News on charged and neutral hadron production from NA61/SHINE

Yuliia Balkova[1]
Maciej Lewicki[2]
for the NA61/SHINE Collaboration

[1] National Centre for Nuclear Research
[2] Institute of Nuclear Physics, Polish Academy of Sciences

Strangeness in Quark Matter, Los Angeles, 2026

The NA61/SHINE Physics Program

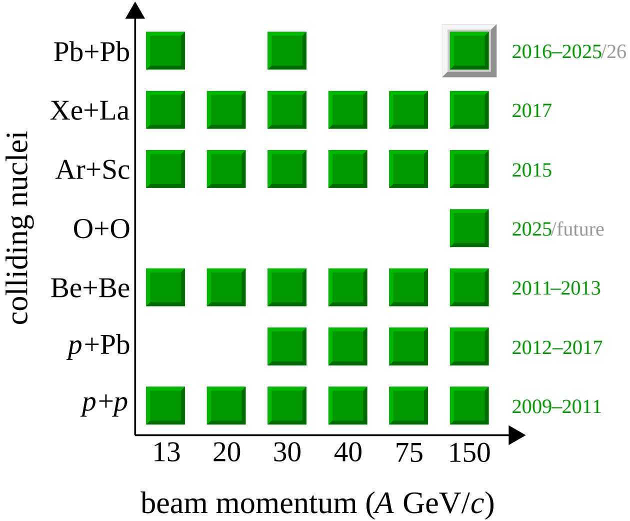
Strong interaction program:

- Study the properties of the **onset of deconfinement**
- Search for the **critical point** of strongly interacting matter
- Study of **strangeness** and **charm** production mechanisms
- Understand the **violation of isospin symmetry** in multiparticle production

Measurements for:

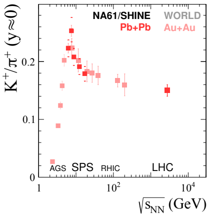
- neutrino programs (J-PARC, Fermilab)
- cosmic-ray physics (Pierre-Auger, KASCADE, satellite experiments)

CERN-SPSC-2006-034
CERN-SPSC-2023-022
CERN-SPSC-2018-008

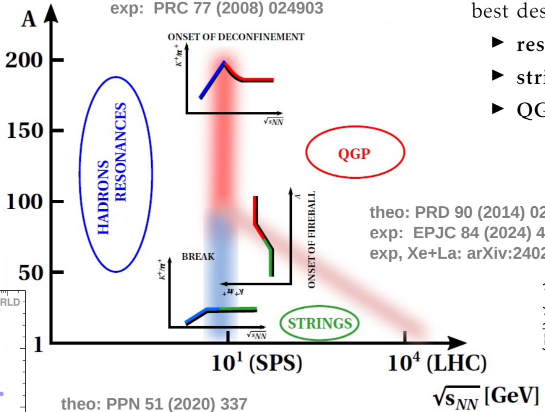


2D scan in collision energy and system size.

Uniqueness of ion results from NA61/SHINE



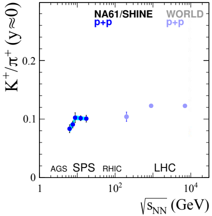
theo: APPB 46 (2015) 1991
exp: PRC 77 (2008) 024903



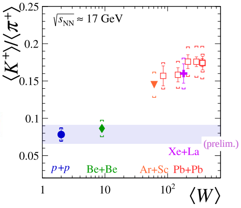
Hypothetical domains of hadron production, best described with models of:

- **resonance** creation and decay
- **string** creation and fragmentation
- **QGP** formation and hadronisation

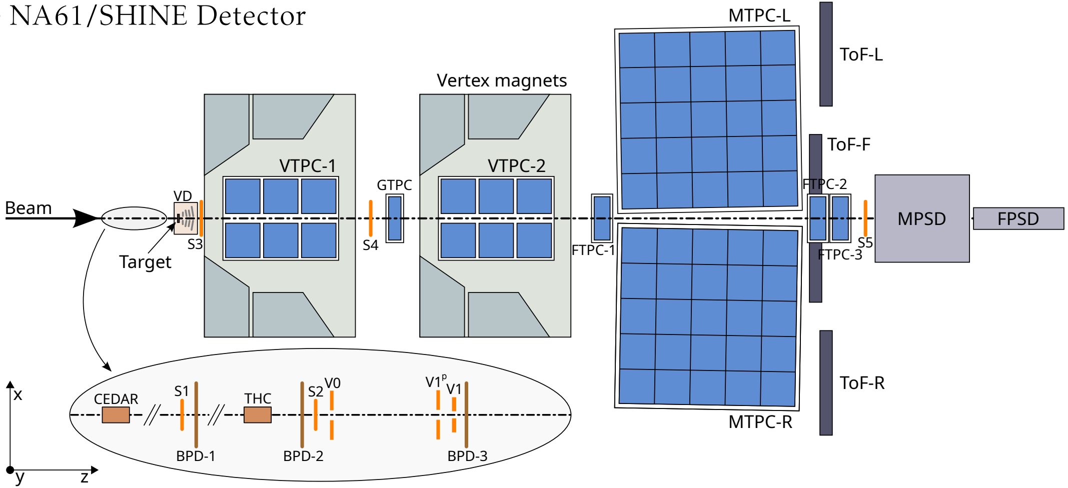
theo: PRD 90 (2014) 025031
exp: EPJC 84 (2024) 416
exp, Xe+La: arXiv:2402.10973 [nucl-ex]



theo: PPN 51 (2020) 337
exp: PRC 102 (2020) 011901



The NA61/SHINE Detector



- **Fixed-target** experiment at CERN SPS
- **Large acceptance** hadron spectrometer
- Full **forward hemisphere, down to** $p_T = 0$
- High-resolution **Time Projection Chambers**
- **Time-of-Flight** (ToF) detectors
- Projectile Spectator Detectors for **centrality** determination

Identifying charged and neutral hadrons

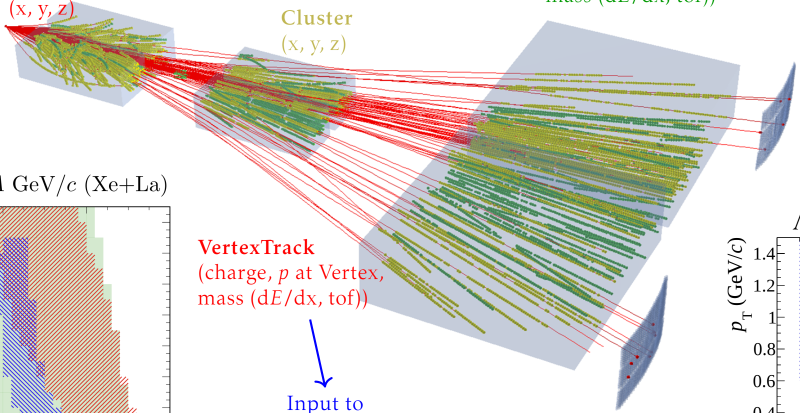
Beam
(xz, yz)

Vertex
(x, y, z)

Cluster
(x, y, z)

Track
(charge, p at first Cluster,
mass (dE/dx, tof))

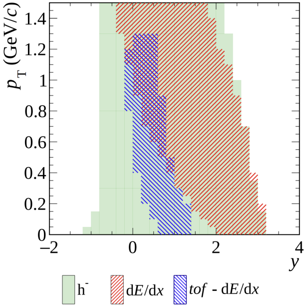
Input to
$K^0_S \rightarrow \pi^+ + \pi^-$
$\Lambda \rightarrow p + \pi^-$
analyses



VertexTrack
(charge, p at Vertex,
mass (dE/dx, tof))

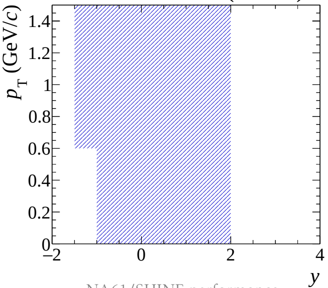
Input to
K^+, K^-
analysis

π^- at 40A GeV/c (Xe+La)



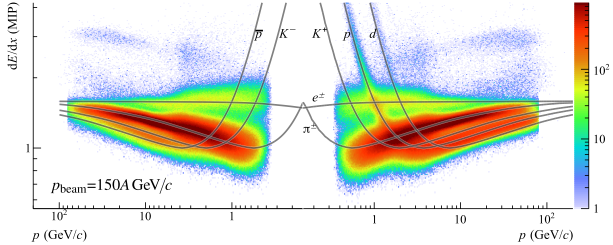
NA61/SHINE performance

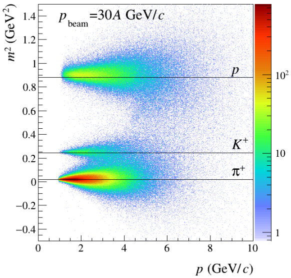
Λ at 40A GeV/c (Ar+Sc)

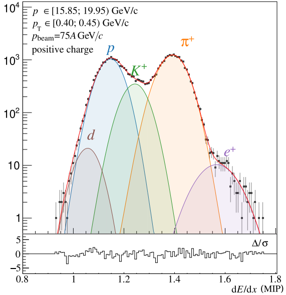


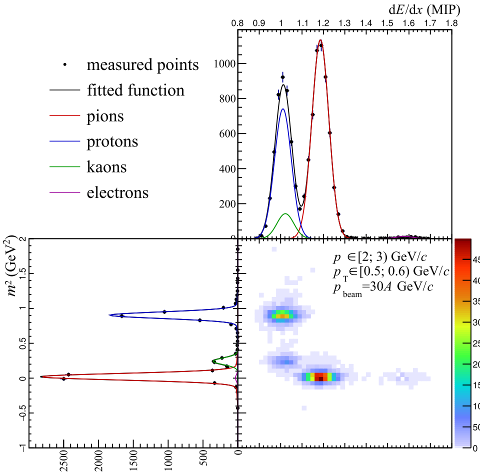
NA61/SHINE performance

Measuring charged hadrons – dE/dx and tof PID







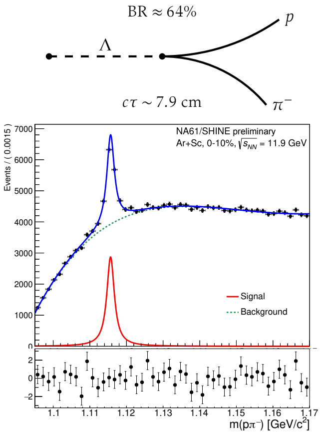


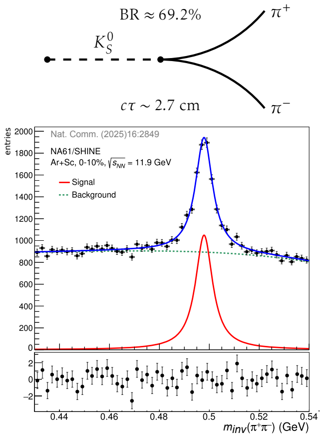
- dE/dx PID used in the region of relativisitic rise of the Bethe-Bloch curve (>5 GeV/c)
- tof resolves the ambiguity in the cross-over region

Ar+Sc collisions, EPJC 84 (2024) 4, 416

Λ and K^0_S reconstruction

- 10% most central Ar+Sc collisions at beam momenta of:
  - Λ: 13A to 150A GeV/c ($\sqrt{s_{NN}} = 5.1 - 16.8$ GeV)
  - K^0_S: 40A, 75A GeV/c ($\sqrt{s_{NN}} = 8.8, 11.9$ GeV)
- Signal described with Breit-Wigner (Lorentzian) function for Λ (K^0_S)
  Background: Chebychev polynomial

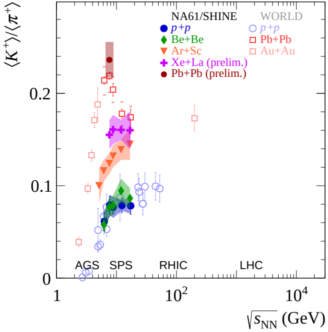




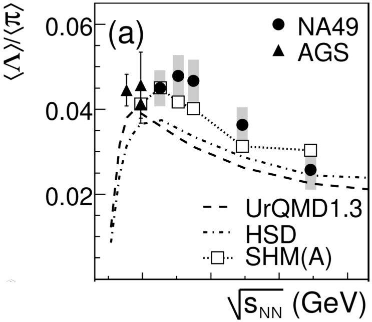
- **Corrections applied**: losses due to geometrical acceptance and reconstruction inefficiency, applied selections, branching ratio, and weak decay feed-down from heavier states
- Quality of analysis tested with **lifetime measurement**

Study of strangeness production mechanisms

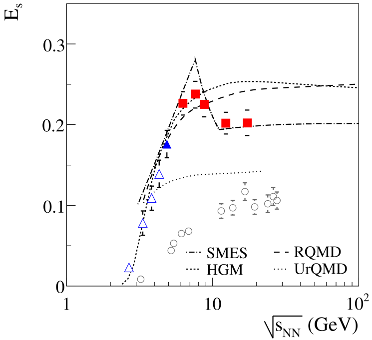
- Strangeness production is a sensitive probe of the **properties of the strongly interacting matter** created in ion collisions
- **Strangeness/entropy ratio** is expected to be different in the confined (hadrons) and QGP phases (quarks, gluons)
- Medium-size collision systems can provide unique information on the **evolution of strangeness production mechanisms** and bridge the gap between proton-proton and heavy-ion interactions



0–10% Ar+Sc and references to $p+p$, Be+Be, world: **NA61, EPJC 84 (2024) 416**
0–20% (16.8 GeV) and 0–10% Xe+La, NA61 0–7.2% Pb+Pb: NA61/SHINE preliminary

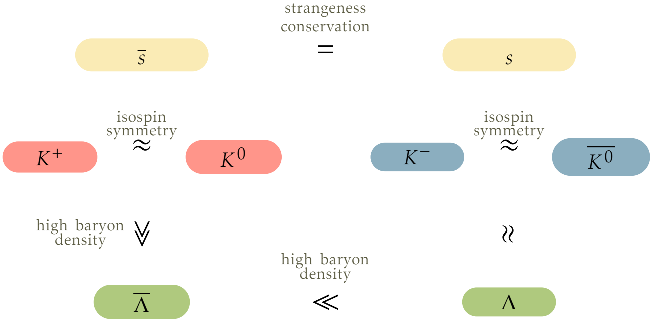


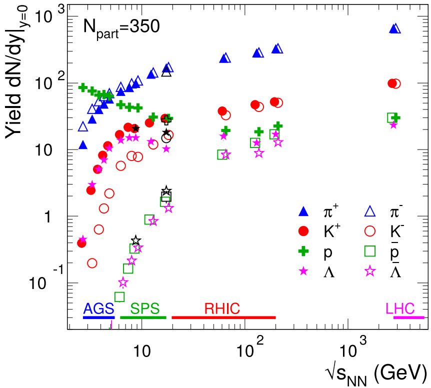
PRC 78 (2008) 034918



PRC 77 (2008) 024903

Main strangeness carriers in A+A collisions at high μ_B





IJPA 29 (2014) 1430047

– sensitive to strangeness content only

– sensitive to strangeness content and baryon density

Strange definitions

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

$$2 \cdot \langle N_{s\bar{s}} \rangle = \langle \Lambda + \overline{\Lambda} \rangle + \langle K + \overline{K} \rangle + \langle \phi \rangle + \ldots$$

At SPS energies:

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

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

The experimental ratio proportional to **strangeness to entropy** can be defined as:

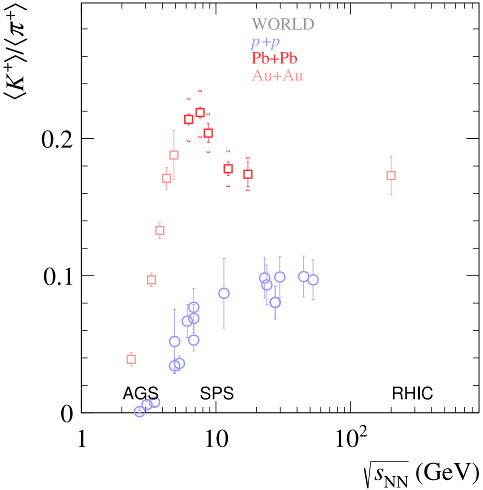
$$E_S = \frac{\langle \Lambda \rangle + \langle K + \overline{K} \rangle}{\langle \pi \rangle} \approx \frac{2 \cdot \langle N_{s\bar{s}} \rangle}{\langle \pi \rangle}$$

Under the assumption of **isospin symmetry**:

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

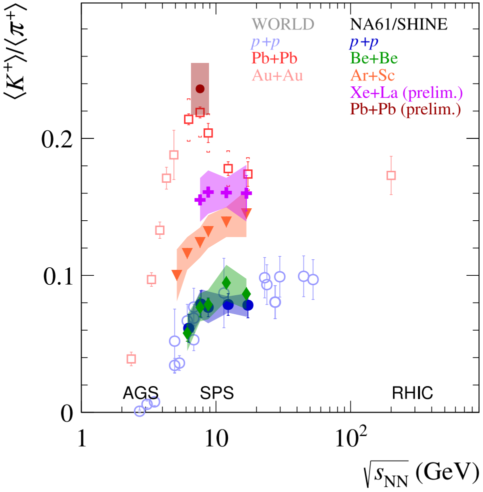
$$\frac{\langle N_{s\bar{s}} \rangle}{\langle \pi \rangle} \approx \frac{2}{3} \frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}, \qquad E_S \approx \frac{4}{3} \frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}, \qquad \text{or (with } \Lambda\text{)} \quad E_S \approx \frac{2}{3} \frac{\langle \Lambda \rangle + 2 \left(\langle K^+ \rangle + \langle K^- \rangle \right)}{\langle \pi^+ \rangle + \langle \pi^- \rangle}$$

Onset of Deconfinement: The "Horn"



- K^+/π^+ ratio is a good proxy for the strangeness/entropy ratio
- K^+/π^+ in central Pb+Pb collisions – **"horn"** at SPS energies
  PRC 77 (2008) 024903

Onset of Deconfinement: The "Horn"

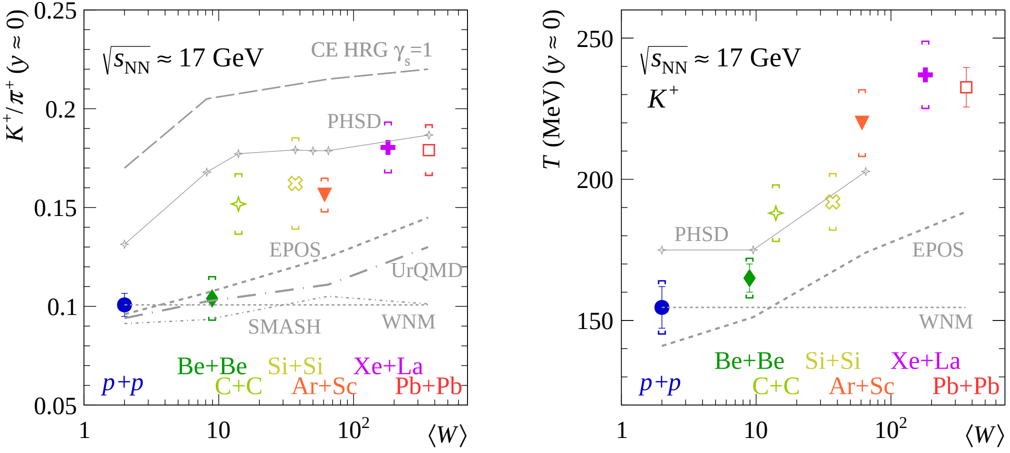


- K^+/π^+ ratio is a good proxy for the strangeness/entropy ratio
- K^+/π^+ in central Pb+Pb collisions – **"horn"** at SPS energies
  PRC 77 (2008) 024903
- **Confirmed by new NA61/SHINE results** in Pb+Pb at $\sqrt{s_{NN}} = 7.6$ GeV

0–10% Ar+Sc and references to $p+p$, Be+Be, world: **NA61, EPJC 84 (2024) 416**
0–20% (16.8 GeV) and 0–10% Xe+La, NA61 0–7.2% Pb+Pb: NA61 preliminary

K^+/π^+ and inverse slope parameter T at $y \approx 0$ – system size dependence

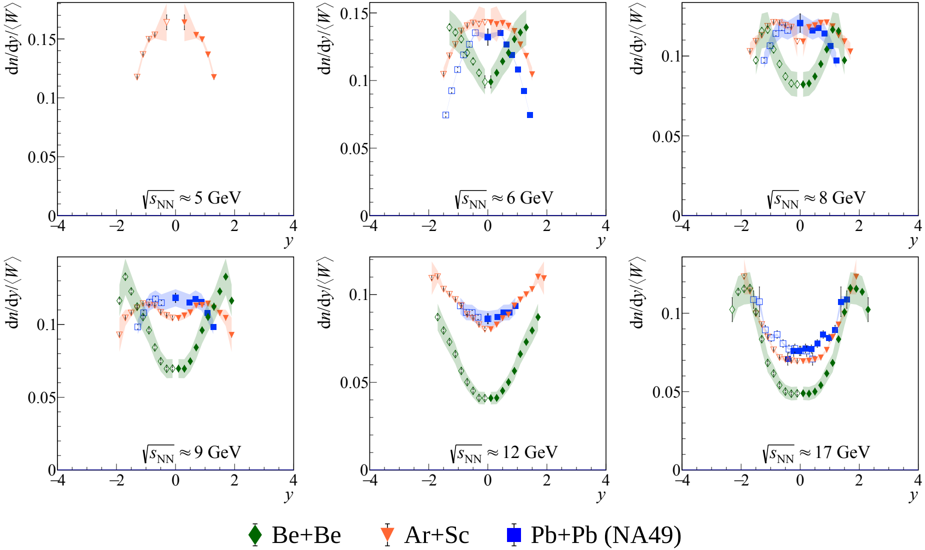
Comparison with models



- None of the models describes data in the whole W range

y ≈ 0: for Xe+La y = 0.4 – 0.6; for NA61 Pb+Pb y = 0.8 – 1.0
0–10% Ar+Sc and references to p+p, Be+Be, world: **NA61, EPJC 84 (2024) 416**
0–20% (16.8 GeV) and 0–10% Xe+La, NA61 0–7.2% Pb+Pb: NA61 preliminary

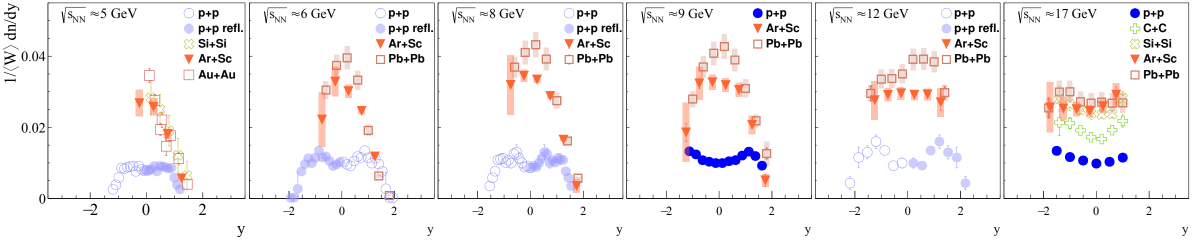
Rapidity spectra of p – transport of **baryon number**



- Baryon density at $y \approx 0$ decreases with increasing energy (baryon transparency) but increases with increasing system size

NA61/SHINE: EPJC 81 (2021) 73, EPJC 84 (2024) 416, NA49: PRC 83 (2011) 014901

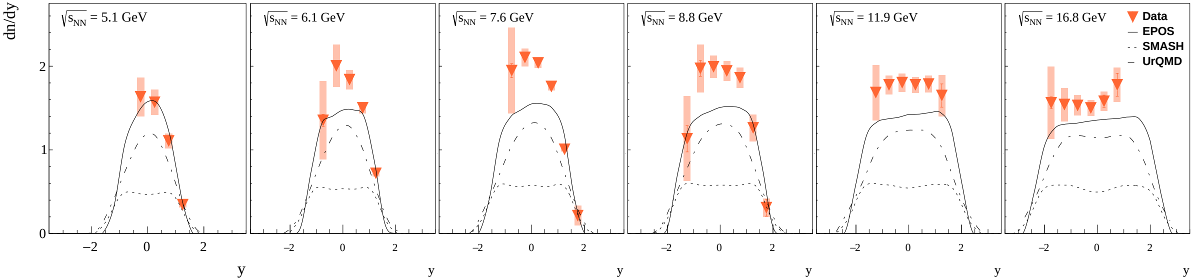
Rapidity spectra of Λ – transport of **baryon number + strangeness enhancement**



- 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.

NA61/SHINE: *p+p* at 158 GeV/*c* EPJC 76 (2016) 198; *p+p* at 40 GeV/*c* and Ar+Sc preliminary
NA49 Pb+Pb: PRL 94 (2005) 052301; C+C, Si+Si: PRC 78 (2008) 034918
E810 Si+Si: PLB 297 (1992) 44-48
E896 Au+Au: PRL 88 (2002) 062301
p+p world: NPB 69 (1974) 454-492, NPB 57 (1973) 77-99, NPB 115 (1976) 269-286

Rapidity spectra of Λ – model predictions

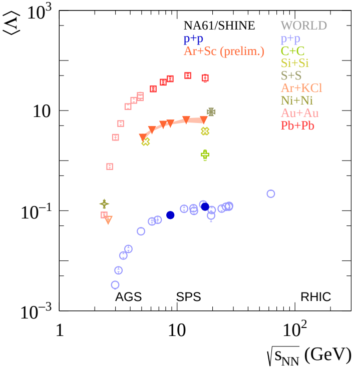


- EPOS, SMASH and UrQMD underestimate Λ production at all analyzed beam momenta
- EPOS is closest to the experimental results

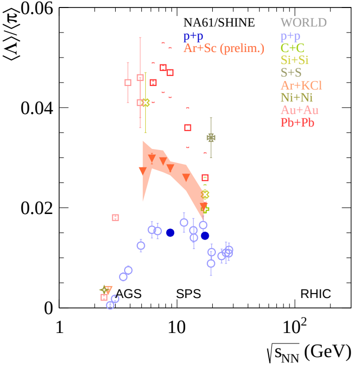
NA61/SHINE preliminary

Strangeness-to-pion ratios in Ar+Sc

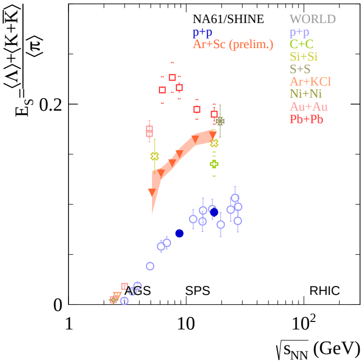
$\langle\Lambda\rangle$ – mean multiplicity



Λ/π ratio



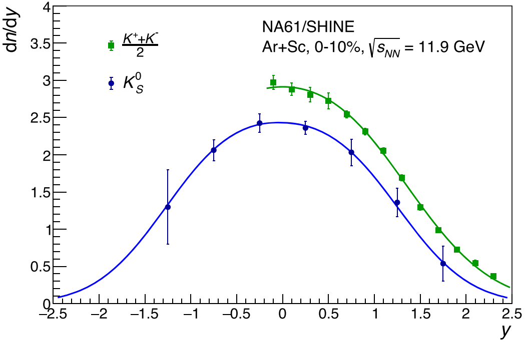
$$E_S = \frac{\langle\Lambda\rangle+\langle K+\overline{K}\rangle}{\langle\pi\rangle}$$

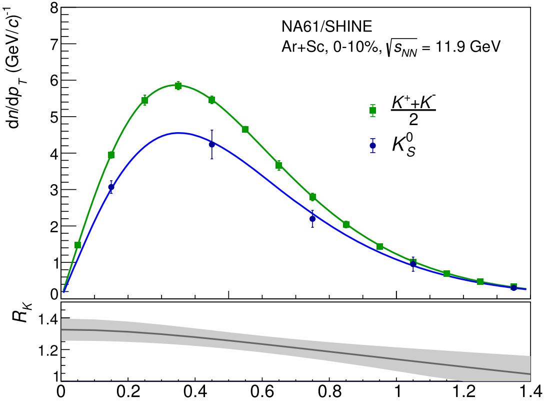


- The Λ yield in Ar+Sc is closer to Pb+Pb than to $p+p$
- Similar behavior of the $\langle\Lambda\rangle/\langle\pi\rangle$ ratio in Ar+Sc to the one observed in Pb+Pb
- No maximum observed in E_S in Ar+Sc contrary to the one observed in Pb+Pb

NA61/SHINE $p+p$ at 158 GeV/c: EPJC 76 (2016) 198, $p+p$ at 40 GeV/c and Ar+Sc preliminary;
NA49 C+C, Si+Si, Pb+Pb: PRL 94 (2005) 052301, PRC 78 (2008) 034918; 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: $p+p$

Excess of charged over neutral kaons

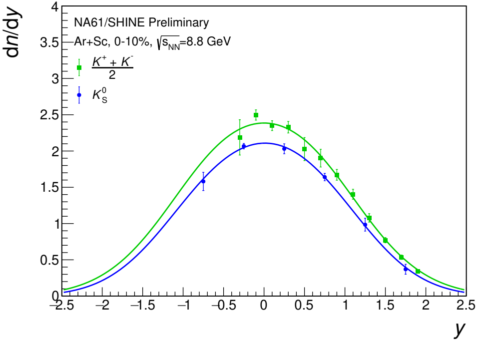


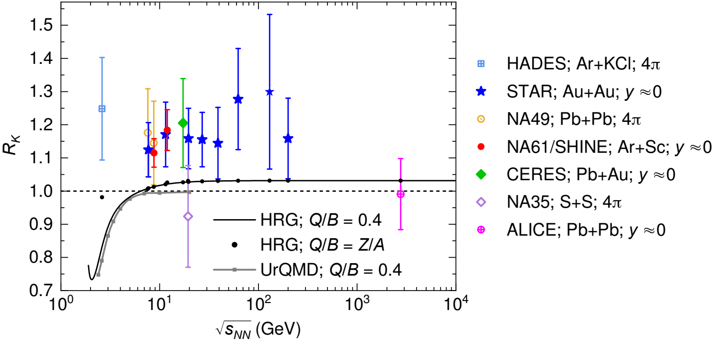


- ~four additional charged K mesons per central Ar+Sc collision (extrapolating to 4π at 11.9 GeV)
- $R_K = (K^+ + K^-)/(2\ K^0_S)$ is maximal at lower transverse momenta and approaches 1.0 at high p_T
- This suggests that the excess of charged kaons over neutral kaons is related to **soft-QCD** processes

EPJC 84 (2024) 4, 416
NC 16 (2025), 2849

Excess of charged over neutral kaons





- Under the assumption of isospin symmetry $R_K = 1$
- $R_K > 1$ in spite of having more neutrons than protons in colliding nuclei which favors neutral kaons

$$R_K = \frac{K^+ + K^-}{2\,K^0_S} \quad \text{for } \frac{\mathrm{d}n}{\mathrm{d}y} \text{ at } y \approx 0:$$

at 8.8 GeV: $R_K = 1.115 \pm 0.043$
at 11.9 GeV: $R_K = 1.184 \pm 0.061$

EPJC 84 (2024) 4, 416
NC 16 (2025), 2849
NA61/SHINE preliminary

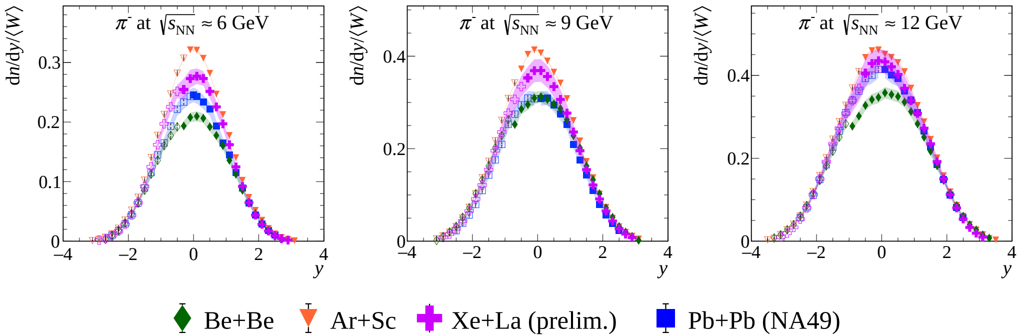
Conclusions

- **Onset of Deconfinement**:
  - **"Horn" structure confirmed** by Pb+Pb at 7.6 GeV
  - No similar structure in Xe+La, Ar+Sc and smaller systems
    - None of the models describes system size dependence of K^+/π^+ ratio in the full $\langle W \rangle$ range
- **Λ Production in Ar+Sc**:
  - Detailed measurement of spectra, Λ/π and E_S ratios across SPS energies
  - Ar+Sc traces the path **between *p*+*p* and heavy ion** collisions, highlighting non-trivial system-size dependencies:
    - Λ/π ratio increases with collision energy, with Ar+Sc results approaching Pb+Pb at higher $\sqrt{s_{NN}}$
    - Rapidity spectra of Λ in Ar+Sc and Pb+Pb collisions come closer with increasing beam momentum
- **Isospin Asymmetry**:
  - The result at $\sqrt{s_{NN}} = 8.8$ GeV **confirms the anomalous excess** of charged kaons over neutral kaons in Ar+Sc
  - Challenges the basics of our understanding of particle production

Backup

Rapidity spectra of π^-

- Spectra are scaled by mean number of wounded nucleons ($\langle W \rangle^*$).
- For all spectra, open points are reflected measured data points.



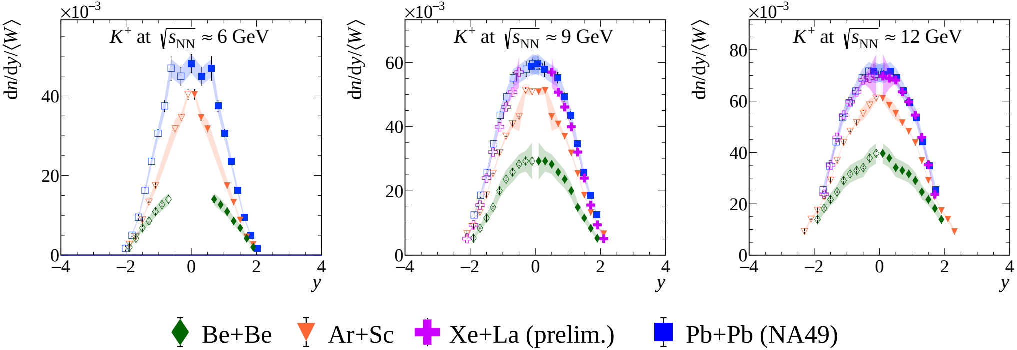
- Non-monotonic dependence of the $\mathrm{d}n/\mathrm{d}y/\langle W \rangle$ at $y \approx 0$ on the system size

*For Be+Be and Ar+Sc, $\langle W \rangle$ estimated using EPOS;
for Xe+La using `web-docs.gsi.de/~misko/overlap`;
systematic uncertainty of $\langle W \rangle$ is not included. NA61/SHINE: EPJC 80 (2020) 961, EPJC 81 (2021) 397

NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903

Rapidity spectra of K^+

- Spectra are scaled by mean number of wounded nucleons ($\langle W \rangle$).
- For all spectra, open points are reflected measured data points.



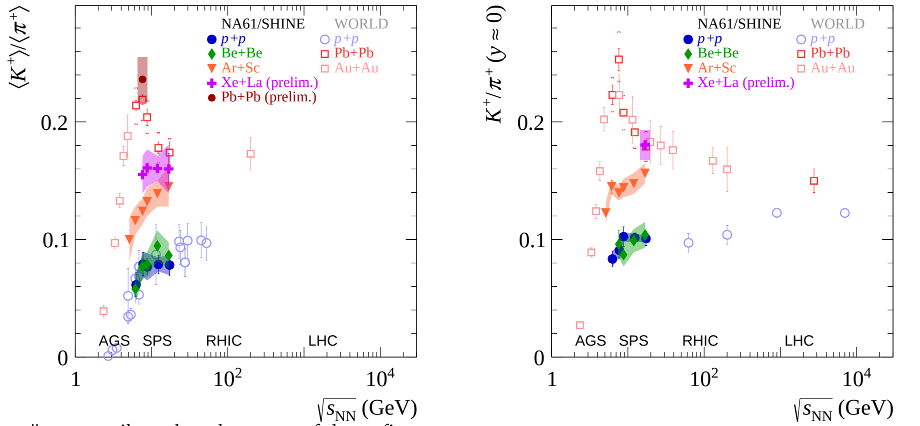
- Monotonic dependence of the $\mathrm{d}n/\mathrm{d}y/\langle W \rangle$ at $y \approx 0$ on the system size:

$$\text{Be+Be} \ll \text{Ar+Sc} < \text{Xe+La} \lesssim \text{Pb+Pb}$$

NA61/SHINE: EPJC 81 (2021) 73, EPJC 84 (2024) 416

NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903

Onset of deconfinement
$\langle K^+\rangle/\langle\pi^+\rangle$ and K^+/π^+ at $y \approx 0$

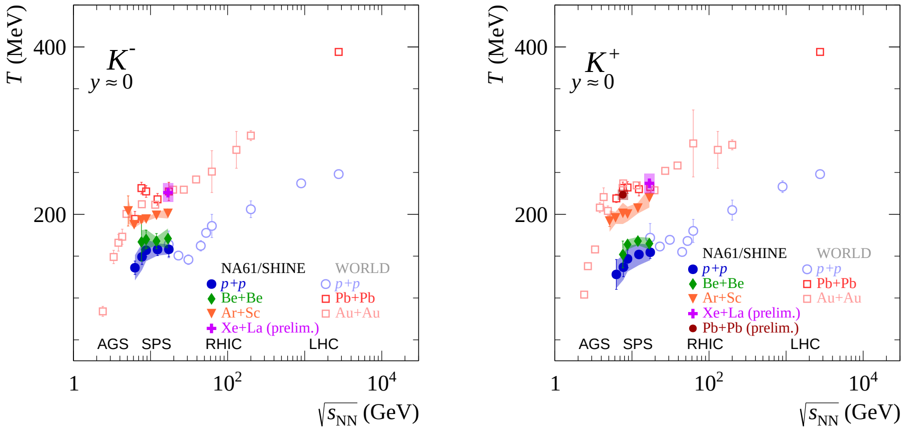


APPB 30 (1999) 2705

- “Horn” was attributed to the onset of deconfinement
- The horn is **not** observed in small and intermediate-size systems!
- $p{+}p \approx$ Be+Be $\ll$ Ar+Sc $\lesssim$ Xe+La $\lesssim$ Pb+Pb

0–10% Ar+Sc and references to $p{+}p$, Be+Be, world: **NA61, EPJC 84 (2024) 416**
0–20% (16.8 GeV) and 0–10% Xe+La, NA61 0–7.2% Pb+Pb: NA61 preliminary

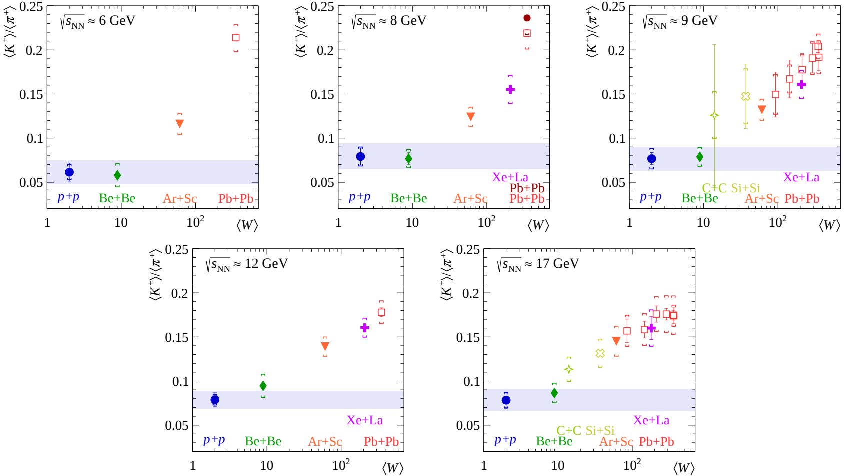
Onset of deconfinement
$T(K^-)$ and $T(K^+)$ at $y \approx 0$



- “Step” was attributed to the onset of deconfinement APPB 30 (1999) 2705
- A step-like structure is visible for all systems

y ≈ 0: for Xe+La y = 0.4 – 0.6; for NA61 Pb+Pb y = 0.8 – 1.0
0–10% Ar+Sc and references to *p*+*p*, Be+Be, world: **NA61, EPJC 84** (2024) **416**
0–20% (16.8 GeV) and 0–10% Xe+La, NA61 0–7.2% Pb+Pb: NA61 preliminary

$\langle K^+\rangle/\langle\pi^+\rangle$ system size dependence

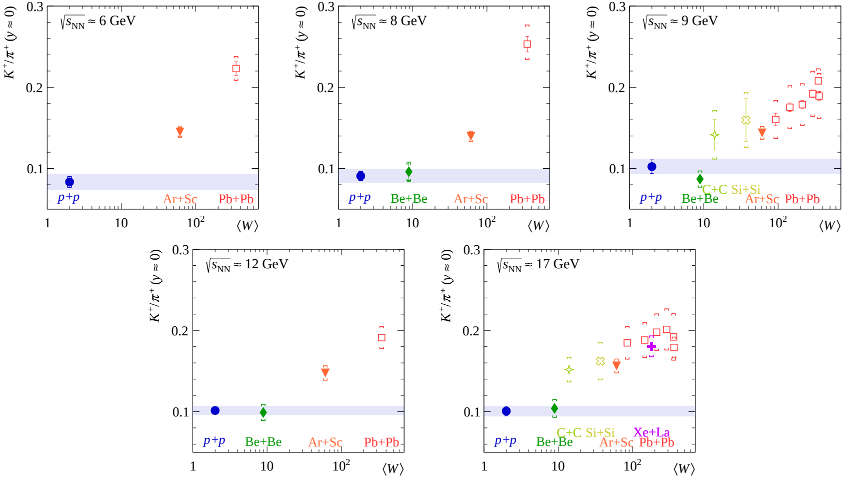


- Increase of $\langle K^+\rangle/\langle\pi^+\rangle$ with the system size
- At top energy, $p+p \approx$ Be+Be $<$ Ar+Sc $\approx$ Xe+La $\approx$ Pb+Pb

NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416, preliminary

NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903

K^+/π^+ at $y \approx 0$ system size dependence

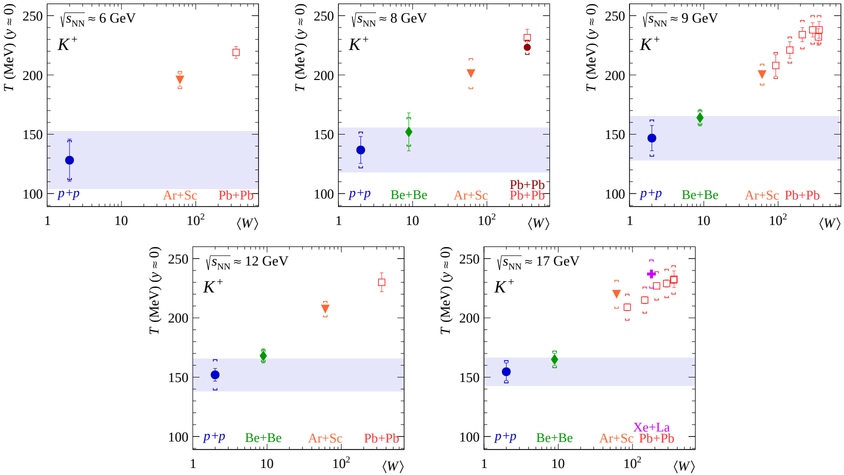


- Increase of K^+/π^+ at $y \approx 0$ with the system size
- At top energy, $p+p \approx$ Be+Be $<$ Ar+Sc $\approx$ Xe+La $\approx$ Pb+Pb

NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416, preliminary

NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903; $y \approx 0$: for Xe+La $y = 0.4 - 0.6$

$T(K^+)$ at $y \approx 0$ system size dependence

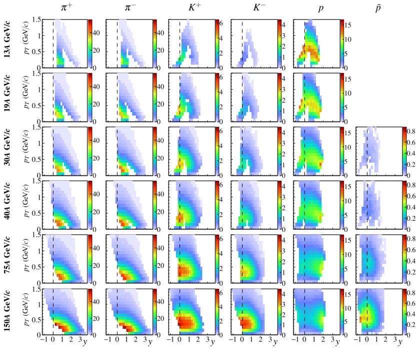


- Increase of $T(K^+)$ at $y \approx 0$ with the system size

$y \approx 0$: for Xe+La $y = 0.4 - 0.6$, for NA61 Pb+Pb $y = 0.8 - 1.0$
NA61/SHINE: EPJC 77 (2017) 671, EPJC 81 (2021) 73, EPJC 84 (2024) 416, preliminary

NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903

Ar+Sc: charged kaon spectra in y and p_T

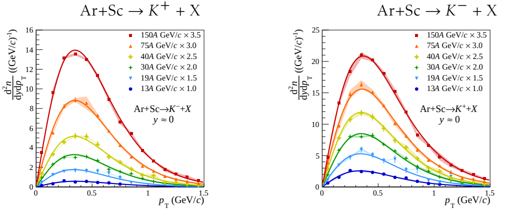


- 10% most central ^{40}Ar+^{45}Sc events
- p_T spectra fitted with:

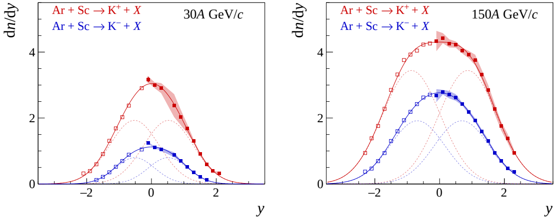
$$\frac{dn}{dy\, dp_T} = \frac{S\, p_T}{T^2 + T\, m_K} \exp\left(- \frac{\sqrt{p_T^2 + m_K^2} - m_K}{T} \right)$$

- Rapidity spectra fitted with a sum of symmetric Gaussians to obtain mean multiplicities $\langle K^+ \rangle, \langle K^- \rangle$

p_T spectra at midrapidity



rapidity spectra



EPJC 84 (2024) 4, 416

Charge Symmetry Breaking (CSB) beyond known effects

Known effects contributing to CSB in kaon production:

(A) Mass effects within strong interactions

- Different u and d quark masses
  $\rightarrow$ different hadron masses within isospin multiplets

  e.g. $m_{K^+} = m_{K^-} = 493.7$ MeV and
  $m_{K^0} = m_{\overline{K}^0} = 497.6$ MeV

  $\Rightarrow \quad R_K \uparrow\ 2\%$ 🚫

- Different kaon masses affect branching ratios:

  e.g. $\phi(1020) \rightarrow K^+K^-$ vs. $\phi(1020) \rightarrow K^0\overline{K}^0$

  $$\frac{\Gamma(\phi \rightarrow K^+K^-)}{\Gamma(\phi \rightarrow K^0\overline{K}^0)} = 1.45$$

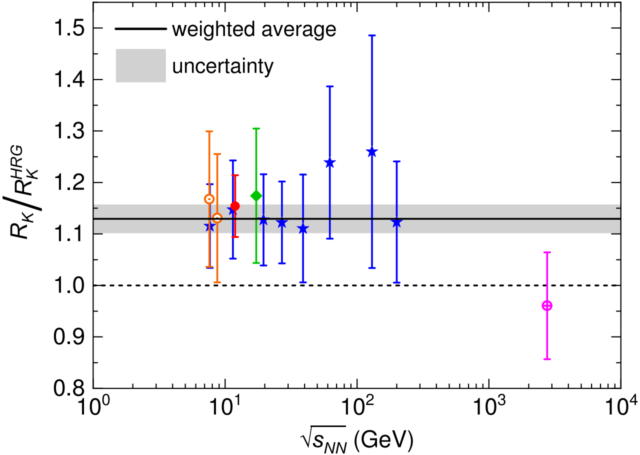
  $\Rightarrow \quad R_K \uparrow\ 3\%$ 🚫

  Other resonances: $a_0(980)$, $f_0(980)$

  $\Rightarrow \quad R_K \uparrow\ 0.5\%$ (up to 3% for extreme assumptions) 🚫

CSB Beyond Known Effects

The mass and $Z < N$ effects are included in popular models:
Hadron-Resonance Gas (HRG) and Ultra-Relativistic Molecular Dynamics (UrQMD) ⃠



$\leftarrow 1.129 \pm 0.027 \;\; (4.7\,\sigma,\ \chi^2/n_{\mathrm{df}} = 0.3)$

CSB Beyond Known Effects

(B) Uncertainties in weak decays

- The weak interaction do **not** obey charge symmetry
- Charged and neutral kaons have different mean lifetimes:

$$c\tau(K^+) = c\tau(K^-) \approx 3.7 \text{ m}, \quad c\tau(K_S^0) \approx 2.7 \text{ cm}$$

- The results are corrected for losses due to weak decays
- The maximum deviation of R_K from unity due to mean K_S^0 lifetime uncertainty is:

$$< 0.13\%$$

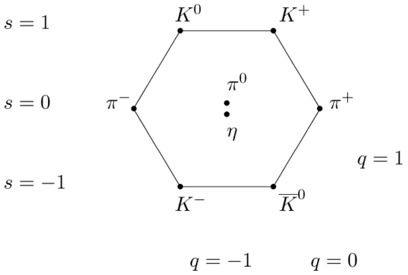
CSB Beyond Known Effects

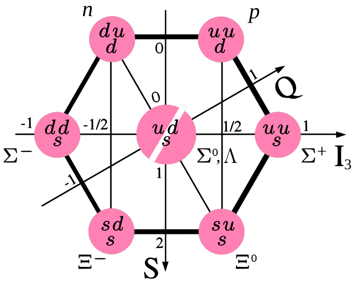
(D) Electromagnetic processes do not obey charge symmetry
because of different electric charges of u and d
(or charged and neutral kaons).

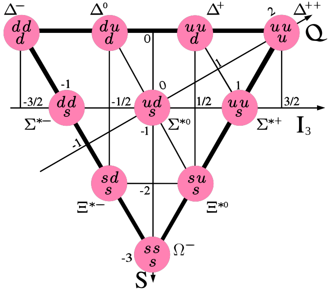
- Hadron EM decays and virtual photon decays to kaons are suppressed by $\alpha^2 \simeq \left(\frac{1}{137}\right)^2$
  ⃠
- EM processes involving total electric charge of nuclei: $Z_1 Z_2 \alpha^2$
  $\Rightarrow Z^2$-dependence of $R_K \rightarrow$ Not observed in the data ⃠
- Electromagnetic interactions break isospin symmetry by favoring $u\bar{u}$ pair creation over $d\bar{d}$ pairs
  $\rightarrow$ enhances the production of charged kaons
  Quantifying these QED effects (e.g. larger effective u-g coupling, fireball's Coulomb potential) requires detailed modeling
  (Large QED corrections to QCD $q\bar{q}$ creation?)

There are **no quantitative calculations** of the effect **?**

Isospin multiplets







Images source: Wikipedia

$$|K^+\rangle = |u\bar{s}\rangle, \quad |K^0\rangle = |d\bar{s}\rangle, \quad |\overline{K}^0\rangle = |s\bar{d}\rangle, \quad |K^-\rangle = -|s\bar{u}\rangle$$

$|\pi^+\rangle = |u\bar{d}\rangle$

$|\pi^0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$

$|\pi^-\rangle = -|d\bar{u}\rangle$

$|\Sigma^+\rangle = |uus\rangle$

$|\Sigma^0\rangle = \frac{1}{\sqrt{2}}(|uds\rangle + |dus\rangle)$

$|\Sigma^-\rangle = |dds\rangle$

$|\Xi^0\rangle = |uss\rangle$

$|\Xi^-\rangle = |dss\rangle$

Σ^+	$\to p\pi^0$	$\sim 51.6\%$
	$\to n\pi^+$	$\sim 48.3\%$
Σ^-	$\to n\pi^-$	$\sim 99.8\%$
Ξ^-	$\to \Lambda\pi^-$	$\sim 99.9\%$
Ξ^0	$\to \Lambda\pi^0$	$\sim 99.5\%$

Report from the ISO-BREAK

Experimental updates:

- It **WAS** measured before, but ignored/disbelieved: talk by H. Stroebele
- New preliminary results from NA61/SHINE at 8.8 GeV: talk by A. Rybicki and S. Kowalski
- ALICE: talk by F. Ercolessi, no isospin breaking in p+p (900 GeV – 13 TeV), p+Pb (5.02 TeV), or **Pb+Pb** (2.76 TeV)
  - Xe+Xe, O+O, Ne+Ne data taken and to be analyzed
- HADES: talk by M. Lorenz

Theory/phenomenology subjective highlights:

- Lattice-QCD: talk by B. Brandt – "no direct results, difficult observable!" – dedicated simulations with $\Delta m_{\mathrm{u,d}} \neq 0$ initiated.
- UrQMD: talk by M. Bleicher – NA61/SHINE data is successfully described when string parameters are tuned to e^+e^- data (where the effect is also present!), by changing the u:d string breaking probability from 1:1 to 3:1.
- Overall lack of success.