Study of the phase diagram of strongly interacting matter in the NA61/SHINE experiment

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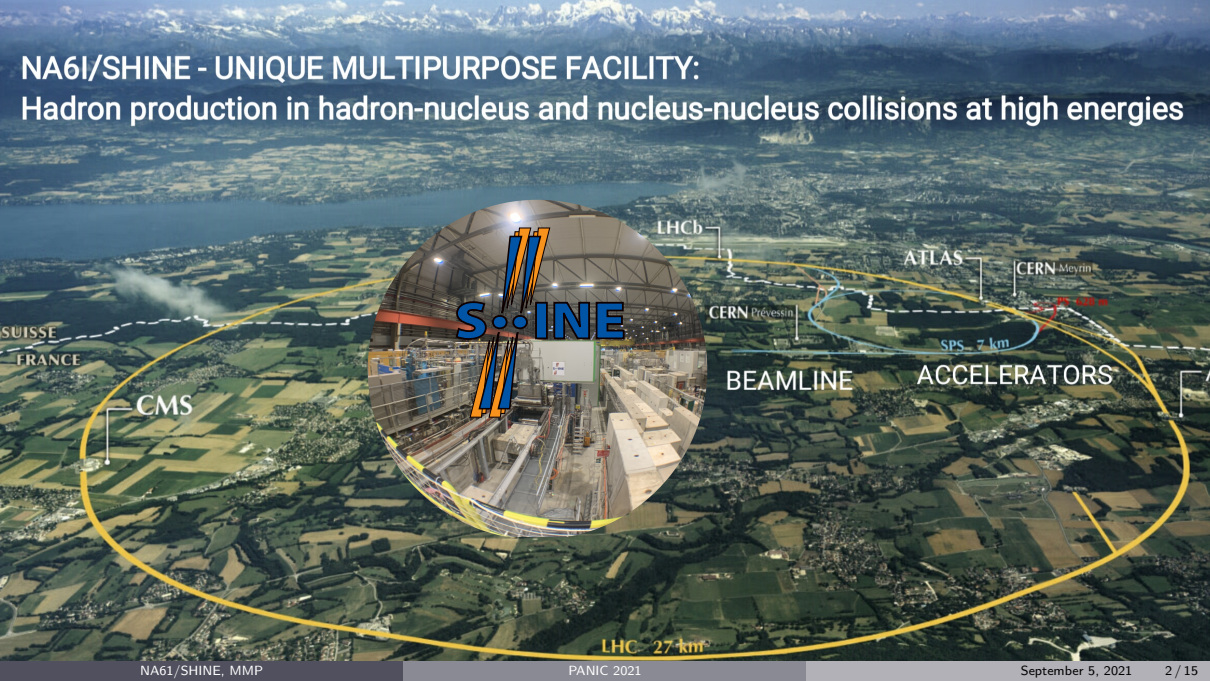
NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY:
Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies

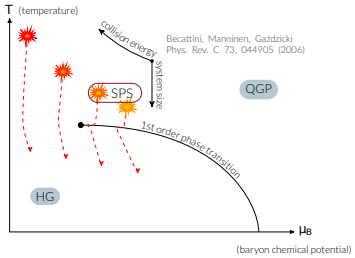


NA61/SHINE programme

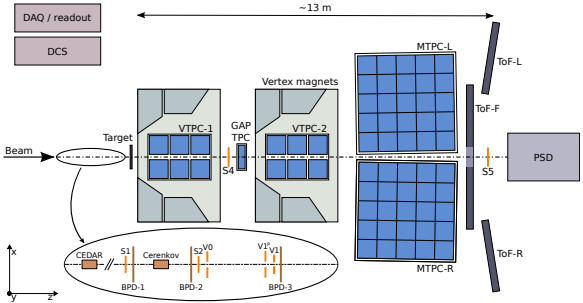
Strong interactions programme:

- **search for the critical point of strongly interacting matter**
- **study the properties of the onset of deconfinement**
- **heavy quarks: direct measurement of open charm at SPS energies**

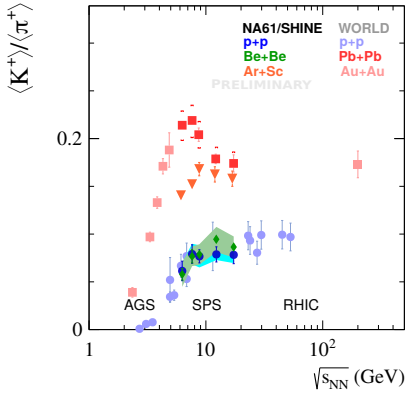
Measurements also for neutrino programs at J-PARC and Fermilab as well as nuclear fragmentation cross section for cosmic rays physics

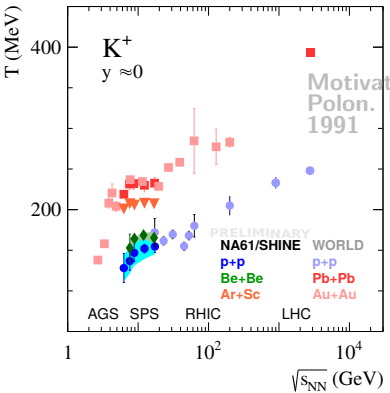


- coverage up to 50% **of produced charged particles** starting from $p_T \approx 0$
- ion (Be, Ar, Xe, Pb) and hadron (p, π, K) beam at 13A-150A(400) GeV/c



Onset of deconfinement - energy and system size dependence





Motivation: Acta Phys. Polon. B46 (2015) 10, 1991

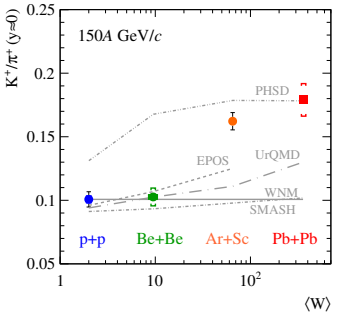
- no horn-like structure in Ar+Sc
- Be+Be closer to p+p

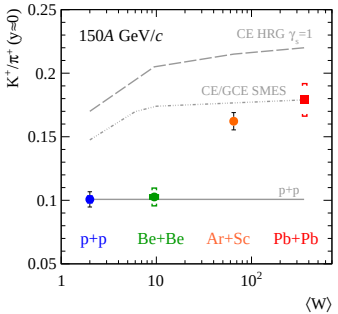
- plateau visible for p+p, Be+Be and Ar+Sc
- Be+Be far from Ar+Sc

p+p$\approx$ Be+Be $\not\approx$ Ar+Sc$\approx$Pb+Pb

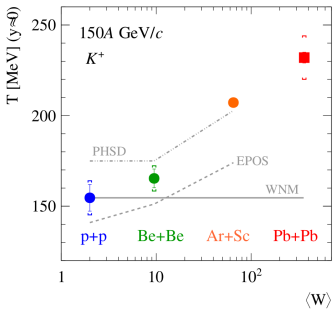
K^+/π^+ and T vs the system size dependence at 150A GeV/c

K^+/π^+





T parameter



None of the models reproduce K^+/π^+ ratio or T for whole $\langle W \rangle$ range

where W stand for number of wounded nucleons in the collision

PHSD: Eur.Phys.J. A56 (2020) 9, 223, arXiv:1908.00451 and private communication

SMASH: J.Phys. G47 (2020) 6, 065101 and private communication

UrQMD and HRG: Phys.Rev. C99 (2019) 3, 034909

SMES: Acta Phys.Polon. B46 (2015) 10, 1991 - recalculated

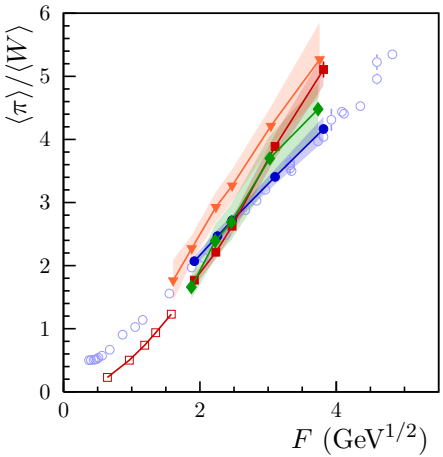
p+p: Eur.Phys.J. C77 (2017) 10, 671

Be+Be: Eur.Phys.J. C81 (2021) 1, 73

Ar+Sc: NA61/SHINE preliminary

Pb+Pb: Phys.Rev. C66 (2002)

Pion multiplicity per number of wounded nucleons



- Ar+Sc systematically higher than the N+N and Be+Be as well as Pb+Pb at lower energies
- Ar+Sc close to Pb+PB results at higher energies
- Be+Be results close to Pb+Pb at lower energies and between N+N and Pb+Pb at higher energies

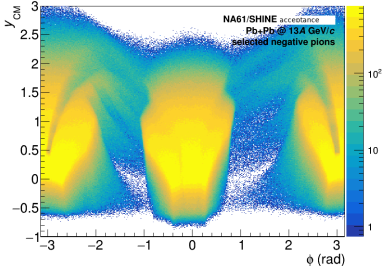
Motivation: SMES, Acta Phys.Polon. B46 (2015) 10, 1991

Fermi's measure of collision energy:

$$F = \frac{(\sqrt{s_{NN}}-2m_N)^{3/4}}{(\sqrt{s_{NN}})^{1/4}} \approx s_{NN}^{1/4}$$

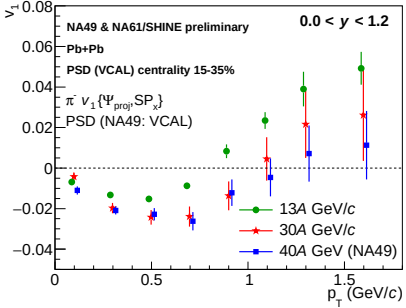
Direct and elliptic flow in Pb+Pb at SPS

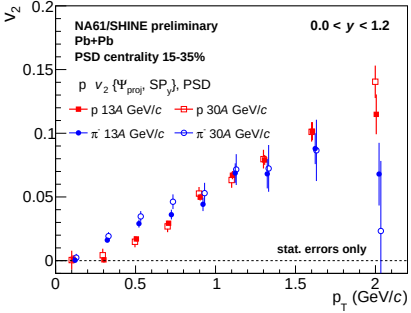
- quantified by Fourier coefficients in the decomposition of the particle azimuthal distribution relative to the collision symmetry plane (Ψ_s).
- Ψ_s can be determined by the projectile (target) spectator deflection Ψ_{proj} (Ψ_{targ}) or the shape of the participant zone Ψ_{pp} .
- **large particle acceptance and Ψ_{proj} estimation with transverse energy projectile spectators are NA61/SHINE highlights**



- Corrections for detector azimuthal anisotropy in flow analysis are applied $p_T - y$ deferentially using an extension of the Qn-Corrections Framework
  Phys. Rev., C77:034904, 2008

Direct and elliptic flow in Pb+Pb at SPS





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

Fluctuations - Intensive quantities

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

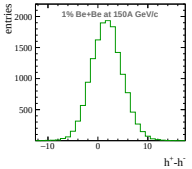
$$\frac{\kappa_2[h^+ - h^-]}{(\kappa_1[h^+] + \kappa_1[h^-])}, \quad \frac{\kappa_3[h^+ - h^-]}{\kappa_1[h^+ - h^-]} \quad \frac{\kappa_4[h^+ - h^-]}{\kappa_2[h^+ - h^-]}$$

where κ_i stands for $i'th$ order cumulant of the distribution

There are **two reference values**:

- 1 for Skellam distribution
- 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 e.g. **Gazdzicki et al., arXiv:2102.11186**

Remarks: Centrality selection differs between experiments and for not the most central events it leads to different sets of events.

Data and analysis acceptance

Presented results refers to charged hadrons produced in strong and electromagnetic processes in:

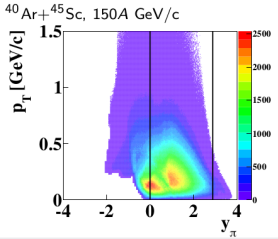
- **p+p – inelastic interactions** corrected for trigger bias, detector inefficiency and feed-down
  ω - NA61/SHINE, EPJC(2016)76:635; MMP, CPOD2016
- **Be+Be – 1% most central collisions** uncorrected with estimate of systematic bias (e.q. feed-down, detector inefficiency, beam and target impurity)
  ω - Seryakov, WPCF2017
- **Ar+Sc – 1% most central collisions** uncorrected with estimate of systematic bias (e.q. feed-down, detector inefficiency, beam and target impurity)
  Cybowska, ISMD2021

All considered results have statistical uncertainty obtained either via sub-sample or bootstrap methods.

Acceptance: **forward rapidity with $p_T < 1.5$ GeV/c:**

- p+p acceptance - full acceptance of NA61/SHINE
  https://edms.cern.ch/document/1549298/1
- A+A acceptance: acceptance with additional rapidity cut: $0 < y_\pi < y_{beam}$.
  https://edms.cern.ch/document/2487456/1

Note: non-uniform acceptance in ϕ



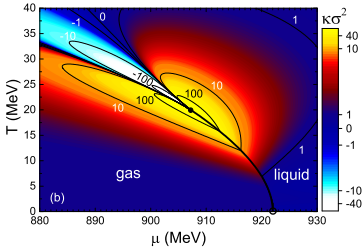
Accepted fraction of particles: $x[h^-] = \frac{h^-_{accepted}}{h^-_{4\pi}} \longrightarrow$

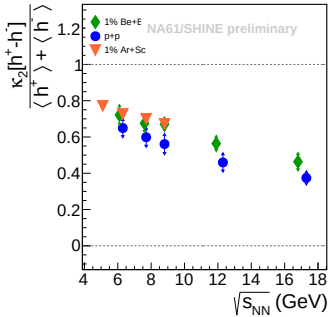
$\sqrt{s_{NN}}$ (GeV)	6.1	7.6	8.7	11.9	16.8
$x[h^-]$	0.27	0.3	0.3	0.4	0.5

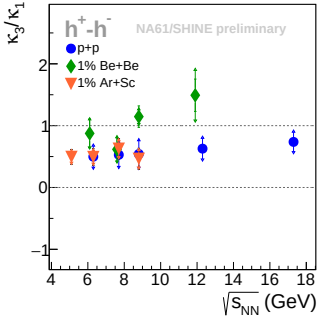
Higher order moments - net-charge

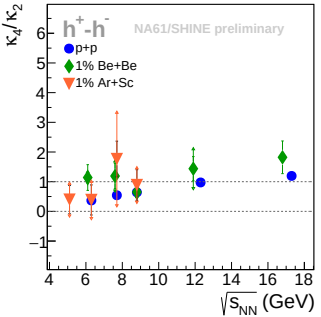
- critical point (CP) $\longrightarrow$ correlation length, ξ
- $\langle N^2 \rangle \sim \xi^2$ $\langle N^4 \rangle \sim \xi^7$
  Stephanov, J.Phys.G 38,124147

Theoretical calculations of phase transition with values of normalized kurtosis for nuclear matter described with van der Waals equations. Vovchenko et al. Acta Phys. Polon. Supp. 10,75 $\longrightarrow$









Second factorial moment - proton intermittency

- using statistically independent points and cumulative variables

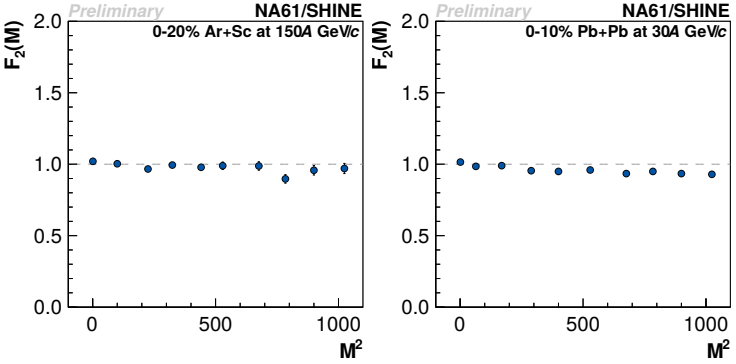
$$F_2(\delta) = \frac{\langle \frac{1}{M}\Sigma_{i=1}^{M} n_i(n_i-1)\rangle}{\langle \frac{1}{M}\Sigma_{i=1}^{M} n_i\rangle},$$

δ - size of each of the $M = \frac{\Delta}{\delta}$ subdivision intervals of the p_T

n_i - number of particles in i-th p_T bin

- at the 2^{nd} order phase transition $F_2(M)$ depends on M as:

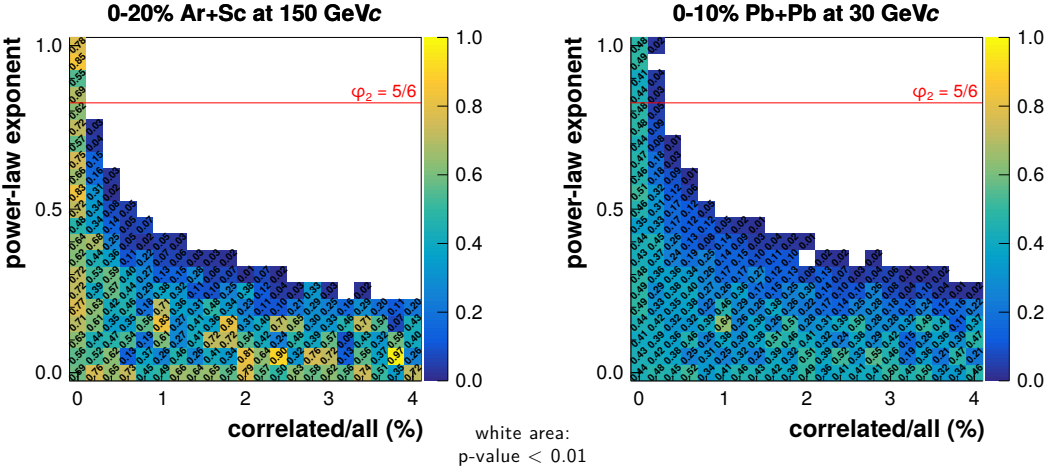
$$F_2(M) \sim (M^2)^{\phi_2}$$



PRL 97 (2006) 032002

$F_2(M)$ of protons for Ar+Sc at 150A GeV/c and Pb+Pb at 30A GeV/c show no indication for power-law increase with a bin size

Exclusion plots for parameters of simple power-law model



The intermittency index ϕ_2 for a system freezing out at the QCD critical endpoint is expected to be $\phi_2 = 5/6$ assuming that the latter belongs to the 3-D Ising universality class.

Conclusions

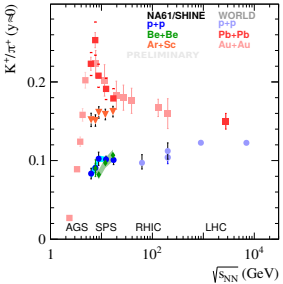
- Unique 2D scan in **system size** and the **collision energy** is completed although analysis are still ongoing - stay tuned for new results
- So-called **step structure** visible in **p+p, Be+Be, and Ar+Sc**
- So-called **horn structure** does **not** appear in **p+p, Be+Be, and Ar+Sc**
- So far, **no indication** of the **critical point**
- **None** of the present **theoretical models** can explain all presented results from NA61/SHINE

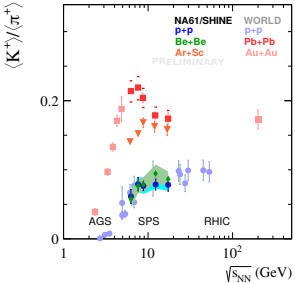
Thank you.

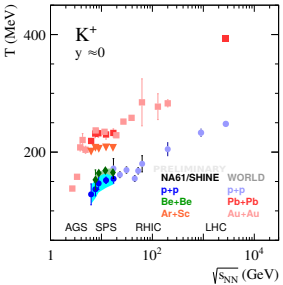
Acknowledgments

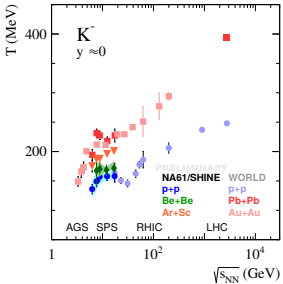
This work was supported by the National Science Centre, Poland under grants no. 2016/21/D/ST2/01983 and by WUT ID-UB.

Onset of deconfinement observables









Acta Phys.Polon.B 46 (2015) 10, 1991

K^+/π^+ and $\langle K^+\rangle/\langle\pi^+\rangle$:

- No horn-like structure in Ar+Sc
- Be+Be close to p+p
- Jump-like change in the system size dependence of k^+/π^+

Inverse slope parameter:

- Ar+Sc significantly above Be+Be
- Be+Be sloghtly above p+p

p+p≈ Be+Be ≉ Ar+Sc≈Pb+Pb

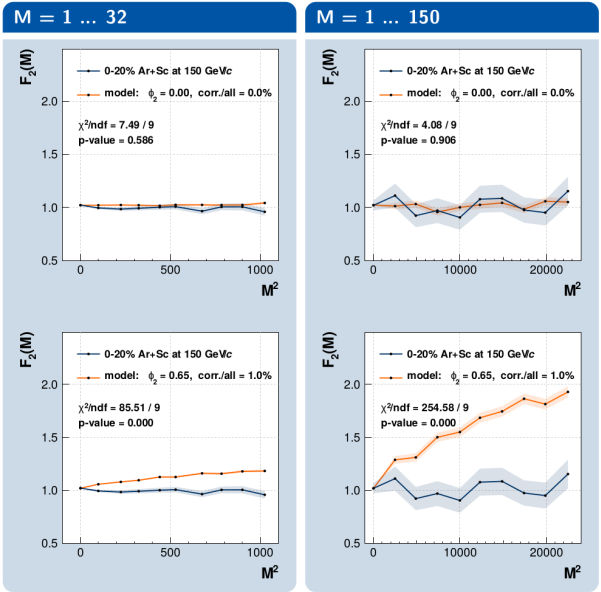
Proton intermittency simple power-low model

Many data-sets generated as:

- correlated-to-all ratio: vary from 0.0 to 4.0% (with 0.2 step)
- power-law exponent: vary from 0.00 to 1.00 (with 0.05 step)

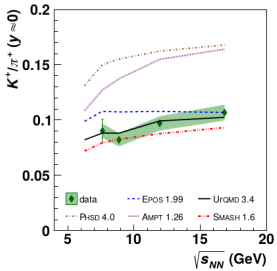
and compare with the experimental data.

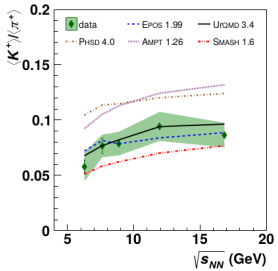
For the construction of exclusion plots, statistical uncertainties were calculated using model with statistics corresponding to the data.

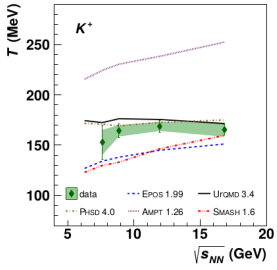


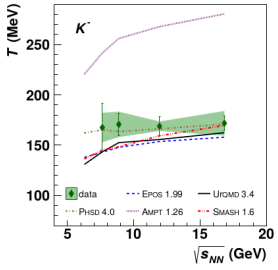
K/π in Be+Be and models

- NA61/SHINE - the only world data for Be+Be collisions
- K^+/π^+ ratio and inverse slope parameter T - smooth energy dependence
  Note the limited energy range of data
- None of actual models describe all measured quantites
  Eur. Phys. J. C 81 (2021) 1, 73

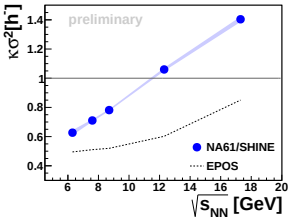




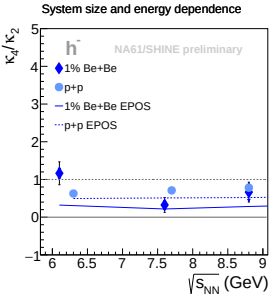


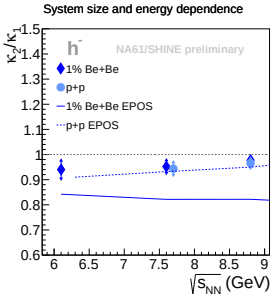


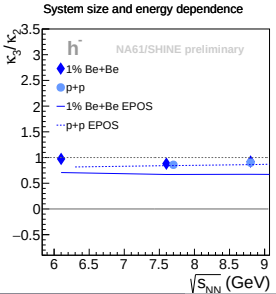
Fluctuations and models



$$\kappa\sigma^2 = \kappa_4/\kappa_2$$







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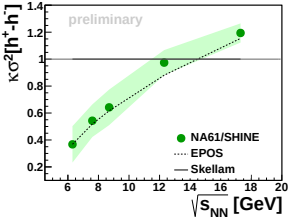

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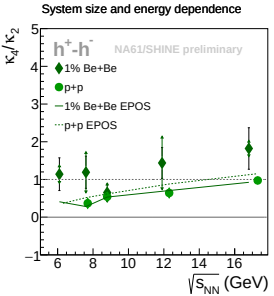
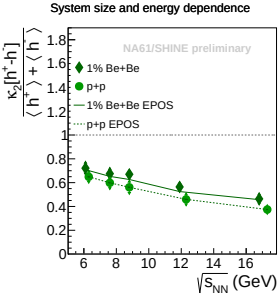
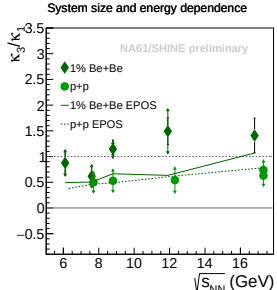
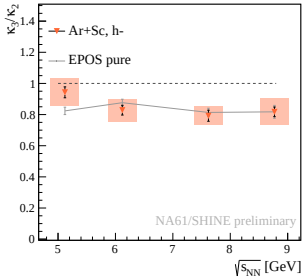
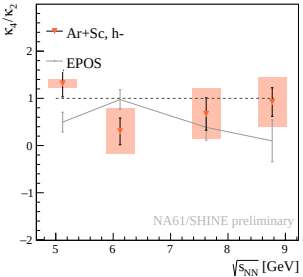


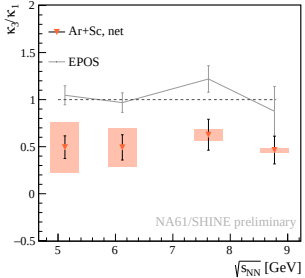


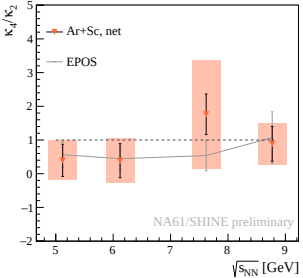


Fluctuations and models - Ar+Sc

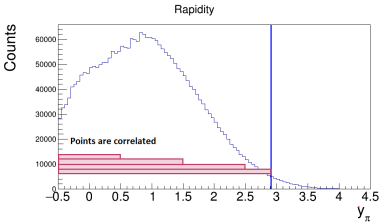






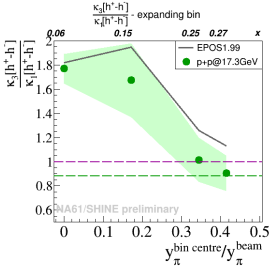


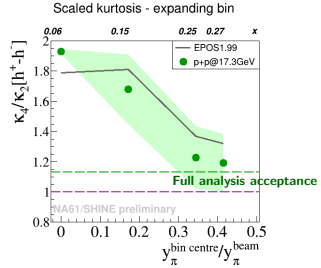
Fluctuations - rapidity dependence in p+p

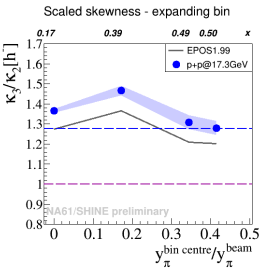


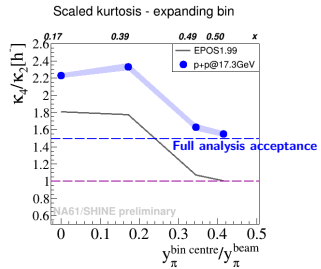
- Comparison of short- and long-range correlations.
- EPOS1.99 similar to the data but underestimates signal for h^-

Note that in case of expanding bin points are correlated.

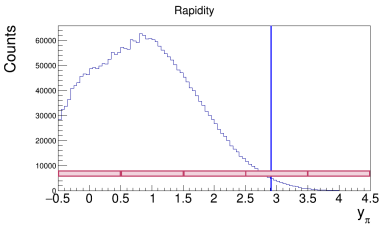








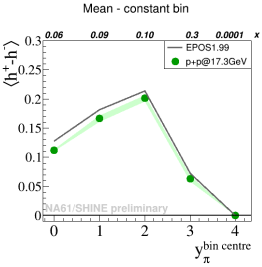
Higher order moments - rapidity dependence in p+p

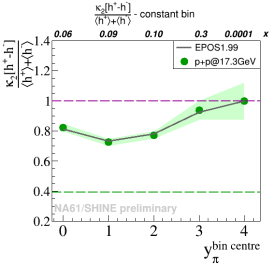


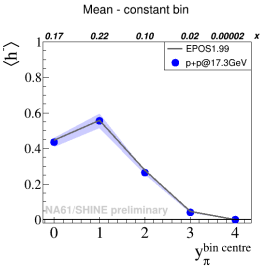
- Sensitivity for different measurements conditions
- The strongest signal visible for $y_\pi < 1.5$
- EPOS1.99 describes the data

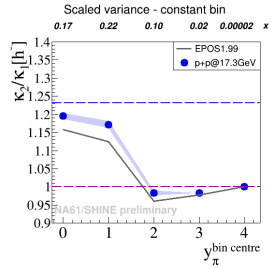
Dashed green and dashed blue line indicates value in full analysis acceptance,

https://edms.cern.ch/document/2487456/1

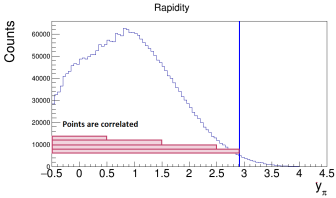




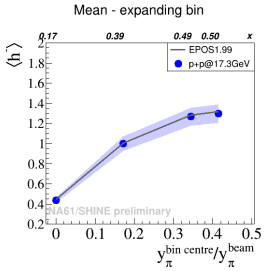


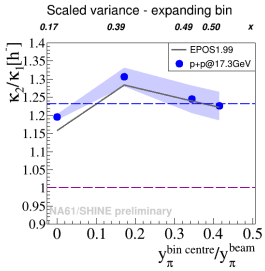


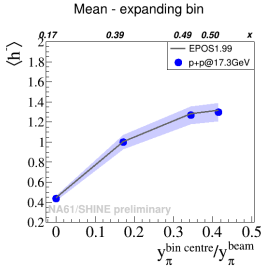
Fluctuations - rapidity dependence in p+p

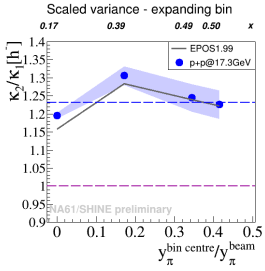


- Comparison of short- and long-range correlations.
- EPOS1.99 does not describe the data



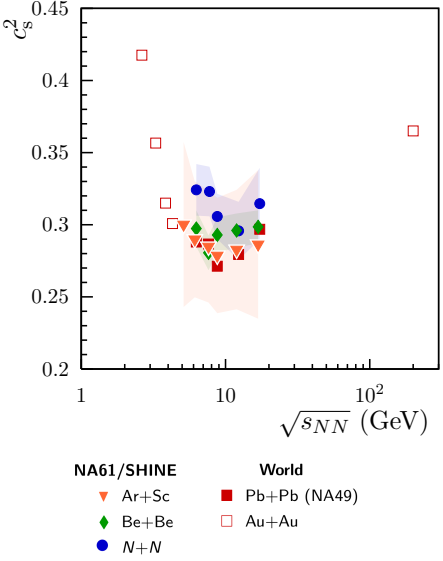






Dashed blue line indicates value in full analysis acceptance,

Width of the y_π distribution - speed of sound



- The collision energy dependence of the rapidity distribution width is associated with the speed of sound c_S:

$$\sigma^2 = \frac{8}{3}\frac{c_S^2}{1-c_S^4} ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$$

E.V.Shuryak, Yad.Fiz., 16, 395–405, 1972

- The results of NA61/SHINE from central Ar+Sc, Be+Be collisions, and inelastic N + N reactions need to be extended to lower energies for conclusion about a possible minimum

Motivation: M. Bleicher, PoS C POD2006, 025 (2006)