

# The charged-vs-neutral kaon anomaly in heavy-ion collisions

Francesco Giacosa

Jan Kochanowski U Kielce – Goethe U Frankfurt

In collaboration with

Wojciech Brylinski, Marek Gazdzicki,  
Mark Gorenstein, Roman Poberezhnyuk,  
Subhasis Samanta, Herbert Stroebele  
+NA61/SHINE

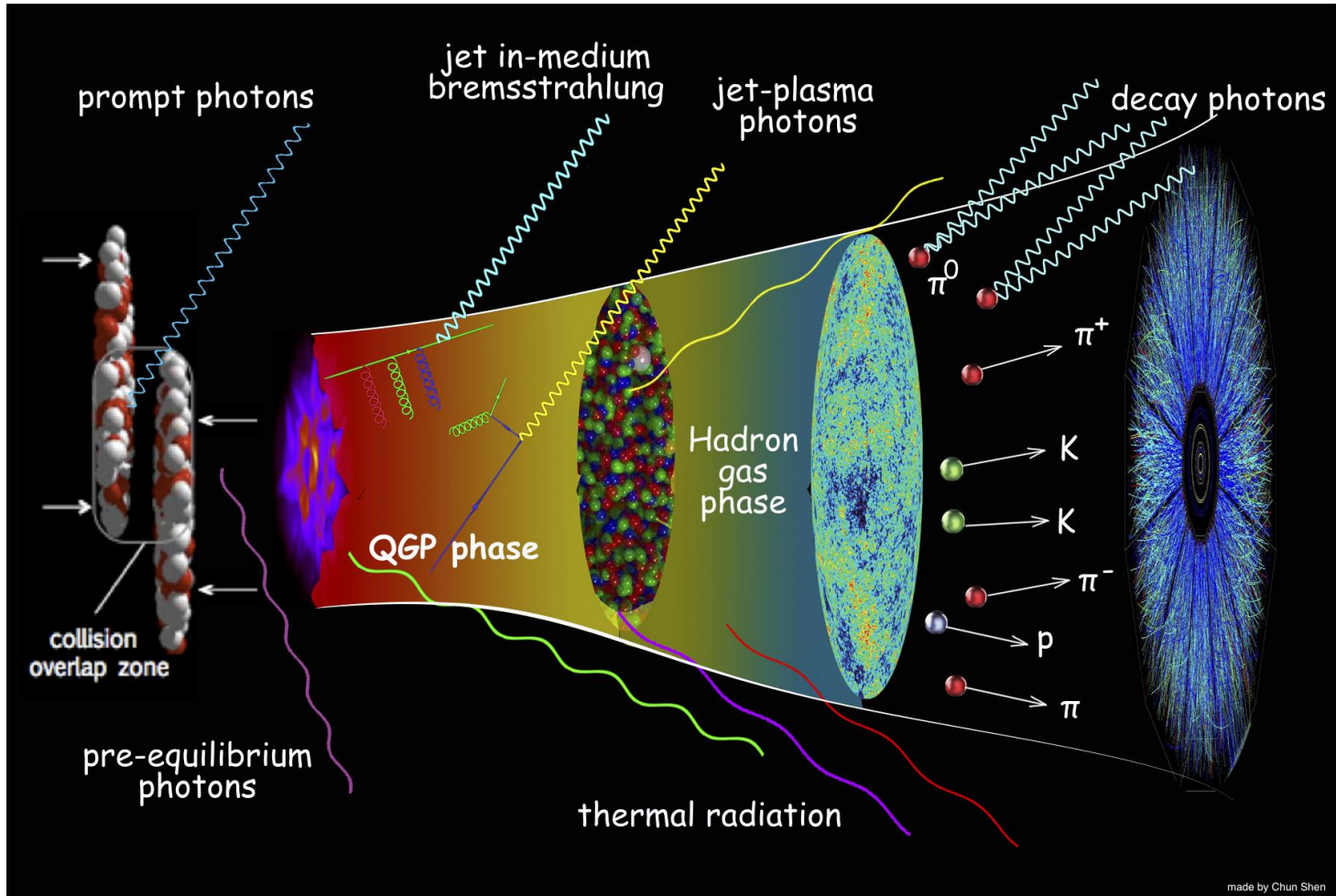
**Zimanyi Winter School 2024**  
**2-6/12/2024 Budapest**

# Outline



1. Heavy-Ion collisions: brief recall
2. Isospin: brief recall
3. Kaon productions
4. Theory vs experiment
5. Conclusions

# Heavy-ion collisions



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

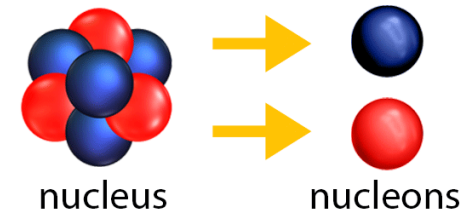
At the freeze-out, the emission of hadrons is well described by e.g. thermal models.

- Here, we concentrate on kaon production, especially on an unexpected large violation of isospin in charged to neutral kaon ratio
- Adhikary et al. [NA61/SHINE], Excess of Charged Over Neutral K Meson Production in High-Energy Collisions of Atomic Nuclei, [arXiv:2312.06572 [nucl-ex]]  
(new vs from October 2024 with both experiment and theory)
- ...as well as to a compilation of other experiments
- Brylinski et al., Large isospin symmetry breaking in kaon production at high energies," [arXiv:2312.07176 [nucl-th]].

# Heisenberg (1932): the nucleon

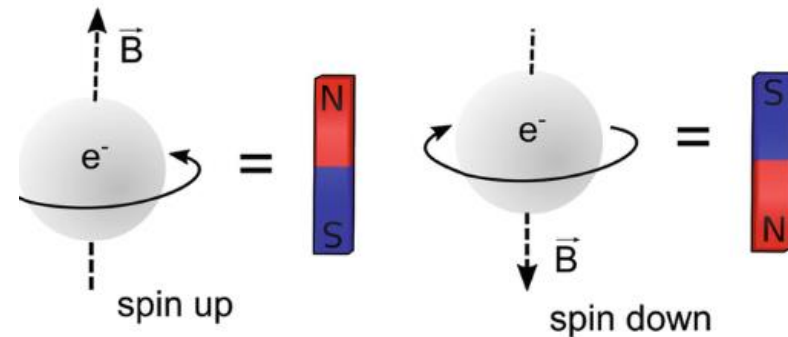
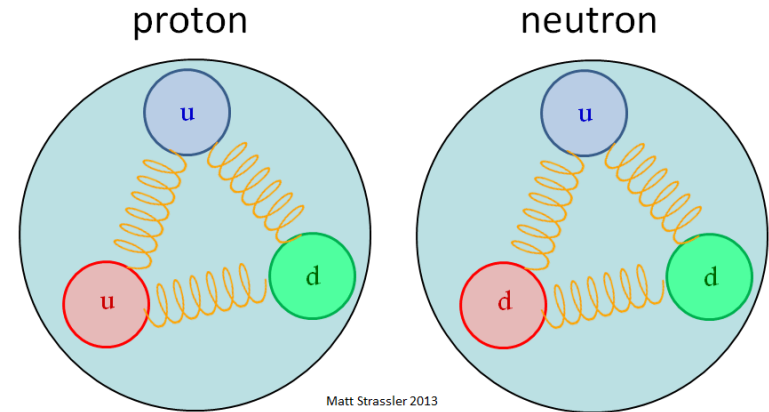
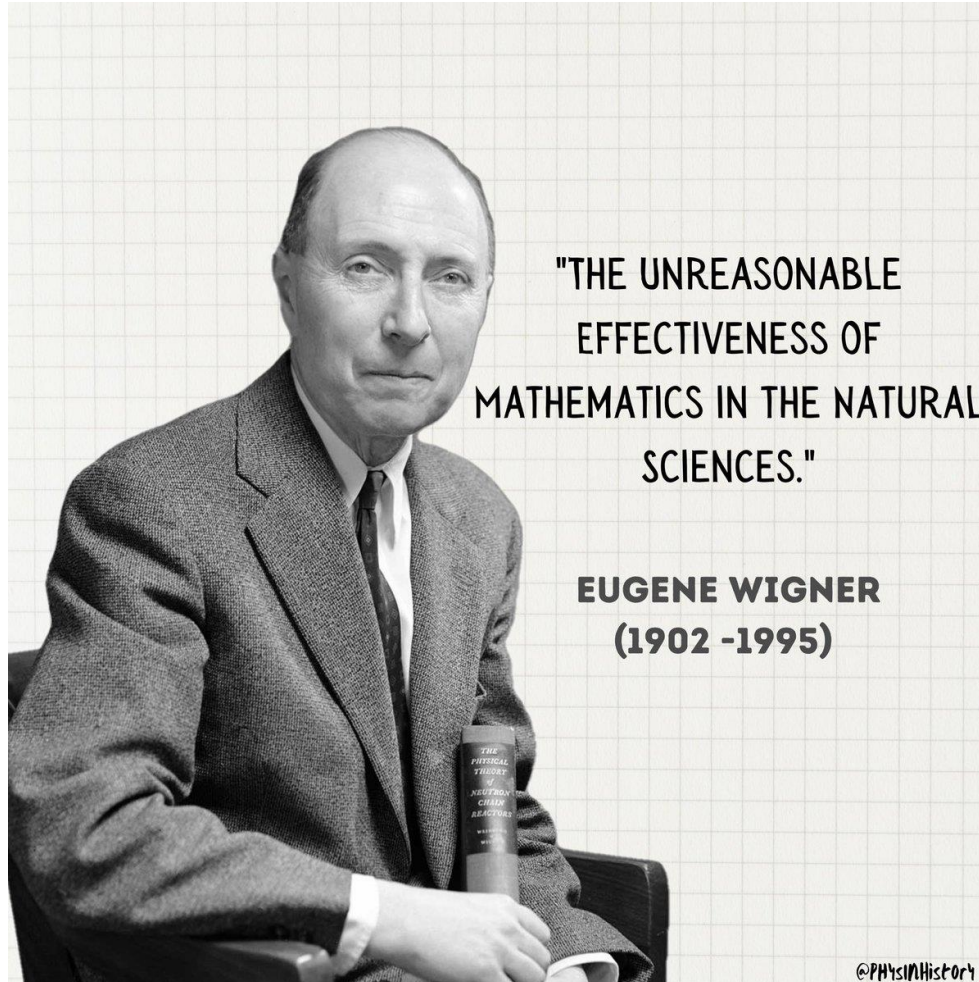


A nucleon is either a proton or a neutron as a component of an atomic nucleus



Proton and neutron merge into the nucleon  
Masses very similar.

# Wigner (1932): isotopic spin, thus isospin



## Nucleon doublet: $I=1/2$

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

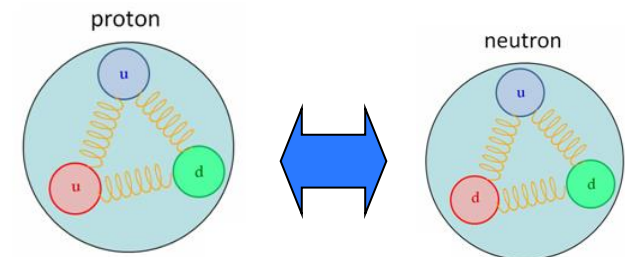
$\hat{O}$  is a  $2 \times 2$  unitary matrix.  $\hat{O} = e^{i\theta_i \sigma_i / 2}$

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

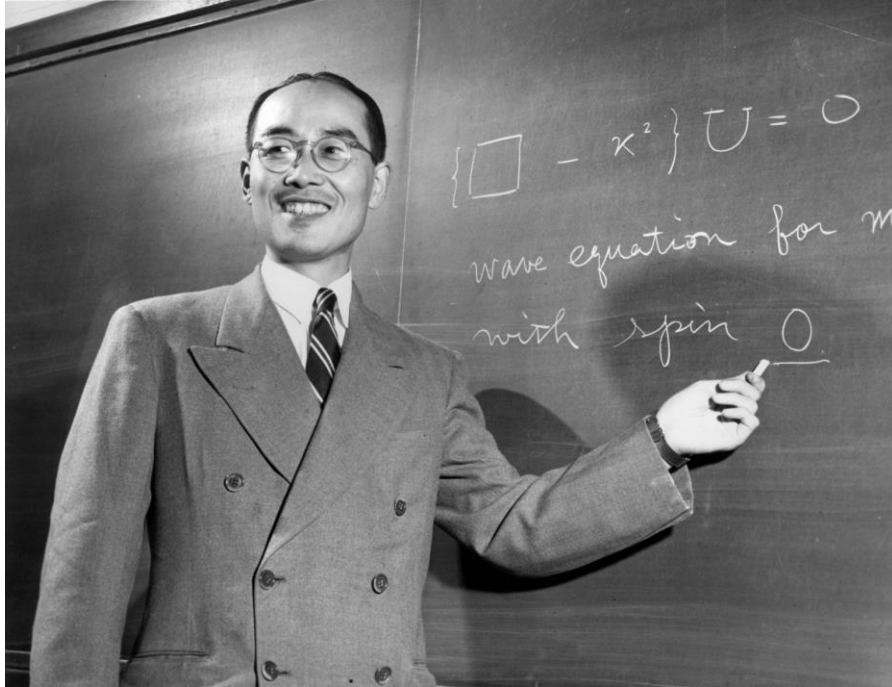
$$\hat{C} = e^{i\pi\sigma_2/2} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Then under  $\hat{C}$ :

$$p \iff n$$



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



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

under  $\hat{C}$ :

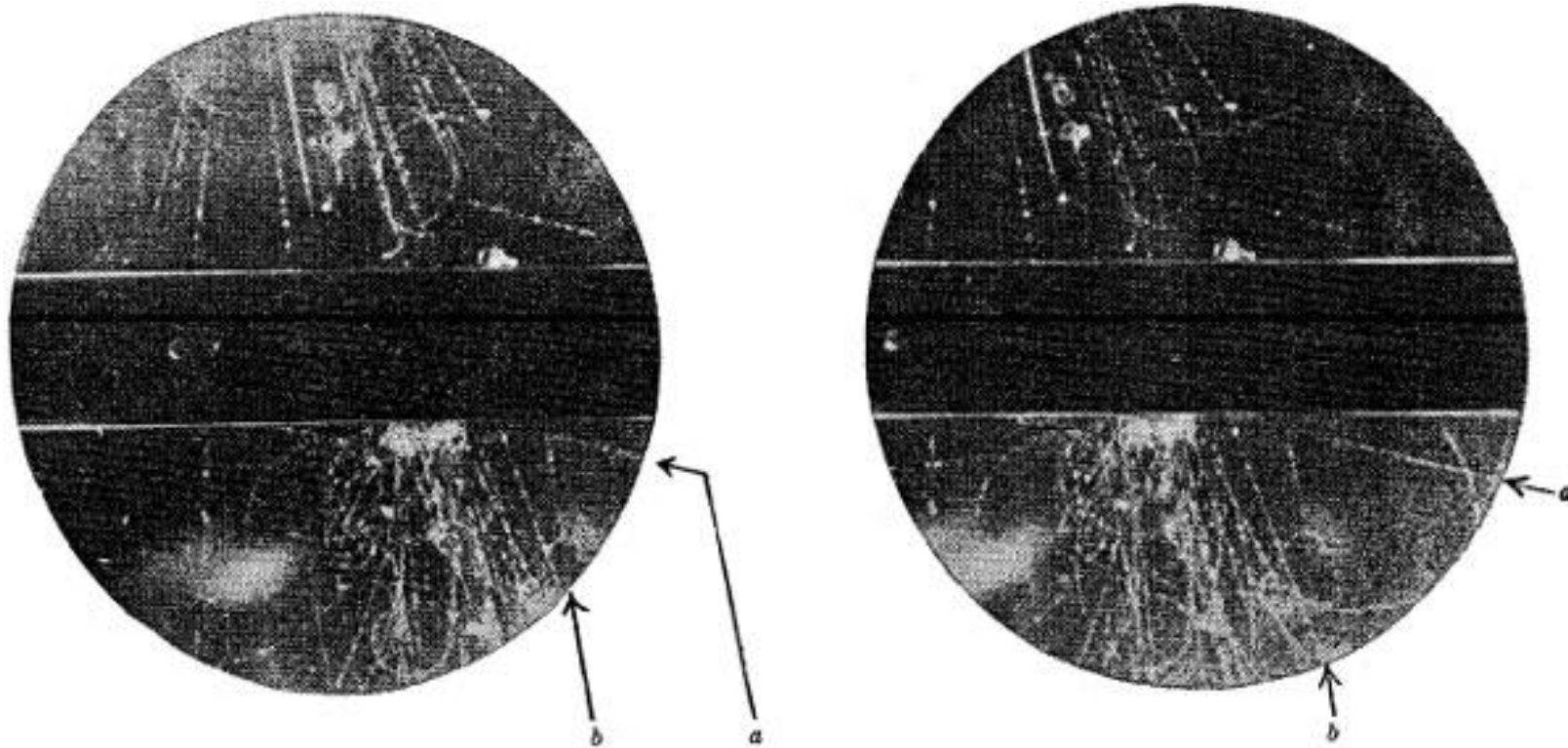
$$\pi^+ \iff \pi^-$$



# Kaons

20 DECEMBER 1947

Clifford Butler and George Rochester discover the kaon;  
first strange particle



Kaons form isospin doublets, just as the nucleon

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

under  $\hat{C}$ :

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

# Quarks and QCD



up



charm



top



down

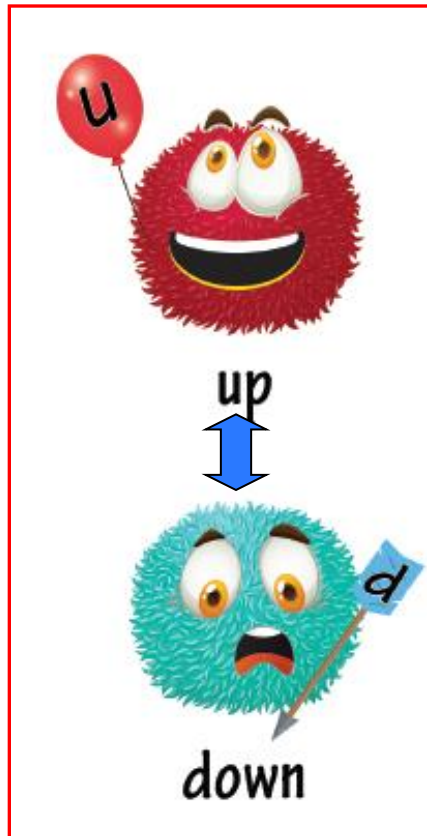


strange



bottom

# Quarks and QCD, isospin:



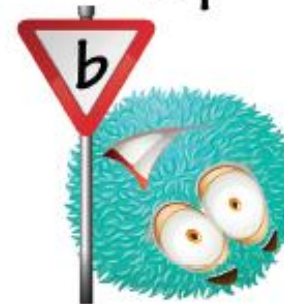
charm



strange



top



bottom

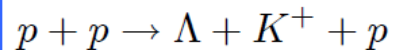
In terms of quarks:  $\begin{pmatrix} u \\ d \end{pmatrix} \rightarrow \hat{O} \begin{pmatrix} u \\ d \end{pmatrix}$

Then under  $\hat{C}$ :  $u \longleftrightarrow d$

# Isospin is an approximate symmetry of QCD

- Mesonic multiplets (nucleon doublet, pion triplet, kaon doublets).
- Reactions: if an initial state has a certain  $(I, I_z)$ , then the final state is also such. Indeed, pion-pion, pion-nucleon and nucleon-nucleon scattering conserve isospin (to a good level of accuracy).

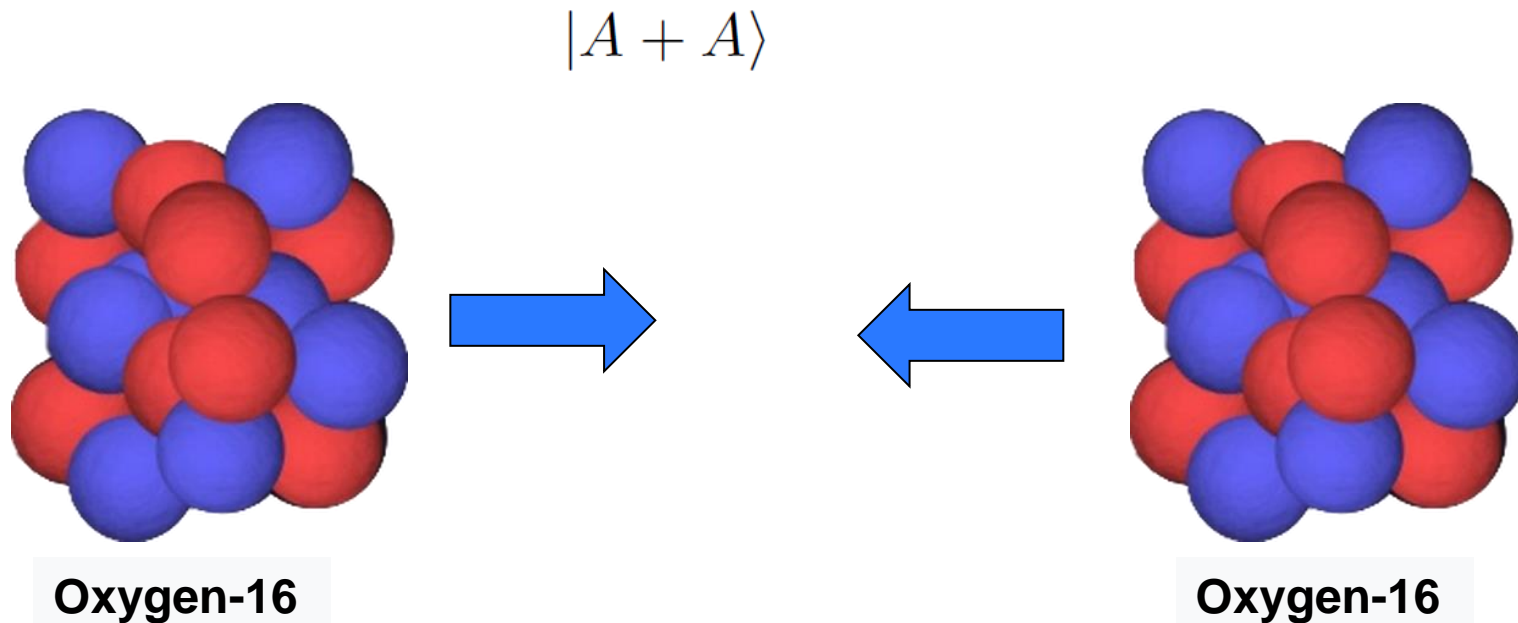
Example:  $(I=I_z=1)$



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

# 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)

## Toward the general initial state

- For total initial  $I = 0$  it is easy to show that  $\langle K^+ \rangle = \langle K^0 \rangle$
- The result can be easily extended to any **fixed** total initial isospin  $I=I_0$ .
- It can be even generalized to initial states that are not isospin eigenstates, provided that an appropriate average is performed.

## 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.

Then:

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

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



# Neutral kaons and the ratio $R_K$

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

$$\langle K_S^0 | = \frac{1}{2} \langle K^0 | + \frac{1}{2} \langle \bar{K}^0 | = \langle K_L^0 | \qquad \langle K^+ | + \langle K^- | = 2 \langle K_S^0 |$$

$$Q/B = 1/2$$

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

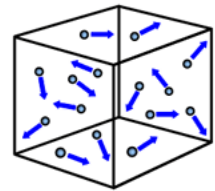
+ isospin exact...

# Theoretical approaches

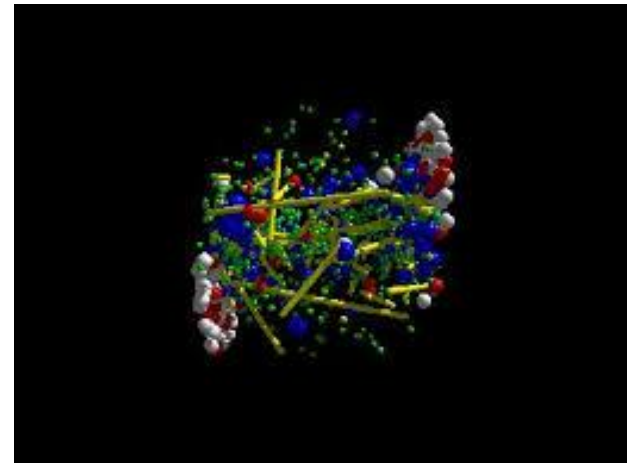
- HRG (hadron resonance gas approach)

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

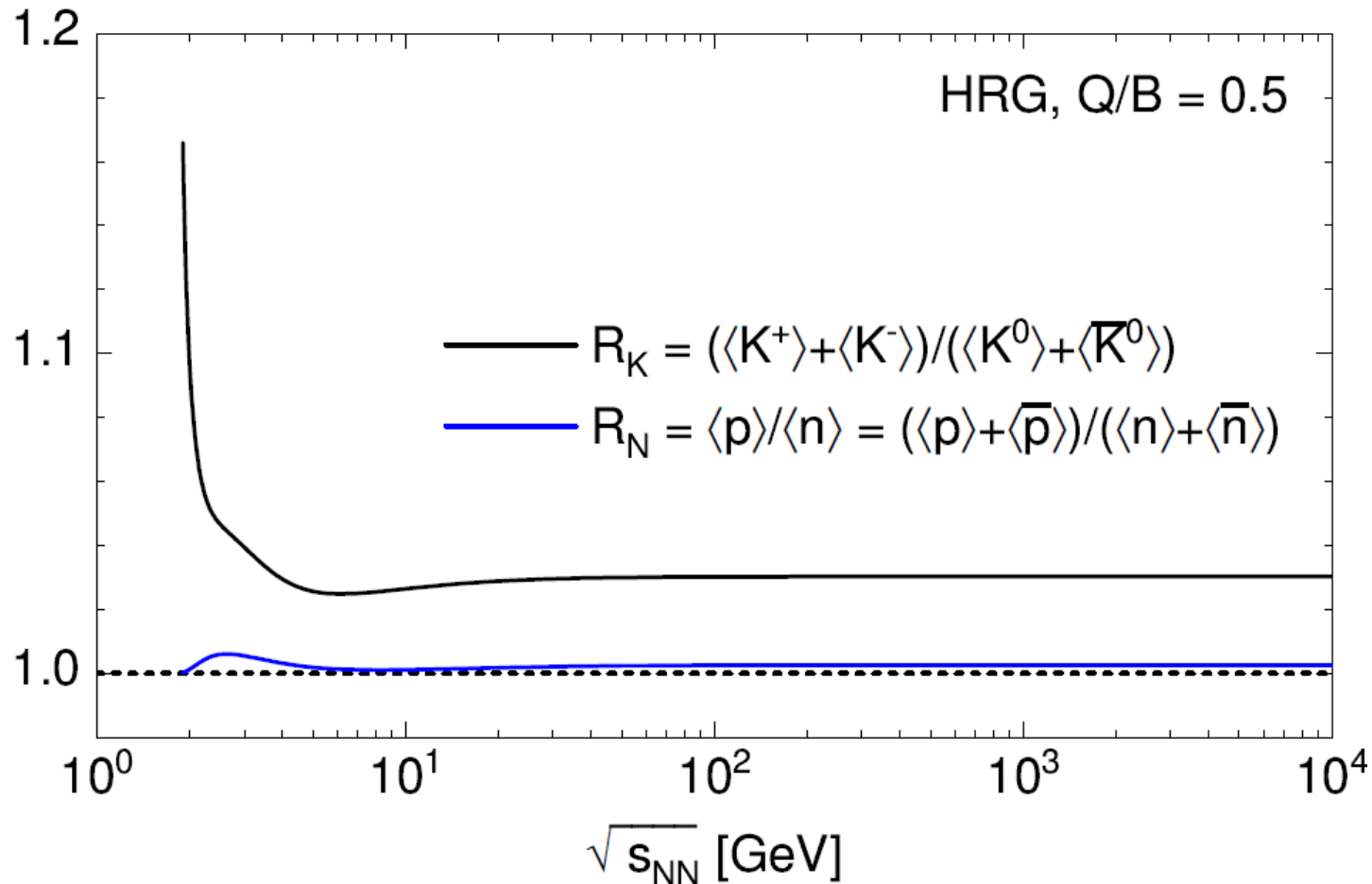
$$\ln Z_k^{\text{stable}, \pm} = f_k V \int \frac{d^3 p}{(2\pi)^3} \ln \left[ 1 \pm e^{-E_p/T} \right]^{\pm 1}$$



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

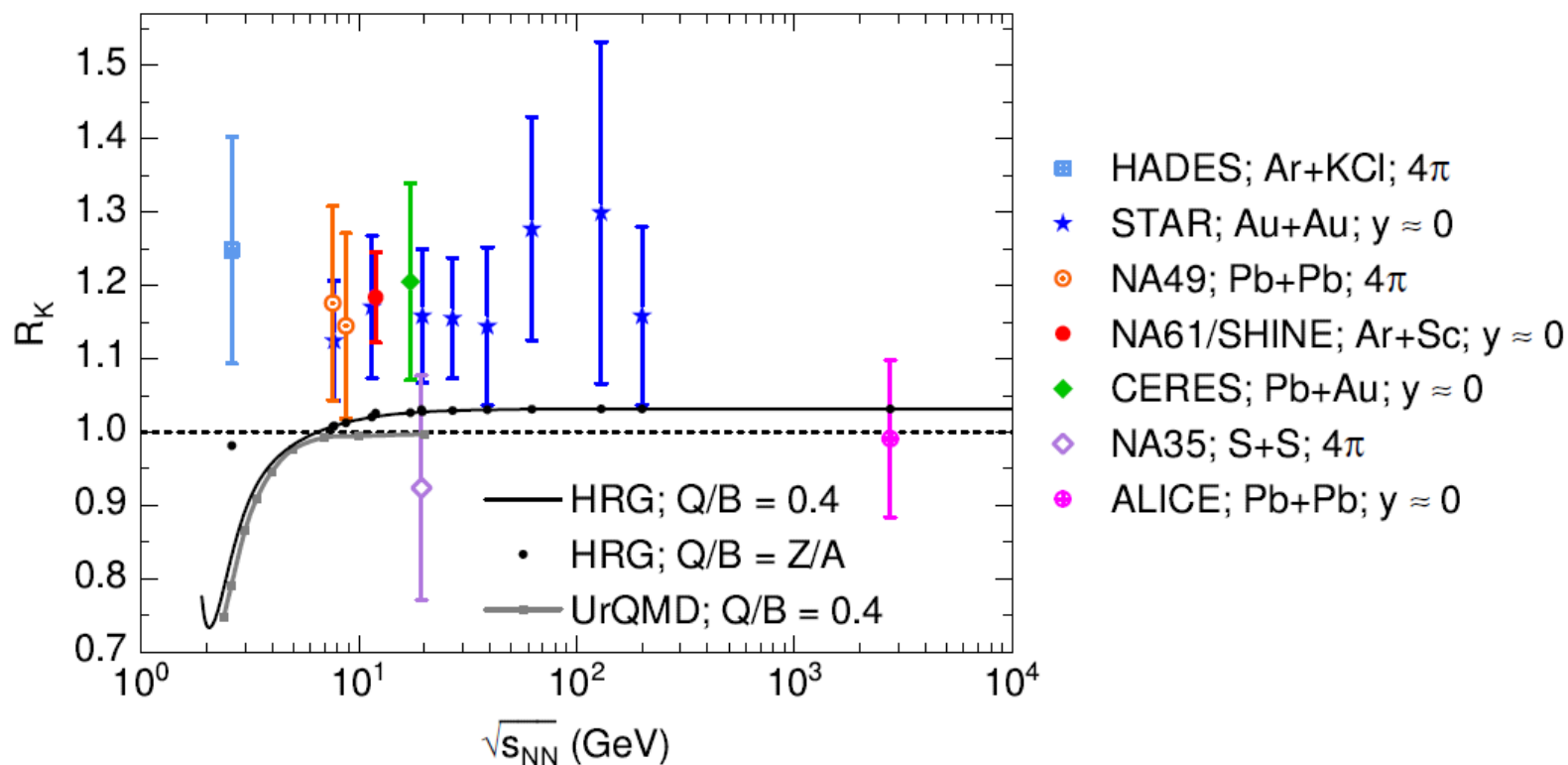


# HRG for $Q/B=1/2$



If we enforce isospin symmetry to be exact,  $R_K = 1$  for any energy. 19

# Experimental results (NA61/SHINE plus others)



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

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

# Experimental data: NA61/SHINE and previous exp

Experiment	Collision system	$\sqrt{s_{NN}}$ (GeV)	$R_K$	$\sigma_{stat}$	$\sigma_{total}$
NA61/SHINE	Ar+Sc	11.9	1.1839	0.0138	0.0615
HADES	Ar+KCl	2.6	1.2483	0.1027	0.1545
STAR (BES I)	Au+Au	7.7	1.1247	-	0.0819
STAR (BES I)	Au+Au	11.5	1.1707	-	0.0973
STAR (BES I)	Au+Au	19.6	1.1584	-	0.0910
STAR (BES I)	Au+Au	27	1.1553	-	0.0819
STAR (BES I)	Au+Au	39	1.1446	-	0.1079

NA49	Pb+Pb	7.6	1.1758	0.0198	0.1325
NA49	Pb+Pb	8.7	1.1447	0.0295	0.1263
CERES	Pb+Au	17.3	1.2052	0.0539	0.1340
NA35	S+S	19.4	0.9238	-	0.1533
STAR	Au+Au	62.4	1.2774	-	0.1525
STAR	Au+Au	130	1.2994	-	0.2331
STAR	Au+Au	200	1.1586	-	0.1214
ALICE	Pb+Pb	2760	0.9909	-	0.1071

# Considerations

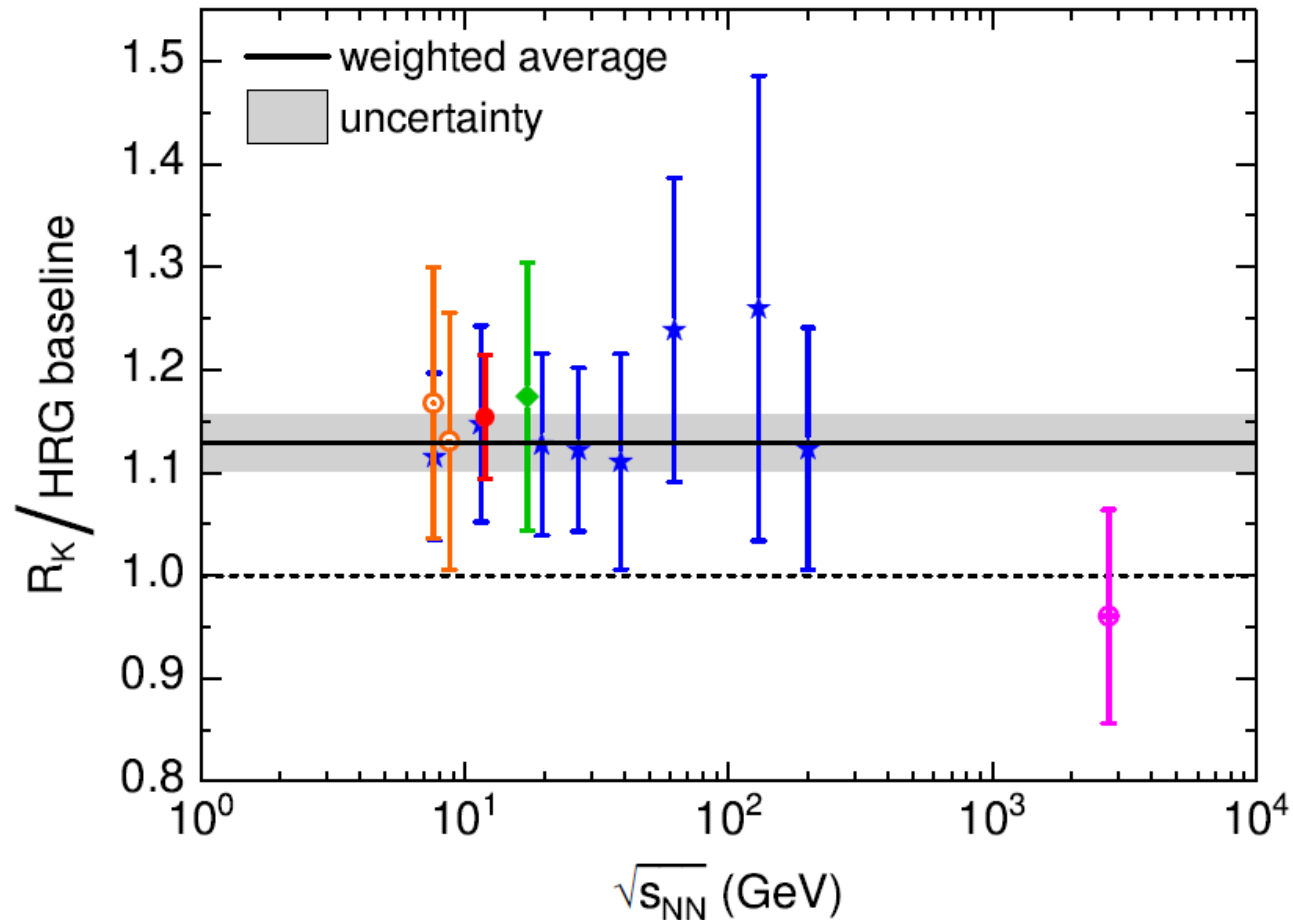
- HRG and UrQMD agree with each other
- $Q/B < 1/2$  favors neutral kaons
- charged kaons are lighter than neutral ones:  
this favors charged kaons

- Non-QCD effects: weak processes are negligible
- Non-QCD effects: electromagnetic processes are small, of the order of  $\alpha^2$ . Nonperturbative effects possible for soft charged kaons.
- Decays of  $\phi(1020)$  meson as well as other asymmetries generate quite small effects Role of  $a_0(980)$  and  $f_0(980)$  is also small.

# Experiment vs theory: ratio

$$1.129 \pm 0.027.$$

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



The exp/th mismatch is  $4.7\sigma$ .



# Summary and conclusions

- Theory (HRG,UrQMD) cannot explain experiment
- Scattering of nuclei with  $Z=N=A/2$  highly desired...

- Easier but equally good? Average over:  $\pi^- + C$  and  $\pi^+ + C$

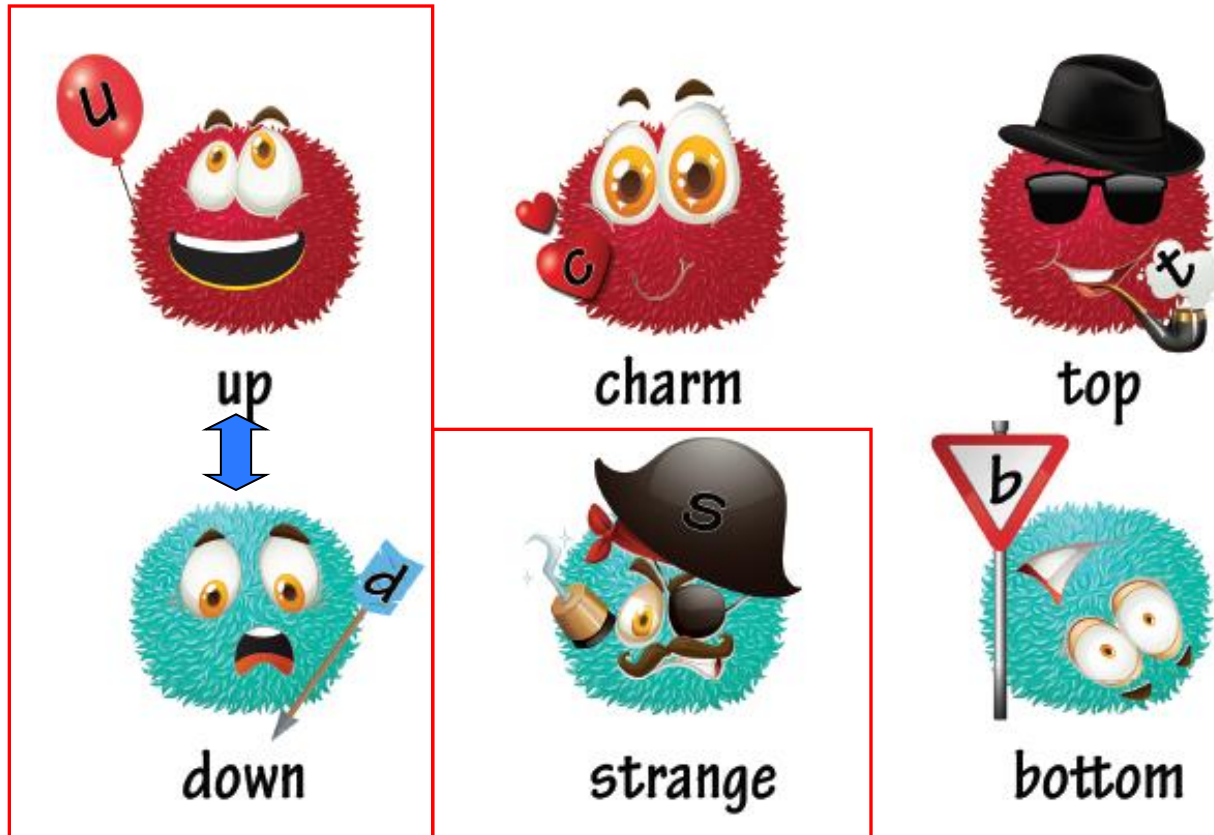
NA61/SHINE

PRD 107 (2003) 062004

- Study other isospin multiplets
- Non-perturbative effects? Chiral anomaly (Pisarski&Wilczek,...)

Thanks!

# Quarks and QCD, flavor symmetry:



Flavor transformation is a rotation in the  $(u,d,s)$  space.  
Isospin is a subgroup of flavor.

# Example of isospin breaking/1



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/84-27

March 8th, 1984

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

IHEP<sup>1</sup>-IISN<sup>2</sup>-LAPP<sup>3</sup> Collaboration

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

# Example of isospin breaking/2

$\phi(1020)$

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

### $\phi(1020)$ MASS

<u>VALUE (MeV)</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>1019.461 ± 0.016</b>	<b>OUR AVERAGE</b>			

### $\phi(1020)$ DECAY MODES

Mode	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level
$\Gamma_1 \quad K^+ K^-$	(49.1 ± 0.5 ) %	S=1.3
$\Gamma_2 \quad K_L^0 K_S^0$	(33.9 ± 0.4 ) %	S=1.2

# Example of isospin breaking/3

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022) and 2023 update

$D^*(2007)^0$

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

$I, J, P$  need confirmation.

$J$  consistent with 1, value 0 ruled out (NGUYEN 77).

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022) and 2023 update

$D^*(2010)^\pm$

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

$I, J, P$  need confirmation.

## $D^*(2007)^0$ DECAY MODES

$\bar{D}^*(2007)^0$  modes are charge conjugates of modes below.

Mode	Fraction ( $\Gamma_i/\Gamma$ )
$\Gamma_1$ $D^0 \pi^0$	$(64.7 \pm 0.9) \%$
$\Gamma_2$ $D^0 \gamma$	$(35.3 \pm 0.9) \%$
$\Gamma_3$ $D^0 e^+ e^-$	$(3.91 \pm 0.33) \times 10^{-3}$

## $D^*(2010)^\pm$ DECAY MODES

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

Mode	Fraction ( $\Gamma_i/\Gamma$ )
$\Gamma_1$ $D^0 \pi^+$	$(67.7 \pm 0.5) \%$
$\Gamma_2$ $D^+ \pi^0$	$(30.7 \pm 0.5) \%$
$\Gamma_3$ $D^+ \gamma$	$(1.6 \pm 0.4) \%$

# Historical recall: „Shmushkevich” rule

An initial ‘uniform’ ensemble of hadronic state (that is, one with an equal mean number of each member of any isospin multiplet, such as the scattering of two isosinglet nuclei) evolves into a uniform final-state ensemble.

## Uniform stays uniform

Shmushkevich, I.: . Dokl. Akad. Nauk SSSR **103**, 235 (1955)

Dushin, N., Shmushkevich, I.: . Dokl. Akad. Nauk SSSR **106**, 801 (1956)

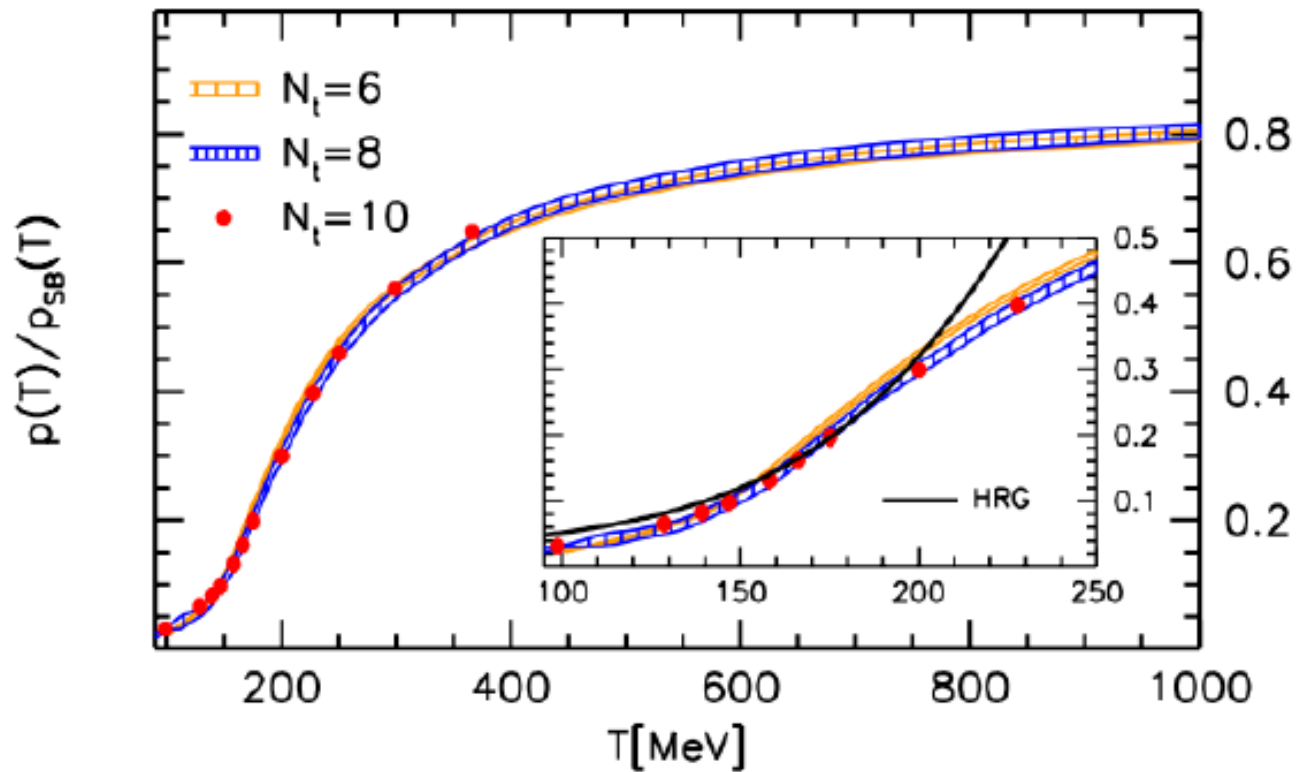
MacFarlane, A.J., Pinski, G., Sudarshan, G.: Shmushkevich’s method for a charge independent theory. Phys. Rev. **140**, 1045 (1965) <https://doi.org/10.1103/PhysRev.140.B1045>

Wohl, C.G.: Isospin relations by counting. American Journal of Physics **50**(8), 748–753 (1982) <https://doi.org/10.1119/1.12743>

Pal, P.: An Introductory Course of Particle Physics -CRC Press, (2014)

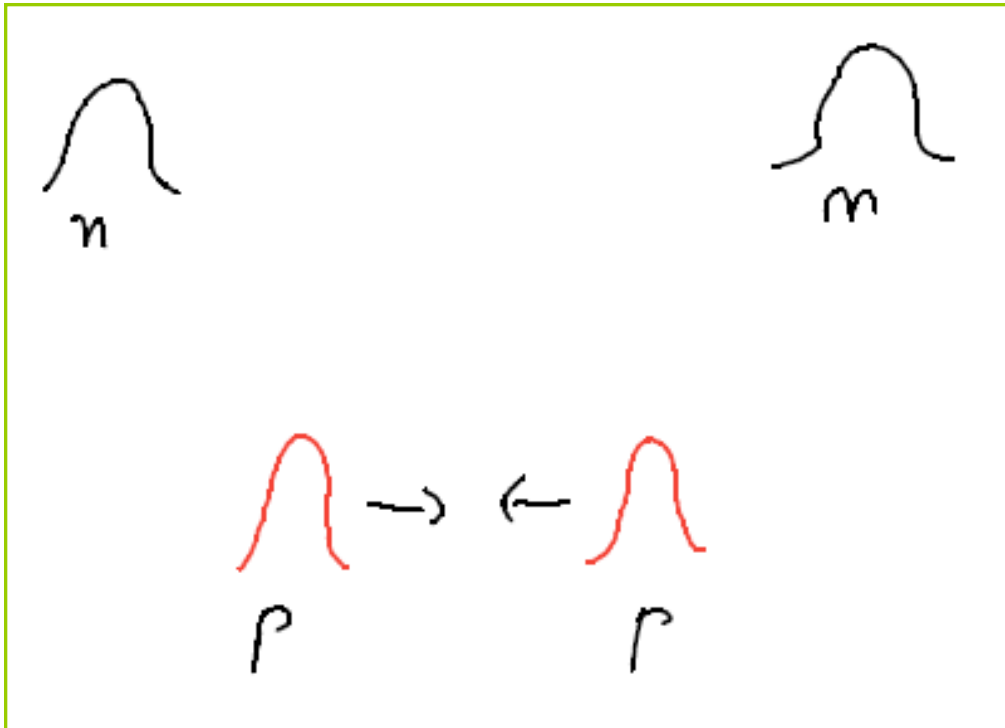
# Hadron resonance gas vs lattice results

- All baryons and mesons ( $m < 2.5$  GeV) from PDG [Borsanyi et al. JHEP11(2010)077]





ppmm  $\mapsto$  ?



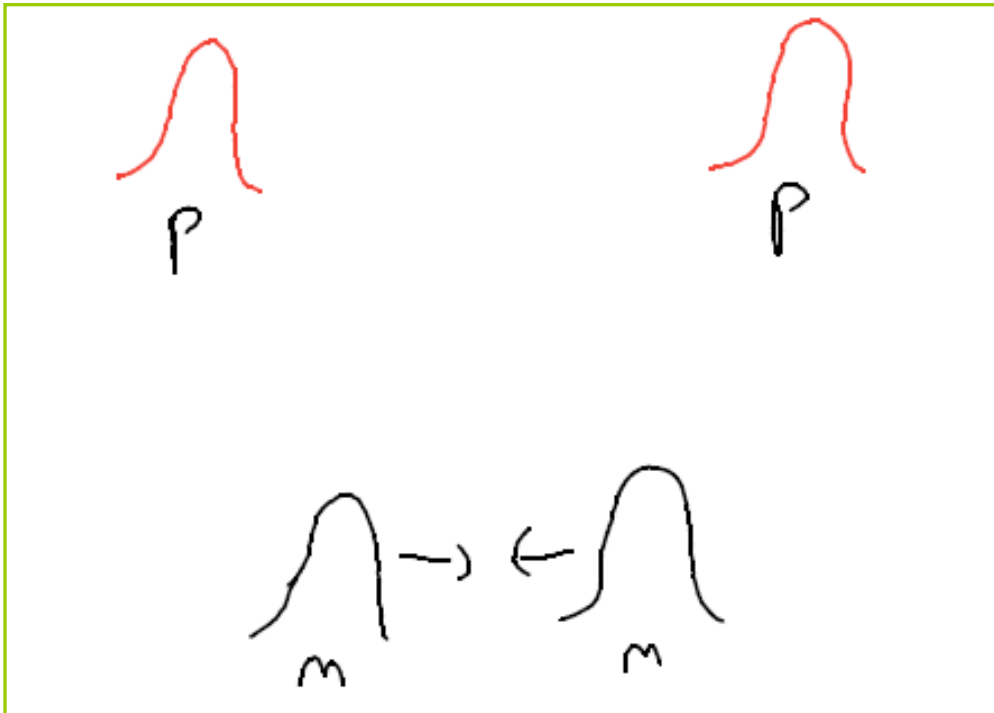
Just as pp!

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 for the previous reaction.

Here, the protons are spectators 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!

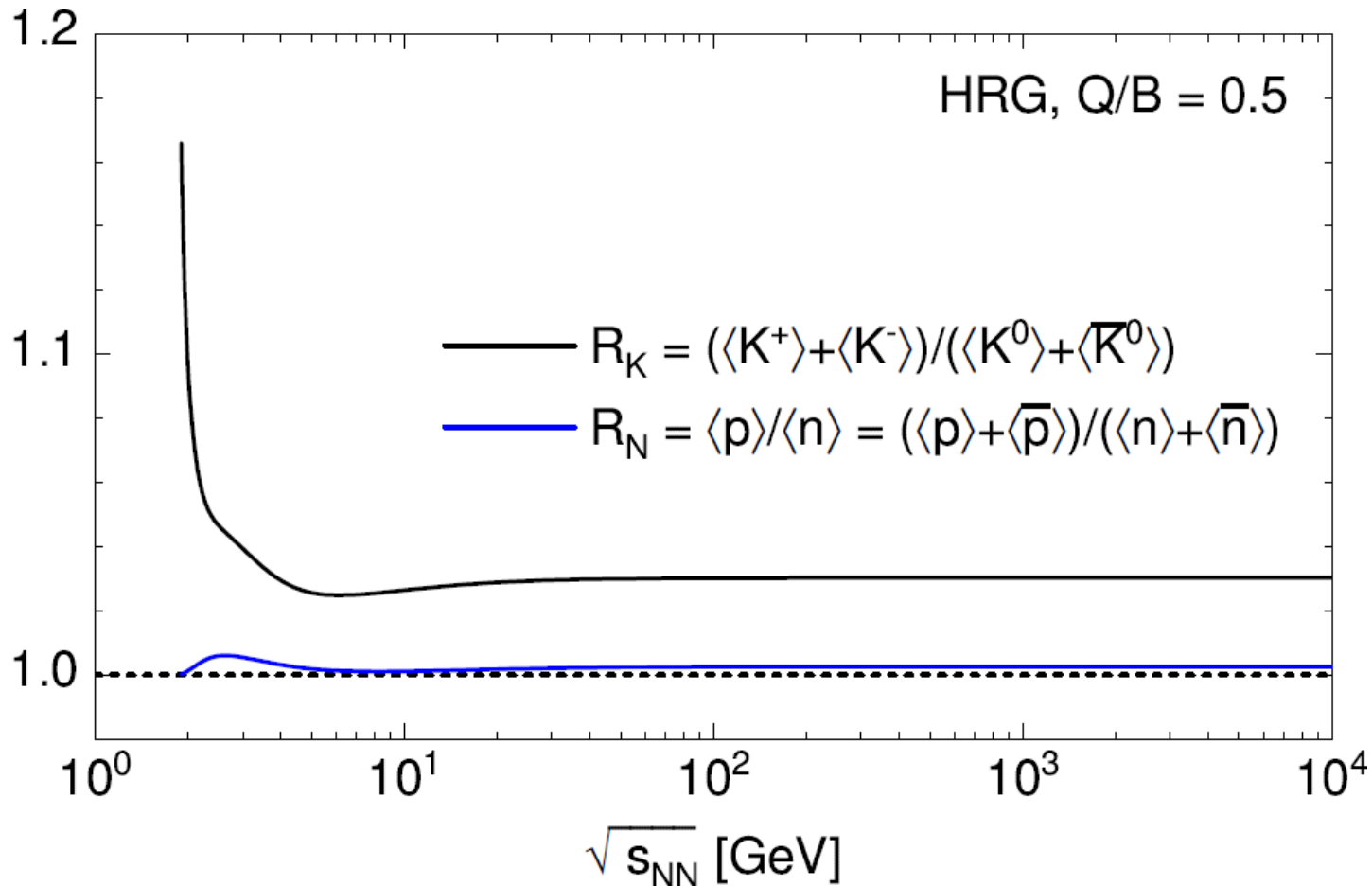
This is a general result!

Formally:

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

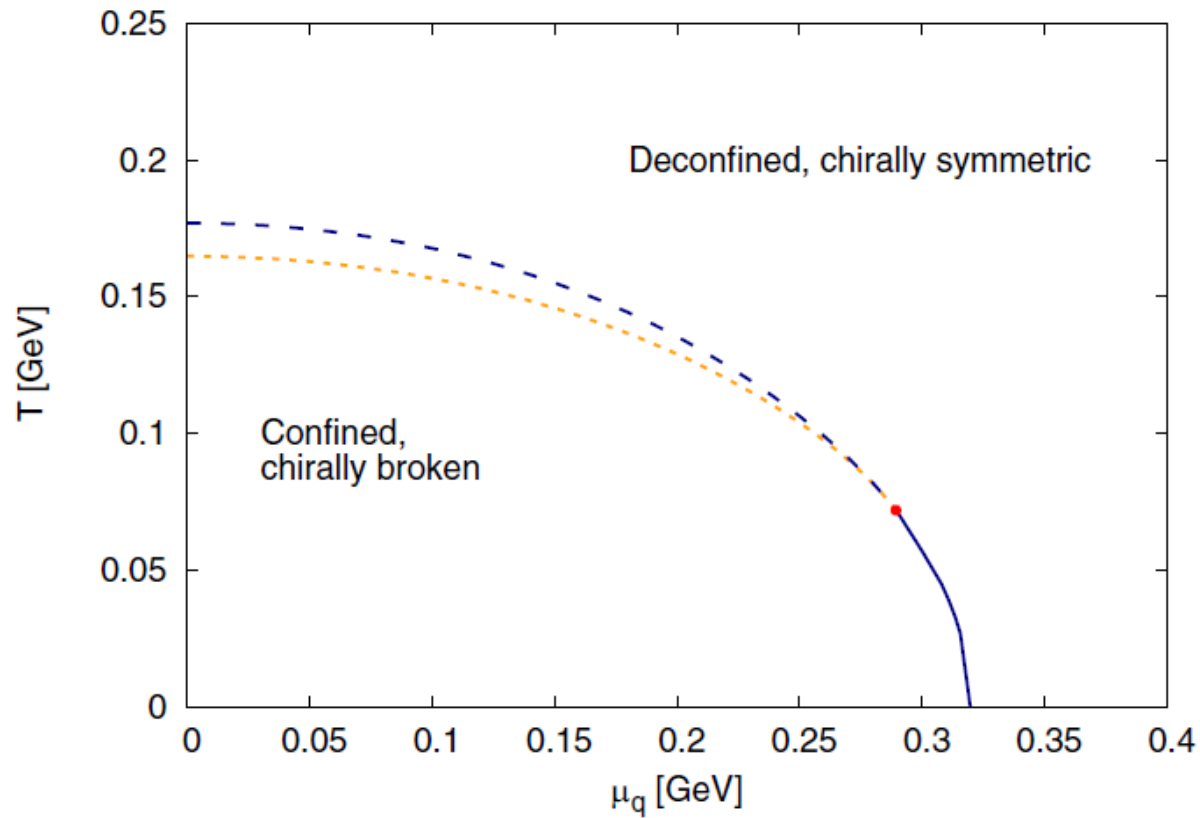
$$\hat{C} \hat{\rho} \hat{C}^\dagger = \hat{\rho}$$

# HRG for $Q/B=1/2$



If we enforce isospin symmetry to be exact,  $R_K = 1$  for any energy. 36

# Phase diagram of the eLSM: $N_c = 3$



Details in 2209.09568

# Schematic phase diagram at large $N_c$

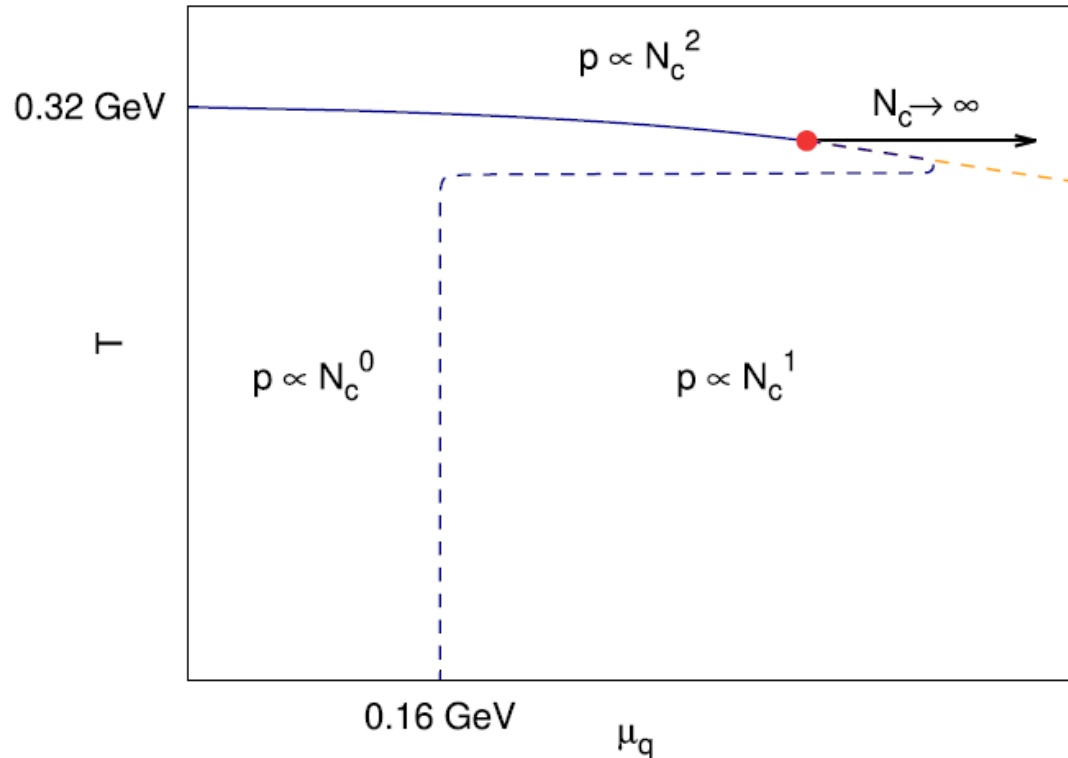


FIG. 13. The schematic phase diagram for large  $N_c$  and the  $N_c$  scaling of the pressure in the different phases.

Details in 2209.09568.

Then, for the QCD diagram: 3 is not a large number!!!!

Comment:

Let us consider an ensemble of initial states being invariant under the charge transformation - probabilities of having initial states related by this transformation are equal. This is the case of nucleus-nucleus collisions where each nucleus has an equal number of protons and neutrons (thus,  $I_z = 0$ ). Then, the invariance under C-transformation holds also for the final state ensemble: