

Emission asymmetry seen by the femtoscopy

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of Physics**

WARSAW UNIVERSITY OF TECHNOLOGY

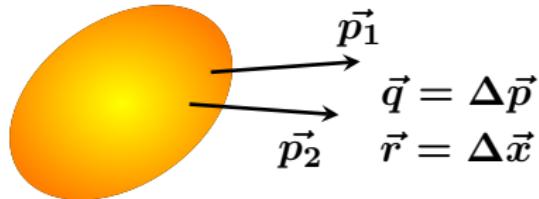


NATIONAL SCIENCE CENTRE
POLAND

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Budapest, Hungary, December 6 - 10, 2021

Femtoscopy

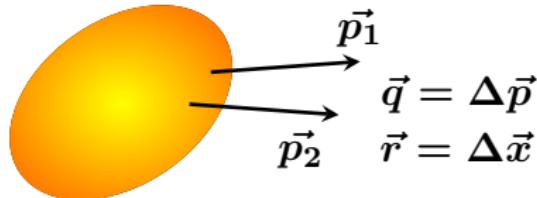


Impossible to examine the particle emitting source directly

size $\sim 10^{-15}$ m
life time $\sim 10^{-23}$ s

Femtoscopy measures space-time characteristics of the source through momentum correlations

Femtoscopy



$$C(\vec{p}_1, \vec{p}_2) = \frac{P_{12}(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P'_1(\vec{p}_2)}$$

experiment

theory (models)

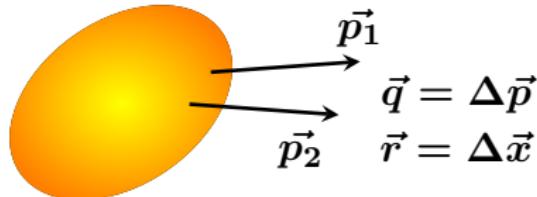
$$C(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}$$

$$C(\vec{q}) = \int d^3r S(\vec{q}) |\Psi(\vec{q}, \vec{r})|^2$$

$A(\vec{q})$ - correlated
 $B(\vec{q})$ - uncorrelated

$S(\vec{q})$ - source function
 $\Psi(\vec{q}, \vec{r})$ - pair wave function

Femtoscopy



$$C(\vec{p}_1, \vec{p}_2) = \frac{P_{12}(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P'_1(\vec{p}_2)}$$

experiment

$$C(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}$$

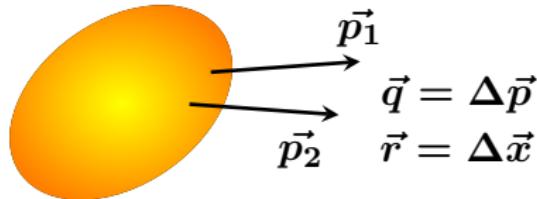
theory (models)

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Femtoscopy



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theory (models)

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Theoretical Models

THERMINATOR 2

- Generates collisions of relativistic ions
- Implements thermal models of particle production with single freeze-out
- Adapted Blast-Wave model for BES energies

***THERMINATOR 2: THERMal heavy
IoN generATOR 2***

Comput.Phys.Commun. 174 (2006) 669-687
M. Chojnacki, A. Kisiel, W. Florkowski,
W. Broniowski

*Adaptation of the terminator model for
BES program*

Proc.SPIE 11581 (2020) 1158104,
H. Zbroszczyk

UrQMD

Microscopic transport theory based on the covariant propagation of all hadrons on classical trajectories in combination with:

- Stochastic binary scatterings
- Color string formation
- Resonance decay

Relativistic Hadron-Hadron Collisions in the Ultra-Relativistic Quantum Molecular Dynamics Model (UrQMD)

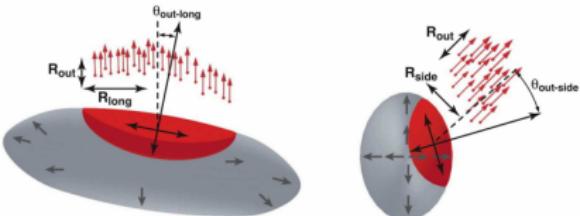
J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859,
M. Bleicher *et al*

Emission asymmetries

Collective behavior

– **radial flow** in the transverse plane:

matter is collectively moving "outward"
from the central axis of the source
to the outside



Ann. Rev. Nucl. Part. Sci. 55, 357 (2005)

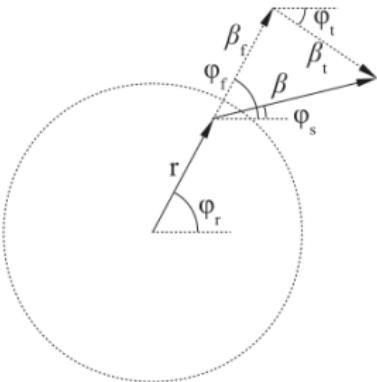
Emission asymmetries

Collective behavior

- **radial flow** in the transverse plane:
matter is collectively moving "outward"
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β_f - flow velocity

β_t - thermal velocity (with random direction)



*Nonidentical-particle femtoscopy at $\sqrt{s_{NN}} = 200 \text{ GeV}$
in hydrodynamics with statistical hadronization*, A. Kisiel

Space-momentum ($x\text{-}p$) correlation:

direction ϕ_f of transverse velocity is aligned with transverse position vector direction ϕ_r

Emission asymmetries

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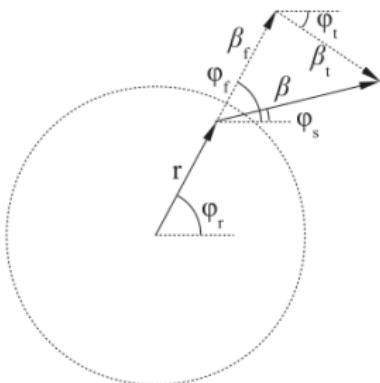
β_f - flow velocity

β_t - thermal velocity (with random direction)

The thermal component has
a smaller impact on heavier particles

*Nonidentical-particle femtoscopy at $\sqrt{s_{NN}} = 200 \text{ GeV}$
in hydrodynamics with statistical hadronization*, A. Kisiel

The final velocity direction of lighter particles, on average,
is less correlated with emission points than that of heavier particles



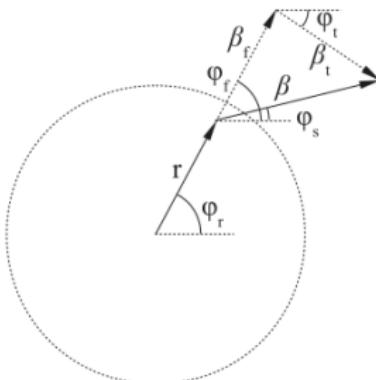
Emission asymmetries

Collective behavior

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from the central axis of the source
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β_f - flow velocity

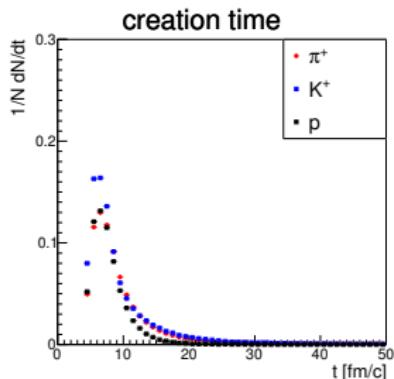
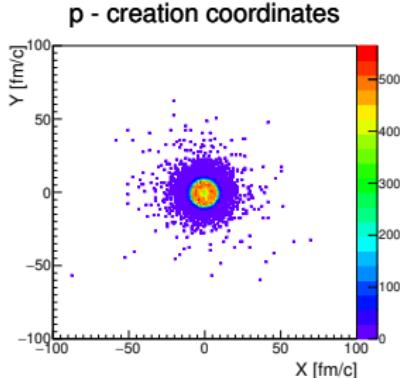
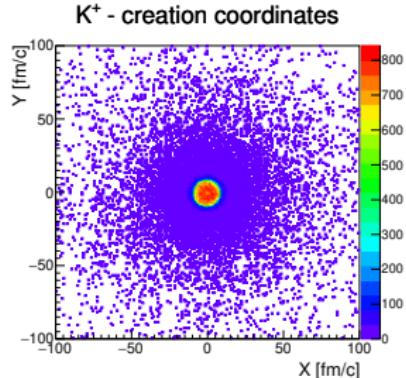
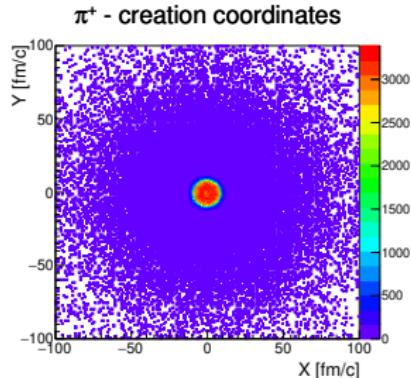
β_t - thermal velocity (with random direction)



*Nonidentical-particle femtoscopy at $\sqrt{s_{NN}} = 200 \text{ GeV}$
in hydrodynamics with statistical hadronization*, A. Kisiel

Emission asymmetry arises in a system where both thermal and collective velocities exist and are comparable in magnitude

XY coordinates of creation (all particles)

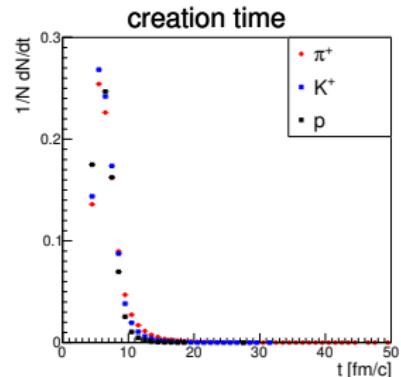
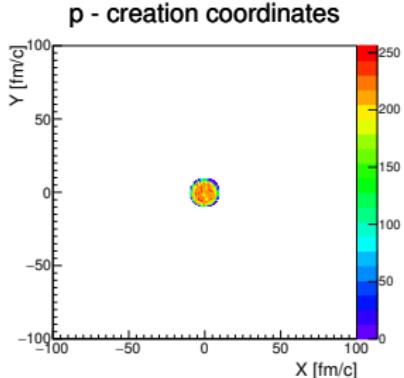
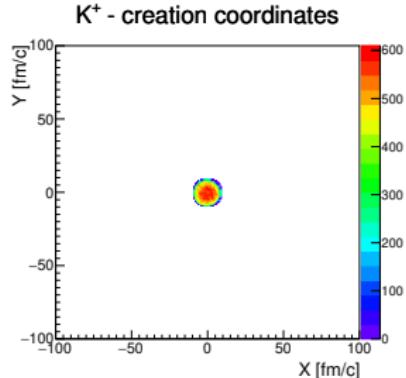
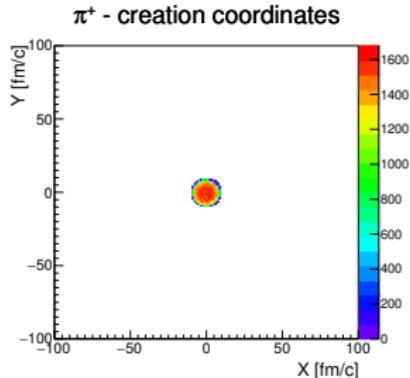


$$\begin{aligned}\langle t_\pi \rangle &= 9.98 \text{ fm/c} \\ \langle t_K \rangle &= 10.61 \text{ fm/c} \\ \langle t_p \rangle &= 7.97 \text{ fm/c}\end{aligned}$$

$$\begin{aligned}\langle x_\pi \rangle &= 0.00 \text{ fm/c} & \langle y_\pi \rangle &= -0.01 \text{ fm/c} \\ \langle x_K \rangle &= 0.05 \text{ fm/c} & \langle y_K \rangle &= -0.01 \text{ fm/c} \\ \langle x_p \rangle &= -0.03 \text{ fm/c} & \langle y_p \rangle &= 0.03 \text{ fm/c}\end{aligned}$$

Terminator 2, 39 GeV

XY coordinates of creation (primary particles)



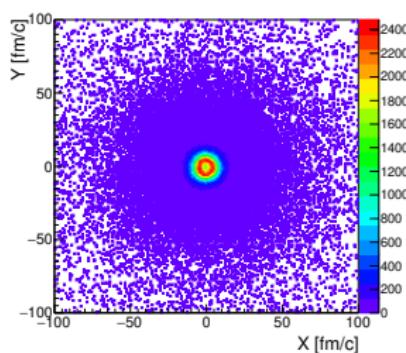
$$\begin{aligned}\langle t_\pi \rangle &= 7.01 \text{ fm/c} \\ \langle t_K \rangle &= 6.67 \text{ fm/c} \\ \langle t_p \rangle &= 6.33 \text{ fm/c}\end{aligned}$$

$$\begin{aligned}\langle x_\pi \rangle &= 0.00 \text{ fm/c} & \langle y_\pi \rangle &= 0.00 \text{ fm/c} \\ \langle x_K \rangle &= 0.03 \text{ fm/c} & \langle y_K \rangle &= -0.02 \text{ fm/c} \\ \langle x_p \rangle &= -0.01 \text{ fm/c} & \langle y_p \rangle &= 0.01 \text{ fm/c}\end{aligned}$$

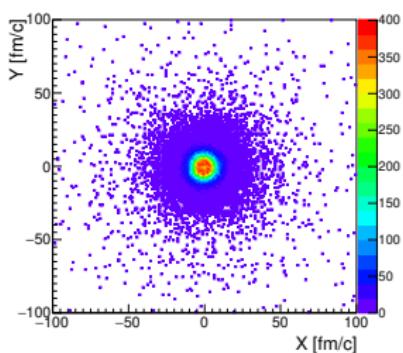
Terminator 2, 39 GeV

XY coordinates of freeze-out (all particles)

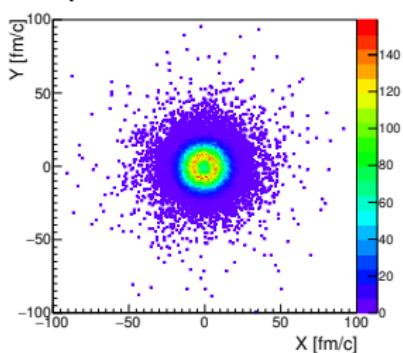
π^+ - creation coordinates



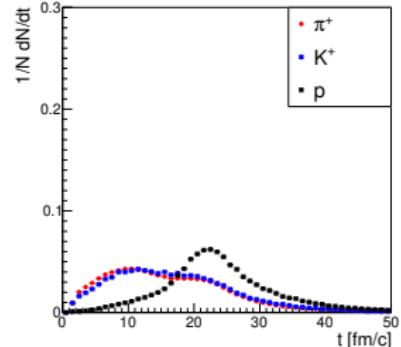
K^+ - creation coordinates



p - creation coordinates



creation time



$$\begin{aligned}\langle t_\pi \rangle &= 16.33 \text{ fm/c} \\ \langle t_K \rangle &= 18.11 \text{ fm/c} \\ \langle t_p \rangle &= 24.78 \text{ fm/c}\end{aligned}$$

$$\begin{aligned}\langle x_\pi \rangle &= 0.01 \text{ fm} \\ \langle x_K \rangle &= -0.02 \text{ fm} \\ \langle x_p \rangle &= 0.01 \text{ fm}\end{aligned}$$

$$\begin{aligned}\langle y_\pi \rangle &= -0.01 \text{ fm} \\ \langle y_K \rangle &= -0.01 \text{ fm} \\ \langle y_p \rangle &= 0.01 \text{ fm}\end{aligned}$$

UrQMD, 39 GeV

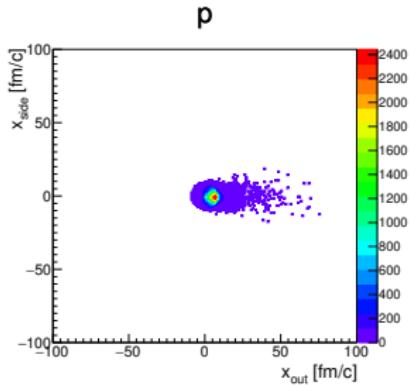
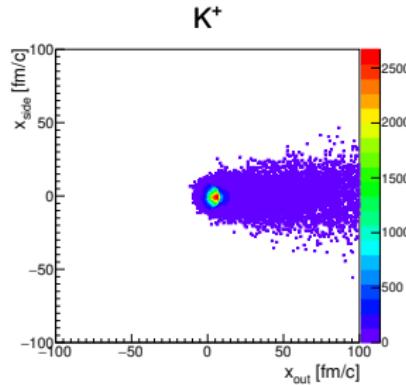
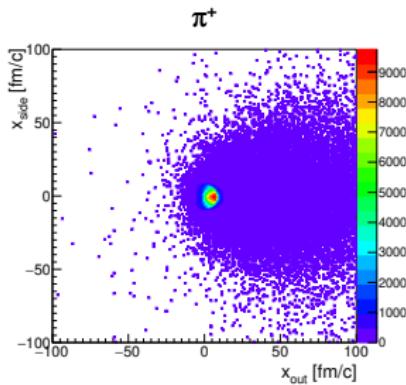
Change of particle frame

- x_{out} — parallel to particle transverse momentum
- x_{side} — perpendicular to particle transverse momentum
- z — no change

Rotate emission vector \vec{x} by momentum \vec{p} azimuth angle:

```
TLorentzVector X(Particle.x ,Particle.y, Particle.z, Particle.t);  
TLorentzVector P(Particle.px ,Particle.py, Particle.pz, Particle.e);  
X.RotateZ(-P.Phi());
```

x_{out} - x_{side} coordinates of creation (all particles)



$$\langle x_\pi \rangle = 6.37$$

$$\langle x_K \rangle = 6.88$$

$$\langle x_p \rangle = 5.75$$

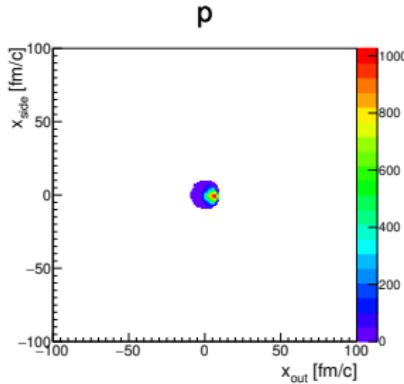
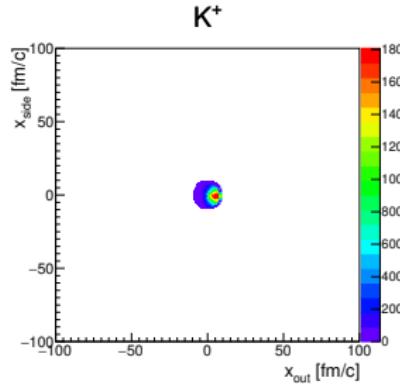
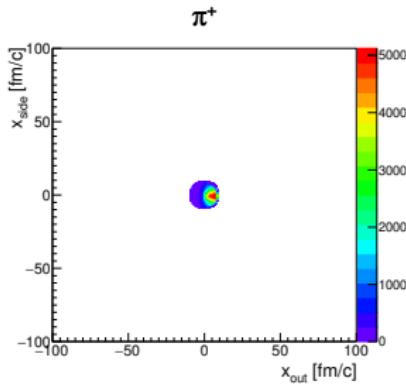
$$\langle y_\pi \rangle = -0.01$$

$$\langle y_K \rangle = 0.01$$

$$\langle y_p \rangle = 0.00$$

Therminator 2, 39 GeV

x_{out} - x_{side} coordinates of creation (primary particles)



$$\langle x_\pi \rangle = 4.03$$

$$\langle x_K \rangle = 4.04$$

$$\langle x_p \rangle = 4.69$$

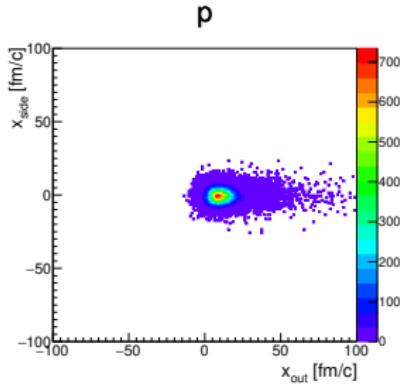
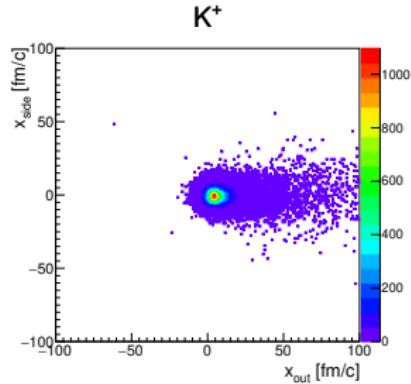
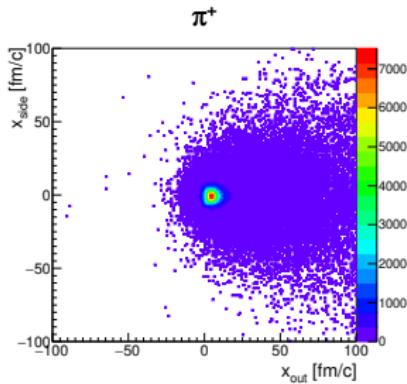
$$\langle y_\pi \rangle = 0.01$$

$$\langle y_K \rangle = 0.00$$

$$\langle y_p \rangle = 0.01$$

Therminator 2, 39 GeV

x_{out} - x_{side} coordinates of creation (all particles)



$$\langle x_\pi \rangle = 7.76$$

$$\langle x_K \rangle = 7.66$$

$$\langle x_p \rangle = 11.47$$

$$\langle y_\pi \rangle = -0.01$$

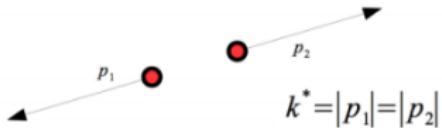
$$\langle y_K \rangle = 0.00$$

$$\langle y_p \rangle = -0.01$$

UrQMD, 39 GeV

Reference frame

Pair Rest Frame (PRF)

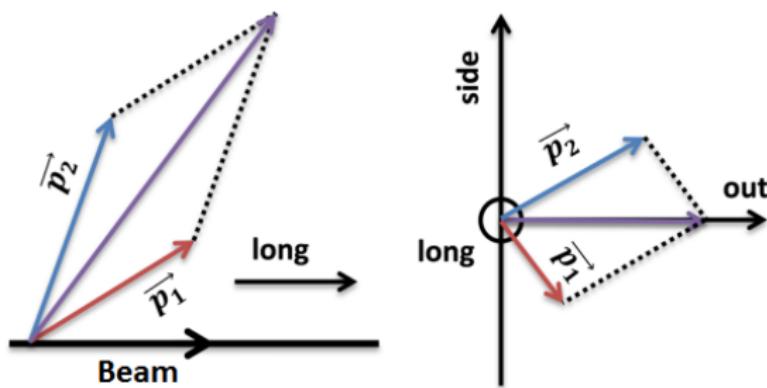


$$k_T = \frac{|p_{T,1} + p_{T,2}|}{2}$$

Longitudinally Co-Moving System (LCMS)

G. Bertsch, et al.
Phys. Rev. C37, 1896, (1988)

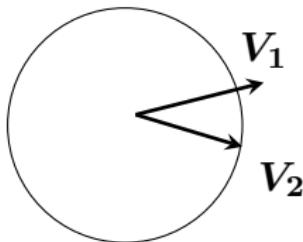
S. Pratt.
Phys. Rev. D33, 1314 (1986)



Non-identical particle combinations

Time asymmetry

$$t_1 \neq t_2 \\ \Delta r = 0$$



$t_1 > t_2$ - Catching up
 $t_1 < t_2$ - Run away

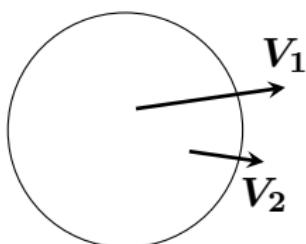
t — emission time

r — emission point distance from the center

R. Lednicky, et al.,
Phys. Lett. B373,
30-34 (1996)

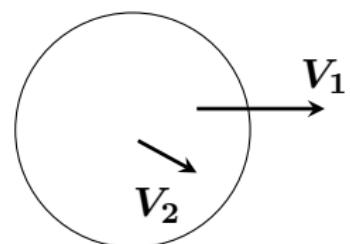
Space asymmetry

$$t_1 = t_2 \\ \Delta r \neq 0$$



Catching up

$$t_1 = t_2 \\ \Delta r \neq 0$$



Run away

Catching up
longer interaction,
strong correlation

Running away
shorter interaction,
weaker correlation

Non-identical particle combinations — femtoscopy

CFs are calculated in two groups of pairs:

- $C_+(k^*)$ — pions catch up with kaons
 - $C_-(k^*)$ — pions move away from kaons
-

C_+ shows a larger deviation from unity than $C_- \rightarrow$ pions and kaons are not emitted at the same place and/or time

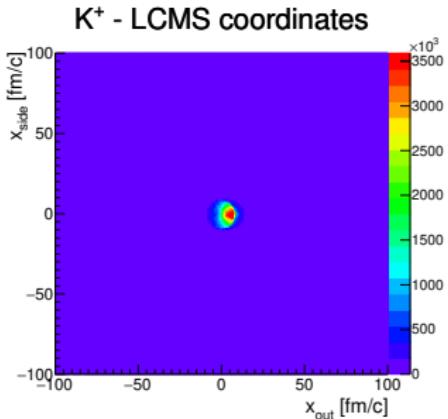
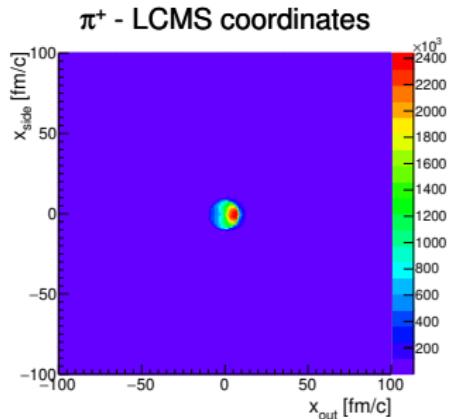
C_+ and C_- are identical \rightarrow the average space-time emission points of pions and kaons

π^+K^+ @ 39 GeV, Therminator 2

All particles

$$\langle x_{out}^\pi \rangle = 3.64$$

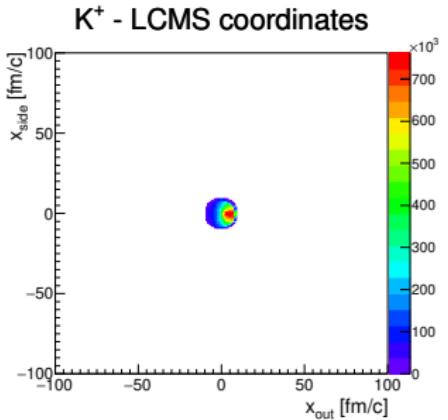
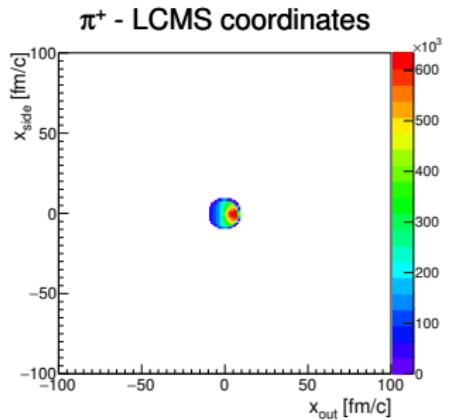
$$\langle x_{out}^K \rangle = 6.88$$



Primary particles

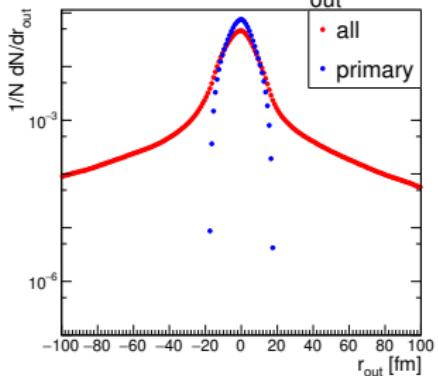
$$\langle x_{out}^\pi \rangle = 2.32$$

$$\langle x_{out}^K \rangle = 2.89$$



π^+K^+ @ 39 GeV, Therminator 2

LCMS space (r_{out})



All particles

$$\langle r_{out} \rangle = -1.11$$

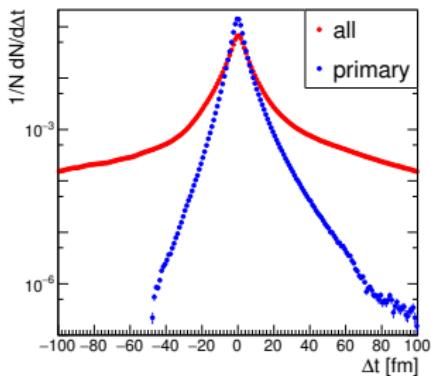
$$\langle \Delta t \rangle = 0.47$$

Primary particles

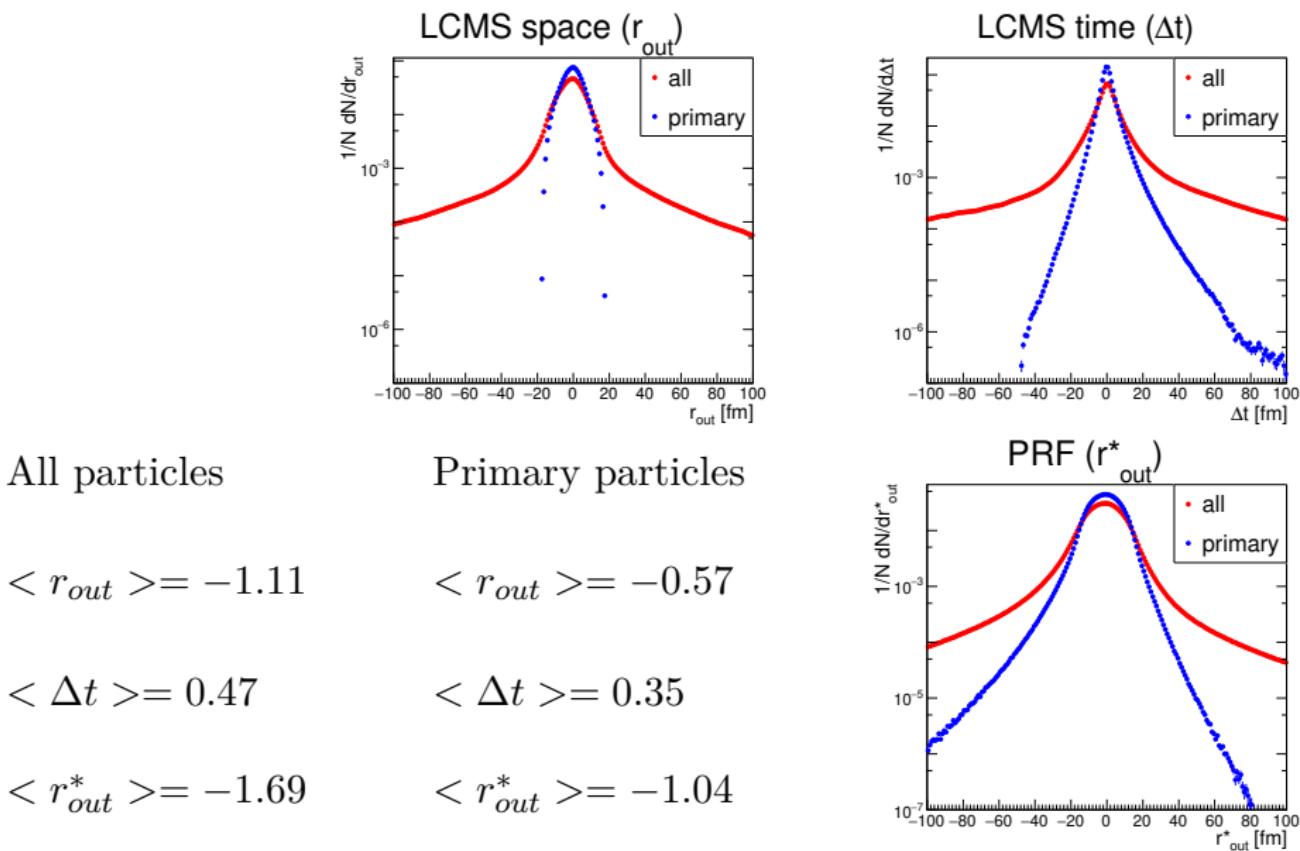
$$\langle r_{out} \rangle = -0.57$$

$$\langle \Delta t \rangle = 0.35$$

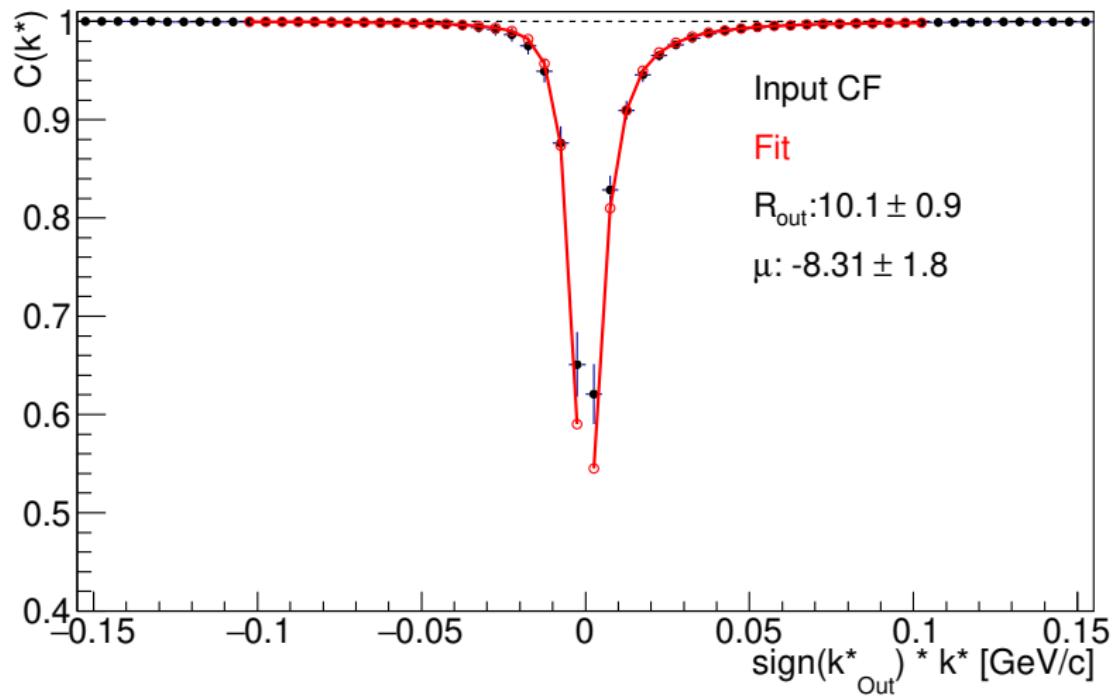
LCMS time (Δt)



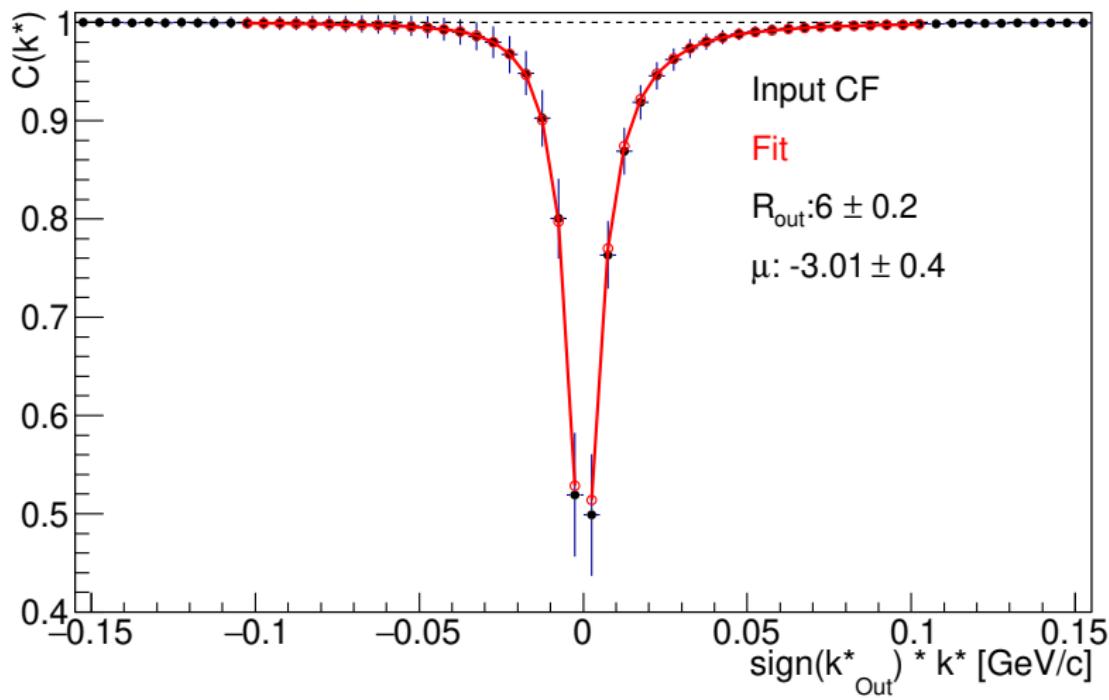
π^+K^+ @ 39 GeV, Therminator 2



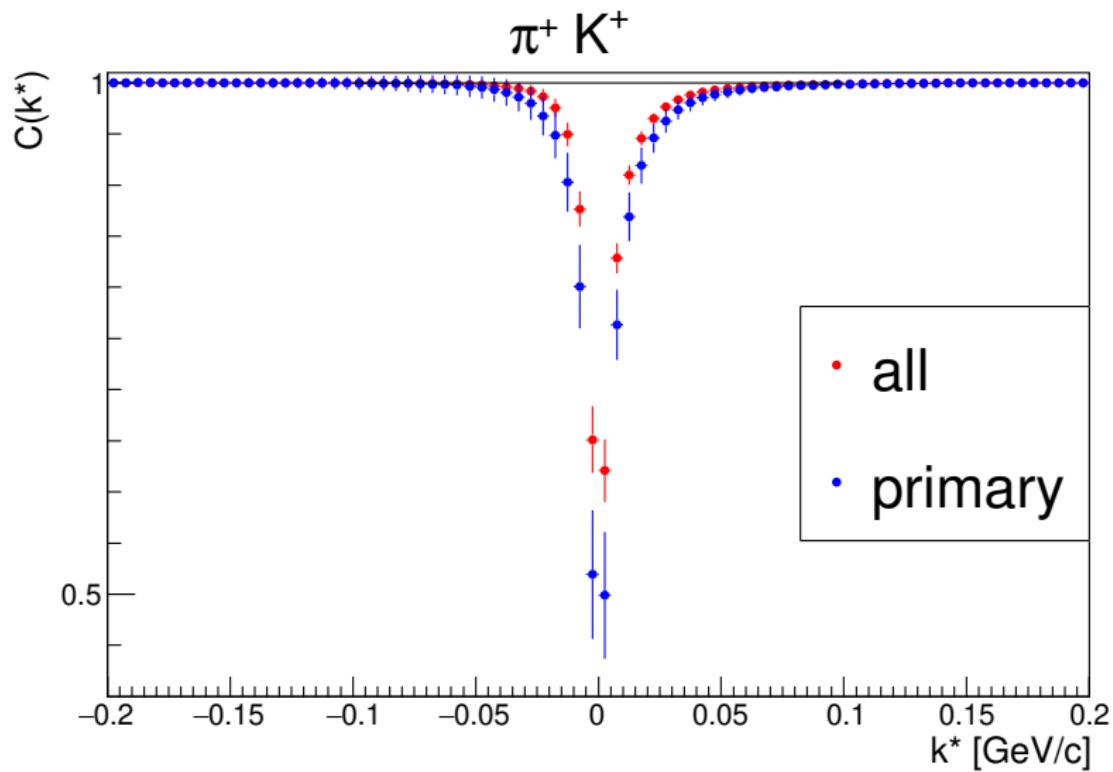
All particles, Therminator 2



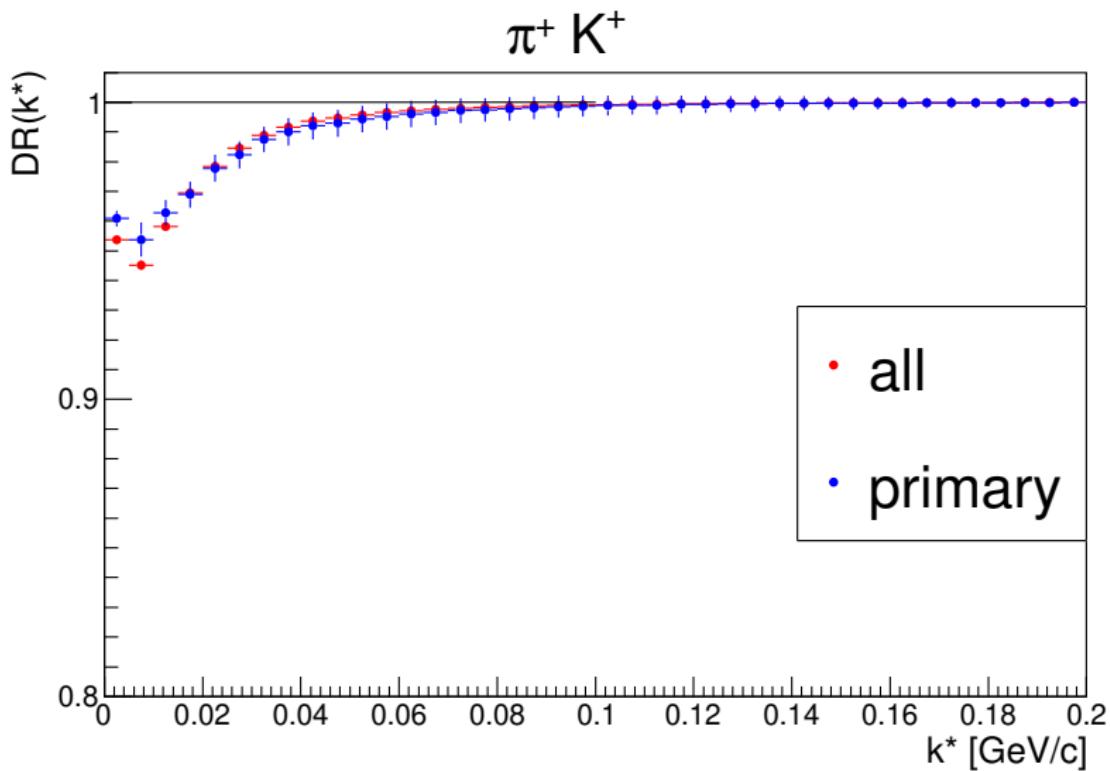
Primary particles, Therminator 2



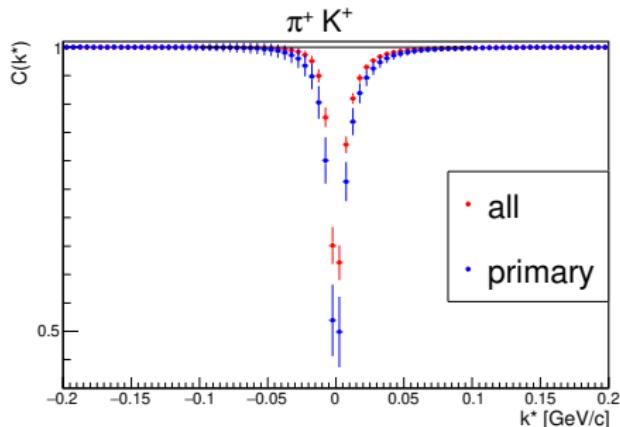
$\pi^+ K^+$ femtoscopy @ 39 GeV, Therminator 2



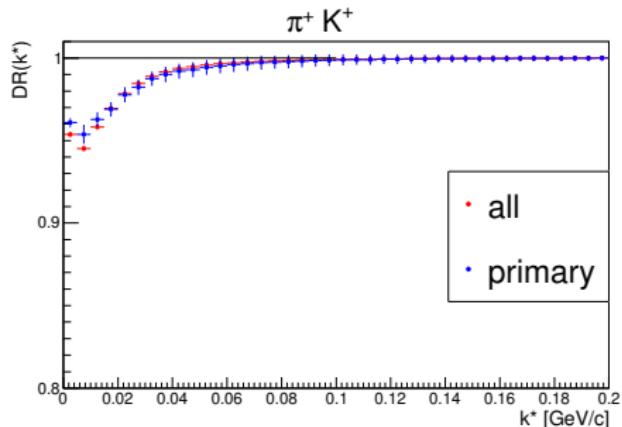
$\pi^+ K^+$ femtoscopy @ 39 GeV, Therminator 2



$\pi^+ K^+$ femtoscopy @ 39 GeV, Therminator 2



All particles



Primary particles

$$R_{out} = 10.1 \pm 0.9 \text{ fm}$$
$$\mu = -8.3 \pm 1.8 \text{ fm}$$

$$R_{out} = 6.0 \pm 0.2 \text{ fm}$$
$$\mu = -3.0 \pm 0.4 \text{ fm}$$

Summary

- Emission asymmetry is seen by theoretical models (Terminator 2, UrQMD)
- Asymmetry is enhanced by particles coming from decays
 - ▶ decays are not the only source of such asymmetry
 - ▶ **main source** is collective behavior

More in: **Nonidentical-particle femtoscopy at $\sqrt{s_{NN}} = 200\text{GeV}$ in hydrodynamics with statistical hadronization, A. Kisiel**

Summary

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More in: **Nonidentical-particle femtoscopy at $\sqrt{s_{NN}} = 200\text{GeV}$ in hydrodynamics with statistical hadronization, A. Kisiel**

Thank you for your attention!

BACKUP

All particles, Therminator 2 @ 39 GeV, 0-5 % centrality

		x_{out} [fm/c]	r_{out} [fm/c]	Δt [fm/c]	r_{out}^* [fm/c]
$\pi^+ K^+$	π^+	3.64	-1.11	0.47	-1.69
	K^+	5.00			
$\pi^+ p$	π^+	2.45	-2.49	3.50	-5.70
	p	5.00			
$K^+ p$	K^+	3.11	-1.56	2.79	-3.82
	p	4.70			

Primary particles, Therminator 2 @ 39 GeV, 0-5 % centrality

		x_{out} [fm/c]	r_{out} [fm/c]	Δt [fm/c]	r_{out}^* [fm/c]
$\pi^+ K^+$	π^+	2.31	-0.57	0.36	-1.04
	K^+	2.89			
$\pi^+ p$	π^+	1.57	-2.44	0.72	-3.61
	p	4.00			
$K^+ p$	K^+	1.85	-1.95	0.36	-2.56
	p	3.81			

Therminator 2

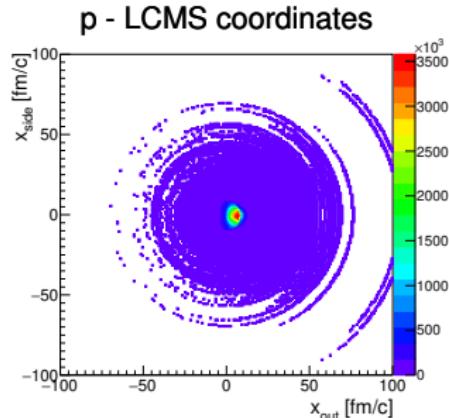
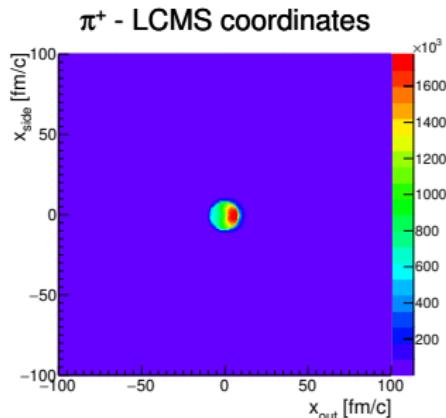
$\pi^+ p$ @ 39 GeV

$\pi^+ p$, Therminator 2

All particles

$$\langle x_{out}^\pi \rangle = 2.45$$

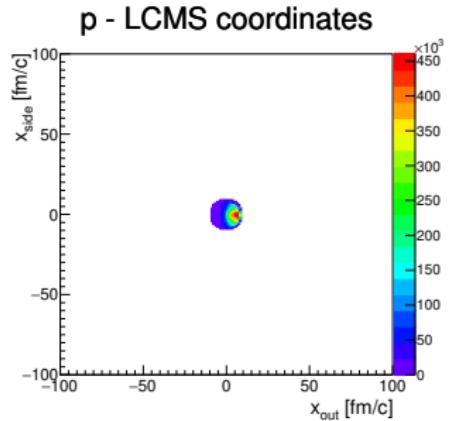
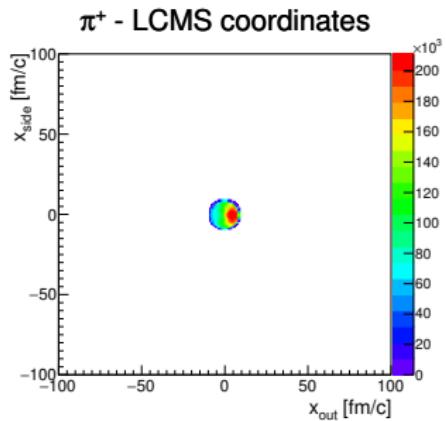
$$\langle x_{out}^p \rangle = 5.00$$



Primary particles

$$\langle x_{out}^\pi \rangle = 1.57$$

$$\langle x_{out}^p \rangle = 4.01$$



All particles

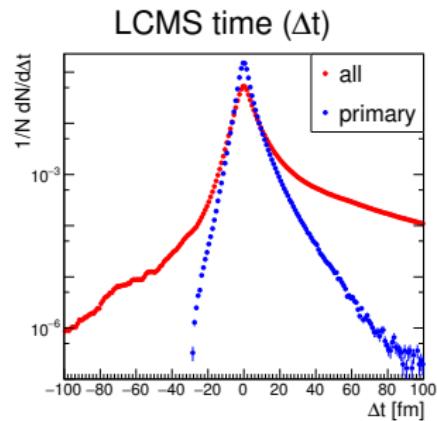
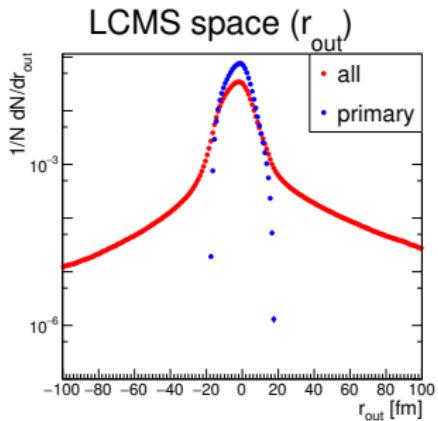
$$\langle r_{out} \rangle = -2.49$$

$$\langle \Delta t \rangle = 3.50$$

Primary particles

$$\langle r_{out} \rangle = -2.44$$

$$\langle \Delta t \rangle = 0.72$$



$\pi^+ p$

All particles

$$\langle r_{out} \rangle = -2.49$$

$$\langle \Delta t \rangle = 3.50$$

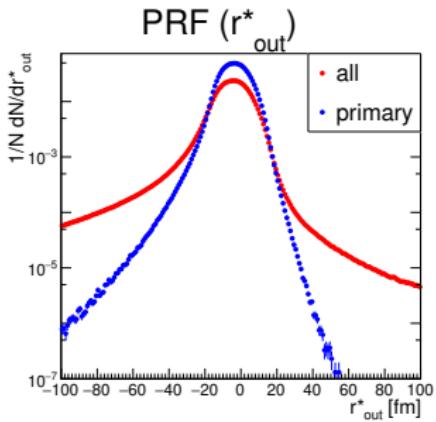
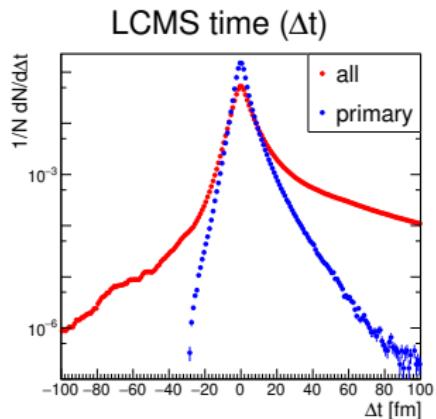
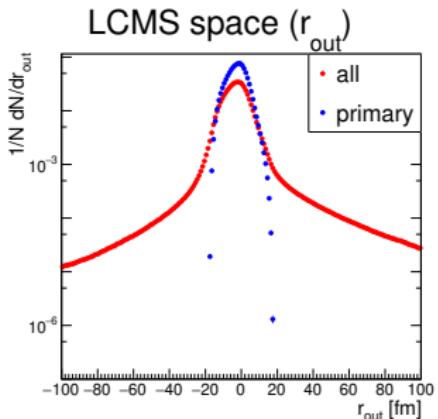
$$\langle r_{out}^* \rangle = -5.70$$

Primary particles

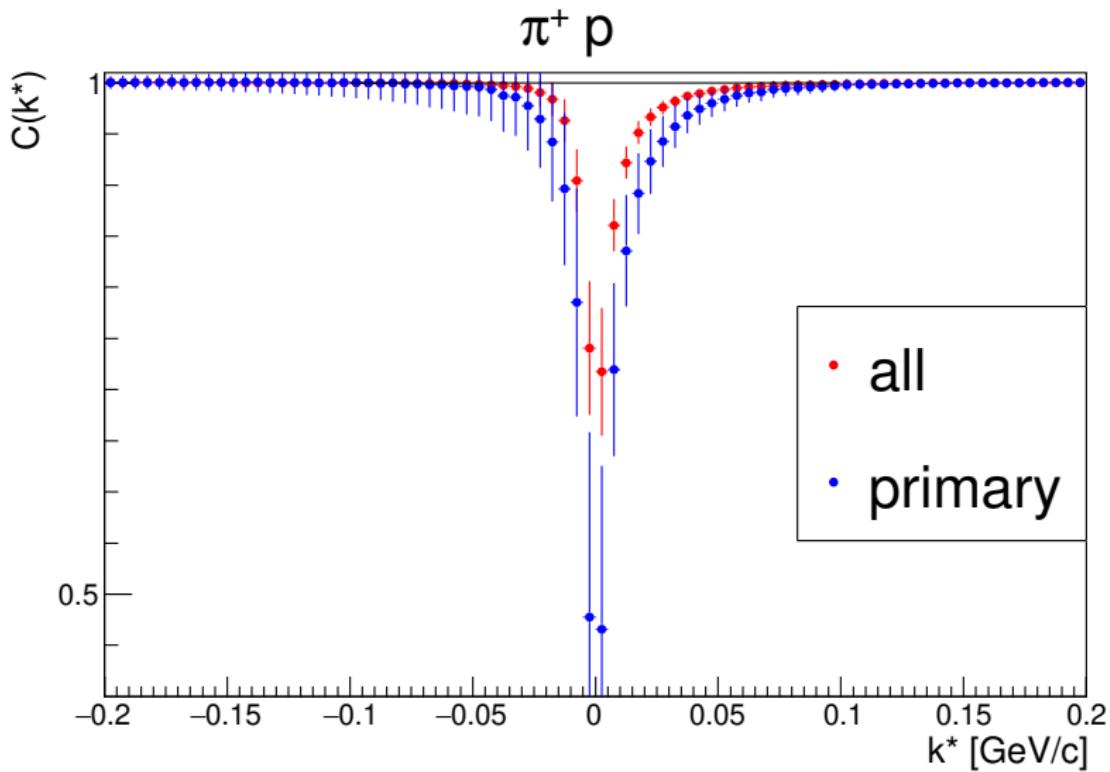
$$\langle r_{out} \rangle = -2.44$$

$$\langle \Delta t \rangle = 0.72$$

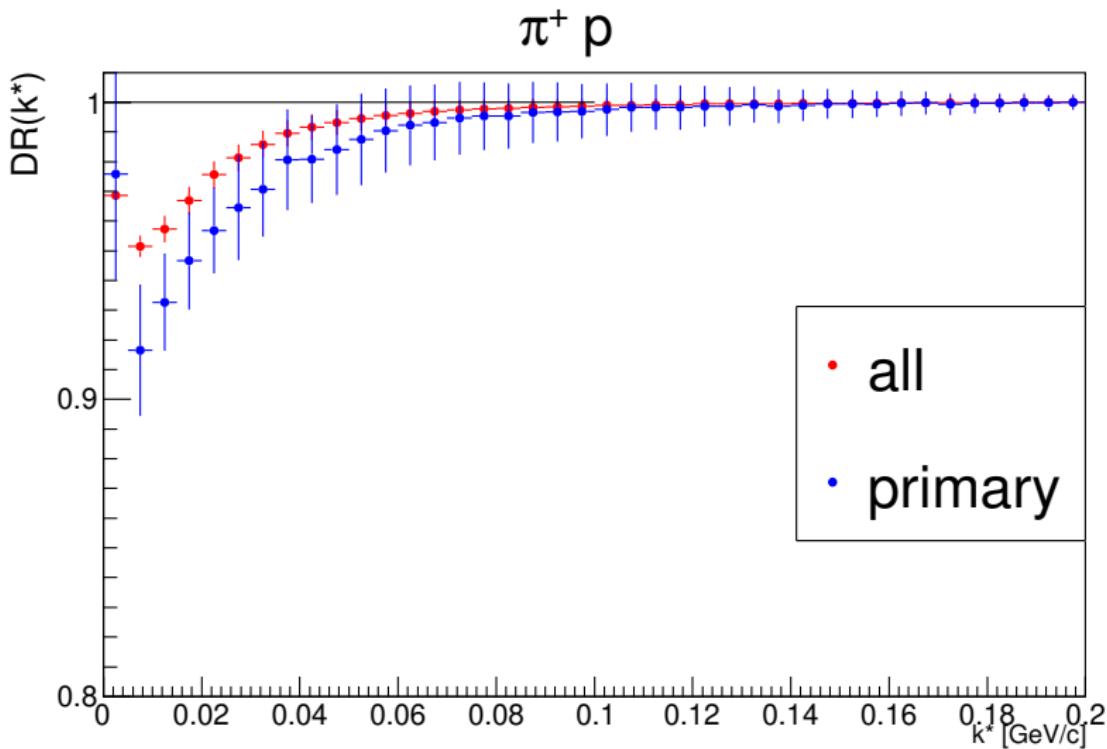
$$\langle r_{out}^* \rangle = -3.61$$



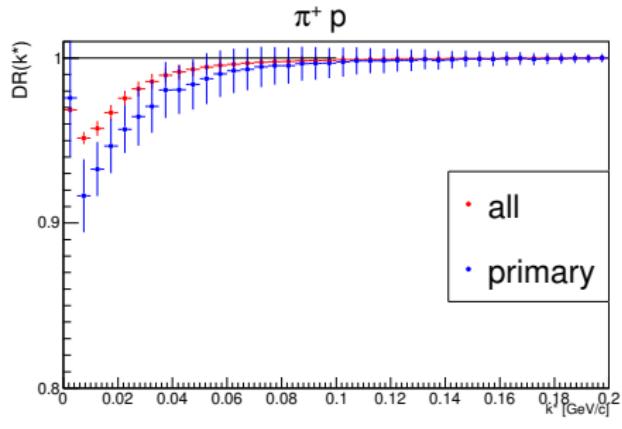
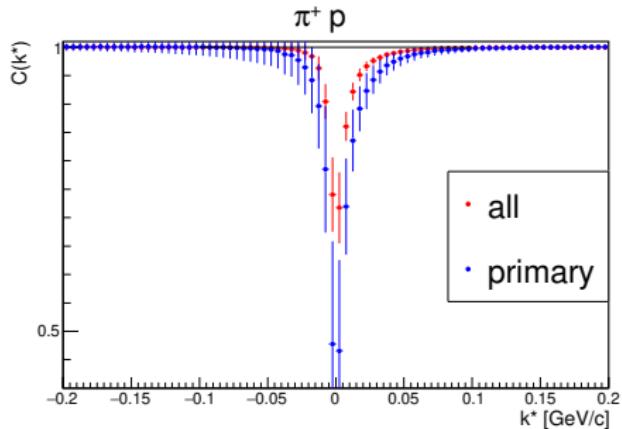
$\pi^+ p$ femtoscopy



$\pi^+ p$ femtoscopy



$\pi^+ p$ femtoscopy



Therminator 2

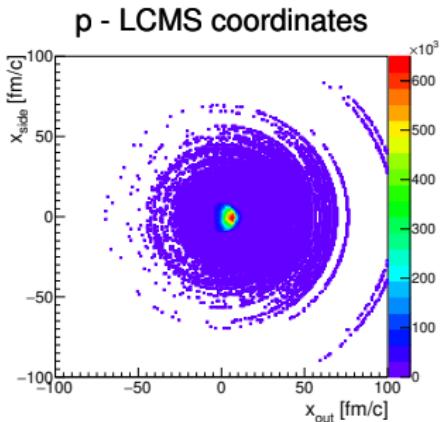
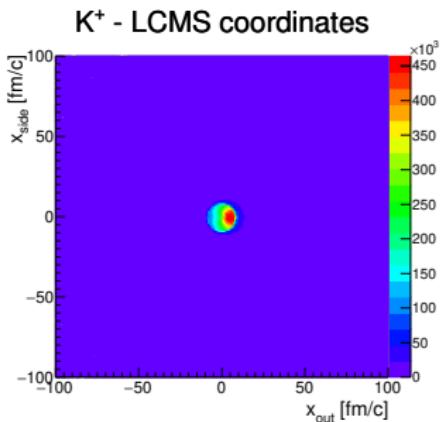
$K^+ p$ @ 39 GeV

$K^+ p$, Therminator 2

All particles

$$\langle x_{out}^K \rangle = 3.11$$

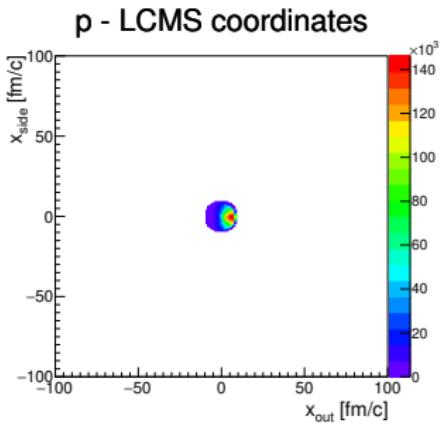
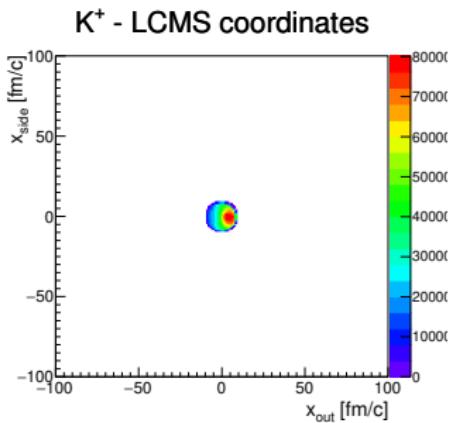
$$\langle x_{out}^p \rangle = 4.70$$



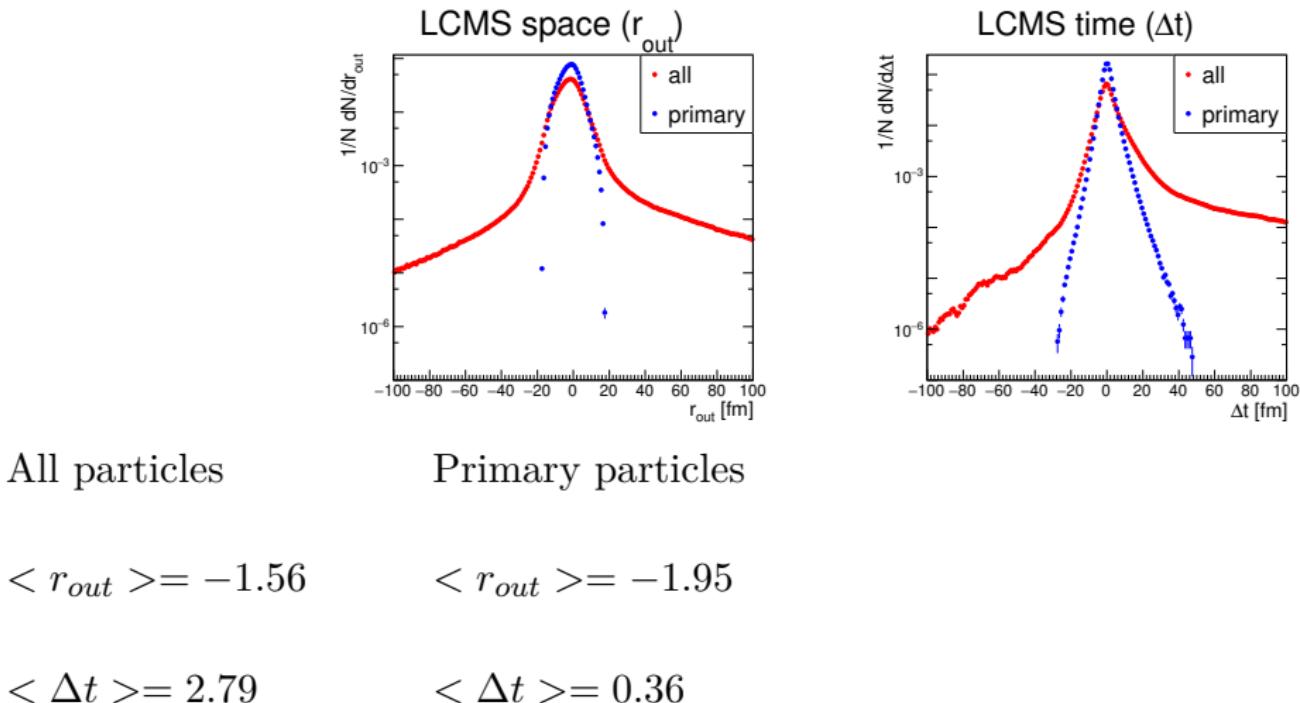
Primary particles

$$\langle x_{out}^K \rangle = 1.85$$

$$\langle x_{out}^p \rangle = 3.81$$



$K^+ p$



All particles

$$\langle r_{out} \rangle = -1.56$$

$$\langle \Delta t \rangle = 2.79$$

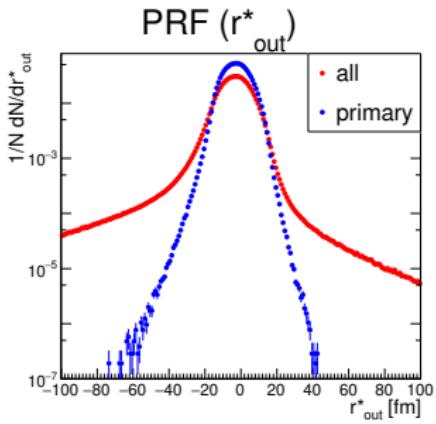
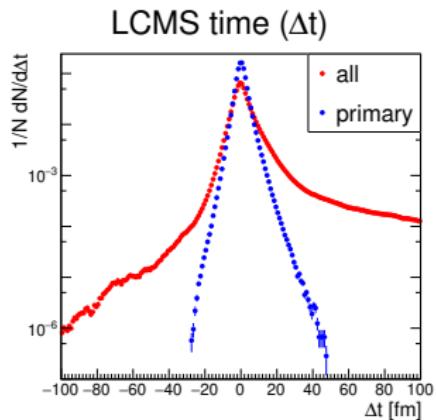
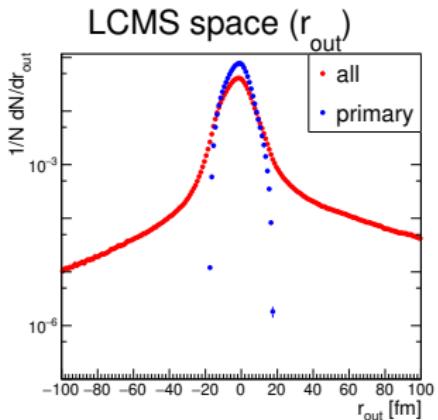
$$\langle r_{out}^* \rangle = -3.82$$

Primary particles

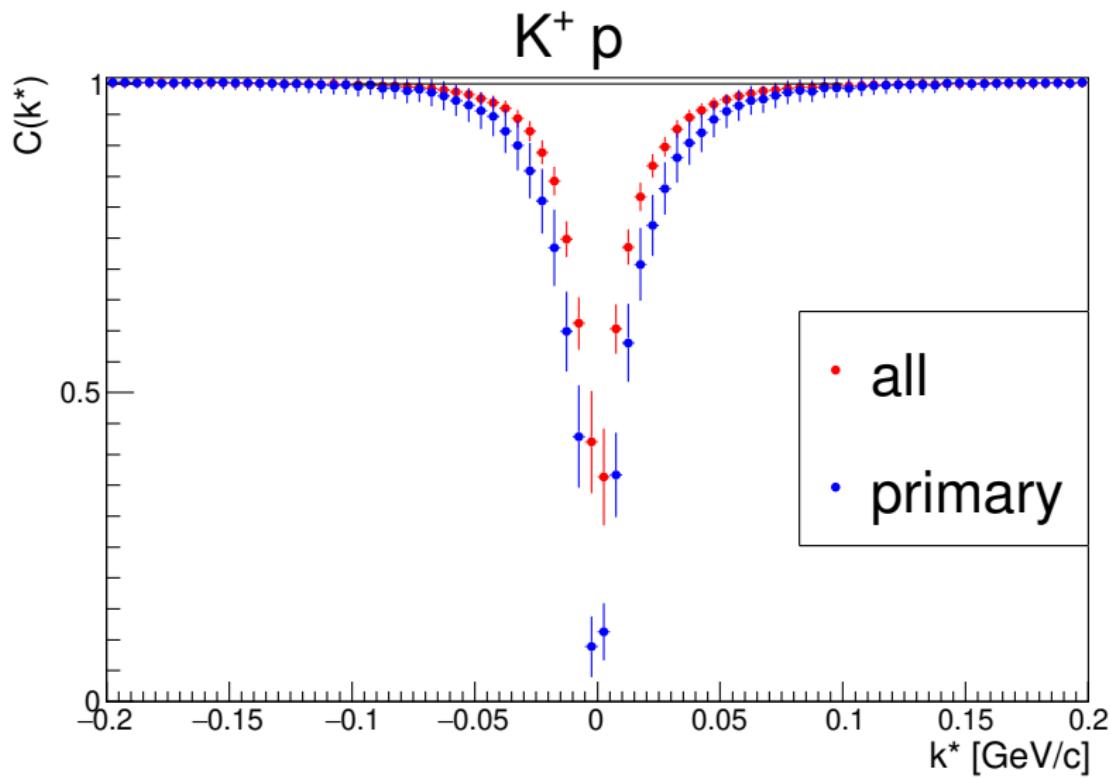
$$\langle r_{out} \rangle = -1.95$$

$$\langle \Delta t \rangle = 0.36$$

$$\langle r_{out}^* \rangle = -2.56$$

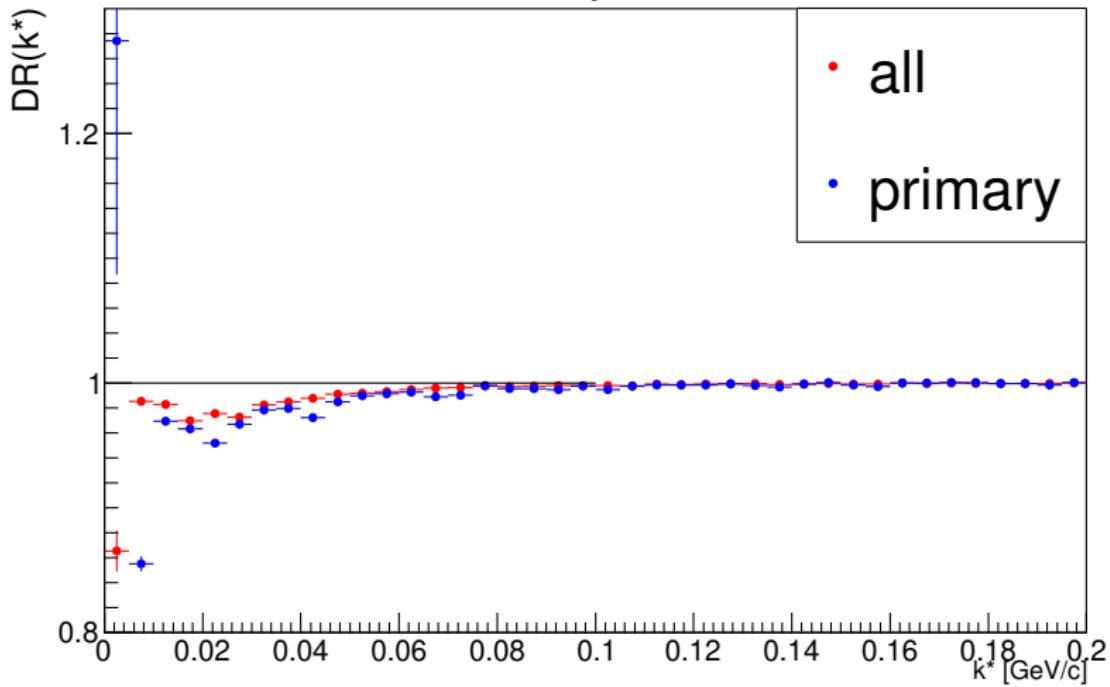


$K^+ p$ femtoscopy

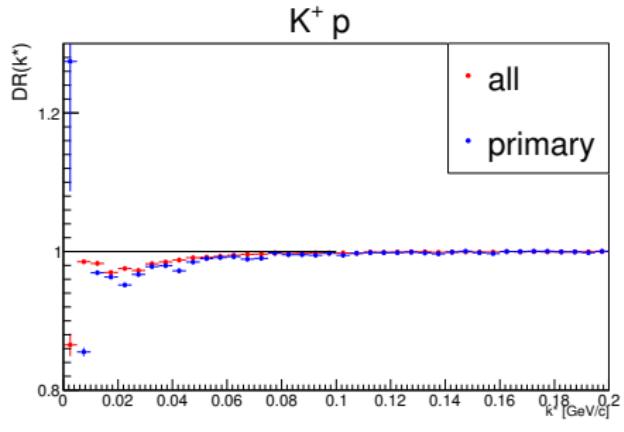
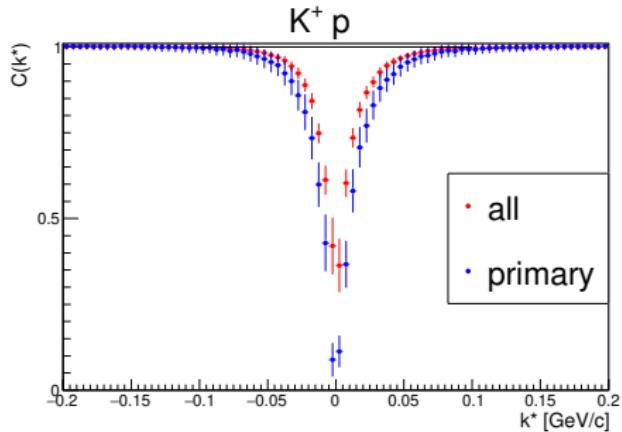


$K^+ p$ femtoscopy

$K^+ p$



$K^+ p$ femtoscopy



UrQMD

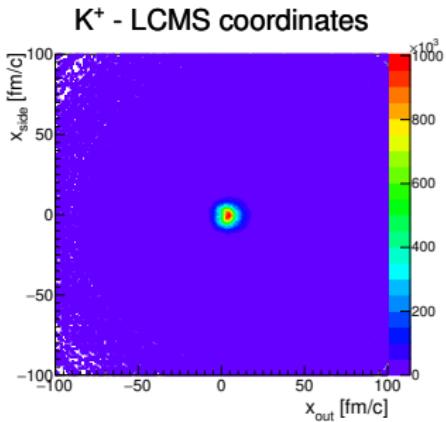
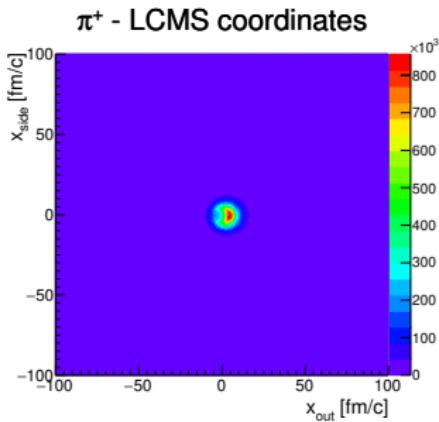
$\pi^+ K^+$ @ 39 GeV

$\pi^+ K^+$, UrQMD

All particles

$$\langle x_{out}^\pi \rangle = 4.29$$

$$\langle x_{out}^K \rangle = 5.52$$



$\pi^+ K^+$, UrQMD

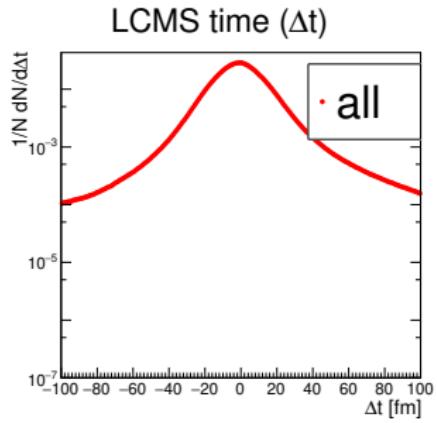
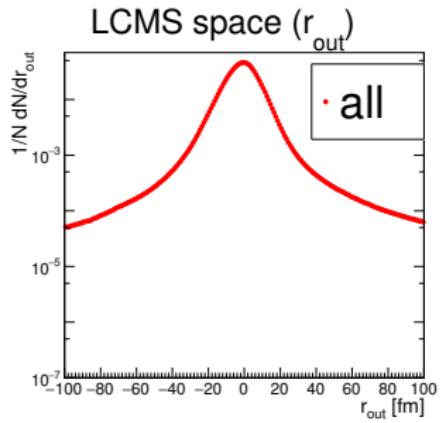
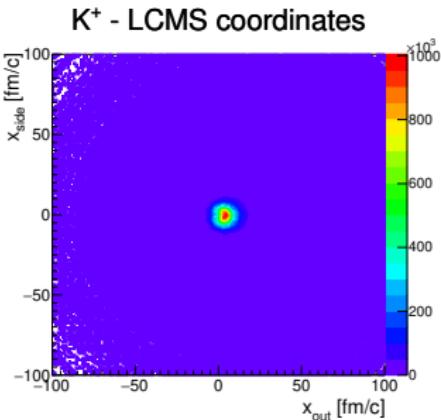
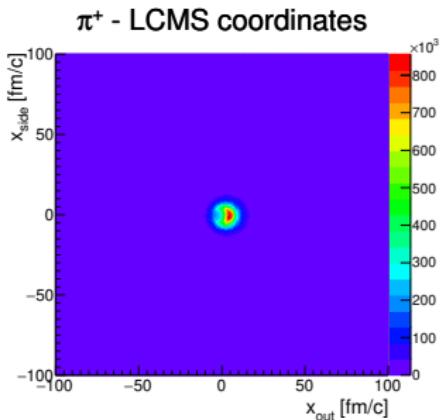
All particles

$$\langle x_{out}^\pi \rangle = 4.29$$

$$\langle x_{out}^K \rangle = 5.52$$

$$\langle r_{out} \rangle = -1.25$$

$$\langle \Delta t \rangle = -0.67$$

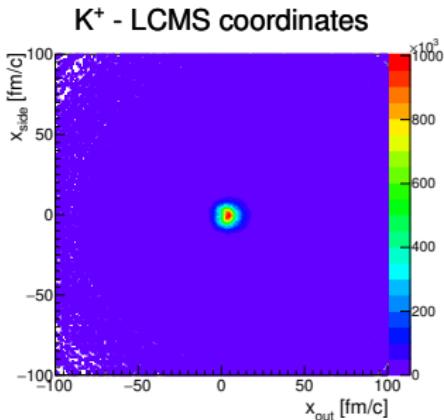
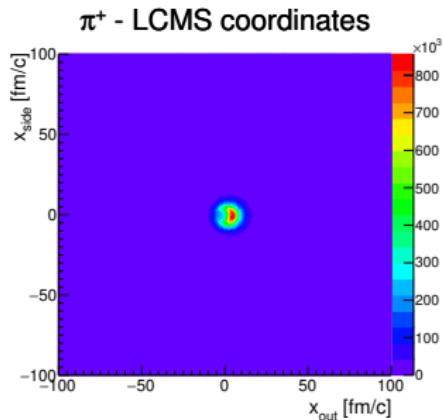


$\pi^+ K^+$, UrQMD

All particles

$$\langle x_{out}^\pi \rangle = 4.29$$

$$\langle x_{out}^K \rangle = 5.52$$

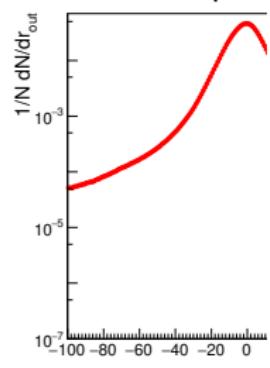


$$\langle r_{out} \rangle = -1.25$$

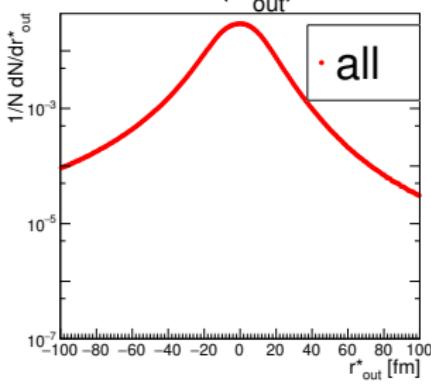
$$\langle \Delta t \rangle = -0.67$$

$$\langle r_{out}^* \rangle = -0.91$$

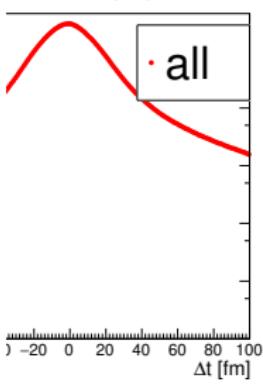
LCMS spac



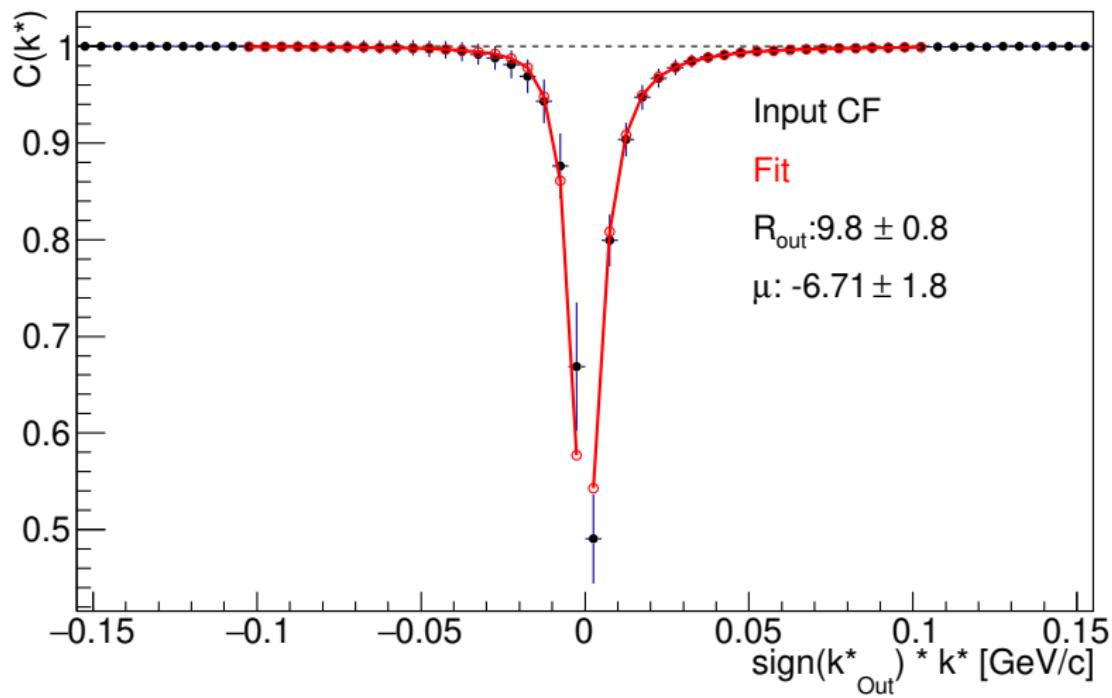
PRF (r_{out}^*)



S time (Δt)



All particles, UrQMD



All particles, UrQMD

