E949 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Results

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- Introduction
- Experimental method
- Results
- Outlook

BROOKHAVEN NATIONAL LABORATORY

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Heavy Quarks and Leptons

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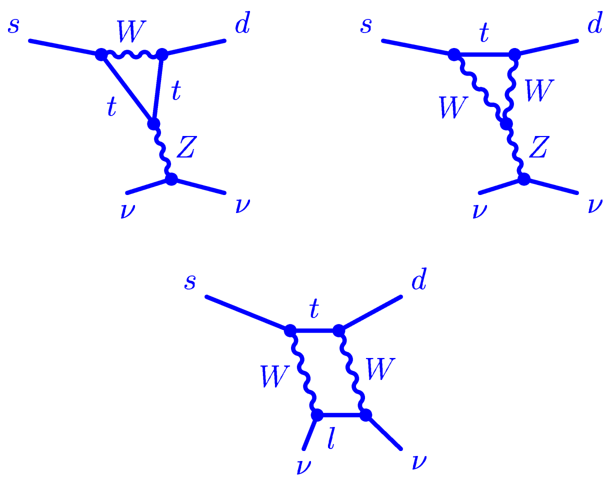
$K \to \pi\nu\bar{\nu}$ in the Standard Model and beyond



- Negligible long distance effects (10^{-13})
- Hadronic matrix element via isospin analog $K^+ \to \pi^0 e^+ \nu$

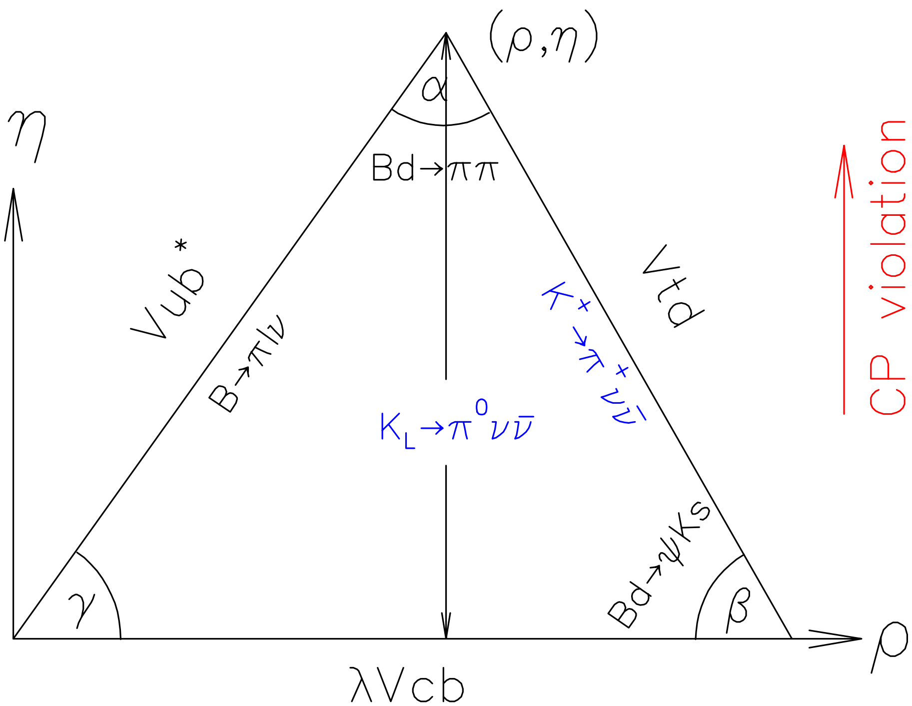
	$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$\mathcal{B}(K^0_L \to \pi^0\nu\bar{\nu})$
top dep.	$\lvert V^*_{ts}\ V_{td}\rvert$	$Im(V^*_{ts}\ V_{td})$
Msmt[a,b,c]	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	$< 5.9 \times 10^{-7}$
		$< 4.4 \times \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}$
SM[d]	$(0.78 \pm 0.12) \times 10^{-10}$	$(0.30 \pm 0.06) \times 10^{-10}$
SM Uncert.[f]	7%	2%
MFV[g]	1.91×10^{-10}	0.99×10^{-10}
EZP[h]	$(0.75 \pm 0.21) \times 10^{-10}$	$(3.1 \pm 1.0) \times 10^{-10}$

Limits are at 90% CL.

References

(a) PRL **88** (2002) 041803 (b) PR **D61** (2000) 072006
(c) PL **B398** (1997) 163 (d) `hep-ph/0405132`
(e) `hep-ph/0212321` (f) `hep-ph/0101336`
(g) Minimal Flavor Violation, Buras, `hep-ph/0310208`
(h) Enhanced Z^0 Penquins, Buras *et al.*, `hep-ph/040211`

"Golden" modes and the CKM unitarity triangle



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, E391a
$\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S}; t)$	BaBar, Belle
$\Delta m_s/\Delta m_d$	CDF, D0

Comparison of β from $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})/\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ and $\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S}; t)$ is perhaps **the** definitive test of CP violation in the SM.

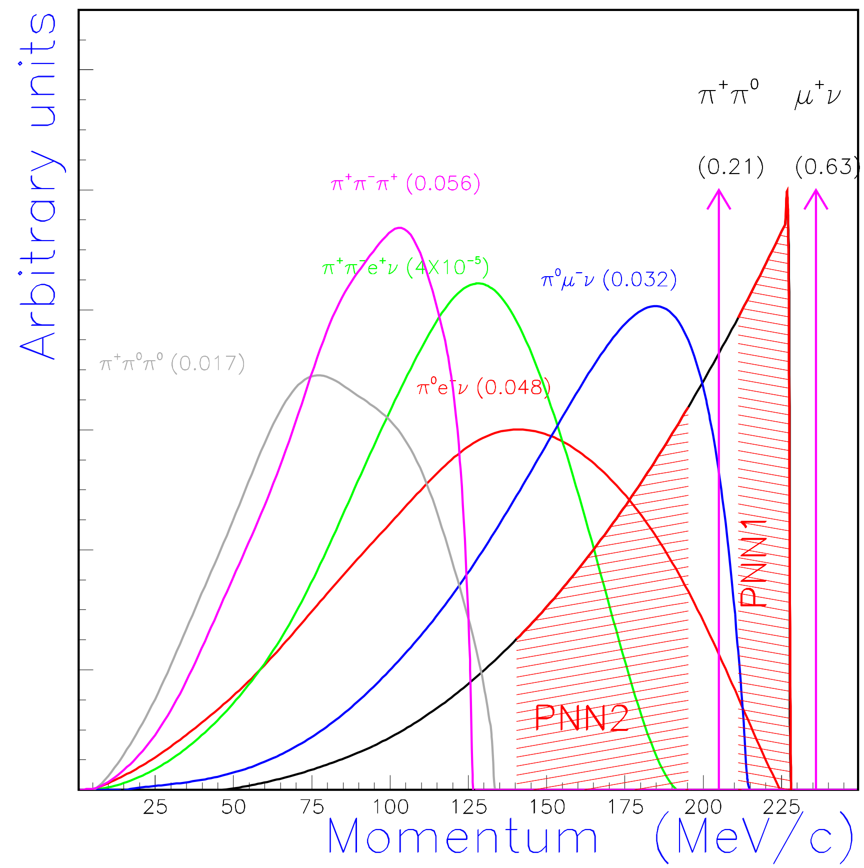
Comparison of $|\mathrm{V}_{\mathrm{td}}|$ from $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ and $\Delta m_s/\Delta m_d$ is an important test of the SM.

Name	**"PNN2"**	**"PNN1"**
P_π (MeV/c)	[140,195]	[211,229]
Years	1996- 97	1995-98
Stopped K^+	1.7×10^{12}	5.9×10^{12}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

E787
$K^+ \to \pi^+ \nu\bar{\nu}$
results

PNN1: PRL **88**, 041803 (2002).

PNN2: Limit at 90%CL is combined result from 1996 (PL **B537**, 211 (2002)) and 1997 (hep-ex/0403034) data.



$K^+ \to \pi^+\nu\bar{\nu}$ and background rates

Measure everything possible.

- Independent measurements of range(R), energy(E) and momentum(P) of π^+
- Positive identification of incoming K^+ and outgoing π^+
- Veto extra photons and charged particles

Background must be suppressed by 10^{11}

Measure background with data — set cuts based on 1/3 of data and evaluate bkgd with remaining 2/3.

Process	Rate
$K^+ \to \pi^+\nu\bar{\nu}$	0.78×10^{-10}
$K^+ \to \pi^+\pi^0$	$2113000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu$	$6343000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu\gamma$	$55000000.00 \times 10^{-10}$
$K^+ \to \pi^0\mu^+\nu$	$327000000.00 \times 10^{-10}$
CEX	$\sim 46000.00 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.00 \times 10^{-10}$

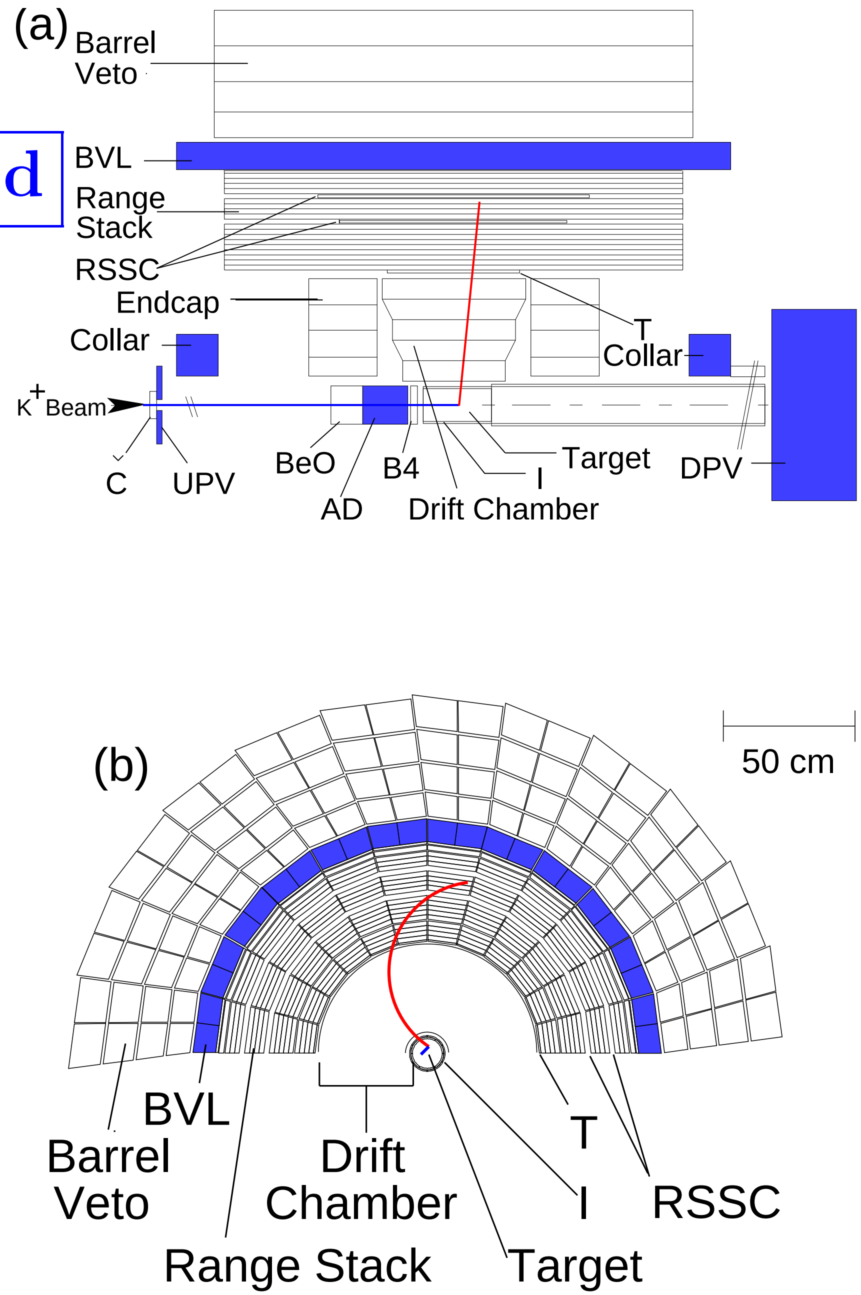
CEX $\equiv (K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+\ell^-\nu$

ℓ^- is μ^- or e^-

$K^+ n \to K^0 X$ rate is empirically determined.

E949 experimental method

- ~ 700 MeV/c K$^+$ beam
- Stop K$^+$ in scint. fiber target
- Wait at least 2 ns for K$^+$ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, charged tracks
- **New/upgraded detector elements**



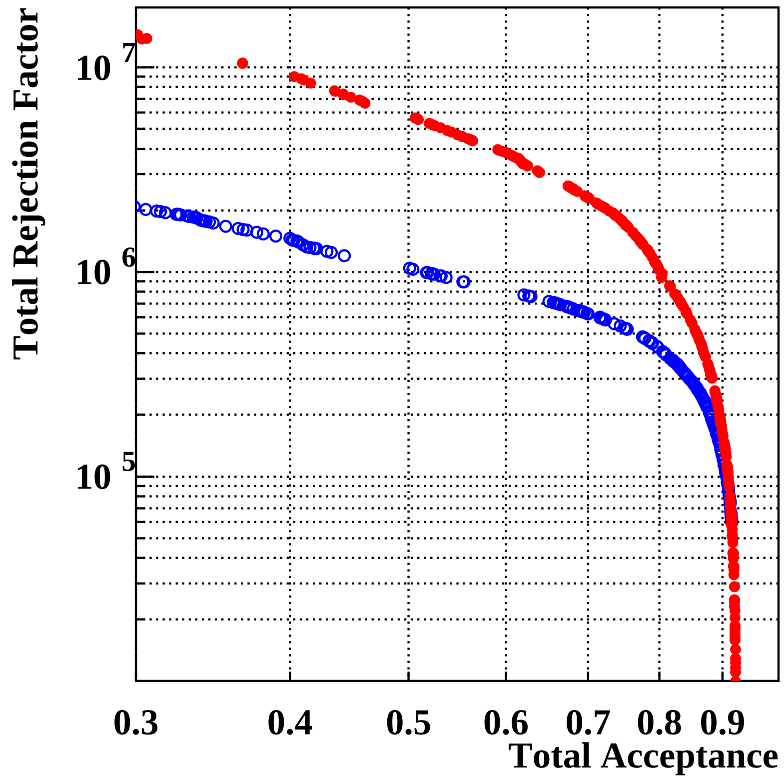
E949 status for 2002 data taking

Upgrades to E787:

- More protons/sec from AGS
- Improved photon veto hermeticity (Figure)
- Improved tracking and energy resolution
- Higher rate capability due to DAQ and trigger improvements

Not optimal in 2002:

1. Spill duty factor.
2. Proton beam momentum.
3. K/π electrostatic separators.



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

E787 and E949 analysis strategy

- **"Blind" analysis. Don't examine signal region until all backgrounds verified.**
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu\bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+\pi^0)$.

Background suppression

Source	Suppresion method: Kinematics	Particle ID	Veto	Timing
$K^+ \to \pi^+\pi^0$	$\surd$		$\surd$	
$K^+ \to \mu^+\nu(\gamma)$	$\surd$	$\surd$	$(\surd)$	
CEX			$\surd$	$\surd$
Scattered beam		$\surd$		$\surd$

$\mathrm{CEX} \equiv K^+n \to K^0p\ ,\ K^0_L \to \pi^+\ell^-\nu$

Particle ID includes K^+/π^+ separation by Cherenkov and dE/dx measurements in beam elements and π^+/μ^+ separation by dE/dx measurements in the target and range stack as well as detection of the $\pi \to \mu \to e$ decay chain in the range stack.

Veto includes both photon and charged particle vetoing

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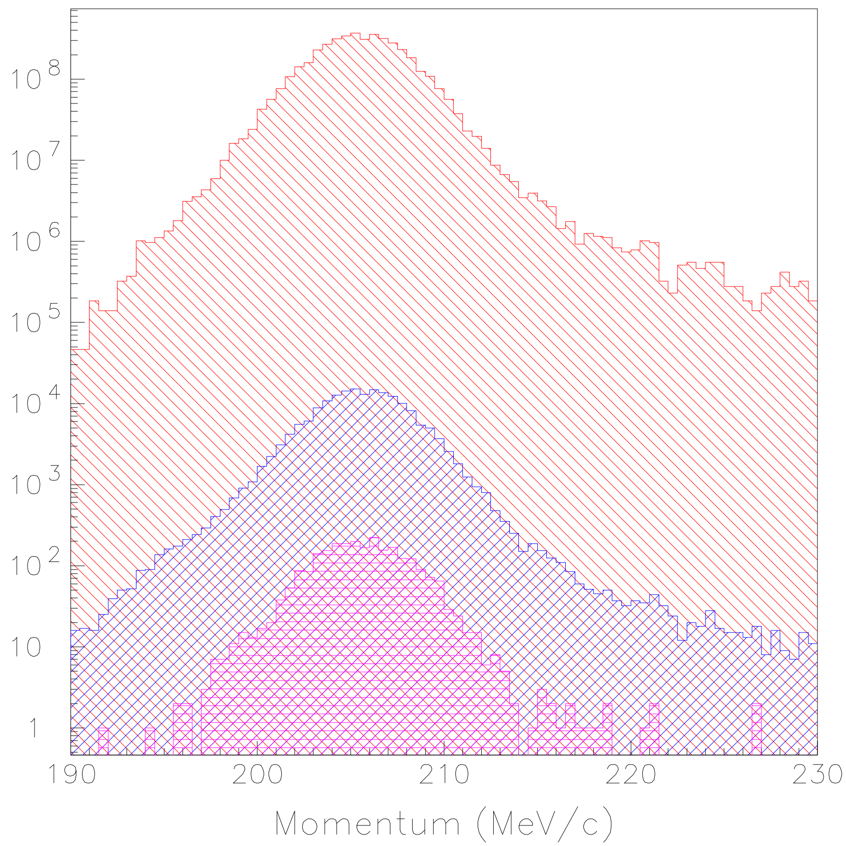
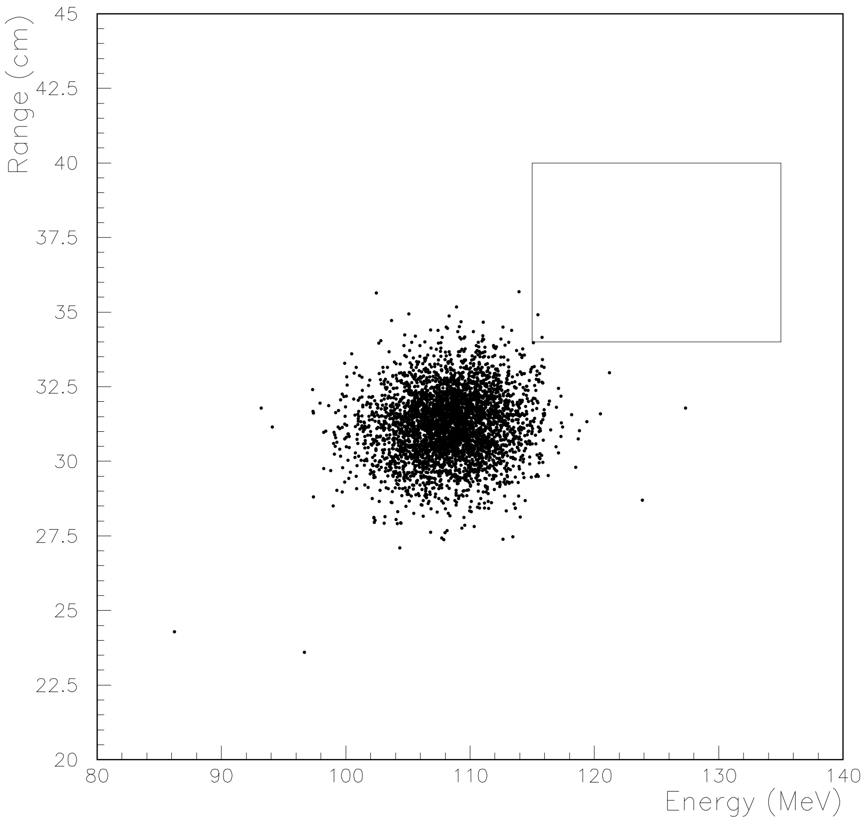
Example: $K^+ \to \pi^+\pi^0$ background rejection





Left: Kinematically select $K^+ \to \pi^+\pi^0$ and apply the photon veto. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in P, R, E.

E787 and E949 analysis strategy

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- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+ \pi^0)$.

Verifying background rates by loosening cuts

Define rejection power $\equiv 1$ when cuts are set to produce pre-determined signal region ("signal box").

Relax cut to reduce rejection by $\times 10$. New, larger region should have $10\times$ background of signal box.

Example: For $K^+ \rightarrow \pi^+\pi^0$ background, simultaneously loosen photon veto (PV) and kinematic (KIN) cuts each by $\times 10$. Expect $10 \times 10 = 100$ times more background than that of the signal box.

Compare background prediction with observation near signal region

	PV×KIN	10×10	20×20	20×50	50×50	50×100
$K_{\pi 2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD×KIN	10×10	20×20	50×50	80×50	120×50
$K_{\mu 2}$	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD×KIN	10×10	20×20	50×20	80×20	80×40
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

$K_{\pi 2} \equiv K^+ \to \pi^+\pi^0$; $K_{\mu 2} \equiv K^+ \to \mu^+\nu$;

$K_{\mu m} \equiv K^+ \to \mu^+\nu\gamma$, $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\pi^0$ with $\pi^+ \to \mu^+\nu$ decay in flight

TD$\equiv \pi \to \mu \to e$ identification, PV≡Photon Veto rej., KIN≡ kinematic rej.
$M \times N \equiv$ reduction in rejection with respect to signal region

Compare background prediction with observation near signal region

Quantify consistency: Fit $N_{\rm obs} = cN_{\rm pred}$ and expect $c = 1$.

Background	c	χ^2 Probability	Total background
$K_{\pi 2}$	$0.85^{+0.12}_{-0.11}$	0.17	0.216 ± 0.023
$K_{\mu 2}$	$1.15^{+0.25}_{-0.21}$	0.67	0.044 ± 0.005
$K_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40	0.024 ± 0.010

Deviation of c from unity is taken into account in evaluation of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

Beam and CEX background is 0.014 ± 0.003

The calculated number of background events in the signal region is 0.30 ± 0.03 from all background sources.

E787 and E949 analysis strategy

- "Blind" analysis. Don't examine signal region until all backgrounds verified.
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+ \pi^0) = 0.215 \pm 0.005$.
  World average value is 0.2113 ± 0.0014.

E949 improved analysis strategy†

1. E787 background estimation methods are reliable.

2. Divide signal region into cells and calculate background (b_i) and signal acceptance (s_i) for each cell. Example: Tighten PV cut to select subregion with 1/10 of the total predicted $K^+ \to \pi^+\pi^0$ background within “signal box”

3. Can calculate $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ using s_i/b_i of any cells containing candidates using likelihood ratio method.

4. Increase total size of signal region to increase acceptance at cost of more total background.

† With age comes wisdom.

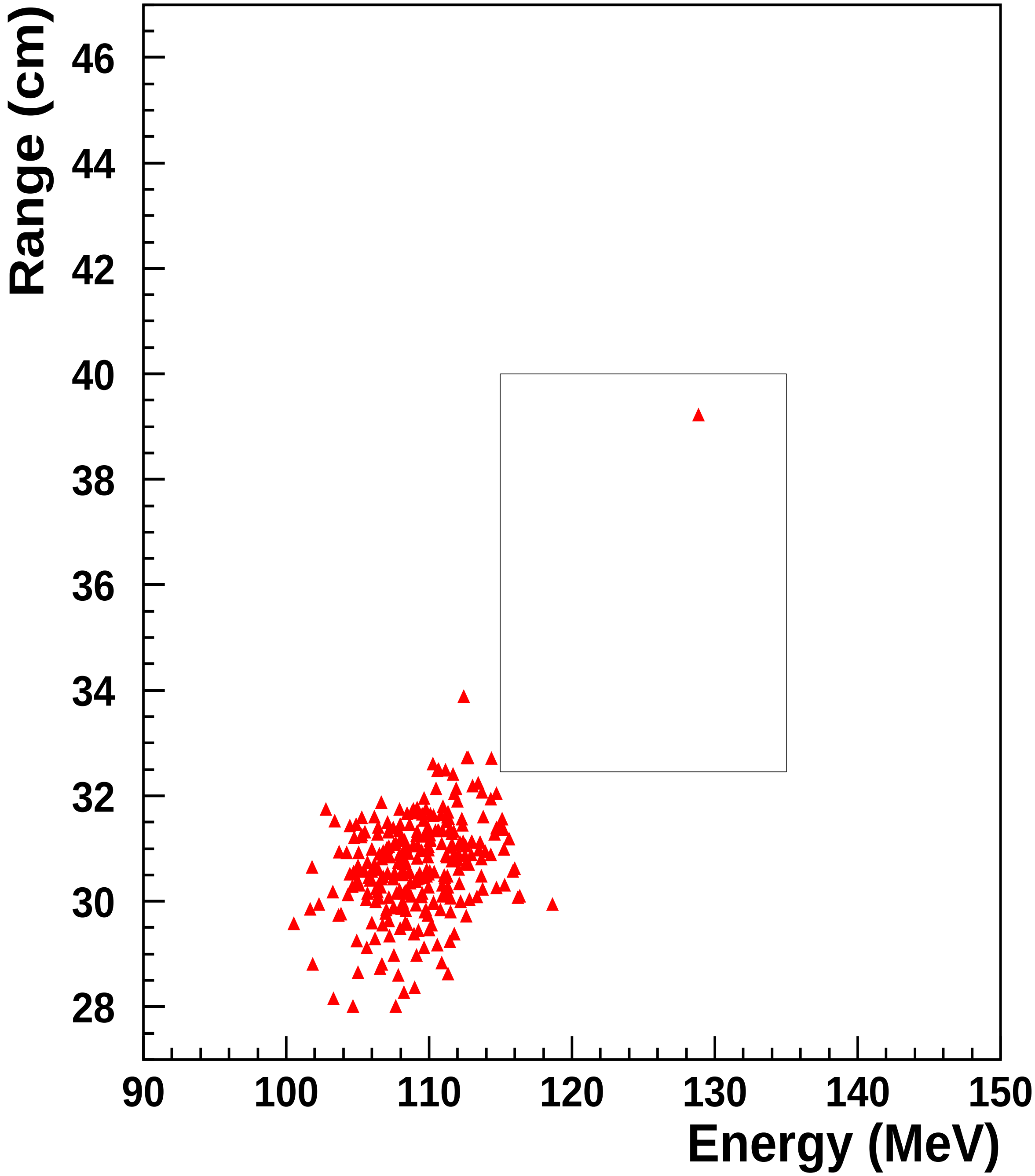
Opening the box

Range (cm) *vs* Energy (MeV) for E949 data after all other cuts applied.

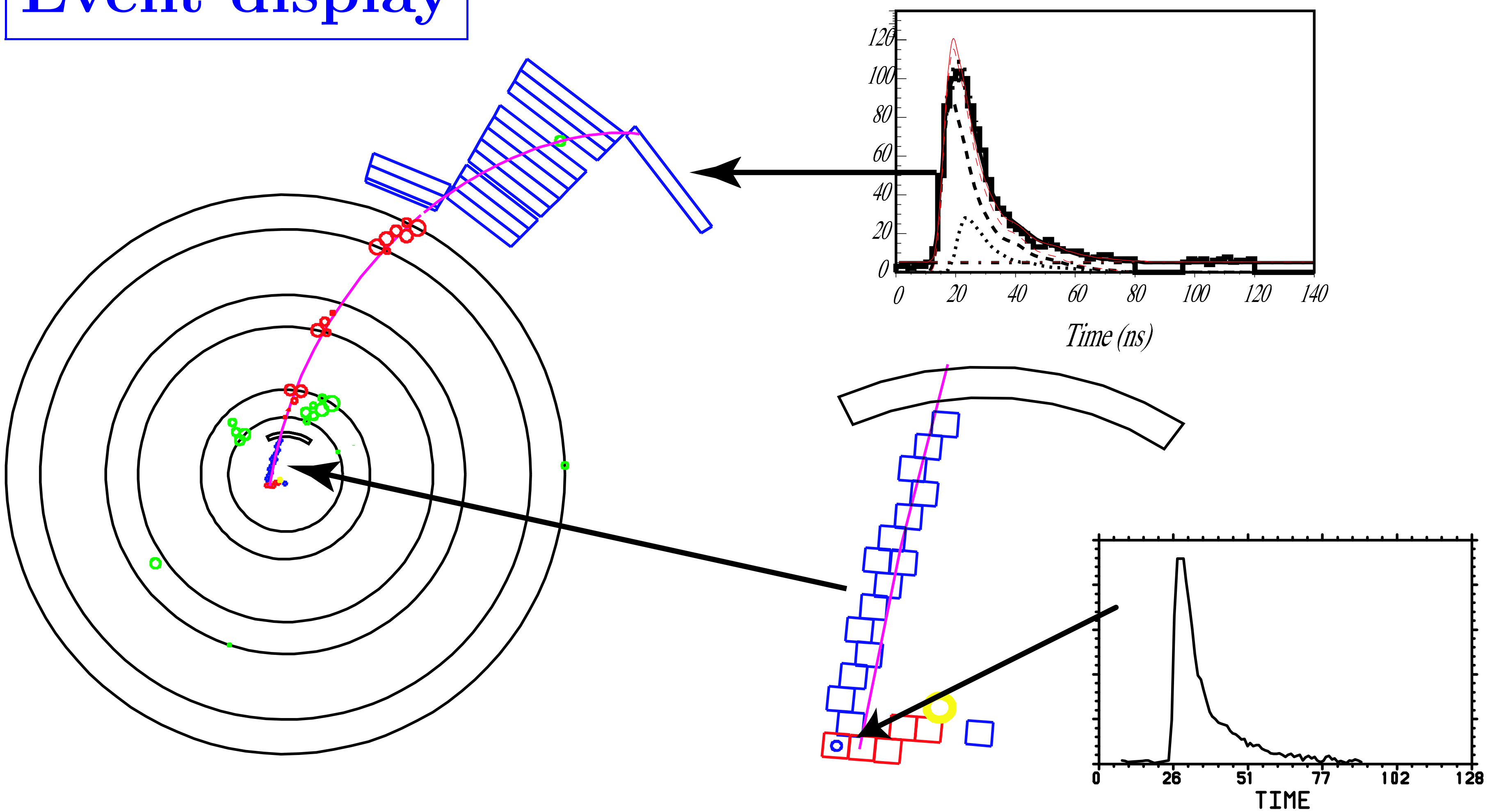
Solid line shows signal region.

Single candidate found.

Cluster near 110 MeV is unvetoed $K^+ \to \pi^+\pi^0$.



Event display



How likely is it that the candidate is due to known background?

Question: Suppose we do 100 experiments, how many will have a candidate from a known background source that is as signal-like or more signal-like than the observed candidate?

Answer: ~ 7

The sum of background in all cells with s_i/b_i greater or equal to the cell containing the observed candidate is 0.077. The probability that 0.077 could produce one or more events is 0.074 ($\sim 7/100$).

The E949 candidate is more likely to be due to background than the two E787 candidates.

Candidate	E787A	E787C	E949A
Probability	0.006	0.02	0.07

	E787		E949
Stopped K^+ (N_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
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
W_i	0.98	0.88	0.48

b_i = background rate of cell containing candidate

$S_i \equiv \mathcal{B} A_i N_K$ = signal rate for cell containing candidate

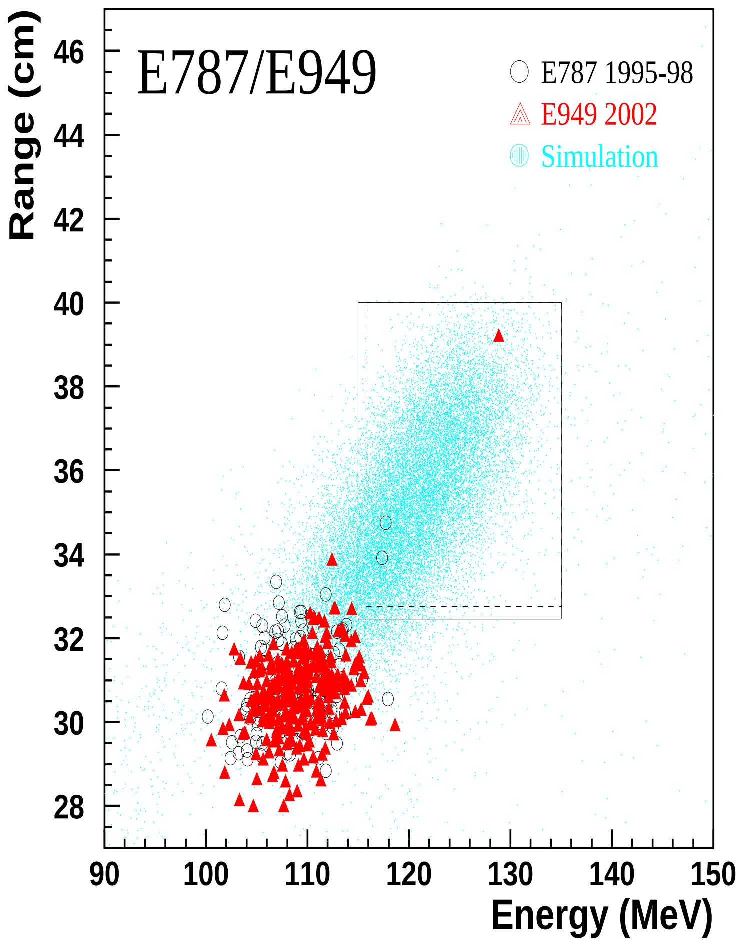
$A_i \equiv$ acceptance

$\mathcal{B}$ = measured central value of $K^+ \to \pi^+ \nu \bar{\nu}$ branching fraction

$W_i \equiv S_i/(S_i + b_i)$ = event weight

Event weight W_i and S_i/b_i assumes SM signal hypothesis as well as calculated background.

Combined E787 and E949 results for $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$



Range (cm) *vs* Energy (MeV) for combined E787 and E949 data after all other cuts applied. Dashed line is E787 signal region.

Solid line is E949 signal region.

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$$
(68%CL interval)

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) > 0.27 \times 10^{-10} \text{ (90\%CL)}$$

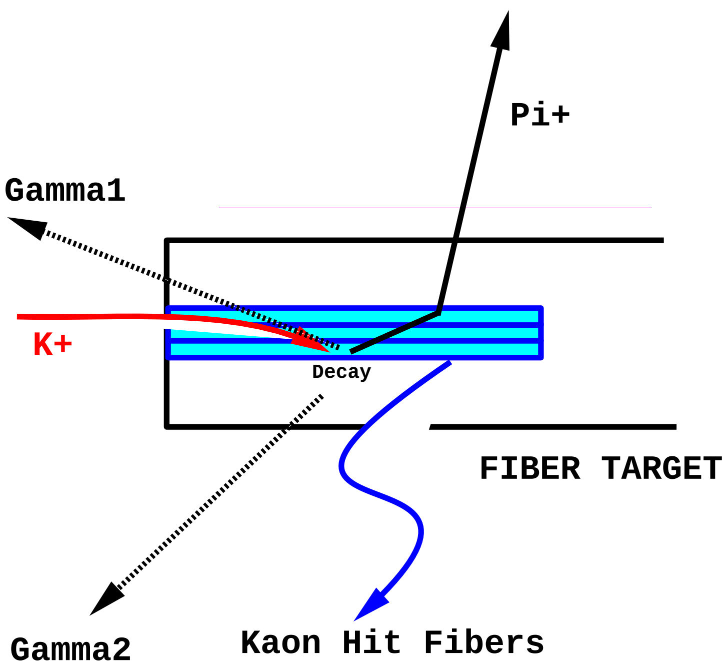
The probability that background alone gave rise to the three observed events or to any more signal-like configuration is 0.001.

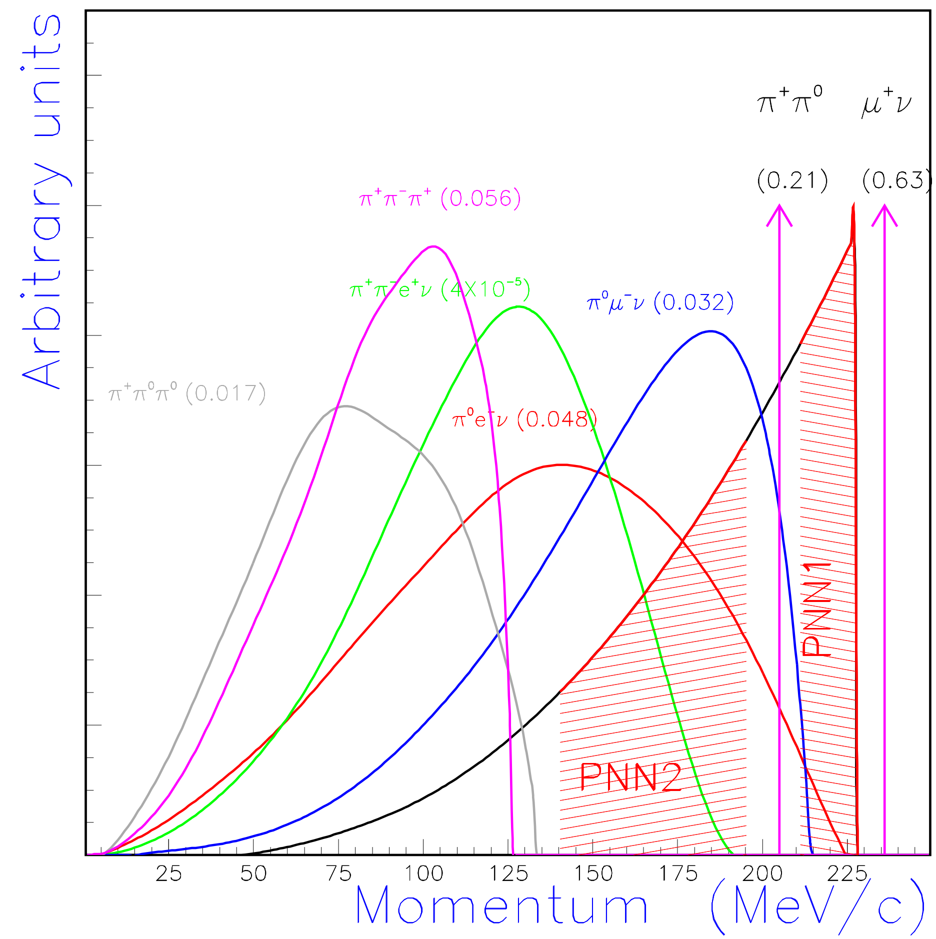
SM: $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (0.78 \pm 0.12) \times 10^{-10}$
Buras, Schwab & Uhlig, hep-ph/0405132

E787: $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$

PNN2: $K^+ \to \pi^+\nu\bar{\nu}$ below $K^+ \to \pi^+\pi^0$ peak

- More phase space than PNN1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \to \pi^+\nu\bar{\nu}$ spectrum
- Main background mechanism is $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.





E949 PNN2 analysis is in progress

Measuring $\mathcal{B}(K^0_L \rightarrow \pi^0 \nu \bar{\nu})$ with KOPIO at BNL

Measure everything possible.

Work in K^0_L CMS

Microbunched K^0_L beam

Measure γ directions in PR

Measure γ energy in CAL

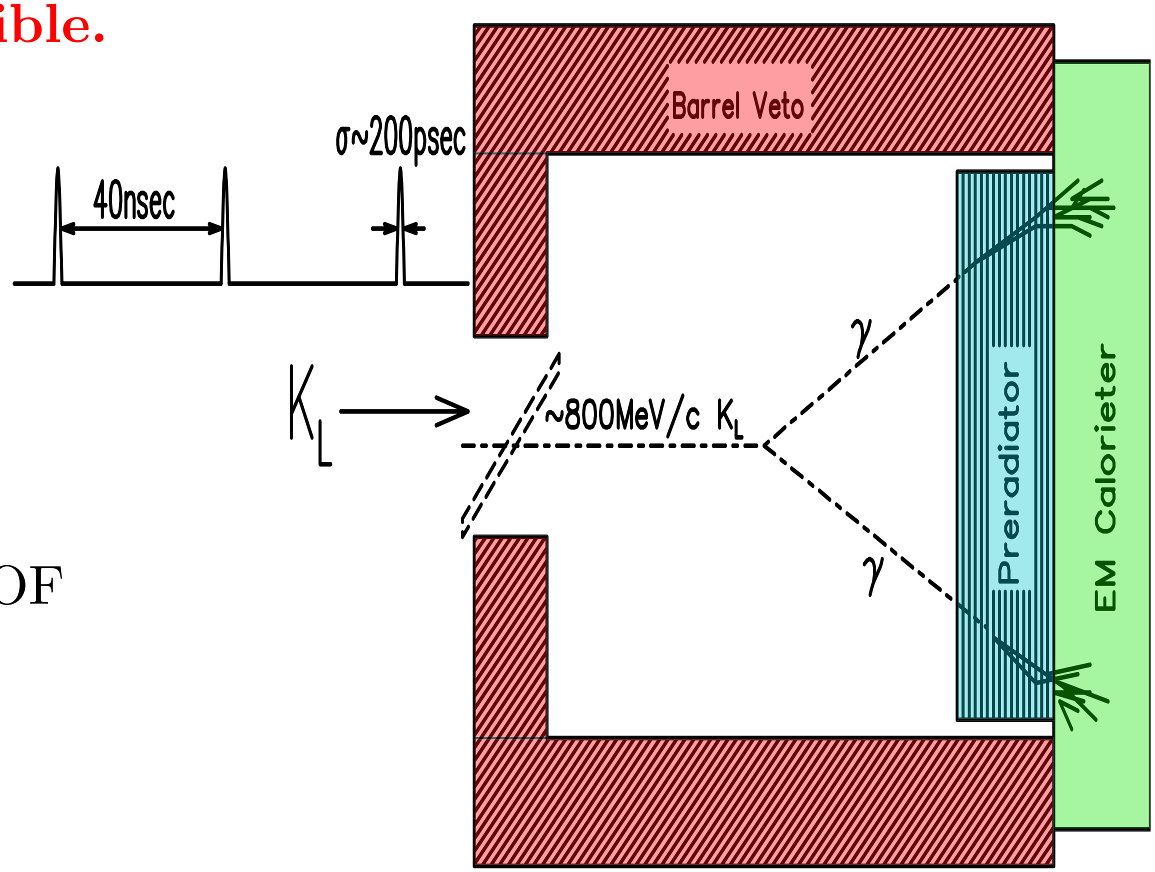
Reconstruct π^0 from $\gamma\gamma$

Measure K^0_L velocity from TOF

Photon veto

Charged track veto

Kinematic veto



Expect $\sim$ 40 $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ events for $\Delta\mathcal{B}/\mathcal{B} \approx 20\%$ or $\Delta\eta/\eta \approx 10\%$ at S/B=2 with KOPIO

Summary and outlook for $K \to \pi\nu\bar{\nu}$

E949 has observed an additional $K^+ \to \pi^+\nu\bar{\nu}$ candidate.

E949 & E787: $\boldsymbol{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}}$

Central value is twice SM prediction. $\boldsymbol{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.78 \pm 0.12) \times 10^{-10}}$

Statistically consistent with SM prediction.

E949 analysis of $K^+ \to \pi^+\nu\bar{\nu}$ for momenta $P(\pi^+) < 195$ MeV/c in progress.

E949: Approved(1999), HEP at AGS halted(2002), other funding sources sought...

Another stopped-K^+ experiment to measure $K^+ \to \pi^+\nu\bar{\nu}$ under consideration at KEK(L-04) in Japan. K^+ decay-in-flight experiments under consideration at FNAL(P940) and CERN(NA48/3). (`http://www3.bnl.gov/FutureK/`)

E391a: ($K^0_L \to \pi^0\nu\bar{\nu}$ at KEK) Began stable data-taking in March 2004

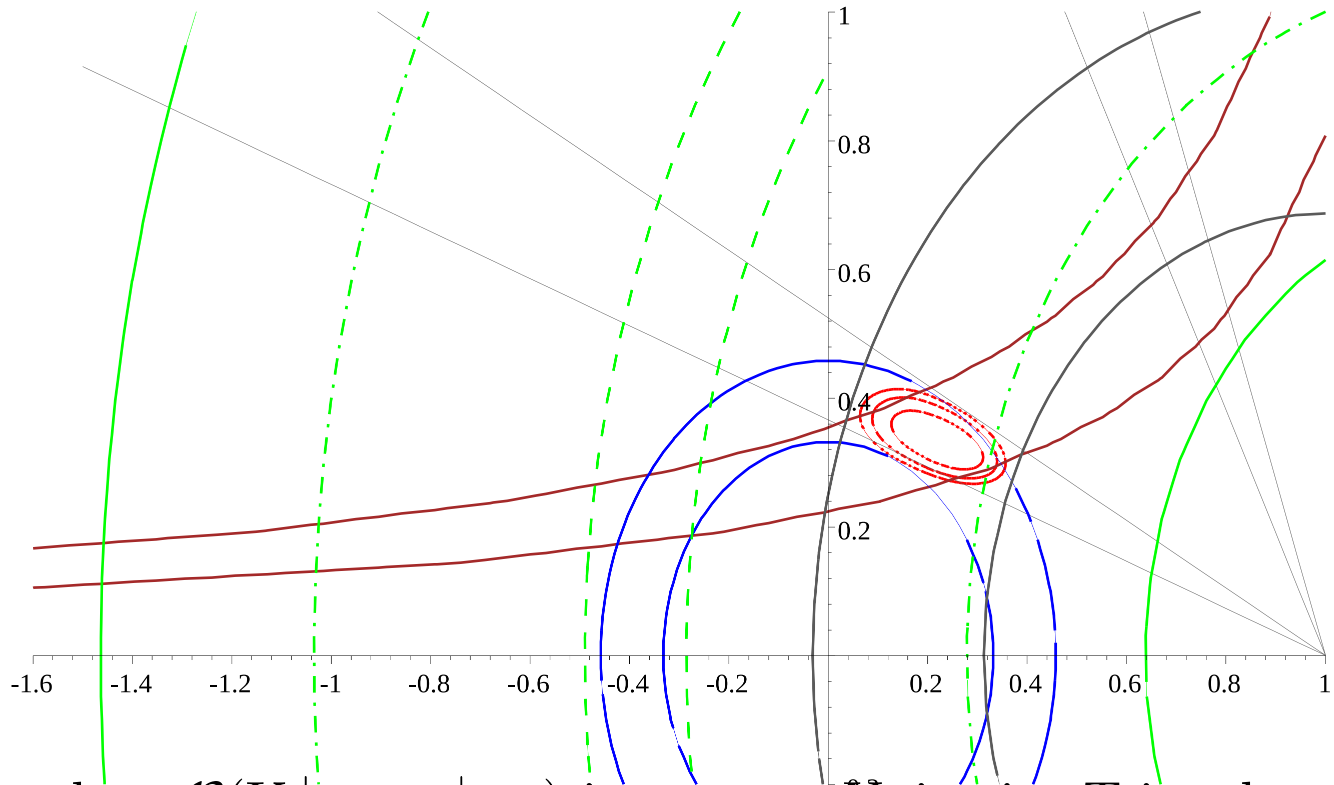
KOPIO: Approved by NSF(2003), construction start in 2005, in need of zealous collaborators.

These experiments would be able to test the precise predictions for $\boldsymbol{K \to \pi\nu\bar{\nu}}$ branching fractions.

Thanks to E949 & KOPIO collaborations.

Extras

Impact of $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ on Unitarity Triangle

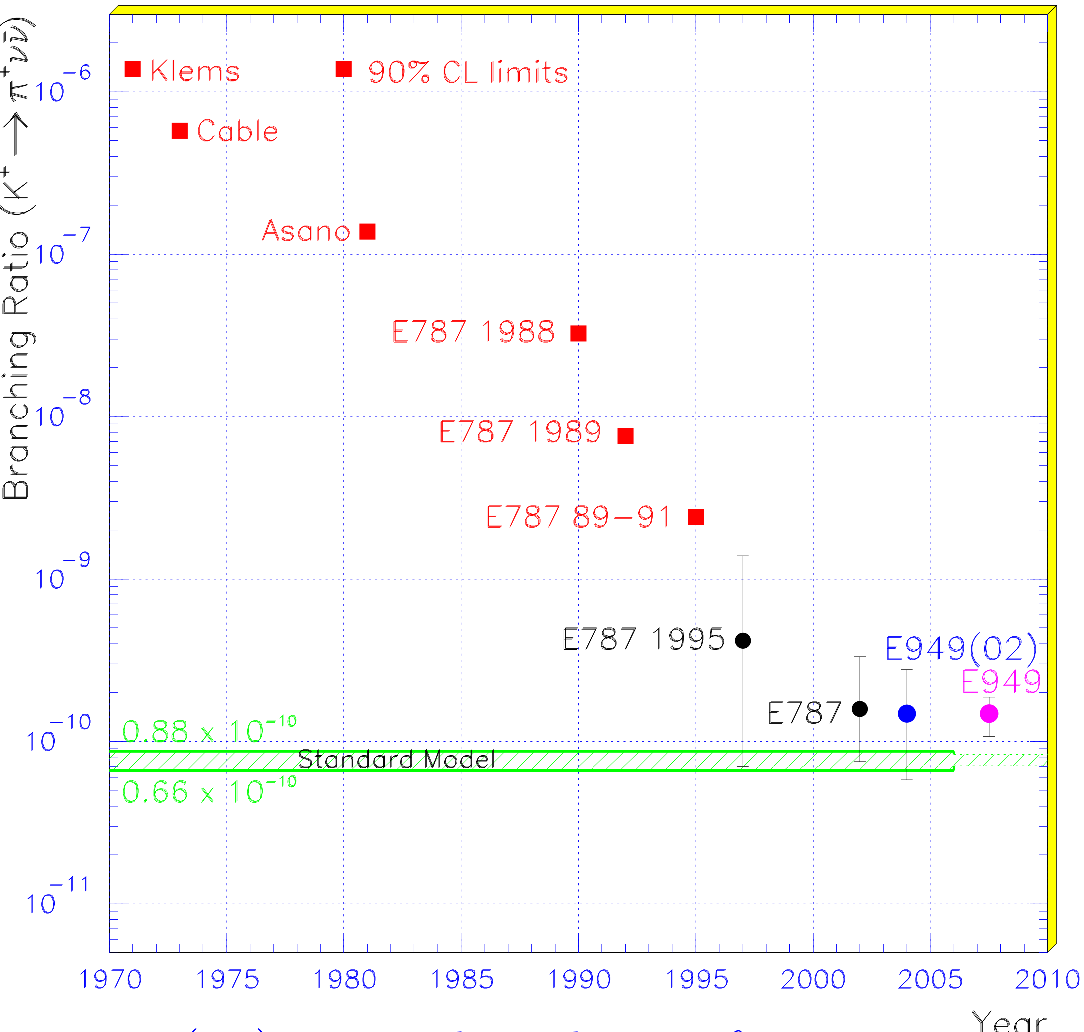


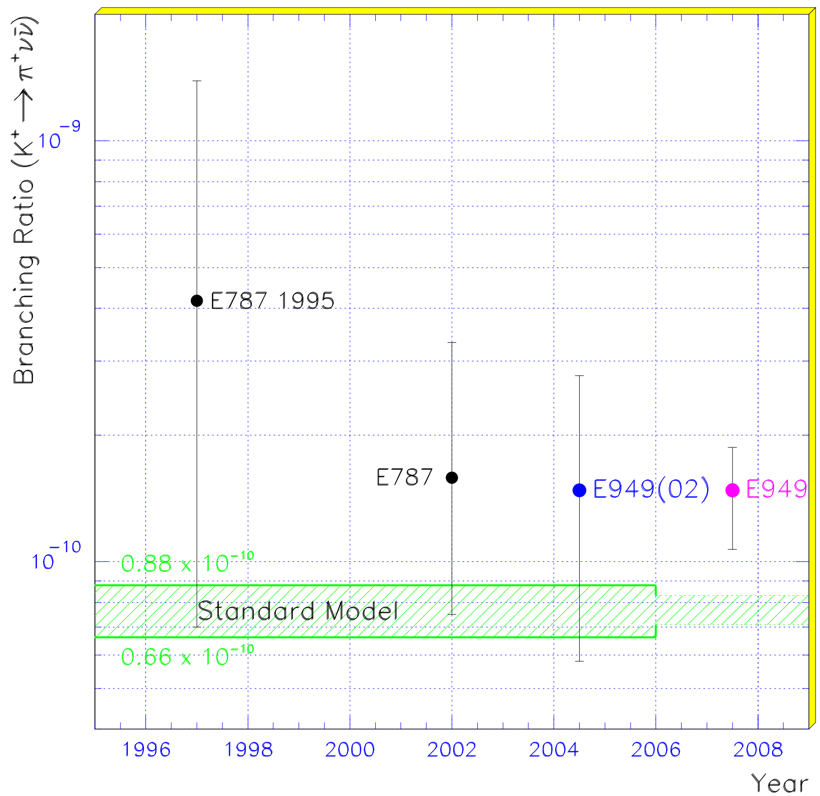
Green lines show $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ impact on Unitarity Triangle: central value (dashed), 68% interval (dot-dash), 90% interval (solid). Theoretical uncertainty is included.

Red ovals show 68%, 90% and 95% areas from other measurements ($|V_{ub}|$, ϵ_K, $\sin 2\beta$, Δm_d, $\Delta m_s/\Delta m_d$)

Provided by Gino Isidori.

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





E949(02) = combined E787& E949.

E949 projection with full running period.

Narrowing of "SM prediction" assumes measurement of B_s mixing consistent with prediction.

$$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = K_+ \left(\left[\mathrm{Im}\lambda_t \frac{X}{\lambda^5}\right]^2 + \left[\mathrm{Re}\lambda_c \frac{P_0}{\lambda} + \mathrm{Re}\lambda_t \frac{X}{\lambda^5}\right]^2 \right)$$

$$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu}) = K_0 \left(\left[\mathrm{Im}\lambda_t \frac{X}{\lambda^5}\right]^2 \right)$$

$$\begin{aligned}
\lambda_i &\equiv V^*_{is}V_{id} \\
K_+ &\equiv r_+ B \\
K_0 &\equiv r_0 B \tau(\mathrm{K}^0_\mathrm{L})/\tau(\mathrm{K}^+) \\
B &\equiv 3\alpha^2\mathcal{B}(\mathrm{K}^+ \to \pi^0 e^+\nu)/2\pi^2 \sin^4\theta_\mathrm{W} \\
X &\equiv X(x_t) \equiv \frac{x_t}{8(x_t-1)}\left(x + 2 + \frac{3x-6}{x-1}\ln x\right) \\
x_t &\equiv (m_t/m_W)^2 \\
r_+ &= 0.901 \\
r_0 &= 0.944 \\
P_0 &= 0.40 \pm 0.06 \text{ (charm)}
\end{aligned}$$

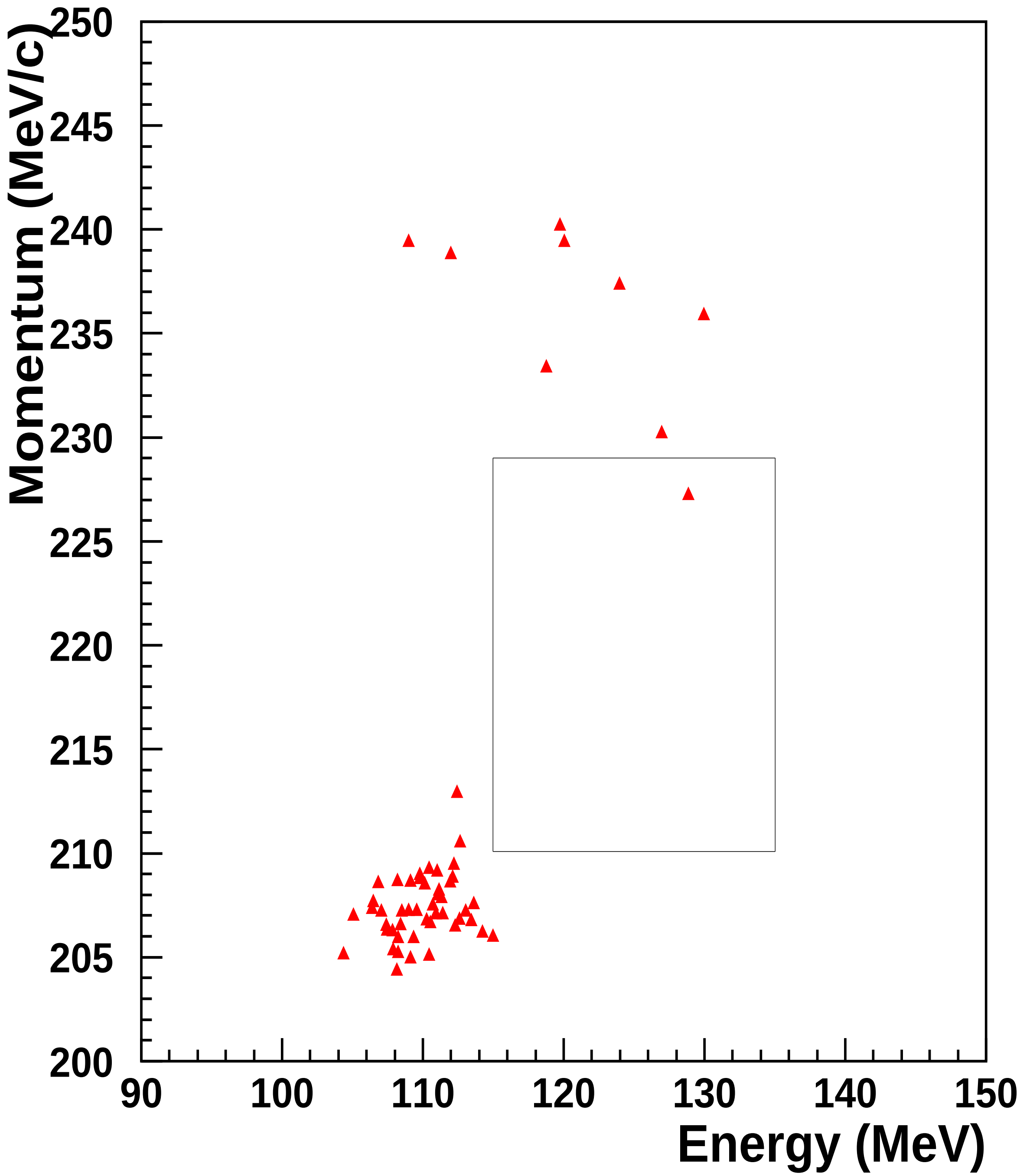
Same candidate, different variables.

Momentum (MeV/c) *vs* Energy (MeV/c) for E949 data after all other cuts applied.

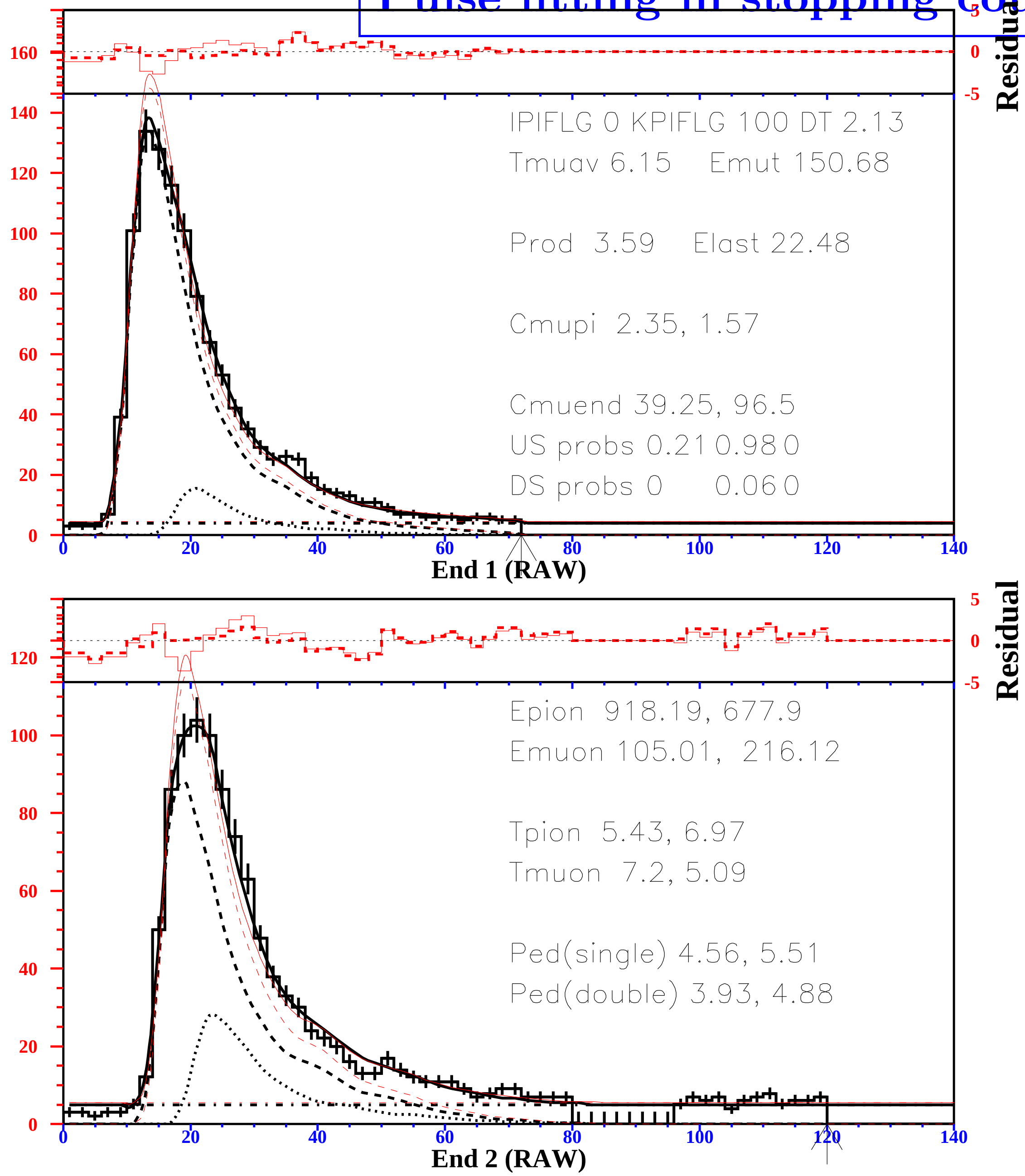
Solid line shows signal region.

Events above signal region are unvetoed $K^+ \rightarrow \mu^+ X$

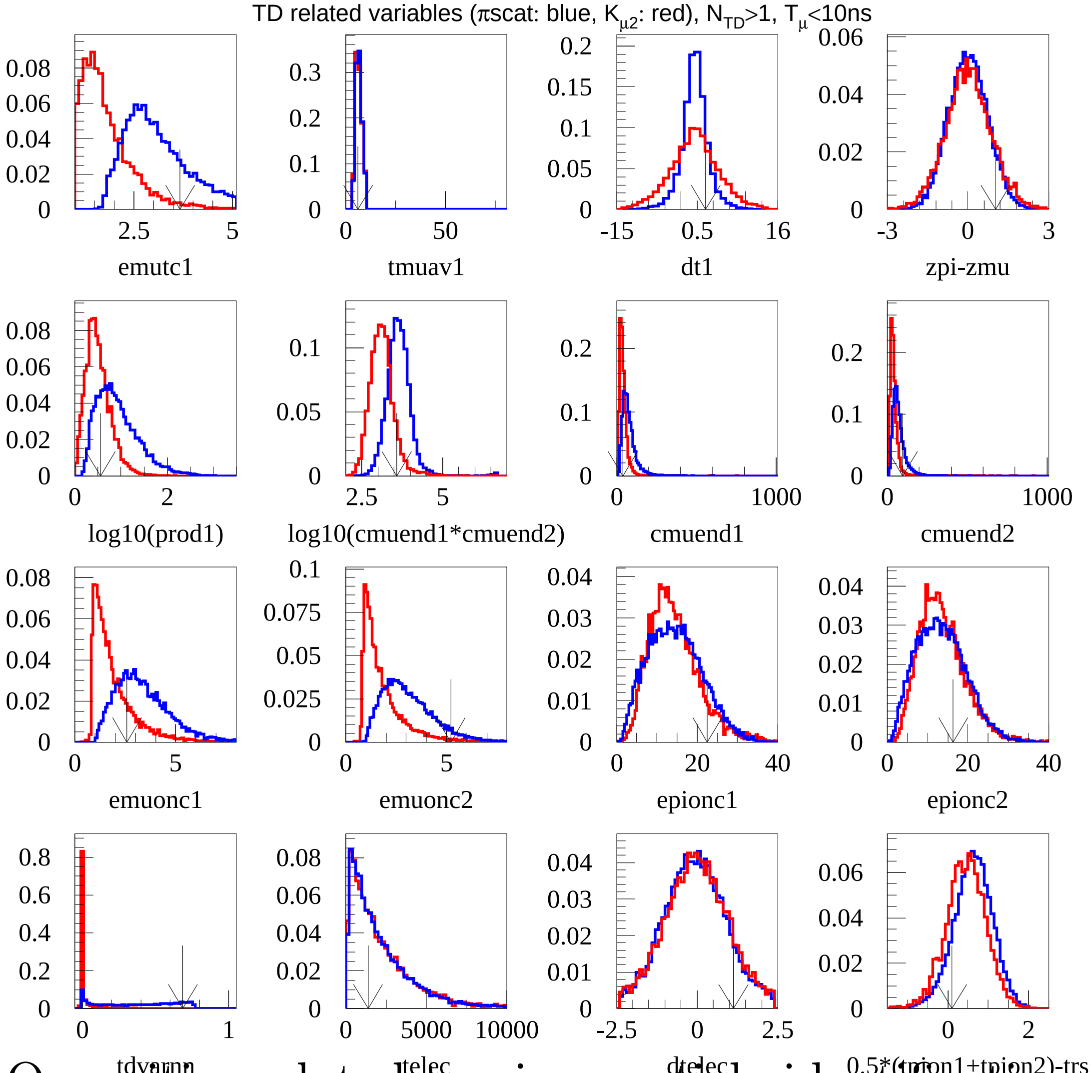
Cluster near 110 MeV is unvetoed $K^+ \rightarrow \pi^+ \pi^0$.



Pulse fitting in stopping counter



Compare TD properties of candidate with π^+ and μ^+ samples



Quantities related to pion particle identification from TD variables. Events with similar background rejection and fitted muon time < 10 ns are selected. The pion signal (blue) and the muon background (red) are shown in the same plots. The arrows indicate the positions of the candidate event.

Remind: E949-2002 beam conditions were not optimized

- a faiulre of the AGS power supply
- reduced operating voltage of one of the DC separators
- 12 weeks

The conditions will be improved in the next run.

		E787	E949-'02	E949 optimized
AGS energy	GeV	24	22	24
beam spill	sec	2.2	2.2	4.1
cycle	sec	4.2	5.4	6.4
duty factor	%	52	41	64
K^+/π^+		4	3	4
N_K in the spill		1.8	2.5	5.0
N_K	MHz	0.8	1.2	1.2
rates in the detector	M		$\times 2$	$\times 2$ or less
beam time	weeks		12	$\geq$60

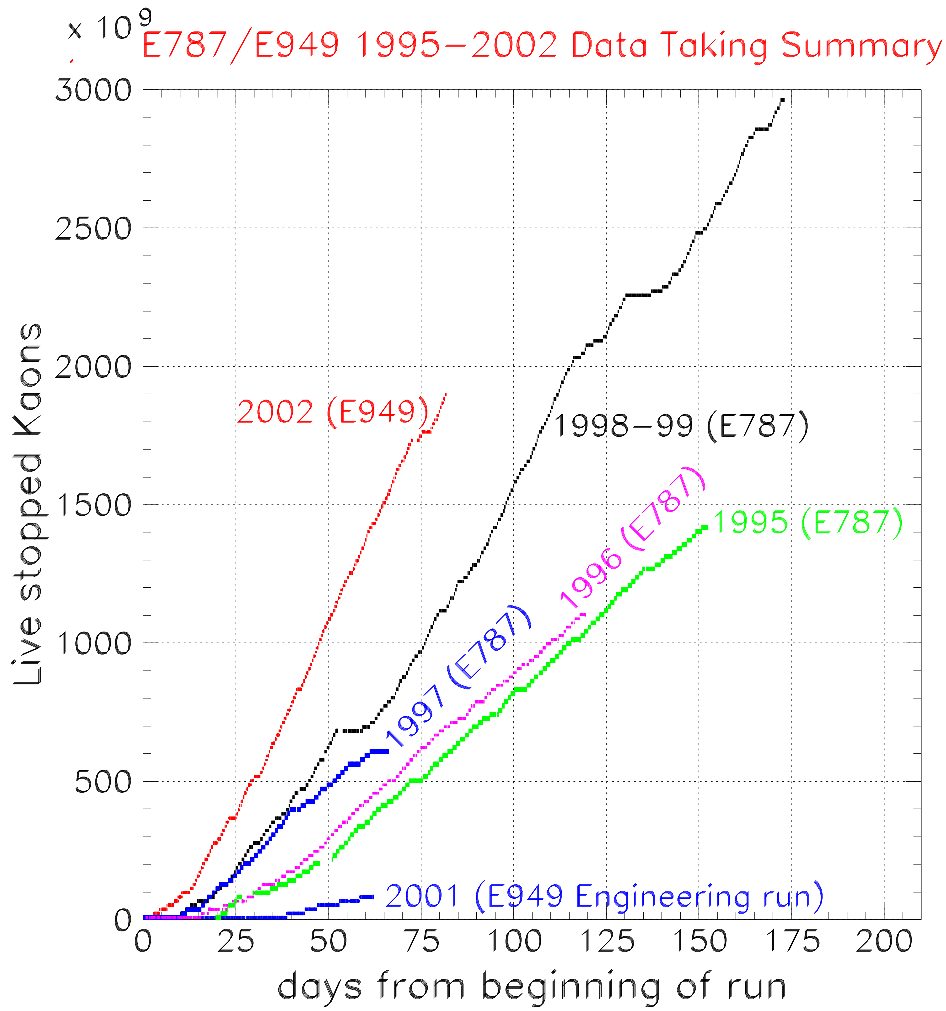
E949 status for 2002 data taking

Upgrades to E787:

- More protons/sec from AGS
- Improved photon veto hermeticity
- Improved tracking and energy resolution
- Higher rate capability due to DAQ and trigger improvements

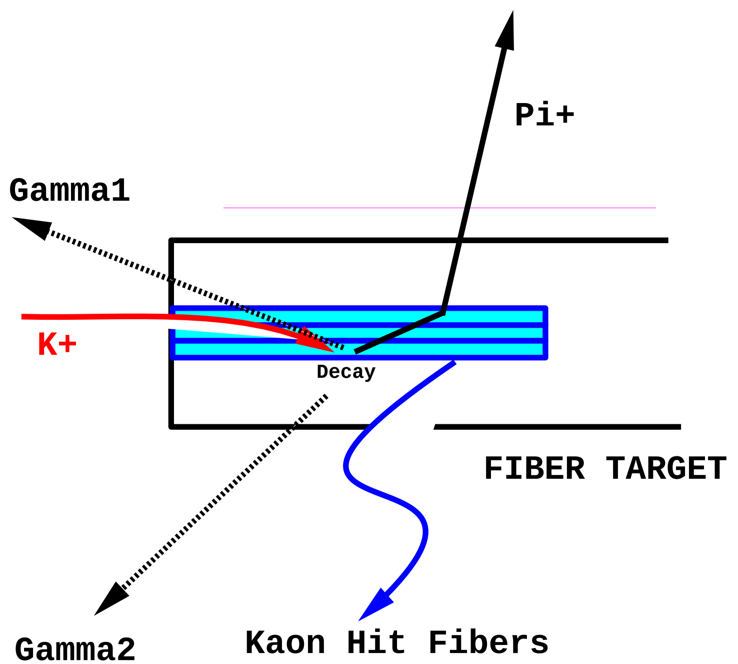
Not optimal in 2002:

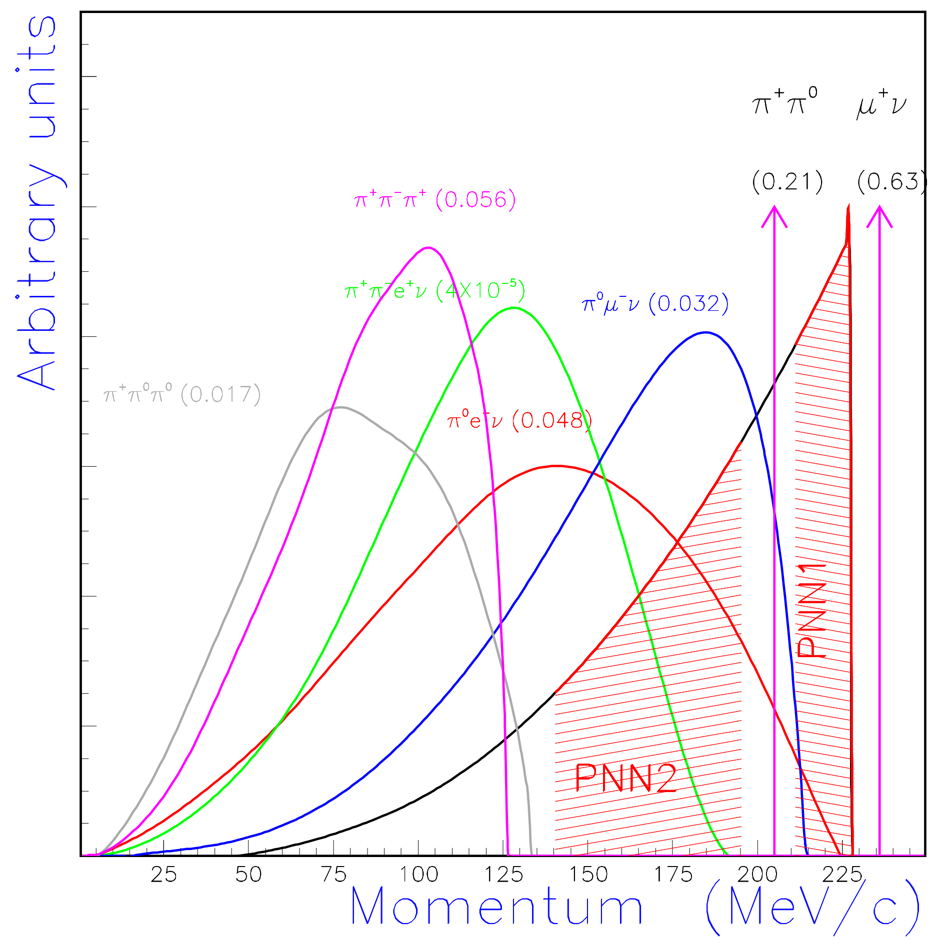
1. Spill duty factor.
2. Proton beam momentum.
3. K/π electrostatic separators.



PNN2: $K^+ \to \pi^+\nu\bar{\nu}$ below $K^+ \to \pi^+\pi^0$ peak

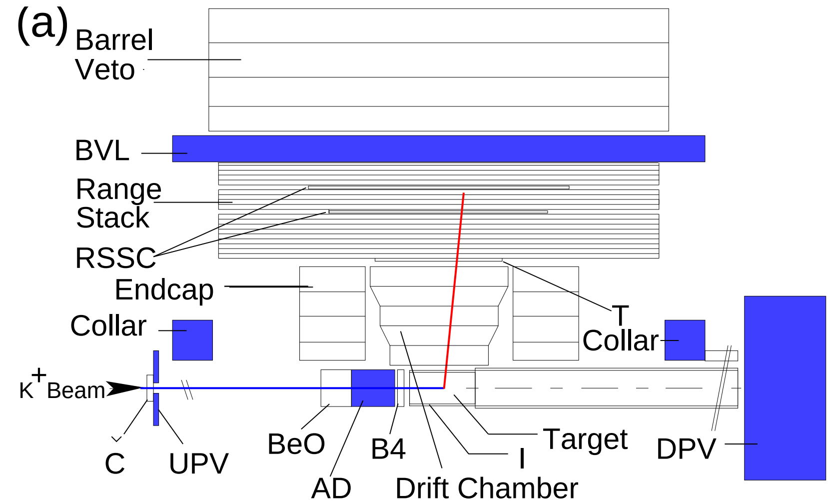
- More phase space than PNN1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \to \pi^+\nu\bar{\nu}$ spectrum
- Main background mechanism is $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.

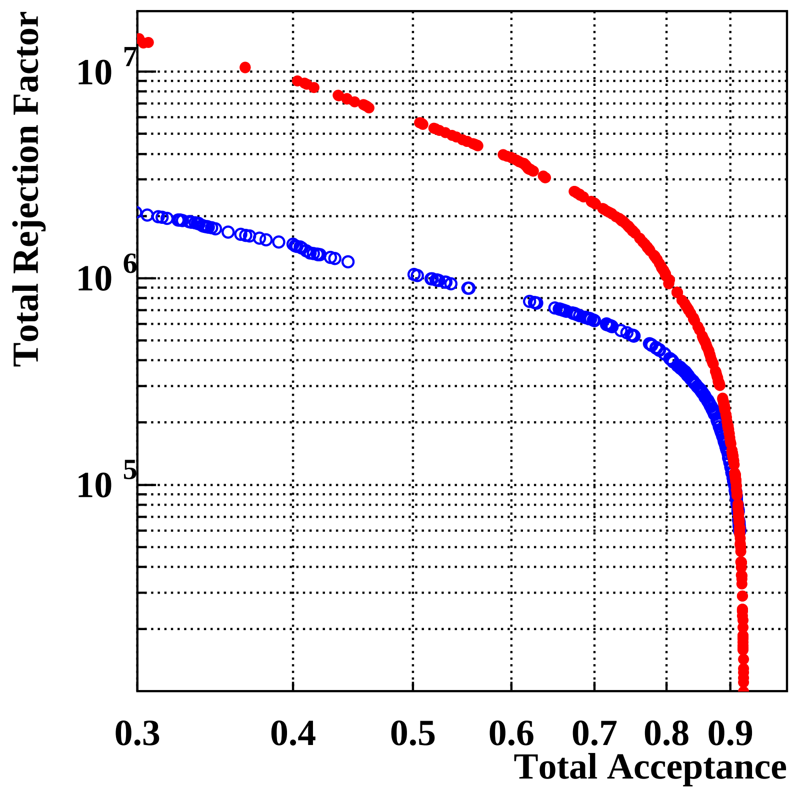




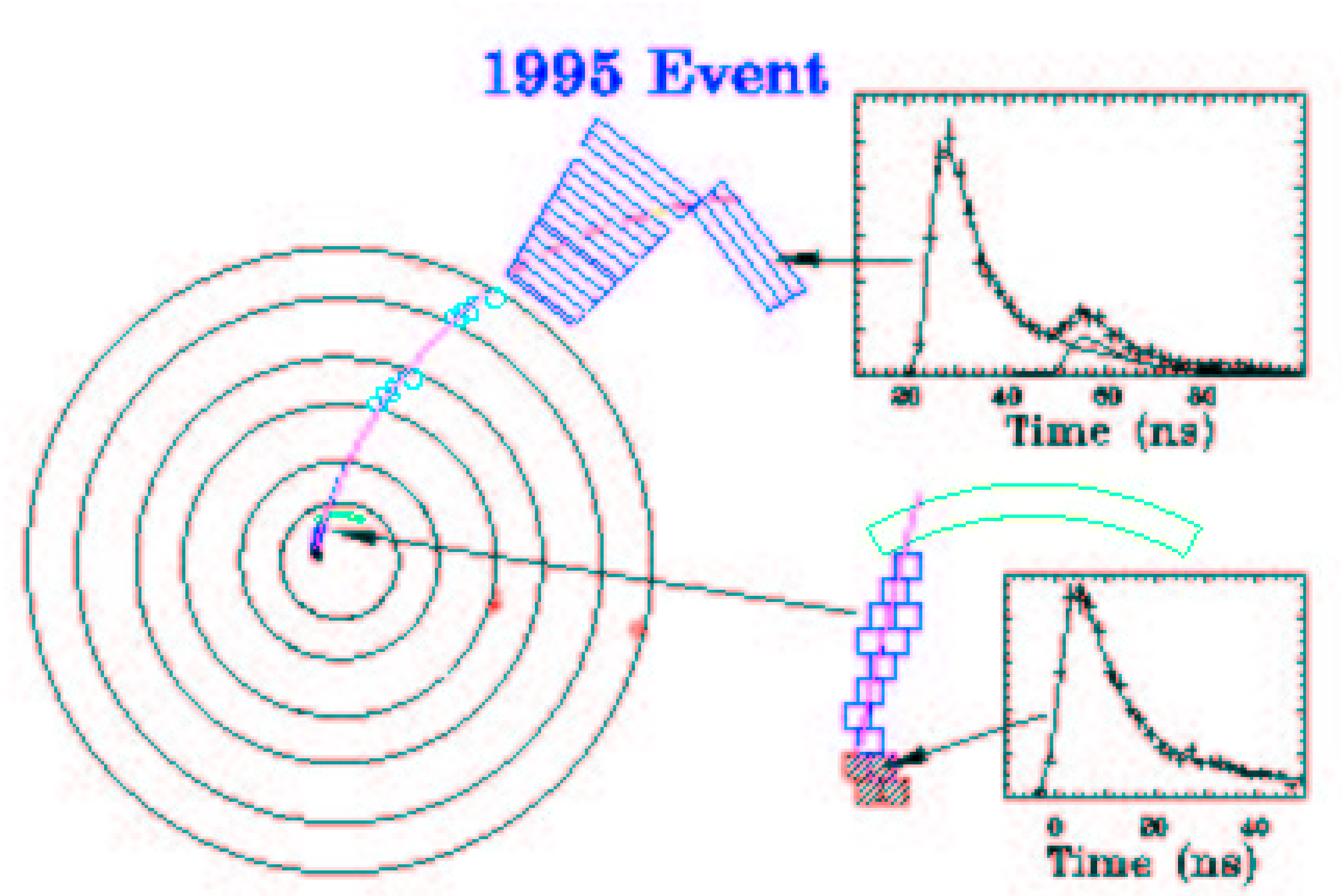
E949 PNN2 analysis

- E787: PNN2 acceptance approx. half PNN1 acceptance
- Goal is equal PNN2 and PNN1 sensitivity with S/B = 1. This implies ×2 increase in acceptance and ×5 increase in background rejection.
- Upgraded photon veto increased PNN1 background rejection. Quantitative assessment of improvement for PNN2 underway.
- Improved algorithms to identify $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.

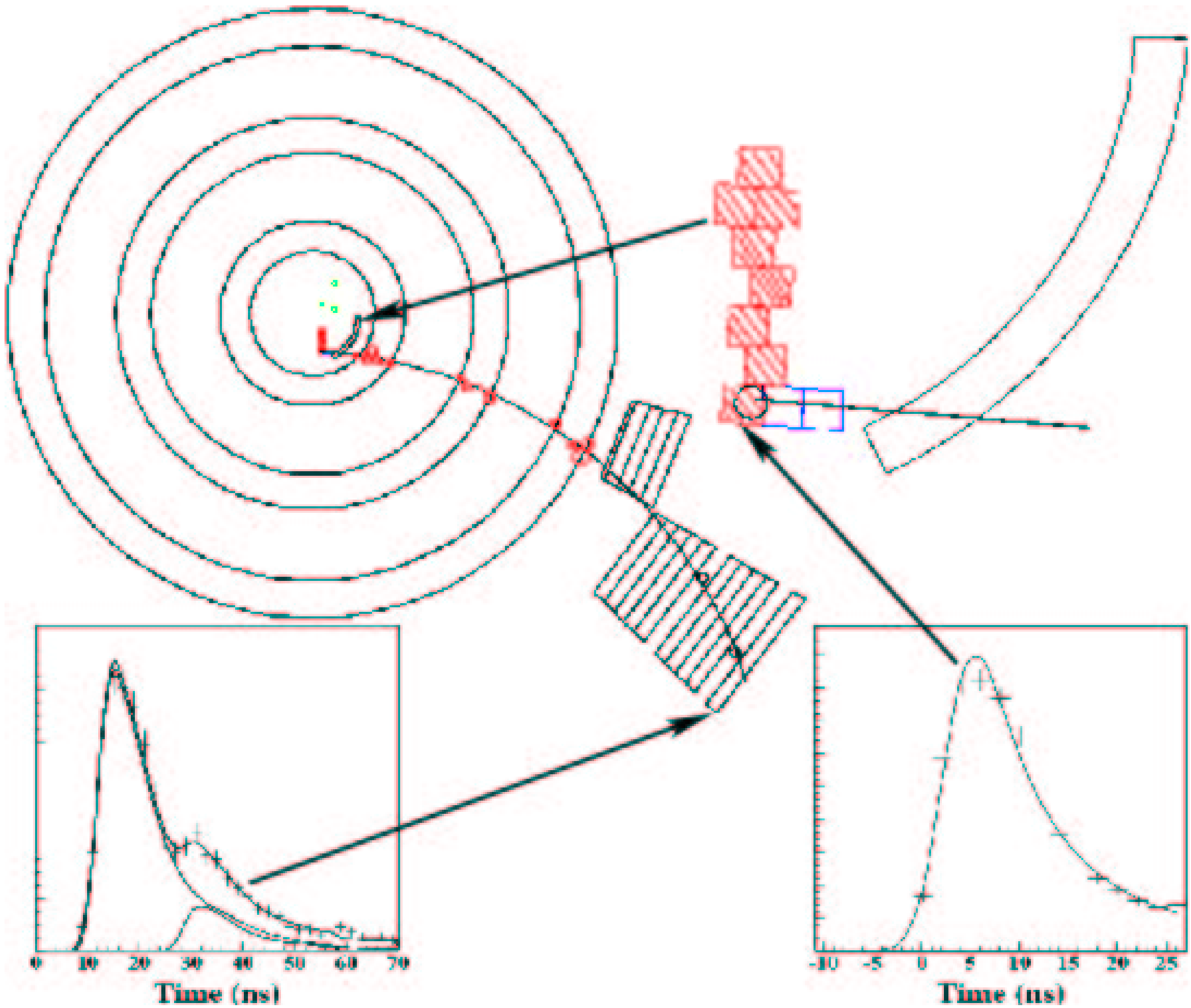


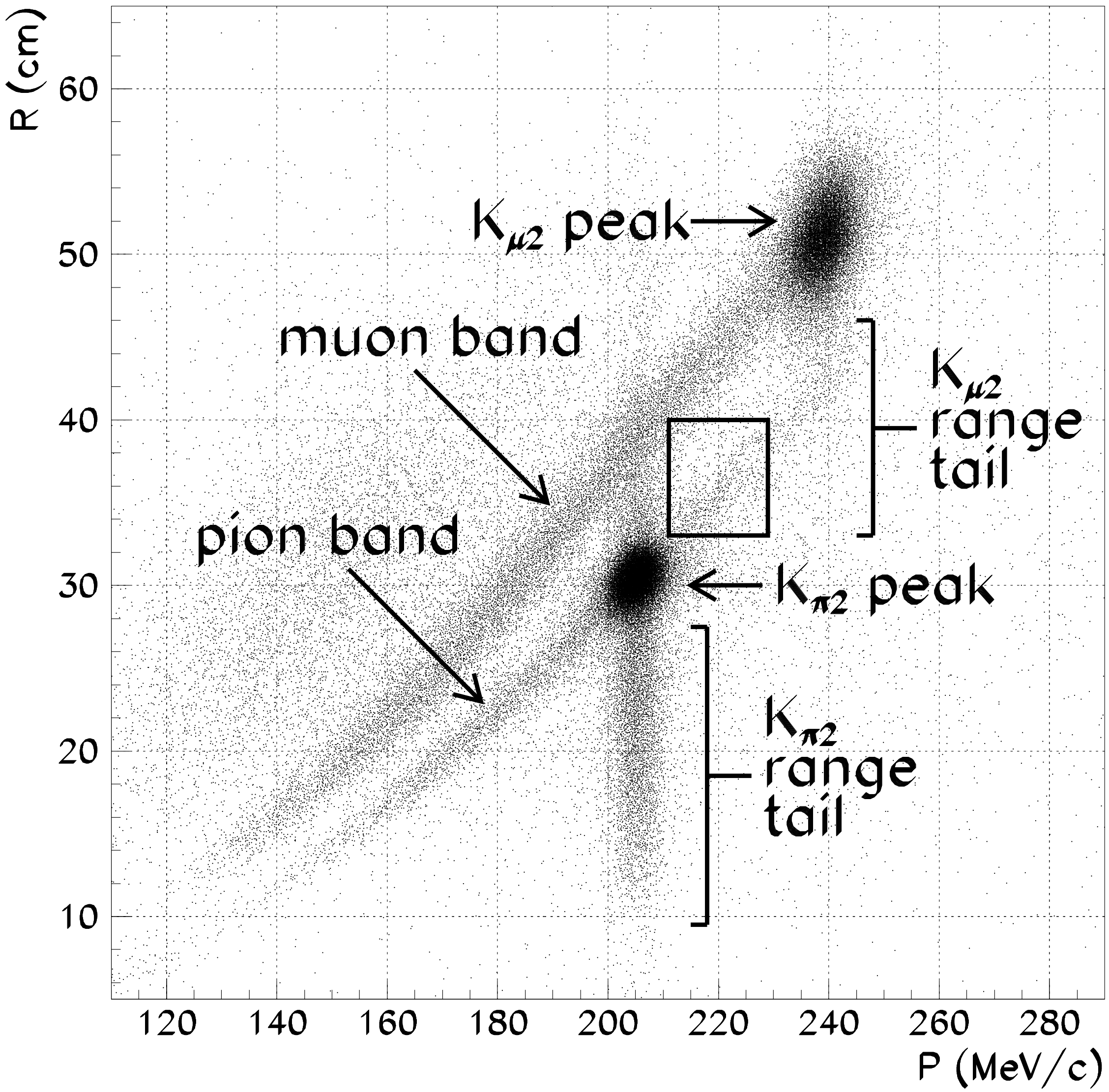


Candidate E787A



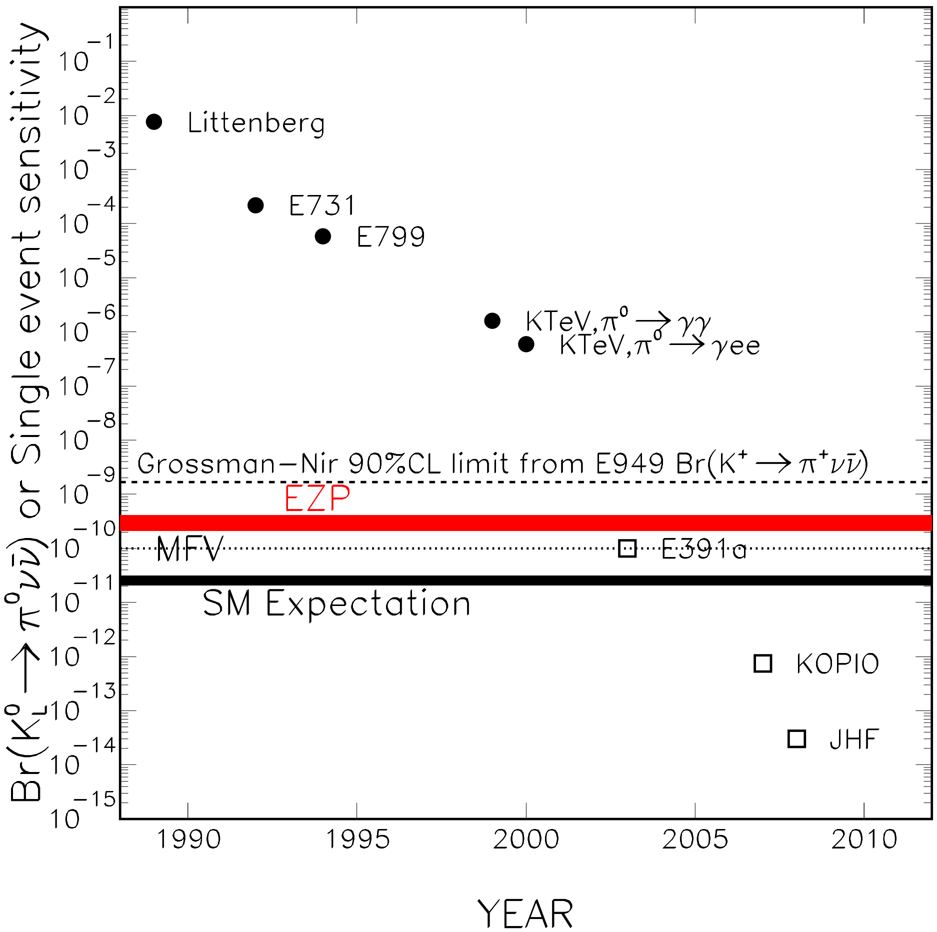
Candidate E787C

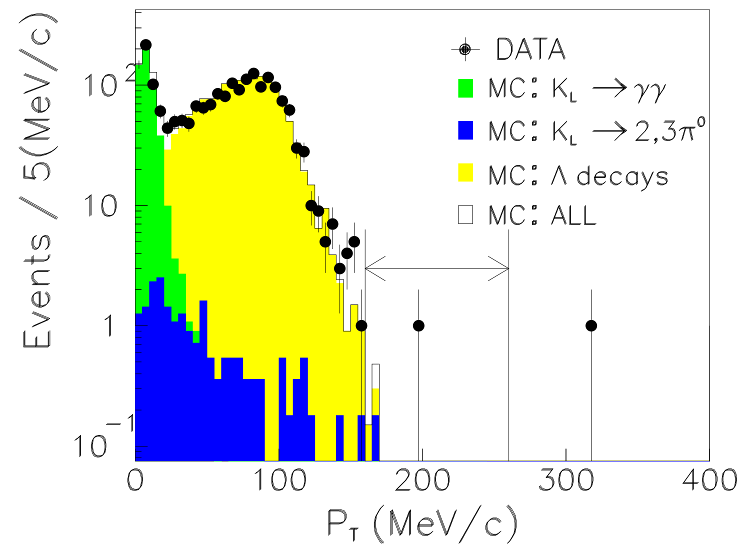




E949 Range *vs* Momentum accepted by trigger

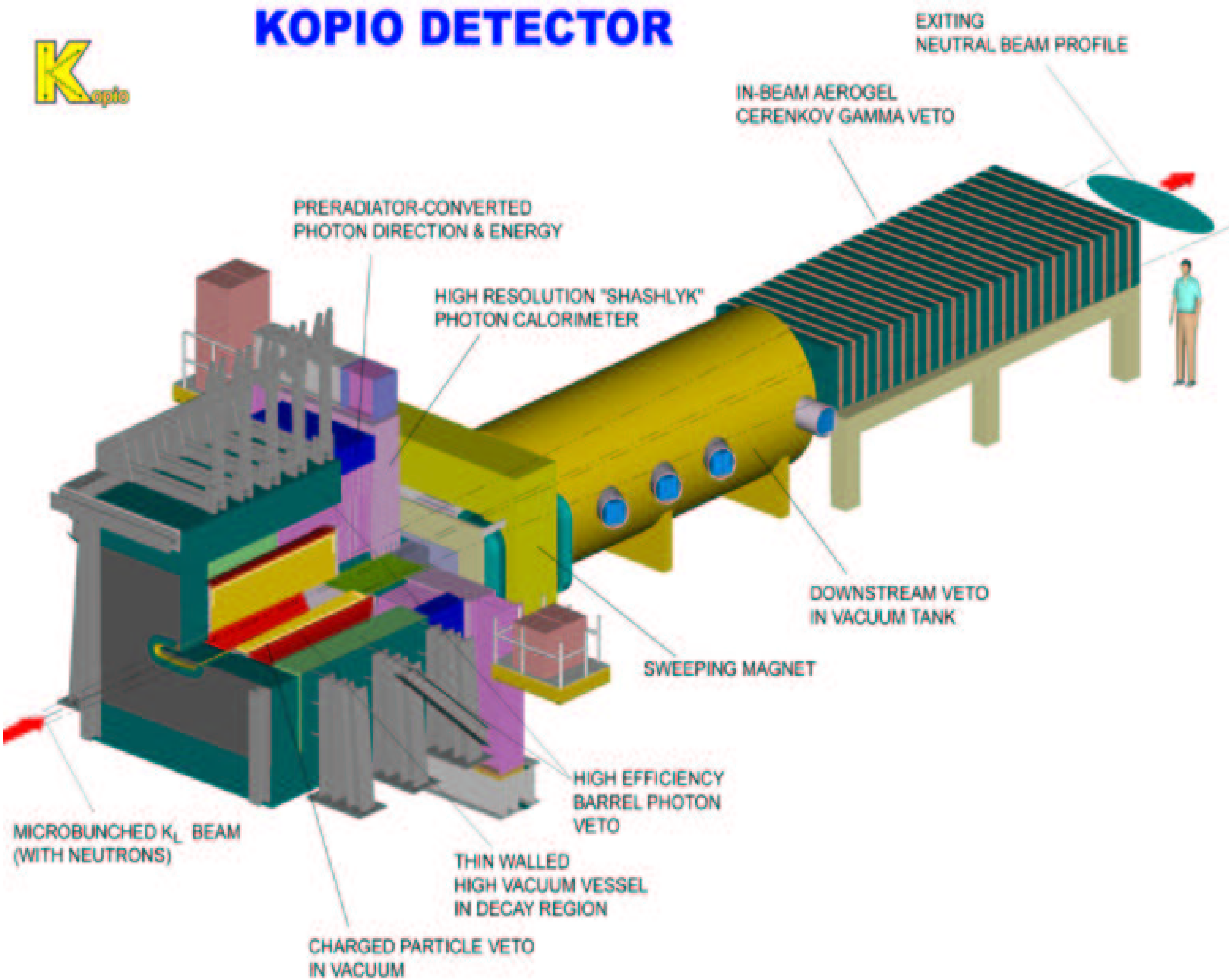
$K_L^0 \to \pi^0 \nu \bar{\nu}$ Progress





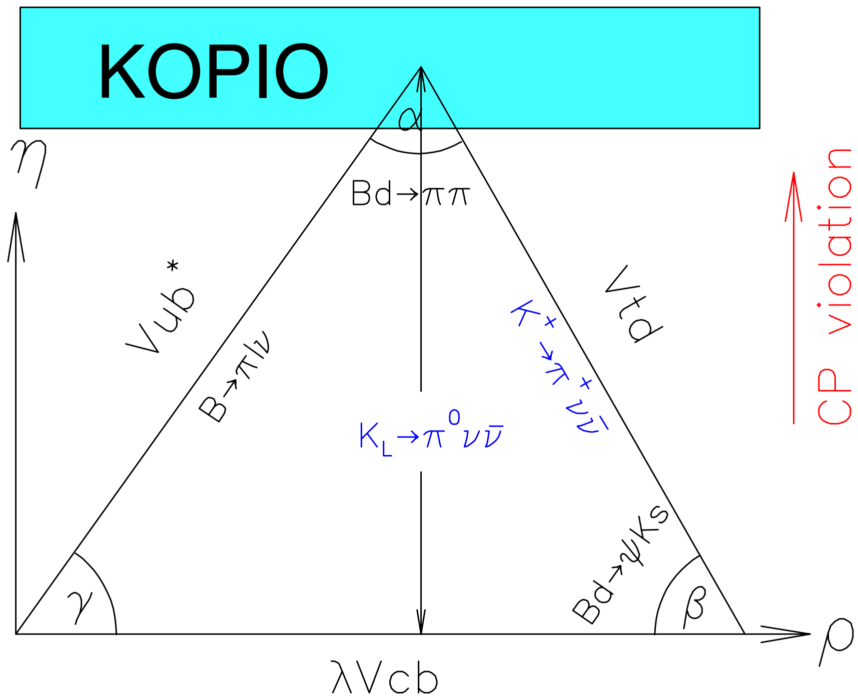
KTeV result with "pencil" K_L^0 beam (PL**B447** (1999) 240). E391a, JHF expts use a similar technique.

D:



KOPIO DETECTOR
EXITING
NEUTRAL BEAM PROFILE
IN-BEAM AEROGEL
CERENKOV GAMMA VETO
PRERADIATOR-CONVERTED
PHOTON DIRECTION & ENERGY
HIGH RESOLUTION "SHASHLYK"
PHOTON CALORIMETER
DOWNSTREAM VETO
IN VACUUM TANK
SWEEPING MAGNET
HIGH EFFICIENCY
BARREL PHOTON
VETO
MICROBUNCHED K_L BEAM
(WITH NEUTRONS)
THIN WALLED
HIGH VACUUM VESSEL
IN DECAY REGION
CHARGED PARTICLE VETO
IN VACUUM

KOPIO signal and background estimates

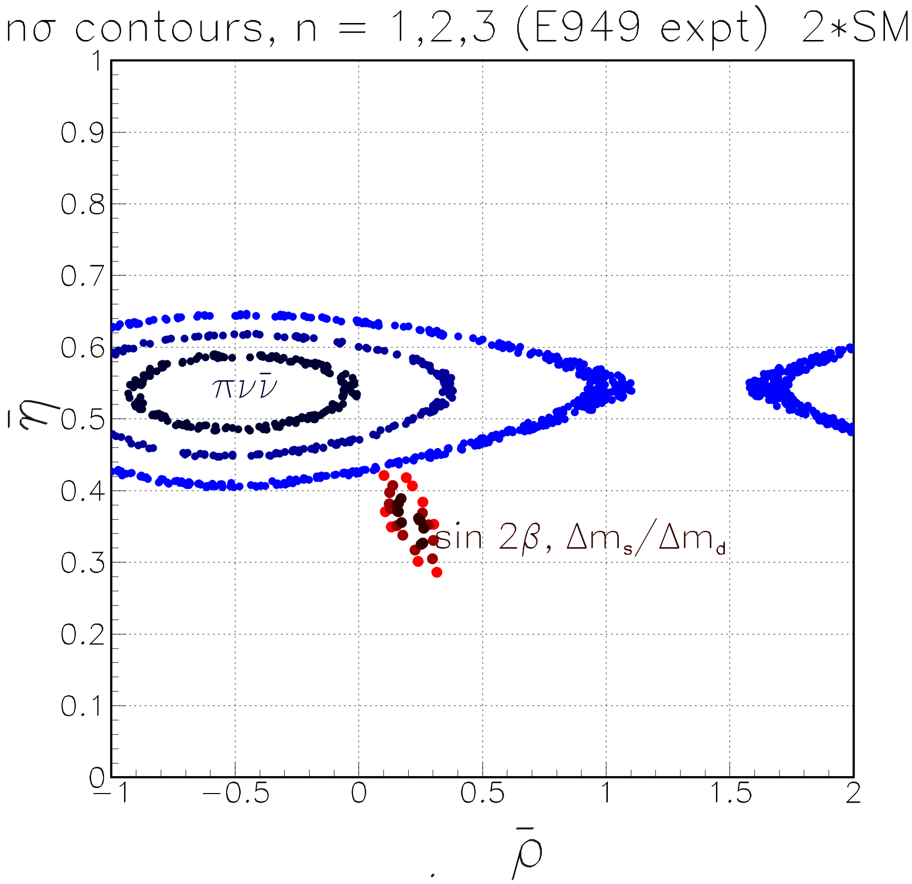


$\Delta\mathcal{B}/\mathcal{B} \approx 20\%$ or

$\Delta\eta/\eta \approx 10\%$ at S/B=2

Process	Events
$K^0_L \to \pi^0\nu\bar{\nu}$ at SM rate	40
$K^0_L \to \pi^0\pi^0$	12.4
$K^0_L \to \pi^\pm e^\mp \nu\gamma$	4.5
$K^0_L \to \pi^-\pi^+\pi^0$	1.7
$K^0_L \to \pi^\pm e^\mp \nu$	0.02
$K^0_L \to \gamma\gamma$	0.02
$\Lambda \to \pi^0 n$	0.01
Interactions ($nN \to \pi^0 X$)	0.2
Accidentals	0.6
Total Background	19.5

Possible impact of E949,KOPIO $\mathrm{K} \to \pi\nu\bar{\nu}$ measurements



Assumptions:

E949 & KOPIO run for approved running period.

$\mathrm{K} \to \pi\nu\bar{\nu}$ rates at twice SM expectation

$\Delta m_s = 17.0 \pm 1.7\ \mathrm{ps}^{-1}$

$\sin 2\beta = 0.70 \pm 0.02$