Theoretical status of the kaon isospin anomaly

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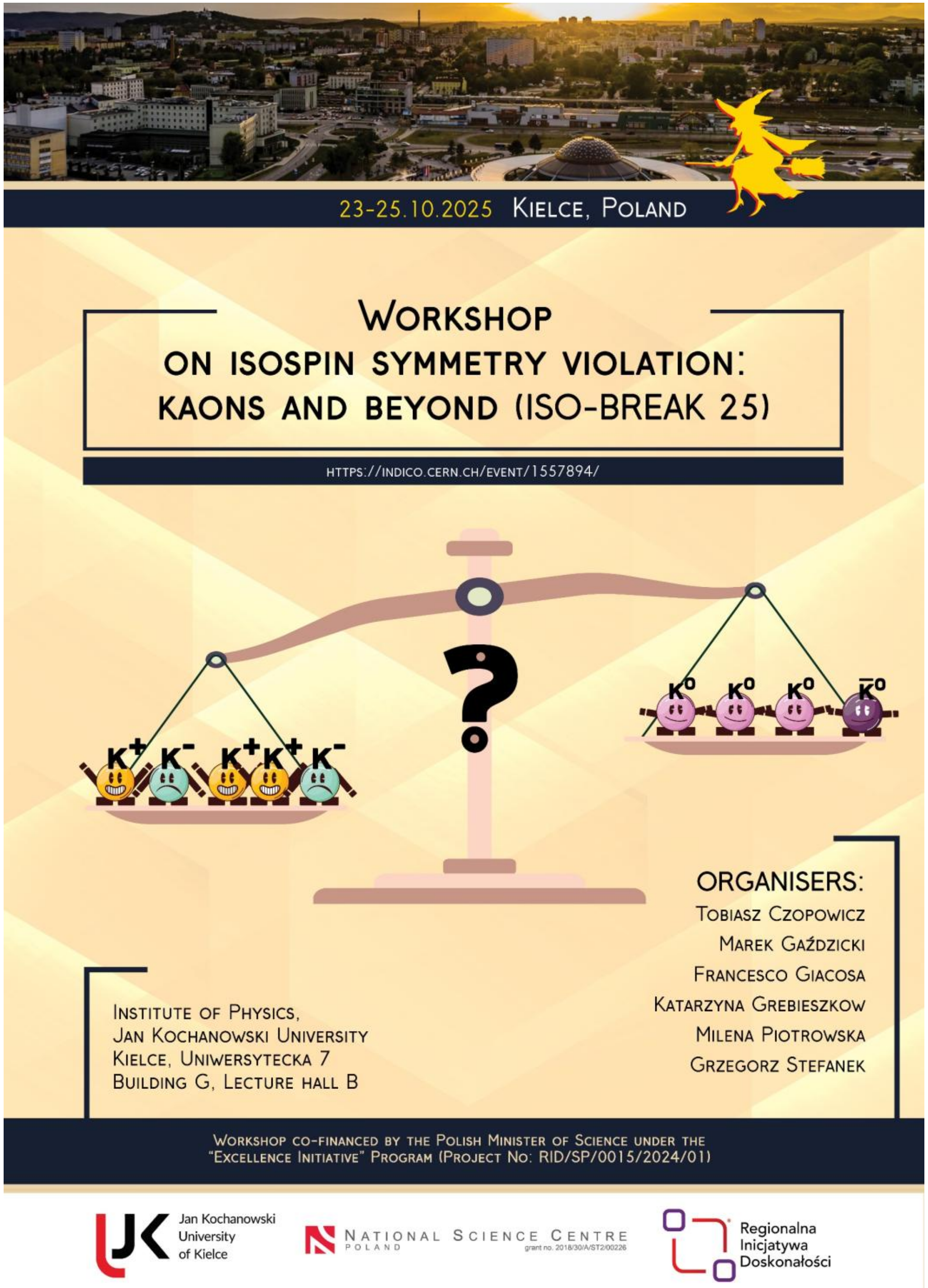
Based on discussions with M. Gazdzicki, M. Rohrmoser, S. Samanta, H. Stroebele, M. Gorenstein, M. Bleicher, A. Rybicki, S. Mrówczyński, L. Tinti, W. Broniowski, R. Poberezhniuk, J. Rafelski, O. Vitiuk, L. Turko, K. Grebieszkow, R. Pisarski, W. Brylinski, NA61 collab., …

XVIII Polish Workshop on Relativistic Heavy-Ion Collisions

Jagiellonian University in Kraków
13-14/12/2025



Uniwersytet Jana Kochanowskiego w Kielcach

Outline

1. The nontrivial emergence of isopsin symmetry in QCD.

2. Kaon isospin anomaly: brief recall.

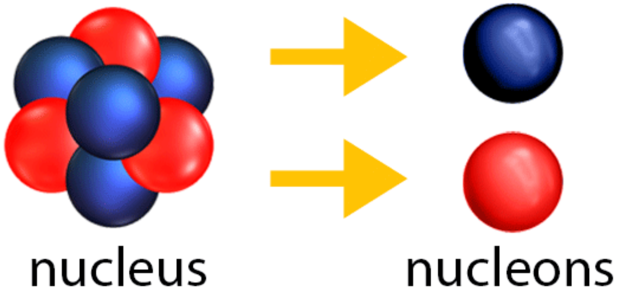
3. Discussions

4. Why do we really need Q/B=1/2

5. Conclusions

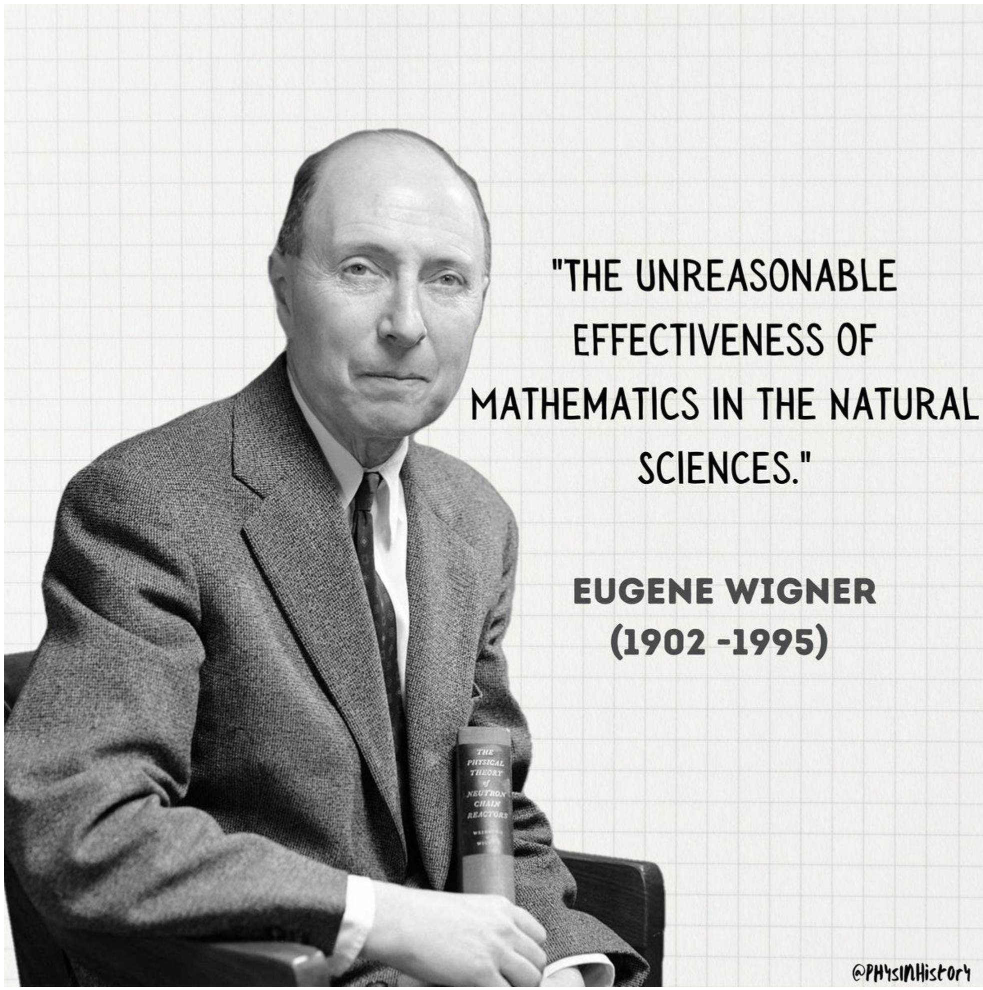
Heisenberg (1932): the nucleon

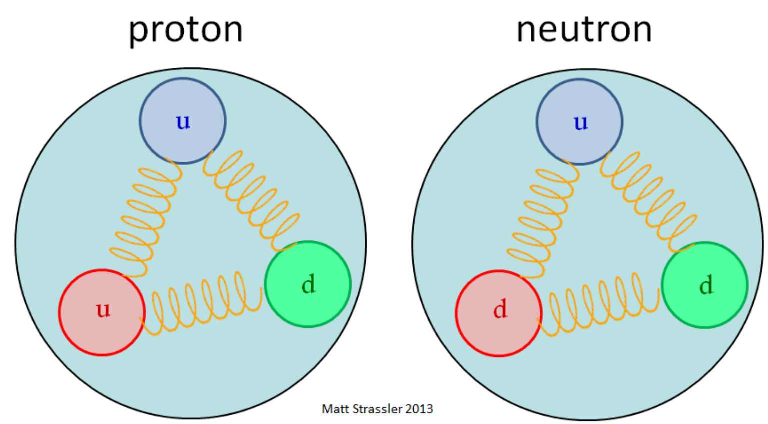
A nucleon is either a proton or a neutron as a component of an atomic nucleus

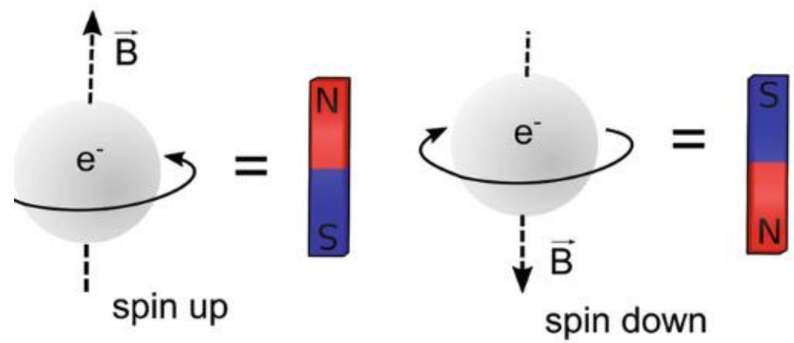


Proton and neutron merge into the nucleon
Masses very similar.

Wigner (1932): isotopic spin, thus isospin







Nucleon doublet: I=1/2

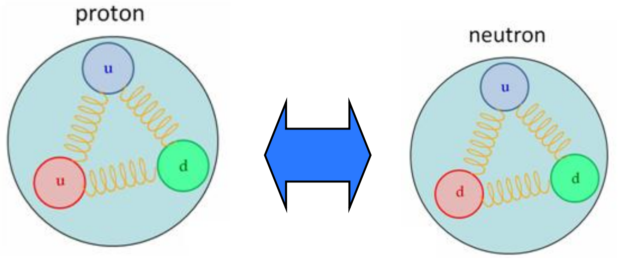
$$\begin{pmatrix} p \\ n \end{pmatrix} \rightarrow \hat{O} \begin{pmatrix} p \\ n \end{pmatrix}$$

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

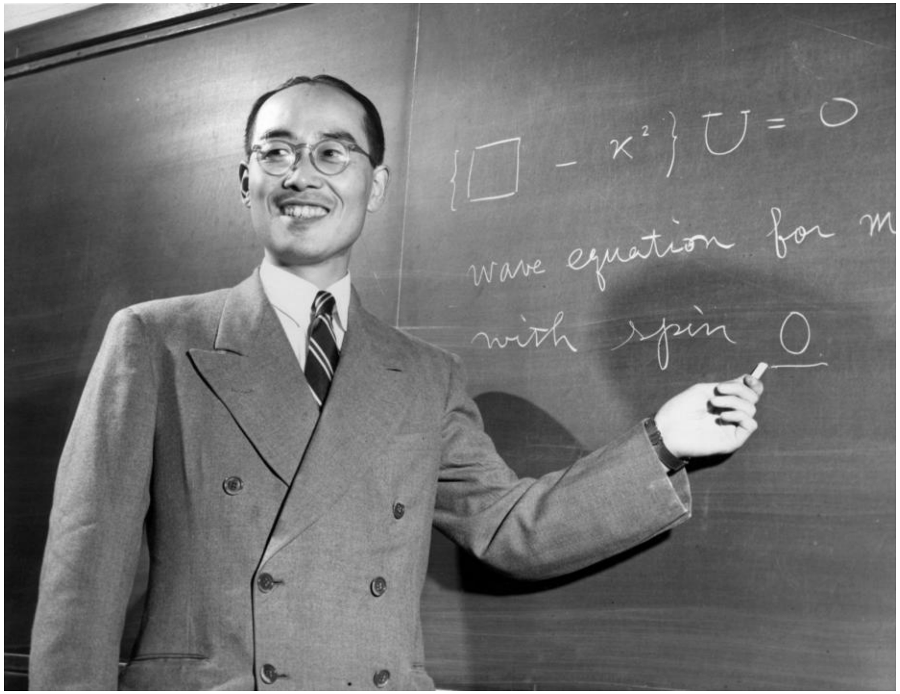
A specific isospin transformation is the so-called charge transformation:

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

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



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



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

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

Kaons form isospin doublets, just as the nucleon

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

under $\hat{C}$:

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

Isospin is an approximate symmetry of QCD

- Mesonic multiplets (nucleon doublet, pion trioplet, kaon doublets).

- Reactions: Isospin is conserved in strong interactions

  Example: (I=Iz=1)

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

- Isopsin 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 breaking

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

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

Is it that simple?

Masses of u and are not equal

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

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

Ratio is far from unity!

Why do we have isospin symmetry at the hadronic level?

Why isospin work/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 work/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 isopsin work/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.

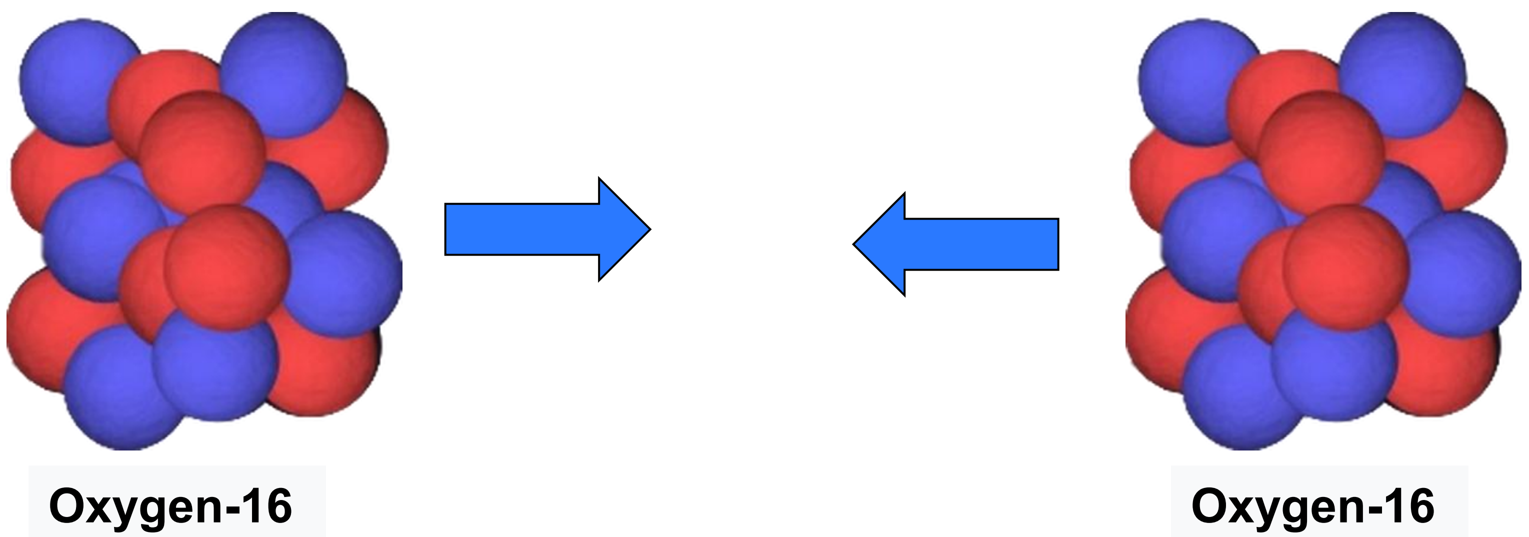
Gross, D.J., Treiman, S.B., Wilczek, F. Light Quark Masses and Isospin Violation
Phys. Rev. D 19, 2188 (1979)
Pisarski, R.D., Wilczek, F. Remarks on the Chiral Phase Transition in Chromodynamics.
Phys. Rev. D 29, 338–341 (1984)

Answer 3: the chiral anomaly protects isospin symmetry.

Nucleus-nucleus collion with equal numbers of protons and neutrons

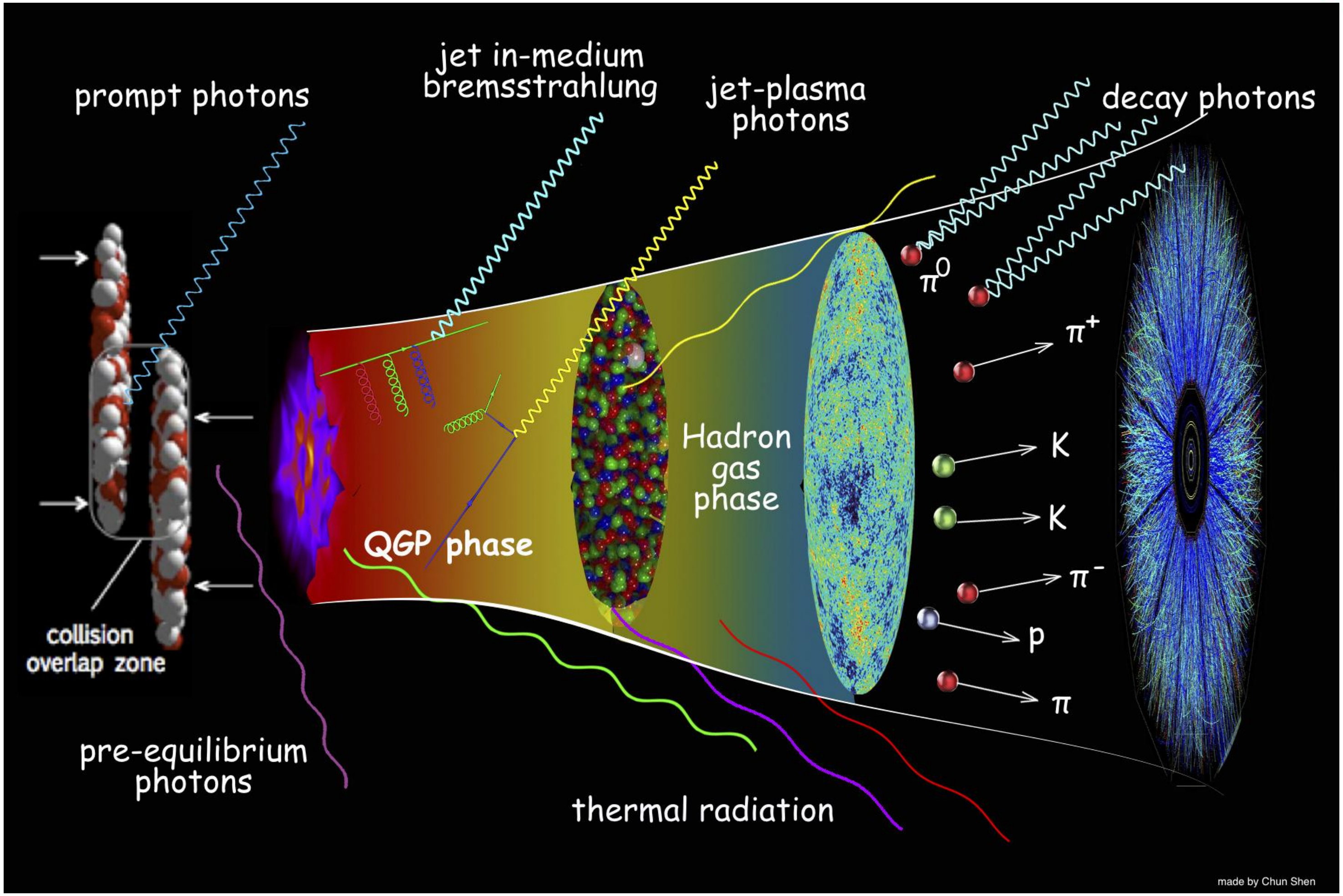
$$Z = N = A/2 \qquad\qquad Q/B = 1/2$$

$$|A + A\rangle$$



$I_z = 0$ (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

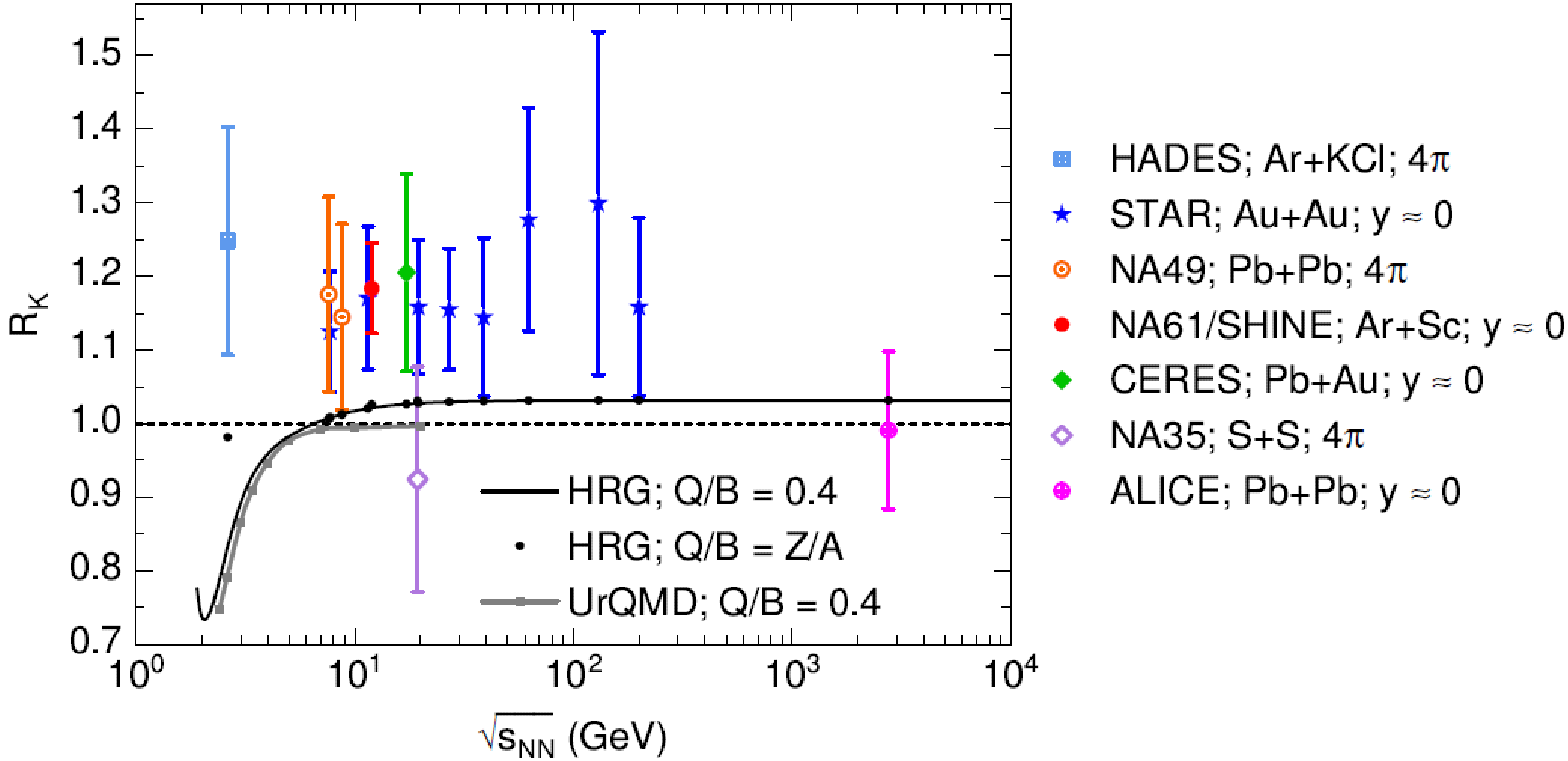
Charge symmetry applied to an ensemble of initial states
for Q/B=1/2 and isospin-symmetric limit

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

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

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

Experimental results (NA61/SHINE plus others)



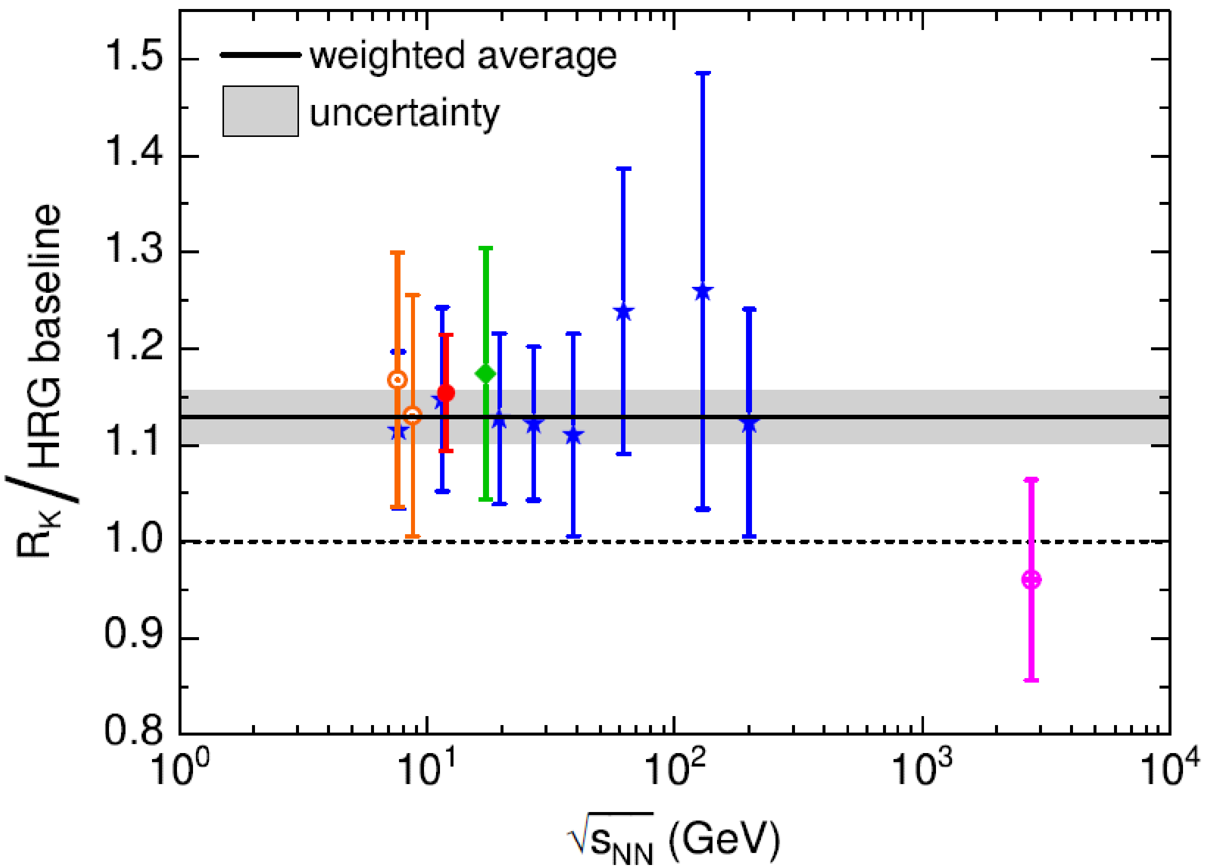
Latest NA61/SHINE result: $R_K = 1.184 \pm 0.061$

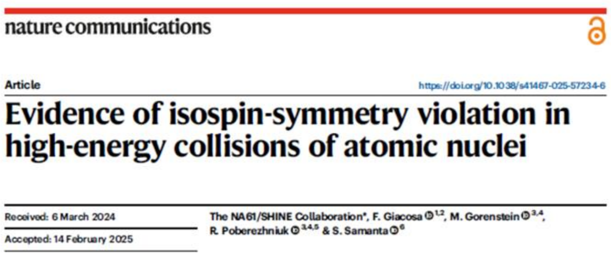
Note, however, most experiments have Q/B < 0.5

Experiment vs theory (HRG): ratio

$$1.129 \pm 0.027.$$

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





nature communications
Article
https://doi.org/10.1038/s41467-025-57234-6

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

Received: 6 March 2024
Accepted: 14 February 2025

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

The exp/th missmatch is 4.7σ.

Considerations

- HRG approach(es)
- UrQMD approach
- Electromagnetic effect
- The ratio Q/B (Pauli blocking, nucleon distributions…)
- The importance of Q/B=1/2 data in the future

HRG, isospin breaking, the phi meson

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$\phi(1020)$

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

$\phi(1020)$ MASS

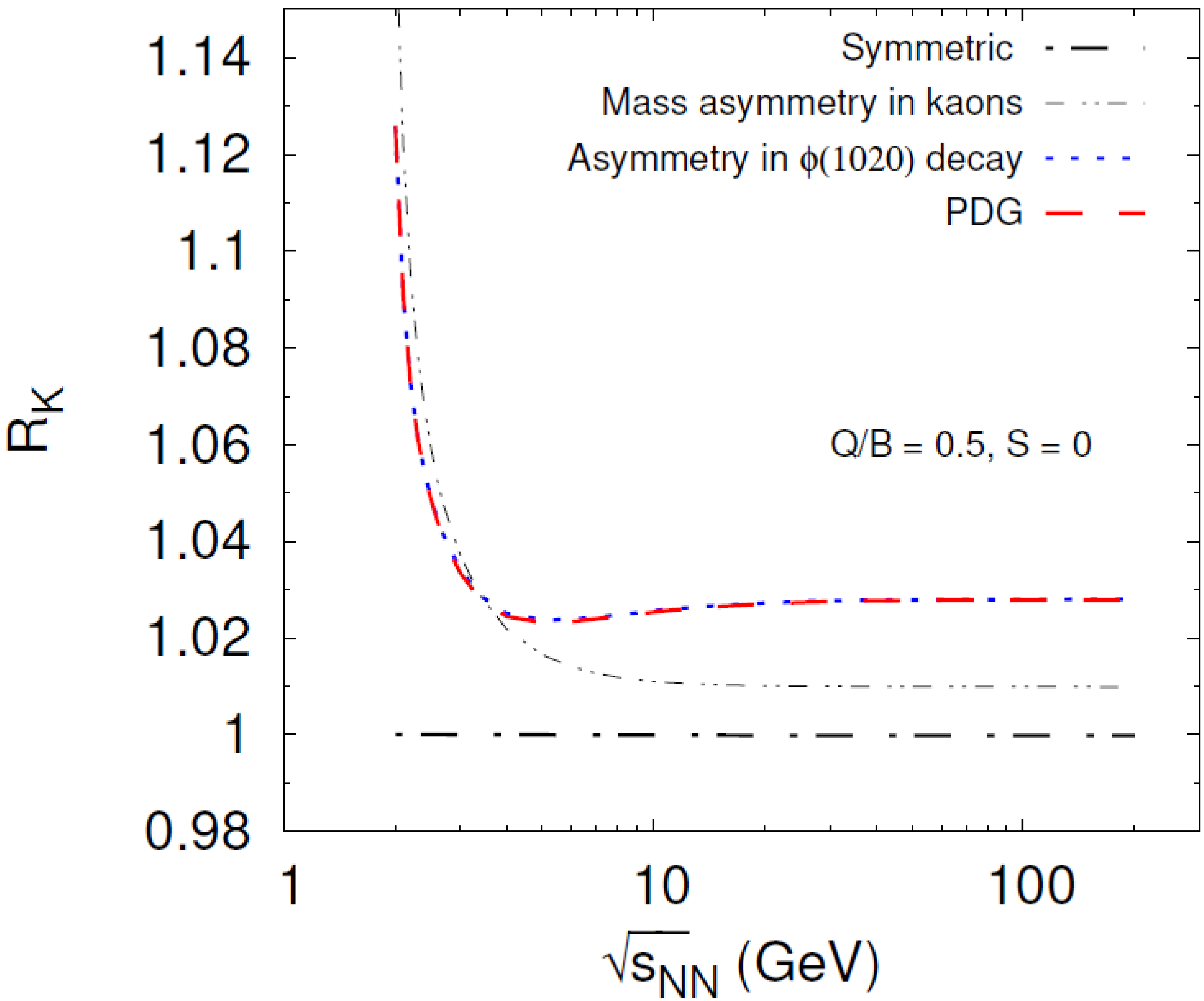
VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1019.461±0.016 OUR AVERAGE				

$\phi(1020)$ DECAY MODES

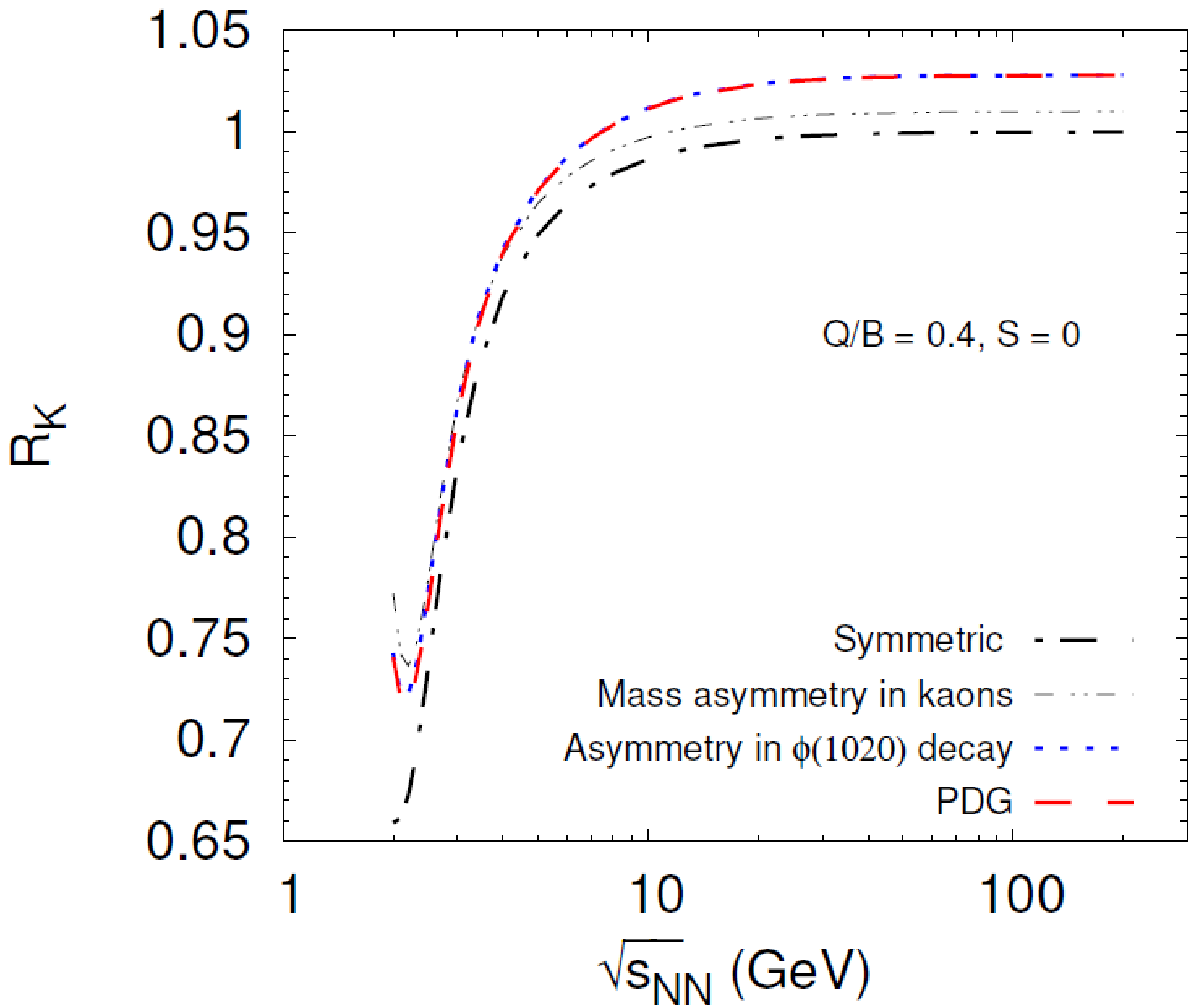
	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.1 ± 0.5) %	S=1.3
Γ_2	$K^0_L K^0_S$	(33.9 ± 0.4) %	S=1.2

This is a delicate threshold effect (even if the interaction is isospin symmetric)

Rκ in HRG, Q/B=1/2



RK in HRG, Q/B=0.4



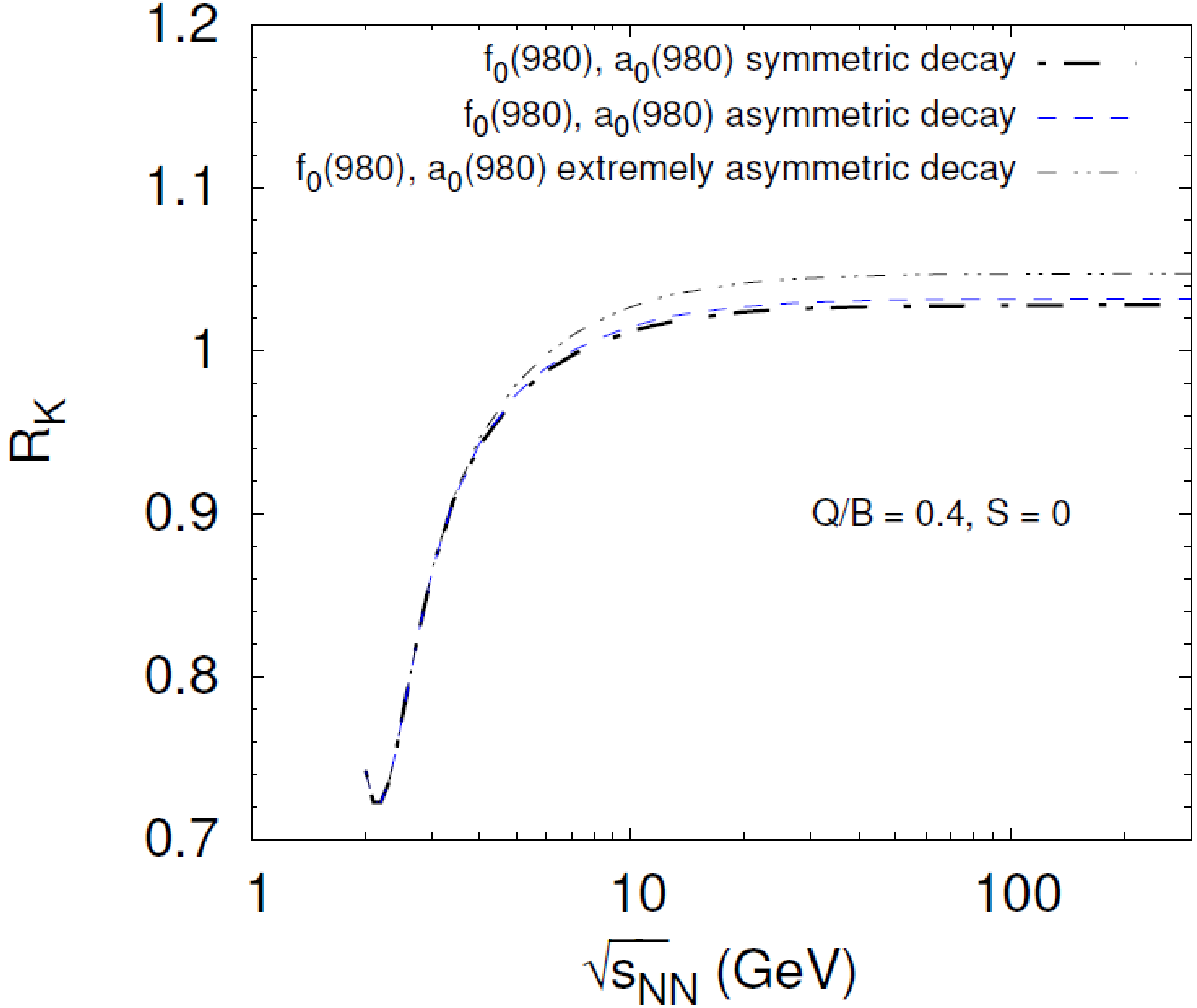
Other resonances

- Other resonances, such as $a_0(980)$ and $f_0(980)$ increase charged/neutral kaon ratio, but only a bit.

- We tried to include heavier states as well

- But, even including all of them, it was not possible to get R_K close to the measured data

RK in HRG, Q/B=0.4, effect of a0(980)/f0(980)



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 over d-dbar ones by a factor 3.

Electromagnetic effects

- Obviously, e.m. interaction breaks isospin symmetry.
- It is α^2 suppressed.
- My own test with charged kaon emission from $a_0(980)$: small effect.
- S. Mrówczyński reported on the topic: small effect (?)

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.

Asymmetry of quark pairs in proton

Article

The asymmetry of antimatter in the proton

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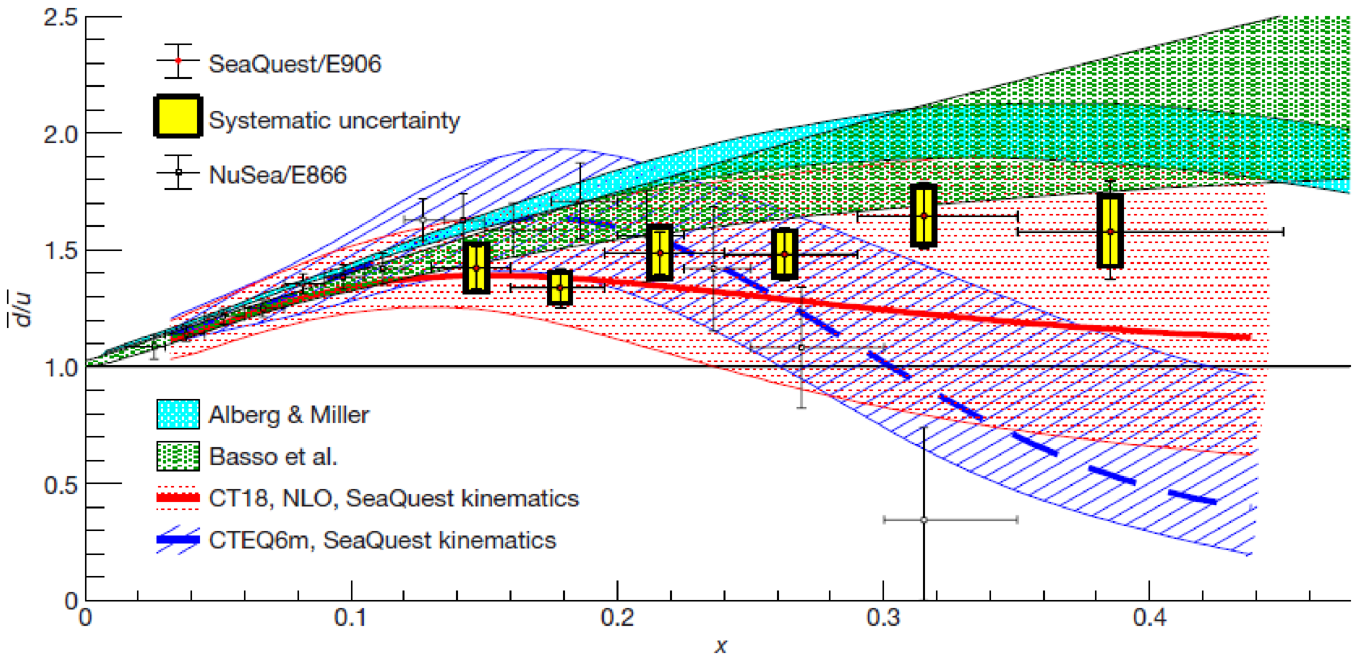
Check for updates

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

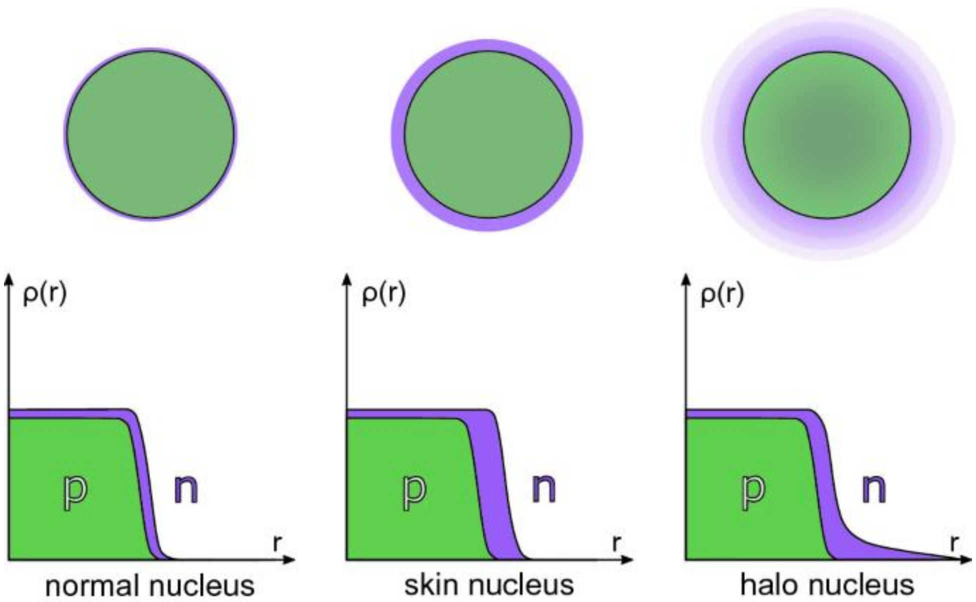
Is Q/B_effective (for interacting nucleons) equal to the nominal Q/B?

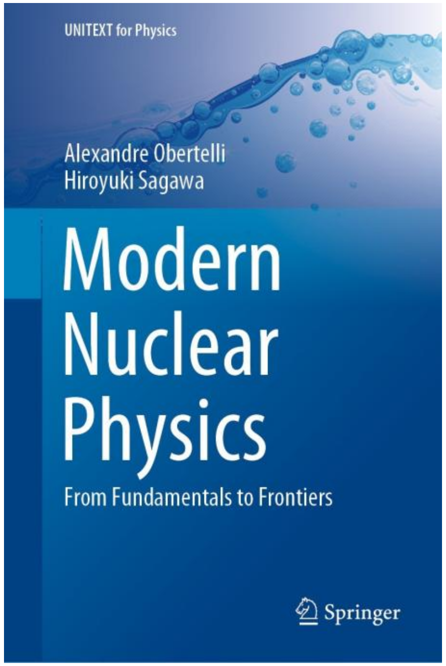
Large nuclei have more neutrons than protons.
In general, inhomogeneous distribution…(neutron skin).

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

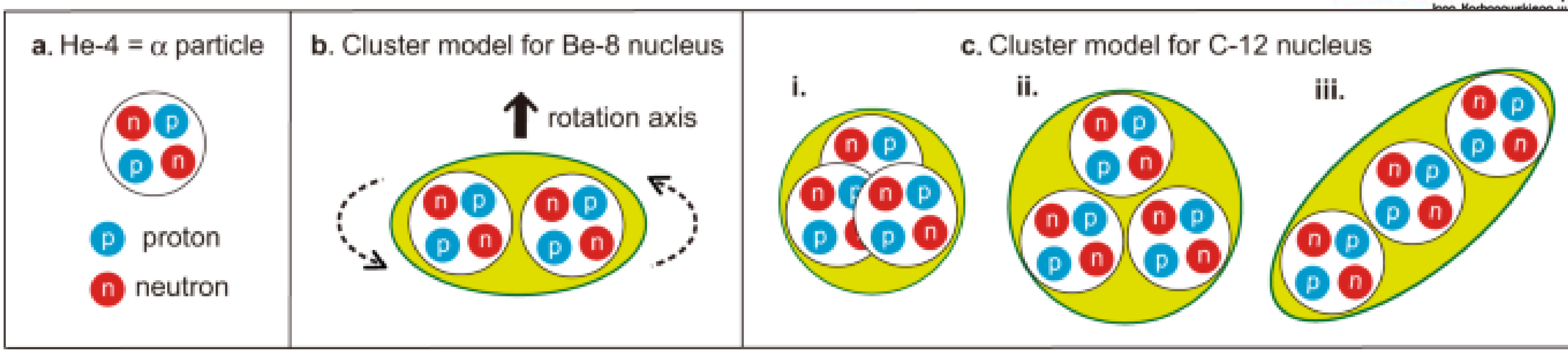




Chapter 6

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

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

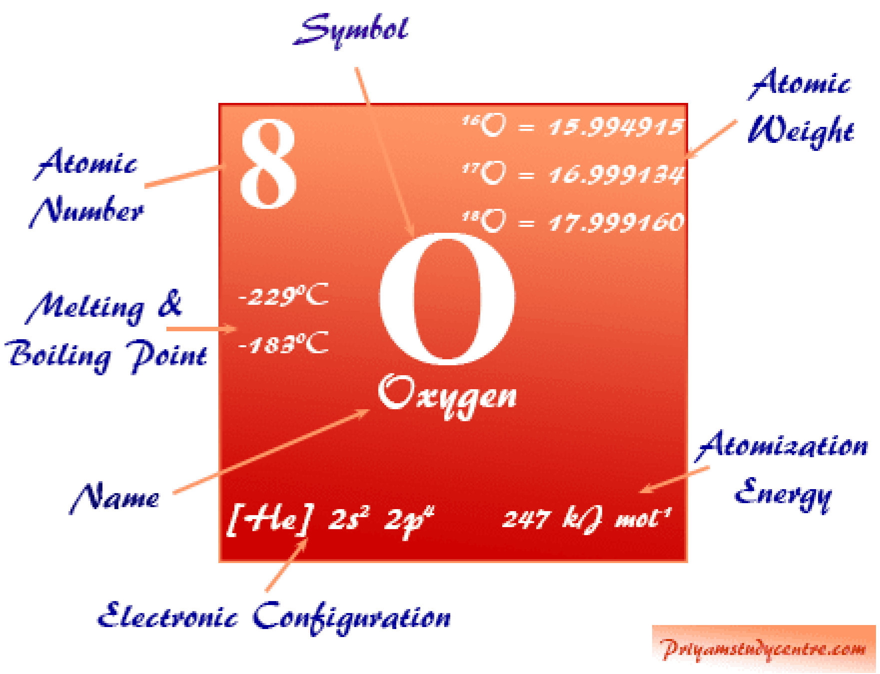
Check for updates

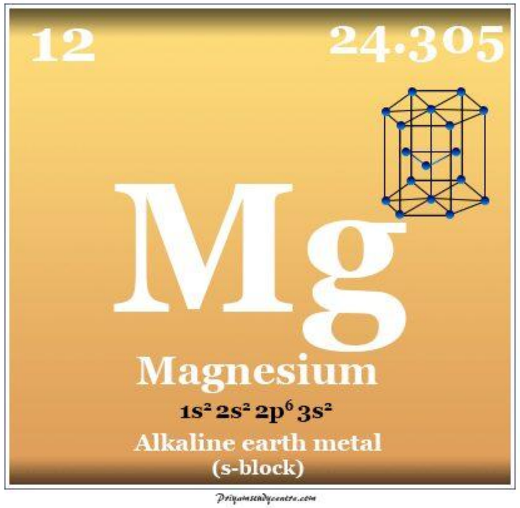
α-Clustering in atomic nuclei from first principles with statistical learning and the Hoyle state character

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





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

Consequences of isospin breaking

Predictions of the quark-coalescence model (Q/B=1/2)

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

Giacosa, F., Rohrmoser, M.: Isospin kaon anomaly and its consequences
Eur.Phys.J.C 85 (2025) 9, 1058 arXiv:2504.02113 [nucl-th]

See also: Stepaniak, J., Pszczel, D.:
On the relation between KS and charged kaon yields in proton-proton collisions EPJC 83 2023 10 928
arXiv:2305.03872 [hep-ph]

Discussion with M. Bleicher about K*(892)

- K*(892): isospin breaking implies that one should get more charged than neutral vector kaons.
- But… charged K*(892) decays twice more often into neutral kaons than charged kaons.
- This would partly cancel the effect, reducing R_K. To get the measured R_K, the isospin breaking should be even larger.
- Even more puzzling…

Pion-Carbon: ongoin analysis

$$\pi^- + C \text{ and } \pi^+ + C$$

NA61/SHINE , pi- C measurement,
PRD 107 (2003) 062004

$$R_K^{\pi^- C} \simeq 1.2$$

In order to have

$$\frac{R_K^{\pi^- C} + R_K^{\pi^+ C}}{2} = 1$$

One would need

$$R_K^{\pi^+ C} \simeq 0.8???$$

Coalescence approach (2504.02113)

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

A similar puzzle but with a clear resolution: D mesons

$$\frac{D^+ + D^-}{D^0 + \bar{D}^0} \approx 0.5 \ .$$

More neutral than charged mesons.

The explanation is simple: vector D* mesons break isospin.

D-mesons: what is going on here

Isospin asymmetry for D mesons

$D^{\pm}$ $I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.66 \pm 0.05$ MeV
Mean life $\tau = (1033 \pm 5) \times 10^{-15}$ s
$c\tau = 309.8$ μm

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

Mass $m = 1864.84 \pm 0.05$ MeV
$m_{D^\pm} - m_{D^0} = 4.822 \pm 0.015$ MeV
Mean life $\tau = (410.3 \pm 1.0) \times 10^{-15}$ s
$c\tau = 123.01$ μm

Mass difference: $\Delta m \approx 5$ MeV
Multiplicity: $\langle D^+ + D^- \rangle < \langle D^0 + \overline{D^0} \rangle$

$D^*(2007)^0$ $I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2006.85 \pm 0.05$ MeV (S = 1.1)
$m_{D^{*0}} - m_{D^0} = 142.014 \pm 0.030$ MeV (S = 1.5)
Full width $\Gamma < 2.1$ MeV, CL = 90%

$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^0$	(64.7 ±0.9) %	43
$D^0\gamma$	(35.3 ±0.9) %	137
$D^0 e^+ e^-$	(3.91±0.33) × 10^{-3}	137

$D^*(2010)^{\pm}$ $I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2010.26 \pm 0.05$ MeV
$m_{D^*(2010)^+} - m_{D^+} = 140.603 \pm 0.015$ MeV
$m_{D^*(2010)^+} - m_{D^0} = 145.4258 \pm 0.0017$ MeV
Full width $\Gamma = 83.4 \pm 1.8$ keV

$D^*(2010)^-$ modes are charge conjugates of the modes below.

$D^*(2010)^{\pm}$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^+$	(67.7±0.5) %	39
$D^+\pi^0$	(30.7±0.5) %	38

- $m(D^+) + m(\pi^-) = 1869.66$ MeV $+ 139.57039$ MeV $= 2009.23039$ MeV $> m(D^*(2007)^0)$ – decay not possible
- $m(D^0) + m(\pi^0) = 1864.84$ MeV $+ 134.9768$ MeV $= 1999.8168$ MeV $< m(D^*(2007)^0)$

Slide from W. Brylinski, NA61/SHINE

Conclusions

No explanation of the isospin kaon anomaly

electron-positron experiment at BESIII: more charged than neutral. Why?

Strong modification of HRG: but how? We sould not spoil where it works.

Check other reactions and other isospin partners

Soon vs2 of
2312.07176 [nucl-th]
with all details

Toward a simple 'quark counting' 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 phi-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

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

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

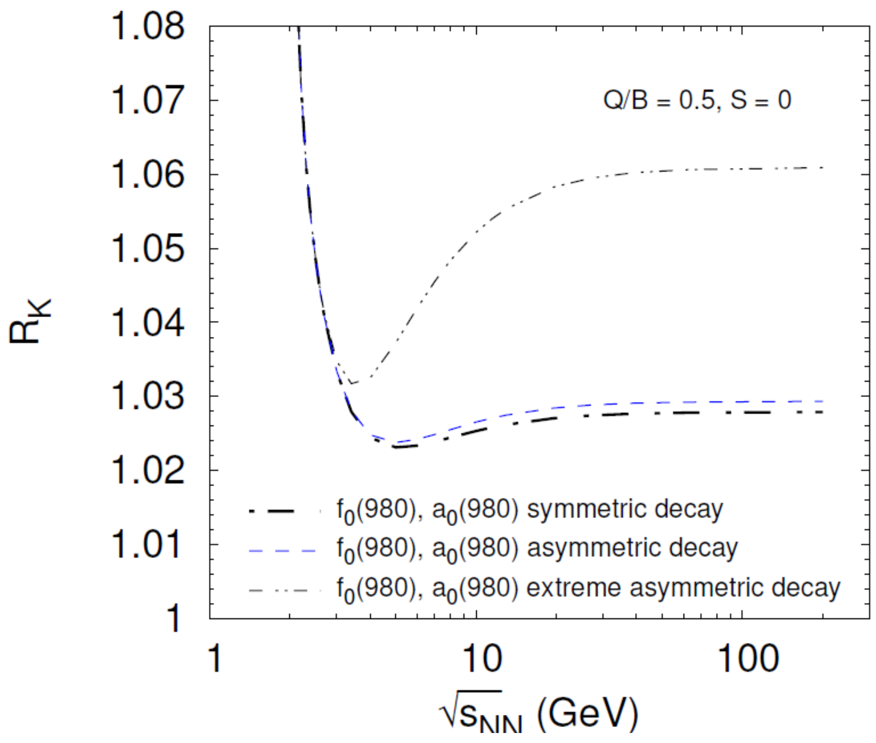
$$R_K = \frac{\langle K^+\rangle + \langle K^-\rangle}{\langle 2K_S^0\rangle} = \frac{n_u + 2\alpha}{n_d + 2\beta}$$

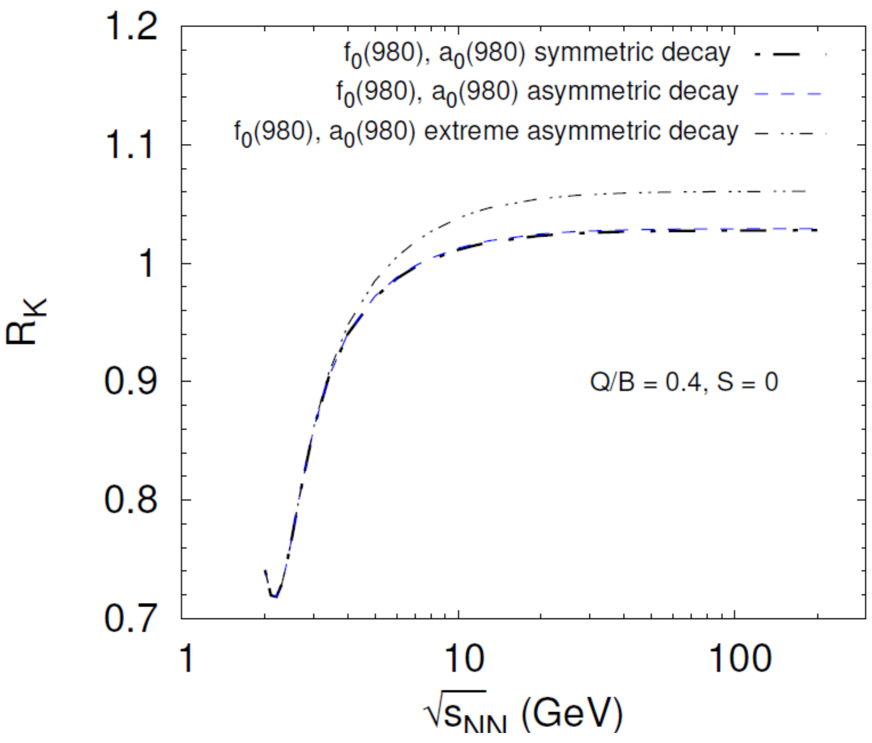
isospin-symmetric limit $(\alpha = \beta)$

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

$$Q/A = 1/2$$

The a0(980) and f0(980)



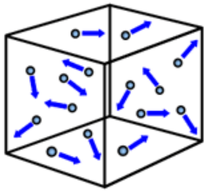


Popular theoretical approaches

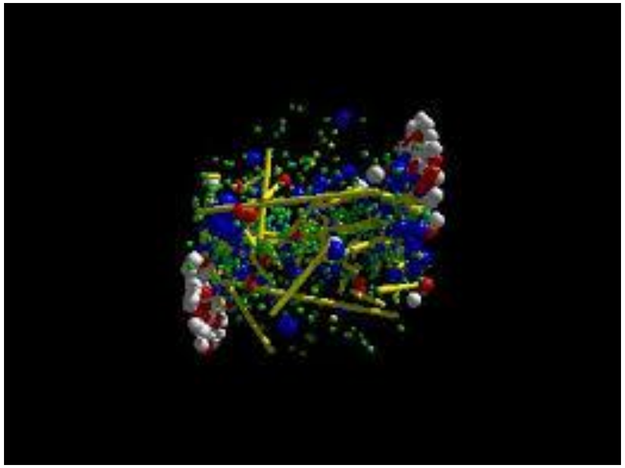
- HRG (hadron resonance gas approach)

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

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



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



‘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 RK to RtildeK

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

2504.02113

isospin-conserved

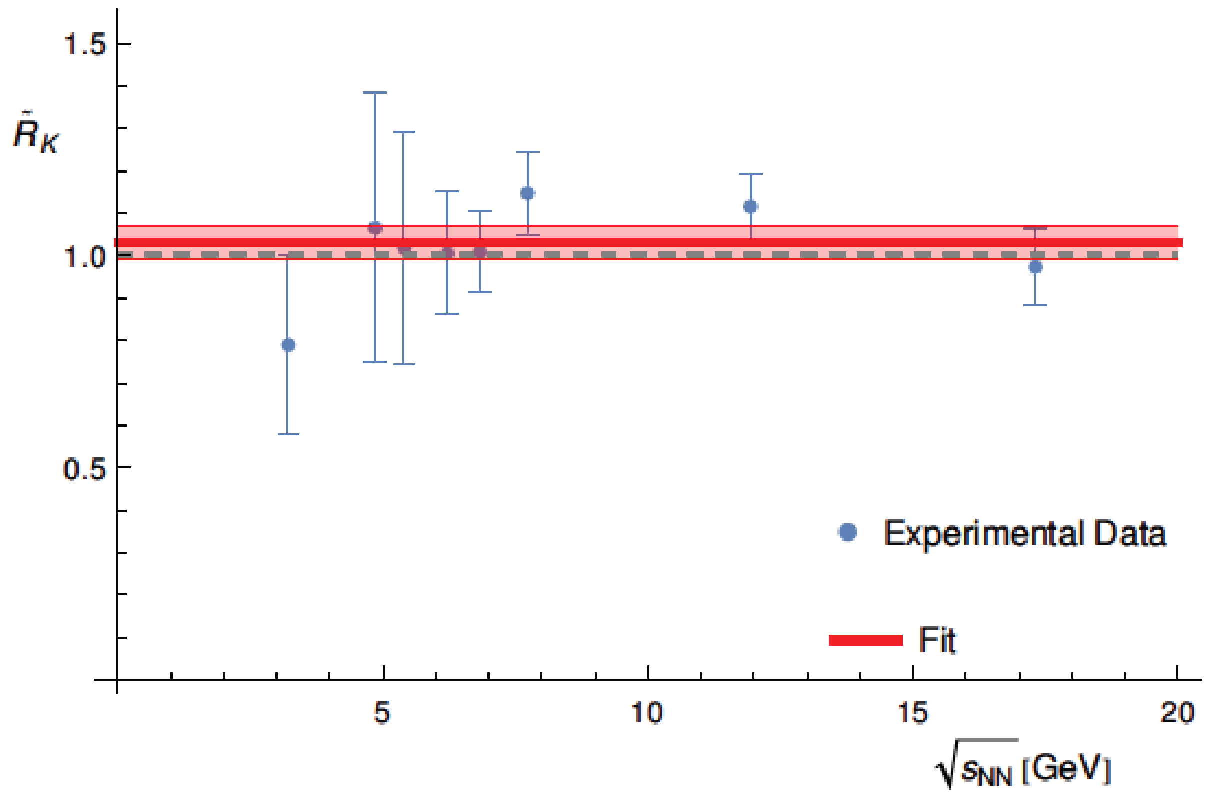
$$\alpha = \beta \quad \Rightarrow \quad \tilde{R}_K = 1$$

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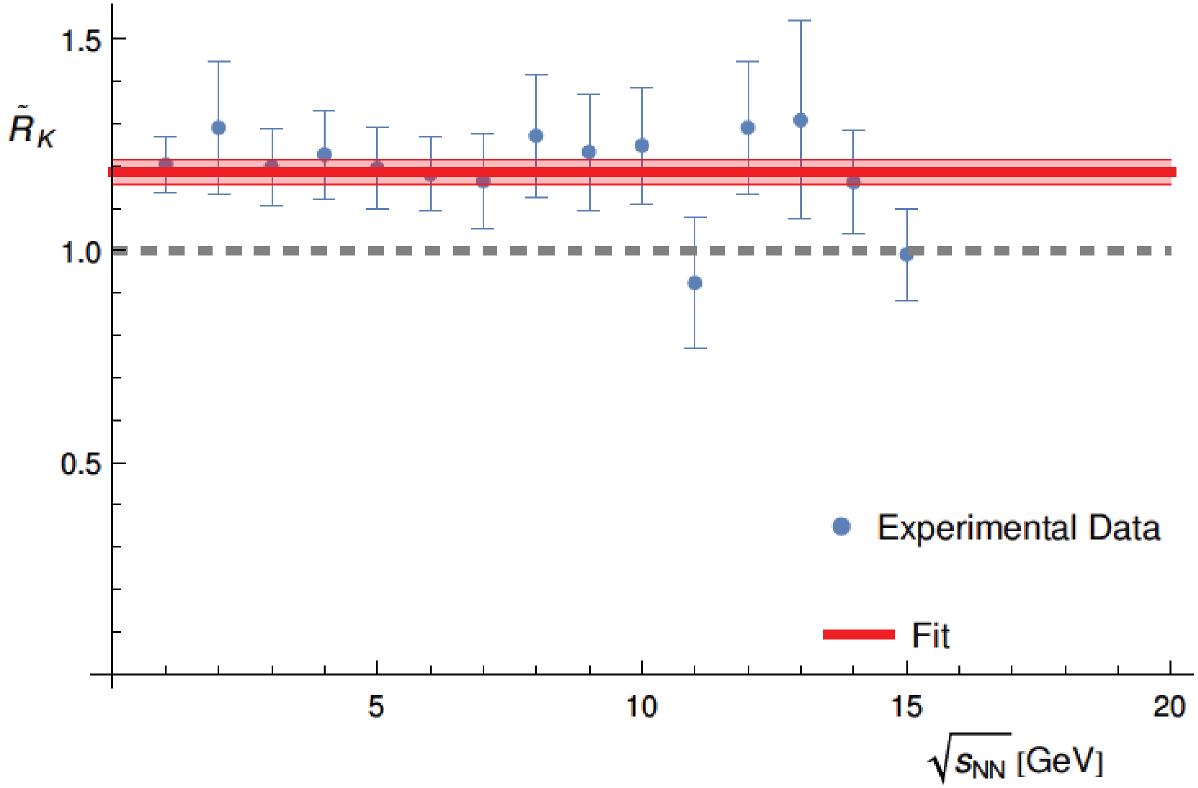
$$\tilde{R}_K = 1.030 \pm 0.038.$$

Nucleus-nucleus results for RtildeK: constant but not 1



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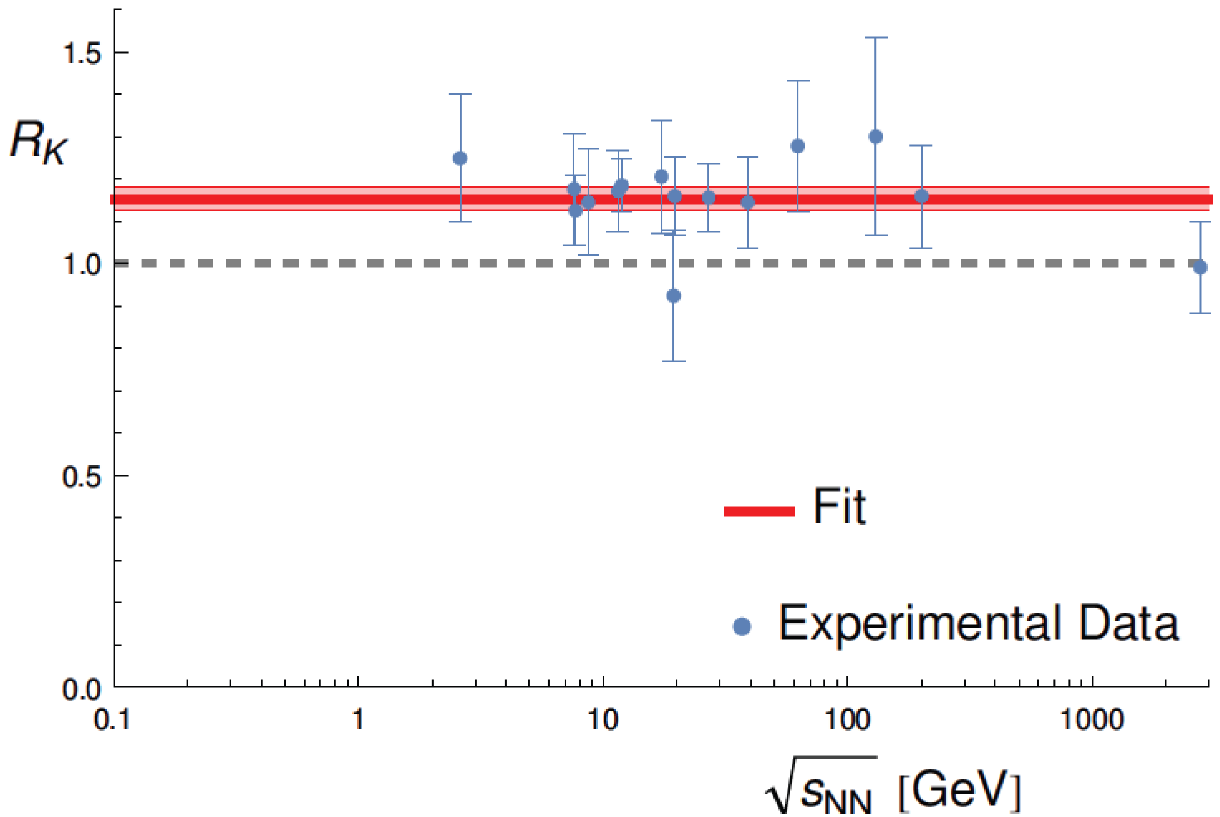
$$\tilde{R}_K = 1.185 \pm 0.029$$

This is 6.4 σ away from 1.

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



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

Predictions

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

Pion-nucleus scattering
antiquarks in the initial state

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

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

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

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, $\quad K^+\Lambda$

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.

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 $\pi^- + C$ and $\pi^+ + C$

nature communications

Article

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Uniwersytet
Jana Kochanowskiego w Kielcach

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.

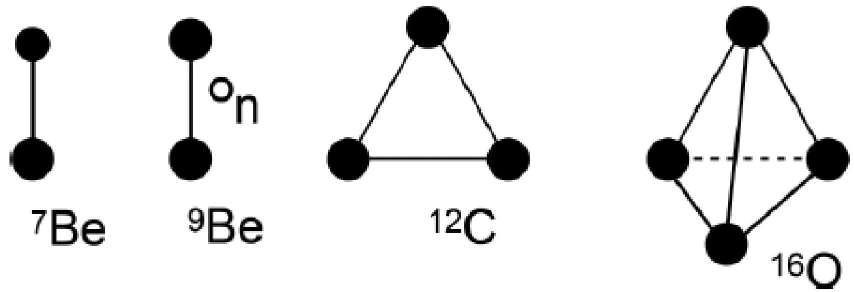

FIG. 1. Schematic view of the cluster structure of light nuclei. The dark blobs indicate α clusters (in the case of ^{7}Be, also the ^{3}He cluster). The additional open circle in ^{9}Be indicates the extra neutron.

PHYSICAL REVIEW C **97**, 034912 (2018)

Editors' Suggestion

Signatures of α clustering in ultrarelativistic collisions with light nuclei

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We explore possible observable signatures of α clustering of light nuclei in ultrarelativistic nuclear collisions involving ^{7,9}Be, ^{12}C, and ^{16}O. The clustering leads to specific spatial correlations of the nucleon distributions in the ground state, which are manifest in the earliest stage of the ultrahigh energy reaction. The formed initial

More on the resonance ϕ(1020)

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

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

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

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

Rescaling

$$\frac{R_K}{R_K^{HRG}} = 1.129 \pm 0.027 \; . \qquad \chi^2_{\rm min}/\mathrm{dof} = 0.3$$

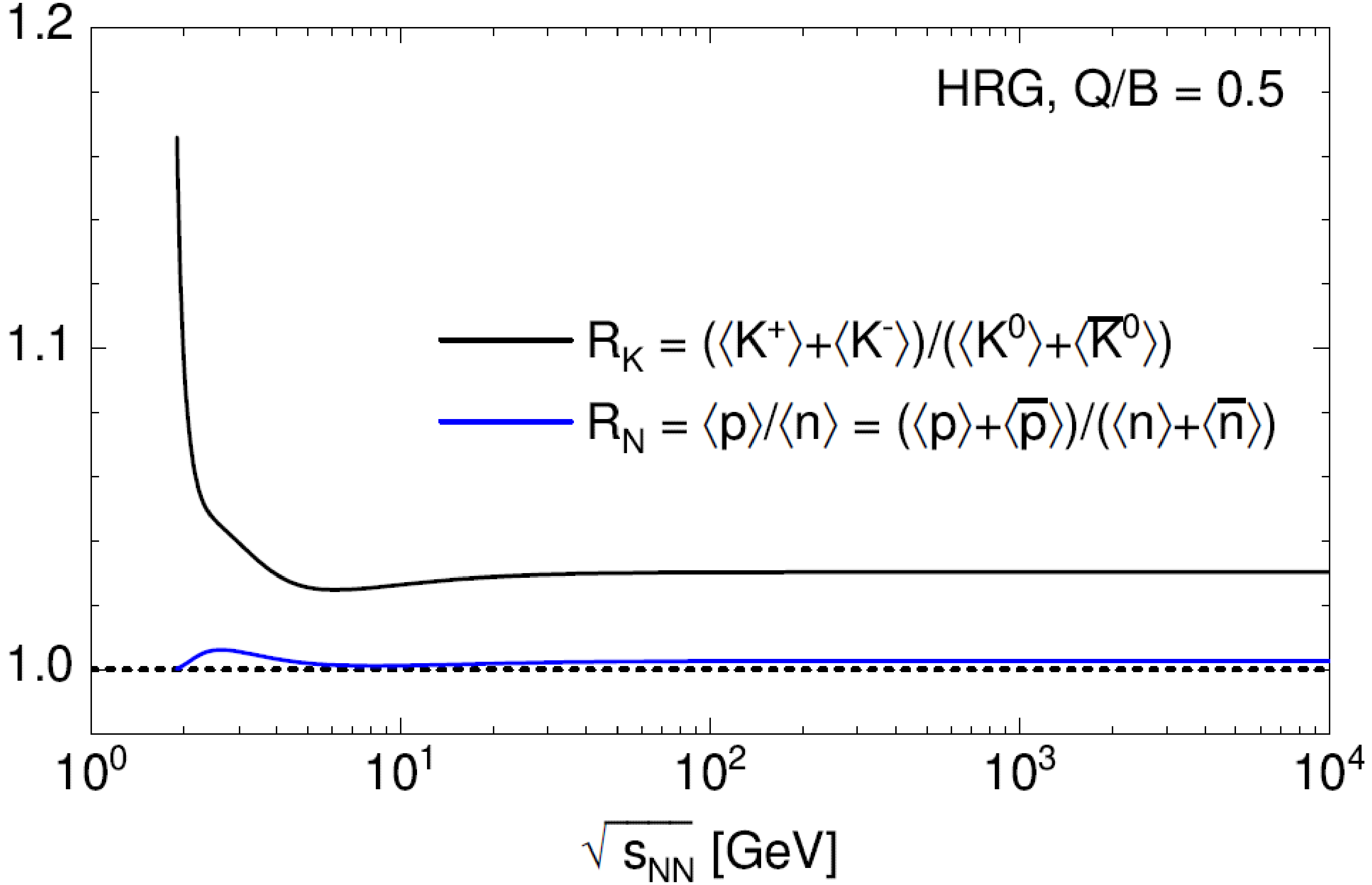
PDG-inspired: Decrease error so to get a chi^2/dof = 1

Procedure assumes the errors are overestimated.

$$\left(\frac{R_K}{R_K^{HRG}}\right)_{\rm rescaled} = 1.129 \pm 0.015$$

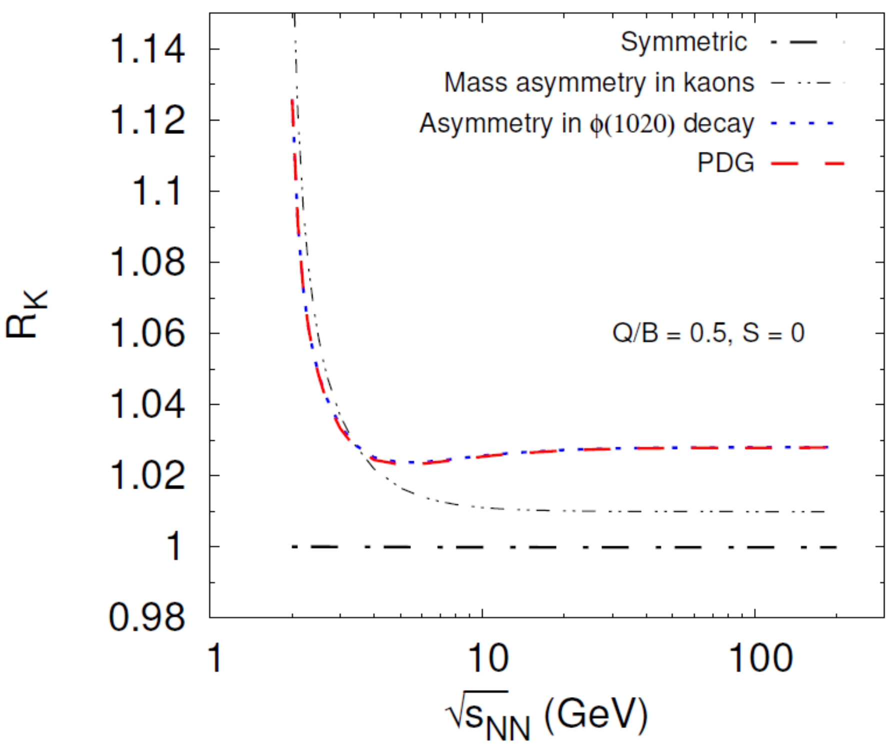
$$8.6\sigma$$

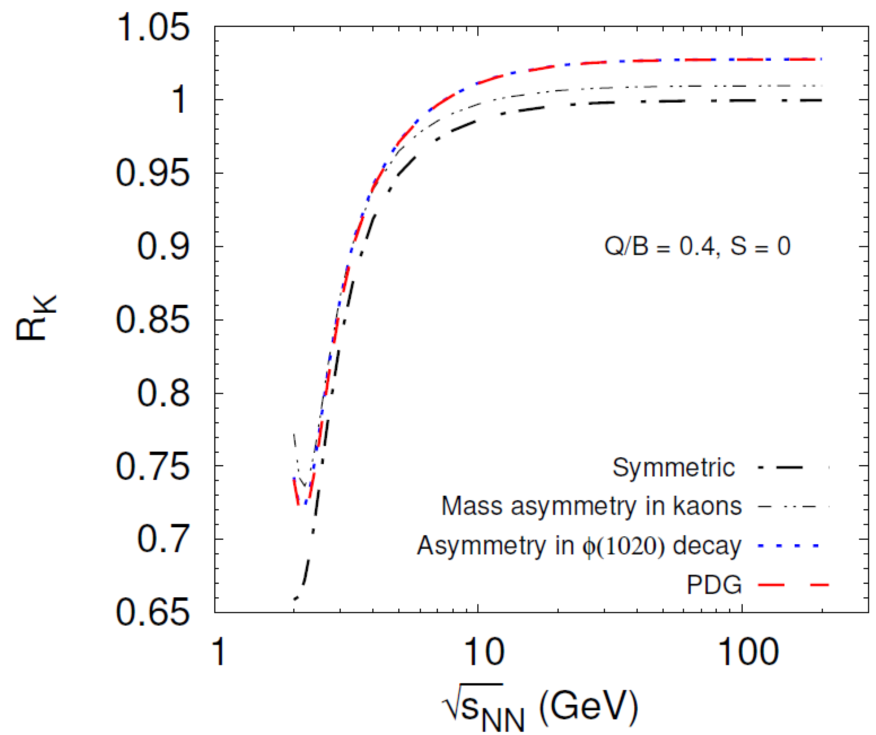
HRG for Q/B=1/2



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

HRG: Effects on RK due to Q/B





Why do we need Q/B=1/2

(Q/B)eff is larger than what expected…

If more neutrons are present, there can be nuclear reactions absorbing neutral kaons.

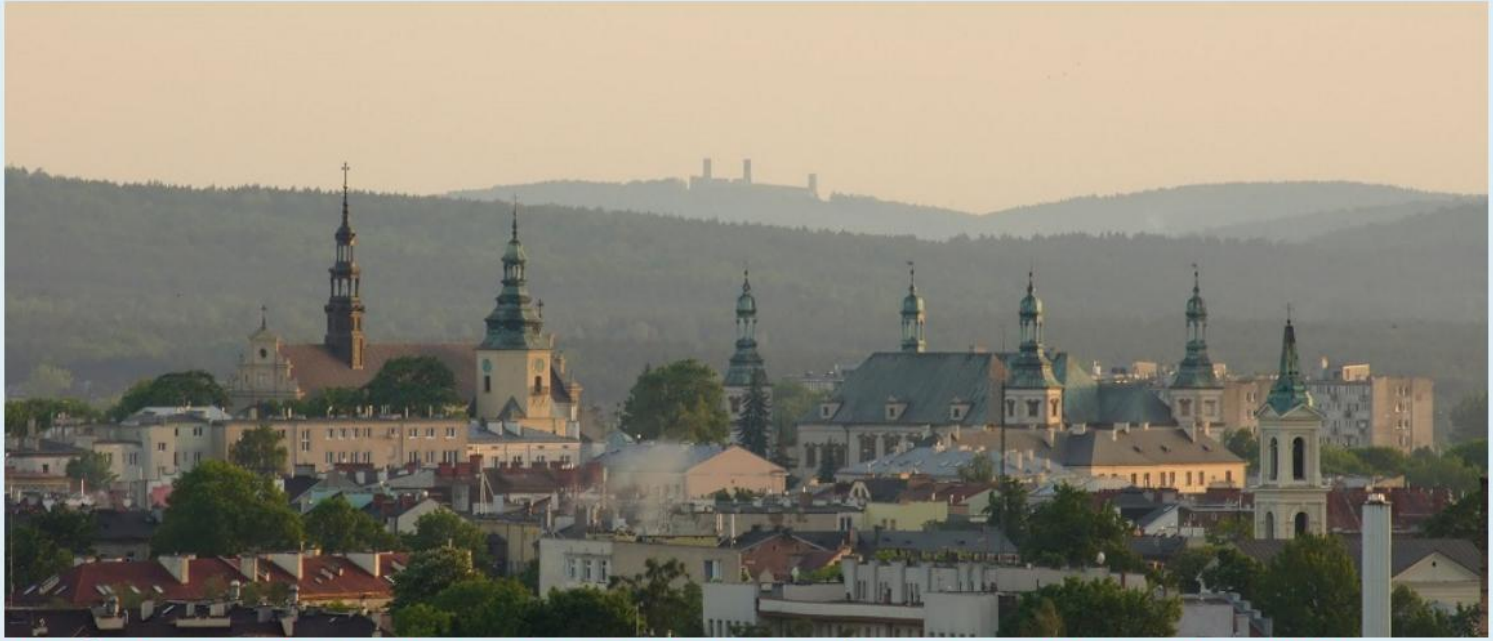
(ongoing discussion involving Λ, Σ, …)

No details yet ☺

Also in this case, Q/B=1/2 eliminates this problem.

Kielce, UJK, ISOBREAK 25

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

Why do we need Q/B=1/2

Q/B < 0.5 makes the symmetry argument less clean.

One may account for it in models (HRG, coalescence)

But …

RK = 1 is a a prediction of charge-symmetry, which requires an equal number of protons and neutrons.

Having nuclei with Q/B=1/2 provides a direct test without modelling…