Recent results from NA61/SHINE strong interaction program

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Outline

- Introduction
- Onset of deconfinement and onset of fireball
- Anomaly in charged over neutral kaon production ratio
- Search for the critical point – intermittency analysis
- Direct measurement of open charm
- Summary and plans

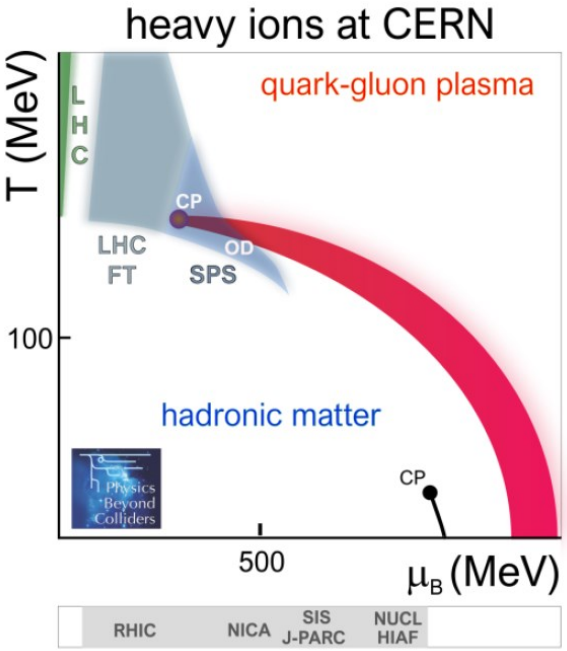
NA61/SHINE physics program

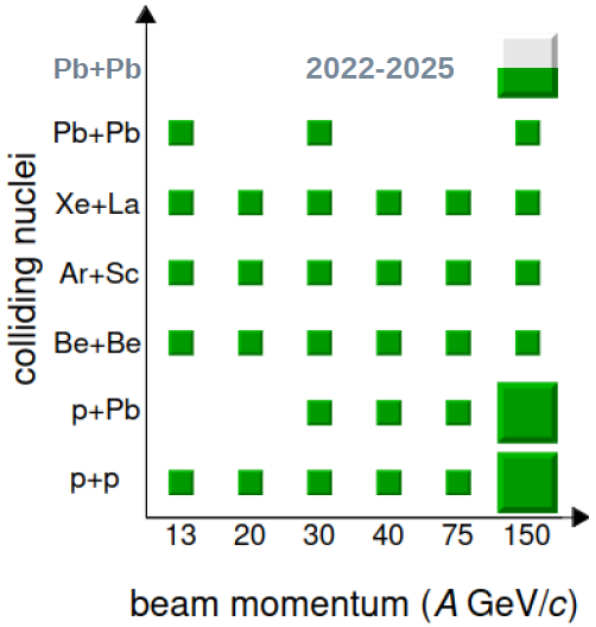
Strong interaction physics:

- 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:

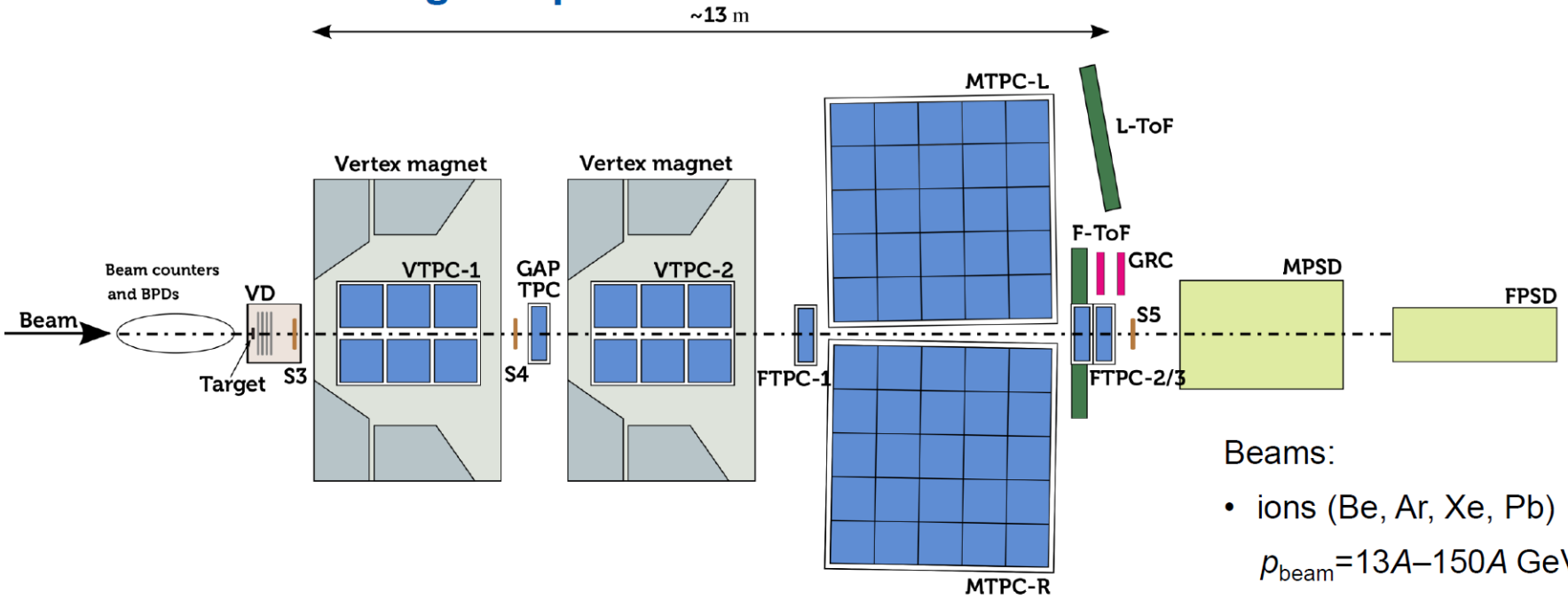
- measurements for neutrino programs at J-PARC and Fermilab
- measurements of hadron production and nuclear fragmentation cross section for cosmic-ray physics





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

- 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**

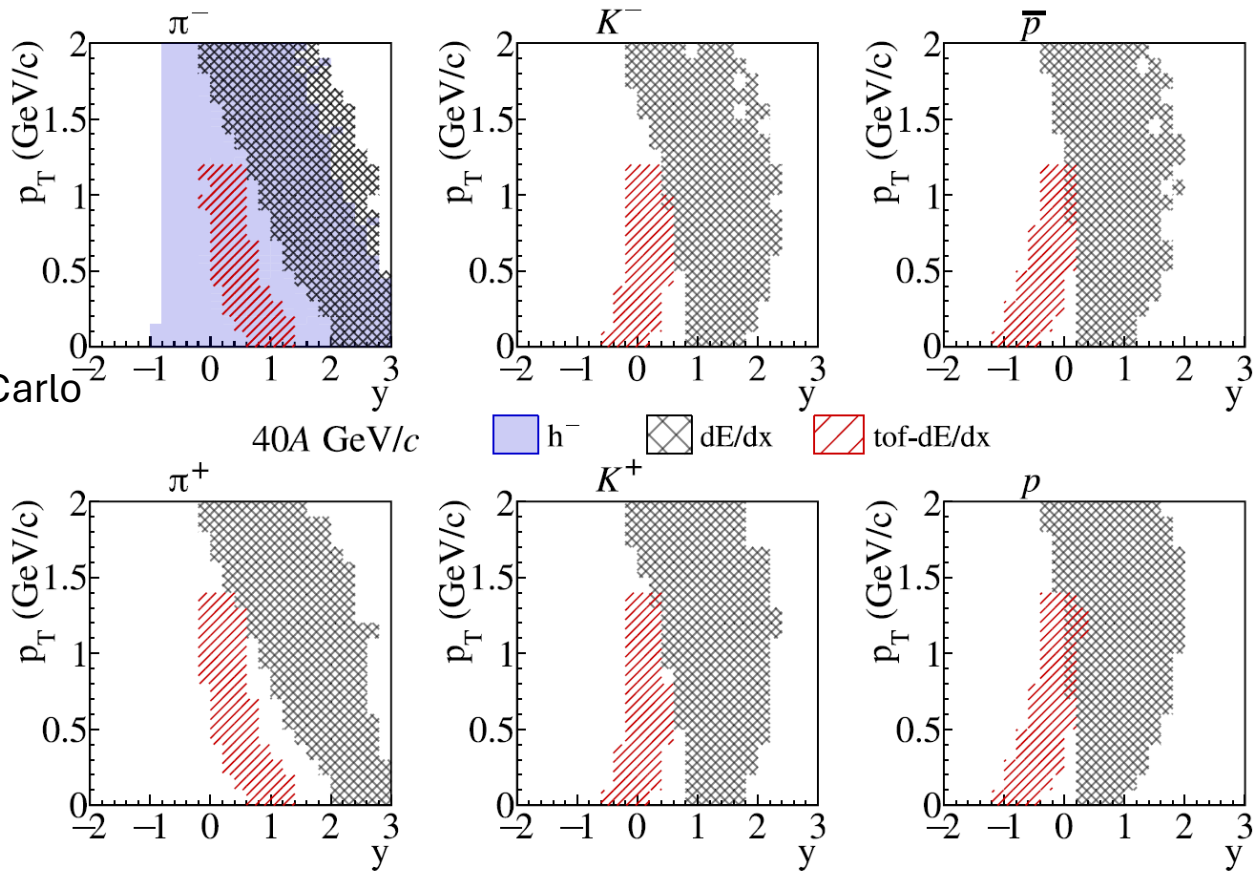
A method based on the fact that the majority of negatively charged particles are π^- mesons
The contribution of other particles is subtracted using EPOS Monte- Carlo

- **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

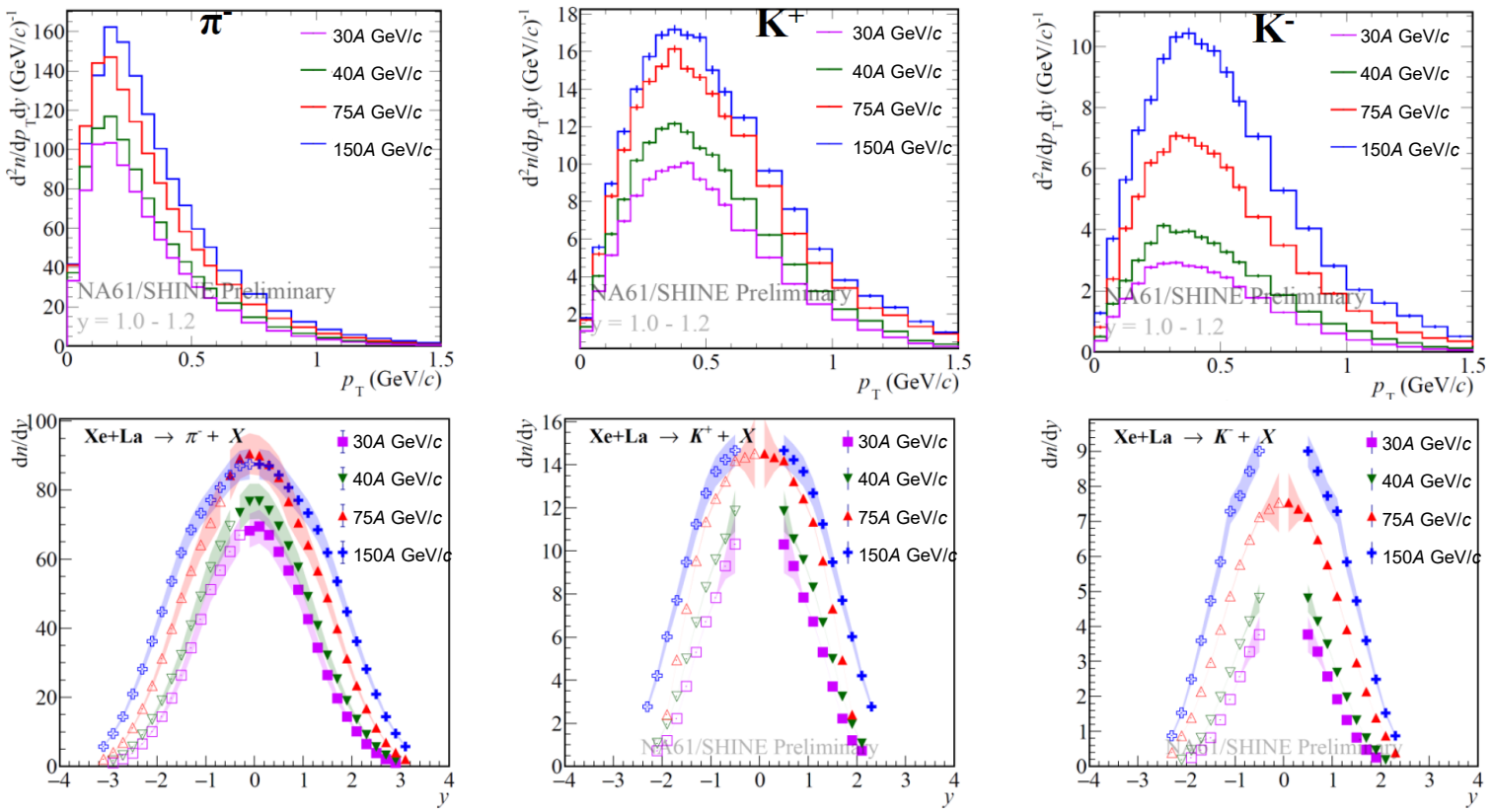


0-10% Ar+Sc at 40*A* GeV/*c*

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

Onset of deconfinement
and
onset of fireball

Spectra

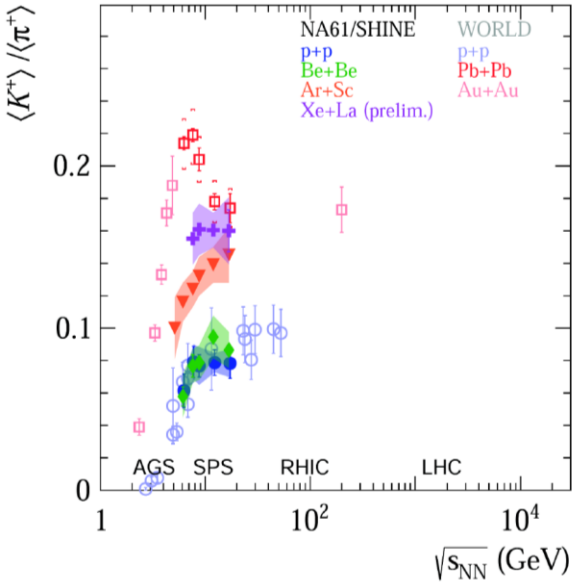


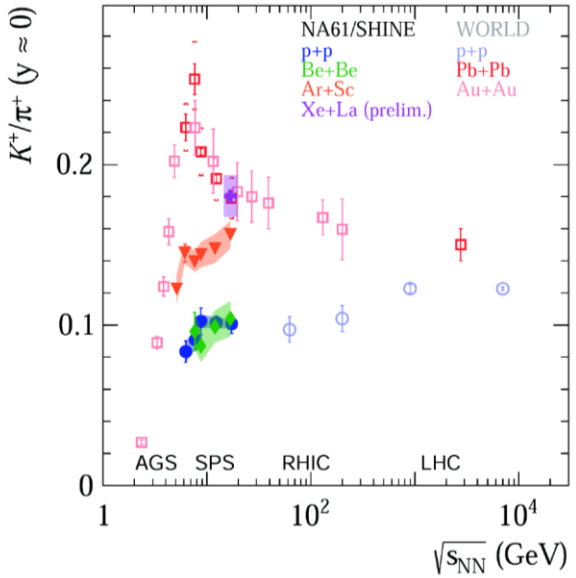
- New preliminary y, p_T spectra of π^- and $K^{\pm}$
- 10% most central Xe+La collisions at 30*A*, 40*A*, 75*A* GeV/*c*
- 20% most central Xe+La collisions at 150*A* GeV/*c*
- Spectra obtained by h^- and dE/dx methods

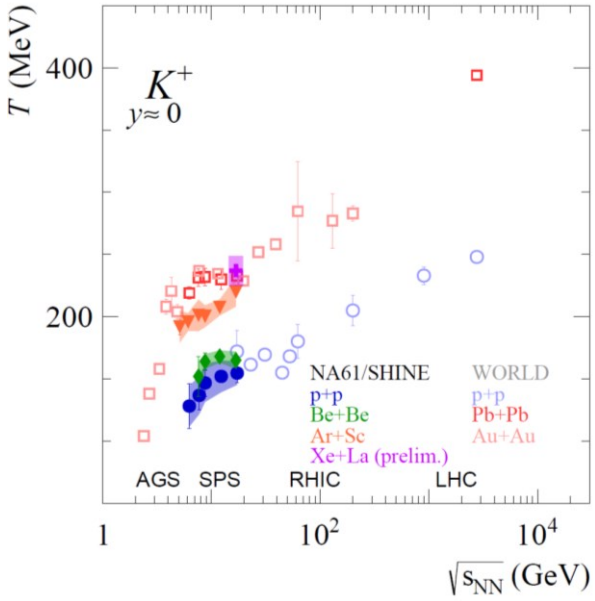
NA61/SHINE: O.Panova, SQM 2024 poster

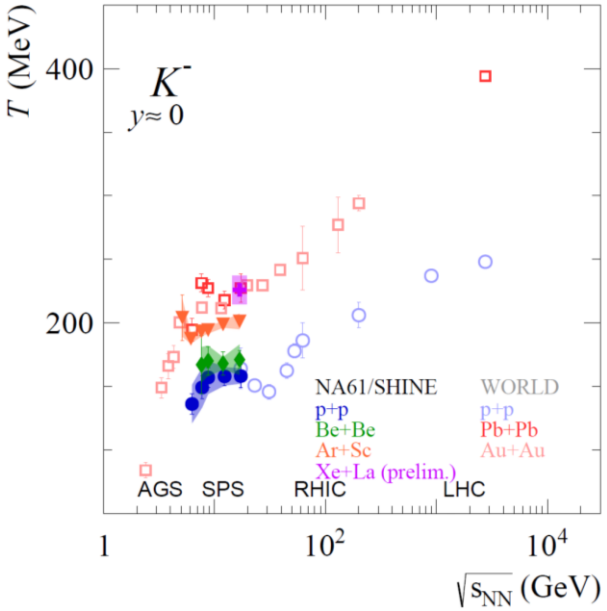
Energy dependence: horn and step

NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416, O.Panova, SQM 2024 poster









Horn

A measure of strangeness to entropy ratio with 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

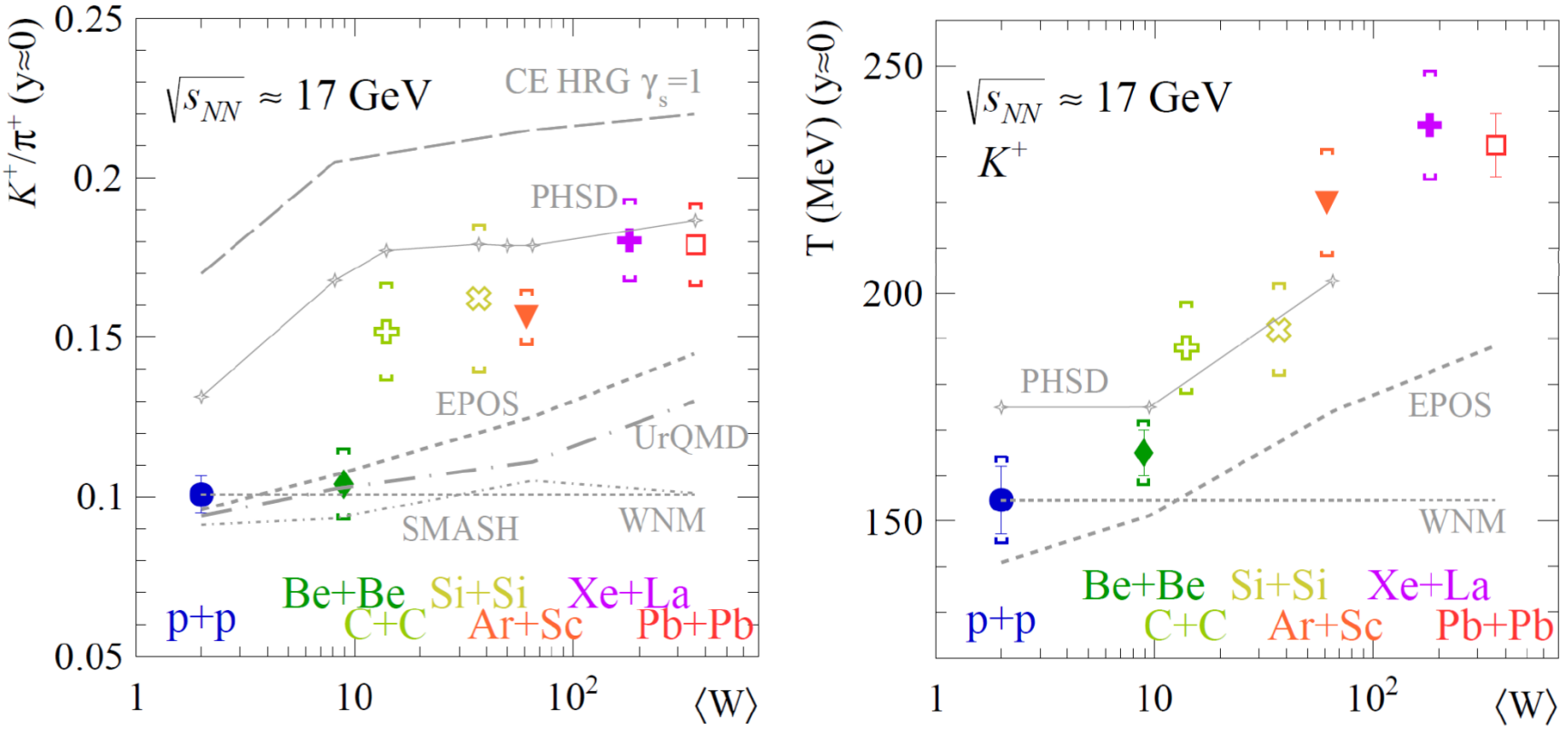
T reflects the thermal freeze-out temperature and the radial flow velocity

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

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



- Increase of K^+/π^+ , T (y≈0) with system size

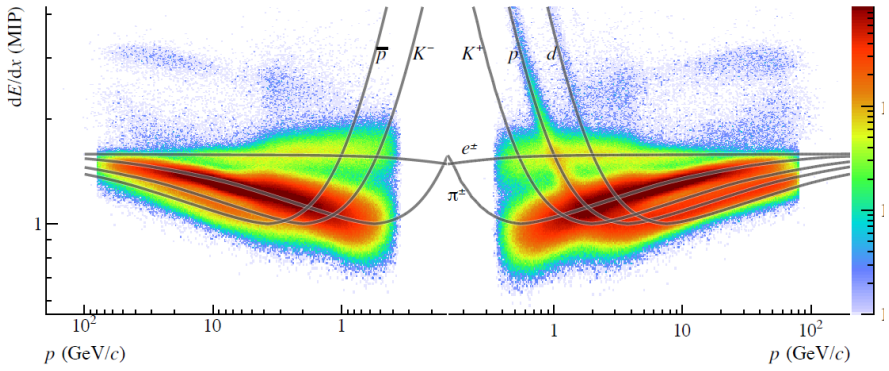
  (p+p ≈ Be+Be) < Ar+Sc < (Xe+La ≈ Pb+Pb)

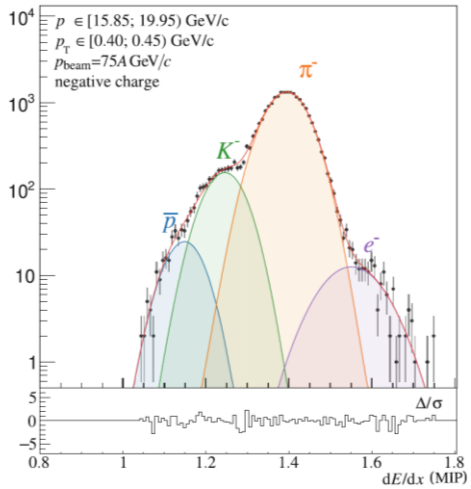
- None of the models reproduces K^+/π^+ and T (y≈0) for the whole ⟨W⟩ range

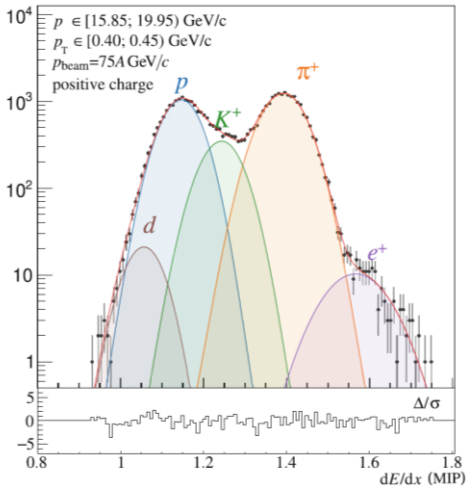
PHSD: EPJA 56 (2020) 9,223, arXiv:1908.00451 and private communication
SMASH: JPG 47 (2020) 6, 065101 and private communication
UrQMD and HRG: PRC 99 (2019) 3, 034909
WNM: NPB 111, 461 (1976)

Anomaly in charged over neutral kaon production

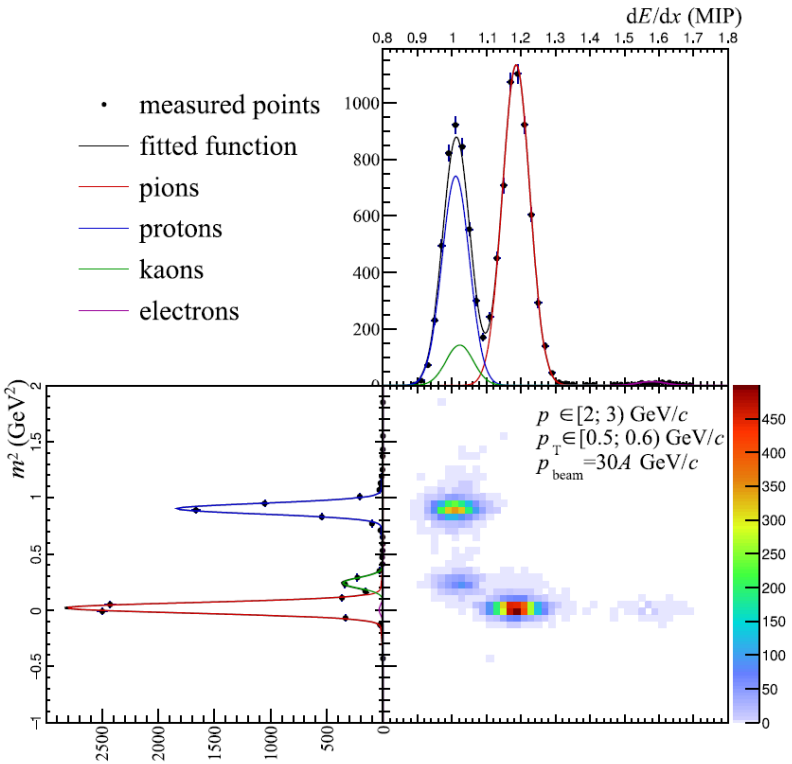
Measurements of K^+, K^- productions







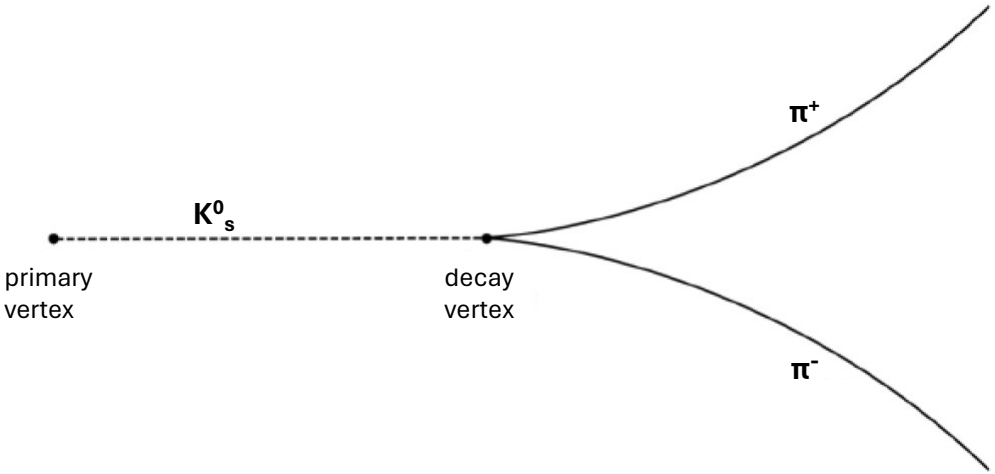
Ar+Sc at 75*A* GeV/*c*

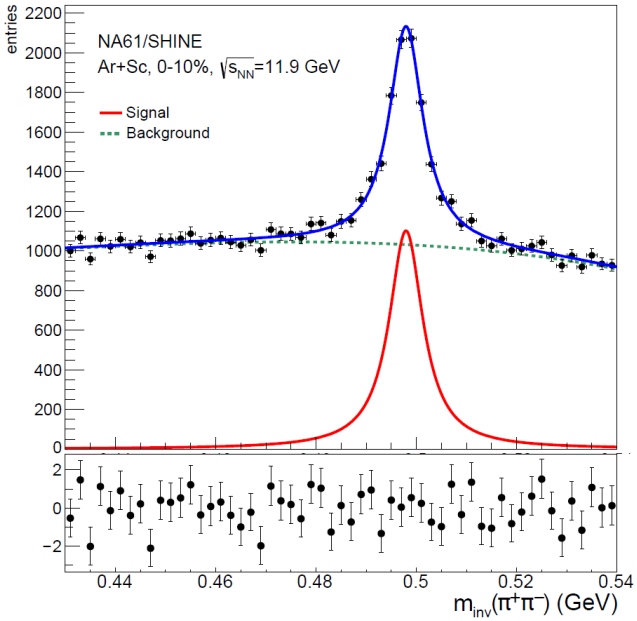


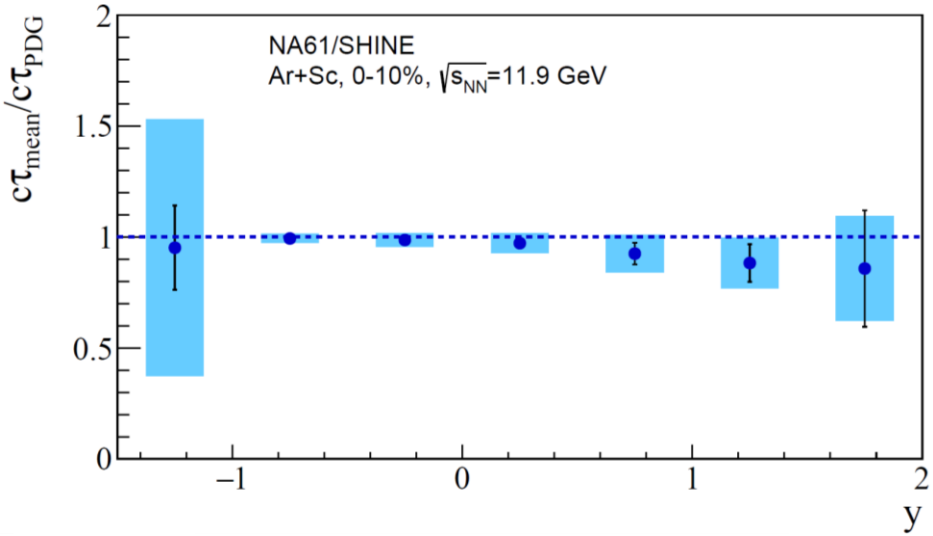
- Measurement based on **dE/dx** and **tof-dE/dx** methods
- Probability method
- Yields corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

NA61/SHINE: EPJC 84 (2024) 416

Measurements of K^0_s production





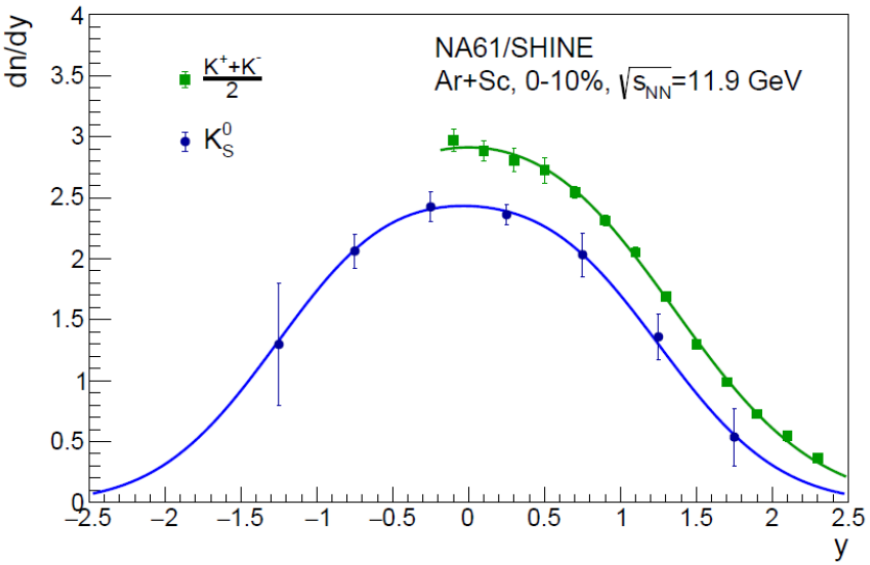


Ar+Sc at 75*A* GeV/*c*

- 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

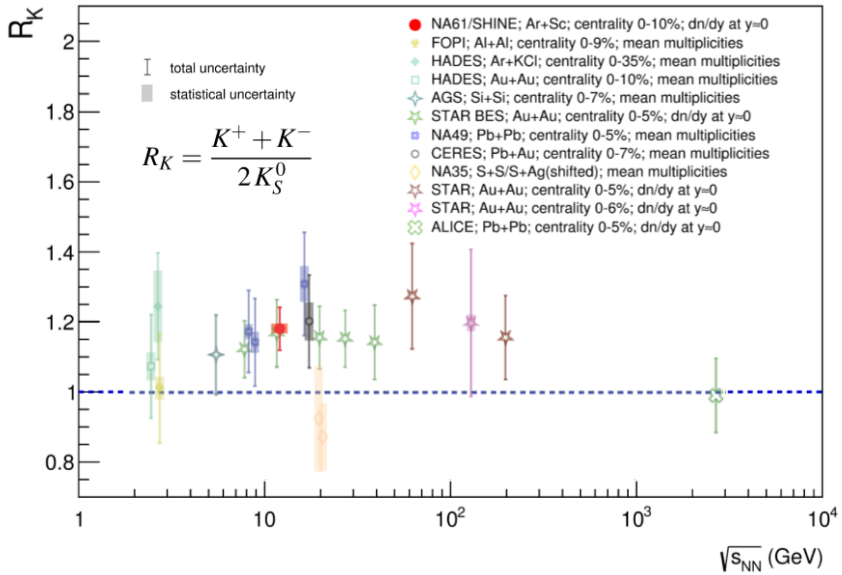
NA61/SHINE: arXiv:2312.06572

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



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

$R_k = 1.184 \pm 0.061$ at $y \approx 0$



R_K significantly higher than 1

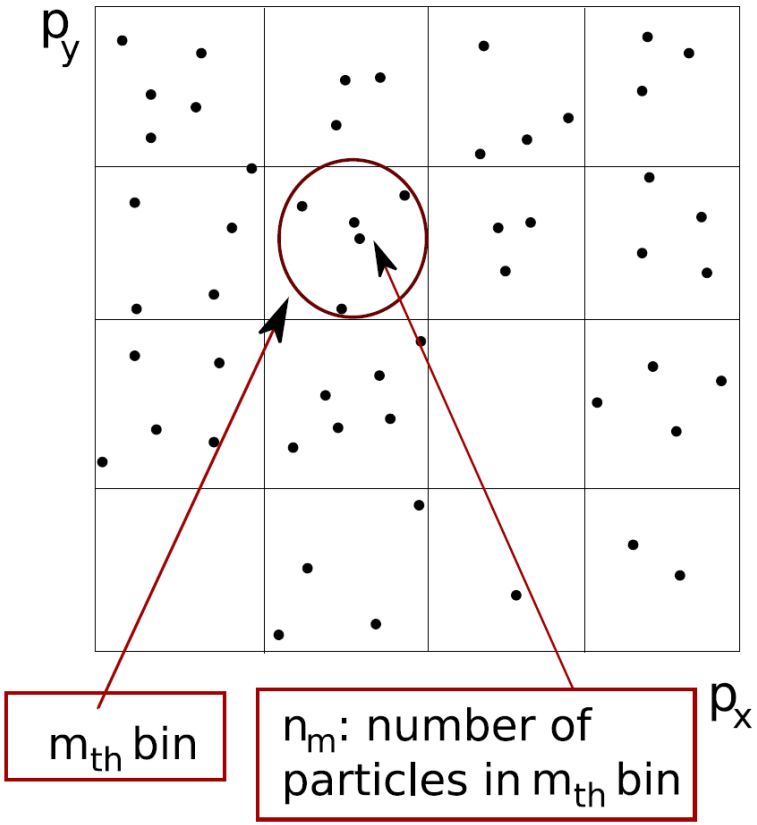
- Excess of charged over neutral K mesons observed in the whole y and p_T range
- Excess equivalent to about 4 additional charged mesons produced per collision
- World data show excess on a similar level
- The size of effect disagrees with the theoretical expectations and statistical model predictions

NA61/SHINE: (K^+, K^-) EPJC 84 (2024) 416 , (K^0_s) arXiv:2312.06572

THEORY: arXiv:2312.07176

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,

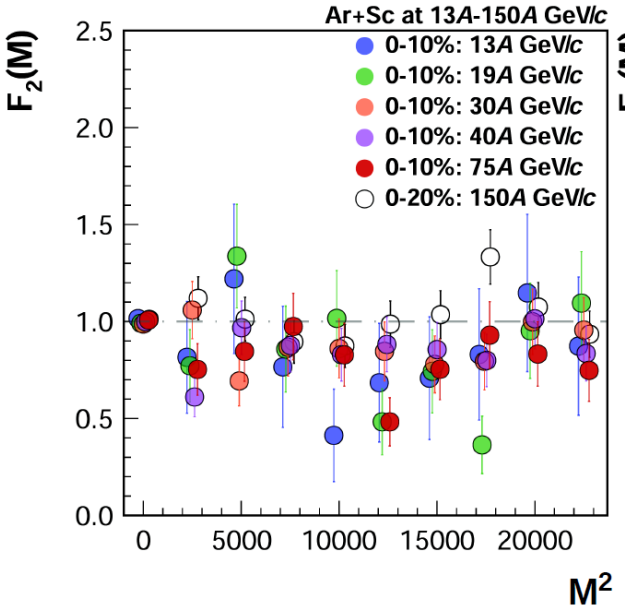
M^2 is the number of bins

NA61/SHINE intermittency analysis uses:

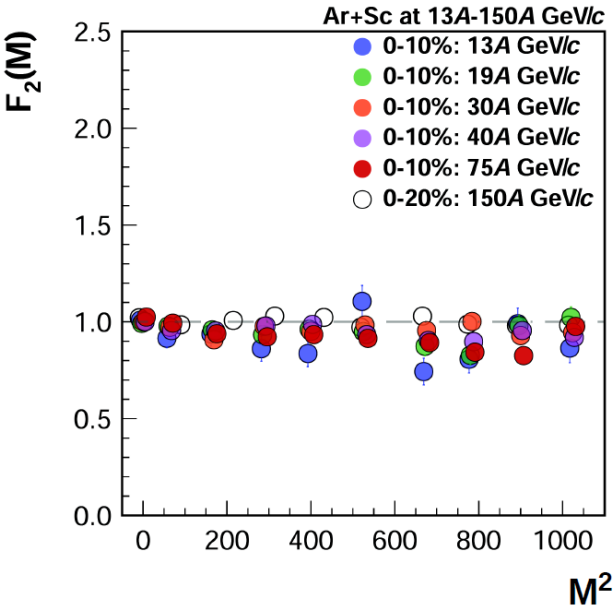
- Statistically independent points
- Cumulative variables

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

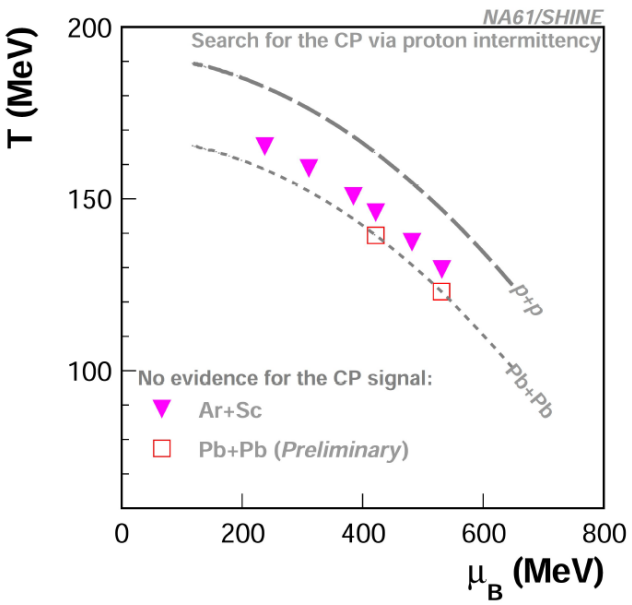
Intermittency of protons - results



$1^2 \le M^2 \le 150^2$



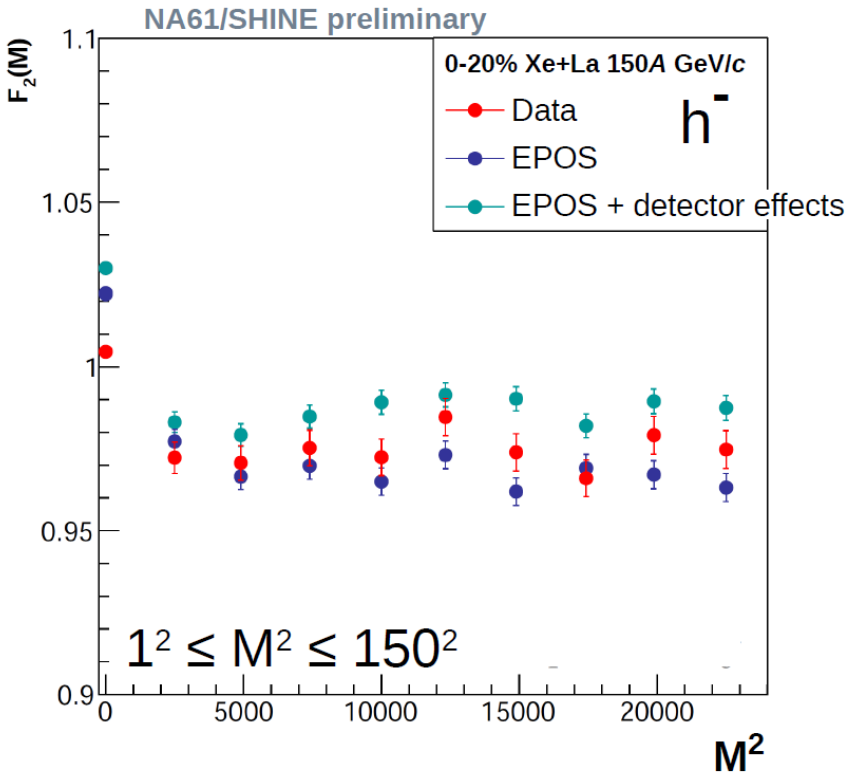
$1^2 \le M^2 \le 32^2$

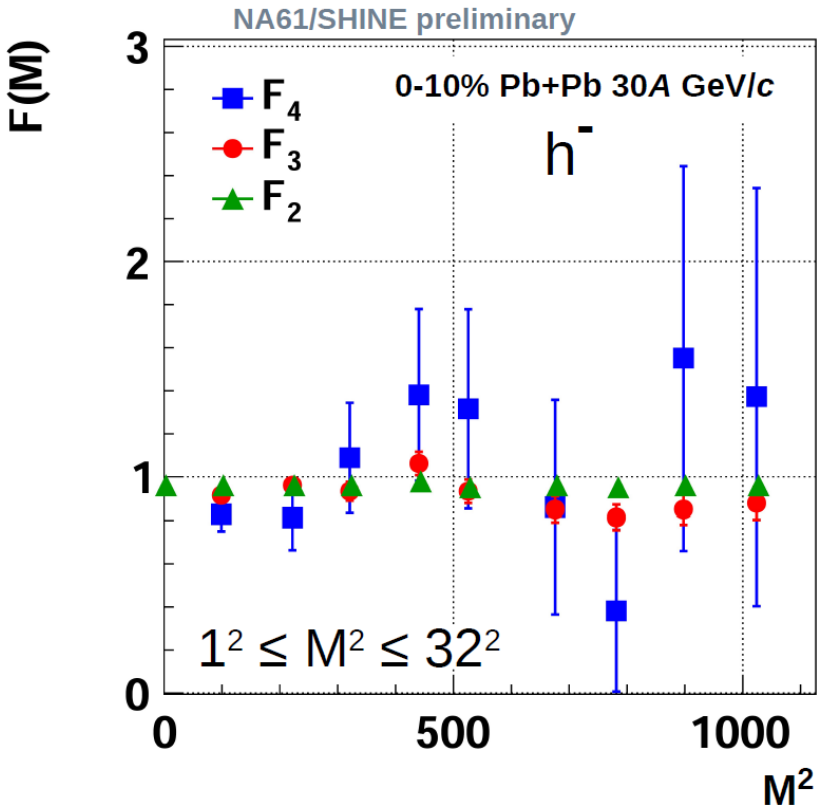


No signal indicating critical point

NA61/SHINE: EPJC 83 (2023) 881, arXiv:2401.03445 (accepted by EPJC)

Intermittency of negatively charged hadrons - results



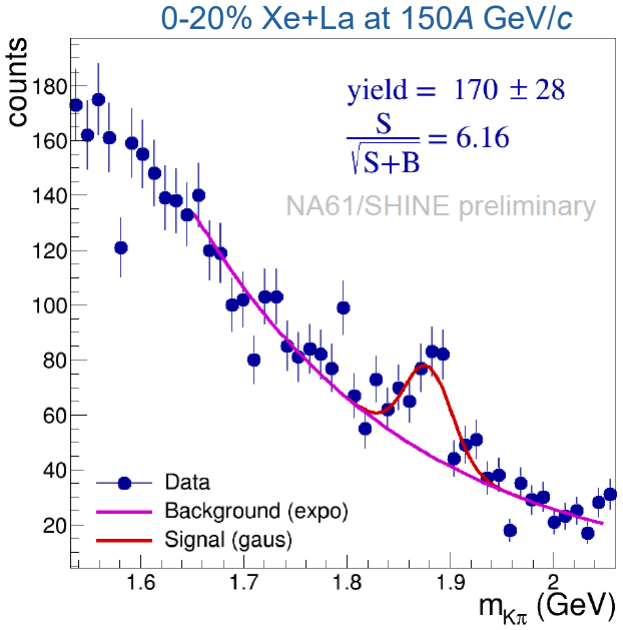


No signal indicating critical point

NA61/SHINE: A.Rybicki, SQM 2024 talk

Direct measurement of open charm

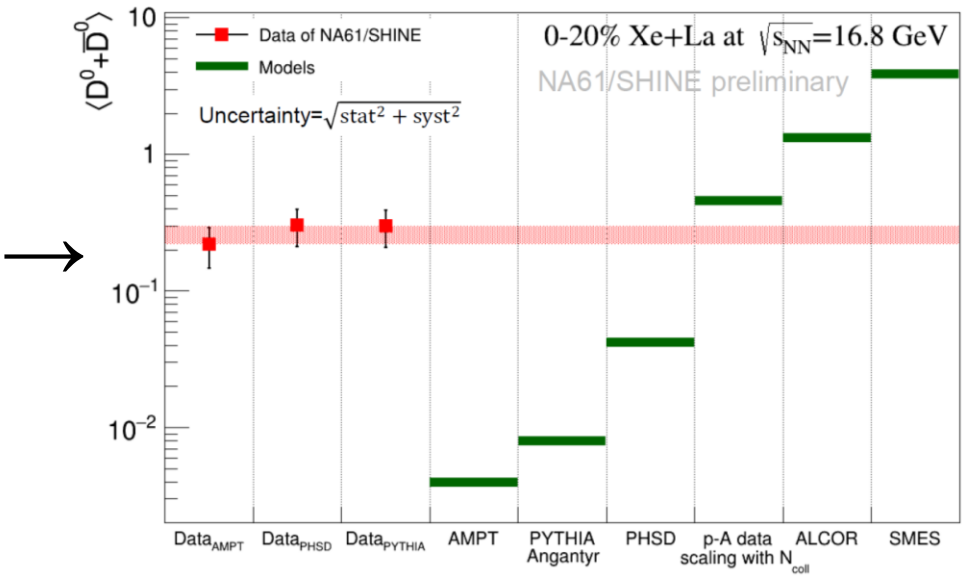
$D^0+\bar{D}^0$ measurement in central Xe+La collisions



- First-ever direct observation of $D^0+\bar{D}^0$ signal 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

$-0.5 < y < 1.0$
$0.2 < p_T < 2.0$ 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: A.Merzlaya, SQM 2024 talk

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 75*A* 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

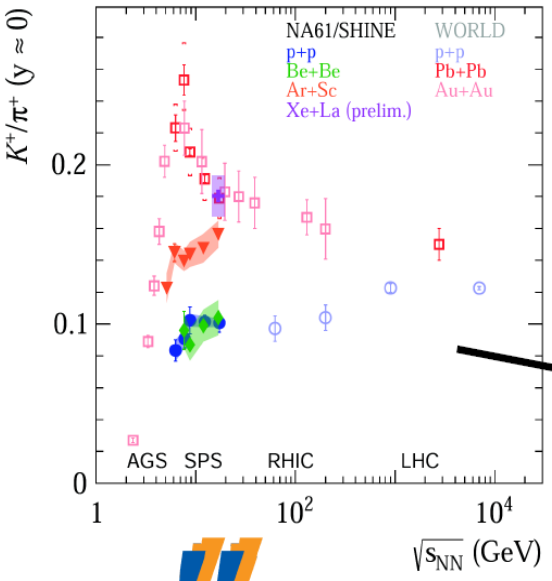
Plans

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

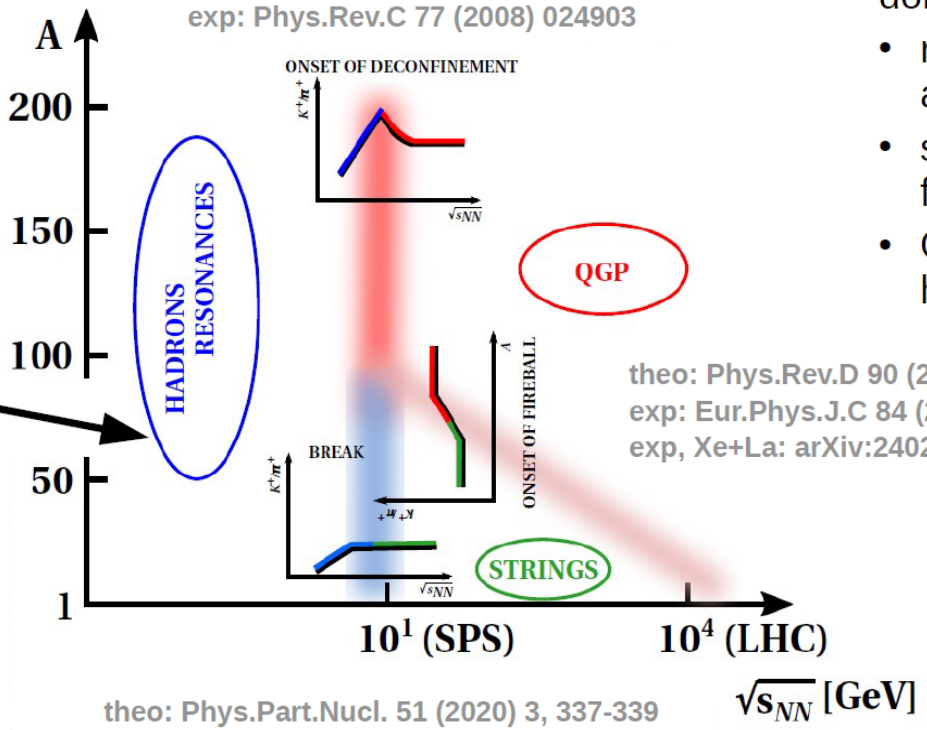
Thank you
for your attention

Extra slides

Diagram of high-energy nuclear collisions



theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77 (2008) 024903

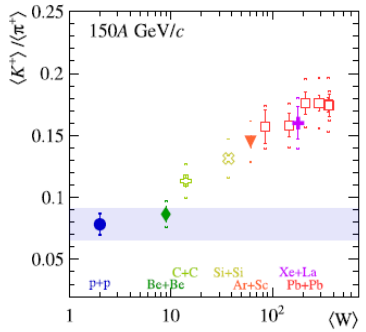


theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Hypothetical domains of hadron production, dominated by:

- resonance creation and decay
- string creation and fragmentation
- QGP formation and hadronisation

theo: Phys.Rev.D 90 (2014) 2, 025031
exp: Eur.Phys.J.C 84 (2024) 4, 416
exp, Xe+La: arXiv:2402.10973 [nucl-ex]



Isospin asymmetry - Kaons

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

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: $\langle K^+ + K^- \rangle > \langle K^0 + \overline{K^0} \rangle$

Indication of violation of isospin symmetry

↓

(unexpected violation of flavour symmetry between u and d quarks)

- Ar, Sc nuclei are nearly isospin-symmetric (valence **u** ≈ **d** within 6%)
- We expect:

$K^+ (u\,\bar{s}) \approx K^0 (d\,\bar{s})$ $\quad u \leftrightarrow d$

$K^- (\bar{u}\,s) \approx \overline{K^0} (\bar{d}\,s)$ $\quad \bar{u} \leftrightarrow \bar{d}$

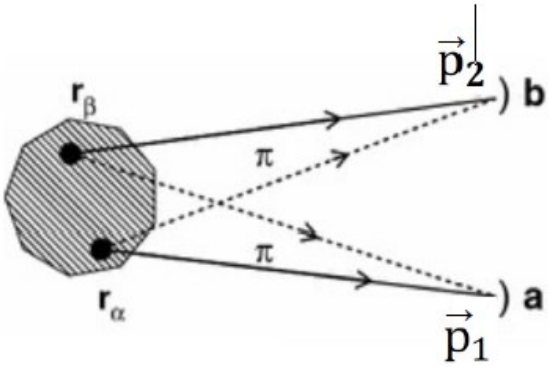
$$\frac{K^+ + K^-}{2} \approx \frac{K^0 + \overline{K^0}}{2} = K^0_S$$

| neglecting CP violation

- Data - excess of charged over neutral kaons:

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

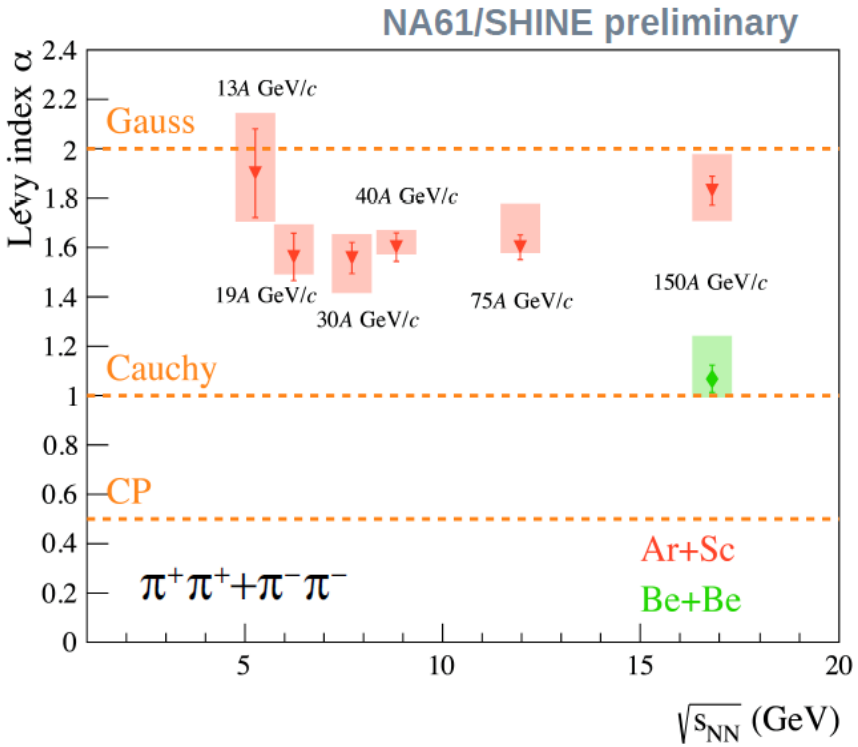
Search for critical point - femtoscopy



Lévy source:

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

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



- Bose-Einstein correlations (femtoscopy) reveal the space-time structure of hadron production
- The Lévy parameter α describes the shape of the source and is sensitive to the system freezing out at the CP

Csörgő, Hegyi, Novák, Zajc, AIP Conf. Proc. 828 (2006) 525

- The new Ar+Sc results are close to Gaussian, and **far from the CP**

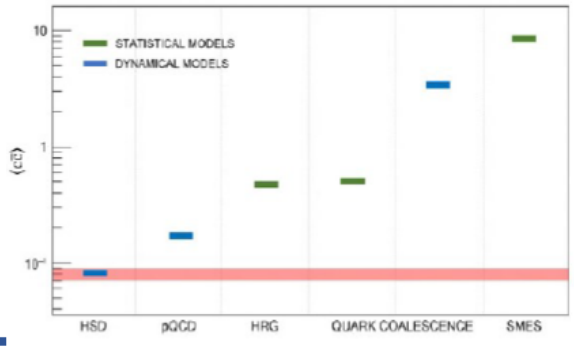
Ar+Sc, 0-10% central, NA61/SHINE preliminary
Be+Be, 0-20% central, NA61/SHINE, EPJC 83 (2023) 919

Open charm measurements – NA61/SHINE program

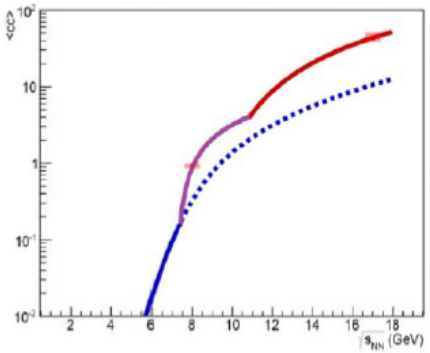
- **What is the mechanism of open charm production?**
- **How does the onset of deconfinement impact open charm production?**
- **How does the formation of quark gluon plasma impact J/ψ production?**

To answer these questions **mean number of charm quark pairs,** $\langle c\bar{c}\rangle$, produced in A+A collisions has to be known. Up to now corresponding experimental **data does not exist** and **only NA61/SHINE can perform this measurement in the near future**.

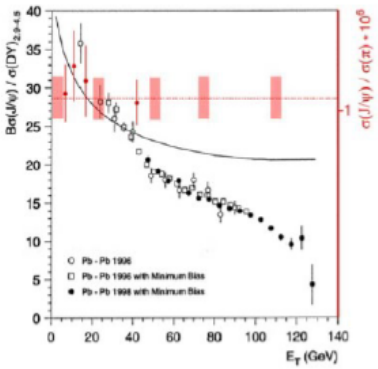
$\langle c\bar{c}\rangle$ and models



$\langle c\bar{c}\rangle$ and onset of deconfinement



$\langle c\bar{c}\rangle$, $\langle J/\psi\rangle$ and QGP



Foreseen NA61/SHINE resolution is sufficient to answer addressed questions

SPSC-P-330-ADD-10