Status of the TREK/E36 Experiment at J-PARC

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C. Djalali & H. Lu, U. Iowa
on behalf of the E36-TREK collaboration

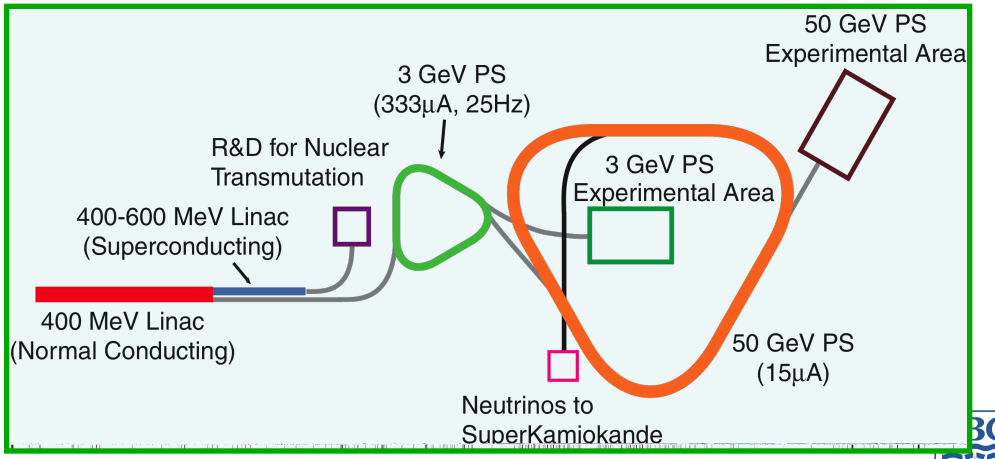
Outline

- **TREK Program** TREK = Time Reversal Experiment with Kaons
  - ✓ *Test of Lepton Violation*
  - ✓ *Search for Dark Photons*
  - ✓ *Search for Heavy Neutrinos*

  } Lower intensity

  Search for Time Reversal Symmetry Violation

- **Theoretical Motivation**
- **Experimental Details**
- **Preliminary Results**
- **Summary & Outlook**



TREK Collaboration

CANADA
University of British Columbia
TRIUMF

RUSSIA
Russian Academy of Sciences (RAS)
Institute for Nuclear Research (INR)--Moscow

USA
Hampton University
T. Jefferson Nat. Acc. Laboratory
University of Iowa
University of South Carolina

JAPAN
Osaka University
High Energy Accelerator Research Org. (KEK)
Chiba University

~20 physicists from 4 countries

Lepton universality in $K_{\ell 2}$ and $\pi_{\ell 2}$ decays

$$R_K^{SM} = \frac{\Gamma\left(K^+ \to e^+\nu_e[\gamma]\right)}{\Gamma\left(K^+ \to \mu^+\nu_\mu[\gamma]\right)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$$

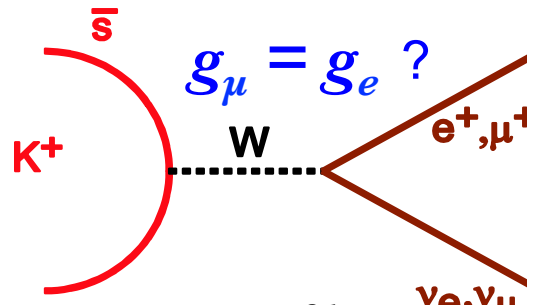
helicity suppression

radiative corrections

- Very precise SM predictions

$R_K^{SM} = (\ 2.477 \pm 0.001) \times 10^{-5}$
$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$

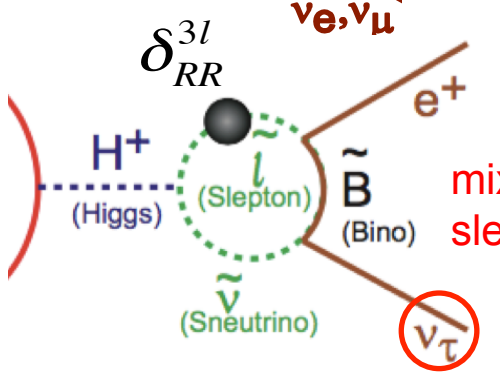
[V. Cirigliano and I. Rosell, Phys. Rev. Lett. 99 (2007) 231801]



Ke2

- High sensitivity to LFV beyond SM

e.g. MSSM with charged-Higgs SUSY-LFV



mixing in the slepton sector

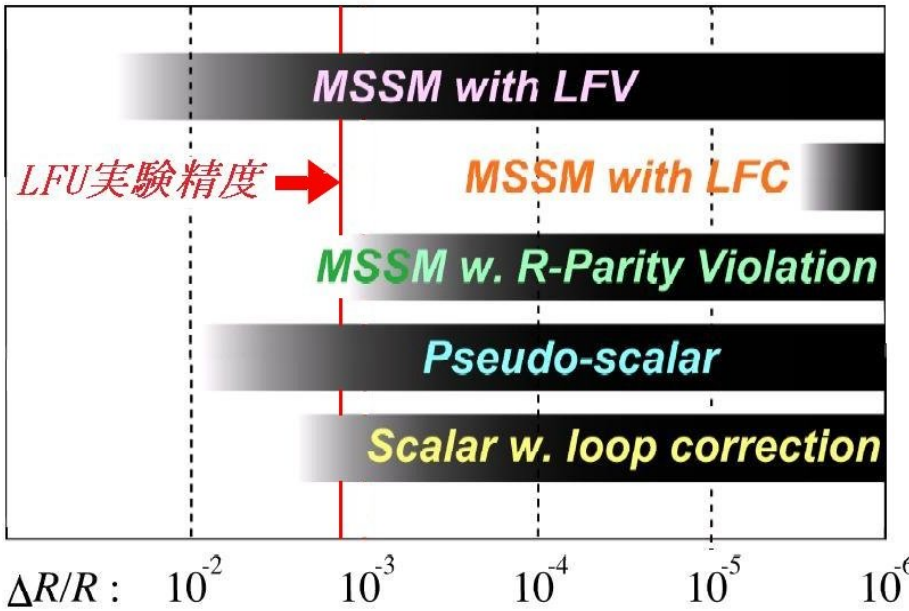
$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H^+}^4}\frac{m_\tau^2}{m_e^2}\Delta_{13}^2 \tan^6\beta\right) \Rightarrow R_K^{LFV} \sim R_K^{SM}(1 + 0.013_{max})$$

[Masiero, Paradisi and Petronzio, Phys. Rev. D74 (2006) 011701, JHEP 11 (2008) 042

Proposed Exp'tal precision (E36) ~ 0.25%

Lepton universality violation in $K_{\ell 2}$

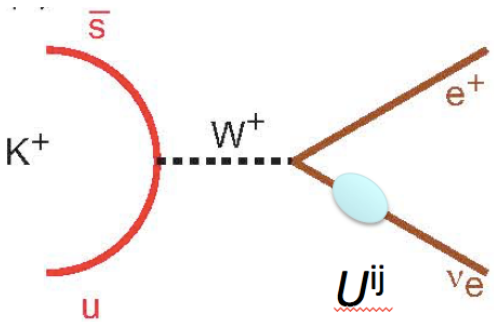
- **Possible New Physics**
  - MSSM with LFV or LFC
  - MSSM with R-Parity violation
  - Pseudo-scalar interaction
  - Scalar with loop correction
  - Neutrino mixing



- **Neutrino mixing**
  - R_K is sensitive to neutrino mixing parameters within SM extensions eg -- 4th generation of quarks and leptons OR heavy sterile neutrinos

H. Lacker and A. Menzel, JHEP 07(2010) 006 or A. Abada et al., JHEP 02(2014) 091

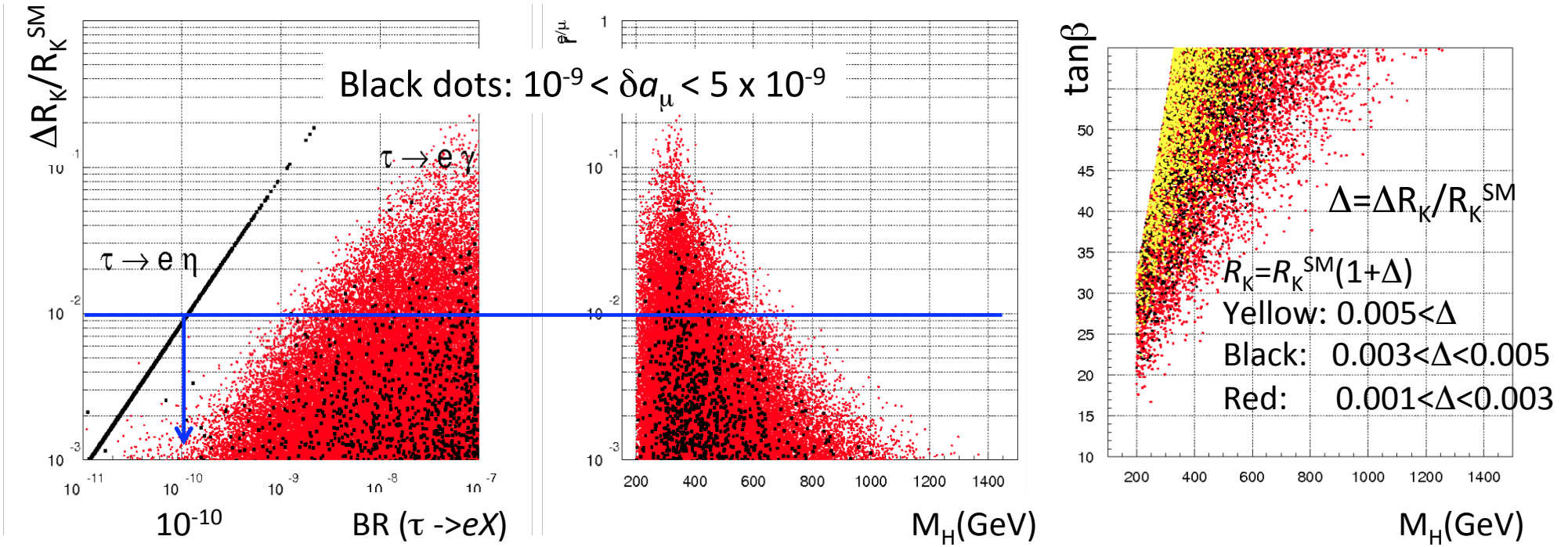
$$\mathcal{L}_{\rm int} = -\frac{g}{\sqrt{2}} U_{\nu}^{ji} \bar{\ell}_j \gamma^\mu P_L \nu_i W_\mu^- + \text{h.c.}$$



LFV in SUSY

[Masiero, Paradisi and Petronzio; JHEP 11 (2008) 042]

- LFV effect may be observed in ΔR_K
- $\Delta R_K/R_K \approx 1\%$ corresponds to $BR\,(\tau \text{-->} eX) \leq 10^{-10}$
  - Strong correlation to $BR\,(\tau \text{-->} e\eta)$
  - Additive to R_K^{SM} (no interference: $R_K > R_K^{SM}$)
- Strong constraint on M_H for large $\tan\beta$ (equal to a_μ)



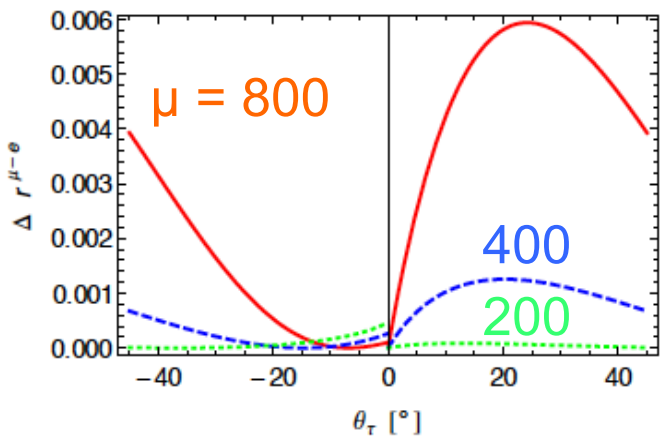
Extended more refined LFV calculation

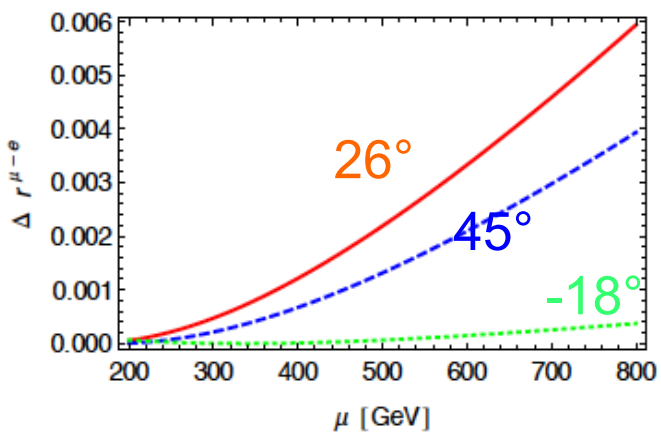
J.Girrbach and U.Nierste -- arXiv:1202.4906

- study of dependence on μ (lighest stau mass), θ_τ(stau), tanβ, M_H

$$\Delta r^{\mu-e}_{\max,\mathrm{LFV}} \approx 0.006 \left(\frac{500\,\mathrm{GeV}}{M_H}\right)^4 \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{\delta^{13}_{RR}}{0.5}\right)^2 \left(\frac{\mu}{800\,\mathrm{GeV}}\right)^2 .$$

valid for $m_{\tilde{\tau}_l} = 120$ GeV, $M_1 = 100$ GeV, $m_{\tilde{e}_R} = 200$ GeV.





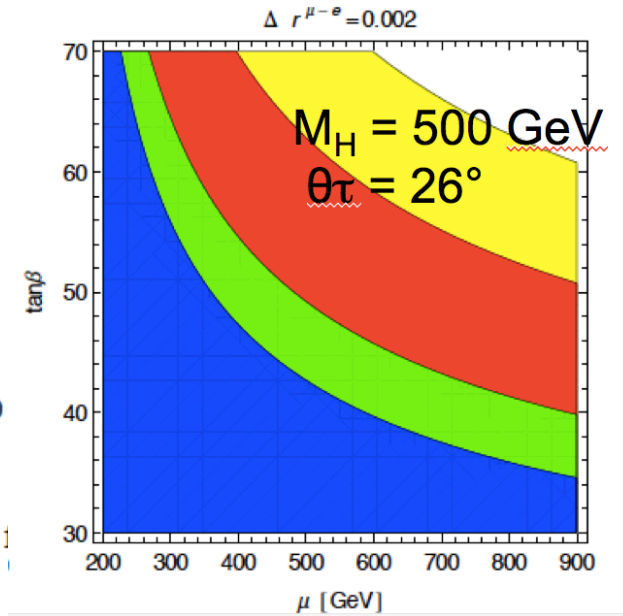


Figure 3: $\Delta r^{\mu-e}$ for $\delta^{13}_{RR} = 0.5$, $M_H = 500$ GeV and $\tan\beta = 50$. Left: As a function of θ_τ f different values of μ: 800 GeV (red), 400 GeV (blue dashed), 200 GeV (green dotted). Right: dependece of μ for different values of θ_τ: 26° (red), 45° (blue dashed), −18° (green dotted).

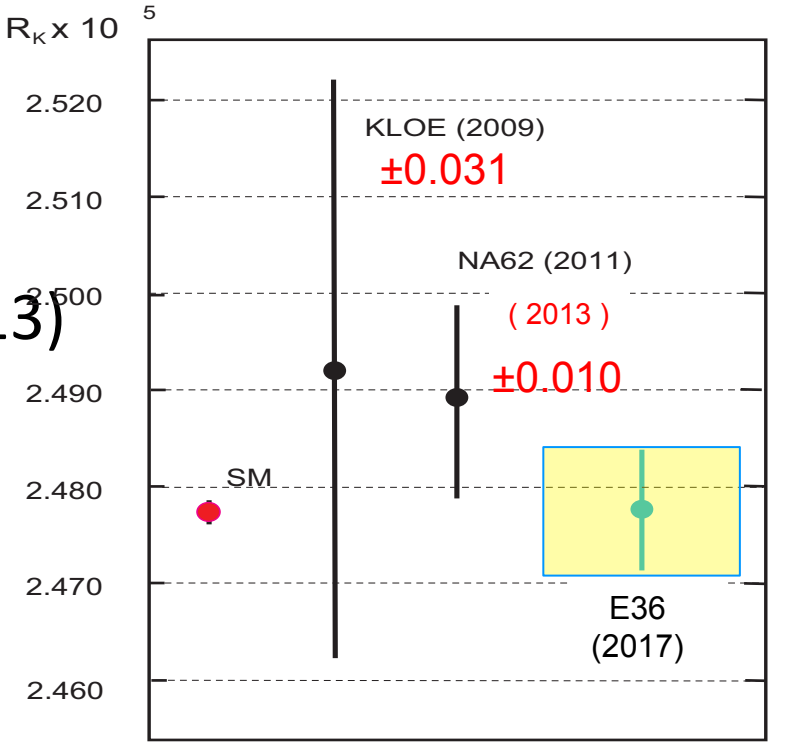
Figure 5: For different values of $\delta^{13}_{RR} = 0.15$ (yellow), 0.25 (red), 0.5 (green), 0.75 (blue) (from top to bottom) we plot the regions in which $\Delta r^{\mu-e}$ is below the future experimental sensitivity of 0.002

Present Experimental Status of R_K

- KLOE @ DAFNE (in-flight decay) (2009)
  - $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$

    [Eur. Phys. J. C64 (2009) 627]
- NA62 @ CERN-SPS (in-flight decay) (2013)
  - $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$

    [Phys. Lett. B719 (2013) 326]
- World average (2013) $\Delta R/R \approx 0.4\%$
  - $R_K = (2.488 \pm 0.010) \times 10^{-5}$



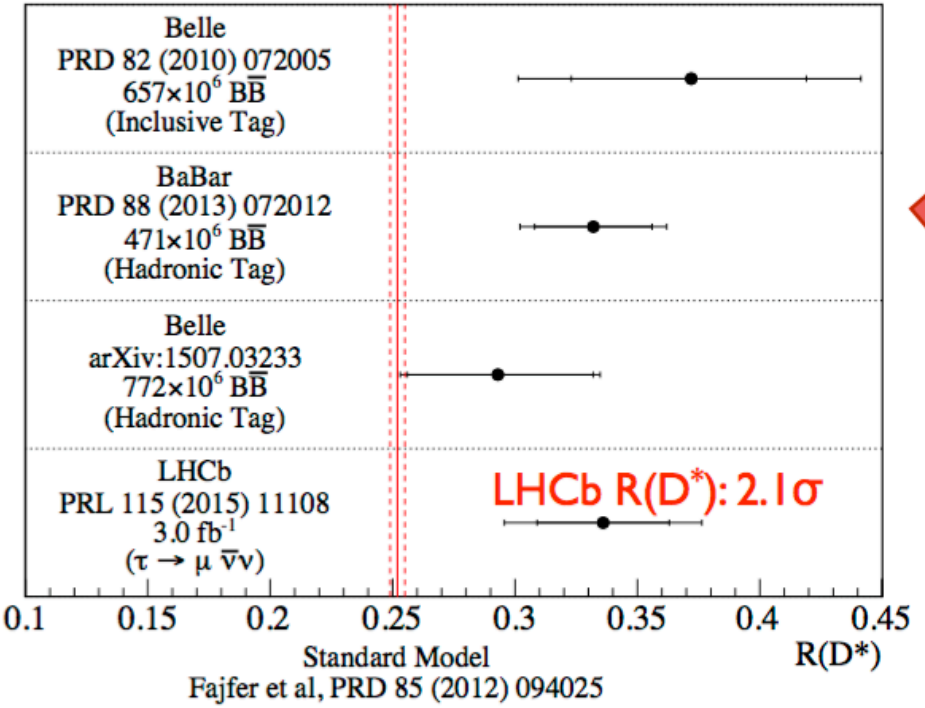
- Different Systematics :
  - In-flight-decay experiments: -- kinematics overlap
  - E36 stopped K^+ decay experiment: --

    detector acceptance and target interactions

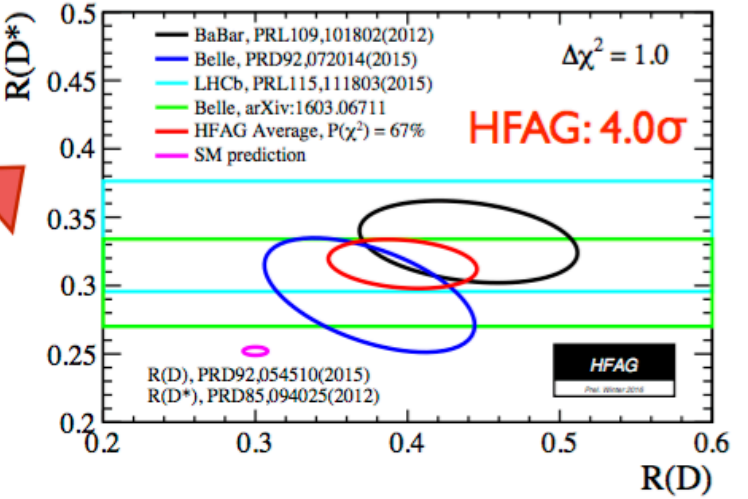
proposed $\Delta R_K/R_K \approx \pm 0.20_{stat} \pm 0.15_{syst}$ %

Lepton universality?

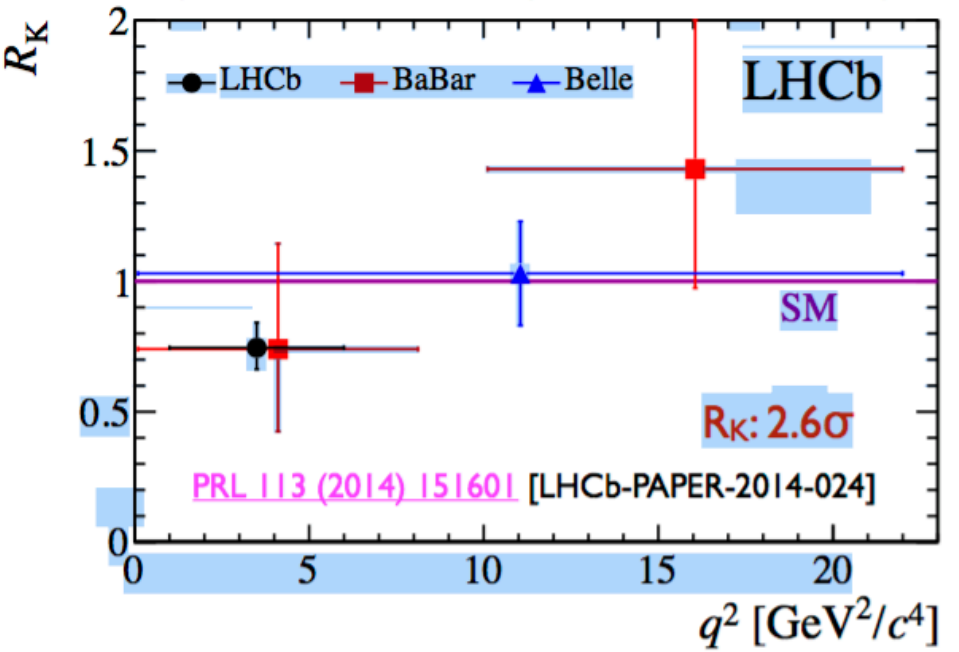
$R(D^*) = \mathcal{B}(\overline{B^0} \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\overline{B^0} \to D^{*+}\mu^-\bar{\nu}_\mu)$



PRL 115 (2015) 111803 [LHCb-PAPER-2015-025]

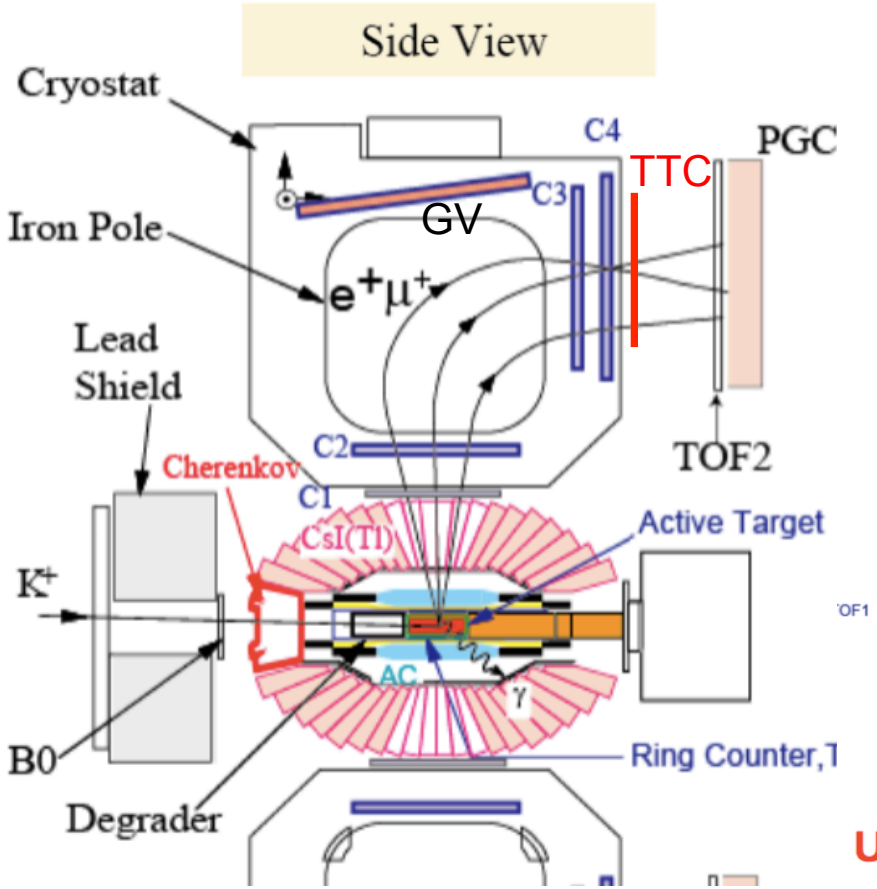


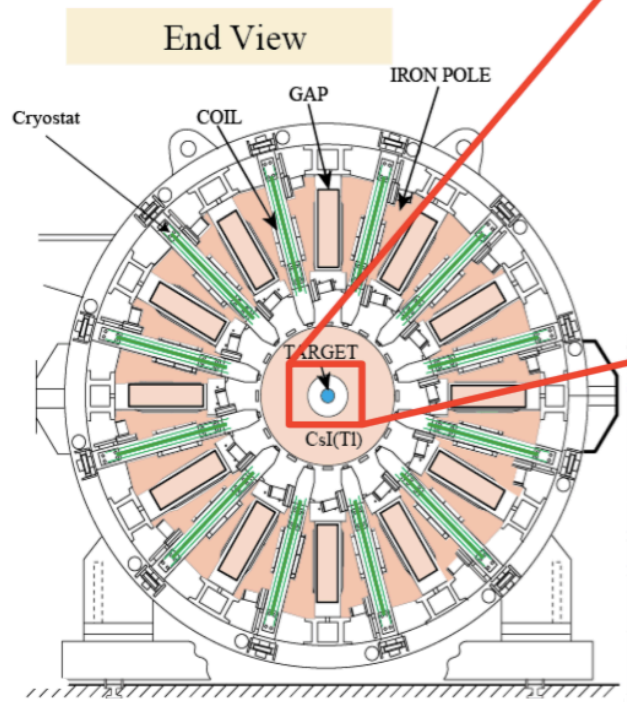
$R_K\ (B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-)$



from Mat Charles –-
LHCP Lund June 2016

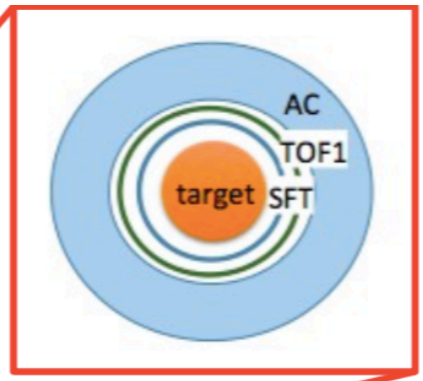
E36 Apparatus

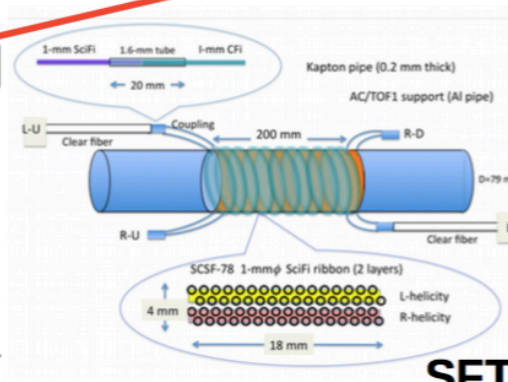




Upgrade of KEK-PS E246 apparatus

Central Detector





SFT

Stopped K Method
- K1.1BR beamline
- Fitch Cherenkov
- K^+ stopping target

Tracking
- MWPC **(C2, C3, C4)**
- SFT
- TTC

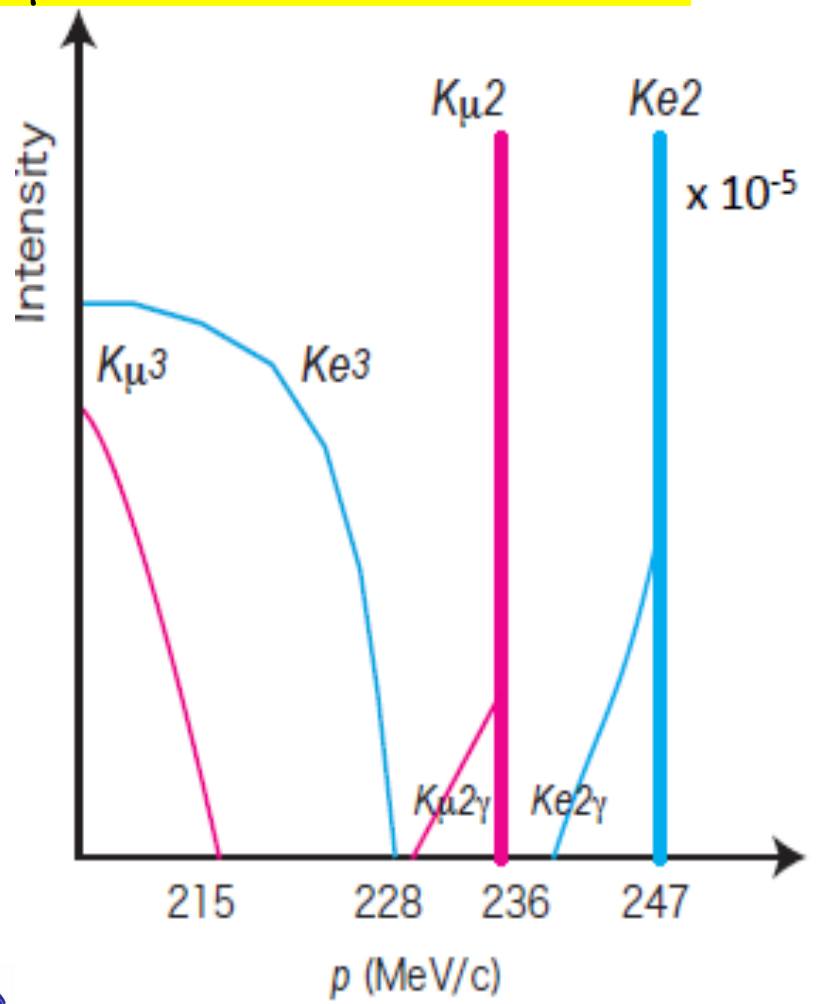
PID
- TOF1,2
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

Gamma Ray
- CsI(Tl)
- Gap Veto (GV)

R_K determination

Schematic momentum spectrum

$N_{\mu 2} / N_{e2} \sim 40{,}000 / 1$



Charged particle momentum spectrum

- including $K_{e2\gamma}$ and $K_{\mu 2\gamma}$
- above 228 MeV

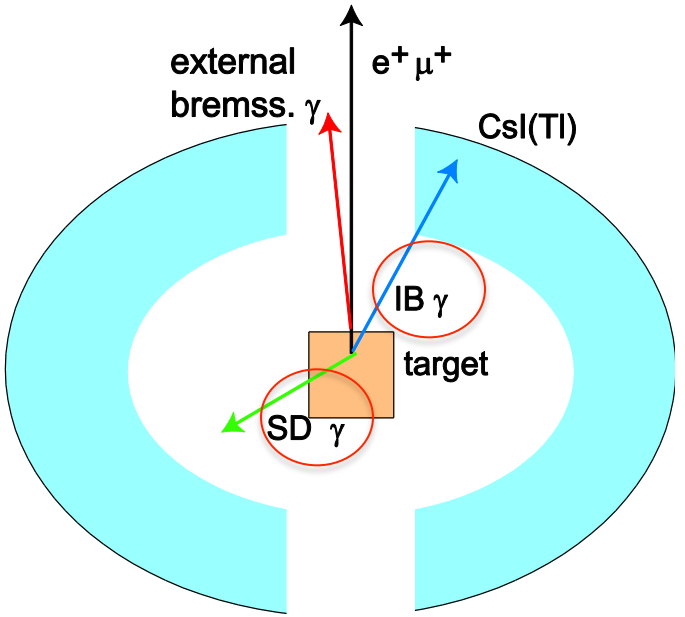
- Rejection of "Structure dependent radiative decay (SD)"
  - rejected as a background
  - with the help of CsI(Tl) calorimeter
- Determination of R_K

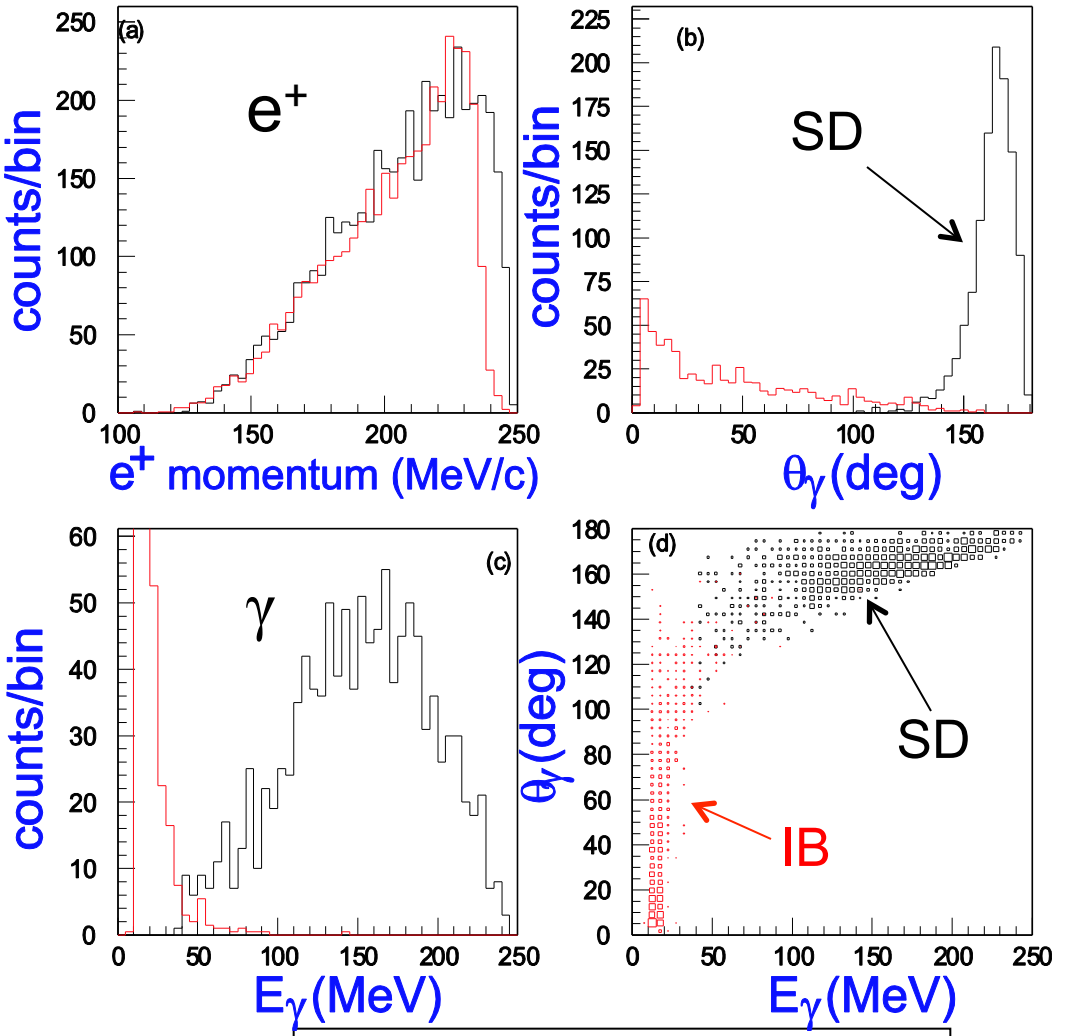
$$R_K = \frac{N\,(K_{e2}+K_{e2\gamma}^{IB})}{N\,(K_{\mu 2}+K_{\mu 2\gamma}^{IB})} \; \frac{\Omega\,(K_{\mu 2}+K_{\mu 2\gamma}^{IB})}{\Omega\,(K_{e2}+K_{e2\gamma}^{IB})}$$

- Comparison of R_K with R_K^{SM}
  - also including $K_{e2\gamma}$ and $K_{\mu 2\gamma}$

Subtraction of SD γ Bkgd

1) K_{e2} including external bremsstrahlung photon (in target)
2) $K_{\mu 2}$
3) Radiative K_{l2} decays





Black: Structure dependent
Red: Internal bremsstrahlung

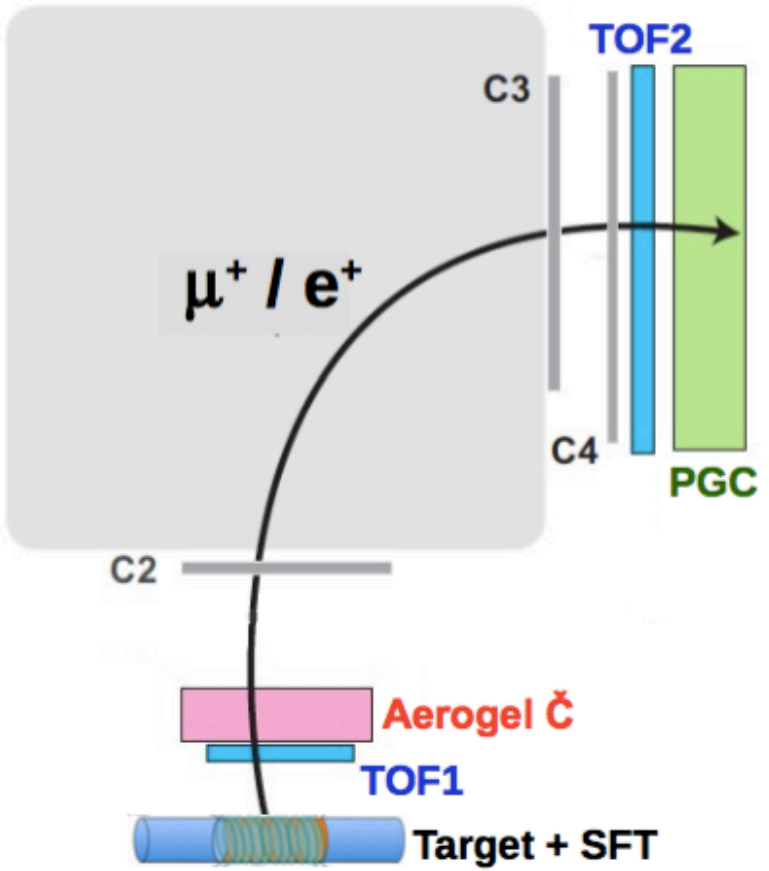
IB and SD – well separated

$\delta R_K/R_K$ (SD) < 0.04%

e/μ Particle Identification

PID done with:

- TOF
- Aerogel Č
- Lead glass (PGC)



TOF

Flight length	250 cm
Time resolution	<100 ps
Mis-ID probability	7×10^{-4}

Aerogel Č counter

Radiator thickness	4.0 cm
Refraction index	1.08
e^+ efficiency	>98%
Mis-ID probability	3%

Lead glass (PGC)

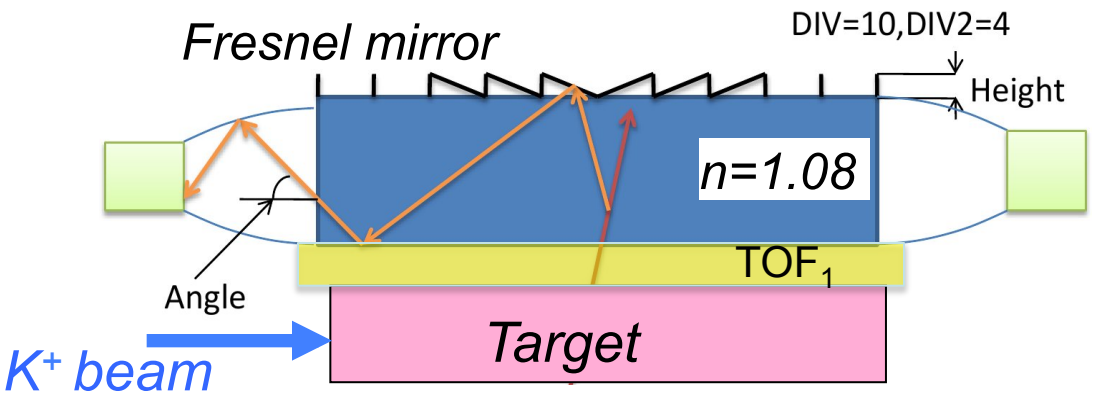
Radiation length	1.69 cm
e^+ efficiency	98%
Mis-ID probability	4%

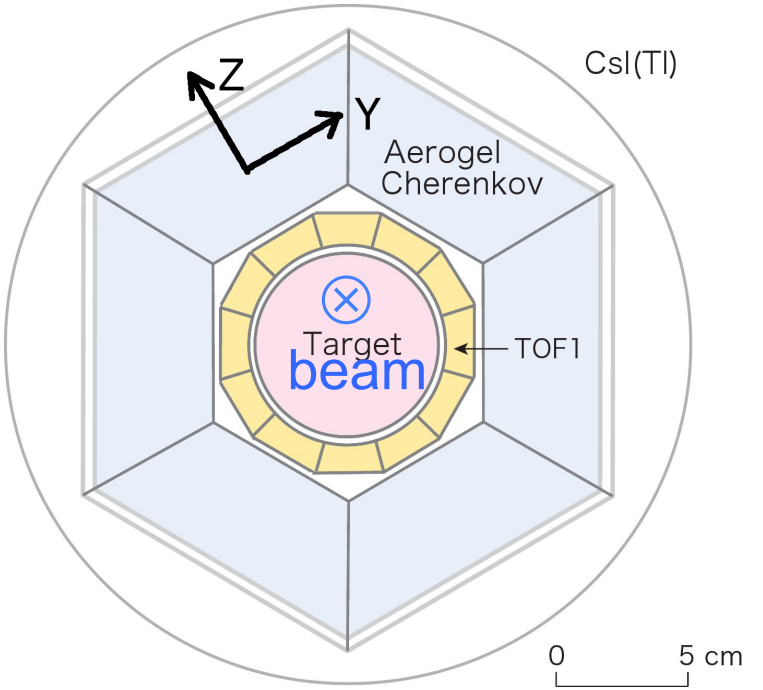
$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{PGC}) = 8 \times 10^{-7} < O(10^{-6})$$

e/μ PID – Aerogel Cherenkov Detector

- Momentum measurement of e^+, μ^+
- TOF measurement between TOF_1 and TOF_2
- e^+ tagged by Aerogel Cherenkov detector, & PGC

β_e (K_{e2}) ~ 1
β_μ ($K_{\mu 2}$) ~ 0.92 = 1 / 1.087
Estimated efficiency = 99.9 ± 0.1%

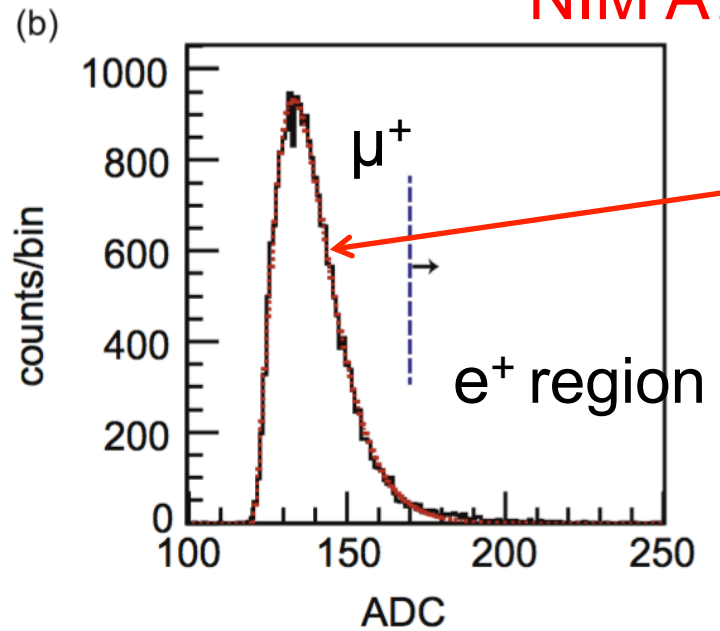


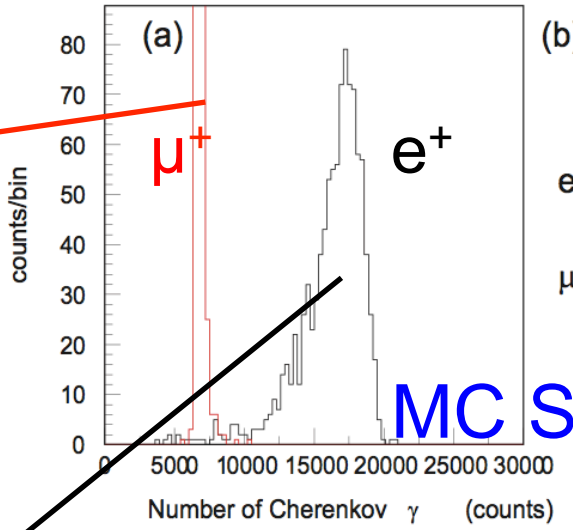


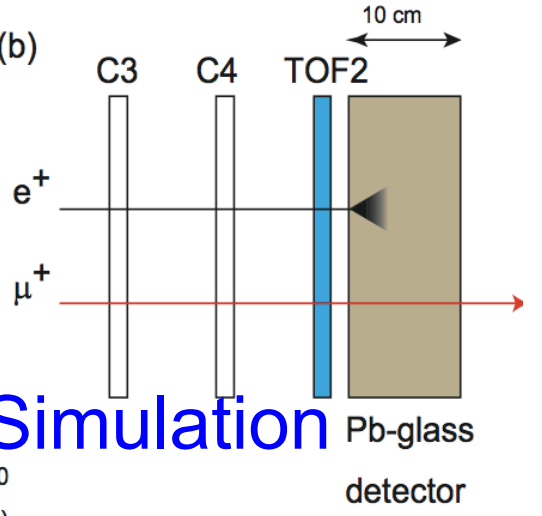
PID performance and detector efficiency can be measured & controlled using K_{e3} and $K_{\mu 3}$ data.

e/μ PID -- PGC Detector

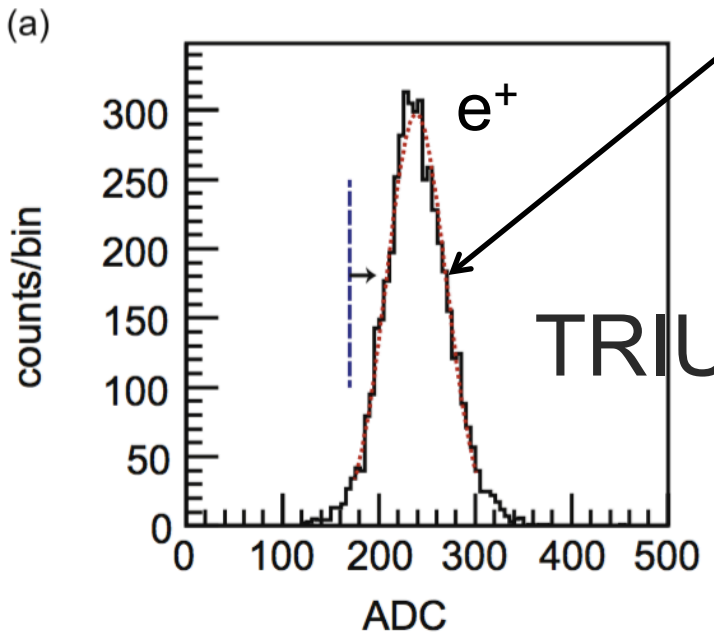
NIM A779 (2015) 013



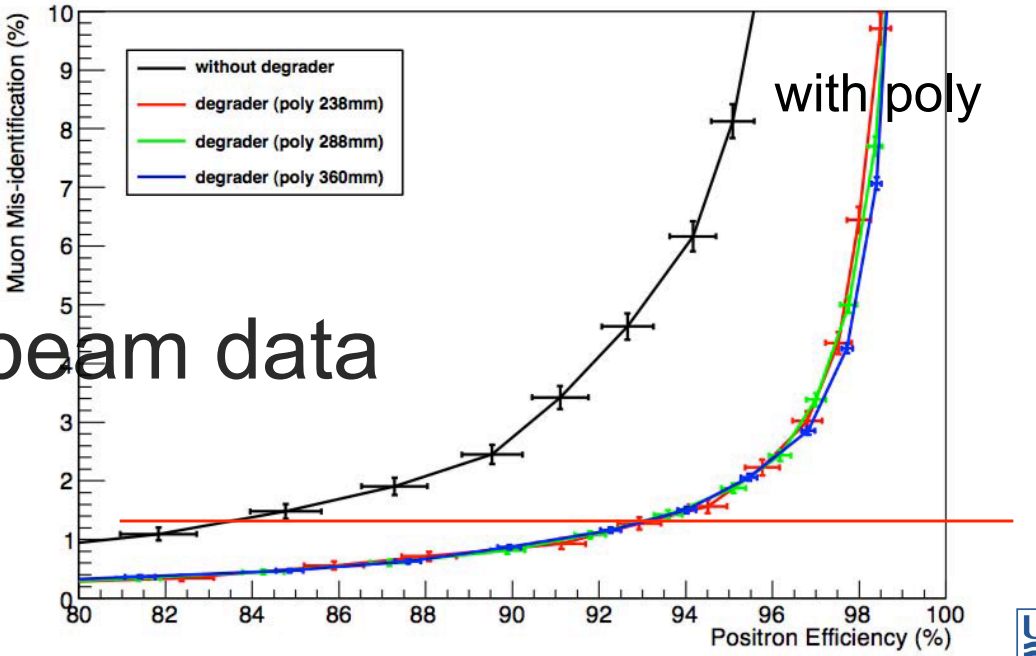




MC Simulation



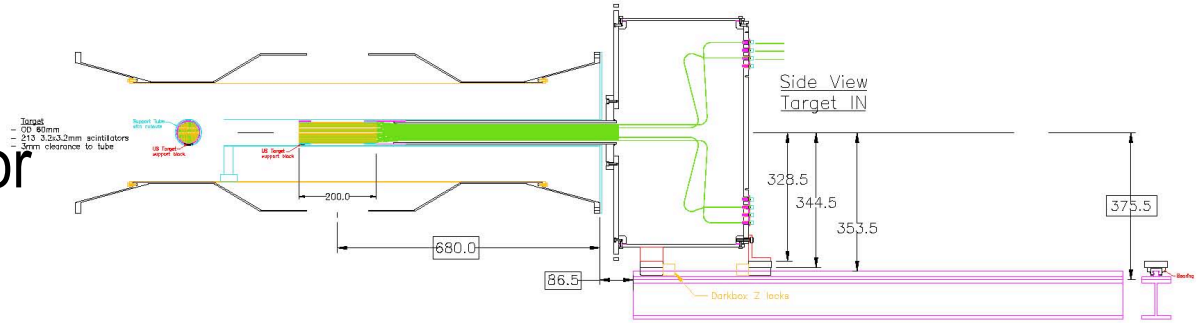
TRIUMF beam data

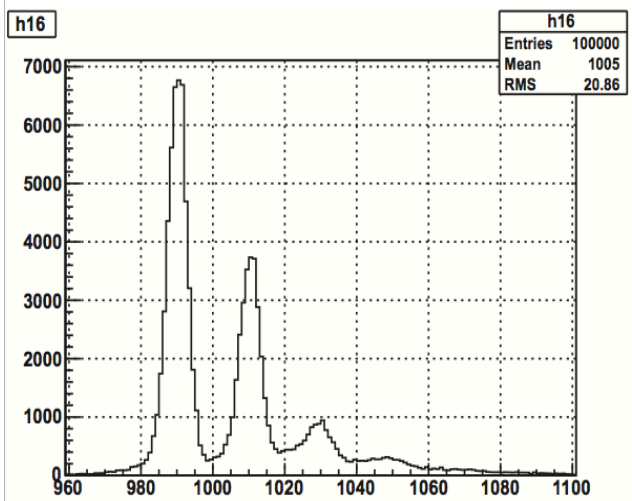


Segmented Scintillating Fibre Target

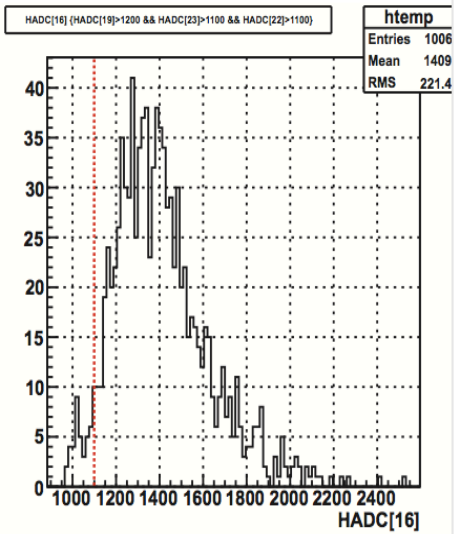
For better tracking resolution

- 256 pieces of
- 3 x 3 x 200 mm^3 Scintillator
- WLS fibre L = 1.4m
- MPPC (SiPMT) readout
- EASIROC electronics
- Production in Canada

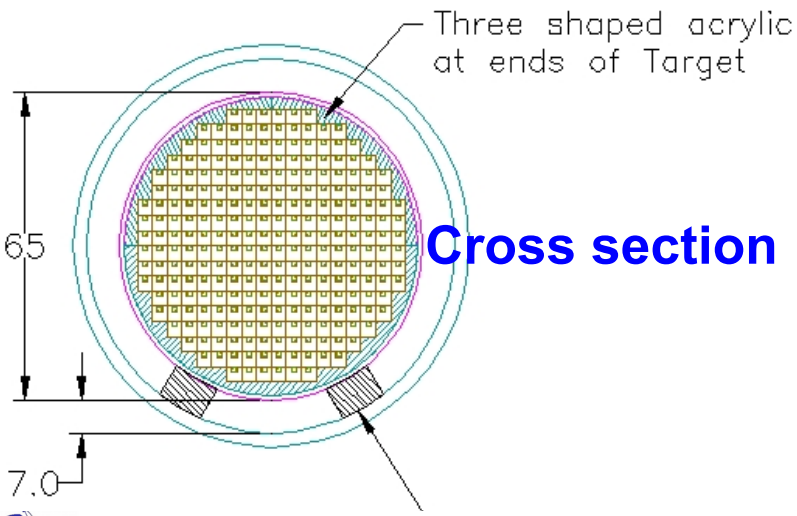




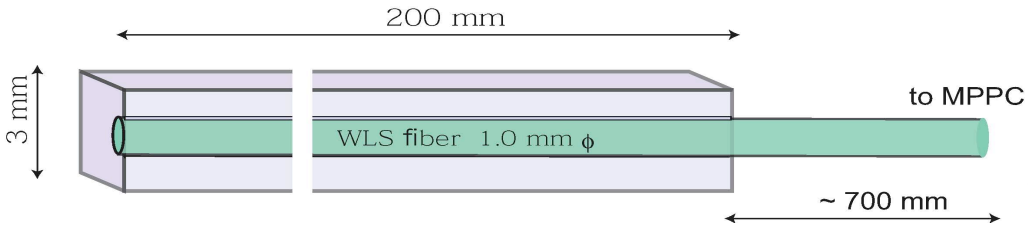
Noise Spectrum
Ped + 1 pe + 2pe



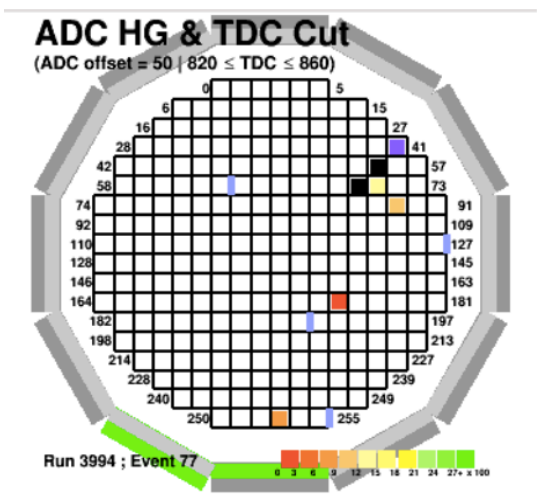
Cosmic Ray Spectrum
~ 30 pe/MeV

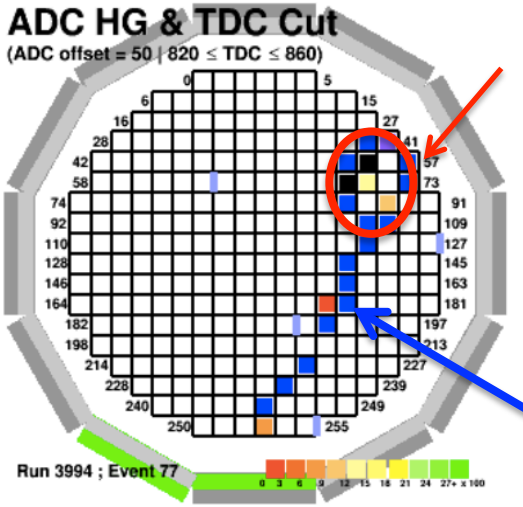


Cross section



Target pattern analysis





Event 77

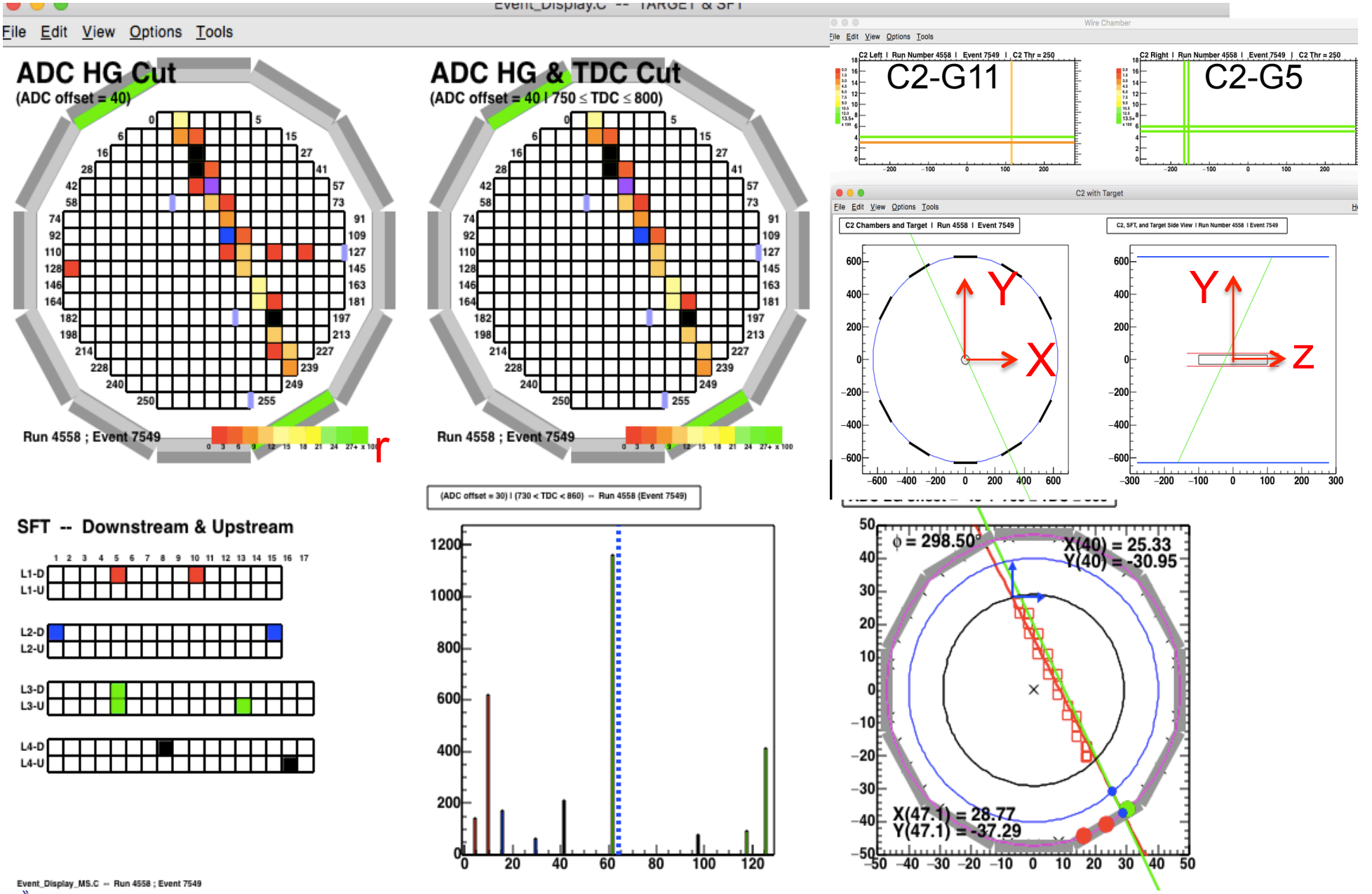
K-stop

Target hit pattern of typical good event

Blue fibres have only a LG signal

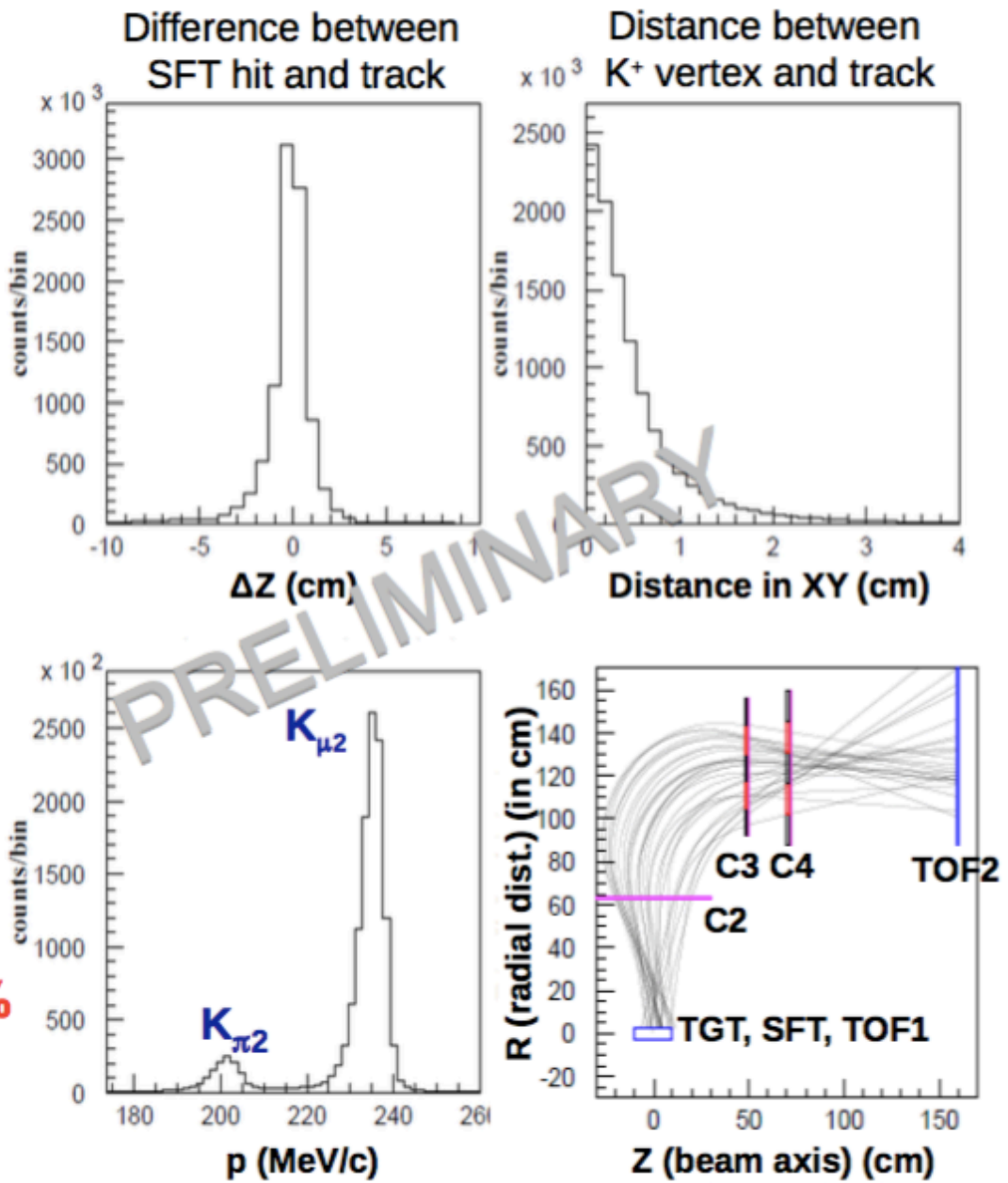
- Determination of K^+ stopping point and lepton depth inside the target
- Measurement of lepton emission azimuthal angle to help determine SFT-Z
- Innermost element for 5-point tracking (intersection point of track and K^+ cluster)
- Inclusion of **LG ADC** completes the target track (when HG signal is missing)
- Development of Target Analysis Algorithm is nearly completed

Cosmic Ray SFT--Tracking Analysis



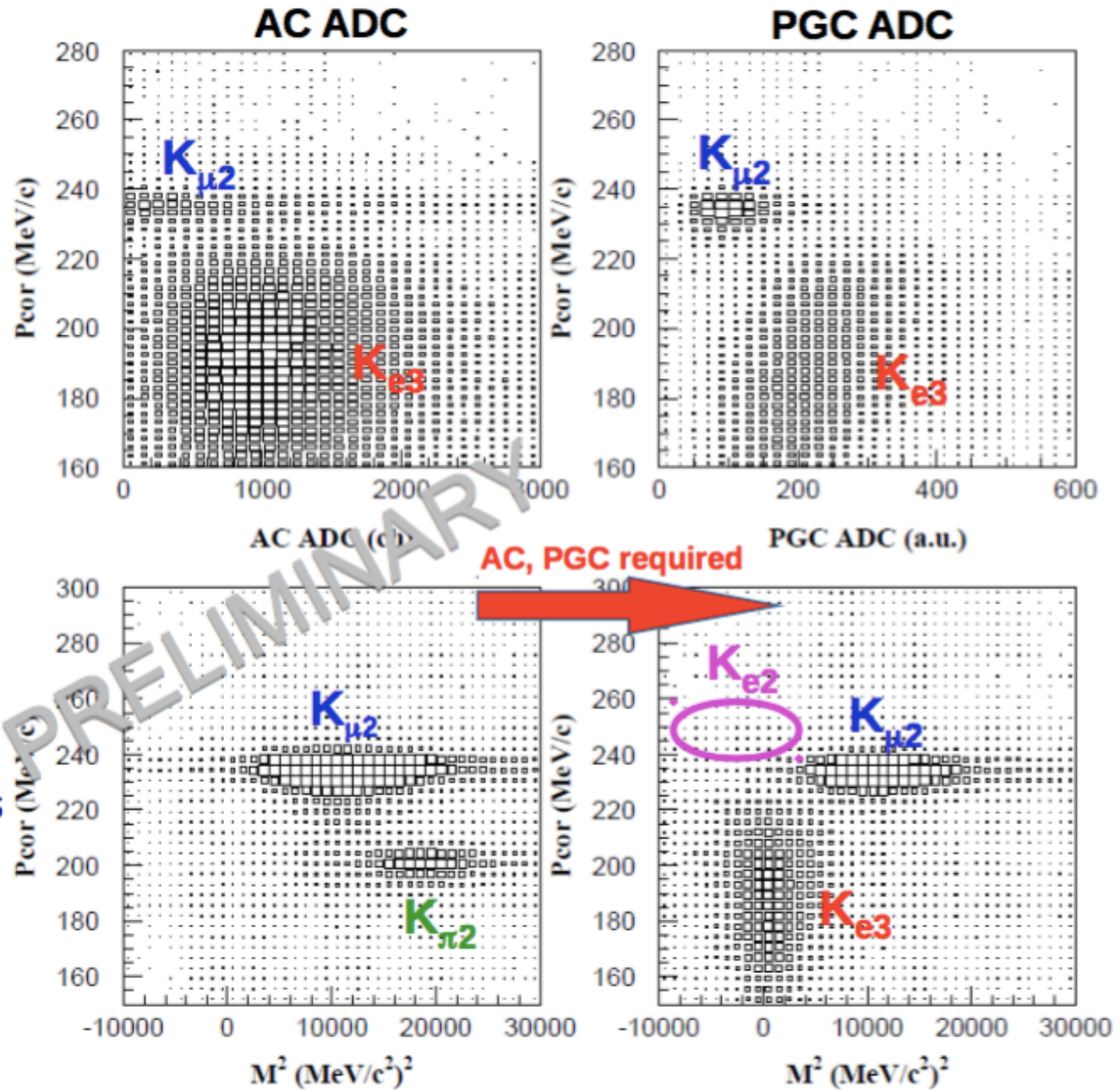
MWPC Momentum analysis

- The charged particle momentum is currently determined by 4 point tracking (C2, C3, C4 MWPCs and target-xy)
- Events are selected by requiring track consistency with the target, SFT and TOF1 - TOF2 gap
- The tracking performance will be improved by introducing the 5 point tracking (C2, C3, C4, MWPCs, target, and SFT-Z)
- Monochromatic peaks due to $K_{\mu 2}$ and $K_{\pi 2}$ are clearly seen
- The momentum resolution $\sigma \sim 1.4\%$ will be improved to 1% by optimizing the target energy loss correction



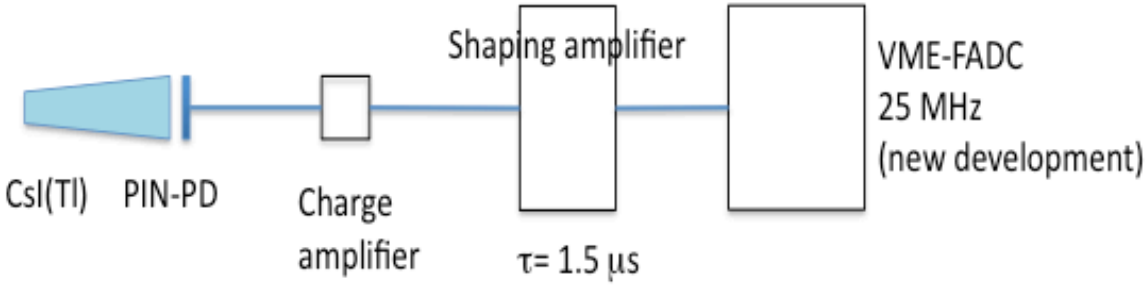
Particle ID by AC, PGC, TOF

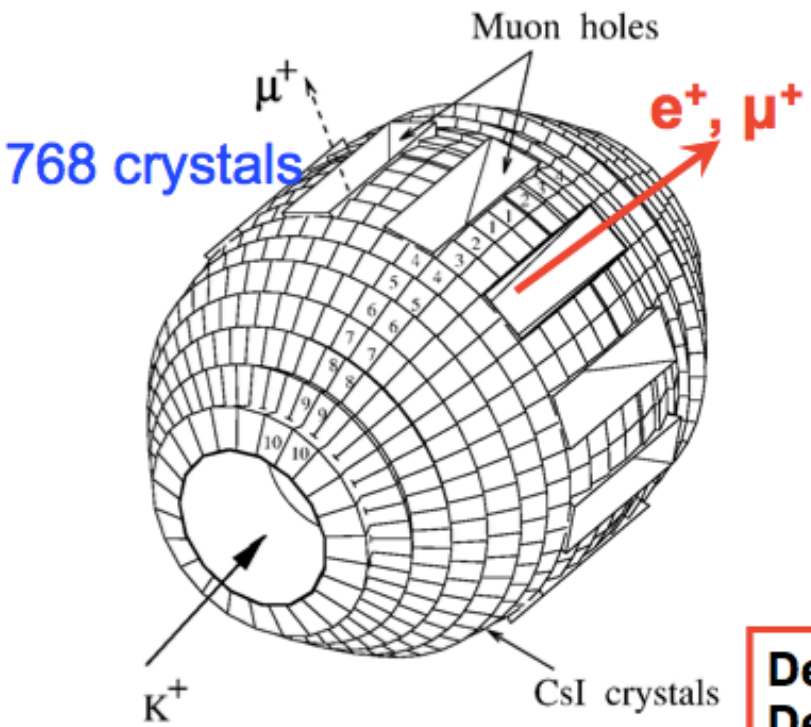
- Positrons are selected by AC, PGC and TOF
- PID performance by combining the three detectors is now being optimized
- Suppression of muon mis-identification below O(10^{-8}) level achievable with refined analysis
- TOF time walk correction has not yet been applied
- Refined analysis of PID performance in progress

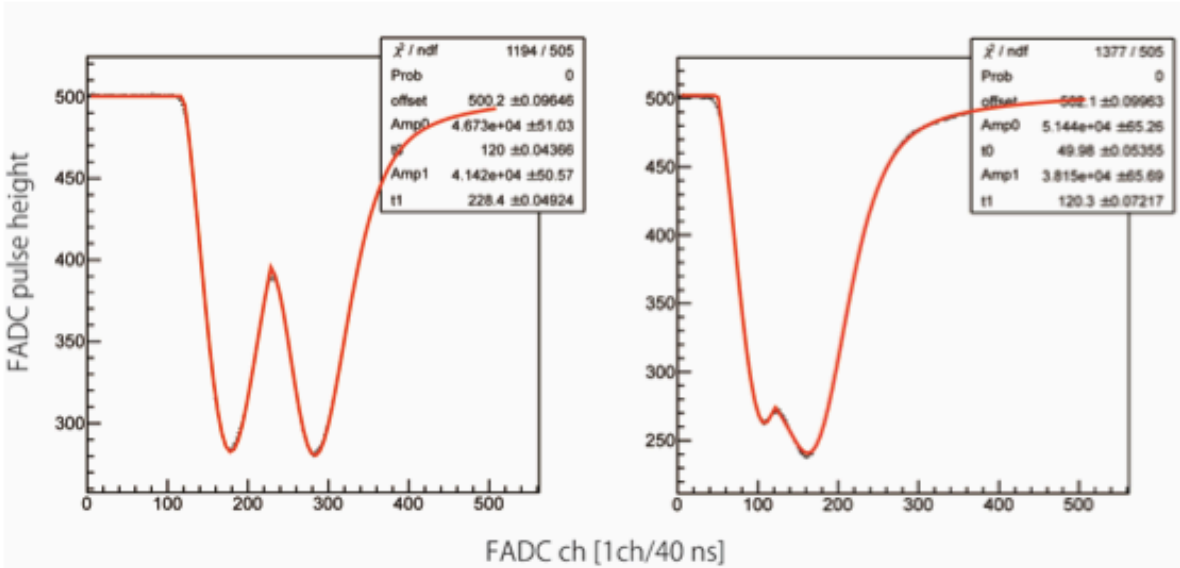


CsI(Tl) Pileup Analysis

Crystal length	**250 mm**
Number of crystals	**768**
Segmentation	**7.5°**
Coverage	**~75%**
Readout	**PIN diodes**
Maximum rate	**~200 kHz**







- *possible to separate with FADC*
- *has been implemented successfully*

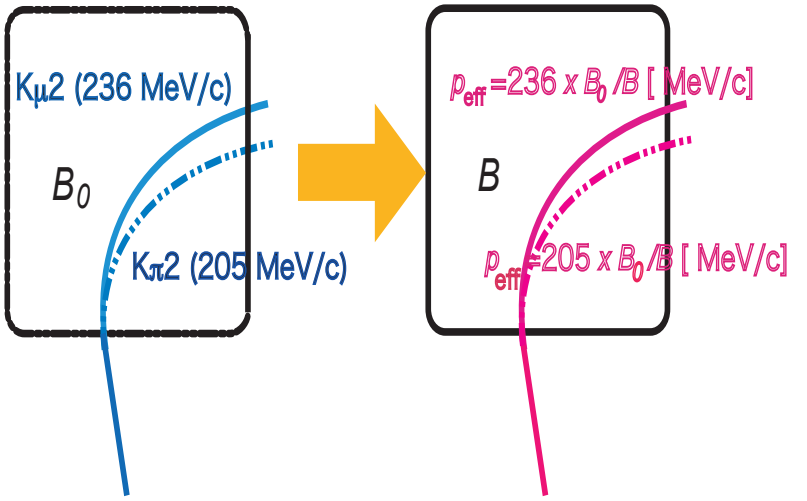
Detection of photons from *$K^+ \rightarrow \mu^+(e^+)\, \nu\, \gamma$* from IB+SD
Detection of *e^+, e^- from dark photon (A') decay*

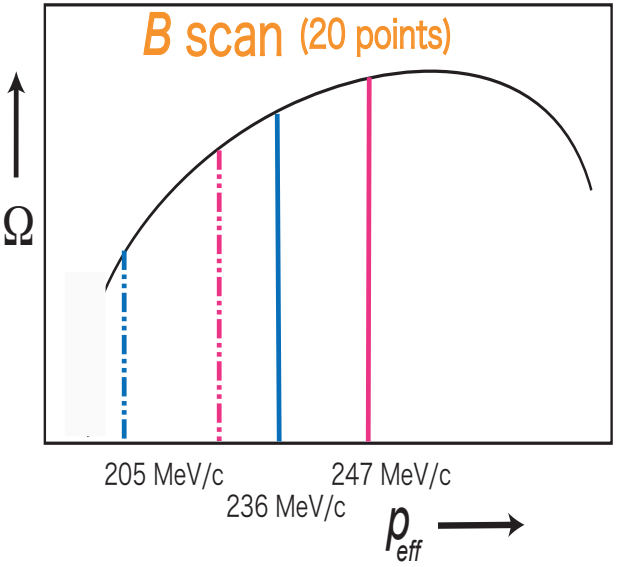
Acceptance: $K_{\pi 2}/K_{\mu 2}$ ratio method

- The $K_{\pi 2}$ and $K_{\mu 2}$ yields are obtained using data with 20 magnetic field settings (1.35--1.53T), and the acceptance ratio is derived.
- We assume that the spectrometer acceptance (Ω) can be described by a polynomial function of the effective momentum, P_{eff} = 236 MeV/c·(B_0/B):

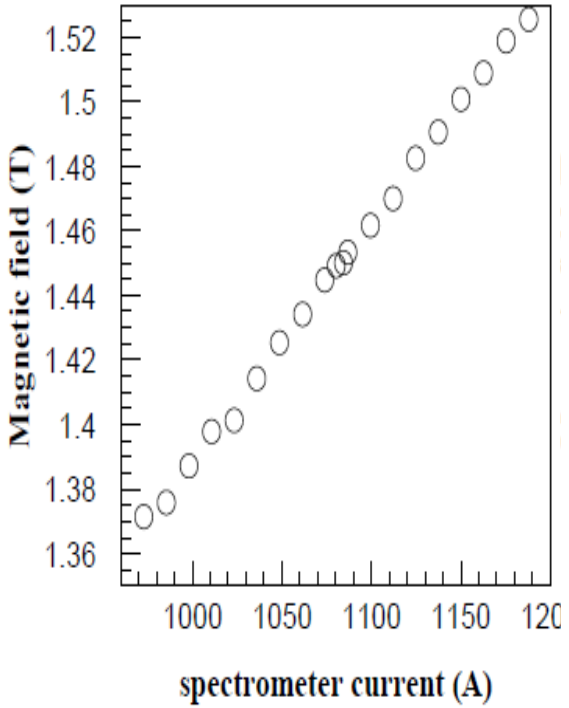
$$\Omega(p) = a_0 + a_1 p + a_2 p^2 + a_3 p^3 + a_4 p^4$$

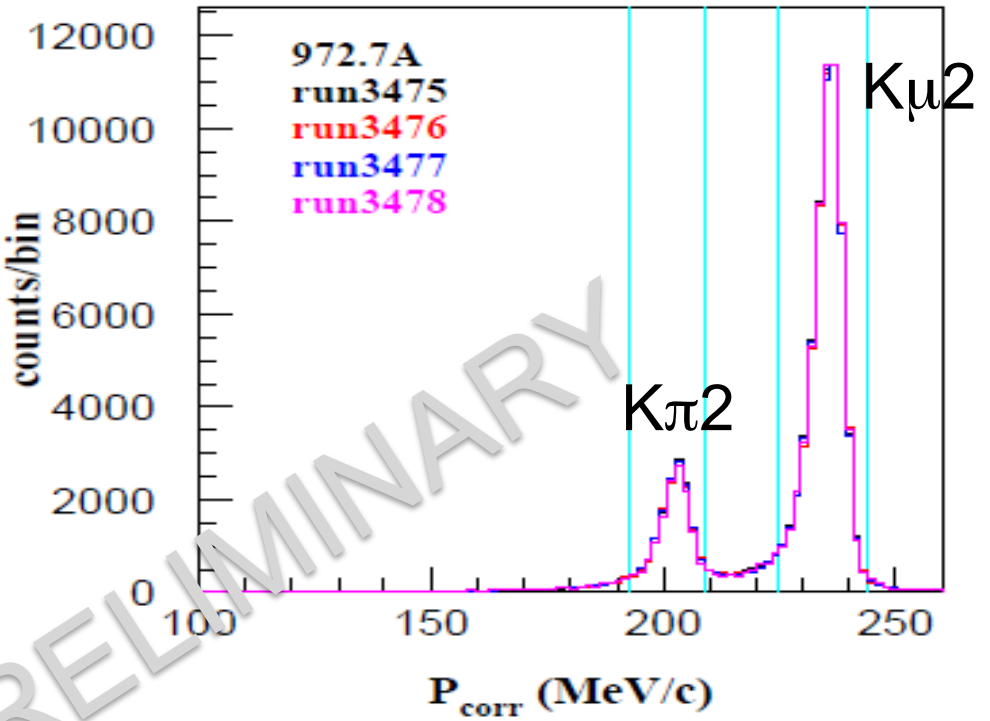
- Parameters a_0 - a_4 can be determined from the 20 measured ratios by fitting.
- Small effect due to magnet non-linearity will be corrected with MC simulation.

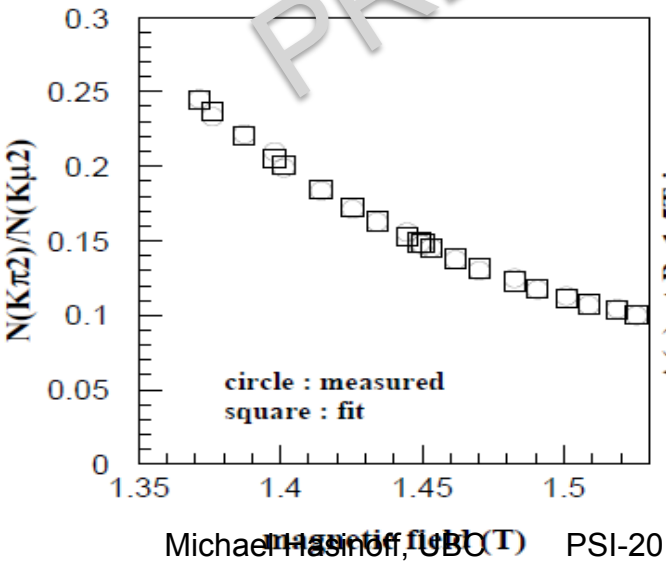


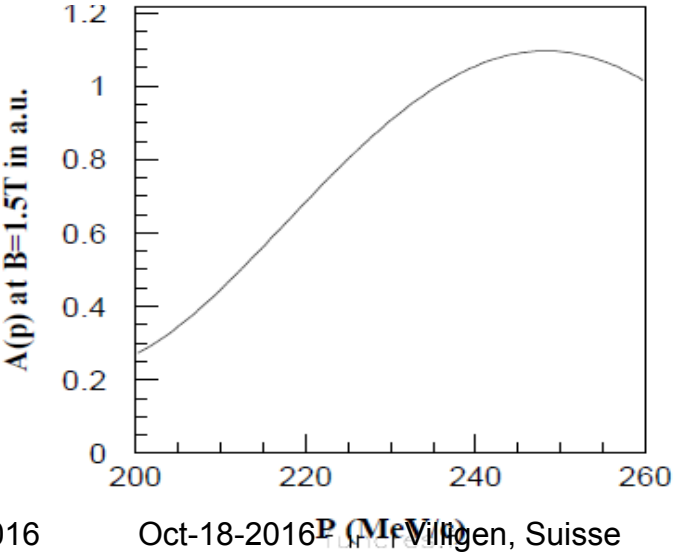


Preliminary results -- $K_{\pi 2}/K_{\mu 2}$ ratio method



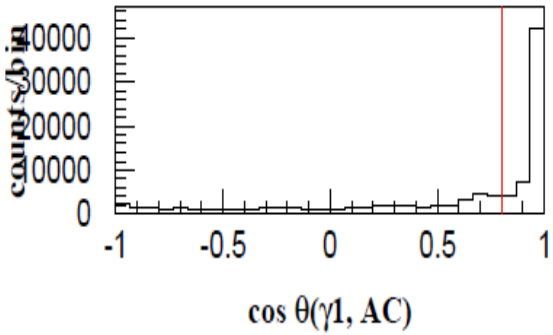


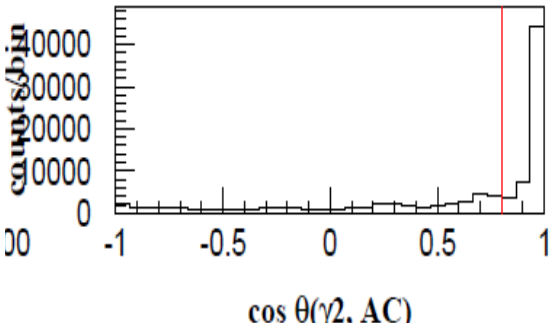


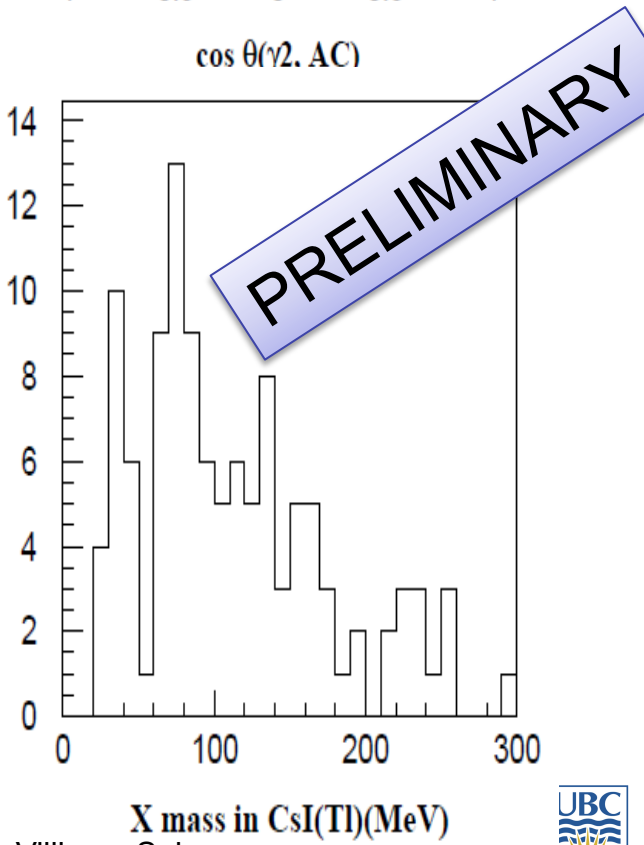


Dark Photon search using $K^+ \rightarrow \ell^+ e^+ e^- \nu$ events

- We can measure $K^+ \rightarrow \ell^+ e^+ e^- \nu$ decays by the Toroidal spectrometer (ℓ^+) and the CsI(Tl) calorimeter ($e^+ e^-$).
- e^+ and e^- are identified by the aerogel Cherenkov counter surrounding the K^+ stopping target.
- Main backgrounds are $K^+ \rightarrow \ell^+ \pi^0 \nu$ and $\pi^0 \rightarrow e^+ e^- \gamma$
- Dark photon A' through $K^+ \rightarrow \ell^+ A' \nu$ $\rightarrow \ell^+ e^+ e^- \nu$ process can be studied.







Summary & Outlook

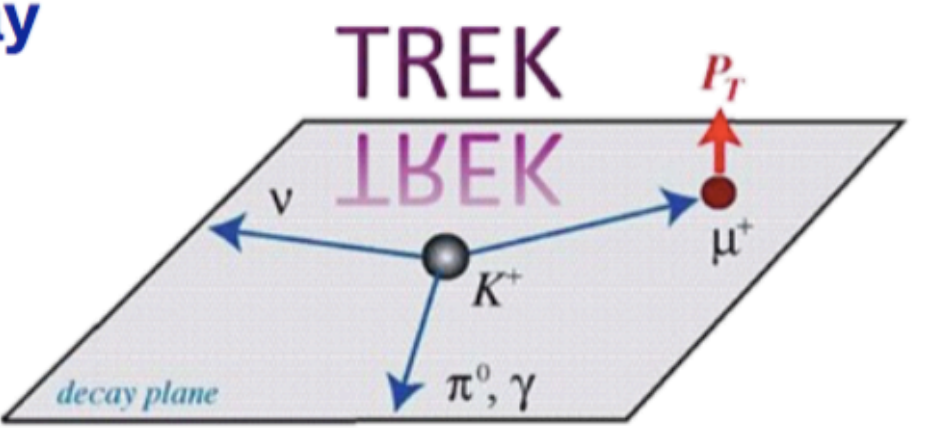
The TREK E36 Collaboration has completed a Lepton Universality Experiment at J-PARC

- $K_{e2}/K_{\mu 2}$ ratio measurement to test lepton universality with the best sensitivity available using stopped kaons
- Search for dark photon / light boson
- Analysis currently in progress

  Calibration, CsI(Tl), PID, momentum and TOF measurements

NEXT Measurement of the T-violationg transverse muon polarization in $K_{\mu 3}$ decay

- E06 experiment @ J-PARC (~202x)
- Requires Hadron Hall extension



Thank you
Merci beaucoup
Danke shön
Arigato Gozaimasu