Properties of the superdense matter and its space-time evolution in ultrarelativistic heavy ion collisions

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In collaboration with
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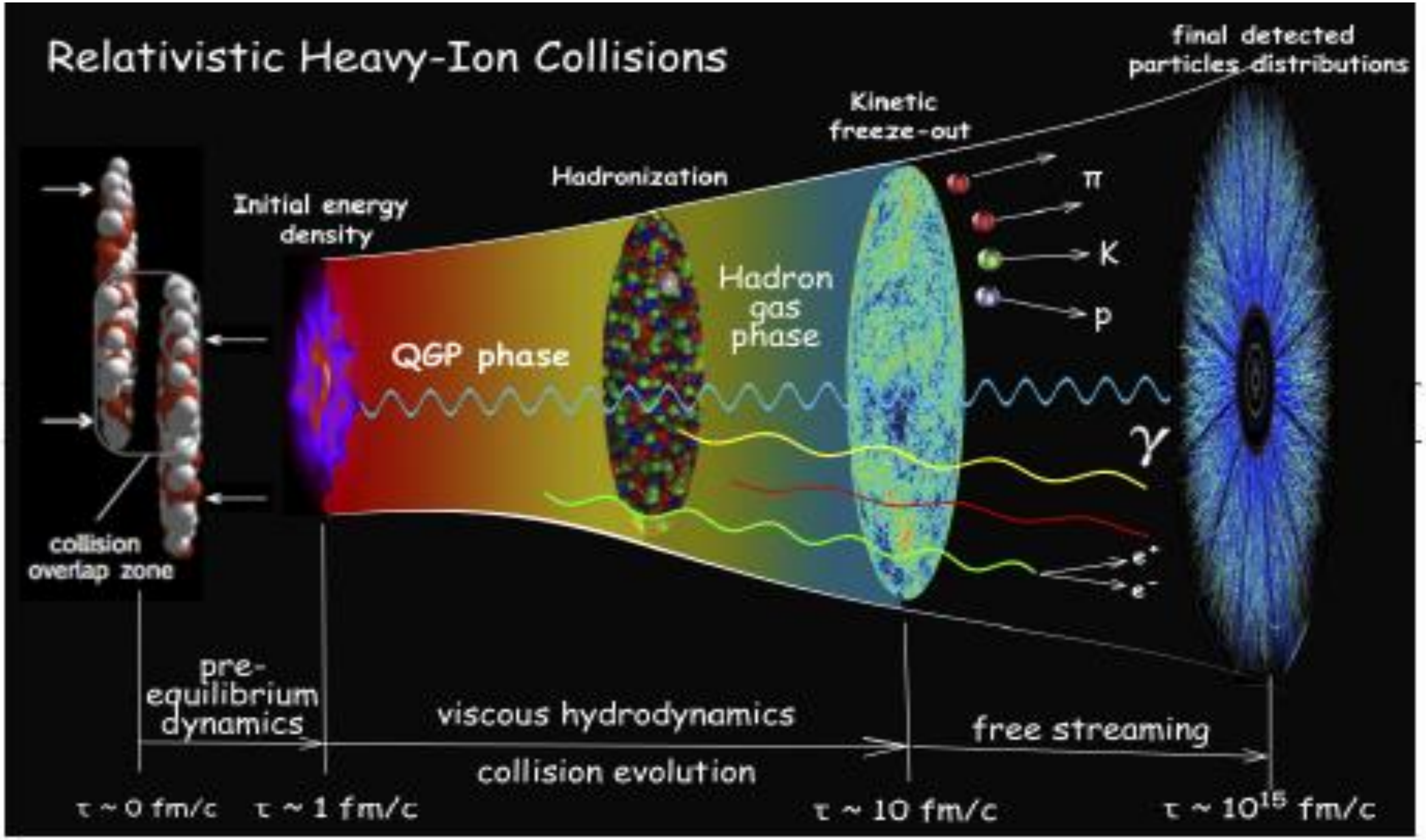
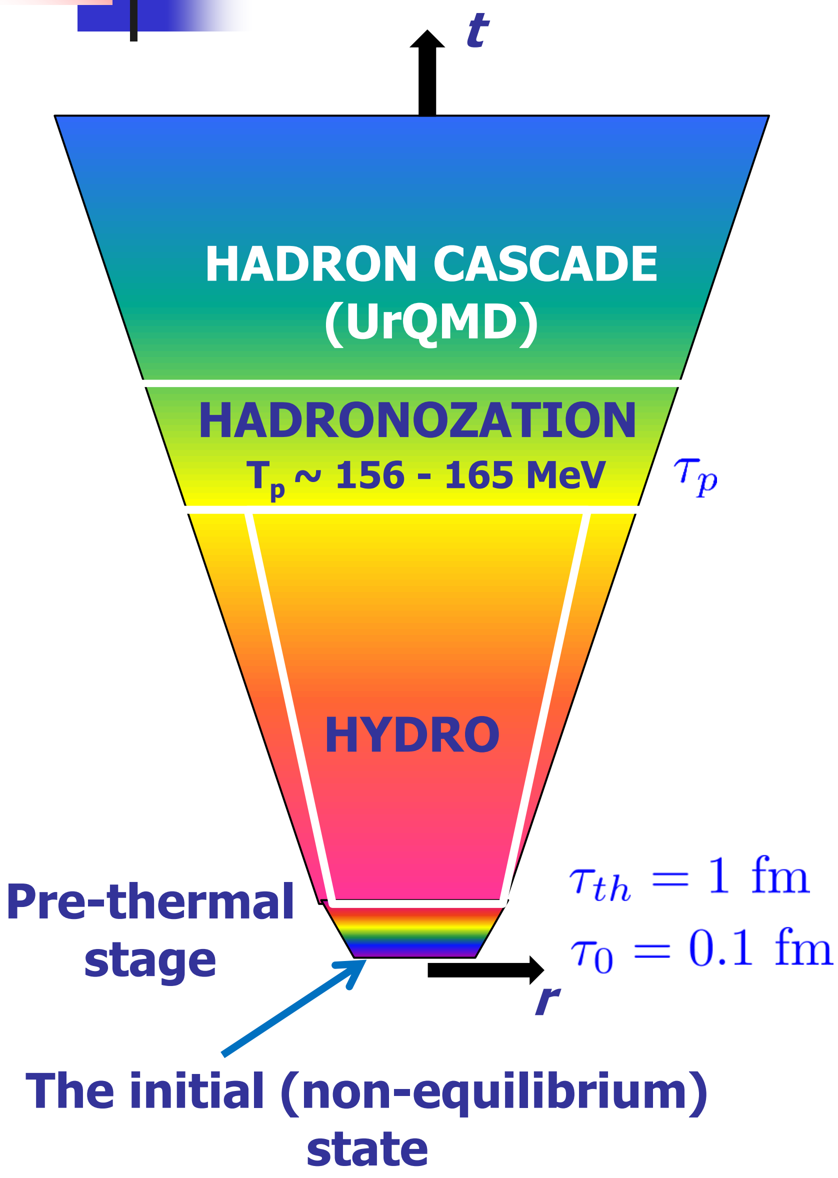
The stages of the matter evolution in A+A collisions

The initial huge kinetic energy of colliding nuclei converts into masses of the final observed particles (several tens of thousands) + the energy of collective flow



Integrated HydroKinetic Model: HKM $\rightarrow$ iHKM



Complete algorithm incorporates the stages:

- **generation of the initial states: (MC Glaub & CGC)**
- **thermalization of initially non-thermal matter;**
- **viscous chemically equilibrated hydrodynamic expansion;**
- **particlization of expanding medium in 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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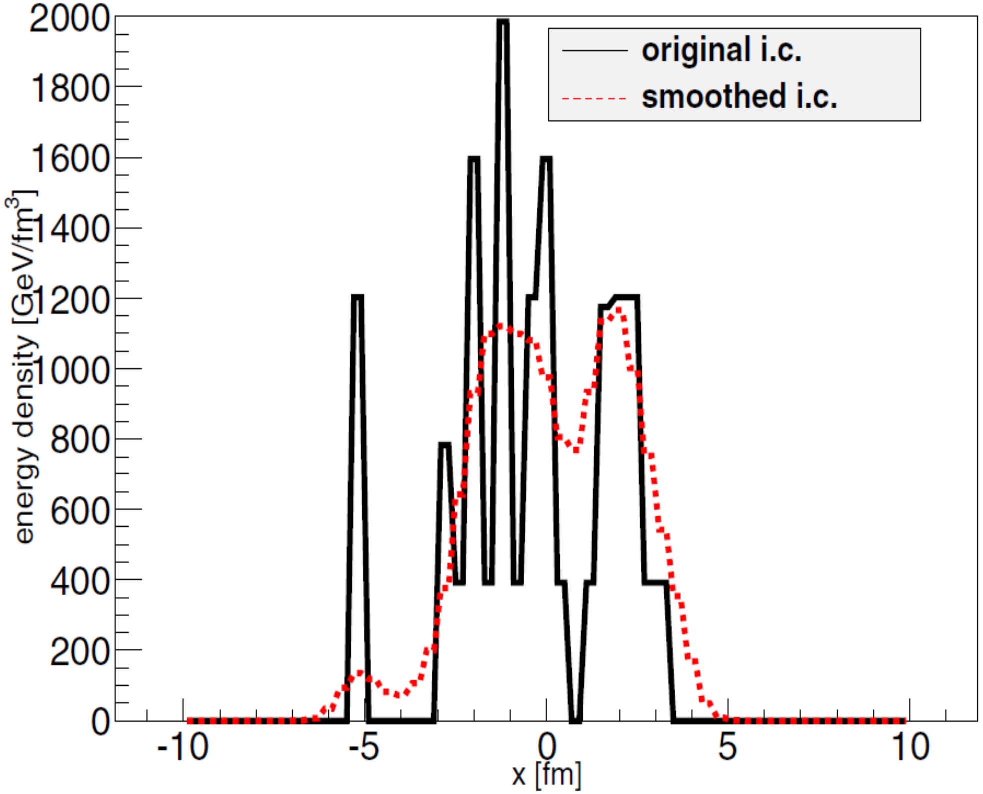
MC-G Initial State (IS) attributed to $\tau_0 = 0.1 \text{ fm/c}$

GLISSANDO 2



- The initial state (IS) is highly inhomogenious.
- It is not locally equilibrated.
- The IS is strongly momentum anisotropic (result from CGC)

$$f(t_{\sigma_0}, \mathbf{r}_{\sigma_0}, \mathbf{p}) = \epsilon(b; \tau_0, \mathbf{r}_T) f_0(p)$$

$$T_0^{\mu\nu}(x) = \int d^3p \frac{p^\mu p^\nu}{p_0} f_{\sigma_0}(x,p); \; T^{00}[f_0(p)] = 1$$

$$f_0^*(p) \propto \exp\left(-\sqrt{\frac{p_T^2}{\lambda_\perp^2} + \frac{p_L^2}{\lambda_\parallel^2}}\right)$$

Florkowski et al

MC-G Hybrid for ensemble of ISs :

$$\epsilon(b; \tau_0, \mathbf{r}_T) = \epsilon_0 \frac{(1-\alpha) N_W(b, \mathbf{r}_T)/2 + \alpha N_{bin}(b, \mathbf{r}_T)}{(1-\alpha) N_W(b=0, \mathbf{r}_T = 0)/2 + \alpha N_{bin}(b=0, \mathbf{r}_T = 0)}$$

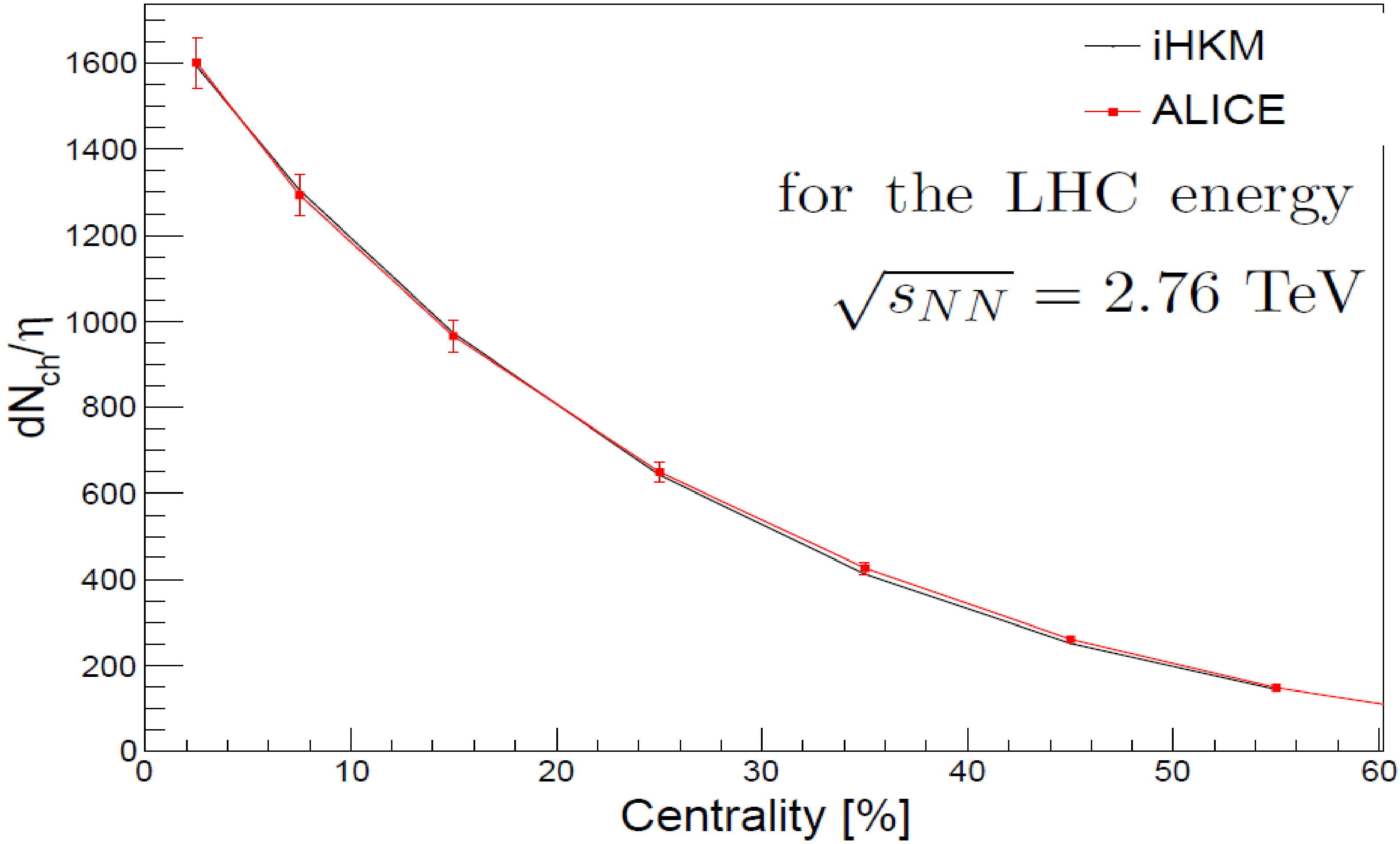
Parameters of IS

$$\Lambda = \lambda_\perp / \lambda_\parallel$$

ϵ_0, α = 0.24

Pb+Pb

Multiplicity dependence of all charged particles on centrality



$\oplus$

Pion transverse spectra

parameter values: $\alpha = 0.24, \tau_{th} = 1\mathrm{fm/c}, \ \epsilon_0 = \mathrm{f}(\tau_0, \tau_{\mathrm{rel}}, \eta/\mathrm{s}, \Lambda, \mathrm{EoS} \rightarrow \mathrm{T_{ch}} \approx \mathrm{T_h})$

The iHKM parameters (at Laine-Shroeder EoS example and $\sqrt{s_{NN}} = 2.76$ TeV)

The $\frac{dN_{ch}}{d\eta}(c)$ is OK at fixed relative contribution of binary collision $\alpha = 0.24$.

but at different max initial energy densities when other parameters change:

The two values of the shear viscosity to entropy is used for comparison:

$\eta/s = 0.08 \approx \frac{1}{4\pi}$ and $\eta/s = 0.2$

The basic result (selected by red) is compared with results at other parameters, including viscous and ideal pure thermodynamic scenarios (starting at τ_0 without pre-thermal stage but with subsequent hadronic cascade).

Model	Λ	τ_{rel}	η/S	τ_0	$\langle\frac{\chi^2}{ndf}\rangle$	ϵ_0 (GeV/fm^3)
Hydro			0	0.1	5.16	1076.5
Hydro			0.08	0.1	6.93	738.8
iHKM	1	0.25	0.08	0.1	3.35	799.5
iHKM	100	0.25	0.08	0.1	3.28	678.8
iHKM	100	0.75	0.08	0.1	3.52	616.5
iHKM	100	0.25	0.2	0.1	6.61	596.9
iHKM	100	0.25	0.08	0.5	5.36	126.7

$\tau_{ol} \approx 0.07,\ 0.005,\ 0.003$ fm/c for energies RHIC $\sqrt{s_{NN}} = 200$ GeV, LHC $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV correspondingly.

Slope of the pion spectra ⟹ $\tau_0 = 0.1$ fm/c $> \tau_{ol}$

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The $\frac{dN_{ch}}{d\eta}(c)$ is OK at fixed relative contribution of binary collision $\alpha = 0.24.$

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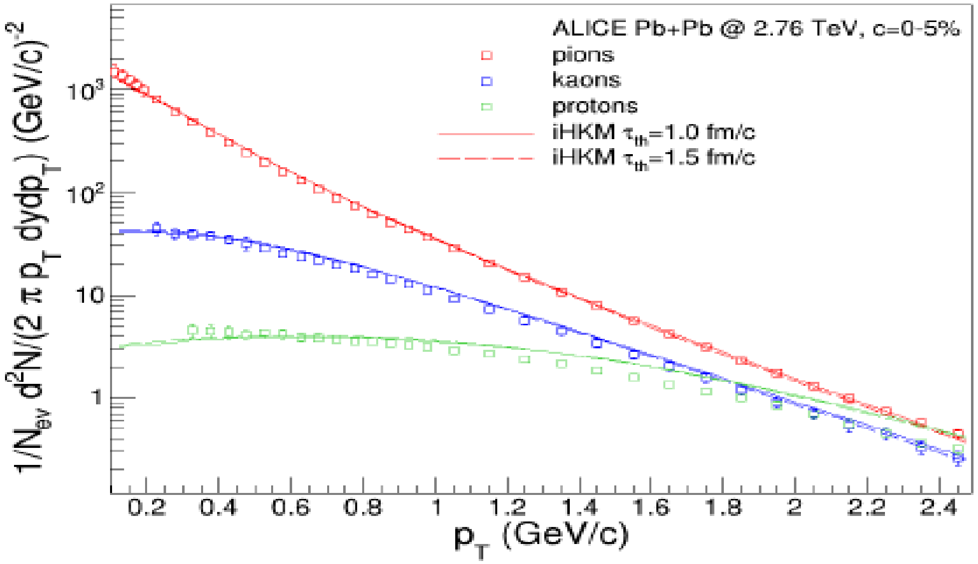
No dramatic worsening of the results happens if simultaneously with changing of parameters/scenarios renormalize maximal initial energy density $\epsilon_0(\tau_0)$.

Slope of the pion spectra → $\tau_0 = 0.1$ fm/c $> \tau_{ol}$

The sensitivity of the results to the model parameters

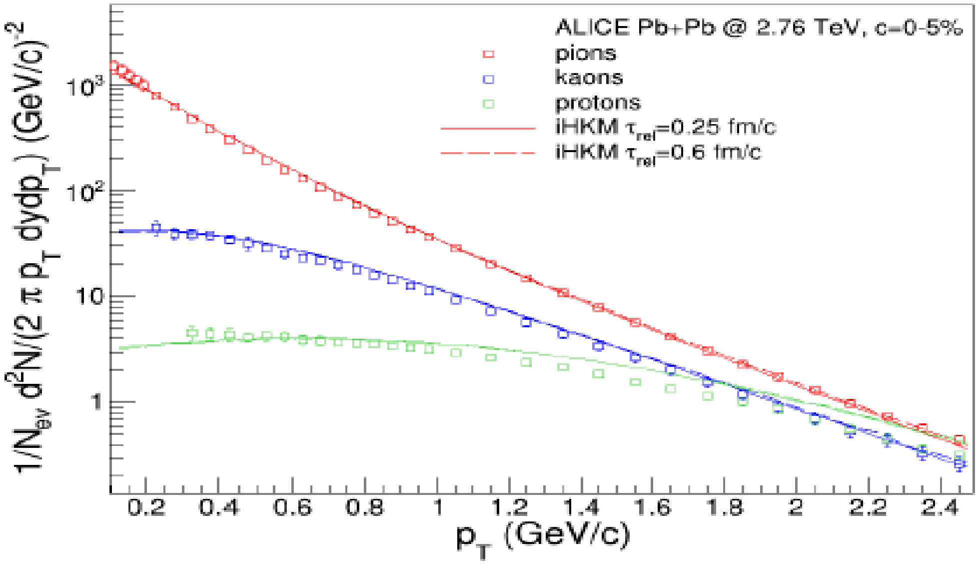
Pre-thermal stage parameters

The observables behavior depends strongly on initial time τ_0



Two thermalization times τ_{th} at fixed $\tau_{rel} = 0.25$ fm/c:

$\tau_{th} = 1.0$ fm/c, $\epsilon_0 = 834$ GeV/fm^3
$\tau_{th} = 1.5$ fm/c, $\epsilon_0 = 681$ GeV/fm^3



Two relaxation times τ_{rel} at fixed $\tau_{th} = 1.5$ fm/c:

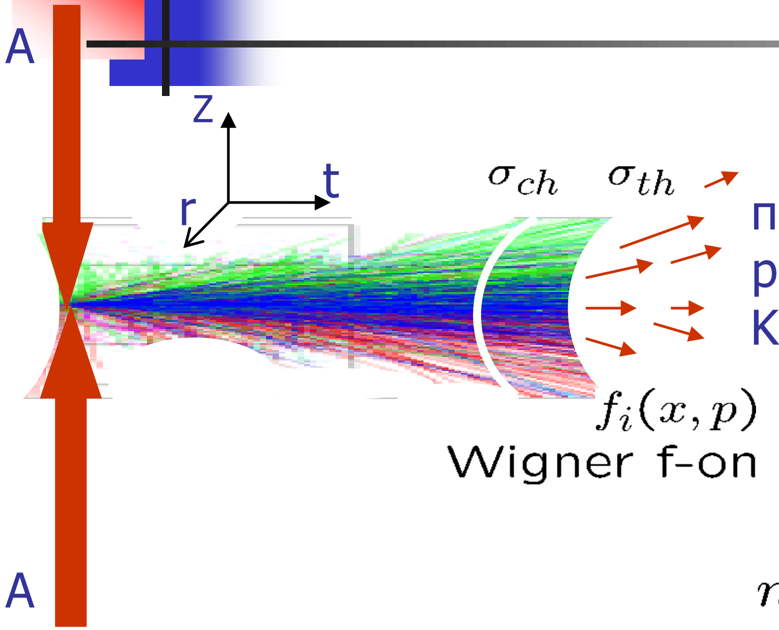
$\tau_{rel} = 0.25$ fm/c, $\epsilon_0 = 681$ GeV/fm^3
$\tau_{rel} = 0.6$ fm/c, $\epsilon_0 = 630$ GeV/fm^3

B. Abelev *et al.* (ALICE Collaboration), Phys. Rev. C **88** (2013) 044910.

+

The variation EoS (and the corresponding hadronization temperature) can be compensated to get the same bulk results by $\epsilon(\tau_0)$. Initial time and ϵ_0 are main param.

Bulk Observables, "Soft Physics" measurements



$T_{f.o.}$

Landau, 1953

$\sigma_{f.o.}$

$$N_i = \int_{\sigma_{ch}} \frac{d^3p}{p^0} d\sigma_\mu p^\mu f_i(x,p)$$

$$n_i(p) \equiv p^0 \frac{d^3 N_i}{d^3 p} = \int_{\sigma_{th}} d\sigma_\mu p^\mu f_i(x,p)$$

$$\sim e^{-\sqrt{m_i^2 + p_T^2}/T_{eff,i}}$$

$$n_i(p_1, p_2) \equiv p_1^0 p_2^0 \frac{d^6 N_i}{d^3 p_1 d^3 p_2} = C(p,q) n(p_1) n(p_2)$$

$p=(p_1+ p_2)/2$

$q= p_1 - p_2$

$\{\frac{N_i}{N_j}\}$ → T_{ch} and μ_{ch} soon after hadronization (chemical f.o.)

$$\frac{d^3N}{dp_t\, dy\, d\varphi} = \frac{d^2N}{dp_t\, dy} \frac{1}{2\pi}(1 + 2v_1 \cos(\varphi) + 2v_2 \cos(2\varphi) + \ldots)$$

Directed flow

Elliptic flow

QS correlation function

$$1 + \lambda \exp\left(-R_L(p)^2 q_L^2 - R_S^2(p)^2 q_S^2 - R_O^2(p) q_O^2\right)$$

Radial flow → $T_{eff,i} \approx T_{f.o.} + m_i \frac{\langle v_T{}^2 \rangle}{2}$

Inverse of spectra slope

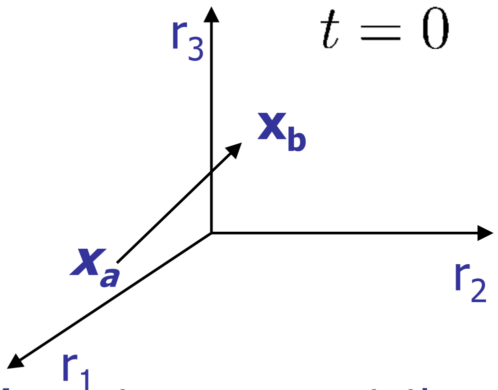
Radii R_i, *i=Long, Side, Out*

||

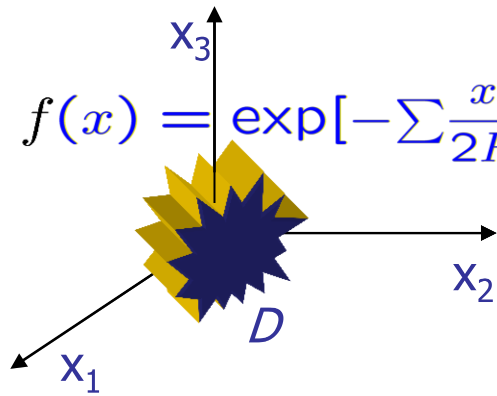
3D geometrical system sizes

Interferometry microscope (Kopylov, Podgoretcky: 1971-1973)

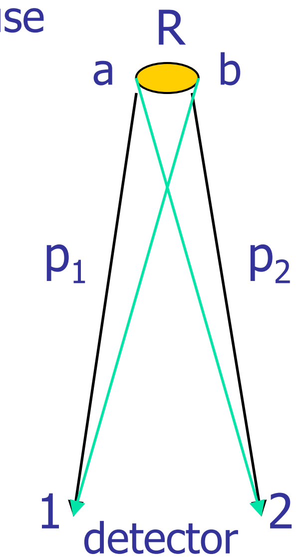
The idea of the correlation femtoscopy is based on an impossibility to distinguish between registered particles emitted from different points because of particle identity.



Momentum representation



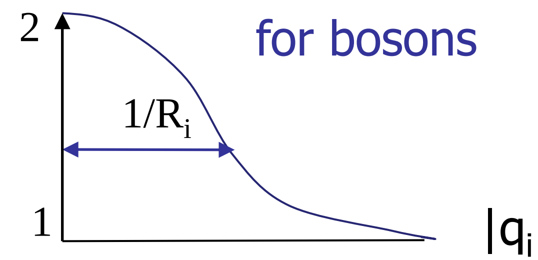
$$f(x) = \exp[-\sum \frac{x_i^2}{2R_i^2}]$$



$$\Psi_{x_a,x_b}(p_1,p_2) = \frac{1}{\sqrt{2}}\left[e^{-i\mathbf{p}_1\cdot\mathbf{x}_a}e^{-i\mathbf{p}_2\cdot\mathbf{x}_b} \pm e^{-i\mathbf{p}_2\cdot\mathbf{x}_a}e^{-i\mathbf{p}_1\cdot\mathbf{x}_b}\right]$$

Probabilities:

$$W_{x_a,x_b}(p_1,p_2) = |\Psi_{x_a,x_b}(p_1,p_2)|^2 = 1 \pm \cos\left[\underbrace{(\mathbf{p}_1 - \mathbf{p}_2)}_{\mathbf{q}} \cdot (\mathbf{x}_a - \mathbf{x}_b)\right]$$



for bosons

The model of independent particle emission

$$W_D(p_1,p_2) = \int_D d^3x_1 d^3x_2 f(x_1) f(x_2) W_{x_1,x_2}(p_1,p_2) = 1 \pm \left|\int d^3x f(x) e^{i\mathbf{q}\mathbf{x}}\right|^2 = 1 \pm \exp\left[-\sum q_i^2 R_i^2\right]$$

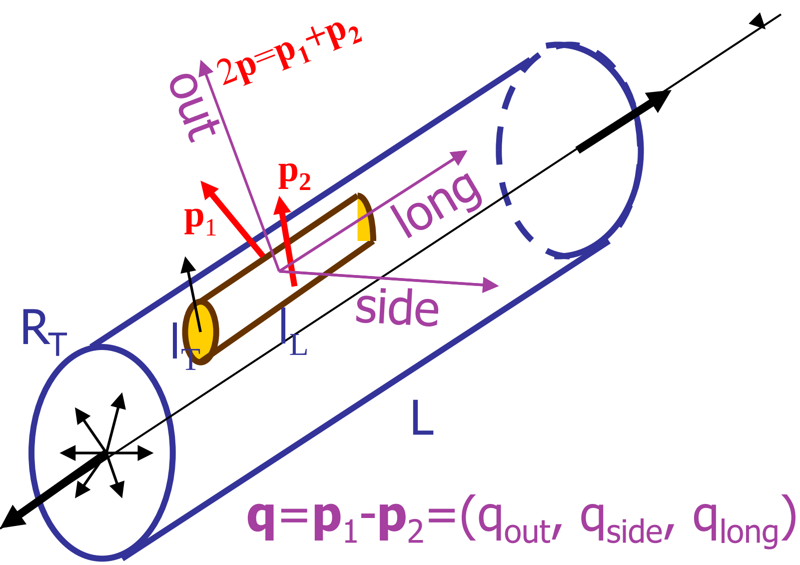
THE DEVELOPMENT OF THE FEMTOSCOPY (Yu.S.1986 – 1995)

To provide calculations analytically one should use the saddle point method and Boltzmann approximation to Bose-Einstein distribution function. Then the single particle spectra are proportional to homogeneity volume:

$$p^0 \frac{d^3N}{d^3p} \propto \prod_i \lambda_i(p)$$

and just these homogeneity lengths forms exponent in Bose-Einstein correlation function

$$C = 1 + \exp\left[-\sum q_i^2 R_i(p)^2\right]$$



Interferomerty radii:

$$R_L(p_T) \approx \lambda_L = \tau\sqrt{\frac{T_{f.o.}}{m_T}}/cosh(y), m_T = \sqrt{m^2 + p_T^2}$$

$$R_S \approx \lambda_T = R_T/\sqrt{1 + Im_T/T_{f.o.}},\ I \propto < v_T^2 >$$

$$R_o^2 \approx \lambda_T^2 + v^2\langle\triangle t^2\rangle_p - 2v\langle\triangle x_o \triangle t\rangle_p, v = \frac{p_{out}}{p_0}$$

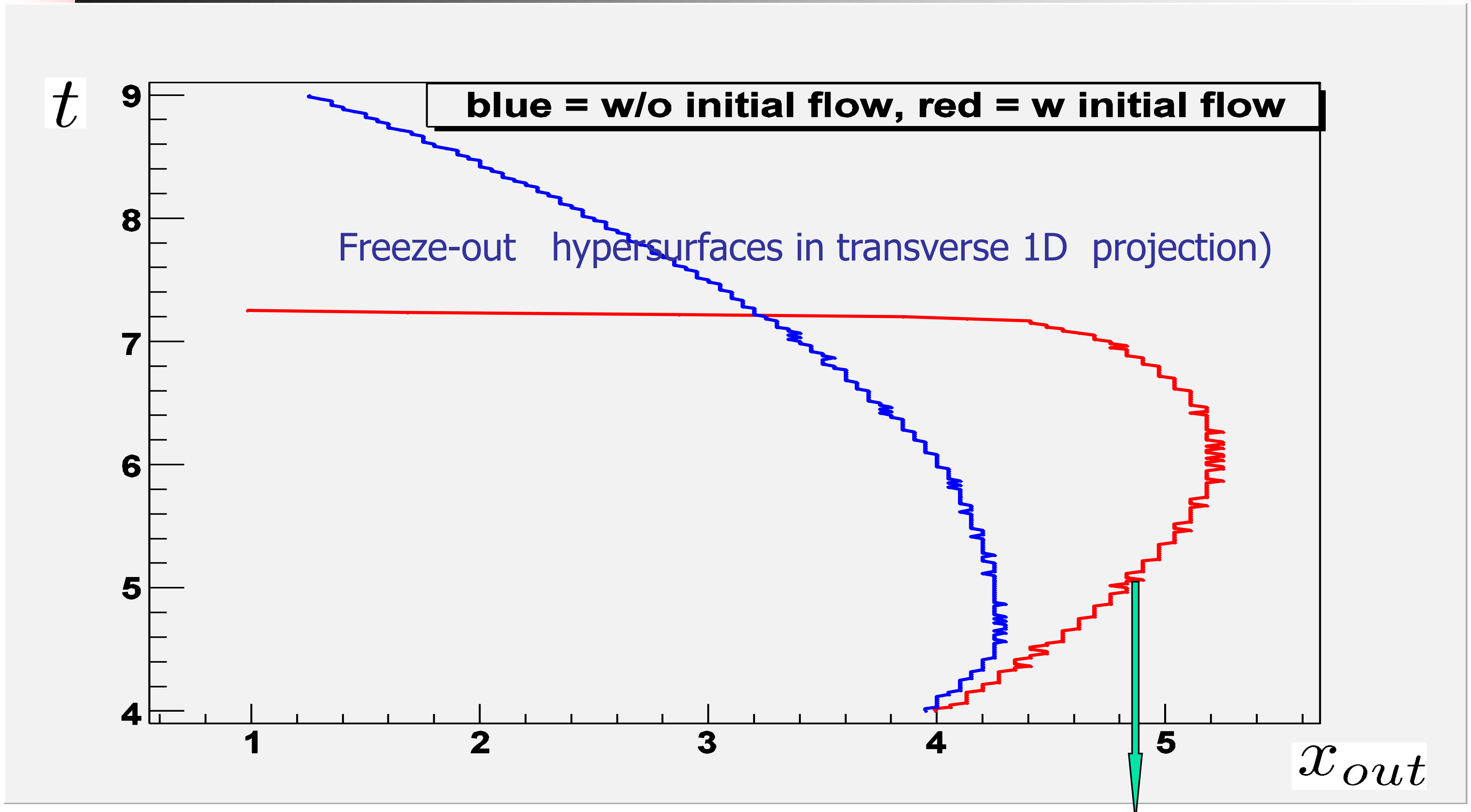
$$C(p,q) = \frac{d^6N/d^3p_1 d^3p_2}{d^3N/d^3p_1 d^3N/d^3p_2} \approx 1 + e^{R_L^2(p)q_L^2 + R_s^2(p)q_s^2 + R_O^2(p)q_O^2}$$

QGP → $R_{out}/R_{side} >> 1$ $Exp: R_{out}/R_{side} \approx 1$ RHIC HBT PUZZLE

HKM → iHKM

Evolution of ideas and main femtoscopy results

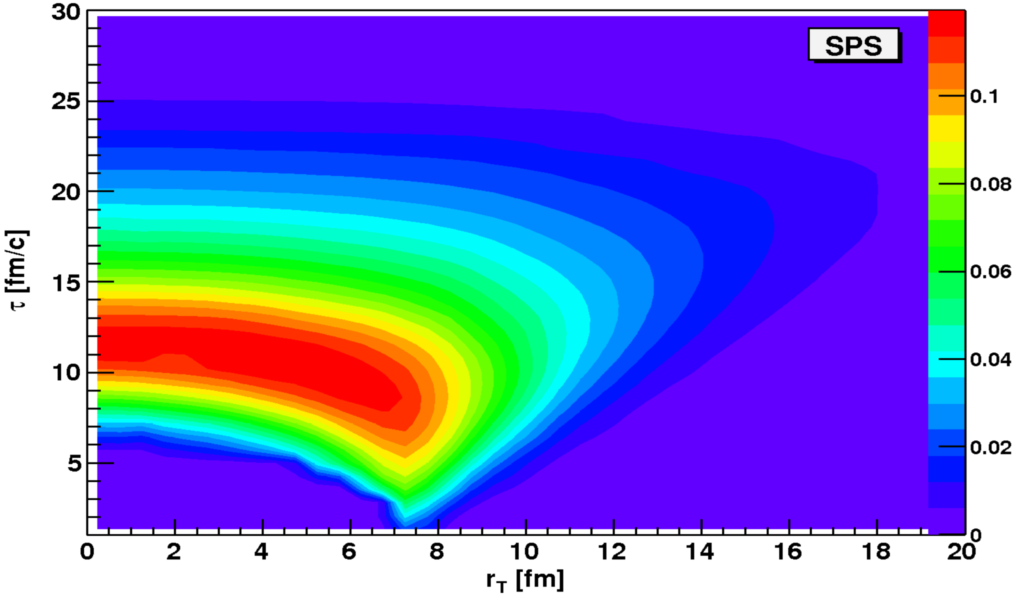
Initial flows and Ro/Rs ratio (t_0=1-2 fm/c)

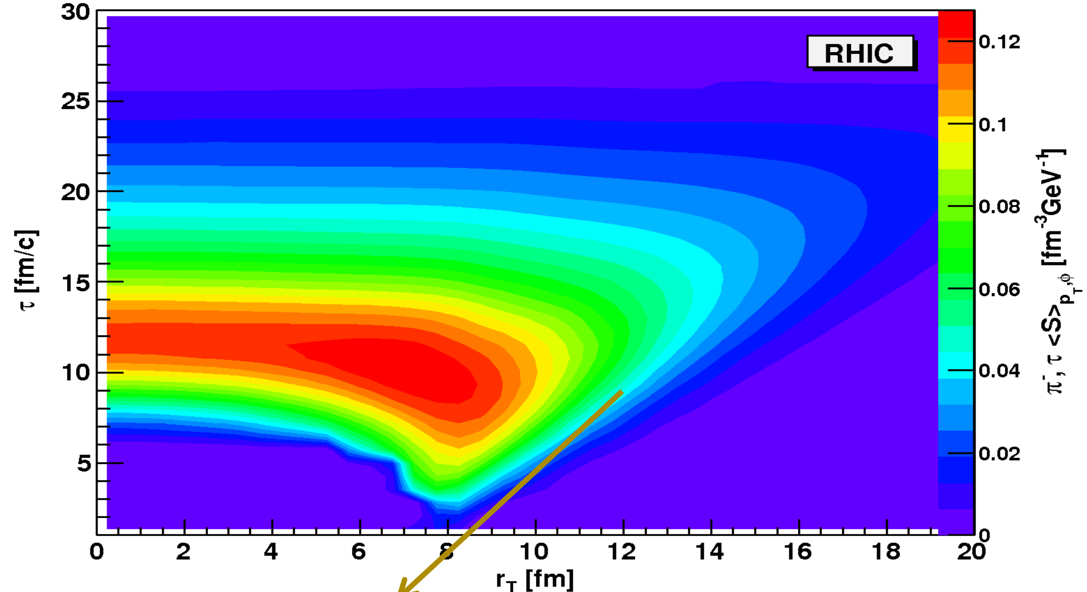


$$R_{out}^2 \approx R_{side}^2 + v^2\langle\triangle t^2\rangle_p - 2v\langle\triangle x_{out}\triangle t\rangle_p, v = \frac{p_T}{p^0}$$

Yu.S. Act.Phys. Polon. B **37** (2006) 3343

Emission functions in HKM for top SPS, RHIC and LHC energies





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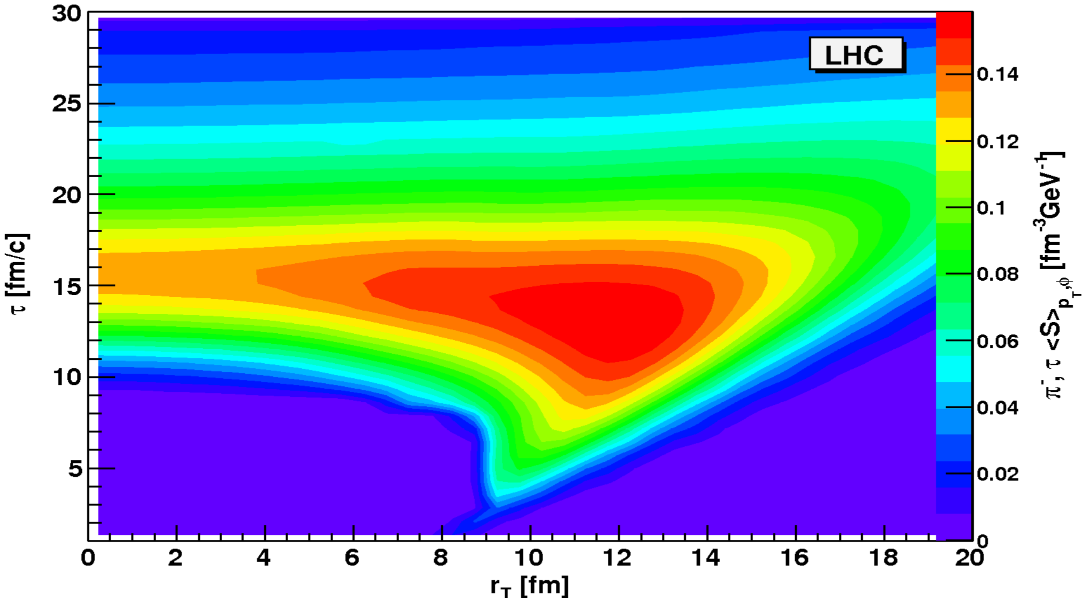


HKM prediction: solution of the HBT Puzzle

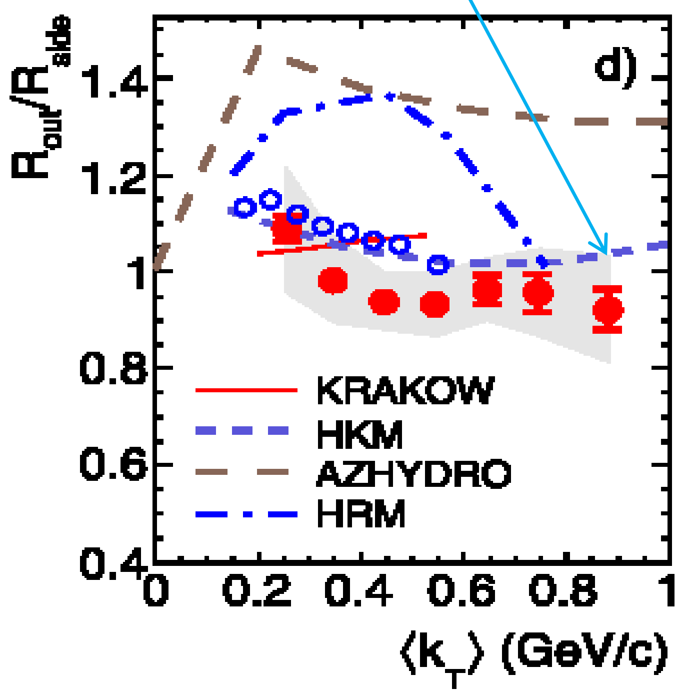
Two-pion Bose–Einstein correlations in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV ☆ ALICE Collaboration Physics Letters B 696 (2011) 328-

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

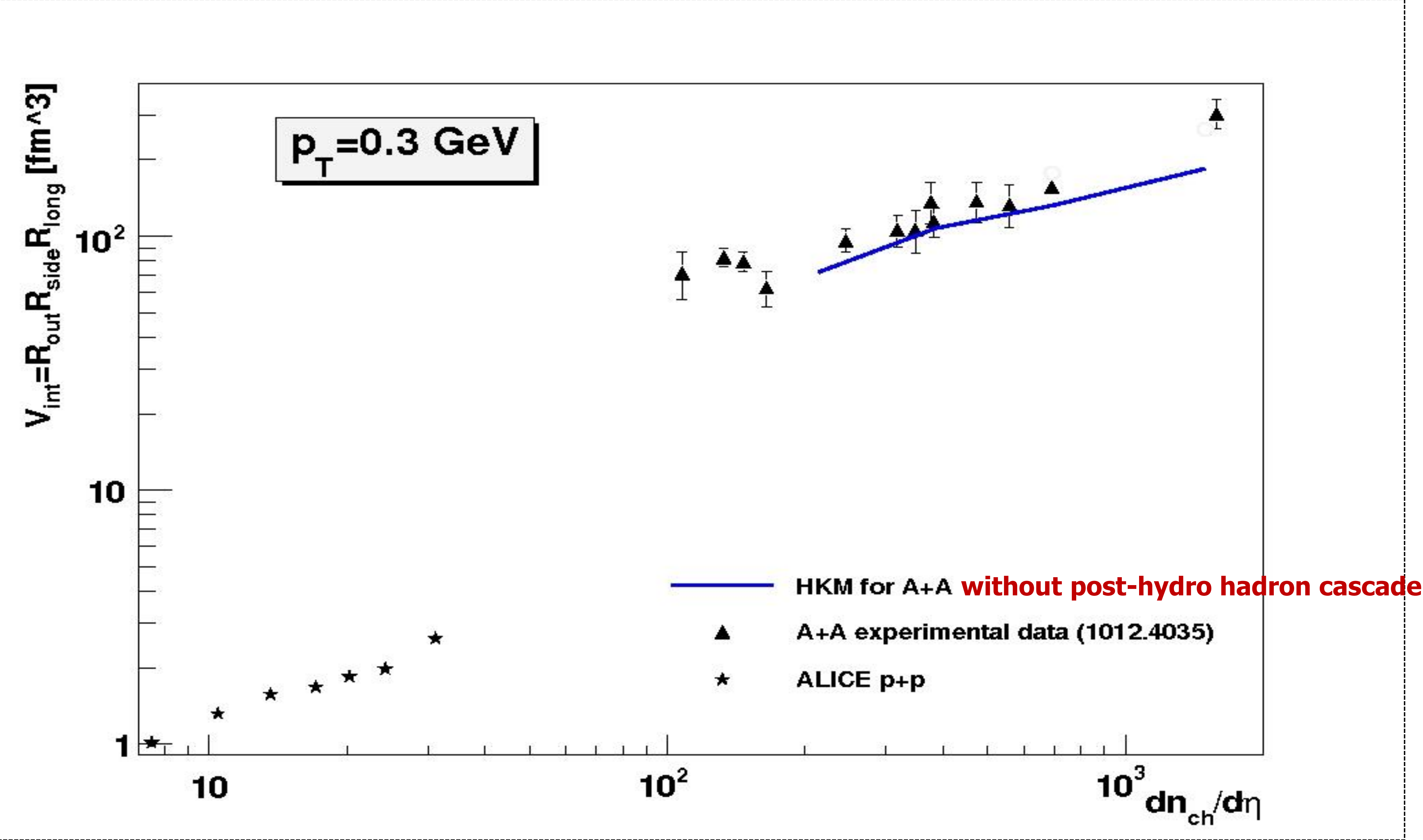


[48] I.A. Karpenko, Y.M. Sinyukov, Phys. Lett. B 688 (2010) 50.
[49] N. Armesto, et al. (Eds.), J. Phys. G 35 (2008) 054001.

iHKM

Femtoscopy scales vs multiplicity and initial system size

Interferometry volume V_{int} in LHC p-p and **central** Au-Au, Pb-Pb collisions



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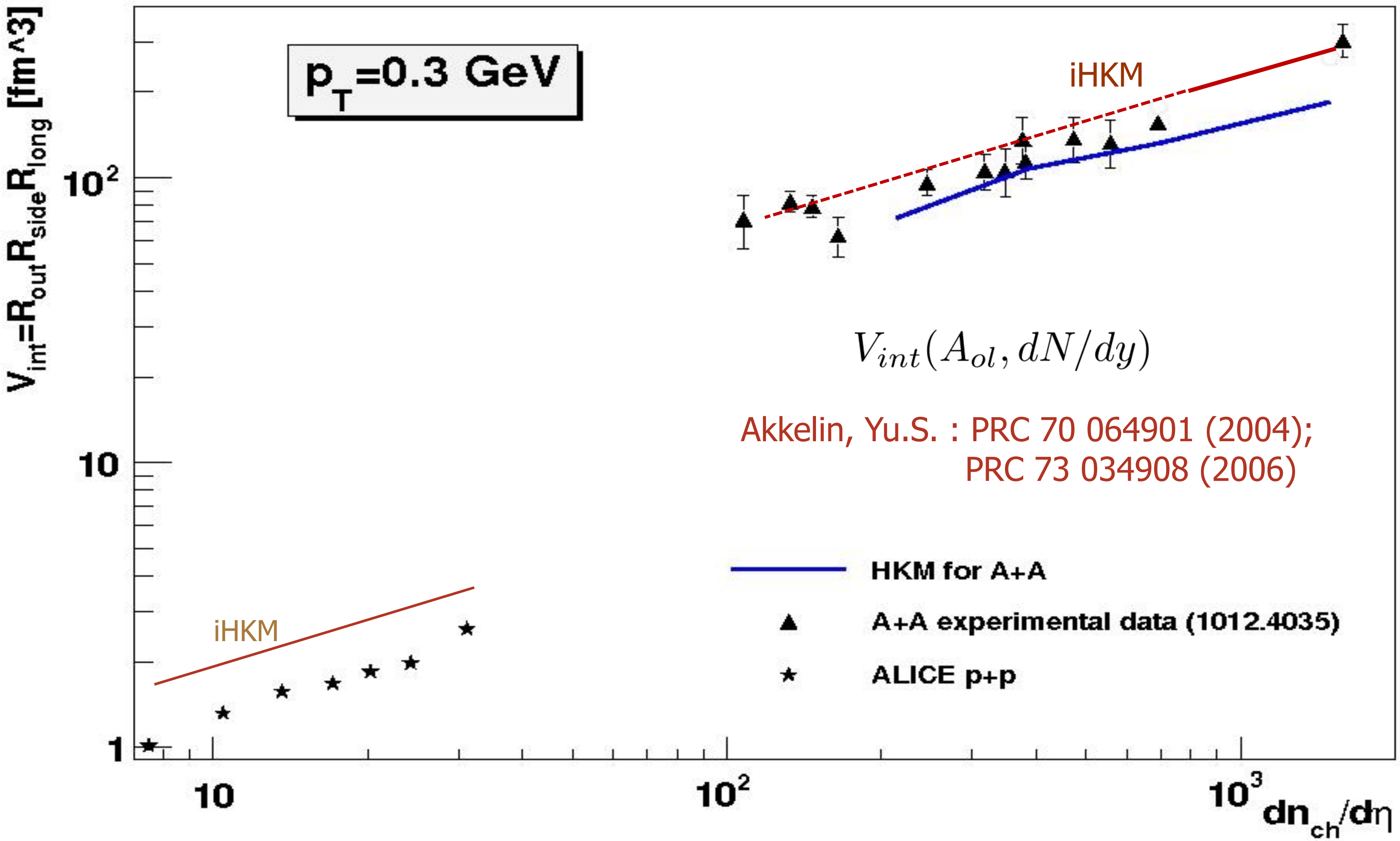
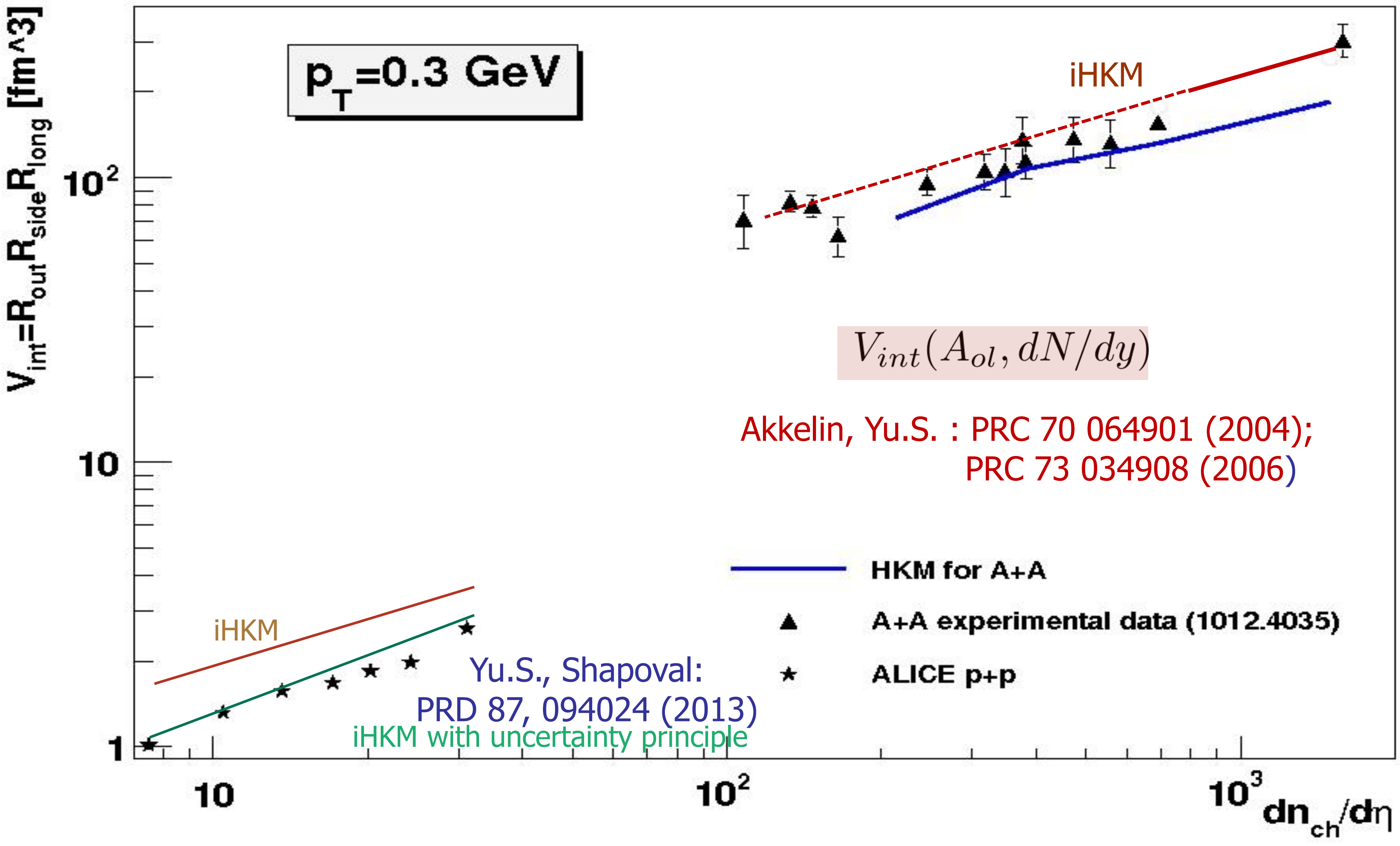
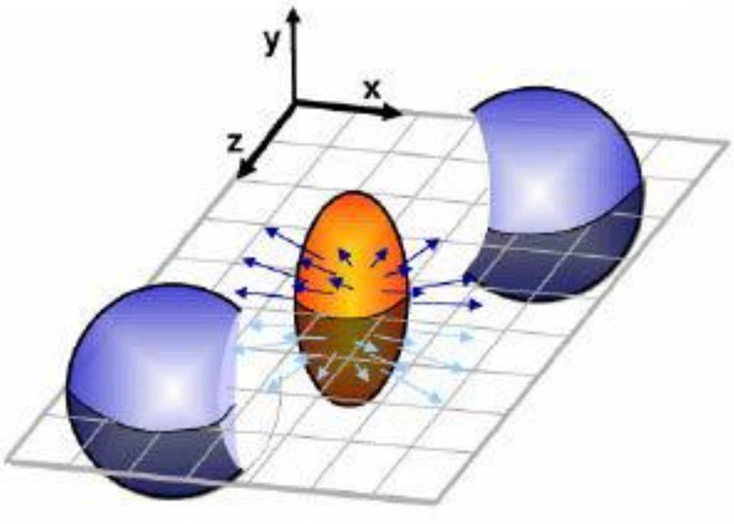


Interferometry volume Vint in LHC p-p and **central** Au-Au, Pb-Pb collisions



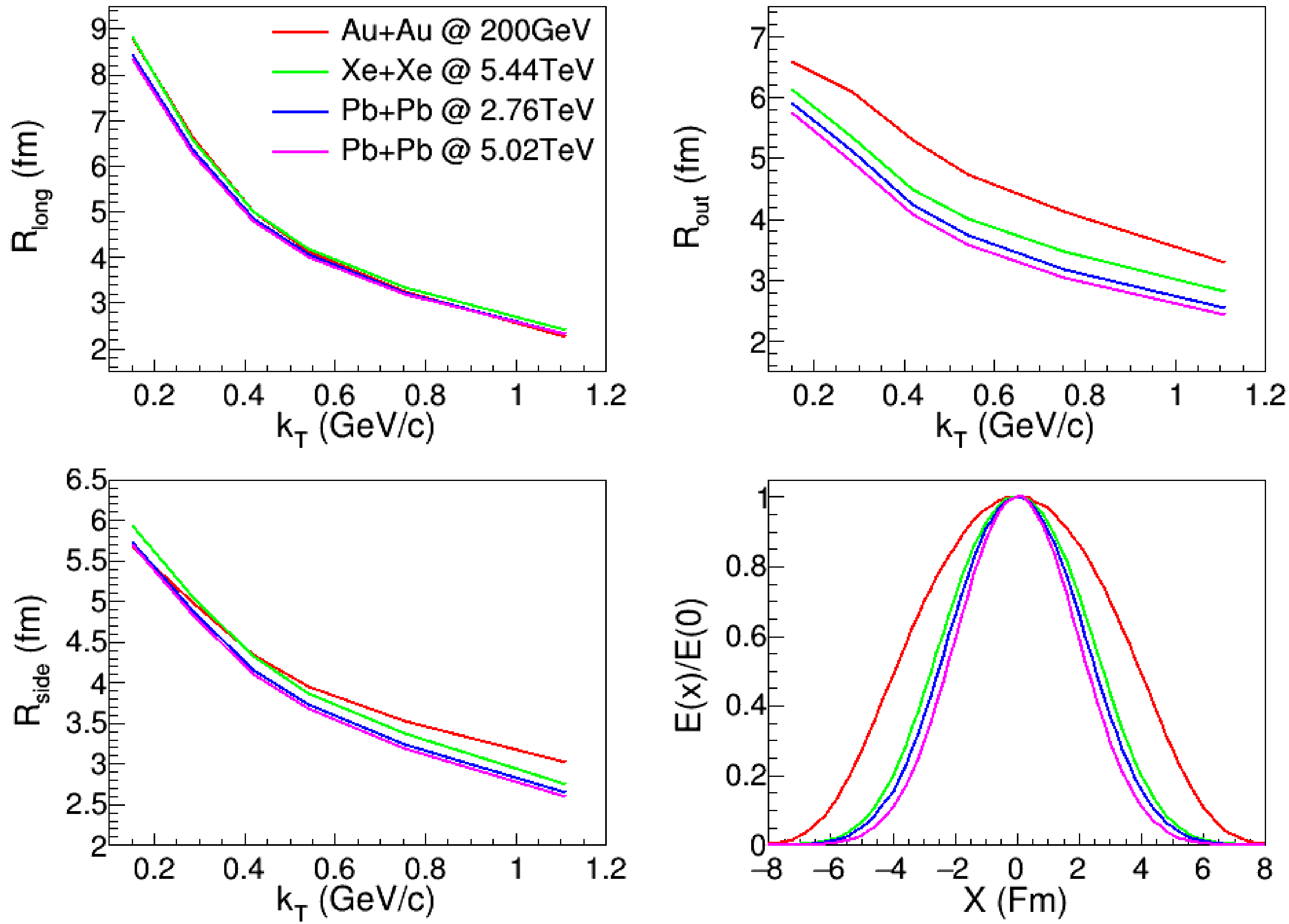
Interferometry volume vs initial overlapping area at the *fixed* multiplicity



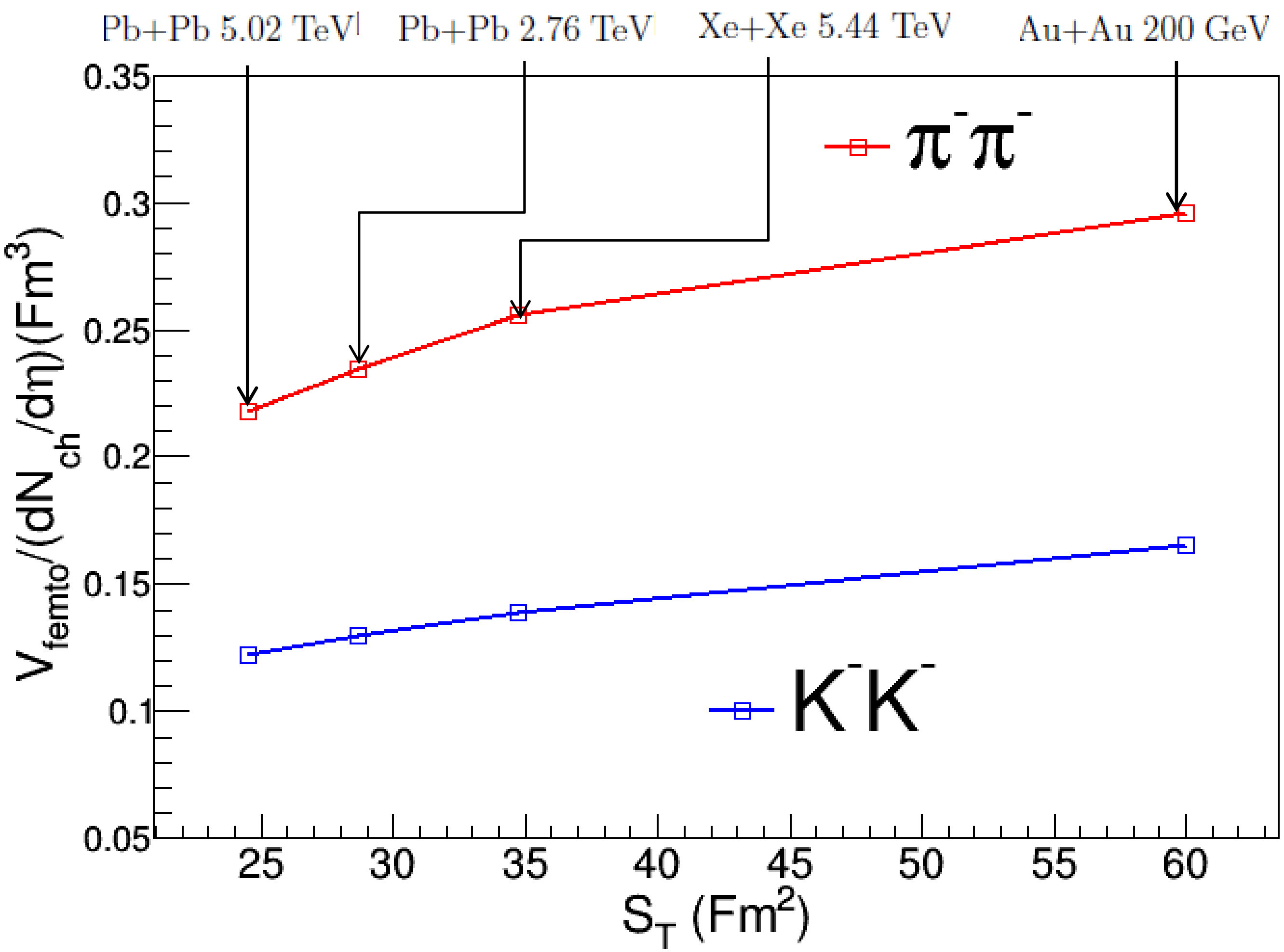
M. Adzhimambetov, Yu.S. , 2019
in preparation

experiment	centrality	$\frac{dN}{d\eta_{ch}}$	α	ϵ_0	EoS	τ_0
Au+Au 200 GeV[1]	0-5%	688	0.18	235 GeV/fm^3	LS	0.1 fm
Xe+Xe 5.44 TeV	10-19%	680	0.44	445 GeV/fm^3	HQCD	0.1 fm
Pb+Pb 2.76 TeV[2]	19-28%	693	0.24	679 GeV/fm^3	LS	0.1 fm
Pb+Pb 5.02 TeV[3]	23-33%	677	0.24	1067 GeV/fm^3	LS	0.1 fm

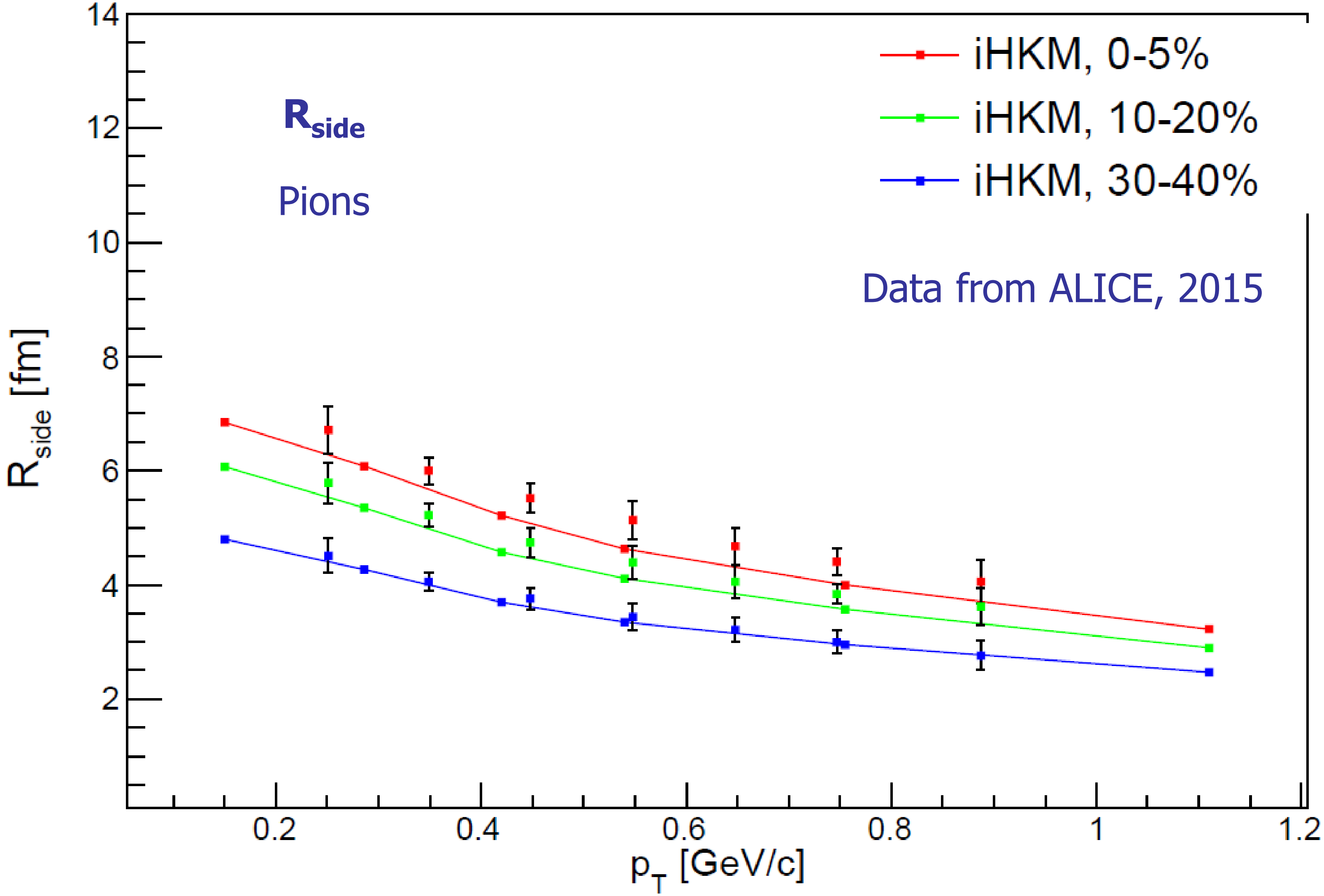
The femtoscopy radii at different energies and the same multiplicity



Femtoscopy volume vs initial transverse overlapping area of creating systems

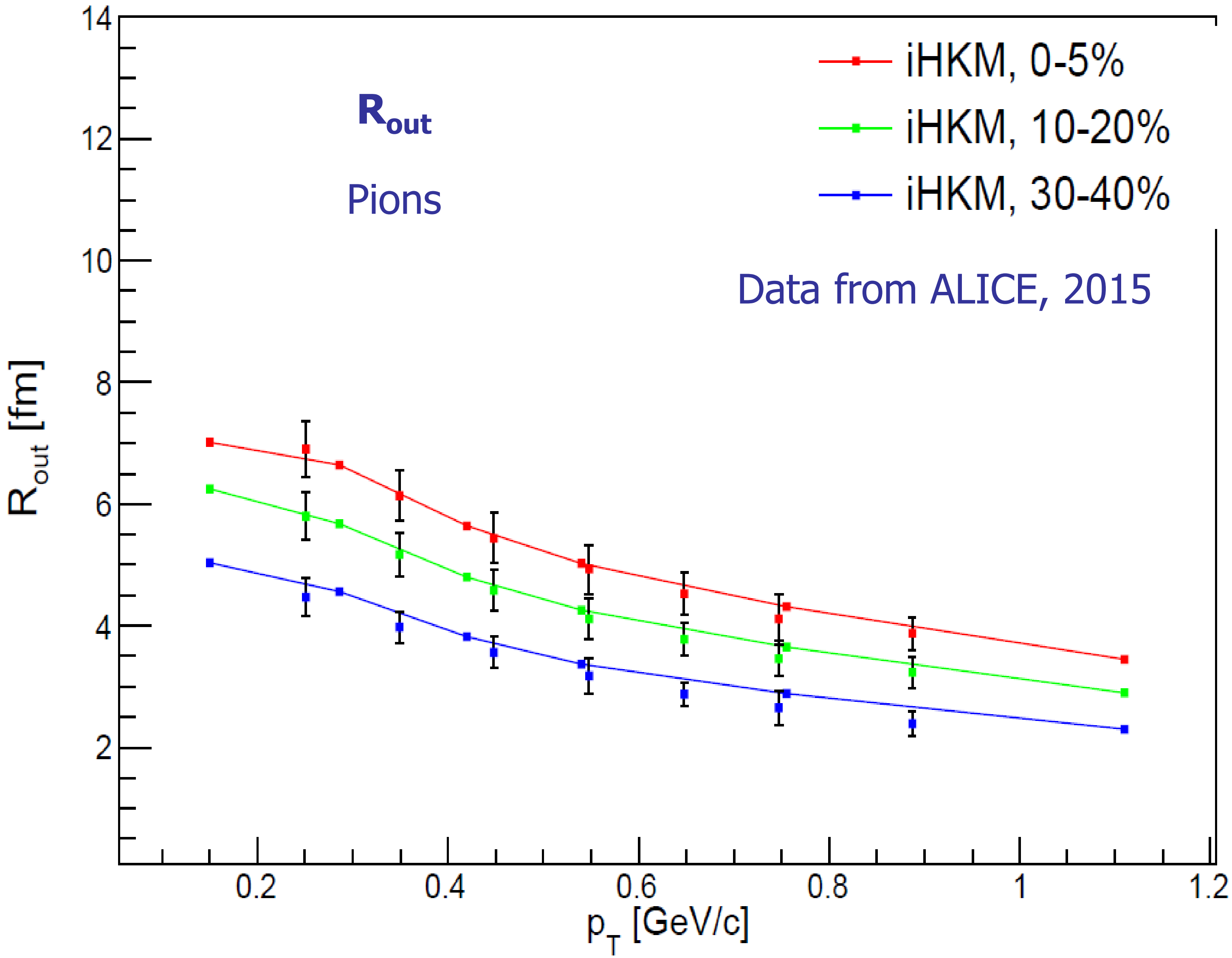


Initial transverse size S_T = effective transverse aria of overlapping nuclei at the initial stage of collision process



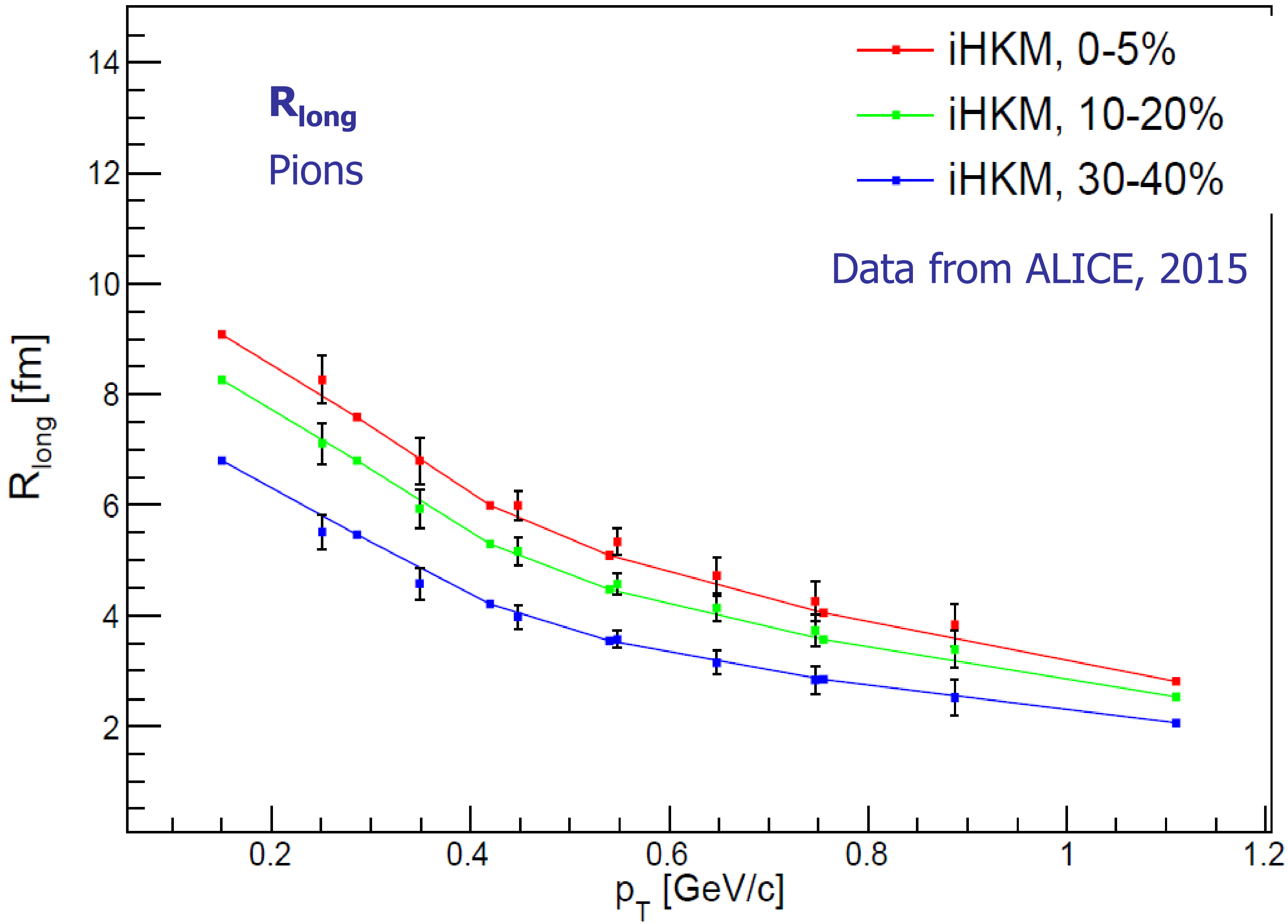
Naboka, Karpenko, Yu.S. PHYS REV C **93**, 024902 (2016)

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].



Naboka, Karpenko, Yu.S. PHYS REV C **93**, 024902 (2016)

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



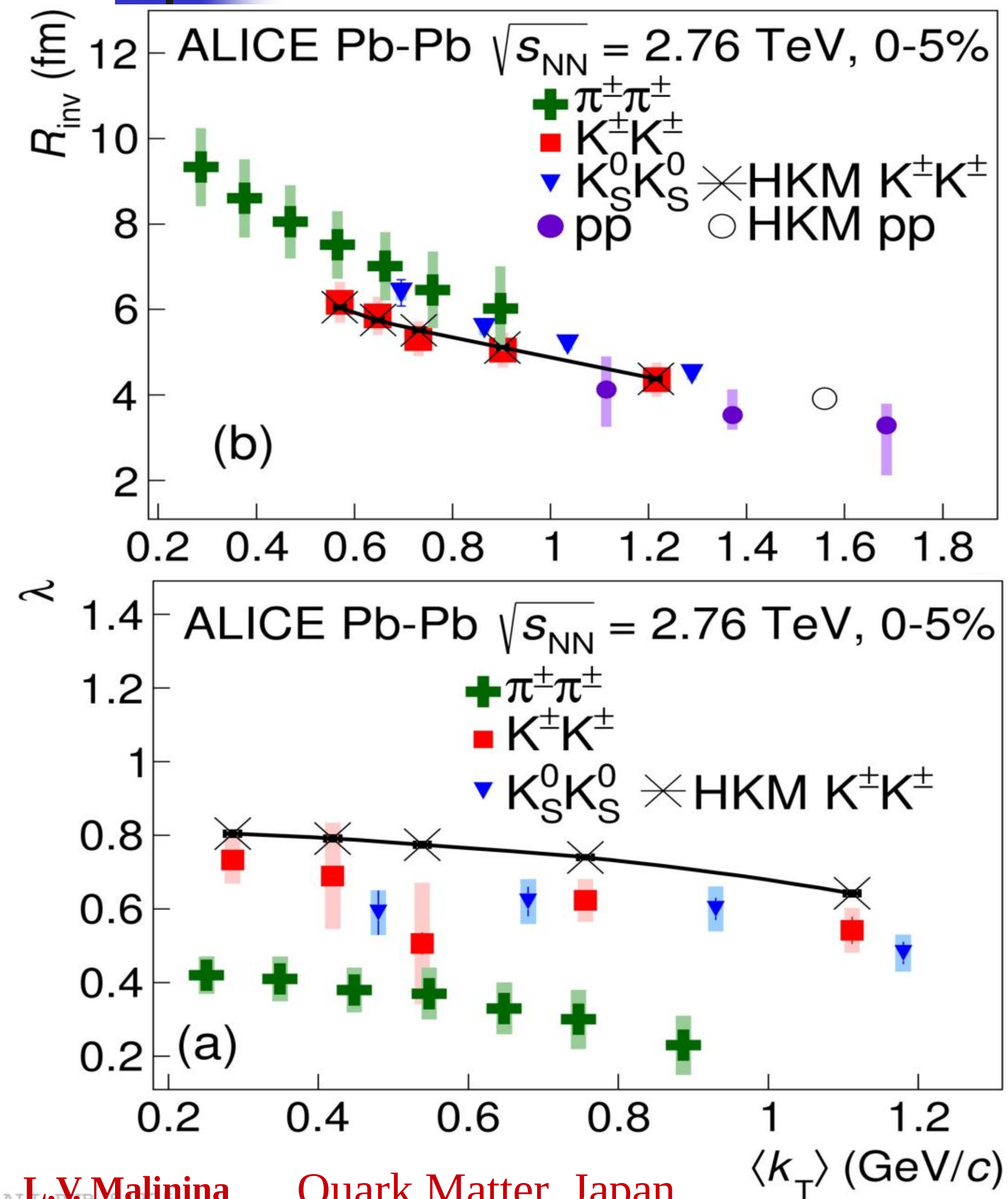
Naboka, Karpenko, Yu.S. PHYS REV C **93**, 024902 (2016)

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

iHKM

Femtoscopy scales: pions vs kaons

$K^{\pm}K^{\pm}$ and $K^0_s K^0_s$ in Pb-Pb: HKM model



New results from ArXiv.org:1506.07884

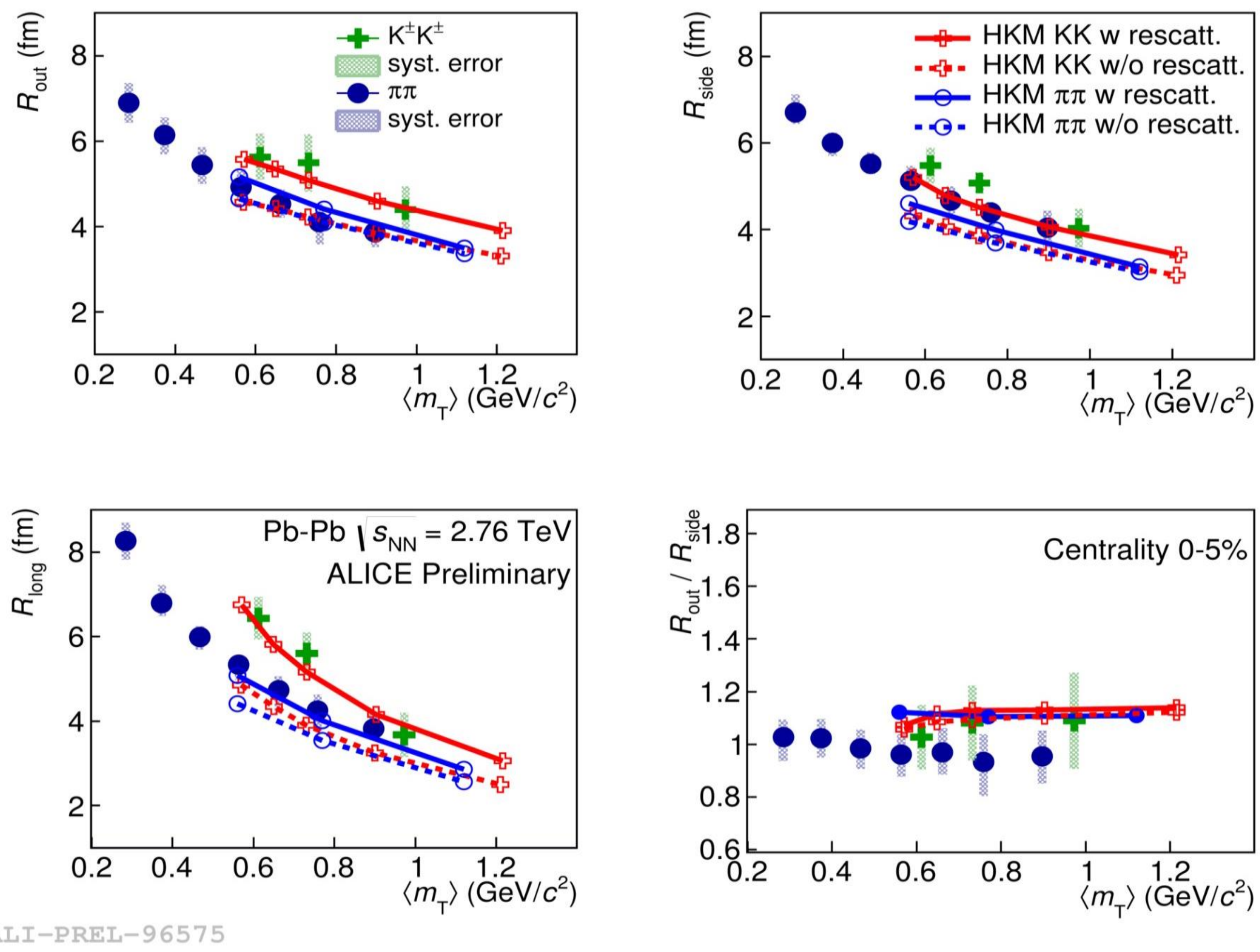
- R and λ for $\pi^{\pm}\pi^{\pm}$, $K^{\pm}K^{\pm}$, $K^0_s K^0_s$, pp for 0-5% centrality
- Radii for kaons show good agreement with HKM predictions for $K^{\pm}K^{\pm}$

(V. Shapoval, P. Braun-Munzinger, I. Karprenko Yu. Sinyukov Nucl.Phys.A929 (2014))

- λ decrease with k_T, both data and HKM
- HKM prediction for λ slightly overpredicts the data
- Λ_{π} are lower λ_K due to the stronger influence of resonances

ALICE Coll. Phys. Rev. C 96 ... (2017)

Comparison with HKM for 0-5% centrality



- HKM model slightly underestimates R_{side} overestimates *R_side /R_out*

- HKM model with re-scatterings (M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov, Nucl.Phys. A 929 (2014) 1.) describes well ALICE π & K data.

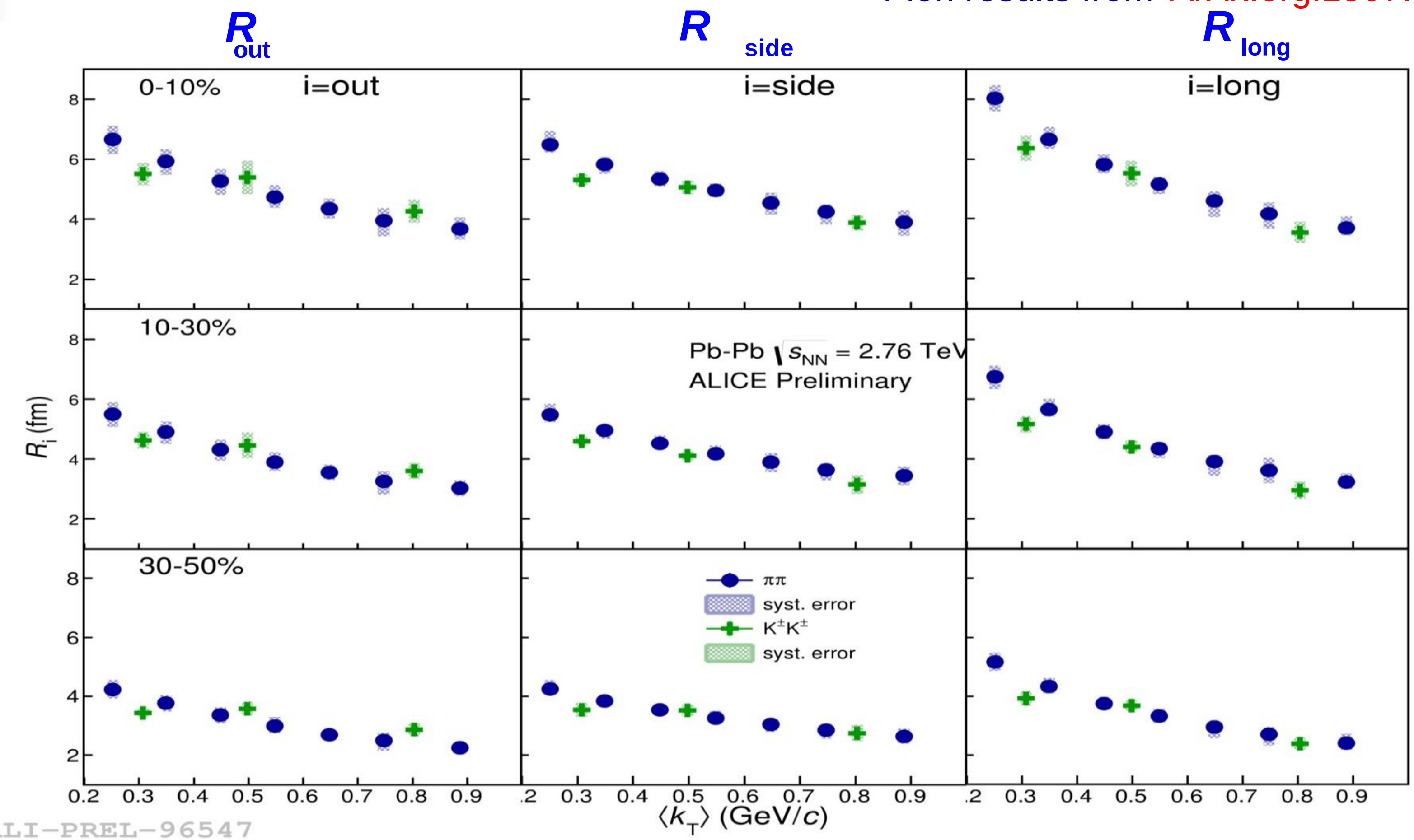
- HKM model w/o re-scatterings demonstrates approximate m_T scaling

  for π & K, but does not describe ALICE π & K data

- The observed deviation from m_T scaling is explained in (M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov, Nucl.Phys. A 929 (2014) by essential transverse flow & re-scattering phase.

3D K±K± & ππ radii versus k_T

Pion results from ArXiv.org:1507.06842



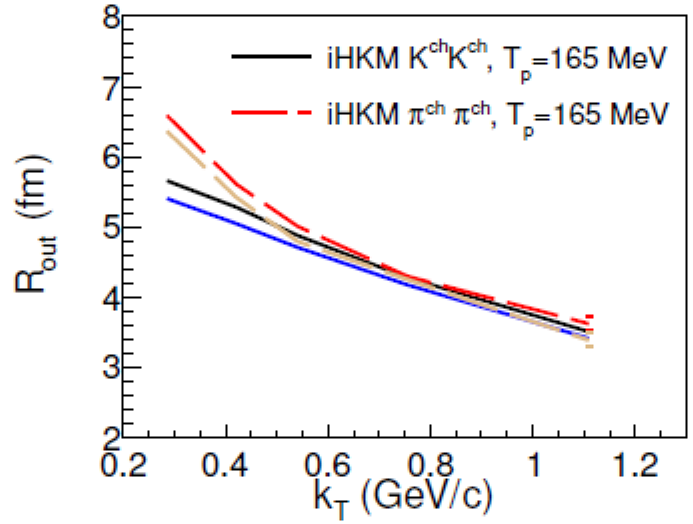
- Radii scale better with k_T than m_T according to HKM

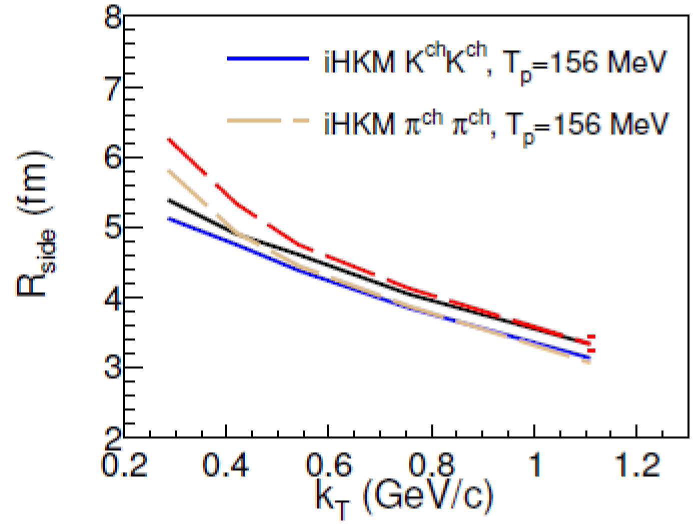
(V. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov, Nucl.Phys. A 929 (2014) 1);

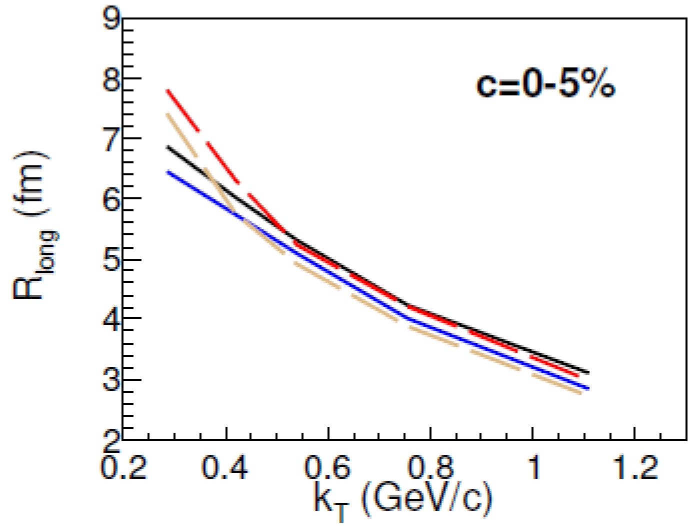
- Similar observations were reported by PHENIX at RHIC (arxiv:1504.05168).

ALICE Coll. Phys. Rev. C 96 … (2017)

Predictions for the pion and kaon femtoscopy scales for LHC energy per nucleon pair 5.02 TeV







The iHKM prediction of the charged pion and kaon interferometry radii k_T dependence for the centrality c=0-5 %. The calculations were performed at the two hadronization temperatures:
165 MeV and 156 MeV.

Yu.S. , Shapoval, to be published in Phys.Rev. C (2019)

Space-time picture of the pion and kaon emission

$$\underbrace{R_l^2(k_T) = \tau^2\lambda^2\left(1+\frac{3}{2}\lambda^2\right)}_{2015} \approx \text{w/o transv. expansion} \approx \underbrace{\tau^2\frac{T}{m_T}}_{1987}\underbrace{\frac{K_2(\frac{m_T}{T})}{K_1(\frac{m_T}{T})}}_{1995}$$

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

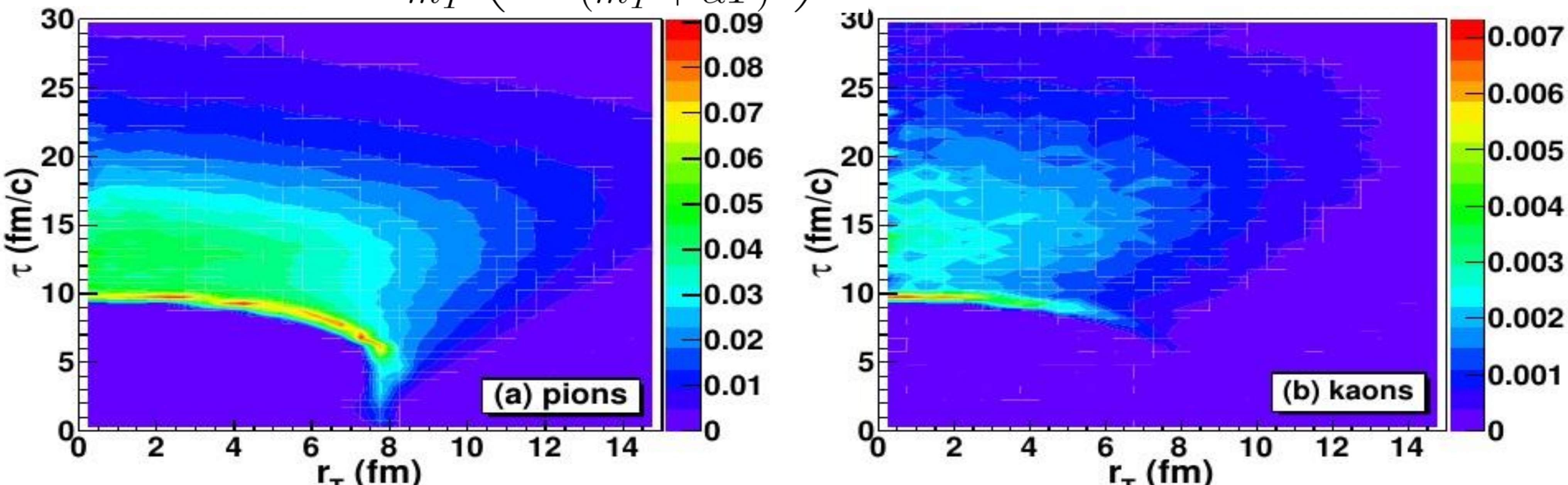


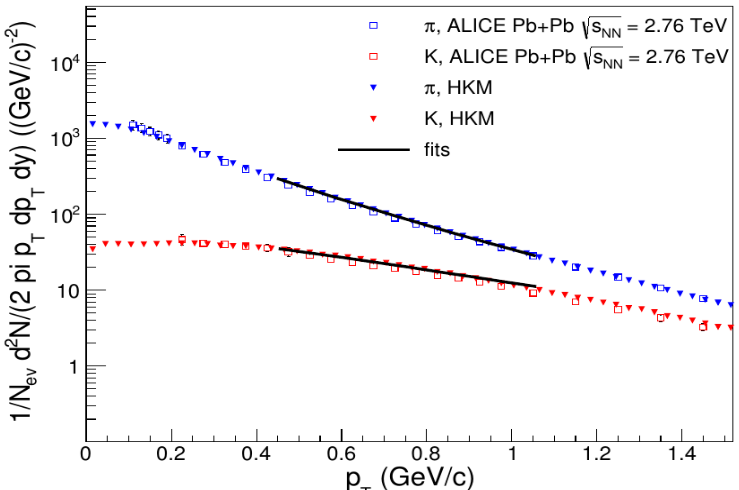
FIG. 4. The momentum angle averaged emission functions per units of space-time and momentum rapidities $g(\tau, r_T, p_T)$ [fm^{-3}] (see body text) for pions (a) and kaons (b) obtained from the HKM simulations of Pb+Pb collisions at the LHC $\sqrt{s_{NN}} = 2.76$ GeV, $0.2 < p_T < 0.3$ GeV/c, $|y| < 0.5$, $c = 0-5\%$.

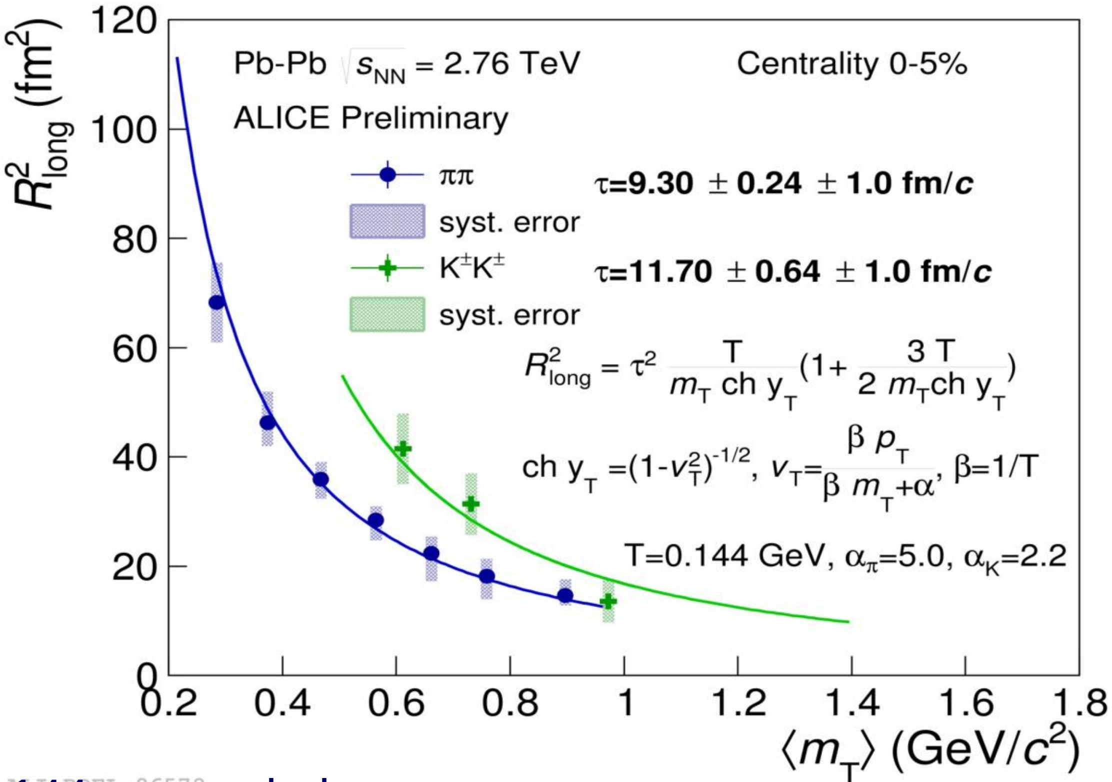
From Yu.S., Shapoval, Naboka, Nucl. Phys. A 946 (2016) 247 (arXiv:1508.01812)

Extraction of emission time from fit R_{long} T

- 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)





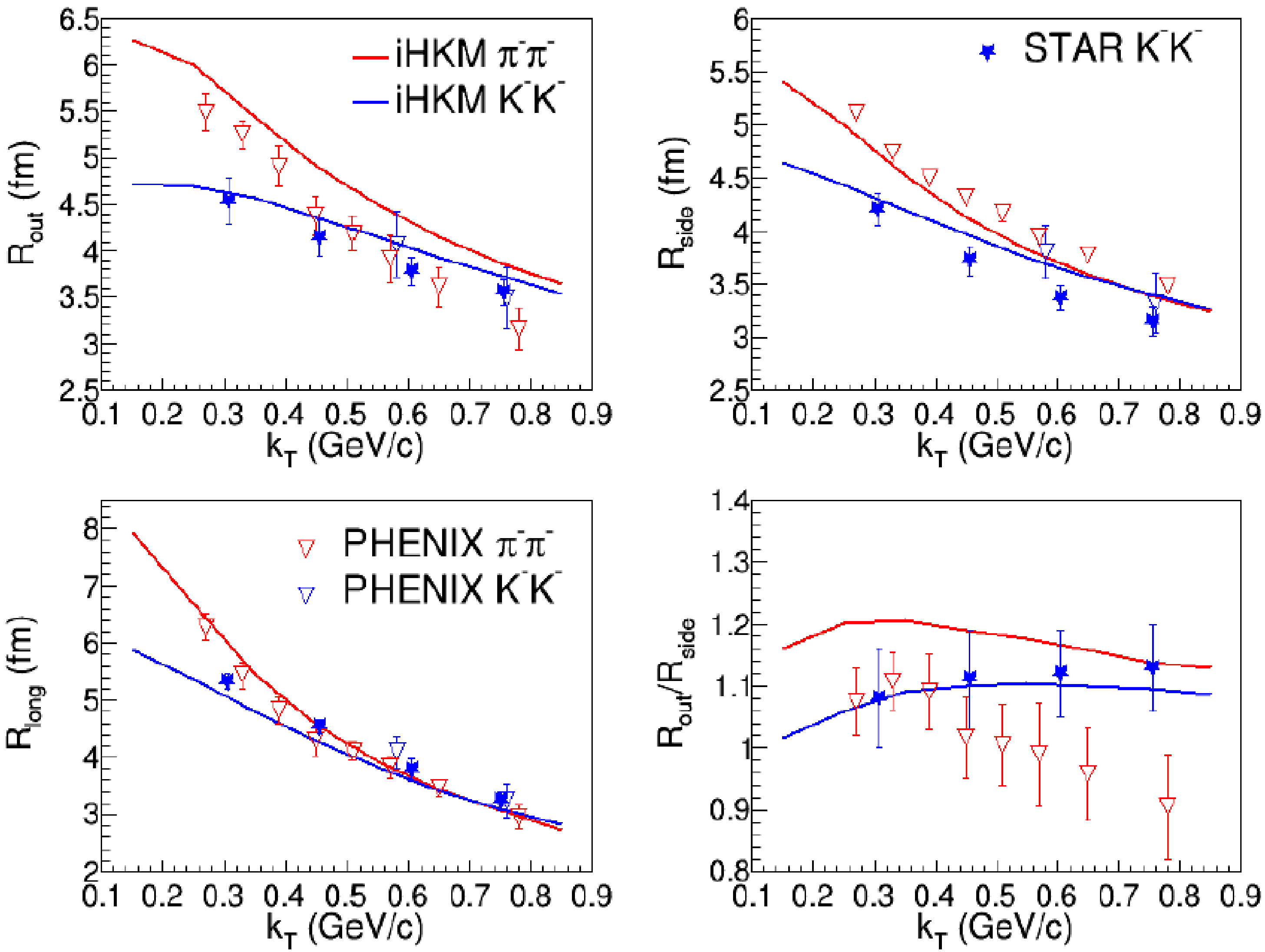
- To estimate the systematic errors: T = 0.144 was varied on ± 0.03 GeV & free α_π , α_K , were used; systematic errors ~ 1 fm/c

- Indication: $\tau_\pi < \tau_K$. Possible explanations (arxiv:1508.01812): HKM includes re-scatterings (UrQMD cascade): e.g. Kπ→K*(892)→Kπ, KN→K*(892)X; (K*(892) lifetime 4-5 fm/c) [πN→N*(Δ)X, N*(Δ)→πX (N*s(Δs)- short lifetime)]

iHKM femtoscopy results for RHIC

M. Adzhimambetov, V. Shapoval, Yu.S.,
Nucl.Phys. A **987** (2019) 321–336.

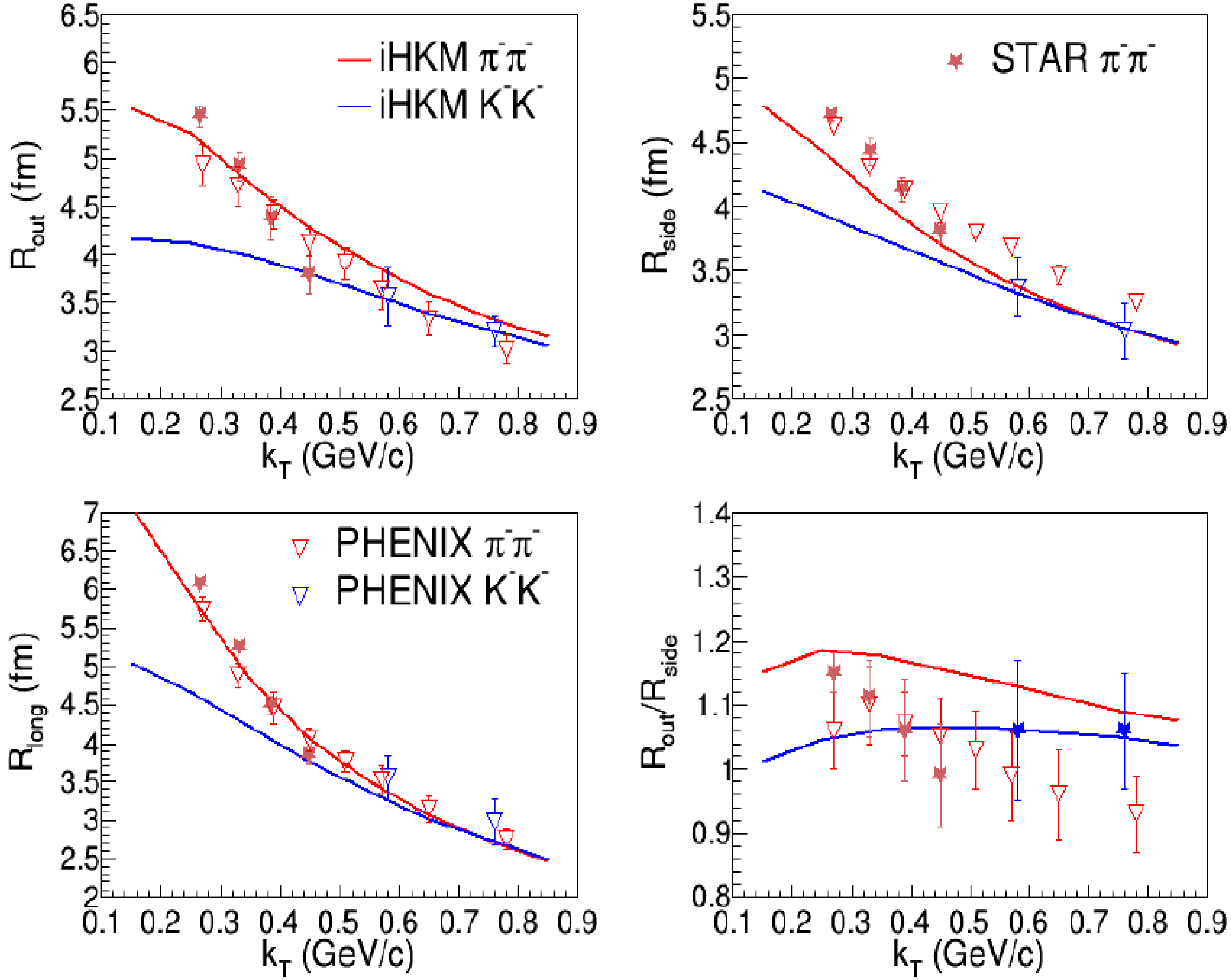
Interferometry radii, $c = 0 - 10\%$



$0.15 < p_T < 1.55$ GeV$/c$, $|\eta| < 1$

G. Nigmatkulov, arXiv:1712.09964v1; J. Adams *et al.* (STAR Collaboration), Phys. Rev. C **71** (2005), 044906; A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. C **92** (2015), 034914.

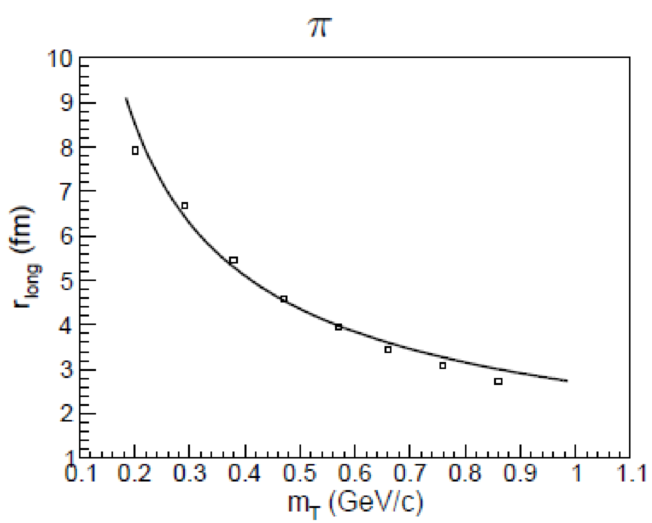
Interferometry radii, $c = 10 - 20\%$

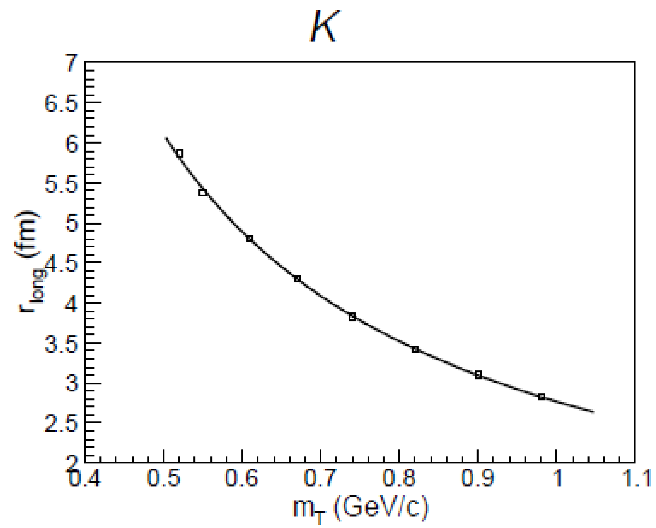


$0.15 < p_T < 1.55$ GeV$/c$, $|\eta| < 1$

G. Nigmatkulov, arXiv:1712.09964v1; J. Adams *et al.* (STAR Collaboration), Phys. Rev. C **71** (2005), 044906; A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. C **92** (2015), 034914.

Time of maximal emission extraction





Combined π and K spectra fit for $0.45 < p_T < 1.0$ GeV$/c$ with the formula

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

gives us the temperature $T = 141$ MeV, $\alpha_\pi = 7.86 \pm 2.11$ and $\alpha_K = 5.54 \pm 2.61$.

Fitting the R_{long} dependence on m_T with the formula

$$R_l^2(k_T) = \tau^2\lambda^2\left(1 + \frac{3}{2}\lambda^2\right)$$

gives the maximal emission times: $\tau_\pi = 7.12 \pm 0.01$ fm$/c$ and $\tau_K = 9.71 \pm 0.02$ fm$/c$.

As for α's, the pion value is in agreement with the spectra fit, $\alpha_\pi = 7.05 \pm 0.17$, while for kaons it is reduced, $\alpha_K = 0.12 \pm 0.02$.

Hadron emission in Au+Au coll. at 200 GeV/n.p. (RHIC)

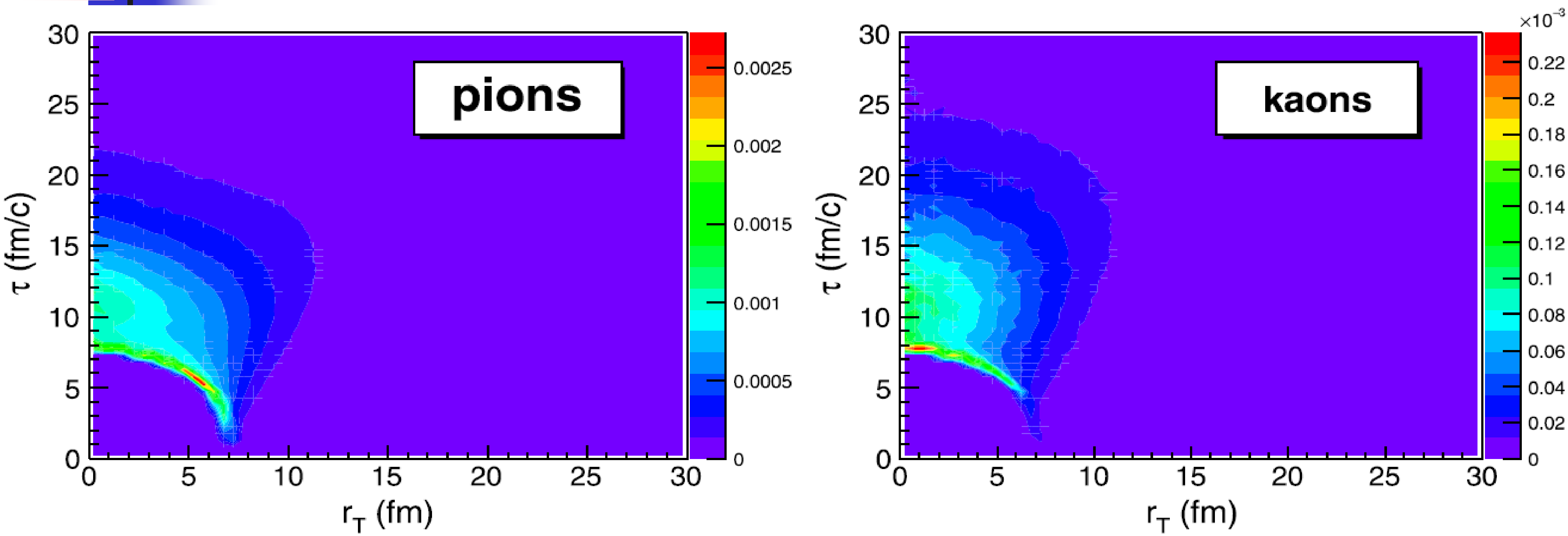
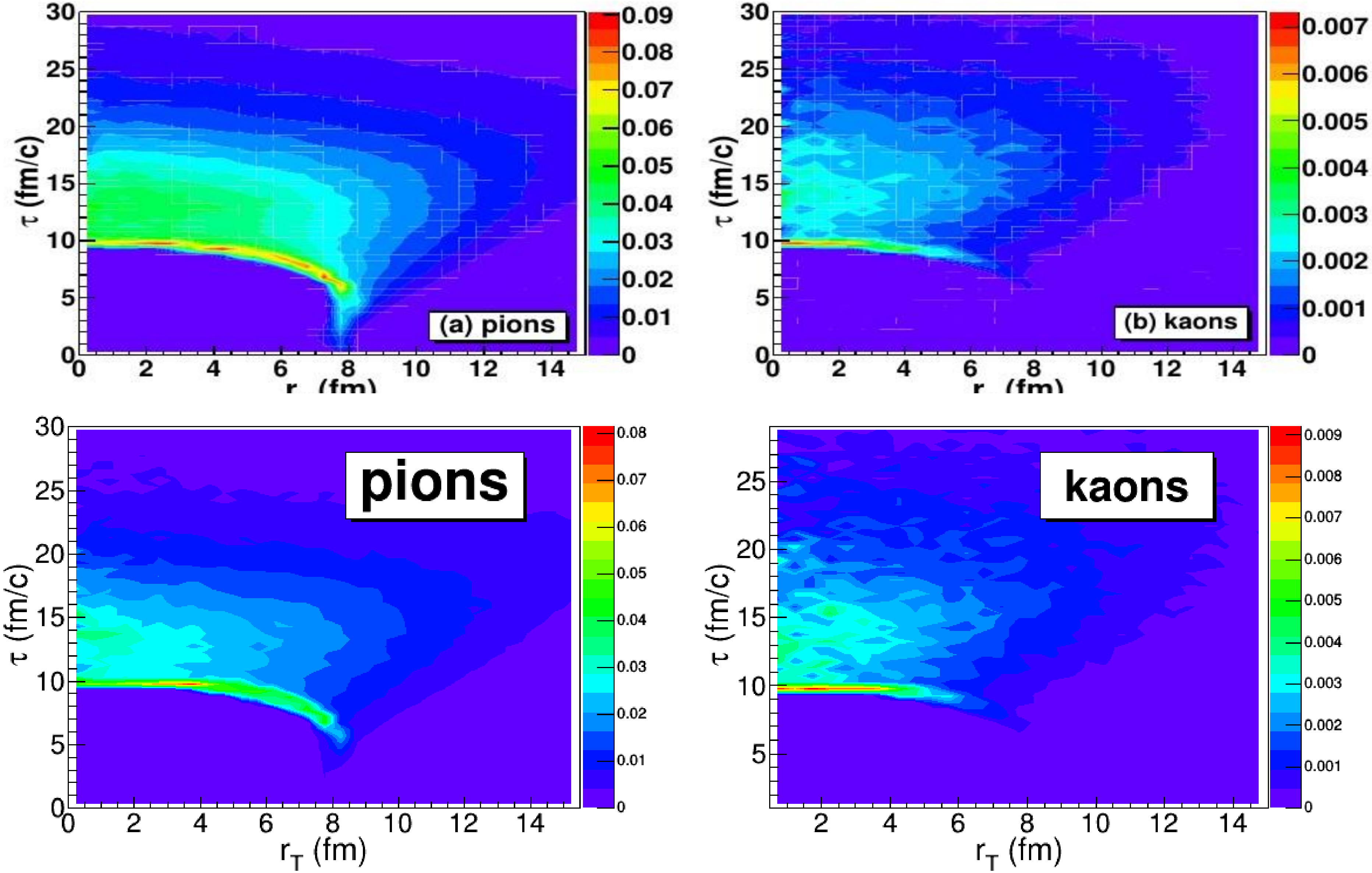


Fig. 18. The pion and kaon emission functions $g(\tau, r_T, p_T)$ [fm^{-3}], averaged over complementary variables, obtained from iHKM for the centrality class $c = 0-10\%$. Particles with $0.2 < p_T < 0.3$ GeV/c and $|\eta| < 1$ were chosen for the analysis.

The maximal emission times are extracted following the procedure, suggested in
Yu.M. Sinyukov, V.M. Shapoval, V.Yu. Naboka, Nucl. Phys. A **946** (2016), 227
and later used by the ALICE Collaboration in their study
S. Acharya *et al.* (ALICE Collaboration), Phys. Rev. C **96** (2017), 064613

Hadron emission in Pb+Pb coll. at 2.76 TeV/n.p. and Xe+Xe at 5.44 TeV/n.p.



Pb+Pb

Xe+Xe

Times of maximal emission at soft p_T in different A+A systems

experiment	T (GeV)	α_π	α_K	τ_π (fm/c)	τ_K (fm/c)
Au+Au 200 GeV[1]	141	7.86	0.12	7.12 ± 0.01	9.71 ± 0.02
Xe+Xe 5.44 TeV	149	4.40	1.49	9.02 ± 0.01	10.75 ± 0.02
Pb+Pb 2.76 TeV[2]	147	8.5	1.5	9.44 ± 0.02	12.40 ± 0.04
Pb+Pb 5.02 TeV[3]	147	5.47	0.75	9.13 ± 0.02	12.04 ± 0.06

[1] M. D. Adzhymambetov, V. M. Shapoval, and Yu. M. Sinyukov, Nuclear Physics A, **987** (2019).

[2] V. Yu. Naboka, Iu. A. Karpenko, and Yu. M. Sinyukov, Phys. Rev. C **93** (2016) 024902.

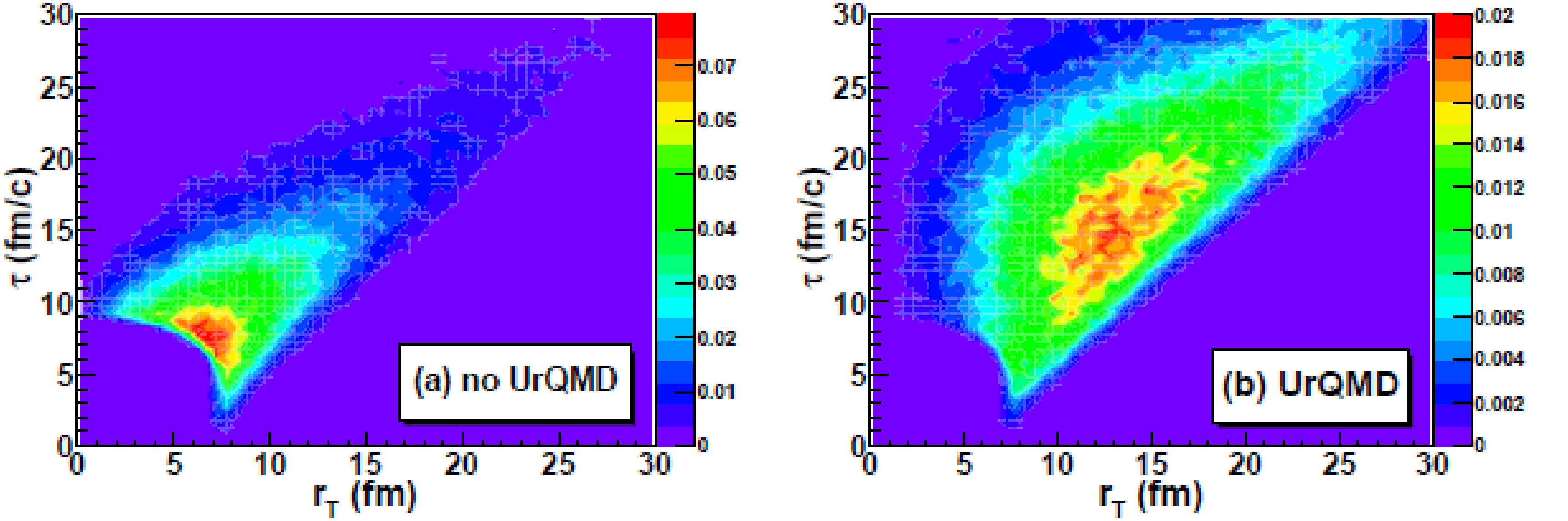
[3] V.M. Shapoval, Yu.M. Sinyukov, arXiv:1809.07400 [hep-ph]. To be published in Phys. Rev. C (2019).

K* probes

$K^*(892)$ life time is 4.2 fm/c

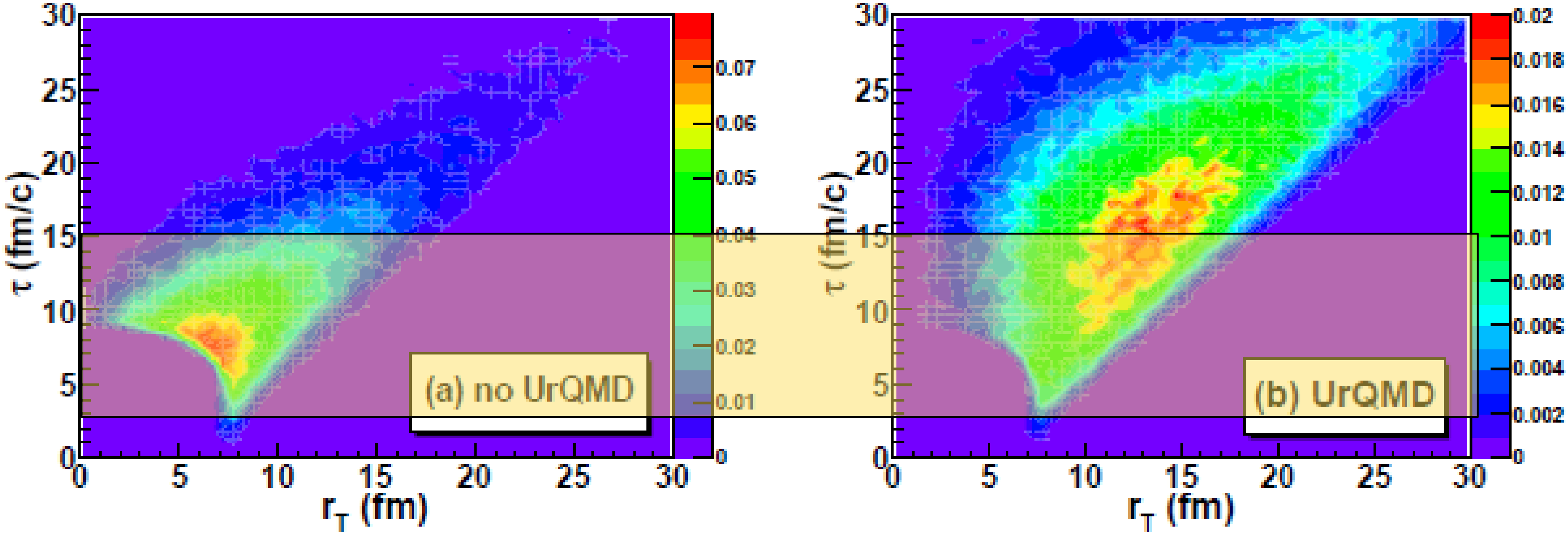
$K^{*0} \to K^+\pi^-$ radiation picture in iHKM. Sudden vs continuous thermal freeze-out at the LHC.

V.Shapoval, P.Braun-Munzinger, Yu.S. Nuclear Physics A 968 (2017) 391



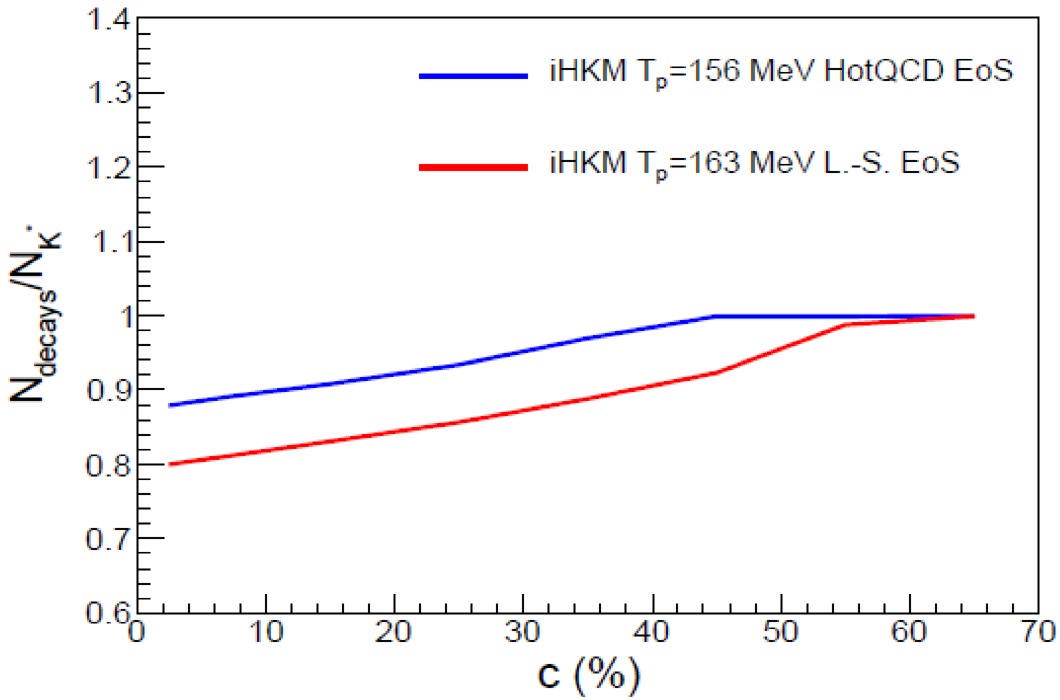
The comparison of the emission functions $g(\tau, r_T)$, averaged over complementary space and momentum components, of $K^+\pi^-$ pairs, associated with $K(892)^{*0}$ decay products, for two cases: (a) free-streaming of the particles and resonances, and (b) UrQMD hadron cascade. The plots are obtained using iHKM simulations of Pb+Pb collisions at the LHC $\sqrt{s_{NN}} = 2.76$ GeV, $0.3 < k_T < 5$ GeV/c, $|y| < 0.5$, $c = 5 - 10\%$.

$K^{*0} \to K^+\pi^-$ radiation picture in iHKM. Sudden vs continuous thermal freeze-out at the LHC.



Less than 30% of direct K* can be seen till 15 fm/c

Suppression of K^{*0} due to continuous thermal freeze-out (LHC)

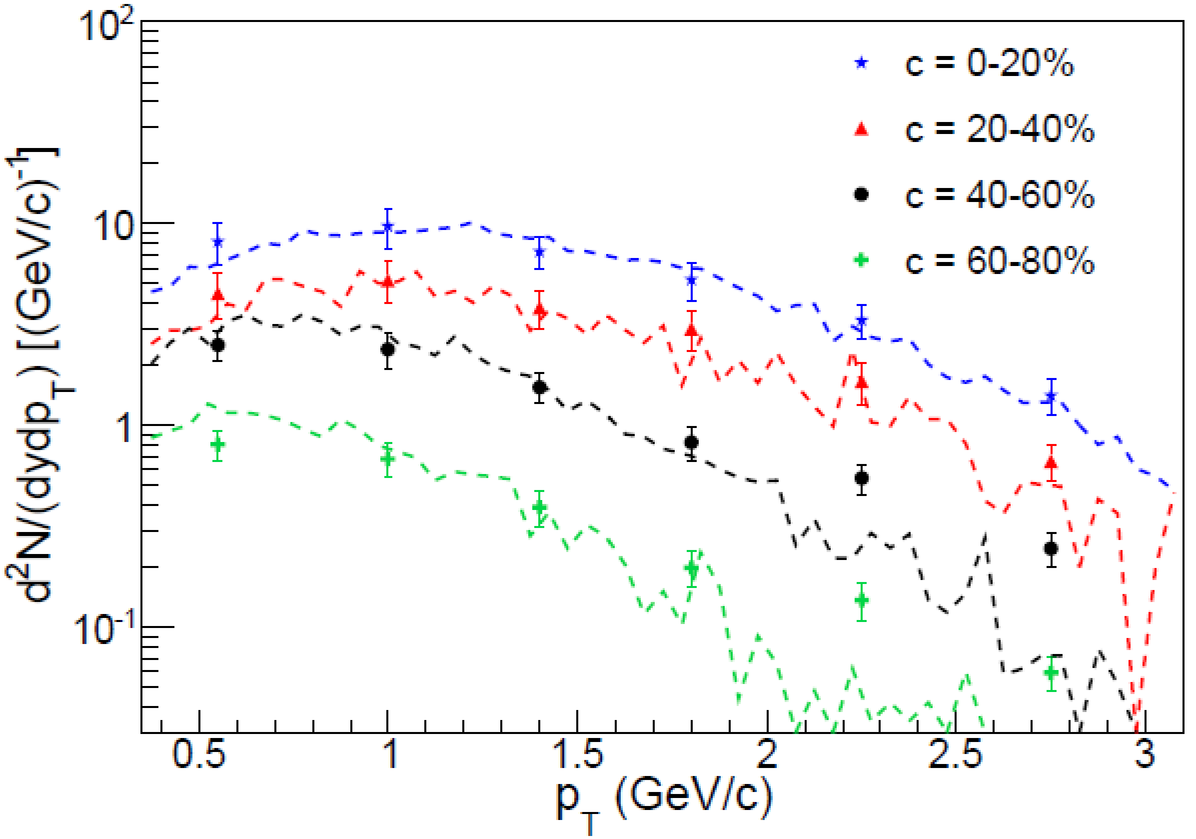


70% - 20% = 50%
Therefore
at least 50% of direct K^{*0} are recreated in reactions:

$$K^+\pi^- \to K^{*0}$$

FIG. 3. The fraction of $K^+\pi^-$ pairs coming from $K(892)^*$ decay, which can be identified as daughters of K^* in iHKM simulations after the particle rescattering stage modeled within UrQMD hadron cascade. The simulations correspond to LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with different centralities. The iHKM results are presented for two cases: the Laine-Shroeder equation of state with particlization temperature $T_p = 163$ MeV (red line) and the HotQCD equation of state with $T_p = 156$ MeV (blue line).

Spectra of K^{*0} (LHC)



The $K(892)^*$ resonance p_T spectra for Pb+Pb collision events with different centralities at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV obtained in iHKM simulations (lines) in comparison with the experimental data [6] (markers).

Summary for space-time structure of ultrarelativistic A+A collisions

- It seems that we understood in detail the femtoscopic picture of ultrarelativistic A+A collisions at the top RHIC and available LHC energies.

- The dependence of the interferometry volume on both main parameters, namely, multiplicity and initial size of the system formed, is obviously demonstrated.

- As for the complete space-time picture of collision process , the femoscopy analysis altogether with $K^{*0}(892)$ probes demonstrate that even at the first 4-5 fm/c (proper time!) after hadronization **at least** 70% of decay products are re-scattered. The intensive re-generation of K* takes place. **At least** 50% of direct $K^{*0}(892)$ are re-combine.

- Quite intensive "afterburner life" at the last hadron evolution stage, leads not only to violation of kaon-pion femtoscopy m_T – scaling, but also to continuous "chemical freeze-out"

Thermal and evolutionary approaches

Yu.S., V. Shapoval,

Phys. Rev. C 97 064901 (2018)

Continuous freeze-out **vs** sudden freeze-out

- Thermal models of particle production **vs** dynamic/evolutionary approaches

Kinetic/thermal freeze-out

Sudden freeze-out

Cooper-Frye prescription

$$p^0 \frac{d^3 N_i}{d^3 p} = \int_{\sigma_{th}} d\sigma_\mu p^\mu f_i(x,p)$$

The σ_{th} is typically isotherm.

Continuous freeze-out

$$p^0 \frac{d^3 N_i}{d^3 p} = \int d^4 x S_i(x,p) \approx \int_{\sigma(p)} d\sigma_\mu p^\mu f_i(x,p)$$

The $\sigma(p)$ is peace of hypersurface where the particles with momentum near p has a maximal emission rate. *Yu.S.* Phys. Rev. C78,

Chemical freeze-out

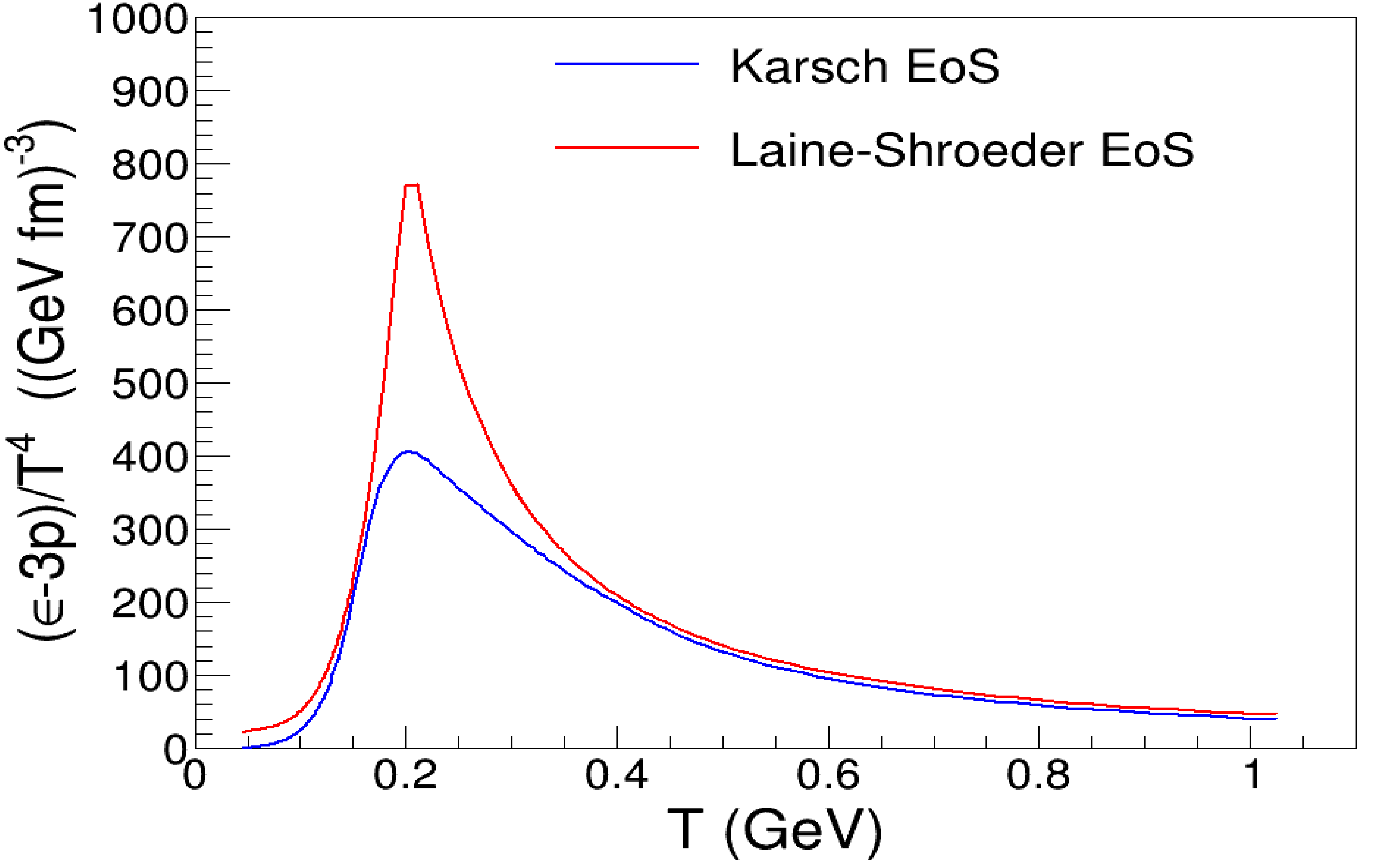
$$N_i = \int_p \int_{\sigma_{ch}} \frac{d^3 p}{p^0} d\sigma_\mu p^\mu f_i\left(\frac{p^\mu u_\mu(x)}{T_{ch}}, \frac{\mu_{i,ch}}{T_{ch}}\right)$$

$$= n_i(T,\mu) V_{eff} \qquad V_{eff} = \int_{\sigma_{ch}} u^\mu d\sigma_\mu$$

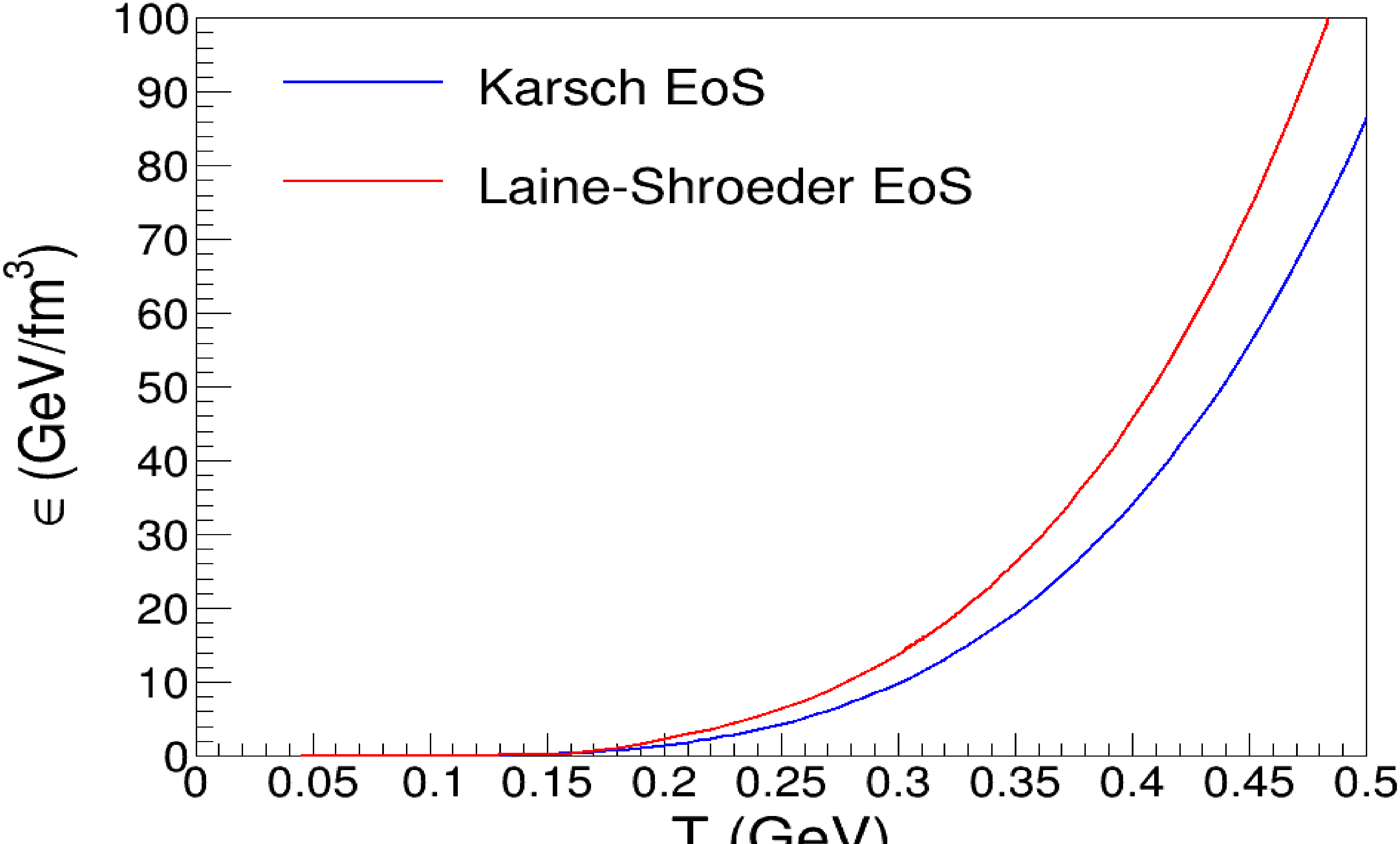
The numbers of quasi-stable particles is defined from N_i with taking into account the resonance decays but **not** inelastic re-scattering.

The T_{ch} is the minimal temperature when the expanding system is still (near) in local thermal and chemical equilibrium. Below the hadronic cascade takes place: $T_{ch} \rightarrow T_{part}$. The inelastic reactions, annihilation processes in hadron-resonance gas change the quasi-particle yields in comparison with sudden chem. freeze-out.

Equation of State



Equation of state



Thermal models **vs** evolutionary approach

Basic matter properties: thermodynamic **EoS**

Evolutionary models

Thermal **models**

$\frac{dN_{charge}}{d\eta}(c)$

$\frac{dN_{\pi}}{p_T dp_T}$

High dense matter formation time τ_0

Max. energy density $\epsilon(\tau_0) \equiv \epsilon_0$

Chemical freeze-out at $T_{ch} \approx T_h$

Particle number ratios $\{\frac{N_i}{N_j}\}$

At the particlization temperature $T_{part} \approx T_h$ hydrodynamic evolution transforms (suddenly or continuously) into interact. hadron gas evolution

EoS: $T_h = 165$ MeV → 156 MeV

L.-S. → HotQCD) Coll. → $\tau_0 = 0.1$ fm/c → 0.15 fm/c **iHKM**

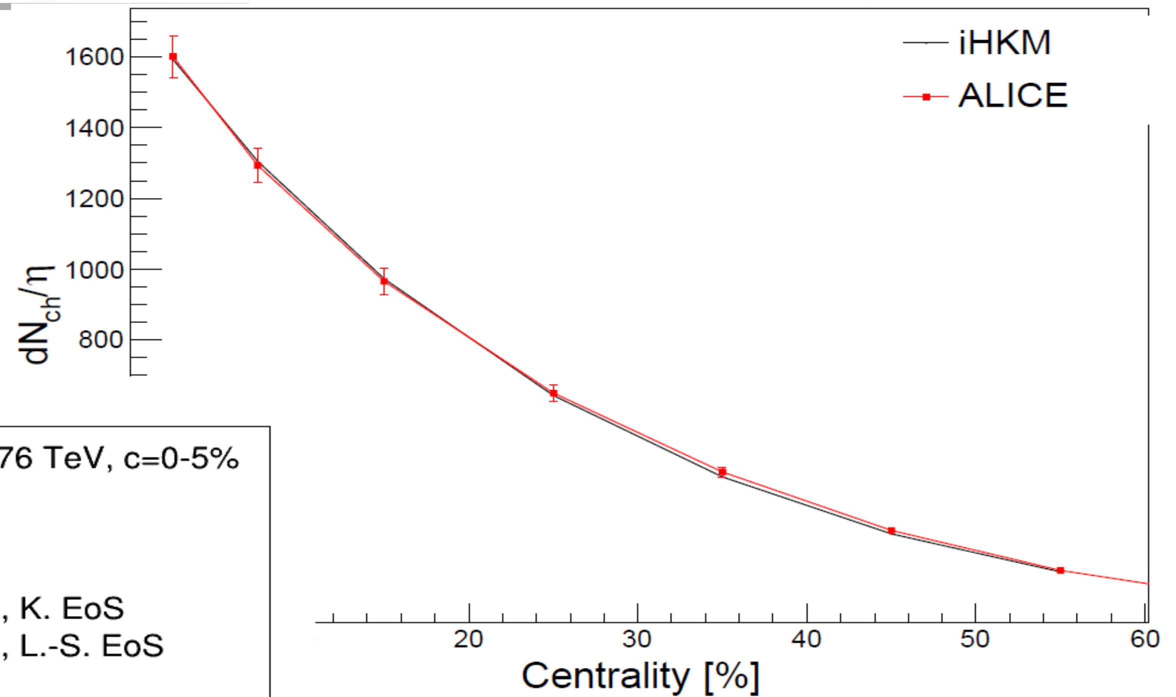
$\epsilon_0 = 679$ GeV/fm^3 → 495 GeV/fm^3

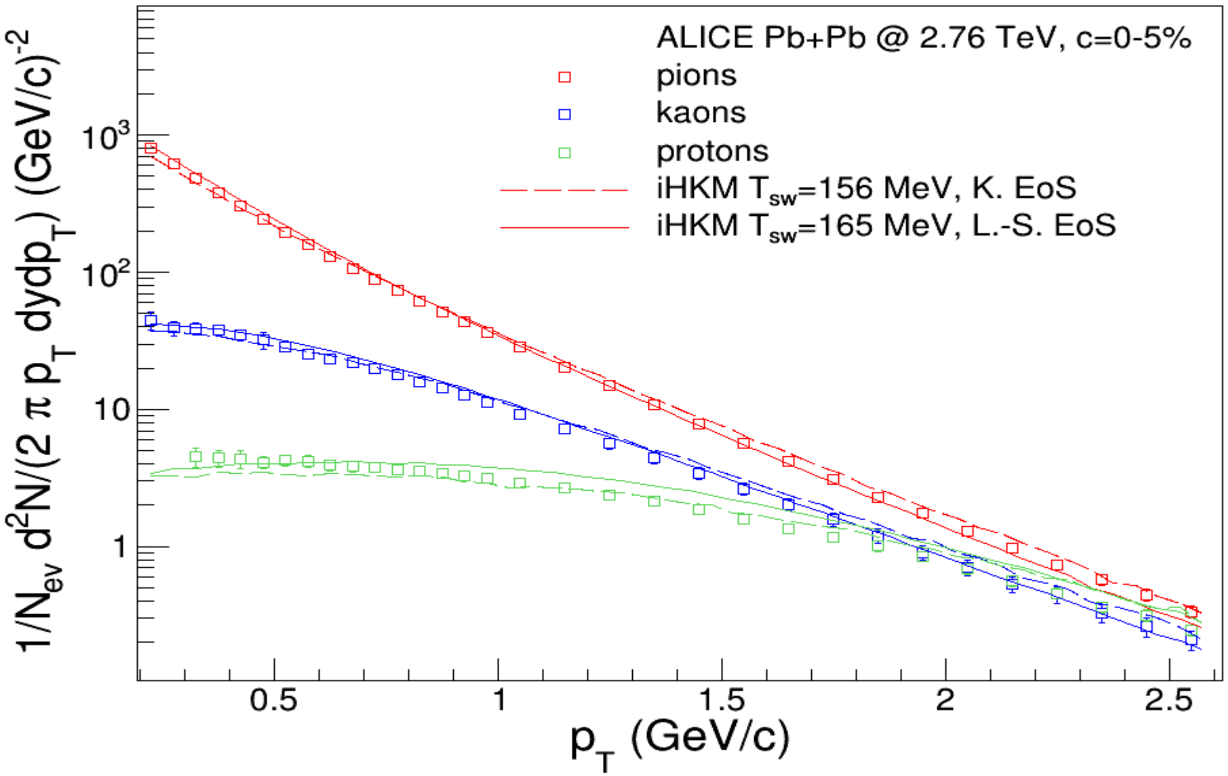
Kinetic freeze-out

«Blast-wave" parametrization of freeze-out hypersurface and transverse flows on it. Spectra $\frac{dN_i}{p_T dp_T} \rightarrow T_{th}$

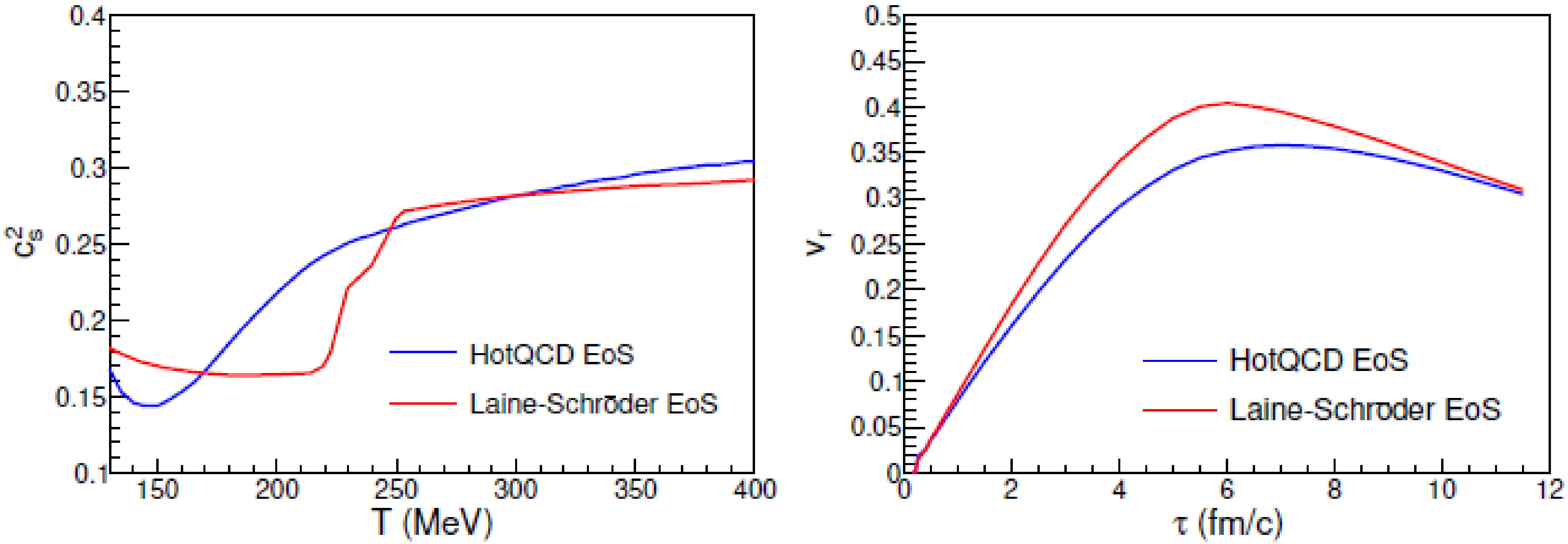
Kinetic freeze-out is continuous, lasts more than 5 fm/c. "Effective temperature" of maximal emission: . $T_{th}(p)$

Multiplicity dependence of all charged particles on centrality and spectra for LHC energy $\sqrt{s_{NN}} = 2.76\ \text{TeV}$



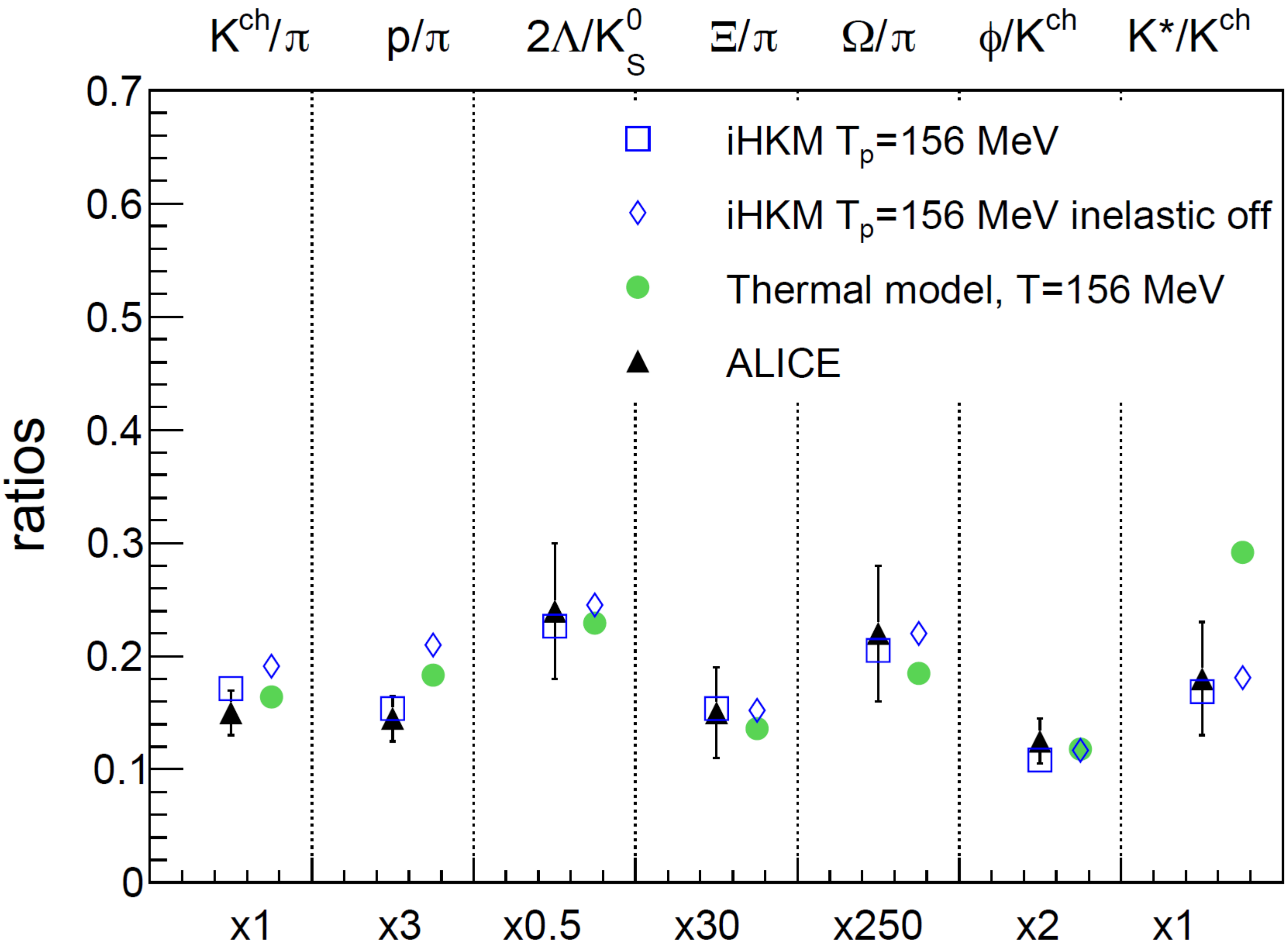


Sound speed and radial velocity development



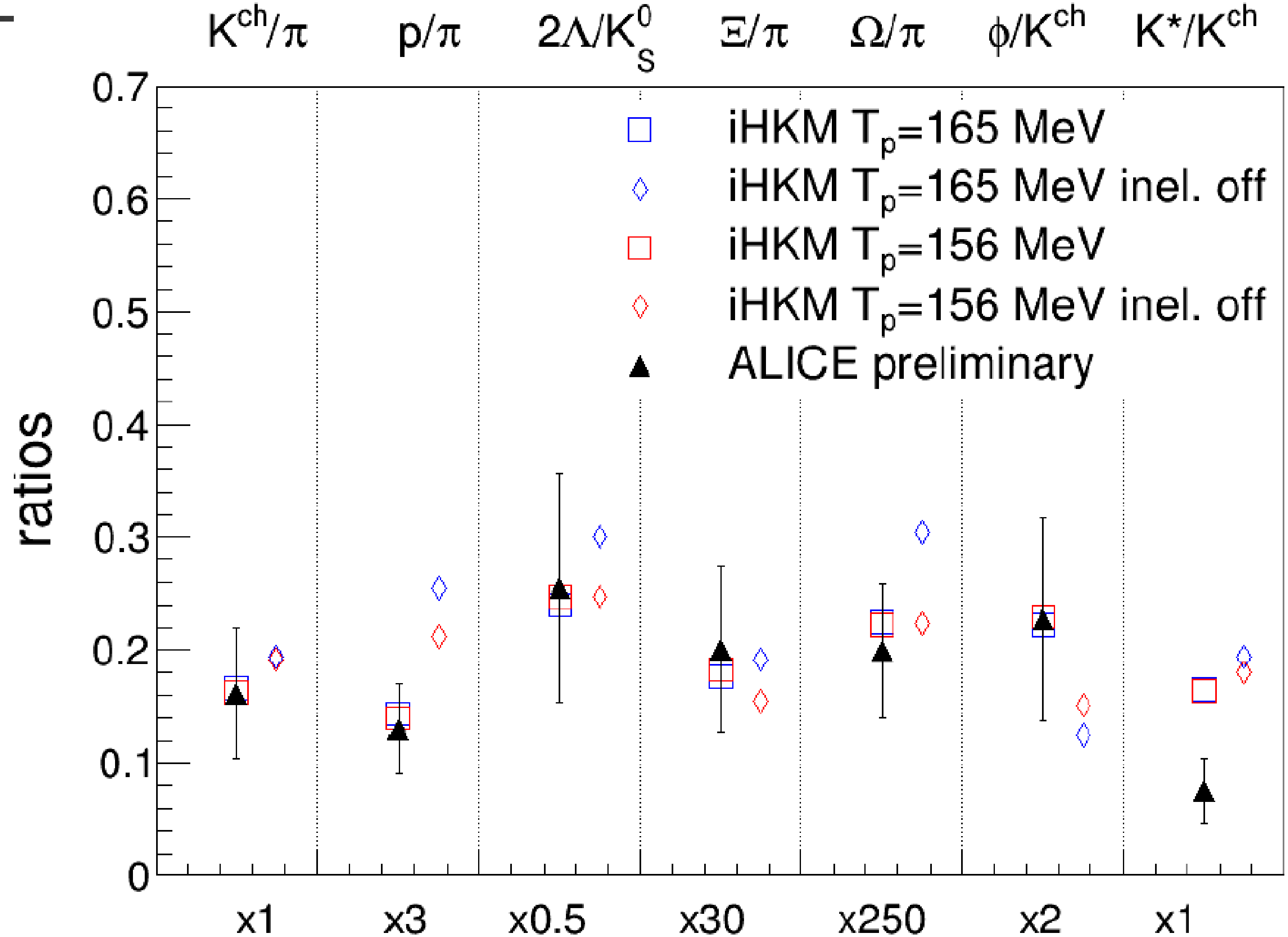
The dependence of square of the speed of sound c_s^2 on the temperature T (left) and radial flow's v_r dependence on τ for $r_T = 3$ fm in iHKM (right) for Laine-Schroeder [8] and HotQCD Collaboration equations of state [9].

Particle number ratios at the LHC 2.76 TeV/n.p., Lattice QCD EoS



Yu.S. , Shapoval,
Phys. Rev. C 97 064901 (2018)

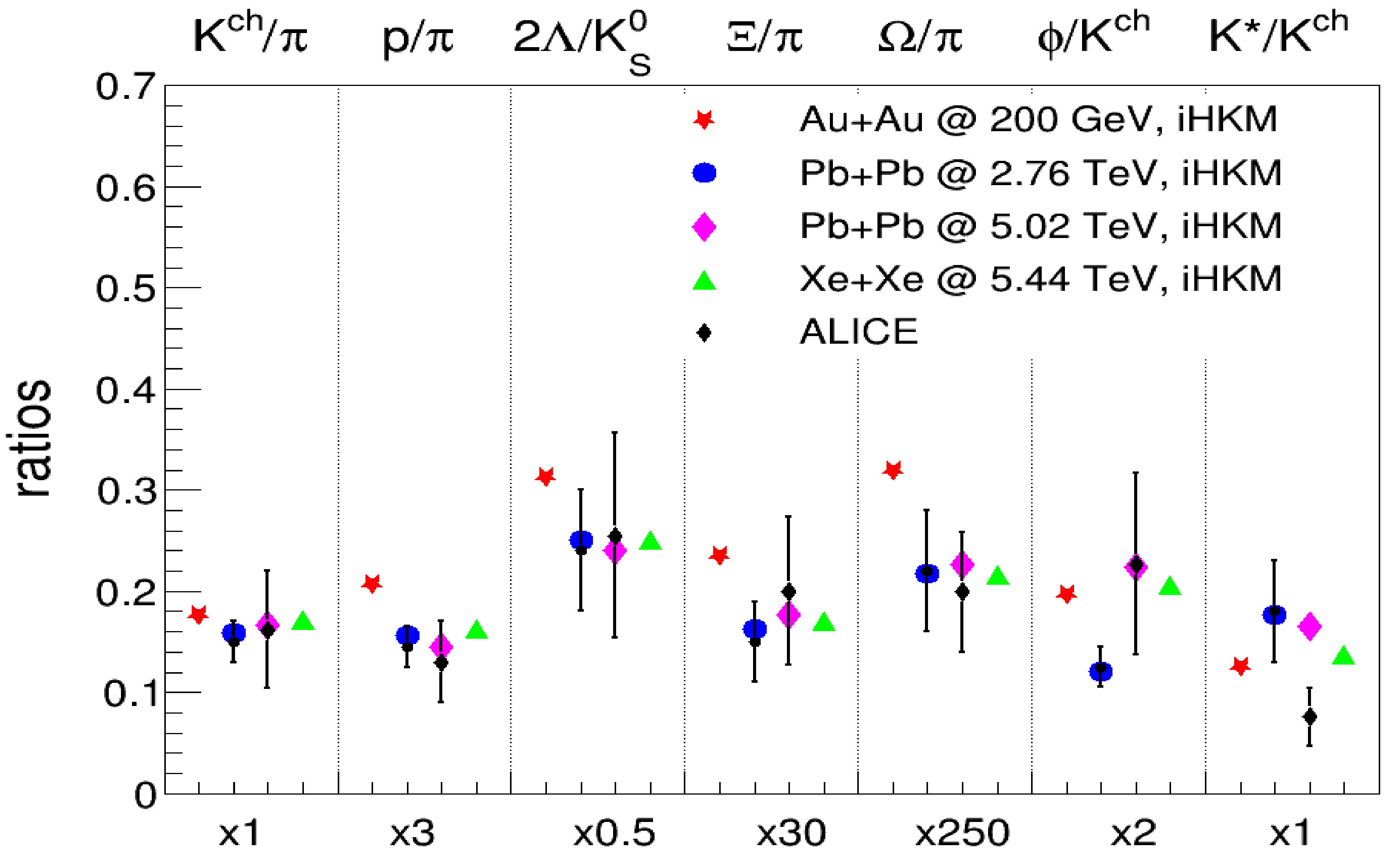
Particle number ratios at the LHC, 5.02 TeV/n.p.



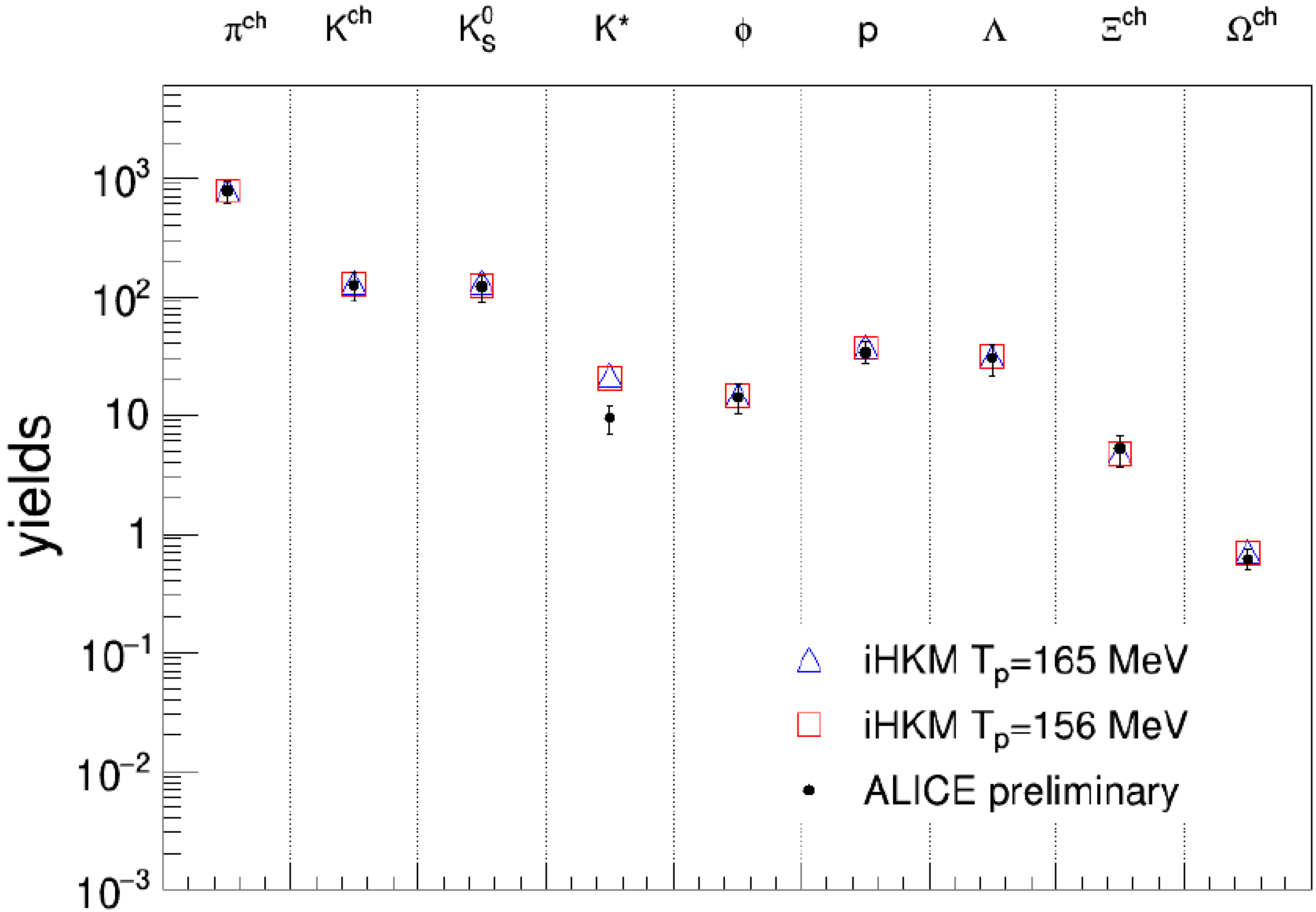
Yu.S. , Shapoval, arXiv:1809.07400 (will be published Phys.Rev. C (2019)].

E. Fragiacomo for the ALICE Collaboration, talk at WPCF 2018, https://indico.ifj.edu.pl /event/199/contributions/1101/attachments/953/1182/WPCF18 EnricoFragiacomo.pdf.

Particle number ratios for different A+A collisions

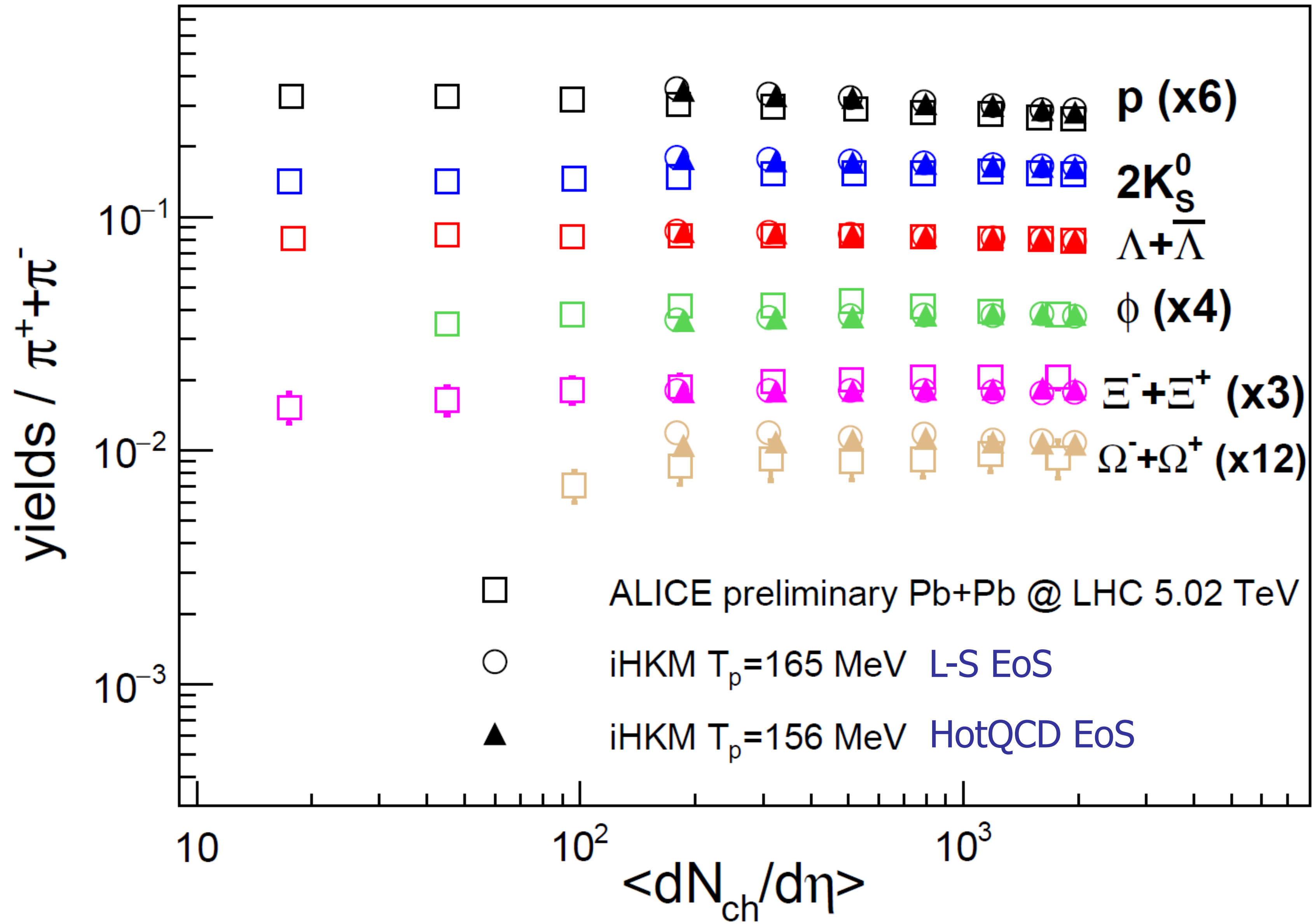


Particle yields at LHC, 5.02 TeV/n.p.

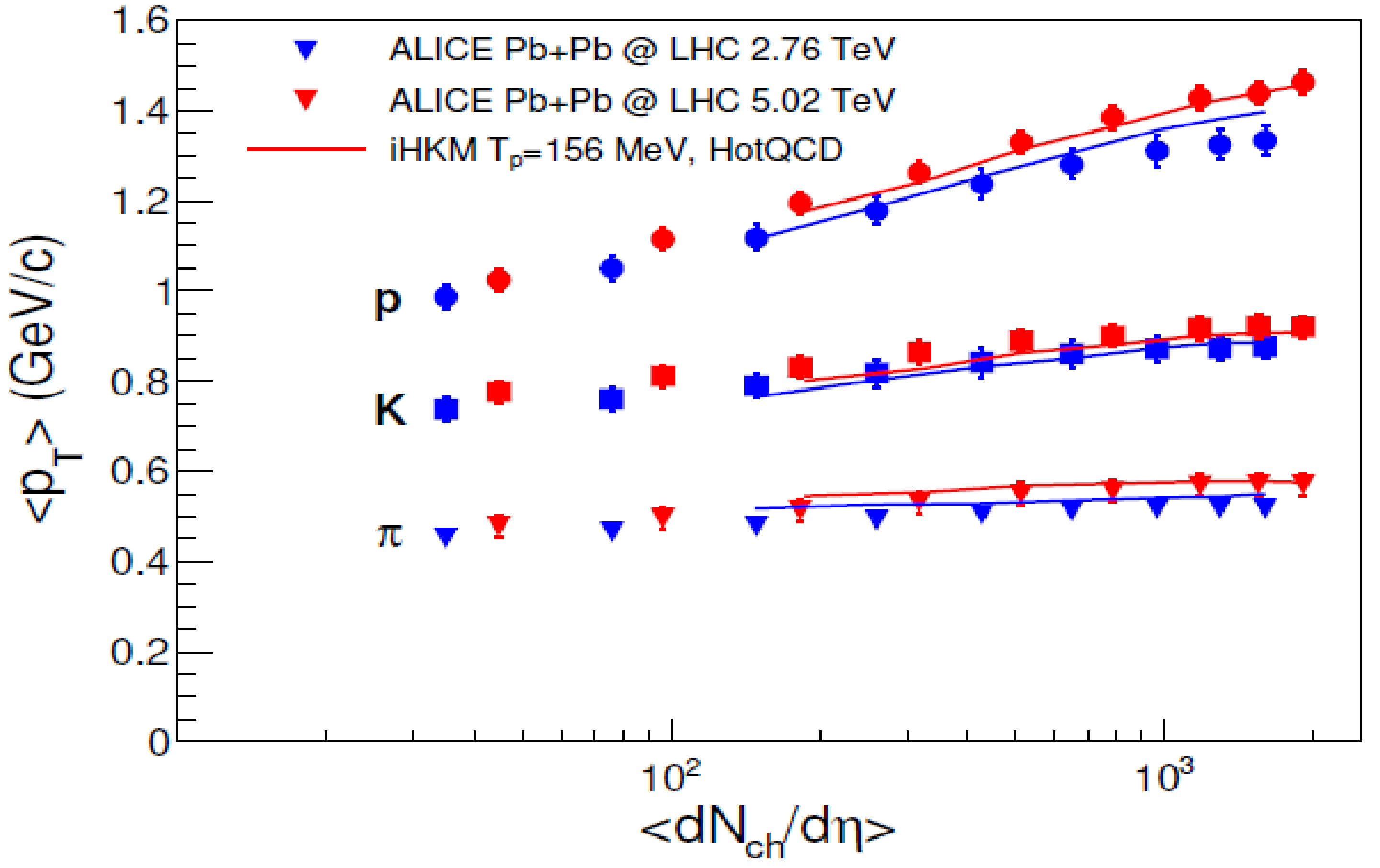


Yu.S. , Shapoval, ready for publication

Particle ratios at LHC, 5.02 TeV/n.p.

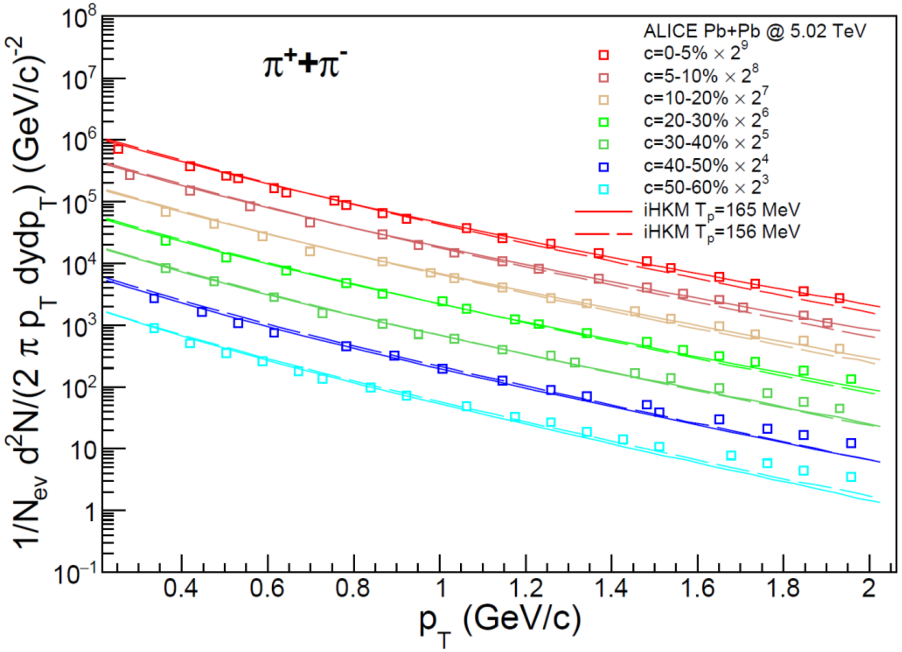


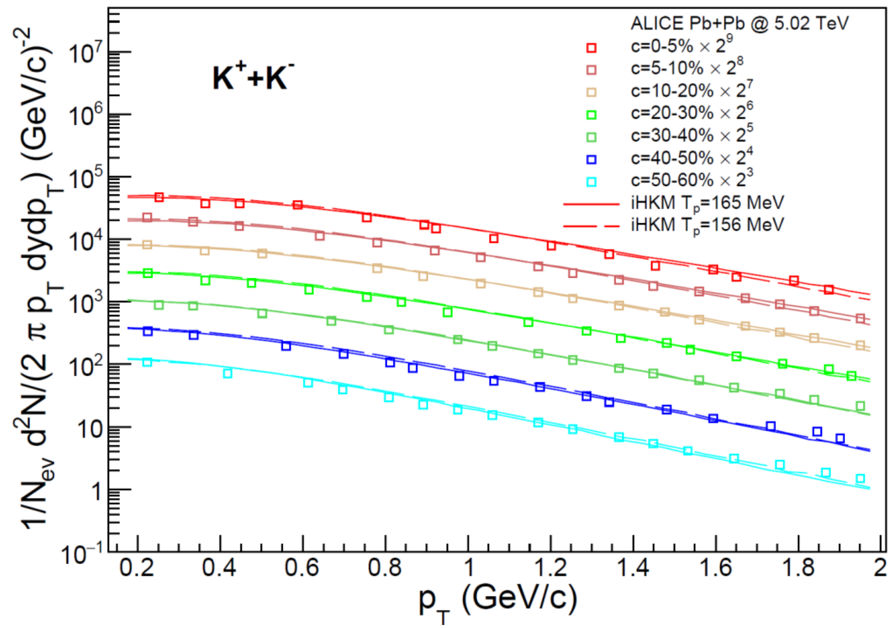
Mean p_T vs multiplicities

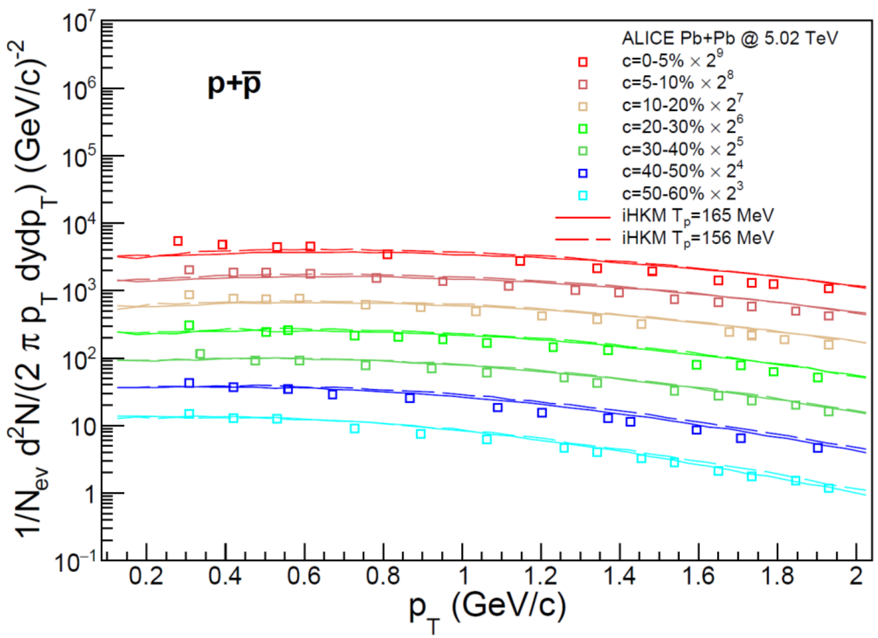


The iHKM results (for $T_p = 156$ MeV and HotQCD Collaboration EoS) on pion, kaon and proton mean p_T (lines) in Pb+Pb collisions at the two LHC energies — $\sqrt{s_{NN}} = 2.76$ TeV (blue) and $\sqrt{s_{NN}} = 5.02$ TeV (red) — for different centrality classes in comparison with the ALICE Collaboration experimental data .

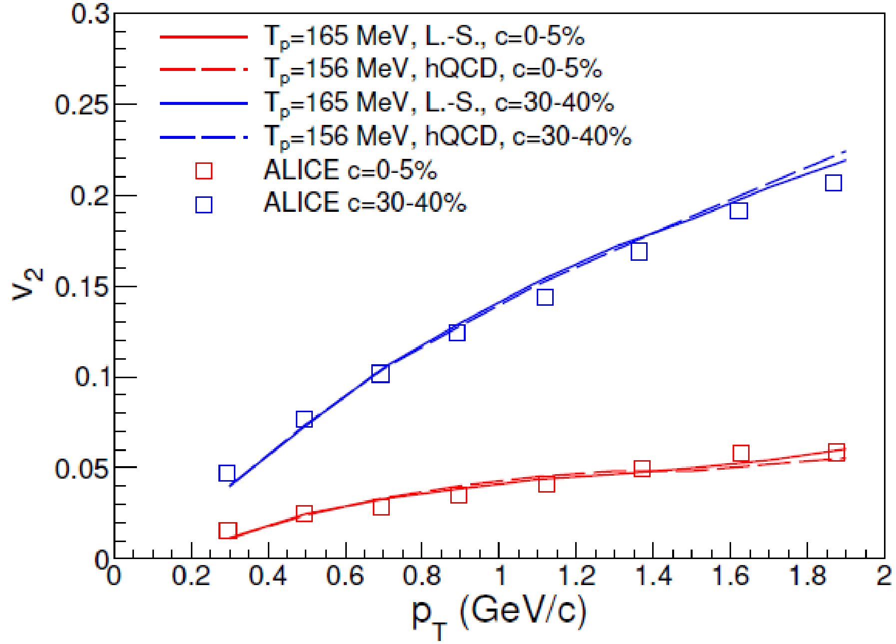
Spectra at LHC 5.02 TeV/n.p

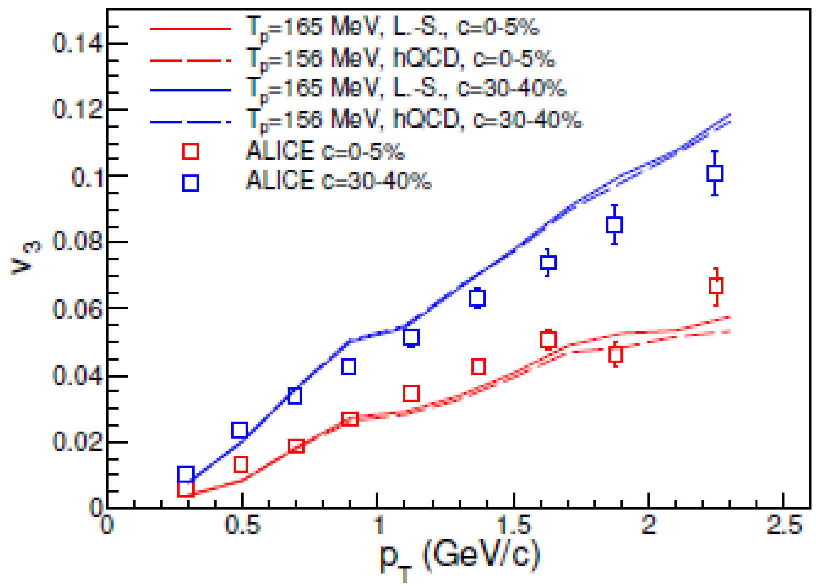


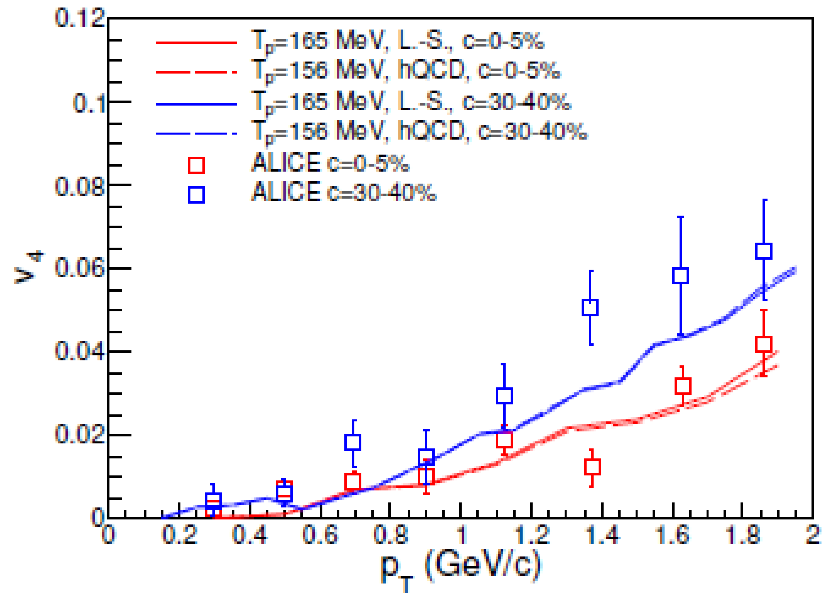




v_2, v_3 and v_4 flow harmonics for Pb+Pb 5.02 TeV/n.p.







Hadron production at top RHIC energy

M. Adzhimambetov, V. Shapoval, Yu.S.,
Nucl.Phys. A **987** (2019) 321–336.

The equation of state   Au+Au, top RHIC energy

We utilize Laine-Schröder equation of state for quark-gluon phase, modified for non-zero baryon and strange chemical potentials:

$$\frac{p(T,\mu_B,\mu_S)}{T^4} = \frac{p(T,0,0)}{T^4} + \frac{1}{2}\frac{\chi_B}{T^2}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{2}\frac{\chi_S}{T^2}\left(\frac{\mu_S}{T}\right)^2. \quad (1)$$

We put $\mu_B = 21$ MeV to obtain the best agreement with the experimental ratio of protons yield to that of antiprotons in central ($c = 0 - 5\%$) collisions.
We also put $\mu_S = 5$ MeV to obtain vanishing strangeness at the hadronization hypersurface:

$$S|_{\sigma_p} = \sum_i (N(i) - \overline{N}(i))\mu_{S,i} = 0,$$

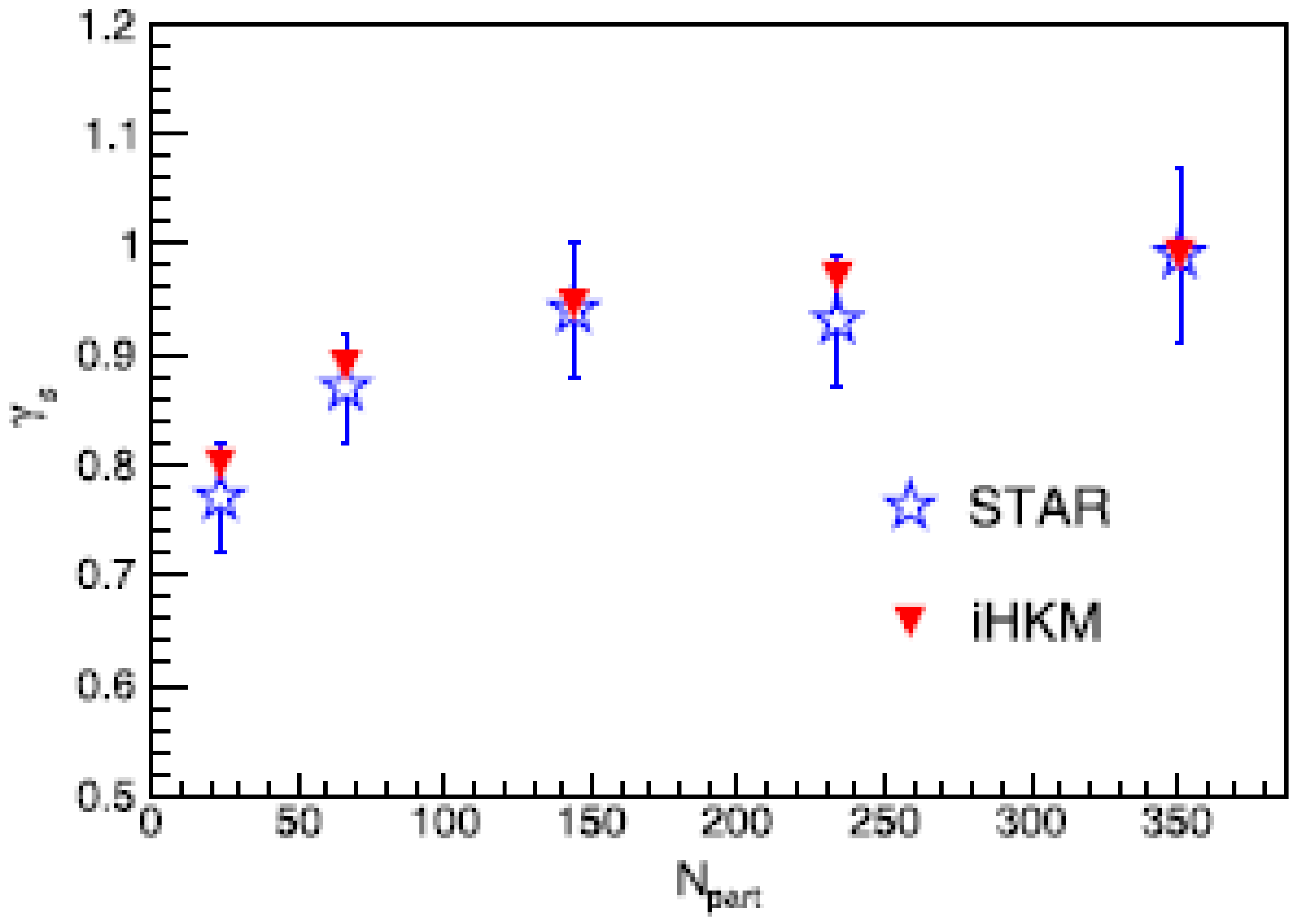
where $N(i)$ and $\overline{N}(i)$ are the numbers of particles and corresponding antiparticles of species i at the hadronization hypersurface, and $\mu_{S,i}$ is the strange chemical potential of the particle species i.

We assume that at considered energy strange quarks do not have enough time to reach the chemical equilibrium in non-central collisions, so that the kaon spectra get down. The same concerns about a half of produced protons, coming from the decays of strange resonances (such as Λ, Σ, Ξ).

To take this into account we introduce an effective downscaling factor $\gamma_S(\tau_p)$, depending on the characteristic particlization time for each given centrality.

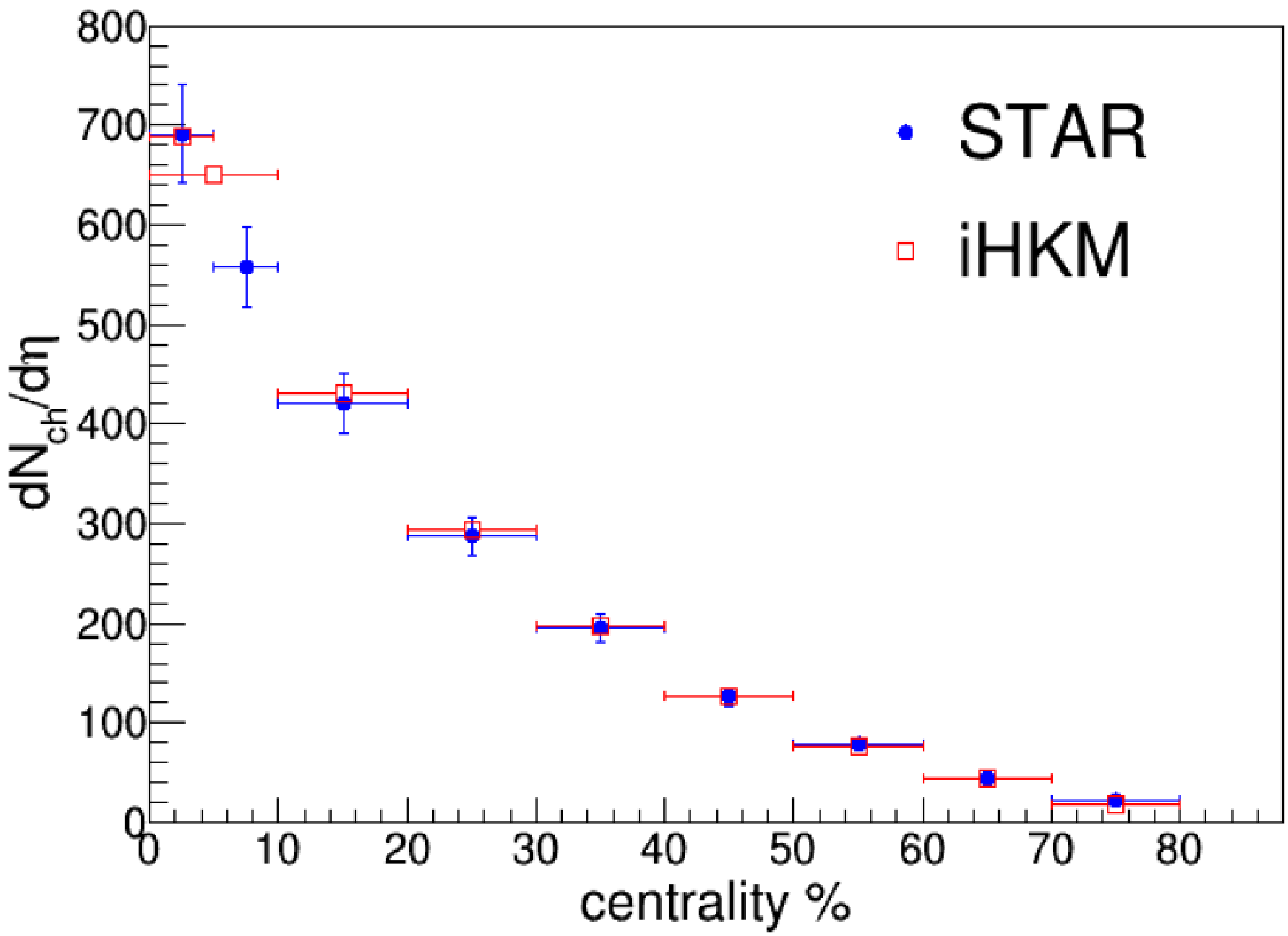
We assume the dependence $\gamma_S(\tau_p) = A\exp(-b/\tau_p)$, with $A = 1.1$ and $b = 0.8$ fm$/c$. This choice guarantees $\gamma_S = 1$ for the most central events and a good description of kaon and proton spectra, together with K/π ratio.

γ_s Au+Au, top RHIC energy



$$\gamma_S(\tau_p) = A\exp(-b/\tau_p) \quad \text{with } A = 1.1 \text{ and } b = 0.8 \text{ fm/}c.$$

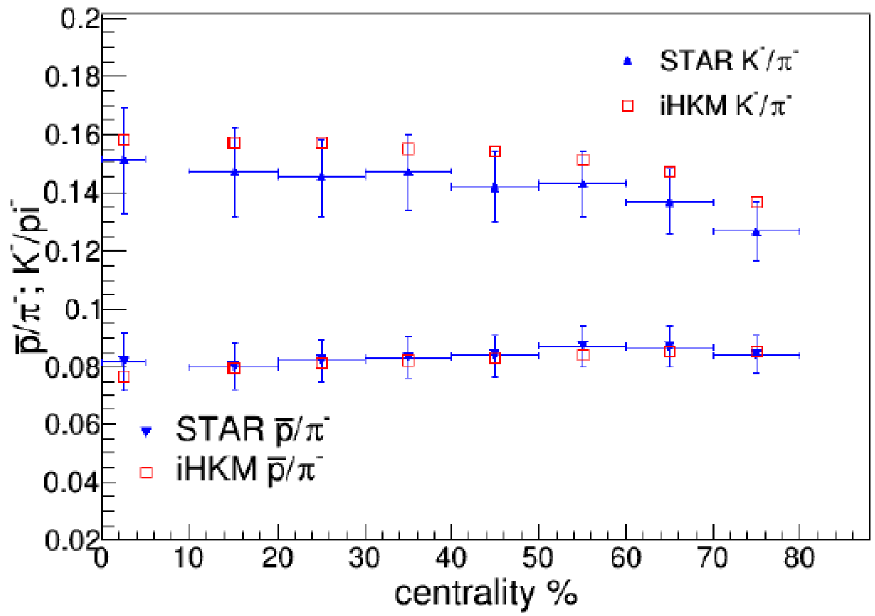
Main model parameters adjustment Au+Au, top RHIC energy



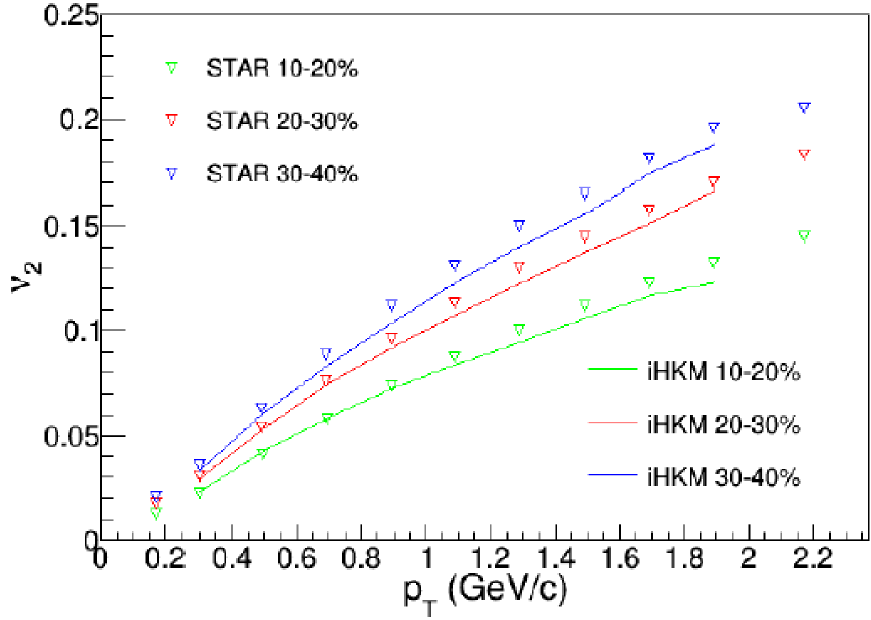
$\epsilon_0 = 235$ GeV/fm^3 at $\tau_0 = 0.1$ fm/c, $\alpha = 0.18$

B.I. Abelev *et al.* (STAR Collaboration), Phys. Rev. C **79** (2009), 034909

Particle number ratios and v_2 Au+Au, top RHIC energy

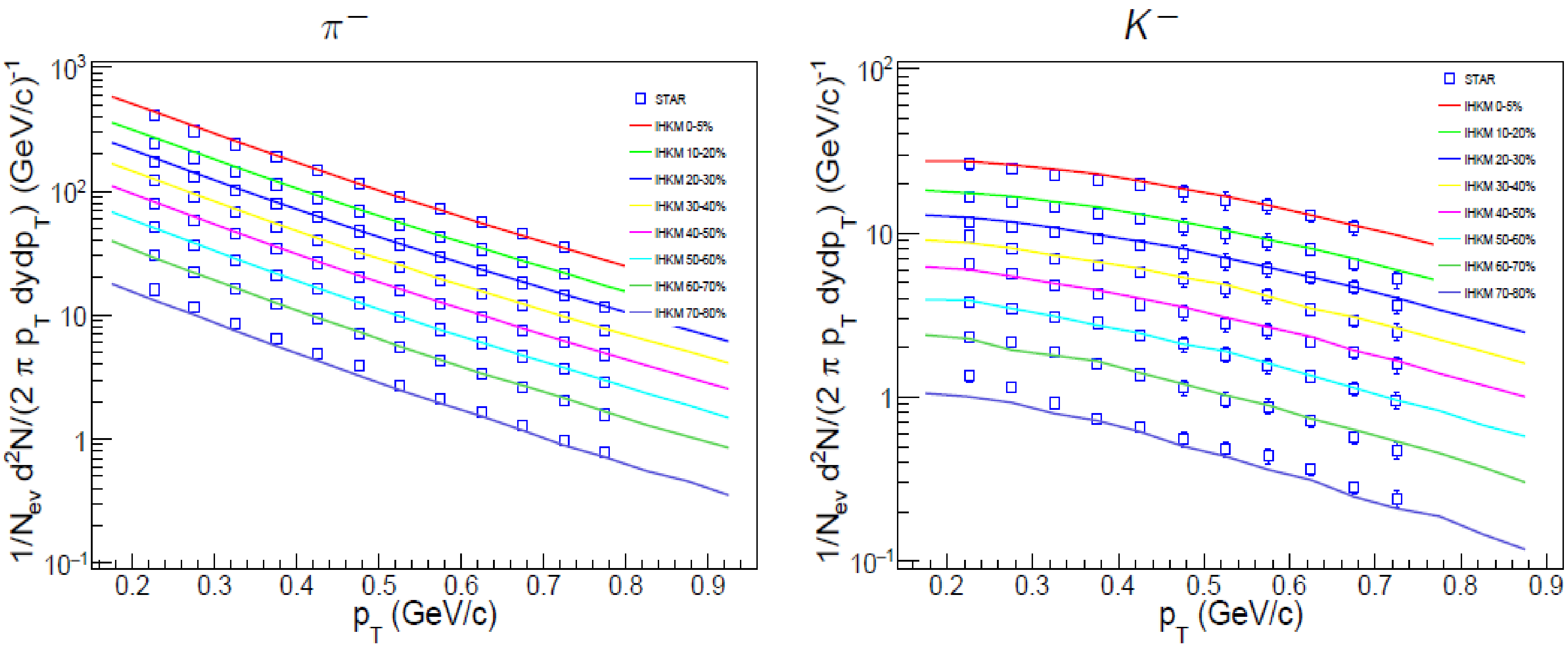


J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92** (2004) 112301



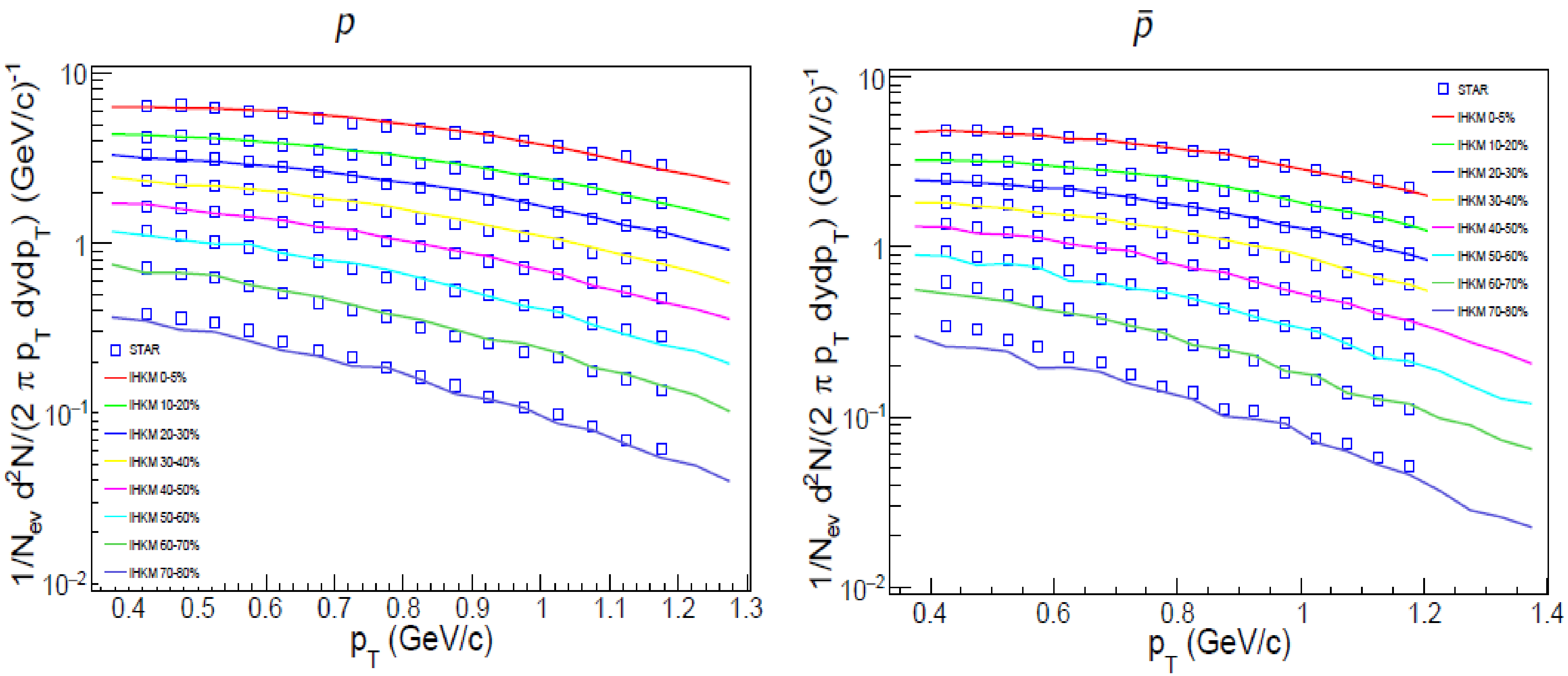
J. Adams *et al.* (STAR Collaboration), Phys. Rev. C **72** (2005), 014904

p_T spectra description, $|y| < 0.1$ Au+Au, top RHIC energy



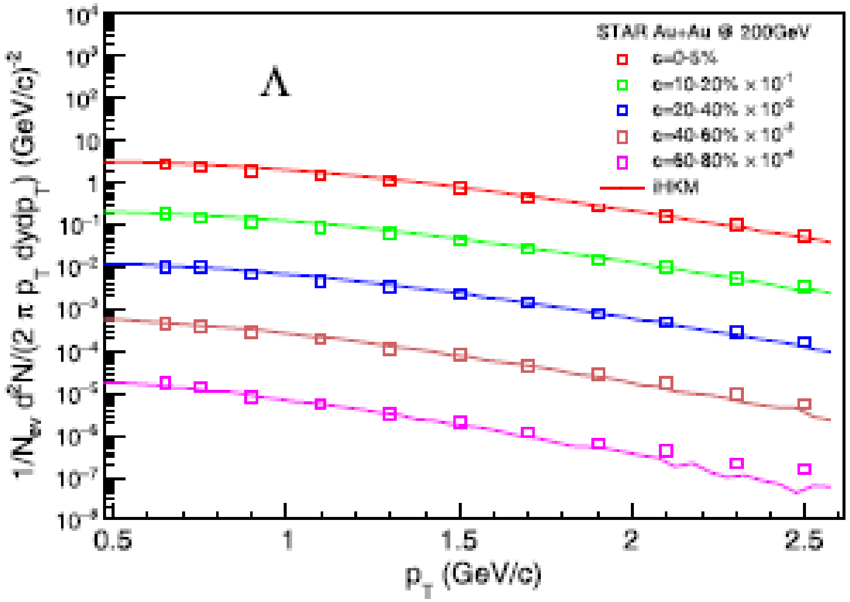
J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92** (2004) 112301

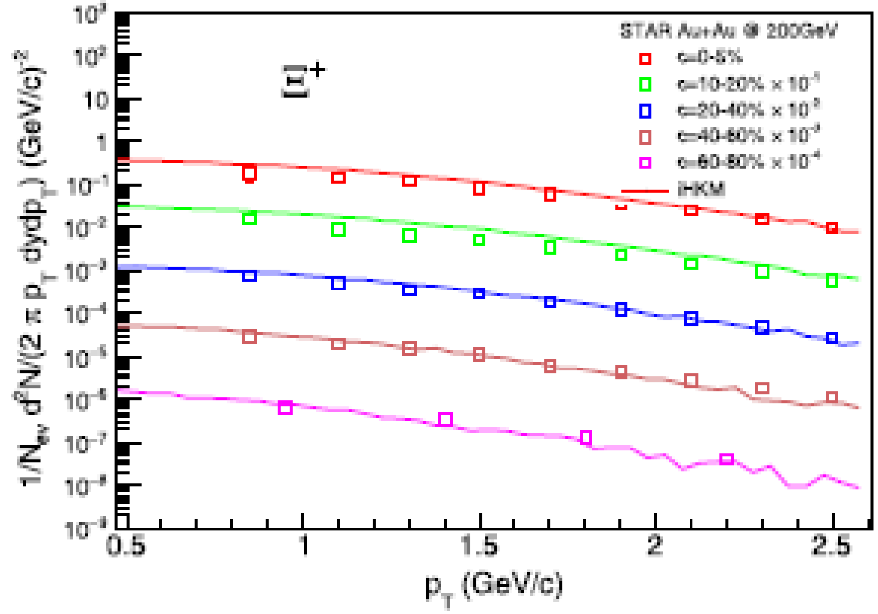
p_T spectra description, $|y| < 0.1$ Au+Au, top RHIC energy

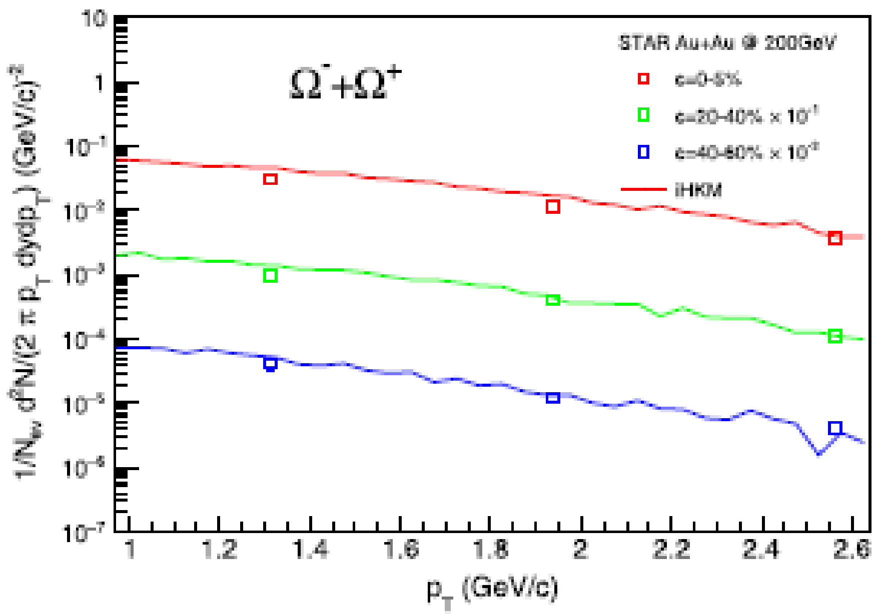


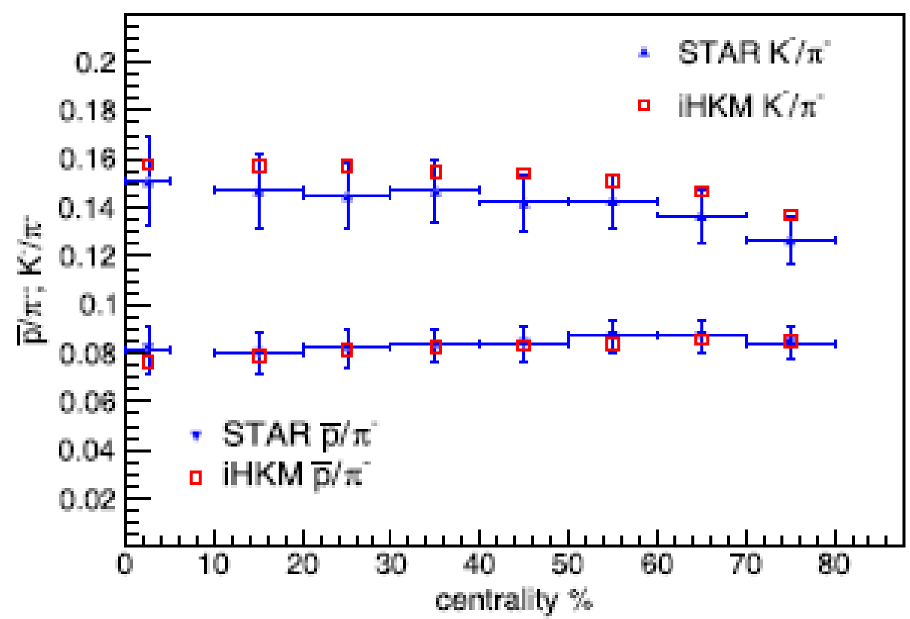
J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92** (2004) 112301

Spectra of strange baryons, $\left\{ \frac{\bar{p}}{\pi^-}, \frac{K^-}{\pi^-} \right\}$ on centrality









Summary on the hadron production

- Neither thermal nor chemical freeze-out cannot be considered as sudden at some corresponding temperatures.

- Particle yield probe $\frac{dN_i}{d\eta}/\frac{dN_j}{d\eta}$ as well as absolute values $\frac{dN_i}{d\eta}$!) demonstrate that even at the minimal hadronization temperature $T_{ch} = T_h = 156$ MeV, the annihilation and other non-elastic scattering reactions in **hadronic phase** play role in formation particle number ratios, especially.

- It happens that the results for small and relatively large T_h are quite similar. It seems that inelastic processes (other than the resonance decays), that happen at the matter evolution below T_h, , play a role of the compensatory mechanism in formation of $\frac{dN_i}{d\eta}/\frac{dN_j}{d\eta}$. Chemical freeze-out is continuous.

- The iHKM works perfectly not only at LHC but also at RHIC energies where non-sero baryon chemical potential is introduced as well as γ_s that is expressed through proper life-time of QGP calculated in the iHKM.

- iHKM describes and predict well with only 3 effective parameters for each energy the total multiplicity; pion, kaon, proton, antiproton, Lambda, Omega, Cascade spectra; various particle number rations, anisotropic flow and femtoscopy scales vs. centrality in different A+A collisions, starting from 200 GeV/n.p. in Au+Au and up to highest LHC energy: 5.44 TeV/n.p. in Xe+Xe.

Acknowledgement

Thank you for your attention

iHKM

DIRECT PHOTONS

PHYSICAL REVIEW C **97**, 054907 (2018)

Direct-photon spectrum and elliptic flow produced from Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the CERN Large Hadron Collider within an integrated hydrokinetic model

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(Received 22 October 2017; revised manuscript received 6 March 2018; published 16 May 2018)

The photon transverse momentum spectrum and its anisotropy from Pb+Pb collisions at the CERN Large Hadron Collider energy $\sqrt{s_{NN}} = 2.76$ TeV are investigated within the integrated hydrokinetic model (iHKM). Photon production is accumulated from the different processes at the various stages of relativistic heavy ion collisions: from the primary hard photons of very early stage of parton collisions to the thermal photons from equilibrated quark-gluon and hadron gas stages. Along the way a hadronic medium evolution is treated in two distinct, in a sense opposite, approaches: chemically equilibrated and chemically frozen system expansion. Studying the centrality dependence of the results obtained allows us to conclude that a relatively strong transverse momentum anisotropy of thermal radiation is suppressed by prompt photon emission which is an isotropic. We find out that this effect is getting stronger as centrality increases because of the simultaneous increase in the relative contribution of prompt photons in the soft part of the spectra. The substantial results obtained in iHKM with nonzero viscosity ($\eta/s = 0.08$) for photon spectra and v_2 coefficients are mostly within the error bars of experimental data, but there is some systematic underestimation of both observables for the near central events. We claim that a situation could be significantly improved if an additional photon radiation that accompanies the presence of a deconfined environment is included. Since a matter of a space-time layer where hadronization takes place is actively involved in anisotropic transverse flow, both positive contributions to the spectra and v_2 are considerable, albeit such an argument needs further research and elaboration.

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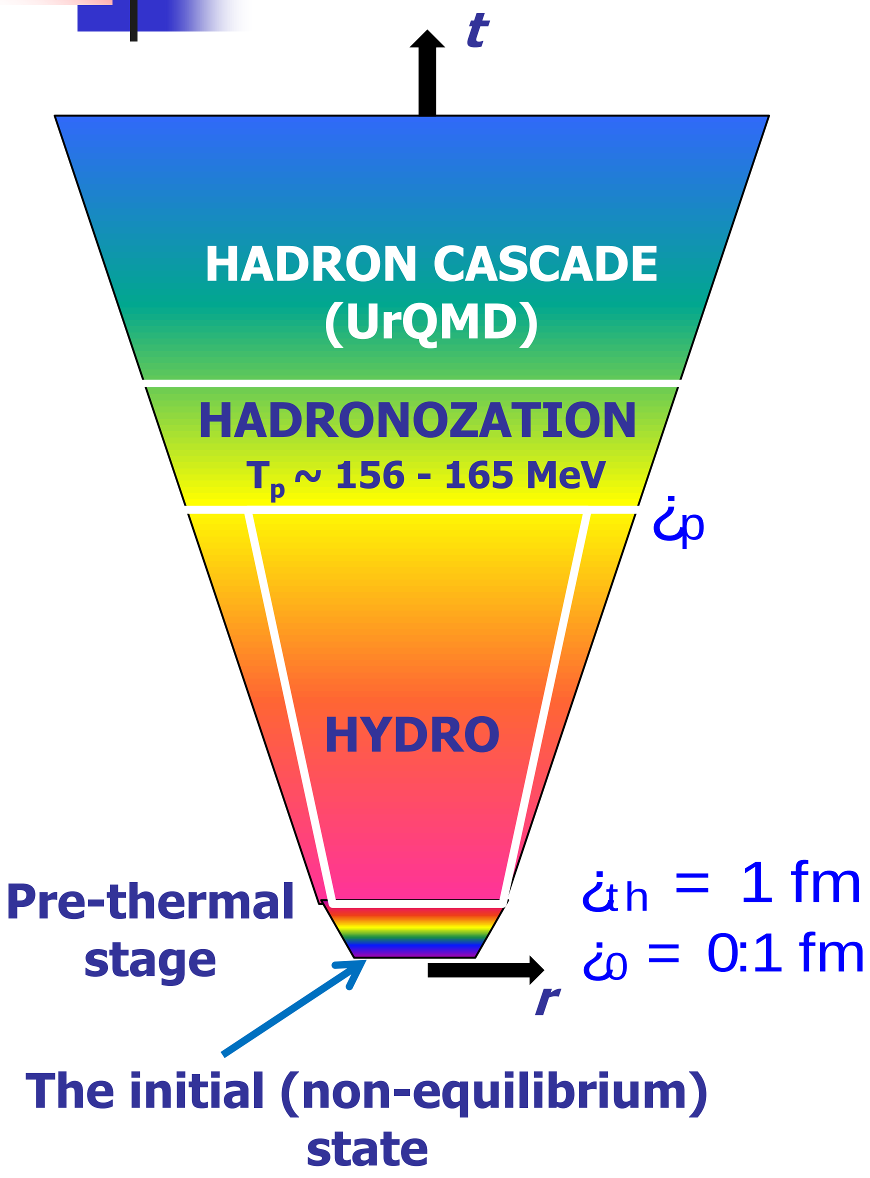
Blow up text

We claim that a situation could be significantly improved if an additional photon radiation that accompanies the presence of a deconfined environment is included. Since a matter of a space-time layer where hadronization takes place is actively involved in anisotropic transverse flow, both positive contributions to the spectra and v_2 are considerable, albeit such an argument needs further research and elaboration.

Photon radiation in **iHKM** →



- **generation of the initial states: (MC Glaub & CGC)**

PROMPT PHOTONS

- **thermalization of initially non-thermal matter;**

PRE-THERMAL PHOTONS

- **viscous chemically equilibrated hydrodynamic expansion;**

THERMAL PHOTONS FROM QGP

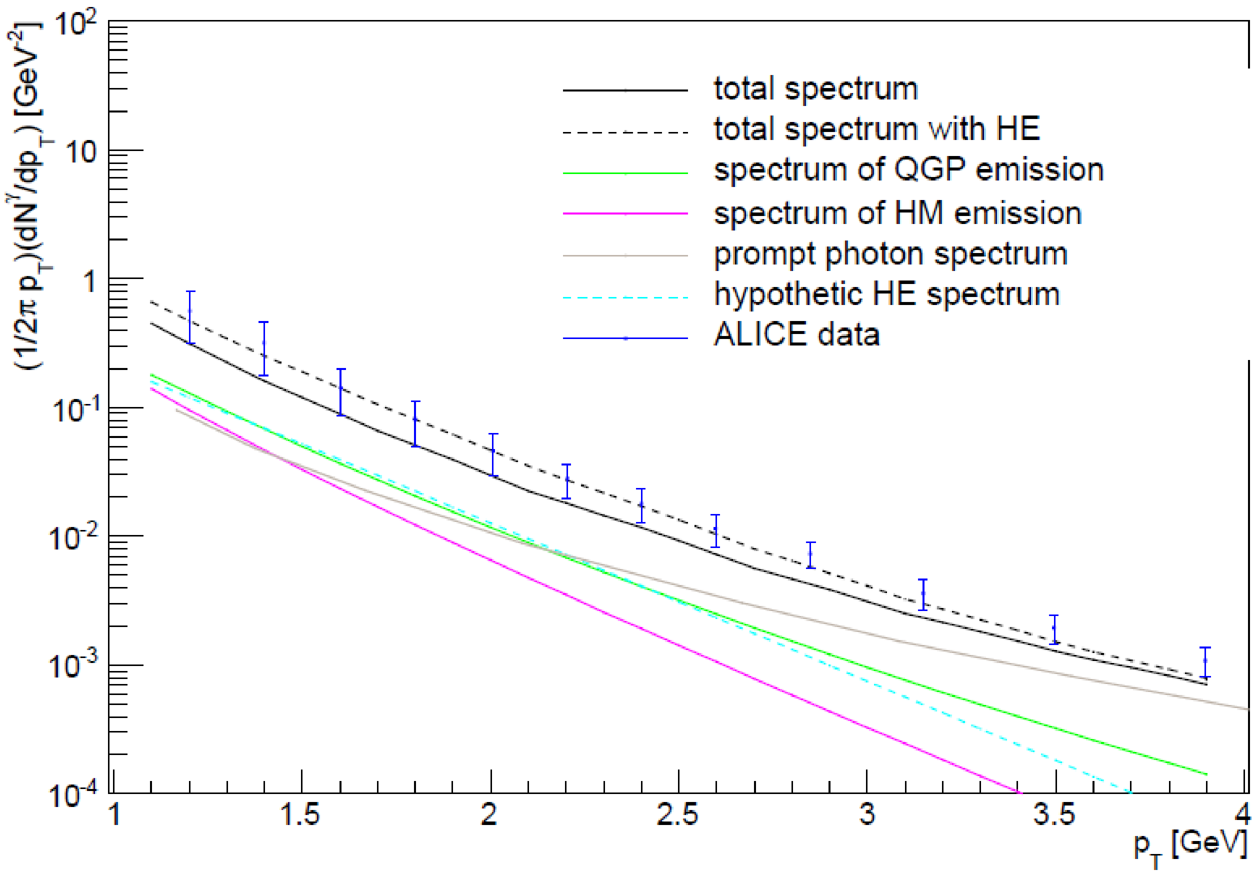
- **hadronization of expanding medium**

HADRONIZATION EMISSION

- **hadron matter expansion**

THERMAL PHOTONS FROM HADRONIC STAGE

Direct photons. Transverse Spectra



We claim that a description of photon spectra and its anisotropy could be significantly improved if an additional photon radiation, that accompanies the presence of deconfined environment, is included.

FIG. 1. Total direct photon spectra in iHKM: thermal QGP + thermal HM + prompt + hadronization emission (HE). Centrality is 0-40%. Experimental results are taken from [7].

Photon puzzle:
Anisotropy of spectra, large v2 coefficients.

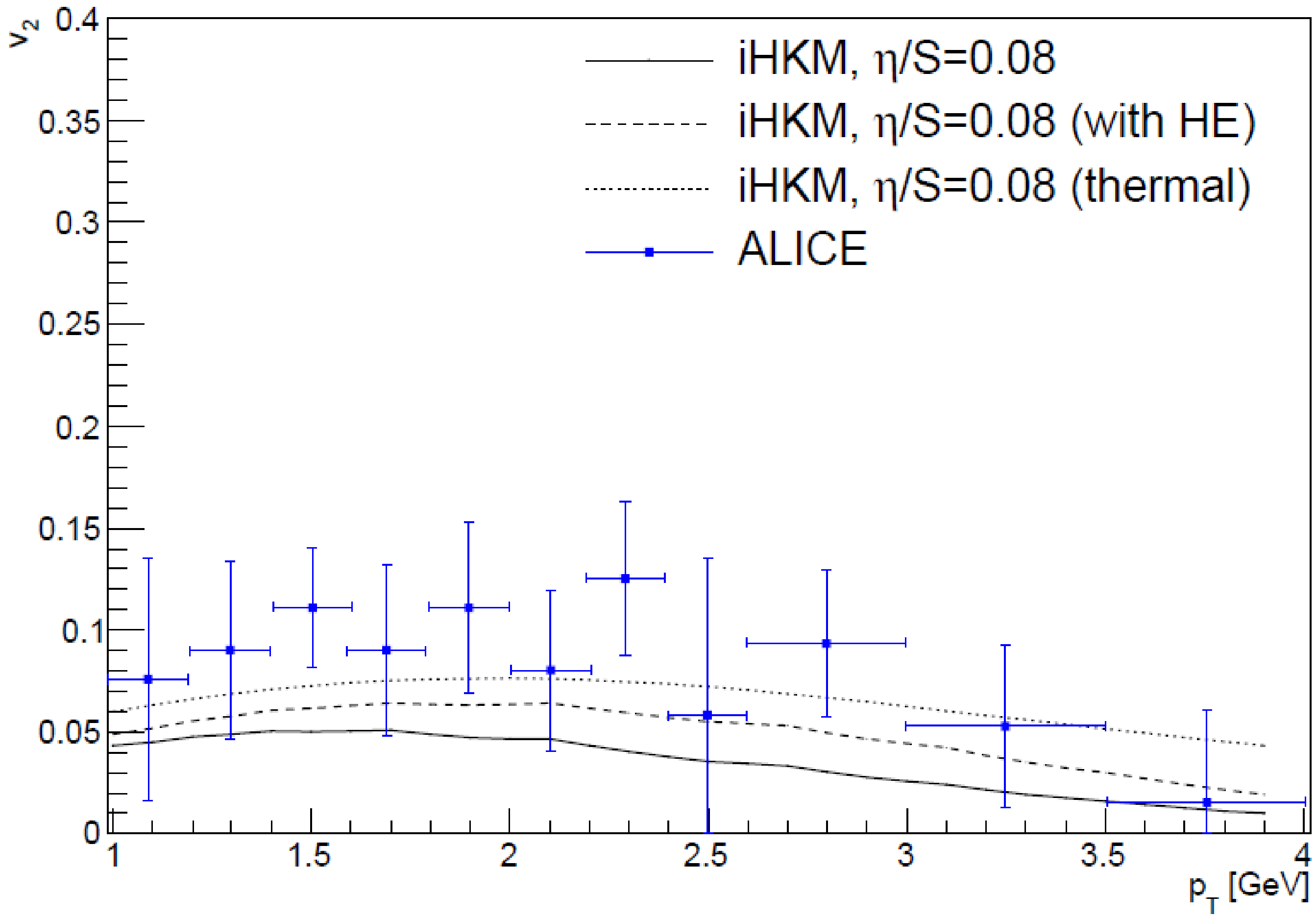


FIG. 2. Photon momentum anisotropy v_2-coefficient for 0-40% centrality. The results including the synchrotron radiation (HE) and results for prompt photons only (without HE) are also presented.

Photons at RHIC

Photon spectra and anisotropic flow in heavy ion collisions at the top RHIC energy within the integrated hydrokinetic model with photon hadronization emission

V. Yu. Naboka[1], Yu. M. Sinyukov[1], , and G. M. Zinovjev[1]

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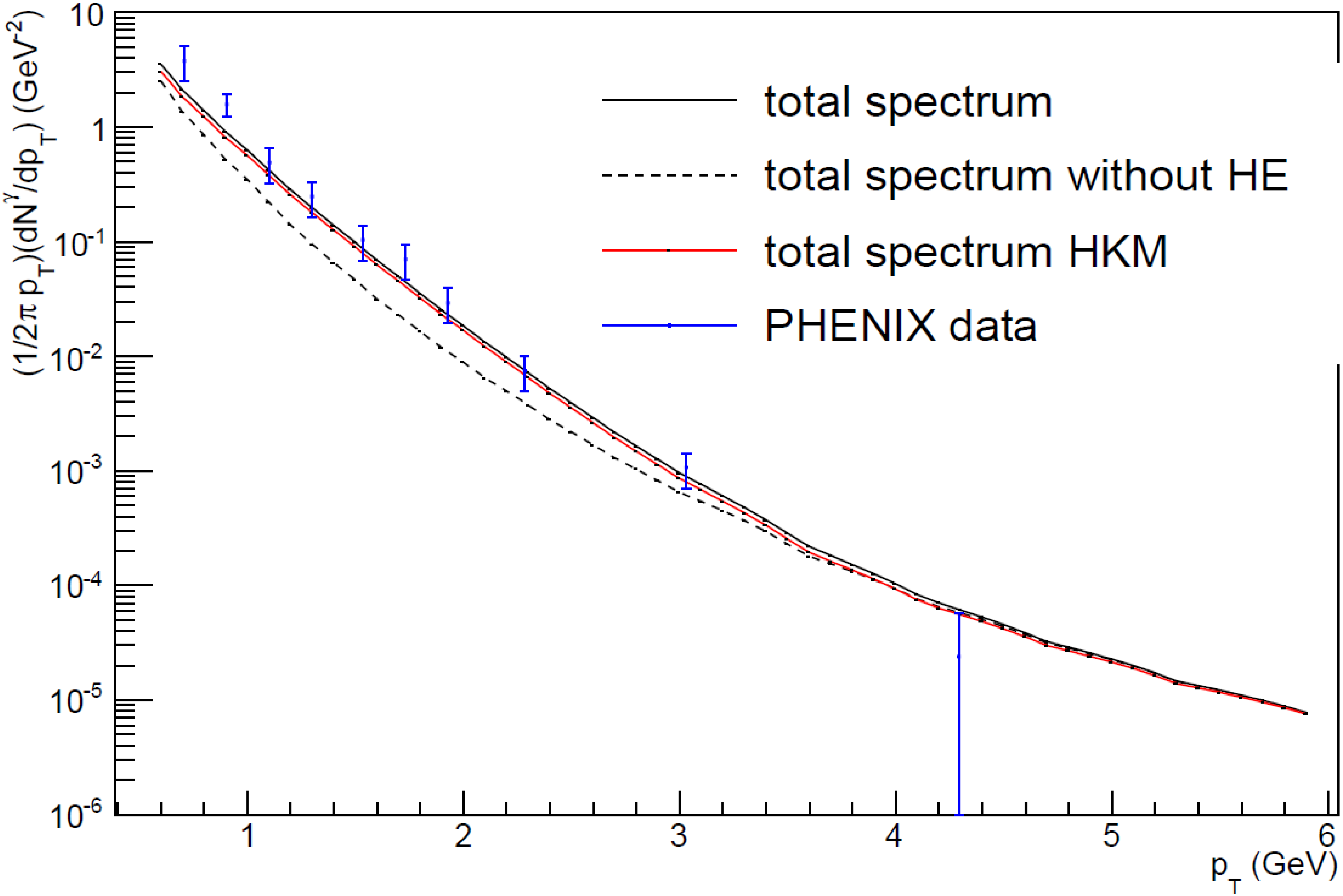
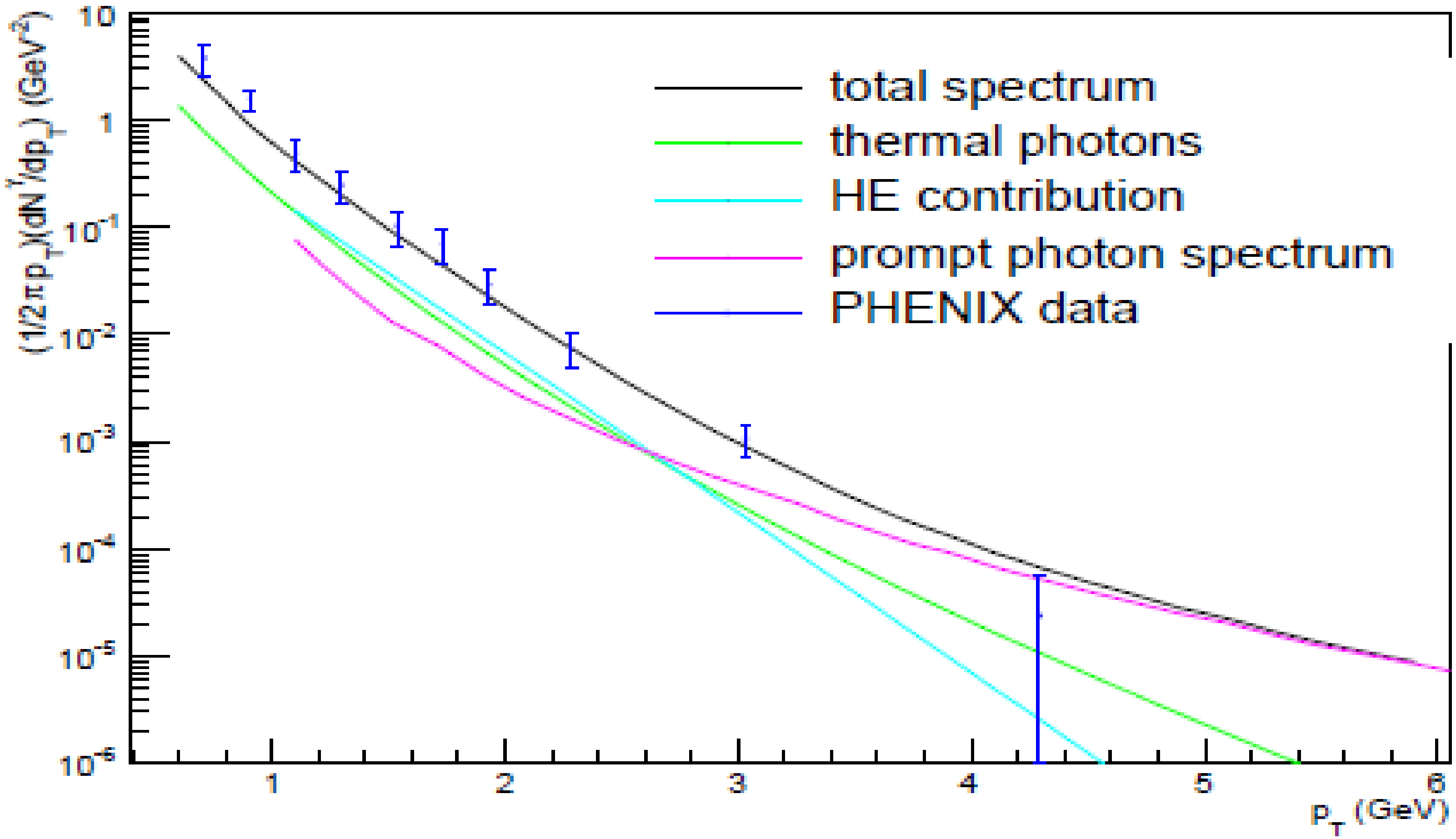
European Physical Journal A - Manuscript ID
EPJA-104987.R1

arXiv:1812.02763

Spectra: Photons at RHIC, c. 10-20 %

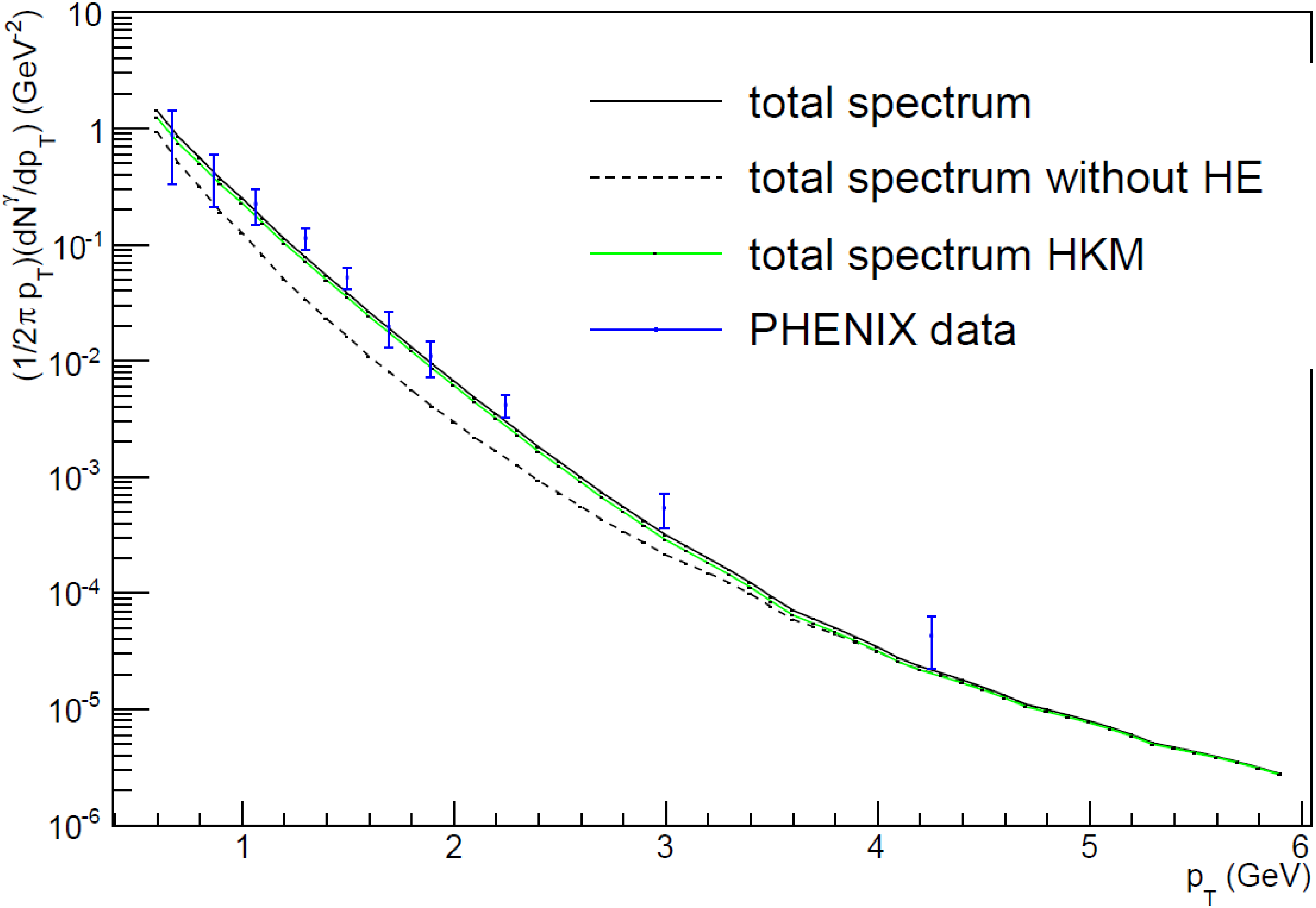


Contributions to photon spectra, c. 0-20%

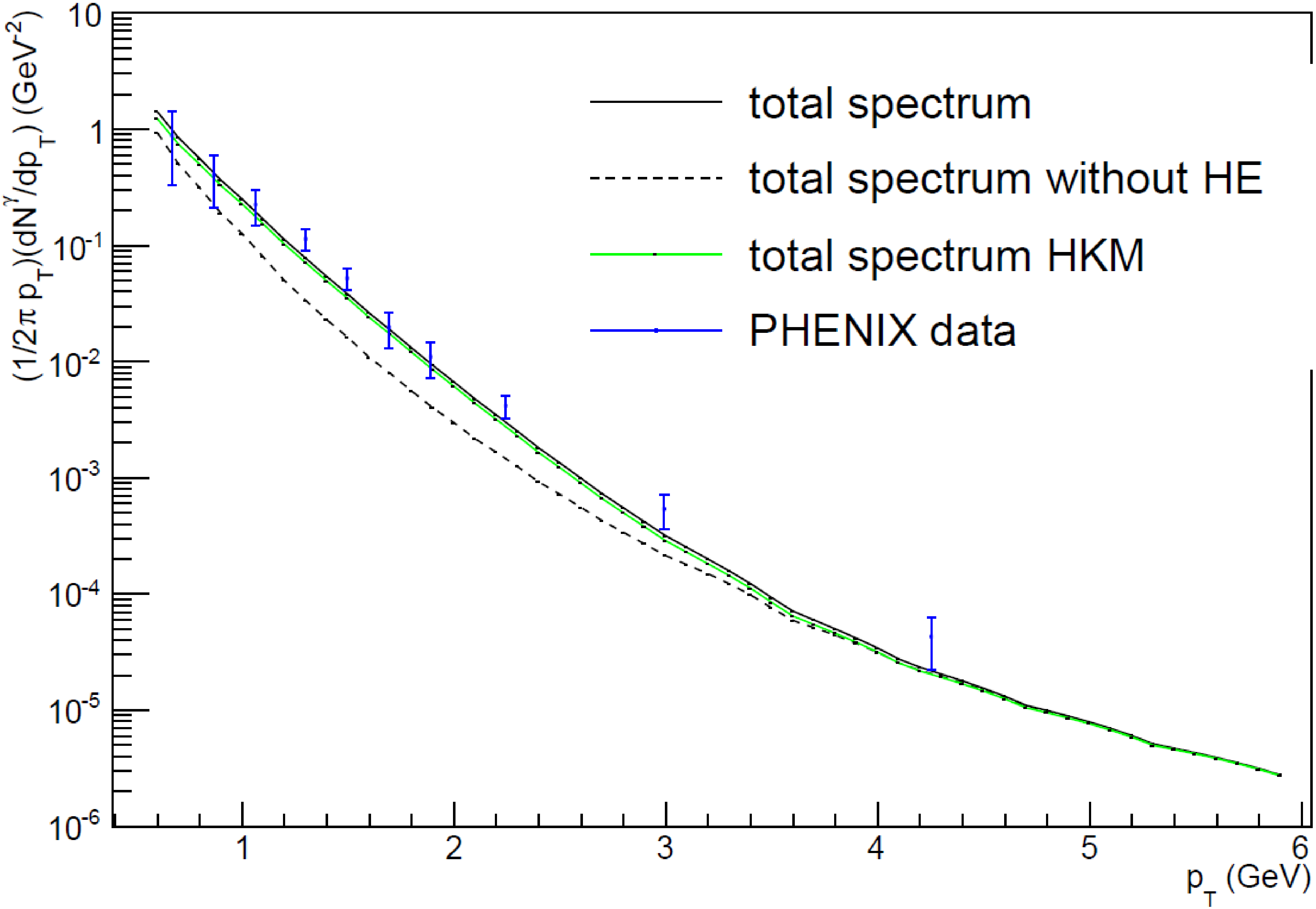


:. Total photon spectra calculated within chemically equilibrated iHKM for 0-20% centrality along with its constituents: thermal (including prethermal) photons, prompt photons, and hadronization emission (HE) contribution. Experimental results are taken from [51].

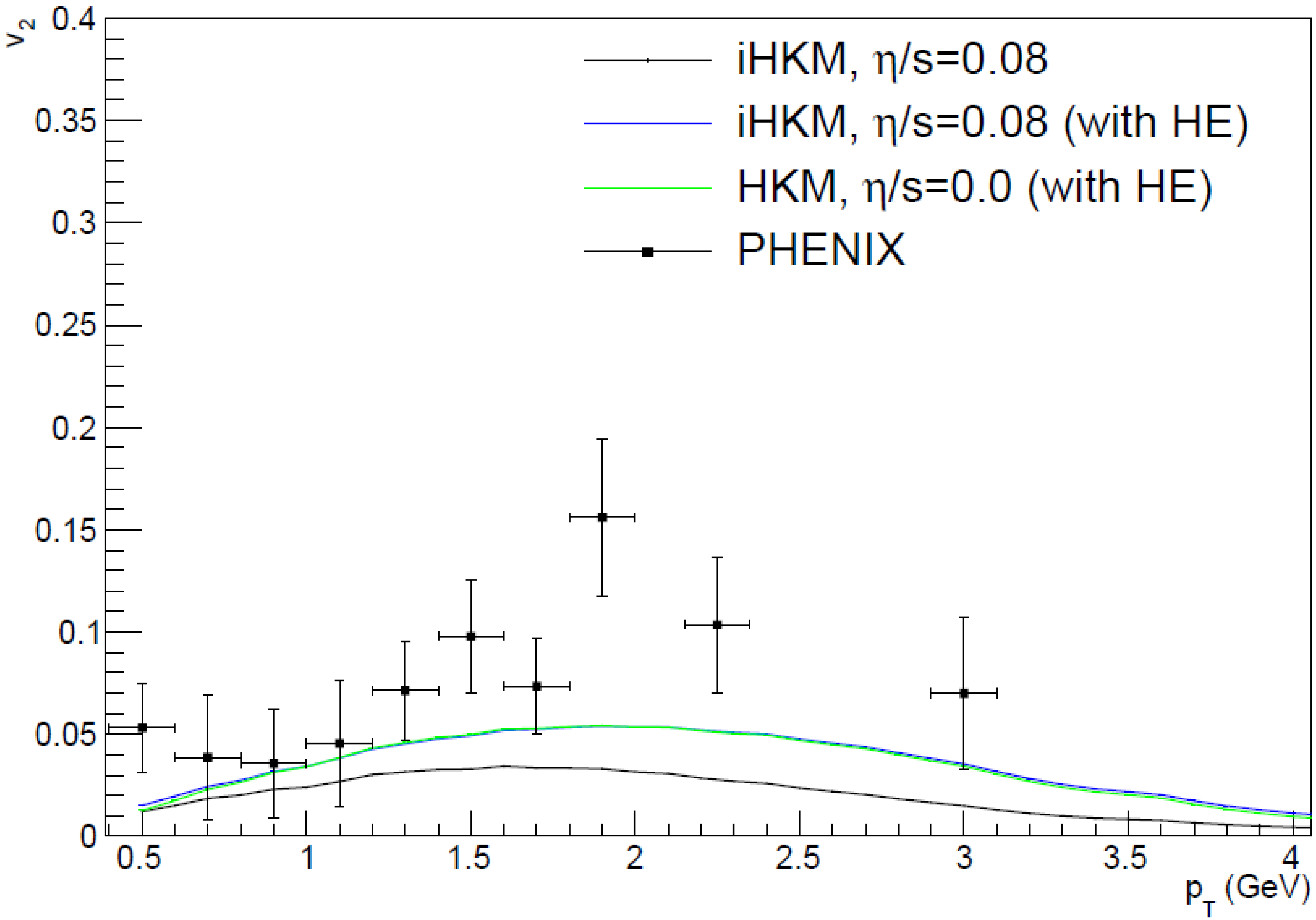
Spectra: Photons at RHIC, c. 20-40 %



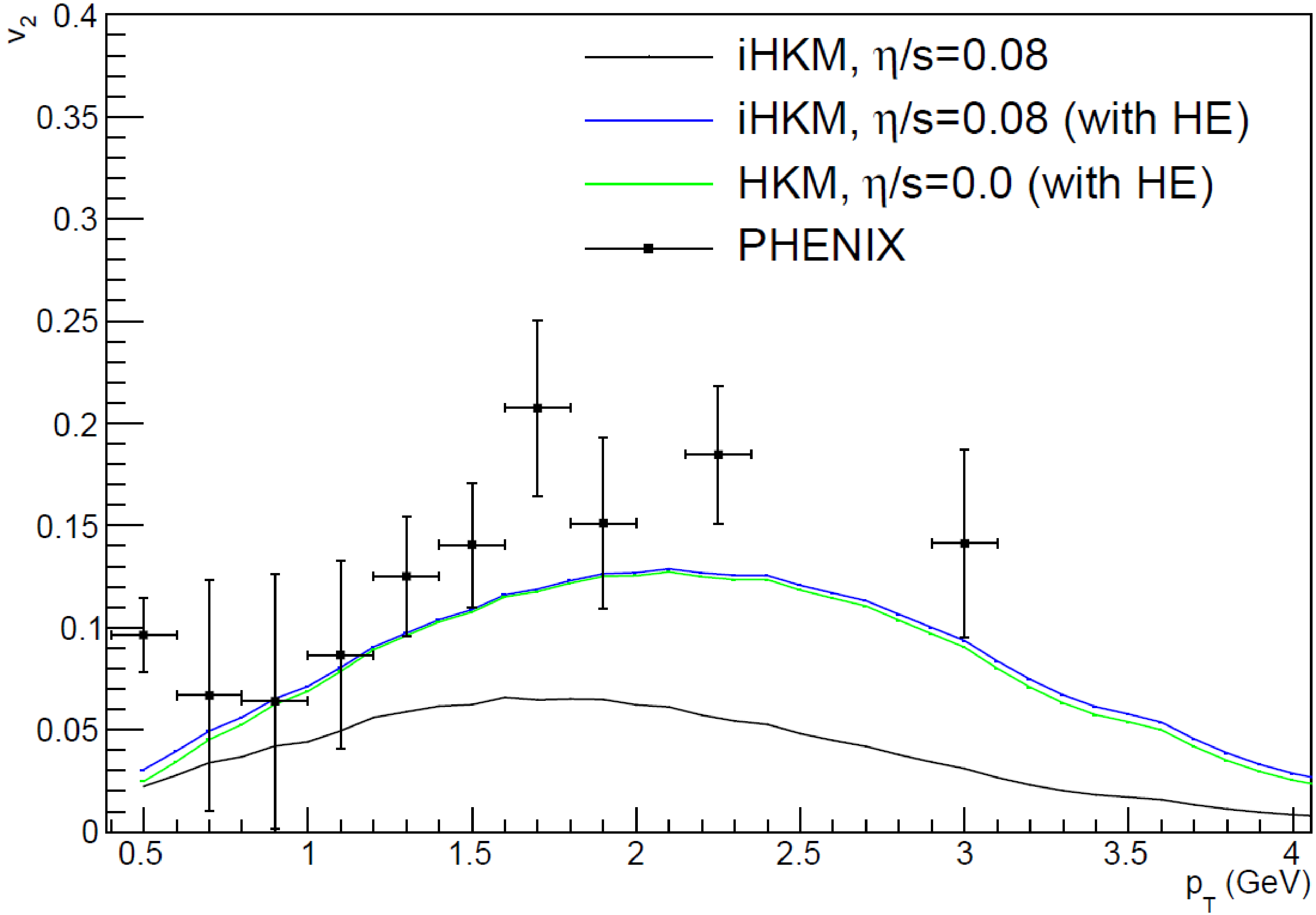
Spectra: Photons at RHIC, c. 40-60 %



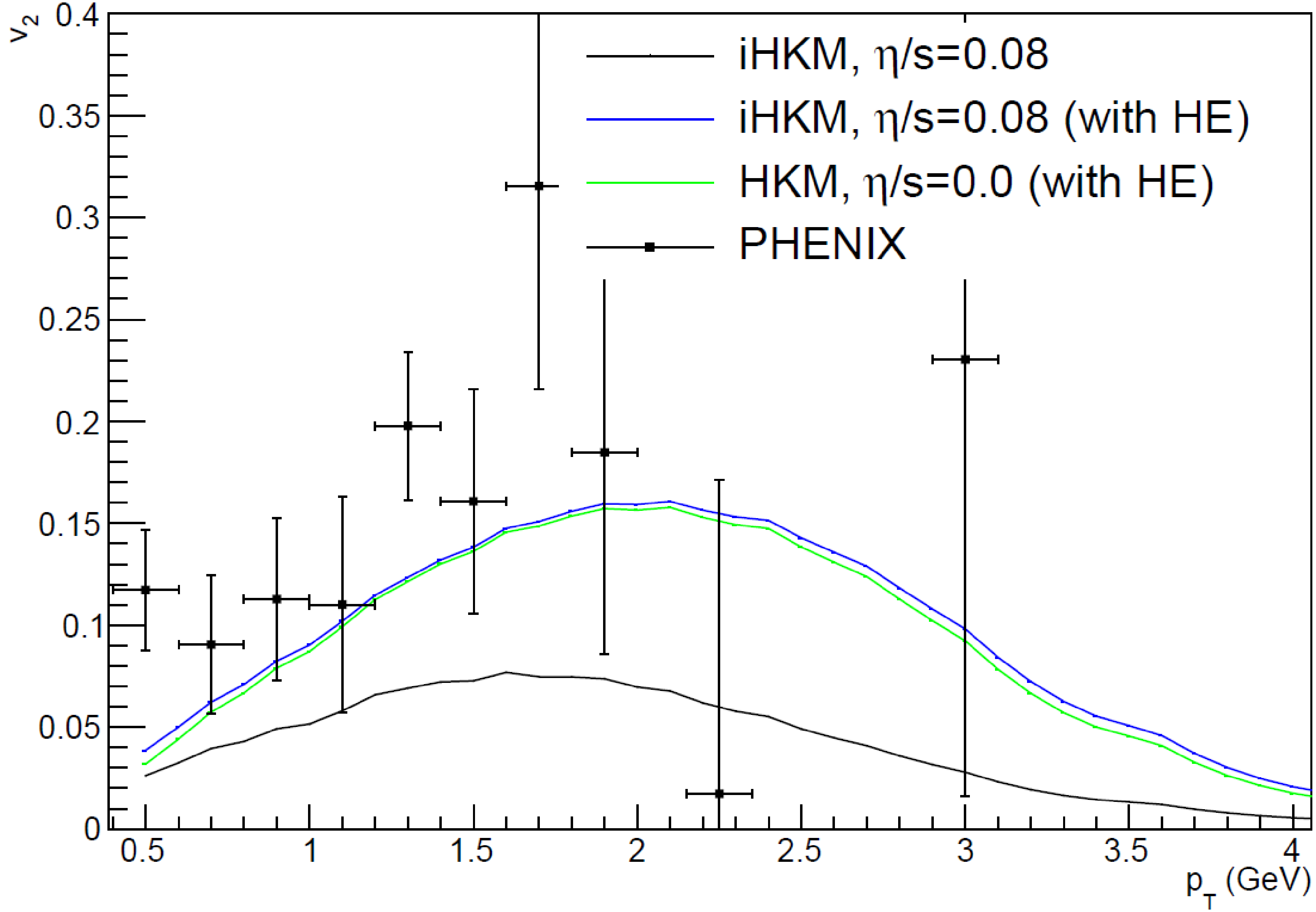
Photons at RHIC, v2 , c. 10 – 20 %



Photons at RHIC, v2 , c. 20 – 40 %



Photons at RHIC, v2 , c. 40 – 60 %



Triangular flow, v_3 coefficients, c. 0-20%

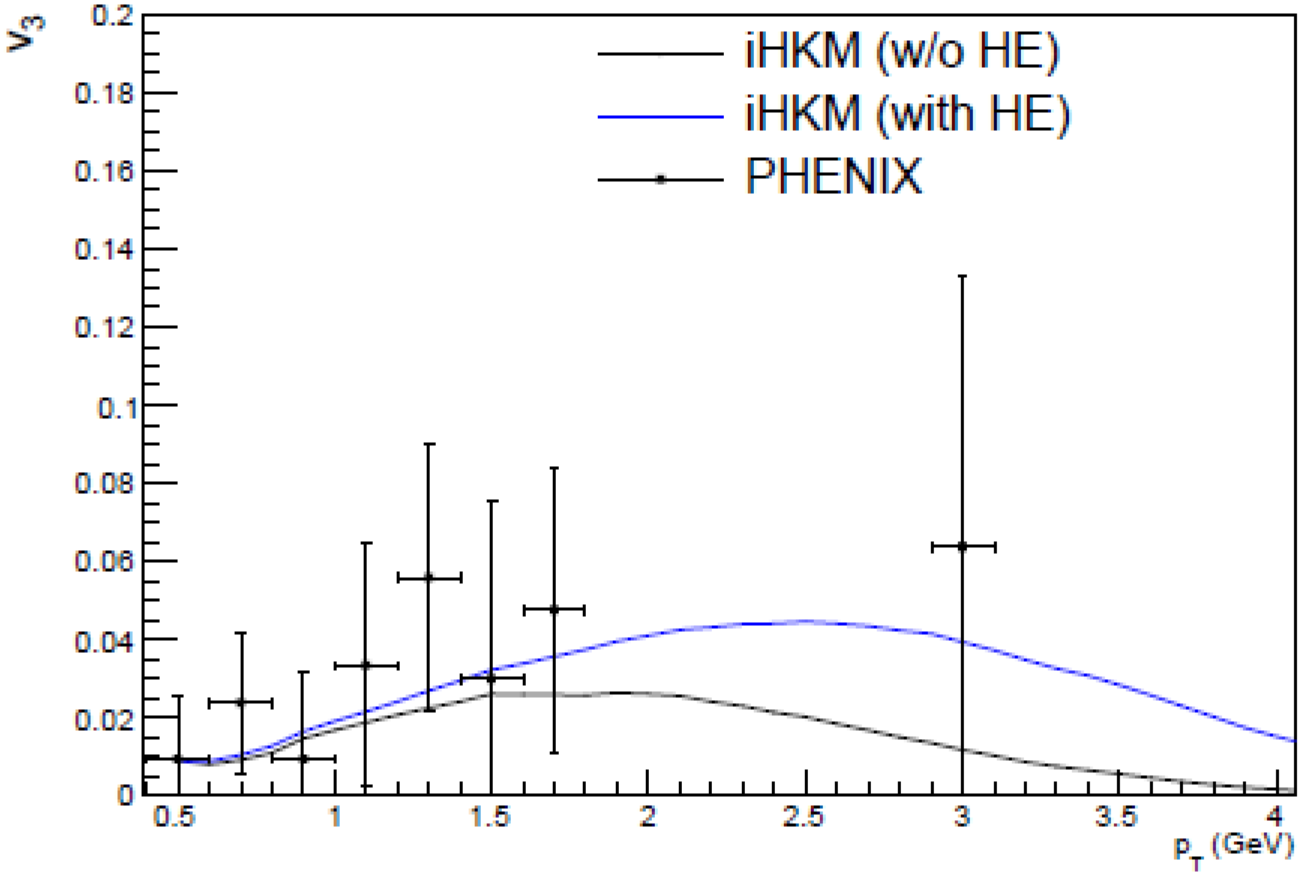
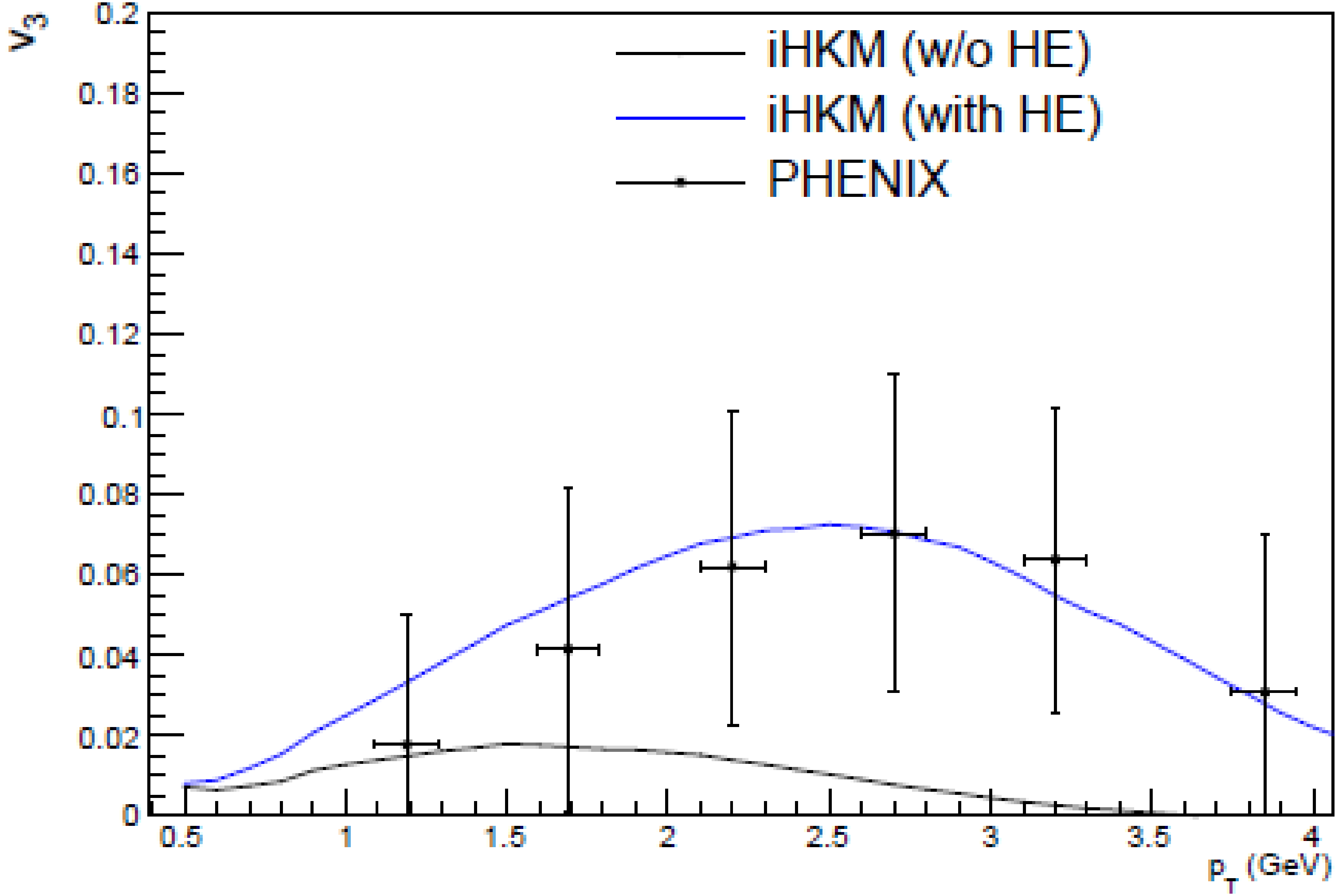
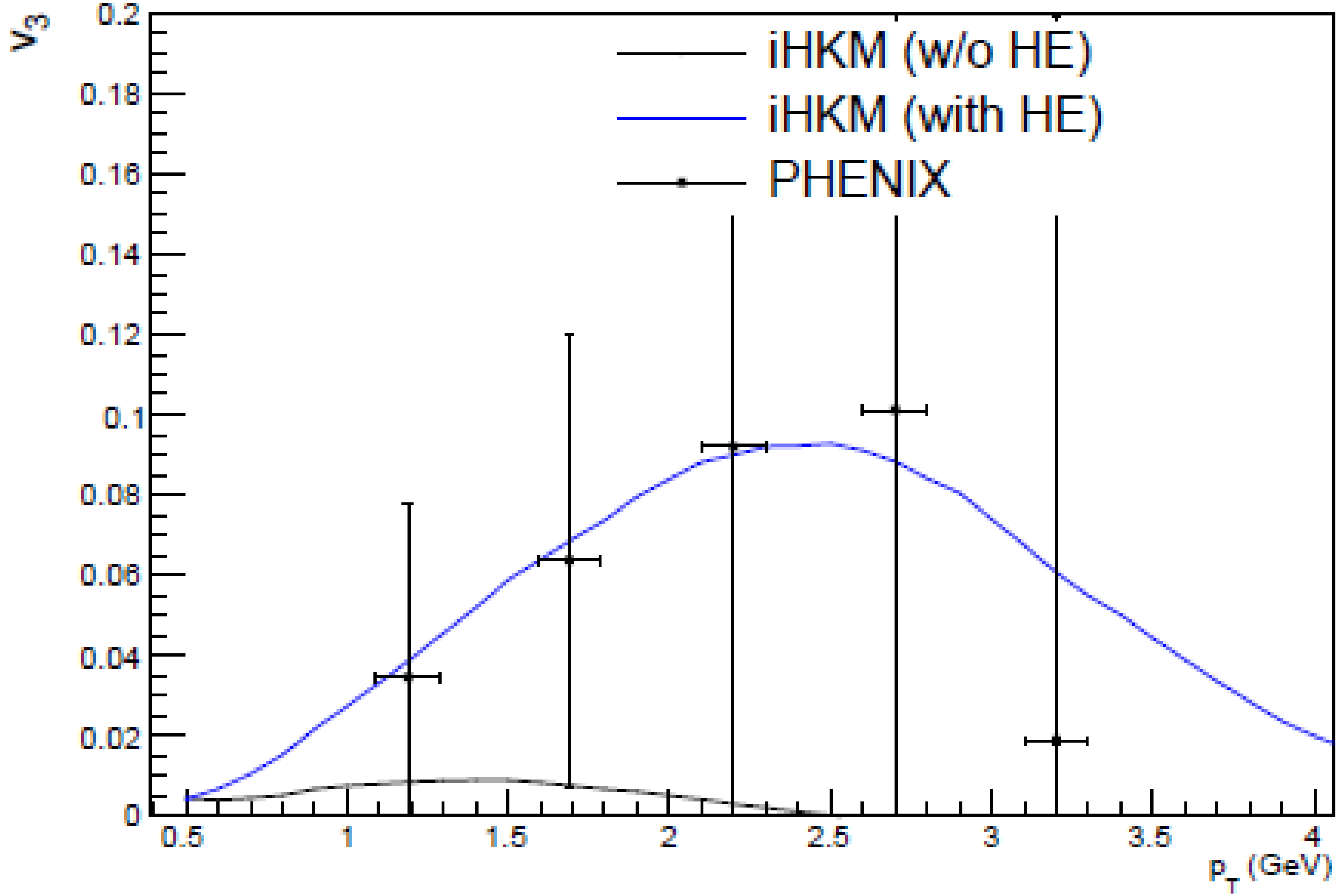


FIG. 6. Triangular flow for 0-20% centrality for the different models: iHKM chemically equilibrated without hadronization emission (thermal and prompt photons only) contribution and iHKM chemically equilibrated with HE contribution. Experimental results are taken from [52].

Triangular flow, v_3 coefficients, c. 20-40%



Triangular flow, v_3 coefficients, c. 40-60%



Summary for photons

The iHKM contains all the stages of the nucleus collision process, has natural zero initial transverse velocity and continuous freeze-out. Being applied here to the photon business, it needs the only additional parameter to describe photon spectra, elliptic and triangular flow at three centralities classes at RHIC. This parameter for the photon rate $\beta = 0.04$ is related to the specific processes of photon radiation that is connected to confining interactions at the hadronization transition. It could probably include photons from additional reaction channels for hadrons with modified properties that just created in hadronizating medium.