Isospin symmetry breaking under extreme conditions

Francesco Giacosa
Jan Kochanowski U Kielce – Goethe U Frankfurt

in collaboration with:
NA61/SHINE, M. Gorenstein, R. Poberezhnyuk, S. Samanta
Nat. Commun. 16 (2025) 1, 2849
W. Brylinski et al, Acta Phys.Polon.B 57 (2026) 3, 3-A5
M. Rohrmoser, EPJC 85 (2025) 9, 1058
M. Gazdzicki and K. Grebieszkow (+ **ISO-BREAK 25 part.**)
ISO-BREAK 25 white paper 2604.16005

66. Cracow School of Theoretical Physics
14-19/6/2026, Krakow, Poland

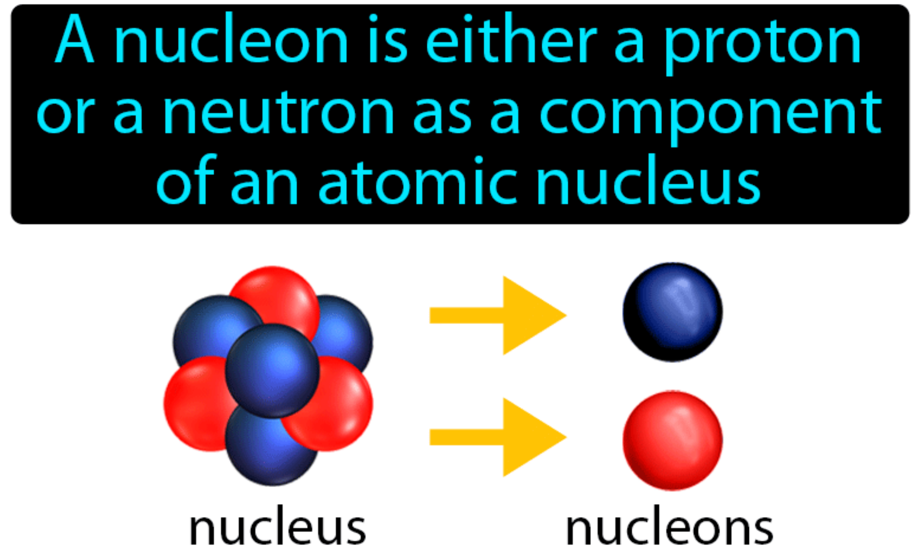
Outline

1. Isospin for hadrons: basics
2. Isopsin kaon anomaly: experimental status
3. Isospin and QCD: not trivial after all
4. Description of data within models
5. Discussion
6. Conclusions

Introduction

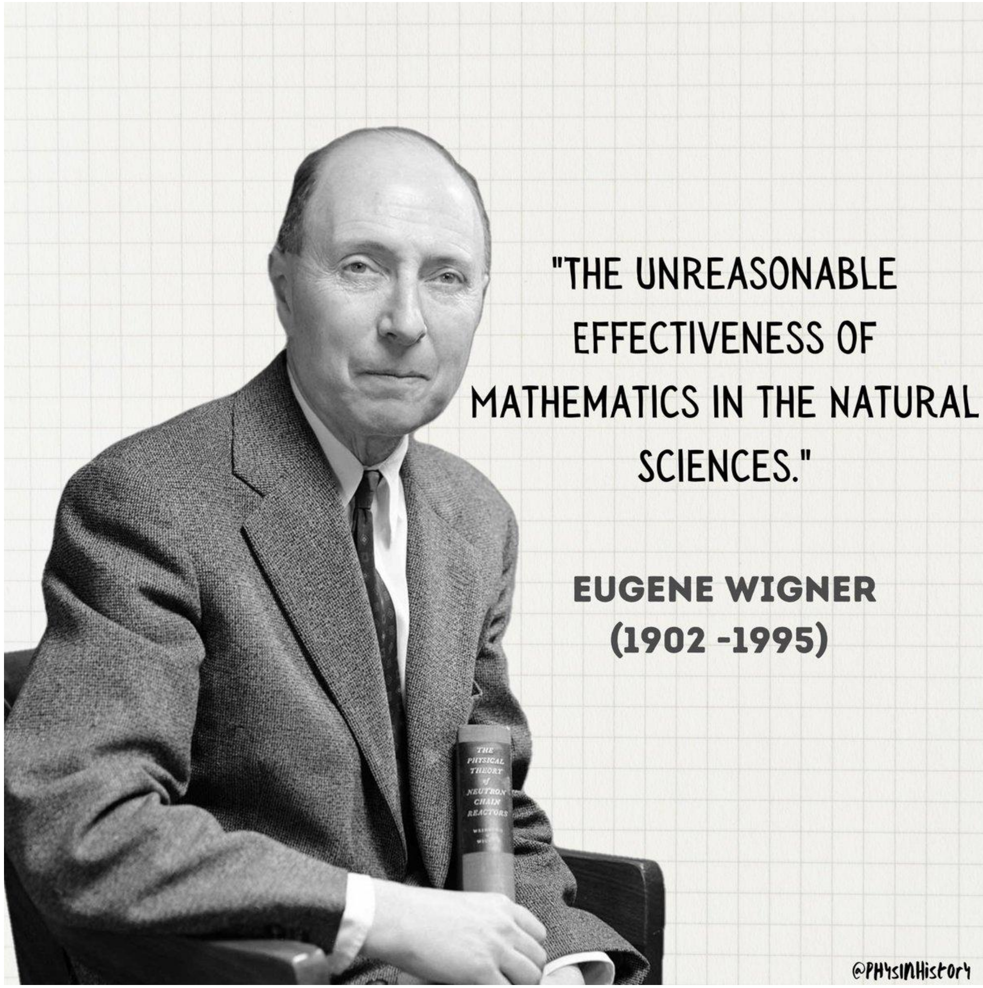
- Isospin symmetry is an approximate symmetry of strong interactions. It originates from nearly degeneracy of u and d quarks.
- Deviations appears in tiny mass differences (proton, neutron, or neutral and changed pions) and suppressed decay widths.
- **What about particle productions in nuclear collisions (and beyond)? Is isospin symmetry still fulfilled at the same degree of accuracy?**

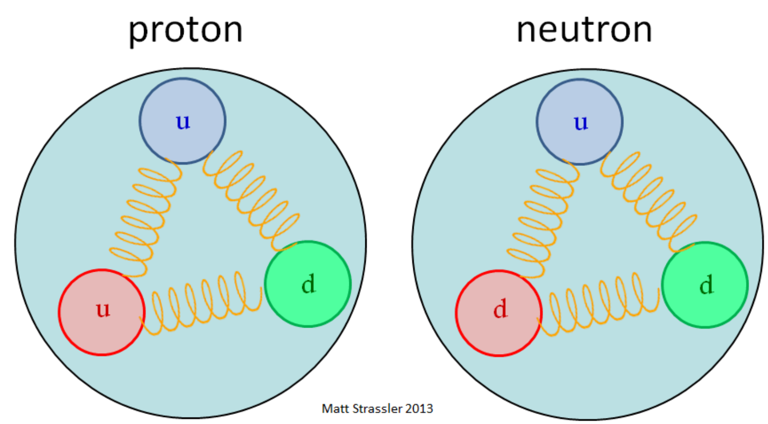
Heisenberg (1932): the nucleon

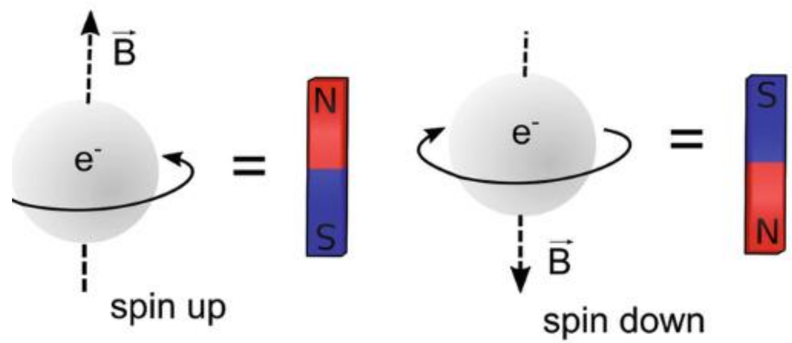


Proton and neutron merge into the nucleon.
Masses very similar.

Wigner (1937): isotopic spin, thus isospin







PDG masses: nucleons

p

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass $m = 1.007276466579 \pm 0.0000000000083$ u

Mass $m = 938.27208943 \pm 0.00000029$ MeV [a]

n

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass $m = 1.0086649161 \pm 0.0000000004$ u

Mass $m = 939.5654219 \pm 0.0000005$ MeV [a]

Isospin transformation. Nucleon doublet: I=1/2

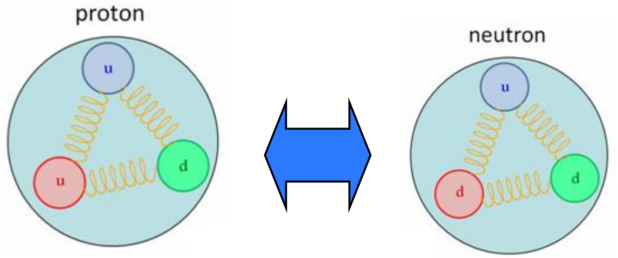
$$\begin{pmatrix} p \\ n \end{pmatrix} \to \hat{O} \begin{pmatrix} p \\ n \end{pmatrix}$$

$\hat{O}$ is a 2×2 unitary matrix. $\hat{O} = e^{i\theta_i \sigma_i/2}$

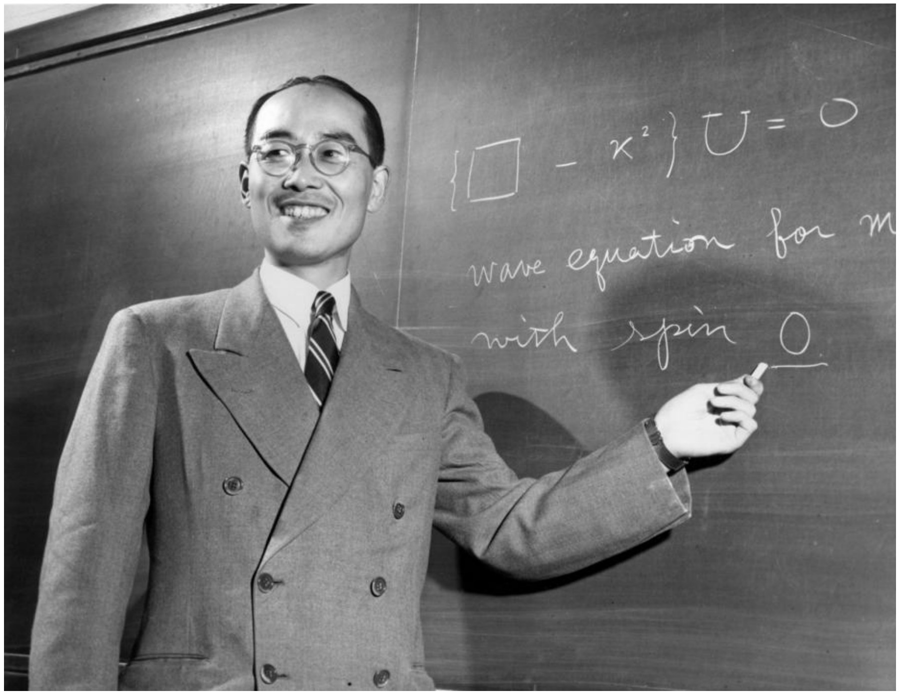
A specific isospin transformation is the so-called charge transformation:

$$\hat{C} = e^{i\pi\sigma_2/2} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Then under $\hat{C}$: $p \Longleftrightarrow n$



Yukawa (1932) and Kemmer (1939): isospin triplet I=1



$$\begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$$

under $\hat{C}$: $\qquad \pi^+ \Longleftrightarrow \pi^-$

PDG masses: pions

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57039 \pm 0.00018$ MeV (S = 1.8)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9768 \pm 0.0005$ MeV (S = 1.1)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.43 \pm 0.13) \times 10^{-17}$ s (S = 1.2)
$c\tau = 25.3$ nm

Kaons form isospin doublets, just as the nucleon

$$\begin{pmatrix} p \\ n \end{pmatrix} \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \begin{pmatrix} -\bar{K}^0 \\ K^- \end{pmatrix} \cdots$$

$$\text{under } \hat{C}:$$

$$\begin{array}{ccc} p & \Longleftrightarrow & n \\ K^+ & \Longleftrightarrow & K^0 \\ \bar{K}^0 & \Longleftrightarrow & K^- \end{array}$$

PDG masses: kaons

$K^{\pm}$

$$I(J^P) = \tfrac{1}{2}(0^-)$$

Mass $m = 493.677 \pm 0.015$ MeV [o] $(S = 2.8)$

Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s $(S = 1.8)$

K^0

$$I(J^P) = \tfrac{1}{2}(0^-)$$

50% K_S, 50% K_L

Mass $m = 497.611 \pm 0.013$ MeV $(S = 1.2)$

$m_{K^0} - m_{K^{\pm}} = 3.934 \pm 0.020$ MeV $(S = 1.6)$

Isospin is an approximate symmetry of QCD

- Mesonic multiplets (nucleon doublet, pion triplet, kaon doublets).
- Reactions: Isospin is well conserved in strong interactions

  Example: (I=Iz=1)

$$p + p \rightarrow \Lambda + K^+ + p$$

- Isospin transformations are a subset of flavor transformations.
- Isospin symmetry is good, but not exact. Masses of u and d not equal (explicit symmetry breaking).

Example of isospin-symmetry breaking decay

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Jana Kochanowskiego w Kielcach

受入
84-4-293
高工研図書室

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/84-27

March 8th, 1984

THE ISOSPIN-VIOLATING DECAY $\eta' \to 3\pi^0$

IHEP[1]-IISN[2]-LAPP[3] Collaboration

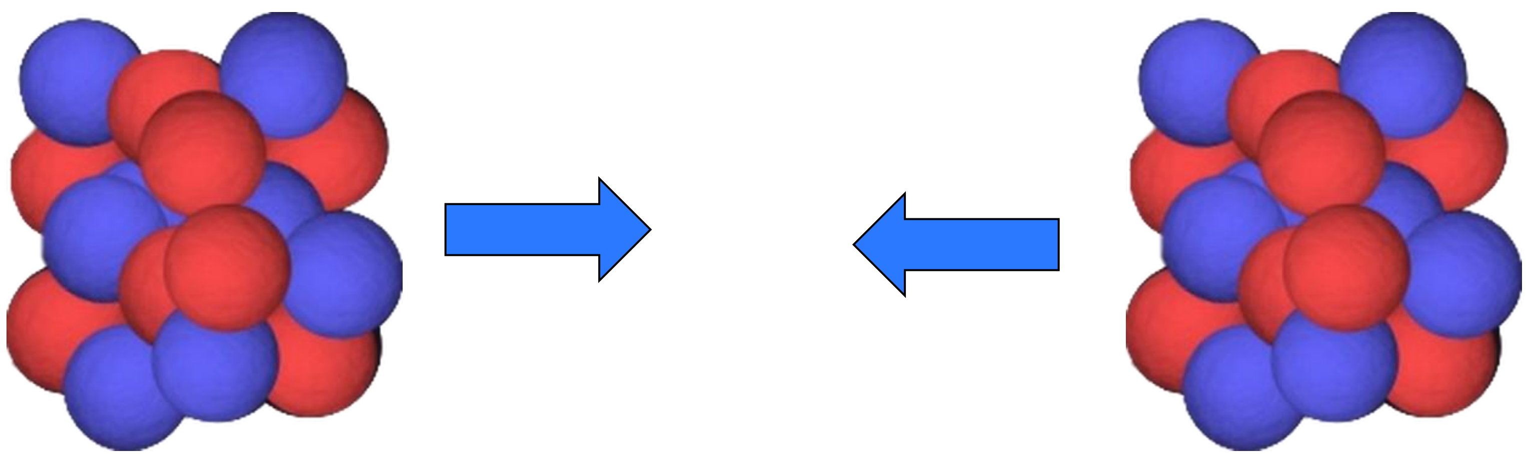
$$BR(\eta' \to 3\pi^0) = 5.2\left(1 - \frac{m_u}{m_d}\right)^2 10^{-3}$$

Isospin-symmetry violation
in nuclear collisions (and beyond)

Nucleus-nucleus collion with equal numbers of protons and neutrons

$$Z = N = A/2 \qquad Q/B = 1/2$$

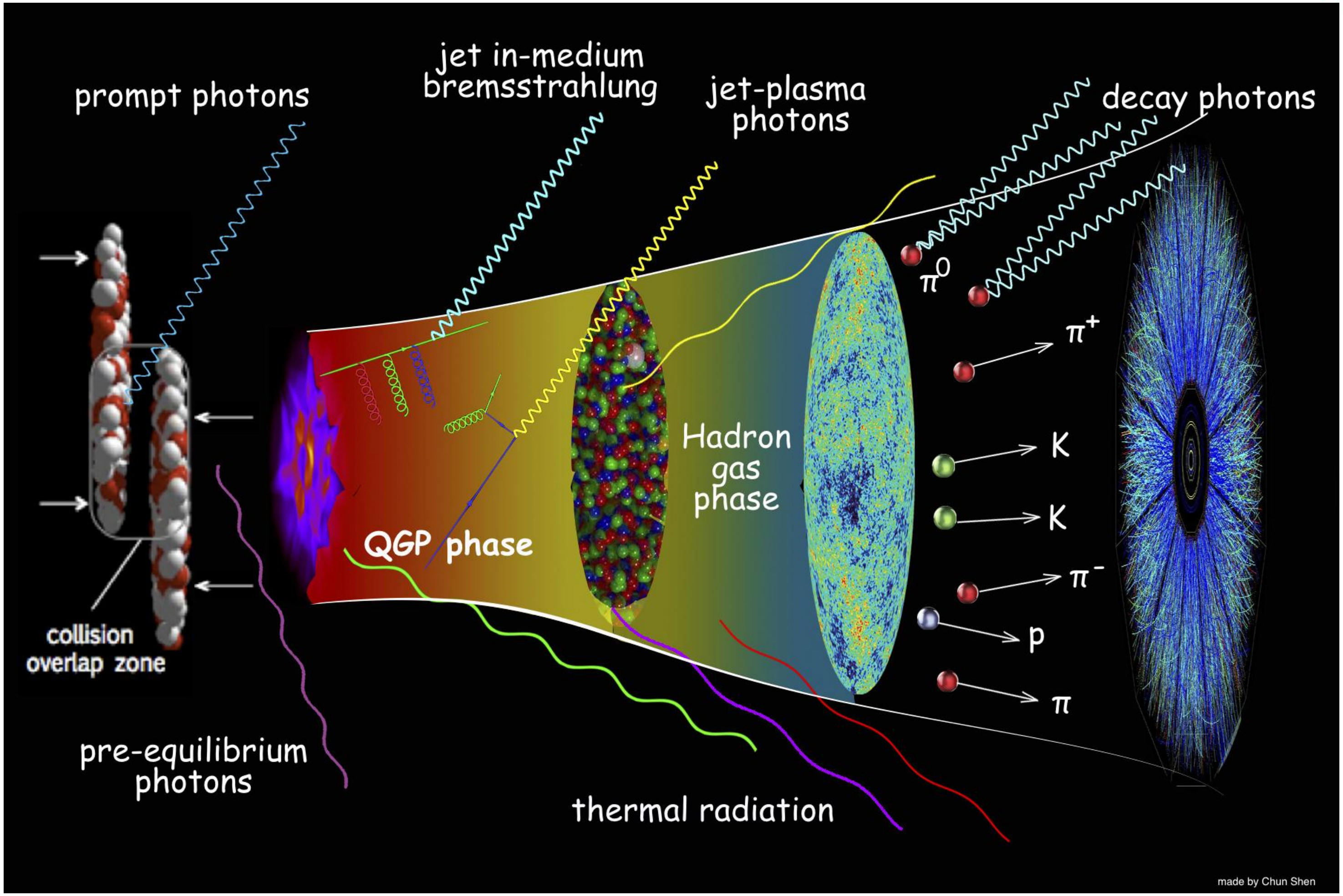
$$|A + A\rangle$$



Oxygen-16 Oxygen-16

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

Heavy-ion collisions



C. Shen, U. Heinz, Nucl. Phys. News 25 (2015) 2, 6-11

At the freeze-out, the emission of hadrons is well described by e.g. thermal models.

Expected kaon multiplicities

For an initial **ensemble** with Q/B=1/2, charge symmetry requires:

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

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

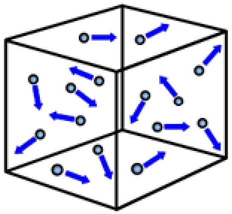
$$R_K \equiv \frac{\langle K^+ \rangle + \langle K^- \rangle}{\langle K^0 \rangle + \langle \bar{K}^0 \rangle} = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2\langle K^0_S \rangle} = 1$$

Well-established theoretical approaches predict R$_K$ close to 1

- HRG (Hadron Resonance Gas) (see e.g., talk of A. Andronic)

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

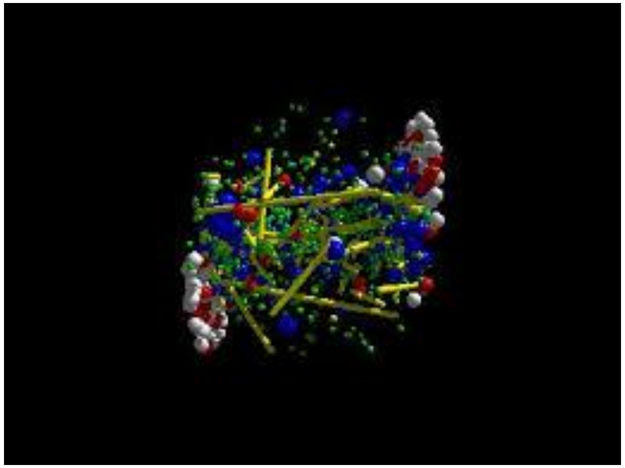
$$\ln Z_k^{\text{stable,}} = f_k V \int \frac{d^3p}{(2\pi)^3} \ln\left[1 \pm e^{-E_p/T}\right]^{\pm 1}$$



- UrQMD

(**U**ltra **r**elativistic **Q**uantum **M**olecular **D**ynamic

Hadron-String transport model, fully integrated Monte Carlo simulation of nucleus-nucleus collisions)



nature communications

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

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Check for updates

The NA61/SHINE Collaboration*, F. Giacosa[1,2], M. Gorenstein[3,4], R. Poberezhniuk[3,4,5] & S. Samanta[6]

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 $\overline{K}^0$) 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 ± 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.

Acta Physica Polonica B **57**, 3-A5 (2026)

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

Wojciech Brylinski

Warsaw University of Technology, Warsaw, Poland

Marek Gazdzicki, Francesco Giacosa†

Jan Kochanowski University, Kielce, Poland

Mark Gorenstein

Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine

Roman Poberezhniuk

University of Houston, Houston, Texas, USA

Subhasis Samanta

Department of Physics, School of Applied Sciences
Kalinga Institute of Industrial Technology, Bhubaneswar, Odisha, India

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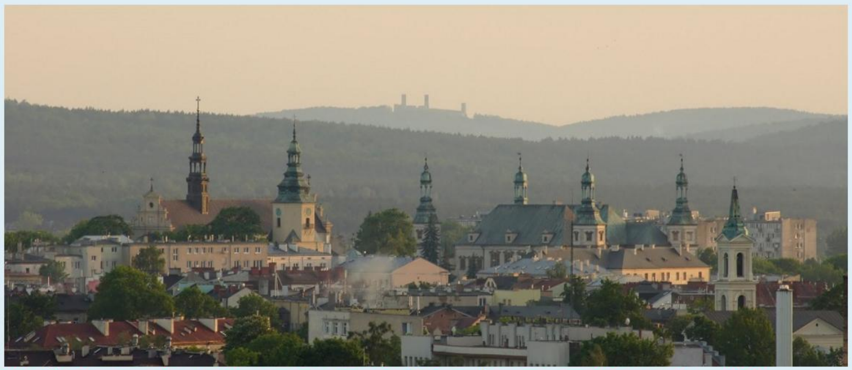
Recently, the NA61/SHINE Collaboration at the CERN SPS reported evidence of isospin-symmetry violation in high-energy nuclear collisions. The effect was observed in the relative yields of charged and neutral kaons and cannot be explained by known sources of isospin-symmetry breaking. In this work, we 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.

DOI:10.5506/APhysPolB.57.3-A5

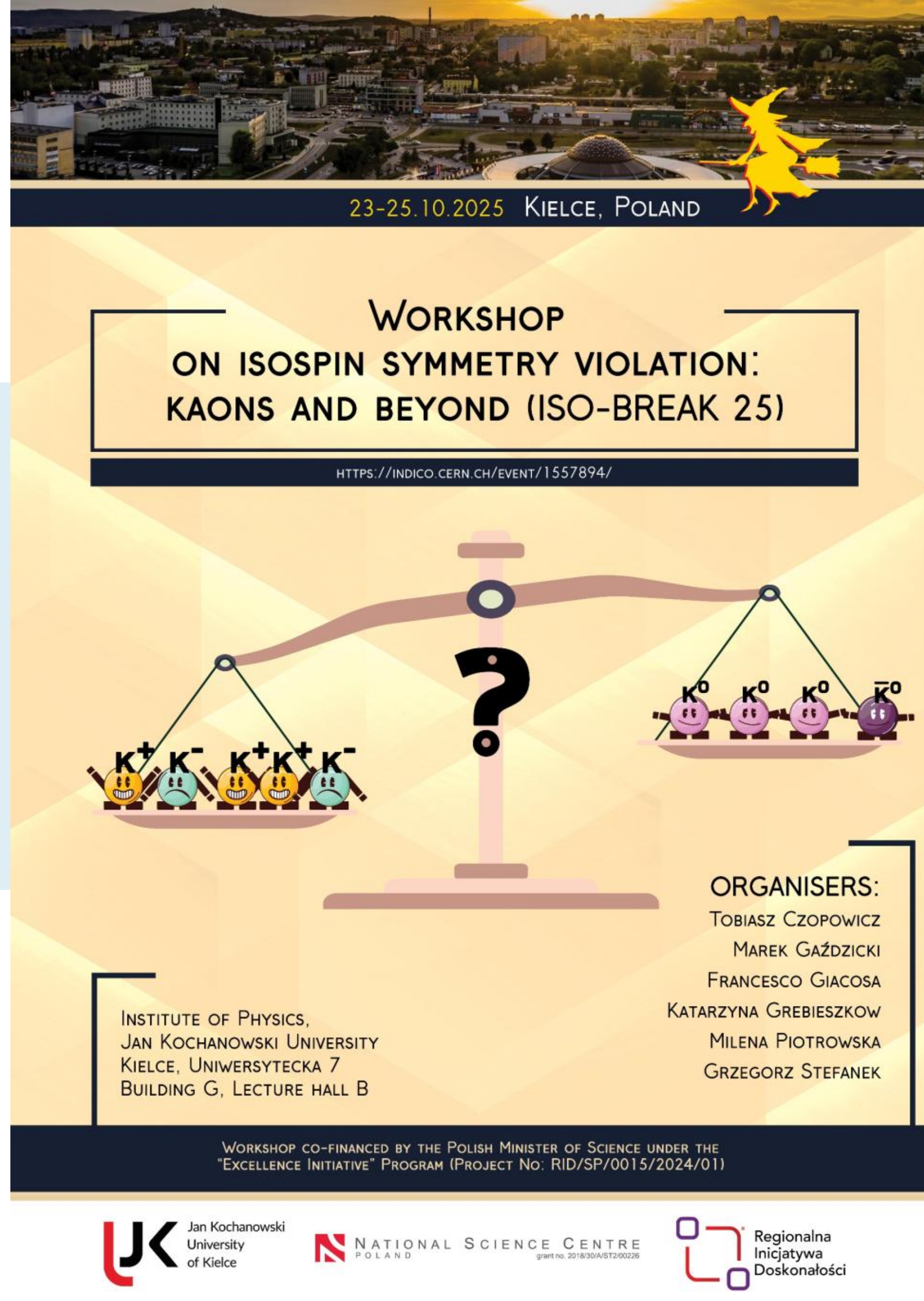
ISO-BREAK 2025

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



White paper: 2604.16005 [nucl-ex]

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Isospin-symmetry violation – kaons and beyond

ISO-BREAK 25: summary and outlook

arXiv:2604.16005v1 [nucl-ex] 17 Apr 2026

Marek Gazdzicki[1] (editor), Francesco Giacosa[1] (editor), Katarzyna Grebieszkow[2] (editor), David Blaschke[3], Marcus Bleicher[4], Bastian Brandt[5], Wojciech Bryliński, Tobiasz Czopowicz[6], Jim Drachenberg[7], Dipangkar Dutta[8], Francesca Ercolessi[9], Mark Gorenstein[10], Linqin Huang[11], Oleksii Ivanytskyi[3], Nicolò Jacazio[12], Joseph Kapusta[13], Seweryn Kowalski[14], Maciej Piotr Lewicki[15], Manuel Lorenz[16], Stanisław Mrówczyński[6], Vitalii Ozvenchuk[15], Oleksandra Panova[1], Roman Płaneta[17], Krzysztof Piasecki[18], Milena Piotrowska[1], Rob Pisarski[19], Damian Pszczel[6], Johann Rafelski[20], Martin Rohrmoser[1], Andrzej Rybicki[15], Maciej Rybczyński[1], Radoslaw Ryblewski[15], Subhasis Samanta[21], Mayank Singh[22], Joanna Maria Stepaniak[6], Grzegorz Stefanek[1], Herbert Ströbele[4], Tatjana Šuša[23], Leonardo Tinti[1], Ludwik Turko[3], Oleksandr Vitiuk[3], Klaus Werner[24], Hanna Zbroszczyk[2]

[1] Jan Kochanowski University, Kielce, Poland

[2] Warsaw University of Technology, Warsaw, Poland

[3] University of Wroclaw, Poland

[4] Goethe University, Frankfurt am Main, Germany

[5] University of Bielefeld, Germany

[6] National Centre for Nuclear Research, Warsaw, Poland

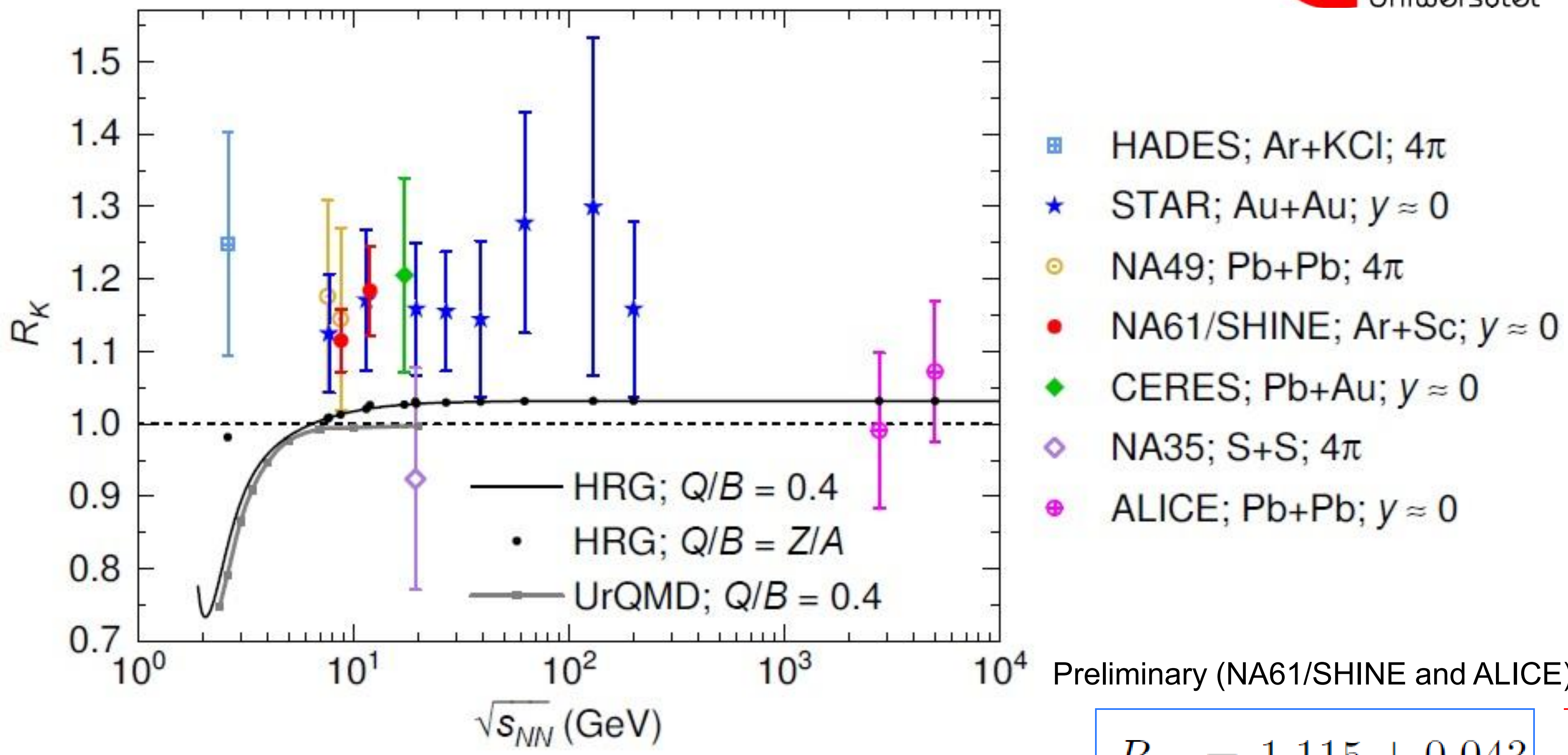
[7] Abilene Christian University, USA

[8] Mississippi State University, USA

[9] Università e INFN, Bologna, Italy

[10] Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine

Experimental results (NA61/SHINE plus others)



Preliminary (NA61/SHINE and ALICE)

$$R_K = 1.115 \pm 0.043$$

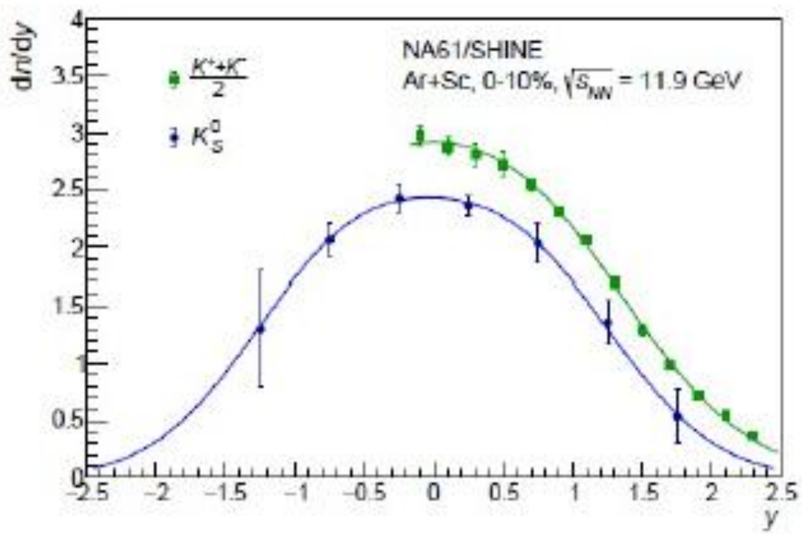
$$R_K = 1.07 \pm 0.09$$

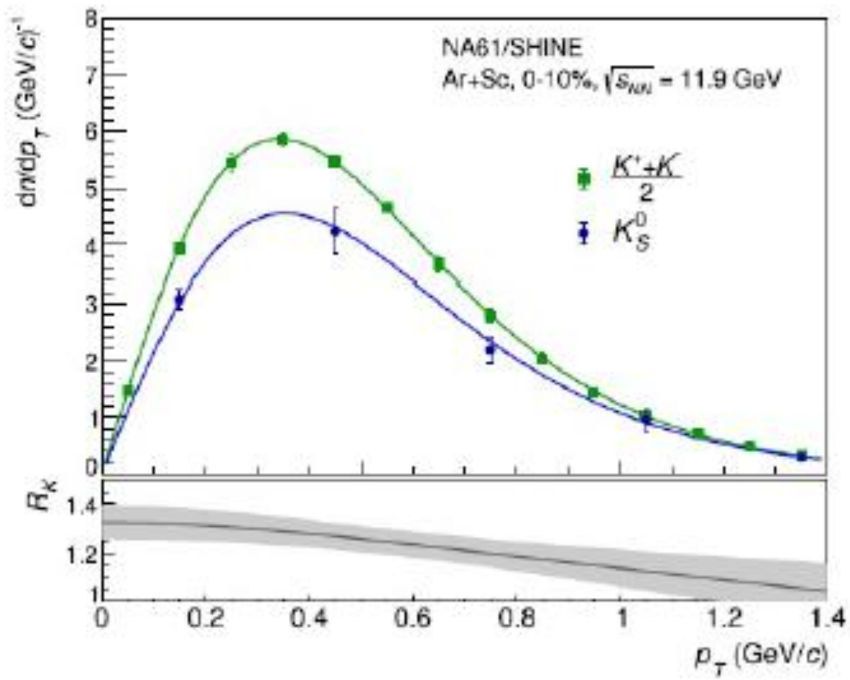
$$R_K = 1.184 \pm 0.061$$

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

NA61/SHINE results as function of y and pT

$$R_K = 1.184 \pm 0.061$$





Nat.comm.16 (2025) 12849

Experiment vs theory (HRG): ratio

$$1.129 \pm 0.027.$$

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

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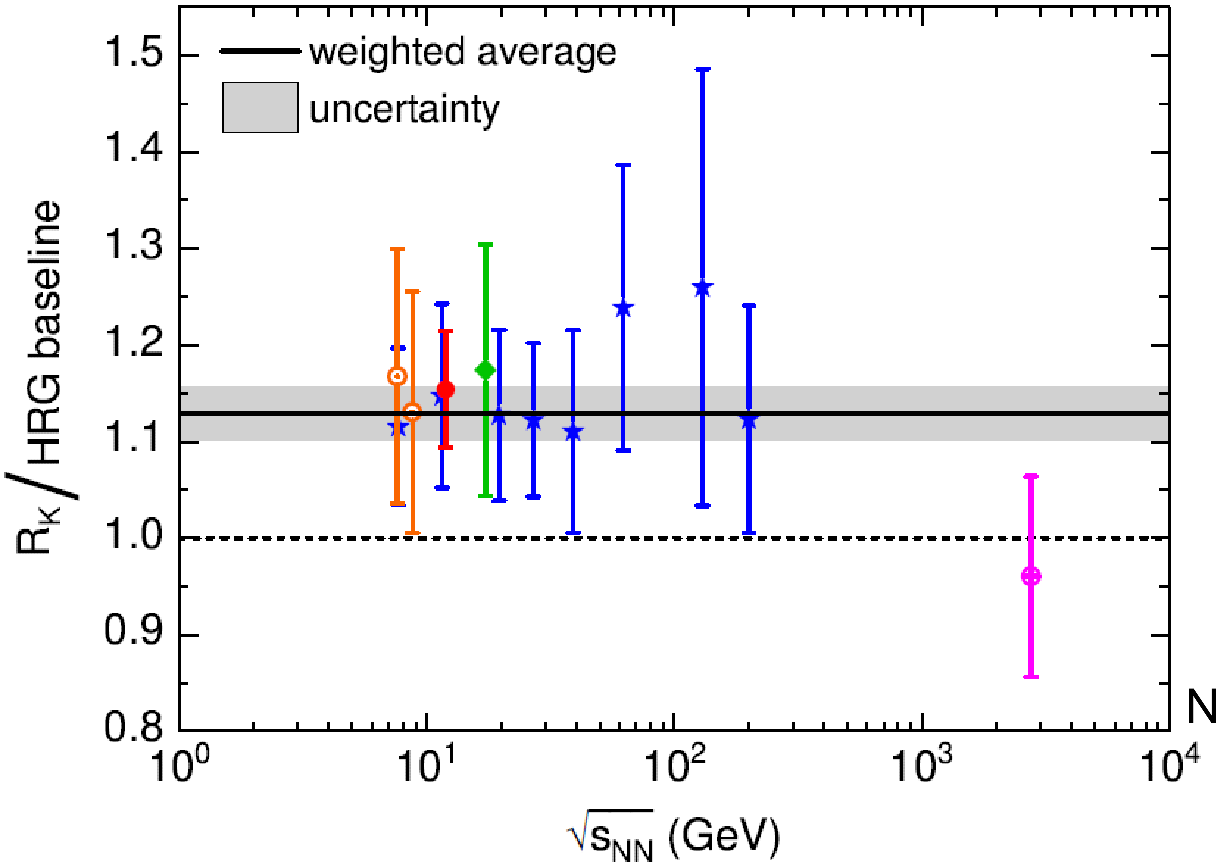

Nat.comm.16 (2025) 12849

The exp/th missmatch is 4.7σ (and reaches 5σ with new data)

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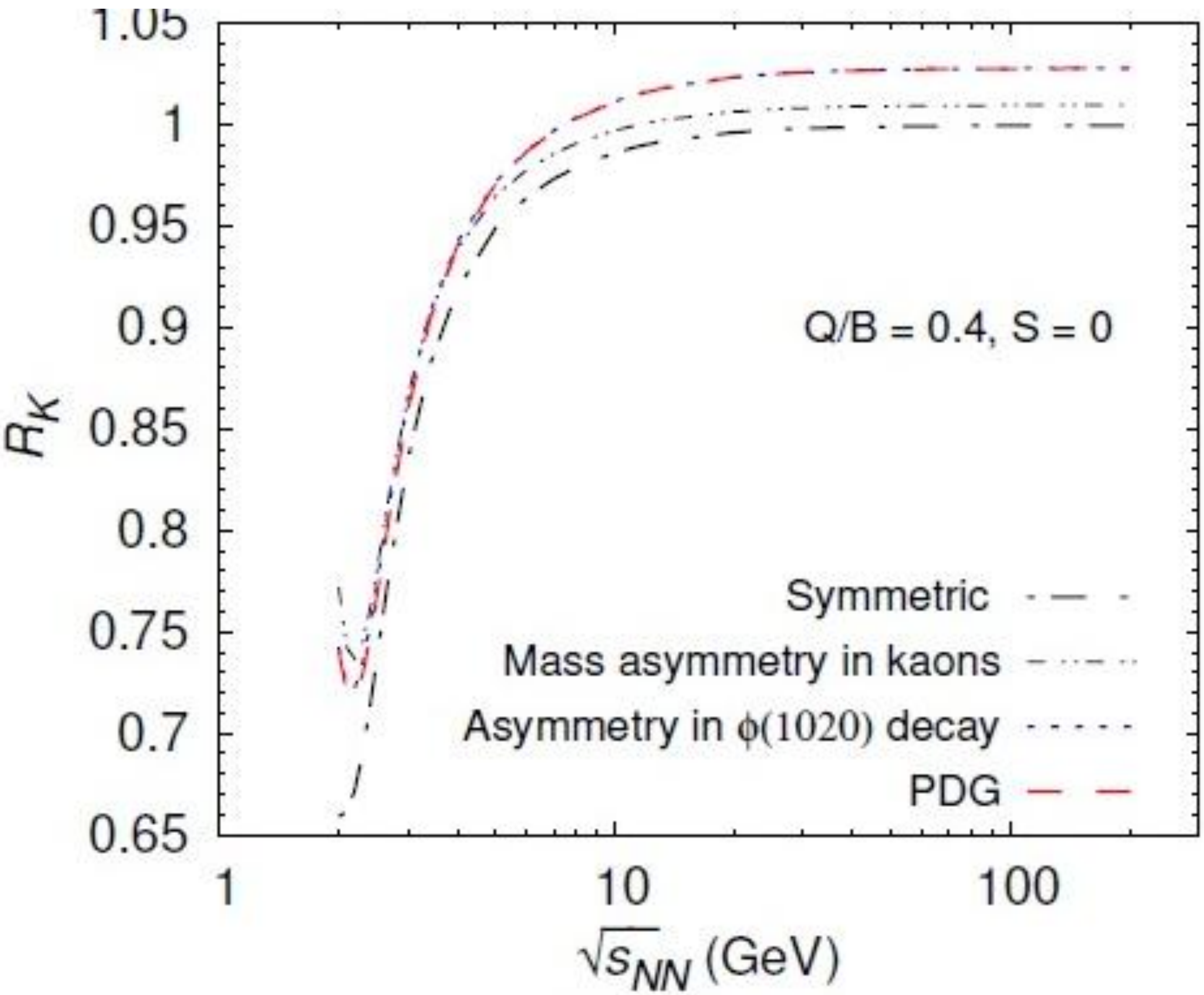
RK in HRG for Q/B=0.4



Acta Phys.Polon.B 57 (2026) 3, 3-A5

More on the resonance ϕ(1020)

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$\phi(1020)$ $I^G(J^{PC}) = 0^-(1^{--})$

ϕ(1020) MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1019.461±0.016 OUR AVERAGE				

ϕ(1020) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
4.249±0.013 OUR AVERAGE	Error includes scale factor of 1.1.			

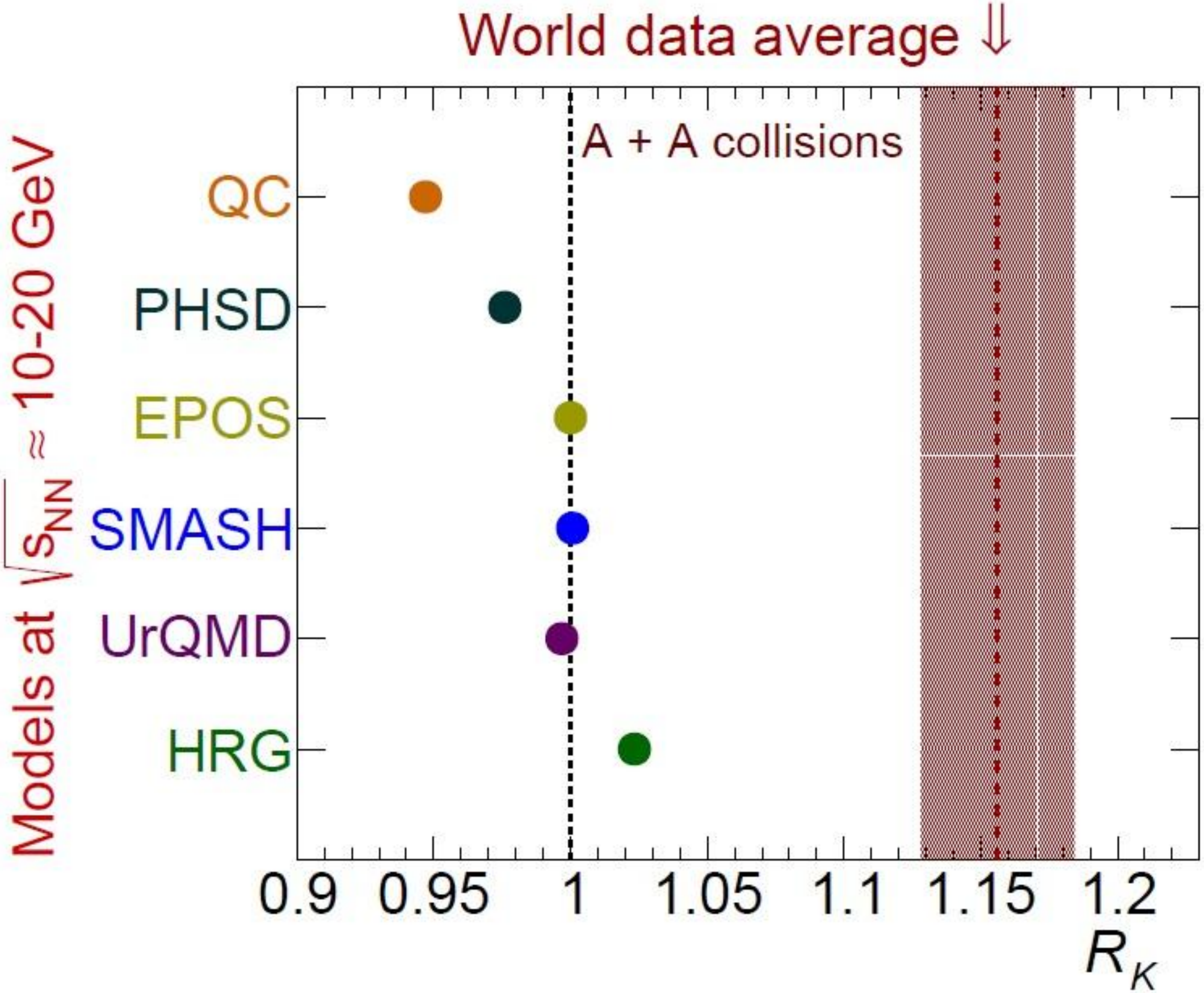
ϕ(1020) DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.1 ±0.5) %	S=1.3
Γ_2	$K^0_L K^0_S$	(33.9 ±0.4) %	S=1.2
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	(15.4 ±0.4) %	S=1.2

$$\frac{\Gamma_{K^+K^-}}{\Gamma_{K^0\bar{K}^0}} = \frac{g^2_{K^+K^-}}{g^2_{K^0\bar{K}^0}} \frac{\left(\frac{m_\phi^2}{4} - m^2_{K^+}\right)^{3/2}}{\left(\frac{m_\phi^2}{4} - m^2_{K^0}\right)^{3/2}} = \frac{g^2_{K^+K^-}}{g^2_{K^0\bar{K}^0}} 1.52 \stackrel{\text{PDG}}{=} 1.45 \pm 0.03$$

$$\frac{g_{K^+K^-}}{g_{K^0\bar{K}^0}} = 0.98 \pm 0.01$$

Not only HRG and UrQMD: more models



2604.16005

White paper: three possibilities

(i) The experimental data are incorrect (central values and/or their uncertainties).

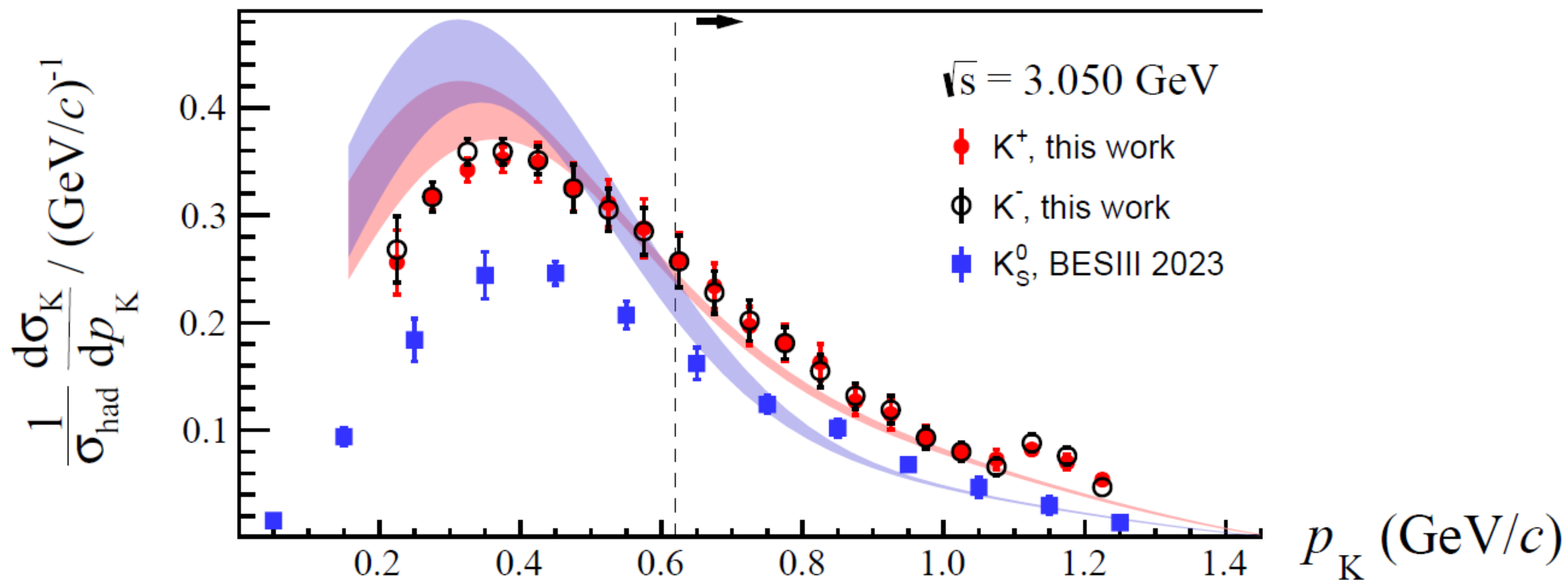
(ii) The models are incorrect.

(iii) Data and models are incorrect.

2604.16005

Not only nuclear collisions: BESIII results

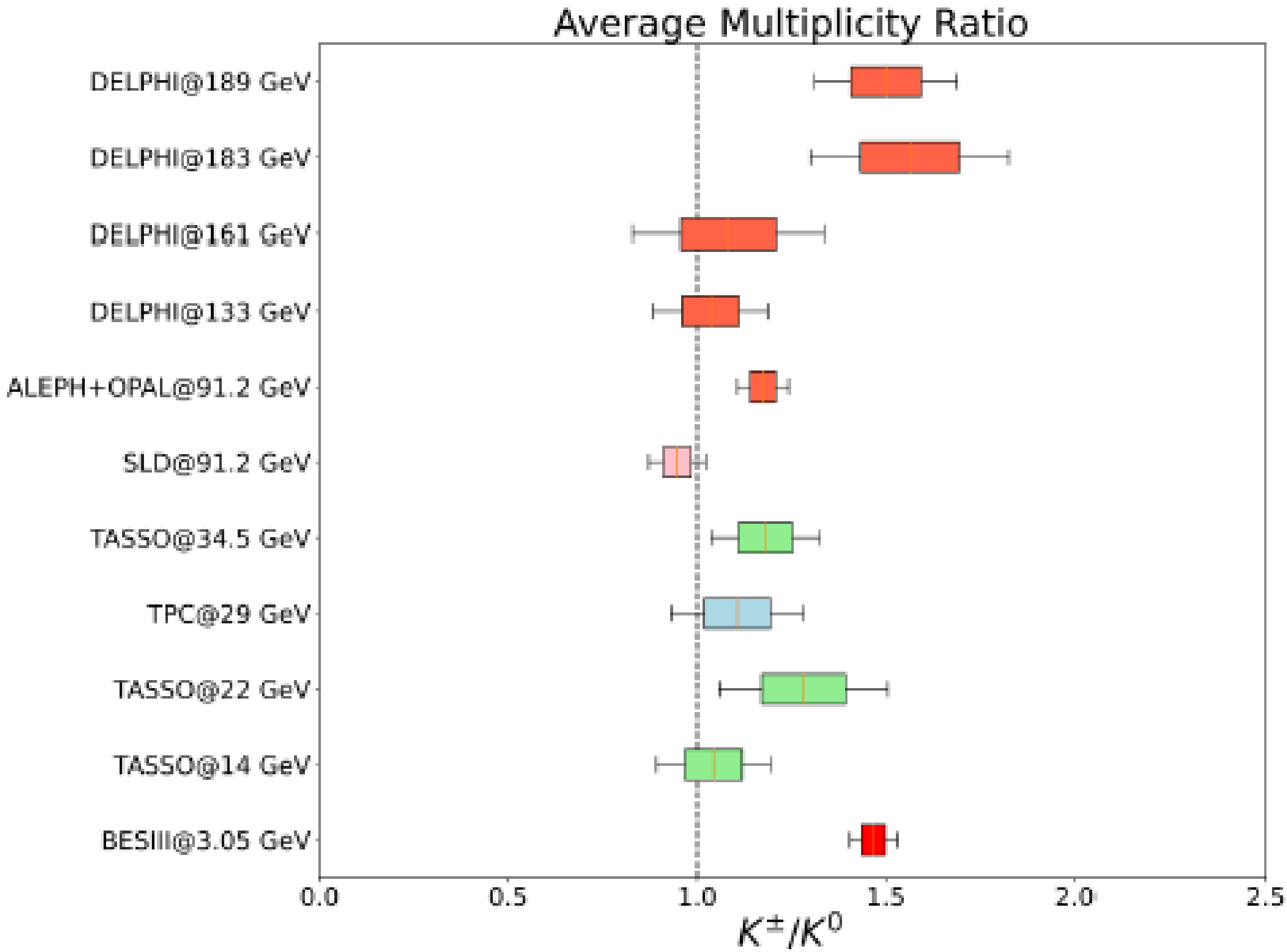
$$e^+ + e^- \to K + X$$



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

Charged kaon excess or not?

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



Average Multiplicity Ratio
DELPHI@189 GeV
DELPHI@183 GeV
DELPHI@161 GeV
DELPHI@133 GeV
ALEPH+OPAL@91.2 GeV
SLD@91.2 GeV
TASSO@34.5 GeV
TPC@29 GeV
TASSO@22 GeV
TASSO@14 GeV
BESIII@3.05 GeV
0.0
0.5
1.0
1.5
2.0
2.5
$K^{\pm}/K^0$

e^-+D inelastic scattering

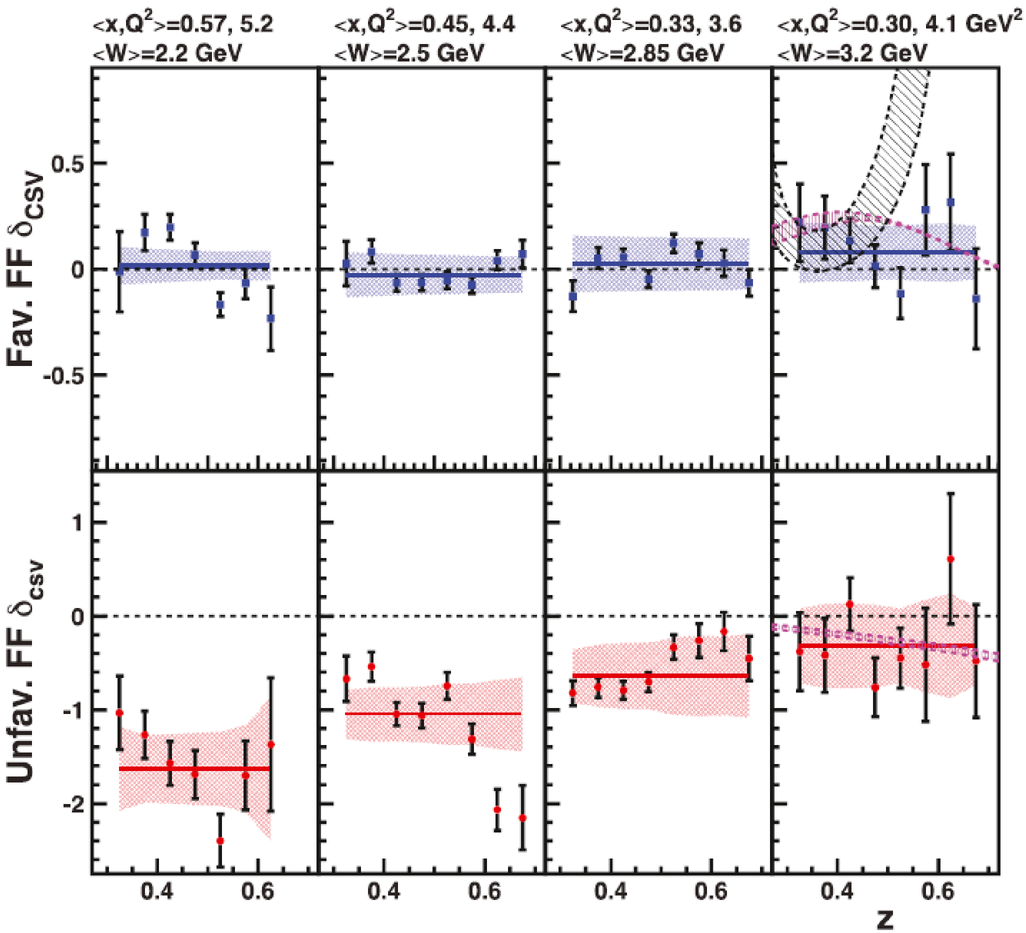


Fig. 4. The z dependence of the CS/IS violating parameter δ_{CSV} for the favored FF (top panels) and unfavored FF (bottom panels). From left to right, the panels are ordered in decreasing values of x (increasing W). The blue (red) solid lines are constant value fits to δ_{CSV}. The shaded bands are the systematic uncertainty. The black dashed lines are expectations assuming CS ($\delta_{CSV} = 0$). In the last panels, the magenta band with vertical hatching is the δ_{CSV} and its uncertainty from Peng and Ma [25], while the black band with angled hatching is from the MAP collaboration [46].

Phys. Lett. B 865 (2025) 139485

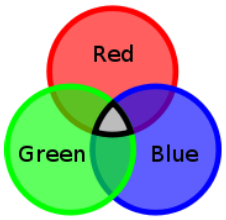
H. Bhatt et al (Dutta as c.a.), Flavor dependence of charged pion fragmentation functions

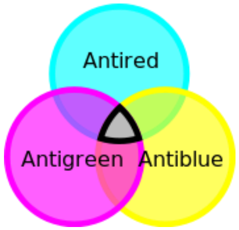
Step back:

Isospin symmetry from QCD

The QCD Lagrangian

Quark: u,d,s and c,b,t R,G,B



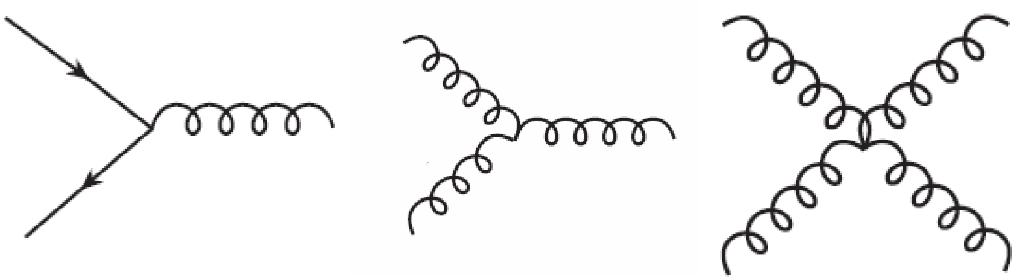


$$q_i = \begin{pmatrix} q_i^R \\ q_i^G \\ q_i^B \end{pmatrix}; \; i = u,d,s,...$$

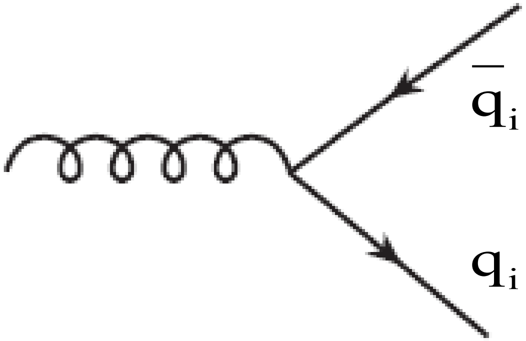
$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$

8 type of gluons (R$\bar{G}$,B$\bar{G}$,…)

$$A_\mu^a \; ; \; a = 1,...,8$$



Flavor symmetry



Gluon-quark-antiquark vertex

It is democratic! The gluon couples to each flavor with the same strength

$$q_i \rightarrow U_{ij} q_j$$

$$\mathrm{U} \in \mathrm{U}(3)_{\mathrm{V}} \rightarrow \mathrm{U}^{+}\mathrm{U} = 1$$

When U(2)v is considered (Nf =2): quark-level isospin symmetry

Is it that so simple?

Masses of u and are not equal (PDG):

$$m_u = 2.16 \pm 0.07 \text{ MeV and } m_d = 4.70 \pm 0.07 \text{ MeV}$$

$$m_u/m_d = 0.462 \pm 0.020$$

Ratio is far from unity!

Why do we have isospin symmetry at the hadronic level?

Why isospin works/1 generic hadronic multiplet

Constituent quark models, NJL model, BS eqs, …

$$m_u^* \simeq m_d^* \sim \Lambda_{QCD} \sim 250 \text{ MeV}$$

$$m_d^* - m_u^* \propto m_d - m_u$$

$$(m_{\rho^+} - m_{\rho^0}) = -0.7 \pm 0.8 \text{ MeV}$$

$$m_{u,d} \ll \Lambda_{QCD}$$

Answer 1: the QCD scale Λ_{QCD} protects isospin symmetry.

Why isospin works/2: kaon masses

$$m_{K^-}^2 = m_{K^+}^2 \propto (m_u + m_s)$$

$$m_{\bar{K}^0}^2 = m_{K^0}^2 \propto (m_d + m_s)$$

$$\frac{m_{K^+}}{m_{K^0}} = \sqrt{\frac{m_u + m_s}{m_d + m_s}} = 0.9870 \pm 0.067 \; ,$$

$$\text{experimental value } 0.99209 \pm 0.00004.$$

$$m_{u,d} \ll m_s \sim \Lambda_{QCD}$$

Answer 2: the s-quark mass protects the isospin symmetry.

Why isospin works/3 isoscalar-pseudoscalar

$$m_{\pi^0}^2 \propto (m_u + m_d)$$

$$m_{\eta_N}^2 \propto (m_u + m_d) + 2c_A$$

$$m_{\eta_S}^2 \propto m_s + c_A$$

In Nature: decoupling of the pion from the two η .
If cA=0, the pion would mix with ηN and would get a mass of roughly 70 MeV.
We would not have an isospin triplet.

Gross, D.J., Treiman, S.B., Wilczek, F. Light Quark Masses and Isospin Violation
Phys. Rev. D 19, 2188 (1979)
Pisarski, R.D., Wilczek, F. Remarks on the Chiral Phase Transition in Chromodynamics.
Phys. Rev. D 29, 338–341 (1984)

Answer 3: the chiral anomaly protects isospin symmetry.

Description of $R_K > 1$ within models

Phys. Lett. B 873 (2026) 140170

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journal homepage: www.elsevier.com/locate/physletb

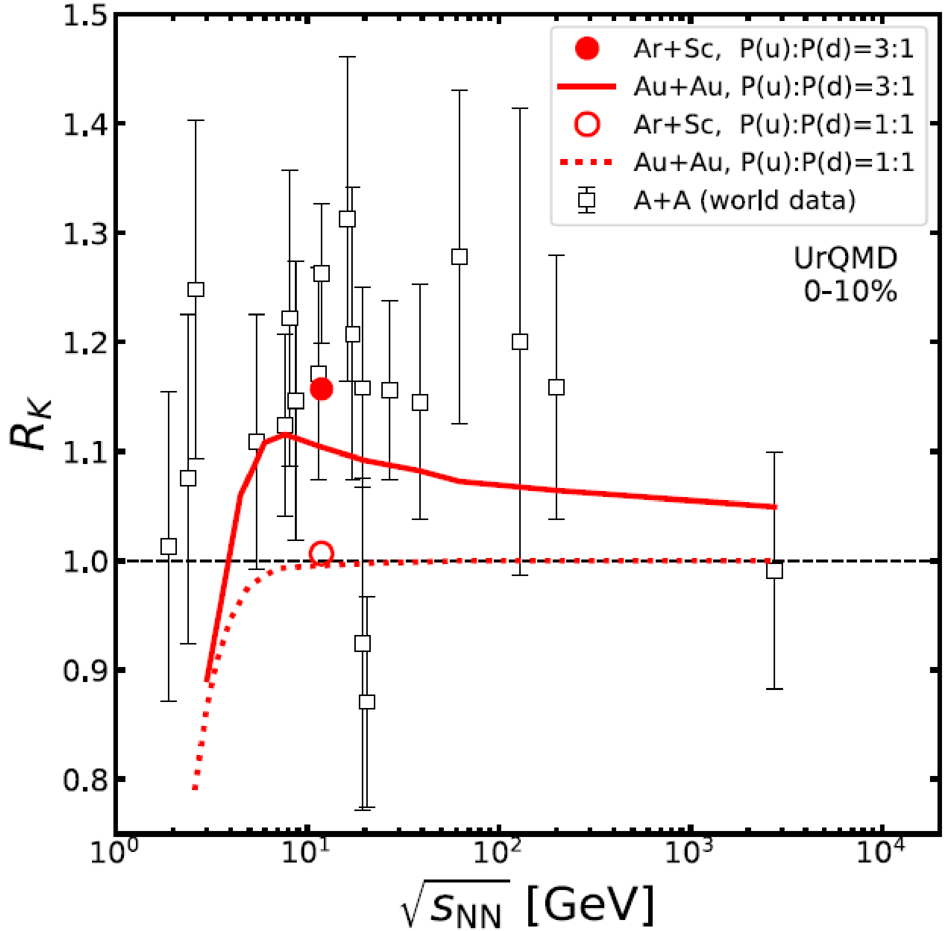
Letter

Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions

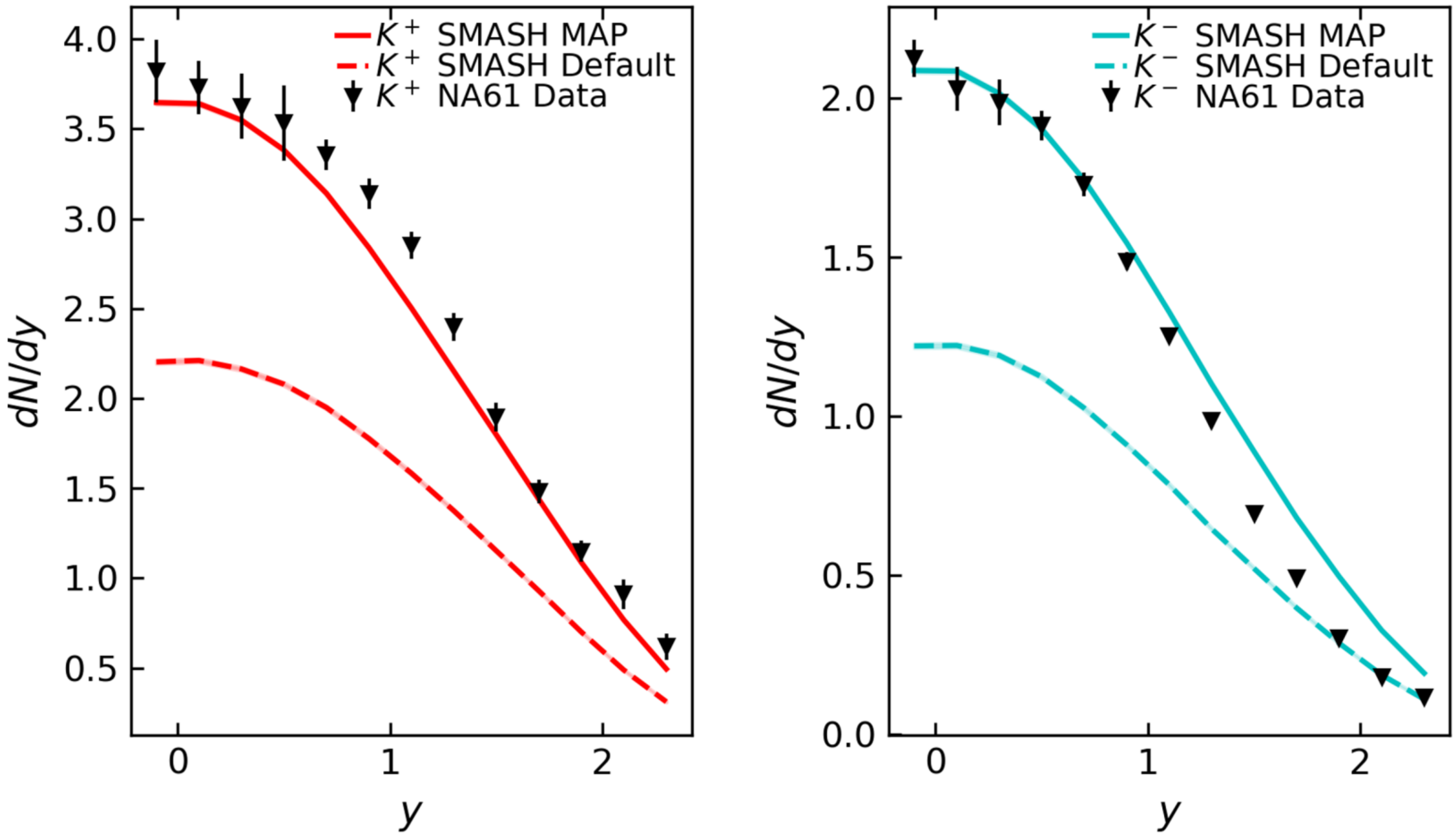
Tom Reichert [a,b,c,d,*], Jan Steinheimer [e,b], Marcus Bleicher [a,c]

UrQMD with string with:

$$P(u\overline{u})/P(d\overline{d}) = 3$$



SMASH+PYTHIA with $P(u\bar{u})/P(d\bar{d}) = 1.89$



Oleskandr Vitiuk, NA61/SHINE and Wroclaw U; see also ISO-BREAK 25 talk

Quark Coalescence (QC) model

$$n_u = n_u^{val}$$

$$n_d = n_d^{val}$$

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

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

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

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

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

Quark Coalescence (QC) 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.

Kaon probabilities

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

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Isospin kaon anomaly and its consequences

Francesco Giacosa, Martin Rohrmoser[a]
Institute of Physics, Jan Kochanowski University, ul. Uniwersytecka 7, Kielce, Poland

2504.02113

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

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

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

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

Uniwersytet Jana Kochanowskiego w Kielcach

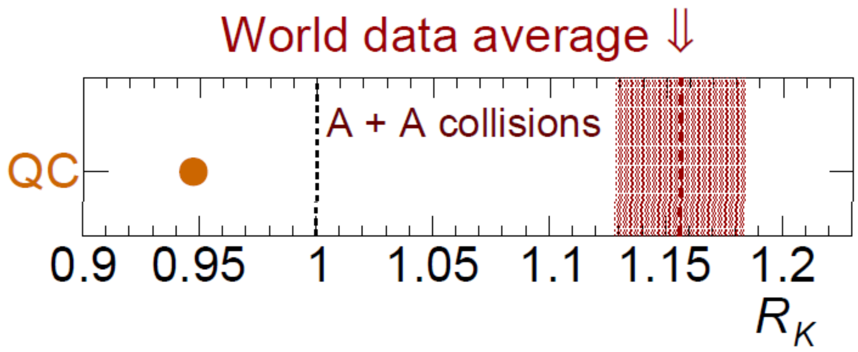
Simple algebra leads to:

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

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

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

$R_K < 1$ for $n_u < n_d$



In Exp Q/B <1. From Rκ to Rtildeκ

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

2504.02113

isospin-conserved

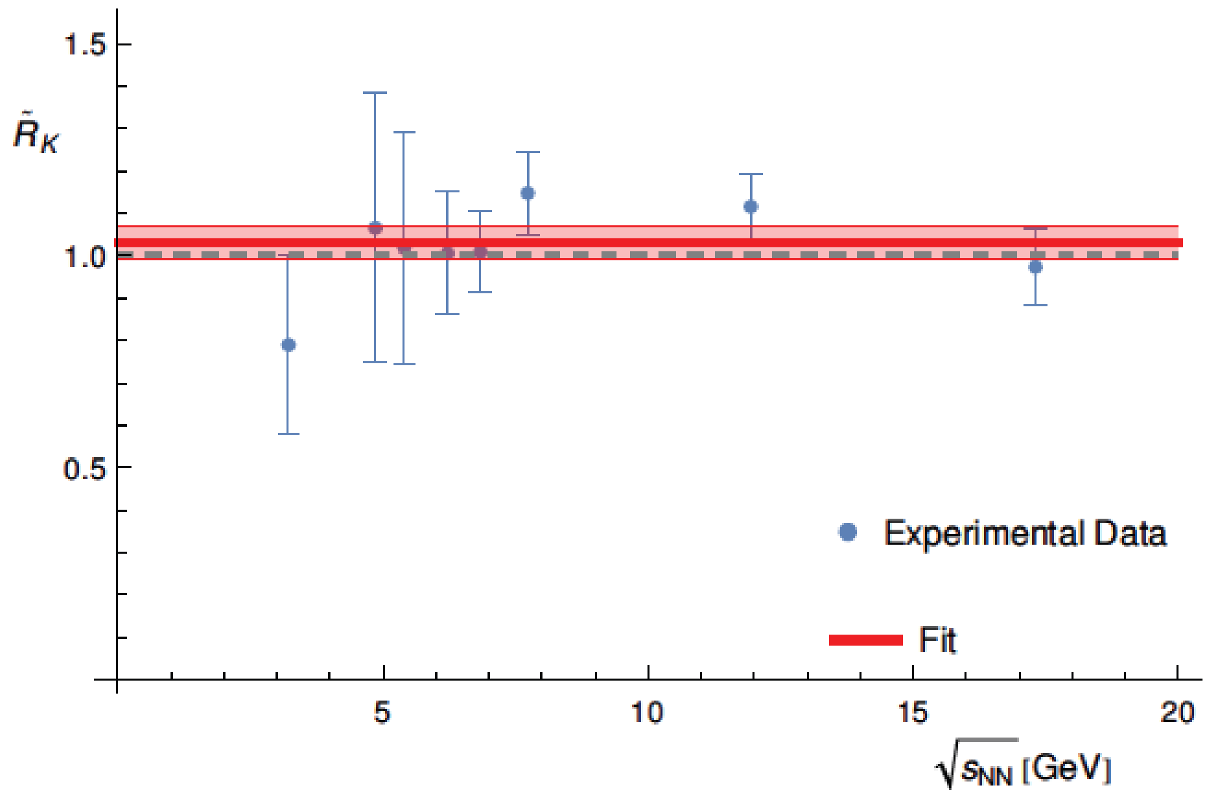
$$\alpha = \beta \Rightarrow \tilde{R}_K = 1$$

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
2305.03872

Proton-proton results: isospin-symmetry ok



$$\alpha = \beta$$

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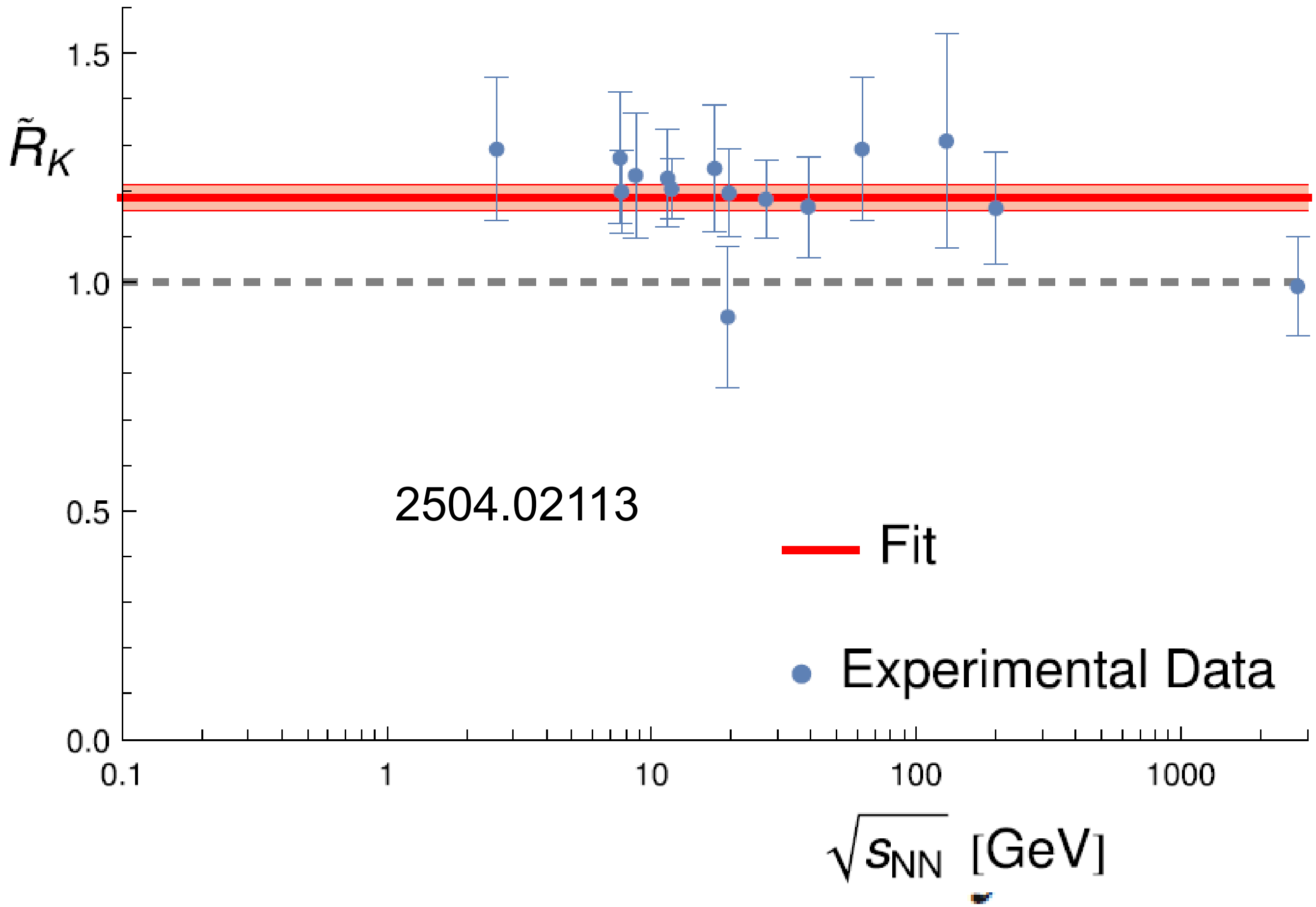
See also: 2305.03872

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

Nucleus-nucleus collions



$$\tilde{R}_K \approx r = 1.185 \pm 0.029.$$

$r = \alpha/\beta$ is the u/d-ratio of quarks produced

QC predictions/1

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^-	$r^2 = 1.404 \pm 0.068$

2504.02113

QC predictions/2

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

2504.02113

Pion-nucleus scattering antiquarks in the initial state

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

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

This is the case for pion-carbon.
(In fact for π+C: n_u = 18+1, n_ubar =0, n_d =18, n_bbar = 1)

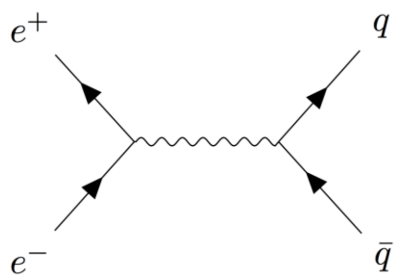
But isospin-symmetry is broken.
Hence our predcition for pion-carbon:

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

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

Quark Coalescence model: in e+-e-: preliminary result

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



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

Flavor-symmetry limit:

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

$R_K > 1$

Is there indeed an excess of charged kaons in e+-e- collisions?
Quantitative study needed

Discussion

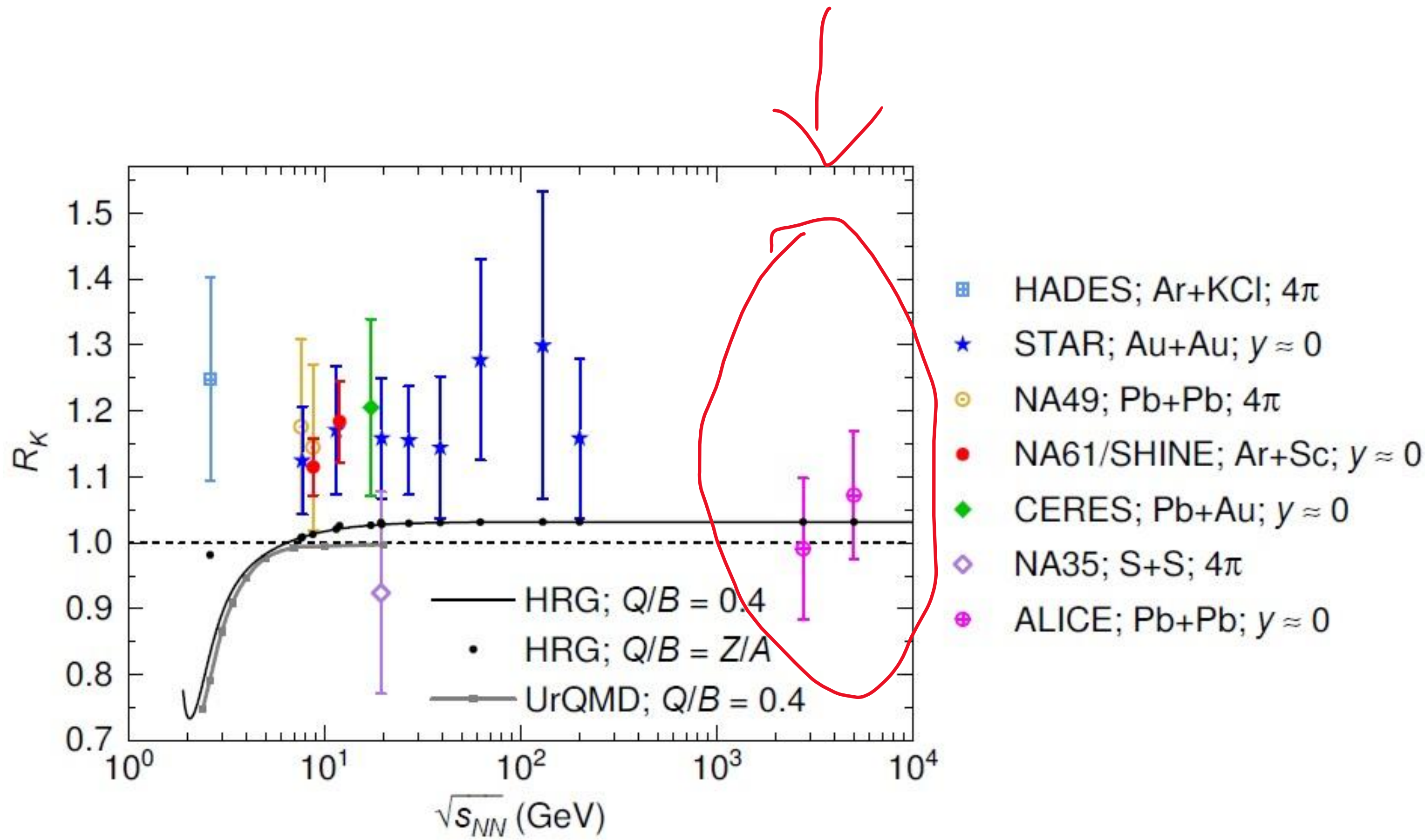
Some brainstorming of the ISO-BREAK 25 paper

2604.16005

Finite-density effect?

Is ALICE result special?

Almost zero baryonic chemical potential



Q/B < 1/2, more uubar than ddbar (Pauli)

Asymmetry of quark pairs in proton

Article

The asymmetry of antimatter in the proton

https://doi.org/10.1038/s41586-021-03282-z
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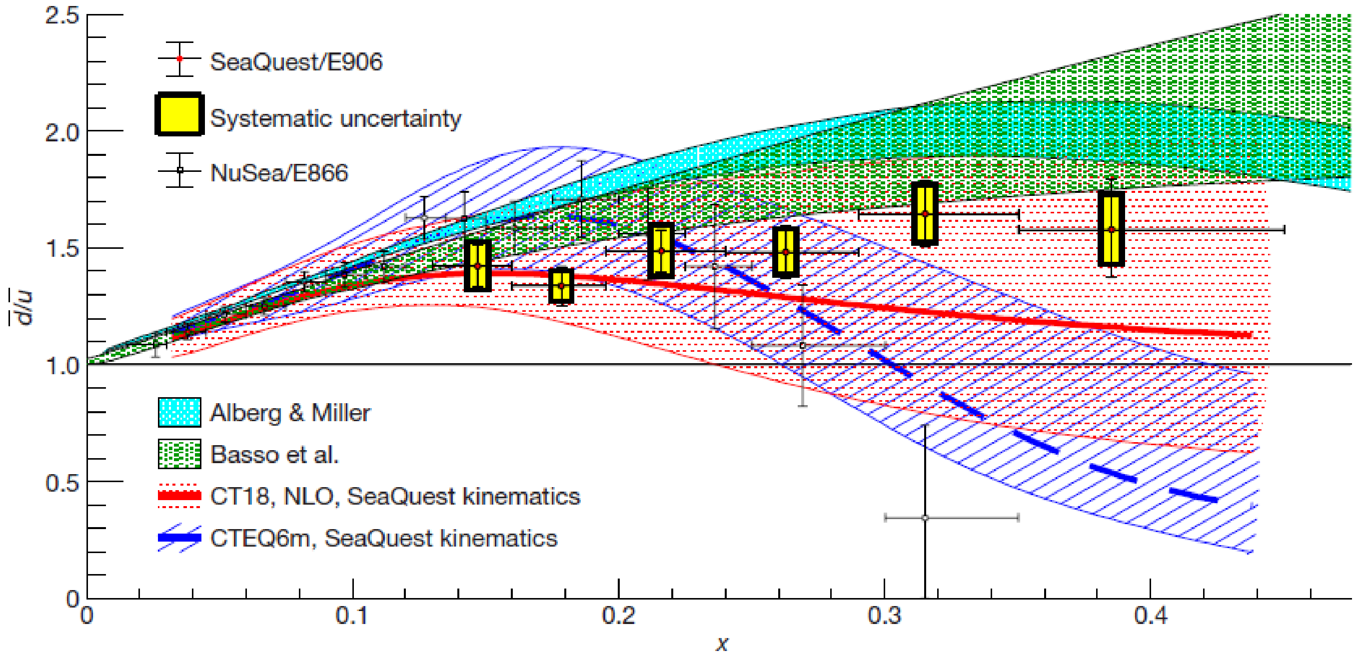
Published online: 24 February 2021
Check for updates

J. Dove[1], B. Kerns[1], R. E. McClellan[1,18], S. Miyasaka[2], D. H. Morton[3], K. Nagai[2,4], S. Prasad[1], F. Sanftl[2], M. B. C. Scott[3], A. S. Tadepalli[5,18], C. A. Aidala[3,6], J. Arrington[7,19], C. Ayuso[3,20], C. L. Barker[8], C. N. Brown[9], W. C. Chang[4], A. Chen[1,3,4], D. C. Christian[10], B. P. Dannowitz[1], M. Daugherity[8], M. Diefenthaler[1,18], L. El Fassi[5,11], D. F. Geesaman[7,21], R. Gilman[5], Y. Goto[12], L. Guo[6,22], R. Guo[13], T. J. Hague[8], R. J. Holt[7,23], D. Isenhower[8], E. R. Kinney[14], N. Kitts[8], A. Klein[6], D. W. Kleinjan[6], Y. Kudo[15], C. Leung[1], P.-J. Lin[14], K. Liu[6], M. X. Liu[6], W. Lorenzon[3], N. C. R. Makins[1], M. Mesquita de Medeiros[7], P. L. McGaughey[6], Y. Miyachi[15], I. Mooney[3,24], K. Nakahara[16,25], K. Nakano[2,12], S. Nara[15], J.-C. Peng[1], A. J. Puckett[6,26], B. J. Ramson[3,27], P. E. Reimer[7]✉, J. G. Rubin[3,7], S. Sawada[17], T. Sawada[3,28], T.-A. Shibata[2,29], D. Su[4], M. Teo[1,30], B. G. Tice[7], R. S. Towell[8], S. Uemura[6,31], S. Watson[8], S. G. Wang[4,13,32], A. B. Wickes[6], J. Wu[10], Z. Xi[8] & Z. Ye[7]



Q/B effective

Is Q/B_effective (for interacting nucleons) equal to the nominal Q/B?

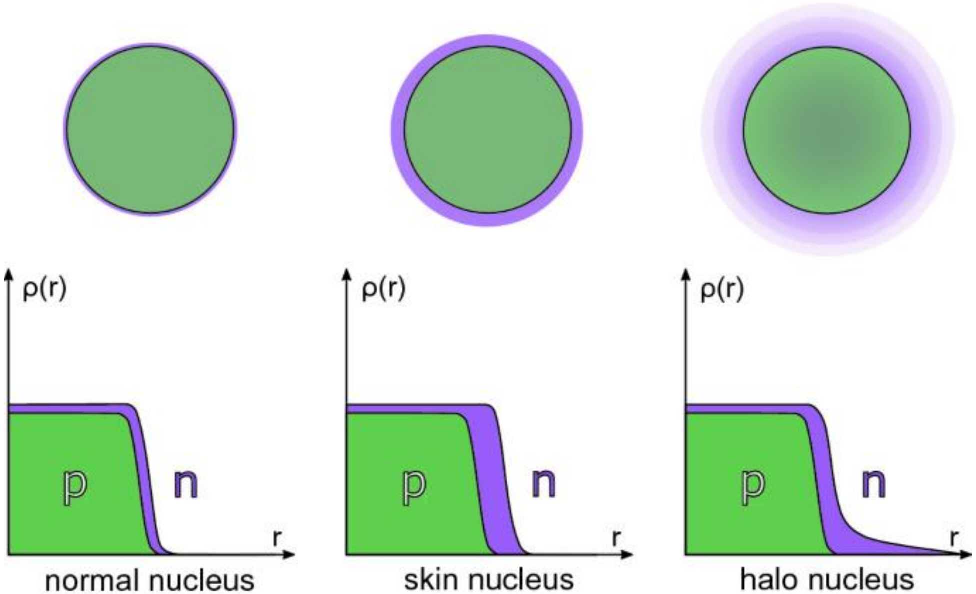
Large nuclei have more neutrons than protons.

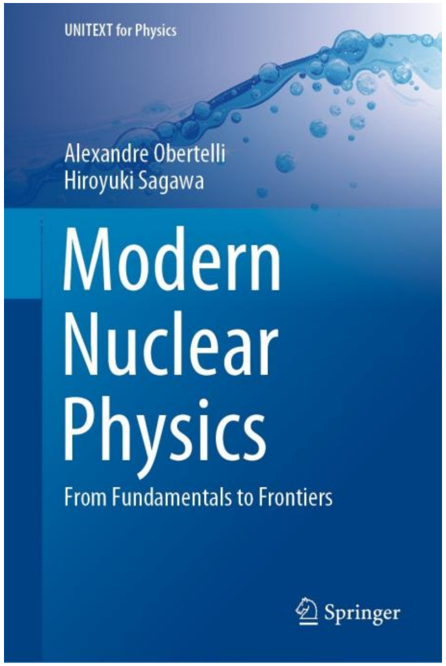
In general, inhomogeneous distribution (neutron skin).

Small nuclei with Q/B=1/2 can be understood as alpha clusters, hence a homogeneous distribution is applicable.

The charge-symmetry argument leading to $R_K=1$ is transparent.

Neutron skin

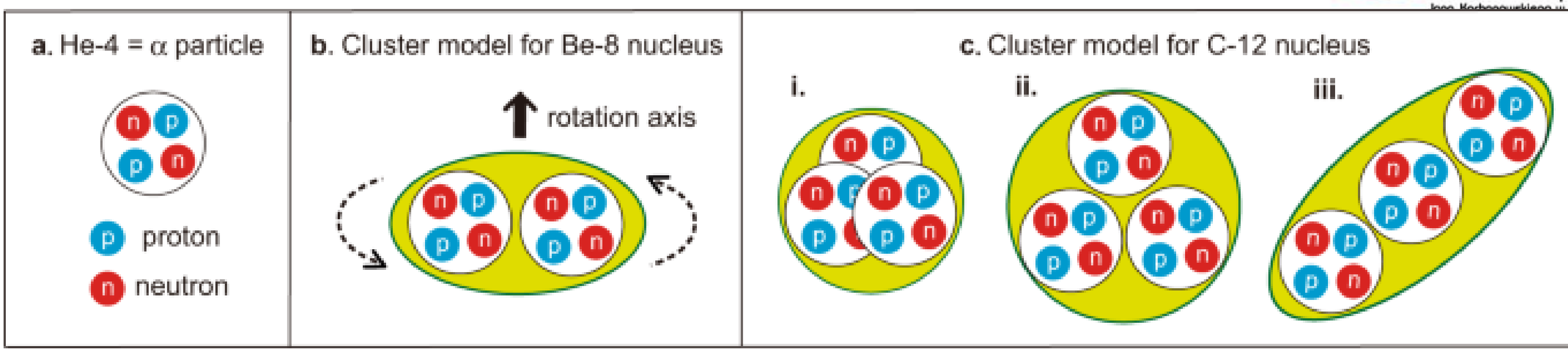




Chapter 6

See also: S. J. Novario, D. Lonardoni, S. Gandolfi and G. Hagen, Trends of Neutron Skins and Radii of Mirror Nuclei from First Principles, PRL 130 (2023) no.3, 032501[arXiv:2111.12775 [nucl-th]].

Clusters of alpha particles




ARTICLE

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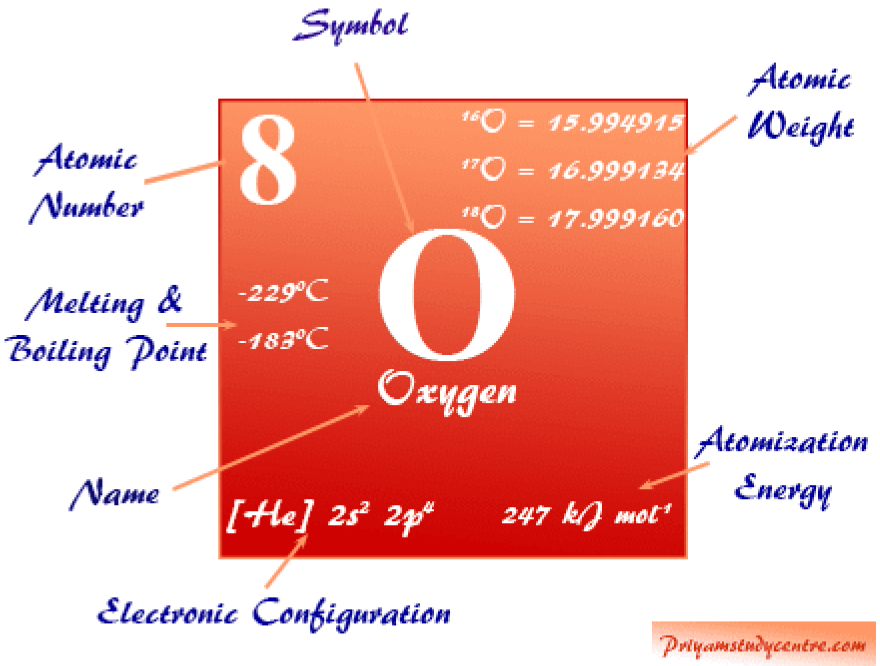
https://doi.org/10.1038/s41467-022-29582-0 OPEN

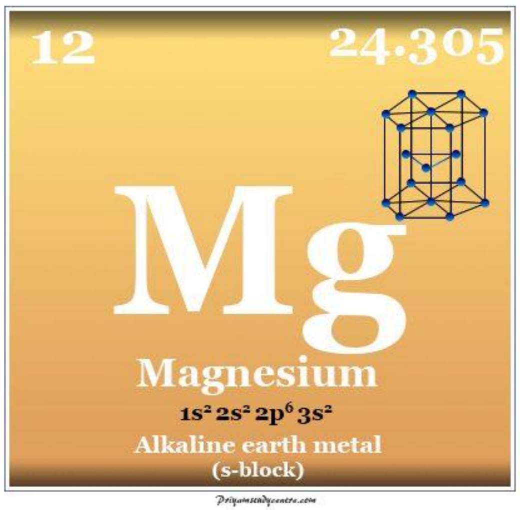
α-Clustering in atomic nuclei from first principles with statistical learning and the Hoyle state character

T. Otsuka [1,2,3], T. Abe [2,4], T. Yoshida[4,5], Y. Tsunoda [4], N. Shimizu[4], N. Itagaki[6], Y. Utsuno [3,4], J. Vary [7], P. Maris [7] & H. Ueno[2]

A long-standing crucial question with atomic nuclei is whether or not α clustering occurs there. An α particle (helium-4 nucleus) comprises two protons and two neutrons, and may be the building block of some nuclei. This is a very beautiful and fascinating idea, and is indeed plausible because the α particle is particularly stable with a large binding energy. However, direct experimental evidence has never been provided. Here, we show whether and how α(-like) objects emerge in atomic nuclei, by means of state-of-the-art quantum many-body simulations formulated from first principles, utilizing supercomputers including K/Fugaku. The obtained physical quantities exhibit agreement with experimental data. The appearance and variation of the α clustering are shown by utilizing density profiles for the nuclei beryllium-8, -10 and carbon-12. With additional insight by statistical learning, an unexpected crossover picture is presented for the Hoyle state, a critical gateway to the birth of life.

Optimal candidates for future experiments: O and Mg – NA61/SHINE program





Both Z and N are even and relatively small, homogeneous distribution of protons and neutrons seems well-suited.

Electromagnetic effects - strong initial fields

Appendix A of 2604.16005: J. Rafelski

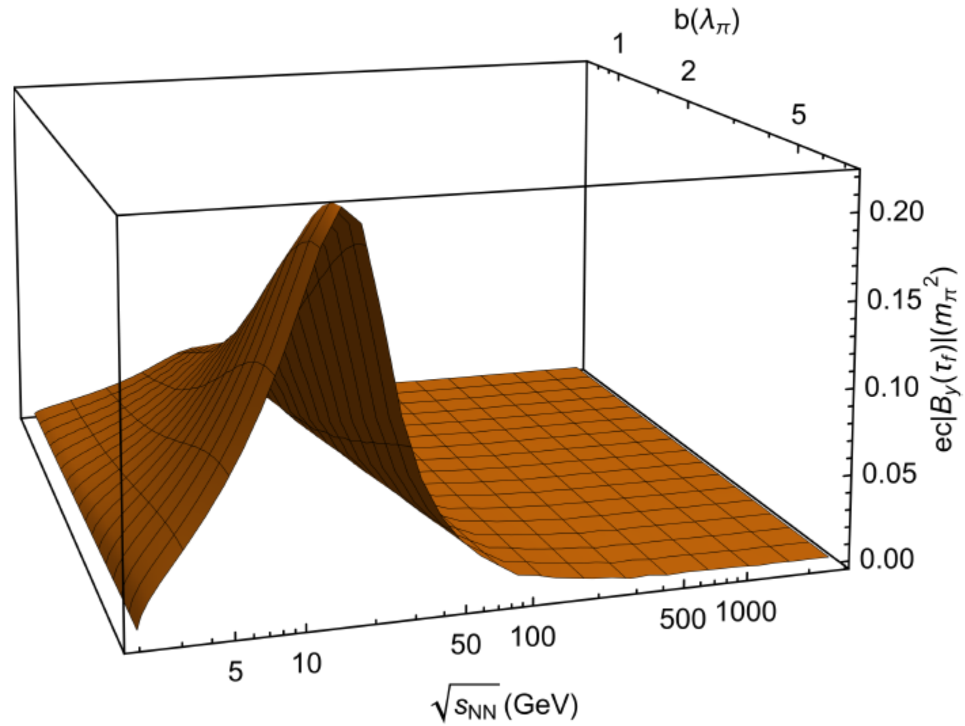


Fig. 10. The magnetic field in heavy-ion collisions as a function of impact parameter and collision energy at time of hadronization, the result courtesy of Chris Grayson, see also Ref. [131].

Quark-antiquark octet interaction and mass differences

Appendix B of 2604.16005: S. Mrowczynski

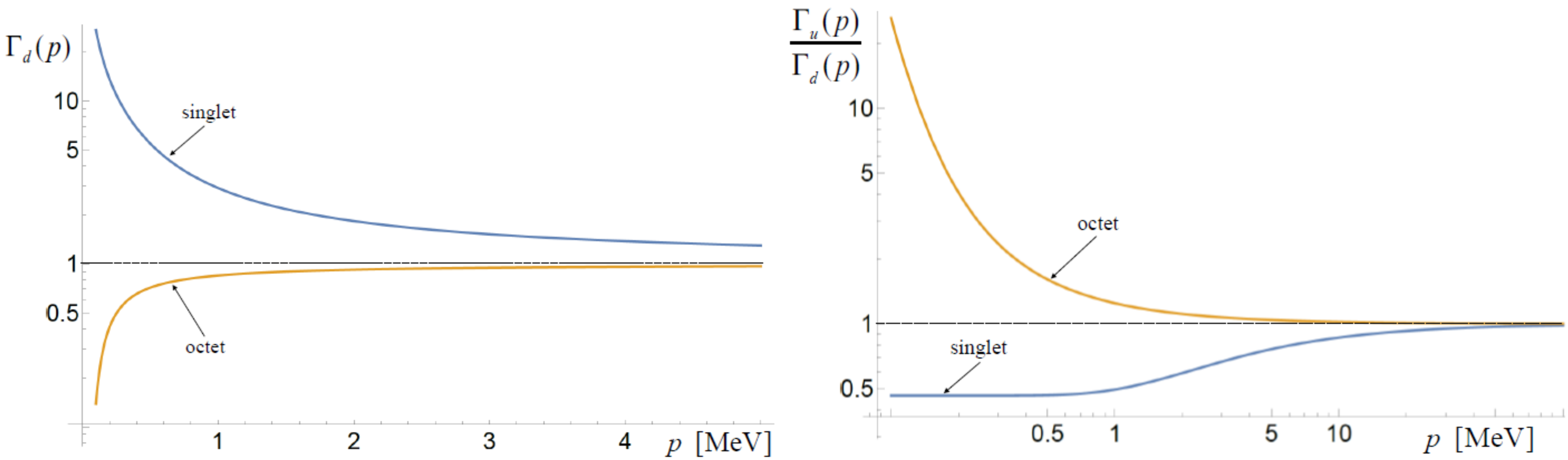


Fig. 12. *Left*: The Gamow factors of $d\bar{d}$ pair in the singlet and octet state as a function of relative momentum. *Right*: The ratios of Gamow factors of $u\bar{u}$ and $d\bar{d}$ quark pairs in the singlet and octet states as a function of relative momentum. The plots are taken from Ref. [109].

Conclusions

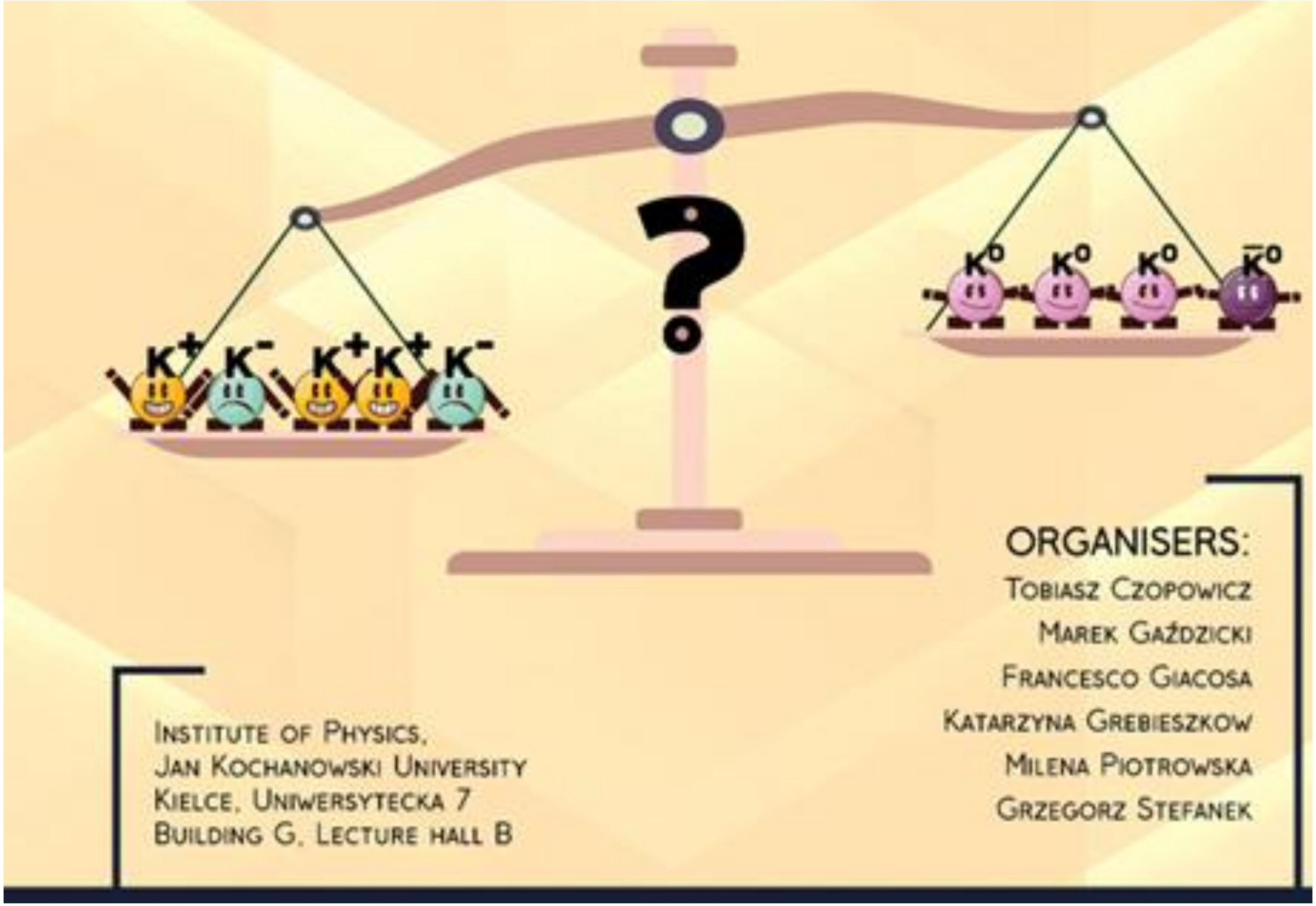
Isospin-symmetry is broken more than expected
in nuclear collisions
(and possibly beyond)

+

ISO-BREAK 2027 at UJK/Kielce (Poland) planned
Between 19-24 April 2027

Thanks ☺

Between 19-24 April 2027



NA61/SHINE experiment					
Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV					
hadron	Yields ($y \approx 0$) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	$3.732 \pm 0.016 \pm 0.148$	0.15	0–10%	$0.0 < y < 0.2$	[18]
K^-	$2.029 \pm 0.012 \pm 0.069$	0.070	0–10%	$0.0 < y < 0.2$	[18]
K^0_S	$2.433 \pm 0.027 \pm 0.102$	0.11	0–10%	$y = 0$	this analysis
HADES experiment					
Ar+KCl collisions at $\sqrt{s_{NN}} = 2.6$ GeV					
hadron	Yields (4π) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	$0.028 \pm 0.002 \pm 0.0014$ (*)	0.0024	0–35%	extrapolated to 4π	[43]
K^-	$0.00071 \pm 0.00015 \pm 0.000032$ (*)	0.00015	0–35%	extrapolated to 4π	[43]
K^0_S	$0.0115 \pm 0.0005 \pm 0.0009$	0.0010	0–35%	extrapolated to 4π	[44]
STAR (BES I) experiment					
Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV					
hadron	Yields ($y \approx 0$) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	20.8	1.7	0–5%	$-0.1 < y < 0.1$	[30]
K^-	7.7	0.6	0–5%	$-0.1 < y < 0.1$	[30]
K^0_S	$12.67 \pm 0.12 \pm 0.44$	0.46	0–5%	$-0.5 < y < 0.5$	[31]

STAR (BES I) experiment					
Au+Au collisions at $\sqrt{s_{NN}} = 11.5$ GeV					
hadron	Yields ($y \approx 0$) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	25.0	2.5	0–5%	$-0.1 < y < 0.1$	[30]
K^-	12.3	1.2	0–5%	$-0.1 < y < 0.1$	[30]
K^0_S	$15.93 \pm 0.12 \pm 0.58$	0.59	0–5%	$-0.5 < y < 0.5$	[31]

STAR (BES I) experiment					
Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 GeV					
hadron	Yields ($y \approx 0$) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	29.6	2.9	0–5%	$-0.1 < y < 0.1$	[30]
K^-	18.8	1.9	0–5%	$-0.1 < y < 0.1$	[30]
K^0_S	$20.89 \pm 0.08 \pm 0.67$	0.67	0–5%	$-0.5 < y < 0.5$	[31]
STAR (BES I) experiment					
Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV					
hadron	Yields ($y \approx 0$) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	31.1	2.8	0–5%	$-0.1 < y < 0.1$	[30]
K^-	22.6	2.0	0–5%	$-0.1 < y < 0.1$	[30]
K^0_S	$23.24 \pm 0.09 \pm 0.70$	0.71	0–5%	$-0.5 < y < 0.5$	[31]
STAR (BES I) experiment					
Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV					
hadron	Yields ($y \approx 0$) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	32.0	2.9	0–5%	$-0.1 < y < 0.1$	[30]
K^-	25.0	2.3	0–5%	$-0.1 < y < 0.1$	[30]
K^0_S	$24.9 \pm 0.1 \pm 1.7$	1.7	0–5%	$-0.5 < y < 0.5$	[31]
NA49 experiment					
Pb+Pb collisions at $\sqrt{s_{NN}}$ = 7.6 GeV					
hadron	Yields (4π) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	$52.9 \pm 0.9 \pm 3.5$ (*)	3.6	0–7.2%	extrapolated to 4π	[40]
K^-	$16.0 \pm 0.2 \pm 0.4$	0.45	0–7.2%	extrapolated to 4π	[40]
K^0_S	$29.3 \pm 0.3 \pm 2.9$	2.9	0–7.2%	extrapolated to 4π	[42]
NA49 experiment					
Pb+Pb collisions at $\sqrt{s_{NN}}$ = 8.7 GeV					
hadron	Yields (4π) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	$59.1 \pm 1.9 \pm 3$	3.6	0–7.2%	extrapolated to 4π	[41]
K^-	$19.2 \pm 0.5 \pm 1.0$	1.1	0–7.2%	extrapolated to 4π	[41]
K^0_S	$34.2 \pm 0.2 \pm 3.4$	3.4	0–7.2%	extrapolated to 4π	[42]
CERES experiment					
Pb+Au collisions at $\sqrt{s_{NN}}$ = 17.3 GeV					
hadron	Yields ($y \approx 0$) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	$31.8 \pm 0.6 \pm 2.5$	2.6	0–7%	$y = 0$	[27]
K^-	$19.3 \pm 0.4 \pm 2.0$	2.0	0–7%	$y = 0$	[27]
K^0_S	$21.2 \pm 0.9 \pm 1.7$	1.9	0–7%	$y = 0$	[28, 29]
NA35 experiment					
S+S collisions at $\sqrt{s_{NN}}$ = 19.4 GeV					
hadron	Yields (4π) $\pm \sigma_{stat} \pm \sigma_{sys}$	σ_{total}	Centrality	y ranges	Ref.
K^+	$12.5 \pm 0.4 \pm 0.375$ (*)	0.55	0–2%	extrapolated to 4π	[38]
K^-	$6.9 \pm 0.4 \pm 0.207$ (*)	0.45	0–2%	extrapolated to 4π	[38]
K^0_S	10.5	1.7	0–2%	extrapolated to 4π	[39]

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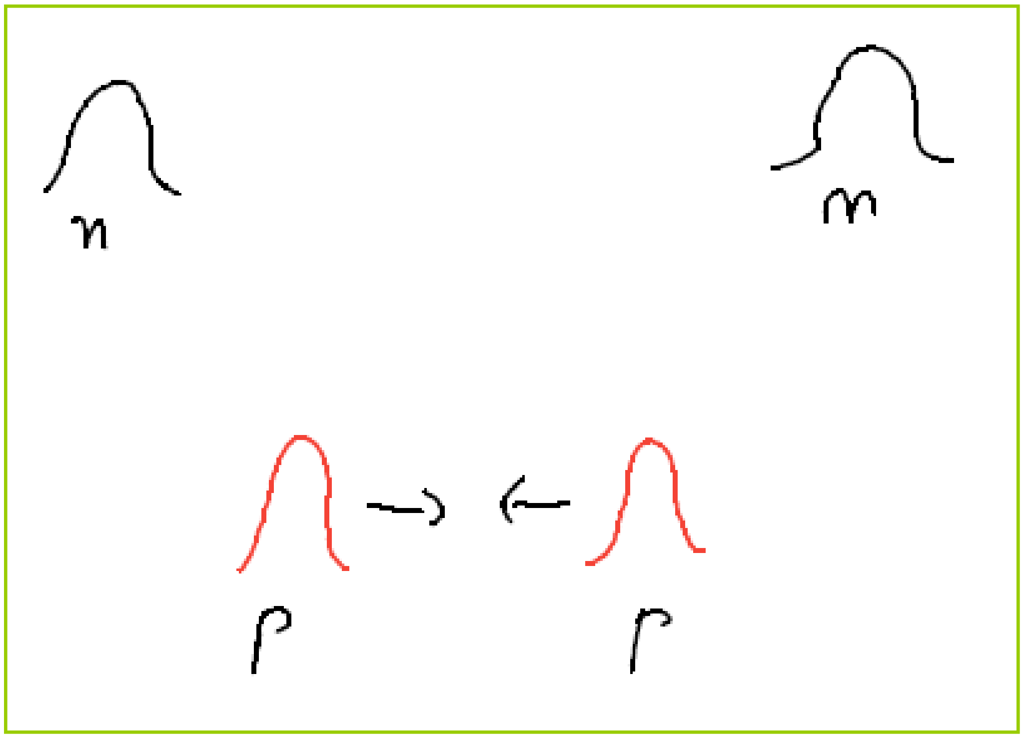
Jana Kochanowskiego w Kielcach

$ppnn \longmapsto$?



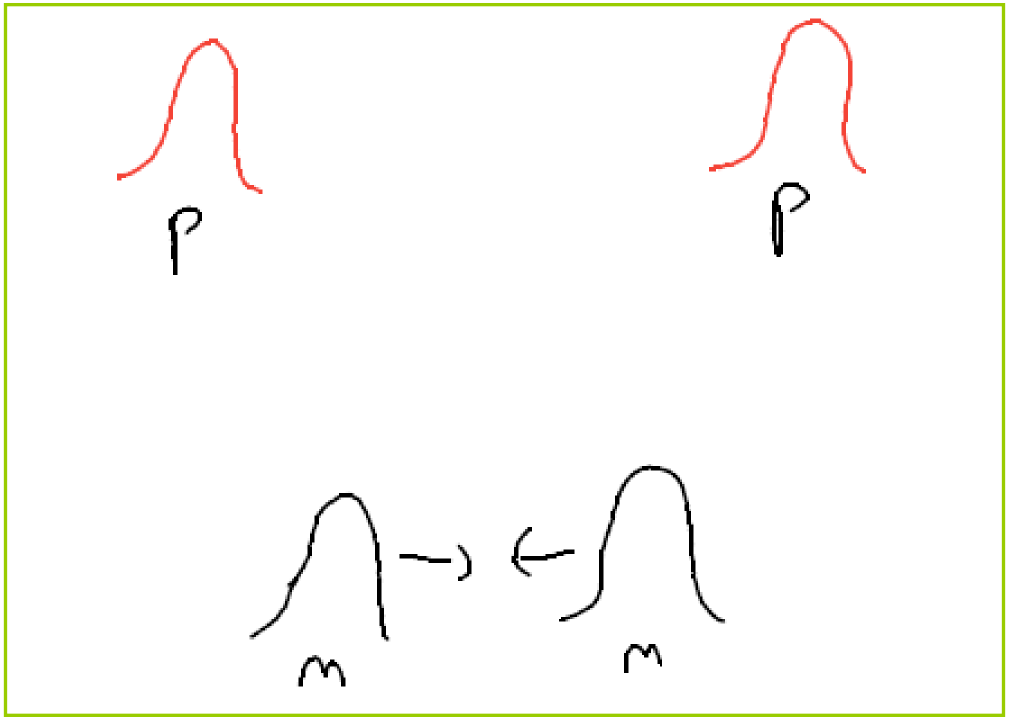
Just as pp!

More K^+ than K^0

Is then the previous argumentation wrong?

No.
One needs to average.

But... $\hat{C}$ transform



This is the C-transformed version fo the previous reaction.

Here, the protons are spectactors and the neutrons interact.

Just as nn scattering!

More K^0 than K^+

Averaging leads to…

If both initial states are equally probable

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

holds!

Formally:

$$\hat{\rho} = \sum_n p_n \left|\Psi_n\right\rangle \left\langle\Psi_n\right|$$

$$\hat{C}\hat{\rho}\hat{C}^{\dagger} = \hat{\rho}$$

This is a general result!

UrQMD

- Standard UrQMD: Similar results to HRG

- Recent UrQMD modification:
  Reichert, Steinheimer, Bleicher:
  Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions,
  e-Print: 2503.10493 [nucl-th]

- String fragmentation favors u-ubar quarks (3 times more probable than d-dbar)

- Similar result in SMASH

The importance of Q/B

If there are more neutrons than protons: Q/B<1/2

More neutral kaons are present: R_K should get smaller

However….

Pauli principle implies more u-ubar pairs than d-dbar pairs from the sea: R_K should get larger.

Which effect is more important?

Having Q/B=1/2 eliminates these issues.

RtildeK for (anti)quarks u and d

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

$$= \frac{n_d + n_{\bar{d}} + 2\alpha}{n_d + n_{\bar{d}} + 2\beta}$$

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

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

η, η', and ϕ, $\quad K^+\Lambda$

QC: Most general case

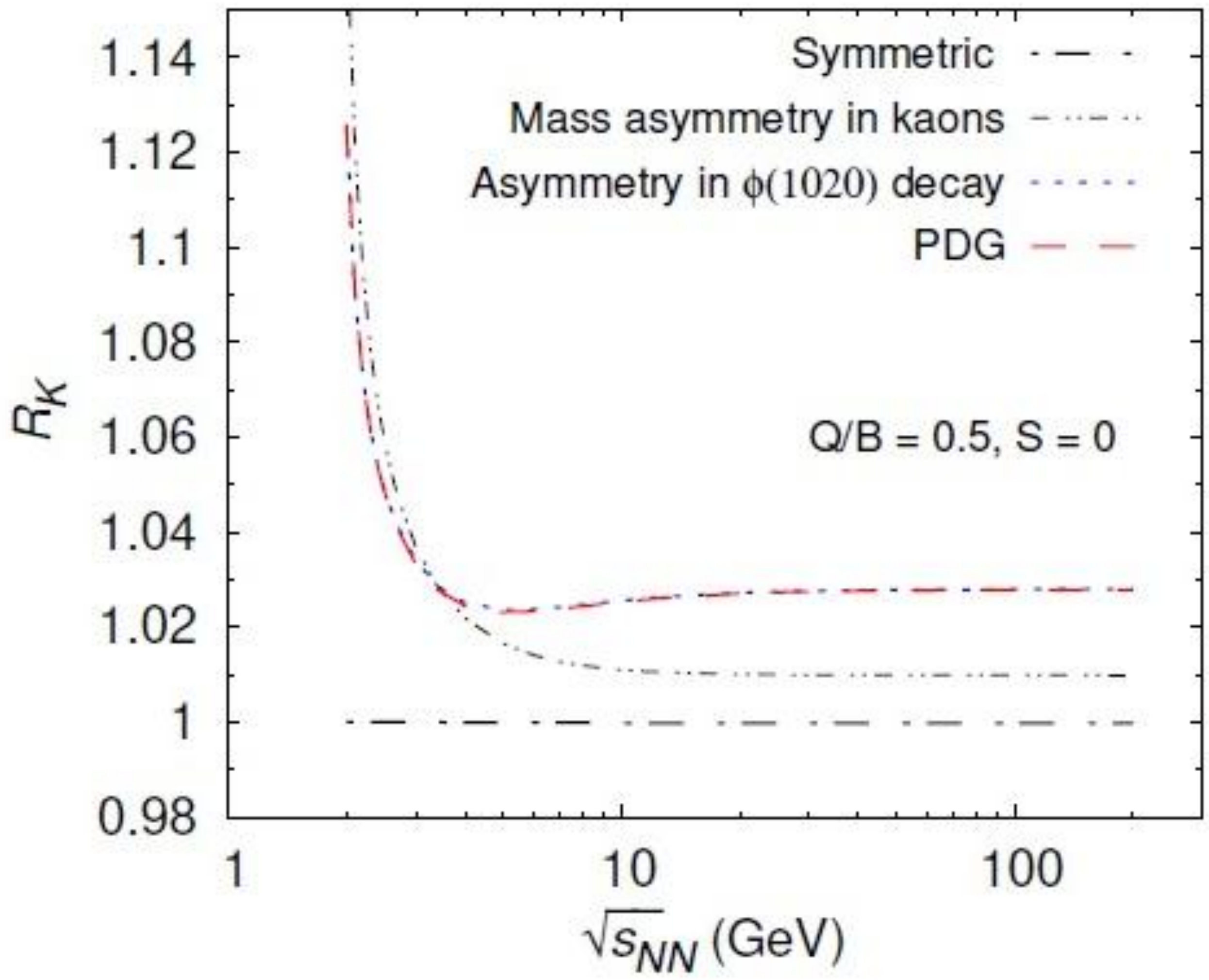
In the most general case with arbitrary $n_{u,d,s}$ and $n_{\bar{u},\bar{d},\bar{s}}$ the quantity $\tilde{R}_K$ reads

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

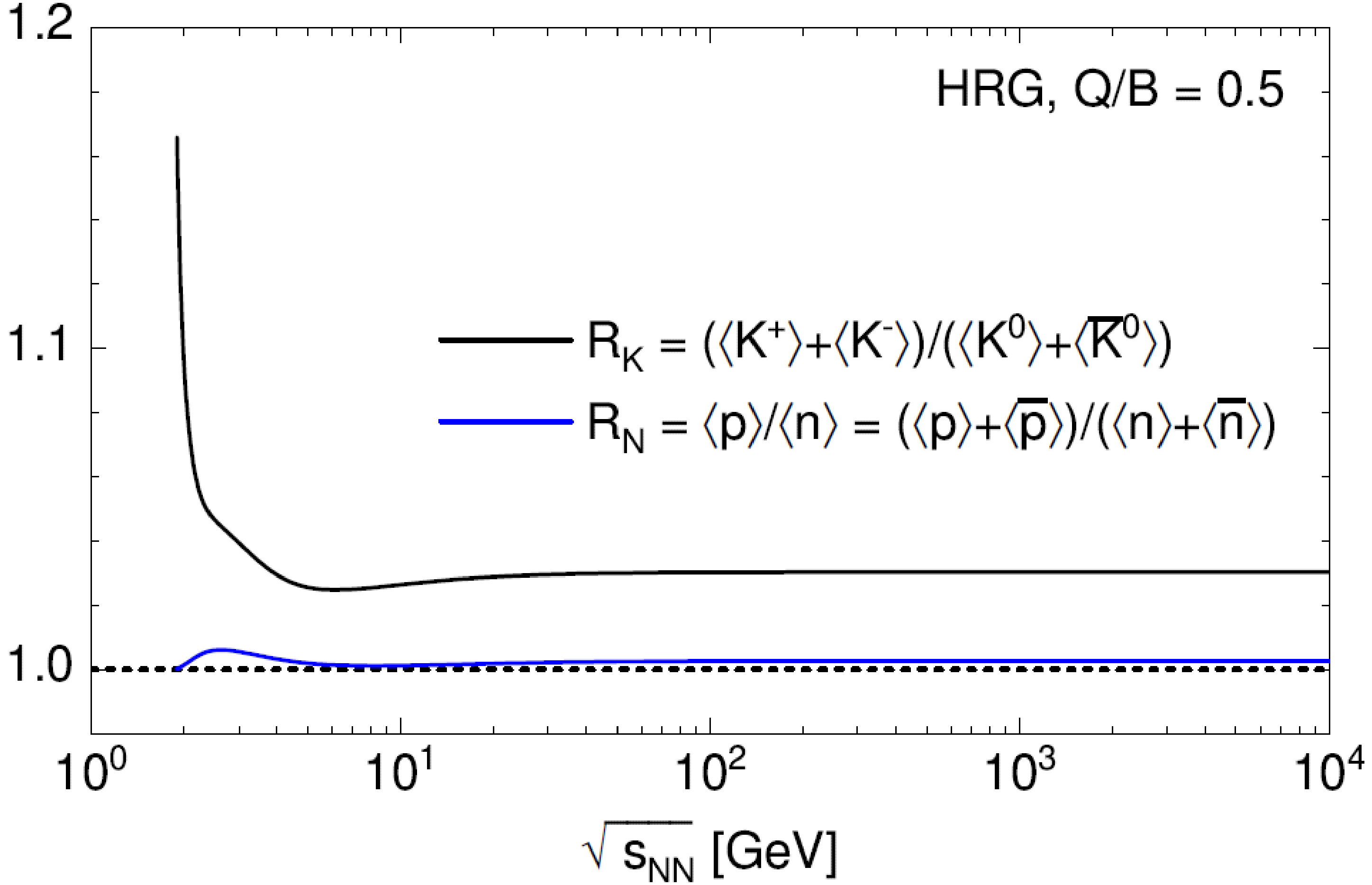
However, it cannot be expressed as a function of the three multiplicities $\langle K^+ \rangle$, $\langle K^- \rangle$, and $\langle K^0_S \rangle$, but it involves separately $\langle K_0 \rangle$ and $\langle \bar{K}_0 \rangle$ [38]. This fact is not convenient because only K^0_S is usually detected.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

- Compilation of brainstorming ideas from 2604.16005
- HRG: corrections; extension ot out of equilibrium.
- More speculative ideas: chiral anomaly, disoriented condensates, Pauli blocking, strong transient e.m. fields, …

RK in HRG for Q/B=1/2



HRG for Q/B=1/2



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

More on the resonance a0(980)

$a_0(980)$ $I^G(J^{PC}) = 1^-(0^{++})$

See the related review(s):
Scalar Mesons below 1 GeV

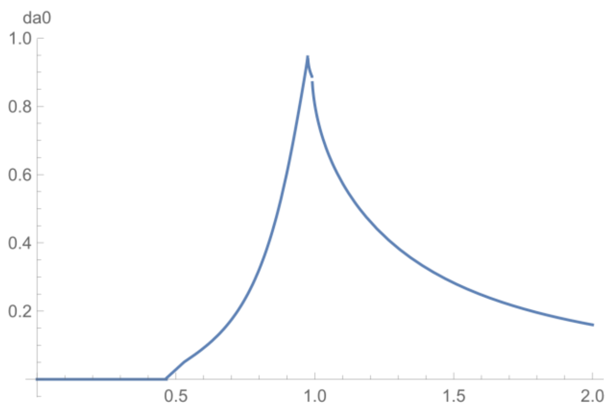
$a_0(980)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma = -2\,\mathrm{Im}(\sqrt{s})$.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(970–1020) − i (30–70) OUR ESTIMATE	(see Fig. 64.2 in the review)		

$a_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi$	seen
Γ_2	$K\overline{K}$	seen
Γ_3	$\eta'\pi$	seen



Using the PDG average $\bar{K}K/\pi\eta = 0.172 \pm 0.019$ amounts to the following $\bar{K}K$ overall branching ratio :

$$\frac{\Gamma_{\bar{K}K}}{\Gamma_{tot}} = \frac{\Gamma_{\bar{K}K}}{\Gamma_{\bar{K}K} + \Gamma_{\pi\eta} + \Gamma_{\pi\eta'}} \simeq \frac{\Gamma_{\bar{K}K}}{\Gamma_{\bar{K}K} + \Gamma_{\pi\eta}}$$
$$= \frac{1}{1 + \frac{\Gamma_{\pi\eta}}{\Gamma_{\bar{K}K}}} = \frac{1}{1 + \frac{1}{\Gamma_{\pi\eta}/\Gamma_{\bar{K}K}}} = 0.15 \pm 0.01 \,.$$

HRG: at first, equal amount for charged and neutral kaons.
Including threshold effects, leads to the branching ratio $K^+K^-/K^0\bar{K}^0 \simeq 1.1$
No significant effect on RK

More on the resonances f0(980)

$f_0(980)$

$I^G(J^{PC}) = 0^+(0^{++})$

See the related review(s):
Scalar Mesons below 1 GeV

$f_0(980)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma = -2\,\mathrm{Im}(\sqrt{s})$.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(980–1010) − *i* (20–35) OUR ESTIMATE (see Fig. 64.4 in the review)			

$f_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	$K\overline{K}$	seen

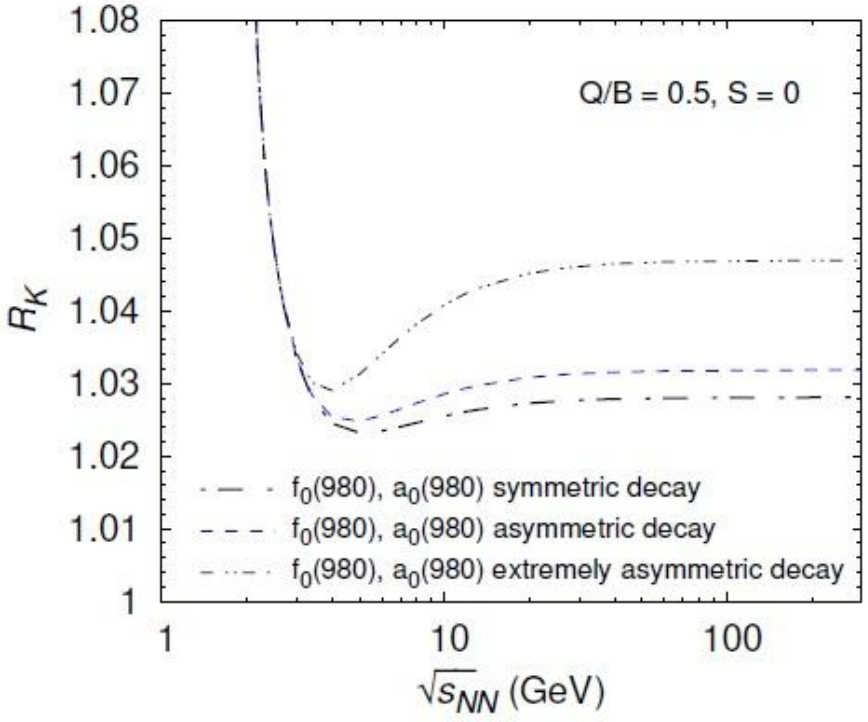
$\Gamma(\pi\pi)/[\Gamma(\pi\pi)+\Gamma(K\overline{K})]$

VALUE	EVTS
• • • We do not use the followin	
0.52 ± 0.12	9.9k
$0.75^{+0.11}_{-0.13}$	
0.84 ± 0.02	
~ 0.68	
0.67 ± 0.09	
$0.81^{+0.09}_{-0.04}$	
0.78 ± 0.03	

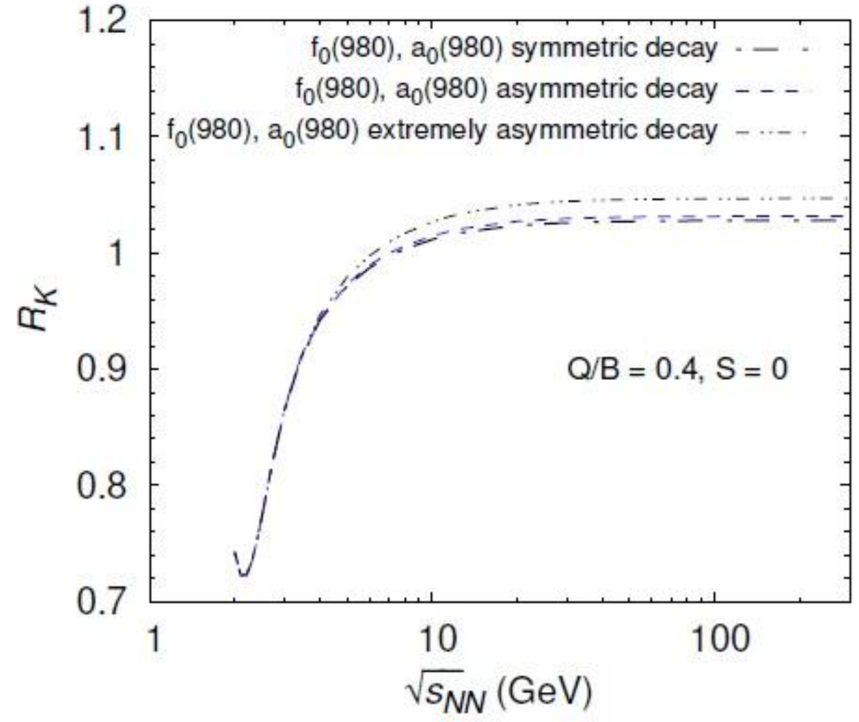
The $\pi\pi$ mode dominates.
Similar consideration as for the a0(980) mesons.

Even including threshold effects,
no significant change of RK.

f0/a0 effect

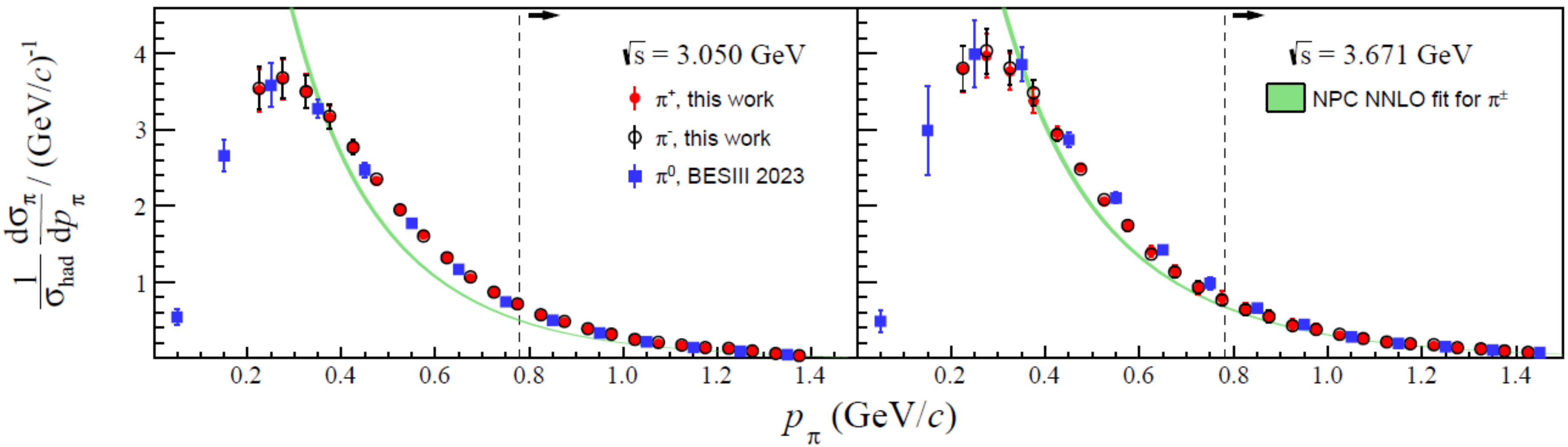


1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
R_K
Q/B = 0.5, S = 0
$f_0(980)$, $a_0(980)$ symmetric decay
$f_0(980)$, $a_0(980)$ asymmetric decay
$f_0(980)$, $a_0(980)$ extremely asymmetric decay
1
10
100
$\sqrt{s_{NN}}$ (GeV)



1.2
1.1
1
0.9
0.8
0.7
R_K
$f_0(980)$, $a_0(980)$ symmetric decay
$f_0(980)$, $a_0(980)$ asymmetric decay
$f_0(980)$, $a_0(980)$ extremely asymmetric decay
Q/B = 0.4, S = 0
1
10
100
$\sqrt{s_{NN}}$ (GeV)

BESIII-pions.



Toward a simple 'quark counting' model: quark coalescence model (QC)

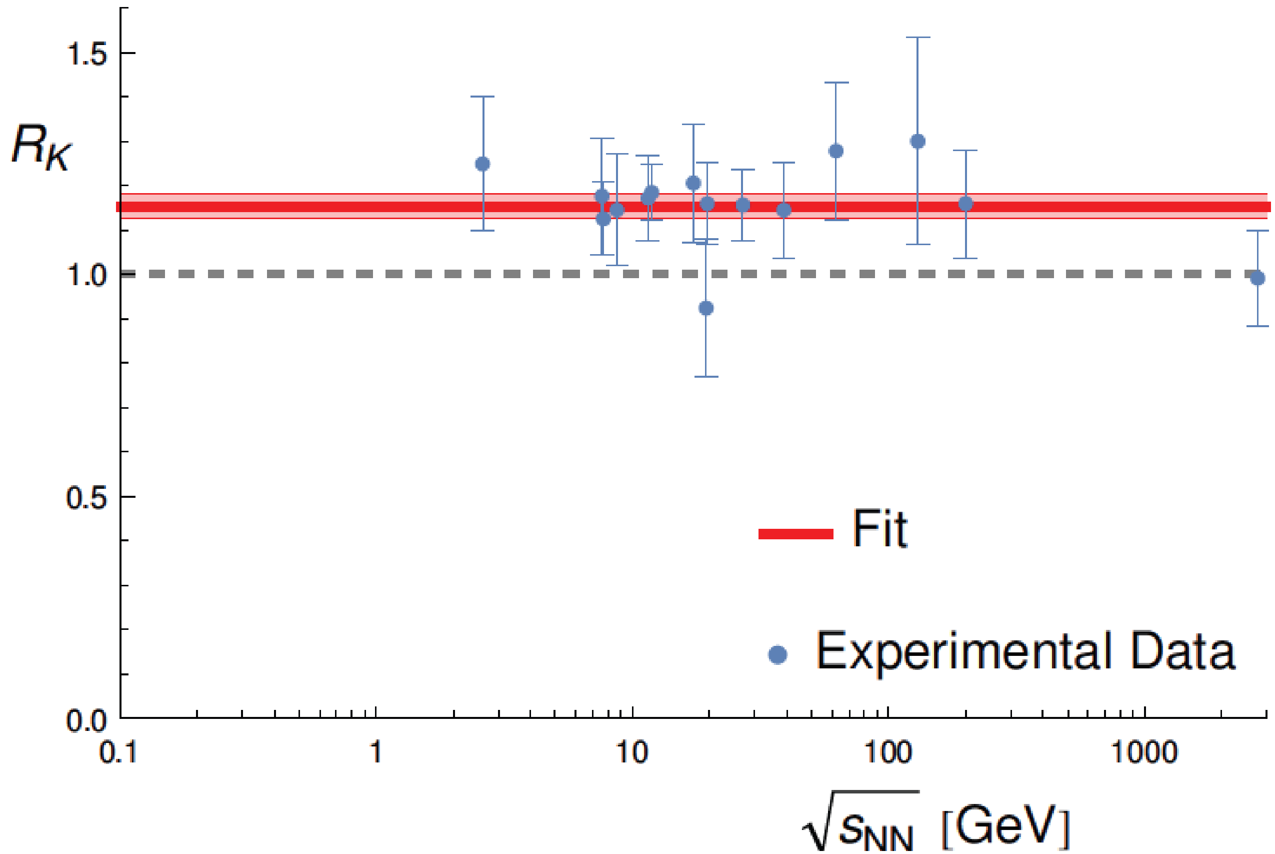
- Provided the large isospin-symmetry breaking is true, two questions can be asked: why and which are its consequences.

- 'Why' is, as usual, a difficult question. Can electromagnetic interaction enhance K+K-? We argued that this is not the case. But a systematic study is needed

- What about a sum over many small effects? All phi-f_0-a_0 etc effects would lead to the measured results.

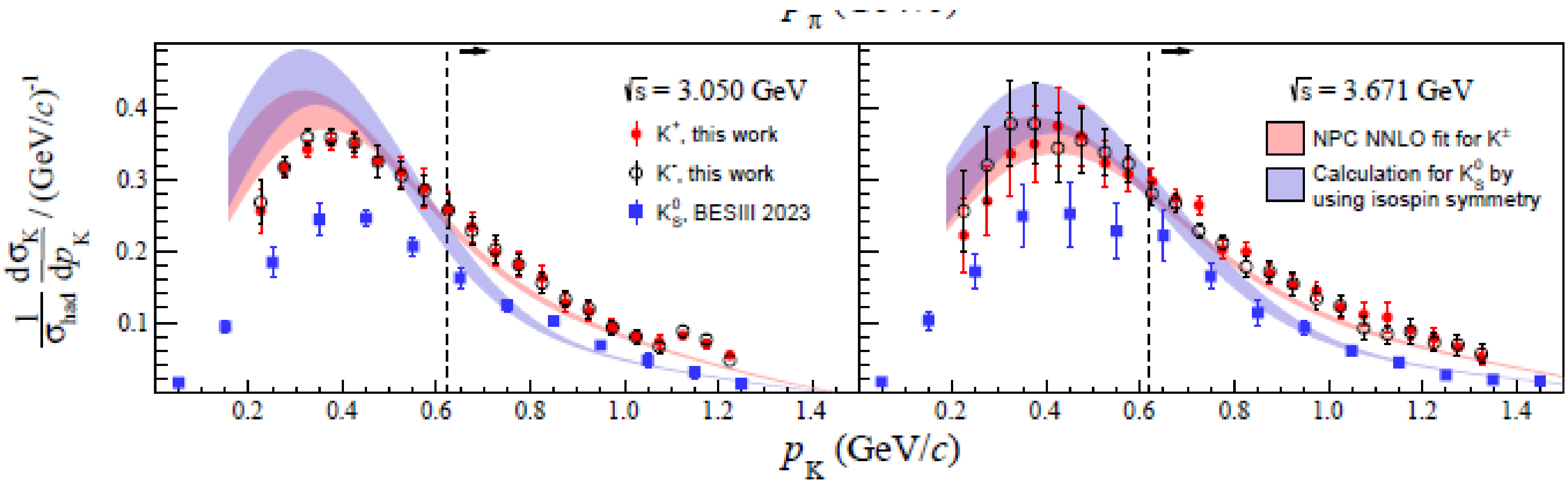
- More speculative explanations?

Nucleus-nucleus results for RK: constant, not 1, and compatible with RtildeK



$$R_K = 1.152 \pm 0.027$$

2504.02113



$\sqrt{s}$ = 3.050 GeV
K⁺, this work
K⁻, this work
K^0_S, BESIII 2023
$\sqrt{s}$ = 3.671 GeV
NPC NNLO fit for K±
Calculation for K^0_S by using isospin symmetry
$\frac{1}{\sigma_{had}} \frac{d\sigma_K}{dp_K}$ / (GeV/c)⁻¹
p_K (GeV/c)

Quark Coalescence model in e+-e-: rough idea