Measurement of charged and neutral kaons in Ar+Sc collisions at the NA61/SHINE experiment

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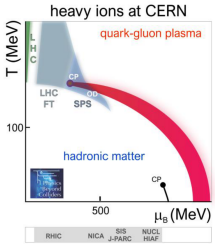
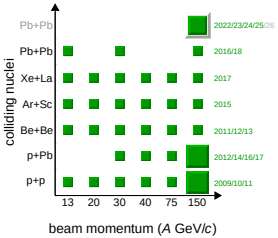
NA61/SHINE experiment

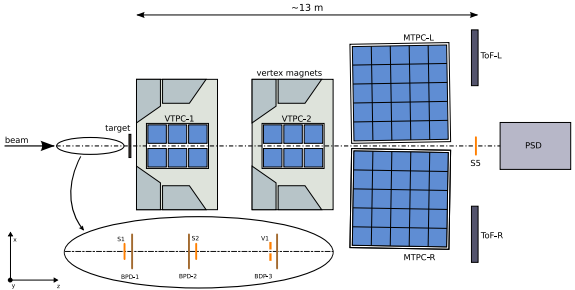
Strong interaction program:

- search for the critical point of strongly interacting matter,
- study of the properties of the onset of deconfinement.

- Fixed-target experiment at CERN SPS.
- Large variety of beams and targets.
- Large acceptance: full forward hemisphere, down to p_T=0.
- Particle identification: dE/dx in Time Projection Chambers, Time-of-Flight detector.
- Collision centrality measured by forward Projectile Spectator Detector (PSD).

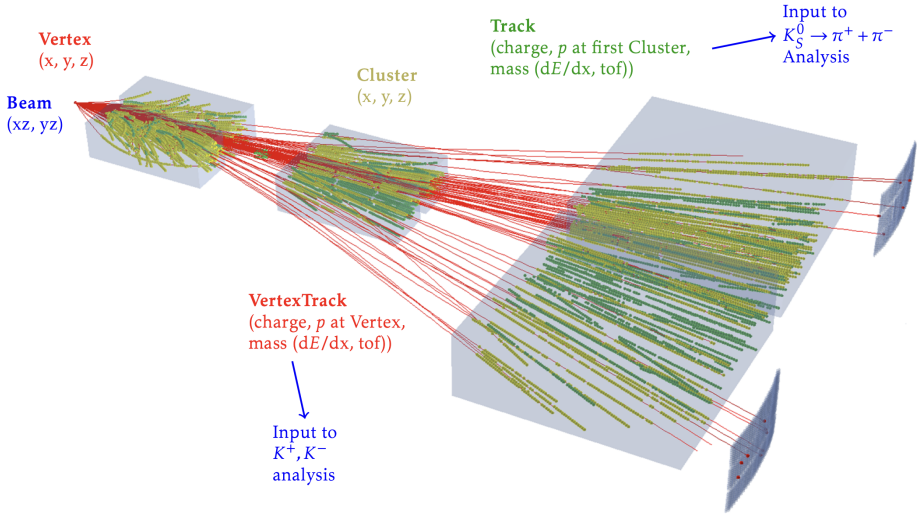






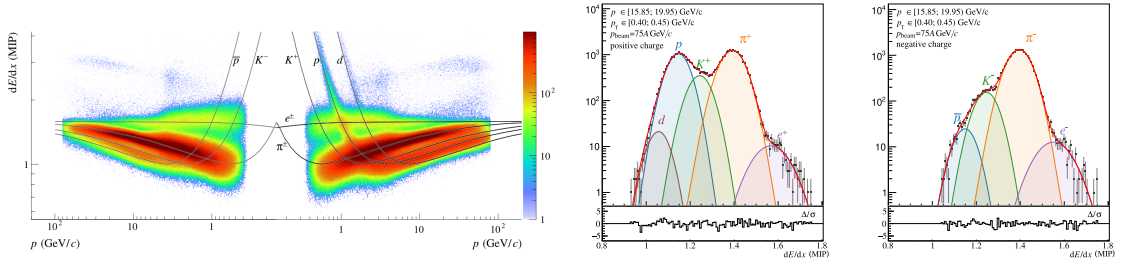
NA61 setup used for Ar+Sc data taking, Eur.Phys.J.C 84 (2024) 4, 416

Measuring charged and neutral kaons



Charged kaons

Charged kaon identification



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- Charged kaons are identified based on a combination of two methods:
  - dE/dx – based on the measurement of energy loss of charged particles along the particle trajectory in Time Projection Chambers ($p > 5$ GeV/c in laboratory frame) with probability method,
  - *tof*-dE/dx – based on the measurement of energy loss of charged particles combined with the measurement of time of flight ($0.5 < p < 10$ GeV/c in laboratory frame).

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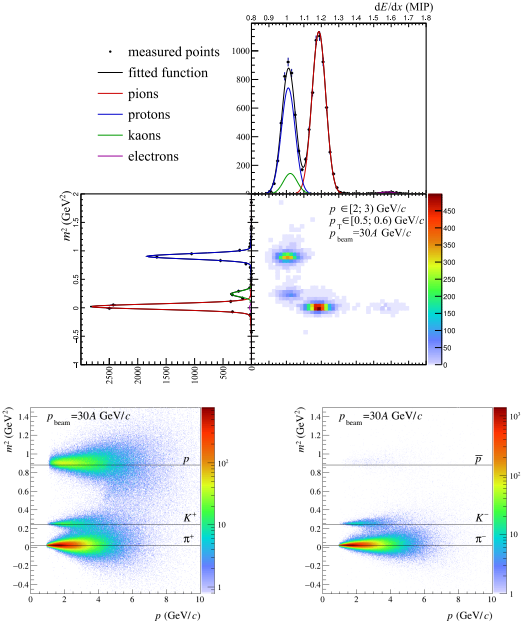

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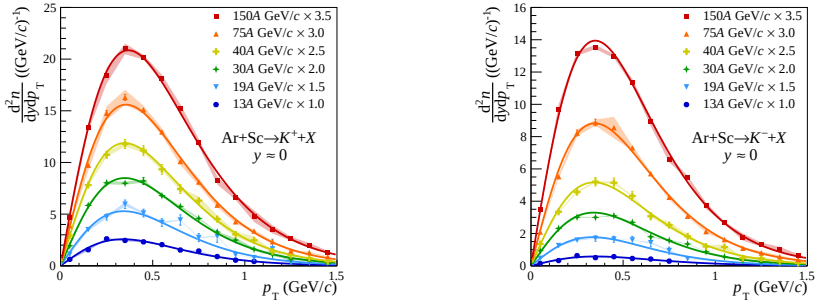
Charged kaon production



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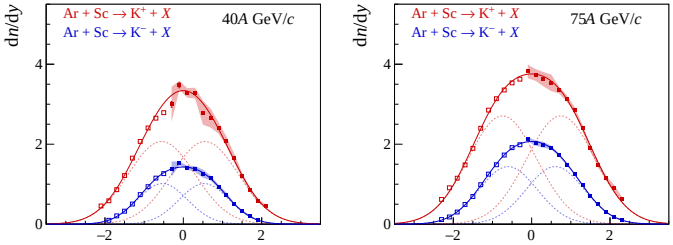
- 10% most central ^{40}Ar+^{45}Sc events.
- p_T spectra fitted with:

$$f(p_T) = \frac{A \cdot p_T}{T(m_K + T)} \exp\left(\frac{m_K - m_T}{T}\right),$$

where: $m_T = \sqrt{p_T^2 + m_K^2}$.

Charged kaon production



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- Rapidity spectra were obtained by integration of the $\mathrm{d}^2n/\mathrm{d}p_T\mathrm{d}y$ spectra and extrapolation using fitted p_T function.
- Obtained rapidity spectra were fitted with double-Gaussian function (all rapidity values are given in collision center-of-mass frame).
- Mean multiplicities of K^+ and K^- calculated as the sum of points increased by the integral of the fit in the unmeasured region.

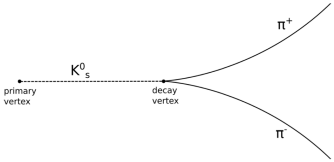
p_{beam} (GeV/c)	$\sqrt{s_{NN}}$	$\langle K^+ \rangle$	$\langle K^- \rangle$
40A	8.77	8.76 ± 0.05 ($stat.$) ± 0.42 ($sys.$)	3.26 ± 0.02 ($stat.$) ± 0.15 ($sys.$)
75A	11.94	11.84 ± 0.08 ($stat.$) ± 0.39 ($sys.$)	5.33 ± 0.01 ($stat.$) ± 0.14 ($sys.$)

Neutral kaons

K^0_S identification

- 10% most central ^{40}Ar+^{45}Sc events.
- Reconstruction based on decay topology.

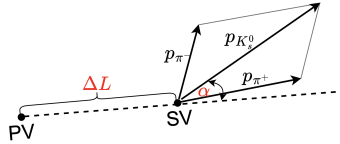
Mass (GeV)	$c\tau$ (cm)	Decay	BR (%)
0.4976	2.68	$\pi^+ + \pi^-$	69.20



- Daughter track selection:
  - number of points in VTPC > 10,
  - p > 0.4 GeV/c.
- K^0_S selection (rapidity dependent):
  - **directional angle (α)**,
  - **distance between the primary and secondary vertices:**

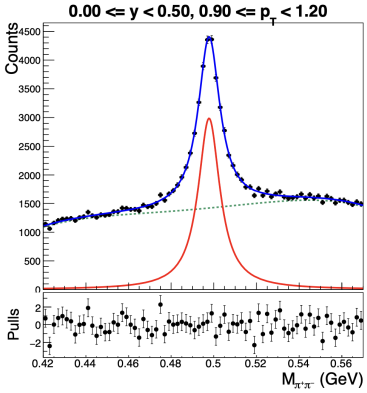
$$\Delta L = \sqrt{\sum_{i=x,y,z}(SV - PV)^2}$$

  - $cos(\alpha)$ and ΔL were optimised using MC simulation.
- In Ar+Sc collisions at 40A GeV/c additional cuts were introduced to further suppress background and remove Λ hyperons.



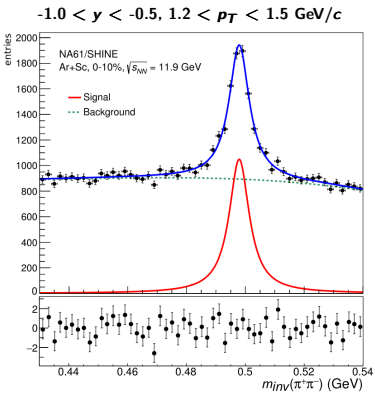
Signal extraction

Example for Ar+Sc at 40A GeV/c



NA61/SHINE preliminary

Example for Ar+Sc at 75A GeV/c



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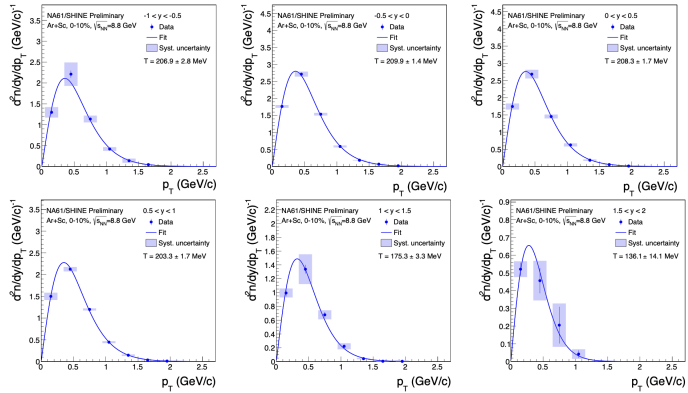
- Signal extracted by fitting:
  - **Lorentzian** (signal) + **Chebyshev Polynomials** (background).
  - Polynomial order: 3th (for 75A GeV/c) or 1st-4th (for 40A GeV/c; lower orders used in the bins with low statistics).

p_T spectra – Ar+Sc at 40A GeV/c

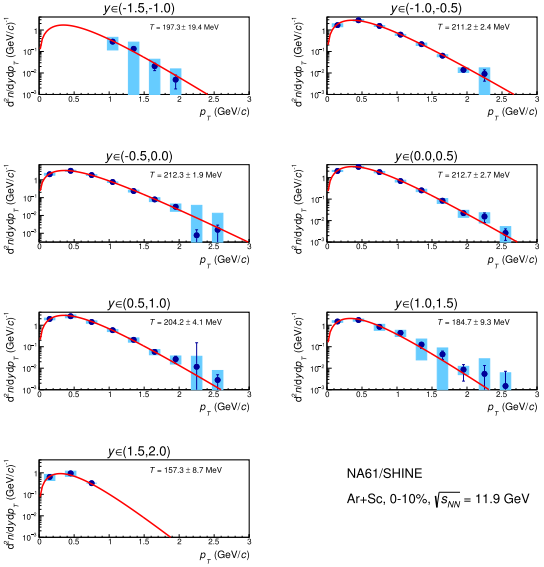


- p_T distributions of K^0_S mesons measured in $y \epsilon (-1; 2)$.
- Excellent p_T coverage in all rapidity bins.
- The systematic uncertainties are shown by the blue shaded boxes.
- $\mathrm{d}^2n/\mathrm{d}p_T\mathrm{d}y$ spectra were fitted with the exponential function: $f(p_T) = A \cdot p_T \cdot \exp\left(-\frac{\sqrt{p_T^2+m^2}}{T}\right)$.

p_T spectra – Ar+Sc at 75A GeV/c

- p_T distributions of K^0_S mesons measured in $y\epsilon(-1.5; 2)$.
- Excellent p_T coverage in almost all rapidity bins.
- The systematic uncertainties are shown by the blue shaded boxes.
- $\mathrm{d}^2n/\mathrm{d}p_T\mathrm{d}y$ spectra were fitted with the exponential function:

$$f(p_T) = A \cdot p_T \cdot \exp\left(-\frac{\sqrt{p_T^2+m^2}}{T}\right) .$$



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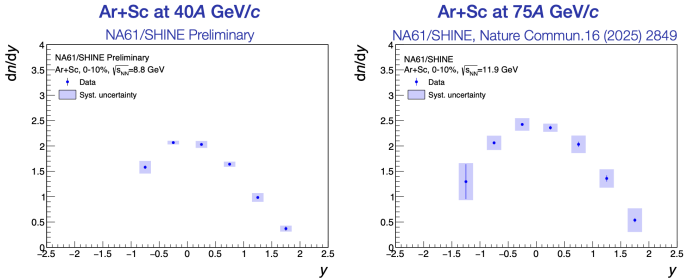
dn/dy distributions



- dn/dy points obtained by:
  - summing-up the measured points and extrapolating to the unmeasured region using the fitted function (for 40A GeV/c),
  - integrating curves fitted to the transverse momentum spectra (for 75A GeV/c).
- The spectra were fitted with a sum of two Gaussian functions.

p_{beam} (GeV/c)	$(\mathrm{d}n/\mathrm{d}y)_{y=0}$	$\langle K^0_S \rangle$
40A	$2.108 \pm 0.016\ (stat.) \pm 0.052\ (sys.)$	$5.15 \pm 0.05\ (stat.) \pm 0.29\ (sys.)$
75A	$2.433 \pm 0.027\ (stat.) \pm 0.102\ (sys.)$	$6.49 \pm 0.10\ (stat.) \pm 0.83\ (sys.)$

Flavor independence test

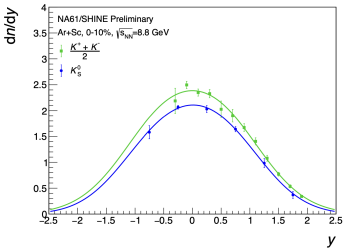
- QCD assumes flavor independence of interactions. In the limit of equal u and d masses and for $Z{=}N$ nuclei, this results in equal creation probabilities of $u\bar{u}$ and $d\bar{d}$ pairs:

$$P(u\bar{u}) = P(d\bar{d}).$$

- **Experimental test:**
  - Use collisions of nuclei with approximately equal numbers of protons and neutrons ($N_u \approx N_d$).
  - Expected: $\langle K^+ \rangle (u\bar{s}) = \langle K^0 \rangle (d\bar{s})$ and $\langle K^- \rangle (\bar{u}s) = \langle \overline{K}^0 \rangle (\bar{d}s)$.
  - Neutral kaons are detected as the physical states K^0_S and K^0_L; neglecting CP violation $\langle K^0_S \rangle = 1/2 \langle K^0 \rangle + 1/2 \langle \overline{K}^0 \rangle = \langle K^0_L \rangle$
- **Expectation:**

$$\frac{K^+ + K^-}{2} \approx \frac{K^0 + \overline{K}^0}{2} = K^0_S.$$

Production of kaons



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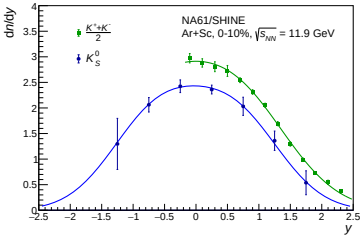

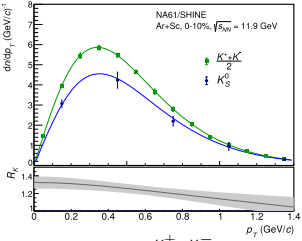

$$R_K = \frac{K^+ + K^-}{2K^0_S}$$

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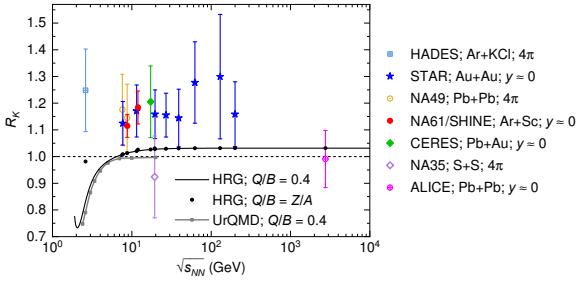
- Ar and Sc nuclei are nearly charge-symmetric (valence $u \approx d$ within 6%).
- Total uncertainties plotted: $\sqrt{sys^2 + stat^2}$.
- Excess of charged to neutral kaons observed in the whole rapidity range.
- Unexpected violation of flavour symmetry between u and d quarks:

$$\frac{K^+ + K^-}{2} > K^0_S$$

Charged to neutral kaon ratio

- Ar: Q=18, B=40, Q/B=0.45.
- Sc: Q=21, B=45, $Q/B \approx 0.47$.
- Black and grey line show the HRG and UrQMD predictions for electric-to-baryon charge $Q/B = 0.4$.
- Black dots represent the HRG baseline for Q/B values specified according to the given types of colliding nuclei.
- HRG and UrQMD models do not reproduce the experimental result on charged-to-neutral kaon ratio.
- Other experiments confirm the effect; see also ISO-BREAK 25.



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

p_{beam} (GeV/c)	R_K
40A	1.115 ± 0.043 ($tot.$)
75A	1.184 ± 0.061 ($tot.$)

Summary

- NA61/SHINE has published results on the K^0_S production in the 10% most central Ar+Sc collisions at 75A GeV/c.
- Preliminary results have been released for the 10% most central Ar+Sc collisions at 40A GeV/c.
- Excess of charged to neutral kaons is observed for both energies in Ar+Sc collisions $\rightarrow$ unexpected violation of isospin symmetry.
- HRG and UrQMD models do not reproduce the experimental result on charged-to-neutral kaon ratio.
- Ongoing analyses for central Ar+Sc collisions at 19A, 30A, and 150A GeV/c, along with continued work to obtain final results at 40A GeV/c.

Thank you!

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