Latest results on the measurement of $K^+ \to \pi^+ \nu \bar{\nu}$

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TRIUMF Seminar

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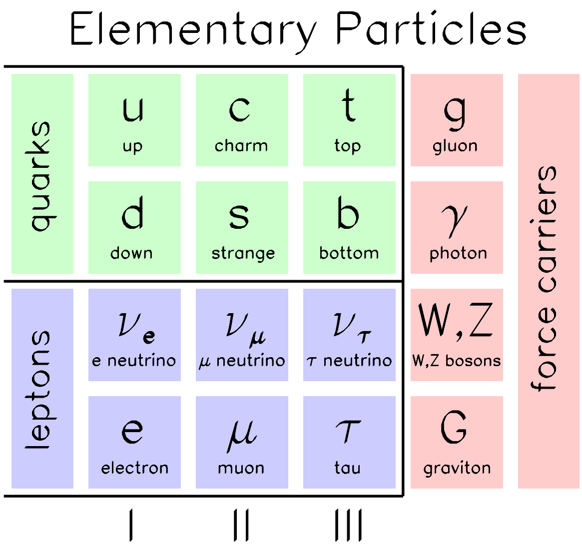
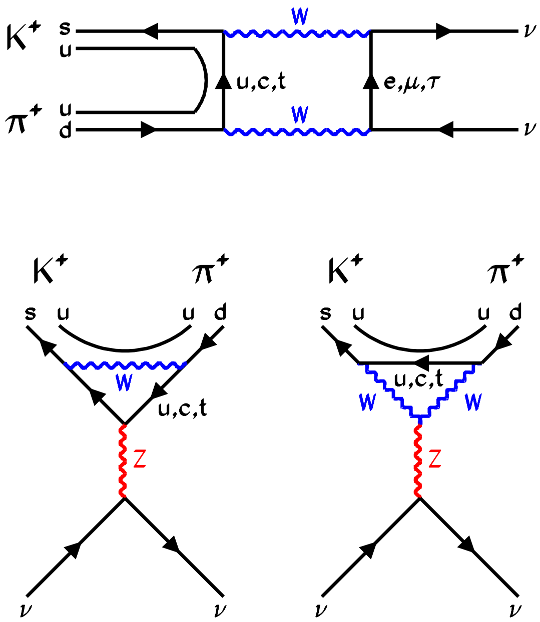
The E787 Collaboration

- Canada
  TRIUMF, UBC, Alberta
- U.S.
  Brookhaven, Princeton
- Japan
  KEK, Osaka

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



3-generation Standard Model:
F.C.N.C. highly suppressed by GIM mechanism



Weak quark couplings specified via CKM matrix:

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity $\Longrightarrow$ 4 independent parameters:

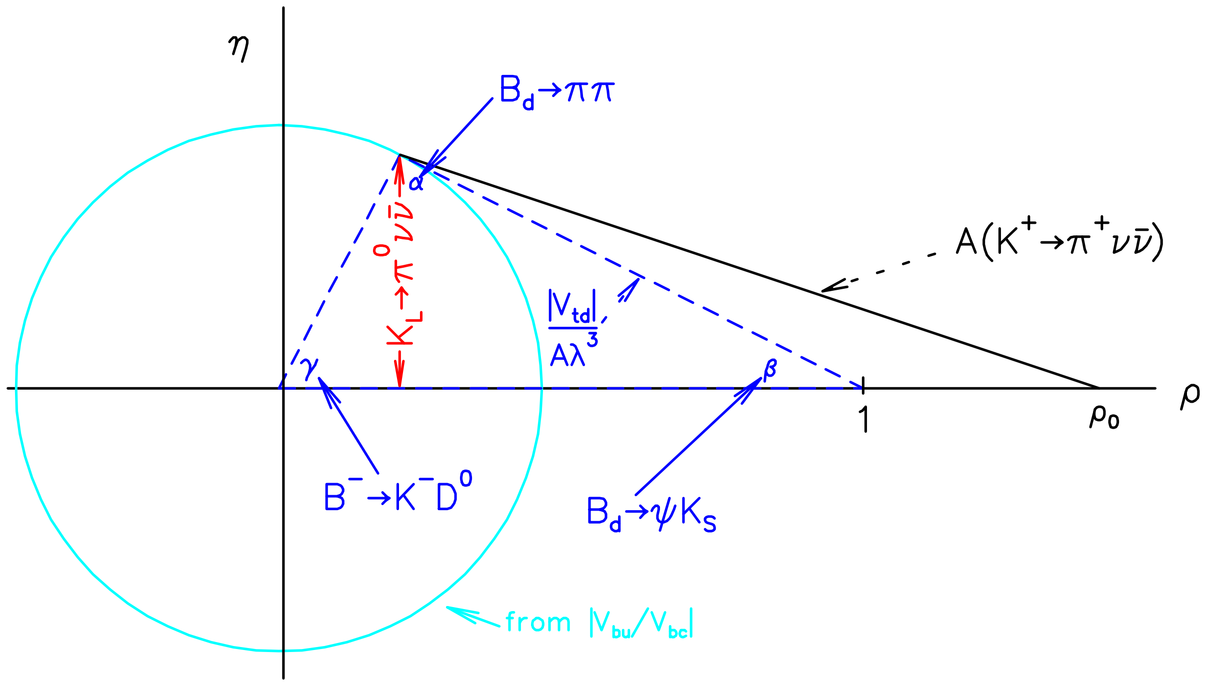
$$U = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 s_3 e^{i\delta} \end{pmatrix}$$

$(c_i \equiv \cos\theta_i ; s_i \equiv \sin\theta_i)$

Wolfenstein parametrization: $\lambda \equiv \sin\theta_c = V_{us}$

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

Standard Model CP violation: η



Extraction of V_{td} from BR$(K^+ \to \pi^+ \nu\bar{\nu})$

- Amplitude contains terms in $V^*{}_{is}V_{id}, i = u, c, t$
- If $|V_{ts}| \simeq |V_{cb}|$, $|V_{td}|$ can be determined.

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

- Hadronic matrix element from isospin analog reaction $K^+ \to \pi^0 e^+ \nu_e$ (+ corrections)
- Long-distance effects small (10^{-13})
- Total theoretical uncertainty $\sim 5\%$

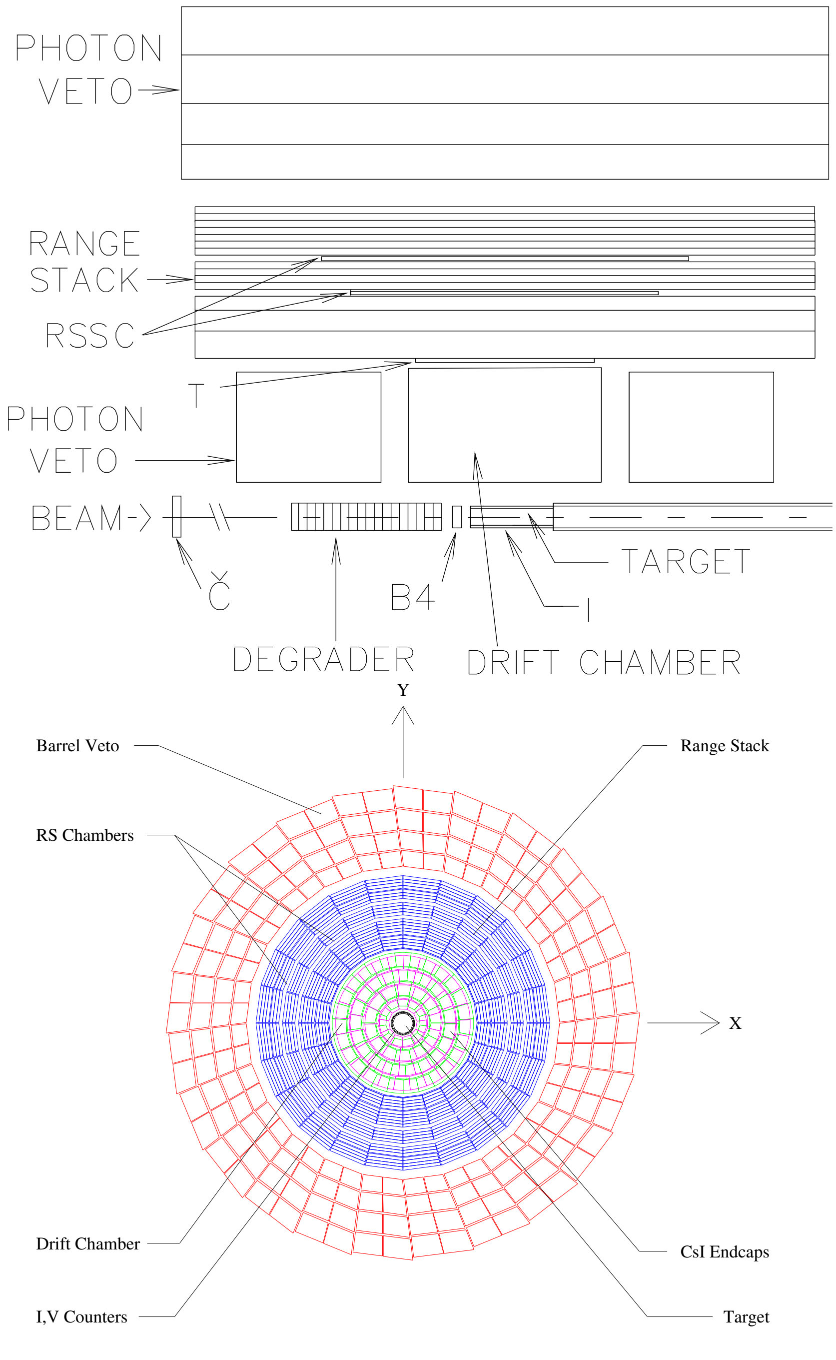
Non-Standard Model Processes

- 4^{th} generation of high-mass fermions
- Supersymmetric intermediate states
- $K^+ \to \pi^+ \nu\bar{\nu}'$
- $K^+ \to \pi^+ X^0 X^{0\prime}$, $\underline{K^+ \to \pi^+ X^0}$ $< 1.1 \times 10^{-10}$ (E787)

Present predicted Standard Model range:

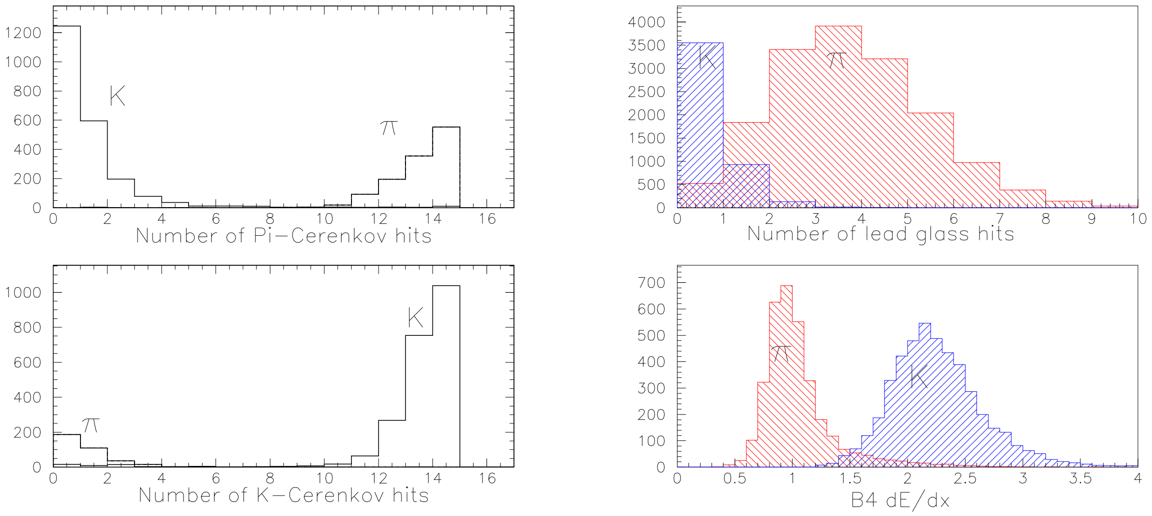
0.5–1.0$\times 10^{-10}$

E787 Detector



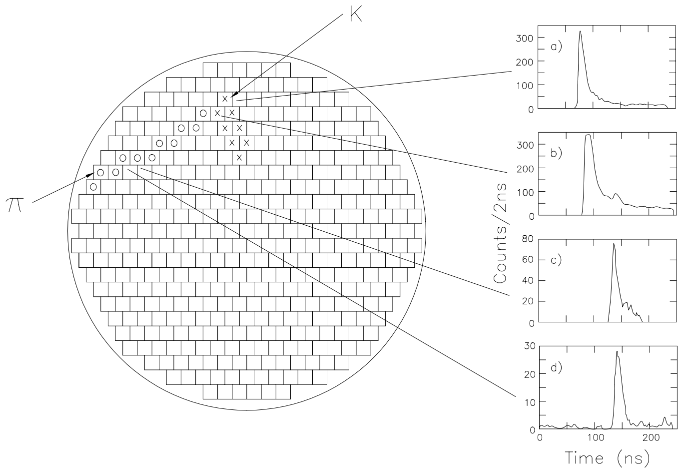
Beamline (LESB3) and instrumentation

- $10^7 K^+/2.5\,s$; $K^+/\pi^+ \sim 4$
- Čerenkov detector
- Lead glass and B4 hodoscope
- Beam wire chambers

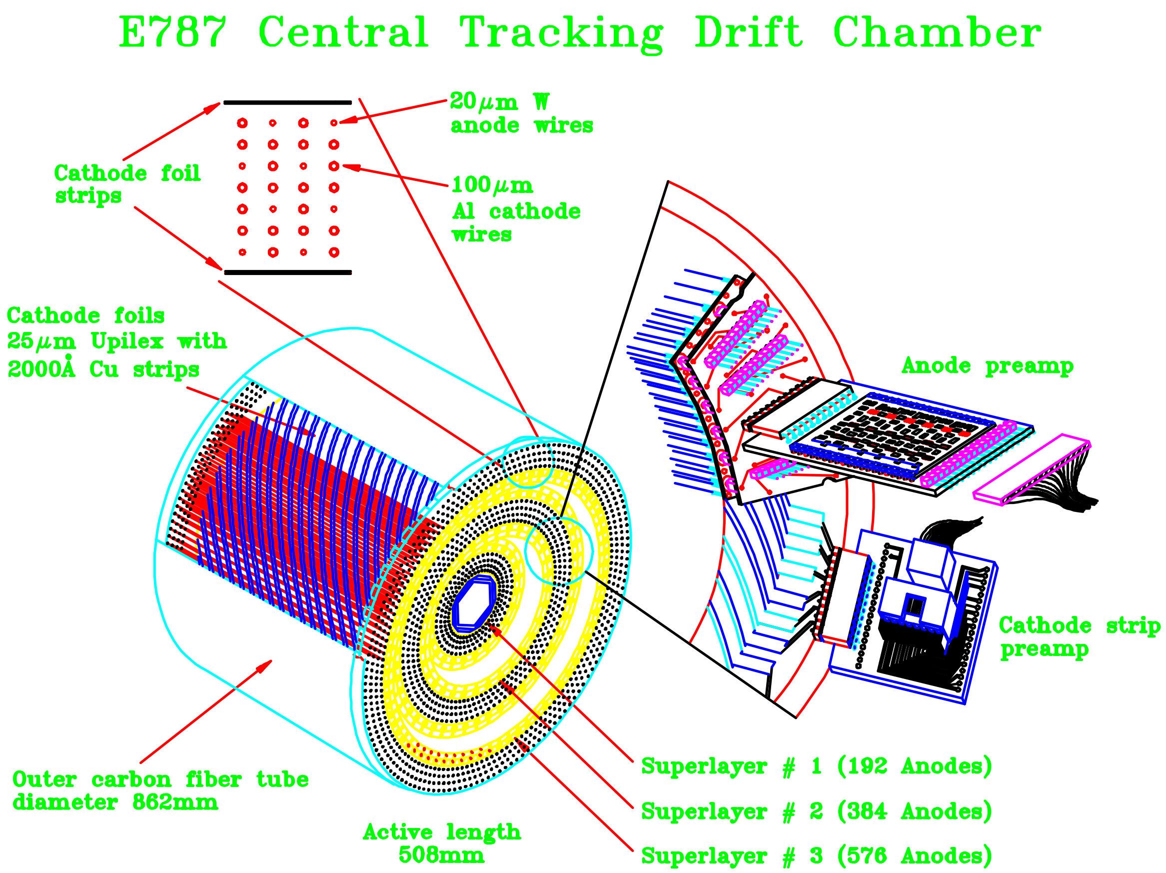


Scintillating fiber target (energy, timing, position)

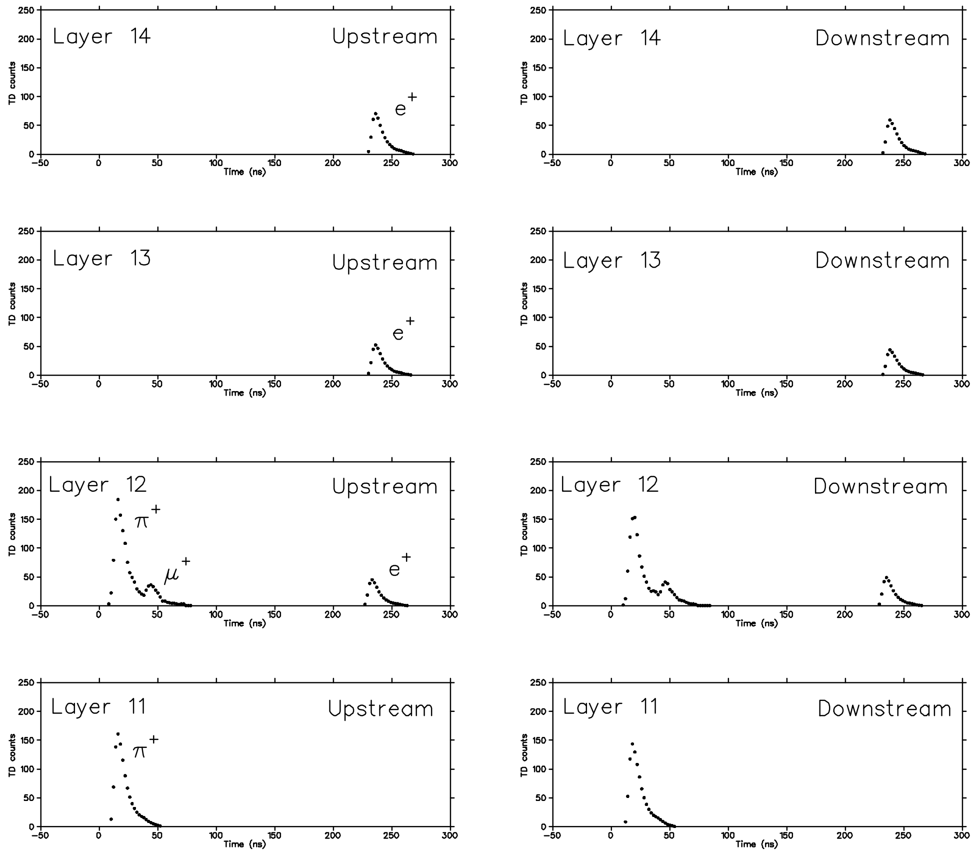
- Read out by 500 MHz GaAs CCD's; $\sigma_t \simeq 600\,\mathrm{ps}$



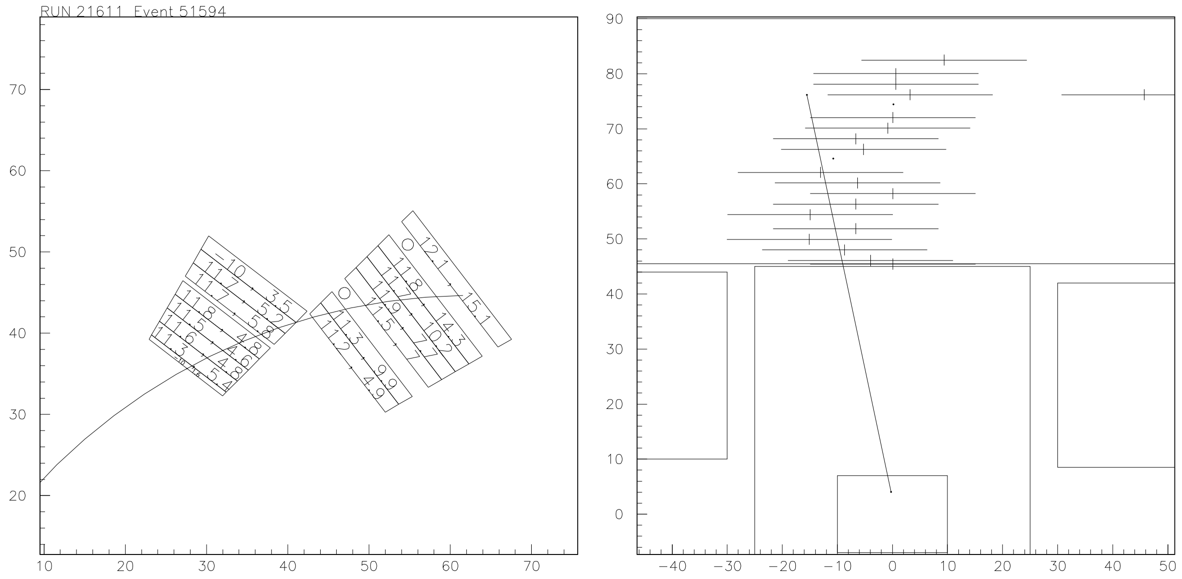
UTC ("Ultra Thin Chamber"): $\sigma_p/p \simeq 1.3\%$



- Range stack: 21 layers of plastic scintillator with 2 layers of embedded straw tubes. Instrumented with 500 MHz transient digitizers (TD's) to record $\pi \to \mu \to e$ decay chain

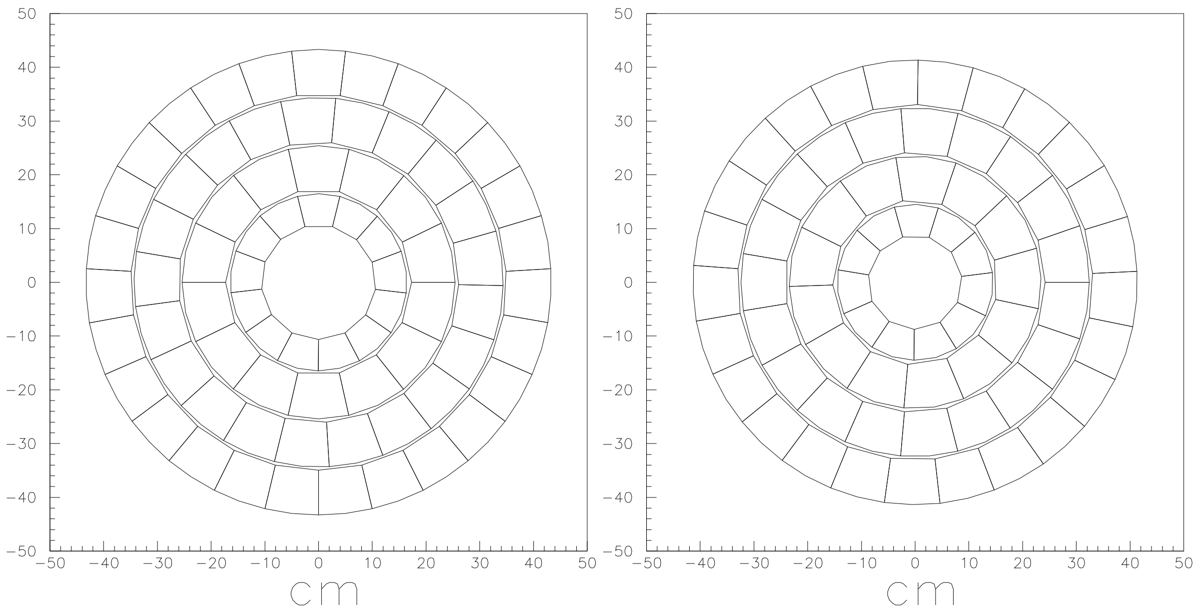


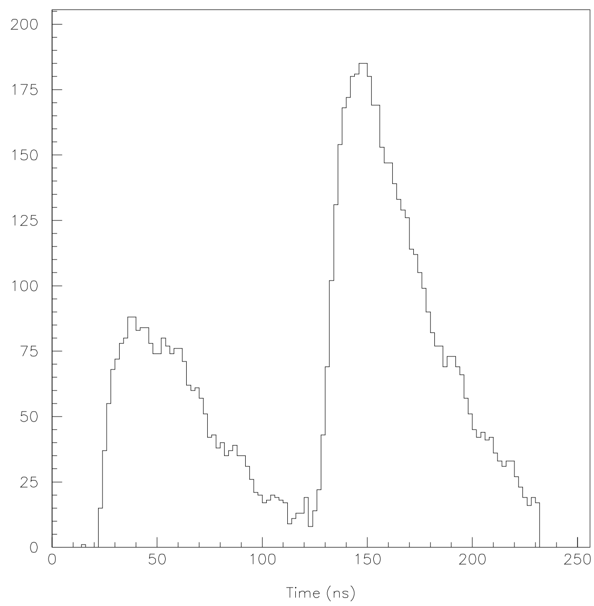
- Range stack straw chambers (RSSC)



- Barrel veto: Lead-scintillator sandwich γ detector
  - 48 azimuthal sectors
  - Covers $\sim 2/3$ of 4π solid angle
  - Pb($1\,$mm)/scintillator($5\,$mm) sandwich
  - Total thickness $15X_0$
  - 48 azimuthal sectors

- End caps: CsI γ detectors, read out by 500 MHz GaAs CCD's.





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.

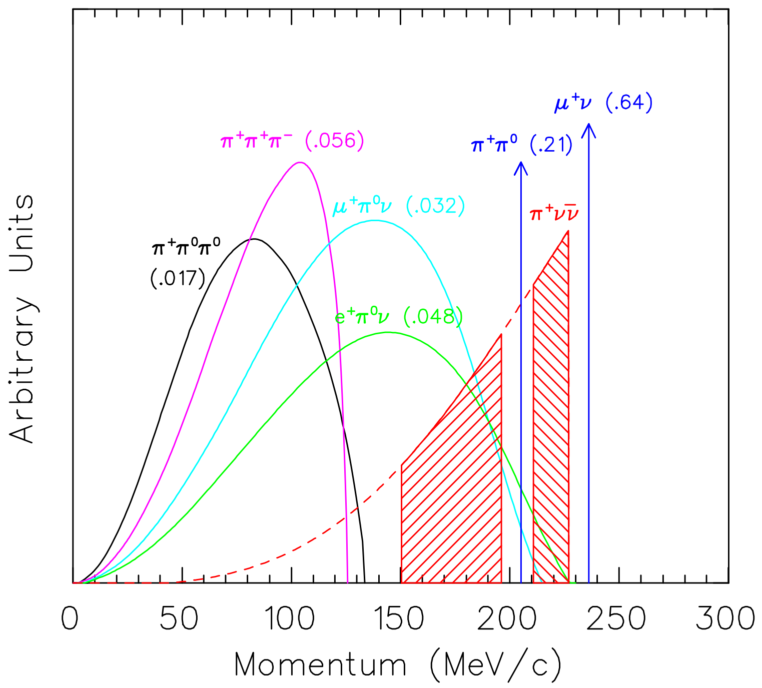
Positive i.d. of decay particle

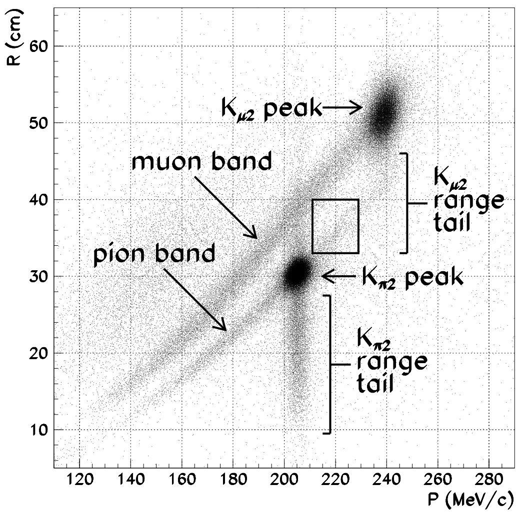
- Precise momentum measurement (UTC).
- Tracking in range stack: measure total energy and range (with target and I-counters).
- Tag $\pi \to \mu \to e$ decay in stopping counter, including μ, e energy/position.

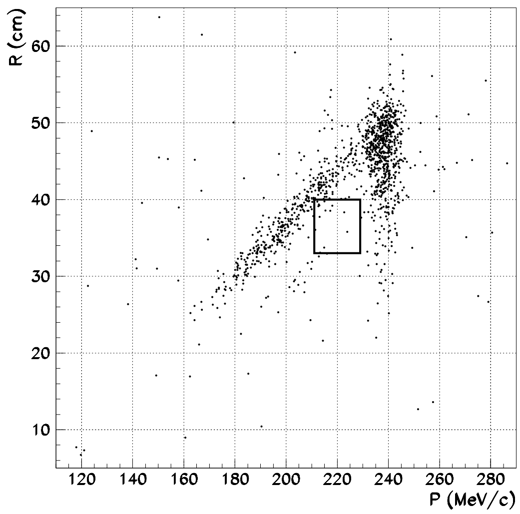
Veto energy *not* associated with $K \to \pi \to \mu \to e$ decay chain

- 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.

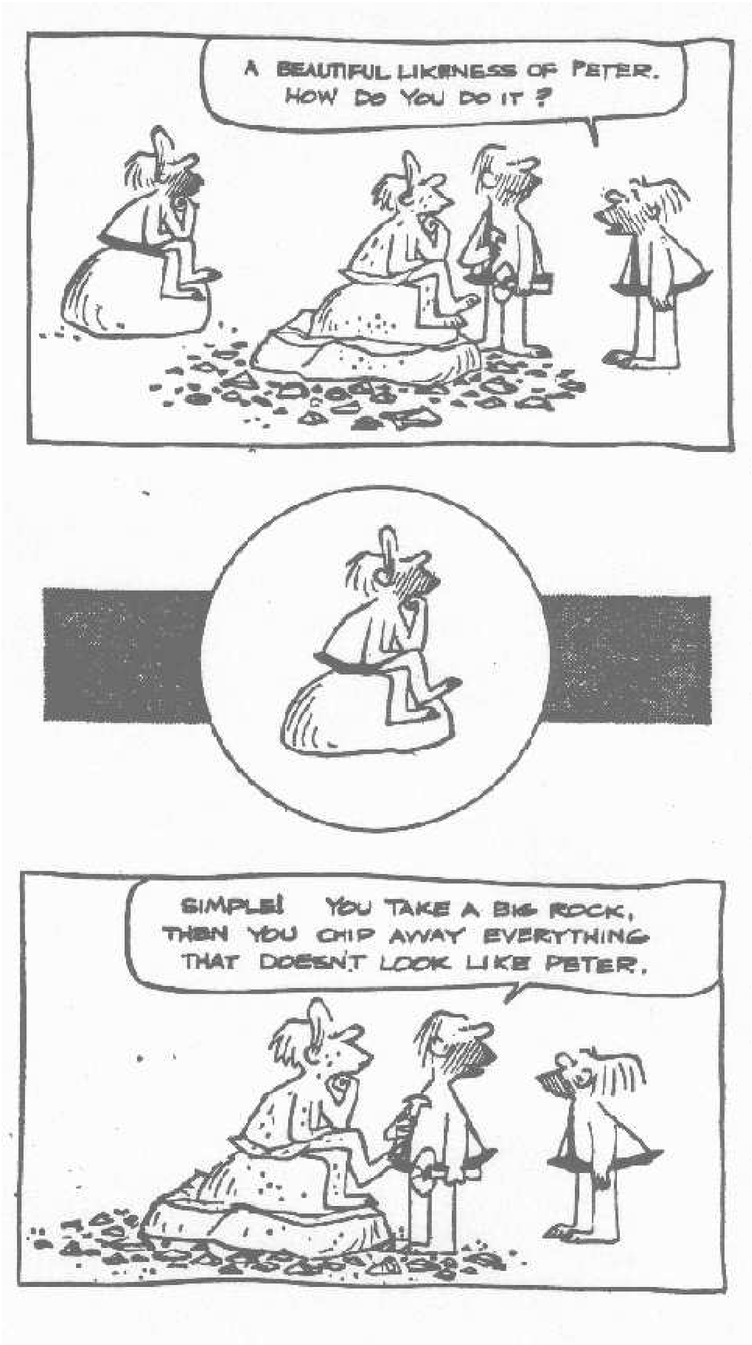
Backgrounds







The Secret of Finding Rare Decays



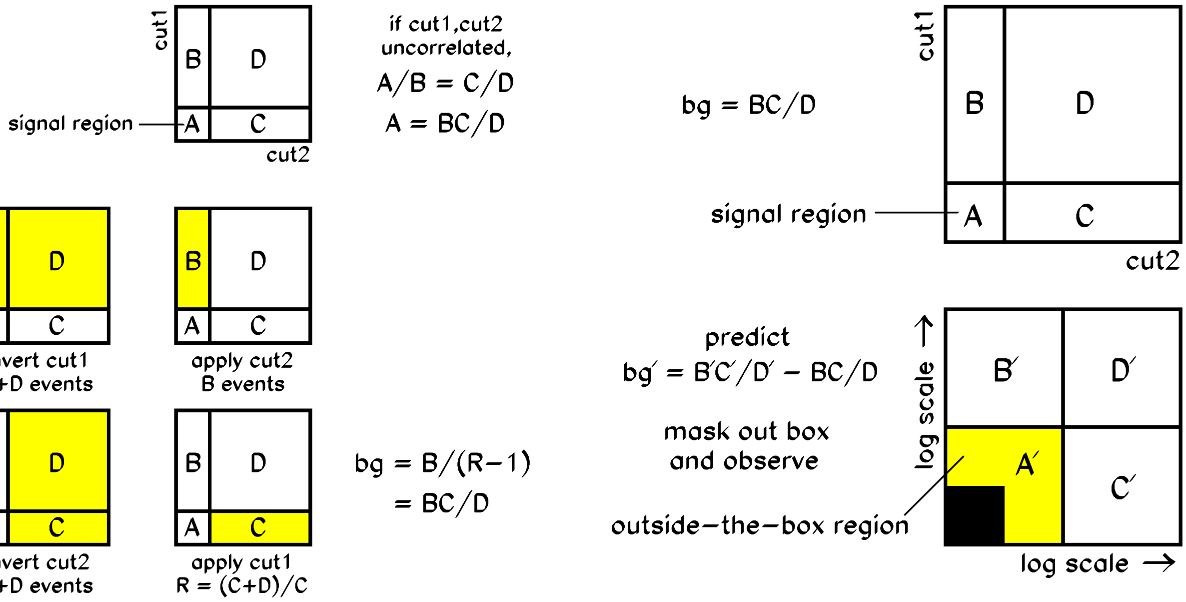
Background		Suppression Methods				
K^+ decays		$\overline{\gamma}$	TD	Kinematics	TG	BM
$\mu^+\nu$	64%		X	X		
$\pi^+\pi^0$	21%	X		X		
$\pi^+\pi^+\pi^-$	5.6%			X	X	
$\pi^0 e^+\nu$	4.8%	X	X	X		
$\pi^0\mu^+\nu$	3.2%	X	X	X		
$\pi^+\pi^0\pi^0$	1.7%	X		X		
$\mu^+\nu\gamma$	0.5%	X	X	X		
π^+-scattering					X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

Aim: Reduce total background to ~ 0.1 event
$\Longrightarrow$ need S/N enhancement of 10^{11}

Background measurement considerations:

- Need to predict b.g. levels *before* looking in signal region to avoid experimental bias.
- Use *data* for background estimates wherever possible.
- How to reliably measure b.g. levels of 10^{-2} events?

Bifurcated Analyses



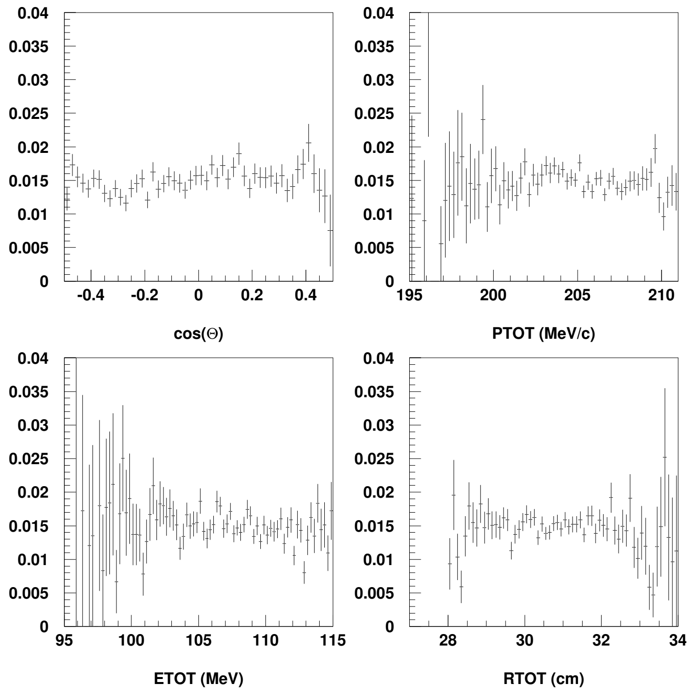
Background	Normalization or crosscheck	Rejection
$K_{\pi 2}$	$\bar{\gamma}$ tagged	Kinematic tagged
$K_{\mu 2}$	TD tagged	Kinematic tagged
Single beam	TG Del. coin. tagged	B4 dE/dx tagged
Double beam	BWPC tagged	B4 2-hit tagged
$K^+ \to K^0$ CEX	CEX cuts tagged	K_S-based M.C.

"Flies in the ointment":

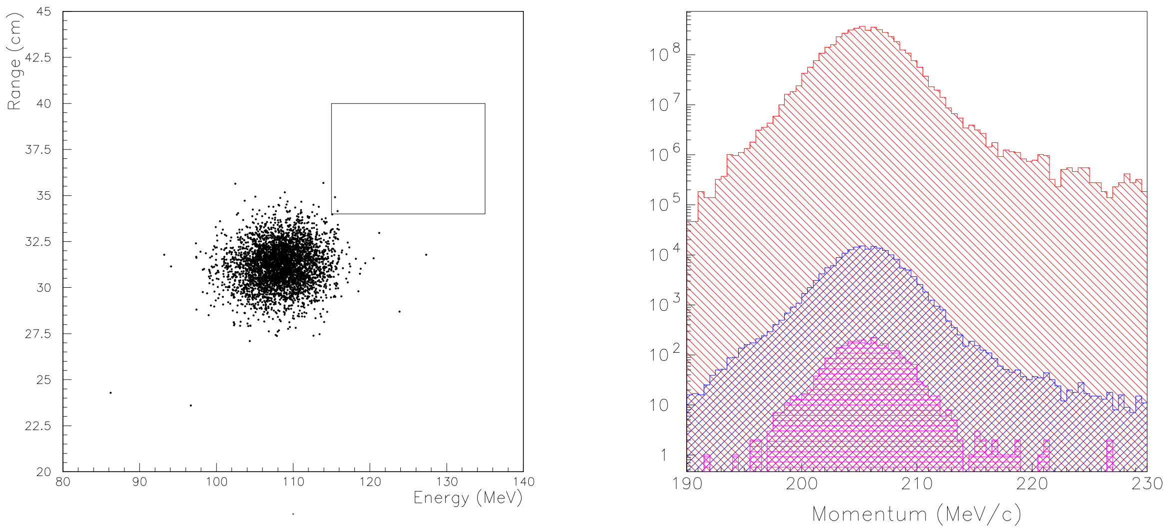
- Undetected correlations
- New or unaccounted-for background

Example: $K^+ \to \pi^+\pi^0$

Check $\bar{\gamma}$ for correlations with kinematics quantities



Bring 2 branches together to make b.g. prediction:



$$N_{b.g.} = N_{Kin.}/R_{\bar{\gamma}}$$

So far: We *think* we know how much background is "inside the box", assuming:

- Bifurcated cuts are not correlated
- All of the backgrounds are accounted for

Construct background probability functions by relaxing and tightening cuts on the different backgrounds:

- $K_{\pi 2}$: adjust kinematics cuts, photon veto parameters
- $K_{\mu 2}$: adjust kinematics cuts, TD cuts
- Beam: adjust coincidence timing windows

Two results:

1. Testable prediction outside the box before looking inside.
2. *A priori* (i.e **unbiased**) evaluation function inside the box for interpretation of events, if any found.

Acceptance: use data wherever possible

- $K_{\mu 2}$
  - Target/UTC/range-stack track reconstruction
  - Target pattern recognition cuts
  - Beam background cuts
  - $\bar{\gamma}$ background cuts

- $K_{\pi 2}$
  - Target dE/dx
  - Range stack/straw chamber z matching

- Beam π-scatter
  - TD cuts (including measurement of τ_{π^+})
  - Kinematics cuts (except target dE/dx)

- $\pi\nu\bar{\nu}$ Monte Carlo
  - Trigger acceptance
  - Geometrical acceptance
  - Momentum acceptance

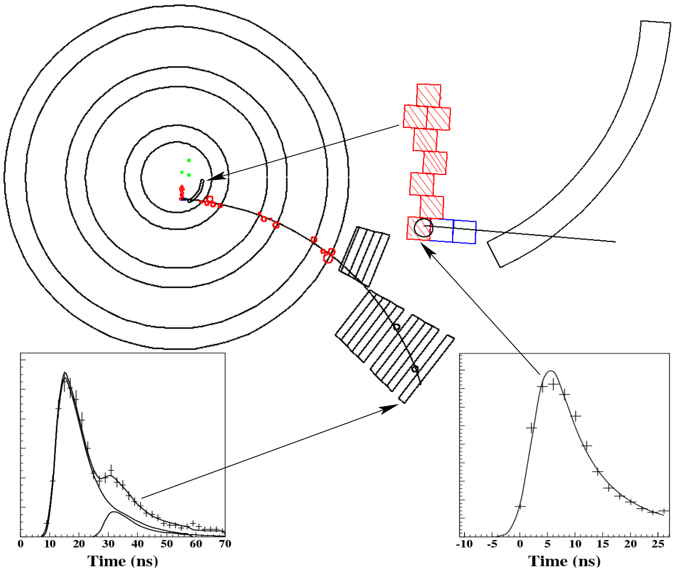
Results from 1995–98 data sets

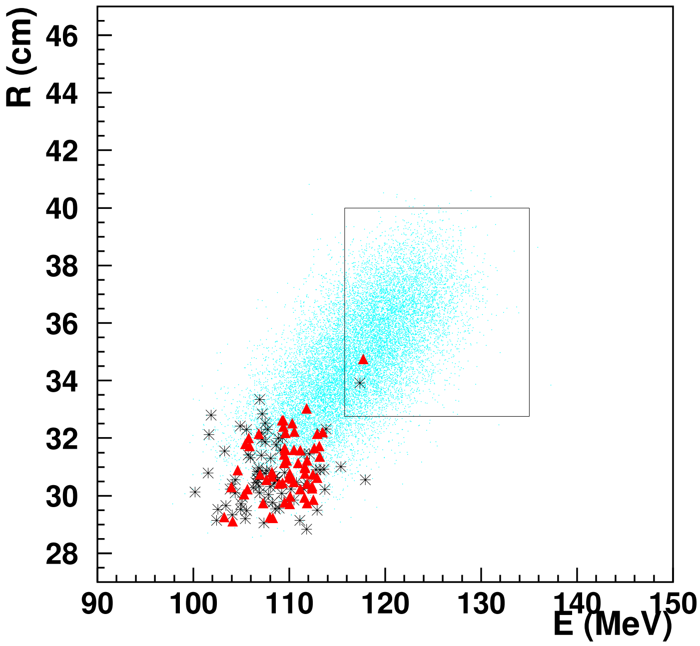
Background	#events in signal region	
	1995–97	1998
$K_{\pi 2}$	0.03 ± 0.01	$0.012^{+0.003}_{-0.004}$
$K_{\mu 2}$	0.02 ± 0.01	$0.034^{+0.043}_{-0.024}$
Beam (1 + 2)	0.02 ± 0.02	0.004 ± 0.001
CEX	0.01 ± 0.01	$0.016^{+0.005}_{-0.004}$
Total background	0.08 ± 0.02	$0.066^{+0.044}_{-0.025}$

Acceptance factors	1995–97	1998
K^+ stop efficiency	0.704	0.702
K^+ decay after 2 ns	0.850	0.851
$K^+ \to \pi^+ \nu \bar{\nu}$ phase space	0.155	0.136
Solid angle acceptance	0.407	0.409
π^+ nucl. int., decay-in-flight	0.513	0.527
Reconstruction efficiency	0.959	0.969
Other kinematic constraints	0.665	0.554
$\pi - \mu - e$ decay acceptance	0.306	0.392
Beam and target analysis	0.699	0.706
Accidental loss	0.785	0.751
Total acceptance	0.0021	0.00196

K^+ stops recorded:
3.2×10^{12} (1995–97)
2.7×10^{12} (1998)
Test by measuring BR$(K^+ \to \pi^+ \pi^0)$

And the answer is. . .





Branching ratio and V_{td}

BR$(K^+ \to \pi^+ \nu\bar{\nu})$ (1995–7) $1.5^{+3.5}_{-1.2} \times 10^{-10}$

BR$(K^+ \to \pi^+ \nu\bar{\nu})$ (1998) $1.9^{+4.4}_{-1.5} \times 10^{-10}$

N.b. Both individual results assume *no background*.

We would like to combine the results, taking backgrounds into account.

We would also like to take maximum advantage of our *unbiased* "inside-the-box" evaluation functions.

Candidate event properties

Define the S/N "figure of merit"

$$f_i \equiv 7.5 \times 10^{-11} A_i N_K / b_i$$

Event	Kinematic quantities			f_i
	P	R	E	
A	218.2 ± 2.7	34.8 ± 1.2	117.8 ± 3.5	35
C	213.8 ± 2.7	33.9 ± 1.2	117.1 ± 3.6	3.6
B2	226.5 ± 2.9	37.2 ± 1.3	121.3 ± 3.7	0.7

Event B2

- Lies "just outside the box"
- Kinematically "perfect", but fails $\pi \to \mu$ i.d. neural net cut, mainly due to small τ_π
- Consistent with b.g. expectations, but *could* be "signal contamination" of background sample.
- *Not* considered in final BR measurement

Use method by T. Junk [NIM **A434**, 435 (1999)]

- Use an optimal "test statistic" X, the likelihood ratio:

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

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

b_i, s_i : ecpected signal, background in each bin
d_i : #observed events in each bin

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

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

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

- Get the conf. lim. by finding (and summing) all sets of d_i that give $X \leq X_{obs}$ for $s+b$, and b only:

$$
\begin{aligned}
CL_{s+b} &= P_{s+b}(X \leq X_{obs}) \\
&= \sum_{X(\{d'_i\}) \leq X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d'_i}}{d'_i!} \\
CL_b &= P_b(X \leq X_{obs}) \\
&= \sum_{X(\{d'_i\}) \leq X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(b_i)}(b_i)^{d'_i}}{d'_i!}
\end{aligned}
$$

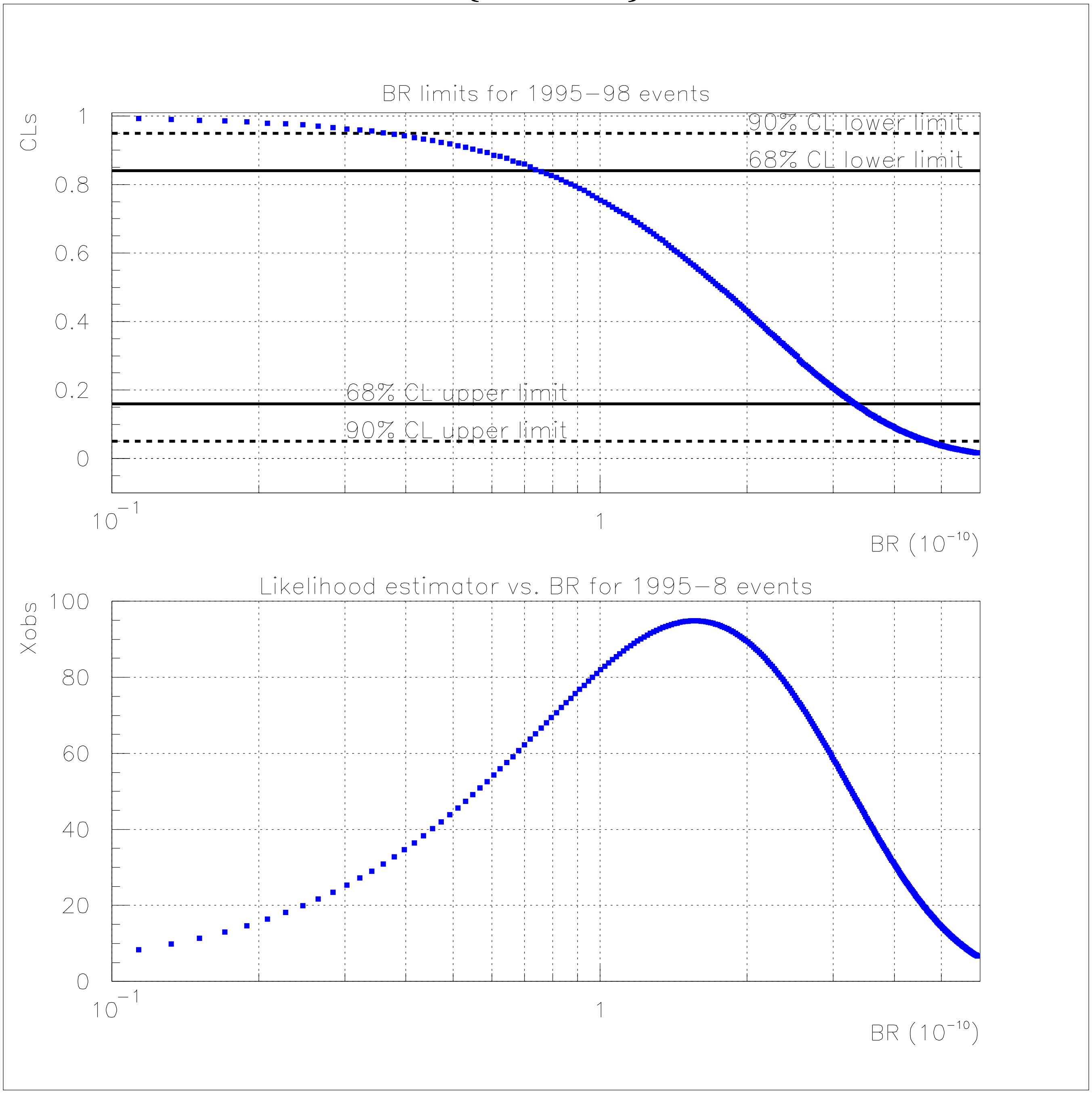
- Finally, get the (upper limit) BR($K^+ \to \pi^+\nu\bar{\nu}$) from the "Modified Frequentist" confidence level:

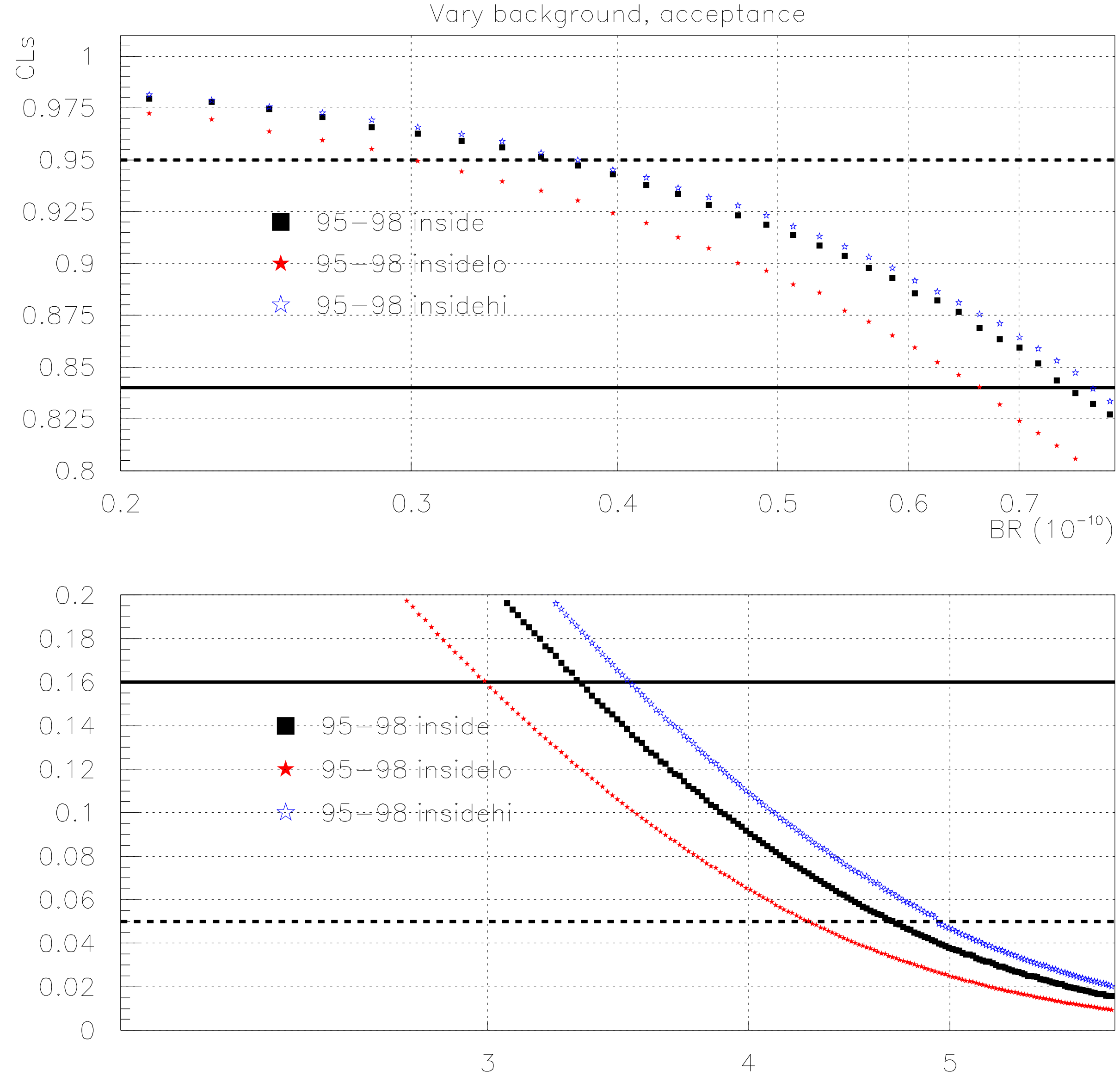
$$CL_s = CL_{s+b}/CL_b$$

- Scan over large range of "expected signal" to get a complete set of confidence limits.

- 1998: divide signal region into 486 bins
- 1995–97: divide signal region into 2 bins

Feed the sets of $\{s_i, b_i, d_i\}$ into CL program





Vary background, acceptance
CLs
1
0.975
0.95
0.925
0.9
0.875
0.85
0.825
0.8
0.2
0.3
0.4
0.5
0.6
0.7
BR (10^{-10})
95−98 inside
95−98 insidelo
95−98 insidehi
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
3
4
5
95−98 inside
95−98 insidelo
95−98 insidehi

$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

84% CL limits (68% CL int.)	90% CL limits (80% CL int.)	95% CL limits (90% CL int.)	99% CL limits (98% CL int.)
[0.749,3.323]	[0.560,3.886]	[0.366,4.694]	[0.132,6.452]
Test effects of “just-outside-the-box” event			
[0.778,3.225]	[0.577,3.754]	[0.381,4.489]	[0.151,6.103]

BR central value (10^{-10})		
median (50% CL)	max likelihood	1 - CLb
1.76	1.570	0.000213

(I.e. Probability of background only: 0.02%)

Extracting $|V_{td}|$

Assume:

- Unitarity,
  $\bar{m}_t(m_t) = 166 \pm 5\,\mathrm{GeV/c^2}$, $V_{cb} = 0.041 \pm 0.002$

But *not*:

- V_{ub}, ϵ_K

$$0.007 < |V_{td}| < 0.030$$

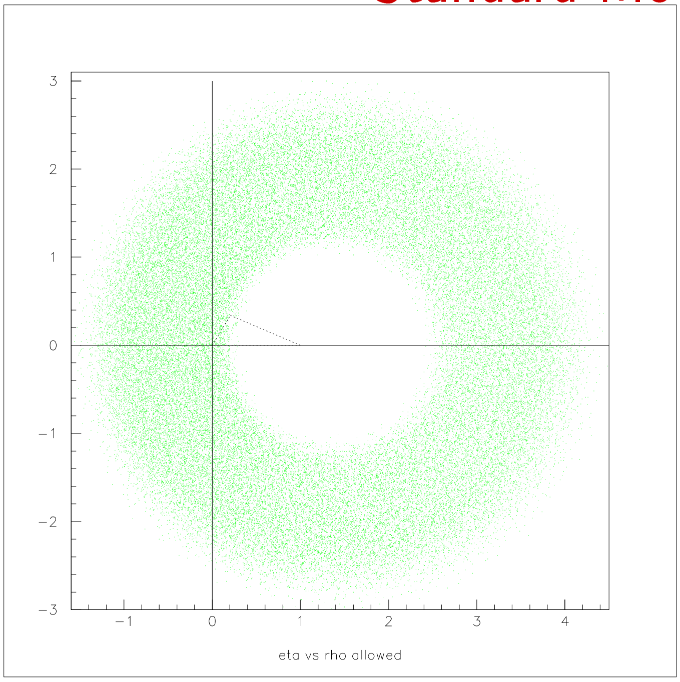
Or: limits independent of B, ϵ_K, ϵ'/ϵ

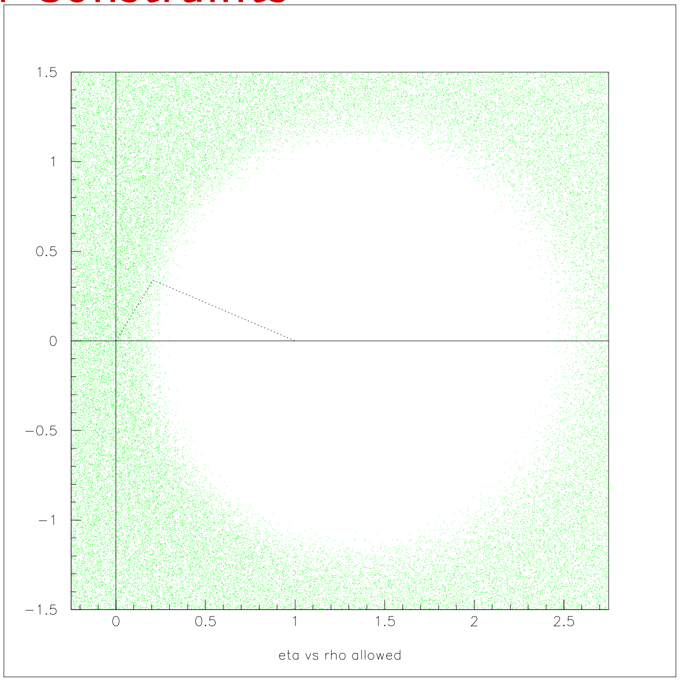
$$2.9 \times 10^{-4} < |\lambda_t \equiv V_{ts}^* V_{td}| < 1.2 \times 10^{-3}$$

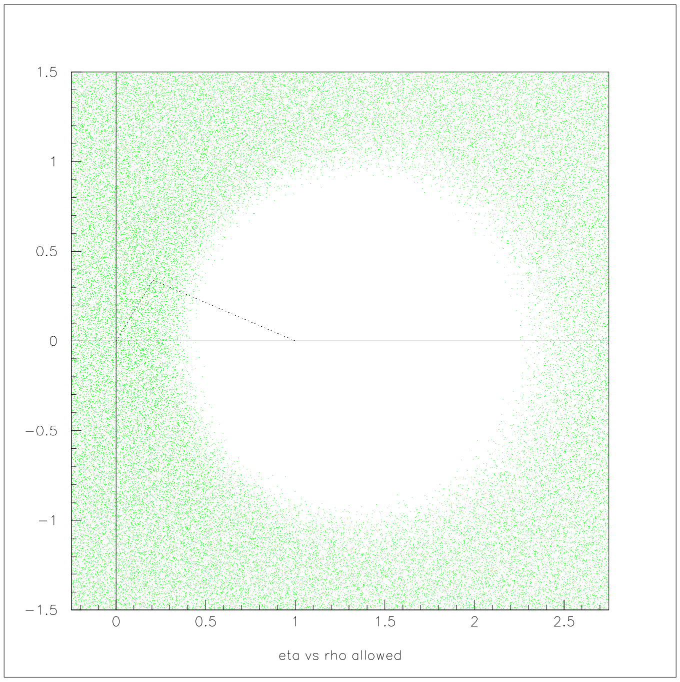
$$-0.88 \times 10^{-3} < Re(\lambda_t) < 1.2 \times 10^{-3}$$

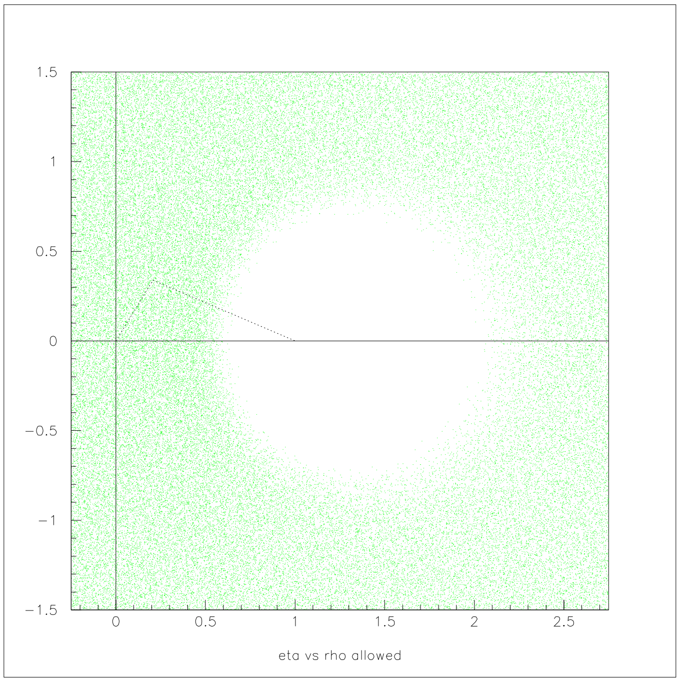
$$Im(\lambda_t) < 1.0 \times 10^{-3}$$

Standard Model Constraints









The E949 Collaboration

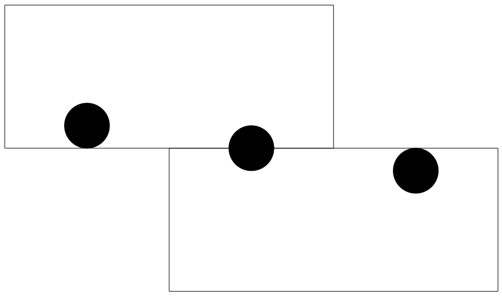
- Canada
  TRIUMF, UBC, Alberta
- U.S.
  BNL, FNAL, New Mexico
- Japan
  Fukui, KEK, Kyoto, Osaka
- Russia
  IHEP, INR

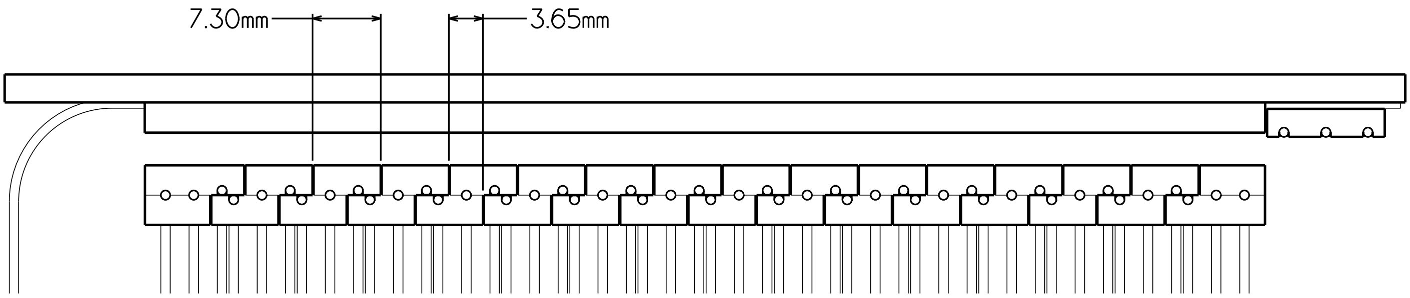
E949 upgrades

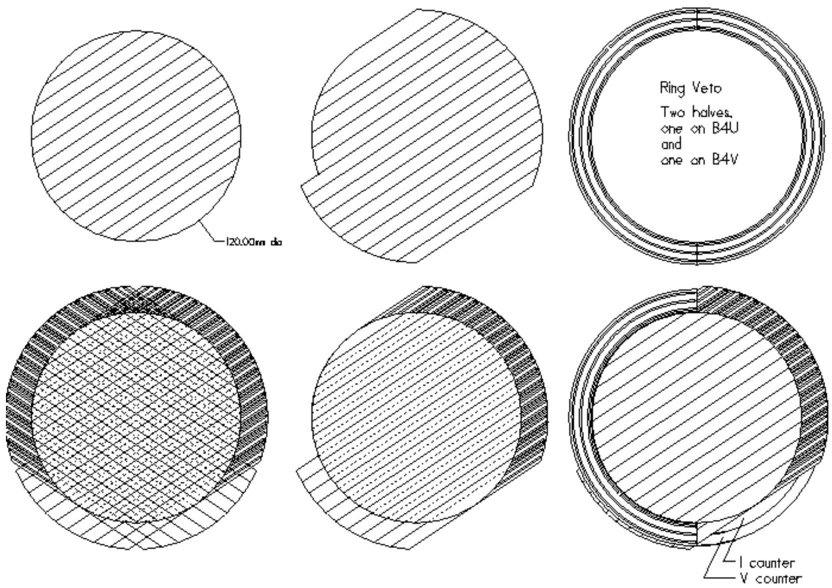
- More, better beam:
  - Longer spill, higher duty factor:
    65 Tp/spill, 4.1 sec. spill out of 6.4 sec. cycle
    5M *live* K stops/spill
  - $p_K = 730\,\mathrm{MeV/c}$
  - 60 weeks of running†
  - Goal: 5–10 SM events

- 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
    Ring veto improves 2-beam background rejection
  - Segmented active degrader
  - Downstream photon veto
  - New PLD trigger boards: Reduced deadtime
  - RS TDC readout: e^+ i.d. without TD info.
    Smaller data size, reduced readout time
  - RS monitor system: Improved energy calibration
  - New RSSC elcectronics: better z in RS

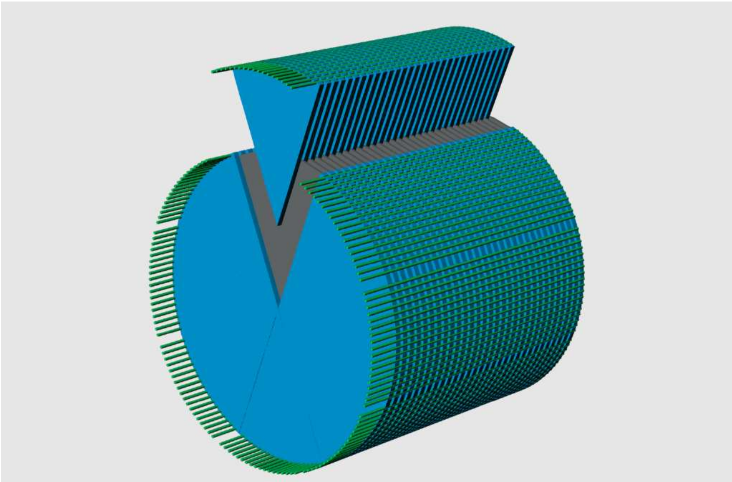
New B4 hodoscope and ring veto

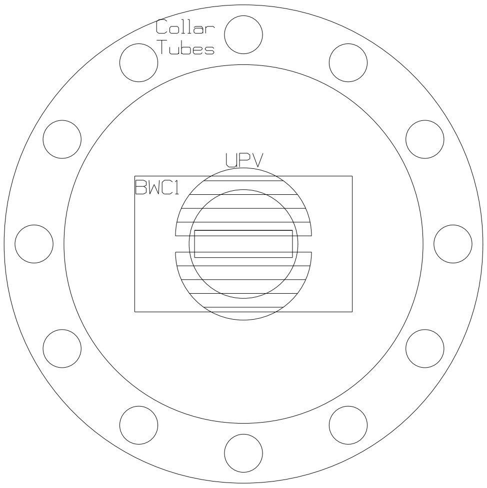






Segmented active degrader and upstream photon veto

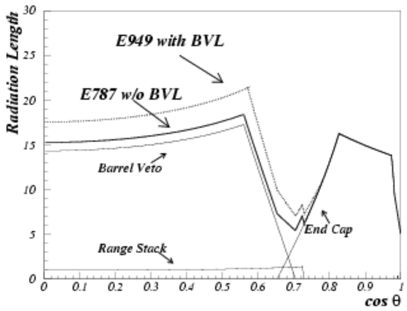


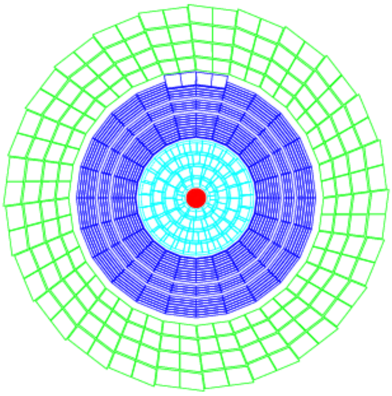


Barrel Veto Liner (BVL)

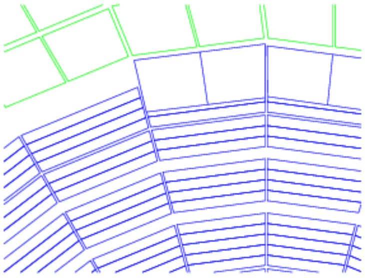
Thickens barrel veto by 2.3 X_0
Plugs 45^o thin spot
Gives factor 2-3 in π^0 rejection

Largest single E949 project



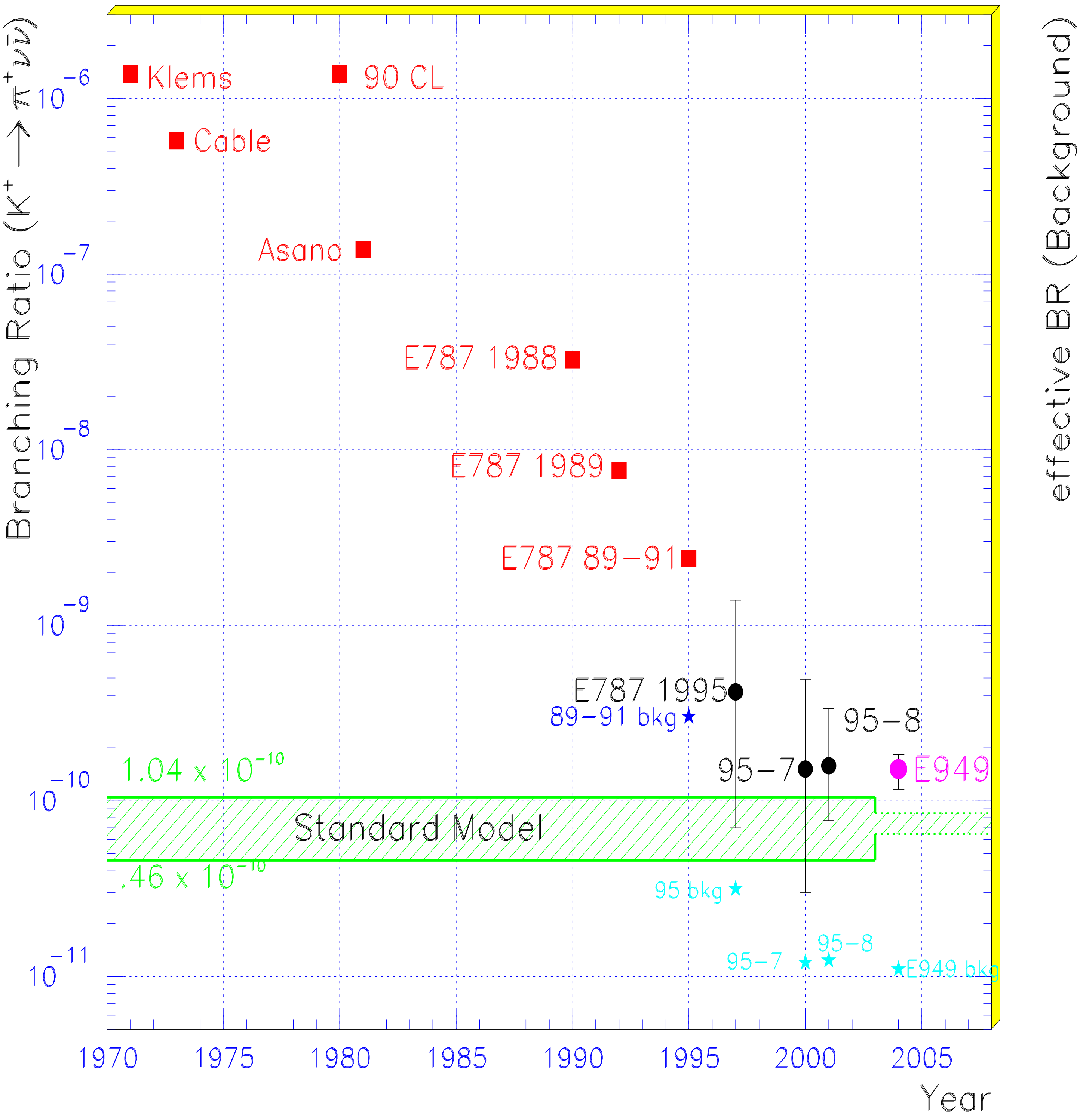


End view with 2 sectors installed



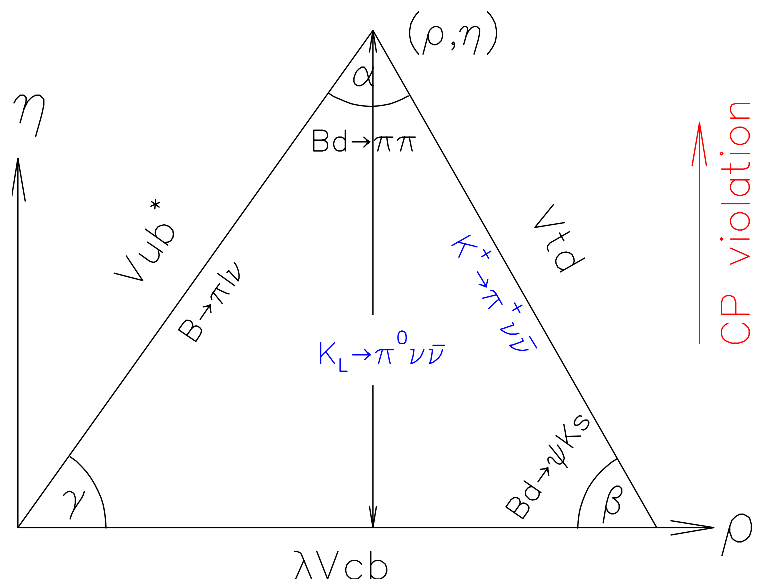
Closer view of end configuration

History of the Search for $K^+ \to \pi^+ \nu \overline{\nu}$



Summary

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



Final E787 Results for $K^+ \to \pi^+ \nu\bar{\nu}$

- 2 events found consistent with $K^+ \to \pi^+ \nu\bar{\nu}$
- $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$
- $P_b \sim 0.02\%$
- $B(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$

- Limits on Standard Model parameters:
  - Assume unitarity, m_t, V_{cb}

$$0.007 < |V_{td}| < 0.030$$

  - Results independent of B system, ϵ_K, ϵ'/ϵ

$$2.9 \times 10^{-4} < |\lambda_t \equiv V_{ts}^* V_{td}| < 1.2 \times 10^{-3}$$

$$-0.88 \times 10^{-3} < Re(\lambda_t) < 1.2 \times 10^{-3}$$
$$Im(\lambda_t) < 1.0 \times 10^{-3}$$

E787→E949: near lower limit of SM predictions

- Now taking data!
- Upgrades for increased intensity, decreased b.g.
- E949: Aimed at $\leq 10^{-11}$ or 5-10 SM events.

- **. . . or possibly 10–20 *non-Standard-Model* events!**