The Kaon Charge Ratio in Accelerator Experiments

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The Kaon Charge Ratio in Accelerator Experiments. ANDREW HOFFMAN (Yale University, New Haven, CT 06520) M. GOODMAN (Argonne National Laboratory, Lemont, IL 60439) P. SCHREINER (Argonne National Laboratory, Lemont, IL 60439)

Charged kaons (K^+ and K^-) are a type of particle that can be produced from various high-energy proton-nucleus interactions due to both cosmic rays and accelerators. Kaons can decay into muons (which are seen by detectors), so the K^+/K^- ratio affects the μ^+/μ^- ratio. A search was conducted for articles relevant to the kaon charge ratio to compare accelerator results to the Main Injector Neutrino Oscillation Search (MINOS) Far Detector (FD) interpretation from cosmic ray muons for the ratio of production rates ($K^+/K^- \approx 2$). Most accelerator experiments that were found used colliding proton beams to produce the kaons, whereas one used a proton beam incident on a carbon target and another the collisions of lead ions. Protons colliding with air would be ideal for studying the atmospheric μ^+/μ^- ratio, but few of these experiments have been done.

The accelerator results are consistent with kaon and pion charge ratios that increase with Feynman $x = \frac{2p_{\parallel,CM}}{\sqrt{s}}$, where $\sqrt{s}$ is the total center of mass energy; it appears that the K^+/K^- ratio is most consistent with MINOS for $x \approx 0.15$–0.20. Several of the experiments used such a value, whereas one used a lower one and others used a range of values. There is a parameterization of the kaon charge ratio vs. $x_R = \frac{2E_{CM}}{\sqrt{s}} \approx x$ that seems rather consistent with the accelerator results.

The muon and kaon charge ratios are important for neutrino physics because decays and interactions of these particles can produce either neutrinos (ν) or antineutrinos ($\overline{\nu}$), depending on the charge of the parent particle. Since it has been shown that the ratios $\nu/\overline{\nu}$ and μ^+/μ^- are closely related in the atmosphere, the muon and kaon charge ratios will be useful for interpreting results from neutrino detectors such as the MINOS FD.

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1 Introduction

Cosmic rays are elementary particles, predominantly protons, which interact in the upper atmosphere. Three of the most common products of these interactions are muons (μ), pions (π), and kaons (K). Interactions producing kaons are interesting to those doing neutrino research because the kaon charge ratio (either of production rates or cross sections) affects the muon charge ratio, which is closely related to the ratio of neutrinos (ν) to antineutrinos ($\overline{\nu}$) in the atmosphere. Such interactions have also been studied in accelerator experiments, in which protons or atomic nuclei are collided together and the products are detected. This paper will summarize and compare the various experiments that have been done to measure the K^+/K^- charge ratio. The π^+/π^- ratio will also sometimes be considered due to its importance to the μ^+/μ^- ratio in order to better compare the accelerator results to cosmic-ray results, which deal primarily with muons.

In accelerator experiments, particles are accelerated towards each other with a known energy. Some experiments focus on low-energy particles, having energy on the order of 1 giga-electron-volt (GeV). Since this paper is concerned with high-energy physics (HEP), experiments looking at energies much below 20 GeV (where geomagnetic effects are important in the atmosphere) are disregarded because they are irrelevant for comparison with the MINOS result.

2 Experiments

Accelerator research on the K^+/K^- ratio has been going on for many years, so results from a large time range will be examined. Papers are presented in chronological order. Energies for experiments with two colliding beams are converted into the energy as they would be if each experiment used a single beam incident on a stationary target. The Feynman scaling variable x (Feynman x) is defined as $\frac{2p^*_\parallel}{\sqrt{s}}$; the radial scaling variable x_R is defined as $\frac{2E^*}{\sqrt{s}}$;

and the rapidity y is defined as $\cosh^{-1}(\frac{E^*}{\sqrt{p_T^2+m^2}})$. Here, * denotes the center of mass frame, the longitudinal momentum $p_\parallel$ is the component of a particle's momentum parallel to its parent particle's momentum, and the transverse momentum p_T is the component that is perpendicular to the parent particle's original momentum.

2.1 ISR 1972

The earliest results found in the search were by M. G. Albrow *et al.* from 1972 [1]. This group used the Intersecting Storage Rings (ISR) at CERN with a single-arm spectrometer to determine several ratios for particles resultant from pp interactions at 550 to 1600 GeV fixed-target equivalent. Feynman x-integrated values of the K^+/π^+ and K^-/π^- ratios and a plot of the π^+/π^- ratio with respect to Feynman x were given in the article. The K^+/π^+ and K^-/π^- ratios were given as 0.13 ± 0.01 and 0.082 ± 0.010, respectively, and the plot is shown in Fig. 1. An approximate average value of the π^+/π^- ratio (1.2 – 1.5) was estimated from the plot and from this the approximate K^+/K^- ratio was calculated ($\frac{K^+}{K^-} = \frac{K^+}{\pi^+} \cdot \frac{\pi^+}{\pi^-} / \frac{K^-}{\pi^-}$). The result was a ratio between 1.9 and 2.2 — this error is due mostly to inaccuracy in approximating the π^+/π^- ratio from the plot.

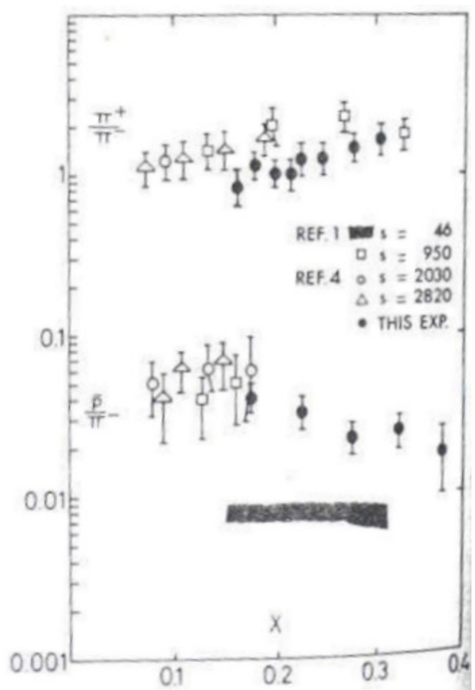


Figure 1: A plot of the pion charge ratio with respect to Feynman x from [1].

Albrow *et al.* updated their paper later in 1972 [2] with more numbers and calculations, including production cross sections (in mb/GeV^2). At a value of Feynman $x = 0.19$ and a range of transverse momentum $0.15 < p_T < 0.95$ GeV/c, the K^+ cross section is given as 1.11 ± 0.05 and the K^- cross section is given as 0.56 ± 0.03, for a K^+/K^- ratio of 1.98 ± 0.14

(errors added in quadrature). Pion cross sections for three values of Feynman x are also given, and the ratios are summarized in Table 1.

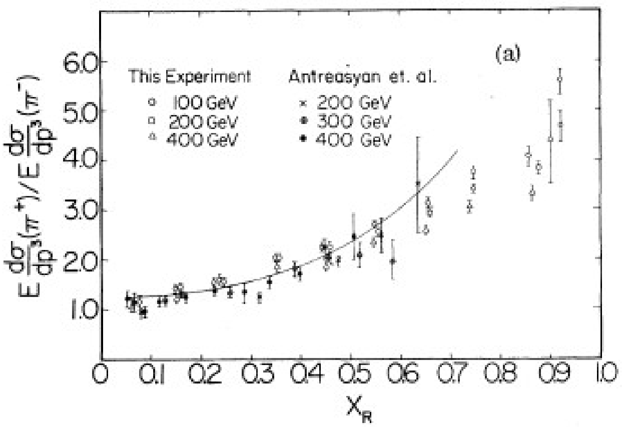
Ratio Type	Feynman x	Ratio Value
K^+/K^-	0.19	1.98 ± 0.14
	0.18	1.64 ± 0.12
π^+/π^-	0.21	1.70 ± 0.16
	0.25	1.84 ± 0.22

Table 1: A summary of the kaon and pion charge ratios with respect to Feynman x in the Albrow *et al.* pp experiment [2] integrated over energies from 21 to 53 GeV.

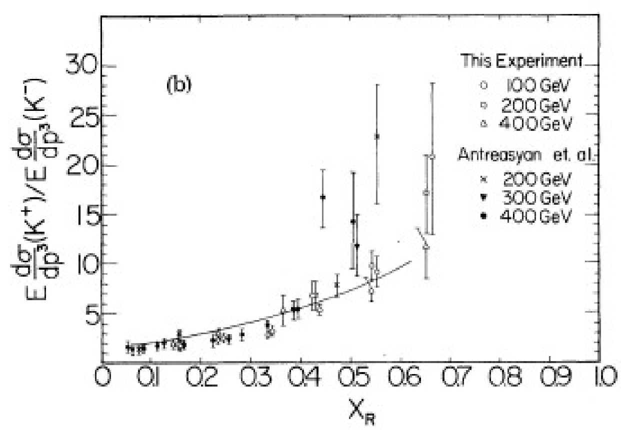
2.2 FNAL-E-0284

In 1977, J. R. Johnson *et al.* wrote an article [3] detailing their pp experiment conducted at Fermilab at energies from 100 to 400 GeV. Their article does not give a single integrated value for the kaon charge ratio but does suggest that the ratio rises, asymptotically to ∞, as the radial scaling variable $x_R = E_{cm}/E_{max}$ tends to 1 (the range of x_R is from 0 to 1).

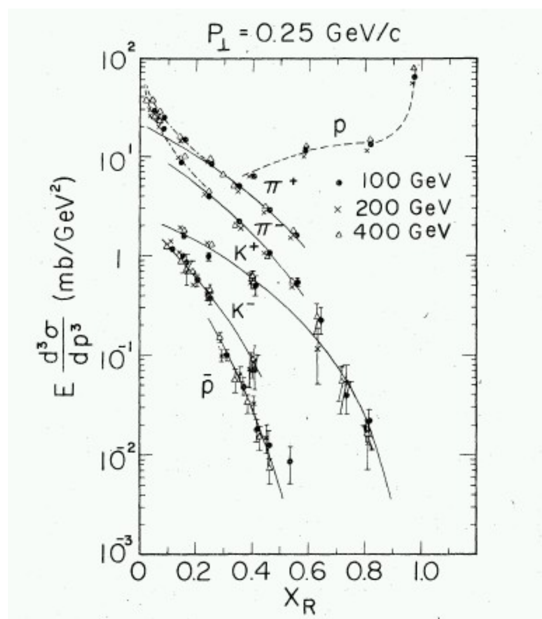
As Albrow *et al.* did, Johnson *et al.* updated their paper with more detailed results in 1978 [4]. Within their paper was a formula in a few parameters that could be integrated over a range of transverse momentum p_T from 0.25 to 1.5 GeV/c to yield the cross section for π^+, π^-, K^+, or K^-. The rises in the charge ratios were still detected, but the cross sections became relatively very small for larger and larger x_R (Fig. 2). Antreasyan *et al.* refers to [9]. Ratios of these cross sections were taken, and the result was a K^+/K^- ratio of 2.5 and a π^+/π^- ratio of 1.75. The errors on these ratio values are not known because systematic errors were not given. It seems likely, however, that the kaon charge ratio of Johnson *et al.* would be fewer than two standard deviations away from the MINOS value of ≈ 2, whereas the pion charge ratio is probably farther than that away.



(a) Pion Charge Ratio

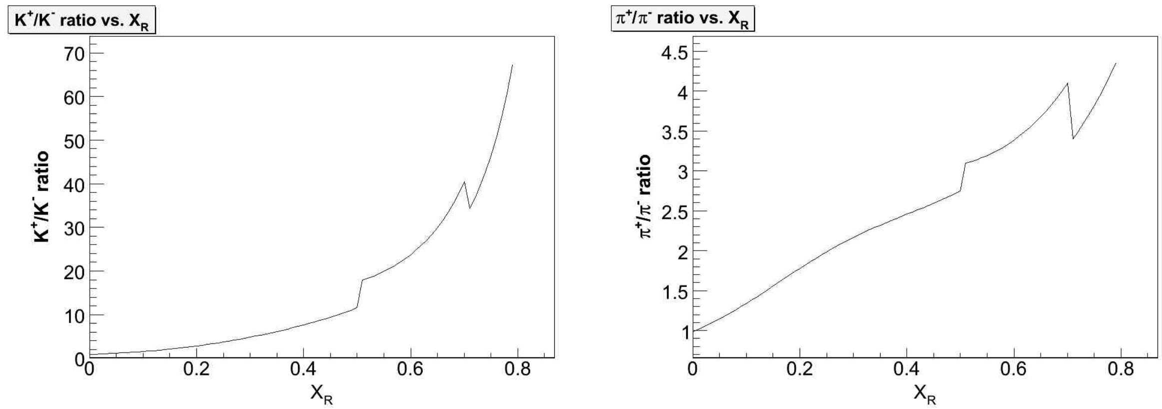


(b) Kaon Charge Ratio



(c) Cross Sections

Figure 2: Plots of the kaon and pion charge ratios and cross sections with respect to x_R, as reported in [3] and [4].



(a) Kaon charge ratio

(b) Pion charge ratio

Figure 3: Kaon and pion charge ratios as a function of x_R in Tan and Ng's [5] parameterization of pp data above 100 GeV.

2.3 Tan-Ng Parameterization

Tan and Ng wrote a 1983 paper [5] detailing a parameterization of kaon and pion cross section values from a collection of pp experiments running at at least 100 GeV (including [1-4], Sections 2.1 and 2.2). They used a 13-parameter fit to the cross sections as a function of the radial scaling variable x_R, which predicted a kaon charge ratio value going from about 0.8 to almost 70 and a pion charge ratio value going from about 1 to about 4.4 over a range of x_R from 0 to 0.8 (see Fig. 3). The "jumps" in each plot at $x_R = 0.5$ and 0.7 come directly from the parameterization formula, which uses a step-function multiplier in one term.

The cross sections, however, went down very steeply (by a factor on the order of 100) through this range of x_R. An integrated average value based on the parameterization gives a π^+/π^- ratio of 1.5 and a K^+/K^- ratio of 3.7. The errors on these values are unknown, so it is difficult to compare these to the MINOS value. It is clear from Fig. 3 that the parameterization would give lower average values (thus closer to the MINOS values) for the charge ratios if the integration were performed only on a lower range of x_R — it is not known which values of x_R dominate the cosmic-ray kaon and pion charge ratios, however, so it is at this point impossible to find the optimal range or weighting function. This could be a subject for future study using Monte Carlo.

2.4 NA49

In 1997, the NA49 collaboration published a paper [6] detailing its experiment at the Super Proton Synchrotron (SPS) at CERN. A beam of lead ions was accelerated at a fixed lead target (Pb + Pb) at 158 GeV per nucleon. Note that the units of GeV per nucleon are chosen for ease of comparison to experiments that use proton beams. Kaon momenta are measured using time projection chambers (TPC) and time of flight detectors (TOF). TPCs measure the momentum of charged kaons by passing the particles through a magnetic field and measuring their energy loss. TOFs measure the time the particle takes to cross a given distance and convert this value into a momentum. The paper gives a K^+/K^- charge ratio of ≈ 1.8 at mid-rapidity ($y = 2.9$, the peak of total kaon flux, corresponding to $x_R = 0.61$); the TPCs and TOFs are in agreement on this value within the errors. Systematic error is cited at $\approx$ 20%, which puts the value of 1.8 well within a standard deviation of the MINOS value of ≈ 2. The collaboration notes that its Pb + Pb experiment yielded a higher K/π ratio (≈ 0.13) than did pp experiments (≈ 0.08), and this fact must be taken into consideration when comparing the NA49 experiment to pp experiments. This difference is probably due at least in part to the fact that lead contains more neutrons than protons, whereas pp experiments do not use neutrons at all; the difference between the proton-proton cross sections and the proton-neutron cross sections could account for much of this discrepancy.

2.5 RHIC

The Ph.D. thesis of C. Mironov [7] presents several experiments measuring kaon and pion production — this paper will focus on a pp experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory at the fixed-target equivalent energy of 21.3 teraelectron-volts (TeV). This experiment was performed at rapidity $|y| < 0.5$, corresponding to $x_R < 0.013$ for kaons. The charge ratio quoted in the paper is $\mathrm{K}^-/\mathrm{K}^+ = 0.926 \pm 0.015$, corresponding to $\mathrm{K}^+/\mathrm{K}^- = 1.08 \pm 0.02$. This value is, of course, many standard deviations lower than the MINOS value of ≈ 2. As suggested by Tan and Ng [5], the near-unity charge ratio value may be due to the experiment's very low value of x_R; the Tan-Ng parameterization gives a ratio of 0.91 for $x_R = 0.013$, which does not exactly match the Mironov result, but does come close.

2.6 MIPP

The Main Injector Particle Production experiment (MIPP) has begun to take measurements of the particles resulting from a 120 GeV proton beam incident on a fixed carbon target (p + C). A recent Ph.D. thesis [8] from MIPP has presented some preliminary results on the kaon and pion charge ratios. The transverse momentum p_T does appear to have an impact on the charge ratio at large values (> 0.5 GeV), but in order to find an integrated value a Monte Carlo would probably be needed. Thus, in this paper, average charge ratios will be taken over the range of $p_T \leq 0.5$ GeV, using a simple arithmetic mean and adding the errors in inverse quadrature. Table 2 shows the kaon and pion ratios as a function of longitudinal momentum p_z for $p_T < 0.5$ GeV, as well as approximate values of Feynman x calculated with the formula $x \approx E_{lab}/E_{beam} \approx p_{lab}/E_{beam}$ and the charge ratios predicted by the Tan-Ng parameterization [5] using the approximation $x \approx x_R$ for each value of x at $p_T = 0.25$ GeV. One MIPP point was excluded from the calculation for kaons (highest bin of p_z, lowest bin of p_T) because it had no average value given.

MIPP's preliminary values of the kaon charge ratio tend to rise with p_z and x. The MINOS value of ≈ 2 is within one standard deviation of the MIPP value for only the lowest value of x and within two almost up to $x = 0.23$, after which the ratio becomes much larger than 2. The pion charge ratios are also consistently (and more significantly) larger than the MINOS value of 1.25. Fig. 4 compares the MIPP $\mathrm{K}^+/\mathrm{K}^-$ values to those predicted by Tan

p_z (GeV/c)	Approx. x	K^+/K^-	Predicted K^+/K^-	π^+/π^-	Predicted π^+/π^-
21.9	0.18	$2.13^{+0.17}_{-0.20}$	2.34	$1.53^{+0.05}_{-0.04}$	1.64
27.2	0.23	$2.49^{+0.22}_{-0.24}$	3.08	$1.74^{+0.05}_{-0.05}$	1.85
35.6	0.30	$3.45^{+0.41}_{-0.46}$	4.40	$1.97^{+0.07}_{-0.07}$	2.10
48.9	0.41	$5.95^{+1.00}_{-0.96}$	7.24	$2.24^{+0.11}_{-0.11}$	2.42
69.0	0.58	$19.6^{+6.83}_{-6.50}$	20.6	$2.41^{+0.21}_{-0.18}$	3.26

Table 2: Kaon and pion charge ratios in MIPP (p + C) as a function of longitudinal momentum p_z for transverse momentum $p_t < 0.5$ GeV, with approximate values of x and predicted kaon ratios from Tan and Ng [5].

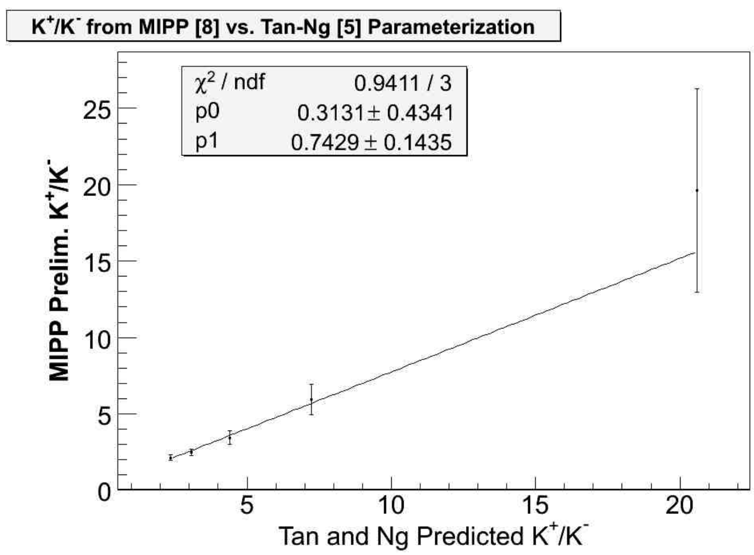


Figure 4: A comparison of the MIPP [8] Preliminary kaon charge ratio with the Tan-Ng parameterization's [5] predicted values for values of x in the range 0.18 – 0.58.

and Ng's parameterization [5].

There does appear to be a significant correlation between the two sets of values, although the MIPP values tend to be lower than the corresponding Tan-Ng values, as is also the case for the pion charge ratio.

3 Summary and Discussion

Table 3 summarizes the results of the above experiments. The MINOS result was intrinsically

Author	Energy (GeV)	x (or x_R)	K^+/K^- Ratio	Year	Collision Type
ISR 1972 [1]	550 – 1600	0.19	1.9 – 2.2	1972	p + p
ISR 1972 [2]	1500	0.19	1.98	1972	p + p
FNAL-E-0284 [3]	200	0-0.7	≥ 2	1977	p + p
FNAL-E-0284 [4]	200	0-0.7	2.5	1978	p + p
Tan and Ng [5]	≥ 100	0-0.8	0.8 – 70	1983	p + p
NA49 [6]	158	0.61	1.8	1997	Pb + Pb
RHIC [7]	21300	0-0.013	1.08	2005	p + p
MIPP (Prelim.) [8]	120	0.18-0.58	2.13 – 19.6	2007	p + C

Table 3: A summary of the experiments listed in Section 2. Energy refers to the (equivalent) lab energy of the beam or beams.

integrated over all values of x_R (or x), so it may be useful to determine which value of x_R gives a value of the kaon charge ratio closest to that observed from cosmic ray events. There may be a different optimal value for pions, as suggested by the fact that the experiments seen above which give values of the kaon charge ratio that are consistent with MINOS tend to give pion charge ratios that are not consistent with MINOS. As seen in Sections 2.2, 2.3, and 2.6, the kaon and pion charge ratios tend to rise with increasing x_R, so an accelerator experiment that uses a value of x_R that is higher than the MINOS average would probably give a charge ratio value which is higher than the MINOS value. For example, MIPP's preliminary results suggest that the MINOS average value of x weighted for the kaon charge ratio may be slightly lower than 0.18 because MIPP's preliminary value of the charge ratio at that value of x is slightly higher than the MINOS value of ≈ 2. If $x_R = 0.15$ is inputted into the Tan-Ng parameterization, a kaon charge ratio of 2.03 is the output, which suggests that the MINOS average x may be around 0.15. In contrast, the Tan-Ng parameterization [5] gives the MINOS value of 1.25 for the pion charge ratio when $x_R = 0.085$; this difference between the values for each particle may be because pions and kaons probably have different x distributions.

The 1972 results from the ISR [1,2] from Section 2.1 are those found in the search that are in the best agreement with the MINOS result of $K^+/K^- \approx 2$. The reader will recall that this experiment used a value of Feynman x of 0.19, which corresponds to an x_R of very close to 0.19 because of the very low value of p_T used in the experiment.

NA49 is not in agreement with the Tan-Ng parameterization (ratio is low for the high value of x_R), and this may be due to the fact that Tan and Ng only considered pp experiments when making their parameterization. A beam of lead may have different particle production distributions from a beam of protons because of lead's large number of component nucleons and also because of possible contributions from neutrons, which comprise more than half of lead's nucleons.

Based on the experiments from Section 2, it appears that the kaon and pion charge ratios are strongly correlated with x (and x_R). Experiments with a low value of x, such as RHIC [7], also had low values for the K^+/K^- ratio, whereas experiments using a value near 0.18 gave values close to the MINOS value of ≈ 2. The experiments presented are consistent with an increasing kaon (and pion) charge ratio for increasing x, as predicted by the Tan-Ng parameterization. Although the exact values found by the experiments did not in general exactly match Tan and Ng, this parameterization appears to be a reasonable approximation. Based on the experiments, it appears that as detected by MINOS, the average kaon that produces a muon in the atmosphere would have a value of x in the range $0.15 - 0.20$ in order to have a charge ratio of ≈ 2. This result may be important and interesting for people doing simulations of or studying data from the MINOS detector or other detectors capable of seeing cosmic rays.

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