Latest Results from the Search for $K^+ \rightarrow \pi^+\nu\bar{\nu}$

BEACH04, Chicago, June 30, 2004

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- **$K^+ \rightarrow \pi^+\nu\bar{\nu}$**
- **Experiment and analysis**
- **Results**
- **$K^+ \rightarrow \pi^+\nu\bar{\nu}$ below the $K^+ \rightarrow \pi^+\pi^0$ peak†**
- **KOPIO†**
- **Summary**

† Time permitting...

The E949 Collaboration

- Canada

  TRIUMF, UBC, Alberta

- U.S.

  BNL, FNAL, New Mexico

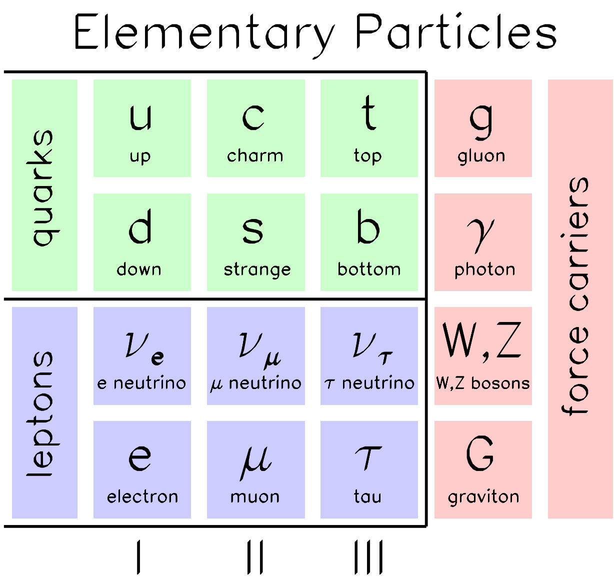
- Japan

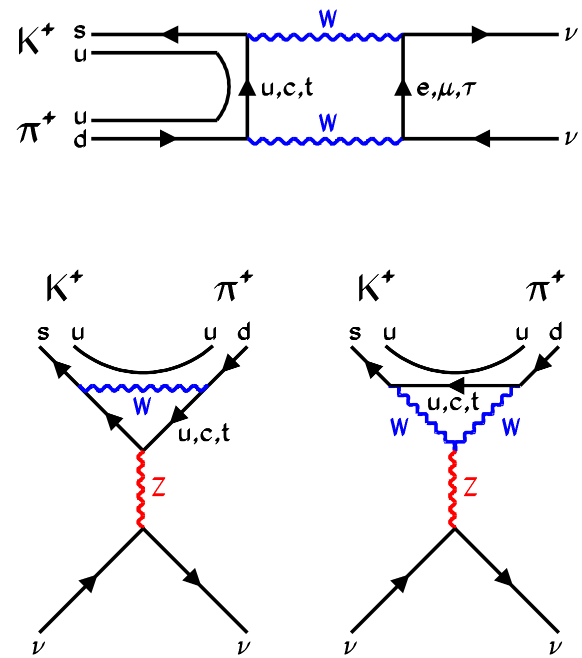
  Fukui, KEK, Kyoto, Osaka

- Russia

  IHEP, INR

$K^+ \to \pi^+ \nu \bar{\nu}$ in the Standard Model





3-generation SM with $m_t >> m_c, m_u$ allows. . .

. . . the flavour-changing neutral current $K^+ \to \pi^+ \nu \bar{\nu}$ decay to proceed only via 2^{nd} order interactions

The unitarity of the CKM mixing matrix. . .

$$\begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{us} & V^*_{cs} & V^*_{ts} \\ V^*_{ub} & V^*_{cb} & V^*_{tb} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

. . . constrains the relations between the matrix elements, e.g.:

$$V_{ud}\, V^*_{ub} + V_{cd}\, V^*_{cb} + V_{td}\, V^*_{tb} = 0$$

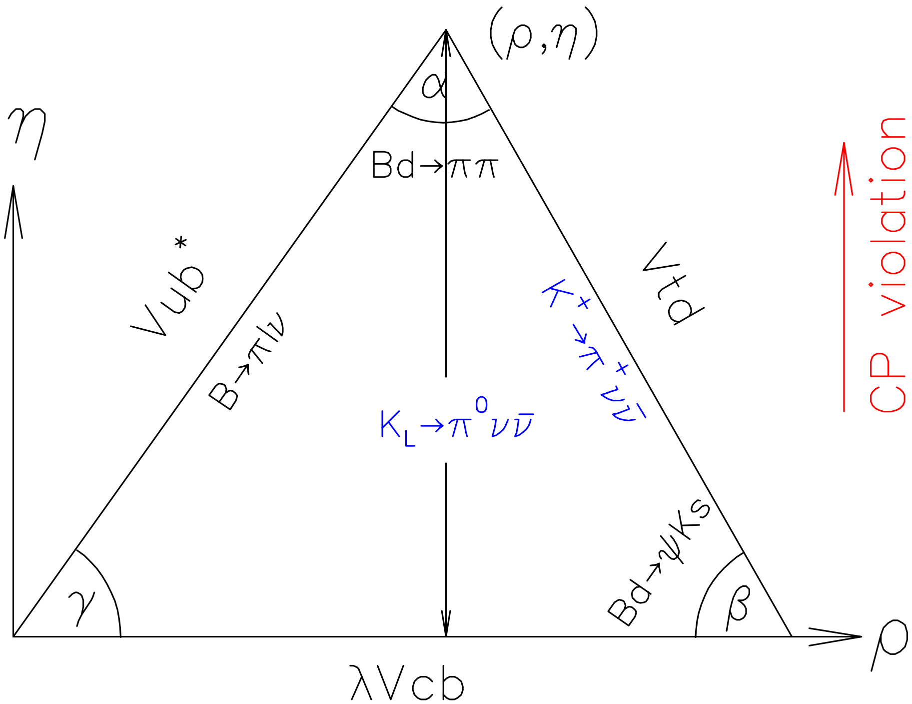
which can be drawn in the complex plane as a "Unitarity triangle".

It is convenient to use the Wolfenstein parametrization in which

$$\lambda \equiv \sin\theta_c = V_{us}$$

$$U = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Processes with small theoretical uncertainties



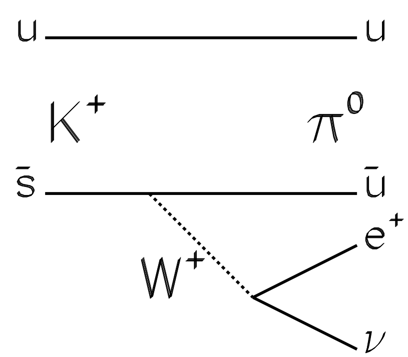
Process	Experiments
$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$	E787/E949
$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$	KOPIO
$\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S}; t)$	BaBar, Belle
time-dependent, CP-violating decay rate asymmetry	
$\Delta m_s/\Delta m_d$	CDF, D0
ratio of "mixing" frequencies of neutral B mesons	

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ measures $\mathrm{V_{td}}$ independently of $\Delta m_s/\Delta m_d$

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$, $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$ *v.* $\sin 2\beta$ from B factories:

Comparison of CP violation in K and B systems

Standard Model prediction of $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu})$



• Hadronic matrix element from isospin analog reaction $K^+ \to \pi^0 e^+ \nu_e$ (+ corrections)

• Long-distance effects small (10^{-13})

• Total theoretical uncertainty $\sim 7\%$

Present predicted Standard Model value:[a]

$(0.78 \pm 0.11) \times 10^{-10}$

[a] Buchalla and Buras, NP**B548** 309 (1999); Isidori, hep-ph/0307014; Buras, hep-ph/0402112

Detection Strategy

Positive i.d. of single K^+ entering, stopping, and decaying in target

• Particle i.d. (Čerenkov, B4 dE/dx) upstream of target.

• Scintillating fiber target for energy, time, and stopping position measurement.

• "Delayed coincidence" (DELCO) between K^+ stop, and subsequent detection of outgoing particle.

Positive i.d. of decay particle

• Precise momentum measurement (UTC).

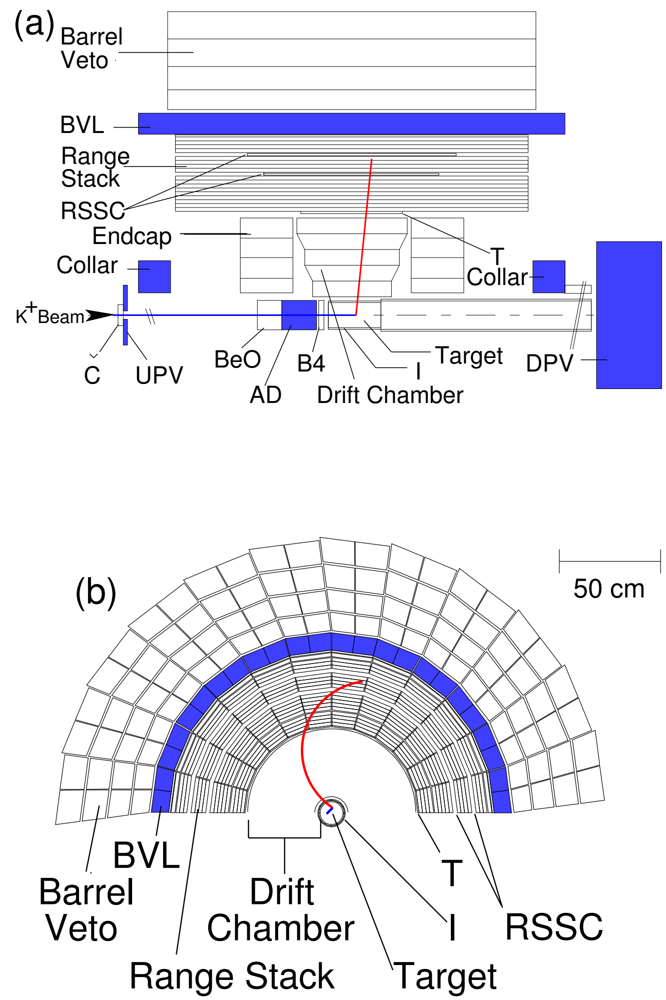
• Tracking in range stack: measure total energy and range (with target and I-counters).

• Observe complete $\pi \to \mu \to e$ decay in stopping counter with 500 MHz Transient Digitizers ("TD")

Veto energy *not* associated with $K \to \pi \to \mu \to e$ decay chain

• Look for extra particles entering the target (B4, BWPC, Čerenkov).

• Look for photon, neutron energy at K^+ decay time, and accidental hits around stopping counter at π^+ decay time.



E949 Upgrades to E787

Detector/electronics/DAQ upgrades

- RS Layers 1–5 replaced: better trigger ϵ, dE/dx
- Barrel veto liner

Adds 2.3 $X_0 \Rightarrow$ Better π^0 rejection

- Higher segmentation (16×16) beam hodoscope (B4)

WLS fiber readout for better position resolution and pile-up rejection

Upstream "ring veto" improves 2-beam background rejection

- Segmented active degrader
- Upstream, Downstream photon vetoes
- New PLD trigger boards: Reduced deadtime
- RS TDC readout: e^+ i.d. without TD info. Smaller data size, reduced readout time
- RS LED monitor system: Improved energy calibration
- New RSSC elcectronics: better z in RS

AGS Upgrades

More, better beam

- 60 weeks of running in FY01–03†
- Longer spill, higher duty factor:

65 Tp/spill, 4.1s/6.4s. duty cycle
5M *live* K stops/spill††

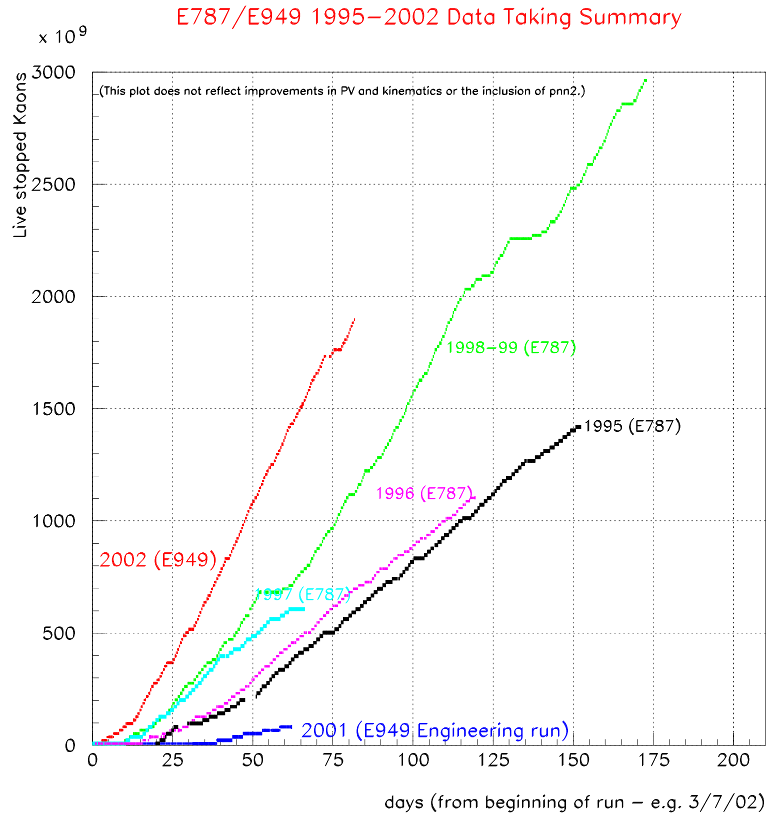
- Goal: 5–10 SM events

†What really happened...

- FY01 : 10 weeks ⇒ 0 weeks (g-2)
- FY02 : 25 weeks ⇒ 12 weeks

(broken generator, separator)

- FY03 : 25 weeks ⇒ 0 weeks
- ††Generator: 22 GeV instead of 24 GeV; 2.2s/5.4s *v.* 4.1s/6.4s; 10% lower K^+/π^+ ratio 2.5M K stops/spill
- Separator: K^+/π^+ further reduced by $\sim$ 20%

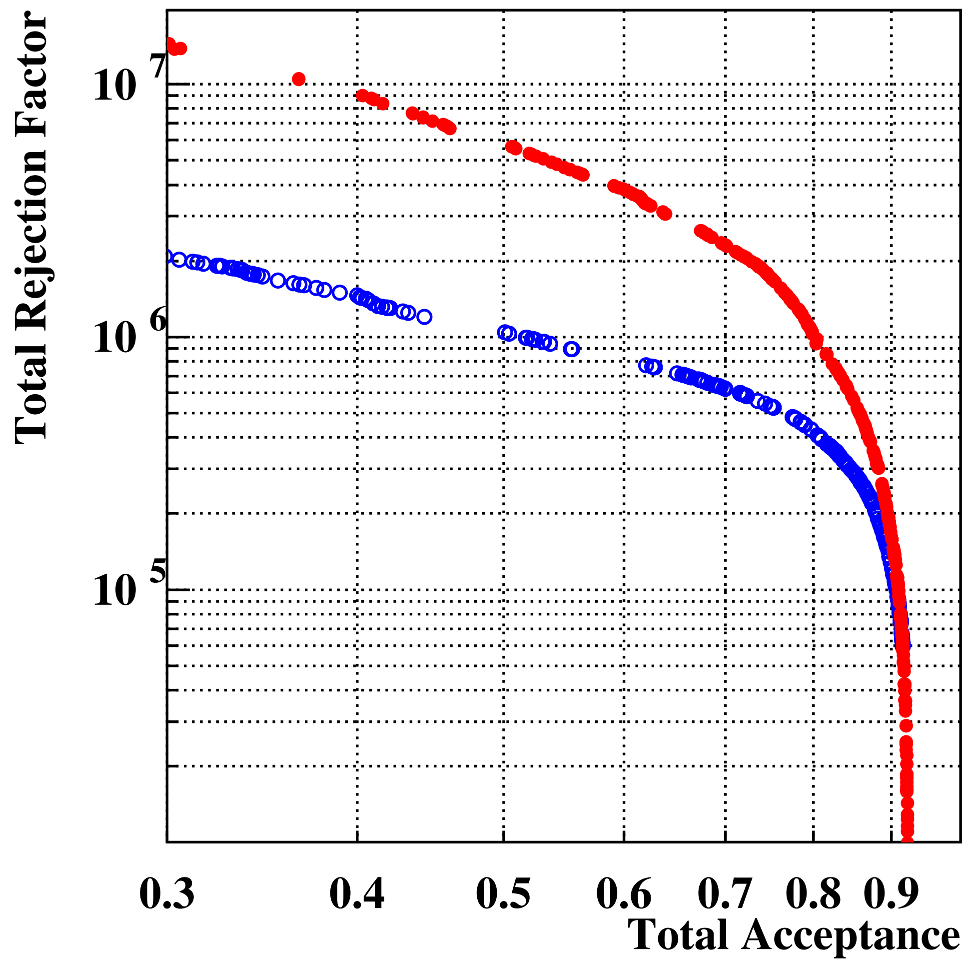


Photon veto improvement

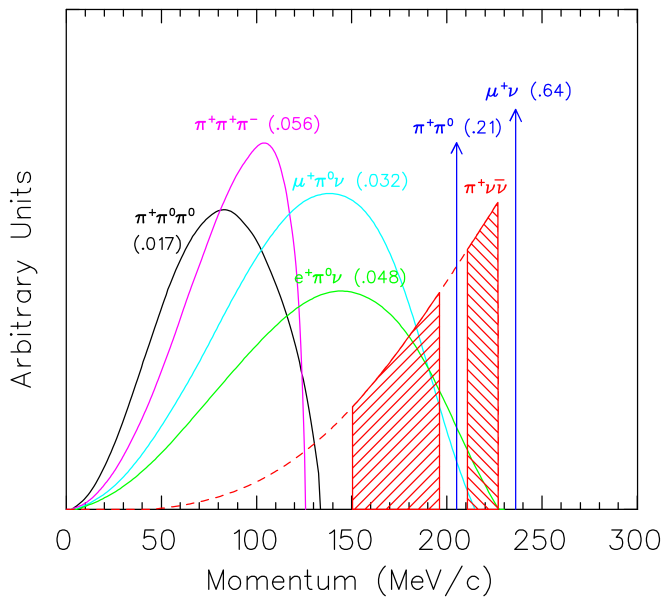
- Better small-angle coverage.
- 2.3 more radiation lengths in barrel

Figure: background **Rejection** as a function of $K^+ \to \pi^+ \nu \bar{\nu}$ signal **Acceptance** for the photon veto cut for E787 and E949.

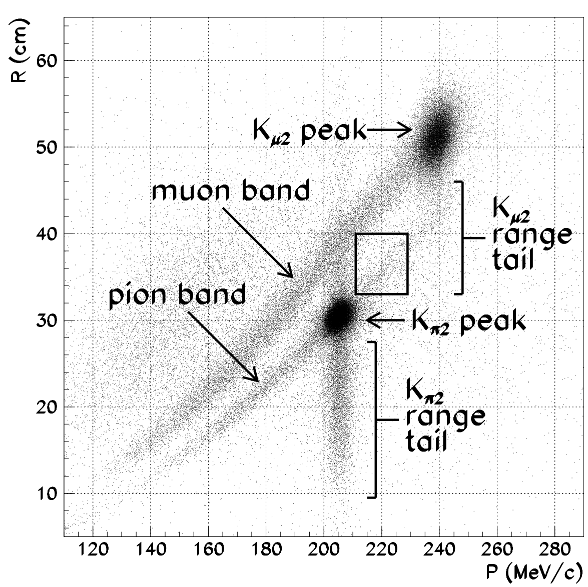
$\sim$ 2$\times$ better rejection at nominal **PNN1** acceptance of 80% *or* $\sim$ 5% more acceptance in E949 with same rejection as E787.

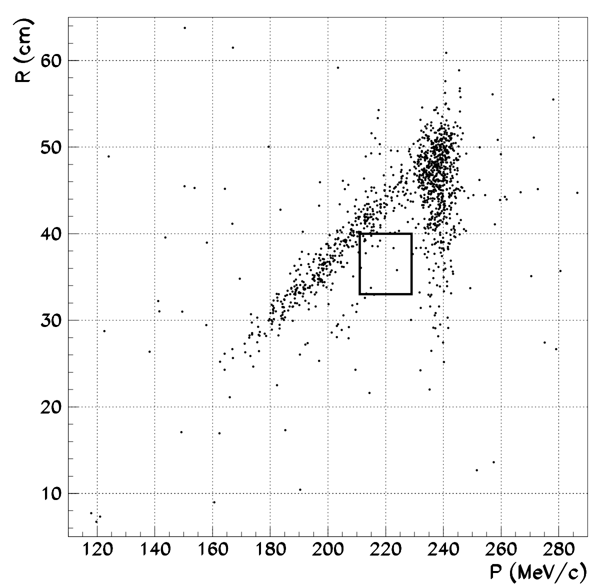


Backgrounds to $K^+ \to \pi^+\nu\bar{\nu}$



Background		Suppression Methods				
K^+ decays		$\overline{\gamma}$	TD	Kin.	TG	BM
$\mu^+\nu$	64%		X	X		
$\pi^+\pi^0$	21%	X		X		
$\pi^+\pi^+\pi^-$	5.6%			X	X	
$\pi^0 e^+\nu$	4.8%	X	X	X		
$\pi^0\mu^+\nu$	3.2%	X	X	X		
$\pi^+\pi^0\pi^0$	1.7%	X		X		
$\mu^+\nu\gamma$	0.5%	X	X	X		
π^+-scattering					X	X
$K^+ \to K^0$ Ch. Exch.				X	X	





Background measurement considerations

- Aim: Reduce total b.g. to $O(0.1)$ event $\Rightarrow$ need S/N gain of $\sim 10^{11}$

Use at least 2 independent cuts for each background

- Need to predict b.g. levels *before* looking in signal region

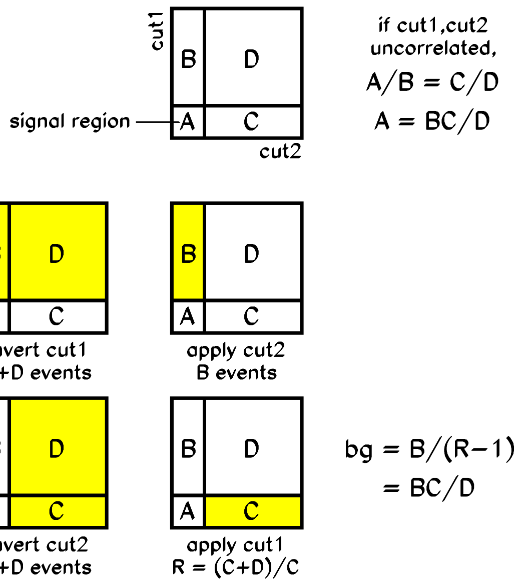
"Blind analysis"

- Use *data* for b.g. estimates wherever possible; need unbiased measurements

Use 1/3 of data to tune/set cuts; other 2/3 to measure backgrounds

- How to measure total background levels of $\sim 10^{-1}$ events?

Bifurcated Analyses



Background	Normalization or crosscheck	Rejection
$K_{\pi 2}$	$\bar{\gamma}$ tagged	Kinematic tagged
$K_{\mu 2}$	TD tagged	Kinematic tagged
Single beam	TG Del. coin. tagged	B4 dE/dx tagged
Double beam	BWPC tagged	B4 2-hit tagged
$K^+ \to K^0$ CEX	CEX cuts tagged	K_S-based M.C.

Potential Problems

- Undetected correlations
- New or unaccounted-for background

Mapping the signal space

Background probability functions

• Constructed by relaxing and tightening cuts on the different backgrounds

$K_{\pi 2}$: adjust kin. cuts, $\bar{\gamma}$ parameters

$K_{\mu 2}$: adjust kin. cuts, TD cuts

Beam: adjust coincidence timing windows

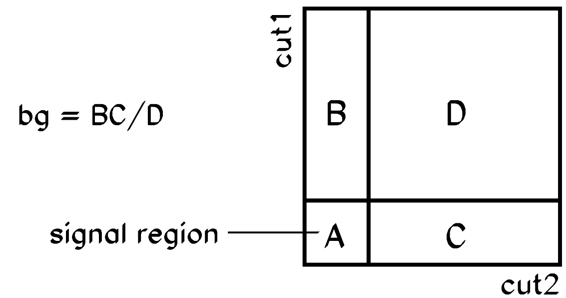
• Two results:

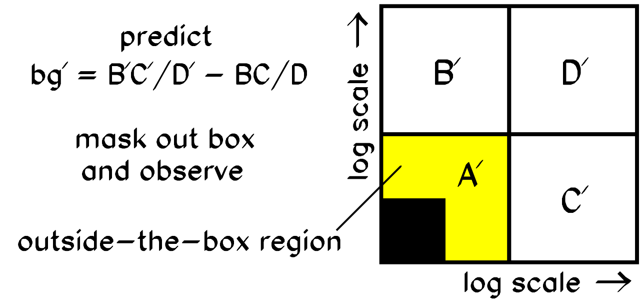
Testable prediction outside the box[†] before looking inside.

A priori (i.e. **unbiased**) evaluation function inside the box for interpretation of candidate events.

[†] box≡generalized signal region

"Outside-the-box" studies





• Correlation studies
• Single-cut/double-cut failures
• Check predicted *v.* measured backgrounds
• Look for anomalies and "loop-holes" in analysis

Signal region definition and candidate event evaluation

Old method: "Cut and count"

- Cut hard: set upper limit on background ($<< 1$ events)
- Measure acceptance, integrated beam to get S.E.S.
- Open box...
- Does not use all available information
- Difficult to assess effects of background, acceptance systematics
- Difficult to combine results from different measurements

New method: Likelihood analysis

- Divide signal region into many small regions, ("cells") ordered by S:N
- Don't worry (too much) about increased background (~ 0.3 events)
- Uses more information
- Increased signal acceptance
- Analysis accounts for background expectations in b.r. and conf. limits
- Assessing effects of systematics easier

Results

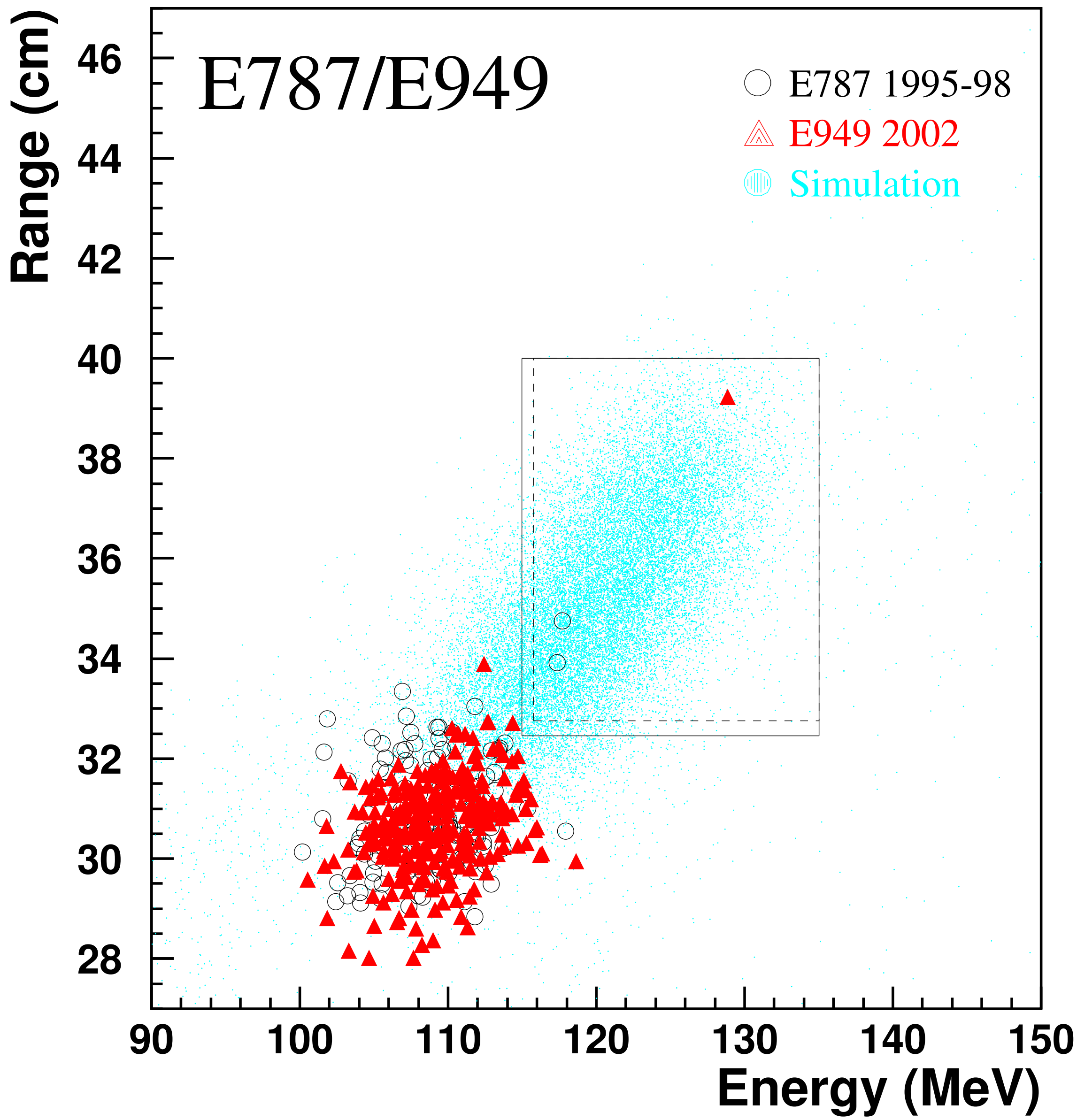
- 2002 background levels

Background	Events
$K_{\pi 2}$	0.216 ± 0.023
$K_{\mu 2}$	0.044 ± 0.005
$K_{\mu m}$	0.024 ± 0.010
1-beam	0.006 ± 0.002
2-beam	0.003 ± 0.002
CEX	0.005 ± 0.001
Total	0.298 ± 0.026

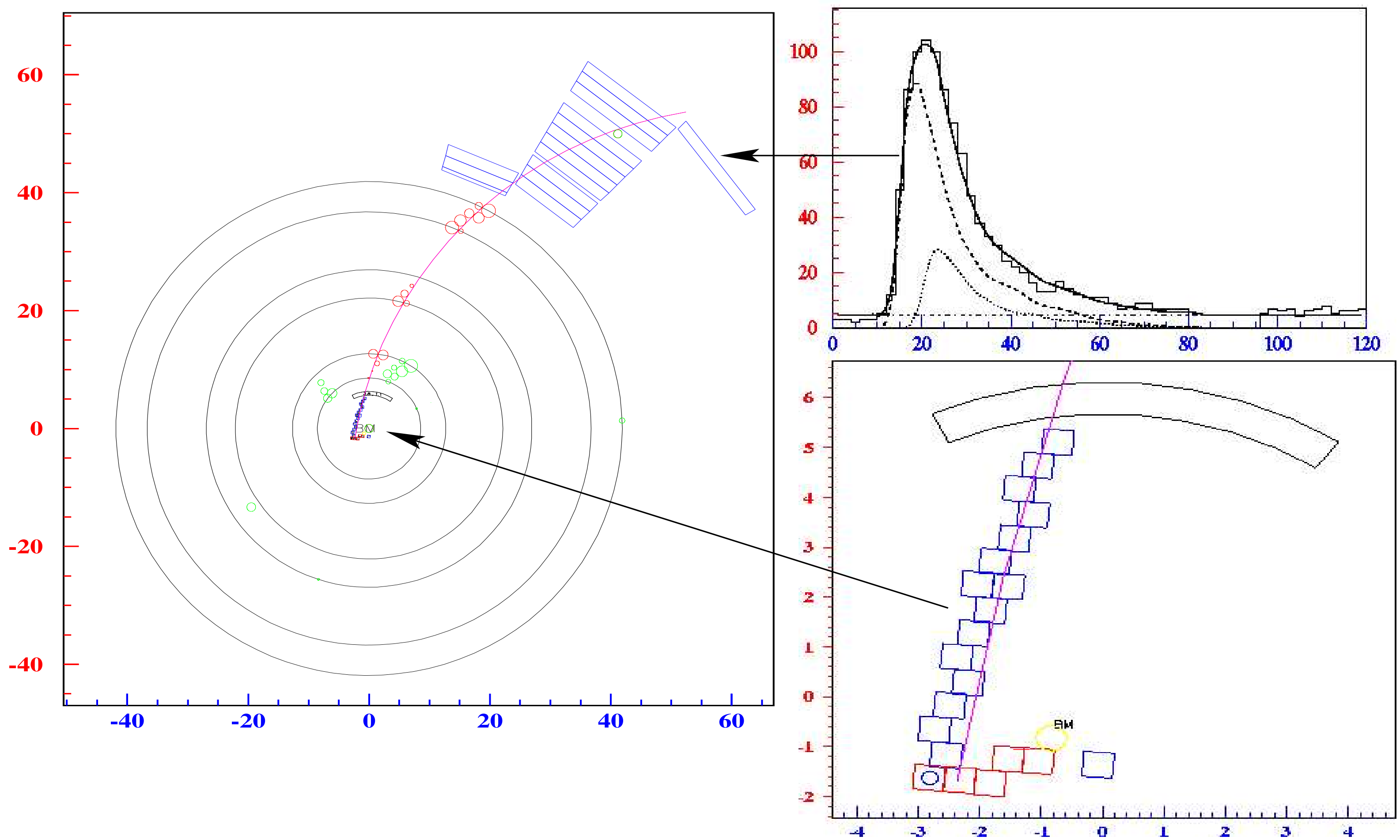
- 2002 sensitivity

	E787	E949
# K^+	5.9×10^{12}	1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002	0.0022 ± 0.0002
Total Background	0.14 ± 0.05	0.30 ± 0.03

Inside the box...

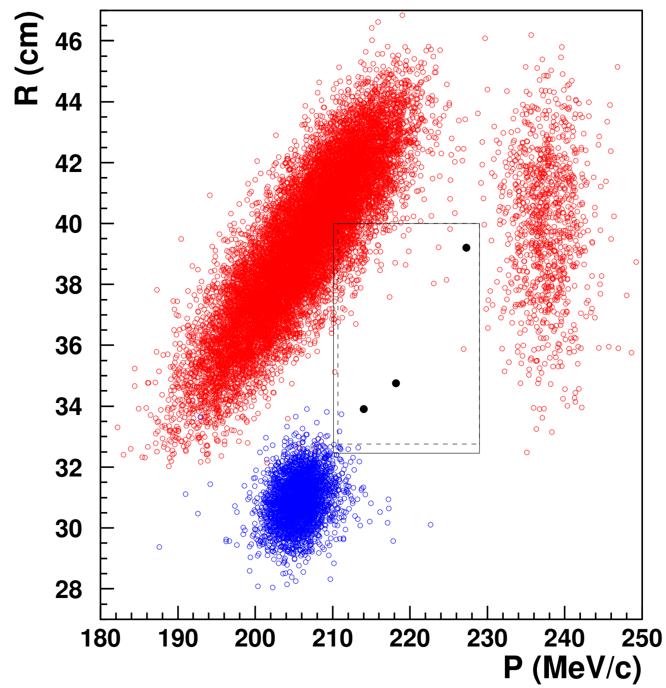


Event display



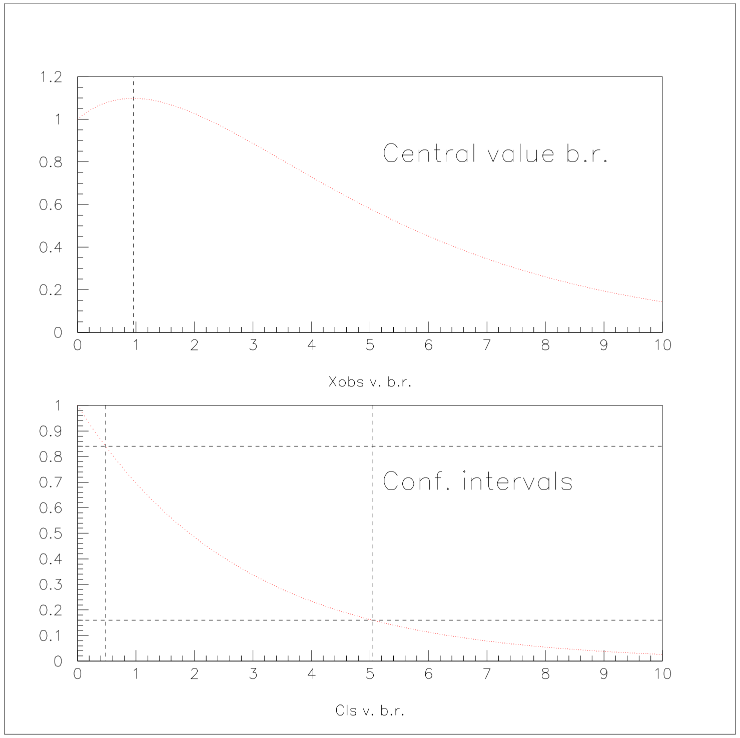
Pertinent details

Date	April 2, 2002
Tape/run/spill/event	30266.3.2/48634/335/76046
Time in spill	1.27s
Kaon energy in target	79.7 MeV
Kaon time in target (t_K)	0.6 ns
z of kaon decay vertex	8.9 cm
(x, y) of kaon decay vertex	(-2.8, -1.6) cm
Pion energy in target	20.8 MeV
Pion range in target	7.6 cm
Pion time in target (t_π)	4.9 ns
Pion time in IC (ictime)	3.8 ns
cos3d pion track	-0.24
Phi0 of the pion track	1.42
P_{total} of pion track	227.3 MeV/c
R_{total} of pion track	39.2 cm
E_{total} of pion track	128.9 MeV
RS stopping sector/layer	3/14
Pion lifetime	6.2 ns
Muon energy	3.7 MeV
Muon lifetime	1370.53 ns
Range-momentum	0.63



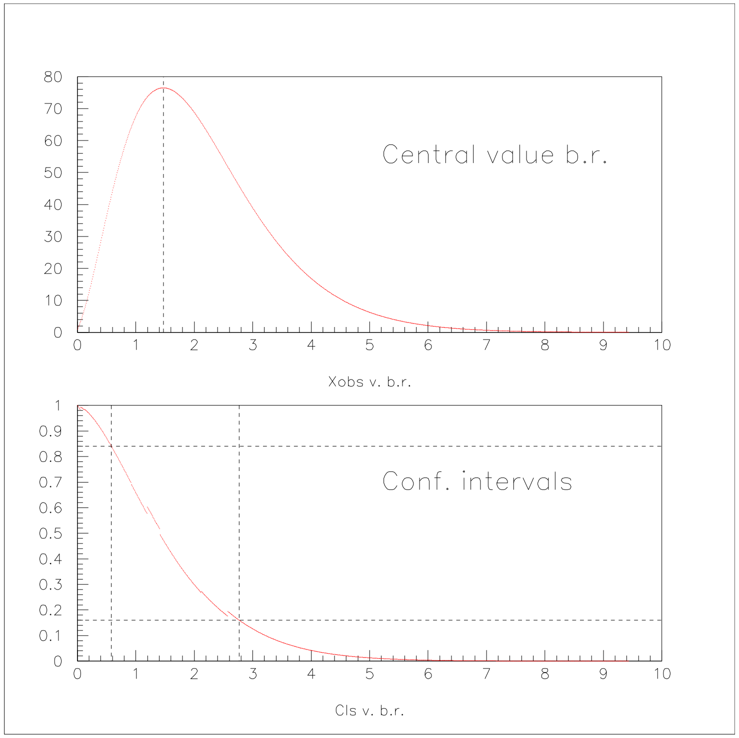
2002 candidate on its own

- Branching ratio: $(0.96^{+4.09}_{-0.47}) \times 10^{-10}$
- $1 - CL_b$: 0.074 (*N.b. a priori*)



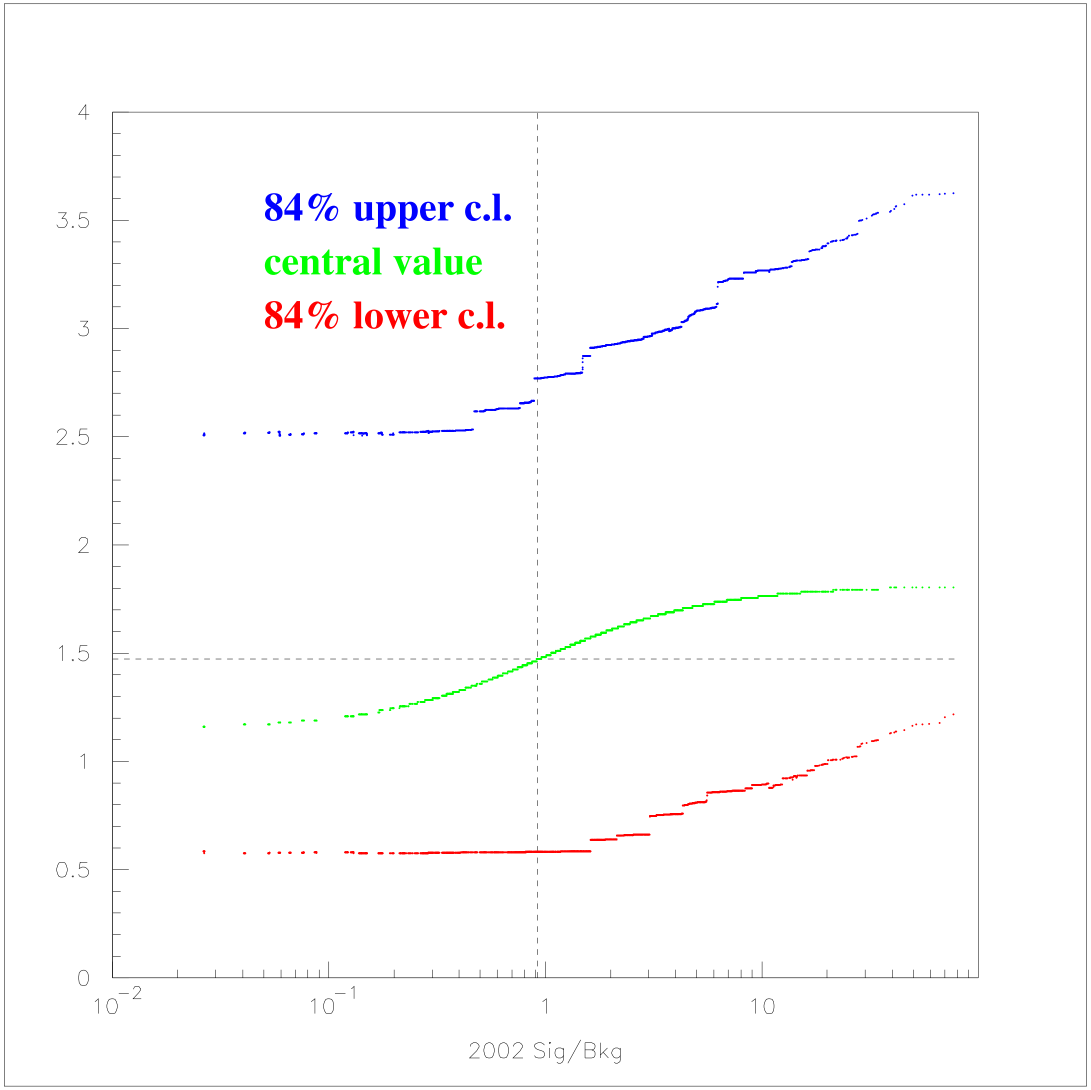
Combined measurement

- Branching ratio: $(1.47^{+1.30}_{-0.89}) \times 10^{-10}$
- $1 - CL_b$: 0.001 (*N.b. A priori*)



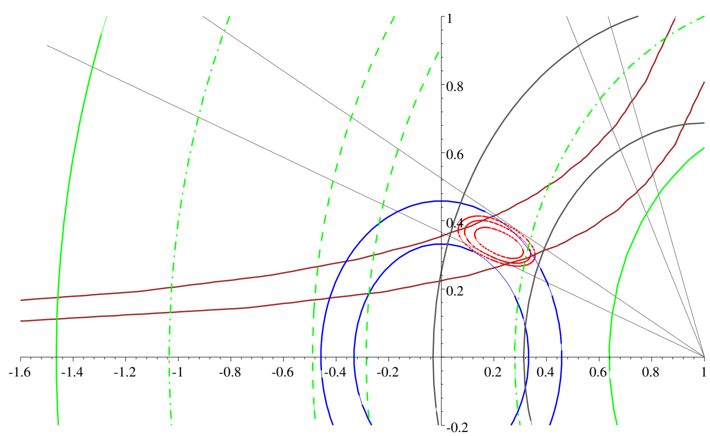
	E787		E949
Candidate	1995A	1998C	2002A
S_i/b_i	50	7	0.9
$W_i \equiv S_i/(S_i + b_i)$	0.98	0.88	0.48
$1 - CL_b$	0.006	0.02	0.07

Dependence on candidate S/B

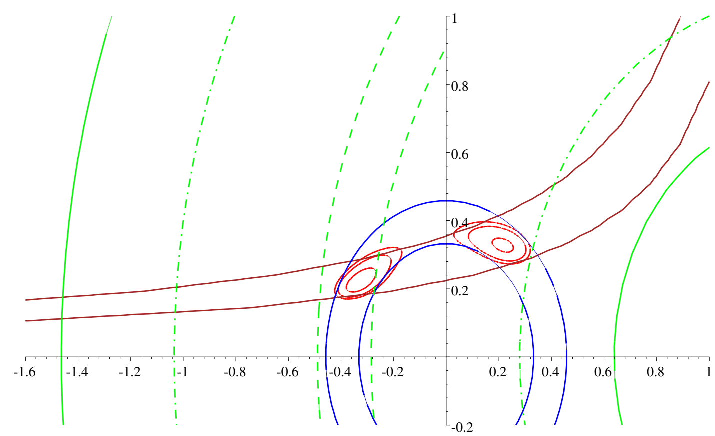


Consistency with/influence on unitarity triangle (G. Isidori)

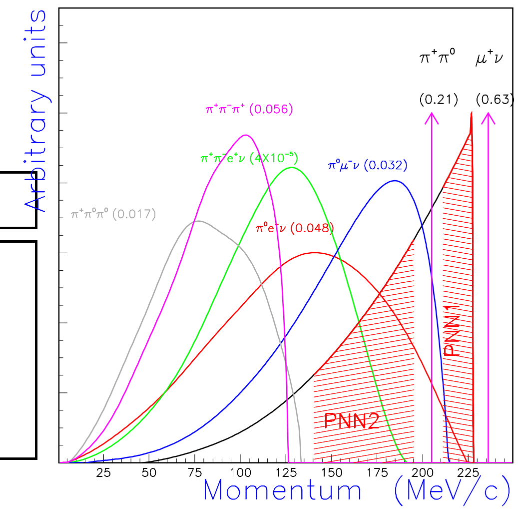
B constraints included



B constraints excluded



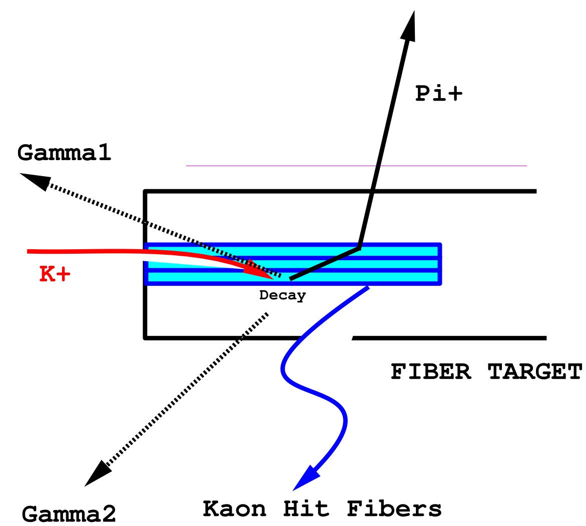
$K^+ \to \pi^+\nu\bar{\nu}$ below the $K^+ \to \pi^+\pi^0$ peak



- Lots of phase space
- Some different K^+ decay modes prominent:

K^+ decay	Branching ratio	Background level
$\pi^+\pi^0$	0.211	0.40 ± 0.15
$\pi^+\pi^0\gamma$	2.8×10^{-4}	0.006 ± 0.002
$\mu^+\nu_\mu\gamma$, $\mu^+\nu_\mu\pi^0$	0.033	0.009 ± 0.009
$\pi^+\pi^-e^+\nu_e$	4.1×10^{-5}	0.026 ± 0.026

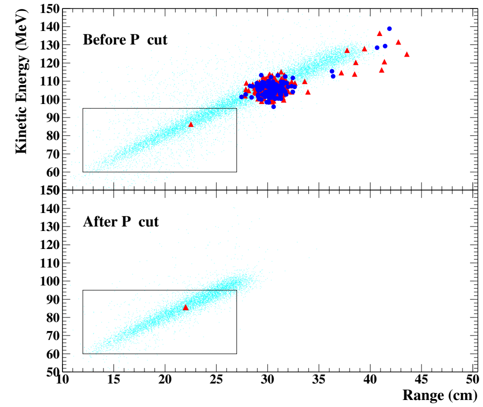
- Problematic background from $\pi^+\pi^0$ where π^+ scatters inelastically in the target
- γ goes off through beam pipe, or "hides" in target
- *correlates kinematics with γ-veto*
- Tag events with "kink" in target track, and/or extra energy in target
- Use digitized pulse shapes from target CCD's to find pulses in K^+ fibres

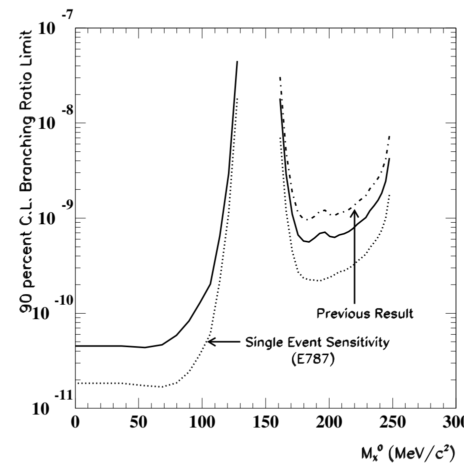


Analysis of 1997 data set now completed; in publication

Name	"PNN2"	"PNN1"
P_π (MeV/c)	[140,195]	[211,229]
Years	1996–97	1995–2002
Stopped K^+	1.7×10^{12}	7.7×10^{12}
Acceptance	$\sim 0.1\%$	$\sim 0.2\%$
Candidates	1	3
Background	1.22 ± 0.24	0.45 ± 0.06
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$

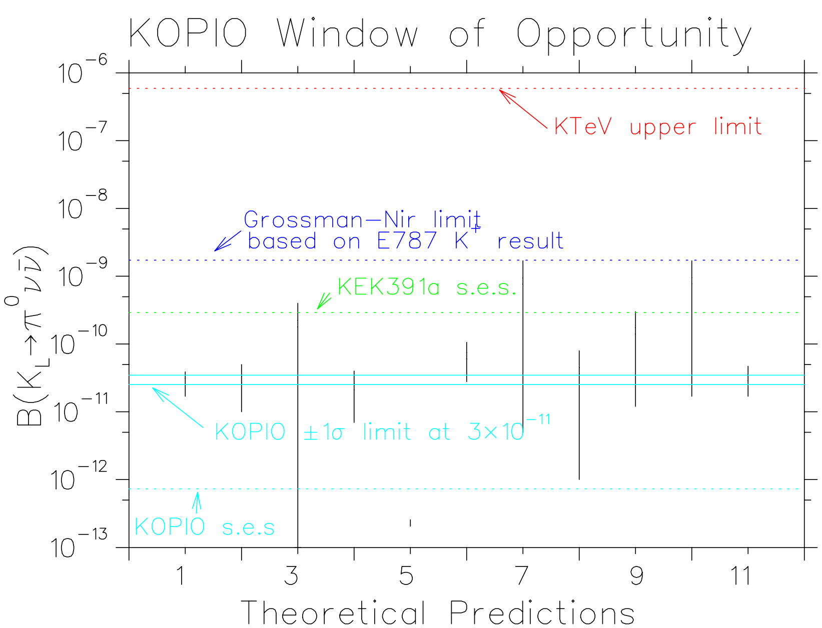
PNN1: Accepted by PRL;
http://arXiv.org/abs/hep-ex/0403036, TRI-PP-04-07
PNN2: limit at 90% CL is combined result from 1996 (PL **B537**, 211 (2002)) and 1997 (hep-ex/0403034) data.





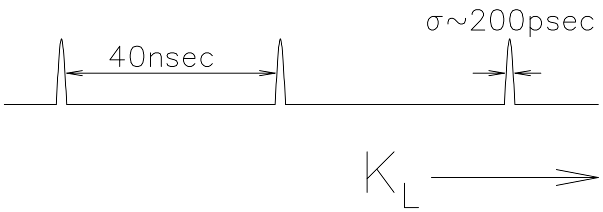
KOPIO: measurement of $\mathcal{B}(K_L^0 \to \pi^0 \nu\bar{\nu})$

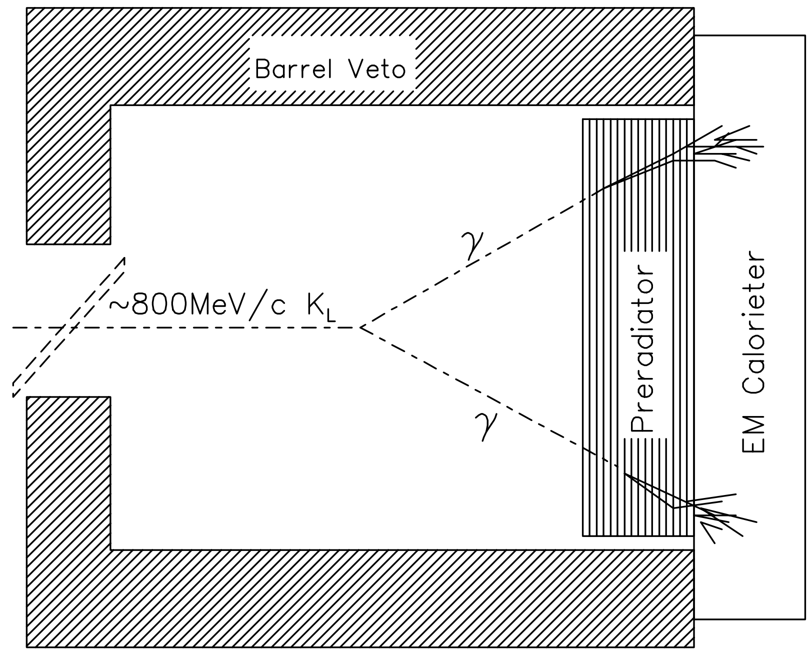
	$K^+ \to \pi^+ \nu\bar{\nu}$	$K_L^0 \to \pi^0 \nu\bar{\nu}$
Top dependence	$\lvert\lambda_t\rvert = \lvert V_{ts}^* V_{td}\rvert$	$\text{Im}(\lambda_t) = \text{Im}(V_{ts}^* V_{td})$
Calc. BR (10^{-10})	0.78 ± 0.11	0.26 ± 0.05
Est. theor. uncert.	7% (charm)	2%



- Improvements over KTEV
  - ◇ Use $\pi^0 \to \gamma\gamma$ ($\sim \times 83$)
  - ◇ More acceptance ($\sim \times 5.6$)
  - ◇ More decaying K_L^0's ($\sim \times 800$)

Background supression strategy

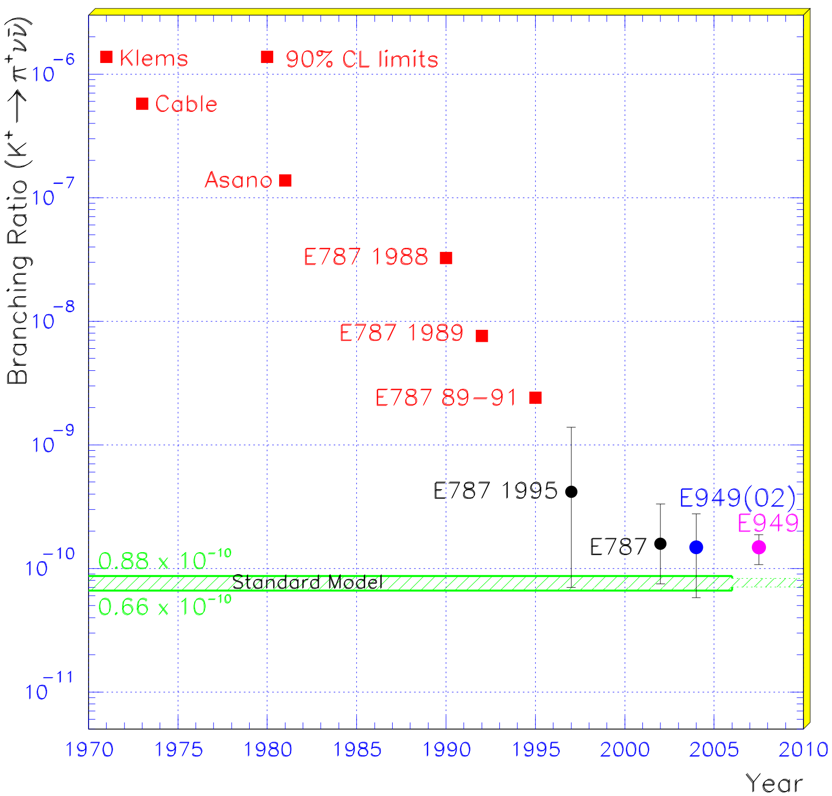


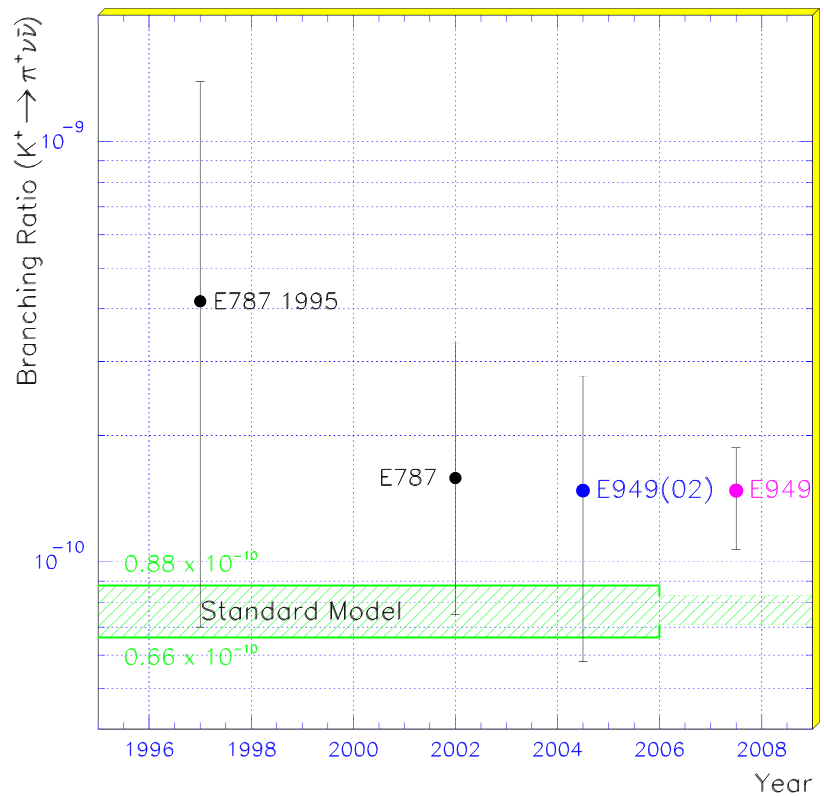


- K_L^0 produced by “micro-bunched” beam:
  $\sigma_{\Delta t} = 200\,\mathrm{ps} \Longrightarrow p_{K_L^0}$ from TOF
- K_L^0 decays in evacuated region
- Preradiator to measure γ PID, position, direction:
  $\Longrightarrow K_L^0$ decay vertex $\Longrightarrow$ Work in C.M. system
- Calorimeter completes γ energy measurement
- Upstream γ spoiler, 4π photon veto, charged-particle veto surrounding decay volume

- 3 years of R&D so far
- $2.5M this year for “advanced planning”
- Baseline review in early 2005
- RSVP onstruction start in FY05 requested in NSF budget

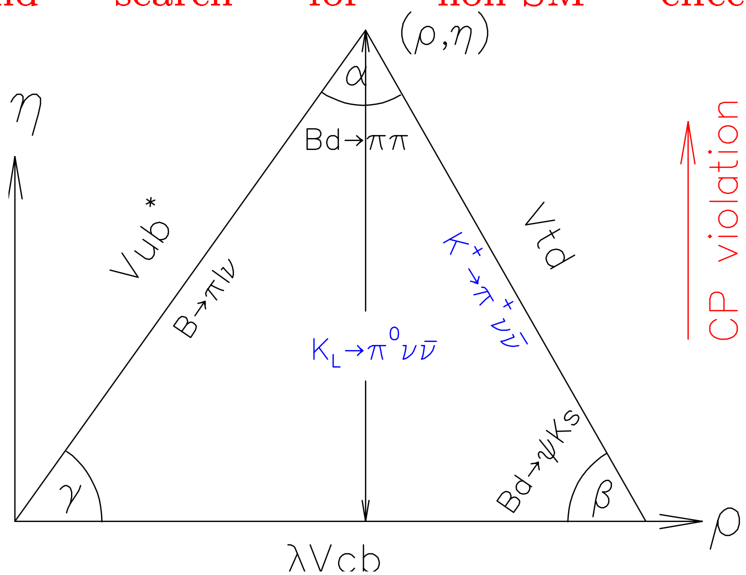
Progress in measuring $K^+ \to \pi^+ \nu\bar{\nu}$





Summary and future prospects

• $K^+ \to \pi^+ \nu\bar{\nu}$: Explore SM physics and search for non-SM effects



• E787/949: demonstrated ability to detect and measure $K^+ \to \pi^+ \nu\bar{\nu}$

• Upgraded detector and electronics able to function in high-rate environment

• Analysis has shown steady improvements from

1. Better understanding of backgrounds and systematics
2. Improved analysis techniques

• Successful transition from "cut and count" to full likelihood analysis

- ◇ Equiv. to background subtraction
- ◇ Increased signal acceptance: No longer require $N_{\mathrm{bkg}} << 1$
- ◇ Ambiguous events accepted and given appropriate weight in branching ratio and limit measurements
- ◇ Quite insensitive to systematic effects

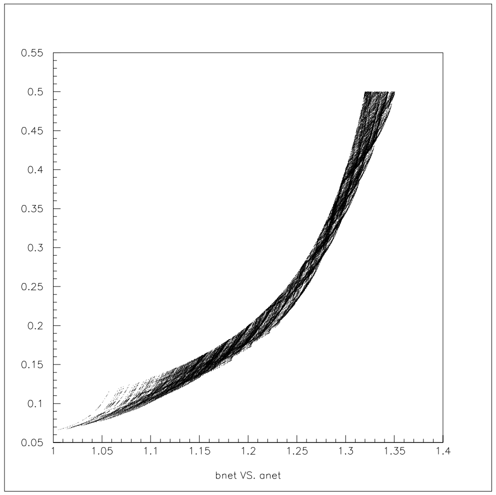
• 1 new candidate found in 2002 data set

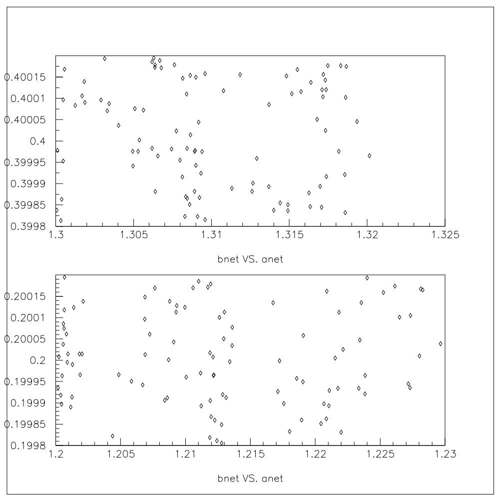
- ◇ Low signal:noise value: ~ 1 at measured b.r.
- ◇ Combined $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$: $(1.47^{+1.30}_{-0.89}) \times 10^{-10}$ $0.005 < |V_{td}| < 0.027$
- ◇ $\mathrm{B}(K^+ \to \pi^+ X^0)$: $< 0.73 \times 10^{-10}$ (based on 2002 candidate; 90% c.l.)

• Present results consistent with Standard Model predictions, but low stat. prec.

• Some hope for future running, based on pending NSF proposal.

“Extended box”





S:N-ordered cell construction

- Background functions are like the basis functions of a 7-d space
- An event’s locality in this space determined by:
  1. γ veto timing windows/energy thresholds (PV) $\Longleftarrow$
  2. Proximity (E, P, R) to $K_{\pi 2}$ peak (Kp2) $\Longleftarrow$
  3. $\pi \to \mu \to e$ properties via NN function (TD) $\Longleftarrow$
  4. Proximity (P) to $K_{\mu 2}$ “tail” (Km2t)
  5. Proximity (R,P) to $K_{\mu 2}$ “band” (Km2b)
  6. Kaon lifetime, or “delayed coincidence” (bm1)
  7. 2nd-hit timing in beam wire chambers (bm2)
- Sample functions at discrete points to form a grid of “cells”; calculate (absolute) background levels (b) and (relative) signal acceptance (s) in each cell.

$$
\begin{aligned}
N_{i;K_\pi 2} &= N_{\text{total};K_\pi 2} \times dN_{Kp2} \times dN_{PV} \times \\
&\quad dA_{TD} \times dA_{bm1} \times dA_{bm2} \\
b_i &= N_{i;K_\pi 2} + N_{i;K_\mu 2t} + N_{i;K_\mu 2b} + \\
&\quad N_{i;bm1} + N_{i;bm2} \\
s_i &= 1 \times dA_{Kp2} \times dA_{PV} \times \\
&\quad dA_{TD} \times dA_{bm1} \times dA_{bm2}
\end{aligned}
$$

Confidence level calculation (T. Junk, NIM A434, 435 (1999))

• Define an optimal "test statistic" X, the Poisson likelihood ratio:

$$X = \prod_{i=1}^{M} X_i$$

$$X_i = \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!} \Big/ \frac{e^{-b_i} b_i^{d_i}}{d_i!} = e^{-s_i}\left(1+\frac{s_i}{b_i}\right)^{d_i}$$

b_i, s_i : expected sig., bkg. in each bin

d_i : #observed events in each bin

• Compute the Poisson probabilities for $s+b$ and b only:

$$P_{s+b} = \prod_{i=1}^{M} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!}$$

$$P_b = \prod_{i=1}^{M} \frac{e^{-b_i} b_i^{d_i}}{d_i!}$$

• Get the conf. lim. by finding/summing all configurations of d_i that give $X \le X_{obs}$ for $s+b$, and b only:

$$CL_{s+b} = P_{s+b}(X \le X_{obs}) = \sum_{X(\{d'_i\}) \le X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d'_i}}{d'_i!}$$

$$CL_b = P_b(X \le X_{obs}) = \sum_{X(\{d'_i\}) \le X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(b_i)}(b_i)^{d'_i}}{d'_i!}$$

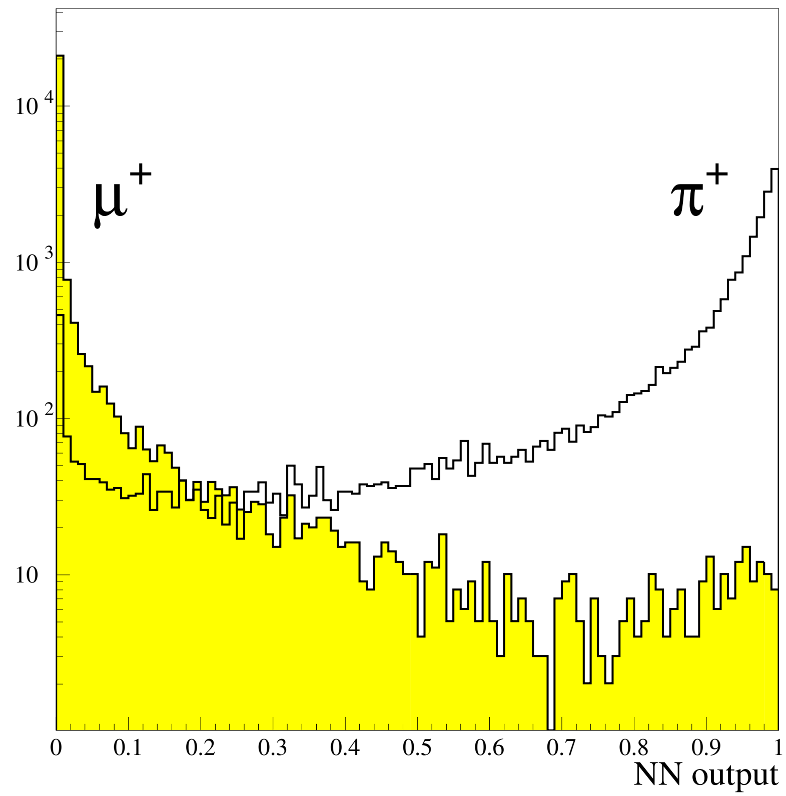
• Get the $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ limits from the "Modified Frequentist" confidence level:

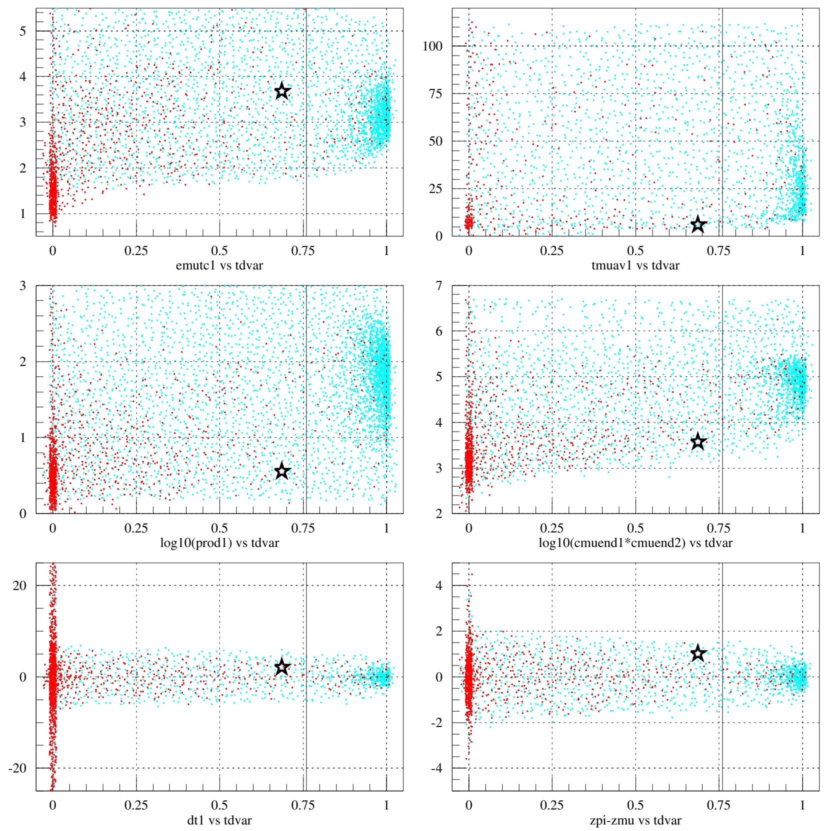
$$CL_s = CL_{s+b}/CL_b$$

• Scan over large range of "expected signal" to get a complete set of confidence levels.

• 1995–97: divide signal region into 2 bins
• 1998: divide signal region into 486 bins
• 2002: divide signal region into 3781 bins
• Combine contiguous (in S:N) *empty* bins

Examine TD properties closely





Conclusion: Inconclusive. . .

Sensitivity to systematic effects

• Magnitudes from outside-the-box correlation fit errors (backgrounds: $\sim 20\%$; Acc.$\times N_K$: $\sim 10\%$)
• Re-measure b.r./limits with various assumed background and sensitivity mismeasurements
• Fold in effects via weighted sum of c.l. v. b.r. curves