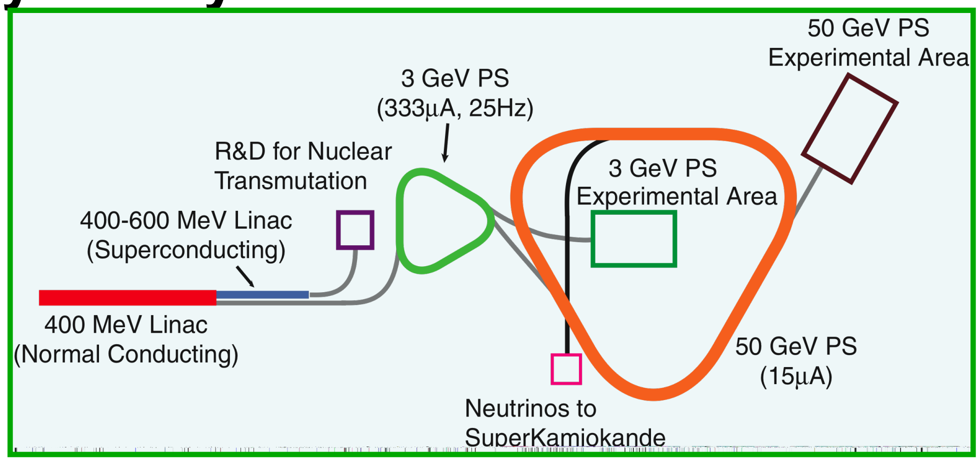
Search for New Physics via a Precision Measurement of $\Gamma(K_{e2}) / \Gamma(K_{\mu 2})$ at J-PARC

Michael D. Hasinoff
University of British Columbia
on behalf of the E36-TREK collaboration

Outline

- **J-PARC Facility**
- **TREK Program** TREK = Time Reversal Experiment with Kaons
  - ✓ **Test of Lepton Universality**
  - ✓ **Search for Dark Photon**
  - **Search for Heavy Neutrinos**
  - (the first three: Lower intensity)
  - **Search for Time Reversal Symmetry Violation**
- **Theoretical Motivation**
- **Preliminary Results**
- **Future Plans**
- **Summary**



Stopped K^+ Experiments @ K1.1BR

- E36 (LFU)

"Measurement of $R_K = \Gamma(K^+ \rightarrow e^+\nu) / \Gamma(K^+ \rightarrow \mu^+\nu)$
and a search for dark photons & heavy sterile neutrinos"
Collected data during Fall 2015 30-45 kW

- E06 (TREK)

"Measurement of the T-violating transverse muon
polarization (P_T) in $K^+ \rightarrow \pi^0\mu^+\nu$ decay"
Stage-1 approved 270 kW (≥ 100 kW)

E06 – awaits a new beamline in the Extended Hadron Hall since K1.1BR has now been decommissioned

TREK Collaboration

CANADA

University of British Columbia
TRIUMF

USA

Hampton University
T. Jefferson Nat. Laboratory
Iowa State University
University of South Carolina

RUSSIA

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

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

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

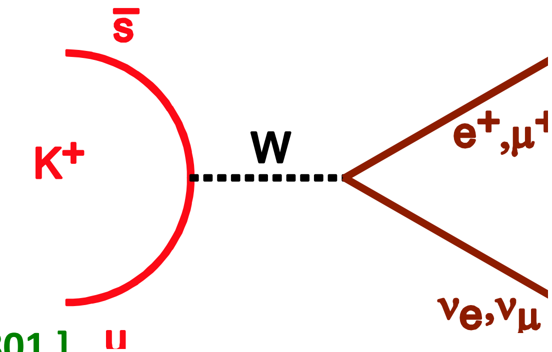
- Very precise SM predictions

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

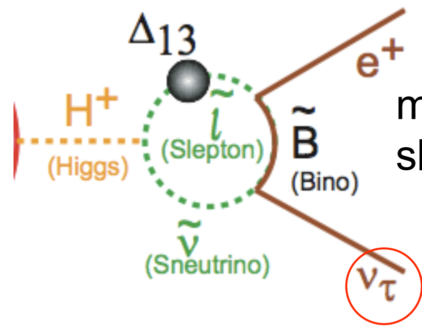
$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$

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

Ke2



- High sensitivity to LFV beyond SM



mixing in the slepton sector

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

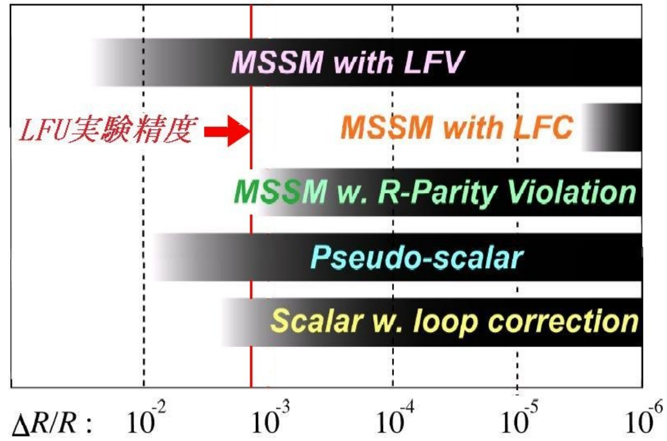
$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H^+}^4} \cdot \frac{m_\tau^2}{m_e^2} \Delta_{13}^2 \tan^6\beta\right) \Rightarrow R_K^{LFV} \sim R_K^{SM}(1 + 0.013)$$

[Masiero, Paradisi and Petronzio, Phys. Rev. D74 (2006) 011701]

Expected Exp' tal precision ~ 0.25%, presentation to PAC11

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

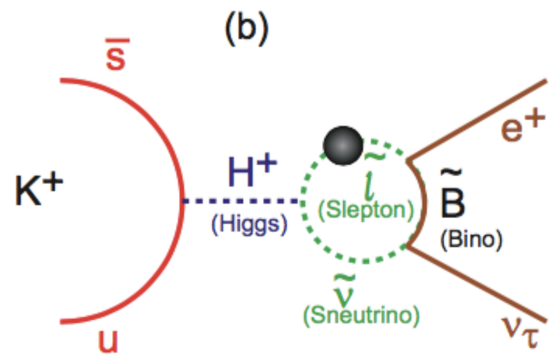
- ## Possible New Physics
  - MSSM with LFV
  - MSSM w. *R*-parity violation
  - Pseudo-scalar interaction
  - Scalar w. loop correction



- ## SUSY with LFV for K_{e2}

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

- Charged Higgs H^+ mediated LFV SUSY
- Large enhancement from m_τ^2/m_e^2
- A sizable effect up to $\Delta R_K/R_K$~1.3% possible



K_{e2}

Masiero, P. Paradisi, & R. Petronzio, Phys Rev D74(2006) 011701, JHEP 11(2008) 042
J. Girrbach and U. Nierste, JHEP 05 (2010) 026; arXiv:1202.4906;

- ## Neutrino mixing
  - R_K sensitive to neutrino mixing parameters within SM extensions with 4th generation of quarks and leptons or sterile neutrinos

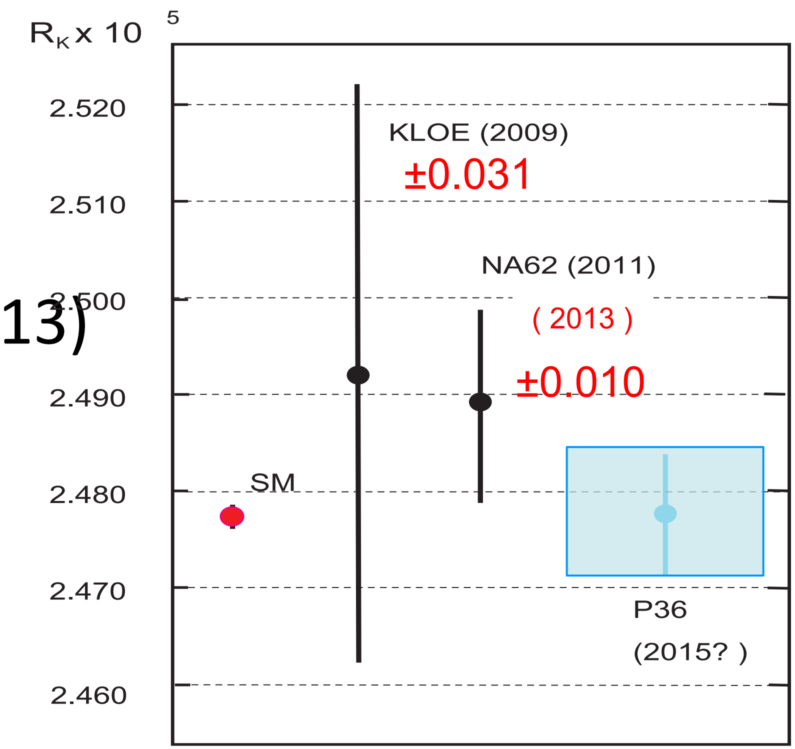
H. Lacker and A.Menzel, JHEP 1007 (2010) 006; A. Abada et al., arXiv: 1211.3052

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: --

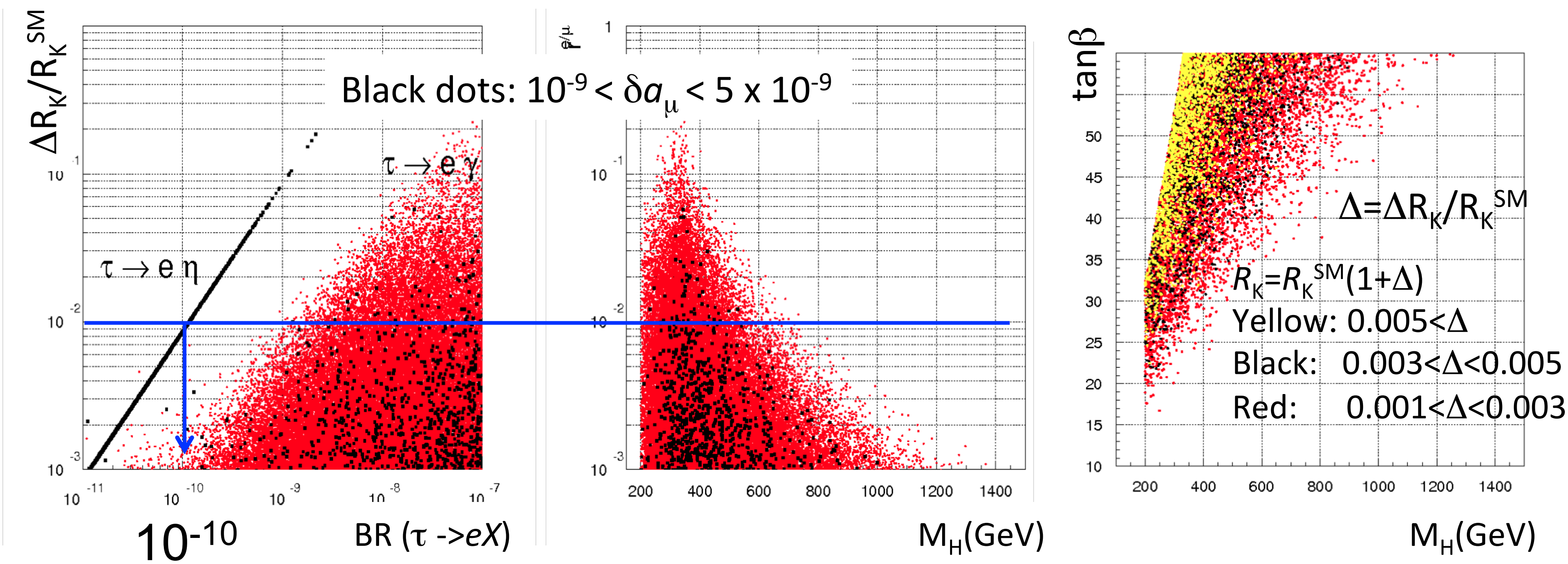
    detector acceptance and target interactions

proposed $\Delta R_K/R_K \approx \pm 0.20 \pm 0.15$ %

LFV in SUSY

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

- LFV effect may be found 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 tanβ (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), $\tan\beta$, M_H

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

valid for $m_{\tilde{\tau}_1} = 120$ GeV, $M_1 = 100$ GeV, $m_{\tilde{e}_R} = 200$ GeV.

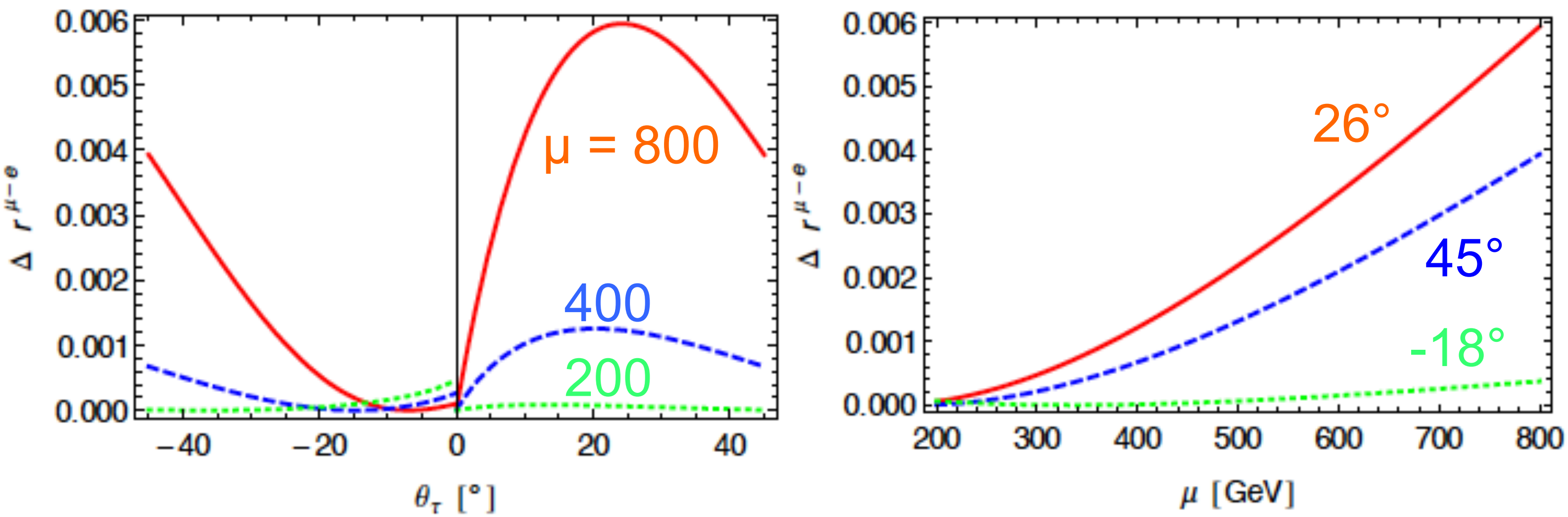


Figure 3: $\Delta r^{\mu-e}$ for $\delta^{13}_{RR} = 0.5$, $M_H = 500$ GeV and $\tan\beta = 50$. Left: As a function of θ_τ for different values of μ: 800 GeV (red), 400 GeV (blue dashed), 200 GeV (green dotted). Right: In dependece of μ for different values of θ_τ: 26° (red), 45° (blue dashed), −18°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

Parameter Constraints

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

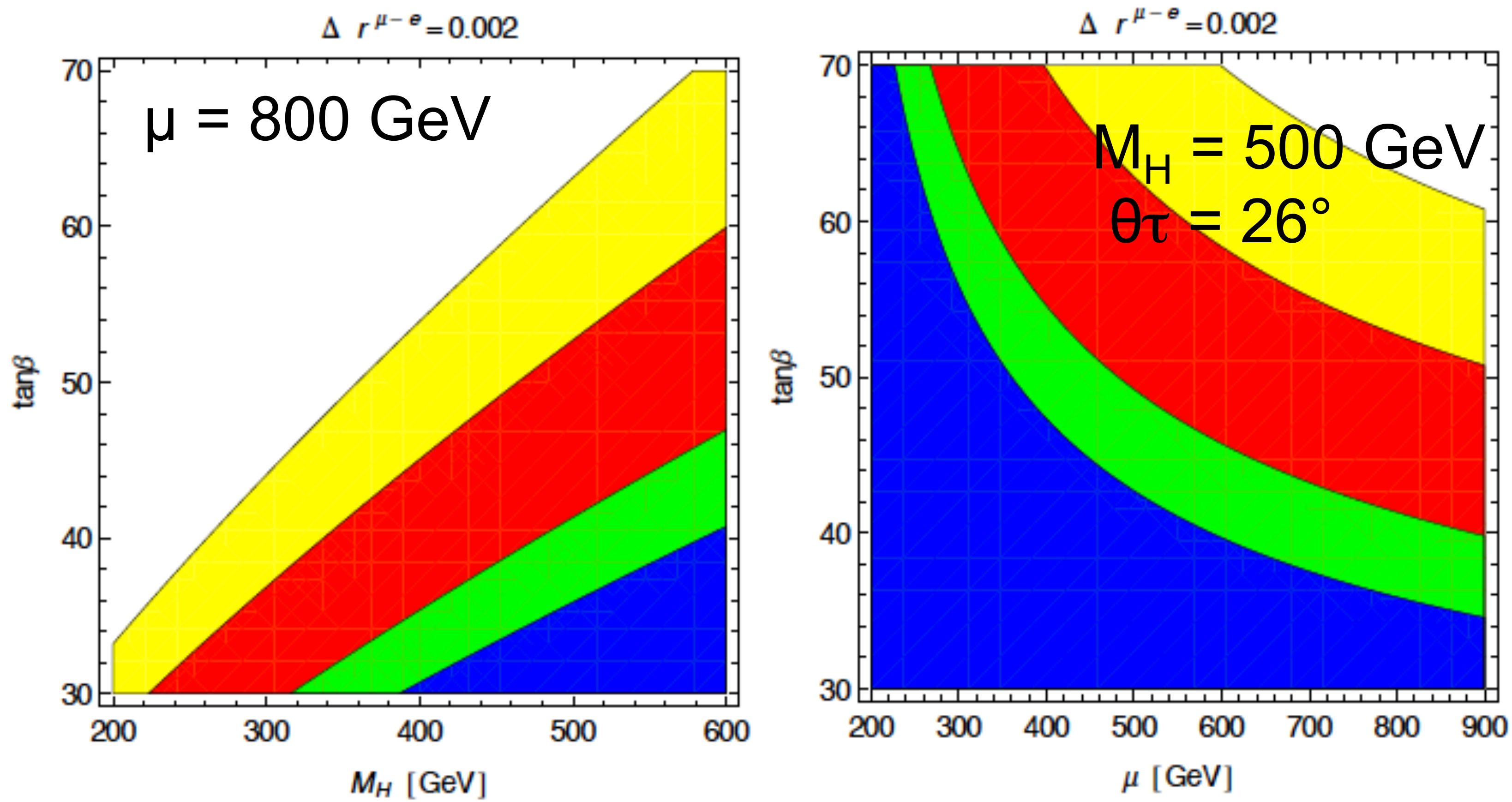


Figure 5: For different values of $\delta_{RR}^{13} = 0.15$ (yellow), 0.25 (red), 0.5 (green), 0.75 (blue) (from top to bottom) we plot the regions in which $\Delta r^{\mu-e}$ is below the future experimental sensitivity of 0.002 in the M_H–$\tan\beta$ plane with $\mu = 800$ GeV (left) and in the μ–$\tan\beta$ plane with $M_H = 500$ GeV (right) and stau mixing angle $\theta_\tau = 26°$. I.e. if $\delta_{RR}^{13} = 0.25$, the white and yellow areas correspond to $\Delta r^{\mu-e} \geq 0.002$.

Model Independent -- $\Delta r_{\text{min, LFC}}$

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

Calculation of LFC contribution from $\delta^{13}_{LL}\delta^{13}_{RR}$

i.e. -- double LFV insertion

$$\Delta r^{\mu-e}_{\text{min,LFC}} = -4\frac{m_K^2 \tan^2\beta}{M_H^2(1+\epsilon_s \tan\beta)} \quad \sim -0.005$$

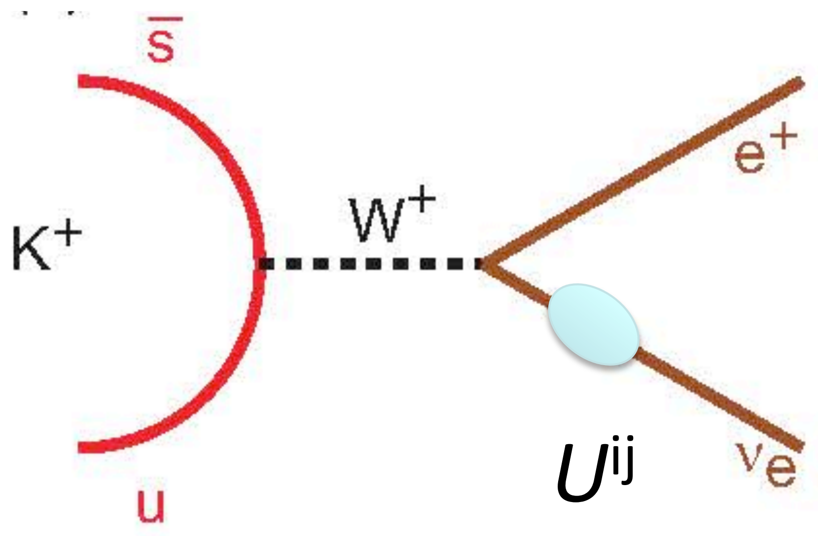
Negative !!

M_H = 300 GeV
$\varepsilon_S \tan\beta = 0.3$

Sterile neutrino mixing

"Tree-level lepton universality violation in the presence of sterile neutrinos: impact for R_K and R_π"

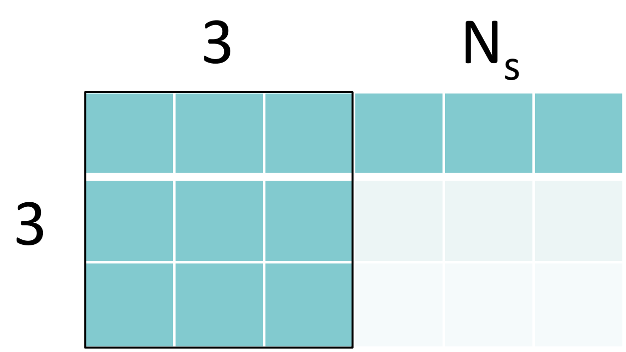
Abada, Das, Teixeira, Vicente & Weiland -- JHEP 02 (2014) 091



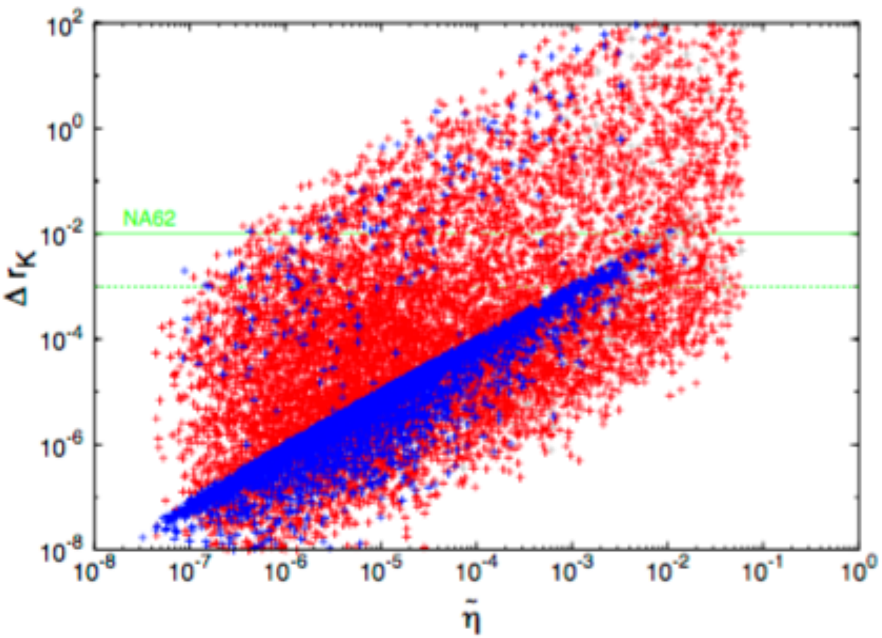
$$\mathcal{L}_{\rm int} = -\frac{g}{\sqrt{2}} U_\nu^{ji} \bar{\ell}_j \gamma^\mu P_L \nu_i W_\mu^- + \text{h.c.}$$

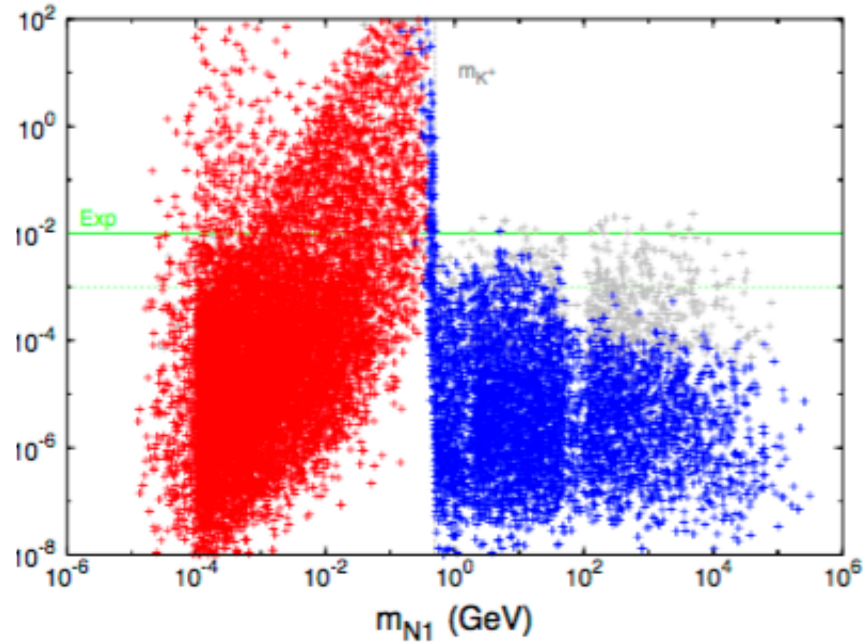
Neutrino mixing matrix : U^{ij}

- SM neutrinos = 3
- Sterile singlet neutrinos = N_s



Inverse seesaw model





$$\tilde{\eta} = 1 - |\mathrm{Det}(\tilde{U}_{\mathrm{PMNS}})|$$

m_{N1} = lightest sterile ν mass

Deviation of mixing matrix from unitarity

Blue : in agreement with standard cosmology
Red : requiring non-standard cosmology
Grey : already excluded by BR(μ->eγ)

New Pseudoscalar Interaction

$$R_K^P \sim R_K^{SM}\left[1 \pm \frac{\sqrt{2}\pi}{G}\frac{1}{\Lambda_{eP}^2}\frac{m_K^2}{m_e(m_d+m_u)}\right]$$

$$\frac{R_K^P}{R_K^{SM}} \sim 1+\left(\frac{1\mathrm{TeV}}{\Lambda_{eP}}\right)^2 \times 10^3,$$

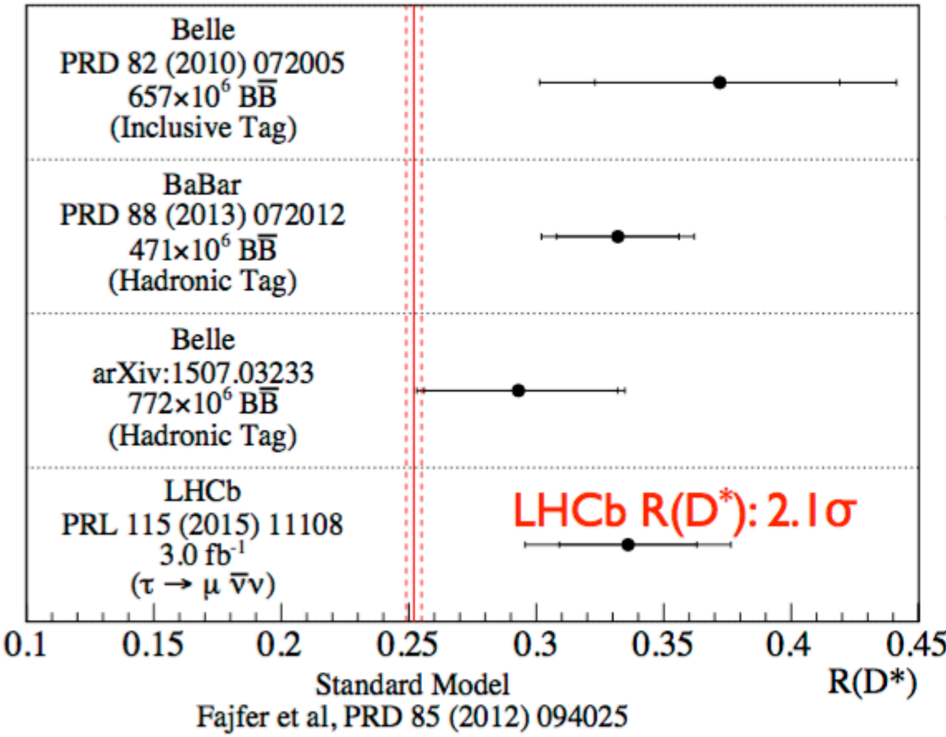
$\Delta R_K/R_K = 0.25\%$

↓

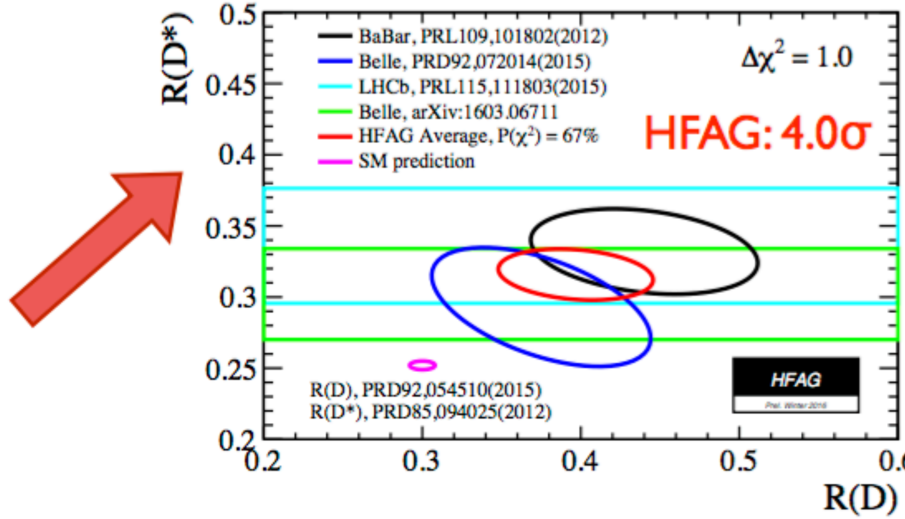
$\Lambda_{eP} \sim 750$ TeV

Lepton universality?

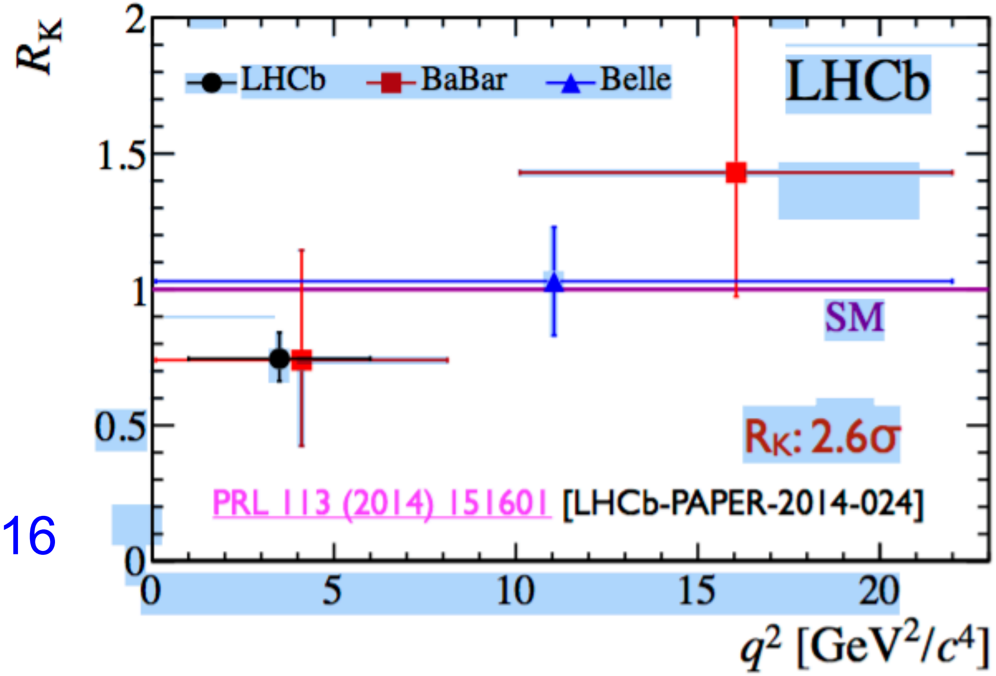
$R(D^*) = \mathcal{B}(\overline{B^0} \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\overline{B^0} \to D^{*+}\mu^-\bar{\nu}_\mu)$



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

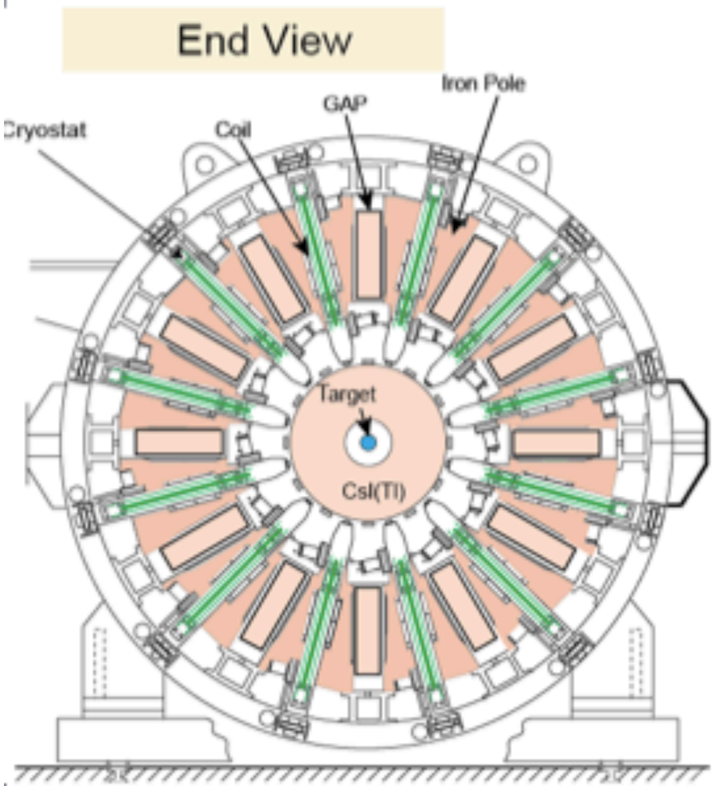


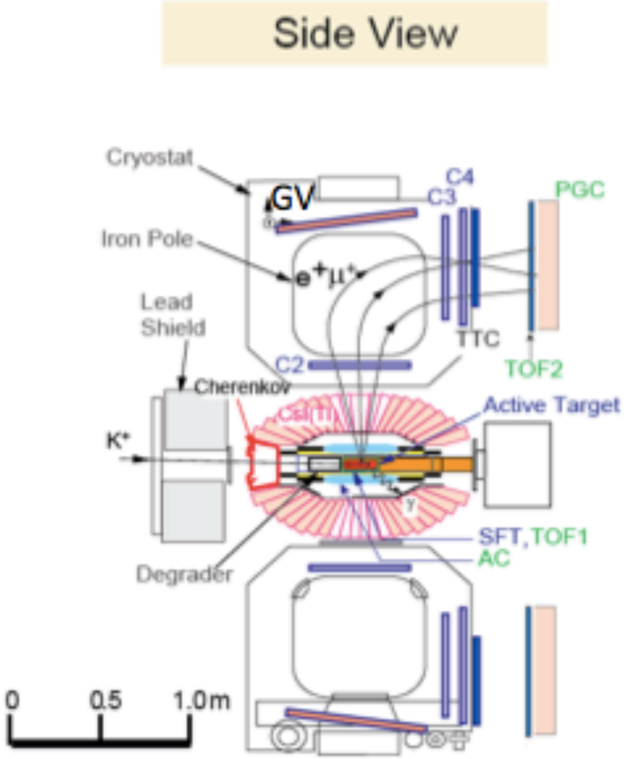
$R_K\ (B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-)$



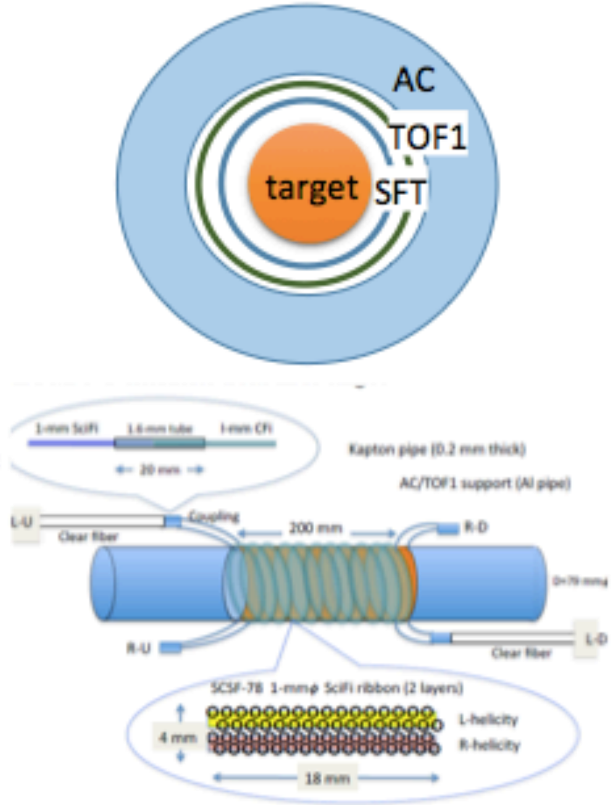
from Mat Charles – LHCP Lund June 2016

E36 Apparatus





Central Detectors



Upgrade of KEK-PS E246 apparatus

Stopped K method
- K1.1BR beamline
- K^+ stopping target

Tracking
- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)
- Thin trigger counter (TTC)

PID
- TOF (TOF1, TOF2)
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

Gamma ray
- CsI(Tl)
- Gap veto (GV)

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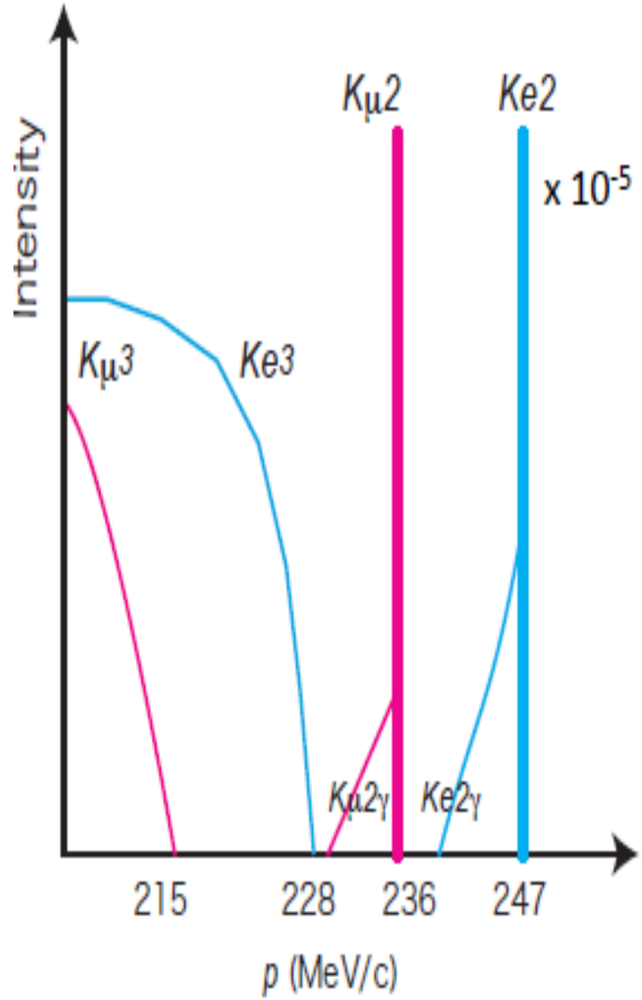
R_K determination

Schematic momentum spectrum

$N_{\mu 2}$ / N_{e2} ~ 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

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

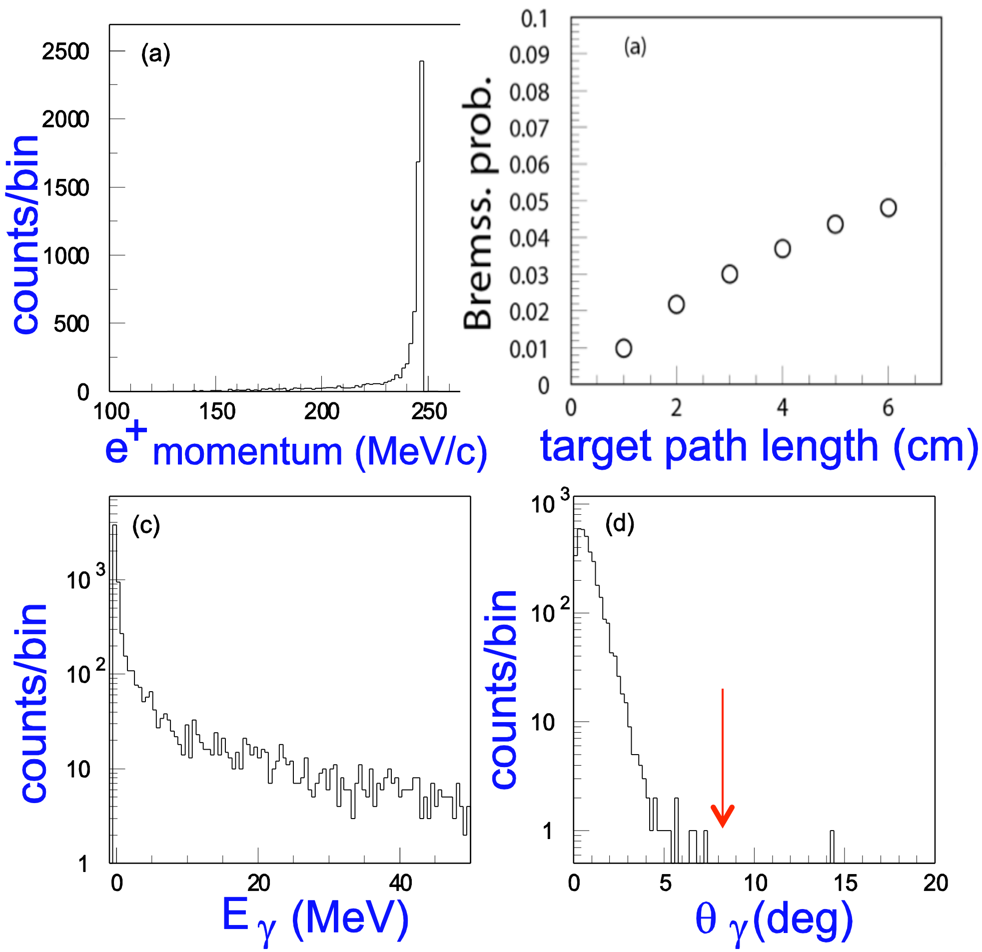
- Comparison of R_K with R_K^{SM}
  - also including $K_{e2\gamma}$ and $K_{\mu 2\gamma}$

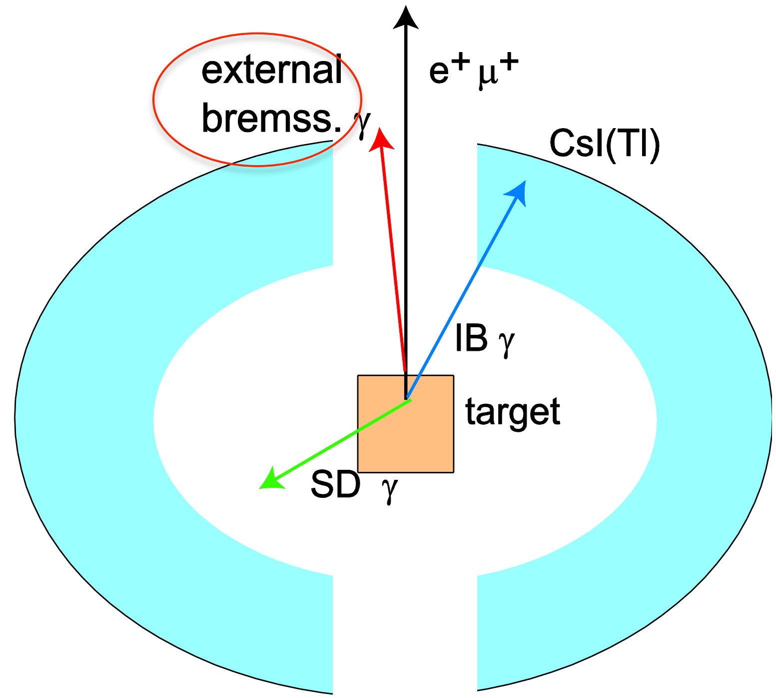
MC – External Brems spectra

(1) K_{e2} including external bremsstrahlung photon (in target)

(2) K_{m2}

(3) Radiative K_{l2} decays



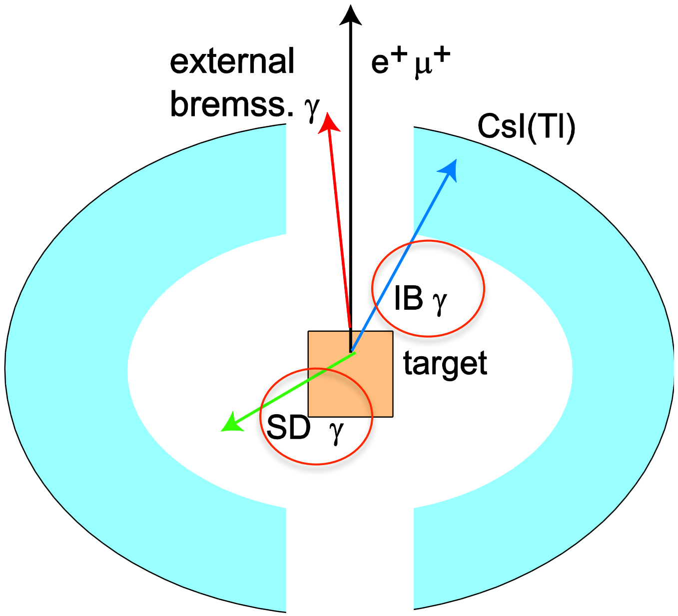


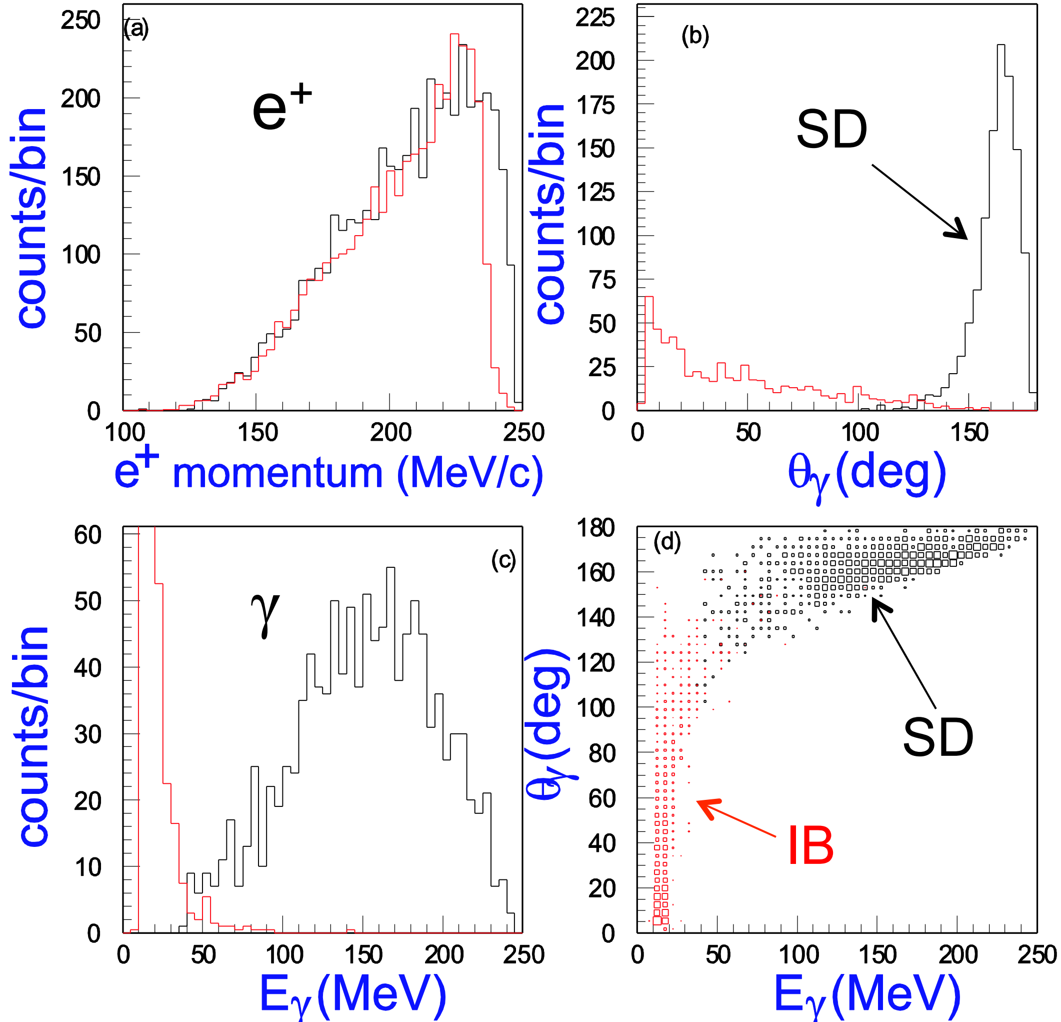
Subtraction of SD γ Bkgd

(1) K_{e2} including external bremsstrahlung photon (in target)

(2) K_{m2}

(3) Radiative K_{l2} decays





Black: Structure dependent
Red: Internal bremsstrahlung

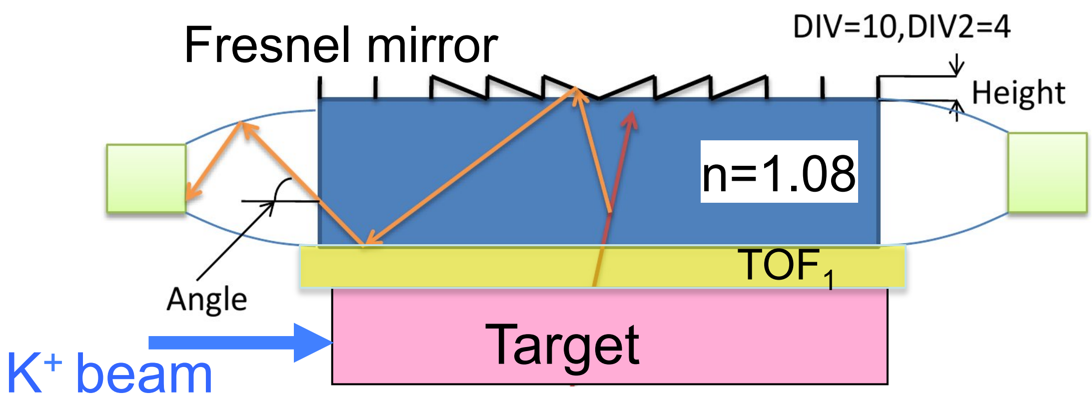
IB and SD – well separated

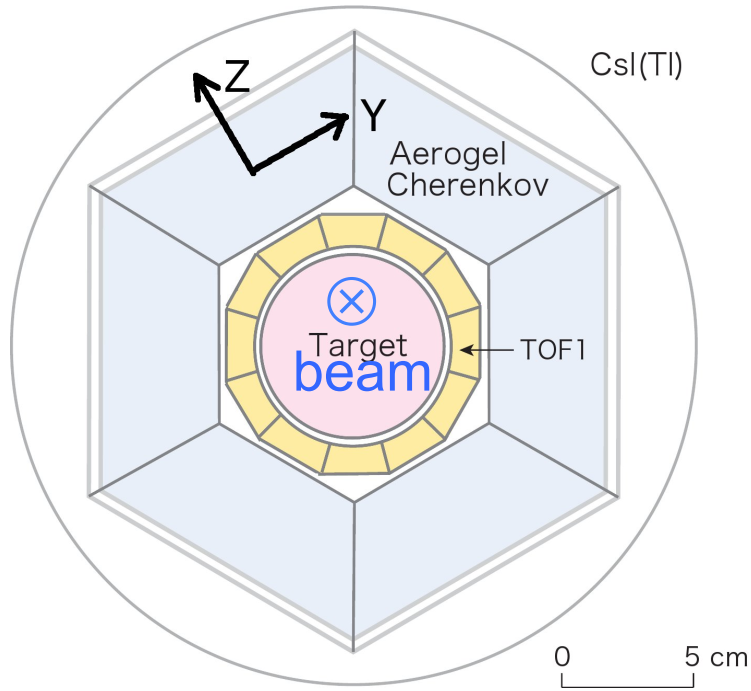
$\delta R_K/R_K$ (SD) < 0.04%

e/μ PID – Aerogel Cherenkov Detector

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

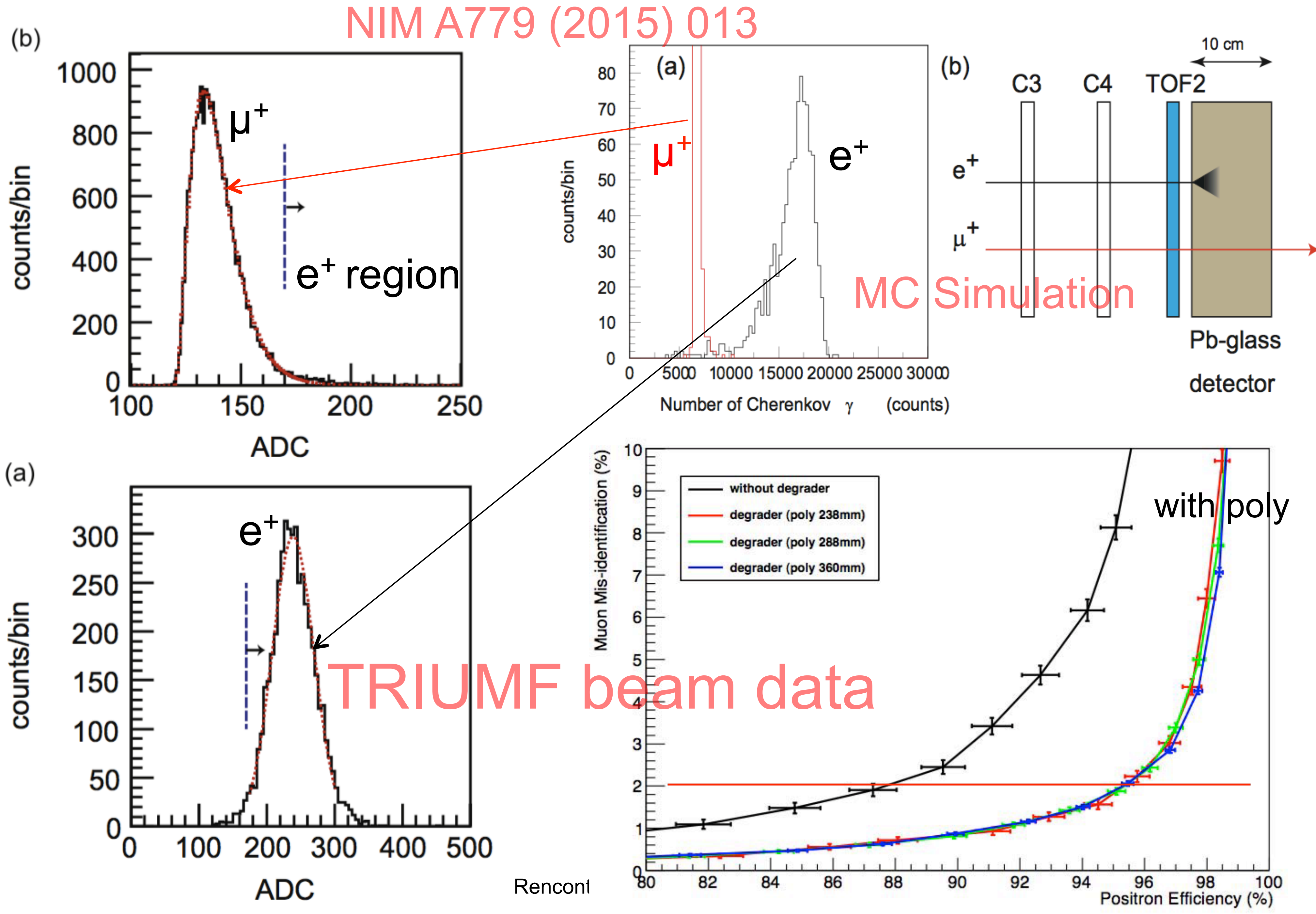
$\beta(e^+ \text{ from } K_{e2}) \sim 1$
$\beta(\mu^+ \text{ from } K_{\mu2}) \sim 0.92 = 1 / 1.087$
Estimated efficiency = 99.9 ± 0.1%





PID performance and detector efficiency can be measured & controlled using K_{e3} and $K_{\mu3}$ data.

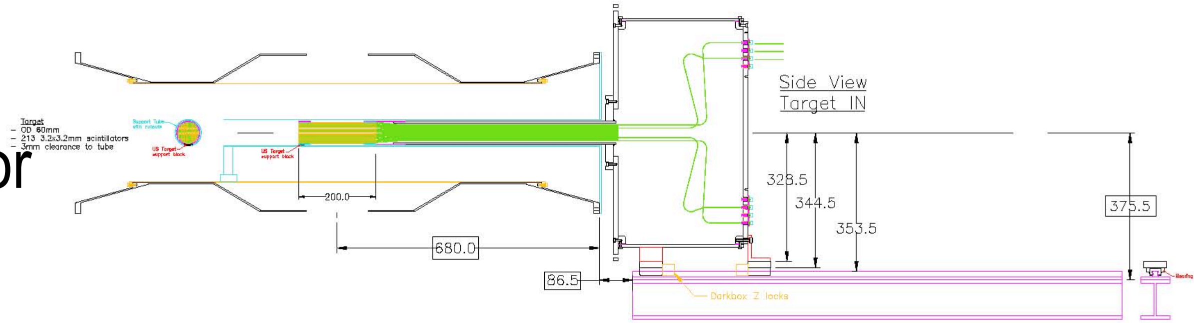
e/μ PID -- PGC Detector

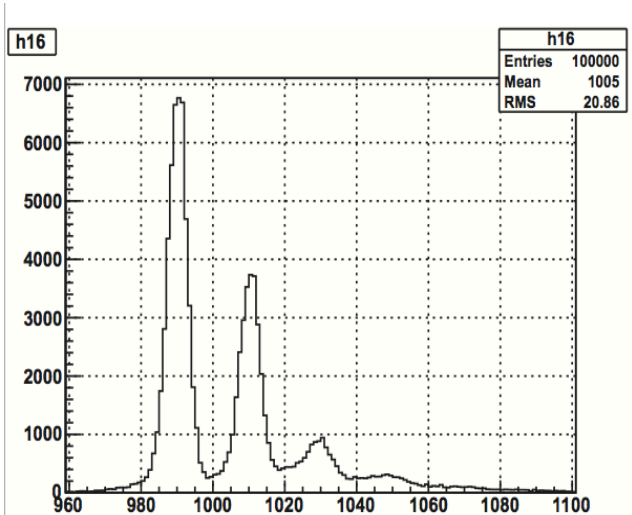


Segmented Scintillating Fibre Target

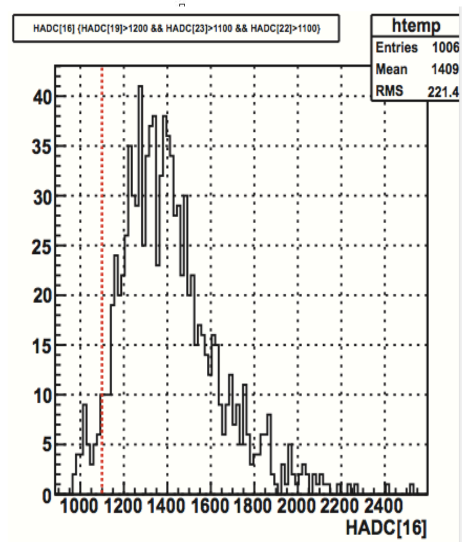
For better tracking resolution

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

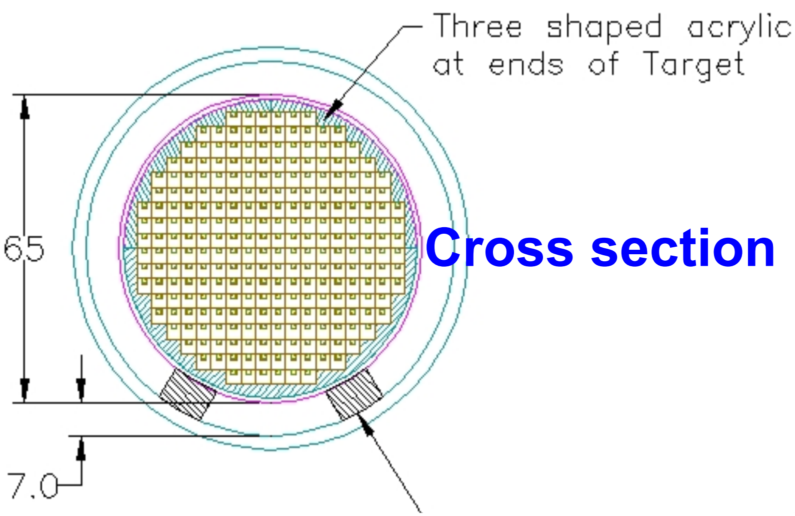




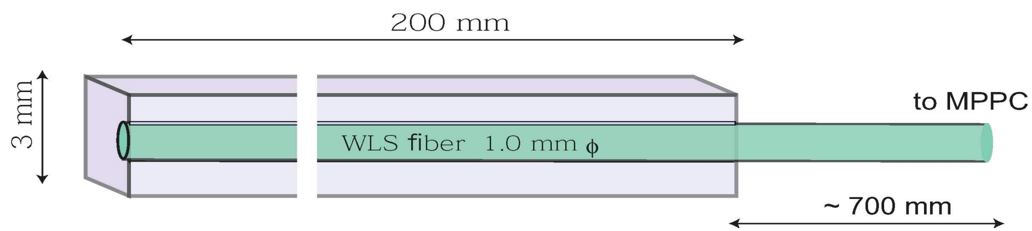
Noise Spectrum
Ped + 1 pe + 2pe



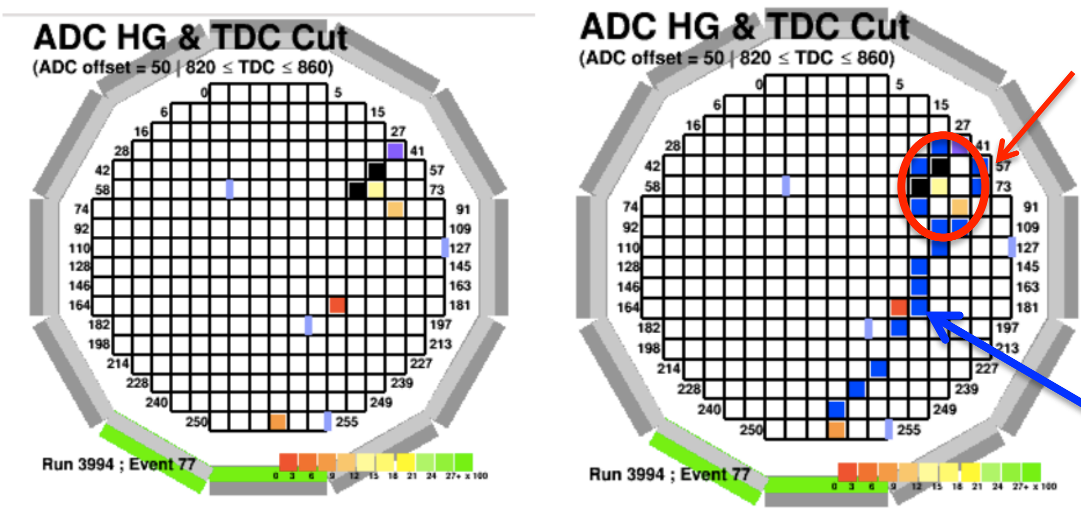
Cosmic Ray Spectrum
~ 30 pe/MeV



Cross section



Target pattern analysis



Event 77

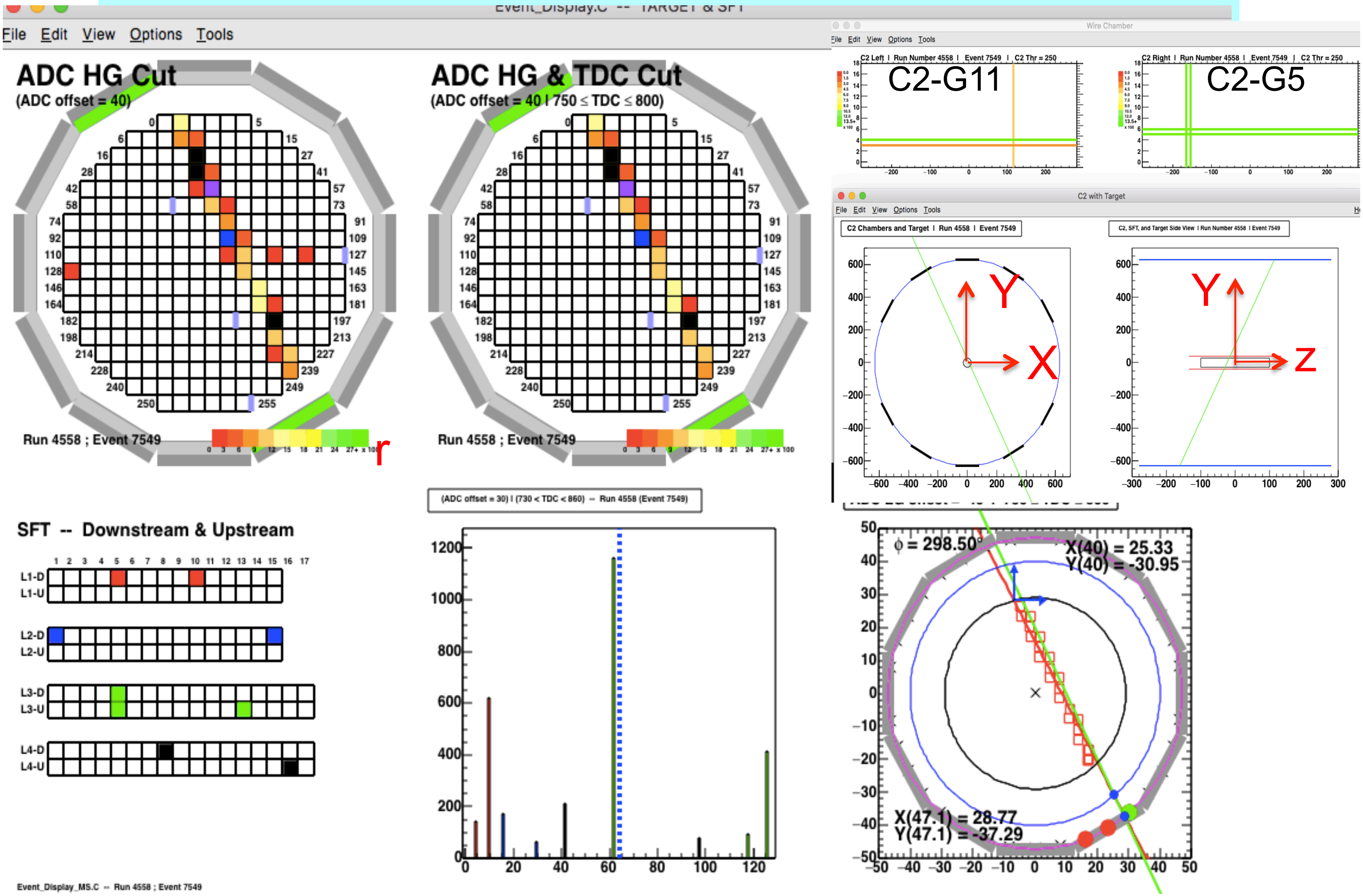
K-stop

Target hit pattern of typical good event

Blue fibres have only a LG signal

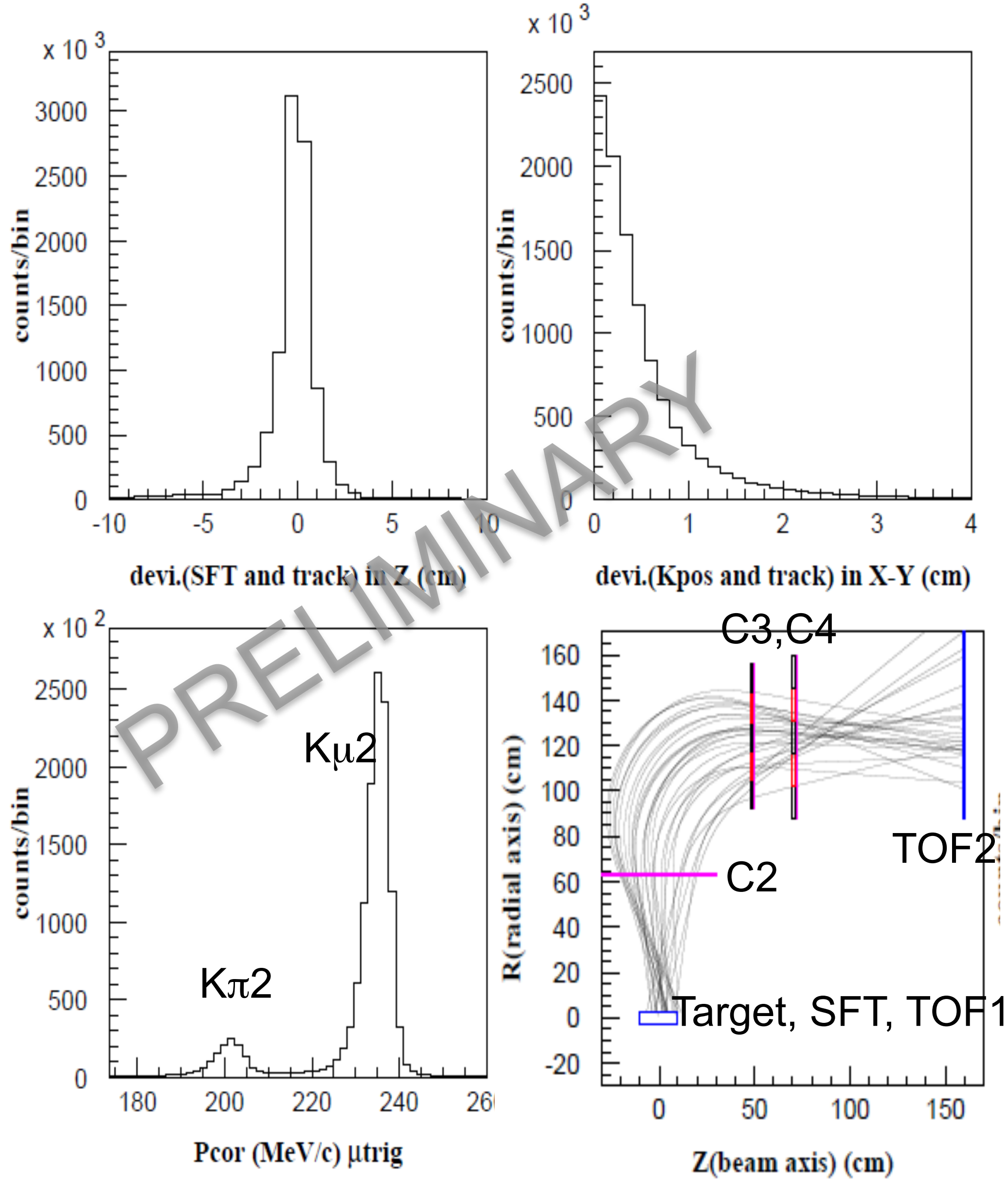
- Determination of K^+ stopping point and lepton depth inside the target
- Measurement of lepton emission azimuthal angle to determine SFT-Z
- Innermost element for 5-point tracking (intersection point of track and K^+ cluster)
- Inclusion of **LG ADC** completes the target track (when HG signal is missing)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

Cosmic Ray SFT--Tracking Analysis



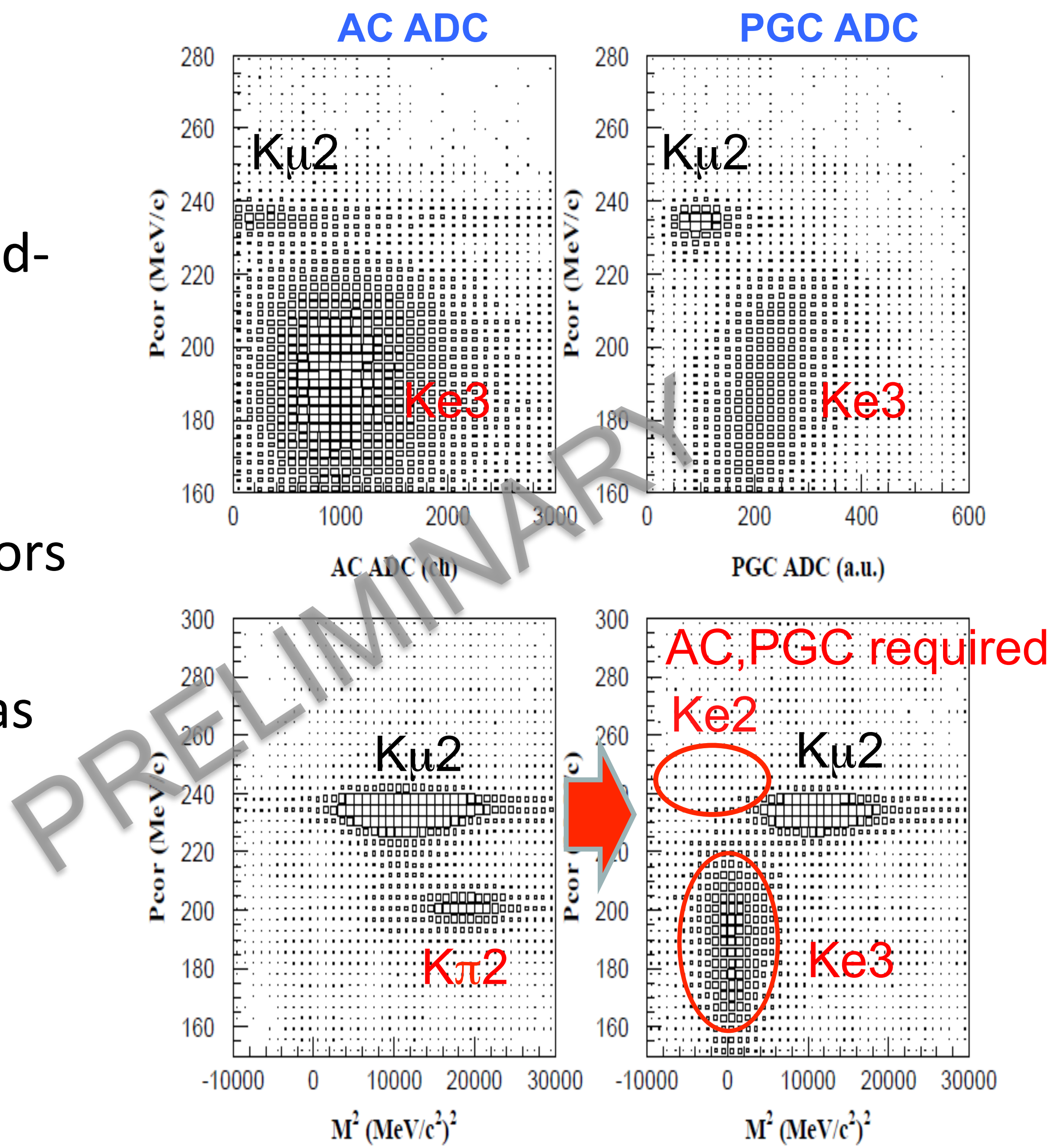
MWPC Momentum analysis

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

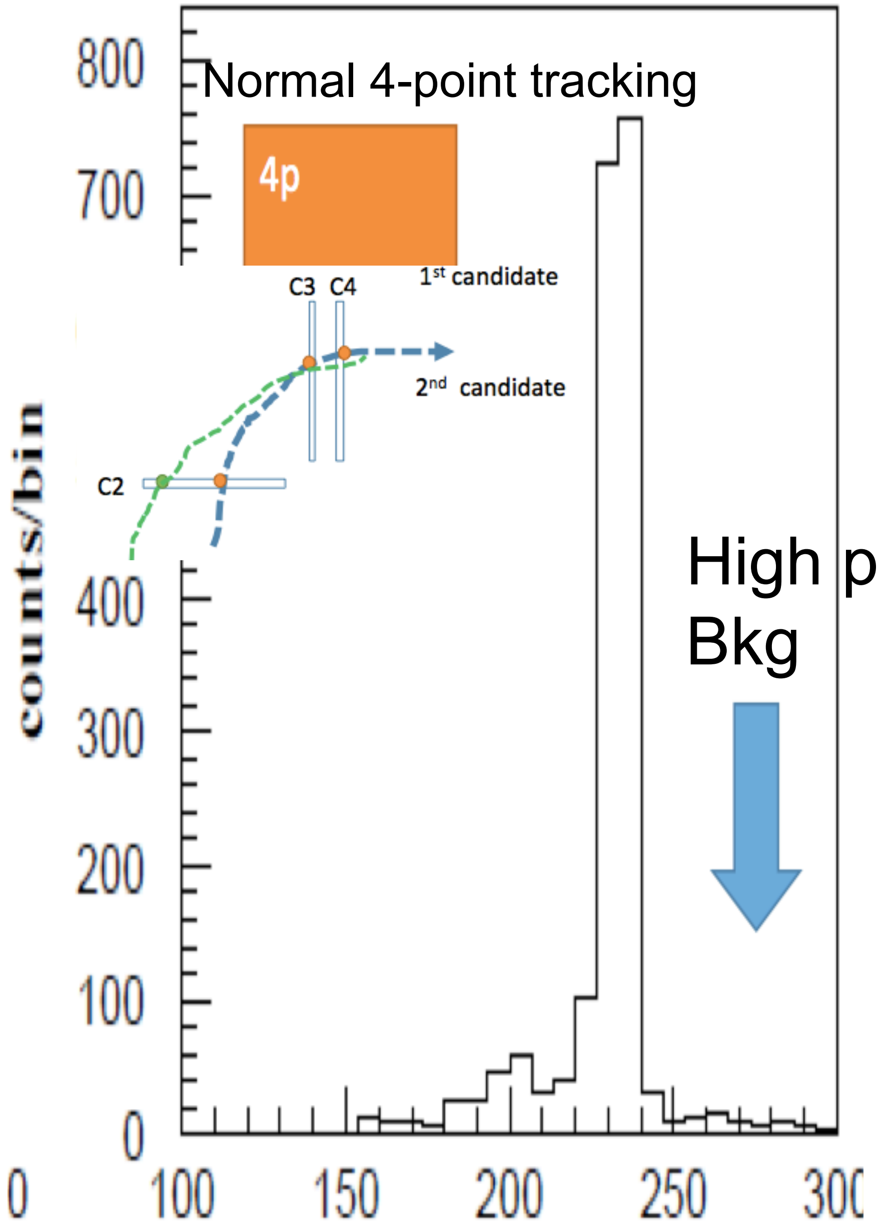


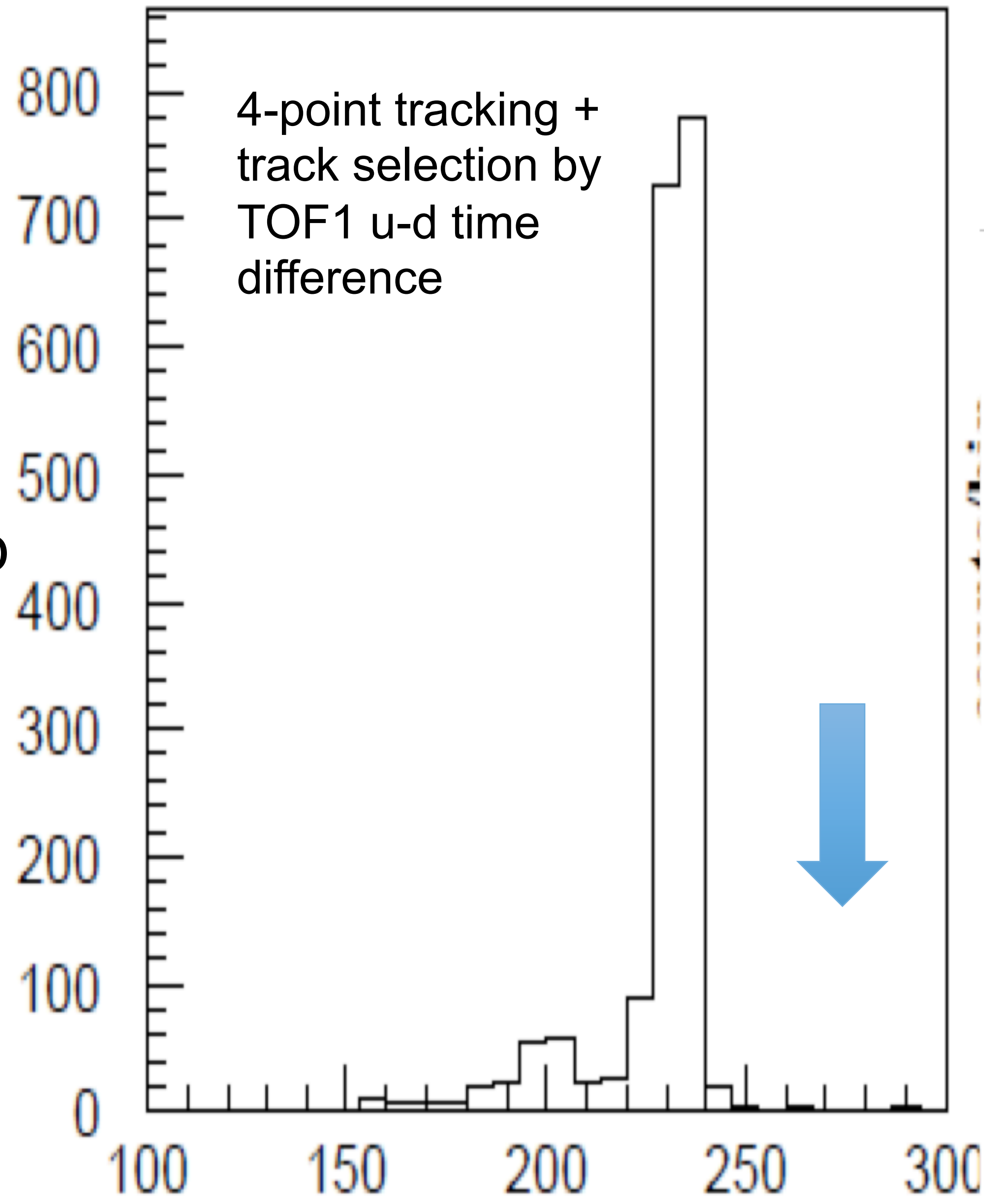
Particle Identification by AC, PGC, and TOF

- Positrons are selected by aerogel Cherenkov (AC), lead-glass Cherenkov (PGC), and TOF PID detectors.
- The PID performance by combining the three detectors is now being optimized.
- TOF time walk correction has not yet been applied.



Improved MWPC Tracking using TOF1(u-d)

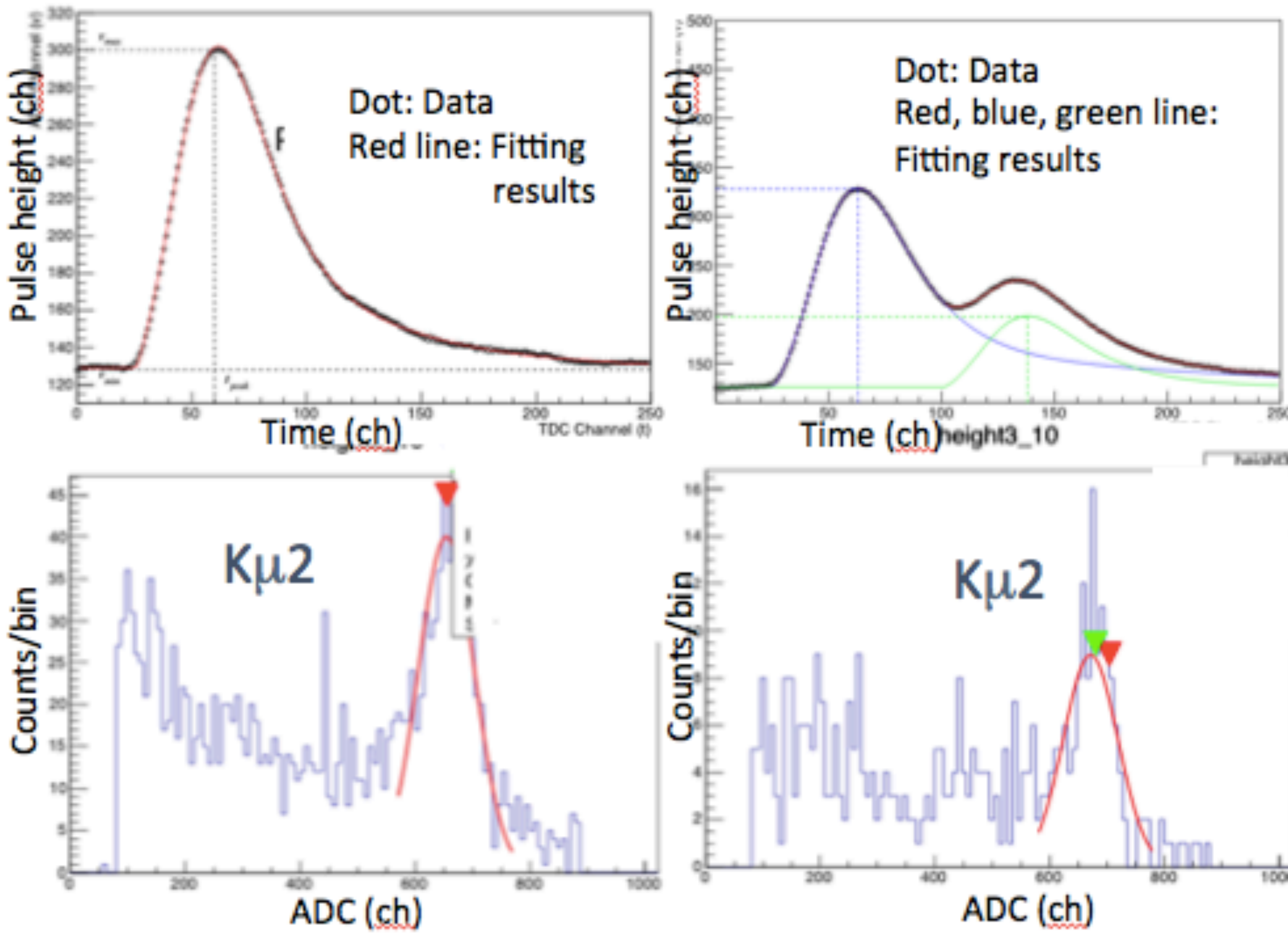




CsI(Tl) Pileup Analysis

CsI(Tl) wave form analysis

- The photon energy and timing were obtained from pulse shape data by FADC (TRIUMF VF48)
- The wave form analysis was established, as well as for the case of pileup.
- *Kμ2* calibration data determines the gain parameters.
- Timing extraction is now being optimized



H. Ito, Chiba Univ

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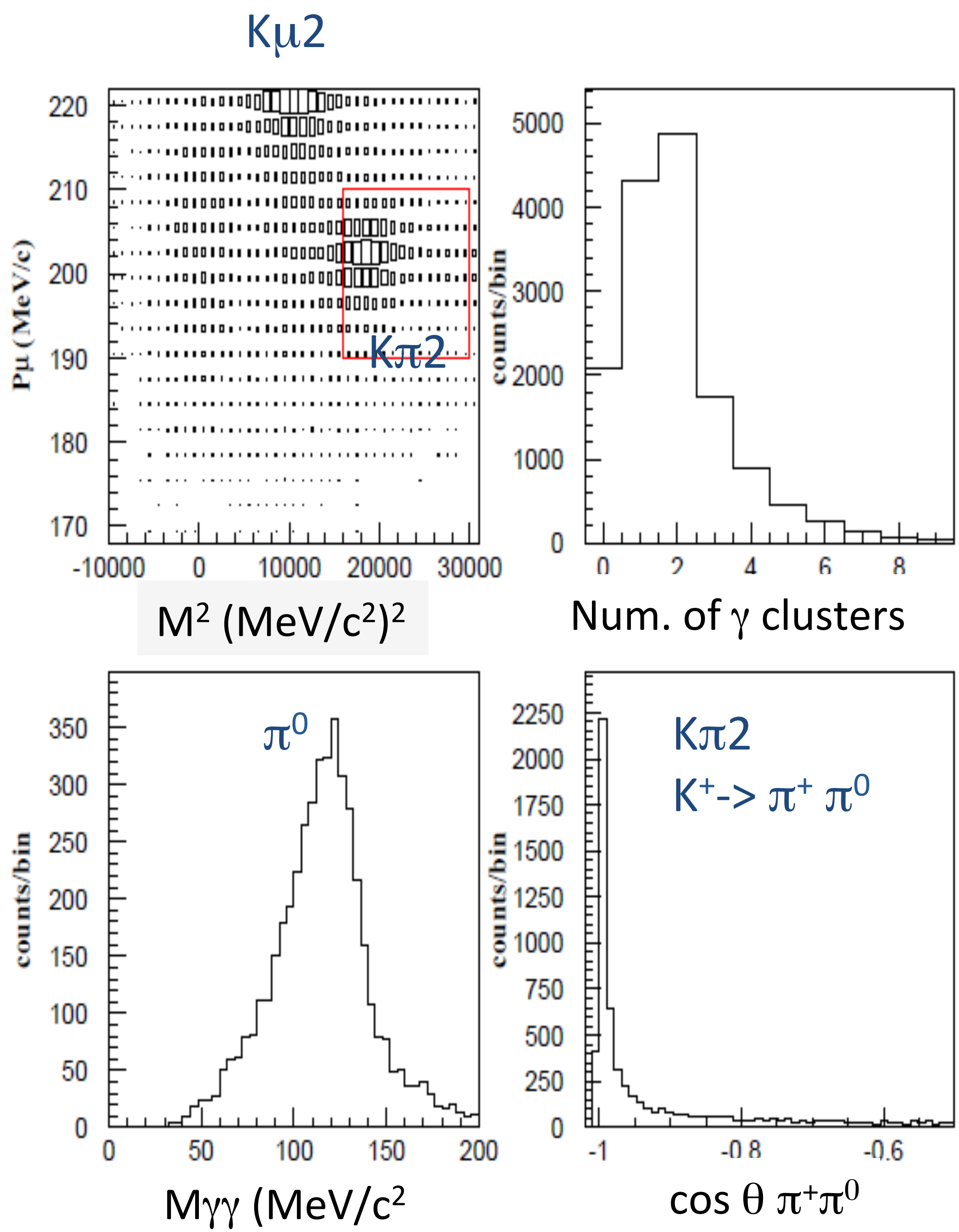
Combined analysis of CsI(Tl) and spectrometer

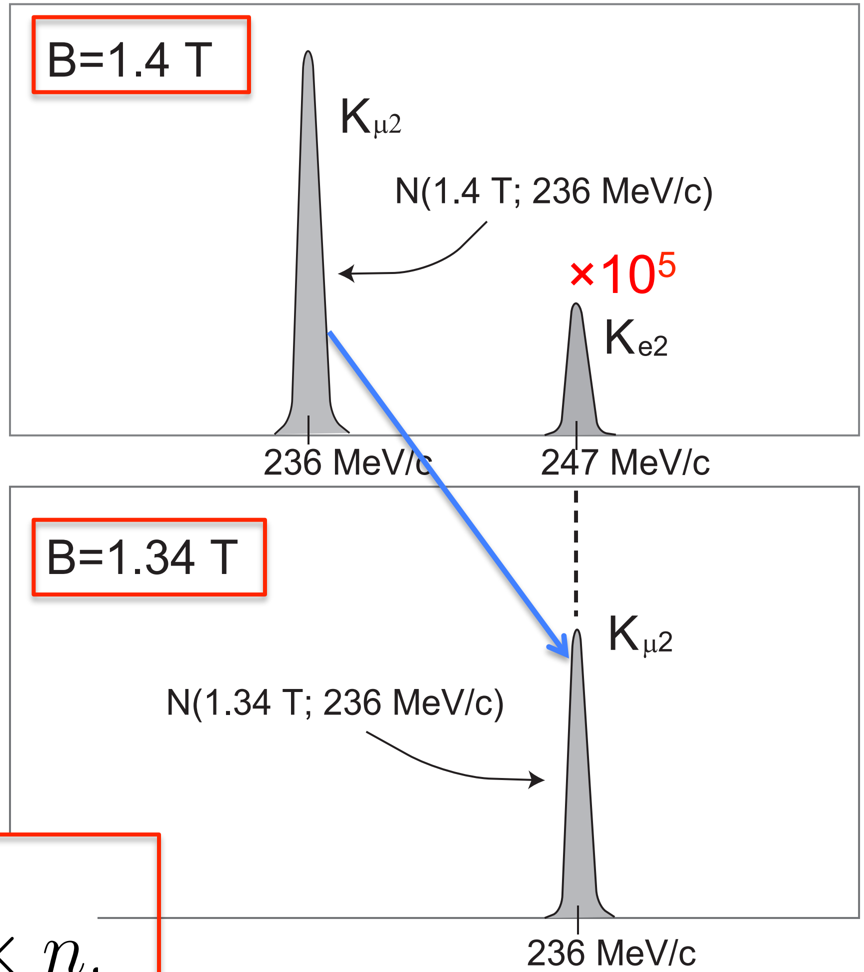
- Kπ2 events are selected by analyzing the momentum and PID.
- π^0 invariant mass is reconstructed by selecting two-cluster events
- Large π^+ -- π^0 opening angle is obtained
- This confirms that the E36 system works correctly and is consistent with E246



Acceptance – Use $K_{\mu 2}$ peak

- Calibration run with reduced B field to create the same trajectory
  (shift the position of the $K_{\mu 2}$ peak)
  – n : requires beam normalization between the two runs
  – β : magnetic field effect

➢ Precise B field calculation and tracking simulation are needed

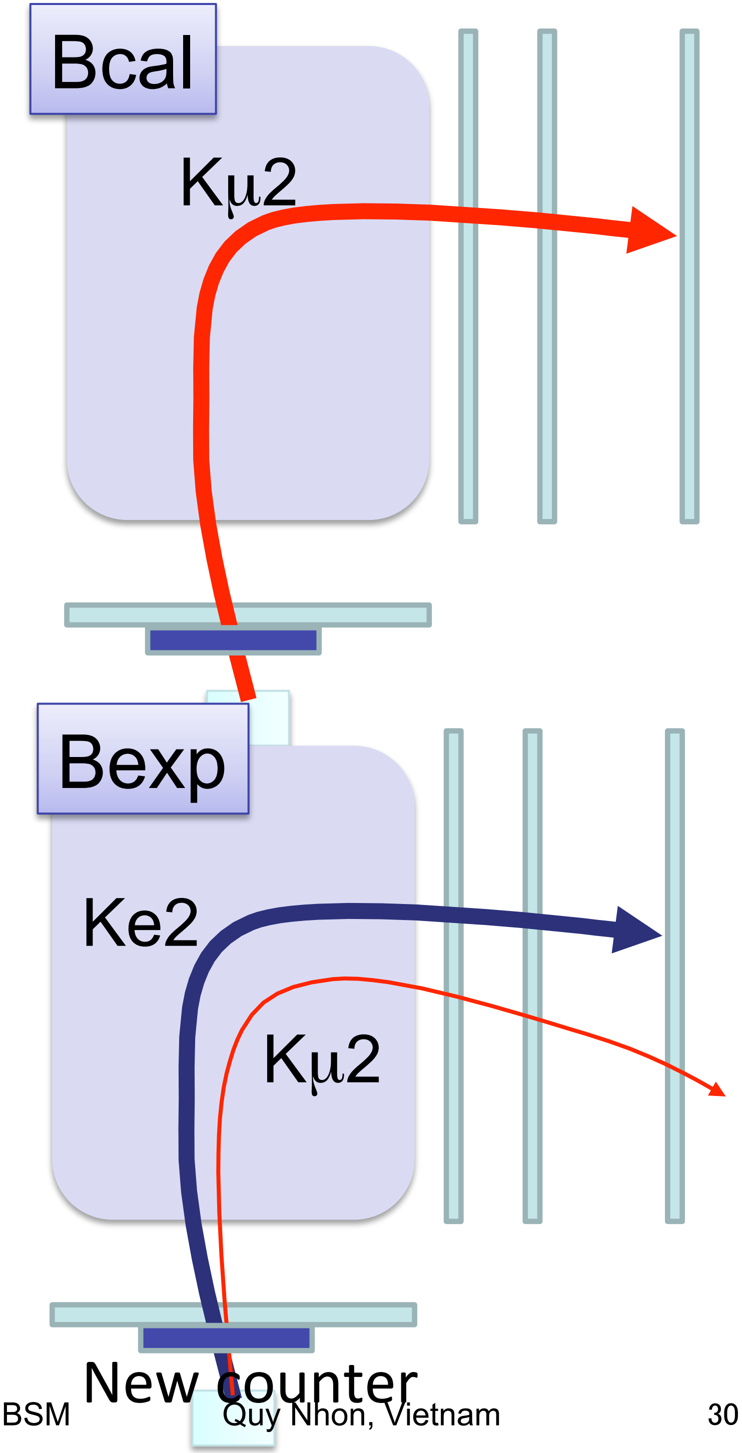


$$Q = \frac{N(K_{\mu 2}; \mathrm{B} = 1.34\ \mathrm{T})}{N(K_{\mu 2}; \mathrm{B} = 1.4\ \mathrm{T})} \times \beta \times n,$$

➢ Error arises from the uncertainty of corrections, *n* and β

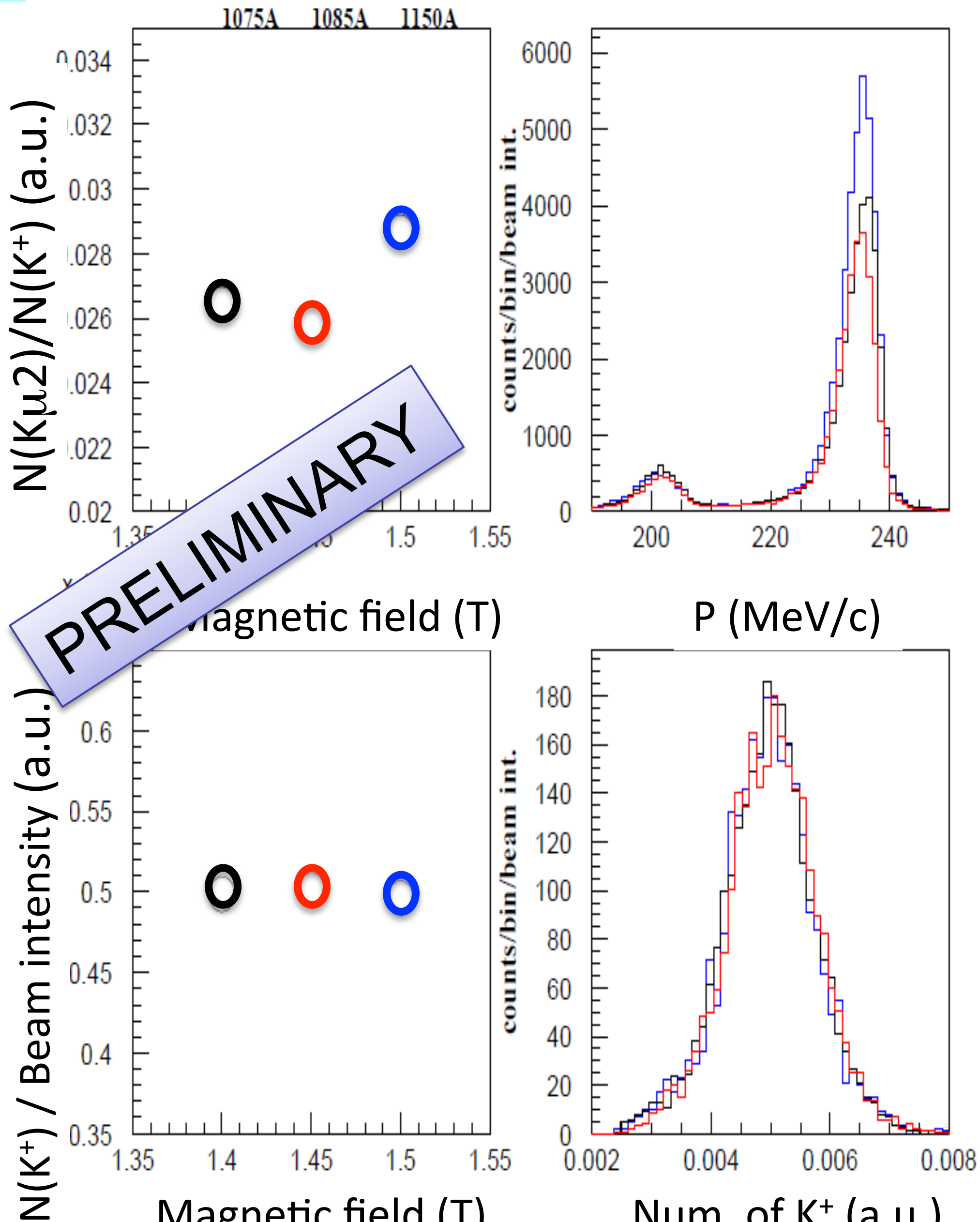
Acceptance calibration: $K_{\mu 2}$ normalization method

- Magnetic field was changed B_{cal} = (236/247) B_{exp}
- The Kmu2 trajectories with B_{cal} field are the same as the Ke2 trajectories in the production runs (B_{exp}).
- The acceptance ratio was determined by normalizing the number of K^+. Therefore, a good stable beam flux was essential.
- A counter telescope was placed at the exit of the muon hole for Gap-12 for beam normalization.
- Small effect due to magnet non-linearity was corrected with MC simulation



Preliminary results for the $K_{\mu 2}$ norm method

- The acceptance defined as $N(K\mu 2)/N_K$ was determined using 3 magnet settings around P_{eff}=247 MeV/*c*.
- We can determine the acceptance ratio using these values.
- Statistical error was estimated.
- Small effect due to DAQ dead time has been corrected

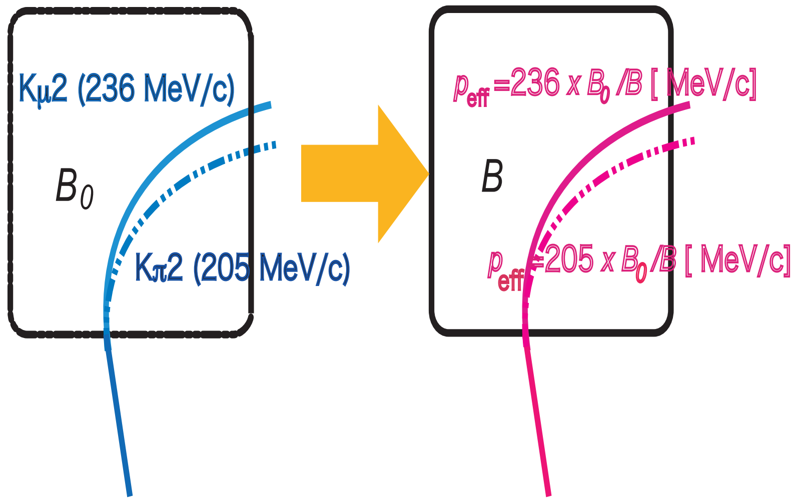


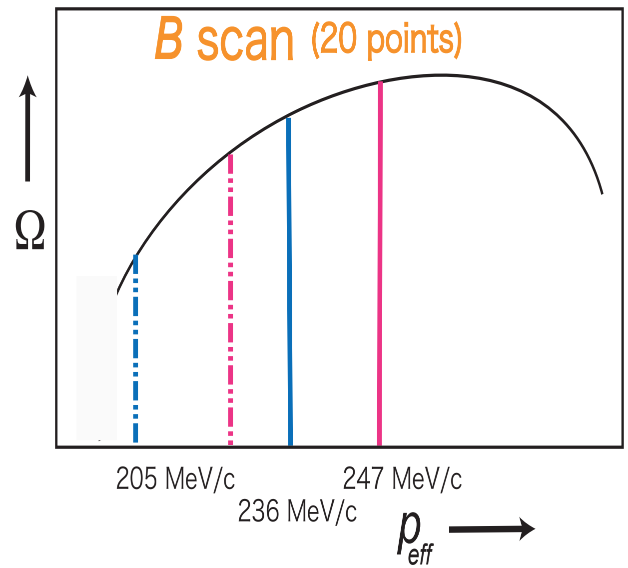
Calibration: $K_{\pi 2}/K_{\mu 2}$ ratio method

- 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, $P_{eff} = 236\text{MeV/c} \cdot (B_0/B)$:

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

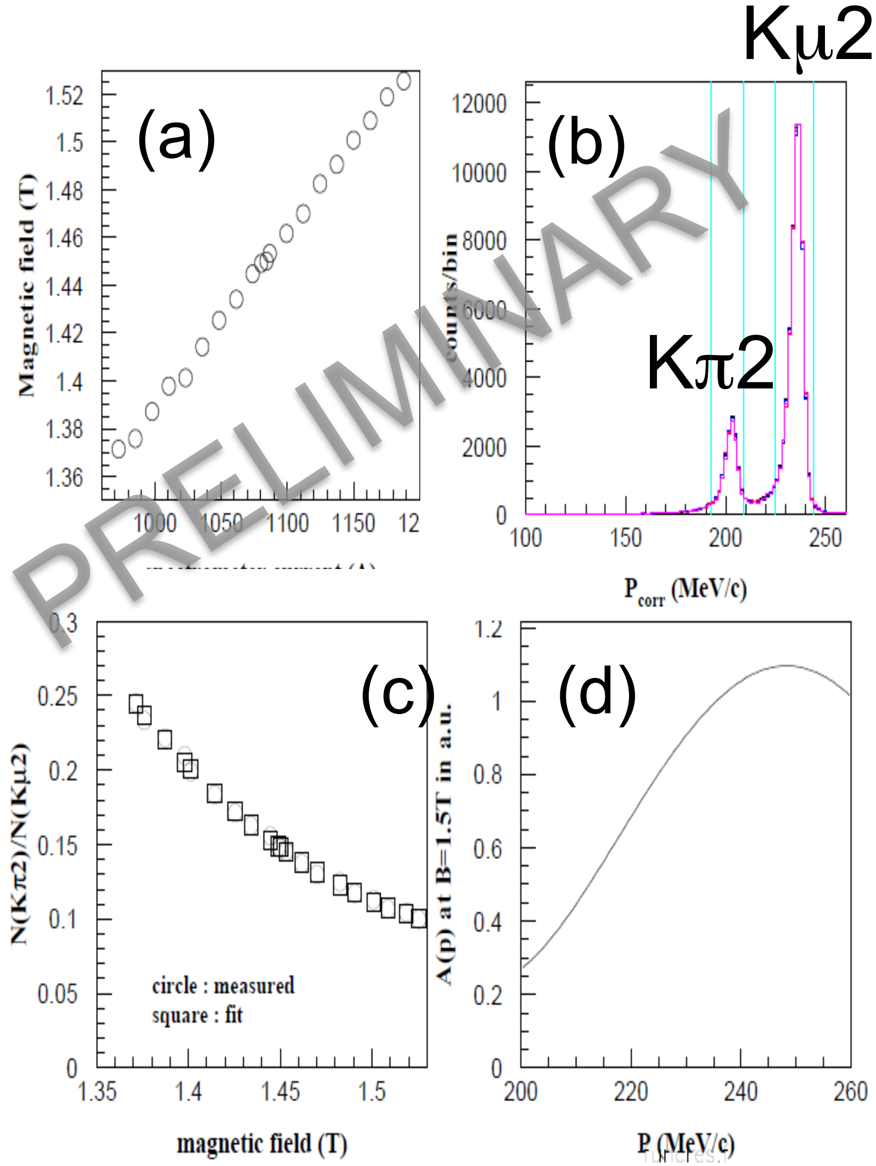
- Parameters a_0 - a_4 can be determined from the 20 measured ratios by fitting.
- Small effect due to magnet non-linearity will be corrected with Monte Carlo simulation.





Preliminary results -- $K_{\pi2}/K_{\mu2}$ ratio method

a. Spectrometer excitation curve
b. Observed momentum spectrum
c. $K_{\pi2}/K_{\mu2}$ as a function of magnetic field.
d. Acceptance curve for B = 1.5T



Search for Dark Photons

Explore U(1) extension of the Standard Model with photon-like massive gauge boson A′.

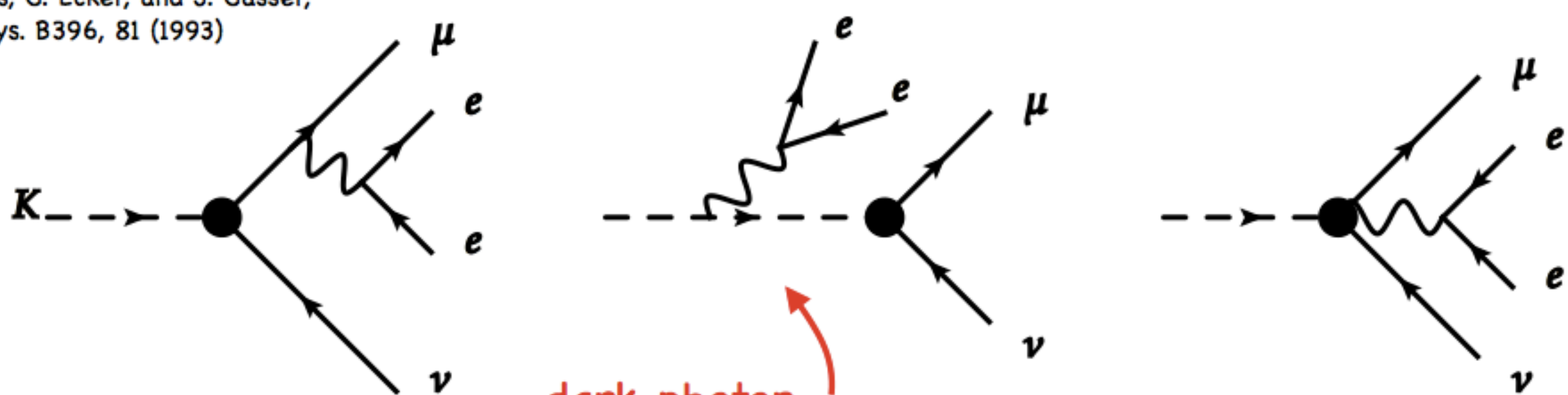
Motivation: Explain anomalies in astrophysics and particle physics, proton radius puzzle, …

Constrain dark photon parameter space with rare kaon-decay data.

$$K^+ \to \mu^+ \nu A'$$
$$A' \to e^+ e^-$$

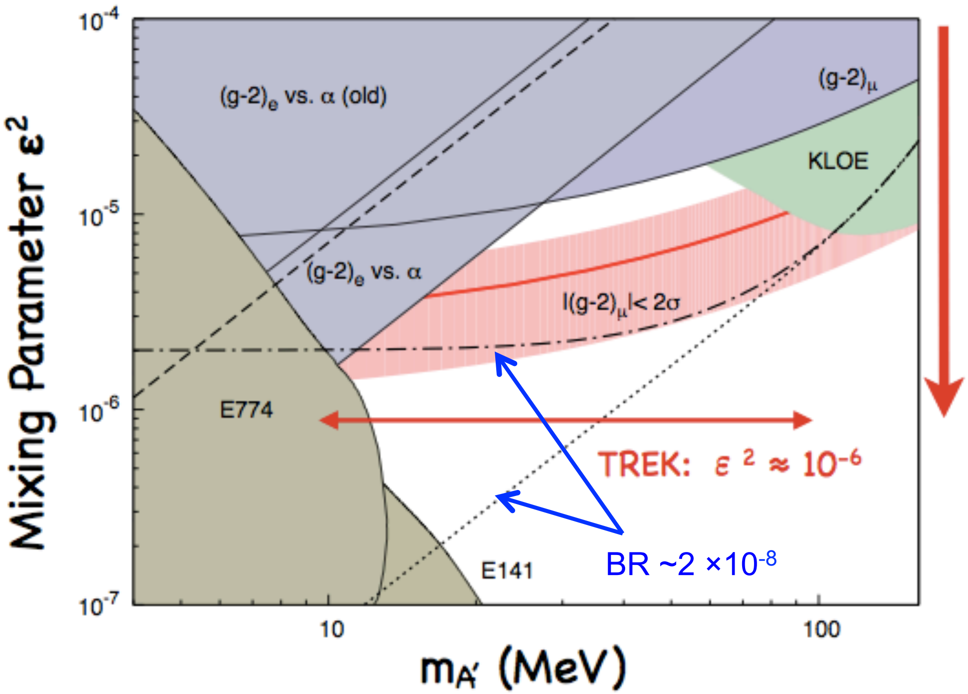
QED background $\Gamma(K^+ \to \mu^+ \nu e^+ e^-) \approx 2.5 \times 10^{-5}$

full phase-space value of:
J. Bijnens, G. Ecker, and J. Gasser, Nucl. Phys. B396, 81 (1993)



dark photon
replaces photon (weak coupling)

A′ Parameter Exclusion Limits



T. Beranek and M. Vanderhaeghen, Phys. Rev. D **87**, 015024 (2013)

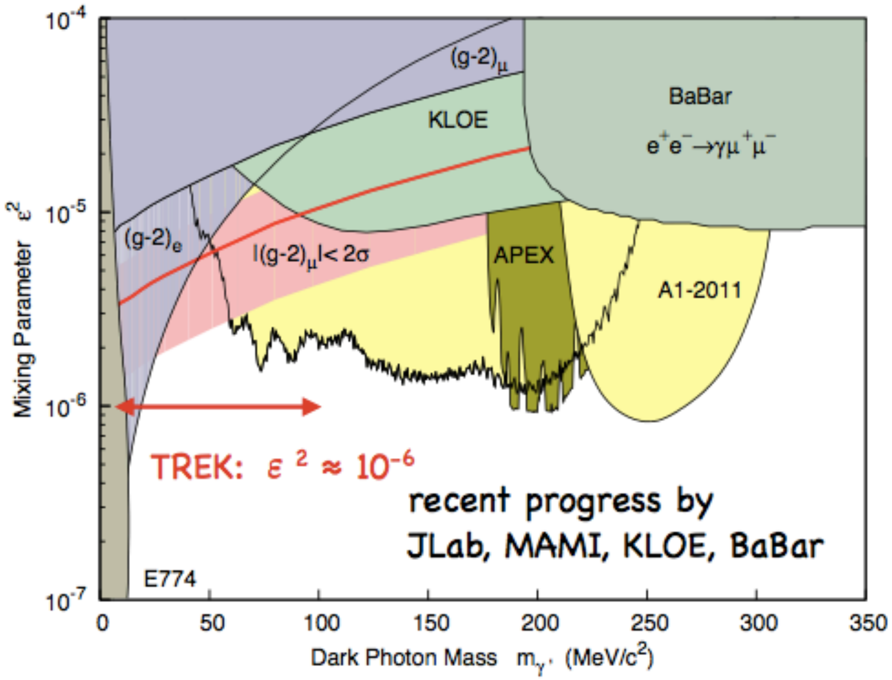


Fig. from M. Pospelov, PEB2013 workshop (2013)

Projected TREK E36

Full reconstruction of the $\mu^+\nu e^+e^-$ and $\pi^+e^+e^-$ final states

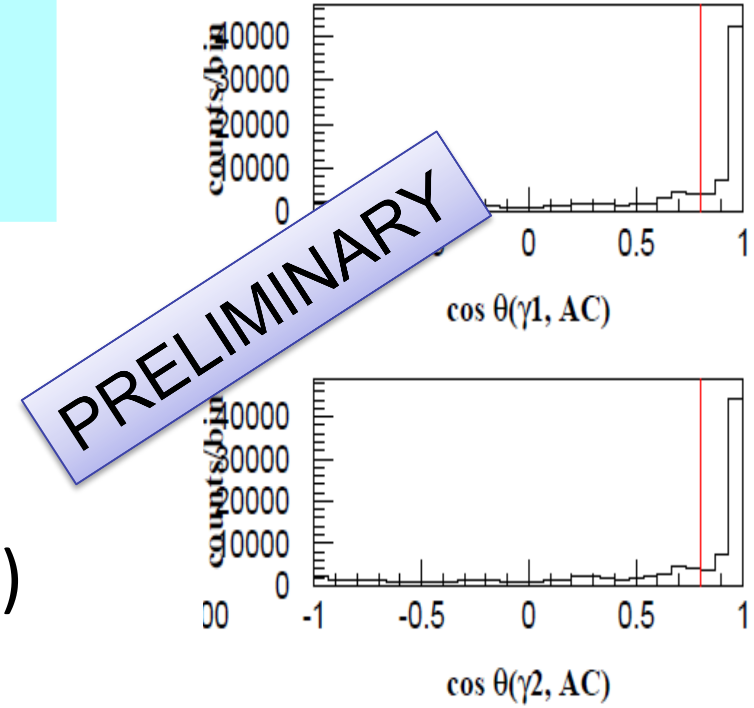
Possible improvement with projected E36 results: $\varepsilon^2 \approx 10^{-6}$

Signal:

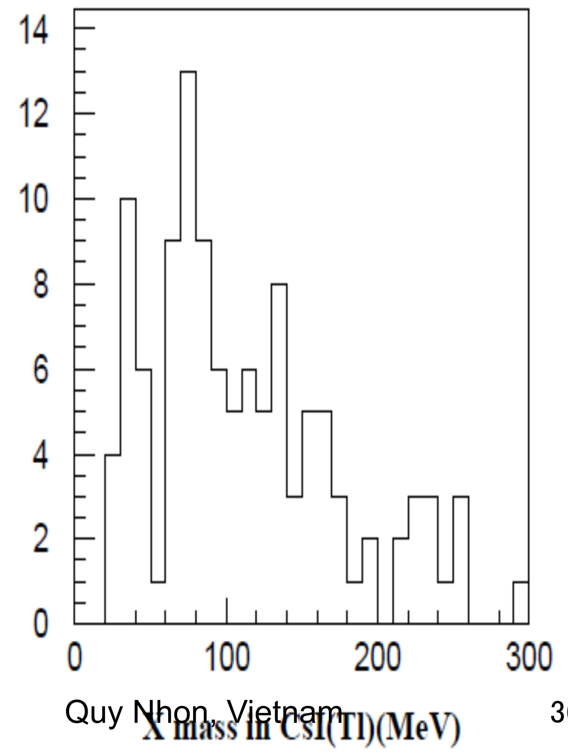
- Peak in $M(e^+e^-)$ spectrum measured in the CsI(Tl) calorimeter
- Peak in the π^+ momentum spectrum for $K^+ \to \pi^+A'$

$$K^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$$
$$K^+ \to \pi^+ A' \to \pi^+ e^+e^-$$

Byproduct studies using $K^+ \to \ell^+ e^+ e^- \nu$ events



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



Summary & Outlook

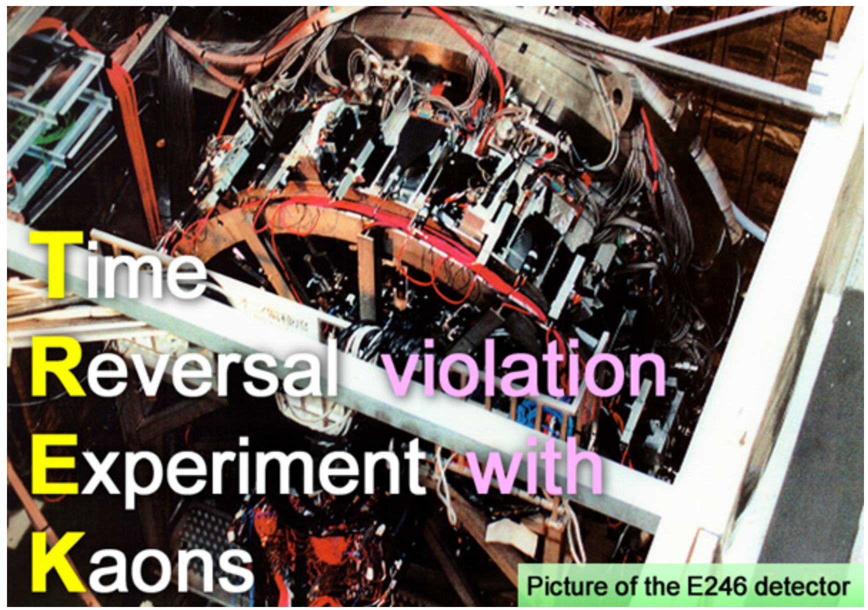
- **TREK has completed a LFV expt at J-PARC**

  $K_{e2}/K_{\mu 2}$ measurement to test lepton universality (2014-15)

  & search for Dark Photons

- **Measurement of the T-violating transverse muon polarization in $K_{\mu 3}$ decay (~201x) – needs Extended HH**

  - Large potential for discovery of New Physics beyond the SM with a fully upgraded E-246 setup and a new stopped K^+ beam.



Picture of the E246 detector

Thank you

Merci beaucoup

cho tôi biết

Arigato Gozaimasu