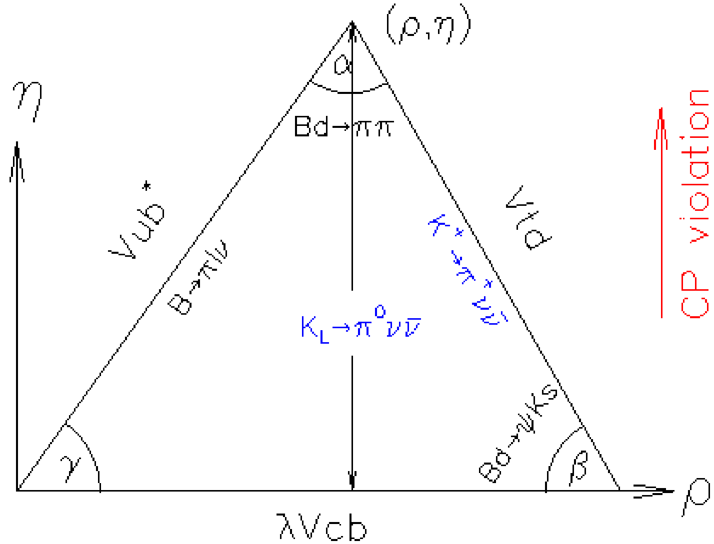
KOPIO

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

Douglas Bryman
University of British Columbia

Standard Model CP Violation



"Jarlskog invariant" $|J_{CP}|$

$$2A = \left|\mathrm{Im}\,V_{ts}^{*}V_{td}\right|\lambda\left(1-\frac{\lambda^{2}}{2}\right)$$

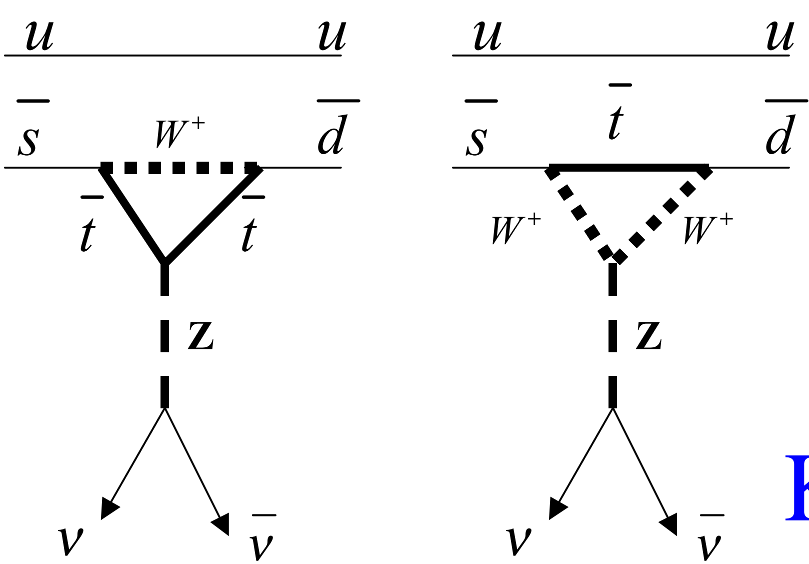
Super-clean processes will challenge the Standard Model:

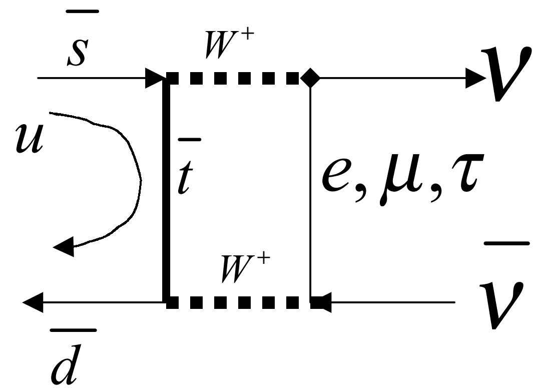
$K^{+}\rightarrow\pi^{+}\nu\bar{\nu}$	$\lvert V_{ts}^{*}V_{td}\rvert$	E949, CKM
$K_{L}^{0}\rightarrow\pi^{0}\nu\bar{\nu}$	$\mathrm{Im}(V_{ts}^{*}V_{td})$	KOPIO

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

Negligible long distance effects. Top quark dominance.

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





	$K^+ \to \pi^+ \nu \bar{\nu}$	$K^0_L \to \pi^0 \nu \bar{\nu}$
Branching Ratio (10^{-11})	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.*

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 $K \to \pi\nu\bar{\nu}$.

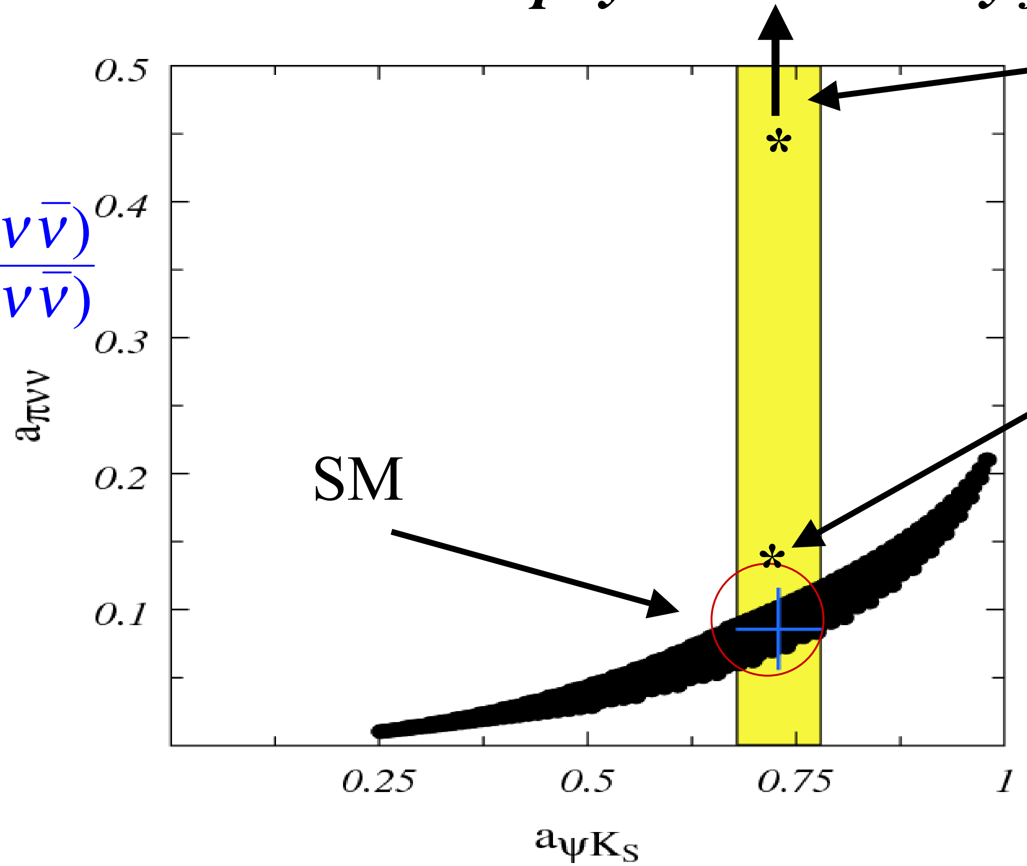
* *If deviations from the SM are indicated:*

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

$\mathbf{B} \to \psi K_S$ *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)

Experiments seeking $K^0 \to \pi^0 \nu \bar{\nu}$

[Limit based on isospin and $K^+ \to \pi^+ \nu \bar{\nu}$:

$$R(K_L^0 \to \pi^0 \nu \bar{\nu}) \equiv \frac{\Gamma(K_L^0 \to \pi^0 \nu \bar{\nu})}{\Gamma(K_L^0 \to all)} < 1.4\, x\, 10^{-9}\ [Grossman, Nir]$$]

- KTEV (FNAL) result: $< 5.9\, x\, 10^{-7}$
- 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.

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

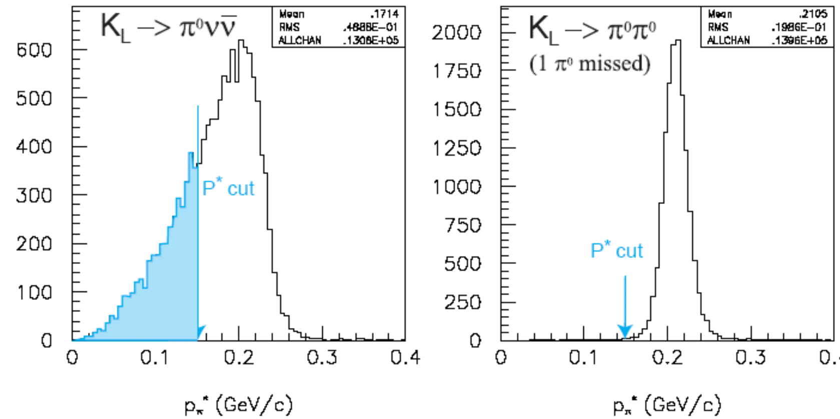
Primary Backgrounds

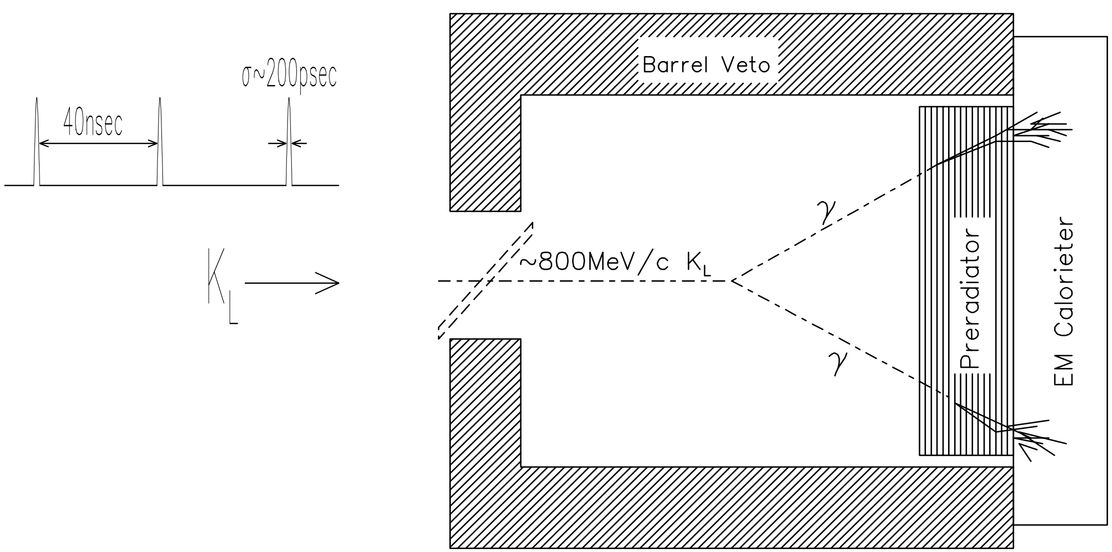
Mode	Branching Ratio
$K_L^0 \rightarrow \pi^0 \pi^0$	$0.93 \; x \; 10^{-3}$
$K_L^0 \rightarrow \pi^- e^+ \nu \gamma$	$0.36 \; x \; 10^{-2}$
$K_L^0 \rightarrow \pi^+ \pi^- \pi^0$	0.1255
Others	

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 $10^{-3} - 10^{-2}$

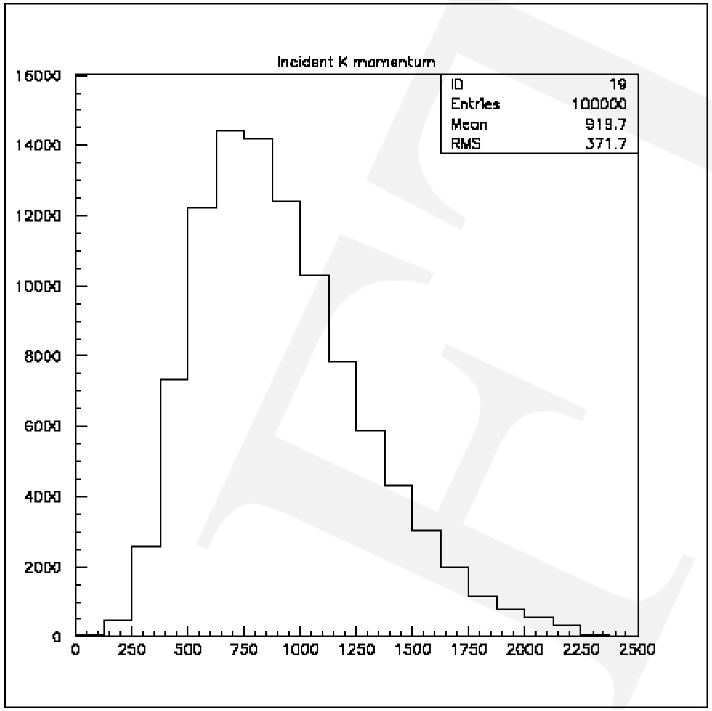
"Kaon Beam":

42.5 degree take-off angle

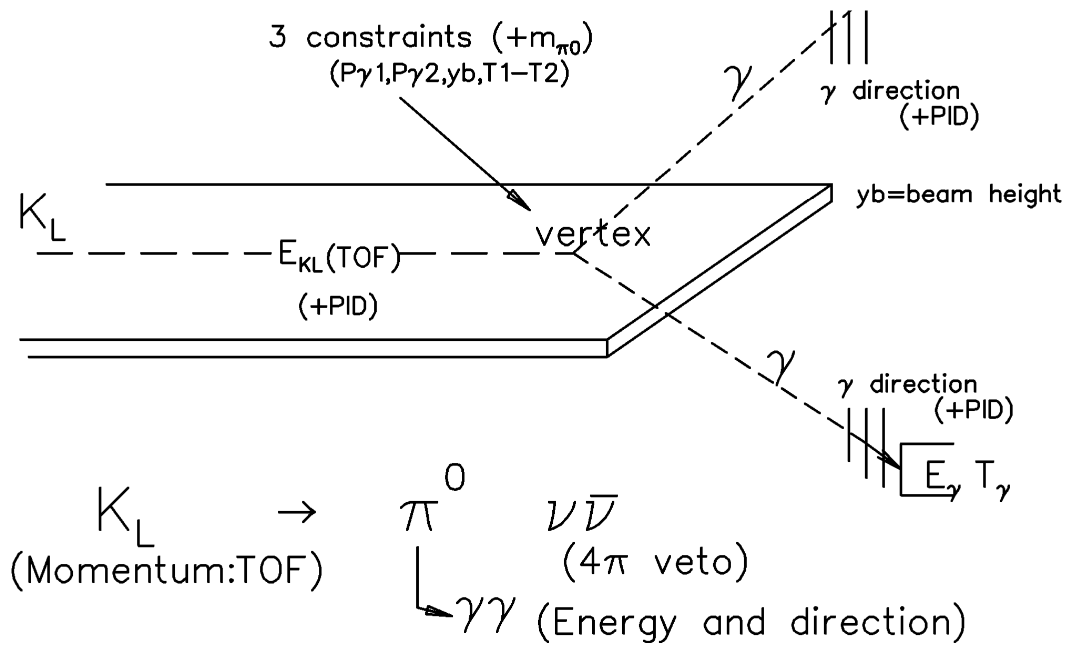
Soft momentum spectrum [0.5,1.5 GeV]

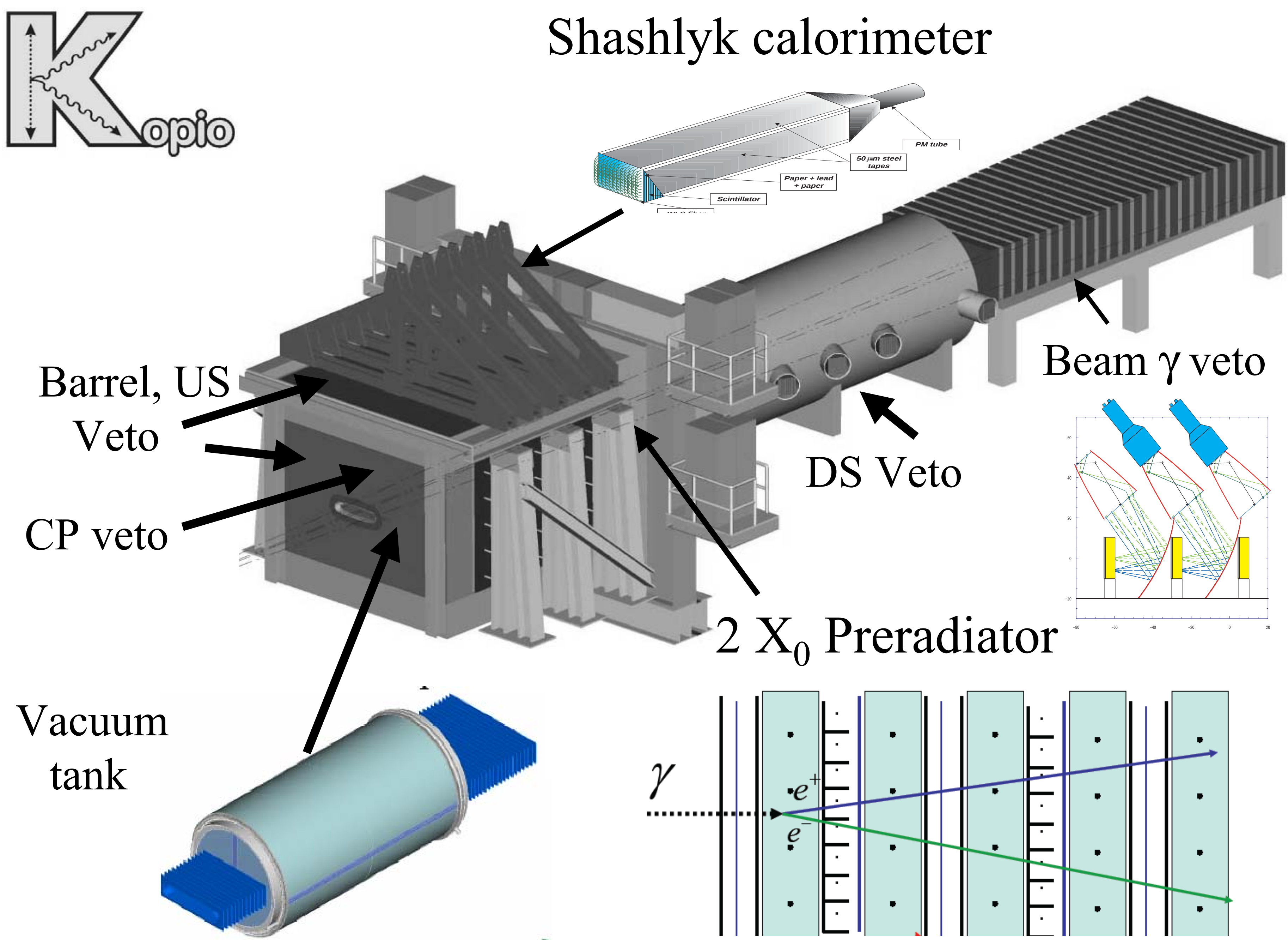
10^{8} K_L / spill, 12 % decay

10^{11} neutrons / spill



KOPIO Beam and Constraints

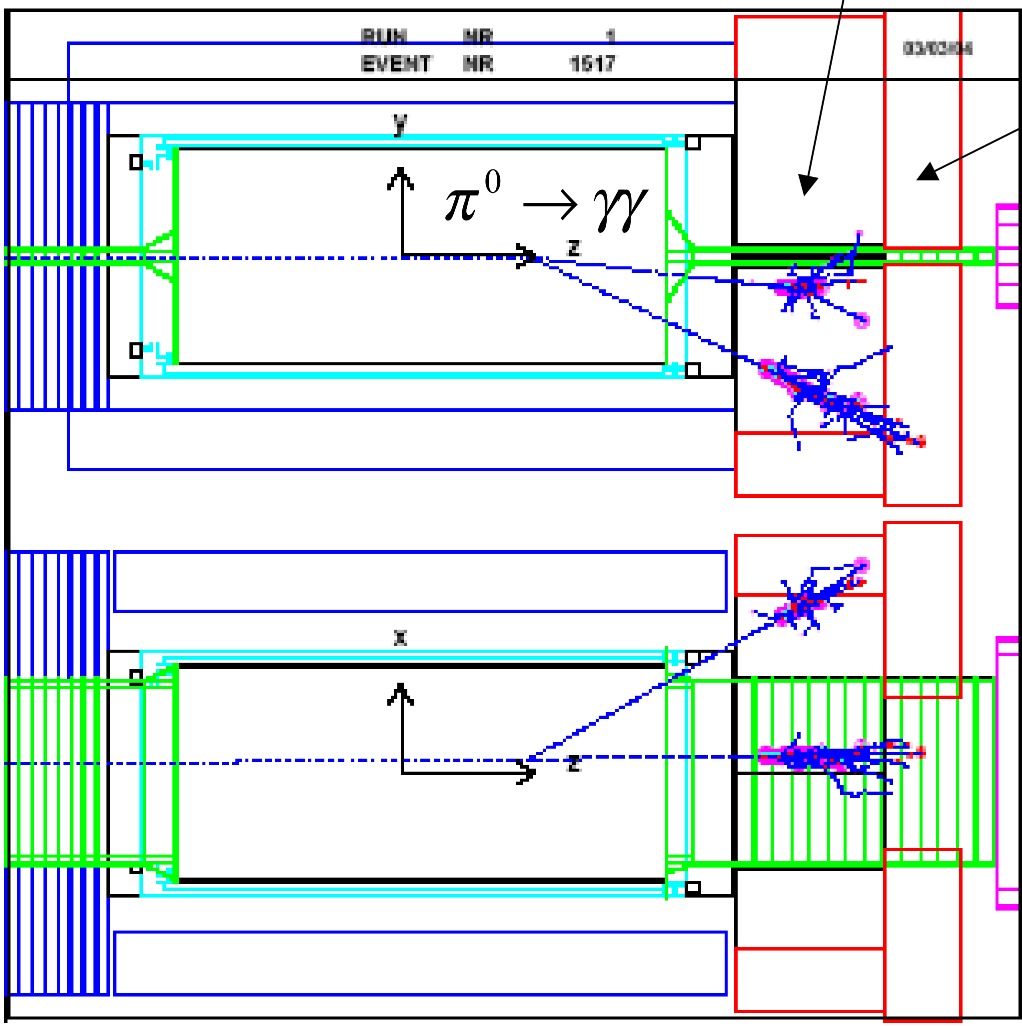



Kopio
Shashlyk calorimeter
PM tube
50 µm steel tapes
Paper + lead + paper
Scintillator
Beam γ veto
Barrel, US
Veto
CP veto
DS Veto
2 X0 Preradiator
Vacuum
tank
γ
e+
e−

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

Preradiator

Calorimeter



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

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

Common Problem:

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

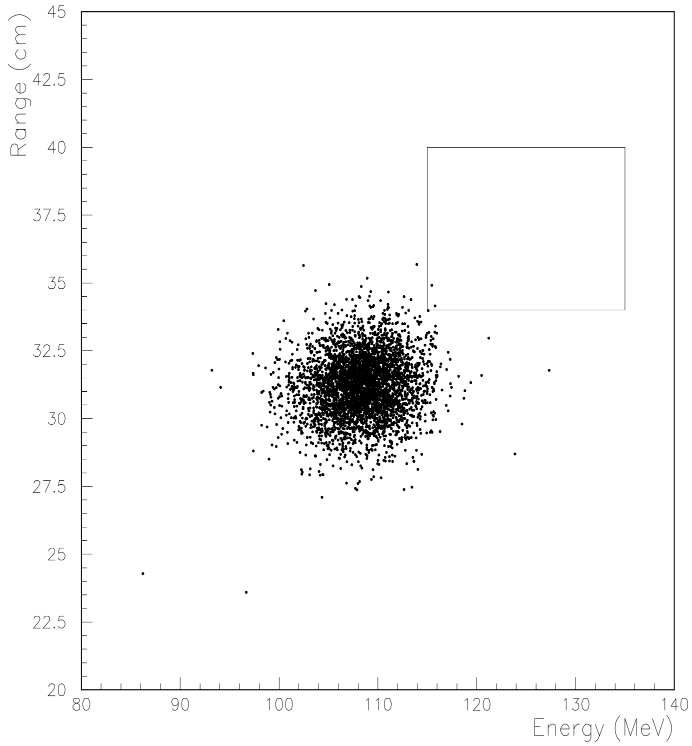
- Measure everything! (energy, position, angle, time)
- Eliminate extra charged particles or ***photons***
    - * E949 π^0 inefficiency $< 10^{-6}$
    - * KOPIO π^0 inefficiency $< 10^{-8}$
- Suppress backgrounds below the signal
    - * Predict backgrounds *from data*: dual cuts
    - * Use "Blind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

$E949$ $K^+ \rightarrow \pi^+\pi^0$ Background Suppression

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

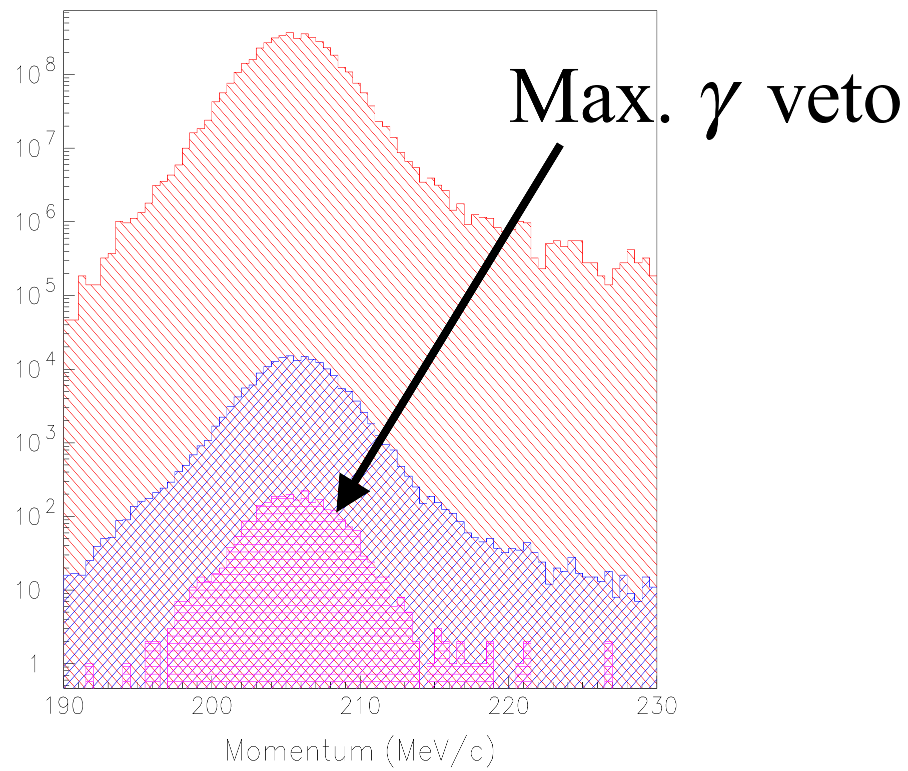
γ Veto Reversed

Range vs. Energy



γ Veto Applied

Momentum



Check for correlations

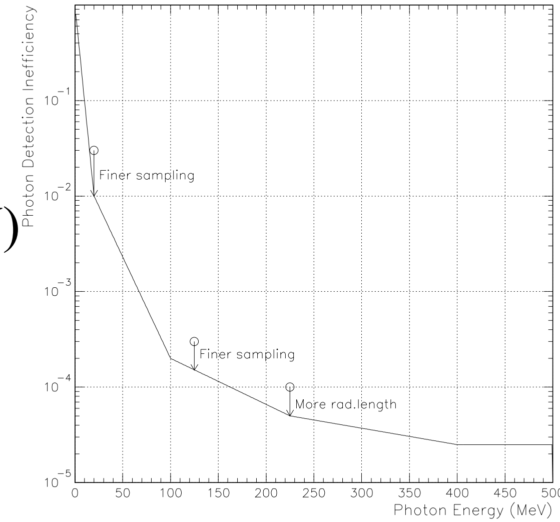
Photon Vetoing

E787

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

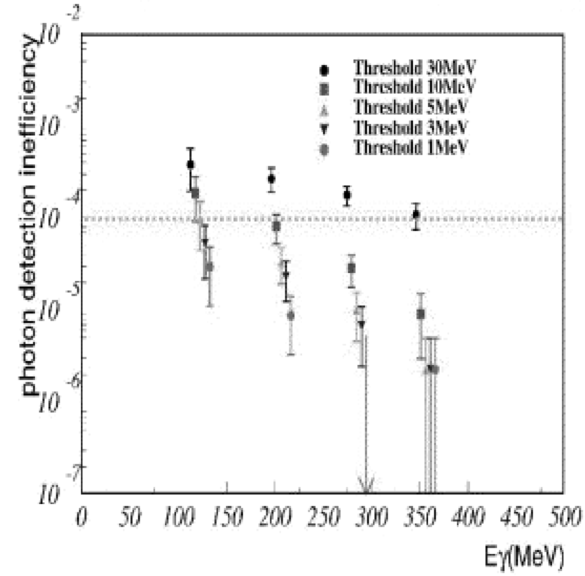
$\sim 10^{-4}$ (100-220 MeV)

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



KEK *Photonuclear*

Inefficiency of γ detection



Photon vetoing & Kinematics:

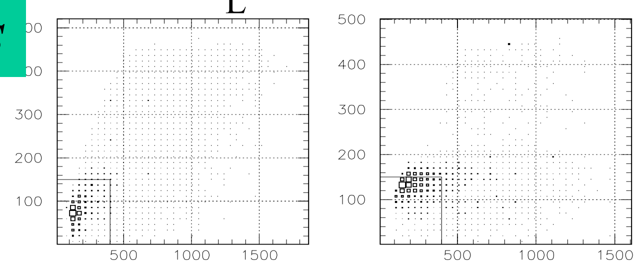
Suppress events with low energy photons

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

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

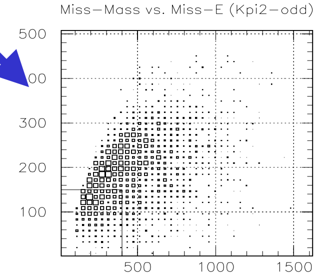
$$\bar{\varepsilon}_{\pi^0} < (10^{-4})(10^{-4}) = 10^{-8}$$

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



Miss−Mass vs. Miss−E (Kpi2−odd)   Miss−Mass vs. Miss−E (Kpi2−even)

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



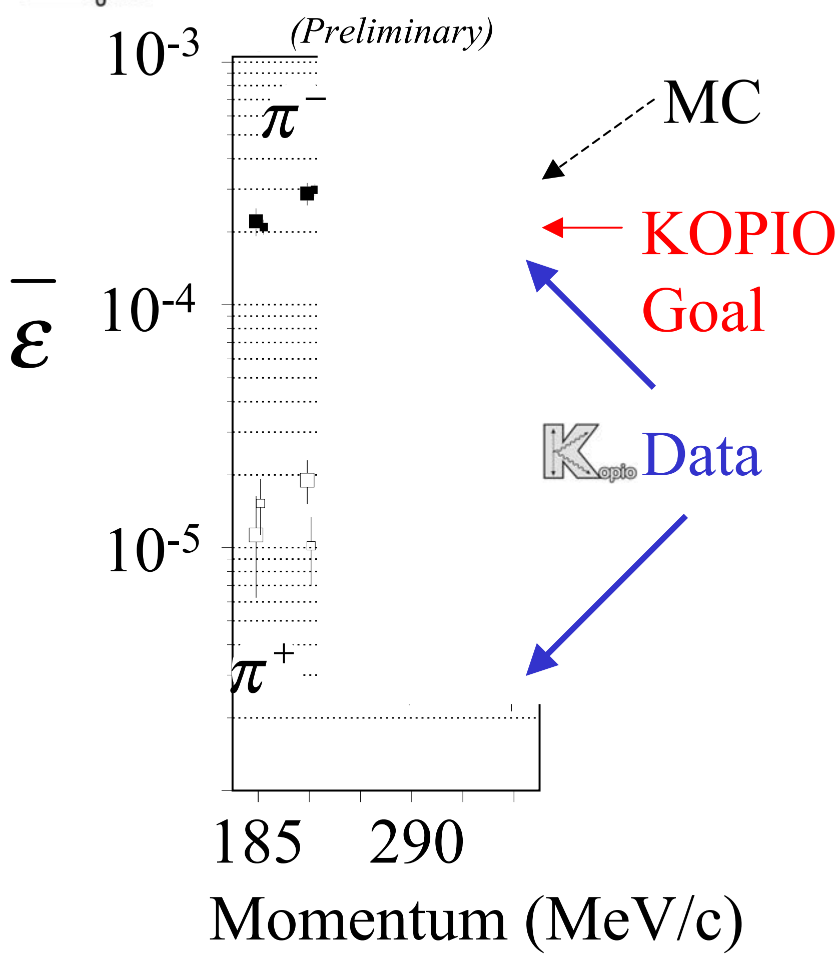
Miss−Mass vs. Miss−E (pinn)

Charged Particle Vetoing

Example Background: $K_L^0 \to \pi^- e^+ \nu \gamma$

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

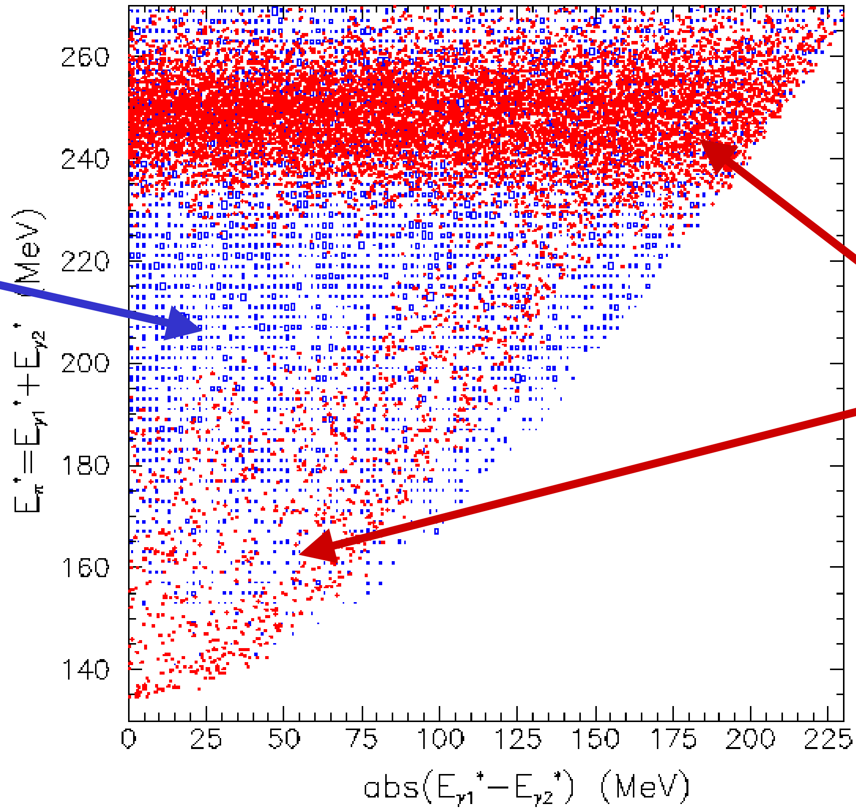
Parameter	Minimal Requirement	Expected Performance
E_γ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
θ_γ resolution(250 MeV)	25 to 30 mrad	23 mrad
t_γ resolution	$100\ \mathrm{ps}/\sqrt{E}$	$50\ \mathrm{ps}/\sqrt{E}$
x_γ,y_γ resolution(250 MeV)	10 mm	< 1 mm
microbunch width	300 ps	200 ps
microbunch extinction	10^{-3}	$< 10^{-3}$
photon veto inefficiency	$0.3\bar{\epsilon}_{\mathrm{E787}}$	$0.3\bar{\epsilon}_{\mathrm{E787}}$
charged veto ineffiency	$10^{-5}(\pi^+), 10^{-4}(\pi^-)$	$< 10^{-5}(\pi^+), < 10^{-4}(\pi^-)$

$0.3\bar{\epsilon}_{\rm E787}$

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

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

$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$



$K^0_L \rightarrow \pi^0 \pi^0$

KOPIO S/N=2

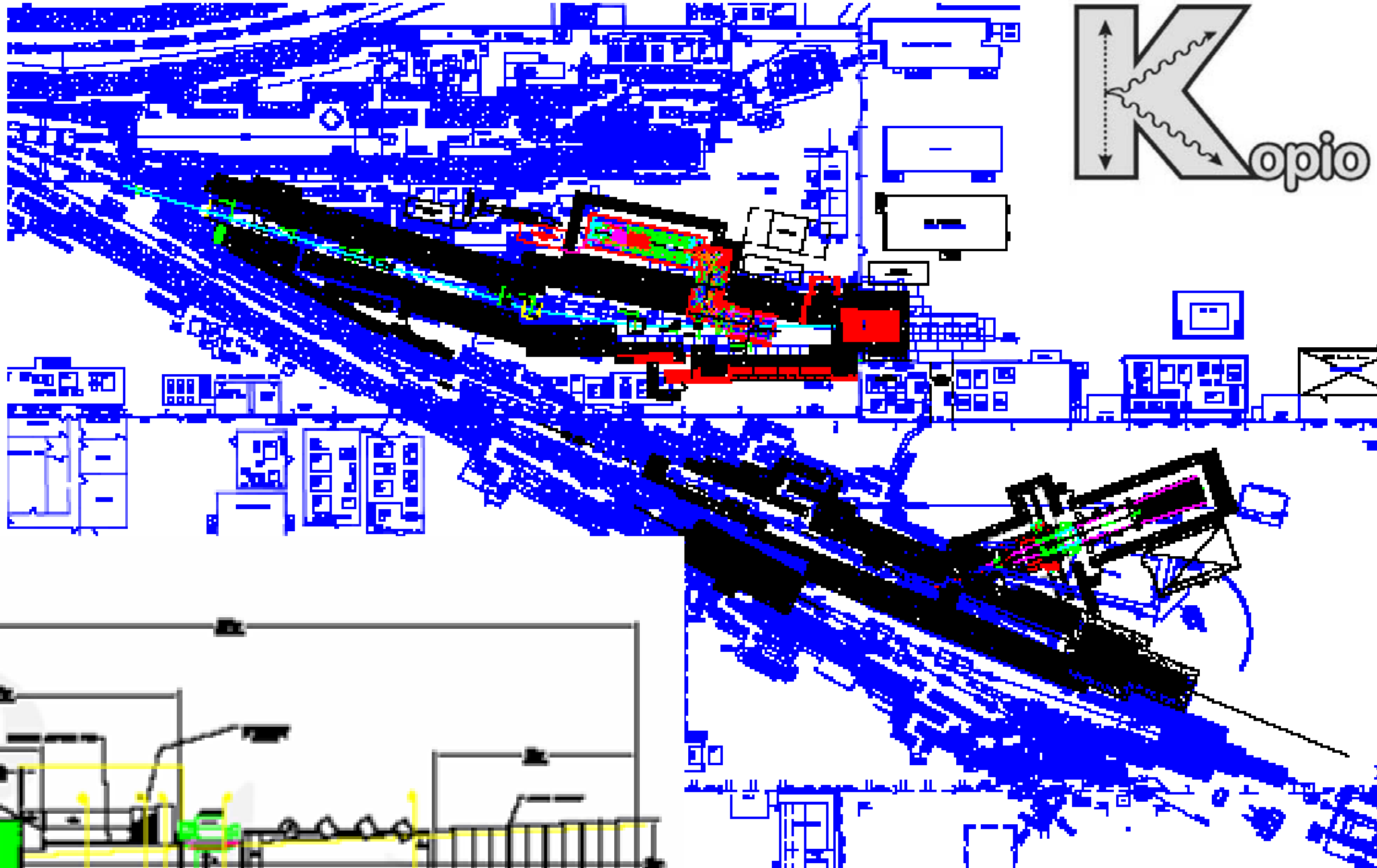
Estimated Background Levels

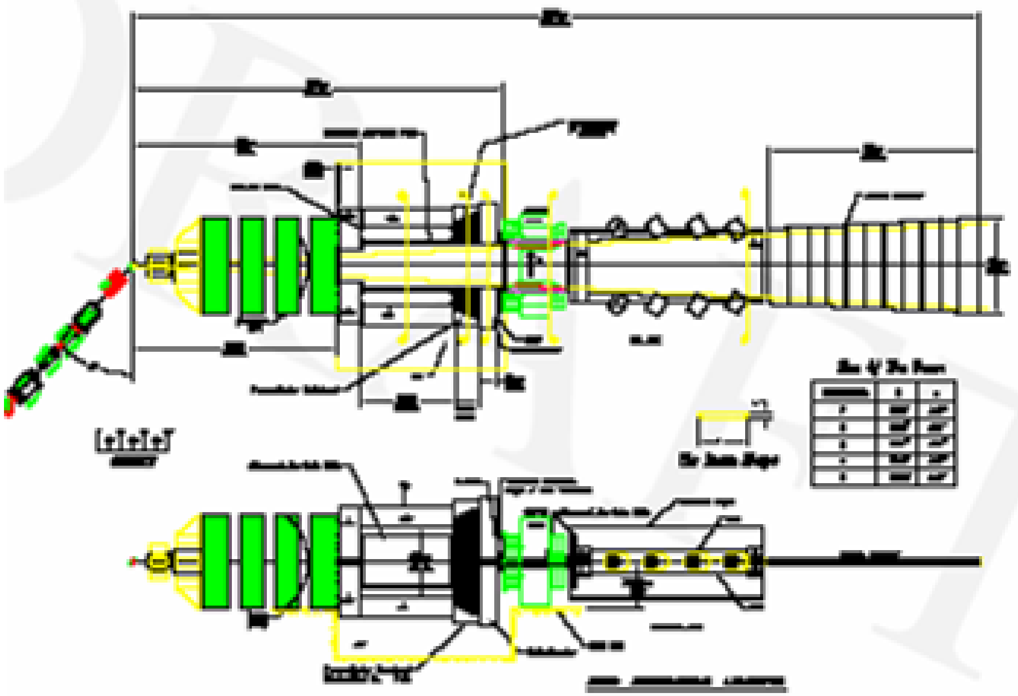
	Branching Ratio	Bkg. Events
$K_L^0 \rightarrow \pi^0\pi^0$	$0.93\ x\ 10^{-3}$	14
$K_L^0 \rightarrow \pi^- e^+ \nu\, \gamma$	$0.36\ x\ 10^{-2}$	5
$K_L^0 \rightarrow \pi^+\pi^-\pi^0$	0.1255	3
Others		1
		*******

Signal: 49 Background: 24

12000 Hours; Acceptance 9×10^{-3}

Kopio



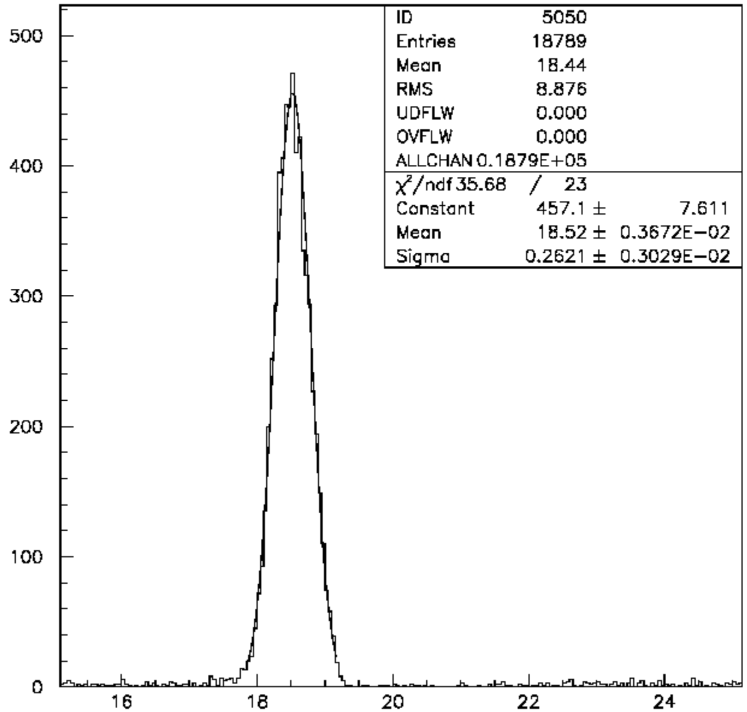


AGS Microbunching Beam test

Microbunch width

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

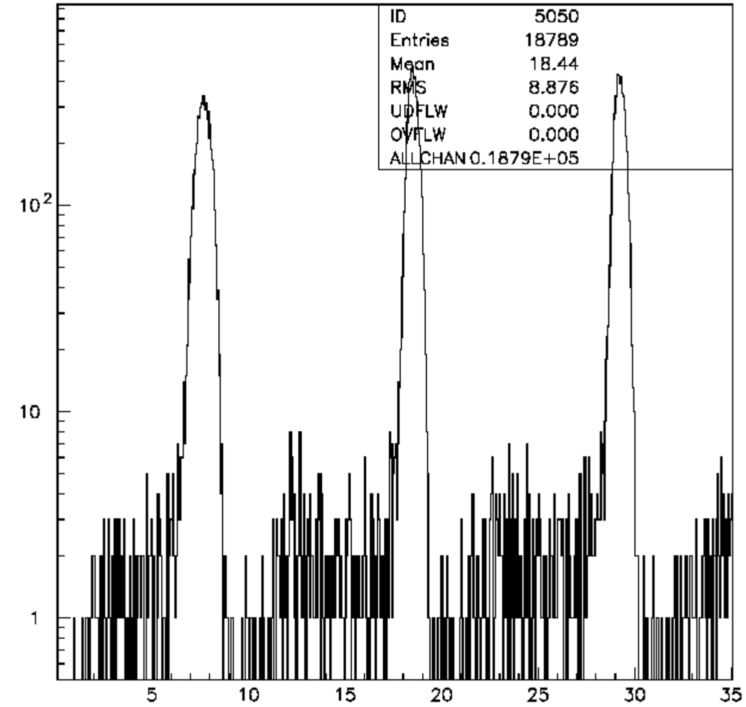
Also developed monitoring methods



Interbunch extinction

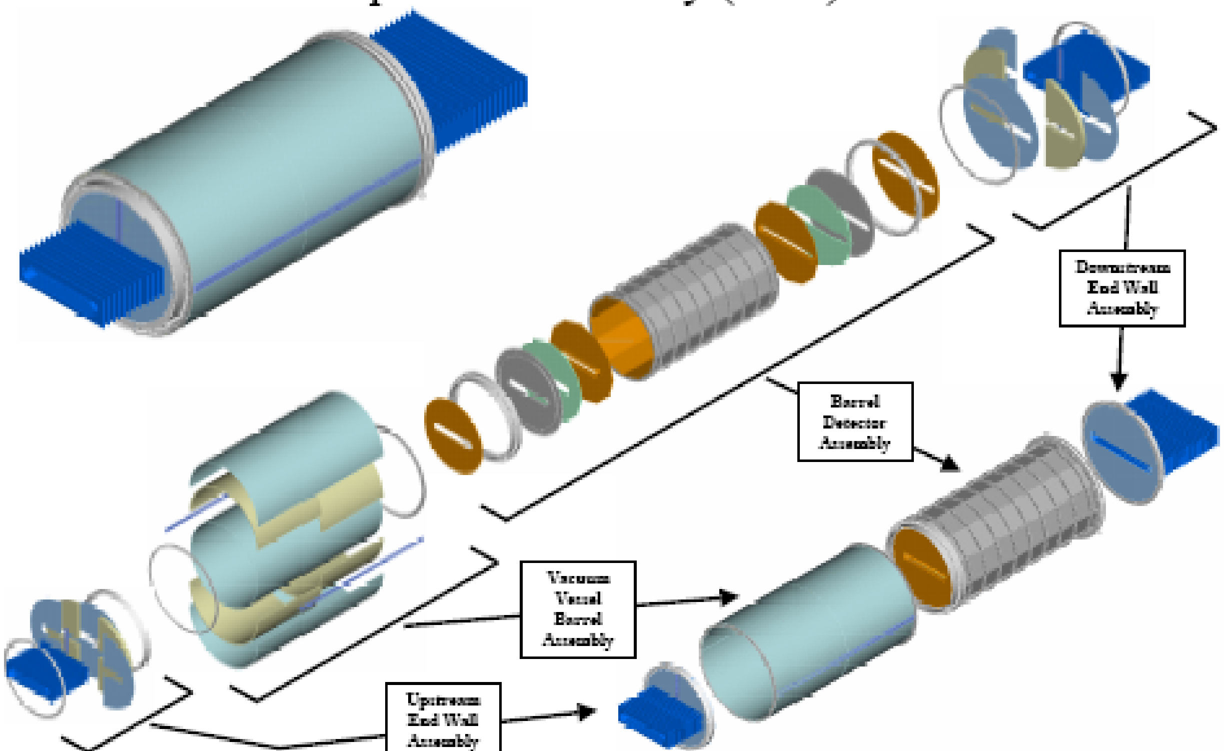
Measured the inter-bunch extinction ratio (flux between bunches/within bunch). Observed a ratio of ~3-4% (could be less) KOPIO requires ~ 10^{-3} - 10^{-2}

Need to control power supply ripple

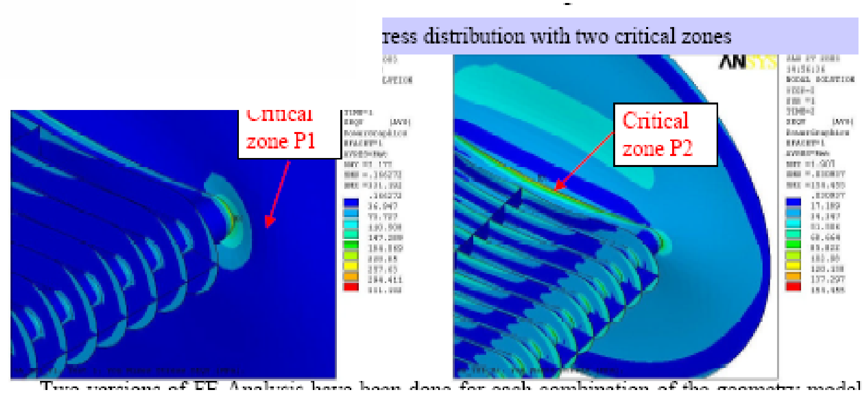


Vacuum System R&D

Exploded Assembly (AES)



Finite element Analysis



Current Design:

Honeycomb vessel and ends

Al core, domed ends

Solid Be beam pipe

Neutral Beam (neutrons) Collimated to Supress Halo

Vertical Collimation Scheme

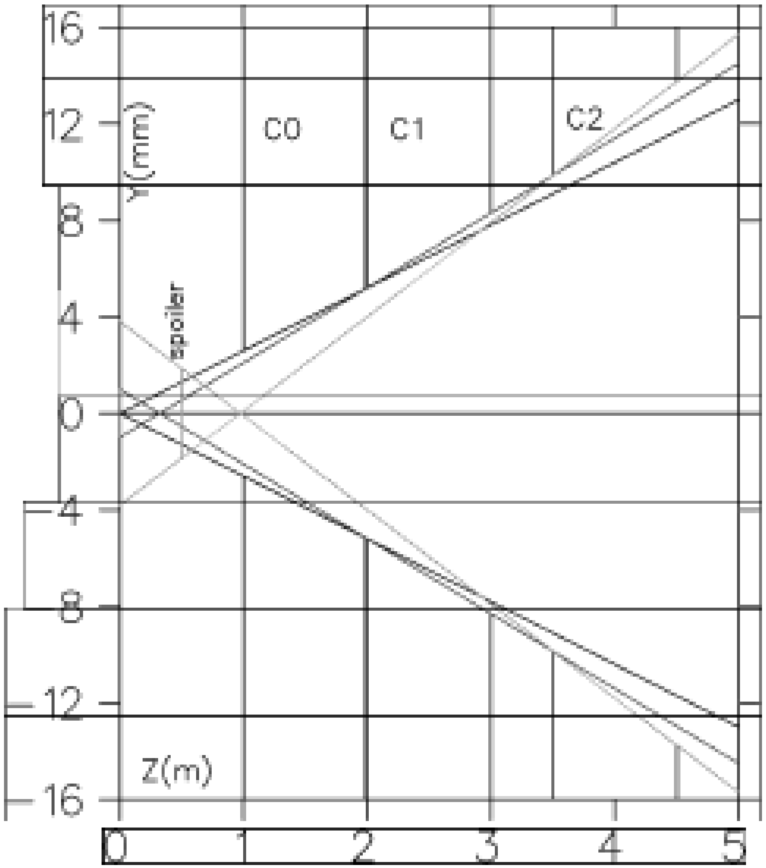


Figure 2: Construction of the vertical apertures of collimators C0 to C2

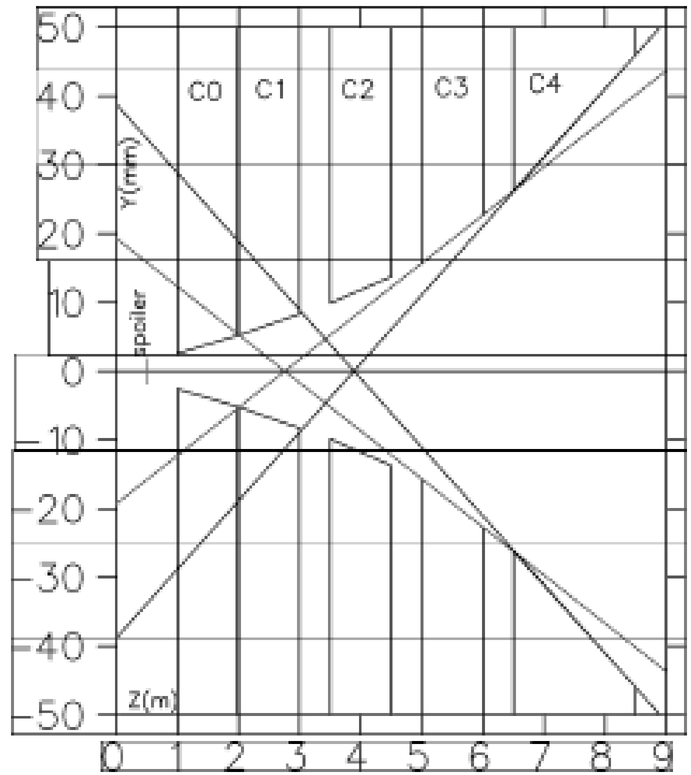


Figure 1: Construction of the vertical apertures of collimators C3 and C4

Simulation of Neutron Collimation

Nominal beam

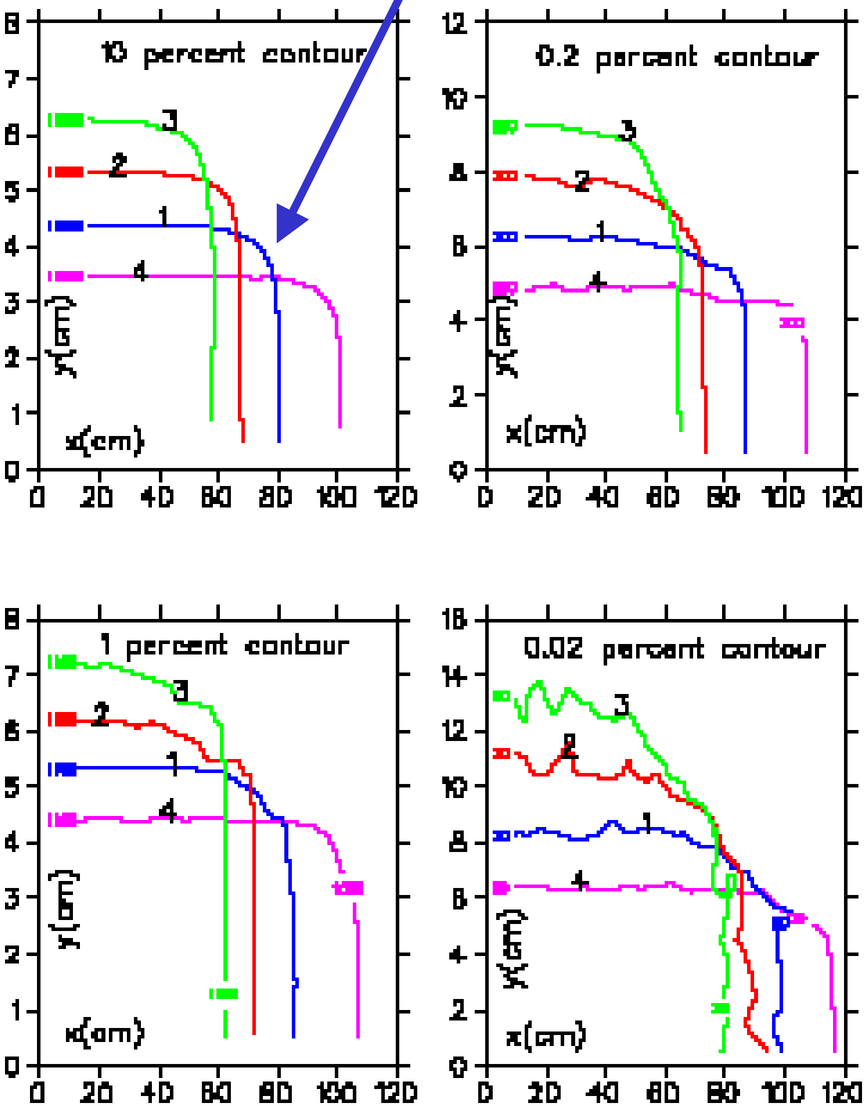
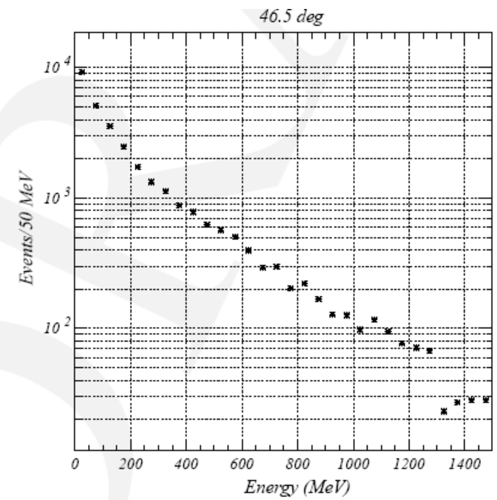
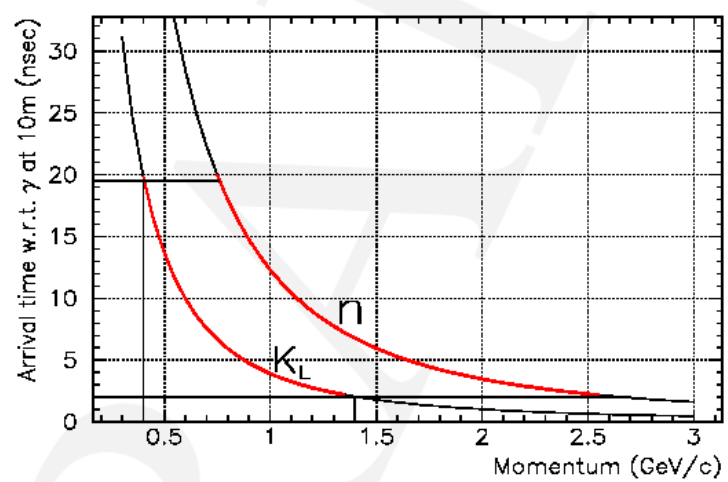


Figure 20: Contour plots at 14 m

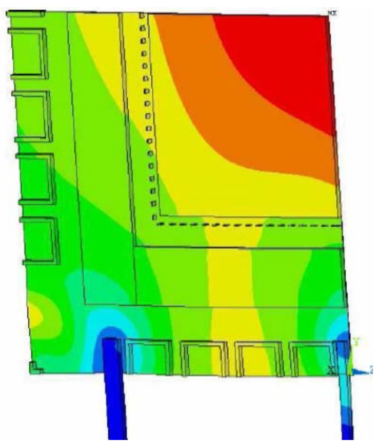
Neutron Energy Spectrum

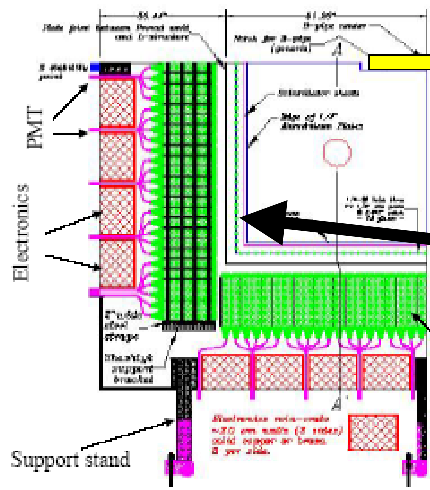


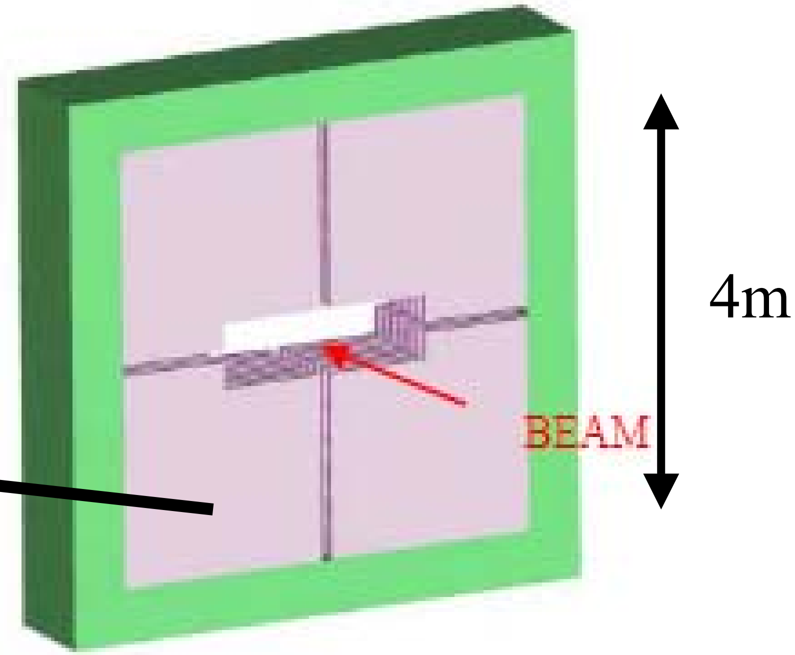


Preradiator R&D

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



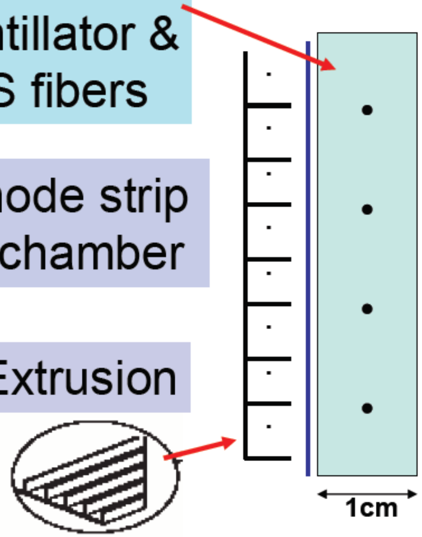




Extruded Scintillator & WLS fibers

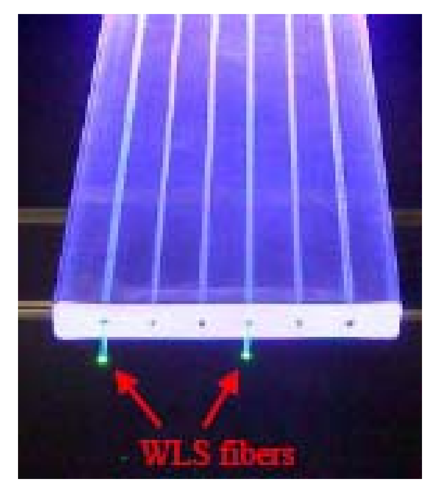
Cathode strip drift chamber

Al Extrusion



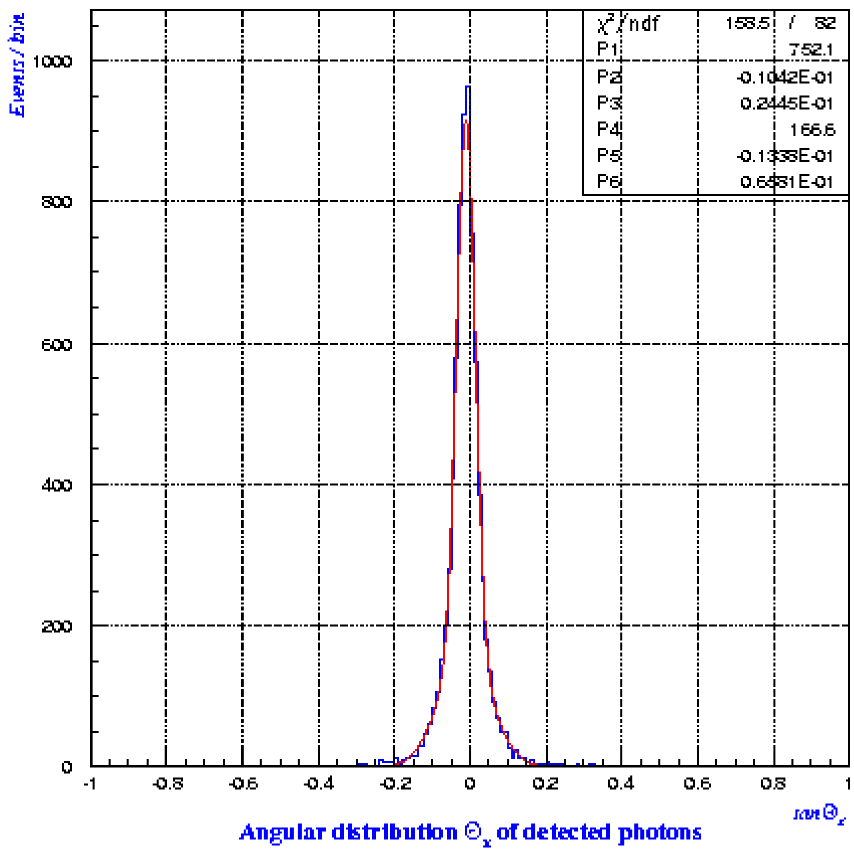
Prototype Cathode Strip Chamber

Extruded Scintillator with WLS fiber



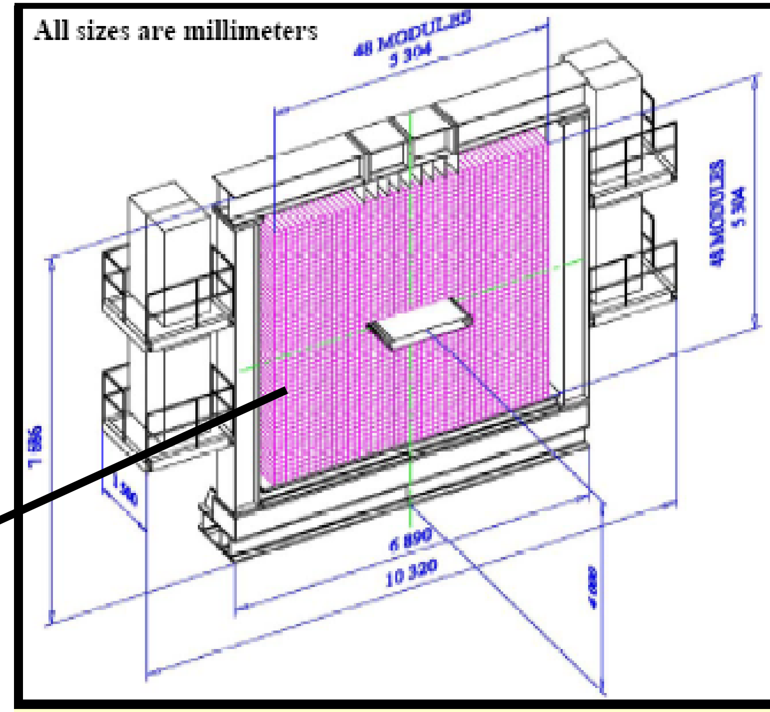
KOPIO Prototype Measurements – Tagged Photon Beams

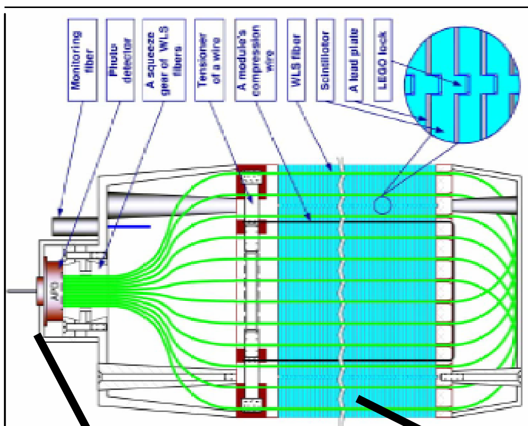
Preradiator Angular resolution:
25 mr at 250 MeV/c



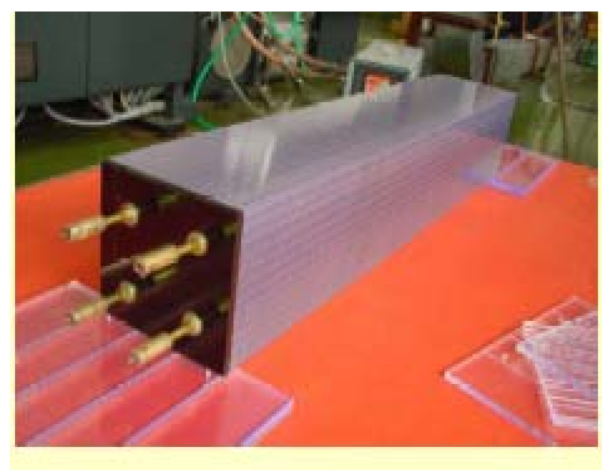
Shashlyk R&D

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

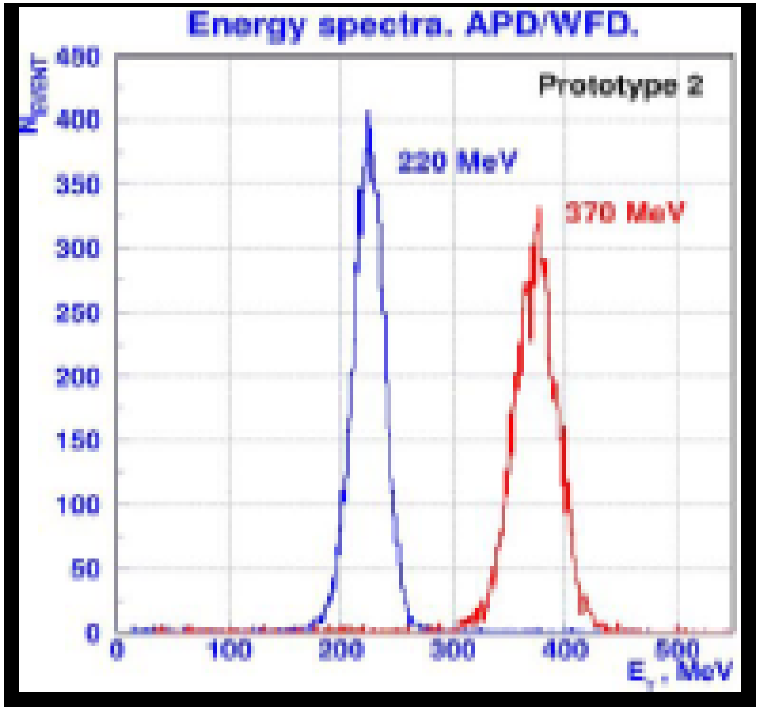


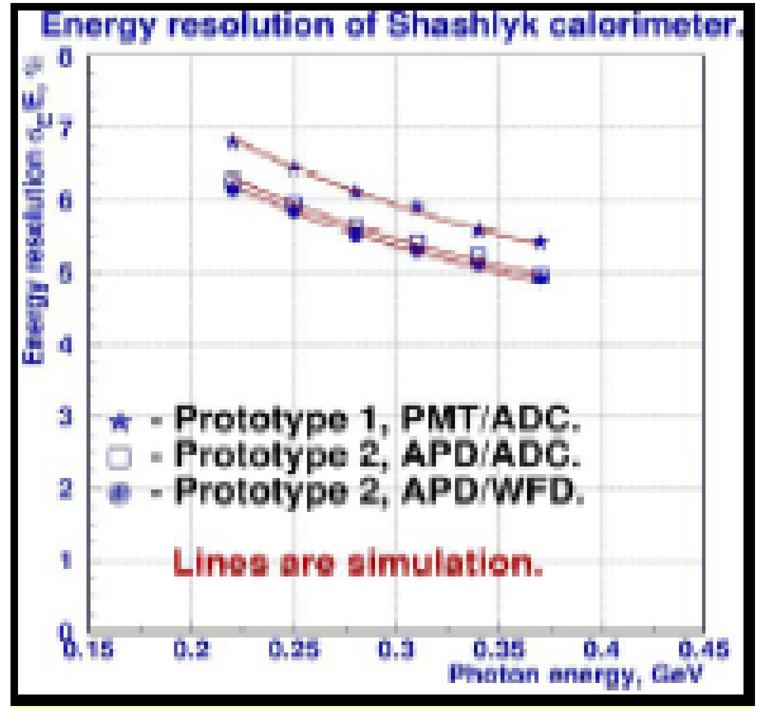


APD



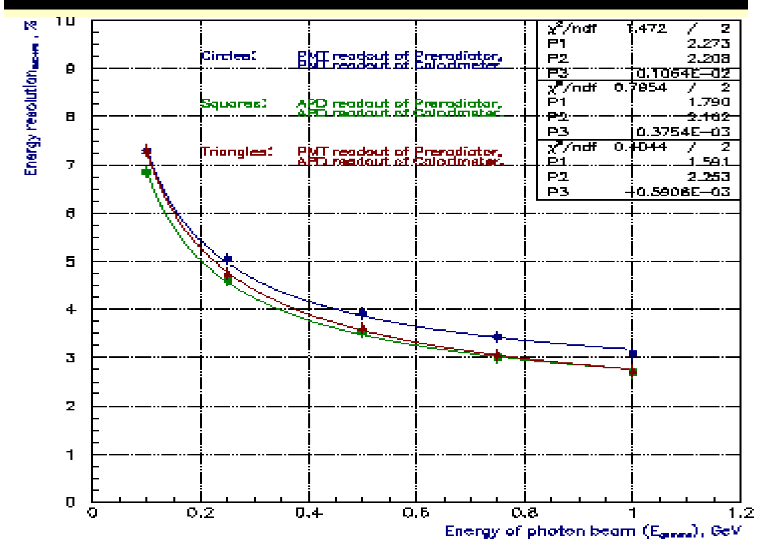
Shashlyk Beam Measurements





Simulation: Combined Energy Resolution

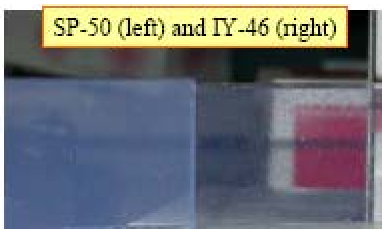
$$\sigma \approx \frac{3\%}{\sqrt{E(GeV)}}$$

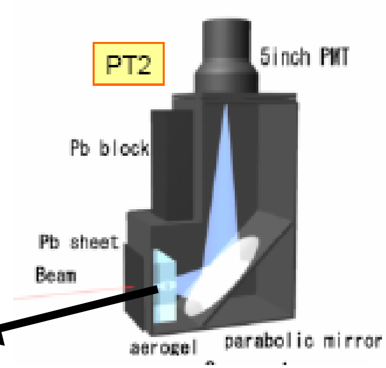


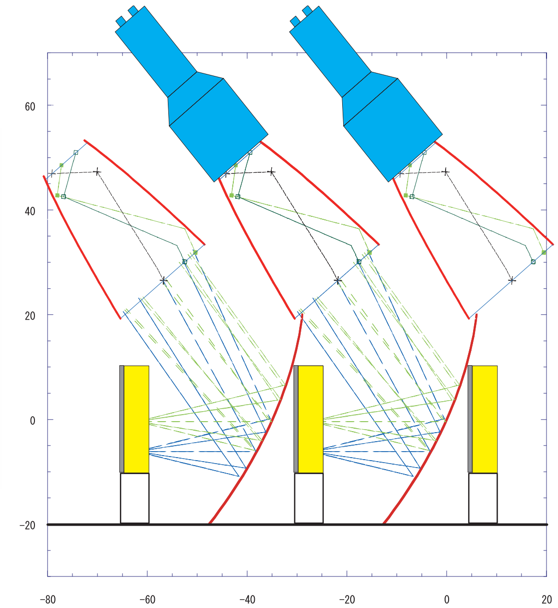
Catcher R&D

Modules prototyped and tested in beams.

New Aerogel tiles



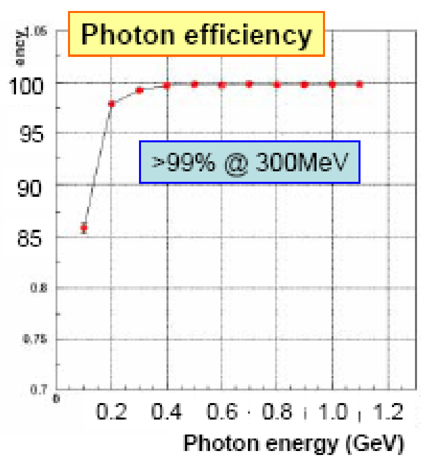


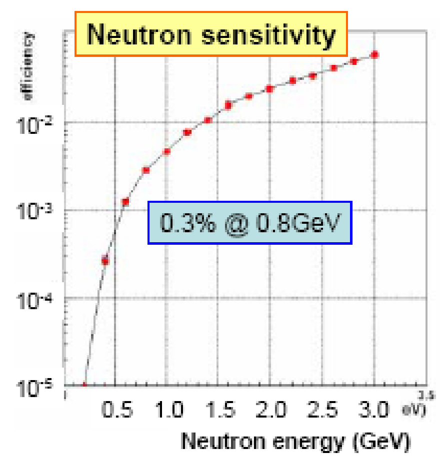


Expected performance with current design

Photon efficiency / Neutron sensitivity

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





KOPIO Funding and Support Partners

- **NSF**
  - **RSVP MREFC and R&D**
  - **University groups**
- **DOE OHEP**
  - **BNL Physics Department group**
  - **Yale group**
- **DOE ONP; BNL CAD (and university groups)**
- **Canadian agencies (NSERC, CFI, TRIUMF)**
- **Japanese agencies**
- **Others (Russia, Switzerland, Italy (INFN))**

DOE-Supported Groups Major Responsibilities

- **Yale**
  - **Shashlyk Calorimeter**
  - **Neutral beam and other simulations**
- **BNL (CAD)**
  - **AGS upgrades, proton beam, target**
  - **Neutral beam**
- **BNL (PHYSICS)**
  - **Detector infrastructure and integration**
  - **Veto detector systems**
  - **DAQ system**
  - **Simulations**

Summary and Outlook

- KOPIO R&D is concluding successfully.
- Advanced planning for the construction phase is beginning.
- US Agencies – NSF and DOE – are cooperating well, and international partners are contributing substantially.