Probing the onset of deconfinement: recent results from the NA61/SHINE experiment

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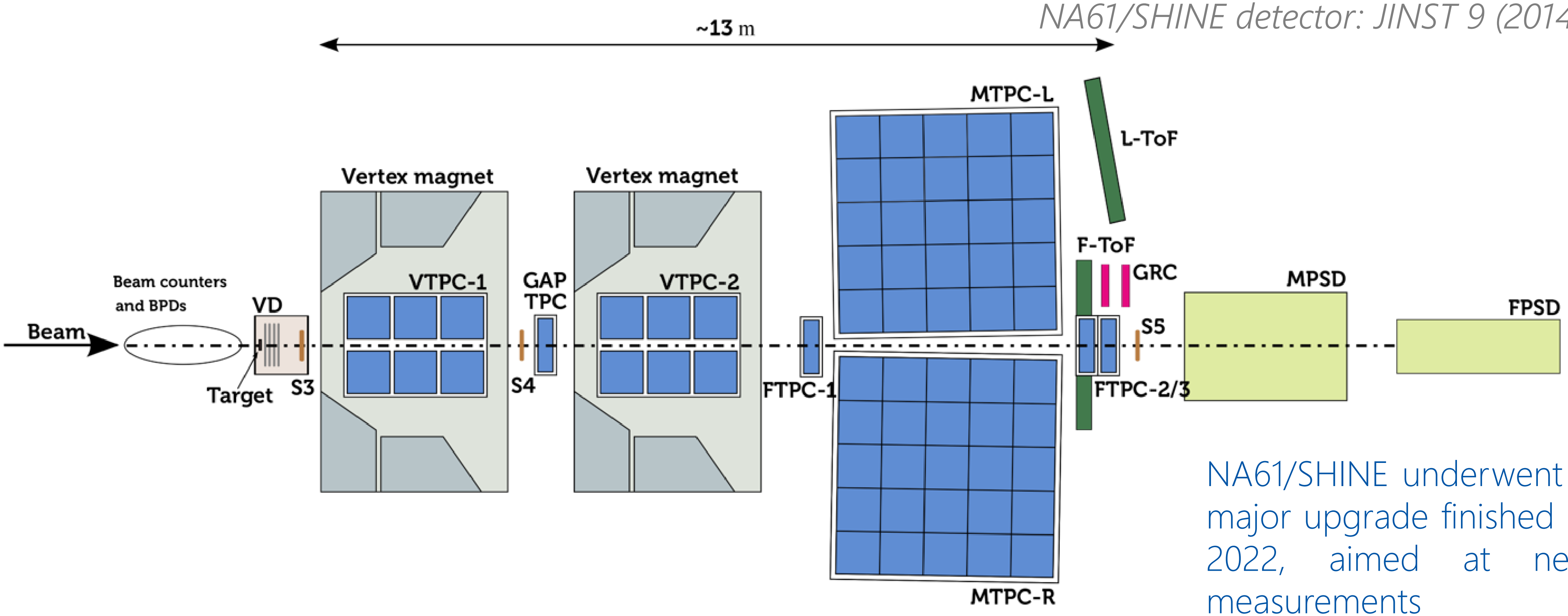
for the NA61/SHINE collaboration

NA61/SHINE experiment at CERN SPS

NA61/SHINE experiment at CERN SPS

NA61/SHINE detector: JINST 9 (2014) P06005



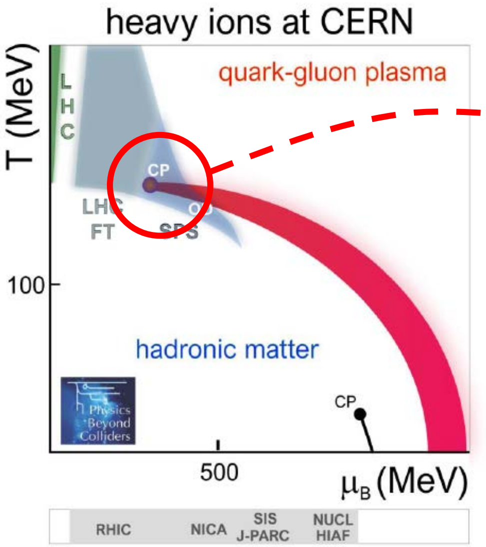
NA61/SHINE underwent a major upgrade finished in 2022, aimed at new measurements

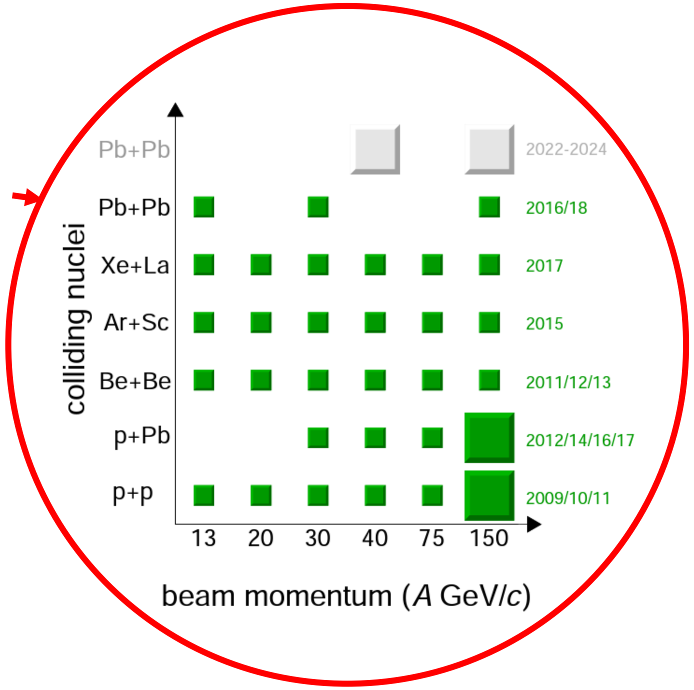
- hadron beams (π, K, p) at 13-400 GeV/*c*
- ion beams (Be, Ar, Xe, Pb) at 13*A*-150*A* GeV/*c*
- $\sqrt{s_{NN}} \approx 5 - 17$ GeV

NA61/SHINE research programme

Strong interactions physics:

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





as well as

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

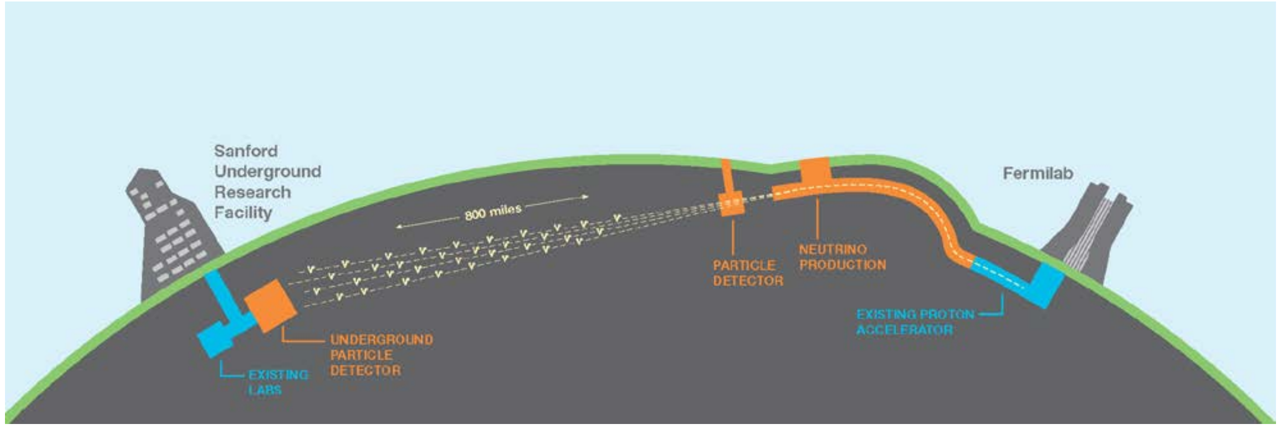
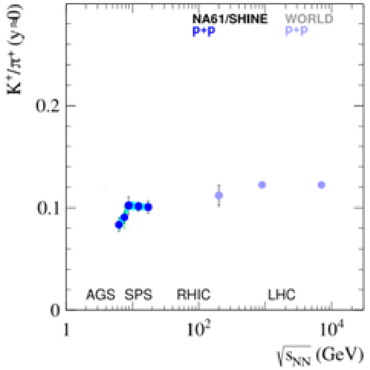


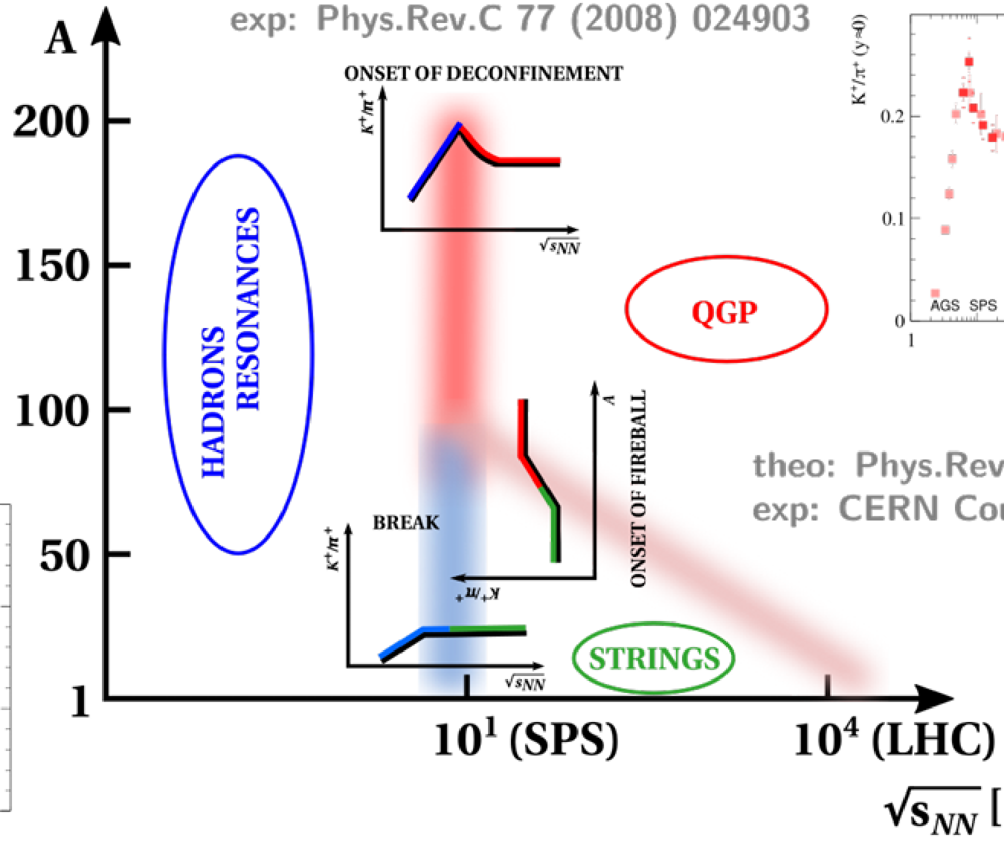
Diagram of high-energy nuclear collisions

Hypothetical domains of hadron production dominated by:

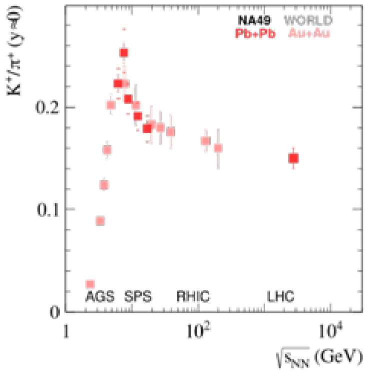
- resonance creation and decays
- string creation and fragmentation
- quark-gluon plasma formation and hadronisation

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

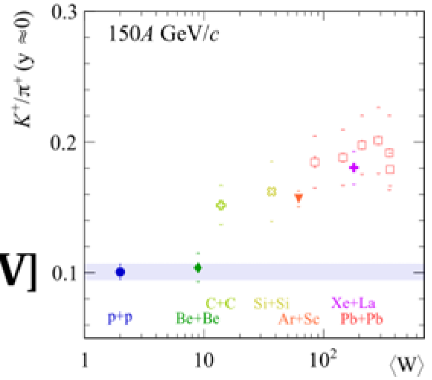




theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77 (2008) 024903



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

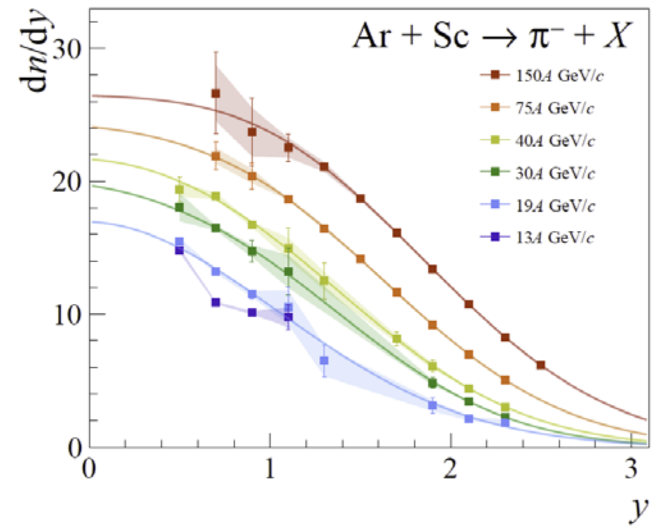


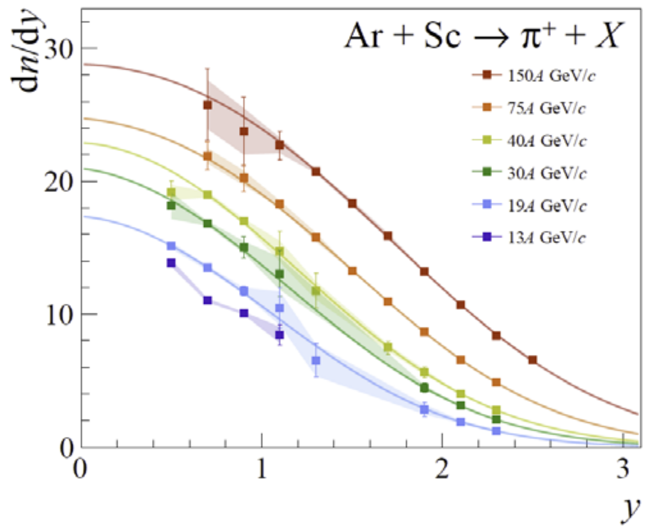
Universe 9 (2023) 2, 106

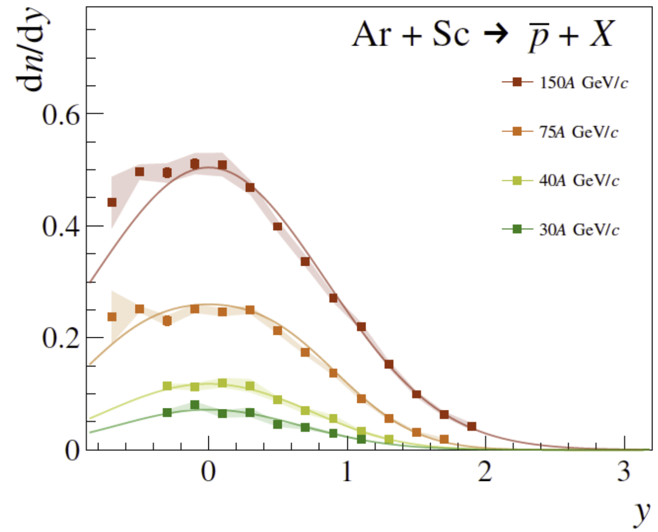
New results on spectra of charged hadrons

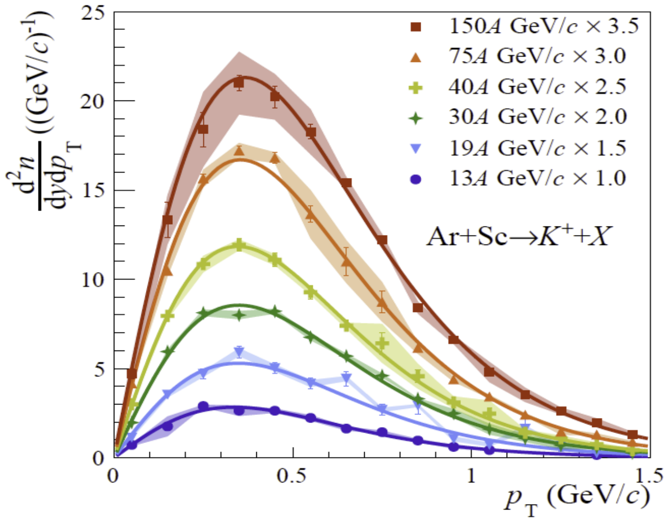
Spectra of charged hadrons in Ar+Sc collisions

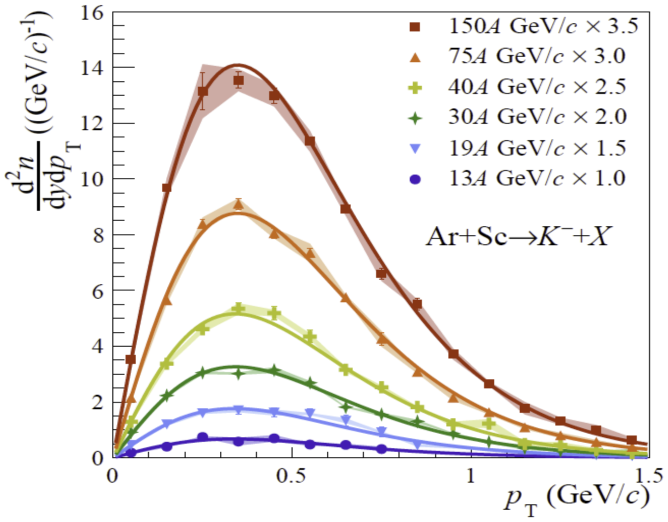
arXiv:2308.16683







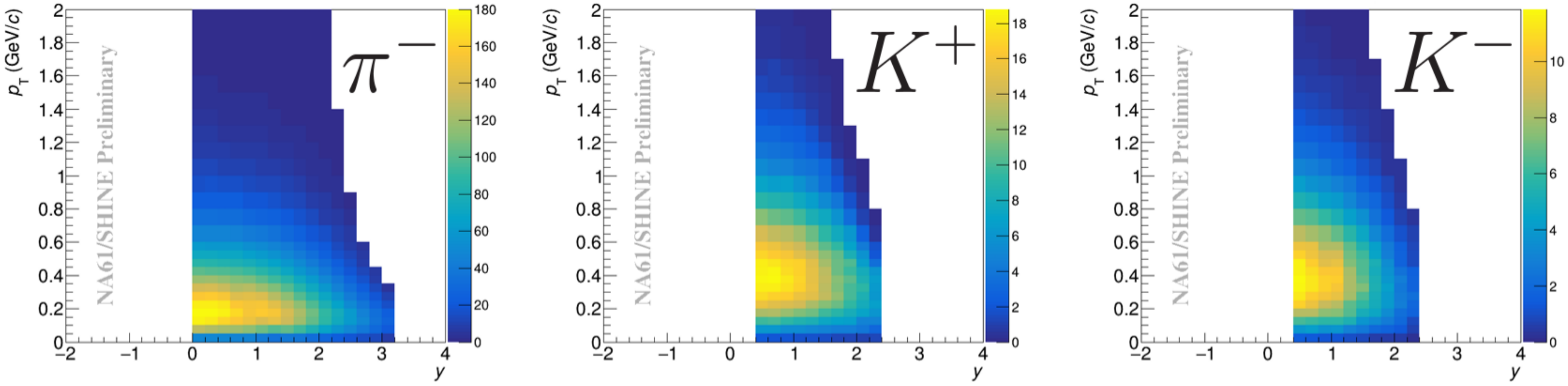


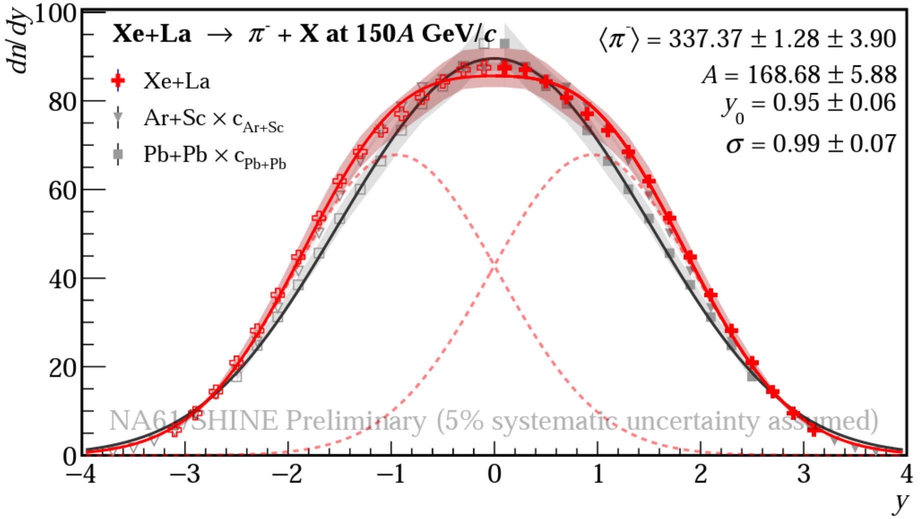


- 10% most central $^{40}Ar + {}^{45}Sc$ events
- new final results on $K^{\pm}$, $\pi^{\pm}$, p and $\bar{p}$ spectra at six beam energies ($\sqrt{s_{NN}} = 5.1 - 16.8$ GeV)

Spectra of charged hadrons in Xe+La collisions

NA61/SHINE
preliminary



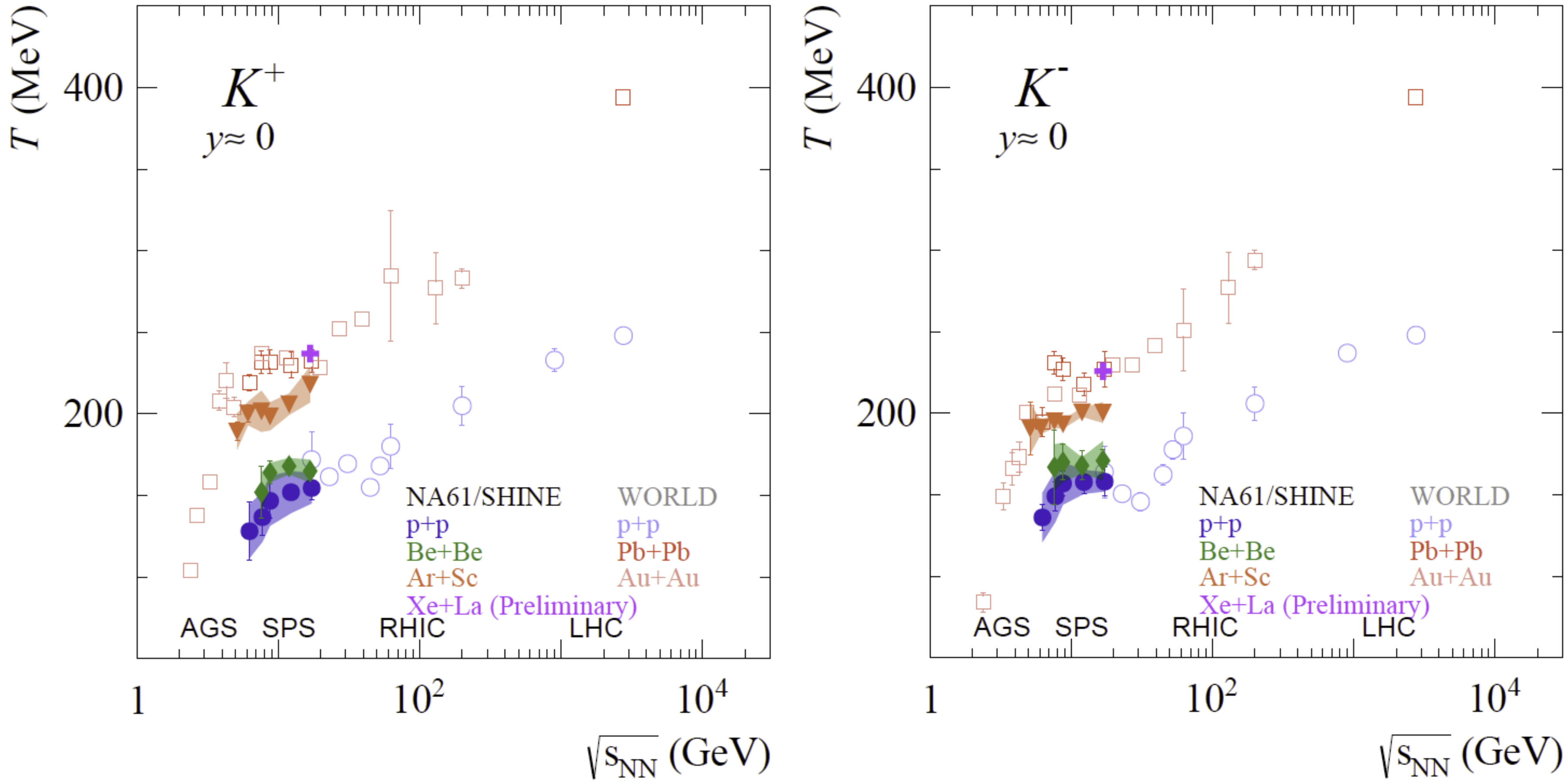


- 20% most central $^{54}Xe + {}^{57}La$ events
- new preliminary results on $K^{\pm}$ and $\pi^{\pm}$ spectra at $\sqrt{s_{NN}} = 16.8$ GeV

Study of the onset of deconfinement

System size dependence of inverse slope parameter

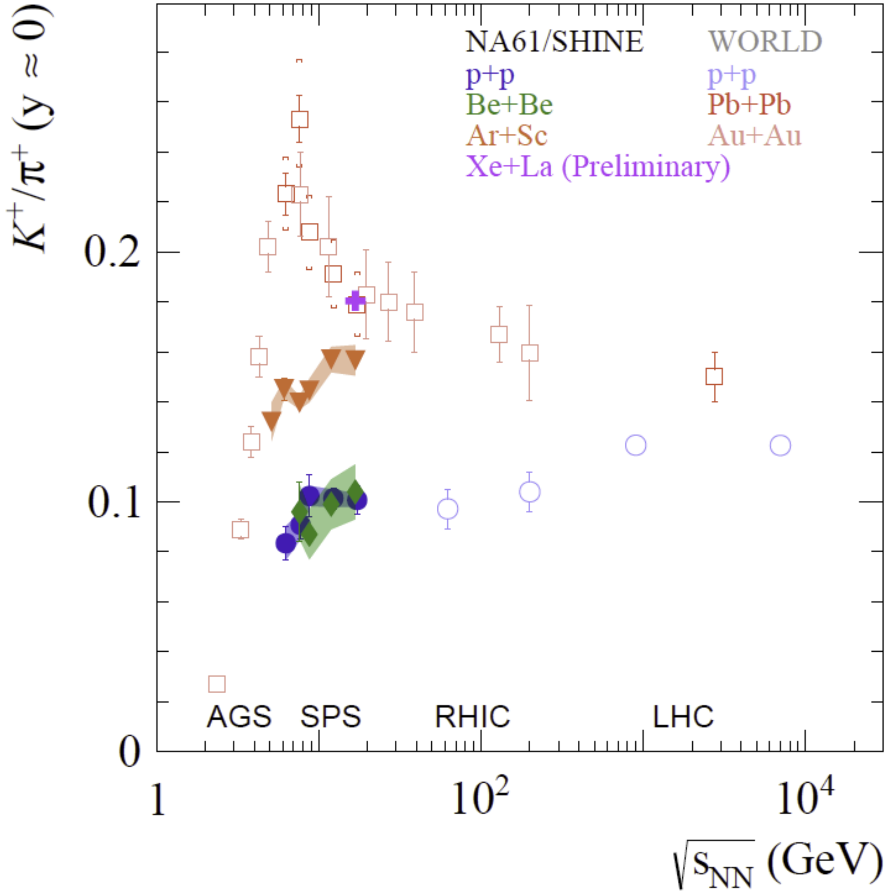
- kaons are only weakly affected by re-scattering and resonance decays during the post-hydro phase (at SPS and RHIC energies)
- connected with temperature of the freeze-out surface and not early-stage fireball

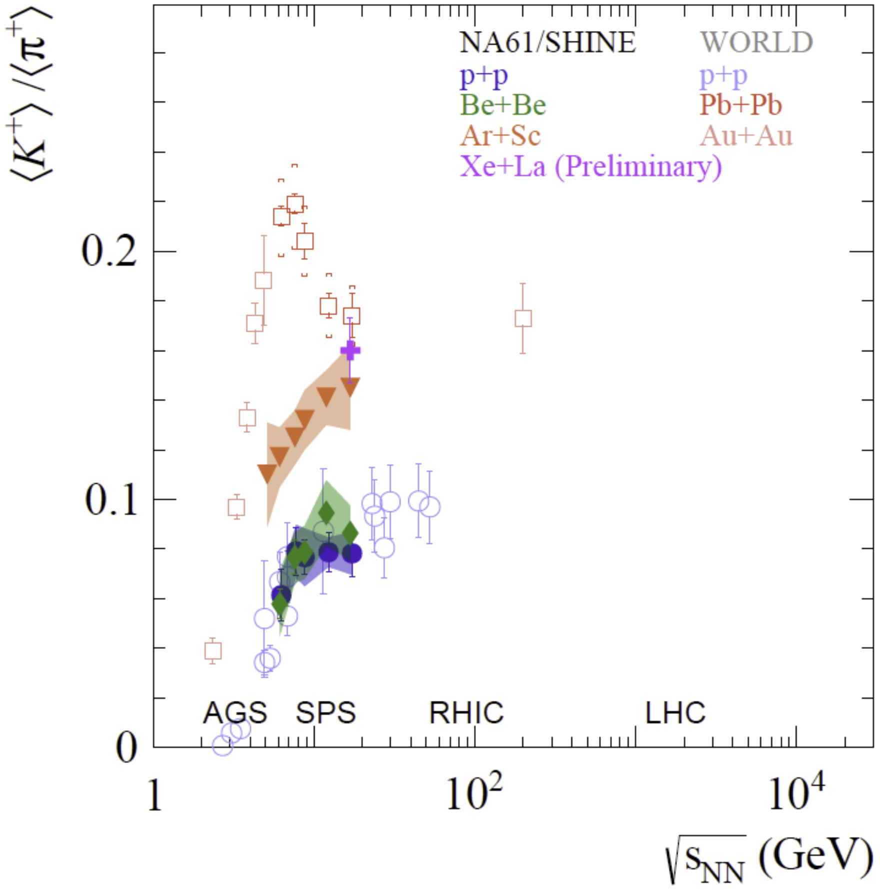


- ➢ qualitatively similar energy dependence is seen for different collision systems
- ➢ magnitude of T increases with the system size

System size dependence of strangeness production

- good measure of the strangeness to entropy ratio, which is different in the confined phase (HG) and deconfined phase (QGP)
- probe of the onset of deconfinement



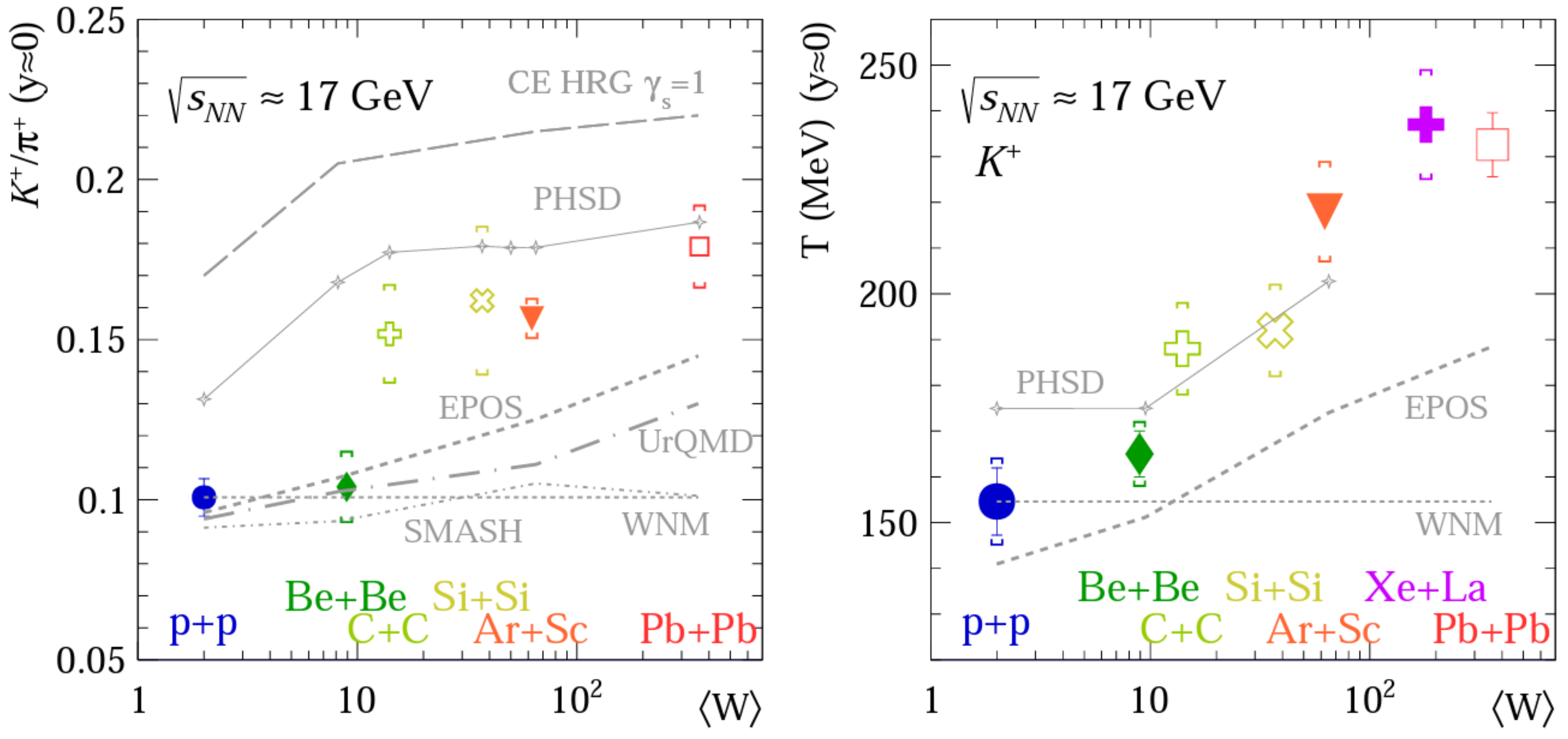


- ➢ plateau-like structure is visible in p+p, Be+Be and Ar+Sc
- ➢ Ar+Sc is higher than p+p and Be+Be
- ➢ Xe+La is close to Pb+Pb

Study of the onset of fireball

System size dependence of particle production properties

- onset of fireball — rapid change of observables when going from small to intermediate and large systems → beginning of the creation of large clusters of strongly interacting matter?



p+p: Eur. Phys. J. C 77 (2017) 10, 671
Be+Be: Eur. Phys. J. C 81 (2021) 1, 73
Ar+Sc: CERN-EP-2023-179
Xe+La: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C 66, 054902 (2002)

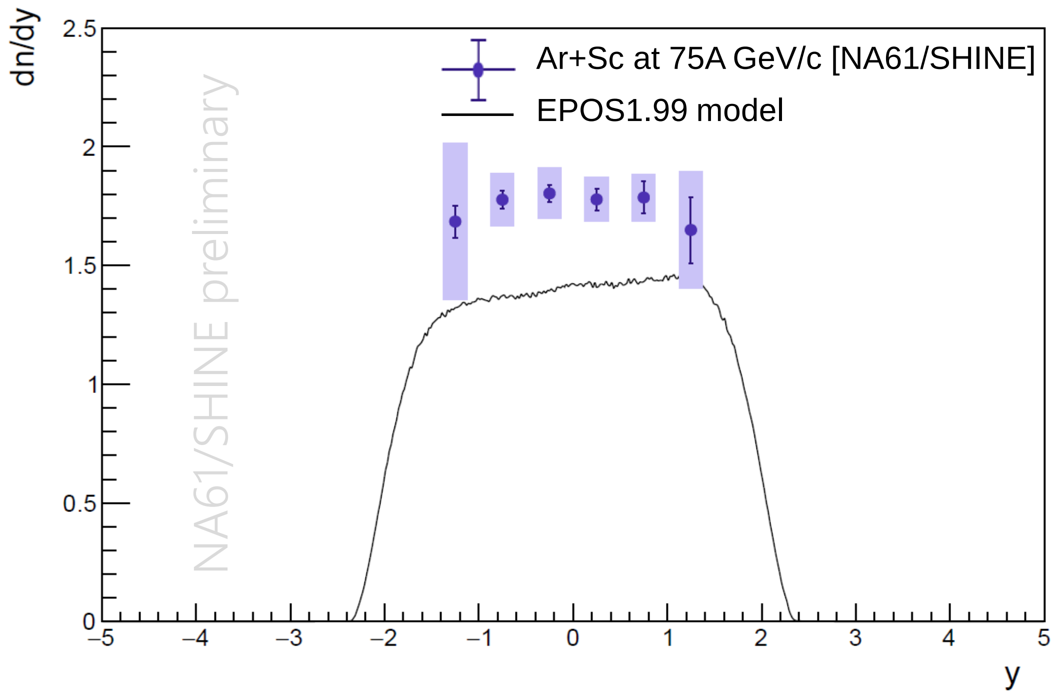
PHSD: Eur. Phys. J. A 56 (2020) 9, 223, arXiv:1908.00451 and private communication
SMASH: J. Phys. G 47 (2020) 6, 065101 and private communication
UrQMD and HRG: Phys. Rev. C 99 (2019) 3, 034909

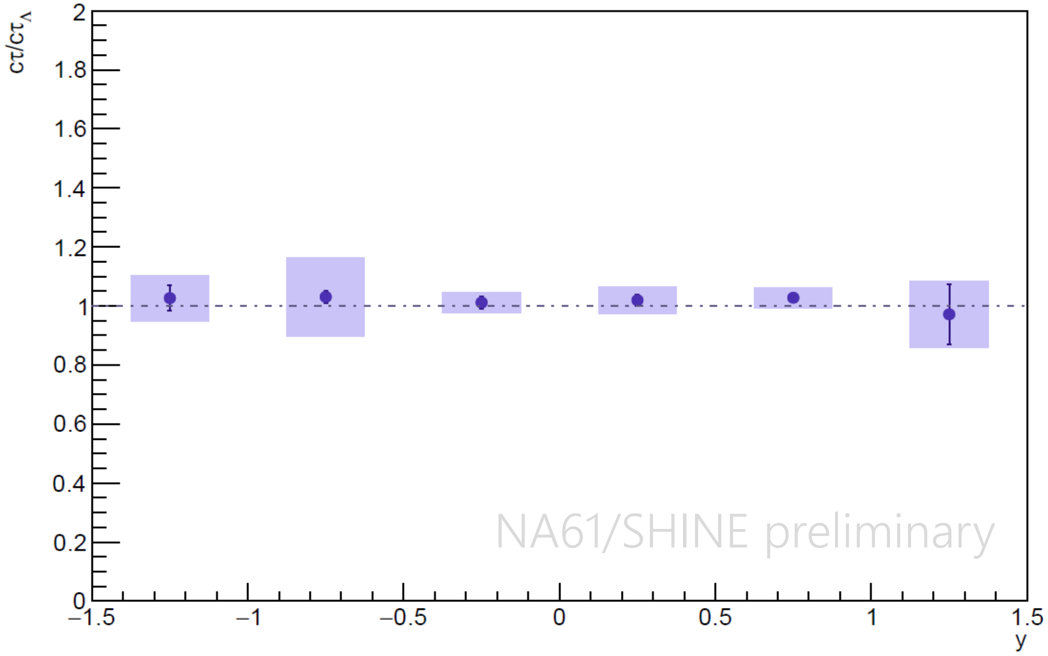
➢ none of the models can reproduce neither $K^+/_{\pi^+}$ nor T for the whole $\langle W \rangle$ range

New results on spectra of neutral hadrons

Λ production in Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV

NA61/SHINE preliminary

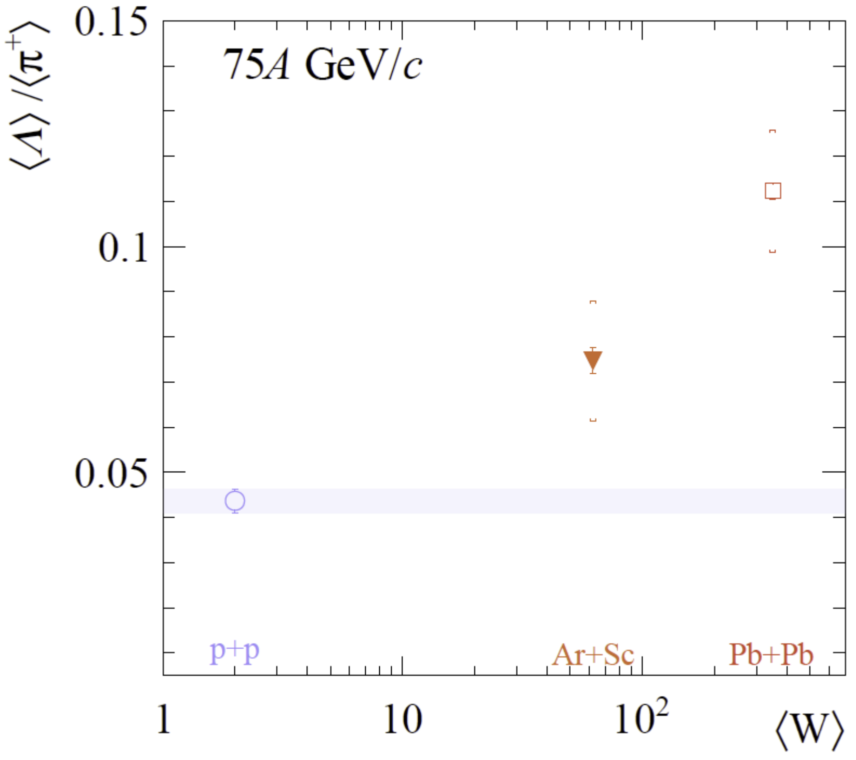


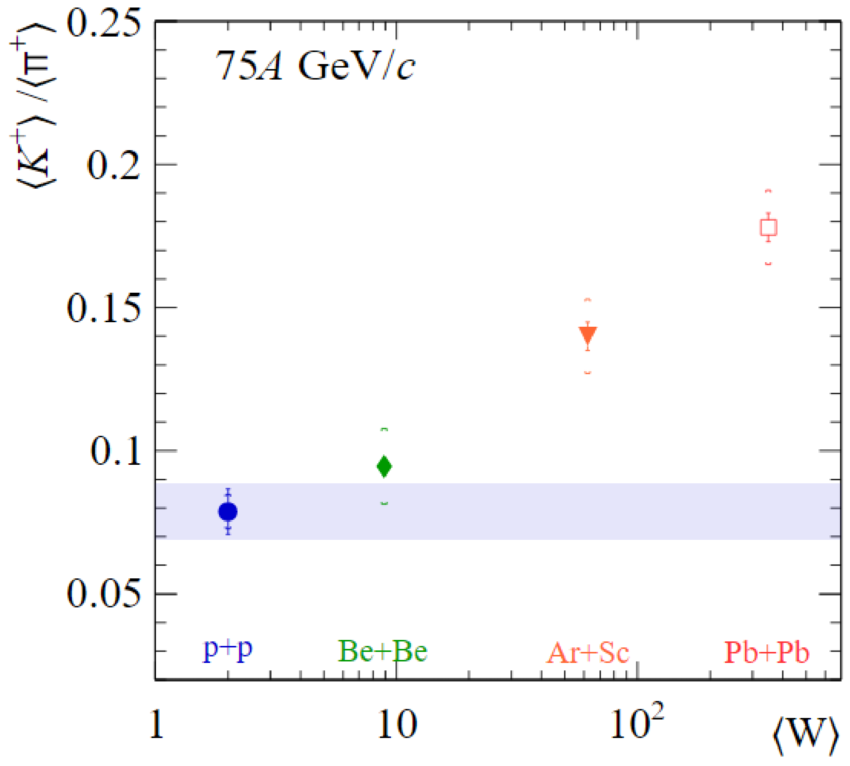


- 10% most central $^{40}Ar + {}^{45}Sc$ events
- reconstruction through $p\pi^-$ decay mode (BR ≈ 63.9 %)
- mean multiplicity: $\langle\Lambda\rangle = 6.44 \pm 0.24\ (stat) \pm 1.10\ (sys)$
- EPOS underestimates the Λ yields by 20-25%

System size dependence of $\langle\Lambda\rangle/\langle\pi^+\rangle$ and $\langle K^+\rangle/\langle\pi^+\rangle$ ratios

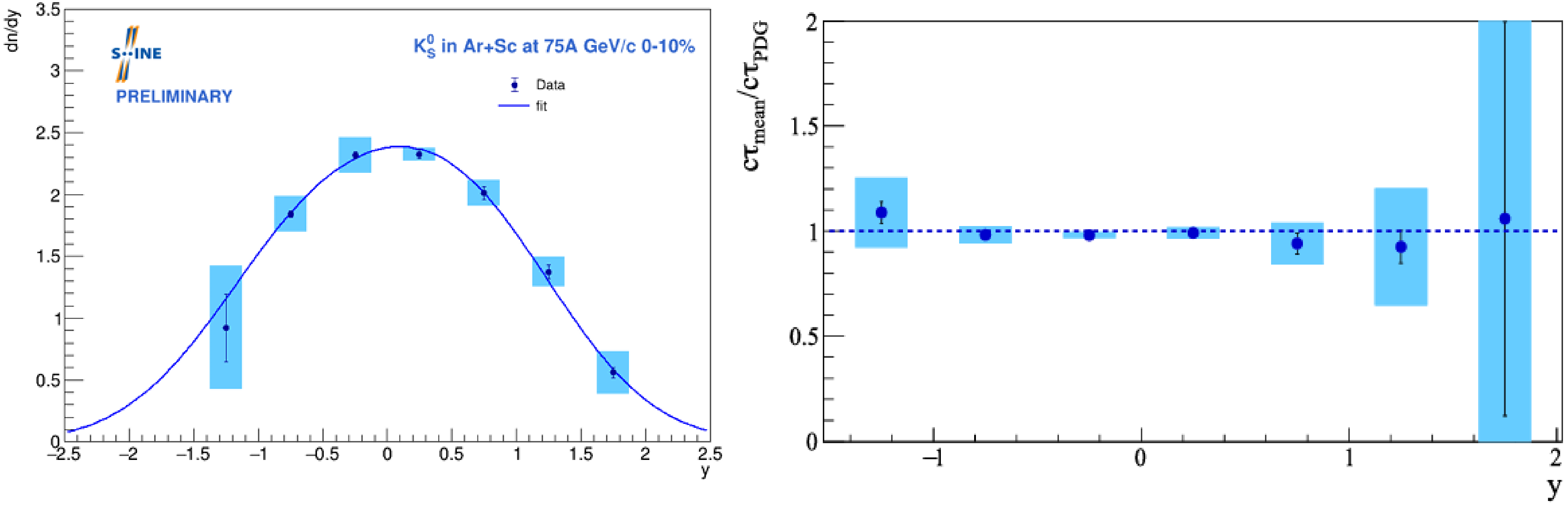
NA61/SHINE preliminary





- $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio follows a similar trend to that of $\langle K^+\rangle/\langle\pi^+\rangle$ ratio for different collision systems

K_S^0 production in Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV

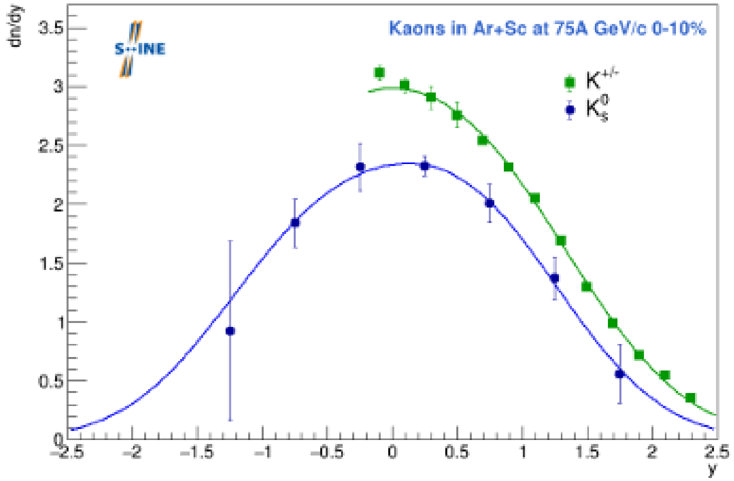


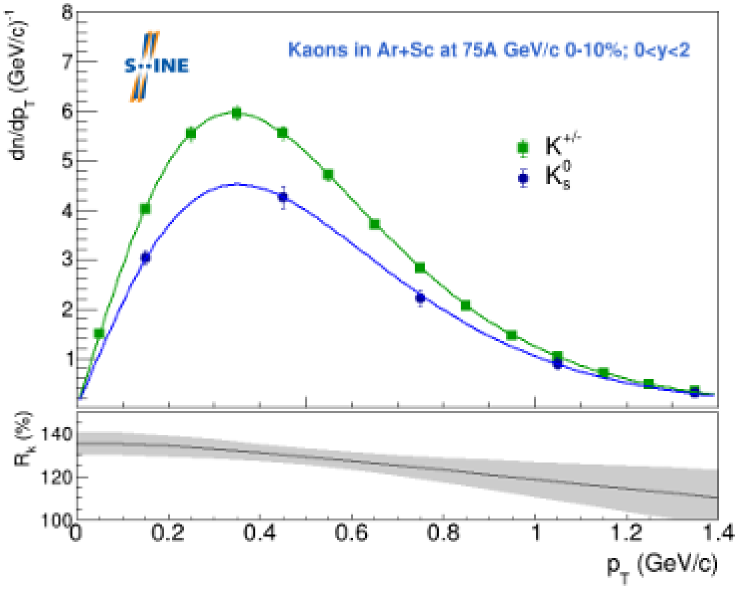
NA61/SHINE preliminary

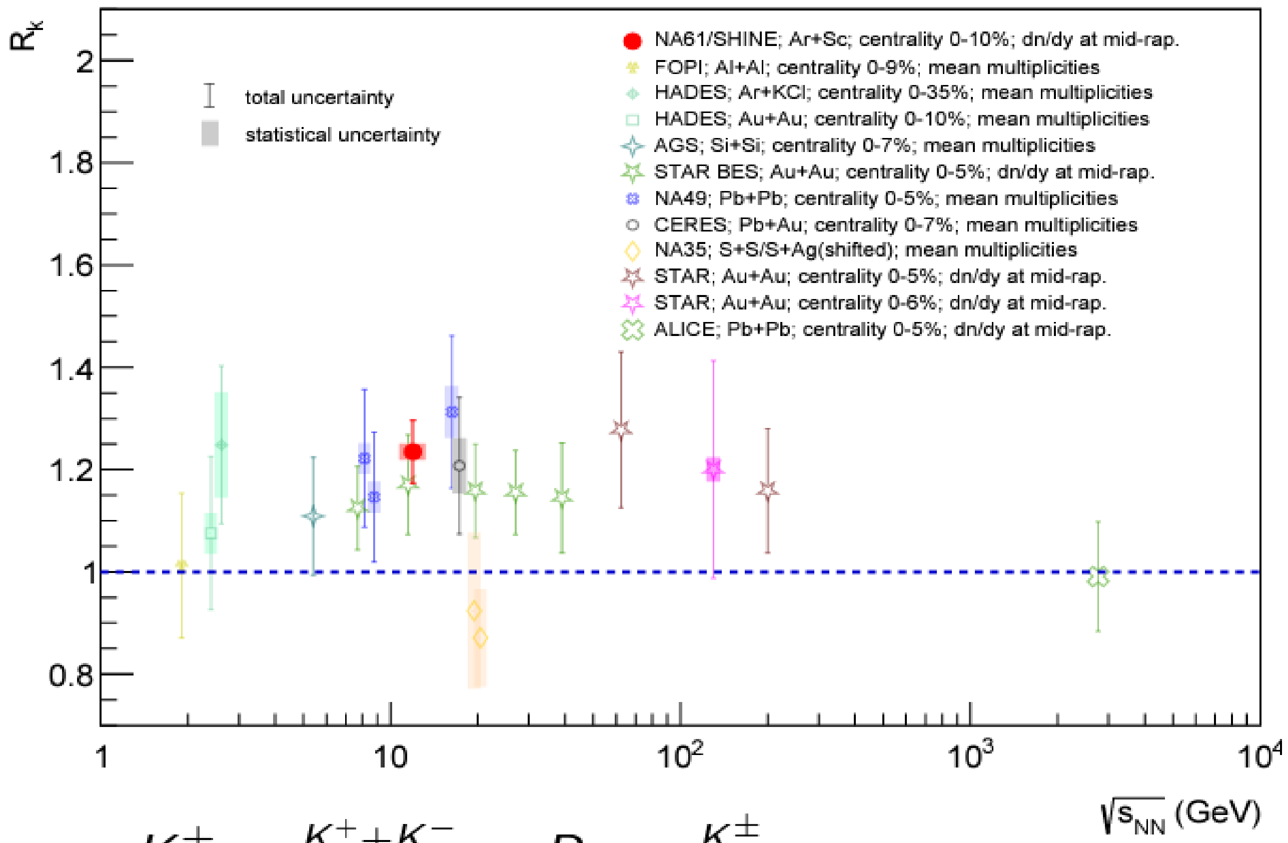
- 10% most central ${}^{40}Ar + {}^{45}Sc$ events
- reconstruction through $\pi^+\pi^-$ decay mode (BR ≈ 69.2 %)
- mean multiplicity: $\langle K_S^0 \rangle = 6.25 \pm 0.09\ (stat) \pm 0.73\ (sys)$

K_S^0 vs. $K^{\pm}$ production in Ar+Sc collisions

NA61/SHINE preliminary







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

- ➢ around 15-30 % difference in the whole rapidity and transverse momentum range

Summary

- ✓ the NA61/SHINE **two-dimensional scan** in system size and collision energy was successfully completed in 2017 with Xe+La data
- ✓ no indication of **horn** in Ar+Sc collisions
- ✓ **unexpected** system size dependence: (p+p ≈ Be+Be) ≠ (Ar+Sc ≠ Pb+Pb ≈ Xe+La)
- ✓ observed **anomaly** in charged over neutral kaon meson production
- ✓ various analyses **ongoing** for p+p, Be+Be, Ar+Sc, Xe+La and Pb+Pb data, and new measurements and results are on the way → **stay tuned**!

Thank you for your attention!

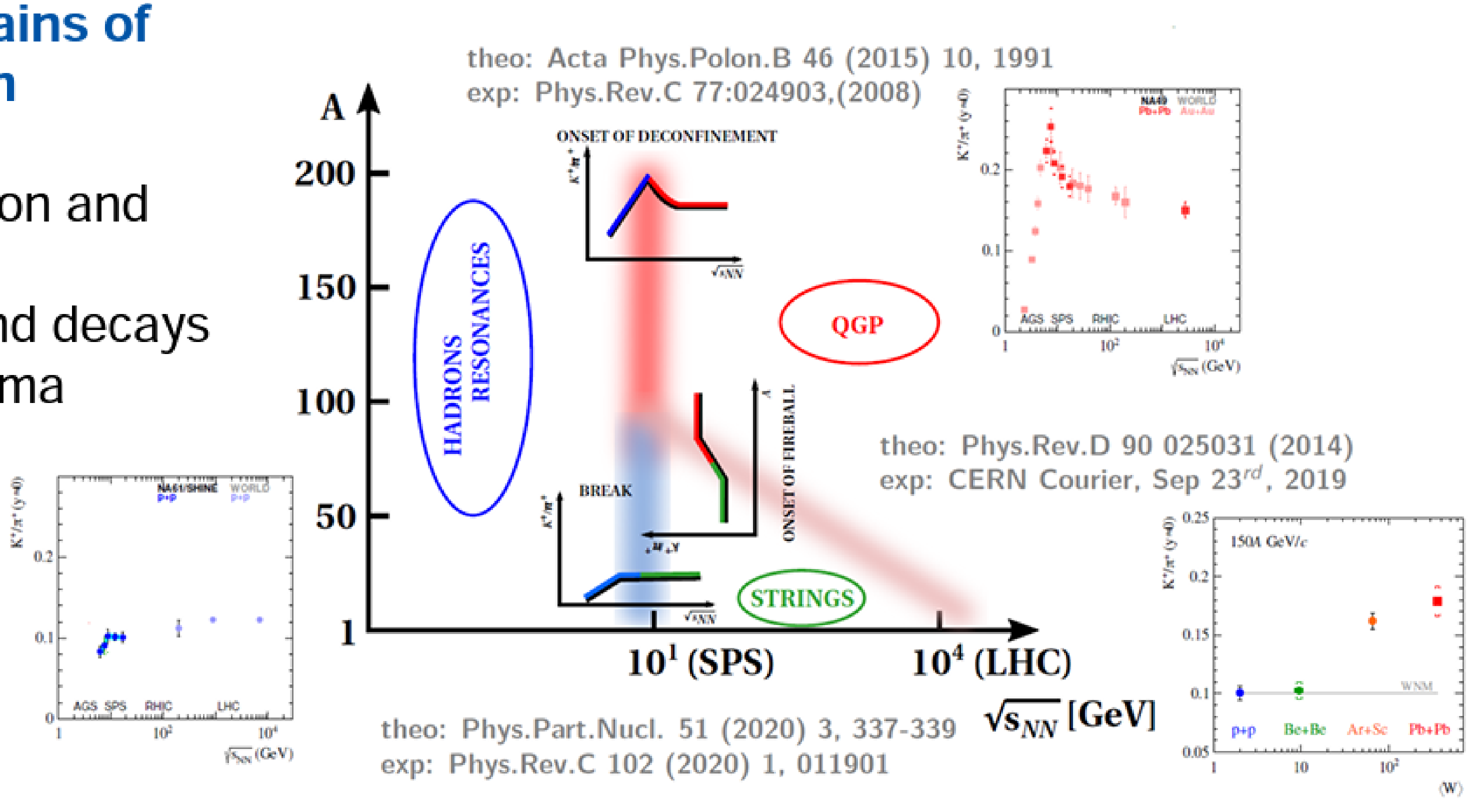
All comments and questions are very welcome:
yuliia.balkova@cern.ch

Backup

Diagram of high-energy nuclear collisions

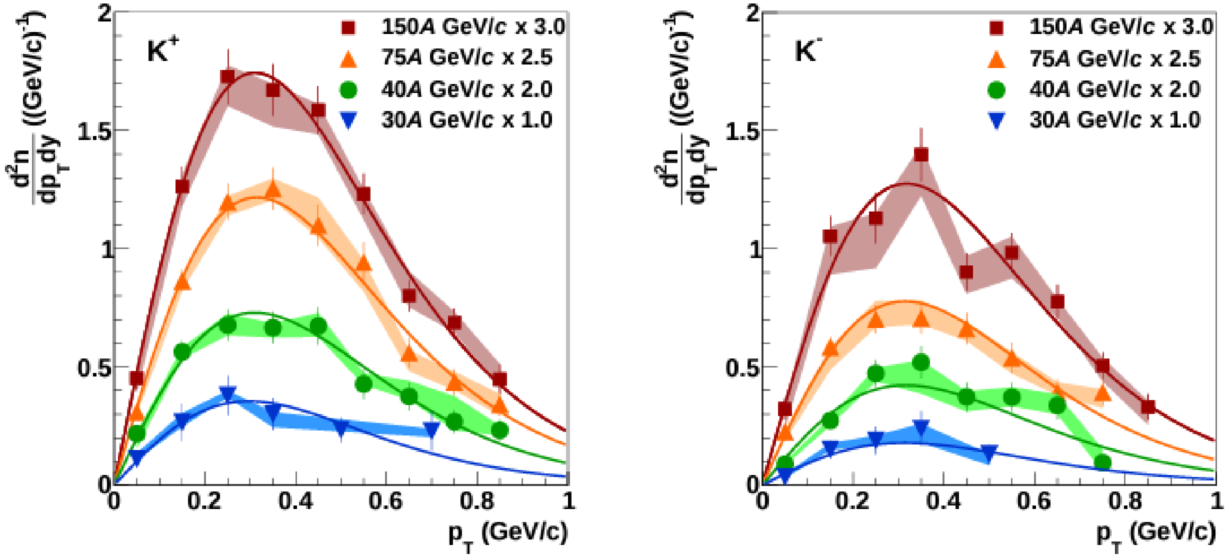
Hypothetical domains of hadron-production dominated by:

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

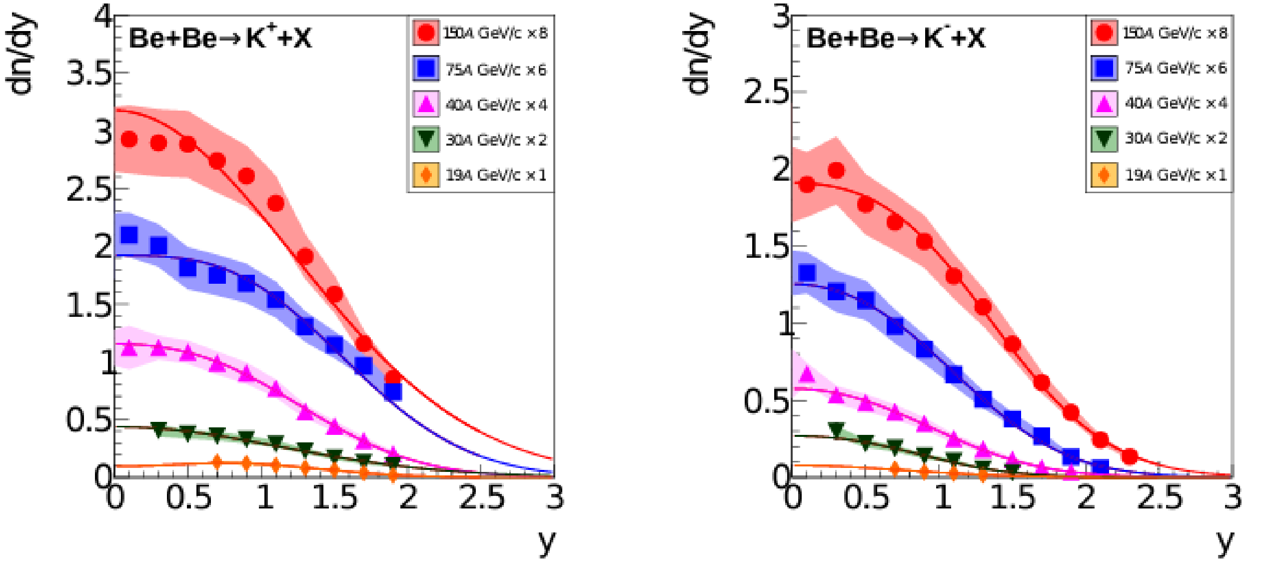


$K^{\pm}$ spectra in Be+Be collisions

p_T spectra at midrapidity



rapidity spectra

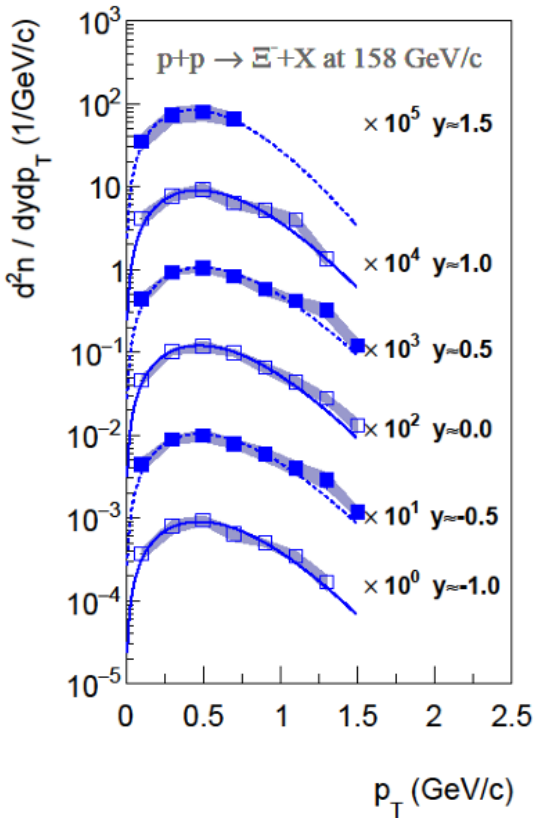


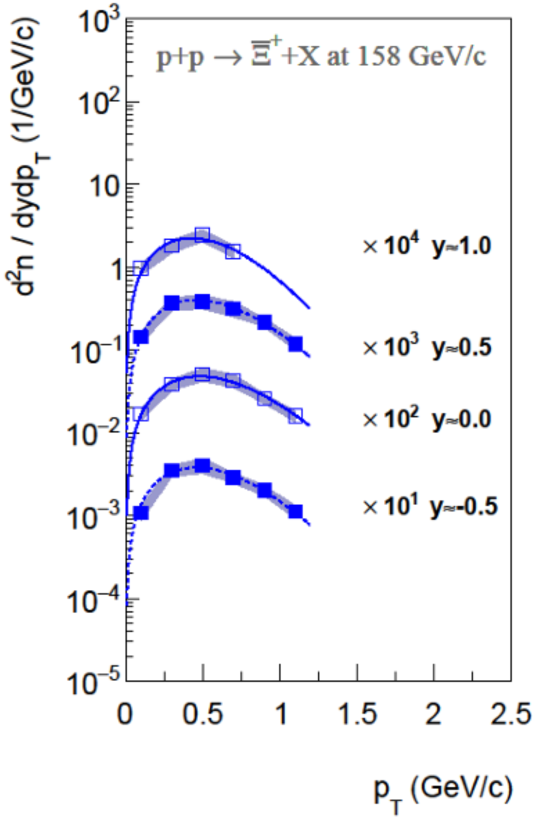
- 20% most central $^{7}Be + {}^{9}Be$ events
- p_T spectra are fitted with $\frac{d^2n}{dp_T\,dy} = \frac{S\,p_T}{T^2 + T\,m_K} exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$
- rapidity spectra are fitted with a sum of Gaussians to obtain mean multiplicities $\langle K^+\rangle, \langle K^-\rangle$

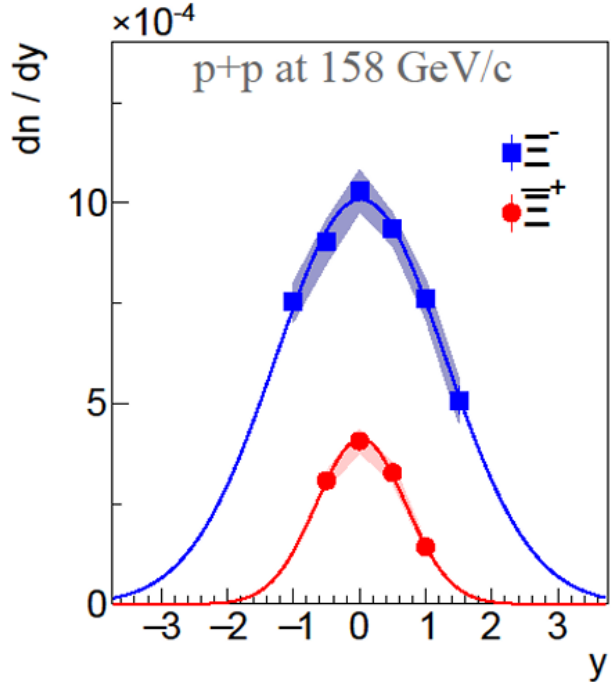
Eur. Phys. J. C 81 (2021) 1, 73

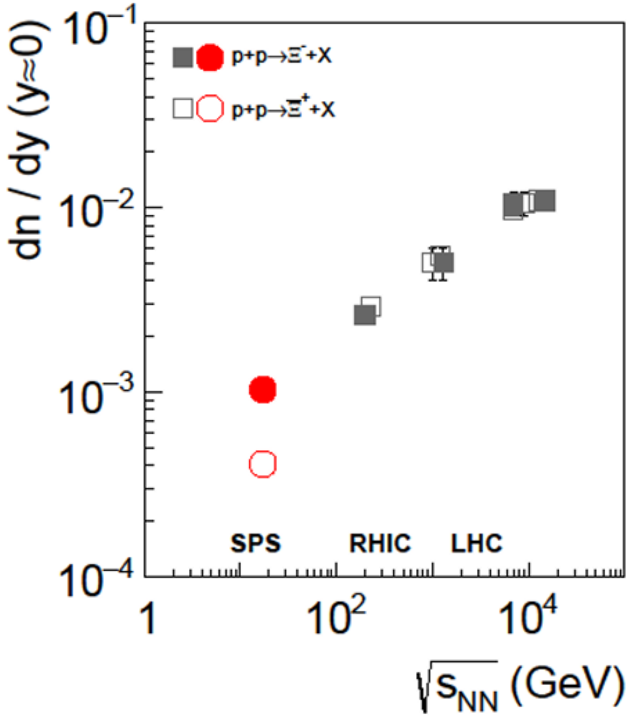
Ξ^- & $\overline{\Xi}^+$ spectra in p+p collisions at 158 GeV/c

- the only results on Ξ^- & $\overline{\Xi}^+$ production in p+p collisions at CERN SPS energy range







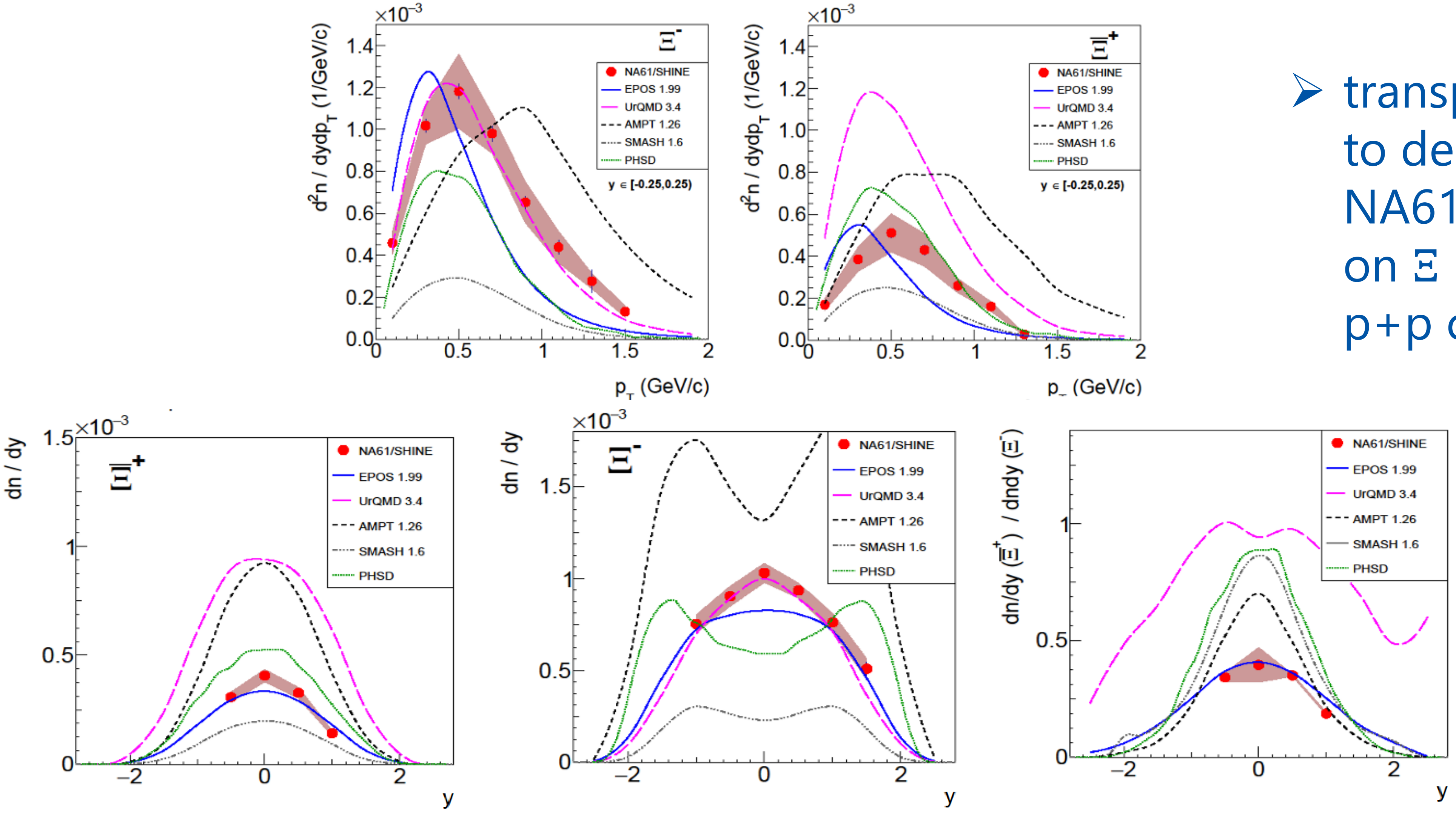


➢ strong suppression of $\overline{\Xi}^+$ production:

$$\langle\overline{\Xi}^+\rangle/\langle\Xi^-\rangle = 0.24 \pm 0.01 \pm 0.05$$

Eur. Phys. J. C 80 (2020) 9, 833, Erratum: Eur. Phys. J. C 82 (2022) 2, 174

Ξ^- & $\overline{\Xi}^+$ spectra in p+p collisions – model comparison

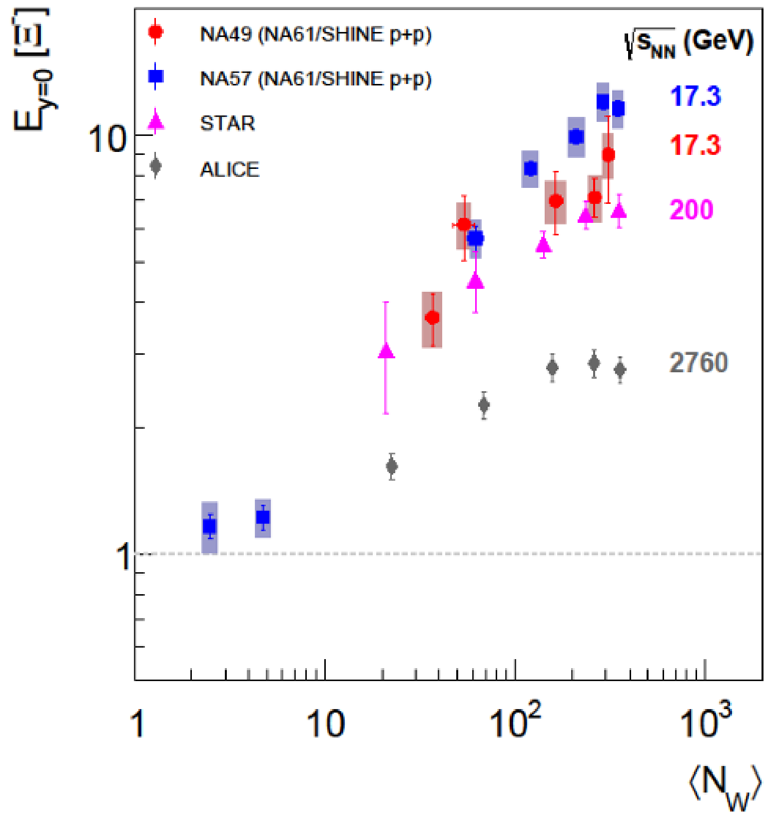


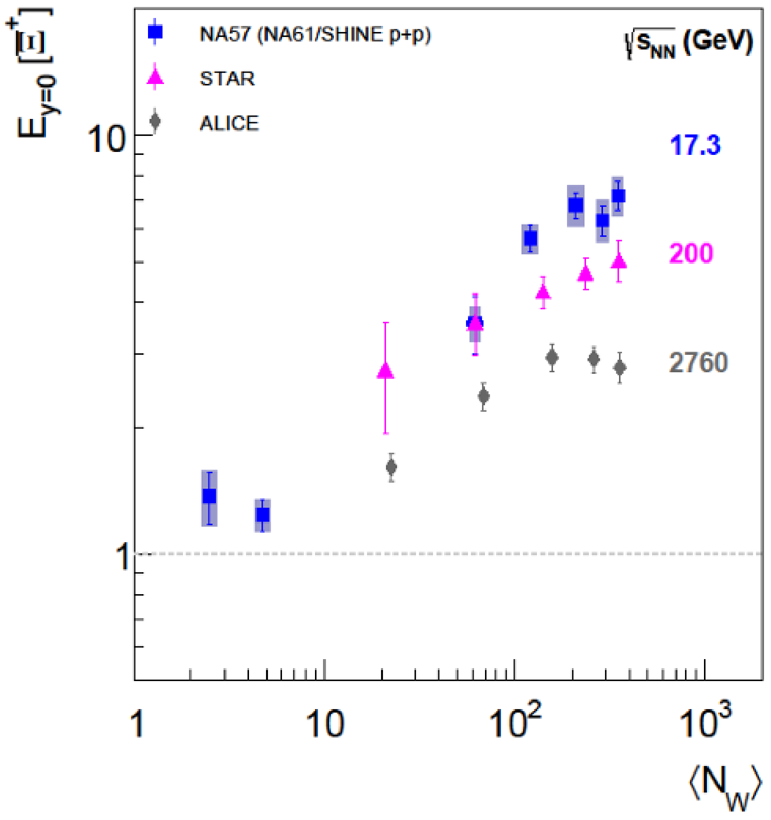
- transport models fail to describe the NA61/SHINE results on Ξ production in p+p collisions

Eur. Phys. J. C 80 (2020) 9, 833, Erratum: Eur. Phys. J. C 82 (2022) 2, 174

Strangeness enhancement factors

- the strangeness enhancement factor: $E = \frac{2}{\langle N_W \rangle} \frac{dn/dy(A+A)}{dn/dy(p+p)}$



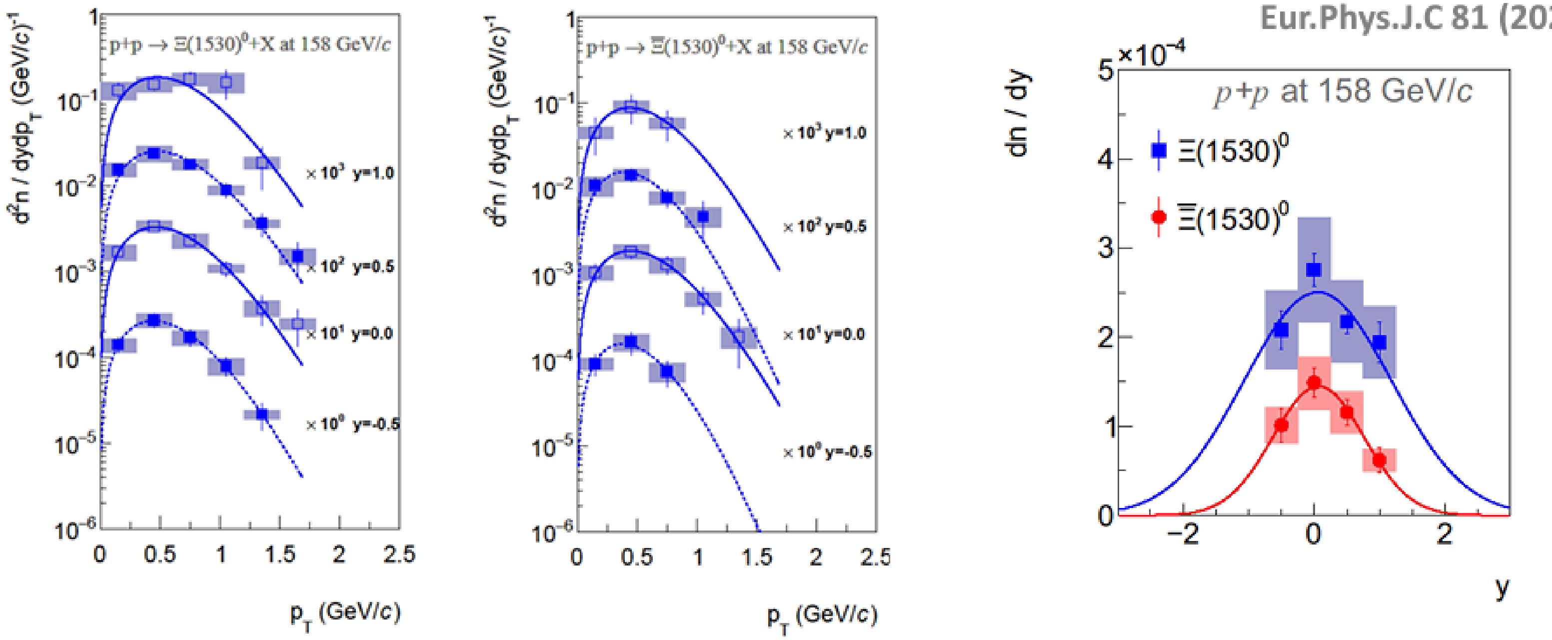


- the strangeness enhancement is recalculated based on the new Ξ reference from NA61/SHINE

Eur. Phys. J. C 80 (2020) 9, 833, Erratum: Eur. Phys. J. C 82 (2022) 2, 174

$\Xi(1530)^0$ production in inelastic *p+p* collisions at 158 GeV/*c*

Eur.Phys.J.C 81 (2021) 10, 911



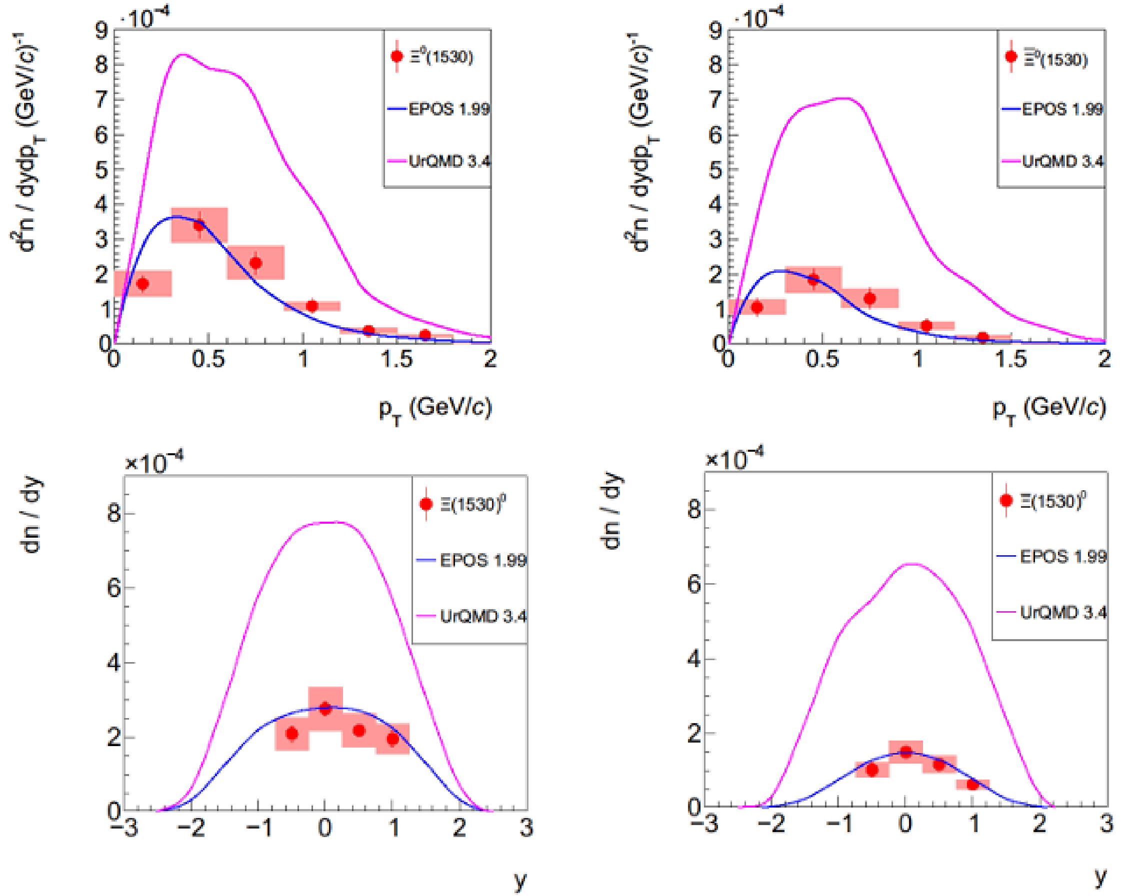
The only results on $\Xi(1530)^0$ production in *p+p* at the SPS energy

The second result on $\Xi(1530)^0$ production in *p+p* (ALICE at 7 TeV Eur.Phys.J.C 75 (2015) 1)

Suppression of $\overline{\Xi}(1530)^0$ production: $\langle\overline{\Xi}(1530)^0\rangle / \langle\Xi(1530)^0\rangle = 0.40 \pm 0.03 \pm 0.05$

Backup

$\Xi(1530)^0$ production in inelastic p+p collisions at 158 GeV/c



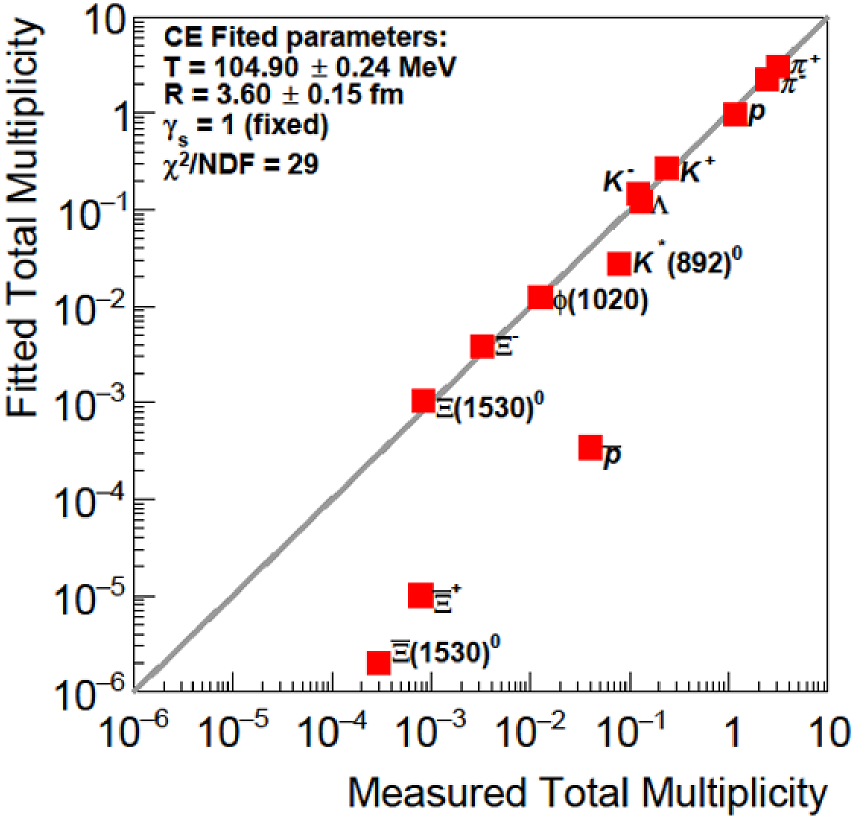
Eur.Phys.J.C 81 (2021) 10, 911

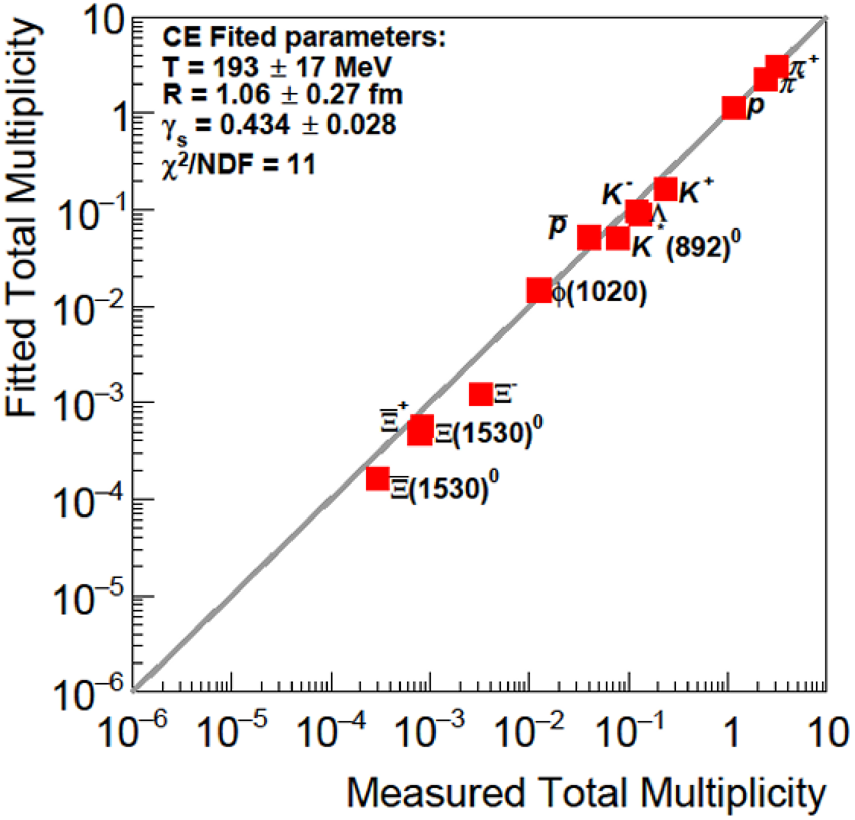
EPOS describes well transverse momentum and rapidity distributions of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$

UrQMD significantly overestimates all spectra of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ hyperons

HRG model in the CE formulation and p+p data

- fit performed with different variants of HRG (THERMAL_FIST1.3):
  - canonical ensemble with fixed strangeness saturation parameter $\gamma_s = 1$
  - canonical ensemble with fitted strangeness saturation parameter γ_s





- ➢ statistical model fails with fixed γ_s
- ➢ the fit with free parameter γ_s finds $\gamma_s = 0.434 \pm 0.028$ – suppression of strange particle production in p+p collisions at CERN SPS energies

Eur.Phys.J.C81(2021)10,911

Backup

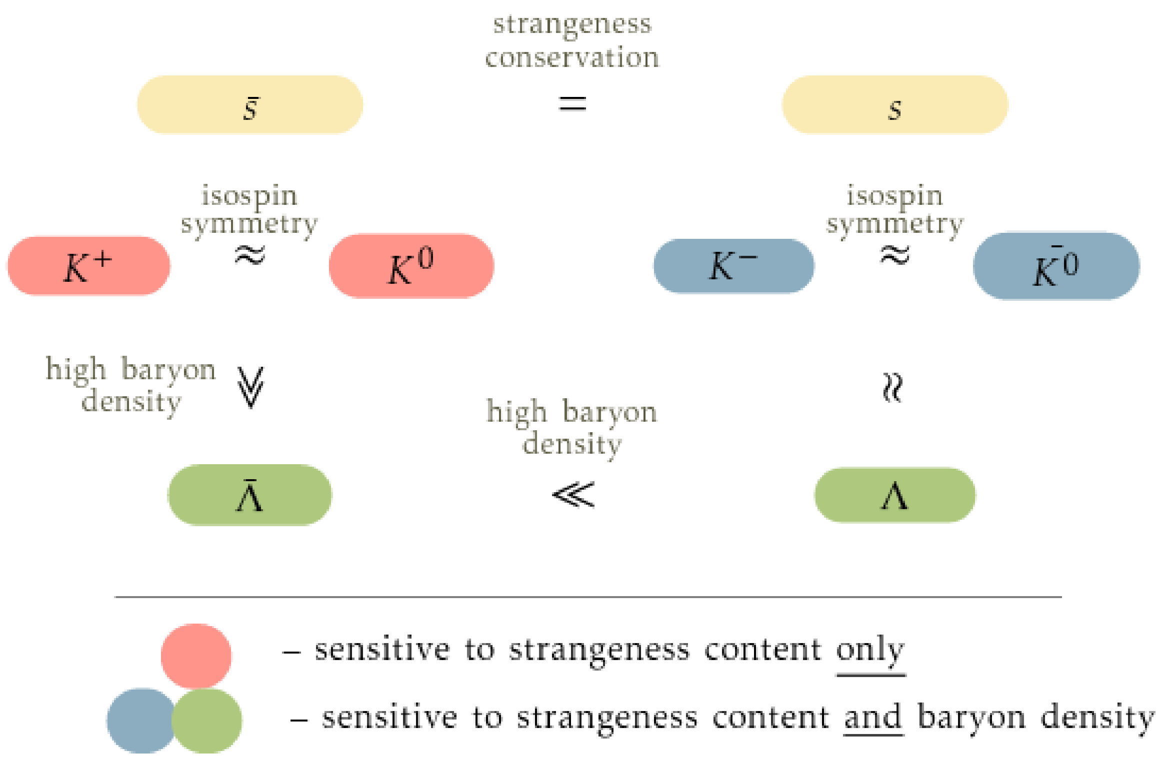
Model comparisons

- **EPOS** – the reaction proceeds from the excitation of strings according to Gribov-Regge theory to string fragmentation into hadrons.
- **UrQMD** starts with a hadron cascade based on elementary cross sections for resonance production which either decay (mostly at low energies) or are converted into strings which fragment into hadrons (mostly at high energies).
- **AMPT** – uses the heavy ion jet interaction generator (HIJING) for generating the initial conditions, Zhang's parton cascade for modeling partonic scatterings and the Lund string fragmentation model or a quark coalescence model for hadronization.
- **PHSD** is a microscopic offshell transport approach that describes the evolution of a relativistic heavy-ion collision from the initial hard scatterings and string formation through the dynamical deconfinement phase transition to the quark-gluon plasma as well as hadronization and the subsequent interactions in the hadronic phase.
- **SMASH** uses the hadronic transport approach where the free parameters of the string excitation and decay are tuned to match the experimental measurements in inelastic p+p collisions.

Selection of events in all model calculations follows the procedure for central collisions corresponding to the experimental results (selection based on forward spectator energy).

Backup

Main strangeness carriers in A+A collisions at high μ_B



$p + p \rightarrow p + \Lambda + K^+ + \pi^0$ $\approx$[GeV] $0.94 + 0.94 \rightarrow 0.94 + 1.12 + 0.49 + 0.14$

$p + p \rightarrow p + p + K^+ + K^-$ $\approx$[GeV] $0.94 + 0.94 \rightarrow 0.94 + 0.94 + 0.49 + 0.49$

The first option is almost 200MeV "cheaper".

Backup

Strange definitions

Strangeness production $\langle N_{s\bar{s}} \rangle$ – number of s-$\bar{s}$ pairs produced in a collision.

$$2 \cdot \langle N_{s\bar{s}} \rangle = \langle \Lambda + \bar{\Lambda} \rangle + \langle K + \bar{K} \rangle + \langle \phi \rangle + \ldots$$
$$2 \cdot \langle N_{s\bar{s}} \rangle \approx \langle \Lambda \rangle + \langle K^+ + K^- + K^0 + \bar{K^0} \rangle$$

Entropy production $\propto$ $\langle \pi \rangle$

The experimental ratio of strangeness to entropy can be defined as:

$$E_S = \frac{\langle \Lambda \rangle + \langle K + \bar{K} \rangle}{\langle \pi \rangle} \approx \frac{2 \cdot \langle N_{s\bar{s}} \rangle}{\langle \pi \rangle}$$

$$\langle N_{s\bar{s}} \rangle \approx \langle K^+ \rangle + \langle K^0 \rangle \approx 2 \cdot \langle K^+ \rangle, \qquad \langle \pi \rangle \approx \frac{3}{2}\left(\langle \pi^+ \rangle + \langle \pi^- \rangle \right)$$

$$\frac{\langle N_{s\bar{s}} \rangle}{\langle \pi \rangle} \approx \frac{2}{3}\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}, \qquad E_S \approx \frac{4}{3}\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}$$