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Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei

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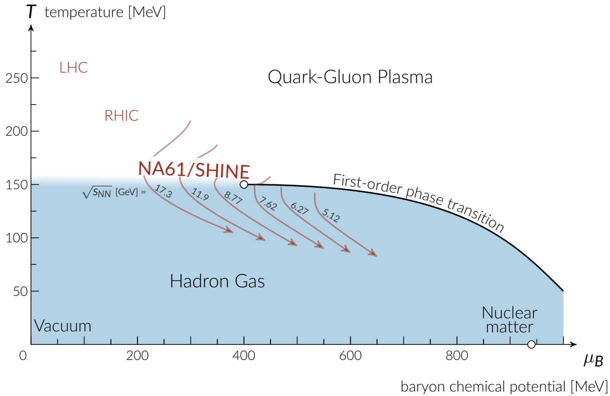
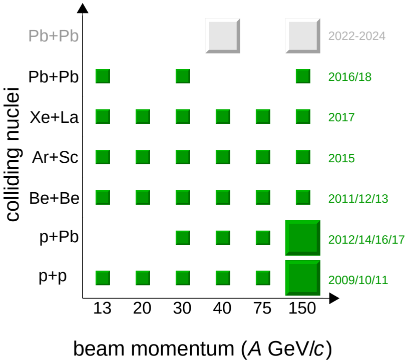
NA61/SHINE strong interactions program

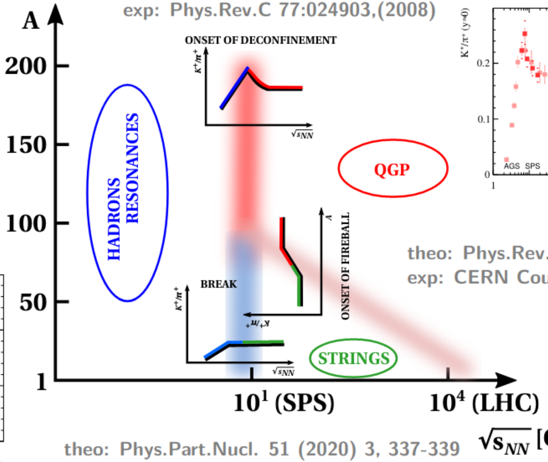
Exploring the phase diagram of strongly interacting matter with a 2D scan in collision energy and system size



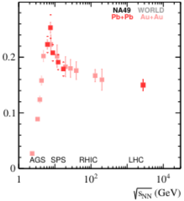


$$\sqrt{s_{NN}} \approx 5 - 17 \text{ GeV}$$

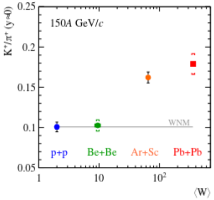
Uniqueness of ion results from NA61/SHINE

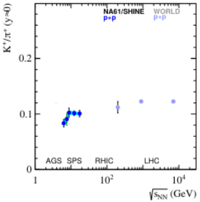


theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)



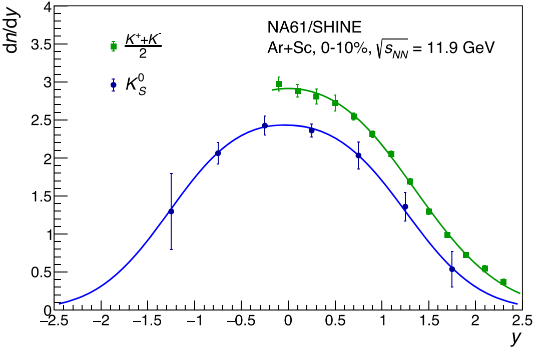
theo: Phys.Rev.D 90 025031 (2014)
exp: CERN Courier, Sep 23rd, 2019

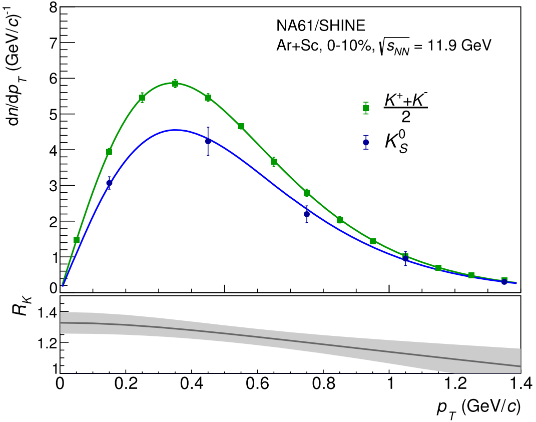




theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Excess of charged over neutral kaons





$$\frac{K^+ + K^-}{2\ K^0_S} \quad \text{for } \frac{\mathrm{d}n}{\mathrm{d}y} \text{ at } y \approx 0 = 1.184 \pm 0.014 \pm 0.060$$

(Eur. Phys. J. C 84 (2024) 4, 416)
(Nature Comm. 16, 2849 (2025))

- ~four additional charged K mesons per central Ar+Sc collision (extrapolating to 4π)

Thank you for your attention!

1. Isospin, charge and flavour symmetries

2. Testing charge symmetry in production of charged and neutral kaons

3. Measuring charged and neutral kaons

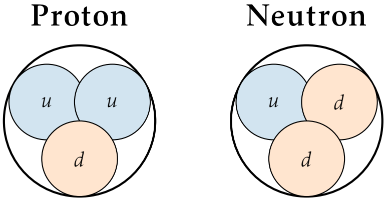
4. Results on charged-to-neutral kaon ratio

5. Symmetry breaking beyond known effects

Isospin, charge and flavour asymmetries

1932: Heisenberg, Wigner → isotopic spin (isospin)

- Use spin formalism
- Proton and neutron – different manifestation of **the same strongly interacting partcile, nucleon**
- Properties of nuclei and hadrons (Kemmer, 1939)



$$\frac{M_n}{M_p} \approx \frac{940}{938} = 1.002$$

Isospin, charge and flavour asymmetries

Nucleon: Isospin doublet: $I = \frac{1}{2}$, p: $I_z = \frac{1}{2}$, n: $I_z = -\frac{1}{2}$

$$\begin{pmatrix} p \\ n \end{pmatrix} \rightarrow \hat{O} \begin{pmatrix} p \\ n \end{pmatrix},$$

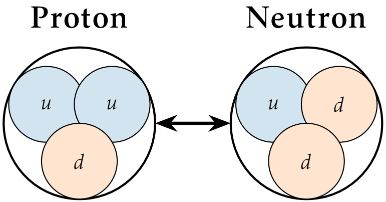
where $\hat{O}$ is a 2×2 unitary matrix:

$$\hat{O} = e^{i\vec{\theta}\cdot\hat{\vec{I}}/2}$$

Charge symmetry transformation is a special isospin transformation:

$$\hat{C} \equiv e^{i\pi\hat{I}_y/2} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Under $\hat{C}$:

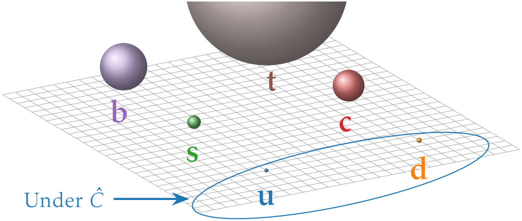


Kaons form isospin doublets, just as the nucleon:

$$\begin{pmatrix} p \\ n \end{pmatrix}, \quad \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}, \quad \begin{pmatrix} -\bar{K}^0 \\ K^- \end{pmatrix}, \ldots$$

Isospin, charge and flavour Symmetries

Within QCD, the isospin symmetry of hadrons is traced back to the isospin symmetry of light quarks:



$$\begin{pmatrix} u \\ d \end{pmatrix} \to \hat{O} \begin{pmatrix} u \\ d \end{pmatrix}$$

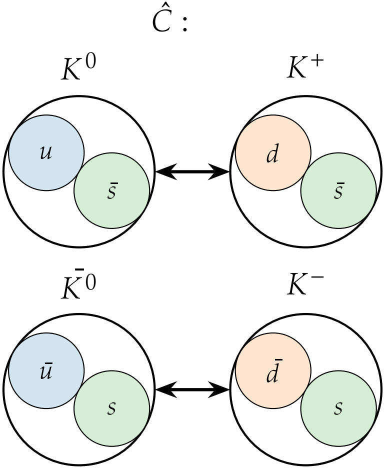
Isospin symmetry is part of flavour symmetry — strong interactions are invariant under the inversion of I_z of every nucleus and hadron of the initial and final states.

Assumption of equal quark masses — good approximation for u and d quarks:

$$m_d - m_u \approx 2.5 \text{ MeV} \ll \Lambda_{\text{QCD}} \approx 200 \text{ MeV}$$

- Mesonic multiplets (nucleon doublet, pion triplet, kaon doublets)
- Reactions conserving isospin (I, I_z), e.g. $p + p \to \Lambda + K^+ + p$

Testing charge symmetry in production of charged and neutral kaons



$$\hat{C} : (p + p \rightarrow K^+ + X) = (n + n \rightarrow K^0 + \hat{X})$$

$$\hat{C} : (p + p \rightarrow K^- + X) = (n + n \rightarrow \bar{K}^0 + \hat{X})$$

But these are difficult to measure!

Testing charge symmetry in production of charged and neutral kaons

Charge symmetry of strong interactions:

$$(p + p \to K^+ + X) = (n + n \to K^0 + \hat{X}) \Rightarrow \langle K^+ \rangle_{pp} = \langle K^0 \rangle_{nn}$$

$$(p + p \to K^0 + X) = (n + n \to K^+ + \hat{X}) \Rightarrow \langle K^0 \rangle_{pp} = \langle K^+ \rangle_{nn}$$

Charge-transformation-invariant initial ensemble:

$$\left\{ \begin{array}{ll} 50\% & p+p \\ 50\% & n+n \end{array} \right\} \quad \Rightarrow \quad \langle K^+ \rangle = \langle K^0 \rangle$$

Charge-transformation invariant final ensemble

Charge symmetry of interactions ⇒ interactions preserve
charge-transformation invariance of ensembles

Testing charge symmetry in production of charged and neutral kaons

Charge-invariant initial ensemble → Interactions preserve charge invariance → Charge-invariant final ensemble

by construction

tested assumption

the prediction

$$\langle K^+ \rangle = \langle K^0 \rangle$$
$$\langle K^- \rangle = \langle \bar{K}^0 \rangle$$

→

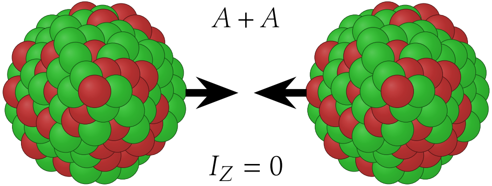
$$R_K \equiv \frac{\langle K^+ \rangle + \langle K^- \rangle}{\langle K^0 \rangle + \langle \bar{K}^0 \rangle} = \frac{\langle K^+ + K^- \rangle}{2\langle K^0_S \rangle} = 1$$

$(m_{K^+} - m_{K^0})/(m_{K^+} + p m_{K^0}) \approx -0.004$

Testing charge symmetry in production of charged and neutral kaons

The first NA61/SHINE friendly test:

- Consider collisions of two nuclei with equal number of protons and neutrons: $Z = N = A/2$
- Visualized as:



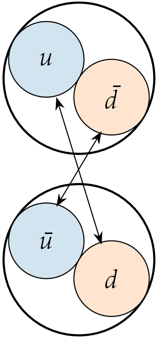
- Then the ensemble of A+A initial nuclei does not change under charge transformation:
  - It is charge (transformation) invariant

It was easy to measure in 2015+

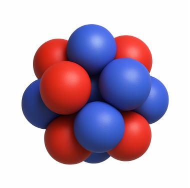
Testing charge symmetry in production of charged and neutral kaons

The second NA61/SHINE friendly test:

- Consider collisions of $\pi^+ + {}^{12}\mathrm{C}$ (50%) and $\pi^- + {}^{12}\mathrm{C}$ (50%)
- Carbon is charge symmetric: $Z = 6$, $N = 6$
- $\hat{C} : \pi^+ \to \pi^-$, $\quad \hat{C} : \pi^- \to \pi^+$



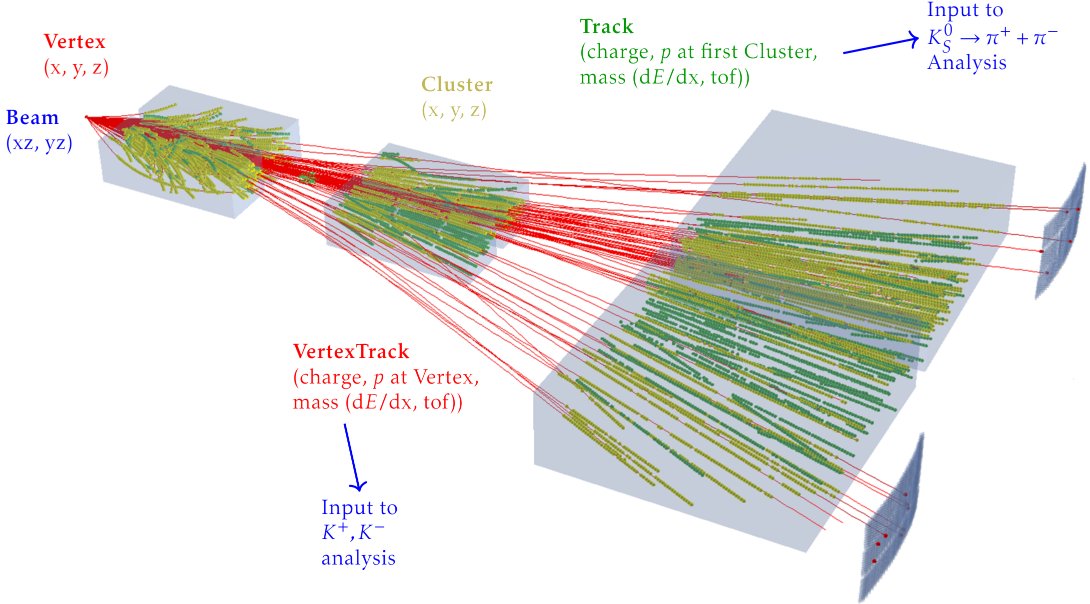
$\Longrightarrow$

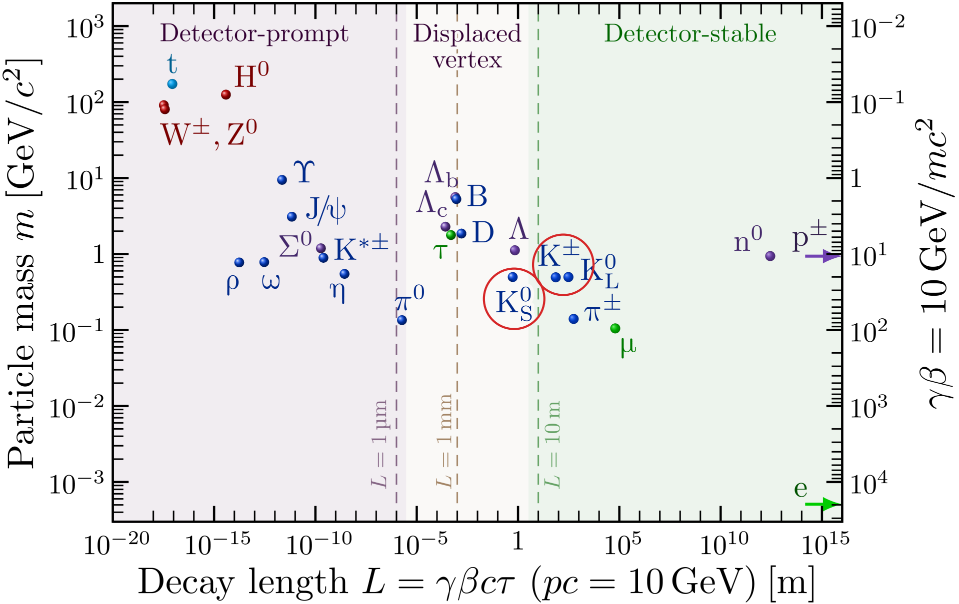


It was easy to measure in 2024

- Then the ensemble of $\pi^+/\pi^- + \mathrm{C}$ initial pions and nuclei does not change under charge transformation — it is charge (transformation) invariant.

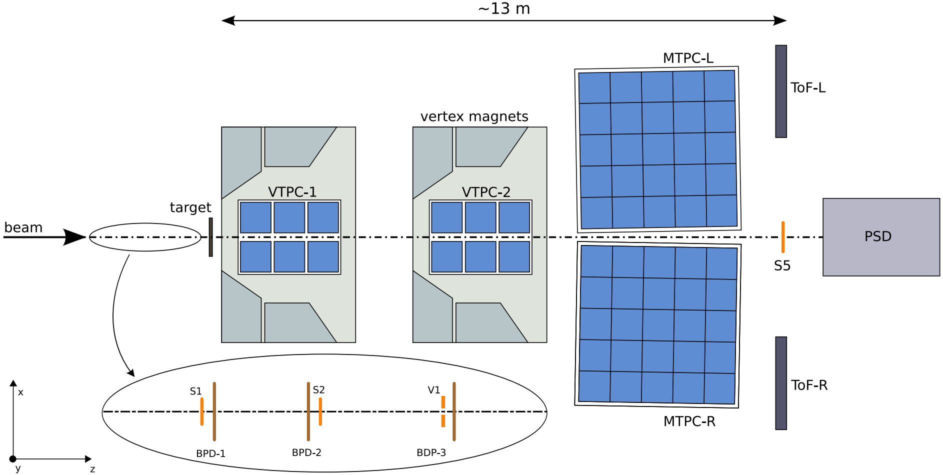
Measuring Charged and Neutral Kaons



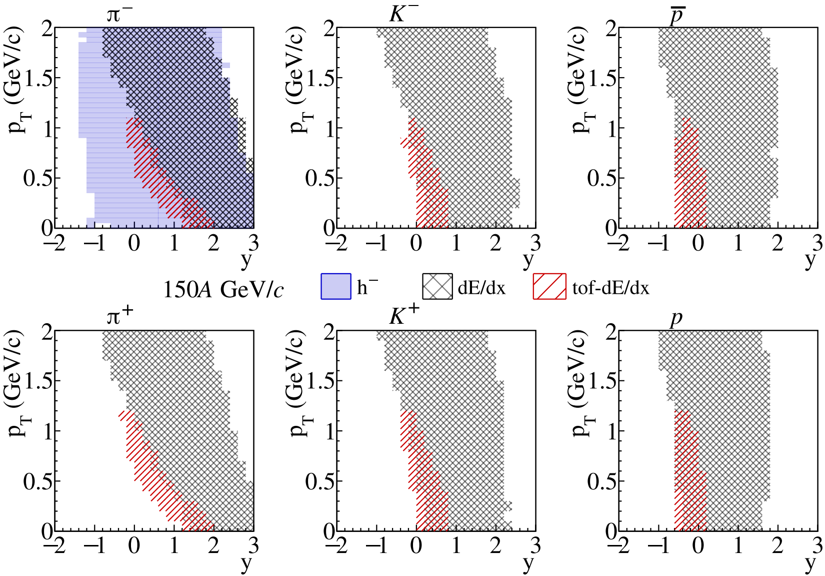


Credit: Izaak Neutelings

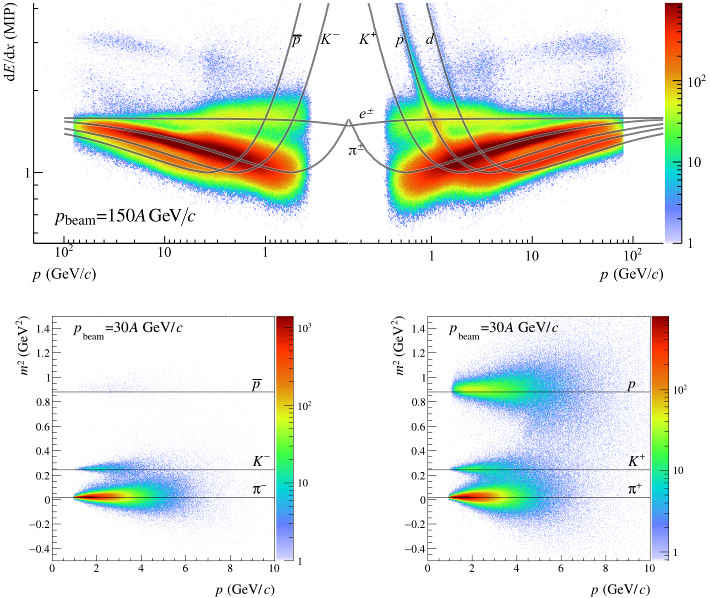
Measuring charged and neutral kaons – NA61/SHINE setup (ca. 2015)



Measuring charged and neutral kaons – dE/dx and tof PID

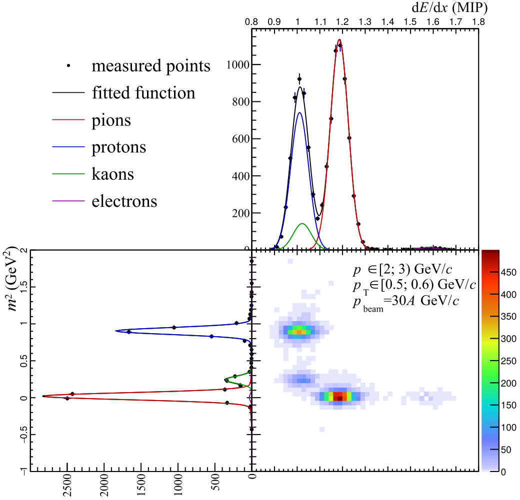


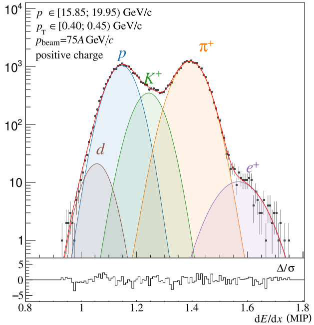
Measuring charged and neutral kaons – dE/dx and tof PID

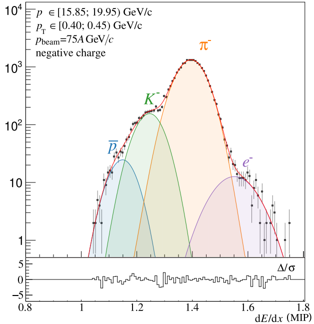


Measuring charged and neutral kaons

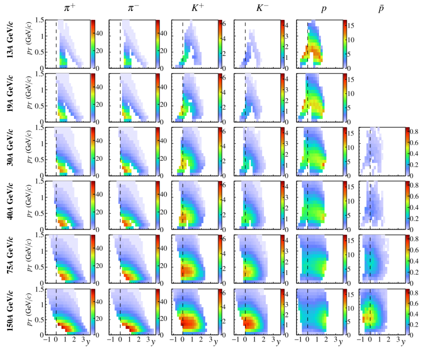
PID neutral kaons







Ar+Sc: charged kaon spectra in y and p_T



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

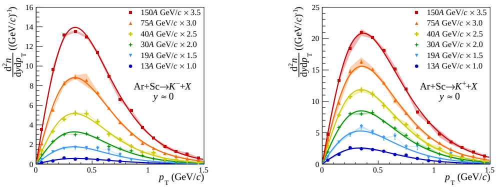
$$\frac{\mathrm{d}n}{\mathrm{d}y\,\mathrm{d}p_T} = \frac{S\,p_T}{T^2 + T\,m_K}\exp\left(-\frac{\sqrt{p_T^2+m_K^2}-m_K}{T}\right)$$

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

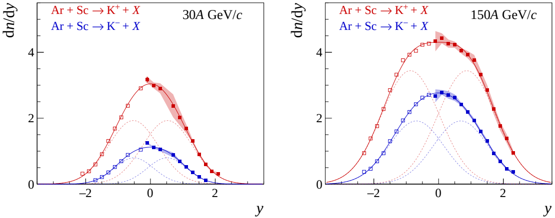
p_T spectra at midrapidity

Ar+Sc $\to K^+$ + X

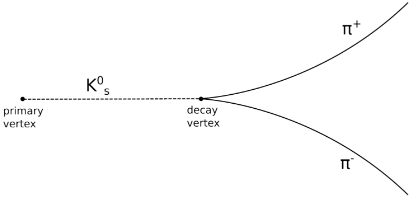
Ar+Sc $\to K^-$ + X

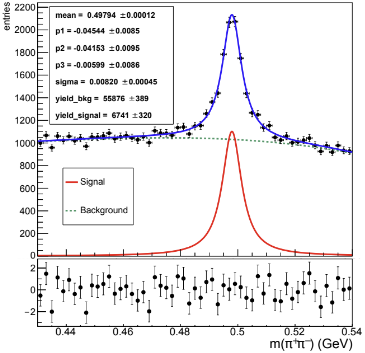


rapidity spectra



Measuring charged and neutral kaons – K_S^0 PID via decay vertex

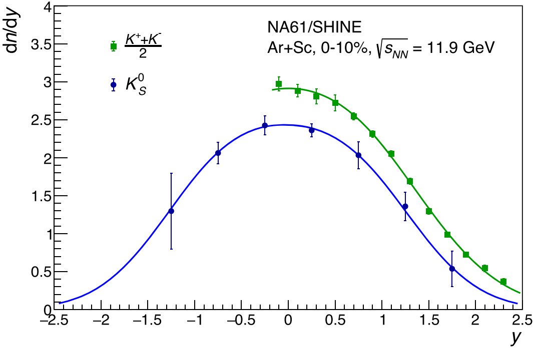


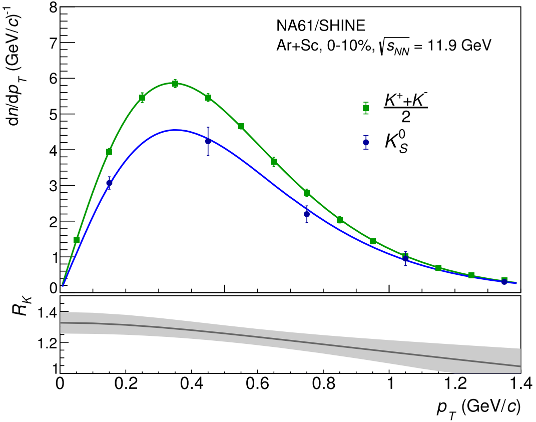


$y \in (0.5, 1.0)$, $p_T \in (1.2, 1.5)$ GeV/c

- Reconstruction based on decay topology
- K_S^0 decays into π^+ and π^- with BR $\approx$ 69.2%
- Breit-Wigner function is used to describe signal

Excess of **charged** over **neutral** kaons



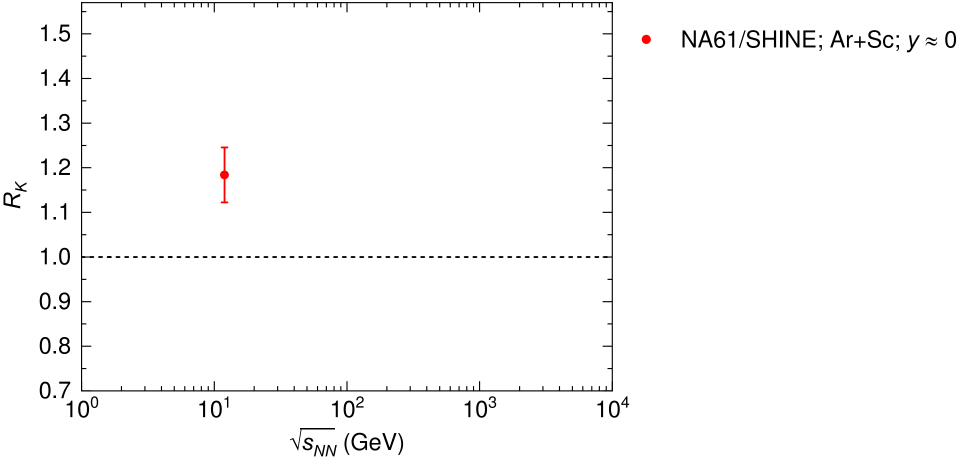


$$\frac{K^+ + K^-}{2\,K^0_S} \quad \text{for } \frac{dn}{dy} \text{ at } y \approx 0 = 1.184 \pm 0.014 \pm 0.060$$

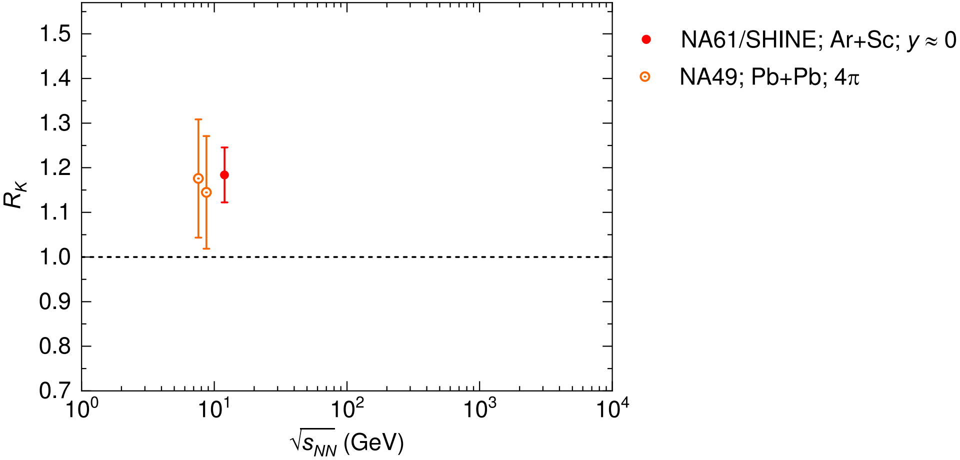
(Eur.Phys.J.C 84 (2024) 4, 416)
(Nat Commun 16, 2849 (2025))

- ~four additional charged K mesons per central Ar+Sc collision (extrapolating to 4π)
- In spite of having more neutrons than protons in colliding nuclei which favors neutral kaons.

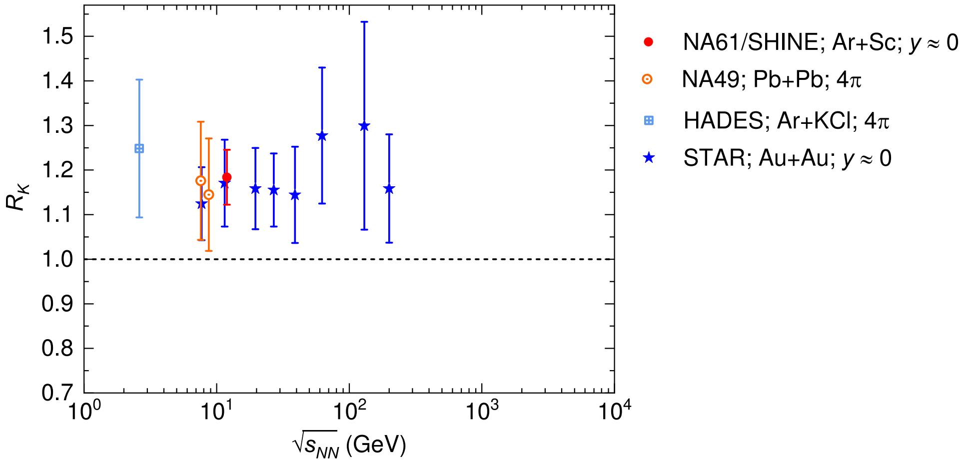
Excess of charged over neutral kaons



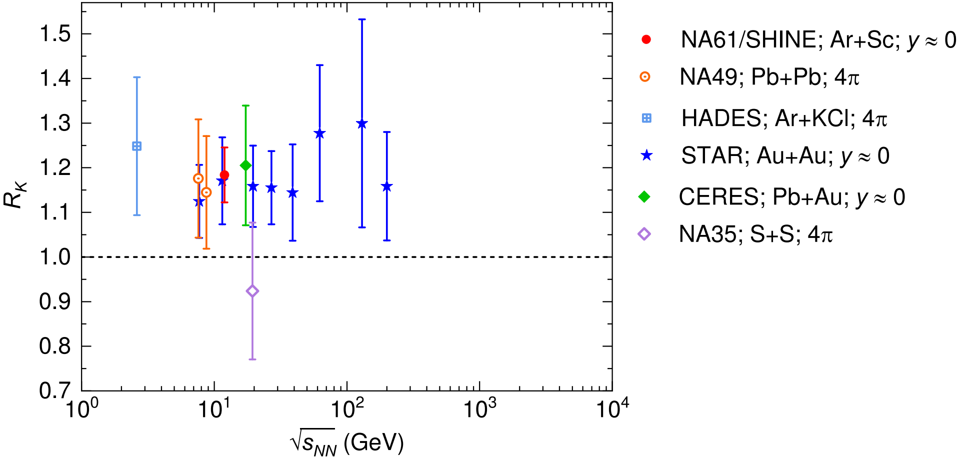
Excess of charged over neutral kaons



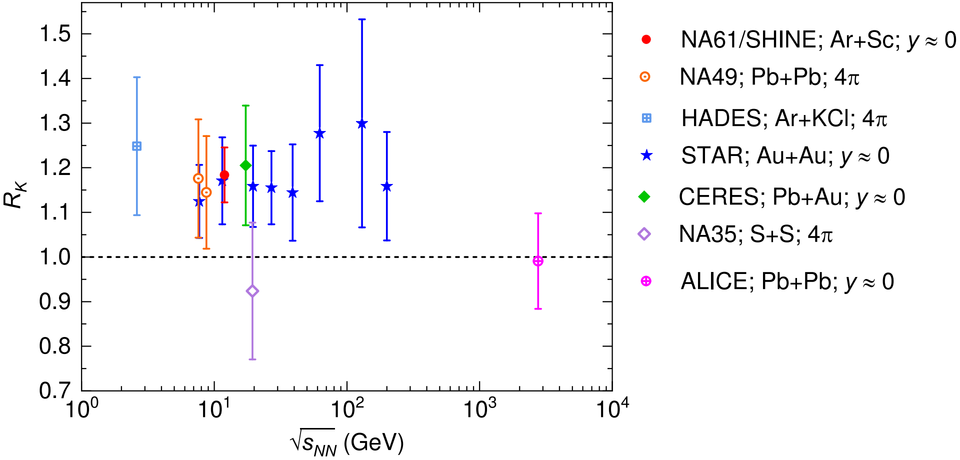
Excess of charged over neutral kaons



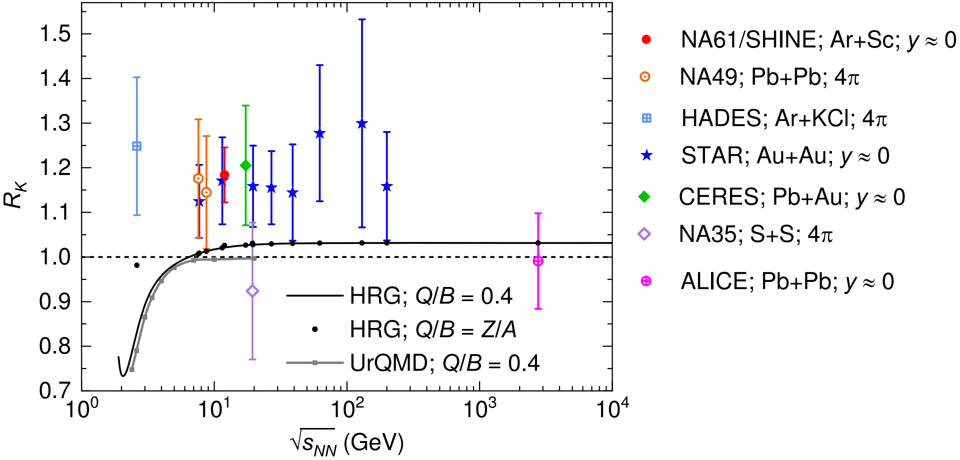
Excess of charged over neutral kaons



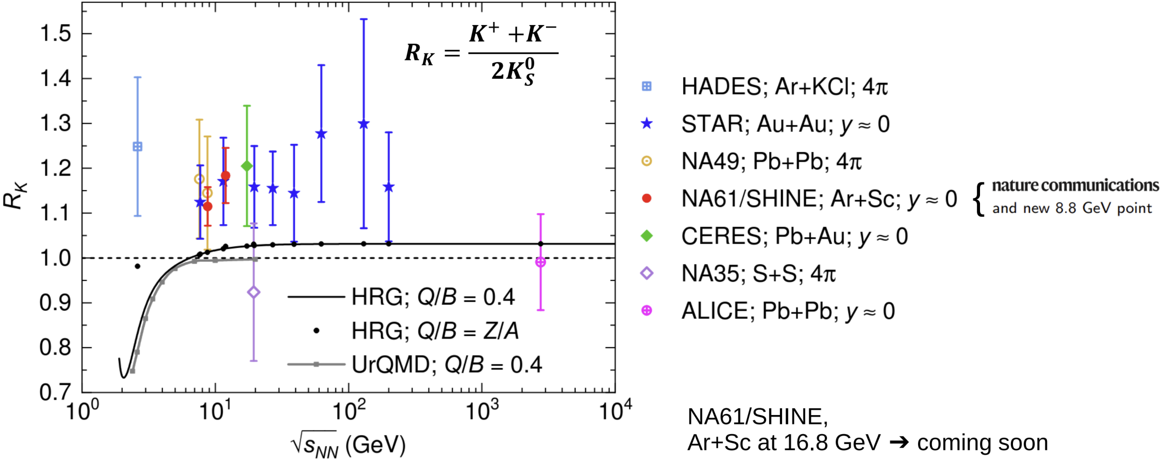
Excess of charged over neutral kaons



Excess of charged over neutral kaons



Excess of charged over neutral kaons – with new preliminary NA61/SHINE measurement



NA61/SHINE,
Ar+Sc at 16.8 GeV ➔ coming soon

Testing charge symmetry in production of charged and neutral kaons

Charge-invariant initial ensemble → Interactions **VIOLATE** charge invariance → Charge-invariant final ensemble

by construction — tested assumption — the prediction

$$\langle K^+\rangle = \langle K^0\rangle$$
$$\langle K^-\rangle = \langle \bar{K}^0\rangle$$

→

$$R_K \equiv \frac{\langle K^+\rangle + \langle K^-\rangle}{\langle K^0\rangle + \langle \bar{K}^0\rangle} = \frac{\langle K^+ + K^-\rangle}{2\langle K^0_S\rangle} \approx 1.15 \neq 1$$

Charge symmetry breaking (CSB)

Profound implications – one of these two:

1. Multiple **experiments are wrong**.
2. **Models are incorrect** (→ QCD is incorrect?).

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
  $m_{K^0} = m_{\bar{K}^0} = 497.6$ MeV

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

- Different kaon masses affect branching ratios:

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

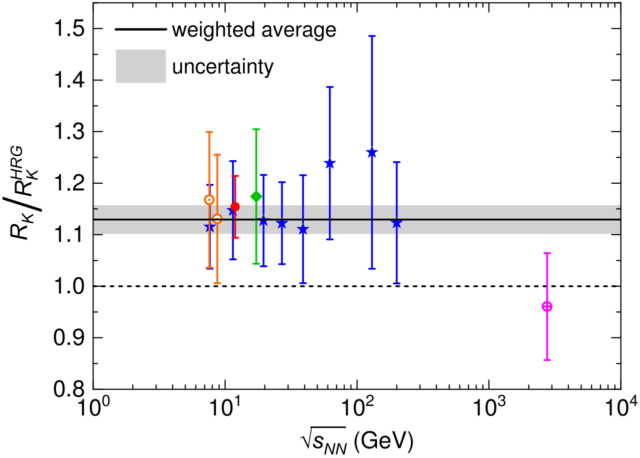
  $$\frac{\Gamma(\phi \rightarrow K^+K^-)}{\Gamma(\phi \rightarrow K^0\bar{K}^0)} = 1.45$$

  (Also: a0(980), f0(980))

  $\Rightarrow \quad R_K \uparrow \ 1\%$ 🚫

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) ⃠



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

HRG and UrQMD agree with each other.

(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 decays.
- The maximum uncertainty of R_K due to mean lifetime uncertainty is:

$$< 0.13\%$$ 🚫

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

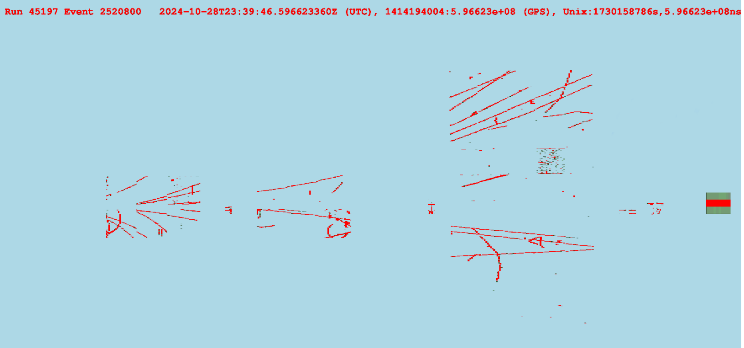
- Hadron EM decays and virtual photon decays to kaons are suppressed by $\alpha \simeq \frac{1}{137}$ ⃠
- EM processes involving total electric charge of nuclei: $Z_1 Z_2 \alpha^2$
  $\Rightarrow Z^2$-dependence of R_K $\rightarrow$ Not observed in the data ⃠
- $u\bar{u}$ and $d\bar{d}$ creation in strong processes may be affected by different EM strengths.
  (Large QED corrections to QCD $q\bar{q}$ creation?)

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

Closing Remarks: The Second NA61/SHINE Friendly Test

Is the CSB specific to A+A collisions,
or is it a general property of interactions?

$\pi^+/\pi^- + \mathrm{C}$ data will answer this important question.



$\pi^\pm + \mathrm{C}$ at 158 GeV/c

Closing Remarks: The Second NA61/SHINE Friendly Test

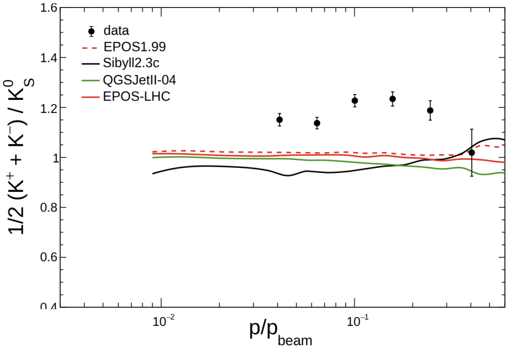
The 2024 data taking on charge symmetry violation
Memorandum requesting use of the allocated test beam for data-taking on $\pi^+ + C$ and $\pi^- + C$ interactions at 158 GeV/c
CERN-SPSC-2024-022 ; SPSC-M-797 – 2024.

In October 2024 NA61/SHINE had two weeks of hadron beam time allocated for tests and calibration.

October 25–30, 2024:

- $\pi^+ + \mathrm{C}$: 30M events recorded
- $\pi^- + \mathrm{C}$: 30M events recorded

$\pi^- + C$ @ p_{beam}=158 GeV/c
PHYS. REV. D 107, 062004 (2023)



If CSB is seen in $\pi^\pm + \mathrm{C}$: it's a general property of interactions.
If not: CSB is specific to A+A collisions.

Closing remarks

Ongoing theoretical efforts to describe the seen effect (UrQMD):

- *Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions*
  T. Reichert et al.; e-Print: 2503.10493 [nucl-th]
  - Effect explained through asymmetric production of quark-pairs in the fragmentation of the color field ($P(u)$ increased ×3 to fit e^+e^- data)

New measurement from BESIII:

- *Single Inclusive $\pi^\pm$ and $K^\pm$ Production in e^+e^- Annihilation at center-of-mass Energies from 2.000 to 3.671GeV*
  e-Print: 2502.16084 [hep-ex]
  - Observed $K^\pm$ vs K_S^0 asymmetry and not $\pi^\pm$ vs π^0 asymmetry.
    → however, both are consistent with the isospin symmetry in parton fragmentation processes

Closing Remarks

- $R_K \approx 1.15$ in A+A

  The first experimental evidence of a large charge-symmetry breaking in kaon production

- It cannot be explained by known processes violating charge symmetry (4.7σ difference)

- $\pi^+/\pi^- + C$ data will answer soon the question:
  - Is the CSB specific to A+A collisions, or
  - Is it a general property of interactions?

Report from the ISO-BREAK

Experimental updates:

- It **WAS** measured before, but ignored/disbelieved: talk by H. Stroebele
- New preliminary results from NA61/SHINE @ 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:

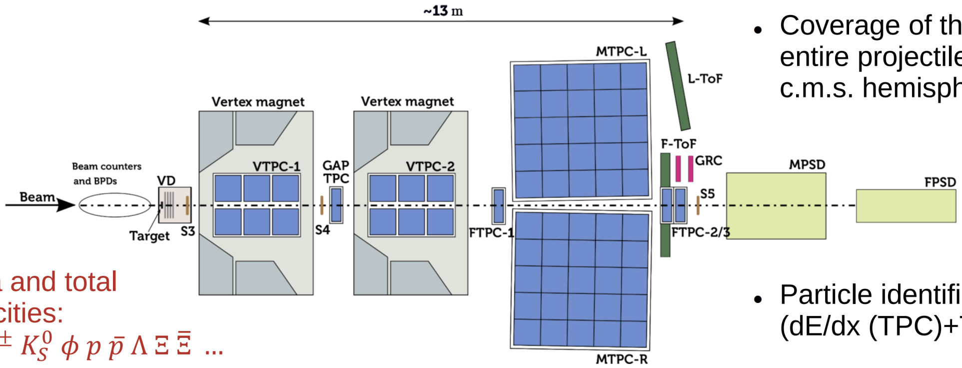
- Lattice-QCD: talk by B. Brandt – "no direct results, difficult observable!" – dedicated simulations with $\Delta m_{\mathrm{u,d}} \neq 0$ initiated.
- UrQMD: talks by M. Bleicher – NA61/SHINE data described when string parameters tuned for e^+e^- data (where the effect is also present!) – u:d=1:1 probability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

Thank you for your attention!

Backup

NA61/SHINE
at CERN SPS

- Multipurpose fixed-target spectrometer with unique capabilitites



- Coverage of the entire projectile c.m.s. hemisphere
- Particle identification (dE/dx (TPC)+ToF)
- Spectra and total multiplicities:
  $\pi^{\pm}\ K^{\pm}\ K_S^0\ \phi\ p\ \bar{p}\ \Lambda\ \Xi\ \bar{\Xi}$ ...
- Heavy quarks:
  D^0 and $\overline{D^0}$
- Correlations, fluctuations, HBT, intermittency...

Kaon math

The neutral kaons are eigenstates of strong interaction, oscillating ($K^0 \leftrightarrow \bar{K}^0$) due to weak interaction. The weak eigenstates are the long-lived 'K-long' K_L^0 and short-lived 'K-short' K_S^0, which decay into three and two pions with mean lifetimes of 15 m/c and 2.8 cm/c, respectively. By neglecting the small CP violation, the weak and strong kaonic eigenstates are related by:

$$\begin{pmatrix} |K_S^0\rangle \\ |K_L^0\rangle \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} |K^0\rangle \\ |\bar{K}^0\rangle \end{pmatrix} , \quad (3)$$

hence, for the mean number of K_S^0 and K_L^0 one gets:

$$\langle K_S^0 \rangle = \frac{1}{2}\langle K^0 \rangle + \frac{1}{2}\langle \bar{K}^0 \rangle = \langle K_L^0 \rangle . \quad (4)$$

Thus, we have an equal number of long-lived and short-lived kaons, even if $\langle K^0 \rangle$ and $\langle \bar{K}^0 \rangle$ are different due to the non-zero baryon number of the initial state.

By combining Eqs. (1) and (2) and using Eq. (4) one finds:

$$\langle K^+ \rangle + \langle K^- \rangle = 2\langle K_S^0 \rangle , \quad (5)$$

Strangeness as a probe of deconfinement

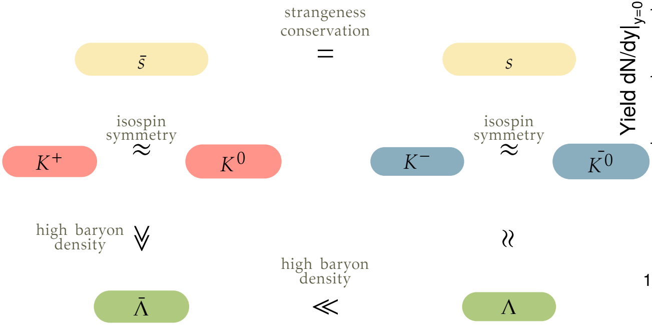
- No strangeness content in colliding nuclei.
- Sensitive to the state of matter created in the fireball.

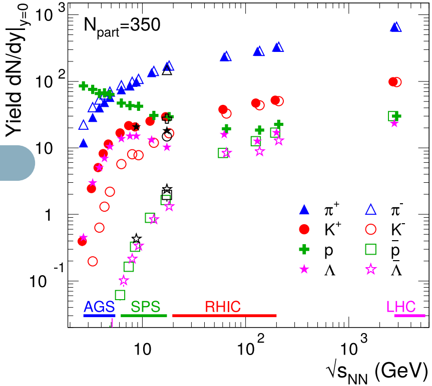
confined matter		quark-gluon plasma
K mesons	$T_C \approx 150$ MeV $\longrightarrow$ Phase transition	(anti-)strange quarks
$g_K = 4$		$g_s = 12$
$2M \approx 2 \cdot 500$ MeV		$2m \approx 2 \cdot 100$ MeV

Lightest strangeness carriers:

- relatively heavy kaons ($M > T_C$) in the confined phase,
- relatively light strange quarks ($m \lesssim T_C$) in QGP.

Main strangeness carriers in A+A collisions at high μ_B





[Int.J.Mod.Phys.A:29,1430047,2014]

– 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.

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

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

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

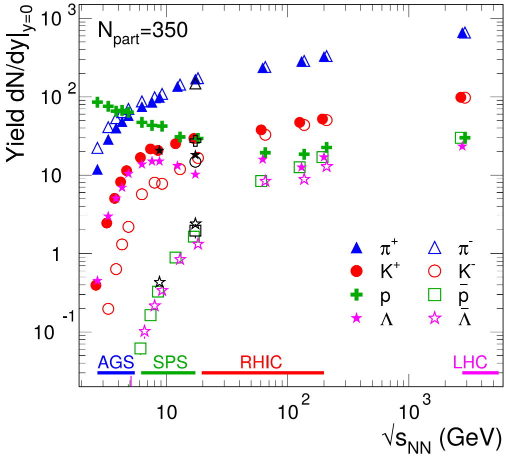
The experimental ratio of strangeness to entropy can be defined as:

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

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

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

Particle yields – input to HRG model



The energy dependence of experimental hadron yields at mid-rapidity for various species produced in central nucleus-nucleus collisions.

[A. Andronic, Int.J.Mod.Phys.A:29,1430047,2014]

Hadron Resonance Gas

Recipe for intepreting K^+/π^+ within HRG:

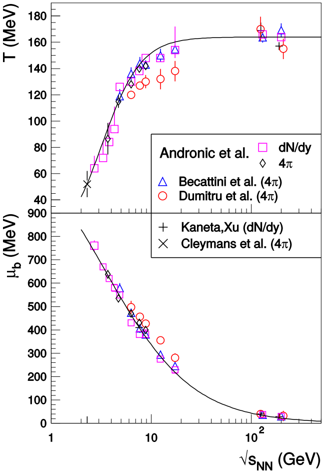
1. Fit V, T, μ_B to experimentally measured yields
2. Parametrize the T, μ_B dependence on s_{NN}
3. Compare to the experimentally measured $K^+/\pi+$

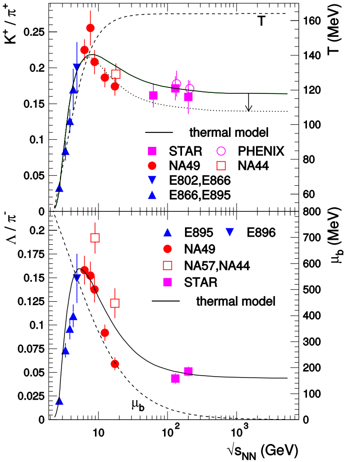
Expected:

- Smoother than data
- Approximately reproduces experimental data (because it was the input)

Notable:

- Fitted T, μ_B evolve smoothly with s_{NN}
- Addition of σ meson and heavier resonances “enhances” the horn-like shape in the K^+/π^+ dependence on s_{NN} (dotted line)





(Andronic, Braun-Munzinger, Stachel; Nucl.Phys. A834 (2010) 237C-240C)

No equilibrium? — dynamical Approach by Rafelski-Müller

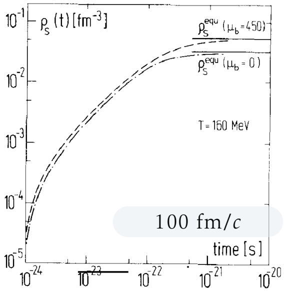
strangeness production <u>in confined matter</u>

$$N + N \to N + Y + K$$

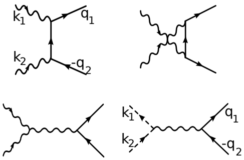
$$\pi + N \to K + Y \qquad \pi + \overline{N} \to \overline{K} + \overline{Y}$$

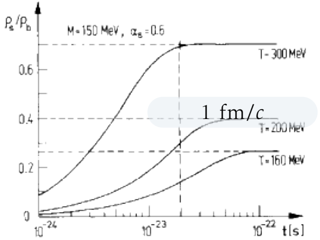
$$\pi + Y \to \Xi + K \qquad \pi + \overline{Y} \to \overline{\Xi} + \overline{K}$$

$$\pi + \Xi \to \Omega + K \qquad \pi + \overline{\Xi} \to \overline{\Omega} + \overline{K}$$



strangeness production <u>in QGP</u>





(Rafelski, Müller, Phys. Rev. Lett. 48 (1982) 1066)

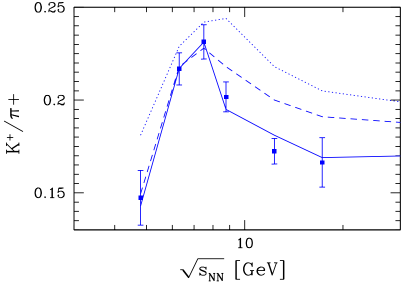
Statistical Hadronization – γ_s, γ_q

Results on strangess in equilibrium HRG were not satisfactory.

Parameter of "phase-space occupancy" γ_s introduced to improve the fits:

$$\langle \frac{N_s}{V} \rangle = \langle \rho_s \rangle = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\lambda_s^{-1}\gamma_s^{-1} e^{E(p)/T} + 1}, \quad \langle \frac{N_{\bar{s}}}{V} \rangle = \langle \rho_{\bar{s}} \rangle = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\lambda_s \gamma_s^{-1} e^{E(p)/T} + 1}$$

Due to larger mass of s quark it requires more time to saturate and so it doesn't reach equilibrium value.
→ $\gamma_s < 1$ at lower collision energies (AGS, SPS).
→ $\gamma_s = 1$ at higher energies (from RHIC).



dotted: $\gamma_q, \gamma_s = 1$
dashed: $\gamma_q = 1, \gamma_s < 1$
solid: $\gamma_q, \gamma_s < 1$

(J. Rafelski; Eur.Phys.J.ST 155 (2008) 139-166)

Similarly, γ_q factor can be introduced to reflect the undersaturation of u, d quarks.

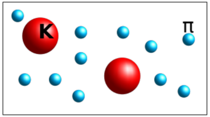
but is it still a statistical model?

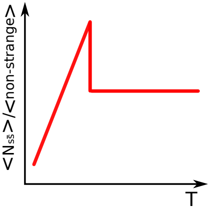
Strangeness in Statistical Model of Early Stage

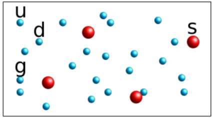
$$\langle n \rangle = \frac{gV}{(2\pi)^3} \int d^3p \frac{1}{e^{E/T} \pm 1}$$

$$\approx \; gV \left(\frac{MT}{2\pi}\right)^{3/2} e^{-M/T}$$ for heavy particles

$$\approx \; gV \frac{2\pi^2}{4 \cdot 45} T^3$$ for light particles



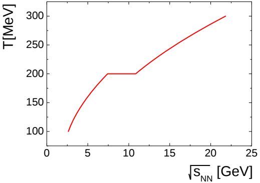




$$\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{MT^{3/2}}{T^3} \cdot e^{-M/T}$$

$$\frac{\langle s \rangle}{\langle u + d + g \rangle} \propto \frac{T^3}{T^3} = \text{const}(T)$$

Temperature dependence on collision energy in SMES



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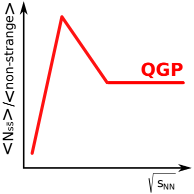
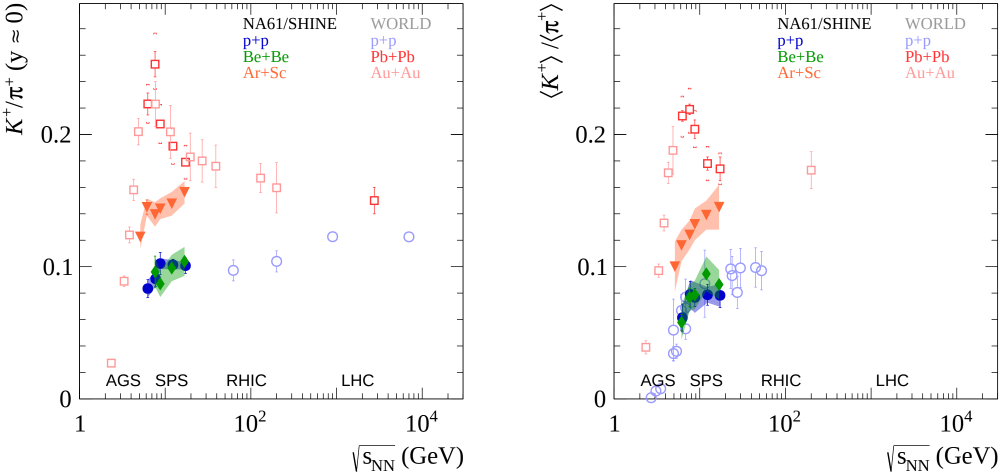


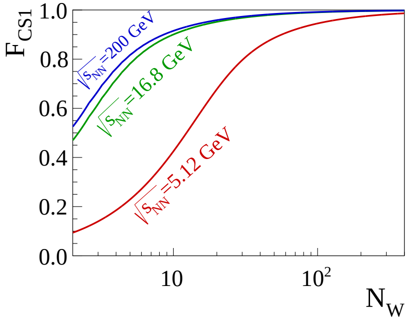
Strange/non-strange particle ratio:

Mareks' horn: [Gaździcki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705]

$K^+/\pi+$ ratio dependence on collision energy

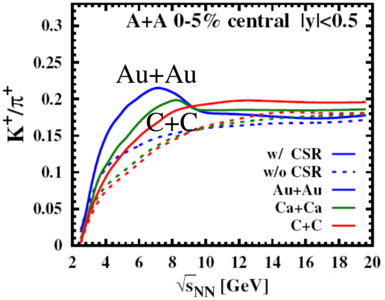


System size dependence in statistical and dynamical models



- Arises due to differences between GC and C formulation.
- Local conservation of quantum numbers severely reduces the phase space available for particle production.

(Tounsi, Redlich; Nucl.Phys.A 715 (2003) 565c-568c)

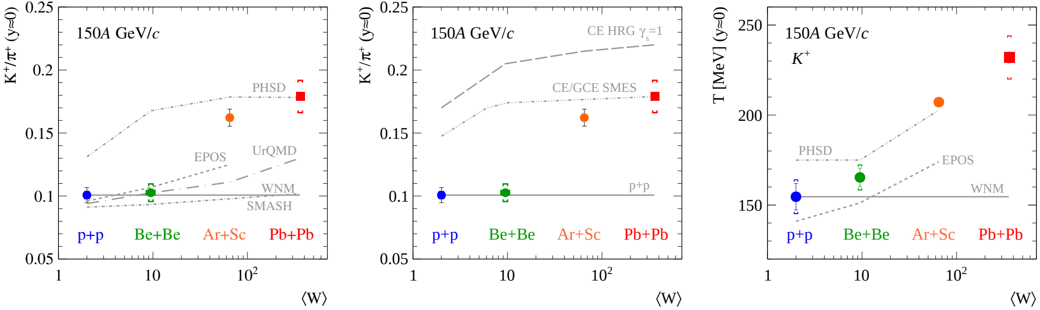


- PHSD features the onset of deconfinement.
- Predicts increase of strangeness production with system size at low collision energies (<10 GeV) and decrease at high collision energies (>10 GeV).

(Palmese et al. , PRC94 (2016) 044912)

K^+/π^+ and T vs the system size at 150A GeV/c

dynamical models | **statistical models** | **dynamical models**



- **Beginning of the creation of large clusters of strongly interacting matter?**

  Rapid change of observables when going from small (p+p, Be+Be) to intermediate (Ar+Sc) and large ones (Pb+Pb).

- None of the models reproduce K^+/π^+ ratio nor T for 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. C99 (2019) 3, 034909
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)