

Isospin Symmetry Violation in Kaon Production

Quark recombination model with isospin breaking

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2504.02113 - EPJC 85 (2025) 9, 1058

**Photoproduction Studies on
the Deuteron and Helium-3 in Hall D**

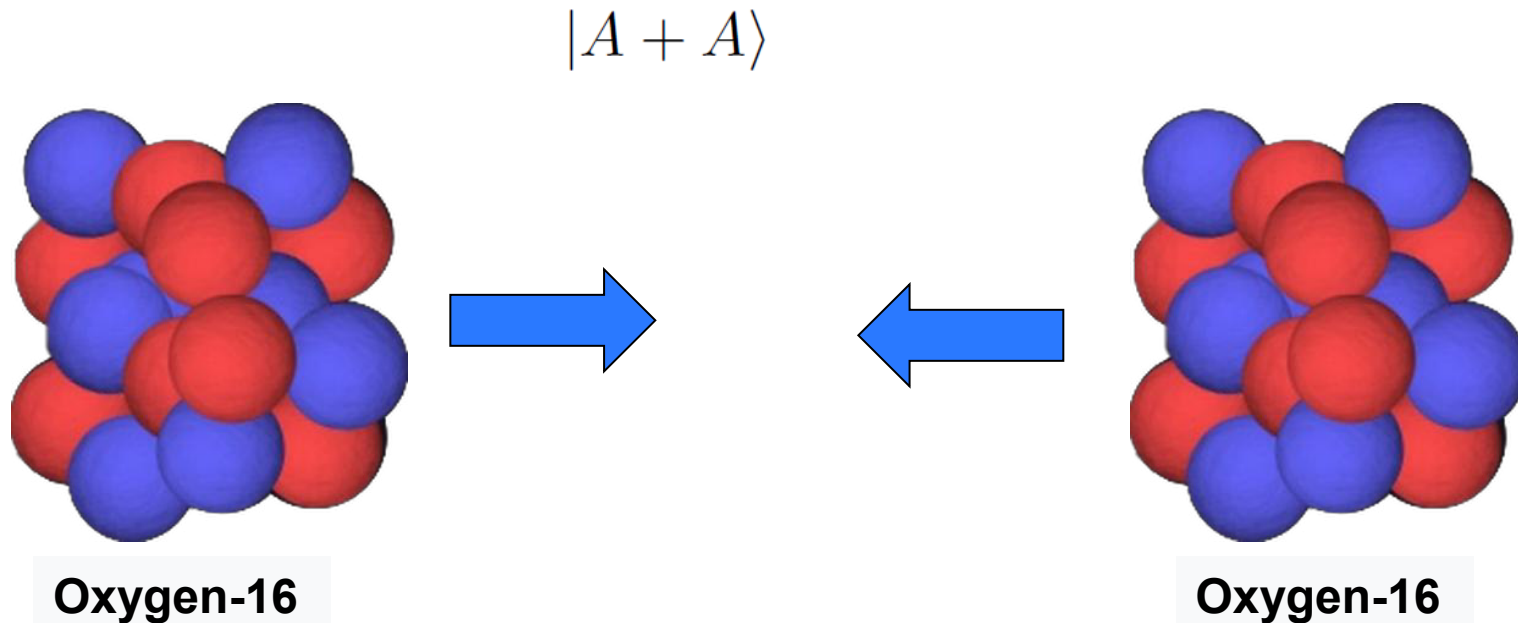
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Outline

1. Kaon isospin anomaly: brief recall
2. Quark recombination model
3. A ratio that does not depend on energy
4. Consequences of a large isospin-breaking
5. Conclusions

Nucleus-nucleus collision with equal numbers of protons and neutrons

$$Z = N = A/2, \quad Q/B = 1/2$$



$I_z = 0$ (typically also $I = 0$ for each nucleus, thus total isospin also vanishing)

Expected kaon multiplicities

Charge symmetry means that strong interactions are invariant under the inversion of the third component of the isospin of hadron of the initial and final states.

$$\langle K^+ \rangle = \langle K^0 \rangle$$

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

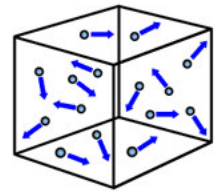
$$R_K \equiv \frac{\langle K^+ \rangle + \langle K^- \rangle}{\langle K^0 \rangle + \langle \bar{K}^0 \rangle} = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2\langle K_S^0 \rangle} = 1$$

Popular theoretical approaches

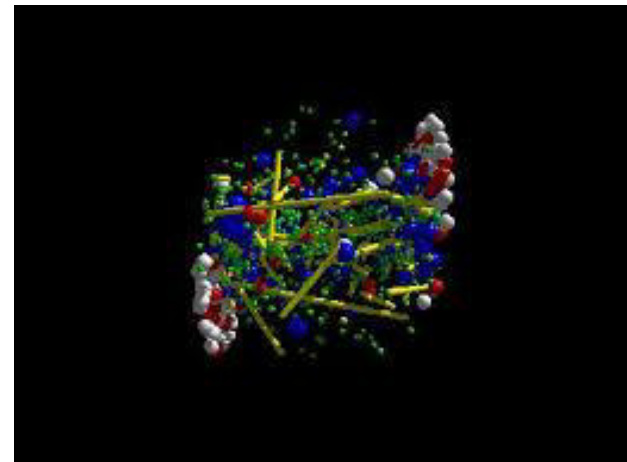
- HRG (hadron resonance gas approach)

$$\ln Z = \sum_k \ln Z_k^{\text{stable}} + \sum_k \ln Z_k^{\text{res}}$$

$$\ln Z_k^{\text{stable}, \pm} = f_k V \int \frac{d^3 p}{(2\pi)^3} \ln \left[1 \pm e^{-E_p/T} \right]^{\pm 1}$$



- UrQMD (Hadron-String transport model, fully integrated Monte Carlo simulation of nucleus-nucleus simulations)










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

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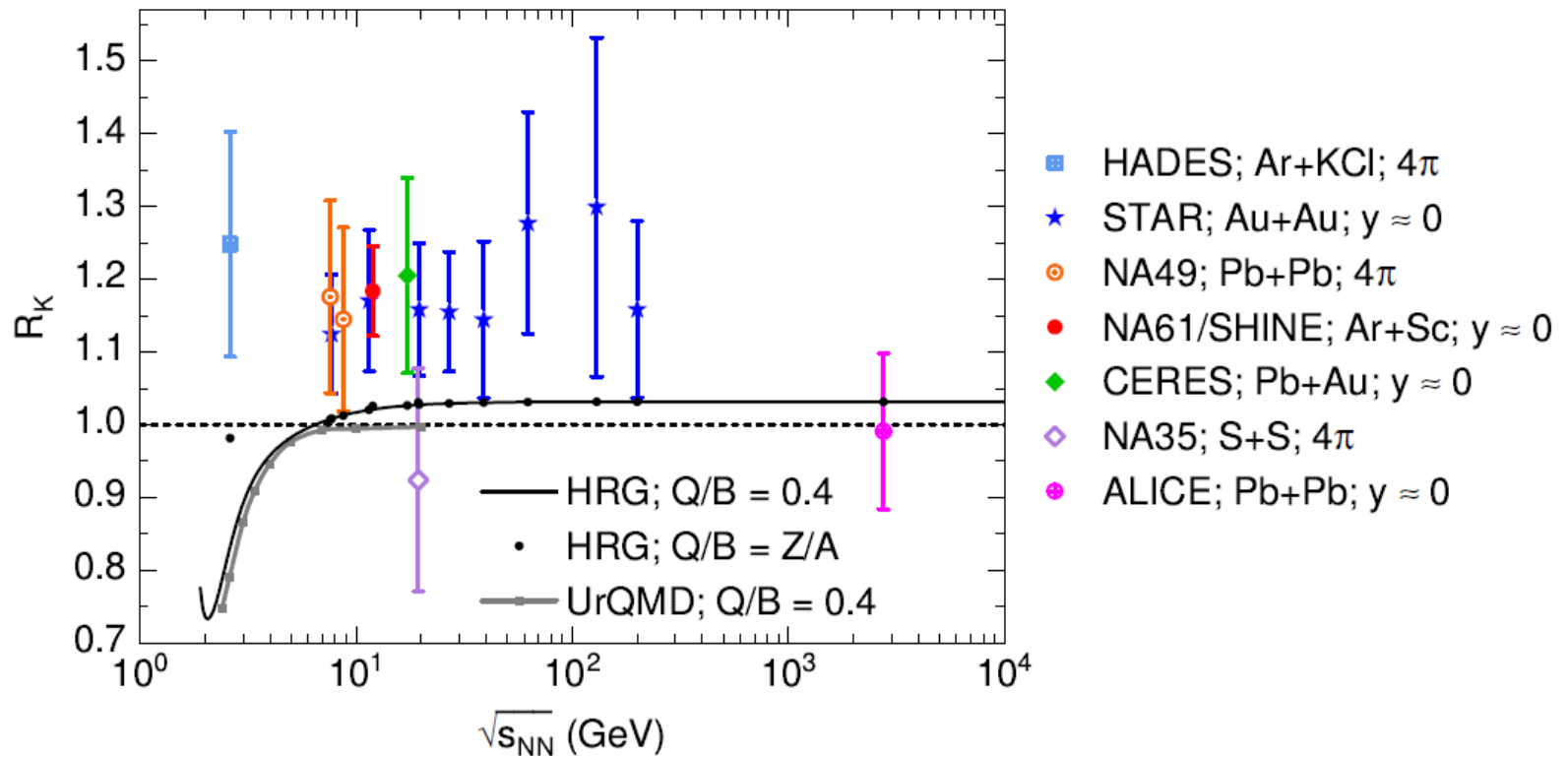
Published online: 23 March 2025

 Check for updates

The NA61/SHINE Collaboration*, F. Giacosa ^{1,2}, M. Gorenstein ^{3,4},
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Strong interactions preserve an approximate isospin symmetry between up (u) and down (d) quarks, part of the more general flavor symmetry. In the case of K meson production, if this isospin symmetry were exact, it would result in equal numbers of charged (K^+ and K^-) and neutral (K^0 and \bar{K}^0) mesons produced in collisions of isospin-symmetric atomic nuclei. Here, we report results on the relative abundance of charged over neutral K meson production in argon and scandium nuclei collisions at a center-of-mass energy of 11.9 GeV per nucleon pair. We find that the production of K^+ and K^- mesons at mid-rapidity is $(18.4 \pm 6.1)\%$ higher than that of the neutral K mesons. Although with large uncertainties, earlier data on nucleus-nucleus collisions in the collision center-of-mass energy range $2.6 < \sqrt{s_{NN}} < 200$ GeV are consistent with the present result. Using well-established models for hadron production, we demonstrate that known isospin-symmetry breaking effects and the initial nuclei containing more neutrons than protons lead only to a small (few percent) deviation of the charged-to-neutral kaon ratio from unity at high energies. Thus, they cannot explain the measurements. The significance of the flavor-symmetry violation beyond the known effects is 4.7σ when the compilation of world data with uncertainties quoted by the experiments is used. New systematic, high-precision measurements and theoretical efforts are needed to establish the origin of the observed large isospin-symmetry breaking.

Experimental results (NA61/SHINE plus others)



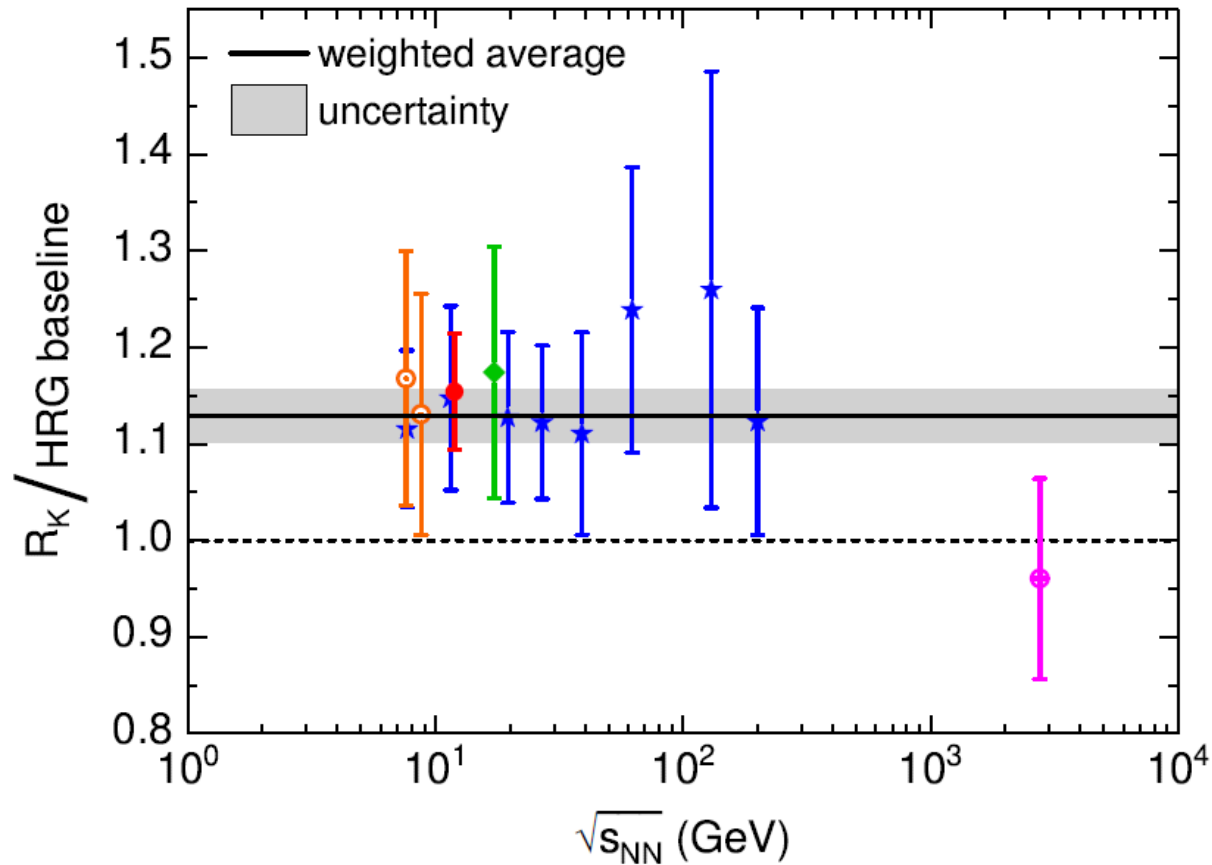
Latest NA61/SHINE result: $R_K = 1.184 \pm 0.061$

Note, however, most experiments have $Q/B < 0.5$

Experiment vs theory (HRG): ratio

$1.129 \pm 0.027.$

$\chi_{min}^2/\text{dof} \approx 0.3$





The exp/th mismatch is 4.7σ .

EVIDENCE OF ISOSPIN-SYMMETRY VIOLATION IN
HIGH-ENERGY COLLISIONS OF ATOMIC NUCLEI:
THEORETICAL AND PHENOMENOLOGICAL
CONSIDERATIONS

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Recently, the NA61/SHINE Collaboration at the CERN SPS reported evidence of isospin-symmetry violation in high-energy nuclear collisions. The effect was observed in the relative yields of charged and neutral kaons and cannot be explained by known sources of isospin-symmetry breaking. In this work, we extend the theoretical and phenomenological aspects of that study. We discuss the historical background and introduce the concepts of isospin transformations and symmetry. Importantly, we relate isospin symmetry to the QCD flavour symmetry, and we present both conceptual and analytical proofs demonstrating the equality of the mean multiplicities of charged and neutral kaons for an initial ensemble of colliding systems that is invariant under charge-symmetry transformation.

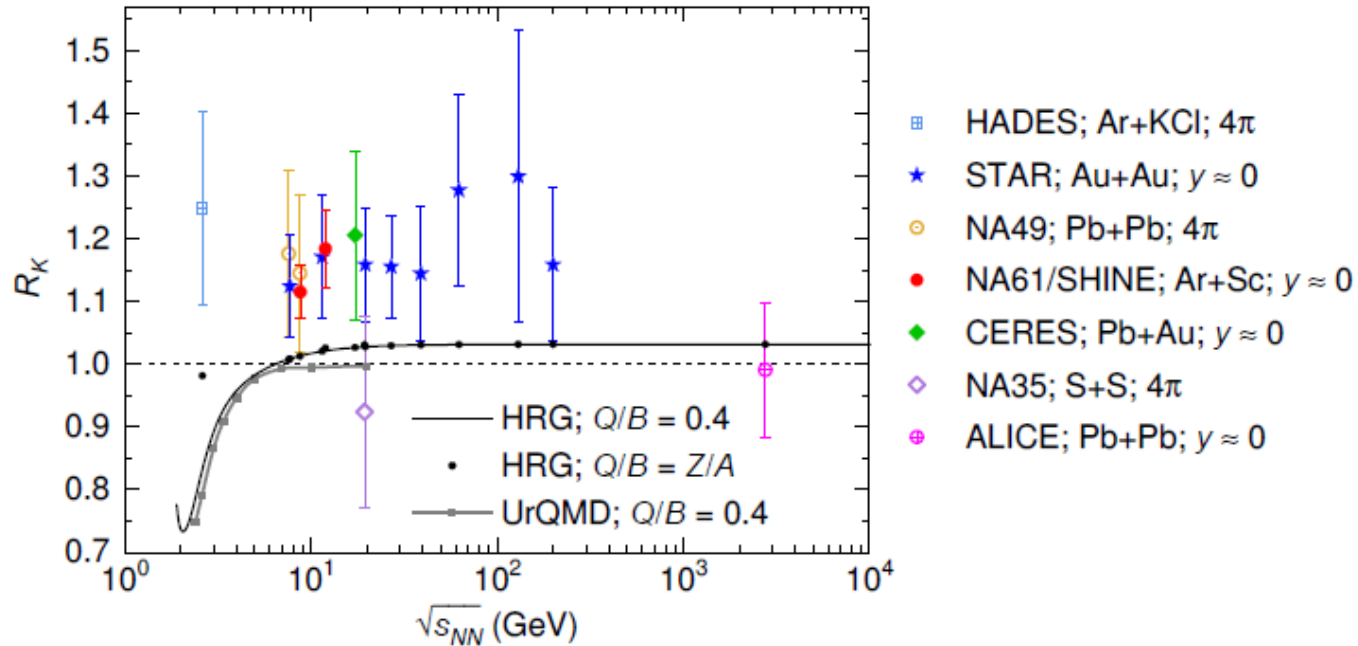
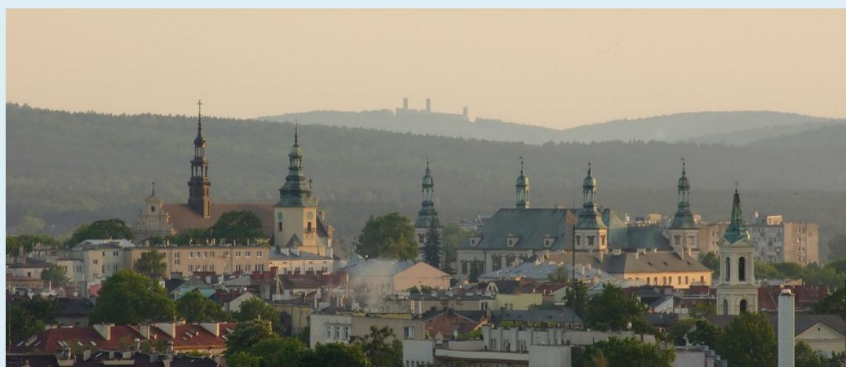


Fig. 1. Ratio R_K of charged-to-neutral K meson yields in nucleus–nucleus collisions as a function of collision energy. The lines show model predictions; see below for explanations. Figure adapted from Ref. [1] with a new preliminary Ar+Sc 8.8 GeV point added [2].

ISO-BREAK 2025

<https://indico.cern.ch/event/1557894/>



Workshop on isospin symmetry violation: kaons and beyond ISO-BREAK 25

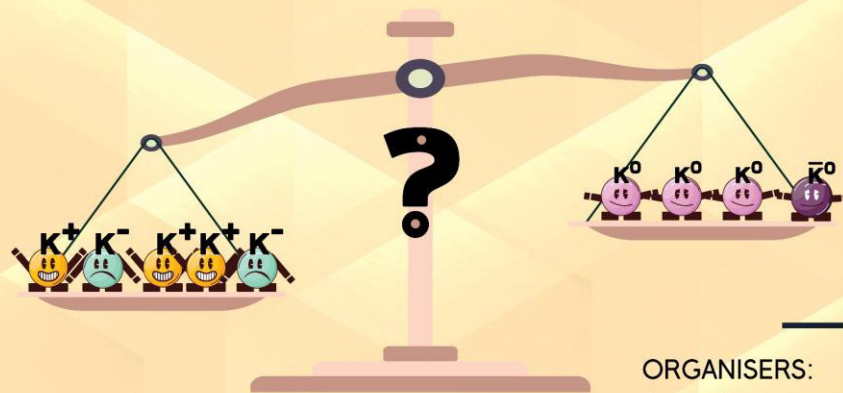
Oct 23–25, 2025
Institute of Physics, Jan Kochanowski University
Europe/Warsaw timezone



23-25.10.2025 KIELCE, POLAND

WORKSHOP ON ISOSPIN SYMMETRY VIOLATION: KAONS AND BEYOND (ISO-BREAK 25)

[HTTPS://INDICO.CERN.CH/EVENT/1557894/](https://indico.cern.ch/event/1557894/)



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White paper: 2604.16005 [nucl-ex]



Isospin-symmetry violation – kaons and beyond

ISO-BREAK 25: summary and outlook

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Toward a simple 'quark counting' model: quark recombination (or coalescence) model



- Provided the large isospin-symmetry breaking is true, two questions can be asked: why and which are its consequences.
- 'Why' is, as usual, a difficult question. Can electromagnetic interaction enhance $K+K^-$? We argued that this is not the case. But...
- What about a sum over many small effects? All ϕ - f_0 - a_0 etc effects would lead to the measured results.
- Eventually a combination of both QED and many small contributions...

Quark recombination model: references

Joanna Stepaniak and Damian Pszczel. On the relation between K_s^0 and charged kaon yields in proton–proton collisions. *Eur. Phys. J. C*, 83(10):928, 2023.

M. Bonesini, A. Marchionni, F. Pietropaolo, and T. Tabarelli de Fatis. On Particle production for high-energy neutrino beams. *Eur. Phys. J. C*, 20:13–27, 2001. As reported in Ref. [25] the model was developed by N. Doble, L. Gatignon, P. Grafstrom, NA31 Internal note 83 (1990). According to the authors, the formula and its derivation are due to Horst Wachsmuth.

Valence and sea quarks

$$n_u = n_u^{val}$$

$$n_d = n_d^{val}$$

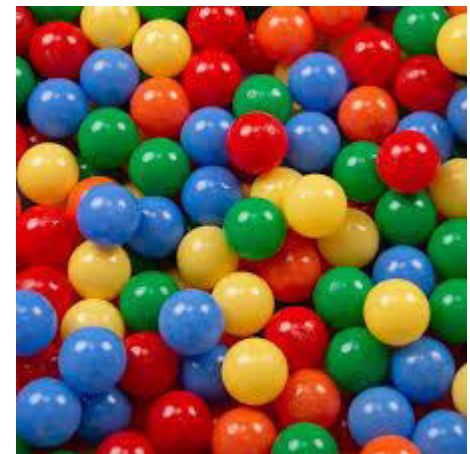
$$\alpha = n_u^{sea} = n_{\bar{u}}^{sea}$$

$$\beta = n_d^{sea} = n_{\bar{d}}^{sea}$$

$$\gamma = n_s^{sea} = n_{\bar{s}}^{sea}$$

$$n_{tot} = n_u + n_d + 2\alpha + 2\beta + 2\gamma$$

$$p(u) = \frac{n_u + \alpha}{n_{tot}}$$



Kaon probabilities

Eur. Phys. J. C (2025) 85:1058
<https://doi.org/10.1140/epjc/s10052-025-14798-3>

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PHYSICAL JOURNAL C



Letter

Isospin kaon anomaly and its consequences

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$$p(K^+) \propto n_u \gamma + \alpha \gamma$$

$$p(K^0) \propto n_d \gamma + \beta \gamma$$

$$p(K^-) \propto \alpha \gamma$$

$$p(\bar{K}^0) \propto \beta \gamma$$

'Grundschulmathematik' leads to:

$$R_K = \frac{\langle K^+ \rangle + \langle K^- \rangle}{\langle 2K_S^0 \rangle} = \frac{n_u + 2\alpha}{n_d + 2\beta}$$

isospin-symmetric limit ($\alpha = \beta$)

$$R_K = 1 \quad \text{if } n_u = n_d$$

$$Q/A = 1/2$$

From R_K to \tilde{R}_K

$$\tilde{R}_K = R_K + \left(\frac{1 - 2\frac{Q}{A}}{1 + \frac{Q}{A}} \right) \frac{\langle K^+ \rangle - \langle K^- \rangle}{2 \langle K_S^0 \rangle} = \frac{n_d + 2\alpha}{n_d + 2\beta}$$

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isospin-conserved

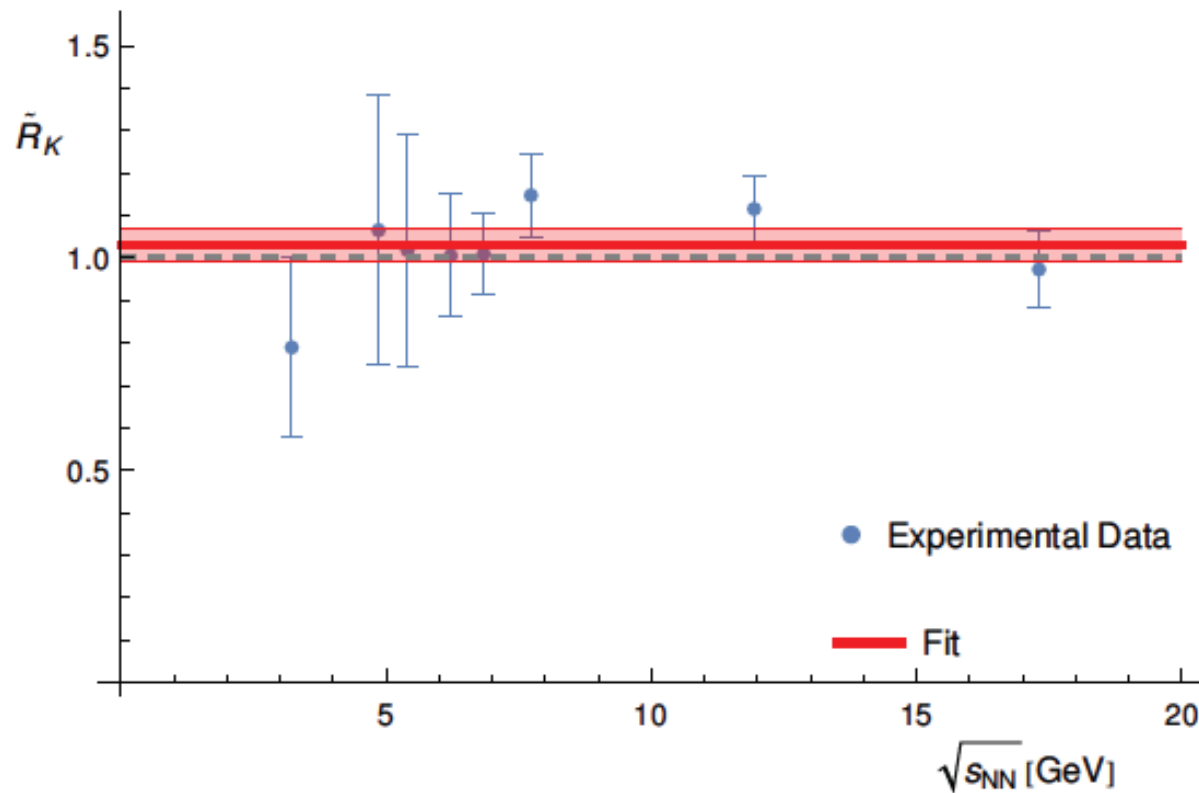
$$\alpha = \beta \quad \rightarrow \quad \tilde{R}_K = 1$$

For pp collisions $Q/A = 1$

$$\langle K^+ \rangle + 3 \langle K^- \rangle = 4 \langle K_S^0 \rangle$$

See J. Stepaniak and D. Pszczel, EPJC 83 2023

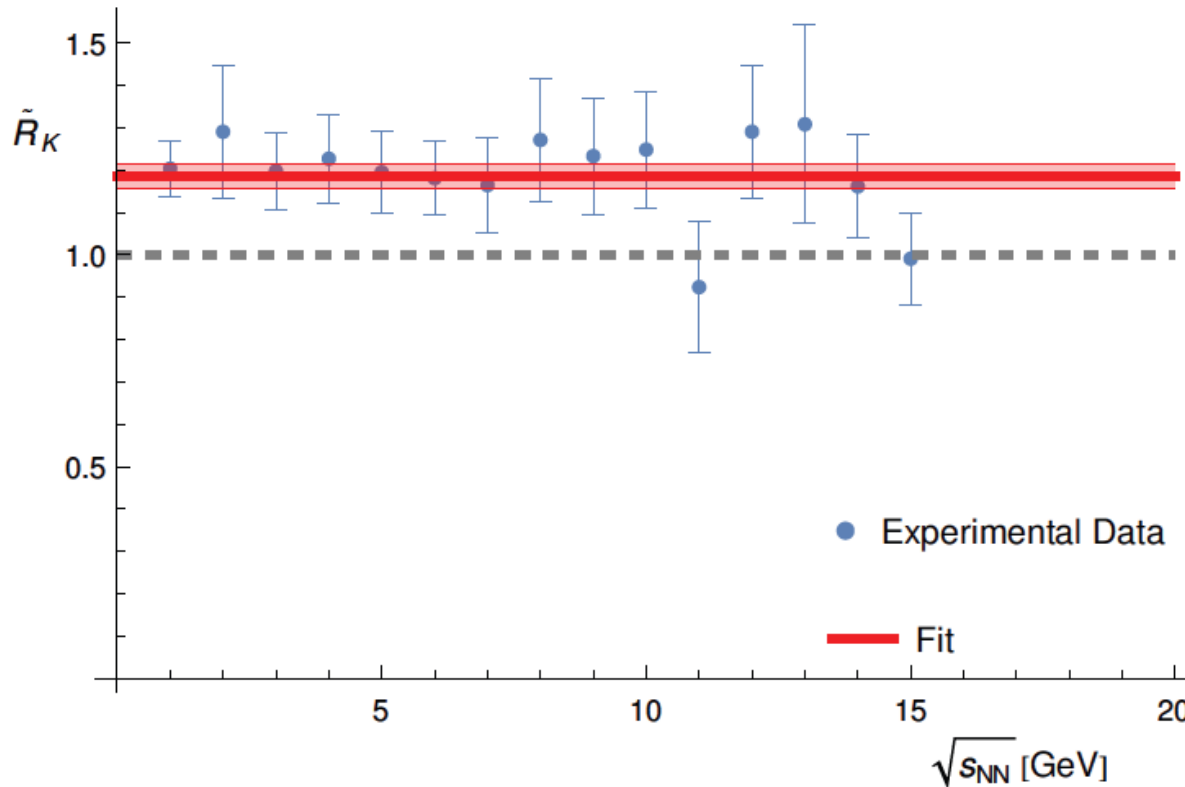
Proton-proton results: isospin ok



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$$\tilde{R}_K = 1.030 \pm 0.038.$$

Nucleus-nucleus results for \tilde{R}_K : consistent with being a constant but not 1

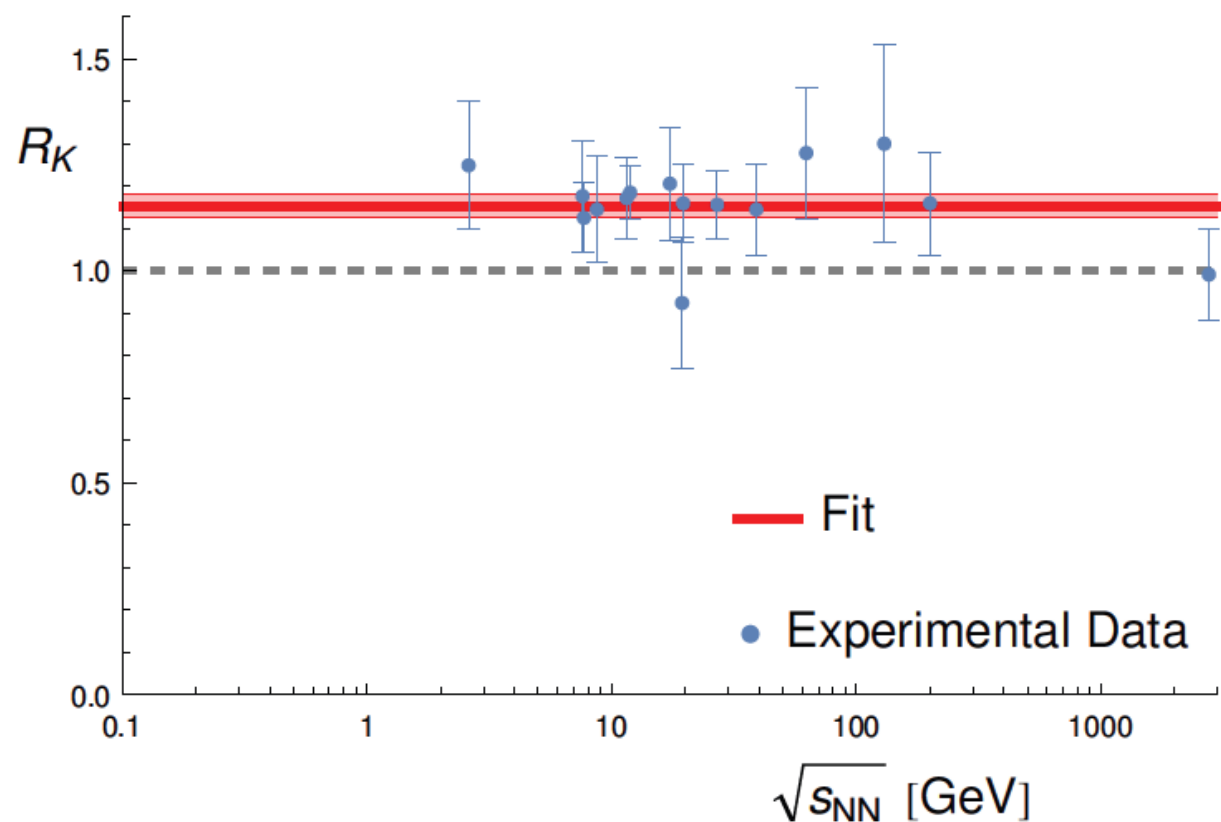


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$$\tilde{R}_K = 1.185 \pm 0.029$$

This is 6.4σ away from 1.

Nucleus-nucleus results for R_K : constant, not 1, and compatible with $R_{\text{tilde}K}$



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$$R_K = 1.152 \pm 0.027$$

Predictions

Ratio	Estimated value
$R_K = \frac{K^+ + K^-}{K^0 + \bar{K}^0}$	$r = 1.185 \pm 0.029$
p/n	$r = 1.185 \pm 0.029$
π^+ / π^0	$\frac{2r}{1+r^2} = 0.986 \pm 0.004$
Σ^+ / Σ^0	$r = 1.185 \pm 0.029$
Σ^+ / Σ^-	$r^2 = 1.404 \pm 0.068$

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Predictions

Ratio	Estimated value
Δ^{++} / Δ^{+}	$r = 1.185 \pm 0.029$
Δ^{++} / Δ^{0}	$r^2 = 1.404 \pm 0.069$
Δ^{++} / Δ^{-}	$r^3 = 1.67 \pm 0.12$

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Pion-nucleus scattering antiquarks in the initial state

$$R_K = \frac{\langle K^+ \rangle + \langle K^- \rangle}{\langle 2K_S^0 \rangle} = \frac{n_u + n_{\bar{u}} + 2\alpha}{n_d + n_{\bar{d}} + 2\beta}$$

$R_K = 1$ in the isospin limit ($\alpha = \beta$)
for $n_u + n_{\bar{u}} = n_d + n_{\bar{d}}$.

This is the case for pion-carbon.

(In fact for π^+C : $n_u = 18+1$, $n_{\bar{u}} = 0$, $n_d = 18$, $n_{\bar{d}} = 1$)

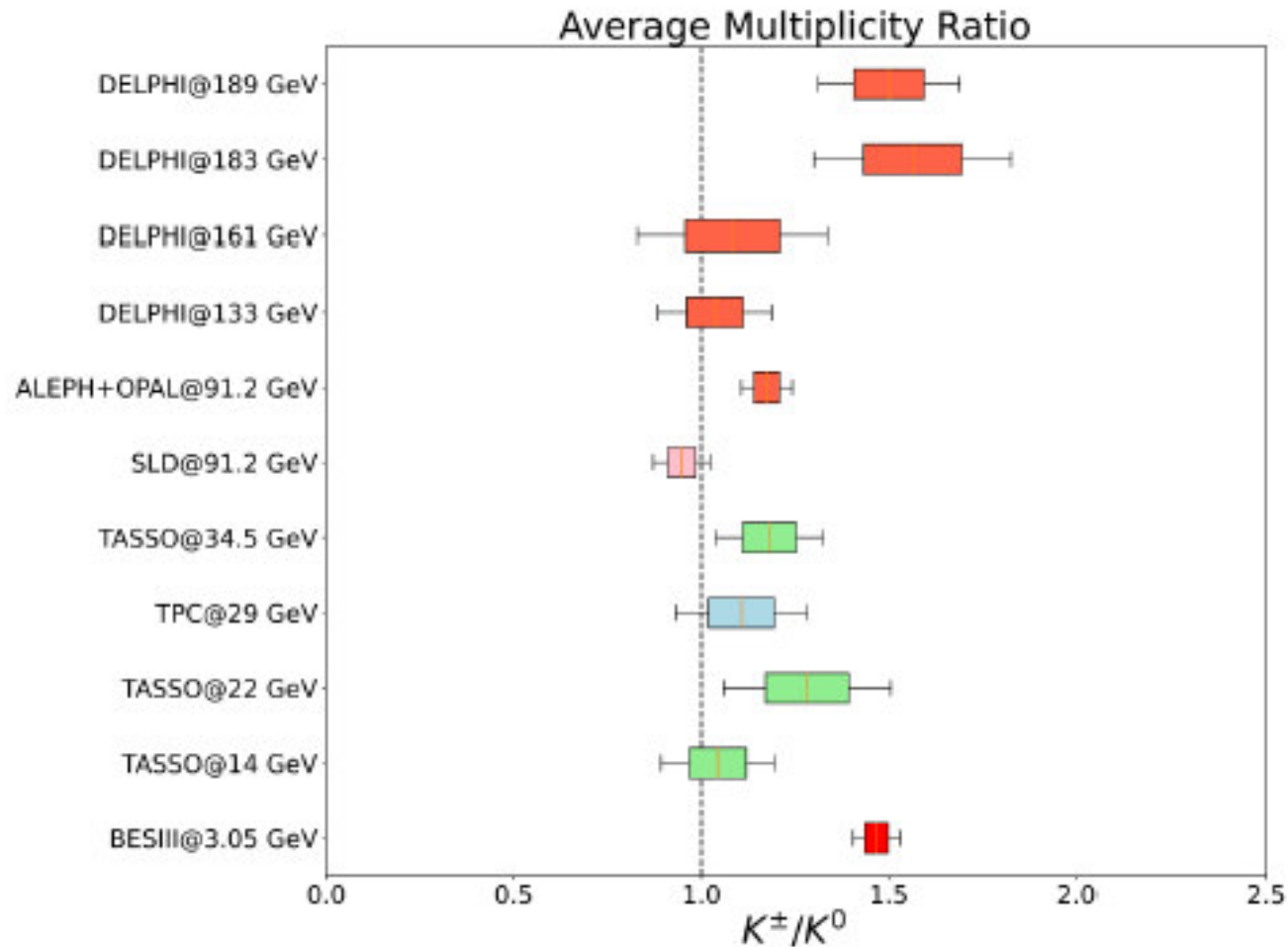
But isospin-symmetry is broken.

Hence our prediction for pion-carbon:

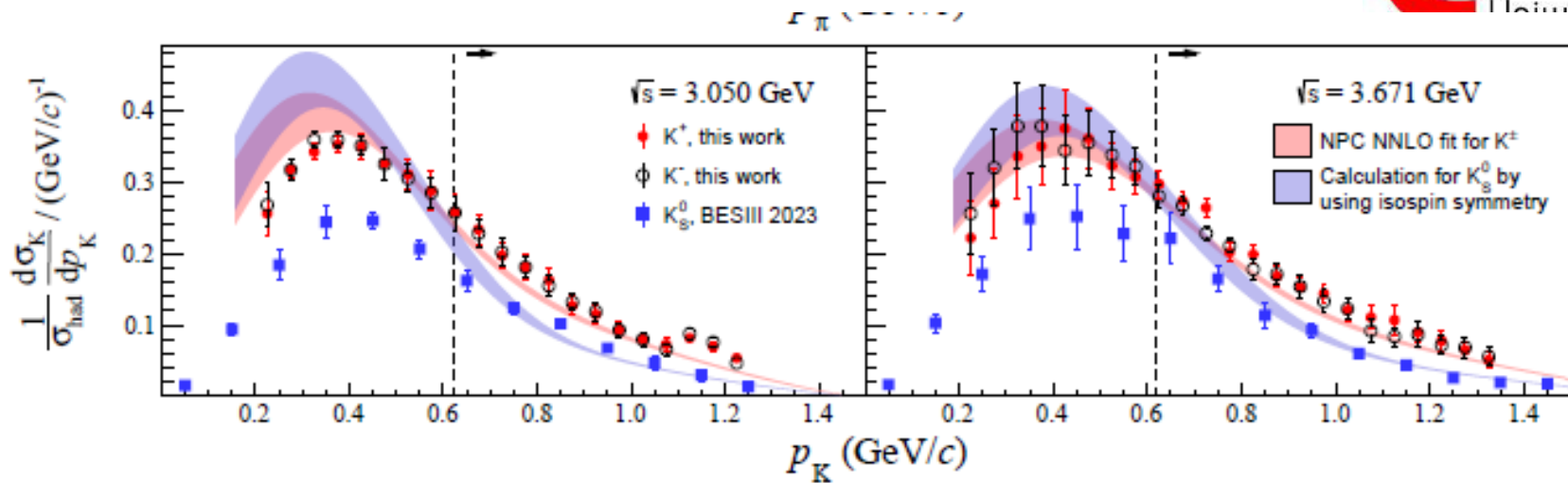
$$R_K^{\pi^+C} = R_K^{\pi^-C} \simeq 1.185 \pm 0.029$$

See NA61/SHINE
PRD 107 (2023) 062004
Where R_K is about 1.2

$$e^+ + e^- \rightarrow K + X$$



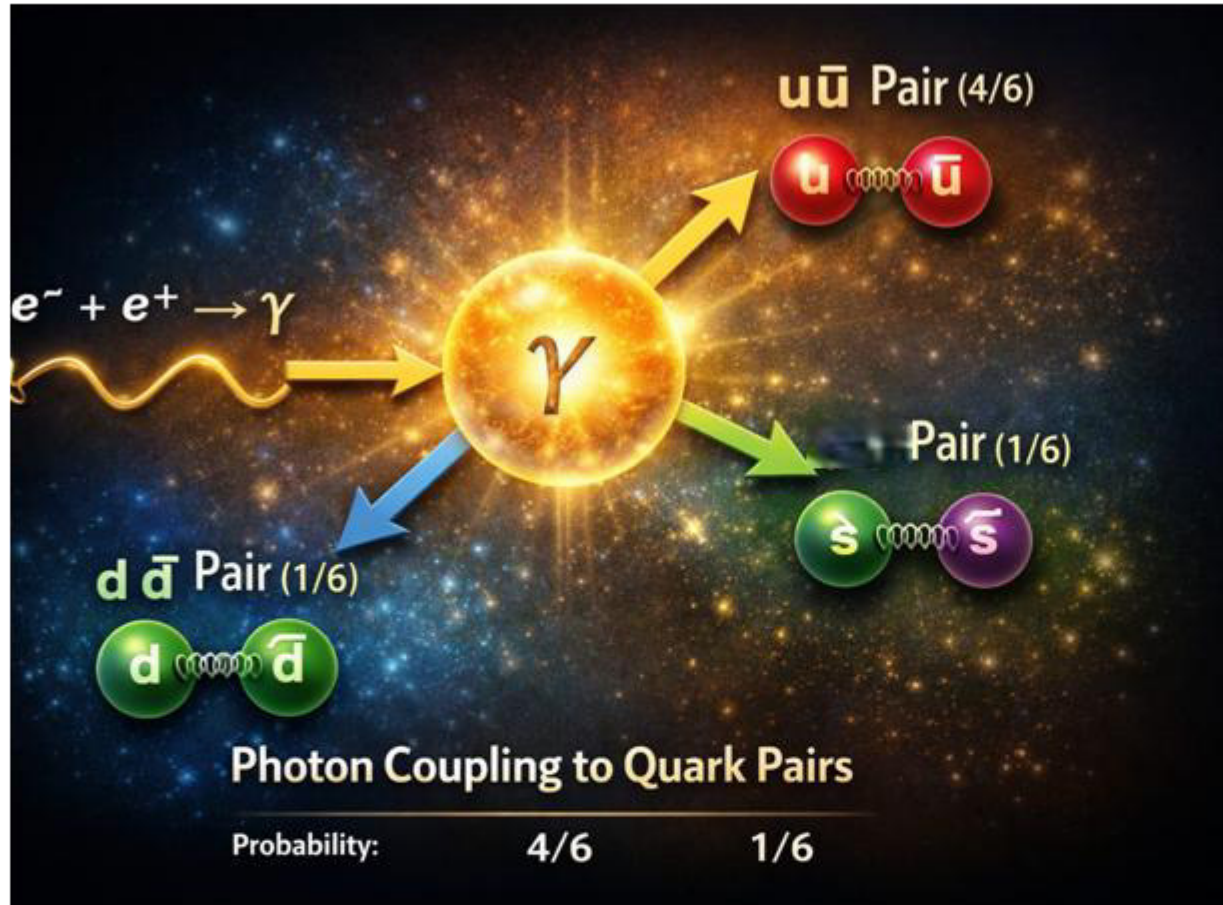
BESIII results



M. Ablikim et al [BESIII], Phys. Rev. Lett. 135 (2025), 151901

Charged kaon excess or not?

Quark recombination model: idea



Quark recombination model: result

$$R_K = \frac{4\gamma + 6\alpha\gamma + \alpha}{\gamma + 6\beta\gamma + \beta}$$

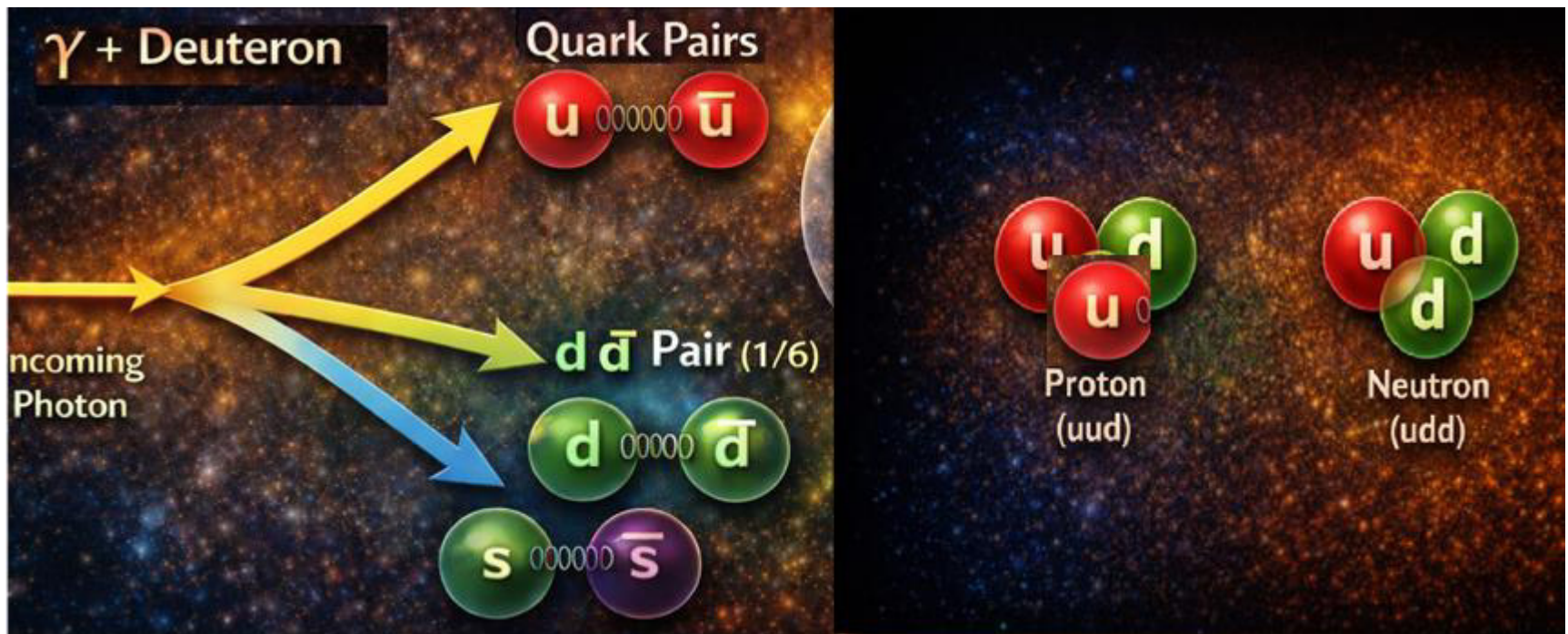
Dependence on alfa, beta, gamma
Fits needed (ongoing work)

Flavor-symmetry limit:

$$\alpha = \beta = \gamma \quad \longrightarrow \quad R_K = 1 + \frac{3}{2 + 6\alpha}$$

JLAB study via QR model: idea

$$\gamma + D \rightarrow K + X$$



JLAB study via QR model: result

$$\gamma + D \rightarrow K + X$$

$$R_K = \frac{3 + 2\alpha + 12\alpha\gamma + 26\gamma}{3 + 2\beta + 12\beta\gamma + 20\gamma}$$

Dependence on all quark types

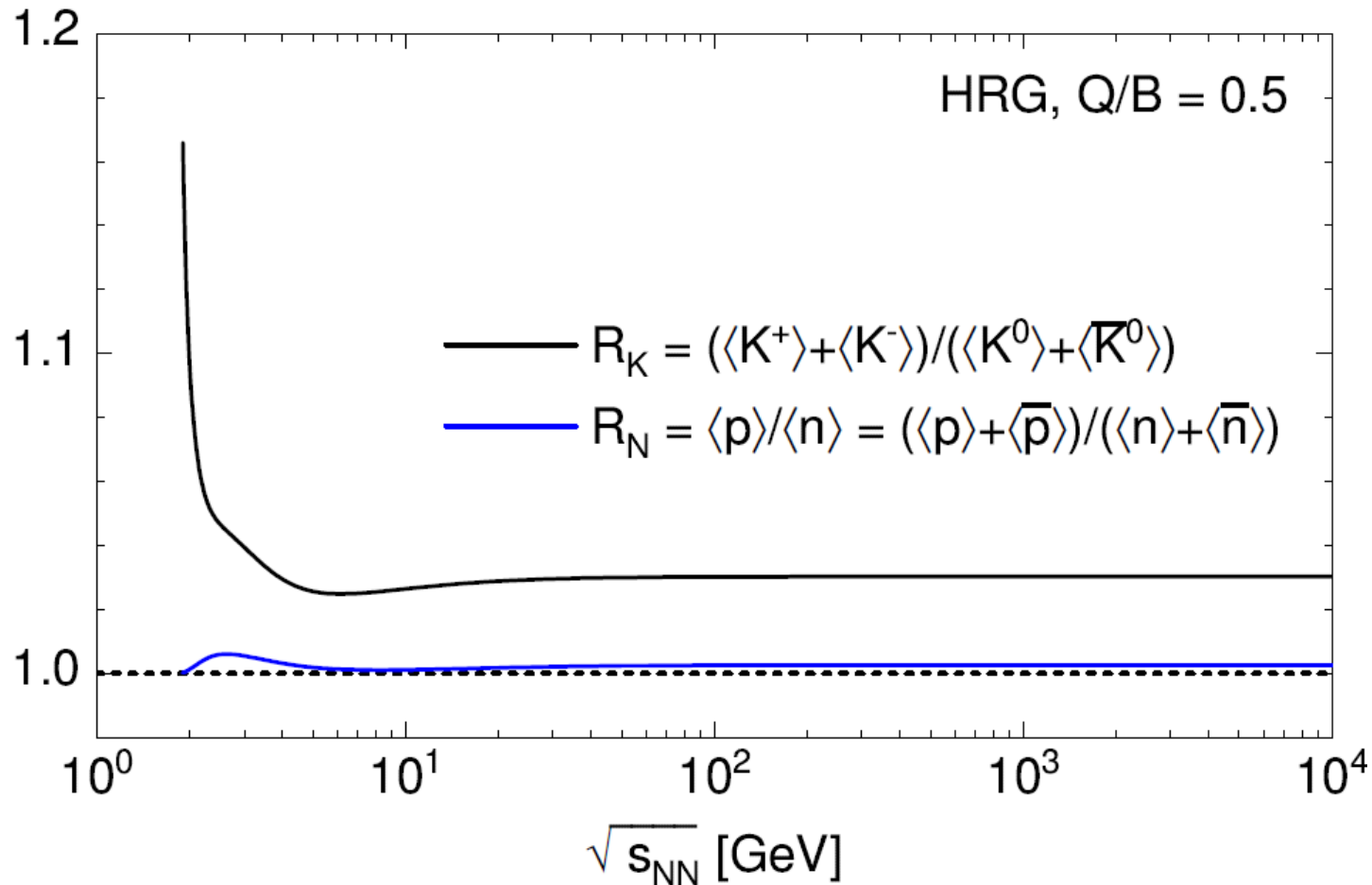
$$\alpha = \beta = \gamma \quad \longrightarrow \quad R_K = 1 + \frac{6\alpha}{3 + 22\alpha + 12\alpha^2} \geq 1,$$

Summary and conclusions

- A simple quark-counting scheme valid for any Q/A shows: proton-proton data agree with isospin symmetry, but nucleus nucleus do not.
- This model reproduces data for a large isospin breaking (about 20% more u than d quarks from QCD vacuum)
- In the future: scattering of nuclei with $Z = N = A/2$ highly desired.
- Study ratios of other isospin multiplets (nucleons, hyperons)
- Predictions for novel reactions involving photons (including gamma-deuteron) are ongoing

Thanks!

HRG for $Q/B=1/2$



If we enforce isospin symmetry to be exact, $R_K = 1$ for any energy. 33

\tilde{R}_K for (anti)quarks u and d

$$\begin{aligned}\tilde{R}_K &= R_K + \frac{n_d + n_{\bar{d}} - n_u - n_{\bar{u}}}{n_u - n_{\bar{u}}} \frac{\langle K^+ \rangle - \langle K^- \rangle}{\langle 2K_S^0 \rangle} \\ &= \frac{n_d + n_{\bar{d}} + 2\alpha}{n_d + n_{\bar{d}} + 2\beta}\end{aligned}$$

$\tilde{R}_K = 1$ in the isospin-symmetric limit

valid also for initial states with $n_s = n_{\bar{s}}$

$\eta, \eta',$ and $\phi, \quad K^+ \Lambda$

Most general case

In the most general case with arbitrary $n_{u,d,s}$ and $n_{\bar{u},\bar{d},\bar{s}}$ the quantity \tilde{R}_K reads

$$\tilde{R}_K = \frac{(n_d + \alpha)(n_{\bar{s}} + \gamma) + (n_{\bar{d}} + \alpha)(n_s + \gamma)}{(n_d + \beta)(n_{\bar{s}} + \gamma) + (n_{\bar{d}} + \beta)(n_s + \gamma)}.$$

However, it cannot be expressed as a function of the three multiplicities $\langle K^+ \rangle$, $\langle K^- \rangle$, and $\langle K_S^0 \rangle$, but it involves separately $\langle K_0 \rangle$ and $\langle \bar{K}_0 \rangle$ [38]. This fact is not convenient because only K_S^0 is usually detected. Moreover, even measuring K_L^0 would not help, since (neglecting a very small CP -breaking) $\langle K_L^0 \rangle = \langle K_S^0 \rangle$, implying that the multiplicities $\langle K_0 \rangle$ and $\langle \bar{K}_0 \rangle$ cannot be obtained.