Femtoscopy using Lévy-type source at NA61/SHINE

42nd International Conference on High Energy Physics

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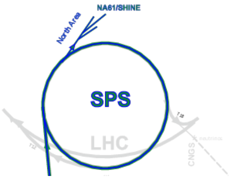
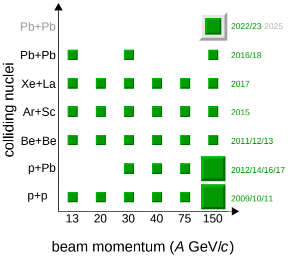
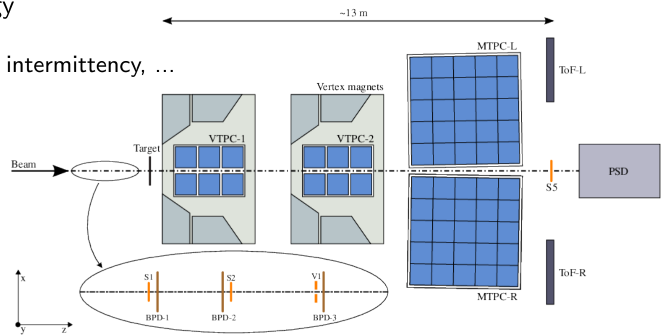
The NA61/SHINE Detector

- Located at CERN SPS, North Area
- Fixed target experiment; upgrade during LS2
- Large acceptance hadron spectrometer (TPC)
  - Covering the full forward hemisphere
  - Outstanding tracking, down to $p_T \approx 0$ GeV/c
- Different systems scanned in beam energy
- Strong interaction program:
  - Search for Critical Point: **femtoscopy**, intermittency, ...





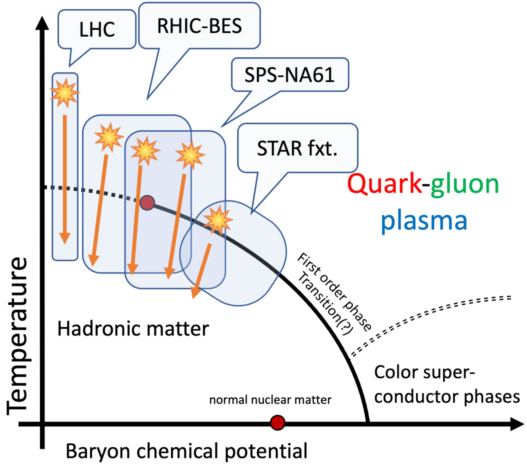


Detector layout during Ar+Sc data taking

Critical Point Search Using Femtoscopy

- System size scan progress at 150(8)A GeV/c: $p+p$, ^{7}Be+^{9}Be, ^{40}Ar+^{45}Sc, ^{129}Xe+^{139}La

Be+Be: NA61/SHINE, EPJC 83 (2023) 10, 919; Ar+Sc: Universe 9 (2023) 7, 298; arXiv:2406.02242; this analysis



- Energy scan in Ar+Sc:
  150A GeV/c, 75A GeV/c, 40A GeV/c
  30A GeV/c, 19A GeV/c, 13A GeV/c
- At Critical Point - fluctuations at all scales
- Power-law in spatial correlations with Critical exponent η, near **C**ritical **P**oint?
- QCD universality class $\leftrightarrow$ 3D Ising:

  Halasz et al., Phys.Rev.D58 (1998) 096007

  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816

  - 3D Ising: $\eta = 0.03631(3)$
    El-Showk et al., J.Stat.Phys.157 (2014) 869
  - Random field 3D Ising $\eta = 0.50(5)$
    Rieger, Phys.Rev.B52 (1995) 6659

Bose-Einstein Correlations in Heavy-Ion Physics

Tool to measure spatial correlations: Bose-Einstein relative mom. correlations

- R. Hanbury Brown, R. Q. Twiss observed Sirius with two optical telescopes

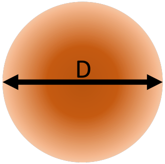
  R. Hanbury Brown and R. Q. Twiss Nature 178 (1956)

  - Intensity correlations as a function of detector distance
  - Measuring apparent angular diameter of point-like sources
- Goldhaber, Goldhaber, Lee and Pais: applicable in high energy physics: (for identical pions)

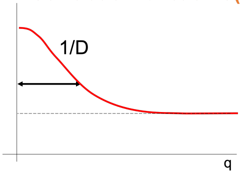
  Goldhaber, Goldhaber, Lee and Pais Phys.Rev.Lett.3 (1959) 181

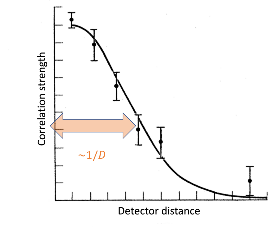
  - Momentum correlation $C(q)$, $q = |p_1 - p_2|$, is related to the source $S(x)$
    $C(q) \cong 1 + |\widetilde{S}(q)|^2$ where $\widetilde{S}(q)$ Fourier transform of $S(q)$

Source function S(r)



Correlation function C(q)



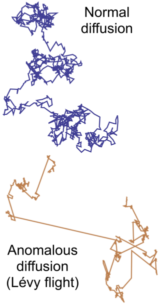


- S(r) frequently assumed to be Gaussian → Gaussian C(q)
  → Exp. data not supporting → CLT not satisfied?

Lévy Distribution in Heavy-Ion Physics

- Generalized CLT? $\rightarrow$ Lévy-stable distribution
- Shape of correlation function with Lévy source: $C(q) = 1 + \lambda \cdot e^{-|qR|^{\alpha}}$
  - $\alpha = 1$: Exponential, $\alpha = 2$: Gaussian Csörgő, Hegyi, Zajc, Eur.Phys.J.C36 (2004) 67, nucl-th/0310042

Lévy-stable distribution: $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^{\alpha}}$



- From generalization of Gaussian, power-law tail: $\sim r^{-(d-2+\alpha)}$
  - $\alpha = 1$ Cauchy, $\alpha = 2$ Gaussian
- Why Lévy source:
  - QCD jets; Anomalous diffusion; Critical phenomena; ...?

Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon.B36 (2005) 329-337

Csanád, Csörgő, Nagy, Braz.J.Phys.37 (2007) 1002

Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc.828 (2006) 525-532

Metzler, Klafter, Physics Reports 339 (2000) 1-77

Kincses, Stefaniak, Csanád, Entropy 24 3 (2022) 308

Kórodi, Kincses, Csanád, Phys.Lett.B 847 (2023)

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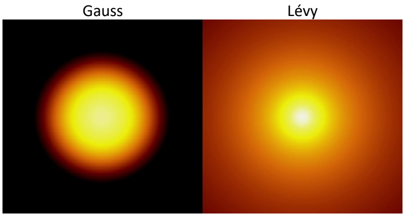
- Why Lévy source:
  QCD jets; Anomalous diffusion; Critical phenomena; ...?
- Lévy distribution leads to power-law spatial correlation
- Spatial correlation at the Critical Point: $\sim r^{-(d-2+\eta)}$
  - Lévy-exponent α identical to correlation exponent η

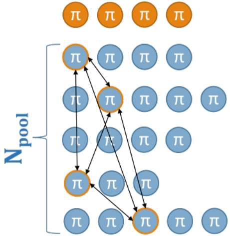


Correlation Function Measurement Details

- Be+Be, 0-20% $\sqrt{s_{\mathrm{NN}}} = 16.8$ GeV
- Ar+Sc, 0-10% $\sqrt{s_{\mathrm{NN}}} = 16.8, 11.9, 8.8, 7.7, 6.2, 5.3$ GeV
- Event and track cuts (centrality, vertex, rapidity, ...)
- Momentum dependent pair cut
- Particle Identification via dE/dx method to select π^-, π^+

Correlation function measurement via mixed event background:

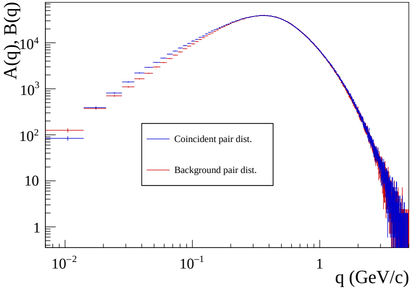
- A(q) - Pairs from same event
- B(q) - Pairs from mixed events
- C(q) - Correlation function, C(q) = A(q)/B(q)

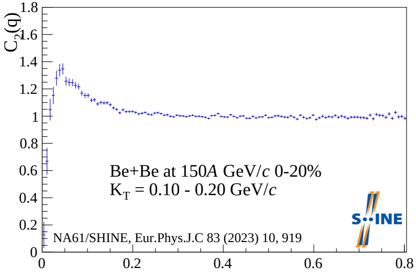


  - Correlation function q_{LCMS} 1D variable
  - LCMS: Longitudinally CoMoving System
  - $m_{\mathrm{T}} \equiv \sqrt{m^2 + (K_{\mathrm{T}}/c)^2}$; $K = (p_1 + p_2)/2$; $K_{\mathrm{T}} = \sqrt{K_x^2 + K_y^2}$
  - No. m_{T} bins: **8** - Ar+Sc 150A GeV/c, **7** - Ar+Sc 75A GeV/c, 40A GeV/c, **6** - Ar+Sc 30A GeV/c
    4 - Ar+Sc 19A GeV/c, 13A GeV/c, Be+Be 150A GeV/c

Bose–Einstein Correlation Function

- $C_2(q)$: B–E peak and Coulomb hole, at low q values:





- Like charged pairs: Coulomb interaction → Coulomb correction (CC)
  - Calc: numerical integral possible Nagy, M., Purzsa, A., Csanád, M. and Kincses, Dániel, Eur.Phys.J.C 83 (2023) 11, 1015
  - Parametrization used before
- Meas.: LCMS, CC.: PCMS (pair center of mass) negligible, BUT 1D spher. symm. source LCMS not spherical PCMS B. Kurgyis, D. Kincses, M. Nagy, and M. Csanád, Universe 2023, 9(7), 328

$$R \to R_{\mathrm{PCMS}} = \sqrt{\frac{1-\frac{2}{3}\beta_T^2}{1-\beta_T^2}} \cdot R_{\mathrm{LCMS}},\ q_{\mathrm{inv}} \approx \sqrt{1-\beta^{2/3}} \cdot q_{\mathrm{LCMS}},\ \beta_T = \frac{K_T}{m_T}$$

Parameters of Lévy-source

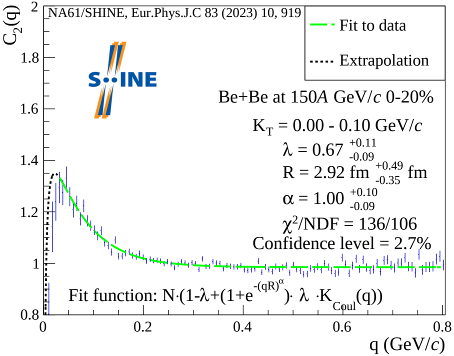
- R Lévy-scale parameter:
  - Length of homogeneity
  - From simple hydro calc.:
    $$R_{\mathrm{HBT}} = R/\sqrt{1+(m_{\mathrm{T}}/T_0)\cdot u_{\mathrm{T}}^2}$$
- λ correlation strength:
  - Core-halo ratio:
    $$\lambda = \left(\frac{N_{\mathrm{core}}}{N_{\mathrm{core}}+N_{\mathrm{halo}}}\right)^2$$
    Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)

    Bolz et al, Phys.Rev.D47 (1993) 3860-3870
  - Core: primordial pions
  - Halo: pions from long-lived resonances
- α Lévy-stability index
  - $\alpha = 2$: Gauss shape, simple hydro
  - $\alpha < 2$: Generalized central limit theorem
  - $\alpha = 0.5$: Conjectured value at CP

Bowler-Sinyukov

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

Yu. Sinyukov et al., Phys.Lett.B432 (1998) 248,
M.G. Bowler, Phys.Lett.B270 (1991) 69



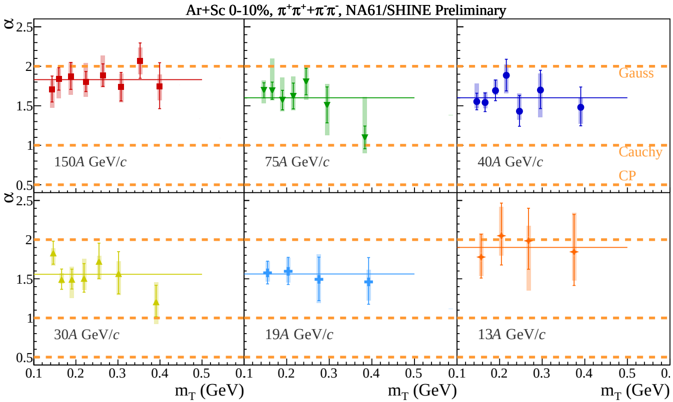
Lévy-stability index α

- Shape of spatial correlation
- Compatible with Lévy assumption ($\alpha < 2$),
  - Ar+Sc: far from Cauchy,

    Decreases from "close to Gaussian"

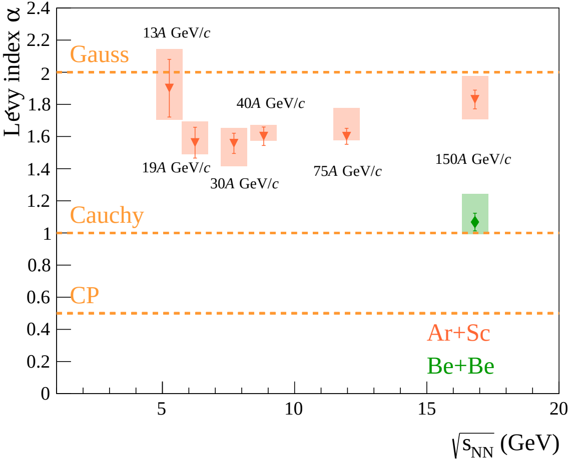
    far from CP ($\alpha = 0.5$)

Constant fit to α unravels interesting trend



Lévy-stability index α

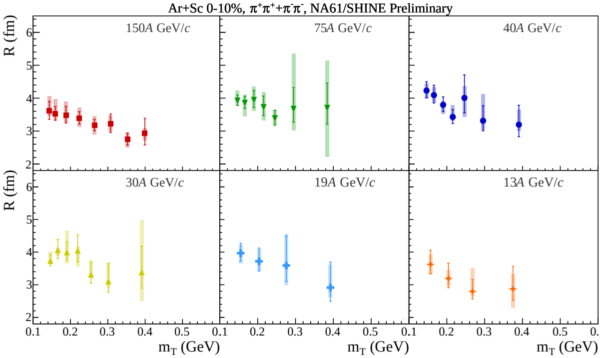
Minimum visible around $\sqrt{s_{NN}}$ = 6-8 GeV
Slightly nonmonotonic trend?
See talk of **D. Kincses** for full comparison



- NA61/SHINE: α
  $\approx$ 1.067 Be+Be, $\sqrt{s_{NN}} \approx$ 16.8 GeV
  Eur.Phys.J.C 83 (2023) 10, 919
  $\approx$ 1.830 Ar+Sc, $\sqrt{s_{NN}} \approx$ 16.8 GeV
  Universe 2023, Volume 9, Issue 7, 298
  $\approx$ 1.601 Ar+Sc, $\sqrt{s_{NN}} \approx$ 12.0 GeV
  $\approx$ 1.602 Ar+Sc, $\sqrt{s_{NN}} \approx$ 8.8 GeV
  arXiv:2406.02242
  $\approx$ 1.557 Ar+Sc, $\sqrt{s_{NN}} \approx$ 7.7 GeV
  $\approx$ 1.562 Ar+Sc, $\sqrt{s_{NN}} \approx$ 6.2 GeV
  $\approx$ 1.901 Ar+Sc, $\sqrt{s_{NN}} \approx$ 5.3 GeV
- PHENIX: α = 1.2 Au+Au, $\sqrt{s_{NN}}$ = 200 GeV
  $p_T > 0.2$ GeV/c
  Phys.Rev.C97 (2018) no.6, 064911
- CMS: α = 1.6-1.9 Pb+Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
  $p_T > 0.5$ GeV/c
  Phys.Rev.C109 (2024), 024914

Lévy-scale parameter R vs. m_T

- Describes length of homogeneity
- From hydro: decrease with m_T
  $R \approx 1/\sqrt{m_T}$ (For non power-law tail)
  Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390-1403
  S. V. Akkelin and Yu. M. Sinyukov,
  Phys.Lett.B356 (1995) 525-530
  S. Chapman, P. Scotto and U. W. Heinz,
  Phys.Rev.Lett.74 (1995) 4400-4403
- Visible m_T dependence
  sign of transverse flow
  Interesting for $\alpha < 2$
  - α anticorrelates with R, λ; increase in α $\rightarrow$ decrease in R



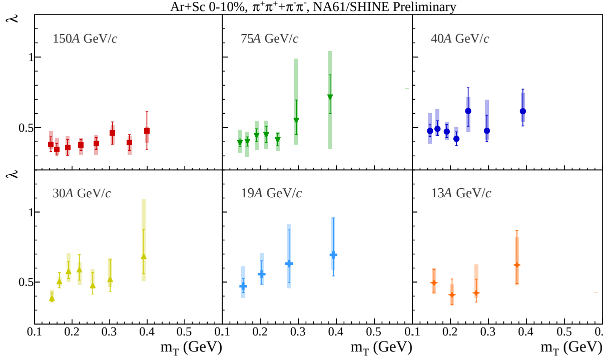
Correlation Strength λ

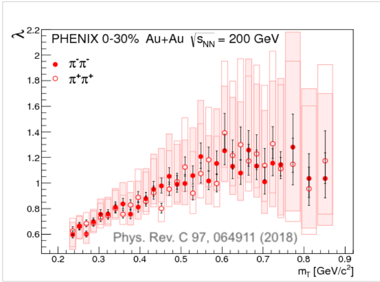
- Describes core-halo ratio
- Compared to RHIC results:
  - Low m_T values show no decrease (sim. to other SPS results)
  - Halo component increases at RHIC (e.g. In-medium mass mod.)

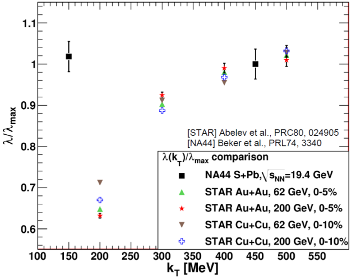
    S. E. Vance et al, Phys.Rev.Lett.81 (1998) 2205-2208

    T. Csörgő et al, Phys.Rev.Lett.105 (2010) 182301

    A. Adare for PHENIX Collaboration, Phys.Rev.C97 (2018) no.6, 064911
- λ values show no clear m_T dependence





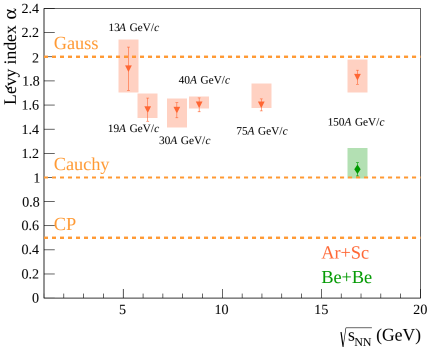


Summary

- NA61/SHINE Lévy HBT analysis
  - ^{7}Be+^{9}Be collisions, 0-20% centrality at 150A GeV/c beam momentum
  - ^{40}Ar+^{45}Sc collisions, 0-10% centrality at 150A, 75A, 40A, 30A, 19A, 13A GeV/c beam momentum
- Measured momentum correlations of sum of like charged π pairs
- Fit done with correlation functions from symmetric Lévy source
- Parameter m_T dependence:
  - $\alpha(m_T)$:
    - ★ Be+Be ≈ 1
    - ★ Ar+Sc $\approx 1.6 - 1.8$
  - $R(m_T)$: visible m_T dependence - sign of transverse flow
  - $\lambda(m_T)$: no dependence, no hole
  - Interesting minimum in $\langle\alpha\rangle$ around $\sqrt{s_{NN}} = $ 6-8 GeV
- $\alpha < 2 \rightarrow$ Symmetric Lévy source is a good assumption

Outlook:

- Larger system energy scan analysis with ^{129}Xe+^{139}La



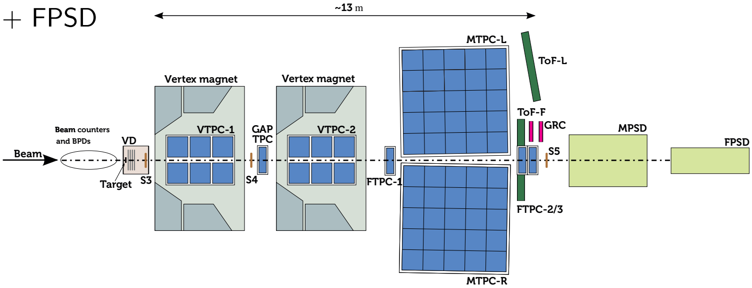
Thank you for your attention!

Supported by the DKOP-23 Doctoral Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

Backup

The NA61/SHINE Detector Post LS2

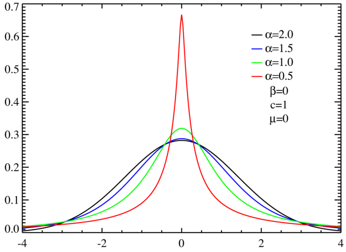
- Upgrade of DAQ + new trigger system (TDAQ)
  - Detector readouts replaced → data taking rate up by 20x
  - TPCs - ALICE; other detectors - DRS4
- Construction of:
  - Vertex Detector - open-charm measurements
  - ToF-F wall
  - Multi-gap Resistive Plate Chamber based ToF-L (ToF-R under constr.)
  - Beam Position Detector
  - Geometry Reference Chamber - drift velocity measurements
- Upgrade of PSD to MPSD + FPSD



Stable distributions

- If a lin. comb. of two indep. random variables with this distribution has the same distribution
- $f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \varphi(q) e^{-ixq} dq$, where the characteristic func.:
- $\varphi(q; \alpha, \beta, R, \mu) = \exp(iq\mu - |Rq|^{\alpha}(1 - \beta \mathrm{sgn}(q)\Phi)$
  α: stability index
  β: skewness, distribution symmetric if $= 0$
  R: scale parameter
  μ: location parameter, if $\beta = 0 \rightarrow$ median

$$\Phi = \begin{cases} \tan(\frac{\pi\alpha}{2}, \alpha \neq 1 \\ -\frac{2}{\pi} \log |t|, \alpha = 1 \end{cases}$$

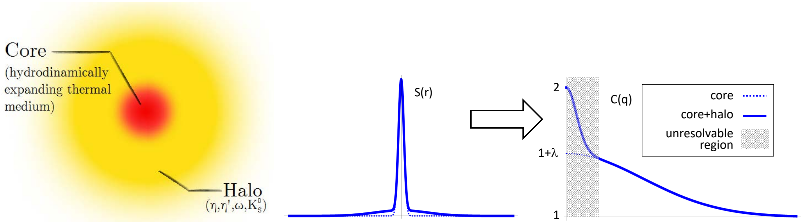


- Sum of two random variables from a stable distribution gives something with the same values of α and β (with possibly different values of μ and R...)
- $\beta = 0 \rightarrow$ Lévy symmetric alpha-stable distribution

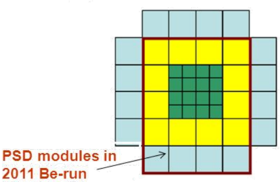
Core-Halo Model

- Hydrodinamically increasing core $\rightarrow$ pion emission
- Results in two component source: $S(x) = S_M(x) + S_G(x)$
- Core $\cong$ 10 fm size, halo$(\omega, \eta \ldots) >$ 50 fm size
- Halo not seen due to detector resolution
- Real q$\rightarrow$ 0, at $C(q = 0) = 2$
- Results show $C(q \rightarrow 0) = 1 + \lambda$, where $\lambda = \left(\frac{N_m}{N_g + N_m}\right)^2$

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



Projectile Spectator Detector



- Centrality measurement with PSD
- Located on beam axis
- measures forward energy (E_F) from spectators
- Intervals in E_F allows to select centrality classes