Progress Report to PAC5

J-PARC E06 Experiment (TREK)

Measurement of T-violating Transverse Muon Polarization (P_T) in $K^+ \rightarrow \pi^0 \mu^+ \nu$ Decays

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June 6, 2007

1. Outline of the TREK experiment
2. Theoretical model descriptions of P_T
3. Funding and collaboration
4. Study of beamline
5. Progress of detector design and R&D
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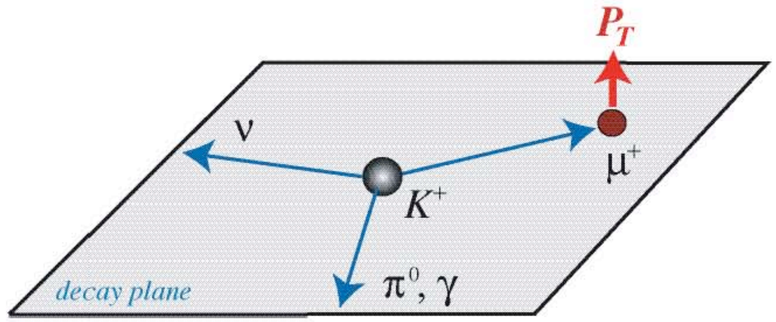
Outline of the TREK experiment

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

$K^+ \to \pi^0 \mu^+ \nu$ 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: $P_T(\mathrm{FSI}) < 10^{-5}$

  Non-zero P_T is a signature of T violation.

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

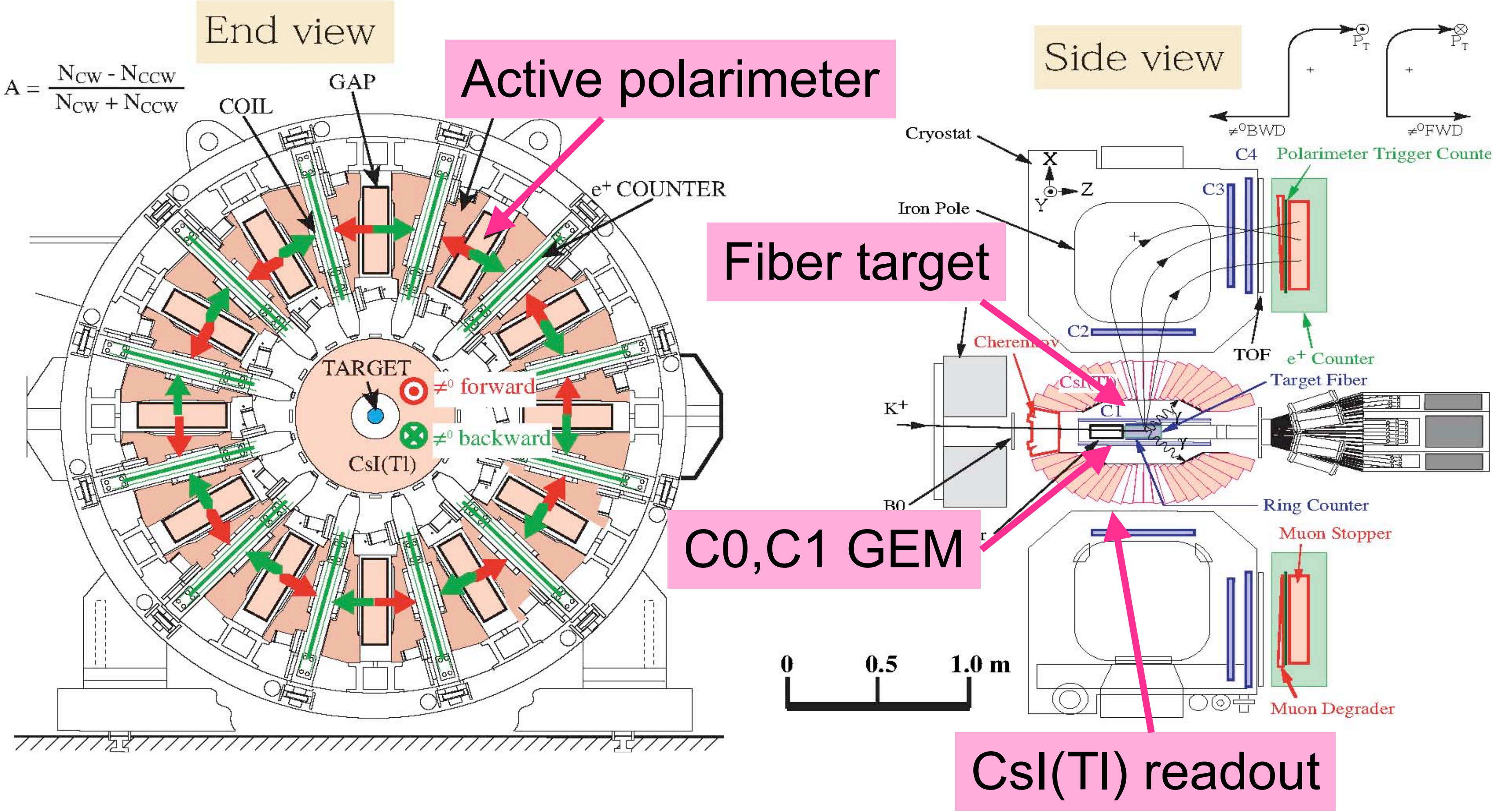
  P_T in the range 10^{-3}~10^{-4} is a sensitive probe of CP violation beyond the SM.

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

P_T measurement

Use of upgraded E246 detector

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



P_T measured as the azimuthal asymmetry A_{e^+} of the μ^+ decay positrons

Stopped beam method

Double ratio experiment

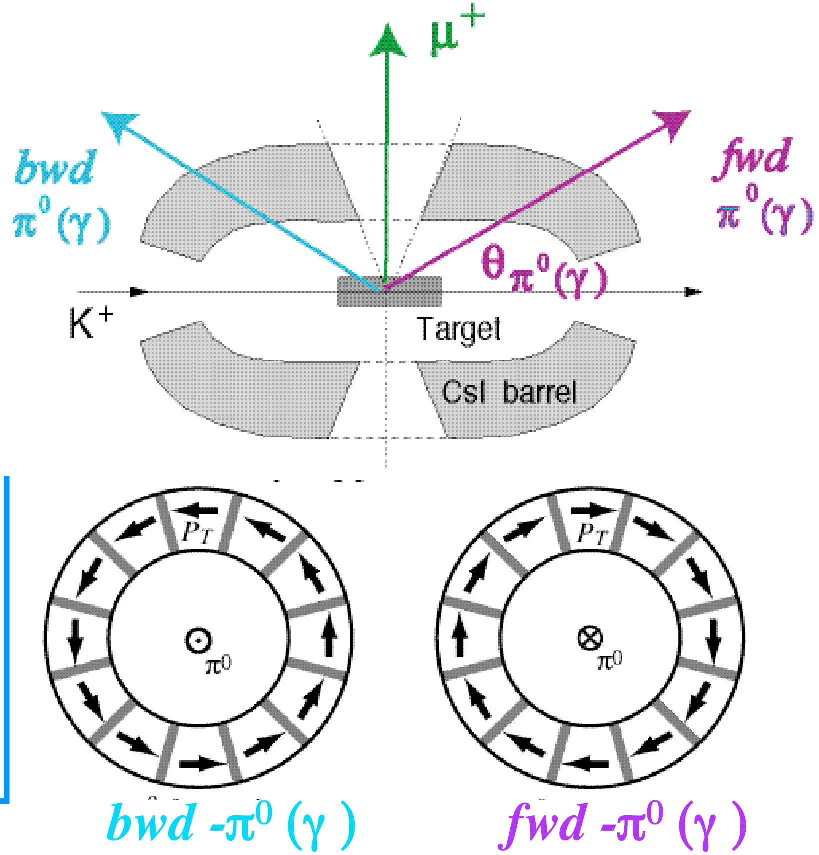
$$A_T = (A^{fwd} - A^{bwd})\,/\,2$$

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

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

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

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



Current limit from E246

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

$(\,|P_T| < 0.0050 : 90\%\ C.L.\,)$

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

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

Statistical error dominant

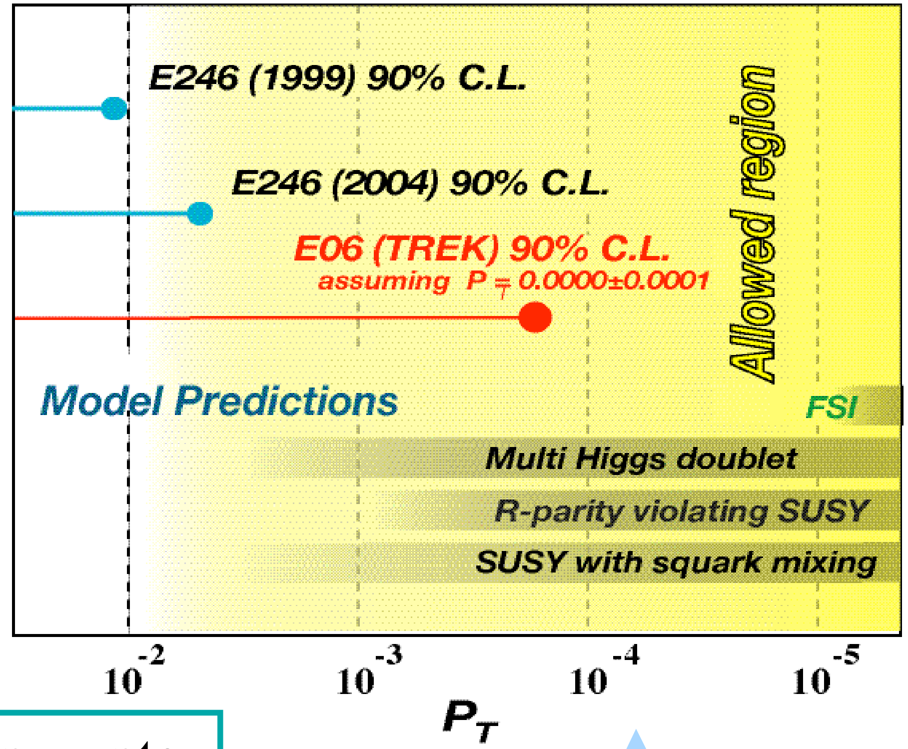
Expected sensitivity in TREK

We aim at a sensitivity of $\delta P_T \sim 10^{-4}$

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

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

- $\delta P_T^{syst} \sim 0.1\ \delta P_T^{syst}$ (E246) $\sim 10^{-4}$

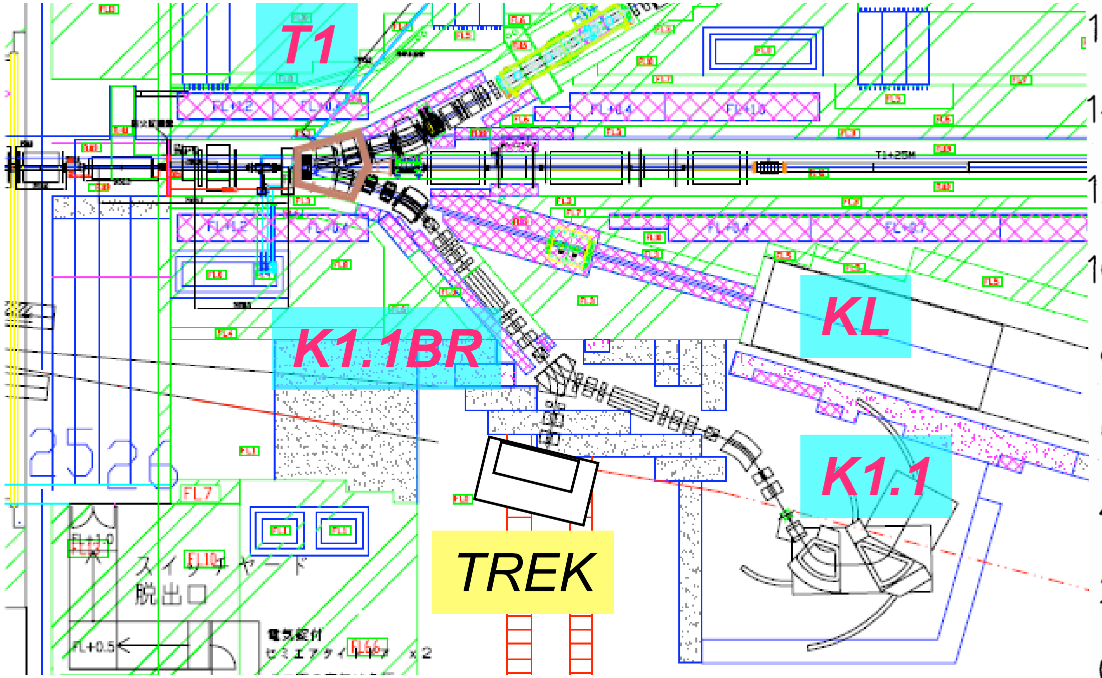


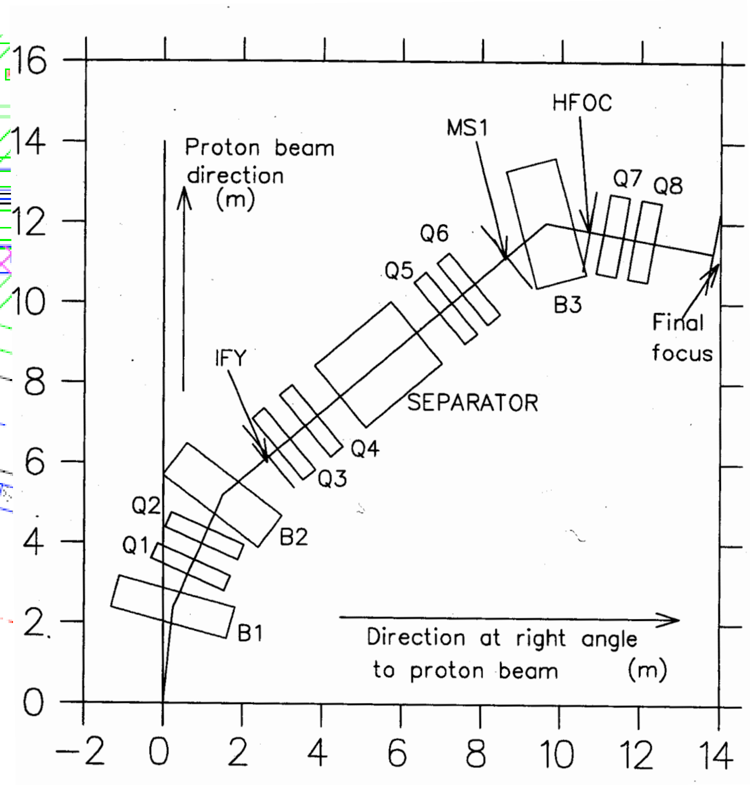
1) Precise calibration of misalignments
2) Correction of systematic effects
3) Precise ***fwd-bwd*** cancellation

Very schematic

K0.8 (K1.1-BR) for stopped K^+

- Use of T1 target sharing with K1.8 and KL
- Macroscopic time sharing with K1.1 if it would be installed





- $I_{K^+} = 2.1 \times 10^6$ /s @ 9 μA- 30 GeV protons on T1
- K/π ratio > 1.0

Theoretical model descriptions of P_T

Exotic scalar interactions

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

- 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

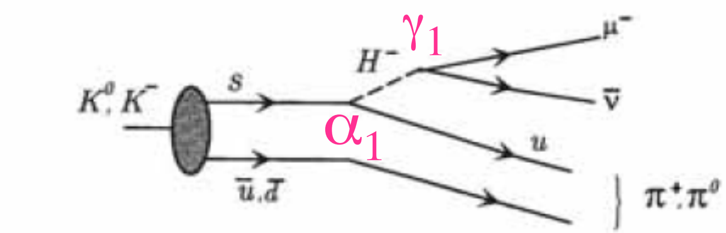
$$P_\perp \sim \left[0.38\Im\mathrm{m}C_S^K - 0.27\frac{p_K \cdot (p_\nu - p_\mu) + m_\mu^2/2}{M_K^2(f_+/f_T)}\Im\mathrm{m}C_T^K\right]\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

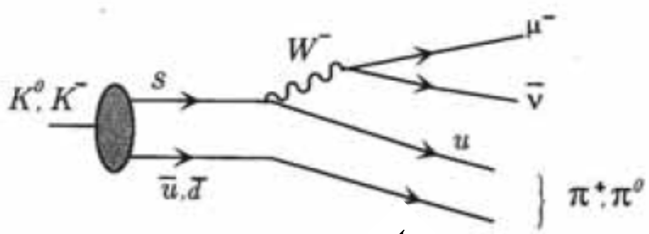
	E246	TREK
$\|\mathrm{ImG_s}\| / G_F$	$< 2.2 \times 10^{-4}$	$< 1 \times 10^{-5}$
$\|\mathrm{Im}\ C_S\|\ (\Lambda/\mathrm{TeV})^2$	$\leq 2 \times 10^{-3}$	$\leq 1 \times 10^{-4}$

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

Three Higgs doublet model

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





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

- c.f. d_n , $b \to s\gamma$ $\propto$ $\mathrm{Im}(\alpha_1\beta_1^*)$, $(\alpha_1\beta_1^*)$

$\mathrm{Im}(\alpha_1\beta_1^*) = -\underline{v_2^2/v_3^2}\,\mathrm{Im}(\gamma_1\alpha_1^*)$

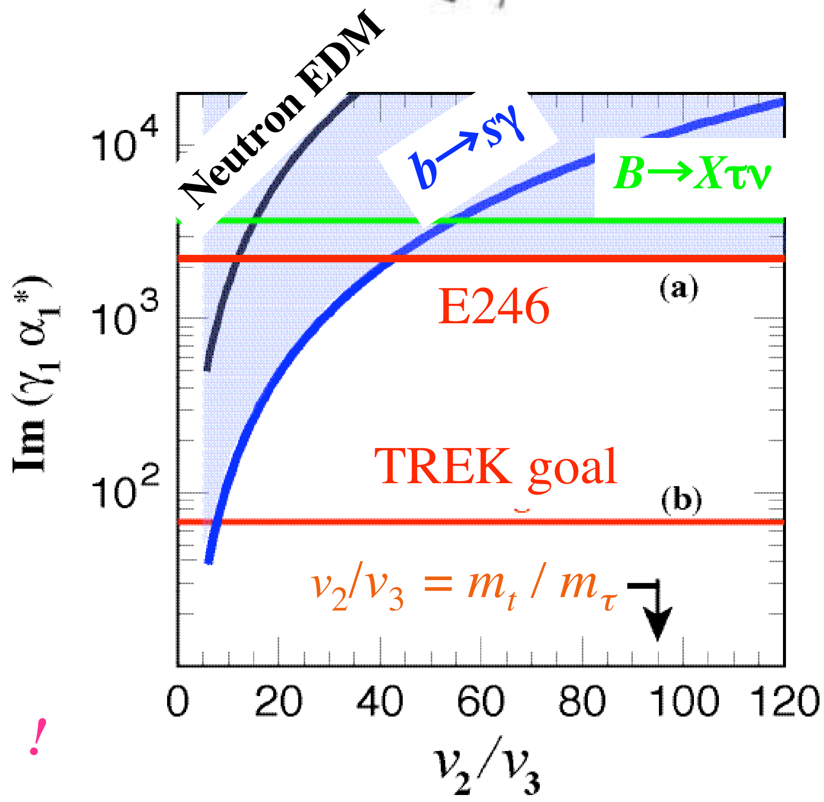
Higgs field v. e. v.

- $B \to X\tau\nu$ and $B \to \tau\nu$ at Super-Belle

corresponds 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* $\mathrm{Im}(\gamma_1\alpha_1^*)$ *!



SUSY with R-parity violation

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

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

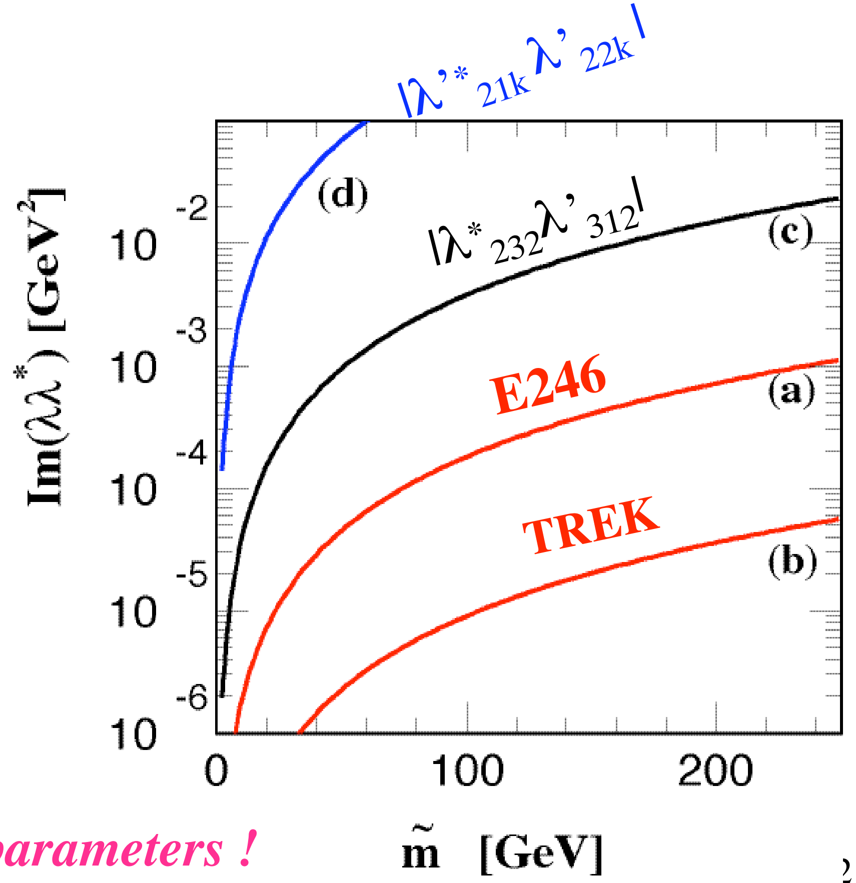
$$\mathrm{Im}\xi = \mathrm{Im}\ \xi^l + \mathrm{Im}\ \xi^d$$

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

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

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 !

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:*

  Because there is no $\Delta I = 1/2$ suppression (~ 20) in the K^+ system

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

-- *unless enhanced couplings to leptons!*

(I. Bigi, CERN Flavor WS, 2007)

Funding and collaboration

Comments from last PAC meeting

….. *Overall the PAC is impressed with the progress of E06 and feels that this is an important measurement to be made at J-PARC. However, before recommending stage-2 approval, the PAC would like to see progress by the TREK collaboration in securing the funding for the experiment both internationally and domestically and in the collaborative effort with the E14 experiment to define and design workable beamlines for both the KL and K1.1 lines.*

Status of TREK collaboration

Table 5: TREK collaboration constituents

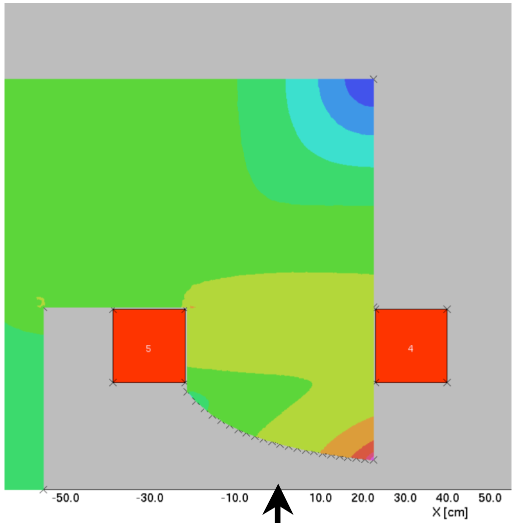
Canada	University of Saskatchewan
	University of British Columbia (UBC)
	TRIUMF
	University of Montreal
U.S.A.	Massachusetts Institute of Technology (MIT)
	University of South Carolina
	Iowas State University
	Hampton University
	Jefferson Laboratory
Japan	Osaka University
	National Defense Academy
	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 participation:
  - Kasetsart University
  - Jefferson Laboratory
  - Tokyo Institute of Technology

- Number of members:
  - 35 in Jan. '08 to 44 now
- 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

Study of beamline

K1.1-BR B1 combined magnet



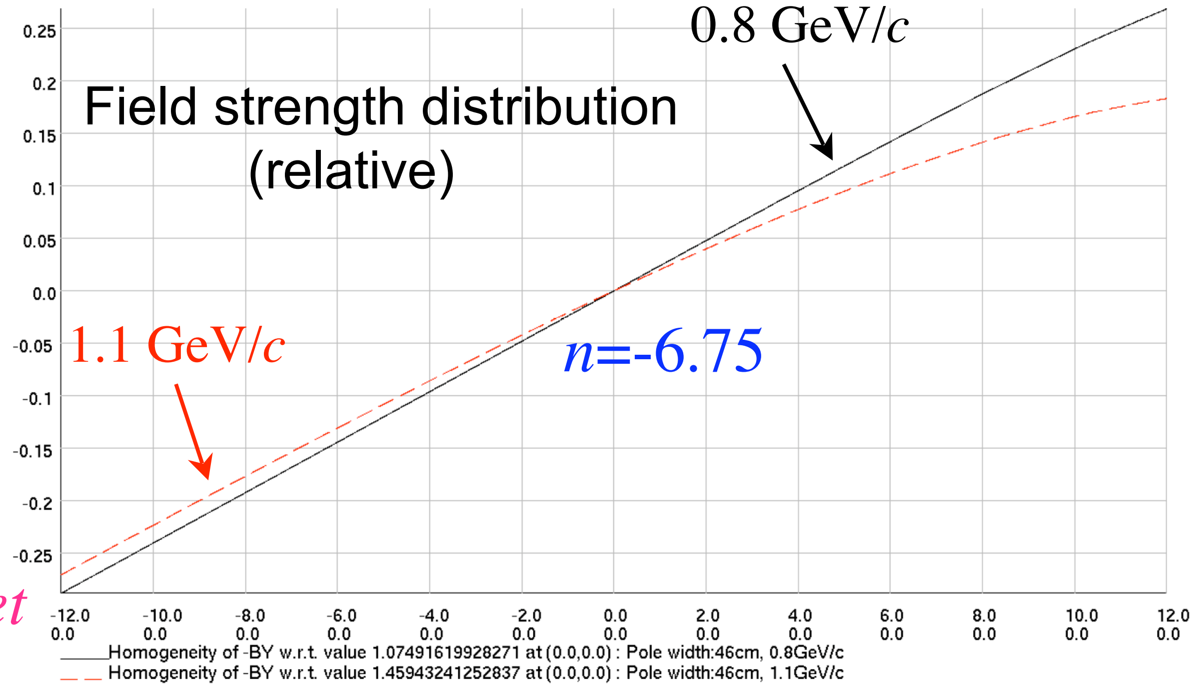
- We proposed a combine function magnet for B1 to increase the beamline acceptance.
- Unfortunately, we found n = -6.75 is not feasible because of magnet saturation *etc*.

B1 condition	Acceptance	Bi construction	K1.1 operation	Conclusion
n = 0	100	feasible	possible	O.K.
n = -2.50	~100 (no gain)	feasible	difficult	no gain
n = -6.75	175	difficult	impossible	not good

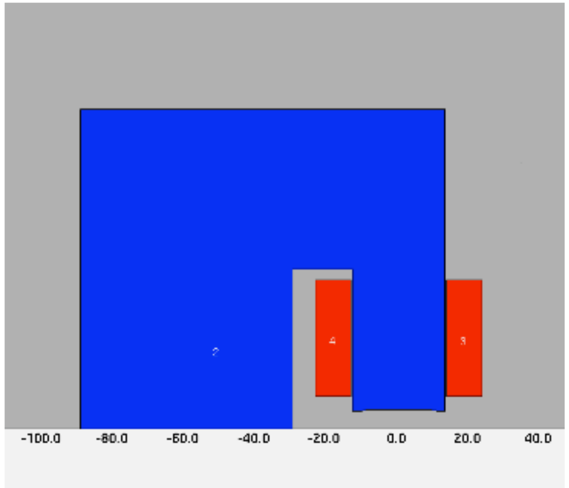
$$B(x)=B_0(1-nx/\rho)$$

- Different dB_y/dx values between 0.8 and 1.1 GeV/c
- Narrow constant field gradient region fo 1.1 GeV/c

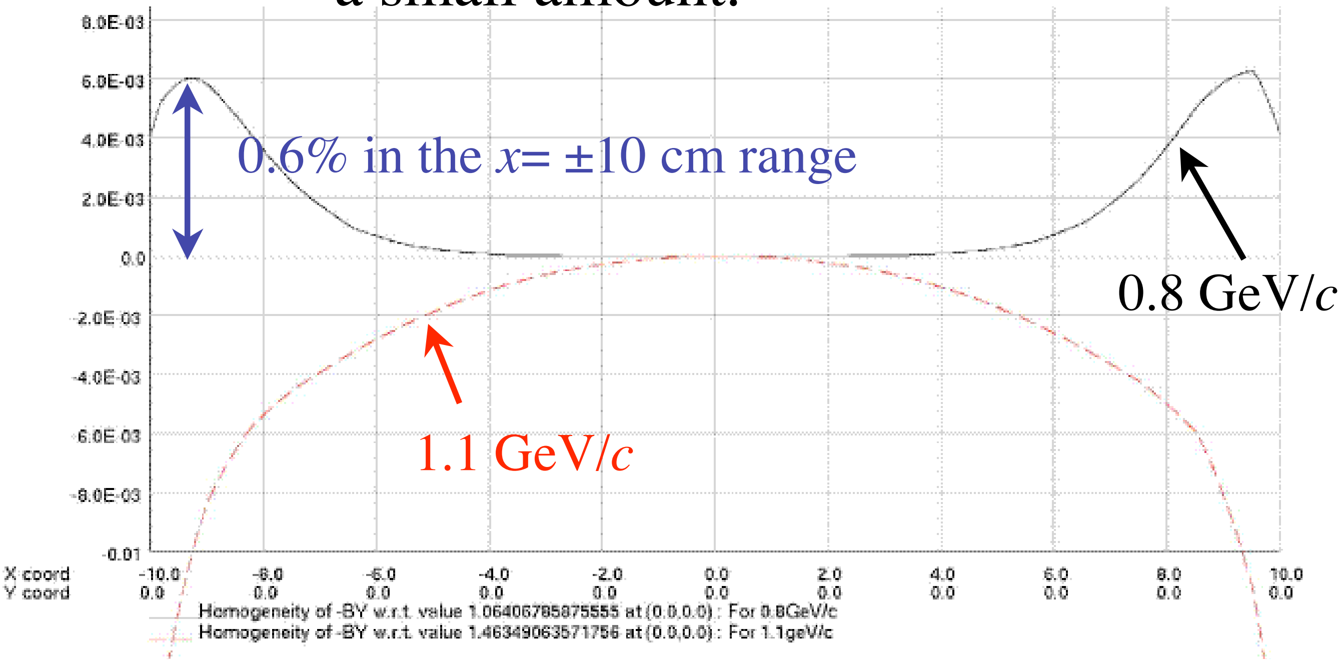
Difficult to adopt the combined function magnet



$n = 0$ solution for B1



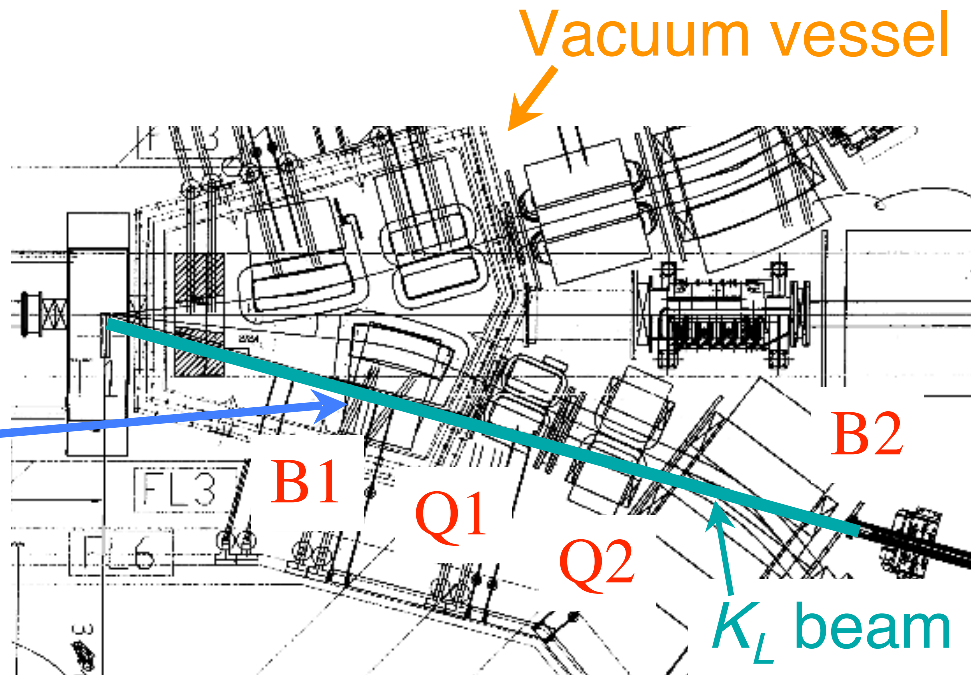
- n=0 is the only possible solution under the conditions of:
  1. 1.1 GeV/c operation in the future
  2. Already fixed beamline space near T1
- Shim was optimized to realize the maximum horizontal width.
- We will pursue the Q6 aperture improvement in order to increase the acceptance even by a small amount.



Comments on the K_L beam

- A 3-cm diameter or square hole in the B1 yoke does not disturb the B1 field quality : no problem
- To accommodate a similar size of the K_L beam path in B2, a special type of window-frame magnet will be required : no problem
- Q1 and Q2 will have such a yoke structure to avoid the K_L beam path : no problem

The installation position accuracy of B1 in the vacuum vessel will be a few 100 μm.



Progress in detector R&D

Progress reported to PAC3 and PAC4

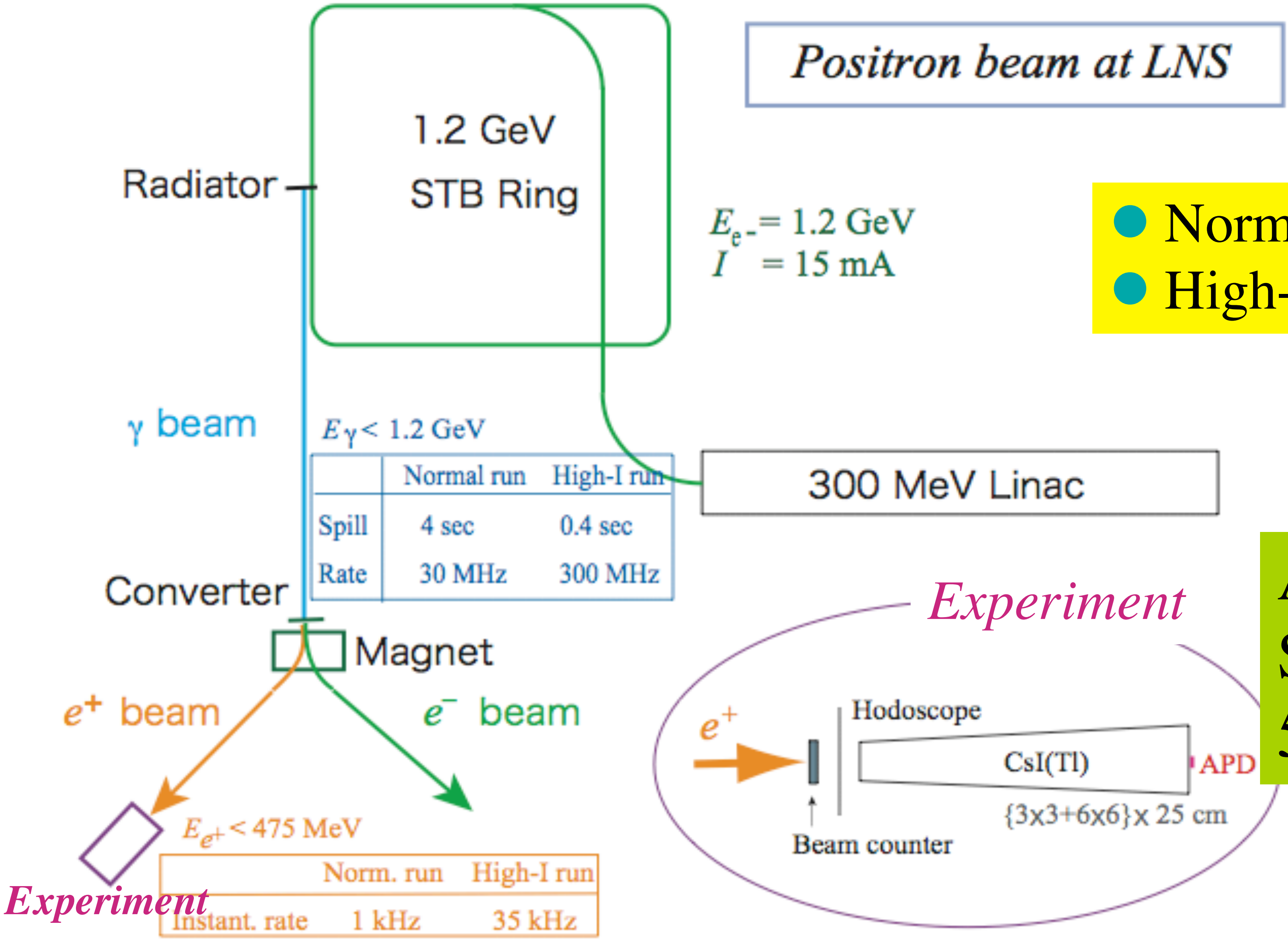
- High rate performance :
  - GEM prototype beam test at FNAL
  - CsI(Tl) APD readout beam test at LNS Tohoku (1)
  - Target MPPC rad. hardness test at RCNP (3)
- Polarimeter muon stopper material :
  - μSR experiment (E1120) at TRIUMF
- Systematic error MC studies :
  - Errors associated with polarimeter misalignments (2)
  - Back ground suppression

Since then:

(1) Analysis of pileup events was continued
(2) MC analysis with high statistics was performed
(3) A more realistic test is now planned at TRIUMF

CsI(Tl) readout test at LNS (Tohoku)

- Test of an E246 prototype module with a variable-energy e^{+} beam
- High rate test analysis at Tohoku and INR(Russia)

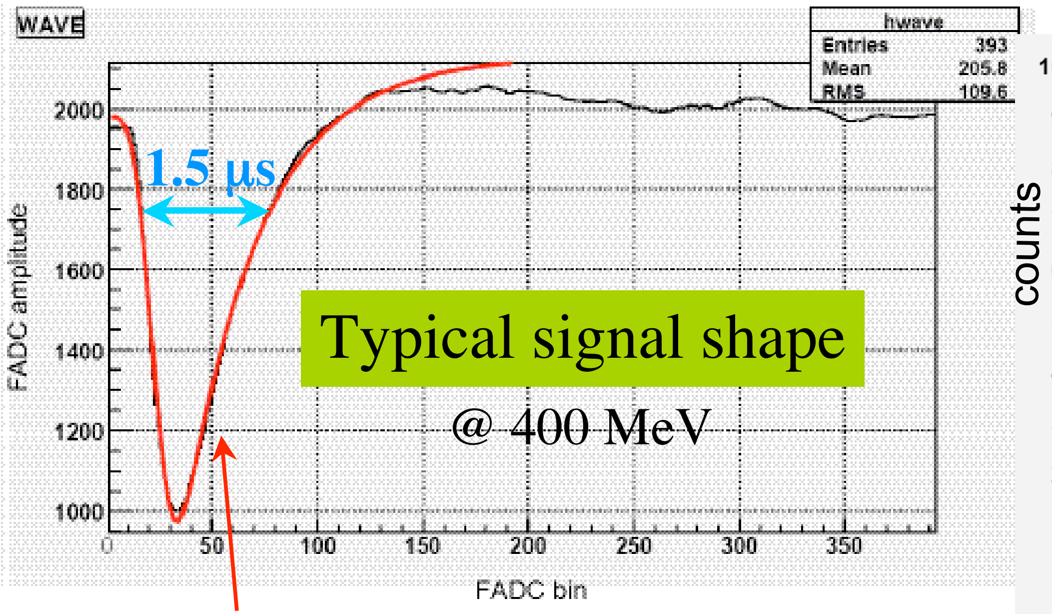


	Normal run	High-I run
Spill	4 sec	0.4 sec
Rate	30 MHz	300 MHz

	Norm. run	High-I run
Instant. rate	1 kHz	35 kHz

APD=
S8664-55
$5x5\ mm^2$

Basic performance



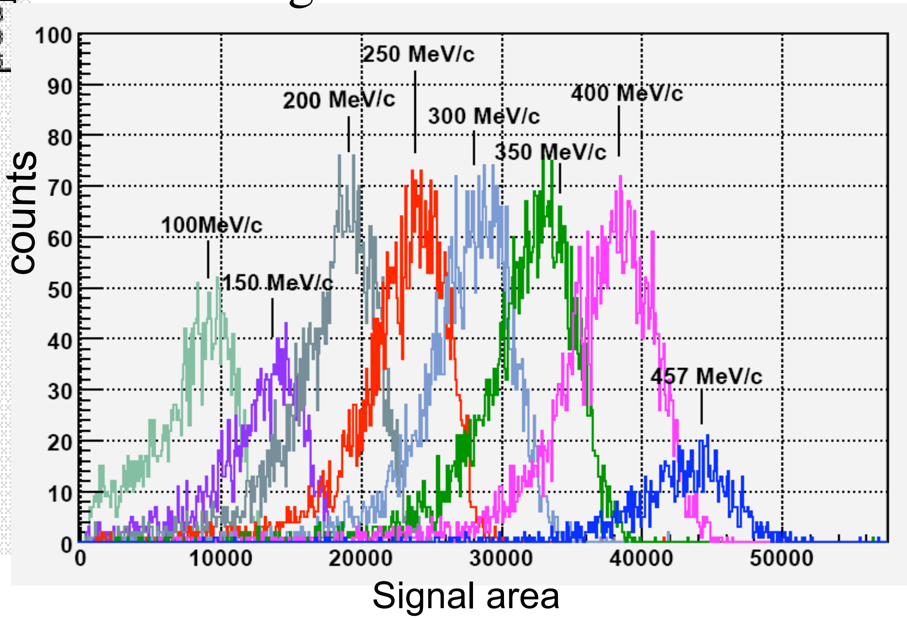
Fit function

$$F(x)=p_0-p_1e^{p_2x}\{p_3\,Erf\,(p_4x-p_5)+p_6\}$$

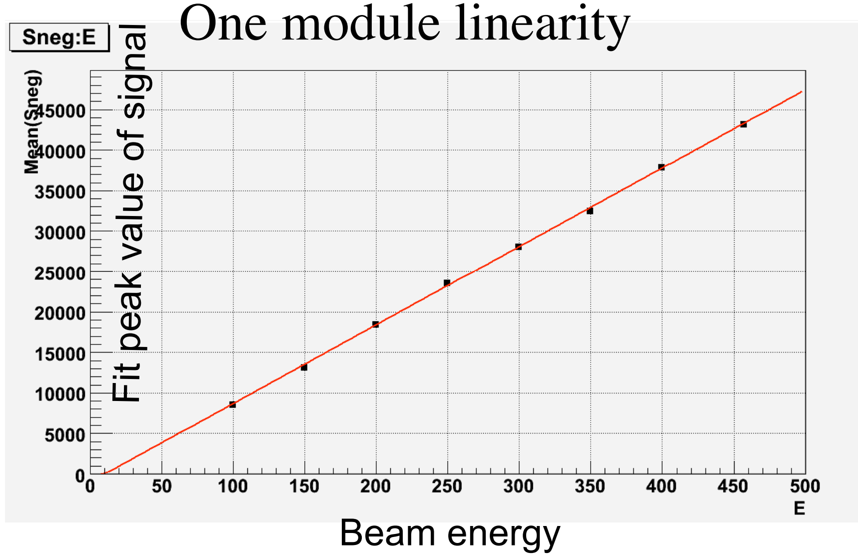
$$Erf\,(x)=\frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$

Careful treatment of overshoot and ringing is necessary

Signal area distribution

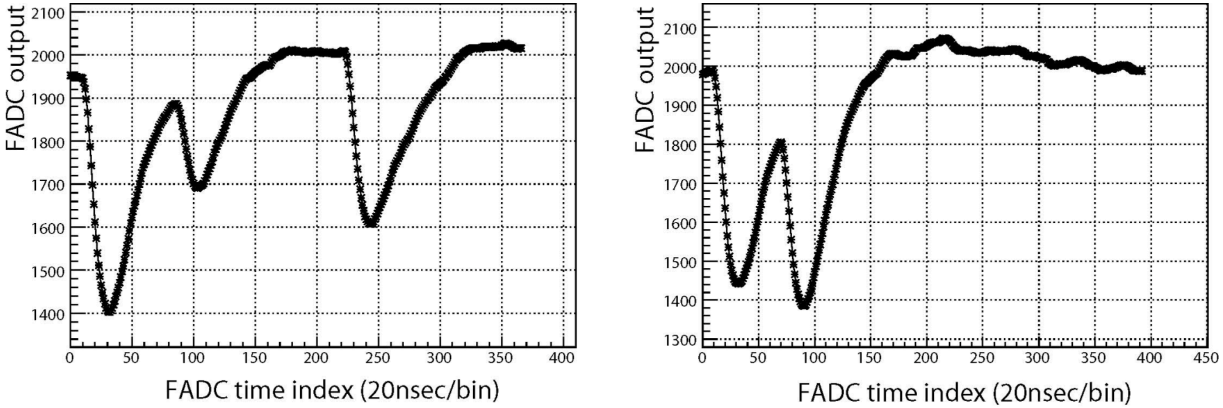


One module linearity



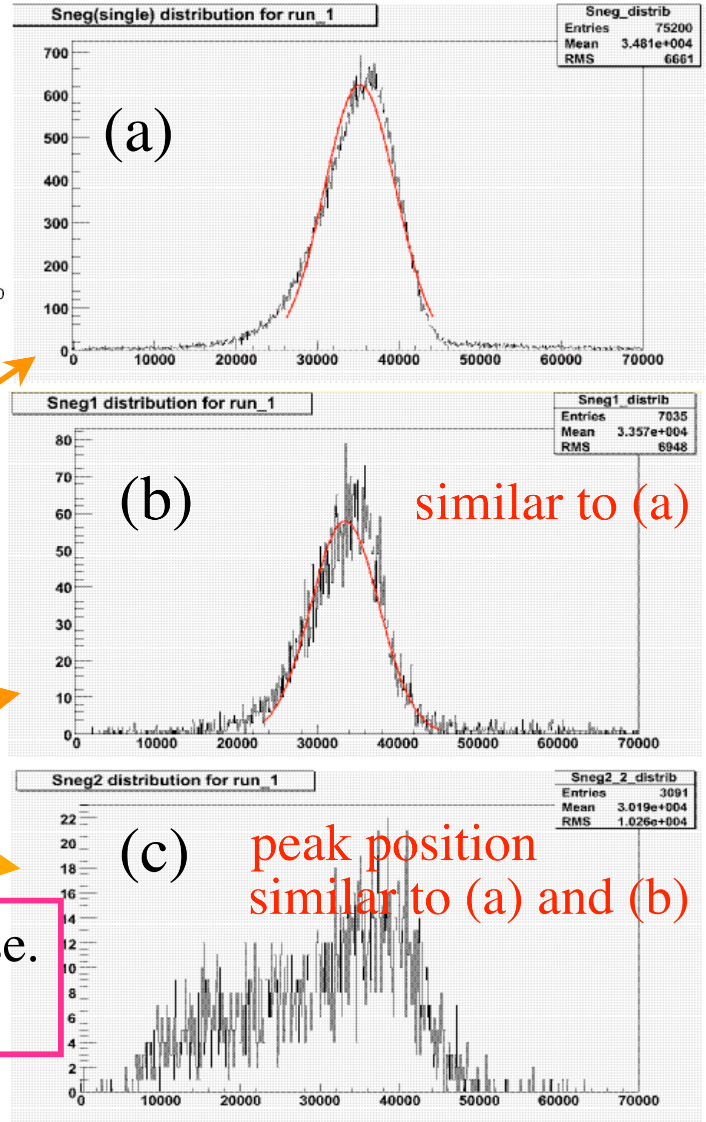
Analysis of pile-up events

- Separation of two pulses-



Typical pile-up events in a high rate run

Signal area distribution

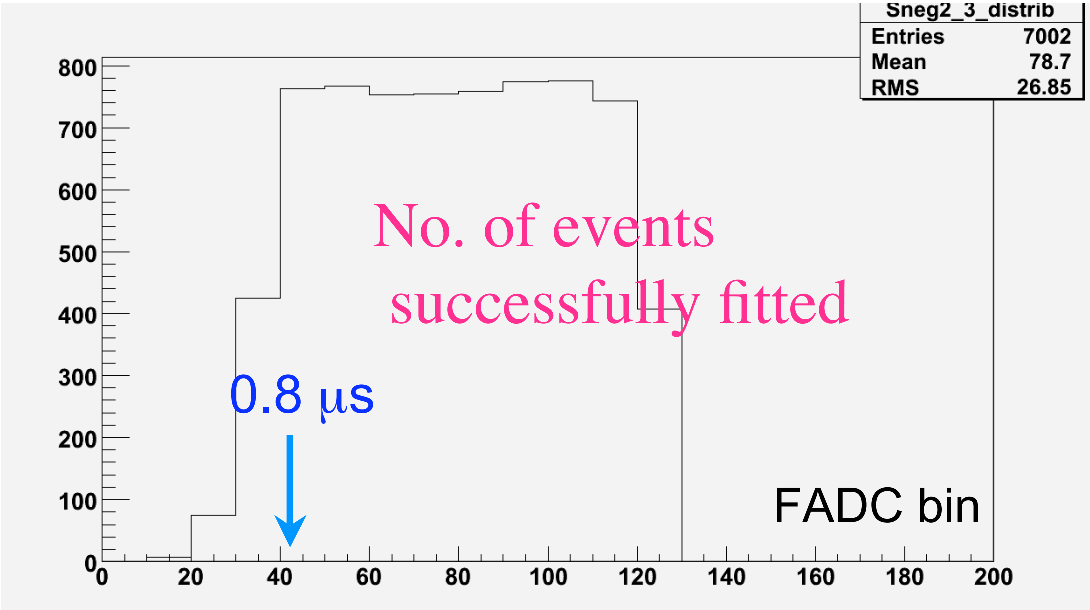


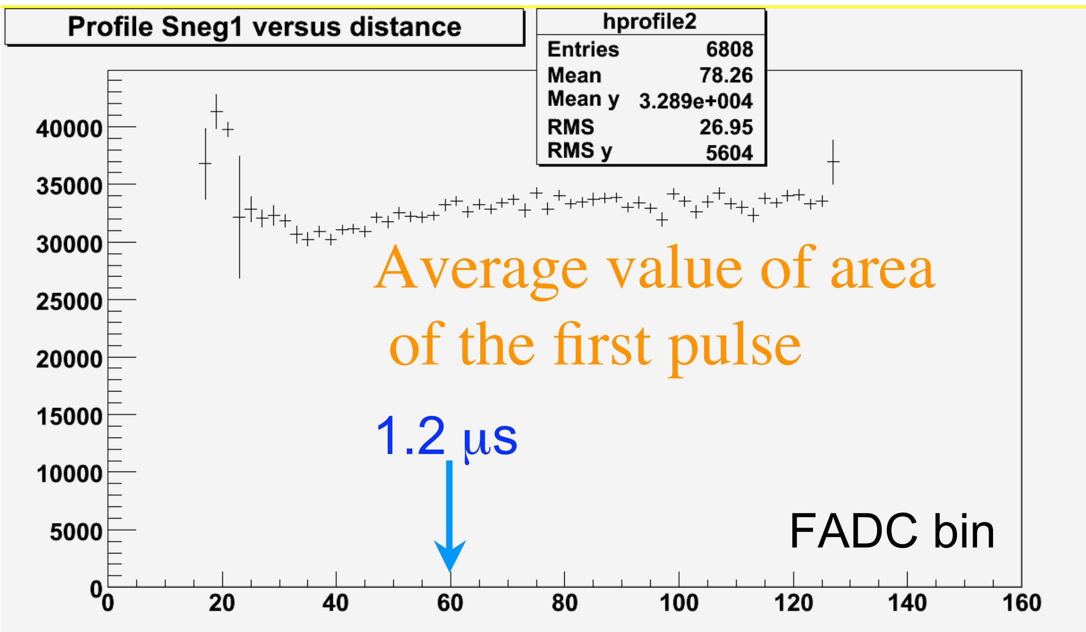
Fit function =
$$a_1F(x) + a_2F(x+\Delta x)$$

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

- Study is underway how to analyze the second pulse.
- An improved amplifier is developed in any case.

Analysis efficiency of the first pulse

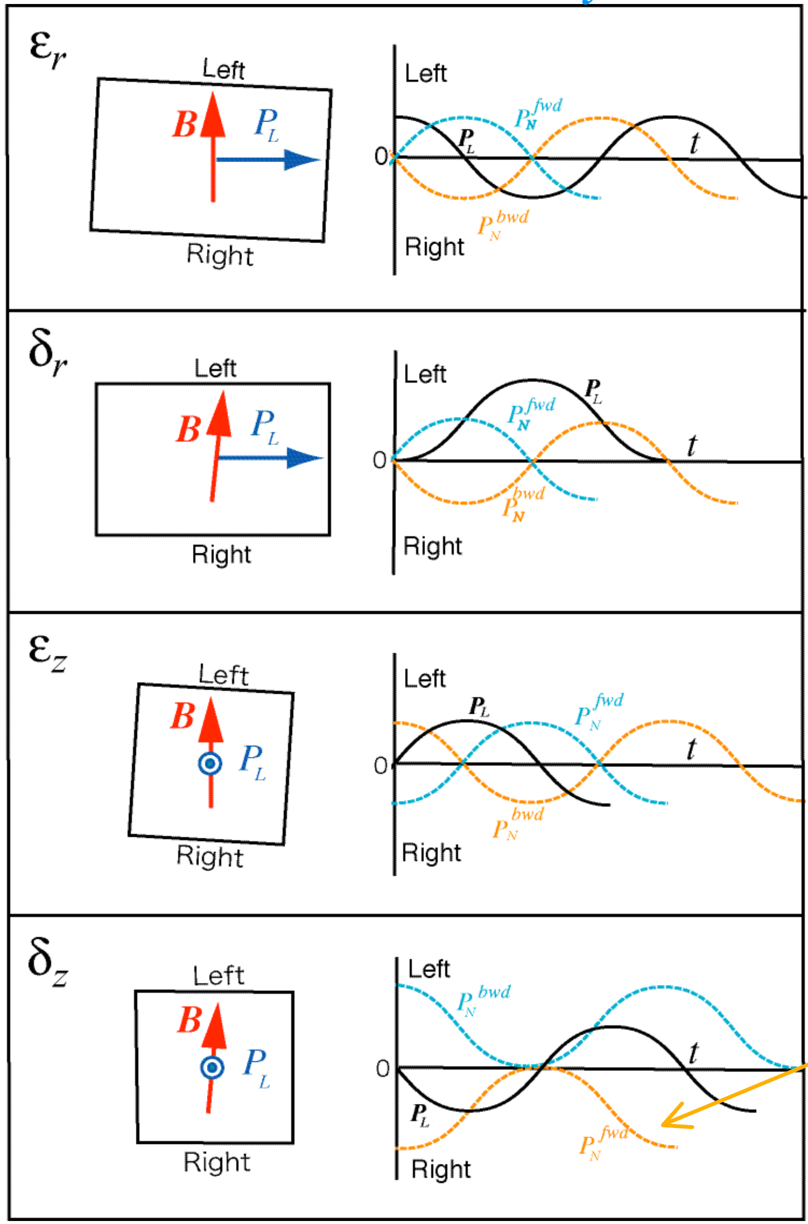




- For pileup pulses with pulse separation larger than 40 bins (0.8 μs), the analysis efficiency is 100%.
- For the separation smaller than 60 bins (1.2 μs), there is an influence on the signal area analysis.

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 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 $K_{\mu 3}$

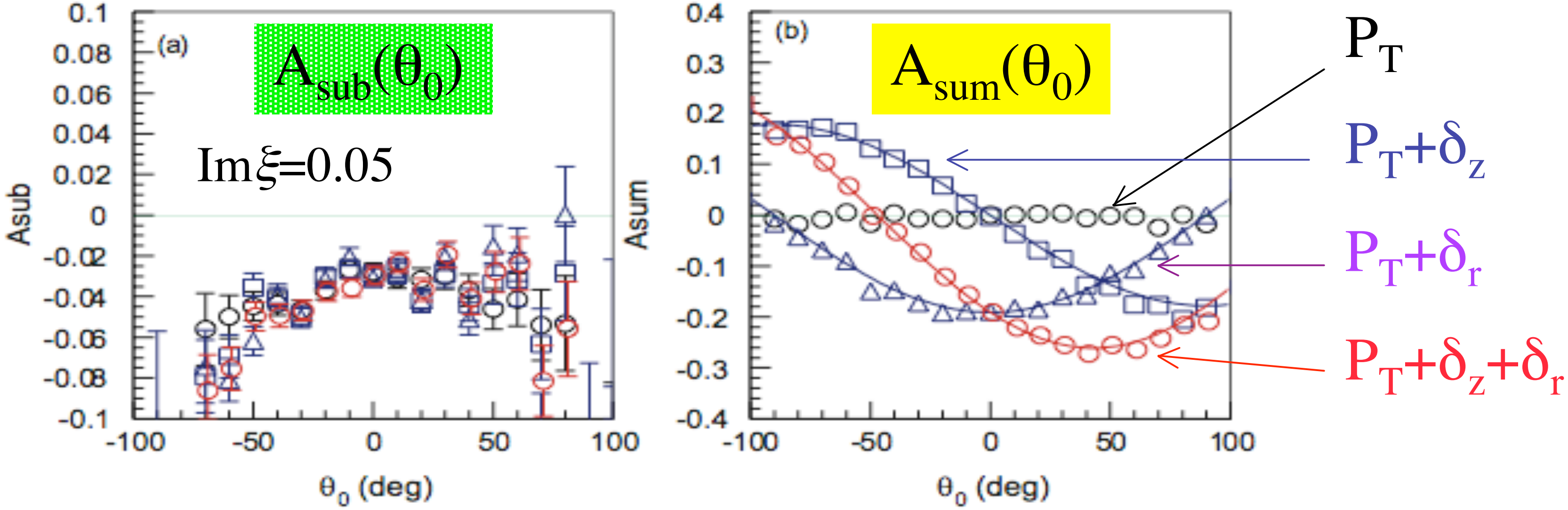
Asymmetry analysis in terms of θ_0 : in plane spin angle from z-axis

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

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

small residual of oscillation

Report to the 3rd PAC meeting

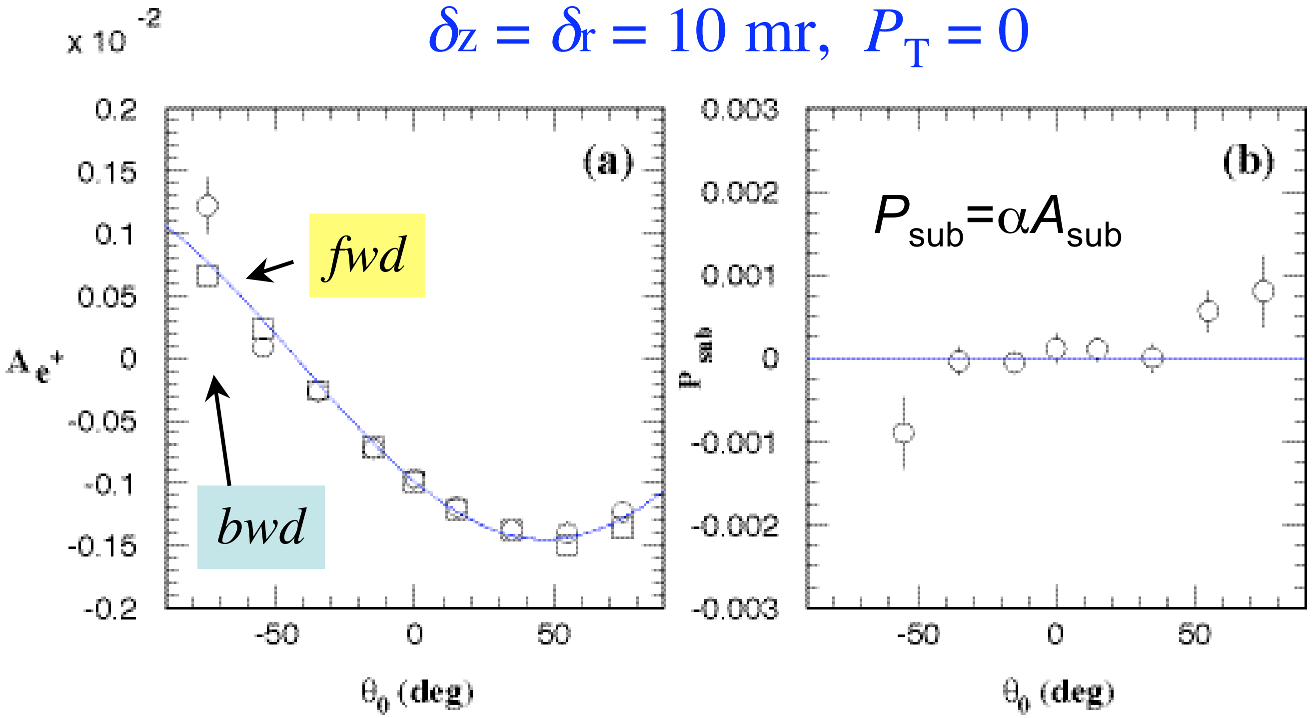


- $\Delta\delta_z \sim \Delta\delta_r \sim 3\times10^{-4}$ for misalignment determination
- $P_T = 0$ and $\delta_z = \delta_r = 5^o = 87$ mr (for systematic error test)
  ==> $\delta P_T = (2\pm7)\times10^{-4}$ for 10^8 events

Result of high statistics MC simulation

25×10^9 $K_{\mu 3}$ events with the inputs of

$\delta z = \delta r = 10$ mr, $P_T = 0$

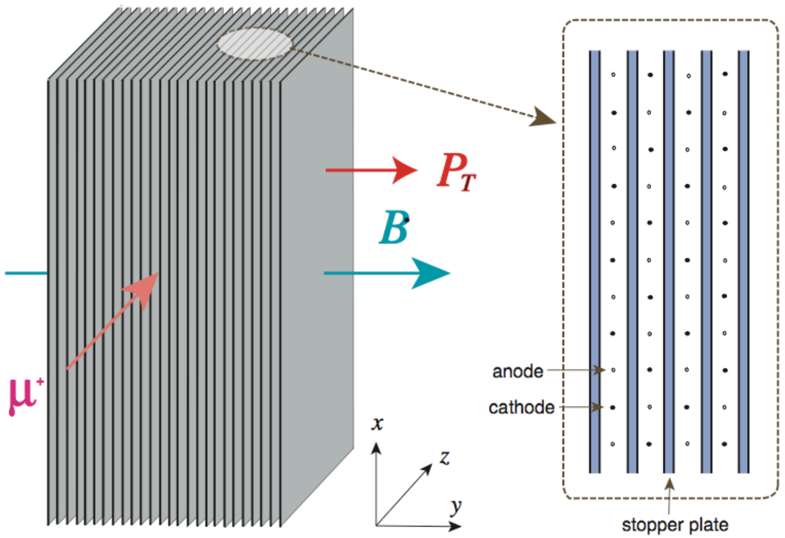


$$P_T^{MC} = \langle P_{sub} \rangle = (3 \pm 6) \times 10^{-5}$$

- Within the statatistical error, no bias was found in the analysis including the used analysis code.
- Final systematics check will be done by using the final analysis code together with the real data analysis later.

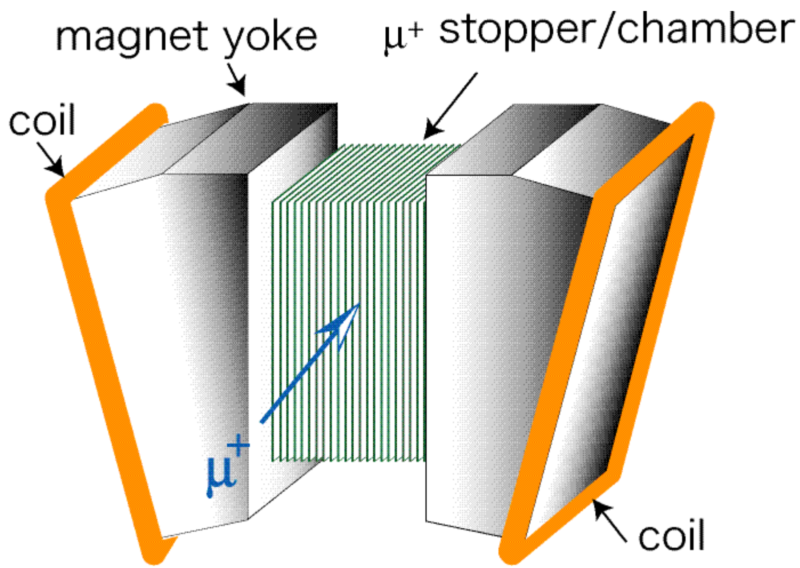
Plan for this year

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

Polarimeter chamber prototype

- Several-layer prototype to test basic DC performance
- One sector full-size prototype to test the polarimeter performance

Item		FY 2008										FY 2009
		Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	
Several-layer prototype	Chamber	design	construction		test							
	Electronics		Perchase		test							
One-gap proof model (full size)	Chamber			design			construction				beam test	Beam test at TRIUMF
	Electronics					design		construction		test	beam test	
Muon field magnet			field calc.		design		construction			field map		

2009 : Muon beam test of the full-sized model at TRIUMF
2010 : Mass-production of 11 or 12 chambers

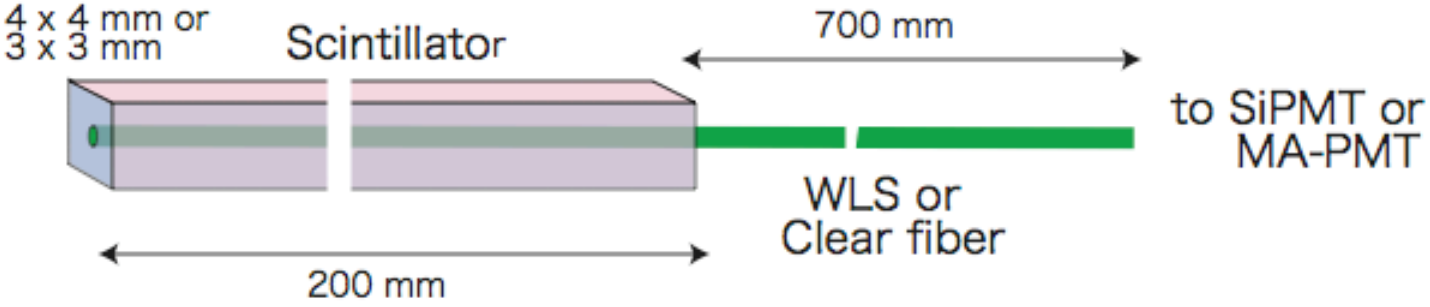
- At the moment : DC cell structure design in Japan and Canada
- Baseline design : Cell width= 8 mm, Half cell length = 8 mm

Detector preparation
(2) Active fiber target

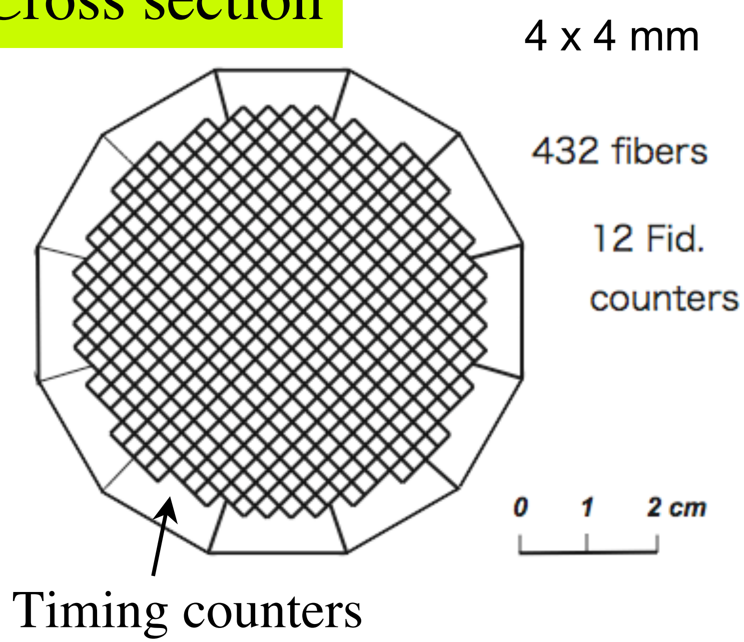
Current baseline design

c.f. E246 Ring counters
PSI FAST target

One element



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 100 MeV/*c* pions at TRIUMF in this year

MPPC radiation damage test

	Particle	Energy	Exposure	Flux density
TREK exp. condition	π^+, K^+, μ^+, $e^\pm$, n	< 200 MeV/c		7×10^7/mm^2 for one year
RCNP proton test (*)	p	53.3 MeV	8 Gy : tolerated	5.4×10^7/mm^2
			21 Gy : dead	14×10^7/mm^2
Reactor neutron test	n	low	similar to p	
TRIUMF pion test	π^+, μ^+, $e^\pm$	100MeV/c		

(*) TREK members took part in the test measurement.

- Use of MPPC (HPK S10362 -050) is marginal?
  - We suggested the use of Multi-anode PMT instead.
  - MPPC is still attractive.
- We will perform a test experiment at TRIUMF in July.
  - Using a pion beam with more realistic condition for TREK
  - 130k π^+ /s/mm^2 amounting 10^8/mm^2 in several hours
- According to the results of the test, we will decide finally:
  - MPPC or MA-PMT
  - Distance from the beam and necessary shielding

Summary

- We have emphasized that P_T physics is important. We want to start the TREK experiment in the early stage of J-PARC.
- We have succeeded to obtain grants for the TREK experiment, at least partially. Now we can start the construction of :
  - **Active polarimeter, and the**
  - **Scintillating fiber target**
- We have shown that the most dangerous systematics from the polarimeter misalignment should be controllable.
  - **Answering the one-year-standing question by PAC**
- We are continuing detector R&D such as the CsI(Tl) readout and showed the proposed plan for this year.
- We want to accelerate the detector design/construction by gaining further grants internationally and domestically. For this the stage-2 approval status is definitely necessary.

End of Slides