Strangeness production in the NA61/SHINE experiment at the CERN SPS energy range

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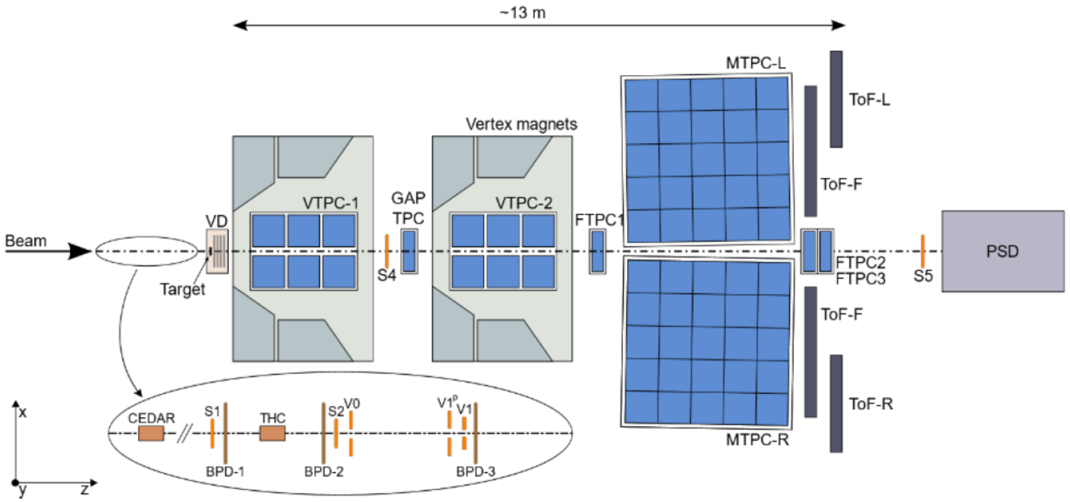
NA61/SHINE experiment at CERN SPS



NA61/SHINE detector: JINST 9 (2014) P06005

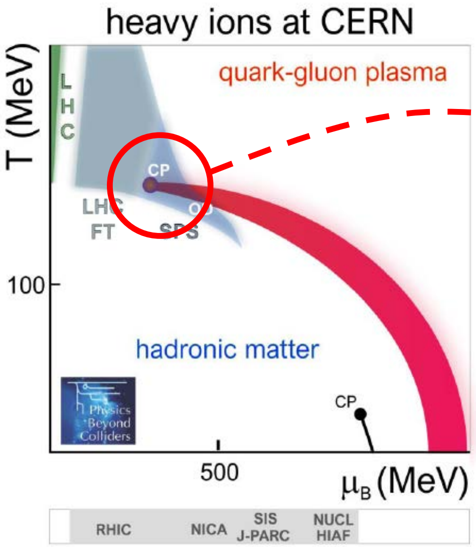
- hadron beams (π, K, p) at 13-400 GeV/c
- ion beams (Be, Ar, Xe, Pb) at 13*A*-150*A* GeV/c

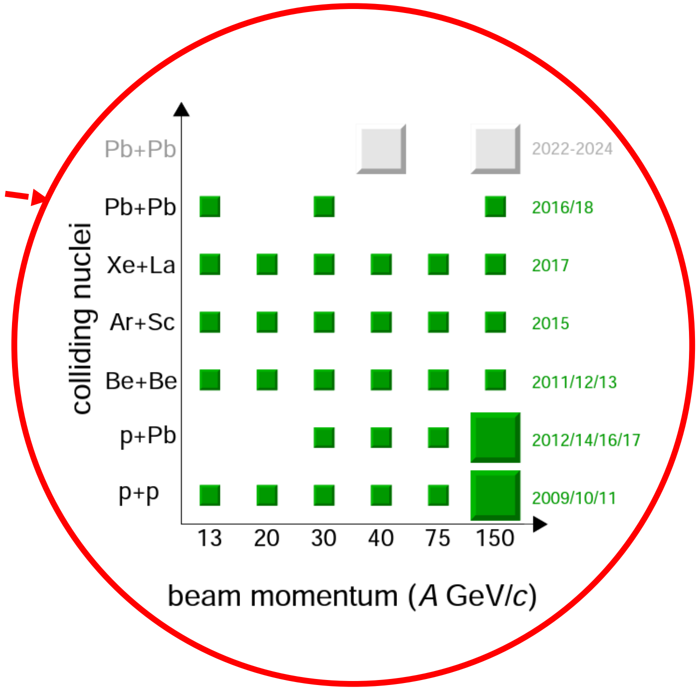
$$\sqrt{s_{NN}} \approx 5 - 17 \text{ GeV}$$

NA61/SHINE research programme

Strong interactions physics:

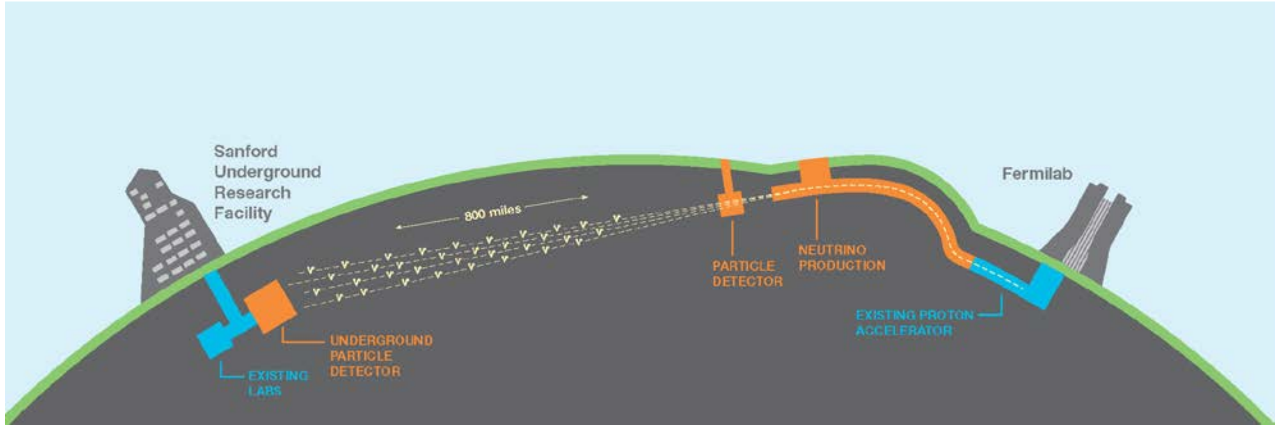
- **study of the properties of the onsets of deconfinement and fireball**
- search for the critical point of the strongly interacting matter
- direct measurement of open charm production





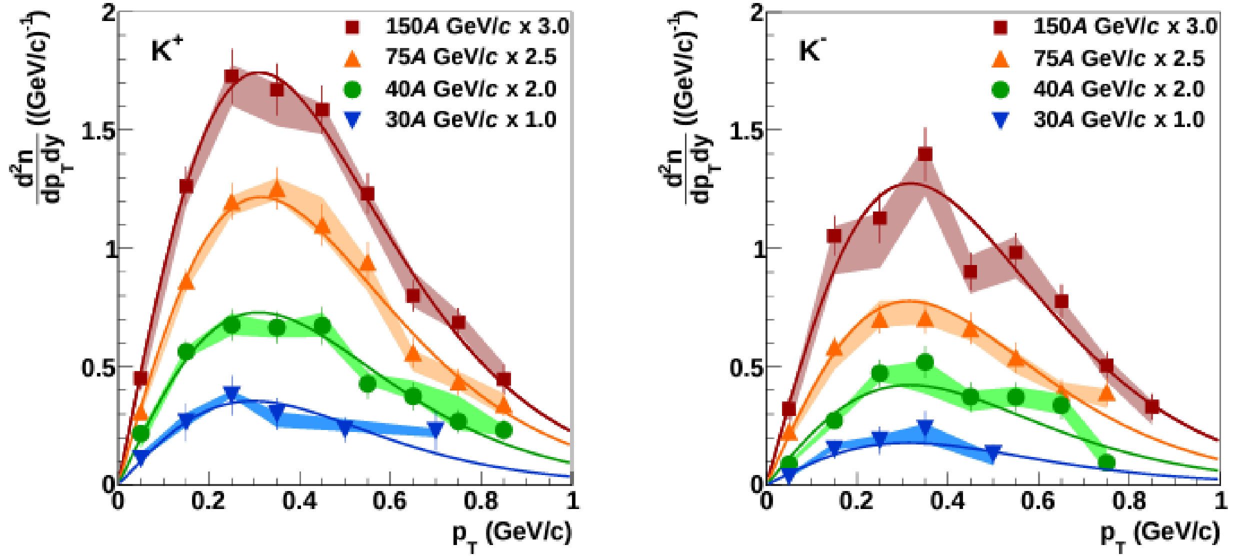
as well as

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

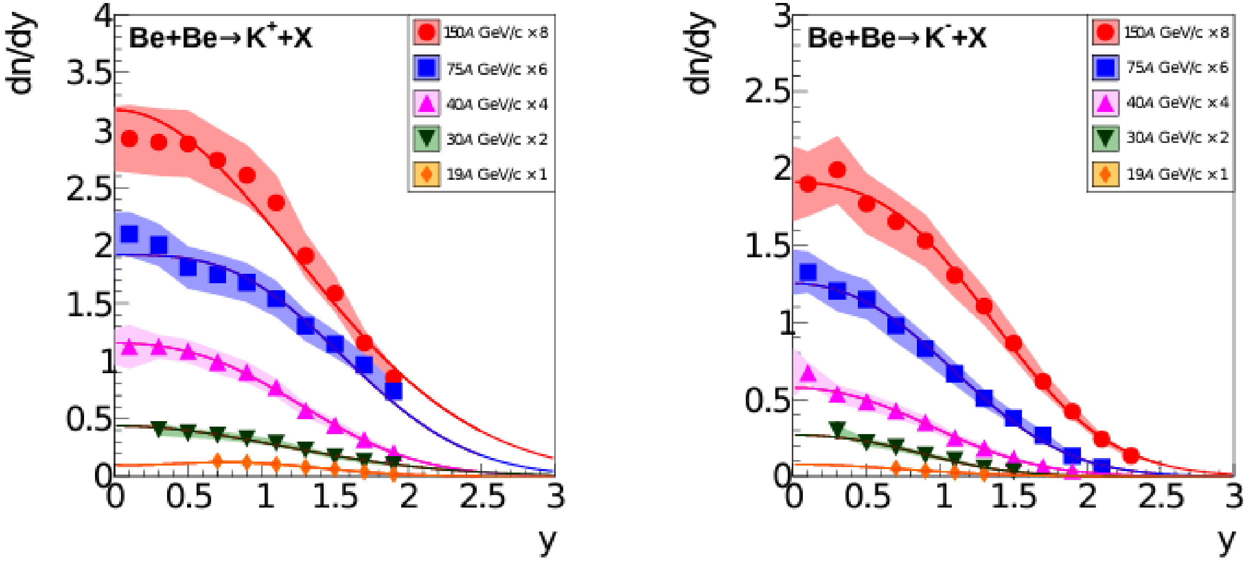


$K^{\pm}$ spectra in Be+Be collisions

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 $\langle K^+\rangle, \langle K^-\rangle$

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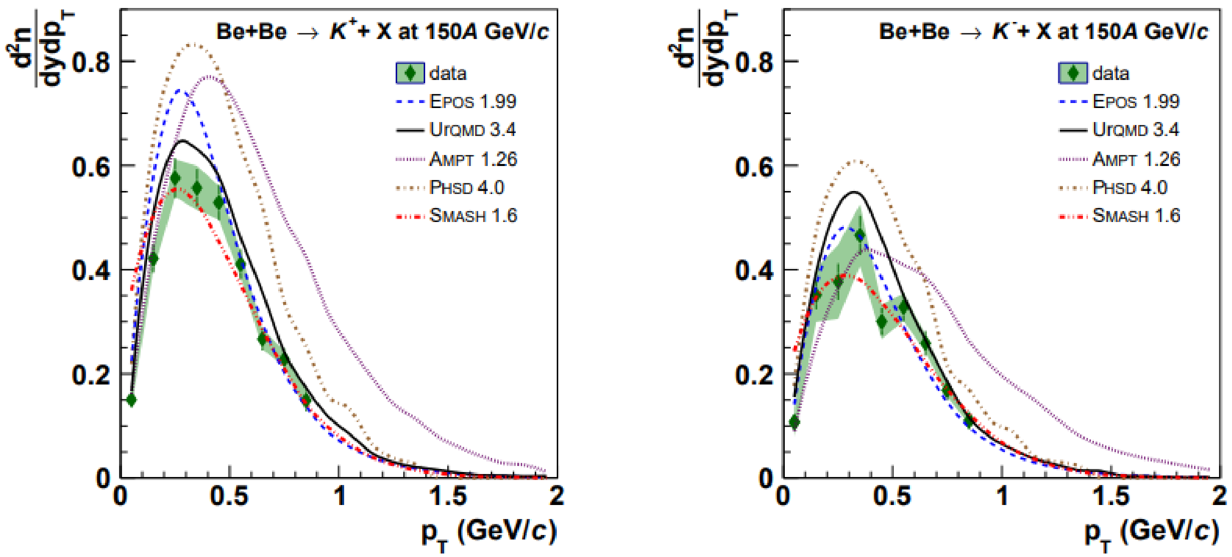
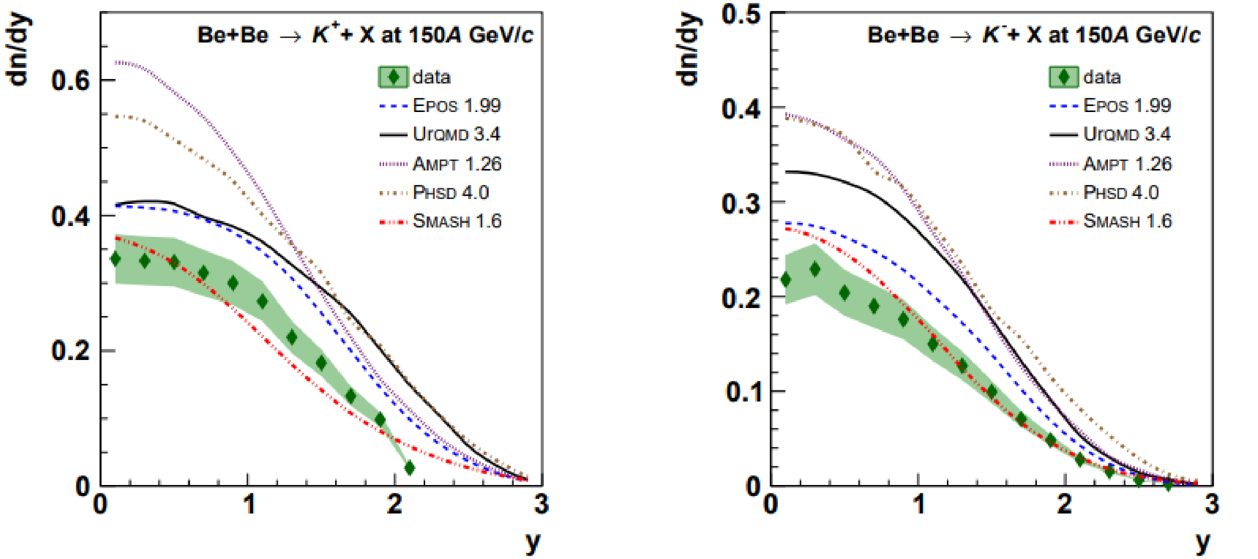
$K^{\pm}$ spectra in Be+Be collisions – model comparison

p_T spectra at midrapidity



rapidity spectra



- good description of the spectra by the SMASH model
- clear tendency of the models to overestimate $K^{\pm}$ spectra

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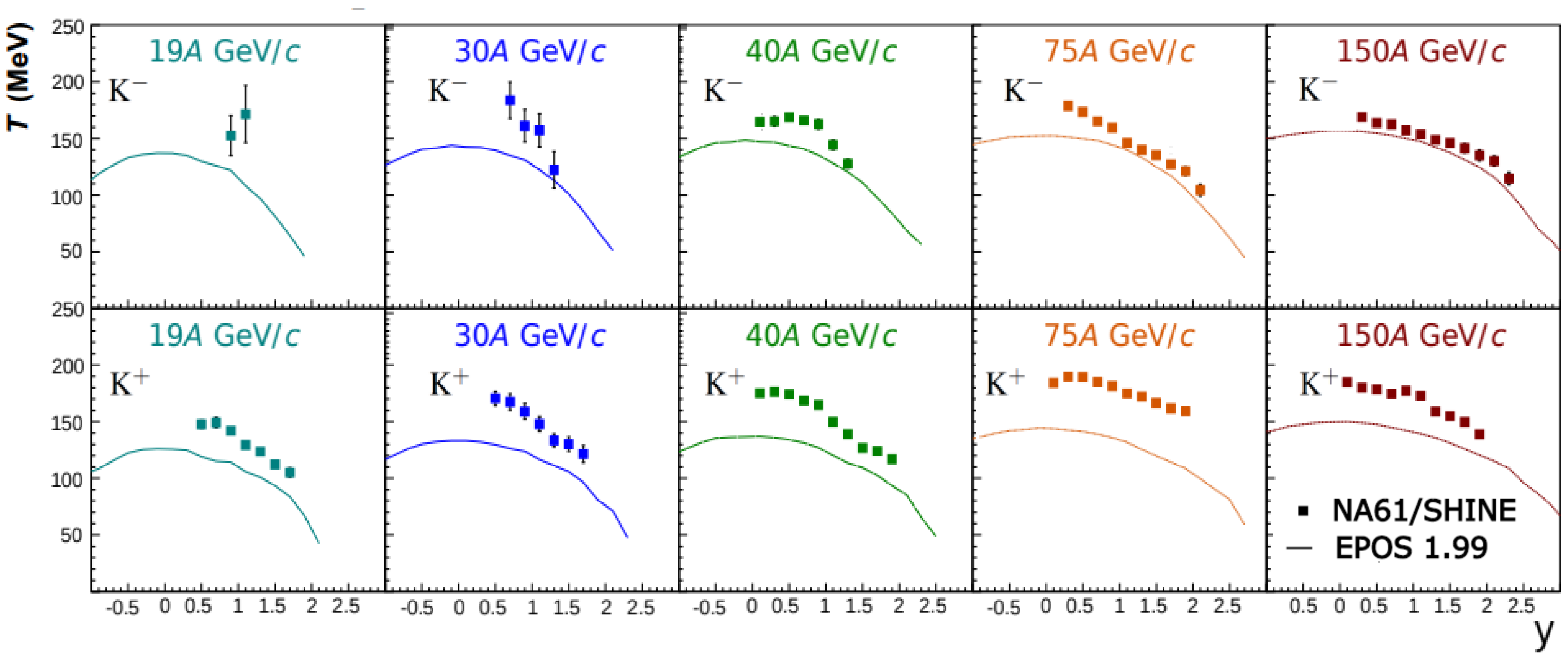
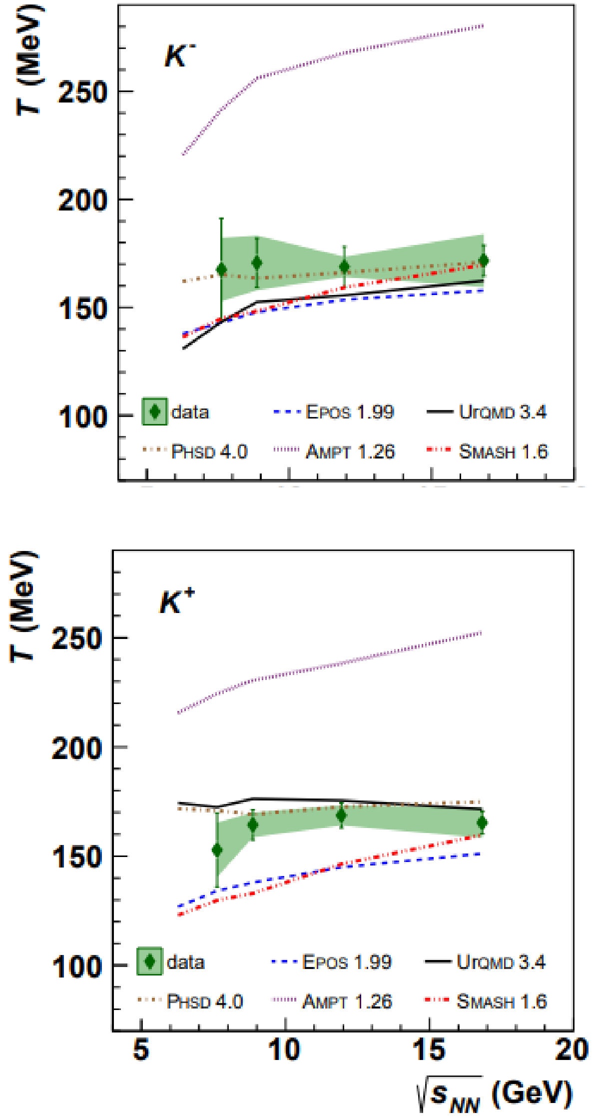
Inverse slope parameter of $K^{\pm}$ spectra in Be+Be collisions





- inverse slope parameter of K^+ spectra at midrapidity is reasonably well reproduced by UrQMD and PHSD; K^- only by PHSD
- EPOS tends to underestimate and AMPT to overestimate the inverse slope parameter of $K^{\pm}$ spectra

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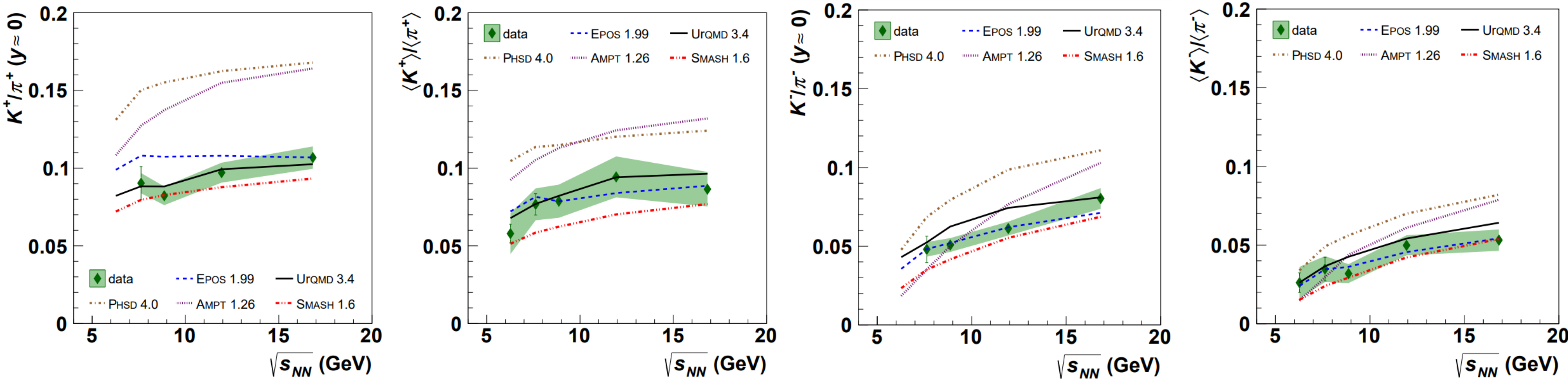
K/π ratio in Be+Be collisions



- K/π ratio is rather well described by UrQMD, SMASH and EPOS
- PHSD and AMPT overall tend to overestimate K/π ratio

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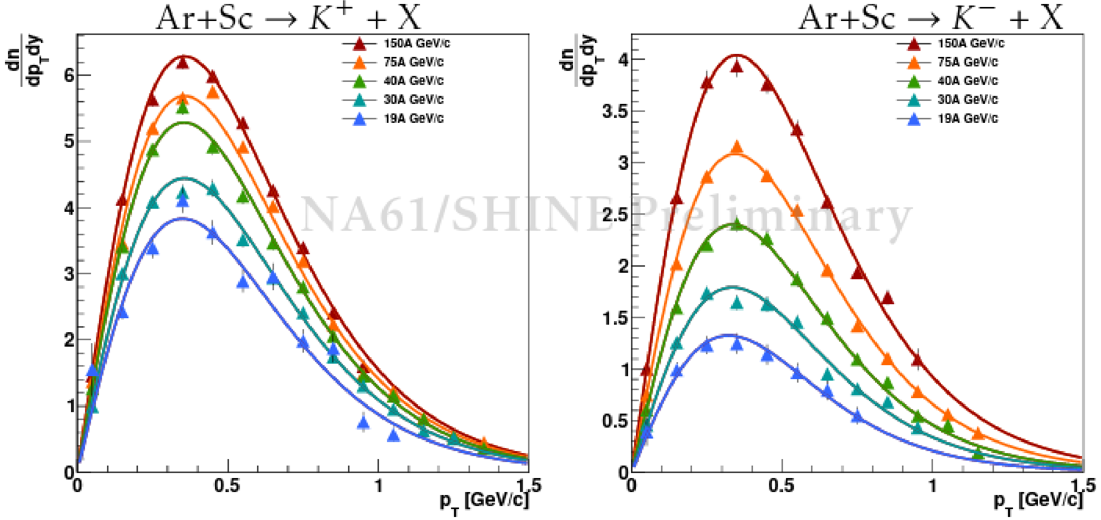
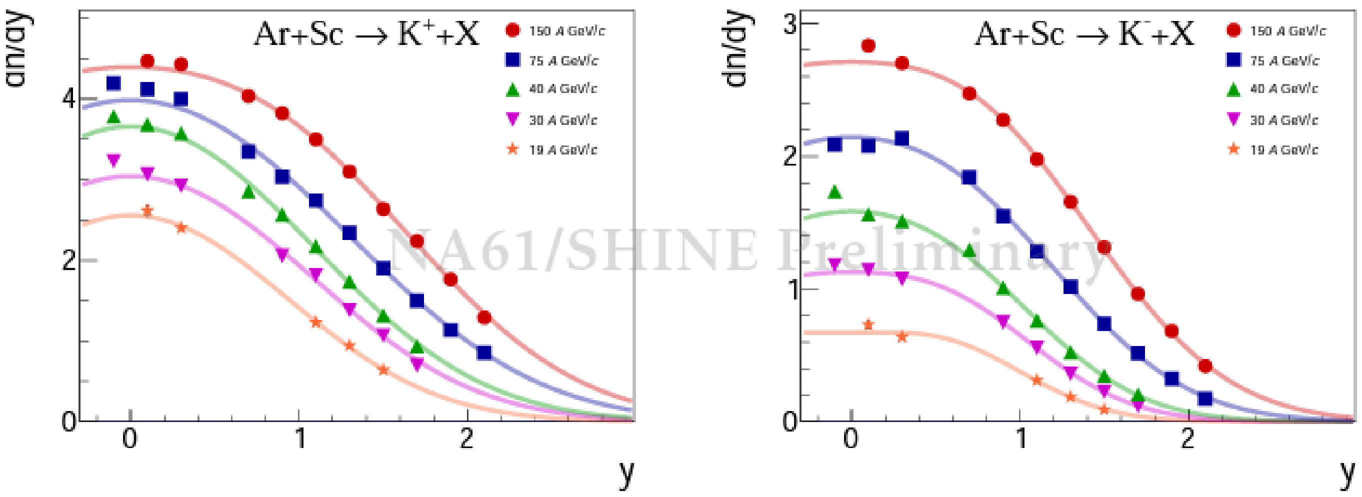
$K^{\pm}$ spectra in Ar+Sc collisions

p_T spectra at midrapidity



rapidity spectra

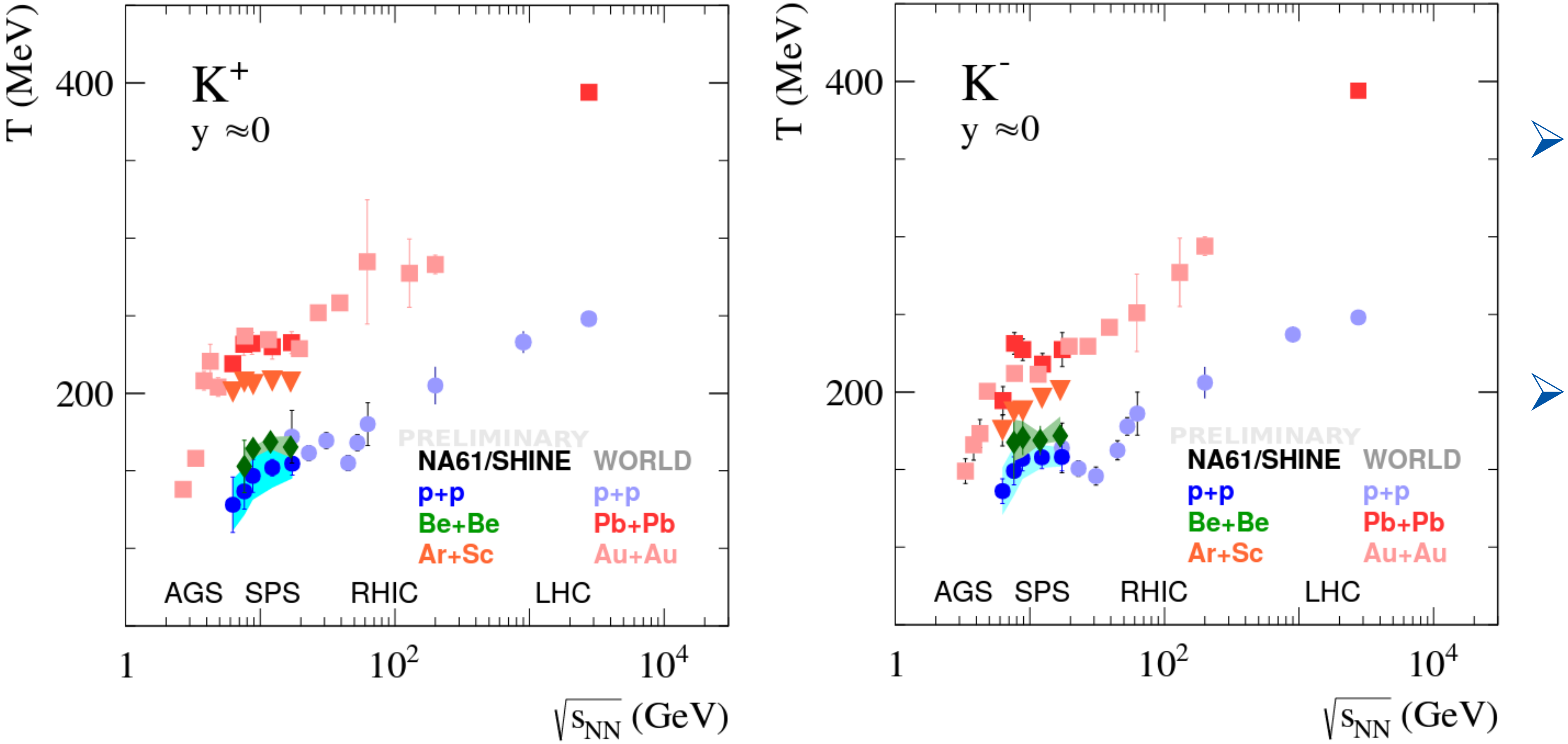


- 10% most central $^{40}Ar + {}^{45}Sc$ events
- p_T spectra are fitted with $\frac{d^2n}{dp_T\,dy} = \frac{S\,p_T}{T^2 + T\,m_K}\exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$
- rapidity spectra are fitted with a sum of Gaussians to obtain mean multiplicities $\langle K^+\rangle, \langle K^-\rangle$

NA61/SHINE preliminary

System size dependence of inverse slope parameter

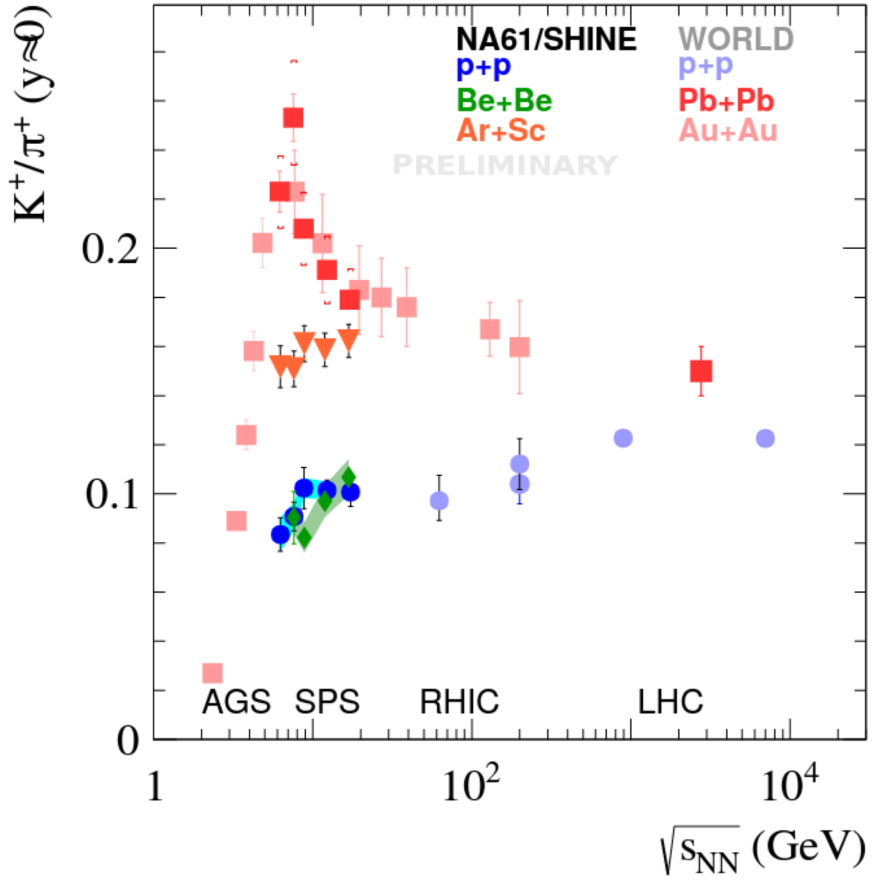
- kaons are only weakly affected by re-scattering and resonance decays during the post-hydro phase (at SPS and RHIC energies)
- connected with temperature of the freeze-out surface and not early-stage fireball

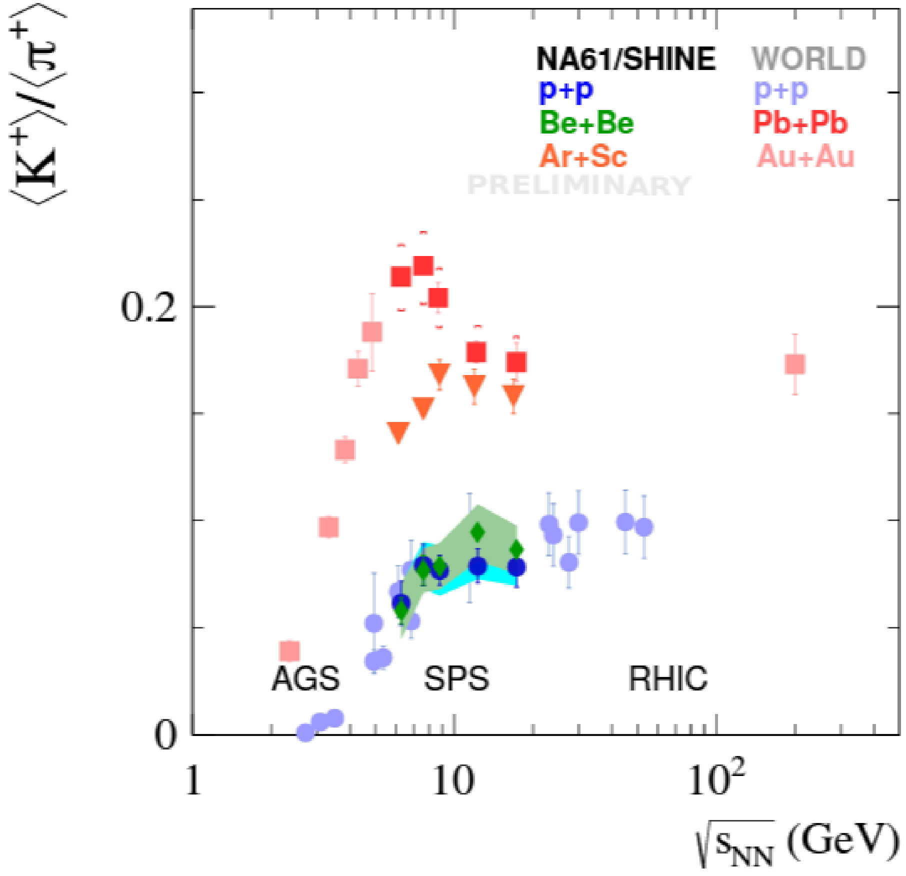


- ➢ qualitatively similar energy dependence is seen for different collision systems
- ➢ magnitude of T increases with the system size

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

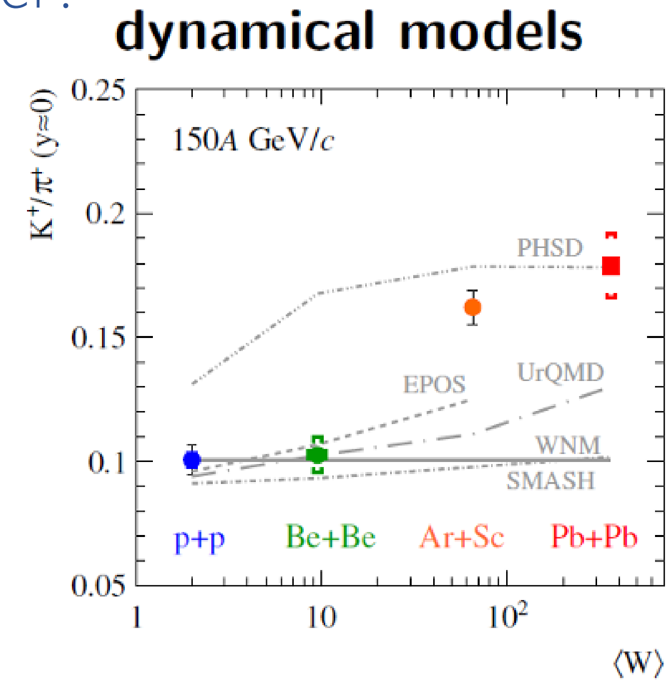


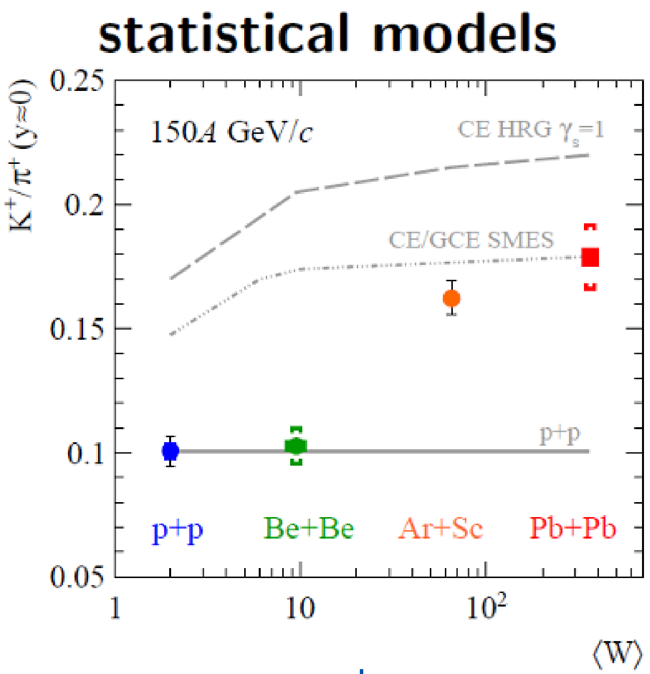


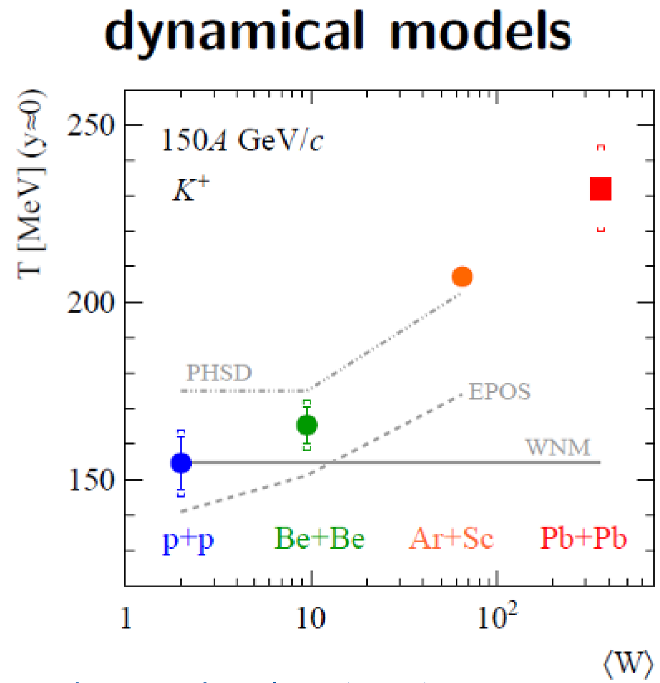
- ➢ plateau-like structure is visible in p+p, Be+Be and Ar+Sc
- ➢ Ar+Sc is higher than p+p and Be+Be

System size dependence of $^{K^+}/_{\pi^+}$ and T at 150A GeV/c

- 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?







➢ none of the models can reproduce neither $^{K^+}/_{\pi^+}$ nor T for the 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. C 99 (2019) 3, 034909;
SMES: Acta Phys. Polon. B 46 (2015) 10, 1991 - recalculated

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

Summary

- ✓ two-dimensional scan in system size and collision energy was successfully completed in 2017 with Xe+La data
- ✓ various analyses ongoing for p+p, Be+Be, Ar+Sc, Xe+La and Pb+Pb data
- ✓ present theoretical models do not describe well the NA61/SHINE results
- ✓ no indication of horn in Ar+Sc collisions
- ✓ unexpected system size dependence: (p+p ≈ Be+Be) ≠ (Ar+Sc ≠ Pb+Pb)

Thank you for your attention!

All comments and questions are very welcome:
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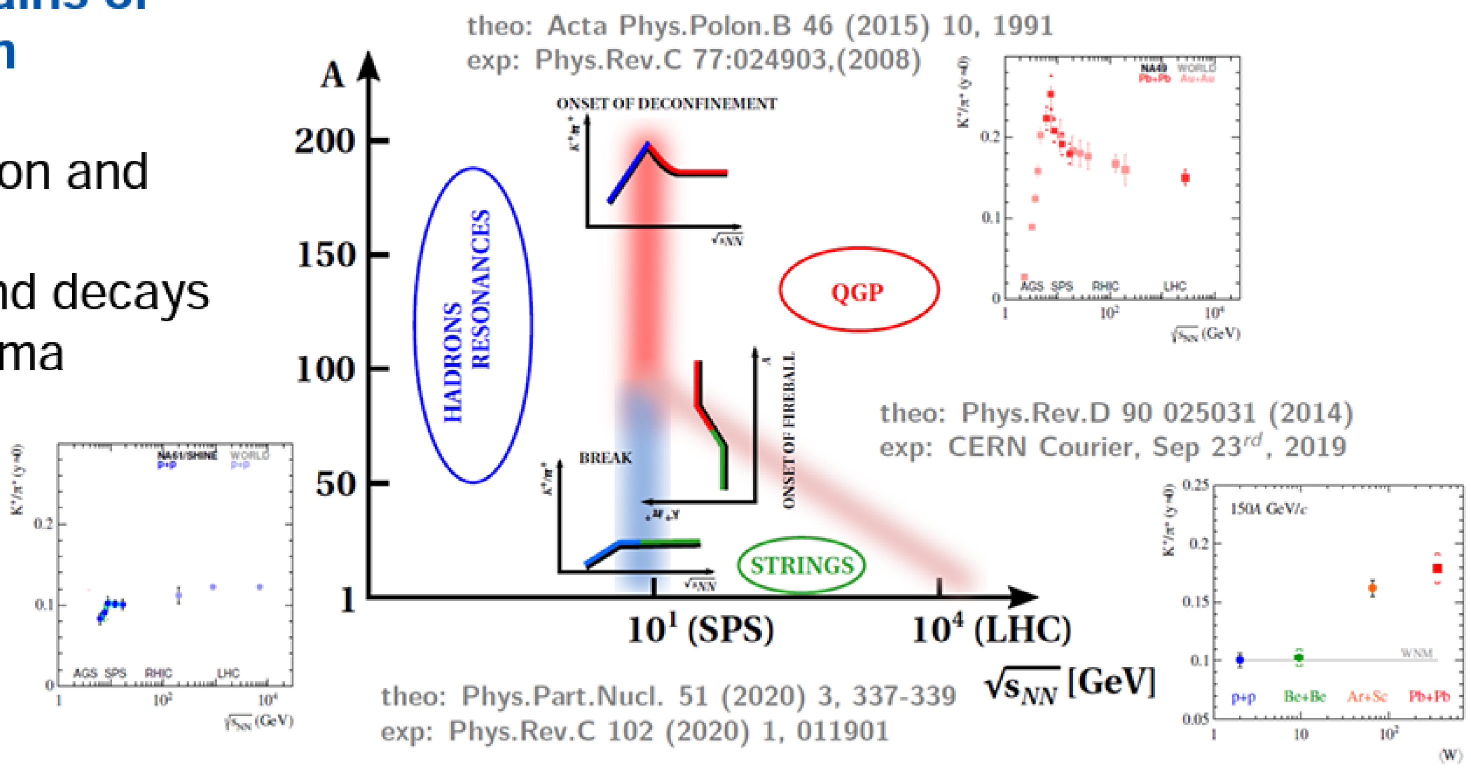
Backup

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



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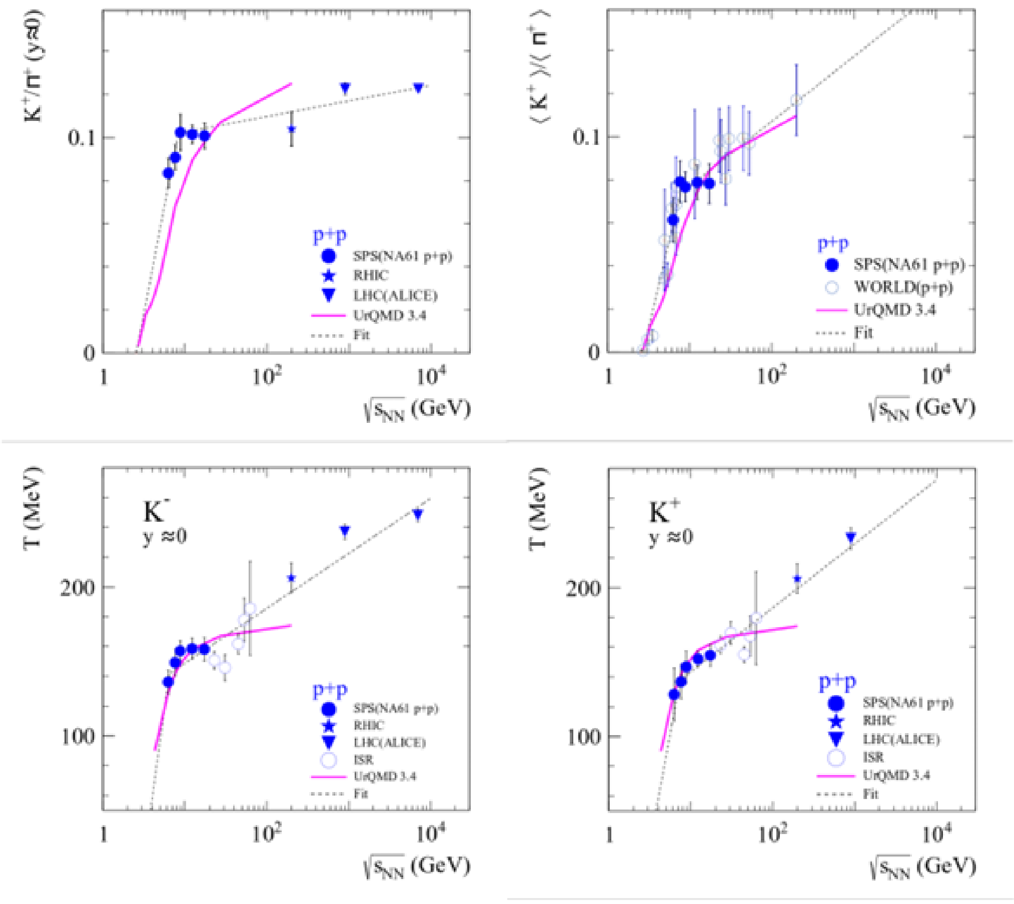
Transition from resonances to strings



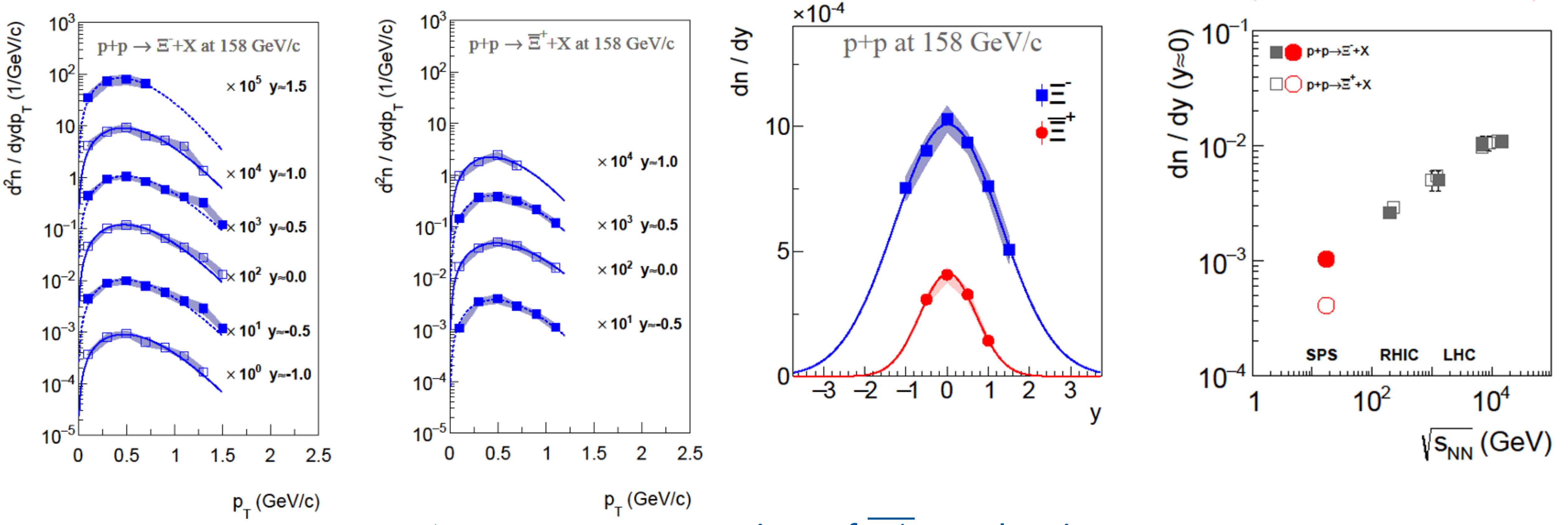
Rates of increase of K^+/π^+ and T change sharply in p+p collisions at SPS energies

The fitted change energy is ≈7 GeV - close to the energy of the onset of deconfinement ≈ 8 GeV

Models assuming change from resonances to string production mechanism show similar trend

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:

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

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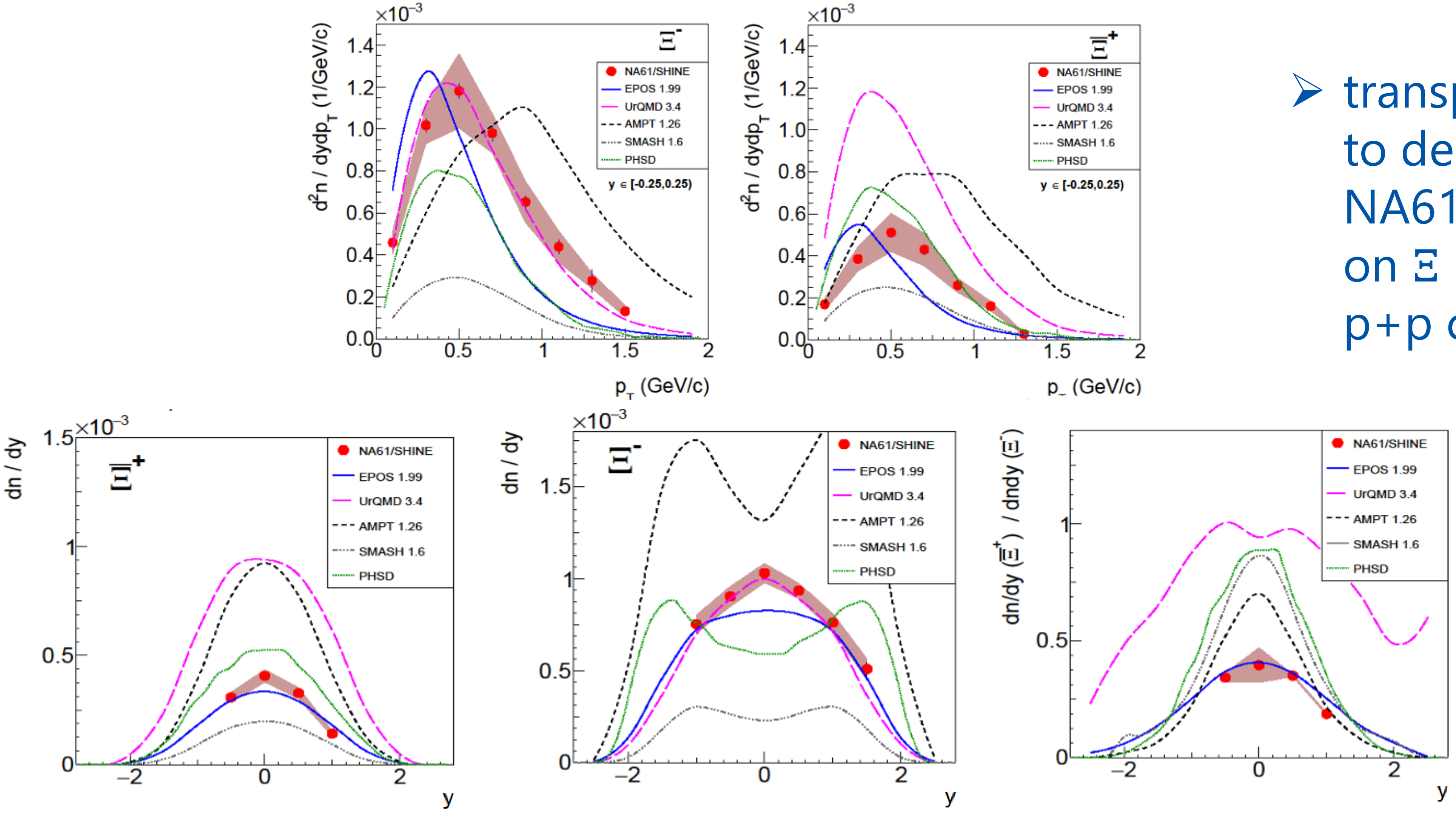
Ξ^- & $\overline{\Xi}^+$ spectra in p+p collisions – model comparison



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

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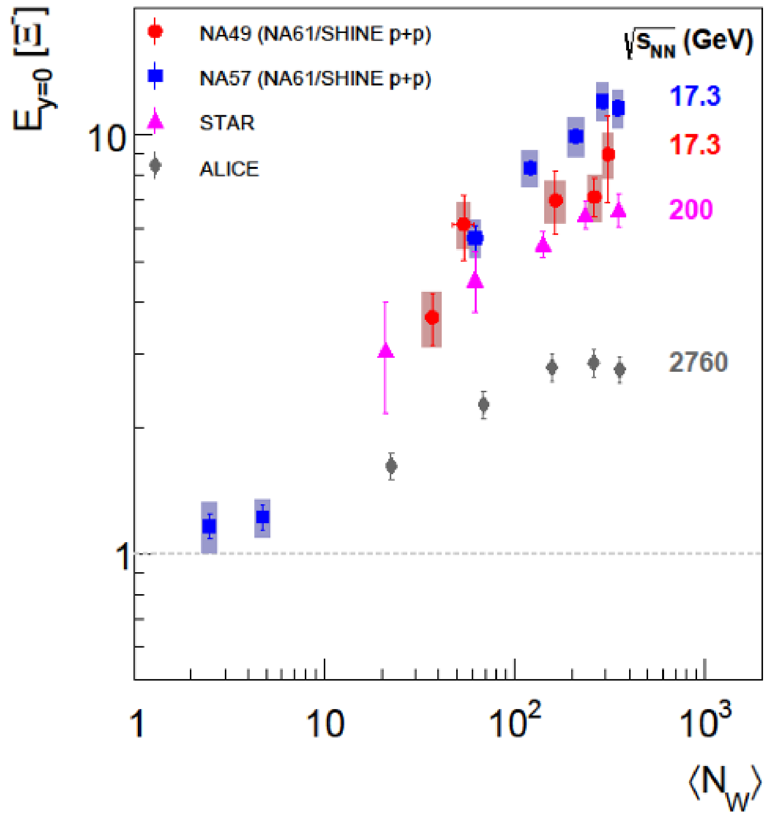
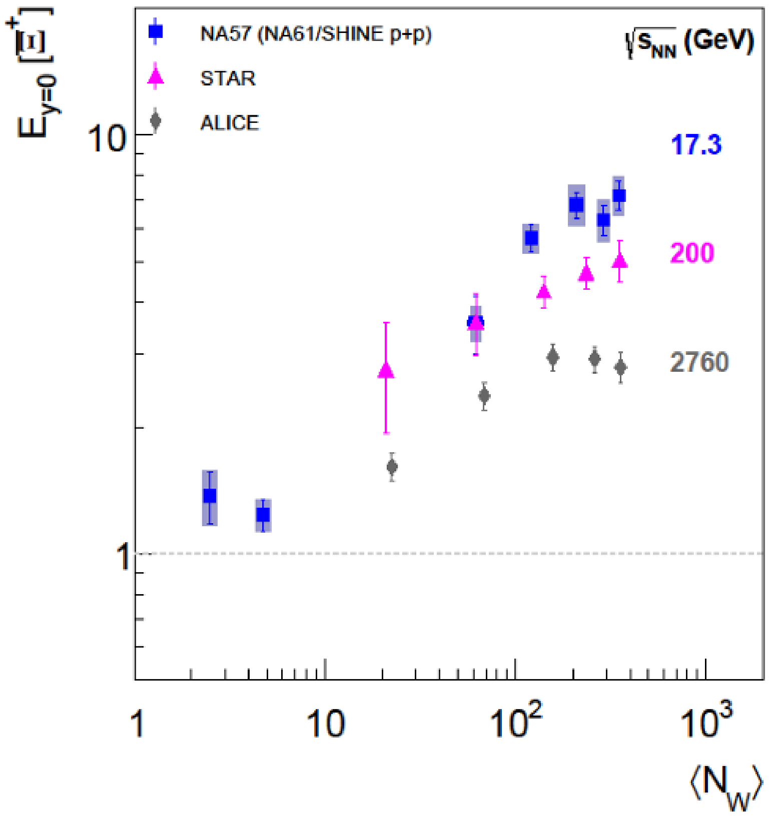
Strangeness enhancement factors

- 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

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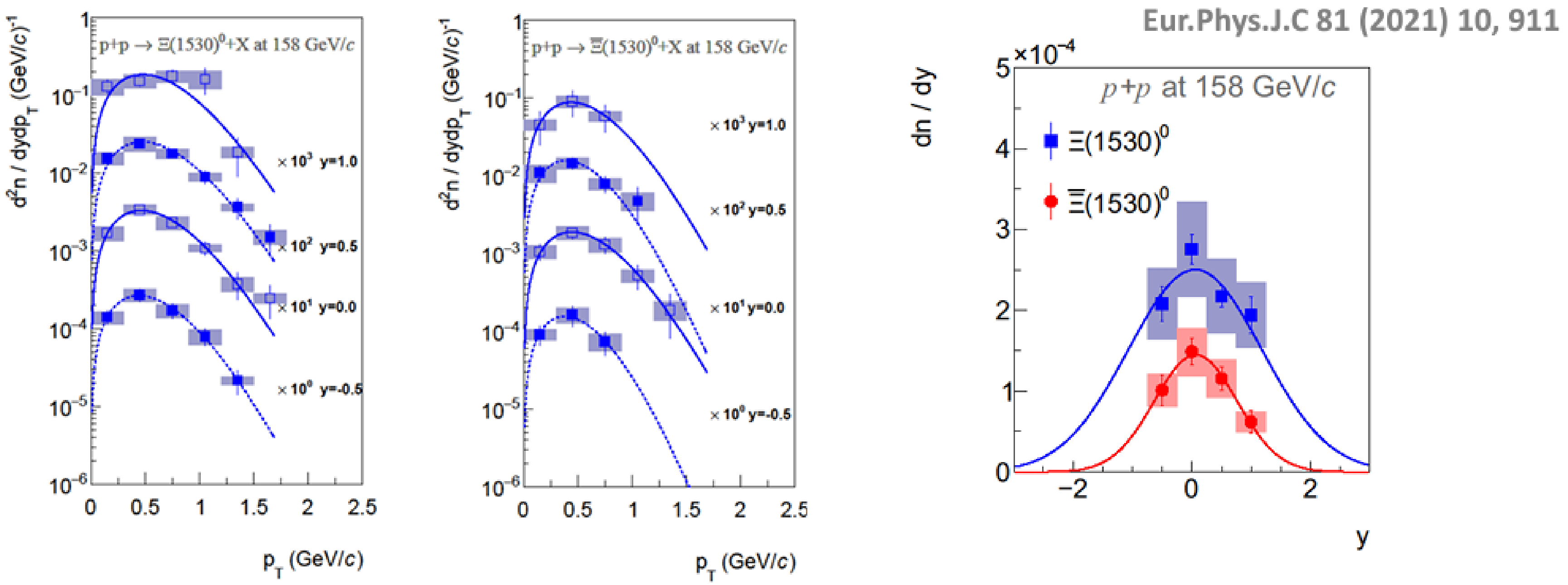
$\Xi(1530)^0$ production in inelastic *p+p* collisions at 158 GeV/*c*

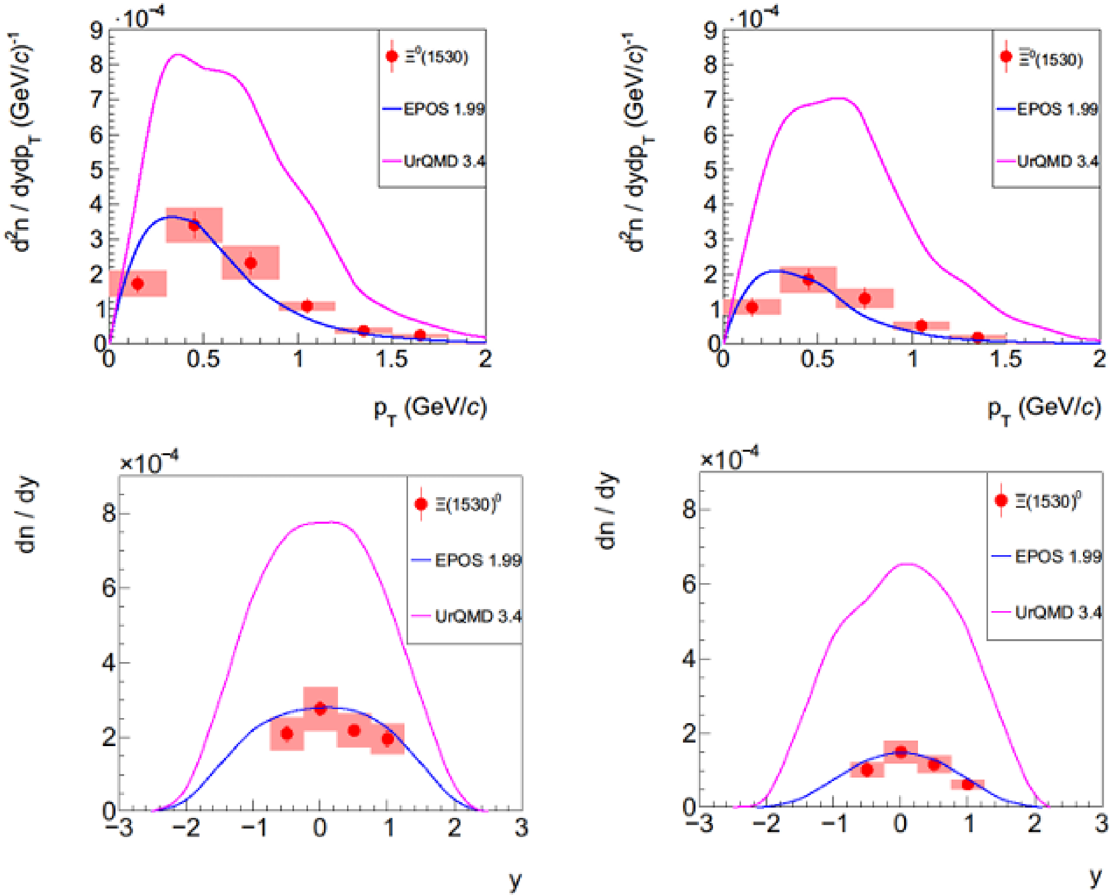


The only results on $\Xi(1530)^0$ production in *p+p* at the SPS energy

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

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



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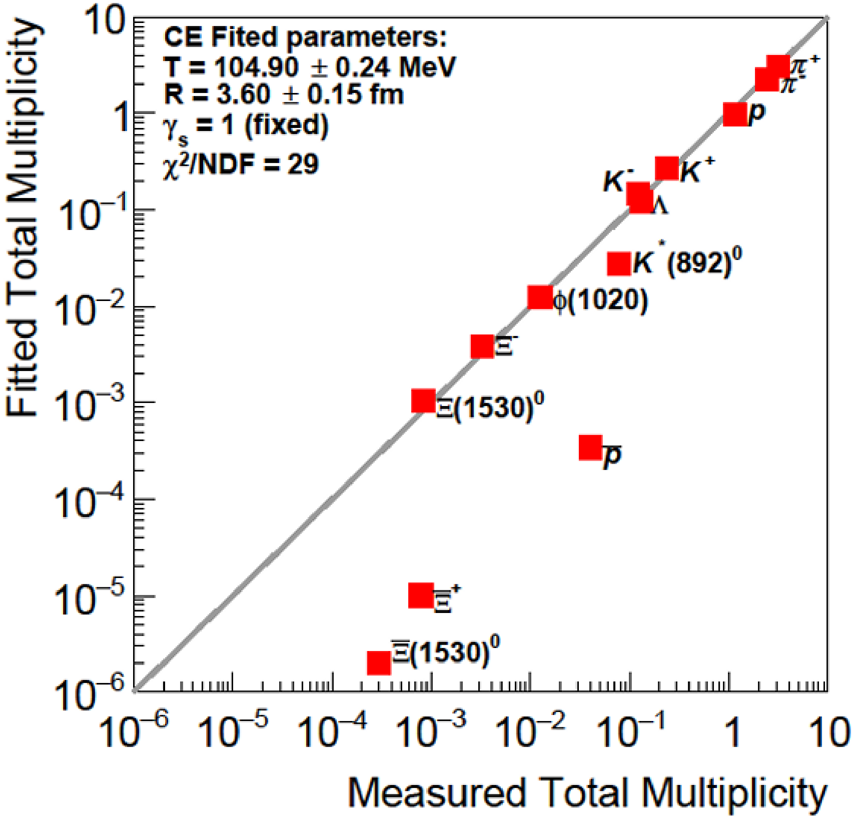
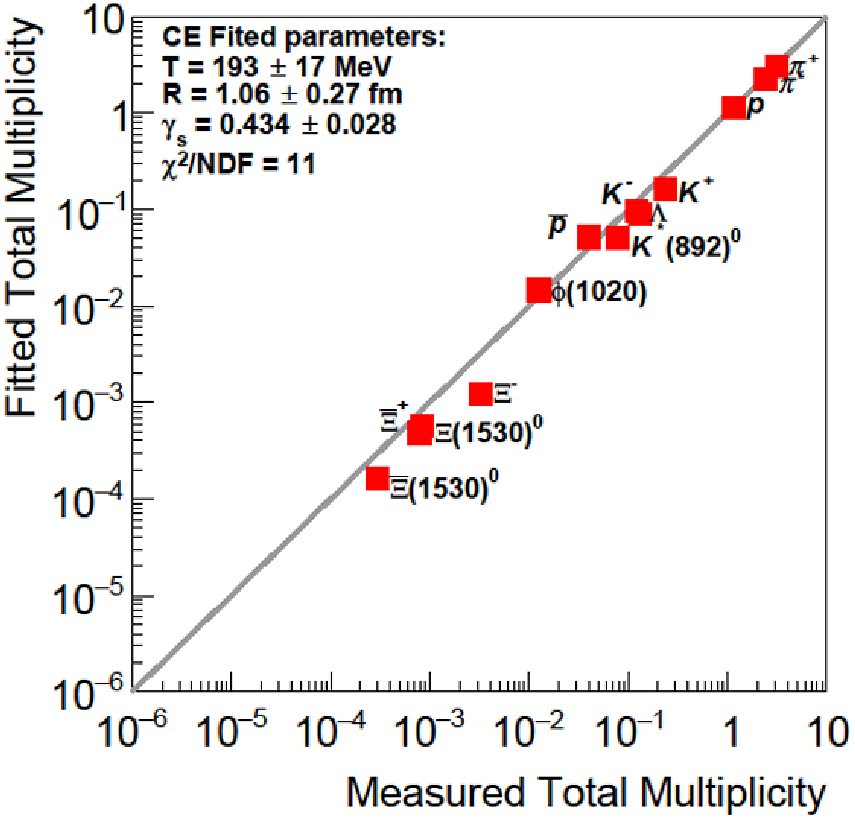
EPOS describes well transverse momentum and rapidity distributions of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$

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

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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).

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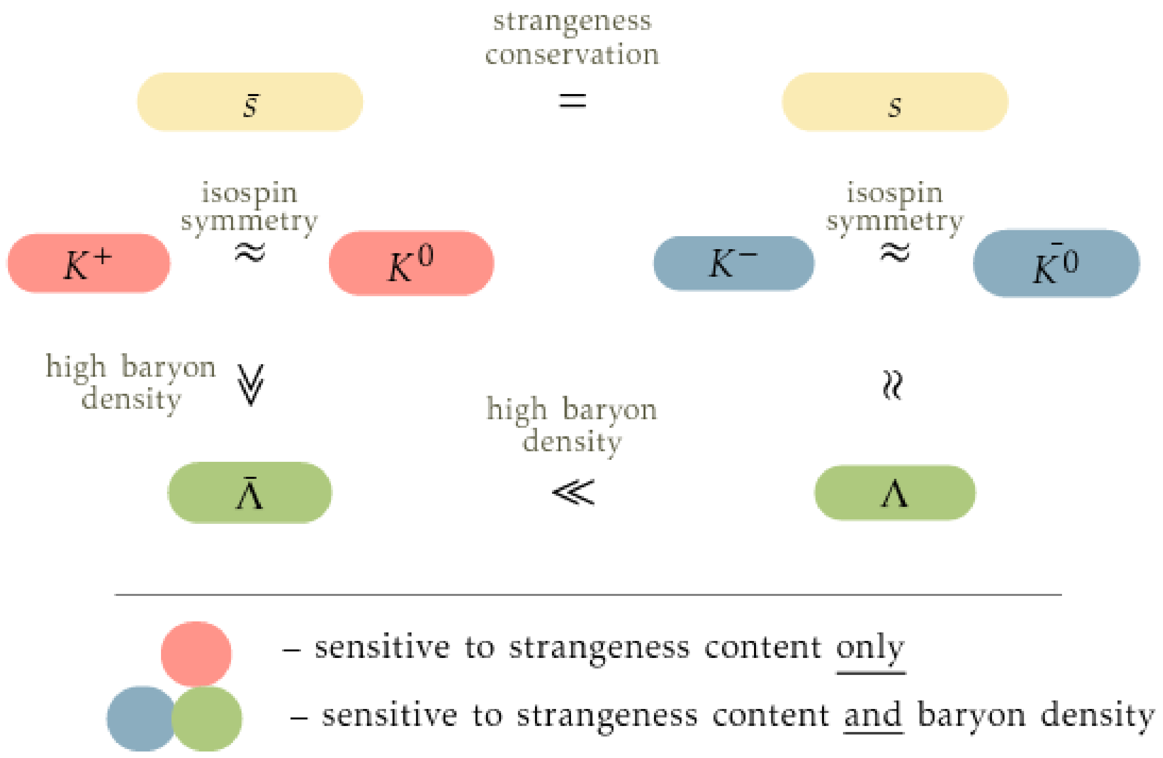
Main strangeness carriers in A+A collisions at high μ_B



$p + p \rightarrow p + \Lambda + K^+ + \pi^0$ $\approx$[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:

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

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

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