Hidden puzzle of the correlation femtoscopy at the top RHIC and LHC energies and its possible solution

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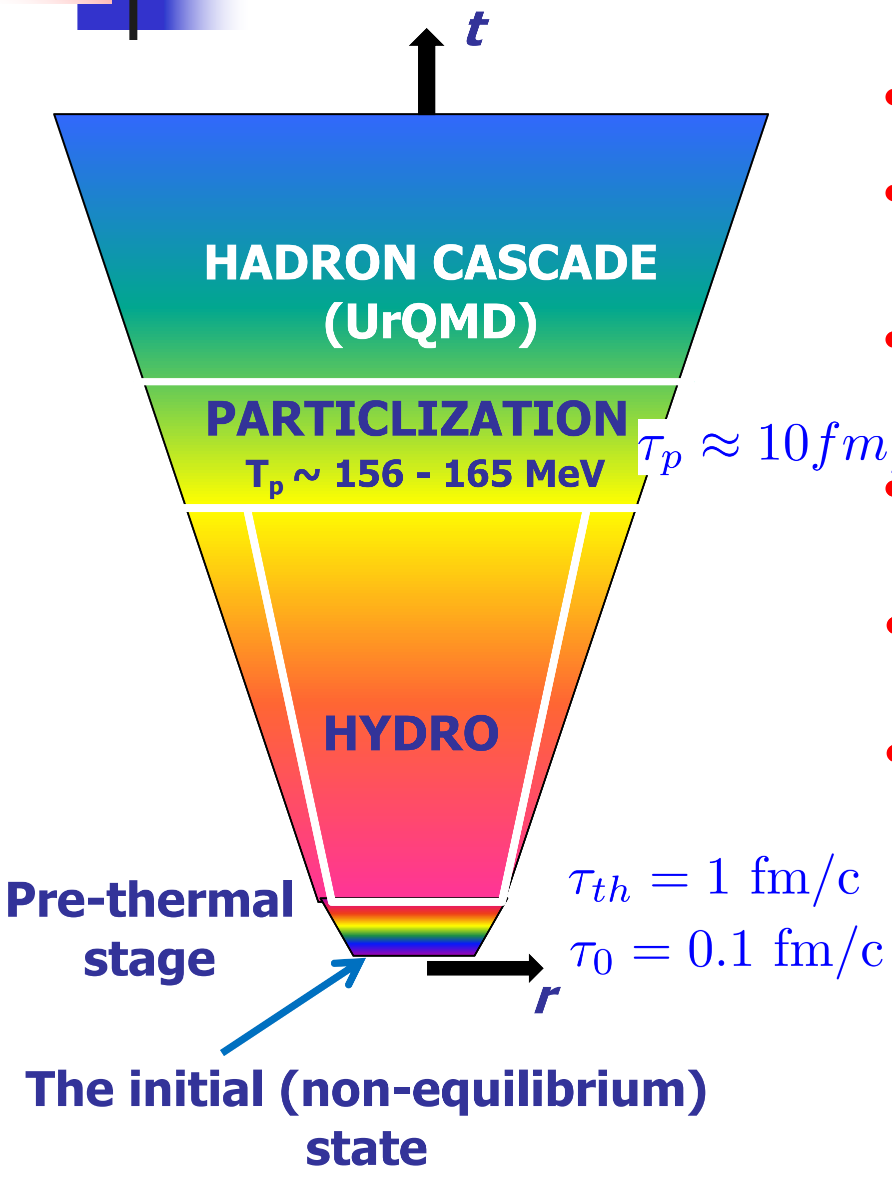
Based on: Yu. S., V. Shapoval, M. Adzhymambetov
Universe 9 433 (2023); arXiv:2310.16233 (2023).

November 2023, WPCF & Resonance

Integrated HydroKinetic Model: HKM → iHKM



Complete algorithm incorporates the stages:

- generation of the initial states: (MC Glaub & CGC)
- thermalization of initially non-thermal matter;
- viscous chemically equilibrated relativistic (Israel-Steward) hydrodynamic expansion,
- particlization of expanding medium at the hadronization area ;
- a switch to UrQMD cascade with near equilibrium hadron gas as input;
- simulation of observables.

Yu.S., Akkelin, Hama: PRL 89 (2002) 052301;
… + Karpenko: PRC 78 (2008) 034906;
Karpenko, Yu.S. : PRC 81 (2010) 054903;
… PLB 688 (2010) 50;
Akkelin, Yu.S. : PRC 81 (2010) 064901;
Karpenko, Yu.S., Werner: PRC 87 (2013) 024914;
Naboka, Akkelin, Karpenko, Yu.S. : PRC 91 (2015) 014906;
Naboka, Karpenko, Yu.S. PRC 93 (2016) 024902.

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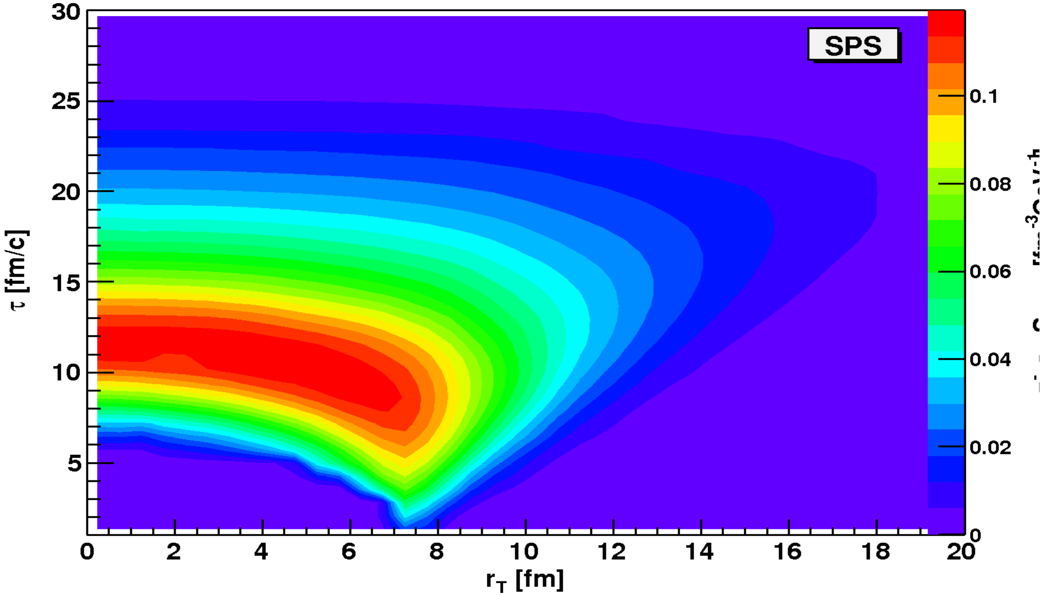
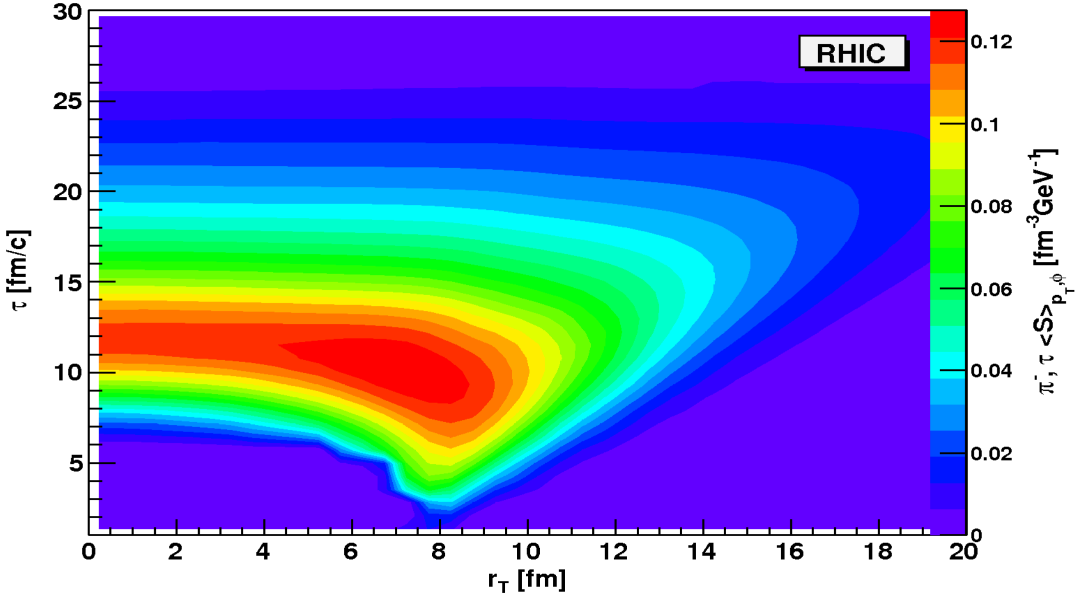
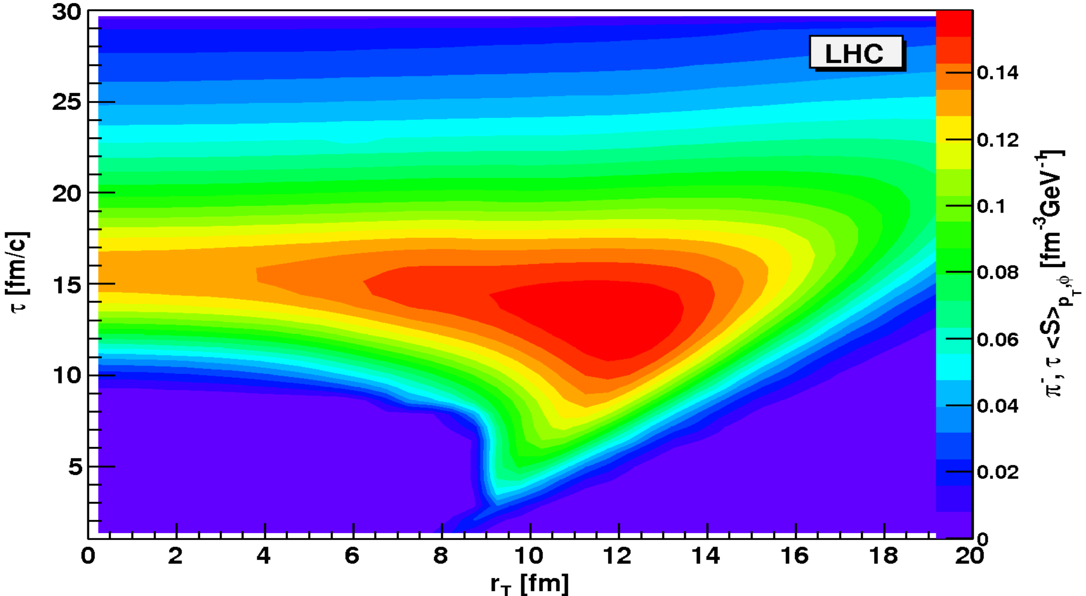
“Ancient” RHIC HBT puzzle (Ro/Rs ~1)





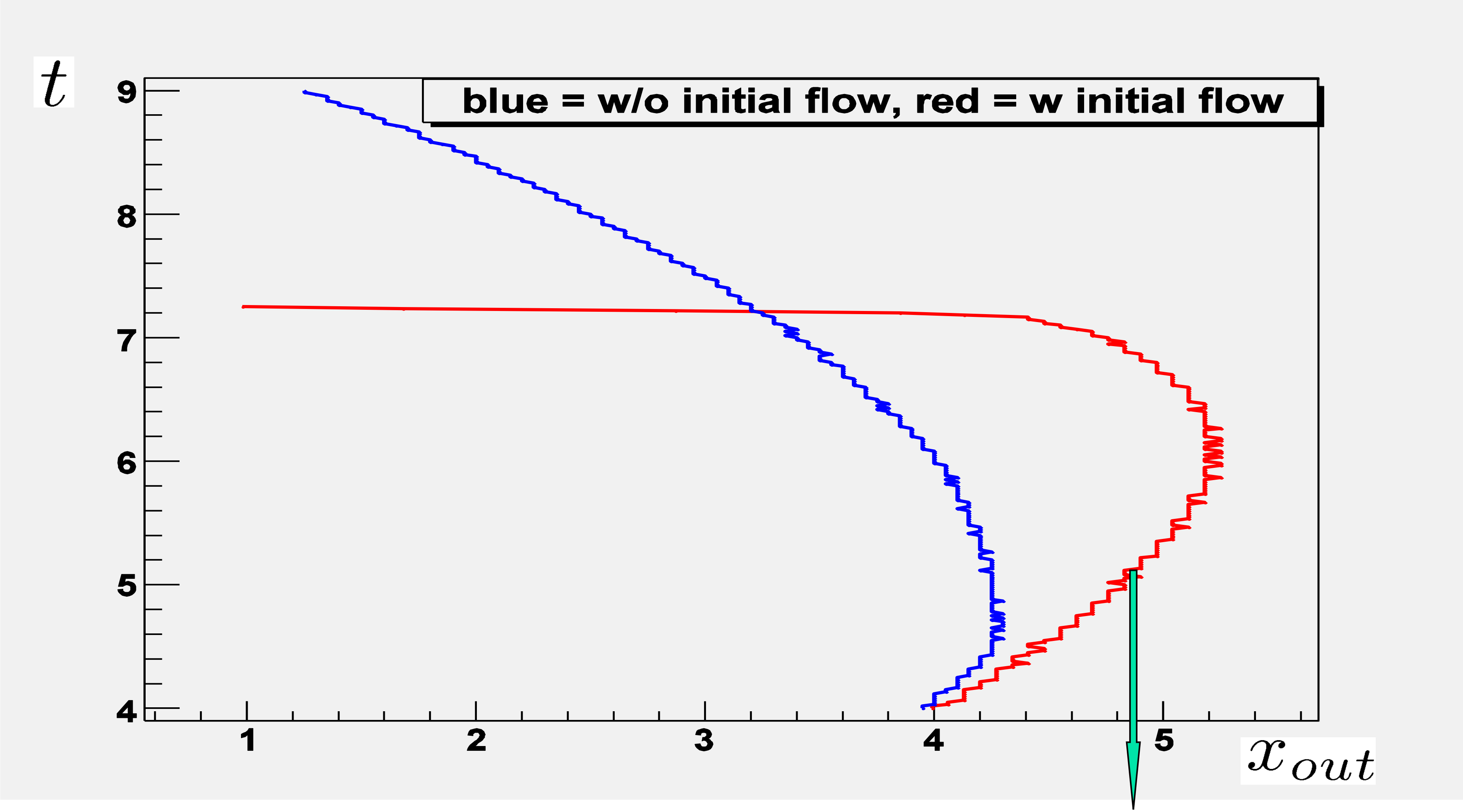
$$R_{out}^2 \approx R_{side}^2 + v^2\langle\triangle t^2\rangle_p - 2v\langle\triangle x_{out}\triangle t\rangle_p, v = \frac{p_T}{p^0}$$

Emission functions for top SPS, RHIC and LHC energies (HKM results)



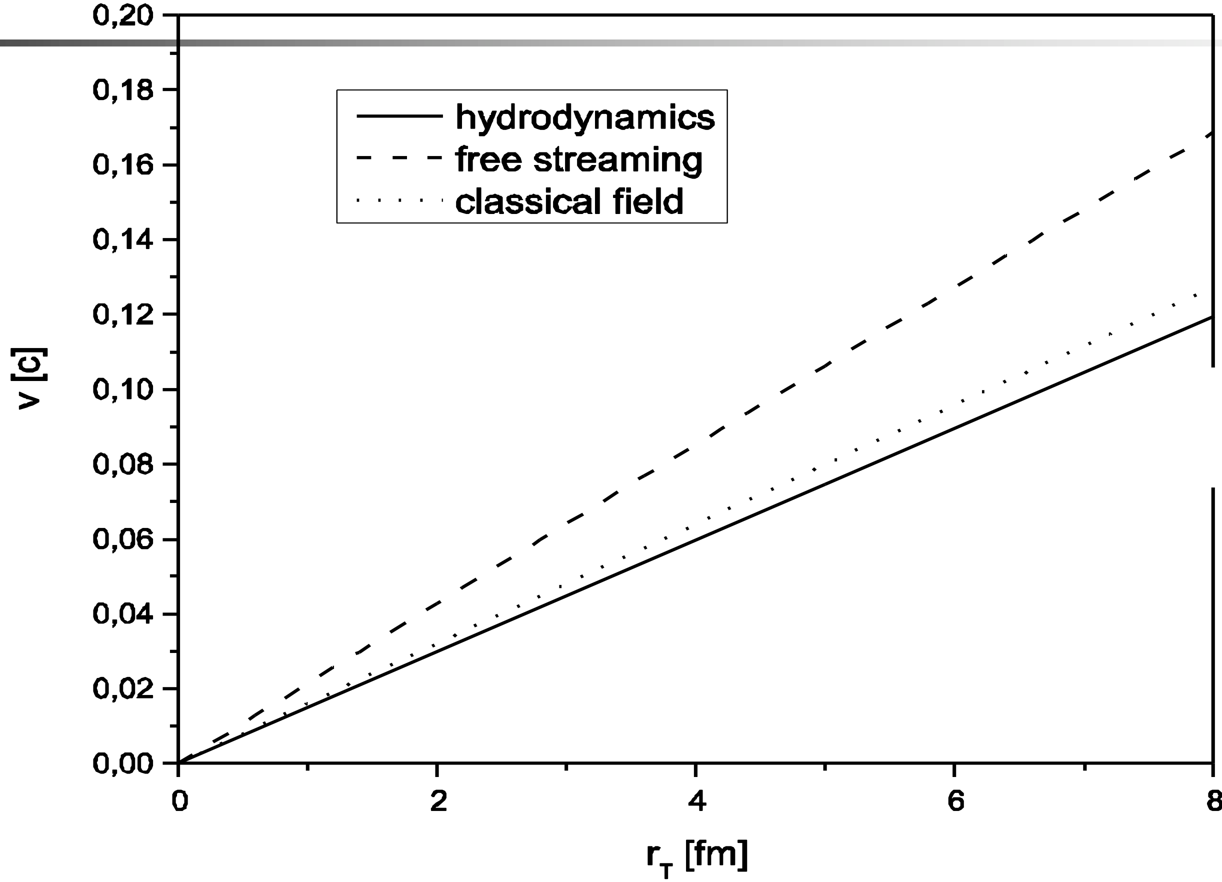
When particle radiation starts – near 1 fm/c from periphery - system already has transverse expansion !

Initial flows and Ro/Rs ratio (t_0=1-2 fm/c)



$$R^2_{out} \approx R^2_{side} + v^2\langle\triangle t^2\rangle_p - 2v\langle\triangle x_{out}\triangle t\rangle_p, v = \frac{p_T}{p^0}$$

Collective velocities developed between τ_0=0.3 and τ=1.0 fm/c



Central collisions

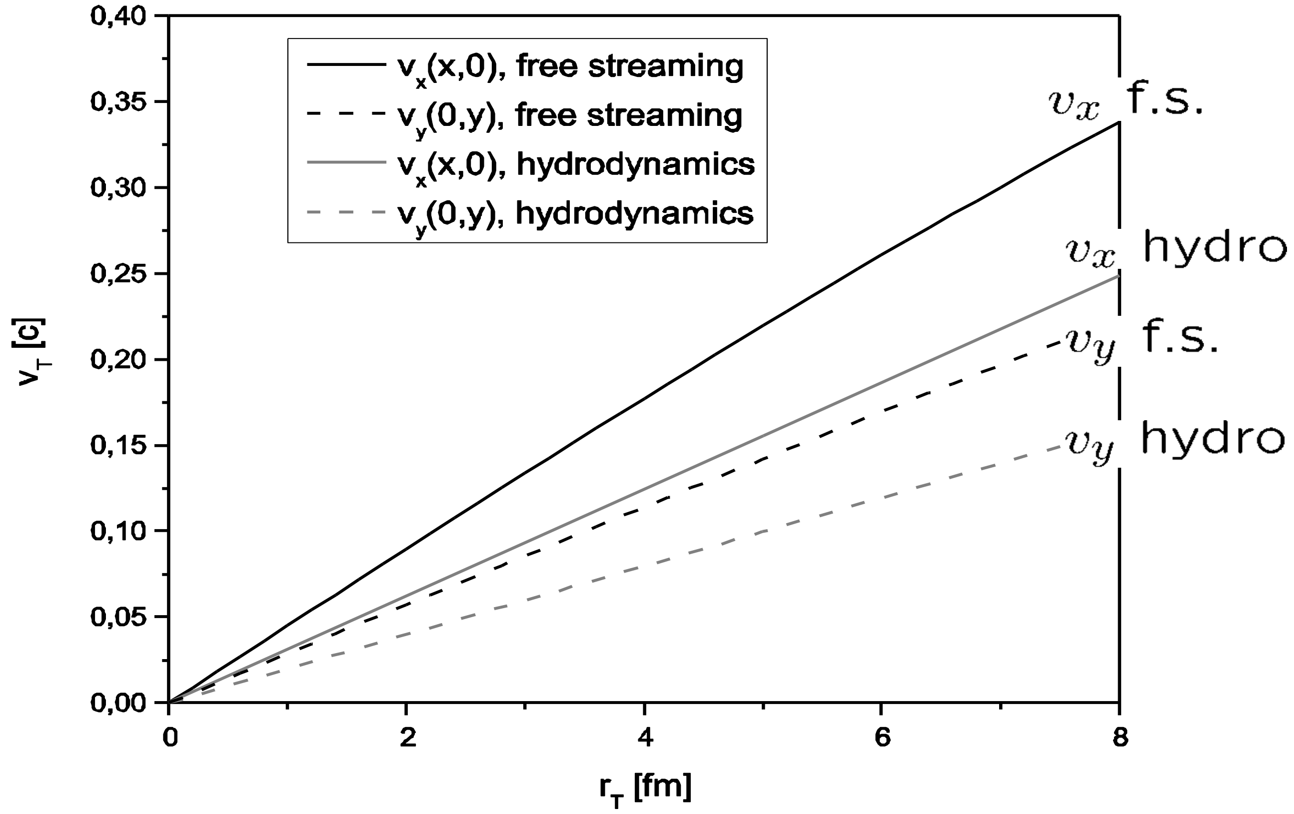
$$T^{\mu\nu}(x) = \int d^3p \frac{p^\mu p^\nu}{p_0} f(x,p)$$

$$u^\mu = \frac{T^{\mu\nu}u_\nu}{T^{\mu\nu}u_\mu u_\nu} = \frac{T^{\mu\nu}u_\nu}{\epsilon}$$

Collective velocity developed at pre-thermal stage from proper time tau_0 =0.3 fm/c by supposed thermalization time tau_th = 1 fm/c for scenarios of partonic free streaming and free expansion of classical field. The results are compared with the hydrodynamic evolution of perfect fluid with hard equation of state p = 1/3 epsilon started at τ_0 . Impact parameter b=0.

Yu.S. Acta Phys.Polon. B37 (2006) 3343**;** Gyulassy, Yu.S., Karpenko, Nazarenko Braz.J.Phys. 37 (2007) 1031. Yu.S., Nazarenko, Karpenko: Acta Phys.Polon. B40 1109 (2009) .

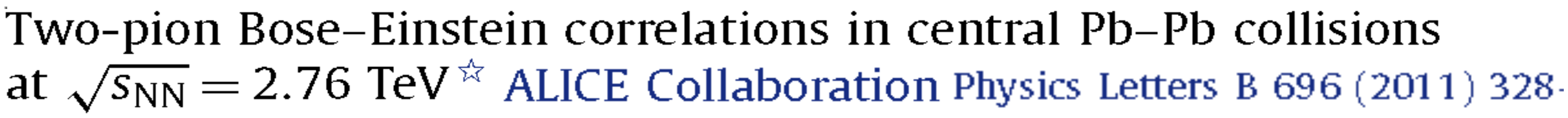
Collective velocities and their **anisotropy** developed between τ_0 = 0.3 and τ =1.0 fm/c



Non-central collisions
b=6.3 fm

Collective velocity developed at pre-thermal stage from proper time τ_0=0.3 fm/c by supposed thermalization time tau_i = 1 fm/c for scenarios of partonic free streaming. The results are compared with the hydrodynamic evolution of perfect fluid with hard equation of state p = 1/3 epsilon started at τ_0 . Impact parameter b=6.3 fm.

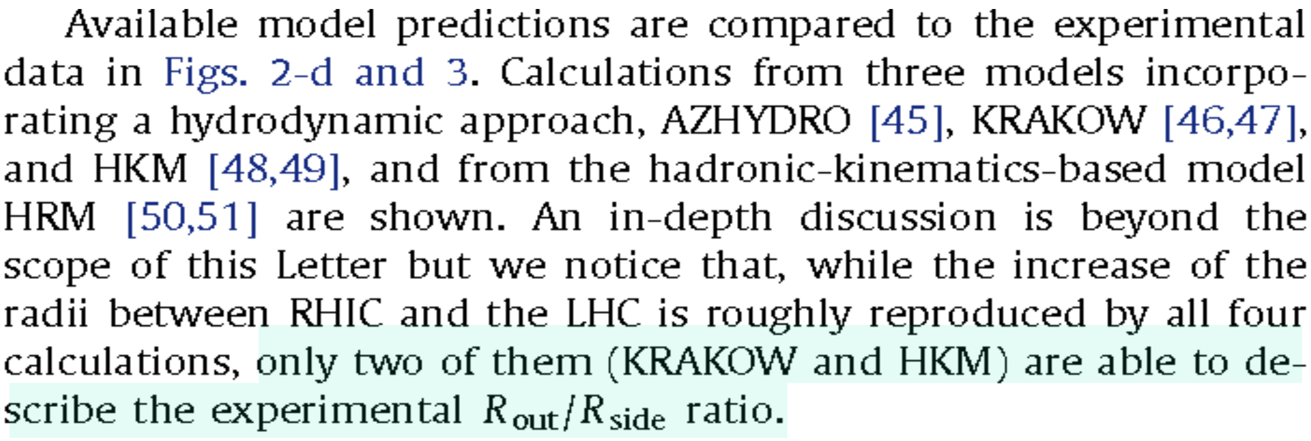
HKM prediction: solution of the HBT Puzzle



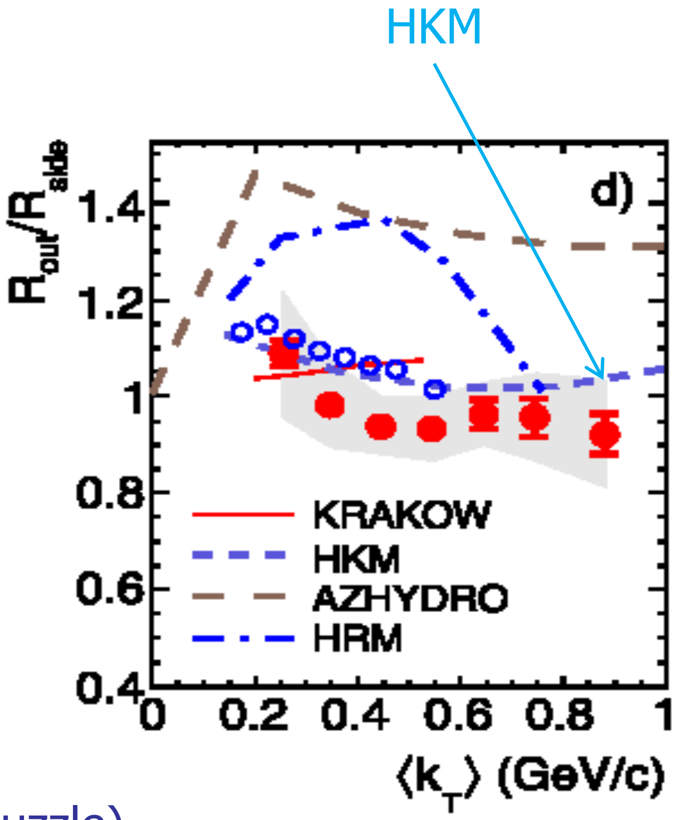
Two-pion Bose–Einstein correlations in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV☆ ALICE Collaboration Physics Letters B 696 (2011) 328-

ALICE

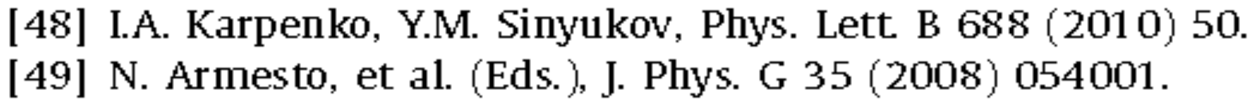
Quotations:



Available model predictions are compared to the experimental data in Figs. 2-d and 3. Calculations from three models incorporating a hydrodynamic approach, AZHYDRO [45], KRAKOW [46,47], and HKM [48,49], and from the hadronic-kinematics-based model HRM [50,51] are shown. An in-depth discussion is beyond the scope of this Letter but we notice that, while the increase of the radii between RHIC and the LHC is roughly reproduced by all four calculations, only two of them (KRAKOW and HKM) are able to describe the experimental R_{out}/R_{side} ratio.



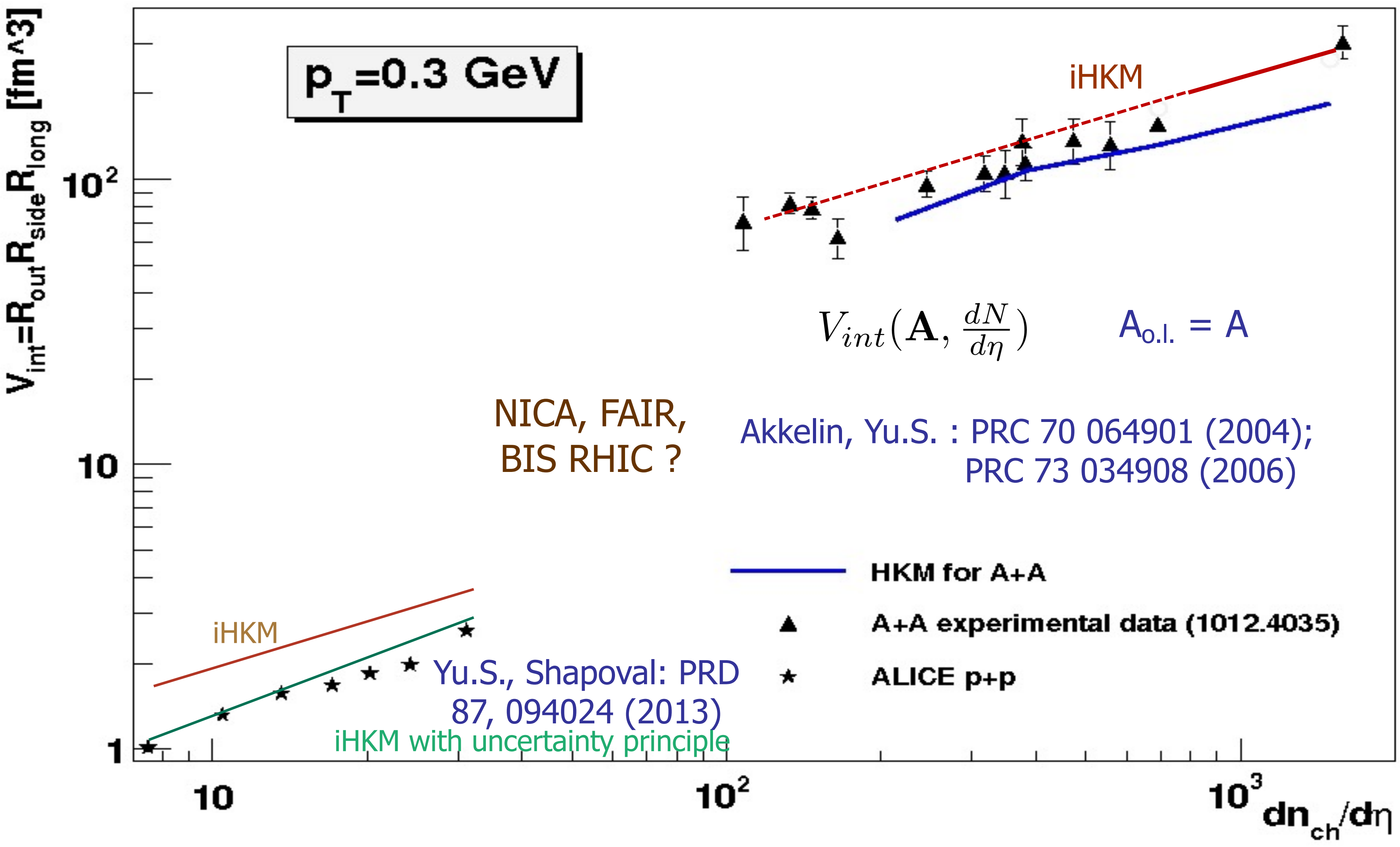
HKM



[48] I.A. Karpenko, Y.M. Sinyukov, Phys. Lett. B 688 (2010) 50.
[49] N. Armesto, et al. (Eds.), J. Phys. G 35 (2008) 054001.

(includes contribution Karpenko, Yu.S. about solution of HBT Puzzle)

Interferometry volume Vint in LHC p-p and **central** Au-Au, Pb-Pb collisions



$$V_{int}(\mathbf{A}, \frac{dN}{d\eta})$$

$A_{o.l.}$ = A

NICA, FAIR,
BIS RHIC ?

Akkelin, Yu.S. : PRC 70 064901 (2004);
PRC 73 034908 (2006)

Yu.S., Shapoval: PRD 87, 094024 (2013)

iHKM with uncertainty principle

$V_{int}(\mathbf{A}, \frac{dN}{d\eta} = fixed)$

Eur. Phys. J. A (2020) 56:260

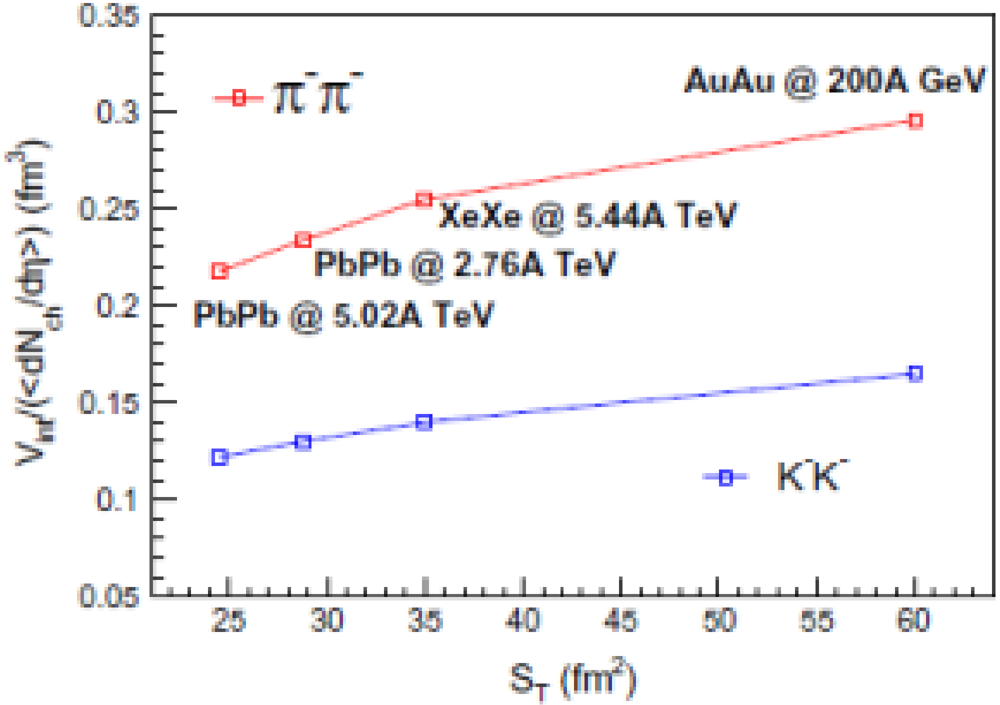
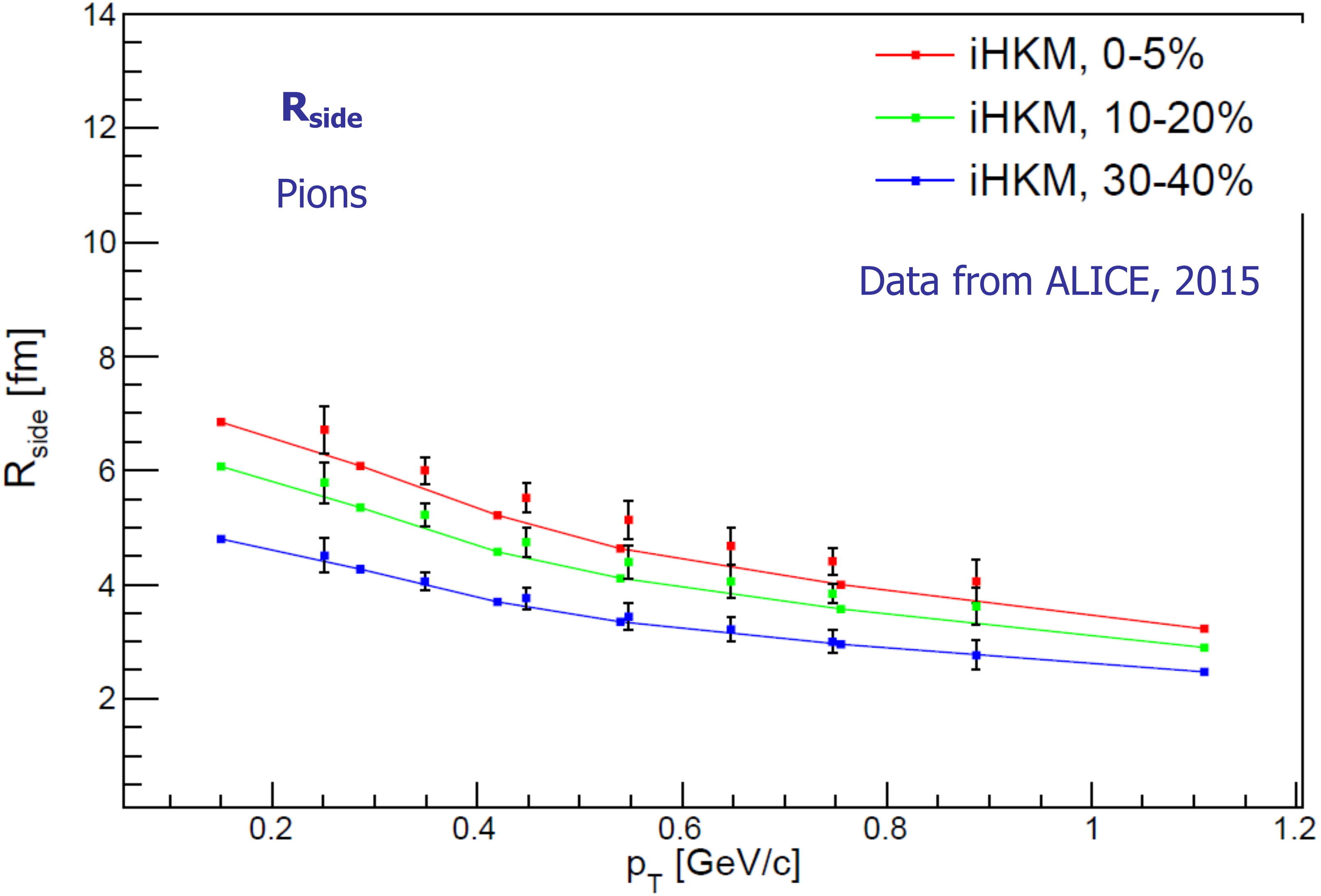
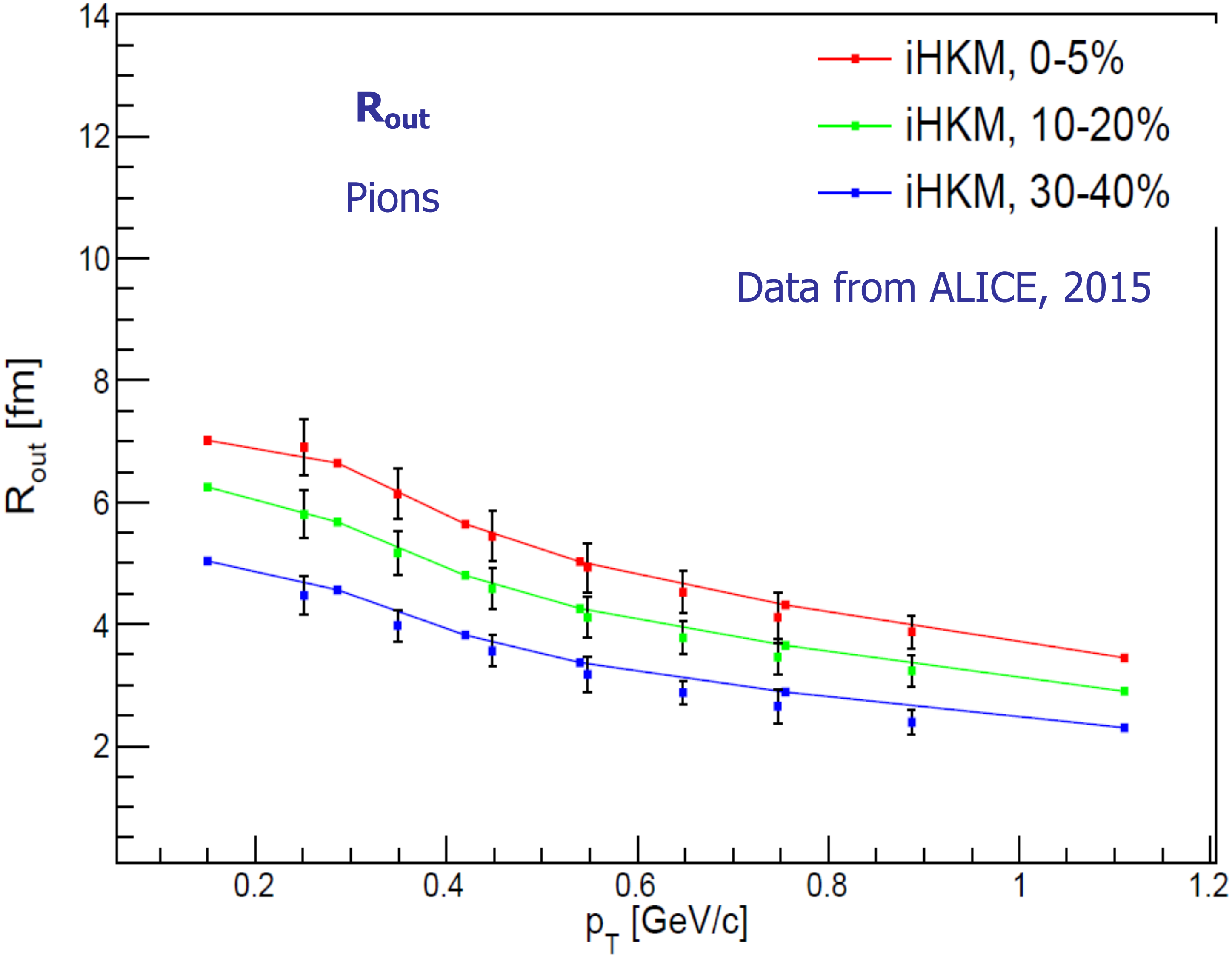


Fig. 15 The pion and kaon interferometry volume $V_{int} = R_{out}R_{side}R_{long}$, divided by the mean charged particle density $\langle dN_{ch}/d\eta \rangle$, calculated in iHKM for different relativistic heavy-ion collisions, characterized by the areas S_T of the colliding nuclei initial transverse overlapping. The corresponding collision centralities can be found in Table 2. The interferometry radii correspond to the pair transverse momentum $0.2 < k_T < 0.3$ GeV/c

Experiment	Centrality (%)	$\langle dN_{ch}/d\eta \rangle$
Au+Au @ 200 GeV	0–5	688
Pb+Pb @ 2.76 TeV	19–28	693
Pb+Pb @ 5.02 TeV	23–33	677
Xe+Xe @ 5.44 TeV	10–19	680



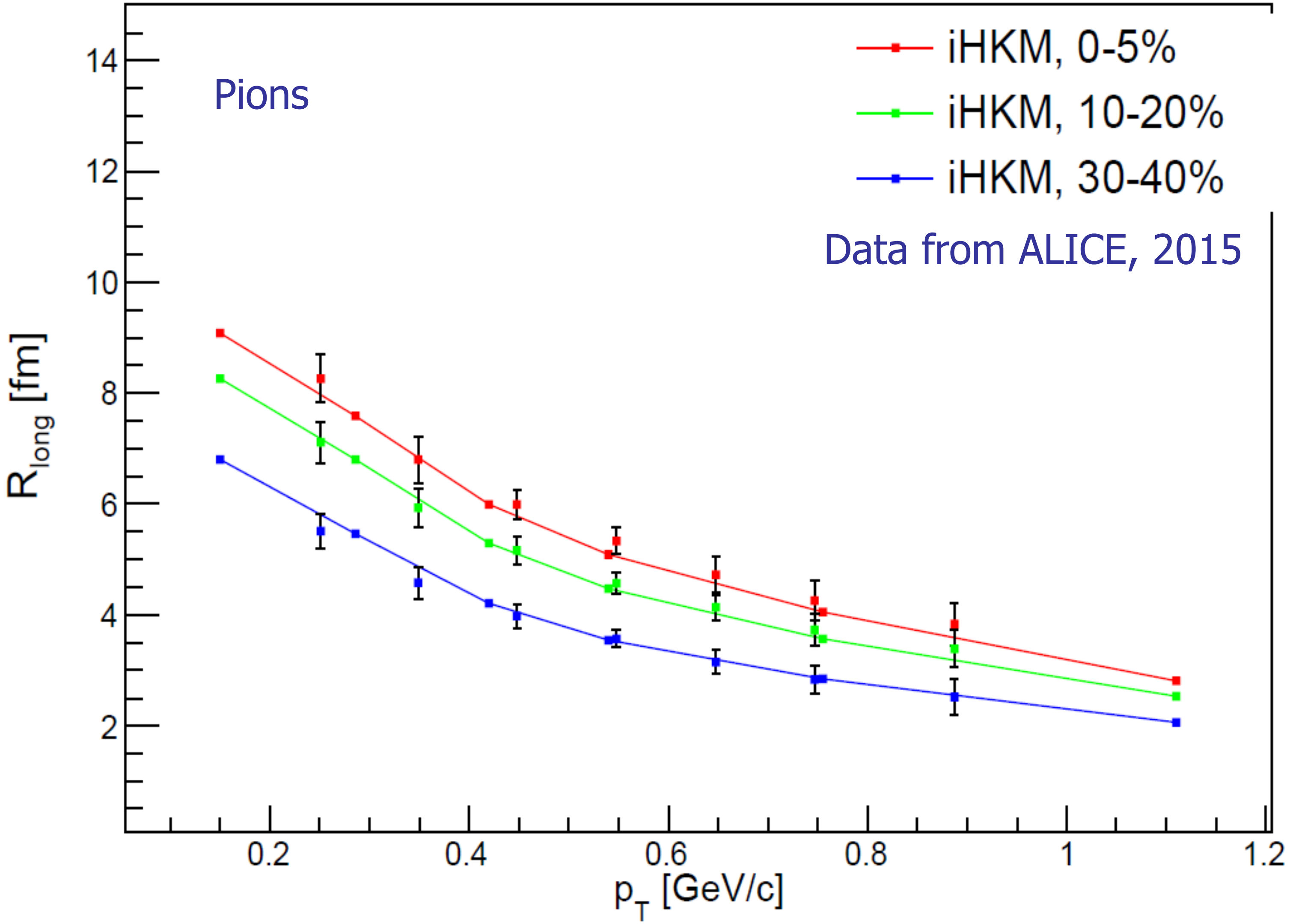
The R_{side} dependence on transverse momentum for different centralities in the iHKM scenario under the same conditions as in Fig. 1. The experimental data are from [33].



The R_{out} dependence on transverse momentum for different centralities in the iHKM basic scenario under the same conditions as in Fig. 1.

General Conclusion: iHKM describes femtoscopy results at top RHIC and LHC energies

quite good/excellently.



Eur. Phys. J. A (2020) 56:260
https://doi.org/10.1140/epja/s10050-020-00266-x

Reviev

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PHYSICAL JOURNAL A

Femtoscopy scales and particle production in the relativistic heavy ion collisions from Au+Au at 200 AGeV to Xe+Xe at 5.44 ATeV within the integrated hydrokinetic model

V. M. Shapoval[1] , M. D. Adzhymambetov[1] , Yu. M. Sinyukov[1],
1 Bogolyubov Institute for Theoretical Physics, 14b Metrolohichna street, Kiev 03143, Ukraint

The recent results on the main soft observables,including hadron and photon yields and particle numberratios, pT spectra, flow harmonics, as well as the femtoscopyradii, obtained within the integrated hydrokinetic model(iHKM) for high-energy heavy-ion collisions are reviewedand re-examined. The cases of different nuclei colliding at different energies are considered: Au+Au collisions at thetop RHIC energy$sNN = 200$ GeV, Pb+Pb collisions at the LHC energies $sNN = 2.76$ TeV and $\surd sNN = 5.02$ TeV, and the LHC Xe+Xe collisions a $sNN = 5.44$ TeV. The effect of the initial conditions and the model parameters,including the utilized equation of state (EoS) for quark-gluon phase, on the simulation results, as well as the role of the finalafterburner stage of the matter evolution are discussed. Thepossible solution of the so-called “photon puzzle” is considered. The attention is also paid to the dependency of the interferometry volume and individual interferometry radii on the initial transverse geometrical size of the system formed in the collision.

Results of saddle point method at the hypersurface of maximal emission

Yu.M. Sinyukov, V.M. Shapoval,
V.Yu. Naboka, Nucl. Phys. A **946**, 227 (2016)

$$p_0 \frac{d^3N}{d^3p} = \int_{\sigma_{m.e.}(p)} d\sigma_\mu p^\mu f_{l.eq.}(x,p),$$

$$C(p,q) \approx 1 + \frac{\left| \int_{\sigma_{m.e.}(k)} d\sigma_\mu k^\mu f_{l.eq.}(x,k) \exp(iqx) \right|^2}{\left(\int_{\sigma_{m.e.}(k)} d\sigma_\mu k^\mu f_{l.eq.}(x,k) \right)^2}.$$

$$p_0 \frac{d^3N}{d^3p} \propto \exp\left[-(m_T/T + \alpha)(1-\bar{v}_T^2)^{1/2}\right],$$

defines transverse slope of the spectra for boost-inv. long expansion

$$R_{\rm long}^2(m_T) = \tau^2 \lambda^2 \left(1 + \frac{3}{2}\lambda^2\right),$$

defines long-femto radius

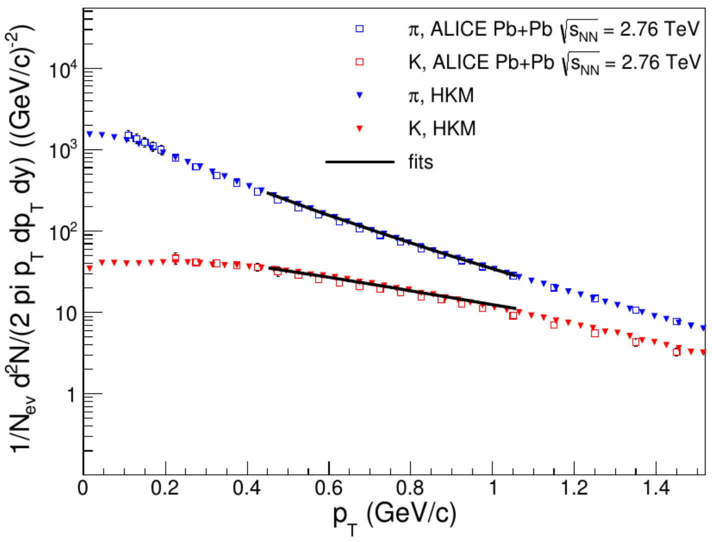
$$\lambda^2 = \frac{T}{m_T}(1-\bar{v}_T^2)^{1/2},\ \bar{v}_T = k_T/(m_T + \alpha T)$$

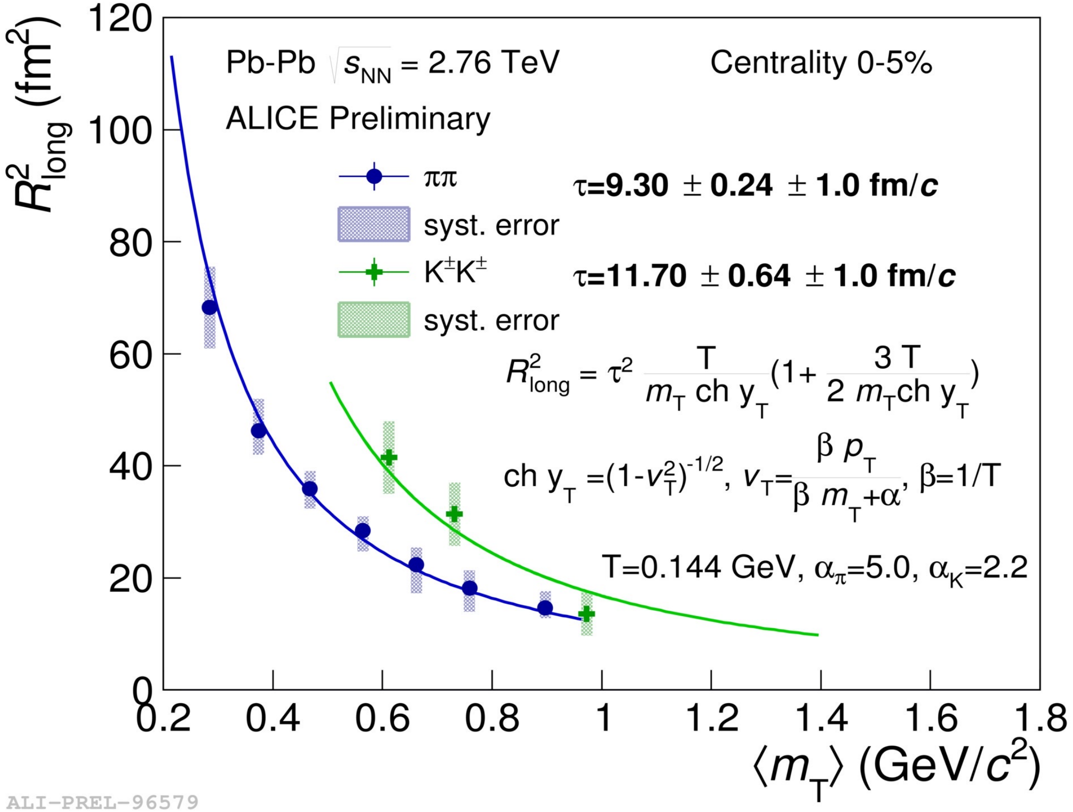
Where τ *is (proper) time*, T *is temperature and* α *defines intensity of the transverse flow at the area of hypersurface of maximal emission in selected momentum interval around* $p \cong k$

Extraction of emission time from fit R_{long}

The new formula for extraction of the maximal emission time for the case of strong transverse flow was used (**Yu. S., Shapoval, Naboka, Nucl. Phys.** A 946 (2016) 227)

The parameters of freeze-out: T and "intensity of transverse flow" α were fixed by fitting π and K spectra (arxiv:1508.01812)





ALI-PREL-96579

ALICE Coll. arXiv:1709.01731 (PRC, 2017)

Other analytic approximations, hydro evolution

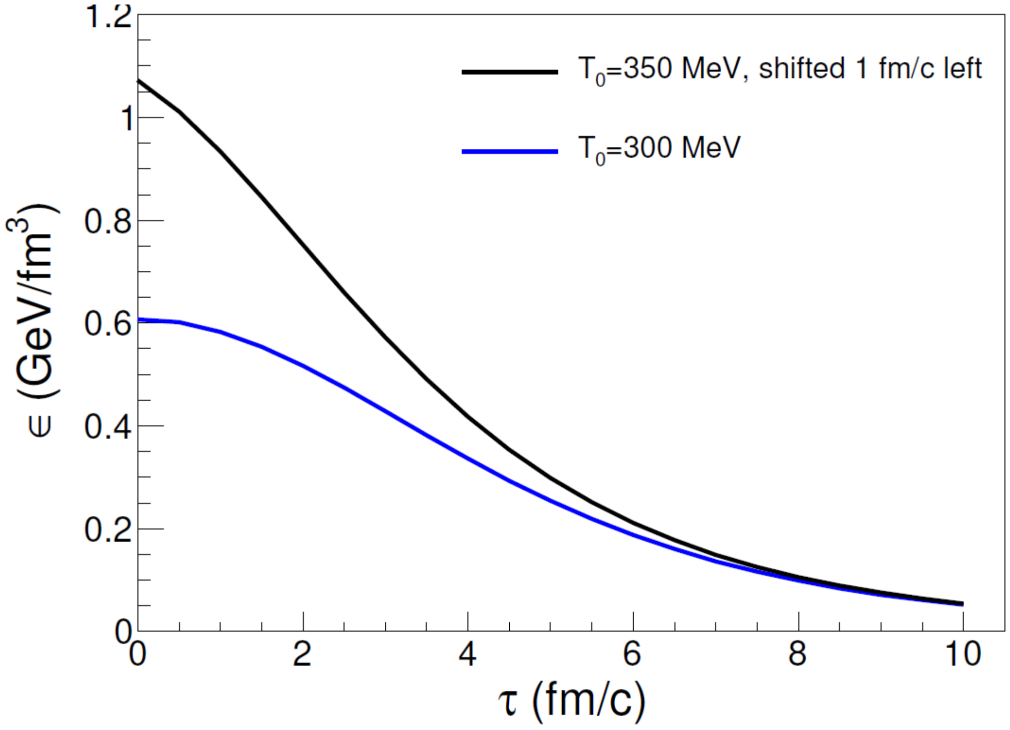
Relativistic hydro 1D Bjerken expansion: $\epsilon(\tau) = \epsilon_0 \tau^{-4/3}$

Relativistic hydro 3D Gubser solution:

$$\epsilon(r_T, \tau) = \frac{\epsilon_0}{\tau^{4/3}} \frac{(2q)^{8/3}}{[1 + 2q^2(\tau^2 + r_T^2) + q^4(\tau^2 - r_T^2)^2]^{4/3}}$$

Non-relativistic solution:
of Hydro + Boltzmann eqs.
(simultaniouslu!!!) :

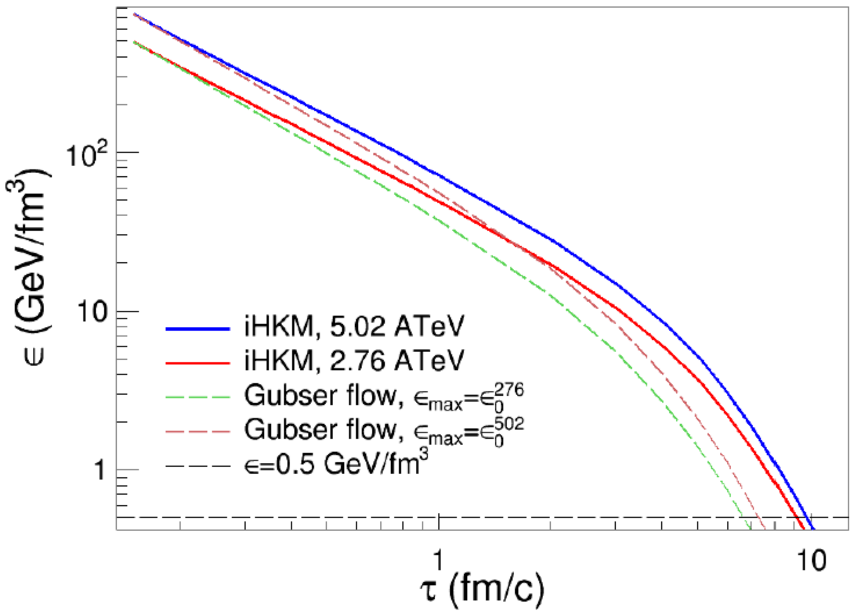
$$\epsilon(\mathbf{x} = 0, t) = \frac{AT_0^4 (mR_0^2/T_0)^{5/2}}{(t^2 + mR_0^2/T_0)^{5/2}}$$

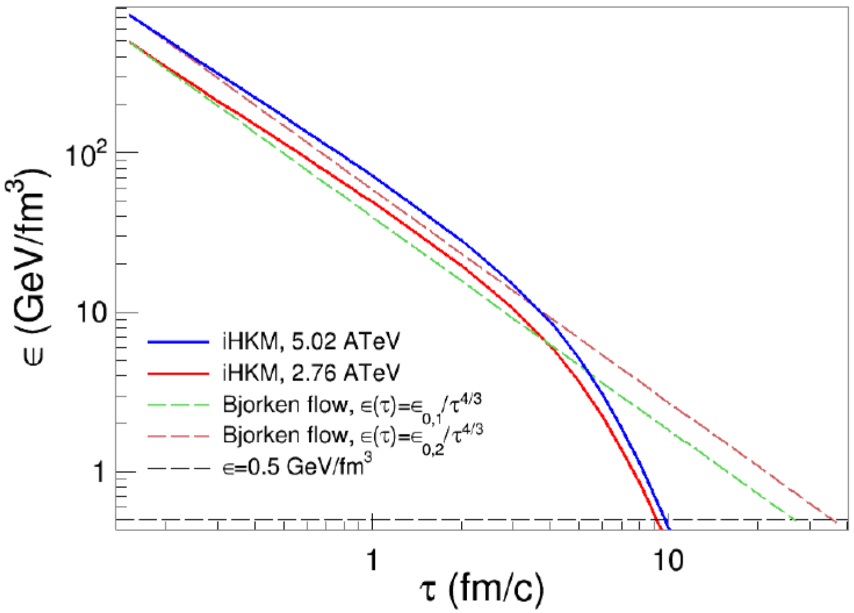


Puzzle I: nearly equal freeze-out times extracted from long-radii starting at top RHIC energy until top LHC one.

Simplest though: More initial energy density at the same initial times (0.1 fm/c) at near the same sizes of colliding nuclei and same initial velocity distributions -> then more time necessary to reach freeze-out (energy density there is the same 0.5 GeV/fm^3). But despite initial energy density between RHIC (200 GeV), LHC (2760 GeV) and LHC (5020 GeV) differs by factors 2-10, the freeze-out times nevertheless are hardly differ: 8.5 – 9 - 10 fm/c (RHIC – LHC).

Explanation:





THE REASON IS: Intensive relativistic transverse expansion starting around 0.4 fm/c in 3D hydro-models of heavy ion collisions.

Puzzle II: *Long*-femto radii and “real” life-time of the system

The sudden freeze-out of the hydro-system, when one transform it (by particlization procedure) to many-particle system cannot be the final stage without afterburner one: in that case the hydro-matter with near zero mean free path (m.f.p.) – according hydro-definition - transforms suddenly in ideal gas that has infinite m.f.p., so particles, that interacted quite strongly suddenly stop to interact, that is physically absurd.

Our aim now is to analyze how long is duration of the afterburner stage, aiming to understand: can we neglect it?

ANSWER**:** IT IS IMPOSSIBLE TO NEGLECT !

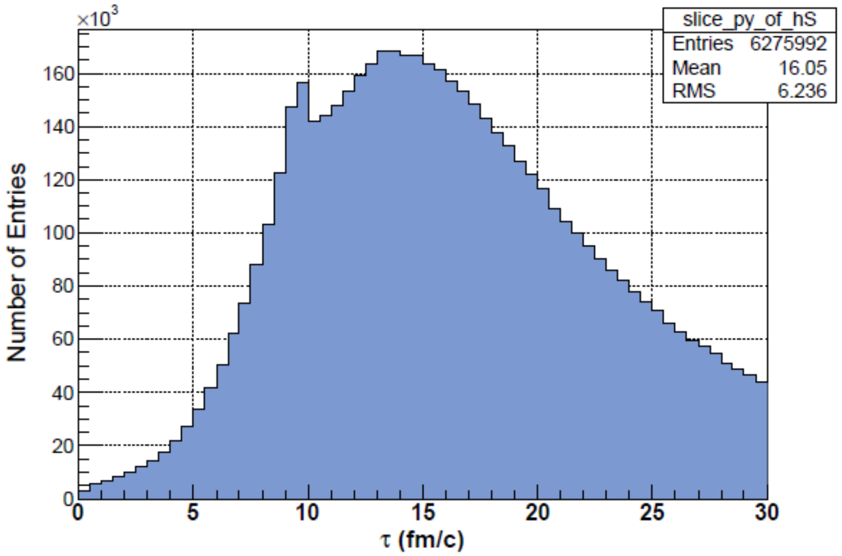
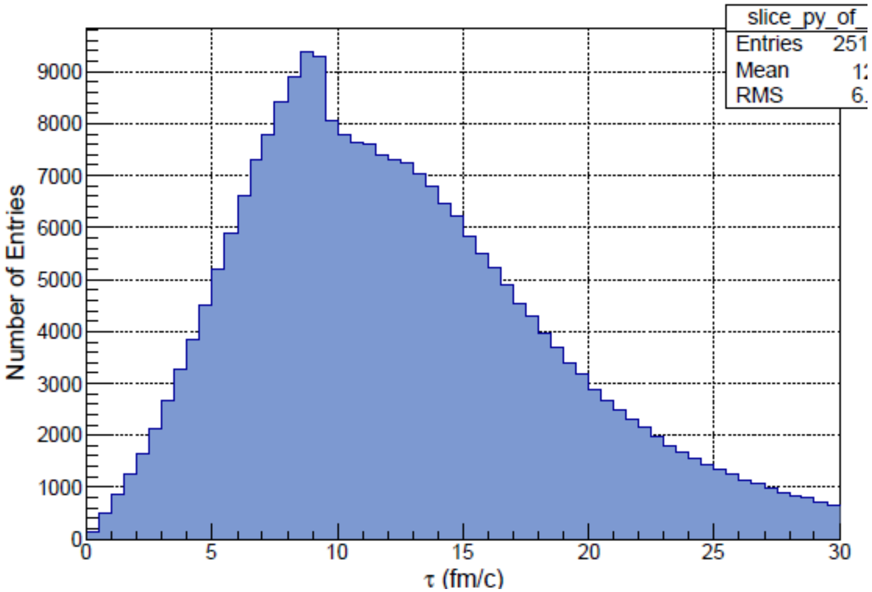
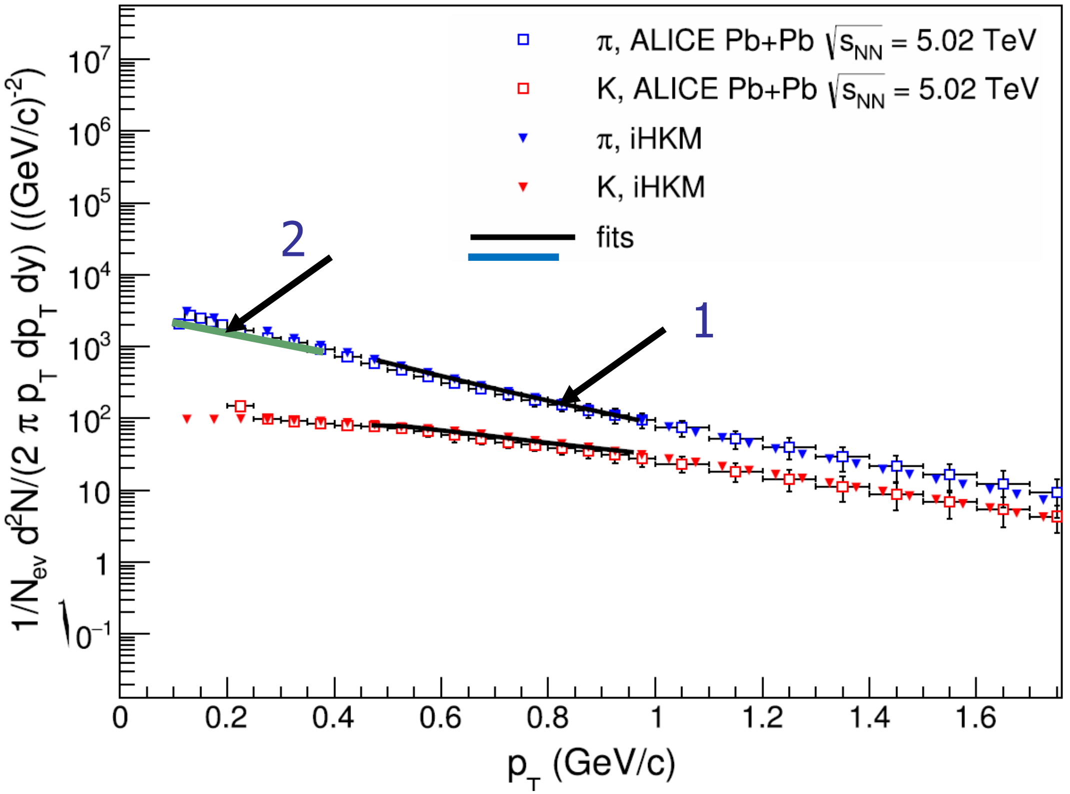


FIG. 1. The time of emission distribution for pions in central Pb+Pb collisions ($c = 0 - 5\%$) at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV simulated within iHKM, $0.2 < p_T < 0.3$ GeV/c, $|y| < 0.5$.



The same as in Fig. 1, but for wide p_T region, $0.5 < p_T < 2.0$ GeV/c.

Puzzle II. Solution



1 – corresponds to fitting in semi-soft and semi-hard p_T/k_T interval of pion spectra and radii. It gives the temperature of max. emission near 140 GeV and $\tau = 10\ fm/c$

2 – corresponds to fitting soft pion spectra (0.2 – 0.4 GeV) with temperature of maximal emission near 105 GeV and $\tau = 14.5\ fm/c$

THE PUZZLE IS COMLETE.

Fig. 4. The iHKM results for pion and kaon p_T spectra compared to the ALICE data [26] for the LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ($c = 0 - 5\%$) together with the lines, representing a combined fit to the iHKM spectra using (8) with the same effective temperature T for pions and kaons.

CONCLUSIONS

We considered the two puzzle femtoscopic observations in ultrarelativistic heavy ion collisions.

- The first one is the closeness of the observed maximal emission times of pions at the quite different collision energies: from top RHIC to top LHC ones.

It is explained by intensive (including all direction) 3D hydro-expansion.

- Another paradoxical effect is that despite the long enough duration of the post-hydro- dynamic/afterburner cascade stage, the observed times of the maximal emission are close to the particlization time.

The explanation is that despite analysis of spectra and long-correlations provided in the soft k_T/p_T momentum region (0.2-0.4 GeV) within detail iHKM model of ultrarelativistic heavy ion collisions gives the time of maximal emission 15 fm/c, the same analysis at the semi-soft & semi-hard momenta (0.5 – 1.5 fm/c) brings such the m.e. time to be 10 fm/c, that coincide with our previous results and also ALICE Collaboration ones for wide k_T/p_T interval. Duration of emission is large enough in both k_T/p_T intervals.

See details in

Yu. Sinyukov, V. Shapoval, M. Adzhymambetov
Universe 9 433 (2023); arXiv:2310.16233 (2023).

Thank you for your attention !

Additional slides to page 14 (“Results of saddle point method…”)

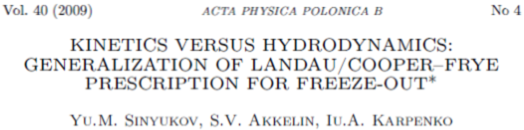
Boltzmann Eqs., continuous emission and Cooper-Frye formula:

FROM

PHYSICAL REVIEW C **78**, 034906 (2008)

Hydro-kinetic approach to relativistic heavy ion collisions

S. V. Akkelin,[1] Y. Hama,[2] Iu. A. Karpenko,[1] and Yu. M. Sinyukov[1]



Vol. 40 (2009) *ACTA PHYSICA POLONICA B* No 4

KINETICS VERSUS HYDRODYNAMICS:
GENERALIZATION OF LANDAU/COOPER–FRYE
PRESCRIPTION FOR FREEZE-OUT*

YU.M. SINYUKOV, S.V. AKKELIN, IU.A. KARPENKO

Saddle point approximation

Spectrum

$$n(t \to \infty, p) = \int d^3r\, f(t_0, \mathbf{r}, p)\mathcal{P}_{t_0 \to t}(t_0, \mathbf{r}, p) + \int d^3r \int_{t_0}^{t} dt' S(t', \mathbf{r}', p)$$

Emission density

$$S(t', \mathbf{r}', p) = f^{\mathtt{leq}}(t', \mathbf{r}' + \frac{\mathbf{p}}{p_0}(t' - t_0), p)Q(t', \mathbf{r}', p)$$

where

$$\boxed{Q(t', \mathbf{r}', p) = \frac{d}{dt'}\mathcal{P}_{t' \to t}(t', \mathbf{r}' + \frac{\mathbf{p}}{p_0}(t' - t_0), p)}$$

Normalization condition

$$\int_{t_0}^{\infty} dt' Q(t', \mathbf{r}', p) = 1 - \mathcal{P}(t_0, \mathbf{r}', p)$$

Eqs for saddle point $t_\sigma(\mathbf{r}, p)$:

$$\frac{dQ(t', \mathbf{r}', p)}{dt'}\Big|_{t' = t'_\sigma} = 0,$$

$$\frac{d^2Q(t', \mathbf{r}', p)}{dt'^2}\Big|_{t' = t'_\sigma} < 0,$$

Physical conditions at $t_\sigma(\mathbf{r}, p)$

$$\frac{1}{\langle v\sigma\rangle(x) n(x)} = \tau_{\mathrm{scat}} \approx \tau_{\mathrm{exp}} = -\left(\frac{1}{n(x)} u^\mu \partial_\mu n\right)^{-1}$$

Cooper-Frye prescription

$$\mathbf{r} = \mathbf{r}' + \frac{\mathbf{p}}{p_0}(t'_\sigma(\mathbf{r}', p) - t_0)$$

Spectrum in new variables ⇨

$$n(t \to \infty, p) \approx \int d^3 r \left| 1 - \frac{\mathbf{p}}{p_0} \frac{\partial t_\sigma}{\partial \mathbf{r}} \right| \int\limits_{t_0}^{t} dt' S(t', \mathbf{r}, p).$$

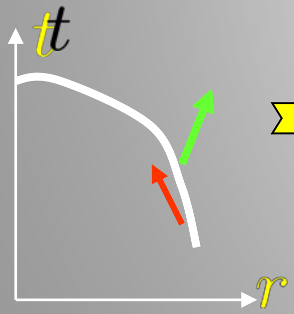
Emission density in saddle point representation ⇨

$$S(t', \mathbf{r}, p) = f^{\mathtt{leq}}(t', \mathbf{r} + \frac{\mathbf{p}}{p_0}(t' - t_\sigma), p)$$

$$\times \frac{\mathcal{P}_{t_\sigma \to \infty}(t_\sigma, \mathbf{r}, p)}{\tau_{\mathtt{rel}}(t_\sigma(\mathbf{r}, p), \mathbf{r}, p)} \exp(-(t' - t_\sigma(\mathbf{r}, p))^2 / 2D^2(\mathbf{r}, p))$$

Temporal width of emission ⇨

$$D(\mathbf{r}, p) = \frac{1}{\sqrt{2\pi}} \tau_{\mathtt{rel}}(t_\sigma, \mathbf{r}, p) \mathcal{P}^{-1}_{t_\sigma \to \infty}(t_\sigma, \mathbf{r}, p) \approx \tau_{\mathtt{rel}}(t_\sigma, \mathbf{r}, p)$$



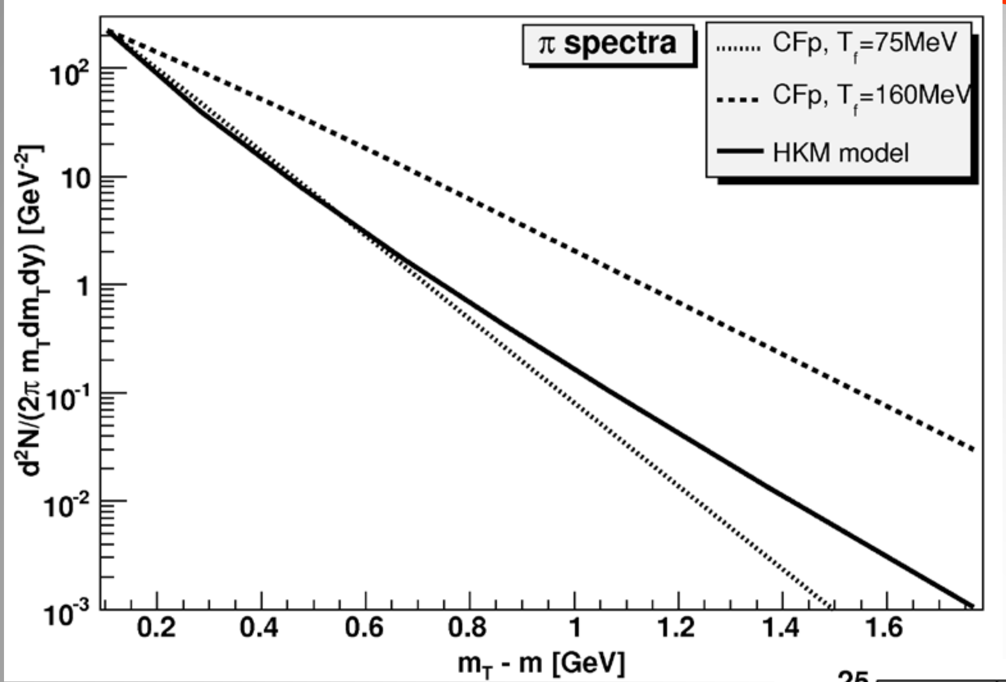
⇨

$$\mathcal{P}^{-1}_{t_\sigma \to \infty} = \exp\left(\underbrace{\int\limits_{t_\sigma}^{\infty} ds \overset{R_{coll}}{\tau^{-1}_{\mathtt{rel}}}(s, \mathbf{r} + \frac{\mathbf{p}}{p^0}(s - t_\sigma(\mathbf{r}, p)), p)}_{\approx 1} \right)$$

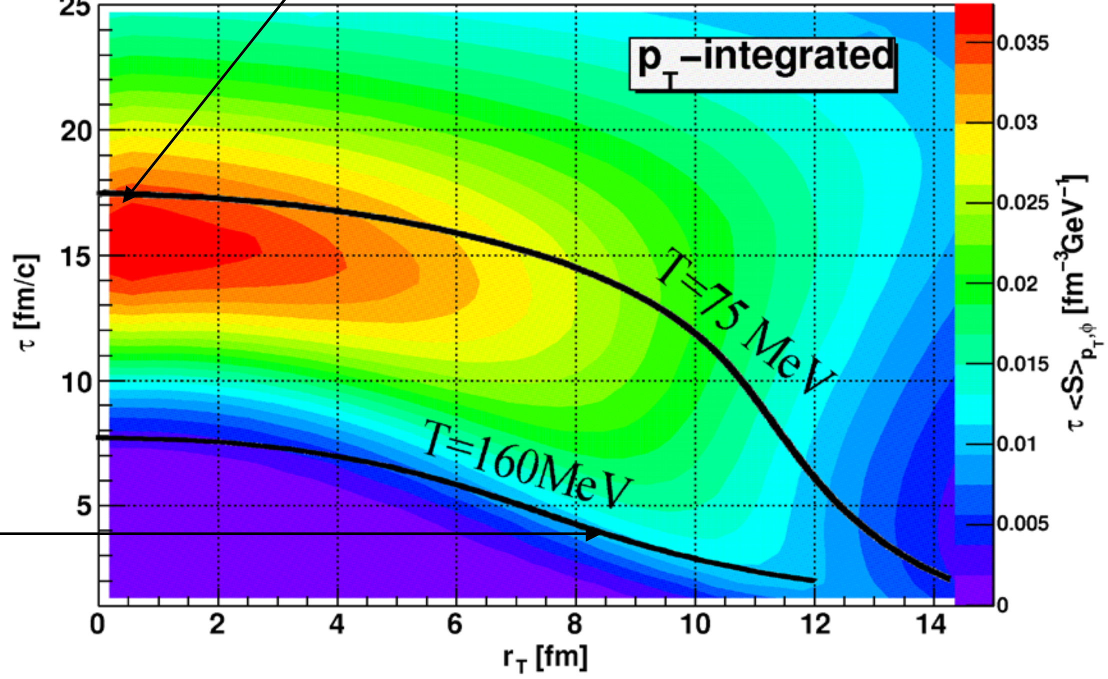
Generalized Cooper-Frye f-la ⇨

$$p^0 n(t \to \infty, p) = \int\limits_{\sigma(p)} d\sigma_\mu p^\mu f^{\mathtt{leq}}(x, p)$$

Transverse Spectra

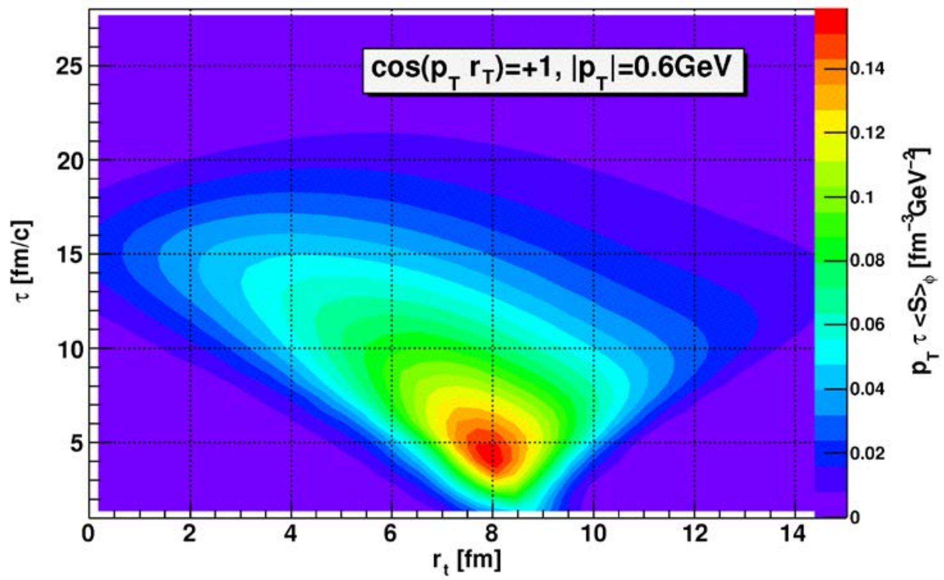


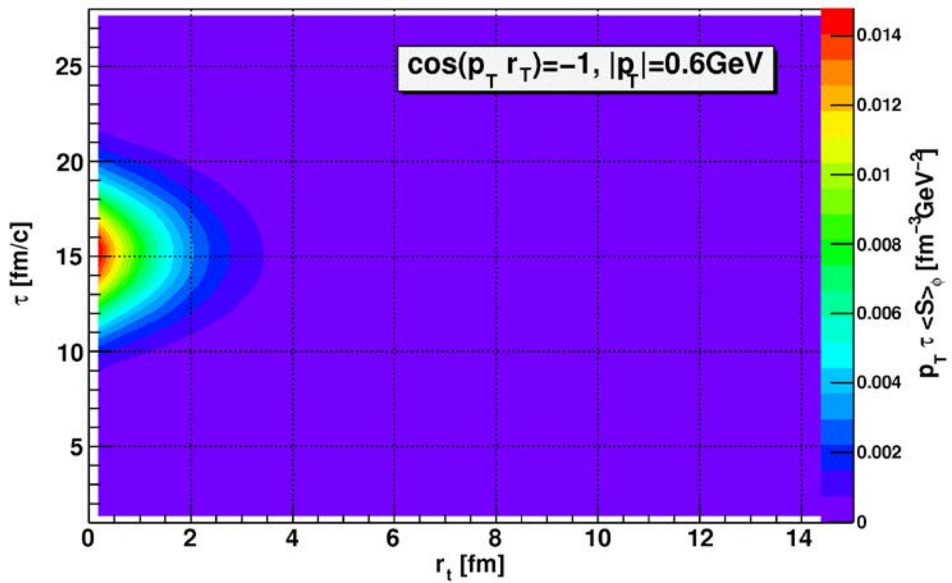
Max at Pt = 0.3 GeV/c



Max at Pt = 1.2 GeV/c

Momentum dependence of freeze-out



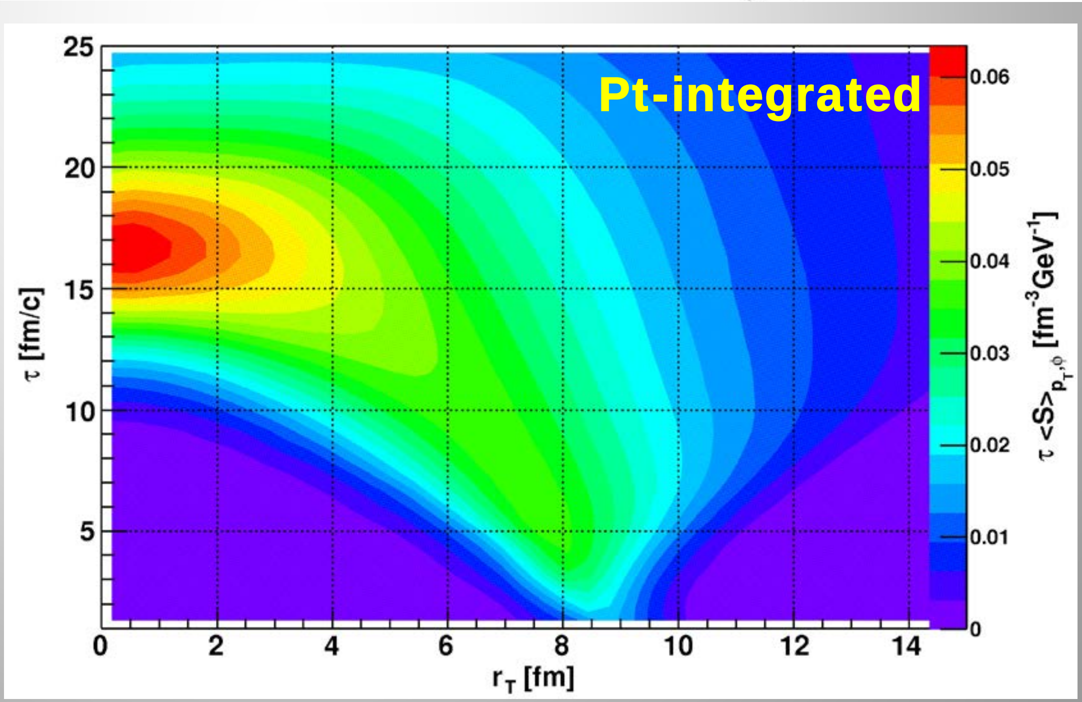


Here and further for Pb+Pb collisions we use:

initial energy density

ϵ_i=6 GeV/fm^3 (T_i= 247 MeV)

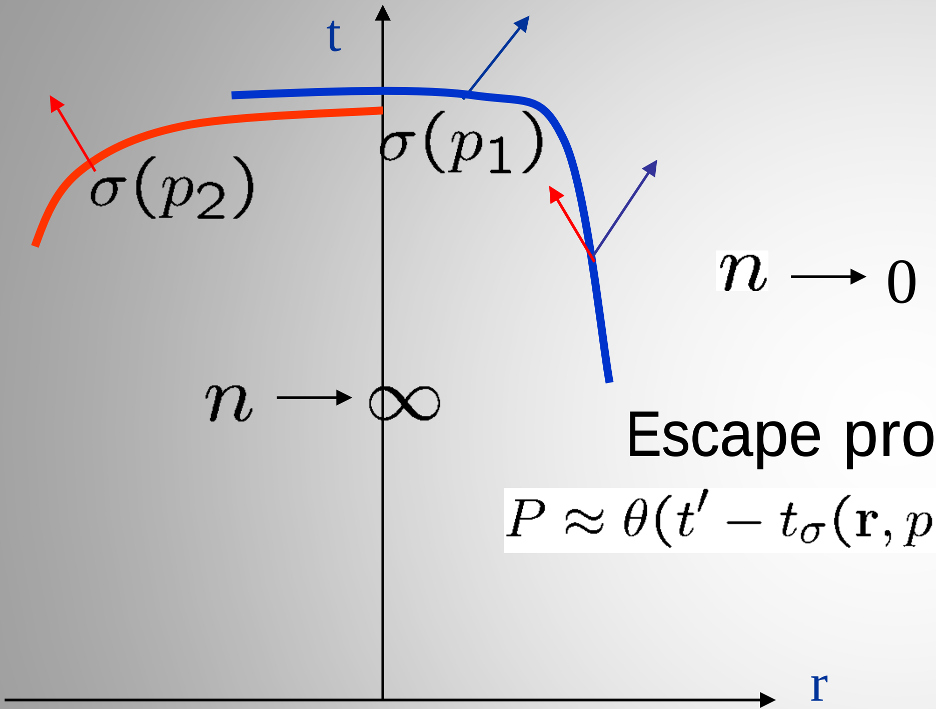
EoS from Lattice QCD when T< 160 MeV, and EoS of chemically frozen hadron gas with 359 particle species at T< 160 MeV.



Generalized Cooper-Frye prescription:

$$p^0\frac{d^3N}{d^3p} = \int\limits_{\sigma(p)} d\sigma_\mu p^\mu f^{l.eq.}(x,p)$$

$$d\sigma_\mu p^\mu > 0$$



Escape probability

$$P \approx \theta(t' - t_\sigma(\mathbf{r},p))\theta(d\sigma_\mu(\mathbf{r},p)p^\mu)$$

$$\cancel{\Downarrow}$$

$$p^0\frac{d^3N}{d^3p} = \int\limits_{\sigma(p)} d\sigma_\mu p^\mu f^{l.eq.}(r,p)\theta(d\sigma_\mu p^\mu)$$

Yu.S. (1987)-particle flow conservation; K.A. Bugaev (1996) (current form)

THE END