Study of the onset of deconfinement in the NA61/SHINE experiment

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Outline

- NA61/SHINE physics program
- Detector setup
- Particle identification and spectra
- Onset of deconfinement signatures
- Future plans
- Summary

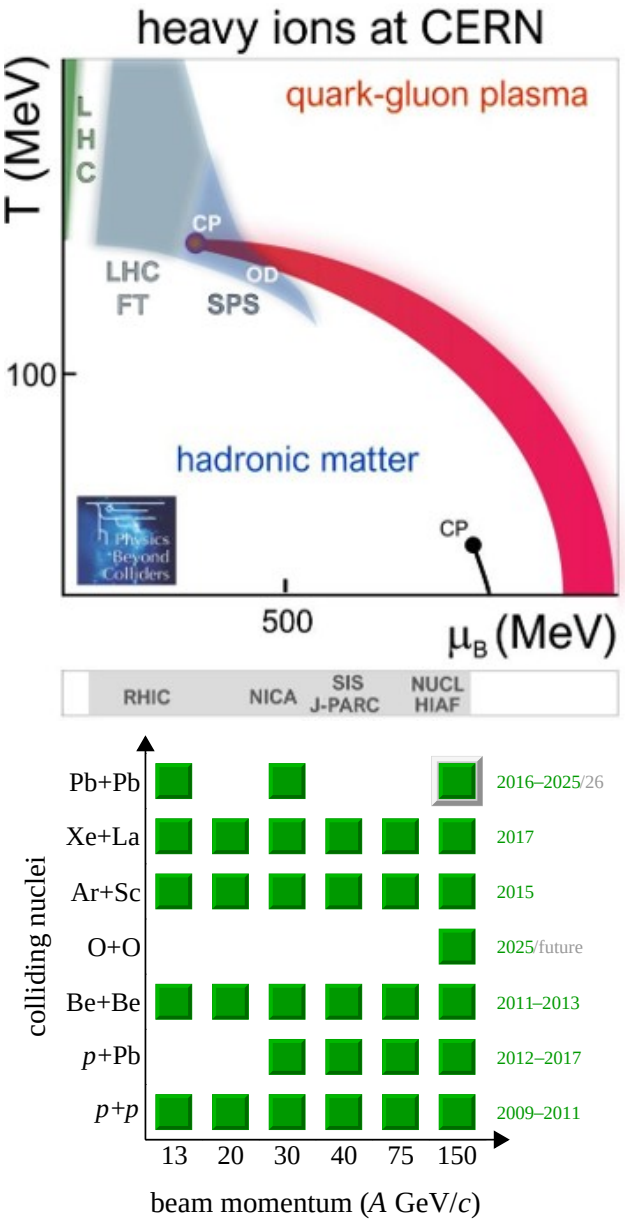
NA61/SHINE physics program

Strong interaction physics:

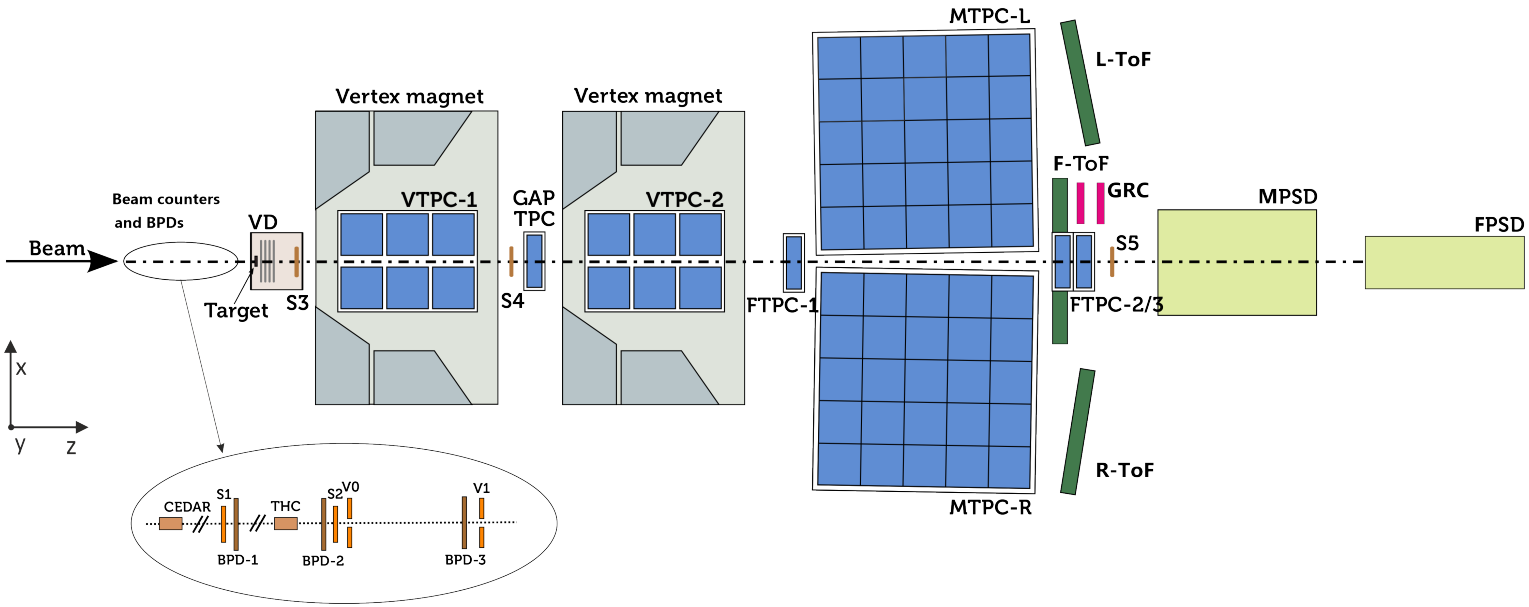
- study properties of the onset of deconfinement
- search for the critical point
- direct measurements of open charm
- measurements of violation of isospin symmetry in multiparticle production

Neutrino & cosmic-ray physics:

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



NA61/SHINE detector

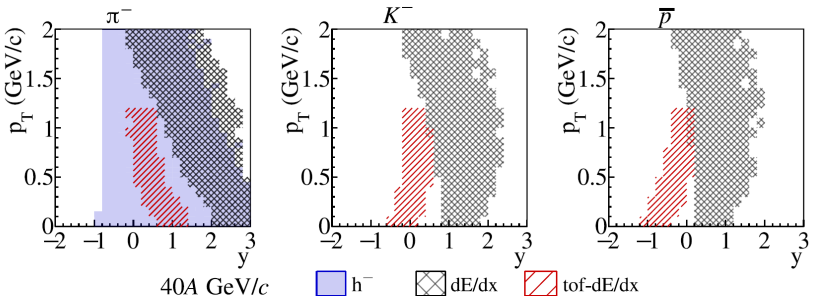


- Multipurpose fixed-target spectrometer operating at CERN SPS
- Large acceptance covering the full forward hemisphere down to $p_{\mathrm{T}} = 0$
- Beam momenta:
  - Ions: $p_{\mathrm{beam}} = 13A$–$150A$ GeV/c
  - Hadrons: $p_{\mathrm{beam}} = 13$–400 GeV/c
- Beams: Be, O, Ar, Xe, Pb (ions) and π, K, p (hadrons)
- $\sqrt{s_{\mathrm{NN}}} = 5.1$–$16.8$ GeV (A+A), 5.1–27.4 GeV (p+p)

Charged particle identification

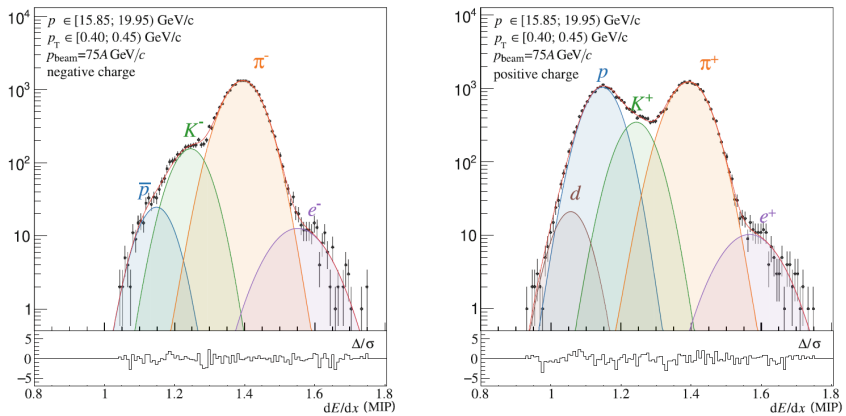
h^- method

- π^- identification in wide y-p_T as the majority of h^- are π^-



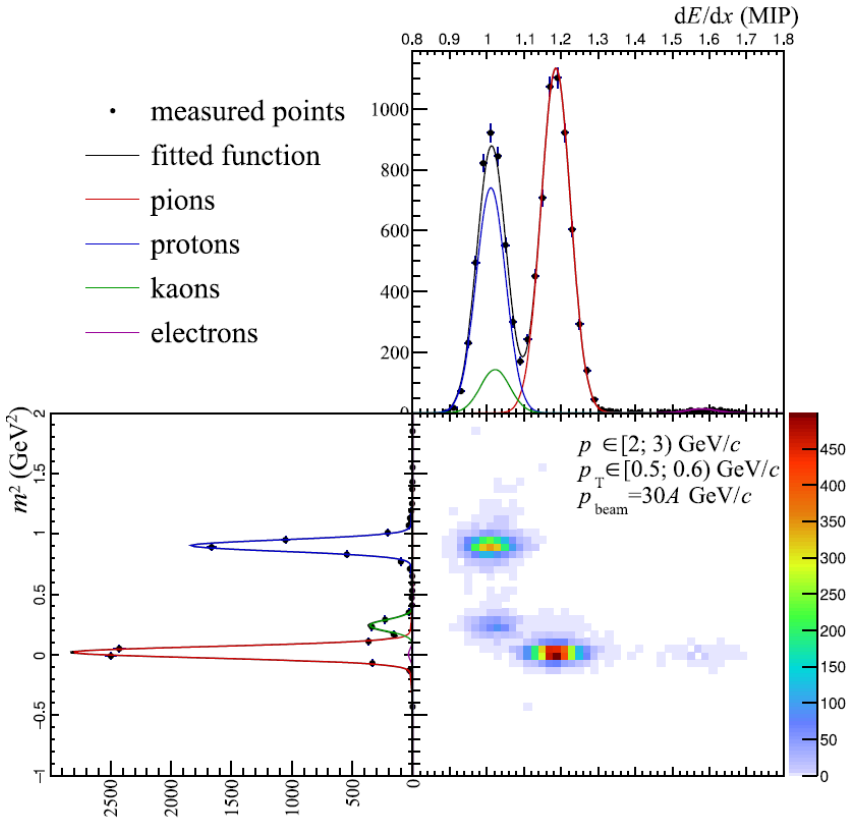
dE/dx method

- TPC energy loss



tof-dE/dx method

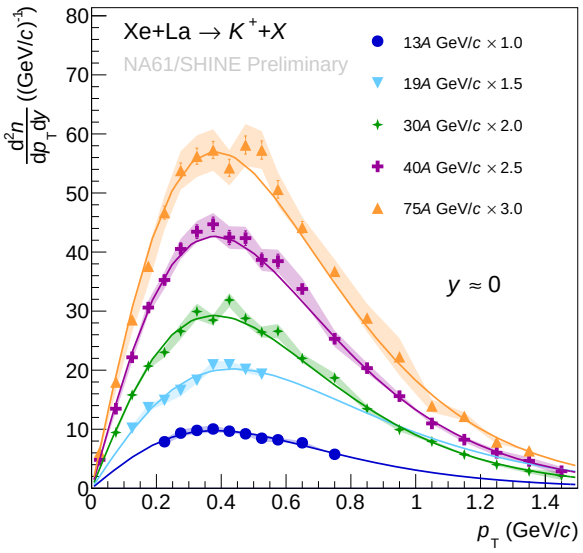
- TPC + ToF information

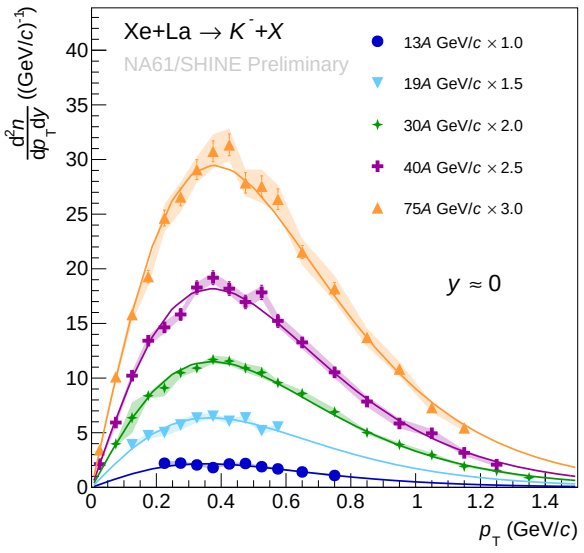


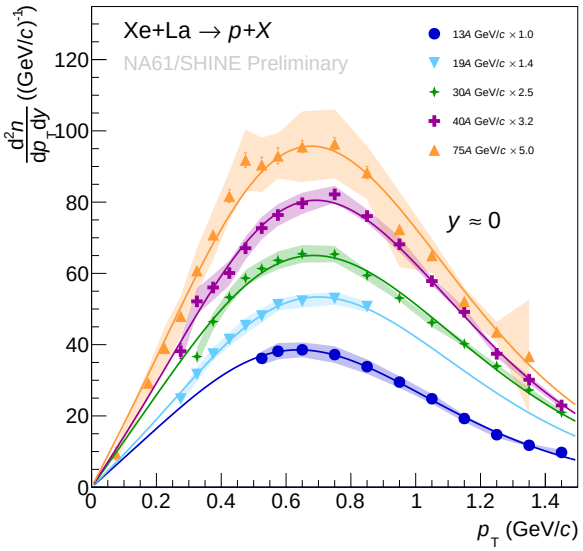
0–10% central Ar+Sc

NA61/SHINE: EPJC 84 (2024) 416

New identified hadron spectra at midrapidity in Xe+La





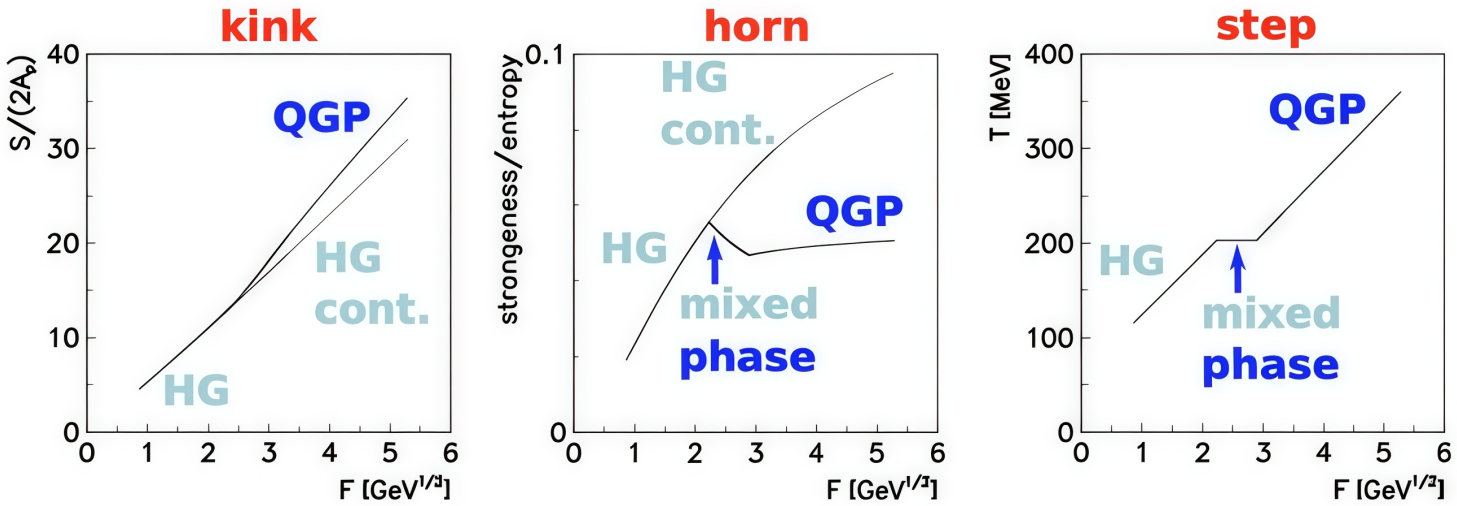


New preliminary results

Xe+La collisions
0–10% centrality
13A–75A GeV/c
tof–dE/dx PID
midrapidity spectra

Theoretical predictions from SMES model

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

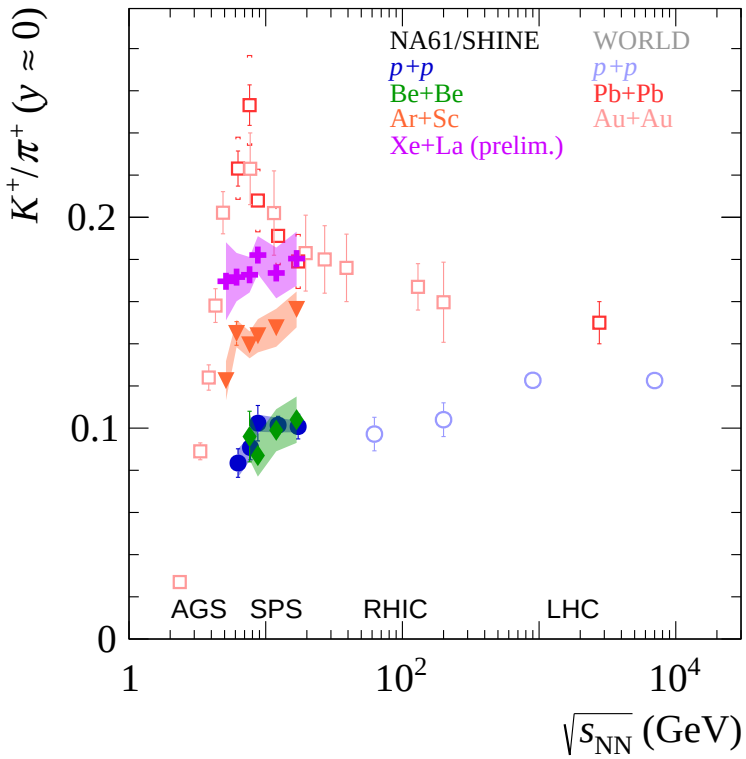


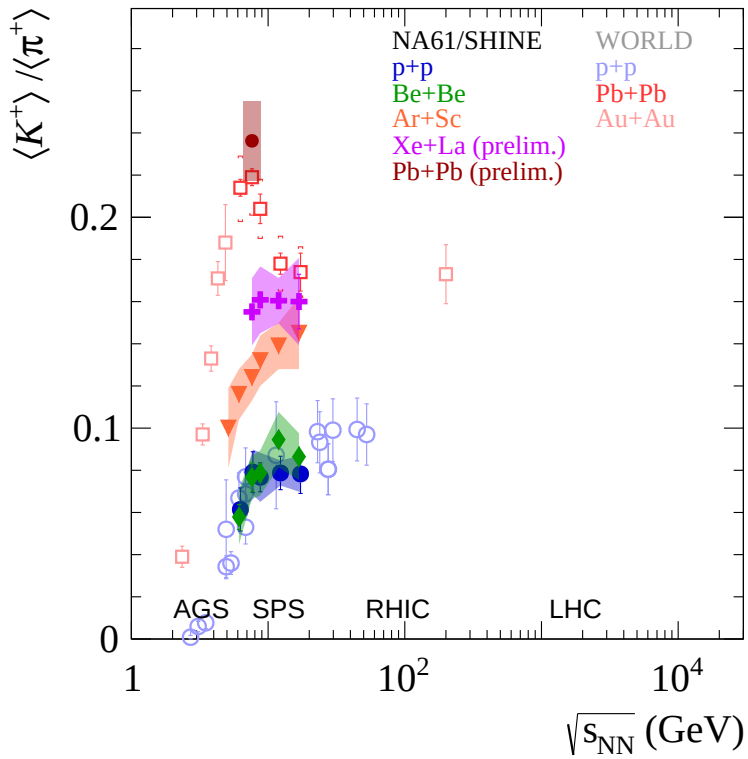
Statistical Model of the Early Stage (SMES): QGP formation by heating up the QCD matter with increasing collision energy

- 1^{st} order phase transition to QGP between top AGS and top SPS energies
- increase of entropy (new degrees of freedom)
- strangeness to entropy (non-monotonic energy dependence)
- temperature (plateau-like structures)

APPB 30 (1999) 2705

Onset of deconfinement: Horn





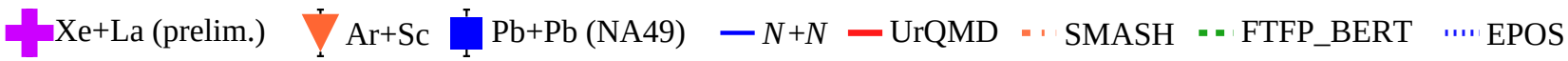
- $K^+/\pi^+ \propto$ strangeness/entropy
- Probe of onset of deconfinement
- Xe+La results: below Pb+Pb/Au+Au, above Ar+Sc/Be+Be/p+p
- New NA61/SHINE Pb+Pb result confirms NA49 data

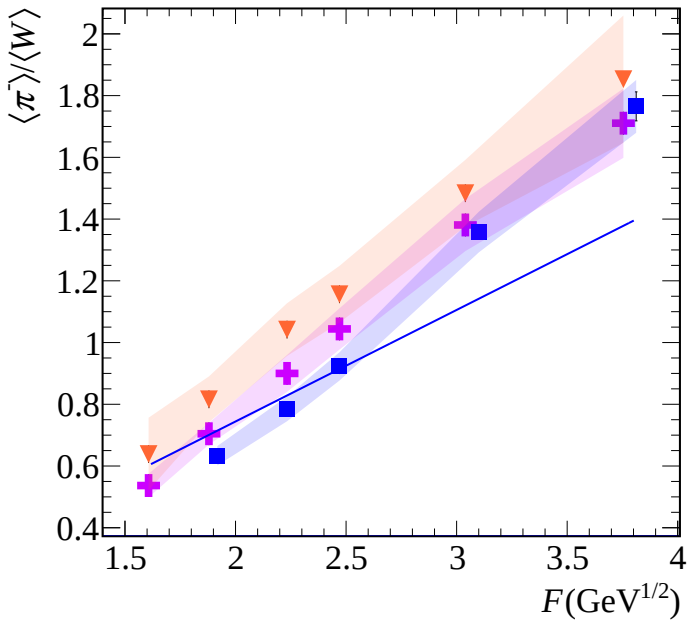
NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416, EPJC 83 (2023) 1, 90 (erratum); world data: see EPJC 84 (2024) 4, 416; NA61/SHINE Preliminary: Xe+La at $y \approx 0$ (0–10%, 13A–75A GeV/c; 0–20%, 150A GeV/c, $0.4 < y < 0.6$), Xe+La 4π (0–10%, 13A–75A GeV/c; 0–20%, 150A GeV/c); Pb+Pb 4π (0–7.2%, 30A GeV/c)

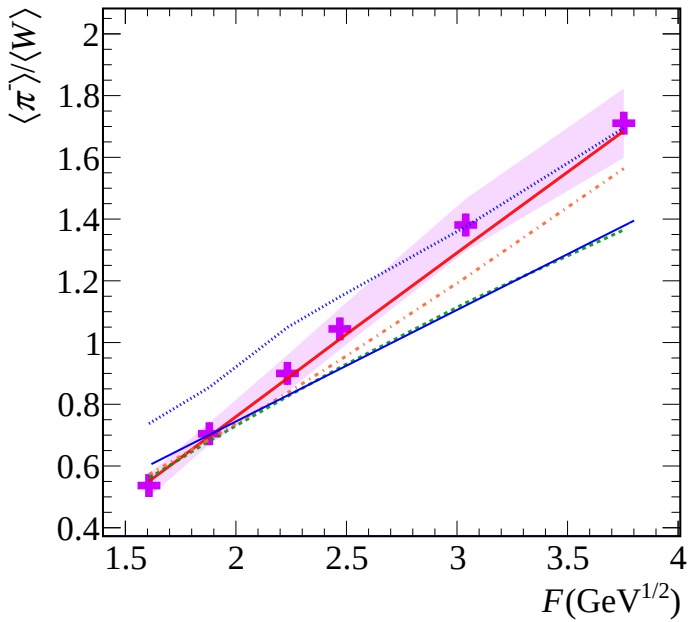
Onset of deconfinement: Kink

Kink: $\langle \pi^- \rangle / \langle W \rangle$ as a function of collision energy

$\langle W \rangle$ - mean number of wounded nucleons





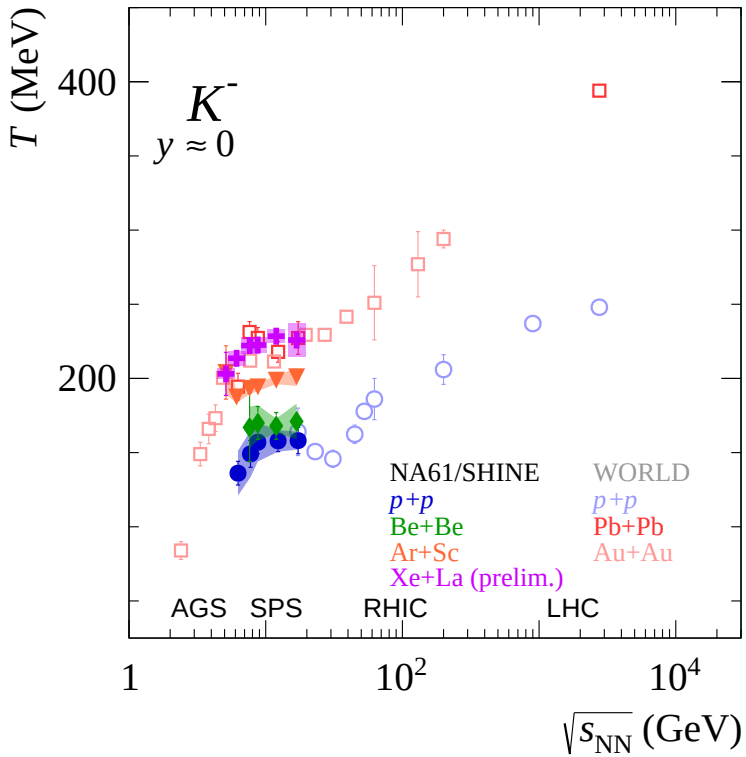


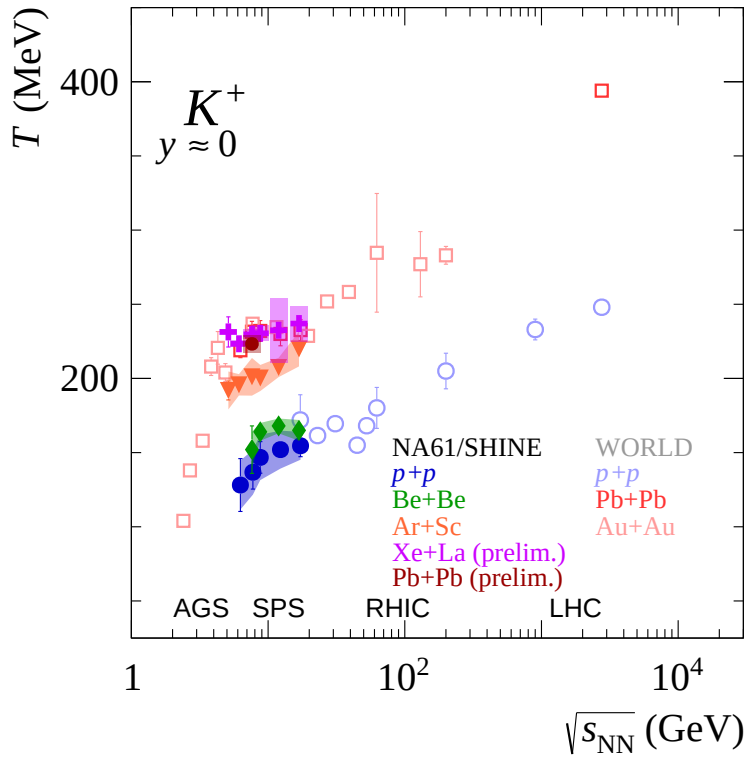
- "Kink" was attributed to the onset of deconfinement

  APPB 30 (1999) 2705
- Xe+La $\approx$ Pb+Pb $>$ $N + N$ at top SPS energies
- Only UrQMD fits Xe+La results well

NA61/SHINE: EPJC 81 (2021) 397;
NA61/SHINE Preliminary: Xe+La (0–10%, 13A–150A GeV/c);
NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903

Onset of deconfinement: Step

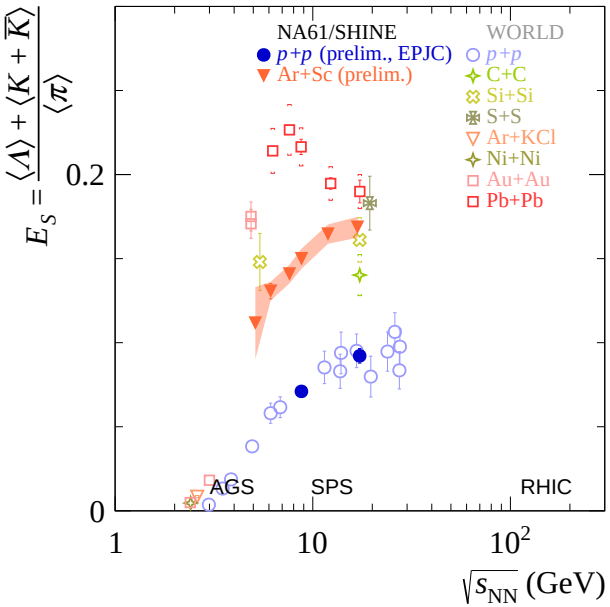


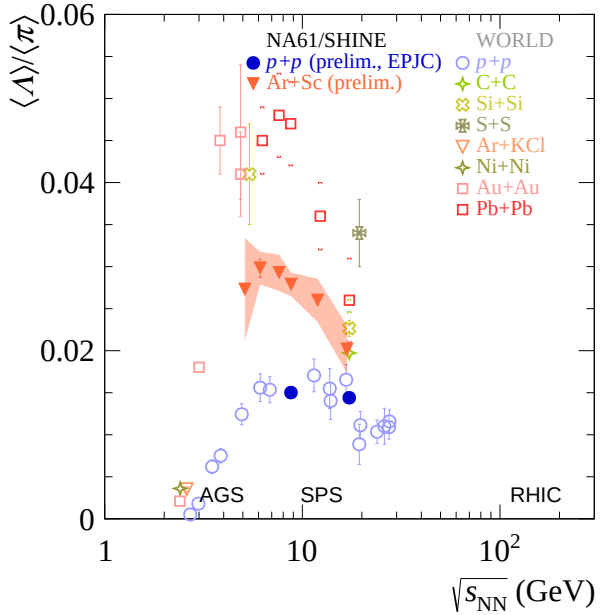


- Inverse slope parameter of transverse momentum/transverse mass spectrum (T) reflects thermal freeze-out + radial flow velocity
- Kaons are weakly affected by rescattering/resonances at SPS
- Step-like structure is visible for all systems
- T increases with energy except the location of horn

NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416, EPJC 83 (2023) 1, 90 (erratum); world data: see EPJC 84 (2024) 4, 416; NA61/SHINE Preliminary: Xe+La at $y \approx 0$ (0–10%, 13A–75A GeV/c; 0–20%, 150A GeV/c, $0.4 < y < 0.6$); Pb+Pb at $y \approx 0$ (0–7.2%, 30A GeV/c, $0.8 < y < 1.0$)

Λ production





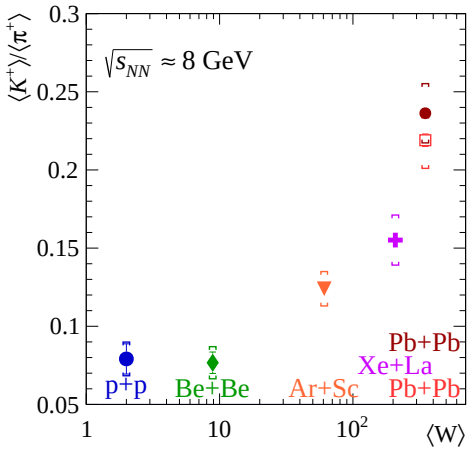
NA61/SHINE:
EPJC 77 (2017) 671,
EPJC 81 (2021) 73,
EPJC 84 (2024) 416,
EPJC 83 (2023) 1, 90 (erratum),
EPJC 82 (2022) 96,
EPJC 84 (2024) 820,
EPJC 76 (2016) 198

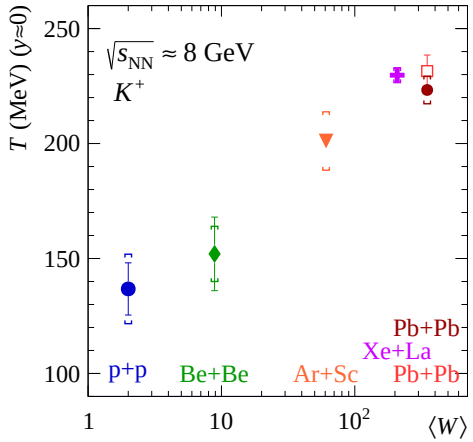
- The $\overline{\Lambda}/\Lambda$ ratio < 0.15 at SPS energies $\Rightarrow$ $\overline{\Lambda}$ contribution to E_S neglected
- In central Pb+Pb and Au+Au collisions, both $\langle\Lambda\rangle/\langle\pi\rangle$ and E_S show a clear maximum near mid-SPS energies
- For Ar+Sc: the $\langle\Lambda\rangle/\langle\pi\rangle$ ratio at SPS follows a trend similar to that observed in heavy Pb+Pb collisions; no horn-like structure in E_S

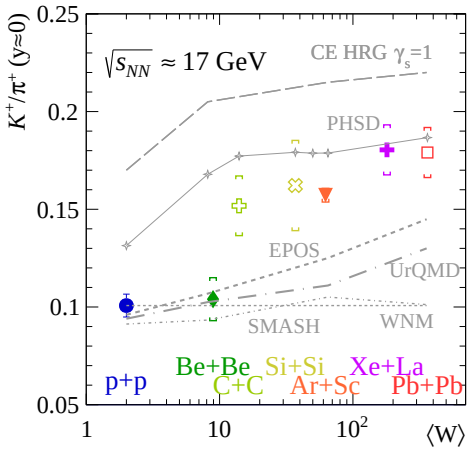
$$\langle\pi\rangle = 1.5 \cdot \left(\langle\pi^+\rangle + \langle\pi^-\rangle\right)$$
$$\langle K + \overline{K}\rangle_{A+A} = 2 \cdot \left(\langle K^+\rangle + \langle K^-\rangle\right)$$
$$\langle K + \overline{K}\rangle_{p+p} = 4 \cdot \langle K^0_S\rangle$$

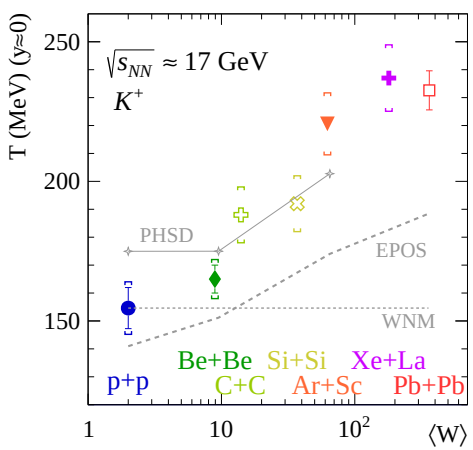
NA61/SHINE Preliminary: Ar+Sc (0–10%, 13A–150A GeV/c), p+p (40A GeV/c)
World data: EPJC 84 (2024) 416,
https://indico.fais.uj.edu.pl/event/48/contributions/360

System size dependence









- K^+/π^+ and T grow with system size
- No model reproduces both K^+/π^+ and $T(y \approx 0)$ over full $\langle W \rangle$

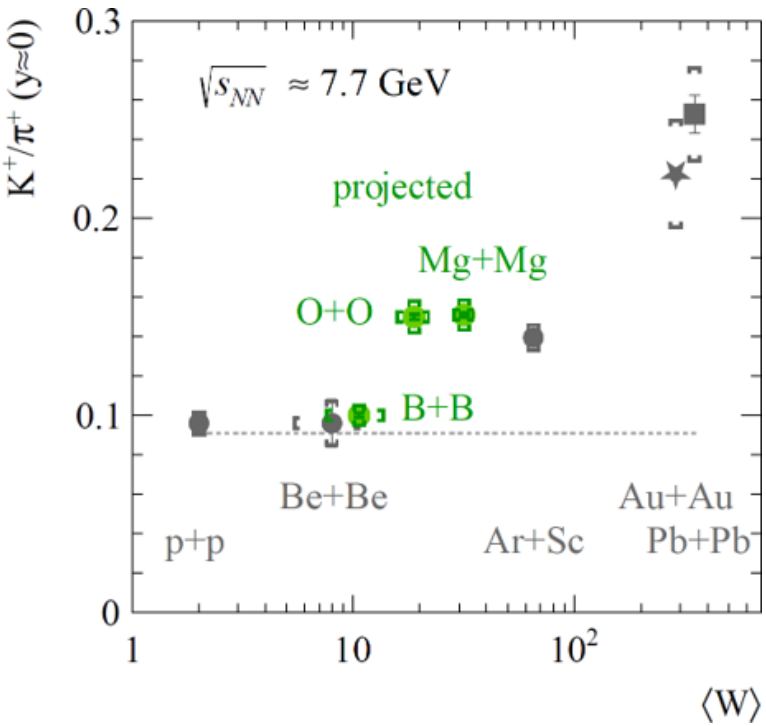
PHSD: EPJA 56 (2020) 9, 223;
SMASH: JPG 47 (2020) 065101;
UrQMD/HRG: PRC 99 (2019) 034909;
WNM: NPB 111 (1976)

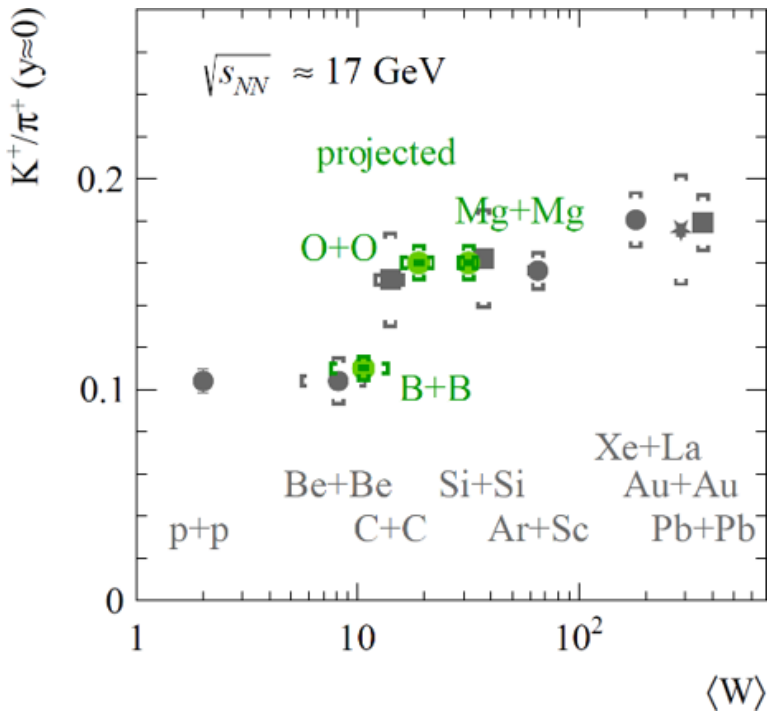
- At the top SPS energy system size hierarchy observed: $(p+p \approx \text{Be+Be}) \leq \text{Ar+Sc} \leq (\text{Xe+La} \approx \text{Pb+Pb})$

NA61/SHINE: EPJC 84 (2024) 4, 416 (Ar+Sc), EPJC 81 (2021) 1, 73 (Be+Be), EPJC 83 (2023) 1, 90 (erratum), EPJC 77 (2017) 10, 671 ($p+p$);
NA61/SHINE Preliminary: Xe+La and Pb+Pb;
see EPJC 84 (2024) 4, 416 for references to world data

Future Plans

- Continuation of 2D scan after LS3 (2029+):
  - B+B (or C+C), O+O, Mg+Mg collisions
- Isospin symmetry violation studies:
  - π^++C, π^-+C (2024 data)
  - Pilot O+O (2025)
- Open charm in high-statistics Pb+Pb





NA61/SHINE: addendum SPSC-P-330-ADD-14 (paper includes preliminary Ar+Sc results)

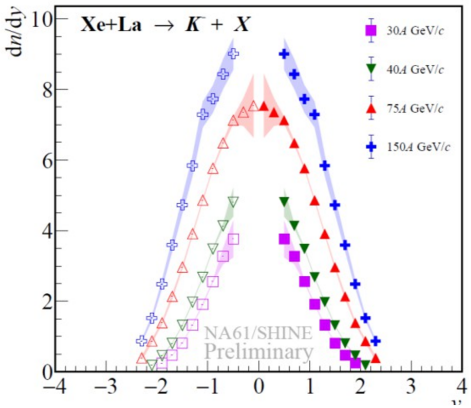
Summary

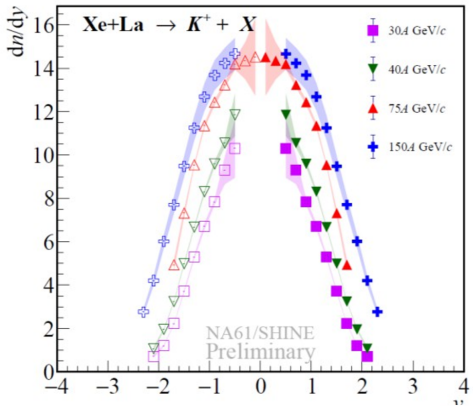
- Unique 2D scan in collision energy and system size is completed
- New results on the onset of deconfinement
  - No horn structure in K^+/π^+ ratio in Xe+La and Ar+Sc collisions
  - No horn structure in E_S for Ar+Sc collisions
- At the top SPS energy system size hierarchy found:
  $(p+p \approx \text{Be+Be}) \leq \text{Ar+Sc} \leq (\text{Xe+La} \approx \text{Pb+Pb})$
- Exciting physics program ahead after LS3

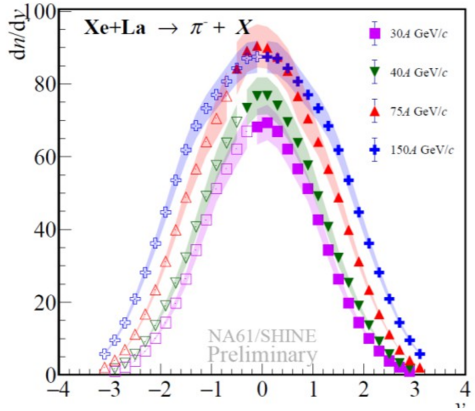
Thank you for your attention!

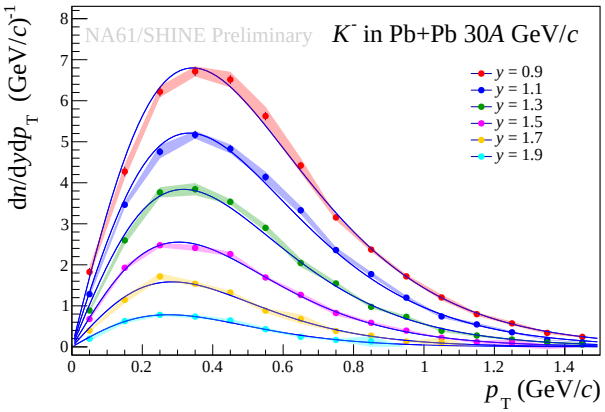
Back Up

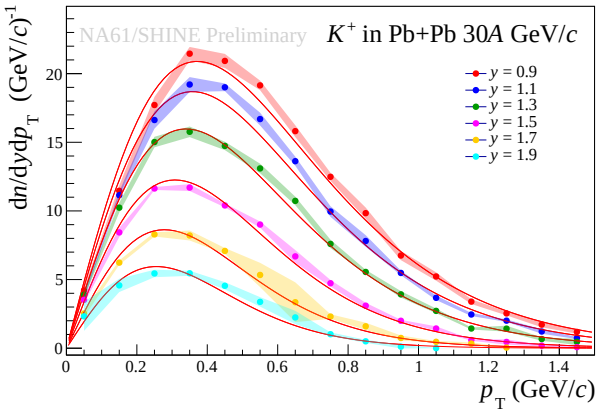
Particle spectra: Xe+La and Pb+Pb

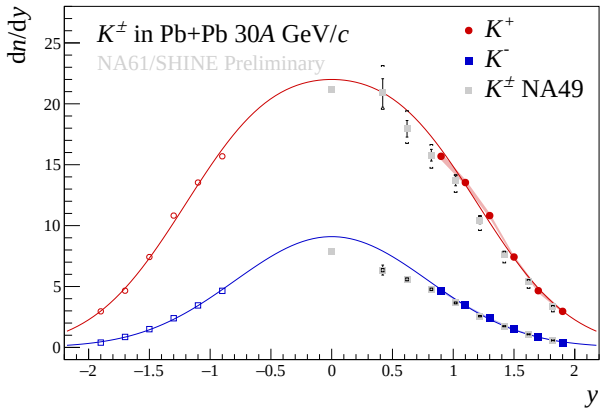












Preliminary spectra:

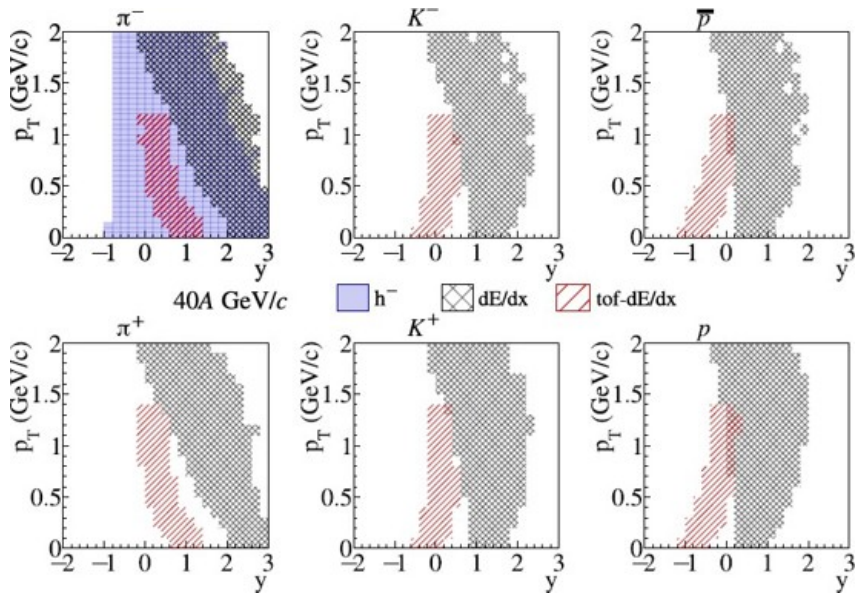
- 10% central Xe+La at 30A, 40A, 75A GeV/c
- 20% central Xe+La at 150A GeV/c
- 7.2% central Pb+Pb at 30A GeV/c
- Spectra obtained via h^- and dE/dx methods

NA61/SHINE: U. Shah, QM 2025 poster

Charged particle identification

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

- h^- analysis based on the fact that the majority of negatively charged particles are π^- mesons. Contribution of the other particles is subtracted using EPOS Monte Carlo
- dE/dx analysis uses TPC energy loss information to identify particles
- *tof*-dE/dx method estimates number of π, K, p using an energy loss and a particle time of flight measurements



NA61/SHINE: EPJC 84 (2024) 416