WHY DID WE TAKE π^+/π^- + C DATA ?

MG CERN 2024

THE FIRST DATA-TAKING DEDICATED TO STUDY CHARGE SYMMETRY

MOTIVATED BY:

Evidence for an excess of charged over neutral K meson production 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]

Large isospin symmetry breaking in kaon production at high energies

Wojciech Brylinski (Warsaw U. of Tech. (main)), Marek Gazdzicki (Jan Kochanowski U., Kielce (main)), Francesco Giacosa (Jan Kochanowski U., Kielce (main) and Goethe U., Frankfurt (main)), Mark Gorenstein (BITP, Kiev and Frankfurt U., FIAS), Roman Poberezhnyuk (BITP, Kiev and Frankfurt U., FIAS) et al. (Dec 12, 2023)

e-Print: 2312.07176 [nucl-th]

#1

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

- 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

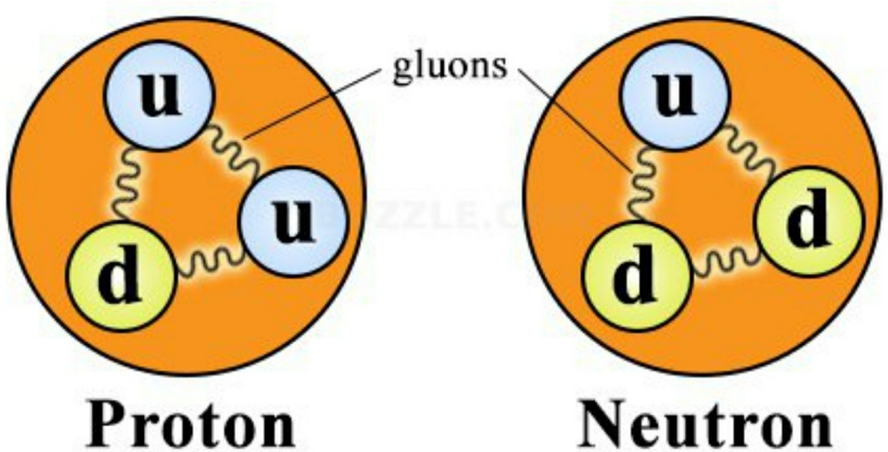
ISOSPIN, CHARGE AND FLAVOUR SYMMETRIES

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: $I_z = -1/2$

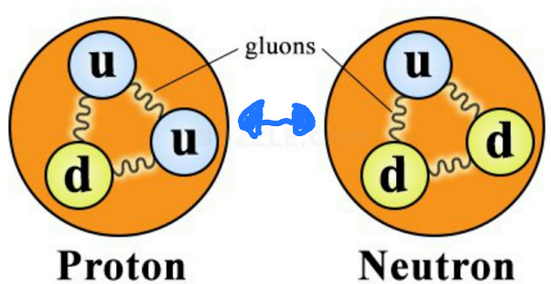
$$\begin{pmatrix} p \\ n \end{pmatrix} \longrightarrow \hat{O} \begin{pmatrix} p \\ n \end{pmatrix},$$

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 $\hat{C}$ →

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

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

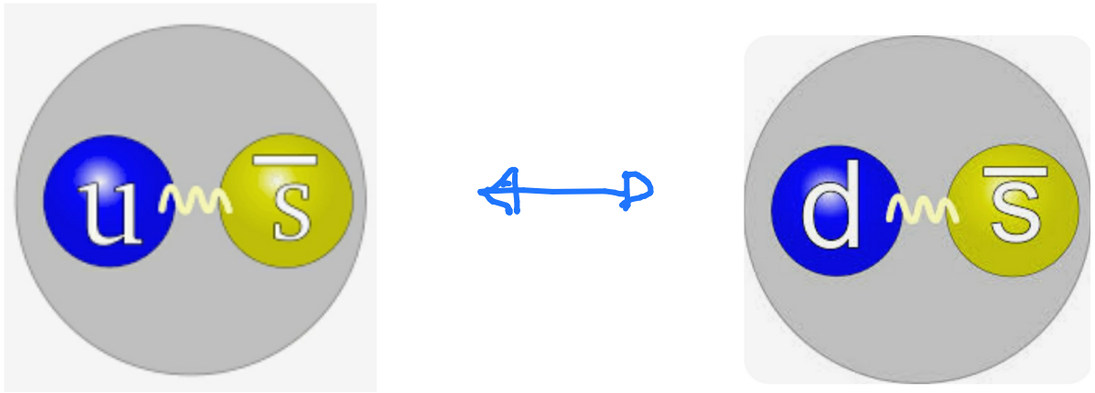
THE LATTER IS A GOOD APPROXIMATION FOR u AND d QUARKS:

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

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

$\hat{C}$:

K^+ $\longleftrightarrow$ K^0



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

$\hat{C}$: $p + p \rightarrow K^+ + X$

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

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

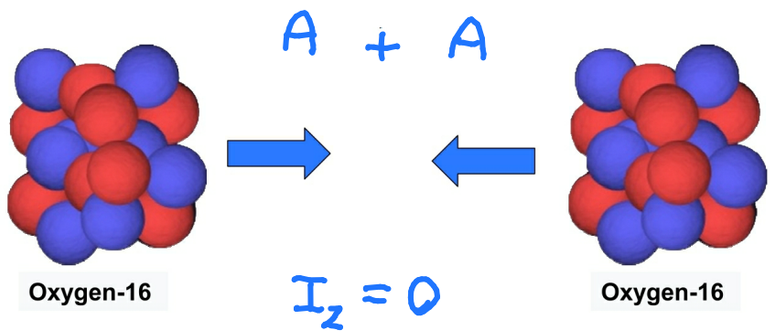
$= n + n \rightarrow \bar{K}^0 + \hat{X}$ (**)

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

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 STATES DOES NOT CHANGE UNDER CHARGE TRANSFORMATION, IT IS CHARGE SYMMETRIC

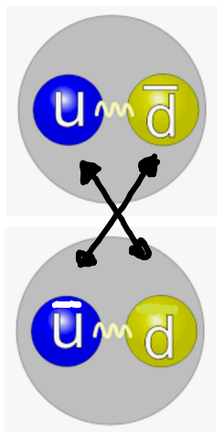
TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

THE SECOND NACI/SHINE FRIENDLY TEST:

CONSIDER COLLISIONS OF $\pi^+ + {}^{12}C$ (50%) AND $\pi^- + C$ (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 $\begin{matrix}\pi^+ \\ \pi^-\end{matrix} + C$ INITIAL STATES DOES NOT CHANGE UNDER CHARGE TRANSFORMATION, IT IS CHARGE SYMMETRIC

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

CHARGE-SYMMETRIC INITIAL ENSEMBLE

BY CONSTRUCTION

→ INTERACTIONS INVARIANT UNDER CHARGE TRANSFORMATION

TESTED ASSUMPTION

→ CHARGE-SYMMETRIC FINAL ENSEMBLE

THE PREDICTION

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

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

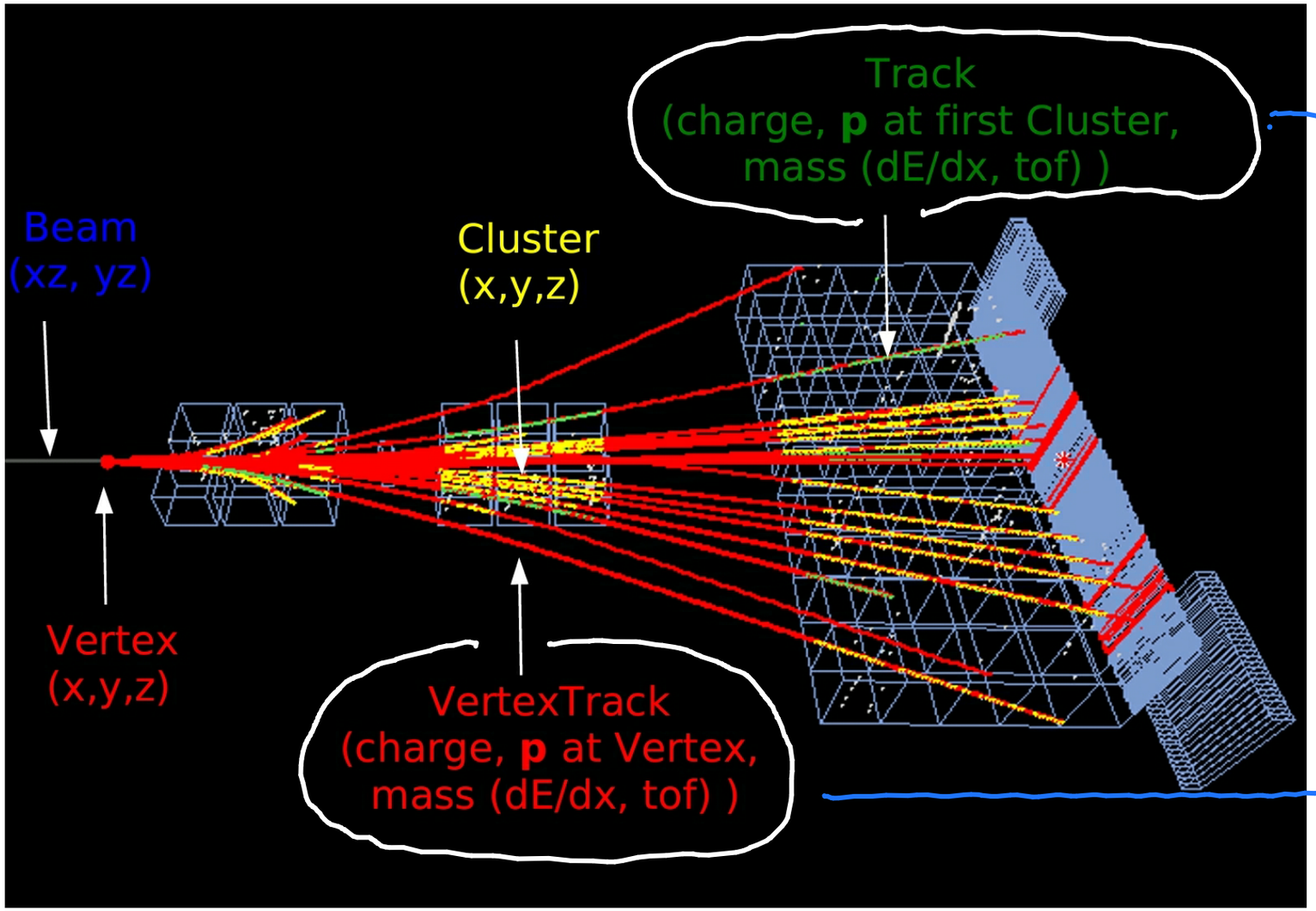
→

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

THE NAGI/SHINE FRIENDLY TEST

MEASURING CHARGED AND NEUTRAL KAONS

NAGI/SHINE AT THE CERN SPS EXAMPLE:

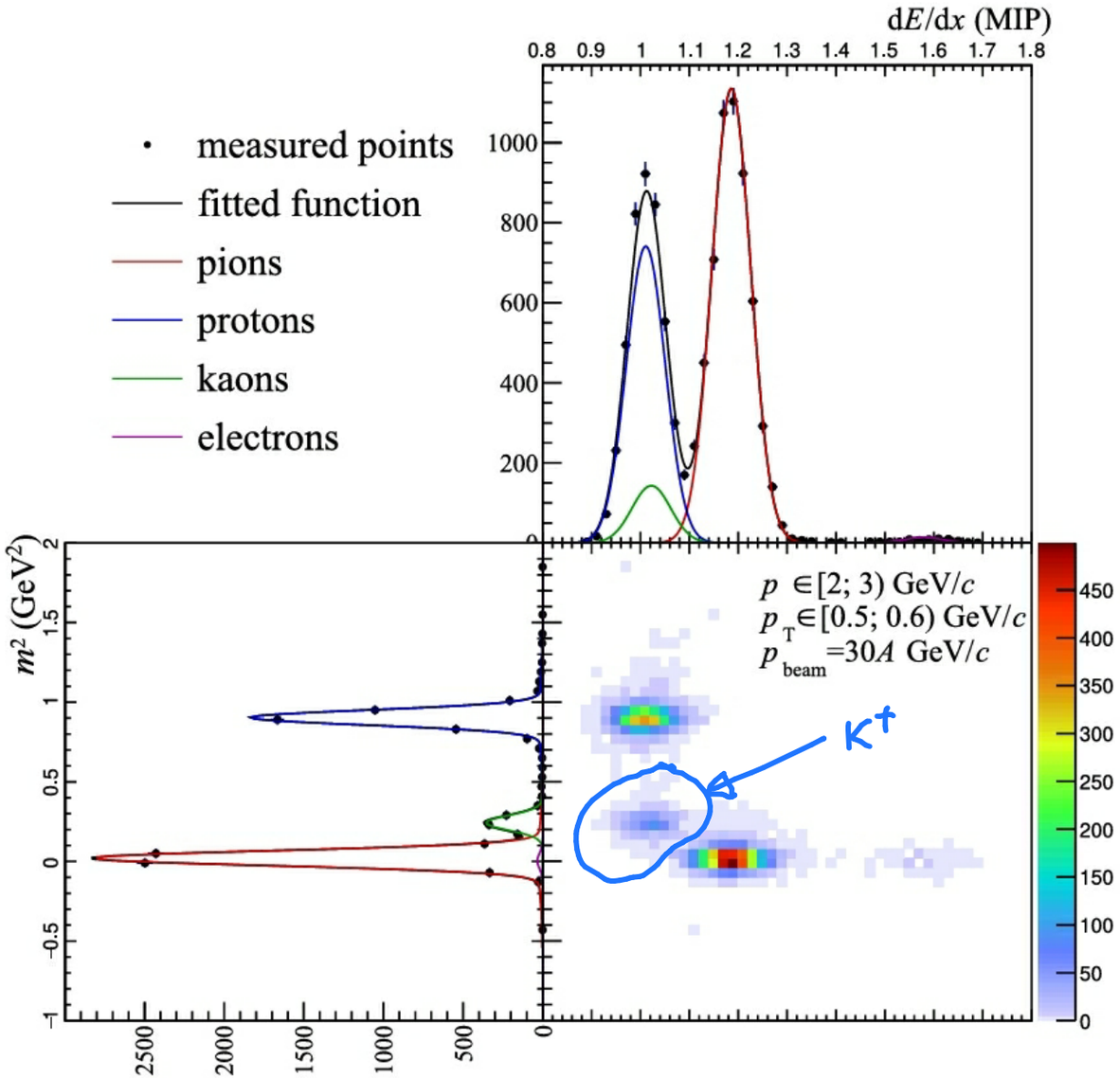


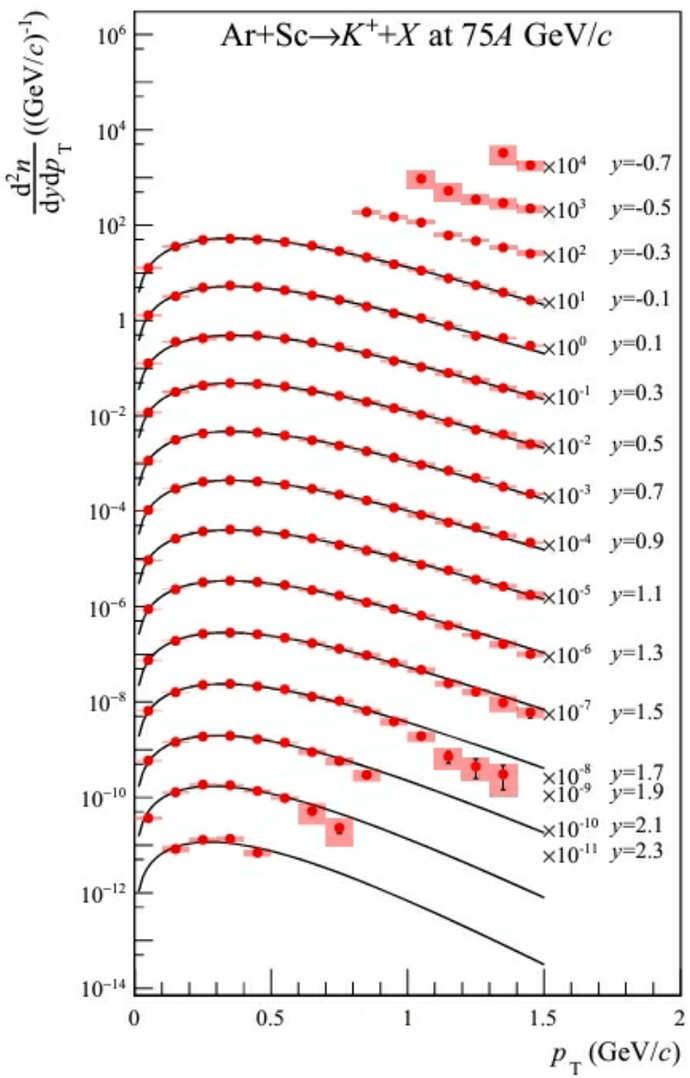
INPUT TO $K^0_S \rightarrow \pi^+ + \pi^-$ ANALYSIS

INPUT TO K^+, K^- ANALYSIS

MEASURING CHARGED AND NEUTRAL KAONS

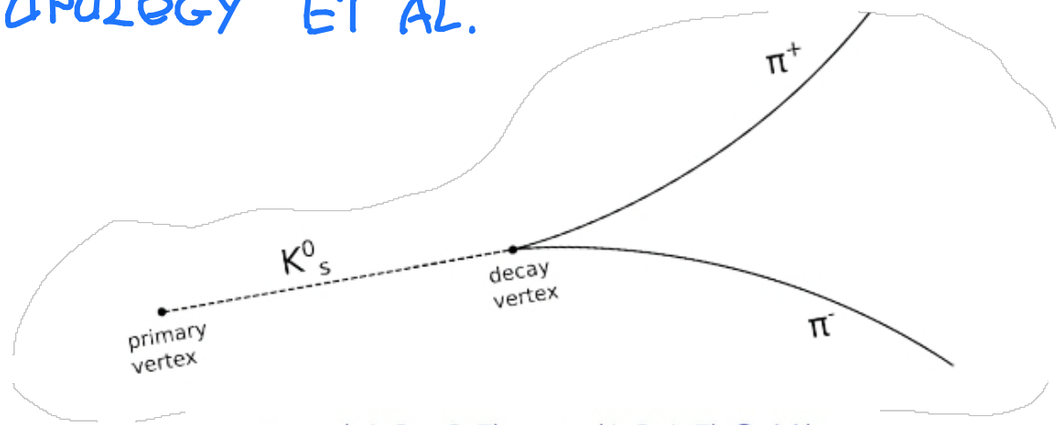
THE MASS MEASUREMENTS · ET AL. → CORRECTIONS → TRANSVERSE MOMENTUM SPECTRA

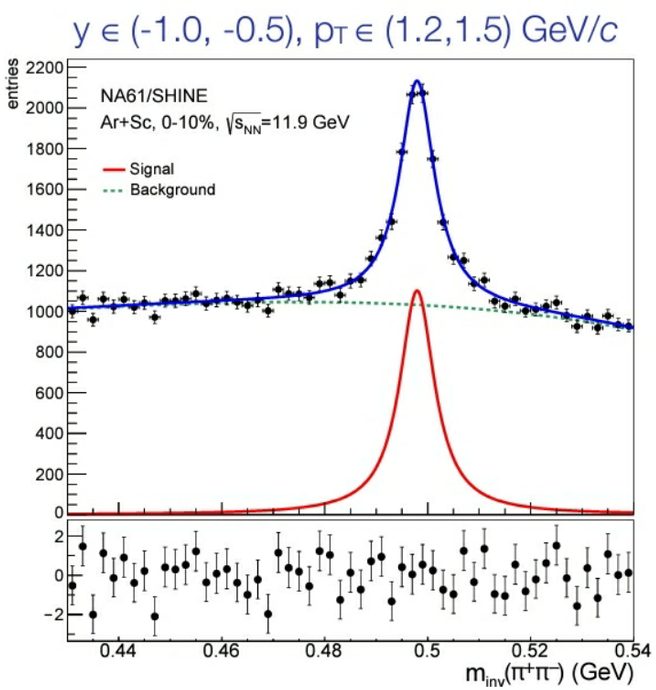


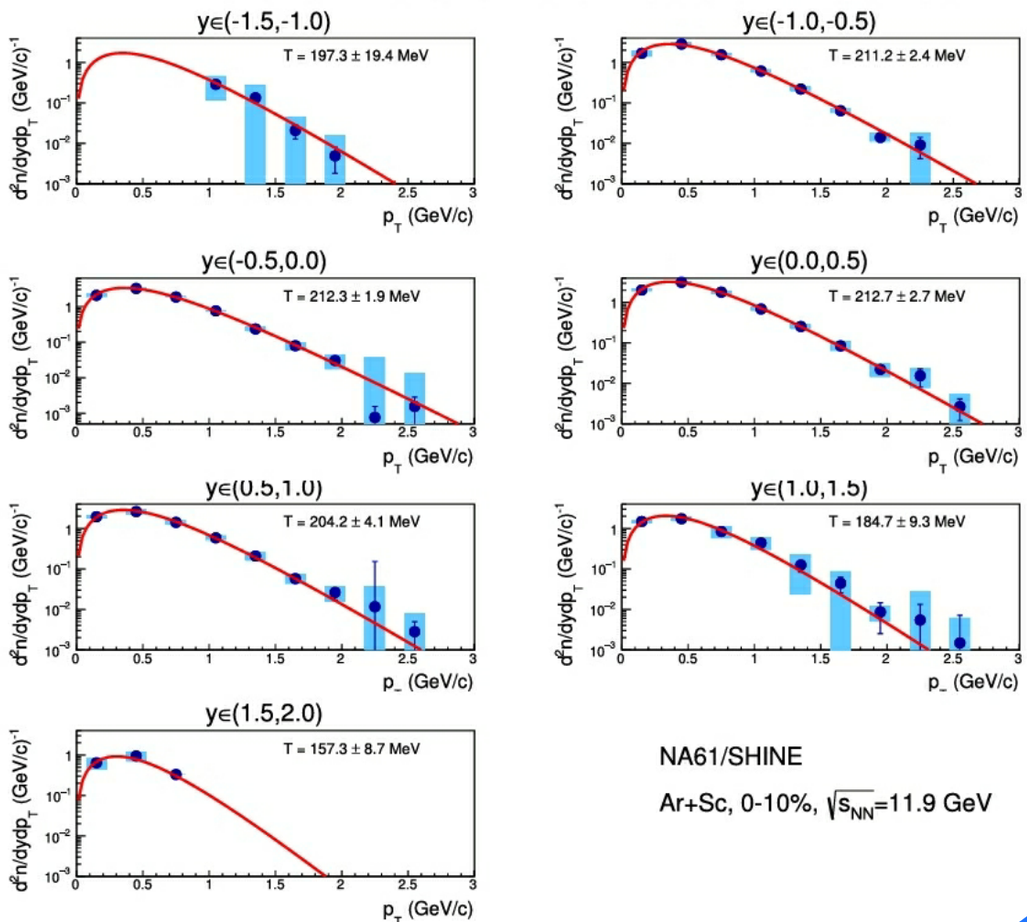


MEASURING CHARGED AND NEUTRAL KAONS

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





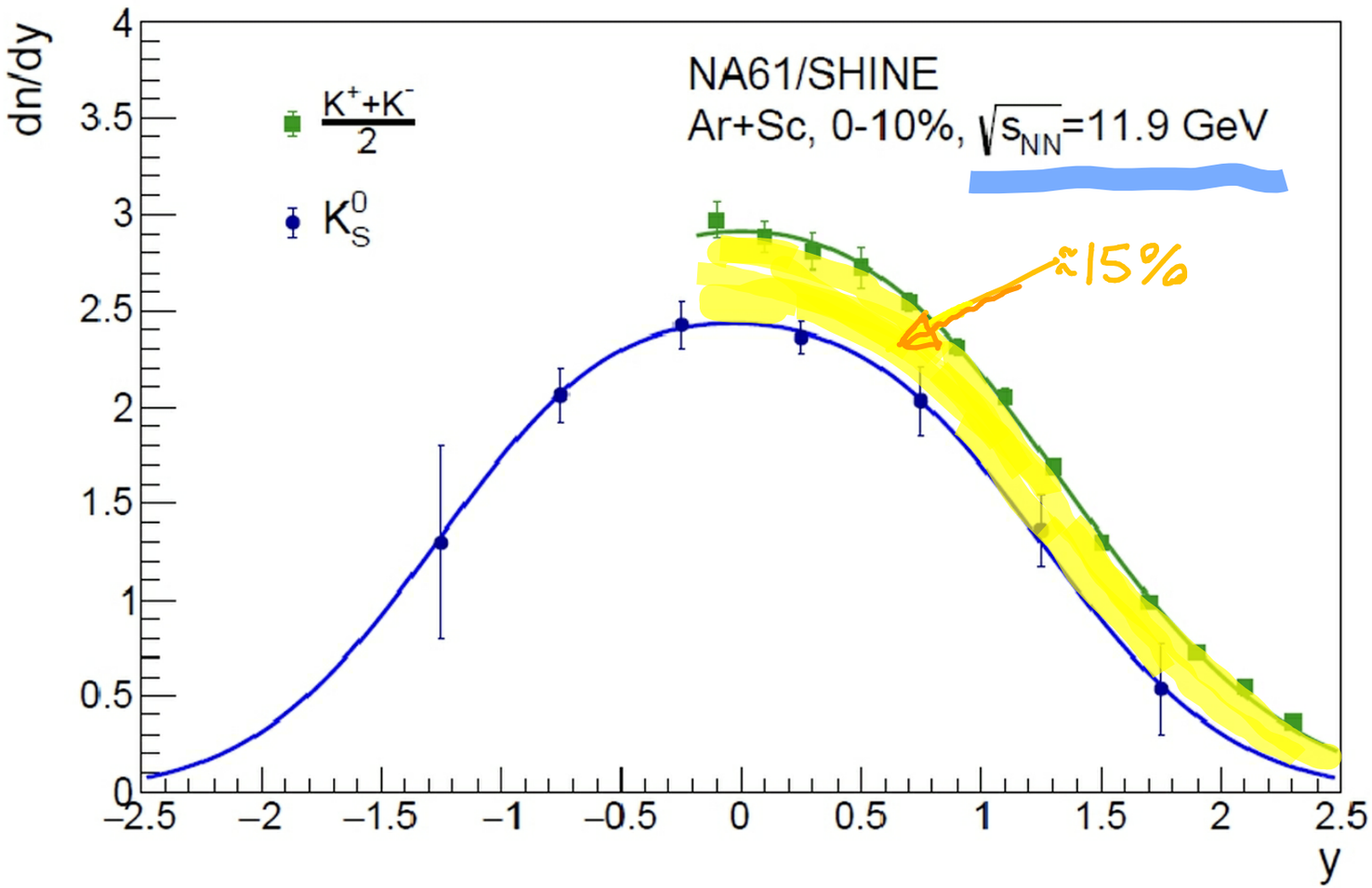


NA61/SHINE

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

MEASURING CHARGED AND NEUTRAL KAONS

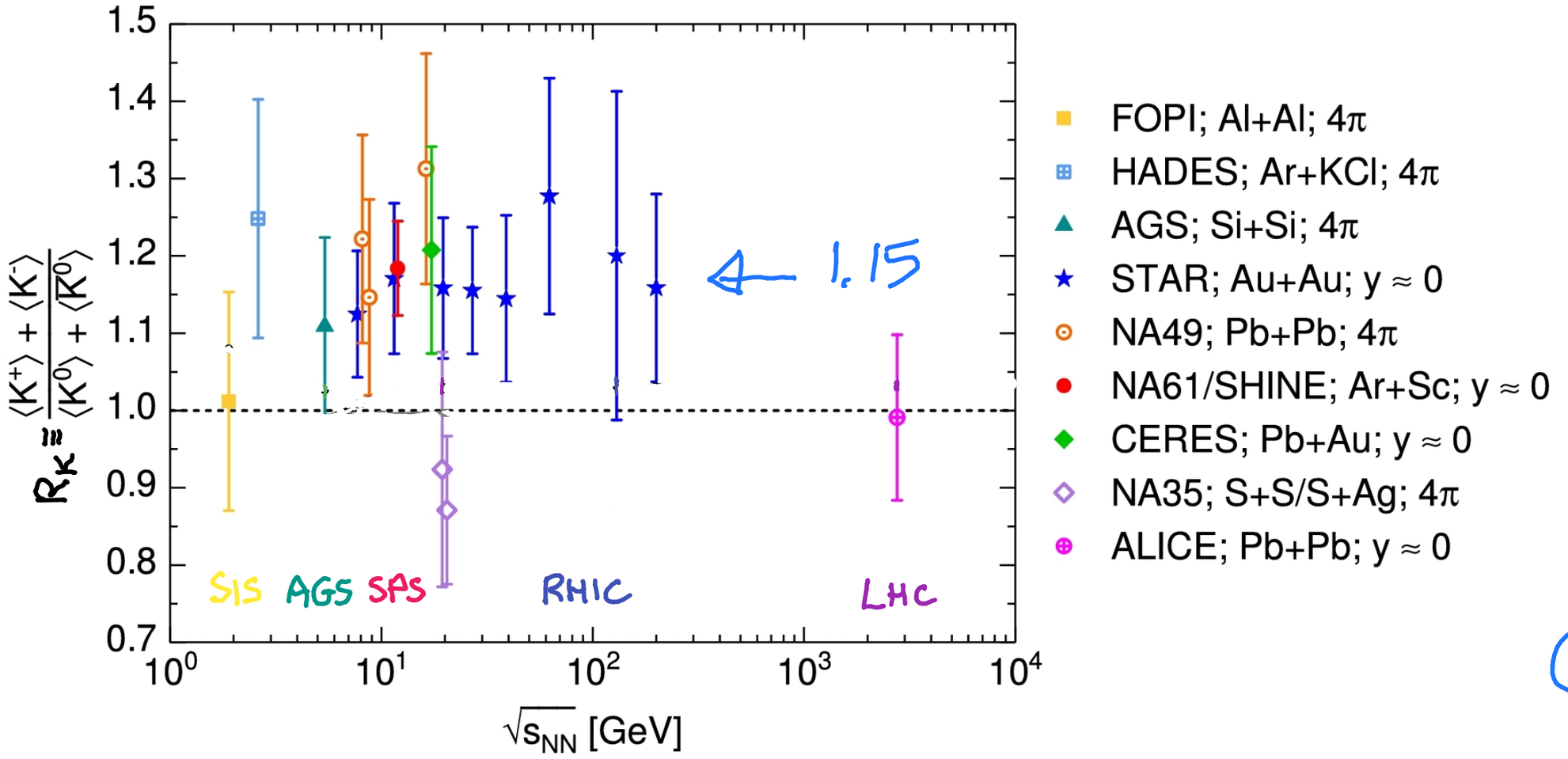
RAPIDITY SPECTRA IN $^{40}_{18}Ar + ^{45}_{21}Sc$



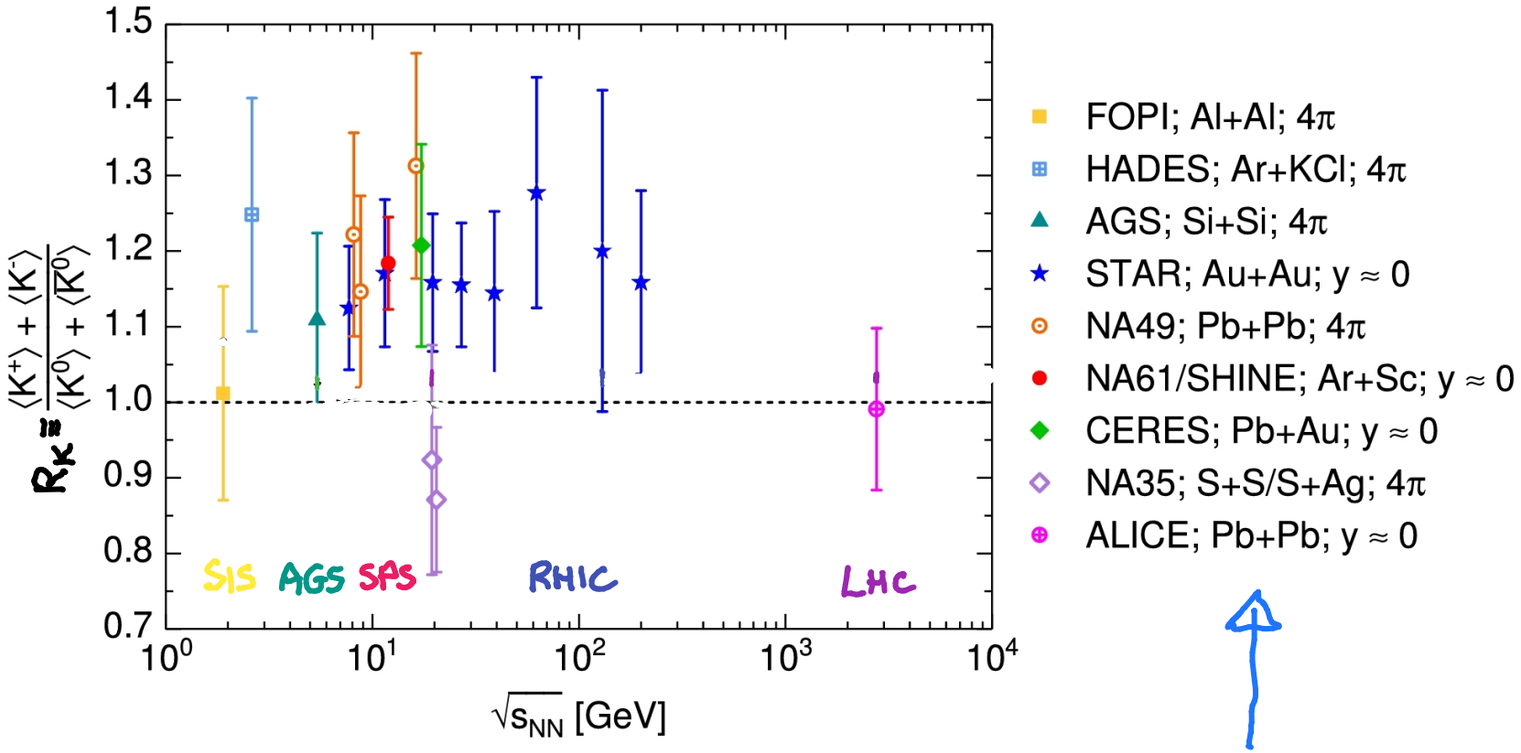
MORE CHARGED THAN NEUTRAL KAONS INSPITE OF HAVING SOMEWHAT MORE NEUTRONS THAN PROTONS IN COLLIDING NUCLEI WHICH FAVOURS NEUTRAL KAONS

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-SYMMETRIC INITIAL ENSEMBLE → INTERACTIONS NOT INVARIANT UNDER CHARGE TRANSFORMATION ← CHARGE-ASYMMETRIC FINAL ENSEMBLE

BY CONSTRUCTION

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

POSSIBLE EFFECTS CONTRIBUTING TO CSB IN KAON PRODUCTION:

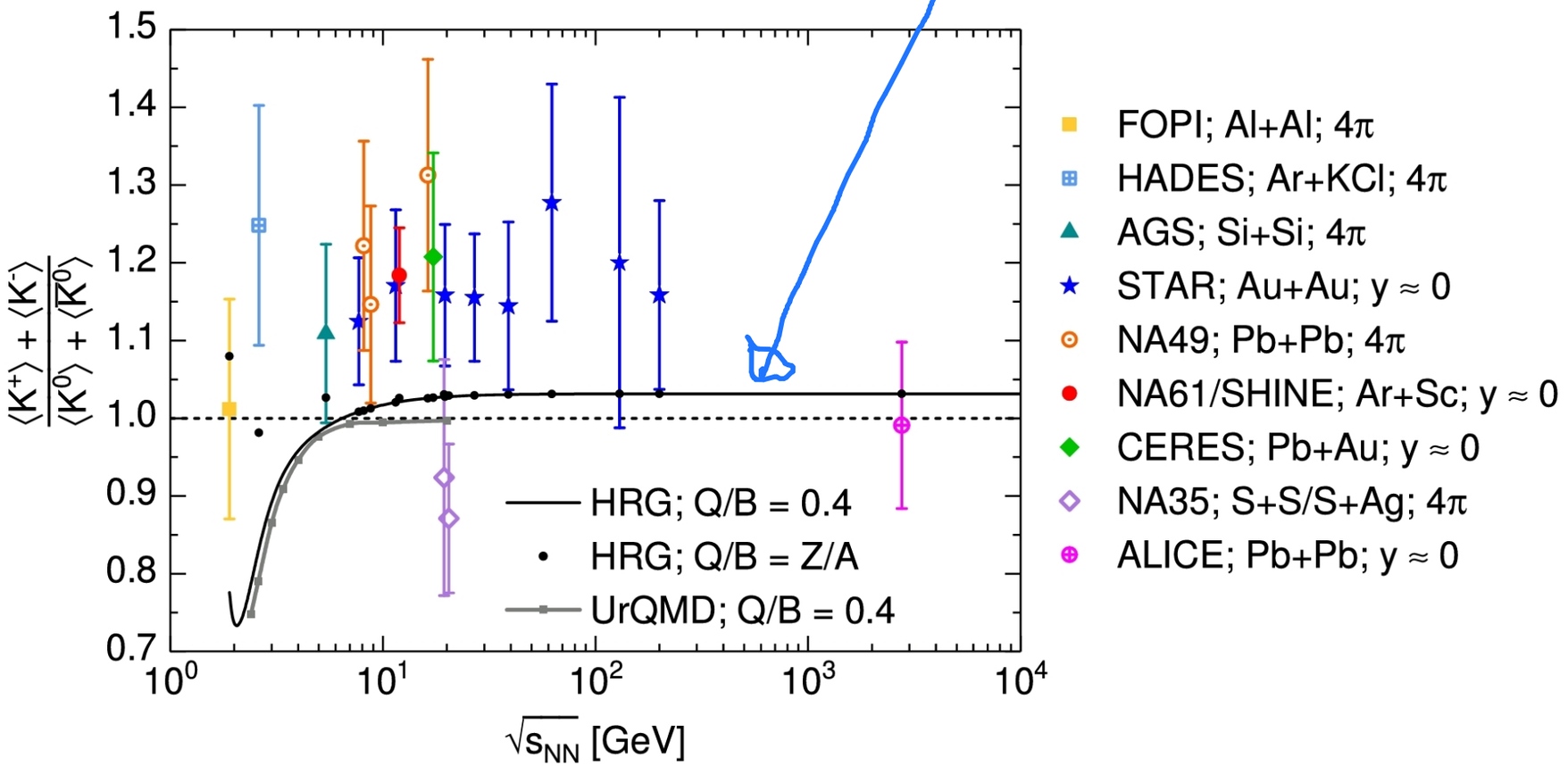
(A) MASS EFFECTS WITHIN STRONG INTERACTIONS

- 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)



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

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% (−)

(C) CHARGE SYMMETRY IS VIOLATED IN CHARM MESON PRODUCTION. DUE TO VERY LOW CHARM YIELD, THIS AFFECTS R_K BY LESS THAN 10^{-3}. (~)

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 ?)

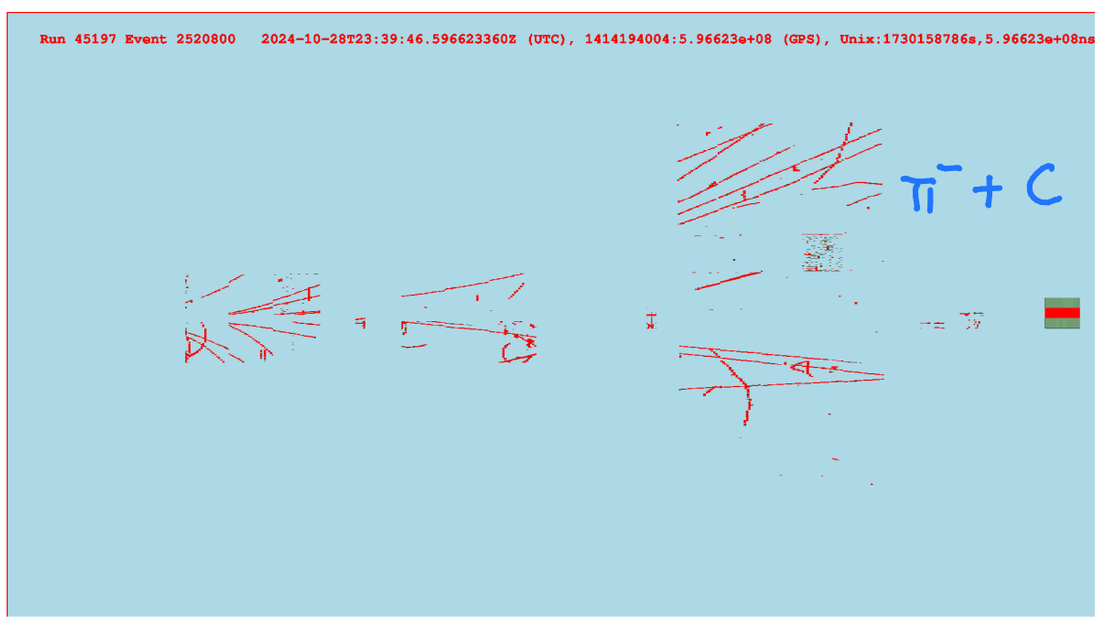
THERE ARE NO QUANTITAVE CALCULATIONS OF THE EFFECT.

(?)

CSB BEYOND KNOWN EFFECTS

(E) IS THE CBS 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

CSB BEYOND KNOWN EFFECTS

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

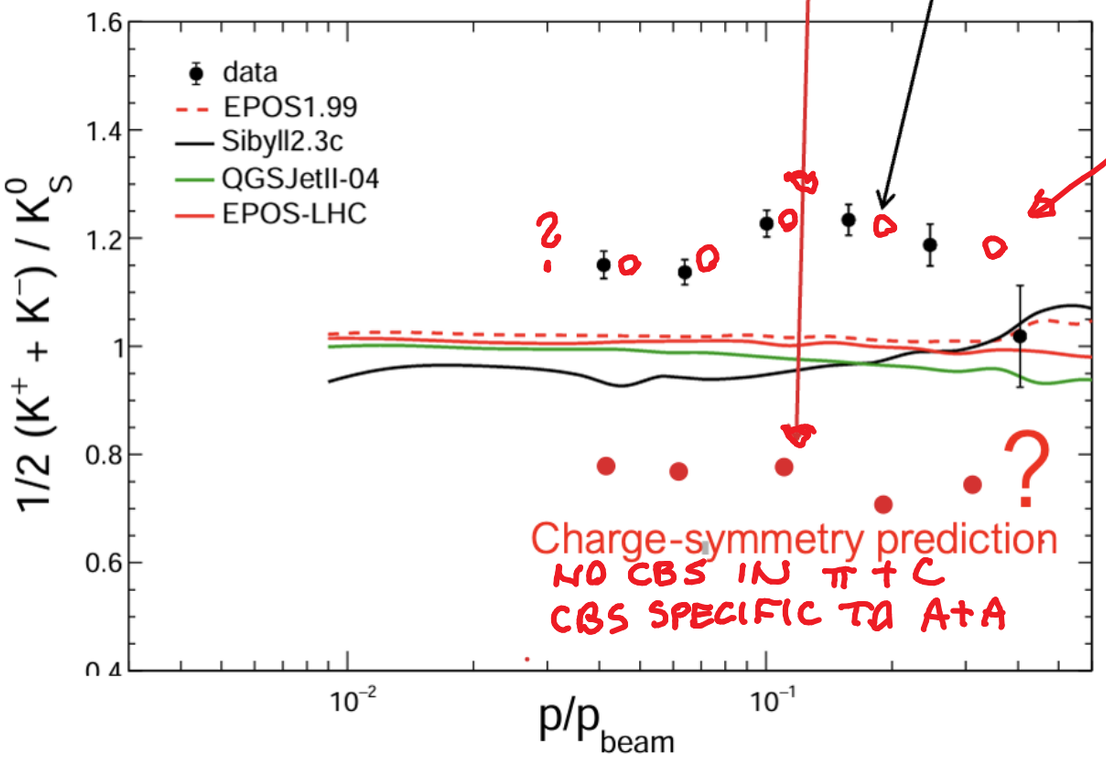
October 25 – 30, 2024:

$\pi^+ + C$

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

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