Isospin Violation in Heavy-Ion Collisions

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+NA61/SHINE feedback

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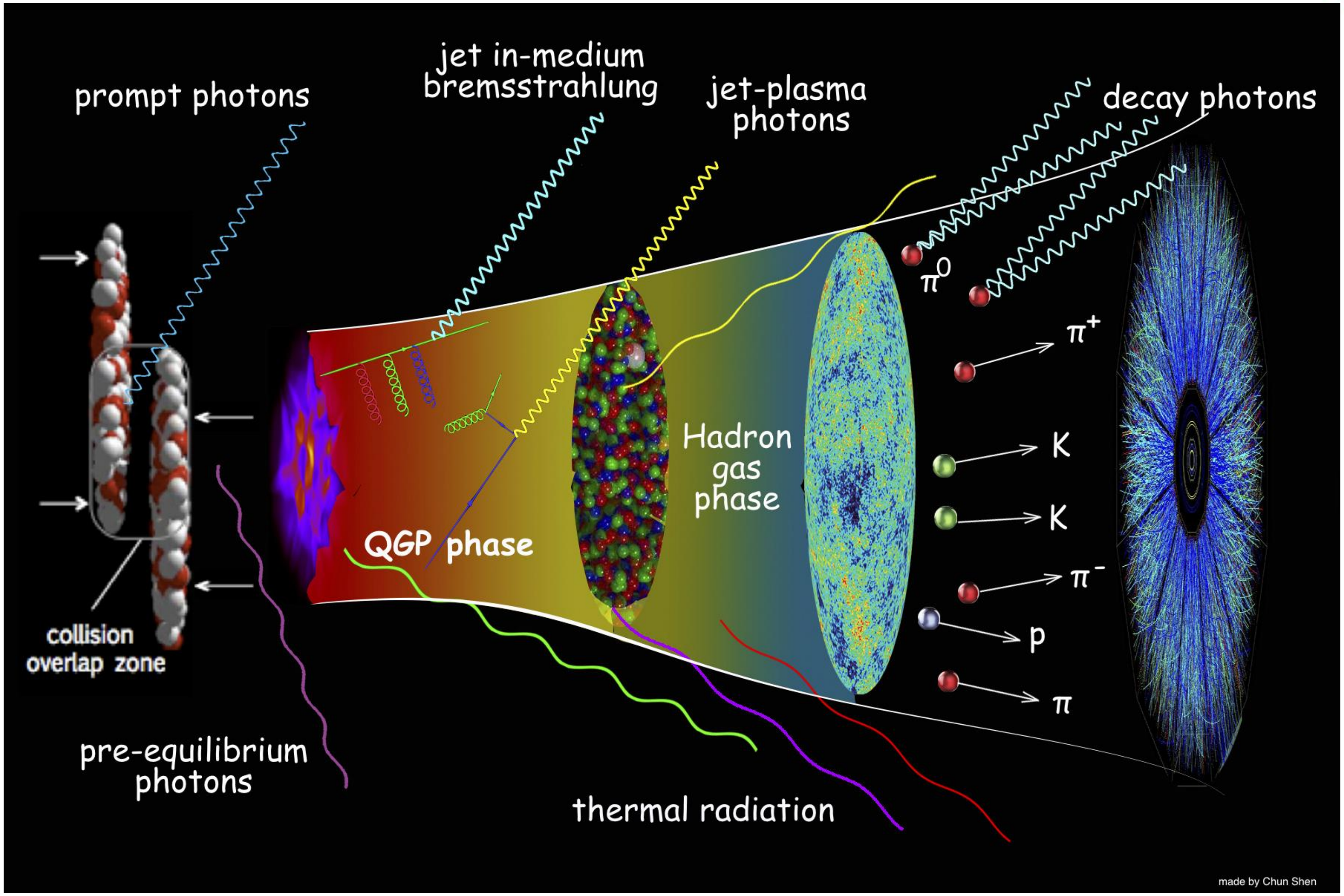
Outline

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

Heavy-ion collisions

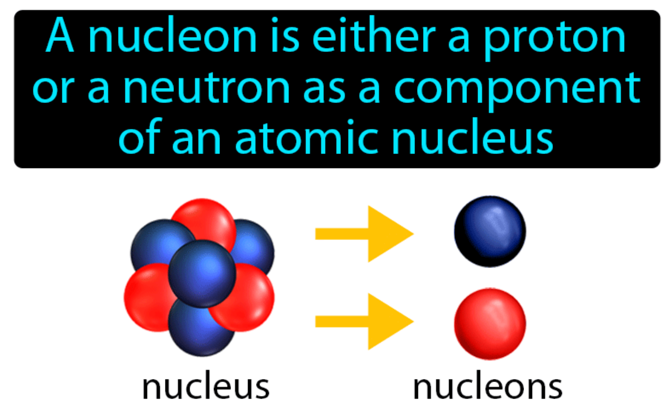


C. Shen, U. Heinz, Nucl. Phys. News 25 (2015) 2, 6-11

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

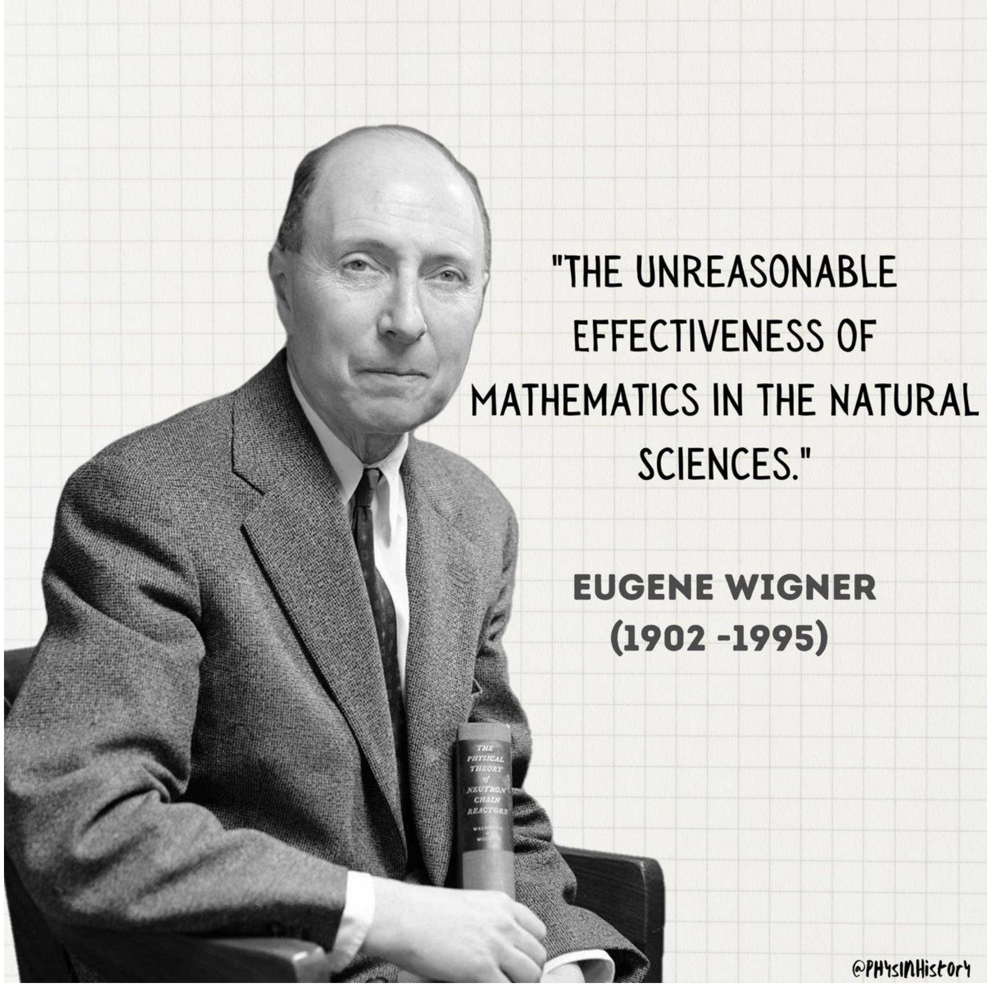
- Here, we concentrate on kaon production, especially on an unexpected large violation of isospin in charged to neutral kaon ratio
- Brylinski et al., Large isospin symmetry breaking in kaon production at high energies," [arXiv:2312.07176 [nucl-th]].
- Adhikary et al. [NA61/SHINE], Excess of Charged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

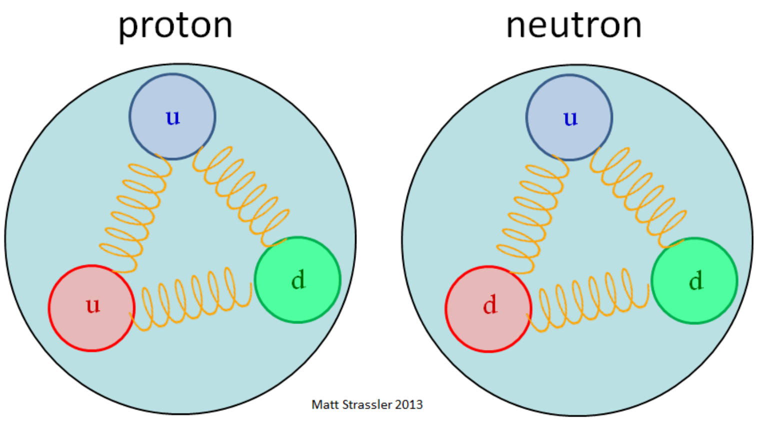
Heisenberg (1932): the nucleon

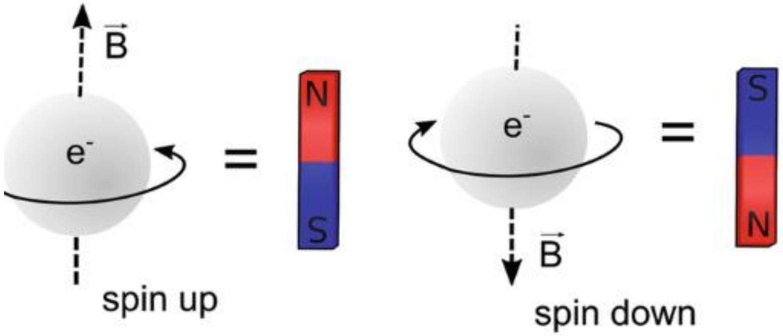


Proton and neutron merge into the nucleon
Masses very similar.

Wigner (1932): isotopic spin, thus isospin







Nucleon doublet: I=1/2

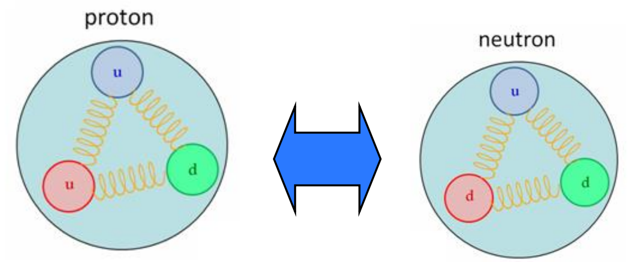
$$\begin{pmatrix} p \\ n \end{pmatrix} \rightarrow \hat{O} \begin{pmatrix} p \\ n \end{pmatrix}$$

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

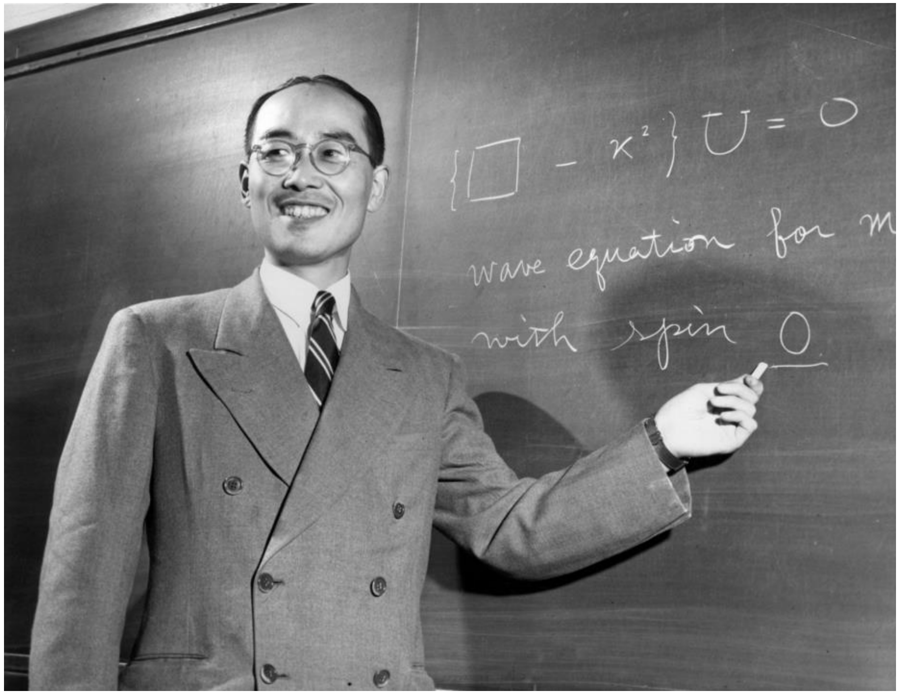
A specific isospin transformation is the so-called charge transformation:

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

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



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



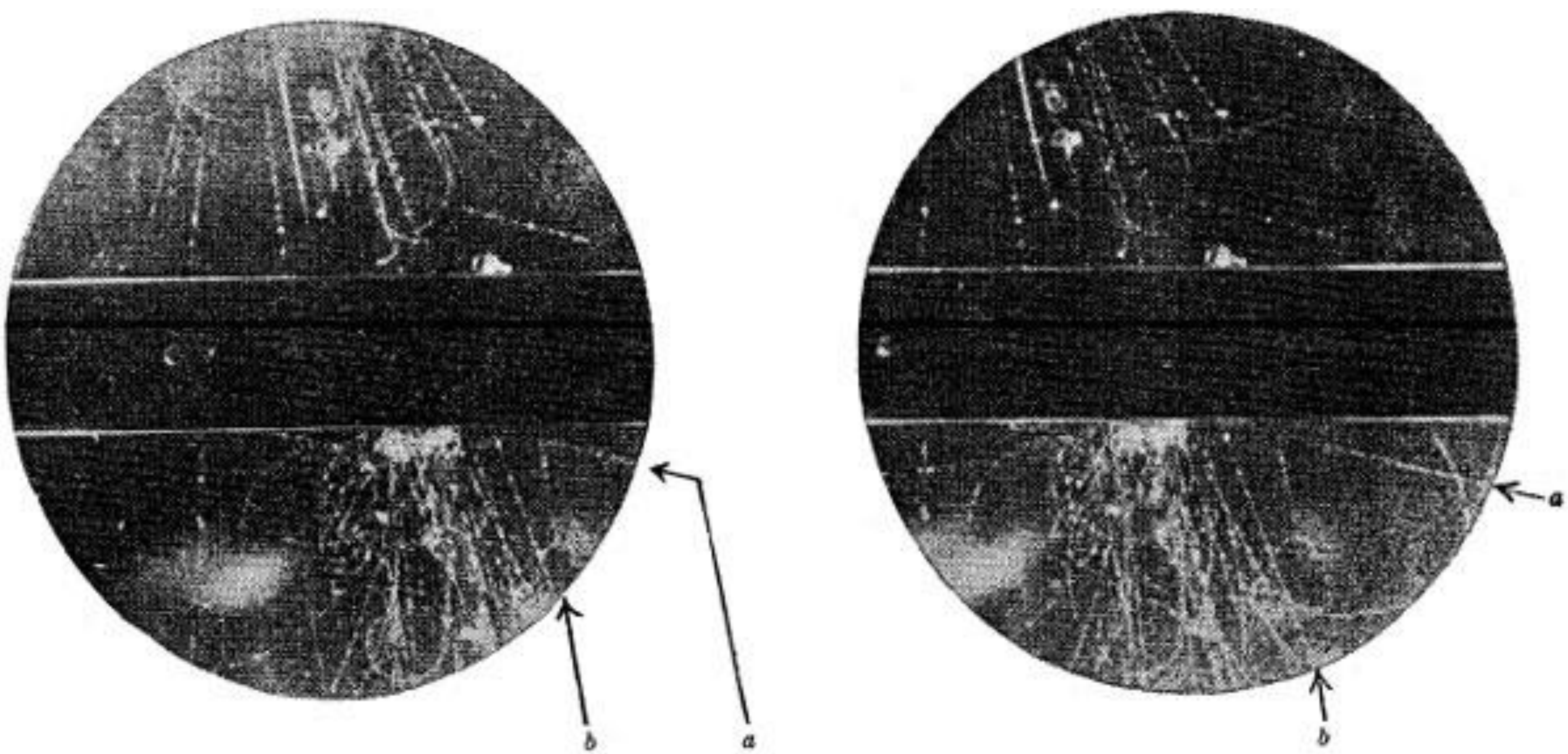
$$\begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$$

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

Kaons

20 DECEMBER 1947

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



Kaons form isospin doublets, just as the nucleon

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

under $\hat{C}$:

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

Quarks and QCD

Quarks and QCD, isospin:

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

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

Quarks and QCD, flavor symmetry:

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

Isospin is an approximate symmetry of QCD

- Mesonic multiplets (nucleon doublet, pion trioplet, 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-nulceon scattering conserve isospin (to a good level of accuracy).

Example: ($I=I_z=1$)

$$p + p \to \Lambda + K^+ + p$$

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

- Isopsin transformations are a subset of flavor transformations.

Example of isospin breaking/1

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

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

Example of isospin breaking/2

$\phi(1020)$

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

$\phi(1020)$ 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

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

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

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^0$	(64.7 ± 0.9) %
Γ_2	$D^0\gamma$	(35.3 ± 0.9) %
Γ_3	$D^0 e^+ e^-$	$(3.91 \pm 0.33) \times 10^{-3}$

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

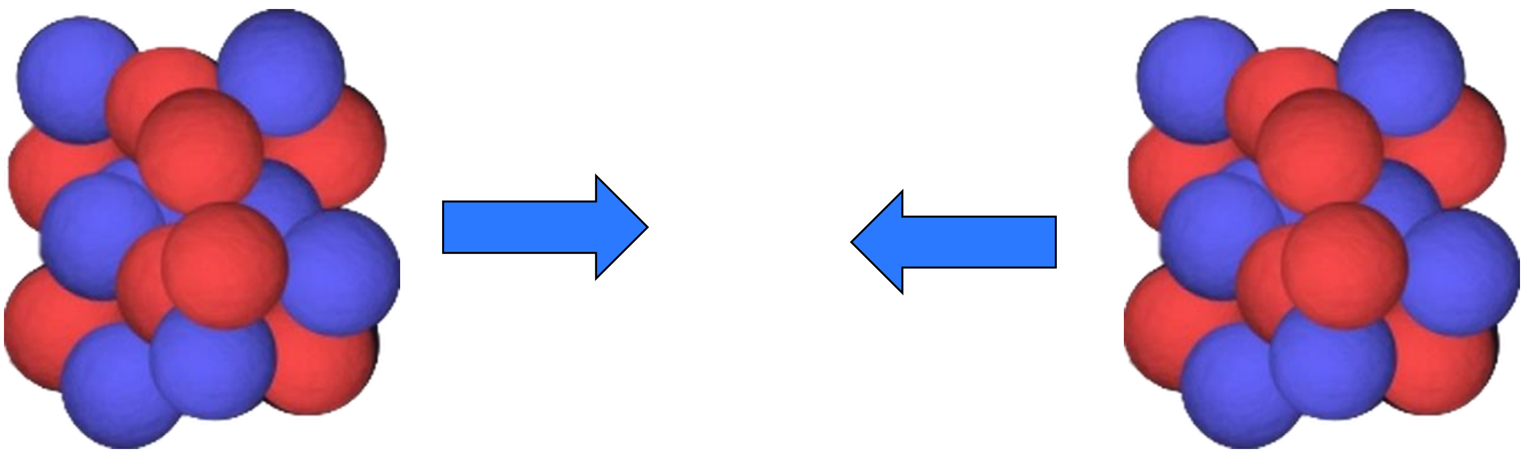
$D^*(2010)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	(67.7 ± 0.5) %
Γ_2	$D^+\pi^0$	(30.7 ± 0.5) %
Γ_3	$D^+\gamma$	(1.6 ± 0.4) %

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**

$I_z = 0$ (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.

Historical recall: „Shmushkevich" rule

Uniwersytet
Jana Kochanowskiego w Kielcach

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)

Expected kaon multiplicities

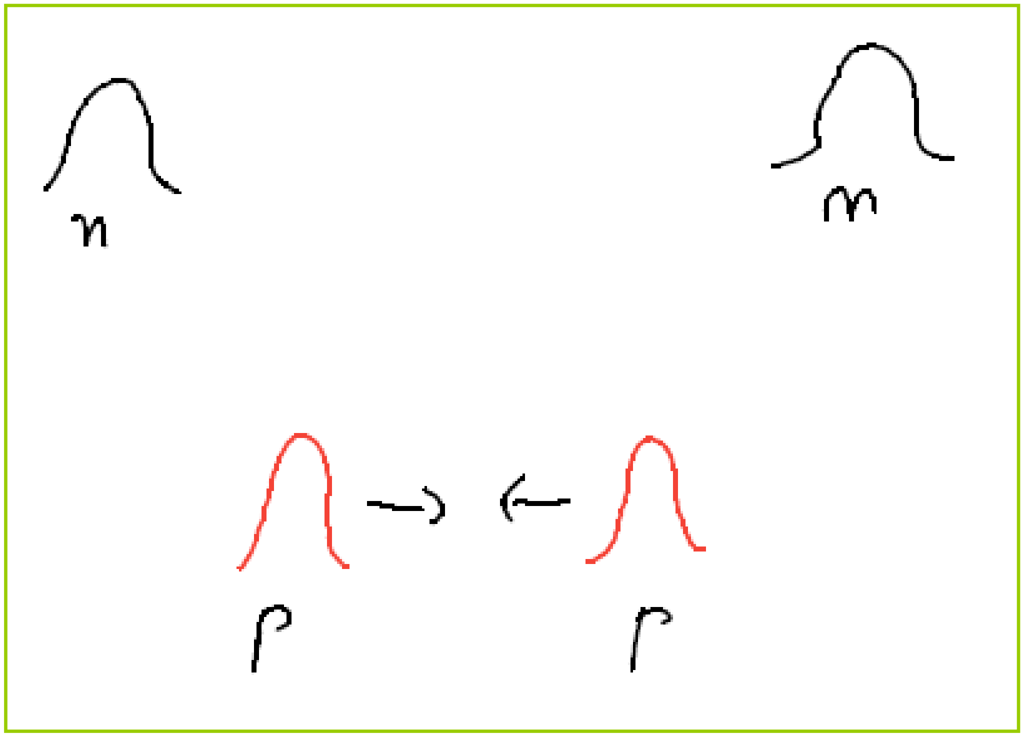
Charge symmetry means that strong interactions are invariant under the inversion of the third component of the isospin of hadron of the initial and final states.

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:

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

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

ppnn $\longmapsto$?



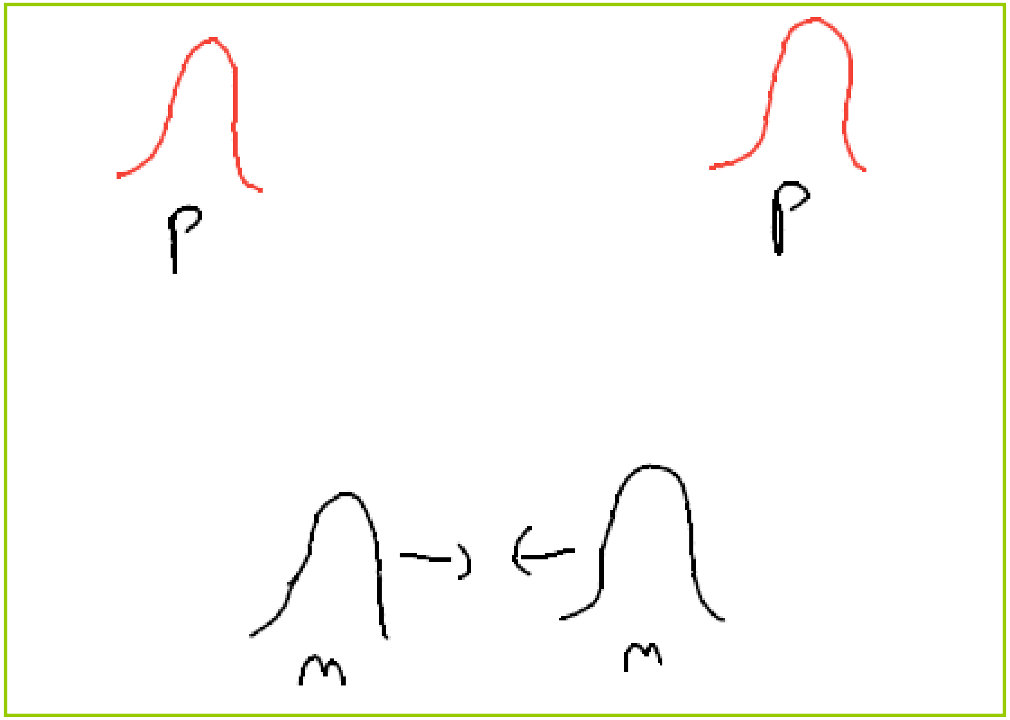
Just as pp!

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!

Neutral kaons and the ratio R_K

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

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

$$\langle K^+ \rangle + \langle K^- \rangle = 2\langle K_S^0 \rangle$$

$$Q/B = 1/2$$

+ isospin exact…

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

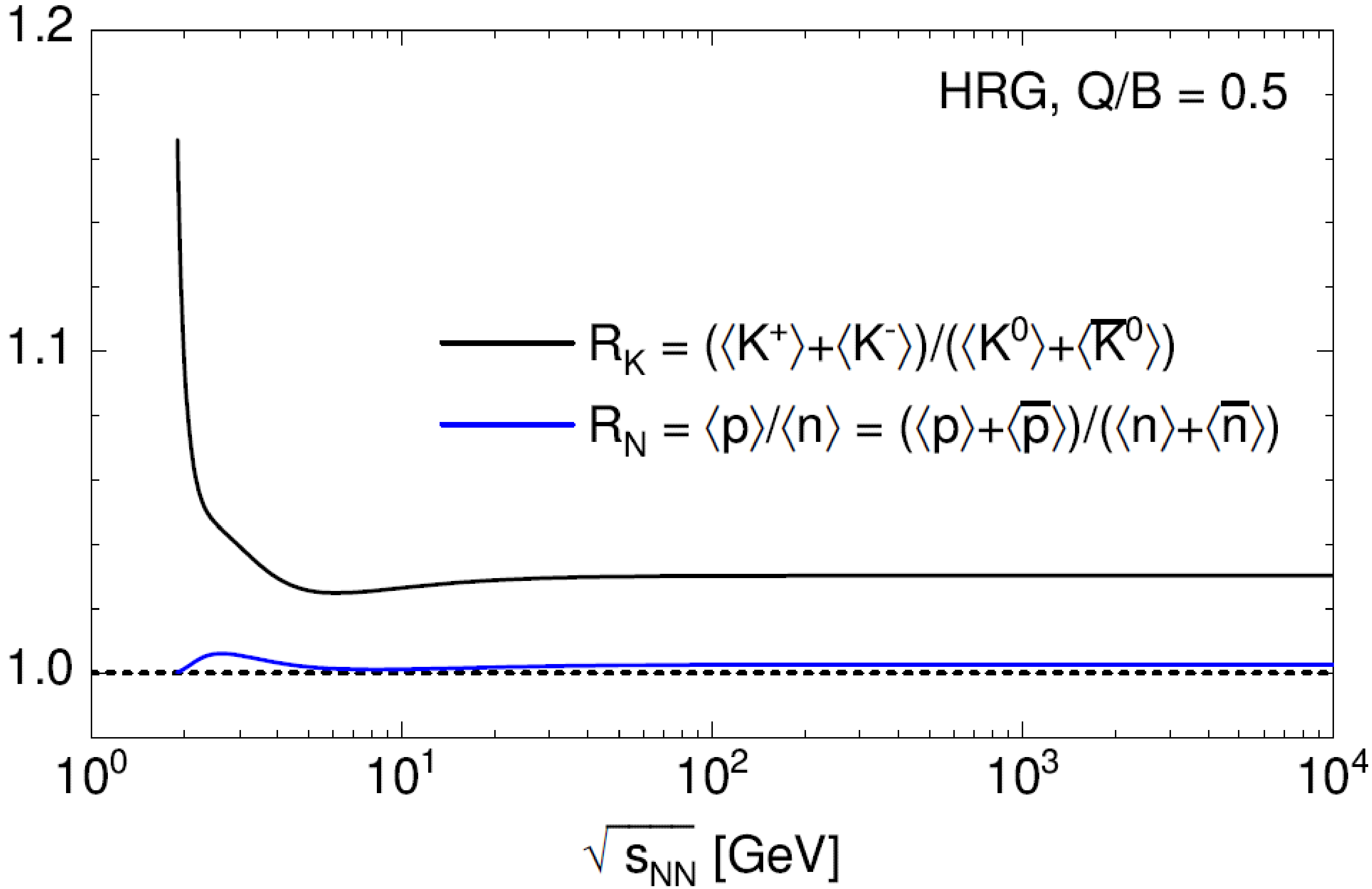
Theoretical approaches

- What does theory predict? We use the well known HRG (hadron resonance gas approach)

  and

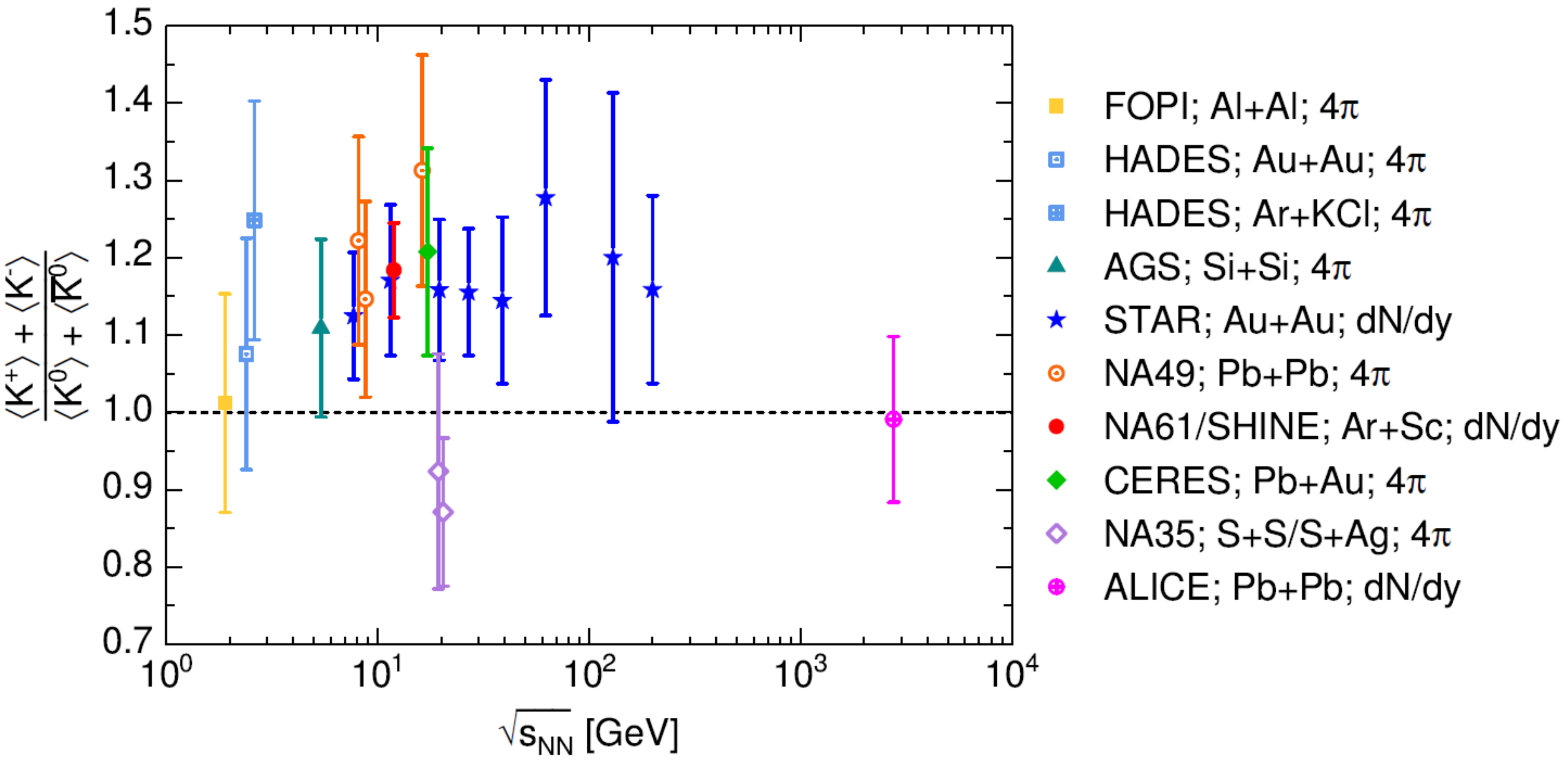
- UrQMD (Hadron-String transport model, fully integrated Monte Carlo simulation of nucleus-nucleus simulations)

HRG for Q/B=1/2



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

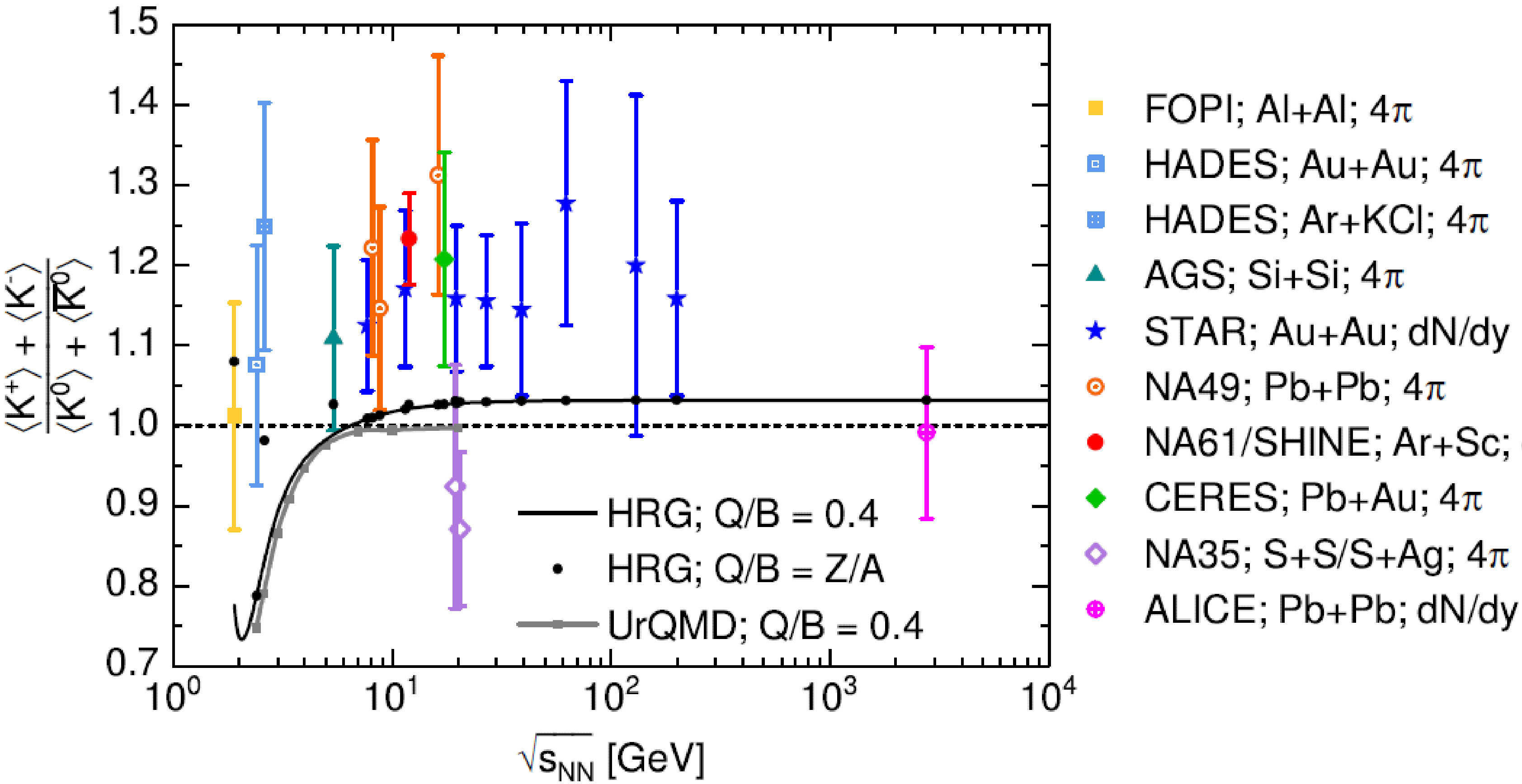
Experimental results (NA61/SHINE plus others)



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

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

Exp vs theory (HRG+UrQMD)



Considerations

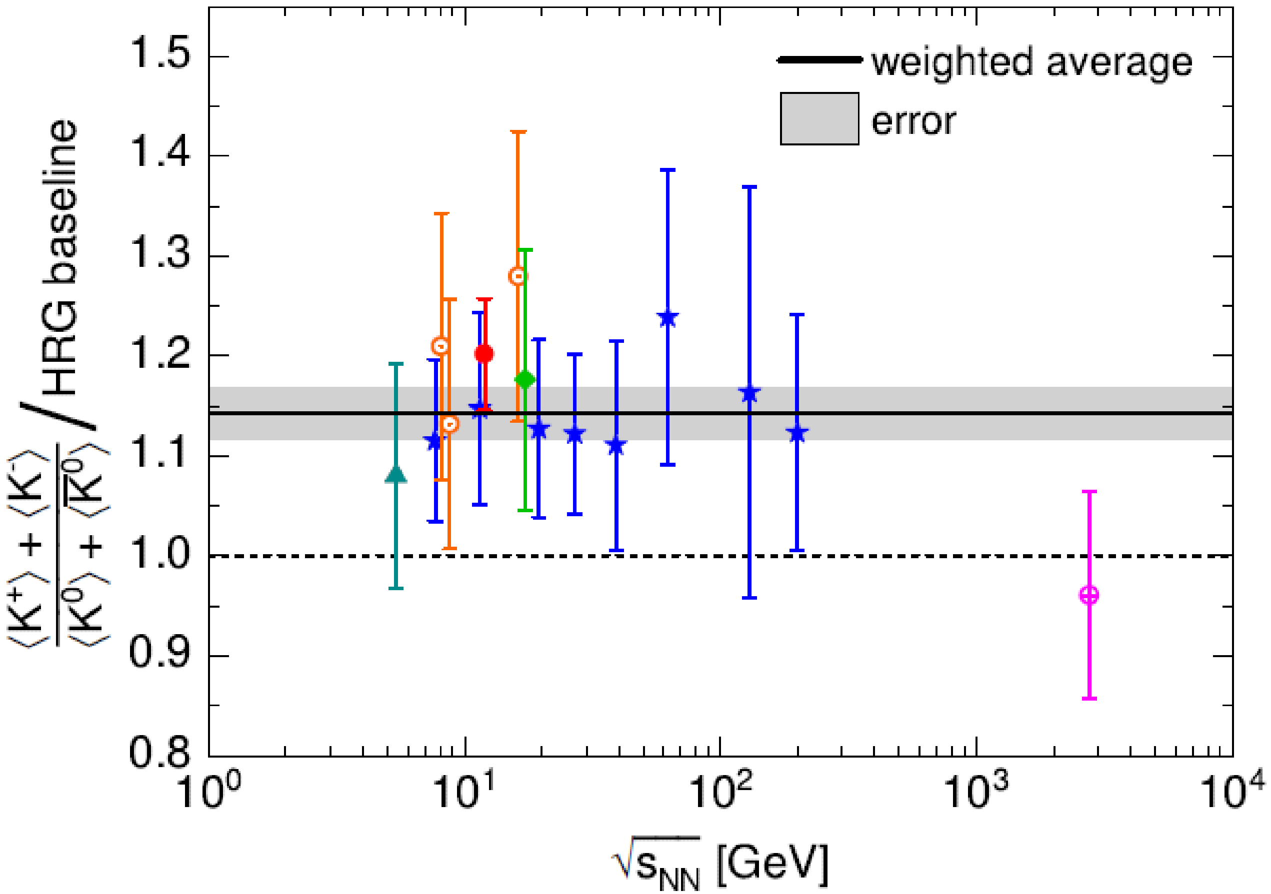
- HRG and UrQMD agree with each other
- Q/B <1/2 favors neutral kaons
- charged kaons are lighter than neutral ones: this favors charged kaons

Considerations/2

- Non-QCD effects: weak processes are negligible
- Non-QCD effects: electromagnetic processes are small, of the order of α^2
- Decays of ϕ(1020) meson as well as other asymmetries generate quite small effects

Experiment vs theory: ratio

1.132 ± 0.026 $\chi^2_{\min}/\mathrm{dof} = 0.38$



The exp/th missmatch is 5.06σ,
and increases to 8.25σ for the PDG-liked scaled errors.

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 $\pi^+ + C$

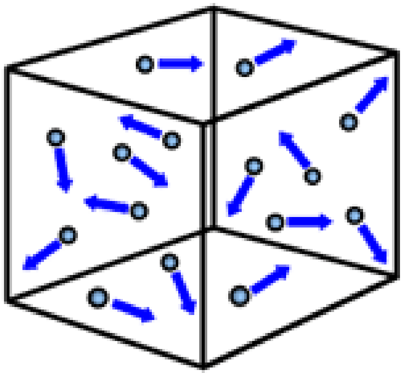
NA61/SHINE
PRD 107 (2003) 062004

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

Thanks!

Theoretical description of a thermal gas

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



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

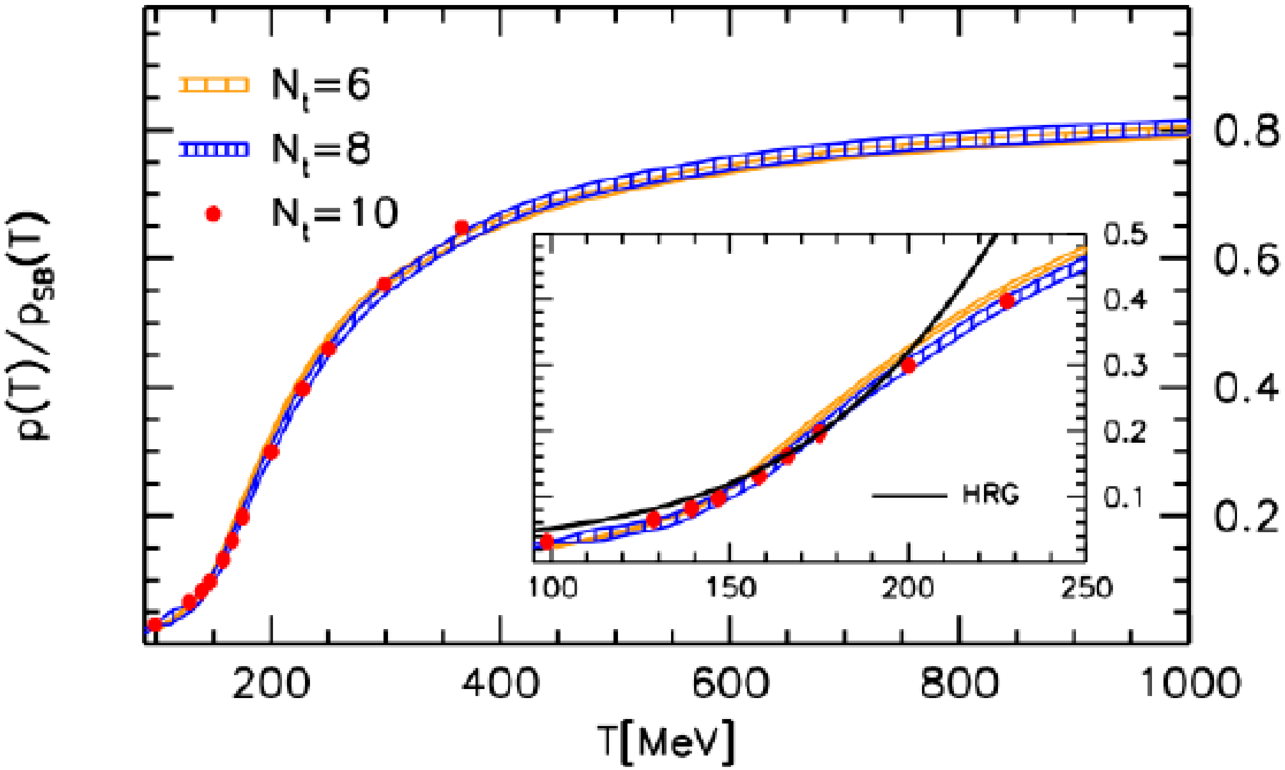
$$E_p = \sqrt{\vec{p}^2 + M_k^2}$$

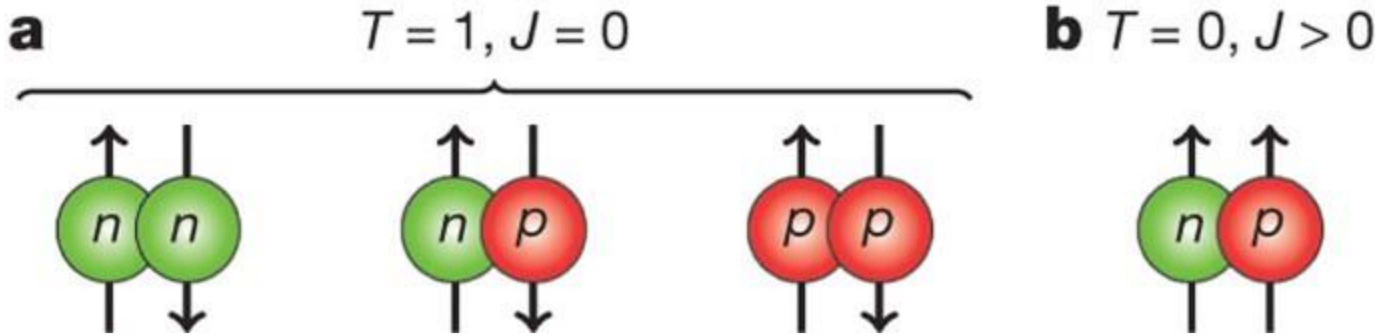
$$P = \frac{T}{V} \ln Z$$

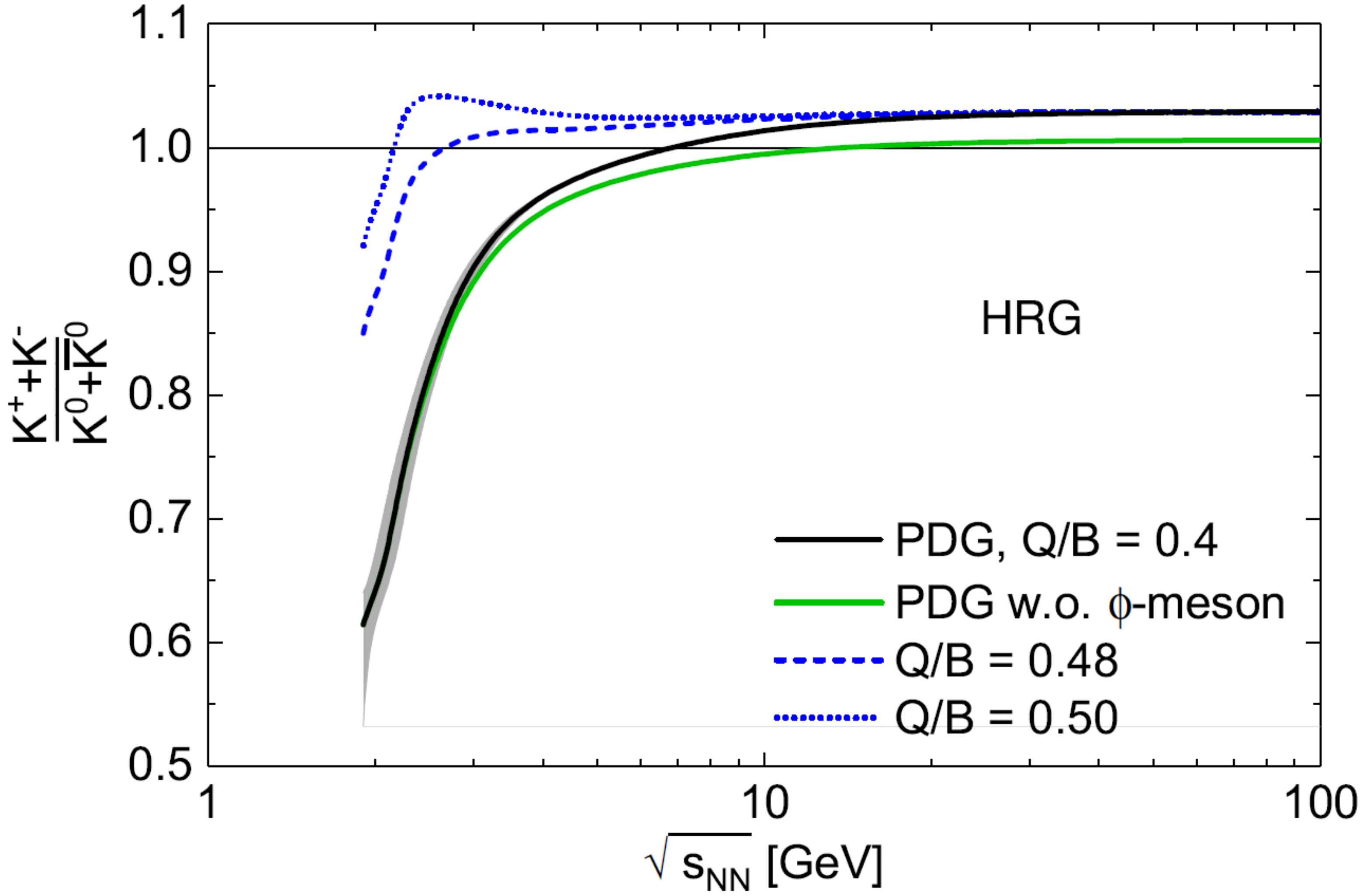
The stable part is “easy”: In first approximation, resonance as stable.
Then, correcting for width, itneraction,…

Hadron resonance gas vs lattice results

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

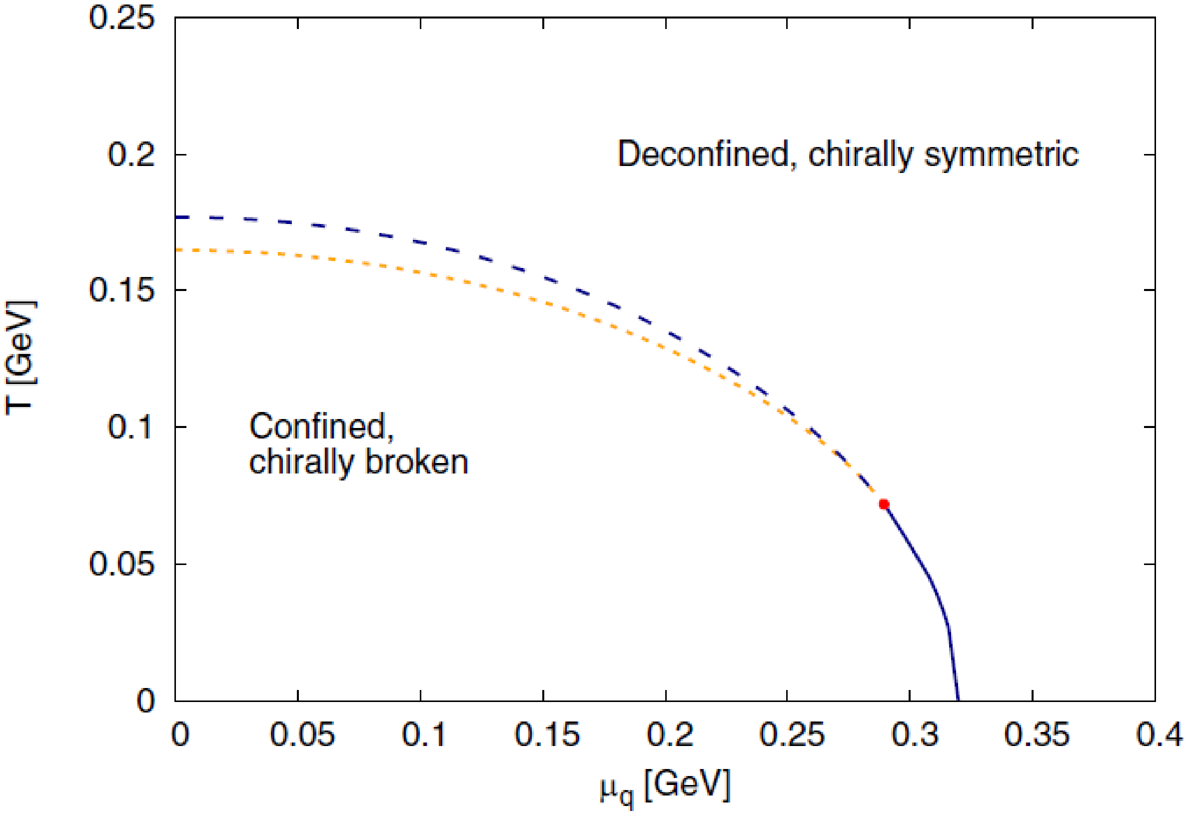



a
T = 1, J = 0
n
n
n
p
p
p
b T = 0, J > 0
n
p



1.1
1.0
0.9
0.8
0.7
0.6
0.5
1
10
100
$\frac{K^+ + K^-}{K^0 + \bar{K}^0}$
$\sqrt{s_{NN}}$ [GeV]
HRG
PDG, Q/B = 0.4
PDG w.o. ϕ-meson
Q/B = 0.48
Q/B = 0.50

Phase diagram of the eLSM: Nc =3



Details in 2209.09568

Schematic phase diagram at large Nc

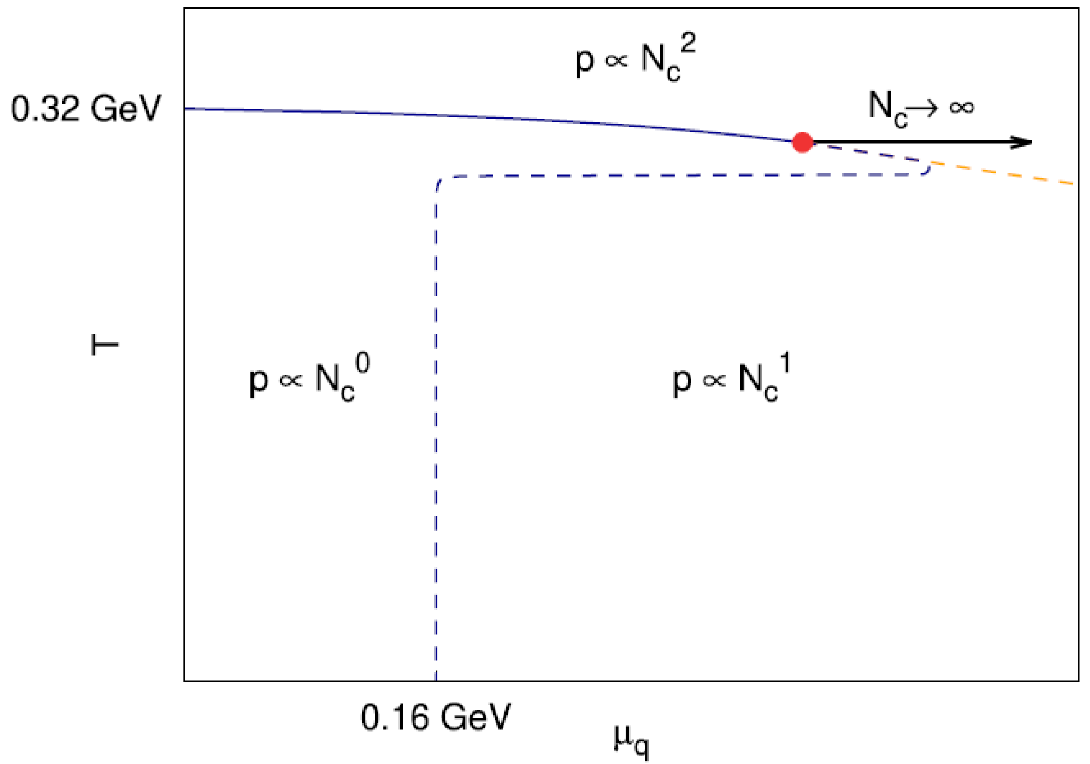


FIG. 13. The schematic phase diagram for large N_c and the N_c scaling of the pressure in the different phases.

Details in 2209.09568.

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