Lambda baryon production in heavy-ion collisions at the NA61/SHINE experiment

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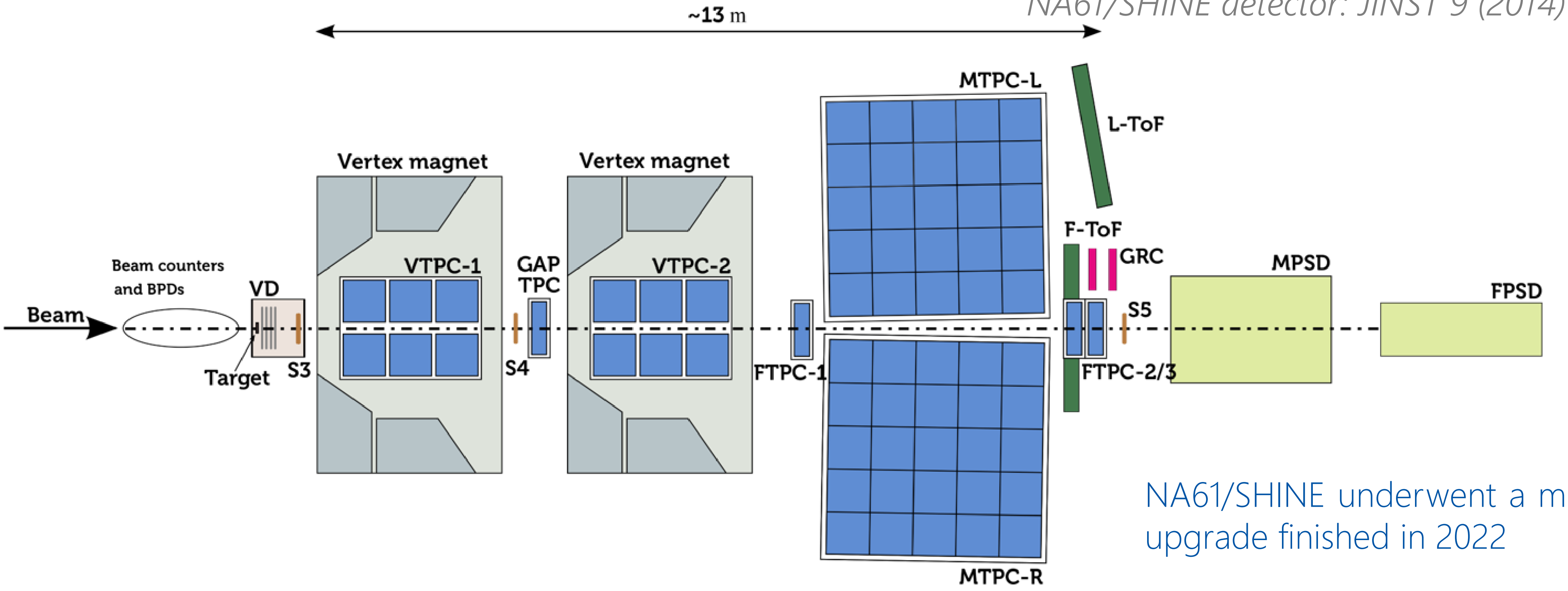
for the NA61/SHINE collaboration

NA61/SHINE experiment at CERN SPS

NA61/SHINE detector

NA61/SHINE detector: JINST 9 (2014) P06005



NA61/SHINE underwent a major upgrade finished in 2022

- 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

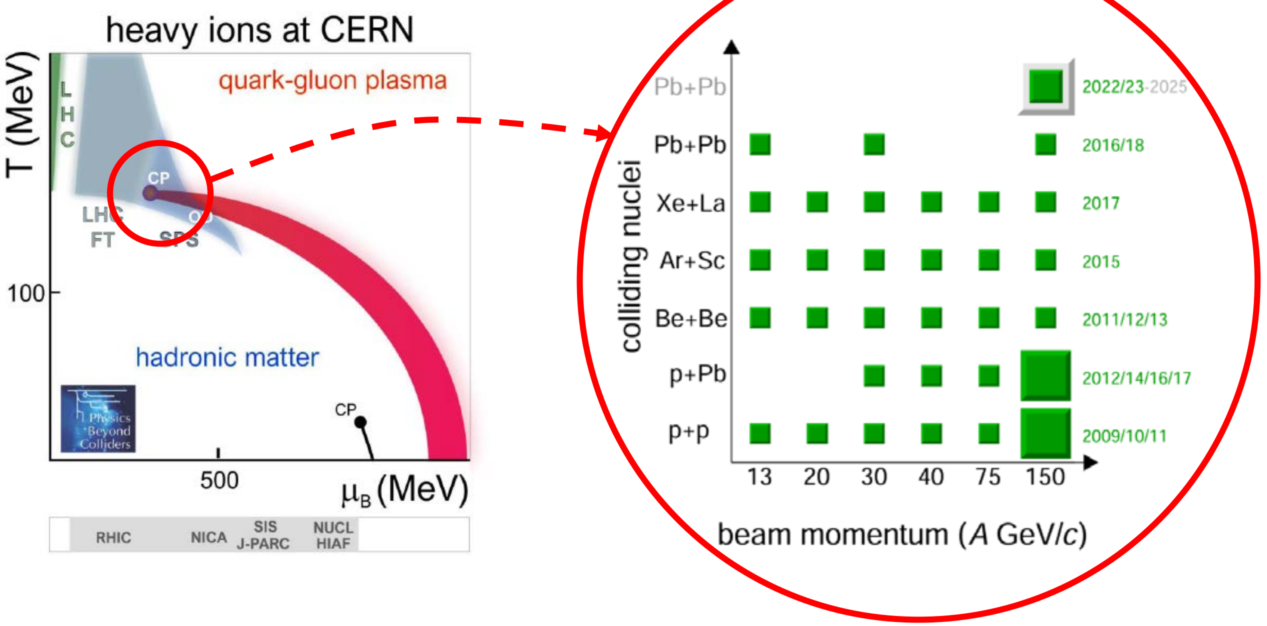
NA61/SHINE research programme

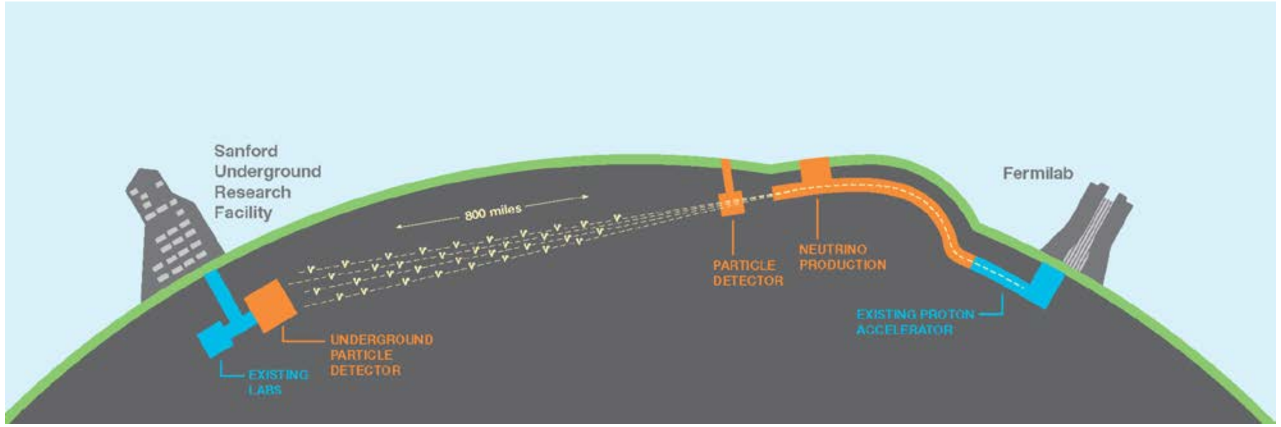
Strong interactions physics:

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

as well as

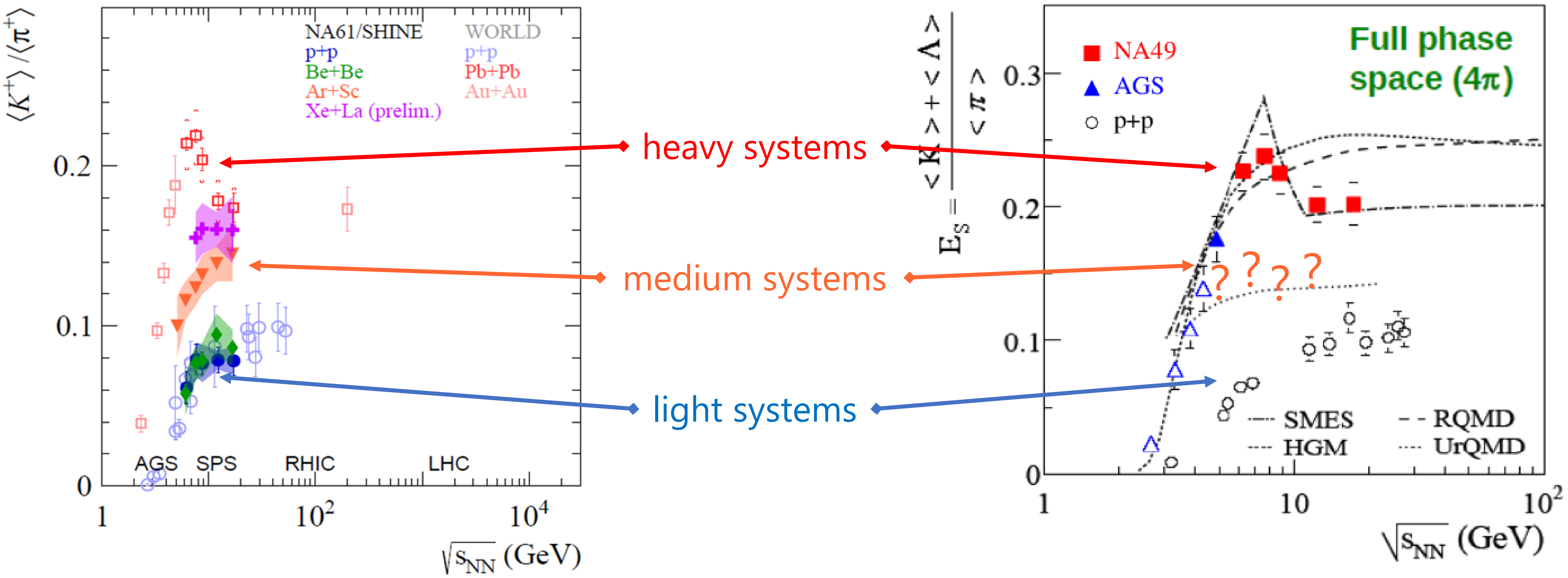
- measurement of hadron production for neutrino programmes at J-PARC and Fermilab
- measurement of nuclear fragmentation cross-sections and hadron production for cosmic-ray physics



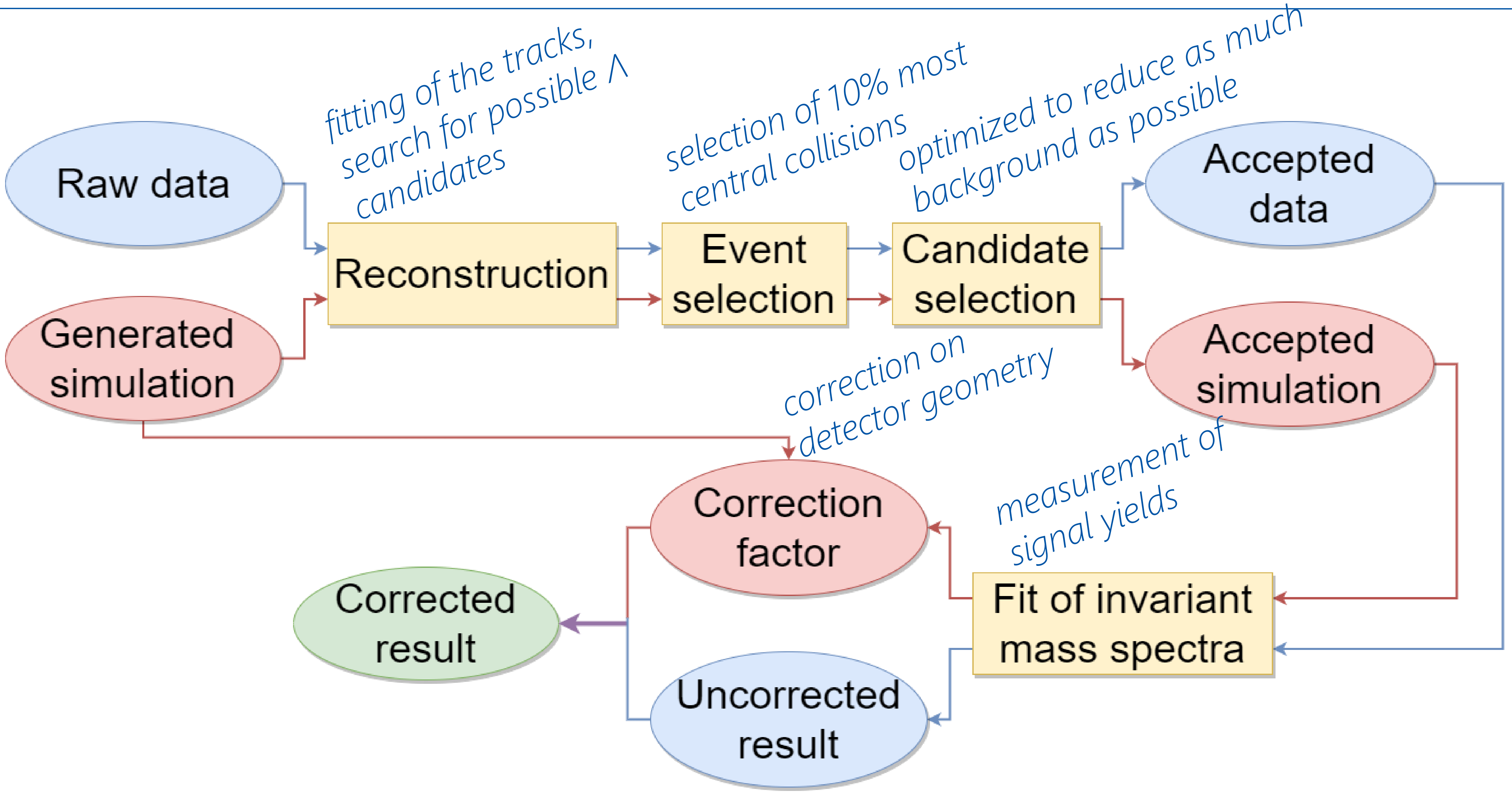


Onset of deconfinement

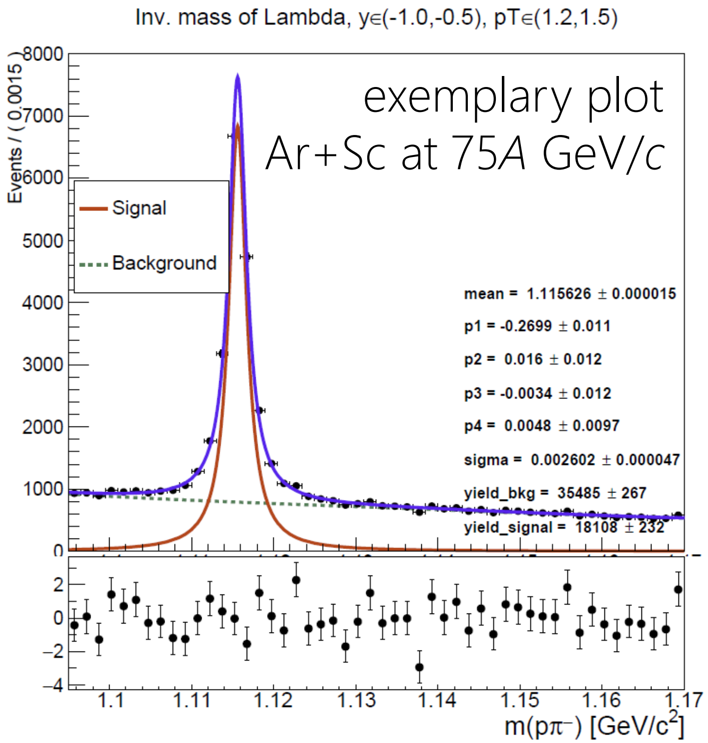
- A measure of strangeness-to-entropy ratio, which differs between the confined phase (hadrons) and the QGP (quarks and gluons) can **probe the onset of deconfinement**
- No maximum observed in systems lighter than Pb+Pb

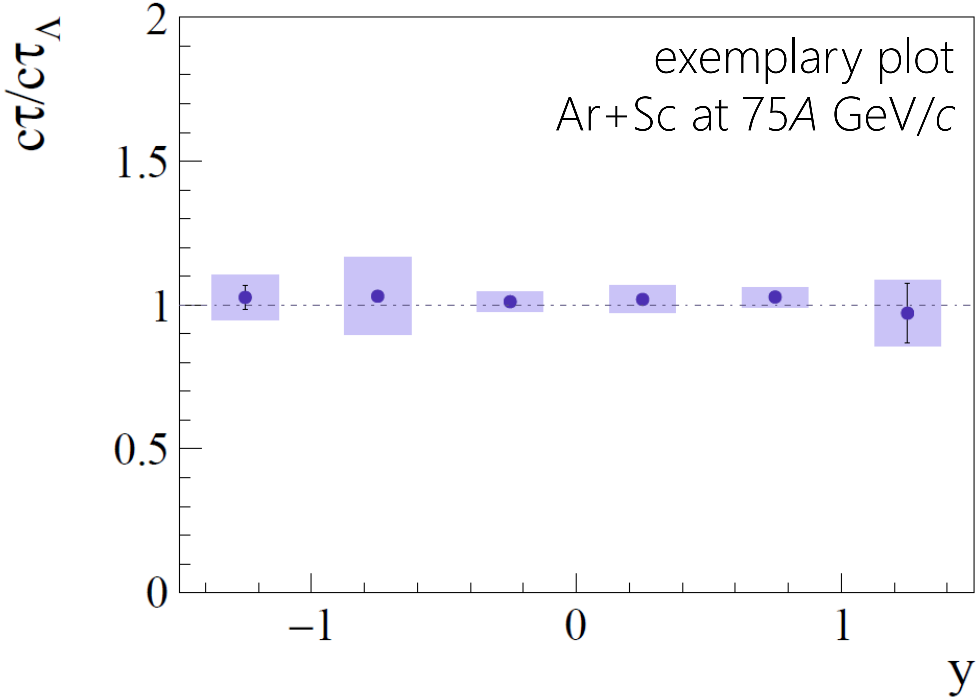


Analysis workflow



Λ identification



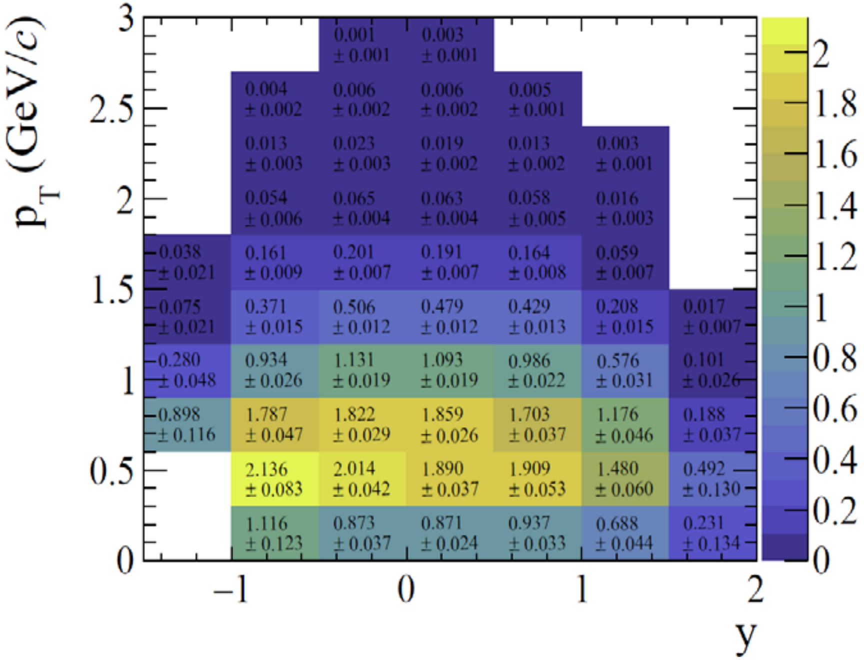


- reconstruction based on decay topology, weak decay channel is used: $\Lambda \rightarrow p\pi^{-}$
- results corrected for losses due to the geometrical acceptance and reconstruction inefficiency, applied selections, branching ratio, and feed-down from the decays of heavier hyperons
- quality of analysis tested with lifetime measurement

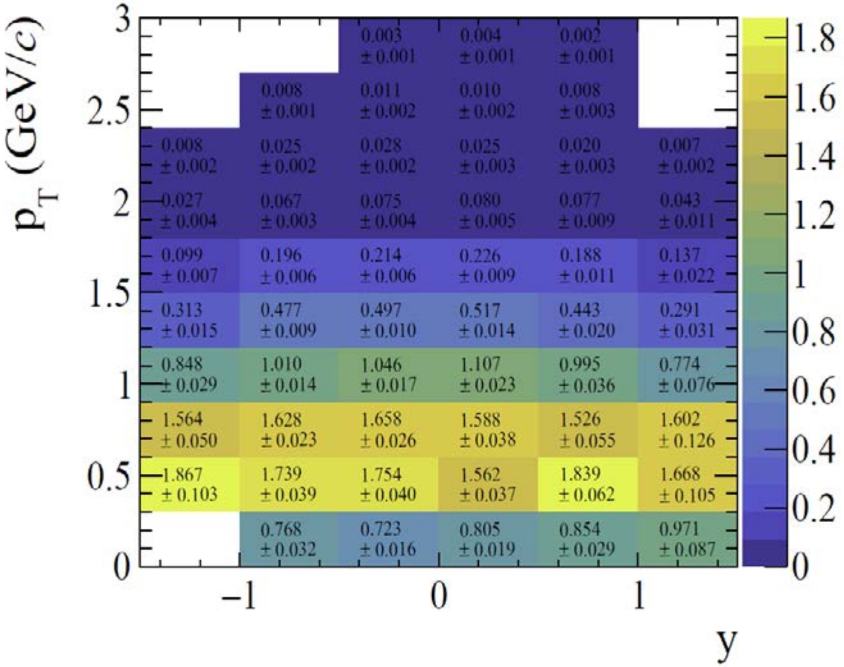
$\frac{d^2n}{dydp_T}$ spectra of Λ produced in 0-10% central Ar+Sc collisions

NA61/SHINE preliminary

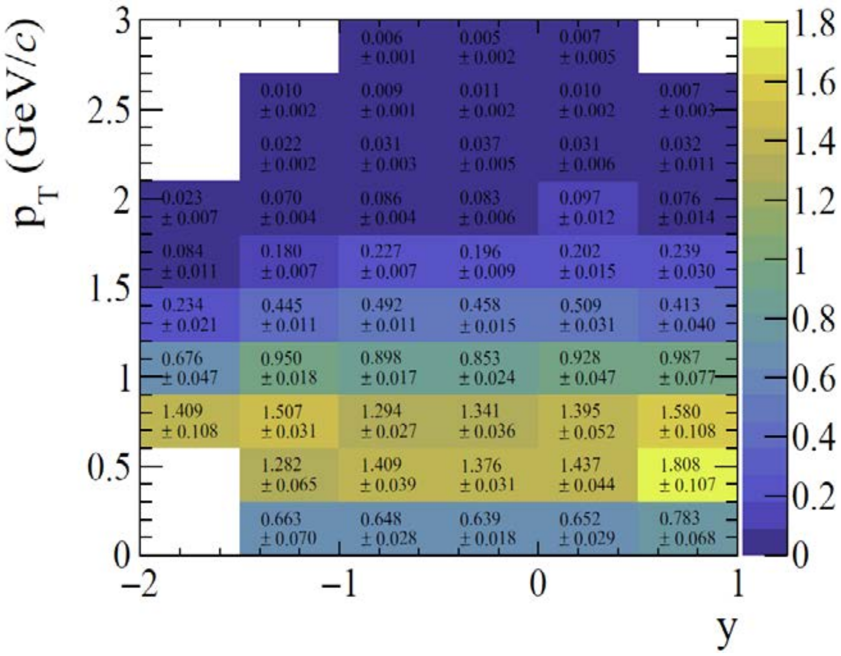
40*A* GeV/c ($\sqrt{s_{NN}}$ = 8.76 GeV)



75*A* GeV/c ($\sqrt{s_{NN}}$ = 11.94 GeV)



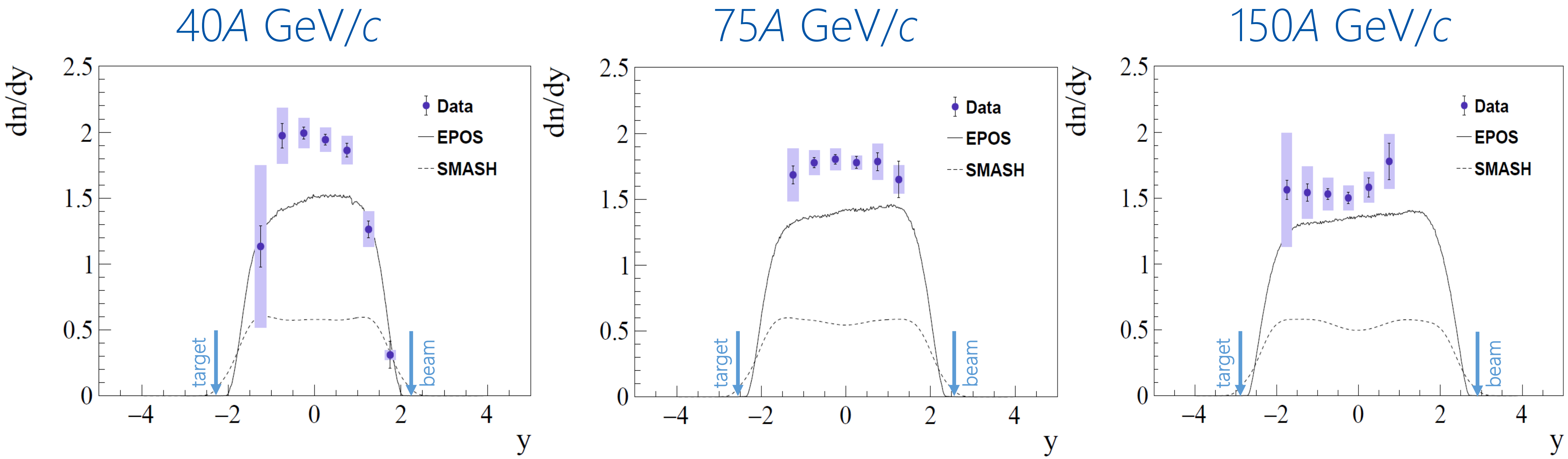
150*A* GeV/c ($\sqrt{s_{NN}}$ = 16.83 GeV)



- **first-ever** double-differential spectra in rapidity-transverse momentum phase space for Λ baryons produced in Ar+Sc collisions

Rapidity spectra of Λ in Ar+Sc collisions

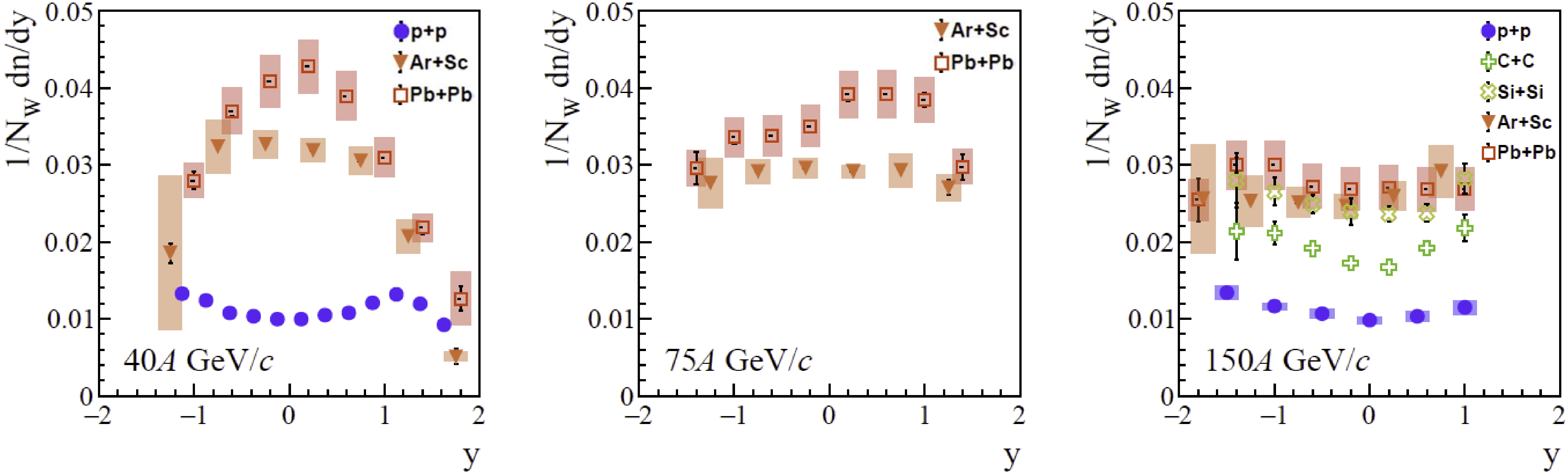
NA61/SHINE preliminary



➢ EPOS and SMASH **underestimate** Λ production at all analyzed beam momenta

Rapidity spectra of Λ in different collision systems

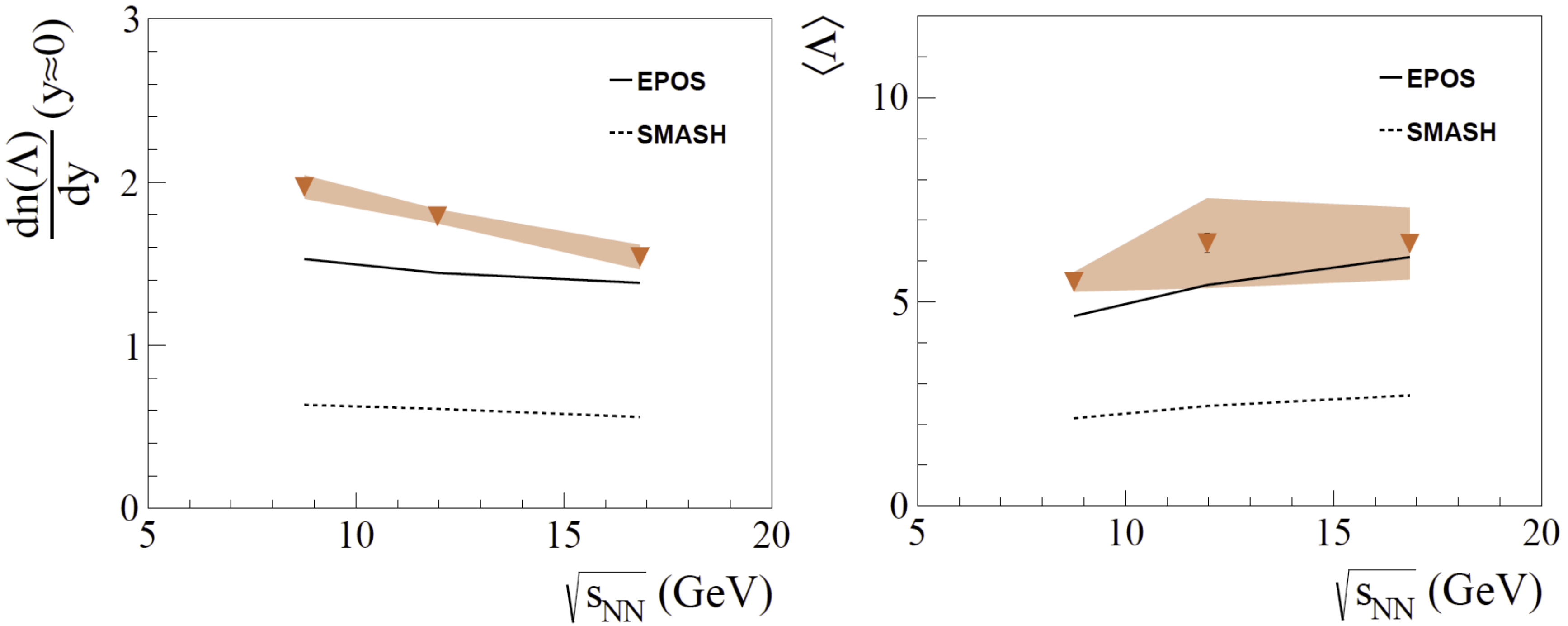
NA61/SHINE: p+p, Ar+Sc
NA49: C+C, Si+Si, Pb+Pb



- spectra are **normalized** by the mean number of wounded nucleons N_W
- spectra of Λ in Ar+Sc and Pb+Pb collisions **come closer** with increasing beam momentum

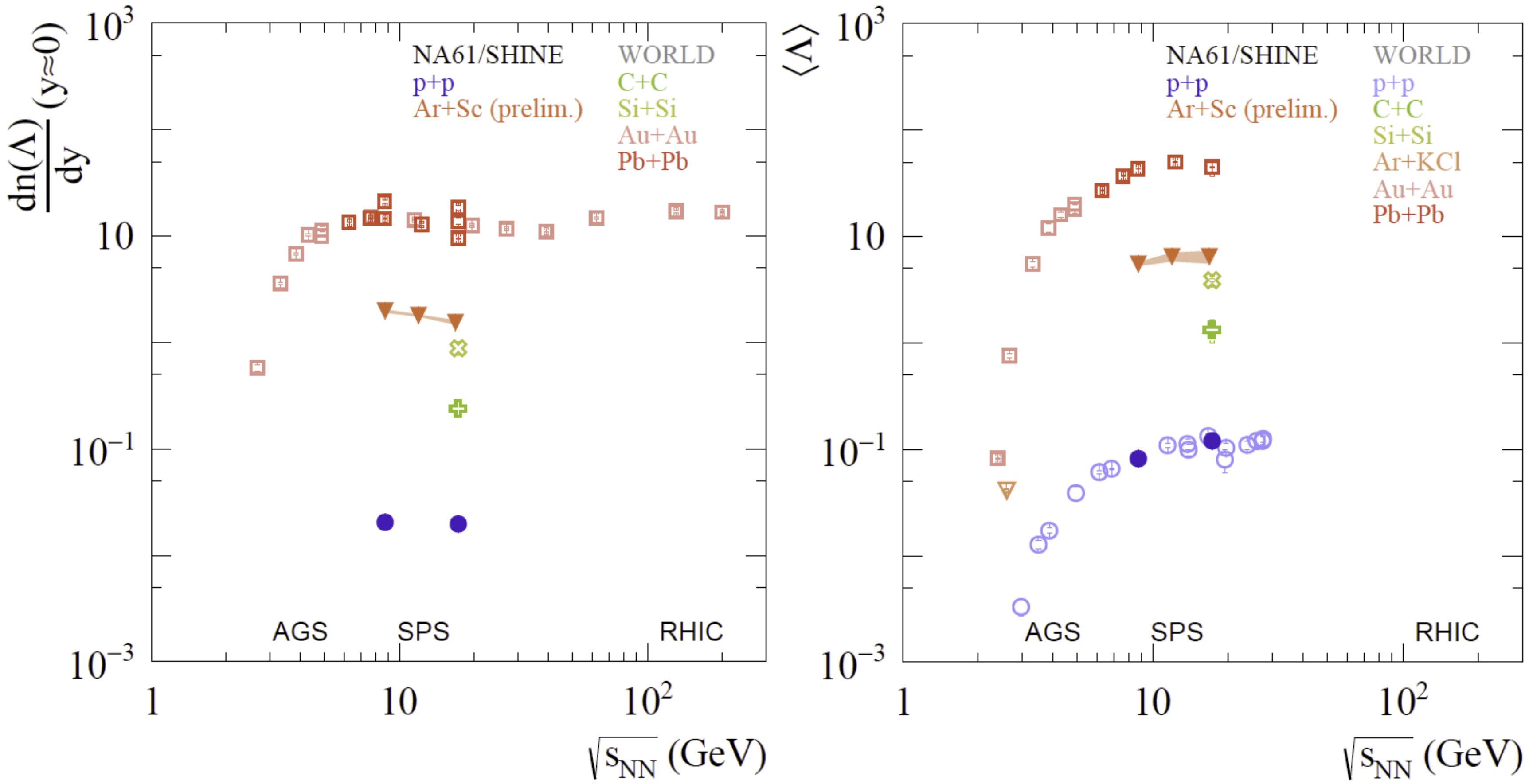
Collision energy dependence of Λ production in Ar+Sc

NA61/SHINE preliminary



- SMASH **underestimates** both the multiplicities at mid-rapidity and the mean multiplicities by more than a factor of two, whereas the EPOS prediction is **closer** to the experimental results, especially at the highest energy

Collision energy dependence of Λ production

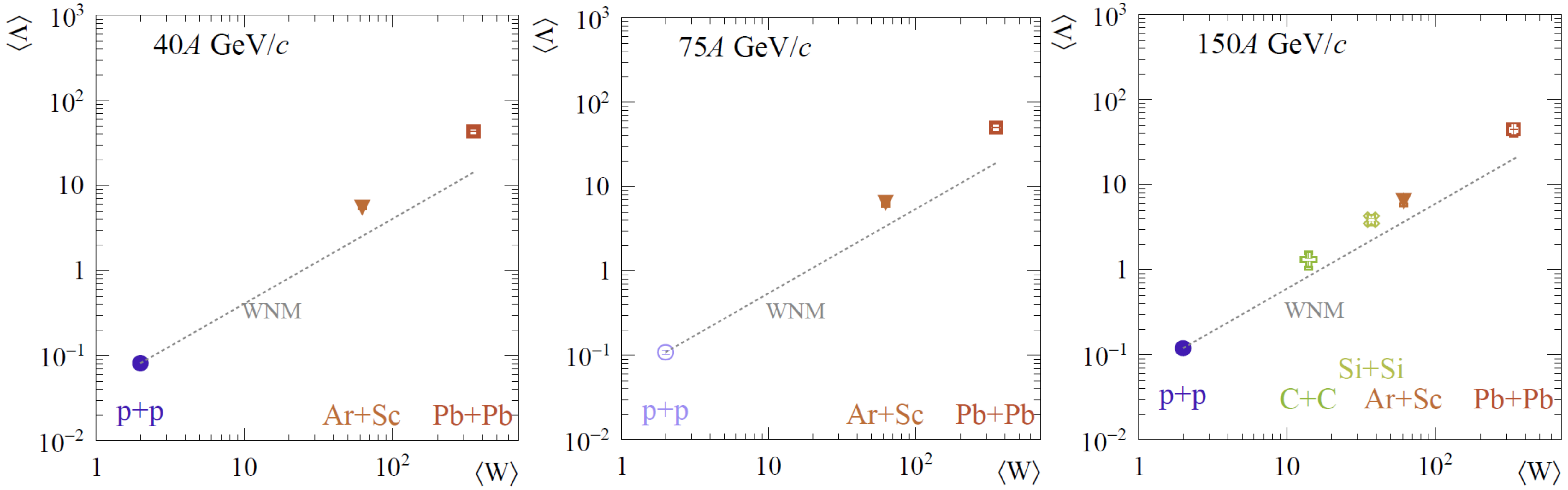


- the values in Ar+Sc are **closer to Pb+Pb** than to p+p
- qualitatively the **same dependence** for mid-rapidity and mean multiplicities of Λ in Ar+Sc as for other collision systems

NA61/SHINE: p+p, Ar+Sc; *NA49*: C+C, Si+Si, Pb+Pb; *NA57:* Pb+Pb;
STAR: Au+Au; *PHENIX*: Au+Au; *E891*: Au+Au; *E895*: Au+Au; *E896*: Au+Au;
HADES: Ar+KCl, Au+Au; *bubble chamber experiments*: p+p

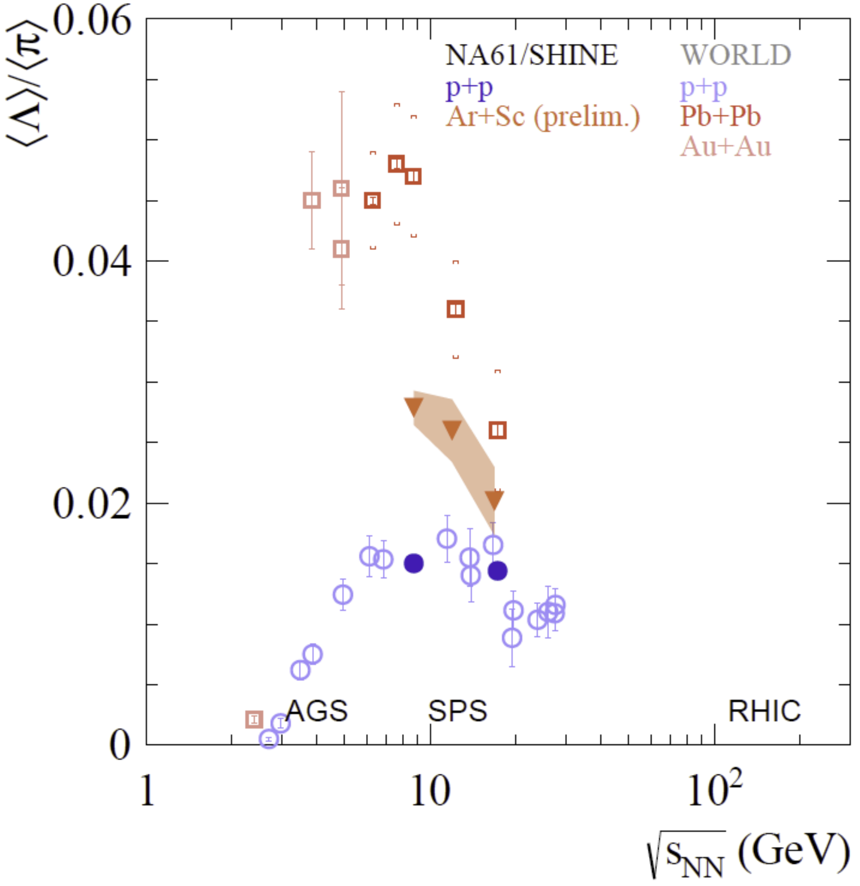
System size dependence of Λ production

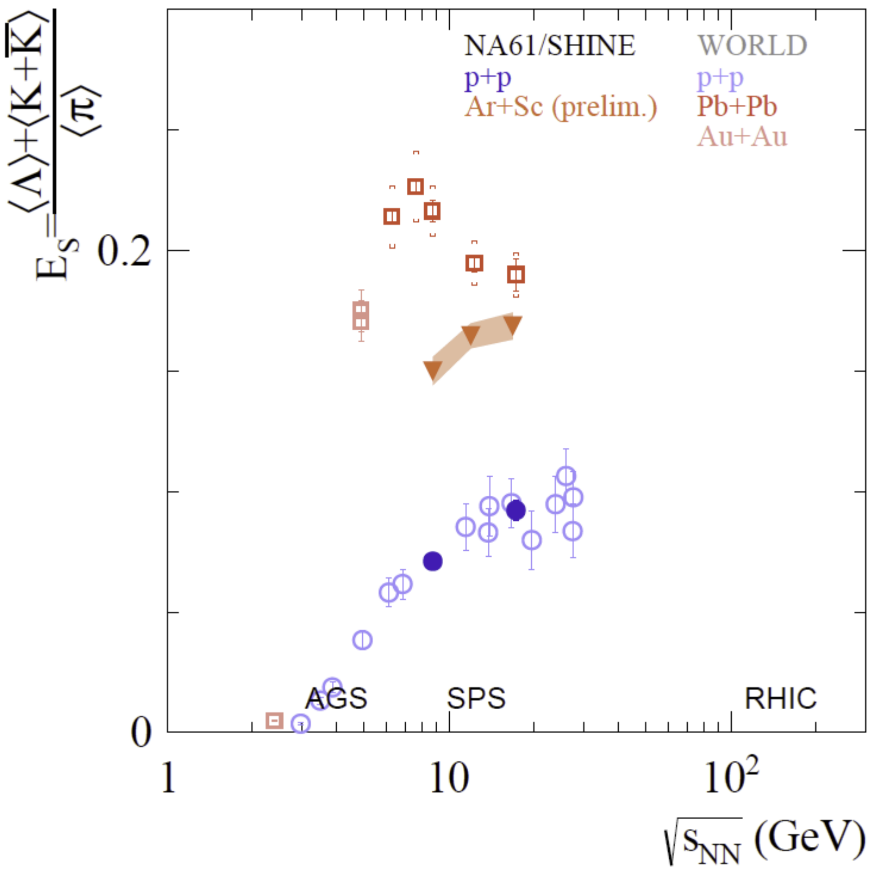
NA61/SHINE preliminary, WNM: Nucl. Phys. B111, 461 (1976)



- **linear scaling** of Λ production with the mean number of wounded nucleons in nuclear collisions
- simple scaling of values from p+p **underestimates** Λ production in heavier systems

Collision energy dependence of strangeness-to-pion ratio





NA61/SHINE: p+p, Ar+Sc; *NA49*: Pb+Pb;
E891: Au+Au; *E895*: Au+Au; *E896*: Au+Au;
bubble chamber experiments: p+p

- **similar decline** of the $\frac{\langle\Lambda\rangle}{\langle\pi\rangle}$ ratio in Ar+Sc to the one observed in Pb+Pb
- **no maximum observed** in E_s in Ar+Sc contrary to the one observed in Pb+Pb

Summary

- analysis of Λ baryon production in the 10% most central Ar+Sc collisions at 40*A* GeV/*c*, 75*A* GeV/*c*, 150*A* GeV/*c* is presented
- EPOS and SMASH models do not describe the presented results satisfactorily
- qualitatively similar system size and energy dependence for Λ production in Ar+Sc collisions as the one observed in heavier systems, such as Pb+Pb
- no maximum observed in the total strangeness-to-pion ratio in Ar+Sc contrary to Pb+Pb
- exciting times for exploring strangeness ahead

Thank you for your attention!

All comments and questions are very welcome:

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SHINE

World data on Λ production

- *NA61/SHINE*: *p+p (40 GeV/c: preliminary, 158 GeV/c: Eur. Phys. J. C **76** (2016), 198), Ar+Sc (preliminary);*
- *NA49*: *C+C, Si+Si (Phys. Rev. Lett. **94** (2005), 052301), Pb+Pb (Phys. Rev. C **78** (2008), 034918);*
- *NA57: Pb+Pb (Phys. Lett. B **595** (2004), 68-74, J. Phys. G **32** (2006), 427-442);*
- *STAR*: *Au+Au (Phys. Rev. C **102** (2020), 034909, Phys. Rev. C **83** (2011), 024901, Phys. Rev. Lett. **89** (2002), 092301, Phys. Rev. Lett. **98** (2007), 062301);*
- *PHENIX*: *Au+Au (Phys. Rev. Lett. **89** (2002), 092302);*
- *E891*: *Au+Au (Phys. Lett. B **382** (1996), 35-39);*
- *E895*: *Au+Au (Nucl. Phys. A **698** (2002), 495-498);*
- *E896*: *Au+Au (Phys. Rev. Lett. **88** (2002), 062301);*
- *HADES*: *Ar+KCl (Eur. Phys. J. A **47** (2011), 21), Au+Au (Phys. Lett. B **793** (2019), 457-463);*
- *bubble chamber experiments*: *p+p (overview at Z. Phys. C **71** (1996), 55-64)*

World data on K production

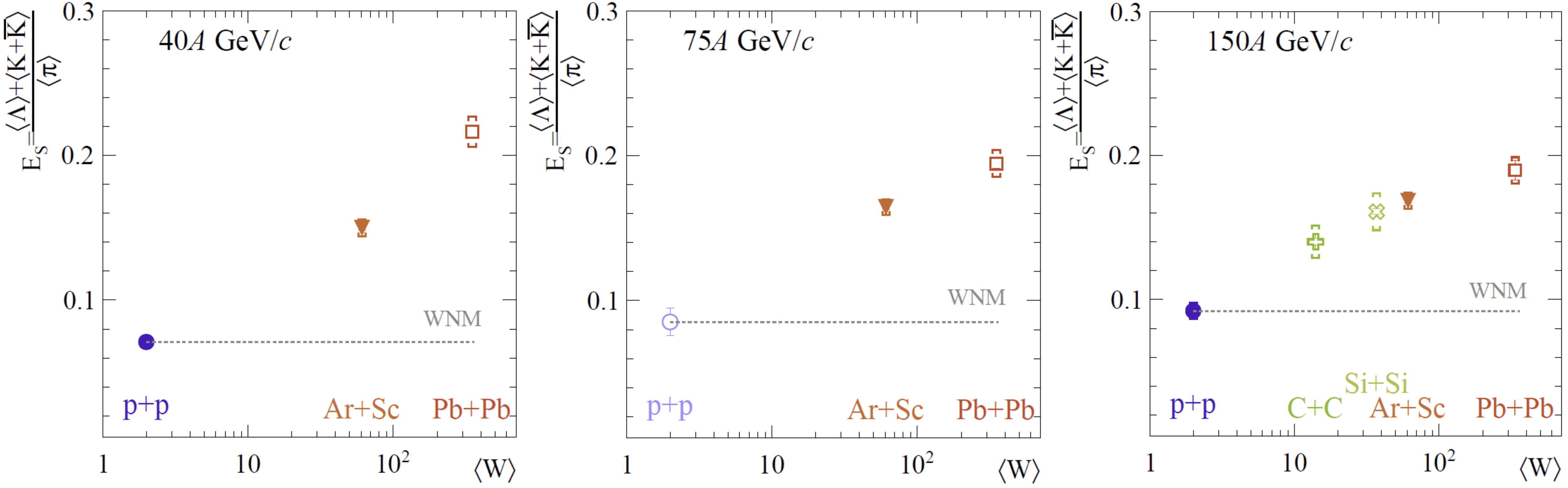
- *NA61/SHINE*: *p+p (40 GeV/c: arXiv:2402.17025, 158 GeV/c: Eur. Phys. J. C* ***82*** *(2022), 96), Ar+Sc (Eur. Phys. J. C* ***84*** *(2024), 416);*
- *NA49*: *C+C, Si+Si (Phys. Rev. Lett.* ***94*** *(2005), 052301), Pb+Pb (Phys. Rev. C* ***77*** *(2008), 024903);*
- *E802:* *Au+Au (Phys. Rev. C* ***58*** *(1998), 3523);*
- *bubble chamber experiments*: *p+p (overview at Z. Phys. C* ***71*** *(1996), 55-64)*

World data on π production

- *NA61/SHINE*: p+p (40 GeV/c: preliminary, 158 GeV/c: EPJC ***76*** (2016), 198), Ar+Sc (preliminary);
- *NA49*: C+C, Si+Si (Phys. Rev. Lett. ***94*** (2005), 052301), Pb+Pb (Phys. Rev. C ***77*** (2008), 024903);
- *E802:* Au+Au (Phys. Rev. C ***57*** (2008), R466);
- *E895*: Au+Au (Phys. Rev. C ***68*** (2003), 054905);
- *bubble chamber experiments*: p+p (overview at Z. Phys. C ***65*** (1995), 215-223)

System size dependence of strangeness-to-pion ratio

NA61/SHINE preliminary, WNM: Nucl. Phys. B111, 461 (1976)



- **saturation** of the strangeness enhancement towards the higher energies

Backup

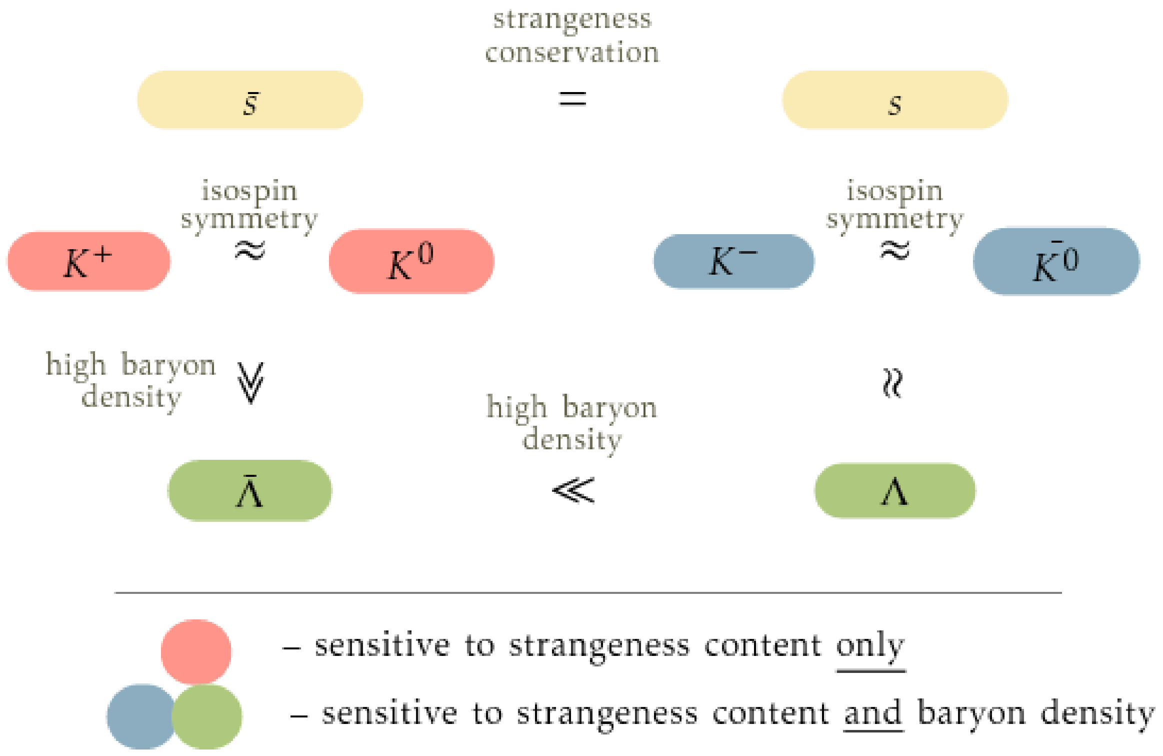
Model comparisons

- **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:

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

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

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