Time Reversal Exp't with Kaons

TREK @ J-PARC in Japan

Search for new Physics beyond the Standard Model using the Transverse Muon Polarization in $K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$ Decay

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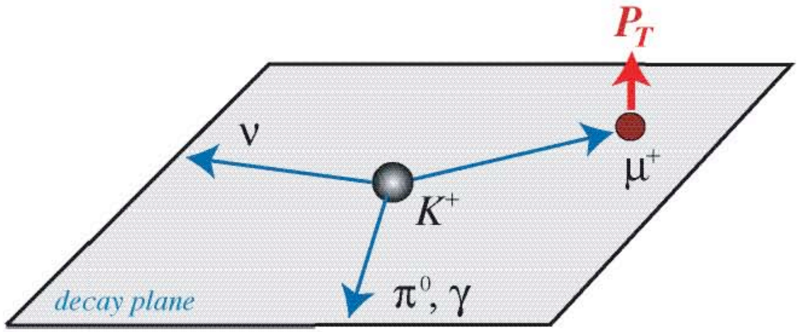
Transverse μ^+ polarization in $K_{\mu 3}$ Decay

$K^+ \rightarrow \mu^+ \pi^0 \nu$ decay

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}$$



- P_T is T-odd, and spurious effects from final state interaction are small: $P_T(\text{FSI}) < 10^{-5}$

  ➔ Non-zero P_T is a signature of T violation.

- Standard Model (SM) contribution to P_T : $P_T(\text{SM}) < 10^{-7}$

  Hence P_T in the range $10^{-3} - 10^{-5}$ is a sensitive probe of CP violation beyond the SM.

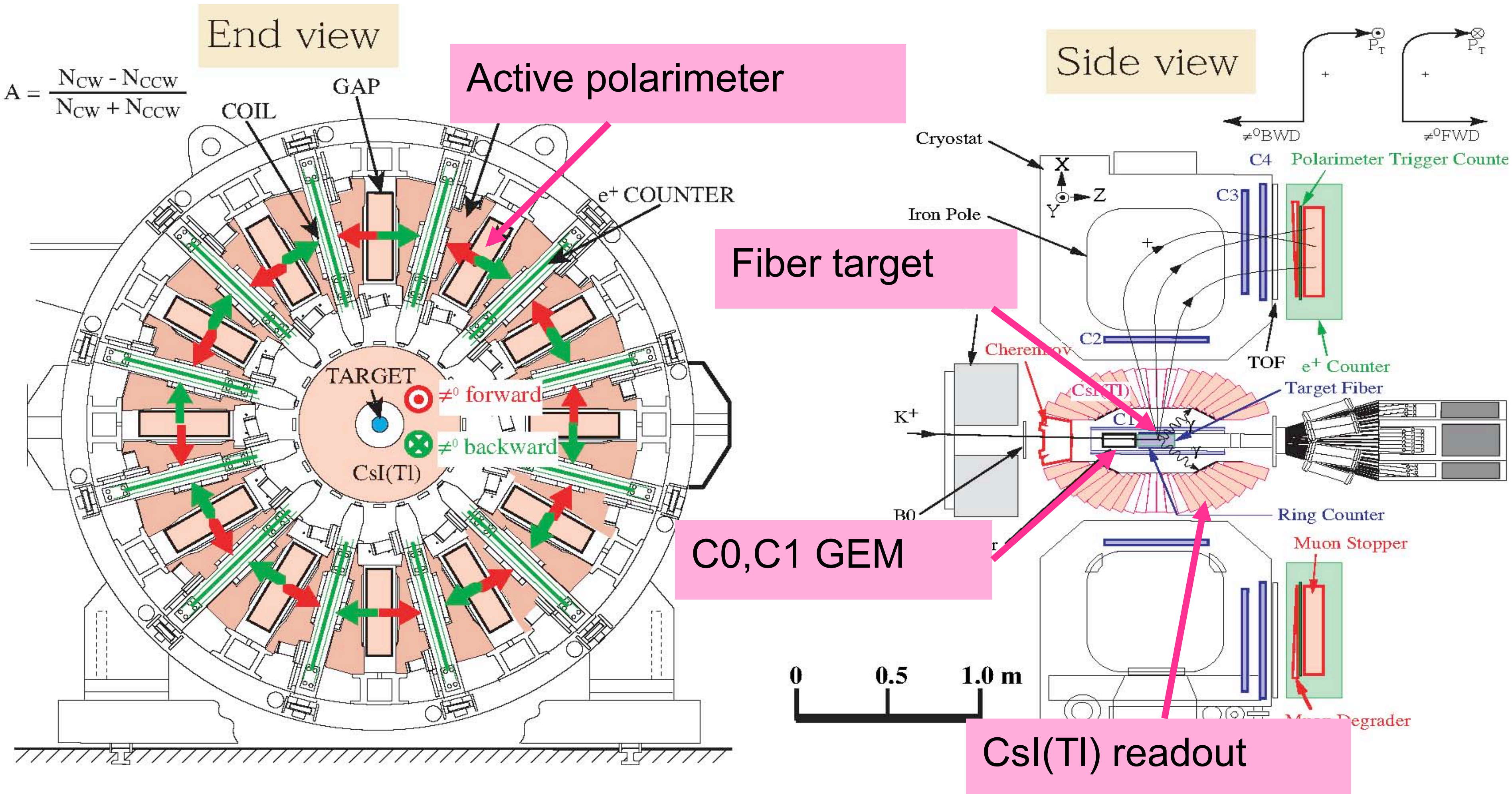
- There are theoretical models of new physics which allow a sizable P_T without conflicting with other experimental constraints.

The TREK experiment aims for a sensitivity of 10^{-4}

P_T measurement

$K^+ \rightarrow \mu^+ \pi^0 \nu$

Use upgraded KEK--E246 detector



P_T is measured as the azimuthal asymmetry A_e^+ of the μ^+ decay positrons

Stopped beam method

Double ratio experiment

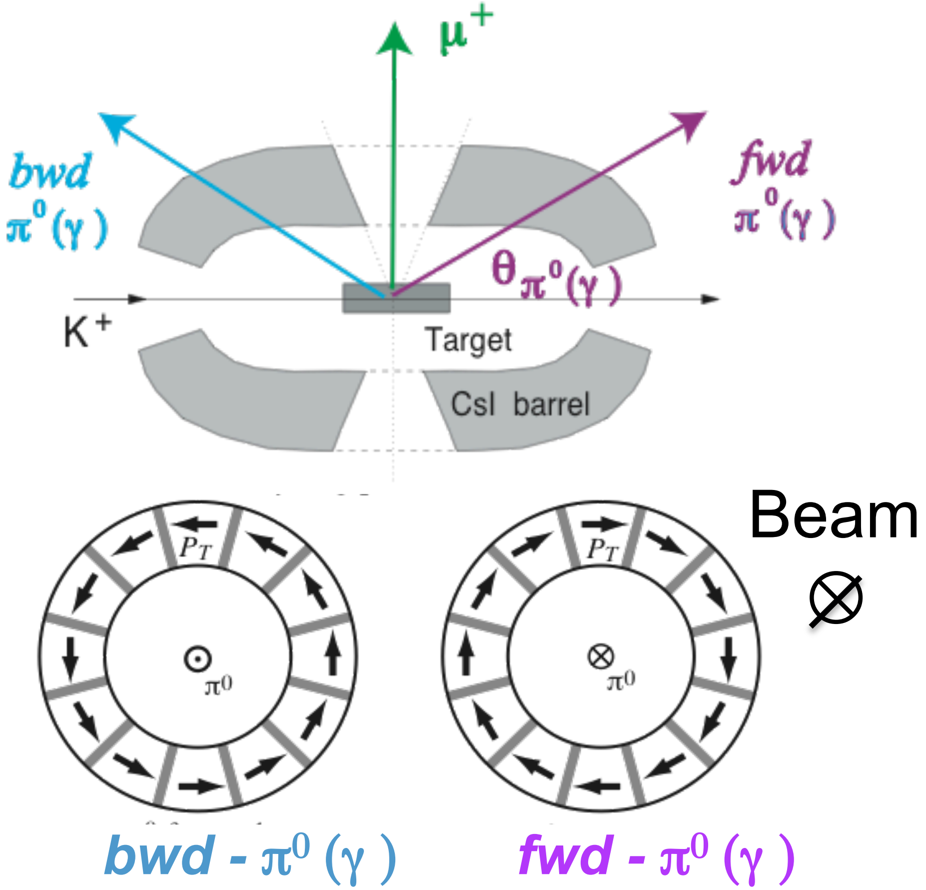
$A_T = (A^{fwd} - A^{bwd}) / 2$

$$A^{fwd(bwd)} = \frac{N_{cw} - N_{ccw}}{N_{cw} + N_{ccw}}$$

$P_T = A_T / \{\alpha \langle\cos\theta_T\rangle\}$

α : analyzing power
$\langle\cos\theta_T\rangle$: attenuation factor

$\mathrm{Im}\xi = P_T / KF$: physics parameter
KF : kinematic factor



Current limit from KEK--E246

$P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$

$|P_T| < 0.005$: 90% C.L.

$\mathrm{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$

$|\mathrm{Im}\xi| < 0.016$: 90% C.L.

Statistical error dominates

Expected sensitivity in TREK

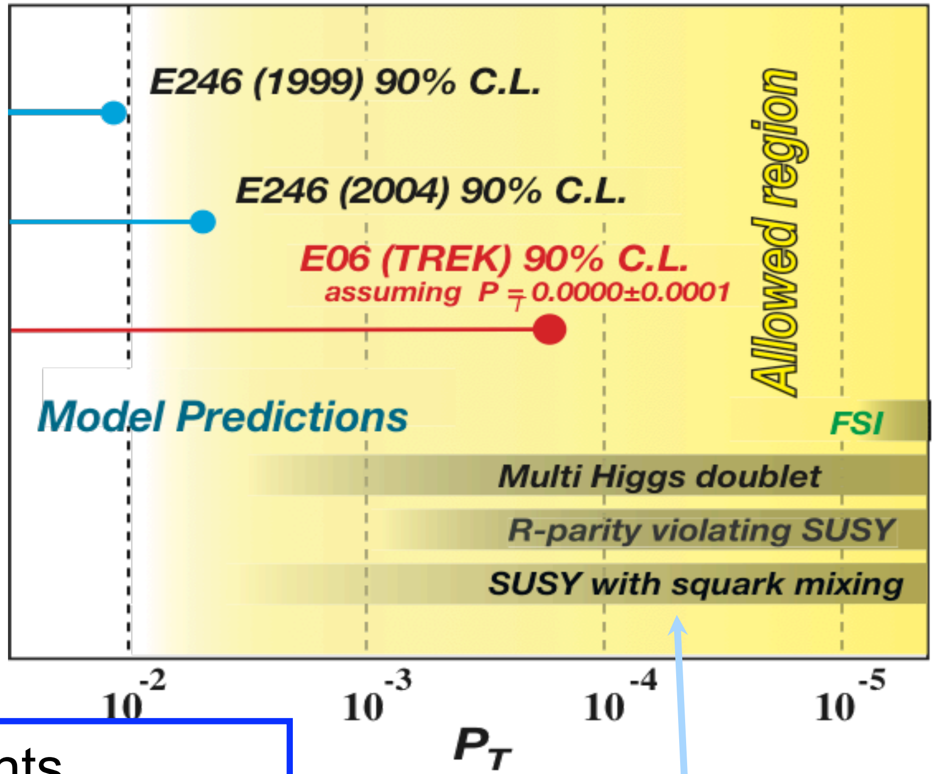
We are aiming for a sensitivity of $\delta P_T \sim 10^{-4}$

- $\delta P_T^{stat} \sim 0.05\ \delta P_T^{stat}(E246) \sim 10^{-4}$:   runtime 1.4×10^{7} sec

1) × 30 beam intensity
2) × 10 detector acceptance
3) Larger analyzing power

- $\delta P_T^{syst} \sim 0.1\ \delta P_T^{syst}(E246)$

  $\sim 10^{-4}$

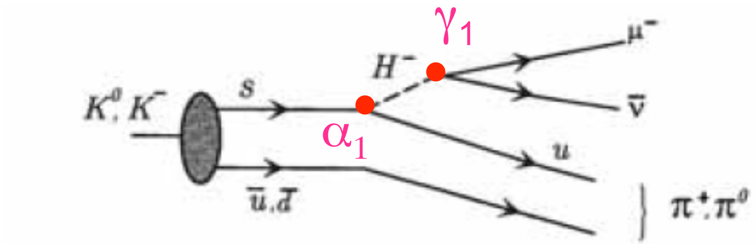


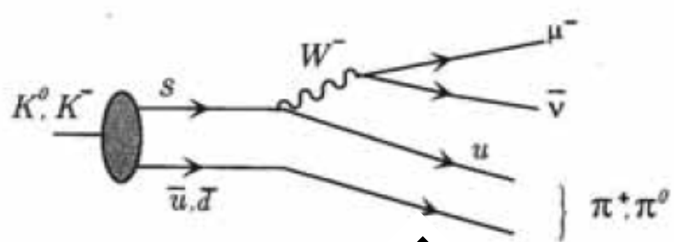
1) Precise calibration of misalignments
2) Elimination/Correction of systematic effects
3) Precise ***fwd-bwd*** cancellation

Very schematic

Three Higgs doublet model

$$L = (2\sqrt{2}G_F)^{\frac{1}{2}} \sum_{i=1}^{2} \{\alpha_i \bar{u_L} V M_D d_R H_i^+ + \beta_i \bar{u_R} M_U V d_L H_i^+ + \gamma_i \bar{\nu_L} M_E e_R H_i^+\} + \text{h.c.},$$





$$\text{Im}\xi = \frac{m_K^2}{m_H^2} \text{Im}(\gamma_1 \alpha_1^*)$$

- c.f. d_n, $b \rightarrow s\gamma$ $\propto$ Im($\alpha_1\beta_1$*), ($\alpha_1\beta_1$*)

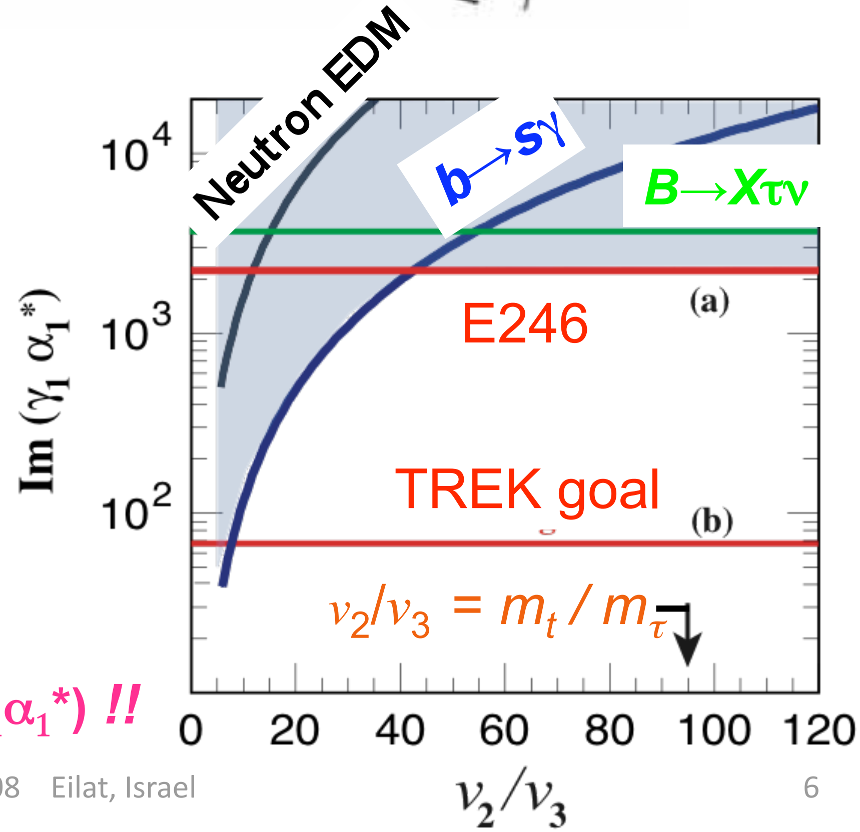
  Im($\alpha_1\beta_1$*) = $-v_2^2/v_3^2$ Im($\gamma_1\alpha_1$*)

  Higgs field vev.

- $B \rightarrow X\tau\nu$ and $B \rightarrow \tau\nu$ at Super-Belle correspond to $P_T < 3 \times 10^{-4}$

  c.f. TREK goal : $P_T \leq 1 \times 10^{-4}$

P_T is most stringent constraint for* Im($\gamma_1\alpha_1$*) *!!



SUSY with R-parity violation

Super potential : $W = W_{SMMS} + W_{RPV}$

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

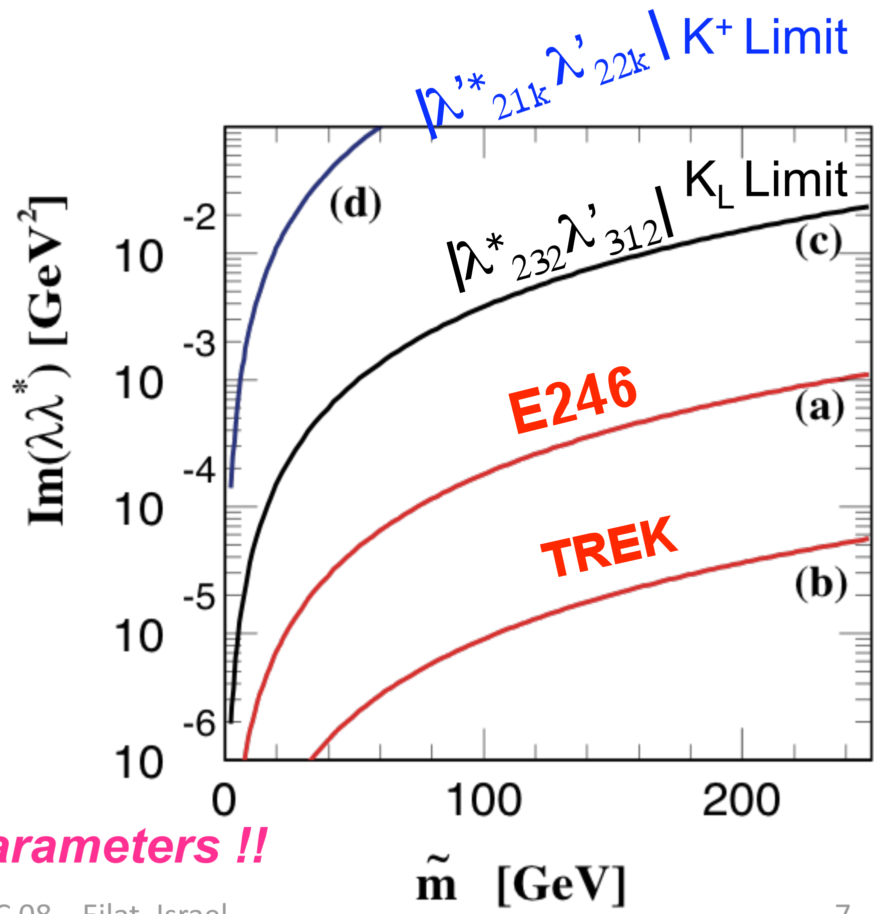
$$\mathrm{Im}\xi = \mathrm{Im}\,\xi^{l} + \mathrm{Im}\,\xi^{d}$$

$$\mathrm{Im}\xi^{\tilde{l}} = \sum_i \frac{\mathrm{Im}[\lambda_{2i2}(\lambda'_{i12})^*]}{4\sqrt{2}G_F \sin\theta_c (m_{\tilde{l}_i})^2} \cdot \frac{m_K^2}{m_\mu m_s}$$

$$\mathrm{Im}\xi^{\tilde{d}} = \sum_i \frac{\mathrm{Im}[\lambda'_{21k}(\lambda'_{22k})^*]}{4\sqrt{2}G_F \sin\theta_c (m_{\tilde{d}_k})^2} \cdot \frac{m_K^2}{m_\mu m_s}.$$

Relevant parameters and constraints

	Paraneter	Upper bound	Experiment
$\mathrm{Im}\xi^{\tilde{l}}$	$\lvert\lambda^*_{232}\lambda'_{312}\rvert$	$3.8 \times 10^{-6} m^2$	$K_L \to \mu^+\mu^-$ [19]
	$\lvert\lambda^*_{212}\lambda'_{112}\rvert$	no constraint	
	$\lvert\lambda^*_{222}\lambda'_{212}\rvert$	no constraint	
$\mathrm{Im}\xi^{\tilde{d}}$	$\lvert\lambda'^*_{211}\lambda'_{221}\rvert$	$2.8 \times 10^{-5} m^2$	$K^+ \to \pi^+\nu\bar{\nu}$ [20]
	$\lvert\lambda'^*_{212}\lambda'_{222}\rvert$	$2.8 \times 10^{-5} m^2$	$K^+ \to \pi^+\nu\bar{\nu}$ [20]
	$\lvert\lambda'^*_{213}\lambda'_{223}\rvert$	$2.8 \times 10^{-5} m^2$	$K^+ \to \pi^+\nu\bar{\nu}$ [20]



P_T is a very stringent constraint for these parameters !!

Exotic scalar interactions

$$P_T = \mathrm{Im}\xi \cdot \frac{m_\mu}{m_K} \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu|\vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K]} \cdot$$

Kinematic factor

- Generic four fermion interaction Lagrangian analysis

$$\mathrm{Im}\xi = \frac{(m_K^2 - m_\pi^2)\mathrm{Im}G_S^*}{\sqrt{2}(m_s - m_u)m_\mu G_F \sin\theta_C}$$

- Effective field theory with Wilson coefficients

$$P_\perp \sim \left[0.38\mathfrak{Im}C_S^K - 0.27\frac{p_K\cdot(p_\nu - p_\mu) + m_\mu^2/2}{M_K^2(f_+/f_T)}\mathfrak{Im}C_T^K\right]\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

	E246	TREK
$\lvert\mathrm{ImGs}\rvert / G_F$	$< 2.2 \times 10^{-4}$	$< 1 \times 10^{-5}$
$\lvert\mathrm{Im}\ C_S\rvert\ (\Lambda/\mathrm{TeV})^2$	$\leq 2 \times 10^{-3}$	$\leq 1 \times 10^{-4}$

- Typical models with scalar interactions allowing a sizable P_T:
  - Multi-Higgs doublet model
  - SUSY with R-parity violation or large squark mixing

Direct CP violation

- Direct CP violation in K^0 system :

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1.66 \pm 0.26) \times 10^{-3} \quad \Rightarrow$$

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\bar{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^+\pi^-)} = (5.04 \pm 0.22) \times 10^{-6} \equiv R$$

- *If this effect is due to Higgs dynamics:*

there will be no ΔI=1/2 suppression (~ 20) in the K^+ system

$$\Rightarrow \quad \boxed{P_T \sim R \times 20 = 5 \times 10^{-6} \times 20 \sim 10^{-4}}$$

-- *unless there is an enhanced coupling to leptons !*

(I. Bigi, CERN Flavor WS, 2007)

Status of TREK collaboration

Table 5: TREK collaboration constituents

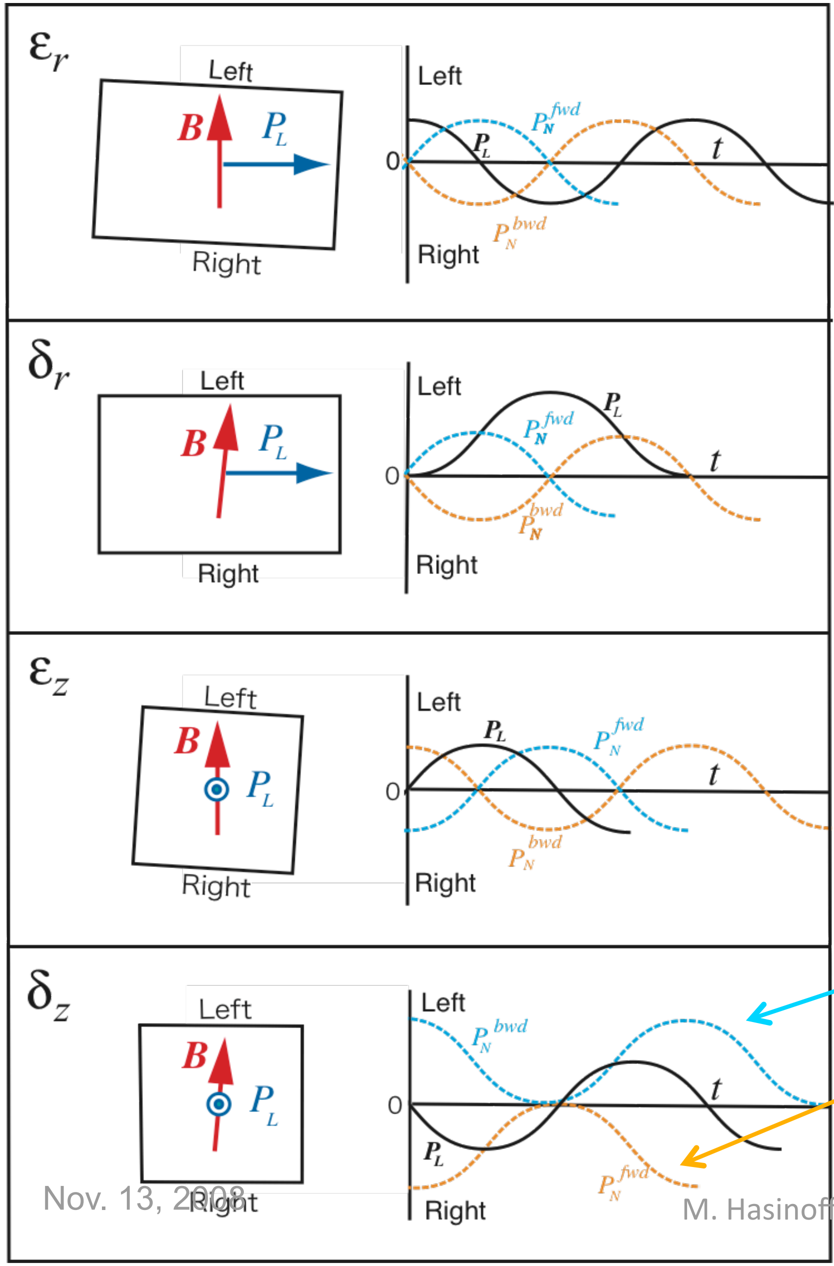
Canada	University of Saskatchewan University of British Columbia (UBC) TRIUMF University of Montreal
U.S.A.	Massachusetts Institute of Technology (MIT) University of South Carolina Iowas State University Hampton University Jefferson Laboratory
Japan	Osaka University National Defense Academy Tohoku University High Energy Accelerator Research Organization (KEK) Kyoto University Tokyo Institute of technology (TiTech)
Russia	Institute for Nuclear Research (INR)
Vietnam	University of Natural Sciences
Thailand	Kasetsart University

- New participants:
  - Kasetsart University, Thailand
  - Jefferson Laboratory
  - Tokyo Institute of Technology

- Number of members:
  - 35 in Jan'08, presently 44
- Collaboration meetings:
  - Feb. 2006 @ KEK
  - Oct. 2006 @ MIT (USA)
  - Feb. 2007 @ KEK
  - Sep. 2007 @ U.Sask.(Canada)
  - Feb. 2008 @ KEK
  - Oct. 2008 @ USC (USA)
- International detector R&D
  - Target : Canada, USA
  - CsI(Tl) readout : Russia
  - Polarimeter : Japan

Most serious systematic error

- Analysis with MC simulations -



e^+ asymmetry due to polarimeter misalignment

	Rotation about	
Component	*r*-axis	*z*-axis
Polarimeter	ε_r	ε_z
Muon B field	δ_r	δ_z

fwd - ***bwd*** : vanishes for ε_r , ε_z , δ_r when *t*-integrated

fwd - ***bwd*** : does **not** vanish for δ_z !

- *Innovative analysis method to separate misalignment effects*

Misalignment analysis using $K_{\mu 3}$

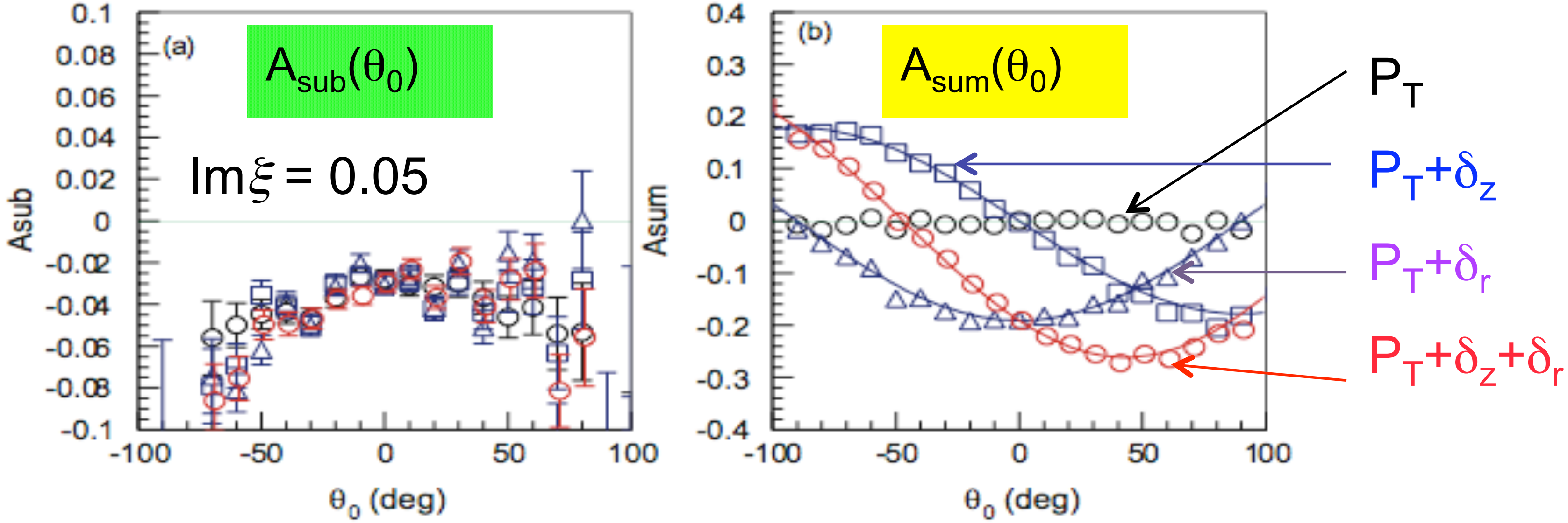
Asymmetry analysis in terms of θ_0 : in-plane muon spin angle from z-axis

$$A_{sum}(\theta_0) = (\bar{A}_{fwd}(\theta_0) + \bar{A}_{bwd}(\theta_0))/2 = \alpha_0\{\delta_r \cos\theta_0 - \delta_z \sin\theta_0 + \eta(\theta_0)\} + \gamma$$

$$A_{sub}(\theta_0) = (\bar{A}_{fwd}(\theta_0) - \bar{A}_{bwd}(\theta_0))/2 = F(P_T, \theta_0).$$

Report to the 3rd PAC meeting

small residual oscillation

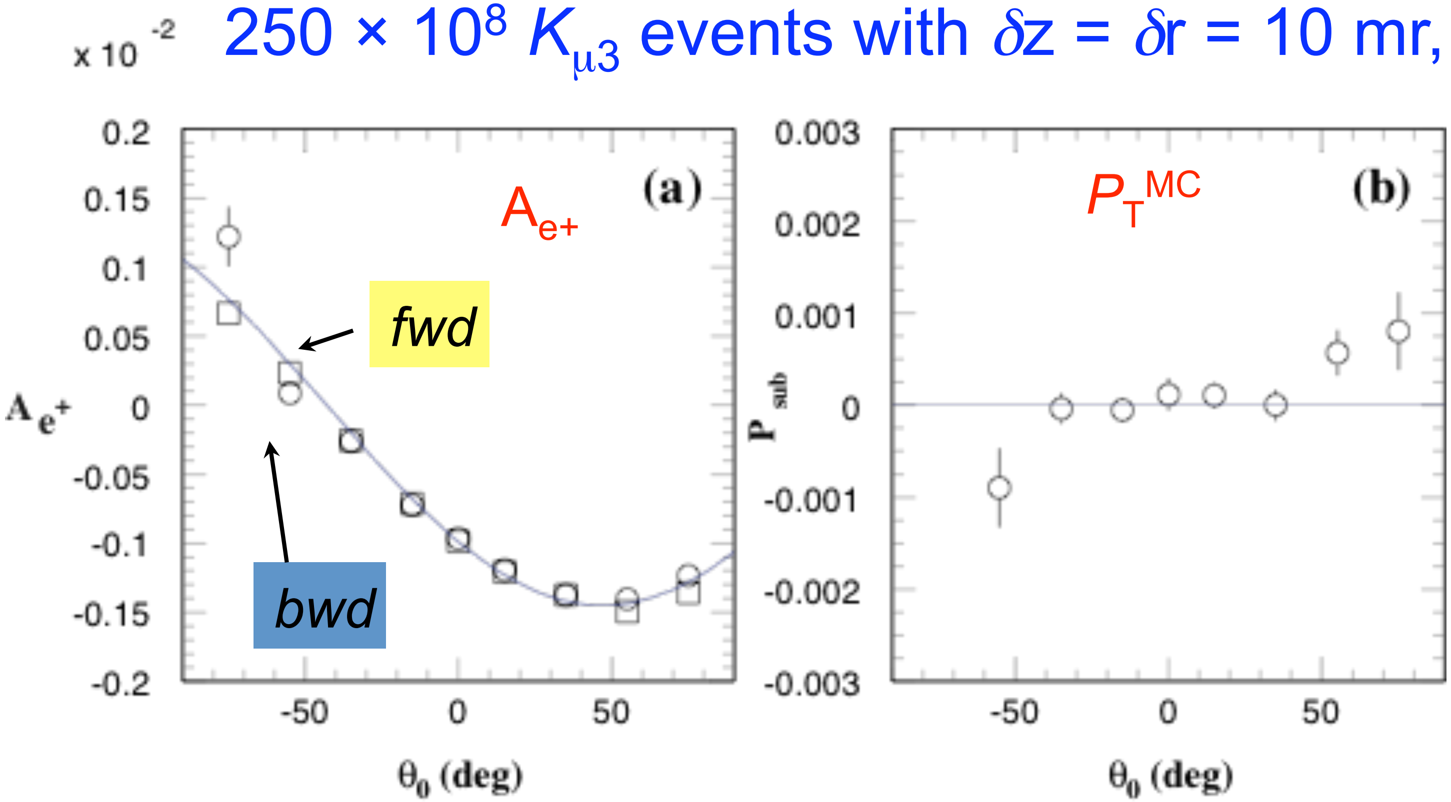


- $\Delta\delta_z \sim \Delta\delta_r \sim 3 \times 10^{-4}$ for misalignment determination
- $P_T = 0$ and $\delta_z = \delta_r = 5^o = 87$ mr (for systematic error test)

  ==> $\delta P_T = (2 \pm 7) \times 10^{-4}$ for 10^8 events

Result of high statistics MC simulation

250×10^8 $K_{\mu3}$ events with $\delta z = \delta r = 10$ mr, $P_T = 0$

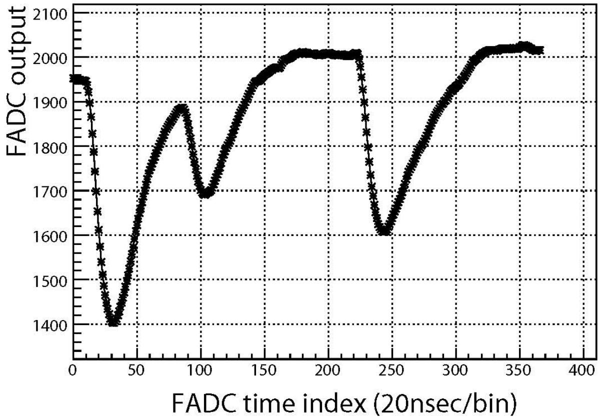


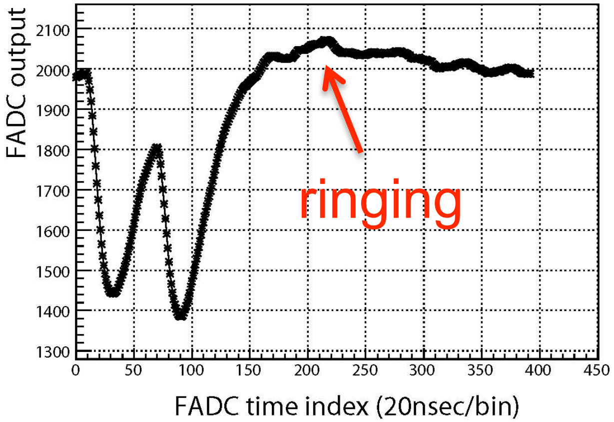
$P_T^{MC} = < P_{sub} > = (3 \pm 6) \times 10^{-5}$

- Within the statistical error, no bias was found in the analysis of this MC data nor the analysis code itself.
- Final systematics check will be done using the final analysis code together with a detailed analysis of real data.

Analysis of CsI pile-up events

- Separation of two pulses



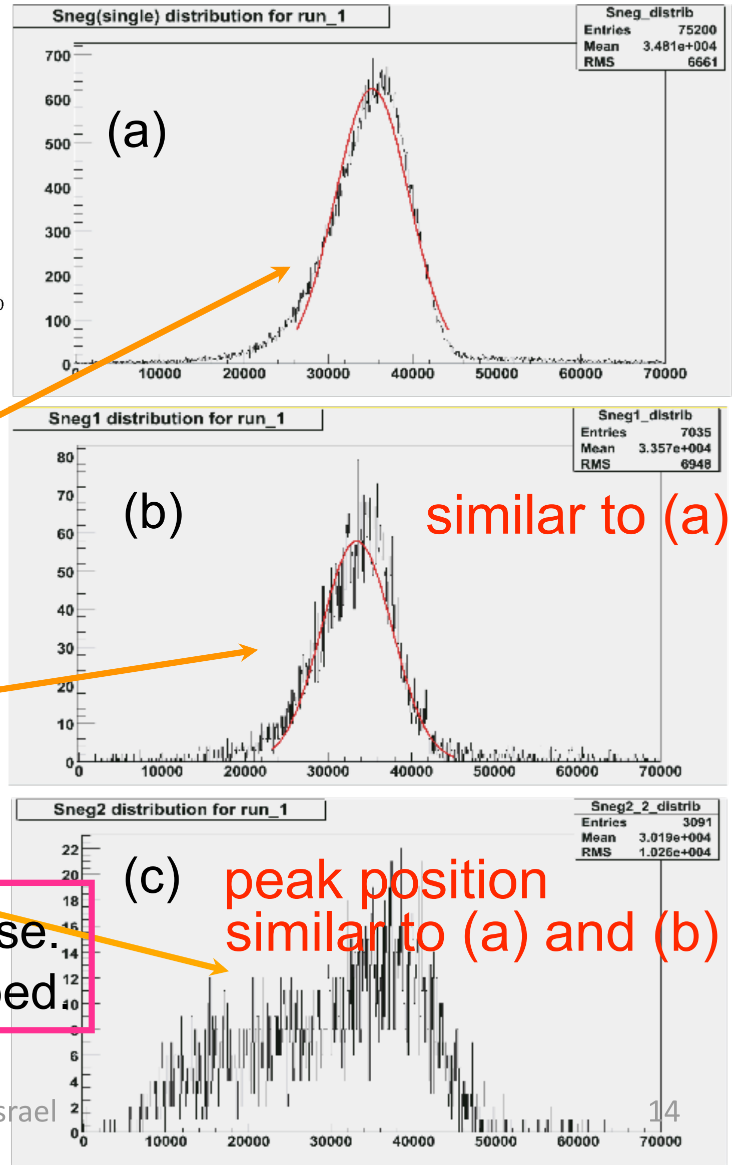


Typical pile-up events in a high rate run

Fitting function =
$a_1F(x) + a_2F(x+\Delta x)$

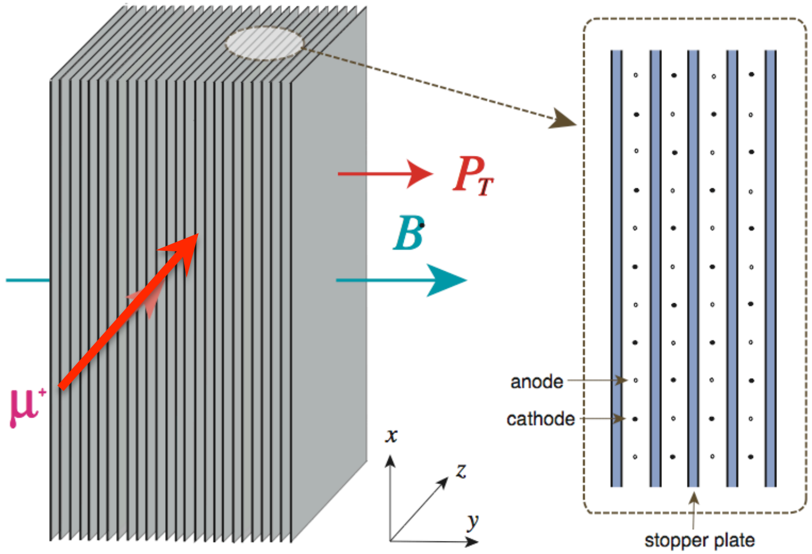
(a) non-pileup events
(b) first pulse in pileup events
(c) second pulse in pileup events

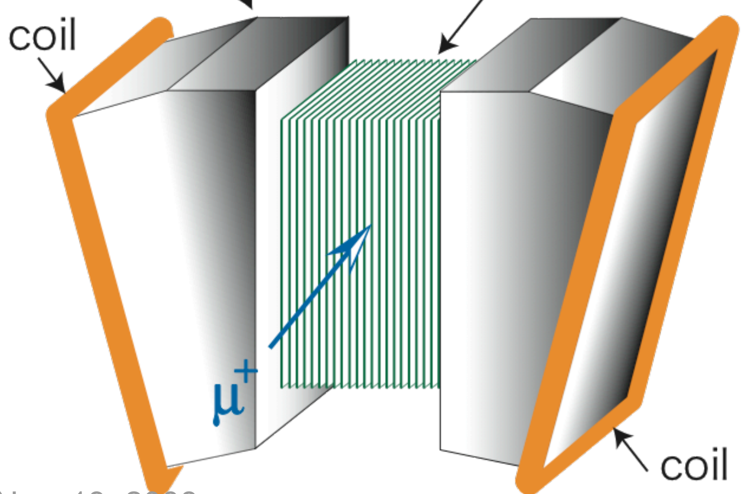
Signal area distribution



- Study is underway on how to analyze the second pulse.
- An improved current amplifier has now been developed.

Detector preparation (1) Active muon polarimeter





Gap wire chambers

Number of plates	31
Plate material	Al, Mg or alloy
Plate thickness	~ 2.5 mm
Plate gap	~ 8 mm
Ave. density	0.24 ρ_{Al}
μ^+ stop efficiency	~ 85%

Muon field magnet

Table 6: Main parameters of the muon field magnet

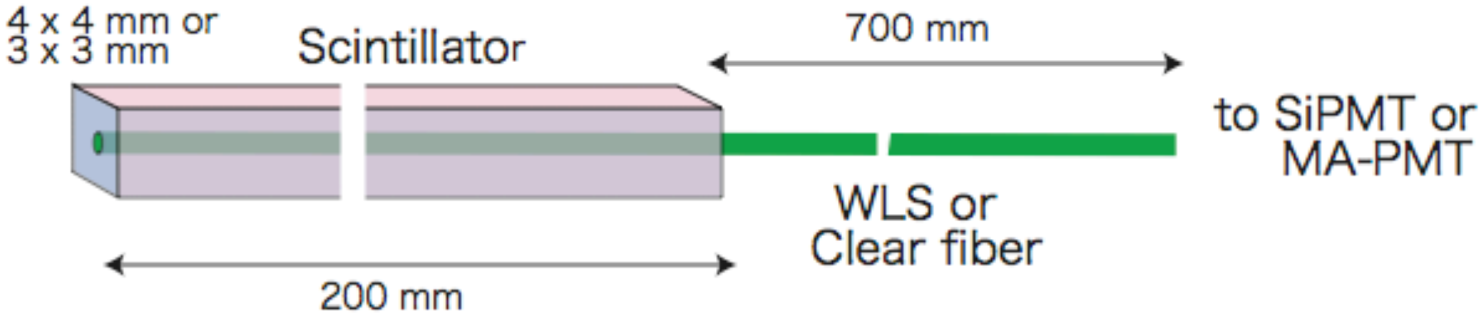
Parameter	Value
B	0.03 T
Gap	30 cm
Pole face	60 cm$^H \times$ 40 cm^W
MMF	7.2 (or 3.6)$\times 10^3$ A·turn/coil
Number of coils	12 (or 24)
Coil size	5$\times$ 10 (or 5) cm^2
Power	500 (250) W /coil
Total power	6 kW
Cooling	indirect water cooling
Total weight	5 ton

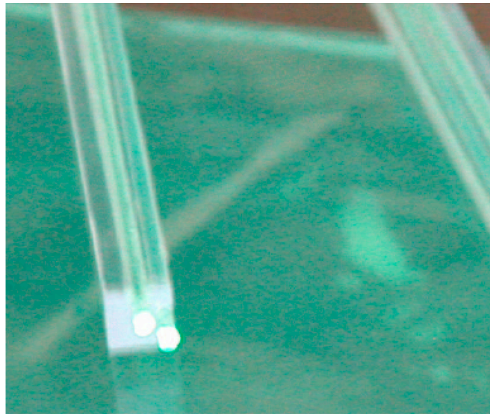
Detector preparation (2) Active fiber target

One element

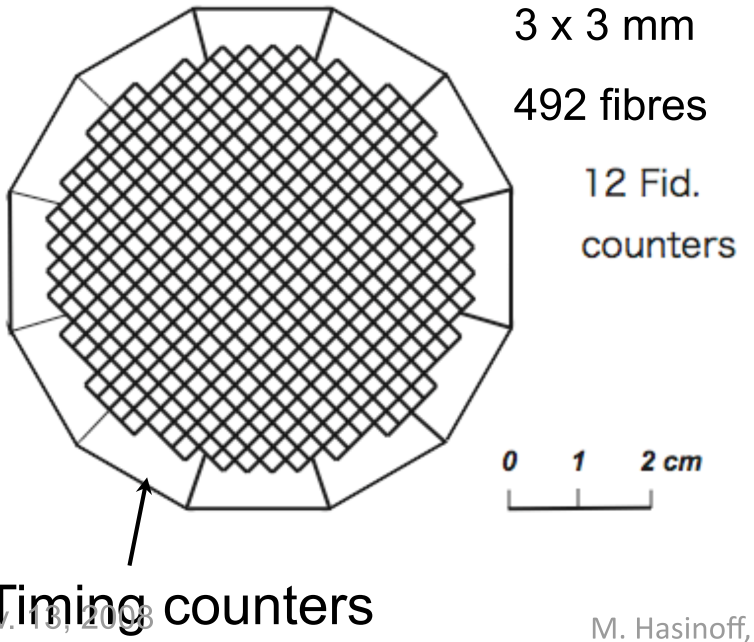
Current baseline design

c.f. E246 Ring counters
PSI FAST target



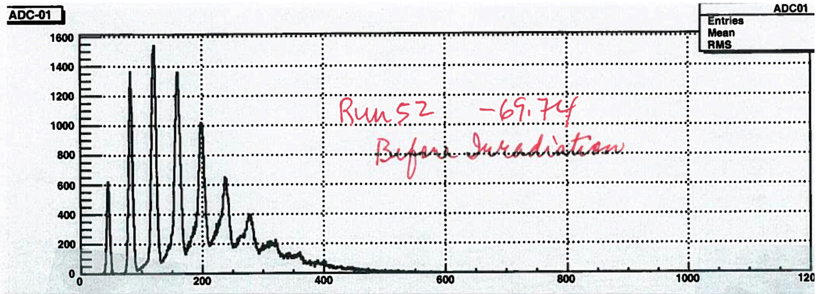


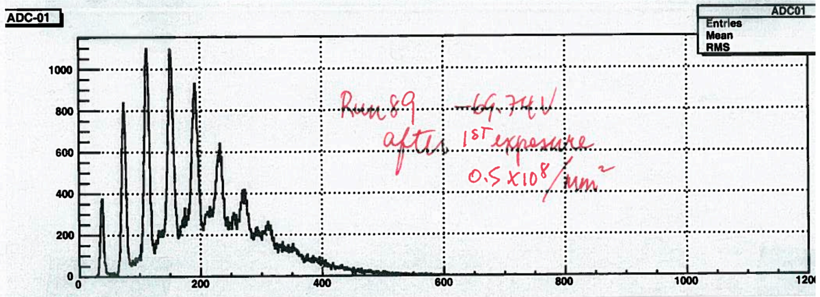
Cross section

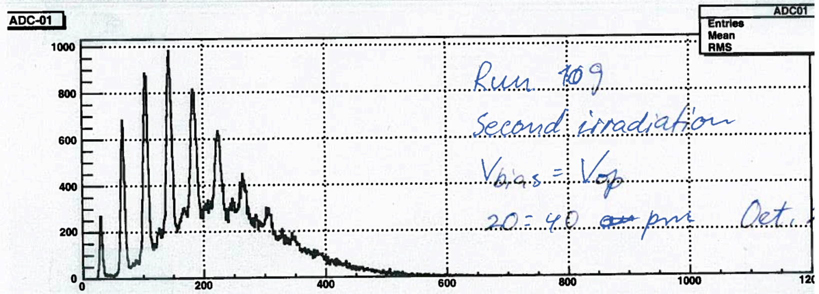


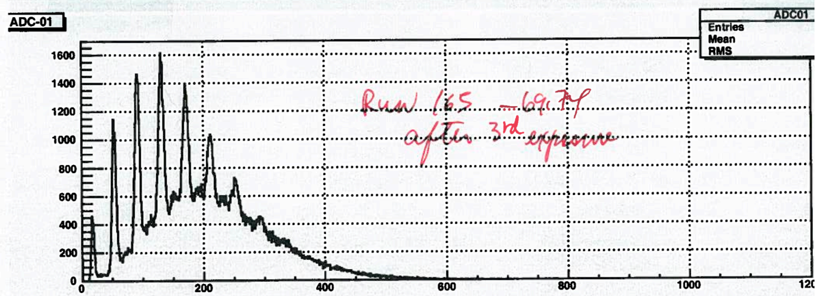
- Light guide:
  Bicron 692 WLS or Kuraray Y11
  WLS or Clear optical fiber
- Readout:
  SiPMT (HPK MPPC) or MA-PMT
- Beam test using 130 MeV/*c* π's
  at TRIUMF in October'08

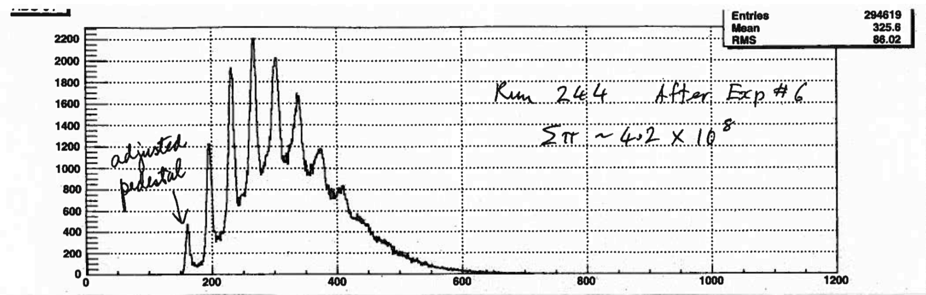
MPPC Test with TRIUMF π^+ Beam

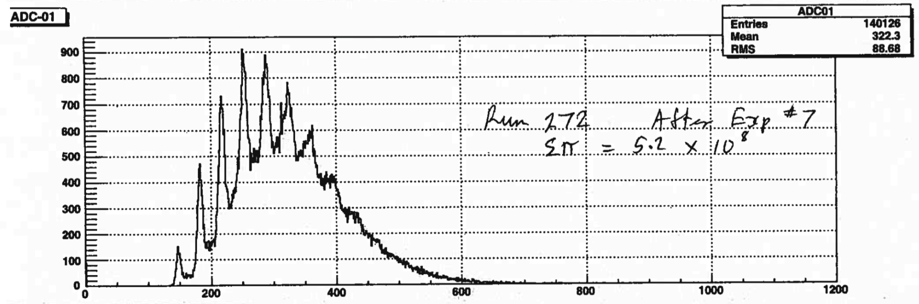


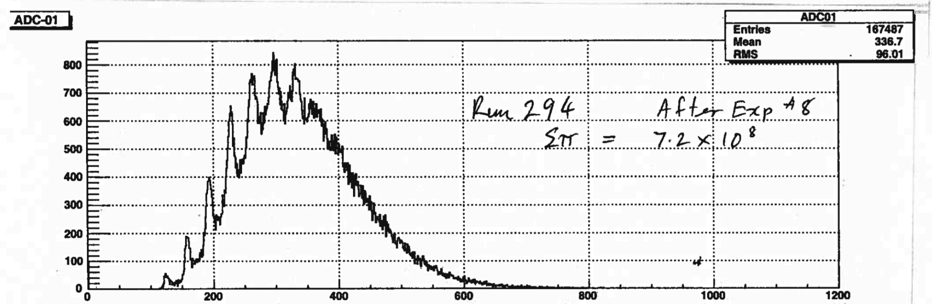


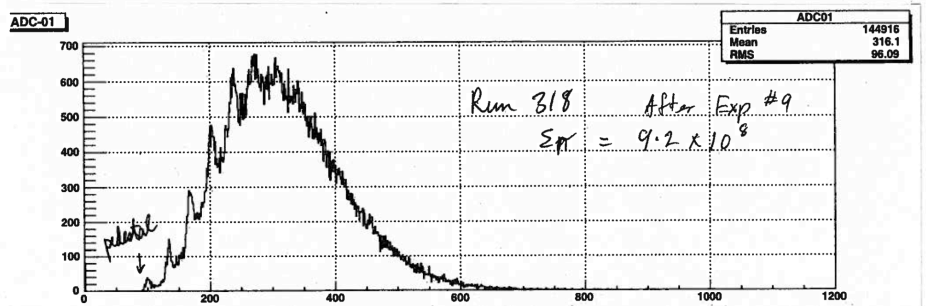












Comparison to Other T-Violation Expts

Neutron Decay ILL-Trine, EmiT, PSI

$$D \frac{\boldsymbol{\sigma}_n}{\sigma_n} \cdot \frac{\boldsymbol{p}_e \times \boldsymbol{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}}$$

P conserving, T violating — sensitive to V,A-- LRS models, Leptoquarks, Exotic Fermions

$$R \frac{\boldsymbol{\sigma}_e}{\sigma_e} \cdot \frac{\boldsymbol{\sigma}_n \times \boldsymbol{p}_e}{\sigma_n E_e}$$

P & T violating — sensitive to Scalar & Tensor Interactions

Present Limit – $D_{avg} < (-3.9 \pm 5.8) \times 10^{-4}$, FSI ~ 1×10^{-5}

Present Limit – R no result , FSI ~ 1×10^{-3}

Present Limit – $P_T < (-1.7 \pm 2.7) \times 10^{-3}$, FSI ~ 1×10^{-5}

EDMs neutron $d_n < 2.9 \times 10^{-26}$ e.cm

Atomic $d_{Hg} < 2.1 \times 10^{-28}$ e.cm

Possible Nuclear Enhancements—^{223}Rn