Femtoscopic analysis of baryon correlations in ultra-relativistic heavy-ion collisions registered by ALICE

Maciej Szymański
University of Chinese Academy of Sciences

Seminar at EPD, IHEP (UCAS)
26.10.2016

About me

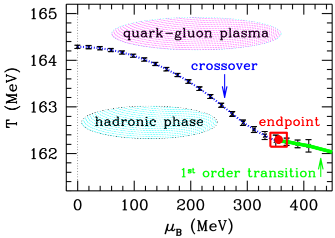
- Maciej Szymański, Poland

- PhD in Physics
  - Faculty of Physics, Warsaw University of Technology
  - 7th of September 2016
  - working for A Large Ion Collider Experiment at LHC on two-particle femtoscopic correlations (this talk)

- Currently, a postdoc at University of Chinese Academy of Sciences (UCAS) in Beijing
  - based full time at CERN
  - working for the LHCb experiment in the Core Software Group

Physics of heavy ion collisions

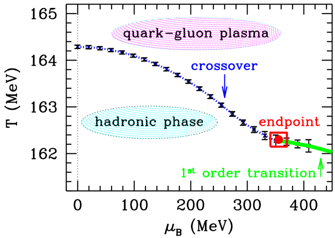
- **Quark–Gluon Plasma**: quarks and gluons not confined in hadrons, but may propagate in the whole volume of the system
- **Heavy ion collisions** at ultra-relativistic energies - a method to create and study the QGP



JHEP,04.2004.050

Physics of heavy ion collisions

- **Quark–Gluon Plasma**: quarks and gluons not confined in hadrons, but may propagate in the whole volume of the system
- **Heavy ion collisions** at ultra-relativistic energies - a method to create and study the QGP
- Evolution of the collision:
  - overlapping fragments of nuclei create a hot, dense sytem of quarks and gluons
  - expanding and coooling down, collective effects observed
  - hadronisation
  - rescattering phase
  - freeze-out
- Analysing particles in the final state, one tries to learn about the initial phase



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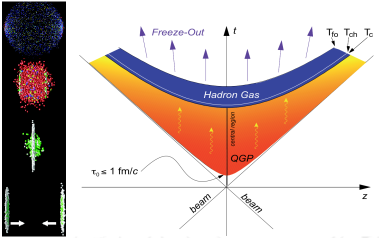

arXiv:0807.1610

ALICE at LHC

- **Large Hadron Collider** (LHC) at CERN
- Circular tunnel of 27 km circmference, 50 to 175 m underground
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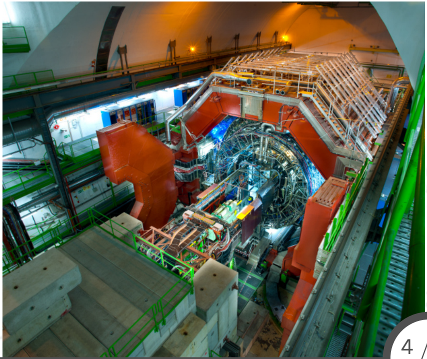

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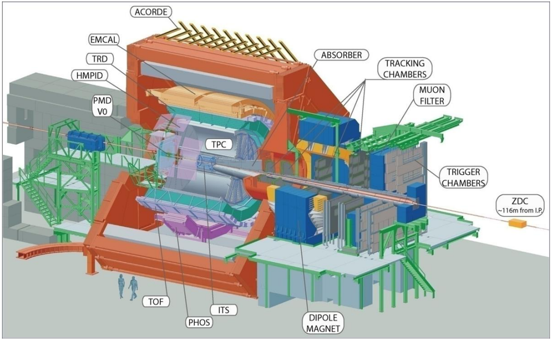
- A Large Ion Collider Experiment designed to study **heavy ion collisions**
- The detector (10^4 t, $16 \times 16 \times 26$ m^3) located in Saint-Genis-Pouilly, France

ALICE detectors

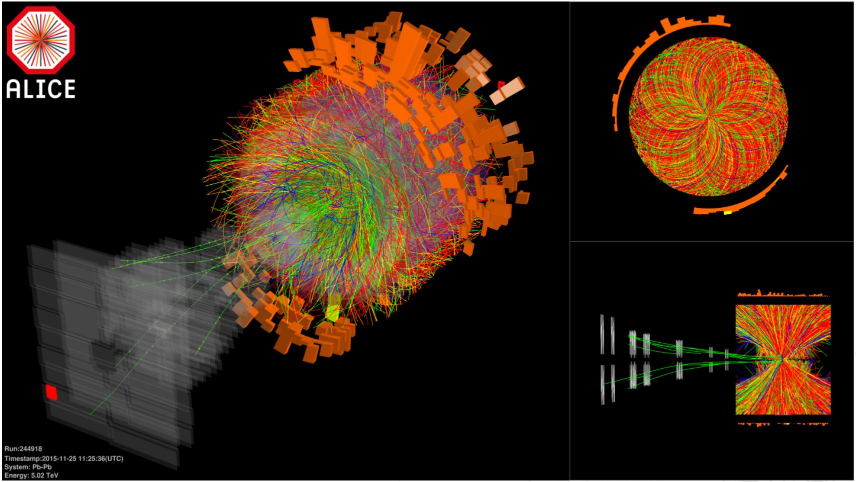


- Central barrel detectors
  - tracking and PID, $|\eta| < 1$
- Forward detectors
  - trigger, centrality, timing
- Muon spectrometer
  - $-4 < |\eta| < -2.5$

- Efficient low-momentum tracking down to 150 MeV/c
- Excellent PID and vertex capabilities

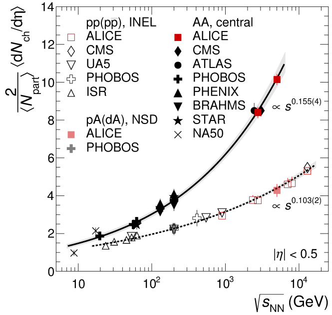
- pp at $\sqrt{s} = 7, 8, 13$ TeV
- p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
- Pb–Pb at $\sqrt{s_{NN}} = 2.76, 5.02$ TeV

Pb–Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV



Results from heavy-ion experiments

- Charged particle pseudorapidity density per participant pair
  - heavy-ion collisions are **not a superposition** of independent collisions of two nucleons



PhysRevLett.116.222302

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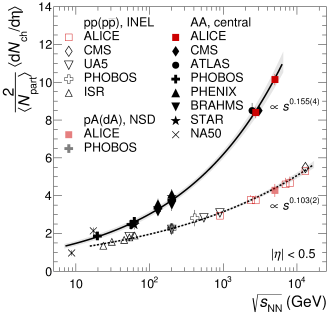
- **Space–time** characteristics of the medium created in heavy-ion collisions
  - the freeze-out volume, i.e. the size of the system at the time when particles do not interact any more is $\sim$ **5000 fm^3**
  - the lifetime exceeds **10 fm/c** (at LHC)



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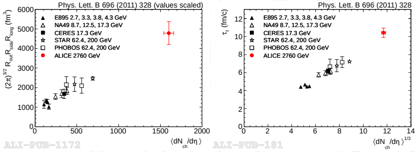

Phys.Lett.B696,2011,328-337

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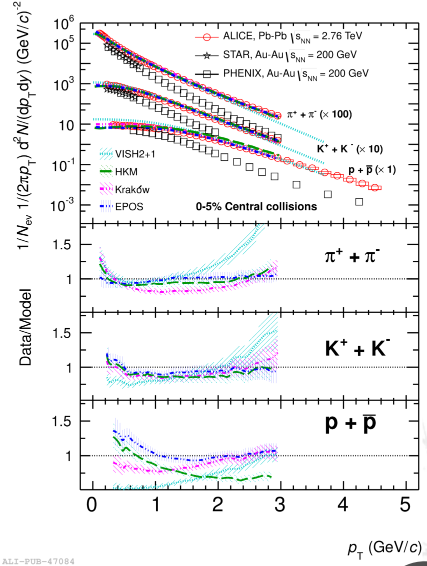

PhysRevC.88.044910

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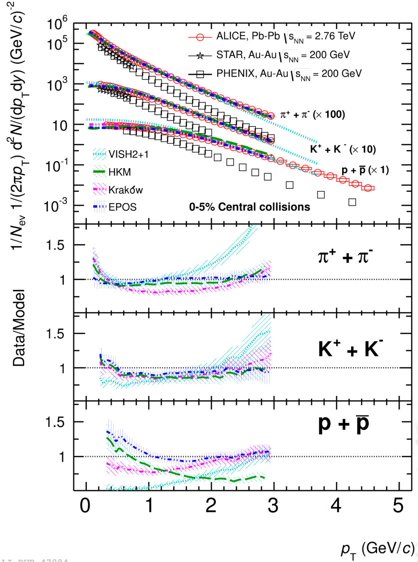

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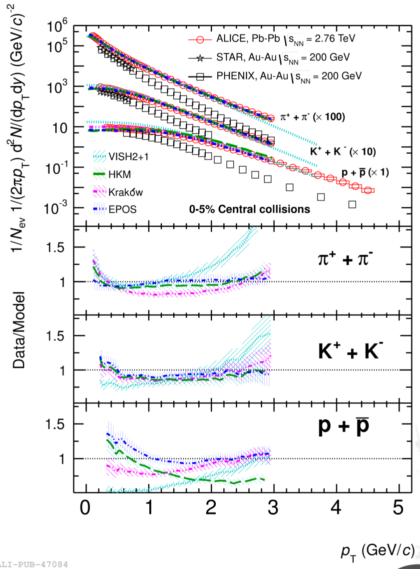

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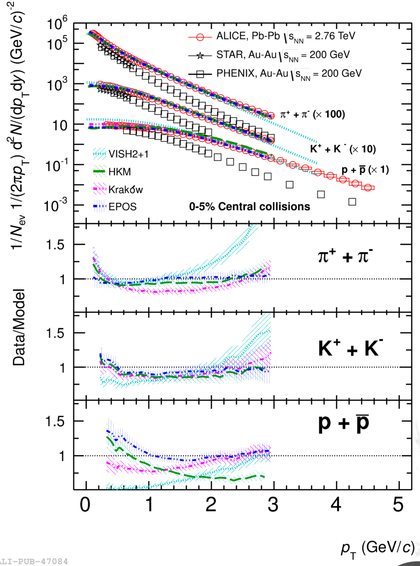

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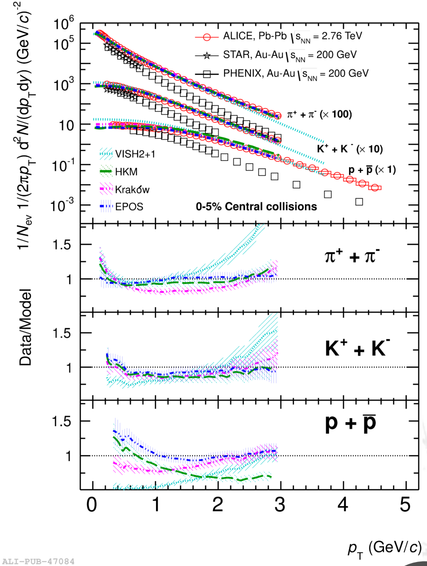
  - Importance of taking into account the **hadronic rescattering** phase after the hydrodynamic stage



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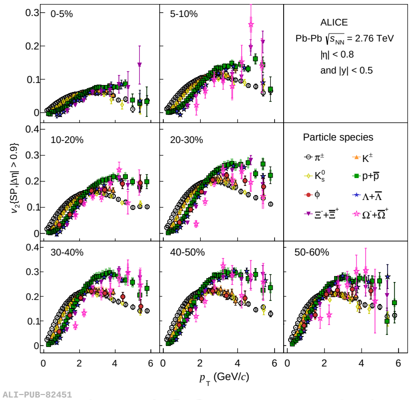

JHEP06(2015)190

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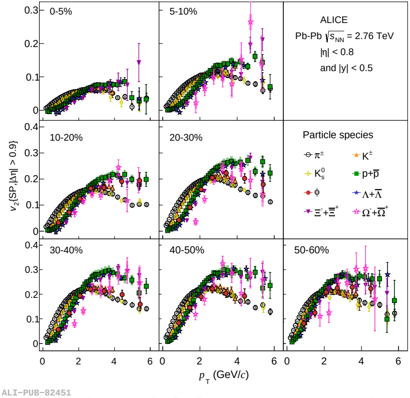
- v_2 increases with increasing transverse momentum up to $\sim 2 - 3$ GeV/c



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- Pair wave function encodes information about quantum statistics and final state interactions
- If Ψ known, one can extract the parameters of the source function (size of the source, femtoscopic (or HBT) radius), otherwise one can estimate parameters of the final state interactions

Femtoscopy of strong interaction

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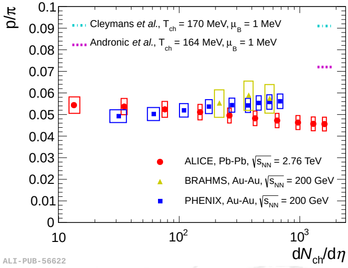
Sov. J. Nucl. Phys.35.770 (1982)

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2}\left|\frac{f^S(k^*)}{r_0}\right|^2\left(1 - \frac{d_0^S}{2\sqrt{\pi}r_0}\right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi}r_0}F_1(2k^*r_0) - \frac{\Im f^S(k^*)}{r_0}F_2(2k^*r_0)\right]$$

Motivation of the baryon femtoscopy

- **Proton yield** at LHC **below thermal model expectations**



Phys. Rev. C88 (2013) 044910

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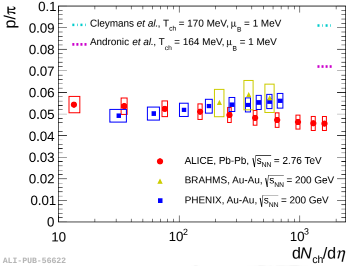

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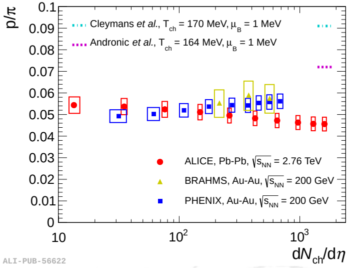

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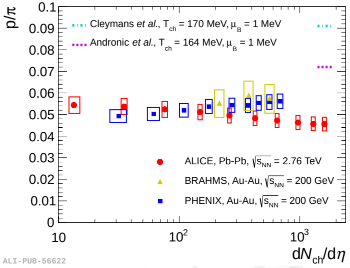
- Possibility to **measure the parameters of interaction** and apply them to model the rescattering phase
- Strong interaction in two-baryon system is one of the **fundamental problems in QCD**
- Baryon-antibaryon interaction includes **annihilation**, but this process is **measured only** for $p\overline{p}$, $p\overline{n}$, $\overline{p}d$



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- To extend the **range of the pair transverse mass** $m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m^2}$, $k_{\mathrm{T}} = |\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}|/2$
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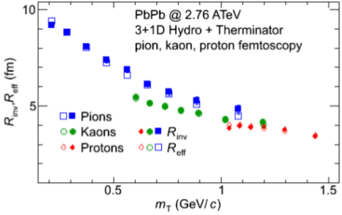

Phys. Rev. C90 (2014) 6, 064914

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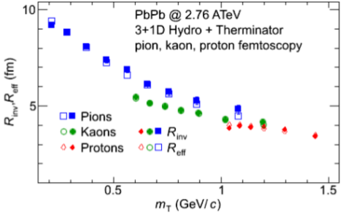

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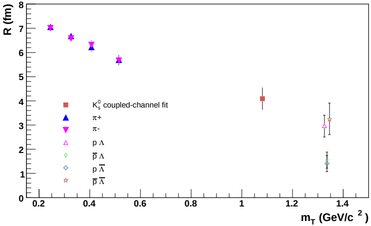

Phys. Rev. C.74.054902

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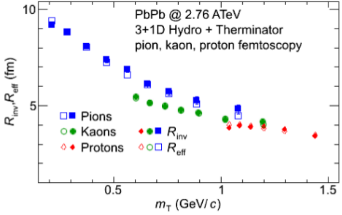
- Surprisingly the **femtoscopic radius** for pΛ was measured to be 50% **larger** than the one for p$\overline{\Lambda}$
- This is **inconsistent** with the predictions from hydrodynamic model and measurements for other particle species



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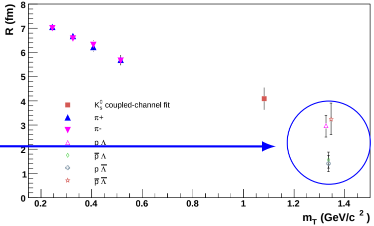

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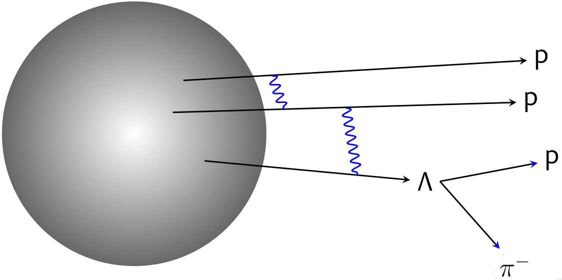
Residual correlations

Femtoscopic correlation of pairs of particles primarily produced in the collision that decay to secondary particles, registered in the detector



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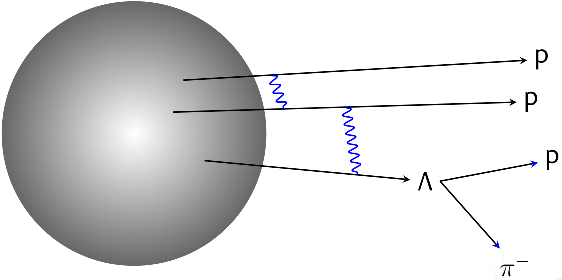

Conditions:

- Strong femtoscopic correlation of primary particles
- Decay momentum comparable to the width of the femtoscopic effect
- Significant fraction of secondary particles in measured sample

The formalism of residual correlations

The fitting formula for $\mathrm{p}\overline{\Lambda}$ correlation taking into account residual contributions

$$C(k^*_{\mathrm{p}\overline{\Lambda}}) = 1 + \lambda_{\mathrm{p}\overline{\Lambda}} \left(C^{\mathrm{p}\overline{\Lambda}}(k^*_{\mathrm{p}\overline{\Lambda}}) - 1 \right) + \sum_{\mathrm{X}\overline{\mathrm{Y}}} \lambda_{\mathrm{X}\overline{\mathrm{Y}}} \left(C^{\mathrm{X}\overline{\mathrm{Y}}}(k^*_{\mathrm{p}\overline{\Lambda}}) - 1 \right)$$

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- Fraction of $p\bar{\Lambda}$ pairs with at least one secondary particle (e.g. proton from Λ decay)
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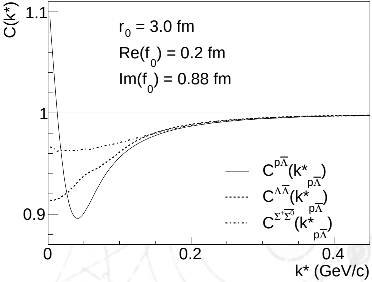
- Correlation functions of residual pairs expressed in terms of $p\bar{\Lambda}$ relative momentum

$$C^{X\bar{Y}}(k^*_{p\bar{\Lambda}}) = \frac{\int C^{X\bar{Y}}(k^*_{X\bar{Y}}) W(k^*_{X\bar{Y}}, k^*_{p\bar{\Lambda}}) \mathrm{d}k^*_{X\bar{Y}}}{\int W(k^*_{X\bar{Y}}, k^*_{p\bar{\Lambda}}) \mathrm{d}k^*_{X\bar{Y}}}$$



Phys. Rev C.89.054916

Reanalysis of the STAR data

- Based on MC simulations, there is **significant fraction of residual pairs** in the selected sample of $p\overline{\Lambda}$ pairs (e.g. primary proton and $\overline{\Lambda}$ from $\overline{\Sigma^0}$ decay constitute 11% of all pairs, whereas there are only 15% pairs of primary particles)

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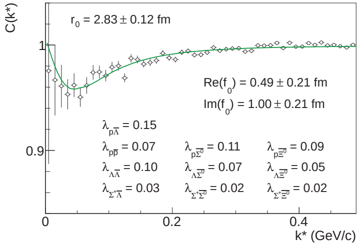

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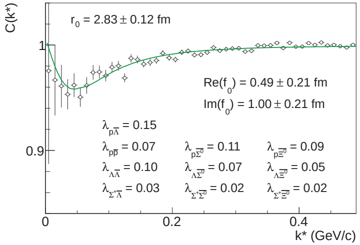

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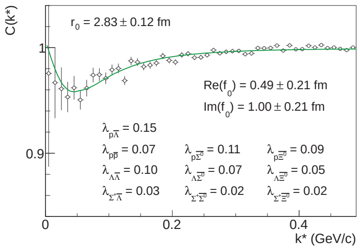
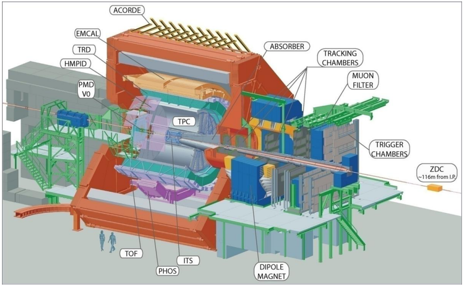


Phys. Rev C.89.054916

- **Residual correlations are essential** to describe the baryon-antibaryon correlations
- The introduced formalism enables to **measure the parameters of the strong interaction** for baryon-antibaryon pairs

Data analysis in ALICE



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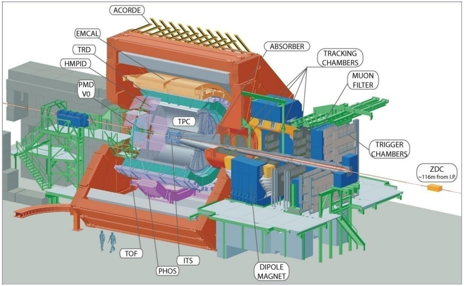

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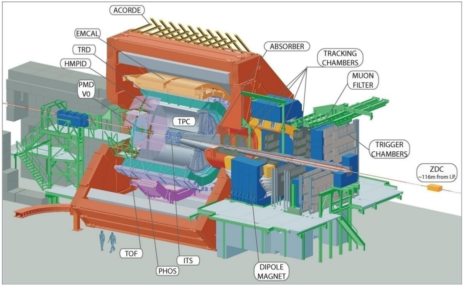
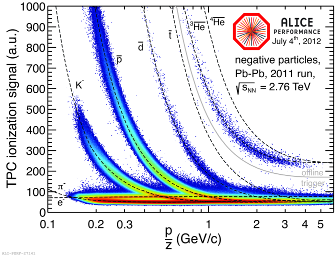
Data analysis in ALICE





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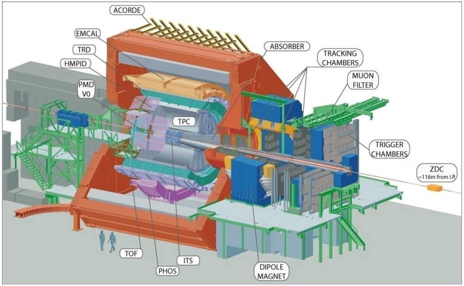

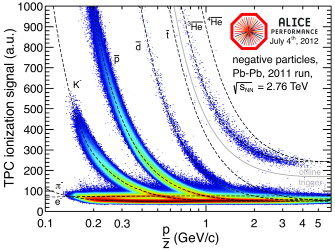

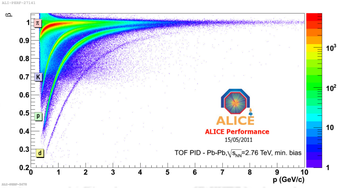

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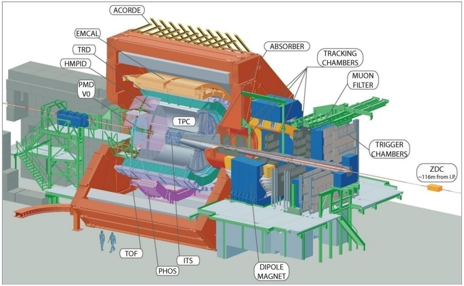

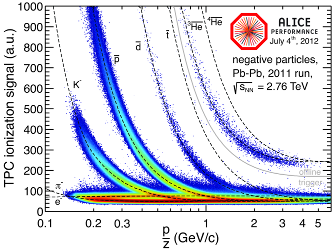

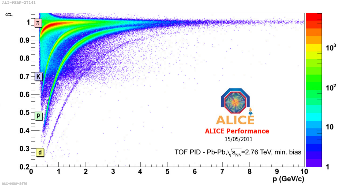

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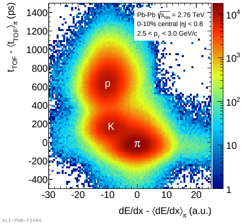
- VZERO detector: centrality determination, trigger

Proton femtoscopy



Int.J.Mod.Phys.A29.1430044

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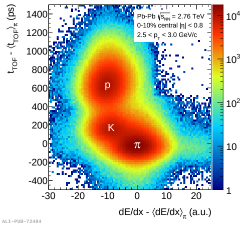

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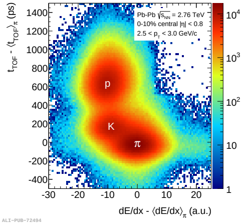

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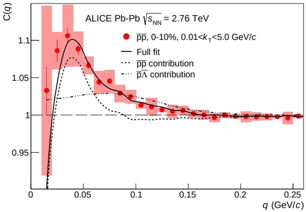

Phys. Rev. C.92.054908

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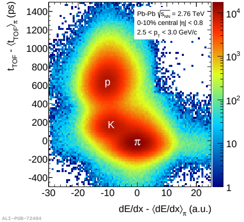

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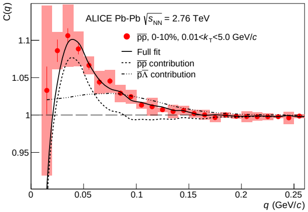

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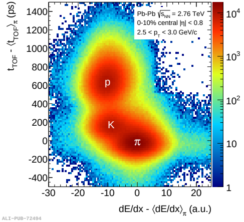

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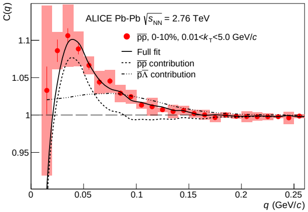

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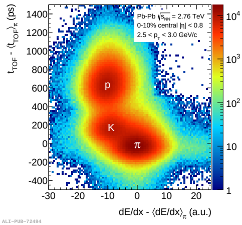

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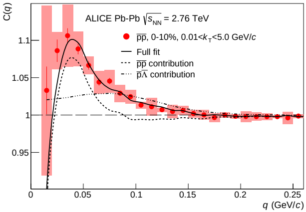

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- π, K and p femtoscopic results: wide range of transverse mass ("collective" flow should apply to all particles), non-trivial consistency checks (different sources of femtoscopic correlations, different detection procedures and systematics)

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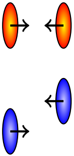

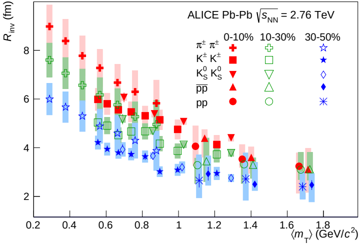

Phys. Rev. C.92.054908

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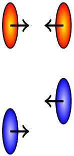

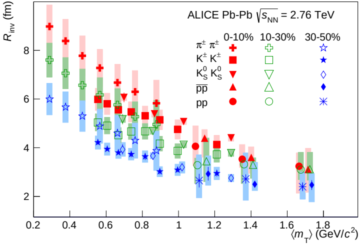

light, slow particles $\rightarrow$ heavy, fast particles

Phys. Rev. C.92.054908

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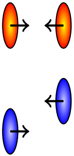
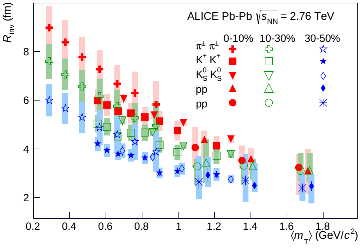
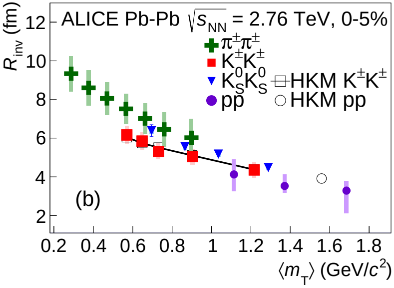
- Femtoscopic radii in **good agreement with predictions of the hydrodynamic model** HKM Nucl.Phys.A929 (2014)







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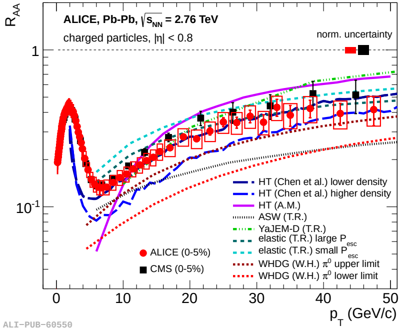
- In particular, **estimation of the imaginary part of the scattering length** describing the annihilation effect for $\overline{\rm p}\Lambda$ i $\rm p\overline{\Lambda}$

Results from heavy-ion experiments

- Nuclear modification factor
  - suppression of high-p_T particles attributed to **strong parton energy loss** in large medium density



Phys. Lett.B720,2013,52-62

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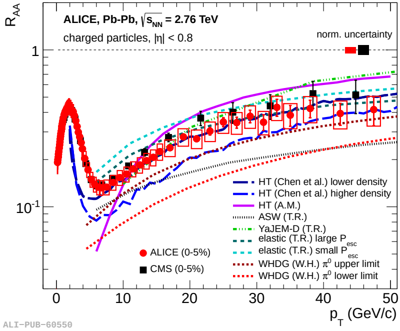
  - signature of the **transition to the quark–gluon plasma**
  - energy threshold for the production of strange quarks smaller in the QGP comparing with the hadron gas



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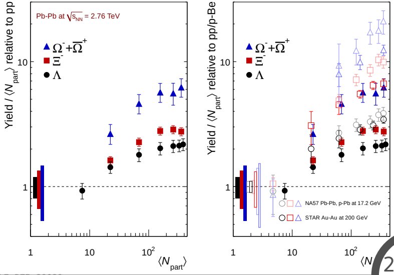


m_T dependence of femtoscopic radii

- m_T scaling: $R \propto m_T^\alpha$, $m_T = \sqrt{k_T^2 + m^2}$
- Ideal 1D hydrodynamics predicts exact m_T scaling for R_{long} with $\alpha = -1/2$

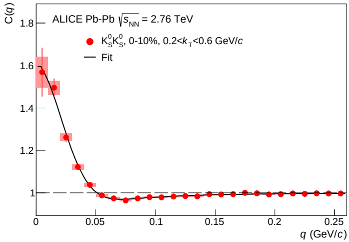
  Sov. J. Nucl. Phys.46 (1987) 345; Z. Phys.C 39 (1988) 69.. Nucl. Phys. A 498 (1989) 151.

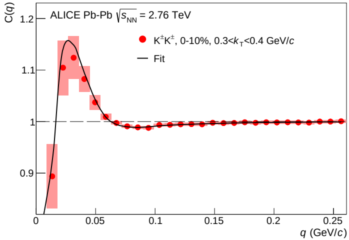
- In 3+1D hydro with viscosity the scaling still exists but only in LCMS with different α for R_{long}, $R_{side,}$, R_{out}

  Phys.Rev. C90 (2014) 064914

  - Indication of flow dominated freeze-out scenario
- Violation of m_T scaling predicted in Nucl.Phys. A 929 (2014)
  - Strong transverse flow, resonance decays influence, rescattering phase

$K^0_S K^0_S$ and $K^{\pm}K^{\pm}$ correlation functions



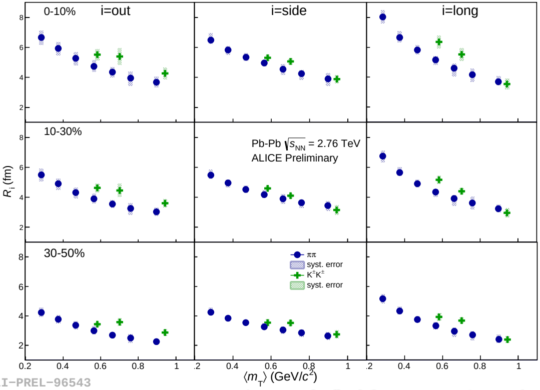


PhysRevC.92.054908

- Neutral kaons
  - PID via $\pi^+\pi^-$ decay channel (purity 95%) - easily identified up to 2 GeV/*c*
  - Strong FSI and Quantum Statistics corroborate to create femtoscopic effect, both included in the fit (Lednicky & Lyuoboshitz Sov.J.Nucl.Phys. 35,770 (1982))
- Charged kaons
  - PID: TPC+TOF for considerable momentum range up to 1.5 GeV/*c*
  - Bose-Einstein enhancement and dip at low *q* due to Coulomb
  - Bowler-Sinyukov fit $C(q) = N[1 - \lambda + \lambda K(q)(1 + \exp(-R^2 q^2)]$

3D pion and kaon femtoscopy

- R_{side} shows approximate m_T scaling
- R_{out}, R_{long} for kaons larger than for pions
- The difference increases for more central collisions
- The effect is more important for R_{long}



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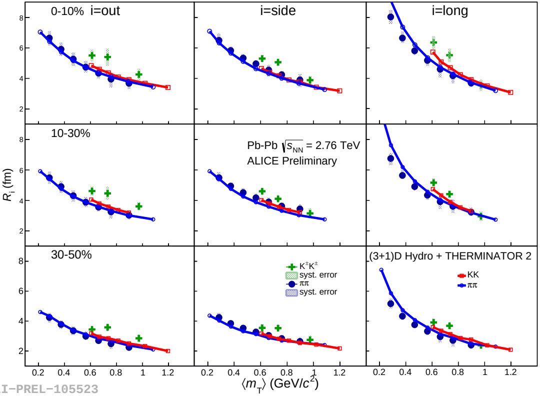
  Phys.Rev. C90 (2014) 064914



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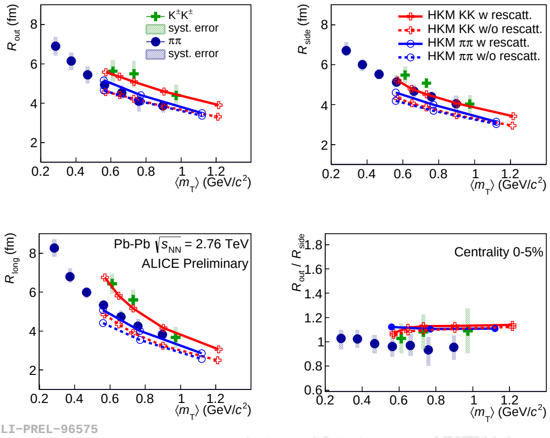
- HKM with rescatterings describes ALICE pion and kaon data
  Nucl.Phys. A 929 (2014)



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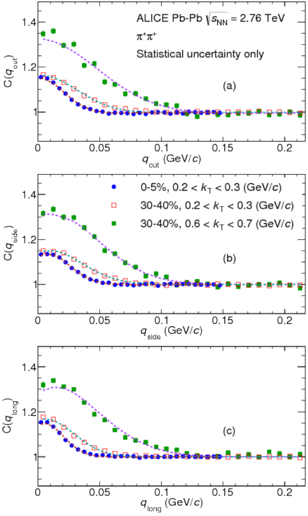
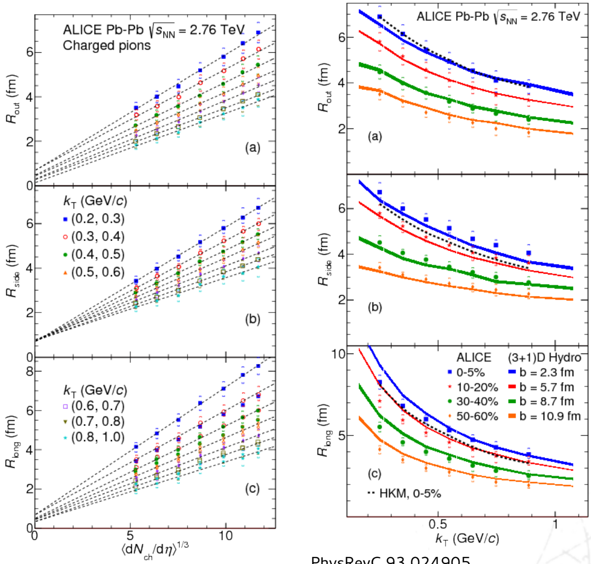
2π correlations in Pb–Pb



PhysRevC.93.024905

- Projections of the cartesian representation of the correlation function
- 2 centrality bins and 2 pair momentum ranges
- Evident growth of the width of the correlation effect $\rightarrow$ decrease of size with decreasing multiplicity and increasing k_T
- Flat background behaviour at large q
- Fitted with $C(\vec{q}) = N[(1-\lambda) + \lambda K(1 + exp(-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long})]$

2π radii in Pb–Pb



PhysRevC.93.024905

- Femtoscopic radii vs. k_T and centrality
- Radii scaling: linear in multiplicity and power-law in k_T
- Both dependencies in agreement with predictions from collective models
- Scaling similar to the one seen at lower energies