A brief review of recent results from the ALICE Collaboration

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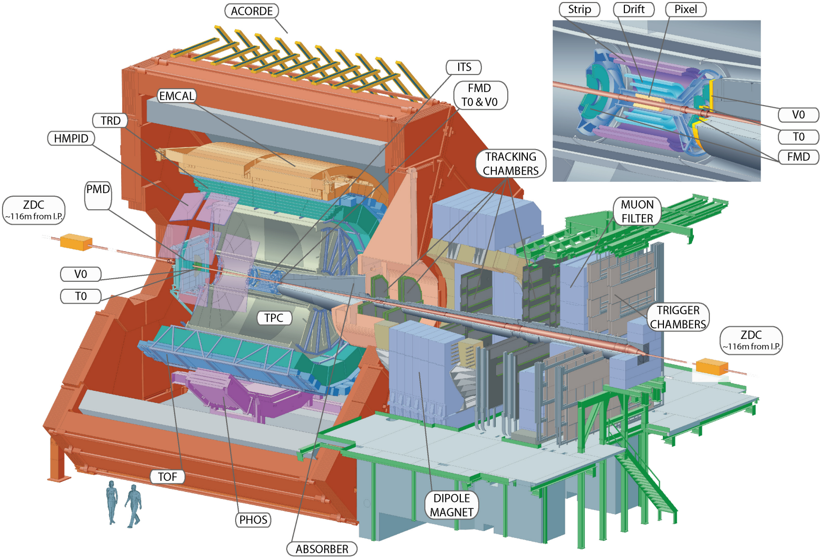
On behalf of the ALICE Collaboration

Lake Louise Winter Institute
Lake Louise, Alberta, Canada
16 February 2014

ALICE



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MUON
FILTER
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~116m from I.P.
TOF
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MAGNET
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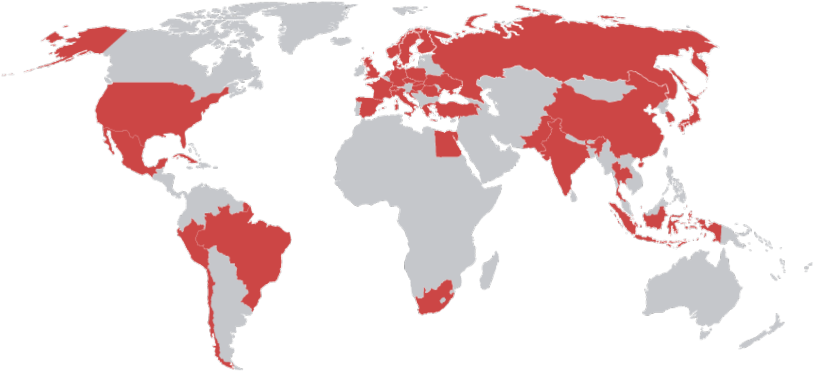
ALICE

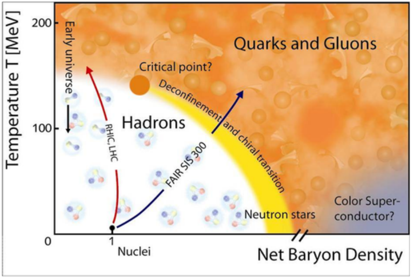


- 37 countries, 151 institutes, 1550 members

At sufficiently high temperature and/or density, the gauge coupling between quarks and gluons becomes sufficiently weak that deconfinement is achieved

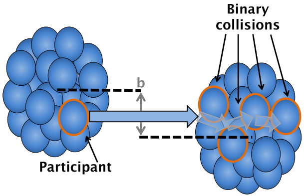
Some basic information about the QGP:

- Particles produced in thermal abundances
- Hydrodynamical models describe the data very well, require fast thermalization at the parton level
- The matter is extremely hot, well in excess of the critical temperature
  $T_c \approx 150$ MeV (10^{12} K)
  –Stellar coronae 10^6 K
  –Core of white dwarf 10^7 K



Centrality

- Use geometrical (Glauber model) simulations to determine the number of participating nucleons N_{part} and the number of binary nucleon-nucleon collisions N_{coll} from detector response



Phys. Rev. Lett. 106 (2011) 032301
Phys. Rev. C 88 (2013) 044909

Centrality	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$
Pb-Pb		
0-5%	382.7 ± 5.1	1685 ± 190
5-10%	329.7 ± 4.6	1316 ± 140
10-20%	260.5 ± 4.4	921 ± 96
20-30%	186.4 ± 3.9	556 ± 55
30-40%	128.9 ± 3.3	320 ± 32
40-50%	85.0 ± 2.6	171 ± 16
50-60%	52.8 ± 2.0	84.3 ± 7
60-70%	30.0 ± 1.3	37.9 ± 3
70-80%	15.8 ± 0.6	15.6 ± 1
p-Pb	7.87 ± 0.55	$\equiv N_{\text{part}} - 1$
pp	$\equiv 2$	$\equiv 1$

Nuclear modification factors

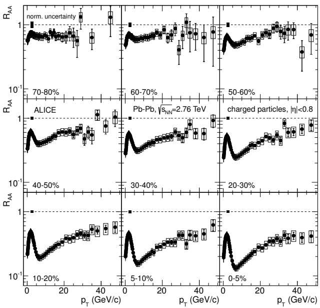
$R_{AB} = \text{Yield}_{AB}/(N_{coll}\text{Yield}_{pp})$

$R_{AB} < 1 \rightarrow$ suppression of particles

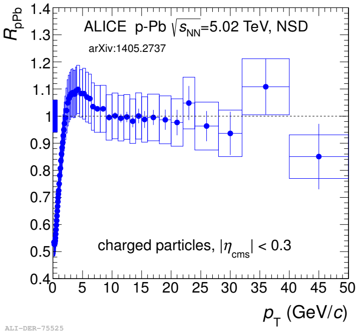
$R_{AB} > 1 \rightarrow$ enhancement of particles

$R_{AB} = 1 \rightarrow$ no modification

Phys. Lett. B 720 (2013) 52-62



Eur. Phys. J. C 74 (2014) 3054



- Significant suppression of particles in Pb-Pb at high p_T
  No suppression of particles in p-Pb at high p_T
- Observed suppression in Pb-Pb is not from "cold nuclear matter" measured in p-Pb—generally understood as partonic energy loss via collisional and radiative energy loss in a color-charged medium

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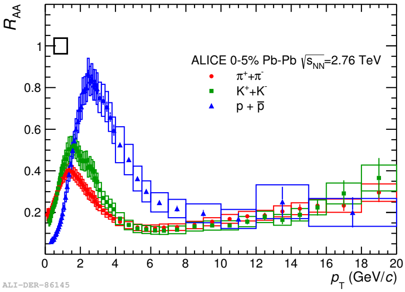
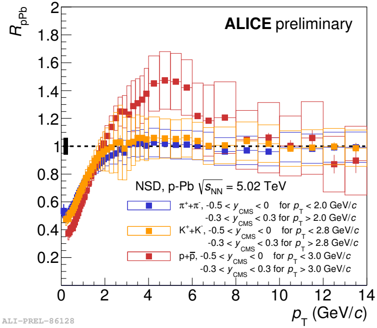
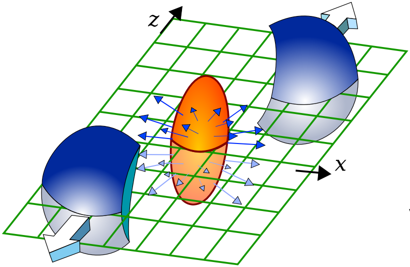
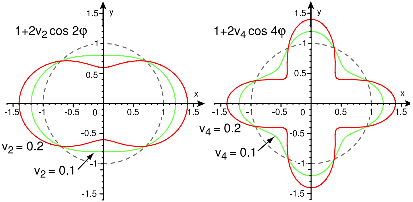
Phys. Lett. B 736 (2014) 196-207





- No particle species dependence at high p_T
  Jet "chemistry" unmodified from vacuum fragmentation (in pp collisions)
- Particle species dependent behavior at intermediate p_T in both systems—generally understood as radial flow and hadronization by parton coalescence in Pb-Pb, but what about p-Pb?



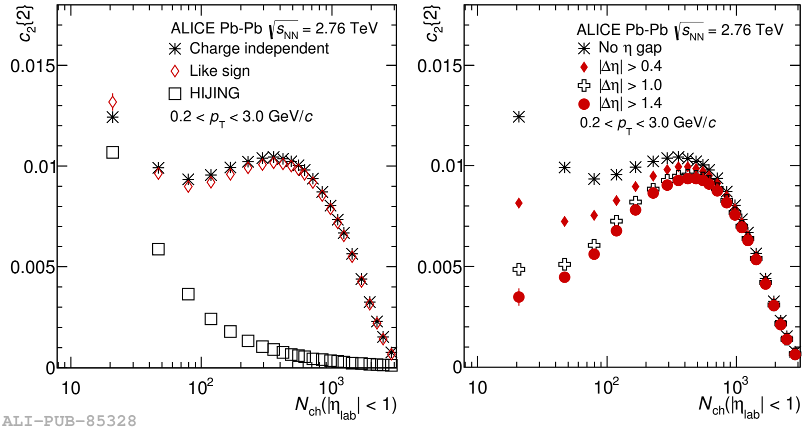


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \psi_n)) \qquad v_n = \langle \cos(n(\varphi - \psi_n)) \rangle$$

- Collisions that are not fully overlapping have almond-shape overlap region
- Pressure gradients drive outward expansion—initial state geometrical anisotropy drives final state momentum space anisotropy
- Symmetry about x-axis suggests vanishing odd-n terms—non zero terms indicate geometrical fluctuations

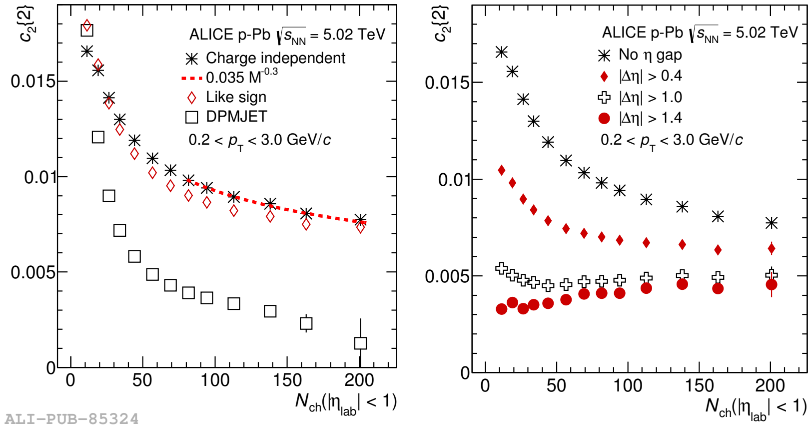
Flow and fluctuations

Phys. Rev. C 90 (2014) 054901



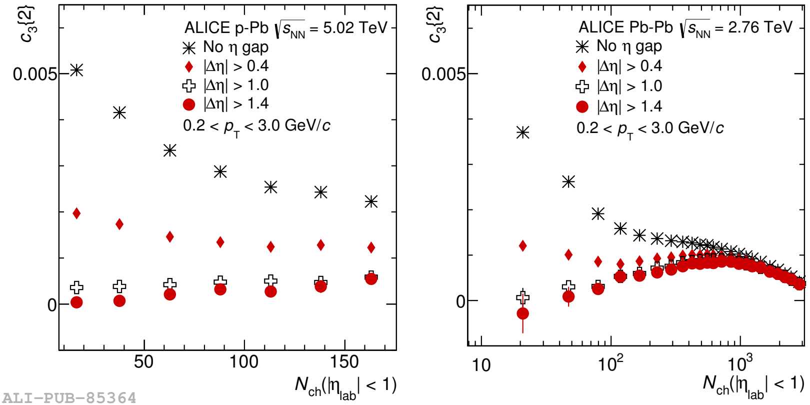
- Two particle correlations are a good probe for global correlations
- Non-flow proportiaonal to $1/N$, collective behavior has no explicit N dependence
- HIJING is an A-A event generator (no flow), shows expected power law behavior
- ALICE Pb-Pb data exhibit collective behavior when non-flow is removed with large $\Delta\eta$ (large η separation between the two particles)

Phys. Rev. C 90 (2014) 054901



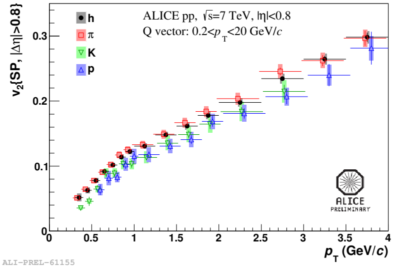
- DPMJET is a p-A event generator (no flow), shows expected power law behavior
- ALICE p-Pb data exhibit similar collective behavior as seen in Pb-Pb when non-flow is removed

Phys. Rev. C 90 (2014) 054901

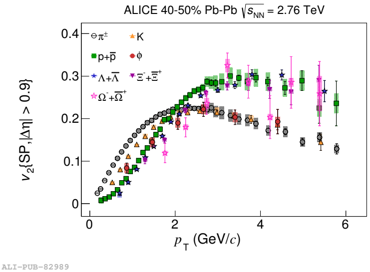


- Third harmonic results also show evidence of collective motion in both systems
- Indicative of geometrical fluctuations causing event by event triangularity in initial geometry

Flow and fluctuations

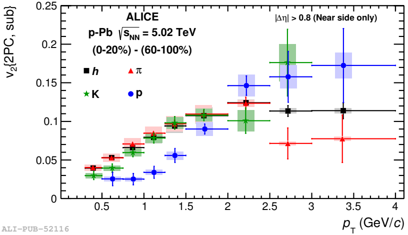


arXiv:1405.4632

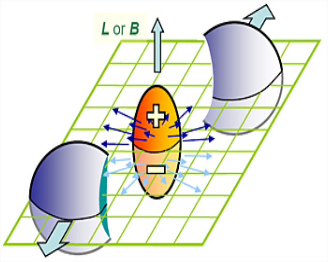


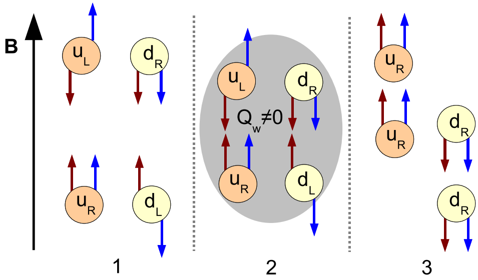
- Collective behavior observed in Pb-Pb
  - –Strong mass ordering
  - –Baryons and mesons flip mass ordering and group together
  - –Understood from hadronization by parton coalescence
- Similar behavior seen in p-Pb
  - –Strong mass ordering, flip of mass ordering of pions and protons
- Very different behavior in pp
  - –Weaker mass ordering with no flip

Phys. Lett. B 726 (2013) 164-177



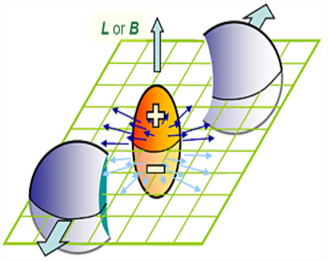
Searches for parity violation in the strong sector

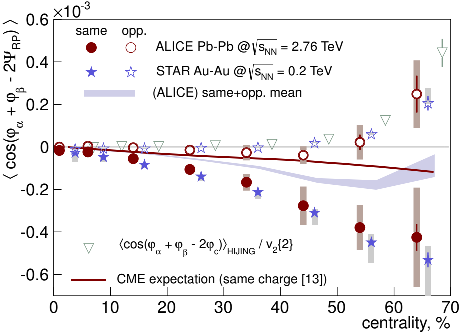




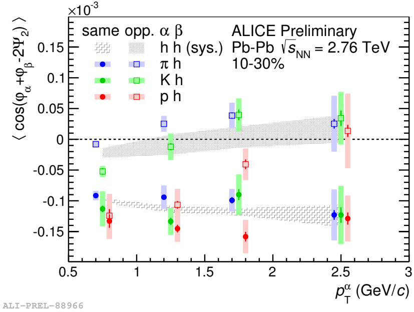
- In off-central heavy ion collisions, the spectators generate an extremely large (but short lived) magnetic field perpendicular to the reaction plane
- Presence of non-zero topological charge induces chiral imbalance
  Connected to the $U(1)_A$ anomaly $\partial_\mu J^\mu_A = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$
- Chiral imbalance leads to electric current when spins aligned by magnetic field $\vec{J}_V = \frac{N_c e}{2\pi^2} \mu_A \vec{B}$

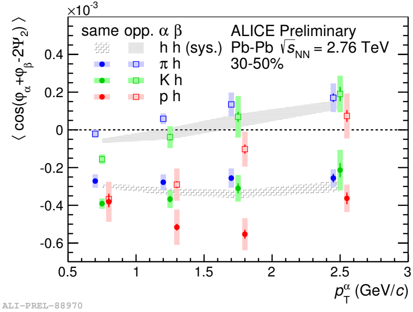
Phys. Rev. Lett. 110 (2013) 012301





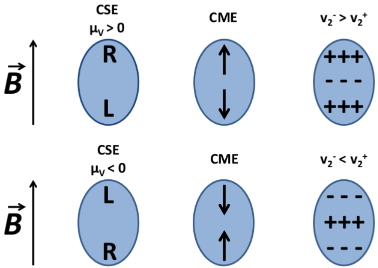
- Measurement of correlator $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi)\rangle$ indicates charge separation along the reaction plane
- Evidence of Chiral Magnetic Effect (CME) and strong parity violation
  –Need to understand contributions from other sources

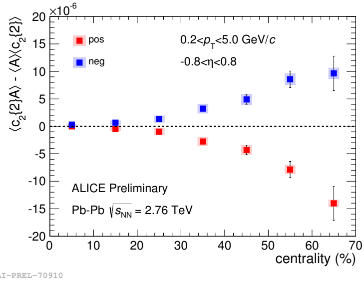


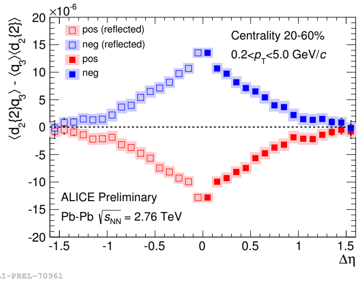


- Measurements of different species may help disentangle background sources
- Opposite sign correlator shows particle species dependence
- Input from theory needed to fully understand backgrounds and PID dependence

Searches for parity violation in the strong sector







- Chiral Magnetic Effect (CME) + Chiral Separation Effect (CSE) = Chiral Magnetic Wave (CMW)
- Observable: Charge dependence of elliptic flow with charge asymmetry
- ALICE data demonstrate $\Delta\eta$ dependence

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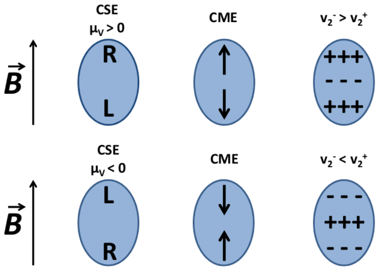
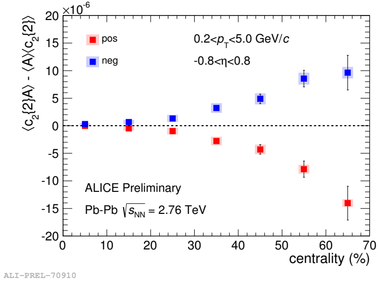
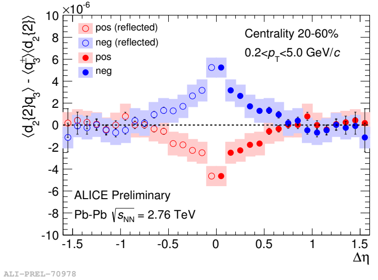






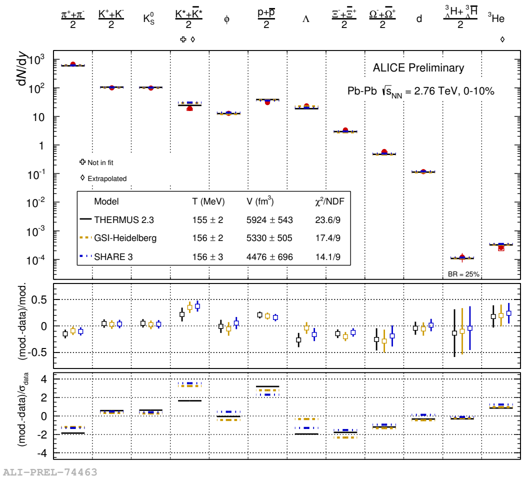
- Chiral Magnetic Effect (CME) + Chiral Separation Effect (CSE) = Chiral Magnetic Wave (CMW)
- Observable: Charge dependence of elliptic flow with charge asymmetry
- ALICE data demonstrate $\Delta\eta$ dependence
- Important to remove charge correlations

Summary

- Many, many more results to show than I have had time for here
  –Heavy ion physics is a rich and diverse field
  –The field is becoming increasingly quantitative
- High p_T particles exhibit suppression in Pb-Pb but no modification in p-Pb
- Intermediate p_T particles show very interesting behavior in Pb-Pb and p-Pb
- Strong evidence of collective motion in Pb-Pb
- Similar (and surprising!) evidence of collective motion in p-Pb
- Hadronization plays a critical role in understanding observables
- Searches for strong parity violation show intriguing results
  –Essential feature of QCD
  –Very important to understand backgrounds

Additional material

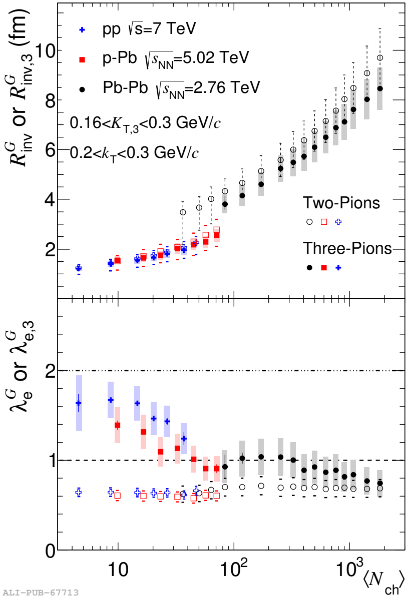
Thermal fits to ALICE data



- Thermal model assumes grand canonical ensemble
- Few parameters—T and V, μ_B fixed in this case (free at lower energies)
- Reproduces integrated yields of many different particle species over many orders of magnitude
- Sometimes ratios are used instead of yields, so V drops out and T and μ_B are the only free parameters
- Works extremely well over a very wide range of energies, from SPS to RHIC to LHC

Quantum correlations and system size

Phys. Lett. B 739 (2014) 139-151



- Quantum correlations can be used to estimate the system size R
  - $\Delta x \Delta p \gg 2\pi\hbar$ (classical)
  - $\Delta x \Delta p \approx 2\pi\hbar$ (quantum)
- Generally 2 indistinguishable particles are used
- ALICE the first to report 3-particle quantum correlations, which do not contain background from other kinds of 2-particle correlations

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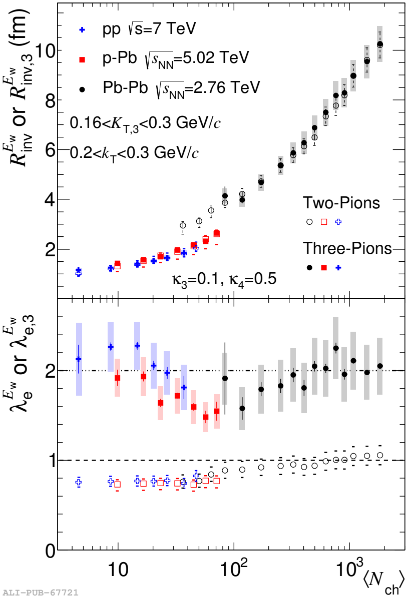

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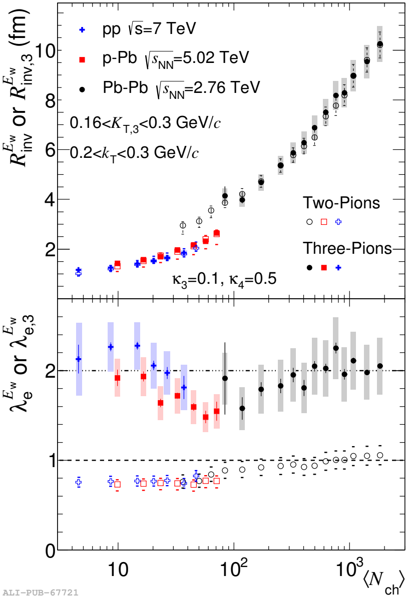
- Use of non-Gaussian function to fit correlation improves quality of fit and agreement between 2- and 3-particle correlations
- Parameter λ very close to chaotic limit—incoherent emission

Quantum correlations and system size

Phys. Lett. B 739 (2014) 139-151



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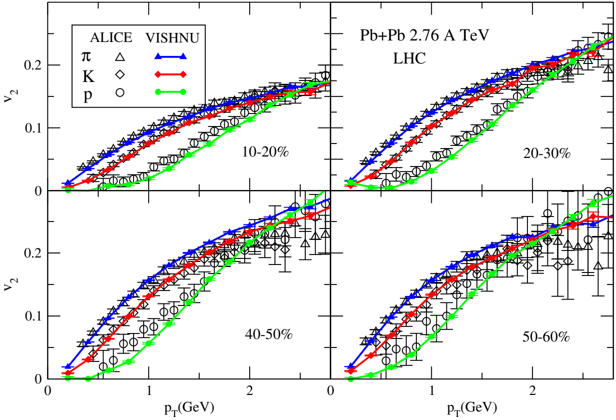
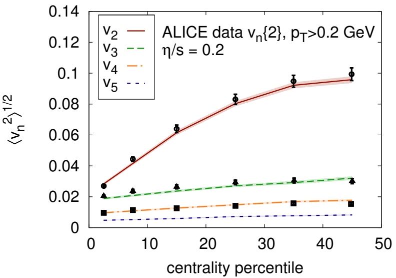
- Parameter λ very close to chaotic limit—incoherent emission
- pp and p-Pb close together, Pb-Pb separate

Hydro model fits to identified particle v_2

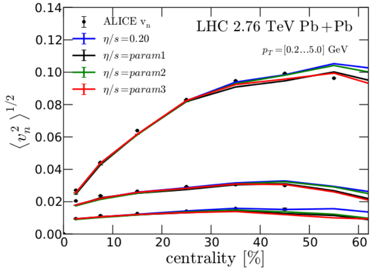


- Song, Bass, and Heinz, Phys. Rev. C 89, 034919 (2014)
- VISHNU—Realistic 3D viscous hydro
- ALICE data (Pb-Pb at 2.76 TeV)

Gale et al, Phys. Rev. Lett. 110, 012302 (2013)



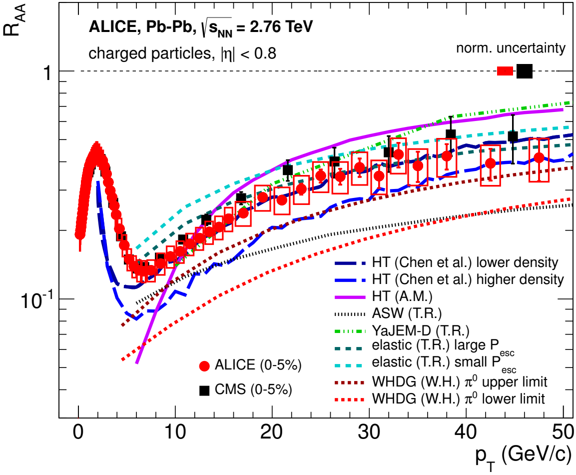
Paatalainen, QM14 Poster



- η/s reasonably well constrainted, but not with T dependence
- ALICE data (Pb-Pb at 2.76 TeV)

Energy loss model fits to R_{AA}

Phys. Lett. B 720 (2013) 52-62



- ALICE and CMS data agree well
- Theoretical models get the trend right, but plenty of room for improvement