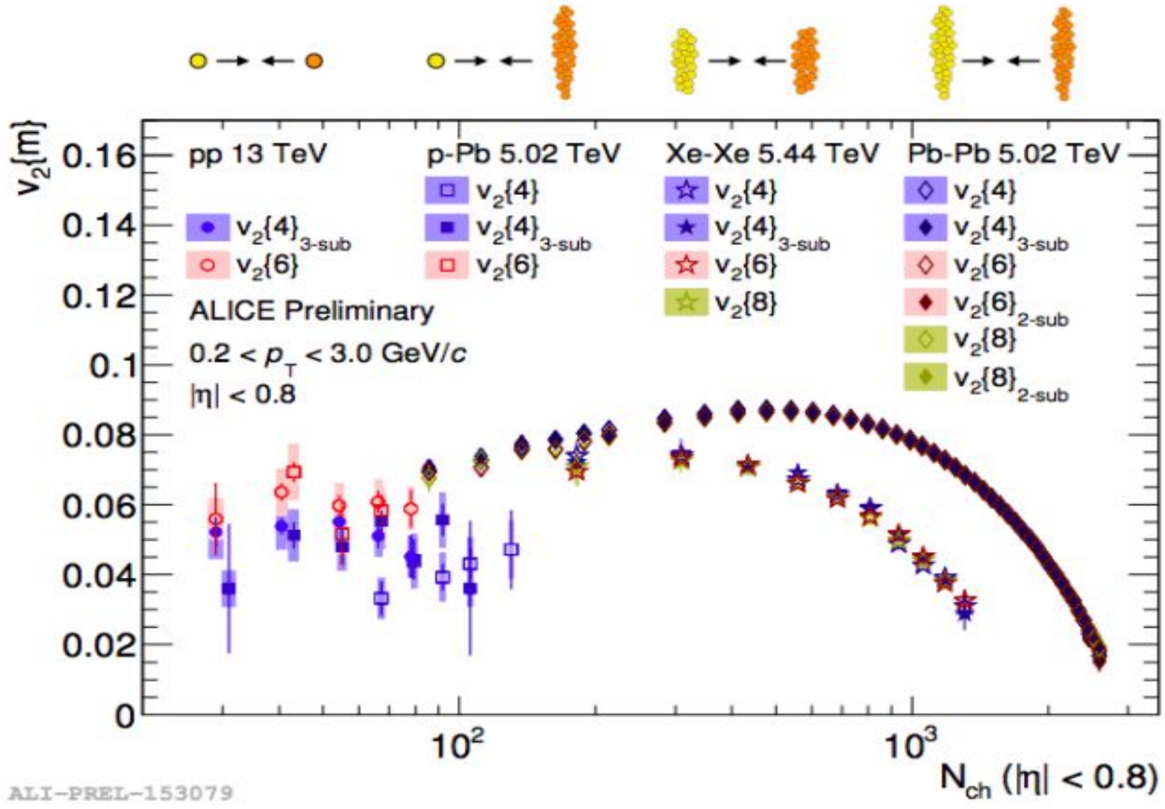
v_n quantify the event anisotropy

- v_2 elliptic flow, v_3 triangular flow, ...

Anisotropic flow is sensitive to the system evolution

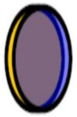
- Constraints initial conditions, EOS, transport properties (e.g. shear viscosity over entropy density ratio (η/s) and bulk viscosity over entropy density ratio (ζ/s)), particle production mechanisms, freeze-out conditions

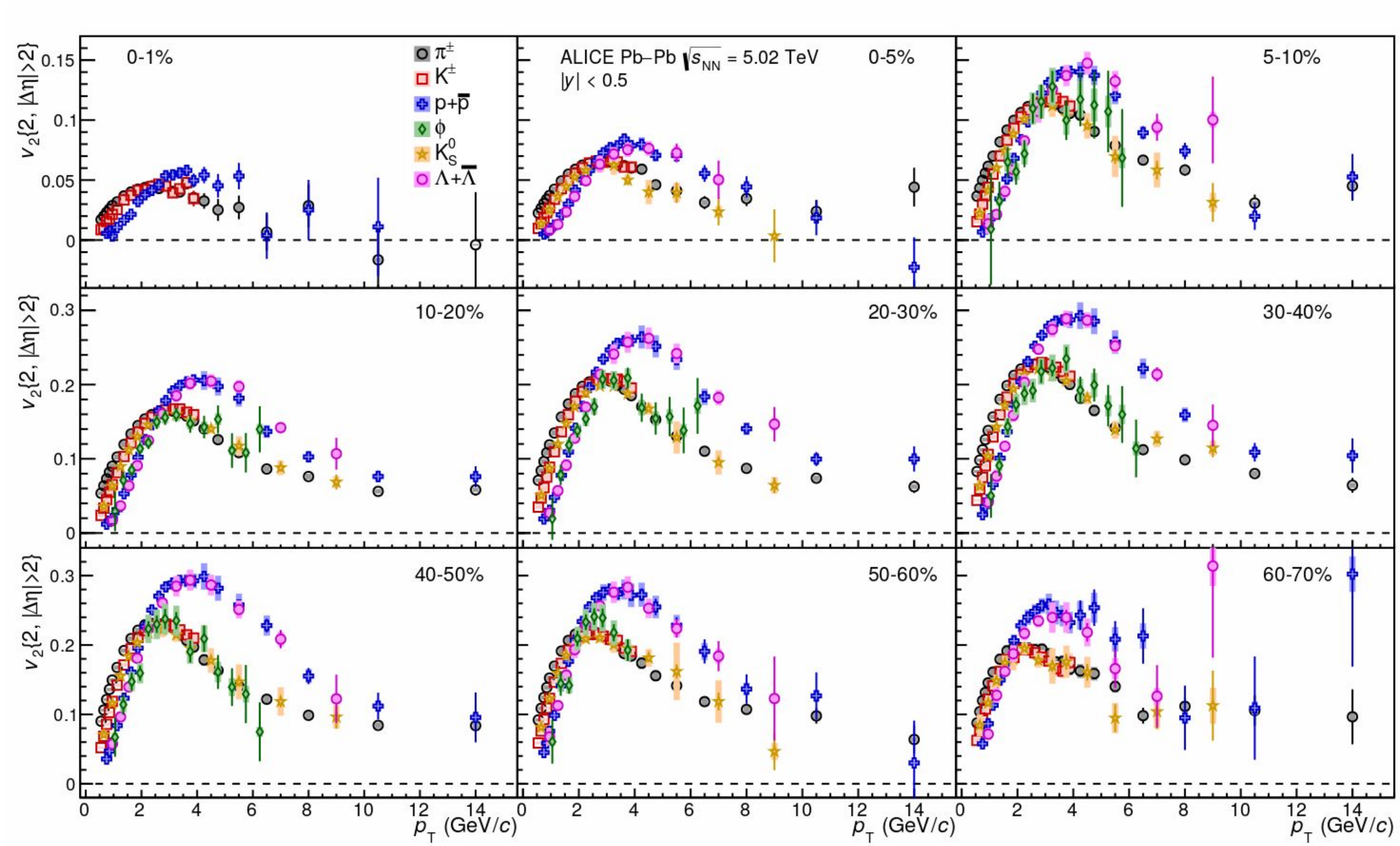
Elliptic flow across the systems

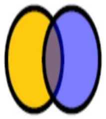


- Pronounced v_2 in peripheral Pb-Pb and at similar multiplicities in p-Pb/p-p
- v_2 extends to small systems → it's enough to have few scatterings in order to build flow

PID v_n in Pb-Pb







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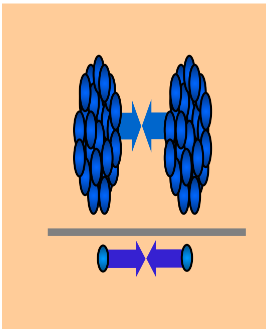
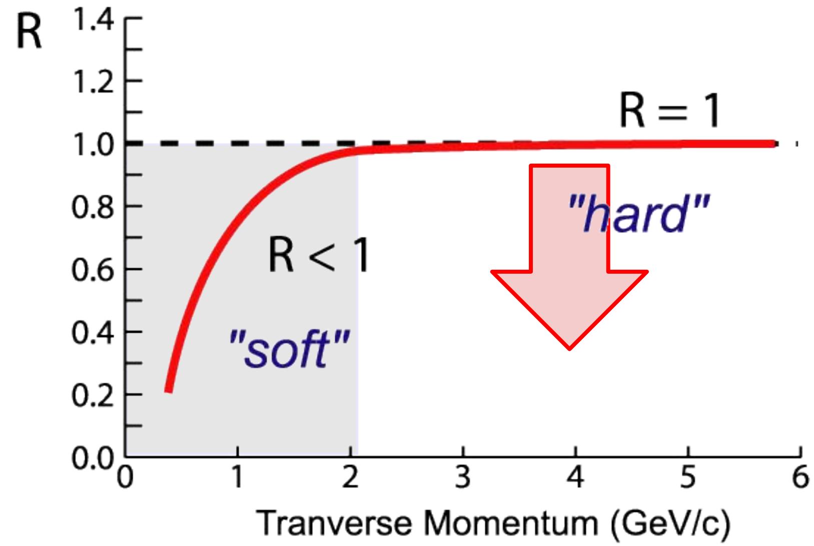
Flow of identified hadrons in Pb-Pb at 5.02 TeV

- for p_T<2-3 GeV/c, v_2 of the different particle species is mass-ordered → indicative of strong radial flow
- for 3<p_T<8-10 GeV/c, particles are grouped according to their number of constituent quarks→ quark coalescence
- the Φ meson v_2 follows proton v_2 at low p_T (similar masses), but π v_2 at intermediate p_T in all centrality classes.

Nuclear modification factor - R_{AA}



$$R_{AA} = \frac{d^2N^{AA}/dp_T dy}{\langle N_{bin}\rangle d^2N^{NN}/dp_T dy}$$

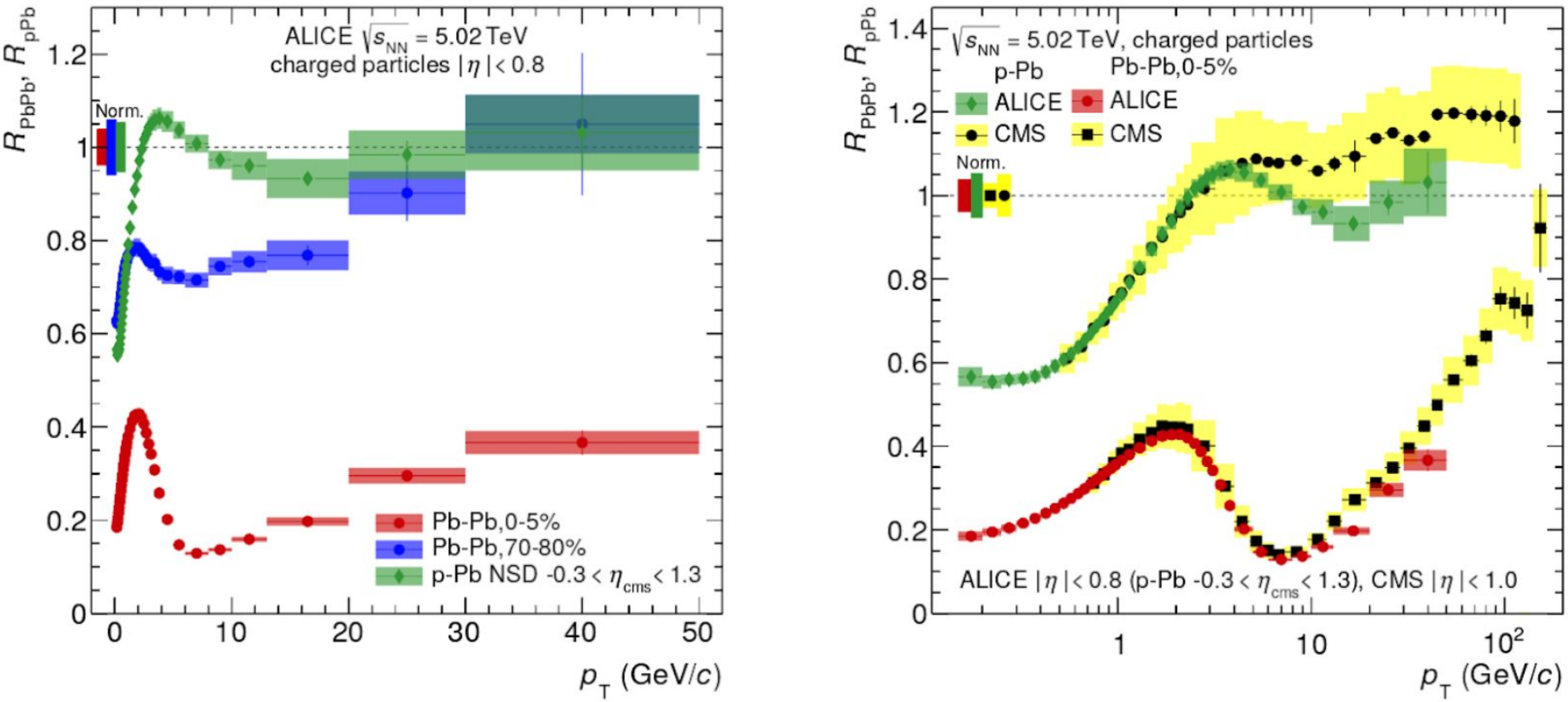


- R_{AA} is expected to be different from 1 in case of nuclear effects that can modify the p_T spectrum → initial and final states effects
- final-state effects such as in-medium energy loss (via collisional and radiative processes), the collective expansion and the in-medium hadronization via coalescence,
- initial state effects (CNM - cold nuclear matter effects) like nuclear modification of PDFs / CGC, kT-broadening (Cronin effect)

$R_{AA} < 1$ at high p_T - the nuclear effects suppress the particle production.

$R_{AA} \sim 1$ at high p_T (binary scaling) – no nuclear effects.

Charged hadrons R_{AA}



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Compared with N_{coll} scaled p-p collisions,

- Large suppression of high p_T particles in most central A-A collisions
  - Described by models including parton energy loss in the QGP medium

- No suppression in peripheral A-A and MB p-A collisions

Centrality dependence

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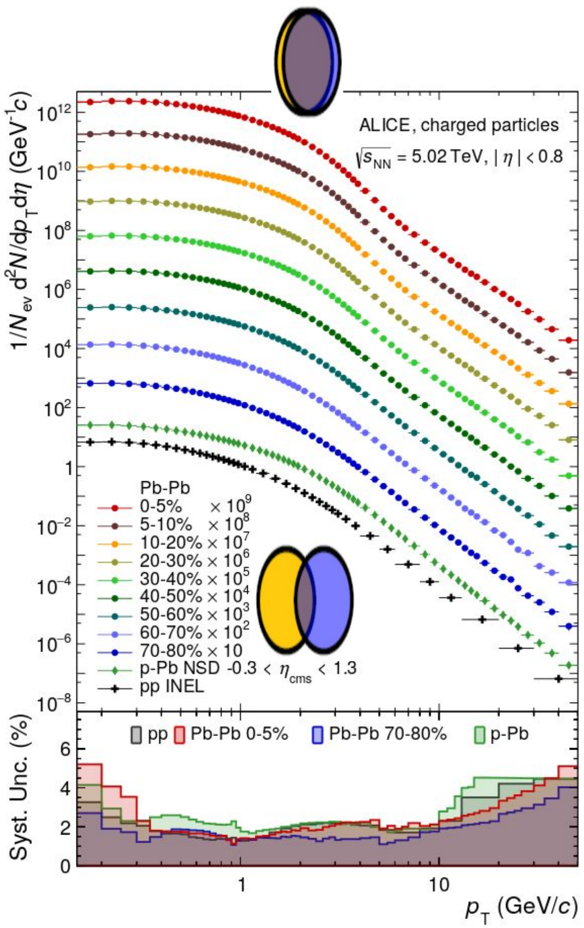
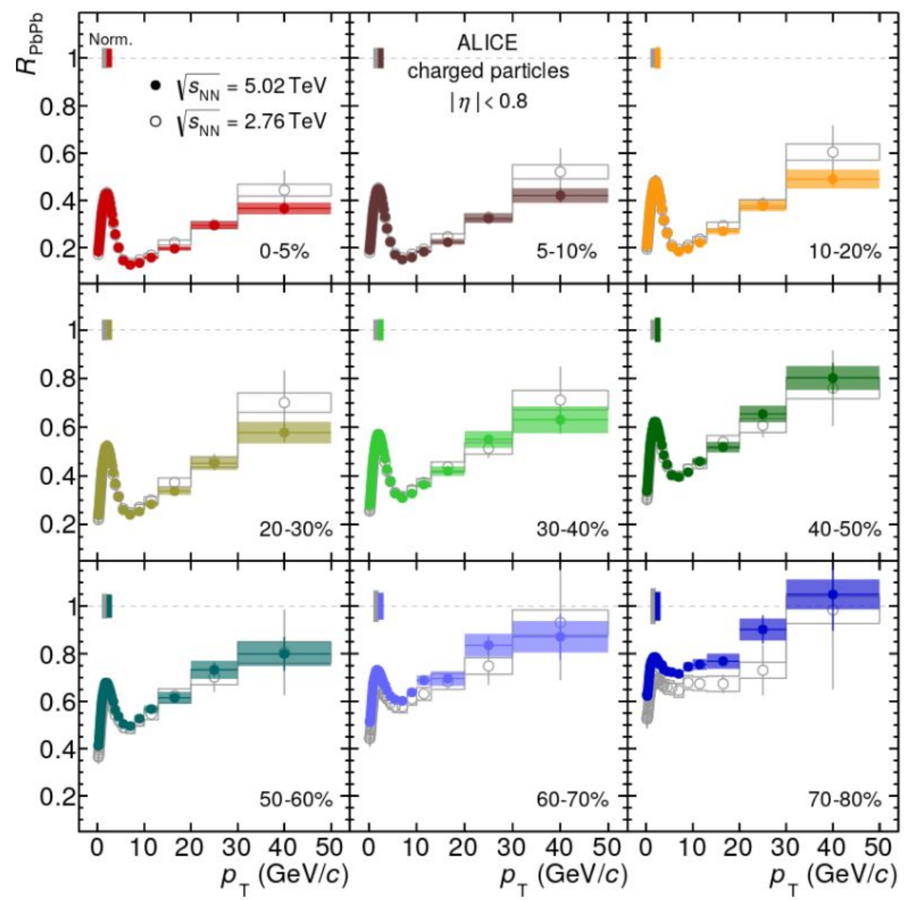
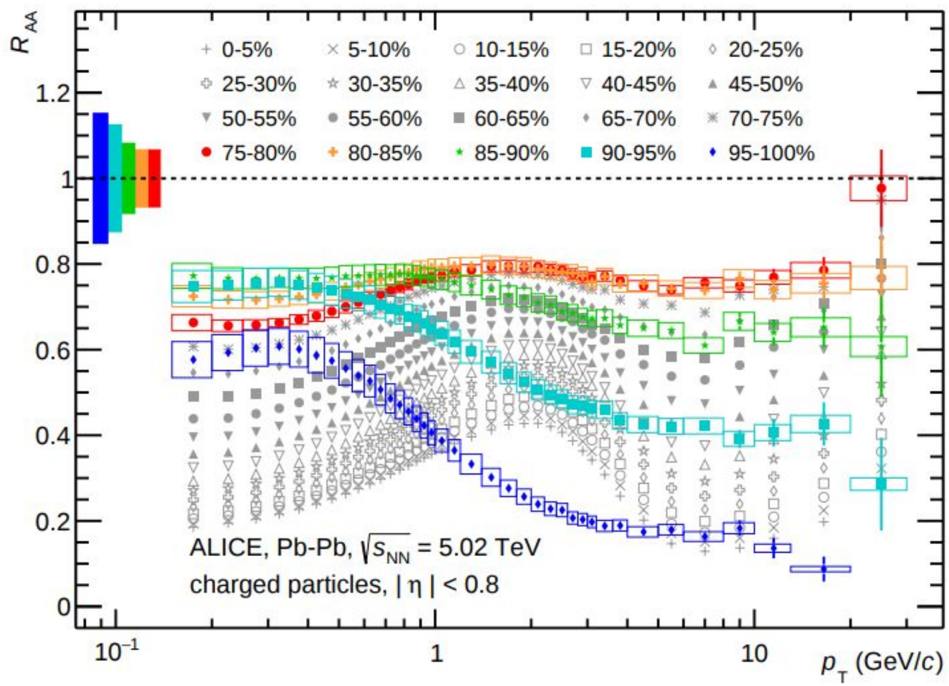


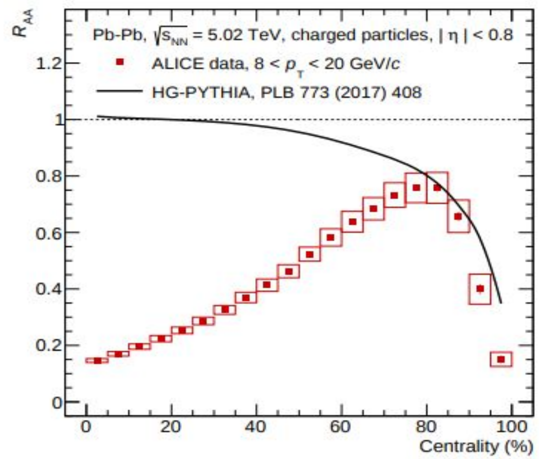


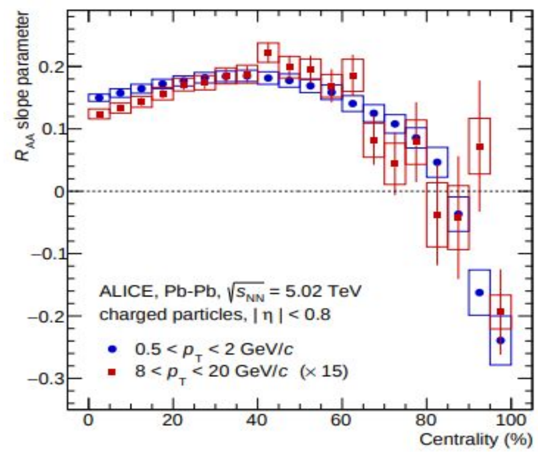
- Multiple hard scatterings → power-law shape spectra for all centralities
- From central to peripheral A-A collisions → less suppression
- Increased suppression with increasing centrality → larger and hotter medium produced in central collisions as compared to peripheral

Most Peripheral AA Collisions

First ever measurements to such peripheral centrality







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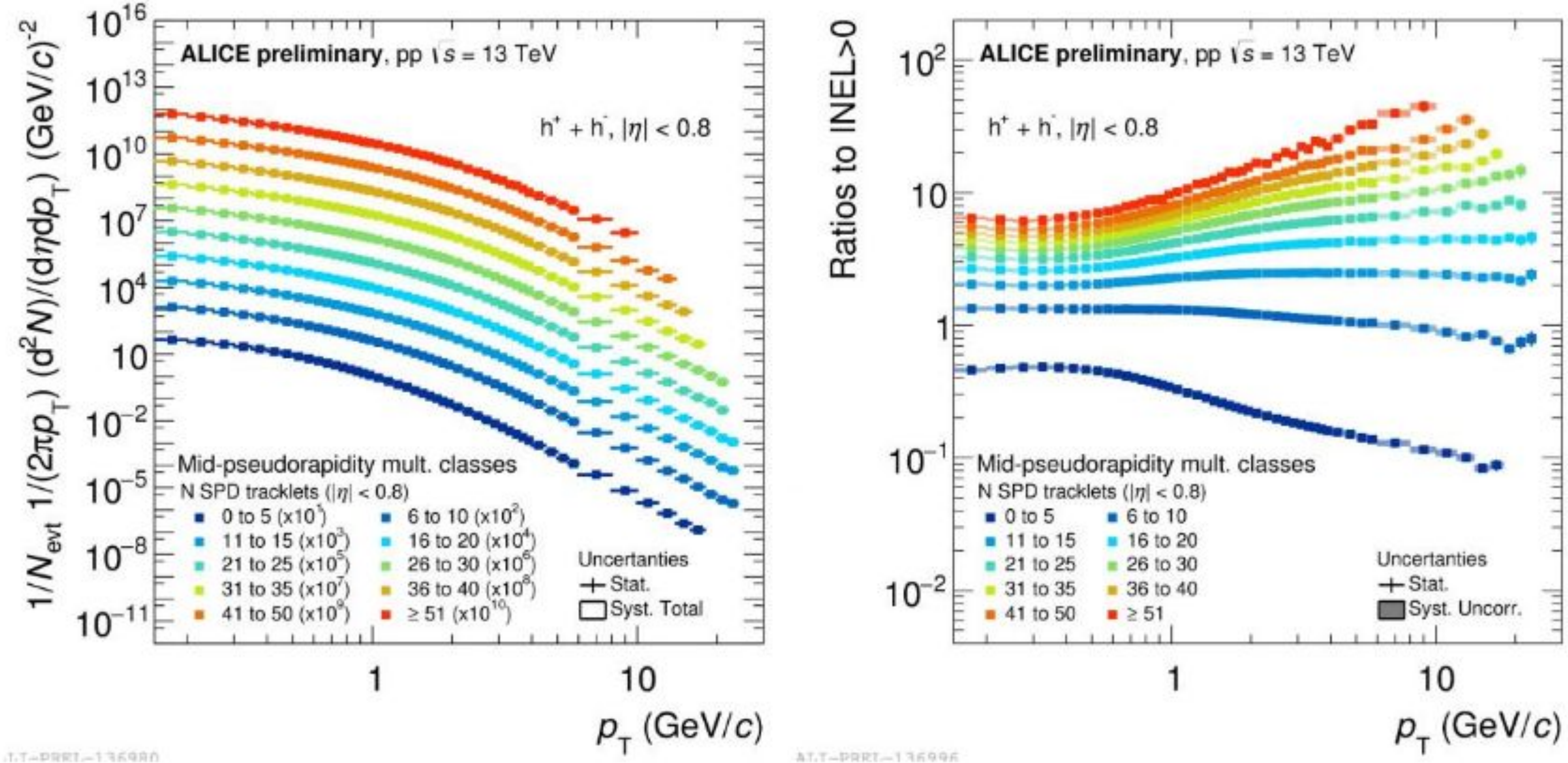
R_{AA} in Pb-Pb decreasing with centrality < 80% ⇒ agreement with HG-PYTHIA (no energy loss)

- HG-PYTHIA (HIJING Glauber PYTHIA) based on the HIJING Glauber model for the initial state and PYTHIA

Progressive reduction of medium induced parton energy loss

Small Systems



- Significant change of underlying p-p reference spectra with multiplicity
- p_T dependent
- the multiplicity of the most peripheral class (95-100% centrality) is lower than pp (because the nucleon-nucleon collisions that occur in a very peripheral Pb-Pb collision are not MB collisions) and therefore the R_{AA} could be influenced by the fact that MB pp is no longer a good reference

Xe-Xe R_{AA}

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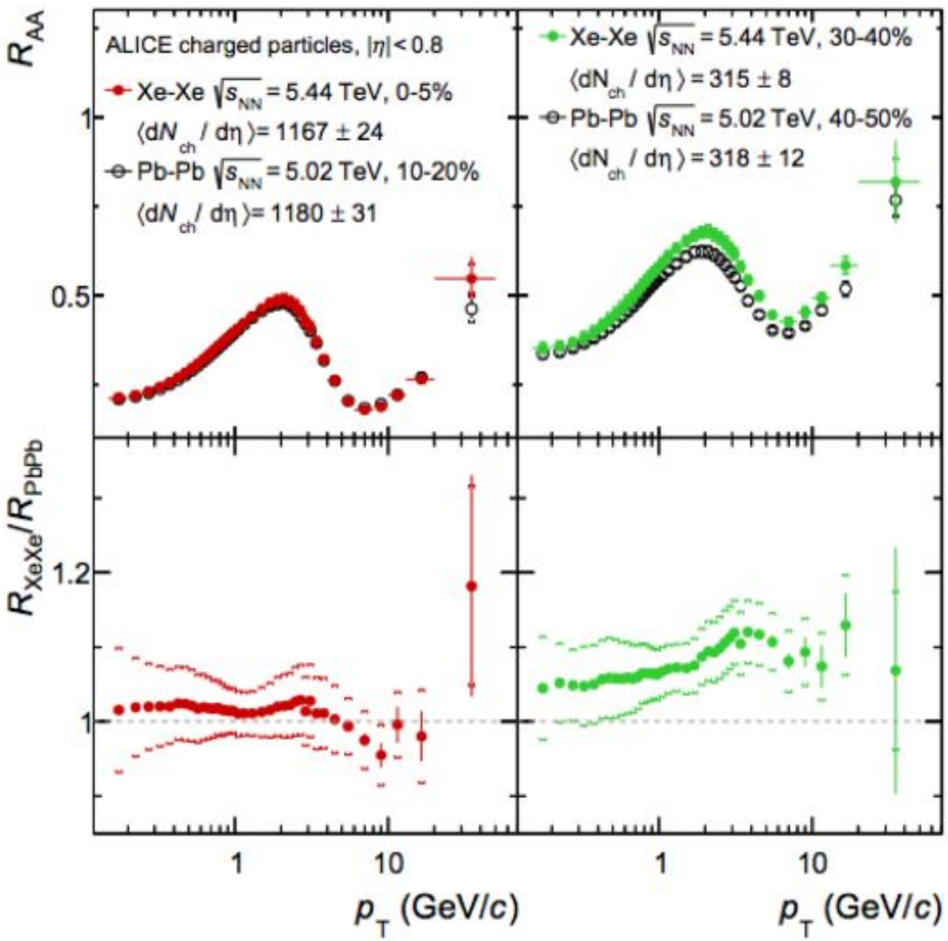
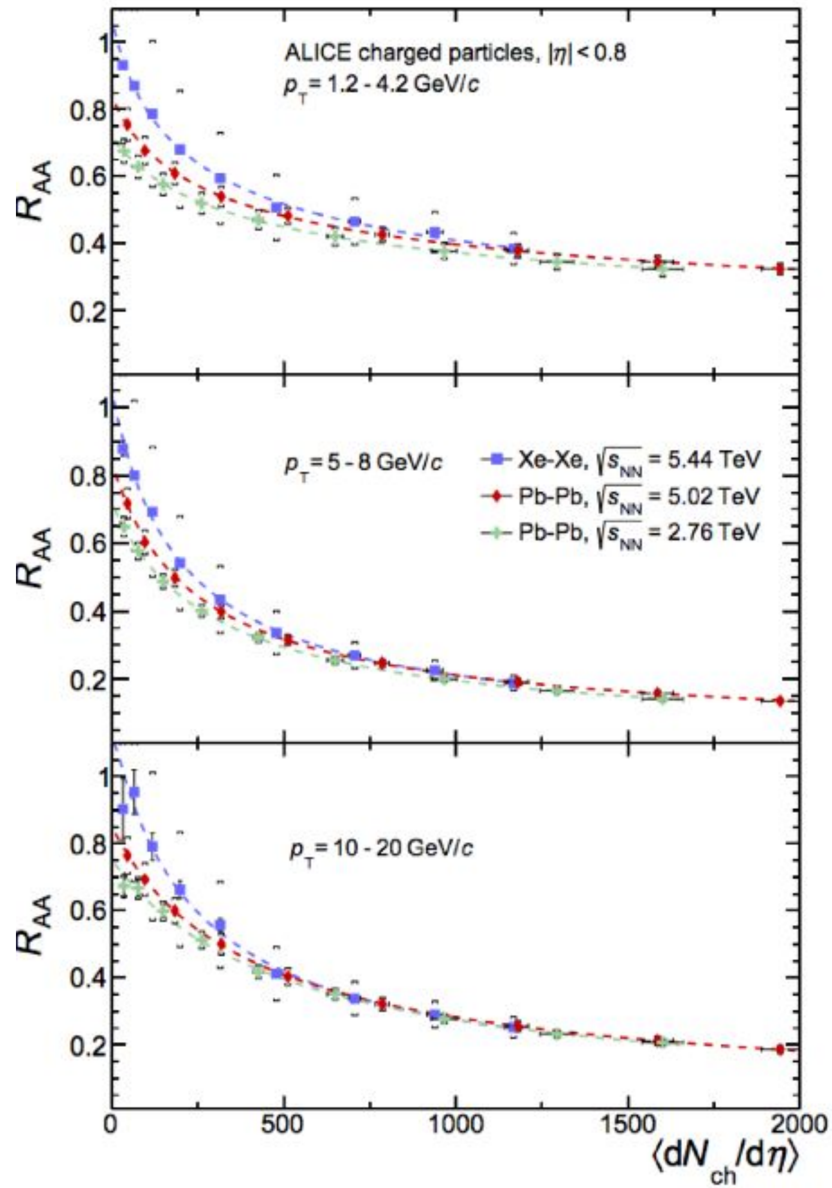
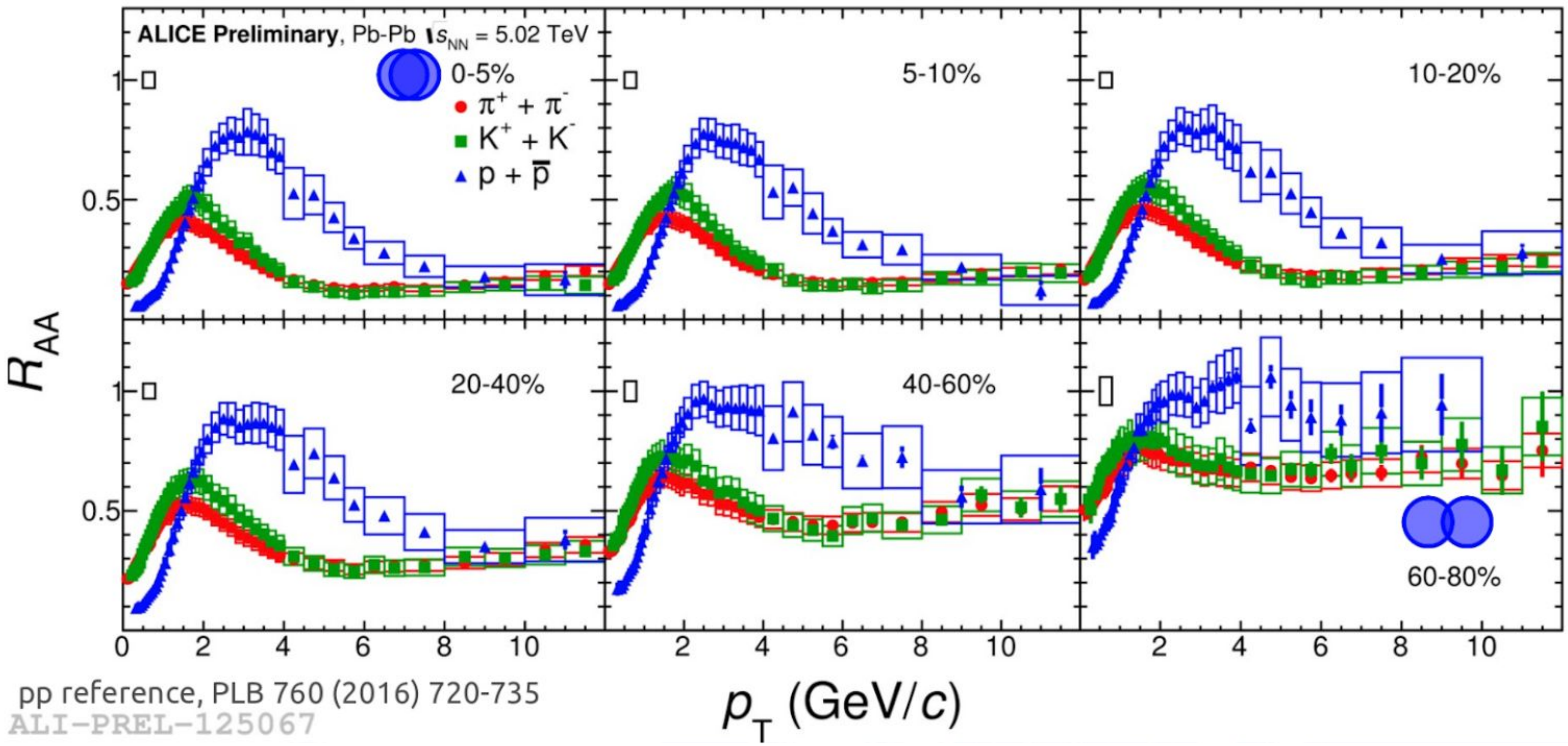




- Similar suppression pattern in both Pb-Pb and Xe-Xe at the same multiplicity ~ similar medium density
- New input to constrain path length dependence of energy loss

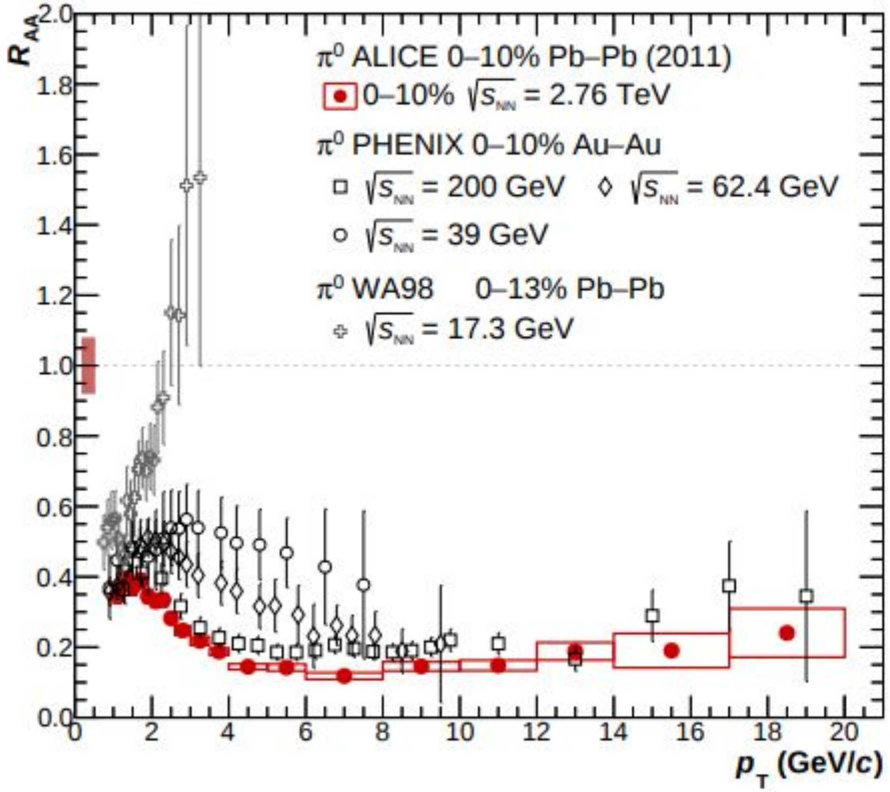
Centrality dependence of Identified R_{AA}



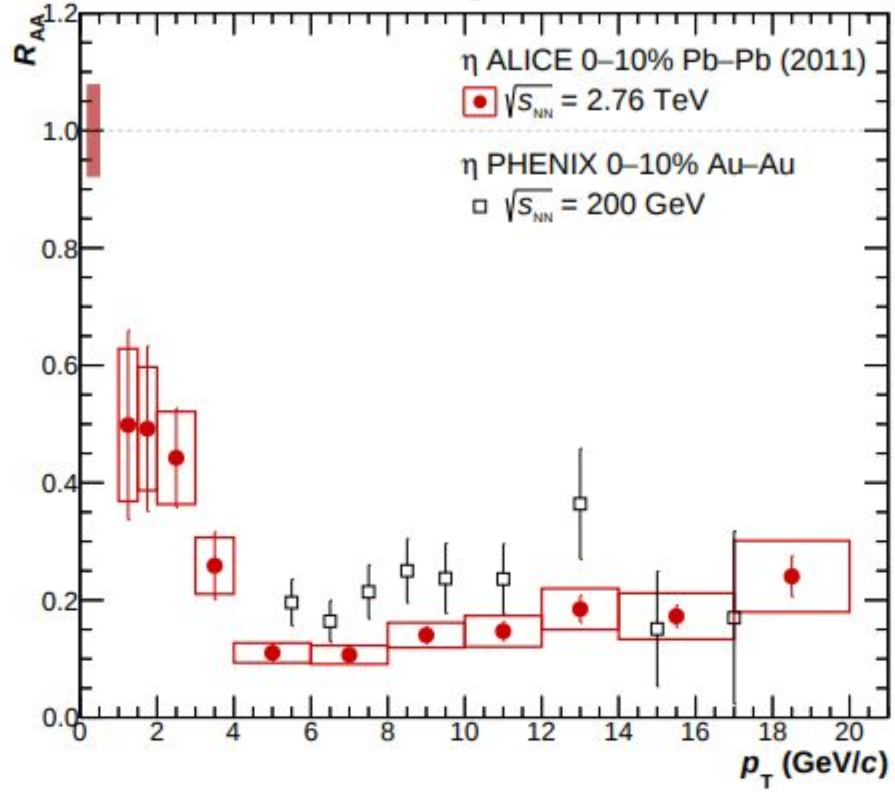
- Different R_{AA} at intermediate p_T due to radial flow (mass dependent push to higher p_T) in addition to recombination
- In Pb-Pb collisions all three species are equally suppressed for all centralities at p_T > 8 GeV/c
- (Light)flavor independent energy loss at high p_T as observed at 2.76 TeV

Energy Dependence of R_{AA}

π^0



η



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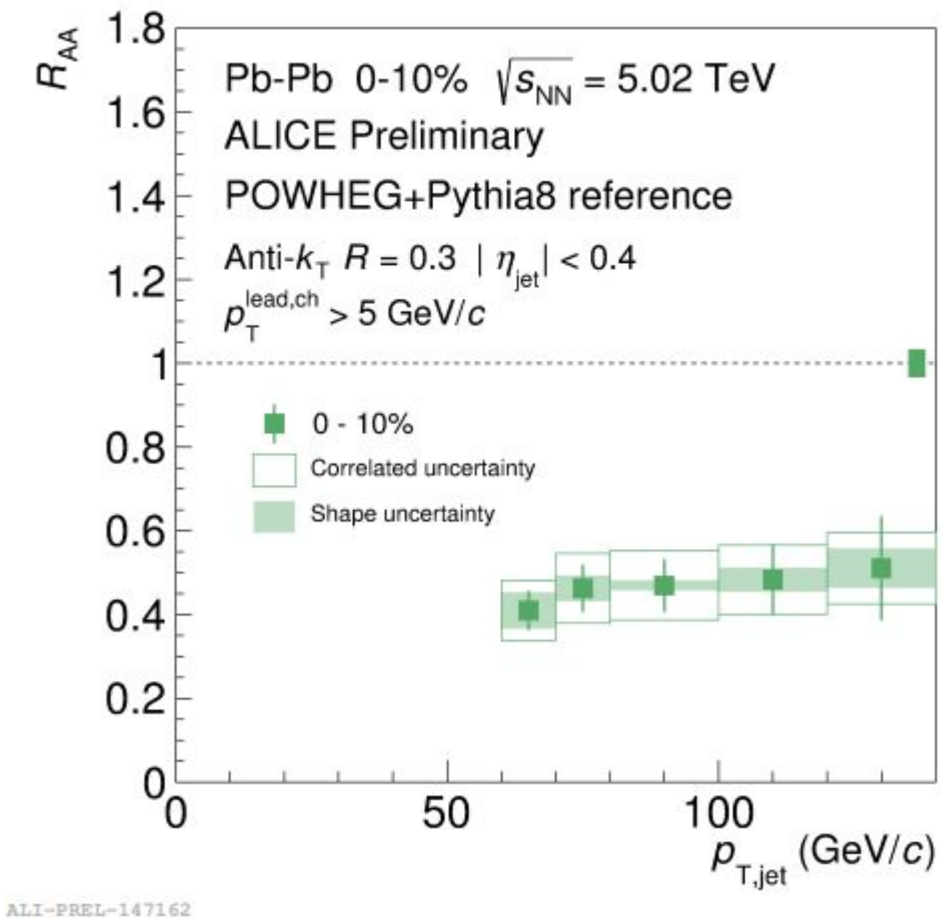
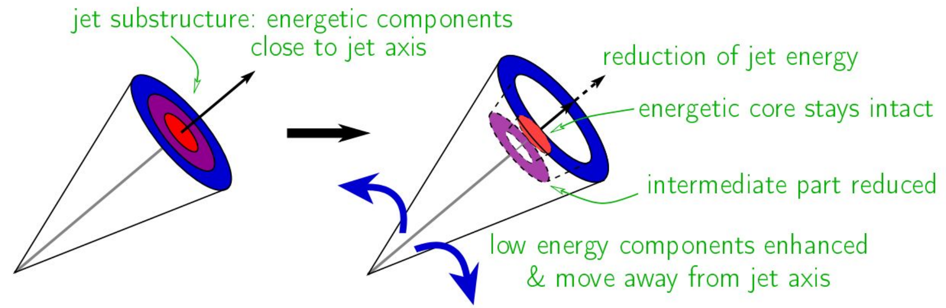
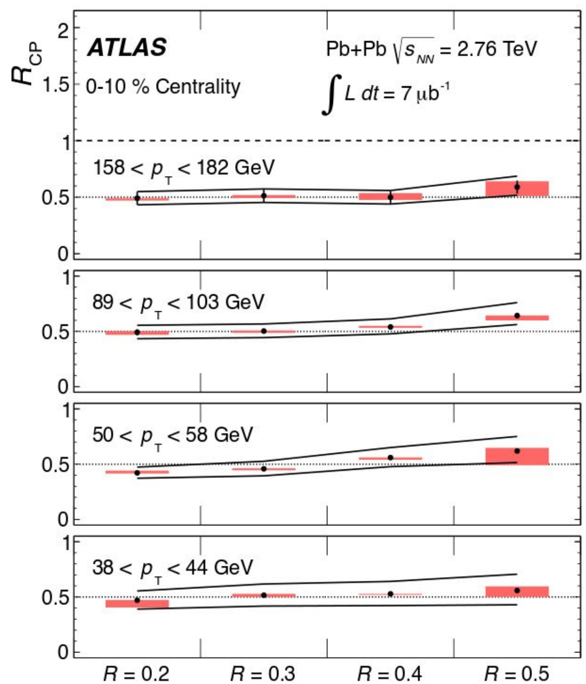
- First measurement of R_{AA} for η meson @ LHC
- High p_T particle suppression gradually sets in with increasing energy

Jets R_{AA}

K. Zapp, QM'18







Phys. Lett. B 719 (2013) 220-241

No p_T dependence

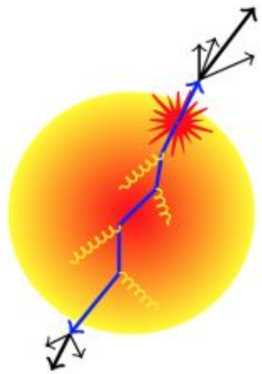
In jets multiple partons lose energy
→ more partons in high energy jets
→ more E_{loss}

Jet core not affected
Corona effect softens p_T of jet constituents,
Slight increase of Raa(R) → more soft contributions to jets

Heavy flavor in heavy ion collisions

Heavy quarks in Pb-Pb collisions at LHC

- Produced early in collision time, through large Q^2, small formation time
  → experience the system full evolution



Open heavy flavors

- c and b quarks lose energy in the medium
  via collisional and radiative energy loss (dead cone effect)
  → smaller energy loss for heavy than for light quarks

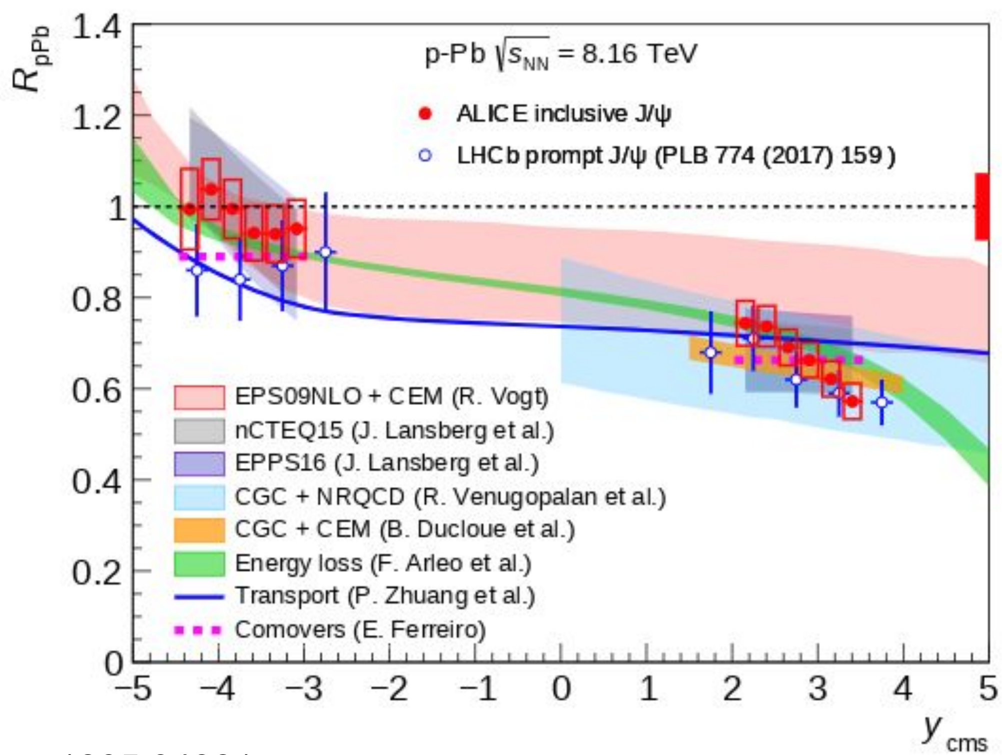
$$E_{loss}(g) > E_{loss}(u,d) > E_{loss}(c) > E_{loss}(b)$$
$$R_{AA}(g) < R_{AA}(c) < R_{AA}(b)$$

- Medium creates a competition between fragmentation (one quark producing a jet) and recombination (the c quark picks up a light quark from the medium)
- Low p_T c-quark thermalization → push from large collective flow, **transport models**

Quarkonia

- Presence of the medium modifies the yield of J/ψ, ψ', Υ
- Different binding energies and radii → melting (Debye screening) in the QGP at different temperatures → thermometer of QGP
- QGP, c (cbar) + cbar(c) → quarkonium → **recombination**

R_{AA} in p-Pb for J/ψ



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p-Pb allows for CNM and initial conditions testing

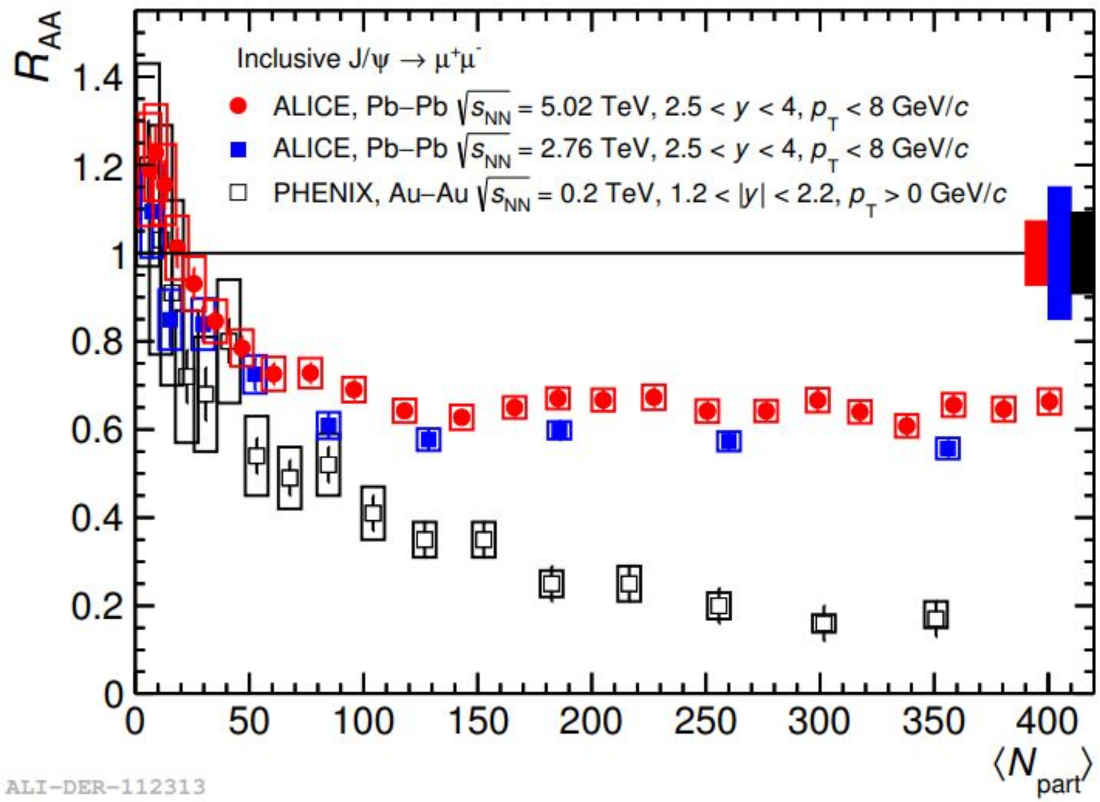
Contribution of hot-matter effects are thought to be negligible

- J/Psi suppression observed at positive rapidity
- For negative y, an increasing trend in RAA is present at low p_T and the data are compatible with unity

Initial conditions
in p-Pb forward/backward rapidity:

Various combinations of CNM effects (pure shadowing, nPDF, CGC) give rather good description for the data

J/ψ R_{AA} in Heavy Ion Collisions



RHIC → LHC
Evidence for increasing recombination for Pb-Pb

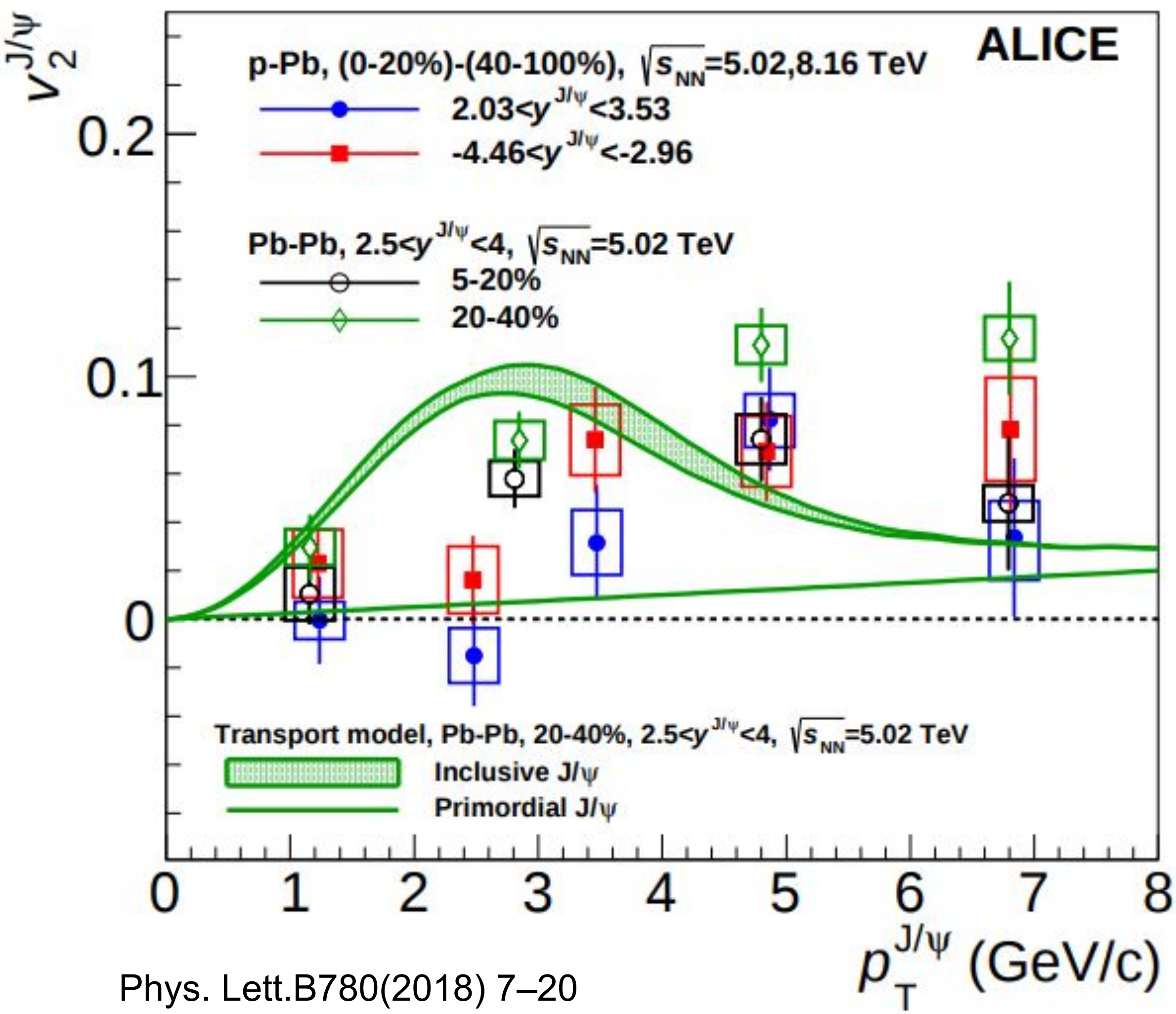
At RHIC top energy:

- J/Psi production is strongly suppressed
- RAA suppression increases with collision centrality

At LHC energies:

- smaller suppression for central collisions compared to PHENIX results
- weaker centrality dependence

J/ψ flow in p-Pb/Pb-Pb collisions



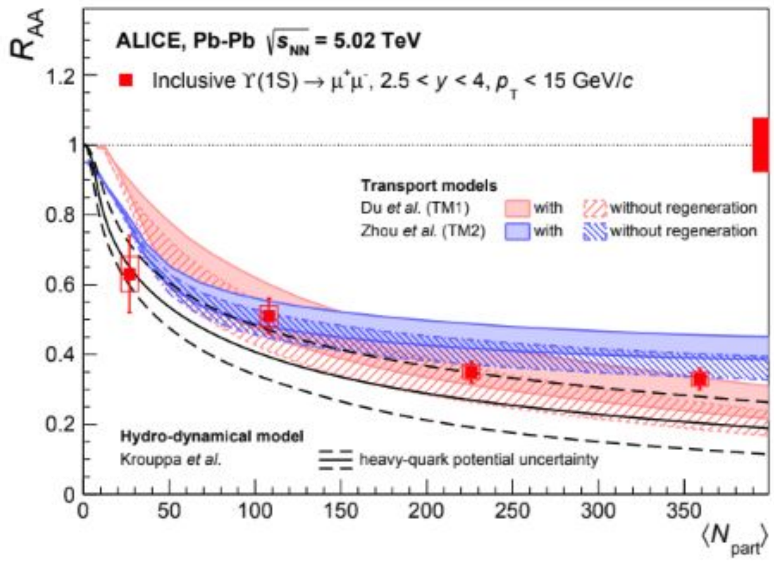
Phys. Lett.B780(2018) 7–20

Similar mechanism responsible for the behavior in both systems

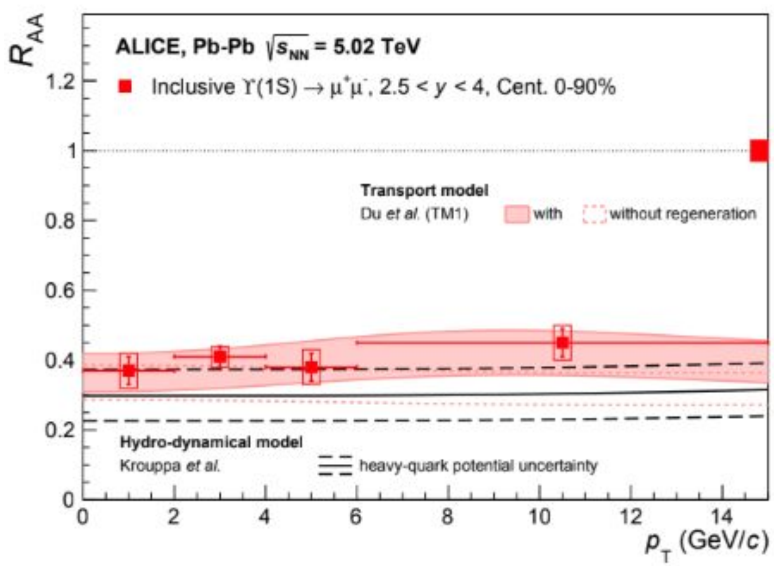
- Transport models
- Thermalization implications
- Collective effects in small systems
- Constraints the R_{AA}/v_2 for models

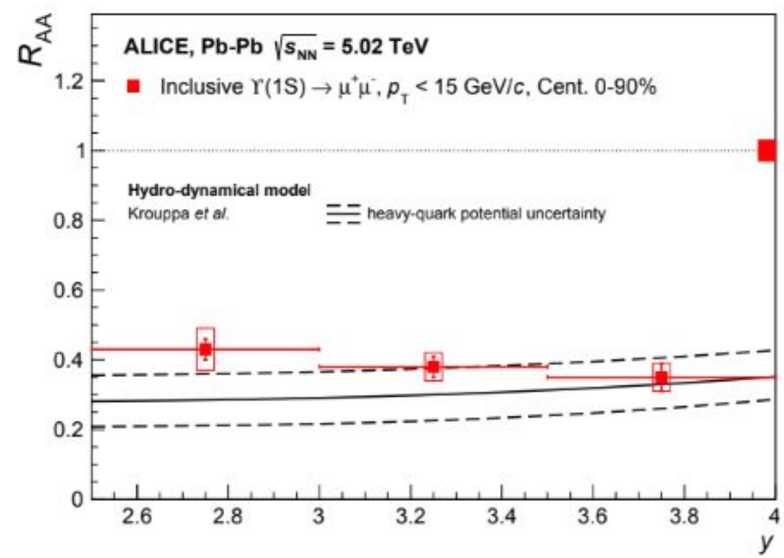
- R_{pPb} ~ 1 & v_2 in pPb > 0 = not a contradiction

R_{AA} Υ(1S) in Pb-Pb



- Extreme precision measurement
- Slight increased suppression with centrality
- Weak p_T/y dependence
- More suppressed than J/ψ
- Models w/ or w/o recombination are able to reproduce data → no clear sign of recombination
- CNM effects?





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Open Heavy Flavor - R_{AA} and v_2 in Pb-Pb

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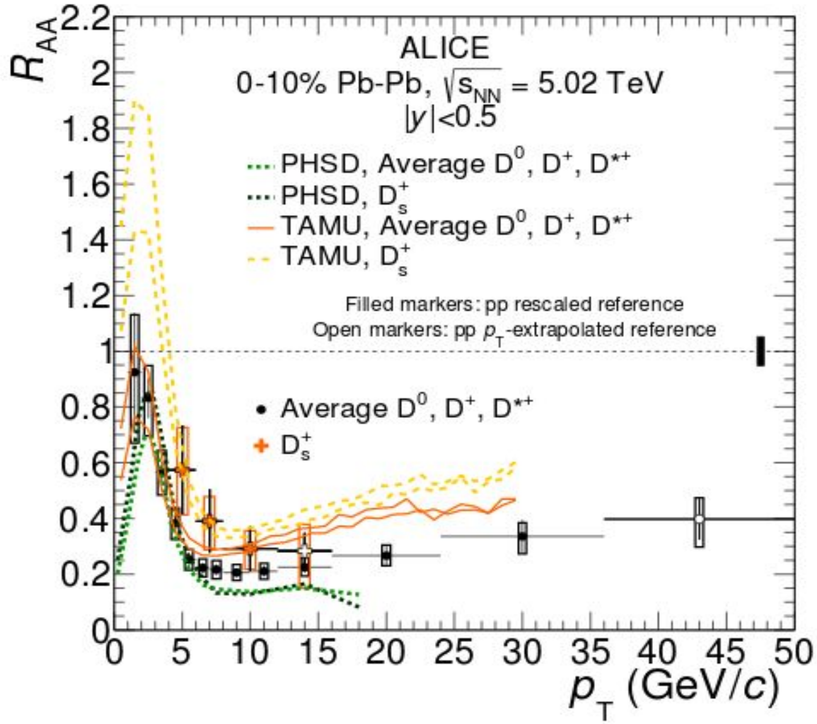
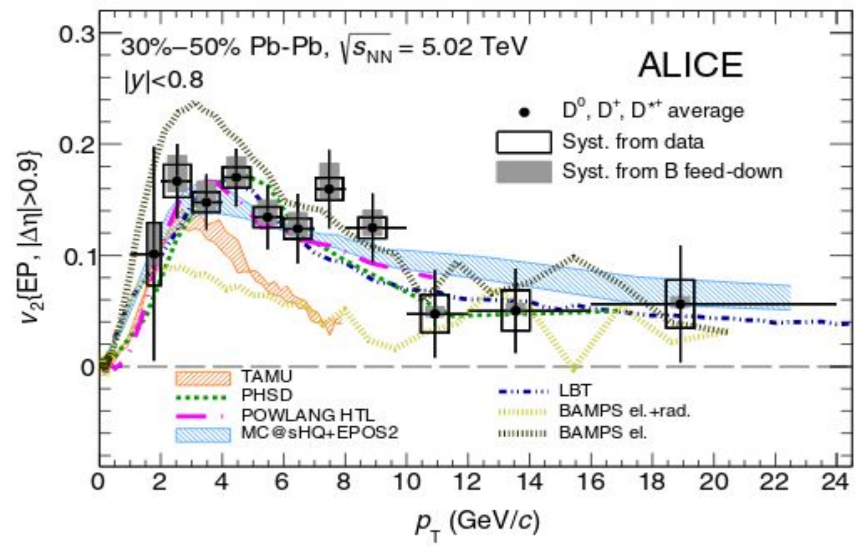
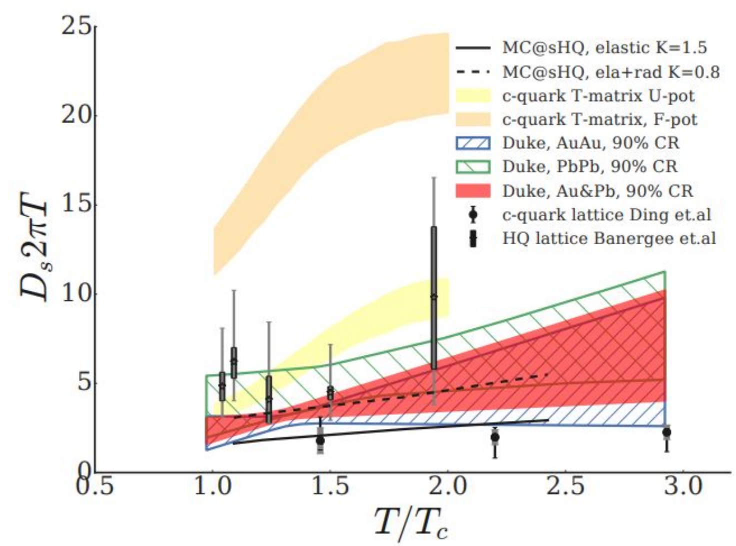
PhysRevLett.120.102301





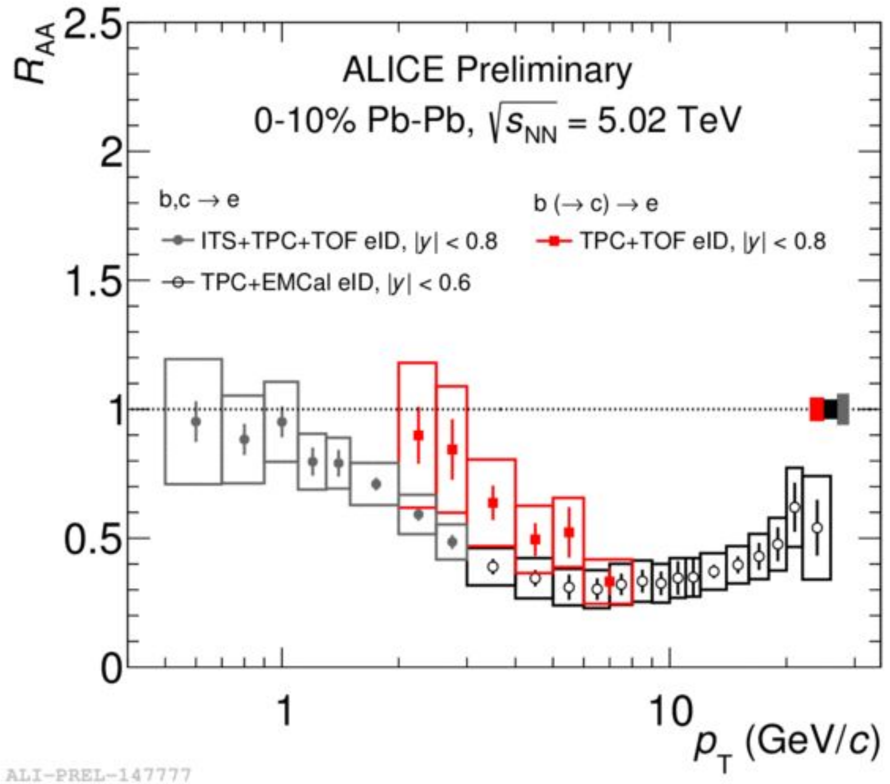


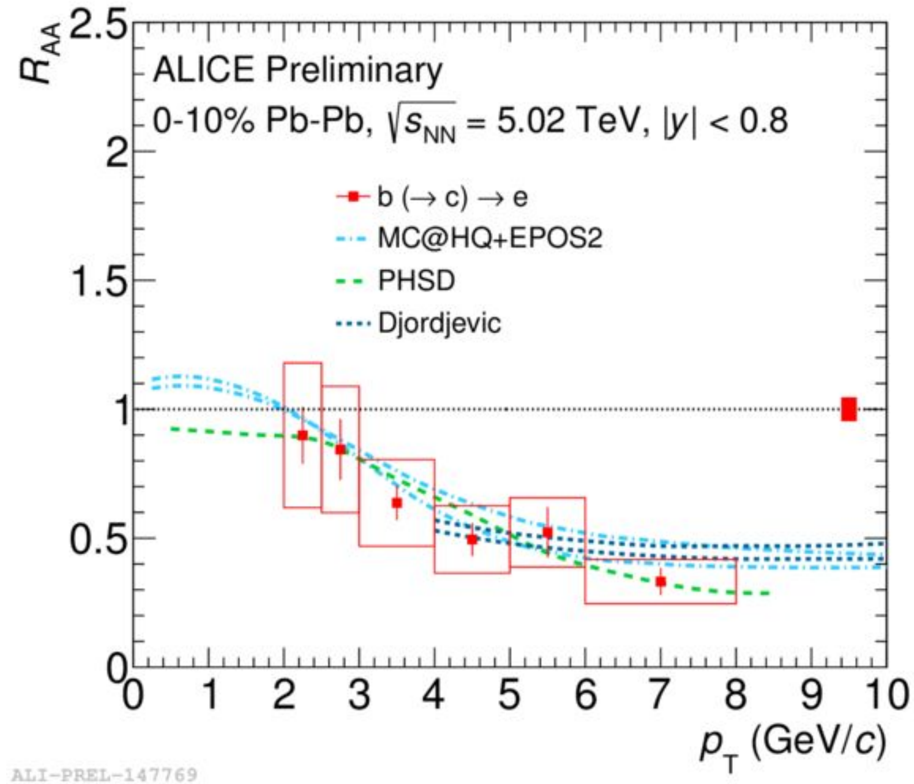
Y.Xu, M.Nahrgang, J.E.Bernhard, S.Cao, S.A.Bass, arXiv:1704.07800 (2017)

First measurements of D_s^+ @ LHC

- Different suppression of D_s with respect to D → due to the recombination of the c quark in the QGP where s quarks are abundant
- Mass ordering at intermediate p_T
- Slow/low p_T D^0 thermalized with QGP and largely affected by collective flow
- Measurement precision with potential to constrain transport models, current D_s (2πT) ~ **1.5 - 7**

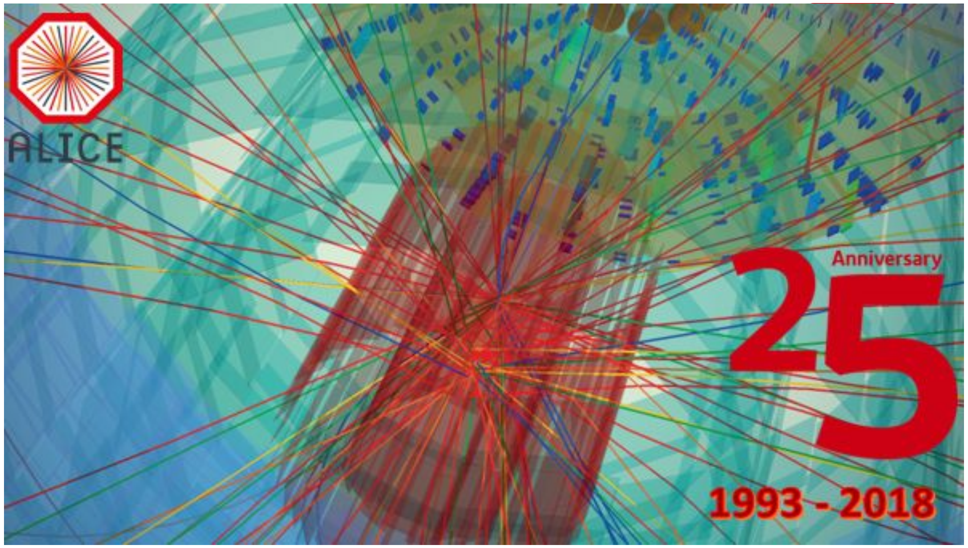
Beauty-decay electrons R_{AA}





- $E_{loss}(c) > E_{loss}(b) \Rightarrow R_{AA}(c) < R_{AA}(b)$
- Data described by models with E_{loss} dependence on quark mass
- $R_{pPb}(b \to c \to e) \sim 1$ - (ALICE, JHEP) ⇒ rules out CNM effects

Conclusions



ALICE provides plethora of precision measurements for many hadron types

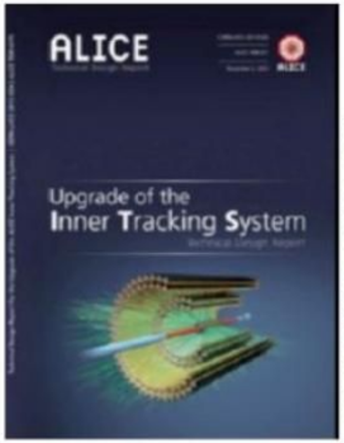
Allowing better understanding and validation of QCD description for LHC collisions

Universality of strangeness production across different systems

Collective behaviour across systems in high multiplicity p-p, p-Pb and A-A collisions

Large suppression of high p_T particles investigations to continue

UPGRADE for RUN3



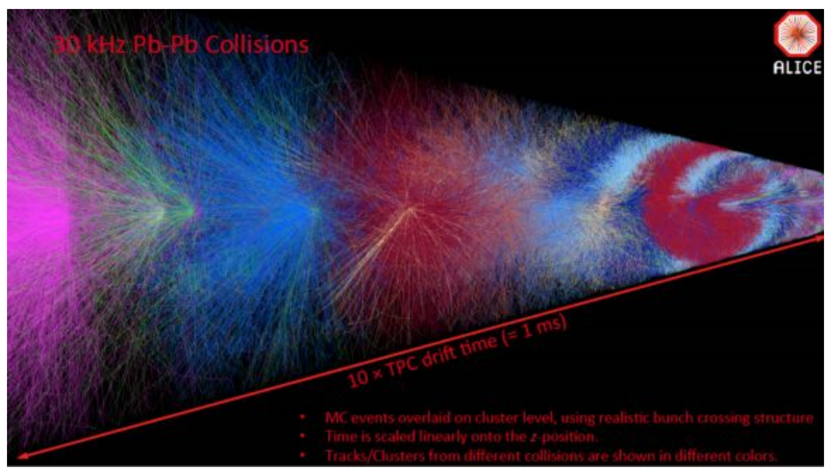
CERN-LHCC-2013-024

CERN-LHCC-2012-012

CERN-LHCC-2015-021

CERN-LHCC-2013-019

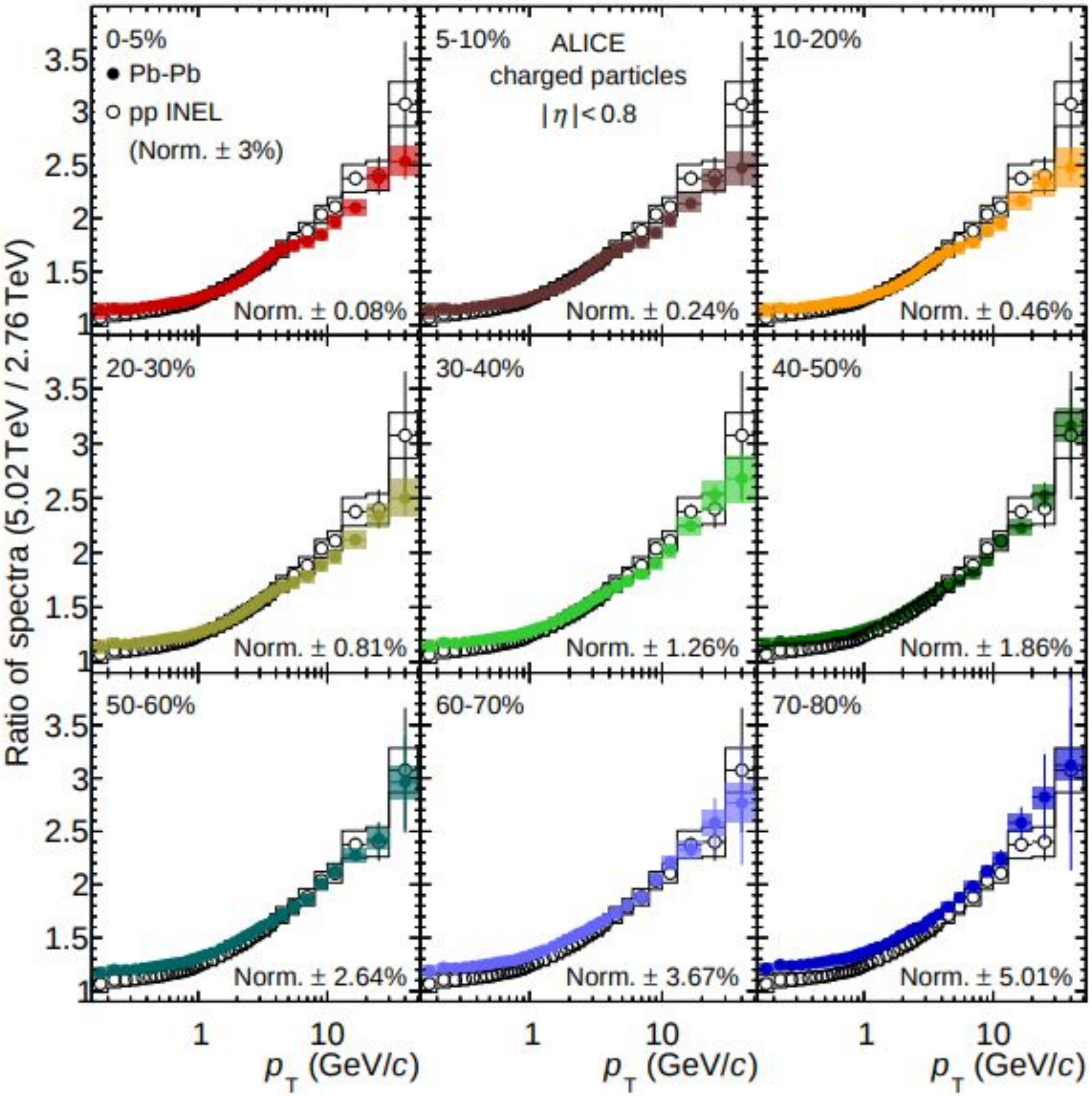
CERN-LHCC-2015-006



Access to more and more rarer probes

BACKUP

Pb-Pb 2.7 vs 5.02 TeV



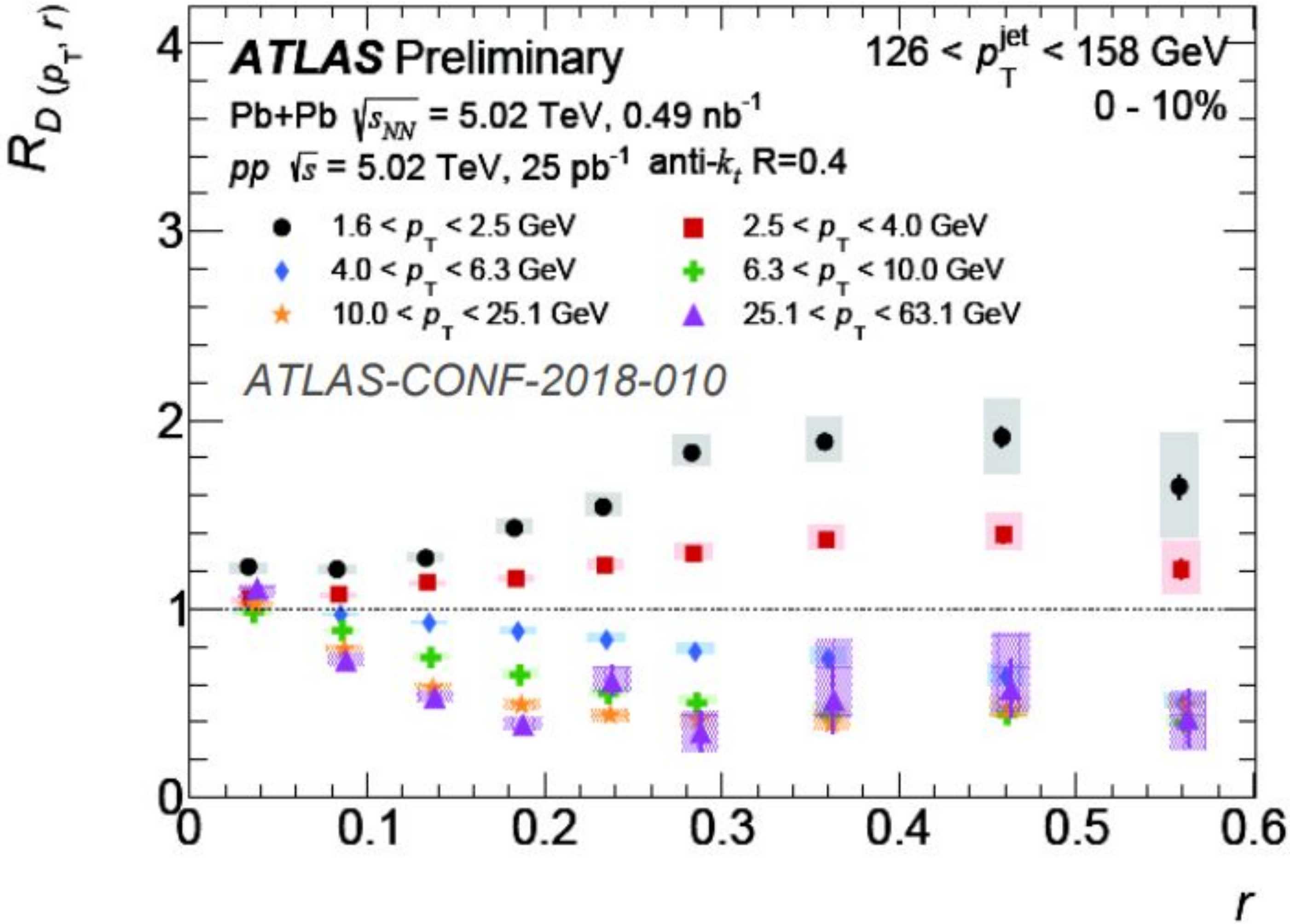
Spectra comparison:

Harder spectra @5.02 for both AA (more parton energy loss) and pp reference

⇒ **similar R_{AA} suppression**

Factor ~2 decrease of system. uncertainties wrt previous published results

1802.09145



ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV, 0.49 nb^{-1}
pp $\sqrt{s}$ = 5.02 TeV, 25 pb^{-1} anti-k_t R=0.4
126 < p_T^{jet} < 158 GeV
0 - 10%
1.6 < p_T < 2.5 GeV
2.5 < p_T < 4.0 GeV
4.0 < p_T < 6.3 GeV
6.3 < p_T < 10.0 GeV
10.0 < p_T < 25.1 GeV
25.1 < p_T < 63.1 GeV
ATLAS-CONF-2018-010
$R_{D(p_T, r)}$
r
0
1
2
3
4
0.1
0.2
0.3
0.4
0.5
0.6