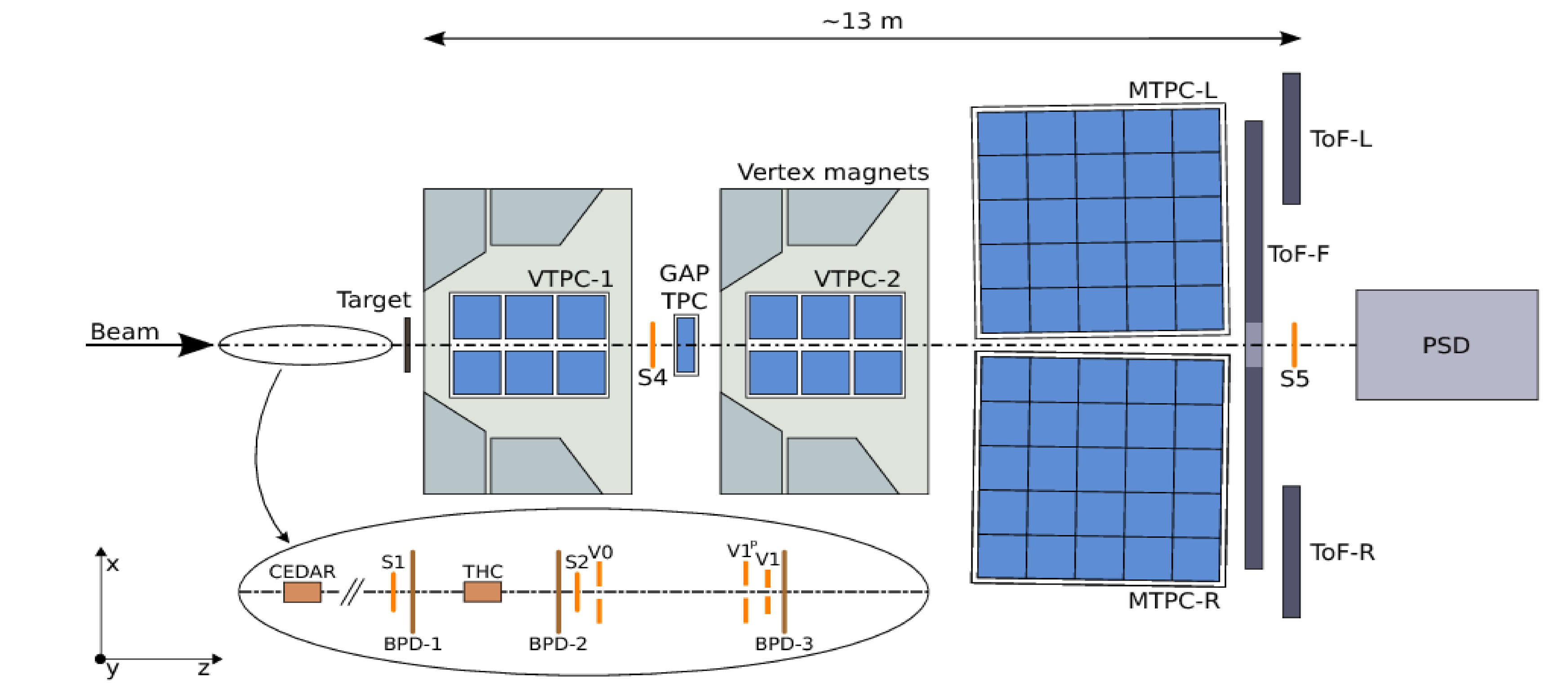
Symmetric Levy HBT measurements at NA61/SHINE

Barnabás Pórfy, Wigner Research Centre for Physics, Eötvös Loránd University
for the NA61/SHINE Collaboration

The NA61/SHINE experiment at SPS

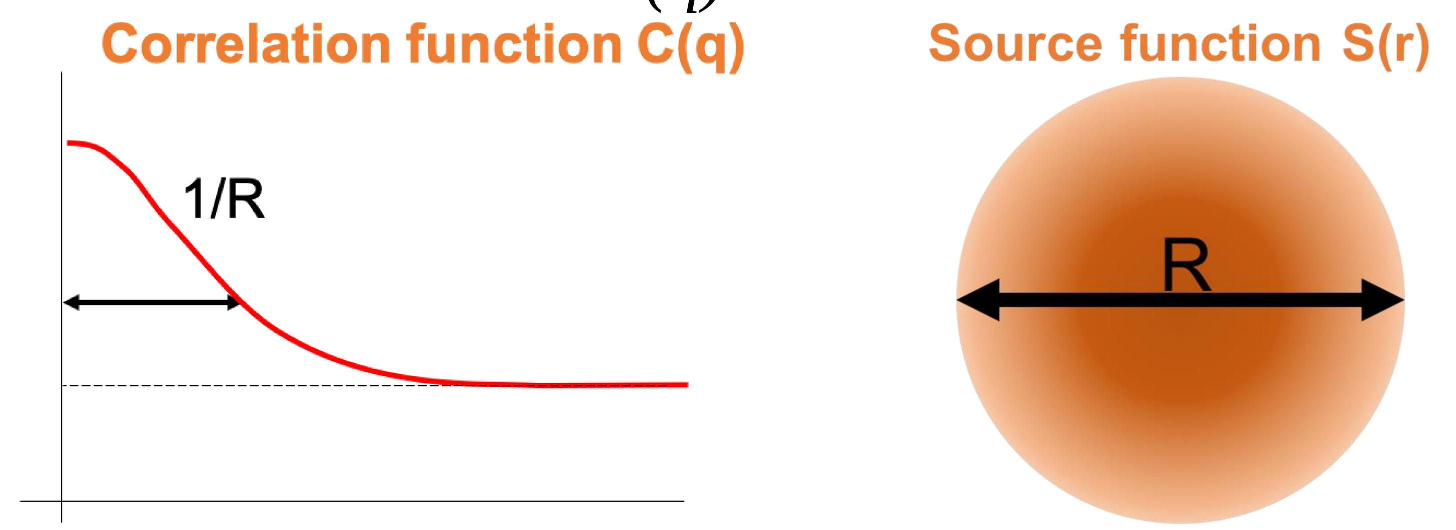


- ❑ Large acceptance hadron spectrometer, full fwd hemisphere
- ❑ Various nuclei at multiple energies
- ❑ Scan progress: Be+Be, Ar+Sc (next: Pb+Pb), 150*A* GeV/*c*
- ❑ PID: dE/dx for π^+, π^-
- ❑ Momentum diff. q in **L**ongitudinally **C**o**M**oving **S**ystem
- ❑ A(q), B(q): same & mixed event distr.; C(q)=A(q)/B(q)
- ❑ Ar+Sc: 8 m_T bins, 0-10% cent., Be+Be: 4 m_T bins, 0-20%

$K_T \equiv 0.5(K_x^2 + K_y^2)^{1/2}$ and, $m_T \equiv \sqrt{m^2 + (K_T/c)^2}$

Bose-Einstein correlations

- ❑ If $p_1 \simeq p_2$: $C(q) \cong 1 + \frac{|\tilde{S}(q)|^2}{|\tilde{S}(q=0)|^2}$, where $\tilde{S}(q)$ is Fourier transform of *S(x, p)*
- ❑ Source *S(x,p)* usually assumed to be Gaussian → Gaussian corr. func. *C(q)*



- ❑ More general: Generalized **C**entral **L**imit **T**heorem: Symmetric Lévy-stable distribution
  - ❑ $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy

$$\mathcal{L}(\alpha, R, r) = (2\pi)^{-3} \int d^3q e^{iqr} e^{-|qR|^\alpha/2}$$

- ❑ Shape of the correlation function with Lévy source:

$$C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$$

Csörgő, Hegyi, Zajc,Eur.Phys.J.C36(2004)67 , Metzler, Klafter, Physics Reports 339(2000)1

Lévy distribution in heavy-ion physics

- ❑ Critical point→ fluctuations at all scales → described by critical exponents (η)

Halasz et al., Phys.Rev.D58(1998)096007
Stephanov et al., Phys.Rev.Lett.81(1998)4816
El-Showk et al., J.Stat.Phys.157 (4-5): 869

- ❑ QCD universality class: $\eta = 0.03631(3)$ ↔ 3D Ising; $\eta = 0.5 \pm 0.05$ ↔ rfd. 3D Ising

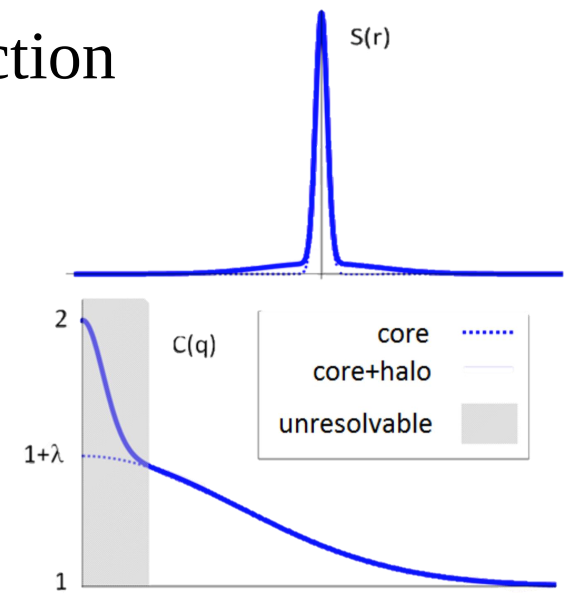
Rieger, Phys.Rev.B52 (1995) 6659

- ❑ η related to spatial correlations $\propto r^{-(d-2+\eta)}$
- ❑ Lévy distributions lead to $\propto r^{-(d-2+\alpha)}$
- ❑ Many possible reasons for Lévy distributions

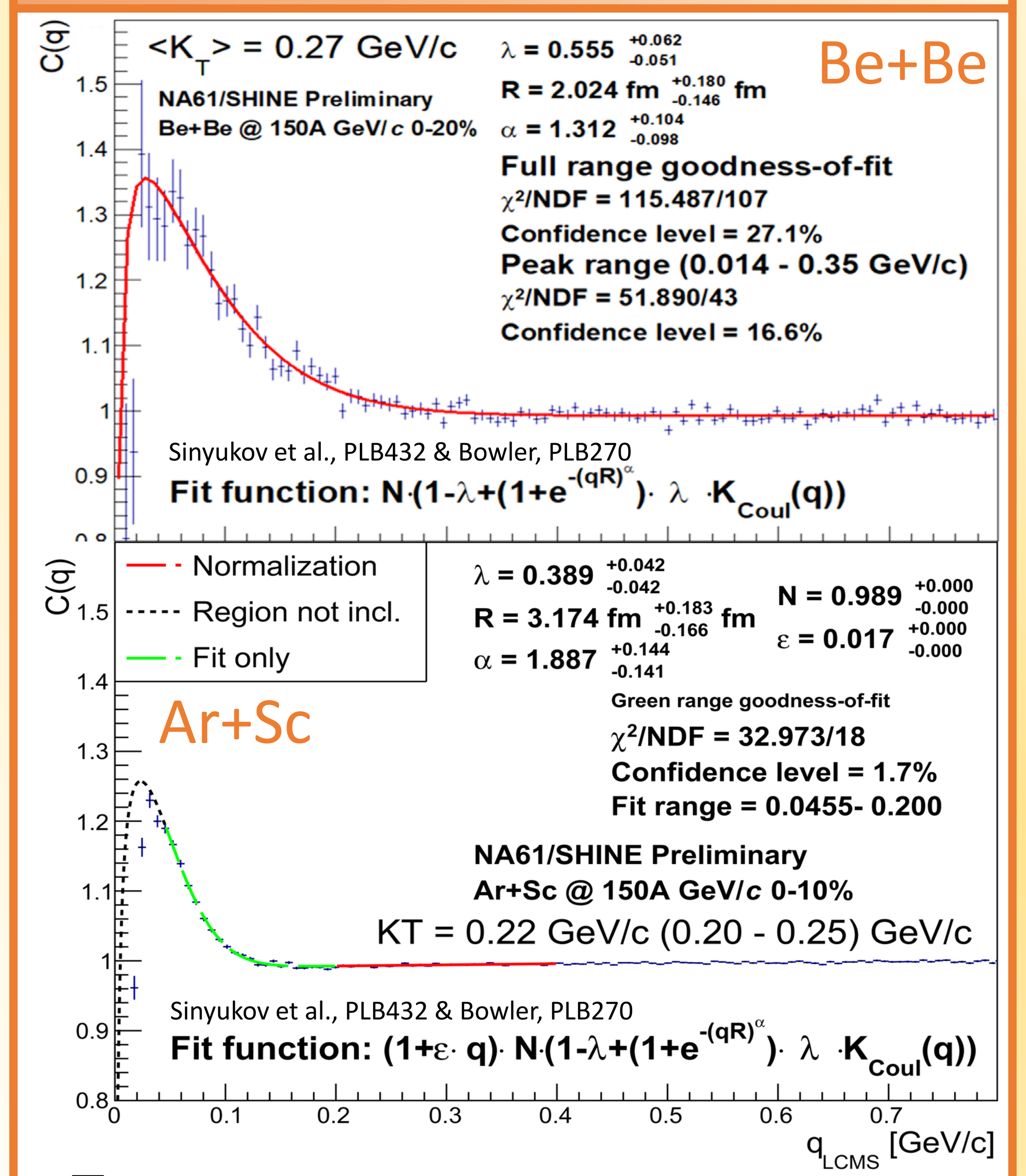
} α related to η — Csörgő et al., AIP Conf. Proc. 828(2006)525

Final state interactions

- ❑ Like-charged π pairs: need Coulomb correction
  - ❑ $C(q)_{BE} = K(q)_{Coul} \cdot C(q)_{meas.}$, different methods for Be+Be and Ar+Sc
- ❑ Resonance pions reduce correlation → two component pion source $S_{\text{Core}} + S_{\text{Halo}}$
  - ❑ Primordial pions: Core, size ≲ 10 fm; Resonance pions: Halo, very large size

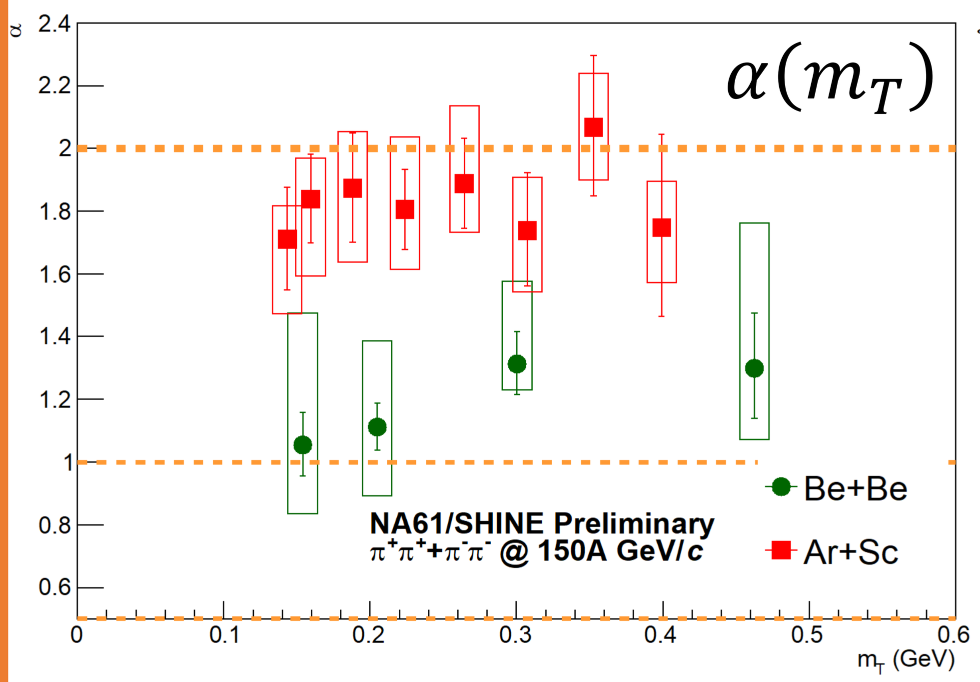


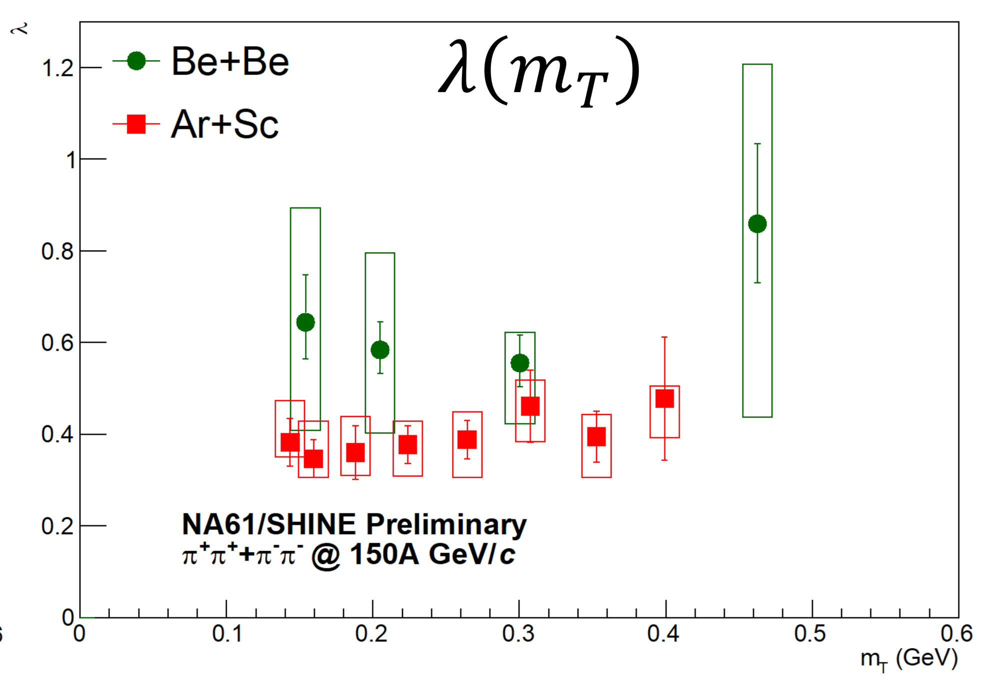
Example fits

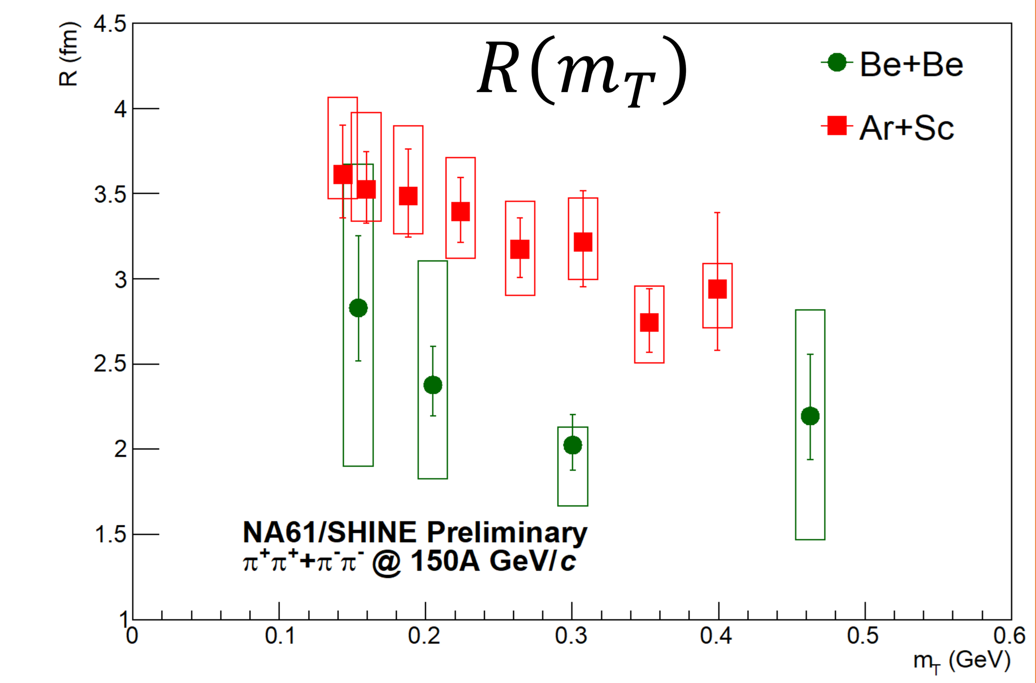


- ❑ Good description of Bose-Einstein peak

Results on Lévy parameters







- ❑ Lévy stability index α values:
  - ❑ for Ar+Sc, around $1.5 - 2.0$
  - ❑ For Be+Be, around $1.0 - 1.5$
- ❑ No clear dependence on transverse mass m_T
- ❑ Lévy assumption is valid:
  - ❑ close to Gauss ($\alpha = 2$) for Ar+Sc
  - ❑ close to Cauchy ($\alpha = 1$) for Be+Be
  - ❑ far **C**ritical **E**nd **P**oint ($\alpha = 0.5$)

- ❑ Correlation strength λ Describes the core-halo ratio

$$\lambda = \left(\frac{N_{\text{core}}}{N_{\text{halo}} + N_{\text{core}}} \right)^2$$

- ❑ Weak m_T dependence
- ❑ No visible hole at low-m_T values
  - ❑ Behavior seen at RHIC energies

Adare et al., Phys.Rev. C97 (2018) no.6, 064911

  - ❑ Can probably be turned off at SPS?

- ❑ Lévy scale parameter R — Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390
  - ❑ Homogeneity length
  - ❑ Hydro: $\sim 1/\sqrt{m_T}$ (predicted for Gaussian source)
  - ❑ m_T dependence: sign of transverse flow
- ❑ Geometrical expectation based on nucleii

$$R_{Ar+Sc} \approx 1.6 \cdot R_{Be+Be}$$

  - ❑ Reduction in R due to $\alpha - R$ anticorrelation

Conclusions

- ❑ NA61/SHINE Lévy HBT analysis
  - ❑ 150*A* GeV/*c* beam energy
  - ❑ Be+Be and Ar+Sc collisions
  - ❑ Momentum correlations of $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs, with PID based in dE/dx
- ❑ Symmetric Lévy assumption: statistically acceptable fits
- ❑ m_T dependence investigated
  - ❑ $\alpha \approx 1.0 - 1.5$ for Be+Be, $\alpha \approx 1.5 - 2.0$ for Ar+Sc
  - ❑ λ slight m_T dependence, no clear low- m_T hole
  - ❑ R visible m_T dependence, sign of transverse flow
- ❑ Ongoing/Future plans:
  - ❑ MC check for low q behaviour, possible residual detector effects
  - ❑ Measure correlations in Pb+Pb

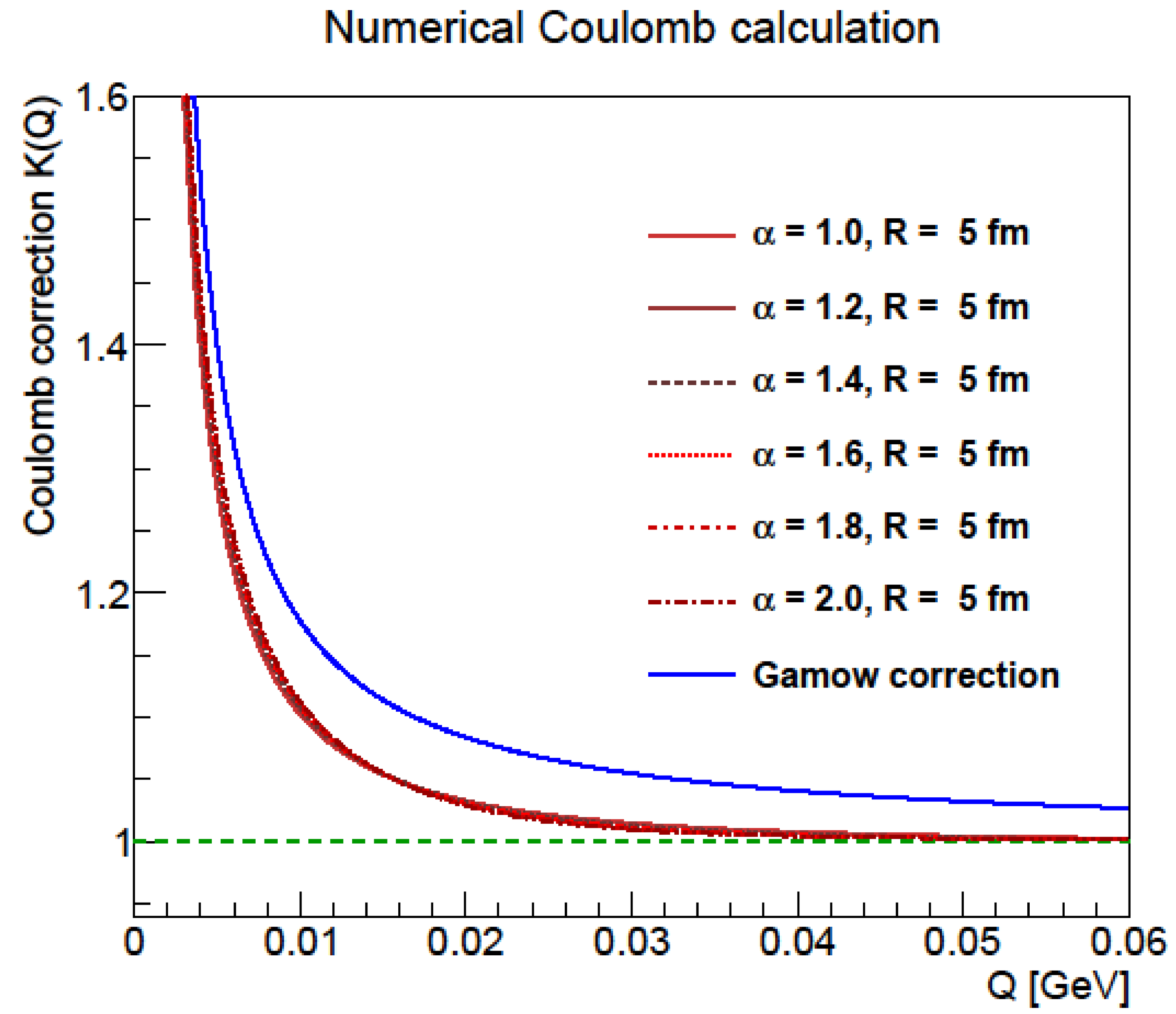
Coulomb interaction

- Be+Be

  CMS, A.M. Sirunyan et al., Phys. Rev. C97 (2018) 064912, 1712.07198

  - Correction: weak dependence on α
  - Correction: $K_{Coulomb}\,(q) = C_2^{Coulomb}\,(q)/C_2^0\,(q)$
    with $C_2^0\,(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$
  - Approximate formula (for α = 1) used at CMS:
  - $K_{Coulomb}\,(q) = Gamow(q) \cdot \left(1 + \frac{\pi \cdot \eta \cdot q \cdot \frac{R}{\hbar c}}{1.26 + q \cdot \frac{R}{\hbar c}}\right)$,

    where Gamow(q) $= \frac{2\pi\eta(q)}{e^{(2\pi\eta(q))} - 1}$ and $\eta(q) = \alpha_{QED} \cdot \frac{\pi}{q}$



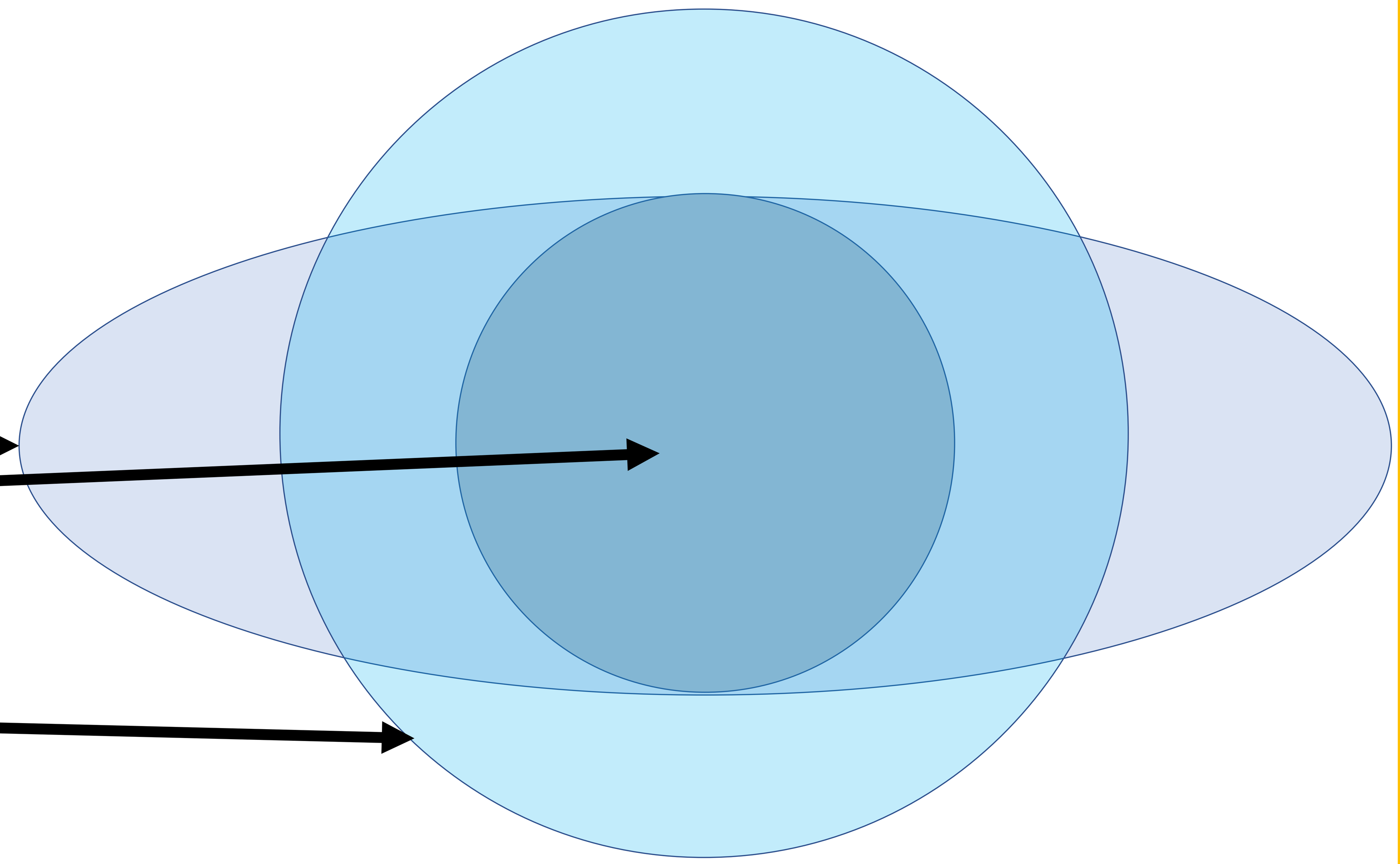
- Ar+Sc: More statistics, need for more precise Coulomb correction:
  Better formula; non-spherical correction

  - Correction: complicated: numerically possible
    via look-up table physical parameter parametrization

  M. Csanád and S. Lökös, and M. Nagy, Phys.Part.Nucl. 51 (2020) 3, 238-242, 1910.02231

  - Measuring in LCMS, but Coulomb correction is in PCMS
  - This is usually neglected, but 1D spherical source in LCMS
    NOT spherical in PCMS
  - Boost R to PCMS: $R_{PCMS} = \sqrt{\frac{1-\frac{2}{3}\beta_T^2}{1-\beta_T^2}} \cdot R$

    where $\beta_T = \frac{K_T}{m_T}$
  - Use this source for Coulomb correction
  - Real Coulomb correction
  - Regular CC: fits into the source
    - smaller in size
  - Boosted CC: same size
    - smaller in longitudinal
    - larger in transversal



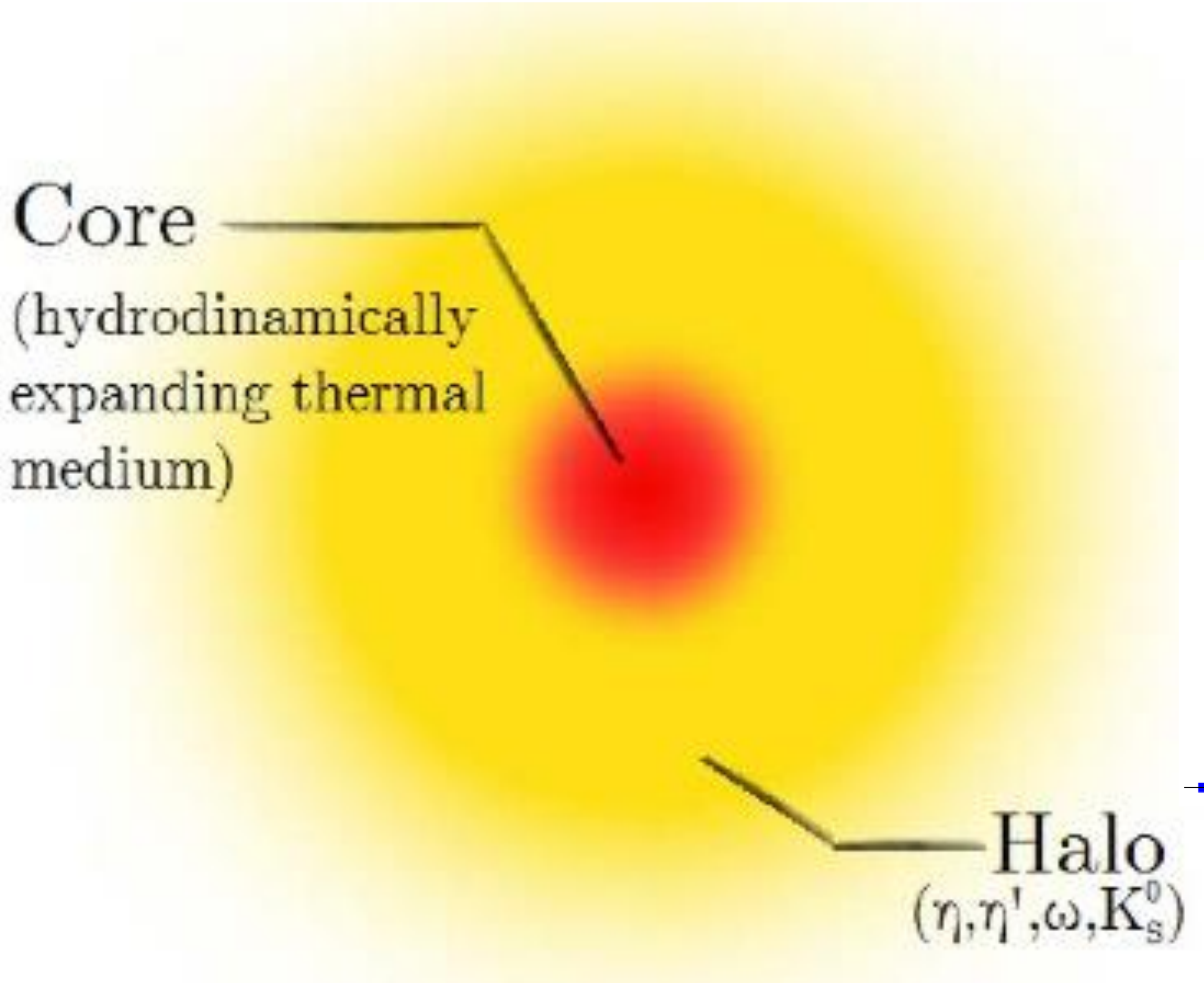
Source

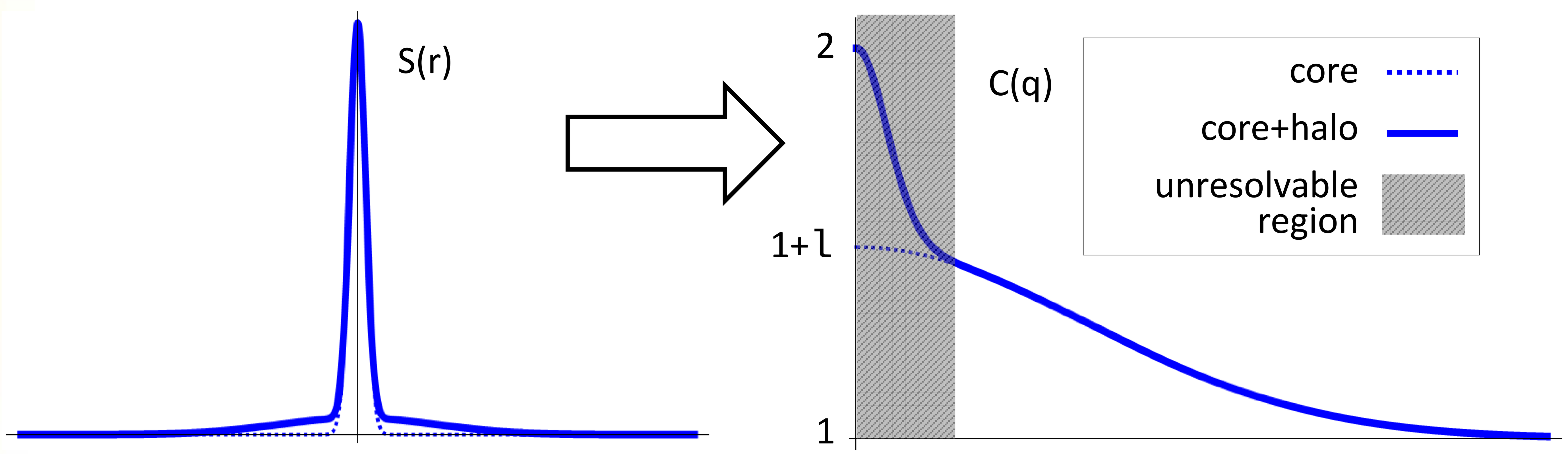
Bálint Kurgyis: Proc. ISD (2020) 677

Core Halo model

- Hydrodinamically increasing core → emits pions during hadronization
- Results in two componetn source: $S(x) = S_C(x) + S_H(x)$
- Core $\lesssim$ 10 fm size, Halo $(\omega, \eta, \ldots)$ > 50 fm size
- Halo not seen by detector resolution
- Real $q \to 0$, at $C(q = 0) = 2$
- Results show $C(q \to 0) = 1 + \lambda$, where $\lambda = \left(\frac{N_{\text{core}}}{N_{\text{halo}} + N_{\text{core}}}\right)^2$

Bolz et al, Phys.Rev. D47 (1993) 3860-3870
Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497





Measurement details

- Measurements done at 150*A* GeV/*c*
  - Be+Be 0-20% centrality
  - Ar+Sc 0-10% centrality
- Event mixing:
  - A(q): Actual event relative momentum distribution pairs from same event
  - B(q): Background event rel. mom. distribution

  pairs from mixed event
- C(q): A(q)/B(q)$\cdot \frac{\int_{q_1}^{q_2} B(q)dq}{\int_{q_1}^{q_2} A(q)dq}$, where $[q_1, q_2]$ intervals where quantumstatistical effects are not present