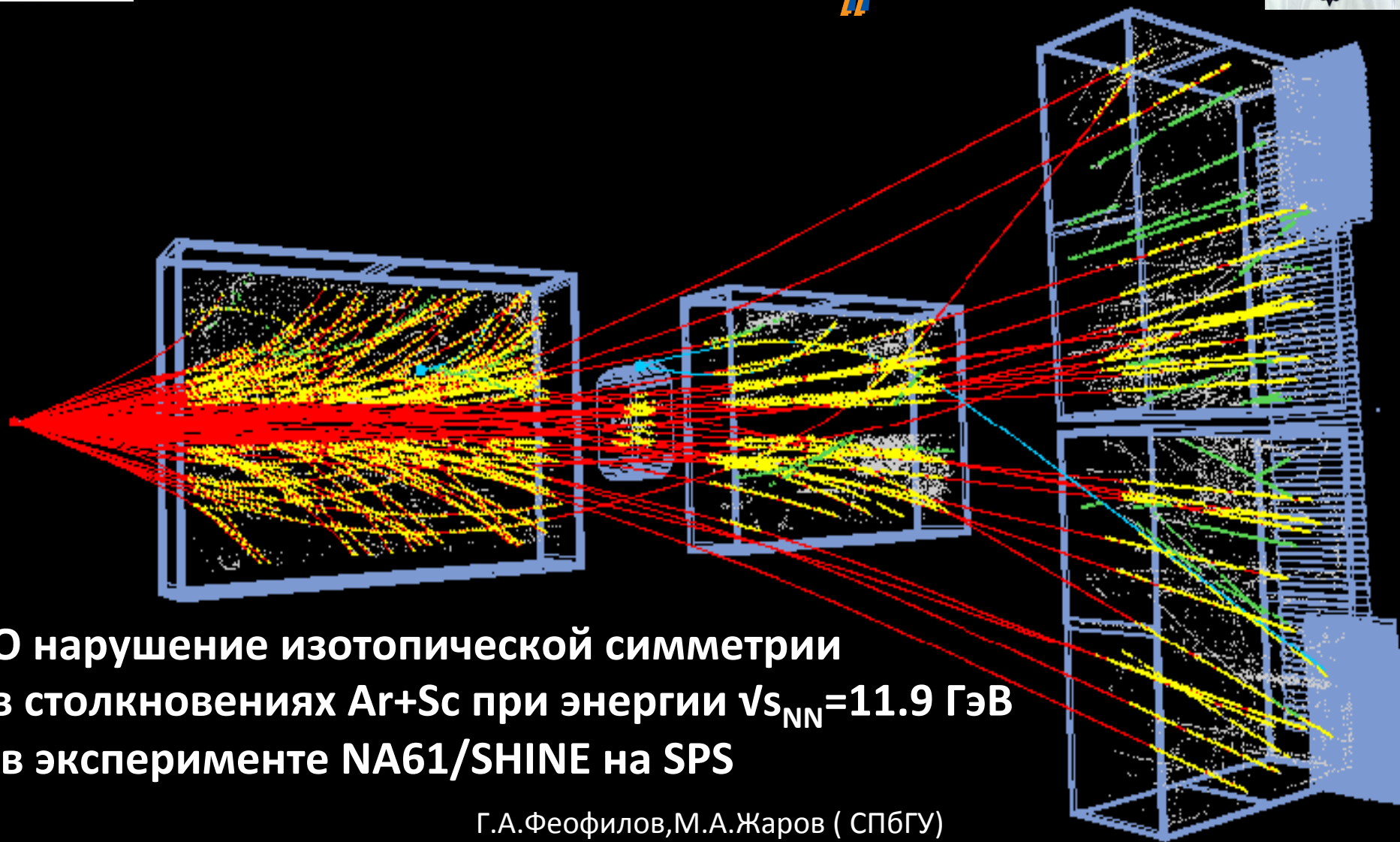




**О нарушение изотопической симметрии  
в столкновениях Ar+Sc при энергии  $\sqrt{s_{NN}}=11.9$  ГэВ  
в эксперименте NA61/SHINE на SPS**

Г.А.Феофилов, М.А.Жаров (СПбГУ)

Вторник, 6 октября 2026, – ПИАФ, Гатчина, 10-30

Supported by Saint Petersburg State University research project ID: 153212394



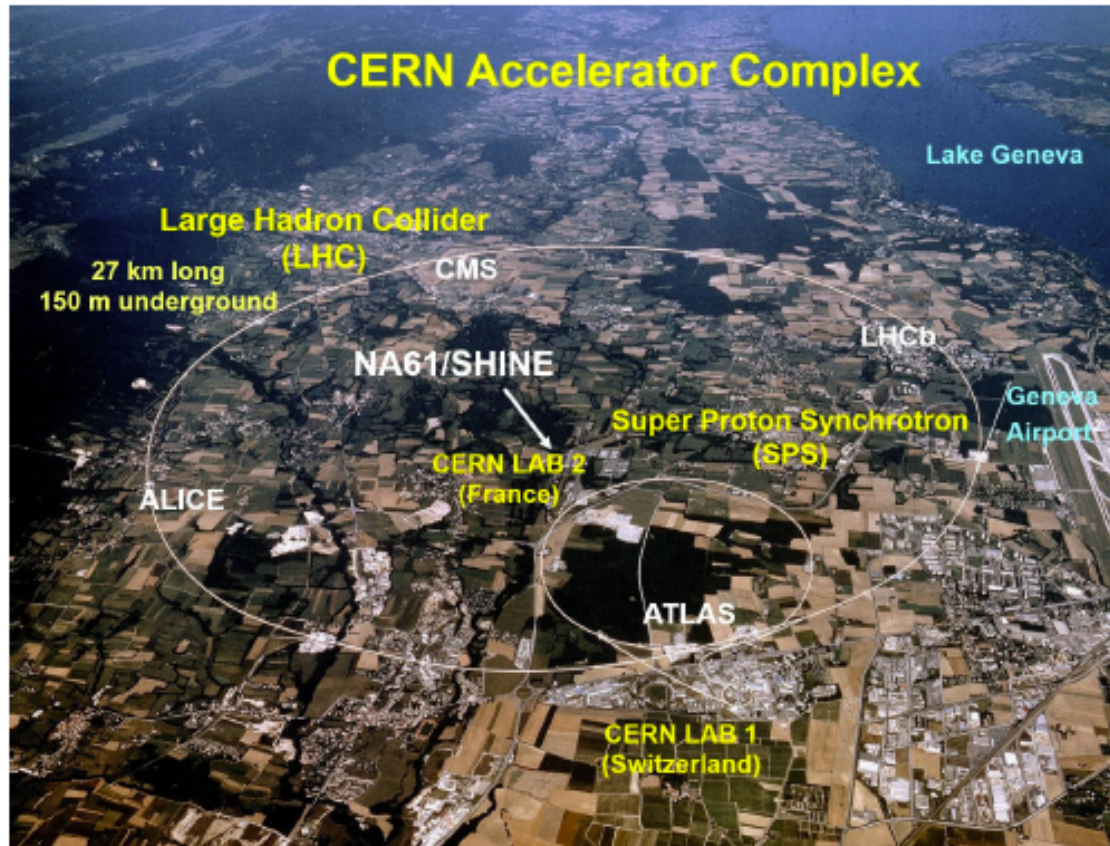
# Talk Layout

- ❑ NA61/SHINE Experiment at CERN
- ❑ Charged particle identification
- ❑ Isotopic Symmetry Breaking in Ar+Sc Collisions
- ❑ Some sources of the detected Isospin Symmetry Breaking
- ❑ Predictions? Possible additional experimental studies.

- ❑ ***Workshop on isospin symmetry violation: kaons and beyond (ISO-BREAK 25), Kielce on October 23–25, 2025***

<https://indico.cern.ch/event/1557894/contributions/6698122/>

# SHINE = SPS Heavy Ion and Neutrino Experiment



- ✧ Strong interaction
- ✧ The onset of deconfinement
- ✧ Search for the critical point
- ✧ Measurement for open charm
- ✧ Measurements for neutrino programs (J-park and Fermilab)
- ✧ Cosmic ray physics
- ✧ Isospin symmetry violation

## Beams for NA61/SHINE Experiment:

Hadron beams:

- p (400 GeV/c)
- Secondary  $\pi$ , K, p (13–350 GeV/c)

Ion beams:

- Ar, Xe, Pb (13–150A GeV/c)
- Secondary Be (13–150A GeV/c) (from Pb fragmentation)

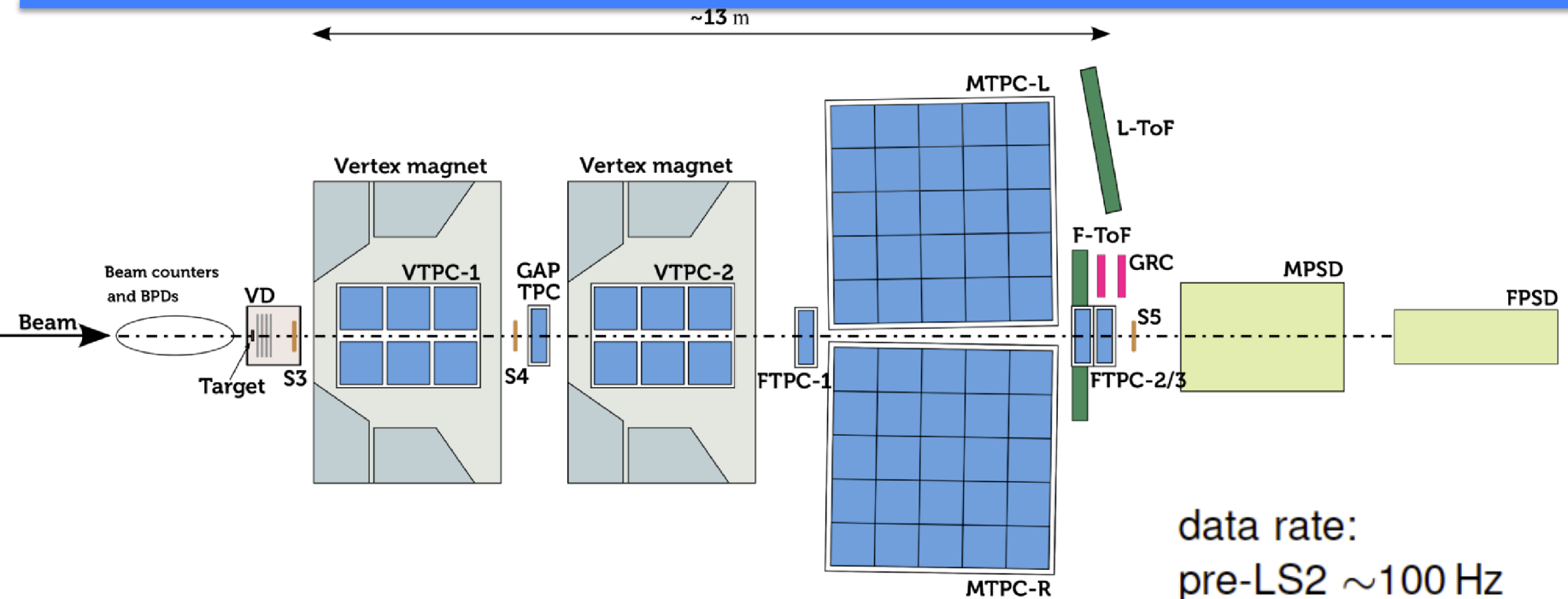
# Collaboration list



National Nuclear Research Center, Azerbaijan  
Faculty of Physics, University of Sofia, Bulgaria  
Ruder Boskovic Institute, Croatia  
LPNHE, University of Paris VI and VII, France  
Karlsruhe Institute of Technology, Germany  
Fachhochschule Frankfurt, Germany  
Institut für Kernphysik, Goethe-Universität, Germany  
Nuclear and Particle Physics Division, University of Athens, Greece  
Wigner RCP, Hungary  
Institute for Particle and Nuclear Studies (KEK), Japan  
University of Bergen, Norway  
Institute of Physics, Jan Kochanowski University, Poland  
National Center for Nuclear Research, Poland  
Institute of Physics, Jagiellonian University, Poland  
Institute of Physics, University of Silesia, Poland  
Faculty of Physics, University of Warsaw, Poland  
Department of Physics and Astronomy, University of Wrocław, Poland  
Faculty of Physics, Warsaw University of Technology, Poland  
**Institute for Nuclear Research, Russia**  
**Joint Institute for Nuclear Research, Russia**  
**St. Petersburg State University, Russia**  
**National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Russia**  
University of Belgrade, Serbia  
ETH Zürich, Switzerland  
University of Bern, Switzerland  
University of Geneva, Switzerland  
University of Colorado Boulder, USA  
Los Alamos National Laboratory, USA  
Department of Physics and Astronomy, University of Pittsburgh, USA  
Fermilab, Neutrino Division, USA



# SHINE = SPS Heavy Ion and Neutrino Experiment



data rate:  
pre-LS2  $\sim 100$  Hz  
post-LS2  $\sim 1000$  Hz

## Fixed target experiment in the North area of SPS at CERN:

- ★ tracking efficiency:  $> 95\%$
- ★ large acceptance: full forward c.m.s. hemisphere, down to  $p_T = 0$
- ★ particle identification:  $dE/dx$  in Time Projection Chambers, Time of Flight
- ★ centrality: forward energy in Projectile Spectator Detector(s)
- ★ ion (Be, Ar, Xe, Pb) and hadron ( $\pi$ ,  $K$ ,  $p$ ) beams, various targets including liquid  $H_2$  and water
- ★  $\pi^\pm$ ,  $K^\pm$ ,  $K_S^0$ ,  $K^{*0}$ ,  $p$ ,  $\Lambda$ ,  $\phi$ ,  $\Xi$ ,  $D^0$ , spectra, correlations, fluctuations, HBT, intermittency...
- ★ Vertex Detector for open charm measurements
- ★ Double-wall He beam-pipe inside the VTPC1 and VTPC2

[1] NA61/SHINE detector overview,

G.Feofilov

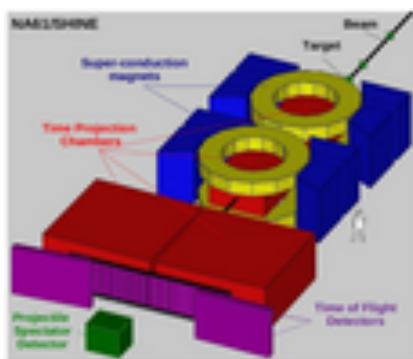
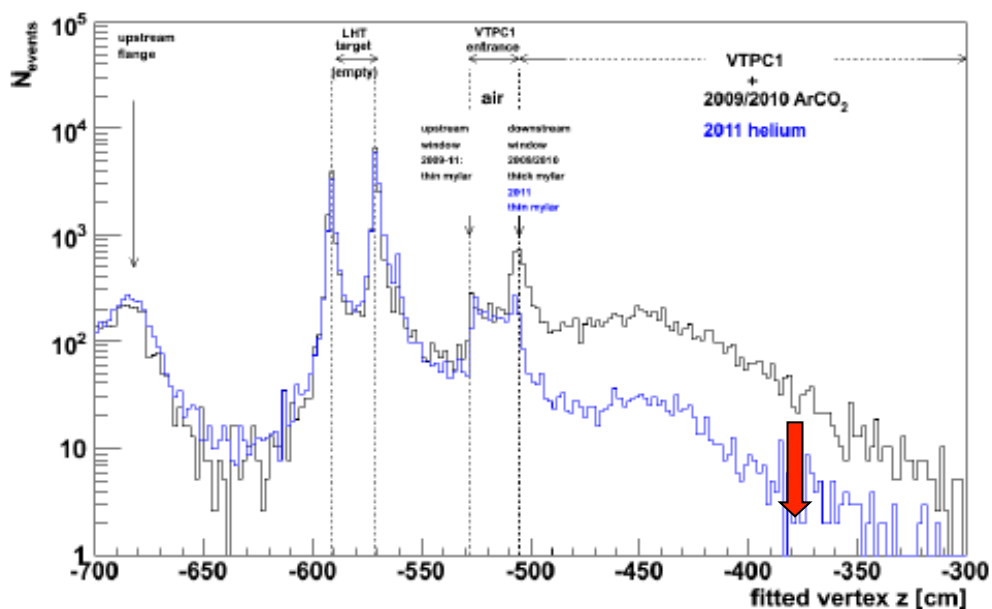
[https://indico.cern.ch/event/1174830/contributions/5174346/attachments/2567605/4426948/na61\\_det.pdf](https://indico.cern.ch/event/1174830/contributions/5174346/attachments/2567605/4426948/na61_det.pdf)



# Example of St.Petersburg State University technologies for NA61(SHINE)

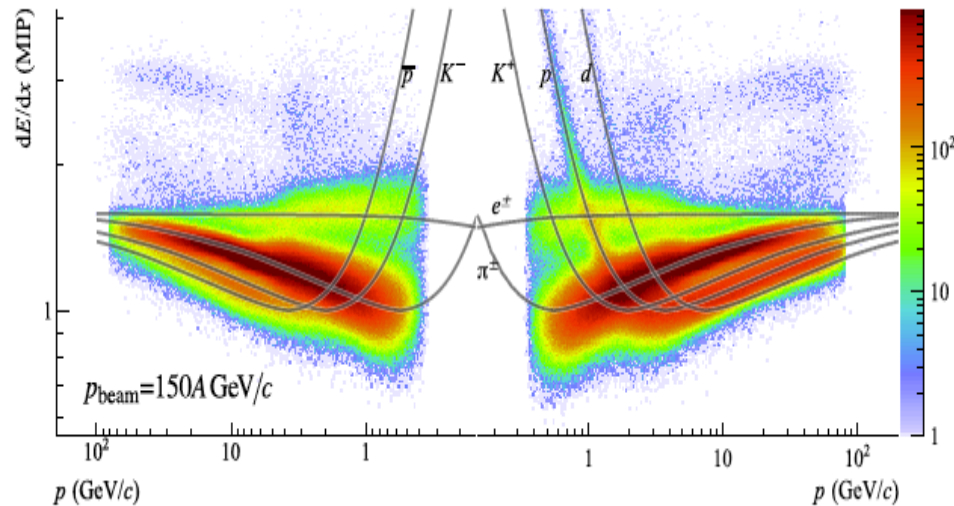


- Left: Extra-thin double-wall **He beam pipe** installed in 2012 in the gas volume between two field cages in the VTPC-1 of NA61(SHINE). The same in VTPC-2
- This **He beam pipe** reduces the background interactions in the VTPCs by about **a factor of 10**.

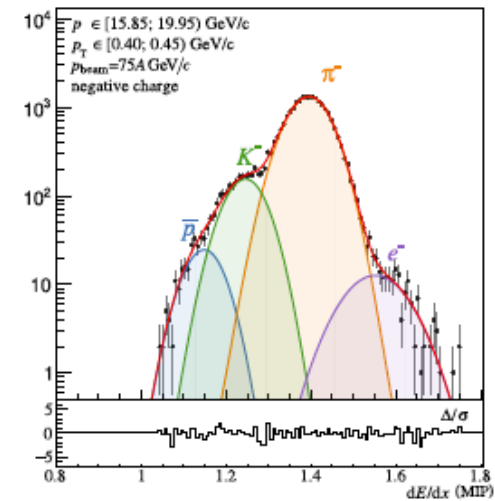


NA61/SHINE facility at the CERN SPS: beams and detector system, 2014 JINST 9 P06005, doi:10.1088/1748-0221/9/06/P06005

# Charged particle identification by **energy loss** measurement in set of TPCs[1]



Distribution of charged particles in  $dE/dx$  --  $p$  plane



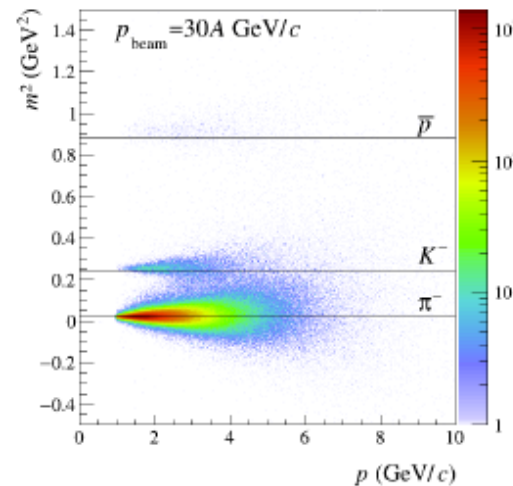
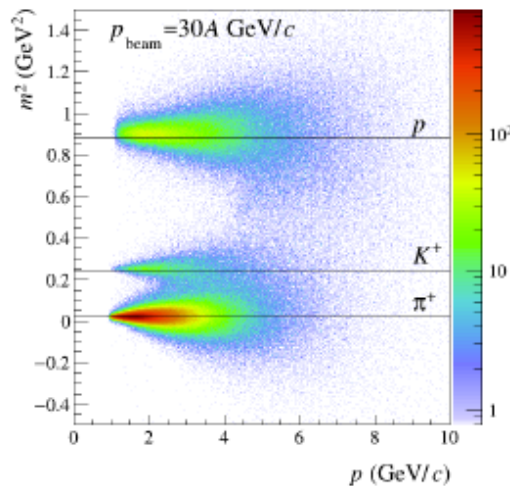
The  $dE/dx$  distributions for negatively charged particles in a selected  $p_T$  bin produced in central Ar+Sc collisions at 75A GeV/c. Solid line -- fits by a sum of Contributions from different particle types

[1] NA61/SHINE Collaboration, Measurements of  $\pi^\pm$ ,  $K^\pm$ ,  $p$  and anti- $p$  spectra in 40Ar+45Sc collisions at 13A to 150A GeV/c, *Eur. Phys. J. C* **84**, 416 (2024).

<https://doi.org/10.1140/epjc/s10052-024-12602-2>

# Charged particle identification

by ToF measurements [1]



$$m^2 = (cp)^2 \left( \frac{c^2 \text{tof}^2}{L^2} - 1 \right)$$

L – length of trajectory

p[GeV/c]

p[GeV/c]

Figure 9: Distribution of particles in the plane laboratory momentum and mass squared derived using time-of-flight measured by ToF-R (right) and ToF-L (left) produced in *central* Ar+Sc collisions at 30A GeV/c. The lines show the expected mass squared values for different hadron species.

[1] NA61/SHINE Collaboration, Measurements of  $\pi^\pm$ ,  $K^\pm$ , p and anti-p spectra in 40Ar+45Sc collisions at 13A to 150A GeV/c, *Eur. Phys. J. C* **84**, 416 (2024).

<https://doi.org/10.1140/epjc/s10052-024-12602-2>

G.Feofilov

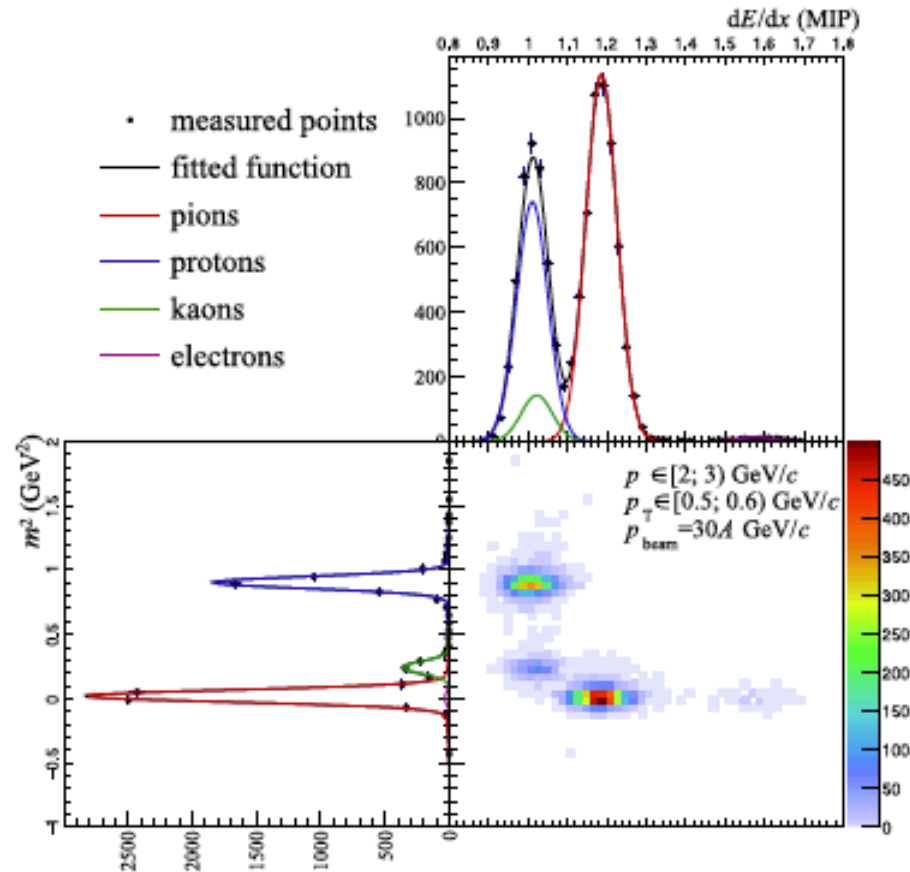
# Charged particle identification by ToF – dE/dx

measurements [1]

Eur. Phys. J. C (2024) 84:416

Page 13 of 54 416

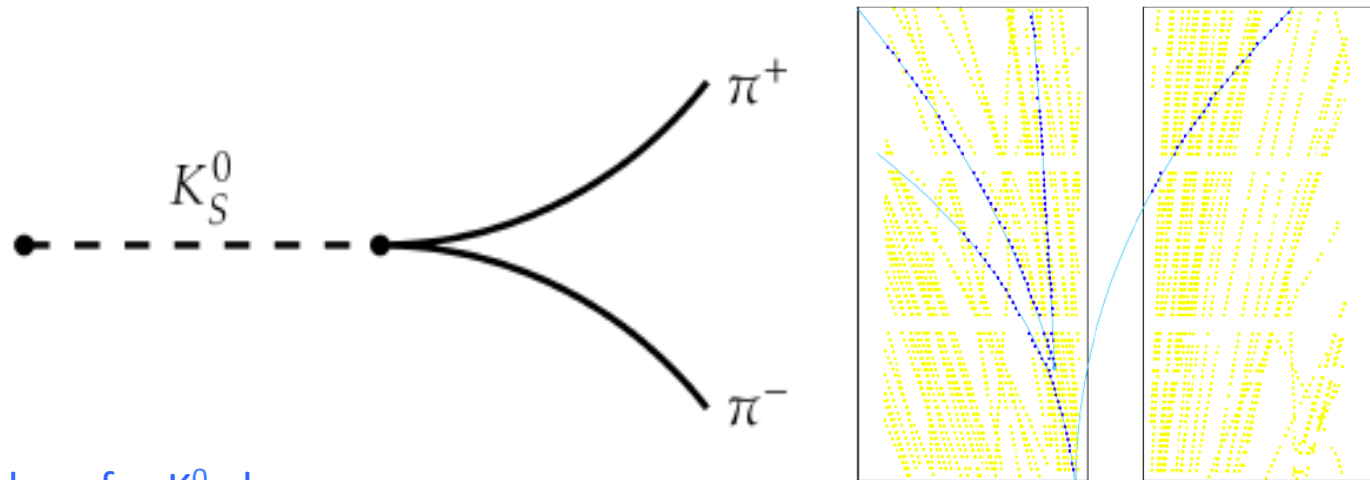
**Fig. 11** Example of the  $tof - dE/dx$  fit (Eq. 4) obtained in a single bin ( $2 < p < 3$  GeV/c and  $0.5 < p_T < 0.6$  GeV/c) for positively charged particles in central Ar+Sc collisions at 30A GeV/c



[1] NA61/SHINE Collaboration, Measurements of  $\pi^\pm$ ,  $K^\pm$ ,  $p$  and anti- $p$  spectra in 40Ar+45Sc collisions at 13A to 150A GeV/c, *Eur. Phys. J. C* **84**, 416 (2024).

<https://doi.org/10.1140/epjc/s10052-024-12602-2>

# Identification of weakly decaying neutral particles by **V0 topology and energy loss** measurement in set of TPCs[1]



Decay topology for  $K_S^0$  decay :

Left: Example of **V0 topology** as for  $K_S^0$  decaying into two pions.

Right: Two reconstructed V0 decays in NA61/SHINE spectrometer.

Yellow points are TPC clusters and blue lines represent two reconstructed V0 decays.

TPC clusters belonging to V0 daughter tracks are marked as blue point

Wojciech Bryliński Thesis, Study of  $K_S^0$  meson production in central Ar+Sc collisions at SPS energies, Warsaw University of Technology, PhD, Submitted: 2023, Defended: 2023-07-12  
<https://repository.cern/records/5fv5z-ez421>



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

Received: 6 March 2024

The NA61/SHINE Collaboration\*, F. Giacosa <sup>1,2</sup>, M. Gorenstein <sup>3,4</sup>,  
R. Poberezhniuk <sup>3,4,5</sup> & S. Samanta <sup>6</sup>

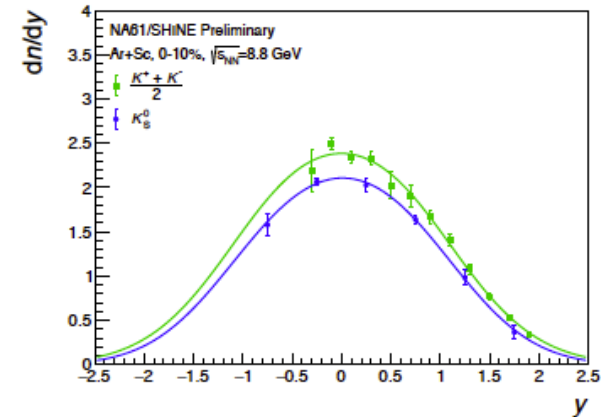
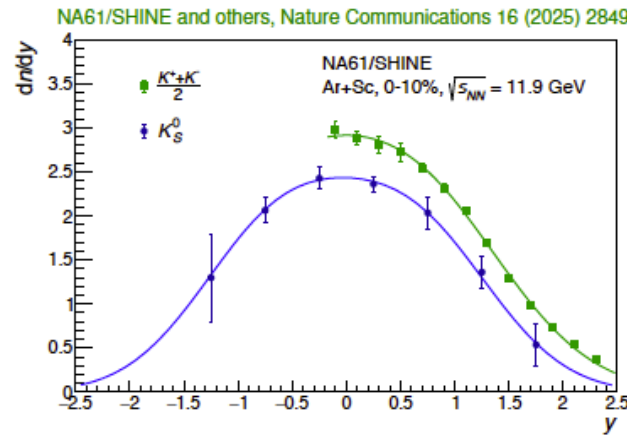
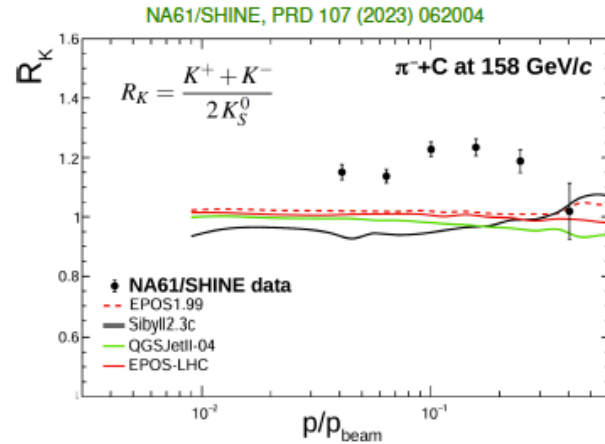
Accepted: 14 February 2025

Published online: 11 March 2025

Strong interactions preserve an approximate isospin symmetry between up ( $u$ ) and down ( $d$ ) quarks, part of the more general flavor symmetry. In the case of  $K$  meson production, if this isospin symmetry were exact, it would result in equal numbers of charged ( $K^+$  and  $K^-$ ) and neutral ( $K^0$  and  $\bar{K}^0$ ) mesons produced in collisions of isospin-symmetric atomic nuclei. Here, we report results on the relative abundance of charged over neutral  $K$  meson production in argon and scandium nuclei collisions at a center-of-mass energy of 11.9 GeV per nucleon pair. We find that the production of  $K^+$  and  $K^-$  mesons at mid-rapidity is  $(18.4 \pm 6.1)\%$  higher than that of the neutral  $K$  mesons

...The significance of the flavor-symmetry violation beyond the known effects is  $4.7\sigma$  when the compilation of world data with uncertainties quoted by the experiments is used. ...

# Evidence of isospin-symmetry violation in kaon production: new data by NA61/SHINE[1]



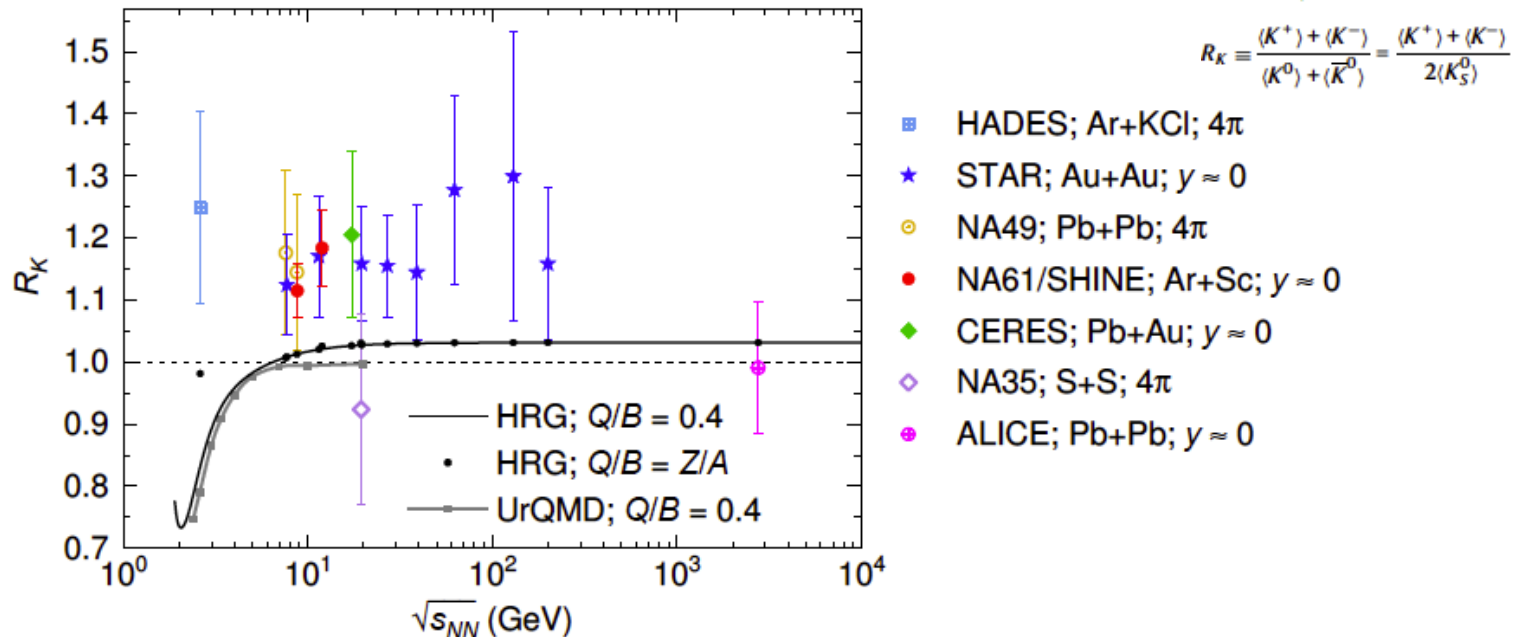
- For exact isospin symmetry ( $m_u = m_d$ ) and collisions of  $Z = N$  nuclei  $\langle K^+ \rangle (u\bar{s}) = \langle K^0 \rangle (d\bar{s})$  and  $\langle K^- \rangle (\bar{u}s) = \langle \bar{K}^0 \rangle (\bar{d}s)$ ; neglecting small CP violation  $\langle K_S^0 \rangle = \frac{1}{2} \langle K^0 \rangle + \frac{1}{2} \langle \bar{K}^0 \rangle = \langle K_L^0 \rangle$
- Therefore expected  $R_K = \frac{\langle K^+ \rangle + \langle K^- \rangle}{\langle K^0 \rangle + \langle \bar{K}^0 \rangle} = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2 \langle K_S^0 \rangle} = 1$
- In both cases of  $\pi^- + C$  and central Ar+Sc collisions, the measured values of  $R_K$  differ from the respective expectations

Small, Intermediate-Size, and Heavy-Ion Systems at SPS Energies, **report at the 18<sup>th</sup> Workshop on Particle Correlations and Femtoscopy, 19 May 2026**, Budapest, Hungary

<https://indico.cern.ch/event/1679596/contributions/>

# Evidence of isospin-symmetry violation in kaon production: world and new data by NA61/SHINE for Ar+Sc at $\sqrt{s_{NN}}=8.8$ GeV[1]

NA61/SHINE and others, Nature Communications 16 (2025) 2849 + new preliminary Ar+Sc point at  $\sqrt{s_{NN}} = 8.8$  GeV



- Effect present in data from other experiments, but uncertainties were too large to notice it
- Combining measurements, gives  **$5.3\sigma$  significance of the isospin-symmetry violation beyond the known effects**

[1] Antoni Marcinek (for NA61/SHINE Collaboration), Strange and Non-Strange Particle Production in Small, Intermediate-Size, and Heavy-Ion Systems at SPS Energies, report at the 18<sup>th</sup> Workshop on Particle Correlations and Femtoscopy, **19 May 2026, Budapest, Hungary**

<https://indico.cern.ch/event/1679596/contributions/>

# Violation of charge-symmetry invariance by known effects.

## Running quark masses [1]

**u**

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

$$\text{Mass } m = 2.16 \pm 0.07 \text{ MeV} \quad \text{Charge} = \frac{2}{3} e \quad I_z = +\frac{1}{2}$$
$$m_u/m_d = 0.462 \pm 0.020$$

**d**

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

$$\text{Mass } m = 4.70 \pm 0.07 \text{ MeV} \quad \text{Charge} = -\frac{1}{3} e \quad I_z = -\frac{1}{2}$$
$$m_s/m_d = 17-22$$
$$\overline{m} = (m_u + m_d)/2 = 3.49 \pm 0.07 \text{ MeV}$$

**s**

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

$$\text{Mass } m = 93.5 \pm 0.8 \text{ MeV} \quad \text{Charge} = -\frac{1}{3} e \quad \text{Strangeness} = -1$$
$$(m_s - (m_u + m_d)/2)/(m_d - m_u) = 27.33^{+0.18}_{-0.14}$$

- These are the values of the "running" quark masses defined in the  $\overline{\text{MS}}$  (Modified Minimal Subtraction) scheme at renormalization scale  $\mu=2\text{GeV}$ [1].
- The masses of up and down quarks,  $m_u = 2.16 \pm 0.07 \text{ MeV}$  and  $m_d = 4.70 \pm 0.07 \text{ MeV}$ [1] are much smaller than the QCD scale,  $\Lambda_{\text{QCD}}$
- The different quark masses lead to different masses of charged and neutral kaons.

[1] Navas, S. et al. Review of particle physics. Phys. Rev. D 110, 030001 (2024).

# Effects of different masses of charged and neutral kaons?

- The difference in the masses of the d and u quarks:  $\Delta=4.7-2.16=2.54$  MeV,
- Accordingly, the relative magnitude of the differences in the masses of kaons is small:  $m_{K^+}=m_{K^-}=493.7$  MeV,  $m_{K^0}=m_{\bar{K}^0}=497.6$  MeV → the difference leads to an increase of  $R_K$  resulting from direct kaon production by about 0.02.
- The influence of this mass difference on  $R_K$  was quantified using the statistical HRG model --by removing resonances from the particle list of HRG. It was numerically verified that HRG for  $Q/B = 1/2$  and with exact isospin symmetry gives  $R_K = 1$ , as expected[1]
- Role of resonances:  $\phi(1020)$  meson decays about 1.45 more frequently into charged kaons than neutral ones (This large difference is because the  $\phi(1020)$  mass is just above the kaon-kaon thresholds). Including the kaon production from resonance decay increases  $R_K$  by about 0.03 [1].
- Role of decay of resonances  $a_0(980)$  and  $f_0(980)$ --one gets an increase of  $R_K$  by about 0.5%. The account of electromagnetic interaction between  $K^+$  and  $K^-$  in this decay leads to the increase of  $R_K$  by at most 3% at the highest collision energy[1].  
**See the next slide →**

[1] The NA61/SHINE Collaboration., Giacosa, F., Gorenstein, M. *et al.*  
Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei. *Nat Commun* **16**, 2849 (2025).  
<https://doi.org/10.1038/s41467-025-57234-6>

# Effects of different quark masses in HRG

and in UrQMD[1]

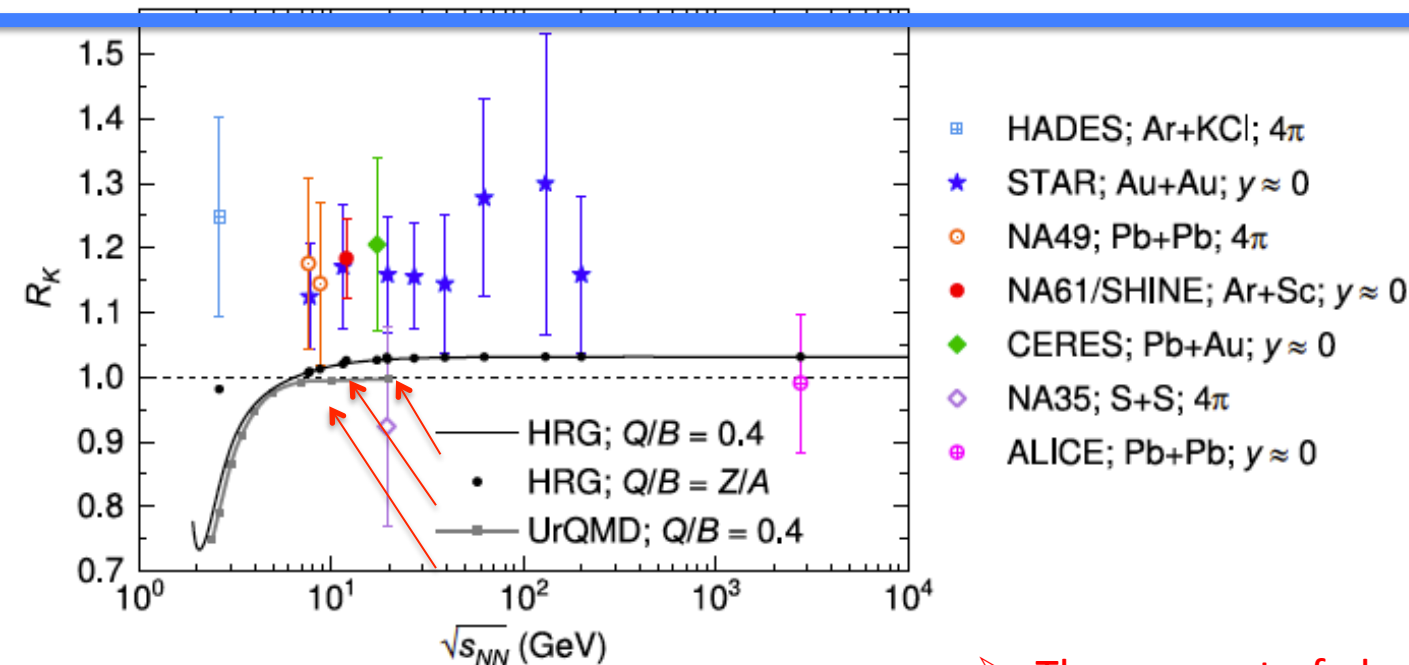


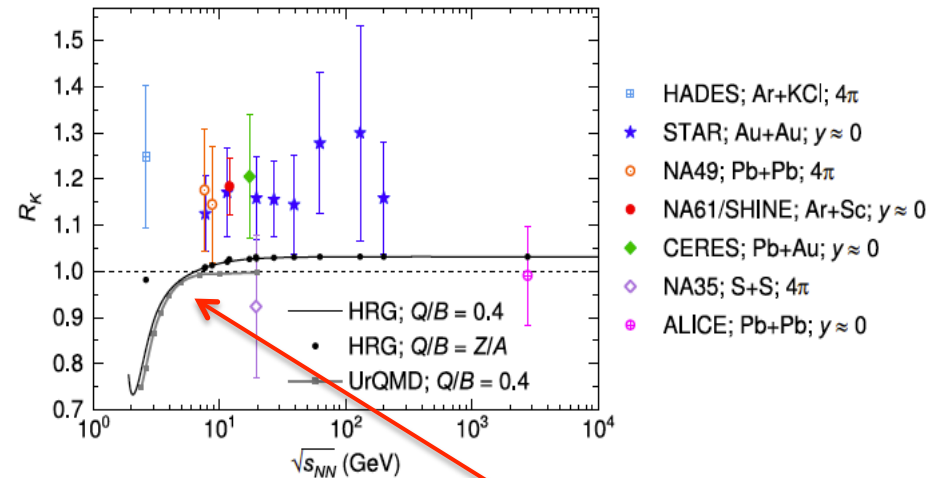
Fig. 3: The charged-to-neutral kaon ratio  $R_K$  as a function of collision energy.

➤ The account of electromagnetic interaction between  $K^+$  and  $K^-$  in this decay leads to the increase of  $R_K$  by at most 3% at the highest collision energy[1].

[1]The NA61/SHINE Collaboration., Giacosa, F., Gorenstein, M. *et al.*  
Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei.  
*Nat Commun* **16**, 2849 (2025). <https://doi.org/10.1038/s41467-025-57234-6>

# Violation of charge-symmetry invariance by known effects

- Electromagnetic interaction between  $K^+$  and  $K^-$  slightly increases the mass of  $K^+$  (both constituents  $u$  and  $s$  have positive charge), but slightly decreases the mass of  $K^0$  (the constituents  $d$  and  $s$  have opposite charges). [1]
- The  $u\bar{u}$  and  $d\bar{d}$  pairs creation in strong processes may be affected by electromagnetic interactions due to different electric charges of up and down quarks. This leads to a different phase space for their production, favoring  $u\bar{u}$  pairs and thus the charged kaons [1].



- Both HRG model and UrQMD show the decrease of  $R_K (<1)$  at energies below  $\sqrt{s_{NN}} \sim 7$  GeV

[1] The NA61/SHINE Collaboration., Giacosa, F., Gorenstein, M. *et al.* Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei. *Nat Commun* **16**, 2849 (2025). <https://doi.org/10.1038/s41467-025-57234-6>

# Effects of $R_K$ deviation from 1 in pp and AA collisions within the similarity approach (BMLZ) [1,2]

in the case of isospin-symmetry conservation at quark level.

- It is shown in [1,2] that “the ratio of charged-to-neutral kaon cross sections  $R_K = (K^+ + K^-)/2K_S^0$  calculated within the similarity approach, including the gluon transverse momentum dependence (TMD) at low QCD scales, and using the Lund model in the form of the MC generator PYTHIA, is above 1 at energies  $\sqrt{s}$  up to 20 GeV, even in the case of isospin-symmetry conservation.” [2]
- “It decreases to 1, when the energy rises to a few TeV (ALICE data). The reason for this is related to the dynamics of kaon production”. [2]
- “This energy behavior of  $R_K$  does practically not depend on the sort of beam or target”. [2]

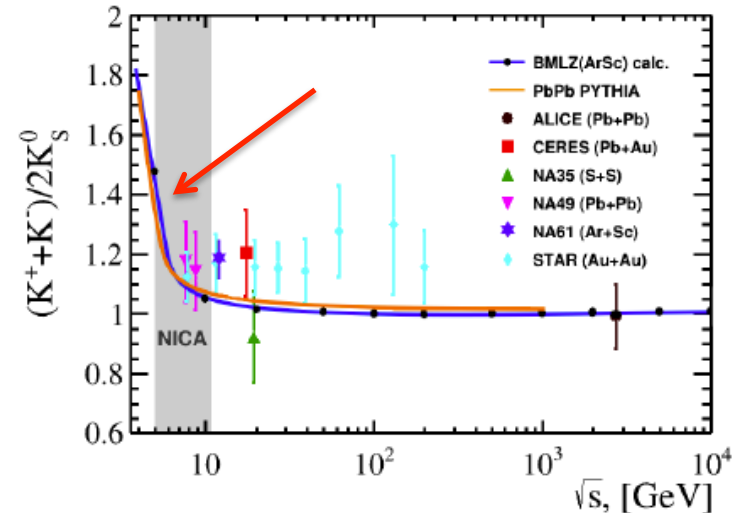


Figure 2: The ratio  $R_K = \frac{\sigma_{K^+} + \sigma_{K^-}}{2\sigma_{K_S^0}}$ , as a function of  $\sqrt{s}$  calculated within the similarity approach termed BMLZ for ArSc collisions [12] (blue line) and the Lund model [5] (yellow line-for PbPb). The experimental data are taken from [6].

- A.V. Guskov, G.I. Lykasov, A.I. Malakhov and A.A. Zaitsev: “Calculations do not contradict to the world data at  $\sqrt{s}_{NN} = 6-40$  GeV and  $\sqrt{s}_{NN} = 3$  TeV.”[1]
- However, the values of  $R_K$  at NICA energy domain **are growing with the decrease of  $\sqrt{s}_{NN}$**  -- contrary to the HRG model and UrQMD (!) – see in the previous slide.

[1] A.V. Guskov, G.I. Lykasov, A.I. Malakhov and A.A. Zaitsev, “K-meson production and isospin-symmetry in pp and AA collisions”, PoS(QCDEX2025)018, QCD at the Extremes (QCDEX2025), 1–5 Sept 2025

[2] A.V. Guskov, G.I. Lykasov, A.I. Malakhov, A.A. Zaitsev, “Isospin-symmetry in pp and AA collisions”, June 10, 2026, arXiv:2606.10707v1

# Effects of $R_K$ deviation from 1 in pp and AA collisions within the similarity approach (BMLZ) [1-3] in the case of isospin-symmetry conservation at quark level.

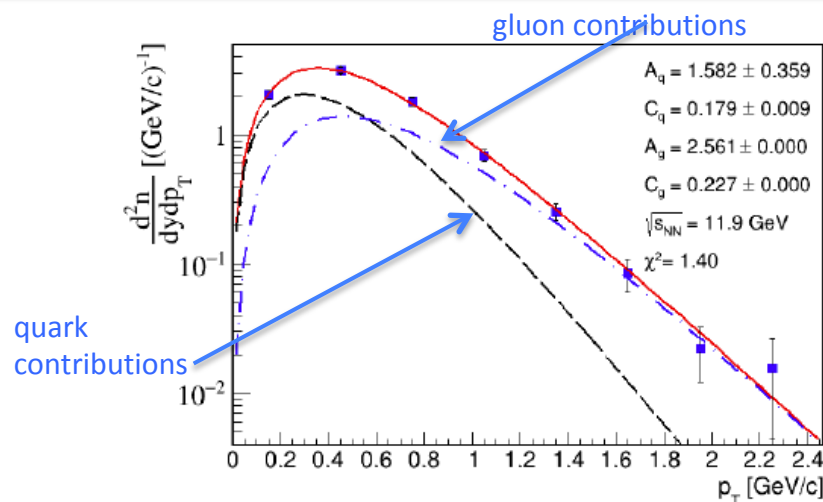


Figure 1 [1]:

“The inclusive  $p_T$  spectrum of  $K^0_s = 1/2(K^0 + \text{anti}K^0_s)$  produced in collisions Ar+Sc at  $\sqrt{s_{NN}} = 11.9$  GeV and  $y=0$  calculated within the similarity approach called as BMLZ [5]; black dashed and blue dashed-dotted lines are the quark and gluon contributions, respectively.”

---“The NA61/SHINE experimental data...”

---??? Data are different from NA61 HEP Data!

--- Both in “Y” and “X” points !

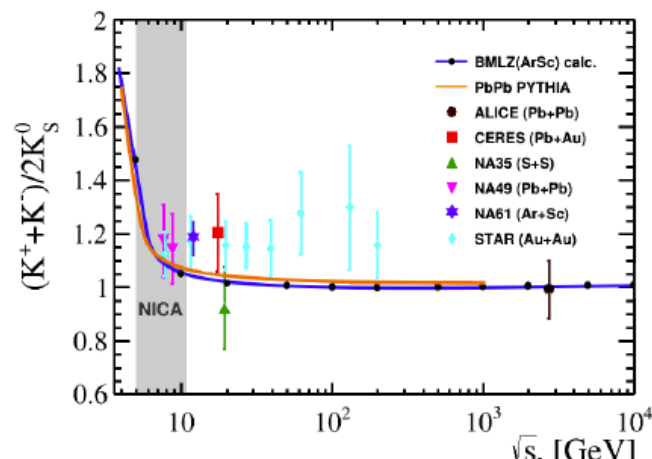


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➤ A.V. Guskov, G.I. Lykasov, A.I. Malakhov and A.A. Zaitsev: “Calculations do not contradict to the world data at  $\sqrt{s_{NN}} = 6-40$  GeV and  $\sqrt{s_{NN}} = 3$  TeV.”[1]

[1] A.V. Guskov, G.I. Lykasov, A.I. Malakhov and A.A. Zaitsev, “K-meson production and isospin-symmetry in pp and AA collisions”, PoS(QCDEX2025)018, QCD at the Extremes (QCDEX2025), 1–5 Sept 2025

[2] A.V. Guskov, G.I. Lykasov, A.I. Malakhov, A.A. Zaitsev, “Isospin-symmetry in pp and AA collisions”, June 10, 2026, arXiv:2606.10707v1

[3] G.I. Lykasov, A.I. Malakhov, A.A. Zaitsev, Eur.Phys. J. A60, 239 (2024).

# BMLZ and our Modified UrQMD results for Ar+Sc $\sqrt{s_{NN}}=11.9$ GeV: pT spectra

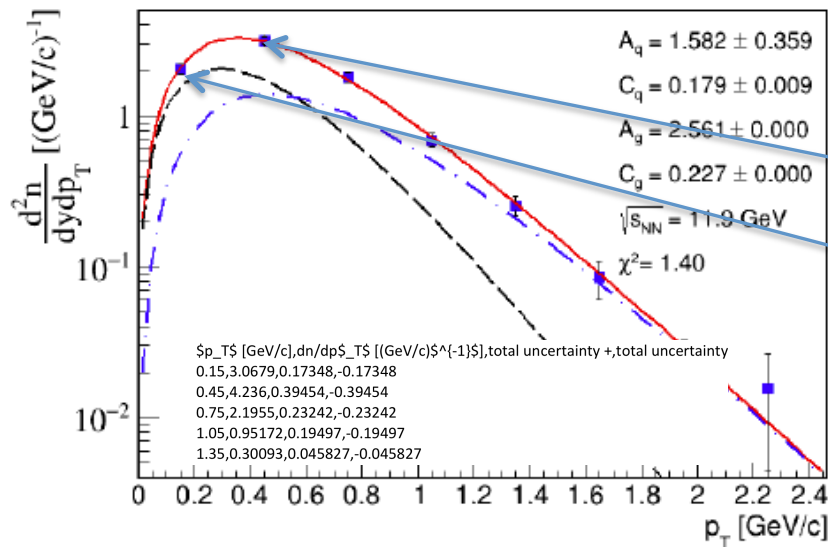


Figure 1:  
“The inclusive pT spectrum of  $K^0_s = 1/2(K^0 + \bar{K}^0)$  produced in collisions Ar+Sc at  $\sqrt{s}=11.9$  GeV and  $y=0$  calculated within the similarity approach called as BMLZ [5]; black dashed and blue dashed-dotted lines are the quark and gluon contributions, respectively. The NA61/SHINE experimental data...”

G.Lykasov et al. results for Ar+Sc

--странно? ---??? Data are different from HEP ! Both in “Y” and “X” points

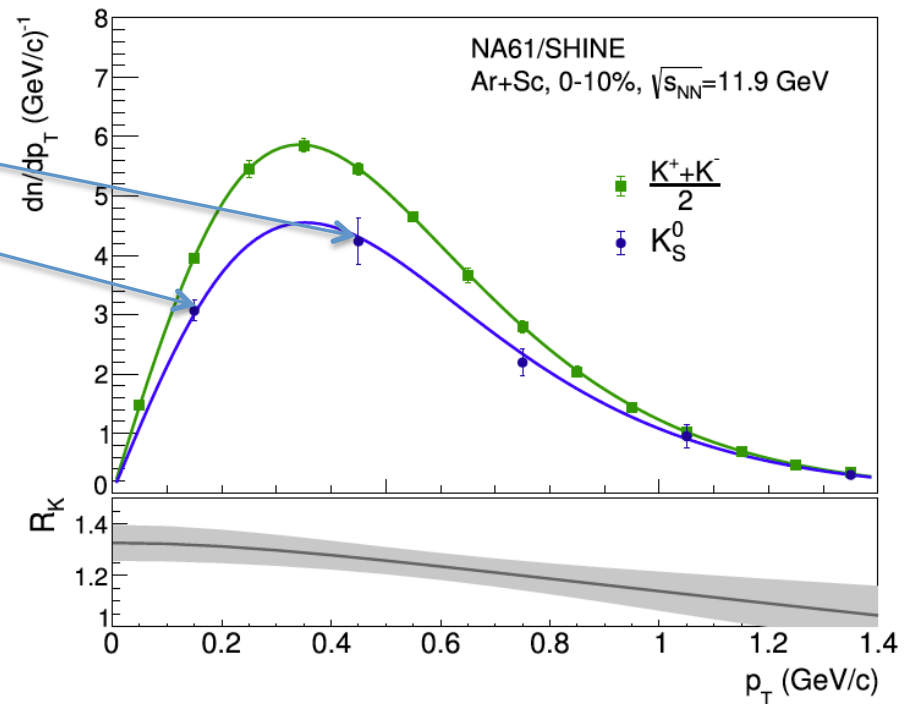


Figure 2: Comparison of transverse momentum spectrum of neutral ( $K^0_s$ ) with the averaged spectrum of charged ( $K^+$  and  $K^-$ ) mesons in the 10% most central Ar+Sc collisions at  $\sqrt{s_{NN}}=11.9$  GeV.

The bottom panel shows the ratio of the two distributions, as defined in Eq. (2). The meaning of the total uncertainties drawn is the same as in Fig. 1.

“Both distributions are integrated over the rapidity range  $0 < y < 2$ .”

# Violation of charge-symmetry invariance by known effects

---

- A model of the space-time evolution of the pair creation is needed to quantify the effect.
- New experimental checks are needed

[1] The NA61/SHINE Collaboration., Giacosa, F., Gorenstein, M. *et al.* Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei. *Nat Commun* **16**, 2849 (2025). <https://doi.org/10.1038/s41467-025-57234-6>

# Violation of charge-symmetry invariance

– novel explanation[1]:

- Quite recently, the UrQMD approach has been modified by including violation of isospin symmetry [1] by the parametrized string breaking: it brings as **three times more probable to produce  $u\bar{u}$  pair than a  $d\bar{d}$  one**;
- Remarkably, in this way, the ratio  $R_K$  is also correctly described for data on kaon productions in  $e+e^-$  and  $pp$  scattering[1].
- See the next slide →

[1] Tom Reichert, Jan Steinheimer, and Marcus Bleicher. Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions. Phys. Lett. B , 873:140170, 2026.

# Violation of charge-symmetry invariance

– novel explanation [1]:

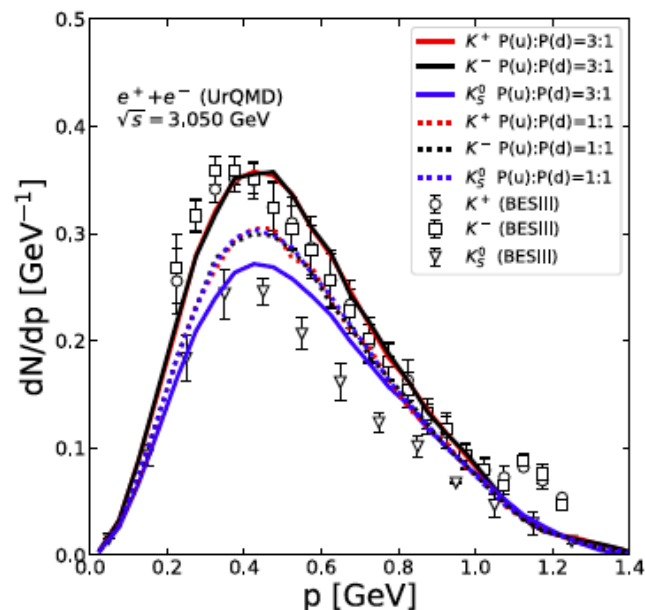


Fig. 1. [Color online] Momentum distributions of  $K^+$  (red)  $K^-$  (black) and  $K_S^0 = (K^0 + \bar{K}^0)/2$  (blue) in  $e^+e^-$  annihilations at  $\sqrt{s} = 3.050$  GeV. The dotted lines show the standard parametrization of the color field fragmentation parameters, the full lines show the refitted parameters which allow for an asymmetry between up- and down-quark production in the color field. The symbols show the experimental data by BESIII [9,10].

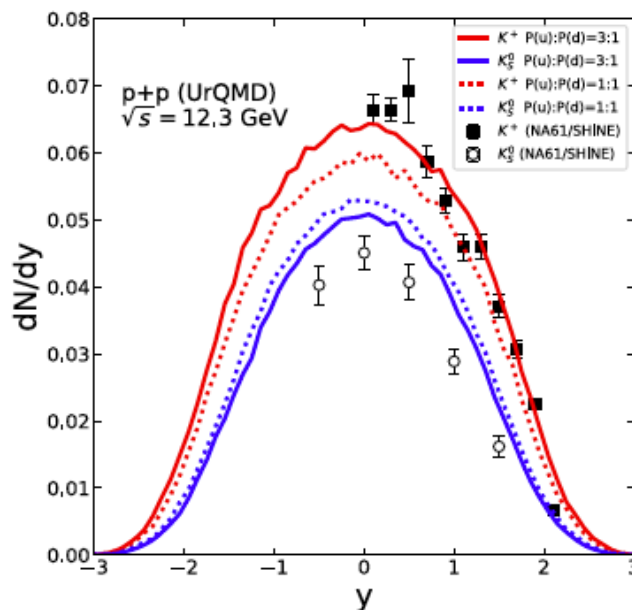
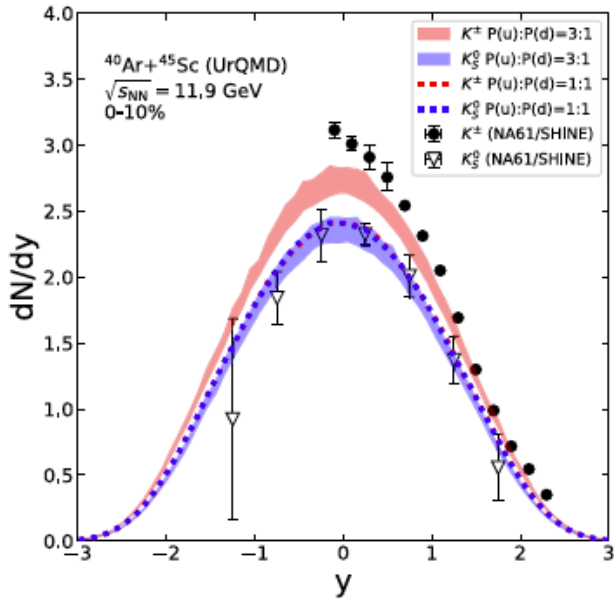


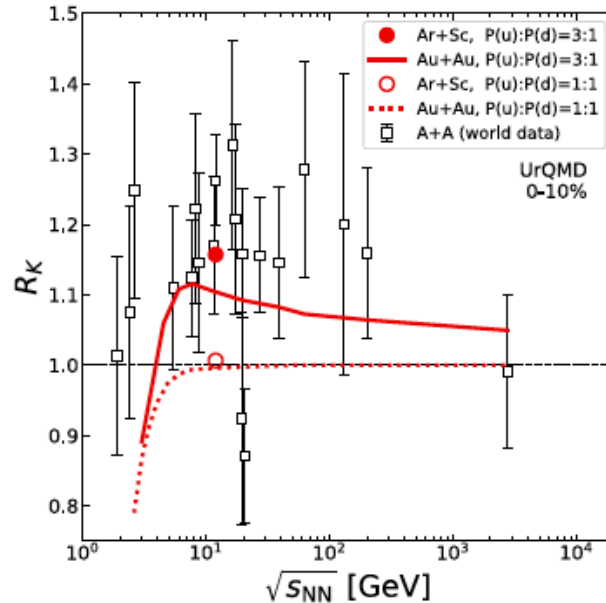
Fig. 2. [Color online] Rapidity distributions of  $K^+$  (red) and  $K_S^0 = (K^0 + \bar{K}^0)/2$  (blue) in proton+proton collisions at  $\sqrt{s} = 12.3$  GeV. The dotted lines show the standard parametrization of the color field fragmentation parameters, the full lines show the refitted string fragmentation parameters. The symbols show the experimental data by the NA61/SHINE experiment [11,12].

[1] Tom Reichert, Jan Steinheimer, and Marcus Bleicher. Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions. Phys. Lett. B , 873:140170, 2026

# Violation of charge-symmetry invariance – novel explanation [1]:



**Fig. 3.** [Color online] Rapidity distributions of  $K^\pm = (K^+ + K^-)/2$  (red) and  $K_S^0 = (K^0 + \bar{K}^0)/2$  (blue) in 0–10% central Ar+Sc collisions at  $\sqrt{s_{NN}} = 11.9$  GeV. The dotted lines show UrQMD calculations with the standard parametrization of the color field fragmentation parameters, the full lines show the UrQMD results using the refitted string parameters. The error band in the calculation is due to the estimation of the centrality ( $\langle N_{wounded} \rangle = 60 - 64$  representing 10% central collisions). The symbols show the experimental data by the NA61/SHINE experiment [1,16].



**Fig. 4.** [Color online] Comparison of the refitted simulations with the world data on the ratio  $R_K = (K^+ + K^-)/(K^0 + \bar{K}^0)$ . The dotted lines show UrQMD calculations for central Au+Au reactions with the standard parametrization of the color field fragmentation parameters, the full lines show UrQMD results using the refitted string fragmentation parameters. We further show the UrQMD results for Ar+Sc collisions (circles) because Ar+Sc has a larger protons/neutron ratio than Au+Au. The black squares show the experimental data in nucleus-nucleus collisions (taken from the compilation in Adhikary [16]).

[1] Tom Reichert, Jan Steinheimer, and Marcus Bleicher. Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions. Phys. Lett. B , 873:140170, 2026

# Our preliminary results on modification of the UrQMD code

## “UrQMD(3:1)”

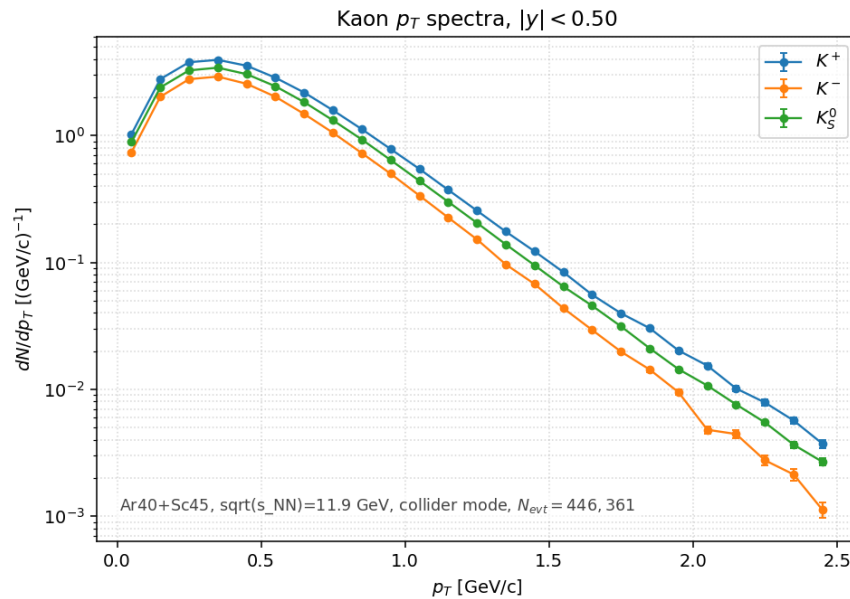
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following the ideas of [1]  
on 3:1 probability to produce  $u\bar{u}$  pair vs.  $d\bar{d}$  one  
and some relevant “UrQMD(3:1)” predictions  
in the fixed target collisions  
for Ar+Sc, 12C+12C and Xe+W

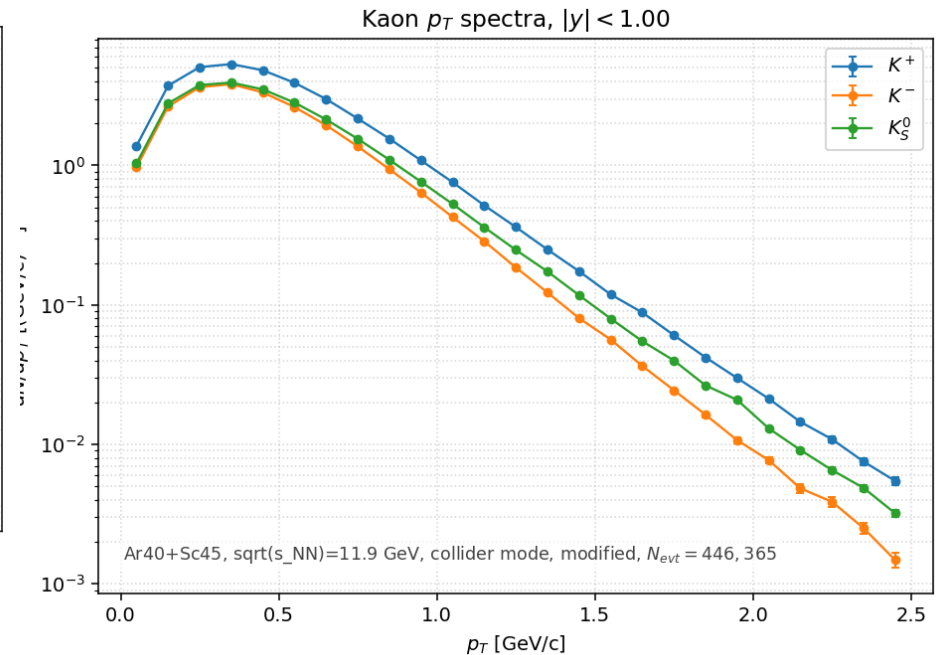
[1] Tom Reichert, Jan Steinheimer, and Marcus Bleicher. Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions. Phys. Lett. B , 873:140170, 2026

# Default and our Modified UrQMD preliminary results for Ar+Sc $\sqrt{s_{NN}}=11.9$ GeV:

## $p_T$ spectra



Our UrQMD (default) results for Ar+Sc

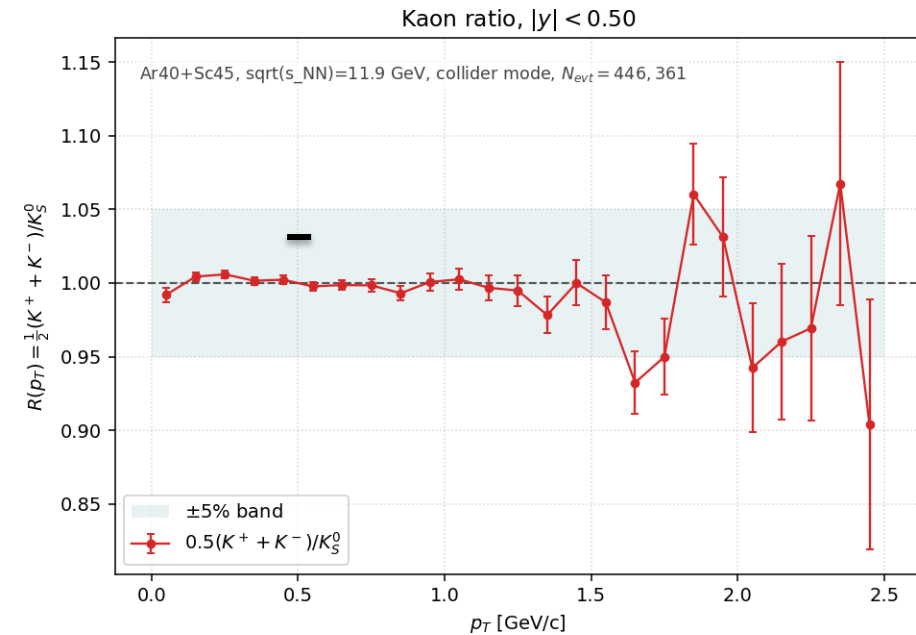


Our modified UrQMD(3:1) results for Ar+Sc  
 $P(u):P(d)=3:1$  (Preliminary)

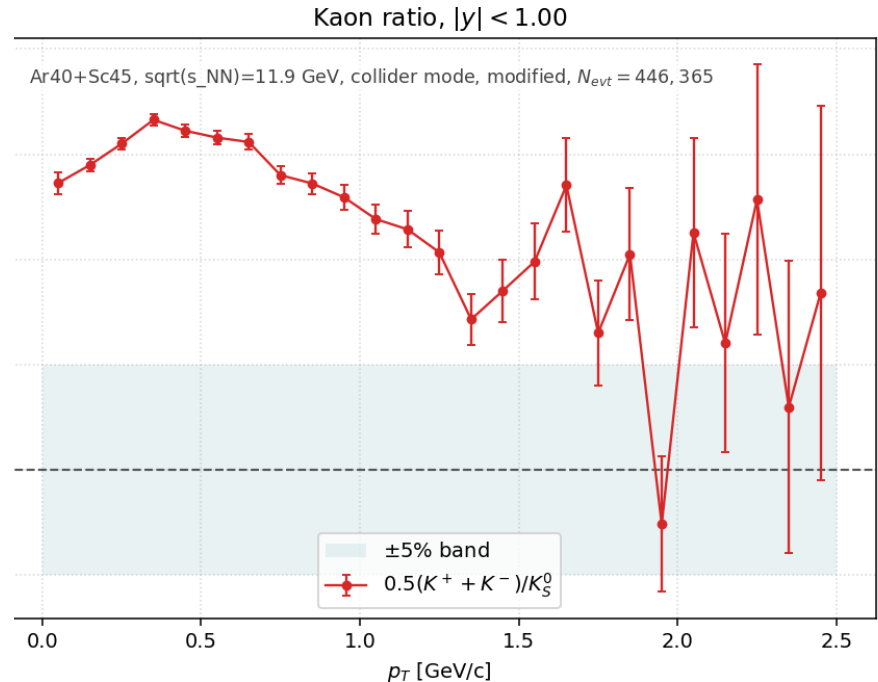
➤ “Soft” part ( $< 2$  GeV/c) of  $p_T$  spectra of kaons appears to be different as **calculated**  
by the **modified UrQMD** in case of  $P(u):P(d)=3:1$

# Default and our Modified UrQMD preliminary results for Ar+Sc $\sqrt{s_{NN}}=11.9$ GeV:

## $R_k$ (pT)



Our UrQMD (default) results for  $R_k(pT)$   
In Ar+Sc at  $\sqrt{s_{NN}}=11.9$  GeV

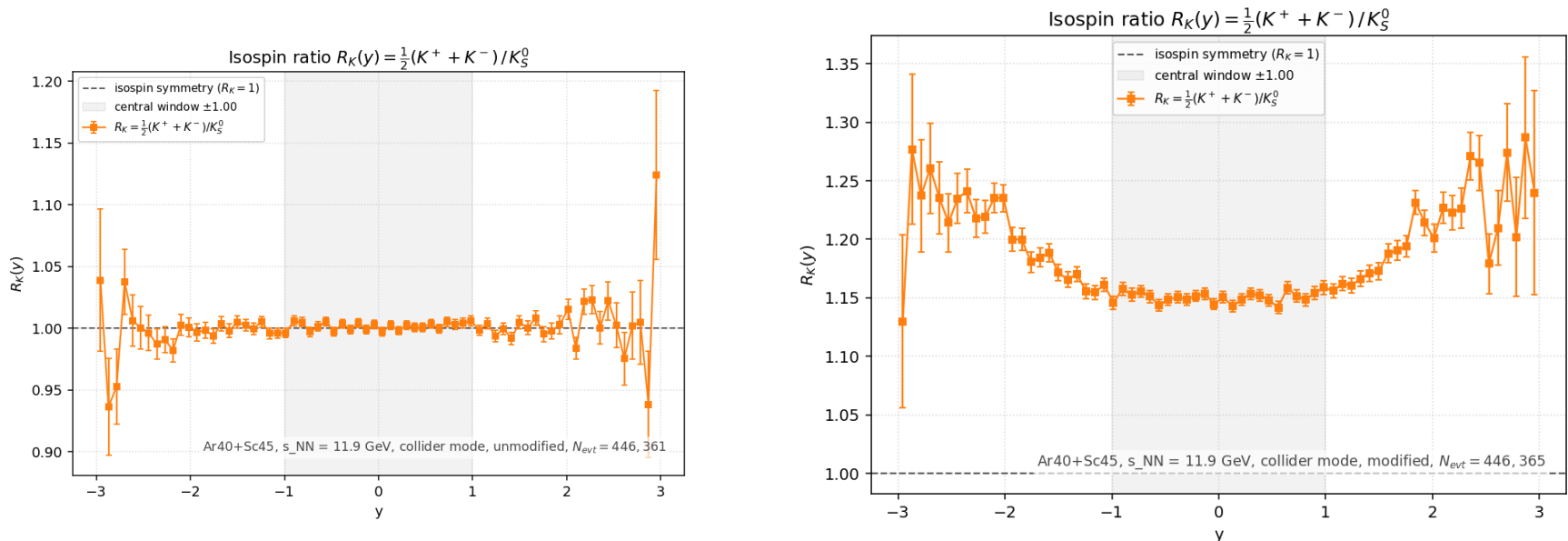


Our “UrQMD(3:1)” results of  $R_k$  (pT)  
for Ar+Sc with  $P(u):P(d)=3:1$  (Preliminary)

➤ Considerable effect of Isotopic Symmetry breaking is observed in  $R_k$  in pT spectra ratios predicted by the modified UrQMD in case of  $P(u):P(d)=3:1$  in the “soft” part ( $< 1.5$  GeV/c) of spectra

# Default and our Modified UrQMD preliminary results for Ar+Sc at $\sqrt{s}_{NN}=11.9$ GeV

## Ratios of rapidity distributions



Our UrQMD (default) results for Ar+Sc

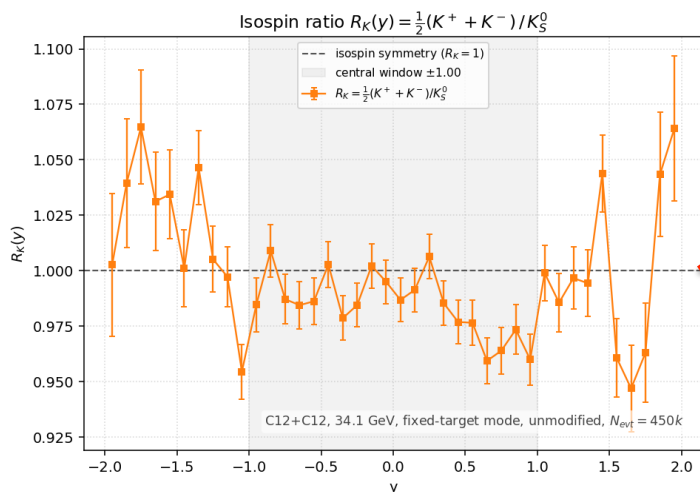
Our “UrQMD(3:1)” results for Ar+Sc  
P(u):P(d)=3:1. (Preliminary)

➤ The shape of “Modified UrQMD(3:1)” rapidity distribution appears to be different from the default UrQMD

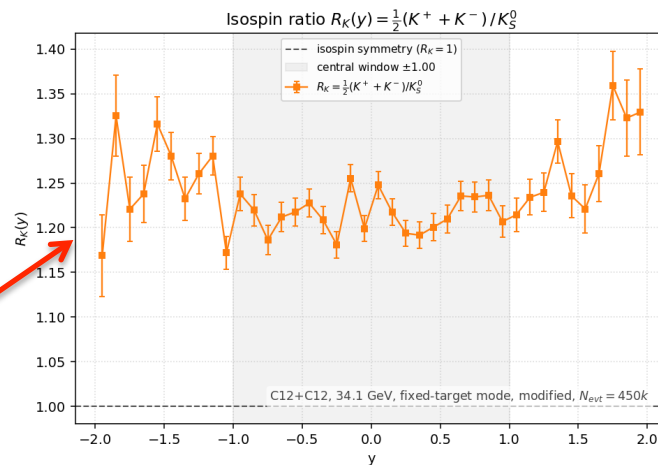
# Default and our Modified UrQMD preliminary results for symmetric (Q/B=0.5) 12C+12C collisions,

-- an example at  $\sqrt{s_{NN}}=34$  GeV:

## Ratios of rapidity distributions



Our UrQMD (default) results

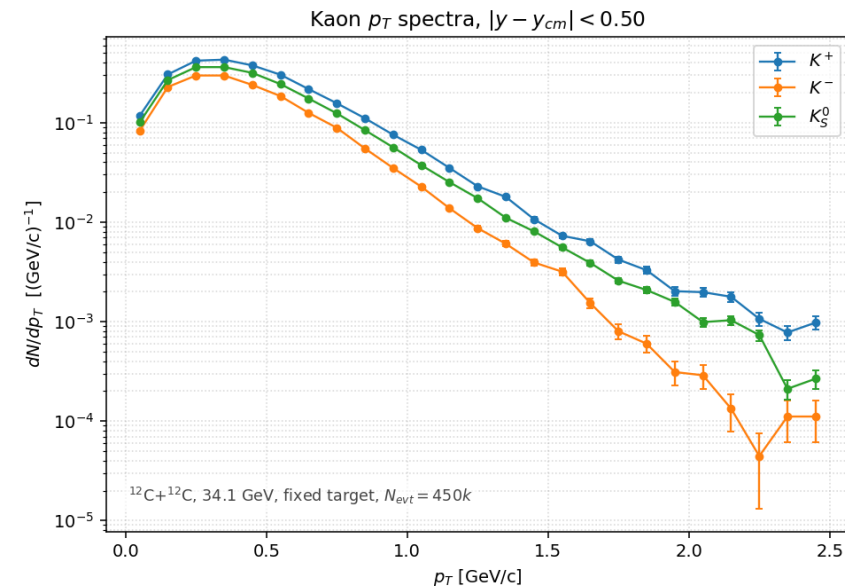


Our “UrQMD(3:1)” results for 12+12C  
 $P(u):P(d)=3:1$

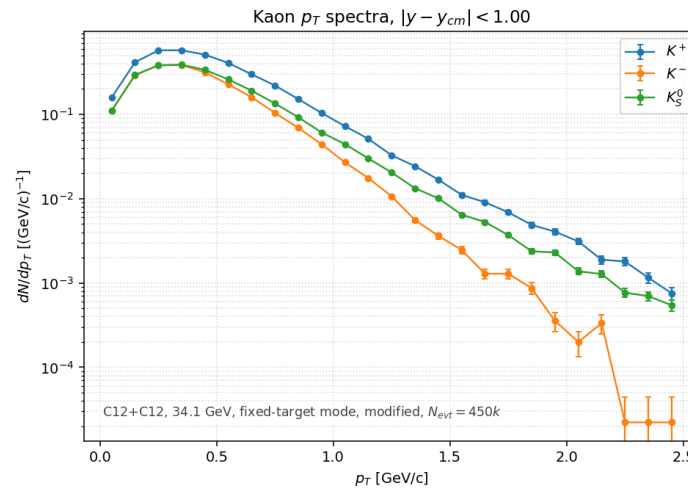
- Considerable effect of Isotopic Symmetry Breaking is predicted by the “Modified UrQMD (3:1)” in ratios of rapidity distributions for the case of 12+12 C collisions at  $\sqrt{s_{NN}}=34$  GeV
- Figure is preliminary, statistics here is to be improved

# Default and our Modified UrQMD results for $^{12}\text{C}+^{12}\text{C}$ -- an example at $\sqrt{s_{\text{NN}}}=34$ GeV:

## pT spectra



Our UrQMD (default) results

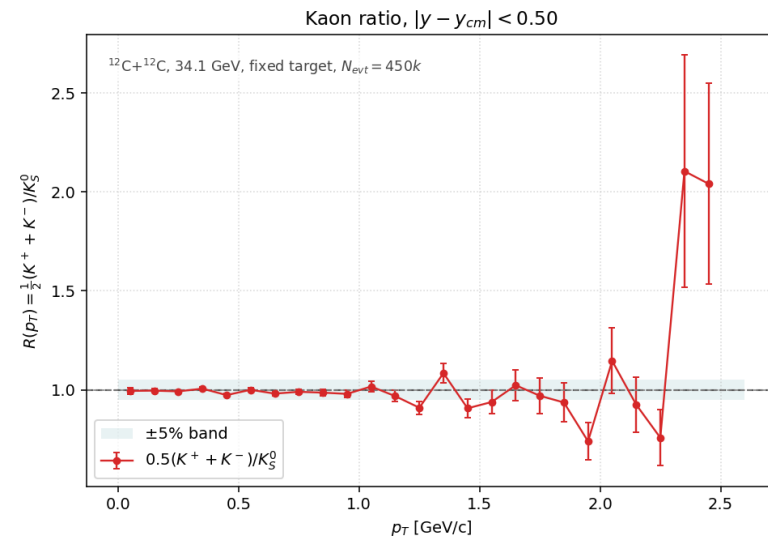


Our “UrQMD(3:1)” results for 12+12C  
P(u):P(d)=3:1 (Preliminary)

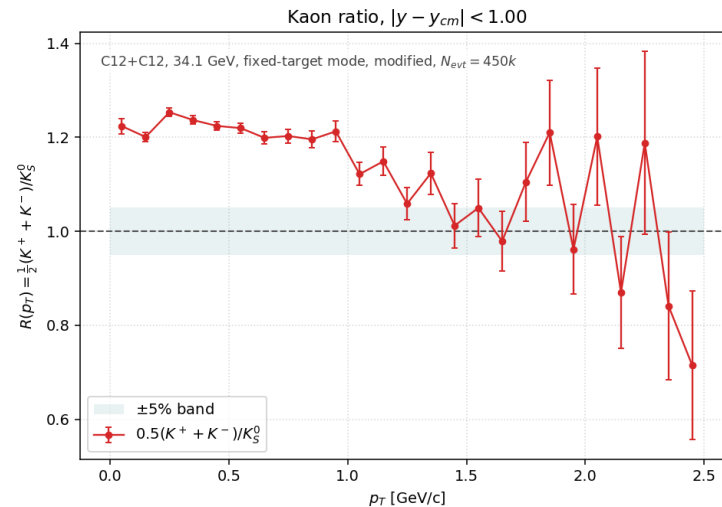
- “Soft” part ( $< 1/5$  GeV/c) of pT spectra of kaons in two versions of the UrQMD is different

# Default and our Modified UrQMD results for 12C+12C -- an example at $\sqrt{s_{NN}}=34$ GeV:

$R_k$  (pT)



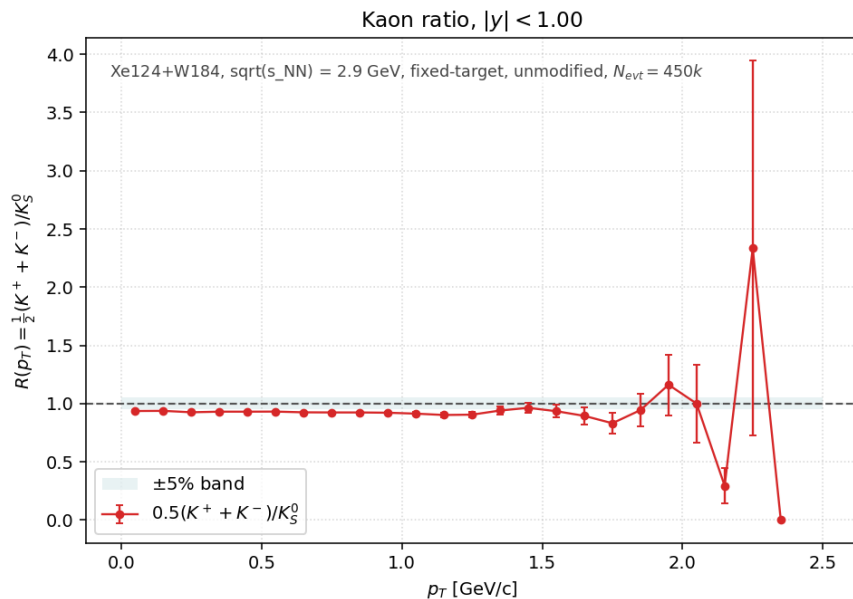
Our UrQMD (default) results



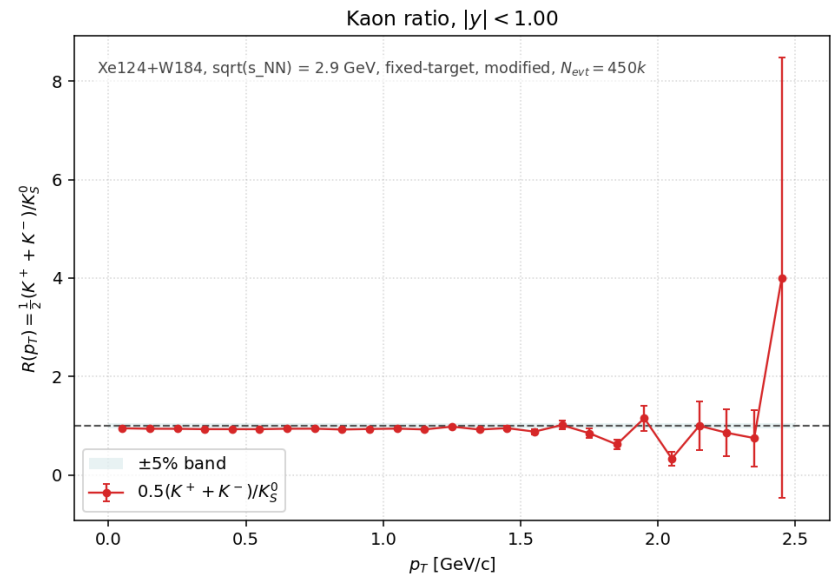
Our “Modified UrQMD(3:1)” results  
for 12+12C with P(u):P(d)=3:1

- Considerable effect of Isotopic Symmetry Breaking is predicted by the modified UrQMD in case of P(u):P(d)=3:1 for 12+12 C collisions at  $\sqrt{s_{NN}}=34$  GeV in the “soft” part ( $<1/5$  GeVc) of pT spectra of kaons

# UrQMD results at NICA energy at $\sqrt{s_{NN}}=2.9$ GeV in case of non-symmetric system (Q/B<0.5): Xe+W 0-10% central collisions class



UrQMD(default)



“UrQMD(3:1)”

- При энергии Xe+W столкновений  $\sqrt{s_{NN}}=2.9$  GeV в генераторе событий “UrQMD(3:1)” уже нет кварк-глюонных струн, а идут процессы с образованием и распадом резонансов.

# Summary

- Unexpected excess of charged-over-neutral kaon production in  $\pi^-+C$  and  $Ar+Sc$  collisions was observed by NA61/SHINE at SPS, thus confirming the earlier world data

**This indicates the violation of isospin symmetry at the level of significance  $5.3\sigma$  beyond the known effects**

- **Explanation** of the observed violation and the fundamental understanding on the base of different (3:1) probabilities of  $uu$  and  $dd$  quark pairs production in the color field, **proposed in** [Phys. Lett. B , 873:140170, 2026], requires both additional experimental checks and theoretical efforts.
- Our Modified UrQMD(3:1) preliminary results for non-symmetric  $Ar+Sc$  ,  $Xe+W$  and for symmetric  $12C+12C$  collisions show also that the level of violation of isospin symmetry could be different:
  - (i) for “soft” and “hard “ parts of  $p_T$  spectra,
  - (ii) for rapidity distributions of  $R_K$  values at midrapidity and at large rapidity,
  - (iii) For different collision energies.
- **New experimental high statistic tests of  $R_K$  are required in the extended rapidity regions both for symmetric ( $Q/B=1/2$ ) and non-symmetric ( $Q/B<1/2$ ) nucleus-nucleus collisions.**

# Back-up slides

# NA61/SHINE

- 1) NA61/SHINE facility at the CERN SPS: beams and detector system, (NA61 Collaboration), N. Abgrall(Geneva U. et al. *JINST* 9 (2014) P06005, e-Print: [1401.4699](#), DOI: [10.1088/1748-0221/9/06/P06005](#)
- 2) Measurements of  $\pi^\pm\pi^\pm$ ,  $K^\pm K^\pm$ , p and  $p^-p^-$  spectra in 40Ar+45Sc collisions at 13A to 150A Ge V / c Ge V /c, (NA61/SHINE Collaboration), H. Adhikary(Jan Kochanowski U. et al., *Eur.Phys.J.C* 84 (2024) 4, 416, e-Print: [2308.16683](#), DOI: [10.1140/epjc/s10052-024-12602-2](#)
- 3) Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei, (NA61/SHINE Collaboration), H. Adhikary(Jan Kochanowski U., et al., *Nature Commun.* 16 (2025) 1, 2849, e-Print: [2312.06572](#), DOI: [10.1038/s41467-025-57234-6](#)