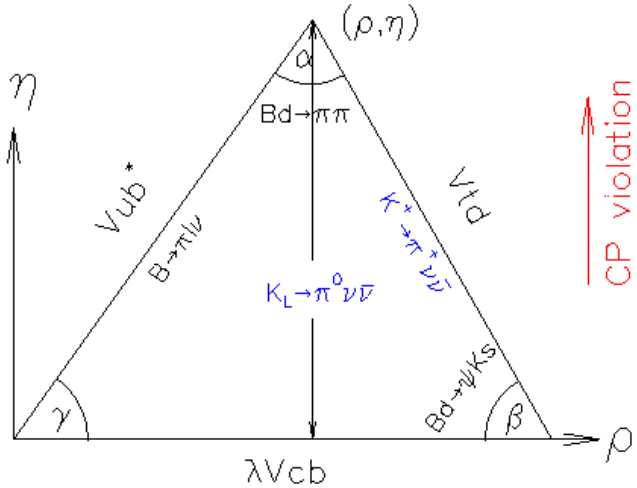
KOPIO
Measurement of $K_L^0 \to \pi^0 \nu \bar{\nu}$

Douglas Bryman
University of British Columbia

May 13, 2004 BNL RHIC AGS Users Meeting K Physics Workshop

Standard Model CP Violation

Super-clean processes will challenge the Standard Model:



$K^+ \to \pi^+ \nu \bar{\nu}$ $\quad |V_{ts}^* V_{td}|$ $\quad$ **E949**, CKM

Compare with $\dfrac{\Delta M_{B_S}}{\Delta M_{B_D}}$

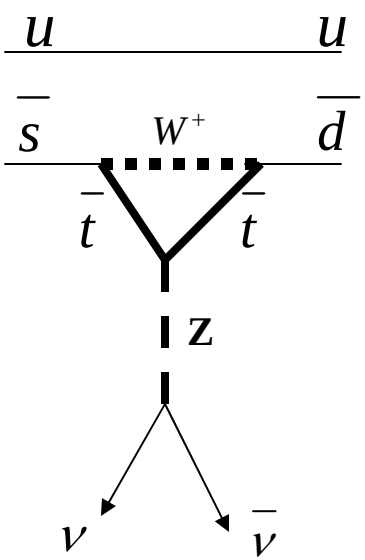
$K_L^0 \to \pi^0 \nu \bar{\nu}$ $\quad \mathrm{Im}\, V_{ts}^* V_{td}$ $\quad$ **KOPIO**

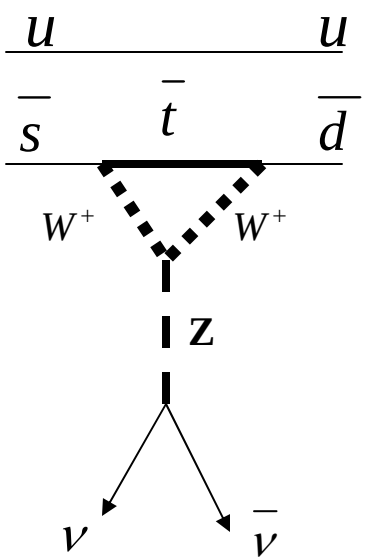
"Jarlskog invariant" $|J_{CP}| = 2A_\Delta = |\mathrm{Im}\, V_{ts}^* V_{td}|\, \lambda \left(1 - \dfrac{\lambda^2}{2}\right)$

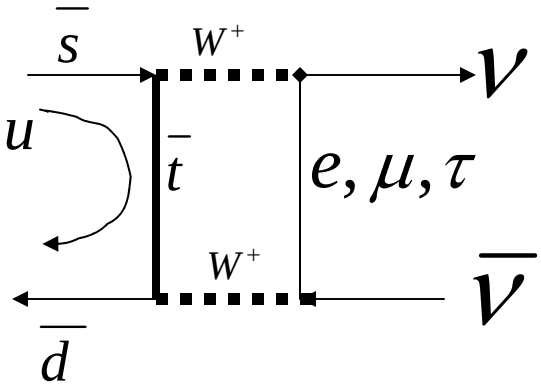
$K \to \pi \nu \bar{\nu}$: Standard Model

Negligible long distance effects. Top quark dominance.

Hadronic matrix elements ($K \to \pi$) from $K \to \pi e \nu$.







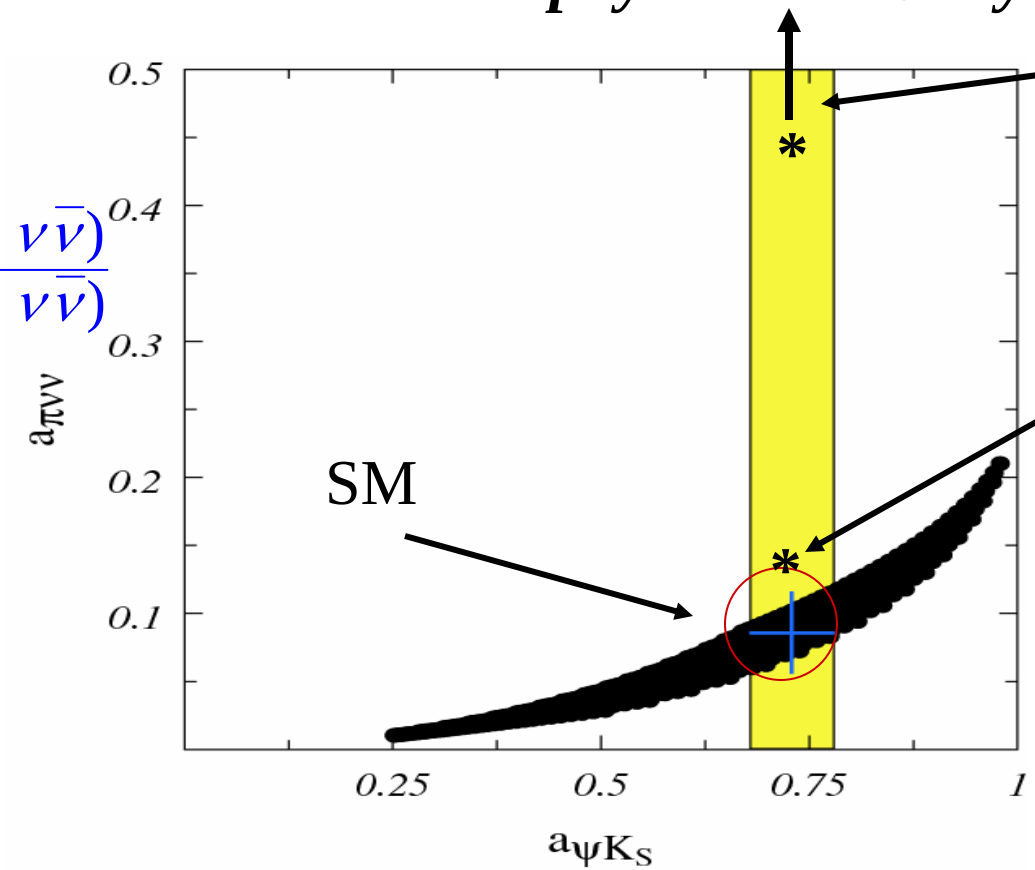
	$K^+ \to \pi^+ \nu \bar{\nu}$	$K_L^0 \to \pi^0 \nu \bar{\nu}$
Branching Ratio $\left(10^{-11}\right)$	8.0 ± 1.1	3.2 ± 0.6
Theoretical Uncert. (est.)	7%	2%

Buchalla and Buras, Nucl. Phys. ***B548****, 309 (1999); Buras et al.,hep-ph/0402112; Isidori,hep-ph/307014.*

$\mathbf{B} \to \psi K_S$ *and* $\mathbf{K} \to \pi\, \nu\, \bar{\nu}$

Differences sensitive to new physics – virtually free of uncertainties.

$$\frac{\Gamma(\mathbf{K}_L^0 \to \pi^0\, \nu\bar{\nu})}{\Gamma(\mathbf{K}^+ \to \pi^+\, \nu\bar{\nu})}$$



* "Enhanced" Z^0 Penguins

$\Gamma(K^+)$ x 1; $\Gamma(K_L^0)$ x 12

$\sin(2\beta_x) = -0.69$

(Buras et al. hep-ph/040211)

* Minimal Flavor Viol.

$\Gamma(K^+)$ x 2; $\Gamma(K_L^0)$ x 4

(Buras hep-ph/0310208)

* Multiple Higgs

* Extra dimensions

* Low energy SUSY

CP asymmetry in $\mathbf{B} \to \psi K_S$

Nir and Worrah, Phys. Lett. **B423**, 319 (1998)

Roles of $K \to \pi\nu\bar{\nu}$ Measurements in Flavor Physics

New flavor physics in the s-d sector may be very different from that in the b sector:

* *If B - physics is consistent with the SM:*

  New physics could be revealed $K \to \pi\nu\bar{\nu}$.

* *If deviations from the SM are indicated:*

  $K \to \pi\nu\bar{\nu}$ would add crucial additional information; the complexity of the flavor sector beyond the SM is foreseen in many models.

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

Limit based on isospin and $K^+ \to \pi^+ \nu\bar{\nu}$: $< 1.4\, x 10^{-9}$ • [Grossman, Nir]

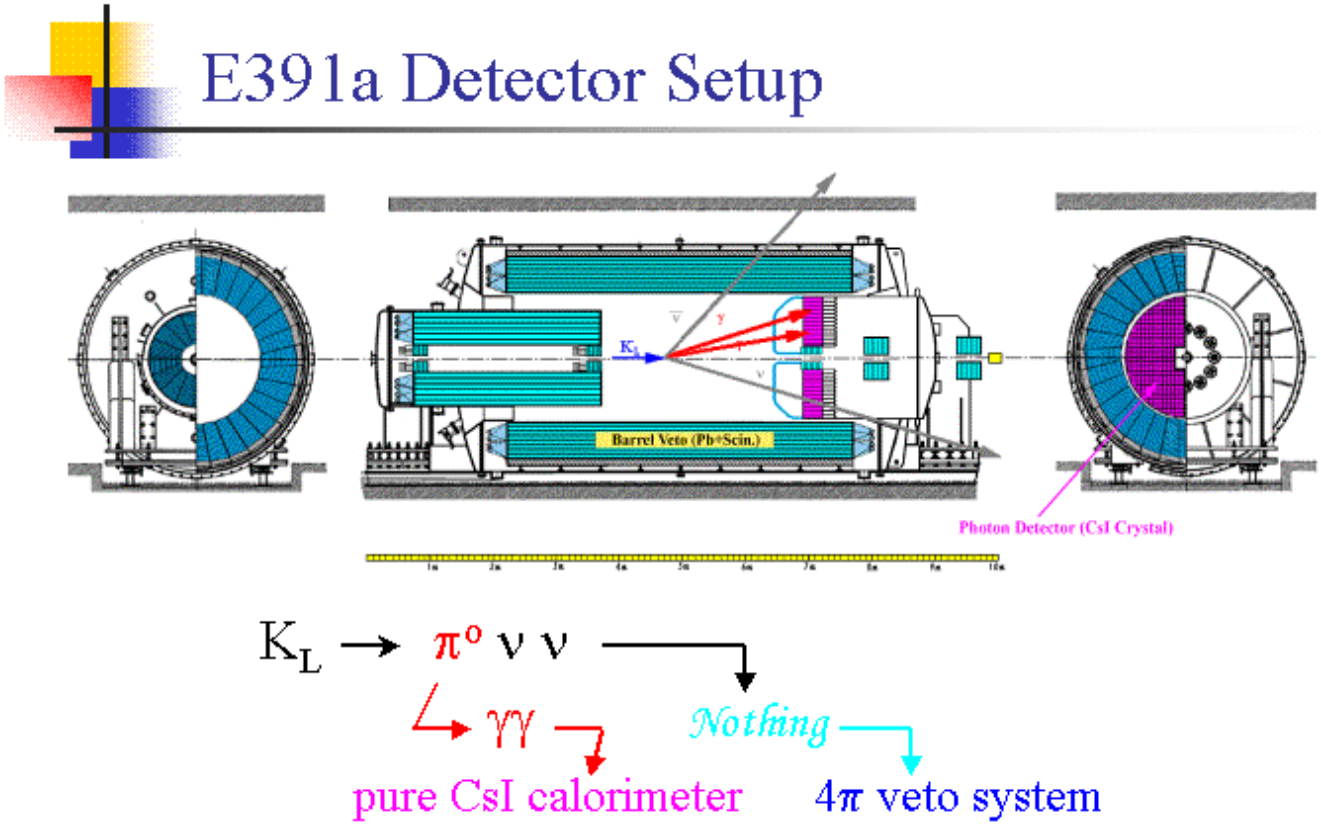
- KTEV (FNAL) result:

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) \equiv \frac{\Gamma(K_L^0 \to \pi^0 \nu\bar{\nu})}{\Gamma(K_L^0 \to all)} < 5.9\, x 10^{-7} \quad (90\% CL)$$

- KEK E391a *goal* : s.e.s. $10^{-10} - 10^{-9}$
- KOPIO (BNL) *goal* : s.e.s. $< 10^{-12}$, >50 events

KOPIO seeks an improvement of 10^5 over present results.

KEK PS



Features: * Pencil Beam
* High acceptance
* High P_T selection
* Pilot Project for JHF
* Test reliance on extreme photon veto efficiency

$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ Measurement

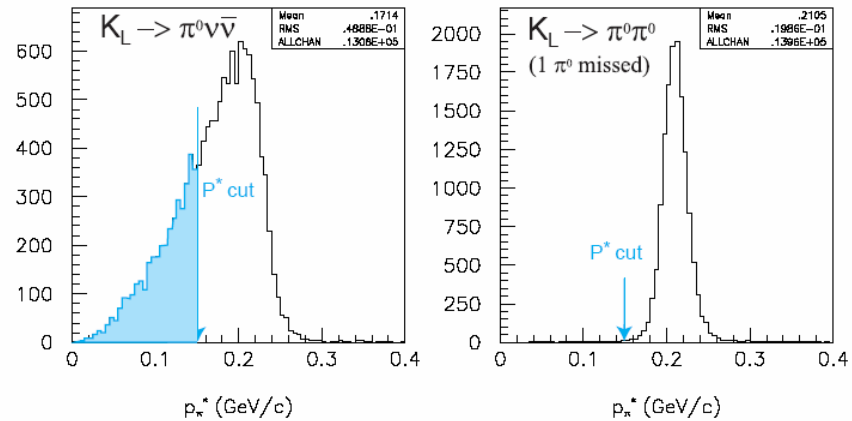
Primary Backgrounds

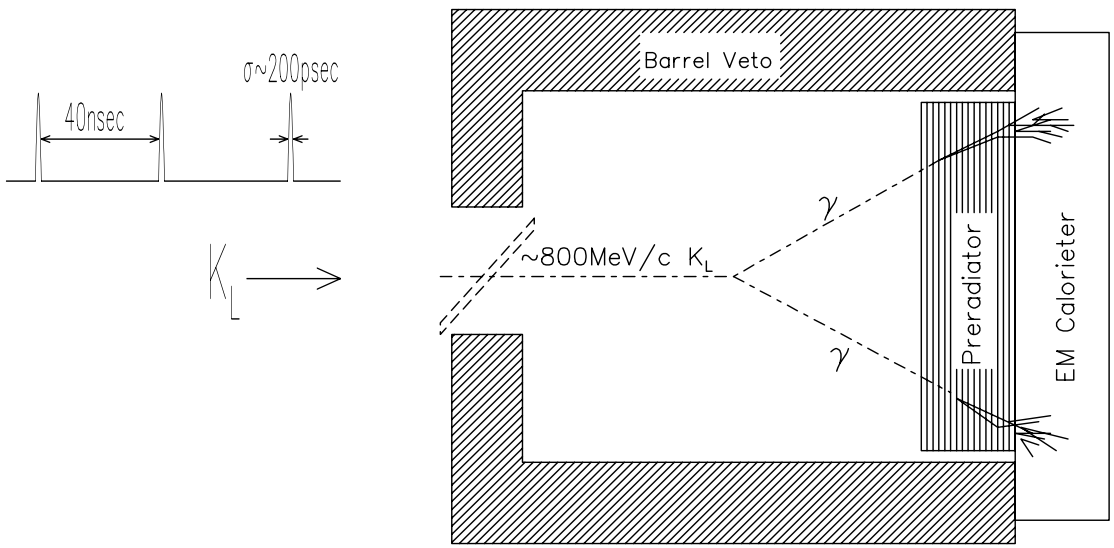
Mode	Branching Ratio
$K_L^0 \rightarrow \pi^0 \pi^0$	$0.93 \ x \ 10^{-3}$
$K_L^0 \rightarrow \pi^- e^+ \nu \gamma$	$0.36 \ x \ 10^{-2}$
$K_L^0 \rightarrow \pi^+ \pi^- \pi^0$	0.1255
Others	

KOPIO: Measurement of $K_L^0 \to \pi^0 \nu \bar{\nu}$

CONCEPTS

- 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.
- Maximize Photon Veto Efficiency
- Maximize Intensity of Microbunched Beam





Nominal Beam Parameters

Proton Beam:

100 Tp/spill (Upgraded from present 70 Tp

2.7 s spill, 2.3 s interspill period

25 MHz micro-buching frequency

Bunch width 200ps

Interbunch extinction 10^{-3}

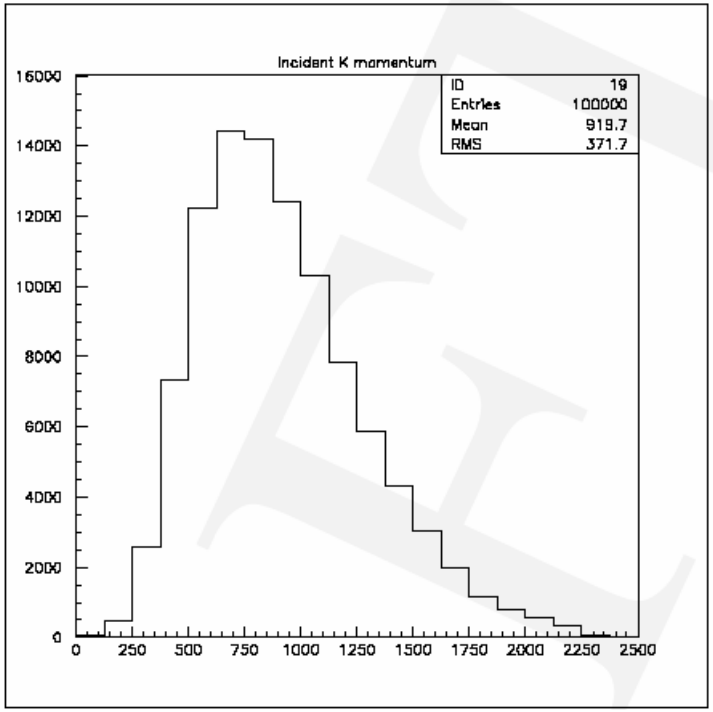
"Kaon Beam":

42.5 degree take-off angle

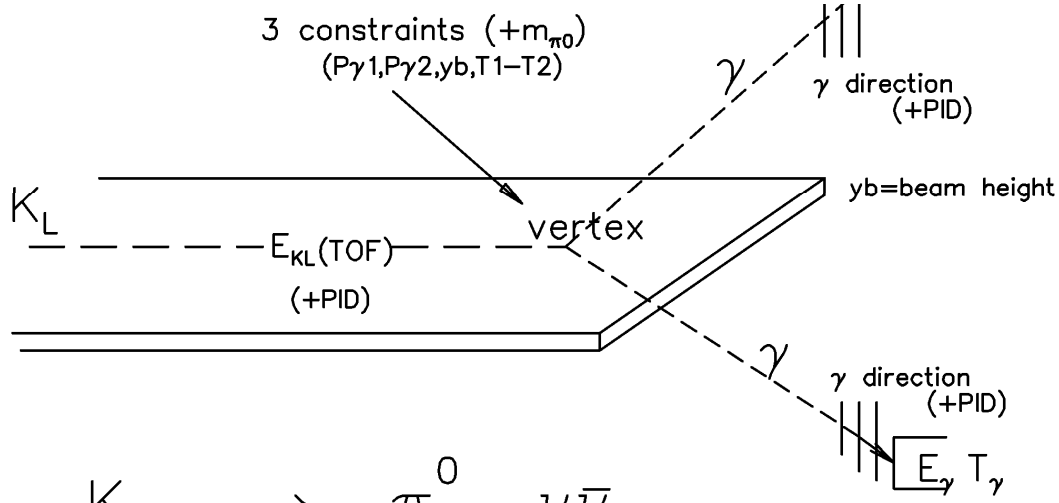
Soft momentum spectrum [0.5,1.5 GeV]

10^{8} K_L / spill, 12 % decay

10^{11} neutrons / spill



KOPIO Beam and Constraints

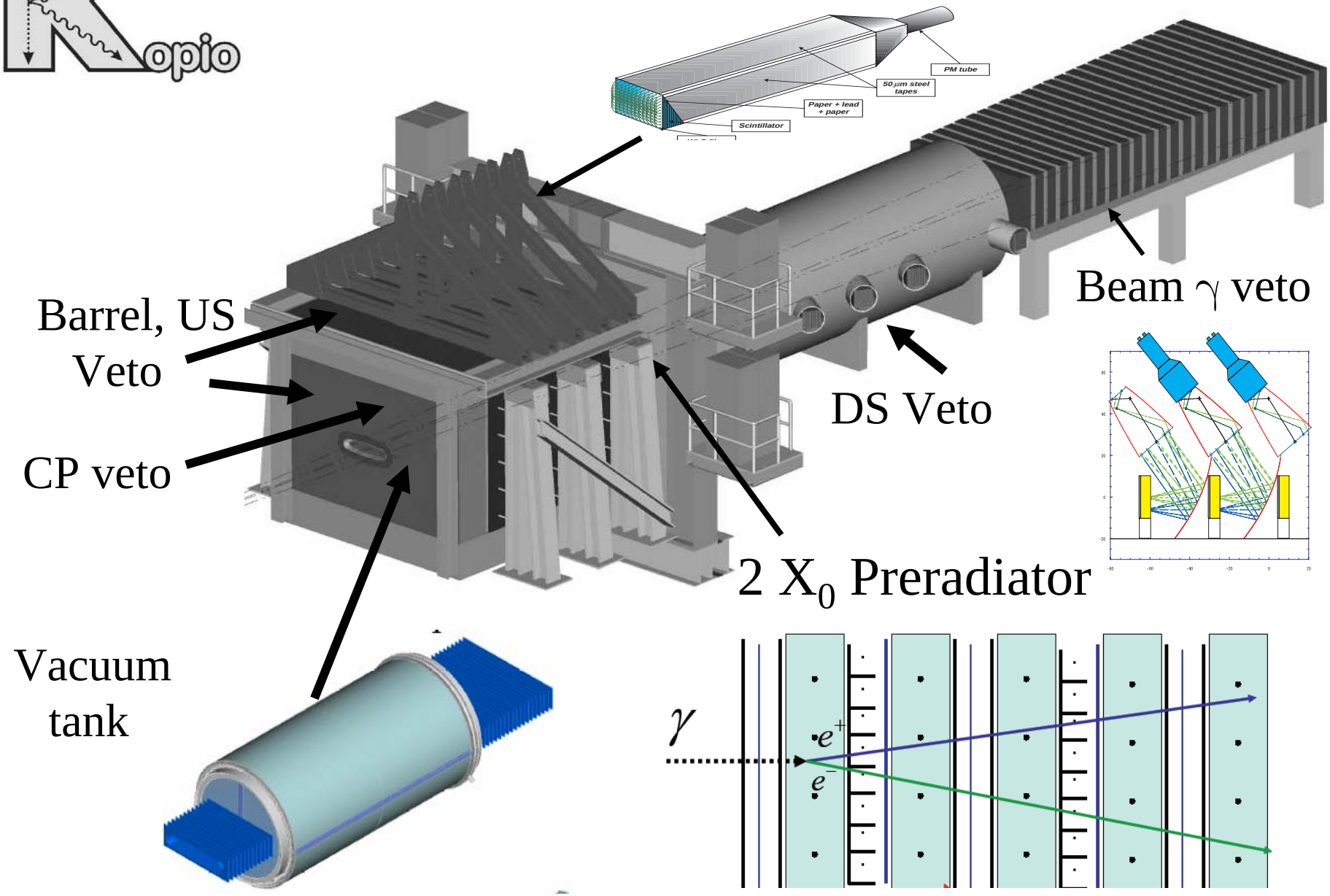


$K_L \rightarrow \pi^0 \; \nu\bar{\nu}$

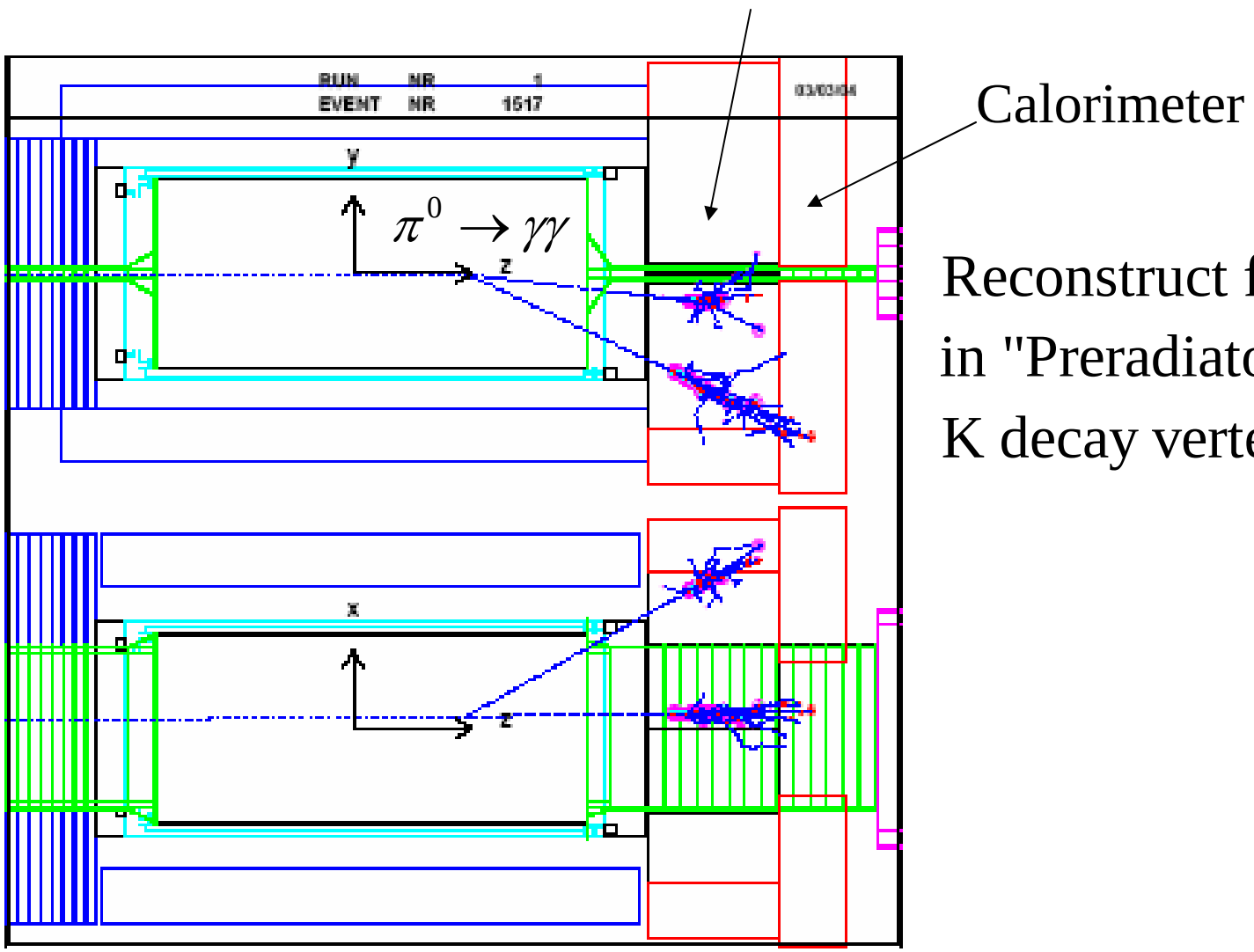
(Momentum:TOF) $\quad$ (4π veto)

$\pi^0 \rightarrow \gamma\gamma$ (Energy and direction)

Shashlyk calorimeter



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



Reconstruct first $\gamma \to e^+e^-$ in "Preradiator" to point to K decay vertex in vacuum.

KOPIO Technique: Lessons from $K^+ \to \pi^+ \nu \bar{\nu}$

Common Problem:

Similar background processes exceed signal $>10^{10}$

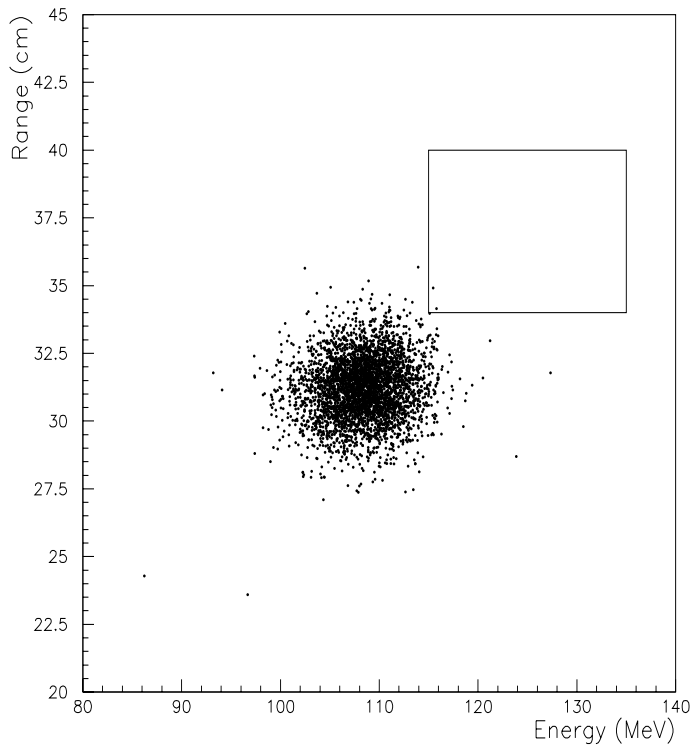
- Measure everything! (energy, position, angle, time)
- Eliminate extra charged particles or ***photons***
  - * E949 π^0 inefficiency $< 10^{-6}$
  - * KOPIO π^0 inefficiency $< 10^{-8}$
- Suppress backgrounds below the signal
  - * Predict backgrounds *from data*: dual cuts
  - * Use "Blind analysis" techniques
  - * Test predictions "outside-the-box"
- Evaluate candidate events with S/N function

$E949$ $\mathbf{K}^+ \rightarrow \pi^+\pi^0$ Background Suppression

Dual cuts: γ Veto and Kinematics (P,R,E...)

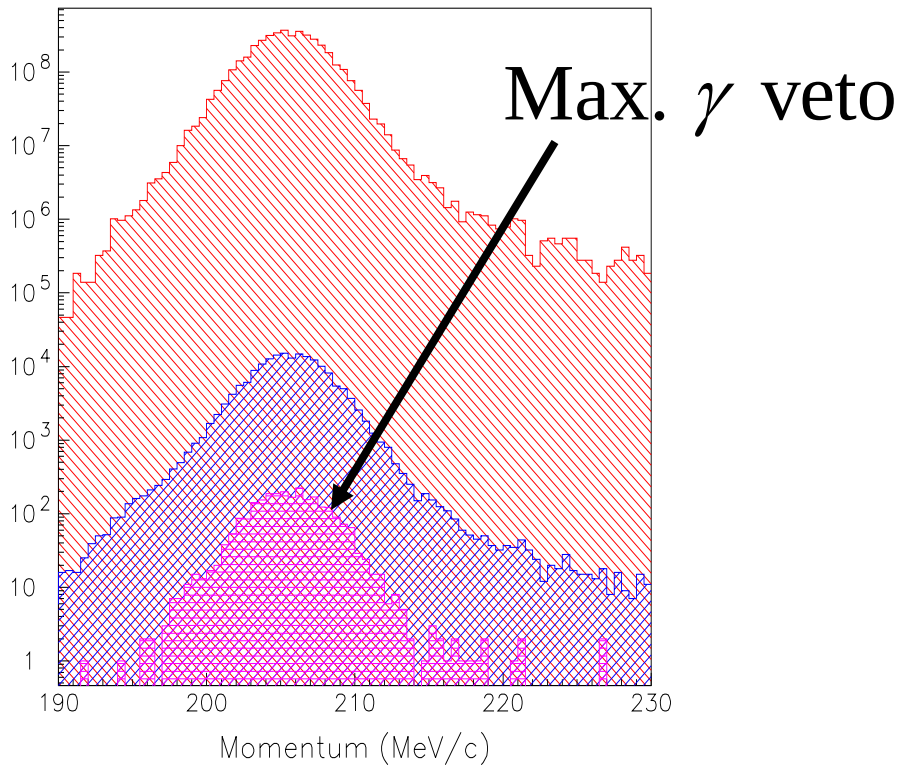
γ Veto Reversed

Range vs. Energy



γ Veto Applied

Momentum



Check for correlations

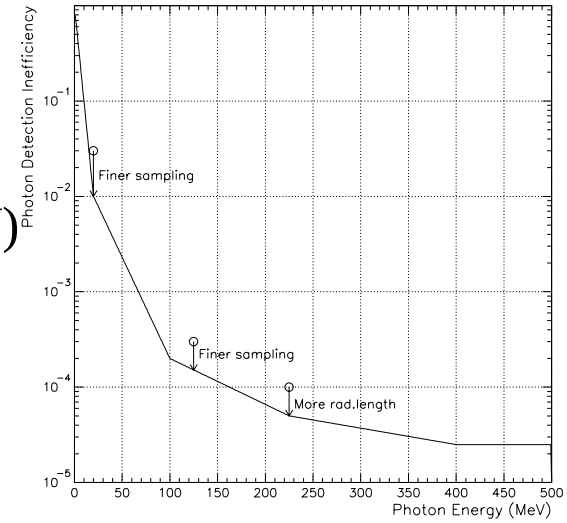
Photon Vetoing

E787

$\bar{\varepsilon}_\gamma \sim 10^{-2}$ (20-100 MeV)

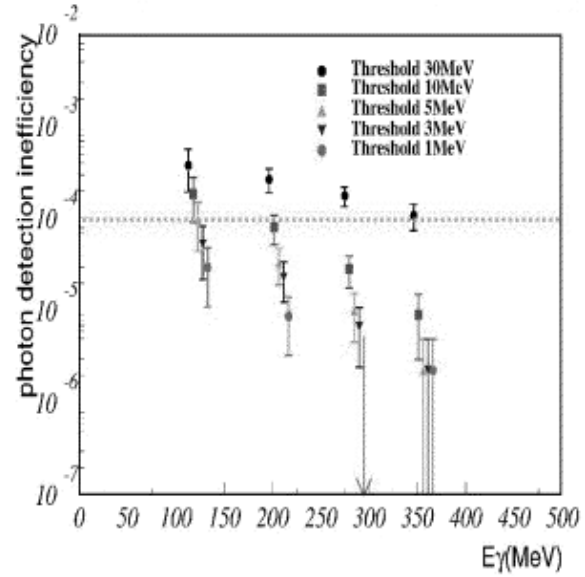
$\sim 10^{-4}$ (100-220 MeV)

$\bar{\varepsilon}\pi^0 < 10^{-6}$



KEK ***Photonuclear***

Inefficiency of γ detection



Photon vetoing & Kinematics:

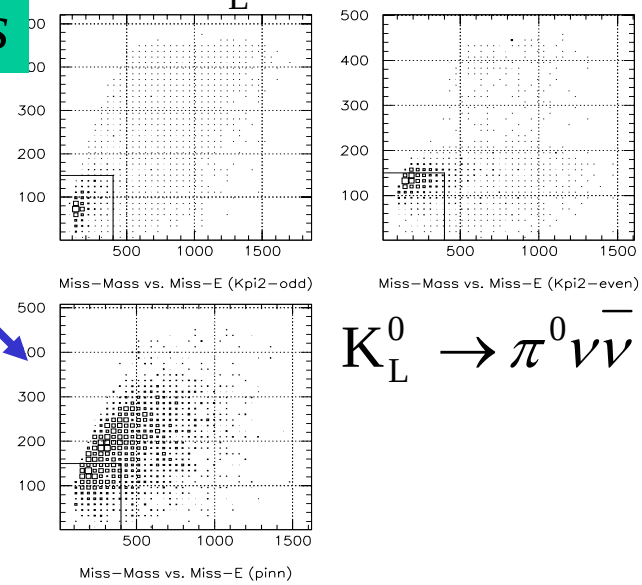
Suppress events with low energy photons

Missing mass $(2E_1^{miss}E_2^{miss}cos\theta_{12})$ vs.

Missing energy $(E_1^{miss} + E_2^{miss})$

$$\bar{\varepsilon}\pi^0 < (10^{-4})(10^{-4}) = 10^{-8}$$

$K_L^0 \to \pi^0\pi^0$



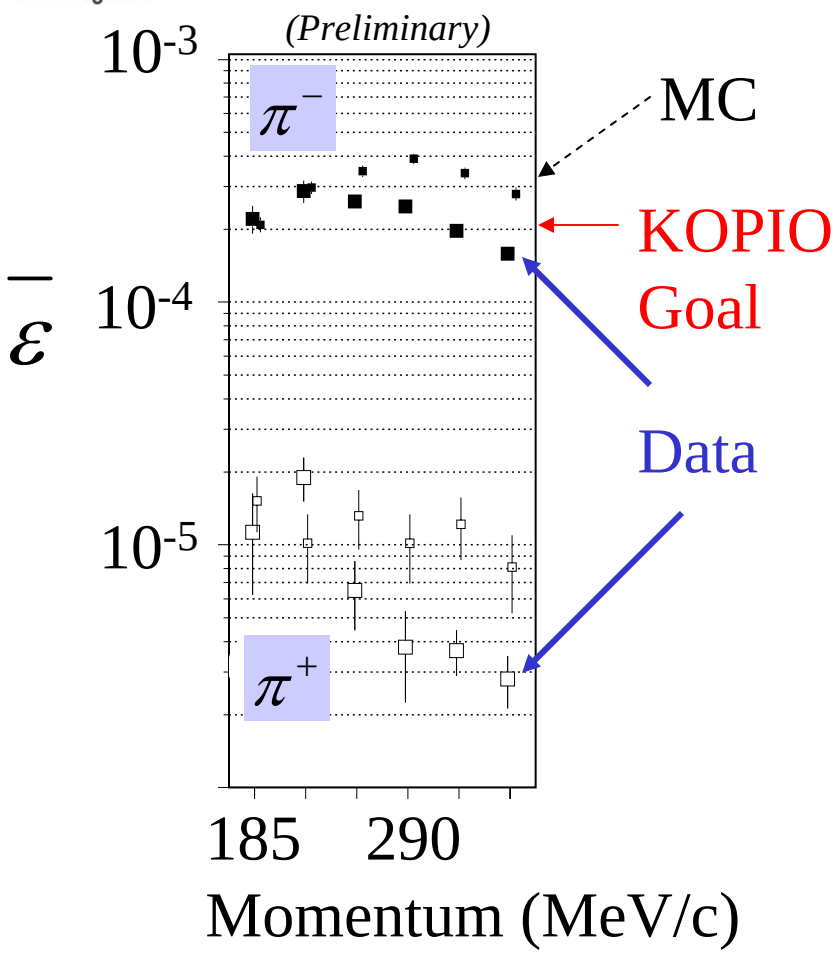
$K_L^0 \to \pi^0\nu\bar{\nu}$

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^-	$(6.0 \pm 0.6)\ x\ 10^{-4}$

NIM **A**359, 478 (1995)

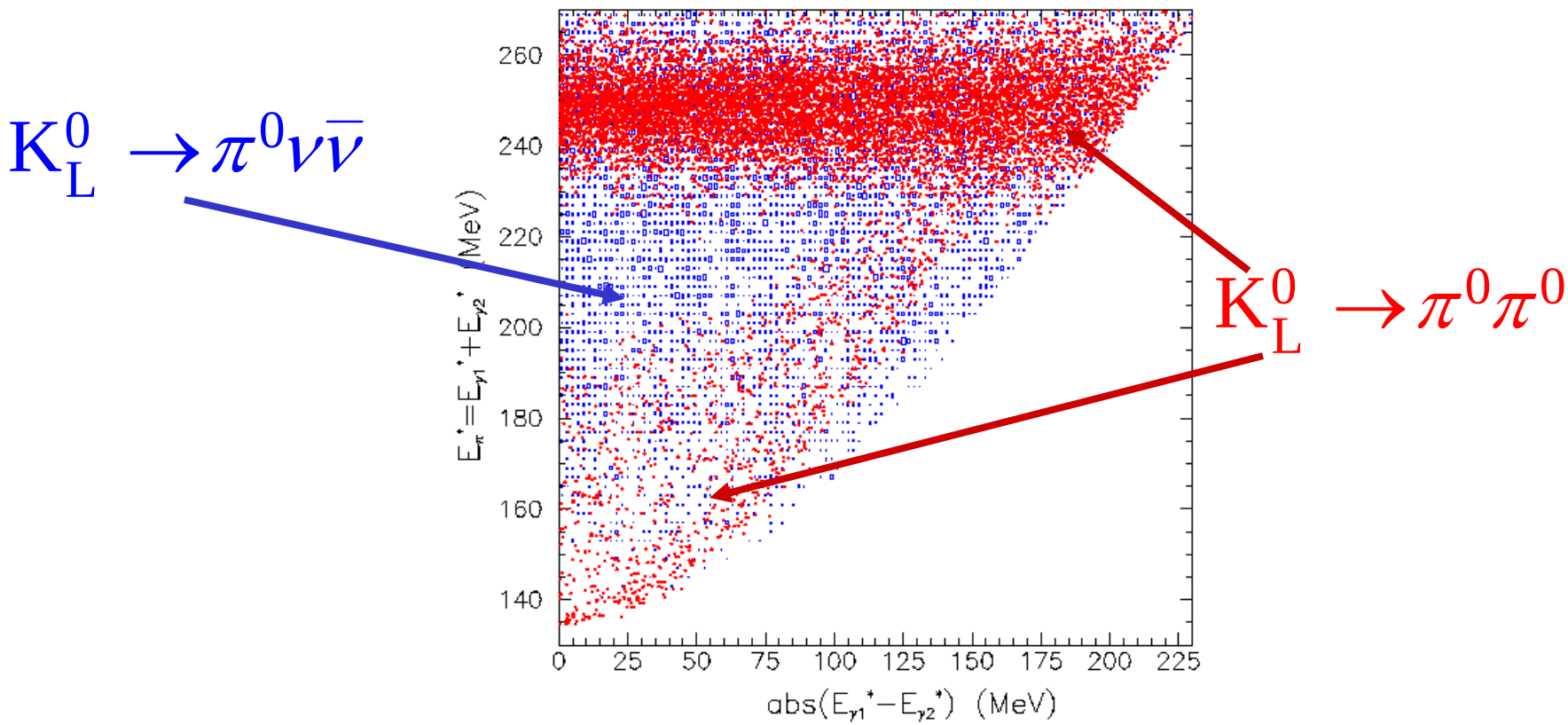
Key features of the KOPIO concept have been established:

- Micro-bunching
- Photon pointing, energy resolution
- Vetoing – including charged particles, photons, catcher

	Expected Performance
μ Bunch Width (Extinction)	200 ps (10^{-3})
θ_γ Resolution (250 MeV)	23 mr
E_γ Resolution	$2.7\% / \sqrt{E_\gamma(GeV)}$
t_γ Resolution	$50ps / \sqrt{E_\gamma(GeV)}$
Photon Veto Inefficiency	0.3 E787
Charged Particle Inefficiency	$10^{-5}(\pi^+), 10^{-4}(\pi^-)$

Kinematic suppression of backgrounds
Goal: >50 Events with S/N>2

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



S/N=2

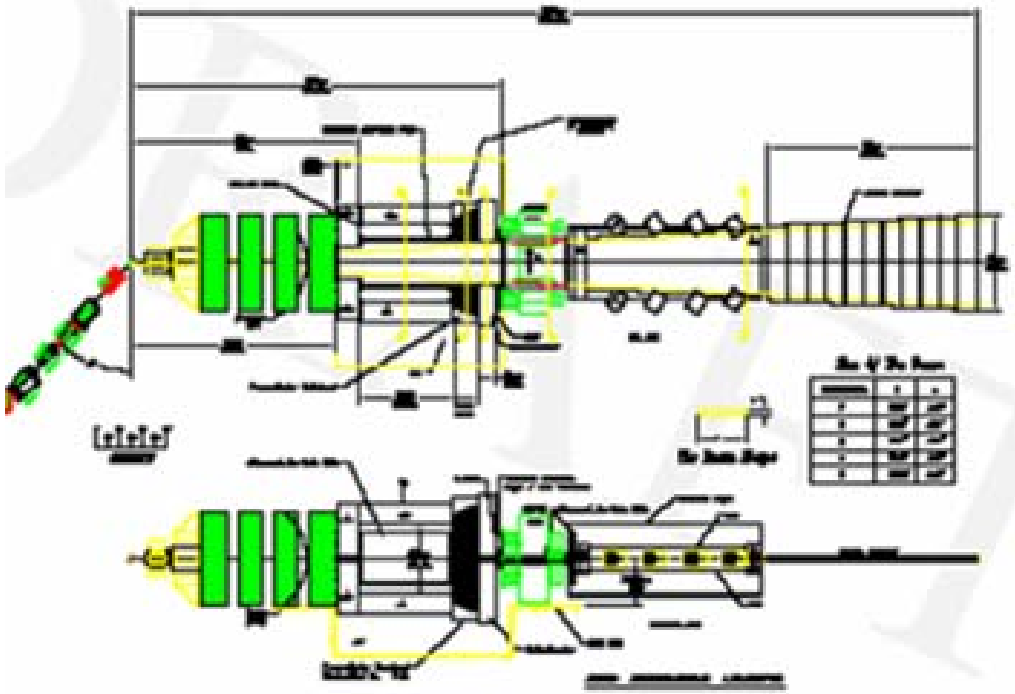
Estimated Background Levels

	Branching Ratio	Bkg. Events
$K_L^0 \rightarrow \pi^0\pi^0$	$0.93 \ x \ 10^{-3}$	14
$K_L^0 \rightarrow \pi^- e^+ \nu \gamma$	$0.36 \ x \ 10^{-2}$	5
$K_L^0 \rightarrow \pi^+\pi^-\pi^0$	0.1255	3
Others		1
		*******

Signal: 49 Background: 24

9600 Hours; Acceptance 9×10^{-3}

Kopio

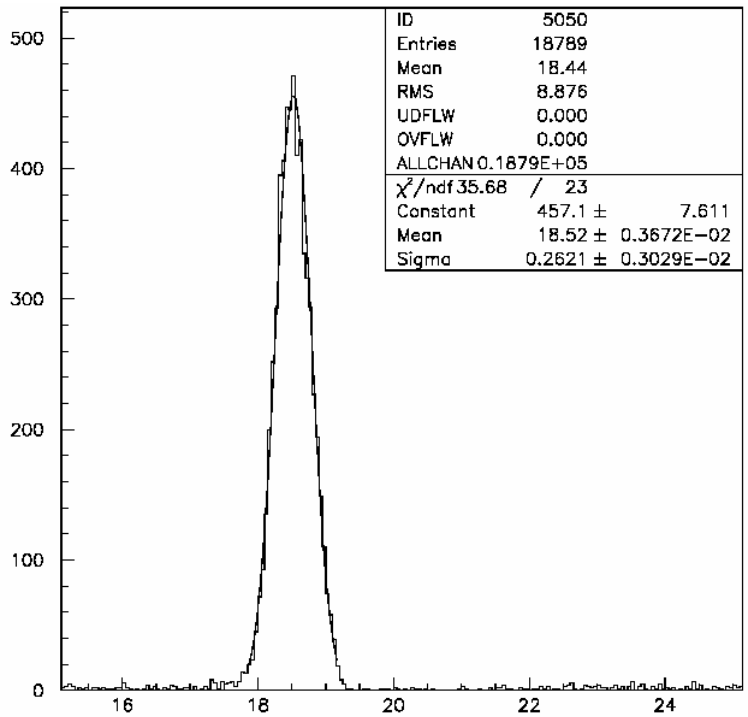


AGS Microbunching Beam test

Microbunch width

Studied the RF extraction mechanism proposed for KOPIO & measured a microbunch rms width of 244 ps -- KOPIO requires a 300 ps rms

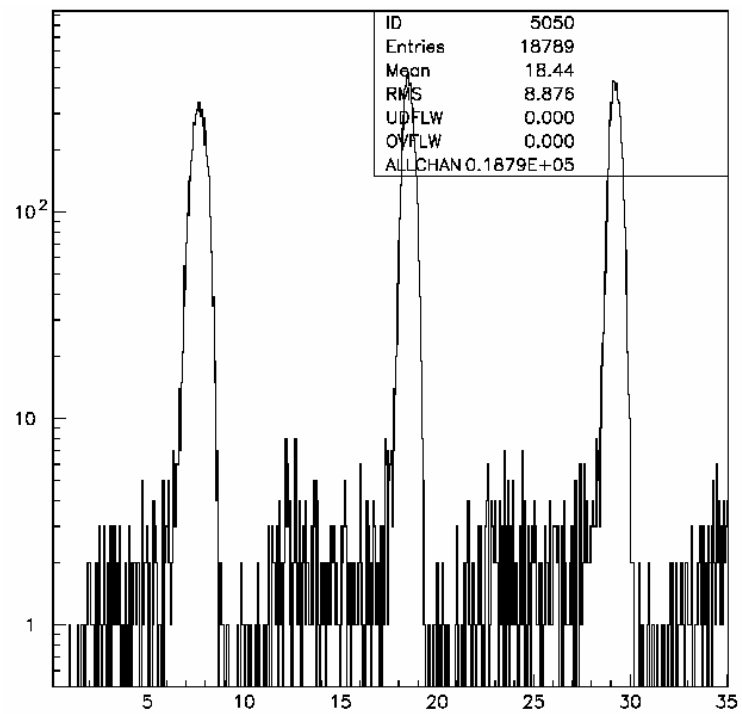
Also developed monitoring methods



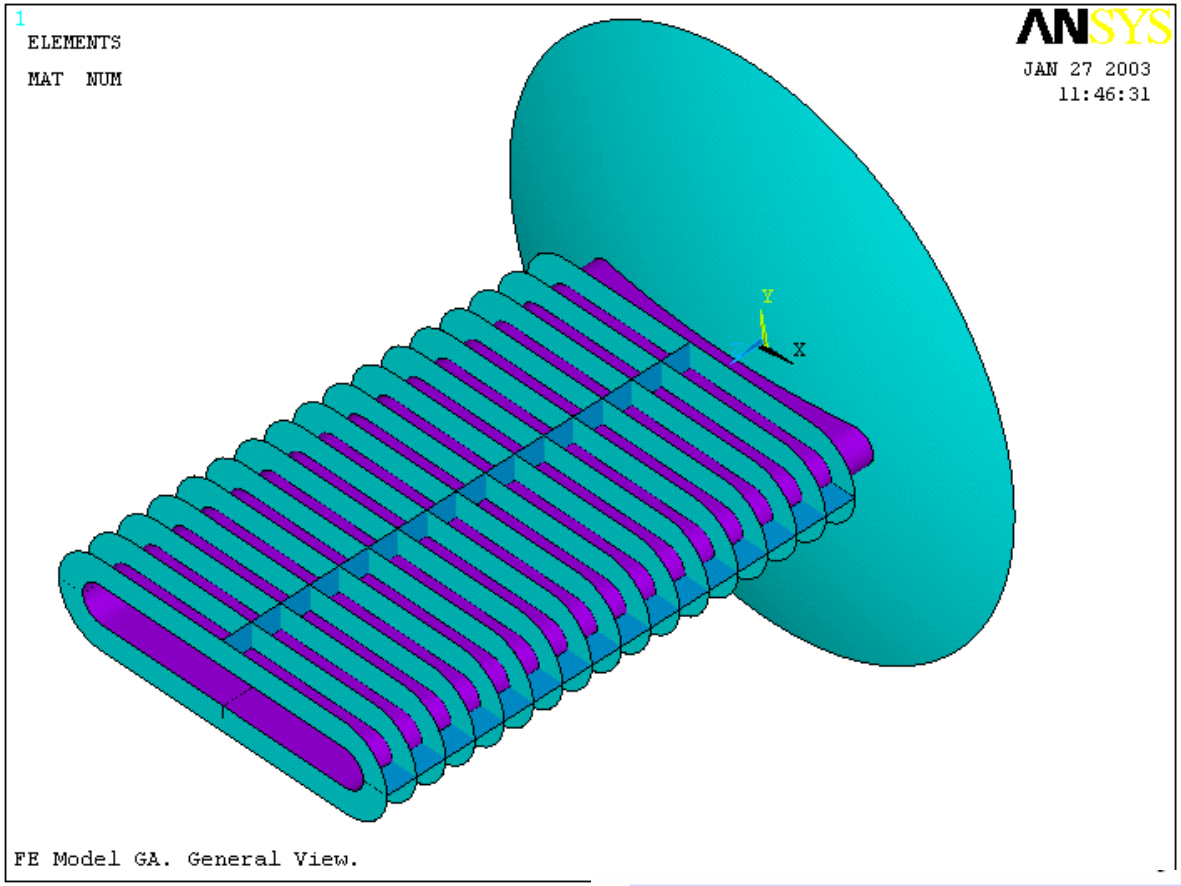
Interbunch extinction

Measured the inter-bunch extinction ratio (flux between bunches/within bunch). Observed a ratio of ~3-4% (could be less) KOPIO requires ~ 10^{-3}

Need to control power supply ripple

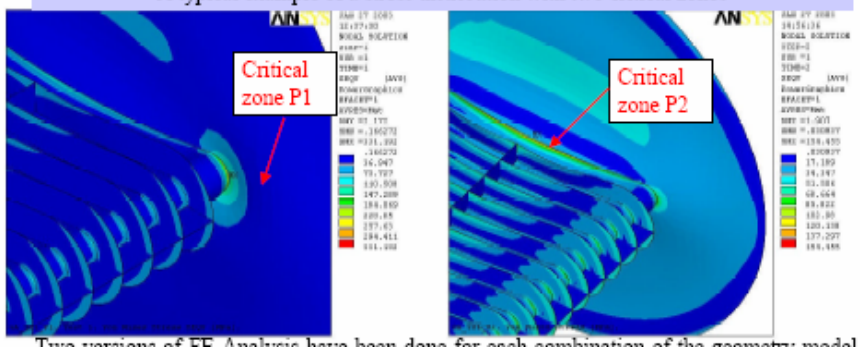


Vacuum Tank: Carbon Fiber Composite



Finite element Analysis

A typical example of a stress distribution with two critical zones



Two versions of FE Analysis have been done for each combination of the geometry model

Neutral Beam (neutrons) Collimated to Supress Halo

Vertical Collimation Scheme

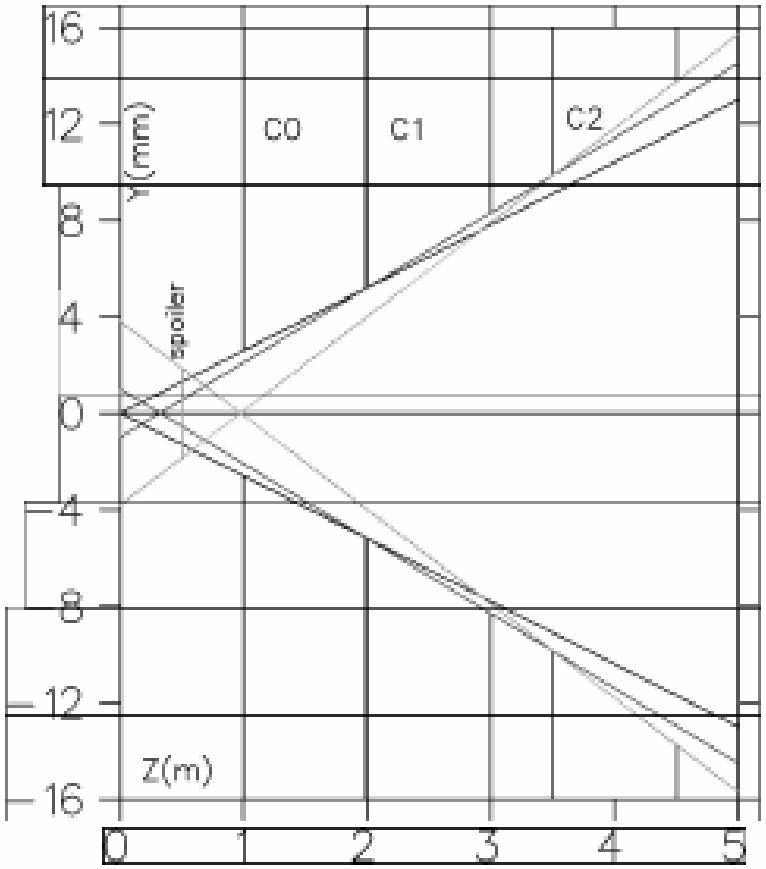


Figure 2: Construction of the vertical apertures of collimators C0 to C2

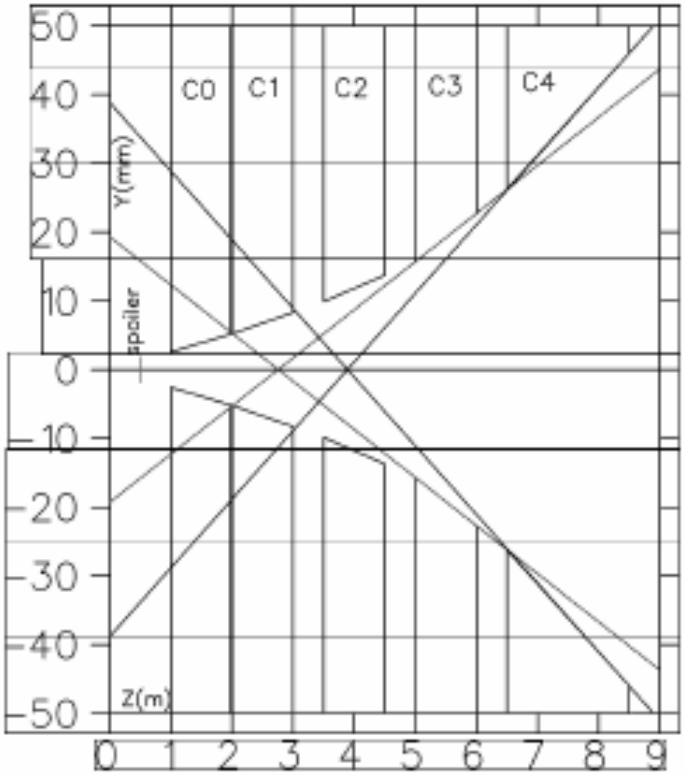


Figure 1: Construction of the vertical apertures of collimators C3 and C4

Simulation of Neutron Collimation

Nominal beam

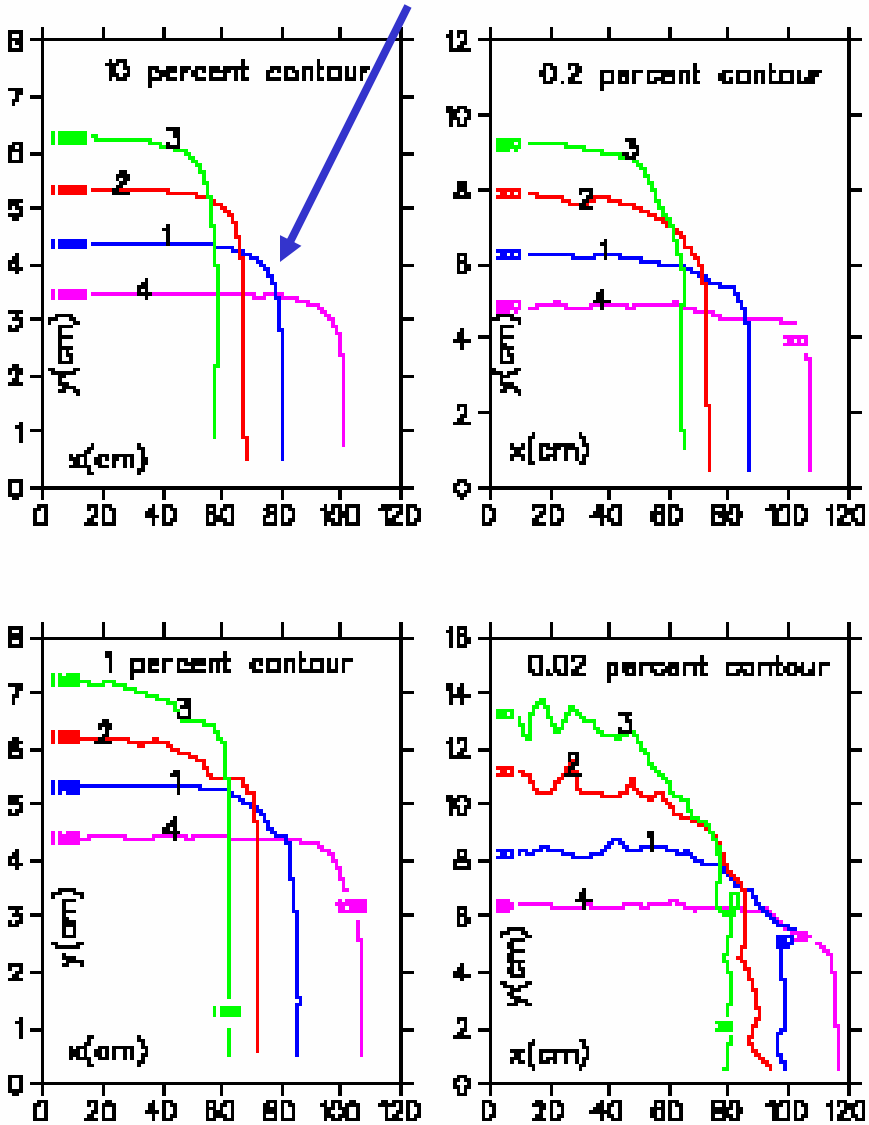
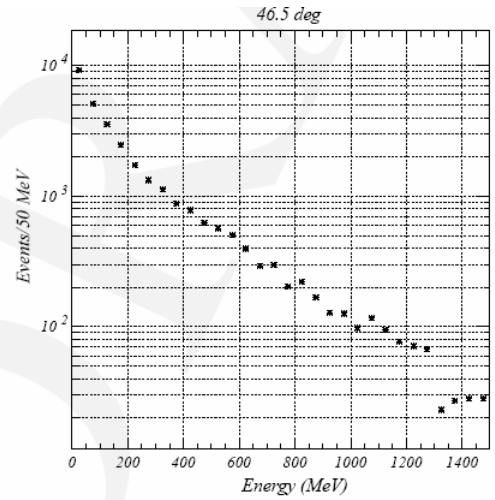
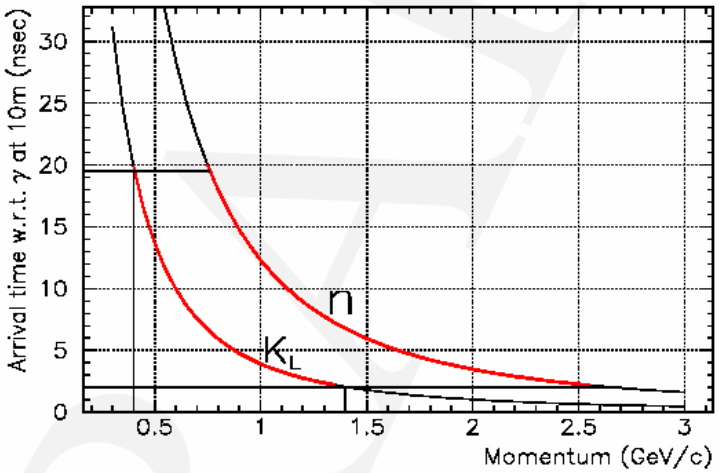


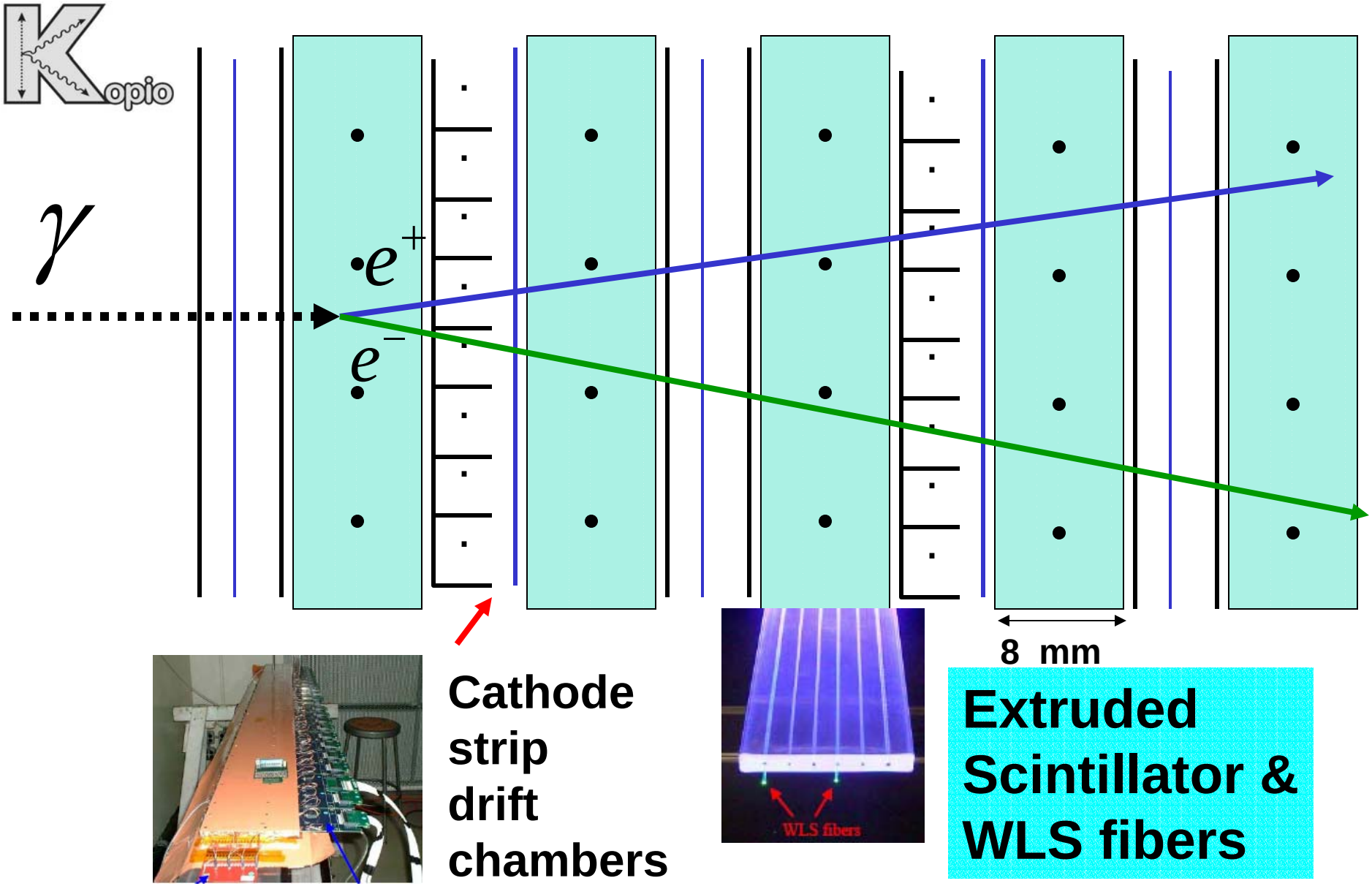
Figure 20: Contour plots at 14 m

Neutron Energy Spectrum



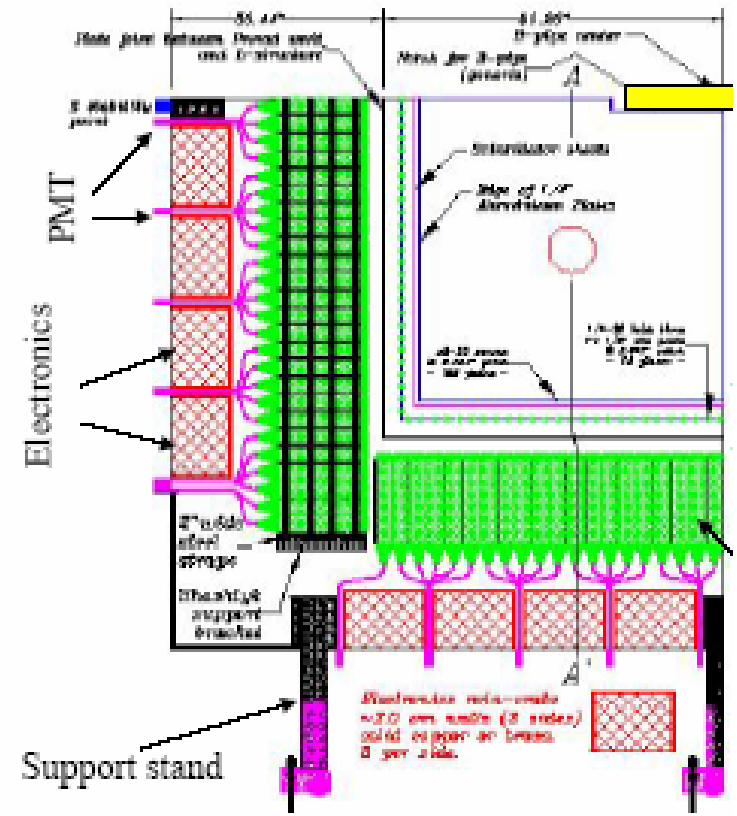


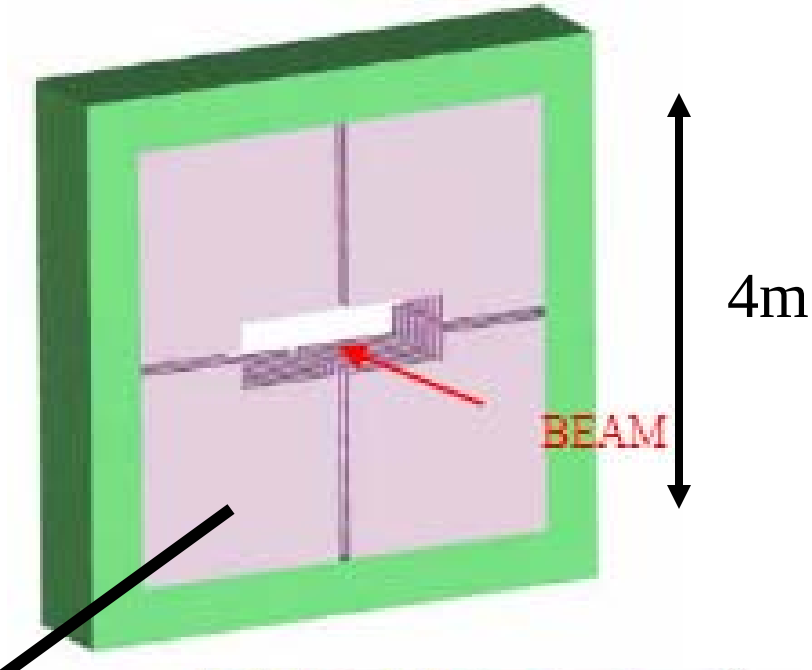
Preradiator Angle Measurement of $\gamma \to e^+e^-$

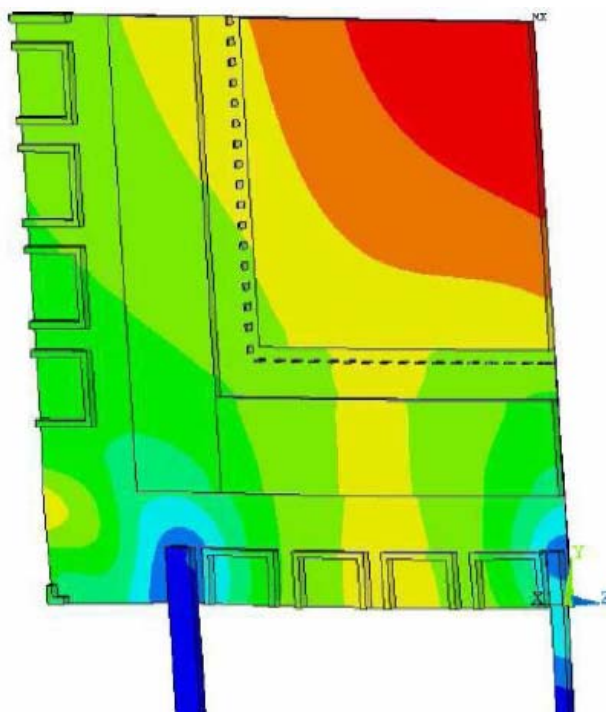


Preradiator R&D

Chambers, electronics, and scintillator prototyped. Mechanical design in progress.

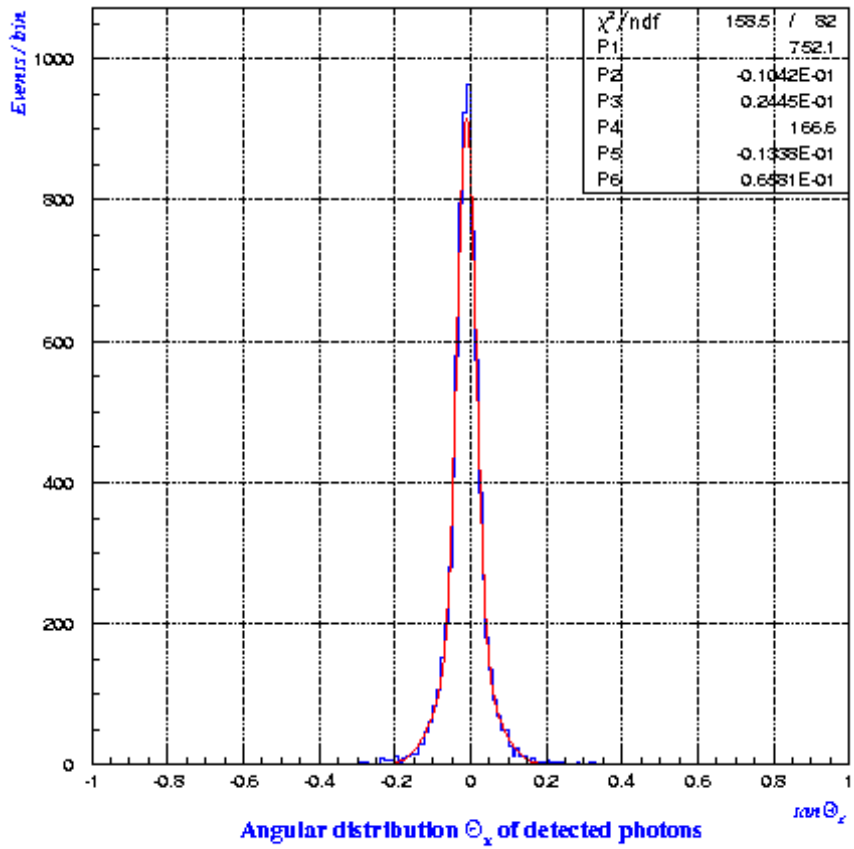






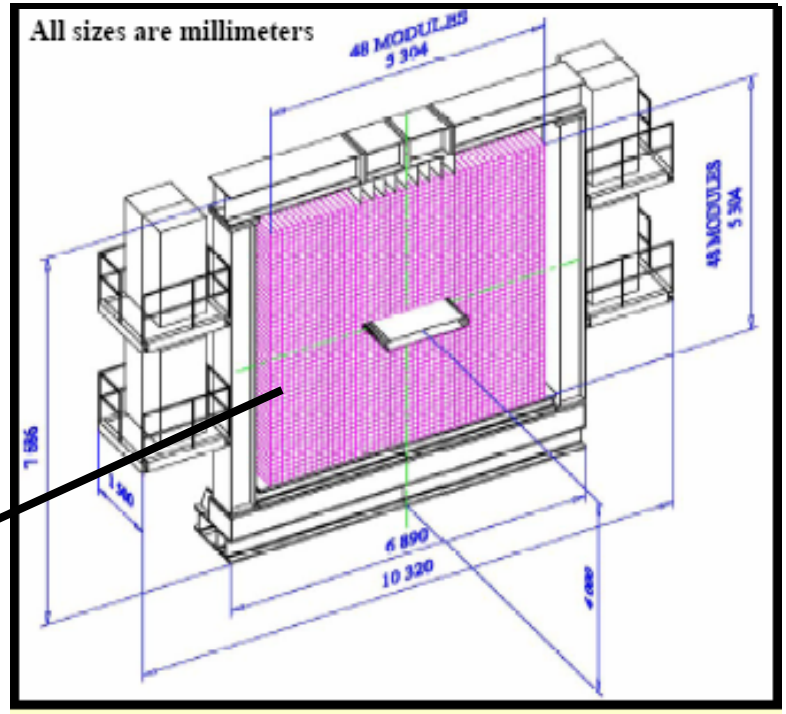
KOPIO Prototype Measurements – Tagged Photon Beams

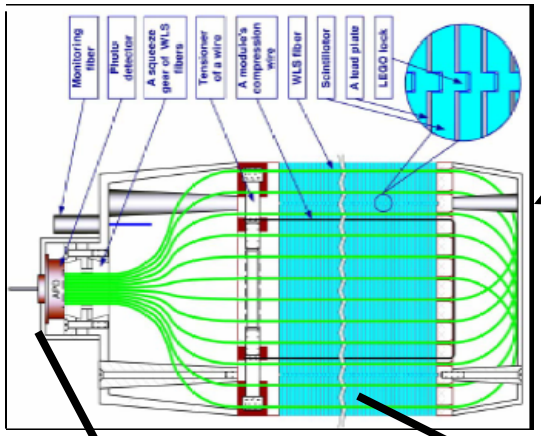
Preradiator Angular resolution:
25 mr at 250 MeV/c



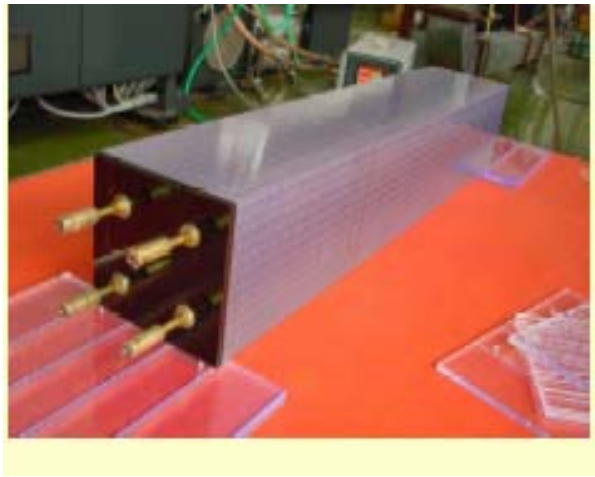
Shashlyk R&D

Shashlyk modules prototyped and tested in beams.
Mechanical design in progress

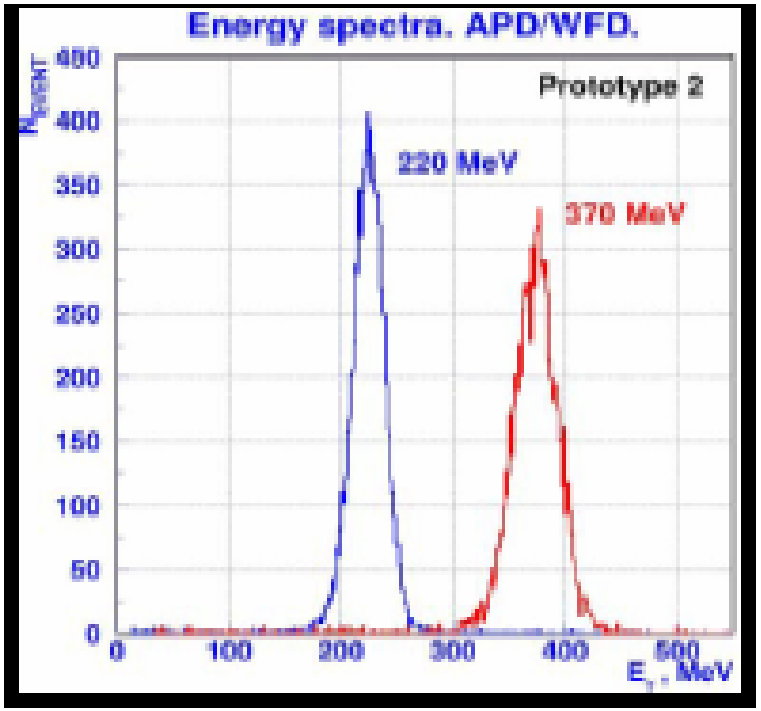


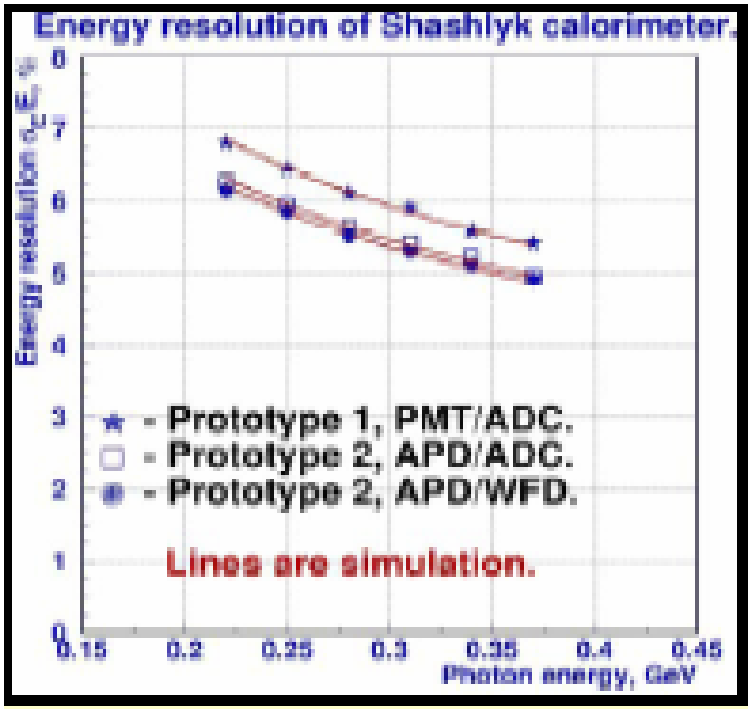


APD



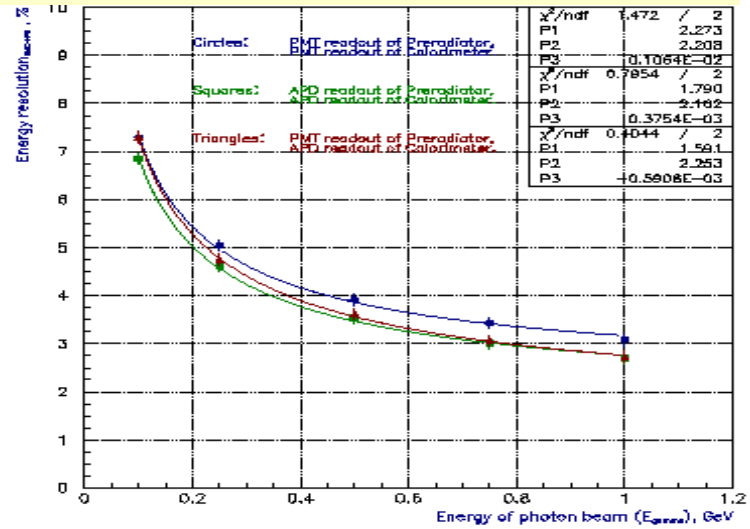
Shashlyk Beam Measurements





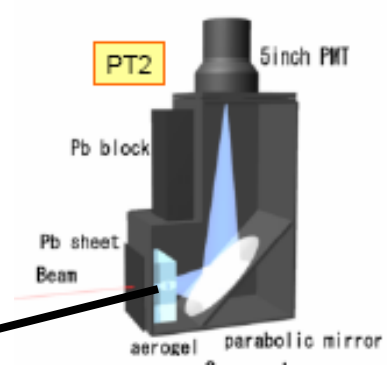
Simulation: Combined Energy Resolution

$$\sigma \sim \frac{3\%}{\sqrt{E(GeV)}}$$

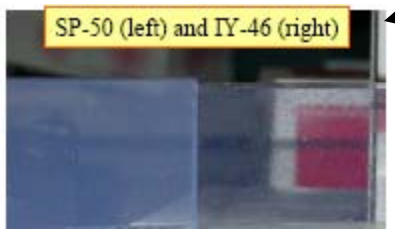


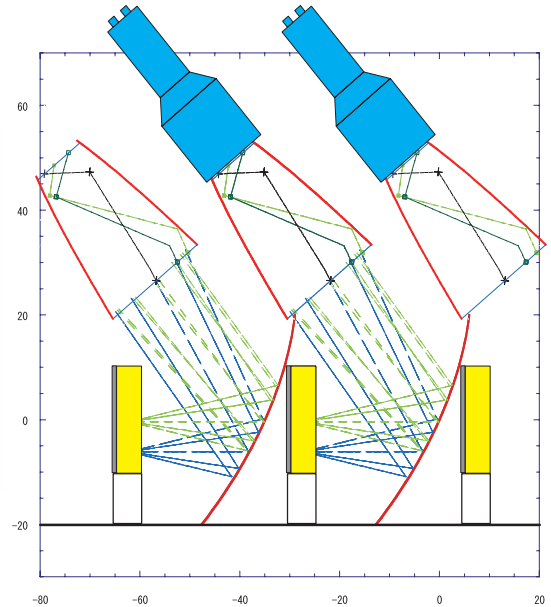
Catcher R&D

Modules prototyped and tested in beams.



New Aerogel tiles

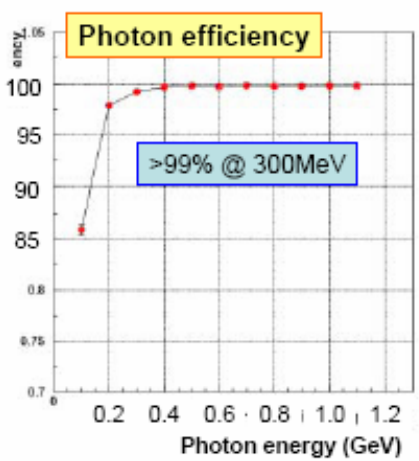


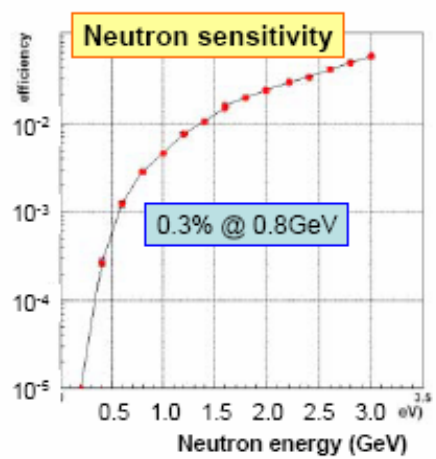


Expected performance with current design

Photon efficiency / Neutron sensitivity

» Average over +/- 10cm(y), normal incident to Catcher





Other Topics of Interest

(Detailed studies not yet done.)

- $\Delta m(K_L^0 - K^+)$

  $K_L^0 \to K^+ e^- \nu$

- "Axions", Gauge Bosons,...

  $\pi^0 \to \nu\bar{\nu},\ \nu\bar{\nu}\gamma,\ XX'$

- CP Violation

  $K_L^0 \to \pi^0 e^+ e^-, \pi^0 \mu^+ \mu^-$

  $\to \pi^0 \pi^0 e^+ e^-$

- Short Distance Physics e.g. V_{td}

  $K_L^0 \to \mu^+ \mu^-$

- Chiral Perturbation Theory

  $K_L^0 \to e^+ e^- (\gamma),\ \mu^+ \mu^- (\gamma)$

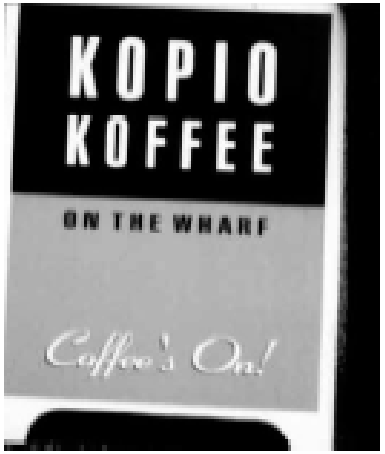
  $K_L^0 \to \pi^0 \pi^0 \gamma,\ \pi^0 \gamma\gamma$

  $K_L^0 \to e^+ e^- e^+ e^-,\ \mu^+ \mu^- e^+ e^-$

  $\pi^0 \to e^+ e^-$

- Lepton Flavor Violation

  $K_L^0 \to \pi^0 \mu^+ e^-,\ \pi^0 \to \mu^+ e^-$

Summary and Outlook

- KOPIO R&D is concluding successfully.
- Advanced planning for the construction phase is beginning.