Femtoscopy analysis of ultrasoft pion trap at energies available at the CERN Large Hadron Collider

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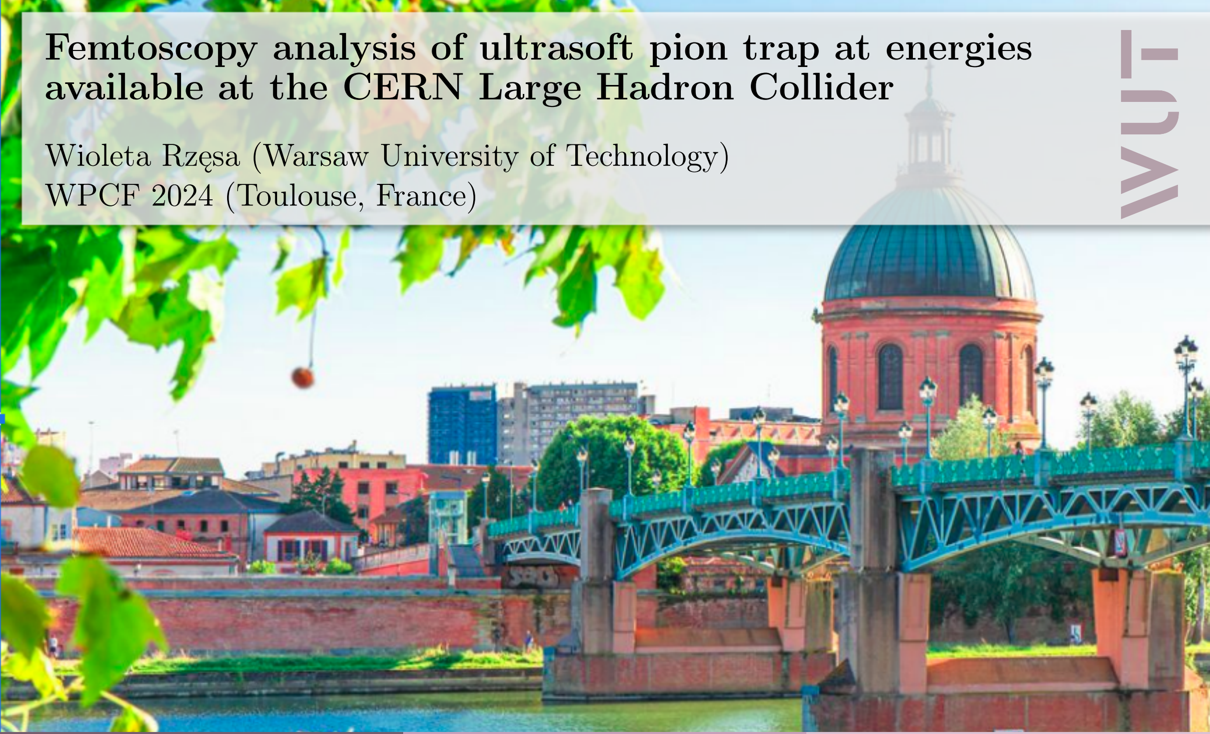
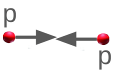
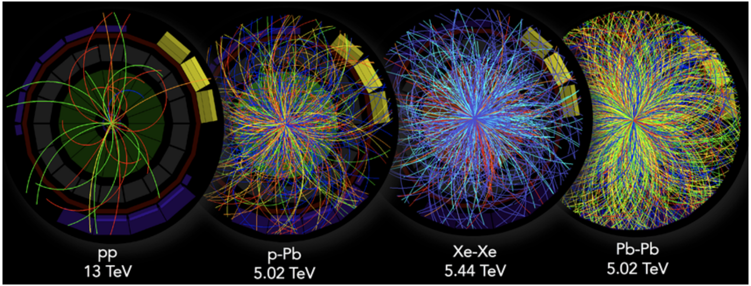
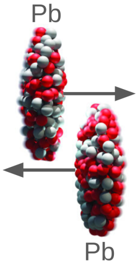
WPCF 2024 (Toulouse, France)



Collisions of relativistic particles and heavy ions

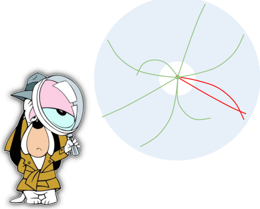


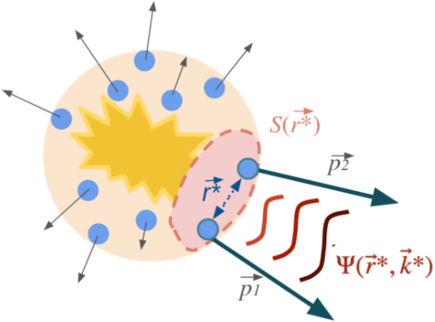




Is there a "pattern" between the tracks?

Femtoscopy





$$C(k^*) = \int S(r^*) \, |\Psi(k^*, r^*)|^2 \, d^3r^*$$

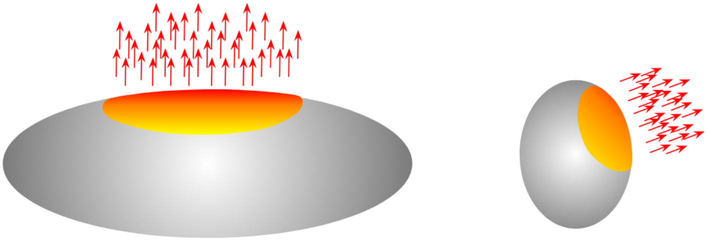
Source function

Wave function

Homogeneity

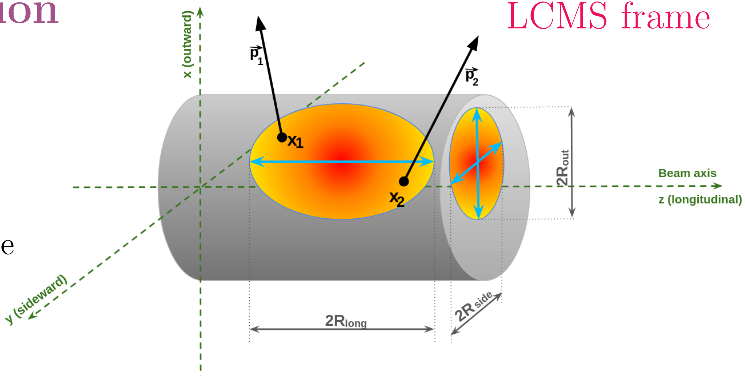
In femtoscopy we study the space-time spread of particles from the emitter identified as its **homogeneity region.**

Homogeneity region → area of the source from which particles are emitted with similar velocities and directions → **it is not the overall source!**



How to describe the homogeneity region? – the source function

LCMS frame



→ Direct information about the size in each direction.

→ Gaussian-based definition

$$S(r) \sim exp\left(-\frac{r_{out}^2}{2R_{ABout}^2} - \frac{r_{side}^2}{2R_{ABside}^2} - \frac{r_{long}^2}{2R_{ABlong}^2}\right),$$

where $R_{AB} = \sqrt{R_A^2 + R_B^2}$ is the homogeneity length for particles A and B of the pair.

How to reflect 3D shape with only one R?

PRF frame*

A center-of-mass of
the pair is at rest

$k^*_{\mathrm{A}} = -k^*_{\mathrm{B}}$

→Not trivial average over 3 directions.

→Gaussian based definition:

$$S(r) \sim exp\left(-\frac{r^2_{out}}{2R^2_{ABout}} - \frac{r^2_{side}}{2R^2_{ABside}} - \frac{r^2_{long}}{2R^2_{ABlong}}\right)$$

$$\downarrow$$

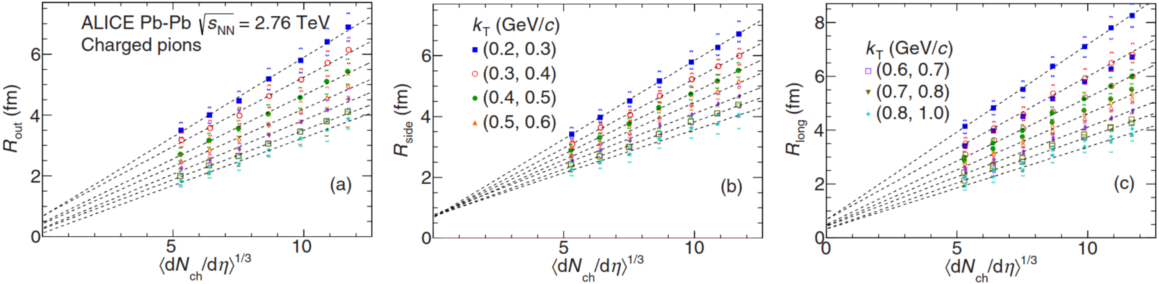
$$S(r^*) \sim r^{*2} exp\left(\frac{r^{*2}}{2R^2_{AB}}\right)$$

Observed scalings of the source sizes

A linear scaling

→ A linear scaling of the femtoscopic radii is universally observed versus cube root of the final state mean particle multiplicity $\langle dN_{ch}/d\eta\rangle^{1/3}$.

→ Observed for different momentum and particle types.



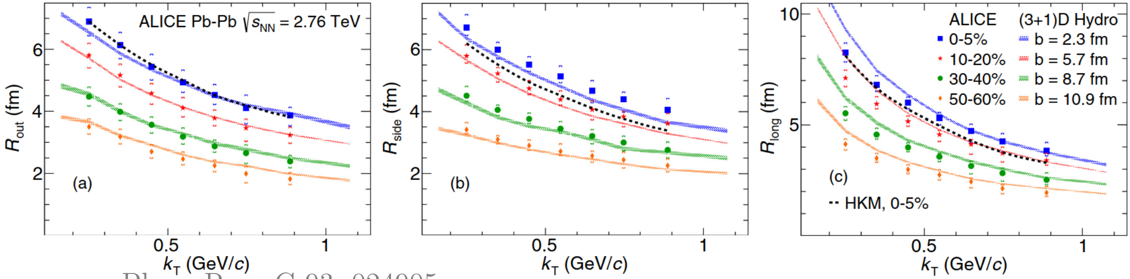
Phys. Rev. C 93, 024905

The more particles produced in the collision
the bigger femtoscopic volume.

A power-law scaling

→ The radii versus the pair transverse momentum exhibit a power-law-like scaling in pair transverse mass m_T.
→ Observed for all femtoscopic radii and all particle types.

$m_{\mathrm{T}} = \sqrt{< k_{\mathrm{T}} >^2 + m_0^2}$, where k_T is pair mean transverse momentum
$k_T = |\mathbf{p}_{T1} + \mathbf{p}_{T2}|/2$, and m_0 is particle mass)



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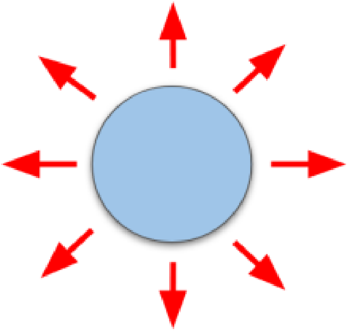
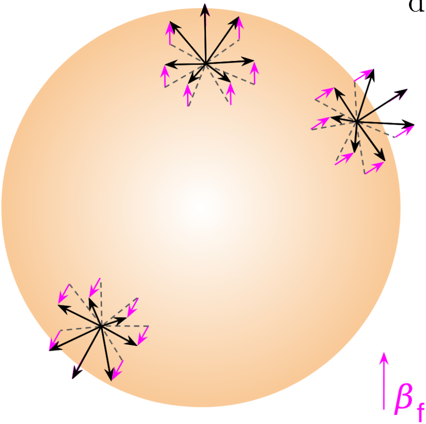
But where this m_T scaling come from?

Collective flow

The particles gain velocity due to hydrodynamic expansion originating from the non zero pressure gradient of the fireball.



Collective motion



All particles emitted close to each other, in radial direction pointing outwards from the center gain a **common velocity,** β_f from the collectivity.

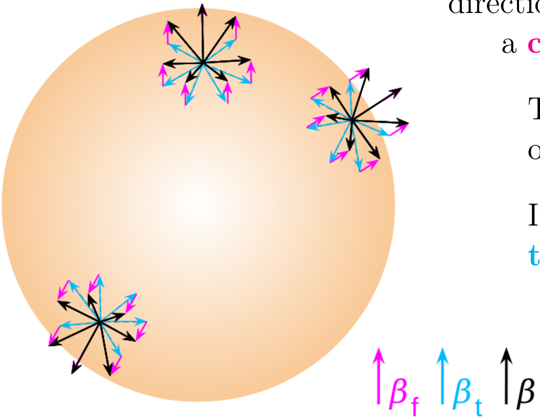
The process drives the space-time evolution of the system. It should apply to all particles.

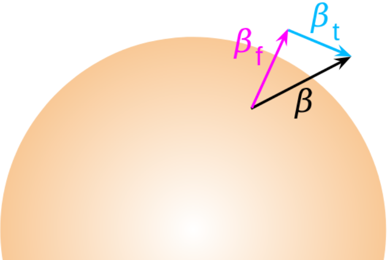
Collective motion

All particles emitted close to each other, in radial direction pointing outwards from the center gain a **common velocity,** β_f from the collectivity.

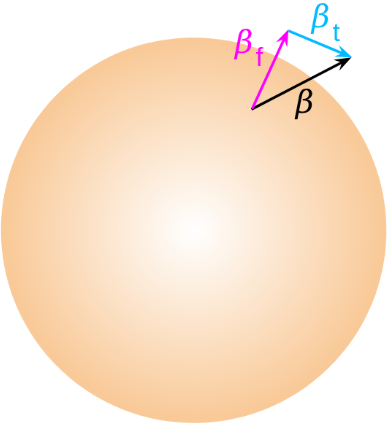
The process drives the space-time evolution of the system. It should apply to all particles.

In addition each particle gain a random **thermal velocity,** β_t.





Collective motion



$$\langle x_{out} \rangle = \frac{\langle r\beta_f \rangle}{\left\langle \sqrt{\beta_t^2 + \beta_f^2} \right\rangle}$$

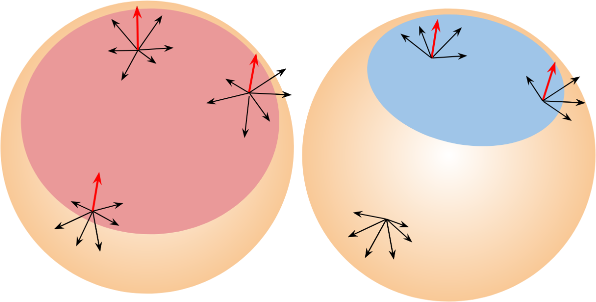
If β_f is dominant → all particles are emitted from the **edge** of the source

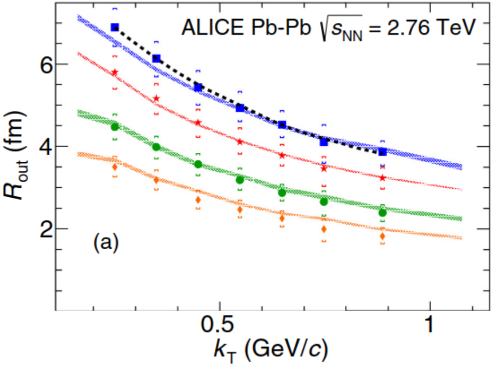
If β_t is dominant → all particles are emitted from the **whole** source

If β_f and β_t are similar → for different p_T we should observe different source sizes and assymmetry (shift).

Consequence of flow

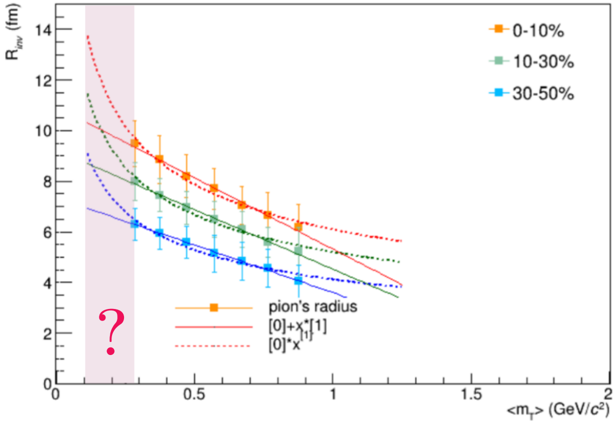
As observed p_{T} grows, the region were pairs with similar velocity and direction can be emitted gets smaller and shifted toward the edge of the source.





Power-law?

But what if power-law is not so universal description?



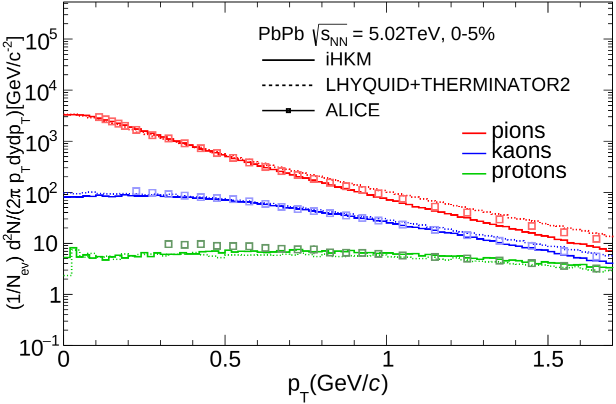
Simulation study of ultra-soft pions

Modeling the hydrodynamic of heavy-ion collisions

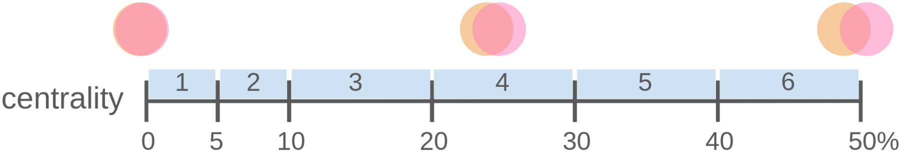
→ integrated HydroKinetic Model: **iHKM**
→ hydrodynamic model LHYQUID coupled to the statistical hadronisation code THERMINATOR2: **LHYQUID+THERMINATOR2**

The two models differ in the initial conditions and the way of modeling the system evolution.

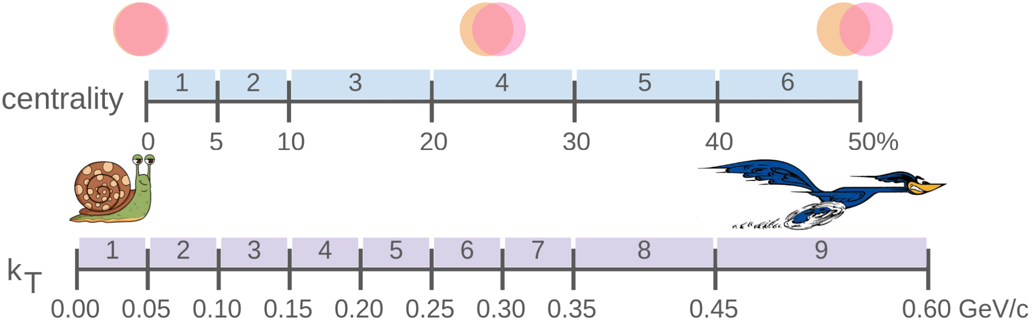
Both well describe measured data.



$\pi^+\pi^+ \oplus \pi^-\pi^-$ pairs



$\pi^+\pi^+ \oplus \pi^-\pi^-$ pairs



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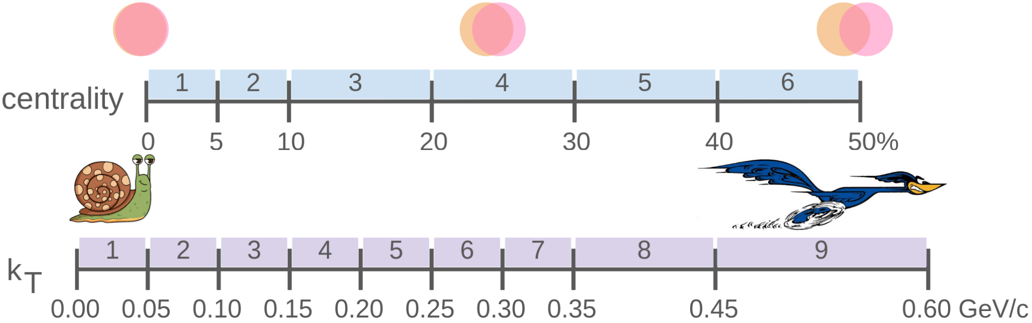


centrality

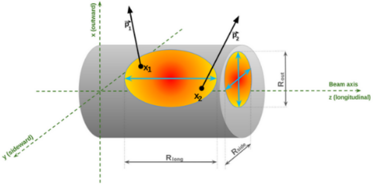
1	2	3	4	5	6

0 5 10 20 30 40 50%

k_T

1	2	3	4	5	6	7	8	9

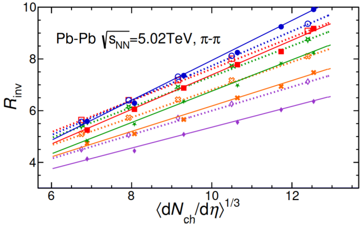
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.45 0.60 GeV/c



Analysis R_{out},R_{side},R_{long}, R_{inv}

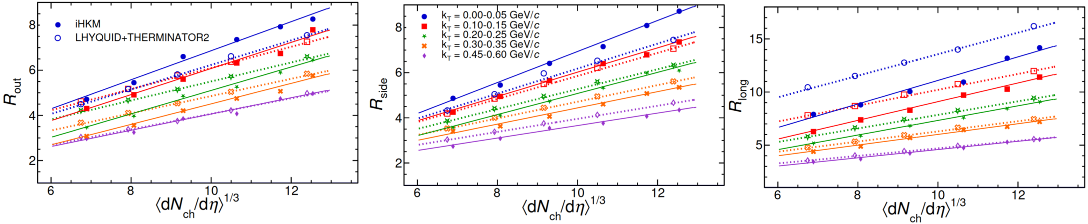
$\langle \mathrm{d}N/\mathrm{d}\eta \rangle^{1/3}$ dependence

1D



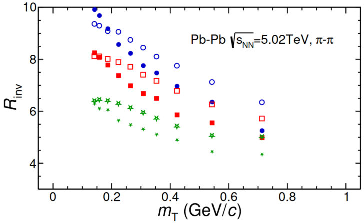
Linear scaling preserved in all k_T bins.

3D



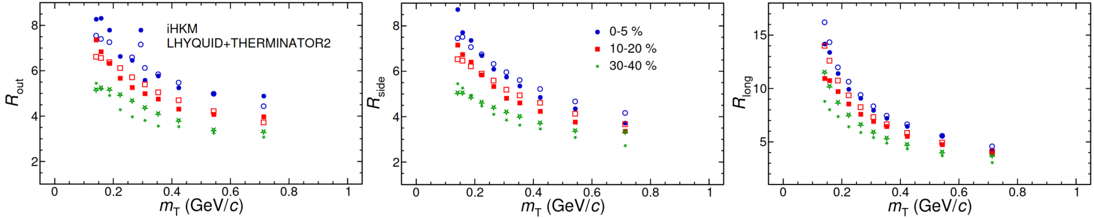
m_T dependence

1D

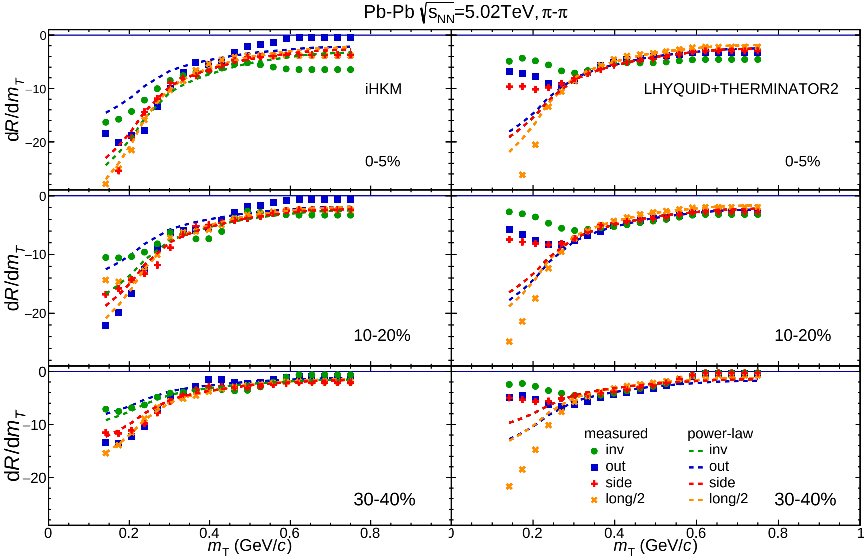


Radii in low m_T visibly change the behavior in most of the cases.

3D



$\mathrm{dR/dm_T}$ dependence



Constant slope in low m_T in R_{inv} and transverse directions of 3D

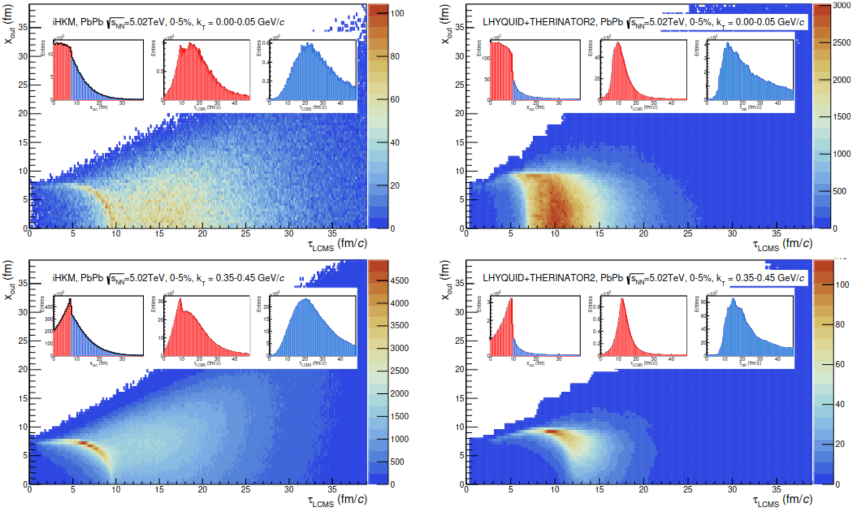
Emission position vs time

model 1

model 2

ultra-soft pions

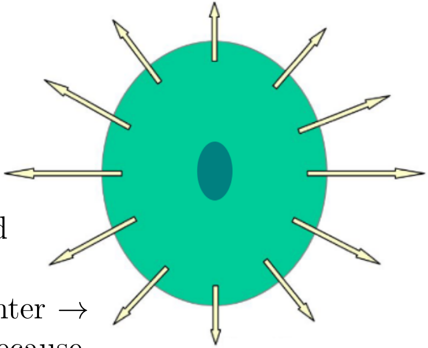
normal pions



Soft pions are kept inside and escape the system later than other pions.

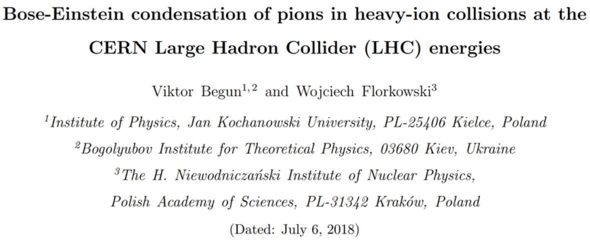
Trap?

The gradient of density is not equal
in the radial directions: it is more strong
at the periphery, and less strong in the center,
where soft hadrons mostly come from.



The hadrons stay together for a longer time
- Very low transverse collective velocity;
- Smaller density gradient in the center as compared to non-central and periphery parts.
- The initially highest density in the geometrical center $\rightarrow$ this high-mass-density region is difficult to expand because of the relatively small transverse pressure gradient in the center.

Condensation of pions?

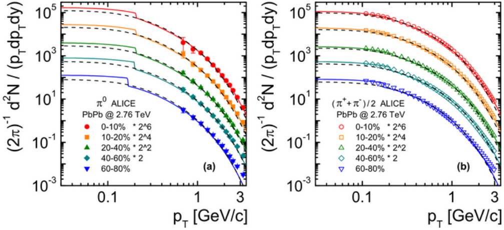


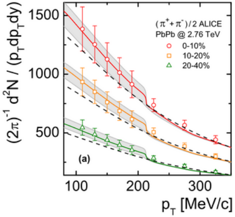
Bose-Einstein condensation of pions in heavy-ion collisions at the CERN Large Hadron Collider (LHC) energies

Viktor Begun[1,2] and Wojciech Florkowski[3]

[1] *Institute of Physics, Jan Kochanowski University, PL-25406 Kielce, Poland*
[2] *Bogolyubov Institute for Theoretical Physics, 03680 Kiev, Ukraine*
[3] *The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Kraków, Poland*

(Dated: July 6, 2018)





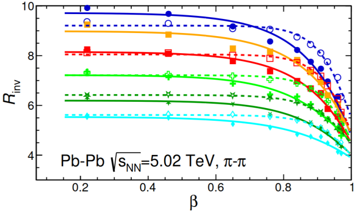
> “Our study shows that the pion condensate rate in the present data is 2% in the most central collisions and 7 – 8% in peripheral collisions (with a sudden increase to 19% in the most peripheral collisions).”

Velocity dependence

$\beta = k_T/m_T$, fitted with: $R(\beta) = \frac{a}{e^{(\beta-b)/c}+1}$

1D

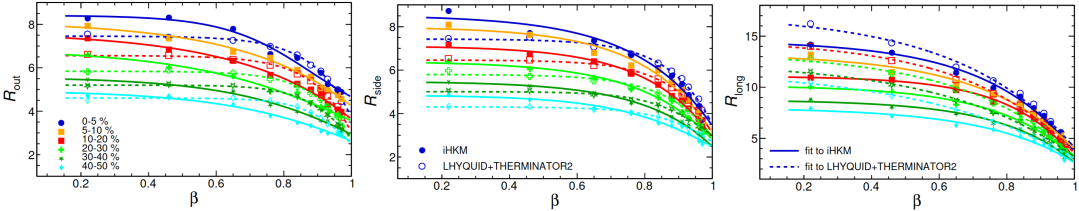
.



β decreases→ R became similar

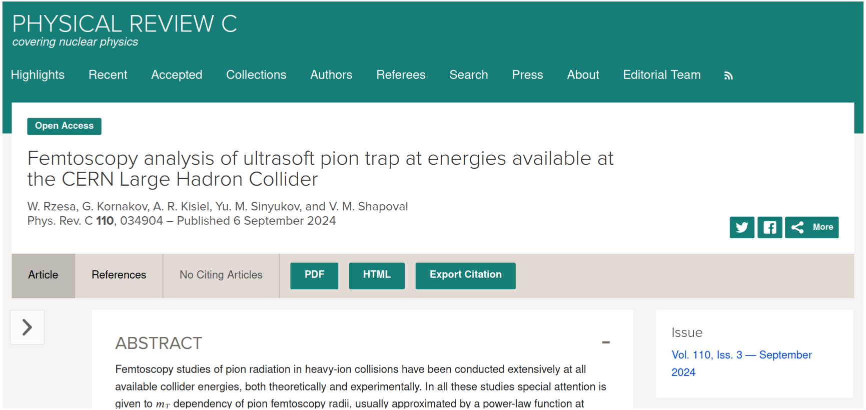
Idea: such value could be used to determine an extrapolated value of the radii for ultra-soft pions, instead of the historically used power-law m_T scaling.

3D



Conclusions from the ultra-soft pion's simulations

The power-low description of pion's source size m_{T}-scaling is not the best solution for ultra-soft region → especially in $1D$ source study the description with the power-law is not satisfactory.



Femtoscopy analysis of ultrasoft pion trap at energies available at the CERN Large Hadron Collider

W. Rzesa, G. Kornakov, A. R. Kisiel, Yu. M. Sinyukov, and V. M. Shapoval

Phys. Rev. C **110**, 034904 – Published 6 September 2024

ABSTRACT

Femtoscopy studies of pion radiation in heavy-ion collisions have been conducted extensively at all available collider energies, both theoretically and experimentally. In all these studies special attention is given to m_T dependency of pion femtoscopy radii, usually approximated by a power-law function at

Issue

Vol. 110, Iss. 3 — September 2024

Thank you for your attention!