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

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for the KOPIO collaborations

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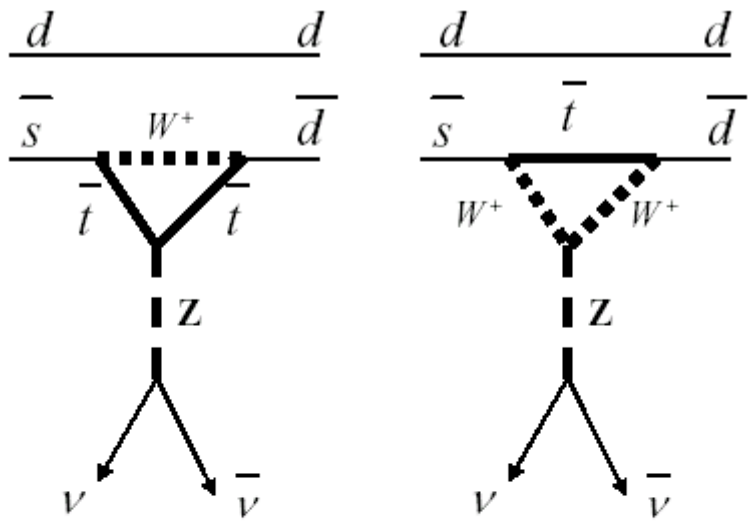
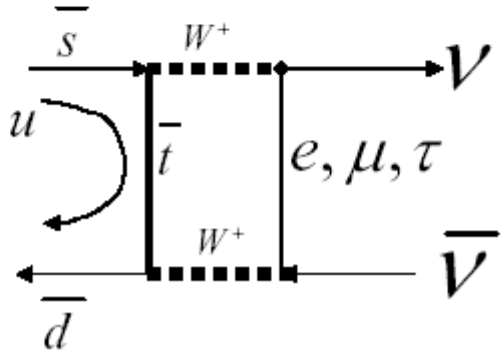
Physics Motivation of KOPIO

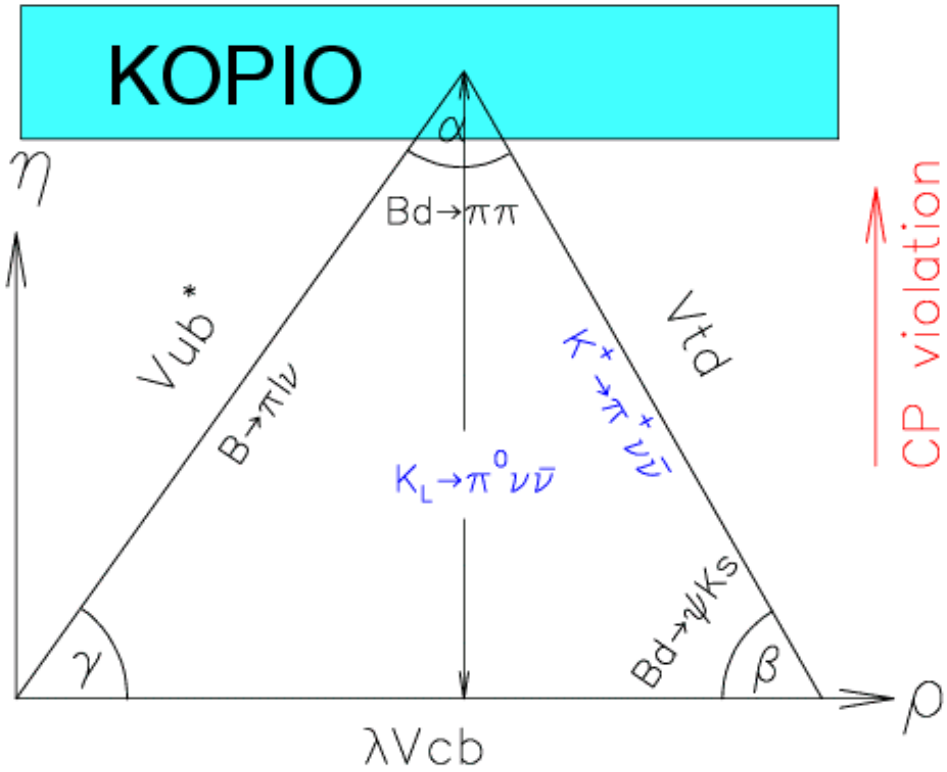
- KOPIO experiment @ BNL
  - $K_L \rightarrow \pi^0 \nu \bar{\nu}$ measurement
- Measures CP parameter η
  - $B(K_L \rightarrow \pi^0 \nu \bar{\nu}) \propto |\mathrm{Im}\,(V_{ts}^* V_{td})|^2$
- One of the "gold-plated" modes
  - Hadronic matrix elements ($K \rightarrow \pi$) from $K \rightarrow \pi\, e\, \nu$
  - Negligible long distance effects
  - Top quark dominance

  $\rightarrow$ small theoretical uncertainty ~ 2-3%





CP violation in $K_L \to \pi^0 \nu \bar{\nu}$



- $B(K^+ \to \pi^+ \nu \bar{\nu}) \propto |V_{ts}^* V_{td}|^2$ E949
- $B(K_L \to \pi^0 \nu \bar{\nu}) \propto |\mathrm{Im}(V_{ts}^* V_{td})|^2$ KOPIO

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

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

$B(K_L \to \pi^0 \nu \bar{\nu})$

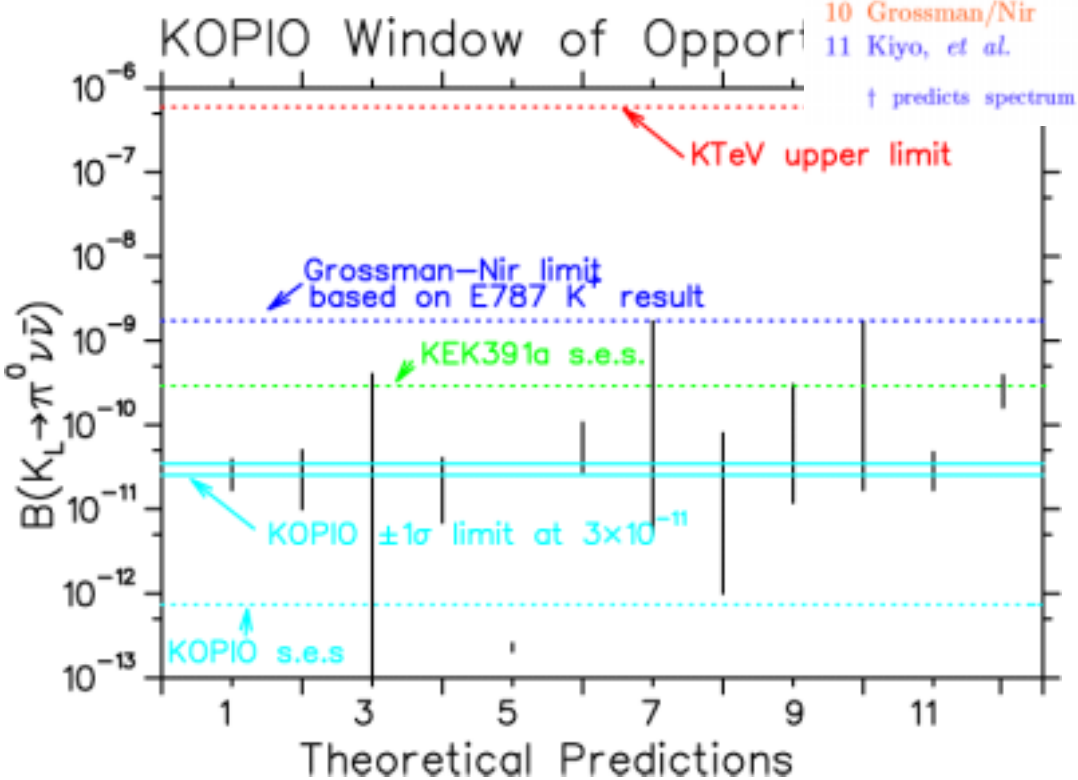
- KTeV (FNAL) Result : $< 5.9 \times 10^{-7}$
- E391a (KEK) goal : $10^{-9} - 10^{-10}$
- KOPIO (BNL) goal : 10^{-12} (~40 events S/N 2)

- $K^+ \to \pi^+ \nu \bar{\nu}$ and isospin limit (Grossman-Nir limit from E949) : $< 1.4 \times 10^{-9}$
- SM prediction : $(3.2 \pm 0.6) \times 10^{-11}$

$K_L \to \pi^0 \nu \bar{\nu}$: Beyond 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	$0.5 - 260$
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	$1.7 - 260$
11	Kiyo, *et al.*	seesaw L-R model†	$(1 - 1.2)\times$ SM

† predicts spectrum will be altered.



12 New prediction by Buras *et al.*

Enhanced EW penguins

$B(K_L \to \pi^0 \nu \bar{\nu}) = (3 \pm 1) \times 10^{-10}$

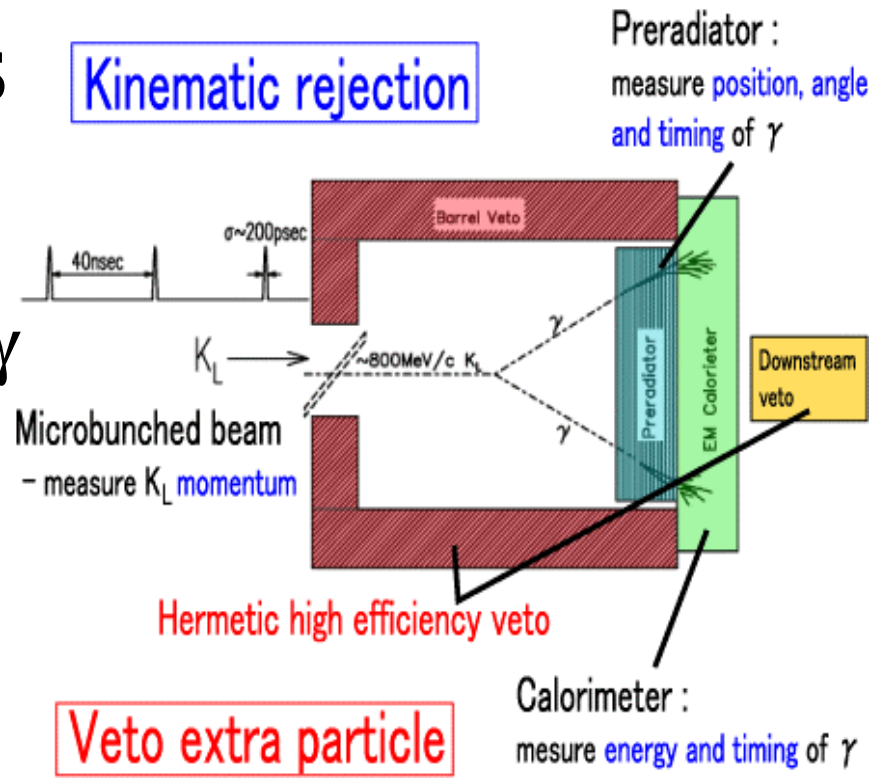
(hep-ph/0312259)

KOPIO Concept

- Detect π^0 and nothing
  ↳ 2γ ↳ veto

Measures as much as possible

- K_L TOF : to work in K_L CMS
  - microbunched p beam
  - 2 γ detection timing
- Reconstruct π^0 decay from $\gamma\gamma$
  - Measure γ directions in PR
  - Measure γ energy in CAL
- Veto : cover 4π solid angle
  - Photon veto
  - Charged particle veto



Kinematic Rejection of $K_L \to \pi^0\pi^0$ BG

- $\pi^0\pi^0$ even

  both γ from same π^0

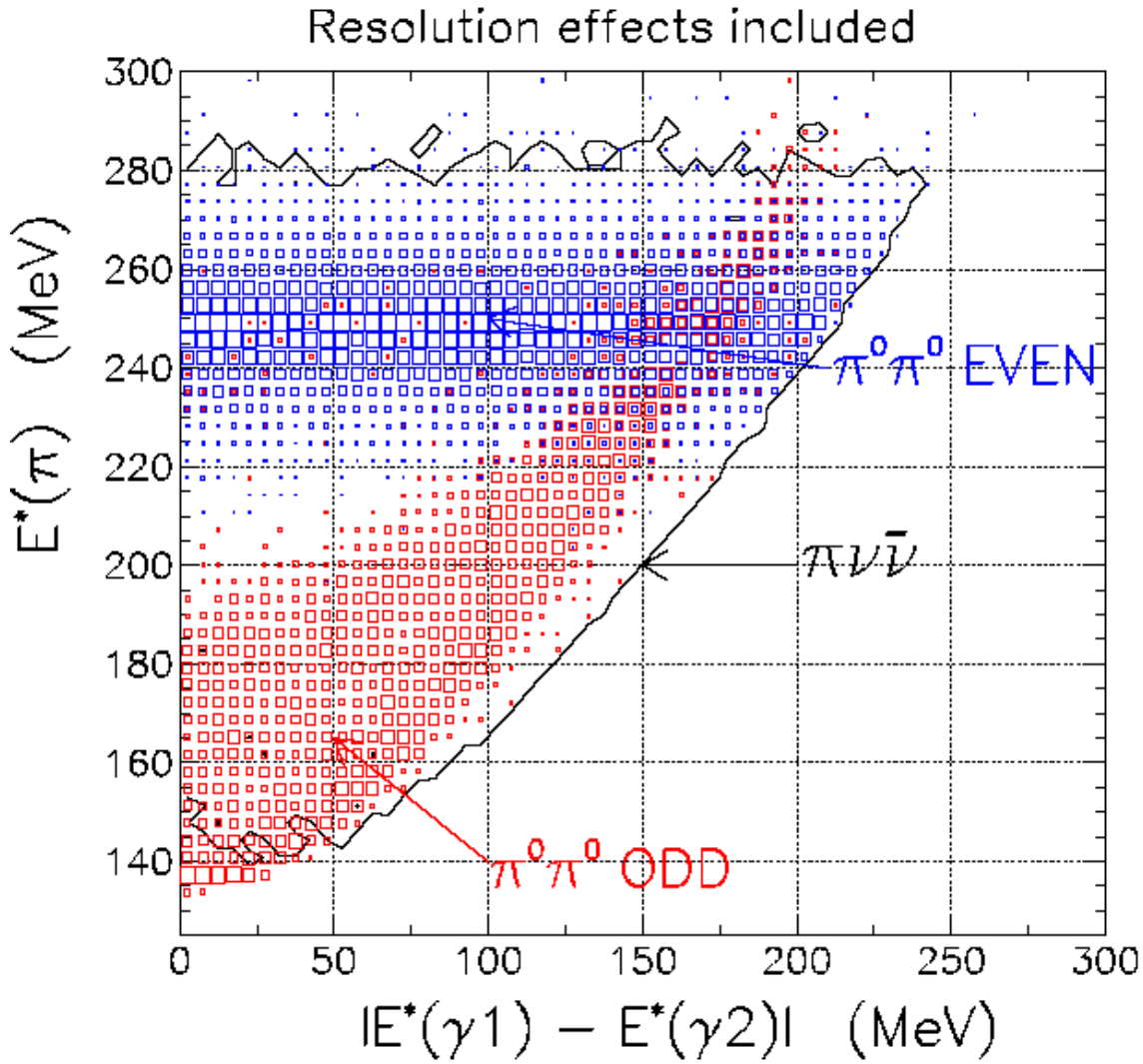
  – Kinematic cut : E_π^*

- $\pi^0\pi^0$ odd

  γ from different π^0

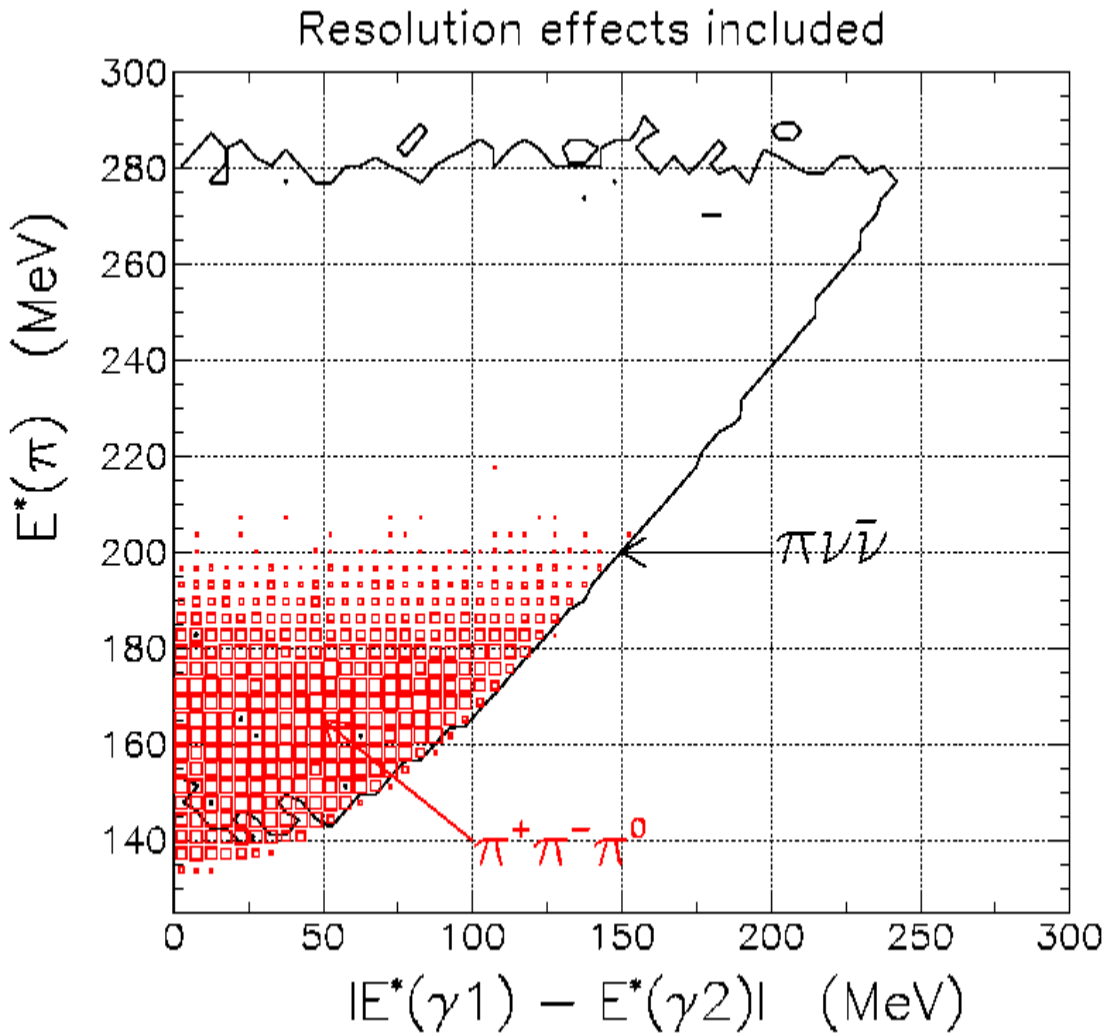
  – Kinematic cut :

  $M_{\gamma\gamma}$, $|E_{1\gamma}^* - E_{2\gamma}^*|$



Kinematic Rejection of $K_L \to \pi\pi\pi$ BG

- $K_L \to \pi^0 \pi^0 \pi^0$
  - easy to veto (have 4 extra γ)
- $K_L \to \pi^+ \pi^- \pi^0$
  - Kinematic cut : E_π^*, E_{MISS}



Signal and Background Estimates

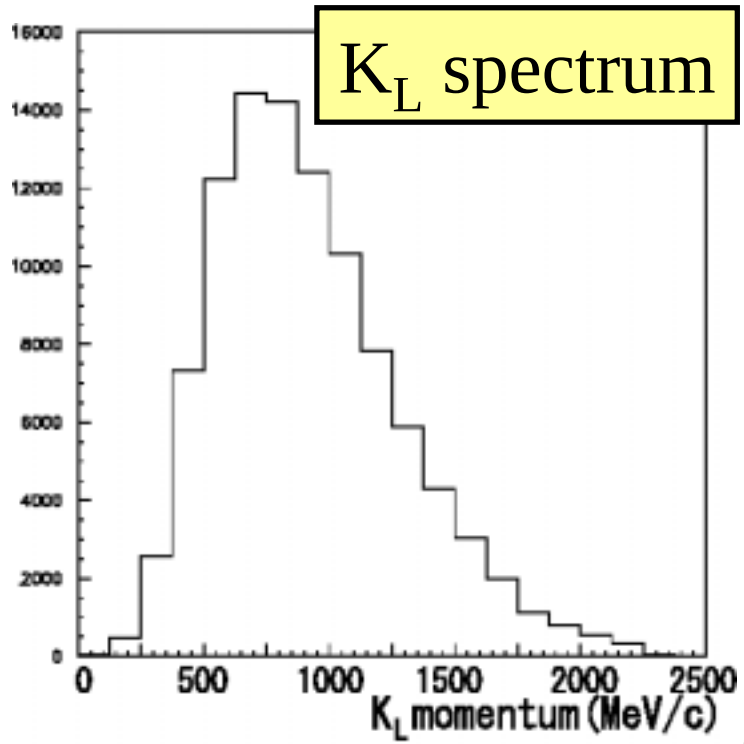
- Signal ~ 40 events
  (at SM rate)
- Background ~ 20 events

- S/N ~ 2
  $\Delta B/B$ ~ 20%
  $\Delta\eta/\eta$ ~ 10%

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

Beam

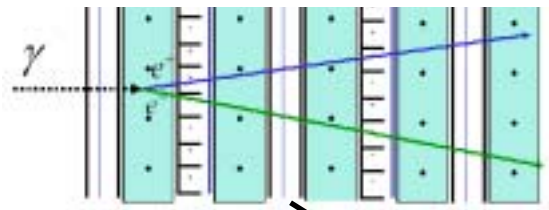
- Proton Beam
  - 100 Tp / Spill
  - 2.7 s spill 2.3 s interspill period
  - 25 MHz micro-bunching frequency
  - Bunch width 200 ps
  - Interbunch extinction 10^{-3}
- Neutral Beam
  - Large take-off angle ~ 45degree
  - Soft momentum : 0.5 – 1.5 GeV/c
  - 3 x 10^{8} KL / spill , 12% decay
  - 3.5 x 10^{10} neutrons / spill

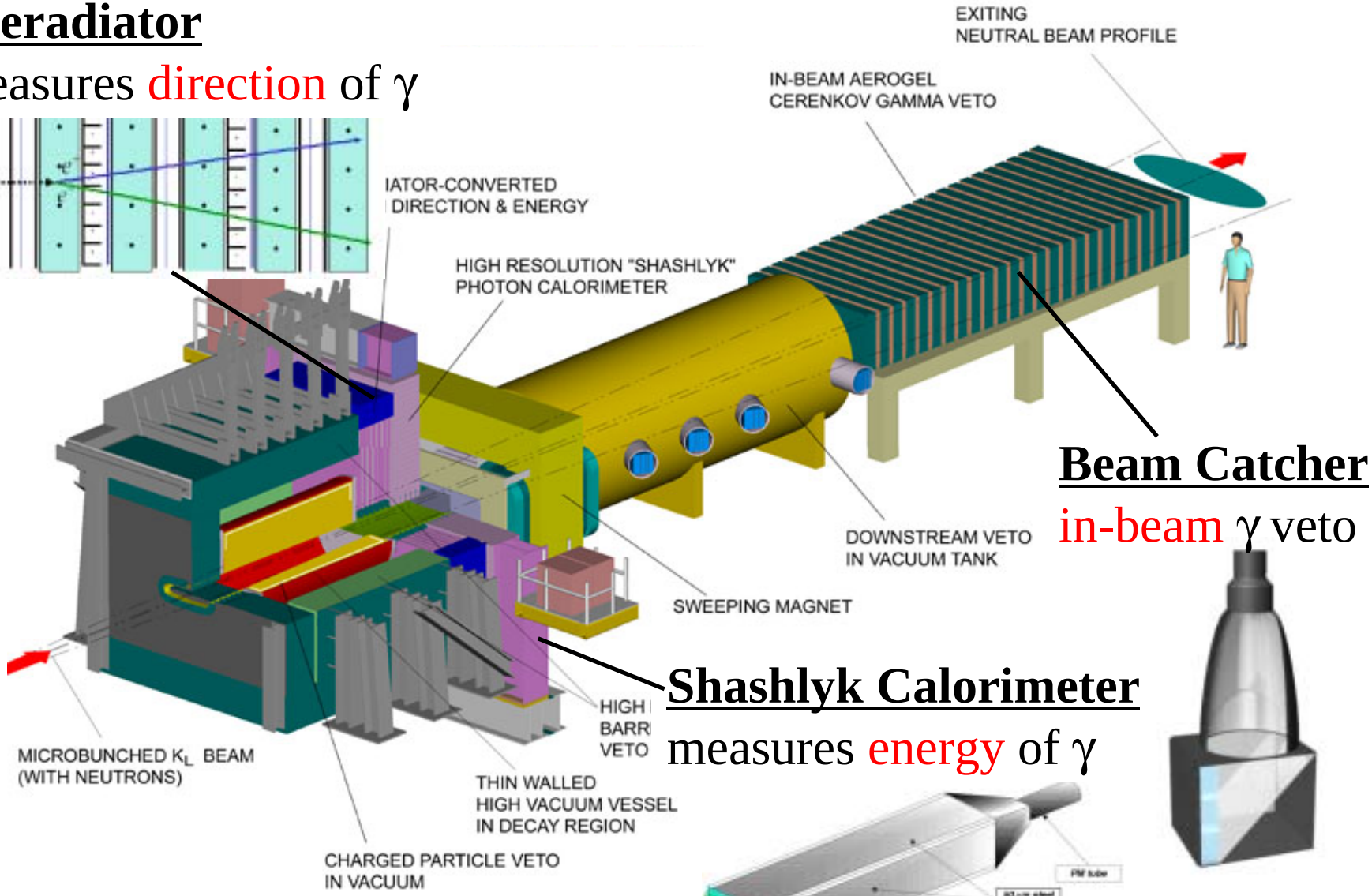


KOPIO Detector

Preradiator

measures direction of γ



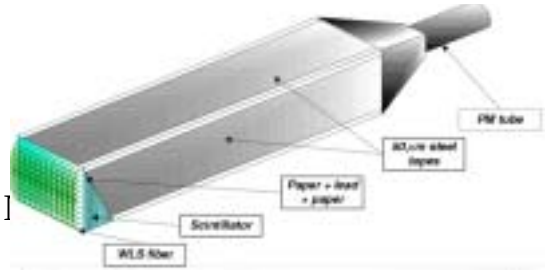


Beam Catcher

in-beam γ veto

Shashlyk Calorimeter

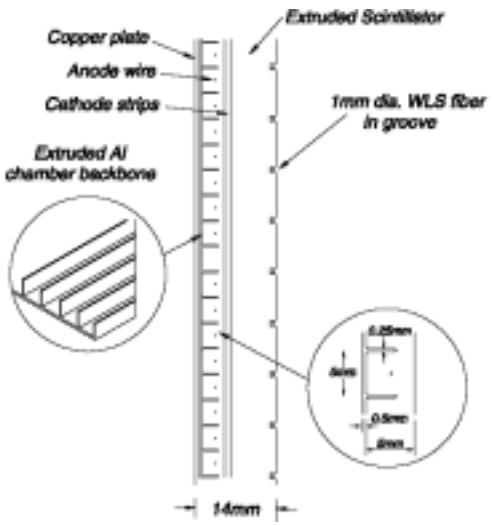
measures energy of γ

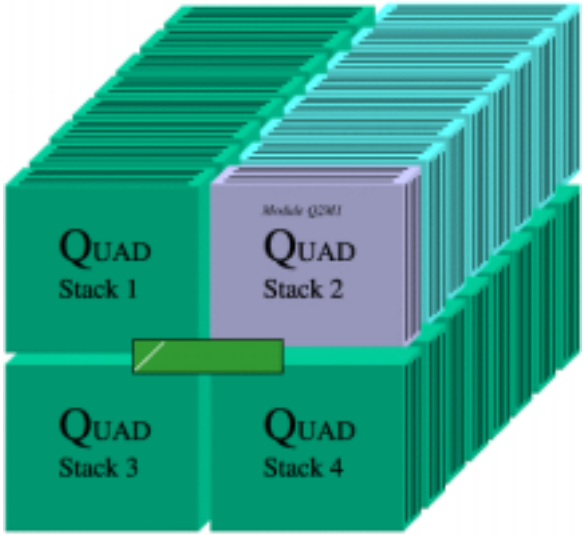


Preradiator

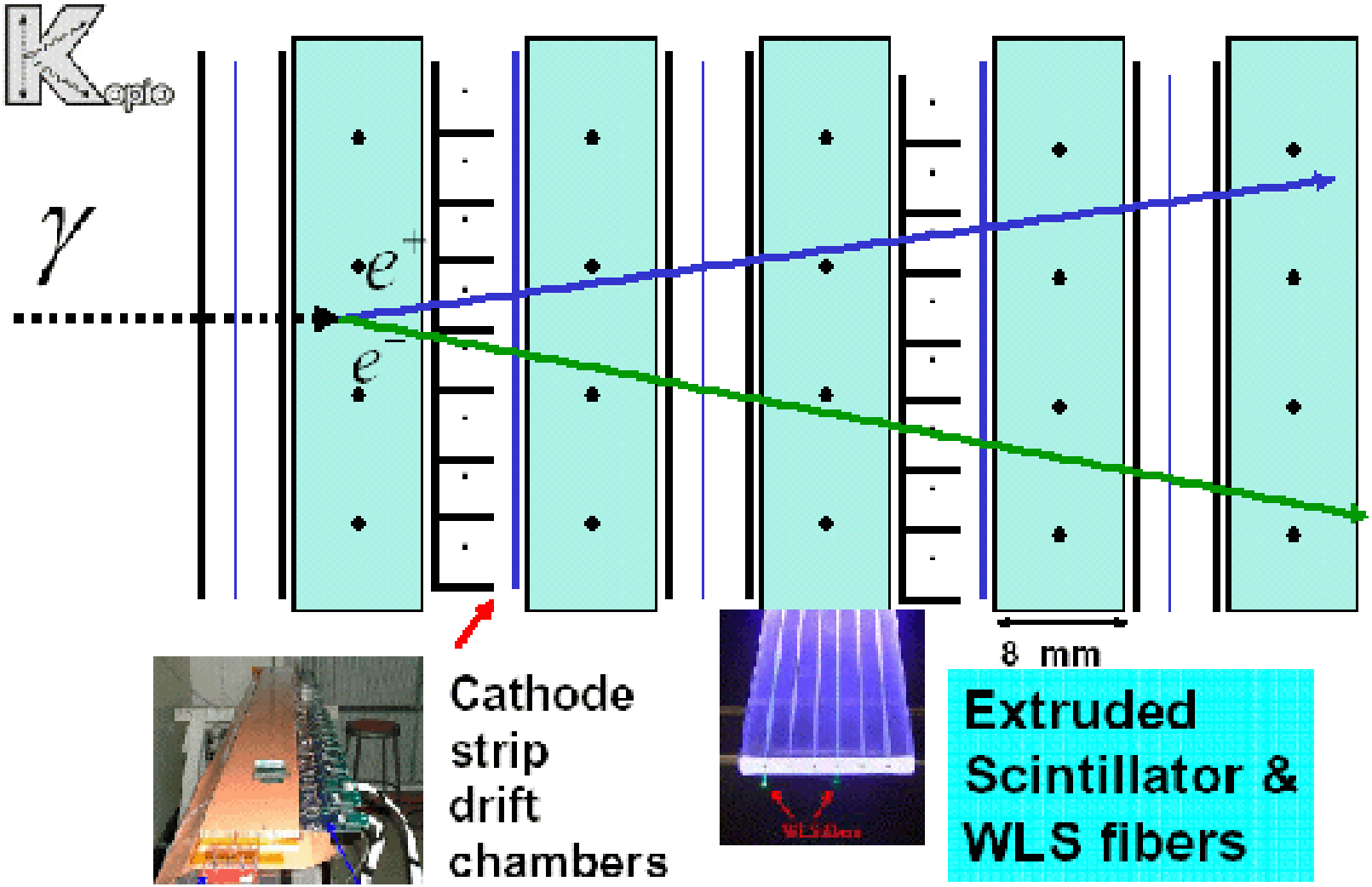
- Measures the position and angle of γ
- Radiation length : $2X_0$ (70% converts)
- Consists of
  - Cu converter
  - drift chamber
  - plastic scintillator

TRIUMF



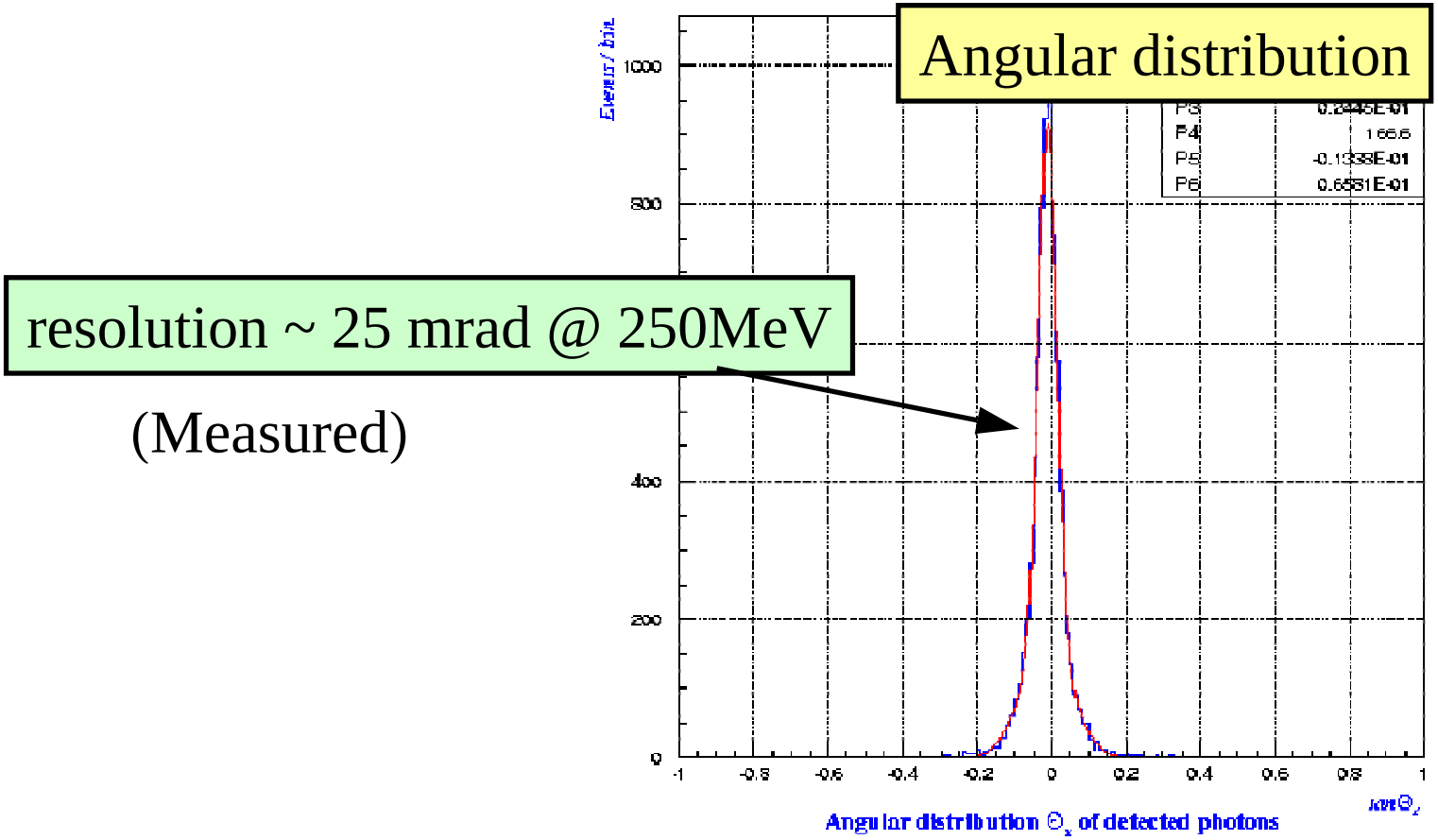


Preradiator



Preradiator – Angle Resolution

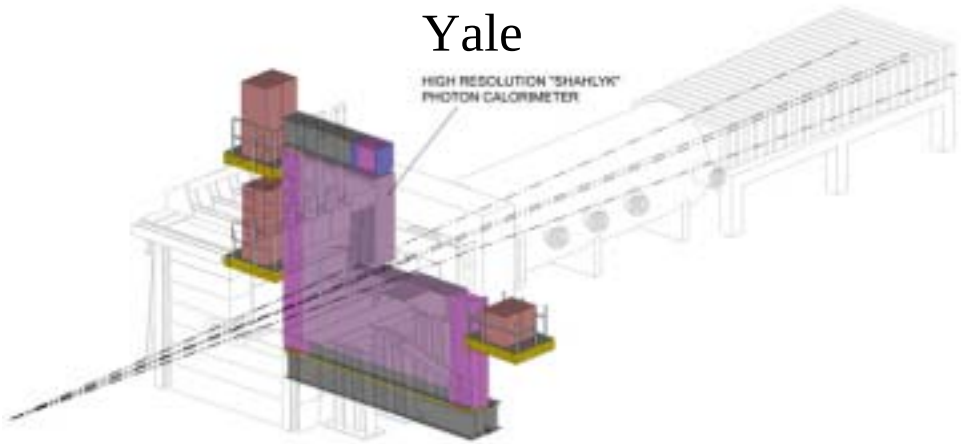
- Angle resolution of 25 mr at 250 MeV



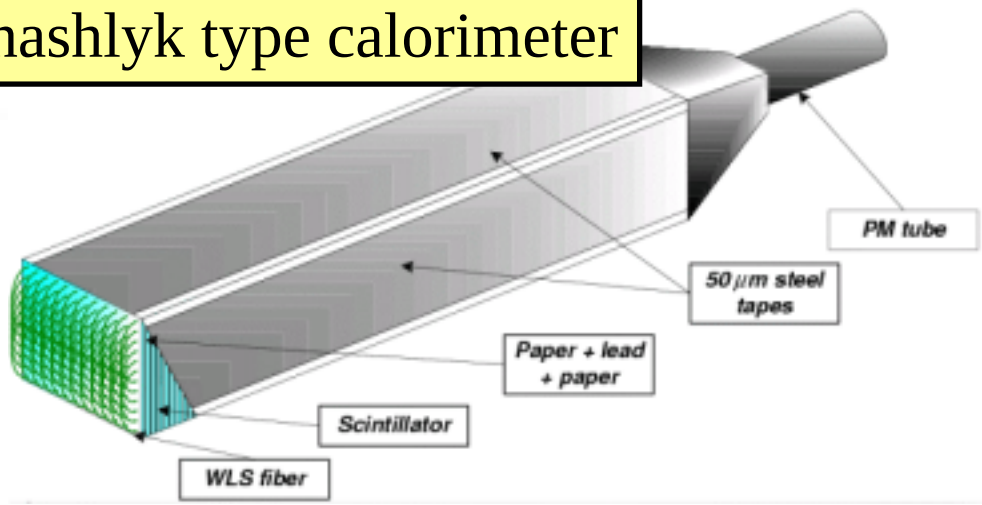
Shashlyk Calorimeter

- Measures energy of γ
- Consists of
  - Pb converter
  - Plastic scintillator
  - penetrating WLS fiber

Yale



Shashlyk type calorimeter



Shashlyk Energy Resolution

- Required resolution :

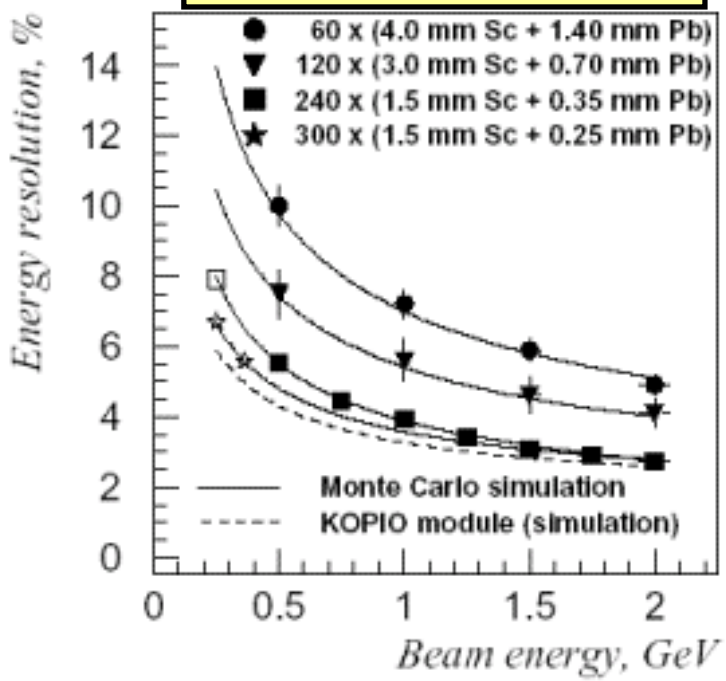
  $3.5\ \% / \sqrt{E}$ (GeV)

- Estimated

(Combined with PR) :

  $\sim 2.7\ \% / \sqrt{E}$ (GeV)

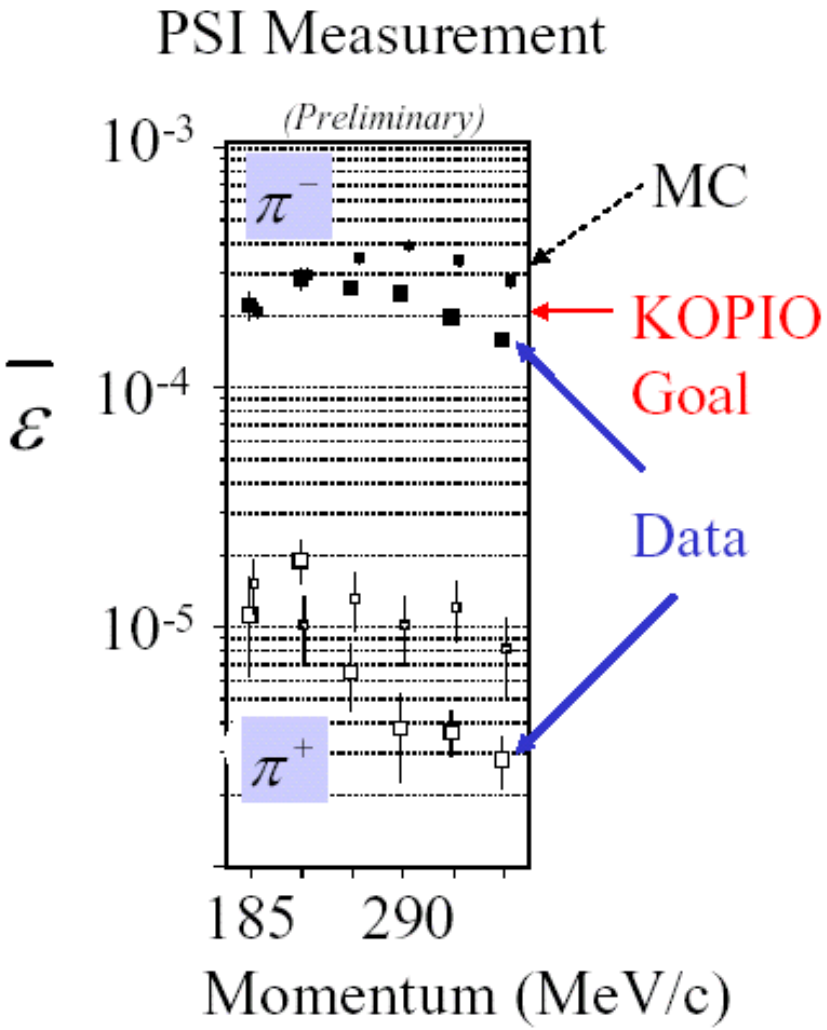
Energy Resolution



- ● BNL E865
- ▼ BNL E923 prototype
- ■ KOPIO prototype
- ★ another KOPIO prototype

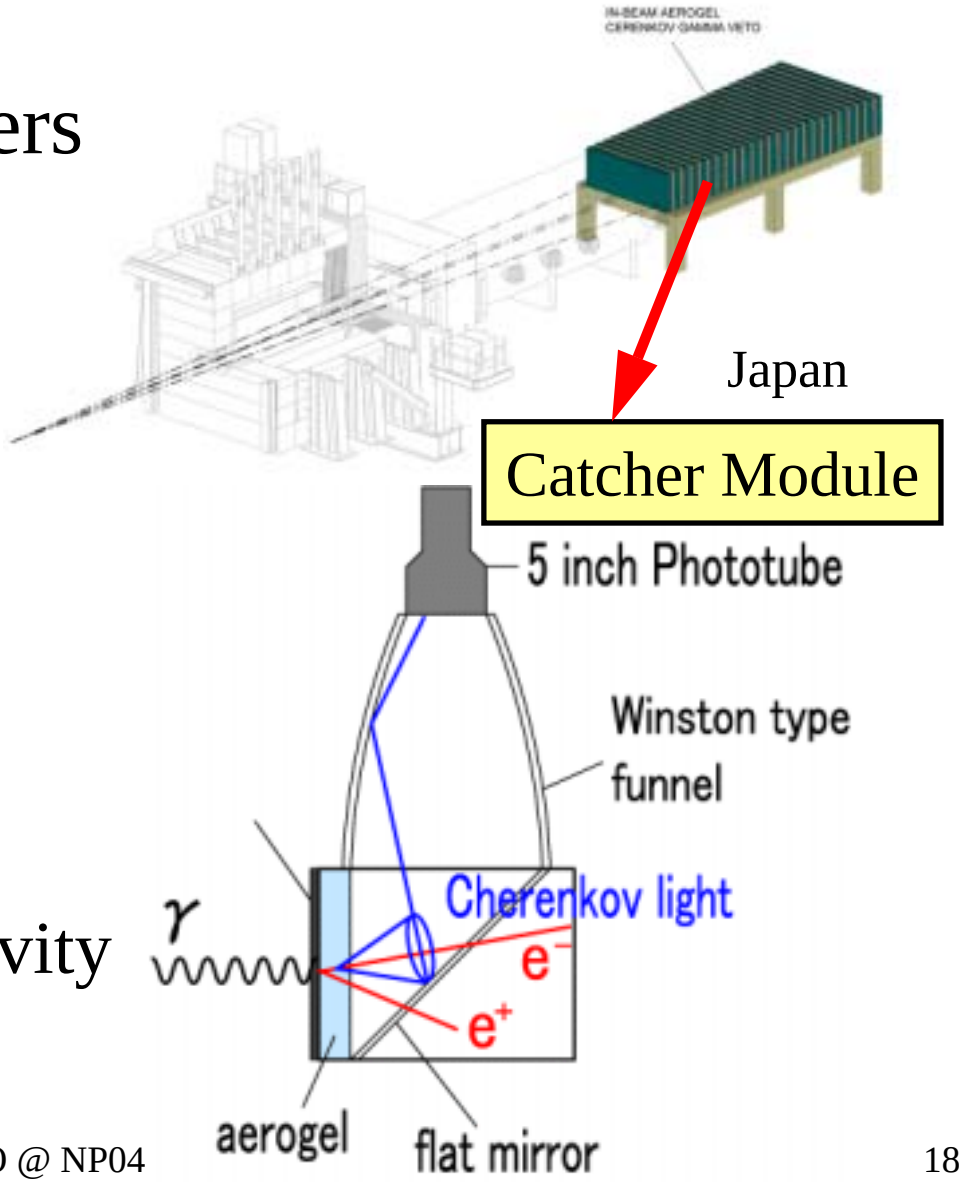
Charged Veto

- Plastic scintillator
- Inefficiency (1 GeV/c):
- e^+ : $(3.2 \pm 0.9) \times 10^{-4}$
- π^+ : $< 1.6 \times 10^{-5}$
- e^- : $< 1.3 \times 10^{-4}$
- π^- : $(6.0 \pm 0.6) \times 10^{-4}$



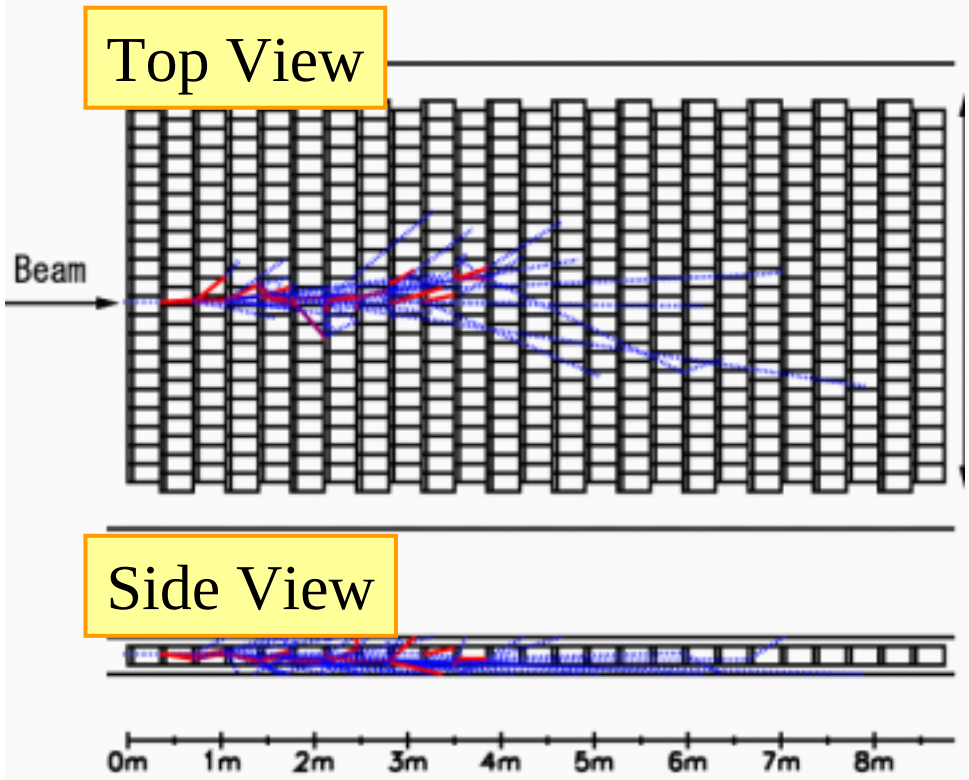
Beam Catcher

- Photon veto which covers beam core region
- under high neutron rate
- Need to be…
  - efficient to γ rays
  - insensitive to neutrons
- Aerogel Cherenkov + distributed geometry
  - suppress neutron sensitivity



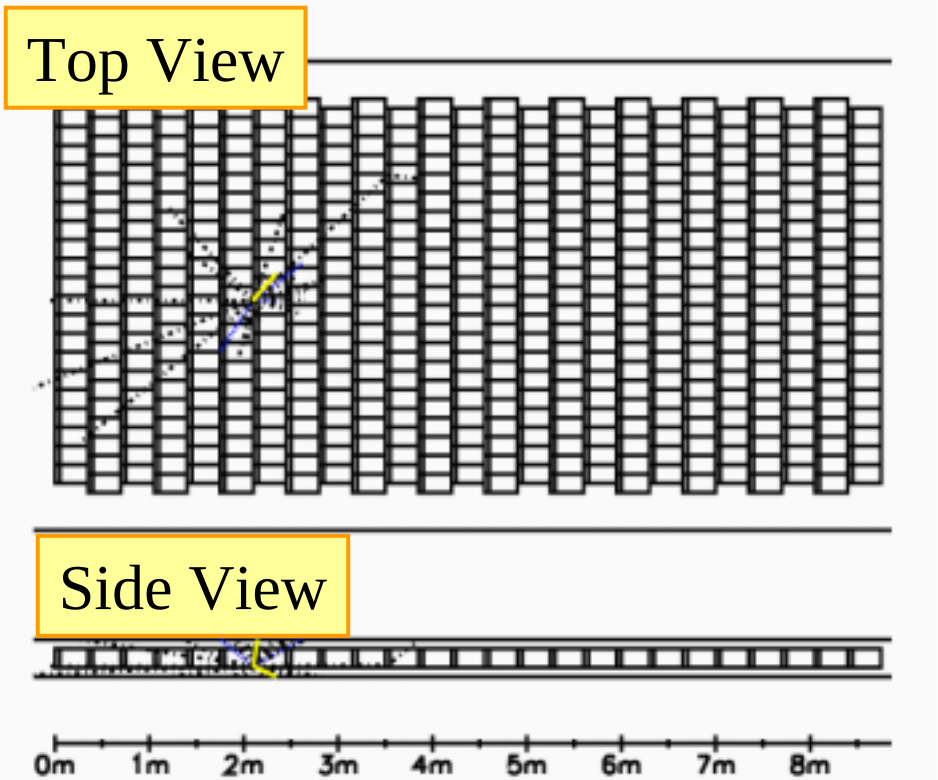
Beam Catcher – MC Event Display

Event Display for γ



Shower spreads forward

Event Display for neutron

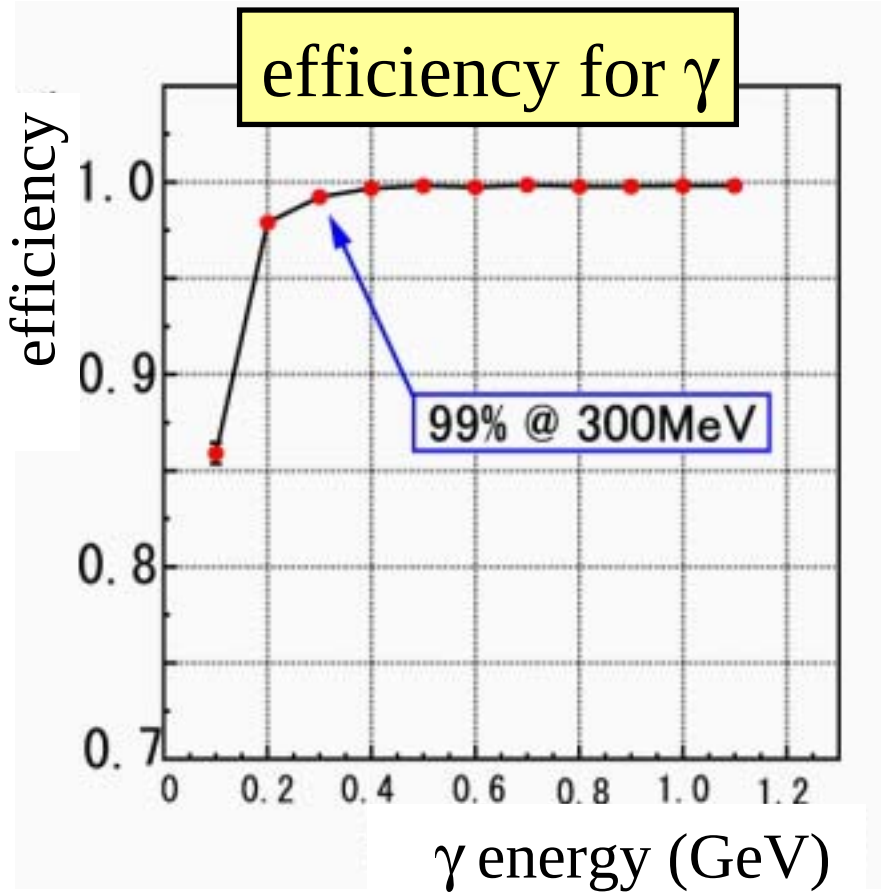


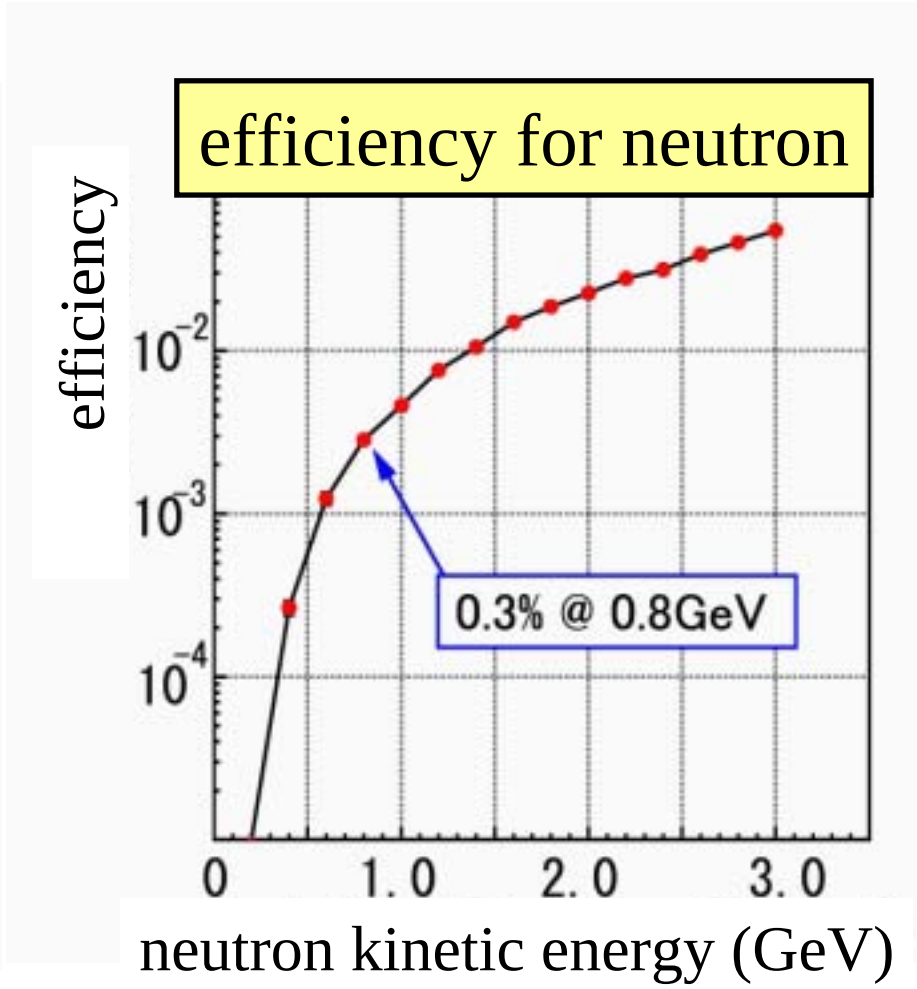
Secondary particles are created isotropically

–> Can distinguish γ from neutron using geometry

Beam Catcher – Expected Performance

- Simulation :

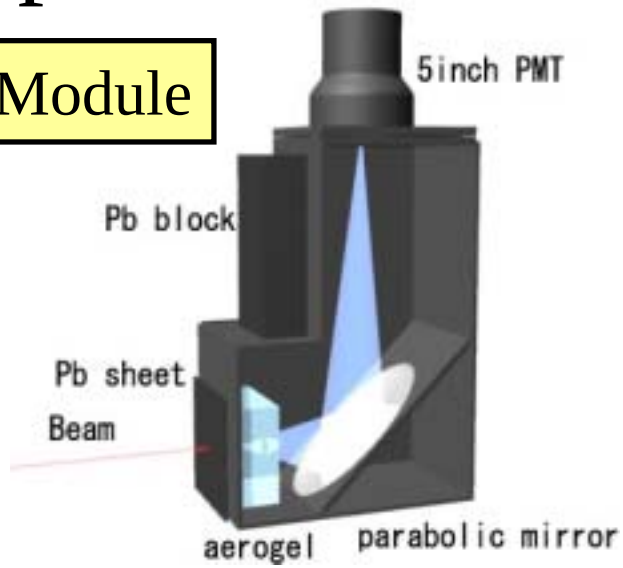




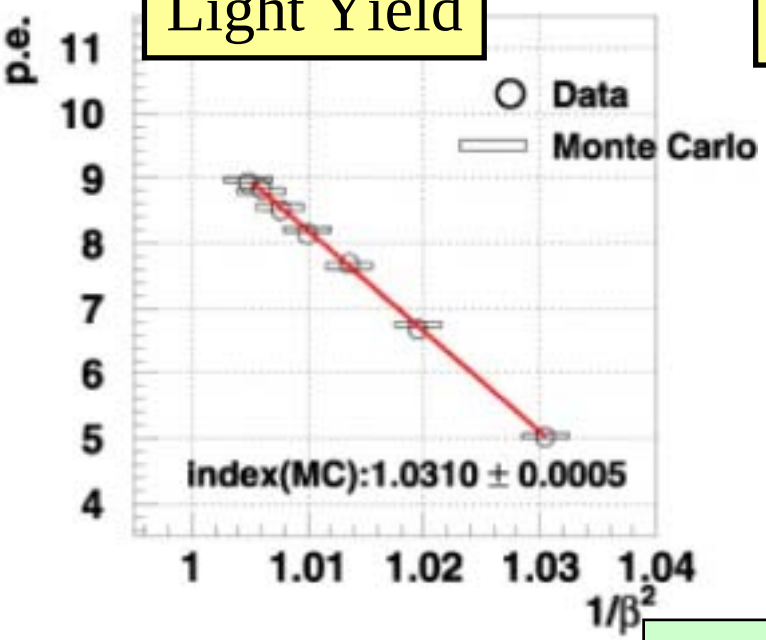
Beam Catcher – Prototype Test

- Light yield – using π^+
- Neutron inefficiency
  - using proton in place of neutrons

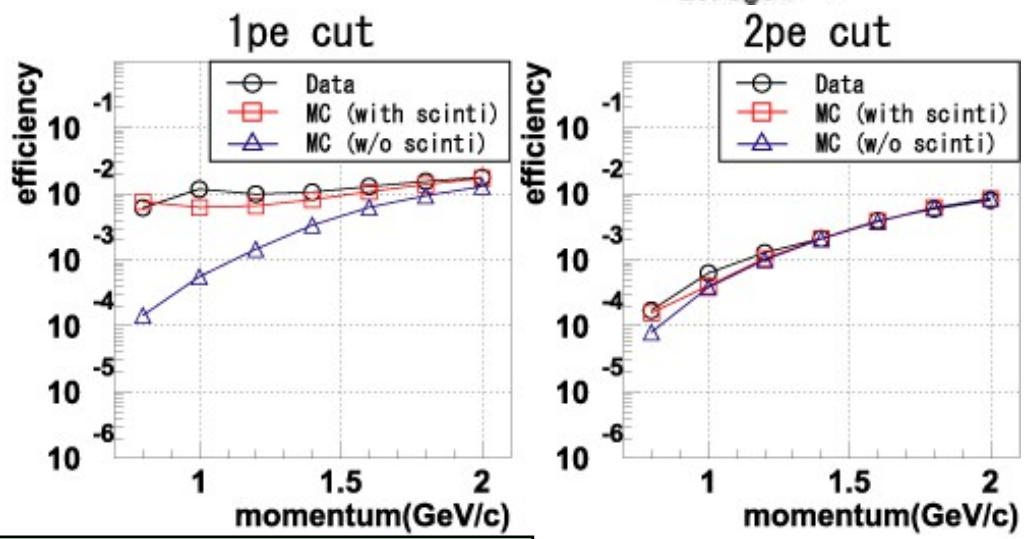
Prototype Module



Light Yield



Proton Efficiency



Data agree MC very well

Prospects of KOPIO

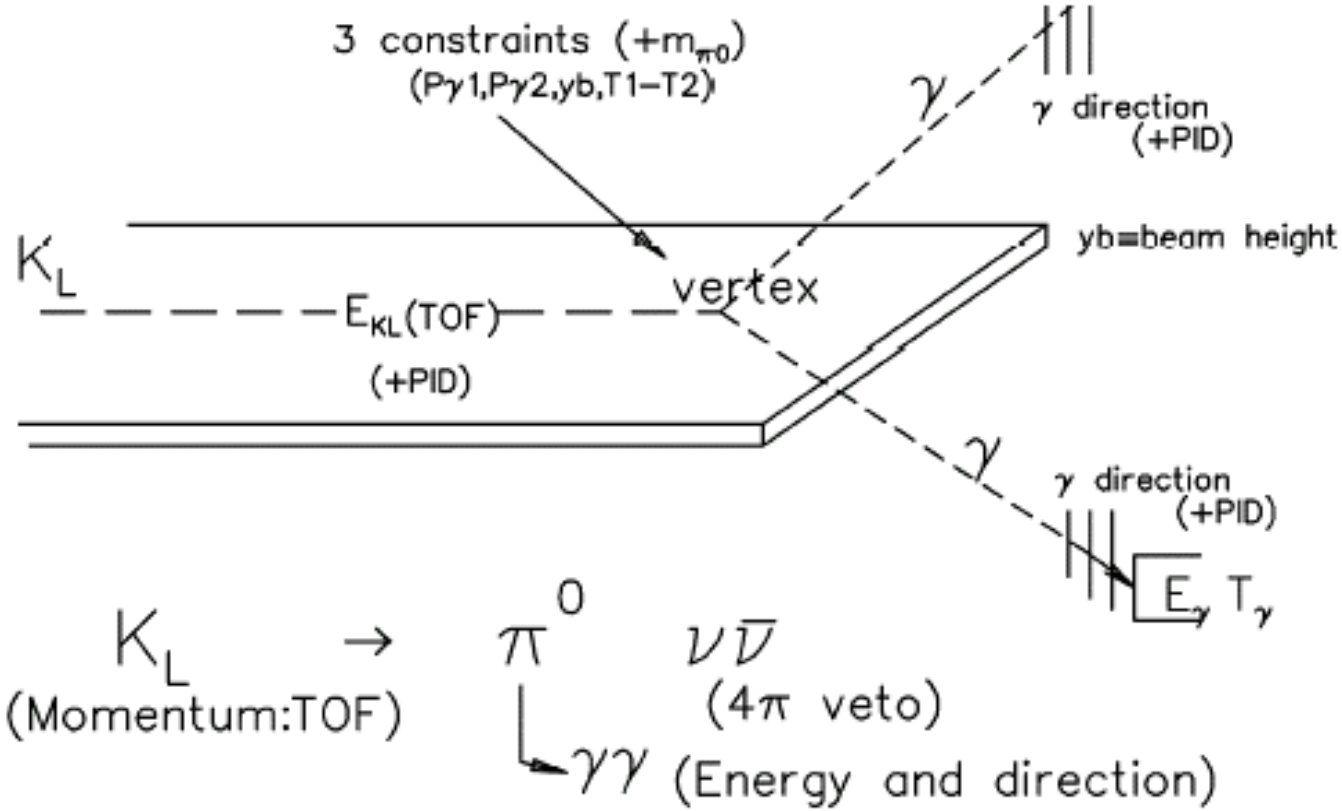
- Approved by NSF(2003), construction start in 2005
- 30M$ RSVP on 2005 presidental budget
- KOPIO schedule
  - 2004 Detector R&D
  - 2005 – 2006 Construction of beam line
    Mass production of detectors
  - 2007 – 2008 Installation of detectors
  - 2009 ~ Engineering run
    Physics run

Summary

- KOPIO experiment measures $K_L \rightarrow \pi^0 \nu \nu$
- Gold-plated mode
  - small theoretical uncertainty
  - measures CP parameter η
- R&D is concluding successfully
- Advanced planning for the construction is undergoing

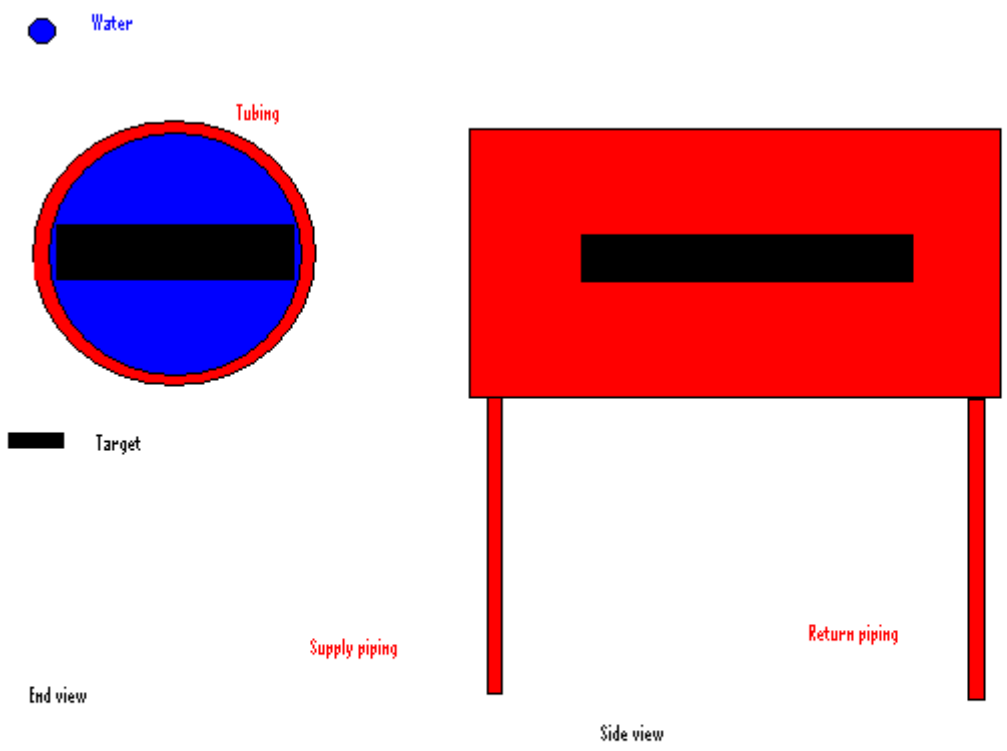
Extras

Kinematic Constraint

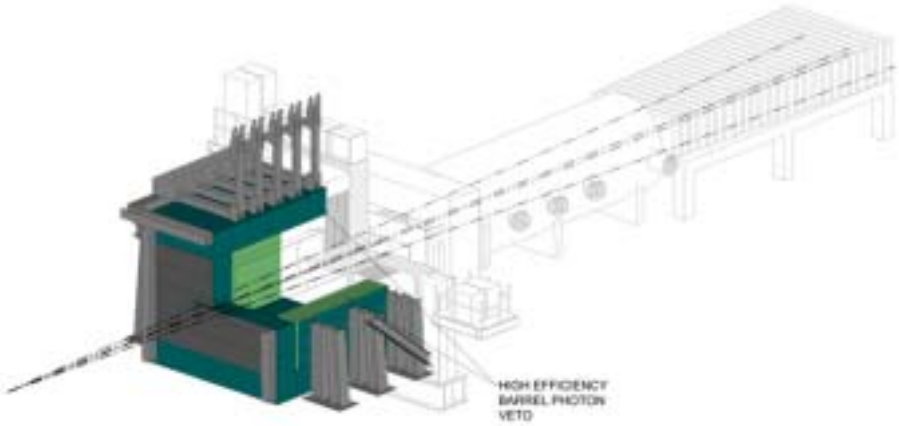


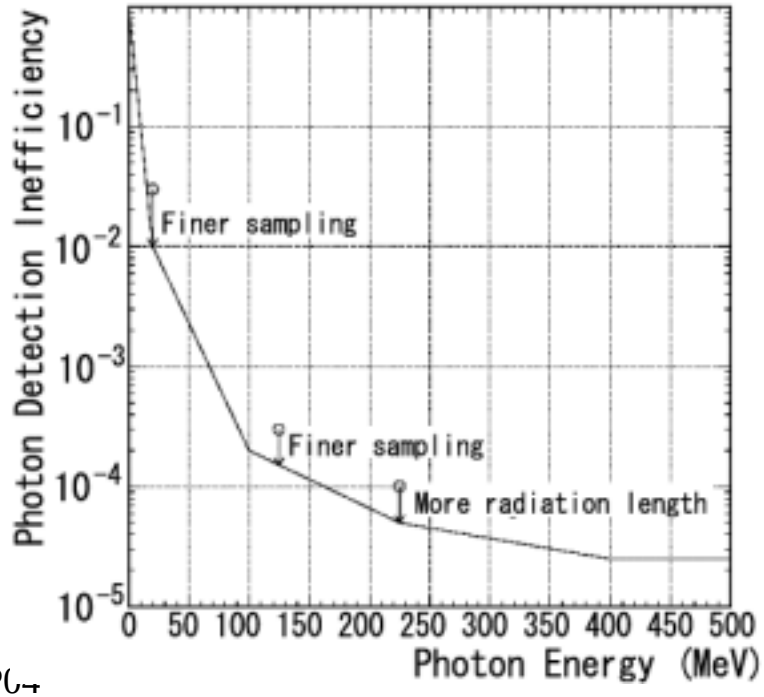
Production Target

- Pt? 10cm long

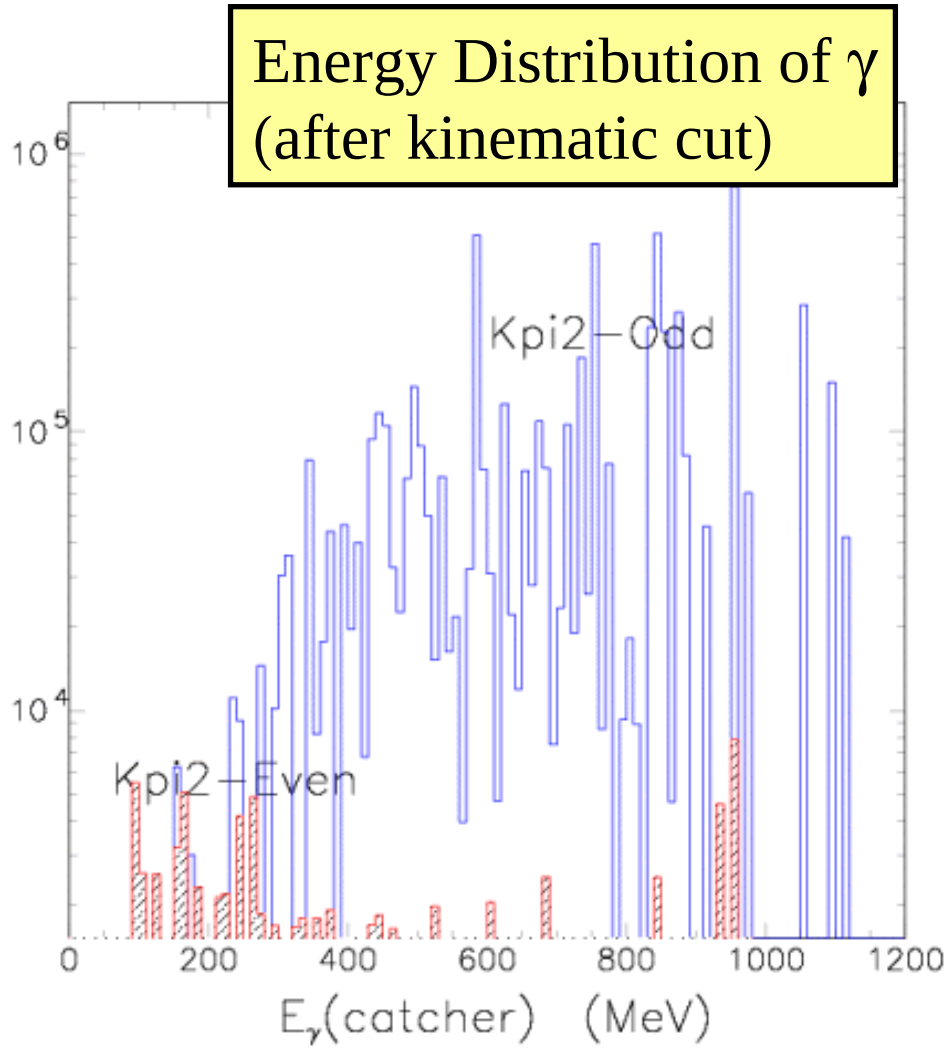


Photon Veto


HIGH EFFICIENCY
BARREL PHOTON
VETO


Photon Detection Inefficiency
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Finer sampling
Finer sampling
More radiation length
0 50 100 150 200 250 300 350 400 450 500
Photon Energy (MeV)

Vacuum

- Very high vacuum (~10^{-7} Torr) is needed to reduce interaction with residual gas
- Vacuum vessel
  - thickness ~ a few % of X_0

Requirement for Catcher