Momentum resolution correction in femtoscopic measurements

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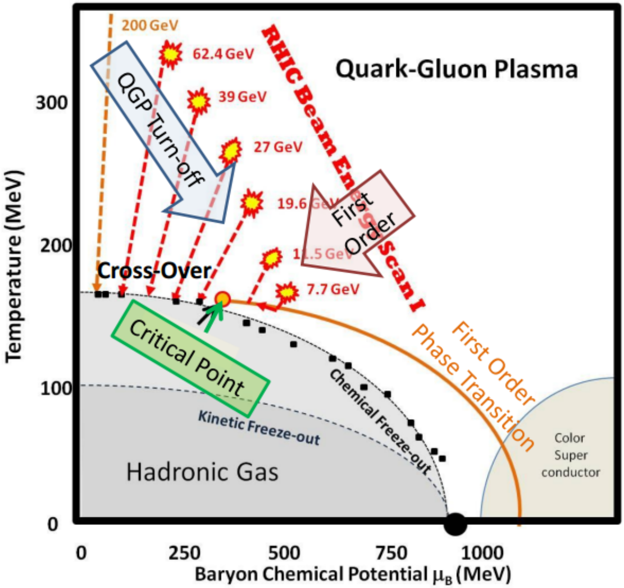
Supported by IDUB-POB-FWEiTE-1 project by WUT

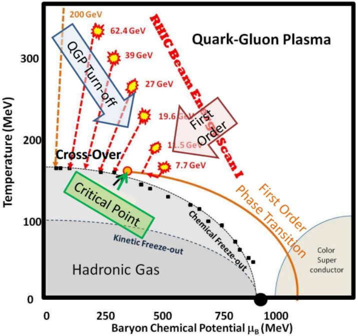
Beam Energy Scan at STAR



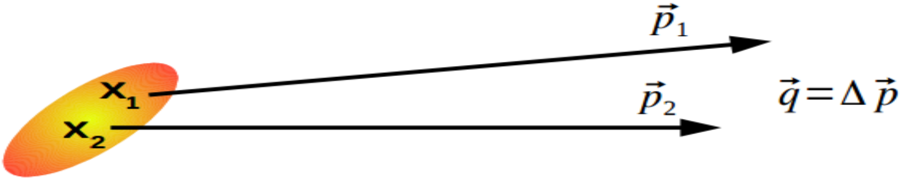
BES goals

Analyze all BES energies and find answers:

- Search for turn-off of QGP signatures
- Search for the QCD critical point
- Search for the signals of phase transition/phase boundary

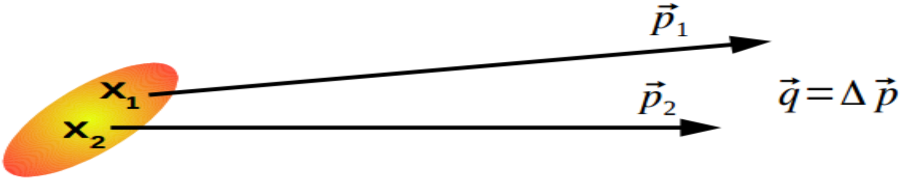


Correlation Function



- analyze many pairs of particles $(\vec{p_1}, \vec{x_1})$ and $(\vec{p_2}, \vec{x_2})$ with relative momentum $\vec{q} = \vec{p_1} - \vec{p_2}$

Correlation Function



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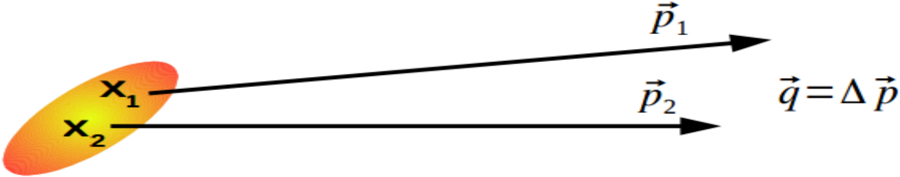
- calculate correlation function (CF) of pairs:

$$CF(\vec{p_1}, \vec{p_2}) = \frac{P_2(\vec{p_1}, \vec{p_2})}{P_1(\vec{p_1})P_1'(\vec{p_2})}$$

$P_2(\vec{p_1}, \vec{p_2})$ — probability of observing two particles with momentum $\vec{p_1}$ and $\vec{p_2}$ at the same time and the same place

$P_1(\vec{p_1})$, $P_1'(\vec{p_2})$ — probability of observing two particles with momentum $\vec{p_1}$ and $\vec{p_2}$ separately

Correlation Function



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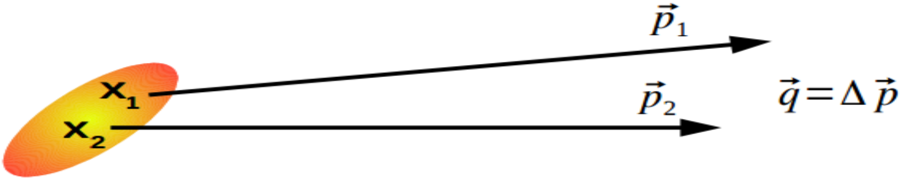
experimental correlation function:

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

Correlation Function



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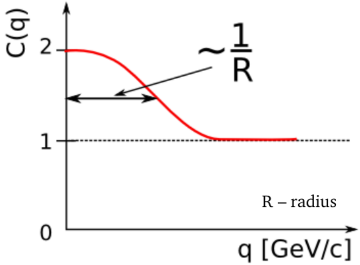
- calculate size of the source



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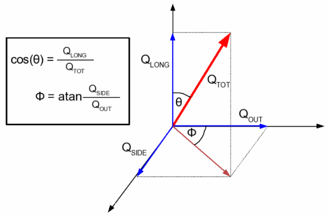
Pion-kaon femtoscopy — Spherical harmonics (SH)

SH representation of 3D correlation function as a set of 1D plots

$$C(\mathbf{q}) = \sum_{l,m} C_l^m(q) Y_l^m(\theta, \phi) \qquad C_l^m(q) = \int_\Omega C(q, \theta, \phi) Y_l^m(\theta, \phi) d\Omega$$

Ω - full solid angle
$Y_l^m(\theta, \phi)$ - spherical harmonic function
$q = |\mathbf{q}|$ - pair relative momentum
θ and ϕ - polar and azimuthal angle



P. Danielewicz and S. Pratt.
Phys. Lett B618, 60 (2005)
Phys. Rev. C75, 034907 (2007)

Z. Chajecki and M. Lisa
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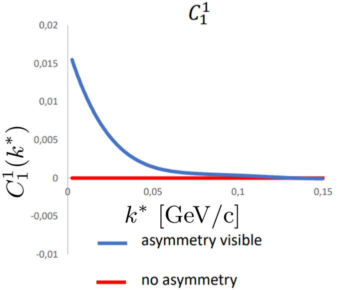
$C_0^0 \rightarrow$ sensitive to the size of the emitting source (shapes same as correlation function)

$C_1^1 \rightarrow$ sensitive to the spacetime emission asymmetry



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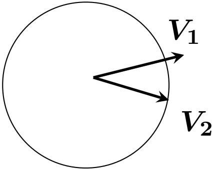
Non-identical particle combinations

Time asymmetry

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

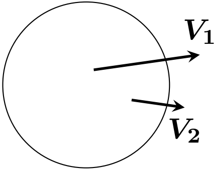


$t_1 > t_2$ - Catching up

$t_1 < t_2$ - Run away

Space asymmetry

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



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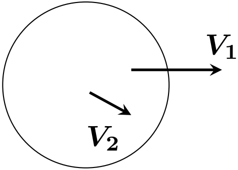

Run away

t — emission time
r — emission point distance from the center

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

Catching up
longer interaction,
strong correlation
Running away
shorter interaction,
weaker correlation

Non-identical particle combinations

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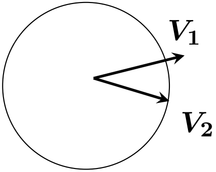
$\Delta r = 0$



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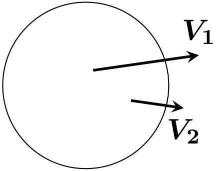

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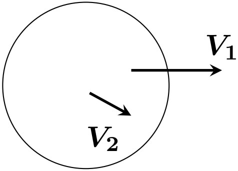

Run away

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

Double Ratio:

$$DR(k^*) = \frac{C_+(k^*)}{C_-(k^*)}$$

THERMINATOR model

THERMal heavy-**I**o**N** Gener**ATOR**

- Generates collisions of relativistic ions
- Uses Monte Carlo methods
- Implements thermal models of particle production with single freeze-out

THERMINATOR: THERMal heavy-IoN generATOR
A. Kisiel,T. Tałuć, W. Broniowski, W. Florkowski.
Comput.Phys.Commun. 174 (2006) 669-687

THERMINATOR is a Monte Carlo event generator designed for studying of particle production in relativistic heavy-ion collisions performed at such experimental facilities as the SPS, RHIC, or LHC. The program implements thermal models of particle production with single freeze-out.

Thermintor for BES program

$\sqrt{s_{NN}}[GeV]$	T [MeV]	μ_B [MeV]	μ_S [MeV]	μ_{I_3} [MeV]
7.7	138.95	406.36	93.026	-10.378
11.5	150.12	303.22	70.369	-7.825
19.6	156.17	196.77	45.951	-5.189
27	157.60	148.99	34.991	-4.006
39	158.38	106.89	25.335	-3.064
62.4	158.78	68.92	16.626	-2.024

T - temperature
μ_B - barion potential
μ_S - strangeness potential
μ_{I_3} - third component of isospin

"Adaptation of the therminator model for BES program",
H. Zbroszczyk
Proc.SPIE Int.Soc.Opt.Eng. 11581 (2020) 1158104

Thermintor for BES program

$\sqrt{s_{NN}}[GeV]$	τ [fm]	ρ_{max} [fm]	V_T
7.7	8.3	8	0.65
11.5	8.35	8	0.8
19.6	8.75	8.2	0.85
27	8.75	8.85	0.8
39	8.6	8.7	0.75
62.4	9.4	9	0.75

V_T - parameter specific to the Blast-Wave model, denoting velocity

τ, ρ_{max} - geometric parameters

$\rho_{max}^2 \cdot \tau \simeq V$

V is the volume of source

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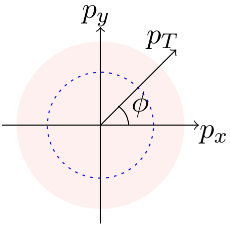
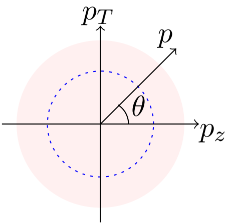
Momentum resolution

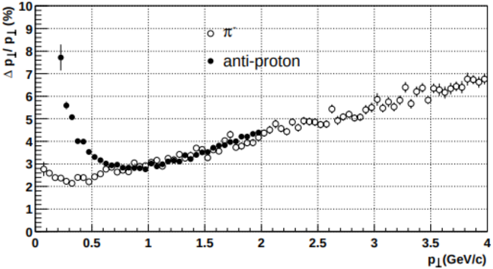


$$p_T = R|q||\vec{B}| = p\sin\theta \qquad p_z = p\cos\theta$$

$$p_x = p_T\cos\phi \qquad p_y = p_T\sin\phi$$

R - radius of fitted helise to points of particle track in TPC





Transverse momentum (p_T) resolution of the STAR TPC for π^- and anti-protons in the 0.25 T magnetic field ($\vec{B}$) (embedding)

Nucl.Instrum.Meth.A499:659-678,2003

Momentum resolution

How to add momentum resolution effect?

Momentum resolution

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Resolution of momentum, azimuthal and polar angles:

$$\Delta p = a_p + b_p p^{\alpha_p} + c_p p$$

$$\Delta \phi = a_\phi + b_\phi \phi^{\alpha_\phi}$$

$$\Delta \theta = a_\theta + b_\theta \theta^{\alpha_\theta}$$

Momentum resolution

How to add momentum resolution effect?

Resolution of momentum, azimuthal and polar angles:

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Standard deviations:

$$\sigma_{p_x}^2 = (|p_x|\frac{\Delta p}{p})^2 + (|p_y|\Delta\phi)^2 + (|\frac{p_x}{\operatorname{tg}\theta}|\Delta\theta)^2$$

$$\sigma_{p_y}^2 = (|p_y|\frac{\Delta p}{p})^2 + (|p_x|\Delta\phi)^2 + (|\frac{p_y}{\operatorname{tg}\theta}|\Delta\theta)^2$$

$$\sigma_{p_z}^2 = (|p_z|\frac{\Delta p}{p})^2 + (|p_z \operatorname{tg}\theta|\Delta\theta)^2$$

Momentum resolution

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$$\sigma_{p_z}^2 = (|p_z|\frac{\Delta p}{p})^2 + (|p_z \operatorname{tg}\theta|\Delta\theta)^2$$

Smeared momentum:

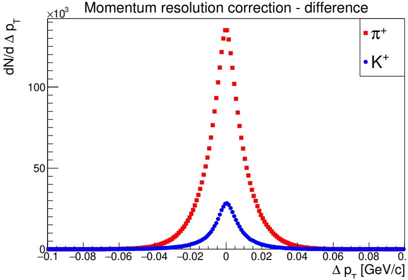
$$p_x^{smeared} = p_x^{real} + \partial p_x$$

$$p_y^{smeared} = p_y^{real} + \partial p_y$$

$$p_z^{smeared} = p_z^{real} + \partial p_z$$

where ∂p_x, ∂p_y and ∂p_z calulated from Gaussian distribution with the above standard deviations and mean 0

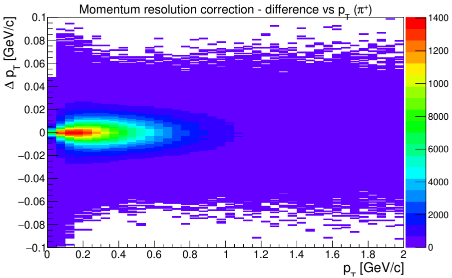
Momentum resolution



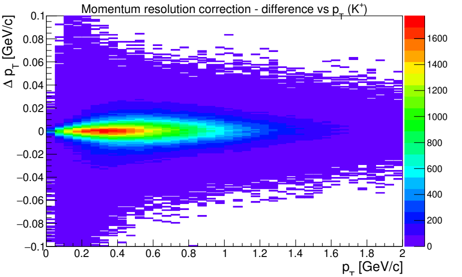
From Therminator 2

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\Delta p_T = p_T^{raw} - p_T^{smeared}$$



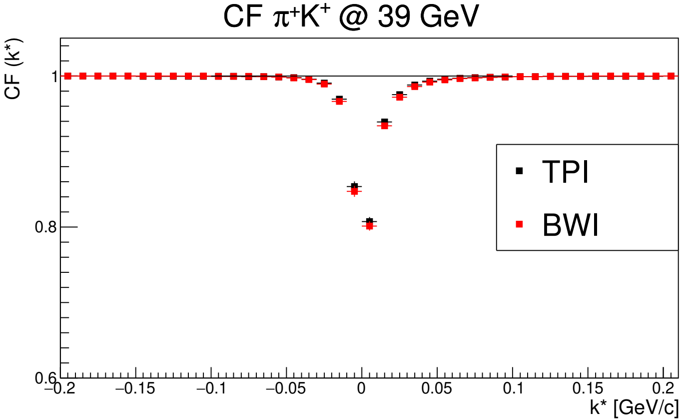
positive pion



positive kaon

Software for calculating correlation functions

- **BWIntegrate** — software created by Richard Lednicky (using Lednicky weights)
- **TPI** — software written by Adam Kisiel (using wave function)



Obtained functions are similar

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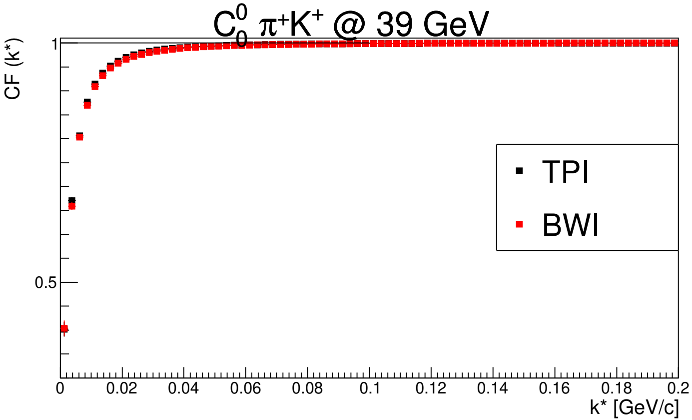

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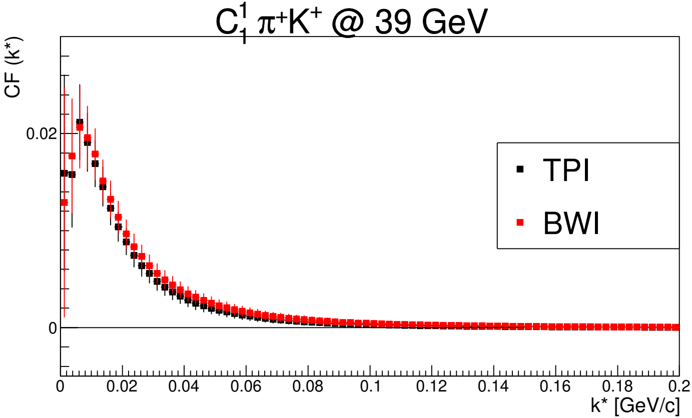

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Therminator2

CF^{raw}

interaction from p^{raw}

k^* from p^{raw}

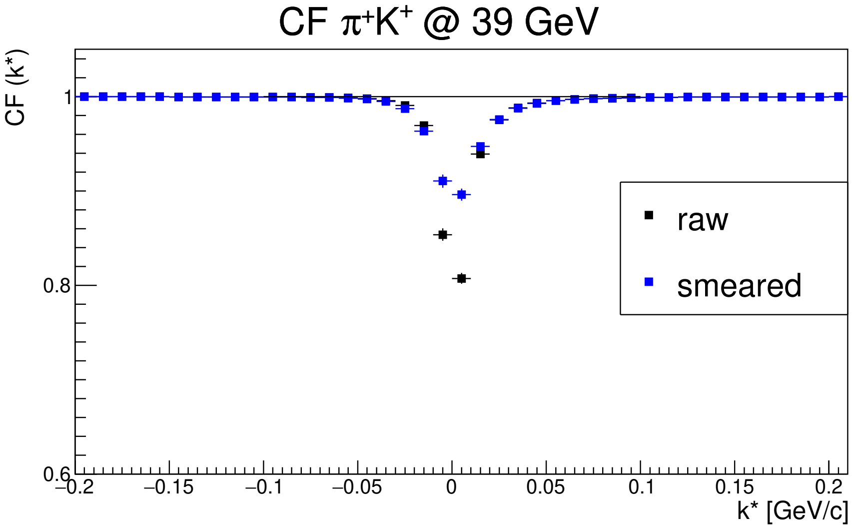
CF^{smear}

interaction from p^{raw}

k^* from p^{smear}

- Particles know their momenta → **weights from true (raw) momenta**
- We measure momentum of the particles → **$\mathbf{k}^*$ from smeared momenta**

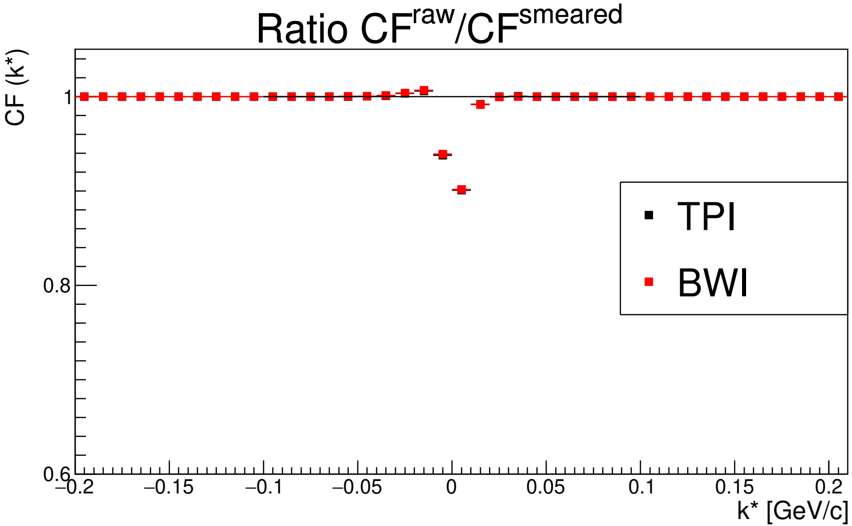
$\pi^+ K^+$ CF @ 39 GeV



Visible effect at low k^*

Only TPI

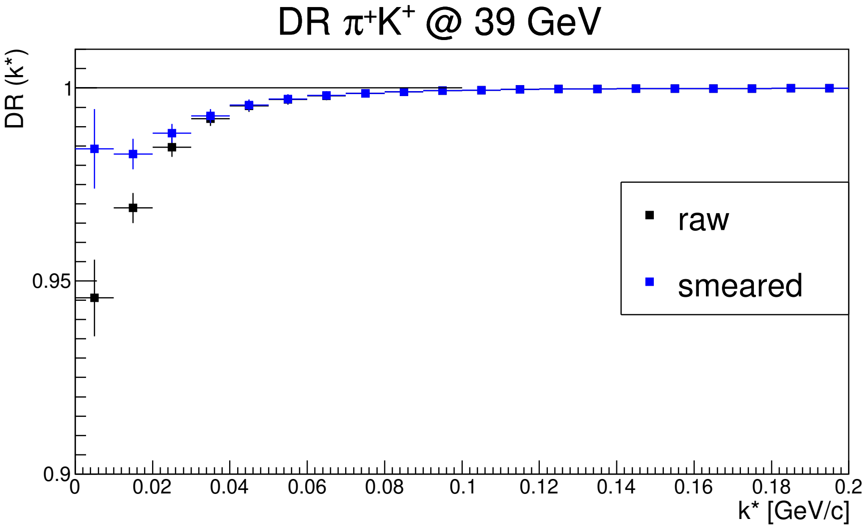
$\pi^+ K^+$ CF @ 39 GeV



At $|k^*| < 0.02$ visible effect

TPI/BWI comparison

π^+K^+ Double Ratio (DR) @ 39 GeV



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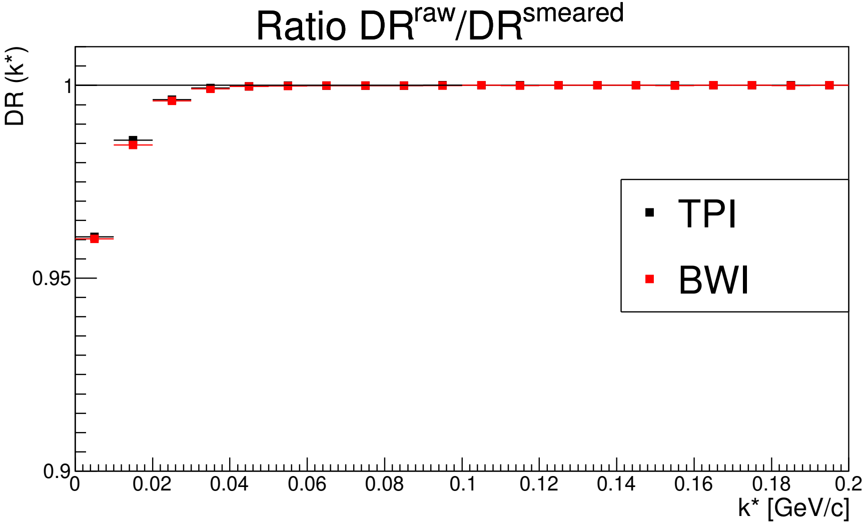
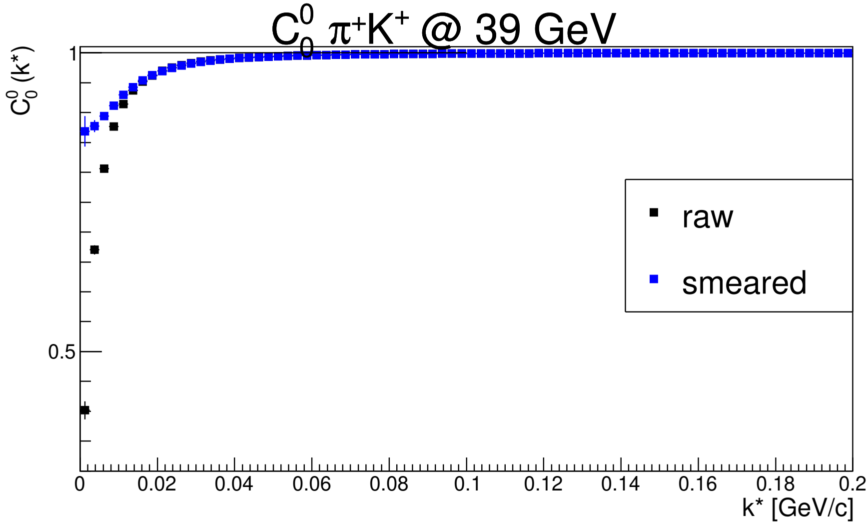


At $|k^*| < 0.04$ visible effect

TPI/BWI comparison

$\pi^+ K^+ \ C_0^0$ @ 39 GeV



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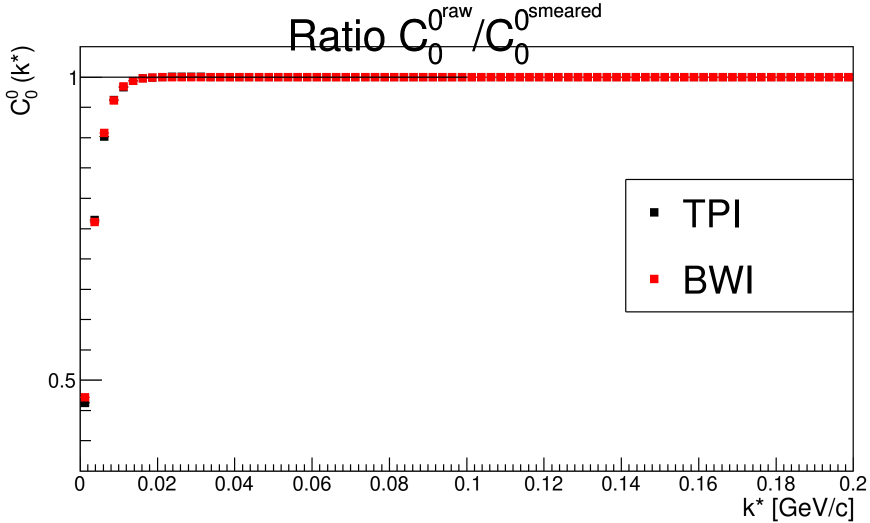

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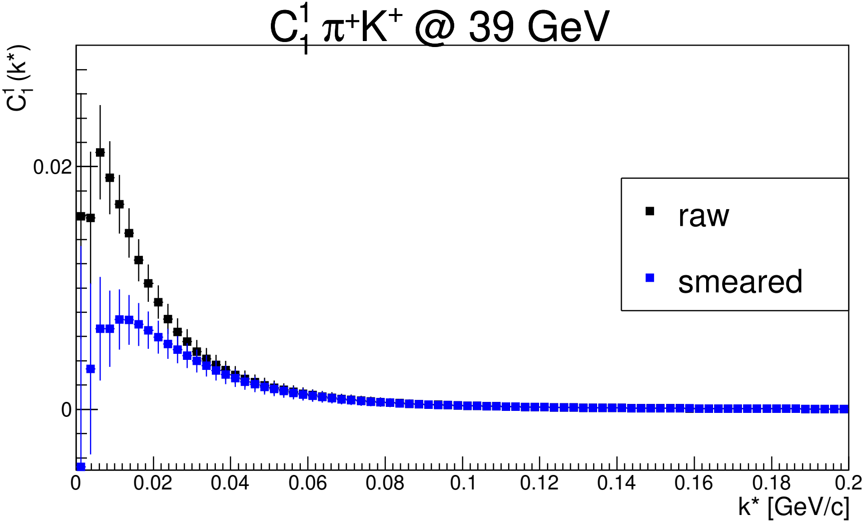
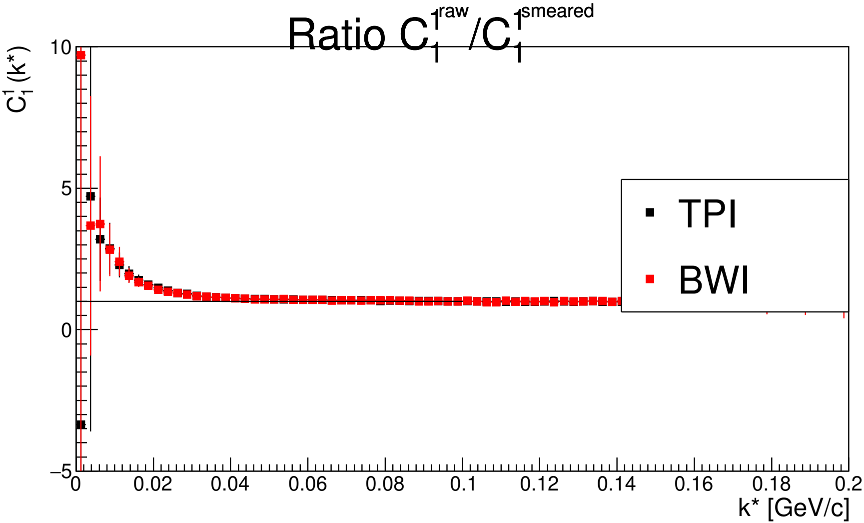
$\pi^+ K^+$ C_1^1 @ 39 GeV



Visible effect at low k^*

Only TPI

$\pi^+ K^+ \ C_1^1$ @ 39 GeV



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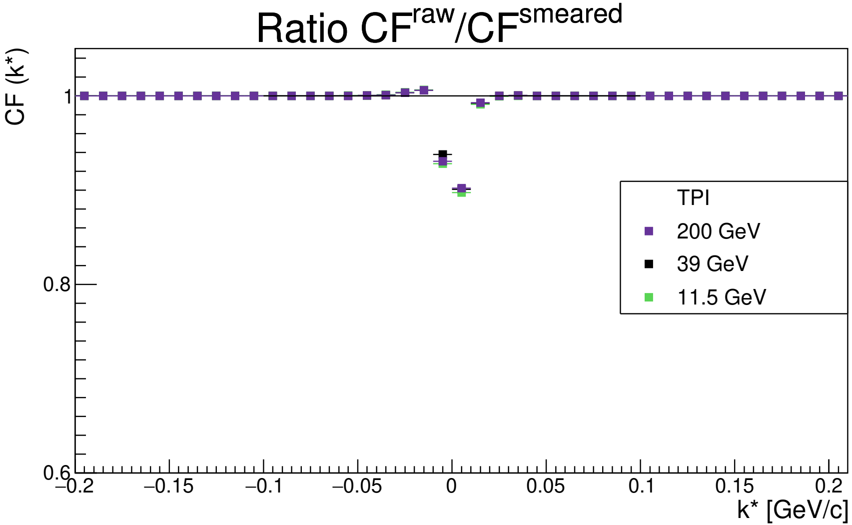
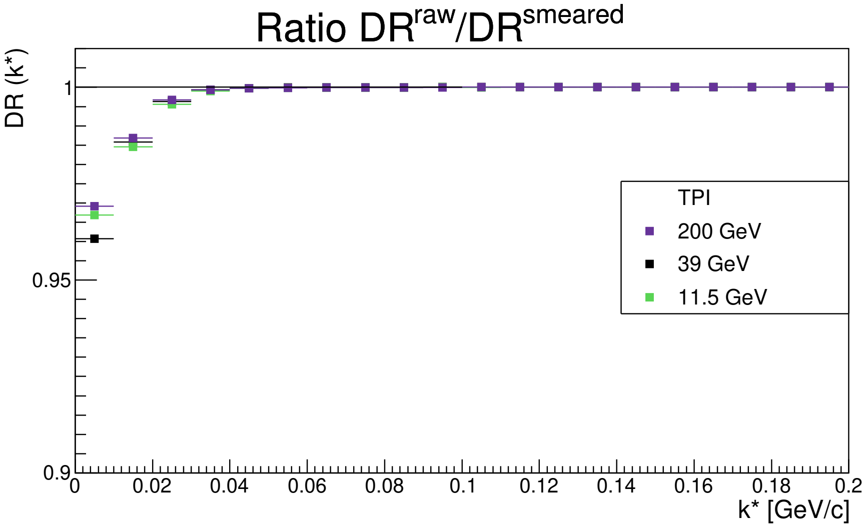
Comparison for other energies — CF



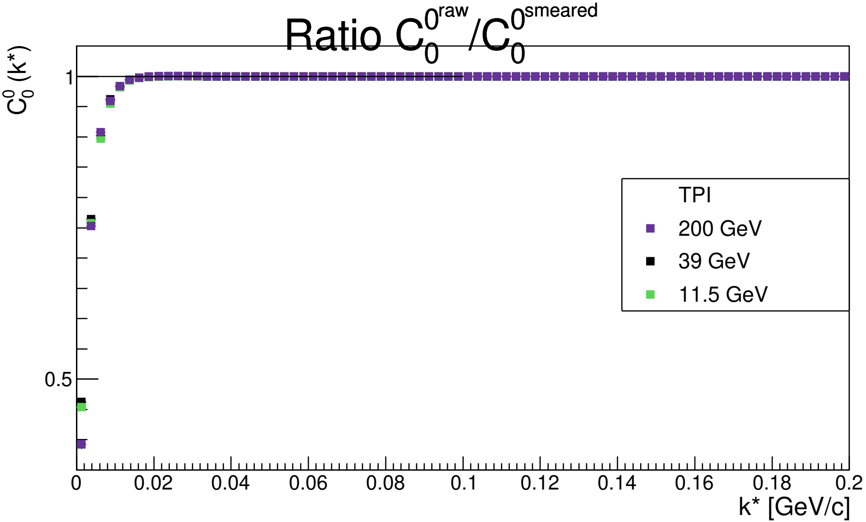
similar effect

Comparison for other energies — DR



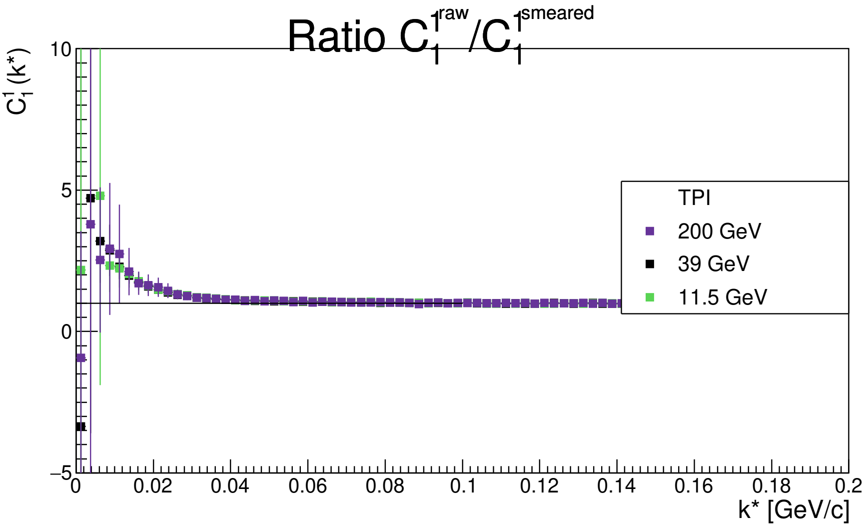
similar effect

Comparison for other energies — C_0^0



similar effect

Comparison for other energies — C_1^1



similar effect

Summary

Studies of momentum resolution effect using Therminator 2 model

- Visible effect of momentum resolution (MR) on CF
- MR should be taken into account in femtoscopic analysis
- similar effect for energies 11.5, 39 and 200 GeV
  - with the same parameters of MR!
- Wider impact on DR and C_1^1 function (asymmetry)

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Thank you for your attention!