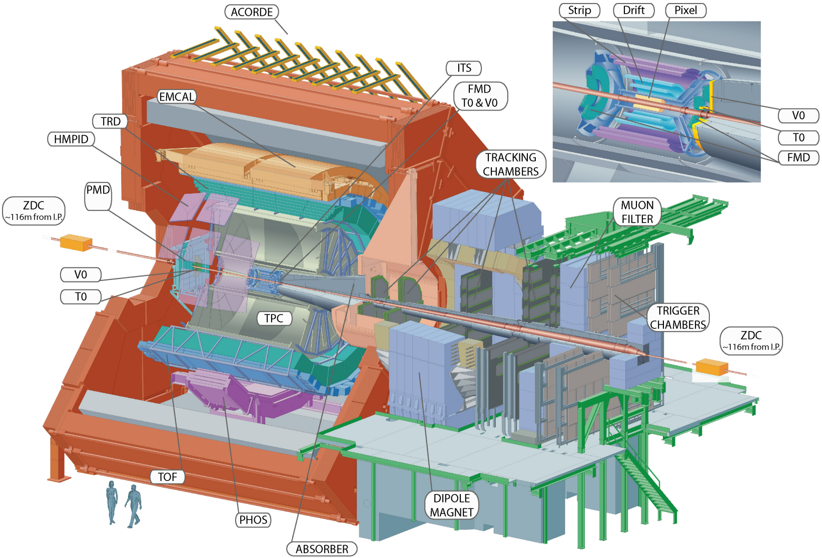
A brief review of recent results from the ALICE Collaboration

Ron Belmont
Wayne State University
On behalf of the ALICE Collaboration

Lake Louise Winter Institute
Lake Louise, Alberta, Canada
16 February 2015

ALICE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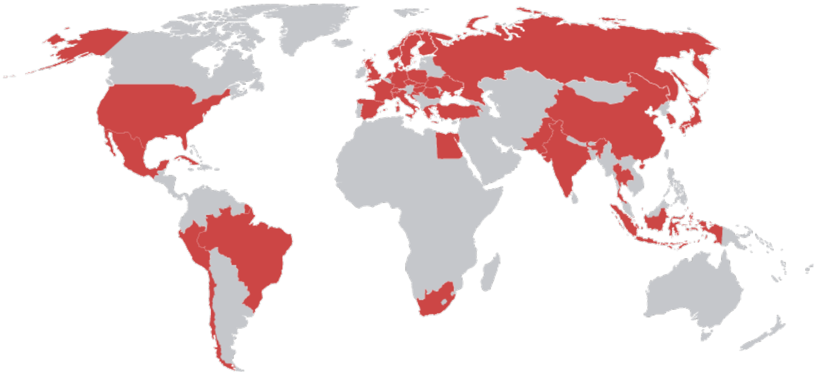
ALICE

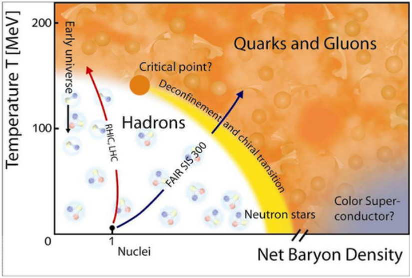


- 37 countries, 151 institutes, 1550 members

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

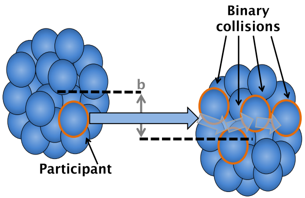
Some basic information about the QGP:

- 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	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$
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	$\equiv N_{part} - 1$
pp	$\equiv 2$	$\equiv 1$

Nuclear modification factors

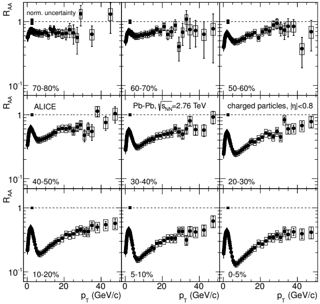
$R_{AB} = \text{Yield}_{AB}/(N_{coll}\text{Yield}_{pp})$

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

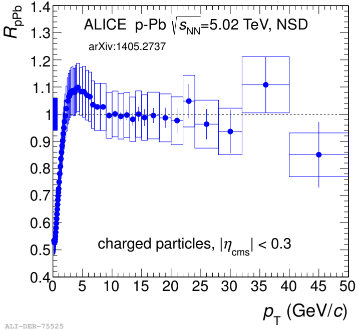
$R_{AB} > 1 \rightarrow$ enhancement of particles

$R_{AB} = 1 \rightarrow$ 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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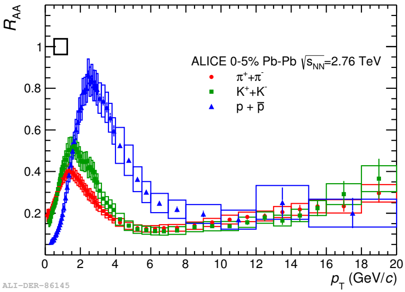
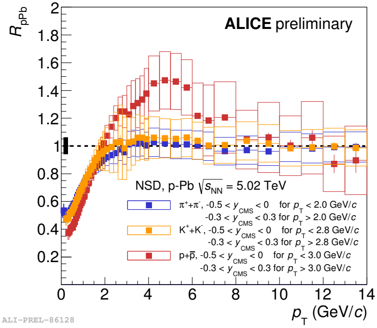
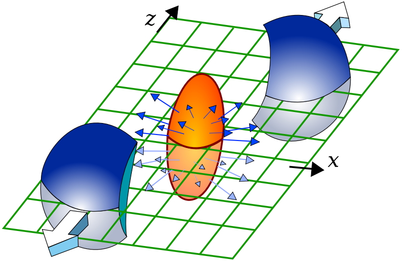
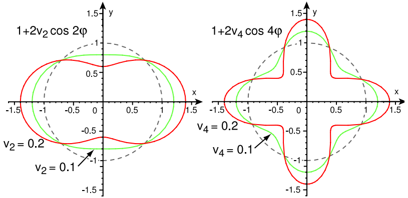
Phys. Lett. B 736 (2014) 196-207





- 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?



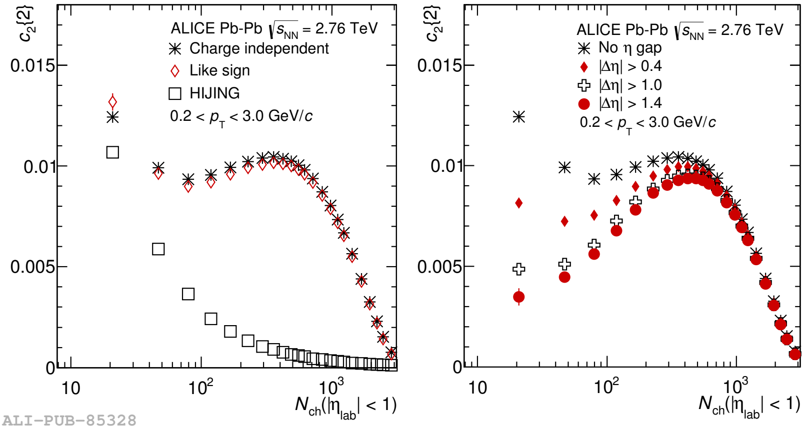


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \psi_n)) \qquad v_n = \langle \cos(n(\varphi - \psi_n)) \rangle$$

- 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 proportional 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)

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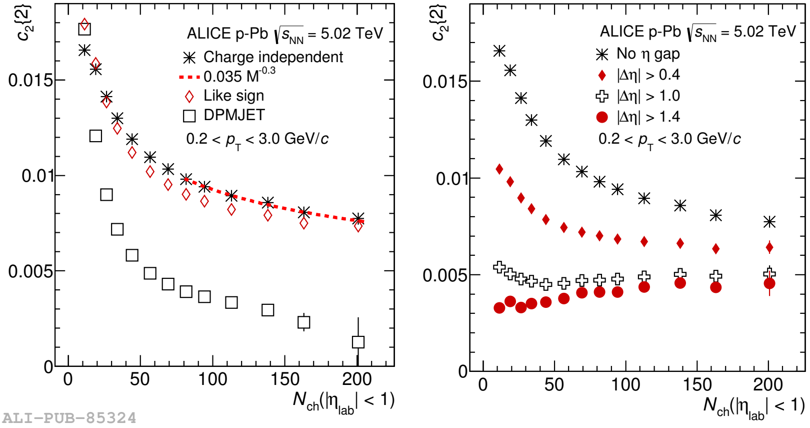
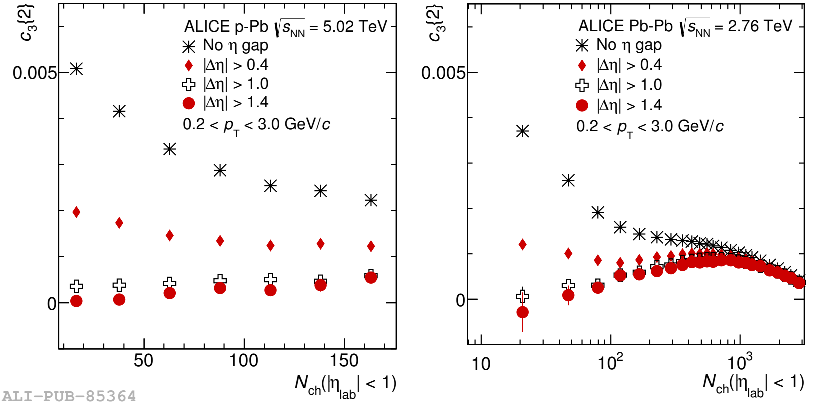


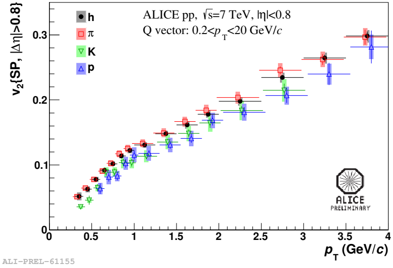
- DPMJET is a p-A event generator (no flow), shows expected power law behavior
- ALICE p-Pb data exhibit similar collective behavior as seen in Pb-Pb when non-flow is removed

Phys. Rev. C 90 (2014) 054901

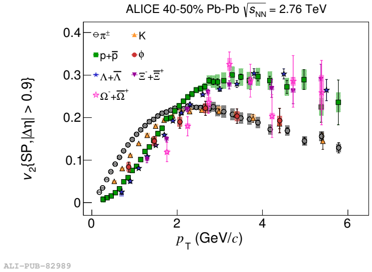


- Third harmonic results also show evidence of collective motion in both systems
- Indicative of geometrical fluctuations causing event by event triangularity in initial geometry

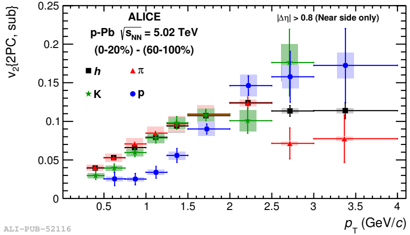
Flow and fluctuations



arXiv:1405.4632

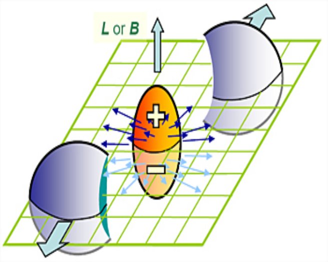


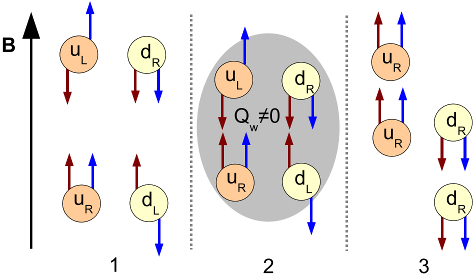
Phys. Lett. B 726 (2013) 164-177



- 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

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
  $\vec{J}_V = \frac{N_c e}{2\pi^2} \mu_A \vec{B}$

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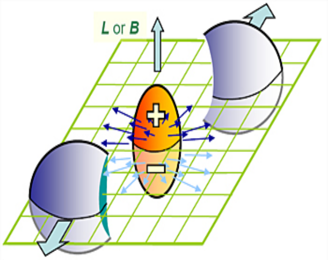
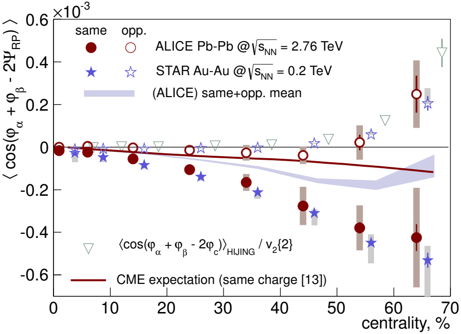


Phys. Rev. Lett. 110 (2013) 012301



- 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

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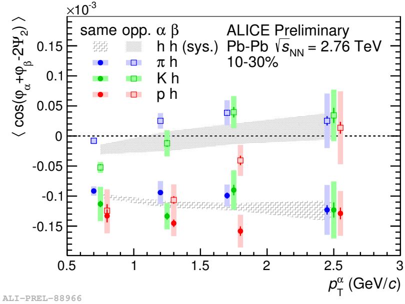
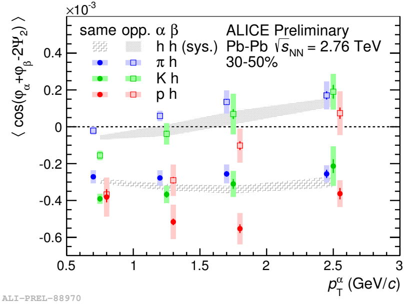
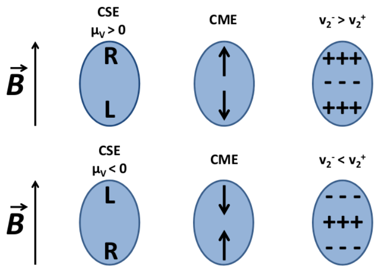
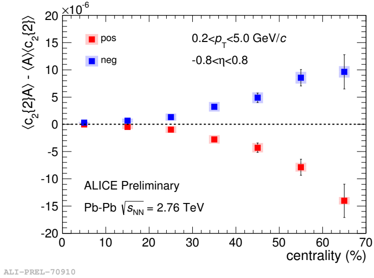


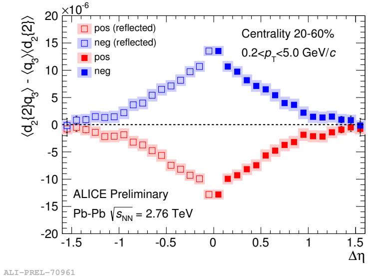


- Measurements of different species may help disentangle background sources
- Opposite sign correlator shows particle species dependence
- Input from theory needed to fully understand backgrounds and PID dependence

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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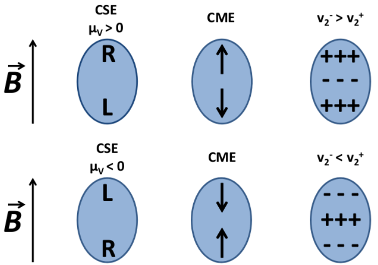

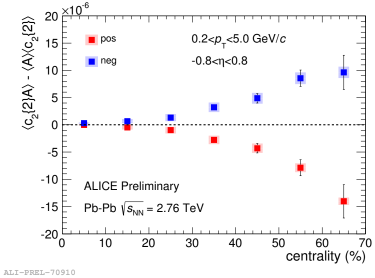

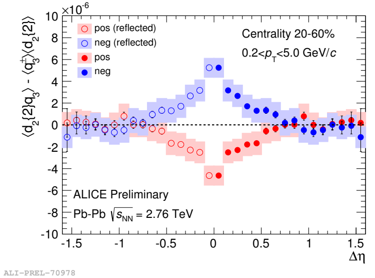

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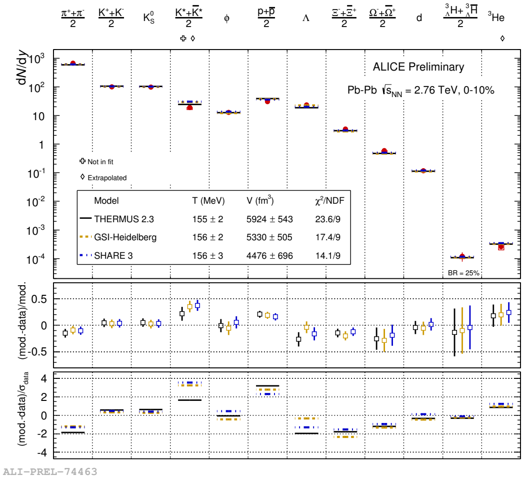
- Observable: Charge dependence of elliptic flow with charge asymmetry
- ALICE data demonstrate $\Delta\eta$ dependence
- Important to remove charge correlations

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

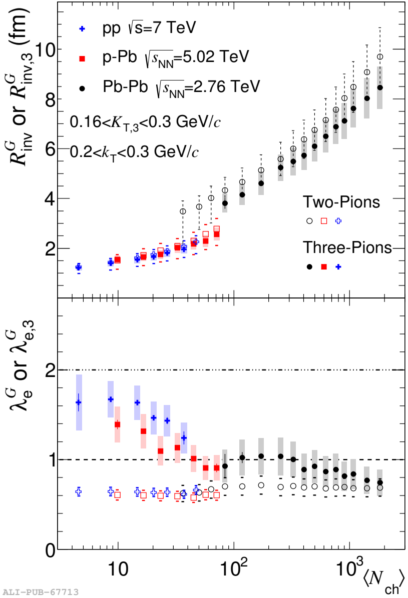
Thermal fits to ALICE data



- 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

Quantum correlations and system size

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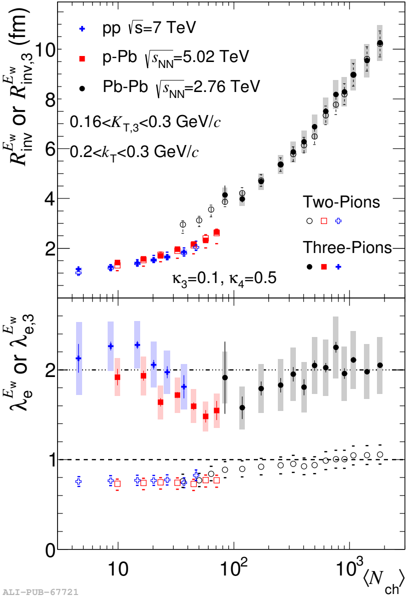

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- Use of non-Gaussian function to fit correlation improves quality of fit and agreement between 2- and 3-particle correlations
- Parameter λ very close to chaotic limit—incoherent emission

Quantum correlations and system size

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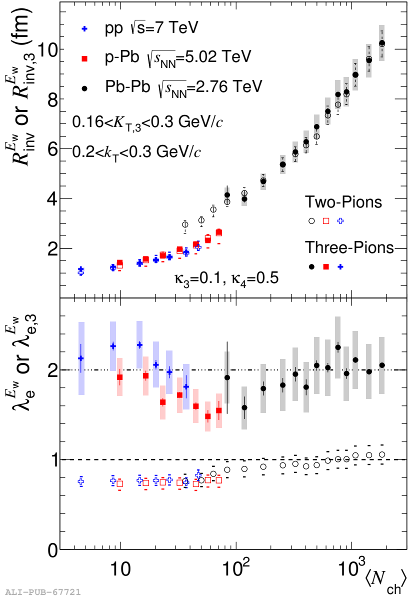

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- Parameter λ very close to chaotic limit—incoherent emission
- pp and p-Pb close together, Pb-Pb separate