$K \to \pi\nu\bar{\nu}$ at Hadron Machines

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Overview

Expt	Mode	Results or Goal
E787	$K^+ \to \pi^+\nu\bar{\nu}$	Completed. 2 candidates.
E949	$K^+ \to \pi^+\nu\bar{\nu}$	1/5 completed. $\mathcal{O}(10)$ SM events
CKM	$K^+ \to \pi^+\nu\bar{\nu}$	100 SM events, $S/B \approx 10$
KOPIO	$K^0_L \to \pi^0\nu\bar{\nu}$	40 SM events, $S/B \approx 2$

Outlook

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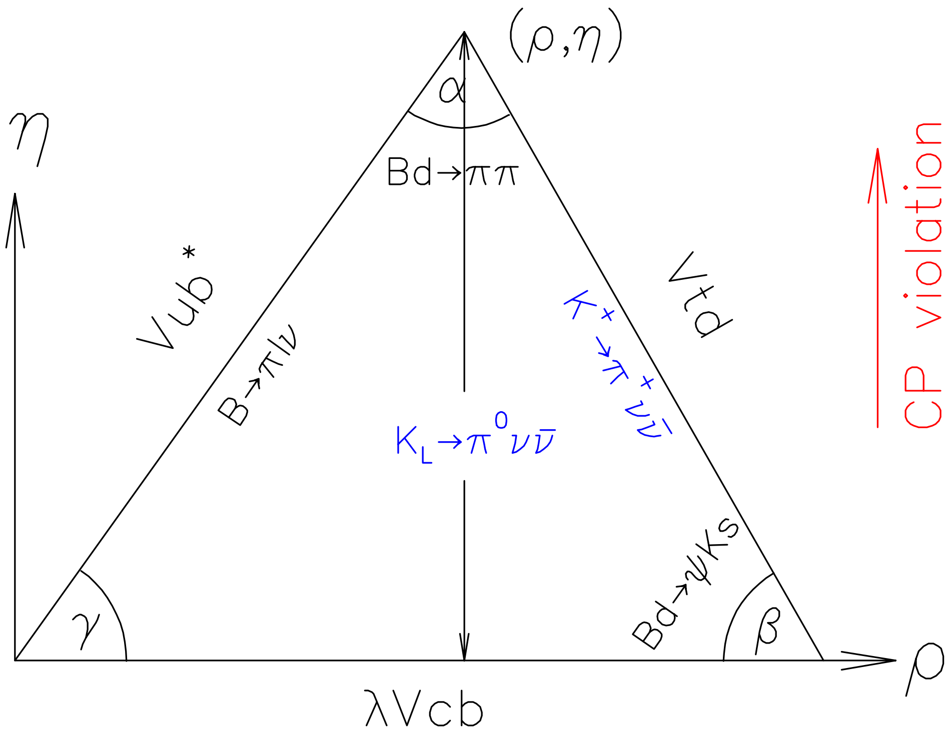
"Golden" modes and the CKM unitarity triangle



Process	Expts
$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$	KOPIO, E391a
$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$	E787/E949, CKM
$\mathcal{A}(B \to J/\psi\mathrm{K}^0_\mathrm{S}; t)$	BaBar, Belle
$\Delta m_s/\Delta m_d$	CDF, D0

Comparison of $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$, $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ and $\sin 2\beta$ provides a clean and direct comparison of CP violation between the K and B sectors.

Measurements and expectations for $\mathrm{K} \to \pi\nu\bar{\nu}$

	$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$	$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$
Measurement	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$ (a)	$< 5.9 \times 10^{-7}$ (b)
		$< 4.4 \times \mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ (c)
Expectation	$(0.7 \pm 0.2) \times 10^{-10}$ (d)	$(0.3 \pm 0.1) \times 10^{-10}$ (d)
	$(0.7 \pm 0.1) \times 10^{-10}$ (e)	
Limiting Uncert.	5% (f)	1% (f)

Limits are at 90% CL.

References

(a) PRL **88** (2002) 041803

(b) PR **D61** (2000) 072006

(c) PL **B398** (1997) 163

(d) `hep-ph/0304132`

(e) `hep-ph/0212321`

(f) `hep-ph/0101336`

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
$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

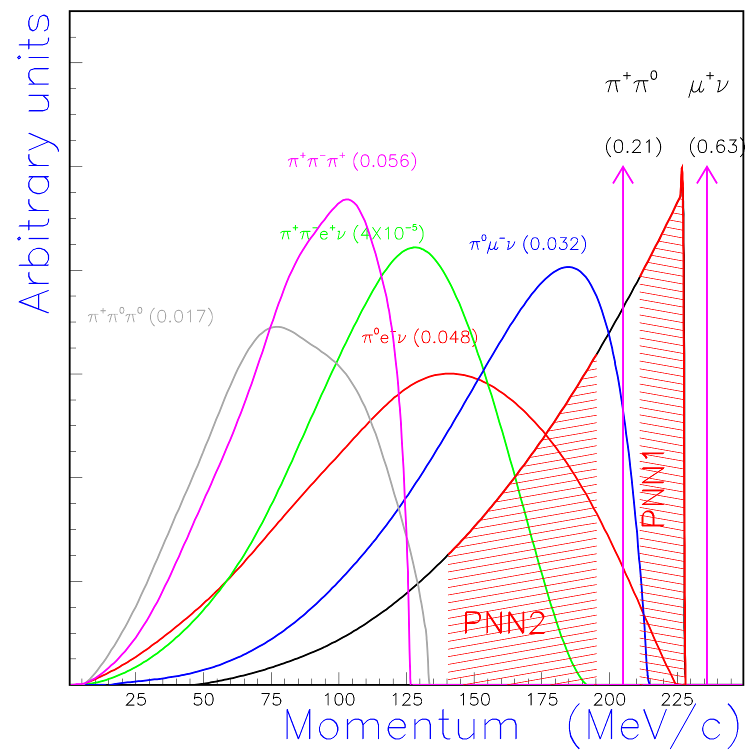
E787

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

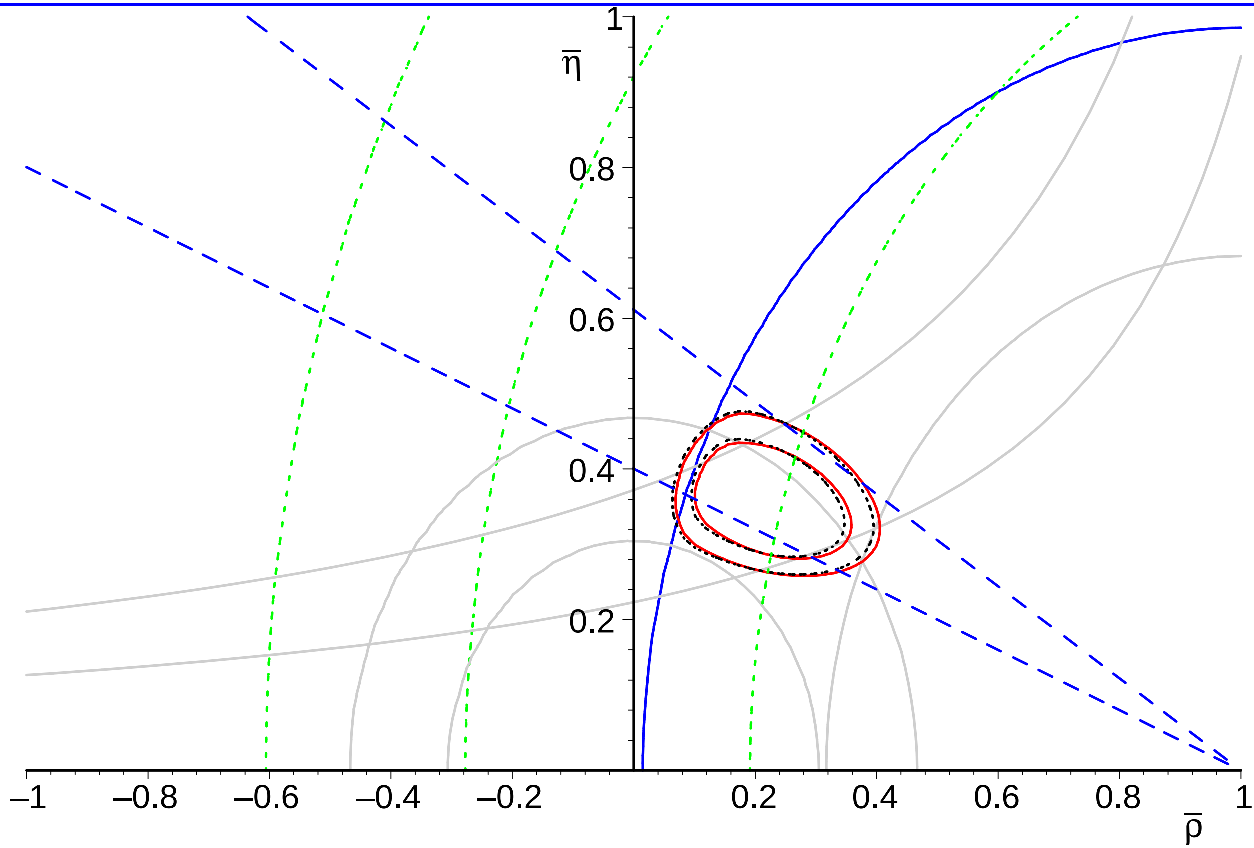
results

Probability that **PNN1** candidates are entirely due to background is 0.02% (PRL **88**, 041803 (2002)).

Preliminary **PNN2** limit at 90%CL is combined result from 1996 (PL **B537**, 211 (2002)) and 1997 data.



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



68% and 90% CL intervals with (dotted) and without (solid) the $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ constraint from **PNN1** region.

G. D'Ambrosio & G. Isidori, PL **B530**, 108 (2002)

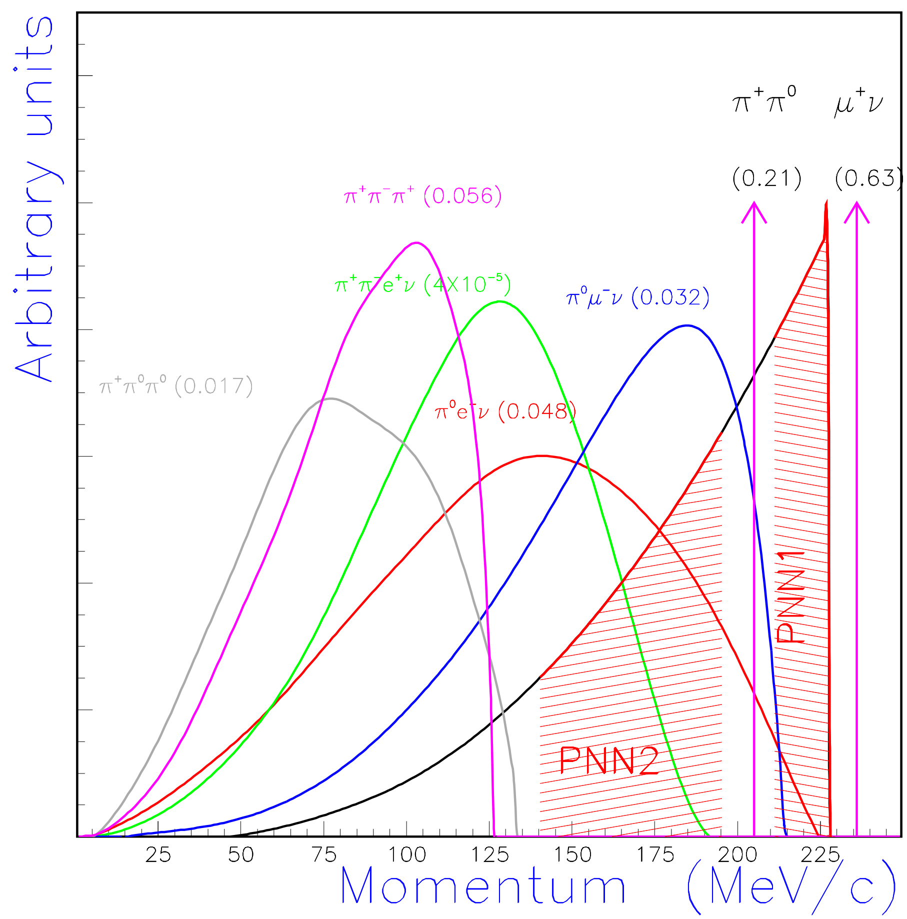
E787 experimental method

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}: Bkgd/S(SM) < 0.1

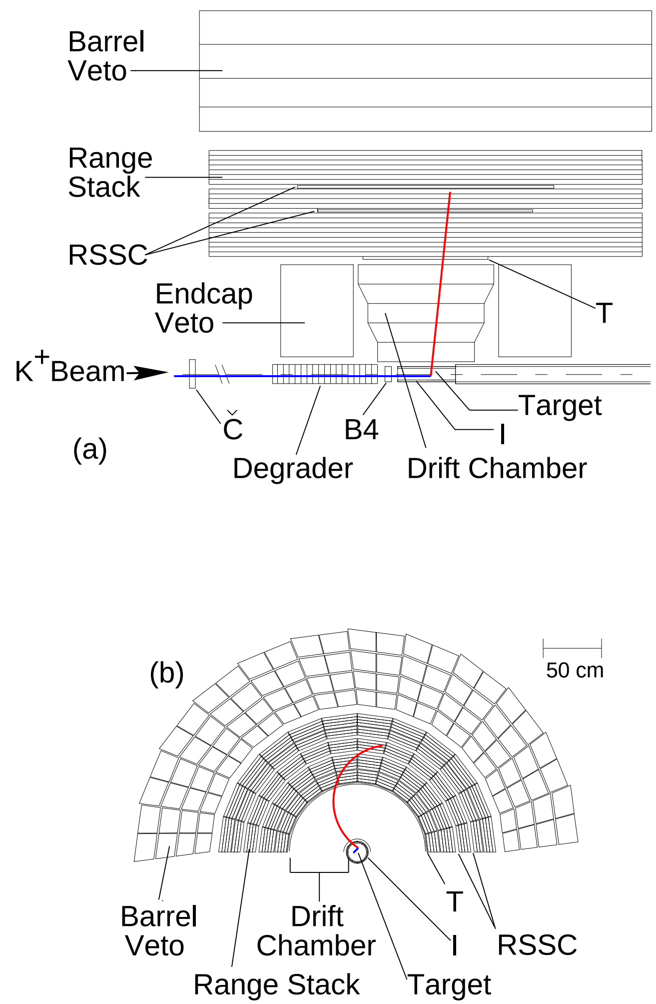
Measure background with data — set cuts based on 1/3 of data and evaluate bkgd with remaining 2/3.



E787 experimental method

- $\sim$ 700 MeV/c K$^+$ beam (K/$\pi \approx 4/1$)
- 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

E787 Spectrometer



E787 analysis strategy

- 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 $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

pnn1 background suppression

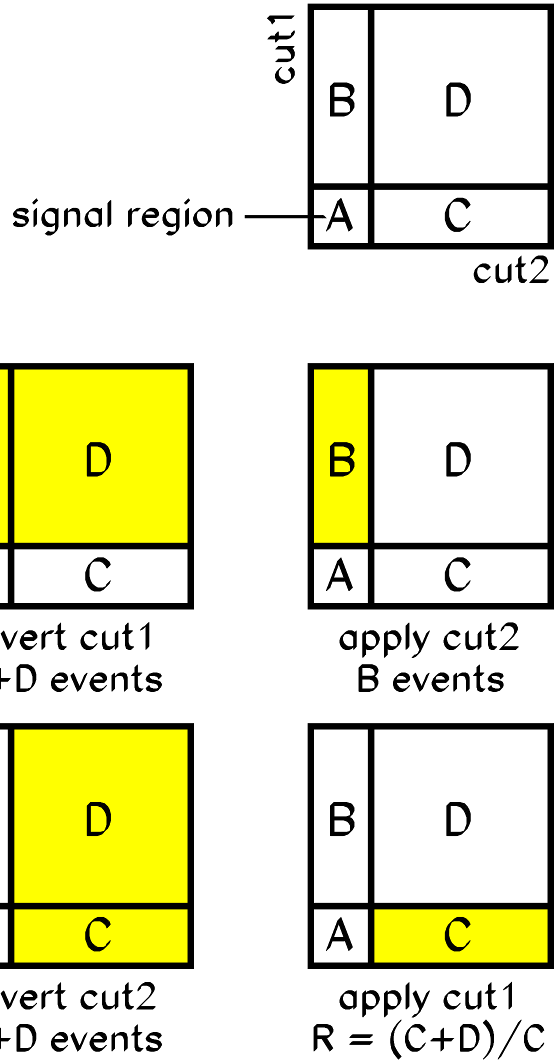
	Suppresion method			
Source	Kinematics	Particle ID	Veto	Timing
$K^+ \to \mu^+\nu(\gamma)$	$\surd$	$\surd$	$(\surd)$	
$K^+ \to \pi^+\pi^0$	$\surd$		$\surd$	
Scattered beam		$\surd$		$\surd$
CEX			$\surd$	$\surd$

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

Particle ID includes beam Cherenkov, dE/dx and $\pi \to \mu \to e$ detection

Veto includes both photon and charged particle vetoing

Measuring background with data



if cut1,cut2 uncorrelated,

$$A/B = C/D$$

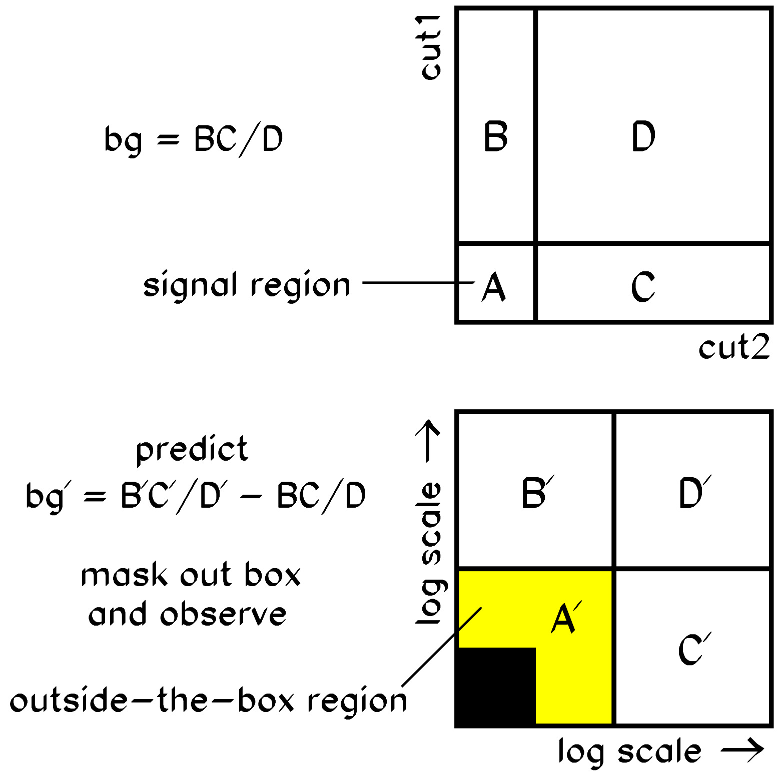
$$A = BC/D$$

$$bg = B/(R-1)$$
$$= BC/D$$

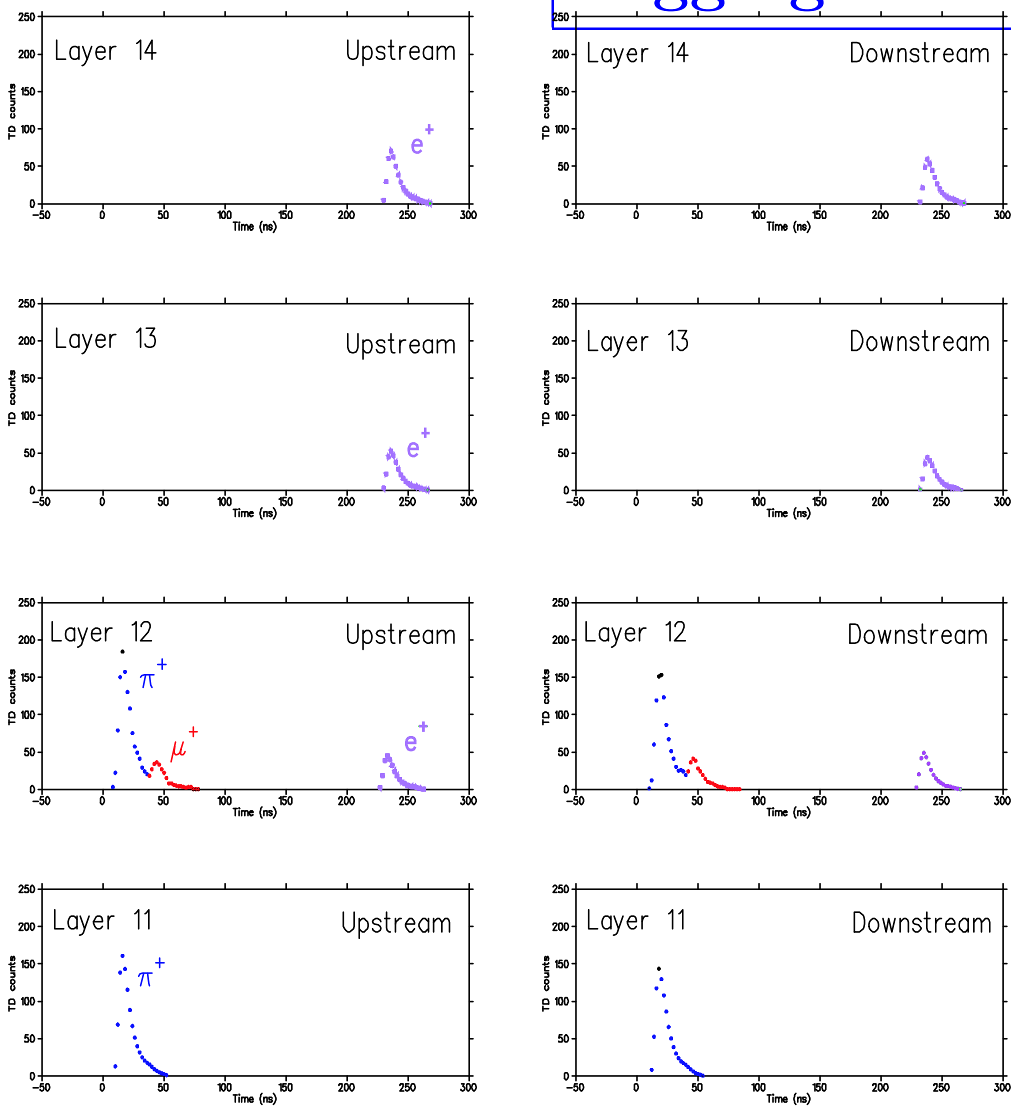
Measuring background with data

Checking for correlations between cuts.

Compare background predictions with observations near signal region.



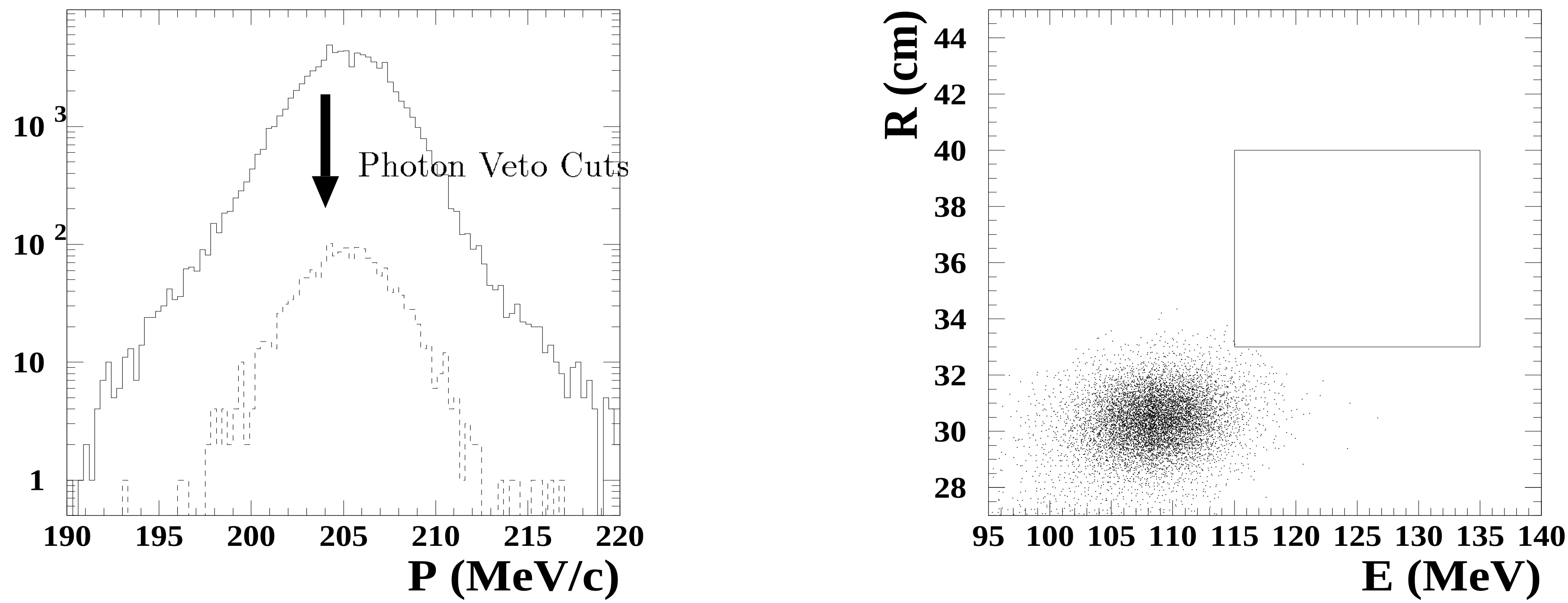
Tagging $\pi^+ \to \mu^+ \to e^+$



- Sample pulse height every 2 ns for 6 μs
- π^+ stops in range stack scintillator (2 cm/layer)
- $\pi^+ \to \mu^+\nu$, $E_\mu = 4.1$ MeV, $R_\mu \sim 1$ mm, $\tau_\pi = 26.0$ ns
- $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, $E_e \leq 53$ MeV, $\tau_\mu = 2.20$ μs

Plots: Pulse height (0 to 250) *vs* time (-50 to 300 ns)

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

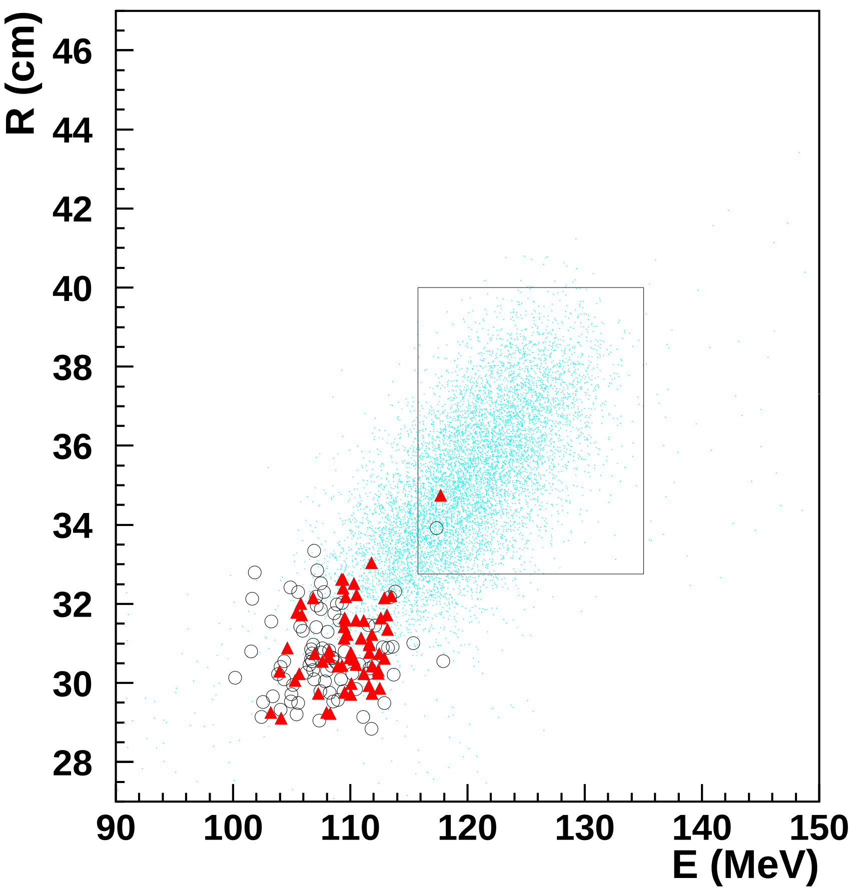


Left: Kinematically selected $K^+ \to \pi^+\pi^0$ with photon veto applied. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

Right: Photon veto inverted. Phase space cuts in P, R, E.

E787 pnn1 results

Range(cm) vs Energy(MeV) after all other cuts applied.

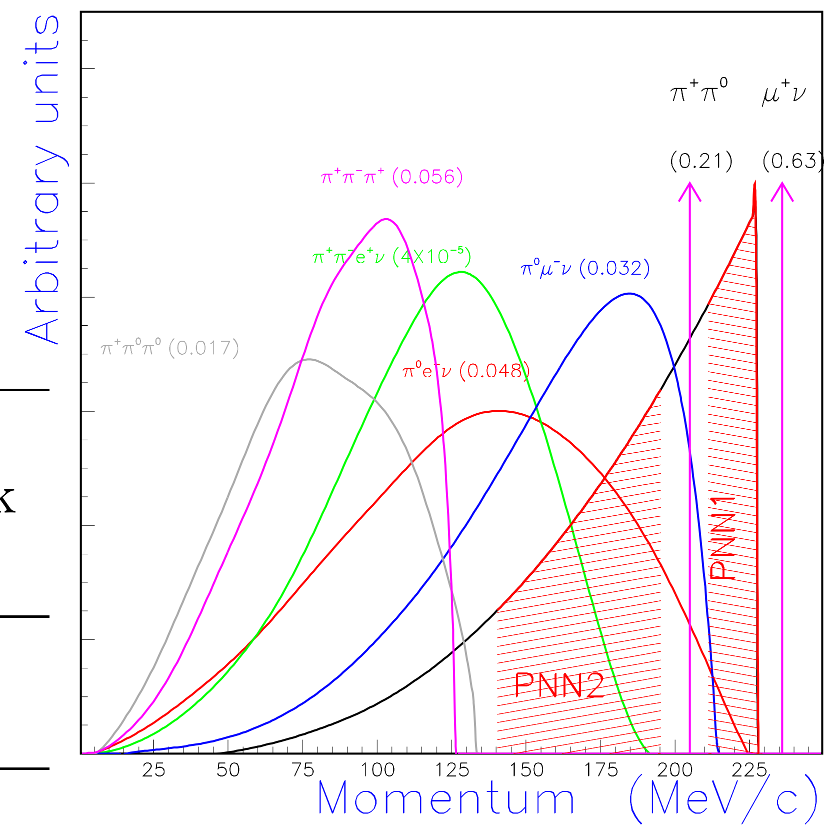


Bkgd	1995-97	1998
$K_{\pi 2}$	0.03 ± 0.01	$0.012^{+0.003}_{-0.004}$
$K_{\mu 2}$	0.02 ± 0.01	$0.034^{+0.043}_{-0.024}$
Beam	0.02 ± 0.02	0.004 ± 0.001
CEX	0.01 ± 0.01	$0.016^{+0.005}_{-0.004}$
Total	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$
N(K)	3.2×10^{12}	2.7×10^{12}
Acc.	0.0021(1)(2)	0.00196(5)(10)
Sens.	1.5×10^{-10}	1.89×10^{-10}
Cand.	1	1
$\mathcal{B}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	

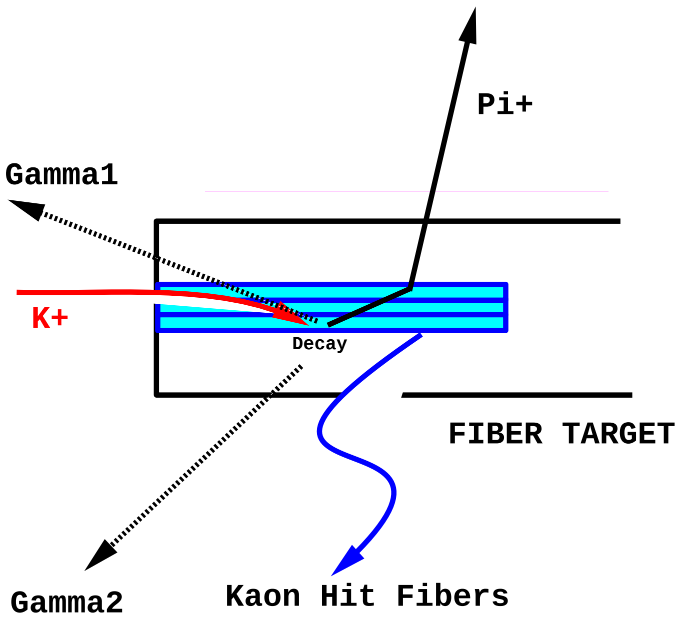
pnn2: $K^+ \to \pi^+\nu\bar{\nu}$ below $K^+ \to \pi^+\pi^0$ peak

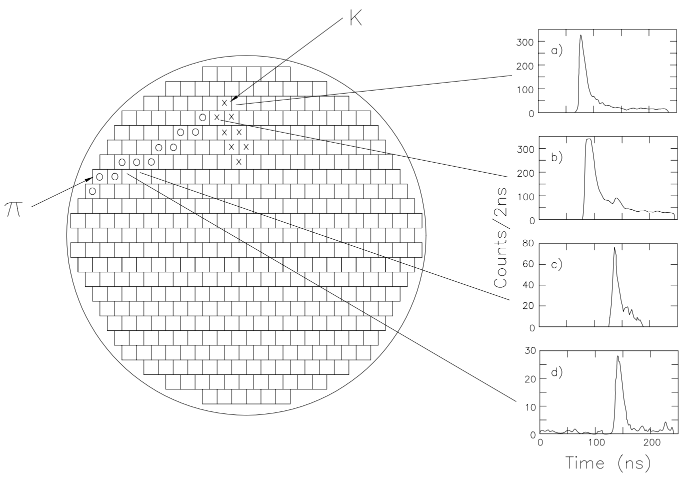
- More phase space than pnn1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \to \pi^+\nu\bar{\nu}$ spectrum
- **Larger backgrounds:**

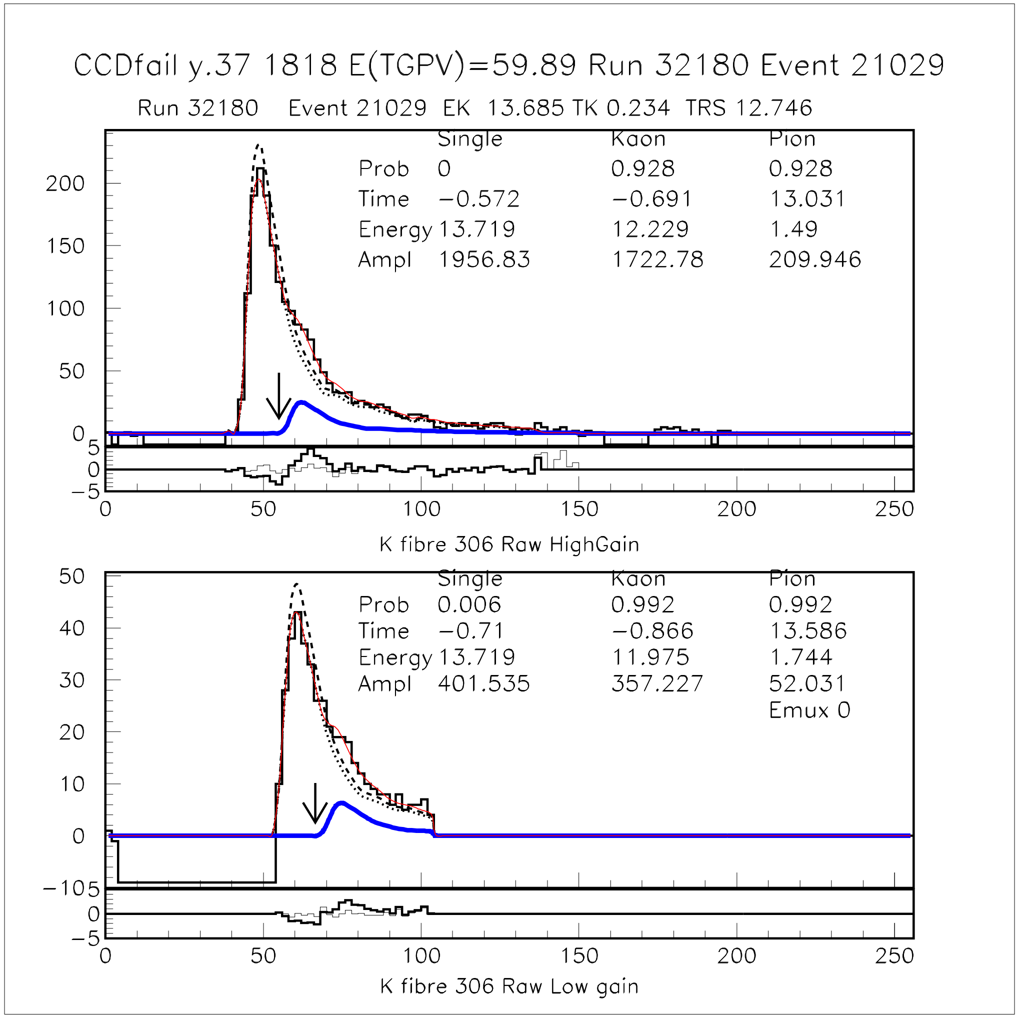
Source ($\mathcal{B}$)	Bkgd mechanism
$K^+ \to \pi^+\pi^0$ (0.21)	π^+ scatter in target $\pi^+\pi^0$ not back-to-back both γ missed
$K^+ \to \pi^+\pi^- e^+\nu$ (4×10^{-5})	π^- absorbed e^+ annihilates
$K^+ \to \pi^+\pi^0\gamma$ (2.75×10^{-4})	all γs missed



Suppression of $K^+ \to \pi^+\pi^0$ scattering background



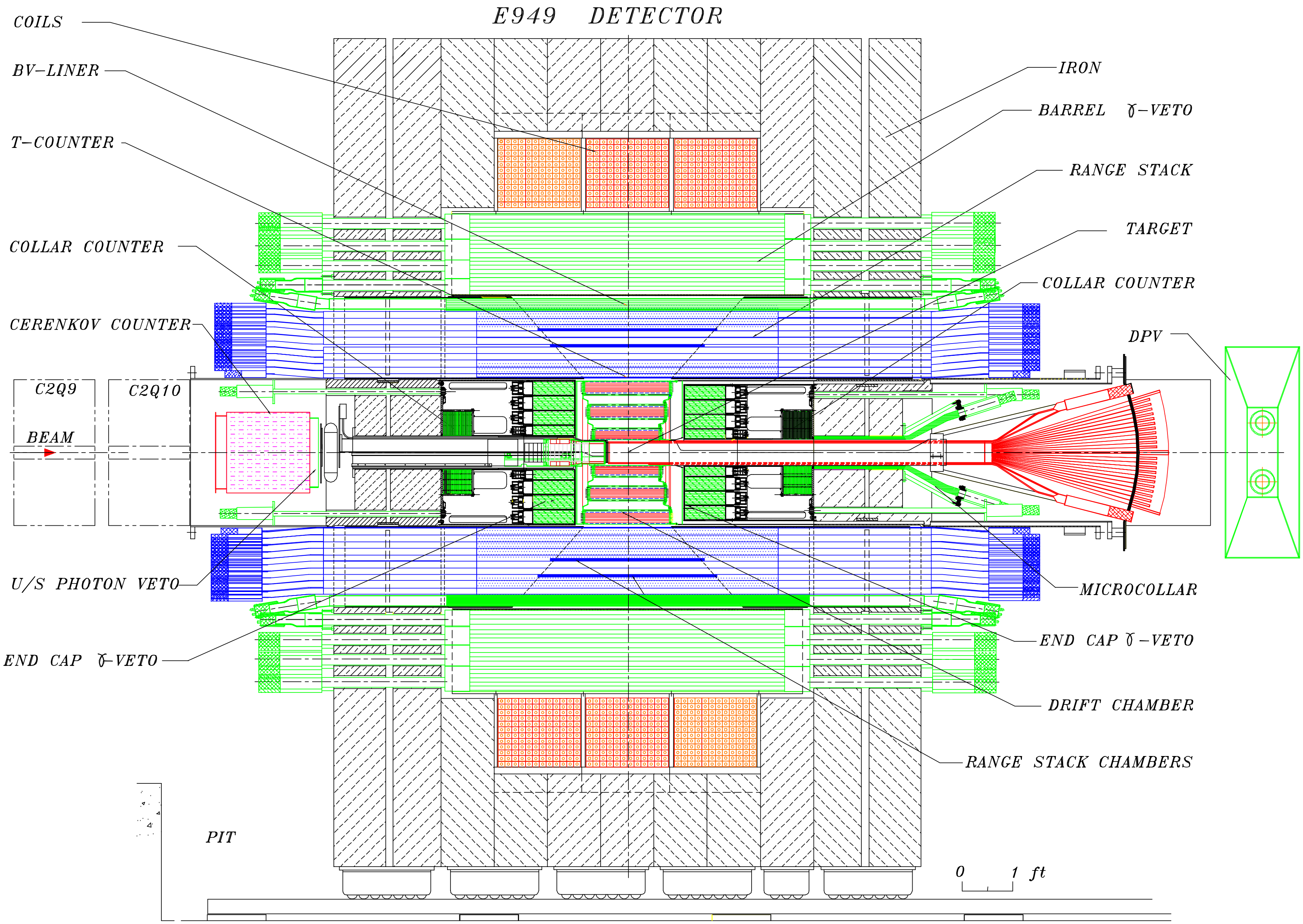




pnn2 and pnn1 summary

Backgrounds		
Source	pnn2	pnn1
$K_{\pi 2}$	1.029 ± 0.227	$0.042^{+0.010}_{-0.011}$
Beam	0.066 ± 0.047	0.024 ± 0.020
K_{e4}	0.052 ± 0.041	NA
$K_{\pi 2 \gamma}$	0.033 ± 0.004	NA
CEX	0.024 ± 0.017	0.026 ± 0.011
$K \to \mu X$	0.016 ± 0.011	$0.054^{+0.044}_{-0.026}$
Total	1.22 ± 0.24	0.15 ± 0.05
N(K)	1.7×10^{12}	5.9×10^{12}
Cand.	1	2

Acceptance (Death of 10^3 cuts)		
Factor	pnn2	pnn1
K stopping eff'y	.683	.703
Delayed K^+ decay	.621	.850
Phase space	.345	.146
Solid angle	.315	.408
π nucl. int. & d.i.f.	.708	.519
Recon. eff'y	.952	.964
Kinematic cuts	.690	.614
$\pi \to \mu \to e$	.526	.345
Beam, target cuts	.199	.702
Accidental loss	.373	.769
Product(**10^{-3}**)	.835	2.04


E949 DETECTOR
COILS
BV–LINER
T–COUNTER
COLLAR COUNTER
CERENKOV COUNTER
C2Q9
C2Q10
BEAM
U/S PHOTON VETO
END CAP γ–VETO
PIT
IRON
BARREL γ–VETO
RANGE STACK
TARGET
COLLAR COUNTER
DPV
MICROCOLLAR
END CAP γ –VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
0 1 ft

E949 status

Upgrades to E787:

Improved photon veto hermeticity

Improved tracking resolution

Higher rate and duty factor

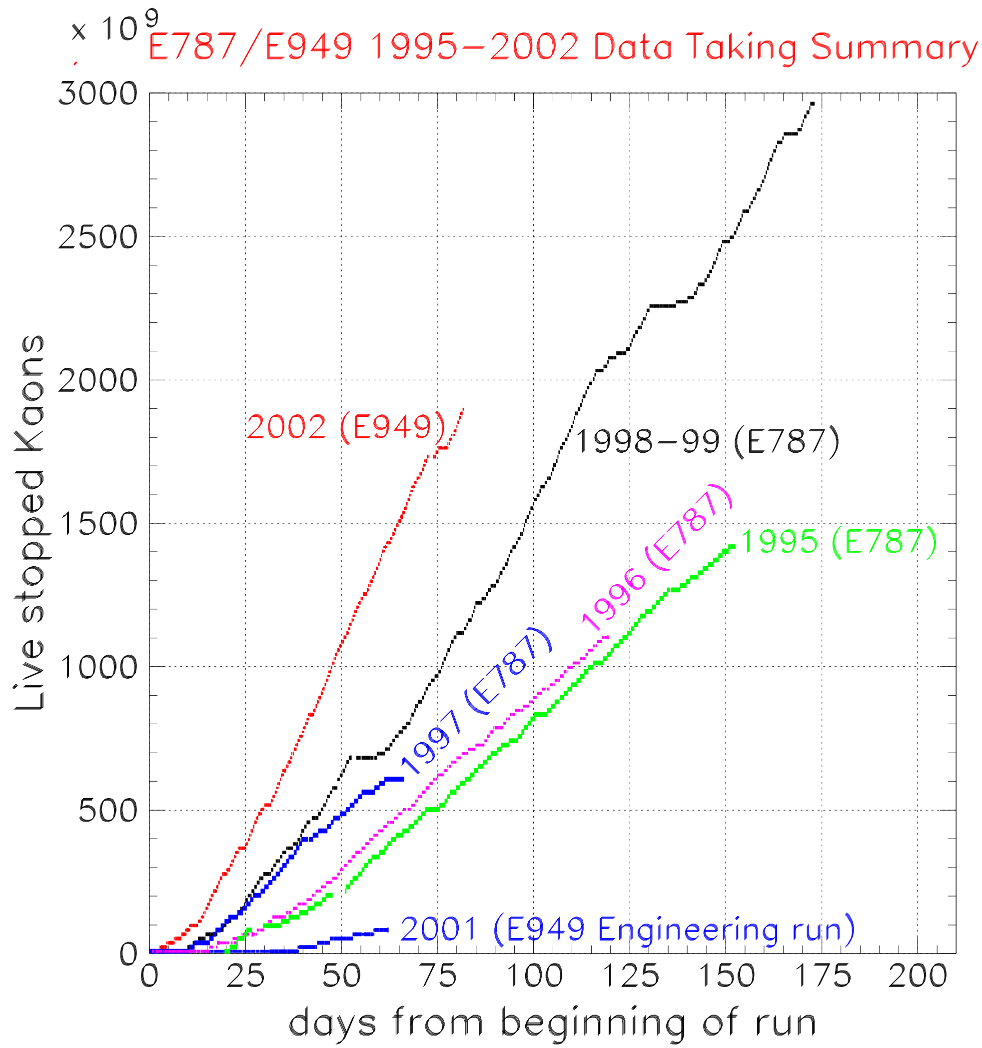
2002 run $\leq$ E787 sensitivity,

$\sim$ 20% of E949 sensitivity goal of $< 10^{-11}$.

pnn1 results: fall 2003.

Not optimal in 2002:

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

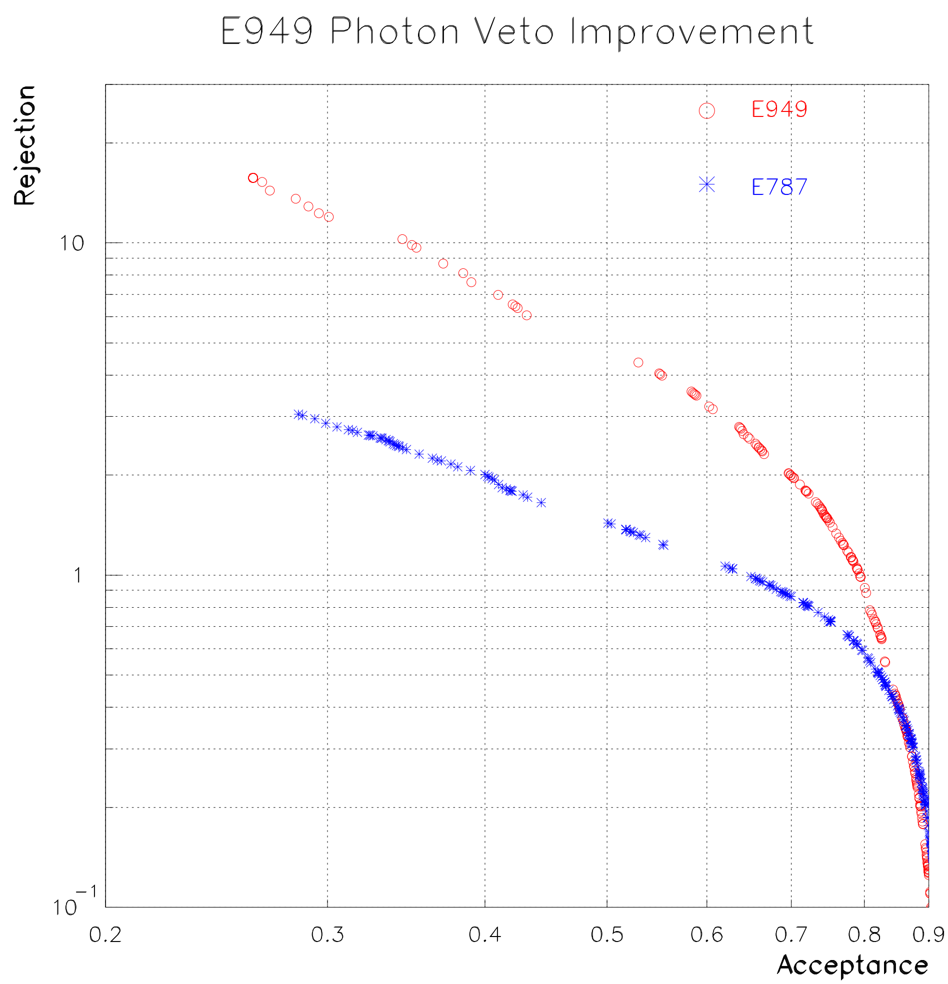


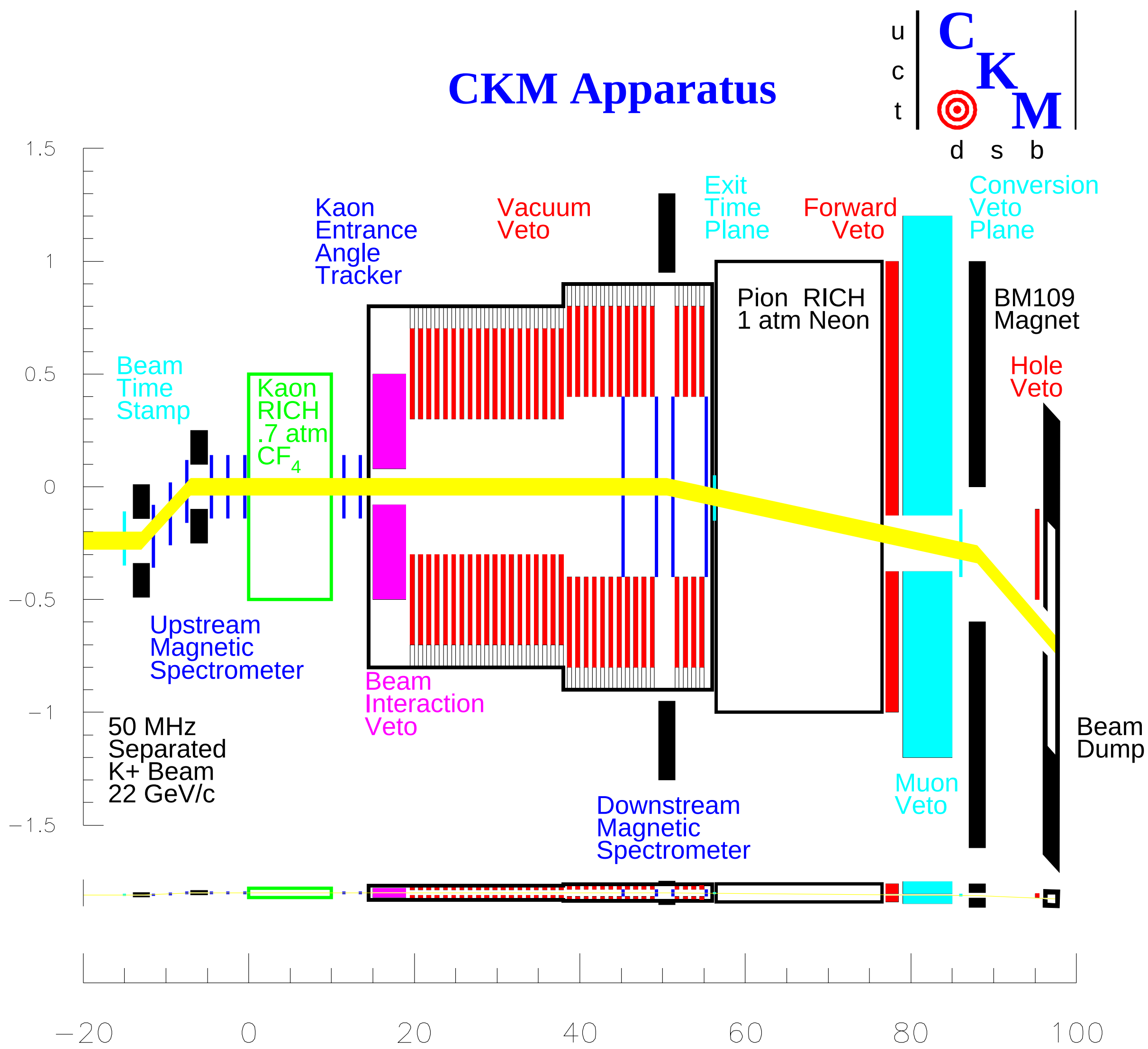
E949: Upgrade of photon veto

Improved photon veto hermeticity.

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

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





Fermilab CKM Experiment

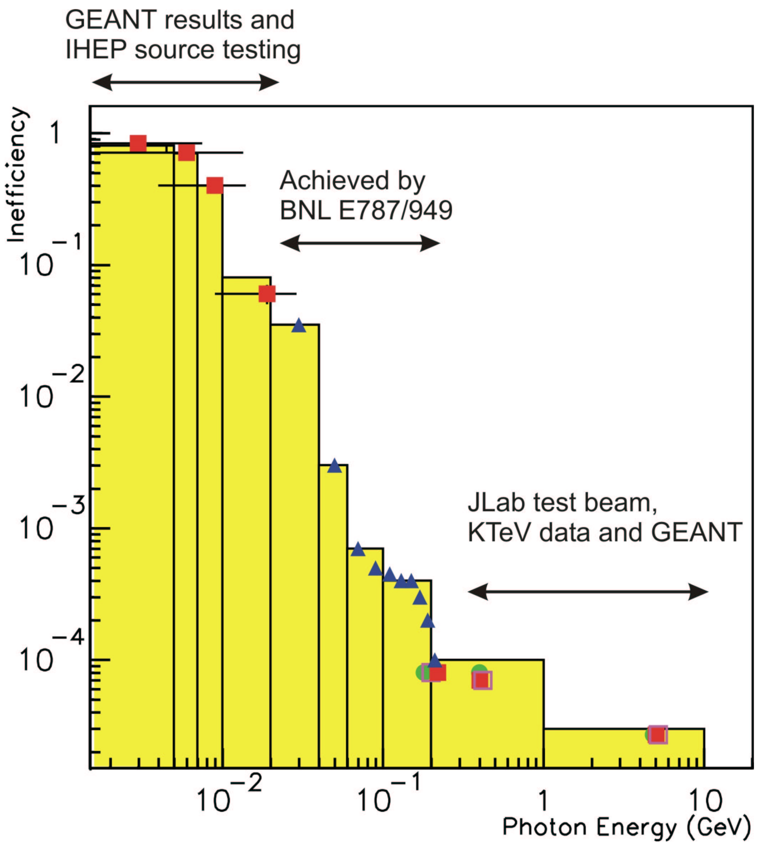
Goal: SES $= 10^{-12}$ or ≈ 100 SM events.

K^+ **decay-in-flight.**

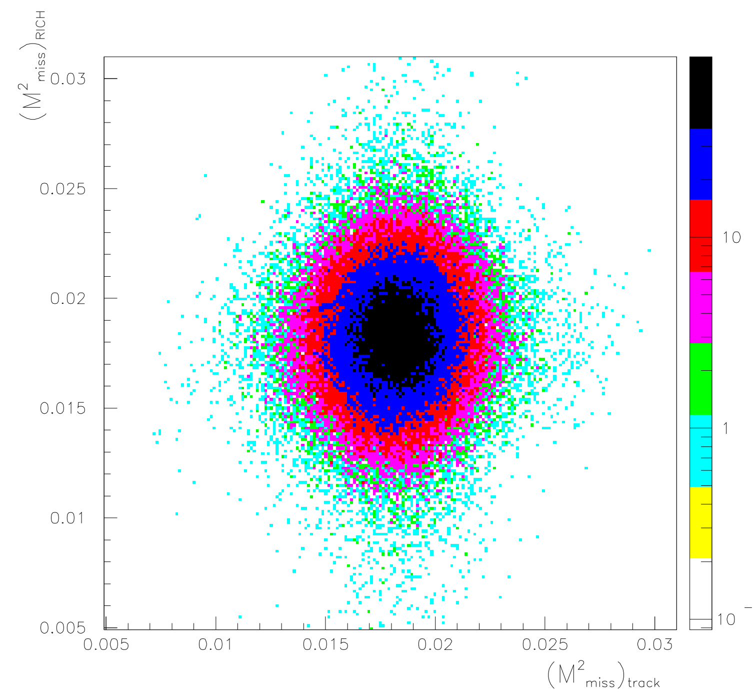
Signal region is above $K_{\pi 2}$ peak.

Need $\bar{\epsilon}_{\gamma\gamma} \sim 10^{-7}$ and $\bar{\epsilon}_{\text{kine}} \sim 10^{-7}$.

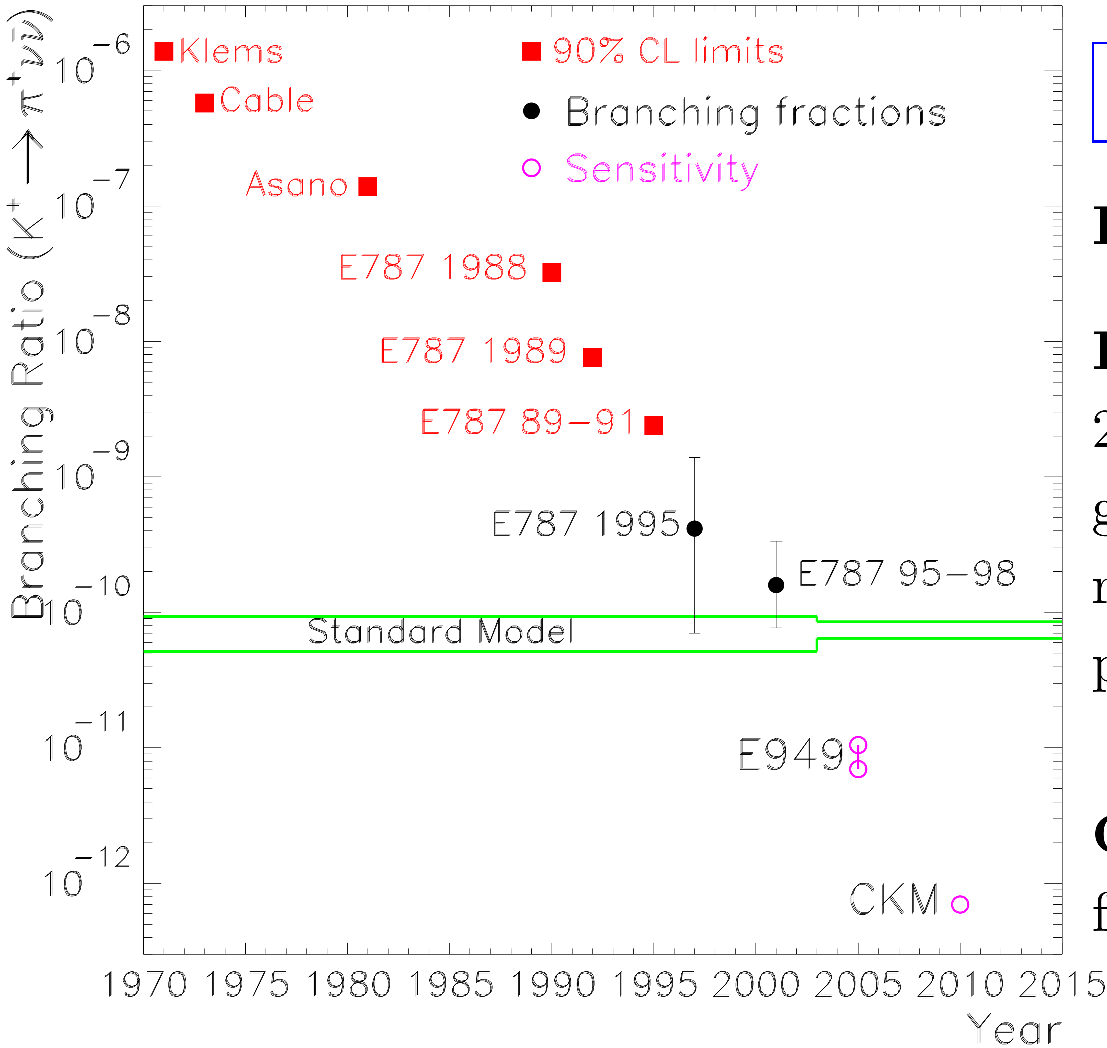
CKM: Achieving $\bar{\epsilon}_{\gamma\gamma} \sim 10^{-7}$ and $\bar{\epsilon}_{\rm kine} \sim 10^{-7}$



Required(histogram) and achieved(points) photon veto inefficiency.



Simulated $M^2_{\rm miss}$ for $K_{\pi 2}$ from tracking (horiz.) and RICH(vert.). Note uncorrelated non-gaussian tails.



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

E787: completed.

E949: 12 week run in 2002, can reach sensitivity goal of $\leq 10^{-11}$ when remaining 48 weeks of approved running is funded.

CKM: Start-up scheduled for 2009.

$K^0_L \to \pi^0 \nu\bar{\nu}$: Fourteen years ago

PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

CP-violating decay $K^0_L \to \pi^0 \nu\bar{\nu}$

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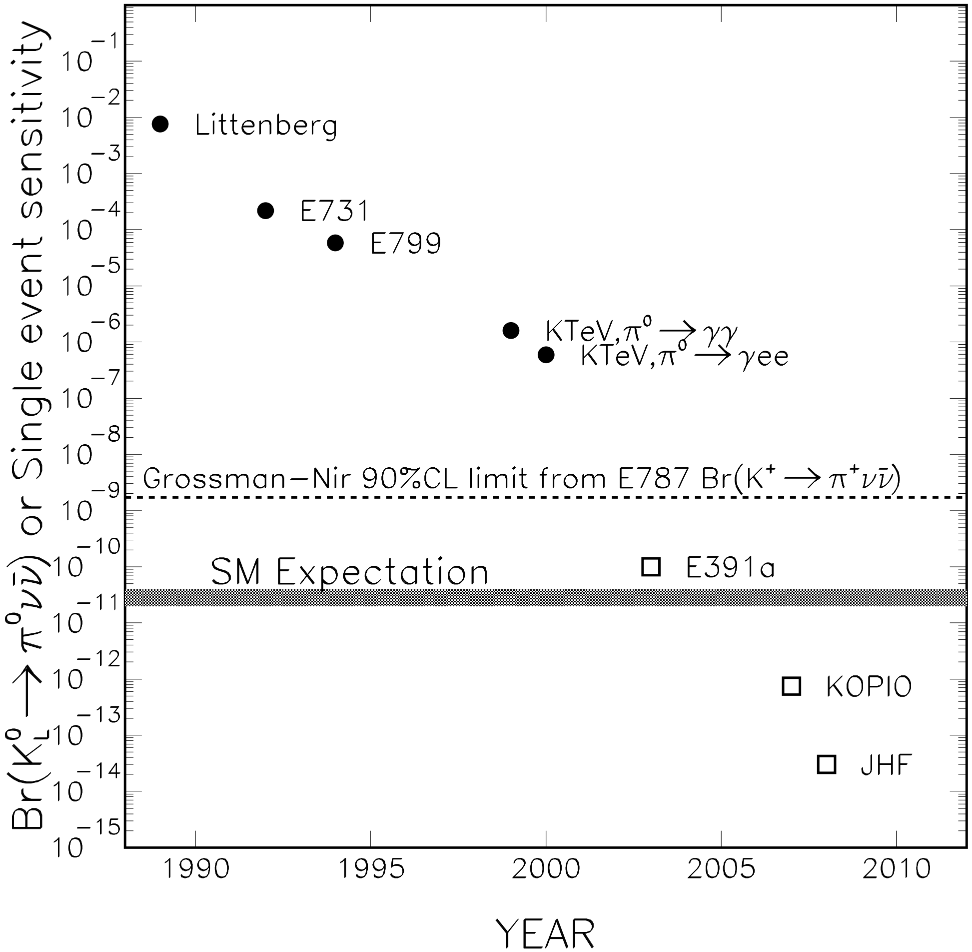
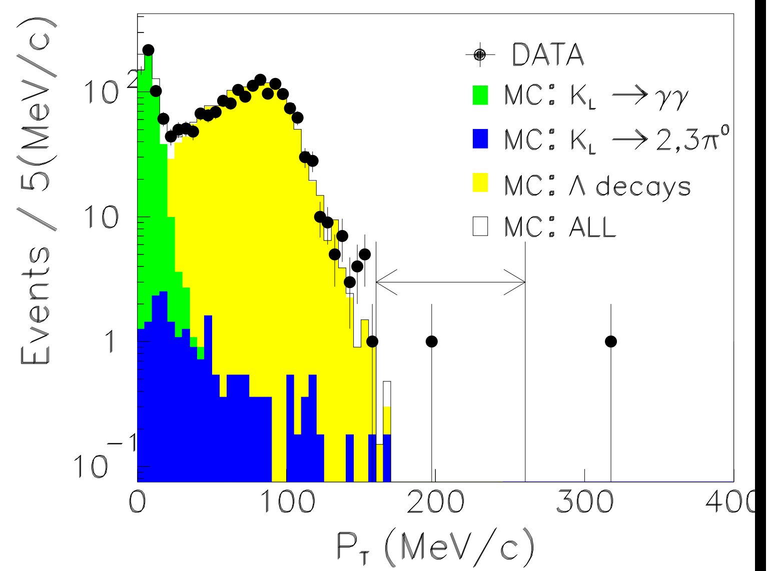
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 6 January 1989)

The process $K^0_L \to \pi^0 \nu\bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of *CP* violation. The largest expected contribution to this decay is a direct *CP*-violating term at $\approx$few$\times 10^{-12}$. The indirect *CP*-violating contribution is some *3 orders of magnitude* smaller, and *CP*-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of $\sim 1\%$ can be extracted from previous data on $K^0_L \to 2\pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin\theta_2 \sin\theta_3 \sin\delta$ can be made.

"Experimentally, the problems are perhaps best represented by the statement that nobody has yet shown that a measurement of this decay is absolutely impossible." F.J.Gilman, "CP Violation in Rare K Decays", *Blois CP Violations* 1989:481-496

History of $K_L^0 \to \pi^0\nu\bar{\nu}$





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

The KOPIO Technique: Work in K_L^0 CMS

Measure everything possible.

Microbunched K_L^0 beam

Measure γ directions in PR

Measure γ energy in CAL

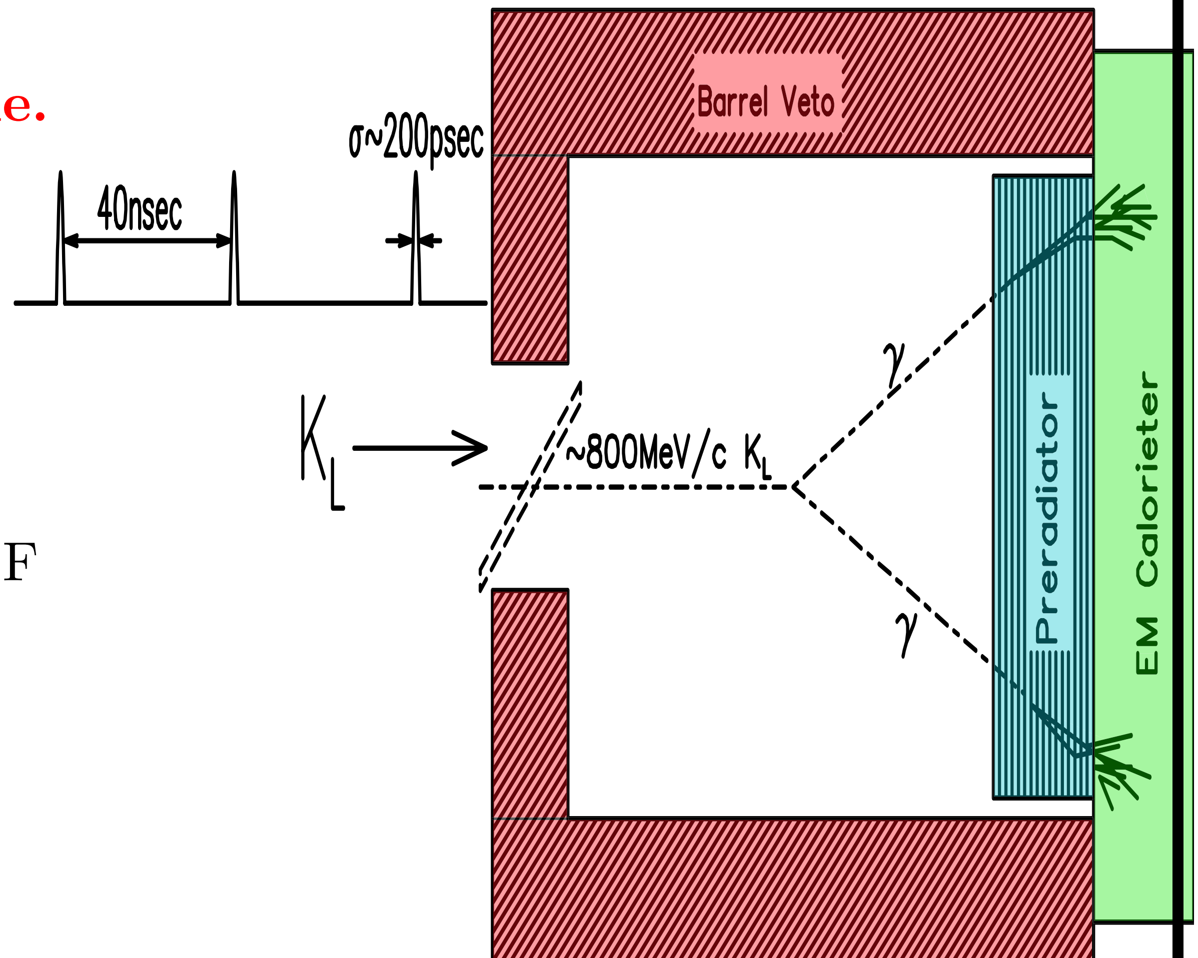
Reconstruct π^0 from $\gamma\gamma$

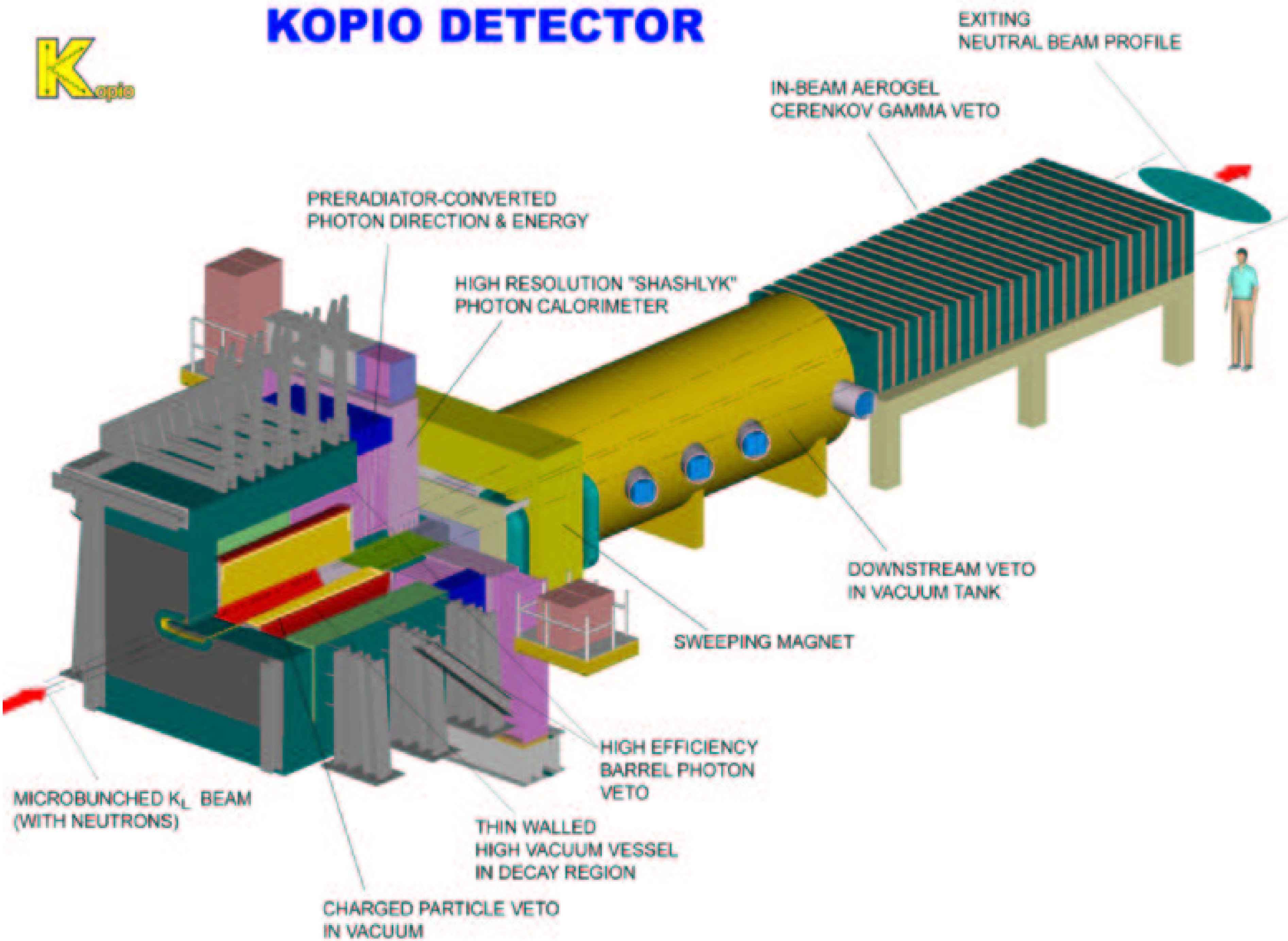
Measure K_L^0 velocity from TOF

Photon veto

Charged track veto

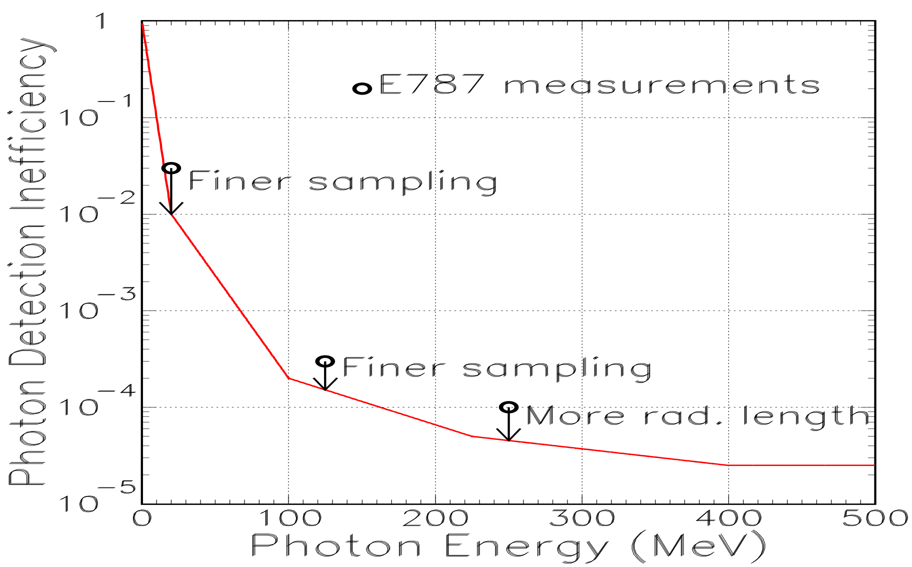
Kinematic veto

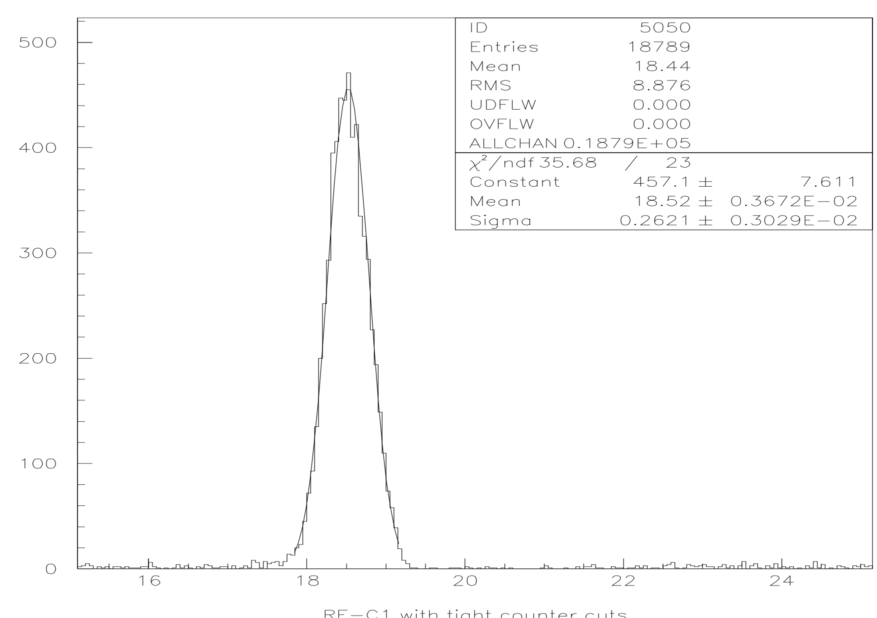



KOPIO DETECTOR
EXITING
NEUTRAL BEAM PROFILE
IN-BEAM AEROGEL
CERENKOV GAMMA VETO
PRERADIATOR-CONVERTED
PHOTON DIRECTION & ENERGY
HIGH RESOLUTION "SHASHLYK"
PHOTON CALORIMETER
DOWNSTREAM VETO
IN VACUUM TANK
SWEEPING MAGNET
HIGH EFFICIENCY
BARREL PHOTON
VETO
MICROBUNCHED K$_L$ BEAM
(WITH NEUTRONS)
THIN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

Critical KOPIO performance requirements

Parameter	Minimal Requirement	Expected Performance
E_γ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
θ_γ resolution(250 MeV)	25 to 30 mrad	23 mrad
t_γ resolution	100 ps$\sqrt{E}$	50 ps$\sqrt{E}$
x_γ,y_γ resolution(250 MeV)	10 mm	<1 mm
microbunch width	300 ps	200 ps
photon veto inefficiency	$\bar{\epsilon}_{\rm E787}$	$0.3\bar{\epsilon}_{\rm E787}$





measured microbunch $\sigma = 262 \pm 3$ ps

Background suppression tools

K^0_L Decay	$\mathcal{B}/3 \times 10^{-11}$	Kinematic	Photon veto	Charged veto
$\pi^0\pi^0$ even	3.1×10^7	E^*_π	$\surd\surd$	
$\pi^0\pi^0$ odd	3.1×10^7	$\lvert E^*_{1\gamma} - E^*_{2\gamma}\rvert$, $M_{\gamma\gamma}$	$\surd\surd$	
$\pi^\pm e^\mp \nu\gamma$	1.2×10^8	$M_{\gamma\gamma}$, χ^2	$\surd$	$\surd$
$\pi^+\pi^-\pi^0$	4.2×10^9	E^*_π, E_{MISS}		$\surd\surd$
$\pi^0\pi^\pm e^\mp\nu$	1.7×10^6	E^*_π		$\surd\surd$
$\pi^0\pi^0\pi^0$	7.0×10^9	E^*_π	$\surd\surd\surd$	
$\pi^0\gamma\gamma$	5.6×10^4		$\surd\surd$	
$\gamma\gamma$	2.7×10^7	$M_{\gamma\gamma}$, E^*_π		

even $\equiv$ both γ from same π^0

odd $\equiv$ γ from different π^0

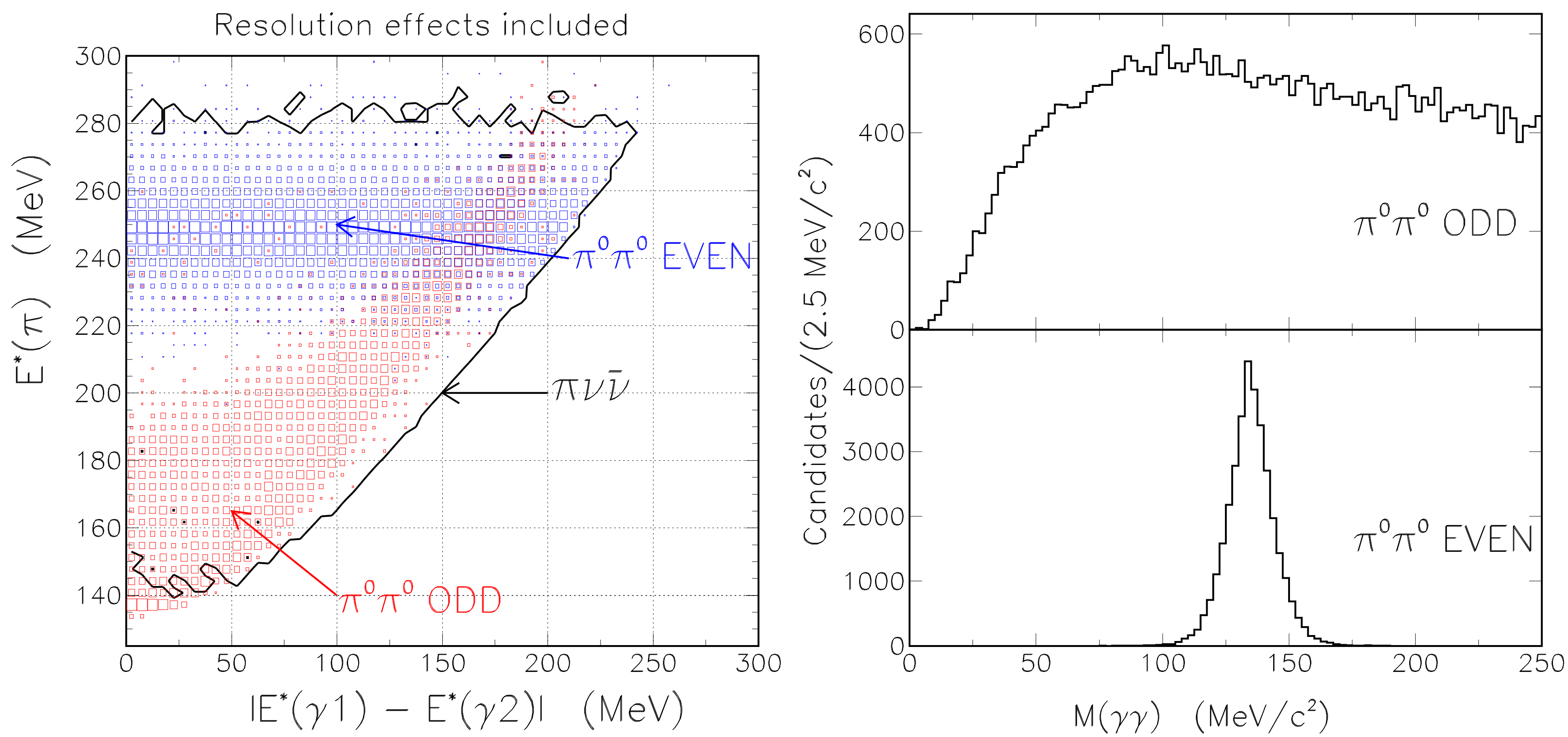
χ^2 $\equiv$ $\chi^2$of fit of γ 3-momenta to a common vertex

$M_{\gamma\gamma}$ $\equiv$ 2 photon invariant mass

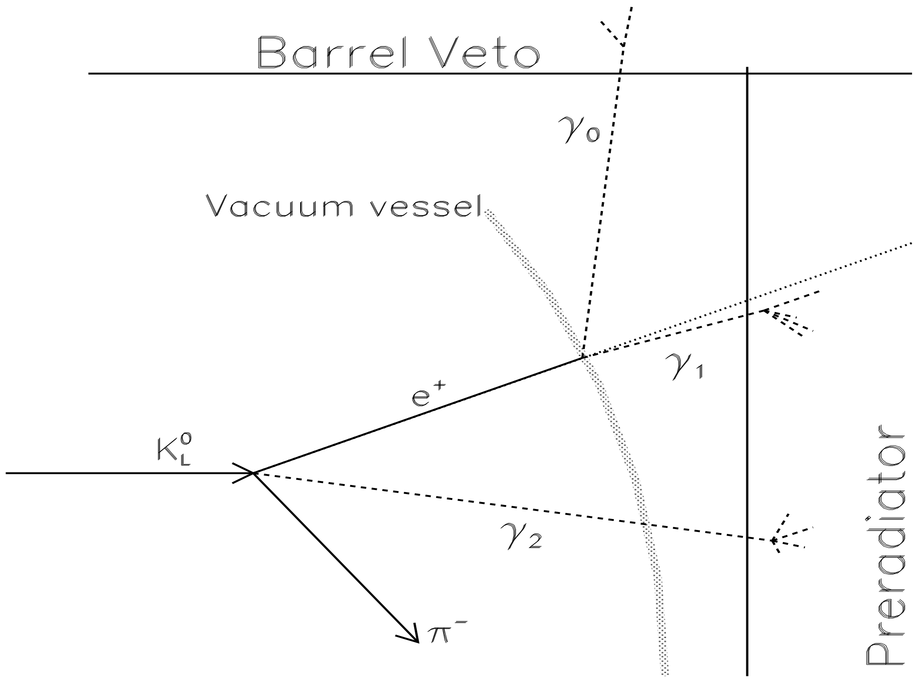
E^*_i $\equiv$ energy in K^0_L rest frame, $i = \pi^0, \gamma_1, \gamma_2$

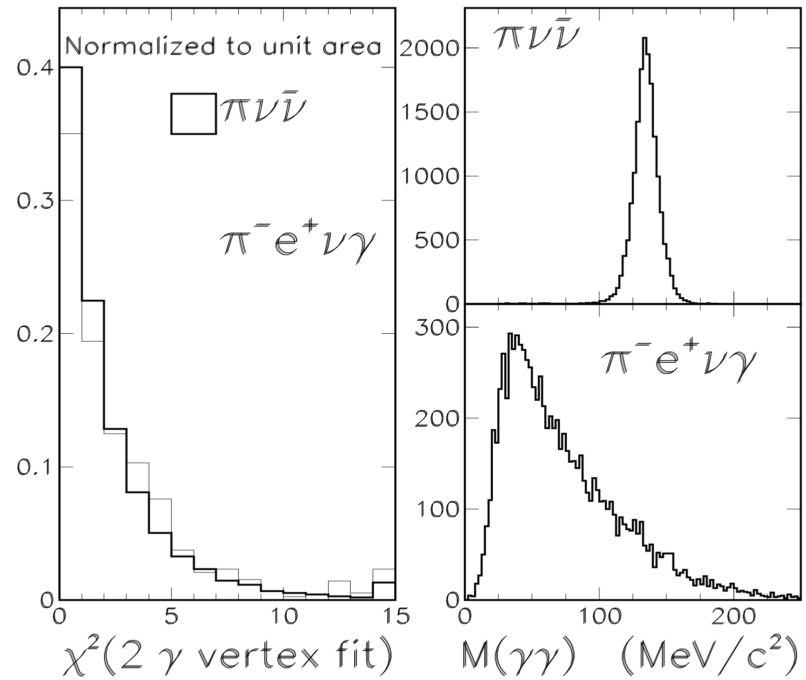
E_{MISS} $\equiv$ $E(K^0_L) - E(\gamma_1) - E(\gamma_2)$

Kinematic rejection of $K^0_L \to \pi^0\pi^0$ background



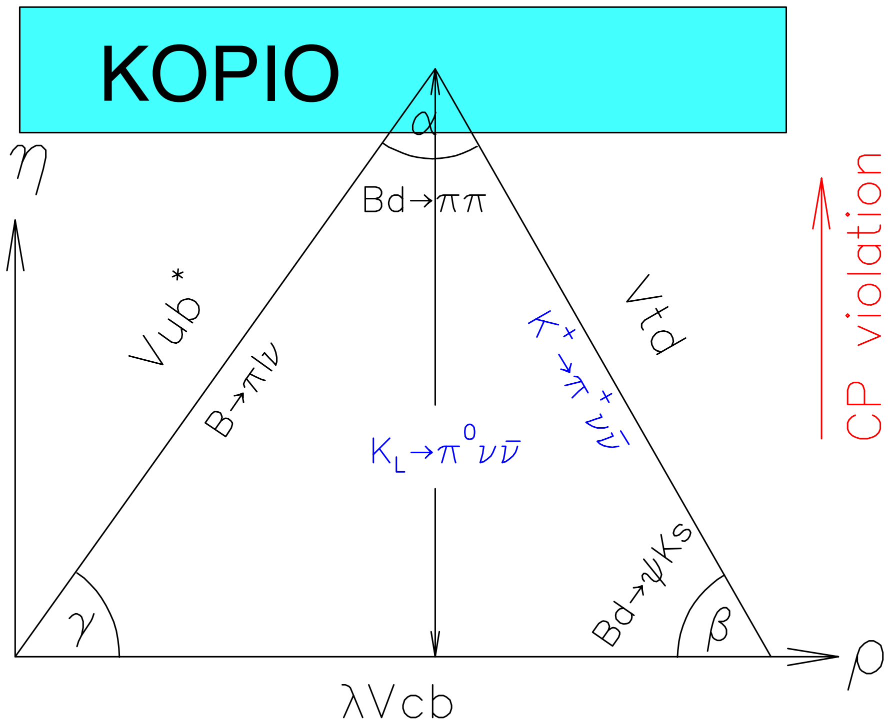
$K^0_L \to \pi^- e^+ \nu \gamma_2$ ($e^+e^- \to \gamma_0\gamma_1$) background





Background from $K^0_L \to \pi^\pm e^\mp \nu \gamma$ occurs when the e^+ converts at the vacuum vessel. π^0 candidates are formed from $\gamma_1\gamma_2$. For $e^+e^- \to \gamma_0\gamma_1$, $p(\gamma_1) \approx p(e^+)$ and $p(\gamma_0) \approx p(e^-)$. Modest rejection possible from lower energy γ_0 and increased χ^2 from slight change of γ_1 from the original e^+ direction.

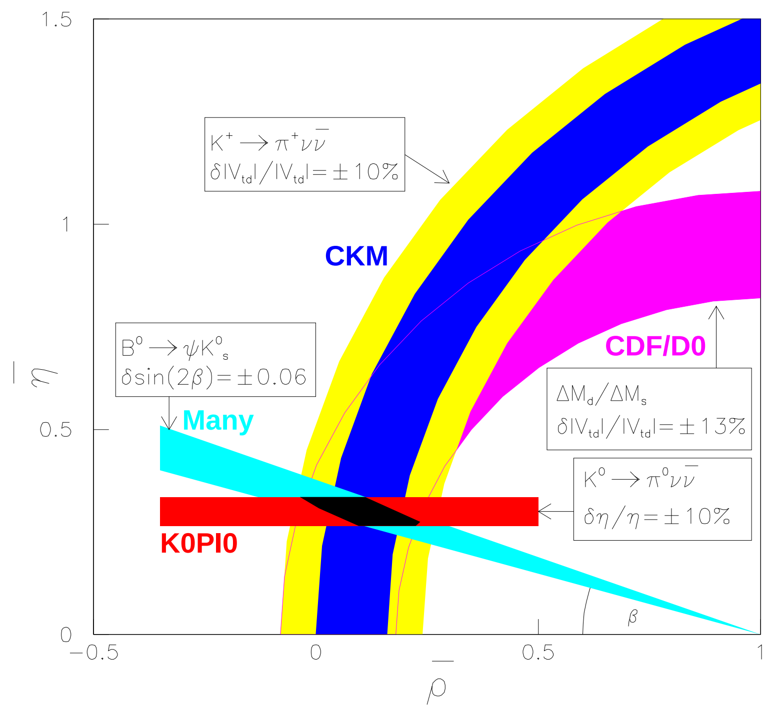
KOPIO signal and background estimates



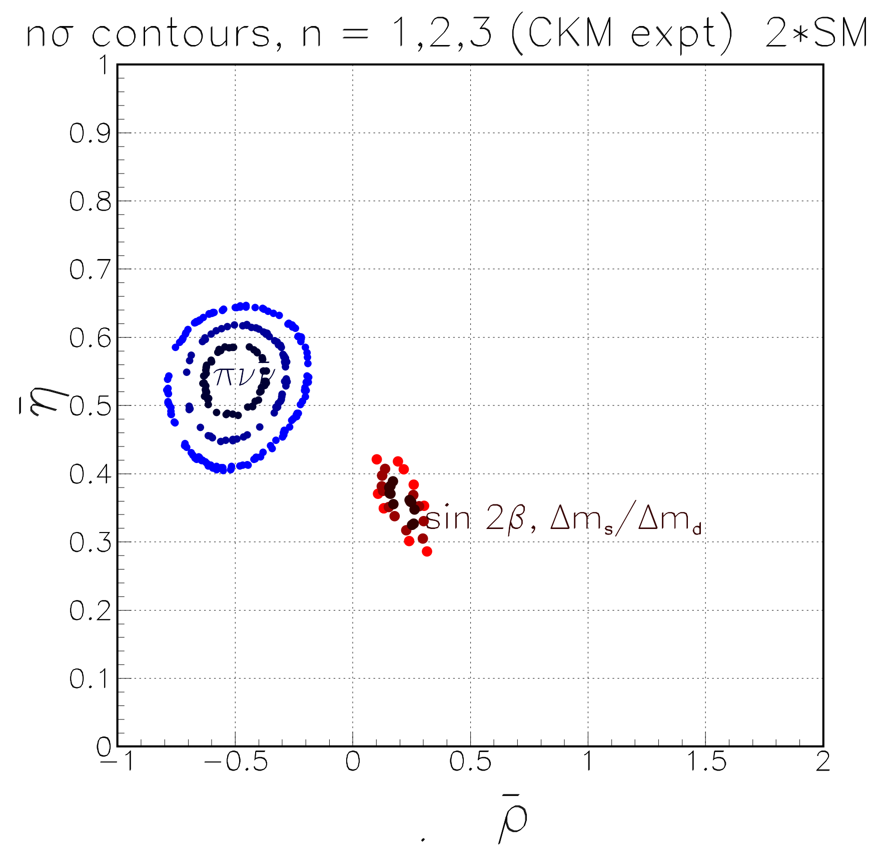
$\Delta\mathcal{B}/\mathcal{B} \approx 20\%$ or
$\Delta\eta/\eta \approx 10\%$ at S/B=2

Process	Events
$K_L^0 \to \pi^0 \nu\bar{\nu}$ at SM rate	40
$K_L^0 \to \pi^0 \pi^0$	12.4
$K_L^0 \to \pi^\pm e^\mp \nu\gamma$	4.5
$K_L^0 \to \pi^- \pi^+ \pi^0$	1.7
$K_L^0 \to \pi^\pm e^\mp \nu$	0.02
$K_L^0 \to \gamma\gamma$	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 $K \to \pi\nu\bar{\nu}$ measurements



All measurements at SM expectation.



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

Outlook for $\mathrm{K} \to \pi\nu\bar{\nu}$ measurements

E787: completed

E949: Approved by DOE(1999), DOE halts HEP at AGS(2002), awaiting funding to continue

CKM: Stage I approval(2001), data taking in 2009(?)

KOPIO: Approved by NSF(2003), construction start in 2005

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

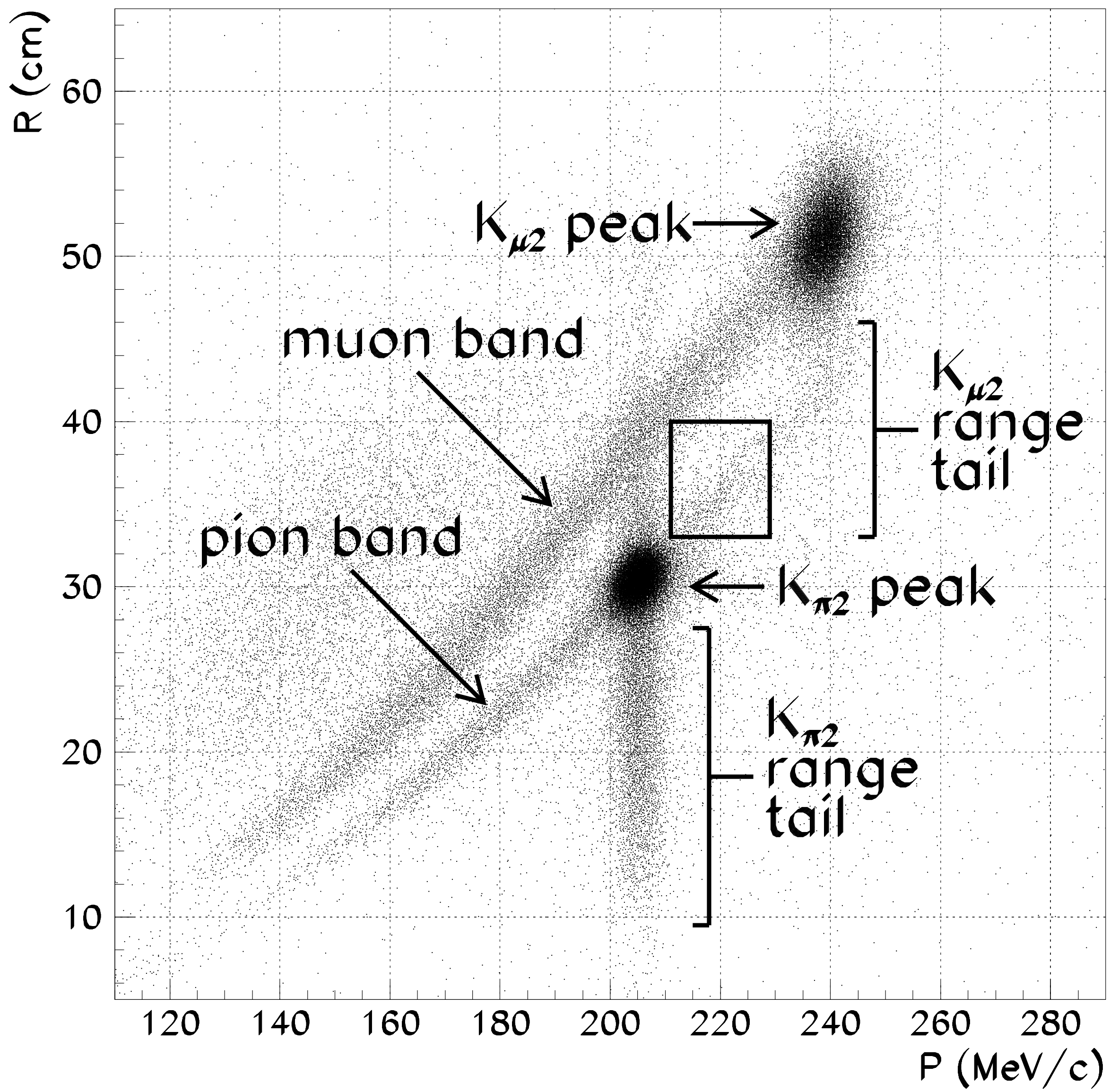
Thanks to P.Cooper, G.Redlinger, S.Kettell, L.Littenberg, K.Nelson, H.Nguyen, R.Tschirhart & E949, CKM, KOPIO collaborations.

Extras

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

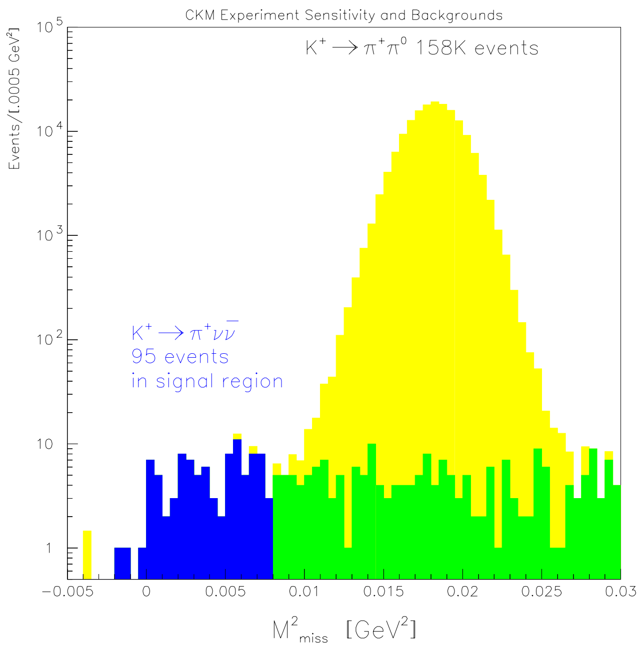
$$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu}) = K_0 \left(\left[\mathrm{Im}\lambda_t \frac{X}{\lambda^5}\right]^2 \right)$$

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



Range *vs* Momentum accepted by trigger

CKM Goal: 100 events with S/N>7



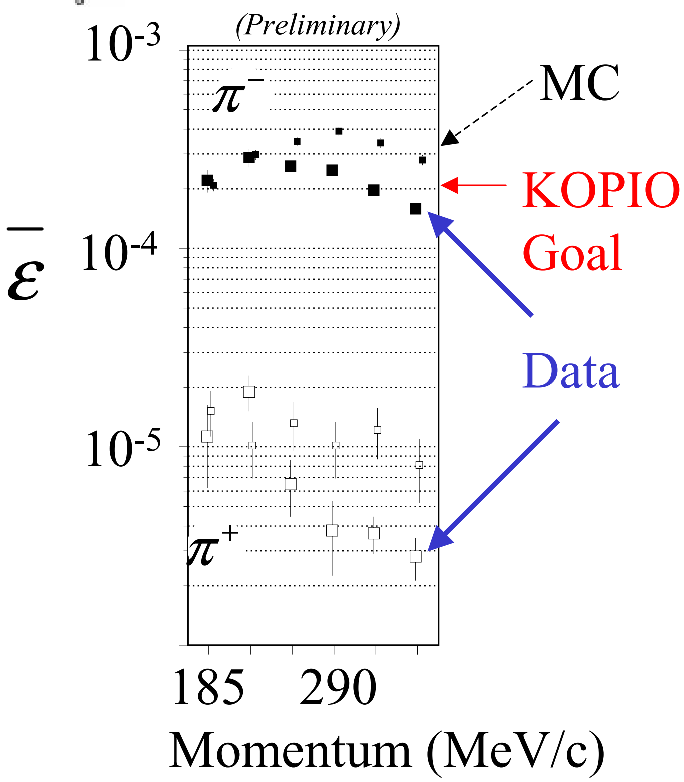
Background source	Effective BR ($\times 10^{-12}$)
$K^+ \to \mu^+\nu_\mu$	< 0.04
$K^+ \to \pi^+\pi^0$	3.7
$K^+ \to \mu^+\nu_m u\gamma$	< 0.09
$K^+A \to K_L X, K_L \to \pi^+ e^- \overline{\nu}_e$	< 0.14
$K^+A \to \pi^+ X$ in trackers	< 4.0
$K^+A \to \pi^+ X$ in residual gas	< 2.1
Accidentals (2 K^+ decays	0.51
Total	< 10.6

Charged Particle Vetoing

Example Background: $\mathbf{K}_L^0 \rightarrow \pi^- e^+ \nu \gamma$

Plastic Scintillator

PSI Measurement



KEK: 1 GeV/c

Particle	$\bar{\varepsilon}$
e^+	$(3.2 \pm 0.9)\ x\ 10^{-4}$
π^+	$< 1.6x10^{-5}$
e^-	$< 1.3x10^{-4}$
π^-	$(6.0 \pm 0.6)\ x\ 10^{-4}$

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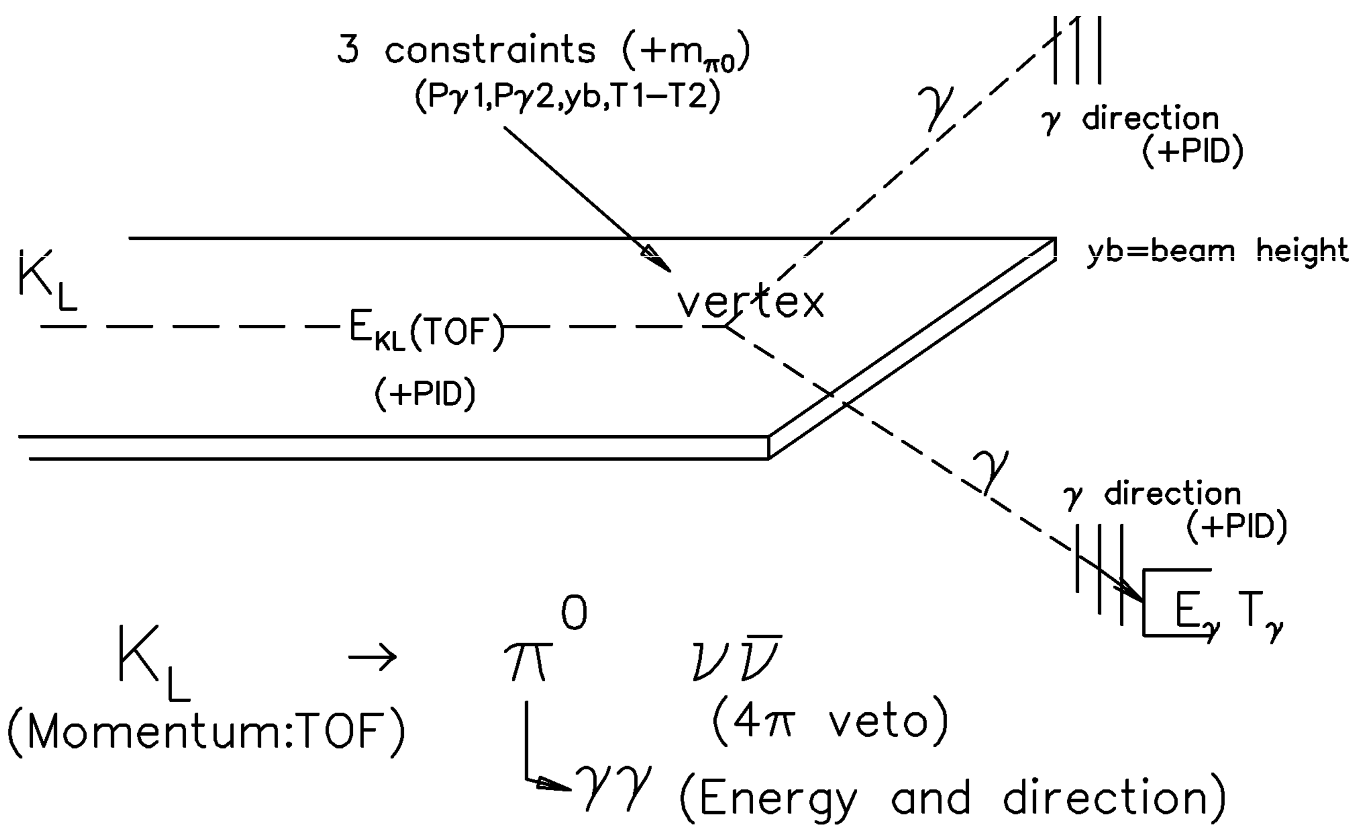
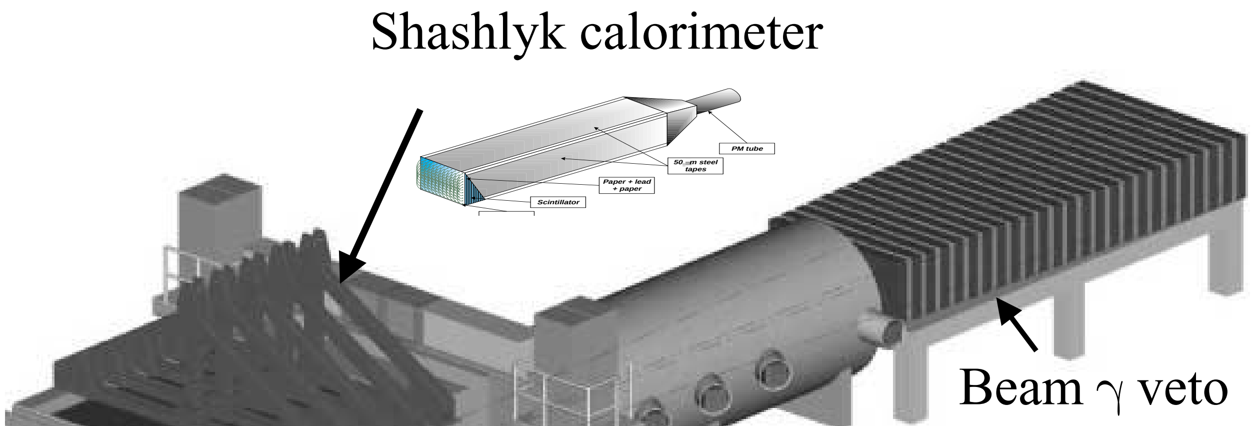
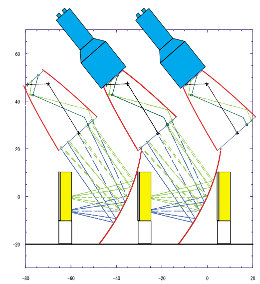
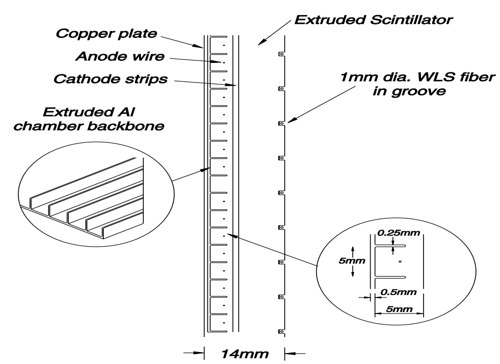
KOPIO Beam and Constraints





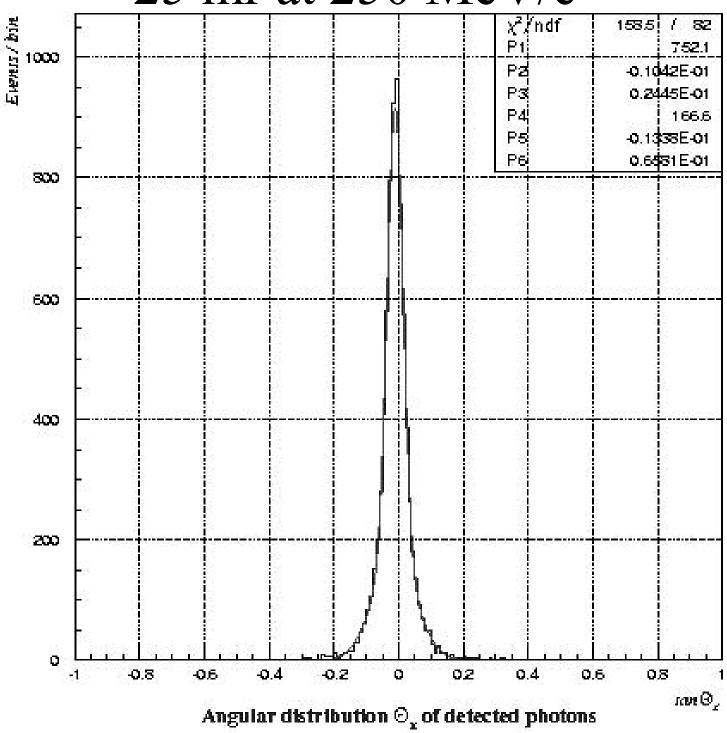




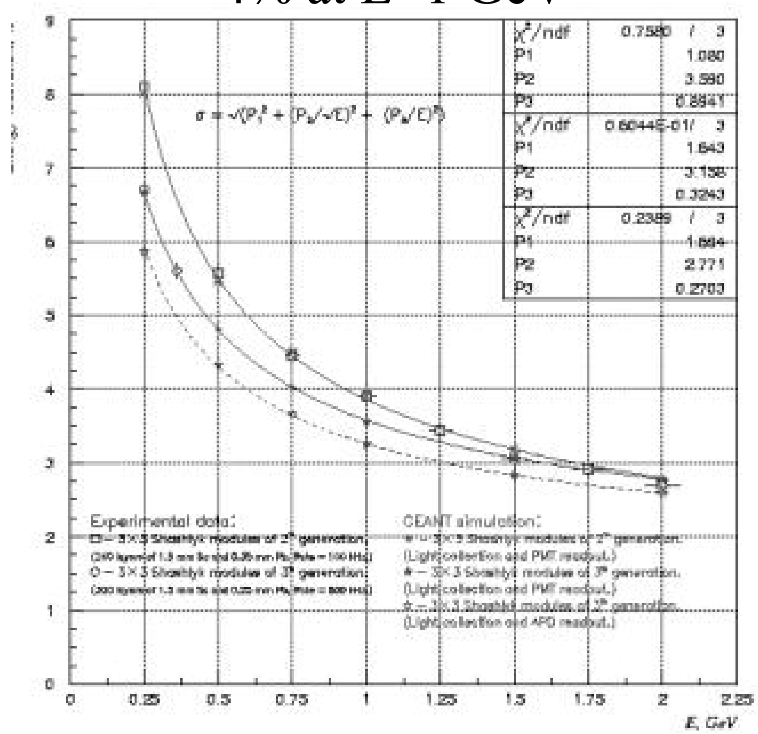
Parameter	Minimal Requirement	Expected Performance
E_γ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
θ_γ resolution (250MeV)	$(25-30)$ mr	23 mr
t_γ resolution	$100ps/\sqrt{E}$	$50ps/\sqrt{E}$
x_γ, y_γ resolution(250MeV)	10mm	$<$ 1mm
μ-bunch width	$300ps$	$200ps$
γ-veto inefficiency	$\overline{\epsilon}_{E787}$	$0.3\overline{\epsilon}_{E787}$

KOPIO Prototype Measurements – Tagged Photon Beams

Preradiator
Angular resolution:
25 mr at 250 MeV/c



Shashlyk
Calorimeter resolution:
<4% at E=1 GeV



Possible impact of $K \to \pi\nu\bar{\nu}$ measurements

Assume $K \to \pi\nu\bar{\nu}$ rates at twice SM expectation and B measurements are consistent with SM.

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.57 \pm 0.12) \times 10^{-10}$$

$$\mathcal{B}(K^0_L \to \pi^0\nu\bar{\nu}) = (6.0 \pm 0.8) \times 10^{-11}$$

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

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