

Unexpectedly large violation of isospin symmetry in nucleus-nucleus collisions at CERN SPS energies



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M E S O N
2 0 2 6

**18th International Workshop
on Meson Physics**

25th - 30th June 2026, Kraków, Poland

Organized by Jagiellonian University,
GSI Helmholtz Centre for Heavy Ion Research,
INFN-LNF Frascati, Institute of Nuclear Physics PAS



Compendium

$\sqrt{s_{NN}} \approx 10 \text{ GeV}$
cms energy per nucleon pair

- This talk will discuss hadron-nucleus and nucleus-nucleus collisions at center-of-mass energies of about 10 GeV

- At these energies, in particle production*, isospin symmetry is believed to be obeyed within, say, 3%

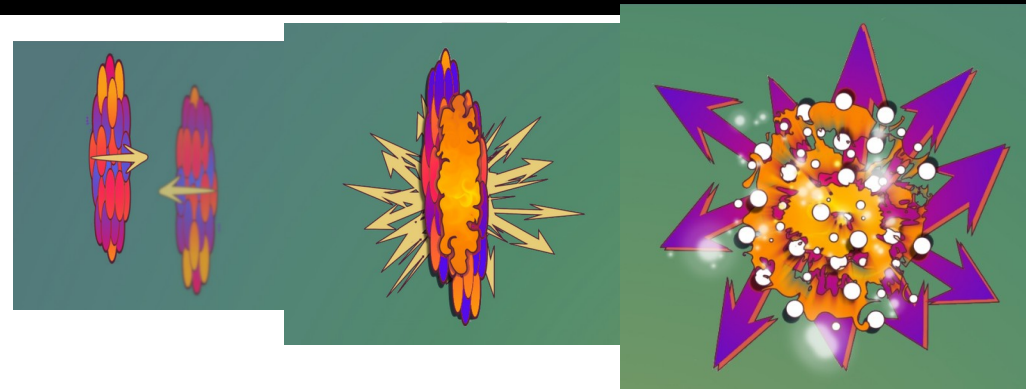
* total multiplicities,
inclusive spectra, etc...

- Nevertheless, the NA61/SHINE experiment at the CERN SPS reports an unexpectedly large isospin symmetry violation of $18 \pm 6\%$ in kaon production

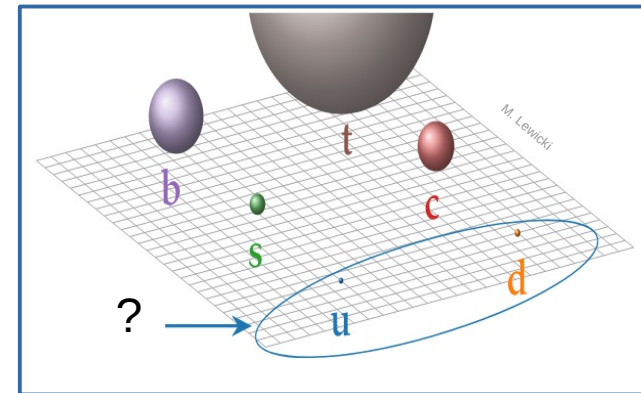
total uncertainty

- Measurements from other experiments over a wide range of energy are consistent with this observation

- The origin of this effect remains unclear



I. Sputowska





- Research program
- Detector
- Data analysis

NA61/SHINE at CERN SPS



Strong interactions

- study the onset of deconfinement
- search for the critical point
- measurement of open charm
- measurements of violation of isospin symmetry in multiparticle production

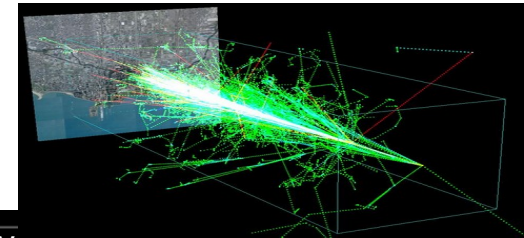
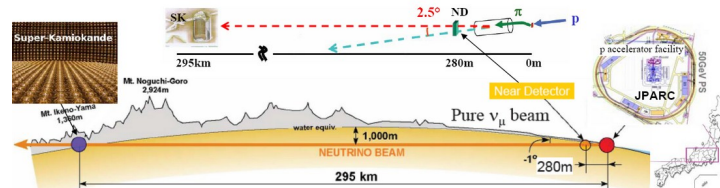
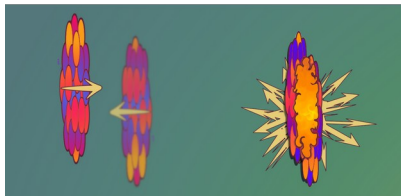
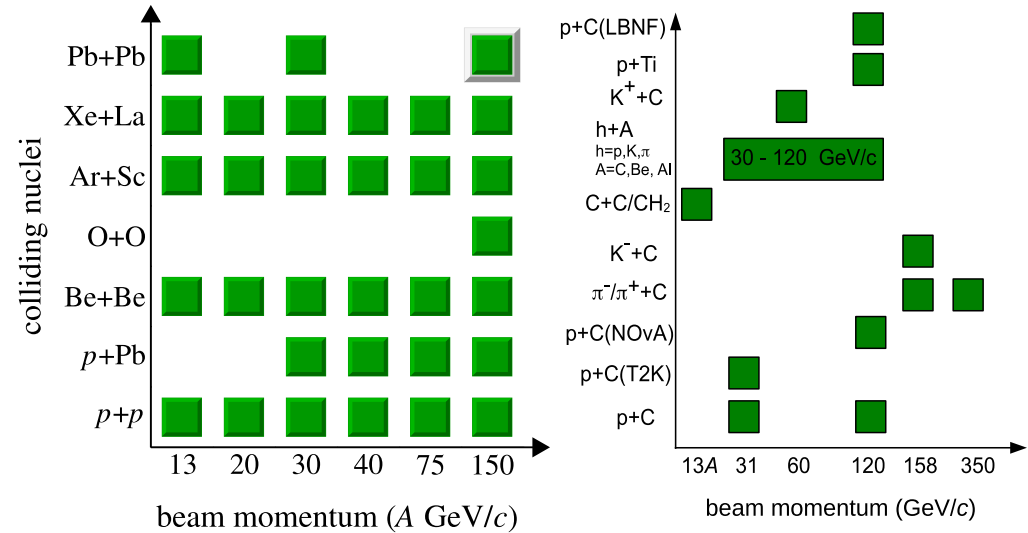
$$\sqrt{s_{NN}} = 5 - 17 / 27 \text{ GeV}$$

cms energy per nucleon pair

NEW!

Neutrino and cosmic-ray physics

- measurements for neutrino programs (J-PARC, Fermilab)
- measurements for cosmic-ray physics (Pierre-Auger, Telescope Array, IceTop)

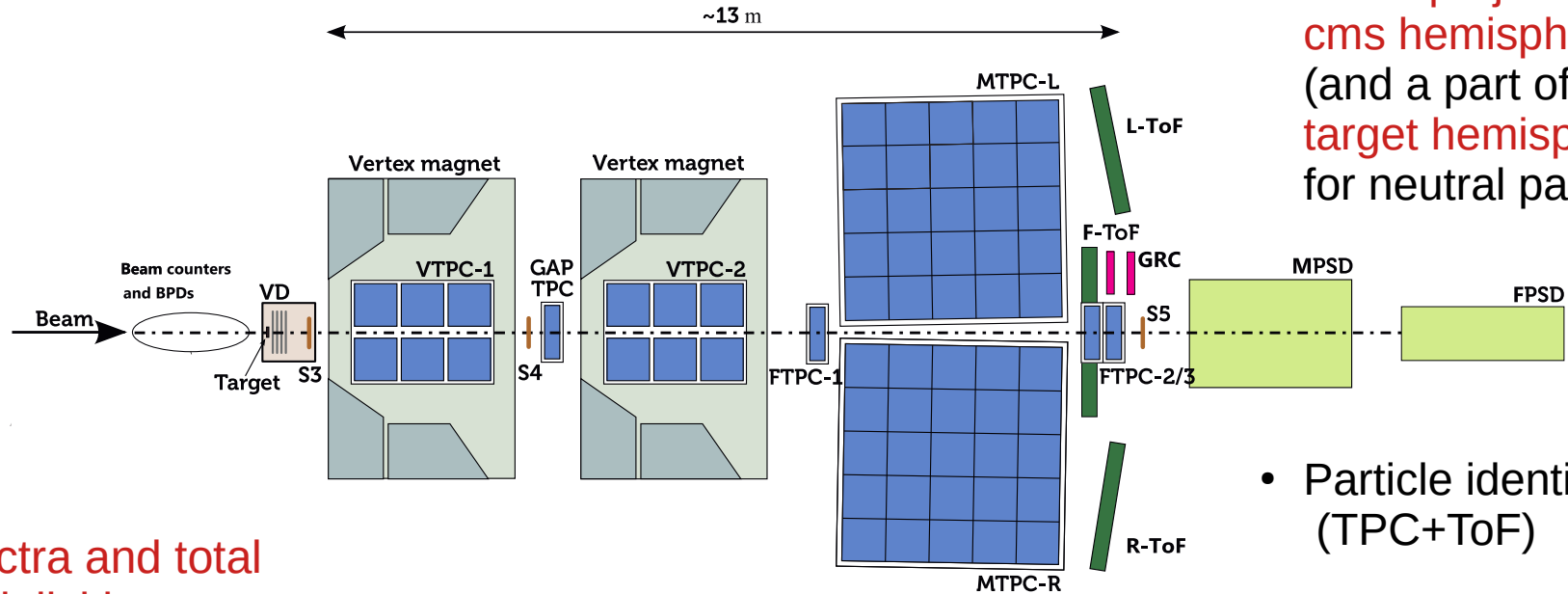


NA61/SHINE

at CERN SPS



- Multipurpose fixed-target spectrometer with unique capabilities



- Coverage of the entire **projectile cms hemisphere** (and a part of the **target hemisphere** for neutral particles)

- Spectra and total multiplicities:

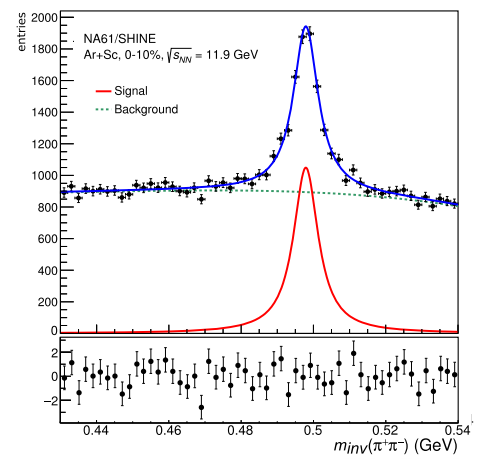
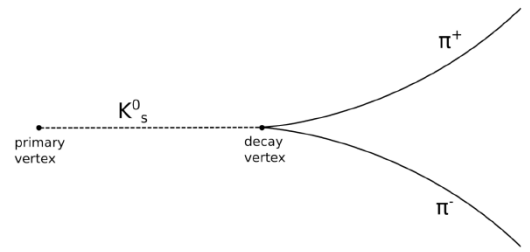
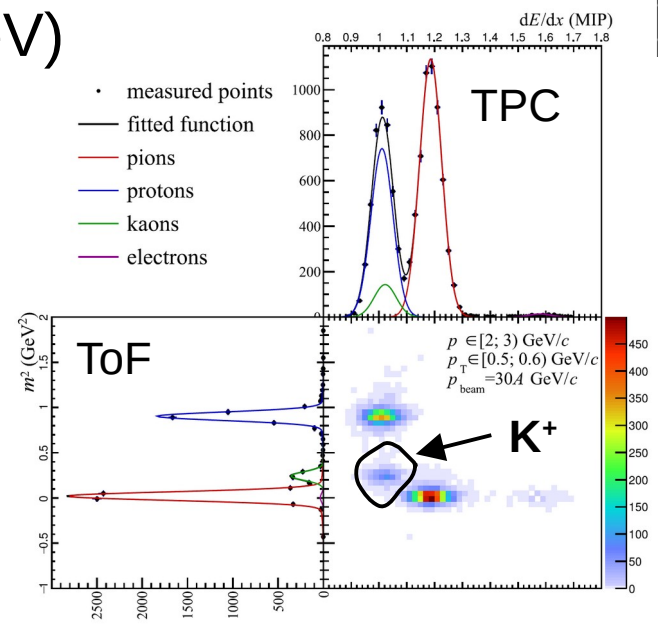
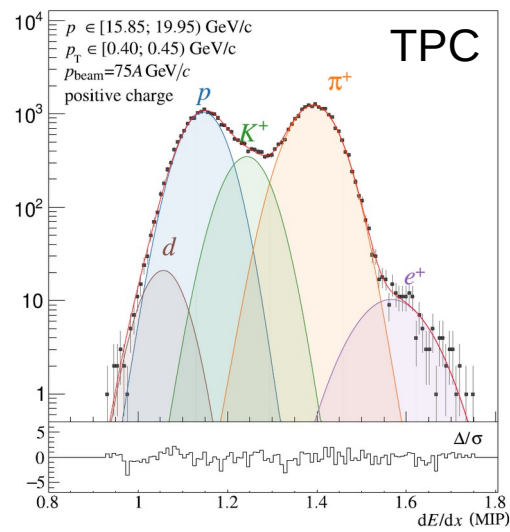
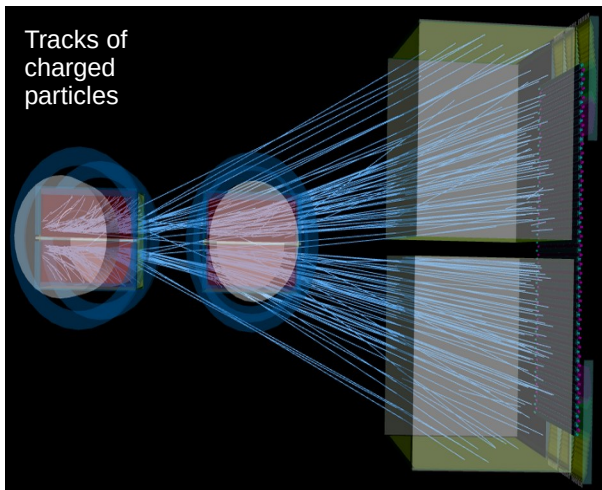
π^\pm , K^\pm , K_S^0 , K^* , ϕ ,
 ρ , $\bar{\rho}$, Λ , Ξ , $\bar{\Xi}$...

- Heavy quarks:
 D^0 and \bar{D}^0

- Correlations, fluctuations, intermittency...

- Particle identification (TPC+ToF)

Analysis (0–10% central Ar+Sc, $\sqrt{s_{NN}}=11.9$ GeV)



- K^+, K^- : measurements based on TPC ($y>0$) and TPC+ToF ($y\approx 0$)
 dE/dx dE/dx versus m^2
- K_s^0 : based on decay topology (V^0)
- The results are **corrected** for detector geometrical acceptance, reconstruction efficiency, weak decays, and secondary interactions

NA61/SHINE, F. Giacosa, M. Gorenstein et al.,
 Nature Commun. 16 (2025) 2849
 NA61/SHINE, Eur. Phys. J. C 84 (2024) 4, 416

Excess of charged over
neutral kaons –
results from

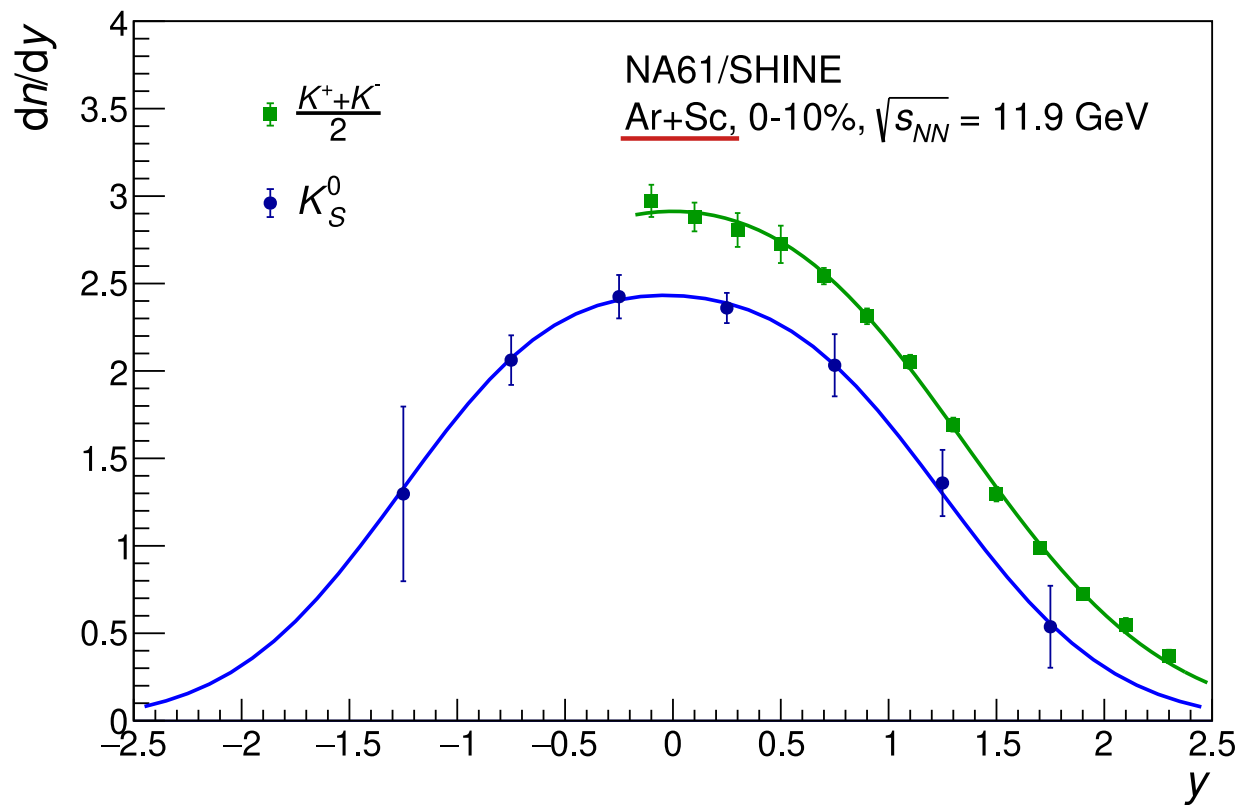


K^+ ,

K^- ,

K_S^0

Part 1: nucleus-nucleus collisions



Uncertainties:
 total (stat, syst)

$$y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right)$$

- Ar, Sc nuclei are nearly charge-symmetric (valence **u** \approx **d** within 6%)

- We expect:

$$K^+ (u \bar{s}) \approx K^0 (d \bar{s}) \quad u \leftrightarrow d$$

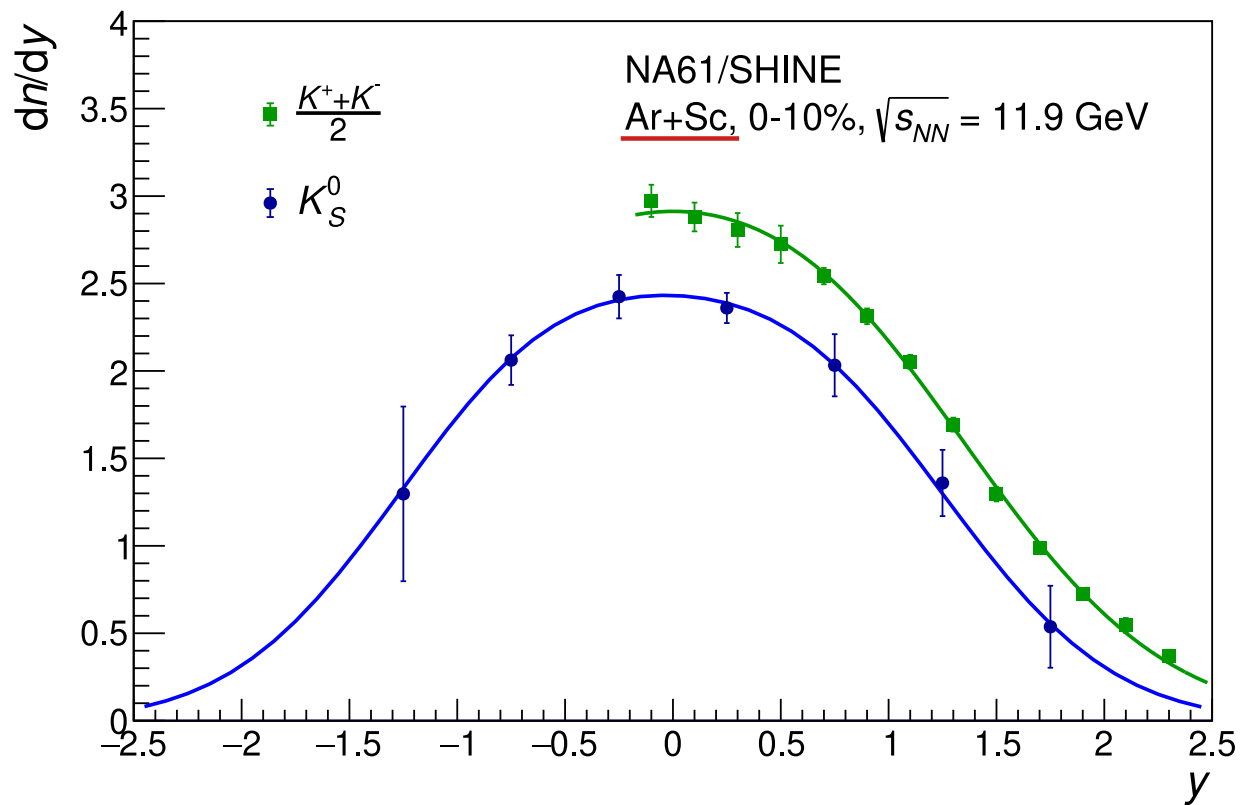
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$$\frac{K^+ + K^-}{2} \approx \frac{K^0 + \bar{K}^0}{2} = K_S^0 \quad \left| \begin{array}{l} \text{neglecting} \\ \text{CP} \\ \text{violation} \end{array} \right.$$

- Data – excess of charged over neutral kaons:

$$\frac{K^+ + K^-}{2} > K_S^0$$

- Unexpected violation of flavor symmetry between **u** and **d** quarks



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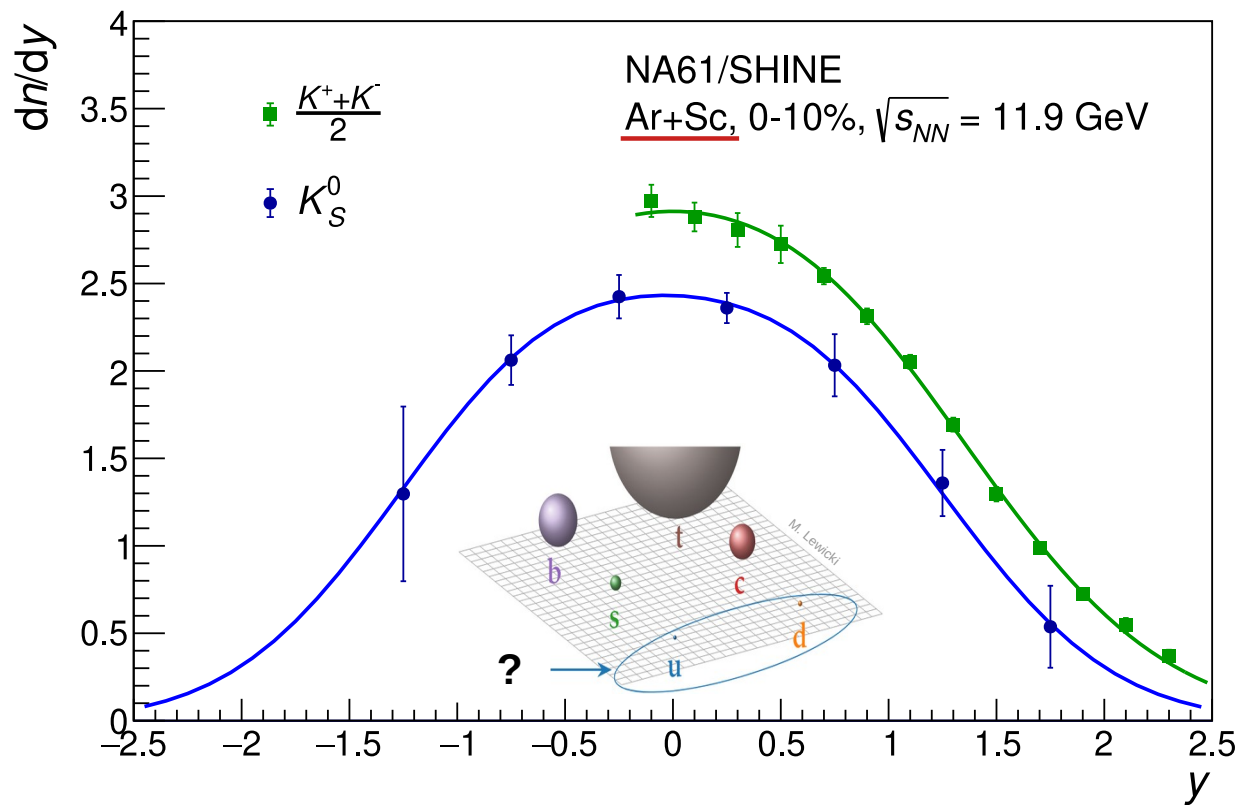
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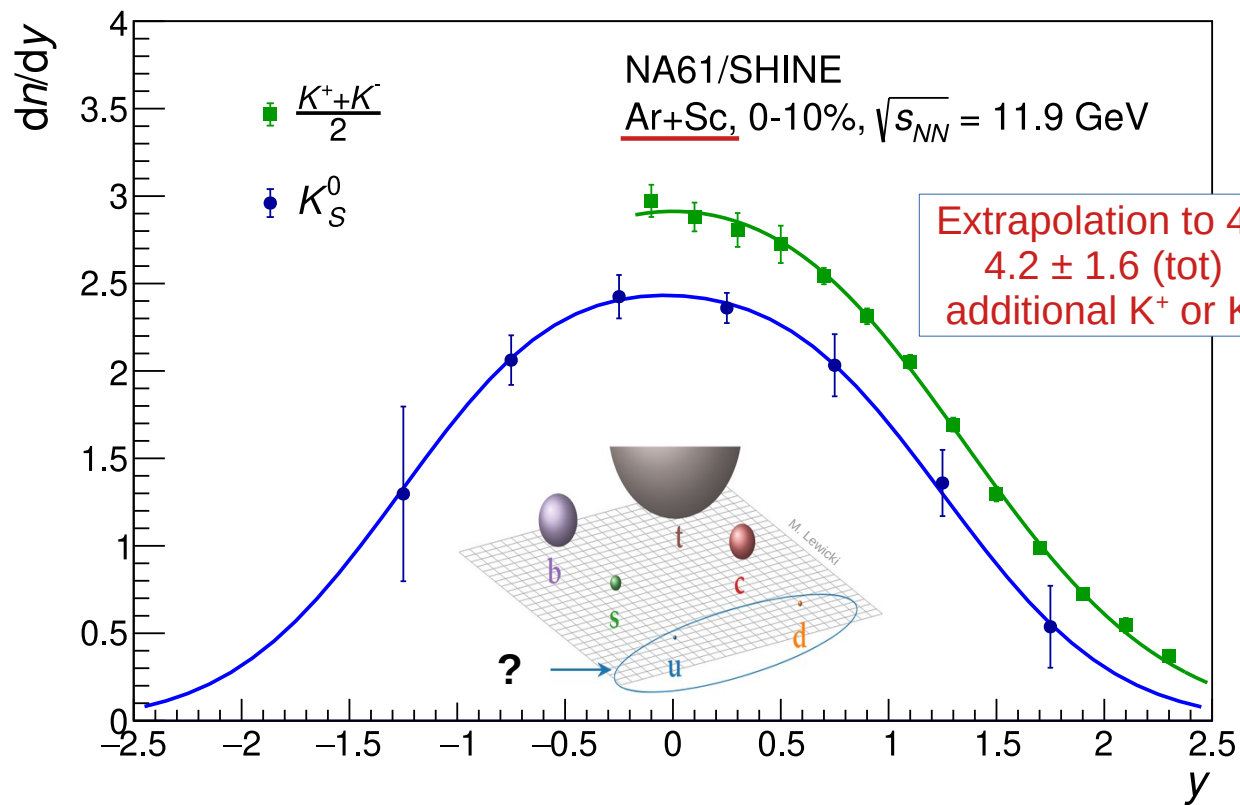
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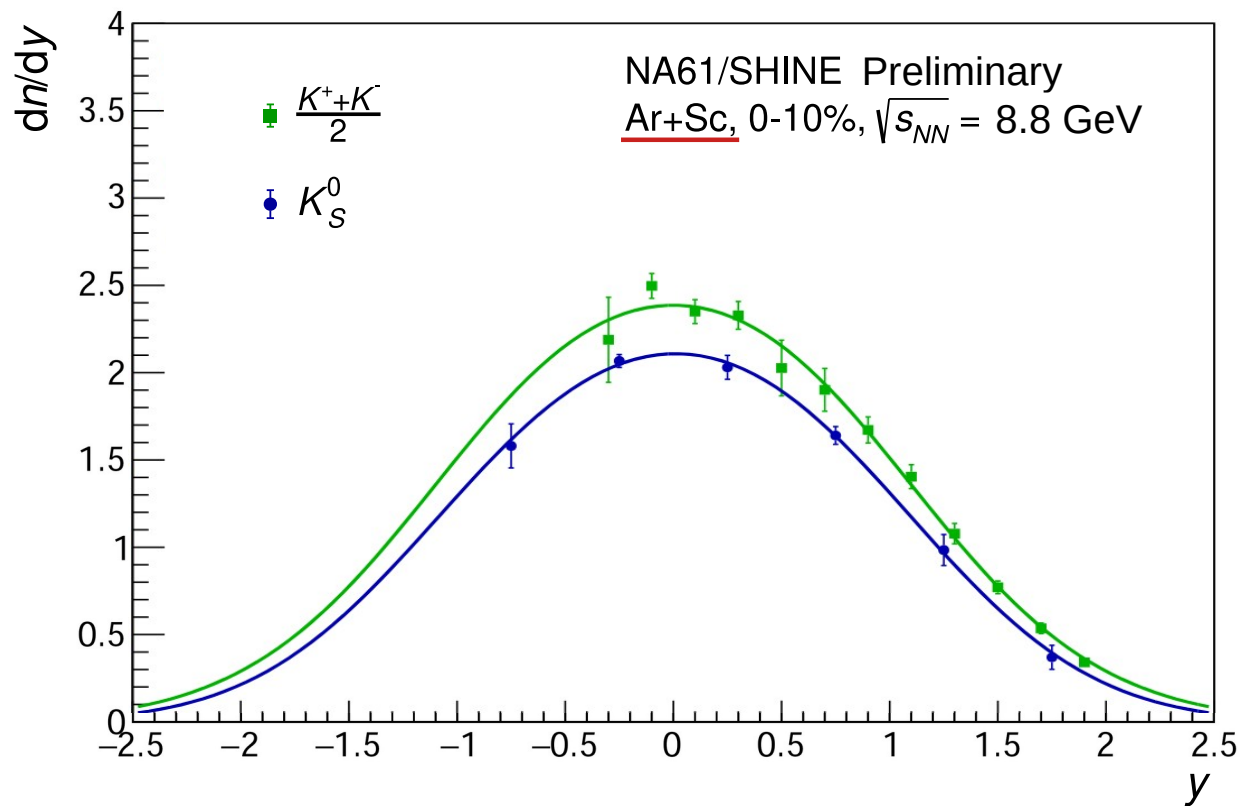
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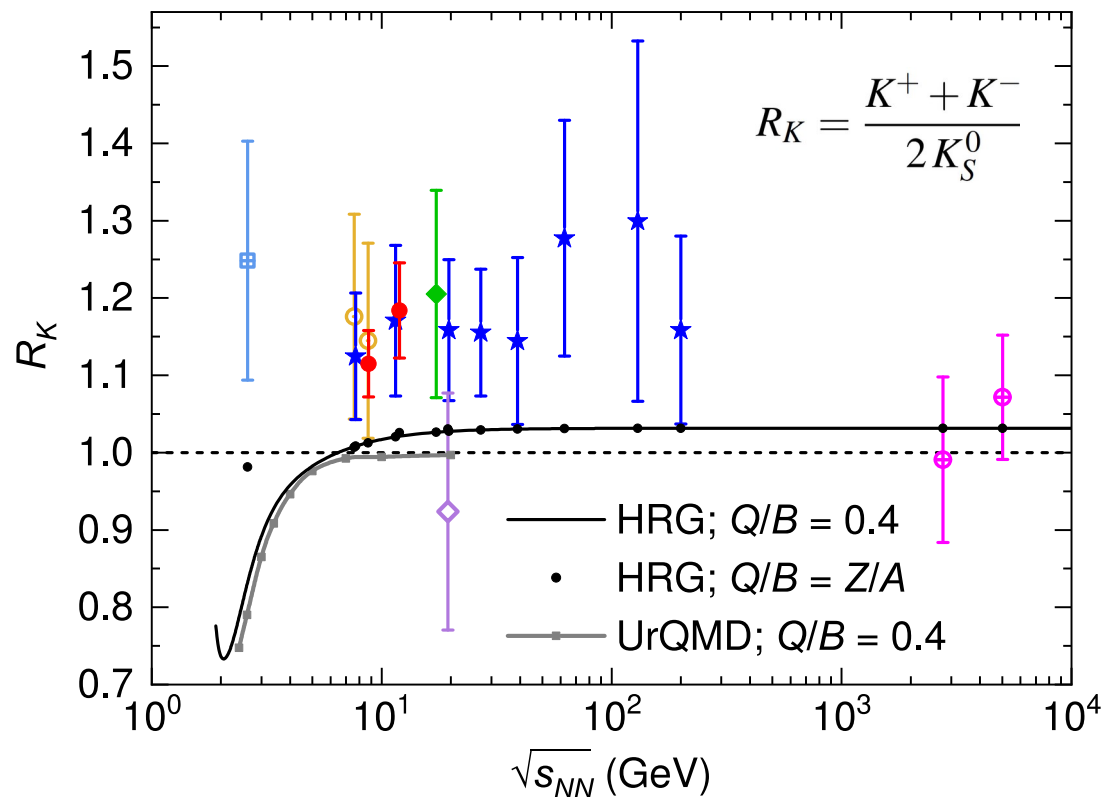
$$\frac{K^+ + K^-}{2} > K_S^0 \quad 12 \pm 4 \% \text{ at } y=0 \text{ (total unc.: stat, syst)}$$

- Unexpected violation of flavor symmetry between **u** and **d** quarks

Energy dependence

See Nature Commun. 16 (2025) 2849 for references and numerical values used to calculate R_K as a function of $\sqrt{s_{NN}}$

Updated with 5.02 TeV data point
(original data ALICE, PRC 101 (2020) 044907, and arXiv:2511.10360)



- HADES; Ar+KCl; 4π
 - ★ STAR; Au+Au; $y \approx 0$
 - NA49; Pb+Pb; 4π
 - NA61/SHINE; Ar+Sc; $y \approx 0$ { nature communications and new 8.8 GeV point
 - ◆ CERES; Pb+Au; $y \approx 0$
 - ◇ NA35; S+S; 4π
 - ⊕ ALICE; Pb+Pb; $y \approx 0$
- ↙ preliminary

Deviation data/theory (HRG)
Significance: 4.7σ

Nature Commun. 16 (2025) 2849

Results from  **S·INE**

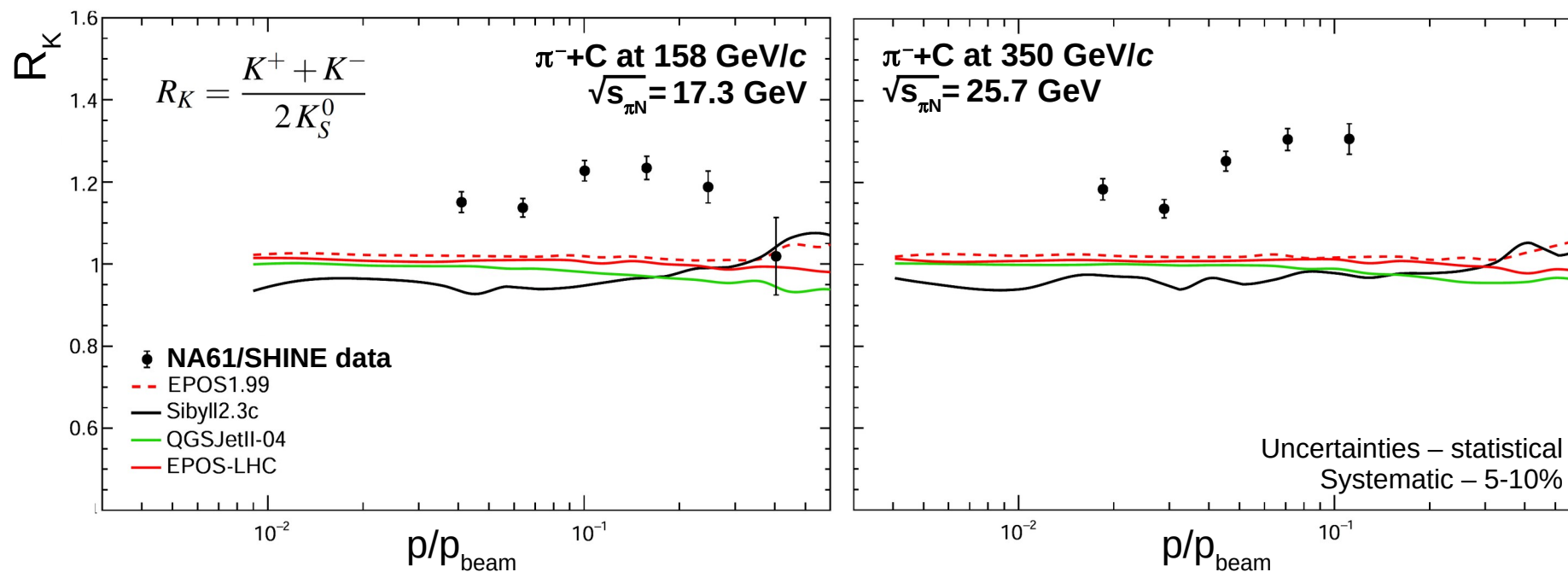
K^+ ,

K^- ,

K_S^0

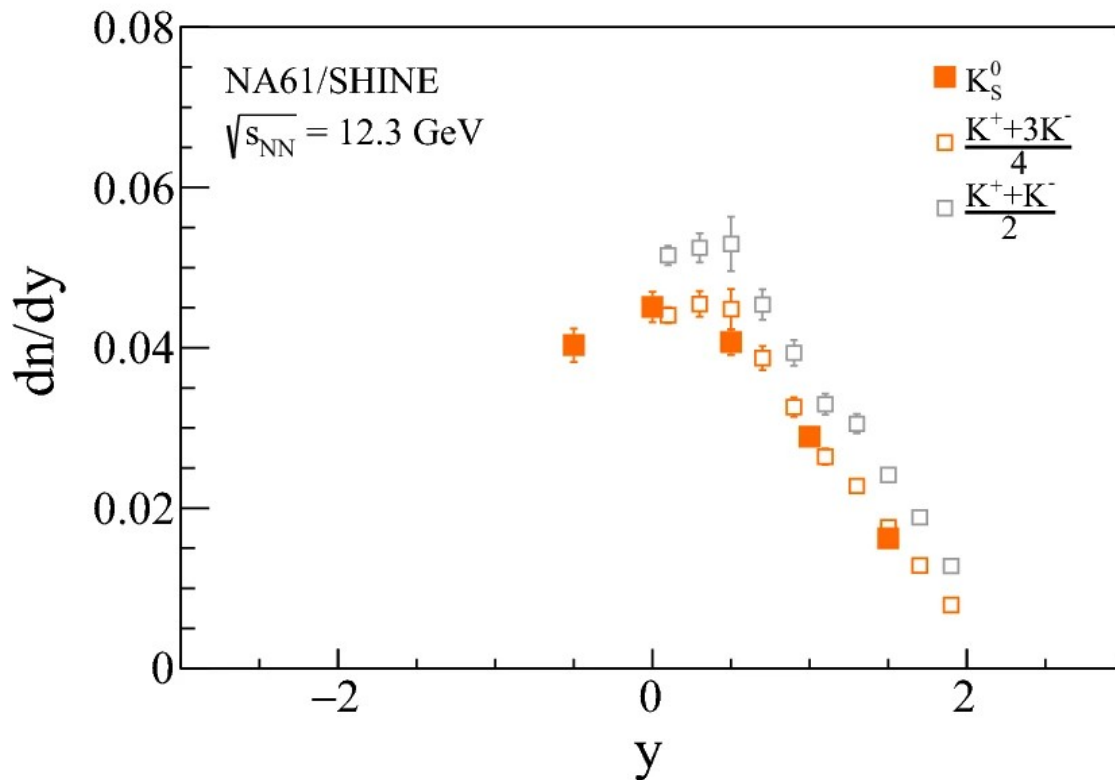
Part 2: hadron-nucleus and proton-proton

Ratio of charged-over-neutral kaons as a function of $x_F(\text{lab}) = p/p_{\text{beam}}$



● $R_K \approx \underline{1.2 - 1.3}$

● failure of models



Uncertainties:
 total (stat, syst)

- The **p+p** system is highly charge-asymmetric (valence **u, u, d**)
- A significant charged-over-neutral kaon excess is observed:

$$\frac{K^+ + K^-}{2} > K_S^0$$

- Can be understood by Quark Coalescence:

$$\frac{K^+ + 3K^-}{4} \approx K_S^0$$

J. Stepaniak, D. Pszczel,
 Eur. Phys. J. C 83 (2023) 10, 928

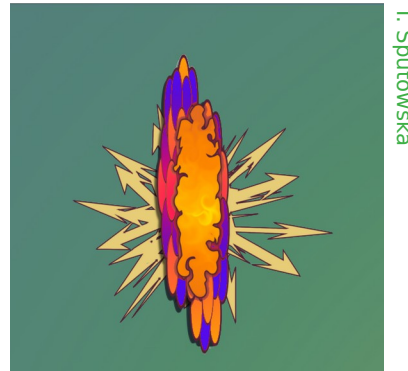
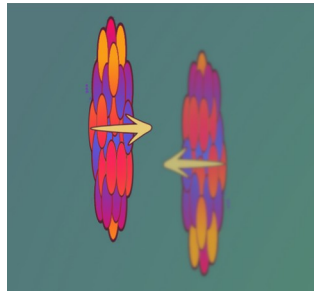
Results from ALICE

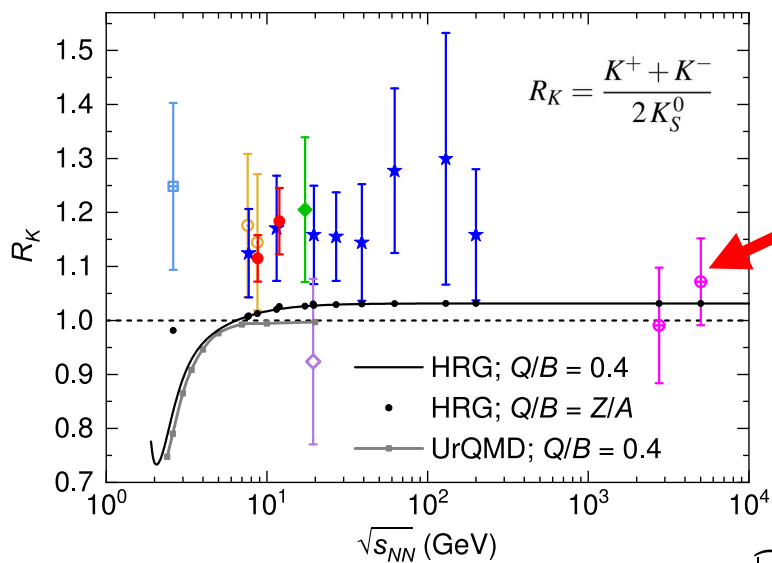


K^+ ,

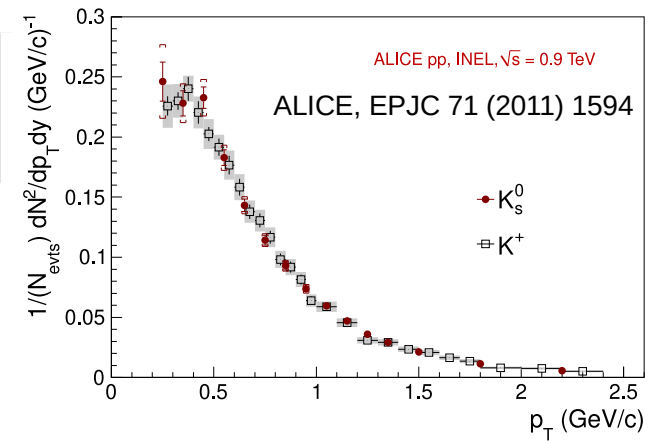
K^- ,

K_S^0

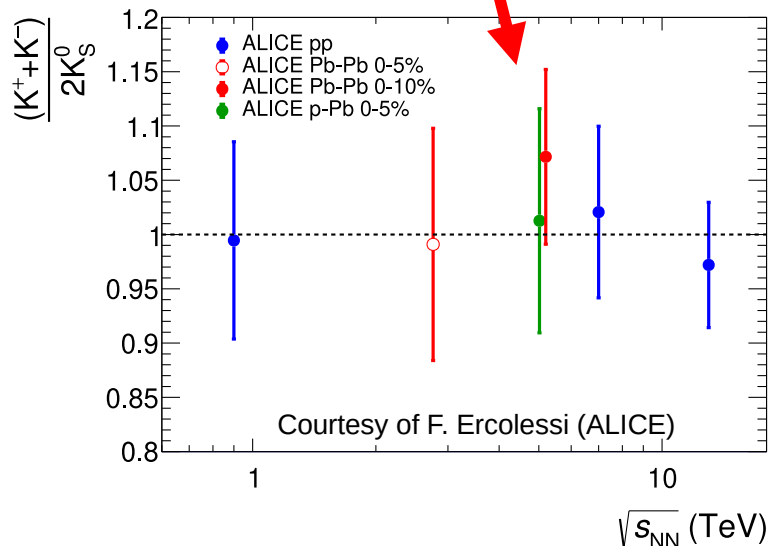




**ALICE data,
 $0.9 < \sqrt{s_{NN}} < 13$ TeV**



• Is the effect fading out at very high energies ?



- pp 900 GeV:**
 Eur. Phys. J. C 71 (2011) 1655
 Eur. Phys. J. C 71 (2011) 1594
- pp 7–13 TeV:**
 Eur. Phys. J. C 81 (2021) 256
 Eur. Phys. J. C 75 (2015) 226
- Pb–Pb 2.76 TeV:**
 Phys. Rev. Lett. 111 (2013) 222301
 Phys. Rev. C 88 (2013) 044910
- Pb–Pb 5.02 TeV:**
 Phys. Rev. C 101 (2020) 044907
 arXiv:2511.10360
- p–Pb 5.02 TeV:**
 Phys. Lett. B 728 (2014) 25–38

Theory (?)



ISO-BREAK 25

*Workshop on isospin symmetry violation:
kaons and beyond, Kielce, Oct 23-25, 2025*

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

White Paper: [arXiv:2604.16005](https://arxiv.org/abs/2604.16005),
to appear in EPJA

Bibliography for the following slide:

QC	M. Bonesini et al., EPJC 20 (2001) 553, 13 J. Stepaniak, D. Pszczel, EPJC 83 (2023) 10, 928 F. Giacosa, M. Rohrmoser, EPJC 85 (2025) 9, 1058 M. Rohrmoser, F. Giacosa, ISO-BREAK 25 M. Rohrmoser, private communication, 2026
PHSD	E. L. Bratkovskaya et al., NPA 539 (2011) 856, 162 V. Ozvenchuk, private communication, 2025
EPOS	T. Pierog et al., PRC 92 (2015) 3, 034906 M. Bleicher, ISO-BREAK 25
SMASH	J. Weil et al., PRC 94 (2016) 5, 054905 O. Vitiuk, ISO-BREAK 25 C. Bierlich et al., SciPost Phys. Codeb. 585 2022 (2022) 8
UrQMD	M. Bleicher, E. Bratkovskaya, PPNP 122 (2022) 103920 M. Bleicher et al., JPG 25 (1999) 1859 NA61/SHINE, F. Giacosa, M. Gorenstein et al., NC 16 (2025) 2849 T. Reichert, J. Steinheimer, M. Bleicher, PLB 873 (2026) 140170
HRG	A. Andronic, P. Braun-Munzinger, J. Stachel, NPA 772 (2006) 167 V. Vovchenko, M. I. Gorenstein, H. Stoecker, PRC 98 (2018) 3, 034906 NA61/SHINE, F. Giacosa, M. Gorenstein et al., NC 16 (2025) 2849 S. Samanta, ISO-BREAK 25
EM	F. Giacosa, ISO-BREAK 25 W. Price et al., Acta Phys. Polon. A 143 (2023) S87 J. Rafelski, ISO-BREAK 25, and references therein
Finite density Chiral anomaly	M. Gazdzicki, F. Giacosa, K. Grebieszko, et al., ISO-BREAK 25 (White Paper) D. J. Gross, S. B. Treiman, and F. Wilczek, PRD 19631 (1979) 2188 R. D. Pisarski and F. Wilczek, PRD 633 (1984) 29, 338 F. Giacosa, S. Jafarzade, and R. D. Pisarski, PRD 109 (2024) 7, L071502 R. Pisarski, ISO-BREAK 25
e^+e^- data	BESIII, M. Ablikim et al., PRL 135 (2025) 151901

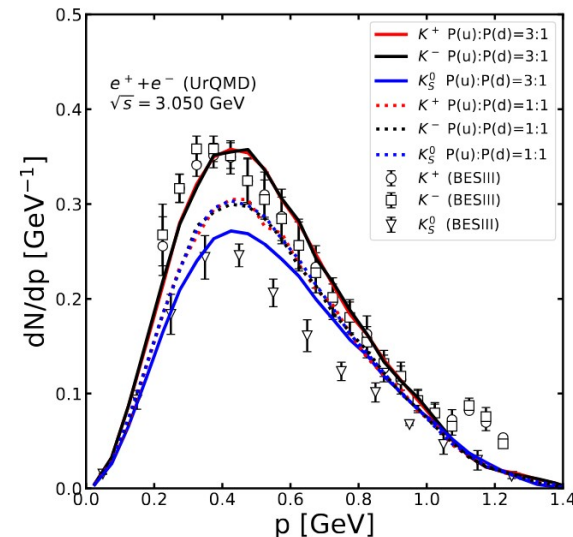
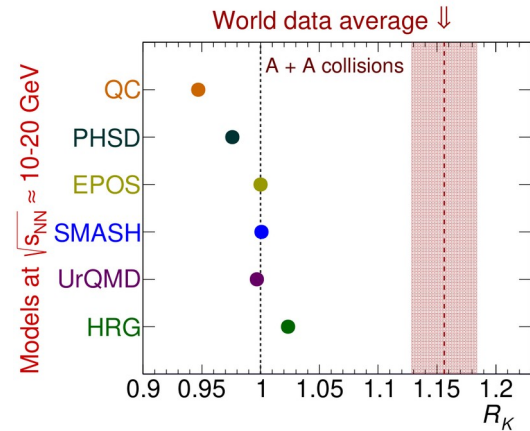
- No explanation so far
- Known effects: $R_K \approx 1$ within 3–6%
- Attempts to fit the exp. data assuming ad hoc u/d asymmetry at the quark level:

UrQMD \rightarrow u/d = 3

SMASH \rightarrow u/d = 1.89

Quark Coalescence (QC) \rightarrow u/d = 1.2

- EM effects, final density, chiral anomaly, ...
– speculative



The modified UrQMD gives a \pm reasonable description of e^+e^- , $p+p$ and nucleus-nucleus data, suggesting a common origin for the observed asymmetries

T. Reichert *et al.*, PLB 873 (2026) 140170, but see also BESIII, PRL 135 (2025) 151901

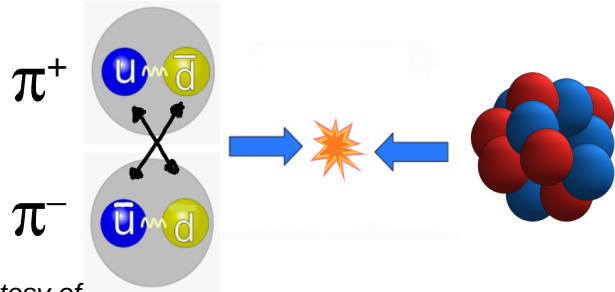
Studying isospin symmetry-violation in NA61/SHINE – prospects



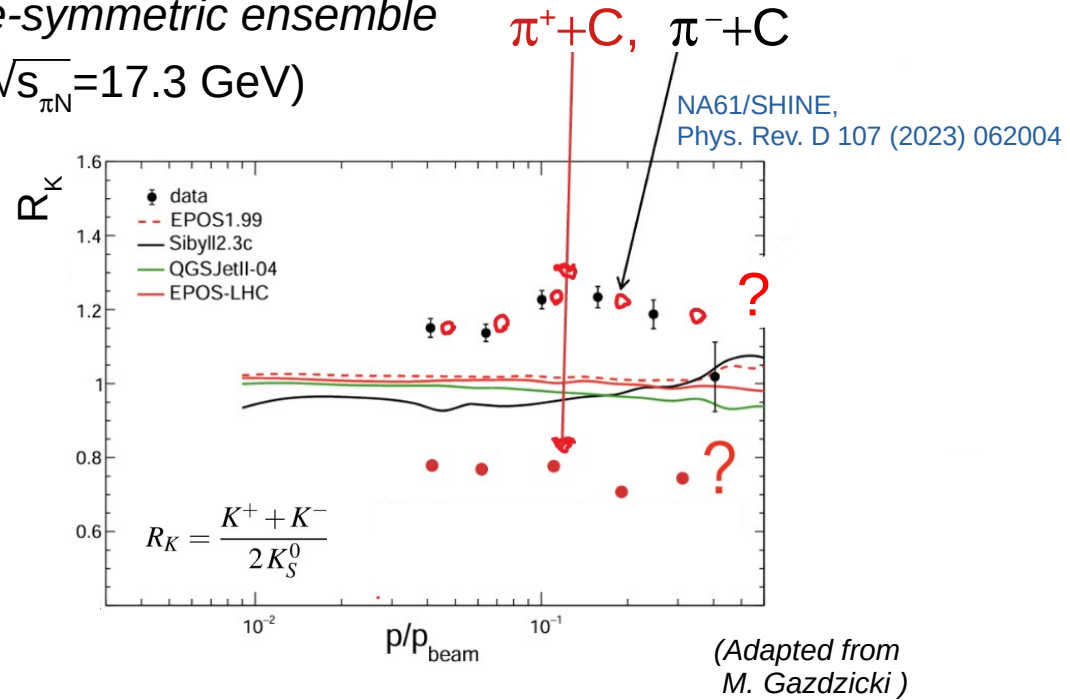
NA61/SHINE prospects (1): pion-carbon collisions

Studies of $\pi^+ + \text{C}$, $\pi^- + \text{C}$ collisions as a *charge-symmetric ensemble*

→ first data already available at 158 GeV/c ($\sqrt{s_{\pi N}} = 17.3$ GeV)



(Courtesy of
M. Gazdzicki)



- Low multiplicity: clean experimental case
- Essential to clarify whether isospin symmetry violation is specific to A+A collisions, or is also present in small systems

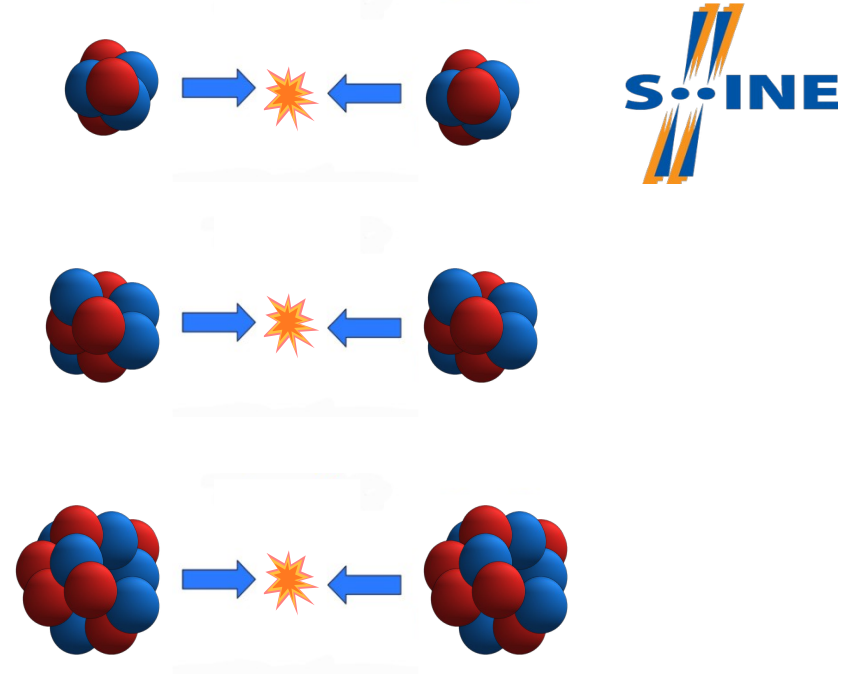


NA61/SHINE prospects (2): light ions

Studies of collisions of light, $Z/A = 1/2$ nuclei:

CERN-SPSC-2023-022

- B+B ($A=10$)
- O+O ($A=16$) First data are available at $\sqrt{s_{NN}} = 16.8$ GeV
- Mg+Mg ($A=24$)
 - $\sqrt{s_{NN}} = 5.1, 7.6, 16.8$ GeV
 - different centralities



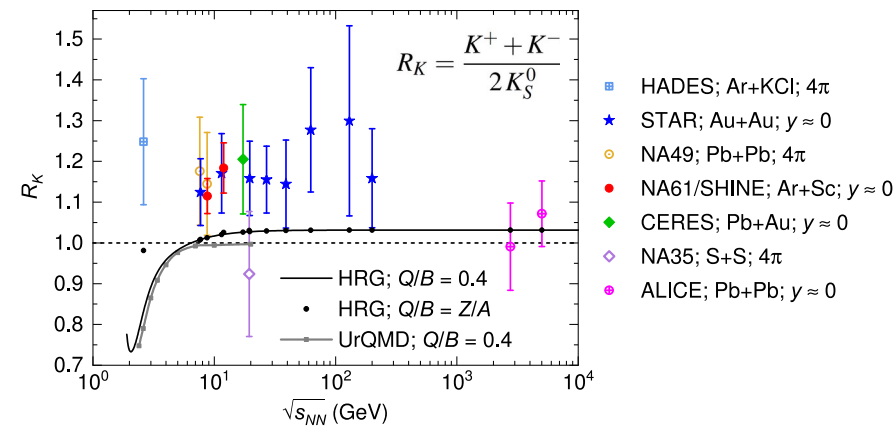
- Low multiplicities → low systematic uncertainties
- Essential for understanding the system-size dependence of isospin symmetry violation

Summary



Summary

1. We report an unexpectedly large violation of isospin symmetry (flavor symmetry between **u** and **d** quarks) in the kaon sector of multiparticle production
2. Within large uncertainties, measurements at $2.6 < \sqrt{s_{NN}} < 200$ GeV are consistent with this observation
3. At $0.9 < \sqrt{s_{NN}} < 13$ TeV, the ratio R_K is consistent with unity (± 0.1)
4. Apart from the A+A sector, similarly unexpected phenomena seem to appear in pion-C, and possibly also e^+e^- collisions --> Here we will contribute with $\pi^\pm+C$, light nuclei
5. Theory: **no clear explanation so far**



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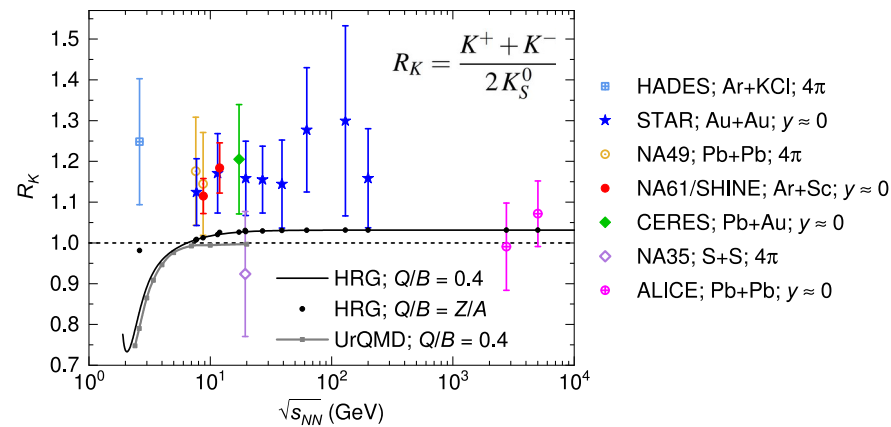
6. This brings **potential heavy consequences** for our understanding of particle production

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It is **essential** that other experiments join this effort with high-precision measurements

---> in the kaon sector

-----> for other multiplets, e.g., $\Delta^{++}(uuu)/\Delta^{-}(ddd)$



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WORKSHOP
ON ISOSPIN SYMMETRY VIOLATION:
KAONS AND BEYOND (ISO-BREAK27)
Around 19-24 April, 2027

ORGANISERS:
TOBIASZ CZOPOWICZ
MAREK GAŹDICKI
FRANCESCO GIACOSA
KATARZYNA GREBIESZKOW
MILENA PIOTROWSKA
GRZEGORZ STEFANEK

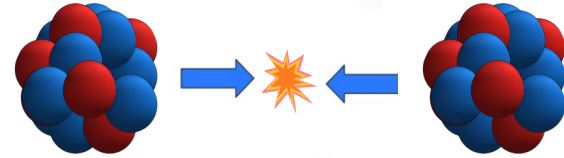
INSTITUTE OF PHYSICS,
JAN KOCHANOWSKI UNIVERSITY
KIELCE, UNIWERSYTECKA 7
BUILDING G, LECTURE HALL B

Thank you :)

Extra slides



NA61/SHINE prospects: studies of Xe+La and high-statistics Pb+Pb collisions



- Xe+La reactions:

→ $\sqrt{s_{NN}} = 5.1, 7.6, 8.8, 11.9, 16.8 \text{ GeV}$

- Pb+Pb collisions:

→ $\sqrt{s_{NN}} = 16.8 \text{ GeV}$



→ data taking to be completed in **2026**

→ high statistics (~500 M)

→ detailed study of the excess of charged over neutral kaons as a function of rapidity, p_T , centrality...

Note:

- $Z \neq A/2$, excess of neutrons in both reactions
- needs to be taken into account in theoretical analyses
- BUT: no indication of strong dependence on Z/A in compiled existing data

Studies of other isospin multiplets:

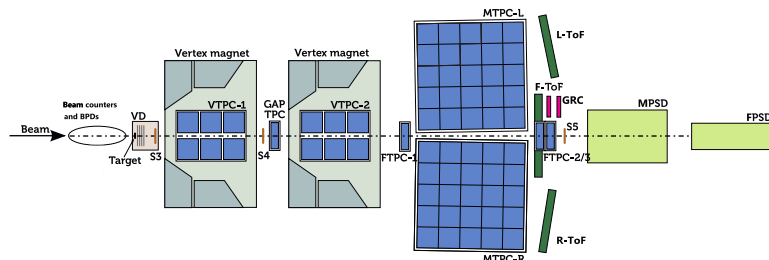
- $\Delta^{++}/\Delta^{+}/\Delta^{0}/\Delta^{-}$ ratios are sensitive to excess of **u** over **d** production
- analyzed in the past (NA49)
- can be studied in, *e.g.*, $\pi^{\pm}+C$ collisions



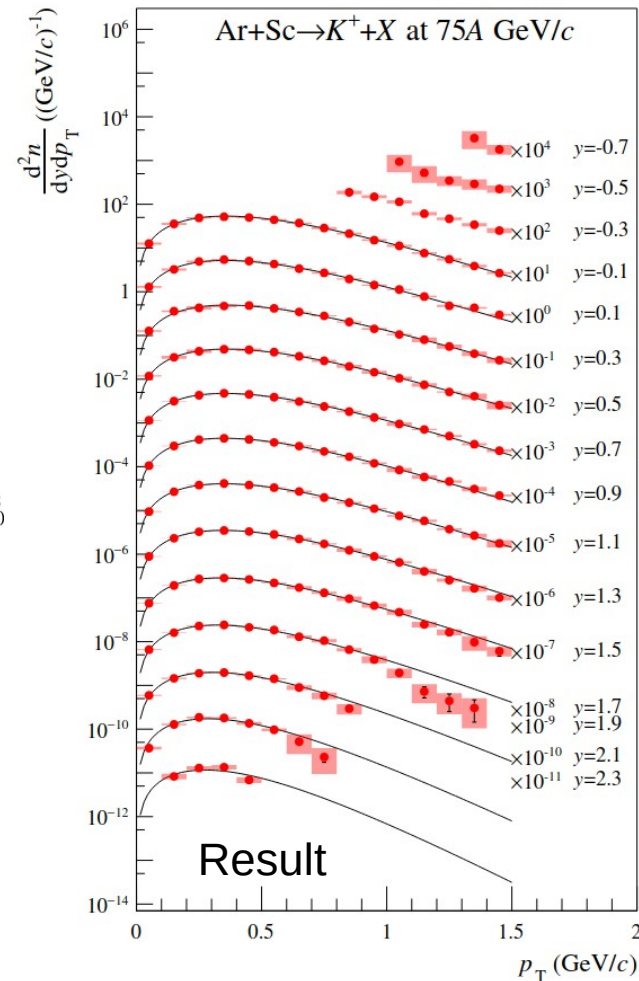
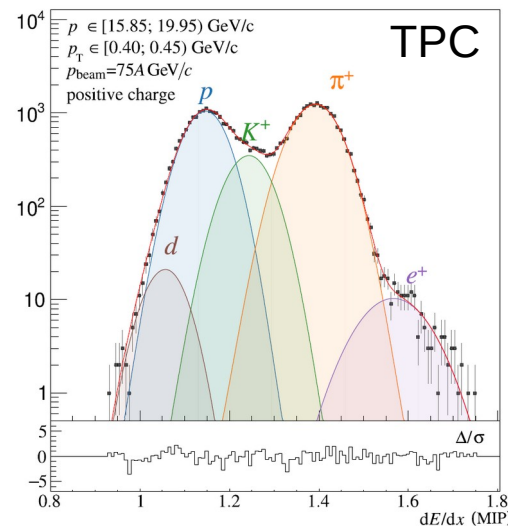
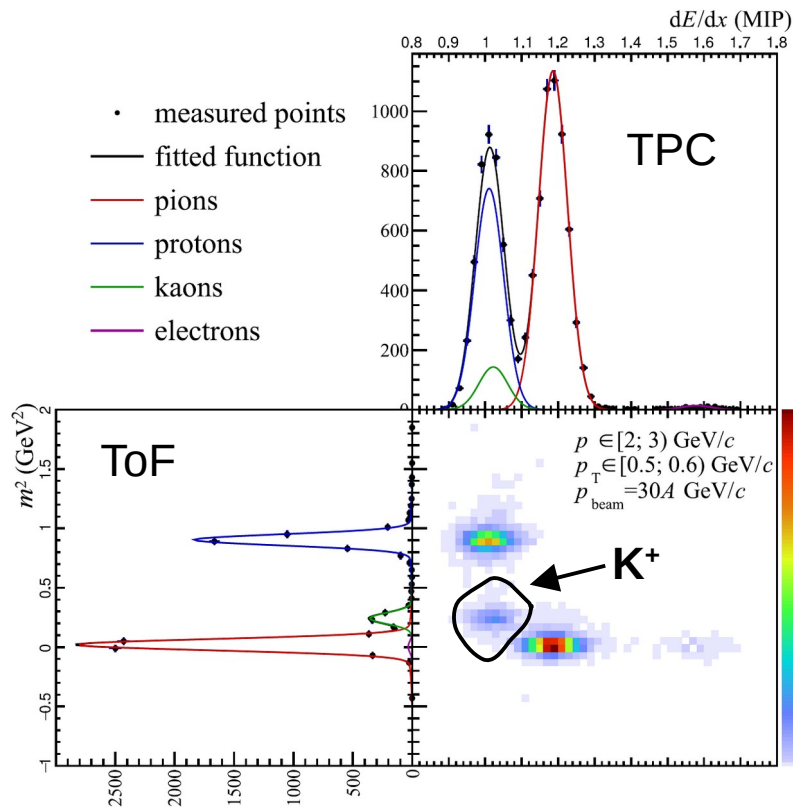
Ratio	Estimated value
Δ^{++}/Δ^{+}	$r = 1.185 \pm 0.029$
Δ^{++}/Δ^{0}	$r^2 = 1.404 \pm 0.068$
Δ^{++}/Δ^{-}	$r^3 = 1.664 \pm 0.120$
Σ^{*+}/Σ^{*0}	$r = 1.185 \pm 0.029$
Σ^{*+}/Σ^{*-}	$r^2 = 1.404 \pm 0.068$
Ξ^{*-}/Ξ^{*0}	$r = 1.185 \pm 0.029$

F. Giacosa, M. Rohrmoser,
Eur. Phys. J. C 85 (2025) 1058

Isospin violation measurements: NA61/SHINE versus collider experiments

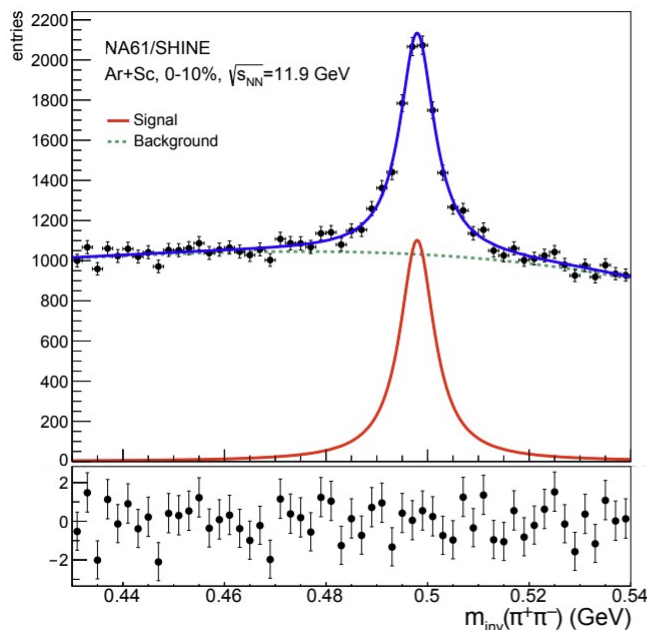
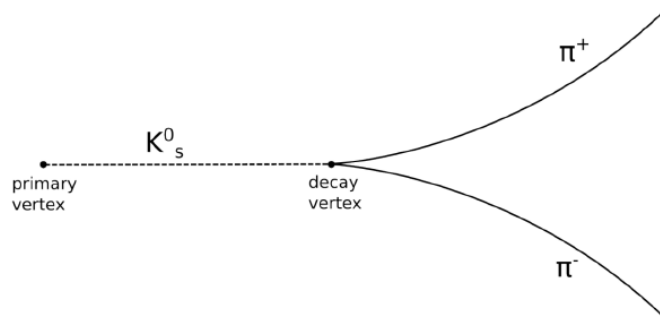


NA61/SHINE	Collider experiments	Comment
p_T coverage starting from $p_T = 0$ (sharp)	p_T coverage starting from $p_T \approx 150$ MeV/c	Isospin violation seems concentrated at low p_T (for kaons)
Rapidity coverage from $y \approx 0$ to $y \approx y(\text{beam})$	Measurements mainly at $y \approx 0$	Isospin violation is visible at any rapidity (for kaons)
Statistics: 1 M – 500 M	Statistics: “very large”	Statistics necessary for NA61/SHINE Nature Communications paper: 1.03 M
Total uncertainty: 4 – 5 %	Total uncertainty: 8 – 19 %	Dominated by systematics

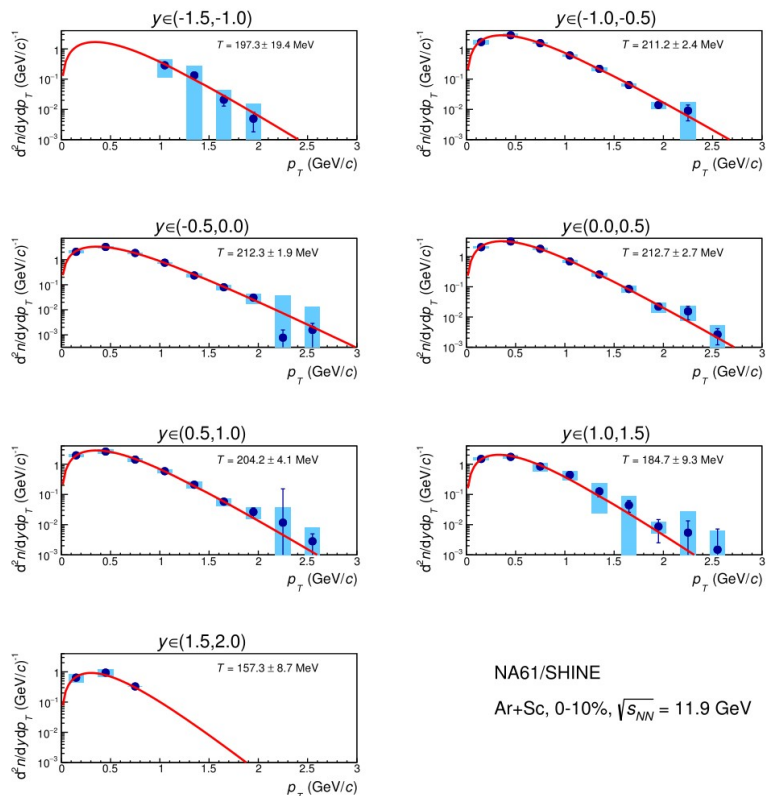


- Measurements based on **TPC** and **TPC+ToF**
 dE/dx dE/dx versus m^2
- Corrected for detector geometrical acceptance, reconstruction efficiency, weak decays, and secondary interactions

- Reconstruction based on decay topology
- K_S^0 decays into π^+ and π^- with BR $\approx 69.2\%$
- Lorentzian function is used to describe the signal
- Corrected for detector geometrical acceptance, reconstruction efficiency, and secondary interactions



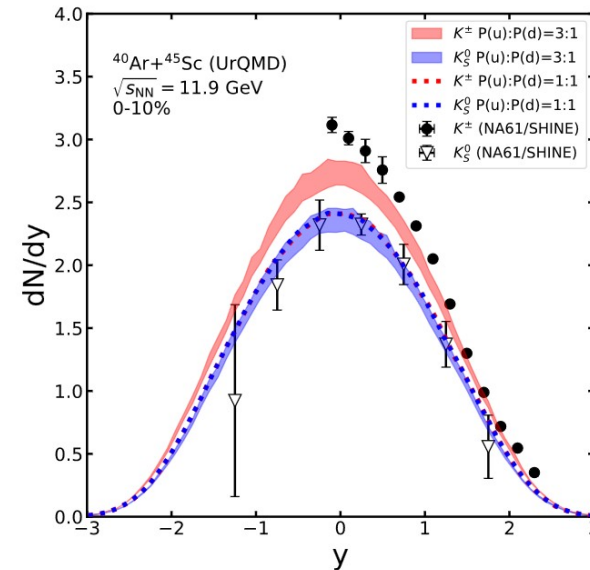
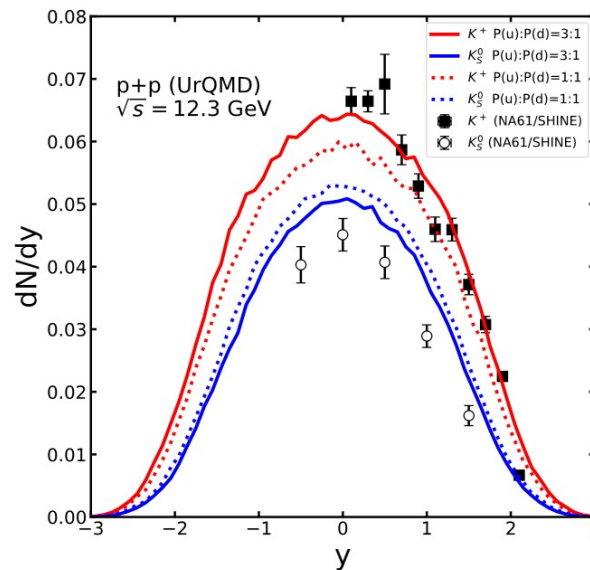
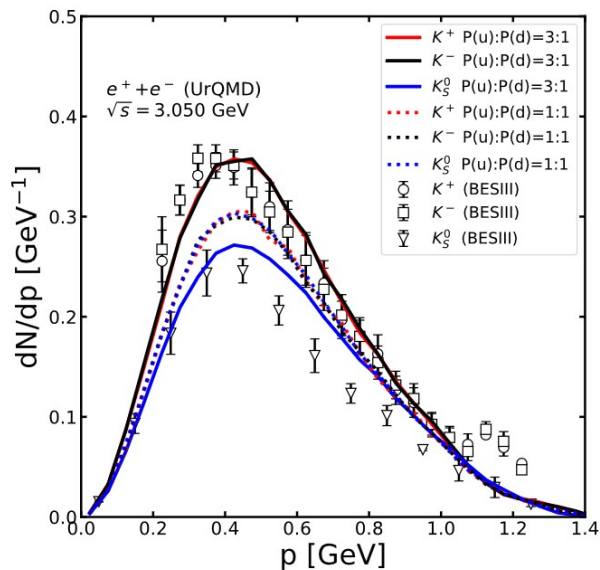
Result



NA61/SHINE
Ar+Sc, 0-10%, $\sqrt{s_{NN}} = 11.9$ GeV

Description of the e^+e^- , p+p, and Ar+Sc data by the modified UrQMD model

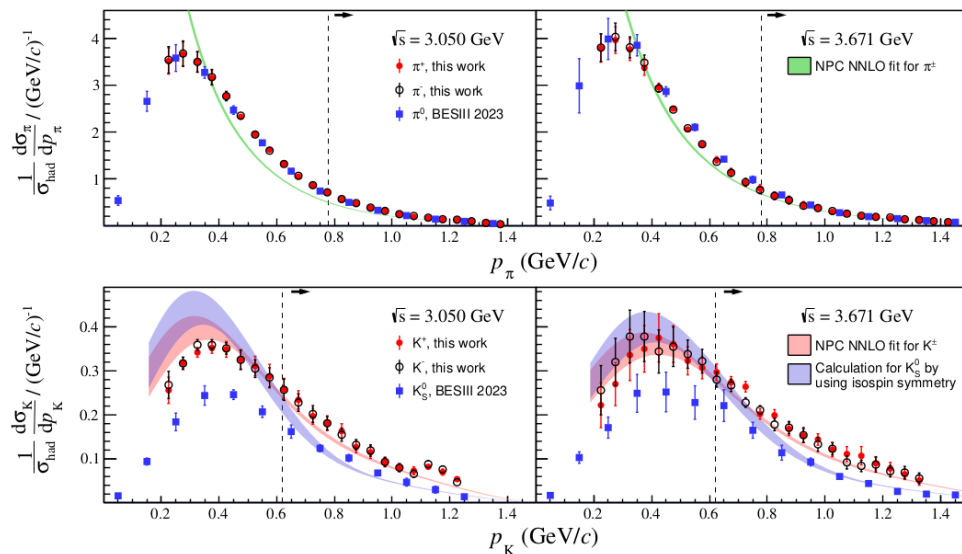
T. Reichert *et al.*, Phys. Lett. B 873 (2026) 140170, and references therein



e^+e^- data: BESIII, Phys. Rev. Lett. 135 (2025) 151901

p+p data: NA61/SHINE, Eur. Phys. J. C 84 (2024) 8, 820

Ar+Sc data: NA61/SHINE, F. Giacosa, M. Gorenstein *et al.*, Nature Commun. 16 (2025) 2849
 NA61/SHINE, Eur. Phys. J. C 84 (2024) 4, 416



Refs. cited in Figure caption:

- [3] BESIII, Phys. Rev. Lett. 135 (2025) 151901,
see also:
BESIII, Phys. Rev. Lett. 130 (2023) 231901
- [30] J. Gao *et al.*, Phys. Rev. D 110 (2024) 11, 114019
- [31] J. Gao *et al.*, Phys. Rev. Lett. 132 (2024) 26, 261903
- [32] L. Huang, ISO-BREAK 25 ([link](#))

Plots taken from Ref. [3]

Fig. 6. Normalized differential cross sections of charged and neutral pions (*top*) and kaons (*bottom*) as a function of hadron momentum in e^+e^- interactions at 3.050 and 3.671 GeV. Vertical bars denote total uncertainties. The green and red bands denote the “NPC” (Nonperturbative Physics Collaboration) NNLO calculations [30, 31] with 1σ limits, based on a new global fit including world data [30] and the new BESIII results. The blue band represents the “NPC” NNLO calculation for K_S^0 using K^\pm fragmentation functions via isospin symmetry. Only the measurements to the right of the dashed lines are used in the fit. The plots are taken from Ref. [3] and presented in Ref. [32].

Figure caption taken from White Paper based on the *Workshop on isospin symmetry violation: kaons and beyond – ISO-BREAK 25*, Kielce, Oct 23-25, 2025, arXiv:2604.16005, to appear in Eur. Phys. J. A ([link](#))

Isospin symmetry violation - known effects in kaon production (1)

(A) Mass effects within strong interactions

Source:

M. Lewicki, Y. Balkova for NA61/SHINE,
SQM2026, [link](#)

- ▶ Different u and d quark masses
→ different hadron masses within isospin multiplets

$$\text{e.g. } m_{K^+} = m_{K^-} = 493.7 \text{ MeV and} \\ m_{K^0} = m_{\bar{K}^0} = 497.6 \text{ MeV}$$

$$\Rightarrow R_K \uparrow 2\% \quad \ominus$$

- ▶ Different kaon masses affect branching ratios:

$$\text{e.g. } \phi(1020) \rightarrow K^+K^- \text{ vs. } \phi(1020) \rightarrow K^0\bar{K}^0$$

$$\frac{\Gamma(\phi \rightarrow K^+K^-)}{\Gamma(\phi \rightarrow K^0\bar{K}^0)} = 1.45$$

$$\Rightarrow R_K \uparrow 3\% \quad \ominus$$

Other resonances: $a_0(980)$, $f_0(980)$

$$\Rightarrow R_K \uparrow 0.5\% \text{ (up to 3\% for extreme assumptions)} \quad \ominus$$

The mass and $Z < N$ effects are included in popular models:

Hadron-Resonance Gas (HRG) and Ultra-Relativistic Molecular Dynamics (UrQMD) \ominus

Isospin symmetry violation - known effects in kaon production (2)

(B) Uncertainties in weak decays

Source:

M. Lewicki, Y. Balkova for NA61/SHINE,
SQM2026, [link](#)

- ▶ The weak interaction do **not** obey charge symmetry
- ▶ Charged and neutral kaons have different mean lifetimes:

$$c\tau(K^+) = c\tau(K^-) \approx 3.7 \text{ m}, \quad c\tau(K_S^0) \approx 2.7 \text{ cm}$$

- ▶ The results are corrected for losses due to weak decays
- ▶ The maximum deviation of R_K from unity due to mean K_S^0 lifetime uncertainty is:

$$< 0.13\% \quad \text{⊘}$$

Isospin symmetry violation - known effects in kaon production (3)

Source:

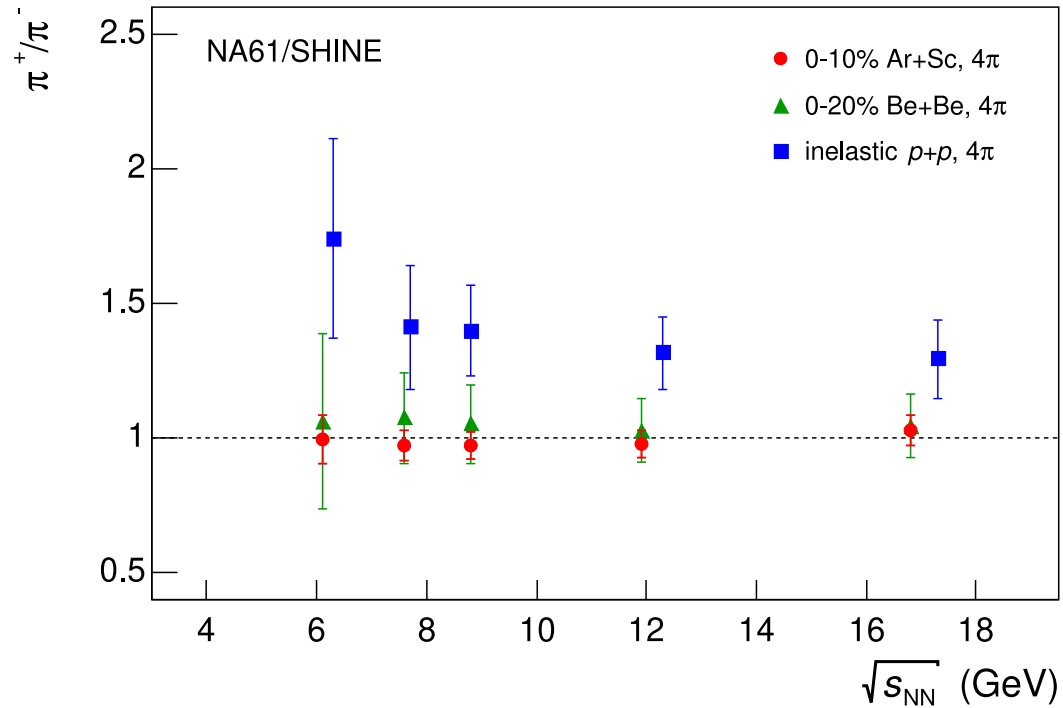
(C) Electromagnetic processes do not obey charge symmetry because of different electric charges of u and d (or charged and neutral kaons).

M. Lewicki, Y. Balkova for NA61/SHINE, SQM2026, [link](#)

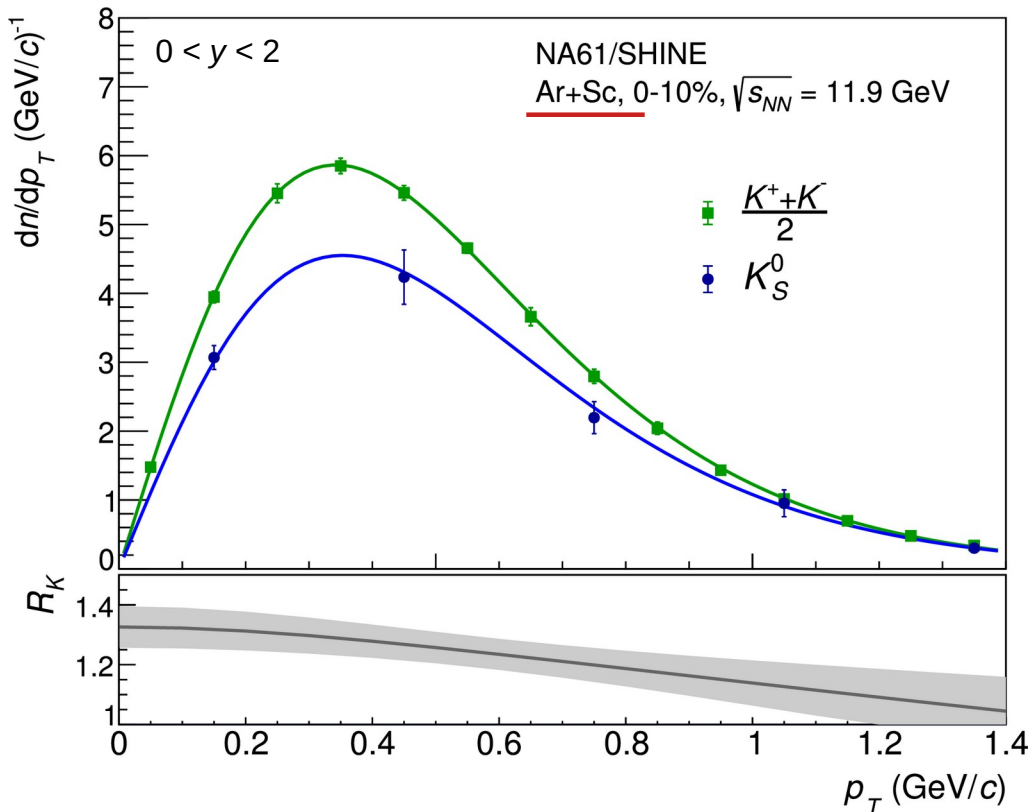
- ▶ Hadron EM decays and virtual photon decays to kaons are suppressed by $\alpha^2 \simeq \left(\frac{1}{137}\right)^2$
⊗
- ▶ EM processes involving total electric charge of nuclei: $Z_1 Z_2 \alpha^2$
 $\Rightarrow Z^2$ -dependence of $R_K \rightarrow$ Not observed in the data ⊗
- ▶ Electromagnetic interactions break isospin symmetry by favoring $u\bar{u}$ pair creation over $d\bar{d}$ pairs
 \rightarrow enhances the production of charged kaons
Quantifying these QED effects (e.g. larger effective u - g coupling, fireball's Coulomb potential) requires detailed modeling
(Large QED corrections to QCD $q\bar{q}$ creation?)

There are **no quantitative calculations** of the effect.

?



NA61/SHINE,
 Eur. Phys. J. C 77.10 (2017), 671,
 Eur. Phys. J. C 81.1 (2021), [Erratum: Eur.Phys.J.C 83, 90 (2023)], 73,
 Eur. Phys. J. C 84.4 (2024), 416.
 Plot from arXiv:2604.16005

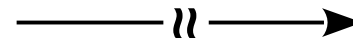


$$R_K = \frac{K^+ + K^-}{2K_S^0}$$

Uncertainties:
total (stat, syst)

“soft QCD”

- The effect seems to be present at low p_T
→ the “soft QCD” regime



- jets ...
- pQCD ...
- etc ...