Evidence for $K^+ \to \pi^+ \nu \bar{\nu}$

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Abstract

The first observation of the decay $K^+ \to \pi^+ \nu \bar{\nu}$ has been reported. The E787 experiment presented evidence for the $K^+ \to \pi^+ \nu \bar{\nu}$ decay, based on the observation of a single clean event from data collected during the 1995 run of the AGS (Alternating Gradient Synchrotron at Brookhaven National Laboratory). The branching ratio indicated by this observation, $\mathrm{B}(K^+ \to \pi^+ \nu \bar{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$, is consistent with the Standard Model expectation although the central experimental value is four times larger. The final E787 data sample, from the 1995–98 runs, should reach a sensitivity of about five times that of the 1995 run alone. A new experiment, E949, has been given scientific approval and should start data collection in 2001. It is expected to achieve a sensitivity of more than an order of magnitude below the prediction of the Standard Model.

Introduction

The rare decay $K^+ \to \pi^+ \nu \bar{\nu}$ is a flavor changing neutral current, mediated in the Standard Model (SM) by heavy quark loops[1,2], and is sensitive to the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{td}|$[3]. This sensitivity arises from the heavy top quark mass, the hard GIM suppression, and the negligible long distance contribution[4-8]. The hadronic matrix element can be determined from the $K^+ \to \pi^0 e^+ \nu_e$ rate, with the inclusion of isospin violating and electroweak radiative effects[9,10]. The small QCD corrections have been calculated to next to leading log[11]. The QCD corrections to the charm quark contribution are the major source of the intrinsic theoretical uncertainty. This leads to a 7% uncertainty in the calculation of the branching ratio[3]. If $B(K^+ \to \pi^+ \nu \bar{\nu})$, m_t, $|V_{ub}/V_{cb}|$, and $|V_{cb}|$ were perfectly known, $|V_{td}|$ could be determined to $\sim$6%. Given the current uncertainties in m_t, m_c, V_{cb}, $|V_{ub}/V_{cb}|$, ϵ_K and $\bar{B} - B$ mixing, the standard model prediction for the branching ratio, is 0.6—1.5$\times 10^{-10}$.

A measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$ is one of the theoretically cleanest ways of determining $|V_{td}|$. Combined with the other 'Golden Mode', $K_L^0 \to \pi^0 \nu \bar{\nu}$, the CKM triangle can be completely determined from the K system. With new measurements of the CKM parameters in the B system expected from the B-factories, additional tests of the Standard Model, comparing results from K's and B's, will be possible. In many extensions to the Standard Model the effects on the K and B system turn out to be discernibly different.

The E787 Experiment

The experimental signature for $K^+ \to \pi^+ \nu \bar{\nu}$ is a single incident kaon track and a single outgoing pion track, with two missing neutrinos. The separation of this signal from the background requires that the particle identification and kinematics of the π must be very well measured and any additional particles must be vetoed with high efficiency.

A drawing of the E787[12] detector is shown in Fig. 1. The detector is located in the C4 beam line at the AGS. This beam line, Low Energy Separated Beam (LESB3)[13], transports kaons of up to 830 MeV/c. At 690 MeV/c it can transmit more than 3 $\times$ $10^6 K^+$/spill with a K/π ratio of >3:1 for 10^{13} protons on the production target. The K^+ are tracked down the beamline and stopped in a scintillating fiber target in the center of the detector. The decay π^+ are tracked through the target and drift chamber[14] into the plastic scintillator range stack (RS). The detector is located in a 1 T, solenoidal magnetic field.

The two most significant backgrounds are the two dominant K^+ decay modes, $K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$) and $K^+ \to \mu^+ \nu_\mu$ ($K_{\mu 2}$), which produce mono-energetic charged particles. The search region for $K^+ \to \pi^+ \nu \bar{\nu}$ excludes these two kinematic peaks. The E787 detector uses redundant measures of the kinematics: momentum (P), energy (E) and range (R). The $K_{\pi 2}$ can also be suppressed by vetoing on the π^0 photons, so the detector is surrounded by a nearly 4π photon veto (PV). The primary components of the PV are the barrel veto (BV) and endcap (EC)[15–18], but, in fact, almost the entire detector not traversed by the π^+
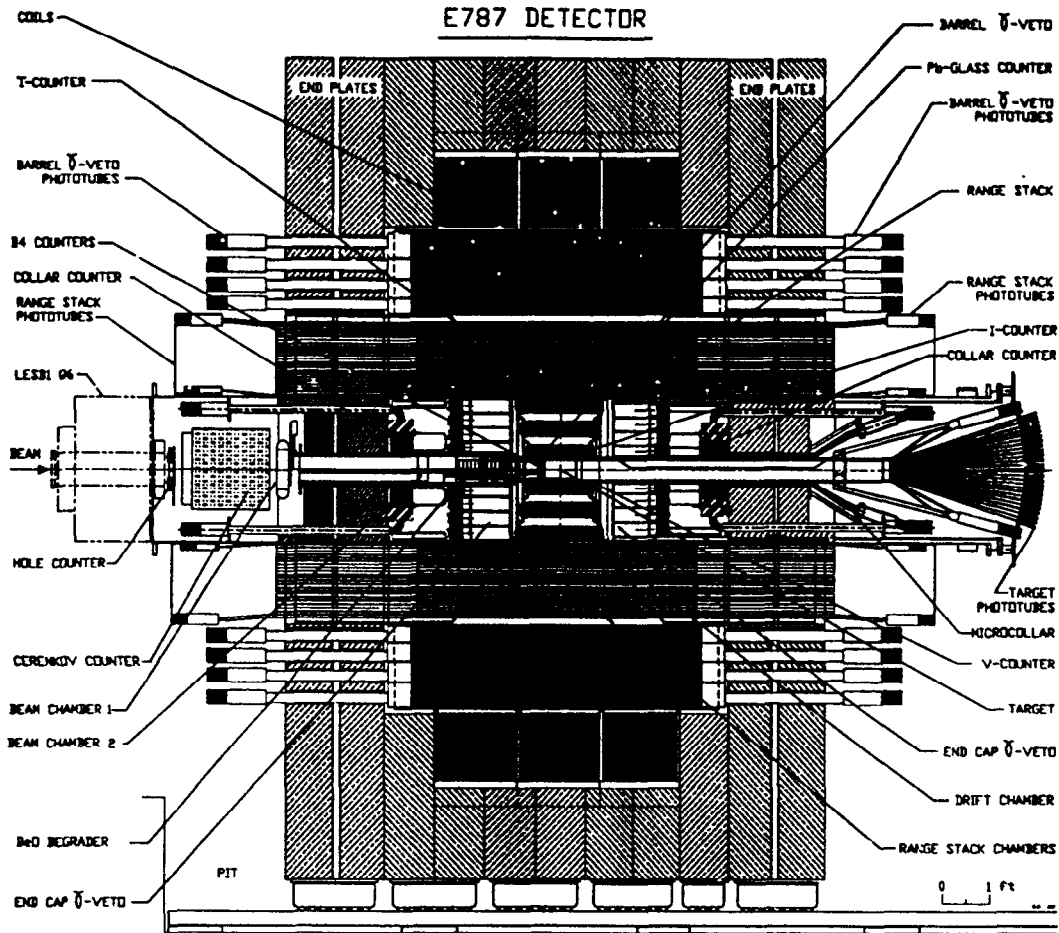
Figure 1: The E787 detector.

is used as a veto. The $K_{\mu2}$ can also be suppressed by dE/dx and by requiring that the π decay to a μ in the RS. The entire $\pi^+ \to \mu^+ \to e^+$ decay chain is observed with 500 MHz, 8-bit transient digitizers(TD)[19] sampling the output of the RS scintillators. The only other significant background comes from scattered beam pions or K^+ charge exchange (CEX). The primary tools for rejecting these events are good particle identification in the beam counters, identification of both the K^+ and π^+ in the fiber target, and the requirement that the π^+ track occur later than the K^+ track.

The search for $K^+ \to \pi^+ \nu\bar{\nu}$ requires an identified K^+ to stop in the target followed, after a delay of at least 2 ns, by a single charged-particle track that is unaccompanied by any other decay product or beam particle. This particle must be identified as a π^+ with P, R and E between the $K_{\pi2}$ and $K_{\mu2}$ peaks. To elude rejection, $K_{\mu2}$ and $K_{\pi2}$ events have to be reconstructed incorrectly in P, R and E. In addition, any event with a muon has to have its track misidentified as a pion — the TD's provide a suppression factor 10^{-5}. Events with photons, such as $K_{\pi2}$ decays, are efficiently eliminated — the suppression of π^0's is 10^{-6} (photon energy threshold of ~ 1 MeV). A scattered beam pion can survive the analysis only by misidentification as a K^+ and if the track is mismeasured as delayed, or

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if the track is missed entirely by the beam counters after a valid K^+ stopped in the target. CEX background events can survive only if the K_L^0 is produced at low enough energy to remain in the target for at least 2 ns, if there is no visible gap between the beam track and the observed π^+ track, and if the additional charged lepton evades detection.

Reliable estimation of backgrounds is one of the most important aspects of the measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ at the 10^{-10} level. For each source of background two independent sets of cuts are established by taking advantage of the redundancy of detector measurements. One set of cuts is relaxed or inverted to enhance the background (by up to three orders of magnitude) so that the other group can be evaluated to determine its power for rejection. In this fashion backgrounds can be studied at sensitivities up to 1000 times greater than the experimental sensitivity. For example, $K_{\mu 2}$ (including $K^+ \to \mu^+ \nu_\mu \gamma$) are studied by separately measuring the rejections of the TD particle identification and kinematic cuts. The background from $K_{\pi 2}$ is evaluated by separately measuring the rejections of the photon detection and kinematic cuts. The background from beam pion scattering is evaluated by separately measuring the rejections of the beam counter and timing cuts. Extensive measurements of K^+ charge exchange in the target were made in 1997. This data combined with Monte Carlo simulation of semi-leptonic K_L decays, allows the CEX background to be determined. Small correlations in the separate groups of cuts are investigated for each background source and corrected for if they existed.

Further confidence in the background estimates and in the measurements of the background distributions near the signal region is provided by extending the method described above to estimate the number of events expected with various degrees of cut loosening so as to allow higher levels of all background types. Confronting these estimates with measurements from the full $K^+ \to \pi^+ \nu\bar{\nu}$ data, where the two sets of cuts for each background type were relaxed simultaneously, tested the independence of the two sets of cuts. The background level for the 1995 data set, b, was measured to be 0.08 events. At the level of $20 \times b$, two events were observed where 1.6 ± 0.6 were expected, and at $150 \times b$, 15 events were found where 12 ± 5 were expected. Under detailed examination, the events admitted by the relaxed cuts were consistent with being due to the known background sources. Within the final signal region, additional background rejection capability is available. Therefore, prior to looking in the signal region, several sets of increasingly tighter criteria were established, to be used only to interpret any events in the signal region.

The Event

E787 published the first observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay[20], based on data from the 1995 run of the AGS. The range and energy of event candidates passing all other cuts is shown in Fig. 2. The box (which encloses the upper 16.2% of the $K^+ \to \pi^+ \nu\bar{\nu}$ phase space) indicates the signal region. One event consistent with the decay $K^+ \to \pi^+ \nu\bar{\nu}$ was observed. The expected number of background events from all sources was 0.08 ± 0.03 events (branching ratio equivalent of 3×10^{-11}). The separate levels of background were: $K_{\mu 2}=0.02 \pm 0.02$, $K_{\pi 2}=0.03 \pm 0.02$, beam-$\pi^+=0.02 \pm 0.01$ and CEX$=0.01 \pm 0.01$. This event was in a particularly clean region where the expected background was 0.008 ± 0.005
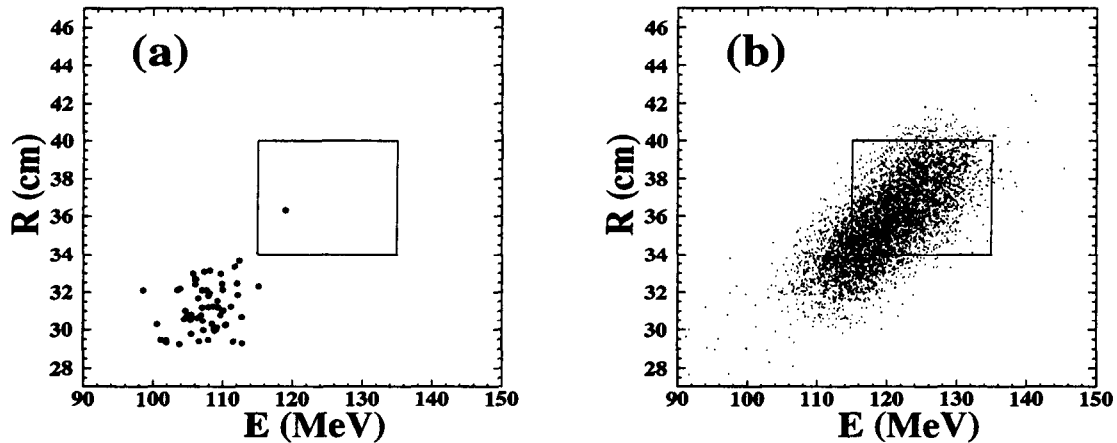
Figure 2: Final event candidate for $K^+ \to \pi^+ \nu \bar{\nu}$: a) Data b) Monte-Carlo

and which contained 55% of the acceptance of the full signal region. A reconstruction of the event is shown in Fig. 3. The kaon decayed to a pion at 23.9 ns, followed by a clean $\pi^+ \to \mu^+$ decay 27.0 ns later, as can be seen in the upper insert in Fig. 3; there was also a clean $\mu^+ \to e^+$ decay at 3201.1 ns.

There was no significant activity anywhere else in the detector at the time of the K^+ decay. The lower insert in Fig. 3 shows one of the target fibers that contains the incident kaon track, yet does not lie on the outgoing π^+ track; there is no activity at the K^+ decay time. The branching ratio for $K^+ \to \pi^+ \nu \bar{\nu}$ implied by the observation of this event

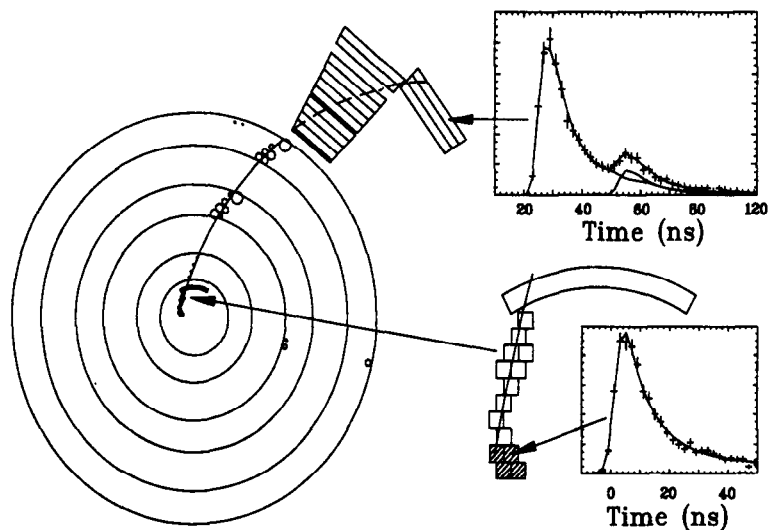Figure 3: The first $K^+ \to \pi^+ \nu \bar{\nu}$ event.

is $B(K^+ \to \pi^+ \nu \bar{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$.

Table 1: Running conditions for E787. The number of stopped kaons with the detector live(KB_L) is the online measure of the experimental sensitivity. As the kaon momentum is lowered the fraction of incident kaons that stop in the target(sf) increases. The duty factor(DF) of the AGS steadily increased. The single event sensitivity(S.E.S.) is measured from the 1995 set and estimated for the later years based on KB_L and the acceptance calculated from the detector rates. The background levels (bck) for 1996–98 are estimated from the reanalysis of the 1995 data.

year	KB_L (10^{12})	$|\vec{p_K}|$	DF (%)	sf (%)	(S.E.S.)$^{-1}$ (10^{10})	bck events
1995	1.49	790	41	18.7	0.24	0.08
1995–97	3.33	670–790	43	22	0.5	0.09
1998	2.97	710	52	27	0.5	0.08
1995–98	6.3	670–790	47	24	1.1	0.16

Expectations for the E787 Final Result

The E787 experiment has had four runs during 1995–98. The typical conditions for the 1995 run were 13 Tp/spill, 5.3 MHz of incident K^+, a stopped kaon rate of 1.2 M/spill, a deadtime of 25%, and an acceptance of 0.16%. The acceptance has been measured to be 60% of the acceptance at zero rate. The rates in most detector elements have been measured to be proportional to the incident flux and not to the stopped kaon flux. This implies that the sensitivity increases with increasing fraction of stopped kaons/incident kaons. Therefore E787 has lowered the momentum of the incident kaons in subsequent years, increasing the sensitivity without increasing the rates in most detector elements. In addition, the duty factor of the AGS has been increased from 37% at the start of 1995 to 55% at the end of 1998. Improvements in the online trigger efficiency, live time from trigger and DAQ upgrades[21–24], and acceptance from running at lower momentum also contribute to the enhanced sensitivity in later years.

A summary of the E787 sensitivity, including the published 1995 result, is shown in Table 1, along with some of the running conditions.

The expected sensitivity from the 1995–97 runs is $\sim \times 2.3$ that of the 1995 data alone, even though these runs were considerably shorter. A preliminary re-analysis of the E787 1995 data with improvements in the analysis software have demonstrated a background rejection that is $\sim \times 2.3$ larger. This background level (roughly equivalent to a branching ratio of 1.5×10^{-11}) is sufficient for future measurements of the $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio. Results of the analysis of the larger data set are expected within a few months.

With the improved running conditions, including an increased duty factor, improved DAQ[25] and the relatively long running period of almost five months in 1998, the final E787 sensitivity for $K^+ \to \pi^+ \nu \bar{\nu}$ should extend below the most probable SM level ($\sim 1 \times 10^{-10}$).

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Table 2: Sensitivity improvement factors for E949, compared to the published E787 result.

Upgrade	Improvement factor
Lower momentum	1.44
Higher duty factor	1.53
Established improvements	1.54
Additional efficiency improvements	1.9
Phase space below $K^+ \to \pi^+\pi^\circ$	2
Total	13

Future Plans — E949

A new experiment to measure the branching ratio $B(K^+ \to \pi^+\nu\bar{\nu})$, E949[26], recently received scientific approval and is expected to run at the AGS starting in the year 2001. This experiment is designed to reach a sensitivity of $(8-14) \times 10^{-12}$, an order of magnitude below the Standard Model prediction and to determine $|V_{td}|$ to better than 27%. It is built around the existing E787 detector to take advantage of the extensive analysis of that detector, allowing a reliable projection of the new experiment to the required sensitivity with a high level of confidence.

The E949 detector will have significantly upgraded photon veto systems, DAQ and trigger compared to the E787 experiment. The PV upgrade includes a barrel veto liner that will replace the outer layers of the RS and fill a gap between the RS and BV. It is 2.3 $X_\circ$ thick and will add substantially to the thin region at 45°. Additional PV upgrades will be installed along the beam direction. The most important DAQ upgrade will be to instrument the RS with TDC's to extend the search time for the Michel electron ($\mu^+ \to e^+$) and to allow the TD range to be shortened. The shortening of the TD range should allow a reduction of deadtime by 30–50%. Trigger upgrades should reduce the deadtime further and reduce the acceptance loss due to the online PV, by improving the timing on the RS and BV. Compared to the E787 running conditions in 1995 an improvement of 50% has already been realized. Additional improvements in these areas and in offline software are expected to gain another 90%. Additional sensitivity gains can be realized by including the region of phase space below the $K_{\pi 2}$ peak and by reoptimizing the analysis algorithms to run at higher rates. Each of these should provide a factor of 2 more sensitivity. The proposal assumes that only one of these factors will be realized.

The operating conditions will be significantly upgraded. E949 will run with a 700 MeV/c K^+ beam, with more than 70 Tp (7×10^{13} protons per spill) and with an AGS duty factor of close to 70%. These conditions are all within the expected AGS operating parameters for the year 2000[27]. They will require replacements for the upstream magnets in the LESB3 beam line, which are already near the end of their lifetime from radiation damage. The gain in sensitivity from these conditions will be a factor of 2.2. A summary of the improvement factors is given in Table 2. The total gain in sensitivity per hour will be 6–13 times over the E787 published result on the 1995 data set. All of the measurements of

deadtime and acceptance as a function of rate; and of the stopping fraction and kaon flux have been included in a calculation of the optimum running conditions. The sensitivity of the 1995 conditions is 1.46×10^6/hr and for E949 is 9.6×10^6/hr, not including the plans for reoptimizing for higher rates or the phase space below the $K_{\pi 2}$ peak.

Conclusions

The prospects for further improvement in the determination of $B(K^+ \to \pi^+ \nu \bar{\nu})$ are bright. The first observation of this rare and interesting decay has recently been published. The data on hand, or soon to be available, from the E787 experiment, should provide almost an order of magnitude more sensitivity. The recently approved experiment E949 should reach at least a factor of five further than E787 and make a very interesting measurement of $|V_{td}|$. There is also a proposal, CKM, at the FNAL Main Injector, to push even further, to 10^{-12} by looking for the decay in flight. A plot showing the progress from past, current and approved experiments for $B(K^+ \to \pi^+ \nu \bar{\nu})$ is shown in Figure 4. The search for this
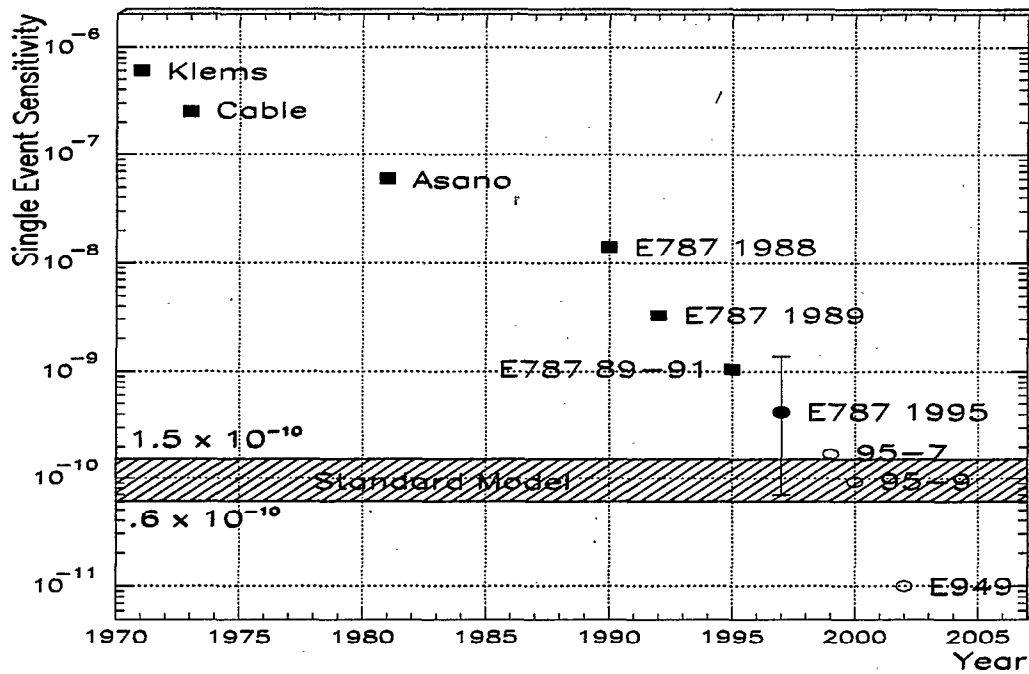

Figure 4: History of progress in the search for $K^+ \to \pi^+ \nu \bar{\nu}$. The sensitivity of experiments setting limits is shown in solid squares. The first actual measurement is shown as a solid circle and the projected future measurements are shown as open circles. The background levels are shown as stars for the recent data.

decay, with its very clean and well understood theory, has had a long and now very fruitful history.

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