КОНФЕРЕНЦИЯ
ФИЗИКА ЧАСТИЦ ПРИ СРЕДНИХ И ВЫСОКИХ ЭНЕРГИЯХ

«ИНСТИТУТ ФИЗИКИ ВЫСОКИХ ЭНЕРГИЙ
ИМЕНИ А.А. ЛОГУНОВА НАЦИОНАЛЬНОГО ИССЛЕДОВАТЕЛЬСКОГО ЦЕНТРА
«КУРЧАТОВСКИЙ ИНСТИТУТ»

2-5 ИЮНЯ 2026
Г.ПРОТВИНО
МОСКОВСКАЯ ОБЛАСТЬ

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.Жаров (СПбГУ)

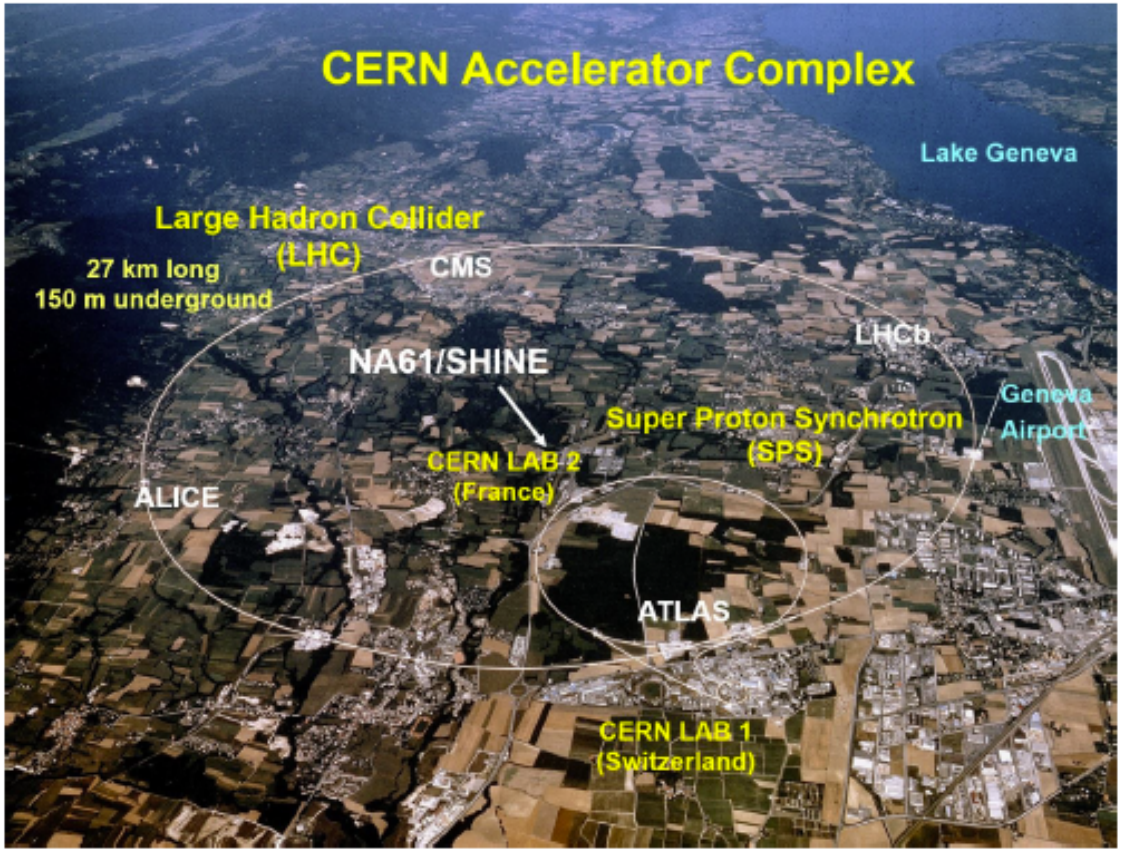
2 июн. 2026 г., 10:10, 25m https://indico.ihep.su/event/922/program

Работа выполнена при поддержке СПбГУ, шифр проекта 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.

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 π, K, p (13–350 GeV/c)

Ion beams:

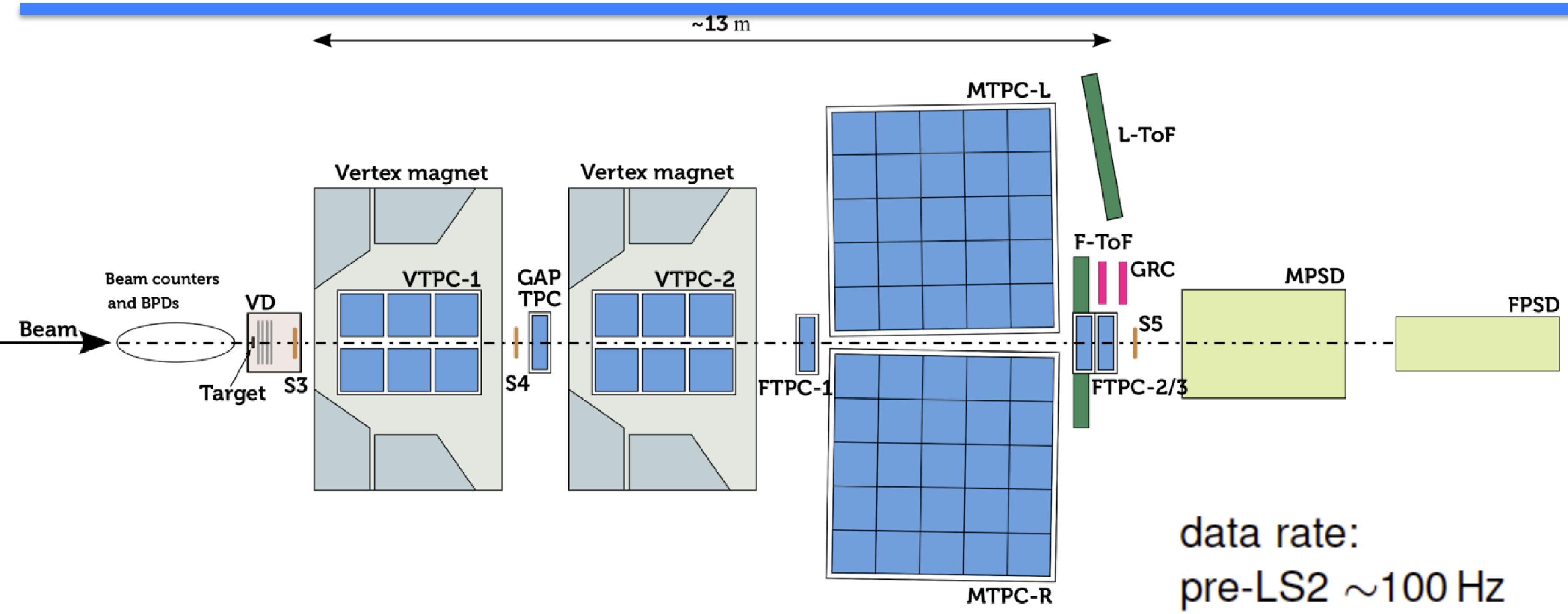
- Ar, Xe, Pb (13–150A GeV/c)
- Secondary Be (13–150A GeV/c) (from Pb fragmentation)

[1] NA61/SHINEdetector overview, https://indico.cern.ch/event/1174830/contributions/5174346/attachments/2567605/4426948/na61_det.pdf

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 Wroclaw, 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

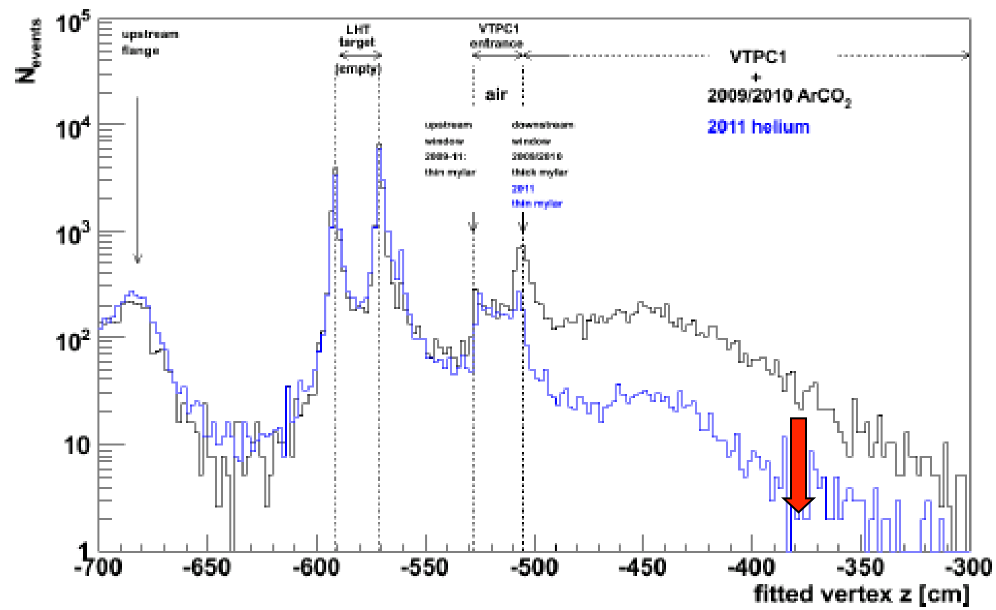
Fixed target experiment in the North area of SPS at CERN:

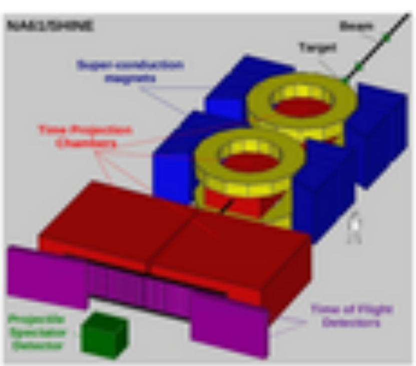
- tracking efficiency: > 95%
- large acceptance: full forward c.m.s. hemisphere, down to $p_T = 0$
- particle identification: $\mathrm{d}E/\mathrm{d}x$ in Time Projection Chambers, Time of Flight
- centrality: forward energy in Projectile Spectator Detector(s)
- ion (Be, Ar, Xe, Pb) and hadron (π, K, p) beams, various targets including liquid H_2 and water
- $\pi^{\pm}$, $K^{\pm}$, K^0_S, K^*, p, Λ, ϕ, Ξ, 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/SHINEdetector overview, https://indico.cern.ch/event/1174830/contributions/5174346/attachments/2567605/4426948/na61_det.pdf

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

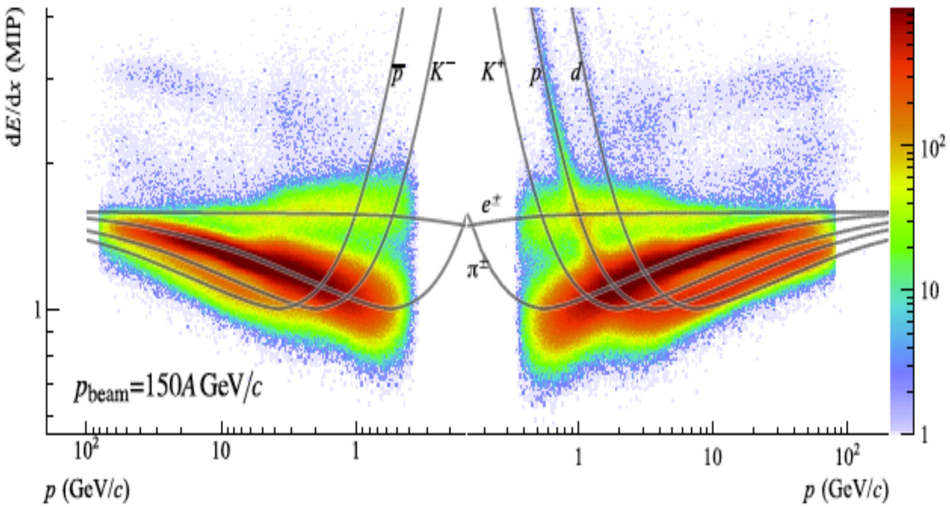
- Left: Extra-thin double-wall **He beam pipe** installed in 2012 in the gas volume between two field cages in the VTPC-1 of NA61(SHINE). The same in VTPC-2
- This **He beam pipe** reduces the background interactions in the VTPCs by about **a factor of 10.**



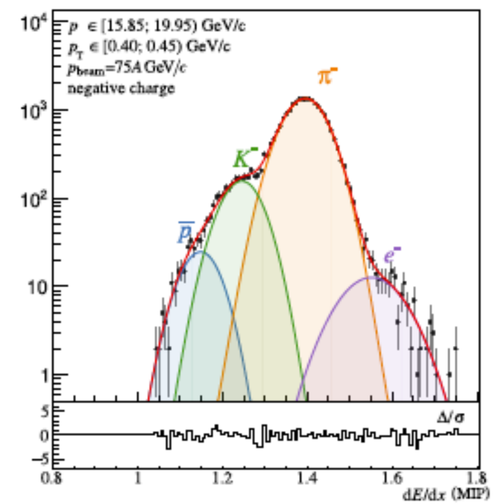


NA61/SHINE facility at the CERN SPS: beams and detector system, 2014 JINST 9 P06005, doi:10.1088/1748-0221/9/06/P06005

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



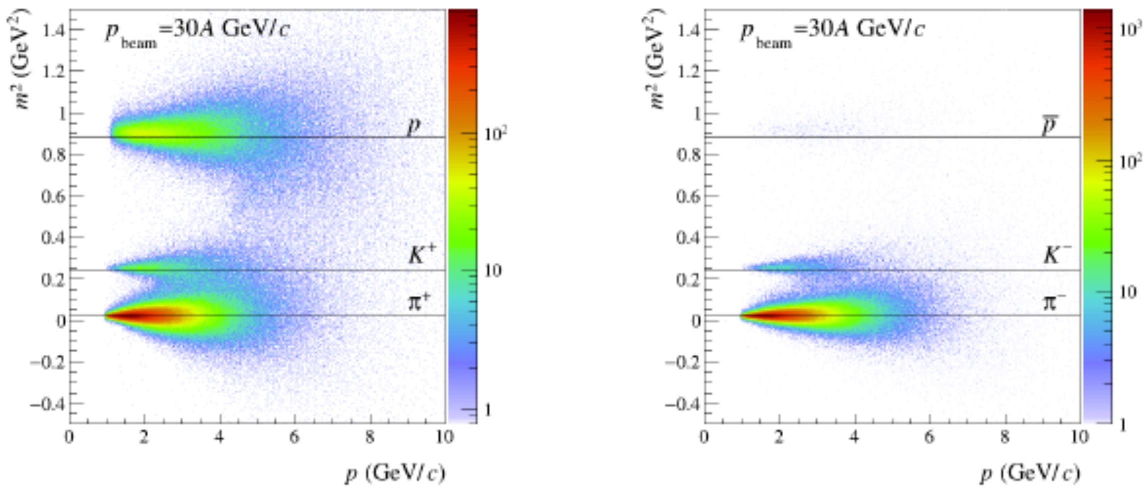
Distribution of charged particles in dE/dx -- *p plane*



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

[1] NA61/SHINE Collaboration, Measurements of π±, K±,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]



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

L – length of trajectory

p[GeV/c]

p[GeV/c]

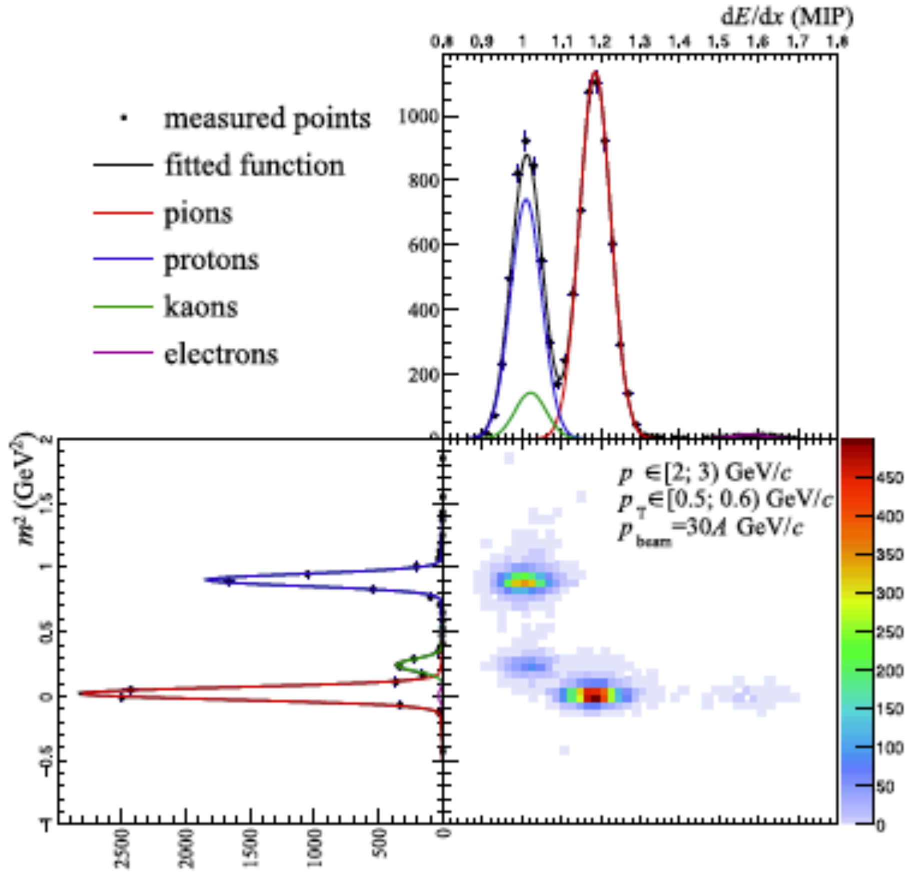
Figure 9: Distribution of particles in the plane laboratory momentum and mass squared derived using time-of-flight measured by ToF-R (right) and ToF-L (left) produced in *central* Ar+Sc collisions at 30*A* GeV/*c*. The lines show the expected mass squared values for different hadron species.

[1] NA61/SHINE Collaboration, Measurements of π±, K±,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 – dE/dx measurements [1]

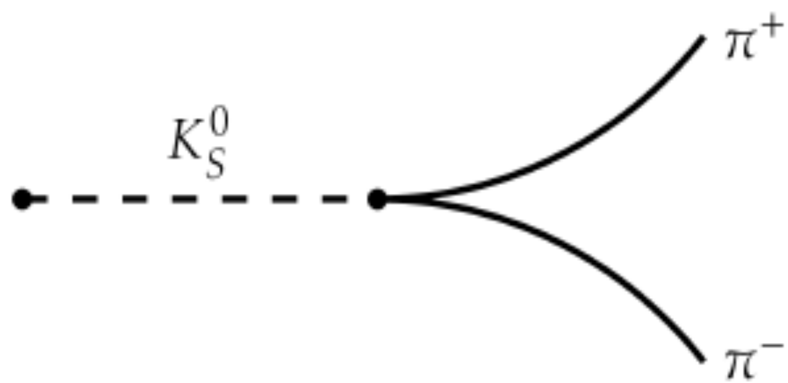
Eur. Phys. J. C (2024) 84:416 Page 13 of 54 416

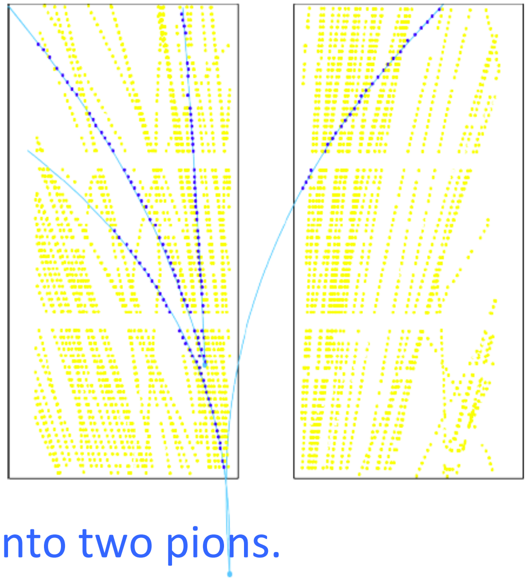
Fig. 11 Example of the *tof* – d*E*/dx fit (Eq. 4) obtained in a single bin ($2 < p < 3$ GeV/*c* and $0.5 < p_T < 0.6$ GeV/*c*) for positively charged particles in *central* Ar+Sc collisions at 30*A* GeV/*c*



[1] NA61/SHINE Collaboration, Measurements of π±, K±,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^0_s decay :

Left: Example of V0 topology as for K^0_S 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^0_S 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

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

Pu

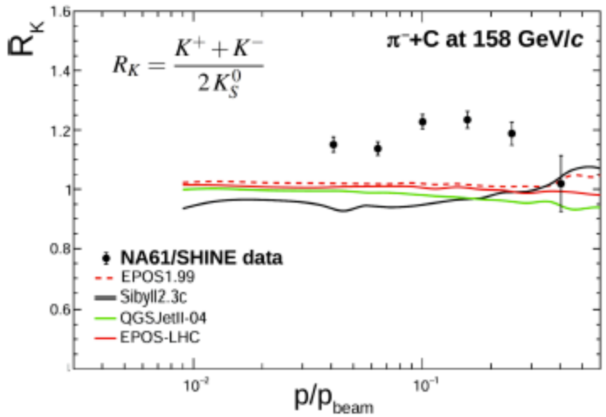
The NA61/SHINE Collaboration*, F. Giacosa[1,2], M. Gorenstein[3,4], R. Poberezhniuk[3,4,5] & S. Samanta[6]

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

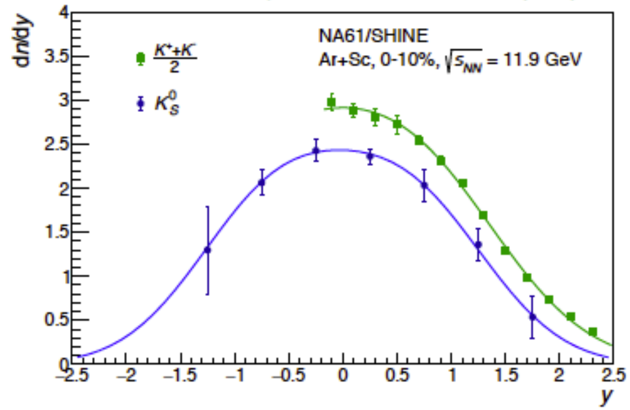
….The significance of the flavor-symmetry violation beyond the known effects is 4.7σ when the compilation of world data with uncertainties quoted by the experiments is used. …

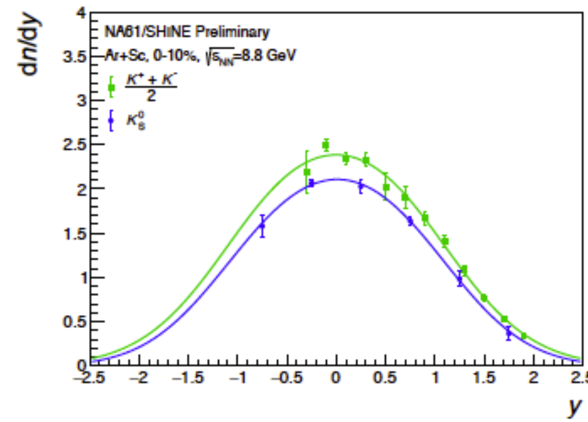
Evidence of isospin-symmetry violation in kaon production: new data by NA61/SHINE[1]

NA61/SHINE, PRD 107 (2023) 062004



NA61/SHINE and others, Nature Communications 16 (2025) 2849



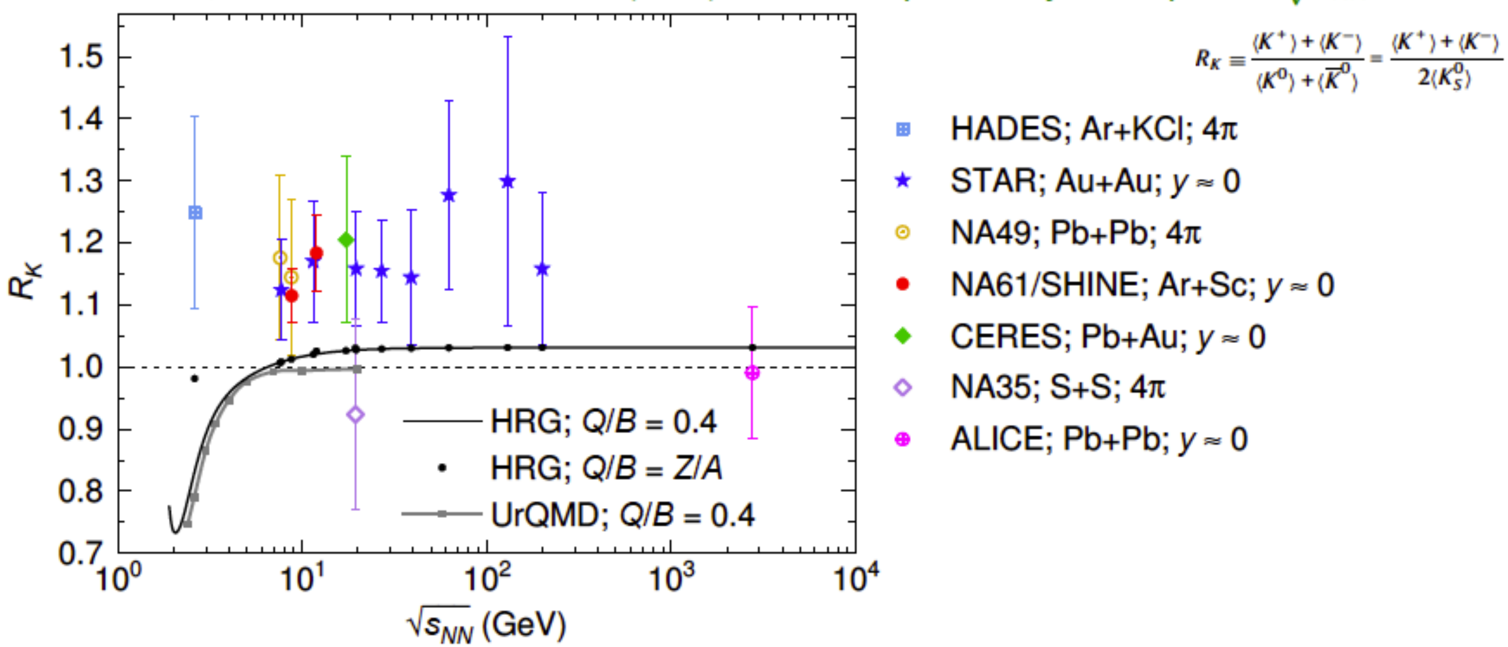


- For exact isospin symmetry $(m_u = m_d)$ and collisions of $Z = N$ nuclei $\langle K^+\rangle\,(u\bar{s}) = \langle K^0\rangle\,(d\bar{s})$ and $\langle K^-\rangle\,(\bar{u}s) = \langle \overline{K}^0\rangle\,(\bar{d}s)$; neglecting small CP violation $\langle K_S^0\rangle = \frac{1}{2}\langle K^0\rangle + \frac{1}{2}\langle \overline{K}^0\rangle = \langle K_L^0\rangle$
- Therefore expected $R_K = \frac{\langle K^+\rangle + \langle K^-\rangle}{\langle K^0\rangle + \langle \overline{K}^0\rangle} = \frac{\langle K^+\rangle + \langle K^-\rangle}{2\langle K_S^0\rangle} = 1$
- In both cases of π^-+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 18th 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 √sNN-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 5.3σ 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 18th Workshop on Particle Correlations a nd 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

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

Mass $m = 2.16 \pm 0.07$ MeV   Charge $= \frac{2}{3}\,e$ $I_z = +\frac{1}{2}$

$m_u/m_d = 0.462 \pm 0.020$

d

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

Mass $m = 4.70 \pm 0.07$ MeV   Charge $= -\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$

$m_s/m_d = 17\text{–}22$

$\overline{m} = (m_u + m_d)/2 = 3.49 \pm 0.07$ MeV

s

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

Mass $m = 93.5 \pm 0.8$ MeV   Charge $= -\frac{1}{3}\,e$ 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 MS (Modified Minimal Subtraction) scheme at renormalization scale μ=2GeV[1].
- The masses of up and down quarks, $m_u = 2.16 \pm 0.07$ MeV and $m_d = 4.70 \pm 0.07$ MeV[1] are much smaller than the QCD scale, Λ_{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: Δ=4.7-2.16=2.54 MeV,
- Accordingly, the relative magnitude of the differences in the masses of kaons is small: $mK^+=mK^-$ = 493.7 MeV, $mK^0=m\bar{K}^0$=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: ϕ(1020) meson decays about 1.45 more frequently into charged kaons than neutral ones (This large difference is because the ϕ(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]

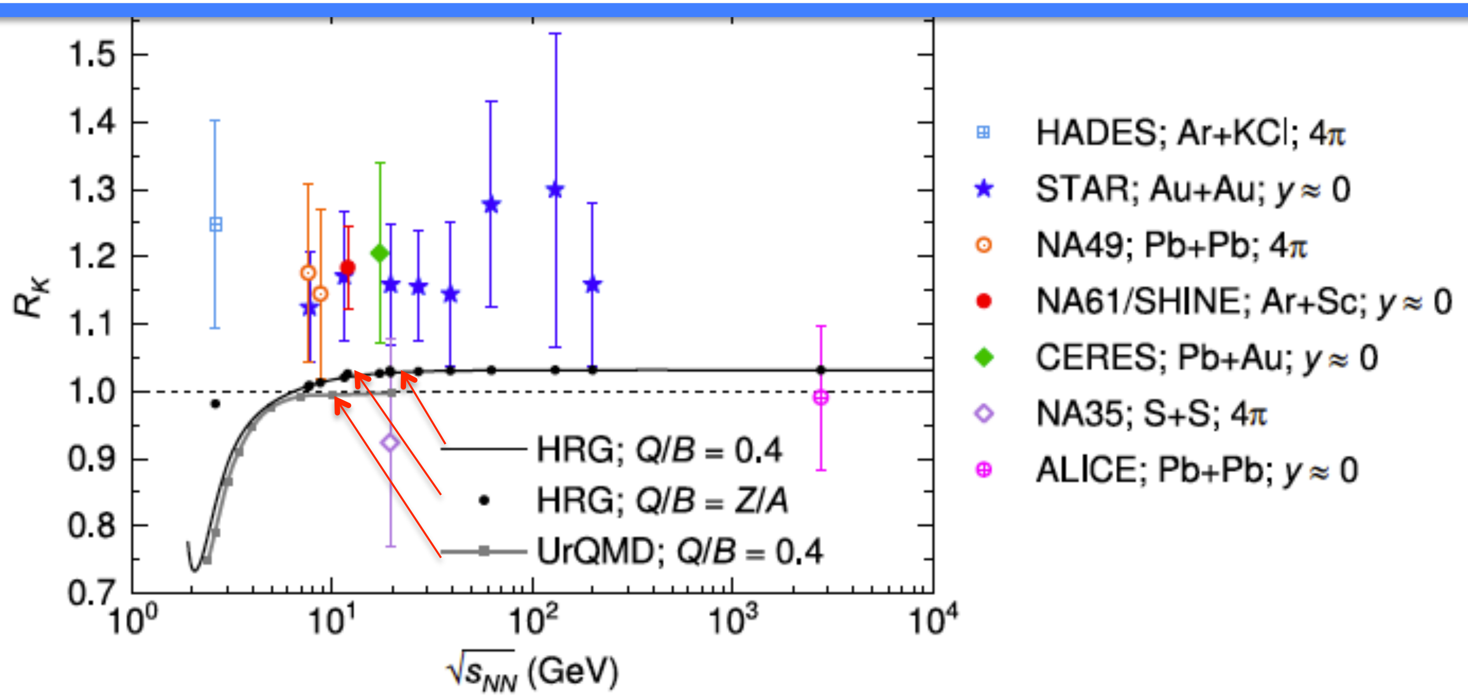


Fig. 3: The charged-to-neutral kaon ratio R_K as a function of collision energy.

[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].

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

[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 corretly 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]:

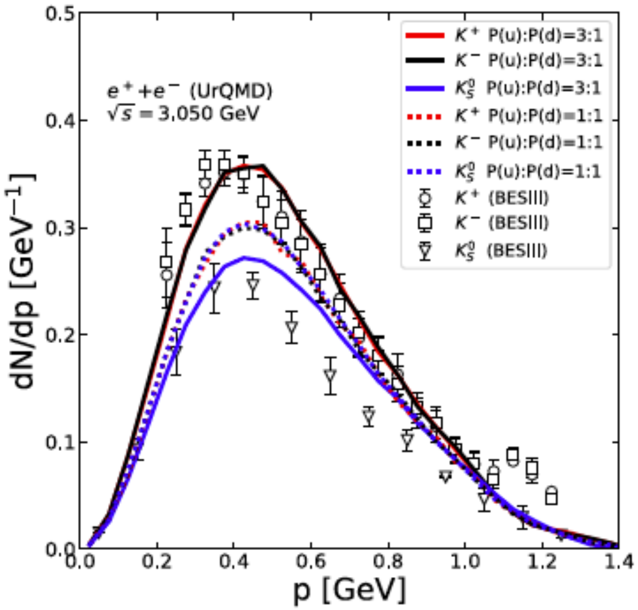


Fig. 1. [Color online] Momentum distributions of K^+ (red) K^- (black) and $K^0_S = (K^0 + \bar{K}^0)/2$ (blue) in e^+e^- annihilations at $\sqrt{s} = 3.050$ GeV. The dotted lines show the standard parametrization of the color field fragmentation parameters, the full lines show the refitted parameters 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].

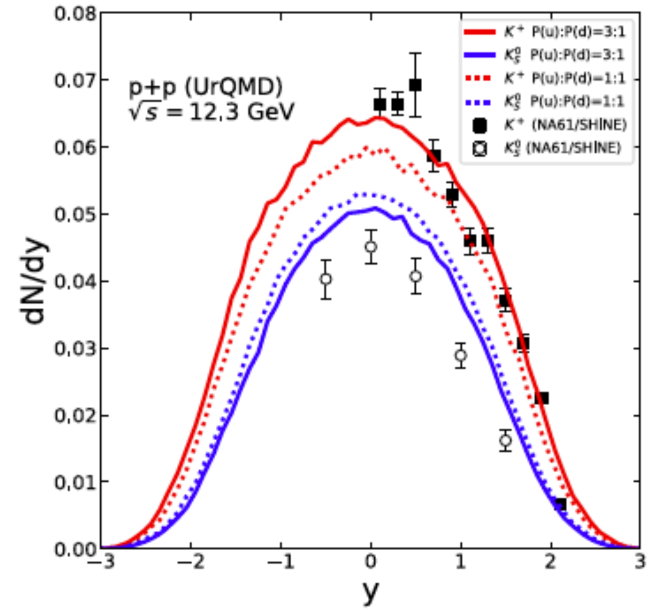


Fig. 2. [Color online] Rapidity distributions of K^+ (red) and $K^0_S = (K^0 + \bar{K}^0)/2$ (blue) in proton+proton collisions at $\sqrt{s} = 12.3$ GeV. The dotted lines show the standard parametrization of the color field fragmentation parameters, the full lines show the refitted string fragmentation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

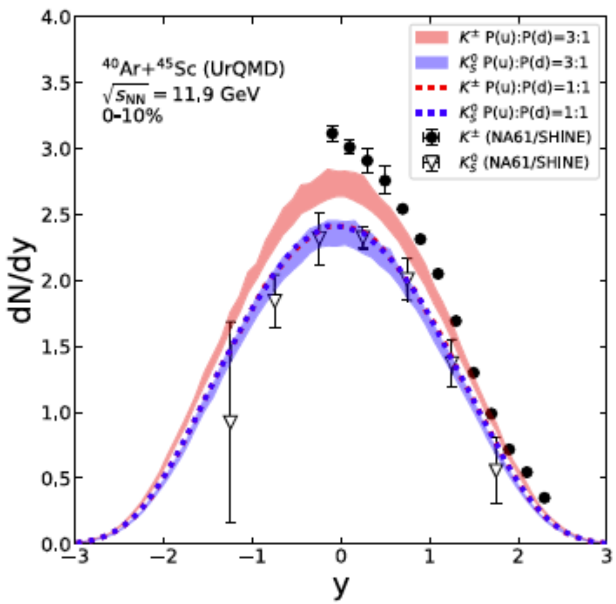


Fig. 3. [Color online] Rapidity distributions of $K^{\pm} = (K^+ + K^-)/2$ (red) and $K^0_S = (K^0 + \bar{K}^0)/2$ (blue) in 0–10% central Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV. The dotted lines show UrQMD calculations with the standard parametrization of the color field fragmentation parameters, 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].

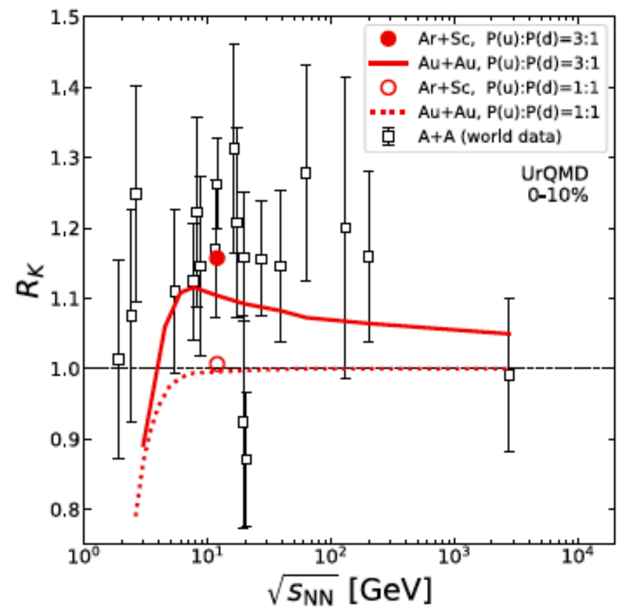


Fig. 4. [Color online] Comparison of the refitted simulations with the world data on the ratio $R_K = (K^+ + K^-)/(K^0 + \bar{K}^0)$. The dotted lines shows UrQMD calculations for central Au+Au reactions with the standard parametrization of the color field fragmentation parameters, the full lines show 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 results on modification of the UrQMD code

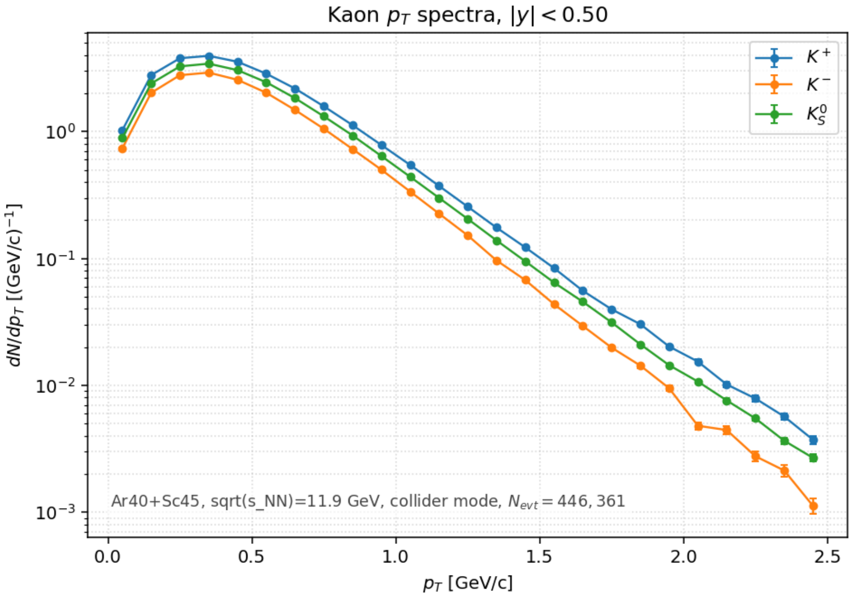
"Modified UrQMD(3:1)"

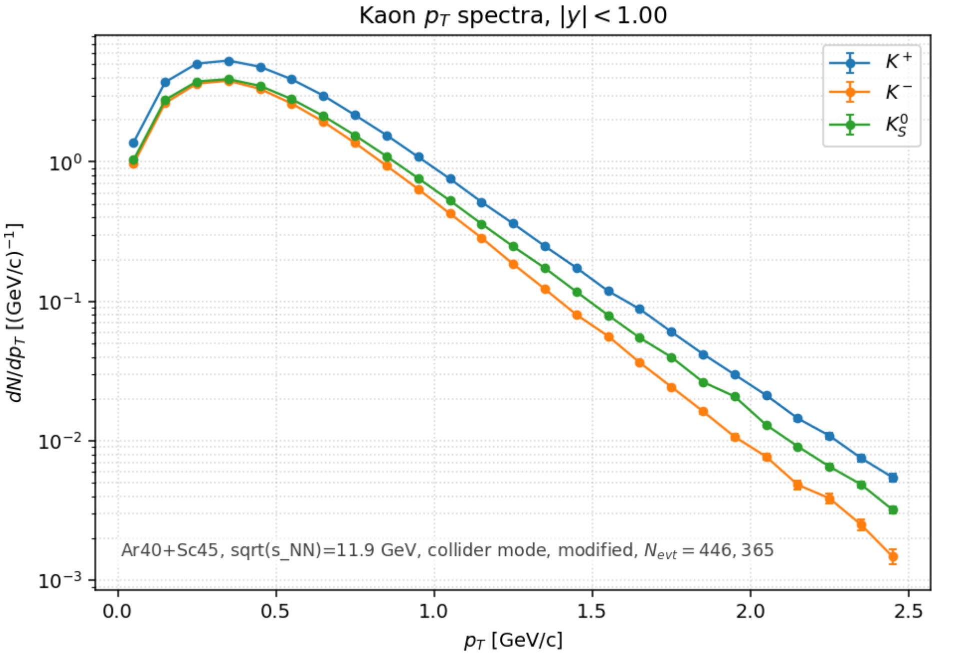
following the ideas of [1]

on 3:1 probalities to produce $u\bar{u}$ pair vs. $d\bar{d}$ one

[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 results for Ar+Sc $\sqrt{s_{NN}}$=11.9 GeV: pT spectra





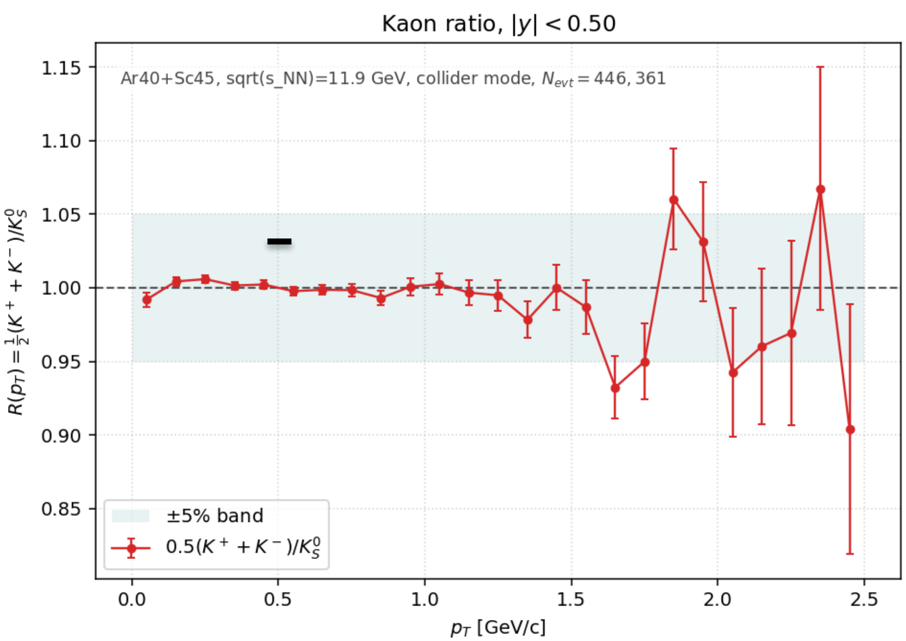
Our UrQMD (default) results for Ar+Sc

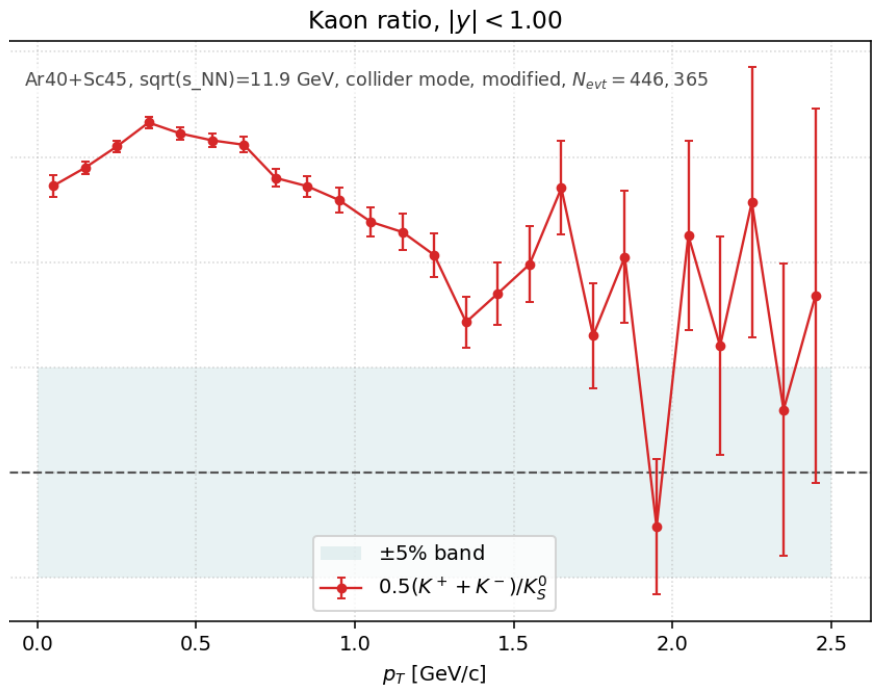
Our modified UrQMD results for Ar+Sc P(u):P(d)=3:1 (Preliminary)

- "Soft" part (< 2 GeVc) of pT 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 results for Ar+Sc $\sqrt{s_{NN}}$=11.9 GeV:

R_k (pT)





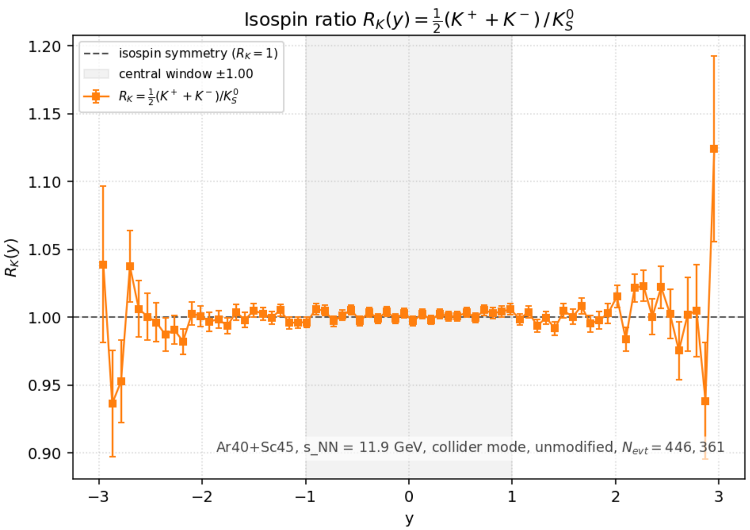
Our UrQMD (default) results foe Rk(pT)
In Ar+Sc at $\sqrt{s_{NN}}$=11.9 GeV

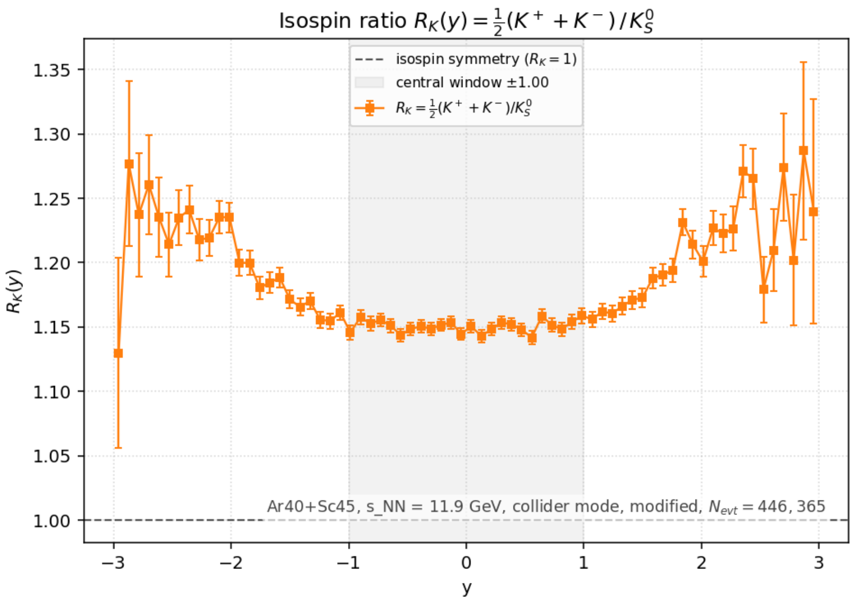
Our "Modified UrQMD(3:1)" results
for Ar+Sc with P(u):P(d)=3:1 (Preliminary)

➢**Considerable effect of Isotopic Symmetry breaking is observed in R_k in pT spectra ratious predicted by the modified UrQMD in case of P(*u*):P(*d*)=3:1 in the "soft" part (< 1.5 GeVc) of spectra**

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

Ratios of rapidity distributions





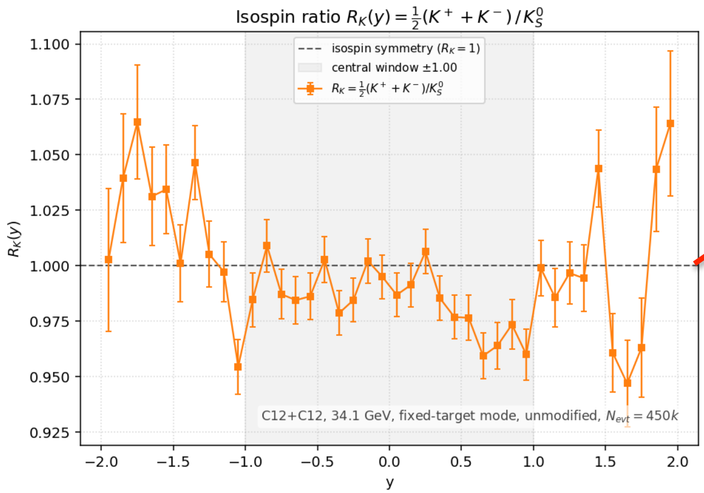
Our UrQMD (default) results for Ar+Sc

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

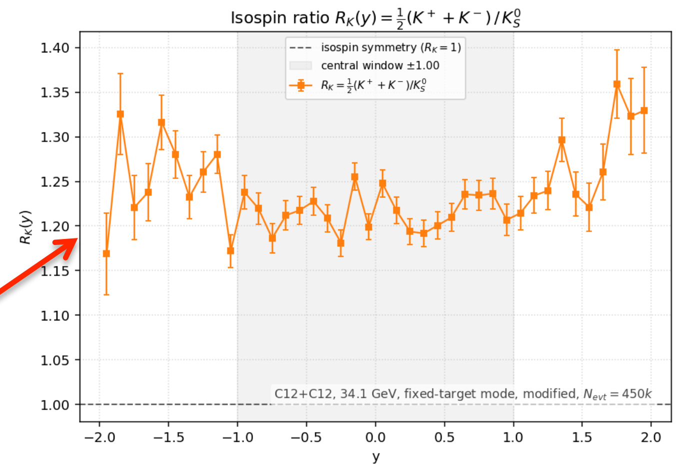
- The shape of "Modified UrQMD(3:1)" rapidity distribution appears to be different from the default UrQMD

Default and our Modified UrQMD results for symmetric (Q/B=1/2) 12C+12C collisions,
-- an example at $\sqrt{s_{NN}}$=34 GeV:

Ratios of rapidity distributions



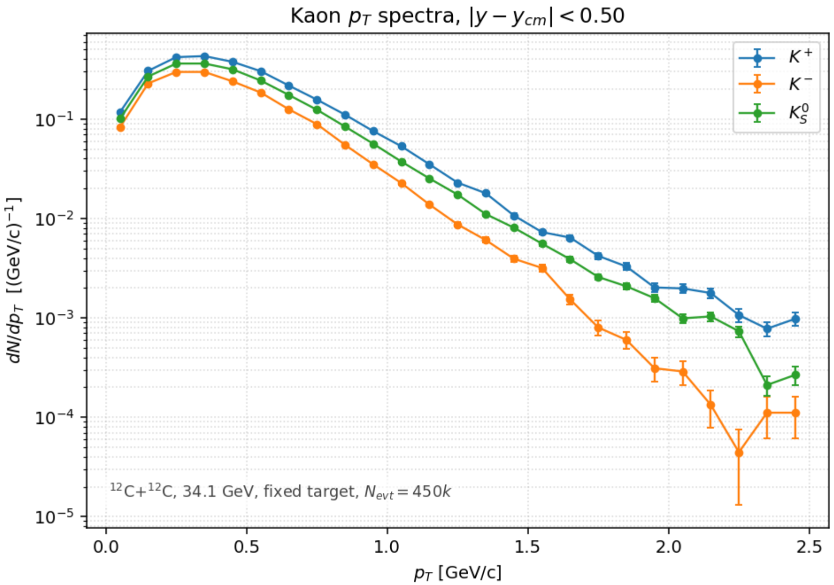
Our UrQMD (default) results

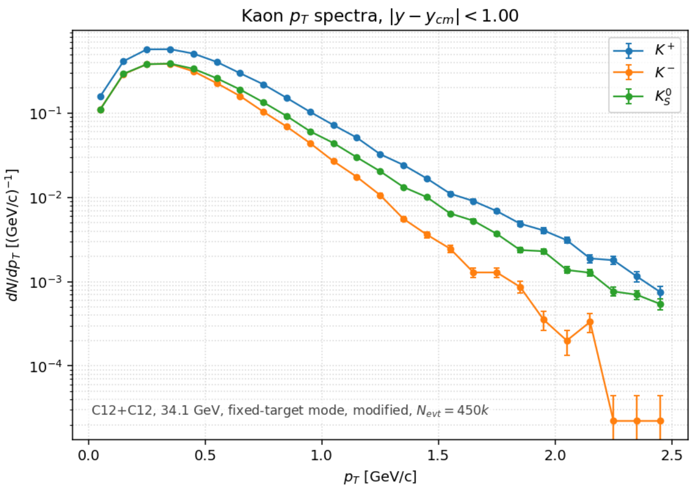


Our modified UrQMD results for 12+12C P(u):P(d)=3:1

- Considerable effect of Isotopic Symmetry Breaking is predicted by the "Modified UrQMD (3:1)" in ratious 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 12C+12C -- an example at $\sqrt{s_{NN}}$=34 GeV: pT spectra



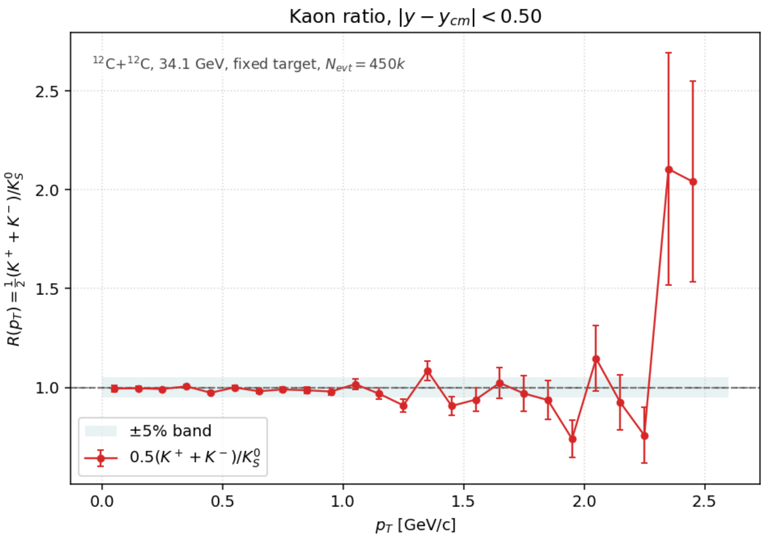


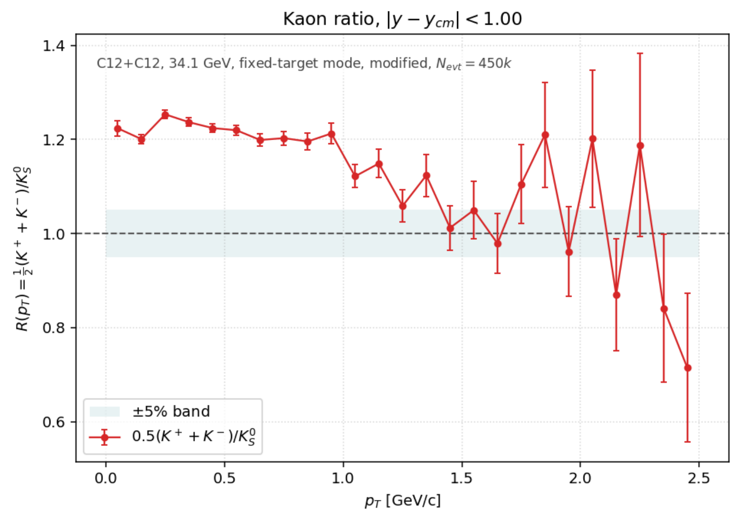
Our UrQMD (default) results

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

- "Soft" part (<1/5 GeVc) 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 predictedby 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

Summary

1) Unexpected excess of charged-over-neutral kaon production in π−+C and Ar+Sc collisions was observed by NA61/SHINE at SPS thus confirming the earlier world data
2) This indicates, in Ar+Sc reactions, the violation of isospin symmetry at the level of significance 5.3σ beyond the known effects
3) Explanation of the observed violation on the base of different probabilities of *uu* and *dd* quark pairs production (3:1) in the color field, proposed in [Phys. Lett. B , 873:140170, 2026], requires additional checks and theoretical efforts for the fundamental understanding
4) Our Modified UrQMD(3:1) results for Ar+Sc and for symmetric 12C+12C collisions show also, in both cases, that the level of violation of isospin symmetry could be different:

   (i) for "soft" and"hard " parts of pT spectra and

   (ii) for rapidity distributions of R_k values at midrapiidity and large rapidity regions.

5) New experimental tests are required both for symmetric (Q/B=1/2) and non-symmetric (Q/B<1/2) nucleus-nucleus collisions

Back-up slides

R_k (pT) <1 in UrQMD in case of non-symmetric collisions (Q/B<1/2): an example for Xe+W 0-10% central collisions