

NA61/SHINE Overview

highlights on ion program since last Quark Matter in Cracow

Piotr Podlaski

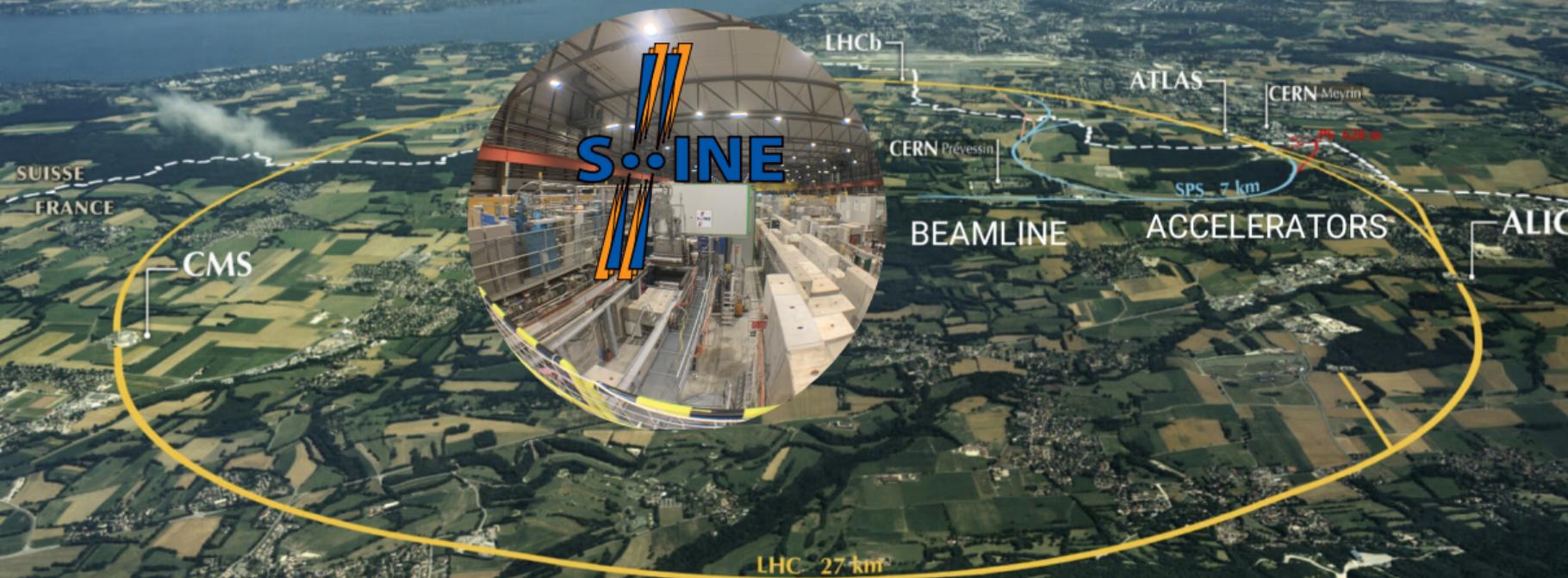
for the NA61/SHINE Collaboration

Faculty of Physics, University of Warsaw

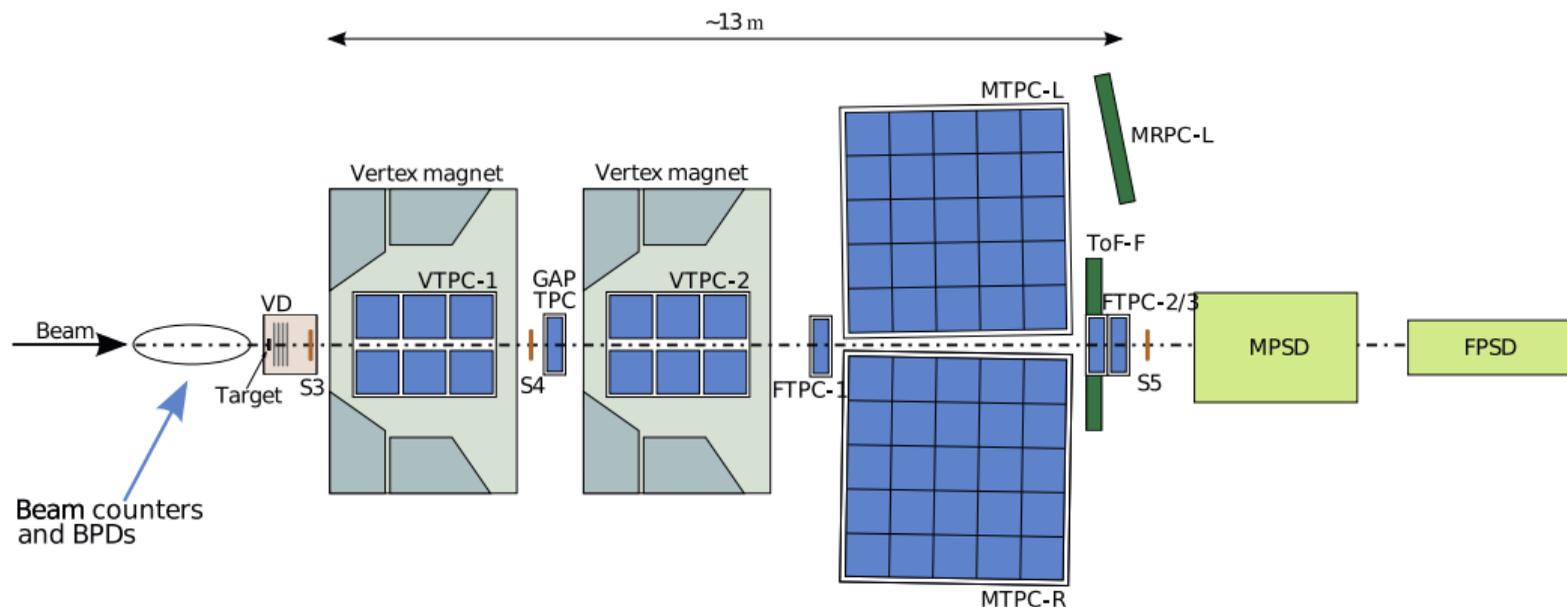
Quark Matter 2023

3-9 September 2023

NA6I/SHINE - UNIQUE MULTIPURPOSE FACILITY: Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies



coverage of the full forward hemisphere, down to $p_T = 0$



- ion beams (Pb and others)
 $p_{beam} = 13A - 150A \text{ GeV}/c$

$$\sqrt{s_{NN}} = 5.1 - 16.8(27.4) \text{ GeV}$$

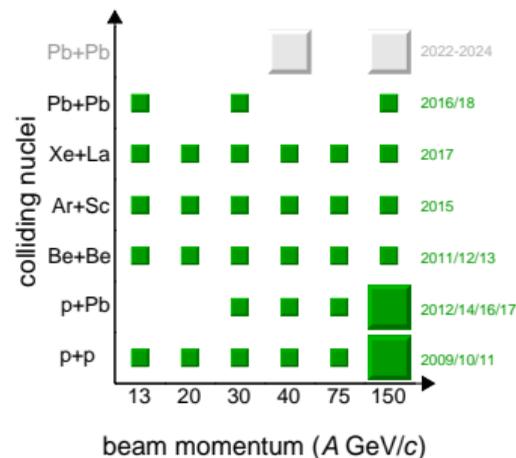
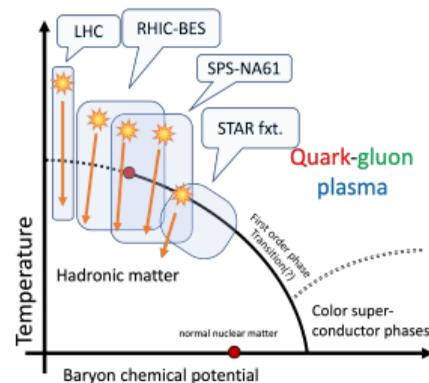
- hadron beams (p, π, K)
 $p_{beam} = 13 - 400 \text{ GeV}/c$

Strong interaction physics:

- study properties of the **onsets of deconfinement and fireball**
- search for the **critical point** of strongly interacting matter
- direct measurements of **open charm**

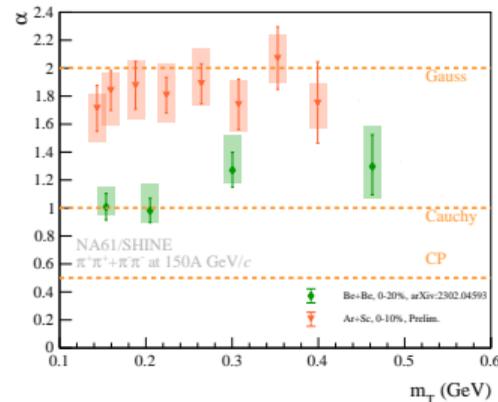
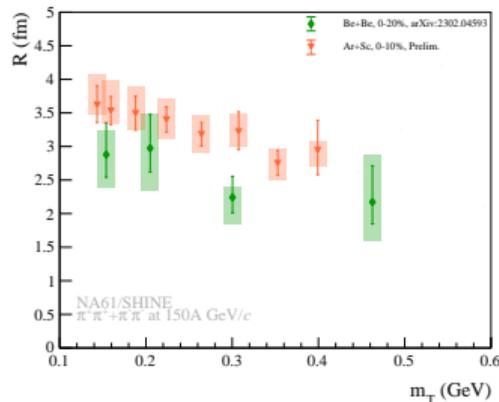
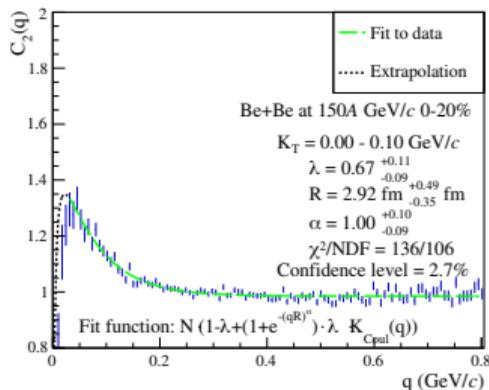
Neutrino and cosmic ray physics:

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

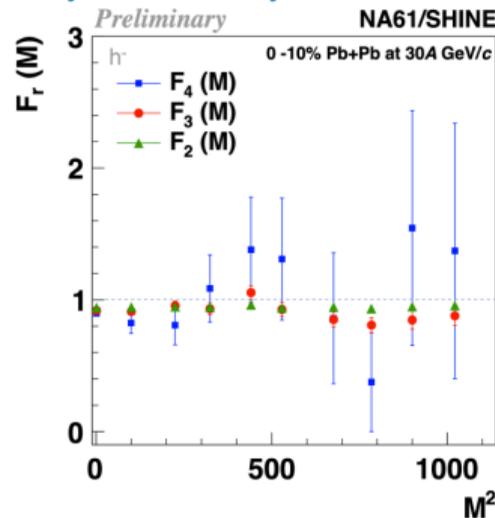
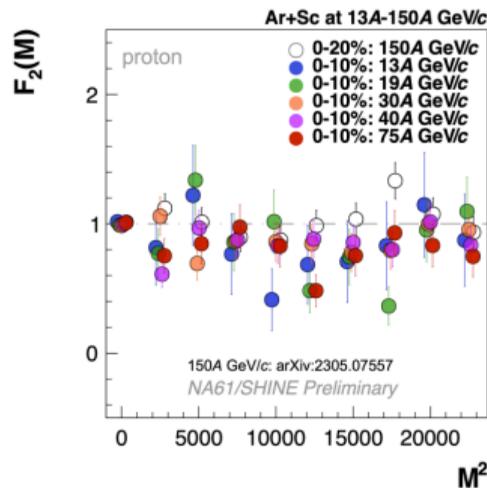
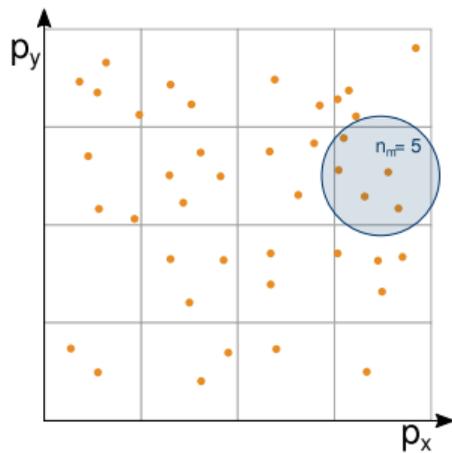




Search of the Critical Point



- System size scan progress: Ar+Sc and Be+Be done, next Pb+Pb
- The Lévy scale parameter R characterizes size of the source
- The Lévy stability parameter α describes shape of the source
- 3D Ising model with random external field predicts $\alpha = 0.50 \pm 0.05$ at critical point [1]
- No indication of the critical point (α significantly larger than 0.5)

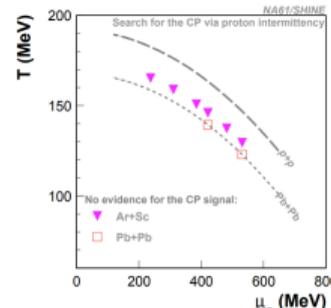


$$F_r(M) = \frac{\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \cdot \dots \cdot (n_m - r + 1) \rangle}{\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \rangle^r}$$

$\langle \dots \rangle$ denotes averaging over events, M is the number of cells

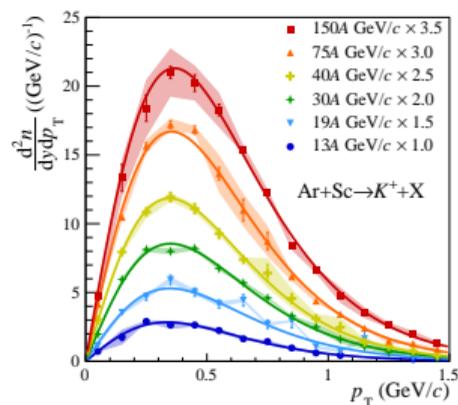
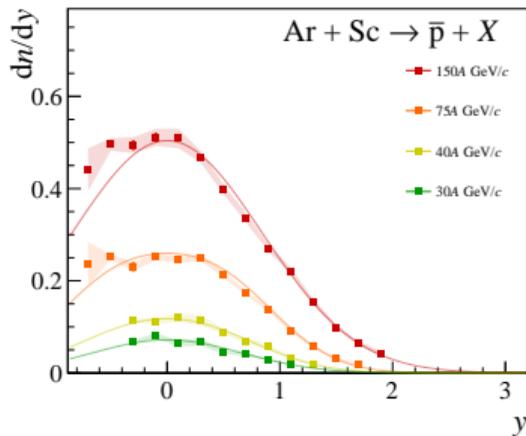
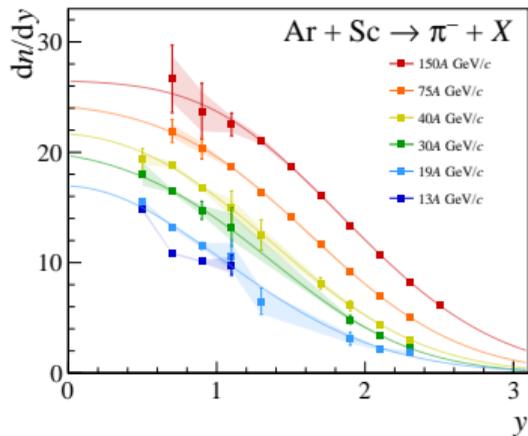
- Statistically independent points and cumulative variables
- No indication of the critical point (power-law scaling of $F_r(M) \sim M^{2\phi_r}$)

Ar+Sc at 150A accepted for publication in EPJC

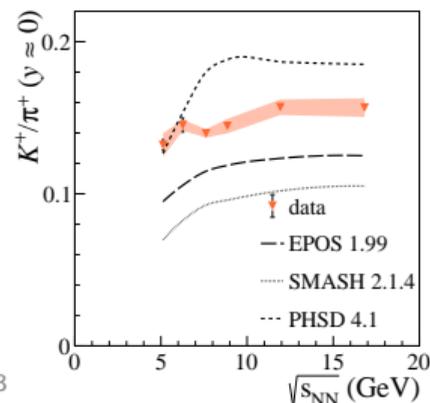




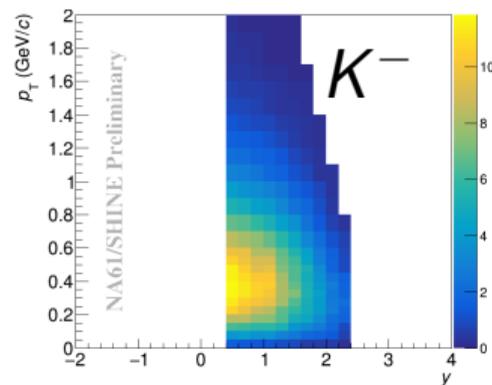
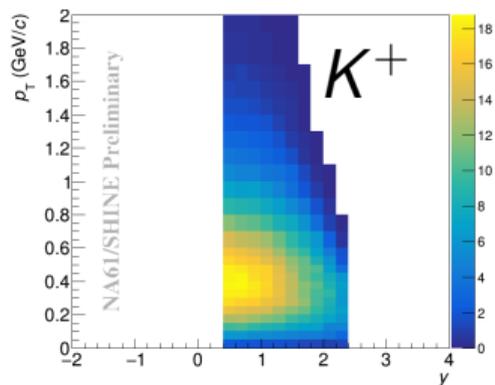
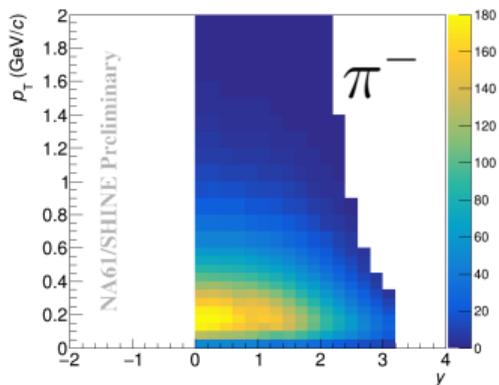
Study of the onset of
deconfinement



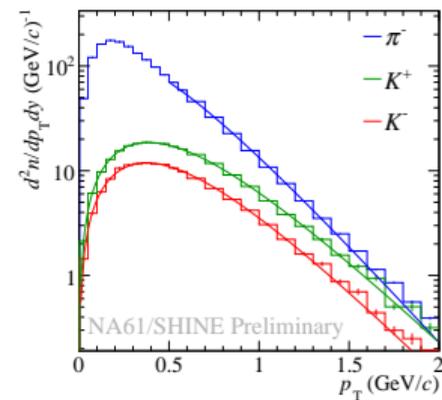
- New final results on K^\pm , π^\pm , p and \bar{p} in Ar+Sc
- 0-10% of the most central collisions
- Data available at six beam energies in range $\sqrt{s_{NN}} = 5.1 - 16.8$ GeV

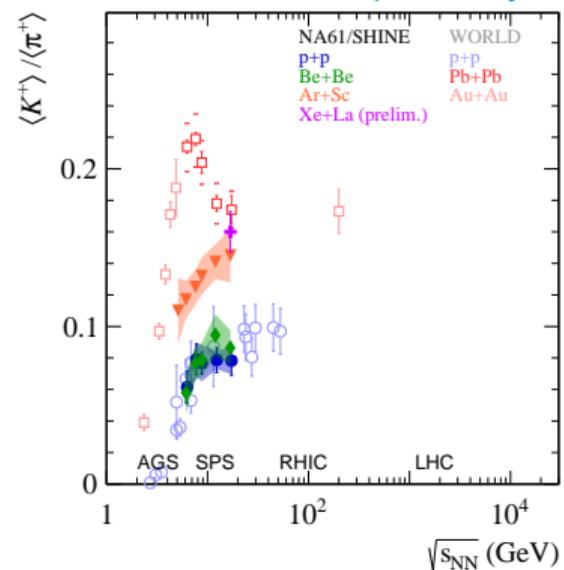
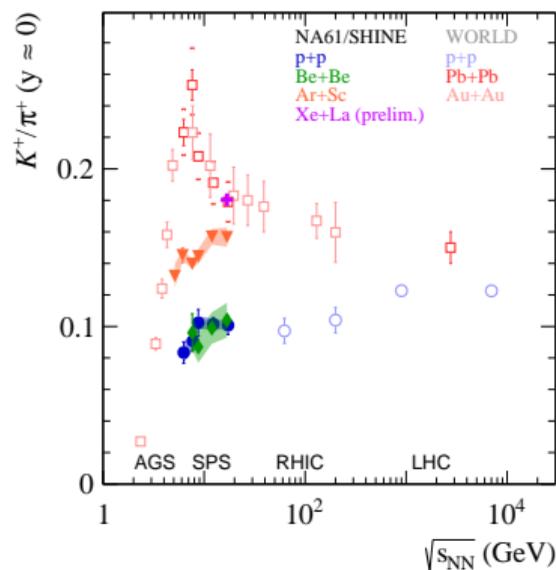


arXiv:2308.16683



- New preliminary results on K^\pm and π^- spectra
- 0-20% of the most central collisions
- Data available at $\sqrt{s_{NN}} = 16.8$ GeV
- p_T spectra shown for $0.4 < y < 0.6$



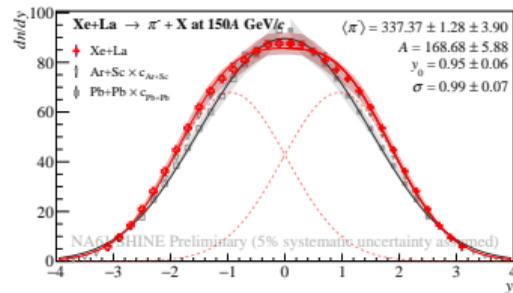
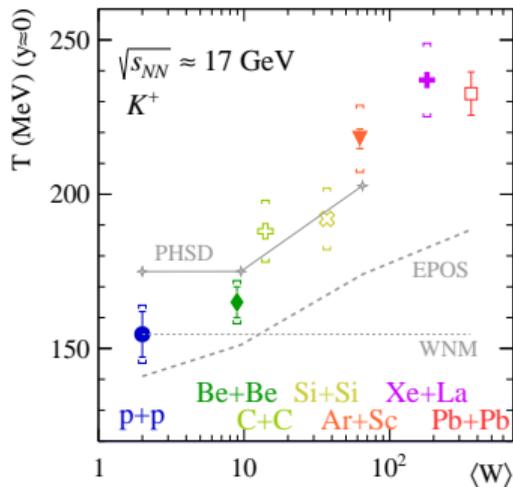
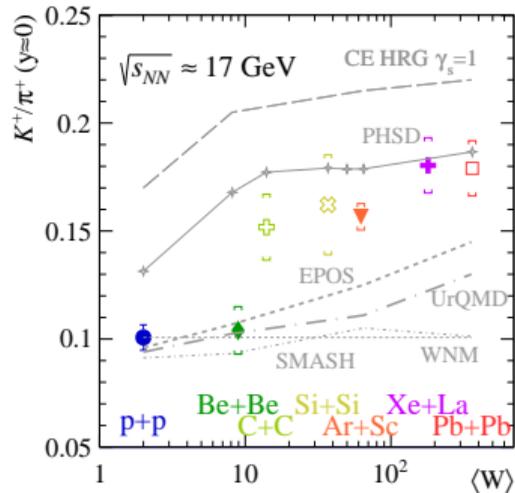


- Rapid change in the energy dependence of K^+/π^+ ratio in Pb+Pb collisions indicated the onset of deconfinement in the SPS energy range, as predicted within SMES
- Plateau-like structure visible in light systems ($p+p$ and Be+Be)
- Ar+Sc systematically higher, Xe+La close to Pb+Pb at $\sqrt{s_{NN}} = 16.8$ GeV



Study of the onset of fireball

System size dependence of particle production properties



- Rich collection of results on system size dependence of particle production in SPS energy range
- None of the models reproduce K^+/π^+ ratio or T in the whole $\langle W \rangle$ range
- Rapidity spectra of π^- on the right plot are scaled by mean numbers of wounded nucleons to central Xe+La $c_X = \langle W_{Xe+La} \rangle / \langle W_X \rangle$

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;

p+p: Eur. Phys. J. C77 (2017) 10, 671
 Be+Be: Eur. Phys. J. C81 (2021) 1, 73
 Ar+Sc: arXiv:2308.16683
 Xe+La: NA61/SHINE preliminary
 Pb+Pb: Phys. Rev. C66, 054902 (2002)

Uniqueness of heavy ion results from NA61/SHINE



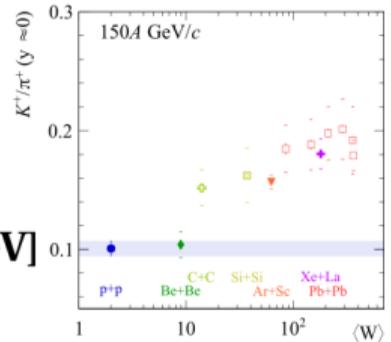
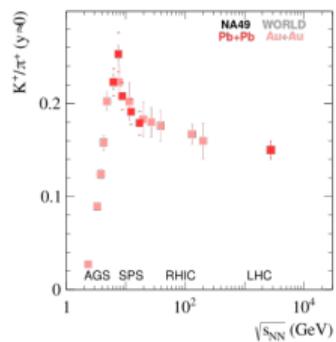
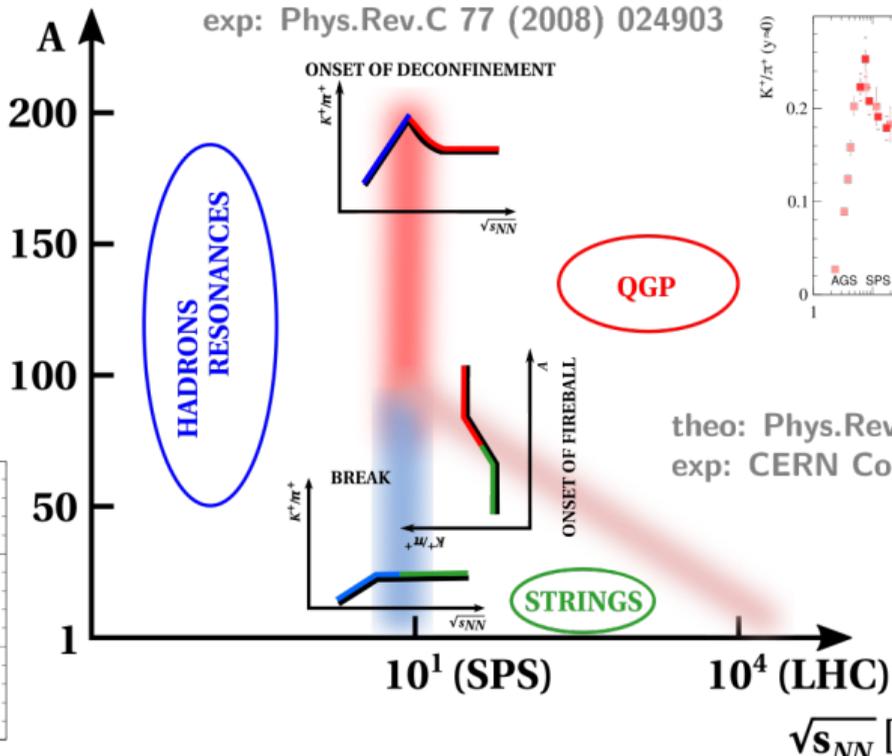
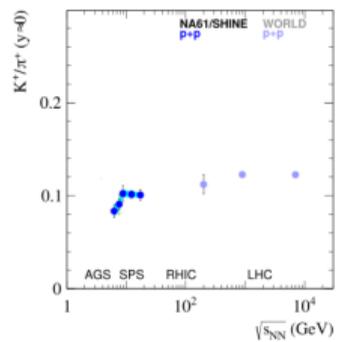
theo: Acta Phys.Polon.B 46 (2015) 10, 1991

exp: Phys.Rev.C 77 (2008) 024903

theo: Phys.Part.Nucl. 51 (2020) 3, 337-339

exp: Phys.Rev.C 102 (2020) 011901

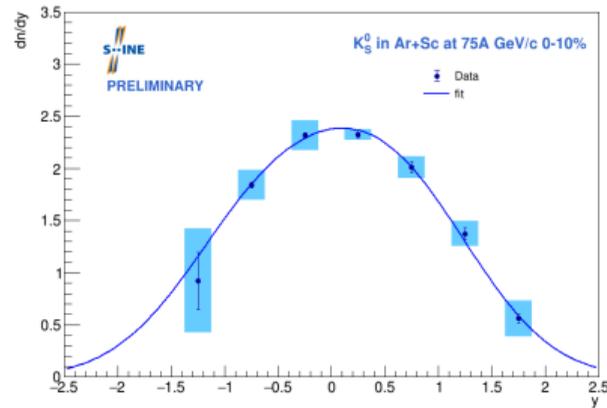
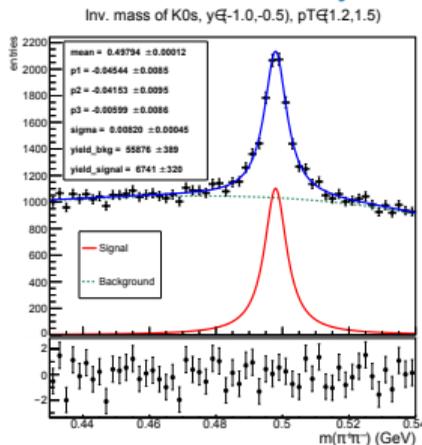
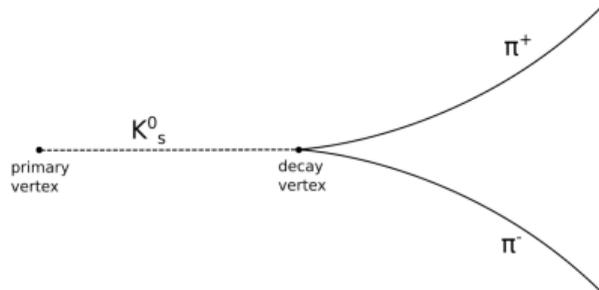
theo: Phys.Rev.D 90 (2014) 025031
exp: CERN Courier, Sep 23rd, 2019



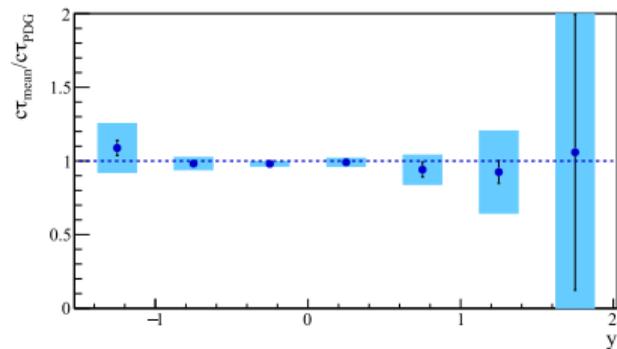
Universe 9 (2023) 2, 106



Anomaly in charged over
neutral K meson production

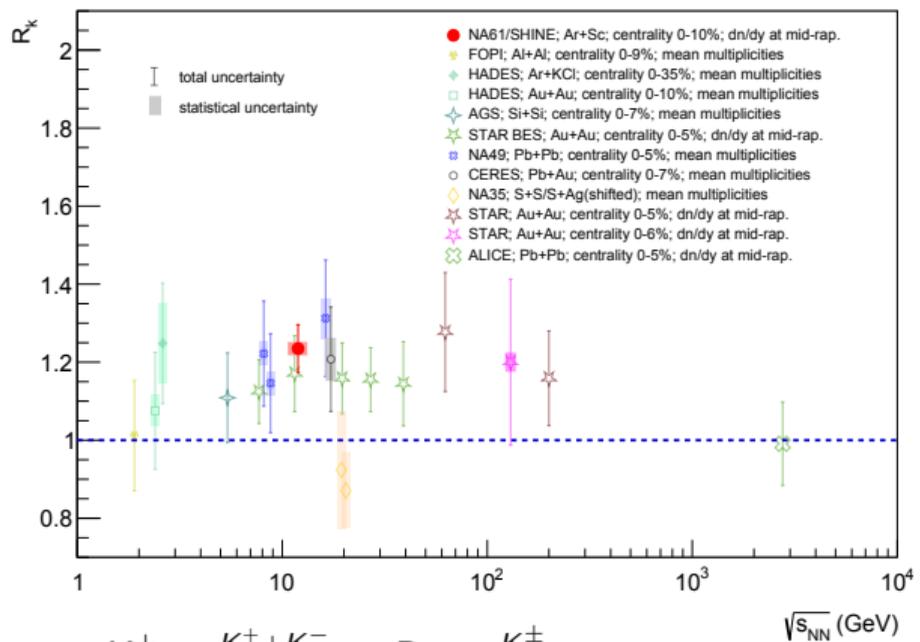
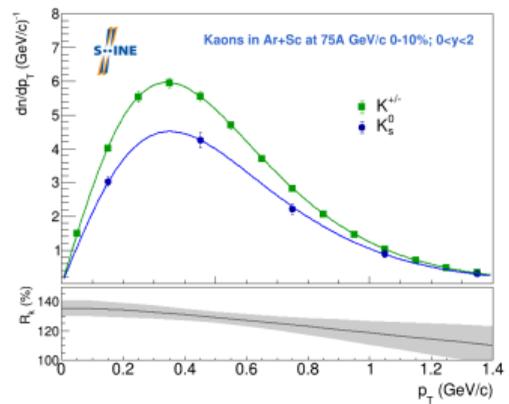
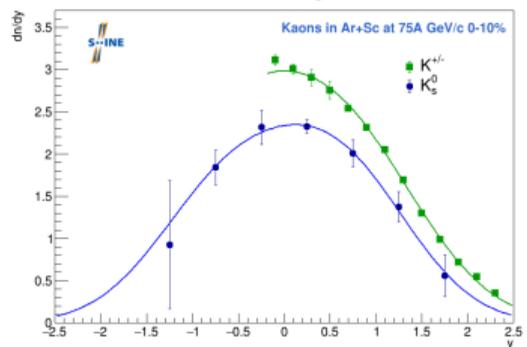


- New preliminary results on K_S^0 in Ar+Sc collisions
- Reconstruction based on decay topology
- K_S^0 decays into π^+ and π^- with $BR \approx 69.2\%$
- Breit-Wigner function is used to describe the signal
- Mean multiplicity: $\langle K_S^0 \rangle = 6.25 \pm 0.09(stat) \pm 0.73(sys)$



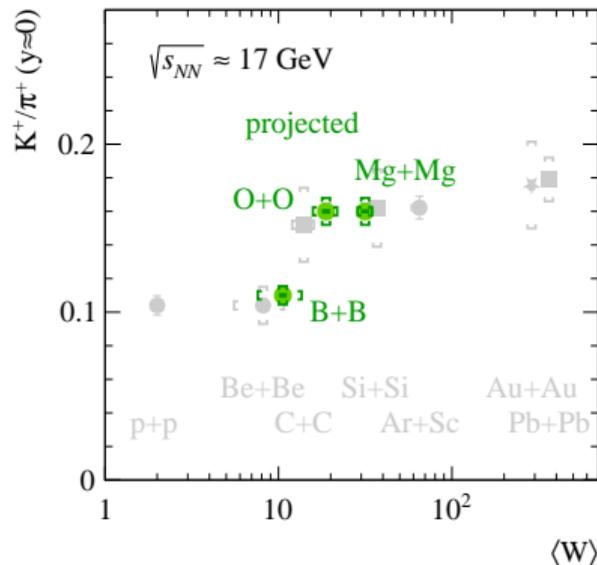
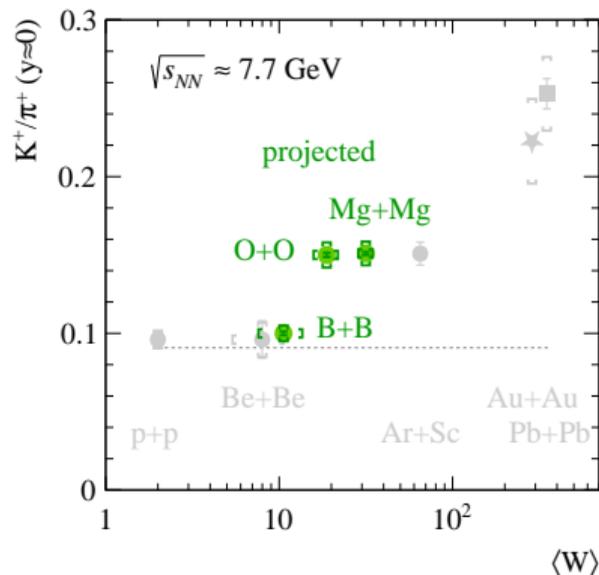
K_S^0 production in Ar+Sc - comparison with charged kaons

K^\pm - arXiv:2308.16683 K_S^0 - NA61/SHINE preliminary See talk by W. Brylinski on Wednesday at 9:50, room C



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

- Around 15-30% difference in the whole rapidity and transverse momentum range.



- Pb+Pb measurements for studies of open charm production at SPS energies ($\sqrt{s_{NN}} = 7.7$ and 17 GeV) in 2022-2025
- Continuation of 2D scan with B+B, O+O and Mg+Mg collisions (latter two are $p - n$ symmetric) after CERN LS3 (2028+) - addendum SPSC-P-330-ADD-14 submitted last month

- Unique 2D scan in collision energy and system size is complete
- So far no indication of the critical point
- New results on spectra in Ar+Sc (final) and Xe+La (preliminary)
- No horn structure observed in Ar+Sc data
- Unexpected system-size dependence: $(p+p \approx \text{Be+Be}) \neq (\text{Ar+Sc} \leq \text{Pb+Pb} \approx \text{Xe+La})$
- Present transport and statistical models do not describe well the NA61/SHINE results on strange particle production
- NA61/SHINE delivers rich information related to the diagram of heavy-ion collisions
- Observed anomaly in charged over neutral K meson production
- Bright future of SHINE experiment with plans for new measurements beyond CERN LS3 (2028+)



Thank you



Backup

- In order to obtain the dn/dy yields, the data is extrapolated beyond the detector acceptance
- Exponential dependence in p_T is assumed:

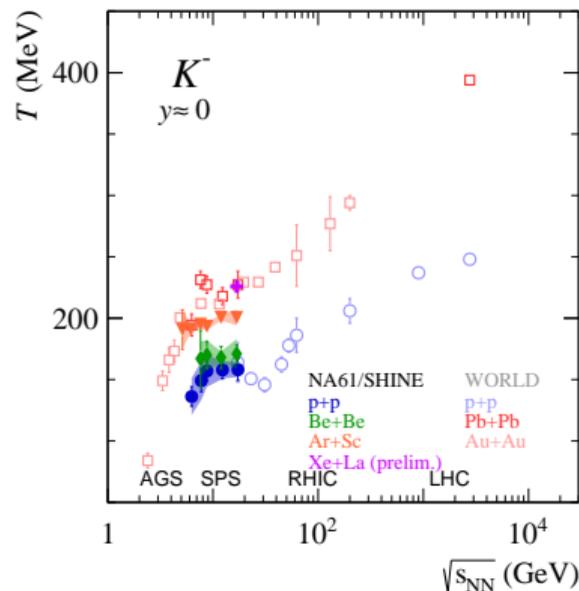
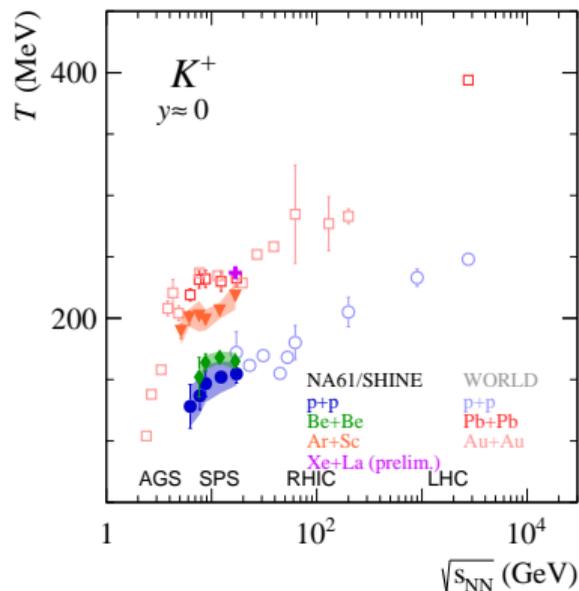
$$f(p_T) = S \cdot p_T \cdot \exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

- To obtain mean multiplicity of produced particles rapidity distribution is fitted with following function:

$$f_{fit}(y) = \frac{A}{\sigma_0 \sqrt{2\pi}} \exp\left(-\frac{(y - y_0)^2}{2\sigma_0^2}\right) + \frac{A}{\sigma_0 \sqrt{2\pi}} \exp\left(-\frac{(y + y_0)^2}{2\sigma_0^2}\right)$$

- A , y_0 and σ_0 parameters are fitted

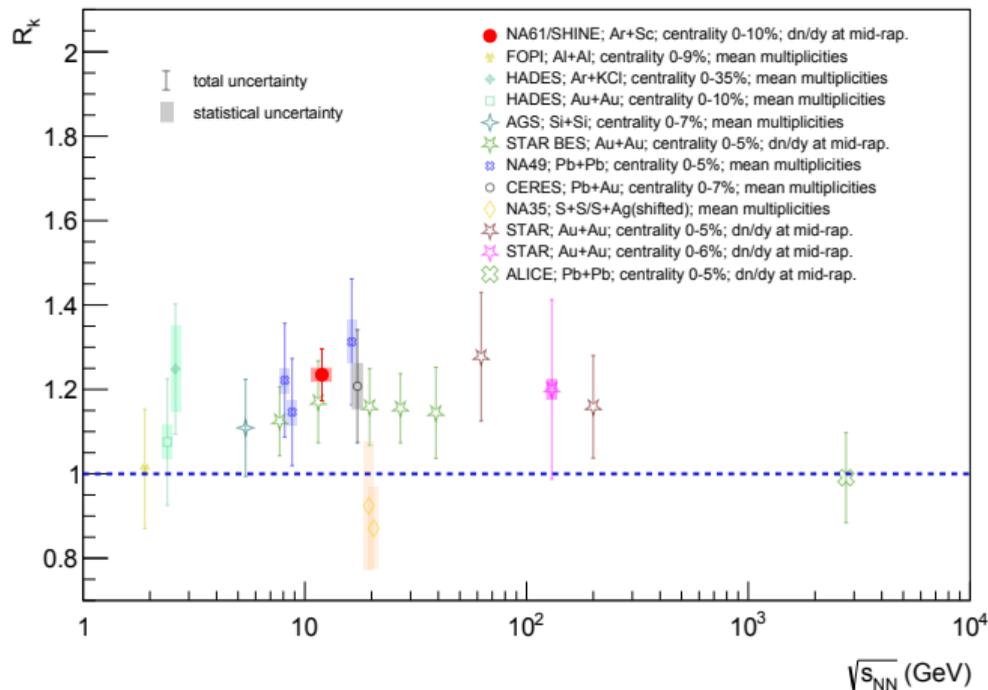
Onset of deconfinement: step



- Plateau in the inverse slope parameter T of m_T spectra of K^\pm spectra in Pb+Pb was predicted within SMES due to mixed phase of hadron gas and QGP *Acta Phys. Polon. B30*, 2705 (1999)
- Similar structures are visible in recently measured reactions
- Magnitude of the T parameter increases with the colliding system size

arXiv:2308.16683 (Ar+Sc)
 Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be)
 Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

Comparison of charged and neutral kaons



NA61/SHINE: preliminary, arXiv:2308.16683
 CERES: M. Kalisky, PhD thesis 2007,
<https://cds.cern.ch/record/1497739>
 STAR BES: Phys. Rev. C **102** (2020) no.3, 034909
 Phys. Rev. C **96** (2017) no.4, 044904
 STAR: Phys. Lett. B **595** (2004), 143-150
 Phys. Rev. C **83** (2011), 024901
 Phys. Rev. Lett. **108** (2012), 072301
 Phys. Rev. C **79** (2009), 034909
 ALICE: Phys. Rev. Lett. **111** (2013), 222301
 Phys. Rev. C **88** (2013), 044910
 AGS and NA35: Z. Phys. C **71** (1996), 55-64
 Z. Phys. C **64** (1994), 195-207
 Z. Phys. C **58** (1993), 367-374
 NA49: C. Strabel, PhD thesis 2006,
<https://edms.cern.ch/document/2693436/1>
 HADES: H. Schuldes, PhD thesis 2016,
<https://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/42489>
 Phys. Lett. B **793** (2019), 457-463
 Phys.Rev.C **80** (2009) 025209
 Phys.Rev.C **82** (2010) 044907
 FOPI: Eur.Phys.J.A **52** (2016) 6, 177
 Phys.Rev.C **81** (2010) 061902

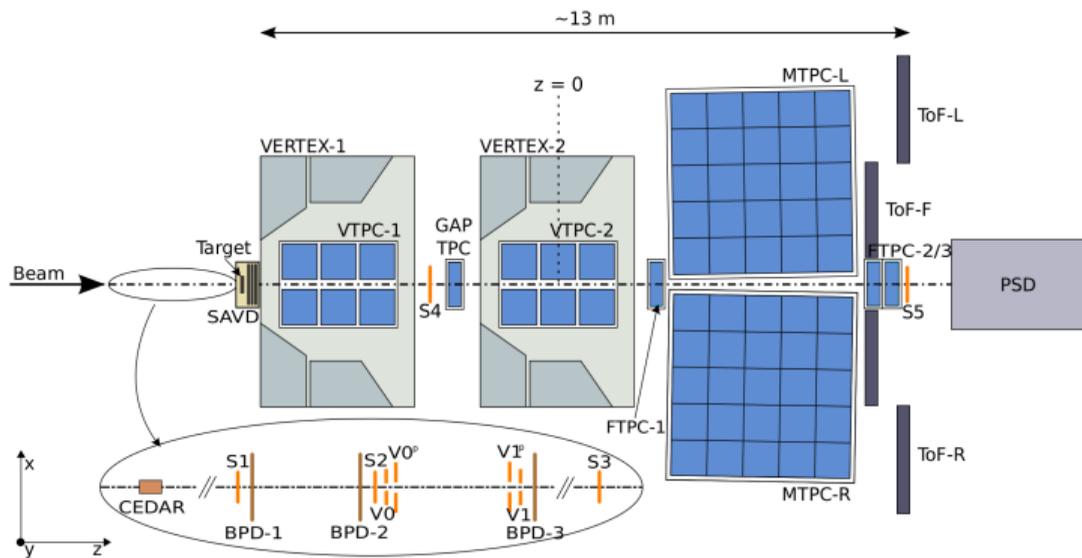
Fixed target experiment located at the CERN SPS accelerator:

Detector setup includes:

- Set of beam and trigger detectors
- 8 Time Projection Chambers
- 3 Time of Flight detectors
- Hadron calorimeter - Projectile Spectator Detector
- Small Acceptance Vertex Detector

Beams:

- hadrons (π , K , p)
 $p_{beam} = 13-400$ GeV/c
- ions (Be, Ar, Xe, Pb)
 $p_{beam} = 13-150A$ GeV/c
- $\sqrt{s_{NN}} = 5.1-16.8(27.4)$ GeV



Large acceptance hadron spectrometer covers the full forward hemisphere, down to $p_T = 0$