LARGE CHARGE – SYMMETRY BREAKING IN KAON PRODUCTION AT HIGH ENERGIES

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BASED ON:

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 #1

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e-Print: 2312.07176 [nucl-th]

→ 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

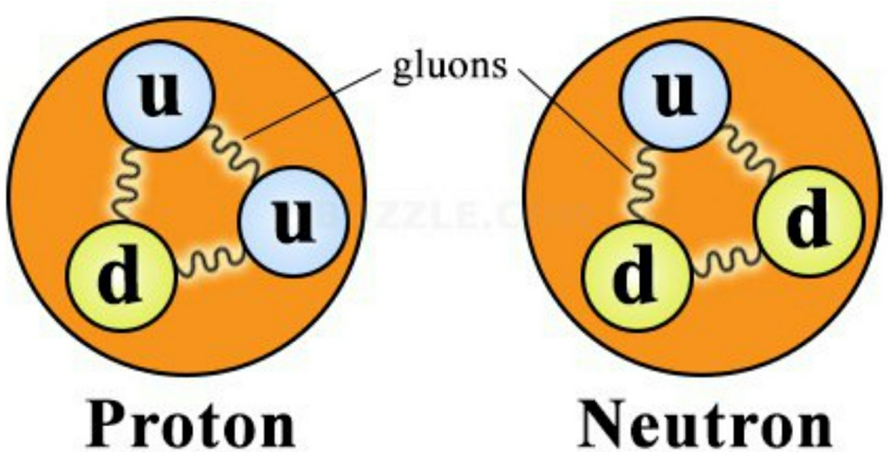
ISOSPIN, CHARGE AND FLAVOUR SYMMETRIES

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: $I_z = -1/2$

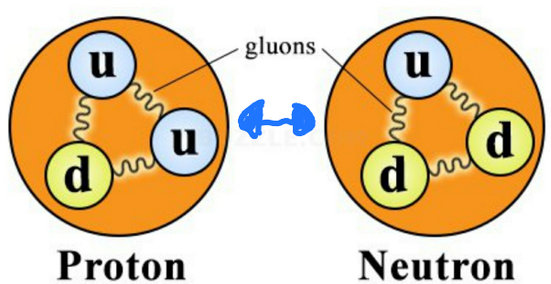
$$\begin{pmatrix} p \\ n \end{pmatrix} \longrightarrow \hat{O} \begin{pmatrix} p \\ n \end{pmatrix},$$

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.

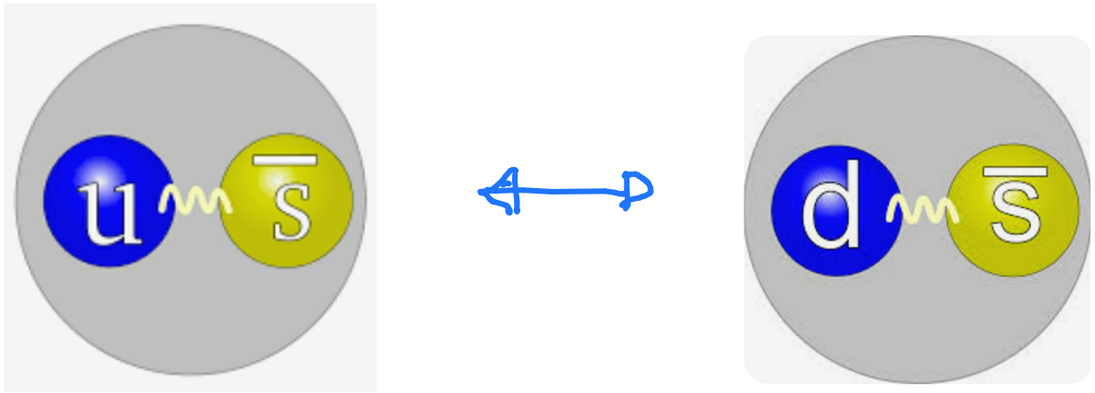
THE LATTER IS A GOOD APPROXIMATION FOR u AND d QUARKS:

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

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

$\hat{C}$:

K^+ $\longleftrightarrow$ K^0



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

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

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

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

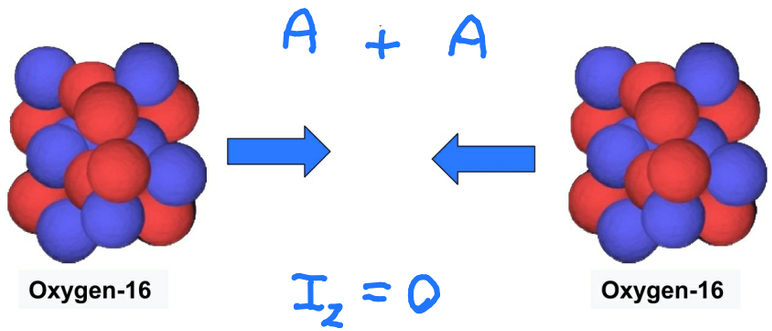
$= n + n \rightarrow \bar{K}^0 + \hat{X}$ (**)

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

TESTING CHARGE SYMMETRY IN PRODUCTION OF CHARGED AND NEUTRAL KAONS

THE EXPEPEREMANTALISTS' FRIENDLY TEST:

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



EASY TO MEASURE

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

CHARGE-SYMMETRIC INITIAL ENSEMBLE

BY CONSTRUCTION

INTERACTIONS INVARIANT UNDER CHARGE TRANSFORMATION

TESTED ASSUMPTION

CHARGE-SYMMETRIC FINAL ENSEMBLE

THE PREDICTION

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

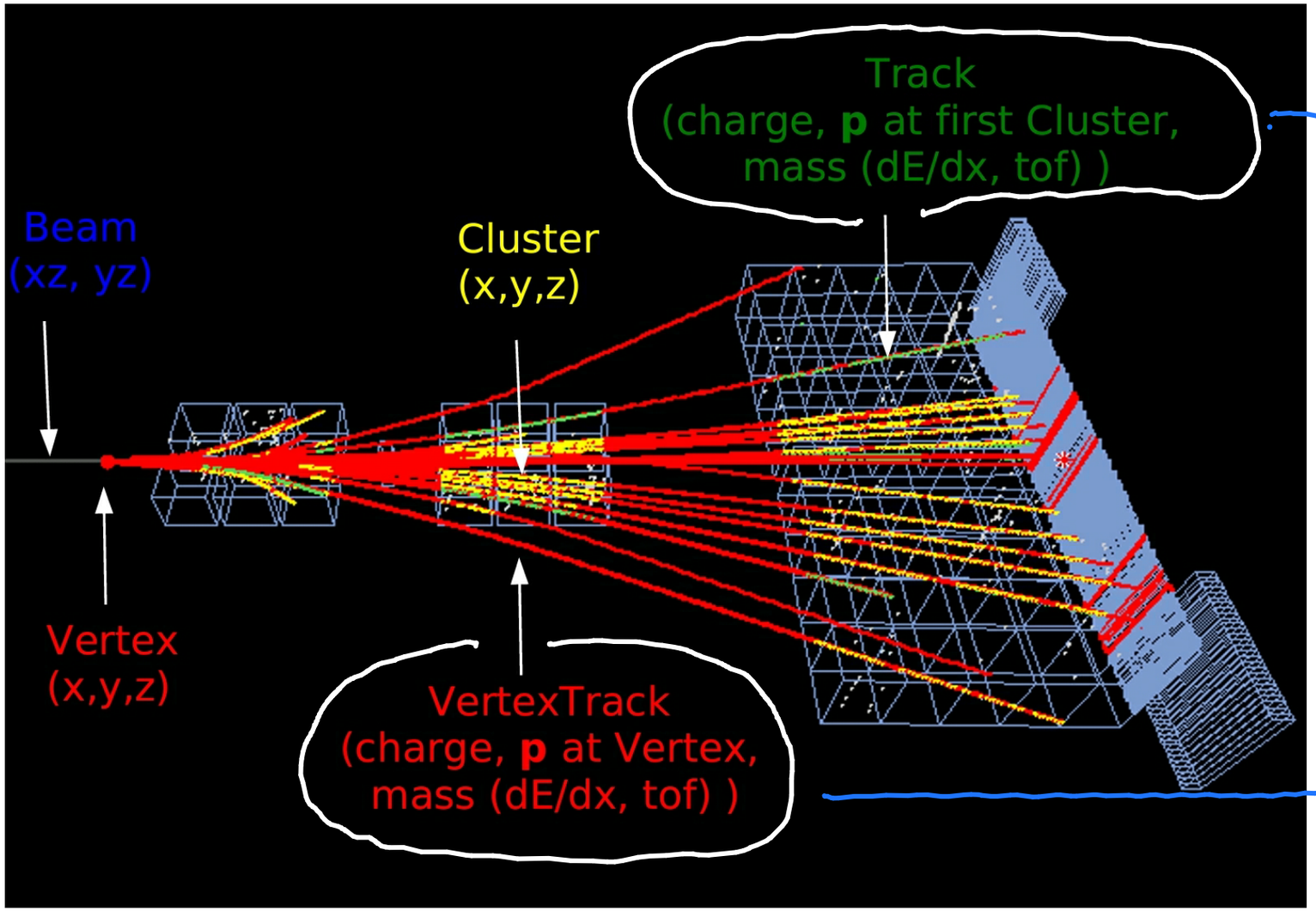
$\langle K^- \rangle = \langle \bar{K}^0 \rangle$

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

THE EXPERIMENTALISTS' FRIENDLY TEST

MEASURING CHARGED AND NEUTRAL KAONS

NAGI/SHINE AT THE CERN SPS EXAMPLE:

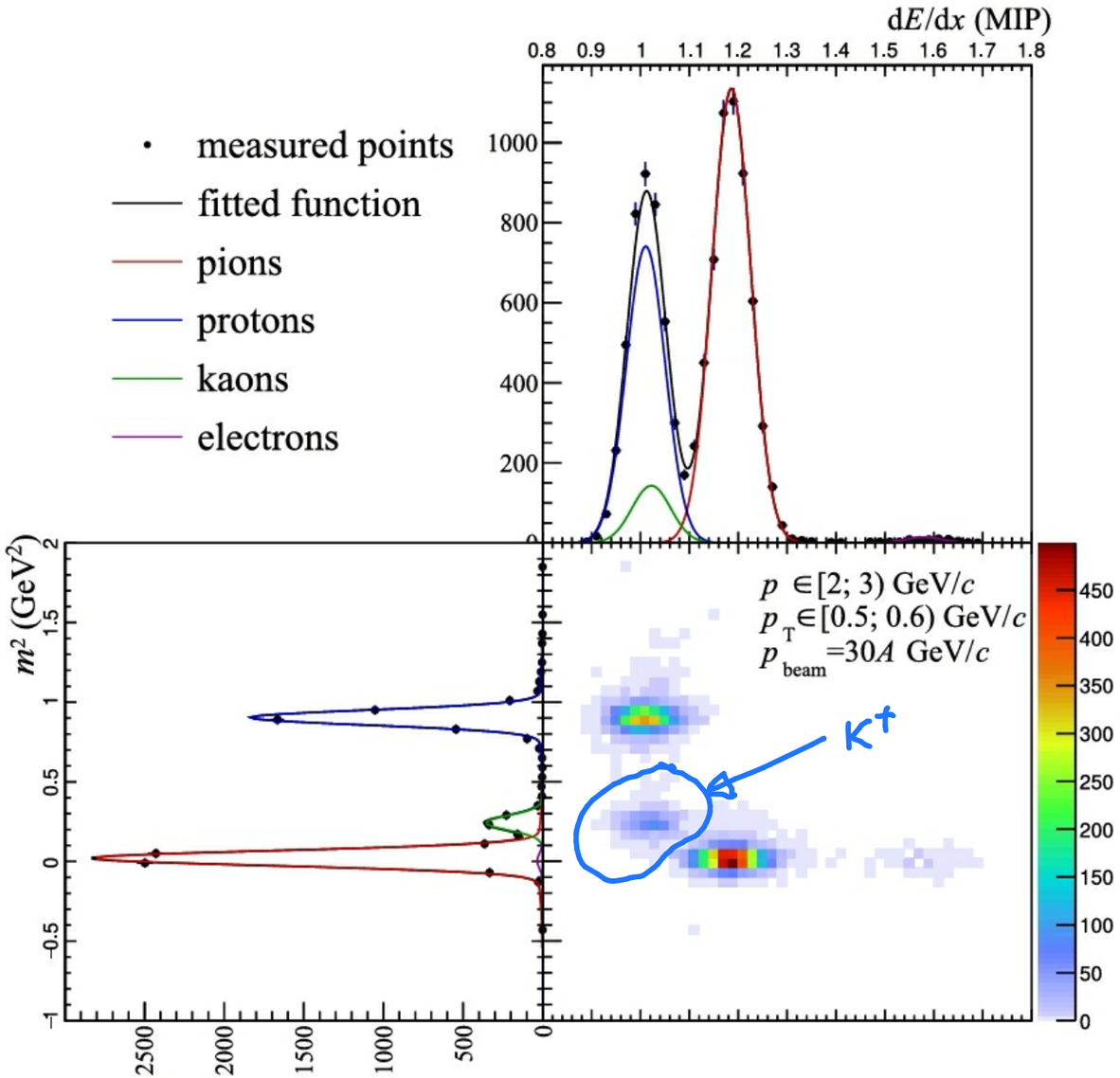


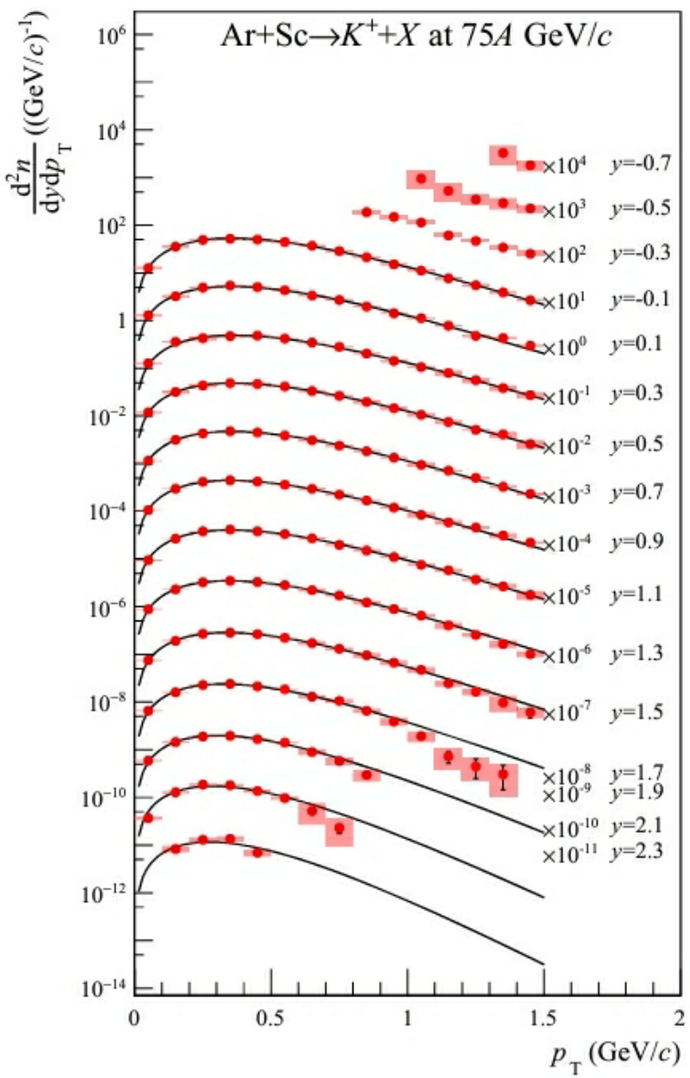
INPUT TO $K^0_S \rightarrow \pi^+ + \pi^-$ ANALYSIS

INPUT TO K^+, K^- ANALYSIS

MEASURING CHARGED AND NEUTRAL KAONS

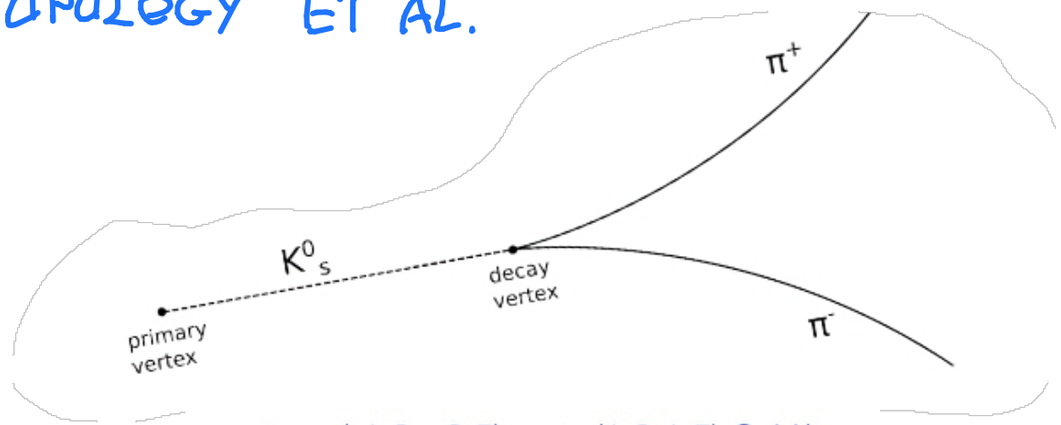
THE MASS MEASUREMENTS · ET AL. → CORRECTIONS → TRANSVERSE MOMENTUM SPECTRA

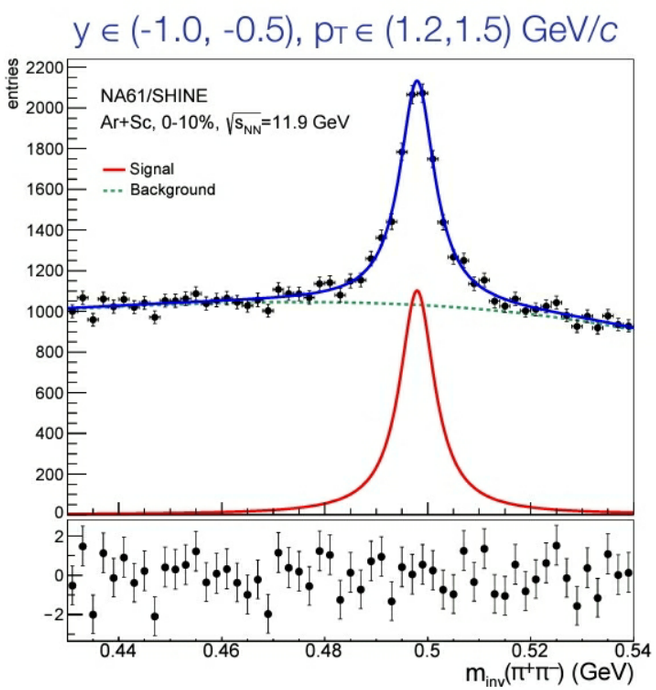


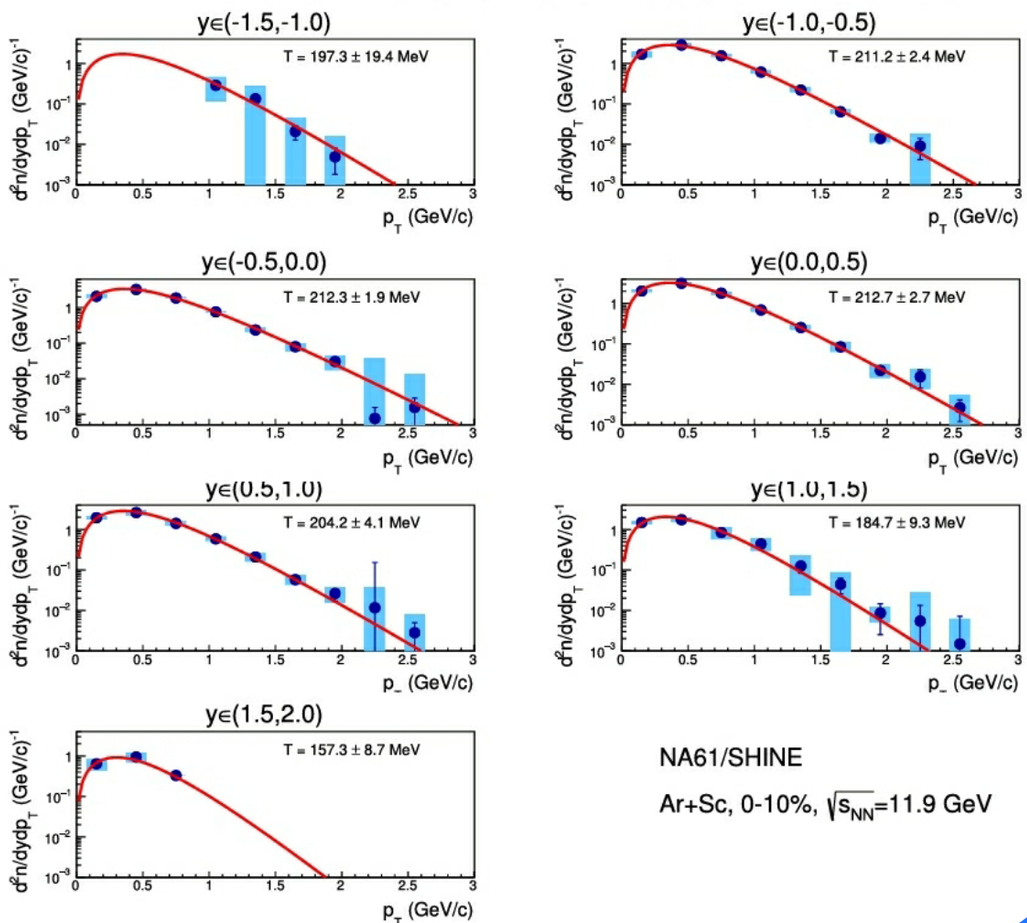


MEASURING CHARGED AND NEUTRAL KAONS

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

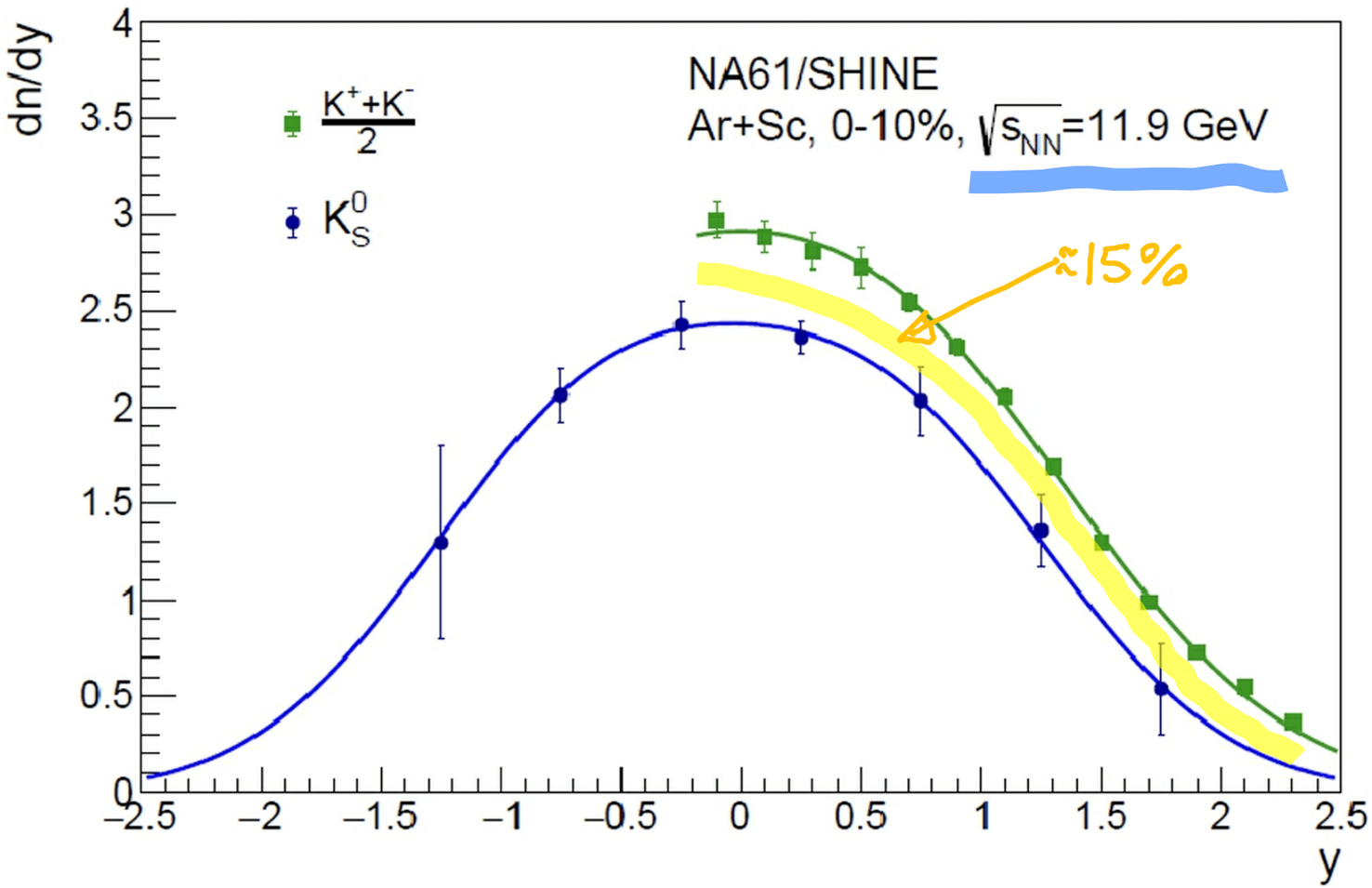






MEASURING CHARGED AND NEUTRAL KAONS

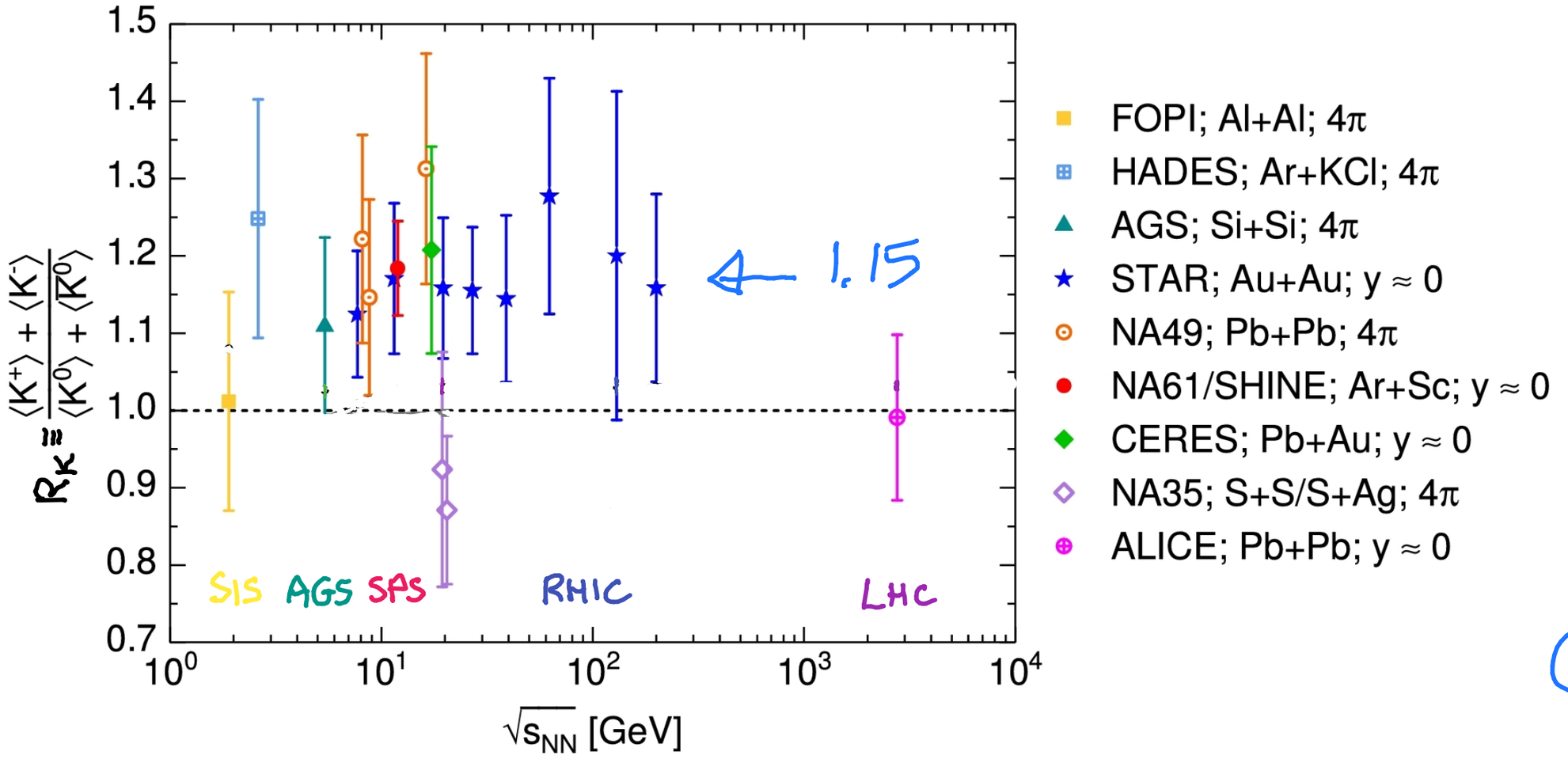
RAPIDITY SPECTRA IN $^{40}_{18}Ar + ^{45}_{21}Sc$



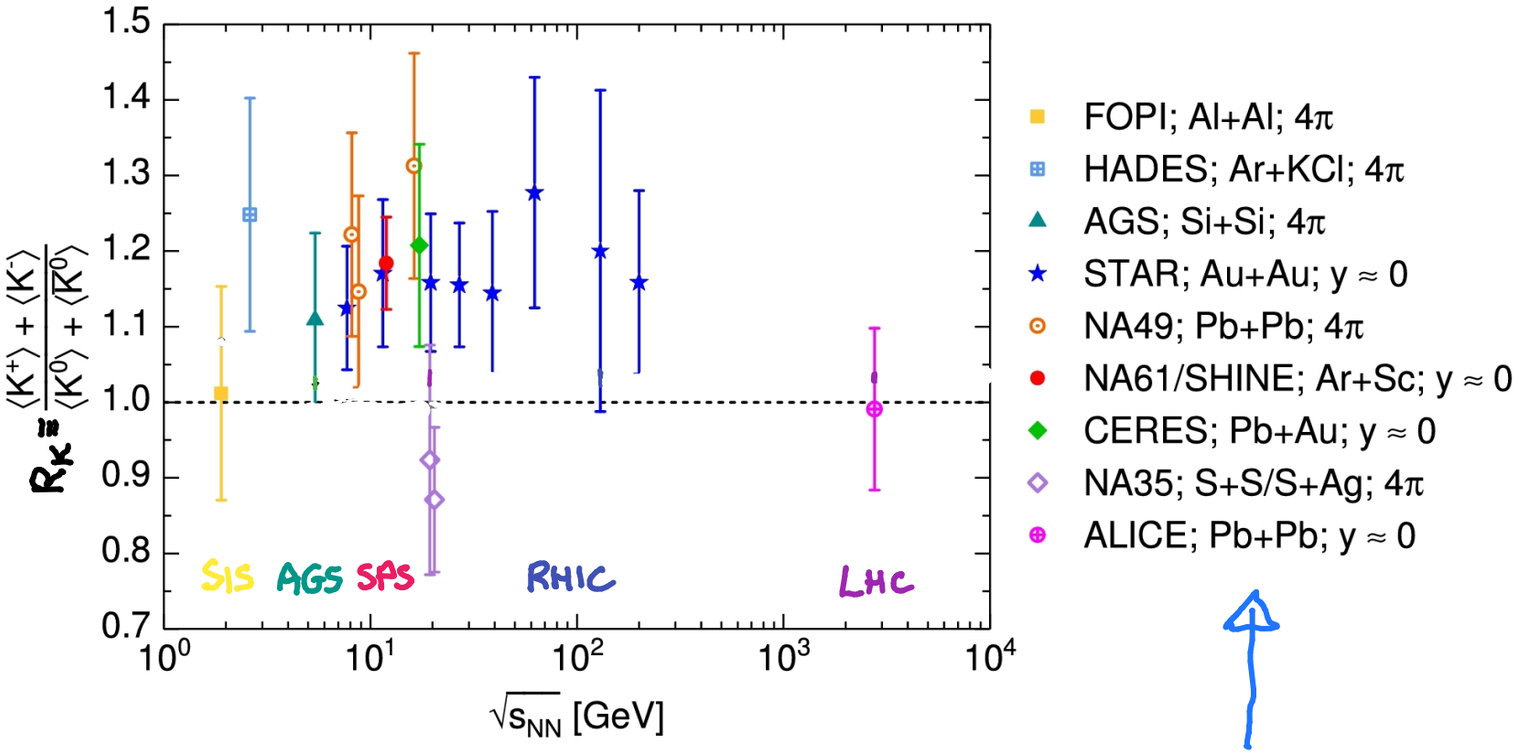
MORE CHARGED THAN NEUTRAL KAONS INSPITE OF HAVING SOMEWHAT MORE NEUTRONS THAN PROTONS IN COLLIDING NUCLEI WHICH FAVOURS NEUTRAL KAONS

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

BY CONSTRUCTION

→ INTERACTIONS NOT INVARIANT UNDER CHARGE TRANSFORMATION

← CHARGE-ASYMMETRIC FINAL ENSEMBLE

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

CHARGE SYMMETRY

EXPERIMENT

→ CHARGE-SYMMETRY BREAKING (CSB)

CSB BEYOND KNOWN EFFECTS

POSSIBLE EFFECTS CONTRIBUTING TO CSB IN KAON PRODUCTION:

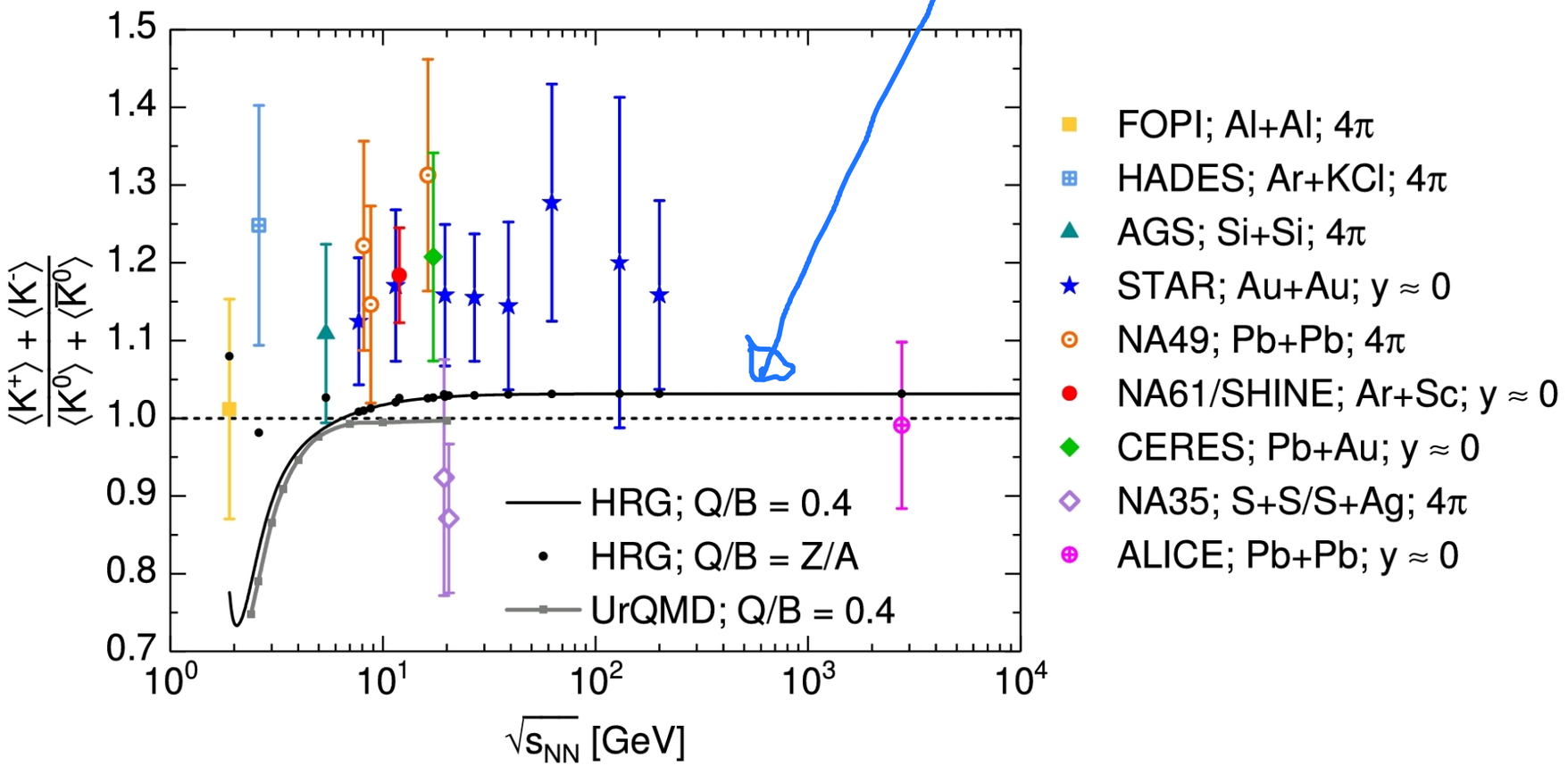
(A) MASS EFFECTS WITHIN STRONG INTERACTIONS

- 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

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

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

(c) 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 $\sim Z_1 Z_2 \alpha^2 \rightsquigarrow Z^2$-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:

- $R_K \approx 1.15$ – THE FIRST EXPERIMENTAL EVIDENCE OF A LARGE CHARGE-SYMMETRY BREAKING IN KAON PRODUCTION

- IT CANNOT BE EXPLAINED BY KNOWN PROCESSES VIOLATING CHARGE SYMMETRY

- DEDICATED STUDIES NEEDED

  EXP: HIGH-PRECISION RESULTS FOR DIFFERENT REACTIONS
  → COLLISION ENERGY- SYSTEM SIZE DEPENDENCE

  TH: QED CORRECTIONS TO QCD $u\bar{u}$ AND $d\bar{d}$ CREATION
  OTHER IDEAS ?