

# NA61/SHINE results on fluctuations and correlations at CERN SPS energies

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for the NA61/SHINE Collaboration

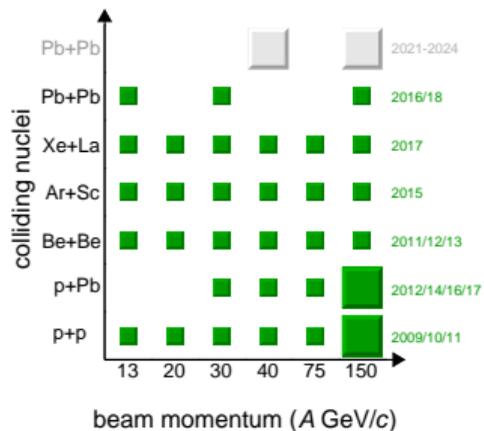
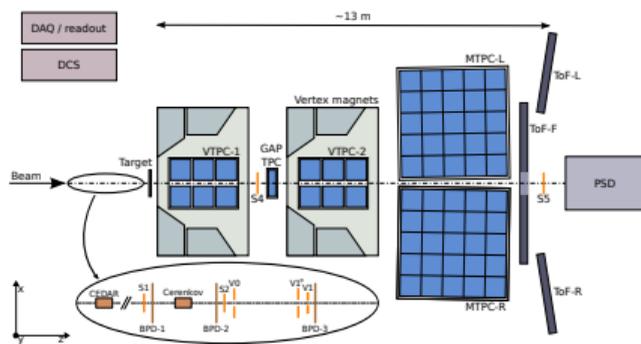
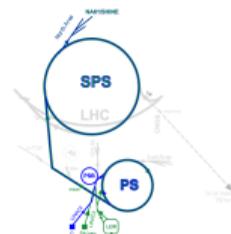
Faculty of Physics, Warsaw University of Technology



# NA61/SHINE

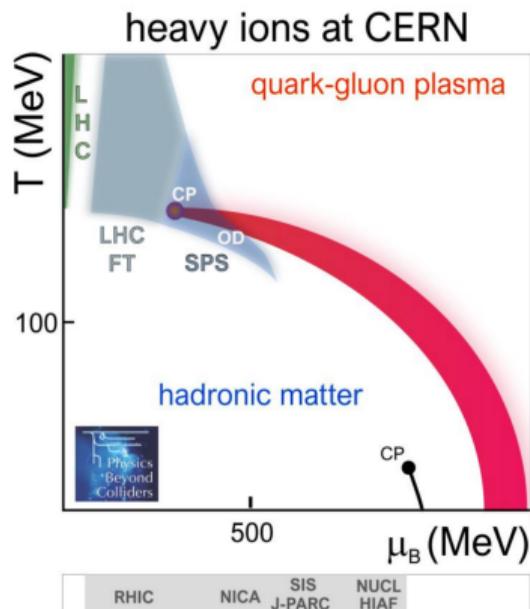
NA61/SHINE is a fixed target experiment located at SPS CERN.  
Two dimensional system size - energy scan of the ion program is focused on:

- the study of the onset of deconfinement (OD)
- search for the critical point (CP)

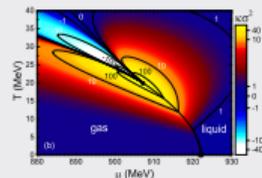


Large acceptance ( $\approx 50\%$  of produced charged particles) combined with precise forward energy measurements makes NA61/SHINE perfect place to measure fluctuations and correlations

# New results on fluctuations and correlations



- net-charge/multiplicity fluctuations → CP



CP →  $\xi$

$\langle N^2 \rangle \sim \xi^2$   $\langle N^4 \rangle \sim \xi^7$   
Stephanov, J.Phys.G 38,124147

Vovchenko et al. Acta Phys.  
Polon. Supp. 10,75

- HBT analysis → CP

The shape of the correlation function with Lévy source:

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

Lévy distribution leads to power-law correlation functions where Lévy-exponent  $\alpha$  identical to correlation exponent  $\eta$   
Csörgő et al., EPJC36

Expected value of  $\alpha$  for CP  $\approx 0.5$

- intermittency → CP

2nd order phase transition → scale invariance → power-law form of correlation function for large distances

↔ small momentum transfer  $\Delta \vec{k}$

Wosiek ,Acta Phys. Polon.B 19,863-869; Bialas and Hwa,PLB 253,436-438; Diakonov et al., PoS (CPD2006)010; Hatta and Stephanov, PRL91, 102003

- flow → OD

Csernai, Rohrich, PLB458,454; Stoecker, NPA750,121; Brachmann et al. PRC61,02909

# Fluctuations - Intensive quantities

Independent of volume  $V$  in Ideal Boltzmann Grand Canonical Ensemble (IB-GCE)

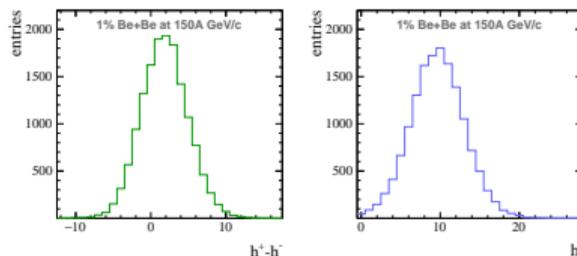
$$\omega[N] = \frac{\kappa_2[N]}{\kappa_1[N]}, \quad S\sigma[N] = \frac{\kappa_3[N]}{\kappa_2[N]}, \quad \kappa\sigma^2[N] = \frac{\kappa_4[N]}{\kappa_2[N]}$$

where  $\kappa_i$  stands for  $i$ 'th order cumulant

There are two reference values:

- 1 for Poisson distribution (e.g. IB-GCE)
- 0 for no fluctuations

Begun and MMP, arxiv:1705.01110[nucl-th]

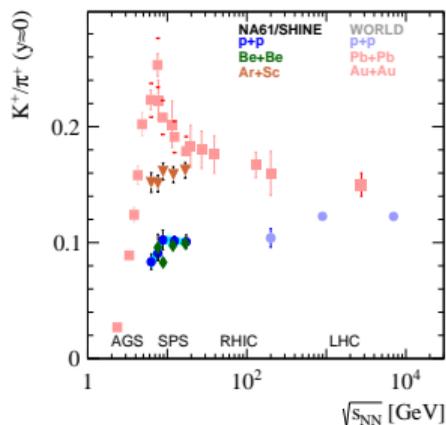


Experimentally we are only able to narrow centrality of the registered events and consider events from a given centrality class. Thus, intensive quantities contain also fluctuations of the system size.

Remarks:

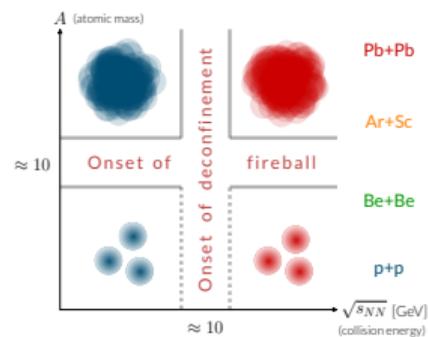
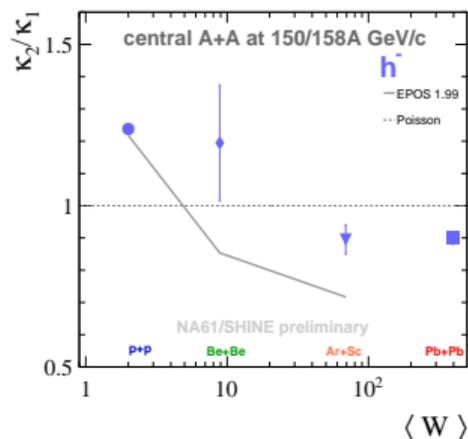
- For net-charge reference distribution is Skellam not Poisson
- Centrality selection differs between experiments and for not the most central events it leads to different sets of events
- The simplest dependence is for  $\omega[N] = \omega[N]_V + \langle n \rangle \frac{\text{Var}[V]}{\langle V \rangle}$ , where  $n$  stands for particle density

# Fluctuations at 150/158A GeV/c - system size dependence



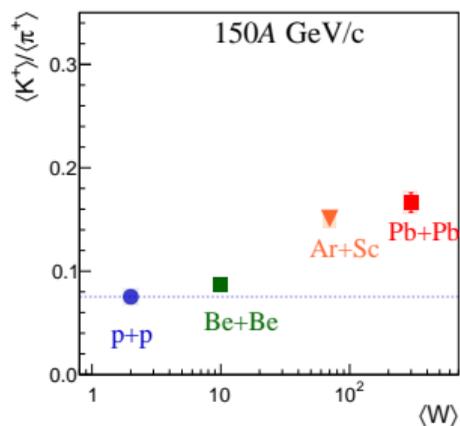
- $K^+/\pi^+$  rapid change between Be+Be and Ar+Sc
- similar change visible in fluctuations at top SPS not reproduced by EPOS1.99
- possible phenomena:

- ▶ percolation  
Baym, Physica 96A,131; Celik, et al., PLB 97:128; Armesto et al. PRL 77:3736
- ▶ AdS/QCD correspondence  
Shuryak, Prog.Part.Nucl.Phys.62:48; Lin, Shuryak, PRD 79: 124015



EPOS1.99: Werner, et al., PRC74:044902

# Fluctuations at 150/158A GeV/c - system size dependence



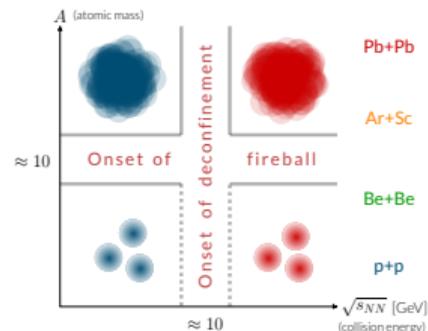
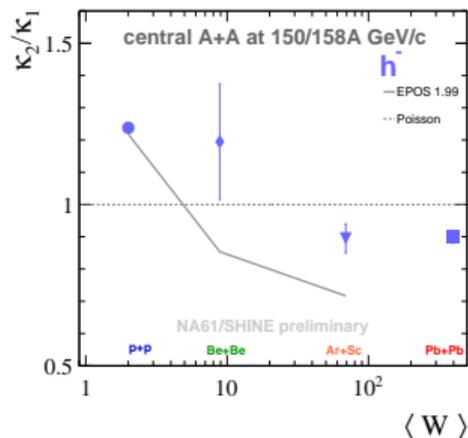
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EPOS1.99: Werner, *et al.*, PRC74:044902

# Fluctuations - data at 150/158A GeV/c

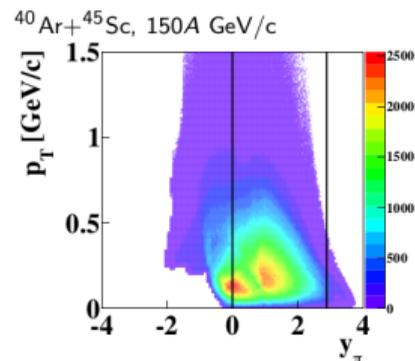
Presented results refers to charged hadrons produced in strong and electromagnetic processes. For 150/158A GeV/c the following results are available:

- **p+p** - minimum bias interactions corrected for trigger bias, detector inefficiency and feed-down  
 $\omega$  - NA61/SHINE, EPJC(2016)76:635; MMP, CPOD2016
- **Be+Be - 1% most central collisions uncorrected with estimate of systematic bias**  
 $\omega$  - Seryakov, WPCF2017
- **Ar+Sc - 1% most central collisions corrected results with systematic uncertainty under study**  
 $\omega$  - Seryakov, WPCF2017

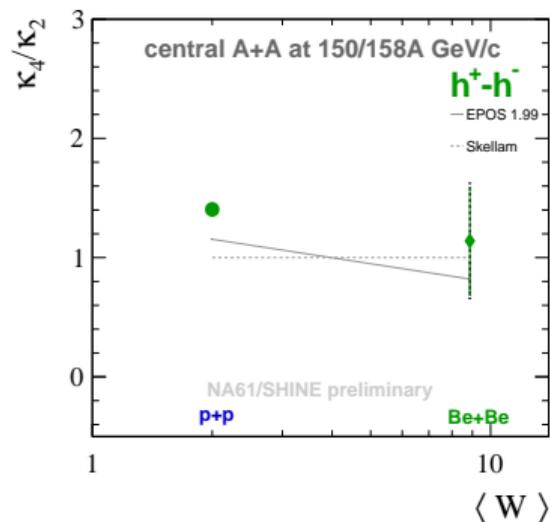
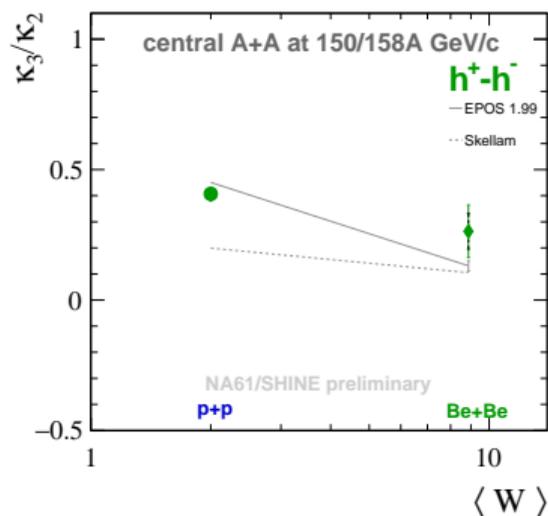
All considered results have statistical uncertainty obtained either via subsample method or with bootstrap method.

Acceptance: forward rapidity with  $p_T < 1.5$ :

- **p+p acceptance** - full acceptance of NA61/SHINE  
<https://edms.cern.ch/document/1549298/1>
- **Be+Be/Ar+Sc acceptance**: NA61/SHINE p+p acceptance with additional rapidity cut:  
 $0 < y_\pi < y_{beam}$



# Fluctuations - net-charge



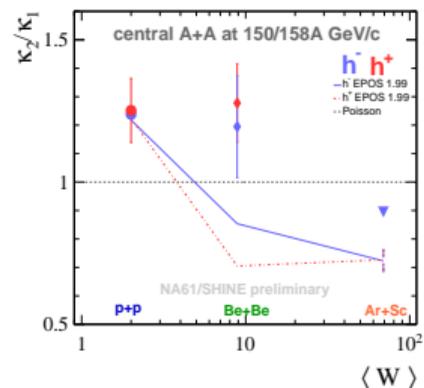
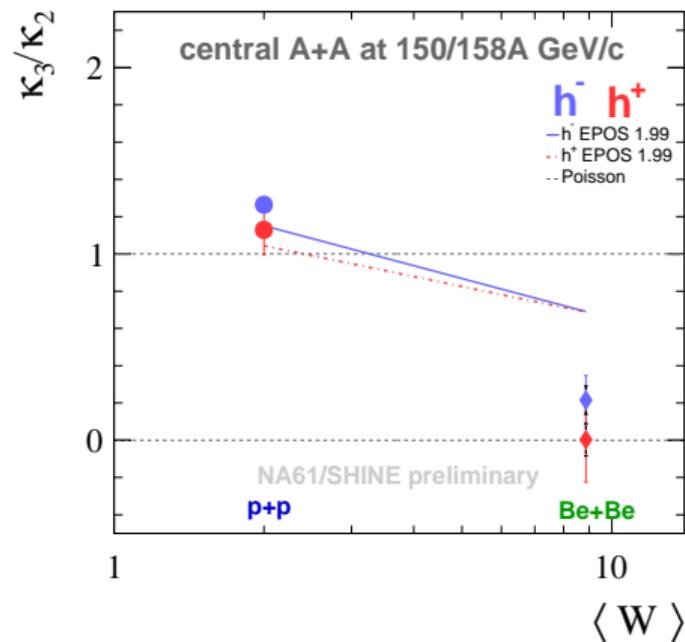
- $p+p \approx Be+Be$  in  $\kappa_3/\kappa_2$  and  $\kappa_4/\kappa_2$
- EPOS 1.99 predictions agree with the measured data
- no indications of CP
- stay tuned for Ar+Sc results

Remarks:

statistical uncertainty of each data point - black dashed lines

systematic uncertainty/estimation of systematic bias - solid line of the same color as marker

# Multiplicity fluctuations - higher order moments



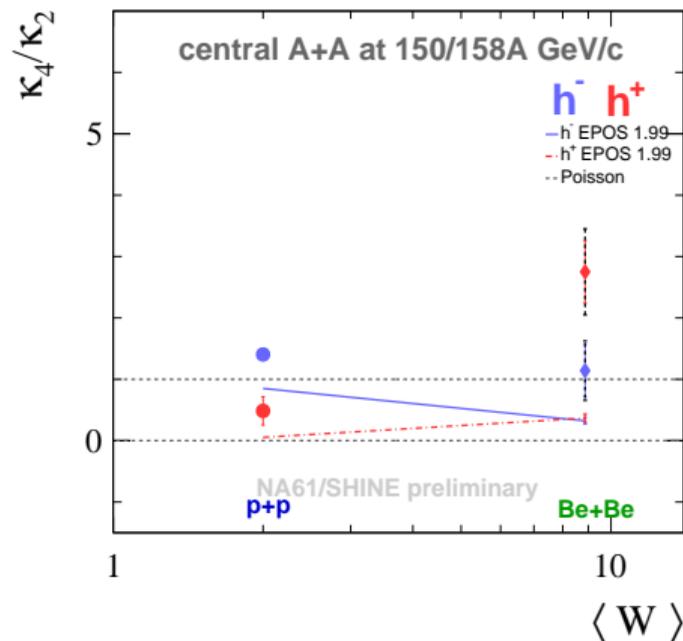
- $\kappa_3/\kappa_2$ : p+p > Be+Be
- EPOS predicts qualitatively system size dependence of  $\kappa_3/\kappa_2$  but predicted decrease in EPOS is too weak
- stay tuned for Ar+Sc results

Remarks:

statistical uncertainty of each data point - black dashed lines

systematic uncertainty/estimation of systematic bias - solid line of the same color as marker

# Multiplicity fluctuations - higher order moments



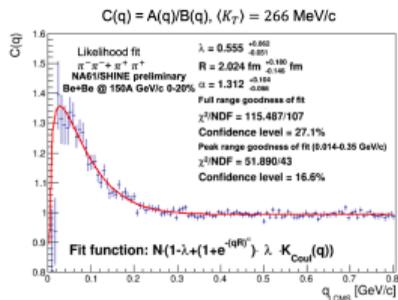
- $h^+$  and  $h^-$  results indicate different system size dependence
- system size dependence predicted by EPOS 1.99 is different then in the data for both  $h^+$  and  $h^-$
- stay tuned for Ar+Sc results

Remarks:

statistical uncertainty of each data point - black dashed lines

systematic uncertainty/estimation of systematic bias - solid line of the same color as marker

# $\pi$ HBT in 20% Be+Be at 150A GeV/c

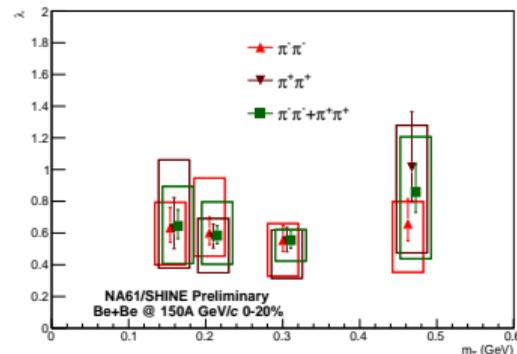
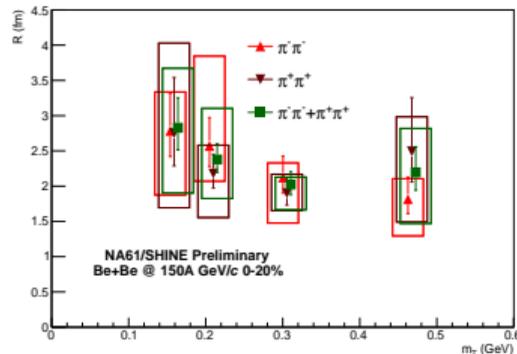


- Bose-Einstein correlations allow to measure spatial correlations
- usually assumed Gaussian shape of source but it can be generalized to Lévy-stable distribution

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

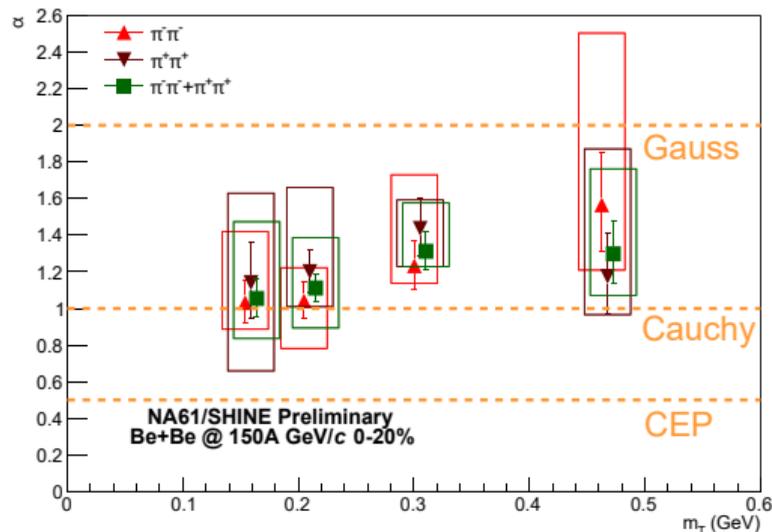
where  $\alpha = 1$  Cauchy,  $\alpha = 2$  Gaussian,  $\alpha < 2$  e.g. anomalous diffusion (Lévy flight)

- $R$  weakly decreases with  $m_T$  (transverse flow) comparable with RHIC and LHC p+p data
- $\lambda$  independent of  $m_T$  with given statistics

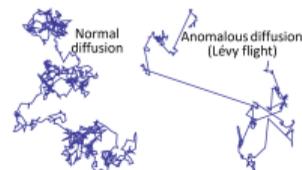


B. Porfy, WPCF2019

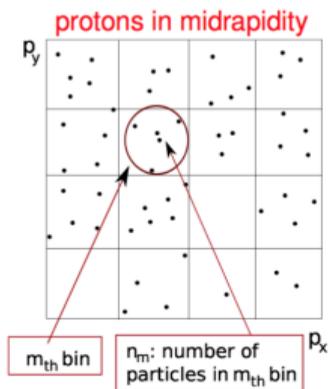
# $\pi$ HBT in 20% Be+Be at 150A GeV/c



- $\alpha$  does not indicate CP in Be+Be (far from 0.5)
- $\alpha$  between Gaussian or Cauchy shape might be the sign of anomalous diffusion

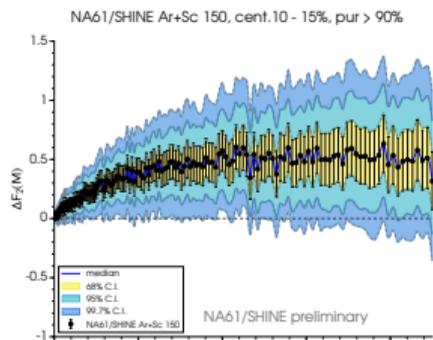


# Intermittency



$$F_2(M) = \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \right\rangle / \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_m \right\rangle^2,$$

where  $\langle \dots \rangle$  indicated averaging over events



Nature of CP should lead to local, **power-law fluctuations of baryon density**, which can be calculated by scaling of 2nd factorial moments with cell size  $\Leftrightarrow$  cells  $M$  in  $p_T$  space (intermittency)

Antoniou *et al*, Phys.Rev.Lett.97,032002

- for critical system  $F_2(M) \sim (M^2)^{\phi_{2,cr}}$ ,  $\phi_{2,cr} = 5/6$
- for noisy system non-critical background moments must be subtracted. Then the correlator

$$\Delta F_2(M) = F_2^{data}(M) - F_2^{mix}(M),$$

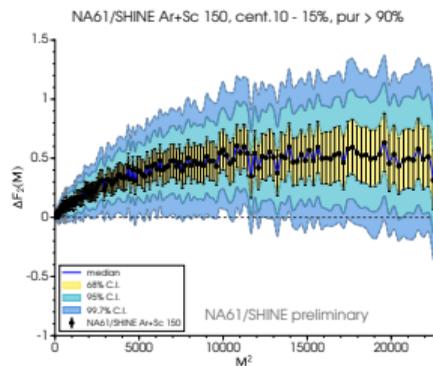
should scale according to power-law for  $M \gg 1$

**In 2018 we have reported indications of intermittency signal at Ar+Sc 150A GeV/c**

Davis, CPOD2018

# Intermittency

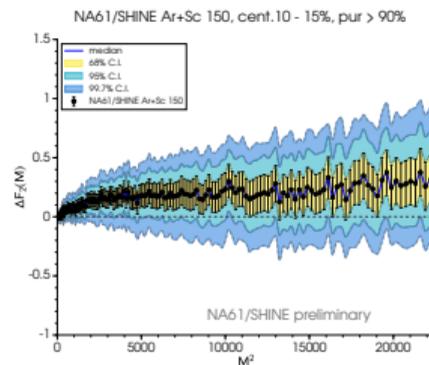
2018 results:



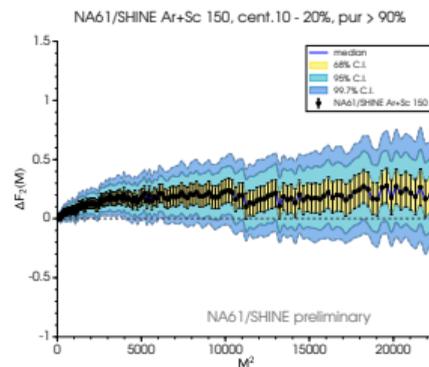
Data statistics: 142.9 k events

Intermittency measurements with larger statistics did not improve the significance of the measured  $\Delta F_2$  - no indication of CP

New results:



Data statistics: 208.2 k events

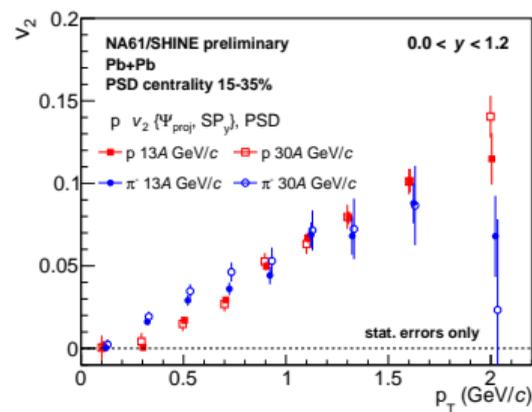
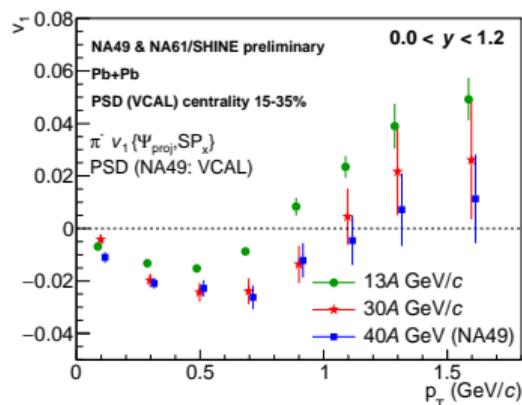


Data statistics: 392.5 k events

# Direct and elliptic flow in Pb+Pb at SPS

See poster CD-15 of E. Kashirin

- SPS beam momentum scan covers **OD**
- large particle acceptance and  $\Psi_{RP}$  estimation with transverse energy projectile spectators



- Pb+Pb at 40A GeV/c measured by NA49 E. Kashirin, WPCF 2019
- $v_1$  measured at 13A GeV/c from 30/40A GeV/c differs in the region of sign change
- elliptic flow of  $\pi^-$  and  $p$  is different but it does not show any energy dependence

# Conclusions

## Search for the critical point

- **fluctuations of net-charge** in p+p and Be+Be at 150/158A GeV/c **do not show indication of CP**
- pion HBT in Be+Be at 150A GeV/c - **no indications of CP**
- intermittency measurements with larger statistics in Ar+Sc at 150A GeV/c did not improve the significance of the measured  $\Delta F_2$  - **no indication of CP**
- multiplicity fluctuations of different charges show interesting dependence which is often not reproduced by the EPOS model - **more systematic measurements needed in order to understand observed dependencies**

## Properties of the onset of deconfinement:

- direct flow in Pb+Pb collisions at 13A GeV/c differs from 30/40A GeV/c

Thank you.

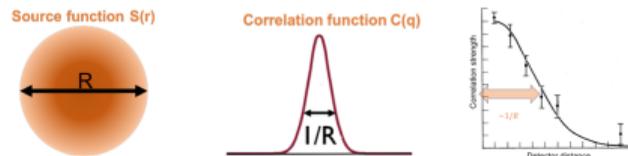


For other results from NA61/SHINE see also A. Tefelska poster SS 41 on  $K^*$  measurements in p+p

### **Acknowledgements**

This work was supported by the National Science Centre, Poland under grants no. 2016/21/D/ST2/01983 and 2014/14/E/ST2/00018.

# $\pi$ HBT in Be+Be



- Bose-Einstein correlations allow to measure spatial correlations
- usually assumed Gaussian shape of source but it can be generalized to Lévy-stable distribution

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

where  $\alpha = 1$  Cauchy,  $\alpha = 2$  Gaussian,  $\alpha < 2$  anomalous diffusion (Lévy flight)

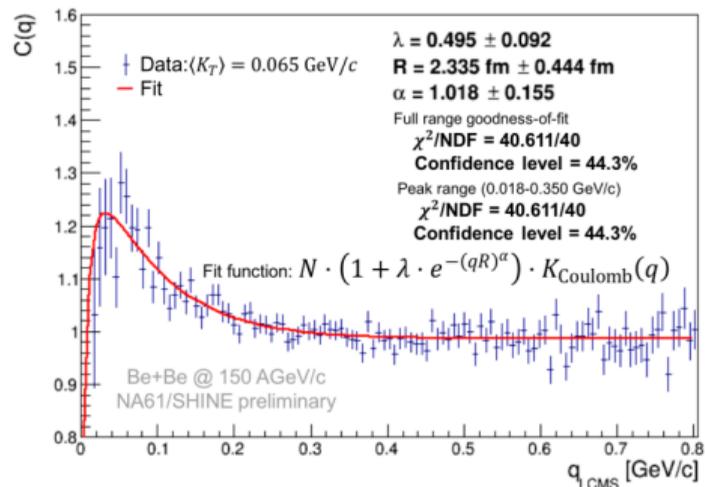
- shape of the correlation function with Lévy source:

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

Lévy distributions leads to power-law correlation functions with Lévy-exponent  $\alpha$  identical to correlation exponent  $\eta$

Csörgő *et al.*, EPJC36

# Parameters of the Lévy Correlation Function



B. Porfy, WPCF2018

Fit parameters:

- $\lambda$  correlation strength  
ratio of primordial pions to sum of primordial pions and resonance decay products
- from hydrodynamical picture:

$$R_{HBT} = \frac{R}{\sqrt{1 + \frac{m_T}{T_0} u_T^2}}$$

- $\alpha$  exponent:
  - ▶  $\alpha = 2$  simple hydrodynamical picture
  - ▶  $\alpha < 2$  anomalous diffusion  $\rightarrow$  generalized limit theorem
  - ▶  $\alpha = 0.5$  conjectured value at the critical point