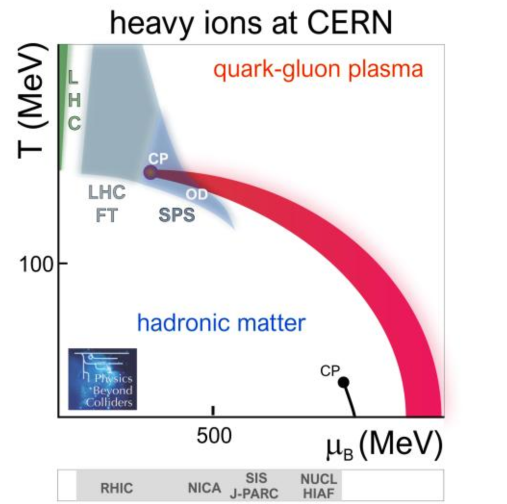
RECENT RESULTS FROM NA61/SHINE STRONG INTERACTION PROGRAM

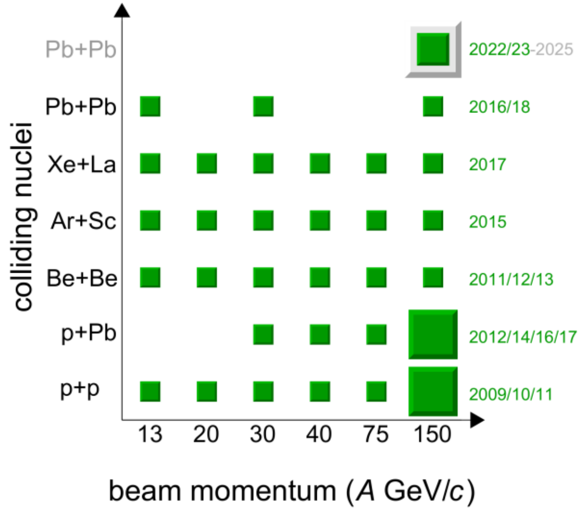
Seweryn Kowalski

for NA61/SHINE

NA61/SHINE physics program

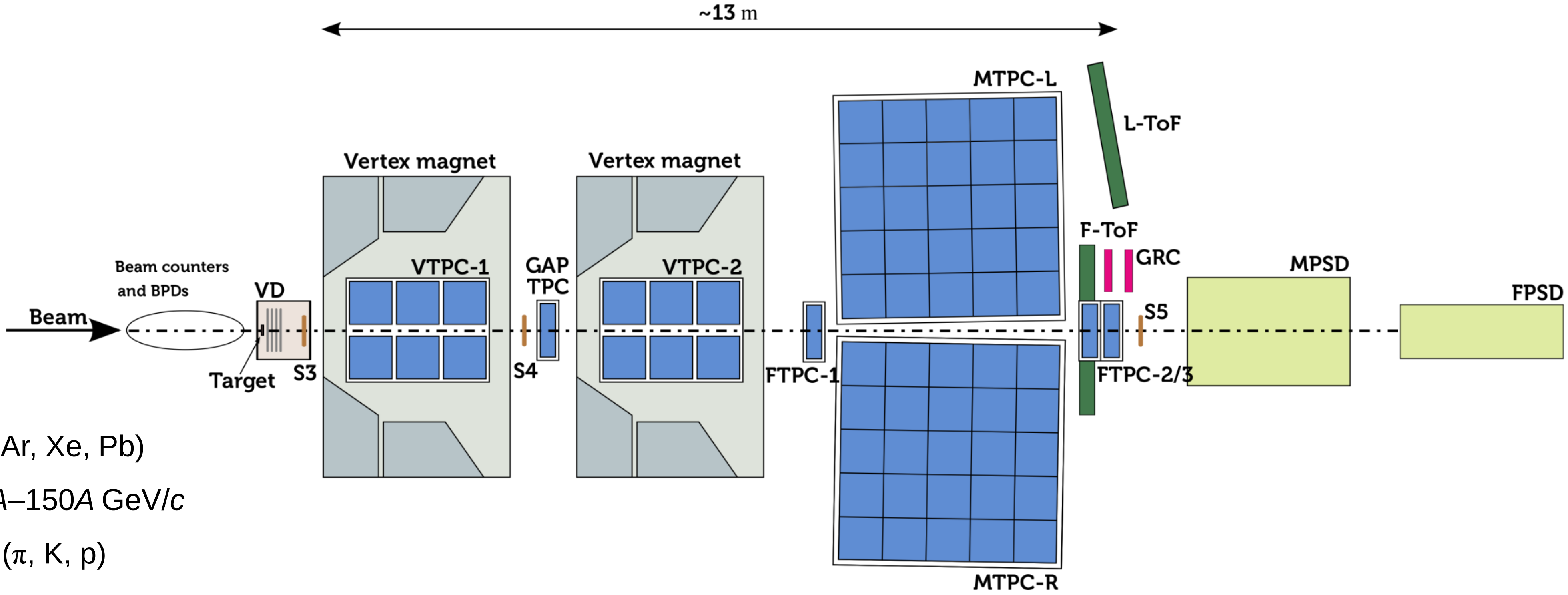
- Strong interaction physics:
  - study properties of the onset of deconfinement and onset of fireball
  - search for the critical point of strongly interacting matter
  - direct measurements of open charm
- Neutrino and cosmic-ray physics:
  - measurements for neutrino programs at J-PARC and Fermilab
  - measurements of hadron production and nuclear fragmentation cross section for cosmic-ray physics





NA61/SHINE detector

Fixed target experiment located at the CERN SPS accelerator



Beams:

- ions (Be, Ar, Xe, Pb)

  p_{beam}=13*A*–150*A* GeV/*c*

- hadrons (π, K, p)

  p_{beam}=13–400 GeV/*c*

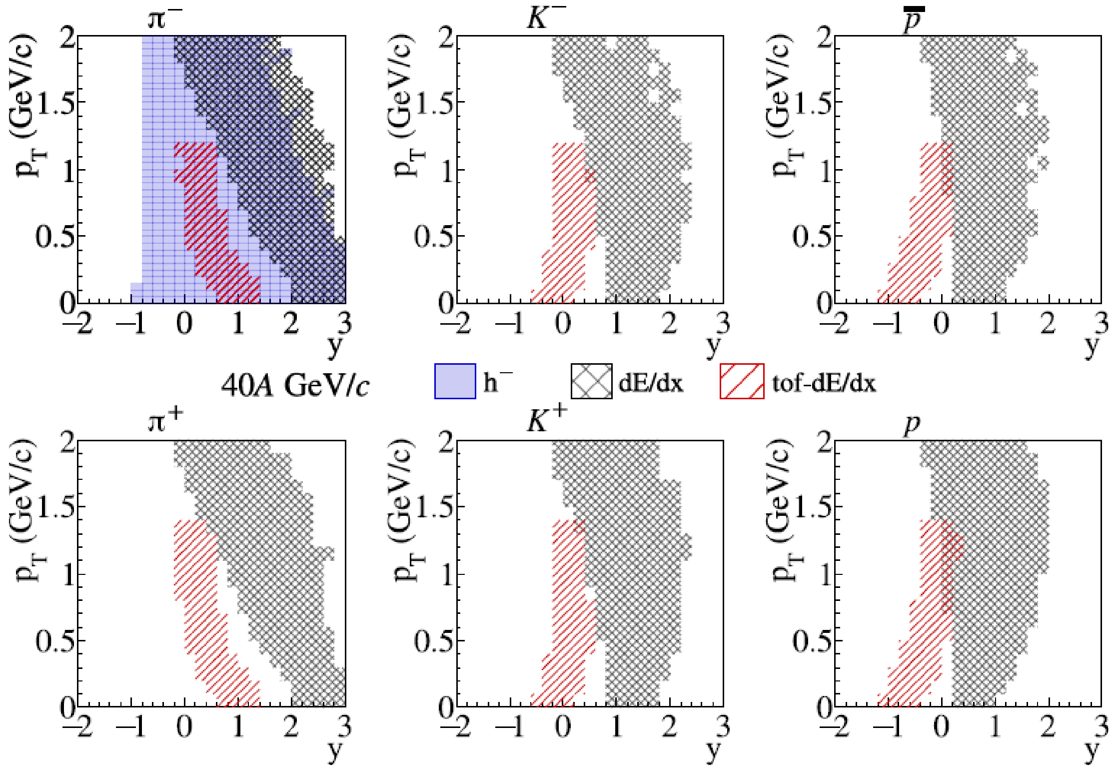
$\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

Large acceptance hadron spectrometer –
coverage of the full forward hemisphere, down to p_T = 0

Charged particle identification

Final results stand for primary particles produced in strong and electromagnetic processes, they are corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

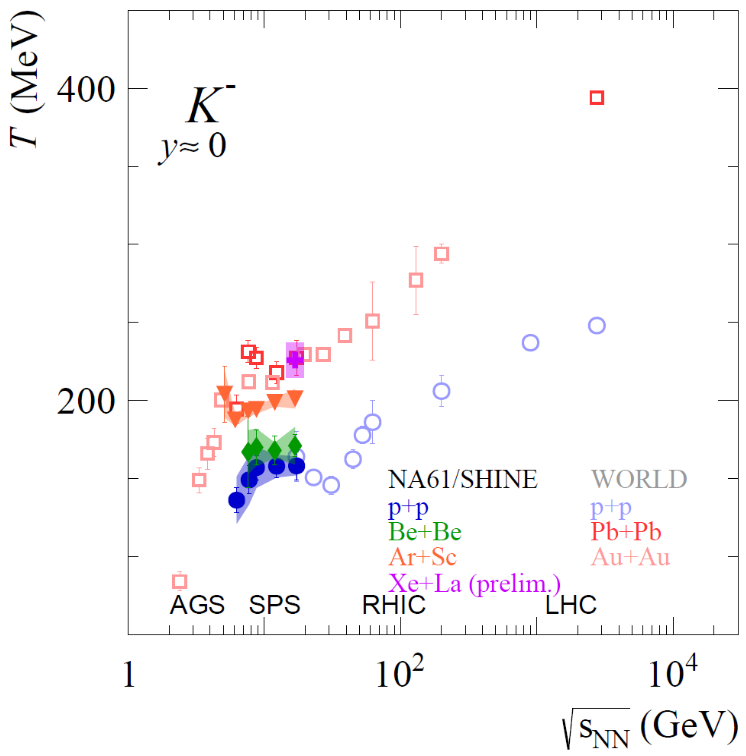
- h^- analysis based on the fact that the majority of negatively charged particles are π^- mesons. Contribution of the other particles is subtracted using EPOS Monte-Carlo
- dE/dx analysis uses TPC energy loss information to identify particles
- tof-dE/dx method estimates number of π, K, p using an energy loss and a particle time of flight measurements

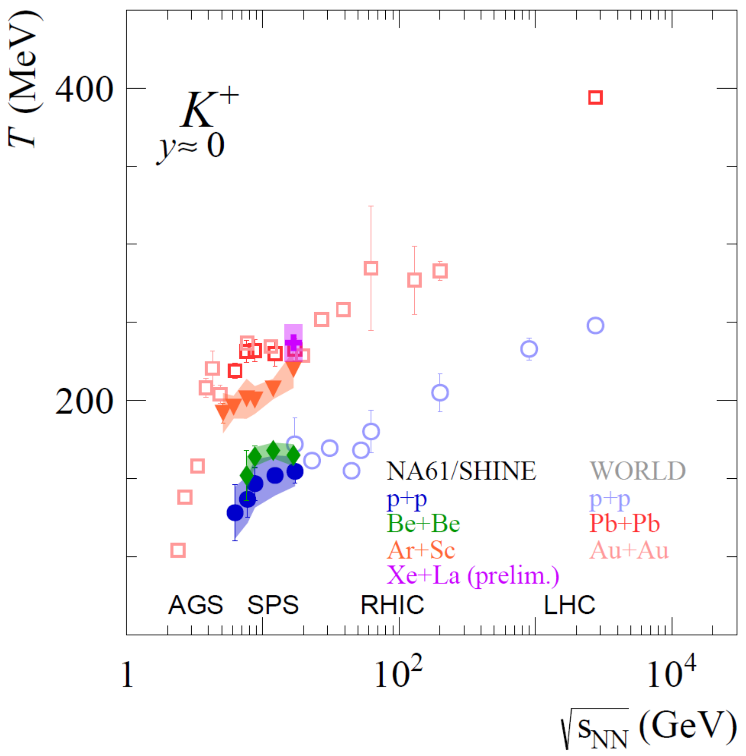


ONSET OF DECONFINEMENT

Onset of deconfinement: step

Qualitatively similar energy dependence is seen in p+p, Be+Be, Ar+Sc, and Pb+Pb.
Magnitude of T increases with the system size





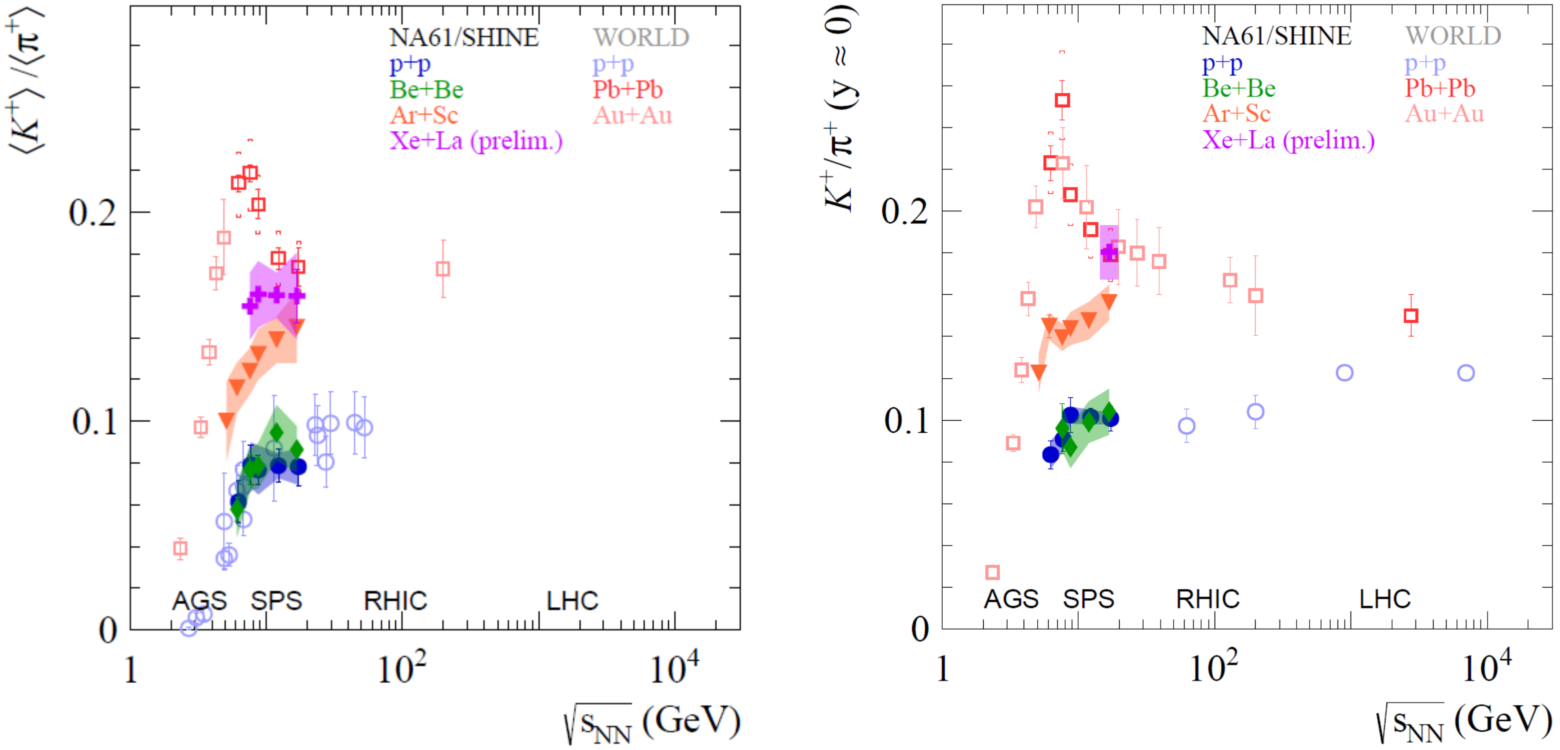
Kaons are only weakly affected by rescattering and resonance decays during the post-hydro phase (at SPS and RHIC energies)

T reflects the thermal freeze-out temperature and the radial flow velocity

NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

Onset of deconfinement: horn

Xe+La below Pb+Pb, while higher than Ar+Sc and Be+Be and p+p



Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons)

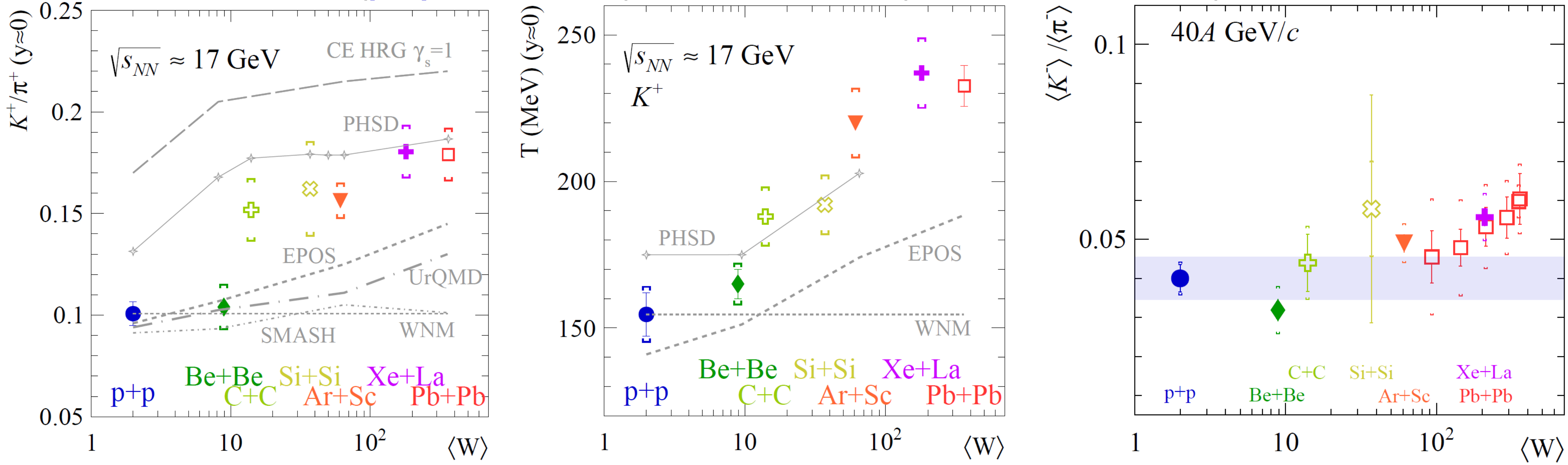
Probe of the onset of deconfinement

NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

SYSTEM SIZE DEPENDENCE

K/π and T vs the system size

(p+p ≈ Be+Be) ⩽ Ar+Sc ⩽ (Xe+La ≈ Pb+Pb)



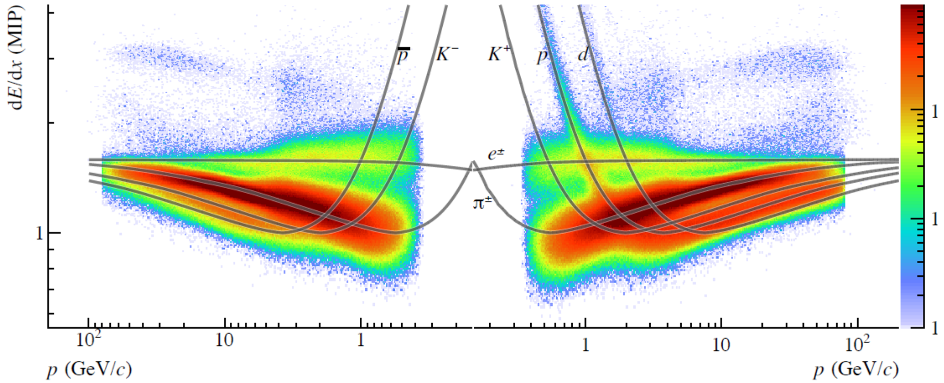
None of the models reproduces K^+/π^+ ratio and T for whole $\langle W \rangle$ range

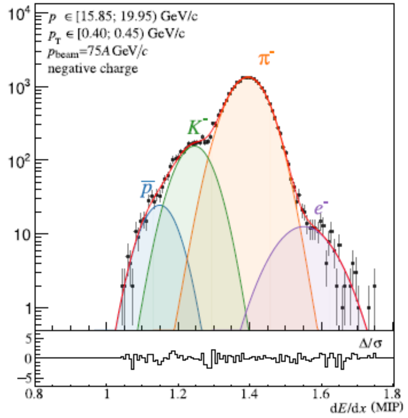
PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909;

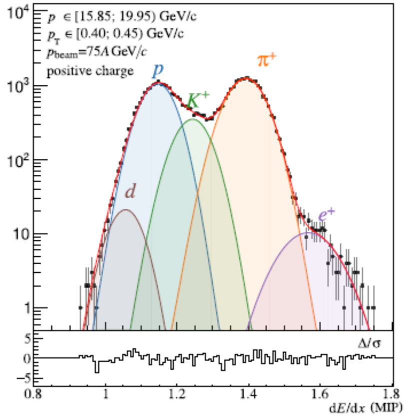
NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

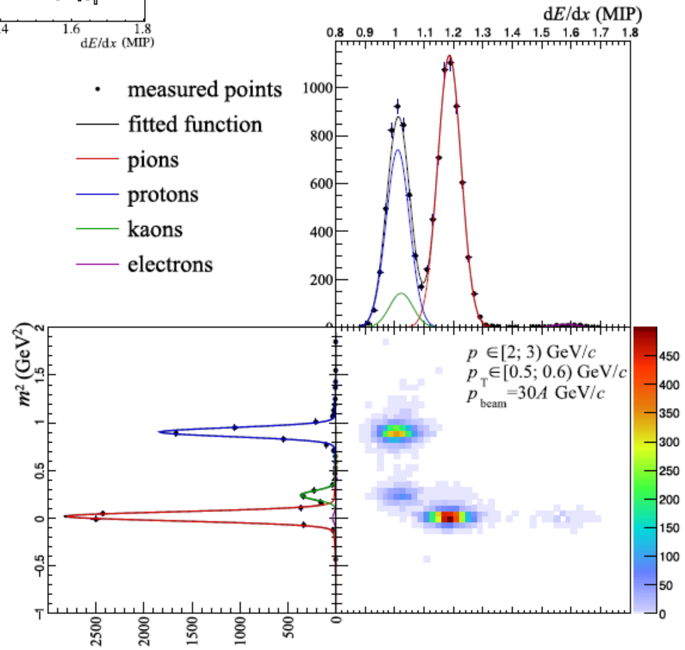
ANOMALY IN CHARGED/NEUTRAL KAON PRODUCTION

Measurements of K^+, K^- production



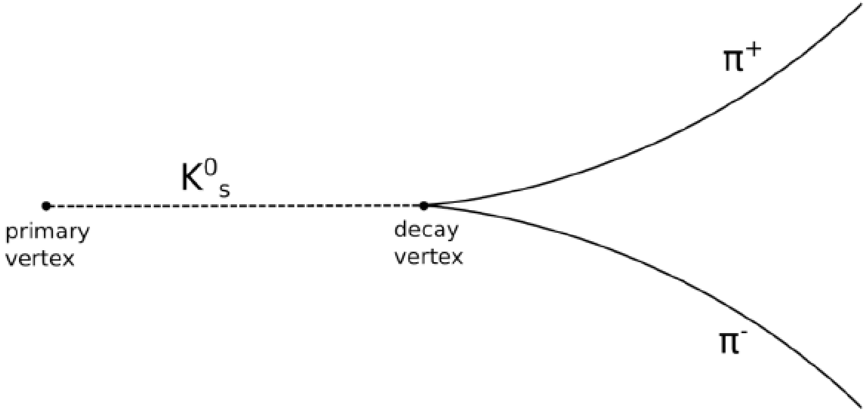


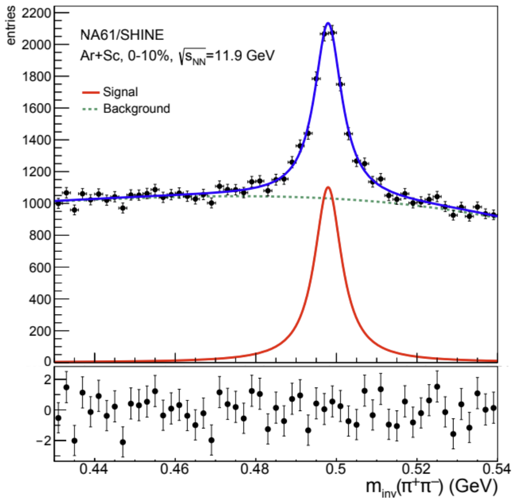


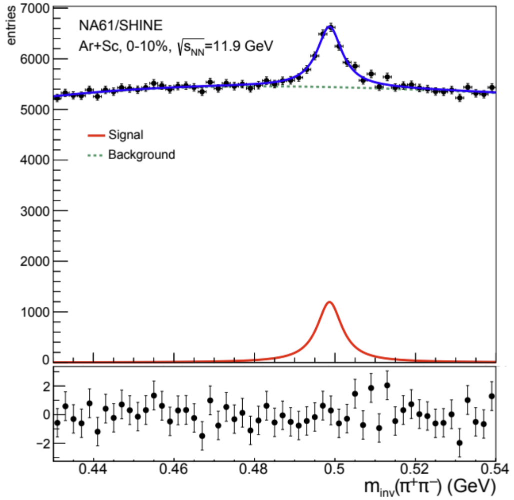


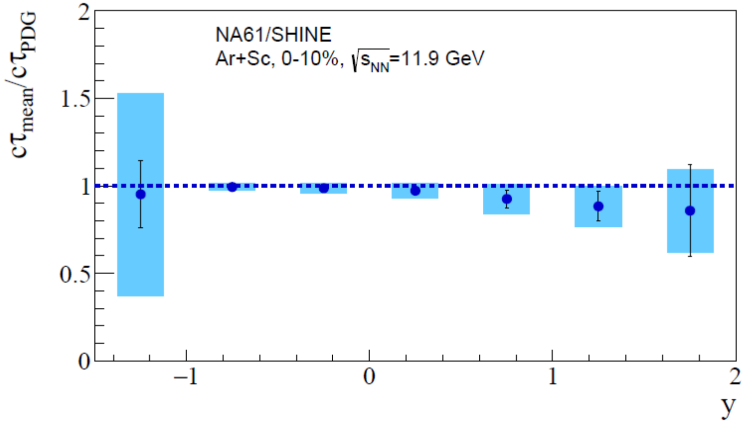
- Measurement based on **dE/dx** and **tof-dE/dx**
- Probability method
- Corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

K_S^0 production in Ar+Sc at 75A GeV/c





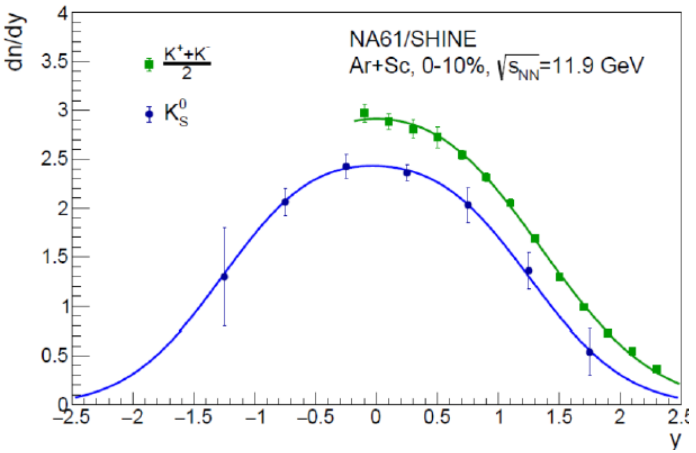




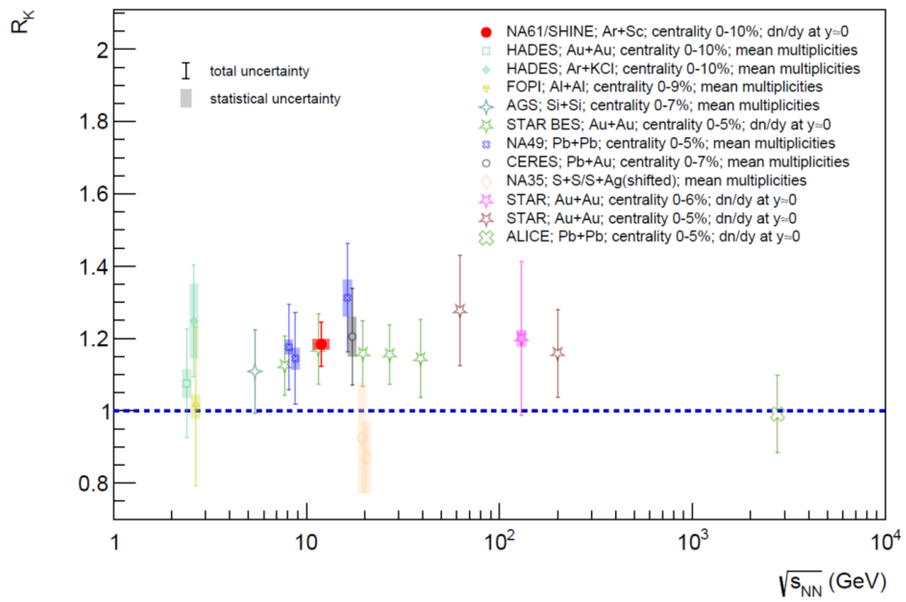
- Reconstruction based on decay topology
- K_S^0 decays into π^+ and π^- with BR ≈ 69.2%
- Breit-Wigner function is used to describe the signal

K_S^0 comparison with $K^+$and K^-

Excess of charged to neutral kaons in the whole rapidity and transverse momentum range



$$R_K = \frac{K^+ + K^-}{2\,K_S^0}$$

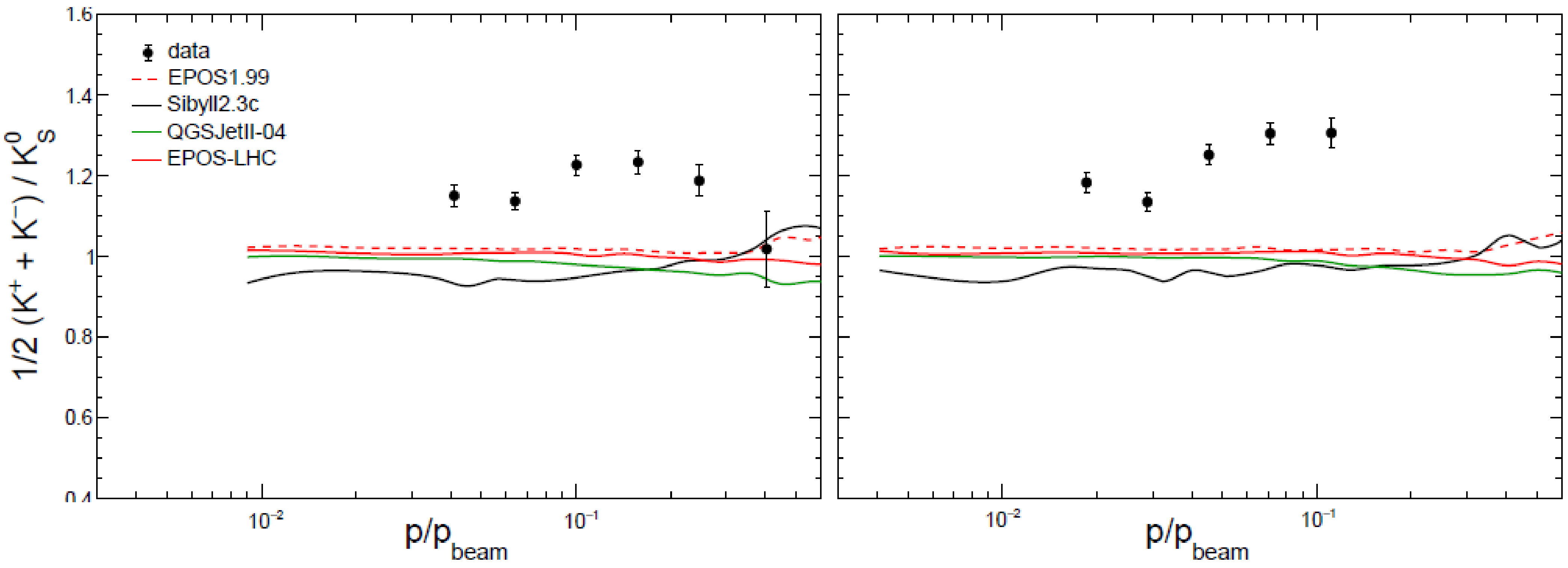


- Unexpected excess of charged over neutral K meson production in central Ar+Sc collisions at 11.9 GeV center-of-mass energy per nucleon pair
- Measured excess corresponds to about four additional K^+ or K^- mesons produced per central Ar+Sc collision

R_K significantly higher than 1

NA61/SHINE, arxiv:2312.06572

K_s^0 comparison with $K^+$and K^-: $\pi^- + C$ at 158 and 350 GeV/c

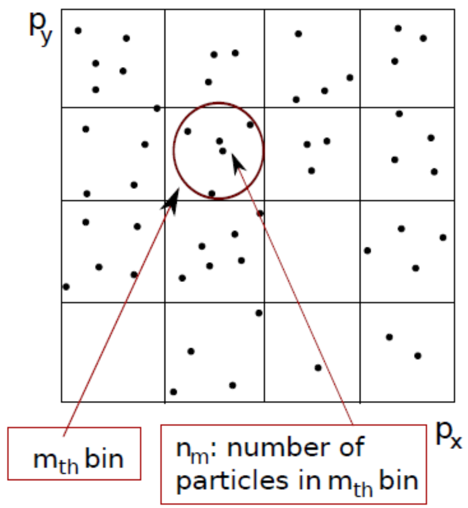


Models fail to describe ratio of charged to neutral kaons even for small asymmetric systems

NA61/SHINE, Phys.Rev.D 107 (2023) 6, 062004

SEARCH FOR CRITICAL POINT

Proton and charge hadron intermittency



$$F_r(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m - 1)...(n_m - r + 1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^r}$$

If the system freezes out near CP, its properties are expected to be different from those of an ideal gas. Such a system represents a simple fractal and $F_r(M)$ follows a power-law dependence

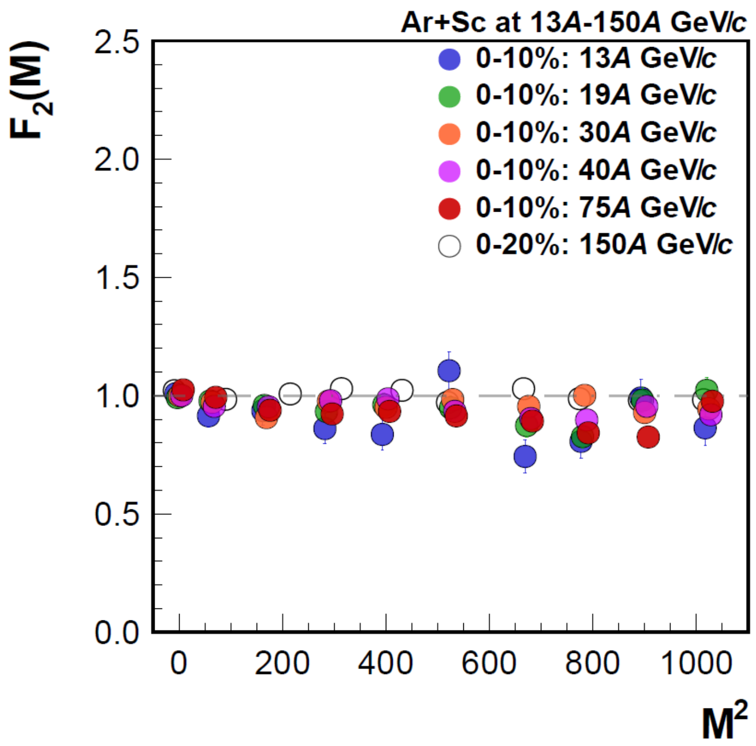
$$F_r(M) = F_r(\Delta) \cdot (M^D)^{\varphi_r}$$

NA61/SHINE used in intermittency analysis:

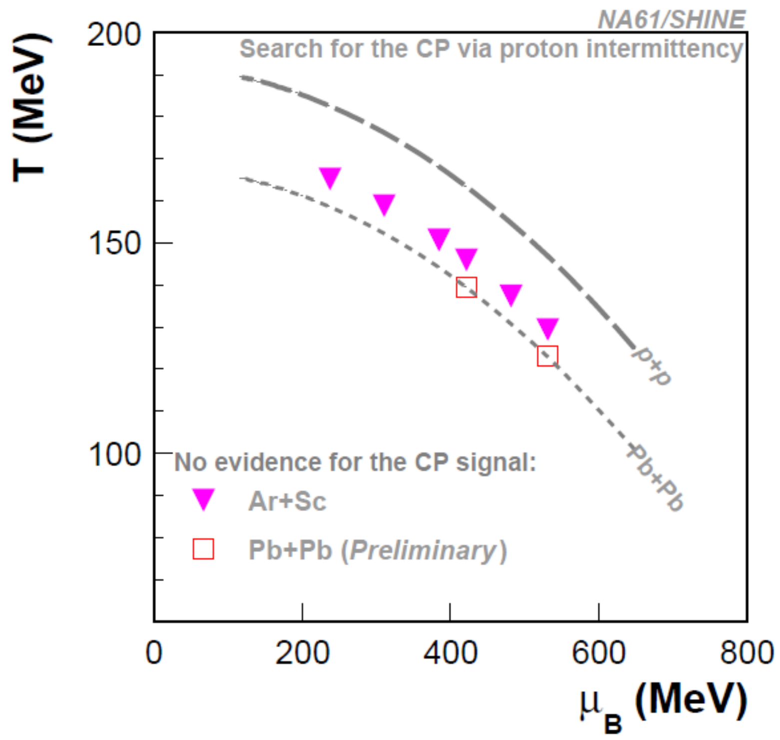
- Statistically independent points
- Cumulative variables

NA61/SHINE: Eur.Phys.J.C 83 (2023) 9, 881; arxiv:2401.03445

Proton intermittency in Ar+Sc



Calculated for number of subdivisions in cumulative transverse momentum space for $1^2 \leq M^2 \leq 32^2$

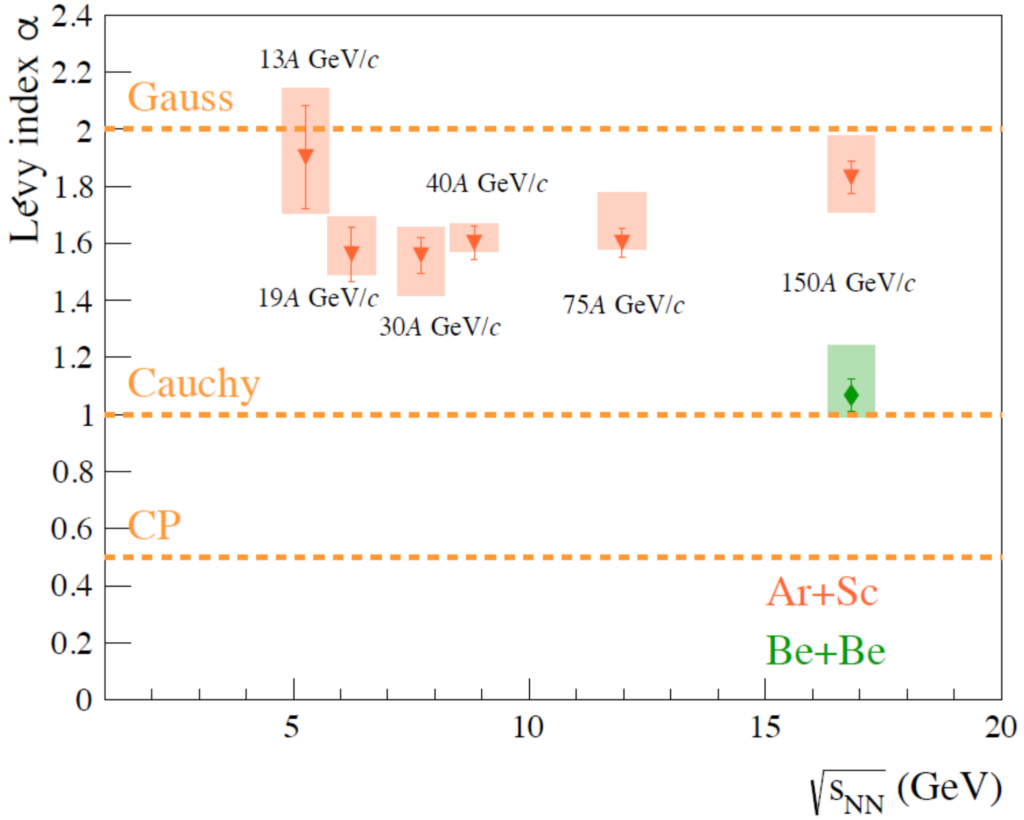


No signal indicating critical point

NA61/SHINE: Eur.Phys.J.C 83 (2023) 9, 881; arxiv:2401.03445; arxiv:2211.10504 (Pb+Pb)

Lévy-stability index α

No indication of critical point (α far from CP predictions)



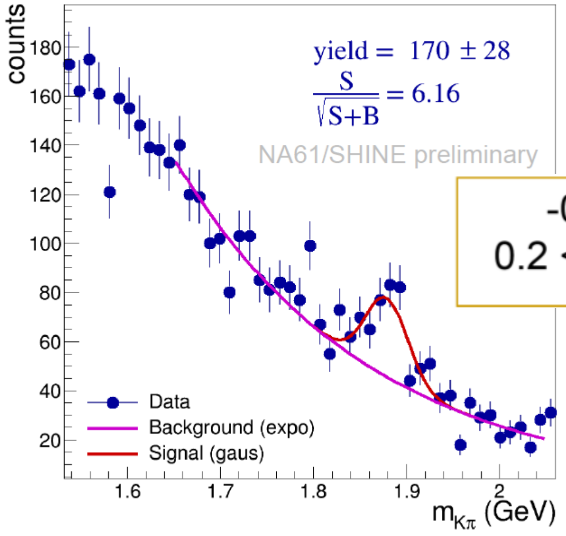
Be+Be:
far from Gaussian (α = 2),
close to Cauchy (α = 1)

Ar+Sc:
far from Cauchy,
decreases from "close to Gaussian"

NA61/SHINE: Eur.Phys.J.C 83 (2023) 10, 919 (Be+Be); Universe 9 (2023) 7, 298

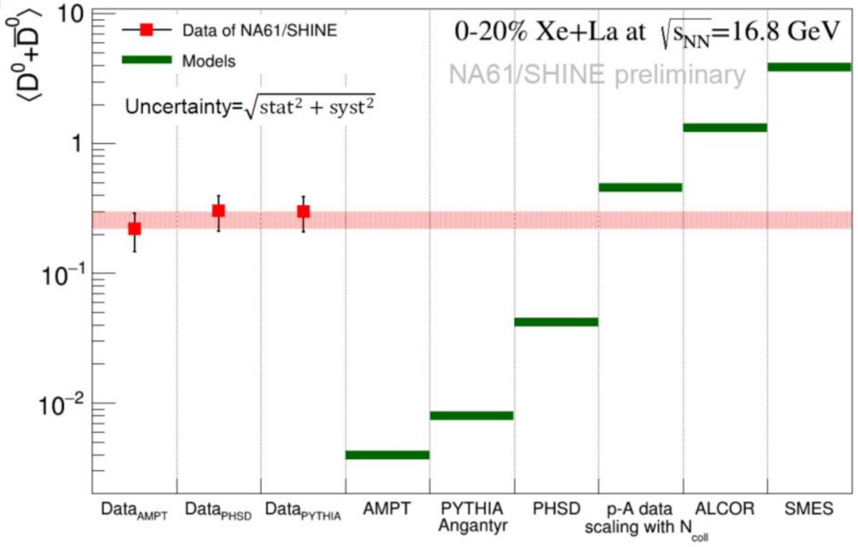
DIRECT MEASUREMENT OF OPEN CHARM

$D^0, \bar{D}^0$ measurement in central Xe+La collisions



-0.5 < y < 1.0
0.2 < p_T < 2.0 GeV/c

Correction made with:	Yield in 4π $\langle D^0 + \bar{D}^0 \rangle$
AMPT	**0.218** ± 0.039(stat) ± 0.060(syst)
PHSD	**0.303** ± 0.054(stat) ± 0.074(syst)
PYTHIA/Angantyr	**0.300** ± 0.052(stat) ± 0.075(syst)

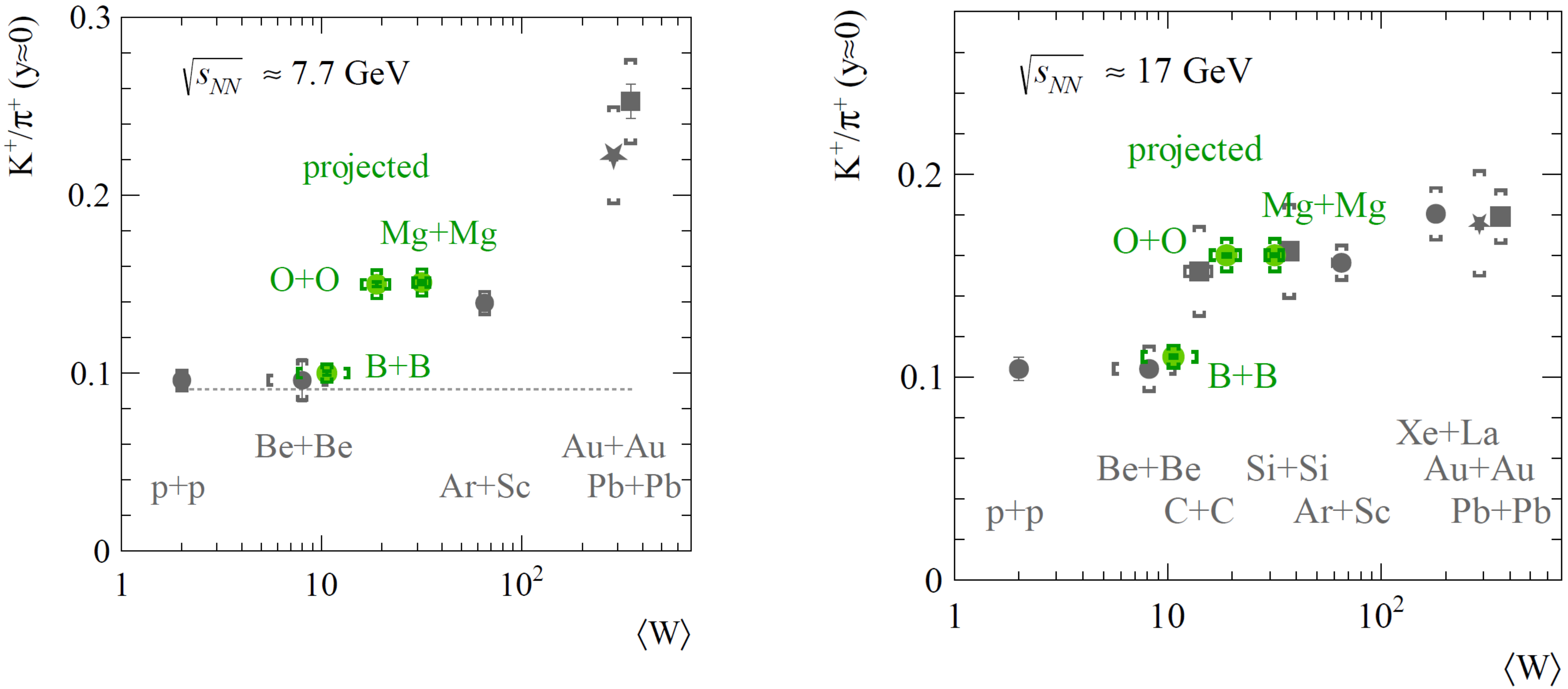


- First-ever direct observation of signal at the SPS energies with significance better than 5 Corrections by GEANT4 simulations with 3 models AMPT, PHSD, PYTHIA/Angantyr
- Precise data to discriminate against various model predictions
- New Pb+Pb events (2022-2023) under analysis
- First-ever direct measurement of open charm in nucleus-nucleus collisions at SPS energies

PLANS

NA61/SHINE after CERN LS3 (2028+)

Continuation of 2D scan with B+B, O+O and Mg+Mg collisions



See NA61/SHINE: addendum SPSC-P-330-ADD-14

Summary and plans

- Summary
  - Unique 2D scan in collision energy and system size completed
  - New preliminary results from Xe+La data released
  - System size dependence found: (p+p ≈ Be+Be) < Ar+Sc < (Xe+La ≈ Pb+Pb)
  - Excess of charged over neutral K meson production in Ar+Sc collisions at 75A GeV/c observed
  - So far no indication of the critical point
  - First-ever direct measurement of open charm production in A+A collisions at SPS energies
- Plans
  - Continuation of 2D scan with B+B, O+O and Mg+Mg collisions

THANK YOU

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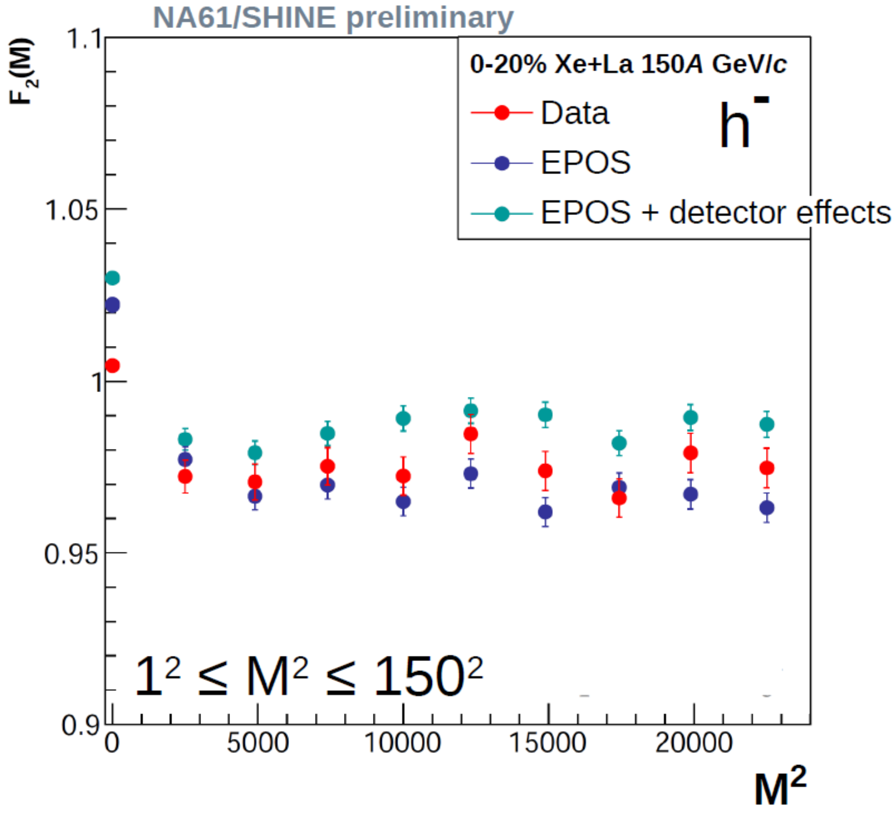
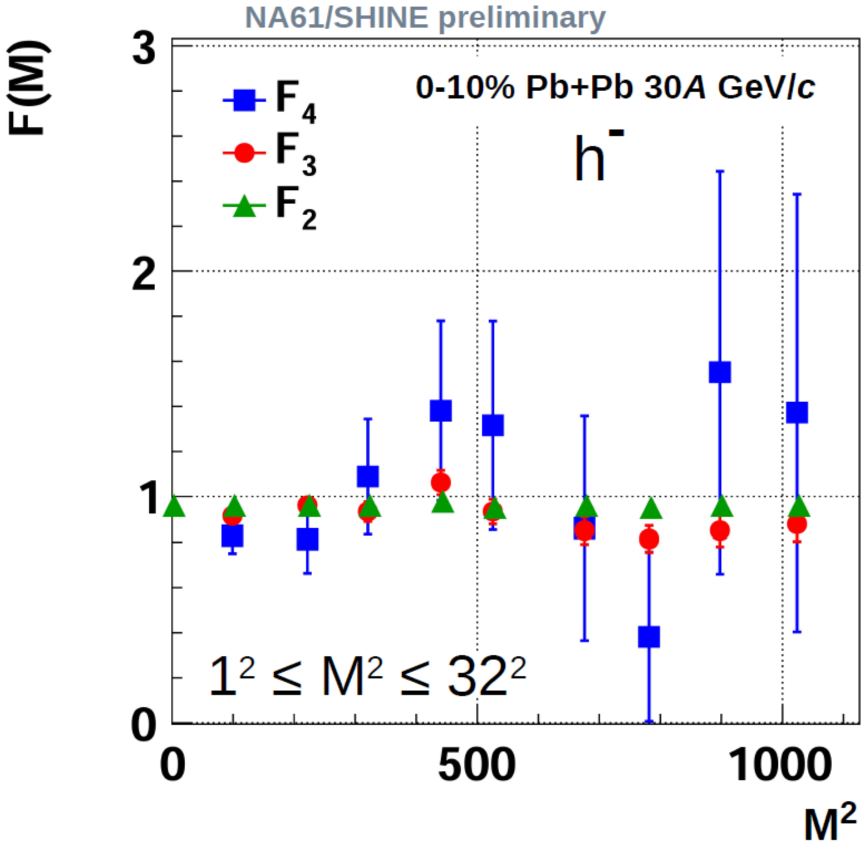
Intermittency of negatively charged hadrons - results

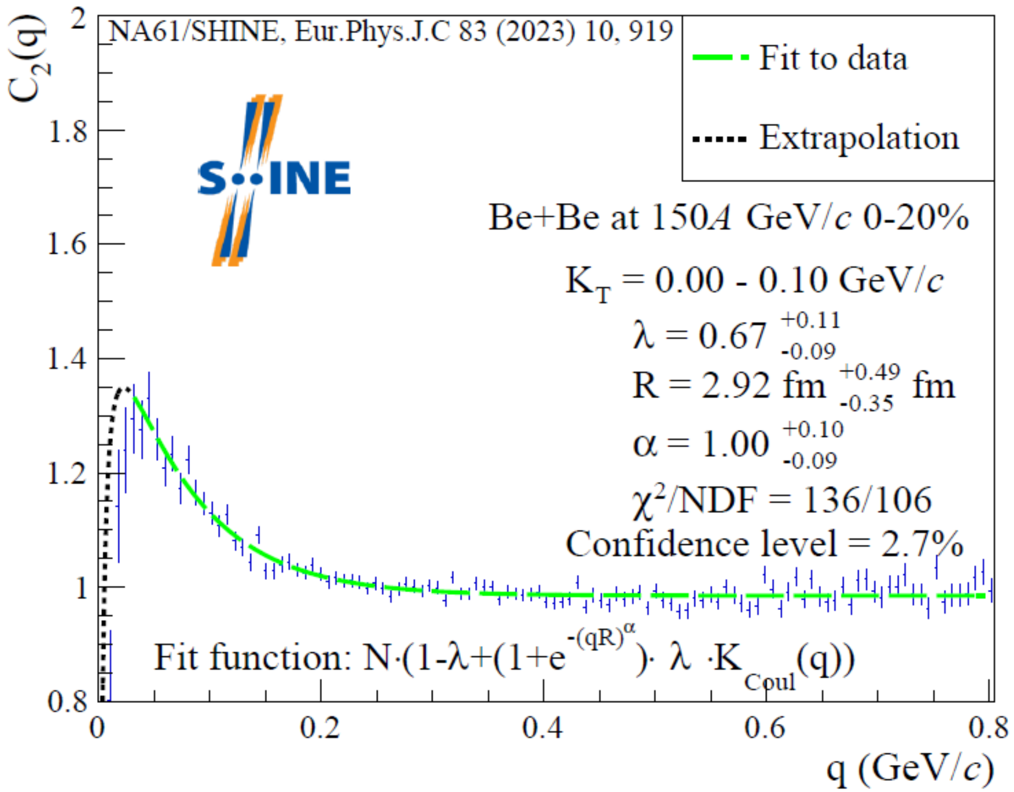




No signal indicating critical point

NA61/SHINE: A.Rybicki, SQM 2024 talk

SYMMETRIC LÉVY HBT CORRELATIONS



Shape of correlation function with Lévy source:

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

where:

$q = |\boldsymbol{p}_1 - \boldsymbol{p}_2|$

R - Lévy-scale parameter (length of homogeneity)

λ - correlation strength

α - Lévy-stability index

- $\alpha = 2$: Gauss shape
- $\alpha < 2$: Generalized central limit theorem
- $\alpha \leq 0.5$: Conjectured value at CP (3D Ising model)

COMPARISON OF ISOSPIN ASYMMETRY FOR D MESONS AND KAONS

$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.66 \pm 0.05$ MeV
Mean life $\tau = (1033 \pm 5) \times 10^{-15}$ s
$c\tau = 309.8\ \mu$m

D^0

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1864.84 \pm 0.05$ MeV
$m_{D^{\pm}} - m_{D^0} = 4.822 \pm 0.015$ MeV
Mean life $\tau = (410.3 \pm 1.0) \times 10^{-15}$ s
$c\tau = 123.01\ \mu$m

Mass difference: $\Delta m \approx 5$ MeV
Multiplicity: $\langle D^+ + D^- \rangle < \langle D^0 + \overline{D^0} \rangle$

$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [a] $(S = 2.8)$
Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s $(S = 1.8)$
$c\tau = 3.711$ m

K^0

$I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L
Mass $m = 497.611 \pm 0.013$ MeV $(S = 1.2)$
$m_{K^0} - m_{K^{\pm}} = 3.934 \pm 0.020$ MeV $(S = 1.6)$

Mass difference: $\Delta m \approx -4$ MeV
Multiplicity: $\langle K^+ + K^- \rangle > \langle K^0 + \overline{K^0} \rangle$

ISOSPIN ASYMMETRY FOR D MESONS

$D^{\pm}$ $I(J^P) = \frac{1}{2}(0^-)$

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$D^*(2007)^0$ $I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2006.85 \pm 0.05$ MeV (S = 1.1)
$m_{D^{*0}} - m_{D^0} = 142.014 \pm 0.030$ MeV (S = 1.5)
Full width $\Gamma < 2.1$ MeV, CL = 90%

$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^0$	(64.7 ± 0.9) %	43
$D^0\gamma$	(35.3 ± 0.9) %	137
$D^0 e^+ e^-$	$(3.91 \pm 0.33) \times 10^{-3}$	137

$D^*(2010)^{\pm}$ $I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2010.26 \pm 0.05$ MeV
$m_{D^*(2010)^+} - m_{D^+} = 140.603 \pm 0.015$ MeV
$m_{D^*(2010)^+} - m_{D^0} = 145.4258 \pm 0.0017$ MeV
Full width $\Gamma = 83.4 \pm 1.8$ keV

$D^*(2010)^-$ modes are charge conjugates of the modes below.

$D^*(2010)^{\pm}$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^+$	(67.7 ± 0.5) %	39
$D^+\pi^0$	(30.7 ± 0.5) %	38

- Simple explanation according to Adv.Ser.Direct.High Energy Phys. 15 (1998) 609-706: "A simple model for estimating the charged-to-neutral D cross section ratio is the following. One assumes isospin invariance in the c→D and c→D* transition. Furthermore, one assumes that the D cross section is one third of the D* cross section, due to the counting of polarization states. Using then the published values of the D* →D branching ratios [R.M. Barnett et al., Phys. Rev. D54(1996)1], the result is roughly $\frac{\sigma(D^+)}{\sigma(D^0)} \approx 0.32$."

ISOSPIN ASYMMETRY FOR KAONS

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$c\tau = 3.711$ m

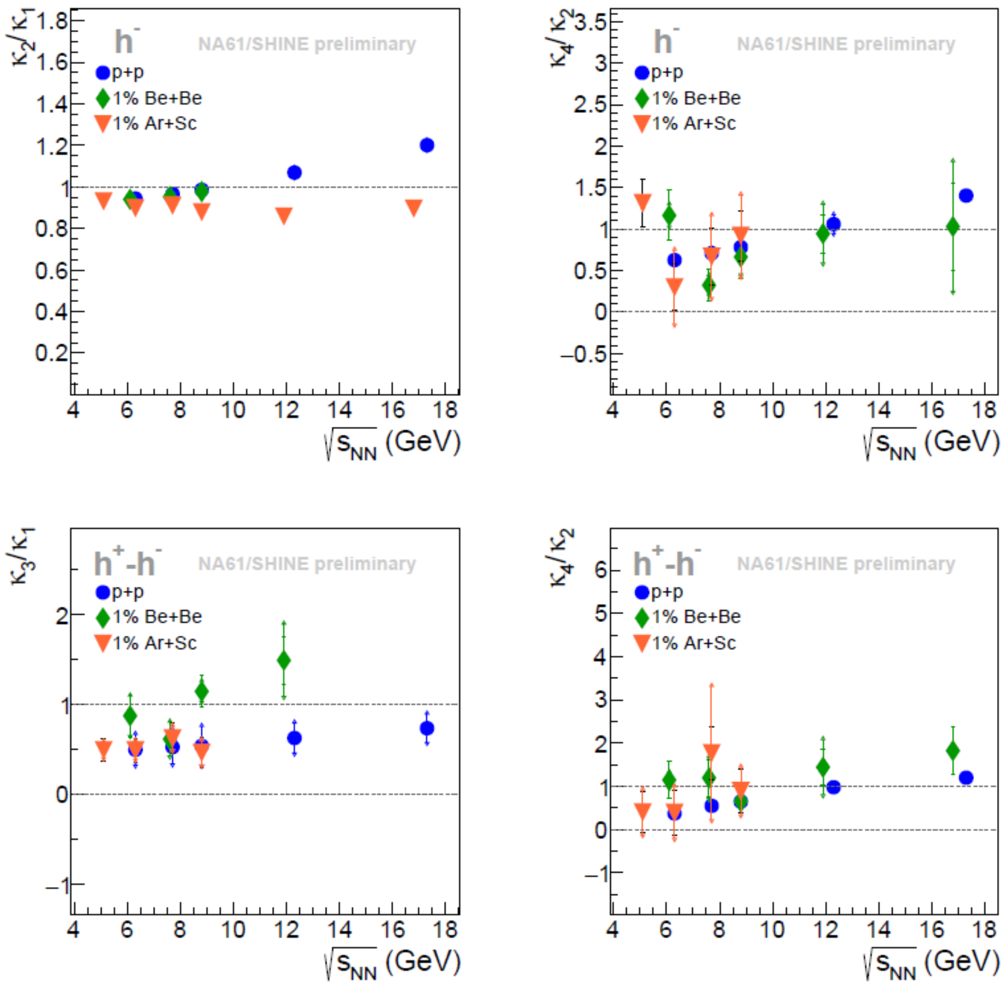
K^0 $I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L
Mass $m = 497.611 \pm 0.013$ MeV (S = 1.2)
$m_{K^0} - m_{K^{\pm}} = 3.934 \pm 0.020$ MeV (S = 1.6)

Mass difference: $\Delta m \approx -4$ MeV
Multiplicity: $\langle K^+ + K^- \rangle > \langle K^0 + \overline{K^0} \rangle$

- For any state going to kaons, there is always a bit more K^+ and K^- because of mass difference.
- But masses of kaon resonances are much larger than sum of decay products (the higher mass of decaying resonance, the smaller difference between charged and neutral kaons).
- First preliminary estimation using statistical model gives the asymmetry $< 5\%$ (thanks to Francesco Giacosa).

No structure indicating critical point



$$\kappa_1 = \langle N \rangle$$
$$\kappa_2 = \langle (\delta N)^2 \rangle = \sigma^2$$
$$\kappa_3 = \langle (\delta N)^3 \rangle = S\sigma^3$$
$$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4$$

where:
N – multiplicity; $\delta N = N - \langle N \rangle$
σ – standard deviation
S – skewness; K – kurtosis

Negatively charge κ_2/κ_1: increasing difference between small systems (p+p and Be+Be) and a heavier system (Ar+Sc) with collision energy

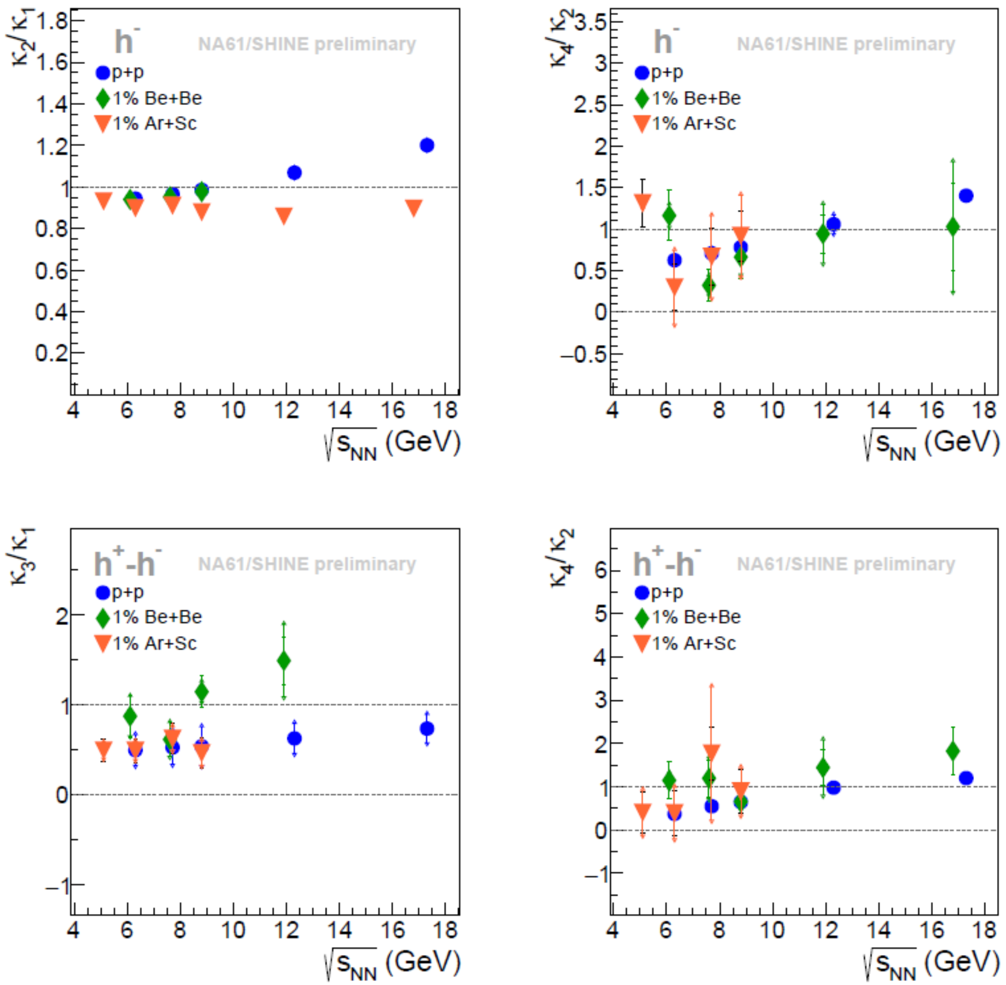
Net-charge κ_3/κ_1:increasing difference between Be+Be and other systems (p+p and Ar+Sc) with collision energy

κ_4/κ_1 : consistent values for all measured systems at given collision energy

see NA61/SHINE, arxiv:2312.13706 for final p+p results

MULTIPLICITY AND NET-CHARGE FLUCTUATIONS IN P+P, BE+BE AND AR+SC

No structure indicating critical point



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