Probing the onset of deconfinement - hadron production properties in the NA61/SHINE experiment at CERN SPS

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Outline

- NA61/SHINE experiment & detector setup
- NA61/SHINE research program
- Theoretical predictions & signatures for phase transition
- Selected results for identified charged hadron production properties in the NA61/SHINE experiment
- Summary

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

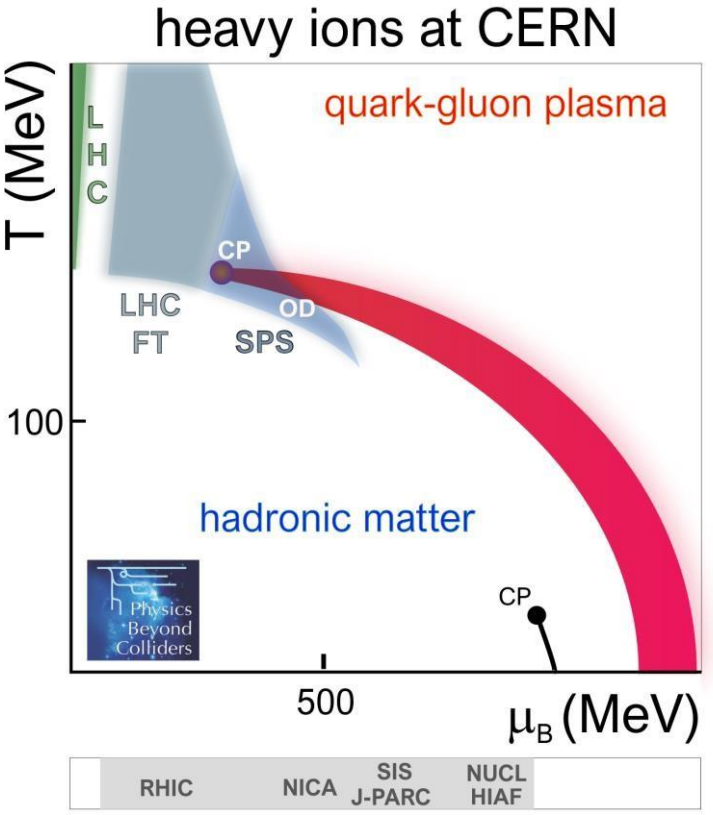
NA61/SHINE research program

Strong interactions

- onsets of deconfinement & fireball
- properties of QCD matter (EoS)
- QCD critical point
- direct measurements of open charm

Neutrino & Cosmic ray physics

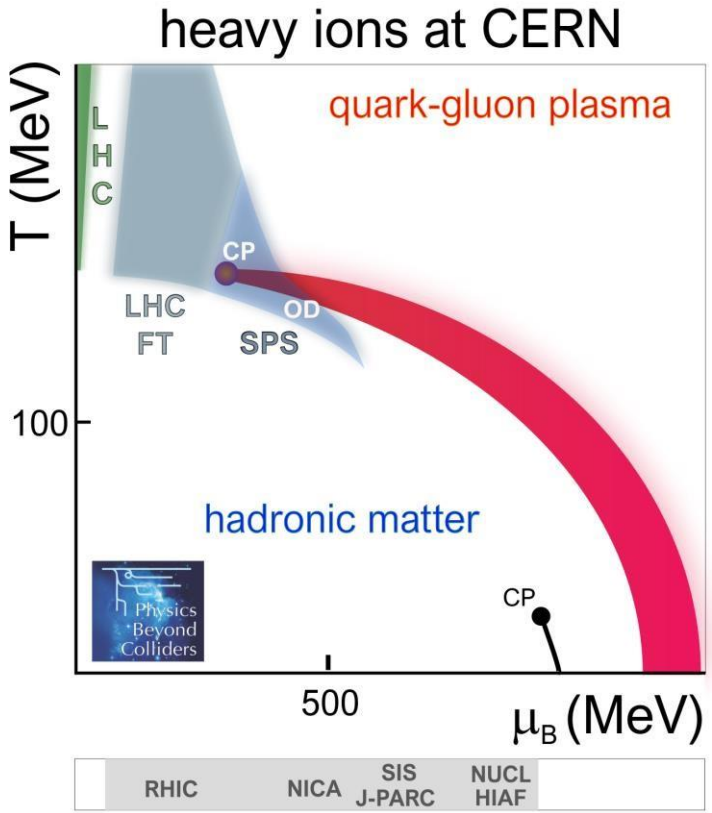
- hadron production cross sections for neutrino flux predictions (J-PARC & Fermilab programs)
- hadron production cross sections for air-shower (Pierre Auger Observatory & KASKADE)
- nuclear fragmentation cross section for cosmic-ray physics

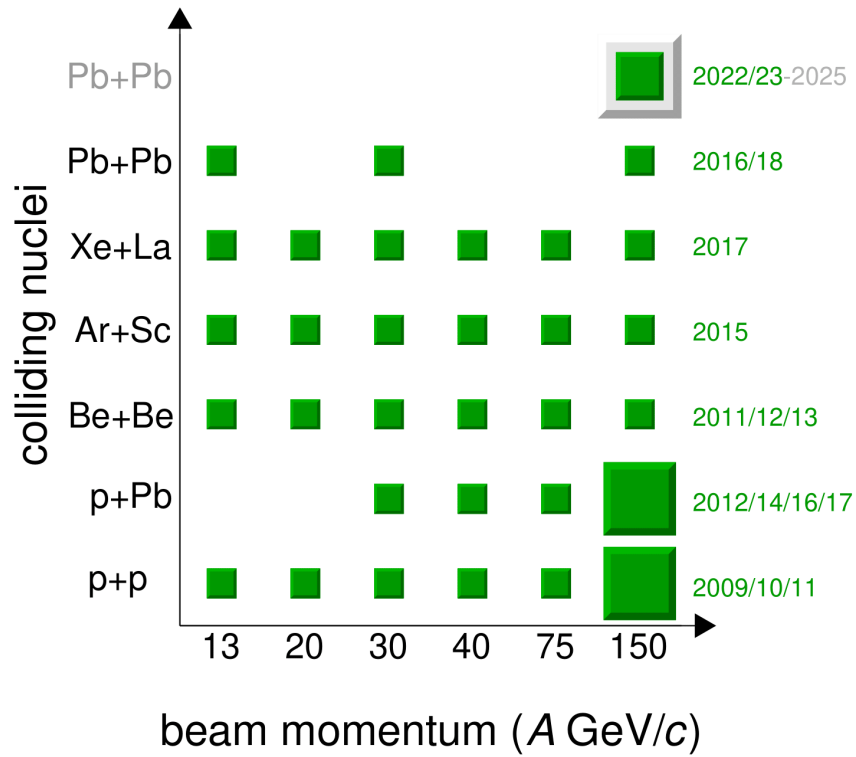


This talk is focused on the selected results for onset of deconfinement & onset of fireball

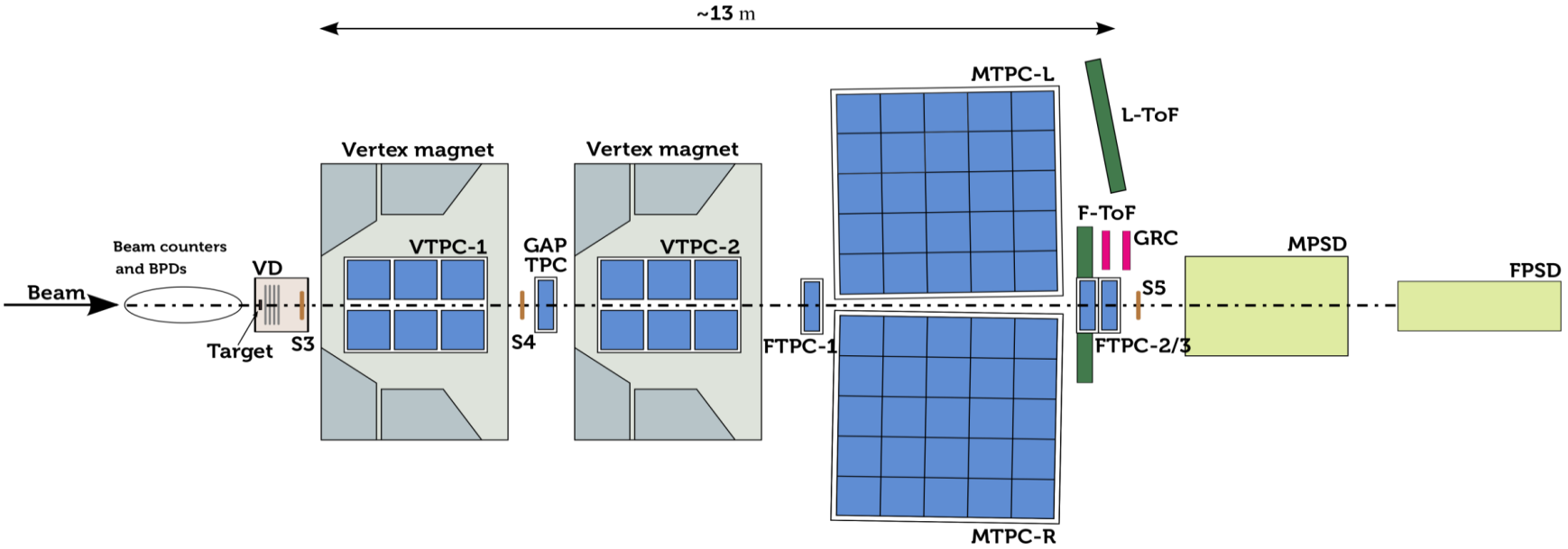
NA61/SHINE two-dimensional scan

NA61/SHINE explores the phase diagram of strongly interacting matter by performing a 2D scan in collision energy and system size



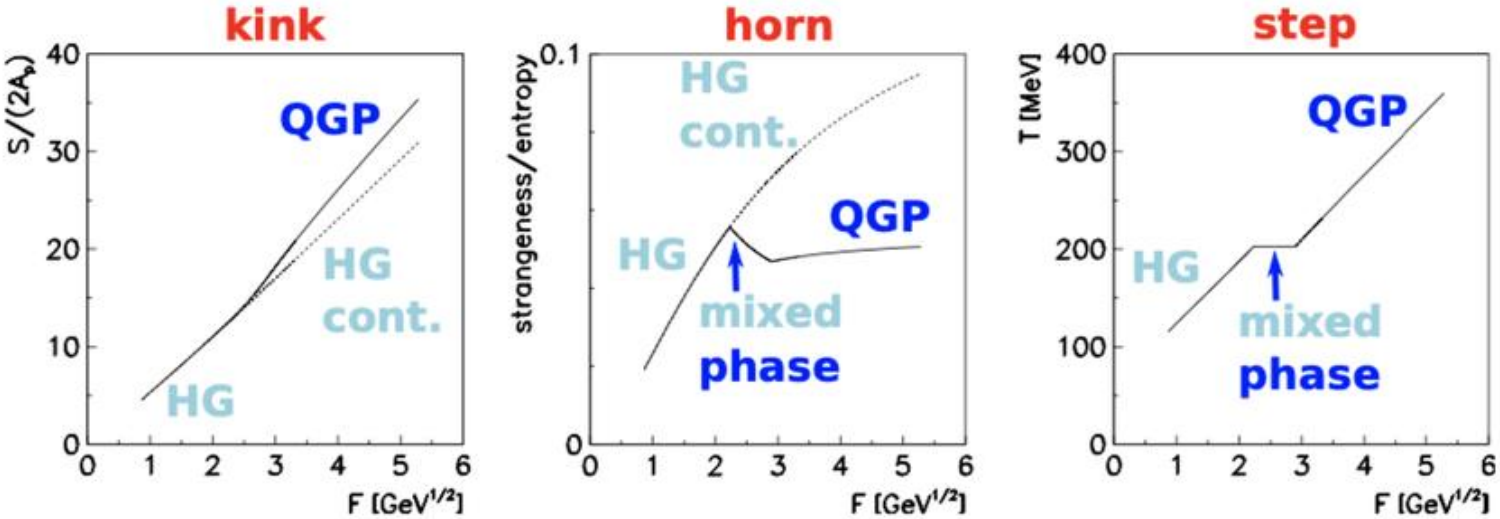


Upgraded NA61/SHINE detector setup



- Fixed target experiment
- Large acceptance hadron spectrometer – coverage of the full forward hemisphere, down to $p_T = 0$
- Ion & hadron beams (π, p, Be, Ar, Xe, Pb)
- $\sqrt{s_{NN}}$ = 5.1 − 16.8 (27.4) GeV

Theoretical predictions from Statistical Model of the Early Stage (SMES)



$$F = \frac{\left(\sqrt{s_{NN}} - 2m_N\right)^{3/4}}{\left(\sqrt{s_{NN}}\right)^{1/4}}$$

$$F \approx s_{NN}^{1/4}$$

Onset of deconfinement

QGP formation by heating up the QCD matter with increasing collision energy

- increase of entropy (new degrees of freedom)
- strangeness to entropy (non-monotonic energy dependence)
- temperature (plateau-like structures)

K^+/π^+ : Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti- quarks and gluons)

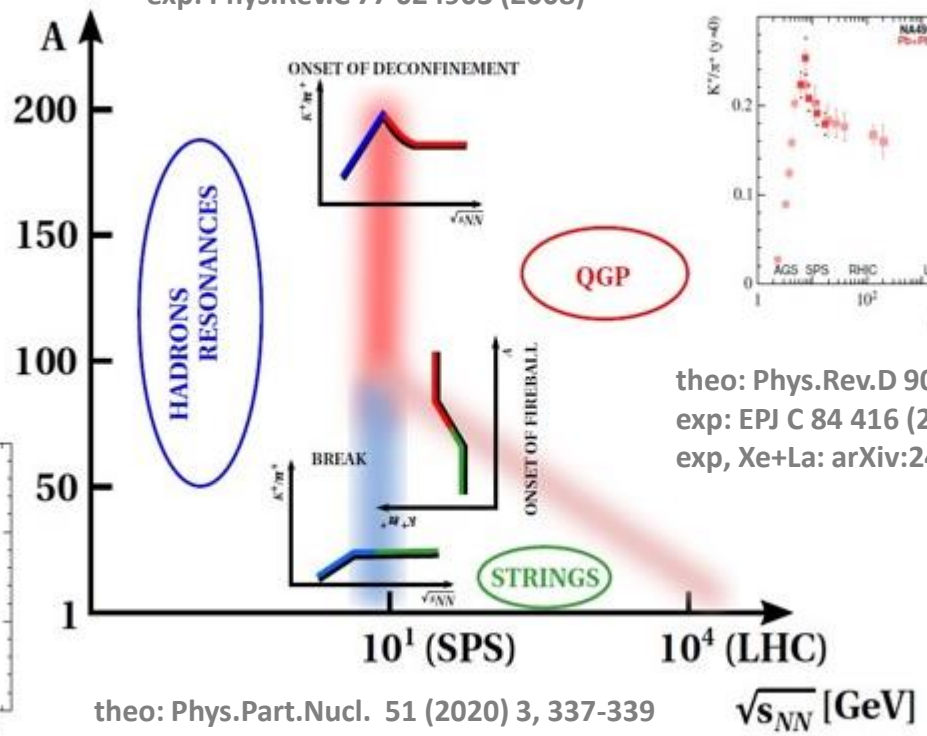
Acta Phys. Polon. B30, 2705 (1999)

Diagram of high-energy nuclear collisions

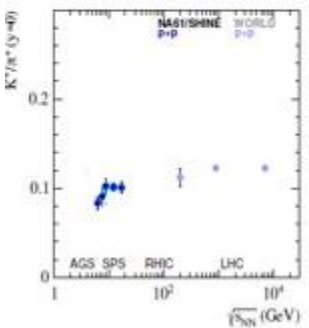
Hadron-production mechanisms dominated by:

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

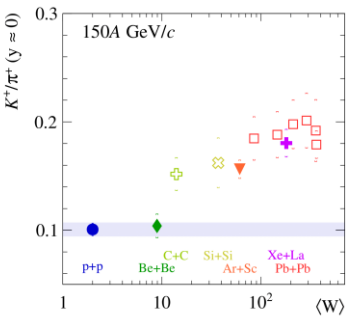
theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77 024903 (2008)



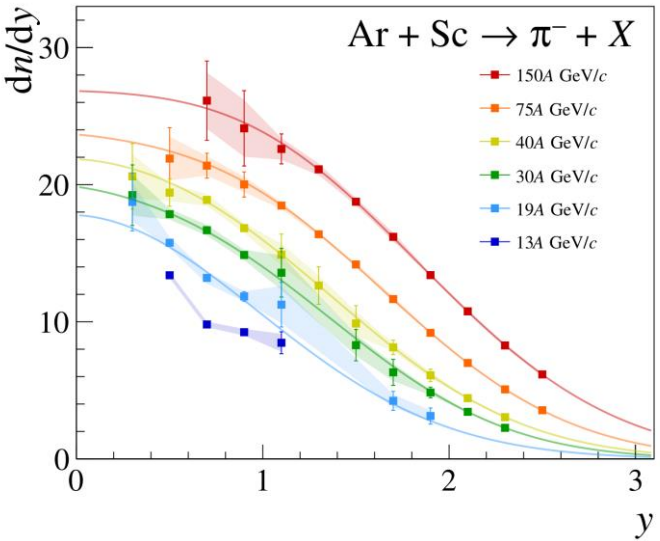
theo: Phys.Rev.D 90 025031 (2014)
exp: EPJ C 84 416 (2024)
exp, Xe+La: arXiv:2402.10973 [nucl-ex]

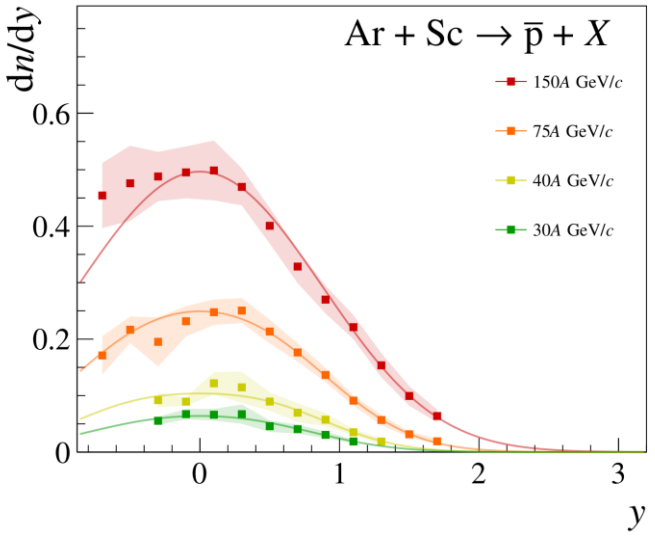


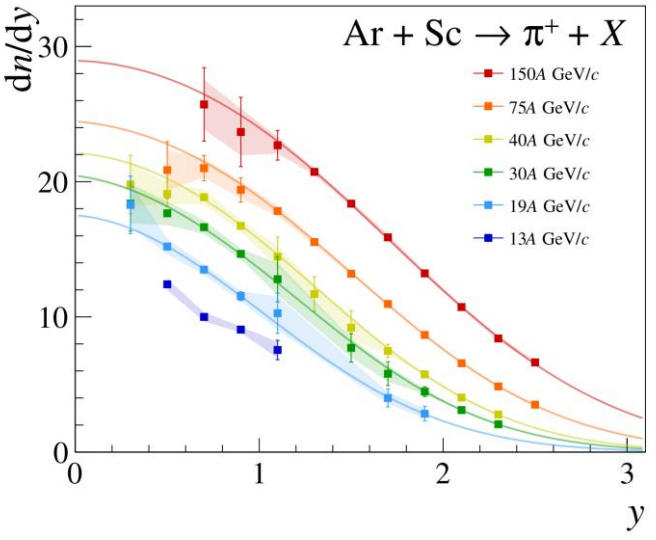
theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901



Spectra of identified charged hadrons in Ar+Sc collisions



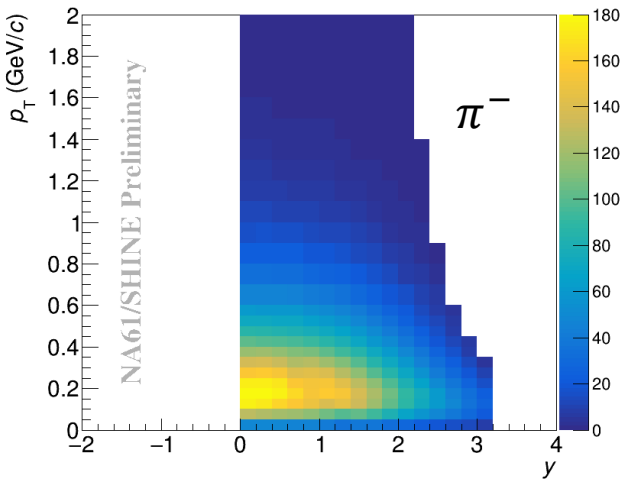


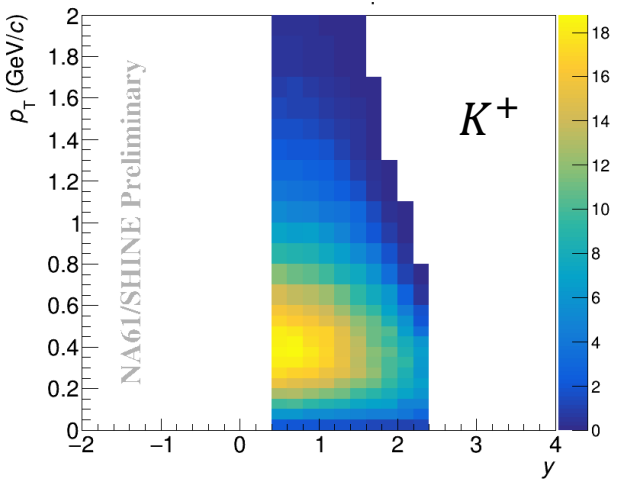


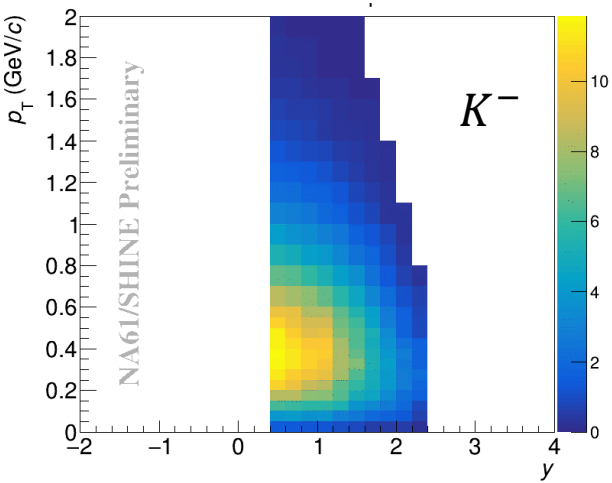
- New final results on $K^{\pm}$, $\pi^{\pm}$, p and $\bar{p}$ in ^{40}Ar+^{45}Sc
- 10% most central ^{40}Ar+^{45}Sc collisions
- Mean multiplicities for charged kaons are obtained by fitting rapidity spectra with sum of two gaussians to obtain mean multiplicities for charged kaons

EPJ C 84 (2024) 416

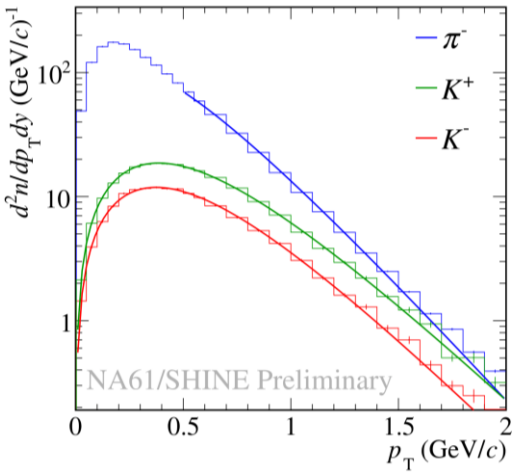
Spectra of identified charged hadrons in Xe+La collisions



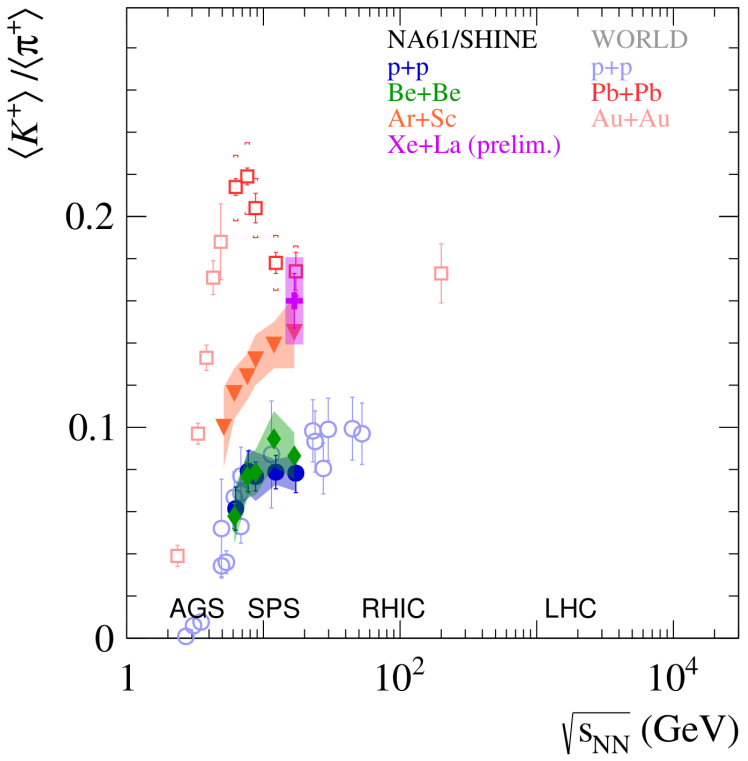




- New preliminary results on $K^{\pm}$, π^- for ^{129}Xe+^{139}La at $\sqrt{s_{NN}}$ = 16.8 GeV
- 20% most central ^{129}Xe+^{139}La collisions
- p_T spectra shown for 0.4 < y < 0.6



Onset of deconfinement: horn



Heavy-ion collisions

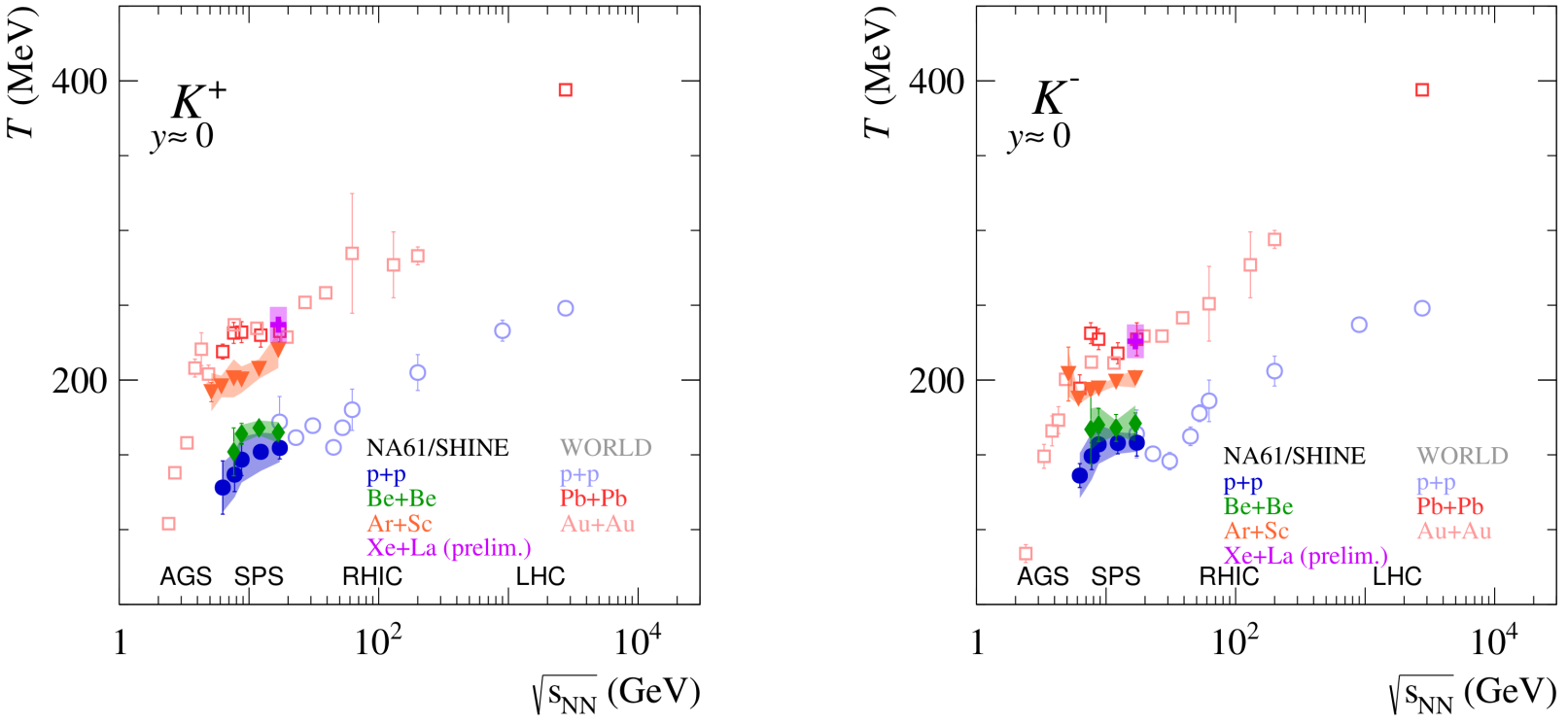
- Non-monotonic behavior of the K^+/π^+ ratio observed in central heavy-ion collisions (Au+Au, Pb+Pb) indicated onset of deconfinement
- Agrees qualitatively with predictions of SMES (Acta Phys. Polon. B30, 2705 (1999))

Intermediate and small size systems

- Plateau like structure visible in p+p and Be+Be
- Ar+Sc systematically higher, Xe+La close to Pb+Pb at $\sqrt{s_{NN}}$ = 16.8 GeV
- None available theoretical description can reproduce the behavior in Ar+Sc

EPJ C 84 (2024) 416 (Ar+Sc), arXiv:2402.10973 [nucl-ex] (Xe+La),
Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be), Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

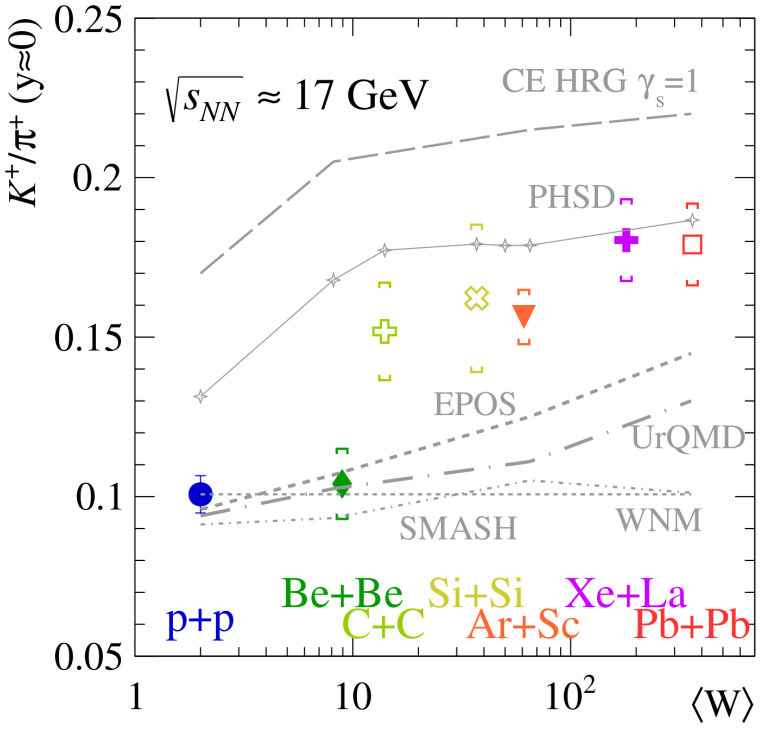
Onset of deconfinement: step

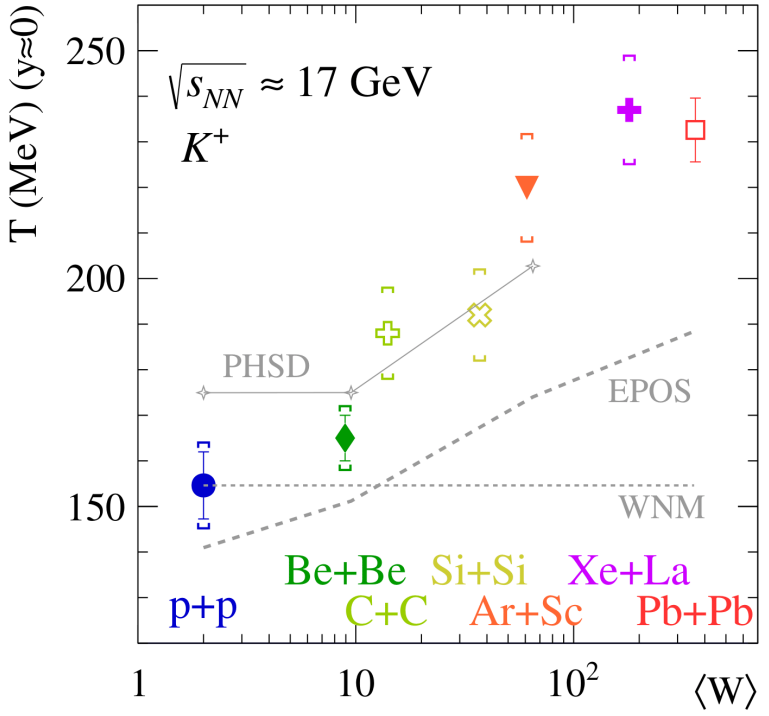


- Qualitatively similar energy dependence of inverse slope parameter (T) in different collision systems
- Characteristic plateau in the SPS energy range (was predicted within SMES for Pb+Pb)
- Magnitude of the T parameter increases with the colliding system size

EPJ C 84 (2024) 416 (Ar+Sc), arXiv:2402.10973 [nucl-ex] (Xe+La),
Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be), Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

System size dependence of K^+/π^+ and T at 150A GeV/c





None of the models reproduces K^+/π^+ ratio or T for whole $\langle W \rangle$ range

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: EPJ C 84 (2024) 416 (Ar+Sc)
Xe+La: arXiv:2402.10973 [nucl-ex]
Pb+Pb: Phys. Rev. C66, 054902 (2002)

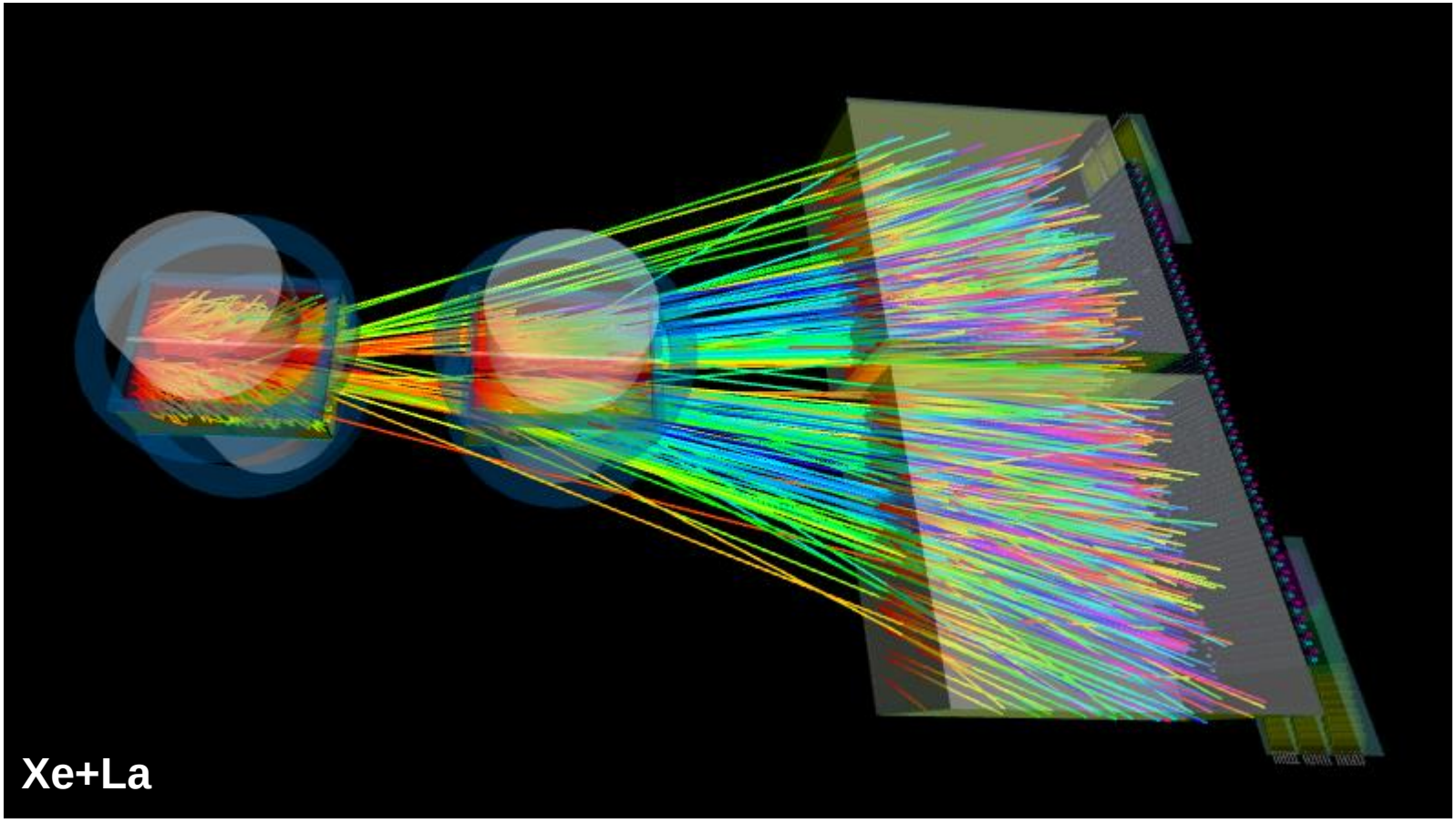
Summary

- 2D scan in system size and collision energy was completed with Xe+La data collection
- New results on identified charged hadron spectra in Ar+Sc (final) and Xe+La (preliminary) are presented
- Analysis for identified charged hadron spectra are ongoing for Xe+La and Pb+Pb data
- Horn structure is not present in p+p, Be+Be, and Ar+Sc
- Unexpected system-size dependence:

  p+p ≈ Be+Be ≠ Ar+Sc ≤ Pb+Pb ≈ Xe+La

- Present theoretical models do not describe well the NA61/SHINE results on strange particle production

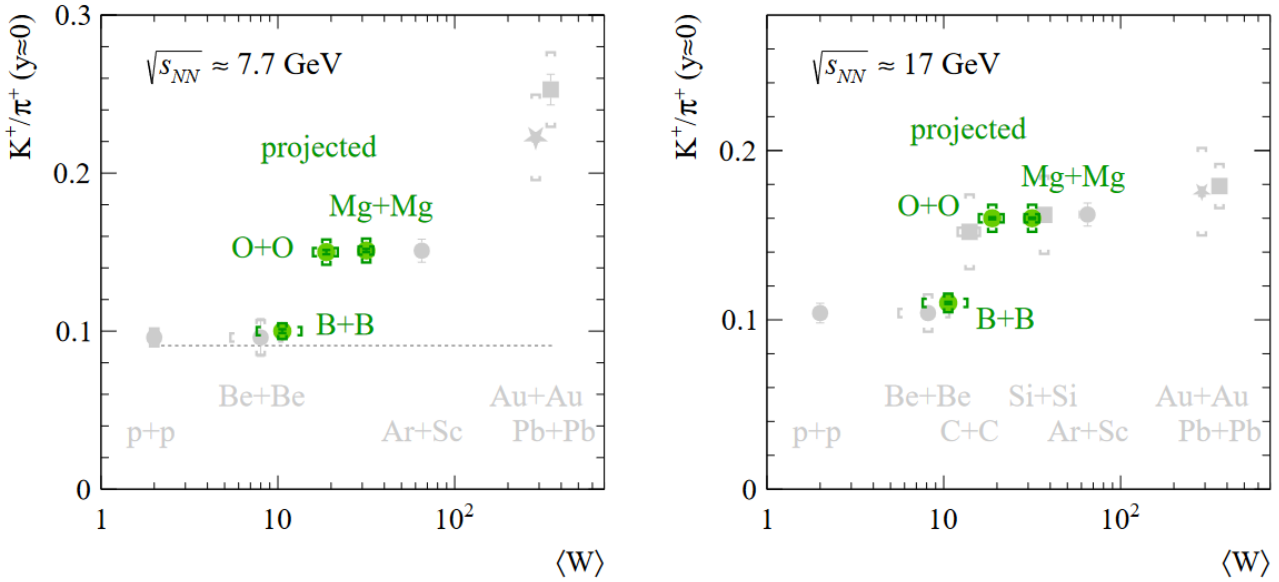
Thank you for your attention!
Have a SHINY day!



Back up

Future plan of the NA61/SHINE experiment

- Pb+Pb measurements for studies of open charm production at SPS energies ($\sqrt{s_{NN}}$=17 GeV) in 2024-2025
- 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 (August 2023)



Kaon spectra parametrization

- In order to obtain the dn/dy kaon yields, the data is extrapolated beyond the detector acceptance
- p_T spectra are fitted with exponential dependence assumed:

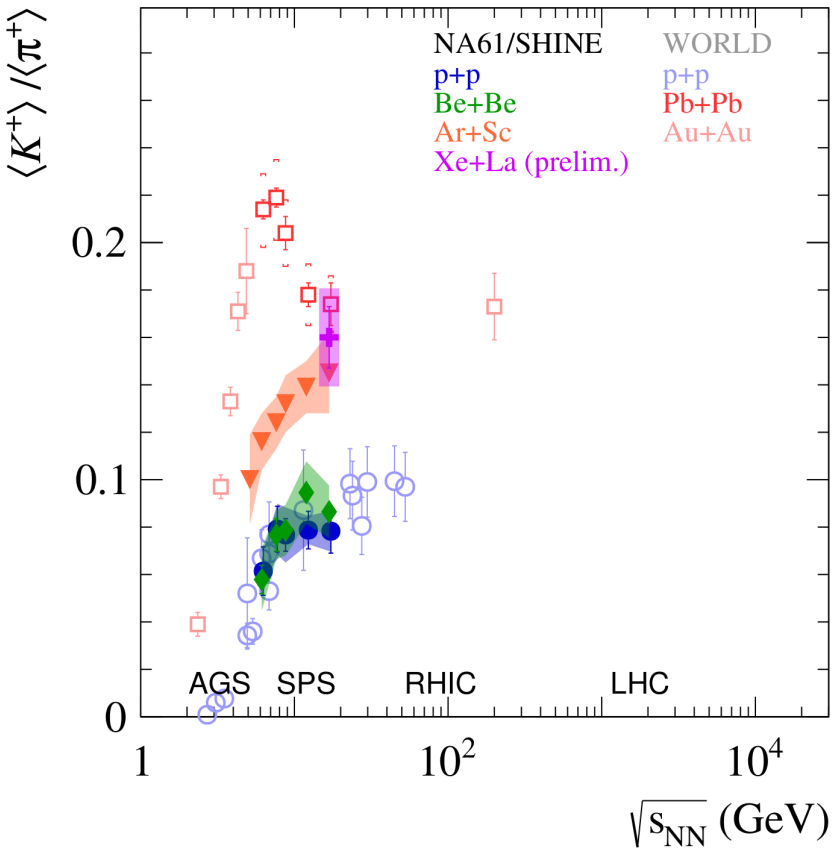
$$f(p_T) = S \cdot p_T \cdot exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

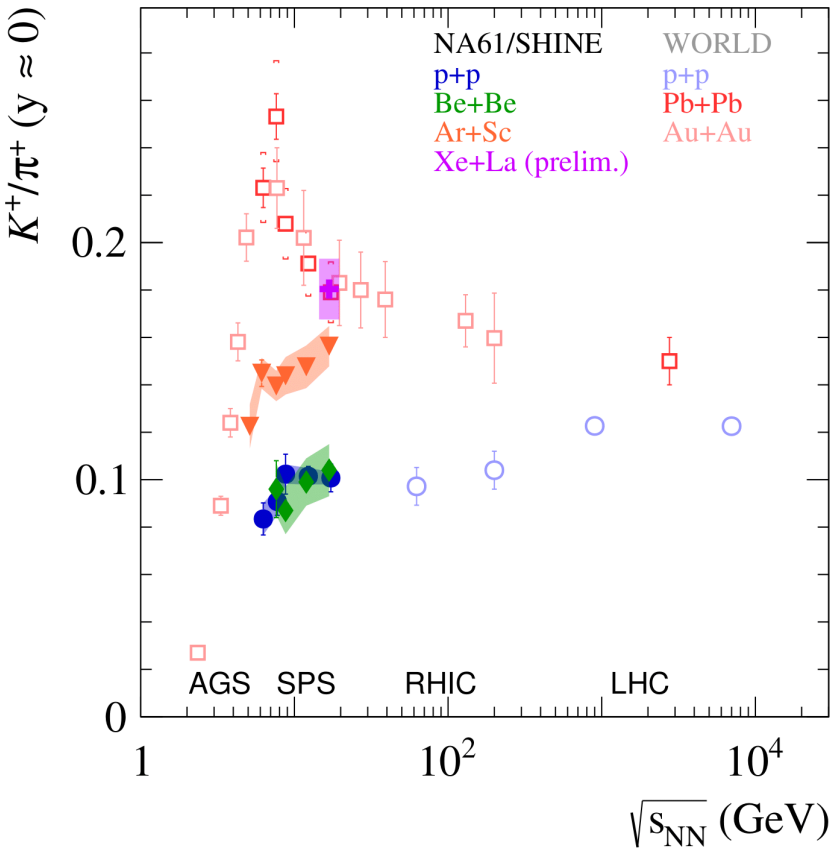
- To obtain mean multiplicity of produced particles rapidity distribution is fitted with following function:

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

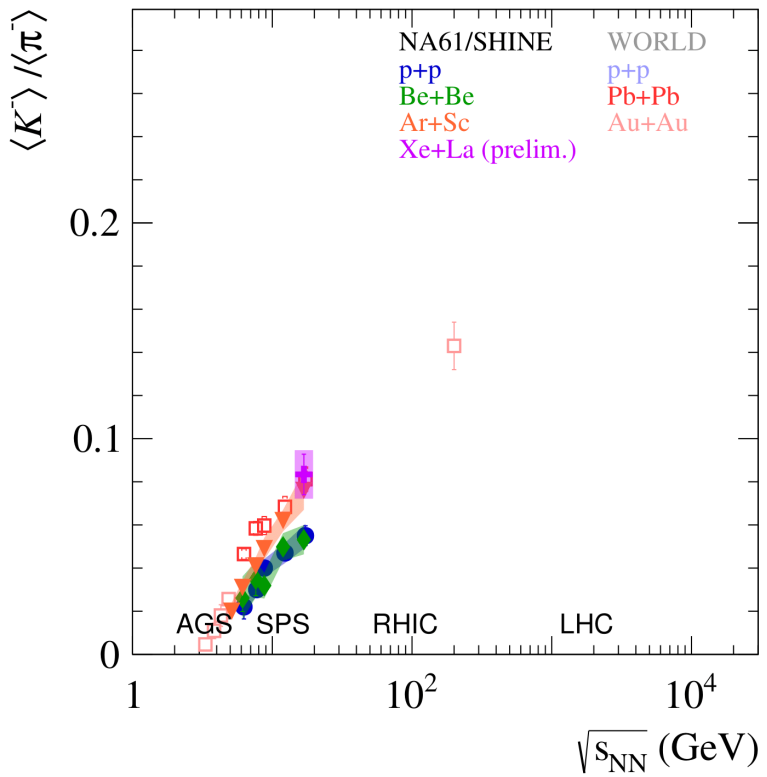
- A, y_0 and σ_0 parameters are fitted

Onset of deconfinement: horn



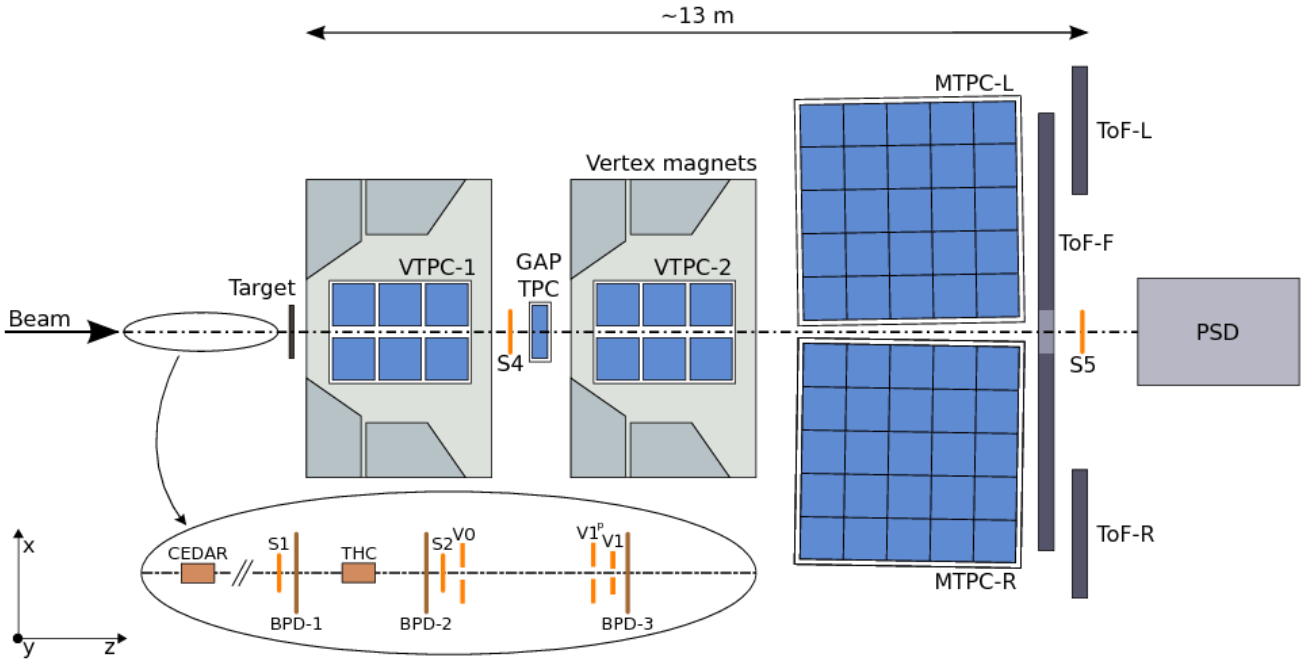


Energy dependence of the K/π ratio for negatively charged particles



- K^+ yields are predominantly sensitive to strangeness content
- K^- production is additionally heavily affected by the baryon density
- A horn is not expected at $\sqrt{s_{NN}} \approx 8$ GeV, all systems studied at SPS energies display an approximately monotonous rise of K^-/π^- ratio towards higher collision energies

NA61/SHINE experiment before upgrade in 2018



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

NA61/SHINE experiment post LS2

- Upgrade of PSD to MPSD + FPSD
- Upgrade of DAQ + new trigger system (TDAQ)
  - Detector readouts replaced → data taking rate up by 20x
  - TPCs - ALICE; other detectors - DRS4
- Detectors build of:
  - Vertex Detector - open-charm measurements
  - ToF-F wall
  - Multi-gap Resistive Plate Chamber based ToF-L (ToF-R under constr.)
  - Beam Position Detector
  - Geometry Reference Chamber - drift velocity measurements