Recent Results from NA61/SHINE Strong Interaction Program

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Uniwersytet Wrocławski

Outline

- NA61/SHINE physics program
- Detector setup
- Onset of deconfinement
- Excess of charged over neutral kaons
- Intermittency analysis
- Multiplicity and net-charge fluctuations
- $\phi(1020)$ enhancement
- HBT correlations with Lévy sources
- Direct measurement of open charm
- Future plans
- Summary

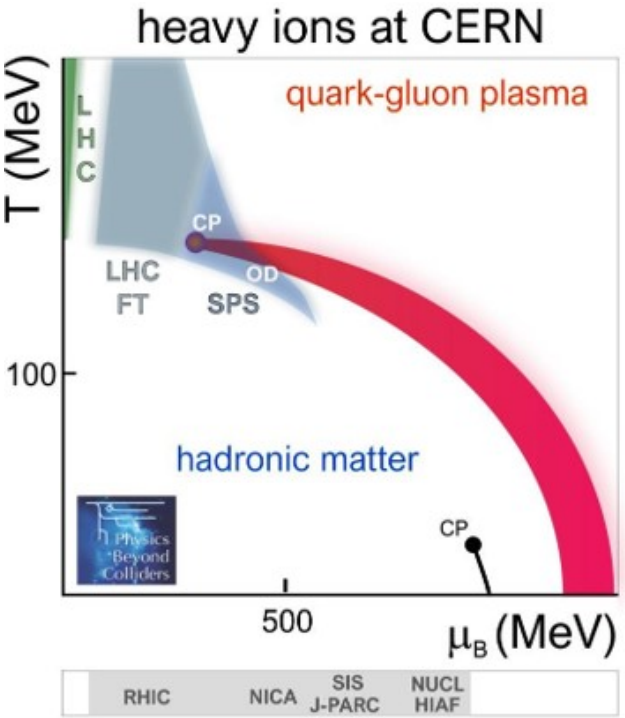
NA61/SHINE physics program

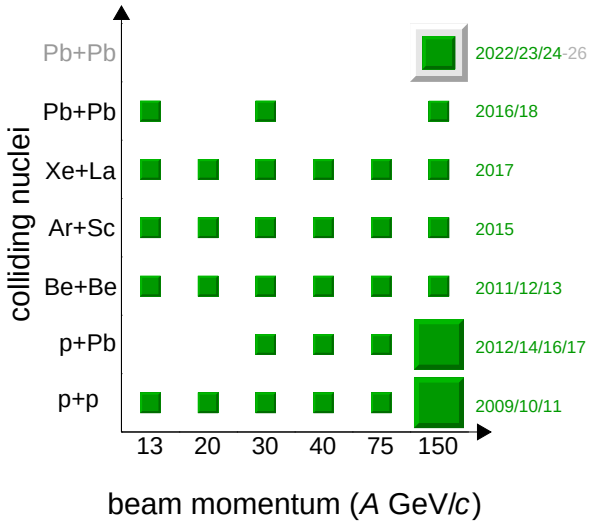
Strong interaction physics:

- study properties of the onset of deconfinement
- search for the critical point
- direct measurements of open charm

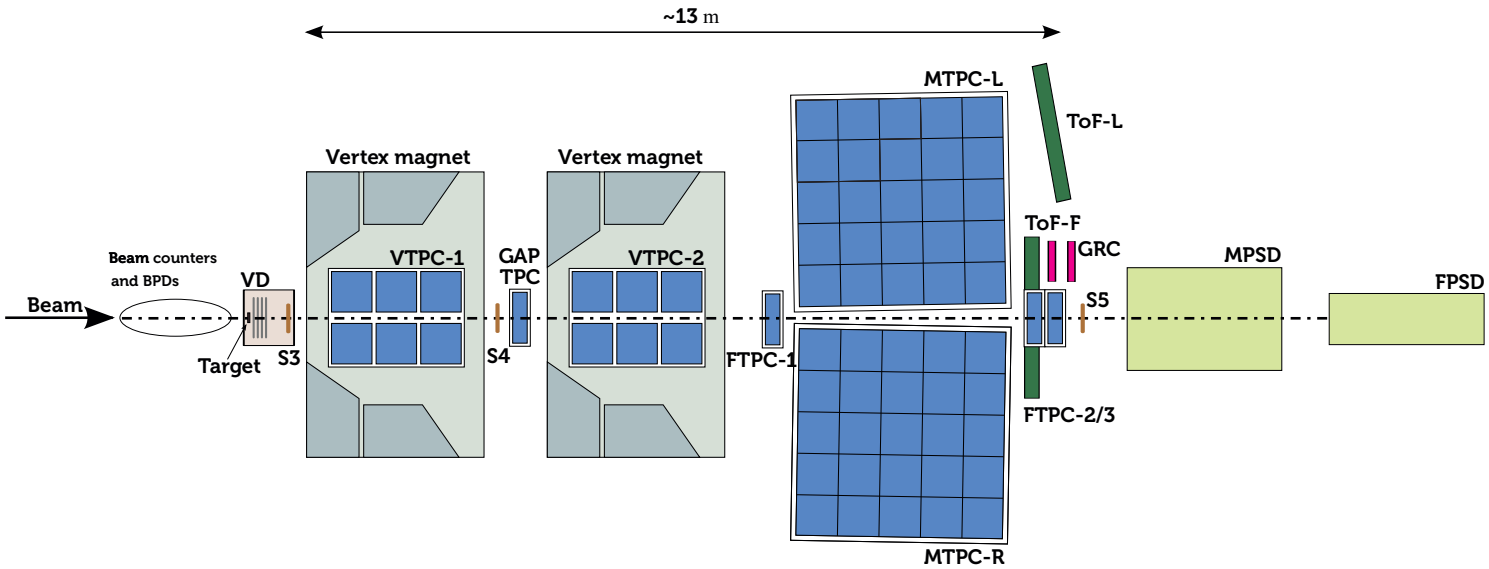
Neutrino & cosmic-ray physics:

- measurements for neutrino program at J-PARC and Fermilab
- measurements of hadron production and nuclear fragmentation cross sections for cosmic-ray physics



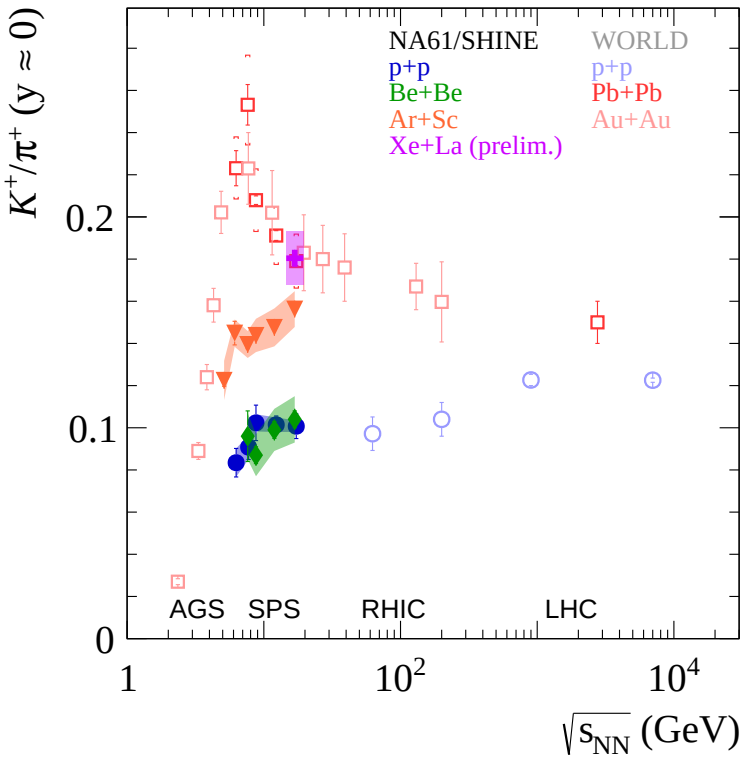


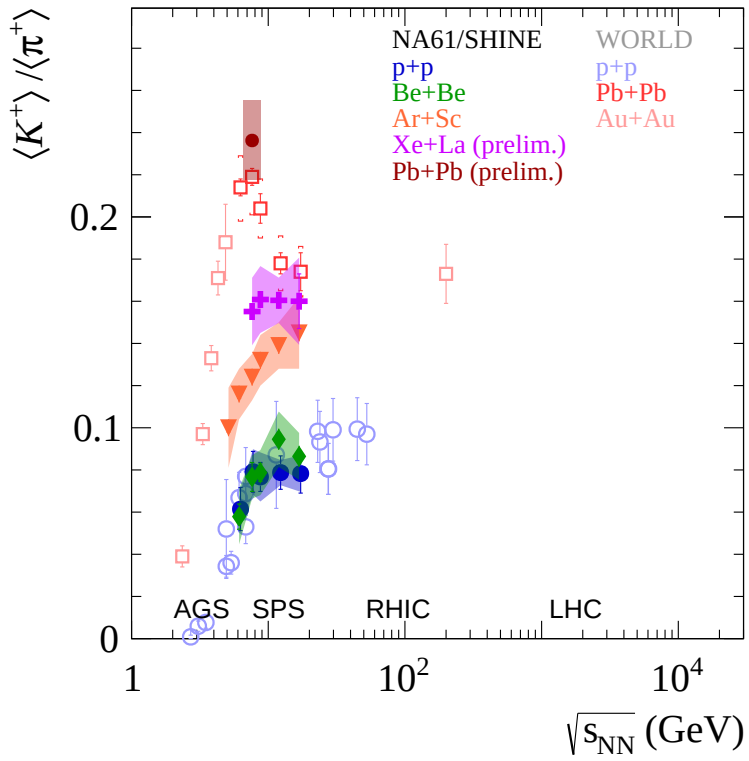
NA61/SHINE detector



- Multipurpose fixed-target spectrometer operating at CERN SPS
- Large acceptance covering the full forward hemisphere down to $p_{\mathrm{T}} = 0$
- Beam momenta:
  - Ions: $p_{\mathrm{beam}} = 13A$–$150A$ GeV/c
  - Hadrons: $p_{\mathrm{beam}} = 13$–400 GeV/c
- Beams: Be, O, Ar, Xe, Pb (ions) and π, K, p (hadrons)
- $\sqrt{s_{\mathrm{NN}}} = 5.1$–$16.8$ GeV (27.4 GeV for p+p)

Onset of deconfinement: Horn

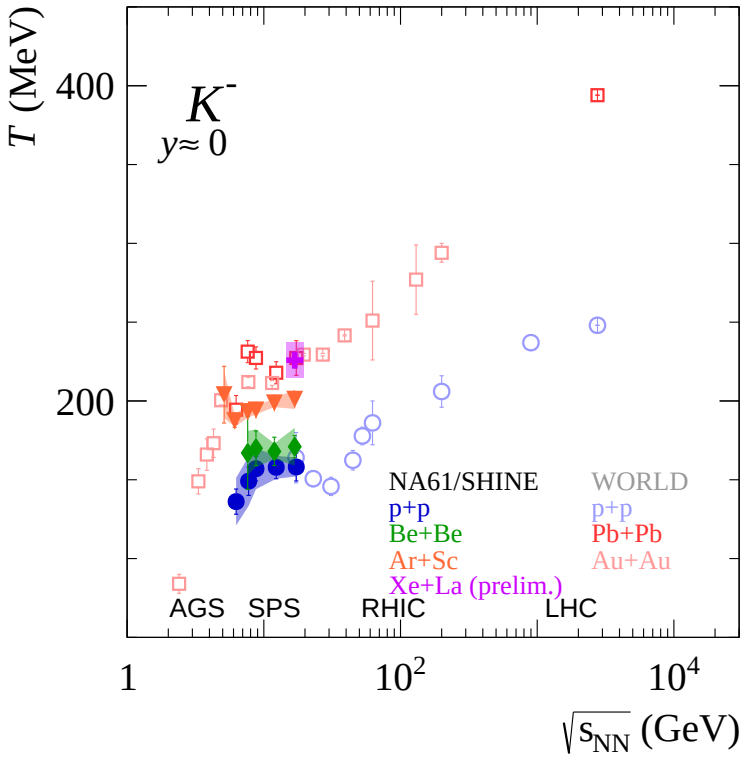


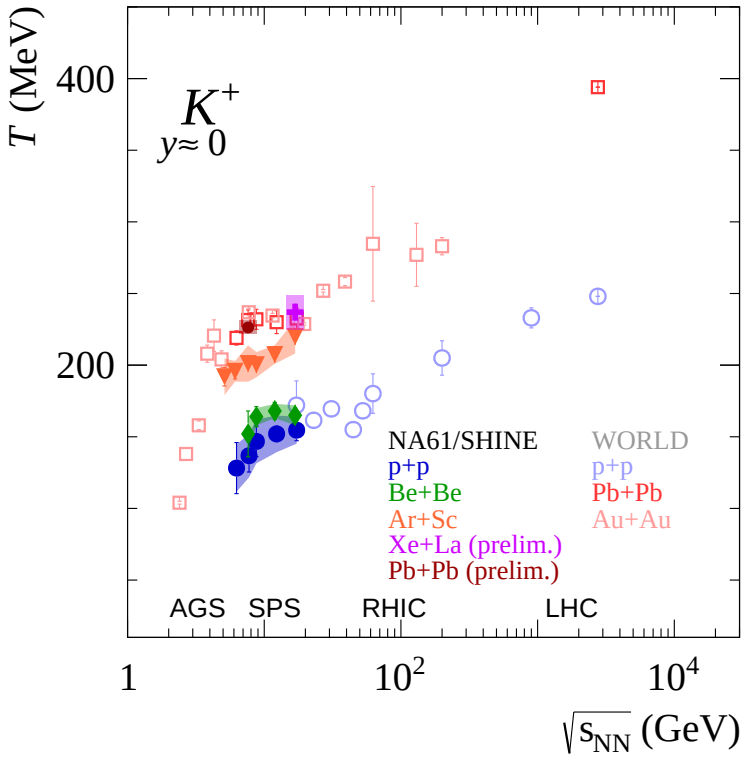


- $K^+/\pi^+ \propto$ strangeness/entropy
- Probe of onset of deconfinement
- Xe+La points: below Pb+Pb, above Ar+Sc/Be+Be/p+p
- New NA61/SHINE Pb+Pb point confirms NA49 data

NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416,
K. Grebieszkow, QM 2025; world data: see EPJC 84 (2024) 4, 416

Onset of deconfinement: Step

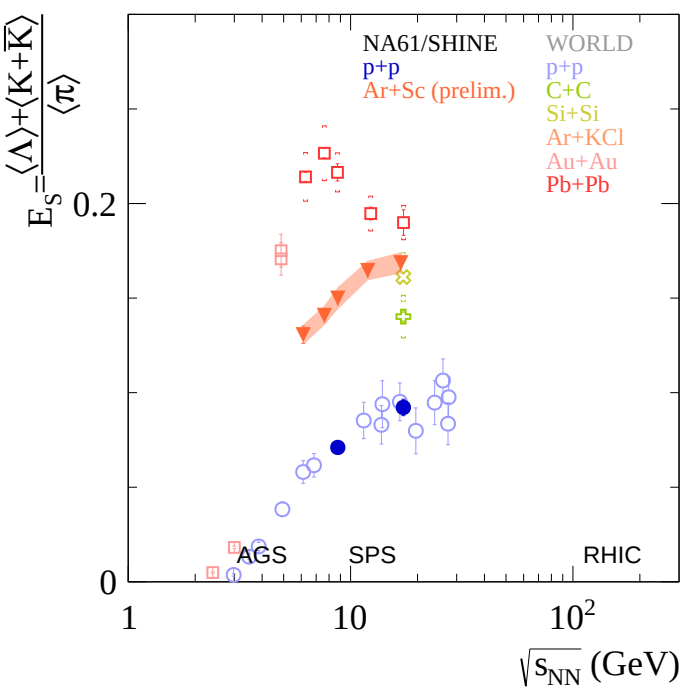


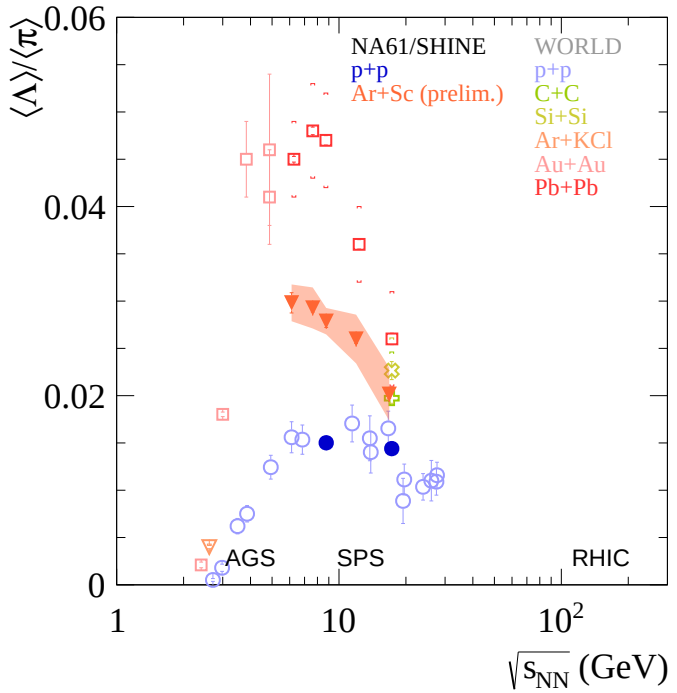


- T reflects thermal freeze-out + radial flow velocity
- Kaons weakly affected by rescattering/resonances at SPS
- Step-like structure is visible for all systems
- T increases with energy except the location of horn

NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416,
K. Grebieszkow, QM 2025; world data: see EPJC 84 (2024) 4, 416

Λ production

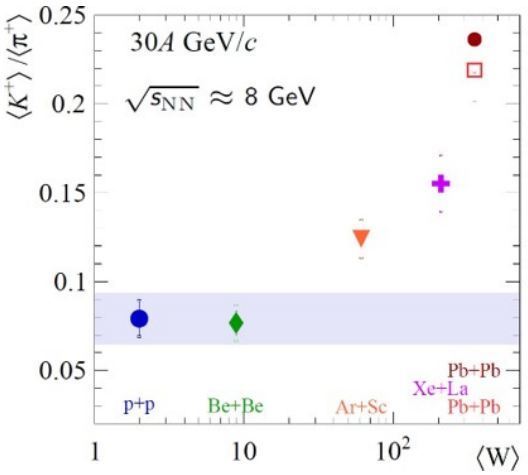


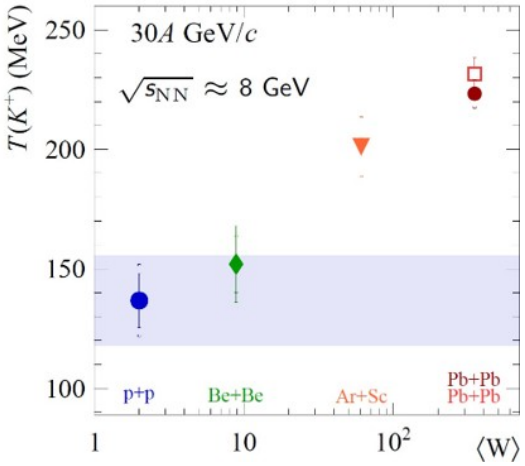


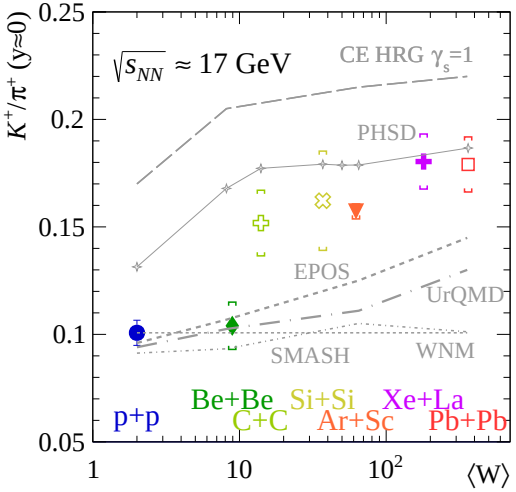
- The $\bar{\Lambda}/\Lambda$ ratio < 0.15 at SPS energies $\Rightarrow$ $\bar{\Lambda}$ contribution to E_S neglected
- In central Pb+Pb and Au+Au collisions, both $\langle\Lambda\rangle/\langle\pi\rangle$ and E_S show a clear maximum near mid-SPS energies
- The $\langle\Lambda\rangle/\langle\pi\rangle$ ratio in Ar+Sc at SPS follows a trend similar to that observed in heavy Pb+Pb collisions
- No horn-like structure in E_S for Ar+Sc

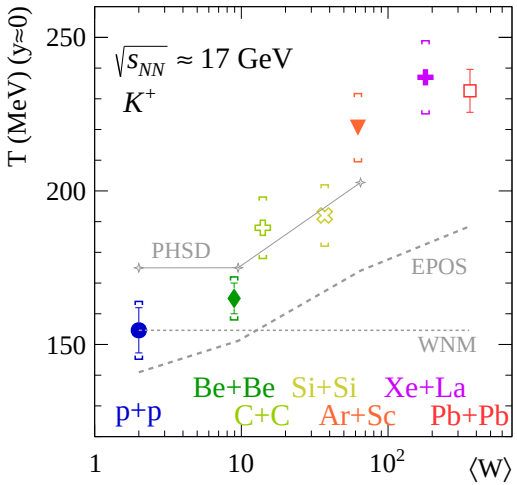
World data: see https://indico.cern.ch/event/1334113/contributions/6308940;
NA61/SHINE: Preliminary (0-10% Ar+Sc),
EPJC 76 (2016) 198 and arXiv:2508.14998 ($p+p$)

System size dependence









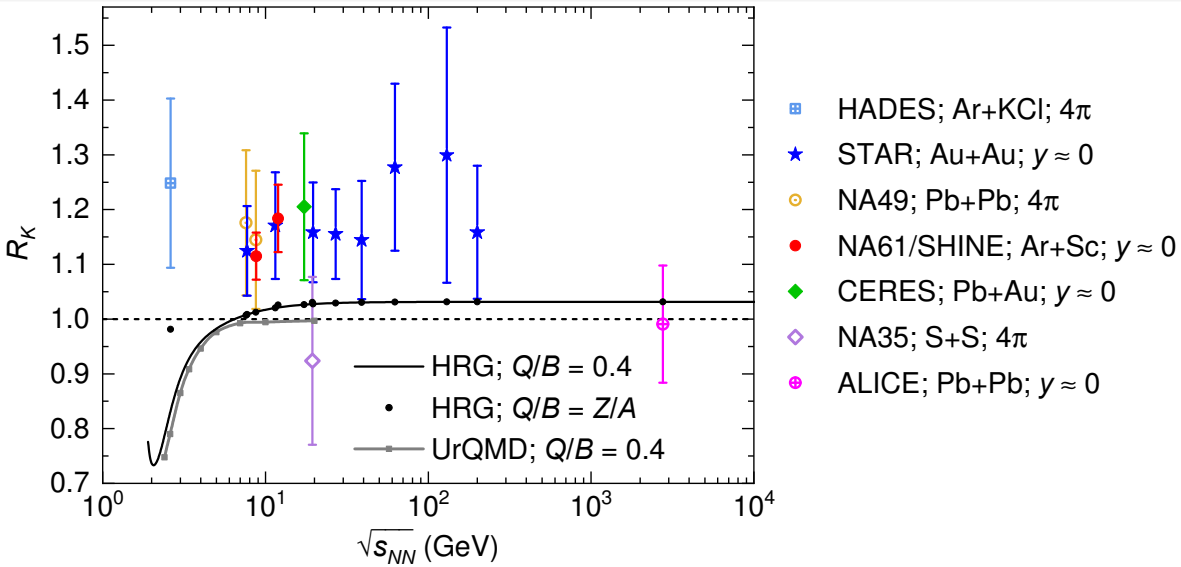
- K^+/π^+ and T grow with system size
- No model reproduces both K^+/π^+ and $T(y \approx 0)$ over full $\langle W \rangle$

PHSD: EPJA 56 (2020) 9, 223;
SMASH: JPG 47 (2020) 065101;
UrQMD/HRG: PRC 99 (2019) 034909;
WNM: NPB 111 (1976)

- System size hierarchy observed:
  $(p+p \approx \text{Be+Be}) \leq \text{Ar+Sc} \leq (\text{Xe+La} \approx \text{Pb+Pb})$

NA61/SHINE: Preliminary (Xe+La), EPJC 84 (2024) 4, 416 (Ar+Sc), EPJC 81 (2021) 1, 73 (Be+Be), EPJC 77 (2017) 10, 671 ($p+p$); see EPJC 84 (2024) 4, 416 for references to world data

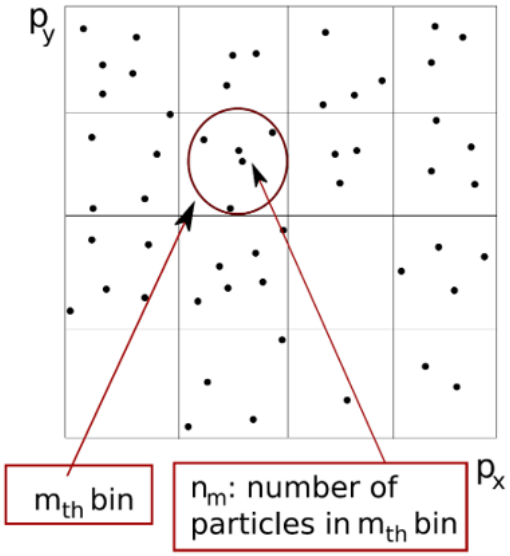
Excess of charged over neutral kaons



- $R_K = \frac{\langle K^+ \rangle + \langle K^- \rangle}{\langle K^0 \rangle + \langle \overline{K}^0 \rangle} = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2\langle K^0_S \rangle}$,
  $R_K = 1$ for exact isospin symmetry and $Z{=}N$ collisions
- NA61/SHINE results at $y \approx 0$ in Ar+Sc:
  $R_K = 1.184 \pm 0.061$ at $75A$ GeV/c ($\sqrt{s_{\mathrm{NN}}} = 11.9$ GeV/c)
  $R_K = 1.115 \pm 0.043$ at $40A$ GeV/c ($\sqrt{s_{\mathrm{NN}}} = 8.8$ GeV/c)
- $K^{\pm}$ excess observed in earlier A+A; not reproduced by models
- Violation of isospin symmetry: 4.7σ: NA61 11.9 GeV + external data,
  5.3σ: NA61 11.9 GeV + 8.8 GeV + external data
- The efforts to solve this puzzle are ongoing [https://indico.cern.ch/event/1557894]

NA61/SHINE: Nature Commun. 16 (2025) 1, 2849 (11.9 GeV) and arXiv:2508.14998 (8.8 GeV)

Intermittency analysis



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

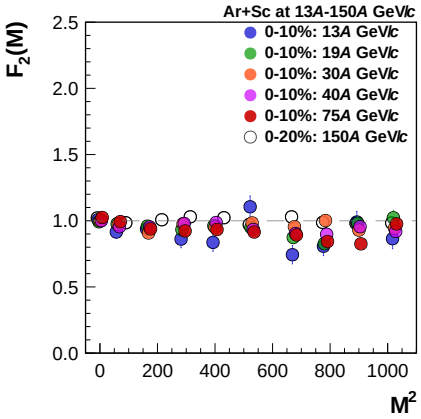
$\langle \ldots \rangle$ – averaging over events, M^2 – number of bins

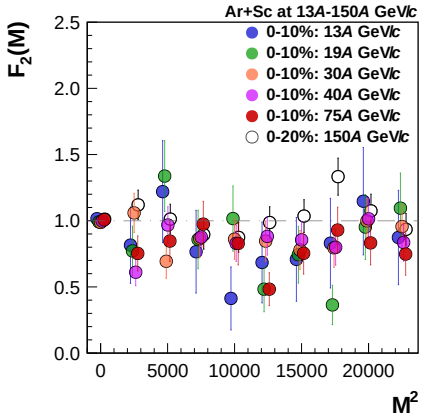
If the system freezes out near critical point, its properties are expected to be different from those of an ideal gas. Such a system represents a simple fractal and $F_r(M)$ follows a power-law dependence:

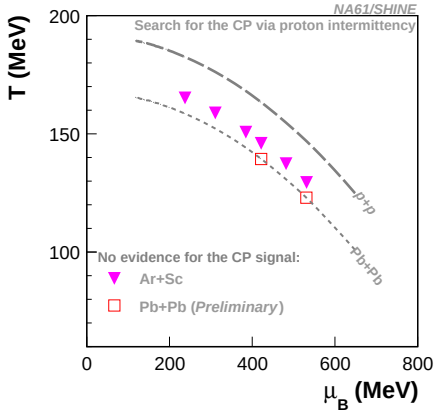
$$F_r(M) \sim (M^2)^{\phi_r}$$

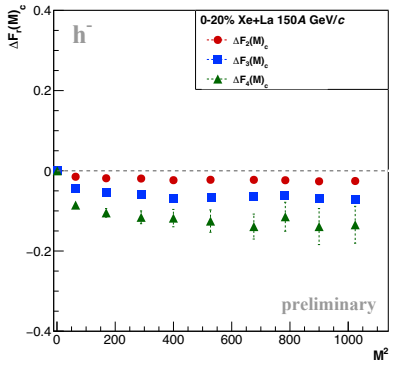
- For protons and $r = 2$, $\phi_2 = 5/6$ is expected [Antoniou et al., PRL 97 (2006) 032002]
- Analysis performed with statistically independent points and cumulative variables [Białas, Gaździcki, PLB 252 (1990) 483; NA61/SHINE: EPJC 83 (2023) 881]

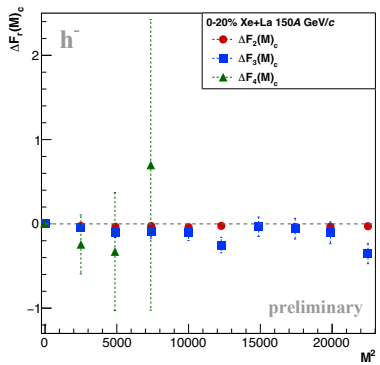
Intermittency results for protons and negatively charged hadrons











$\Delta F_r(M)_c = F_r(M) - F_r(1)$,
with $F_r(M) = F_r(1)$ for uncorrelated particles

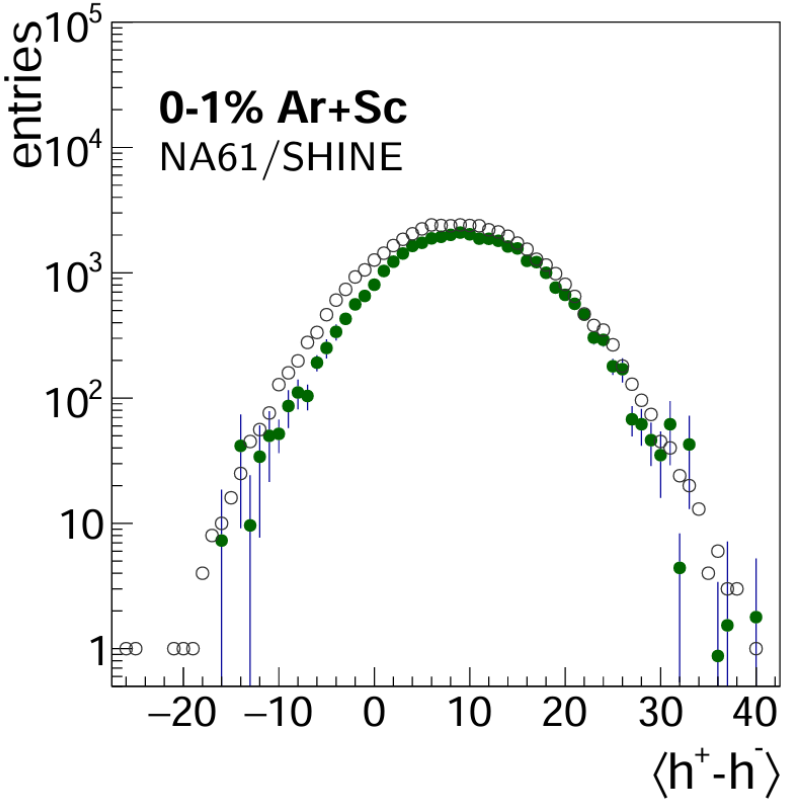
- No power-law signal in protons and negatively charged hadrons
- No indication of critical point in Ar+Sc (13A–150A GeV/c), Pb+Pb (13A and 30A GeV/c; not shown), and Xe+La (150A GeV/c) collisions

NA61/SHINE: EPJC 83 (2023) 9, 881 (Ar+Sc), EPJ Web Conf. 274 (2022) 06008 (Pb+Pb), V. Reyna, QM 2025 poster, K. Grebieszkow, QM 2025

Multiplicity and net-charge fluctuations in Ar+Sc

- First measurement of multiplicity and net-charge fluctuations in 0–1% central ^{40}Ar+^{45}Sc collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.1, 6.1, 7.6, 8.8, 11.9, 16.8 GeV

- Intensive cumulant ratios (volume-independent, used to search for the QCD critical point):
  - For h^+, h^-, $h^+ + h^-$: κ_2/κ_1, κ_3/κ_2, κ_4/κ_2
  - For net-charge $h^+ - h^-$: $\kappa_2/(\kappa_1^+ + \kappa_1^-)$, κ_3/κ_1, κ_4/κ_2
- Reference values: 0 → no fluctuations, 1 → Poisson/Skellam (independent particles)

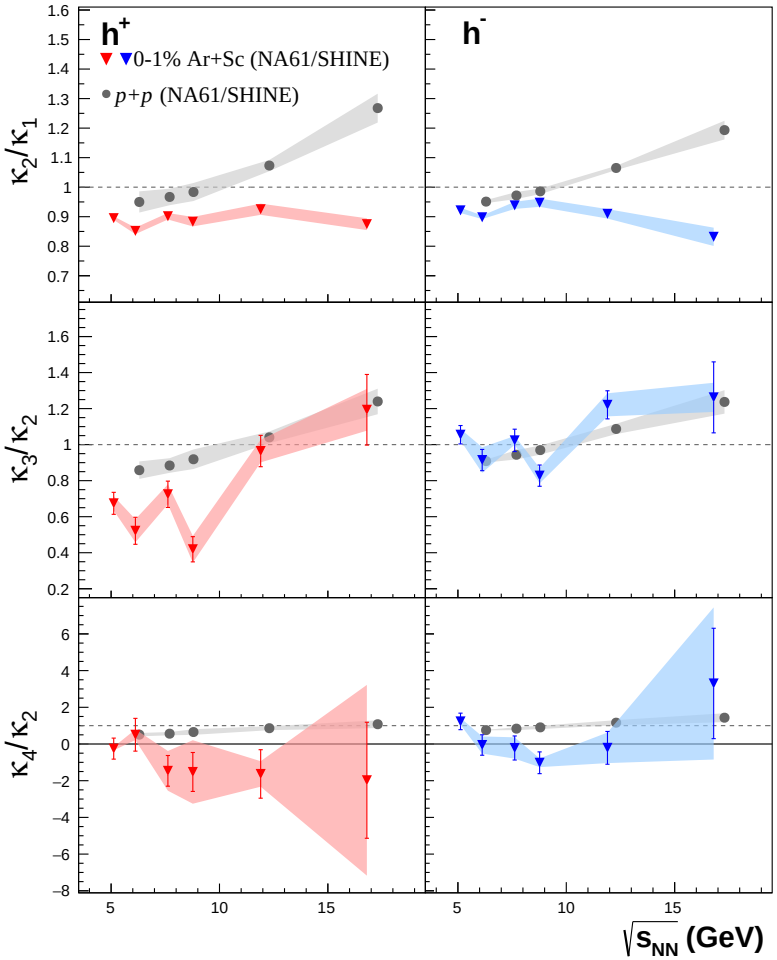


Ar+Sc at 16.8 GeV

Measured (open) → corrected via unfolding (full circles)

NA61/SHINE: EPJC 85 (2025) 8, 918 (0–1% Ar+Sc)

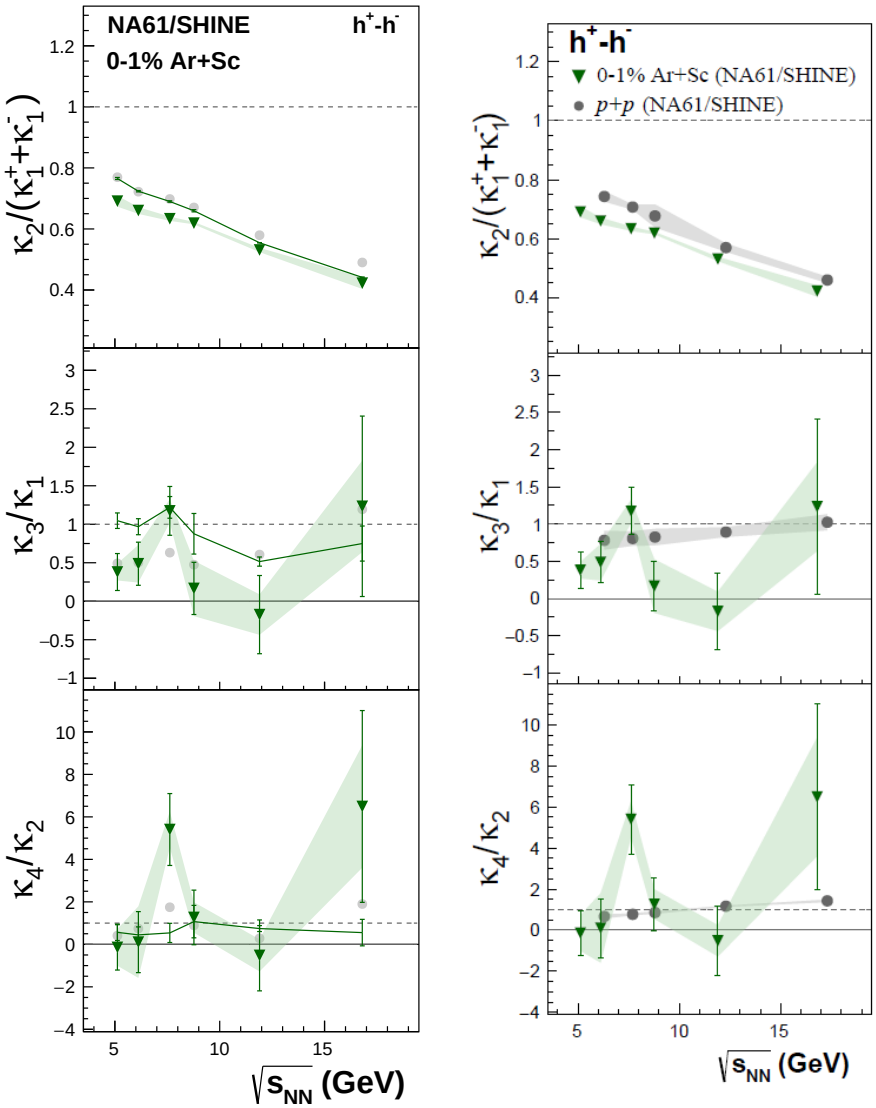
Multiplicity fluctuations in 0-1% central Ar+Sc



- Cumulant ratios in 1% central Ar+Sc compared with p+p (gray)
- Distributions narrower than Poisson ($\kappa_2/\kappa_1 < 1$); but overall no strong deviations from 1
- System size dependence (Ar+Sc vs. p+p): largest deviation in κ_2/κ_1 at top SPS energies; κ_3/κ_2 differs most at lower energies; κ_4/κ_2 shows differences at mid-SPS, but uncertainties are large
- Experimental results suggest no CP indications

NA61/SHINE: EPJC 85 (2025) 8, 918 (0–1% Ar+Sc); p+p: EPJC 84 (2024) 921, EPJC 85 (2025) 341 (erratum)

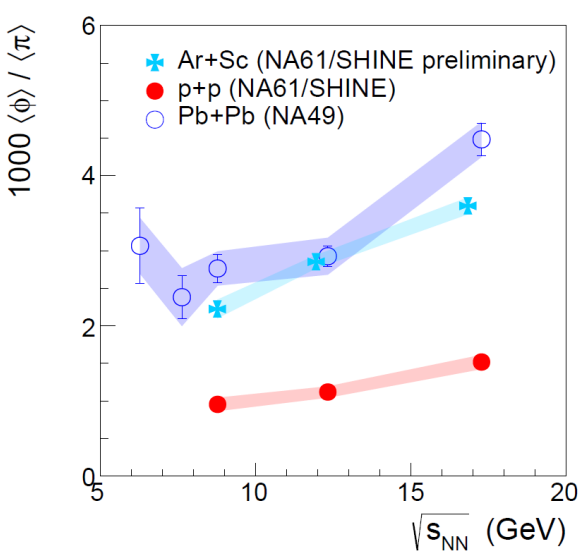
Net-charge fluctuations in 0-1% central Ar+Sc

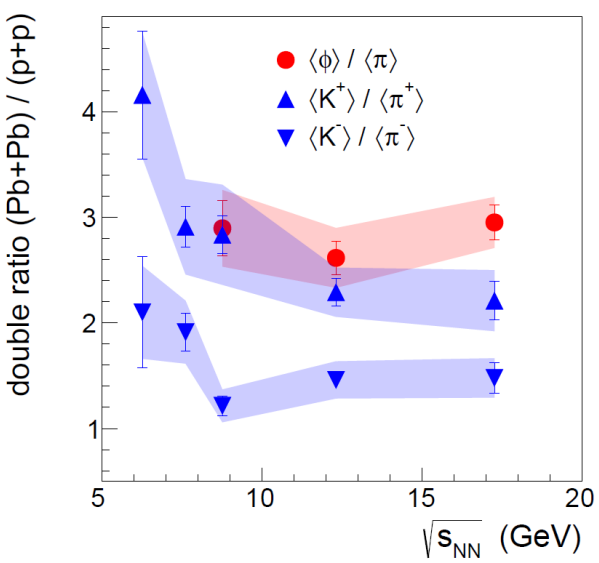


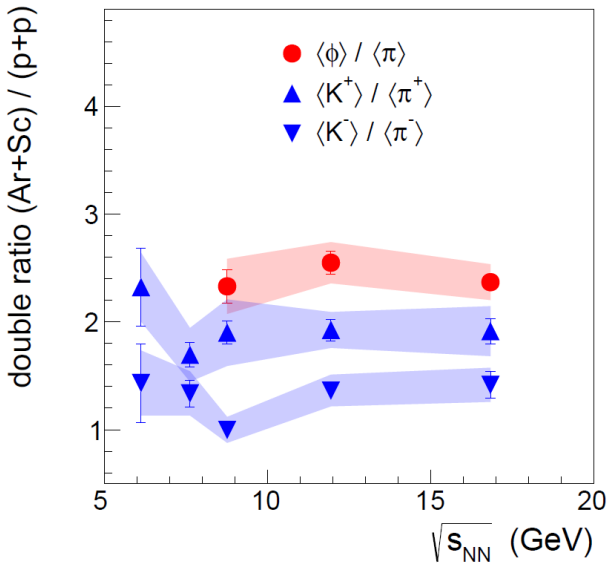
- Left (model comparison):
  green points – 0-1% Ar+Sc;
  green lines – EPOS1.99;
  gray points – uncorrected results
  (stat. uncertainties not shown)

  EPOS1.99 reproduces magnitude; largest deviations in κ_3/κ_1, κ_4/κ_2 at mid-SPS (7–12 GeV) – hint of non-monotonic behavior
- Right (system size): Hint of non-monotonic behavior in central Ar+Sc for κ_3/κ_1, κ_4/κ_2 in comparison to p+p
- Large statistical uncertainties; possible solution: using strongly intensive cumulants that can be utilized in larger centrality bins

$\phi(1020)$ enhancement



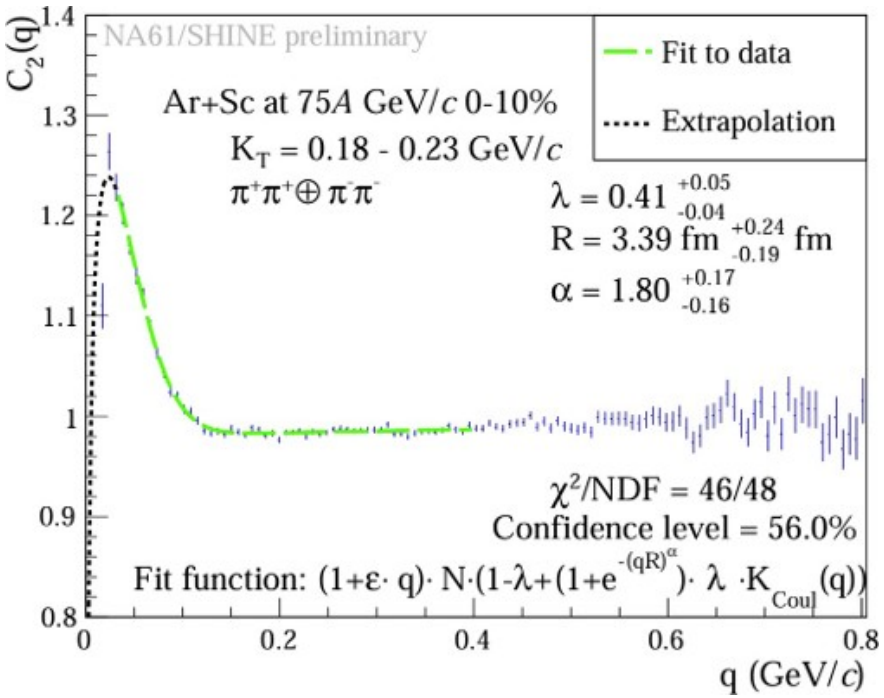




- First measurements of $\phi(1020)$ production in intermediate-size (Ar+Sc) systems at SPS energies ($\sqrt{s_{\mathrm{NN}}} = 8.8$, 11.9, 16.8 GeV)
- ϕ spectra obtained via invariant-mass ($\phi \to K^+K^-$) analysis using the tag-and-probe method
- ϕ/π in Ar+Sc is comparable to Pb+Pb and significantly above p+p
- ϕ enhancement relative to p+p is slightly stronger than for kaons and shows weak dependence on energy

NA61/SHINE: EPJC 80 (2020) 199 (ϕ in p+p), EPJC 77 (2017) 671 ($\pi^{\pm}$, $K^{\pm}$ in p+p), EPJC 84 (2024) 416 ($\pi^{\pm}$, $K^{\pm}$ in Ar+Sc);
NA49: PRC 78 (2008) 044907 (ϕ in Pb+Pb), PRC 66 (2002) 054902 ($\pi^{\pm}$, $K^{\pm}$ in Pb+Pb)

HBT correlations with Lévy sources



Two-particle Bose-Einstein correlation function with Lévy source:

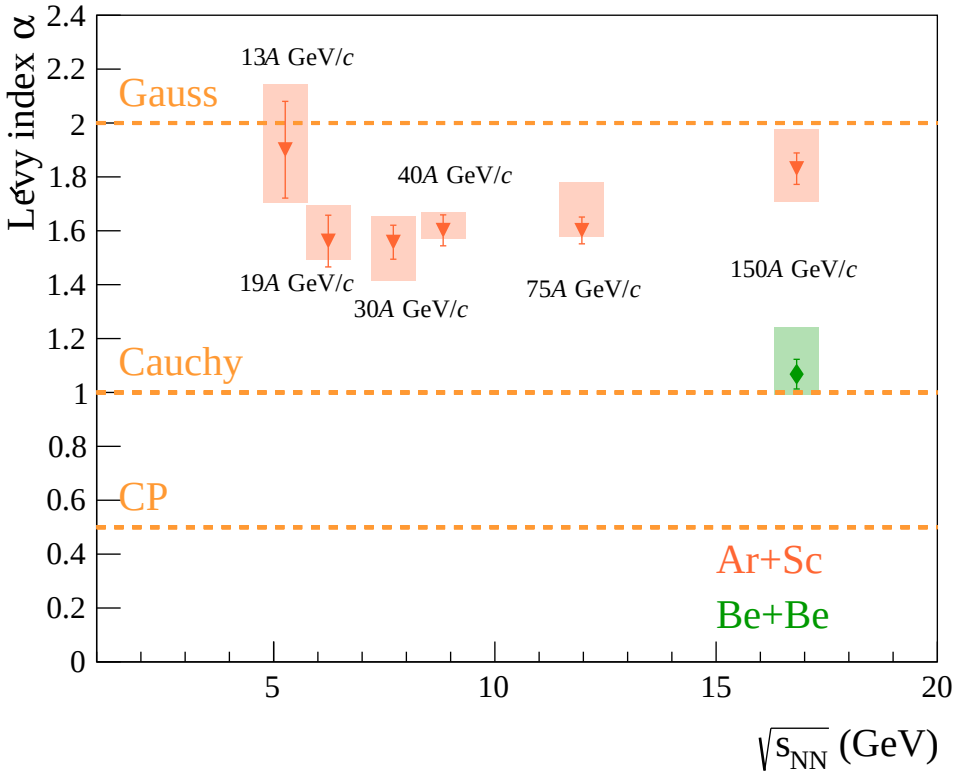
$$C_2(q) = 1 + \lambda\, e^{-|qR|^\alpha}$$

$q =$ $|p_1 - p_2|$ (relative momentum)
$R -$ Lévy scale parameter
$\lambda -$ correlation strength
$\alpha -$ Lévy stability index

- $\alpha = 2$: Gaussian source
- $\alpha = 1$: Cauchy source
- $\alpha \lesssim 0.5$: expected near the critical point

Theory: H. Rieger, PRB 52 (1995) 6659;
NA61/SHINE: EPJC 83 (2023) 919

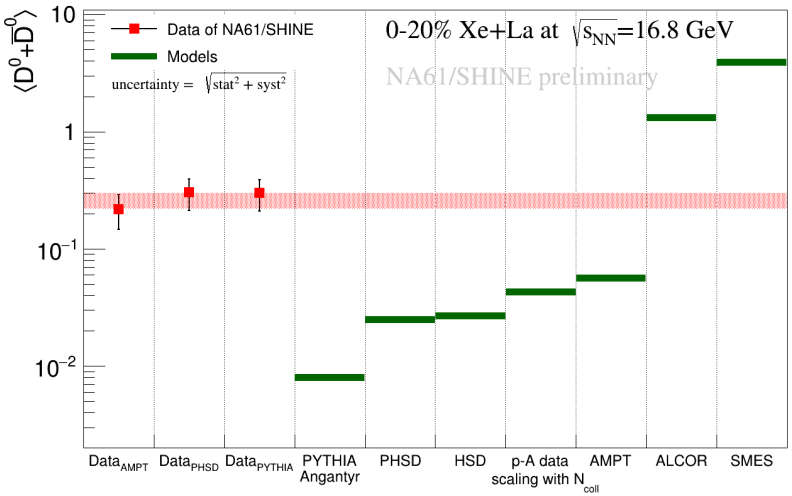
Results for Lévy stability index α



- Be+Be: $\alpha \approx 1$ (Cauchy-like)
- Ar+Sc: α decreases from near-Gaussian at mid-SPS energies
- No indication of critical point (α is far away from CP predictions)

NA61/SHINE: EPJC 83 (2023) 10, 919 (Be+Be); B. Porfy, PoS ICHEP2024 (2025) 603

Direct open charm measurement

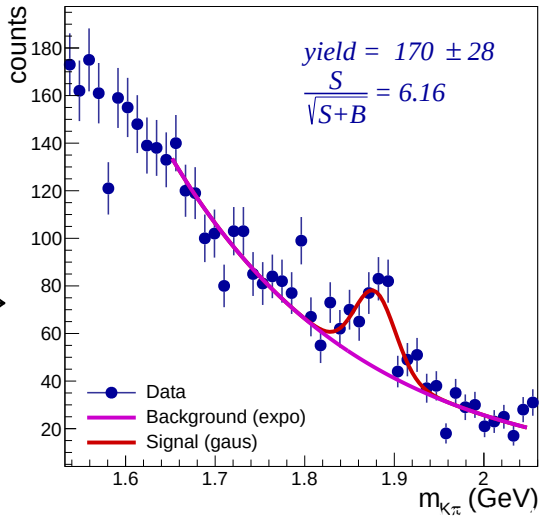


NA61/SHINE: EPJ Web Conf. 316 (2025) 04004

- First direct $D^0+\overline{D}^0$ observation in nucleus-nucleus collisions at SPS energies
- 0–20% central Xe+La at 150A GeV/c
- Corrections via GEANT4 simulations (AMPT, PHSD, PYTHIA/Angantyr)

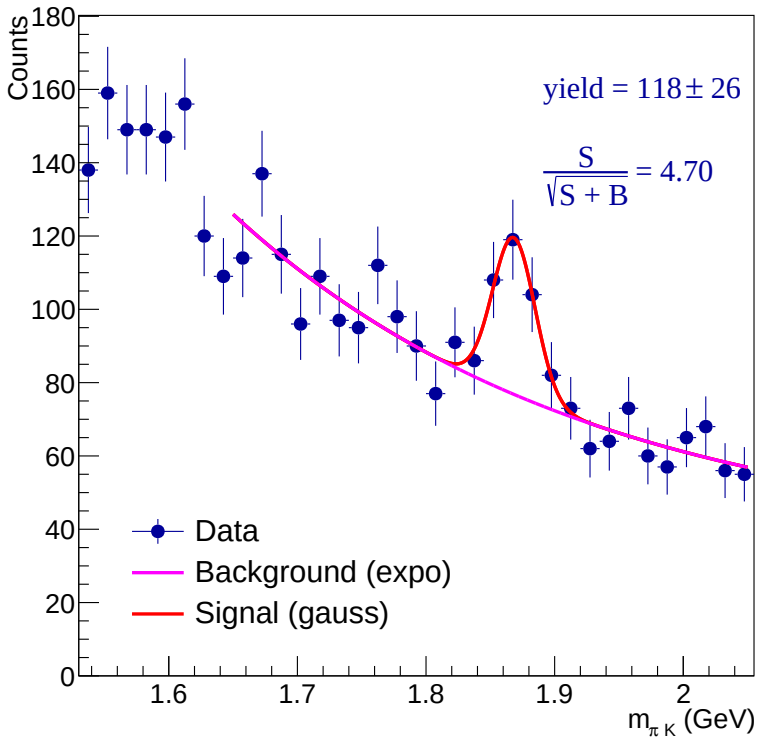
$-0.5 < y < 1.0,$
$0.2 < p_T < 2.0$ GeV/c

Correction with:	**Yield in 4π $(D^0 + \overline{D}^0)$**
AMPT	$0.218 \pm 0.039 \pm 0.060$
PHSD	$0.303 \pm 0.054 \pm 0.074$
PYTHIA/Angantyr	$0.300 \pm 0.052 \pm 0.075$



Direct open charm measurement

- Since LS2 upgraded Vertex Detector (ALPIDE sensors)
- 2x acceptance, 10x readout rate
- Pilot Pb+Pb (2022) confirms capability (data rate $\sim$ 1kHz)
- High-statistics Pb+Pb (2022–2024) under analysis

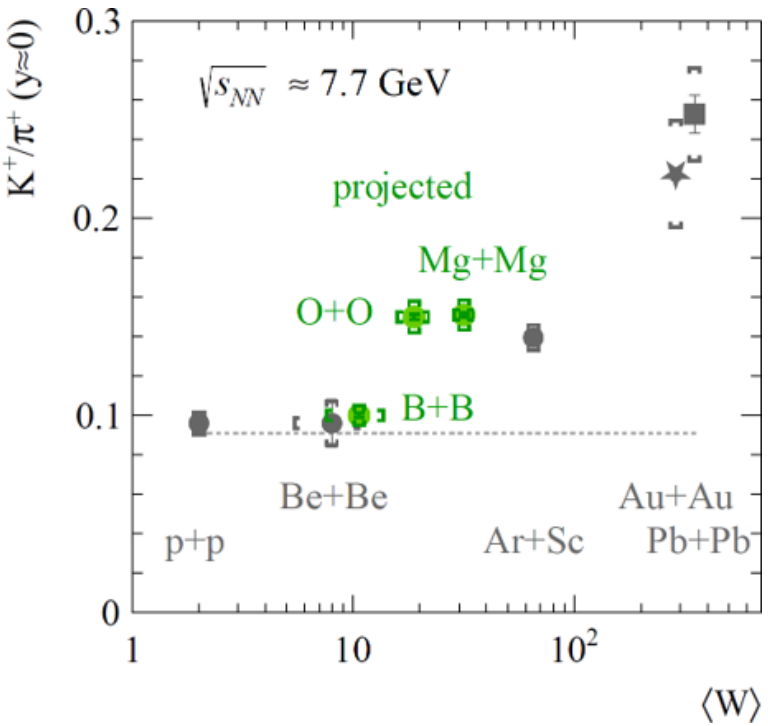


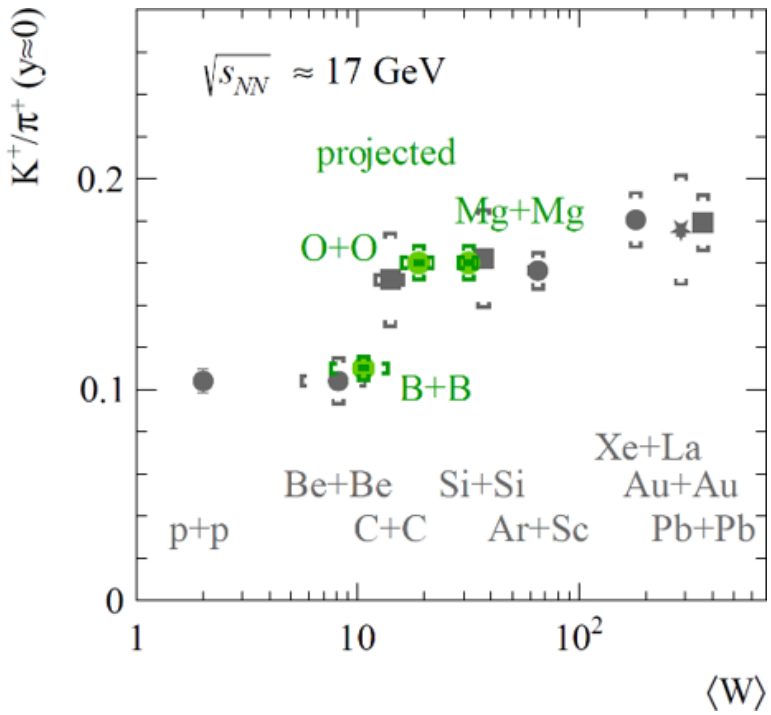
NA61/SHINE: M. Bajda, QM 2025 poster

2022 pilot Pb+Pb at 150A GeV/c

Future Plans

- Continuation of 2D scan after LS3 (2028+):
  - B+B, O+O, Mg+Mg collisions
- Isospin symmetry violation studies:
  - π^++C, π^-+C (2024 data)
  - Pilot O+O (2025)
- High-statistics open charm in Pb+Pb





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

Summary

- Unique 2D scan in collision energy and system size is completed
- New results on the onset of deconfinement
  - No horn structure in K^+/π^+ ratio in Xe+La and Ar+Sc collisions
  - No horn structure in E_S for Ar+Sc collisions
- System size hierarchy found:
  $(p+p \approx \text{Be+Be}) \leq \text{Ar+Sc} \leq (\text{Xe+La} \approx \text{Pb+Pb})$
- Observed excess of charged over neutral kaons in Ar+Sc
- No critical point signal in intermittency or HBT analysis found
- First direct open charm measurement in nucleus-nucleus collisions at SPS energies
- Net-charge fluctuations in 0-1% Ar+Sc show hints of non-monotonic behavior at mid-SPS energies, deviating from EPOS1.99 and $p+p$ (but uncertainties are large)
- First-ever hidden-strangeness ($\phi \rightarrow \text{K}^+K^-$) results in intermediate-size system (Ar+Sc) at the CERN SPS
- Exciting physics program ahead after LS3

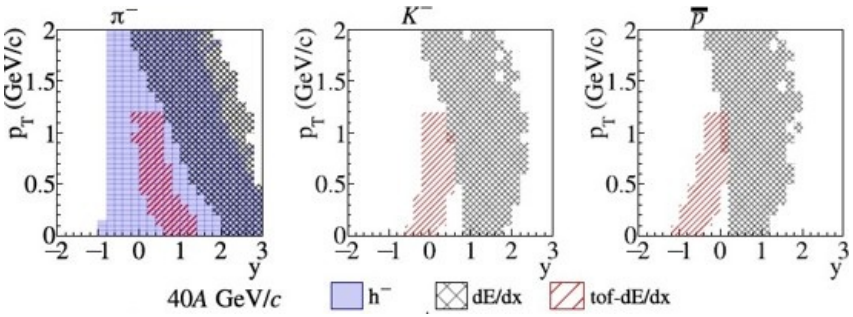
Thank you for your attention!

Back Up

Charged particle identification

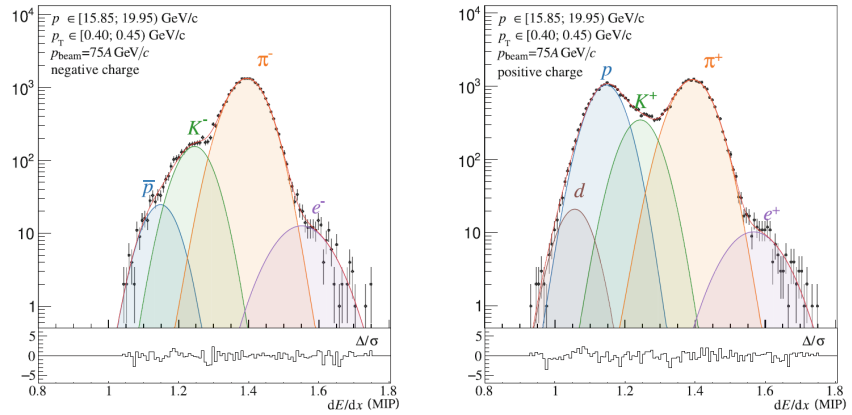
h^- method

- π^- identification in wide y-p_T as the majority of h^- are π^-



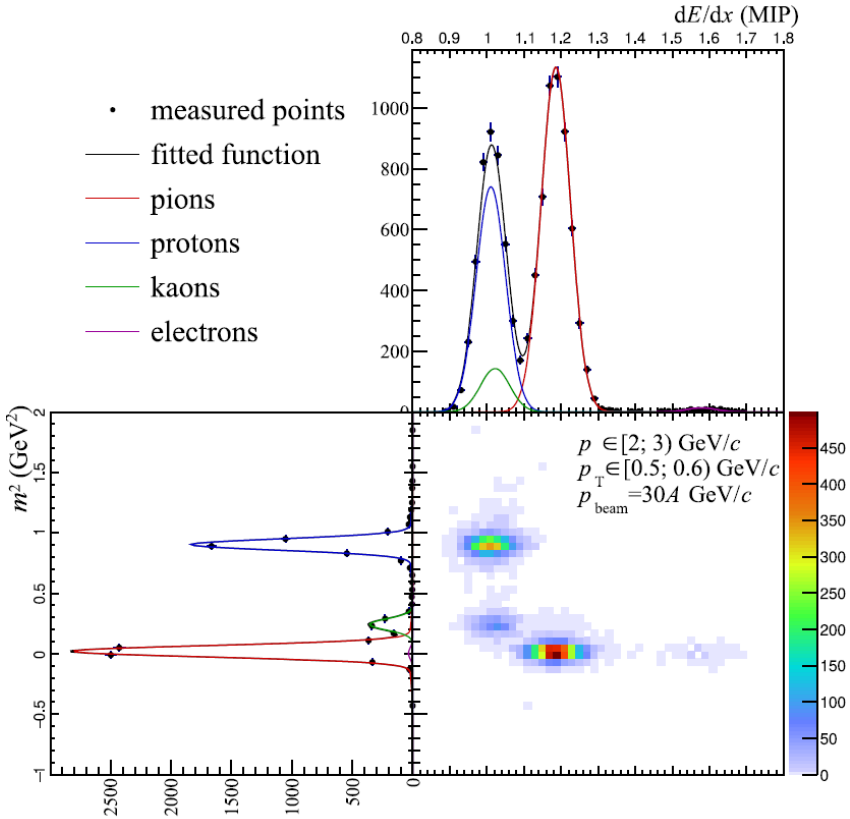
dE/dx method

- TPC energy loss



tof-dE/dx method

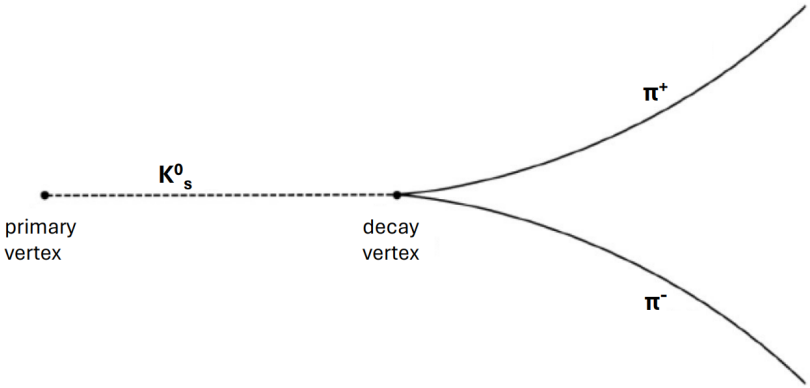
- TPC + ToF information

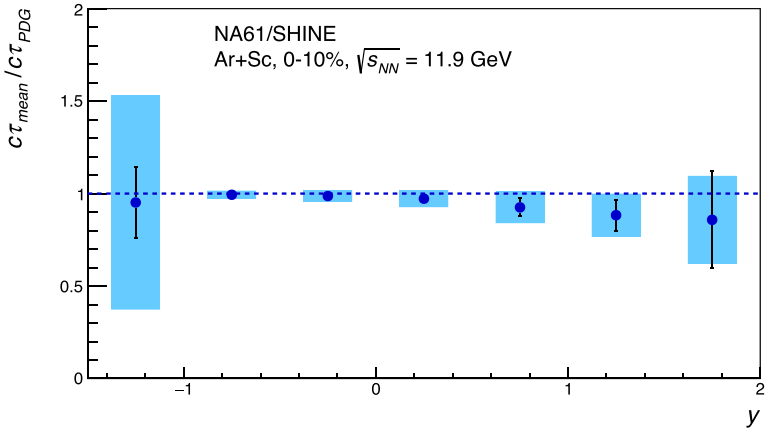


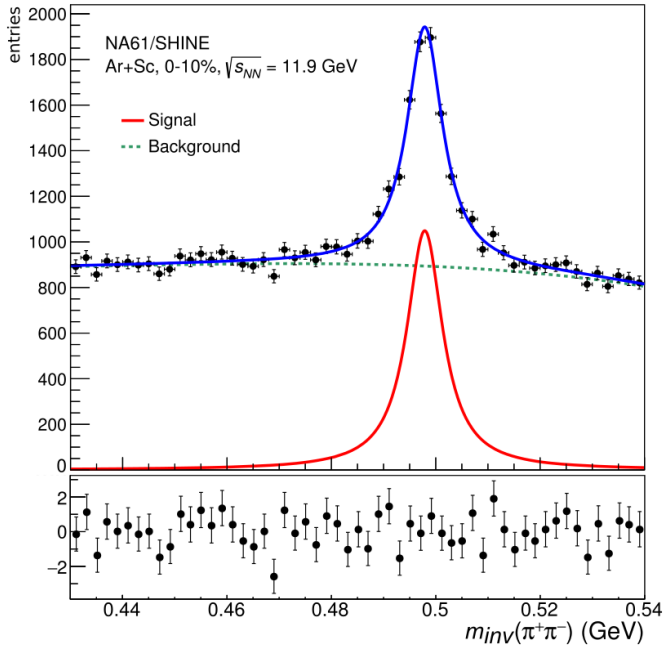
NA61/SHINE: EPJC 84 (2024) 416

Neutral hadron reconstruction

For K^0_S:





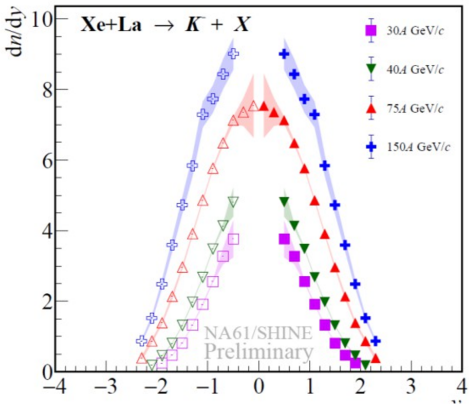


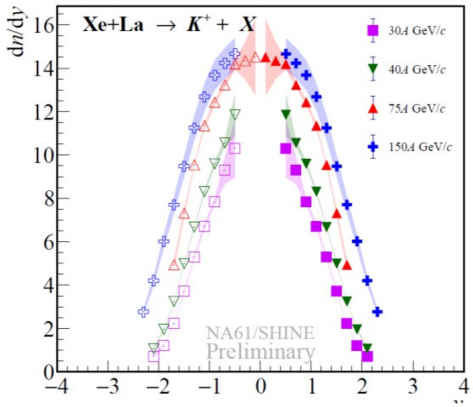
Ar+Sc at 75*A* GeV/*c*

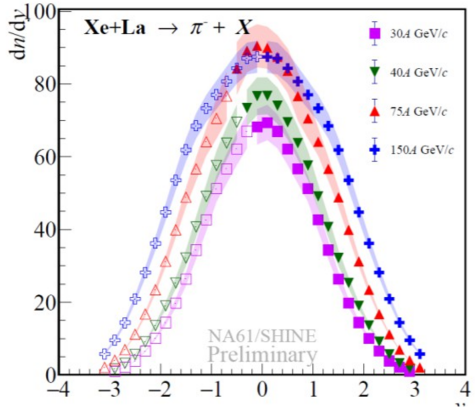
- $K^0_S \to \pi^+\pi^-$ (BR $\approx$ 69.2%)
- Decay topology reconstruction
- The fitted signal function is taken as a Lorentzian, and the background function is a third-order Chebychev polynomial

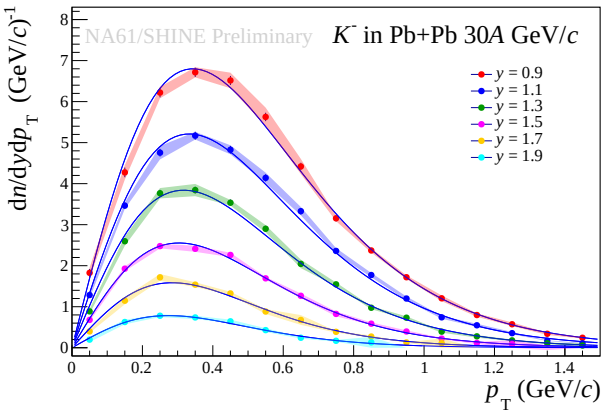
NA61/SHINE: Nature Commun. 16 (2025) 1, 2849

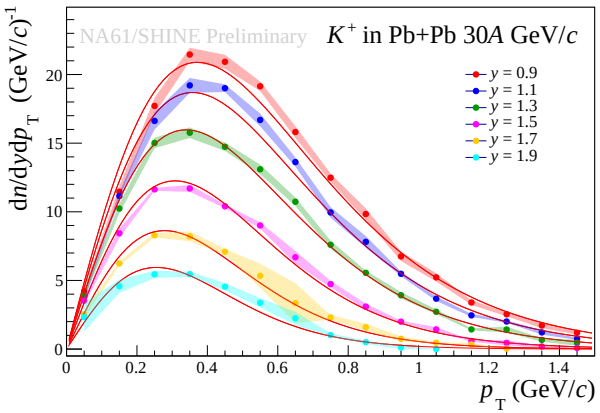
Particle spectra: Xe+La and Pb+Pb

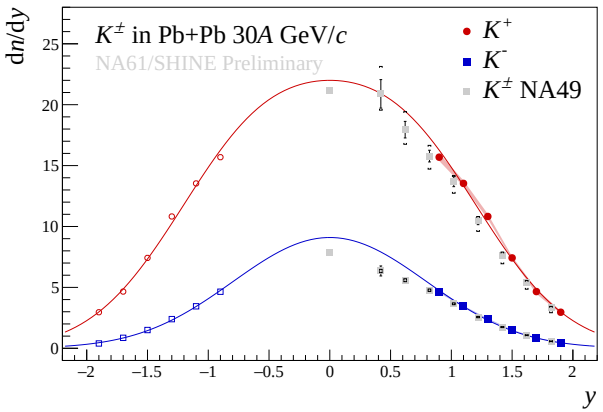










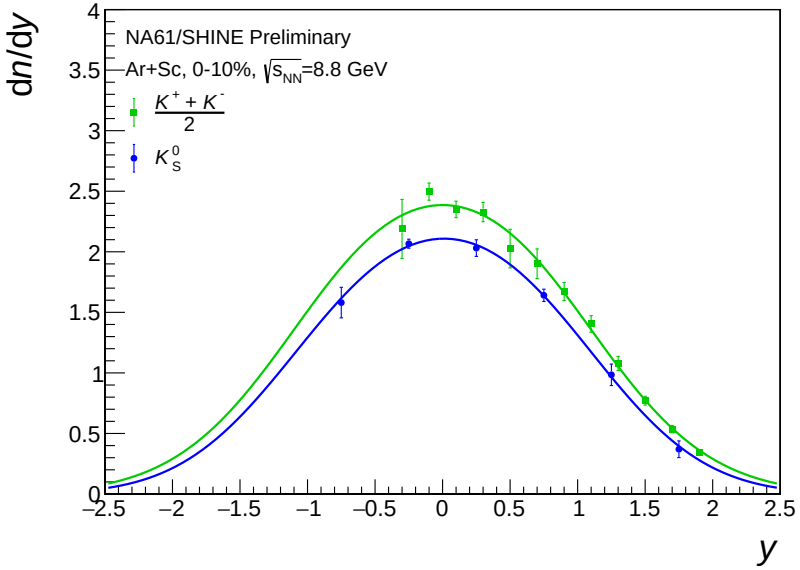


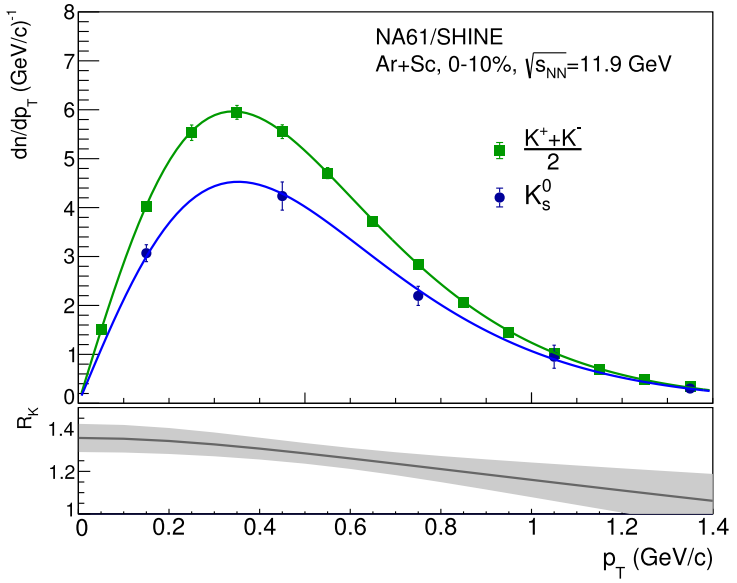
Preliminary spectra:

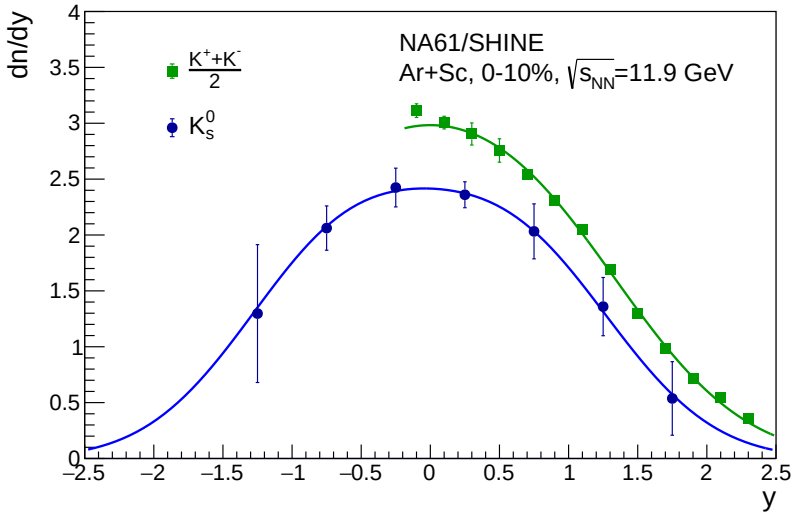
- 10% central Xe+La at 30A, 40A, 75A GeV/c
- 20% central Xe+La at 150A GeV/c
- 7.2% central Pb+Pb at 30A GeV/c
- Spectra obtained via h^- and dE/dx methods

NA61/SHINE: U. Shah, QM 2025 poster

K^0_S in Ar+Sc



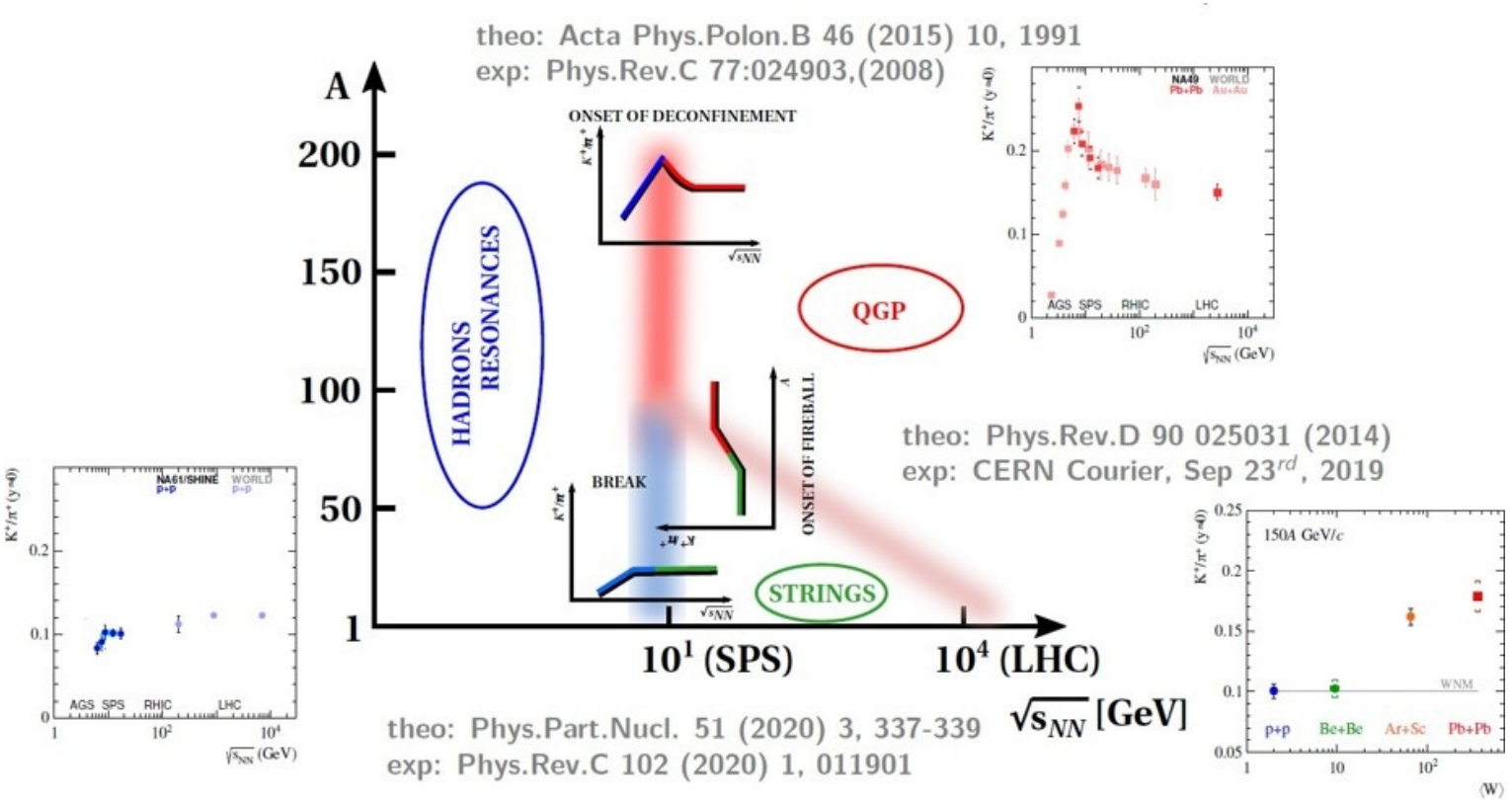




- For exact isospin symmetry and $Z=N$ collisions:
  $\langle K^+(u\bar{s})\rangle = \langle K^0(d\bar{s})\rangle$
  $\langle K^-(\bar{u}s)\rangle = \langle \overline{K}^0(\bar{d}s)\rangle$
  $\langle K^0_S\rangle = \frac{1}{2}\langle K^0\rangle + \frac{1}{2}\langle \overline{K}^0\rangle = \langle K^0_L\rangle$
- Excess of charged to neutral kaons in the whole rapidity and transverse momentum range

NA61/SHINE: Nature Commun. 16 (2025) 1, 2849; EPJC 84 (2024) 4, 416

Diagram of high-energy nuclear collisions



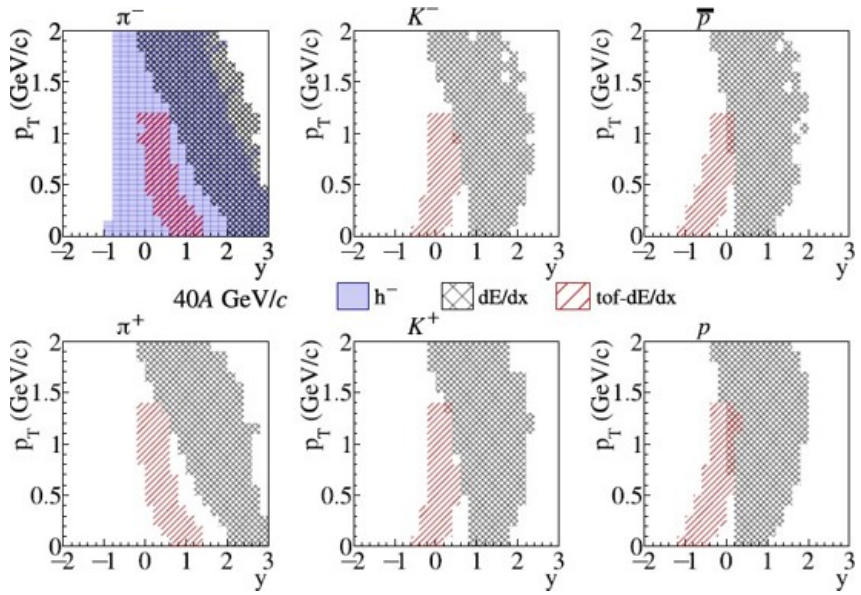
Hypothetical domains of hadron-production dominated by:

- resonance creation and decays
- string creation and decays
- quark-gluon plasma formation and hadronisation

Charged particle identification

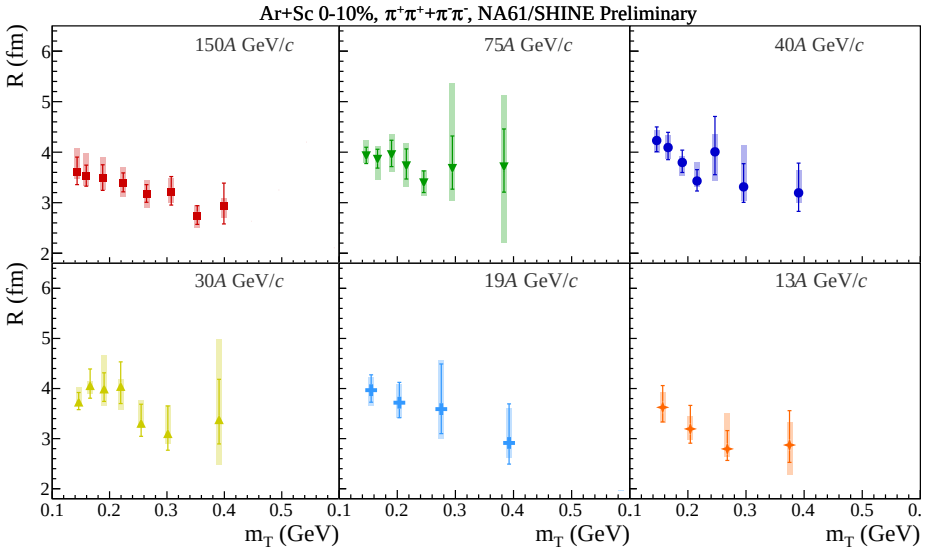
Final results stand for primary particles produced in strong and electromagnetic processes, they are corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

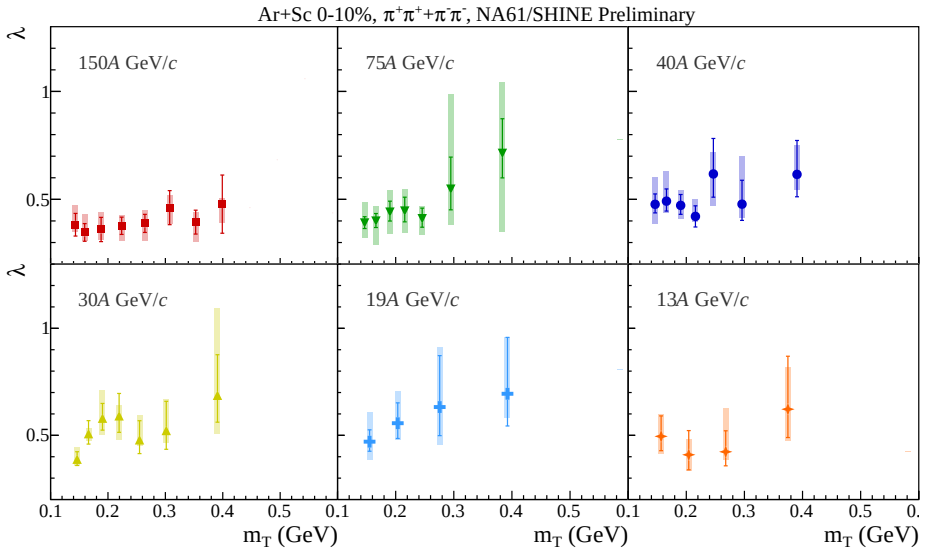
- h^- analysis based on the fact that the majority of negatively charged particles are π^- mesons. Contribution of the other particles is subtracted using EPOS Monte Carlo
- dE/dx analysis uses TPC energy loss information to identify particles
- *tof*-dE/dx method estimates number of π, K, p using an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



NA61/SHINE: EPJC 84 (2024) 416

Lévy-scale parameter R and correlation strength λ





Lévy scale R:

- Describes length of homogeneity
- Visible m_{T} dependence – sign of transverse flow

λ correlation strength:

- Describes core-halo ratio
- Shows no m_{T} dependence

NA61/SHINE: B. Porfy, Proc. ICHEP2024 476 (2025)

Excess of charged over neutral kaons

- **Neutron excess:** More neutrons than protons in colliding nuclei ($Q/B < 1/2$) reduces R_K, but the effect is negligible above 10 GeV (included in HRG, UrQMD)
- **Kaon mass difference:** Isospin-symmetry breaking from the K mass difference (mainly via ϕ decays) increases R_K by ~ 0.03 at $\sqrt{s_{\mathrm{NN}}} > 10$ GeV. Included in HRG, not in UrQMD
- **Scalar resonances:** $a_0(980)$ and $f_0(980)$ decays raise R_K by $\sim 0.5\%$, up to 3% under extreme assumptions (HRG test)
- **Centrality bias:** Higher Q/B for participants (protons concentrated near the center [Thiel et al., J. Phys. G 46 (2019) 093003]) – effect small since R_K shows no system-size dependence

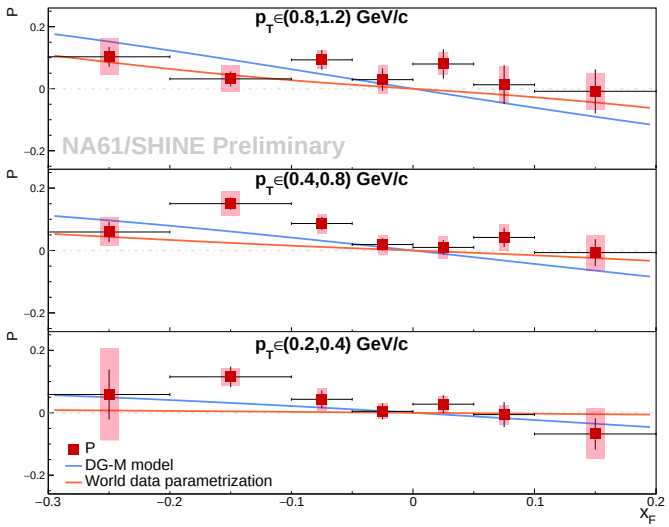
Model insight: In Ref. [Reichert, Steinheimer, Bleicher, arXiv:2503.10493] is proposed within UrQMD a unified description of e^+e^- (BESIII), p+p, and A+A data, attributing the R_K excess to asymmetric u/d quark production ($P(u) = 3 \times P(d)$). *Yet, the large u-d asymmetry in e^+e^- remains an open puzzle.*

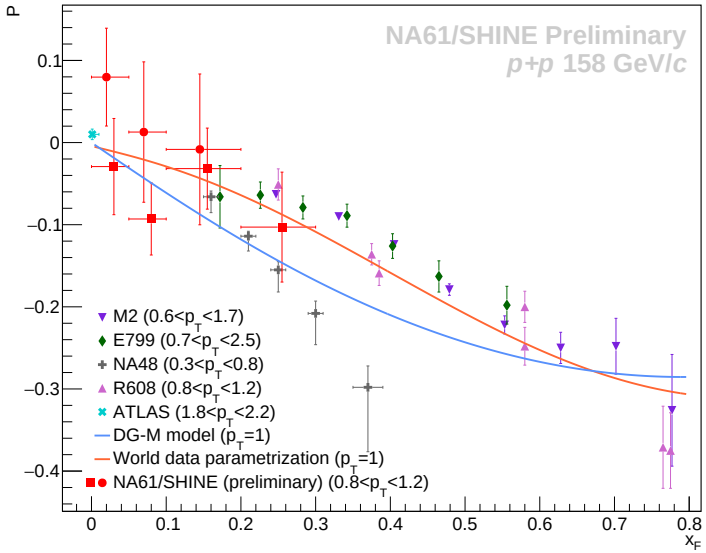
Λ transverse polarization in p+p

The transverse Λ polarization is extracted from the decay $\Lambda \to p+\pi^-$.
The distribution of proton direction in Λ rest frame normal to the production plane is described by :

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_x} \propto 1 + \alpha_\Lambda P \cos\theta_x$$

- $\alpha_\Lambda = 0.746 \pm 0.009$ (PDG 2024)
- parity conservation $\Rightarrow P_y = P_z = 0$





Right: comparison with world data at $p_\mathrm{T} \approx 1$ GeV/c. Points at $x_\mathrm{F} < 0$ (red squares) are mirrored using $P(\text{-}x_\mathrm{F}) = \text{-}P(x_\mathrm{F})$.

World data: parametrization (hep-ph/0111128), M2 pBe: PRD 40 (1989) 3557, E799 pBe: PLB 338 (1994) 403, R608: PLB 185 (1987) 209, ATLAS: PRD 91 (2015) 032004, NA48 pBe: EPJC 6 (1999) 265