LaThuile
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Prospects for Measuring $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ at BNL

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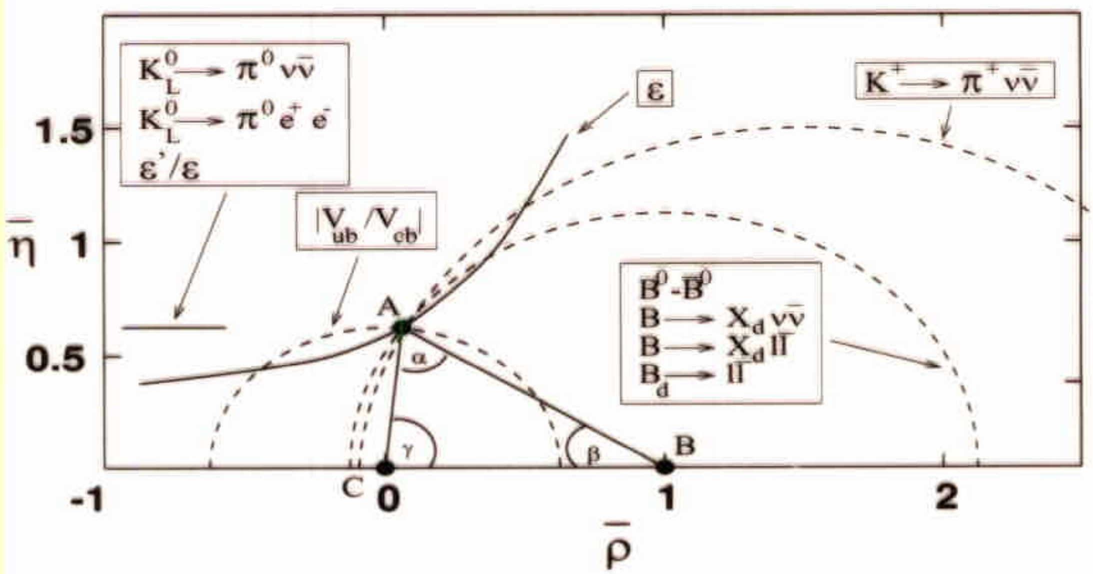
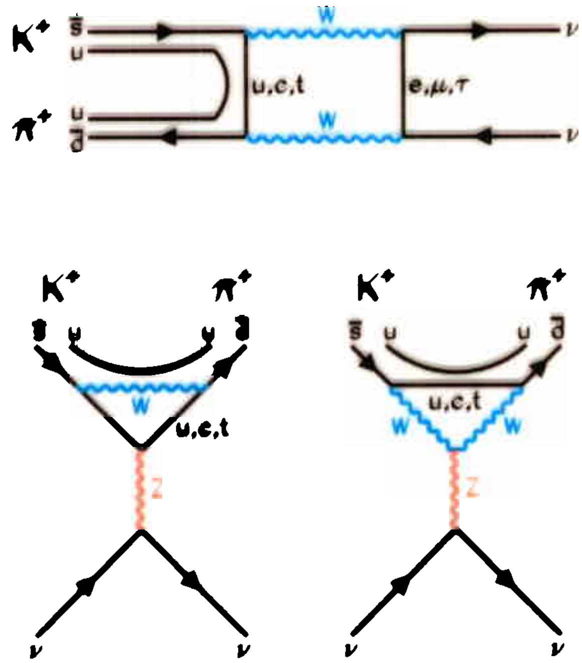
Unitarity relations e.g. $V_{ub}^*V_{ud}+V_{cb}^*V_{cd}+V_{tb}^*V_{td}=0$



Four "Super-clean" K and B physics inputs will test the SM CP-V picture. (Buras)

$K^+ \to \pi^+\nu\bar{\nu}$	BNL-E787,E949, FNAL-CKM
$K_L^0 \to \pi^0\nu\bar{\nu}$	BNL KOPIO, FNAL KAMI
$B_d \to \Psi K_s$	BABAR,BELLE,CDF,HERA-B
$\frac{x_s}{x_d} = \frac{B_s-\overline{B_s}}{B_d-\overline{B_d}}$	CDF, $D0$, BTEV, LHCB

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



	$K^+ \to \pi^+\nu\bar{\nu}$	$K_L^0 \to \pi^0\nu\bar{\nu}$
Top Dependence	$\lvert\lambda_t\rvert = \lvert V_{ts}^* V_{td}\rvert$	$\mathrm{Im}(\lambda_t) = \mathrm{Im}(V_{ts}^* V_{td})$
Calc. BR (10^{-10})	0.82 ± 0.32	0.28 ± 0.1
Est. Theory Uncertainty	5% (charm)	1%

- Negligible long distance effects (10^{-13}).
- Hadronic matrix elements from isospin analog $K^+ \to \pi^0 e^+ \nu_e$.

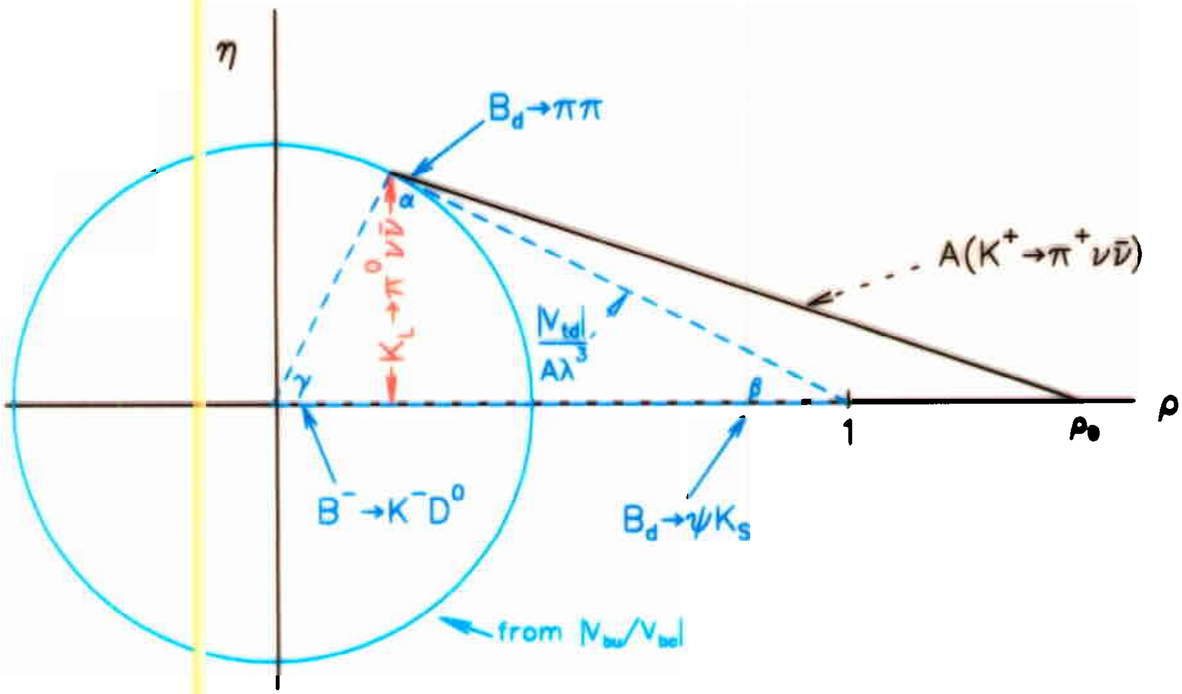
$K_L \to \pi^0 \nu\bar{\nu}$ in the Standard Model

Pure direct CP-violating (state-mixing very small)

Calculation in terms of fundamental parameters good to $\lesssim 2\%$

In terms of usual unitarity triangle parameterization:

$$B(K_L \to \pi^0 \nu\bar{\nu}) = 4 \cdot 10^{-10} A^4 \eta^2$$



Gives height of UT without triangulation
- with $K^+ \to \pi^+ \nu\bar{\nu}$ can determine ρ as well

Also note that

$$B(K_L \to \pi^0 \nu\bar{\nu}) = 1.56 \cdot 10^{-4} [Im(V_{ts}^* V_{td})]^2 \equiv 1.56 \cdot 10^{-4} [Im\lambda_t]^2$$

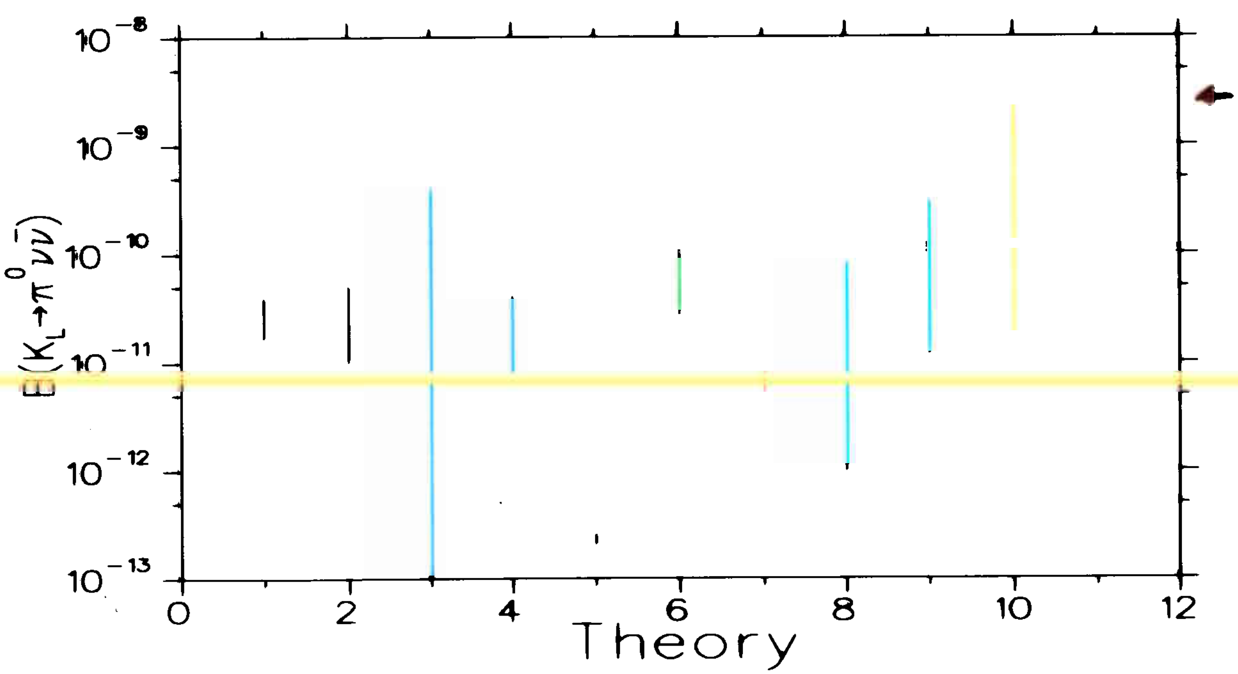
$Im\lambda_t$ presently triangulated to $\sim 22\%$,
KOPIO could directly measure it to $\sim$ 8%

There are only a few solid measurements on the UP
- none is better!

$K_L \to \pi^0 \nu\bar{\nu}$ Beyond the Standard Model

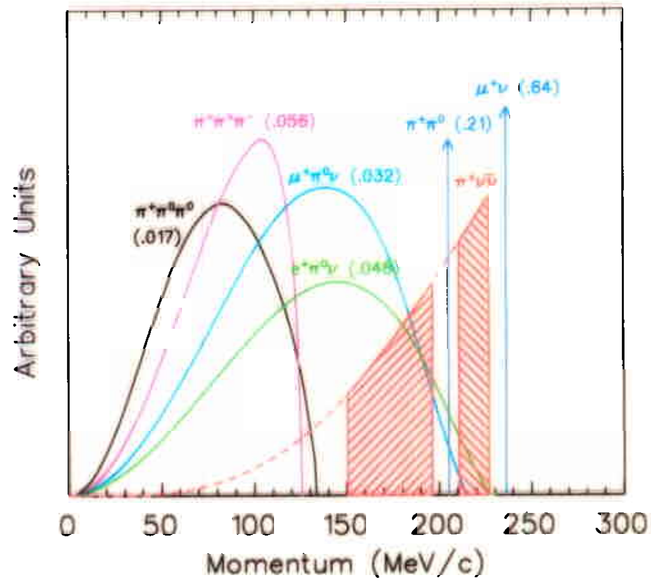
	Who	What	$10^{11} B(K_L \to \pi^0 \nu\bar{\nu})$
1	Buchalla	Standard Model CKM fit	2.8 ± 1.1
2	Plaszczynski/Schune	Conservative SM fit	$1 - 5$
3	Buras, *et al.*	Generic SUSY w/min. part. content	$0 - 40$
4	Buras, *et al.*	MSSM w/o new flavor or CP viol.	$(0.41 - 1.03)\times$ SM
5	Brhlik, *et al.*	all CP-viol. due to SUSY	$\sim .023$
6	Chanowitz	$SU(2)_L \times SU(2)_R$ Higgs	$2.8 - 10.6$
7	Hattori *et al.*	4th generation	$0.5 - 220$
8	Xiao, *et al.*	top-color assisted technicolor	$0.1 - 8$
9	Xiao, *et al.*	multiscale walking technicolor	$1.2 - 30$
10	Grossman, Nir	Extra vector like quarks	$1.7 - 210$
11	Kiyo, *et al.*	seesaw L-R model†	$(1 - 1.2)\times$ SM

† predicts spectrum will be altered.



Grossman, Nir
$B(K_L^0 \to \pi^0 \nu\bar{\nu}) < 4.4\, B(K^+ \to \pi^+ \nu\bar{\nu})$

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



$K^+ \to$	π^+	$\nu\bar{\nu}$
Stopped $K \to \pi$	Momentum	4π Veto
C.M. system	Energy	
	Range	
	$\pi \to \mu \to e$	

PHILOSOPHY:

- Get as much information as possible!
- Suppress backgrounds ($K \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, ...) S/N = 10.
- Perform "blind" analysis to avoid bias.

E787/E949 COLLABORATIONS

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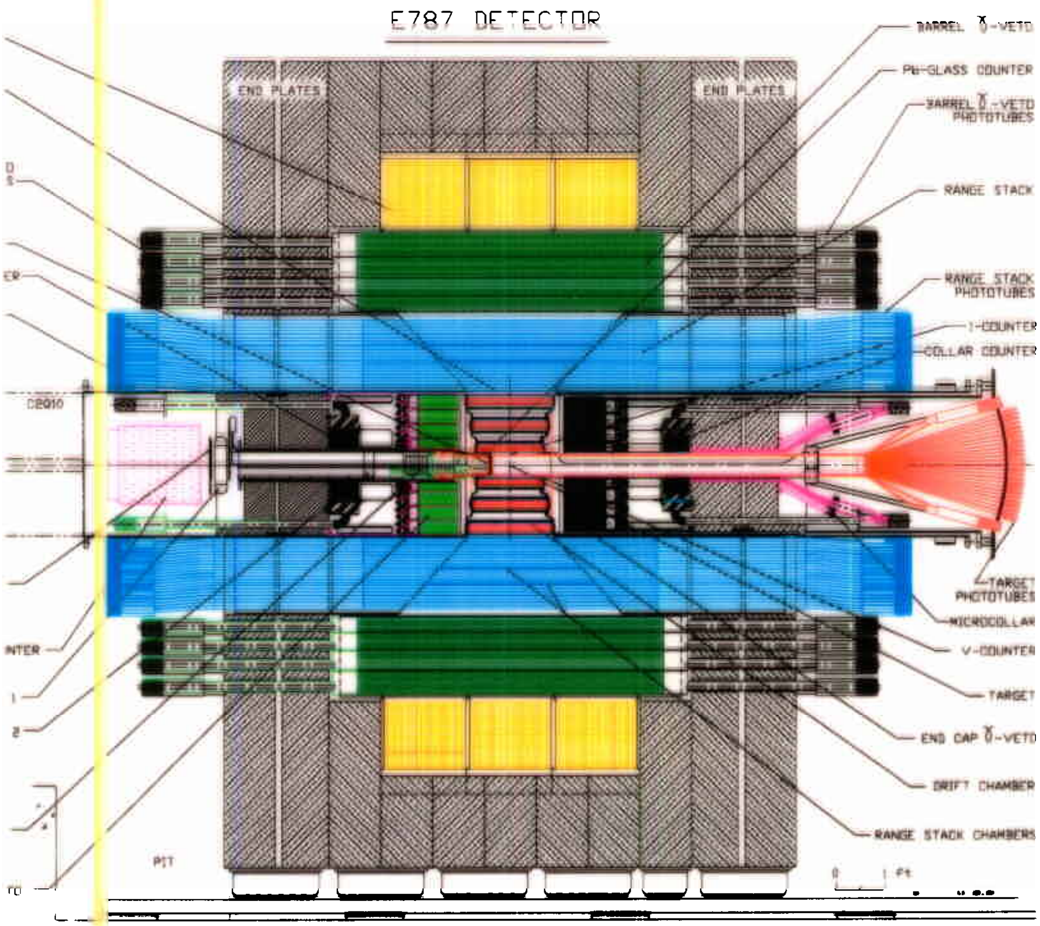


$K : \pi \sim 4 : 1 \longrightarrow \check{C}_K \longrightarrow$ BeO degrader $\longrightarrow$
active, segmented target

$\pi^+ \longrightarrow$ 1.0 T drift chamber $\longrightarrow$
21-layer, segmented range stack

photon veto: 14 X_0 barrel, 13.5 X_0 CsI endcap, Pb glass, collars

data acquisition: $\sim 1.0 \times 10^6$ K^+ stops in target per 1.5-sec spill
~ 200: $K^+ \rightarrow \pi^+\nu\bar{\nu}$ triggers per spill

Backgrounds

- K^+-decay backgrounds suppressed via
  - kinematics: stopped K^+ beam, dE/dx, R vs. P
  - high efficiency photon detection
  - π^+/μ^+ particle ID: $\pi \longrightarrow \mu \longrightarrow e$ decay sequence
- non-K^+-decay backgrounds suppressed via
  - high efficiency identification of beam K^+
  - non-coincident beam and track activity ("delayed coincidence")

Background	BR	kin.	PV	PID	>1 tr.	$\check{C}_{K,\pi}$	DC
$K^+ \rightarrow \mu^+\nu_\mu$	0.64	✓		✓			
$K^+ \rightarrow \pi^+\pi^0$	0.21	✓	✓				
$K^+ \rightarrow \pi^0 l^+ \nu_l$	0.08		✓	✓			
$K^+ \rightarrow 3\pi$	0.07	✓	✓		✓		
$K^+ \rightarrow \mu^+\nu_\mu\gamma$	5×10^{-3}	✓	✓	✓			
$K^+ \rightarrow \pi^+\gamma\gamma$	1×10^{-6}		✓				
beam π^+						✓	✓
$K^0_L \rightarrow \pi^+ l^- \bar{\nu}_l$					✓		✓

Analysis Strategy

require $> 10^{10}$ suppression of backgrounds

$\longrightarrow$ low statistics bias

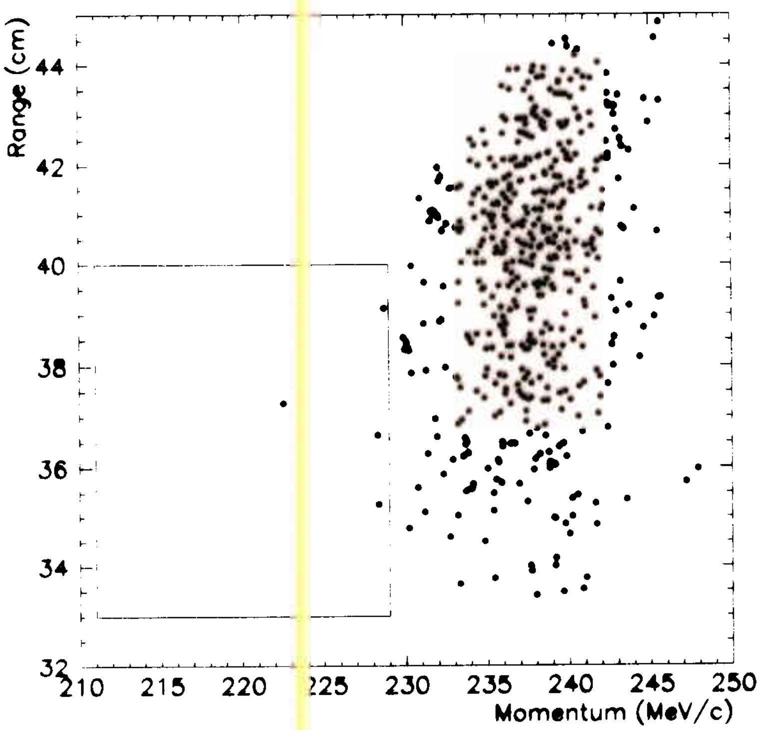
- blind analysis
  - identify background sources *a priori*
  - define a "box" where signal:background is highest
  - do not establish cuts by examining events in the box; instead perform:
- bifurcated analyses
  - enhance statistics for background estimation
  - background samples isolated from the real data where possible – all potential event pathologies are taken into account
  - perform outside-the-box tests of correlation in the bifurcations
- test for bias on independent data samples

Goal: expected background in box $\ll 1$ event, with rejection in reserve for evaluation of candidate events

Bifurcated Background Estimates

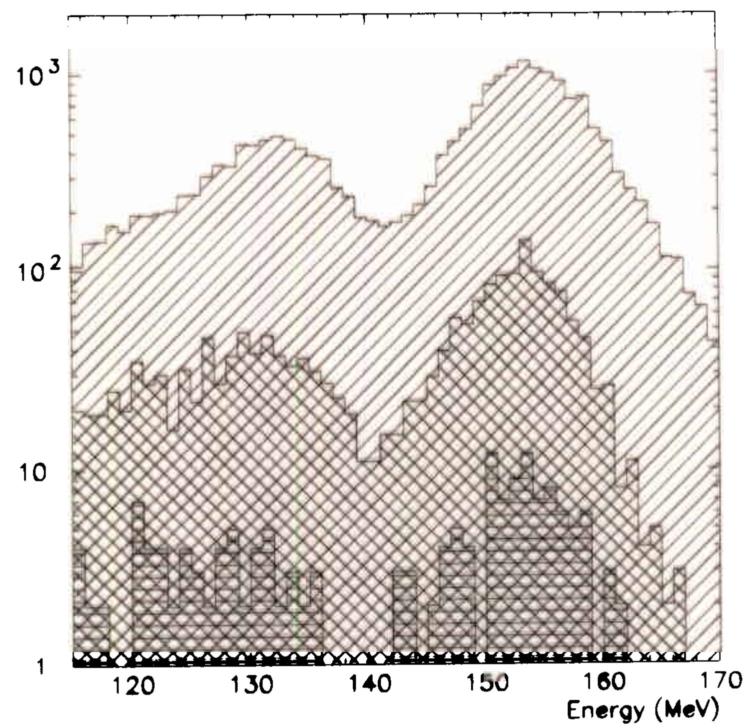
PID reversed

$\sim 1000\times$ enhanced



Select $K_{\mu 2}$ momentum peak

$\sim 150\times$ enhanced



$$\text{Background} = N_{K_{\mu 2}} \,/\, (R_{PID} - 1)$$

Background	Normalization	Rejection
$K_{\pi 2}$	kinematics	photon veto
$K_{\mu 2}$	kinematics	PID $\pi \to \mu \to e$
single beam	$\check{C}_K$,$\check{C}_\pi$ time, B4 dE/dx	delayed coincidence
double beam	B4 time	BWC,$\check{C}_K$,$\check{C}_\pi$ time
charge exchange	K^0_S data	Monte Carlo

Background Levels

Background	1995-7
$K_{\pi 2}$	0.022 ± 0.005
$K_{\mu 2}$	0.028 ± 0.010
BM1	0.005 ± 0.004
BM2	0.016 ± 0.015
CEX	0.010 ± 0.007
total	0.08 ± 0.02

"golden" region #1: 0.010 ± 0.003
background events
at 36% signal region acceptance

"golden" region #2: 0.006 ± 0.002
background events
at 33% signal region acceptance

Acceptance

	1995-7
K^+ stop efficiency	$0.704 \pm 0.004^{stat} \pm 0.009^{syst}$
K^+ decay after 2 ns	0.850 ± 0.001
$K^+ \to \pi^+ \nu\bar{\nu}$ phase space	$0.155 \pm 0.001^{stat} \pm 0.001^{syst}$
Solid angle acceptance	0.407 ± 0.001
π^+ nucl. int., decay-in-flight	0.513 ± 0.005^{stat}
Reconstruction efficiency	0.959 ± 0.001
Other kinematic constraints	$0.665 \pm 0.007^{stat} \pm 0.020^{syst}$
$\pi - \mu - e$ decay acceptance	$0.306 \pm 0.005^{stat} \pm 0.004^{syst}$
Beam and target analysis	0.699 ± 0.001
Accidental loss	0.785 ± 0.002
Total acceptance	$[0.208 \pm 0.005^{stat} \pm 0.021^{syst}]\%$

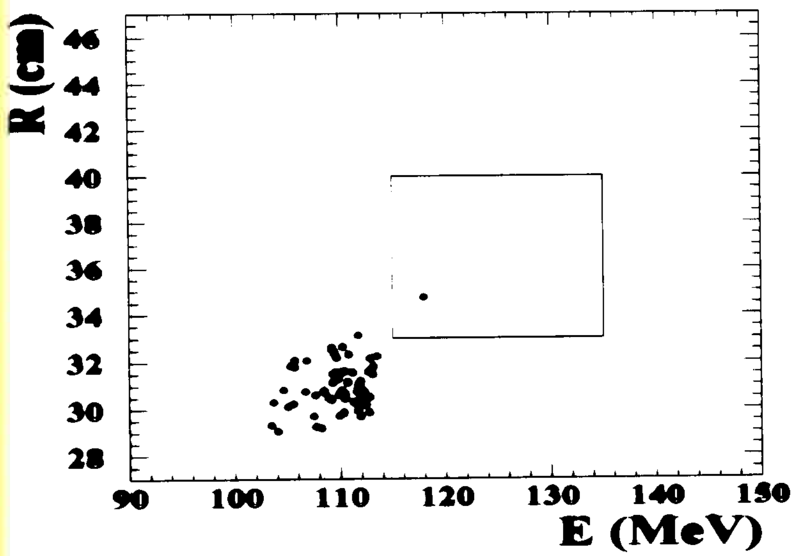
exposure: 3.24×10^{12} K^+
entered the target

Evidence for the Decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ (E787)

1995-97 Data: One event observed.

Estimated background: $n_b = 0.08 \pm 0.02$.

$N_K = 3.24 \times 10^{12}$ Acceptance= $0.208 \pm 0.005(stat) \pm 0.021(syst)$



Results:

$$R(K^+ \rightarrow \pi^+\nu\bar{\nu}) = \frac{\Gamma(K^+ \rightarrow \pi^+\nu\bar{\nu})}{\Gamma(K^+ \rightarrow all)} = 1.5^{+3.4}_{-1.2} \times 10^{-10}$$

$$0.002 < |V_{td}| < 0.04$$

$K^+ \to \pi^+ x$ and Global Family Symmetry

[Wilczek (1982), Gelmini et al. (1983), Feng et al. (1998)]

Motivation: Explain the replication of families

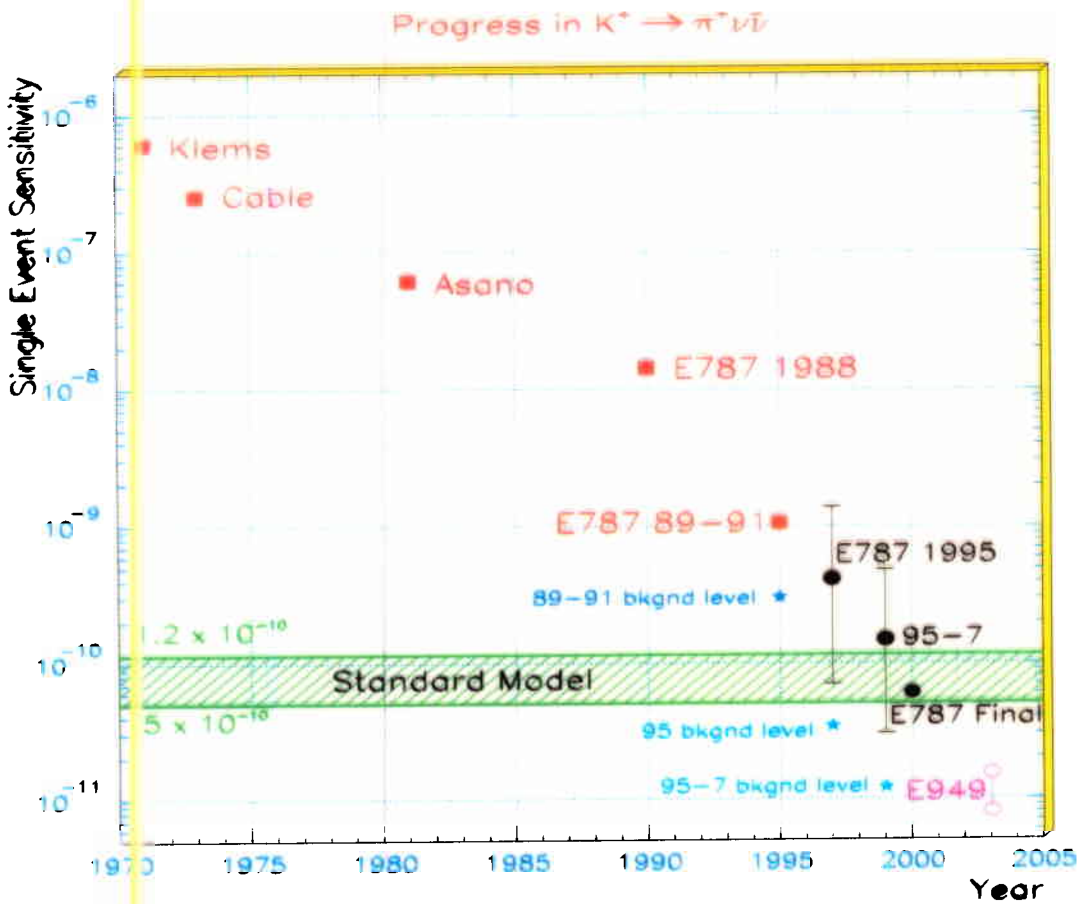
Postulate: Global Family Symmetry spontaneously broken at large mass scale (F) → Goldstone Boson "FAMILON (f)".

$L_{eff} = \frac{1}{F} J_\mu \delta_\mu f \quad \mu \to e + f$ and $s \to d + f$

	GFS	Experiment	F Limit (GeV)
$B(K^+ \to \pi^+ f)$	$\frac{1.310^{14} GeV^2}{F^2}$	$< 1.110^{-10}$ (E787)	$> 1.110^{12}$
$B(\mu \to ef)$	$\frac{2.510^{14} GeV^2}{F^2}$	$< 2.610^{-6}$ (Jodidio)	$> 10^{10}$
$B(\tau \to ef)$	$\frac{2.510^{14} GeV^2}{F^2}$	$< 2.610^{-3}$ (ARGUS)	$> 310^{6}$
COSMOLOGY			$10^9 < F < 10^{12}$

Constraints on New Physics

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



- Background in E787 95-97 data OK for measurement.
- E787 1998 data comparable in sensitivity to previous total.
- E787 now becomes E949 aiming for 5x sensitivity of E787. Running starts at the AGS in 2001.
- CKM proposal at FNAL aims for 10x greater sensitivity.

KOPIO - a search for $K^0 \to \pi^0 \nu \bar{\nu}$

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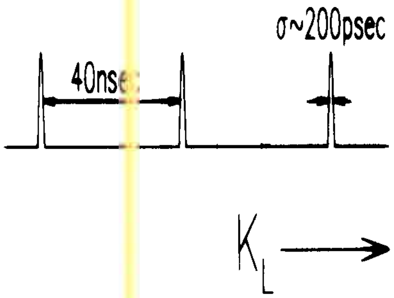
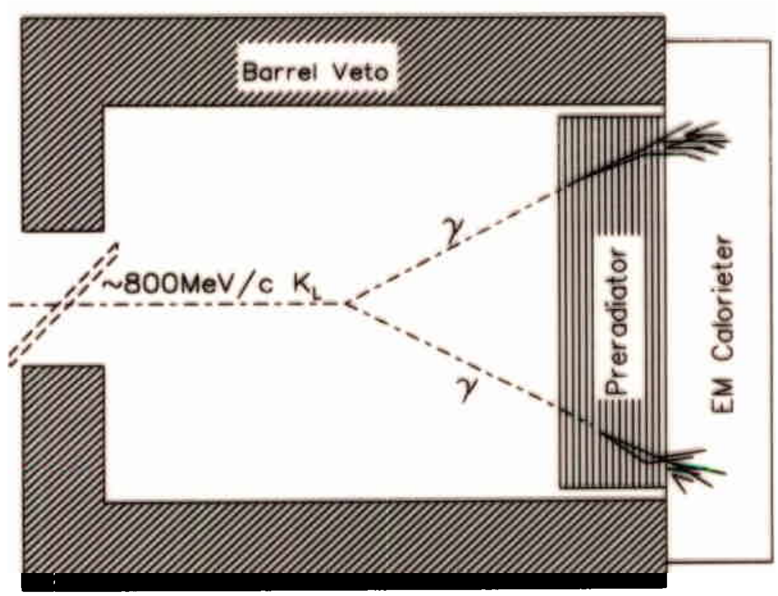
KOPIO: A Proposal to Measure $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

Lessons from E787:

- Measure as much as possible:
  Energy, position and *ANGLE* of each photon.
- Work in the C.M. system :
  Use TOF to get the K_L^0 momentum.
- Photon Veto limited by photonuclear interactions at low energies.





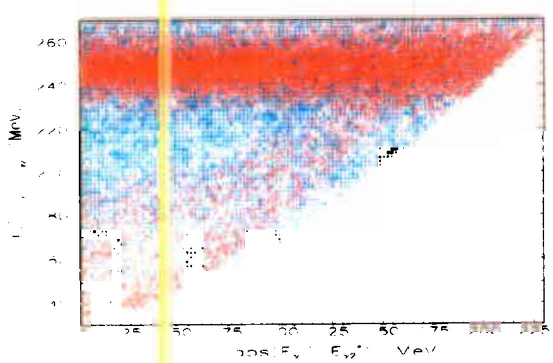
KOPIO: Challenges and Goals

GOAL: 65 Events with S/N=2.

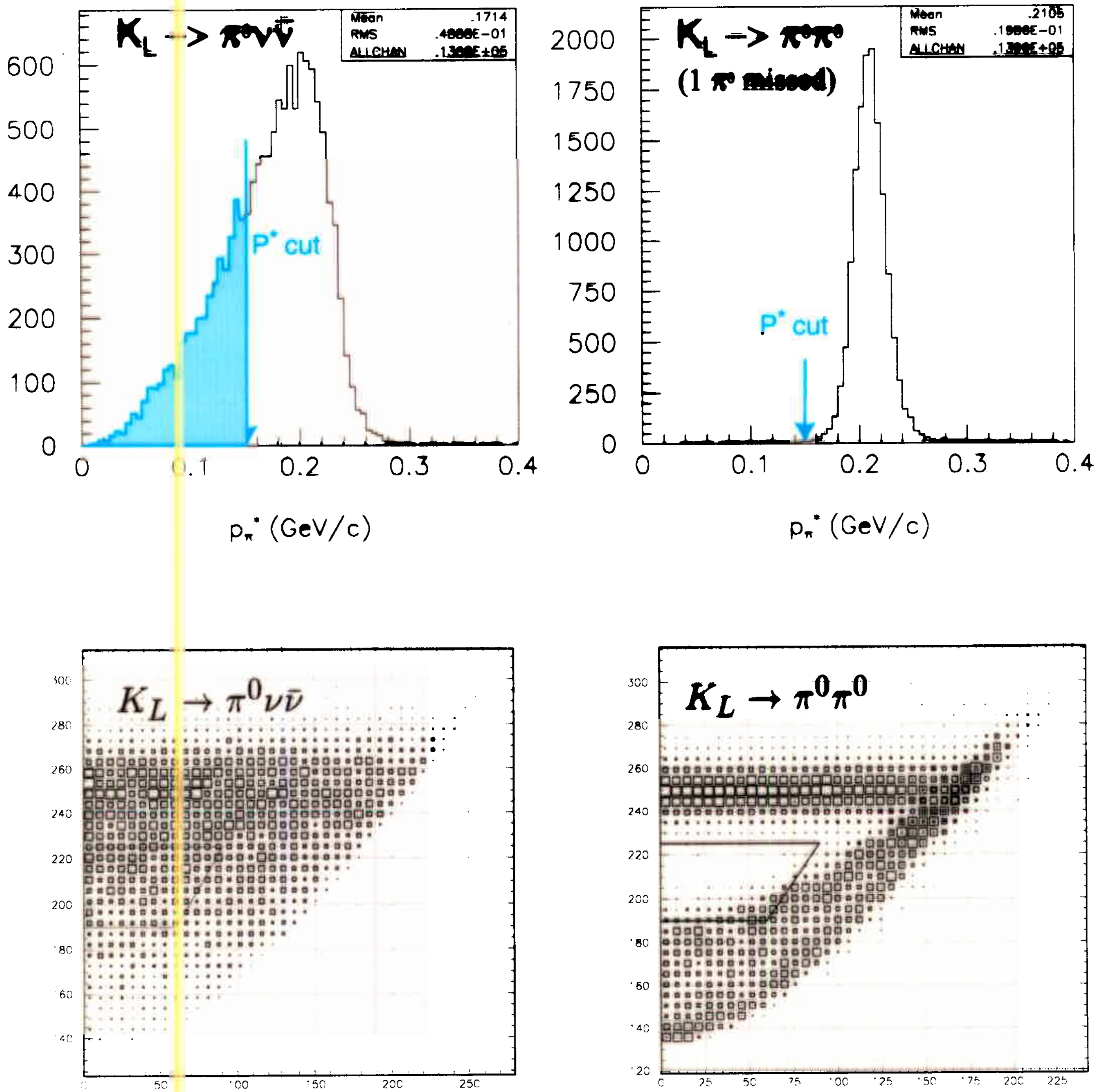
- Largest background source $K_L^0 \rightarrow \pi^0\pi^0$.
  Weapons: Kinematic reconstruction, photon veto.
  Eliminate events with missing low energy photons.
- **Photon inefficiency : 10^{-4} at 200 MeV.**
  (Comparable to E787).
- Photon angular resolution : 17 mr at 350 MeV
  (10 mr achieved by GLAST)
- **Energy resolution : $\frac{3.5\%}{\sqrt{(E(GeV)}}$.**
  (Achievable with "Shashlik")

$K_L^0 \rightarrow \pi^0\pi^0$ Background

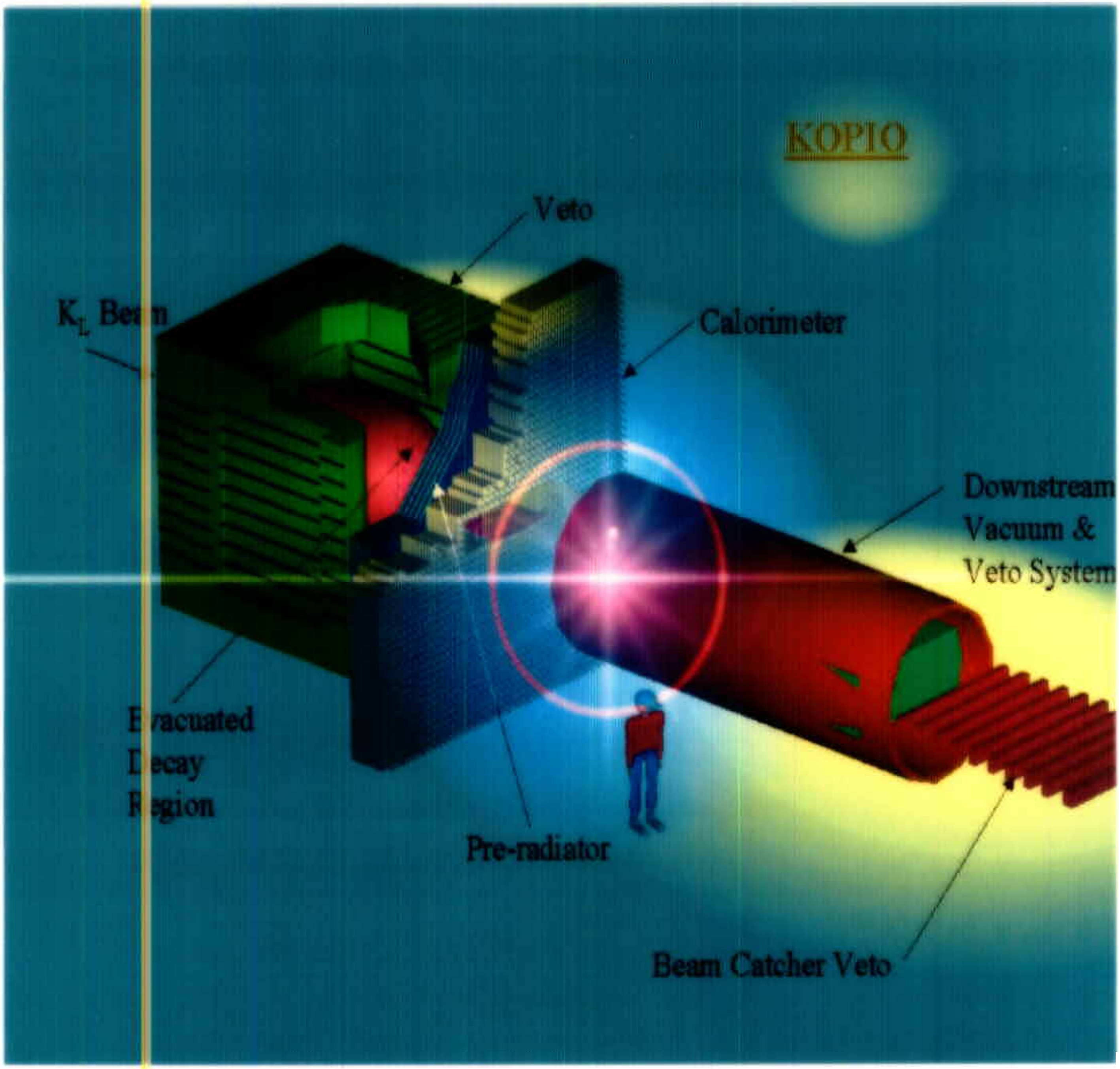
$E^*_{\pi^0}$ vs. $|E^*_{\gamma 1} - E^*_{\gamma 2}|$



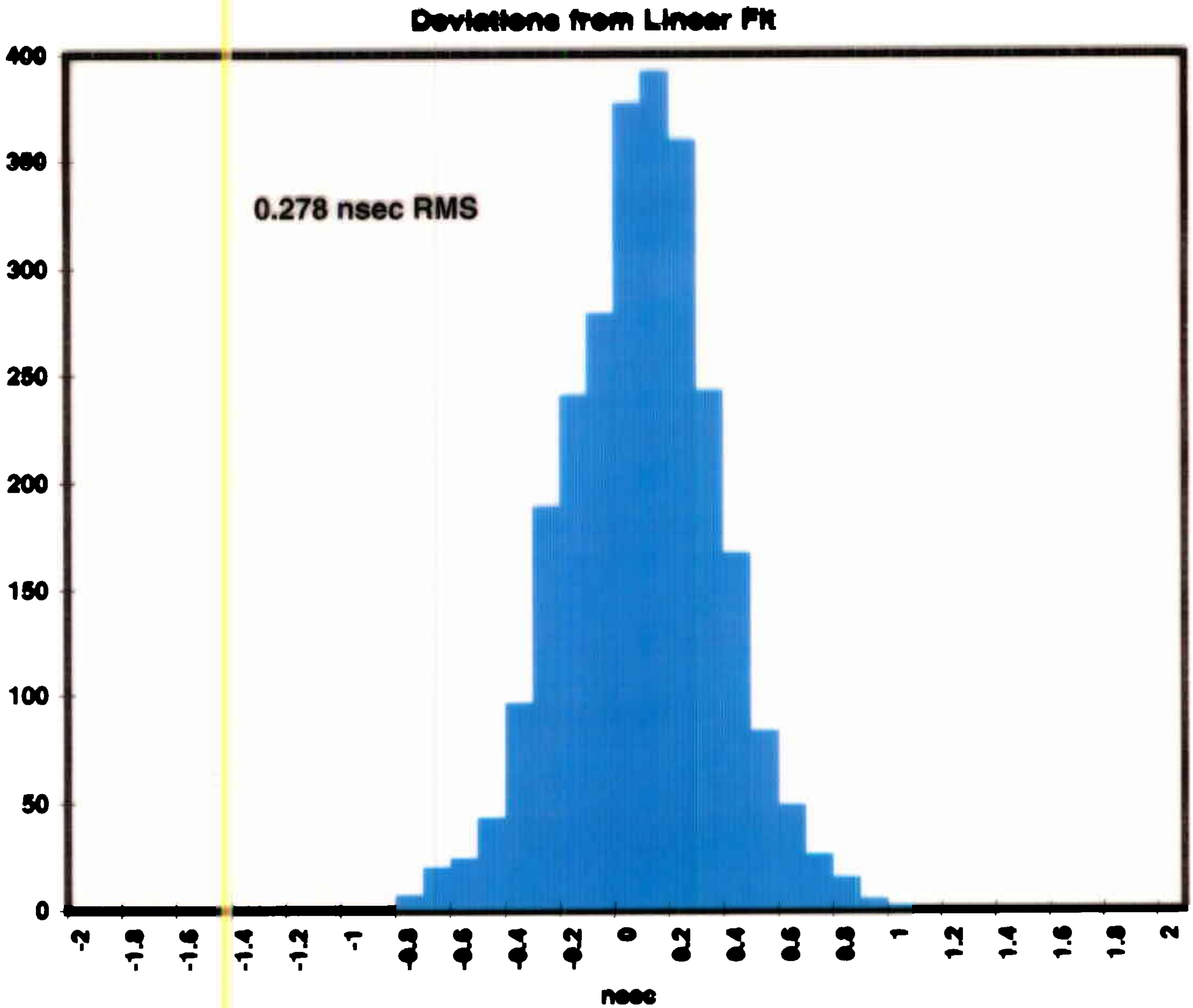
$K_L \to \pi^0\nu\bar{\nu}$ and $K_L \to \pi^0\pi^0$ identification



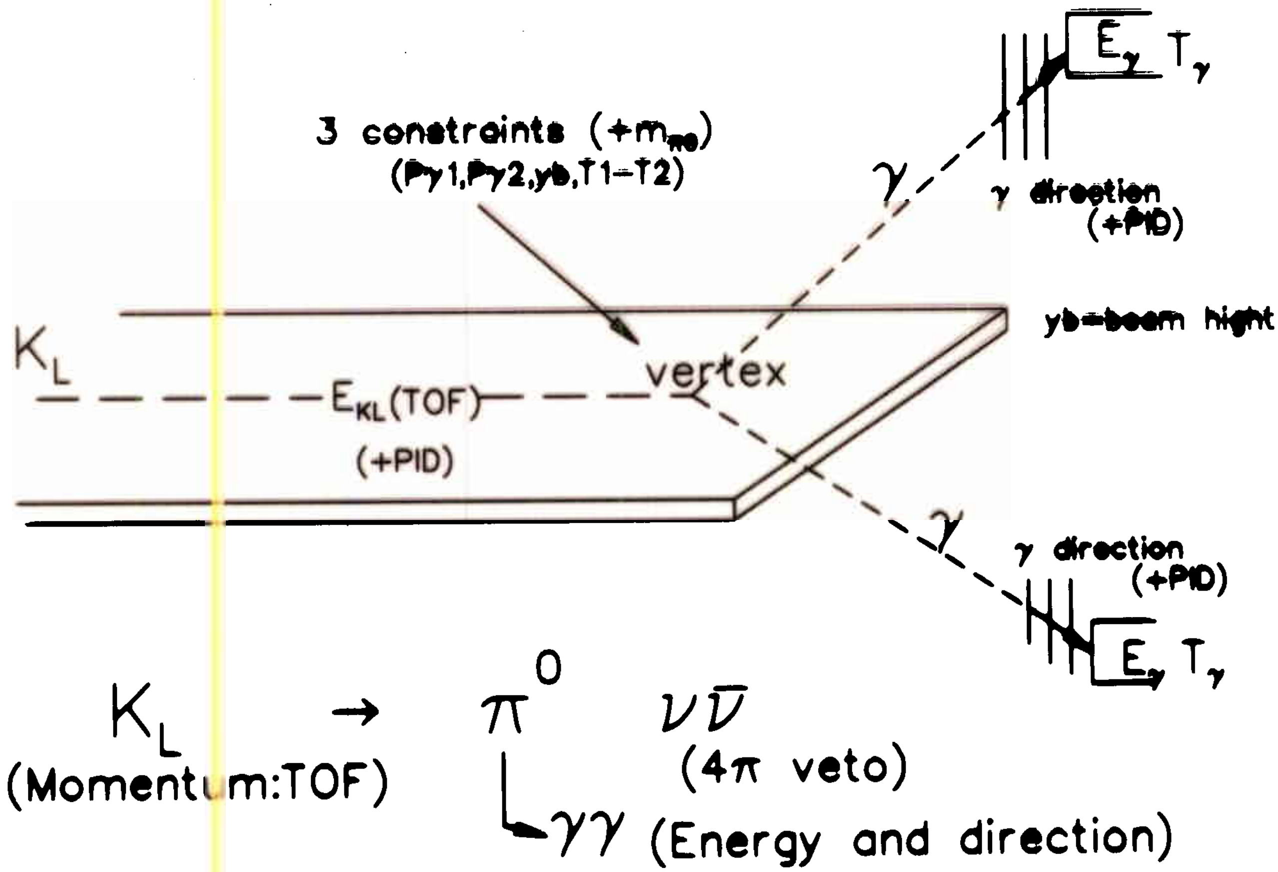
Energy of the purported π^0 (vertical) vs absolute value of the difference of the energies of the two detected γ's (horisontal) both in the K_L cm system.

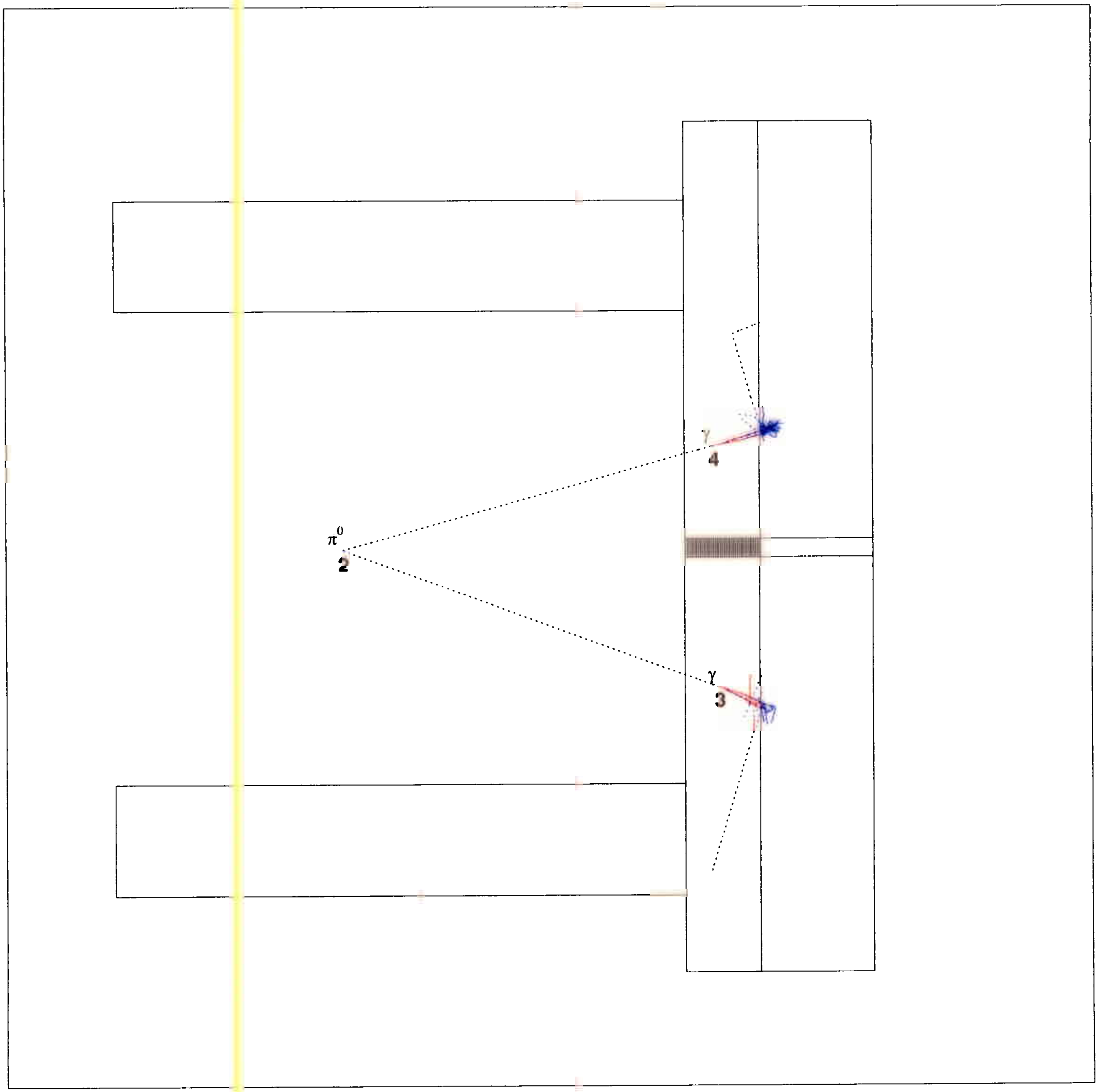

KOPIO
Veto
K_L Beam
Calorimeter
Downstream
Vacuum &
Veto System
Evacuated
Decay
Region
Pre-radiator
Beam Catcher Veto

Test of microbunching on extraction at AGS



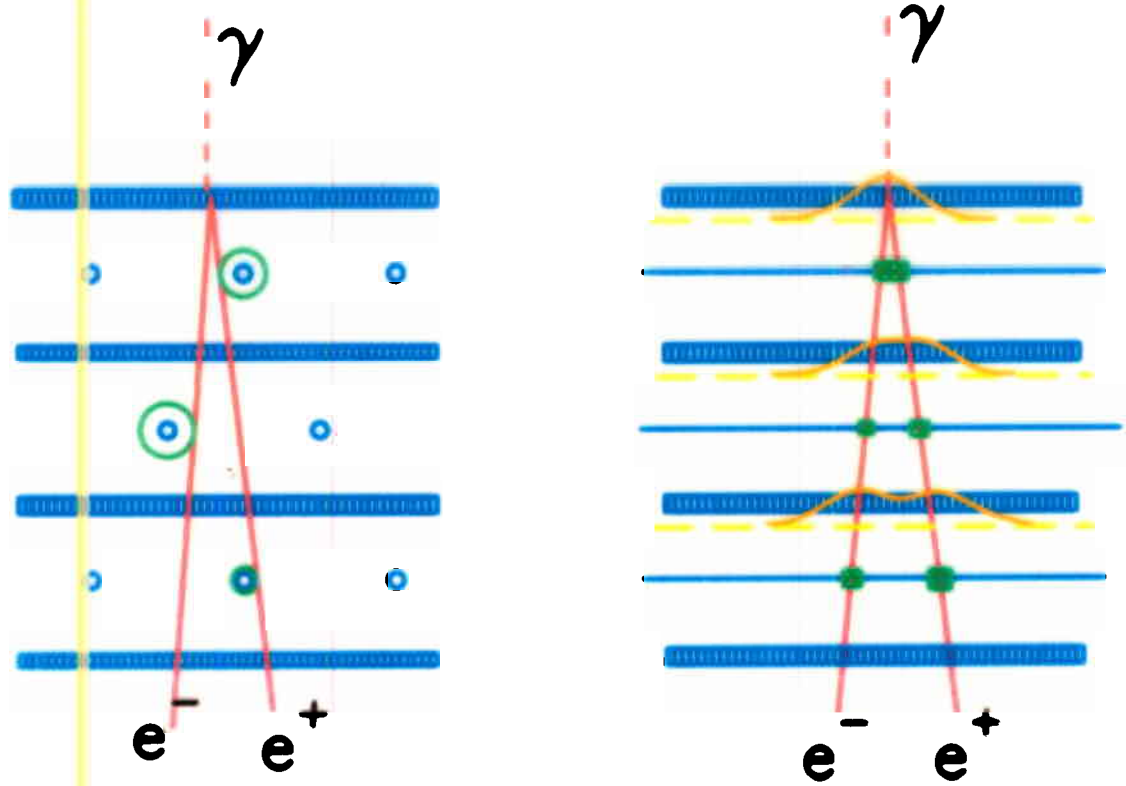
Technique now well established
Very successfully used to smooth AGS spill


3 constraints (+m$_{\pi0}$)
(Pγ1,Pγ2,yb,T1−T2)
γ
γ direction
(+PID)
E_γ T_γ
yb=beam hight
K_L
vertex
E_{KL}(TOF)
(+PID)
γ
γ direction
(+PID)
E_γ T_γ
K_L → π^0 $\nu\bar{\nu}$
(Momentum:TOF)
(4π veto)
γγ (Energy and direction)



π^0
2
γ
4
γ
3

Angle measurement



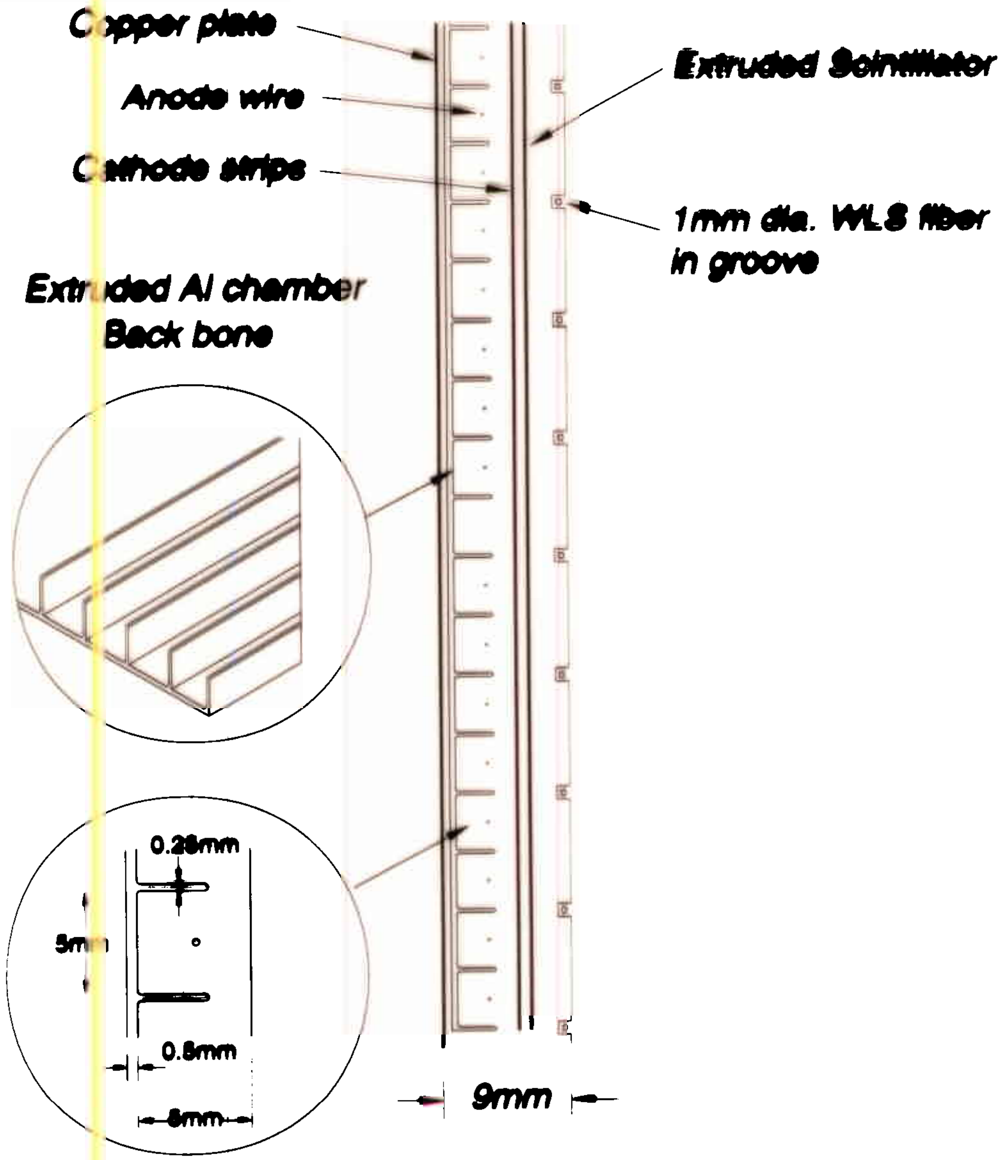
Cathode

- e^-e^+ pair
- 150 μm resolution

Anode

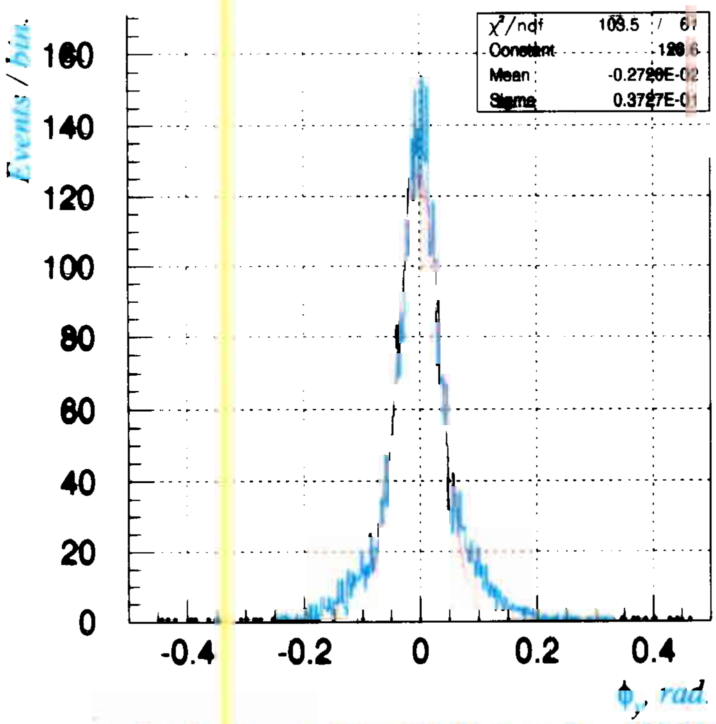
- 150 μm resolution
- less angle dep.

PRERADIATOR ELEMENT DESIGN

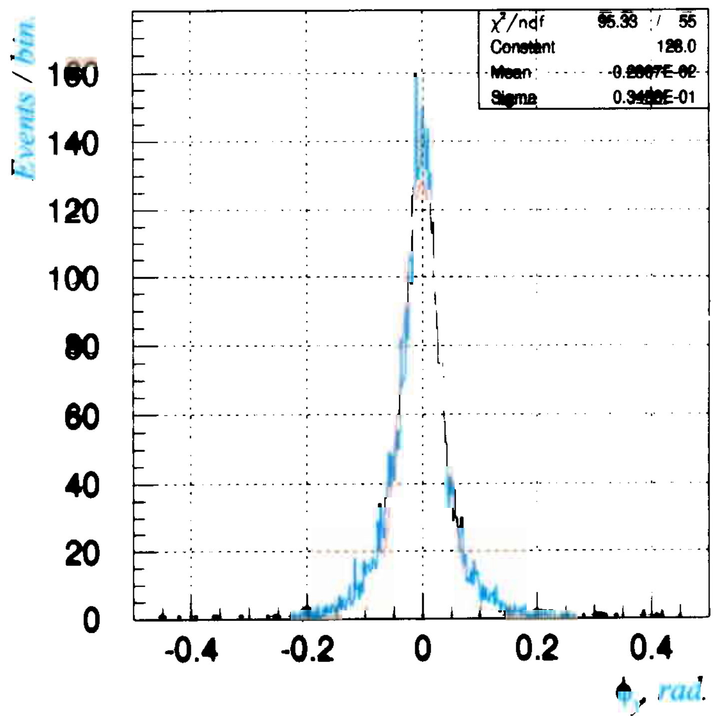


KOPIO. Preradiator Prototype Test. Gamma beam.

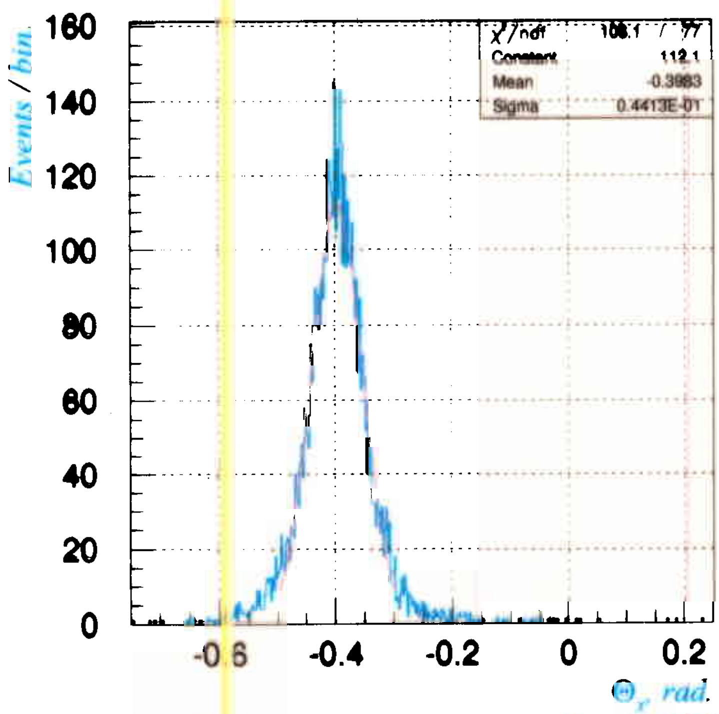
LEGS MEASUREMENTS & SIMULATIONS AGREE



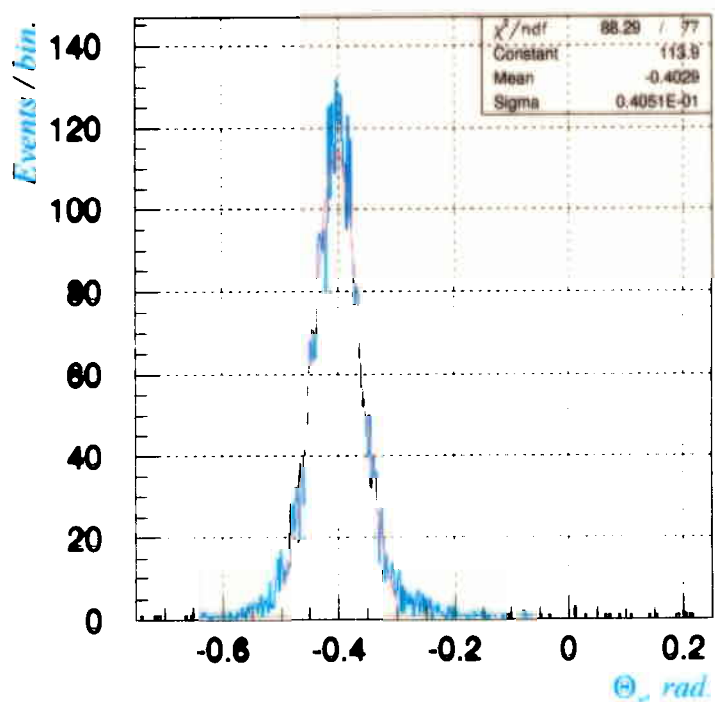
ϕ_y distribution of detected photons. E_γ = 150 MeV.



ϕ_y distribution of detected photons. E_γ = 250 MeV



Θ_x distribution of detected photons. E_γ = 150 MeV.



Θ_x distribution of detected photons. E_γ = 250 MeV

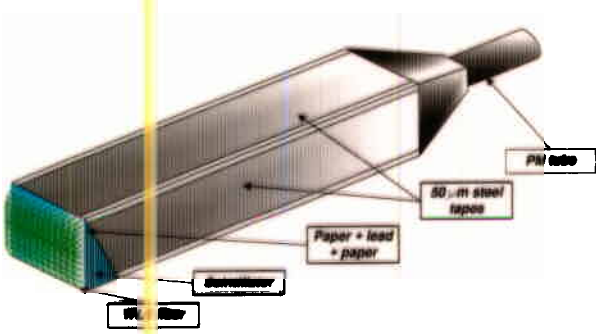
Calorimeter

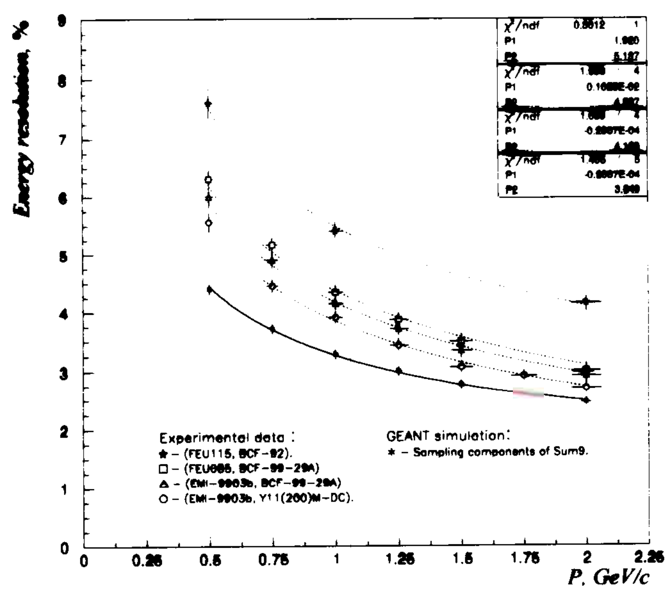
Need $\sigma_E/E \propto 0.03/\sqrt{E}$

Use well-understood shashlik technology

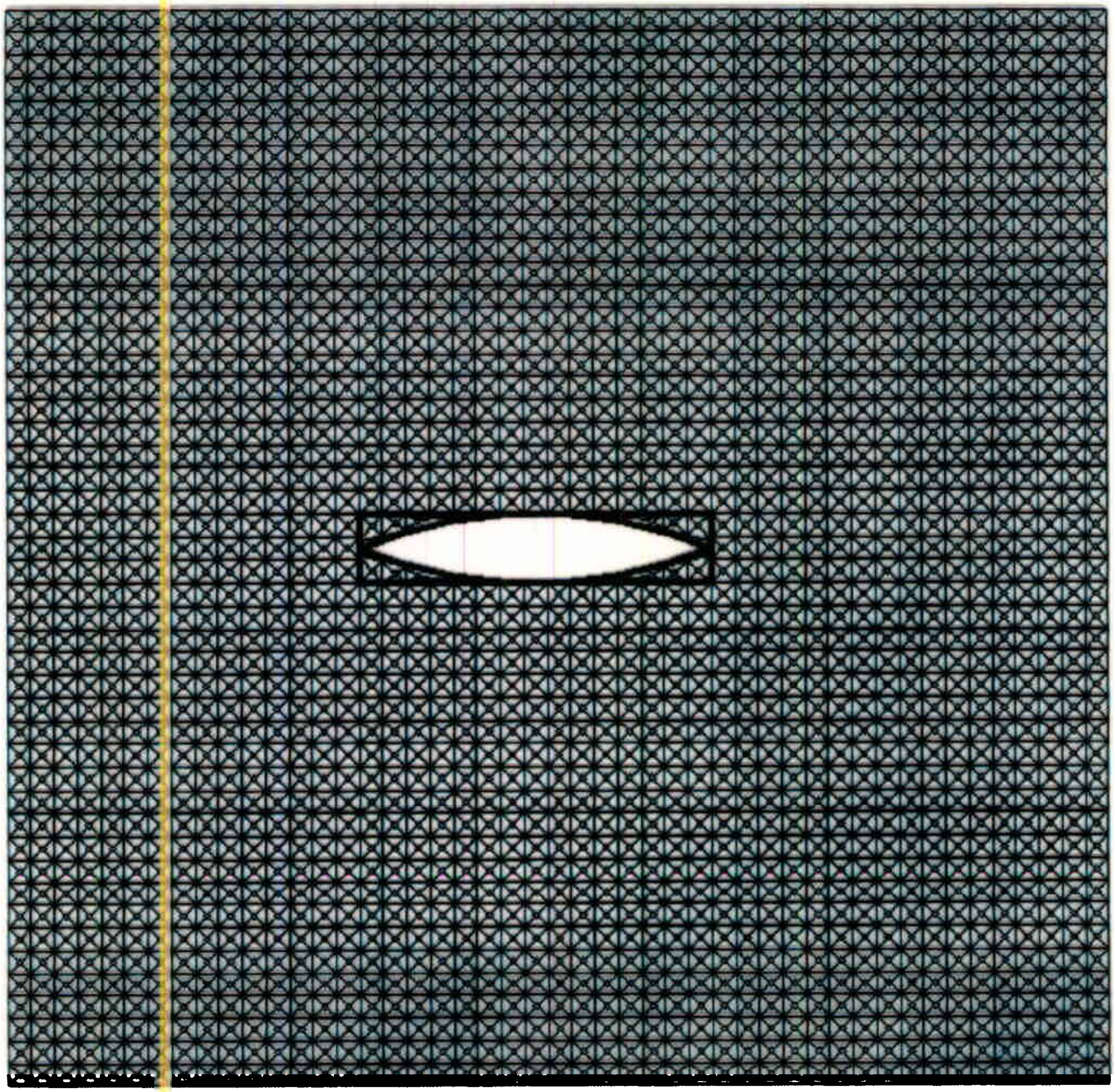
Better than $0.04/\sqrt{E}$ already demonstrated

MC indicates goal can be straightforwardly reached



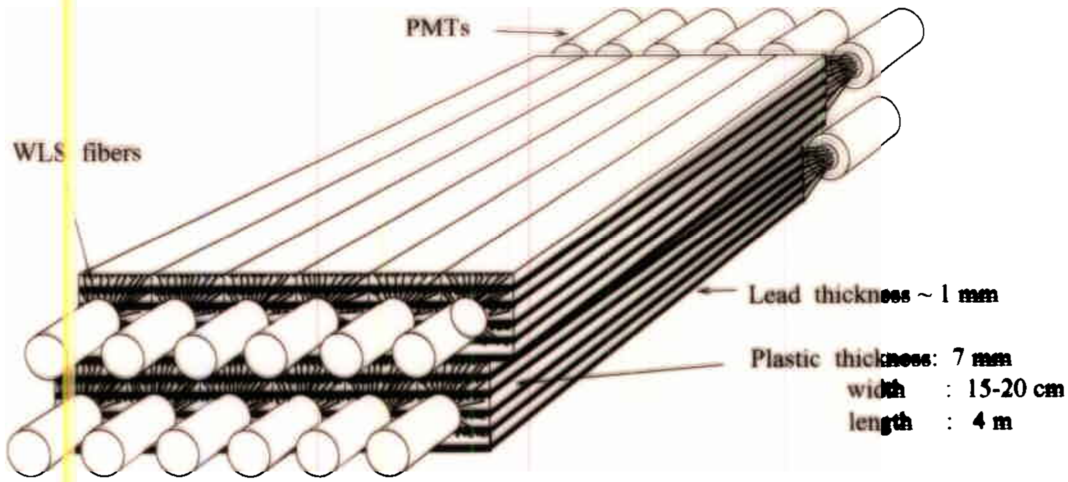


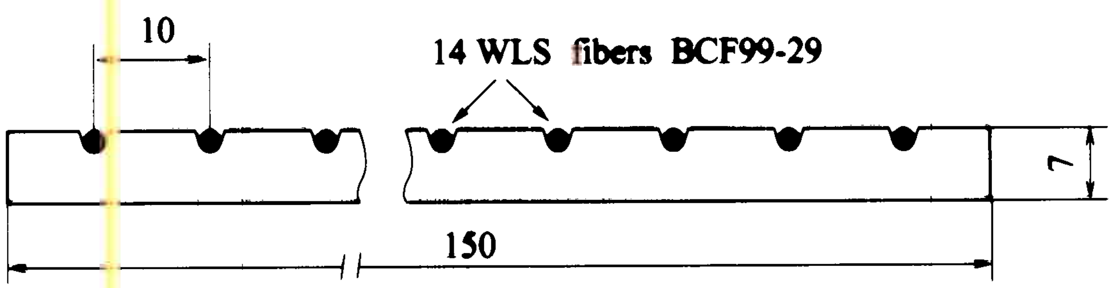
KOPIO EXPERIMENTAL APPARATUS

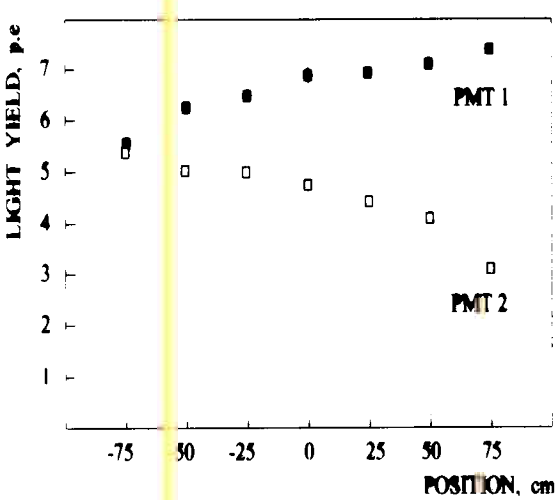


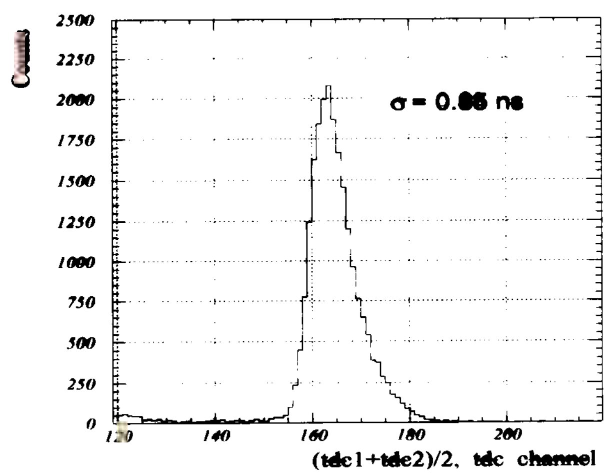
CALORIMETER
(END VIEW)

E926 Photon Veto

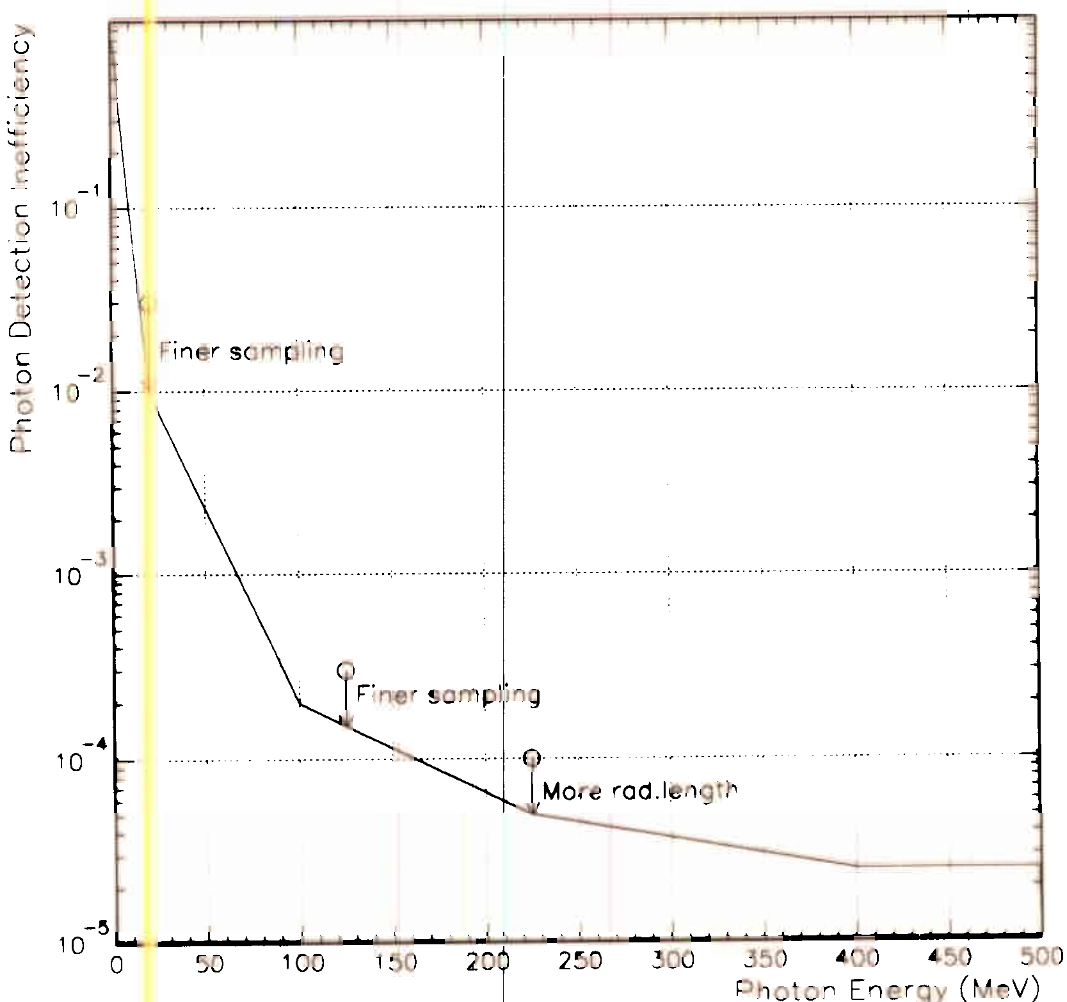




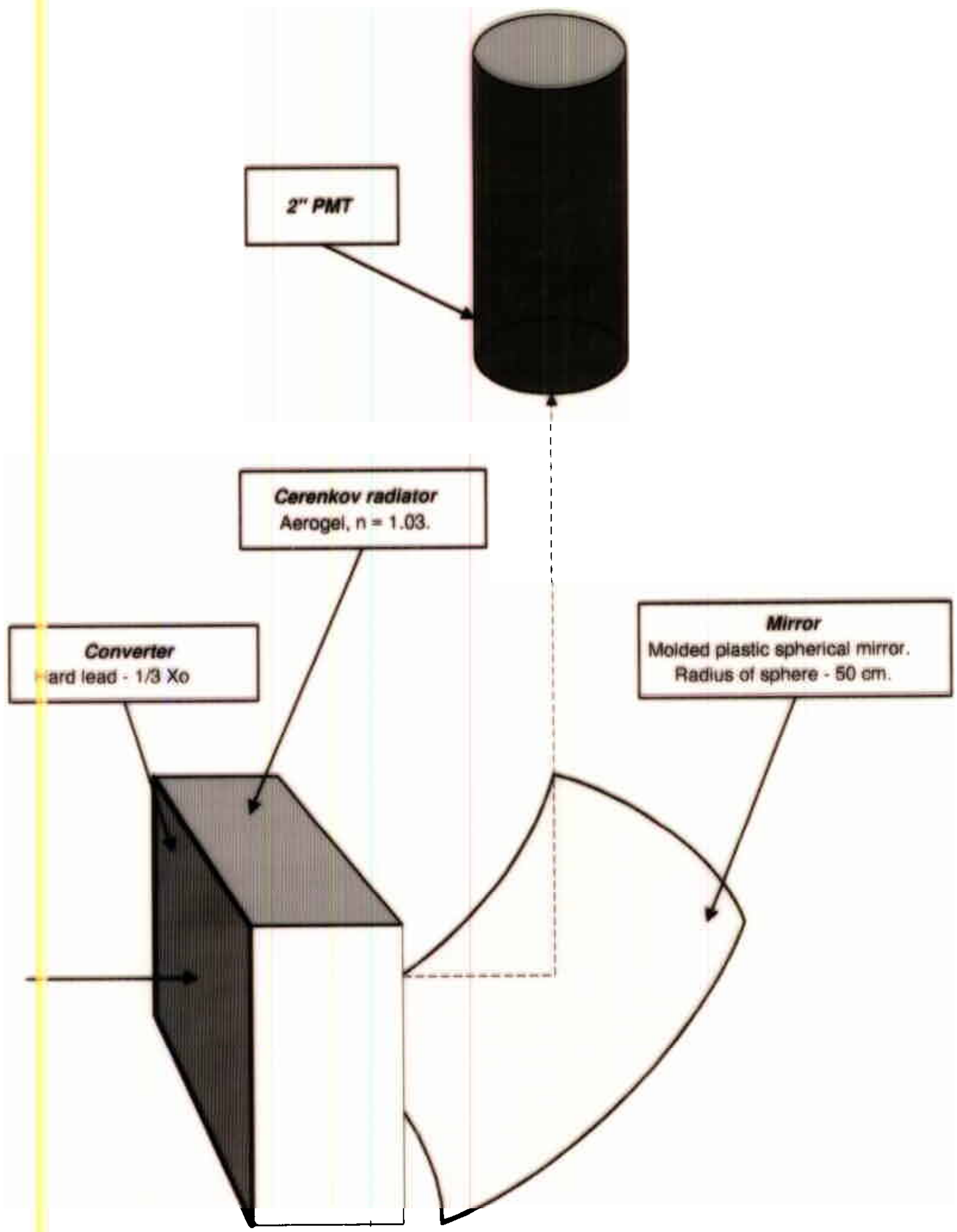




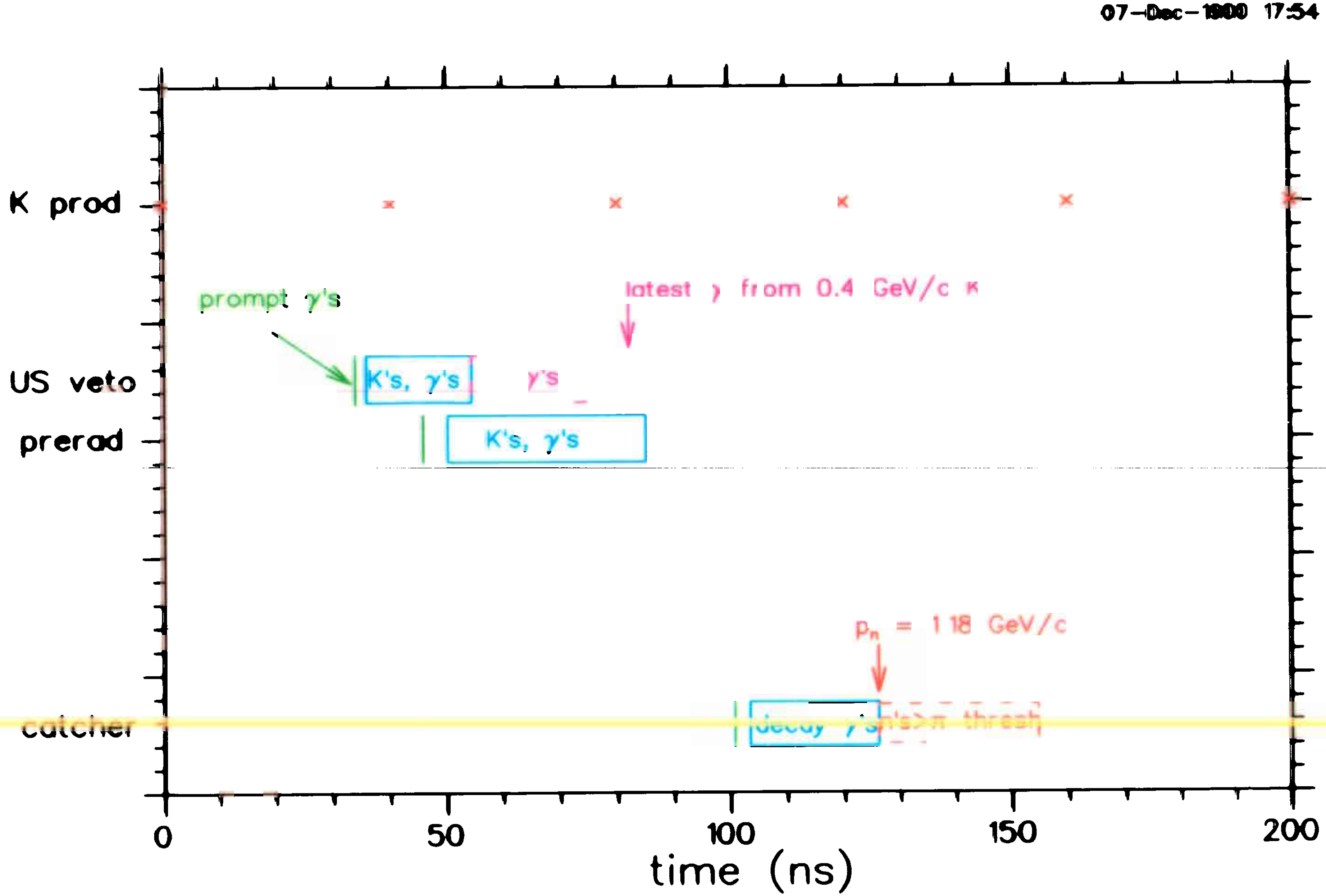
Photon Detection Inefficiency

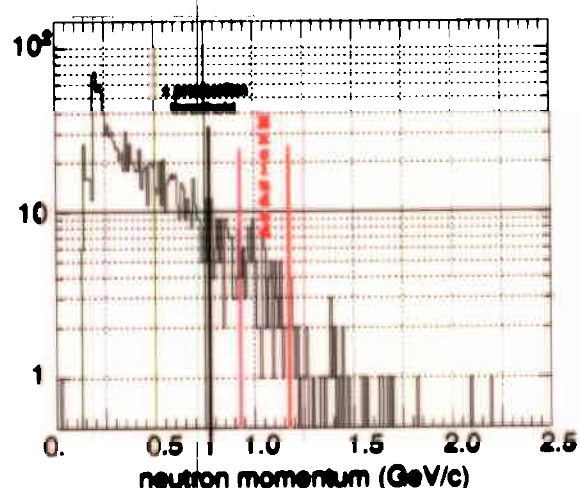


KOPIO Beam Catcher Module



KOPIO Timeline





10²
10
1
0.
0.5
1.0
1.5
2.0
2.5
neutron momentum (GeV/c)

Estimated event levels for signal and backgrounds.

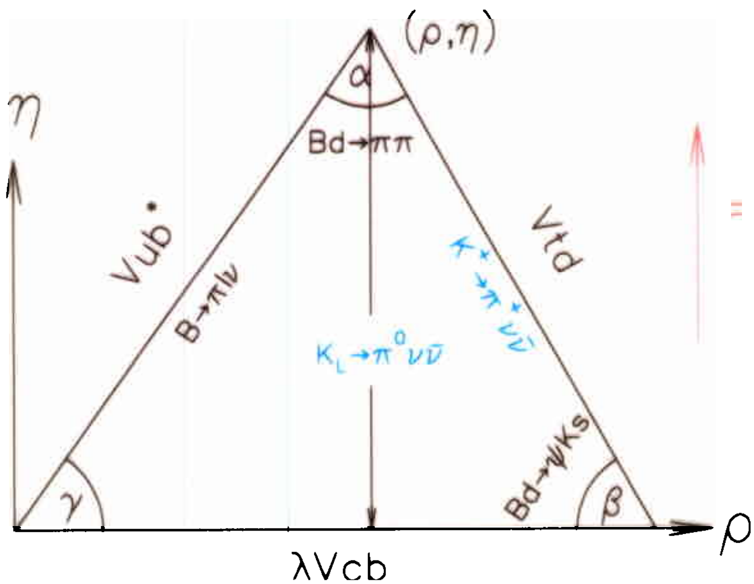
Process	Modes	Main source	Events
$K_L^0 \to \pi^0 \nu \bar{\nu}$			65
K_L decays ($\bar{\gamma}$)	$\pi^0\pi^0, \pi^0\pi^0\pi^0, \pi^0\gamma\gamma$	$\pi^0\pi^0$	24
$K_L \to \pi^+\pi^-\pi^0$			9
$K_L \to \gamma\gamma$			0.04
K_L decays ($\overline{charge}$)	$\pi^\pm e^\mp \nu, \pi^\pm \mu^\mp \nu, \pi^+\pi^-$	$\pi^- e^+ \nu$	0.06
K_L decays ($\bar{\gamma}, \overline{charge}$)	$\pi^\pm l^\mp \nu\gamma$, $\pi^\pm l^\mp \nu \pi^0, \pi^+\pi^-\gamma$		0.1
Other particle decays	$\Lambda \to \pi^0 n, K^- \to \pi^-\pi^0, \Sigma^+ \to \pi^0 p$	$\Lambda \to \pi^0 n$	0.03
Interactions	n, K_L, γ	$n \to \pi^0$	0.5
Accidentals	n, K_L, γ	n, K_L, γ	1.5
Total Background			35

Precision of KOPIO $K_L^0 \to \pi^0 \nu \bar{\nu}$ measurement

S/N	Signal (events)	Precision [Statistical error]	Precision [incl. syst. error]
1	94	0.15	0.19
2	65	0.15	0.17
3	48	0.17	0.18
5	32	0.20	0.20

SUMMARY

$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ offer unique opportunities to explore SM physics and search for non-SM effects.



E787 → E949: **heading below SM predictions**

- E787 95-97 combined data still has one event!
- E787 -98 data will reach about 0.8×10^{-10}
- E949 aimed at $\leq 10^{-11}$ or 5-10 SM events

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

A direct window into CP violation.

- Best way to determine η
- Complementary to B system - compare results to search for new physics.

KOPIO

- Goal: 50 "SM" events
- Low background
- $\sim 7\%$ measurement of $Im\lambda_t$.
- Explore from 10^{-8} down to $\sim 10^{-12}$

(less than 1% of which is allowed by S.M.)

Very likely to show new physics if at work in ϵ'/ϵ.

KOPIO: **exploits special conditions at the AGS**

- Proton intensity 10^{14}/pulse, micro-bunching
- Highly effective constraints and cross-checks
- Experience of recent AGS exps.

$K^+ \to \pi^+ \nu \bar{\nu}$ (E787): vetoes, electronics, analysis

$K^+ \to \pi^+ \mu e$ (E865) rates, calorimetry