The KOPIO Experiment

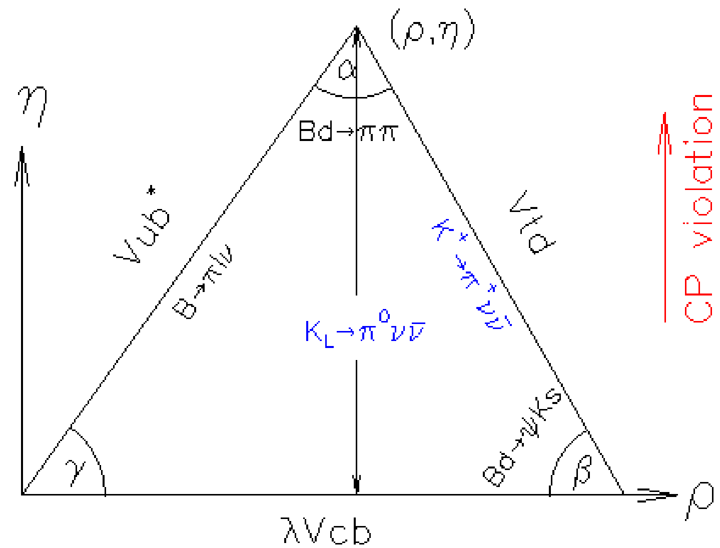
The KOPIO experiment was one of the Rare Symmetry Violating Processes (RSVP) project in search of a valuable insight about the CP violation and flavor mixing in the Standard Model. The design was accepted at the Alternating Gradient Synchrotron (AGS) accelerator of Brookhaven National Laboratory (New York). The contributions of the Virginia Tech group to the detector prototyping and the beam-tests to-date is summed up.

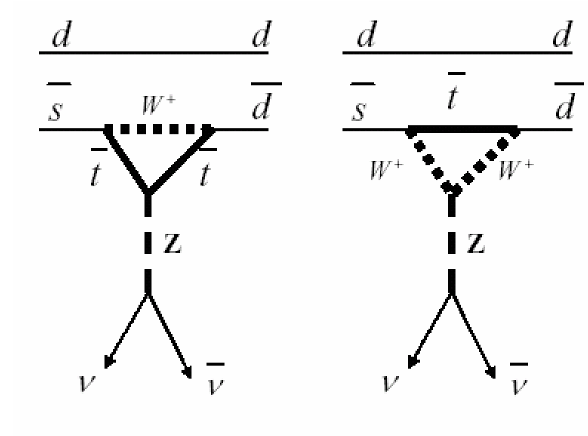
Athans Hatzikoutelis

Overview

- Standard Model predictions
- Decay Signature & Detection Challenges
- Neutral Beam & Trigger
- Main Detector Prototypes
- Latest Beam Tests
- Magnet Veto
- Detector Prototyping & Results.
- Current Status & Future Plans

Standard Model CP Violation

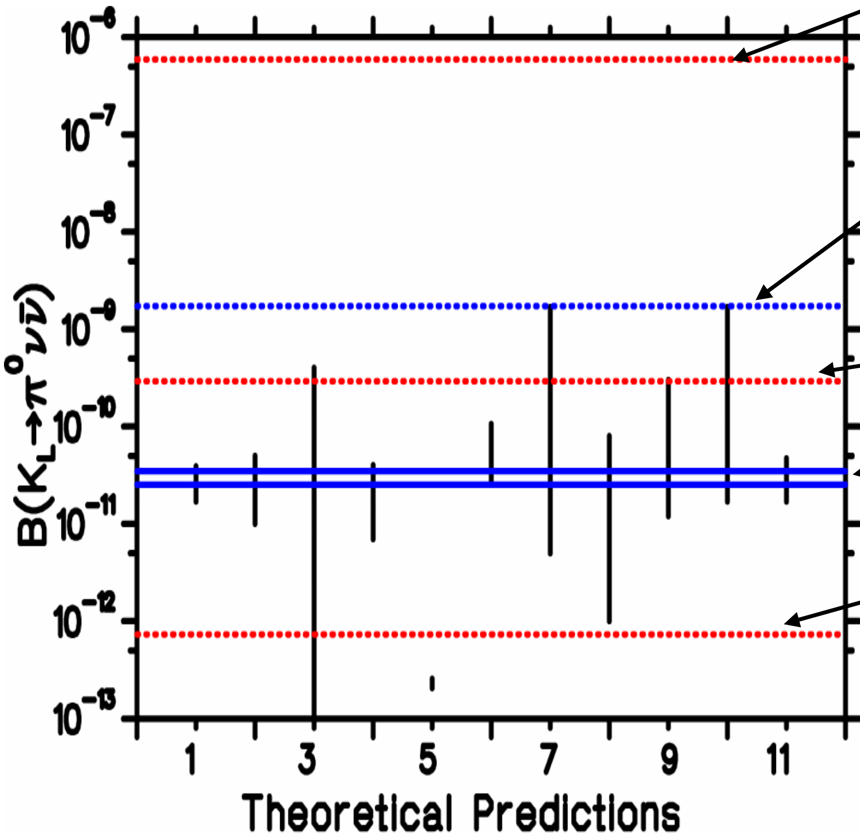




$K_L^0 \to \pi^0 \nu \bar{\nu}$	$\mathrm{Im}(V_{ts}^* V_{td})$	KOPIO
$K^+ \to \pi^+ \nu \bar{\nu}$	$\lvert V_{ts}^* V_{td} \rvert$	E949, ~~CKM~~
$B_d \to \psi K_S$	$\sin(2\beta)$	BABAR, BELLE, CDF, D0
$\frac{x_s}{x_d}$	$\left\lvert \frac{V_{ts}}{V_{td}} \right\rvert$	CDF, D0, LHCB, BTEV

Buras et.al. hep-ph/0405132

Limits of Branching Ratio



- Current experimental upper limit of $K_L^0 \to \pi^0 \nu\bar{\nu}$ branching ratio (BR) is 5.9×10^{-7} (KTEV)
- Theoretical upper bound using $K^+ \to \pi^+ \nu\bar{\nu}$ events is 1.4×10^{-9} (Grossman-Nir)
- KEK391 proposes to reach single event sensitivity of 3×10^{-10}
- Standard Model predicts BR of 3×10^{-11}
- *KOPIO proposed to measure 40 events at sensitivity below 10^{-12}*

Many theoretical models of new physics predict BR's in this region

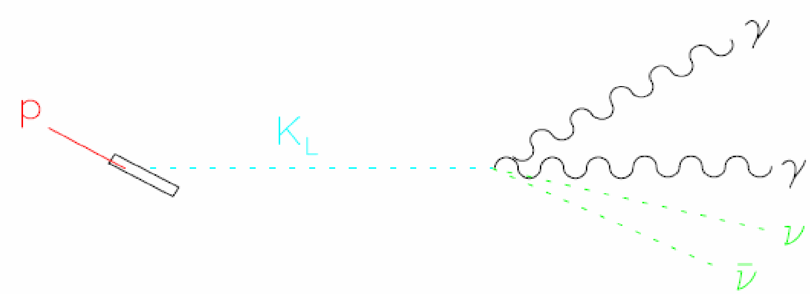
Bryman et.al. hep-ph/0505171v1

Method, Signature

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

- KOPIO proposed an innovative process of background reduction
  - Microbunched proton beam with high flux.
    - Requires the AGS – the most intense source in the world
  - Pancake neutral beam with vertex localization
    - Measuring K velocity allows work in CoM
  - Measuring γ directions and energy allows kinematic selection
    - Must discriminate similar decays, (e.g. $K_L \to \pi^0 \pi^0$ is10^8 more probable)

- Very efficient hermetic veto.
  - A lot of experience with high efficiency γ vetos from the E787/949 experiments at BNL.



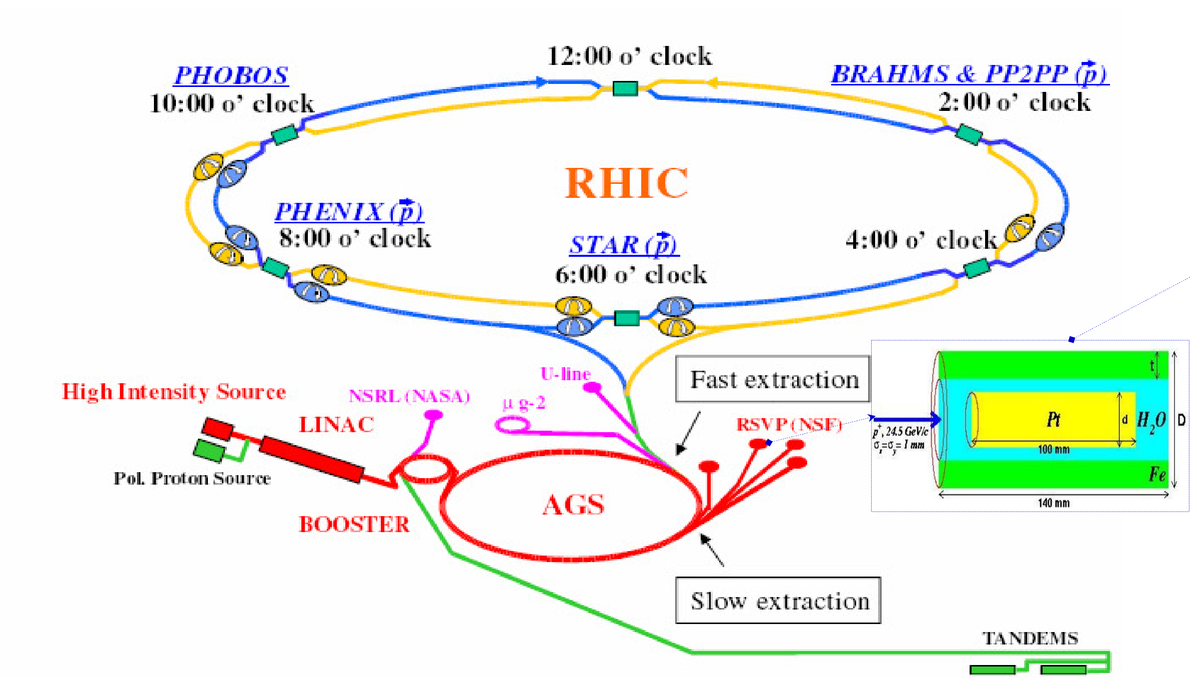
Simulated K_L modes / bkgrd study

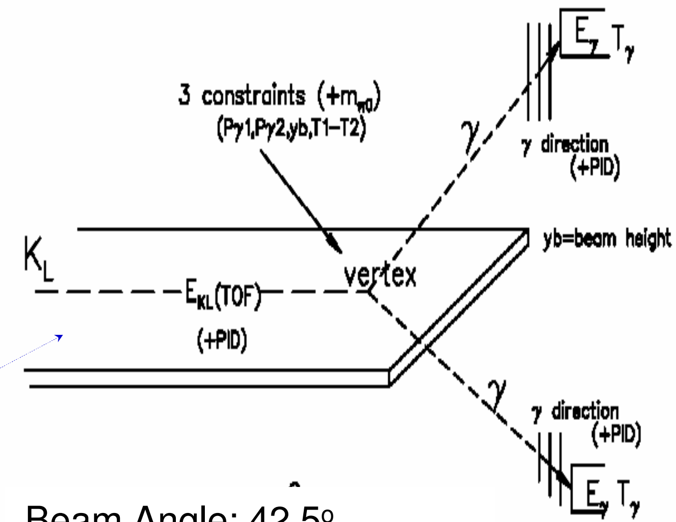
Name	Final state	Branching fraction	$\mathcal{B}/\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$
Kpnn	$\pi^0\nu\bar{\nu}$	0.3000×10^{-10}	1.000
Kp2	$\pi^0\pi^0$	0.9320×10^{-3}	0.31×10^8
Kcp2	$\pi^+\pi^-$	0.2090×10^{-2}	0.70×10^8
Kgg	$\gamma\gamma$	0.5900×10^{-3}	0.20×10^8
Kp3	$\pi^0\pi^0\pi^0$	0.2105	0.70×10^{10}
Kcp3	$\pi^+\pi^-\pi^0$	0.1259	0.42×10^{10}
Ke3	$\pi^\pm e^\mp\nu$	0.3881	0.13×10^{11}
Km3	$\pi^\pm\mu^\mp\nu$	0.2719	0.91×10^{10}
Ke3g	$\pi^\pm e^\mp\nu\gamma$	0.3530×10^{-2}	0.12×10^9
Km3g	$\pi^\pm\mu^\mp\nu\gamma$	0.5700×10^{-3}	0.19×10^8
Kpgg	$\pi^0\gamma\gamma$	0.1410×10^{-5}	0.47×10^5
Ke4	$\pi^0\pi^\pm e^\mp\nu$	0.5180×10^{-4}	0.17×10^7
Km4	$\pi^0\pi^\pm\mu^\mp\nu$	0.1400×10^{-4}	0.47×10^6
Ke2g	$e^+e^-\gamma$	0.1000×10^{-4}	0.33×10^6
Km2g	$\mu^+\mu^-\gamma$	0.3590×10^{-6}	0.12×10^5

Orders of magnitude more prolific than the targeted decay

K_L beam from the AGS

- Primary Proton Beam Momentum 25.5 GeV/c intensity 100 TPPP
- Kaon Beam 0.5-1.5 GeV/c 3×10^8 K_L/spill 8% decay ~0.2 K^L decay per microbunch <u>in the decay range</u>
- Target dimensions: Cylindrical Platinum Rod, 4mm diameter x 106mm long.
- Neutrons 10 GHz

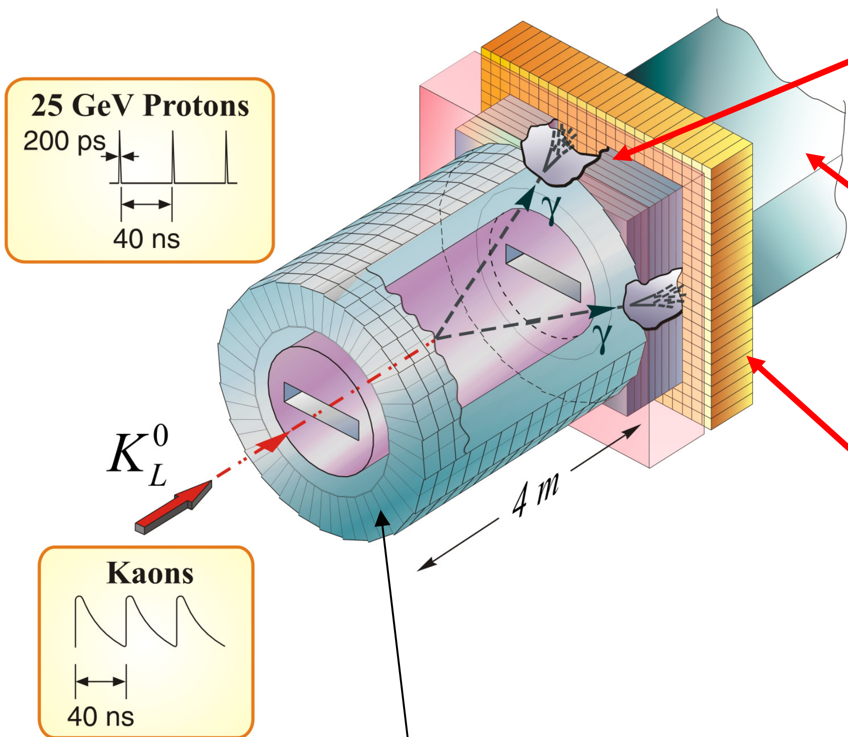


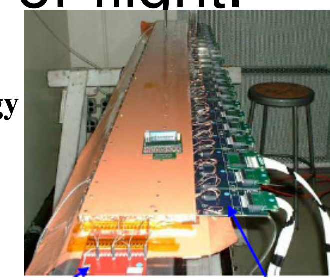


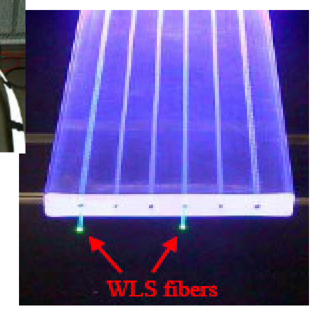
Beam Angle: 42.5°
Asp.Ratio.: 90 mr x 4 mr

Main Detectors

Reconstruction of the neutral Kaon achieved by measuring the momentum by time-of-flight.



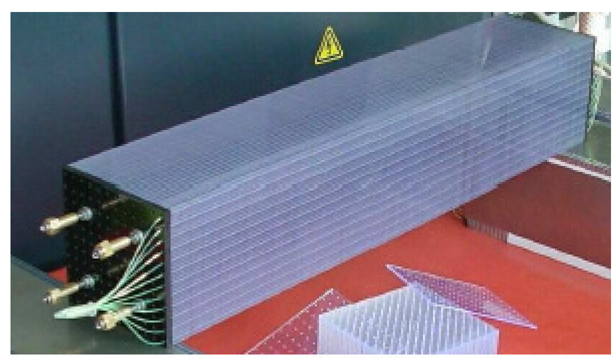




Preradiator –
γ angle & energy

Downstream Sweeping-magnet Veto

High resolution Calorimeter ~3%/√E

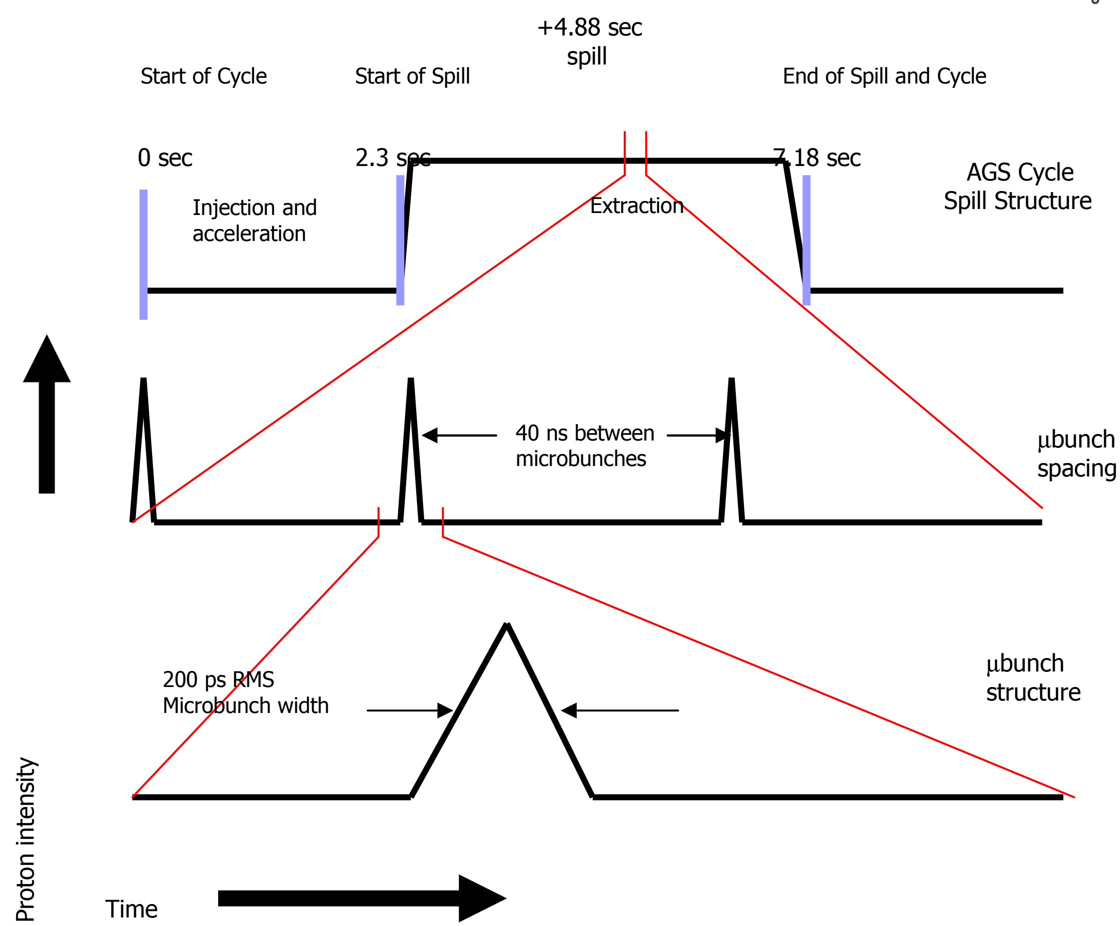


Microbunched beam
- measure velocity of K_L

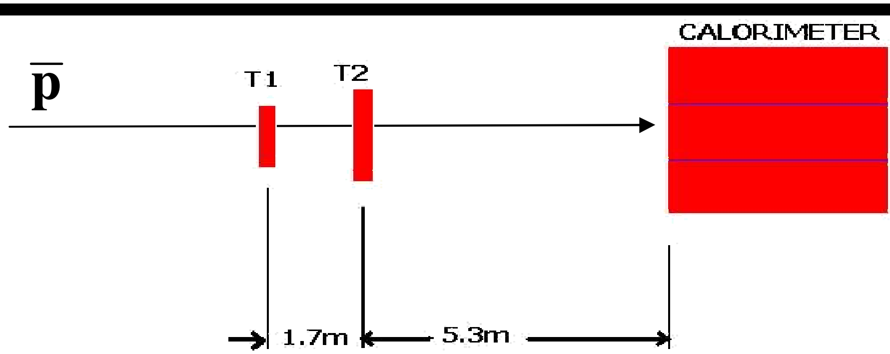
Hermetic high efficiency veto

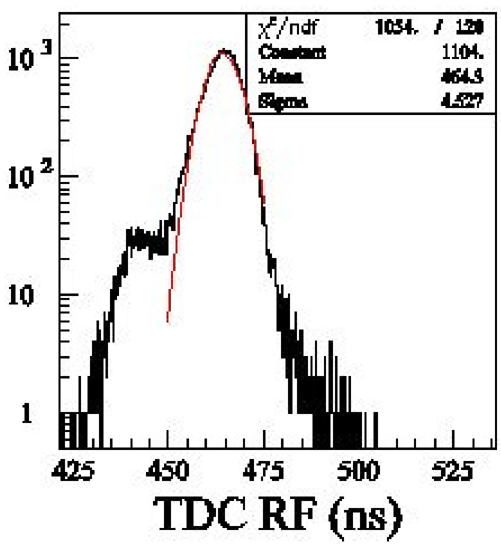
Time Profile of the K_L Beam

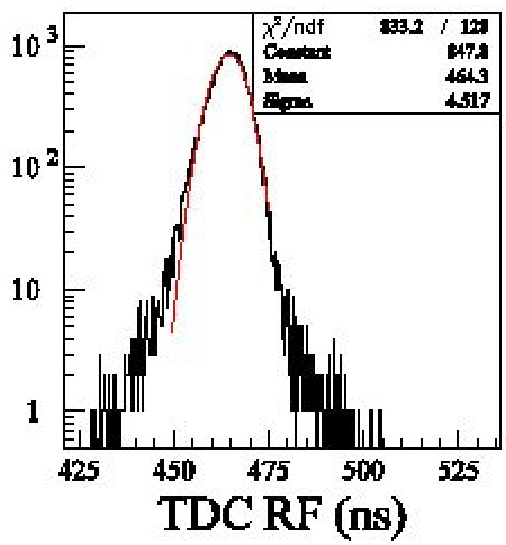
- Microbunch separation determined by the length of time required to clear out kaons from the previous microbunch.
- Spill length of ~4.9 seconds
- Inter-spill = 2.3 seconds

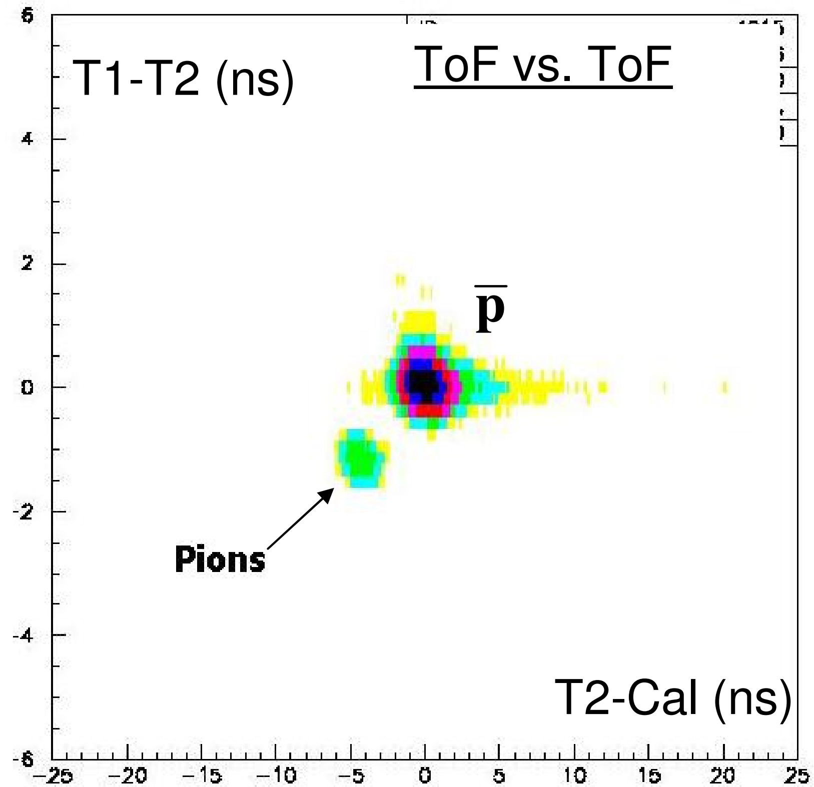


Anti-proton test beam









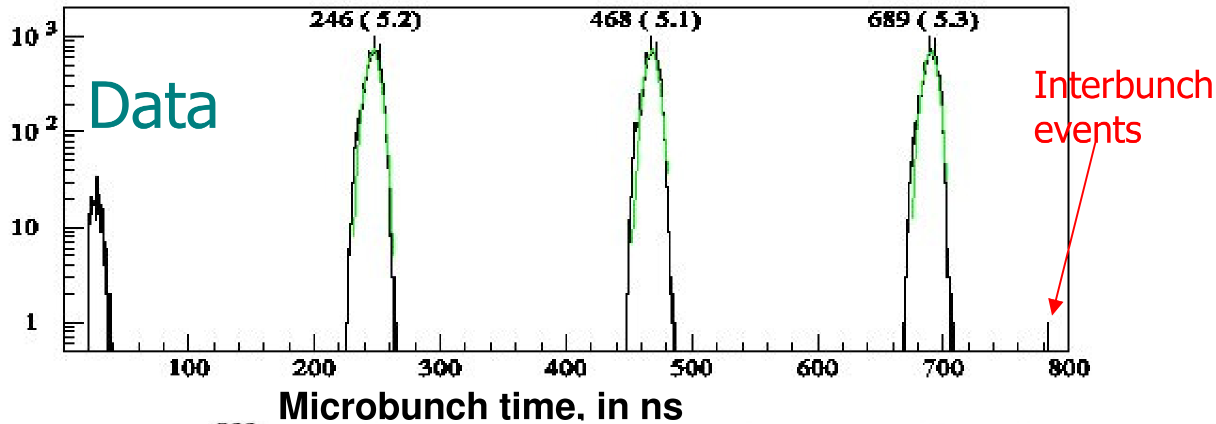
Arrival time of the particles at the trigger counters relative to the RF signal. In a sample of all triggers (left), the pion shoulder at early times is visible. When a cut is made to remove events with T1-T2 time-of-flight inconsistent with antiprotons, the pion shoulder is removed (right).

2004 Test Beam Results: Interbunch Extinction

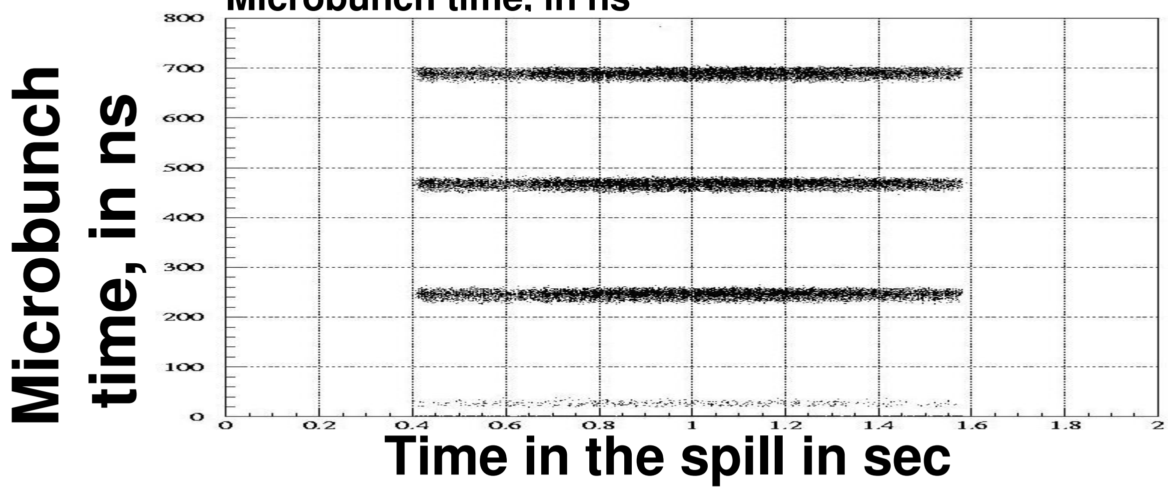
cavity OOP: 4.45272 MHz at 270 kV

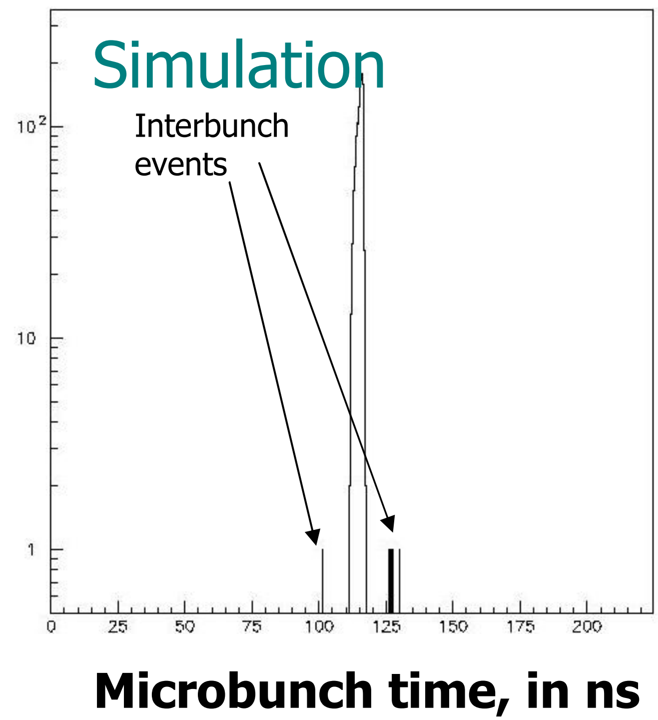
5σ = 3.85 ns **e** = 4.57 (+/- 6.47) x 10^{-6}

Simulation
93 MHz cavity at 22 kV
gave σ = 217 ps.



Simulation
4.5 MHz cavity at 130 kV
gave ε = 1.7 (+/- 0.9) x 10^{-3}.

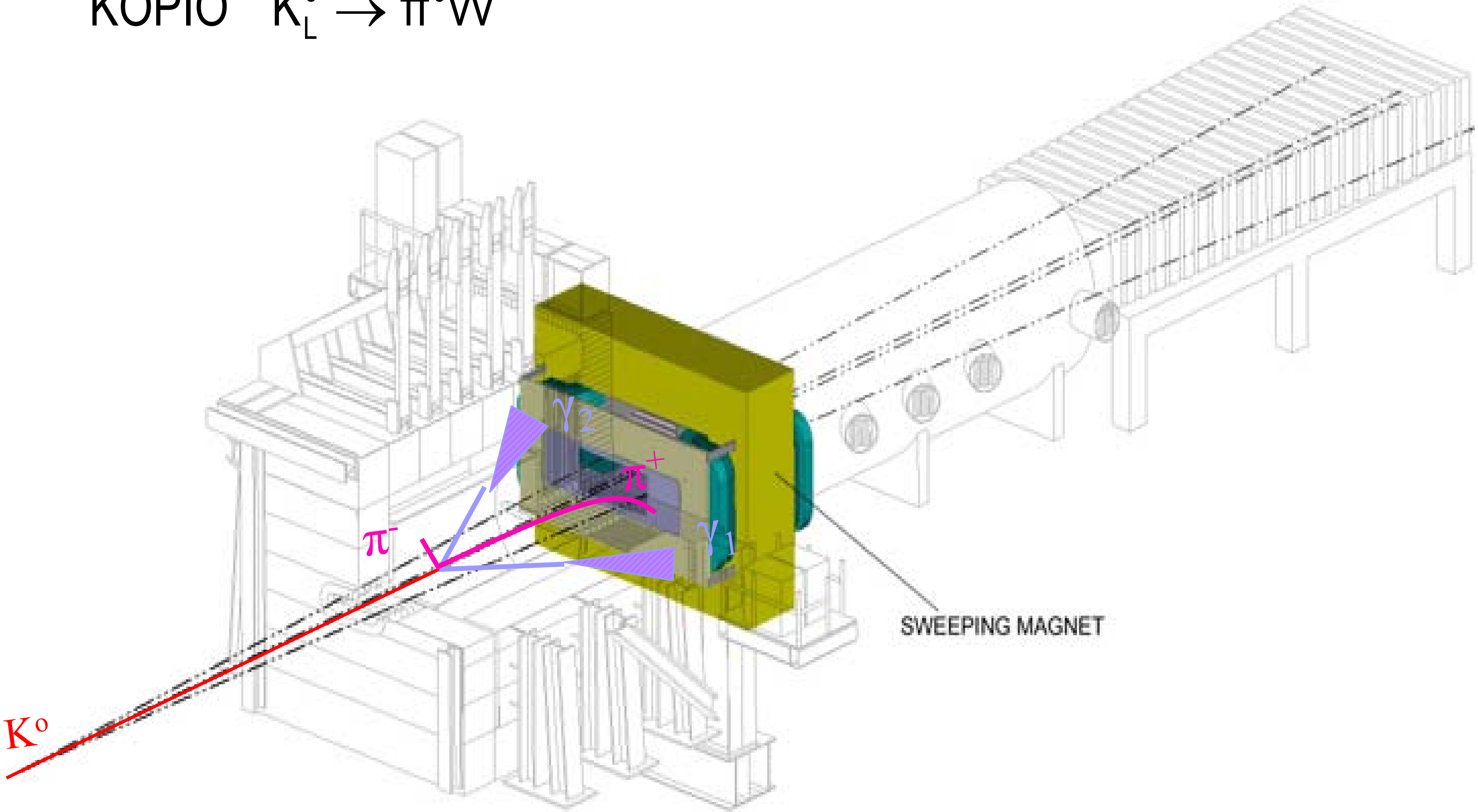




There is no macro-bunching in the microbunches

Background event being vetoed

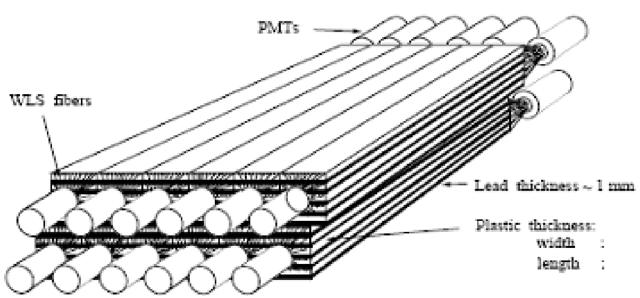
KOPIO $K_L^0 \to \pi^0 \nu\bar{\nu}$

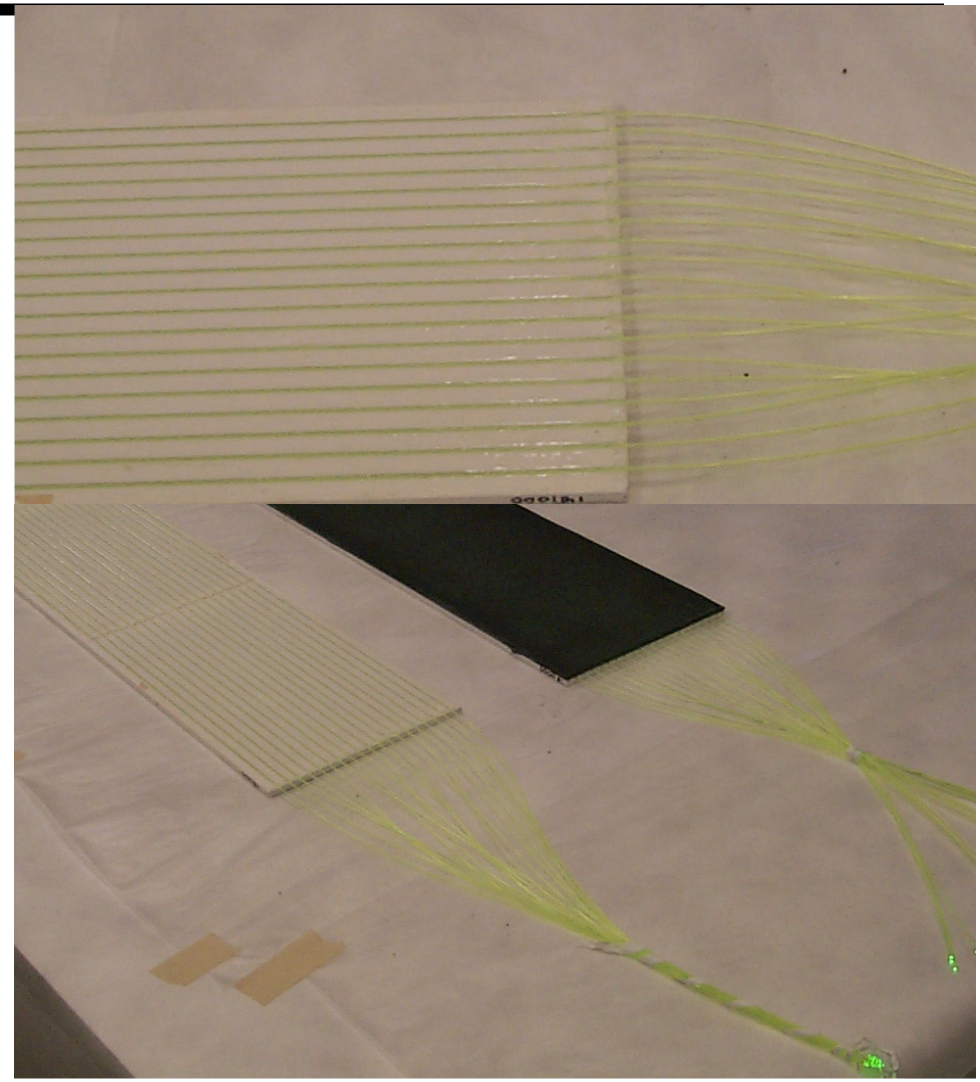


veto example $K_L^0 \to \pi^0\pi^-\pi^+$

The Sweeping magnet Veto Logs

- Scintillator –Pb sandwiches
  - Tile thickness 5mm
  - 1mm fiber per 7mm
- 21 tiles x 2m x 15.5cm
- Extruded Polystyrene scint. (80% BC408)
- White reflective paint etched.

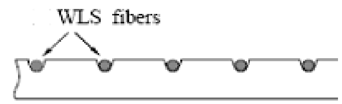


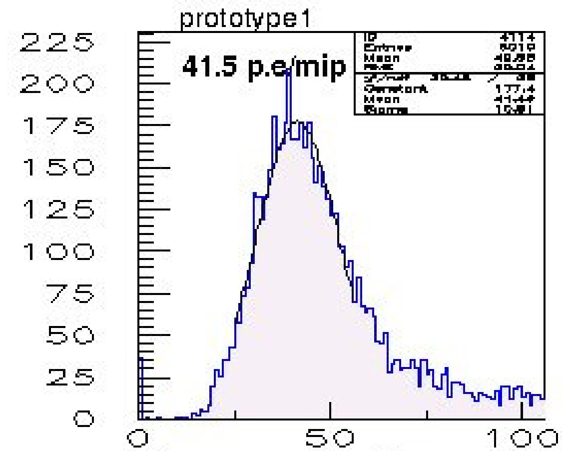


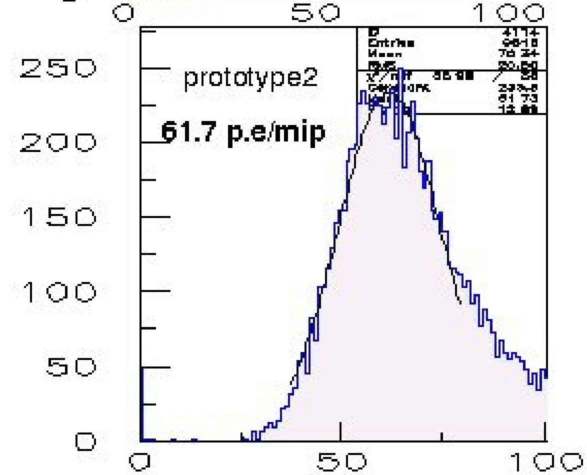
Energy and timing output from cosmics

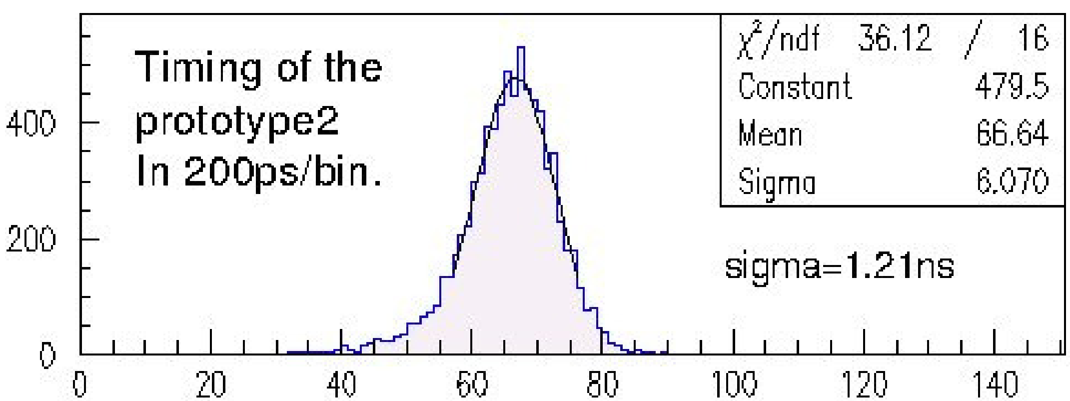
- Detector readout:

1. Kuraray Y11-200 multi-clad wave-shifting fibers.
2. BC-600 perm. epoxy-coupling to scintillator grooves.
   - Maximized light output of single-tile detector protot
     - cosmic radiation mostly 2GeV muons
     - depositing ~1.15 MeV/mip/5mm-tile in the scintillator
     - Max light 60 p.e./mip (photo-electrons per minimum ionizing particle of cosmic rays total from both ends)
   - Minimized timing response
     - Measured parameter: average time of a signal to rea the pmts at the ends of the tile after the mip trigger.









Light transport

$$I = I_0\left(Ae^{-x/\lambda_s} + Be^{-x/\lambda_L}\right)$$

- Very few pmt's can work inside high fields.
- Light needs transport of ~10m.
- WLS fibers attenuate with 2 characteristic lengths : short=0.88m, long= 5.83m or ~1dB/m.
- Although we achieved fiber-coupling arrangements of 0.64dB no "suitable" light-guide was found among clear thin fibers, lucite-rods, 5mm thick fibers, etc. .
- Extending the already embedded readout up to the pmt location was optimum (economic & efficient).

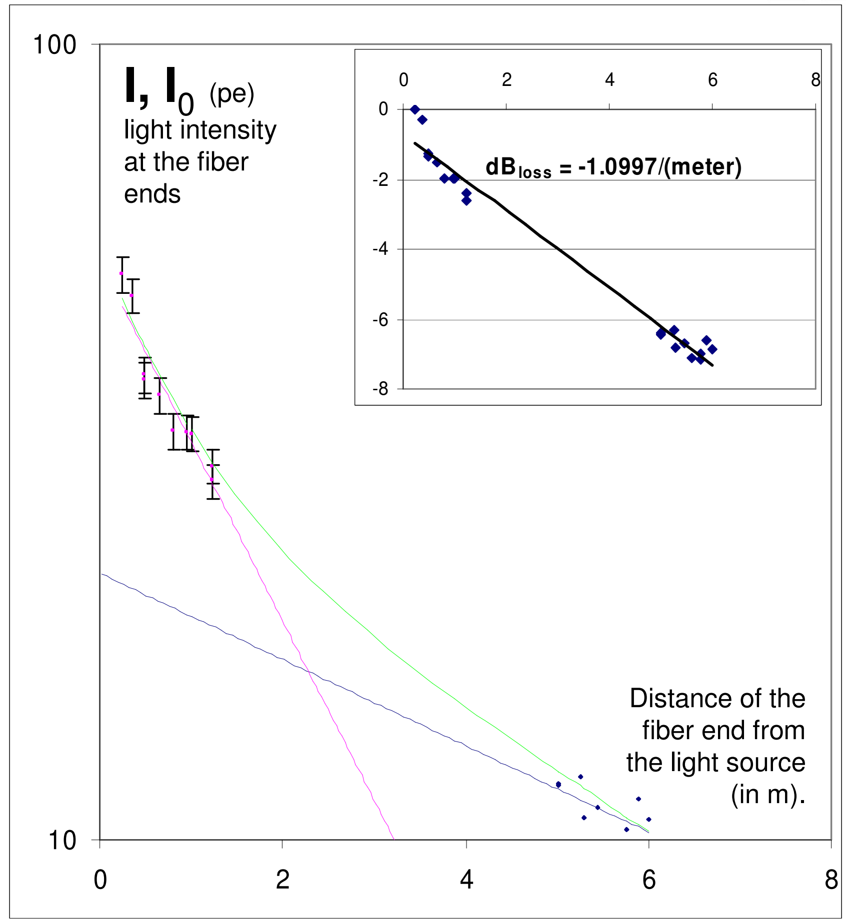
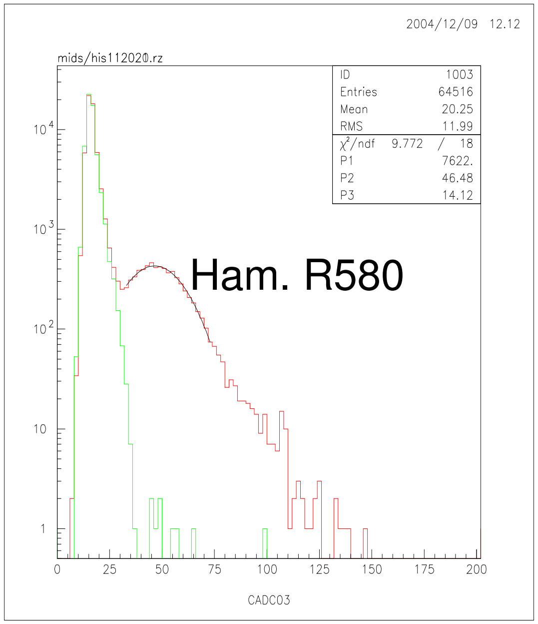
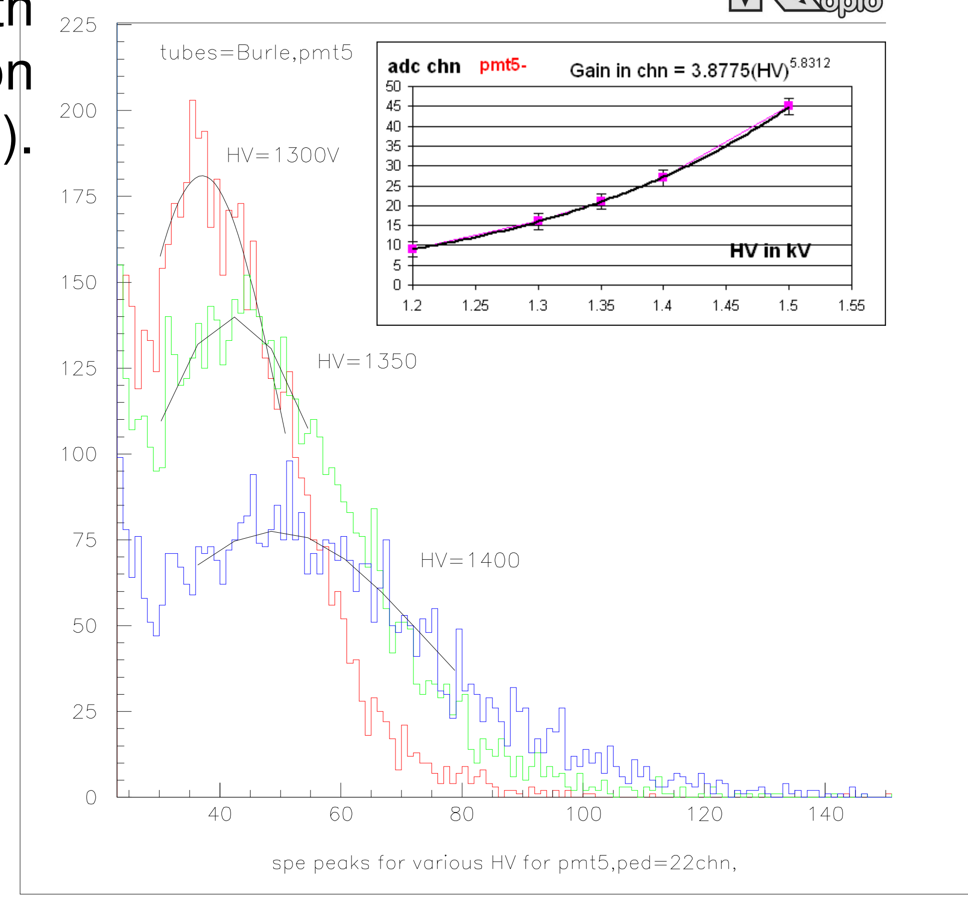


Photo-readout choices



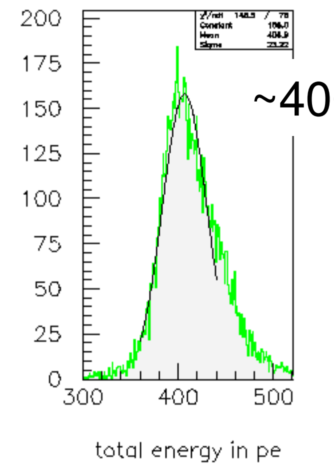
- Photomultiplier calibrations with Single Photo-Electron peak (SPE).



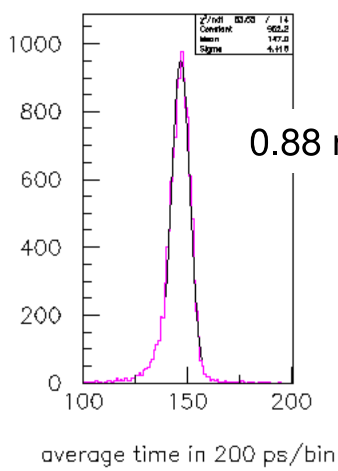
- Hamamatsu R580 (od. 2inch);
  - the industry standard of quiet pmt's clear spe.
  - Very low gain 2.10^6; amp for every channel.
- Burle 83112-511 (od 1inch) with newly improved spe and full calibration curve.
  - Q.E ~25% for 450 nm
  - Economical, gain 27.10^6 at 1500 V
  - very noisy >100Hz
  - When sampled with light of 0.1 pe at 1kHz the spe is revealed.

Final prototype

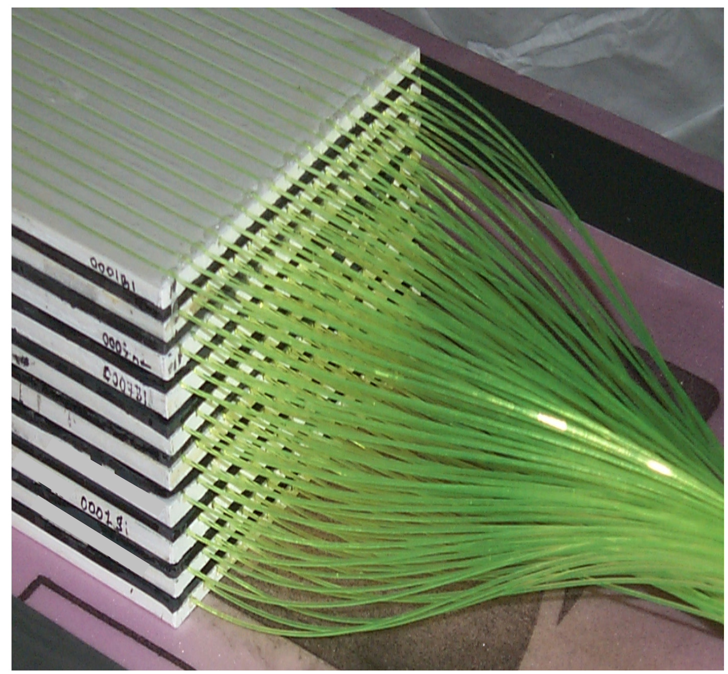
- Dimensions:
  - 10 scint +9 Pb tiles
  - 50cm x 15.5cm.
  - 1.3 m WLS-KMC fibers.
- Tested with cosmic rays at VTech.
- Also with pions and thermal neutrons at BNL (in schedule).



~400 p.e./m.i.p.



0.88 ns



Conclusion

"…Or watch the things you gave your life to, broken,
And stoop and build' em up with worn-out tools;…"

- **The KOPIO experiment could either confirm the SM picture of CP violation to be consistent with present knowledge and the relevant parameters measured accurately, or the need for new physics beyond SM would have been unequivocally demonstrated.**
- **Results from this measurement <u>will</u> be needed to interpret non-SM physics discoveries at BABAR, BELLE, CDF/D0, and the**
- **Demonstrated *Proof of Principle* for all parts of the experiment, with both test measurements and simulations**
- **Next phase was about to start when:**

  "These are compelling experiments, (n.a. RSVP) *and the scientific rationale for doing them is still strong," says Michael Turner, head of NSF's math and physical sciences directorate. "It was a very difficult decision, but the increased costs were too much to bear".* Science 08/19/2005

- **Possible futures: KOPIO@FermiLab or KOPIO@JPARC ?**