Recent results from NA61/SHINE strong interaction program

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Outline

- Introduction
- Spectra and onset of deconfinement
- Search for the critical point – intermittency analysis
- Excess of charged over neutral kaon production
- Direct measurement of open charm
- Summary and plans

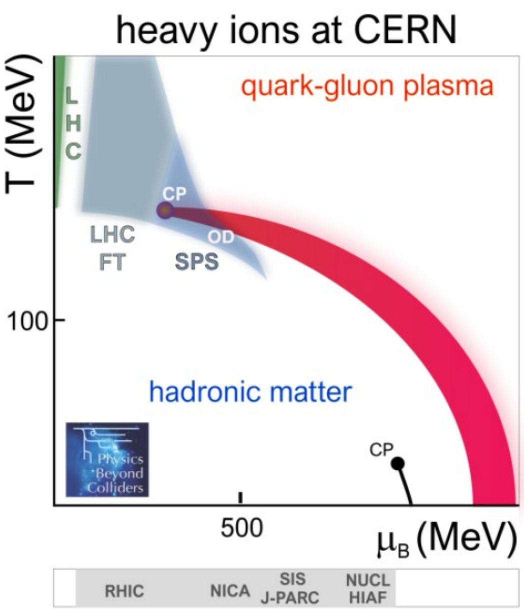
NA61/SHINE physics program

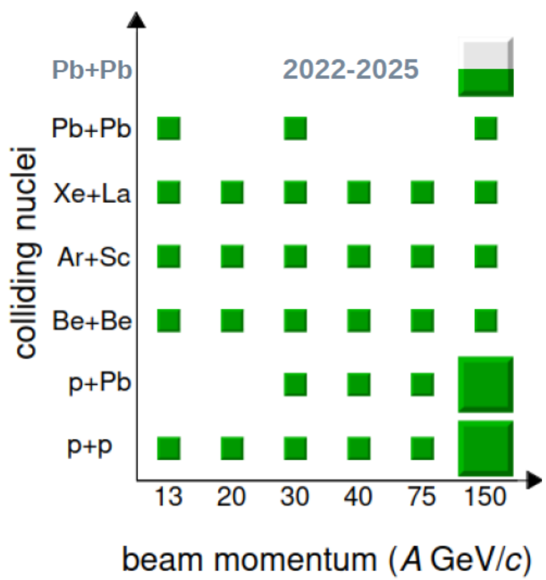
Strong interaction physics:

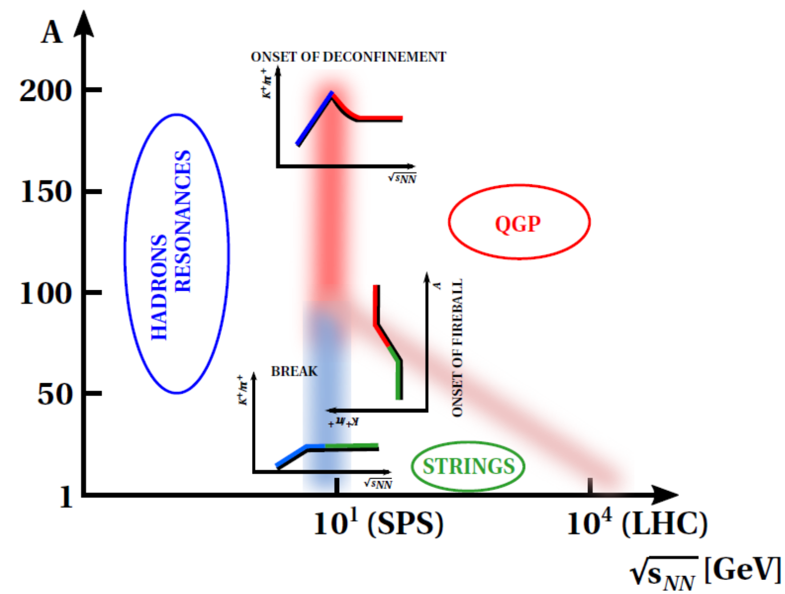
- study properties of the onset of deconfinement
- search for the critical point of strongly interacting matter
- direct measurements of open charm

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

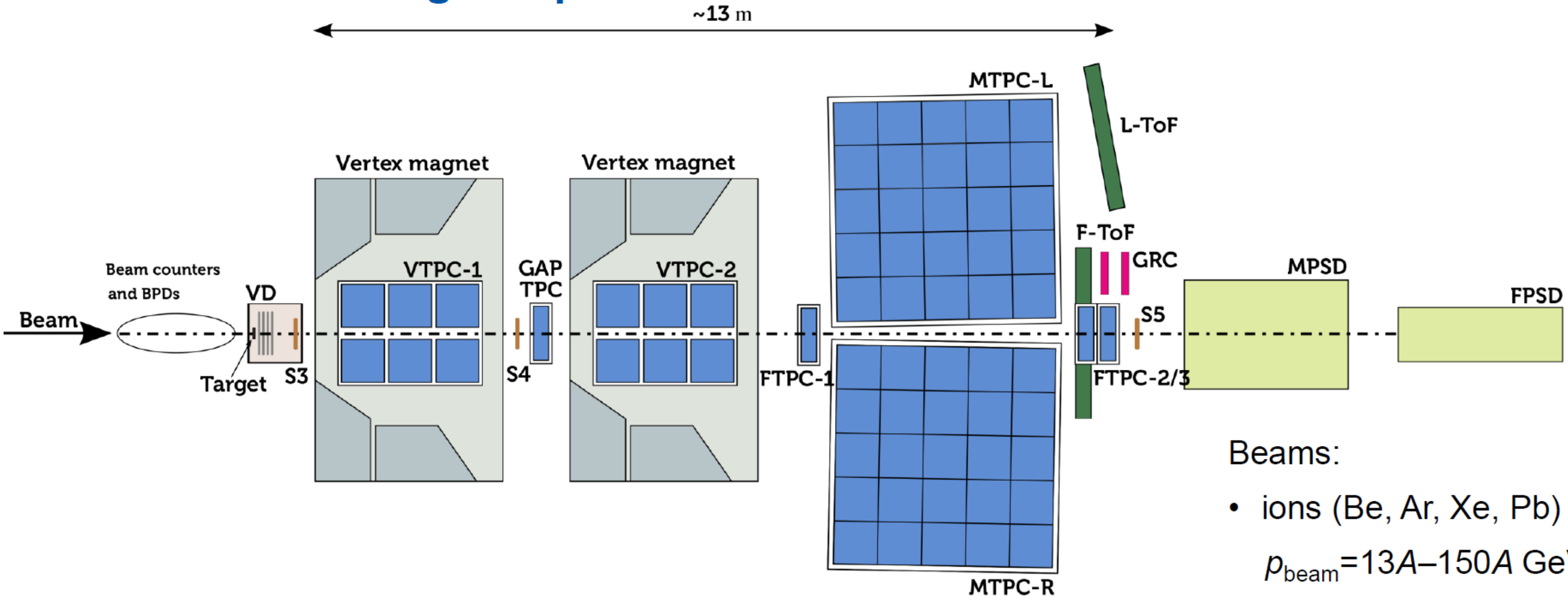






NA61/SHINE detector

Fixed target experiment located at the CERN SPS accelerator



Beams:
- ions (Be, Ar, Xe, Pb)
  p_{beam}=13A–150A 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

- y, p_T spectra of particle species
- Strangeness in quark matter: K^+, K^-, K^0_s, K^*, Λ, ϕ
- Correlations, fluctuations, HBT, intermittency
- Heavy quarks: D^0 and $\overline{D}^0$

Charged particle identification

NA61/SHINE: EPJC 84 (2024) 416

- **h^- analysis**

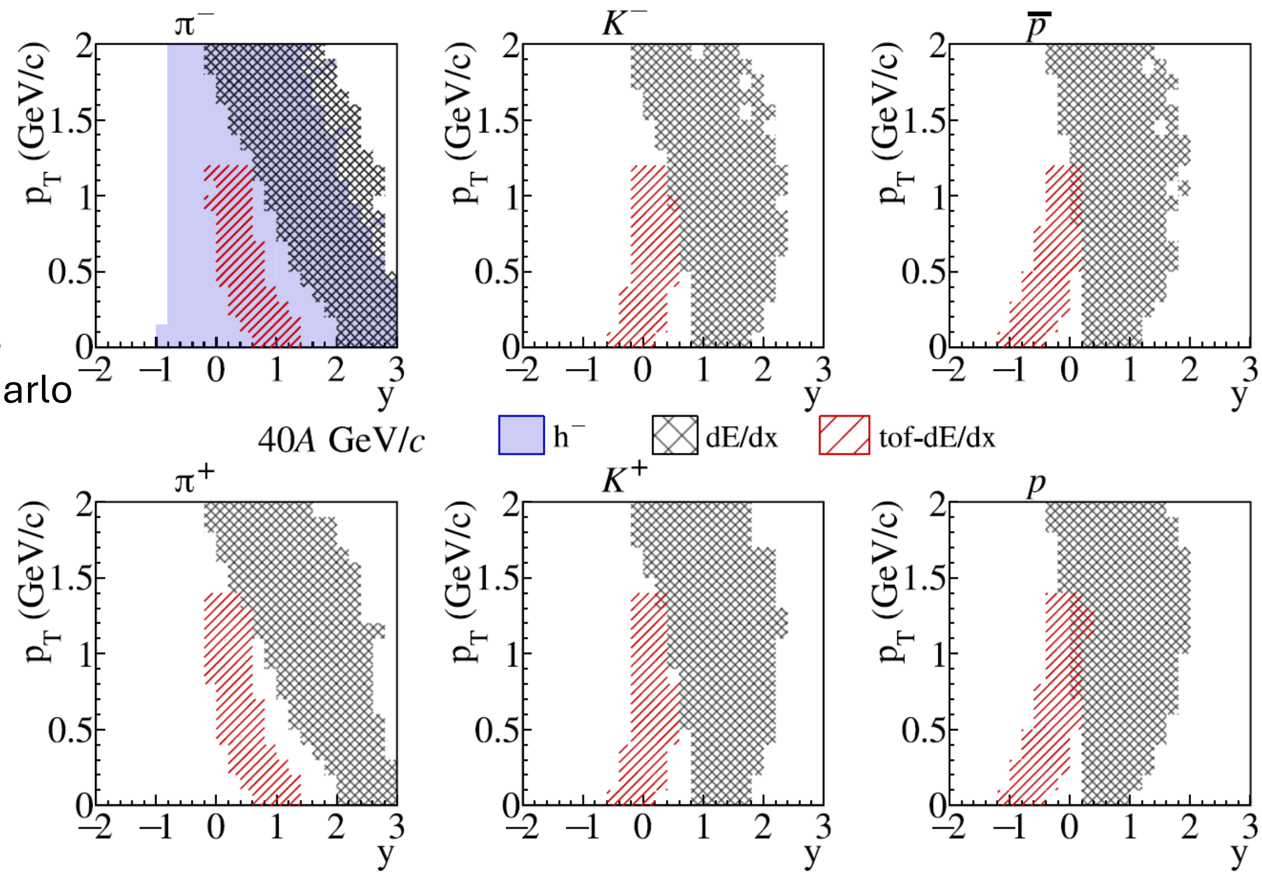
A method based on the fact that the majority of negatively charged particles are π^- mesons
The contribution of other particles is subtracted using EPOS Monte Carlo

- **dE/dx**

A method uses TPC energy loss to identify particles

- **tof-dE/dx**

A method uses TPC energy loss and ToF info to identify particles

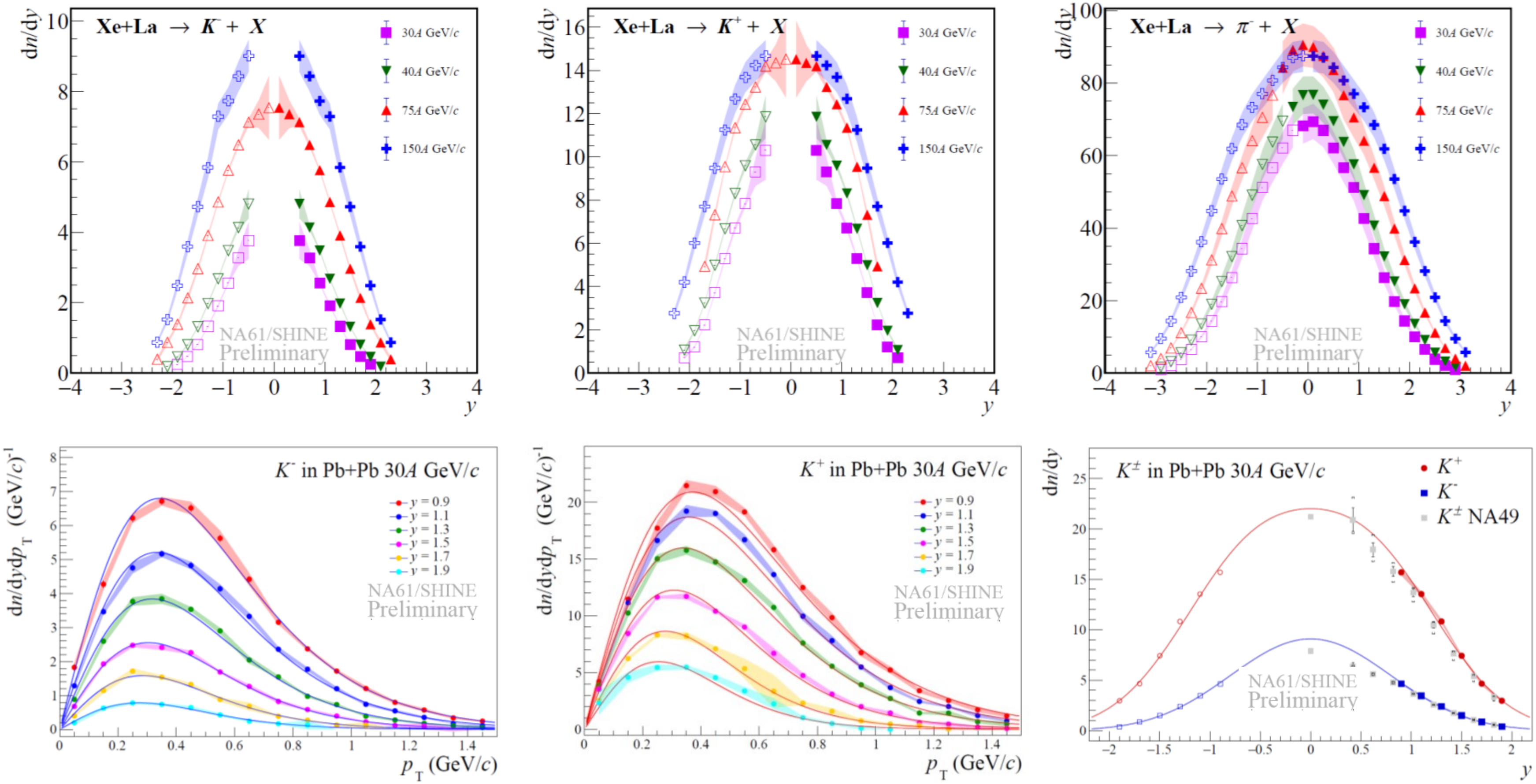


0-10% Ar+Sc at 40*A* GeV/*c*

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

Particle spectra
and
onset of deconfinement

Spectra

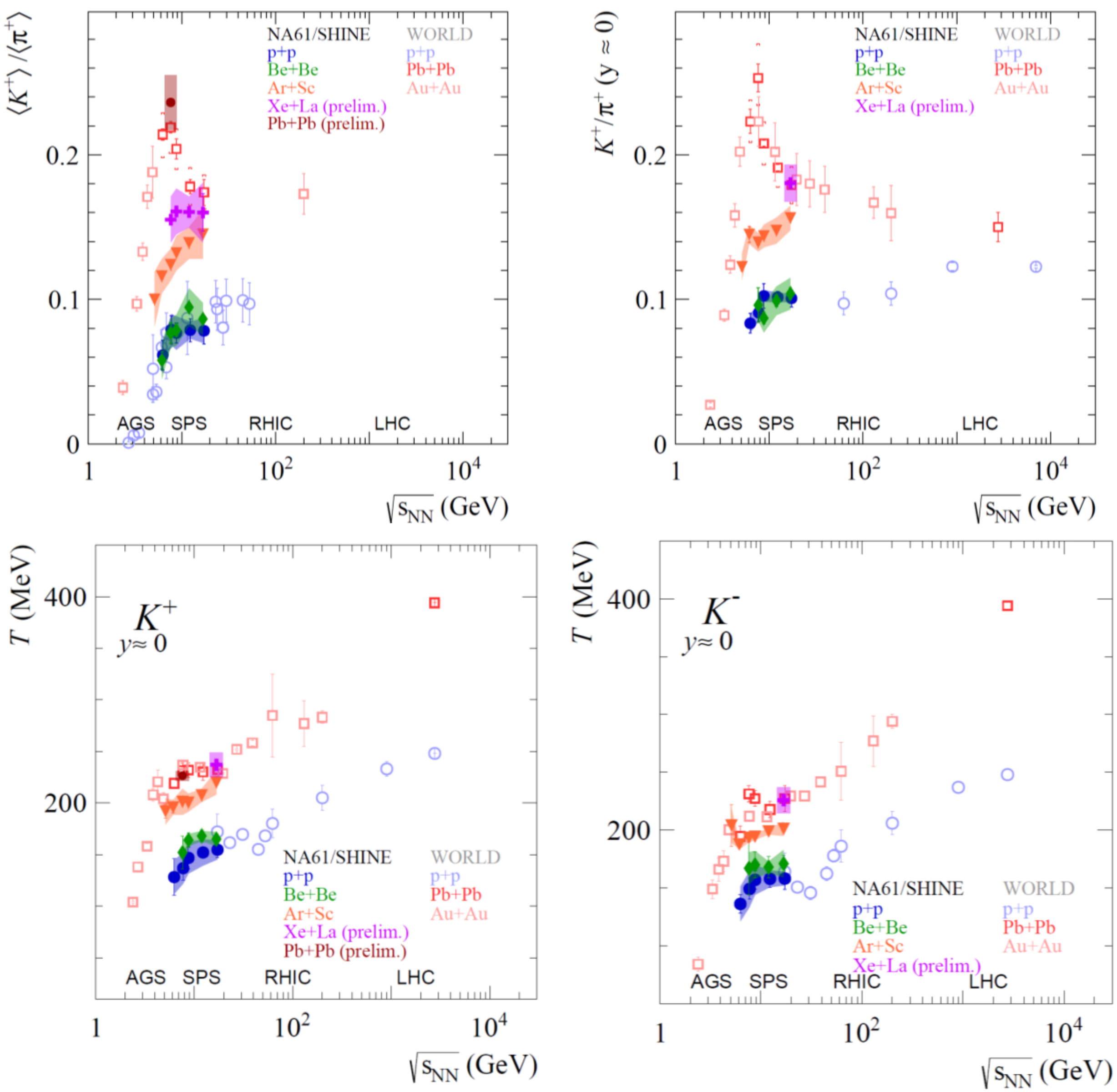


NA61/SHINE: U. Shah, QM 2025 poster

- New NA61/SHINE preliminary y, p_T spectra of π^- and $K^\pm$
- 10% most central Xe+La collisions at 30*A*, 40*A*, 75*A* GeV/*c*
- 20% most central Xe+La collisions at 150*A* GeV/*c*
- 7.2% most central Pb+Pb collisions at 30*A* GeV/*c*
- Spectra obtained by h$^-$ and dE/dx methods

Energy dependence: horn and step

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



Horn

K^+/π^+ proportional to strangeness to entropy ratio; different number of degrees of freedom in QGP and hadron phase

Probe the onset of deconfinement

Xe+La points below Pb+Pb and above Ar+Sc, Be+Be, and p+p

Step

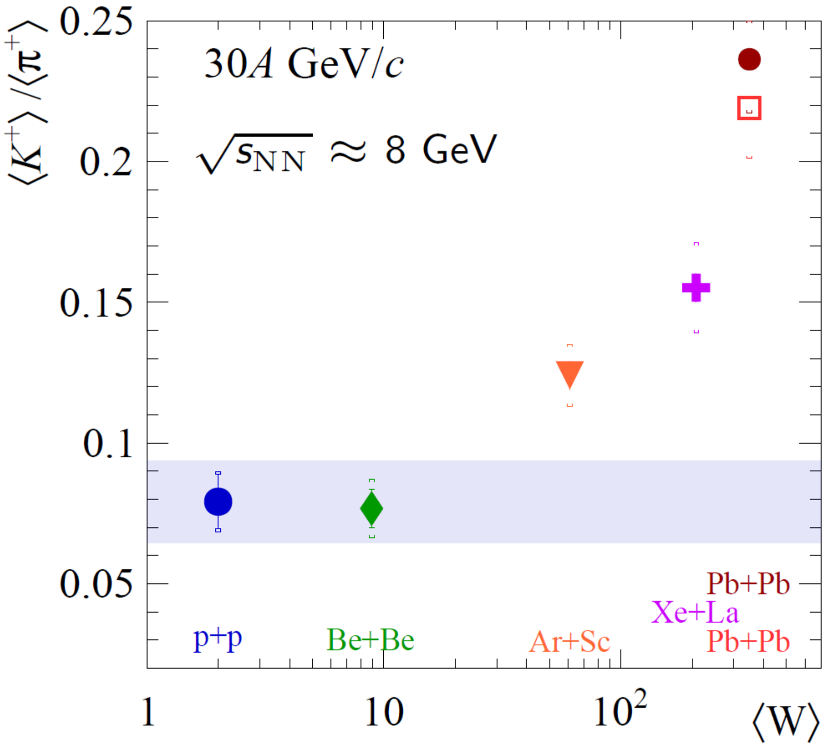
Kaons are only weekly affected by rescattering and resonance decays during post-hydro phase at SPS energies

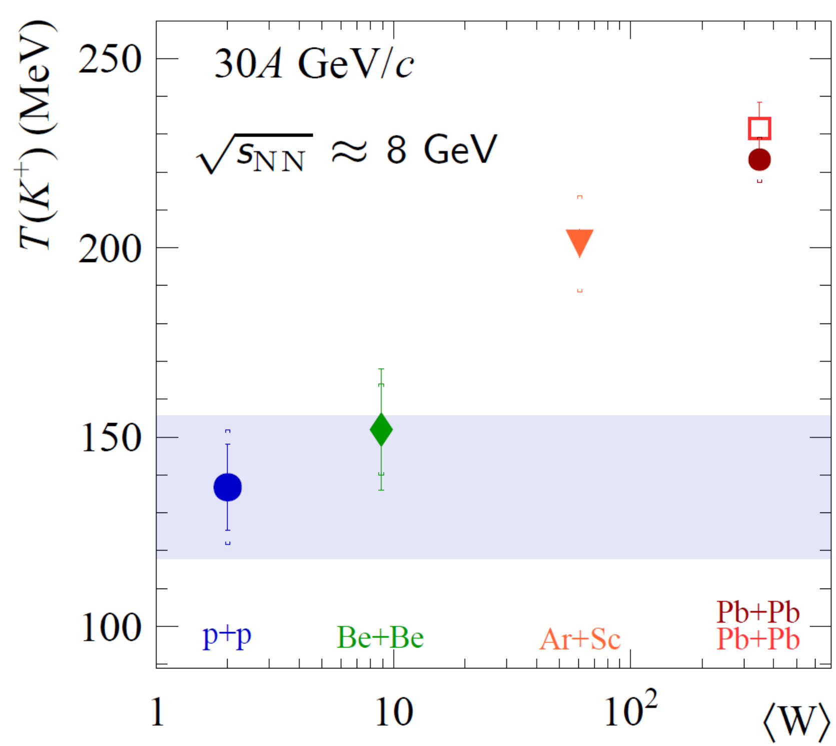
T (inverse slope parameter of m_T or p_T) reflects the thermal freeze-out temperature and the radial flow velocity

Similar energy dependence is seen in p+p, Be+Be, Ar+Sc, and Pb+Pb

T grows with energy except of the range where Horn is located

System size dependence





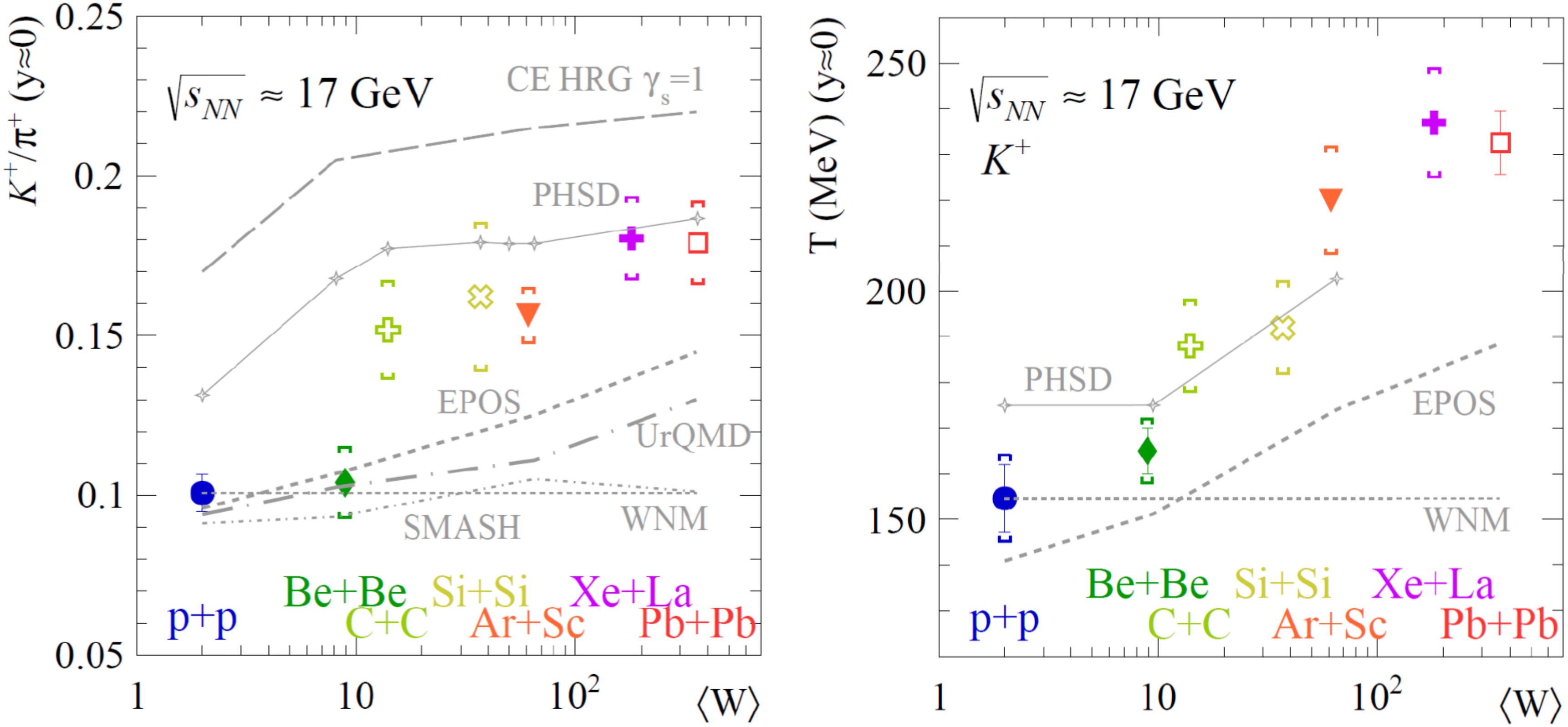
- Increase of $\langle K^+ \rangle / \langle \pi^+ \rangle$, $T(K^+)$ with system size

(p+p ≈ Be+Be) < Ar+Sc < Xe+La < Pb+Pb

NA61/SHINE p+p, 0-20% Be+Be, 0-10% Ar+Sc: see NA61, EPJC 84 (2024) 416;
NA61/SHINE 0-10% Xe+La (7.6 GeV), 0-7.2% Pb+Pb (7.6 GeV): NA61 preliminary;
T in NA61 Pb+Pb for $0.8 < y < 1.0$

System size dependence

A+A at 150*A*/158*A* GeV/*c*

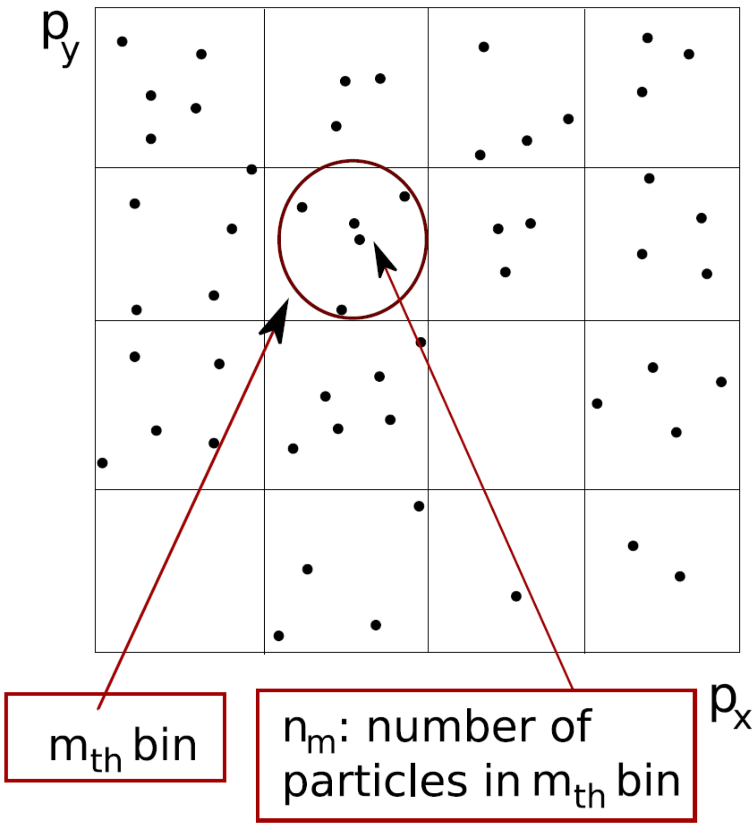


- None of the models reproduces K^+/π^+ and T (y≈0) for the whole ⟨W⟩ range

PHSD: EPJA 56 (2020) 9, 223, arXiv:1908.00451 and private communication
SMASH: JPG 47 (2020) 6, 065101 and private communication
UrQMD and HRG: PRC 99 (2019) 3, 034909
WNM: NPB 111, 461 (1976)

Search for the critical point (intermittency analysis)

Intermittency analysis



The system that freezes out at CP is simply fractal and factorial moments follow a power-law dependence

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

For protons and r=2 ϕ_2=5/6 is expected

Białas, Peschanski, NPB 273 (1986) 703; Wosiek, APPB 19 (1988) 863; Asakawa, Yazaki, NPA 504 (1989) 668; Barducci et al., PLB 231 (1989) 463; Satz, NPB 326 (1989) 613; Antoniou et al., PRL 97 (2006) 032002

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

where ⟨...⟩ denotes averaging over events and,

M^2 is the number of bins

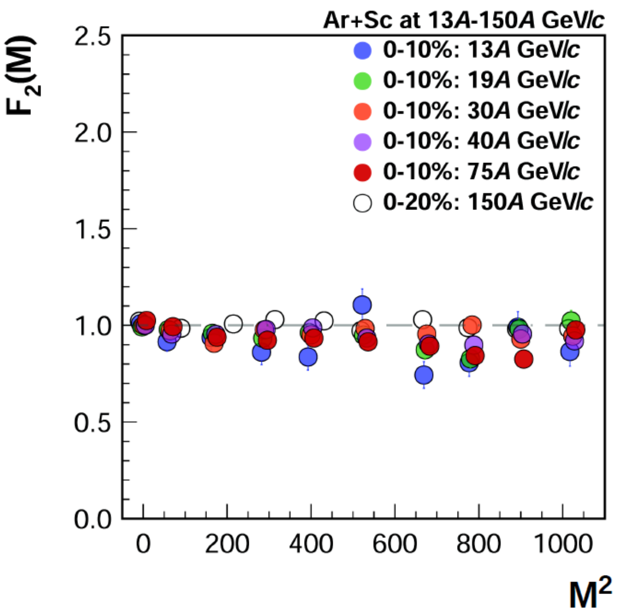
NA61/SHINE intermittency analysis uses:

- Statistically independent points
- Cumulative variables

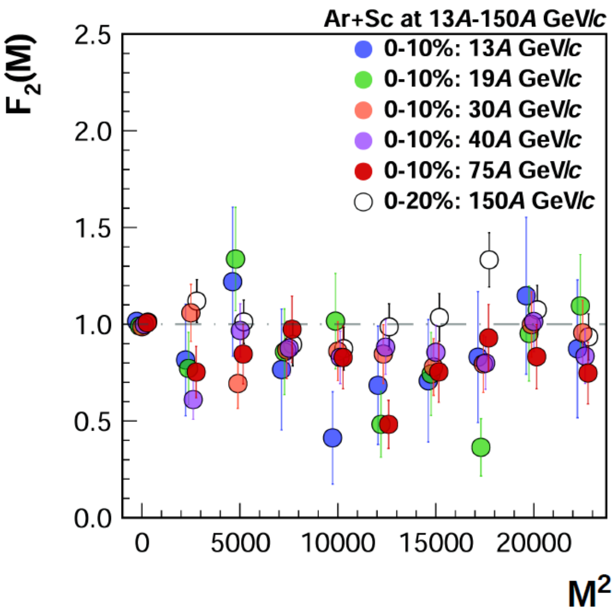
NA61/SHINE, EPJC 83 (2023) 881; Białas, Gazdzicki, PLB 252 (1990) 483

Intermittency of protons - results

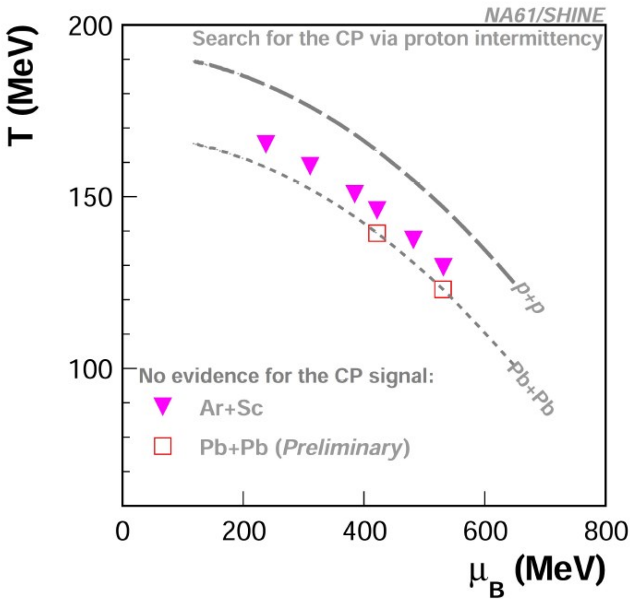
Expected power-law dependence for the system that freezes out at CP



$1^2 \leq M^2 \leq 32^2$



$1^2 \leq M^2 \leq 150^2$

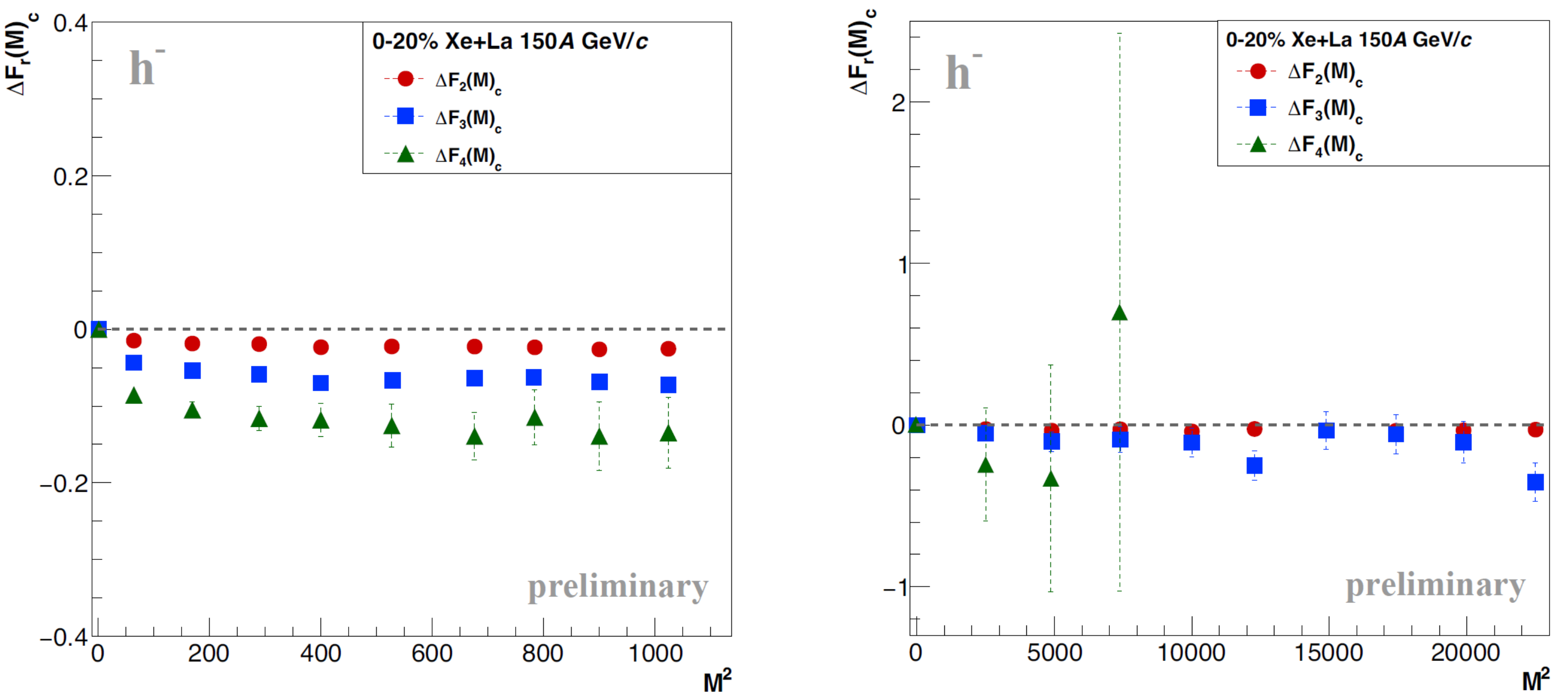


No signal indicating critical point

NA61/SHINE: EPJC 83 (2023) 881, EPJC 84 (2024) 741)

Intermittency of negatively charged hadrons

Cumulative bining, $\Delta F_r(M)_c = F_r(M) - F_r(1)$; $F_r(M) = F_r(1)$ for uncorrelated particles

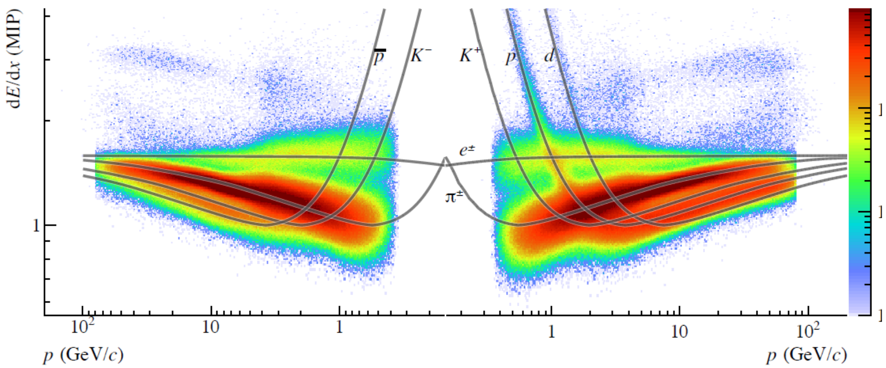


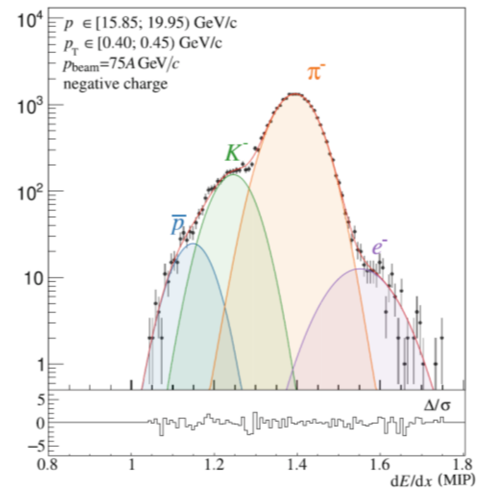
NA61/SHINE: V. Reyna, QM 2025 poster; K. Grebieszkow, QM 2025

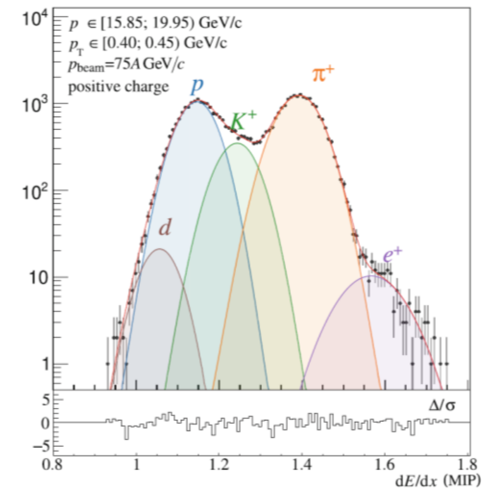
No signal indicating critical point

Excess in charged over neutral kaon production

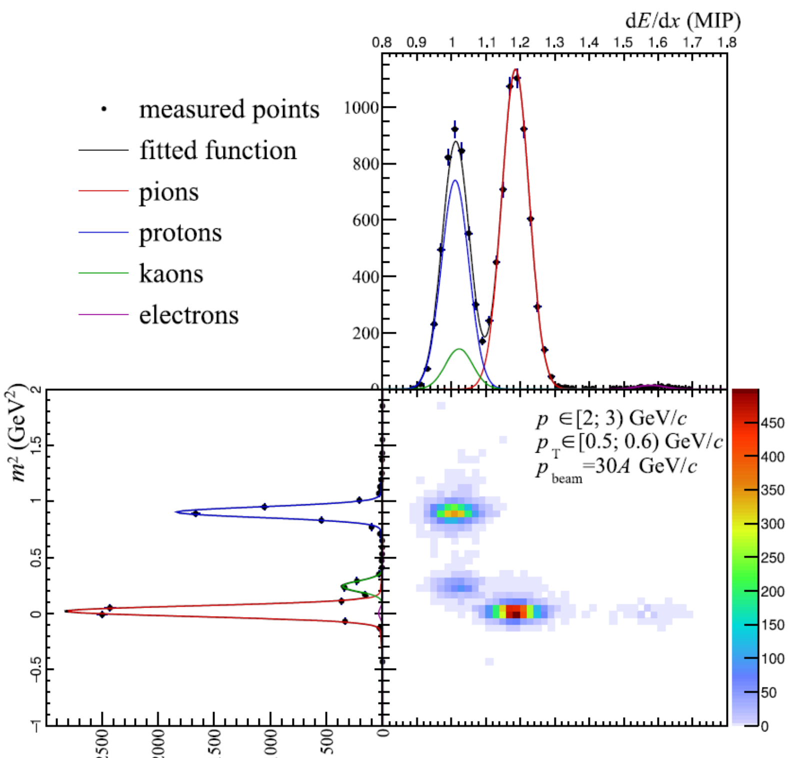
Measurements of K^+, K^- productions







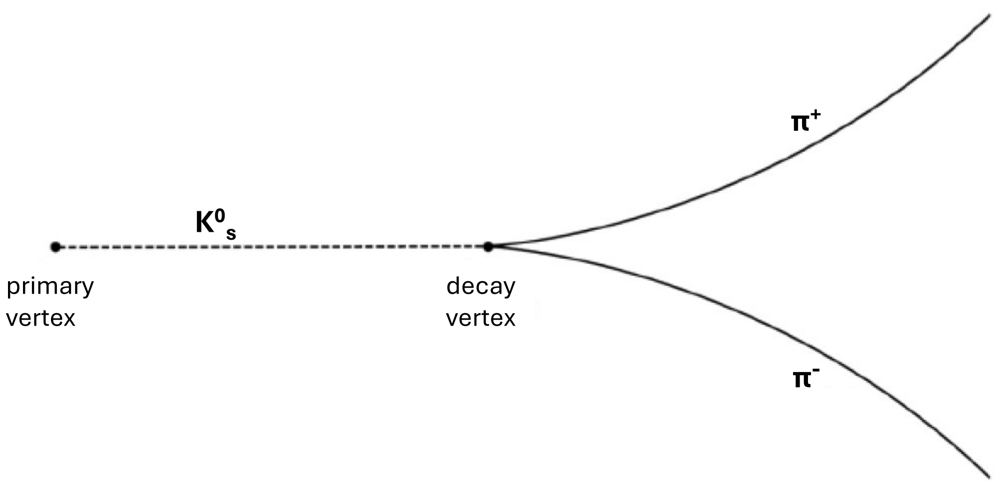
Ar+Sc at 75*A* GeV/*c*

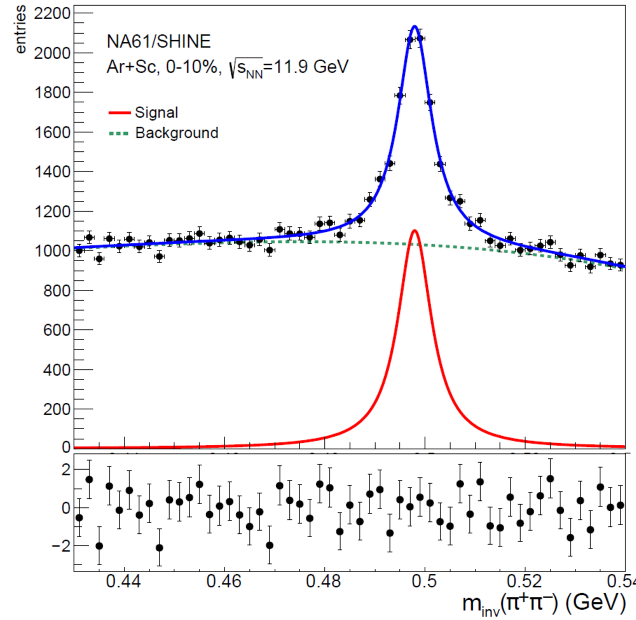


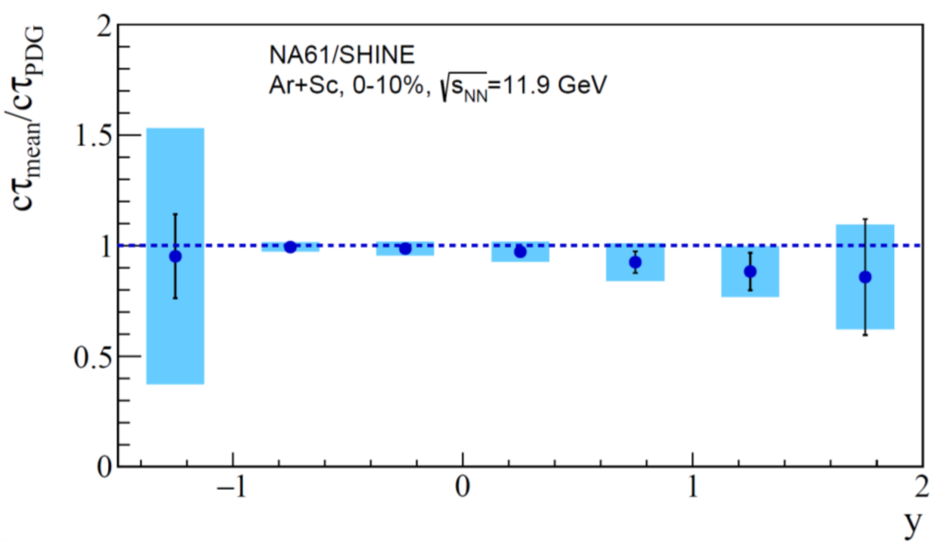
- Measurement based on **dE/dx** and **tof-dE/dx** methods
- Probability method
- Yields corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

NA61/SHINE: EPJC 84 (2024) 416

Measurements of K^0_s production





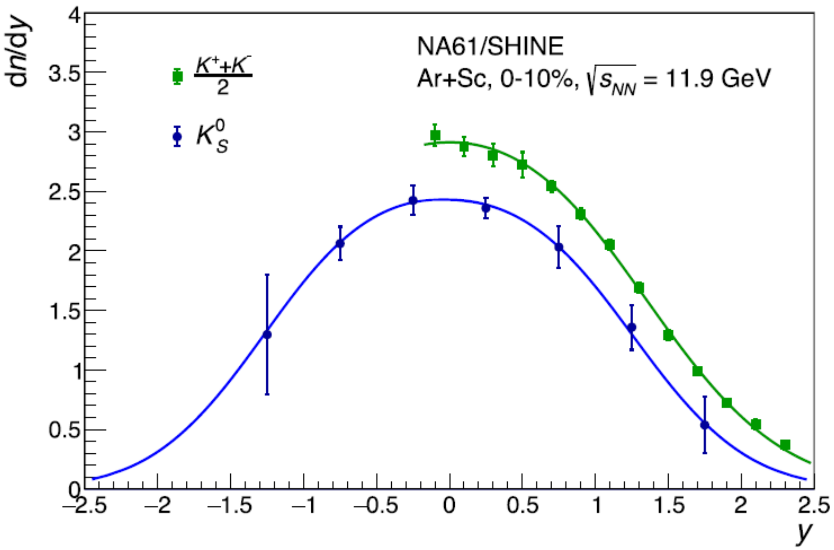


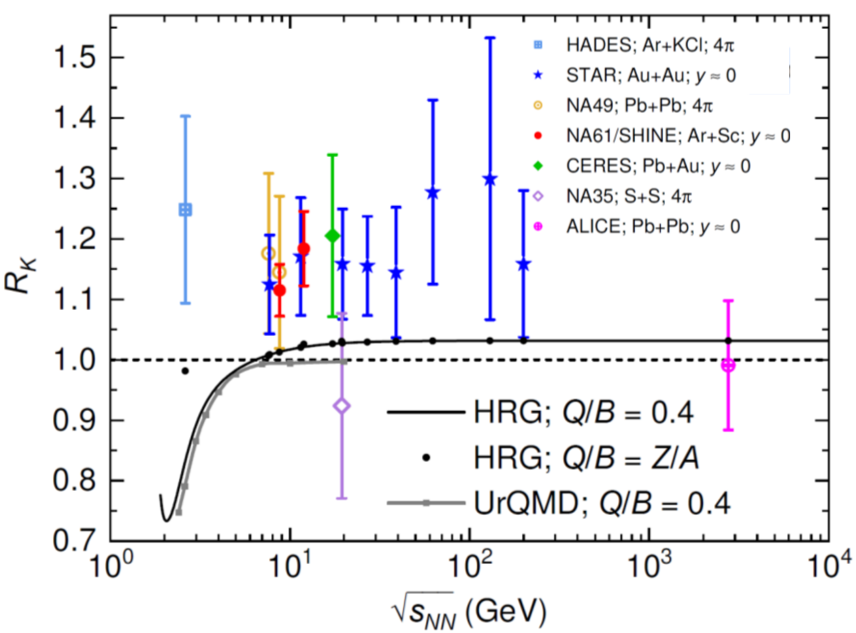
Ar+Sc at 75*A* GeV/*c*

- Reconstruction based on decay topology
- K^0_s decay into π^- and π^+ with BR≈69.2%
- Breit-Wigner function used to describe signal and polynomial function for background

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

Comparison of K^0_s and K^+, K^- productions





Expected from isospin symmetry

$$R_K \equiv \frac{\langle K^+\rangle + \langle K^-\rangle}{\langle K^0\rangle + \langle \overline{K}^0\rangle} = \frac{\langle K^+\rangle + \langle K^-\rangle}{2\langle K^0_S\rangle} = 1$$

NA61/SHINE Ar+Sc at 75*A* GeV/*c*

R_k = 1.184 ± 0.061 at $y \approx 0$

- Excess of charged over neutral *K* mesons observed in the whole *y* and p_T range
- Excess equivalent to about 4 additional charged mesons produced per collision

NA61/SHINE Ar+Sc at 40*A* GeV/*c* ($\sqrt{s_{\rm NN}} = 8.8$ GeV)

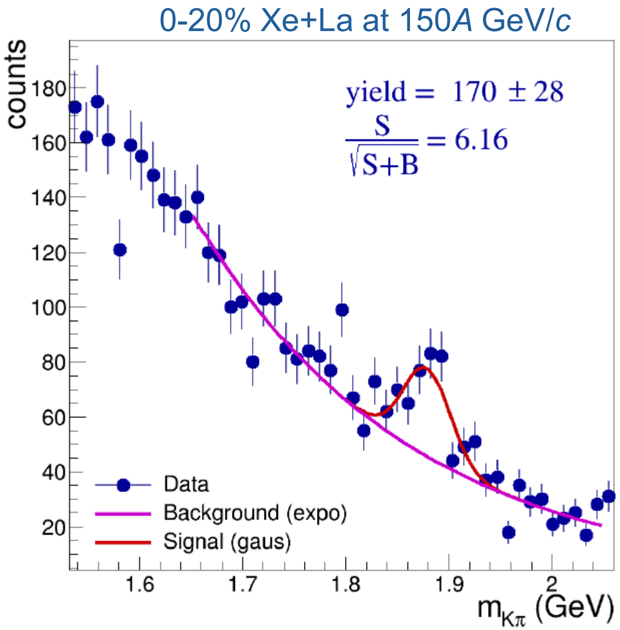
R_k = 1.115 ± 0.043 at $y \approx 0$ preliminary

- World data show an excess on a similar level
- The size of the effect disagrees with model predictions
- 4.7σ (5.3σ with 8.8 GeV point) violation of isospin symmetry beyond known effects

NA61/SHINE: (K^+, K^-) EPJC 84 (2024) 416 , (K^0_s , R_k) Nature Commun. 16 (2025) 1, 2849 THEORY: Nature Commun. 16 (2025) 1, 2849

Direct measurement of open charm

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

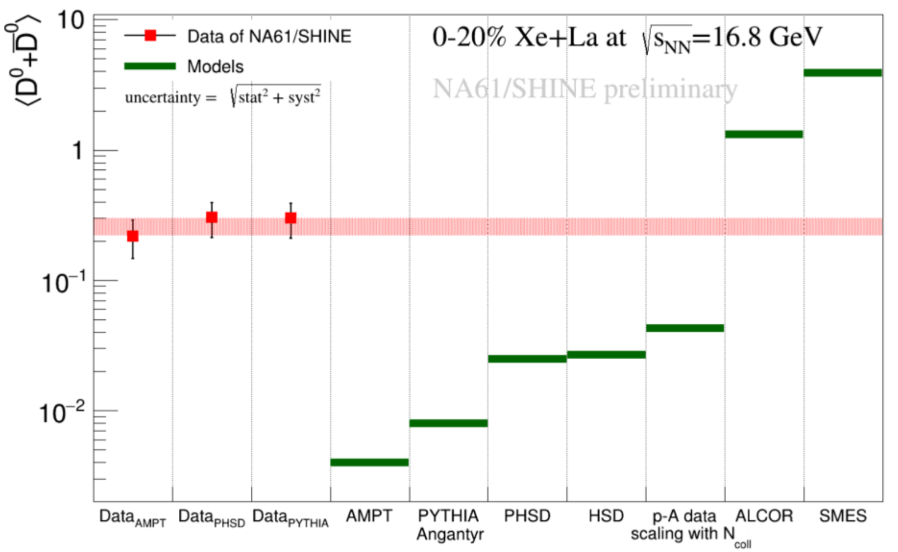


- First-ever direct observation of $D^0+\bar{D}^0$ signal in nucleus-nucleus collisions at the SPS energies
- Corrections by GEANT4 simulations with 3 models AMPT, PHSD, Pythia/Angantyr
- Precise data to discriminate against various model predictions
- New Pb+Pb events (2022–2024) under analysis

$-0.5 < y < 1.0$
$0.2 < p_T < 2.0$ 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)

→

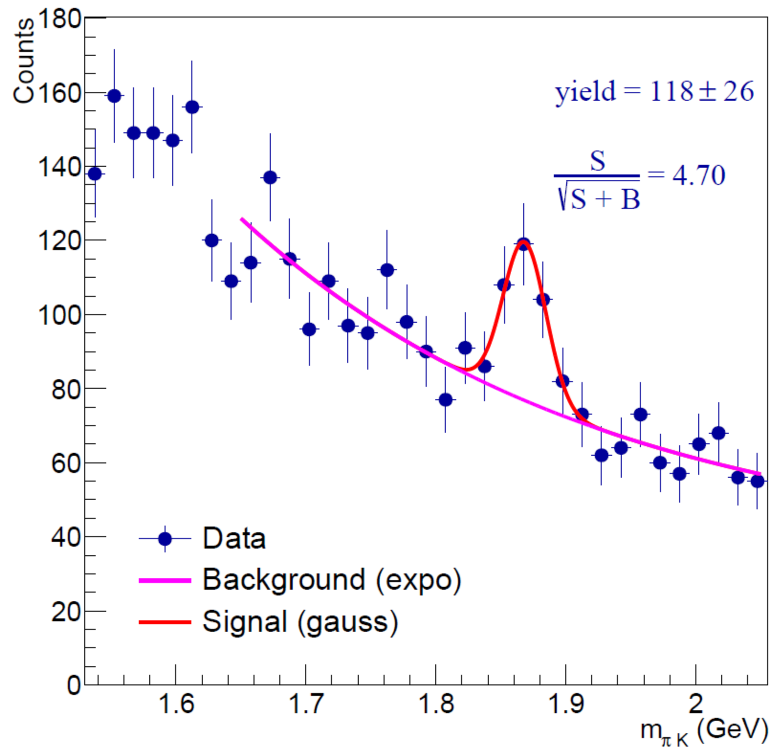


NA61/SHINE: M. Bajda, QM 2025 poster

$D^0+\bar{D}^0$ measurement in minimum-bias Pb+Pb collisions

- Upgraded Vertex Detector with modern ALPIDE sensors used
- Twice increased geometrical acceptance, 10 times higher read-out rate and higher radiation resistance
- Confirmation of the ability to identify charm hadron decays using pilot 2022 Pb+Pb collisions at 150*A* GeV/*c*
- Ongoing analysis based on high-statistics datasets collected 2022–2024

2022 pilot Pb+Pb at 150*A* GeV/*c*



NA61/SHINE: M. Bajda, QM 2025 poster

Summary and plans

Summary

- Unique 2D scan in collision energy and system size completed
- New preliminary results from Xe+La, Pb+Pb data released
- System size dependence found: (p+p ≈ Be+Be) < Ar+Sc < Xe+La < Pb+Pb
- So far no indication of the critical point
- Excess of charged over neutral *K* meson production in Ar+Sc collisions at 75*A* GeV/*c* and 40*A* GeV/*c* observed
- 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 (after LS3)
- Isospin-symmetry violation mesurements in π^++C, π^-+C collisions collected in 2024 and a pilot O+O data measured in 2025

Thank you
for your attention