Λ hyperon production in central Ar+Sc collisions at CERN SPS energies

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Strange and Heavy Flavor Physics
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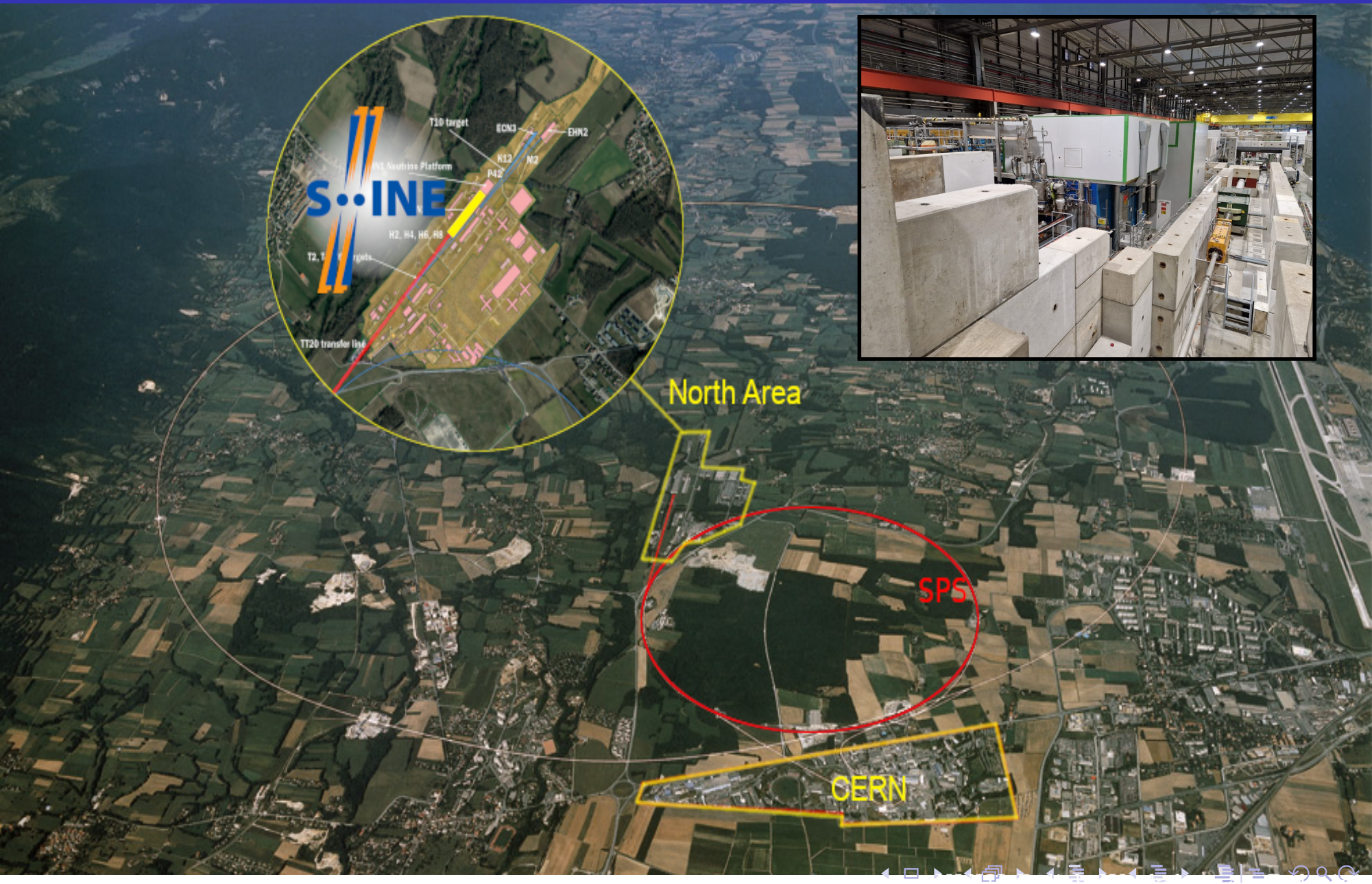
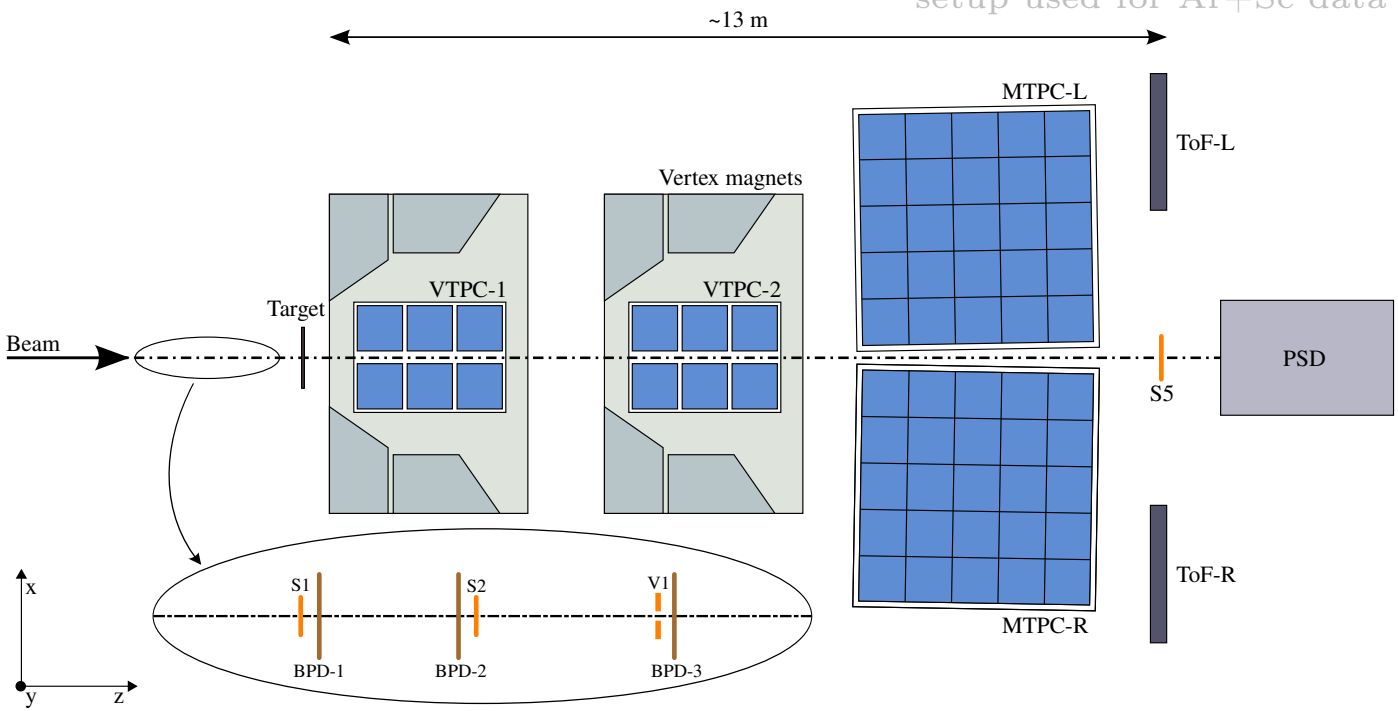
NA61/SHINE experiment at CERN North Area



NA61/SHINE detector

NA61/SHINE, Eur.Phys.J.C 84 (2024) 4, 416
setup used for Ar+Sc data taking

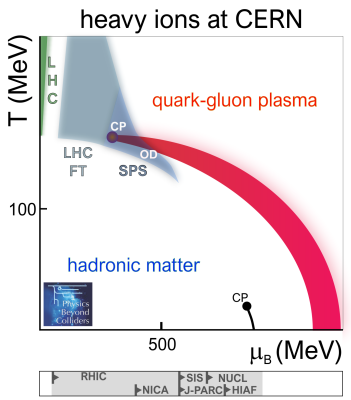


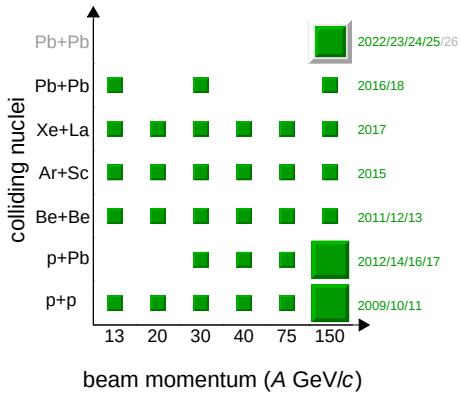
- Multipurpose fixed-target spectrometer located at the CERN SPS
- Particle identification (TPC, ToF)
- Centrality determination (PSD)
- Coverage of the entire projectile hemisphere; down to $p_{\mathrm{T}} = 0$
- Operation with hadron and ion beams; ion beam momenta: $13A$–$150A$ GeV/c $\leftrightarrow$ $\sqrt{s_{\mathrm{NN}}} = 5.1$–$16.8$ GeV

NA61/SHINE research program

Strong interaction physics:

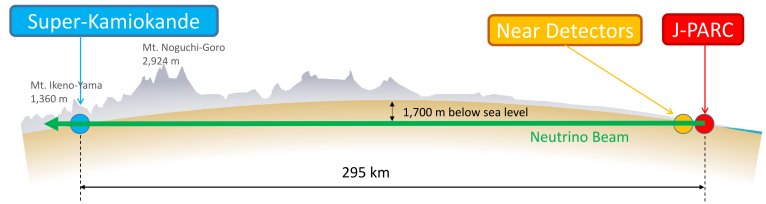
- **study of the properties of the onset of deconfinement**
- search for the critical point of the strongly interacting matter
- direct measurement of open charm production

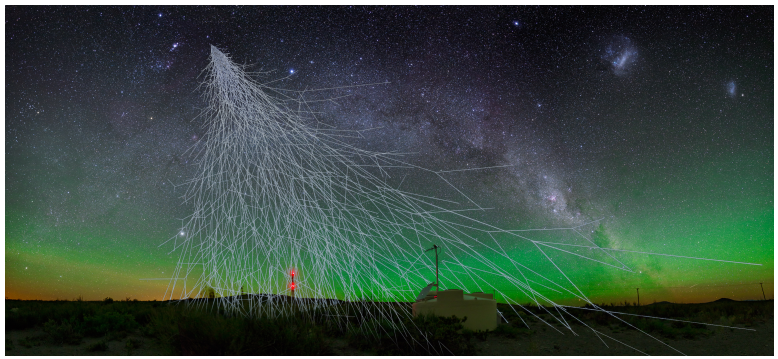




as well as

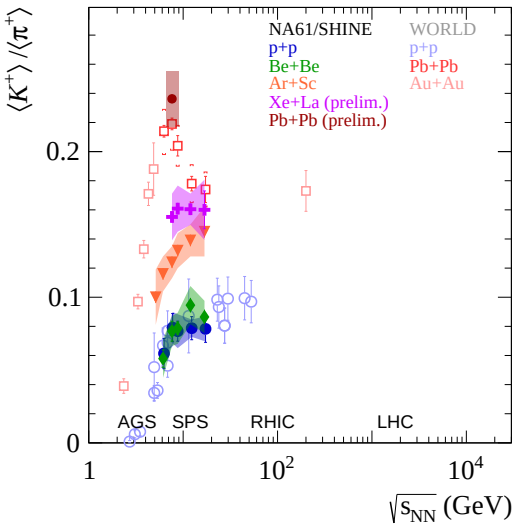
- measurement of hadron production for neutrino programs at J-PARC and Fermilab
- measurement of nuclear fragmentation cross sections and hadron production for cosmic-ray physics



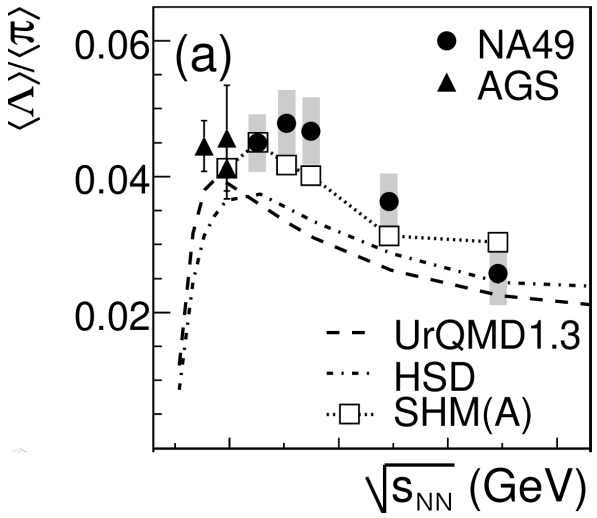


Study of strangeness production mechanisms

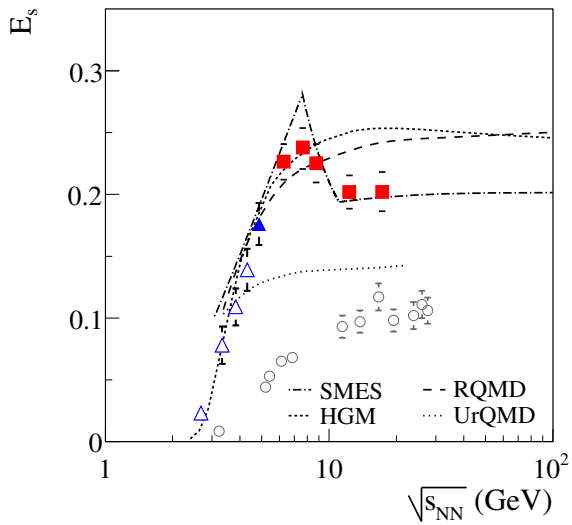
- Strangeness production is a sensitive probe of the **properties of the strongly interacting matter** created in heavy-ion collisions
- Medium-size collision systems can provide unique information on the **evolution of strangeness production mechanisms** and bridge the gap between proton-proton and heavy-ion interactions



NA61/SHINE preliminary



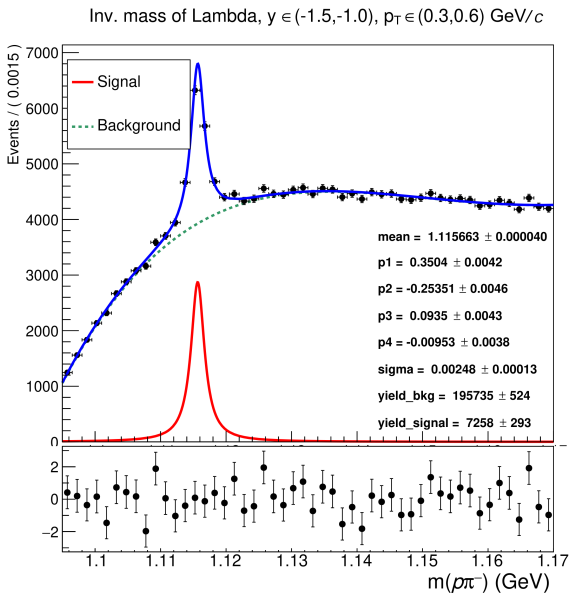
NA49, Phys.Rev.C 78 (2008) 034918

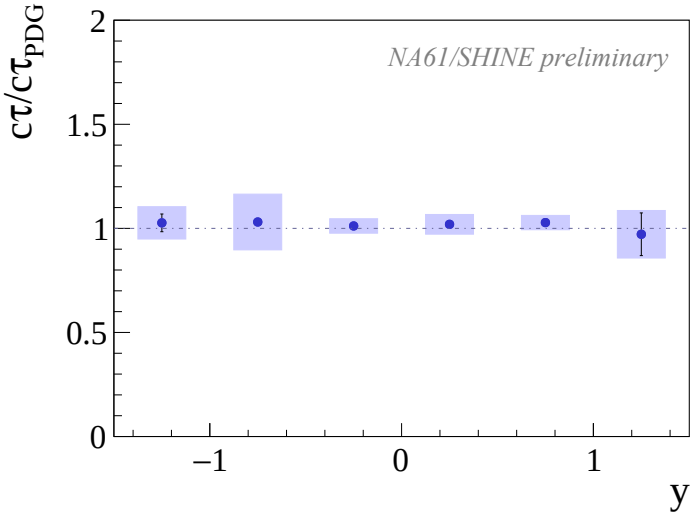


NA49, Phys.Rev.C 77 (2008) 024903

Λ identification

exemplary plots Ar+Sc at 75A GeV/c

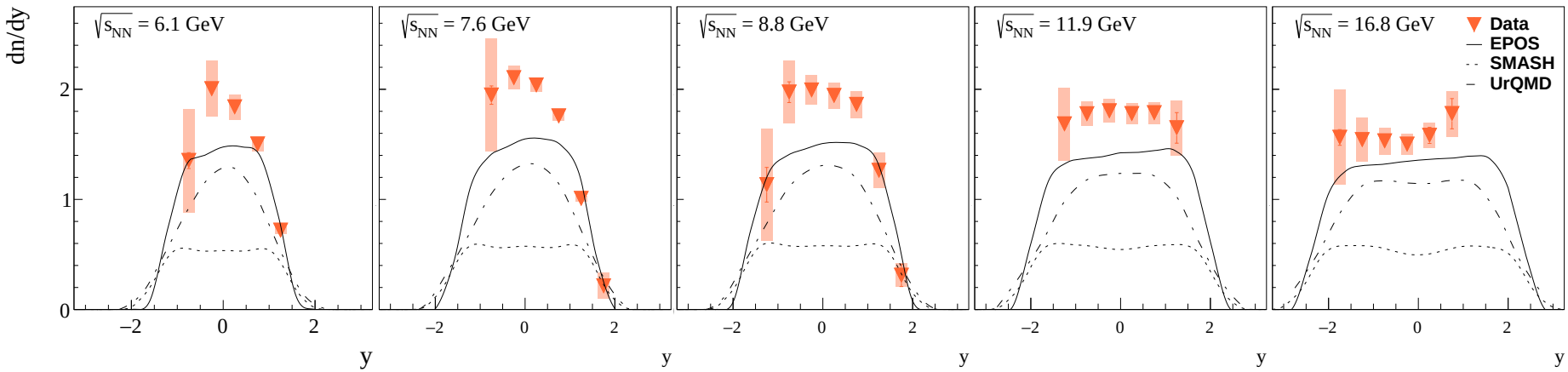




- Analysis performed for the 10% most central ^{40}Ar + ^{45}Sc events
- Reconstruction based on decay topology, weak decay channel is used: $\Lambda \to p\pi^-$ (BR $\approx 63\%$)
- Results corrected for losses due to the geometrical acceptance and reconstruction inefficiency, applied selections, branching ratio, and feed-down from the weak decays of heavier hyperons
- Quality of analysis tested with lifetime measurement

Rapidity spectra of Λ in Ar+Sc collisions

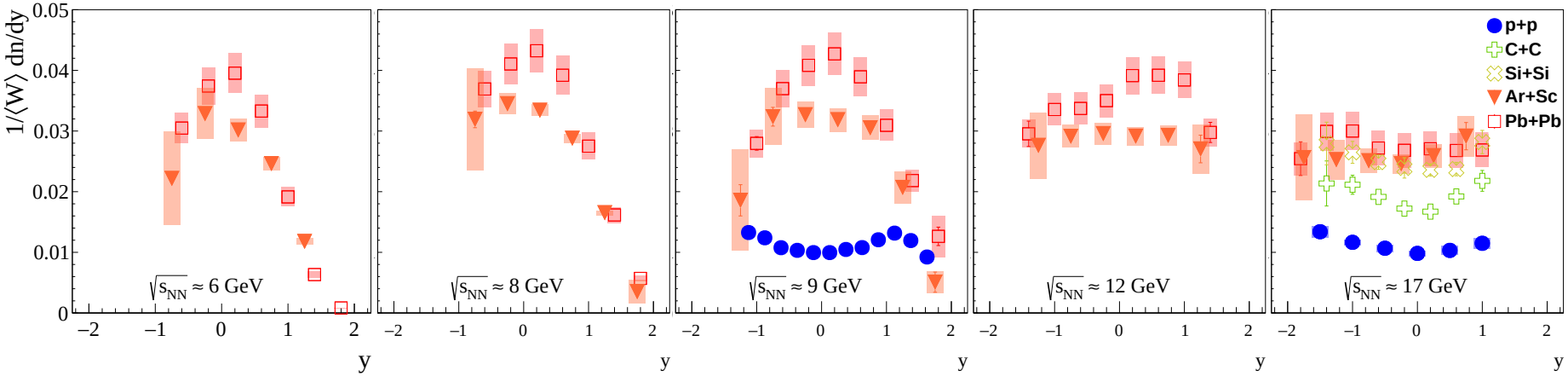
NA61/SHINE preliminary



- EPOS, SMASH and UrQMD **underestimate** Λ production at all analyzed beam momenta with EPOS being **closest** to the experimental results

Rapidity spectra of Λ in different collision systems

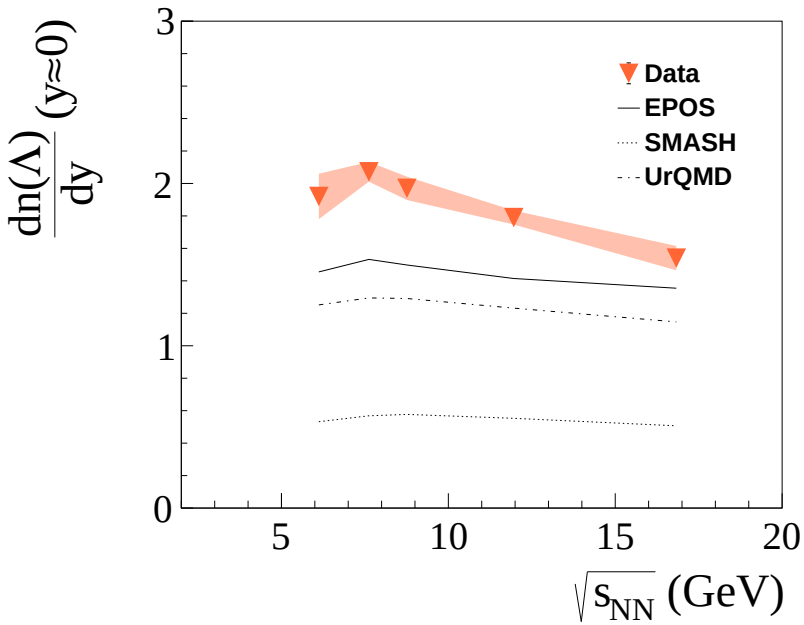
NA61/SHINE: p+p, Ar+Sc, NA49: C+C, Si+Si, Pb+Pb (refs. in backup)

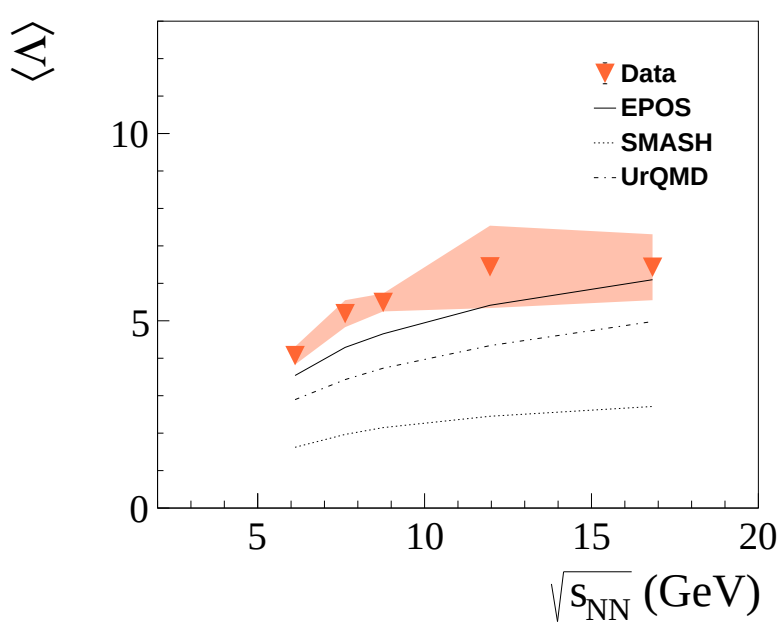


- Spectra are **normalized** by the mean number of wounded nucleons $\langle W \rangle$
- Spectra of Λ in Ar+Sc and Pb+Pb collisions **come closer** with increasing beam momentum

Collision energy dependence of Λ production in Ar+Sc

NA61/SHINE preliminary

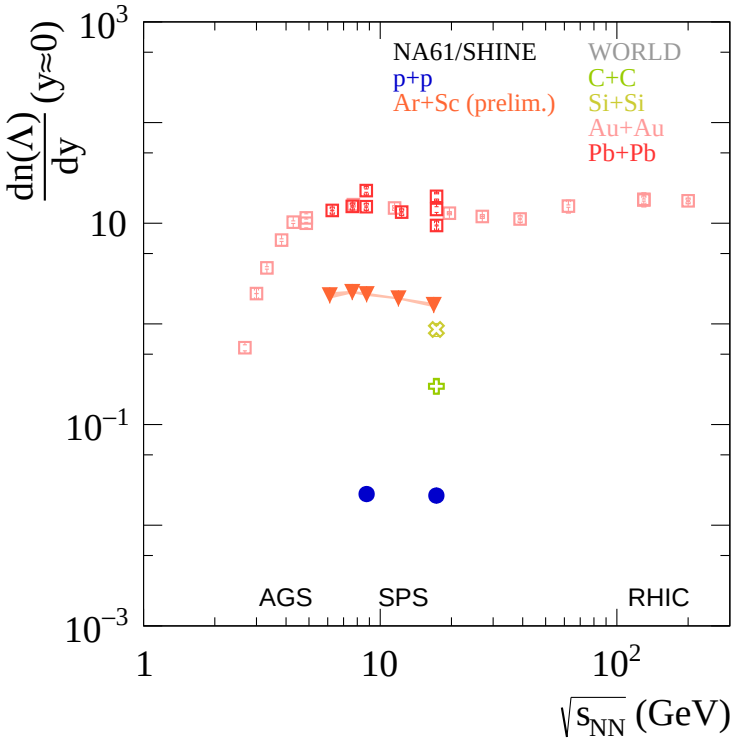


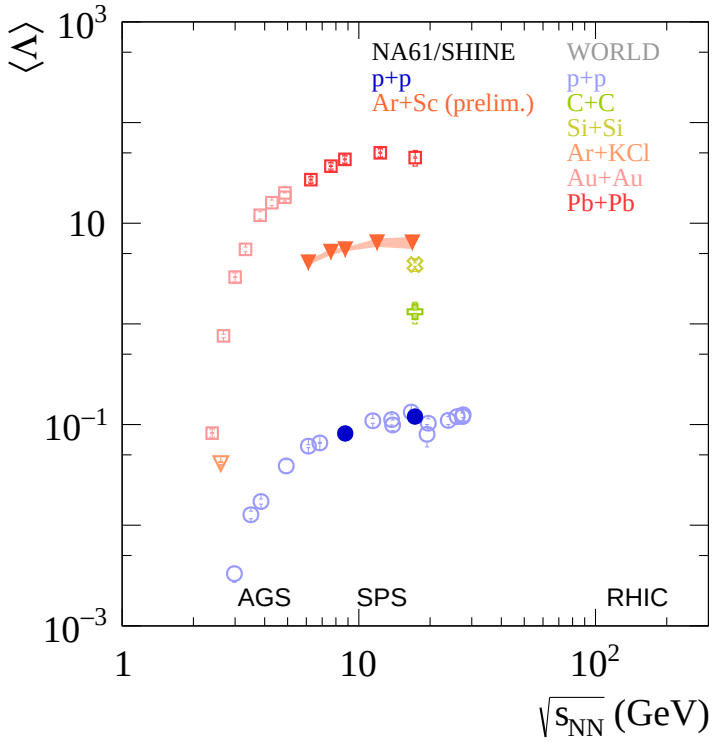


- SMASH **significantly underestimates** both the yields at mid-rapidity and the mean multiplicities, whereas the EPOS and UrQMD predictions are **closer** to the experimental results, especially at the highest energy

Collision energy dependence of Λ production

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 (refs. in backup)

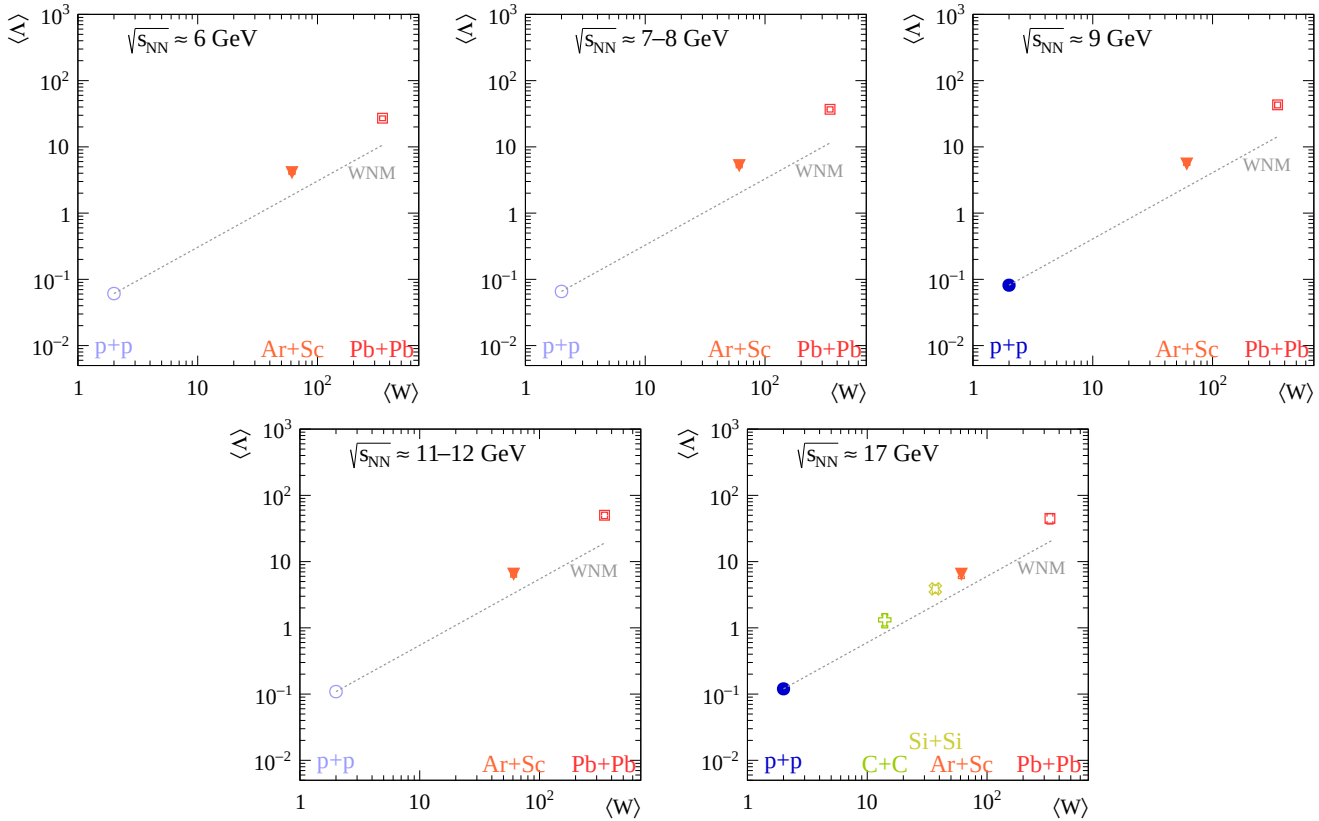




- The values in Ar+Sc are **closer to Pb+Pb** than to p+p
- Qualitatively the **same dependence** for mid-rapidity and mean multiplicities of Λ in Ar+Sc as for other collision systems

System size dependence of Λ production

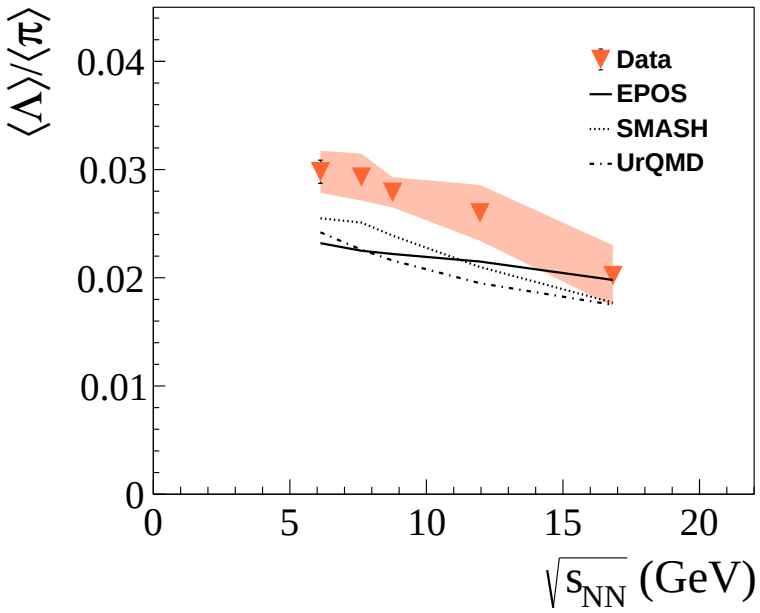
NA61/SHINE: p+p, Ar+Sc; NA49: C+C, Si+Si, Pb+Pb; bubble chamber exp.: p+p (refs. in backup),
WNM: A. Białas, M. Bleszyński, W. Czyż, Nucl.Phys.B111, 461 (1976)

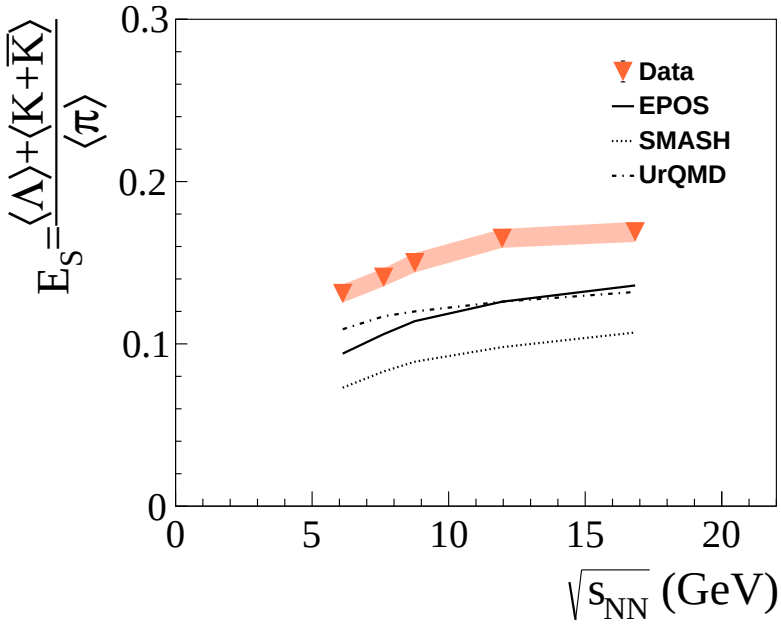


- **Approximately linear scaling** of Λ production with the mean number of wounded nucleons in nuclear collisions
- Simple scaling of values from p+p **underestimates** Λ production in heavier systems

Collision energy dependence of $\langle\Lambda\rangle/\langle\pi\rangle$ and E_S in Ar+Sc

NA61/SHINE preliminary

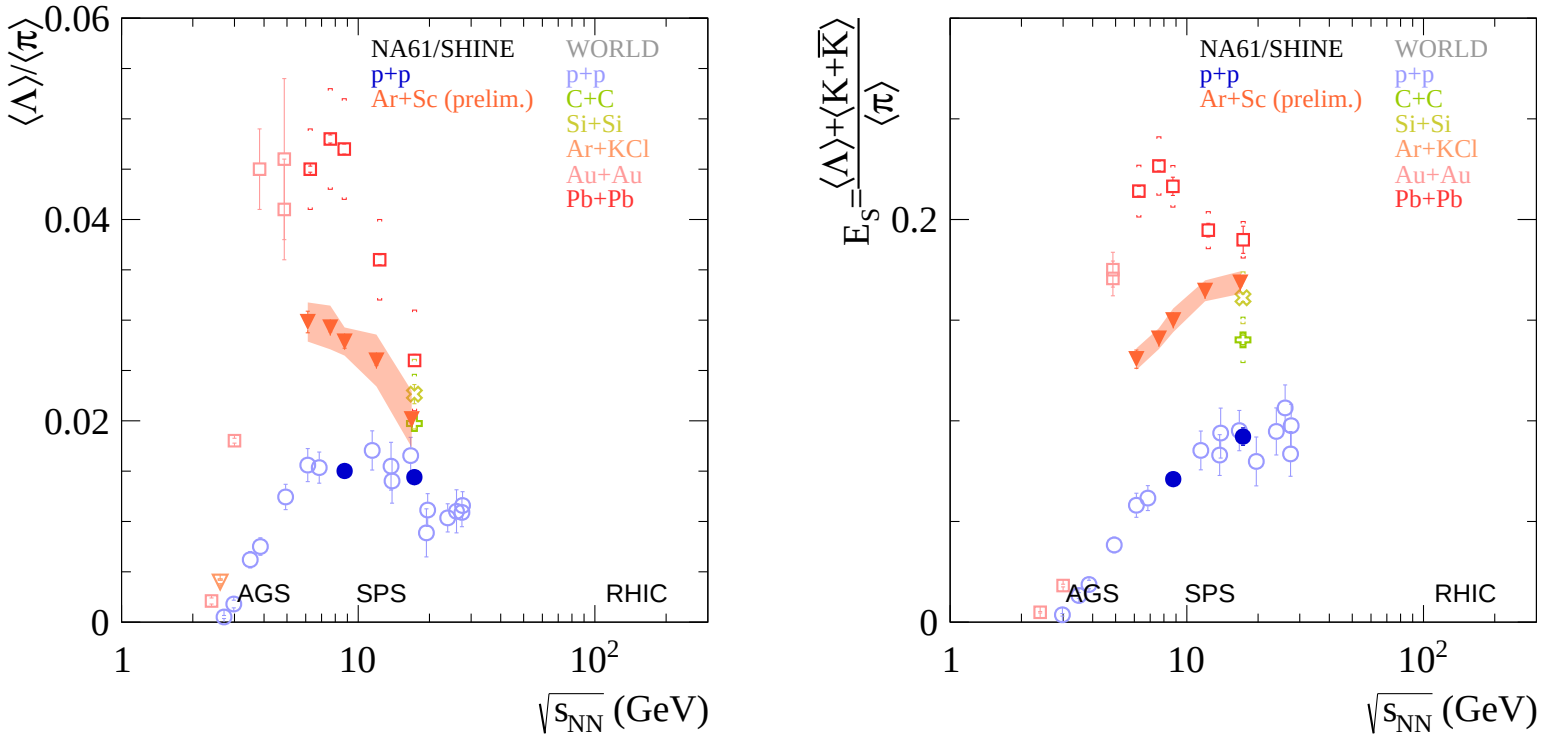




- All three models show **approximately linear decrease with energy** in the $\langle\Lambda\rangle/\langle\pi\rangle$ ratio with predictions close to the experimental result at the highest energy
- All three models **underestimate** strangeness-to-pion ratio E_S

Collision energy dependence of $\langle\Lambda\rangle/\langle\pi\rangle$ and E_S

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 (refs. in backup)



- **Similar behavior** of the $\langle\Lambda\rangle/\langle\pi\rangle$ 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

- Results on Λ **baryon production** in the 10% most central Ar+Sc collisions at 19A–150A GeV/c are presented
- EPOS, SMASH and UrQMD models **do not describe** the presented results satisfactorily
- Qualitatively **similar energy dependence** for $\langle\Lambda\rangle/\langle\pi\rangle$ ratio in Ar+Sc collisions as the one observed in heavier systems, such as Pb+Pb
- **No maximum observed** in the strangeness-to-pion ratio in Ar+Sc contrary to Pb+Pb

Thank you for your attention!

Backup

Models

Model comparisons

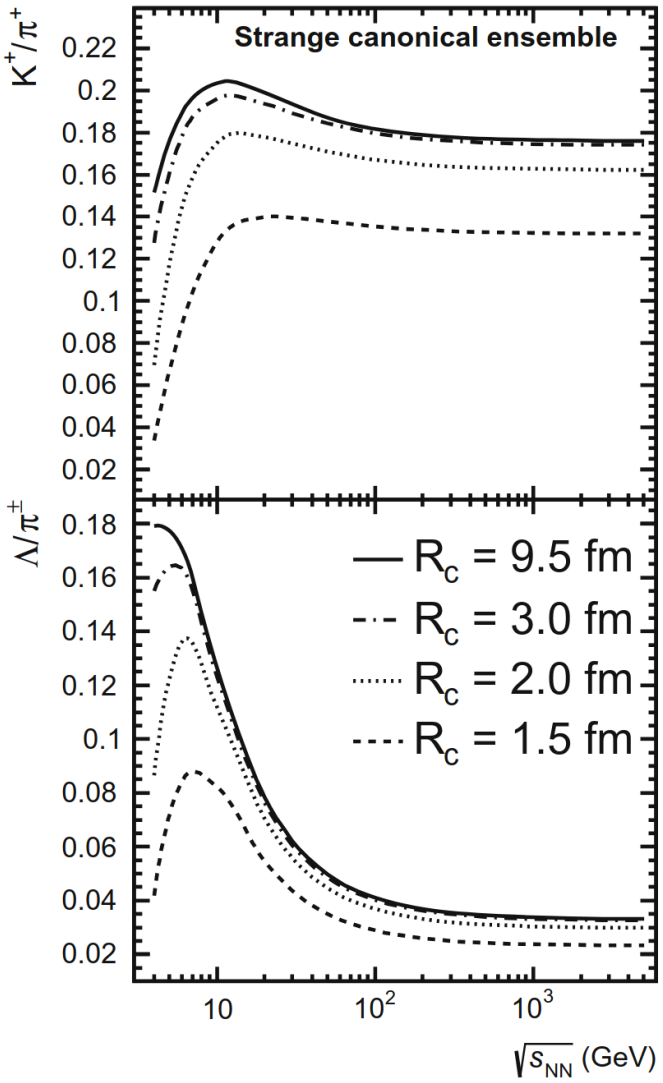
- **EPOS** – the reaction proceeds from the excitation of strings according to Gribov-Regge theory to string fragmentation into hadrons.
- **UrQMD** starts with a hadron cascade based on elementary cross sections for resonance production which either decay (mostly at low energies) or are converted into 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).

Model versions used for comparison: EPOS 1.99, SMASH 2.0, URQMD 3.4

Thermal model expectations

H. Oeschler, J. Cleymans, B. Hippolyte, K. Redlich, N. Sharma, Eur.Phys.J.C (2017) 77, 584



Abstract: ... The pattern of the maxima of strange-particles-to-pion ratios as a function of beam energy is quite special, as they do not occur at the same beam energy and are sensitive to the system size. In particular, the Λ/π^+ ratio shows a clear maximum even for small systems while the maximum in the K^+/π^+ ratio is less pronounced in small systems.

E_S information

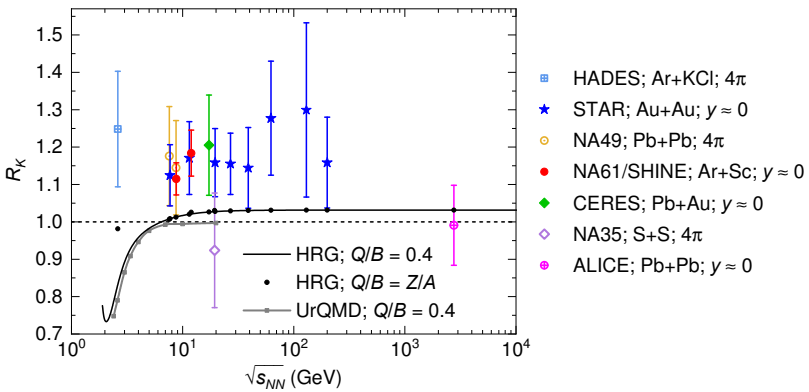
$$E_S = \frac{\langle \Lambda \rangle + \langle K + \overline{K} \rangle}{\langle \pi \rangle} \ (\propto \text{strangeness-to-entropy ratio})$$

$$\sigma(E_S) = E_S \times \sqrt{\left(\frac{\sigma(\text{Str})}{\text{Str}}\right)^2 + \left(\frac{\sigma(\pi)}{\pi}\right)^2}$$

$$\langle \pi \rangle = 1.5 \times \left(\langle \pi^+ \rangle + \langle \pi^- \rangle\right)$$

$$\langle K + \overline{K} \rangle = 2 \cdot \left(\langle K^+ \rangle + \langle K^- \rangle\right) \quad \text{for A+A}$$

$$\langle K + \overline{K} \rangle = 4 \cdot \langle K^0_S \rangle \quad \text{for } p\text{+}p$$



NA61/SHINE, Nat.Commun.16 (2025) 2849

Note the potential change in normalization due to the isospin symmetry violation observed by NA61/SHINE and confirmed by data from other experiments (see talk by Angelika Tefelska)

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: Eur.Phys.J.C 84 (2024), 820, 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, 158 GeV/c: Eur.Phys.J.C 74 (2014), 2794), 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 Λ production

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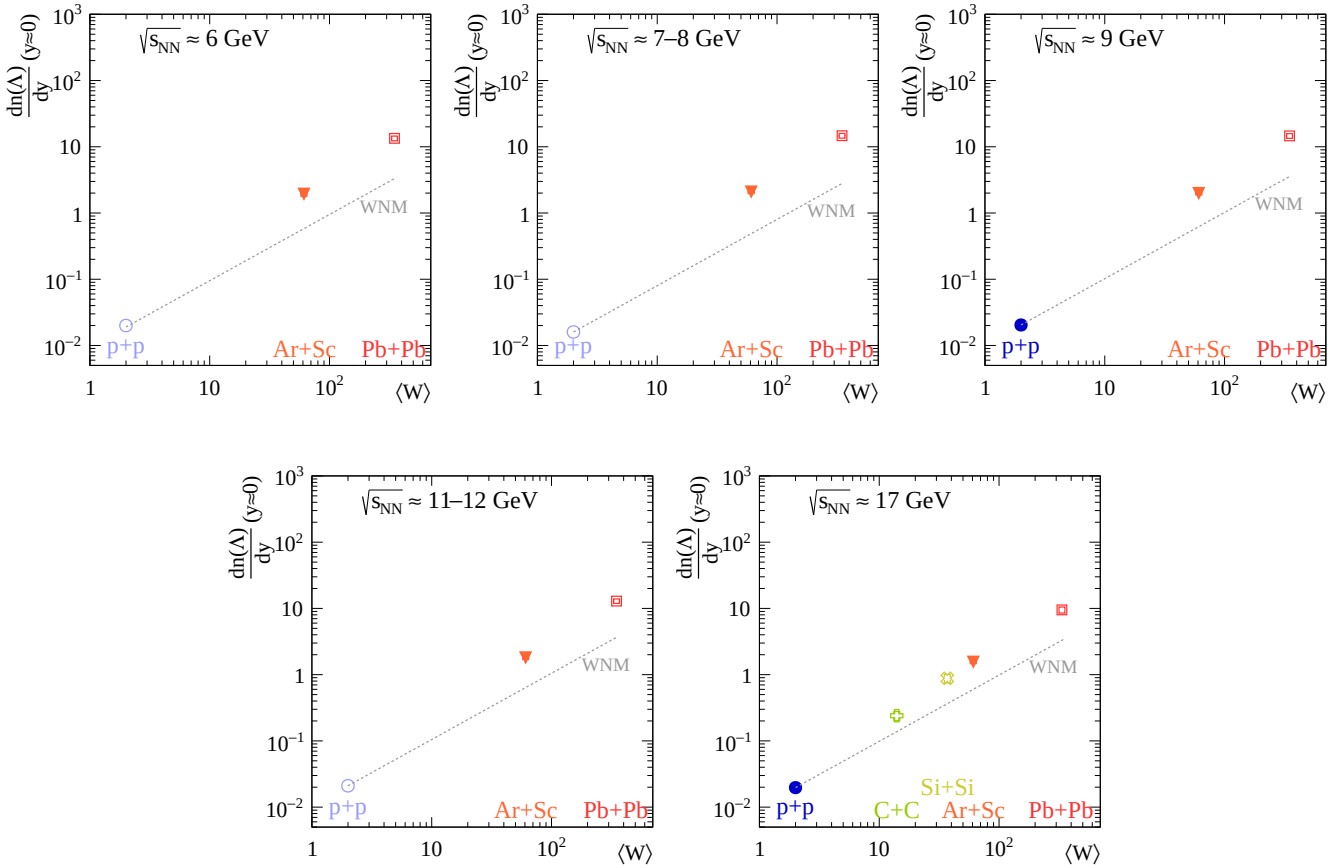
WNM: A. Białas, M. Bleszyński, W. Czyż, Nucl.Phys.B111, 461 (1976)



System size dependence of $\langle\Lambda\rangle/\langle\pi\rangle$

NA61/SHINE: p+p, Ar+Sc; NA49: C+C, Si+Si, Pb+Pb; bubble chamber exp.: p+p (refs. in backup),
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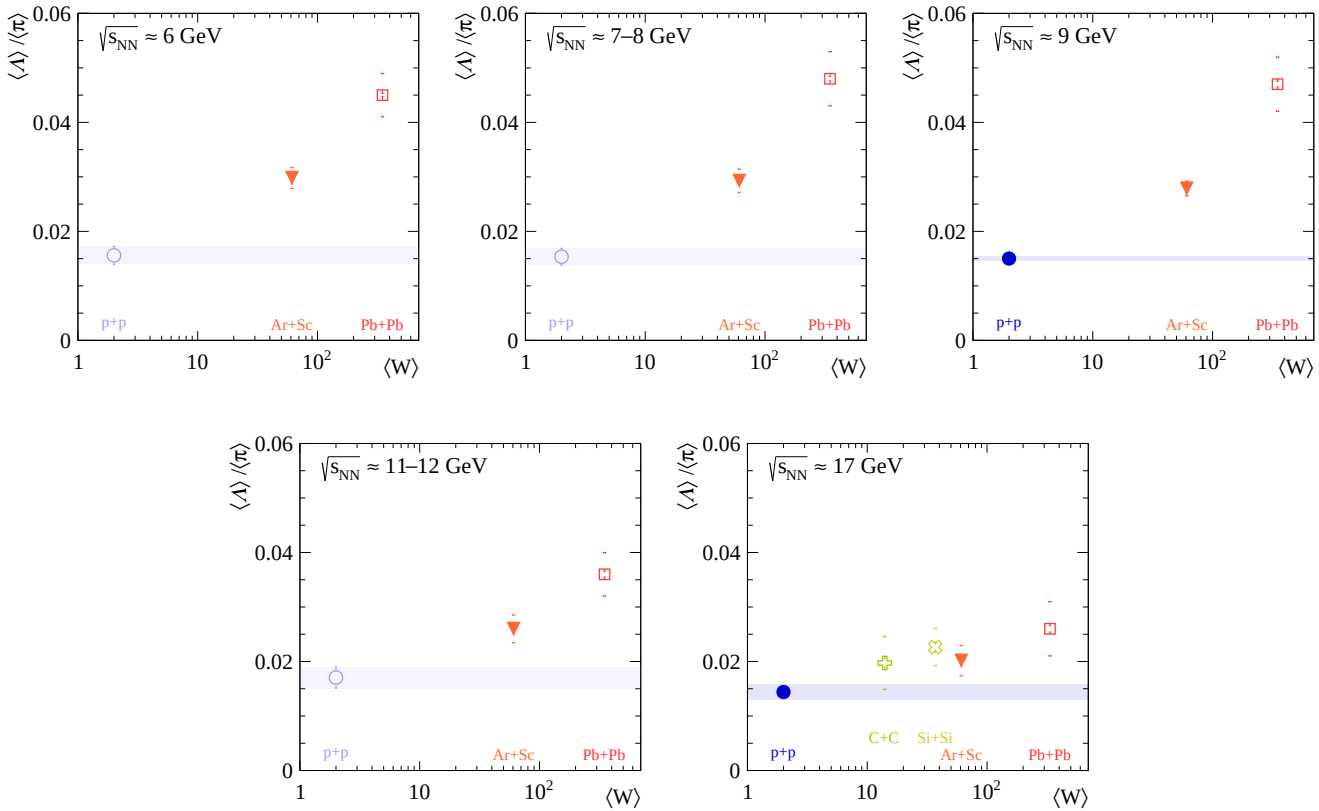

System size dependence of E_S

NA61/SHINE: p+p, Ar+Sc; NA49: C+C, Si+Si, Pb+Pb; bubble chamber exp.: p+p (refs. in backup),
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