Femtoscopy in BES

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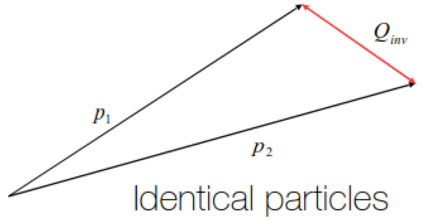
2023 RHIC/AGS Annual Users' Meeting

Femtoscopy/Motivation

- Access to the spatial and temporal information about a particle-emitting source
- Different particle species are sensitive to various effects (FSI, shear and bulk viscosity, temperature, space and time emission asymmetries, etc...)
- Strong model constraints

Q_{inv}

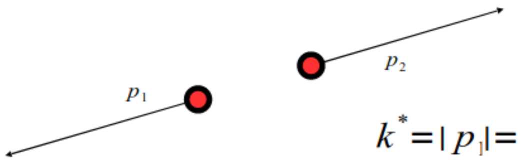
Longitudinal Co-Moving System - **LCMS**



Identical particles

k^*

Pair Rest Frame - **PRF**



$k^* = |p_1| = |p_2|$

Nonidentical particles

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

1) determined | assumed | measured

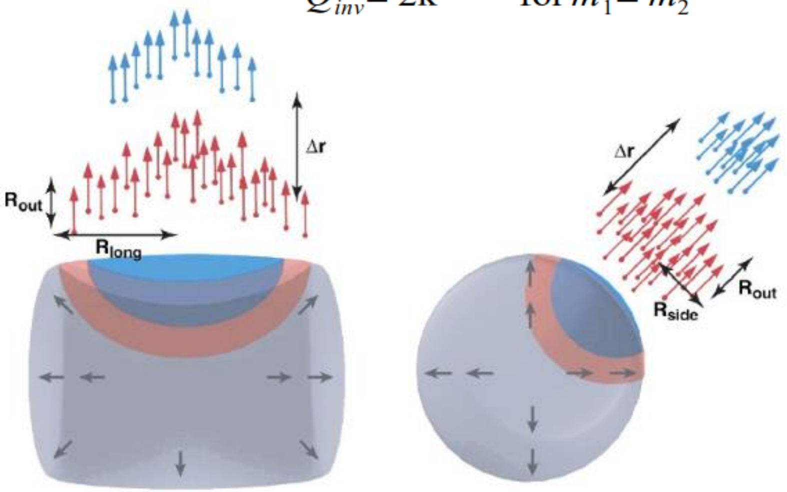
$$C(k^*, r^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 d^3 r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

$S(r^*)$ - emission function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

2) assumed | determined | measured

$$C(k^*, r^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 d^3 r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

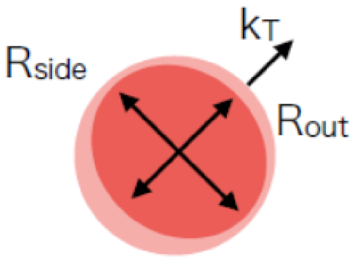


Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

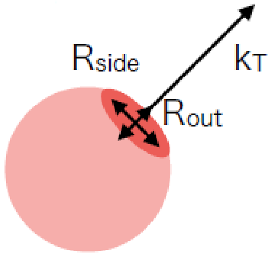
Pions in BES

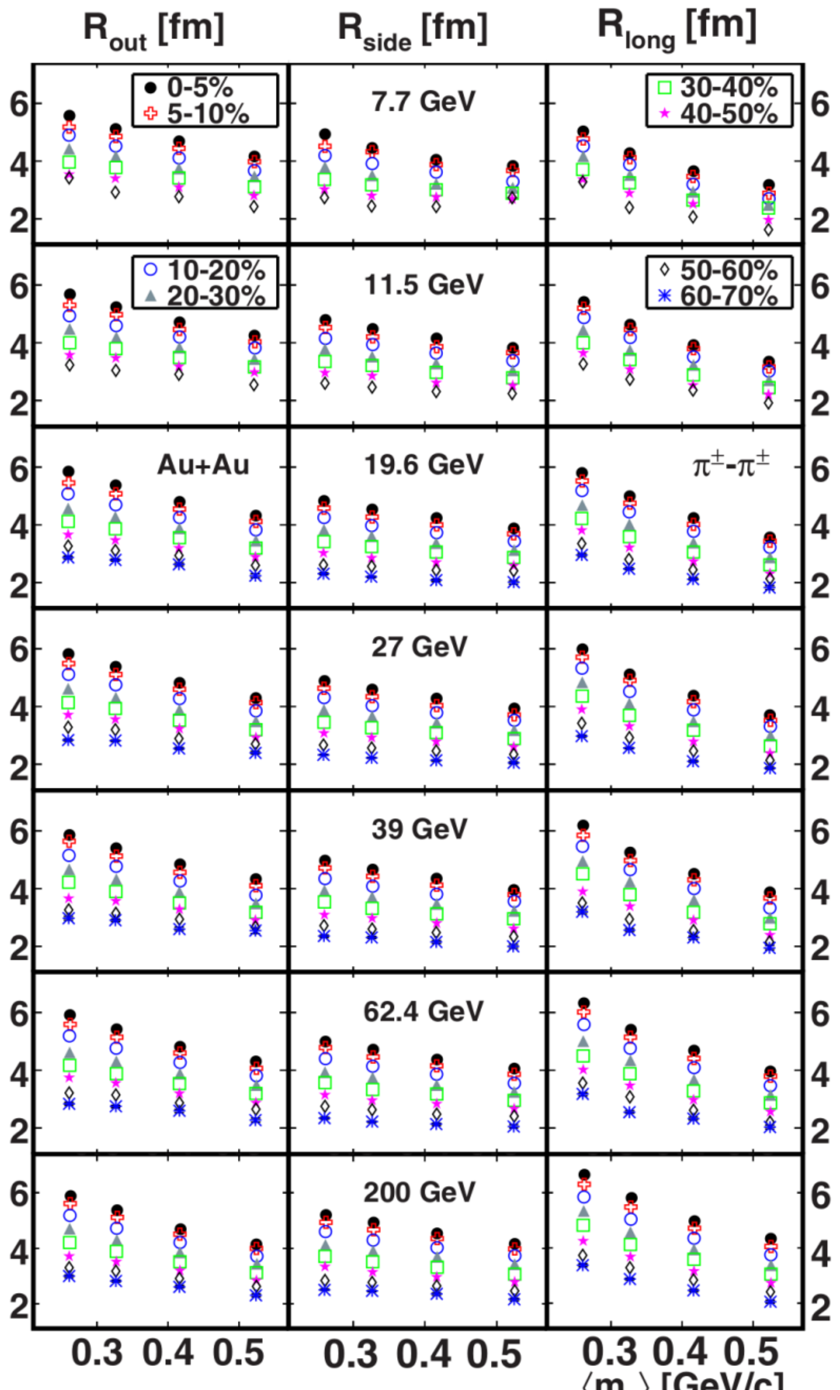
- The radii decrease for more peripheral events due to the smaller geometric size of the initial participant region and the subsequent emission region at freezeout.
- For R_{long} , the slopes appear to remain similar for the different energies, but the magnitude of R_{long} increases with energy for all centralities.
- The decrease in transverse and longitudinal radii at higher m_T are attributed to transverse and longitudinal flow.
- Larger m_T pairs are emitted from smaller emission regions with less correspondence to the size of the entire fireball. For both R_{out} and R_{side} the different beam energies show similar trends both in magnitude and slope.

Low k_T



High k_T





Phys.Rev.C 92 (2015) 1, 014904

Pions in BES

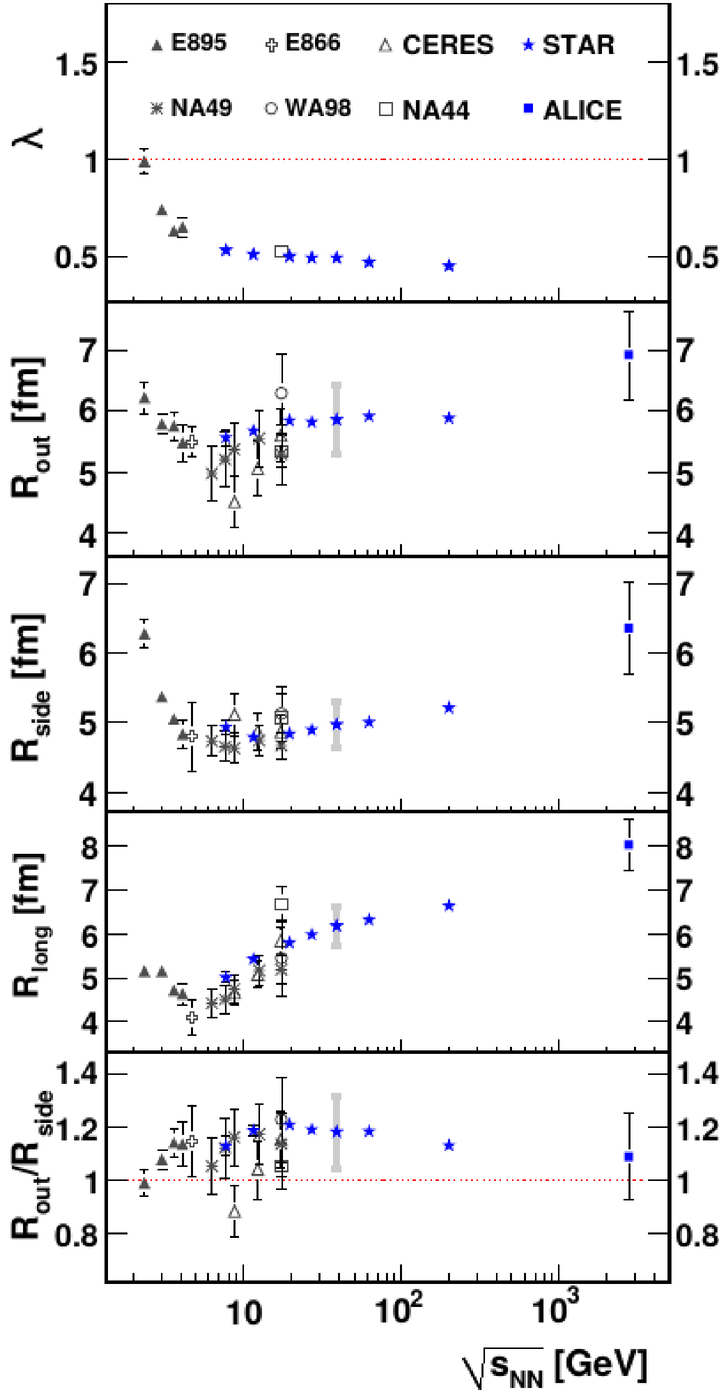
Fraction of correlated pairs entering the analysis

Radial flow and emission duration

Geometrical size

Longitudinal flow and evolution time

As a search of a phase transition



Phys.Rev.C 92 (2015) 1, 014904

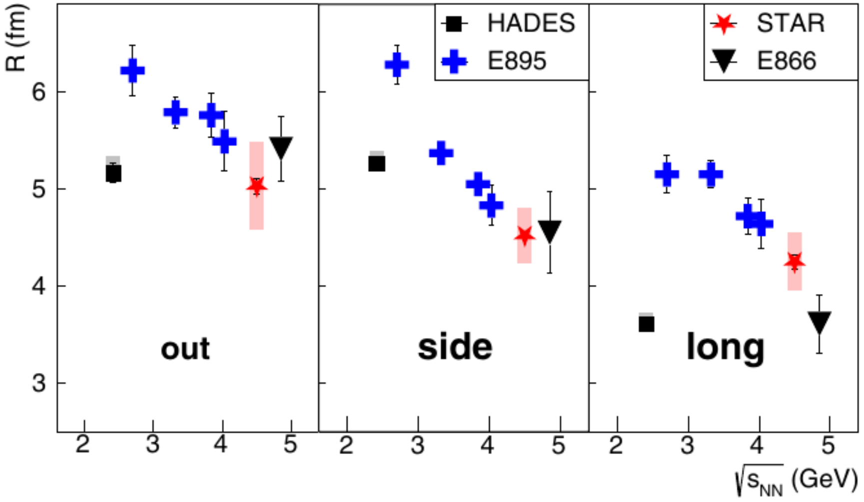
Pions in BES

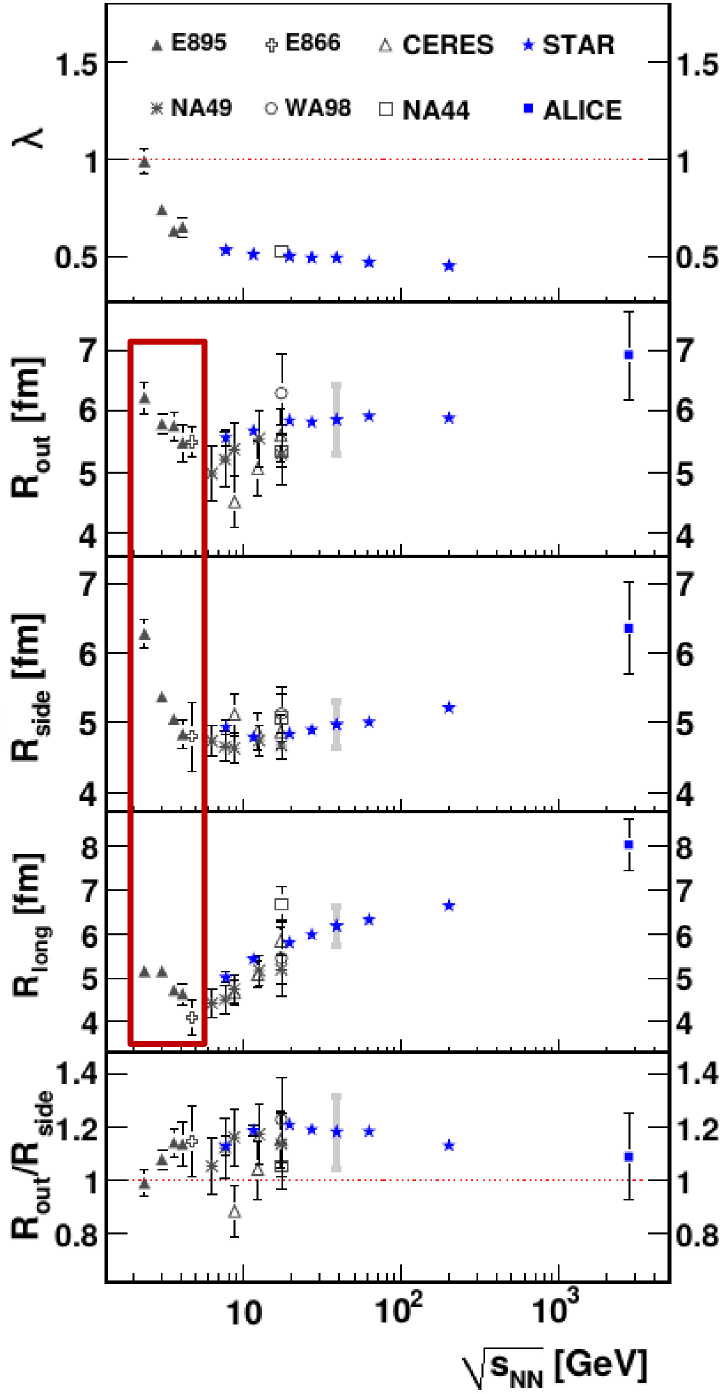
- The λ parameter primarily represents the fraction of correlated pairs entering the analysis. This suggests that the fraction of pions in this kT range from long-lived resonances increases at lower energy but remains rather constant at higher energies (same for mT dependence)

BES-II data

More data on Quark Matter 2023

The fixed-target STAR points are consistent with this trend within the uncertainties.





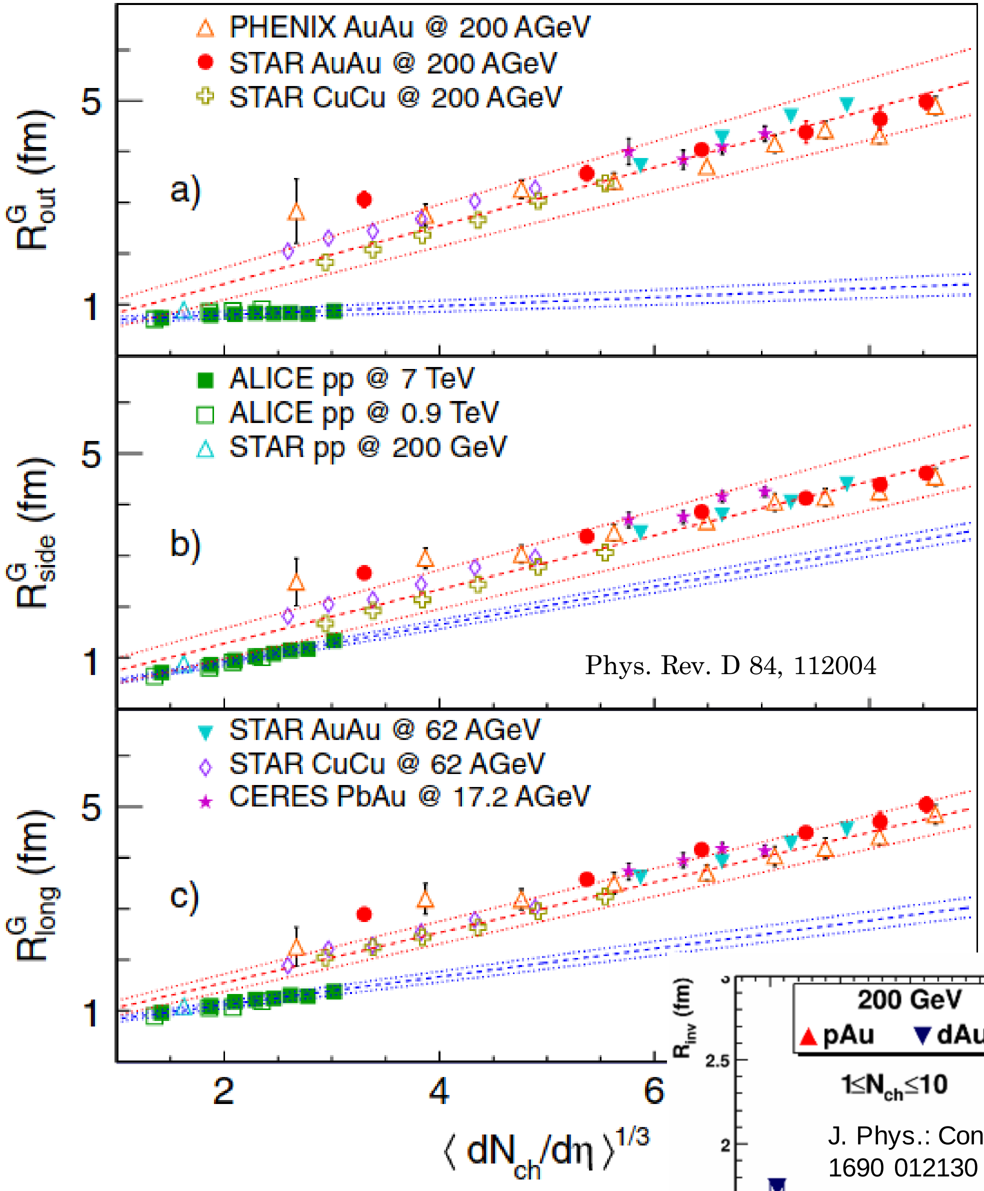
- Difference between experiments can be due to acceptance effects, centrality determination and choice of analyzing charges separate or together

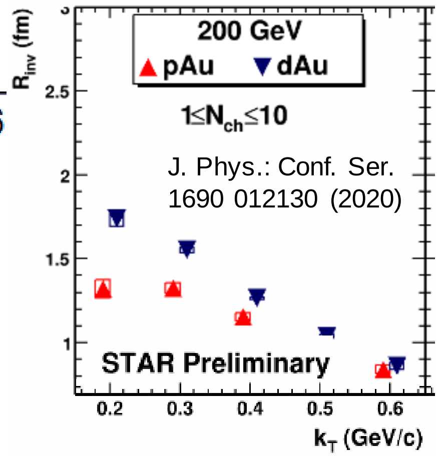
- Interesting behavior of HADES data → importance of the BES-II results

Phys.Rev.C 92 (2015) 1, 014904
Phys.Rev.C 103 (2021) 3, 034908

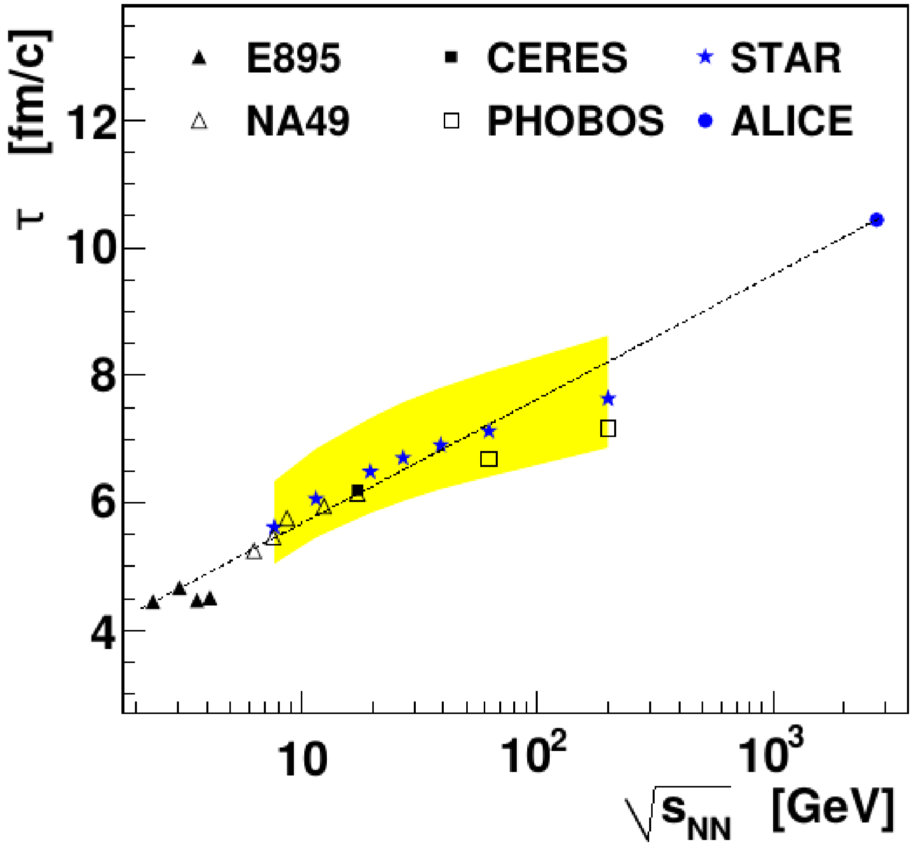
Pions in BES

- Space and time scale as ~ multiplicity^1/3
- Radii follow a common universal trend independent of the collision species?
- “Universal” scaling of femtoscopic radii with final state multiplicity is violated by the pp data.
- It shows that any scaling law must take into account the initial configuration of the collision.
- The difference may be due to the interactions in the bulk medium formed in heavy ion collisions.





Pions in BES



Phys.Rev.C 92 (2015) 1, 014904

- The created system lives longer, however no sudden jumps in timescales in R_{long}
- One may significantly underestimate the actual lifetimes due to use of, which do not take non-zero flow into account:

$$R_{\mathrm{long}} = \tau\sqrt{\frac{T}{m_T}\frac{K_2(m_T/T)}{K_1(m_T/T)}}$$

$$R^2_{\mathrm{long}} = \tau^2_{\mathrm{max}}\frac{T_{\mathrm{max}}}{m_{\mathrm{T}}\cosh y_{\mathrm{T}}}\left(1+\frac{3T_{\mathrm{max}}}{2m_{\mathrm{T}}\cosh y_{\mathrm{T}}}\right)$$

- More results → **Quark Matter 2023**

Pions in BES

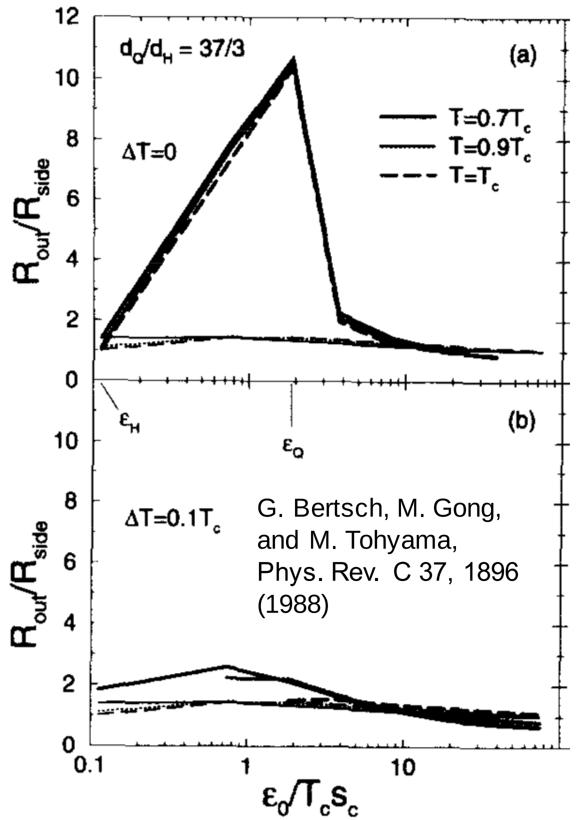
- Now that the predicted Rout /Rside energy systematic has been revealed, it deserves theoretical attention from hydro and transport modelers. The magnitude and width of the structure may allow an estimate of the latent heat of the QCD deconfinement transition.

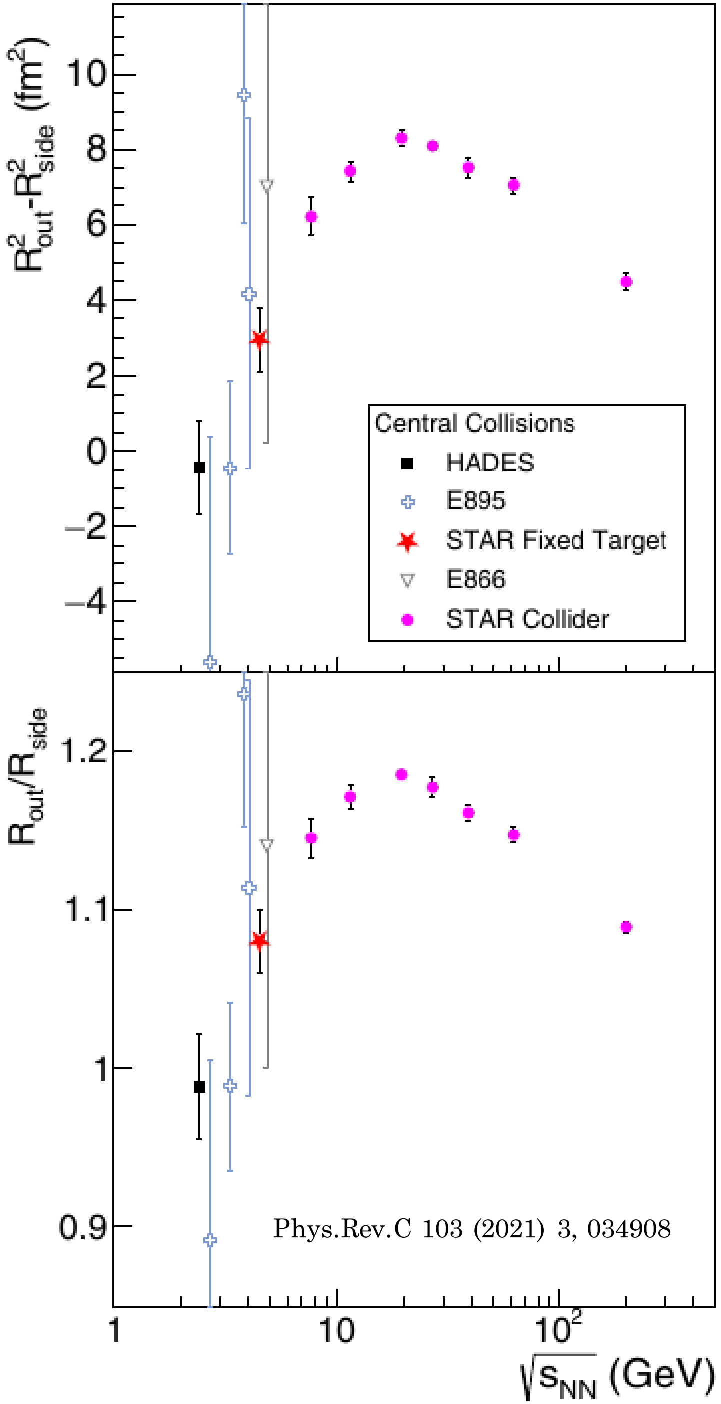
- While collective flow complicates the interpretation, an extended emission timescale will increase Rout relative to Rside. A long emission timescale may arise if the system equilibrates close to the deconfinement phase boundary and then evolves through a first-order phase transition in the QCD phase diagram

F. Retière and M. A. Lisa, Phys. Rev. C 70, 044907 (2004).

- Both quantities exhibit a clear peak at ~ 20 GeV, an interesting energy where other observables show nontrivial trends with energy.

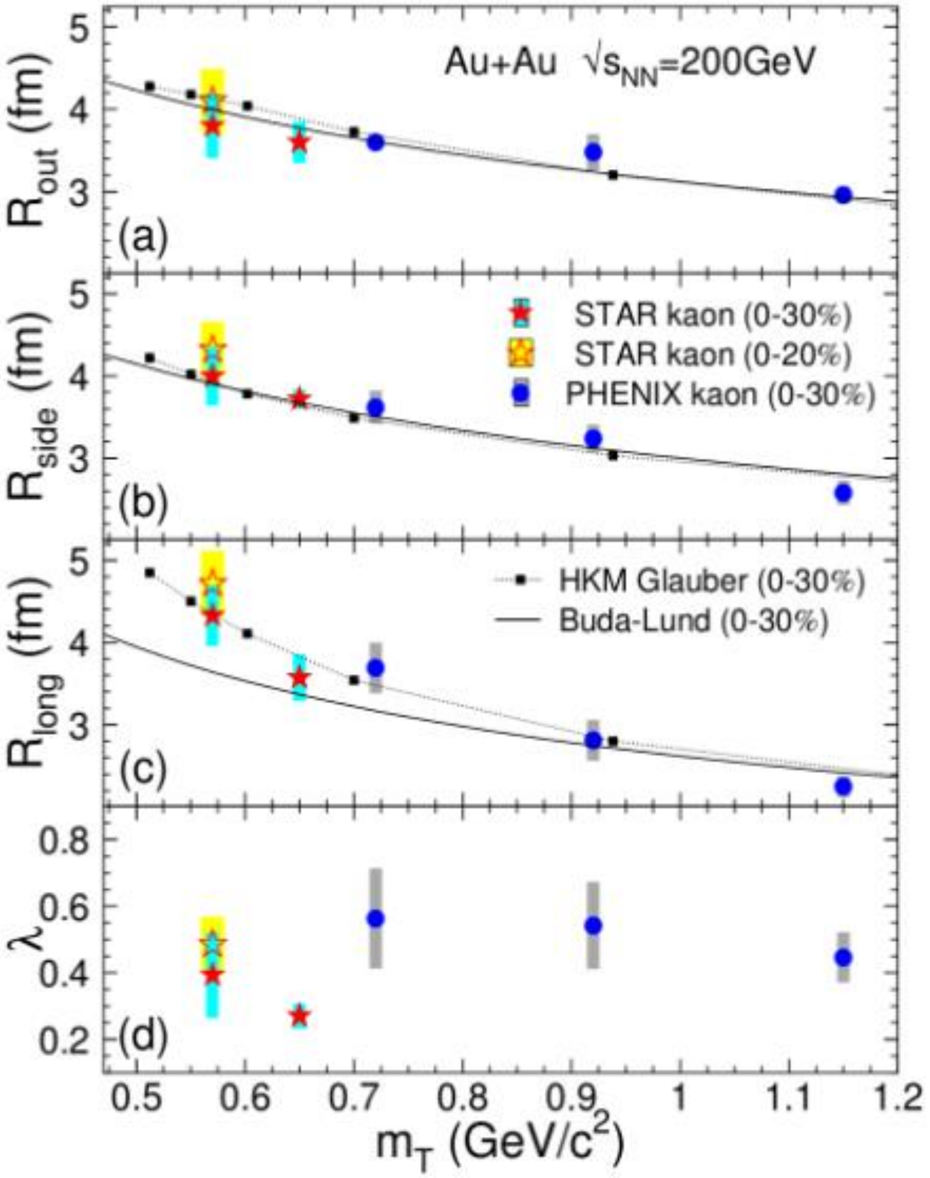
- Long-sought peak structure that may be caused by the system evolving through a first-order phase transition from the QGP to the hadronic phase.





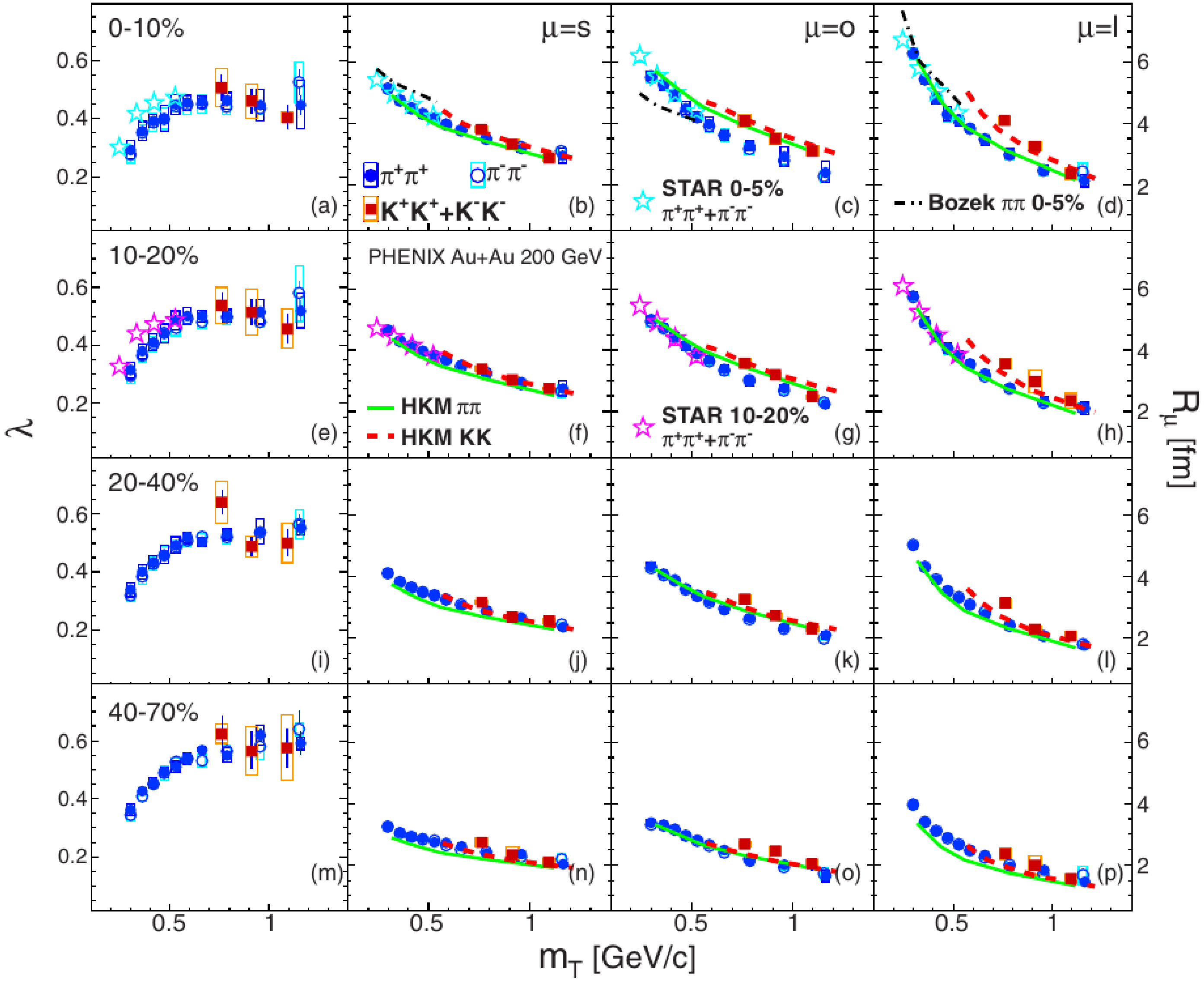
Kaons in BES

- To test assumptions:
  - Larger fraction of primarily produced charged kaons as compared to pions
  - More penetrating probe (smaller kaon-nucleon cross-section w.r.t pions)
  - Due to the strange quark content, may carry information about different collision stage
- Both pions and kaons provide constraints on theoretical models
  - Possibility to distinguish between different model scenarios
- Check for m_T dependence → determine freeze-out conditions



PHENIX, PRL 103 (2009) 142301
STAR, PRC 88 (2013) 034906

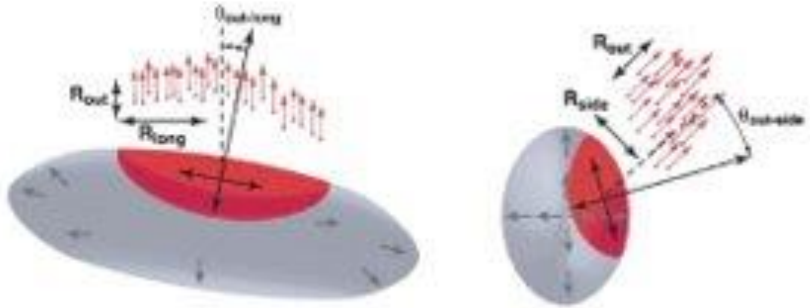
Kaons in BES



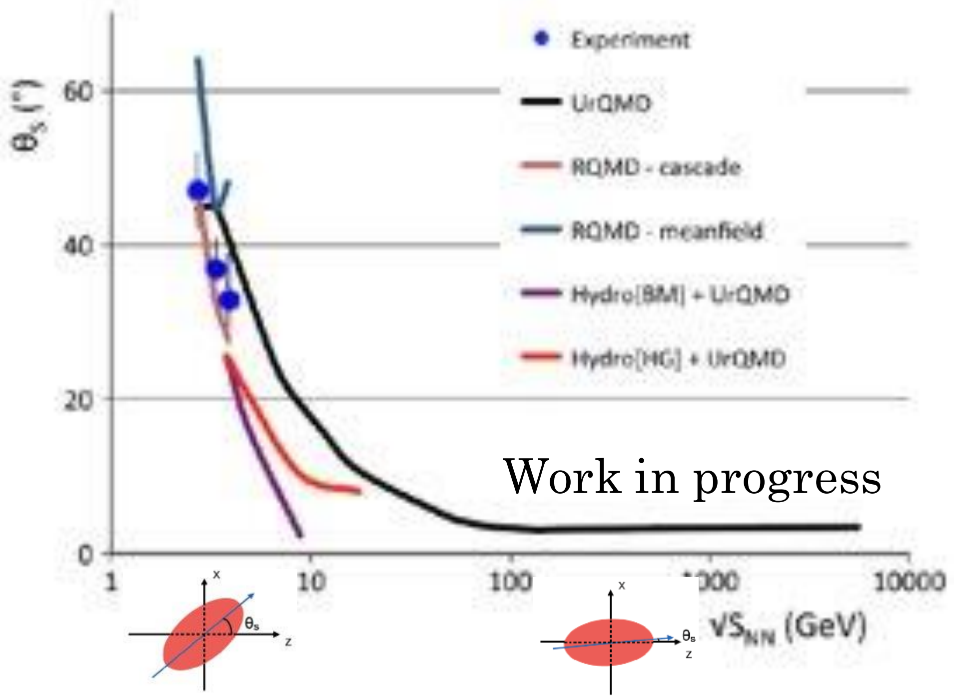
PHYSICAL REVIEW C 92, 034914 (2015)

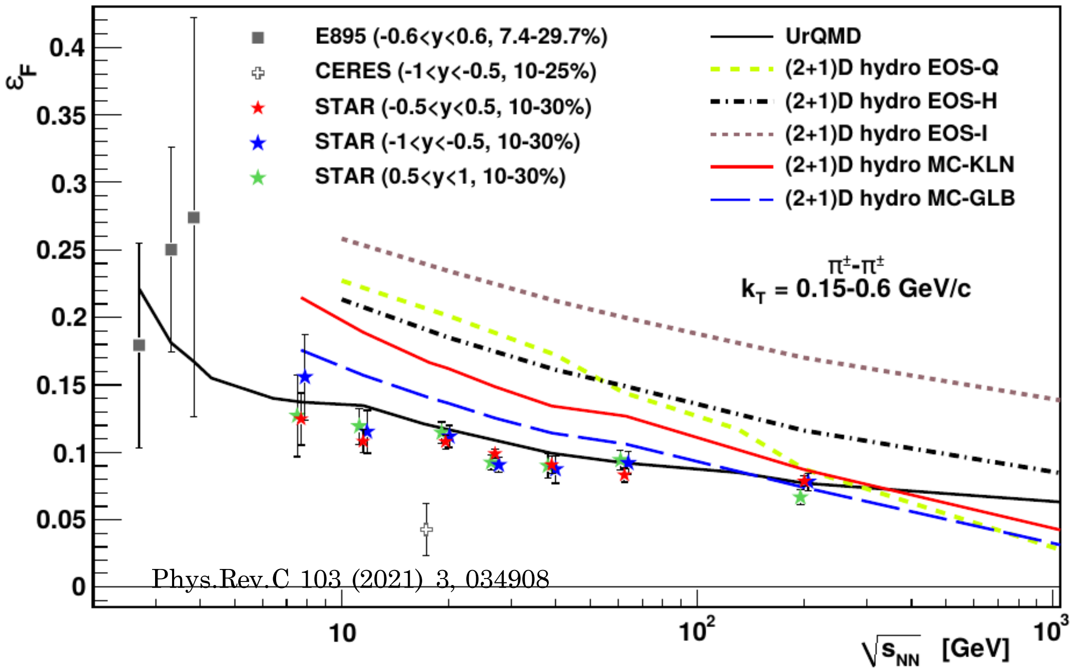
- m_T-scaling breaks for individual radii
- Longer emission duration of kaons than of pions
- Models cannot describe the differences in the outward direction well
- STAR also observes the m_T-scaling breaking

Pions in BES: asHBT



- None of the models predict all observables simultaneously. The UrQMD model, while it matches the freeze-out shapes well, matches the momentum space observables less well. And the hydrodynamic models, while they are able to describe the momentum space p_T spectra and v_2 results, do less well at predicting the eccentricity and trends observed in HBT analyses.
  - Sensitive to the equation of state used in the hydrodynamic models.
  - Has the potential to resolve ambiguities between models with different initial conditions and values of η/s.



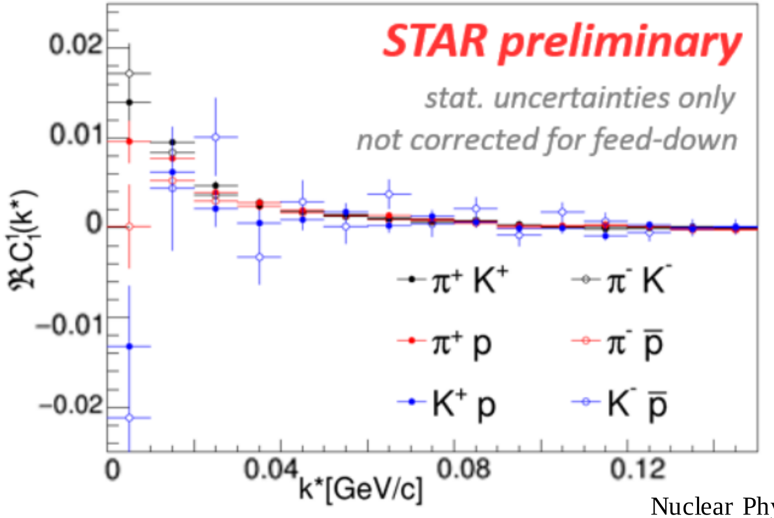


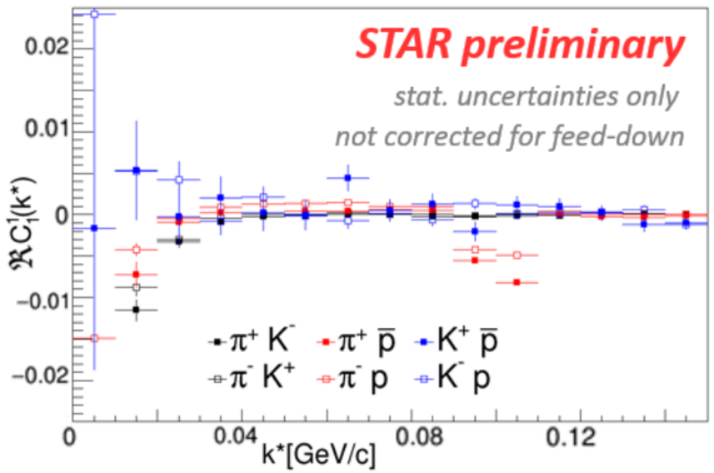
Space-time asymmetry in emission process

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

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

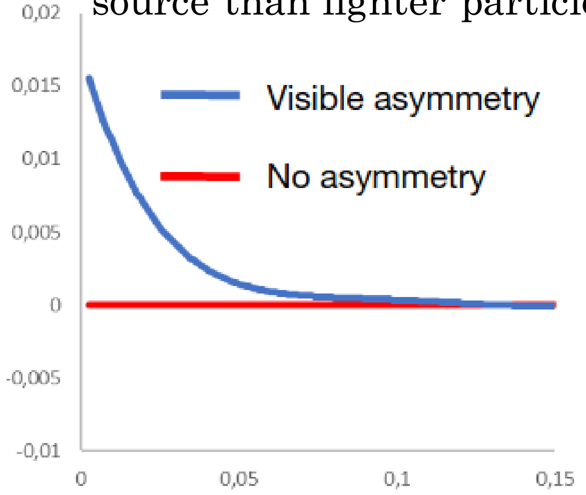
Ω – full solid angle
$Y_l^m(\theta,\phi)$ – spherical harmonic function
$q = |\boldsymbol{q}|, \theta, \phi$ – spherical coordinates

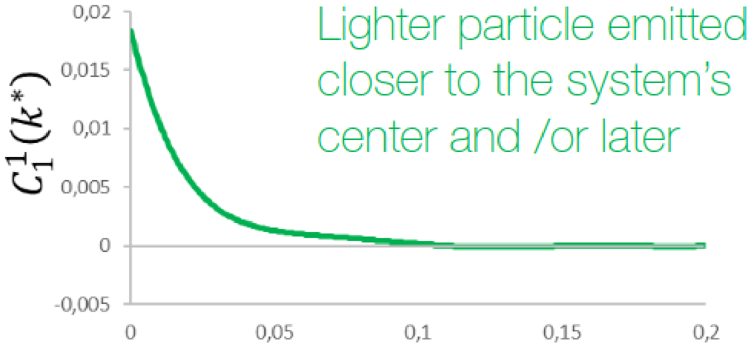


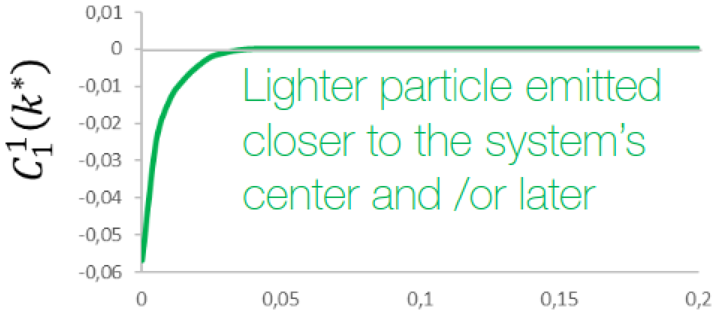


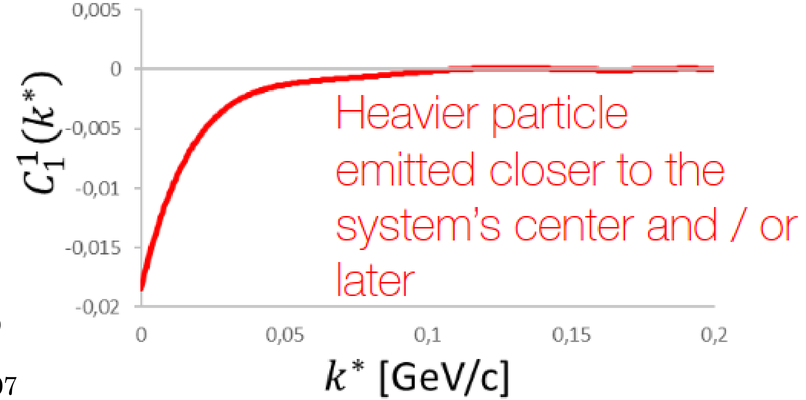
Nuclear Physics A 982 (2019) 359–362

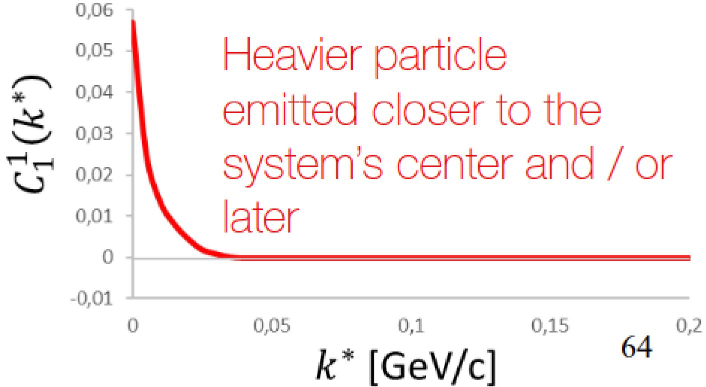
- Lighter particles are emitted closer to the center of the source and/or later than heavier particles. Heavier particles have stronger push towards the edge of the source than lighter particle







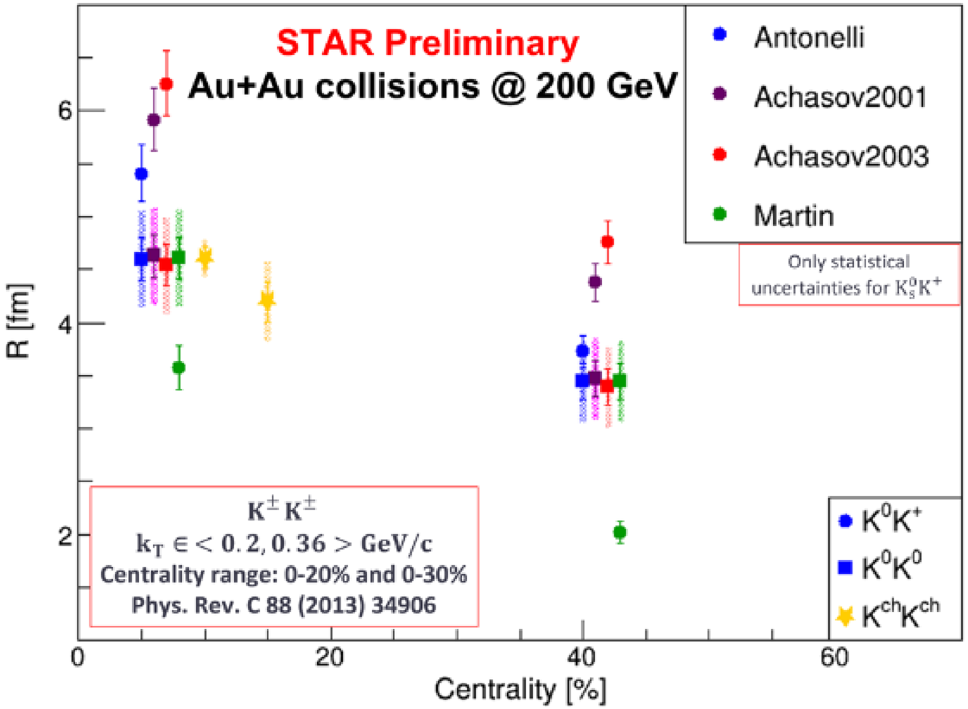


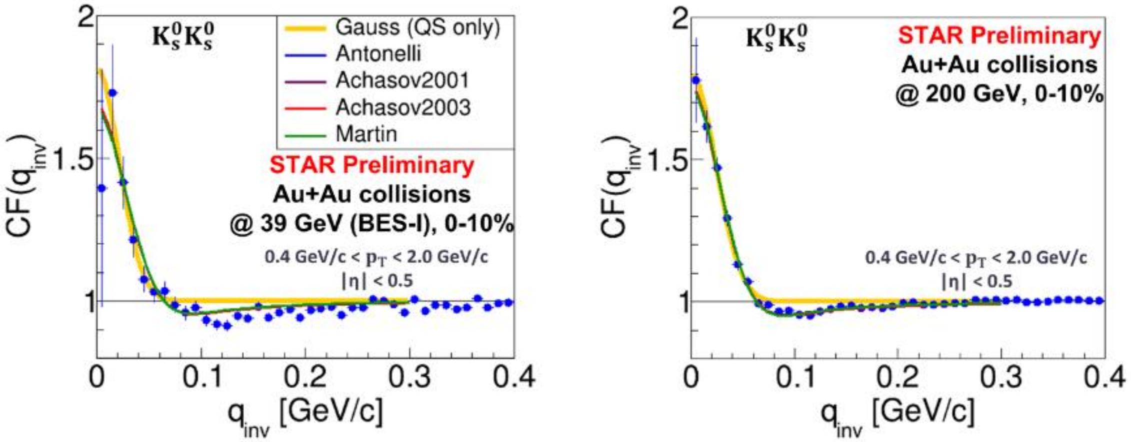


A. Kisiel Phys. Rev. C81:064906 2010
A. Kisiel and D. A. Brown Phys. Rev. C80:064911 2009
P. Danielewicz and S.Pratt. Phys. Lett. B618: 60 2005
P. Danielewicz and S.Pratt. Phys. Rev. C75:034907 2007

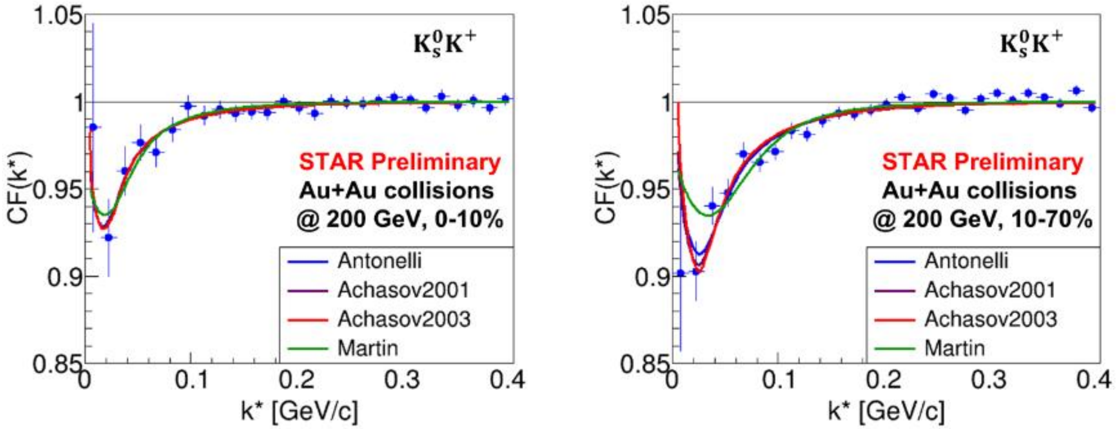
Neutral kaons in BES

$$CF(q_{inv}) = 1 + \lambda\left(e^{[-R_{inv}^2 q_{inv}^2]} + \frac{1}{2}\left[\left|\frac{f(k^*)}{R_{inv}}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R_{inv}}F_1(q_{inv}R_{inv}) - \frac{2\Im f(k^*)}{\sqrt{\pi}R_{inv}}F_2(q_{inv}R_{inv})\right]\right)$$





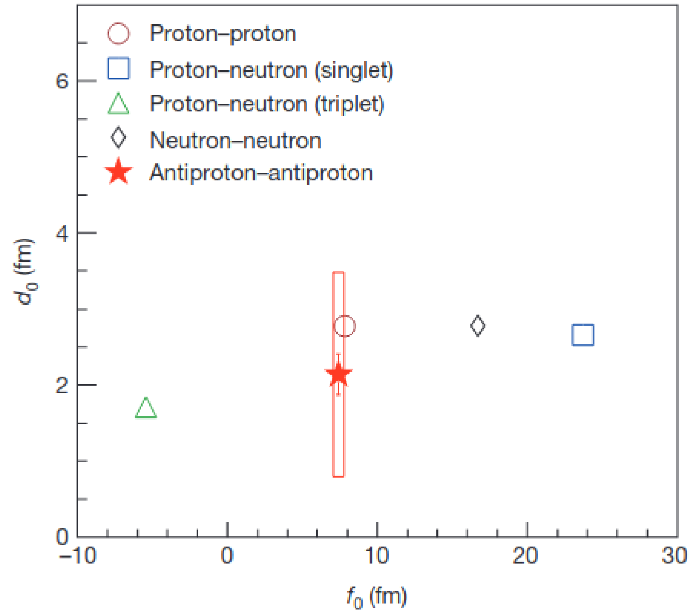
EPJ Web of Conferences 276, 01016 (2023)



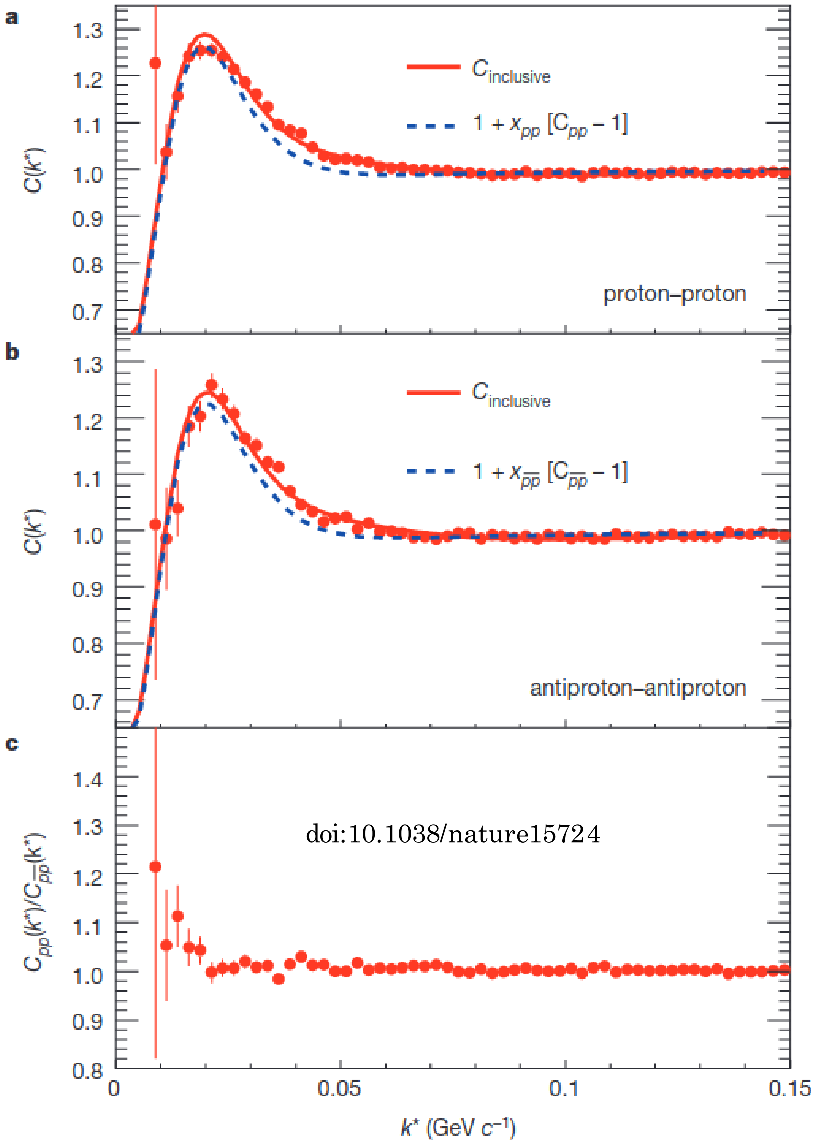
- The obtained source sizes are the biggest in the case of parametrization with the larger resonance mass (Achasov)
- Obtained source sizes for Antonelli parametrization are consistent among all the kaon combinations, which favors the assumption that a0(980) resonance could be a tetraquark

- Correlation functions are fitted with different theory predictions for strong parameters
- K0S K0S analysis
  - Final state SI significantly affects these correlations due to two near-threshold resonances a0(980) and f0(980)
- K0S K± analysis
  - Parametrization with a0(980) perfectly represents the signal region in the correlation function

Antiproton-antiproton corre

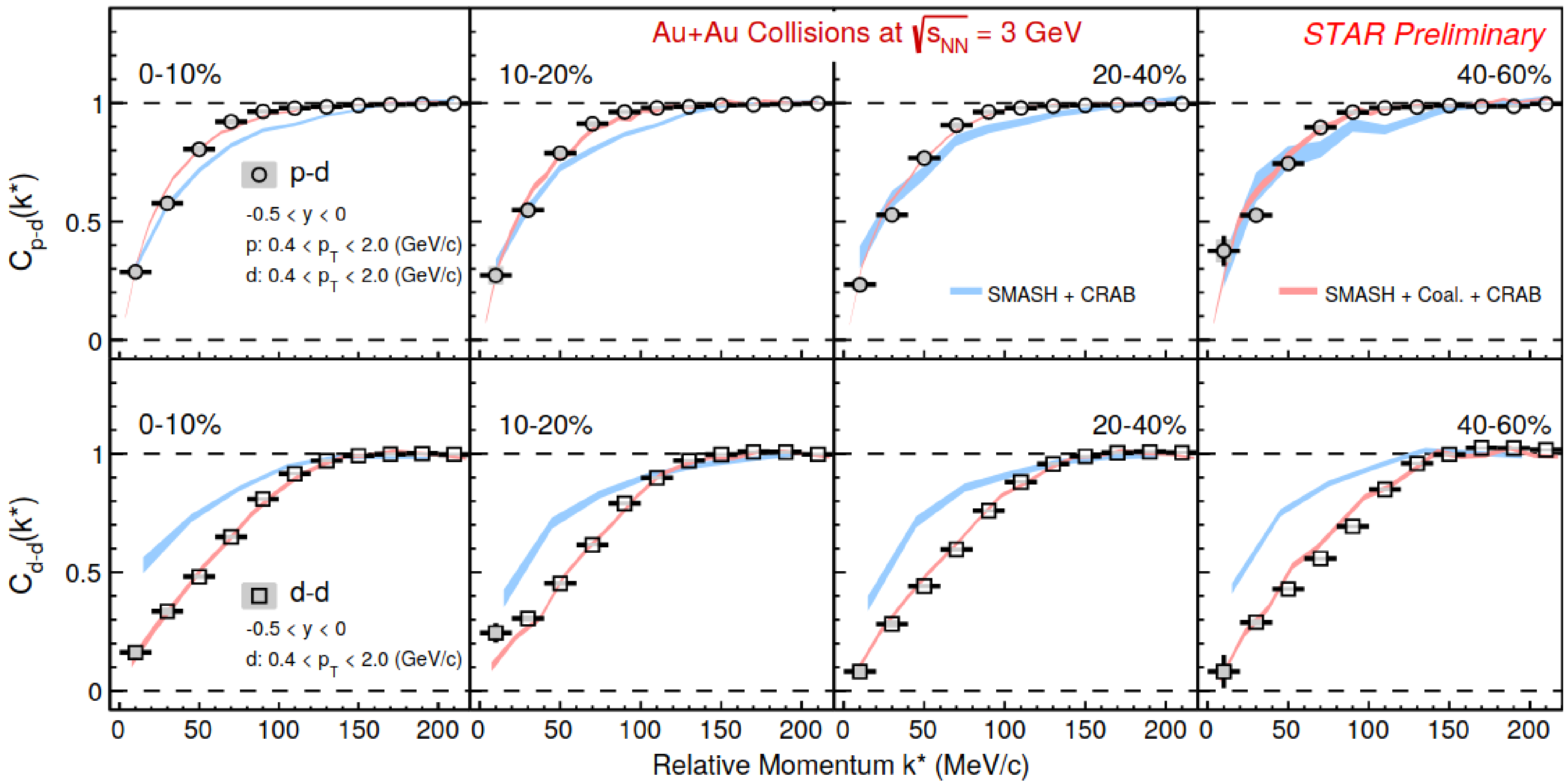


- First measurement of antiproton-antiproton final strong interaction
- f_0 and d_0 for the antiproton-antiproton interaction consistent with parameters for the proton-proton interaction
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined
- A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei



The scattering length f_0: determines low-energy scattering. The elastic cross section, σ_e, (at low energies) determined solely by the scattering length, d_0 - the effective range of strong interaction between two particles. It corresponds to the range of the potential in an extremely simplified scenario - the square well potential. f_0 and d_0 - two important parameters of strong interaction between two particles. Theoretical correlation function depends on: source size, k_*, f_0 and d_0.

Proton-deutron correlations



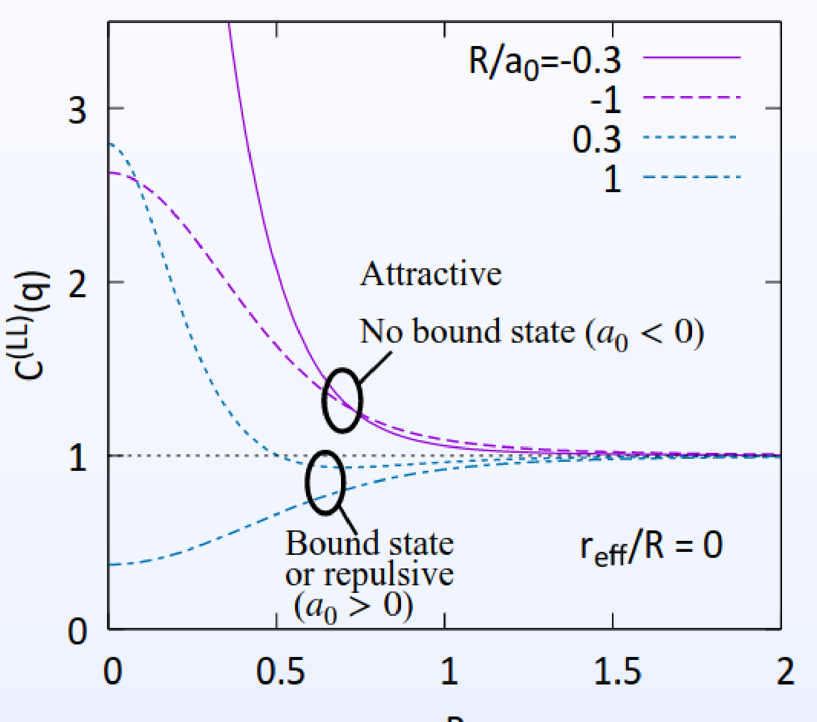
Acta Phys.Polon.Supp. 16 (2023) 1, 91

- Correlation functions with directly produced deuterons from SMASH can only qualitatively reproduce the overall trends, but over/under estimate the data depending on the particle pair

- Experimental data are well reproduced by the SMASH plus coalescence calculations
  - Deuterons are likely formed via the nucleon coalescence processes

Proton-hyperons correlations

- Search for a possible bound state of Y-N and Y-Y
- Search of exotic hadronic states such as H-dibaryon (uuddss)
  R. L. Jaffe, PRL 38 (1977), 195
- Hyperons are expected to appear in the core of neutron stars
- Hyperons softens the EoS, which leads to reduction on maximum neutron star mass
- Not consistent with the experimental results -> hyperon puzzle
- One of the possible solution: EoS stiffness by repulsive two- and three-body hyperonic interactions
- Strength of these interactions at high density can not be fully constrained by the present experimental data on YN scattering and hypernuclei
  - A detailed understanding of the interaction among nucleons has been obtained by studies of deuteron properties and scattering experiments On the contrary, the interaction of baryons containing strange quarks, so-called hyperons, is only barely known
  - Opportunity to measure strong interaction potential and scattering length



Morita, et al., PRC101 (2020)

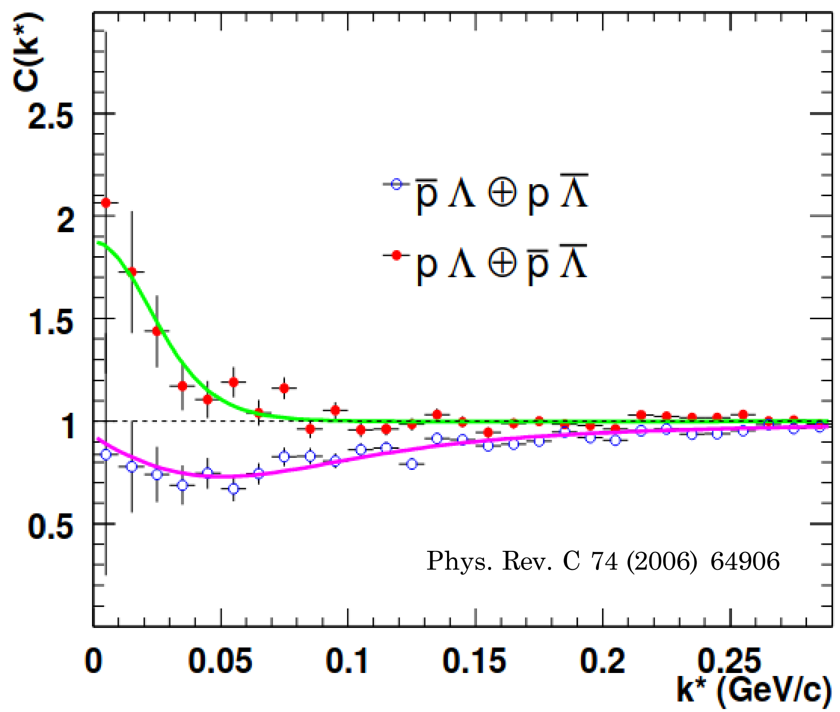
Yuki Kamiya SQM (2021)

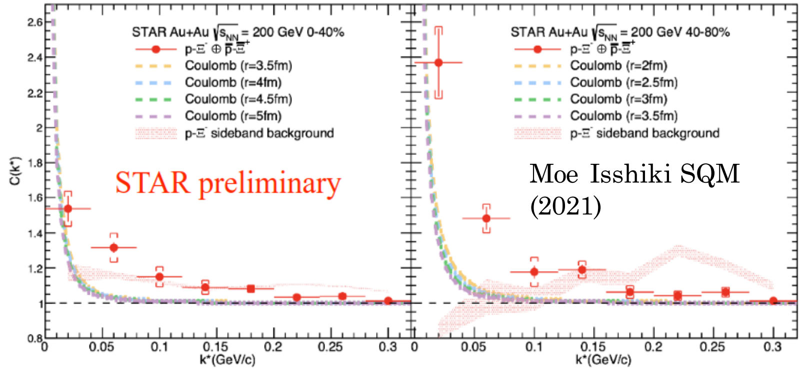
Strange correlations

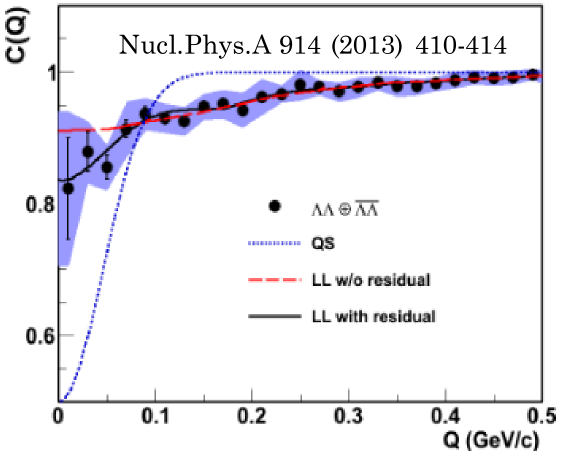
- pΛ
  - Attractive potential between protons and lambdas
  - Femtoscopic radius was extracted - 50% lower then the one for regular BB pairs -> residual correlations in baryon-antibaryon femtoscopic correlations

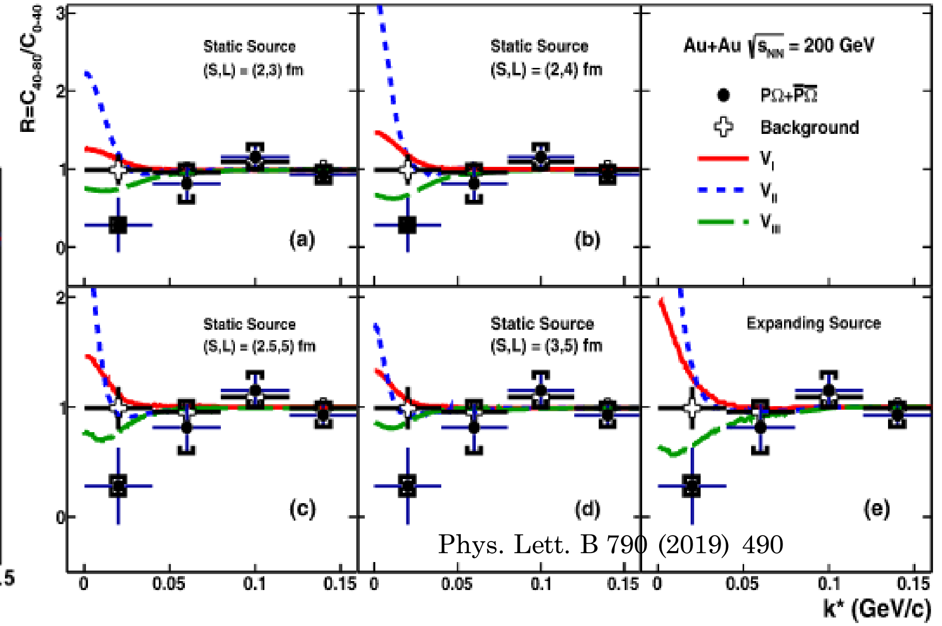
Phys. Rev. C 89 (2014) 5, 054916

- pΩ
  - Scattering length is positive and favor pΩ bound state hypothesis
- pΞ
  - Sensitive to system size, more attractive in peripheral collisions (smaller collision system)
- ΛΛ
  - Weak attraction, no signal of H-dibaryon



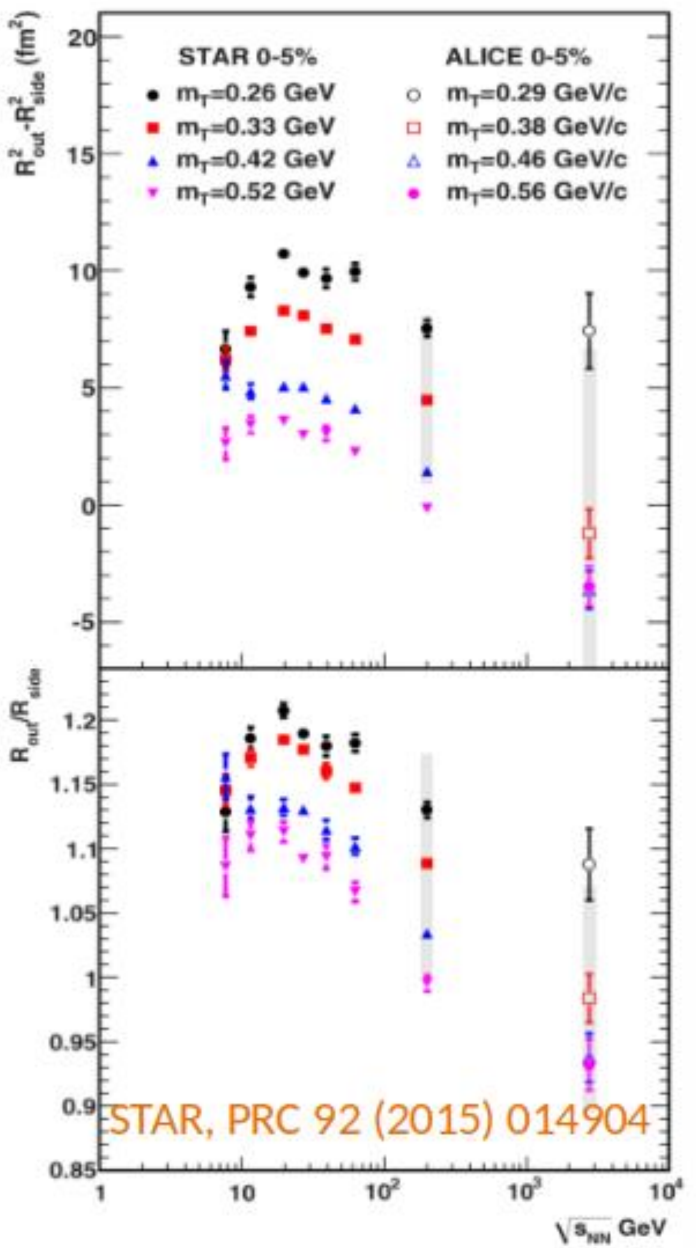






- Femtoscopy allows one to explore:
  - Size of the emission source (one-dimentional, three-dimensional femtoscopy)
  - Lifetime (R_{out})
  - Emission duration (R_{long})
  - System dynamics (k_T, m_T, energy dependences, non-identical particle correlations)
  - Source shape (asHBT w.r.t second-order event plane, Levy-analysis)
  - Orientation (asHBT w.r.t first-order event plane)
  - Interactions (non-traditional femto.)
  - Search for bound states (non-traditional femto.)
- Powerful tool for the constraint of models

Thank you for the attention!



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

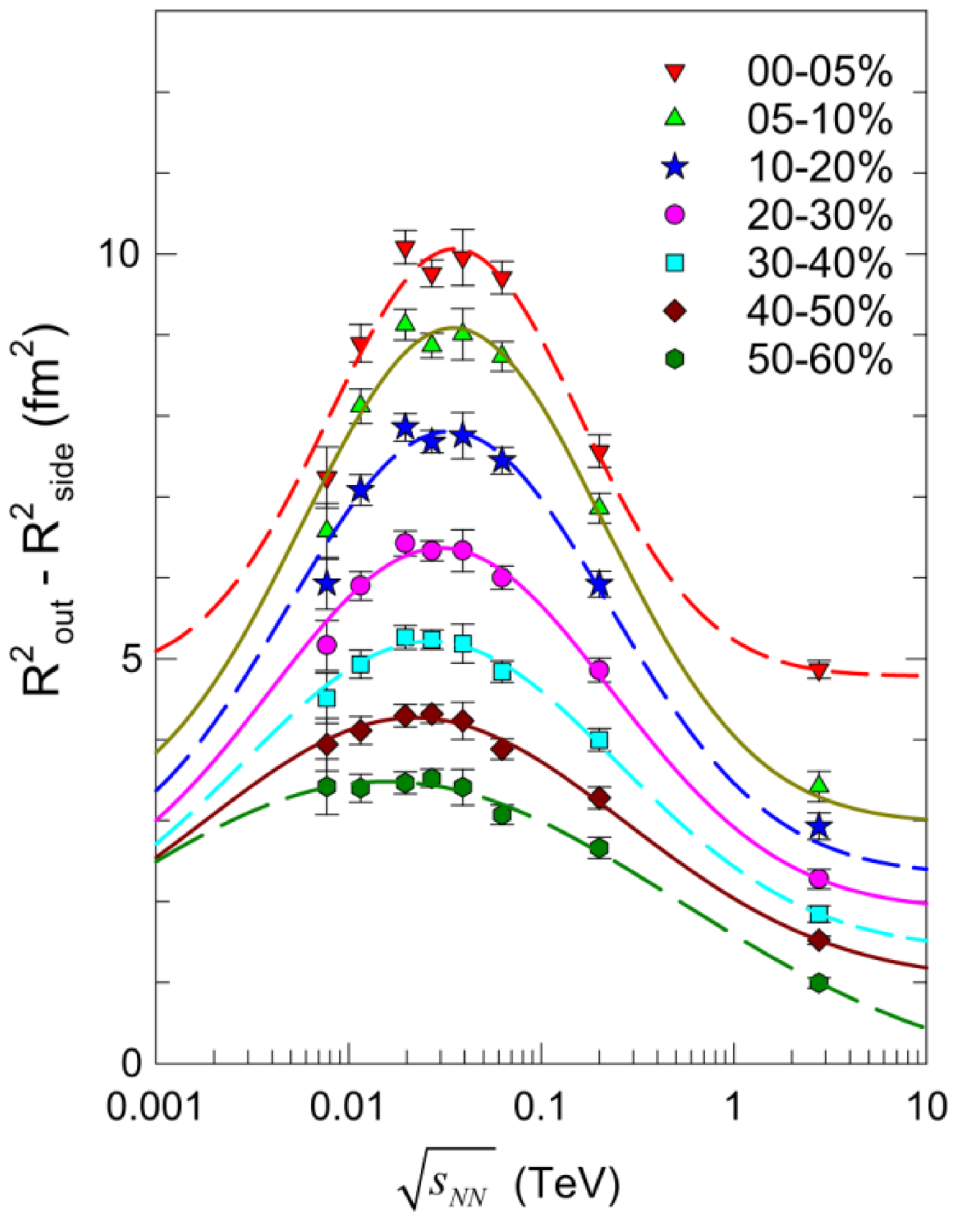
- Finite-size scaling:
  - At critical point, susceptibilities diverge for infinite system → delta function
- For finite system:
  - No divergence
  - Peaking at CP and shift of the peak position
  - Broadened peaks

The radius R_{side} is primarily associated with the spatial extent of the particle-emitting region, whereas R_{out} is also affected by dynamics [23,24] and is believed to be related to the duration of particle emission [63,64].

It has long been suggested [50,51,63] that a long particle-emission duration could result in R_{out} becoming much larger than R_{side}. In the simplest scenario of a static, nonflowing source, the emission time is given by [65]

$$(\beta\Delta\tau_{static}) = R_{out}^2 - R_{side}^2, \quad (17)$$

where $\beta = \frac{k_T}{m_T}$ is the speed of one of the pions in the source rest frame. For a flowing source such as those created at RHIC, however, Eq. (17) is unreliable [22] as the dimensions of the homogeneity region probed by low-q pion pairs is affected differently in the out and side directions. Indeed, for some sources R_{out} may be smaller than R_{side} [23], in which case Eq. (17) would yield imaginary emission times.



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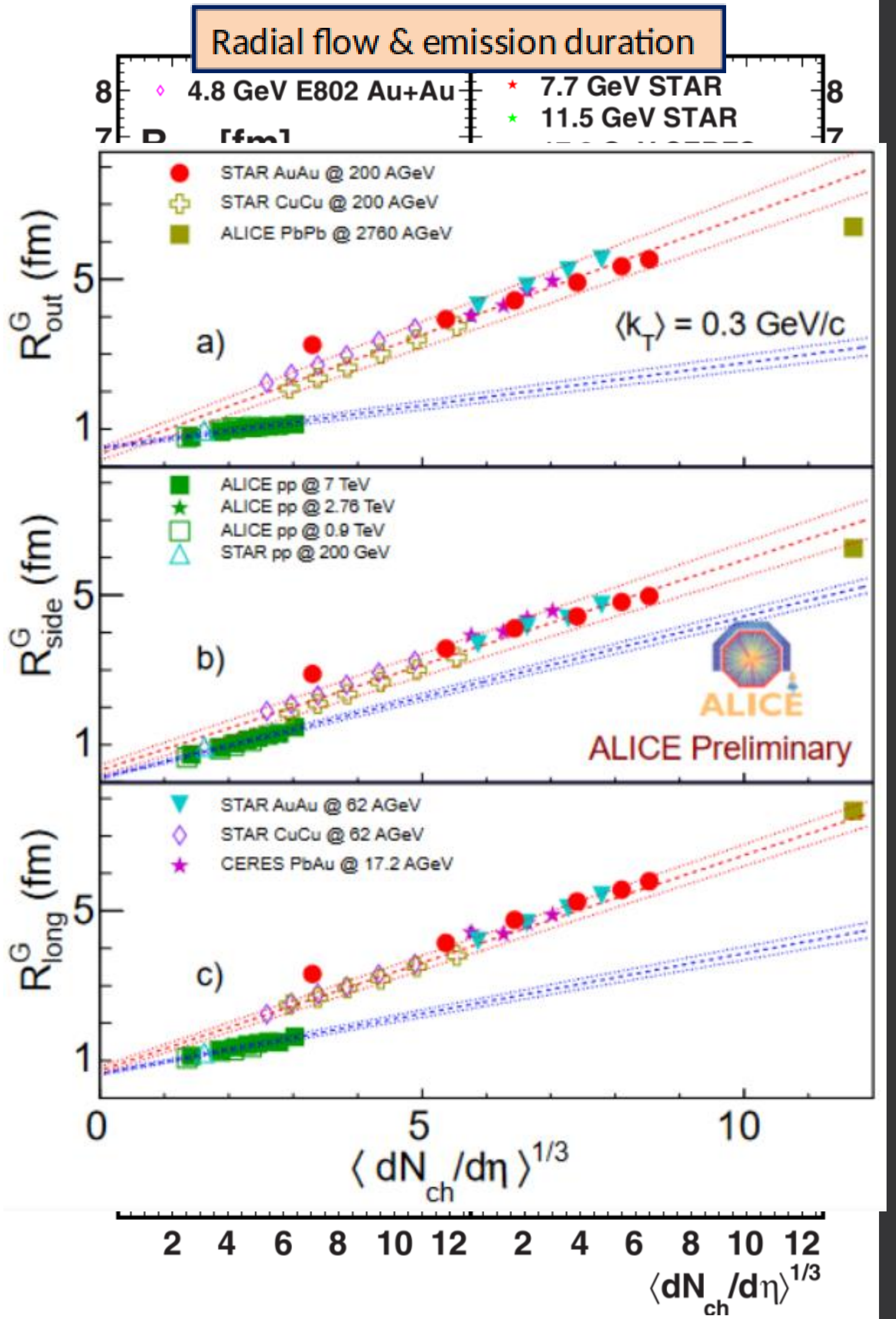
Pions in BES

- Rside and Rlong both follow a common universal trend independent of the collision species.
- Regardless of which subset of data is fitted, the heavy-ion radii do not scale in the same way than the pp ones, in all directions.
- "Universal" scaling of femtoscopic radii with final state multiplicity is violated by the pp data.
- It shows that any scaling law must take into account the initial configuration of the collision.
- The difference may be due to the interactions in the bulk medium formed in heavy ion collisions.



- EOS-I (ideal, massless quark gluon gas) and EOS-H (hadronic gas)
- MC-KLN and MC-GLB correspond to different initial conditions and are more realistic than the earlier results as they allow to incorporate viscous effects