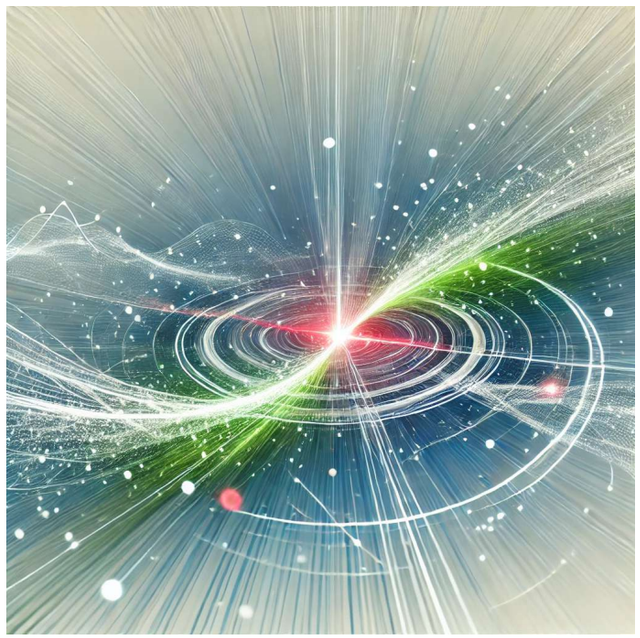
Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei

NA61/SHINE Collaboration • H. Adhikary (Jan Kochanowski U.) et al. (Dec 11, 2023)

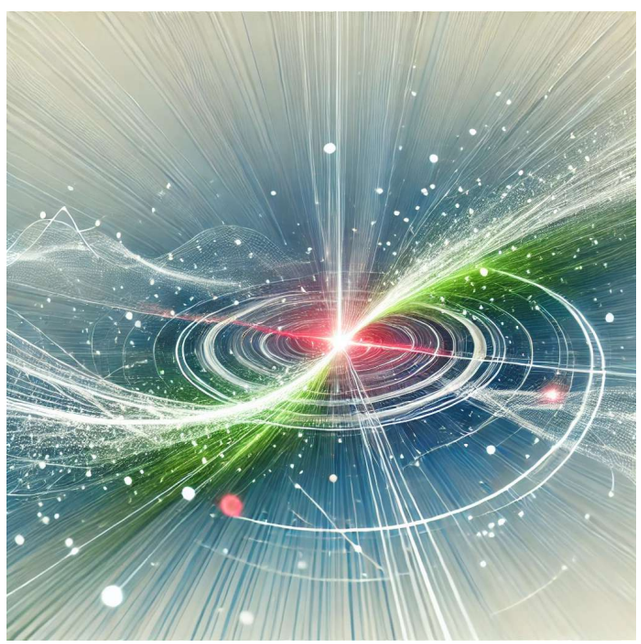
e-Print: 2312.06572 [nucl-ex]

UNDER REVIEW BY
NATURE COMMUNICATIONS

MG, UJK KIELCE
NA61/SHINE



- ISOSPIN, CHARGE AND FLAVOUR SYMMETRIES
- TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS
- MEASURING CHARGED AND NEUTRAL KAONS
- RESULTS ON CHARGED-TO-NEUTRAL KAON RATIO
- SYMMETRY BREAKING BEYOND KNOWN EFFECTS



CHARGE SYMMETRY BREAKING IN π^{+}_{-} + C COLLISIONS RECORDED BY NA61/SHINE IN 2024

BY CHATGPT

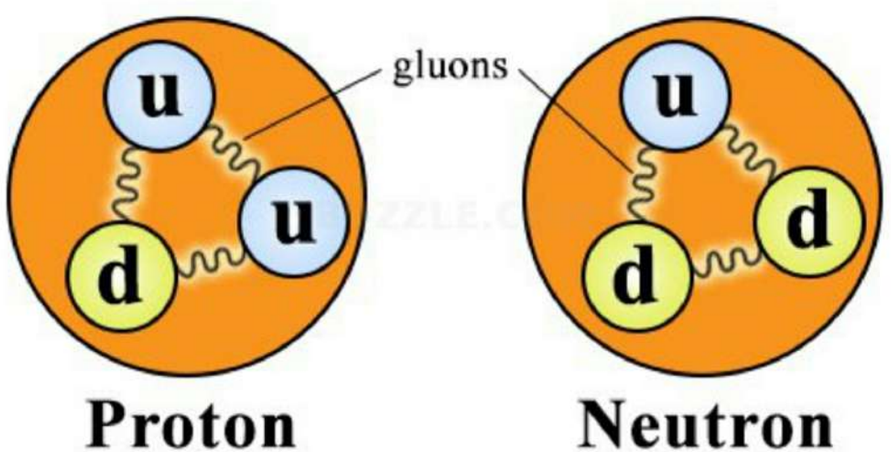
ISOSPIN, CHARGE AND FLAVOUR SYMMETRIES

1932: HEISENBERG, WIGNER → ISOTOPIC SPIN (ISOSPIN)

→ PROTON AND NEUTRON DIFFERENT MANIFESTATION OF THE SAME STRONGLY INTERACTING PARTICLE: NUCLEON

→ USE SPIN FORMALISM.

→ PROPERTIES OF NUCLEI AND HADRONS (KEMMER 1939)



$$\frac{M_n}{M_p} \approx \frac{940}{938} \approx 1.002$$

ISOSPIN, CHARGE AND FLAVOUR SYMMETRIES

NUCLEON: ISOSPIN DUBLET: $I = 1/2$, p: $I_z = 1/2$, n: $I_z = -1/2$

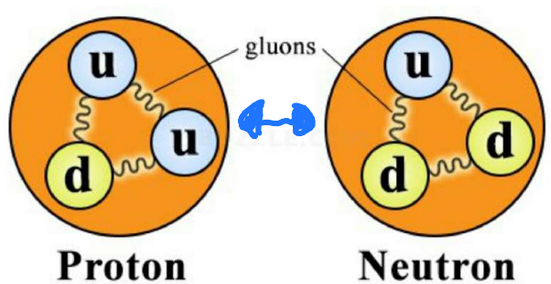
$$\begin{pmatrix} p \\ n \end{pmatrix} \longrightarrow \hat{O} \begin{pmatrix} p \\ n \end{pmatrix},$$

WHERE $\hat{O}$ IS 2x2 UNITARY MATRIX: $\hat{O} = e^{i\vartheta_i \hat{I}_i/2}$

CHARGE TRANSFORMATION IS A SPECIAL ISOSPIN TRANSFORMATION:

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

UNDER $\hat{C}$:



ISOSPIN, CHARGE AND FLAVOUR SYMMETRIES

WITHIN QCD, THE ISOSPIN SYMMETRY OF HADRONS IS TRACED BACK TO THE ISOSPIN SYMMETRY OF LIGHT QUARKS

UNDER $\hat{C}$ →

$$\begin{pmatrix} u \\ d \end{pmatrix} \to \hat{O} \begin{pmatrix} u \\ d \end{pmatrix}$$

ISOSPIN SYMMETRY IS PART OF FLAVOUR SYMMETRY – STRONG INTERACTIONS ARE INDEPENDENT OF QUARK FLAVOUR ASSUMING QUARK MASSES ARE EQUAL.

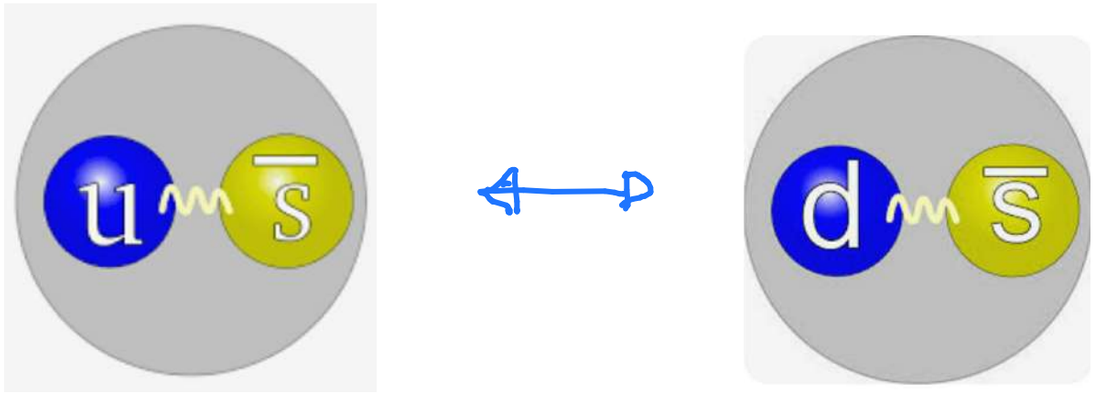
THE LATTER IS A GOOD APPROXIMATION FOR u AND d QUARKS:

$$m_d - m_u \approx 2.5\ \text{MeV} \ll \Lambda_{QCD} \approx 200\ \text{MeV}$$

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

$\hat{C}$:

K^+ $\longleftrightarrow$ K^0



K^- $\longleftrightarrow$ $\bar{K}^0$

$\hat{C}: (p+p \to K^+ + X) =$

$(n+n \to K^0 + \hat{X})$ (*)

$\hat{C}: p+p \to \tilde{K}^- + X$

$= n+n \to \tilde{K}^0 + \hat{X}$ (**)

BUT (*) AND (**) ARE DIFFICULT TO MEASURE

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

CHARGED SYMMETRY OF STRONG INTERACTIONS:

$$(p+p \to K^+ + X) = (n+n \to K^0 + \hat{X}) \Rightarrow \langle K^+ \rangle_{pp} = \langle K^0 \rangle_{nn}$$

$$(p+p \to K^0 + X) = (n+n \to K^+ + \hat{X}) \Rightarrow \langle K^0 \rangle_{pp} = \langle K^+ \rangle_{nn}$$

$\Downarrow$

CHARGE-TRANSFORMATION-INVARIANT INITIAL ENSEMBLE:

$$\left\{ \begin{array}{ll} 50\% & p+p \\ 50\% & n+n \end{array} \right\} \to \langle K^+ \rangle = \langle K^0 \rangle$$

CHARGE-TRANSFORMATION INVARIANT FINAL ENSEMBLE

CHARGE SYMMETRY OF INTERACTIONS $\Rightarrow$ INTERACTIONS PRESERVE CHARGE-TRANSFORMATION INVARIANCE OF ENEMBLES

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

CHARGE INVARIANT INITIAL ENSEMBLE

BY CONSTRUCTION

→ INTERACTIONS PRESERVE CHARGE INVARIANCE

TESTED ASSUMPTION

→ CHARGE INVARIANT FINAL ENSEMBLE

THE PREDICTION

FOR KAONS

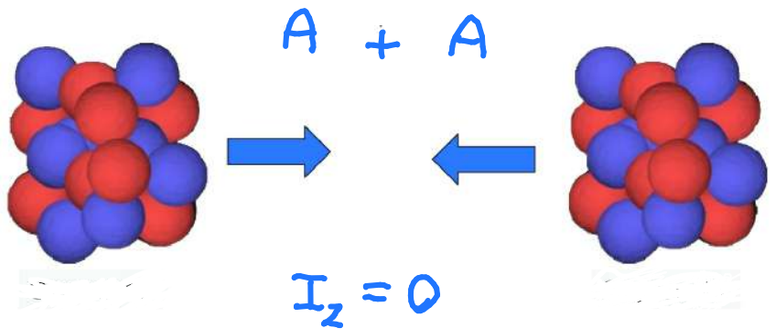
$$\langle K^+ \rangle = \langle K^0 \rangle$$
$$\langle K^- \rangle = \langle \bar{K}^0 \rangle$$

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

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

THE FIRST NAGI/SHIUE FRIENDLY TEST:

CONSIDER COLLISIONS OF TWO NUCLEI WITH EQUAL NUMBER OF PROTONS AND NEUTRONS, $Z = N = A/2$



IT WAS EASY TO MEASURE IN 2015+

THEN THE ENSEMBLE OF A+A INITIAL NUCLEI DOES NOT CHANGE UNDER CHARGE TRANSFORMATION, IT IS CHARGE (TRANSFORMATION) INVARIANT

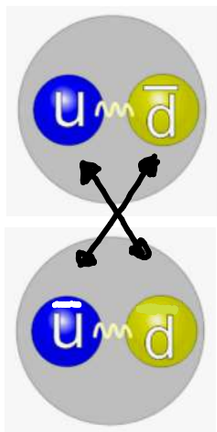
TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

THE SECOND NACI/SHINE FRIENDLY TEST:

CONSIDER COLLISIONS OF $\pi^+ + {}^{12}C$ (50%) AND $\pi^- + {}^{12}C$ (50%),
CARBON IS CHARGE SYMMETRIC ($Z = 6$, $N = 6$), $\hat{C}: \pi^+ \to \pi^-$, $\hat{C}: \pi^- \to \pi^+$

π^+

π^-

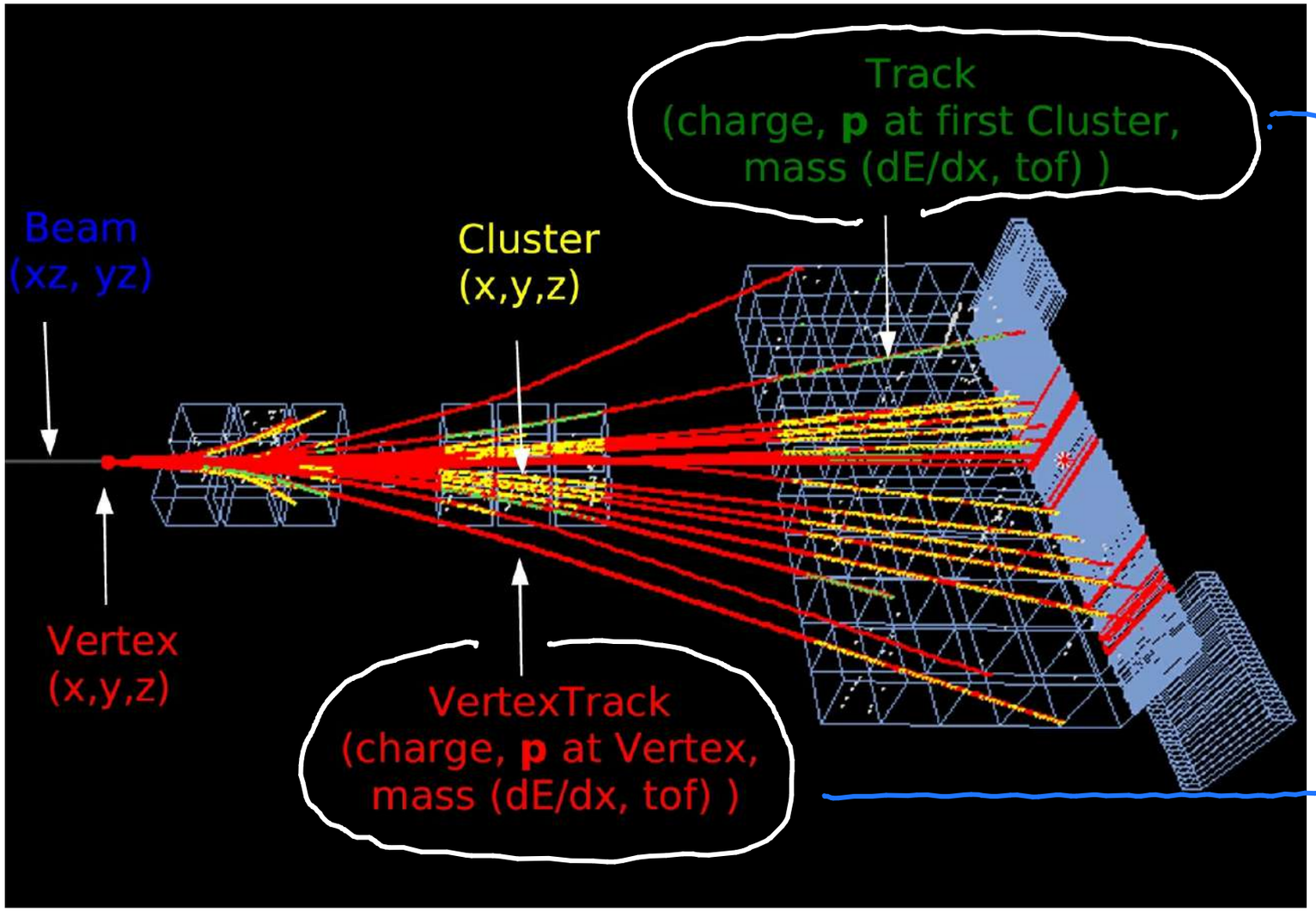


IT WAS EASY TO MEASURE IN 2024

THEN THE ENSEMBLE OF $\begin{matrix}\pi^+ \\ \pi^-\end{matrix} + {}^{12}C$ INITIAL PIONS AND NUCLEI DOES NOT CHANGE UNDER CHARGE TRANSFORMATION, IT IS CHARGE (TRANSFORMATION) INVARIANT

MEASURING CHARGED AND NEUTRAL KAONS

NAGI/SHINE AT THE CERN SPS EXAMPLE:

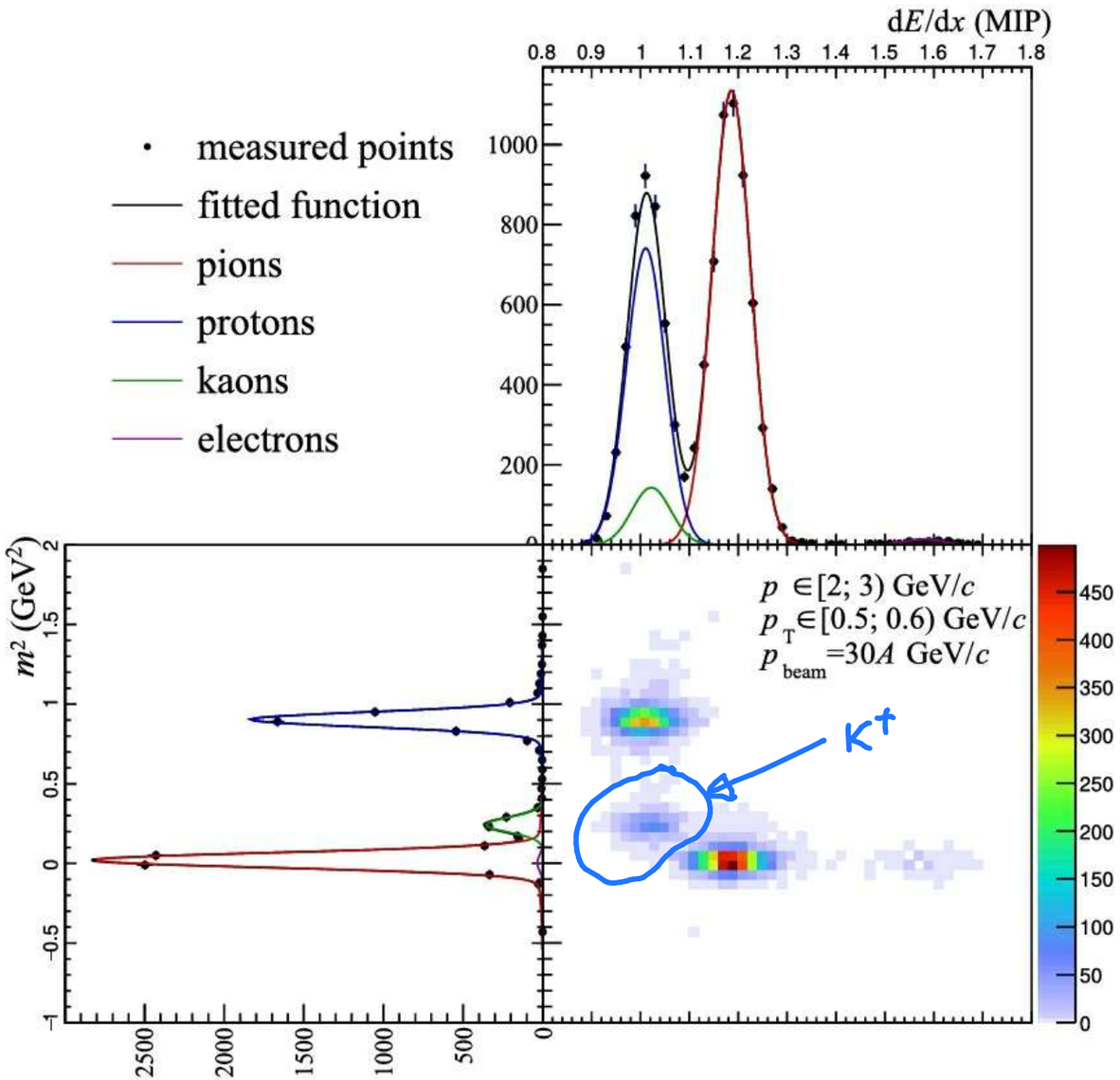


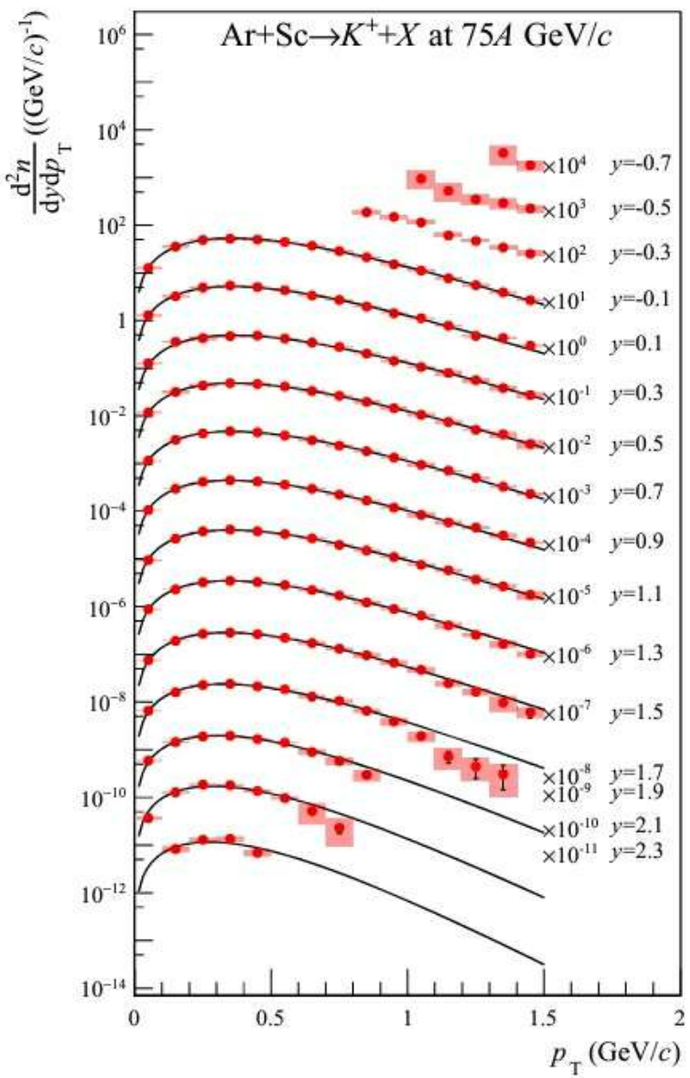
INPUT TO $K^0_S \rightarrow \pi^+ + \pi^-$ ANALYSIS

INPUT TO K^+, K^- ANALYSIS

MEASURING CHARGED AND NEUTRAL KAONS

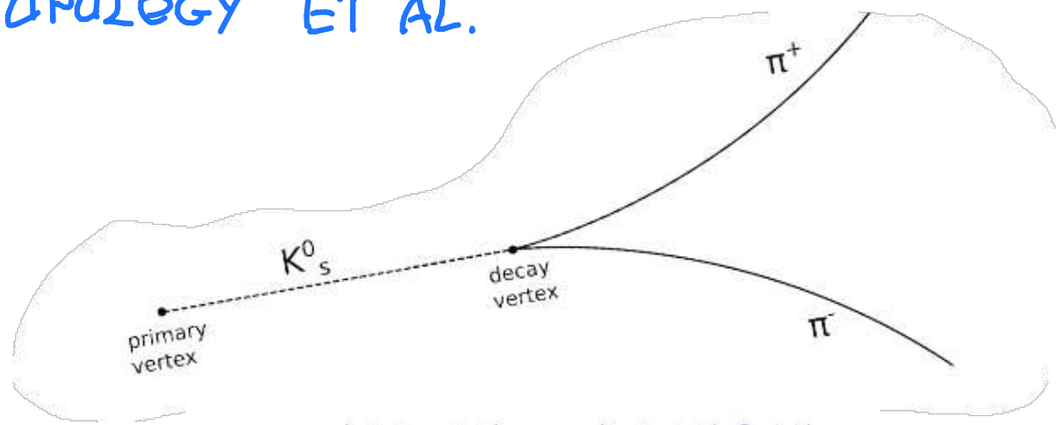
THE MASS MEASUREMENTS · ET AL. → CORRECTIONS → TRANSVERSE MOMENTUM SPECTRA

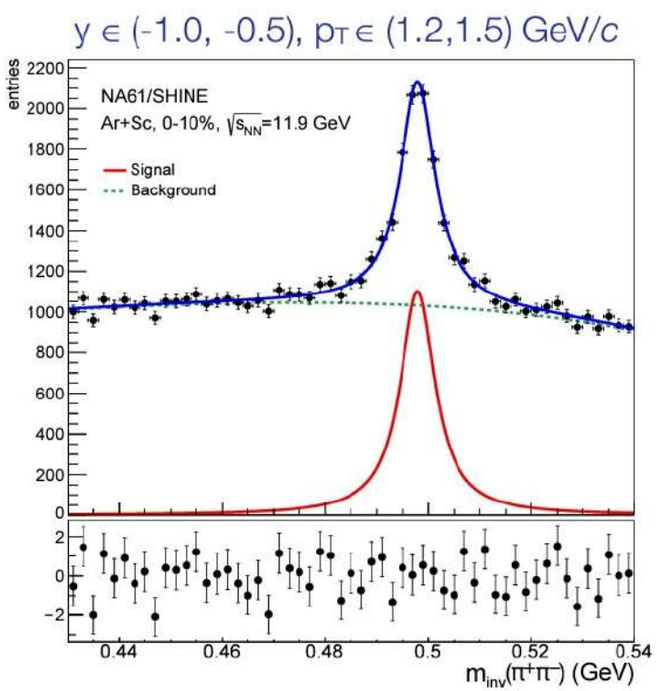


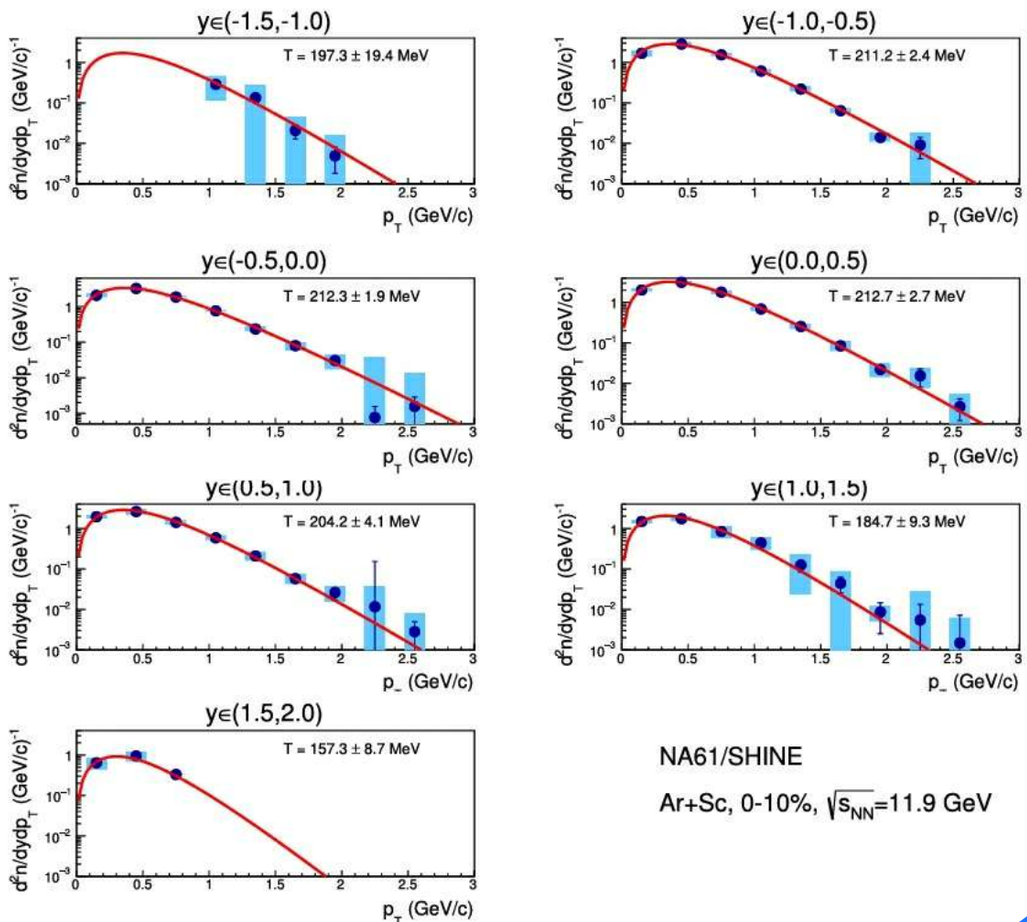


MEASURING CHARGED AND NEUTRAL KAONS

RECONSTRUCTING DECAY TOPOLOGY ET AL. → CORRECTIONS → TRANSVERE MOMENTUM SPECTRA





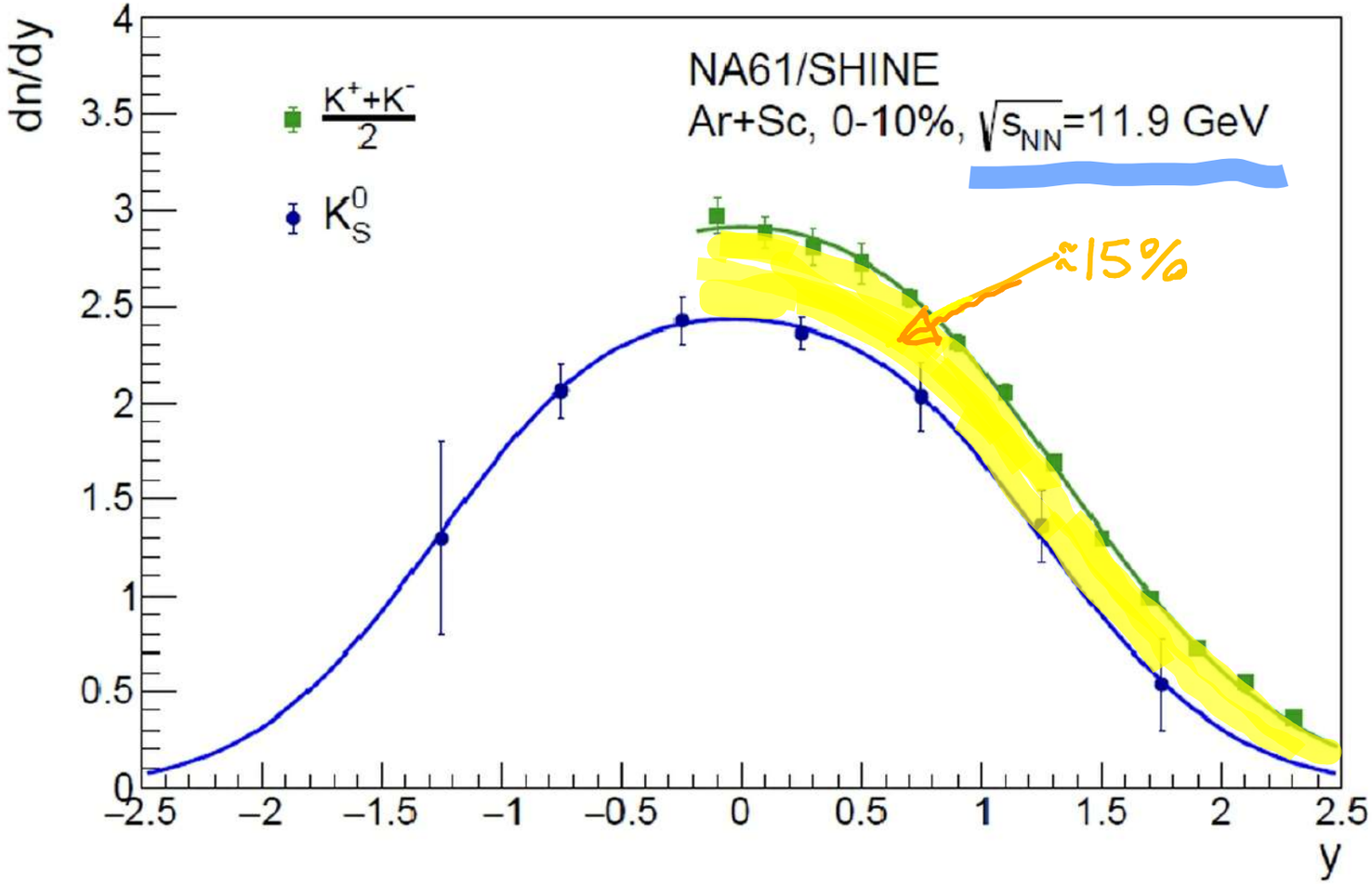


NA61/SHINE

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

MEASURING CHARGED AND NEUTRAL KAONS

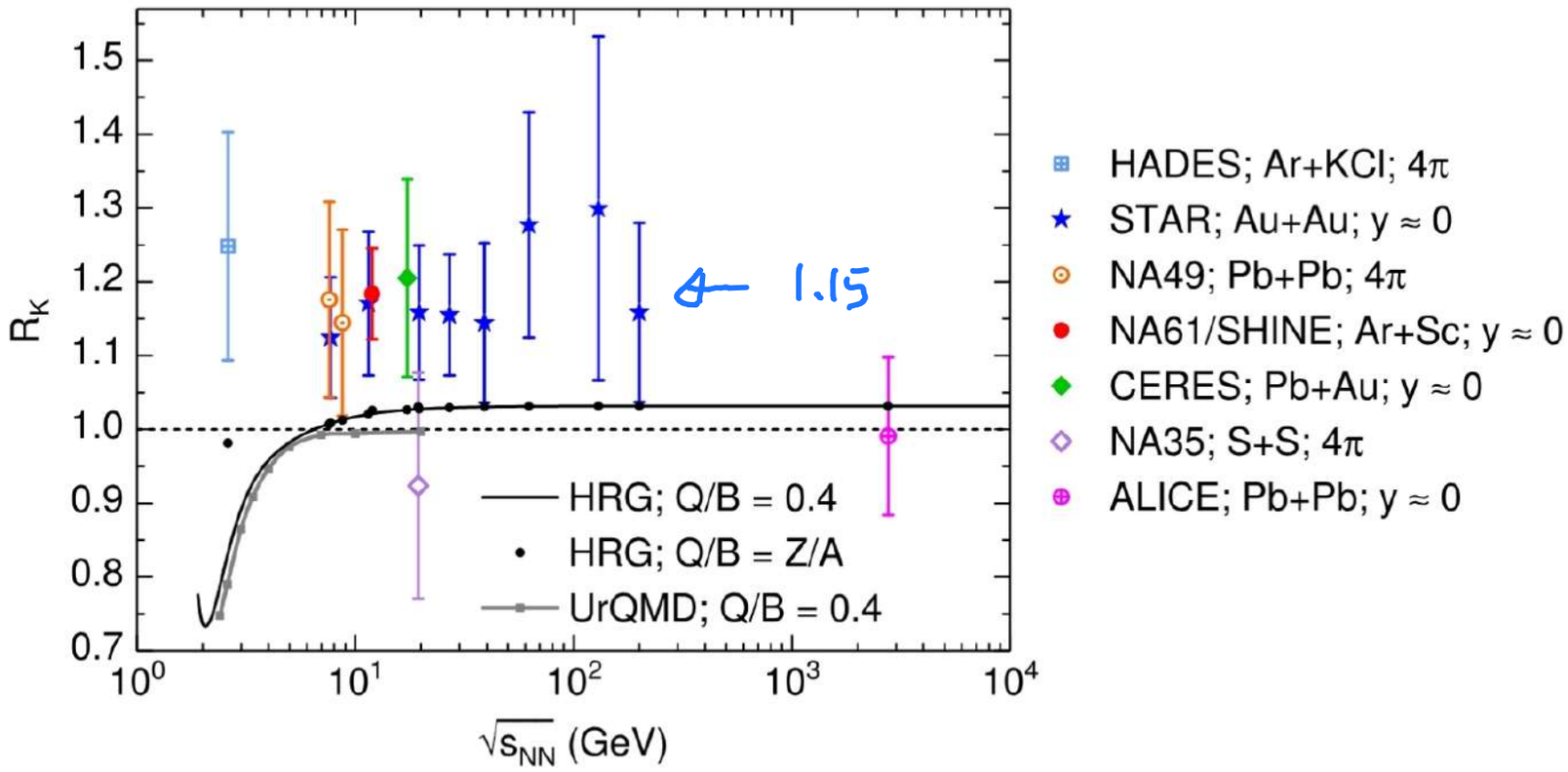
RAPIDITY SPECTRA IN $^{40}_{18}Ar + ^{45}_{21}Sc$



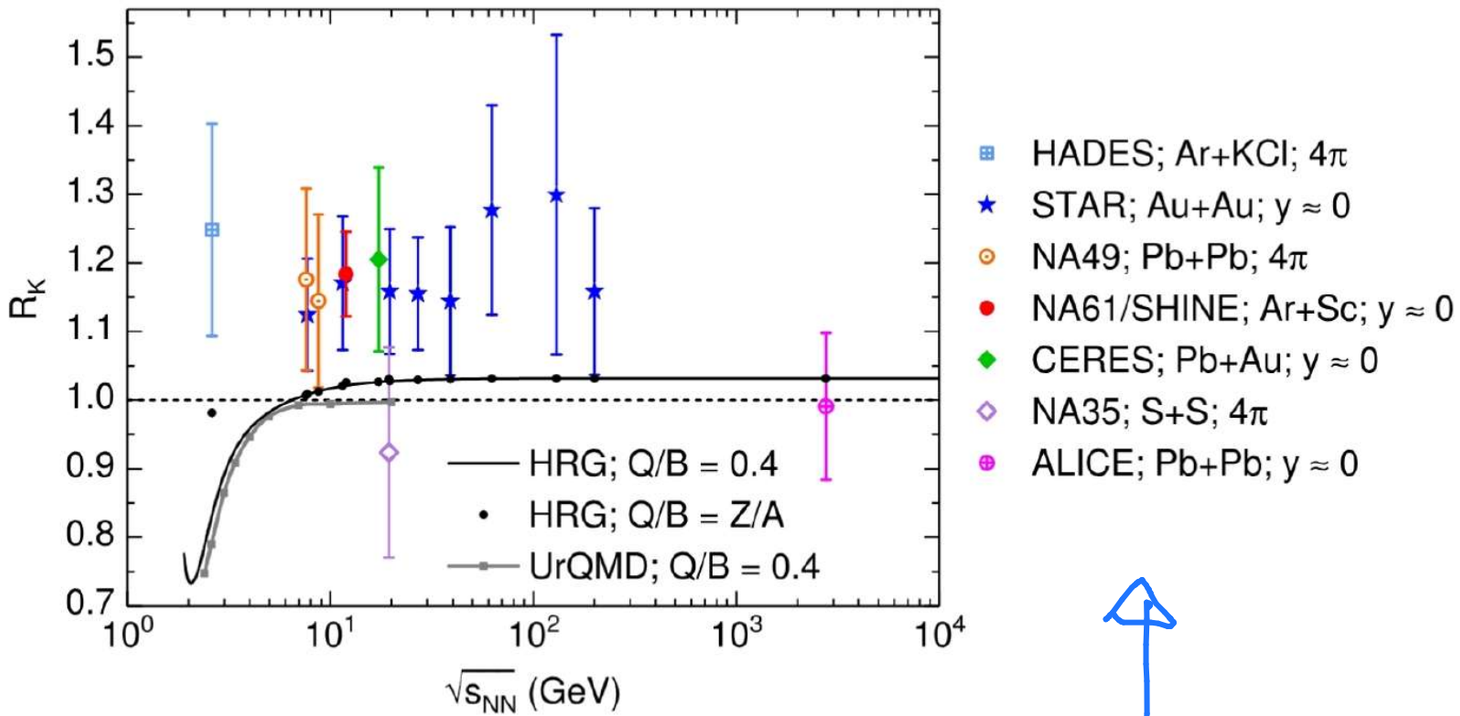
MORE CHARGED THAN NEUTRAL KAONS INSPITE OF HAVING SOMEWHAT MORE NEUTRONS THAN PROTONS IN COLLIDING NUCLEI WHICH FAVOURS NEUTRAL KAONS

RESULTS ON CHARGED-TO-NEUTRAL KAON RATIO

THE WORLD DATA ON R_K ARE SYSTEMATCALLY HIGHER THAN ONE - THE PREDICTION FOR EXACT CHARGE SYMMETRY AND COLLISIONS OF Z=N NUCLEI.



RESULTS ON CHARGED-TO-NEUTRAL KAON RATIO



ALL RESULTS CONCERN COLLISIONS OF NUCLEI WITH $Z < N$,
THIS FAVOURS PRODUCTION OF NEUTRAL OVER CHARGED KAONS,
AND CANNOT EXPLAIN $R_K > 1$.

RESULTS ON CHARGED-TO-NEUTRAL KAON RATIO

SUMMARIZING:

CHARGE INVARIANT INITIAL ENSEMBLE

BY CONSTRUCTION

→ INTERACTIONS VIOLATE CHARGE INVARIANCE ←

CHARGE NON-INVARIANT FINAL ENSEBLE

CHARGE SYMMETRY

$$R_K = \frac{\langle K^+ + K^- \rangle}{2\langle K^0_S \rangle} \approx 1.15 \neq 1$$

EXPERIMENT

→ CHARGE-SYMMETRY BREAKING (CSB)

CSB BEYOND KNOWN EFFECTS

KNOWN EFFECTS CONTRIBUTING TO CSB IN KAON PRODUCTION:

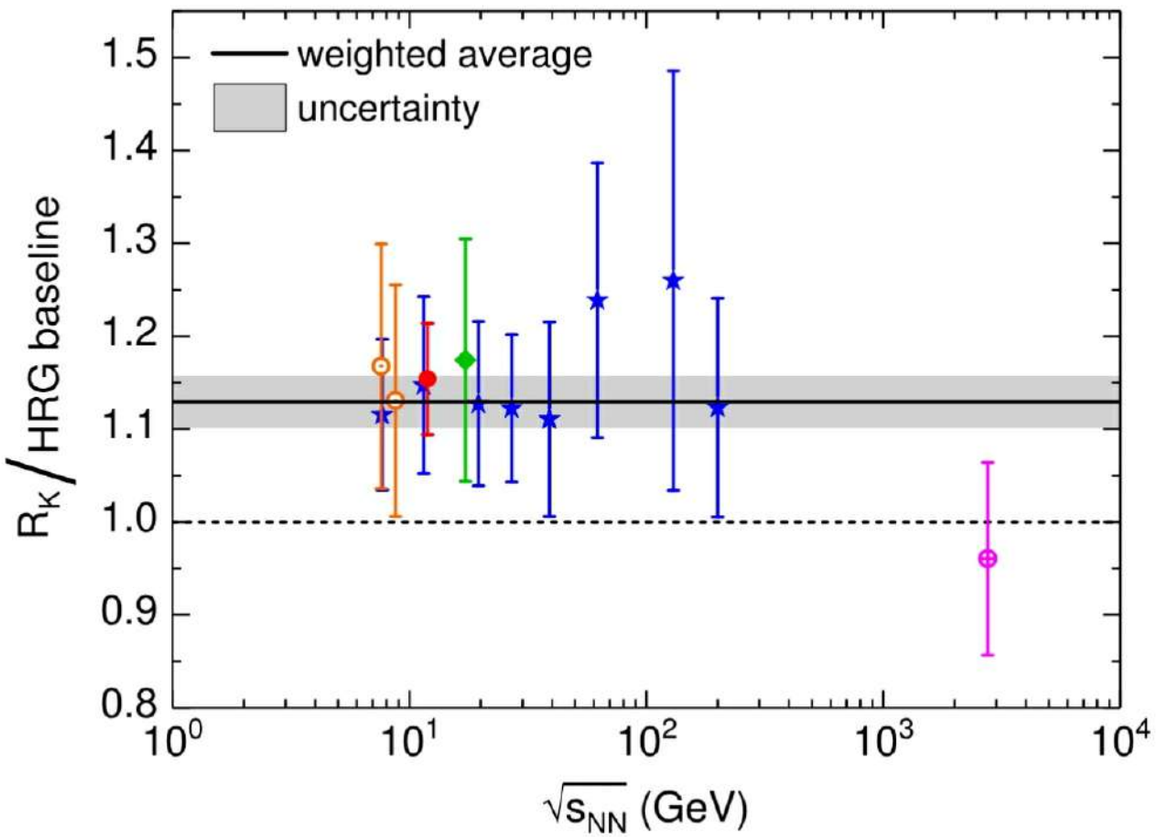
(A) MASS EFFECTS WITHIN STRONG INTERACTIONS

- DIFFERENT u AND d QUARK MASSES → DIFFERENT HADRON MASSES WITHIN ISOSPIN MULTIPLETS (E.G. $m_{K^+} = m_{K^-} = 493.7$ MeV AND $m_{K^0} = m_{\bar{K}^0} = 497.6$ MeV), $R_K \nearrow$ 2% (−)

- DIFFERENT KAON MASSES AFFECT BRANCHING RATIOS (E.G. $(\phi(1020) \to K^+ + K^-) / (\phi(1020) \to K^0 + \bar{K}^0) = 1.45$) $R_K \nearrow$ 1% (−)

CSB BEYOND KNOWN EFFECTS

THE MASS AND Z/N EFFECTS ARE INCLUDED IN POPULAR MODELS: HADRON-RESONANCE GAS (HRG) AND ULTRA-RELATIVISTIC MOLECULAR DYNAMICS (UrQMD) ☹



← 1.129 ± 0.027
$(4.7\,\sigma)$

CSB BEYOND KNOWN EFFECTS

(B) UNCERTAINTIES IN WEAK DECAYS.

THE WEAK INTERACTIONS DOES NOT OBEY THE CHARGE SYMMERY. CHARGED AND NEURAL KAONS HAVE DIFFERENT MEAN LIFETIMES

$(c\tau(K^+) = c\tau(K^-) \simeq 3.7\ m\ ,\ c\tau(K_S^0) \simeq 2.7\ cm)$

THE RESULTS ARE CORRECTED FOR LOSSES DUE TO DECAYS. THE MAXIMUM UNCERTAINTY OF R_K DUE TO UNCERTAINTY OF THE MEANLIFE TIME IS 0.13% (—)

CSB BEYOND KNOWN EFFECTS

(D) ELECTROMAGNETIC PROCESSES DOES NOT OBEY CHARGE SYMMETRY BECAUSE OF DIFFERENT ELECTRIC CHARGES OF u AND d (OR CHARGED AND NEUTRAL KAONS).

- HADRON EM DECAYS AND VIRTUAL PHOTON DECAYS TO KAONS ARE SUPPRESSED BY $\alpha \simeq 1/137$. (−)
- EM PROCESSES INVOLVING TOTAL ELECTRIC CHARGE OF NUCLEI ~ $Z_1 Z_2 \alpha^2$ ⇝ Z^2-DEPENDENCE OF R_K NOT OBSERVED IN THE DATA. (−)
- $u\bar{u}$ AND $d\bar{d}$ CREATION IN STRONG PROCESSES MAY BE AFFECTED BY DIFFERENT STRENGHT OF EM INTERACTIONS. (LARGE QED CORRECTIONS TO QCD $q\bar{q}$ CREATION ?)

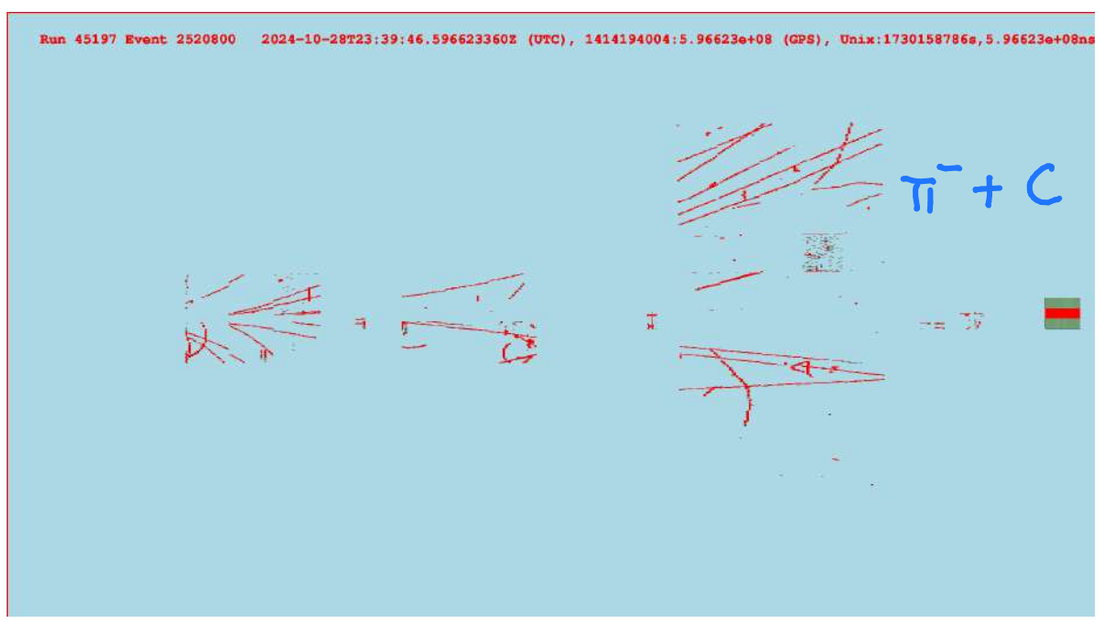
THERE ARE NO QUANTITAVE CALCULATIONS OF THE EFFECT.

(?)

CLOSING REMARKS: THE SECOND NA61/SHINE FRIENDLY TEST

IS THE CSB SPECIFIC TO A+A COLLISIONS, OR IT IS A GENERAL PROPERTY OF INTERACTIONS ?

π^+ / π^- + C DATA WILL ANSWER THIS IMPORTANT QUESTION.



π^- + C AT 158 GeV/c

CLOSING REMARKS: THE SECOND NA61/SHINE FRIENDLY TEST

The 2024 data taking on charge symmetry violation

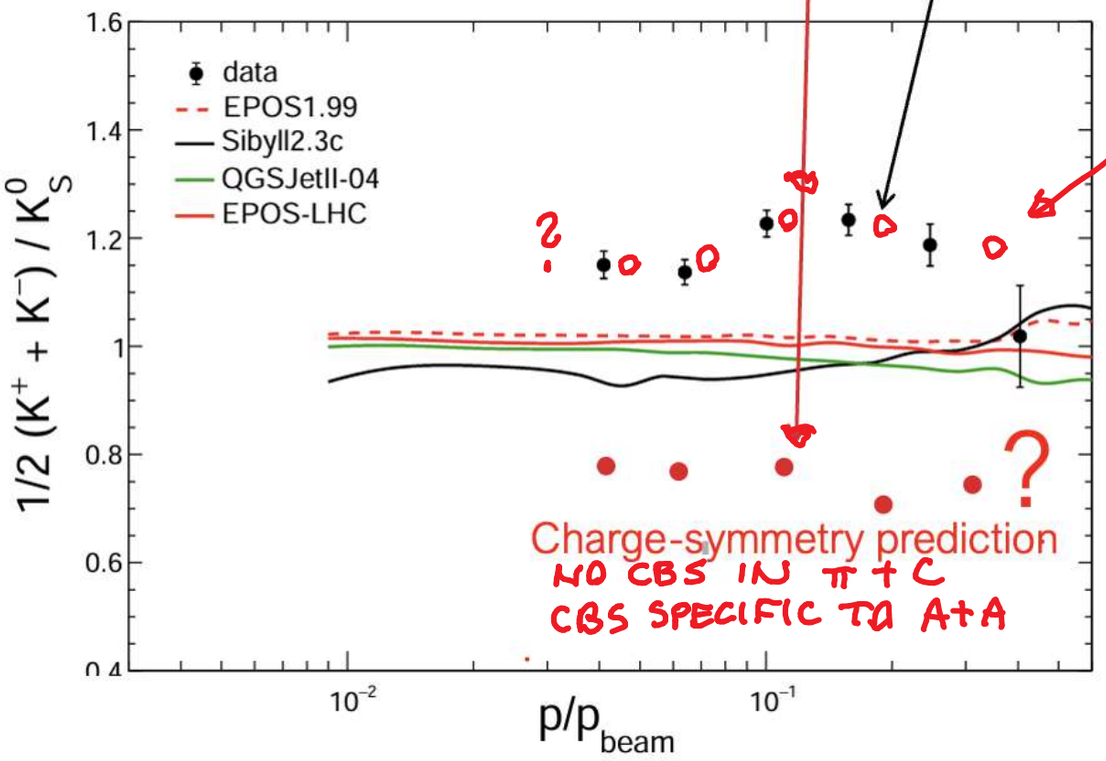
Memorandum requesting use of the allocated test beam for data-taking on π^+ + C and π^- + C interactions at 158 GeV/c

In October 2024 NA61/SHINE has two weeks of the hadron beam time allocated for tests and calibration. [...]

CERN-SPSC-2024-022 ; SPSC-M-797. - 2024.

NA61/SHINE

Phys.Rev.D 107 (2023) 6, 062004



CBS IN π+C
CBS GENERAL PROPERTY OF INTERACTIONS

October 25 – 30, 2024:

$\pi^+ + C$
30M events recorded

$\pi^- + C$
30M events recorded

CLOSING REMARKS:

- $R_K \approx 1.15$ IN A+A

  THE FIRST EXPERIMENTAL EVIDENCE OF A LARGE CHARGE-SYMMETRY BREAKING IN KAON PRODUCTION

- IT CANNOT BE EXPLAINED BY KNOWN PROCESSES VIOLATING CHARGE SYMMETRY (4.7 σ DIFFERENCE)

- $\frac{\pi^+}{\pi^-}$ + C DATA WILL ANSWER SOON THE QUESTION:
  - IS THE CSB SPECIFIC TO A+A COLLISIONS OR
  - IS IT A GENERAL PROPERTY OF INTERACTIONS?