Non-identical femtoscopy results from the STAR experiment

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- Introduction to correlation femtoscopy
- STAR experiment at RHIC
- Experimental results on non-identical correlation
- Conclusion

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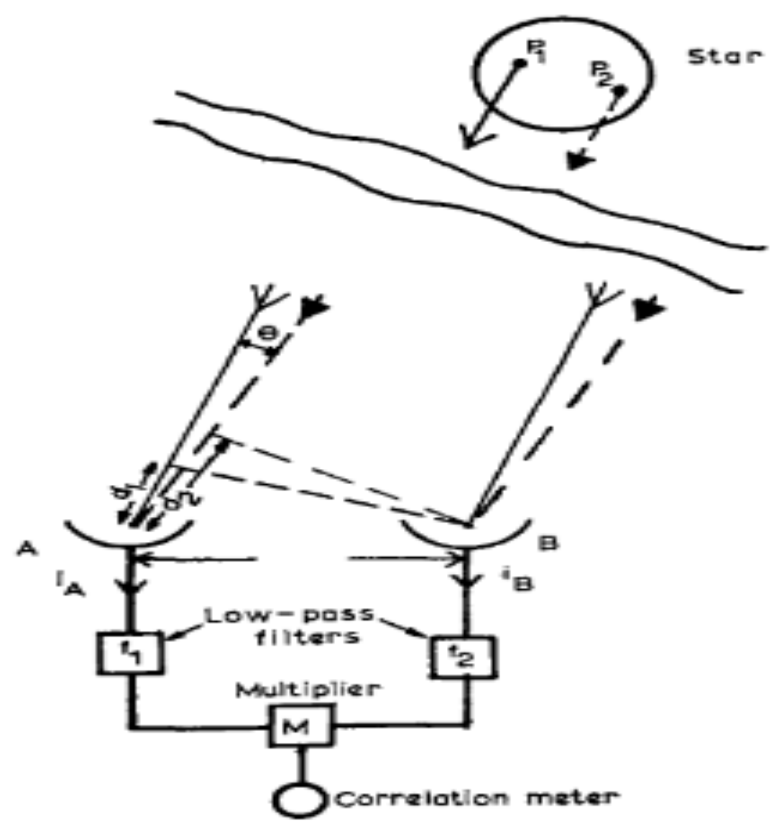
HBT and femtoscopy

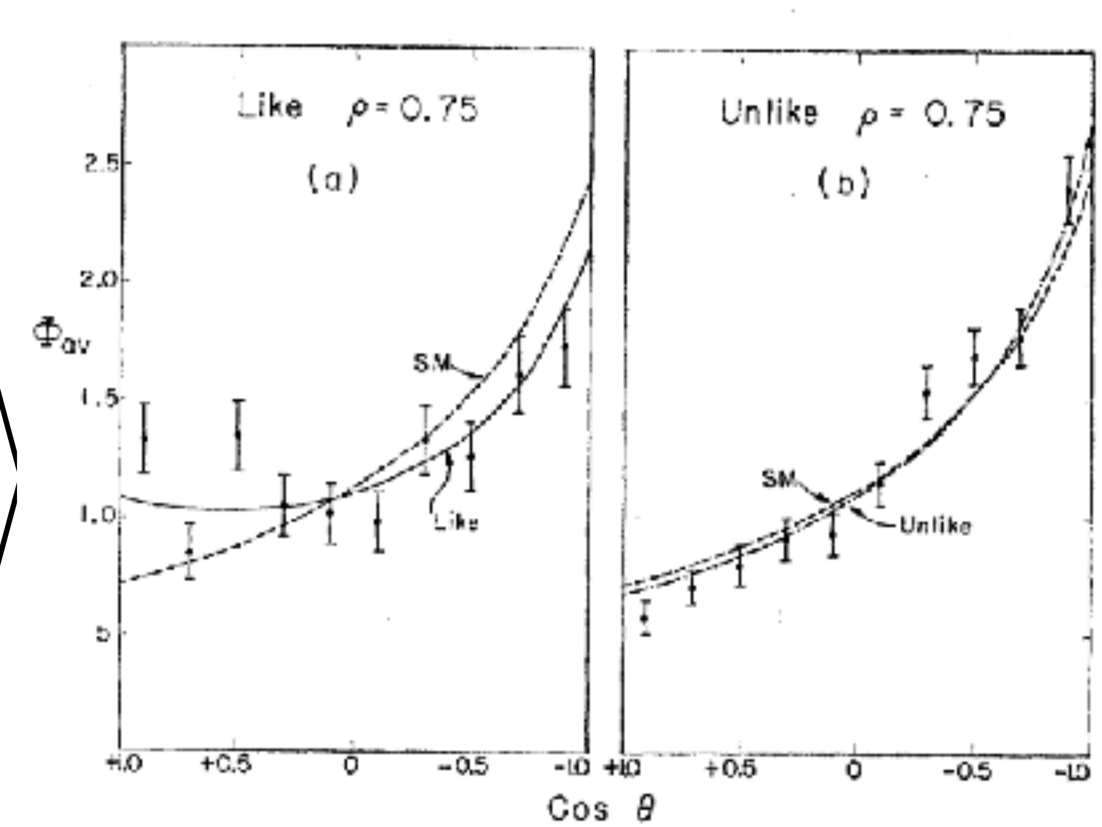
Method to probe geometric and dynamic properties of the source



Hanbury Brown, R. Taylor & Francis, (1974)

Angular Size of Sirius

$\pi - \pi$ correlation



Goldhaber et al, Phys. Rev. 120, 300 (1960)

Correlation femtoscopy

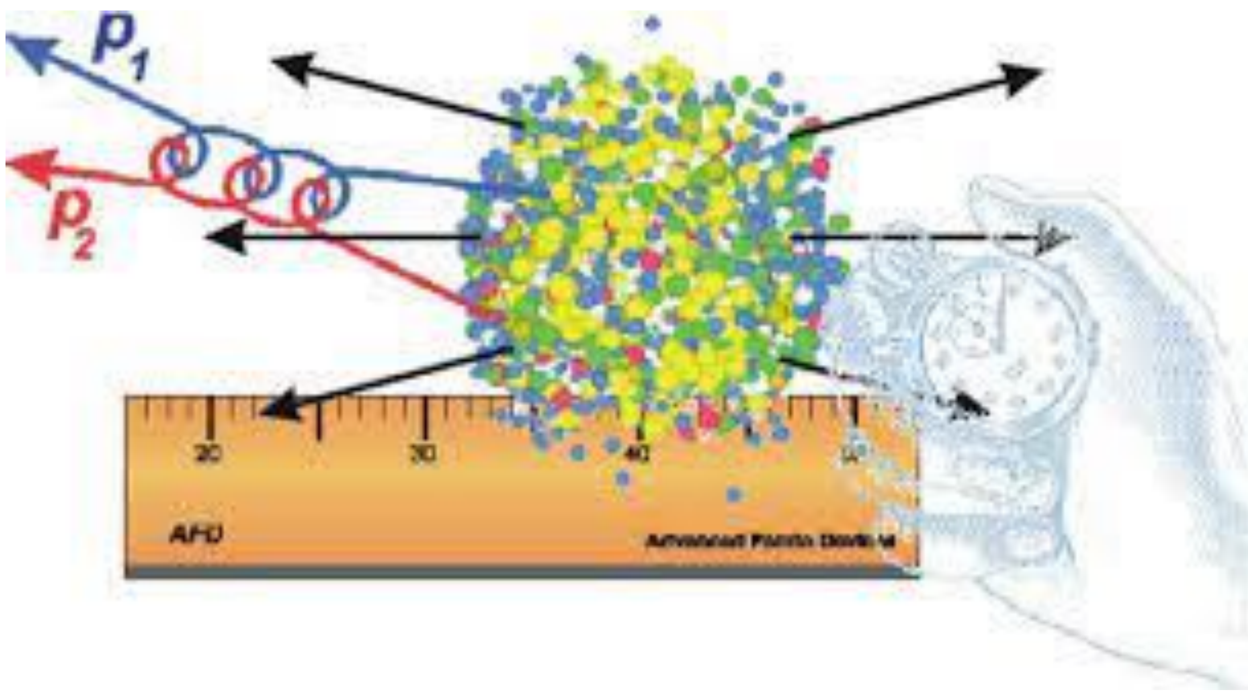
particle correlations in momentum space

particle emitting source

Koonin-Pratt Equation:

$$C(k^*) = \int S(r^*) |\psi(k^*, r^*)|^2 \, d^3r^*$$

$S(r^*)$ is the source function,
$\psi(k^*, r^*)$ is two particle wave function,
k^* and r^* are relative-momentum and relative-separation.



from M. Lisa and S. Pratt

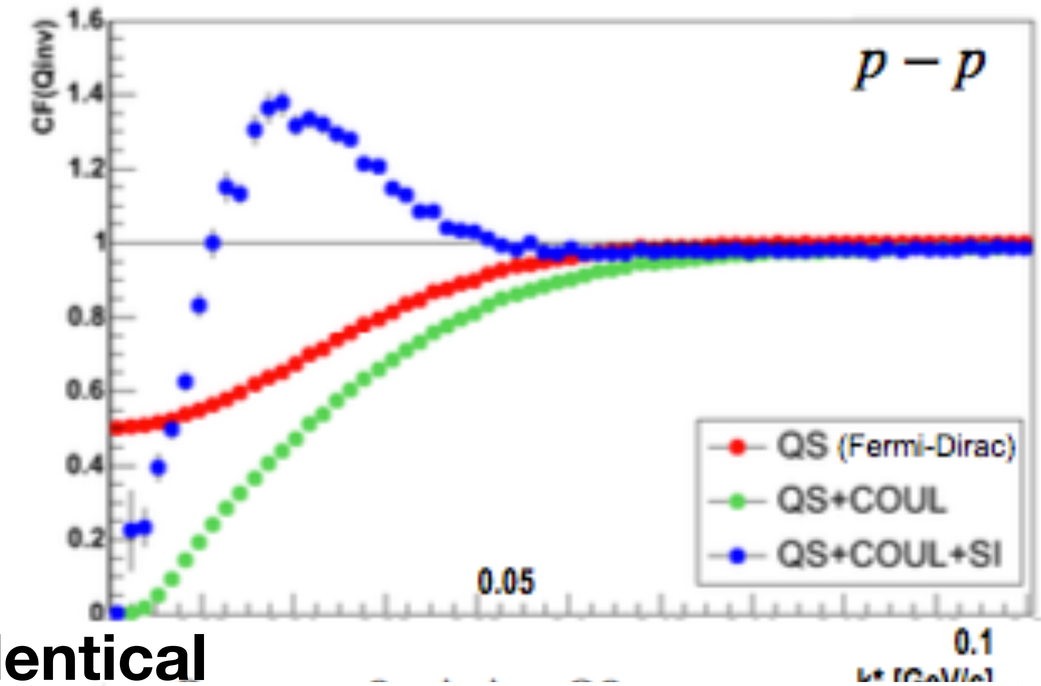
Steven E. Koonin, Phy Lett B 70, 43 (1977)
S. Pratt et al., Phys. Rev. C 42, 2646 (1990)

Sources of correlation:

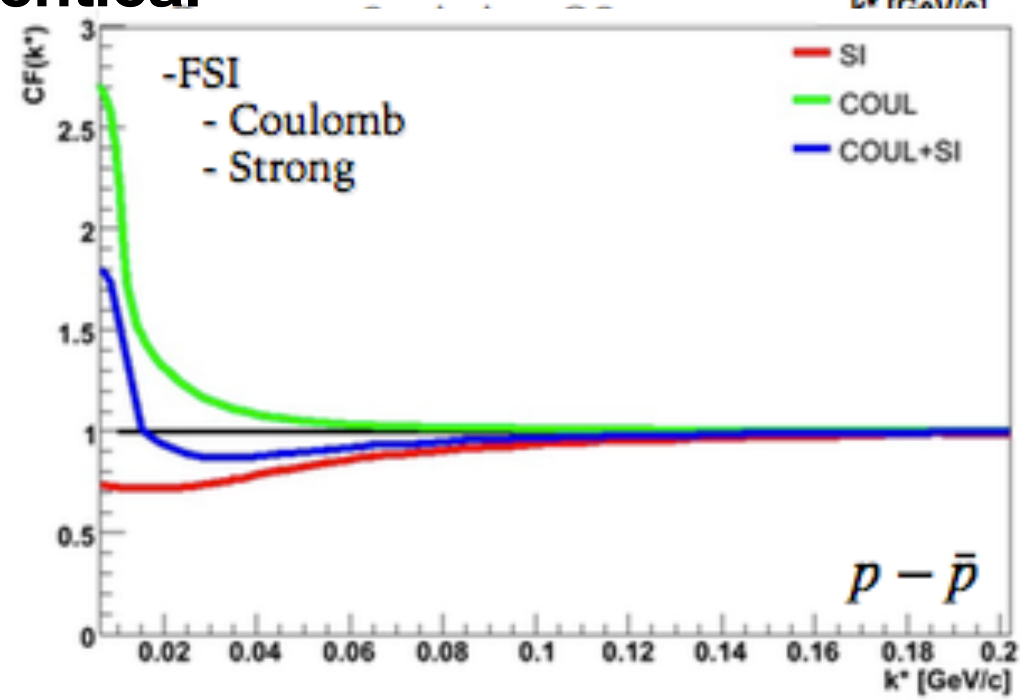
Quantum Statistics
Fermi-Dirac
Bose-Einstein

Final state interaction
Strong interactions
Coulomb interaction

Identical



Non-identical



H. Zbroszczyk, Ph.D. thesis

Correlation function

$$C(k^*) = \int S(r^*)|\psi(k^*, r^*)|^2 \, d^3r^*$$

source function: (traditional femtoscopy) measures spatial evolution of source

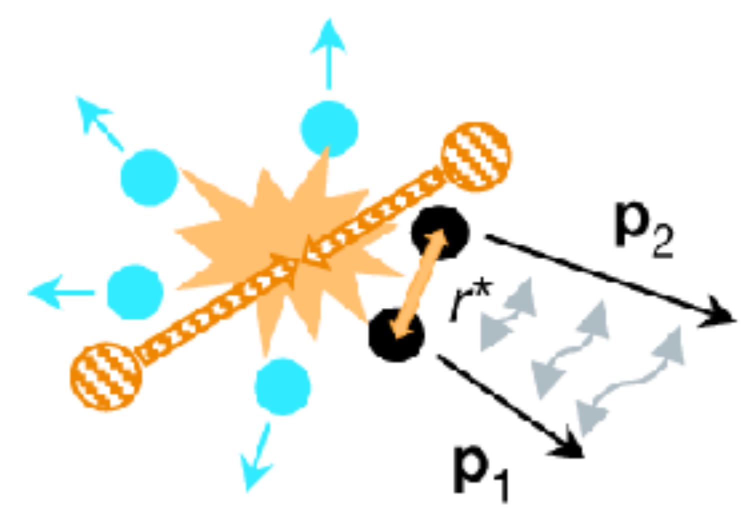
$$S(r) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^2}{4r_0^2}\right)$$

S(r): Source function
r_0 is source radius

1.Gauss :
Standard approach

2.Levy :
anomalous diffusion/Jet fragmentation

3.Exponential, Cauchy ..



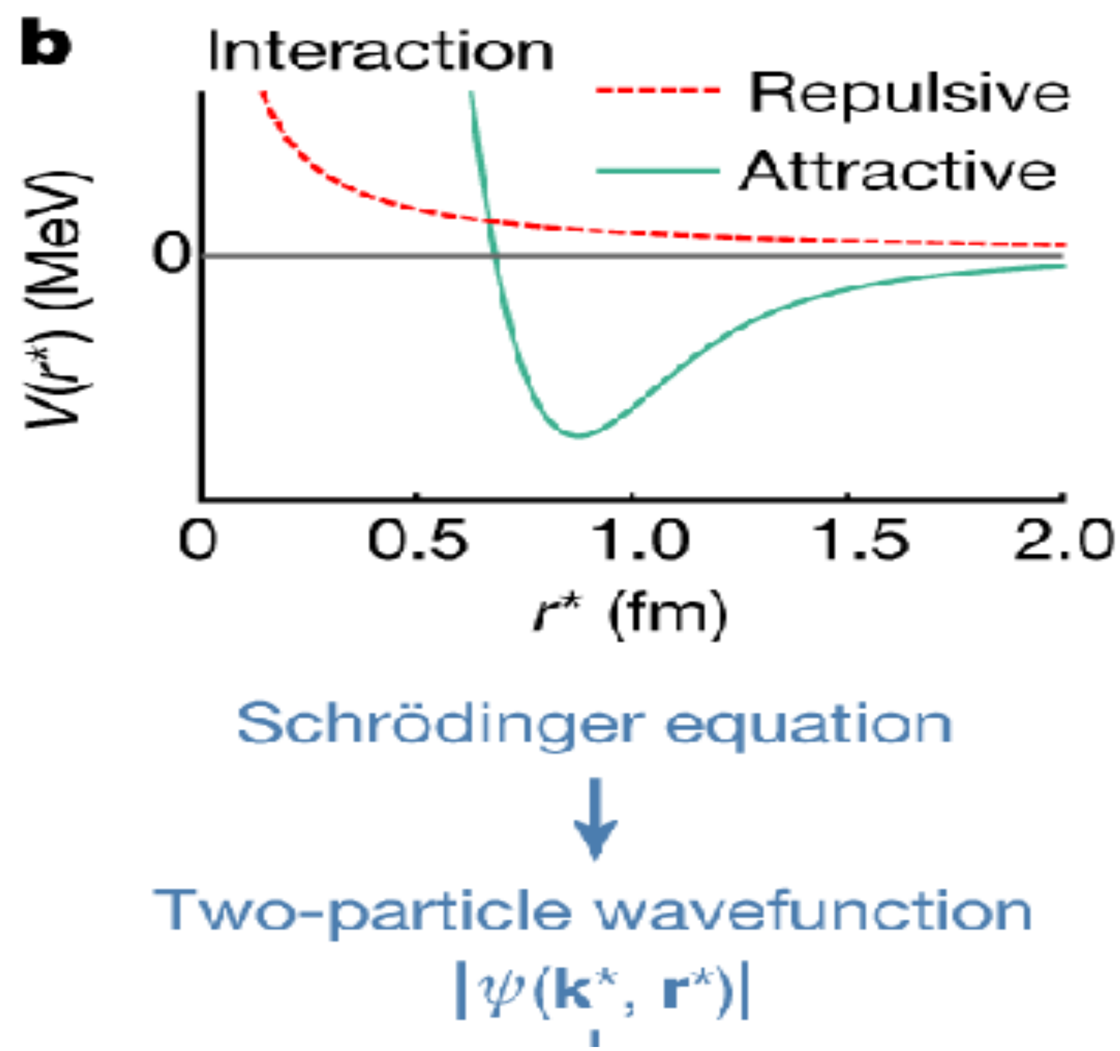
Emission source $S(r^*)$

Nature 588, 232–238 (2020)

Correlation function

$$C(k^*) = \int S(r^*)|\psi(k^*, r^*)|^2 \, d^3r^*$$

Two particle wave function: (non-traditional femtoscopy) measures final state interactions



Lednicky Approach:
f_0 (scattering length), d_0 (effective radius)

Sov. Journ. Nucl. Phys. 35 (1982) 770

Nature 588, 232–238 (2020)

Lednicky Approach:

$$\Psi^{(+)}_{-\vec{k}^*}(\vec{r^*}) = \sqrt{A_C(\varepsilon)}\frac{1}{\sqrt{2}}\Big[e^{-i\vec{k}^*\times\vec{r}^*}F(-i\varepsilon, 1, i\zeta^+) + f_C(\vec{k}^*)\frac{\tilde{G}(\rho,\varepsilon)}{r^*}\Big],$$

Assumptions:

- Independent emission
- Single particle source
- Source size is bigger than the range of interaction (~1fm)
- s-wave component dominant in FSI description (for close relative velocities)

A_C is Gamow factor
$\zeta^{\pm} = k^* r^* (1 \pm cos\theta^*)$
$\epsilon = 1/(k^* a_c)$
F is the confluent hypergeometric function
$\tilde{G}$ is the combination of the regular and singular s-wave Coulomb functions
$f_c(k^*)$ is the strong-interaction scattering amplitude modified by the Coulomb component:

$$f_c^{-1}(k^*) = \frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(k^* a_c) - ik^* a_c$$

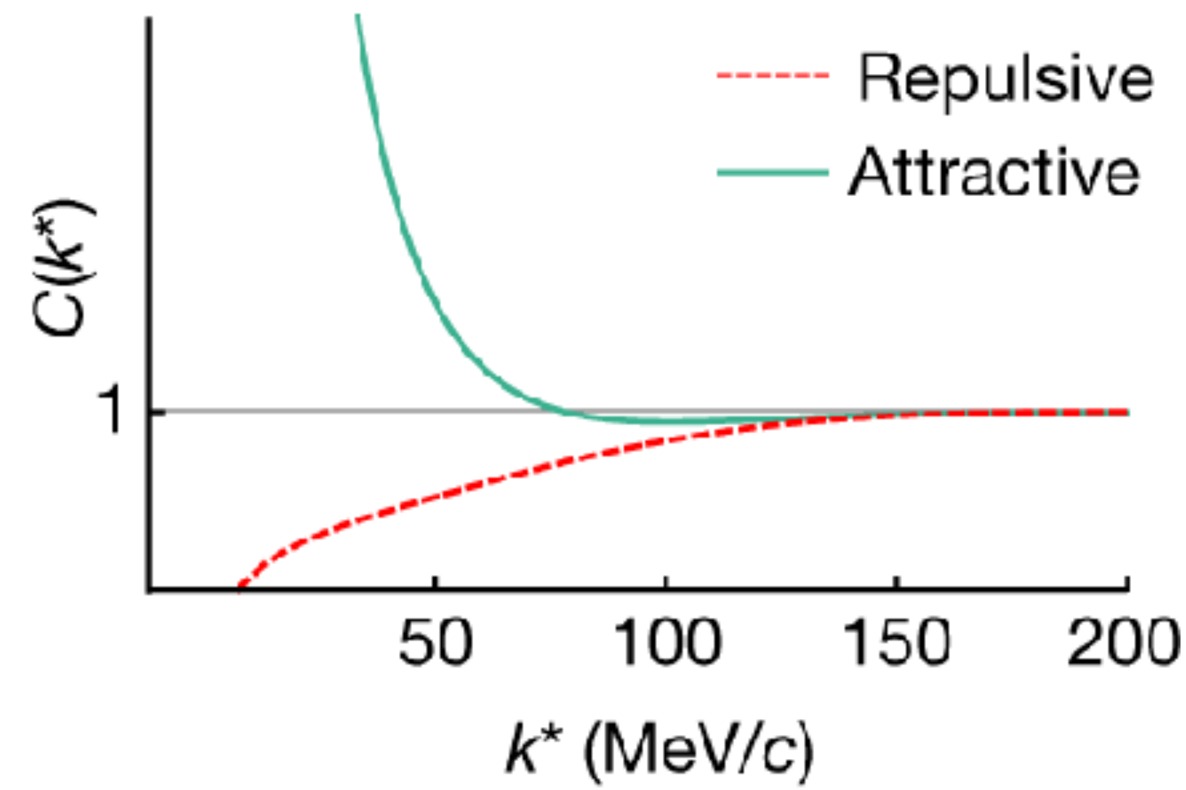
Scattering parameters appears directly in Lednicky approach.
=> connection to strong interaction.

Sov. Journ. Nucl. Phys. 35 (1982) 770

Correlation function

$$C(k^*) = \int S(r^*)|\psi(k^*, r^*)|^2 \, d^3r^*$$

Correlation function: measured experimentally



Nature 588, 232–238 (2020)

C(k*) = A(k*)/B(k*)
A(k*): same event distribution
B(k*): mixed event distribution

$k^* = |\vec{p_1}| = |\vec{p_2}|$

Where $\vec{p_1}$ and $\vec{p_2}$ are three momentum of particles.

How to quantify

Correlation function in spherical coordinates

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

where harmonic components are:

$$C_l^m(q) = \int_\Omega C(q, \theta, \phi) Y_l^m(\theta, \phi) d\Omega$$

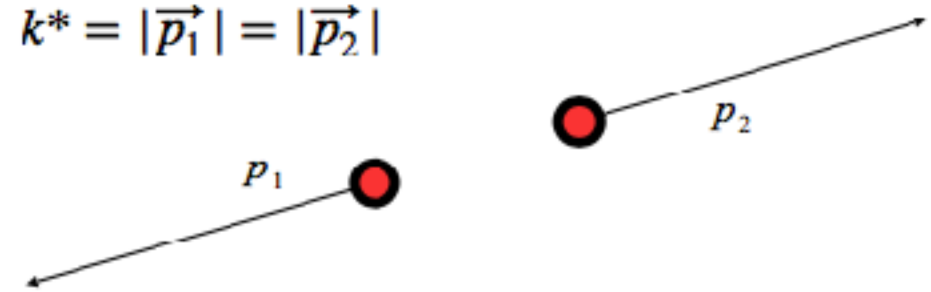
Ω - full solid angle
$Y_l^m(\theta, \phi)$ - spherical harmonic function
$q = |\mathbf{q}|$ - pair relative momentum
θ and ϕ - polar and azimuthal angle

C_0^0 :sensitive to size of the emitting source (shapes same as correlation function)

C_1^1 :sensitive to the spacetime emission asymmetry

Pair Rest Frame - **PRF**

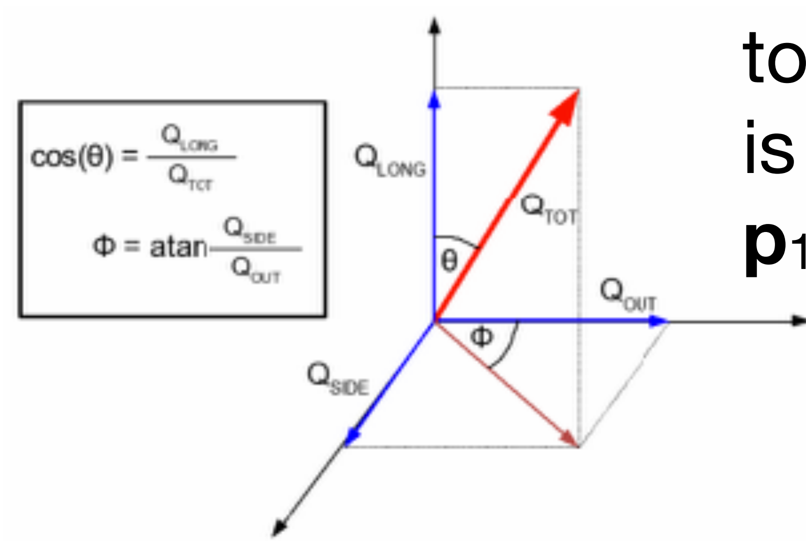
$k^* = |\vec{p_1}| = |\vec{p_2}|$



$Q_{inv} = 2k^*$ if $m_1 = m_2$

From Hanna Zbroszczyk

Pair Rest Frame (PRF): total momentum of pair is zero,
$\mathbf{p}_1 + \mathbf{p}_2 = 0$



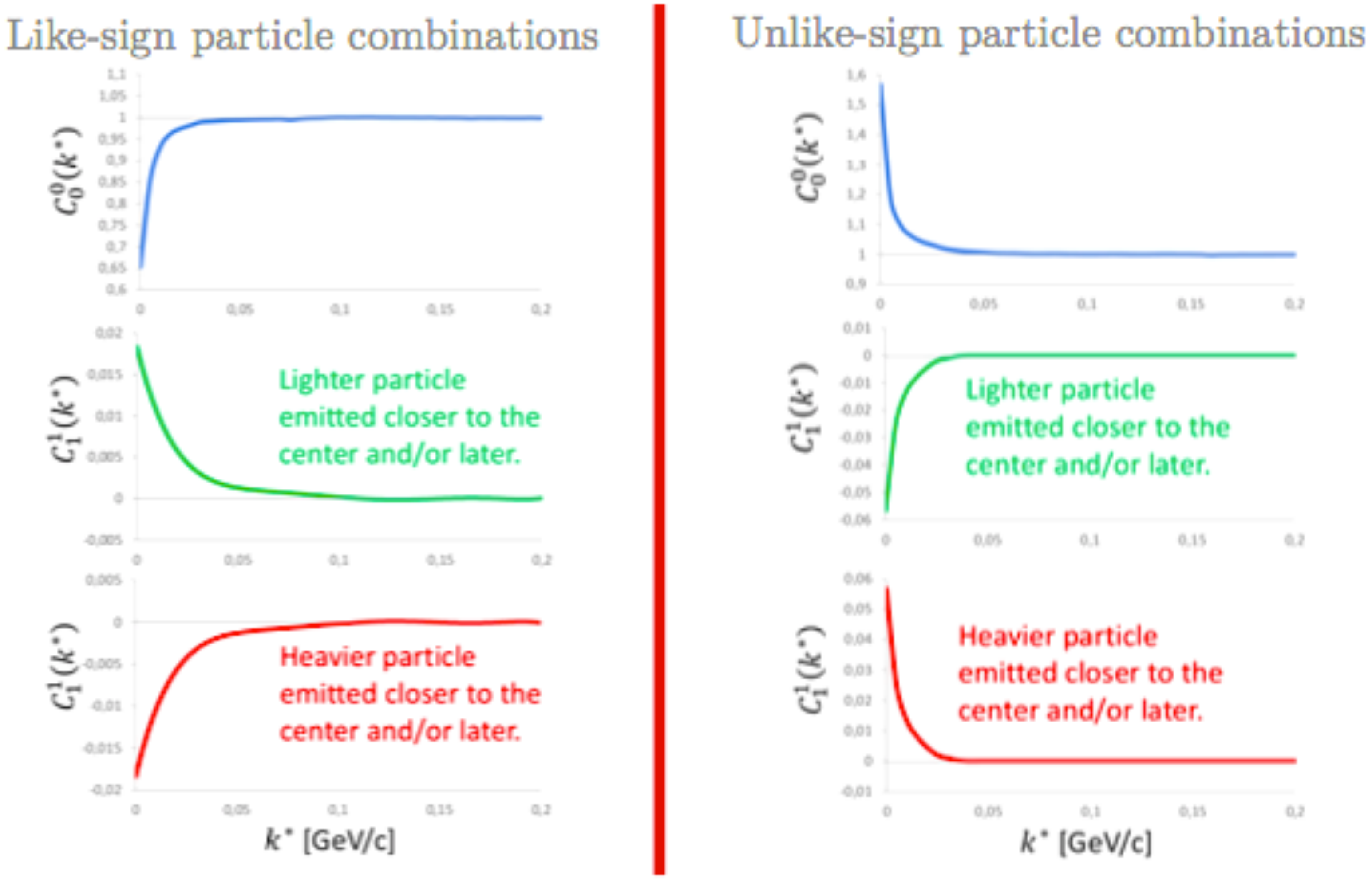
From Zbigniew Chajecki

P. Danielewicz and S. Pratt., Phys. Lett B618, 60 (2005) Phys. Rev. C75, 034907 (2007)
Z. Chajecki and M. Lisa Phys. Rev. C78, 064903 (2008)
Kisiel and D.A. Brown Phys. Rev. C80, 064911 (2009)
A. Kisiel Phys. Rev. C81, 064906 (2010)

Pion-Kaon system: asymmetry

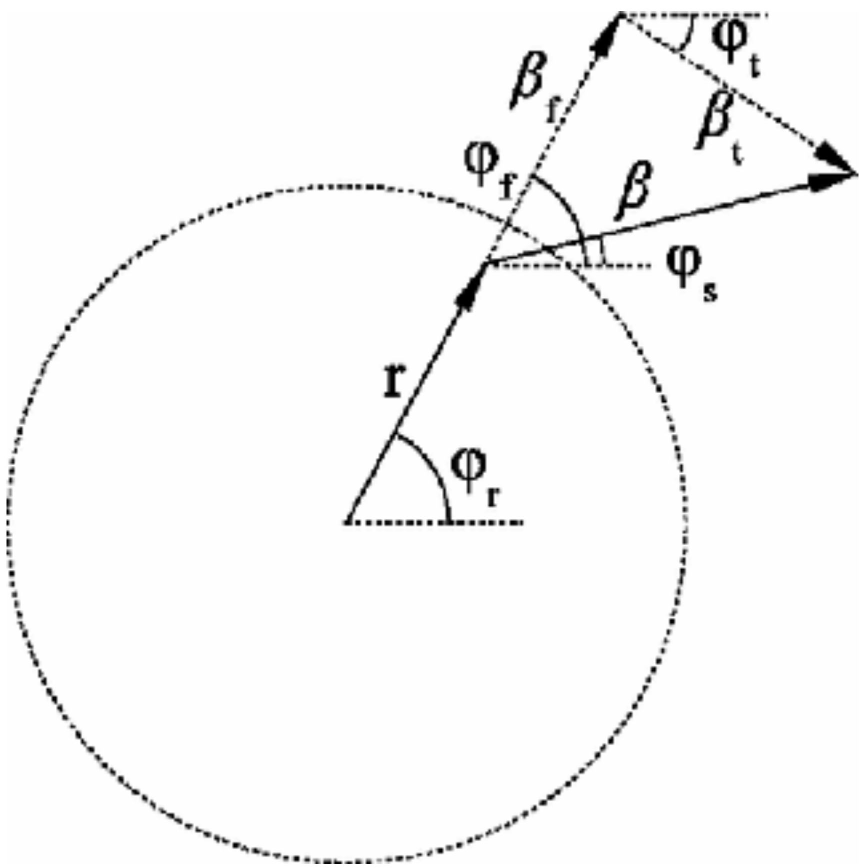
Time asymmetry:
particles are assumed to be emitted from the same positions; viz. kaon (anti-proton) is considered as emitted first, the pion (proton) second

Spatial asymmetry:
particles are assumed to be emitted at the same time;
viz. pion (proton) is assumed to be emitted closer (to the center of system) and kaon (anti-proton) is considered as emitted further from the system center



Emission asymmetry arises in a system where both thermal and collective velocities exist and are comparable in magnitude
Lighter particles are emitted closer to the centre/later than heavier particles

Pion-Kaon system: asymmetry



In a hydrodynamical induced system :

$$\beta_{particle} = \beta_f + \beta_t$$

β_f: collective (flow) velocity
β_t: thermal (random) velocity

component of mean emission point of a single particle parallel to the velocity

$$\langle x_{out} \rangle = \frac{\langle r\beta_f \rangle}{\langle \sqrt{\beta_t^2 + \beta_f^2} \rangle} = \frac{r_0 \beta_0 \beta}{\beta_0^2 + T/m_t}$$

Adam Kisiel Phys. Rev. C 81, 064906 (2010)

For more details:
Talk by Adam Kisiel, 8/11/23

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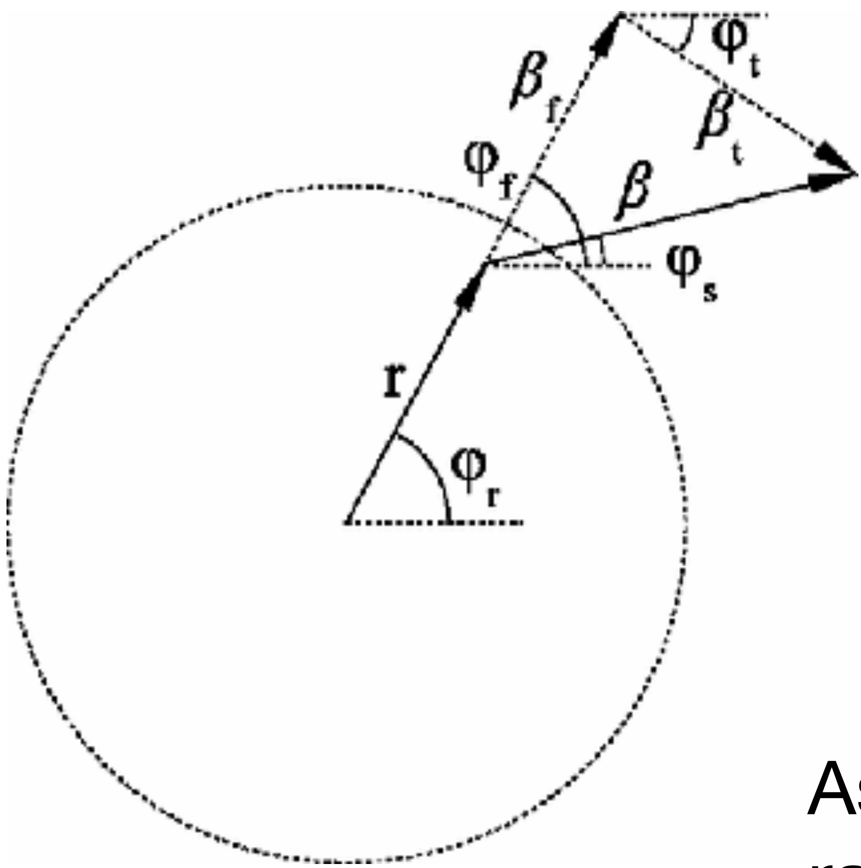

Adam Kisiel Phys. Rev. C 81, 064906 (2010)

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Assuming Gaussian density profile,
radius r_0, linear transfer velocity profile $\beta_f = \beta_0/r_0$

$$S(r^*) = exp\left(-\frac{(r_{out} - \mu_{out})^2}{\sigma_{out}^2} - \frac{r_{side}^2}{\sigma_{side}^2} - \frac{r_{long}^2}{\sigma_{long}^2} \right)$$

$$\mu_{out}^{light,heavy} = \langle r_{out}^{light,heavy} \rangle = \langle x_{out}^{light} - x_{out}^{heavy} \rangle$$

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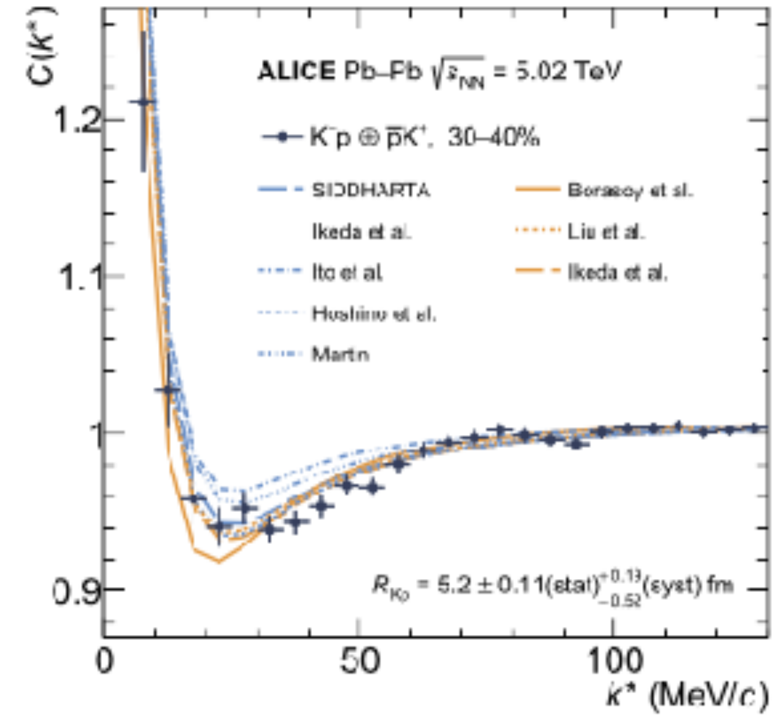
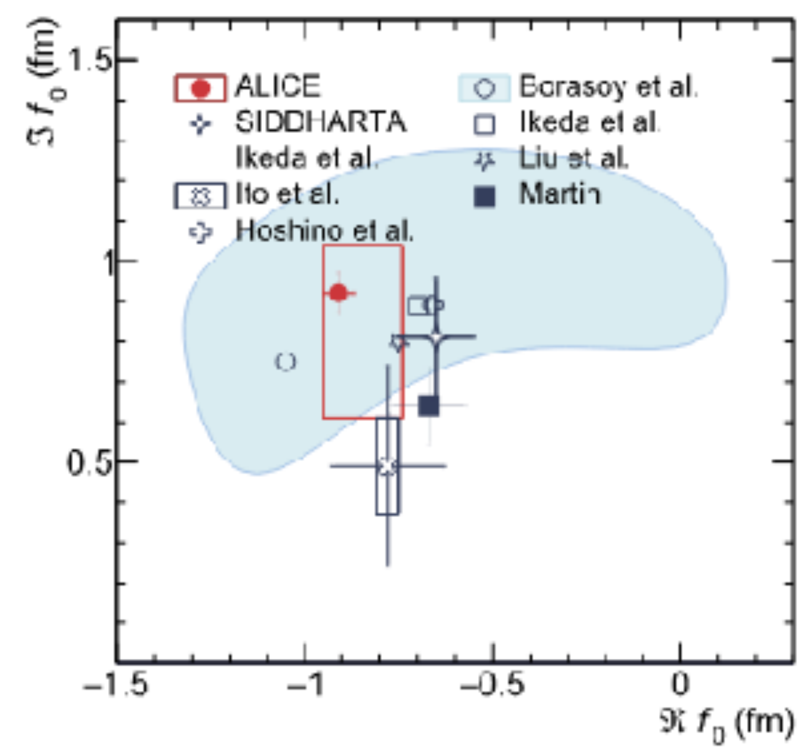
Kaon-proton system: Strong interaction

- Kaons are less affected by the decay of resonances than pions
- Radius of particle emitting source - geometry of source
- Kaon-proton scattering parameters that describe the strong interaction

=>Scattering length f_0
=>effective range d_0

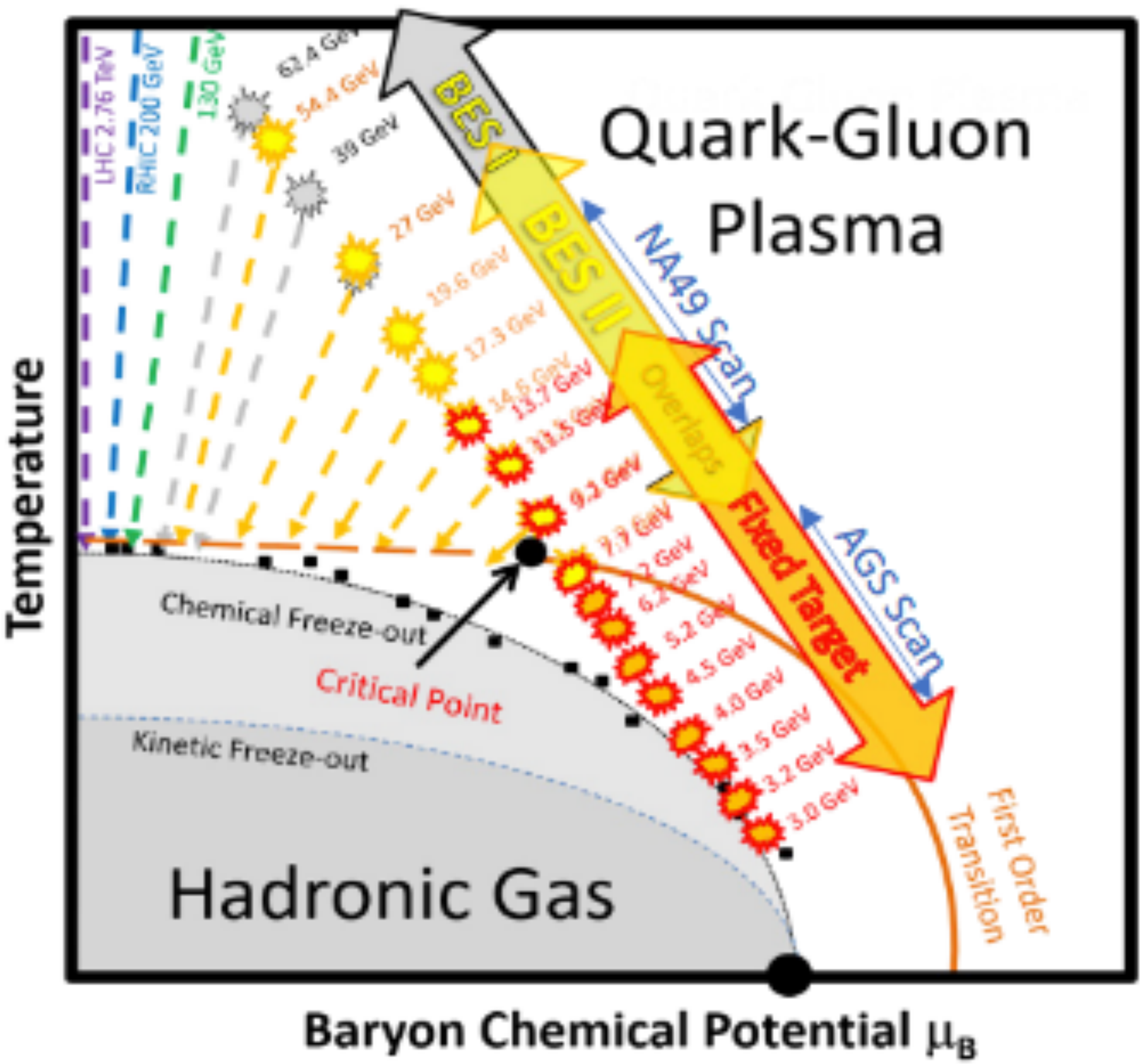
For more details:
Talk by Malgorzata Janik, 7/11/23

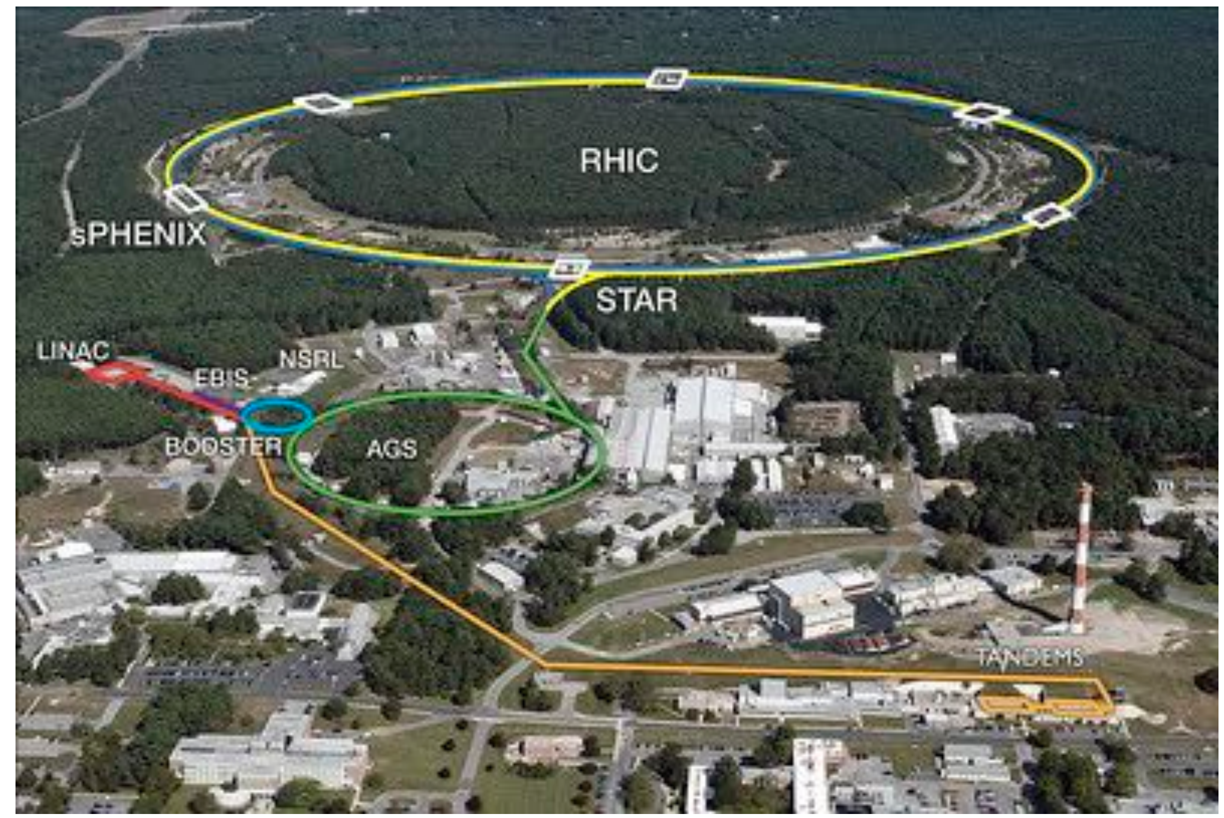




Kaon–proton, PbPb 5.02 TeV, ALICE Collaboration
Phy Let B 822 (2021) 136708

STAR experiment at RHIC



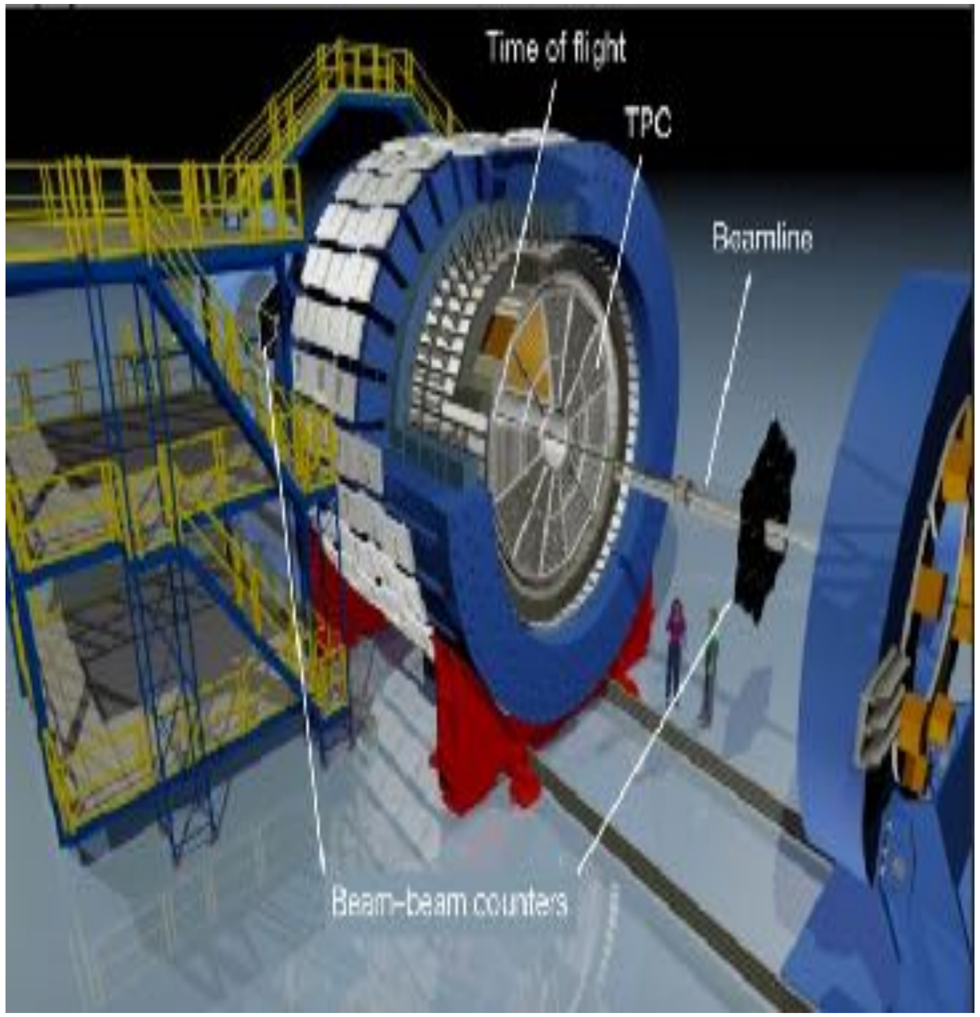


https://indico.cern.ch/event/1139644/contributions/5343956/

Energy:
$\sqrt{s_{NN}}$ = 3- 200 GeV (500 GeV for p+p)

Systems:
p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U

Particle Identification



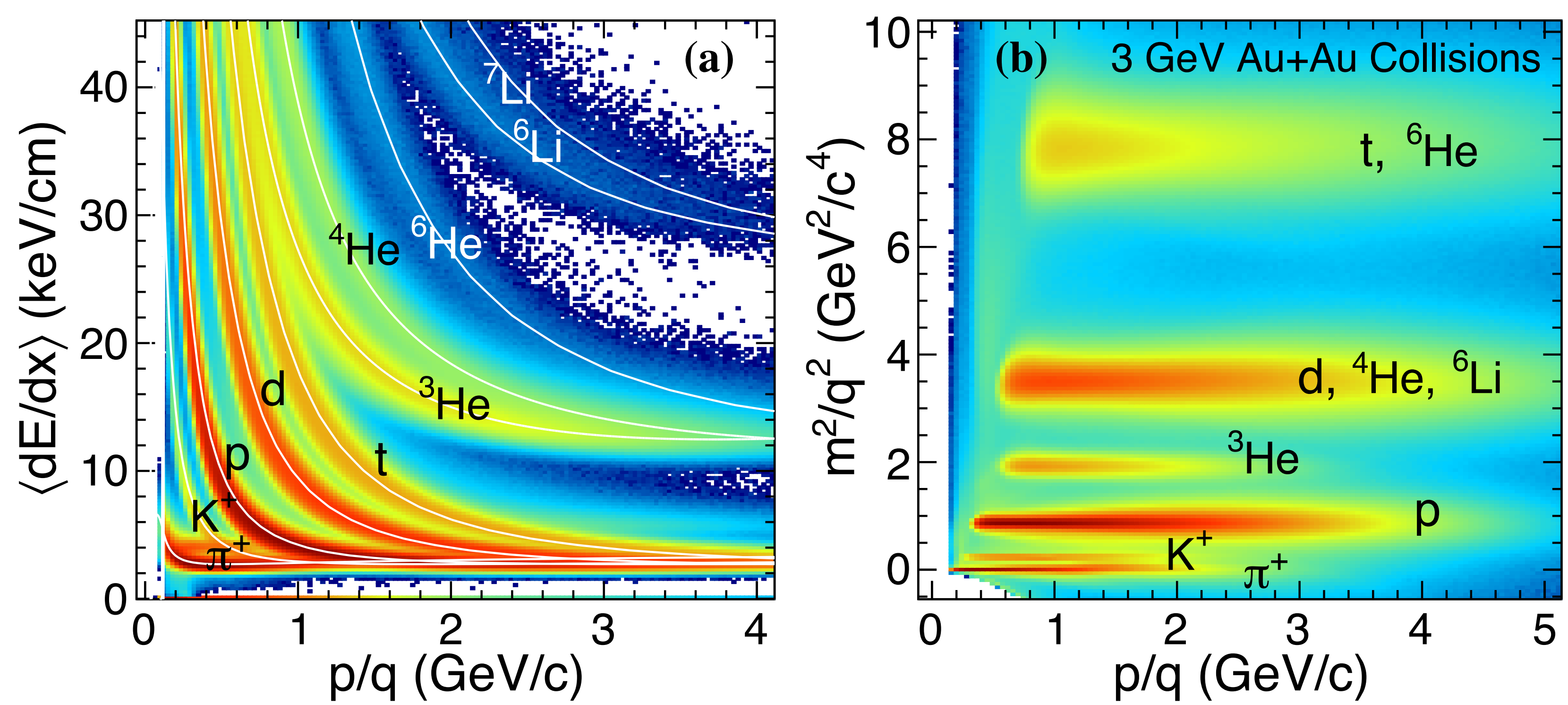
https://doi.org/10.1038/nature23004

Large acceptance:|η|<1.8, 0<ϕ<2π
Excellent particle identification capabilities (Time Of Flight and Time Projection Chamber)

$\sqrt{s_{NN}}$	7.7	11.5	39 (0-10%)	39 (10-30%)	39 (30-70%)
#Events (in mln)	0.24	1.3	11.7	25.7	45.4

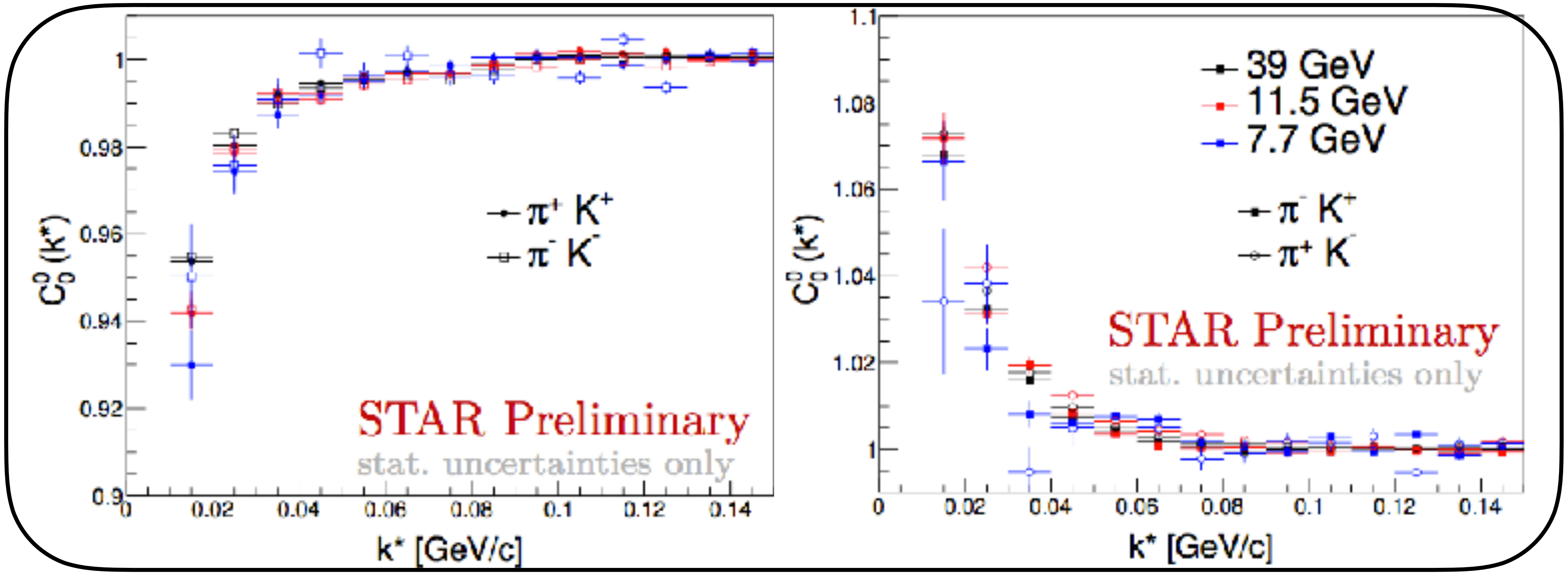
TPC - ionization energy loss

From TOF - mass^2

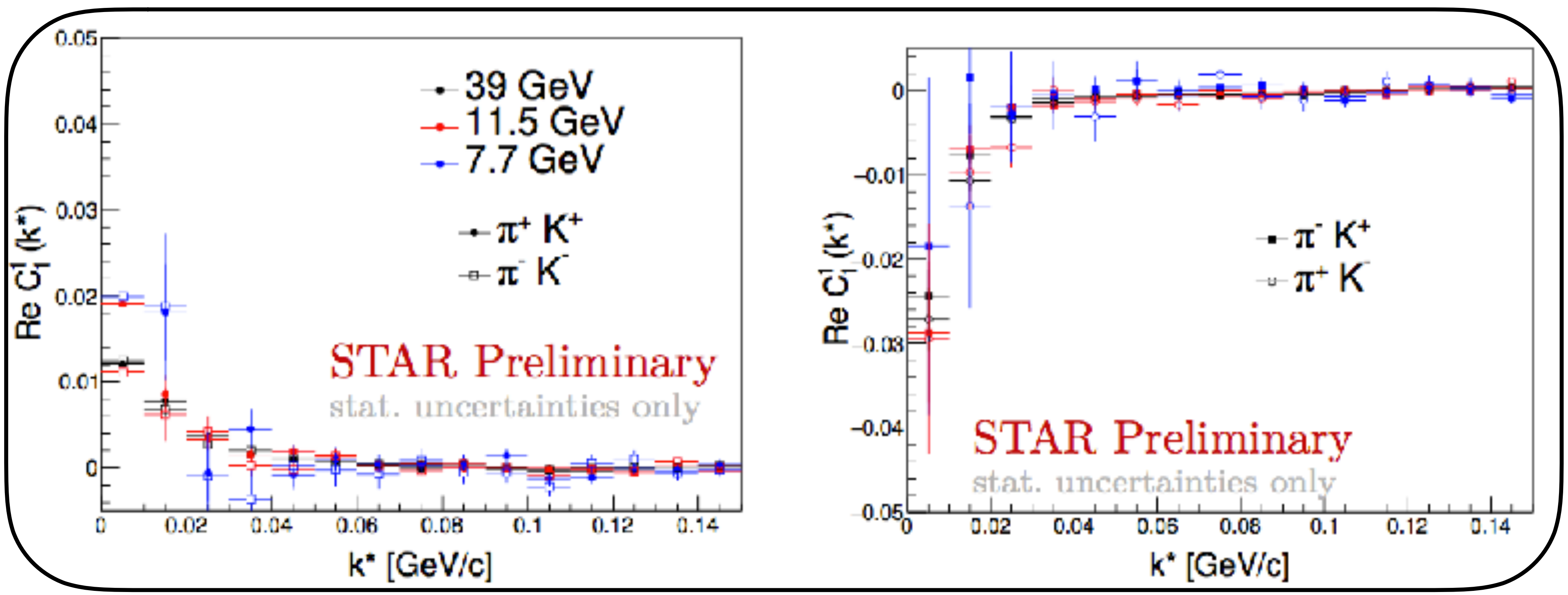


STAR collaboration
Phys. Lett. B 827 (2022) 136941

Collision energy dependence

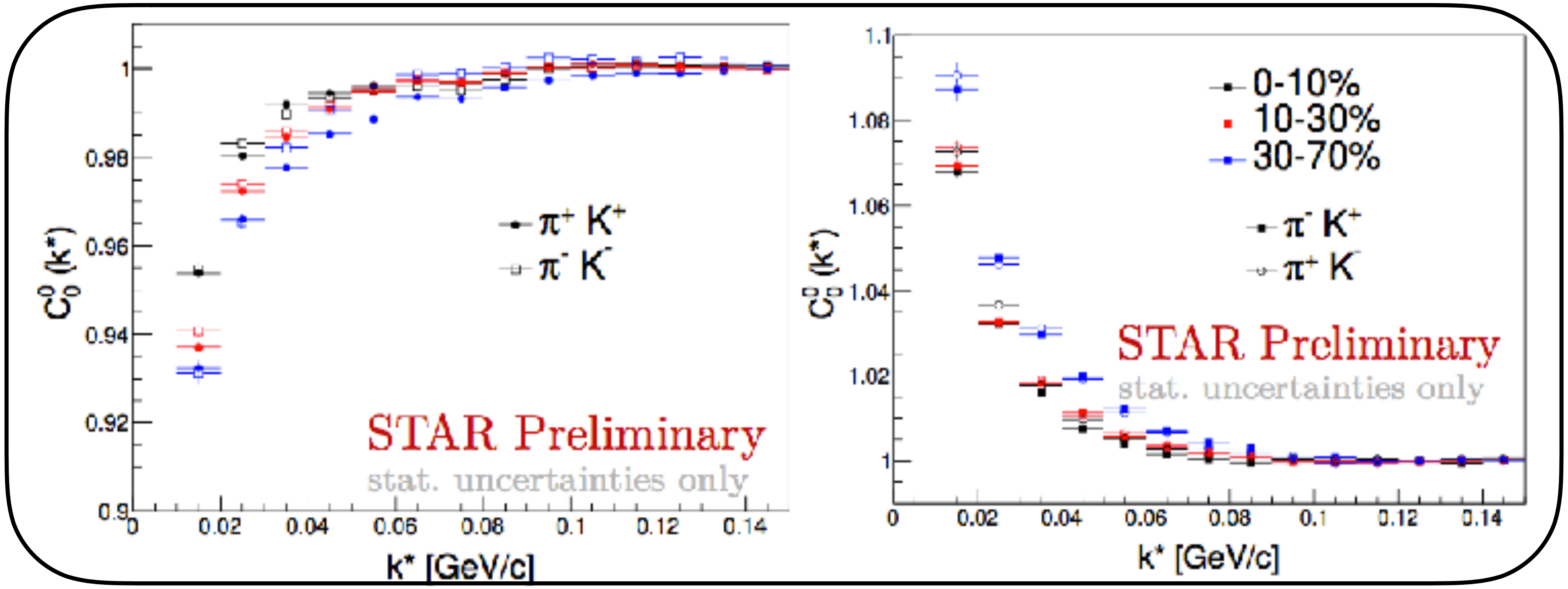


Visible energy dependence

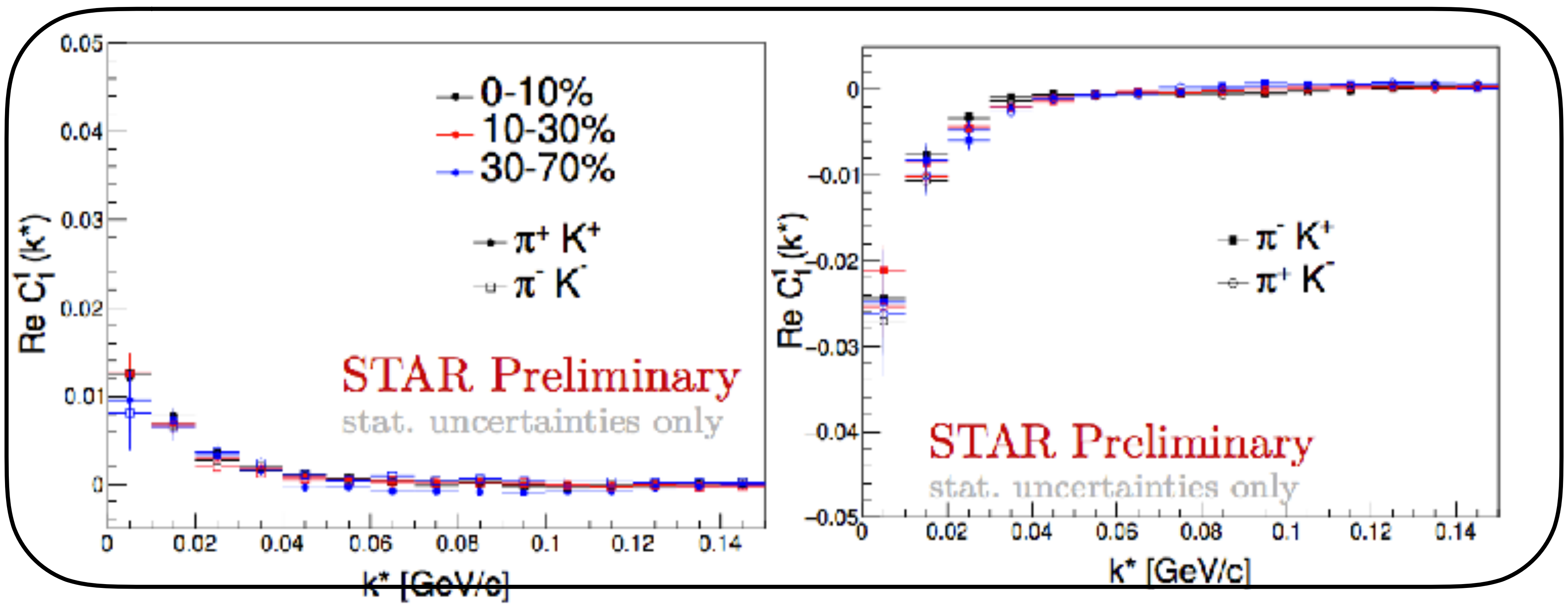


<Zero: signal of emission asymmetry

Centrality dependence

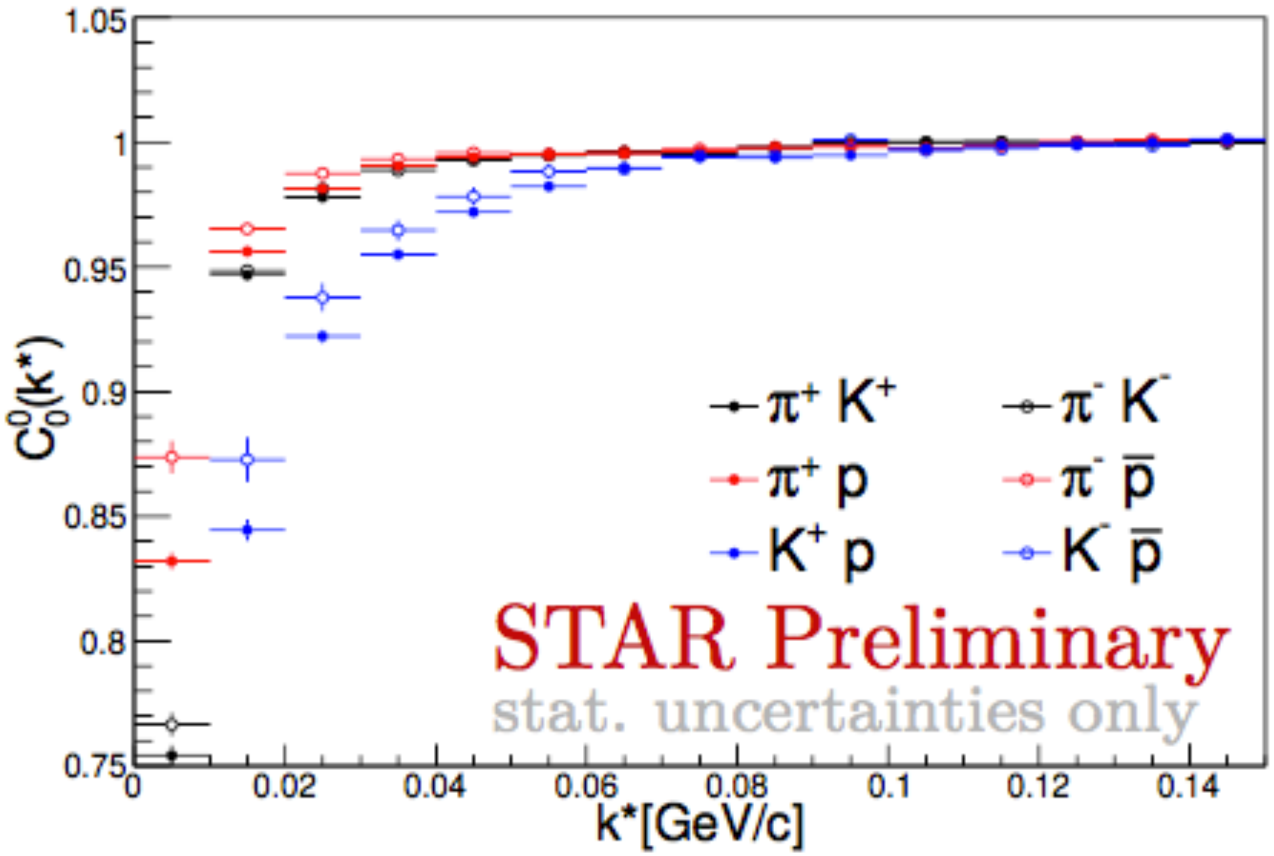


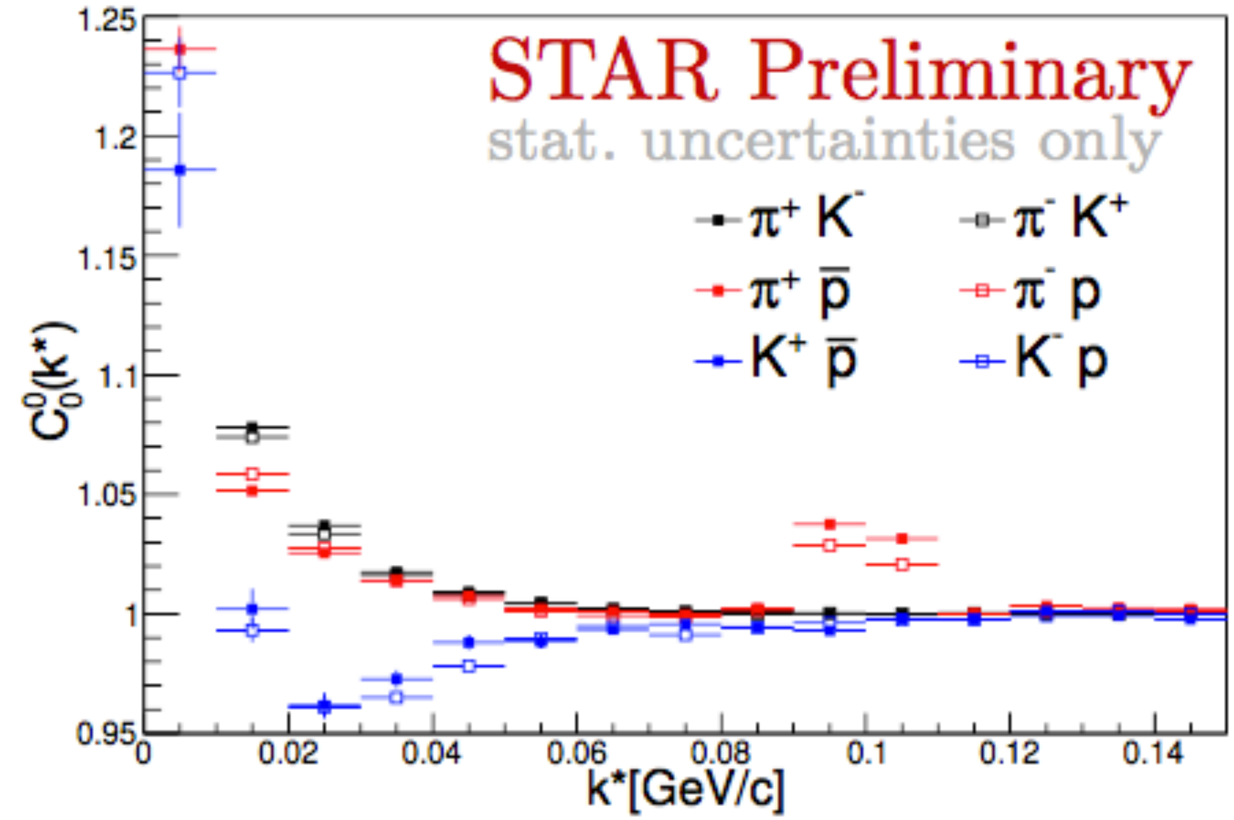
Visible centrality dependence



<Zero: signal of emission asymmetry

System dependence

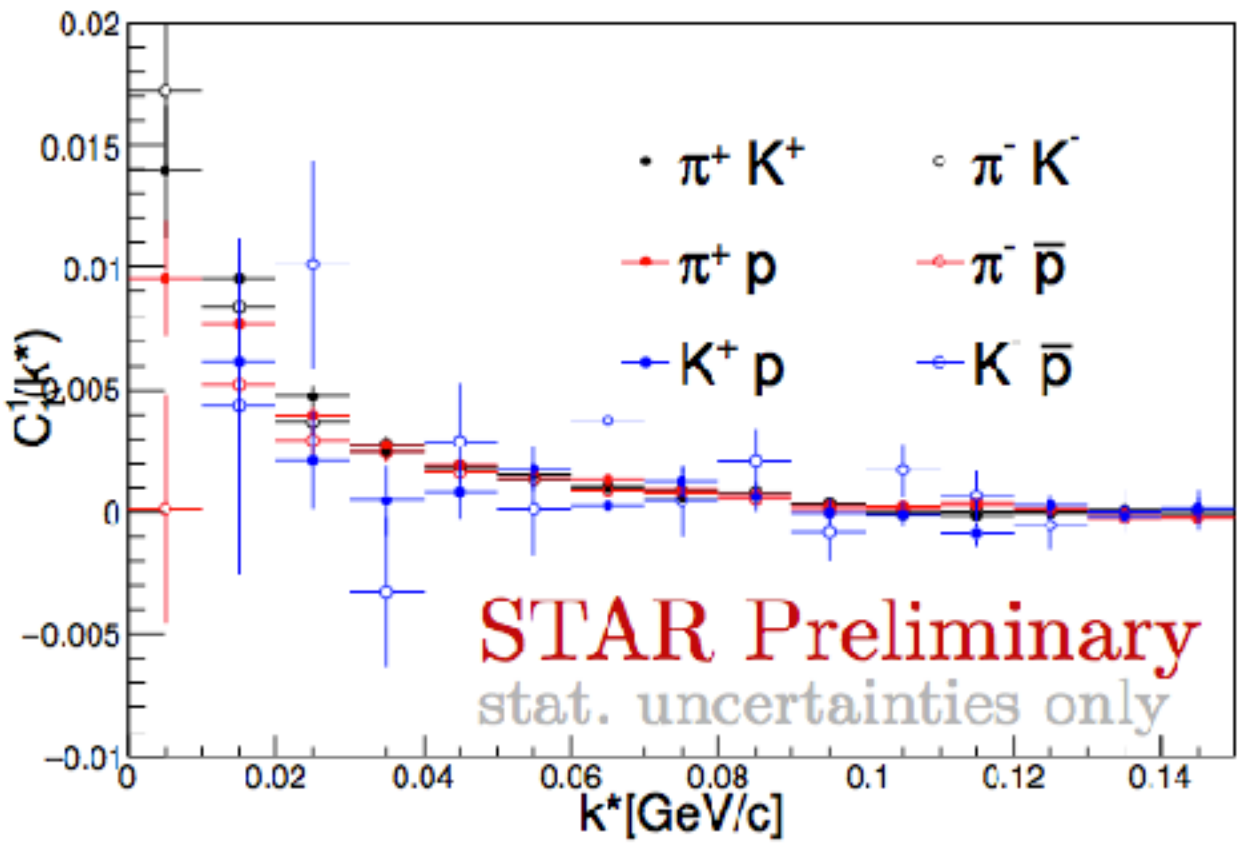




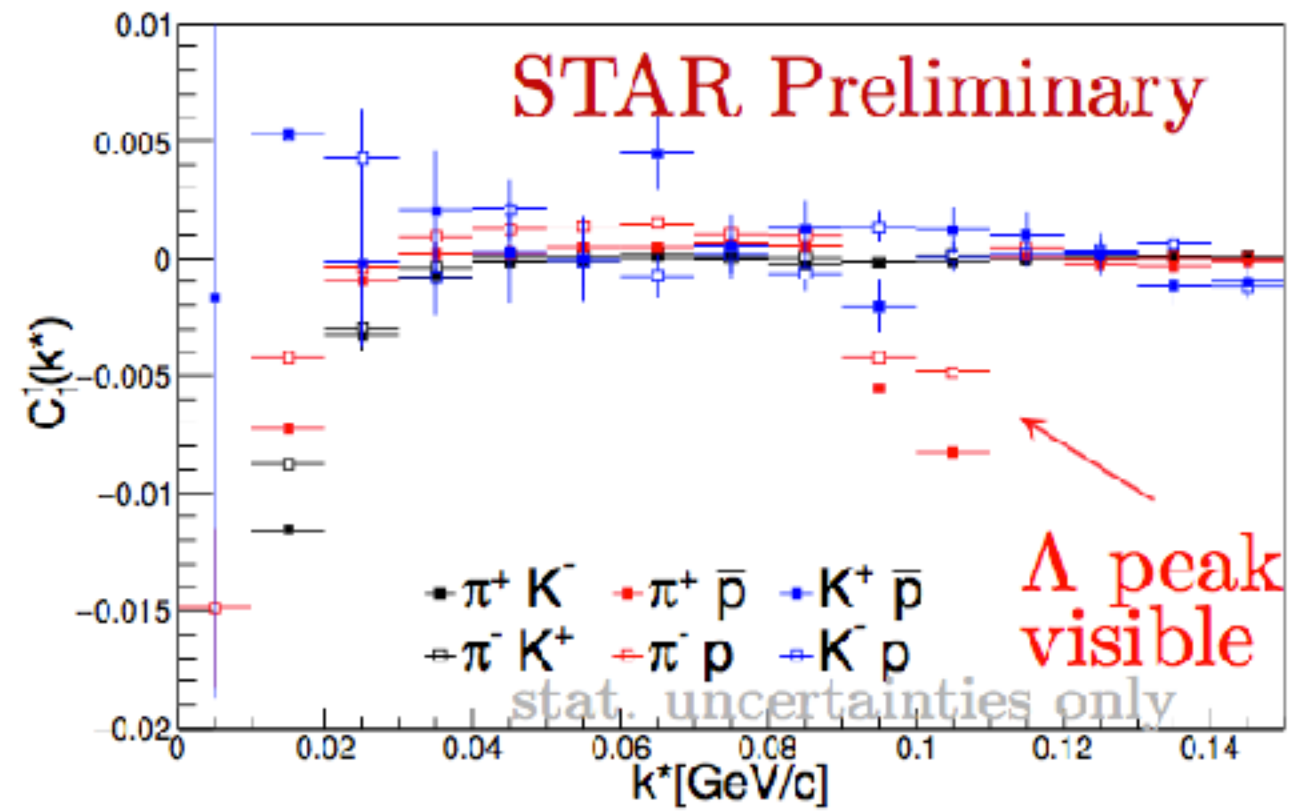
- Clear system dependence.
- Correlation function dominated by Coulomb interaction.
- Kaon-proton → strongest correlation.

- Λ(1116) peak visible in pion-proton.
- Kaon-proton pairs have significant strong interaction.

System dependence



Visible signal of emission asymmetry



Expected ordering of particles -> sensitive to collective effects

Conclusion

☑ Geometry:
Visible centrality, system and energy dependence of source size at BES energies.

☑ Dynamics:
Clear signal of emission asymmetry for pion-kaon systems
=>collectivity effects
Lighter particles are emitted closer to the center and/or later

☑ Interactions:

A. Repulsive strong interaction appears below unity in the region of k^* ~10-50 MeV/c for Kaon-proton pair.

B. Like Sign correlation function:

Like sign pairs are dominated by Coulomb.

Kaon-proton → strongest correlation.

C. Unlike sign correlation function:

Λ(1116) peak visible in pion-proton.

Kaon-proton correlation function sensitive to strong interaction.

Outlook

- ☑ Exploring kaon-proton interaction
- ☑ Parameter of strong interaction - to be extracted

Thank you !