vHLLE+UrQMD model

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015)

Pre-thermal phase → Hydrodynamic phase → Hadronic cascade

UrQMD | vHLLE (3+1)-D viscous hydrodynamics | UrQMD

Parameters τ_0 , $R_\perp$, R_η and η/s adjusted using basic observables in the RHIC BES-I region.

$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8 (SPS)	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3 (SPS)	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

Model tuned by matching with existing experimental data from SPS and BES-I RHIC

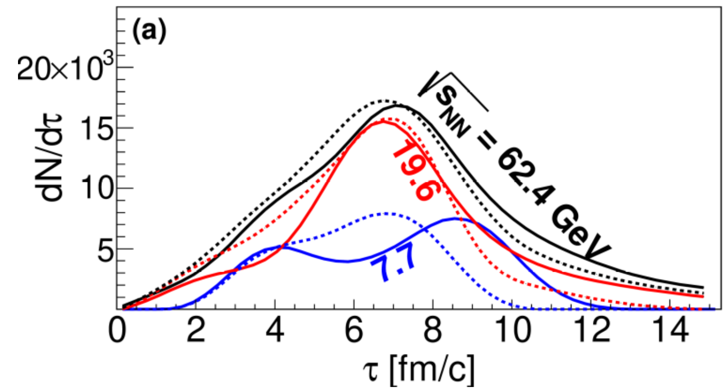
EoS to be used in the model

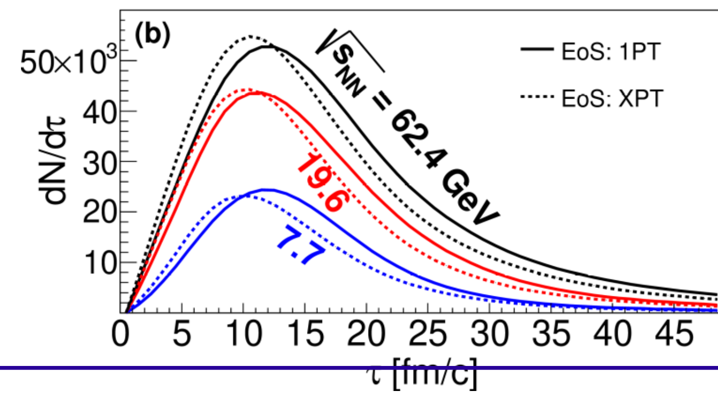
- Chiral EoS - crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model 1st-order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

Hydrodynamic phase lasts longer with 1PT, especially at lower energies but cascade smears this difference.

Pion emission time

(a) - after hydrodynamic phase
(b) - after cascade





vHLLE+UrQMD model

Pre-thermal phase	→	hydrodynamic phase	→	hadronic cascade
UrQMD		vHLLE		UrQMD

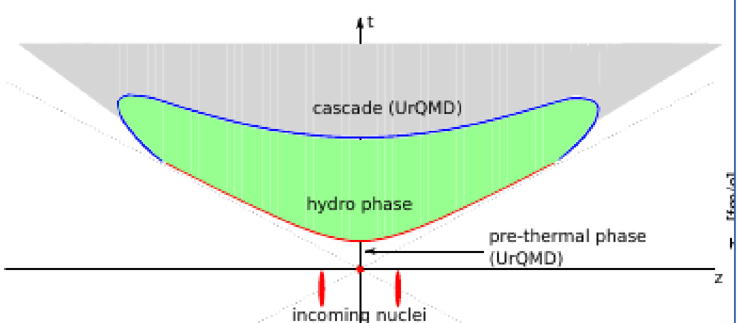
Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751 , talk QM2015

vHLLE code: free and open source, https://github.com/yukarpenko/vhlle, Comput. Phys. Commun. 185 (2014), 3016

The transition to hydrodynamical description occurs at a hyper-surface of constant longitudinal proper time τ_0

The minimal value of the starting time τ0 - average time for the two colliding nuclei to completely pass through each other:

$$\tau_0 = 2R/\sqrt{(\sqrt{s_{\rm NN}}/2m_N)^2 - 1},$$



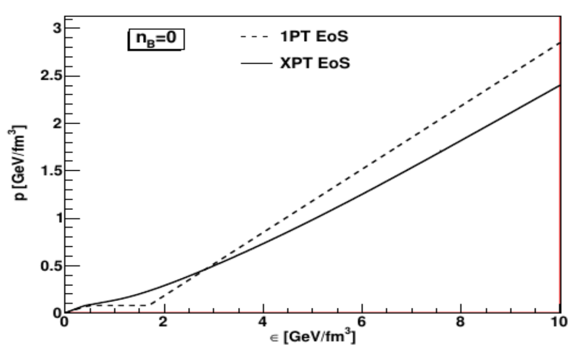
At τ = τ0 energy, momentum and baryon/electric charges of hadrons are distributed to fluid cells ijk around each hadron's position according to Gaussian profiles

VHLLE (3+1)-D viscous hydrodynamics

HadronGas + Bag Model → 1st order PT (1PT) P.F. Kolb, et al, PR C 62, 054909 (2000)

Chiral EoS → crossover PT (XPT) J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

Thermodynamic pressure as a function of energy density, evaluated at zero baryon density from the equations of state used in the hydrodynamic stage XPT & 1PT



Fluid to particle transition, or particlization, is set to happen at a hypersurface of constant (hydrodynamic) energy density sw = 0.5 GeV/fm3 ,

The particlization hypersurface is reconstructed with the CORNELIUS subroutine.

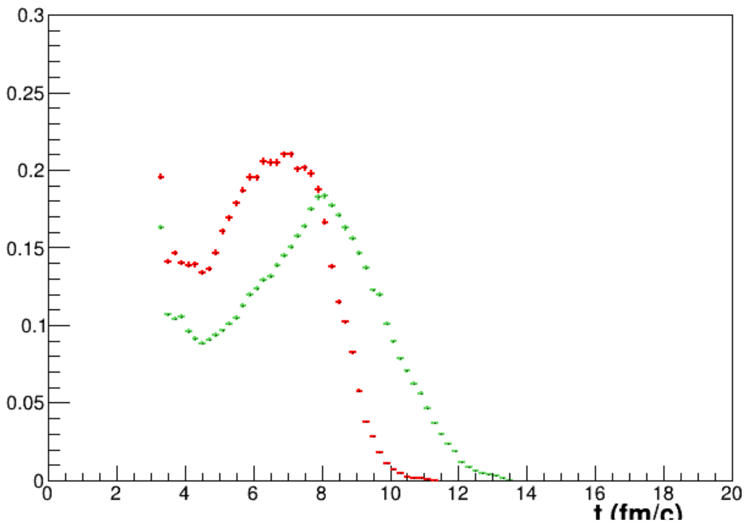
At this hypersurface, individual hadrons are sampled using the Cooper-Frye formula including shear viscous corrections to the distribution functions. The hadronic rescatterings and decays are treated with the UrQMD cascade.

Time distributions with VHLEE and vHLLE+UrQMD

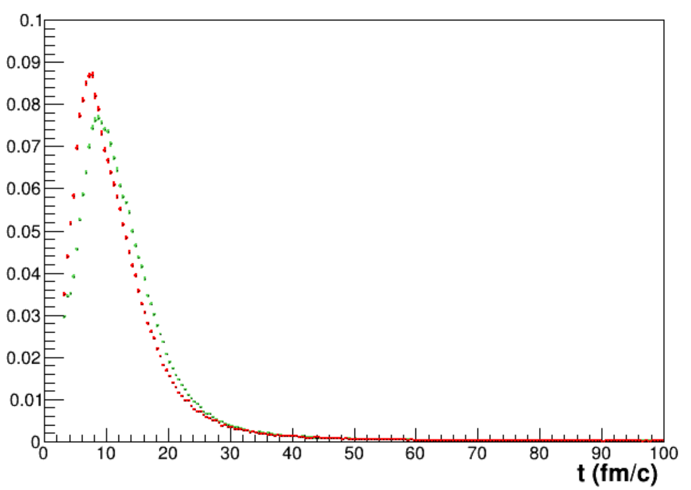
vHLEE+UrQMD model with both EoS Olga's selections |eta| < 1 & pT>0.5 GeV/c

π^{+-}, 7.7 GeV

Pion emission time after hydrodynamic phase

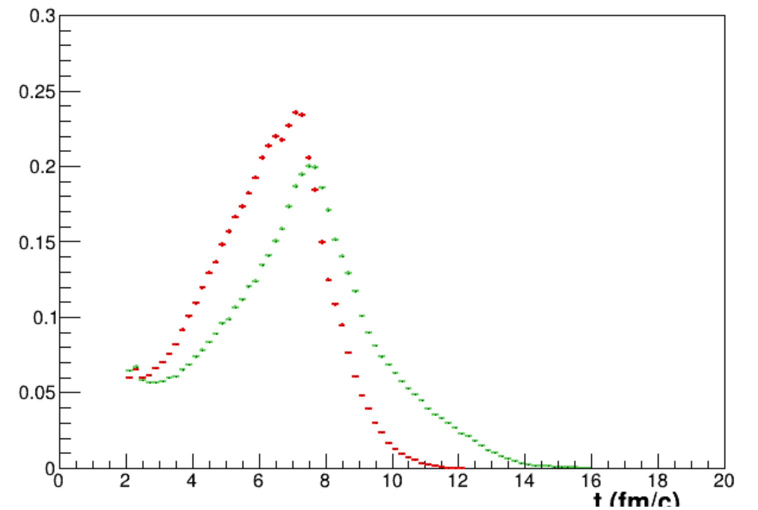


Pion emission time after cascade

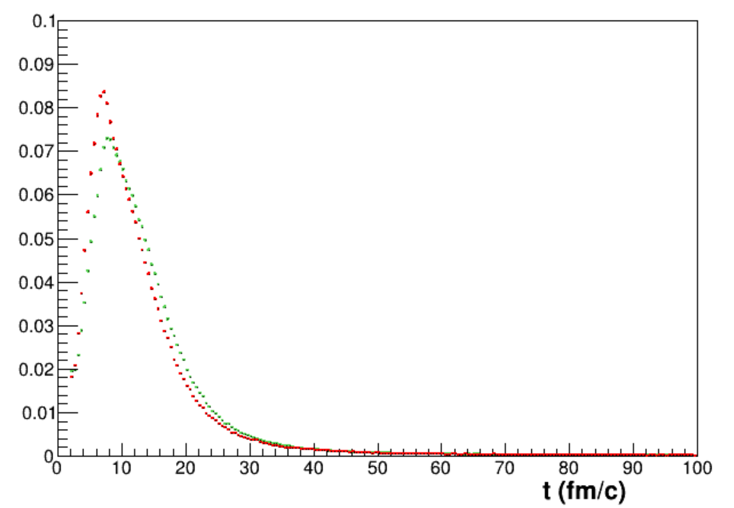


π^{+-}, 11.5 GeV

Pion emission time after hydrodynamic phase



Pion emission time after cascade



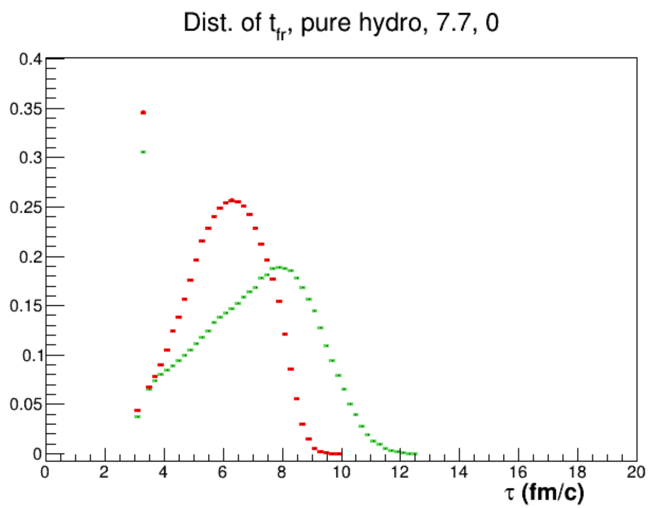
Space-time distributions with vHLLE: tau

vHLEE+UrQMD model with both EoS Olga's selections |eta| < 1 &

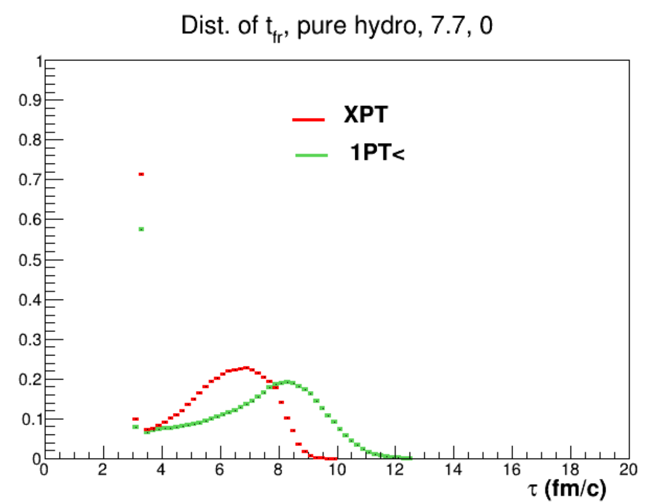
π^{+-}, 7.7 GeV

Pion emission time after hydrodynamic phase

pT>0.5 GeV/c



All pT



$$\tau_0 = 2R/\sqrt{(\sqrt{s_{NN}}/2m_N)^2 - 1},$$

$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8 (SPS)	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3 (SPS)	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

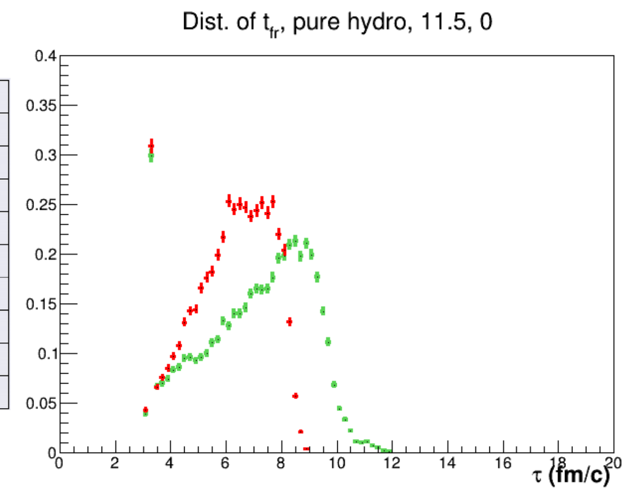
$$\tau = \sqrt{t^2 - z^2}$$

Pion emission from the edge of fireball is rather strong effect In vHLLE.
Such pions are seen even after cascade.
Cut on pT>0.5 kill ~50% of such pions.
Strong dependence on EoS.

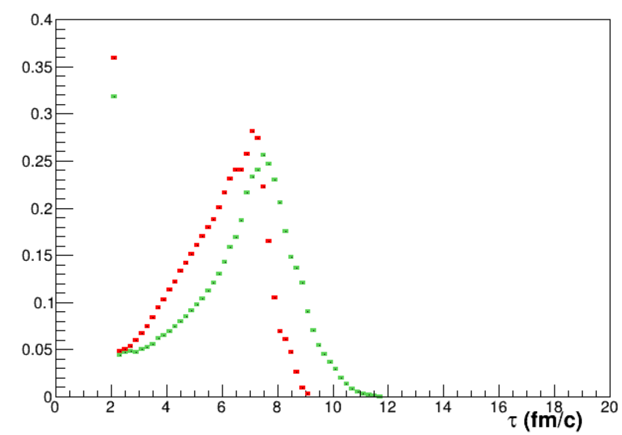
π^{+-}, 11.5 GeV

Pion emission time after hydrodynamic phase

pT>0.5 GeV/c



All pT

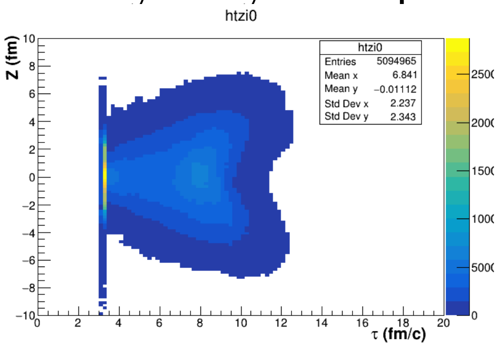


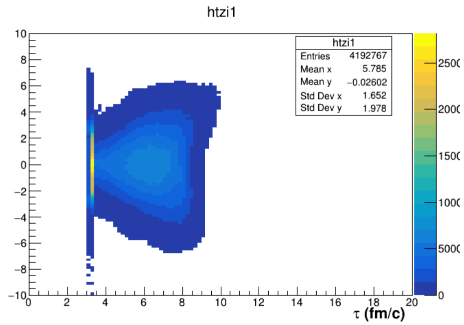
Time distributions with VHLEE and vHLLE+UrQMD

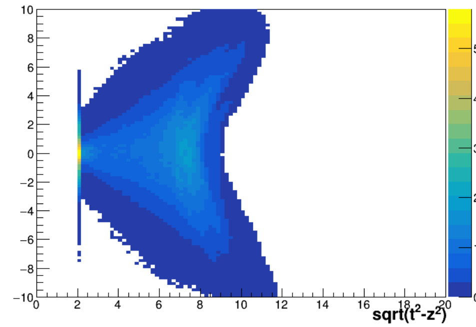
vHLEE+UrQMD model with both EoS Olga's selections |eta| < 1 & pT>0.5 GeV/c

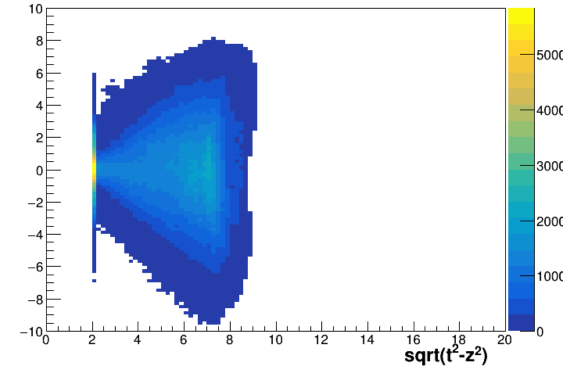
π^{+-}, 7.7 GeV **π^{+-}, 11.5 GeV**

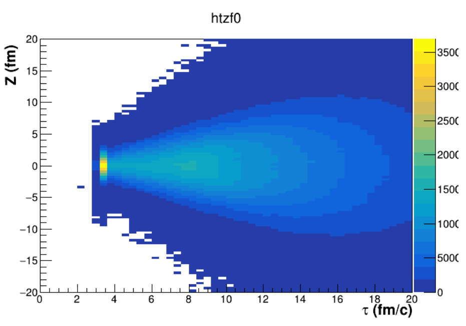
after hydrodynamic phase 1PT τ-z after hydrodynamic phase 1PT τ-z XPT τ-z

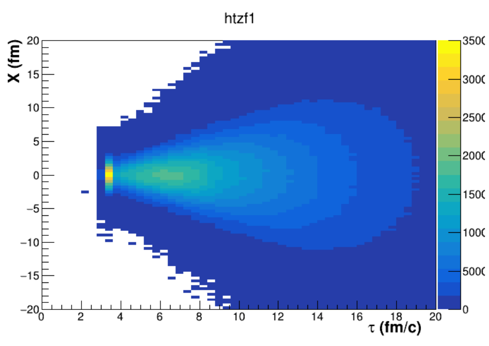


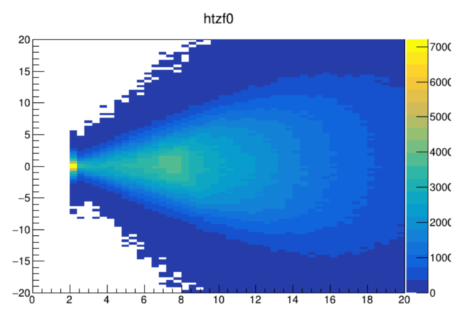


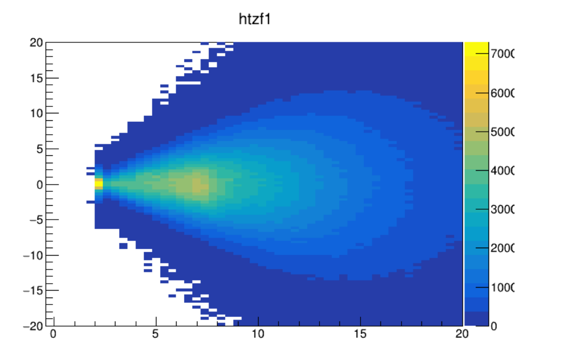












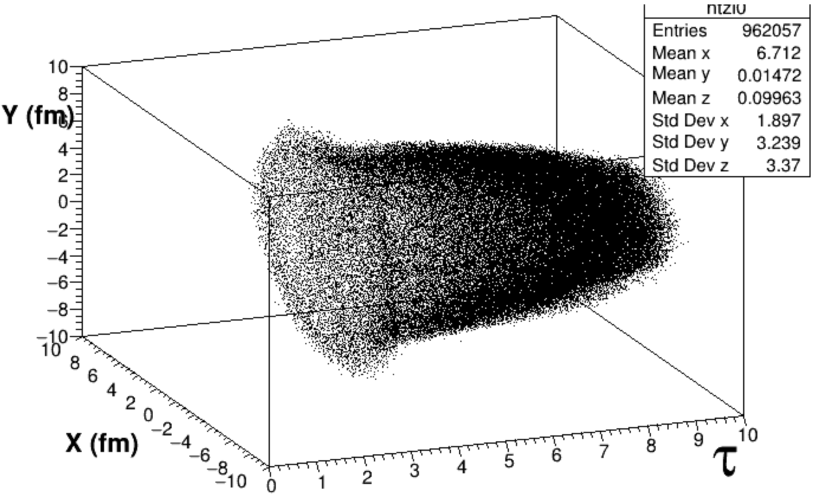
Pion emission for 1PT lasts longer and has wider distribution especially in Z-direction.
Emission from the edge of fireball is well seen even after cascade.

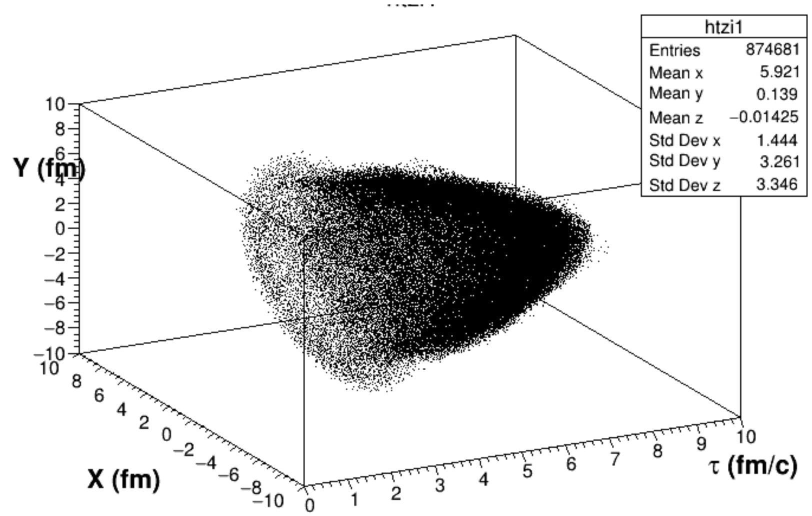
Space-time distributions with vHLLE 7.7 GeV

π^{+-}, 7.7 GeV

1PT Pion emission τ-Z after hydro phase

XPT Pion emission τ-Z after hydro phase

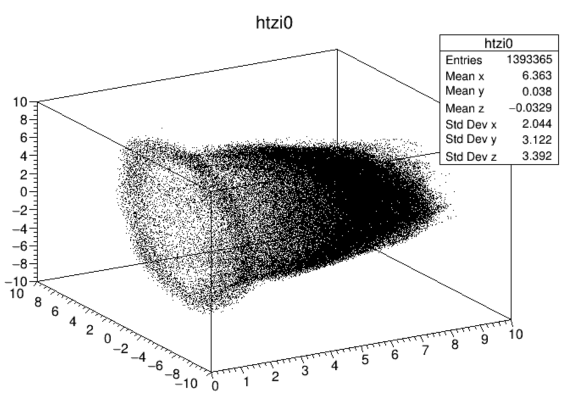


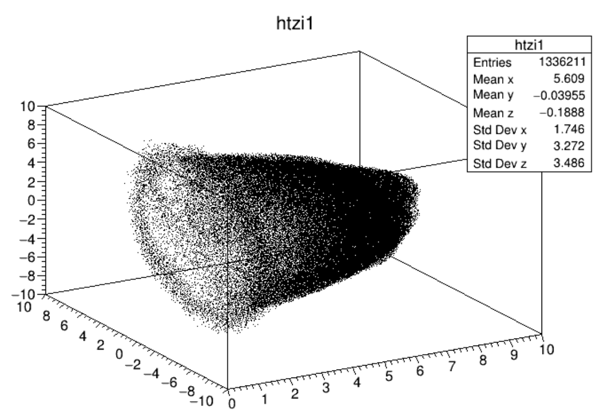


π^{+-}, 11.5 GeV

1PT Pion emission τ-Z after hydro phase

XPT Pion emission τ-Z after hydro phase



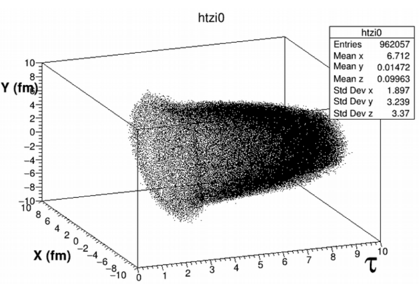


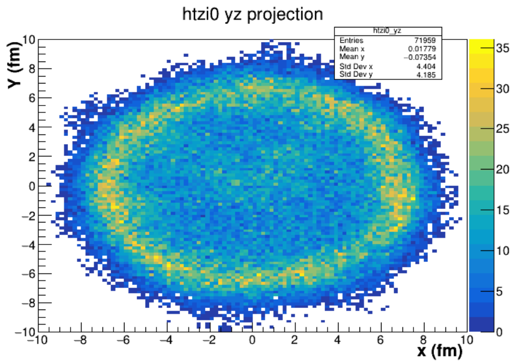
Pion emission for 1PT lasts longer then XPT

X:Y Space-time distributions with vHLLE 7.7 GeV

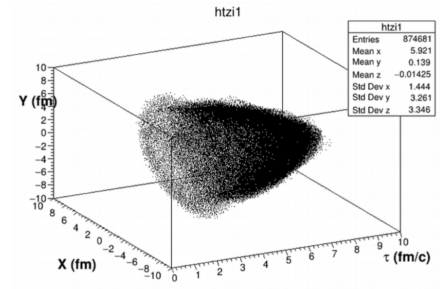
1PT Pion emission x-y after hydro phase

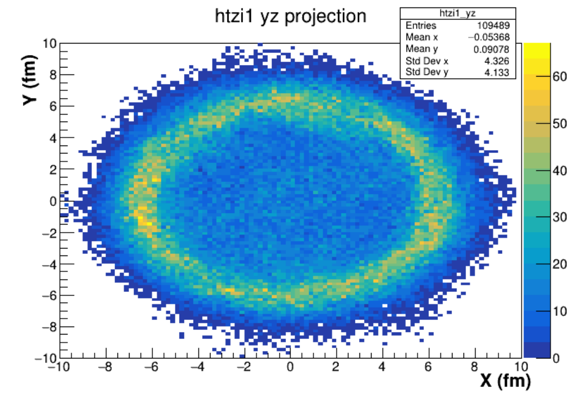
XPT Pion emission x-y after hydro phase





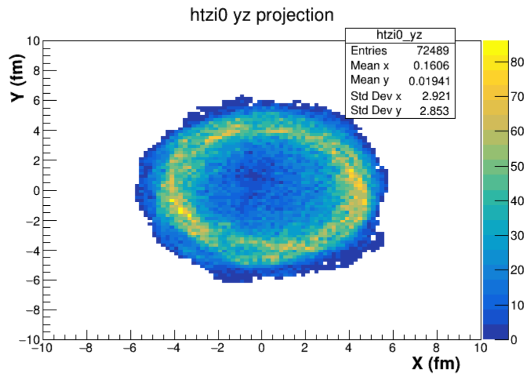
τ =τ0



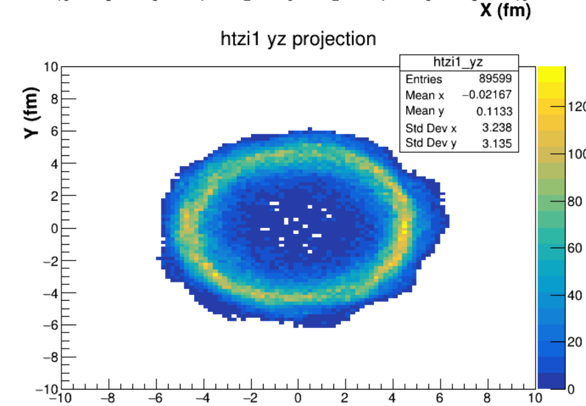


τ =τ0

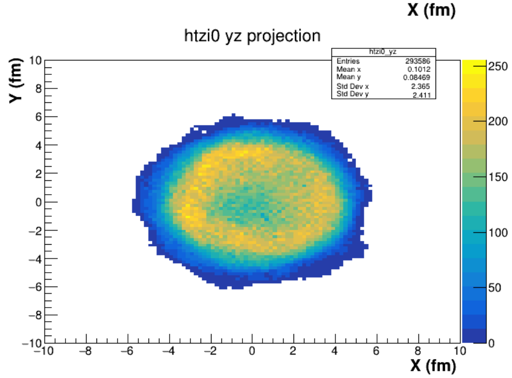
τ= Max emission



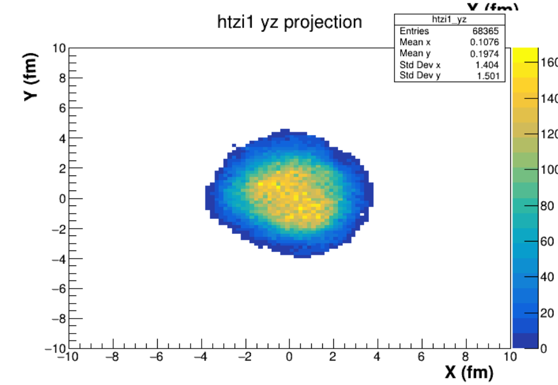
τ= Max emission



τ= 8-10 fm/c



τ= 8-10 fm/c

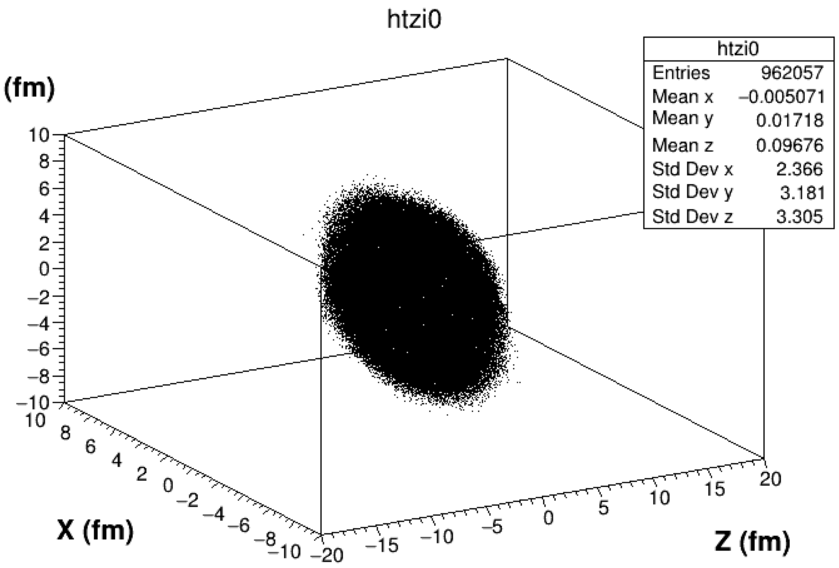


Dynamics of expansion is very different for 1PT (slower) and XPT (faster).
But if we integrate by time we lost such information – integrated X:Y distributions are rather similar

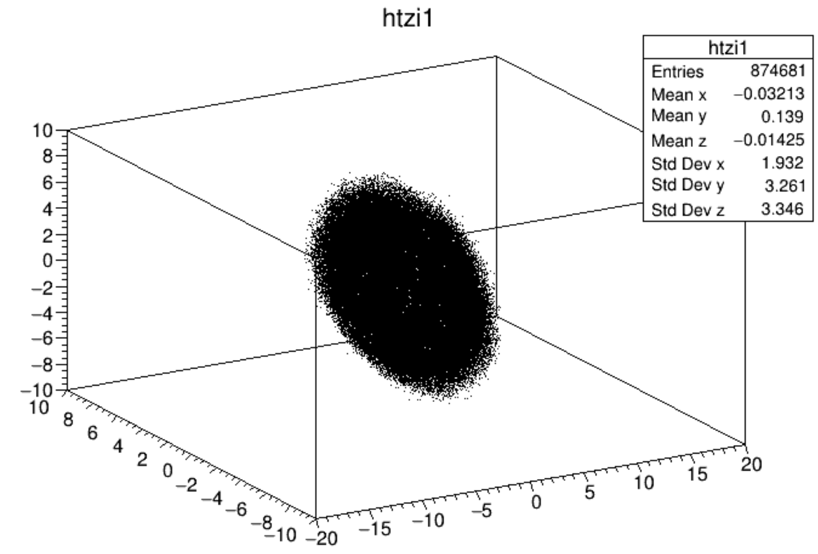
XYZ Space-time distributions with vHLLE 7.7 GeV

π^{+-}, 7.7 GeV

1PT Pion emission XYZ after hydro phase



XPT Pion emission XYZ after hydro phase



π^{+-}, 11.5 GeV

1PT Pion emission XYZ after hydro phase

XPT Pion emission XYZ after hydro phase

7.7 GeV: XYZ Integral 1PT 0.961 $\cdot 10^6$ for 50000 ev ,XPT ~ 0.874 $\cdot 10^6$ for 50000 ev – 10%

11.5 GeV: XYZ Integral 1PT 1.256 $\cdot 10^6$ for 40000 ev ,XPT ~ 1.253 $\cdot 10^6$ for 40000 ev – no diff.

Three-fluid Hydrodynamics-based Event Simulatons Extended by UrQMD final State interactions (THESEUS)

hydrodynamic phase → Hadronic cascade

3FH

Starts from
baryon density nB = 0.15 fm−3

Energy density 0.14 GeV/fm3o

UrQMD

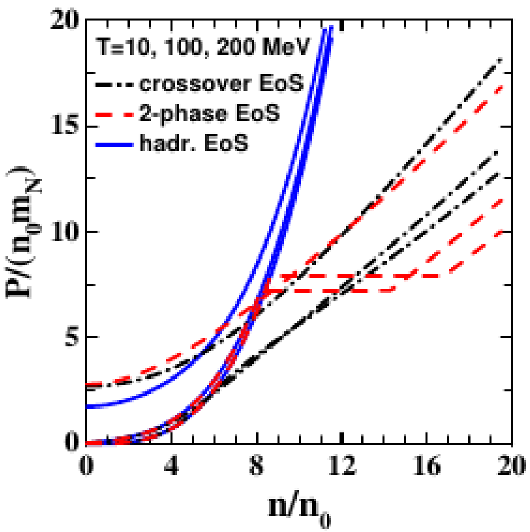
Total energy density
ε < εfrz,=0.4 GeV/fm

Pressure scaled by the product of normal nuclear density (n0 = 0.15 fm−3) and nucleon mass (mN) versus baryon density scaled by the normal nuclear density for three considered equations of state. Results are presented for three different temperatures T = 10, 100 and 200 MeV (from bottom upwards for corresponding curves).

Three-fluid hydrodynamics (3FH): Yu. B. Ivanov, V. N. Russkikh and V. D. Toneev, Phys. Rev. C 73, 044904 (2006);

EoS :

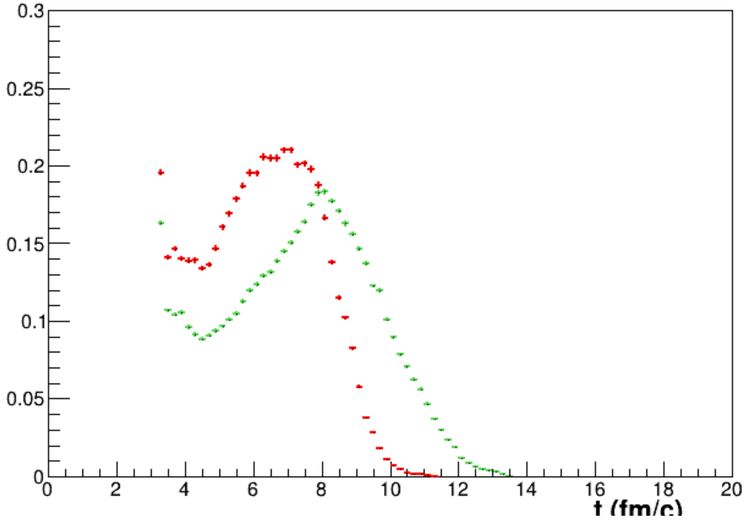
- **Hadron Gas**
- **Crossover and 1PT EoS:**
- A. S. Khvorostukin, V. V. Skokov, V. D. Toneev and K. Redlich, Eur. Phys. J. C 48, 531 (2006).
  Based on the quasi-particle description of the QCD medium atfinite temperature and densitywe formulate the phenomenological model for the equation ofstate that exhibits crossover or the firstorder deconfinement phase transition



Time distributions with VHLEE and THESEUS

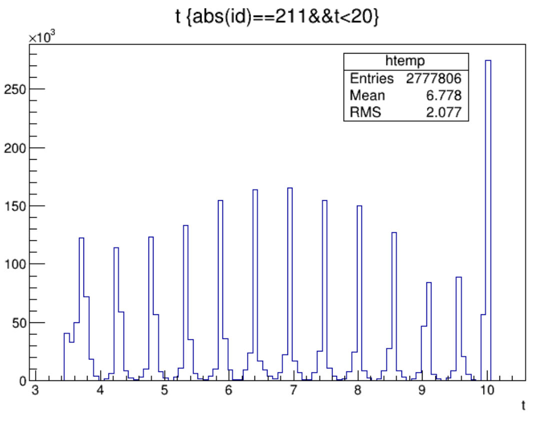
π^{+-}, 7.7 GeV vHLEE

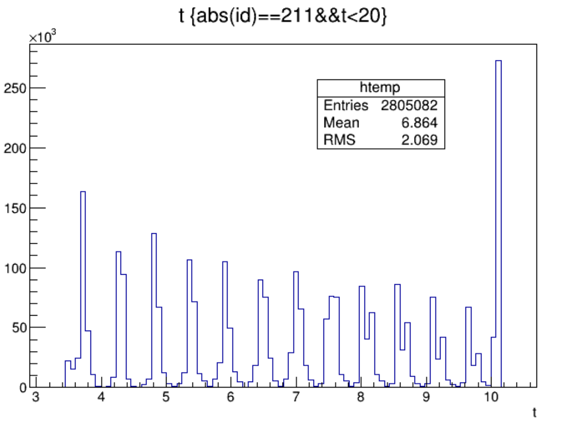
Pion emission time after hydrodynamic phase



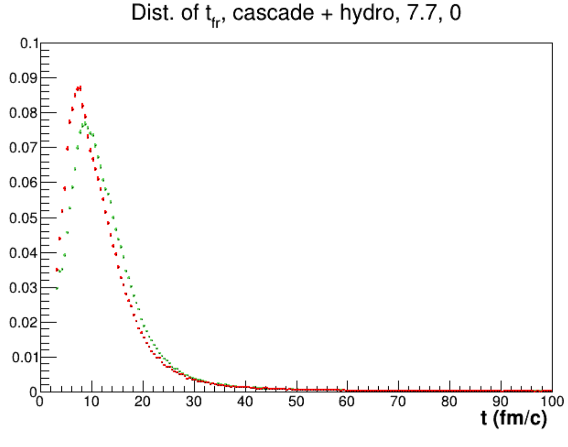
π^{+-}, 7.7 GeV

TH3 Pion emission time after hydrodynamic phase

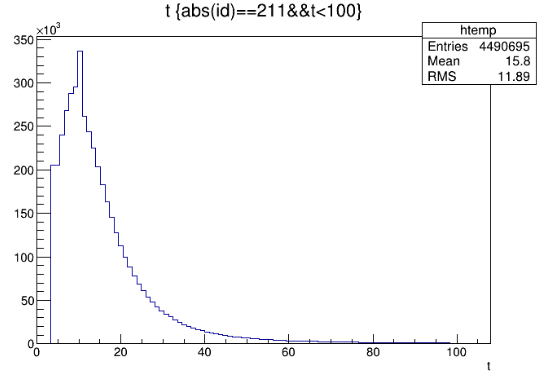


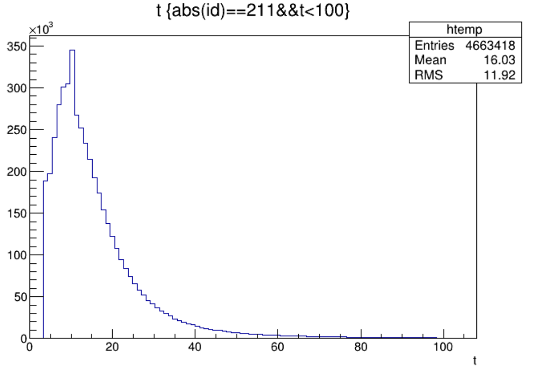


Pion emission time after cascade
VHLEE+UrQMD



THESEUS Pion emission time after cascade



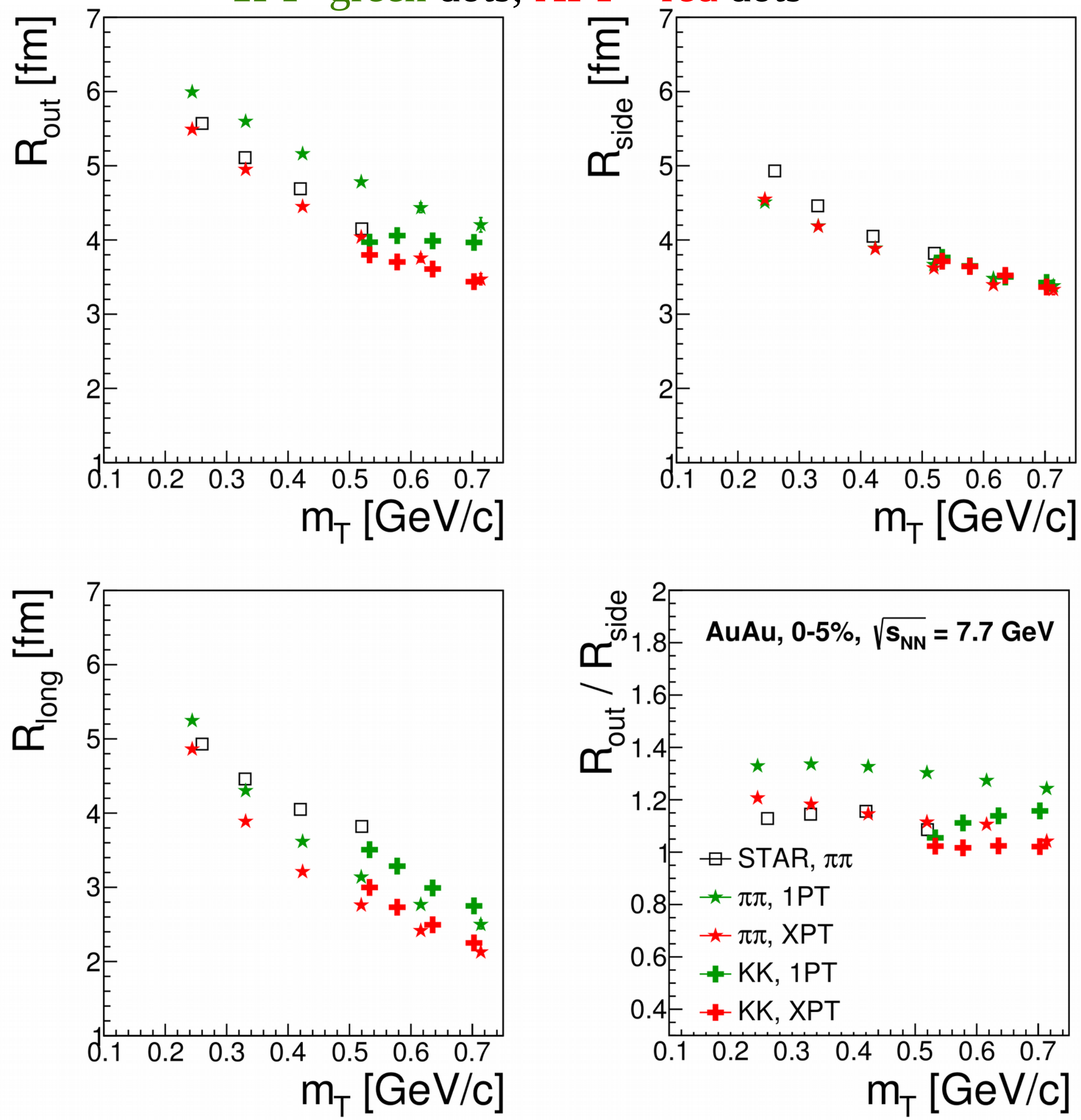


Additional slides

Is it a special feature of vHLLE or it is present in the other models ?

Radii π and K vs. mT with vHLLE+UrQMD (7.7GeV)

1PT -green dots; XPT – red dots



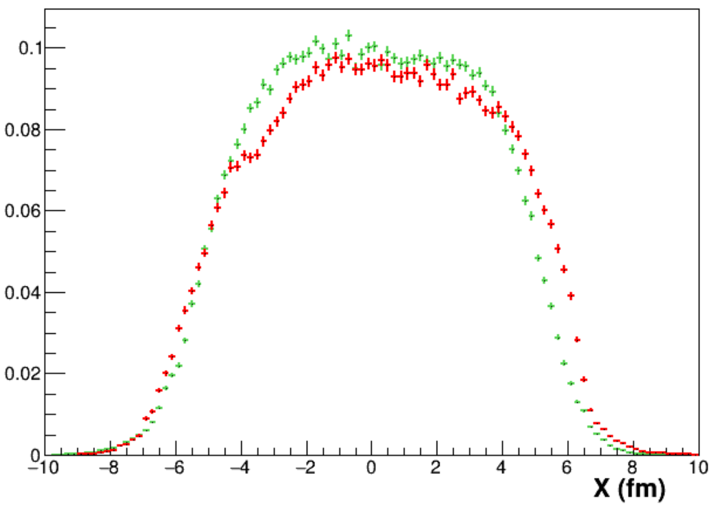
- AuAu, $\sqrt{s_{NN}}$ = 7.7 GeV
- 0-5% centrality
- **All as for 11.5 AGeV (slide 11) and model does not predict significant differences.**
- As well as for π kaon out and long radii greater for 1PT than for XPT
- Approximate m_T scaling for pions and kaons observed only for "side" radii
- It is important to measure both kaons and pions

Space-time distributions with vHLLE+UrQMD:

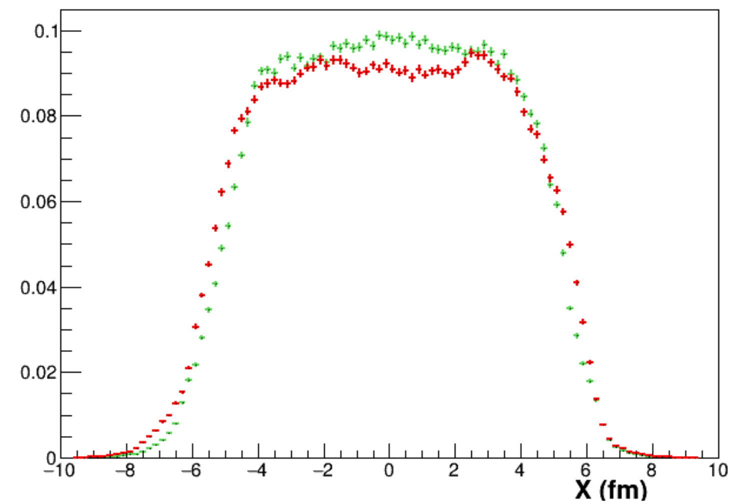
vHLEE+UrQMD model with both EoS Olga's selections |eta| < 1 & pT>0.5 GeV/c

π^{+-}, 7.7 GeV/s | **π^{+-}, 11.5 GeV/s**

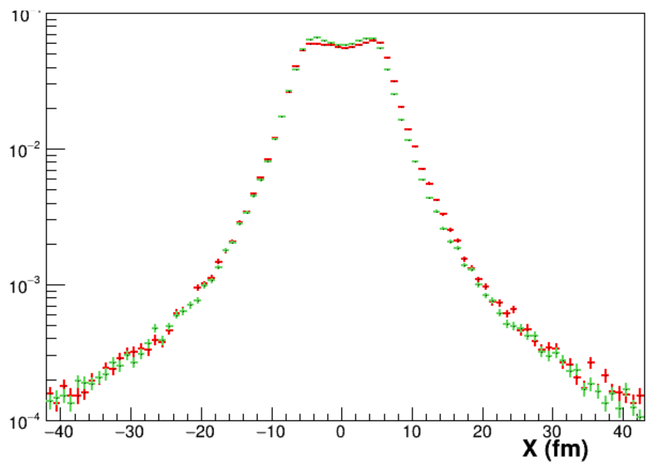
Pion emission X-ccord. after hydrodynamic phase



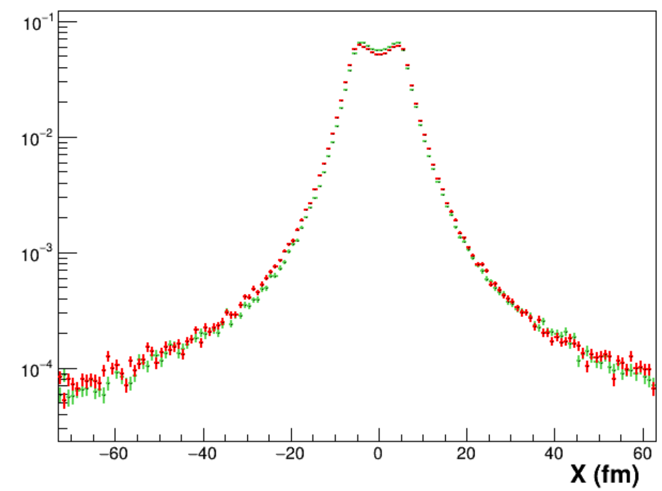
Pion emission X-coord. after hydrodynamic phase



Pion emission X-coord. after cascade



Pion emission X-coord. after cascade

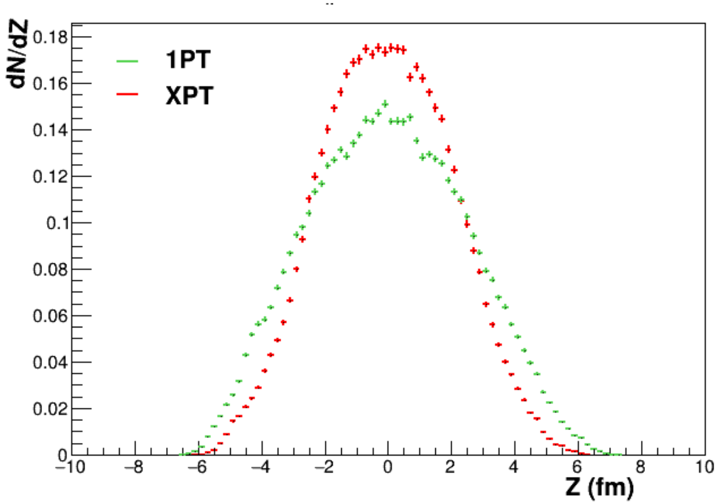


Space-time distributions with vHLLE+UrQMD:

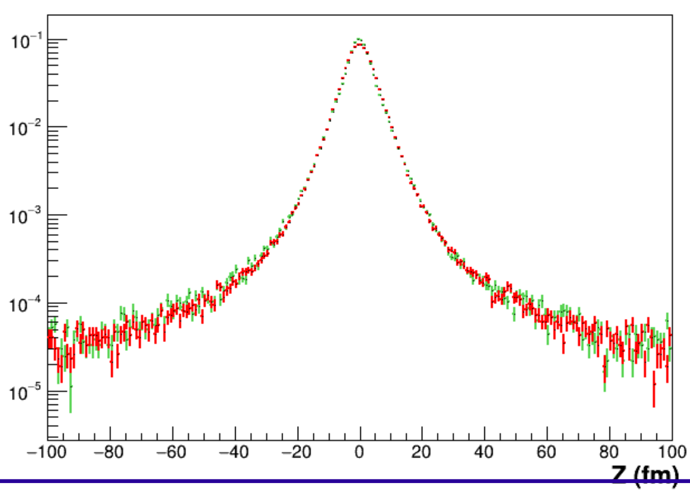
vHLEE+UrQMD model with both EoS Olga's selections |eta| < 1 & pT>0.5 GeV/c

π^{+-}, 7.7 GeV/s

Pion emission Z-ccord. after hydrodynamic phase

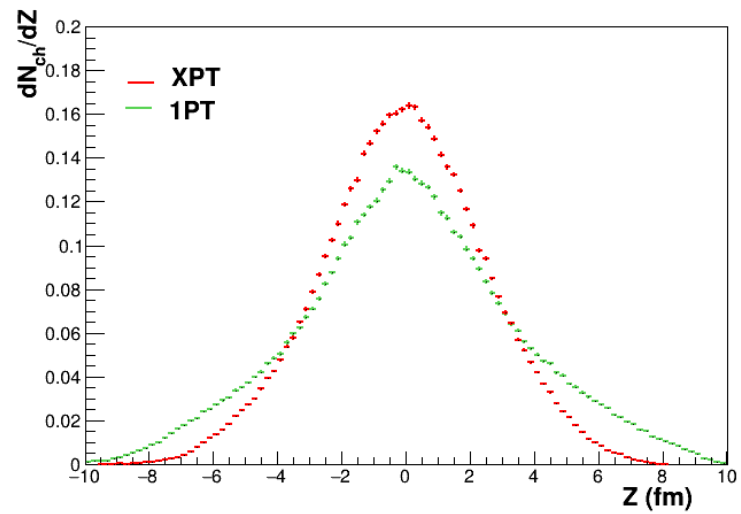


Pion emission Z-coord. after cascade

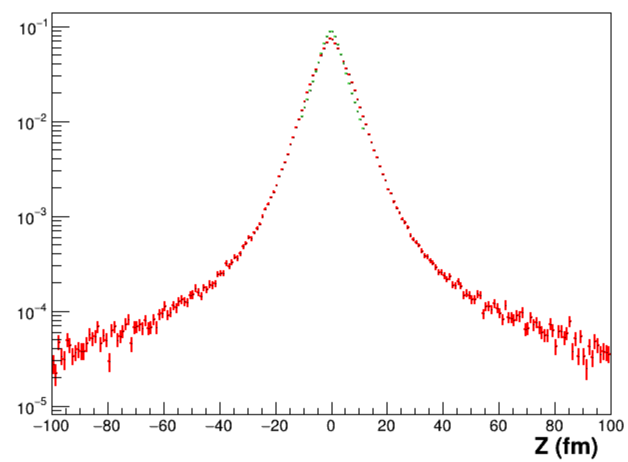


π^{+-}, 11.5 GeV/s

Pion emission Z-coord. after hydrodynamic phase



Pion emission Z-coord. after cascade

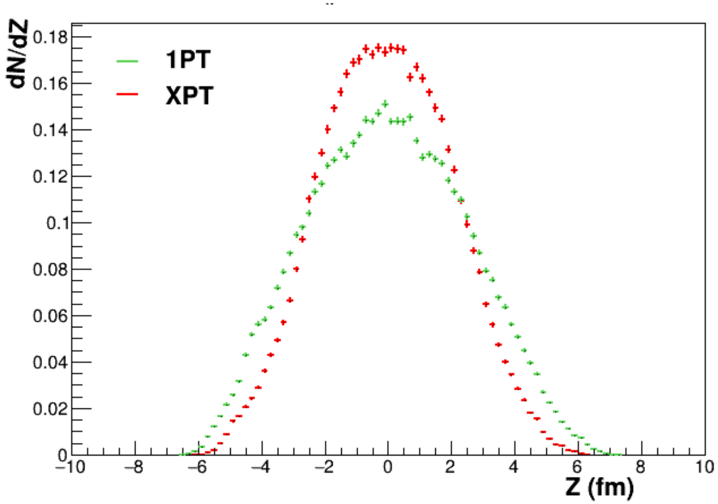


Space-time distributions with vHLLE+UrQMD:

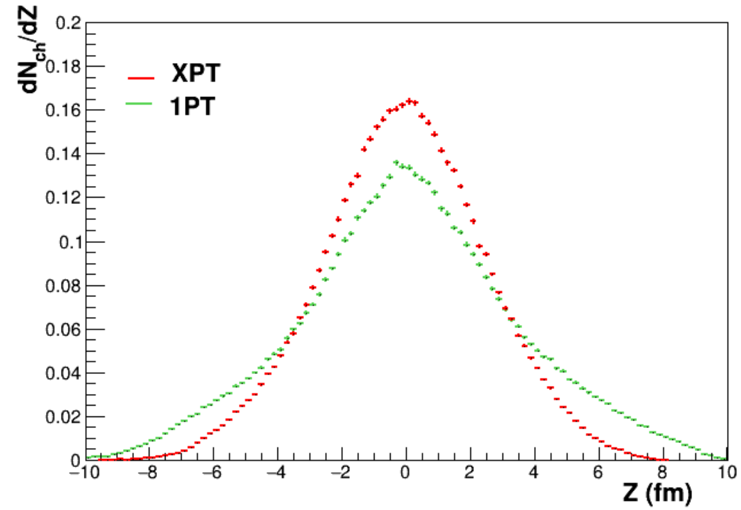
vHLEE+UrQMD model with both EoS Olga's selections |eta| < 1 & pT>0.5 GeV/c

π^{+-}, 7.7 GeV/s **π^{+-}, 11.5 GeV/s**

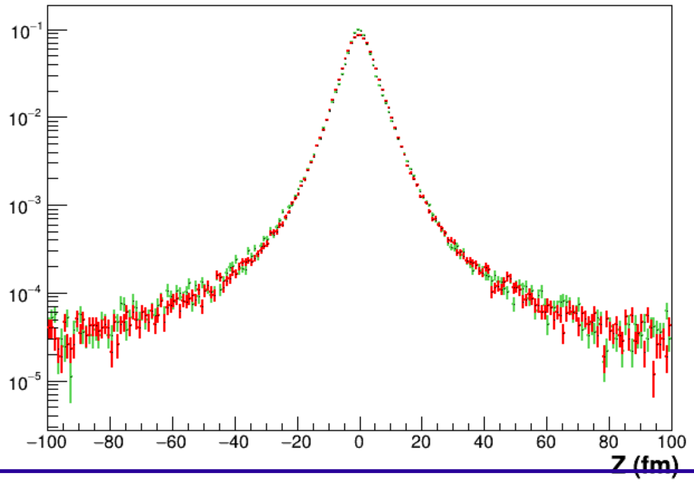
Pion emission Z-ccord. after hydrodynamic phase



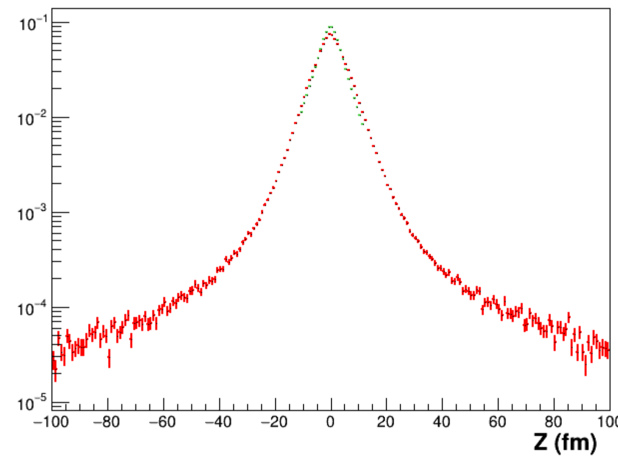
Pion emission Z-coord. after hydrodynamic phase



Pion emission Z-coord. after cascade



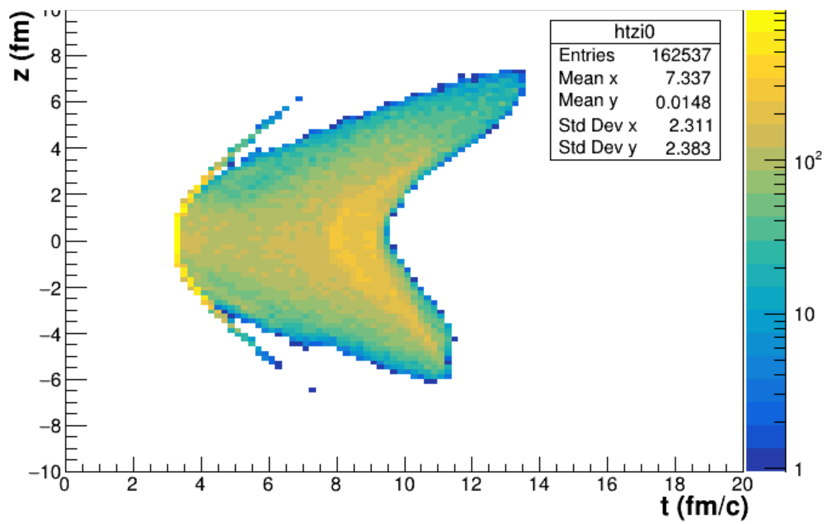
Pion emission Z-coord. after cascade



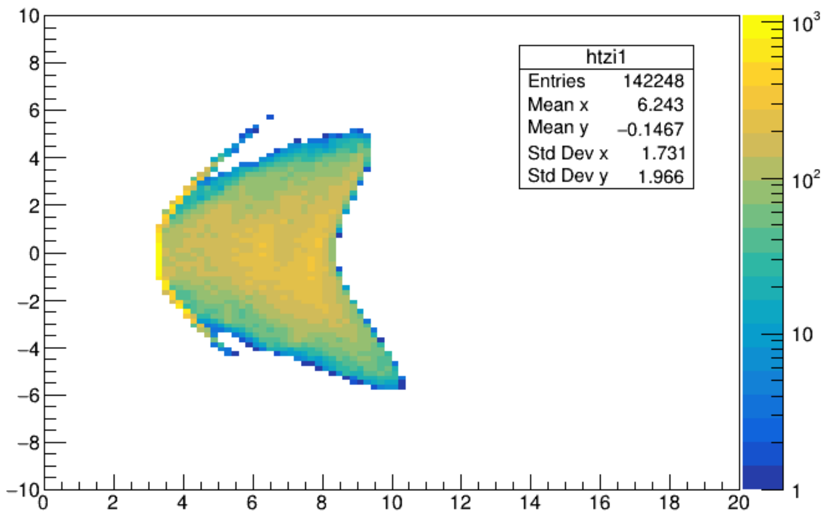
Space-time distributions with vHLLE+UrQMD:

π^{+-}, 7.7 GeV/s

1PT Pion emission t-Z after hydrodynamic phase

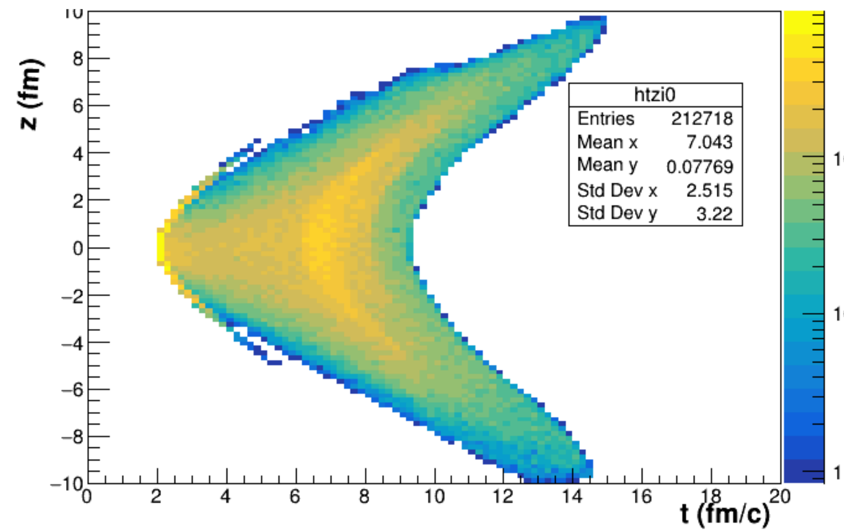


XPT Pion emission t-Z after hydrodynamic phase

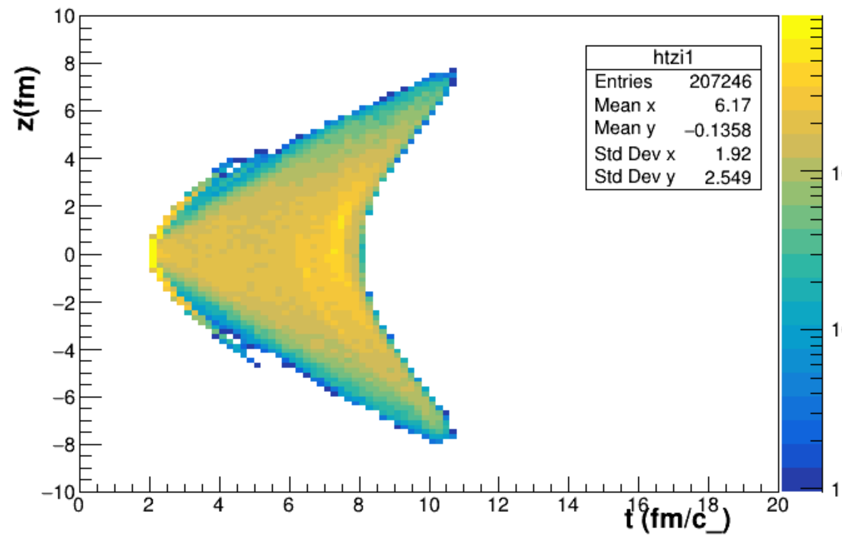


π^{+-}, 11.5 GeV/s

1PT Pion emission t-Z after hydrodynamic phase



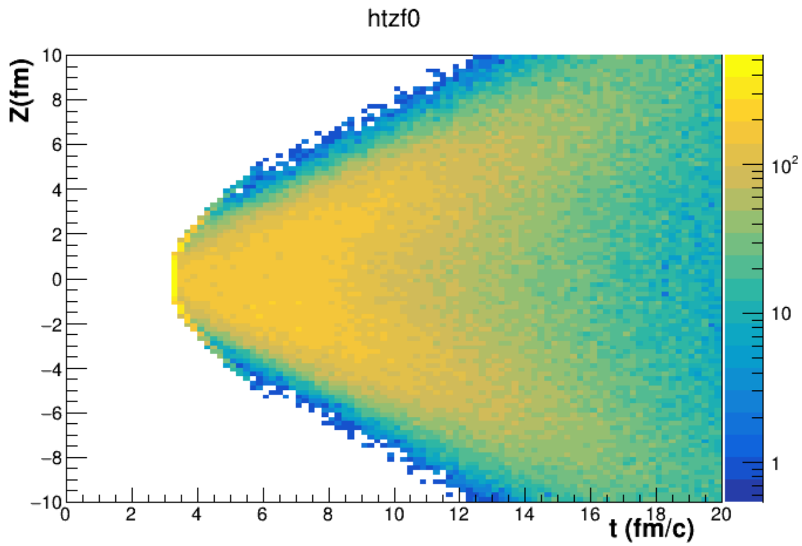
XPT Pion emission t-Z after hydrodynamic phase



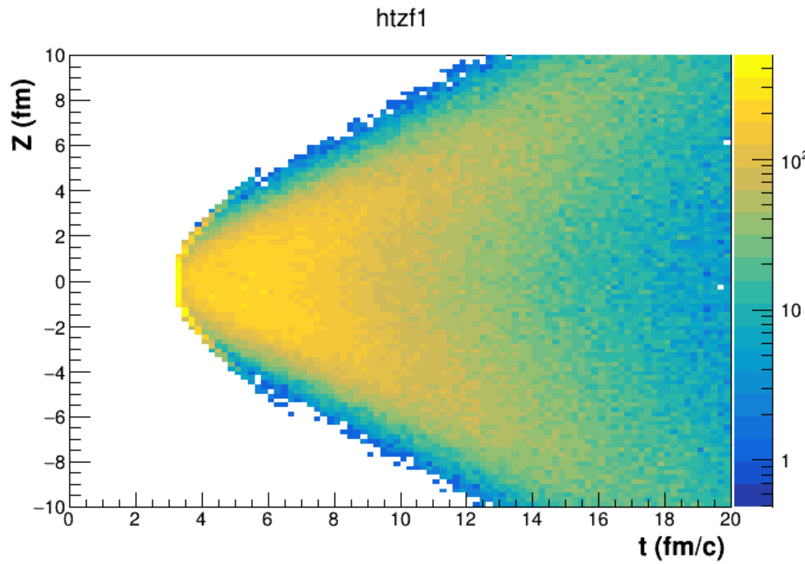
Space-time distributions with vHLLE+UrQMD:

π^{+-}, 7.7 GeV/s

1PT Pion emission t-Z after cascade

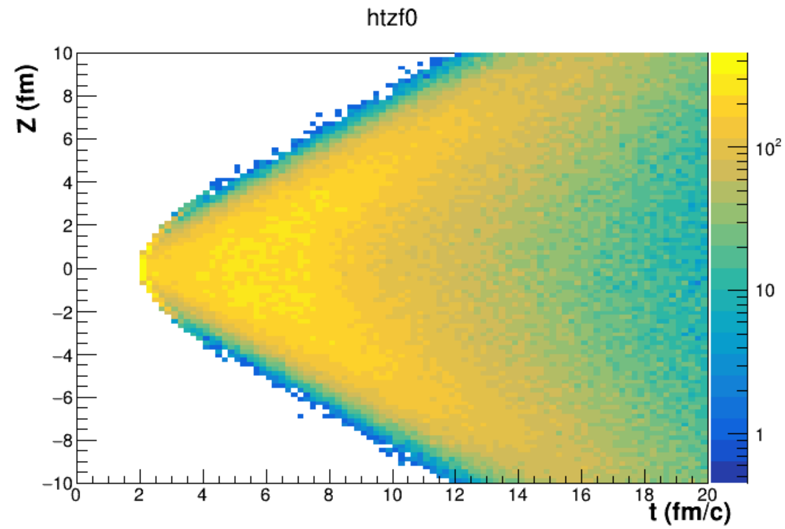


XPT Pion emission t-Z after cascade

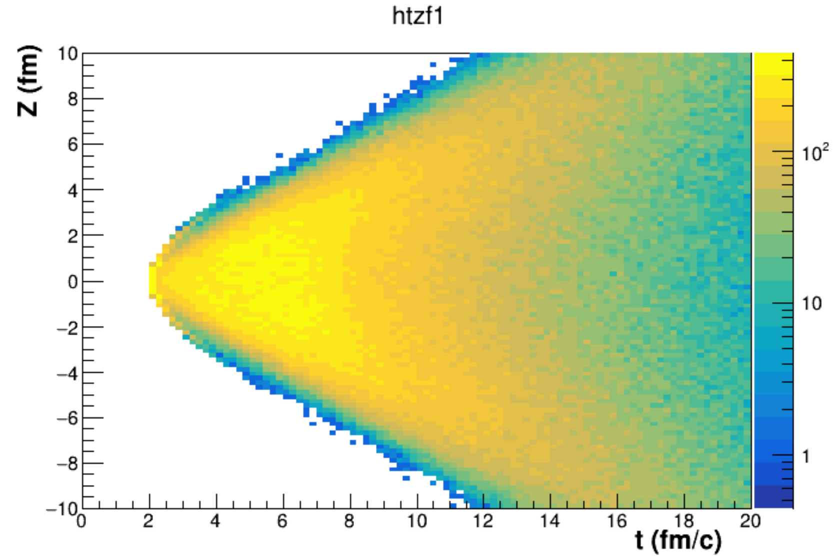


π^{+-}, 11.5 GeV/s

1PT Pion emission t-Z after cascade



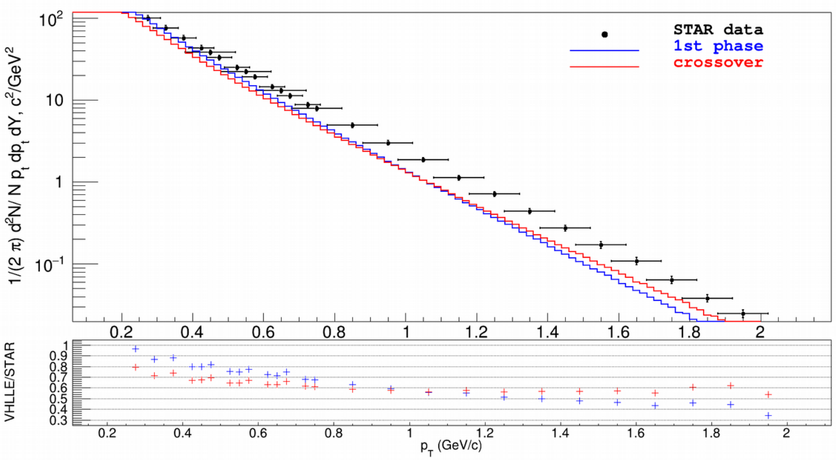
XPT Pion emission t-Z after cascade



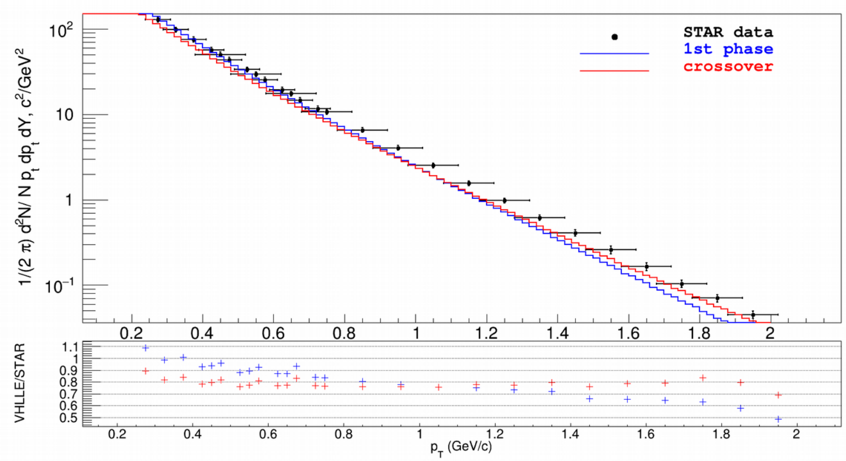
pT- spectra of π and K with vHLLE+UrQMD

STAR, PHYSICAL REVIEW C 96, 044904 (2017)

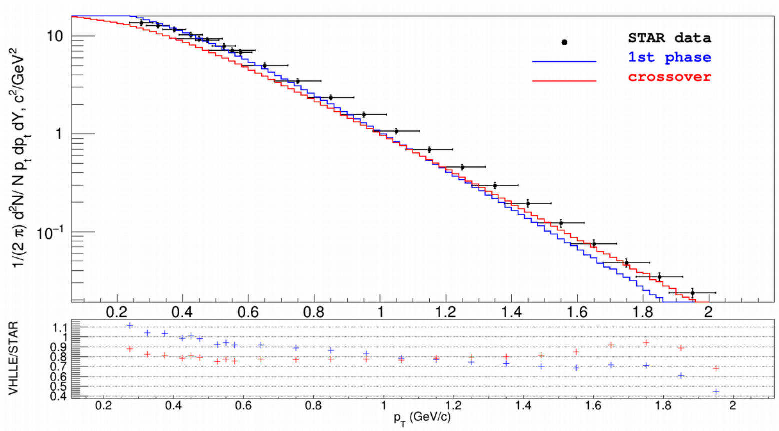
π^+, 7.7 GeV/s



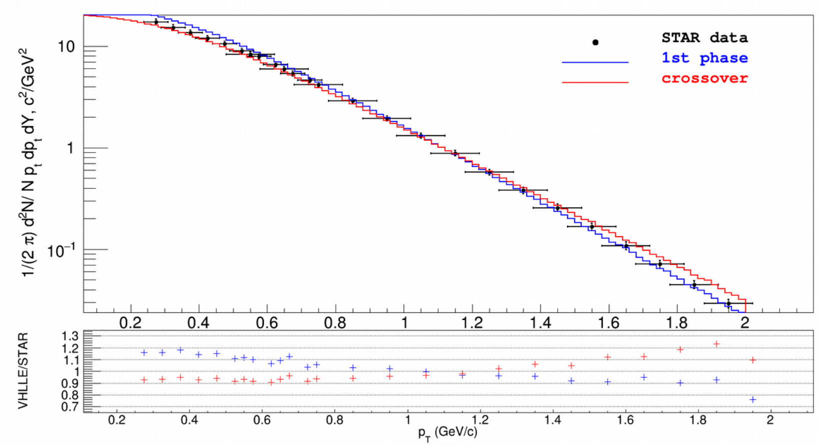
π^+, 11.5 GeV/s



K^+, 7.7 GeV/s



K^+, 11.5 GeV/s



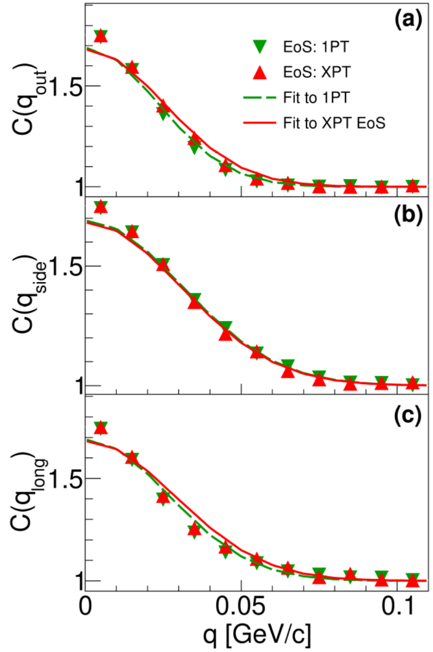
vHLEE+UrQMD model with both EoS describe reasonably (<20%) pT-spectra of pions and kaons at pT< 1 GeV/c

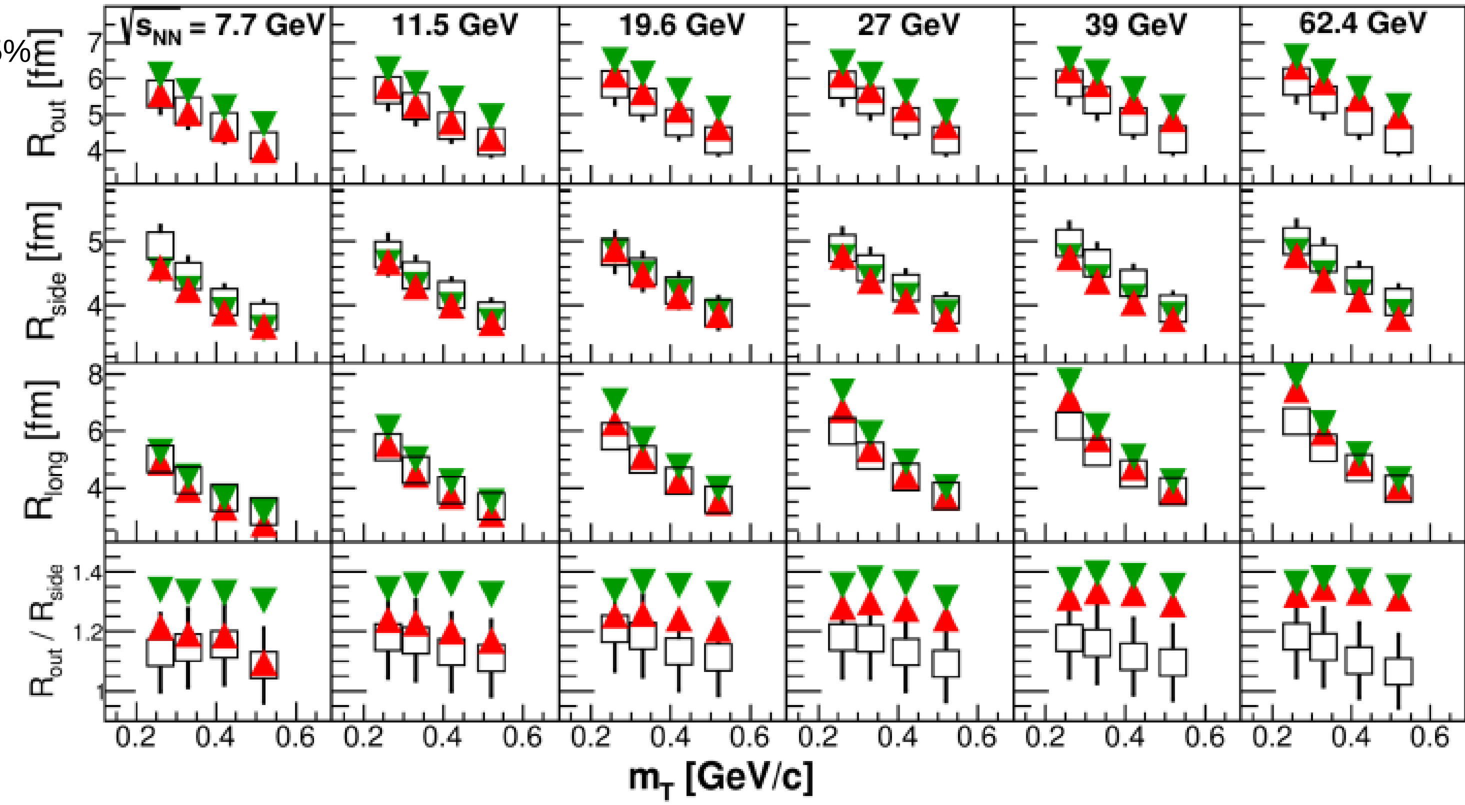
3D Pion radii versus m_T with vHLLE+UrQMD

P. Batyuk, Iu. Karpenko, R. Lednicky, L. Malinina, K. Mikhaylov, O. Rogachevsky D. Wielanek
Phys.Rev. C96 (2017) no.2, 024911

STAR, Phys.Rev. C92 (2015) 1, 014904: 0-5%
vHLLE+UrQMD: impact 0-3.3 fm

Projections of 3D Model CF

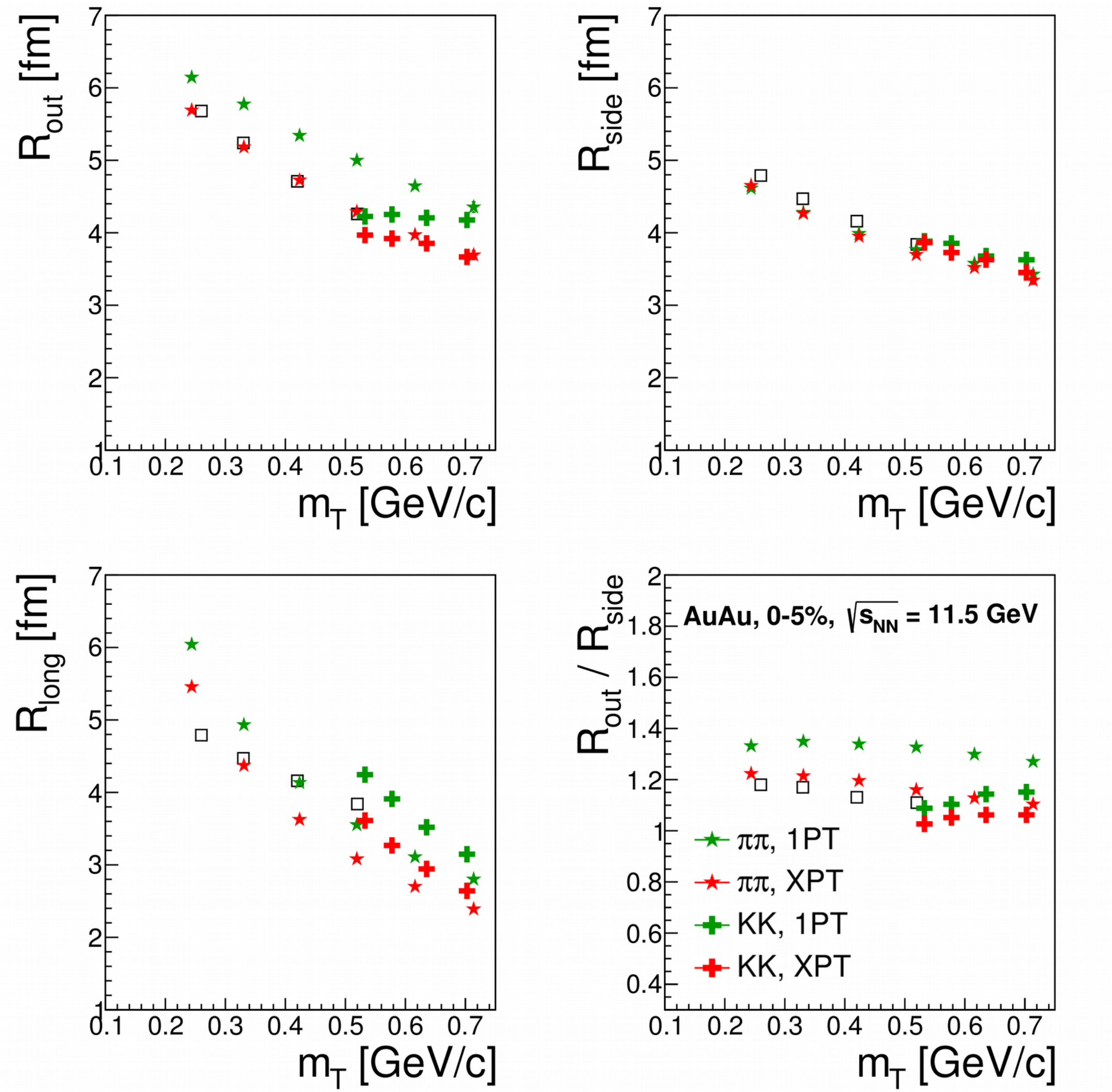




- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS describes better R(mT) dependencies, especially at low energies
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ∼1-2 fm.**
- R_{out} /R_{side} (XPT) agrees with almost all STAR data points , while R_{out} /R_{side} (1PT) overestimates the data.

Radii π and K vs. mT with vHLLE+UrQMD (11.5GeV)

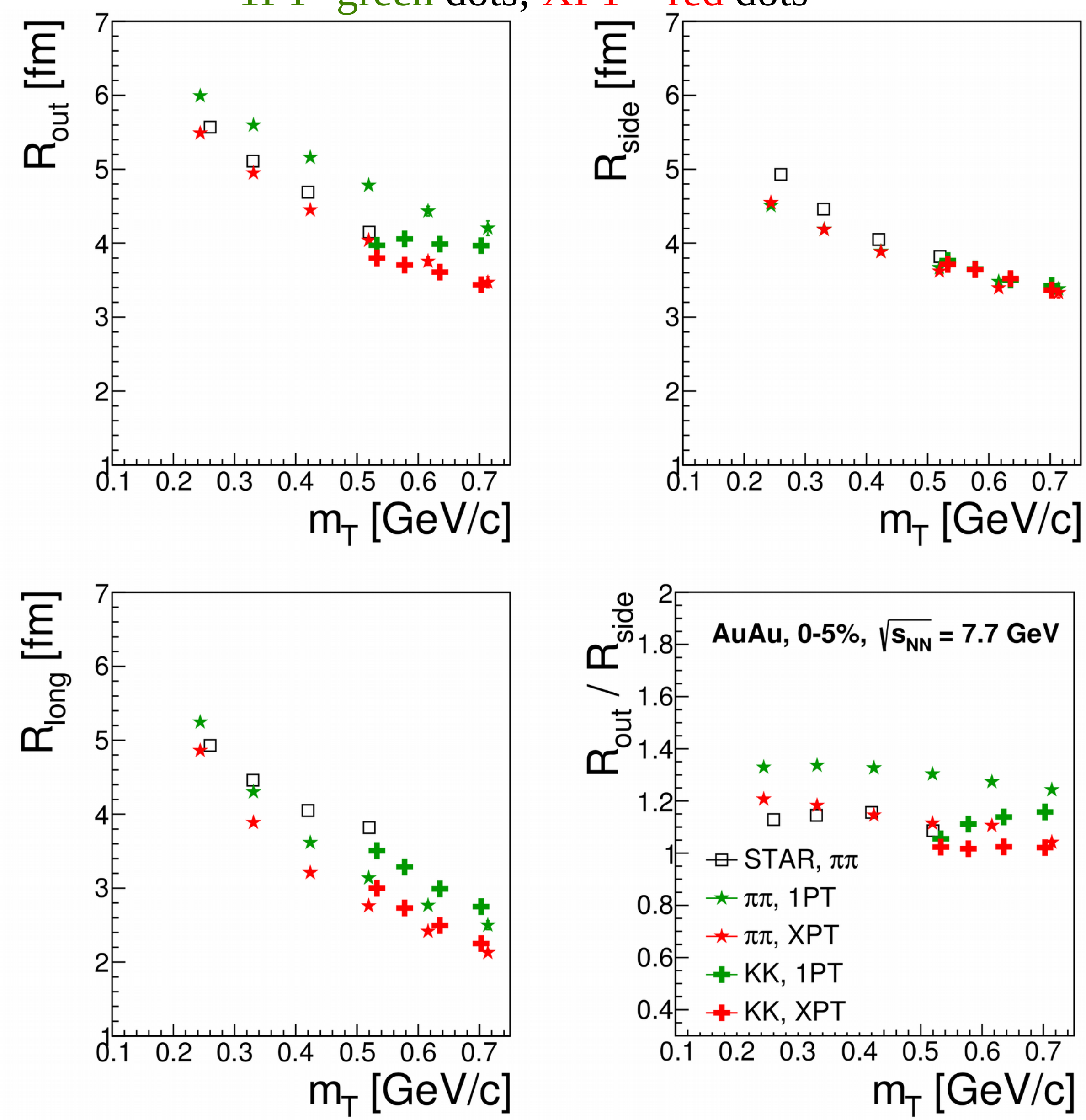
1PT -green dots; XPT – red dots



- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- 0-5% centrality
- As well as for π, kaon out and long radii greater for 1PT than for XPT
- Approximate m_T-scaling for pions and kaons observed only for “side” radii
- R_{out} almost flat for 1PT
- R_{long}(KK) is greater than R_{long}(ππ) kaons on average emitted later than pions
- Rout/Rside(KK) for kaons is less than for pions

Radii π and K vs. mT with vHLLE+UrQMD (7.7GeV)

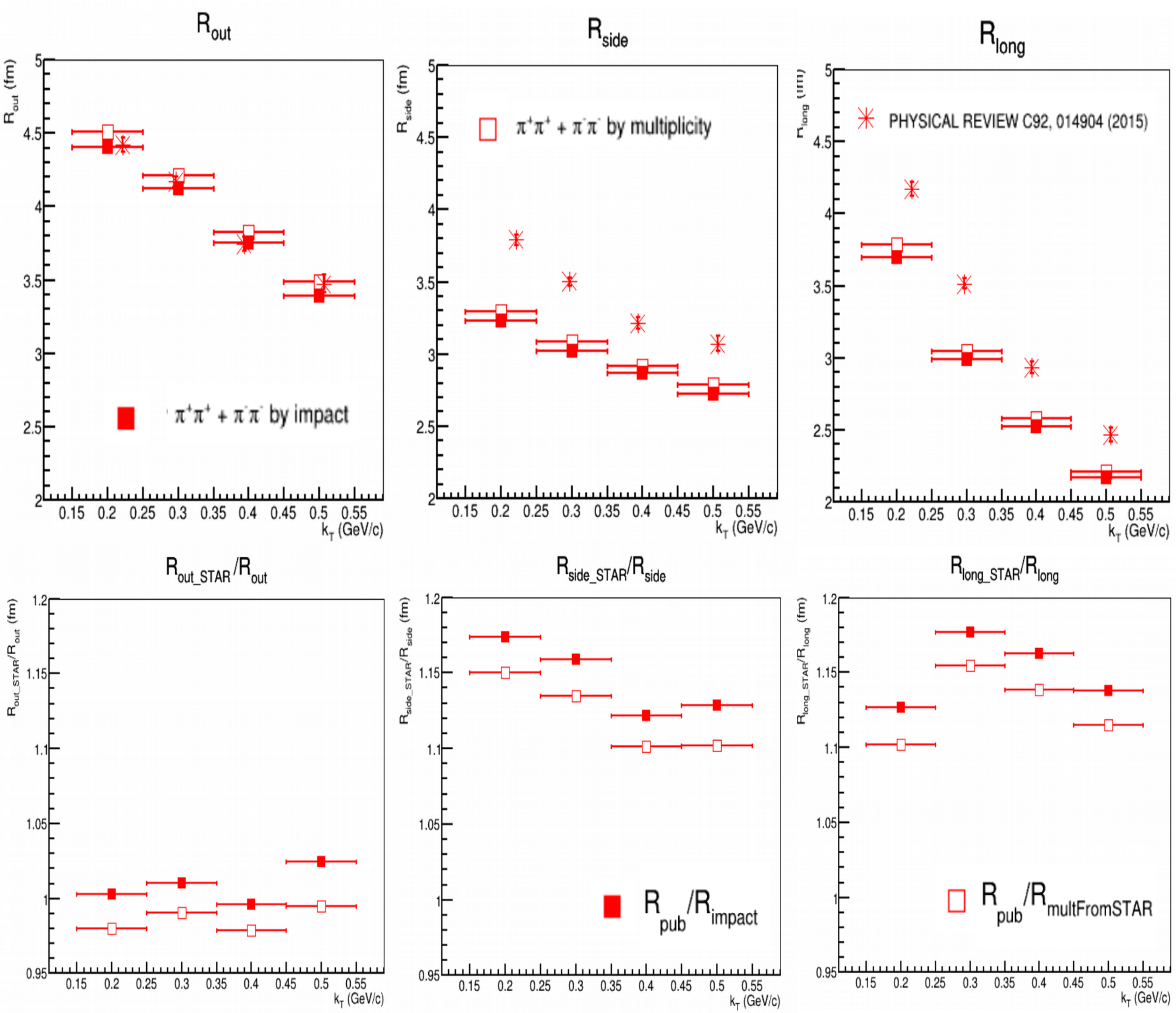
1PT -green dots; XPT – red dots



- AuAu, $\sqrt{s_{NN}}$ = 7.7 GeV
- 0-5% centrality
- **All as for 11.5 AGeV (slide 11) and model does not predict significant differences.**
- As well as for π kaon out and long radii greater for 1PT than for XPT
- Approximate m_T scaling for pions and kaons observed only for “side” radii
- It is important to measure both kaons and pions

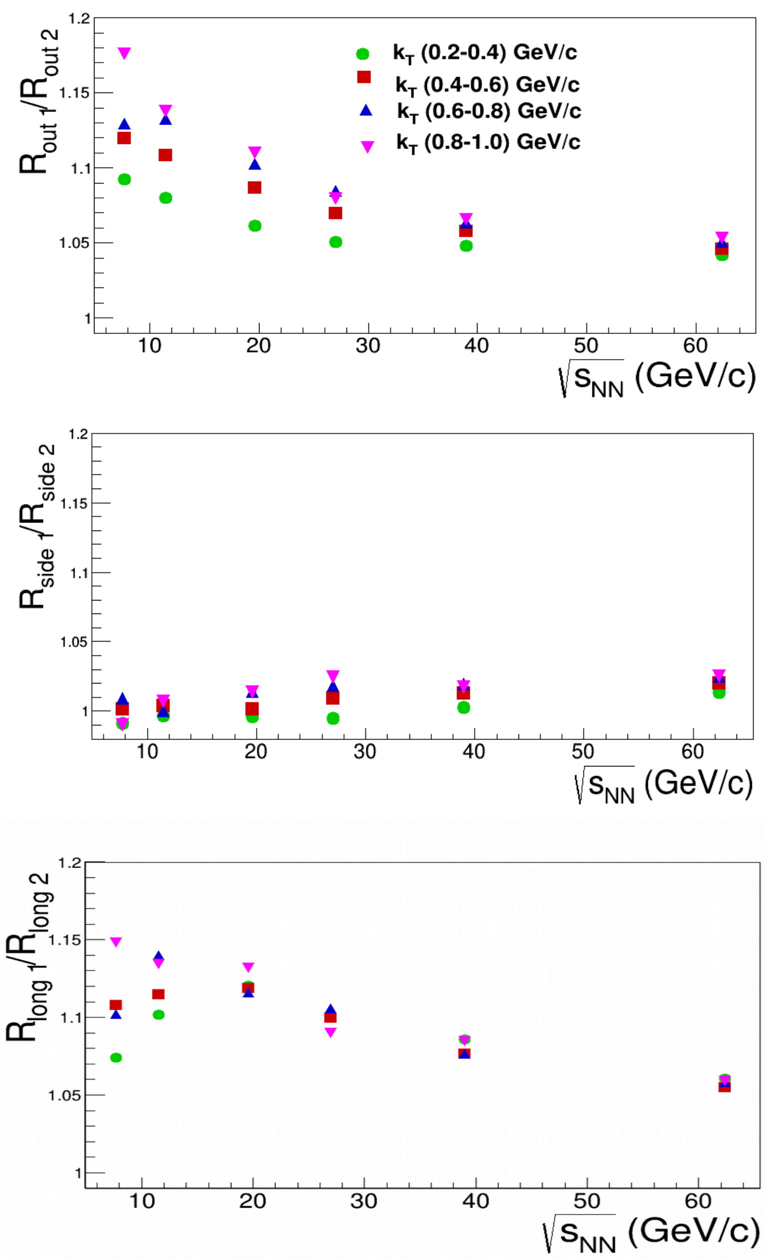
Pion R(kT) with UrQMD (7.7GeV)

- Analysis was performed using the MpdFemto package developed by our group



- Femtoscopic weigths were estimated using R. Lednicky codes incorporated in MpdFemto
- Centrality bin (20-30%) was estimated by:
  - Impact parameter: 6.6 — 8.1 fm (solid markers)
  - Reference multiplicity range (charged particles with pT > 0.1 GeV/c and η<0.5): 72 — 106 (open markers)
- Both centrality definitions give similar results (< 5% difference)
- Both agree with STAR data **PHYSYCAL REVIEW C92, 014904 (2015)**

Ratio of $R_{out,side,long}(1PT)/R_{out,side,long}(XPT)$ vs. $\sqrt{s_{NN}}$



- Pion k_T divided into 4 bins
- R_{side} ratio practically coincide for both scenarios
- R_{out} and R_{long} ratios for 1PT EoS are greater than for XPT EoS and demonstrating a strong k_T -dependence at low energy

- The difference comes from a weaker transverse flow developed in the fluid phase with 1PT EoS as compared to XPT EoS and its longer lifetime in 1PT EoS

-0.3–0.3

PT pt = 0.910758 Ro = 3.302278 +/- 0.083238 Rs = 3.115587 +/- 0.075613 Rl = 1.949938 +/- 0.053026 lambda = 0.861800 +/- 0.029641
---PT kt = 0.243885 Ro = 5.853203 +/- 0.012983 Rs = 4.526370 +/- 0.009281 Rl = 5.833690 +/- 0.012950 lambda = 0.658185 +/- 0.001811
---PT kt = 0.330877 Ro = 5.598684 +/- 0.014158 Rs = 4.195386 +/- 0.010687 Rl = 4.805280 +/- 0.013206 lambda = 0.708856 +/- 0.002439
---PT kt = 0.423651 Ro = 5.193342 +/- 0.018885 Rs = 3.922484 +/- 0.014245 Rl = 4.044926 +/- 0.015979 lambda = 0.751327 +/- 0.003731
---PT kt = 0.519114 Ro = 4.836977 +/- 0.026219 Rs = 3.690928 +/- 0.019877 Rl = 3.473926 +/- 0.020433 lambda = 0.780513 +/- 0.005787
---PT kt = 0.616019 Ro = 4.531916 +/- 0.037128 Rs = 3.536752 +/- 0.028458 Rl = 3.044261 +/- 0.027003 lambda = 0.804450 +/- 0.009016
---PT kt = 0.713779 Ro = 4.220105 +/- 0.052365 Rs = 3.437618 +/- 0.041513 Rl = 2.723916 +/- 0.036582 lambda = 0.825396 +/- 0.013981
---PT kt = 0.812084 Ro = 3.997510 +/- 0.075017 Rs = 3.289712 +/- 0.059044 Rl = 2.440464 +/- 0.048373 lambda = 0.844451 +/- 0.021316
---PT kt = 0.910758 Ro = 3.657446 +/- 0.104587 Rs = 3.214776 +/- 0.087869 Rl = 2.214615 +/- 0.067071 lambda = 0.839029 +/- 0.032464
---PT kt = 0.243885 Ro = 5.411381 +/- 0.013912 Rs = 4.563718 +/- 0.010675 Rl = 5.295265 +/- 0.013668 lambda = 0.656190 +/- 0.002073
---PT kt = 0.330877 Ro = 5.059964 +/- 0.014262 Rs = 4.203624 +/- 0.011842 Rl = 4.299572 +/- 0.013220 lambda = 0.704119 +/- 0.002692
---PT kt = 0.423651 Ro = 4.602196 +/- 0.017958 Rs = 3.910818 +/- 0.015146 Rl = 3.577279 +/- 0.015007 lambda = 0.744026 +/- 0.003955
---PT kt = 0.519114 Ro = 4.238570 +/- 0.023966 Rs = 3.675051 +/- 0.020513 Rl = 3.061379 +/- 0.018277 lambda = 0.776345 +/- 0.005963
---PT kt = 0.616019 Ro = 3.938548 +/- 0.032299 Rs = 3.486268 +/- 0.028082 Rl = 2.671821 +/- 0.023823 lambda = 0.800573 +/- 0.008929
---PT kt = 0.713779 Ro = 3.667737 +/- 0.044284 Rs = 3.348105 +/- 0.039276 Rl = 2.334432 +/- 0.029975 lambda = 0.810706 +/- 0.013239
---PT kt = 0.812084 Ro = 3.425650 +/- 0.060489 Rs = 3.233699 +/- 0.055566 Rl = 2.146808 +/- 0.040374 lambda = 0.835272 +/- 0.020103
---PT kt = 0.910758 Ro = 3.302278 +/- 0.083238 Rs = 3.115587 +/- 0.075613 Rl = 1.949938 +/- 0.053026 lambda = 0.861800 +/- 0.029641

-0.3–0.3

1PT pt = 0.910758 Ro = 3.360135 +/- 0.084346 Rs = 3.162874 +/- 0.076645 Rl = 1.987813 +/- 0.053820 lambda = 0.870050 +/- 0.029926
---PT kt = 0.243885 Ro = 5.850547 +/- 0.012821 Rs = 4.524329 +/- 0.009246 Rl = 5.830706 +/- 0.012766 lambda = 0.658011 +/- 0.001773
---PT kt = 0.330877 Ro = 1.000000 +/- 0.000000 Rs = 1.000000 +/- 0.000000 Rl = 1.000000 +/- 0.000000 lambda = 1.200000 +/- 0.000000
---PT kt = 0.423651 Ro = 5.192562 +/- 0.018849 Rs = 3.921940 +/- 0.014221 Rl = 4.044249 +/- 0.015947 lambda = 0.751256 +/- 0.003729
---PT kt = 0.519114 Ro = 4.837971 +/- 0.026163 Rs = 3.691619 +/- 0.019842 Rl = 3.474721 +/- 0.020388 lambda = 0.780612 +/- 0.005785
---PT kt = 0.616019 Ro = 4.535630 +/- 0.037050 Rs = 3.539349 +/- 0.028411 Rl = 3.047022 +/- 0.026943 lambda = 0.804851 +/- 0.009014
---PT kt = 0.713779 Ro = 4.228637 +/- 0.052281 Rs = 3.443672 +/- 0.041474 Rl = 2.730012 +/- 0.036524 lambda = 0.826396 +/- 0.013986
---PT kt = 0.812084 Ro = 4.016945 +/- 0.075048 Rs = 3.303330 +/- 0.059126 Rl = 2.453023 +/- 0.048417 lambda = 0.846782 +/- 0.021353
---PT kt = 0.910758 Ro = 3.723361 +/- 0.106028 Rs = 3.264411 +/- 0.089212 Rl = 2.257075 +/- 0.068092 lambda = 0.847838 +/- 0.032777
---PT kt = 0.243885 Ro = 5.408008 +/- 0.013875 Rs = 4.560913 +/- 0.010642 Rl = 5.291495 +/- 0.013622 lambda = 0.655946 +/- 0.002071
---PT kt = 0.330877 Ro = 5.048172 +/- 0.014196 Rs = 4.194477 +/- 0.011789 Rl = 4.288460 +/- 0.013156 lambda = 0.703066 +/- 0.002686
---PT kt = 0.423651 Ro = 4.602145 +/- 0.017966 Rs = 3.910777 +/- 0.015079 Rl = 3.577236 +/- 0.015167 lambda = 0.744021 +/- 0.003954
---PT kt = 0.519114 Ro = 4.238437 +/- 0.023832 Rs = 3.674946 +/- 0.020457 Rl = 3.061273 +/- 0.018606 lambda = 0.776330 +/- 0.005960
---PT kt = 0.616019 Ro = 3.939678 +/- 0.032177 Rs = 3.487171 +/- 0.027996 Rl = 2.672666 +/- 0.023699 lambda = 0.800714 +/- 0.008924
---PT kt = 0.713779 Ro = 3.676295 +/- 0.044161 Rs = 3.354970 +/- 0.039200 Rl = 2.340260 +/- 0.029899 lambda = 0.811838 +/- 0.013243
---PT kt = 0.812084 Ro = 3.451959 +/- 0.060611 Rs = 3.255637 +/- 0.055731 Rl = 2.164562 +/- 0.040470 lambda = 0.839209 +/- 0.020172
---PT kt = 0.910758 Ro = 3.360135 +/- 0.084346 Rs = 3.162874 +/- 0.076645 Rl = 1.987813 +/- 0.053820 lambda = 0.870050 +/- 0.029926