日本物理学会2018年秋季大会
信州大学松本キャンパス

15aS13-7

Ke2　　Kμ2

J-PARC E36実験$\Gamma(K^+ \to e^+\nu_e)/\ \Gamma\left(K^+ \to \mu^+\nu_\mu\right)$測定によるレプトン普遍性破れ探索実験の解析進捗(2)

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Topic: study of $K^+ \rightarrow e^+\nu_e\gamma$ ($K_{e2\gamma}$)

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5. e+ momentum spectra inE36
6. Form factor determination for $K_{e2\gamma}$
7. Summary

1. Introduction (1)

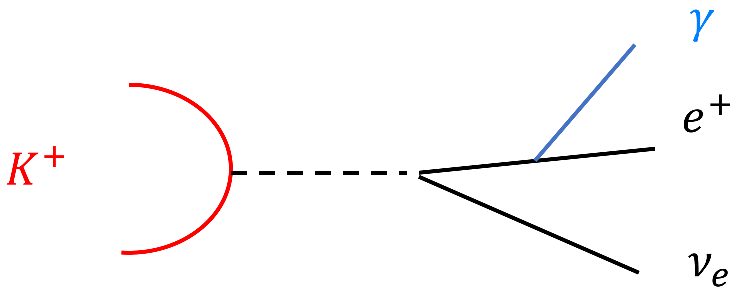
Main background: radiative decay to $K^+ \rightarrow e^+ \nu_e \gamma$

$$R_K = \frac{\Gamma(K_{e2}) + \Gamma(K_{e2\gamma}(IB))}{\Gamma(K_{\mu2}) + \Gamma(K_{\mu2\gamma}(IB))}$$

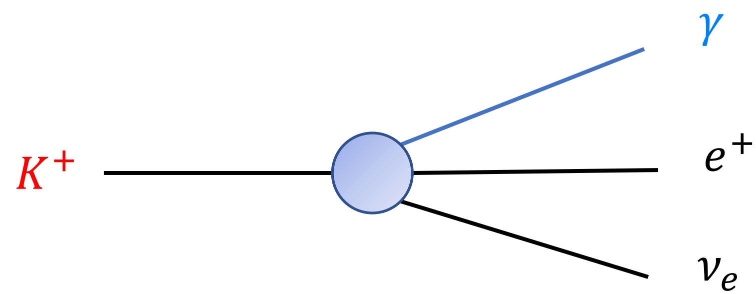
Γ(Ke2) ~ 1.58 x 10^{-5}

Γ(Ke2γ(SD)) ~ 9.4 x 10^{-6}

PDG'18/Eur. Phys. J. C 64 (2009) 627.

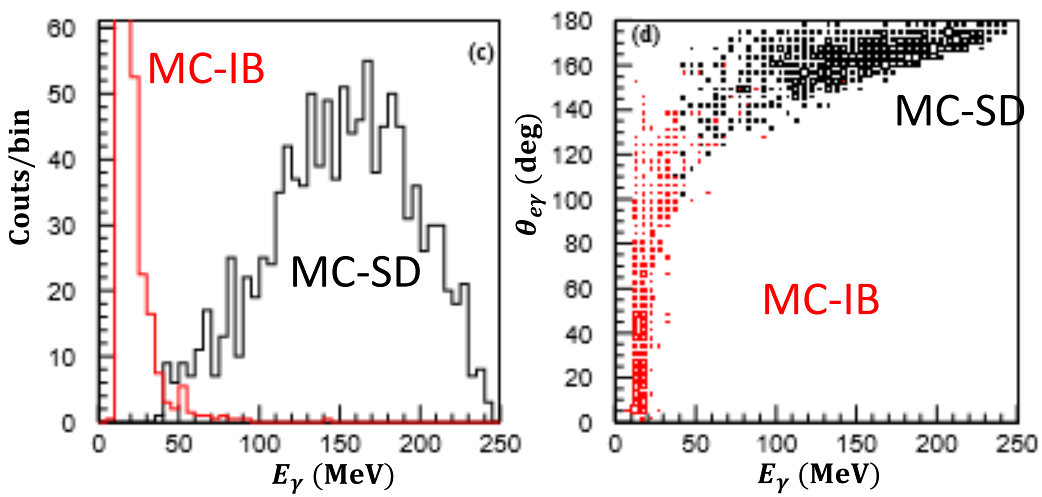


Internal Bremsstrahlung (IB)

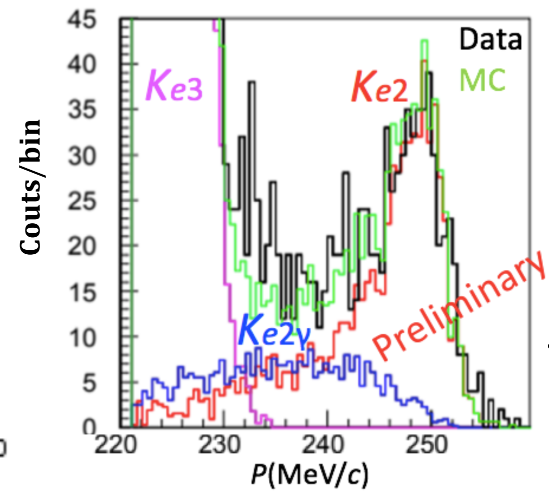


Structure Dependent (SD)

Monte Carlo (MC) simulation



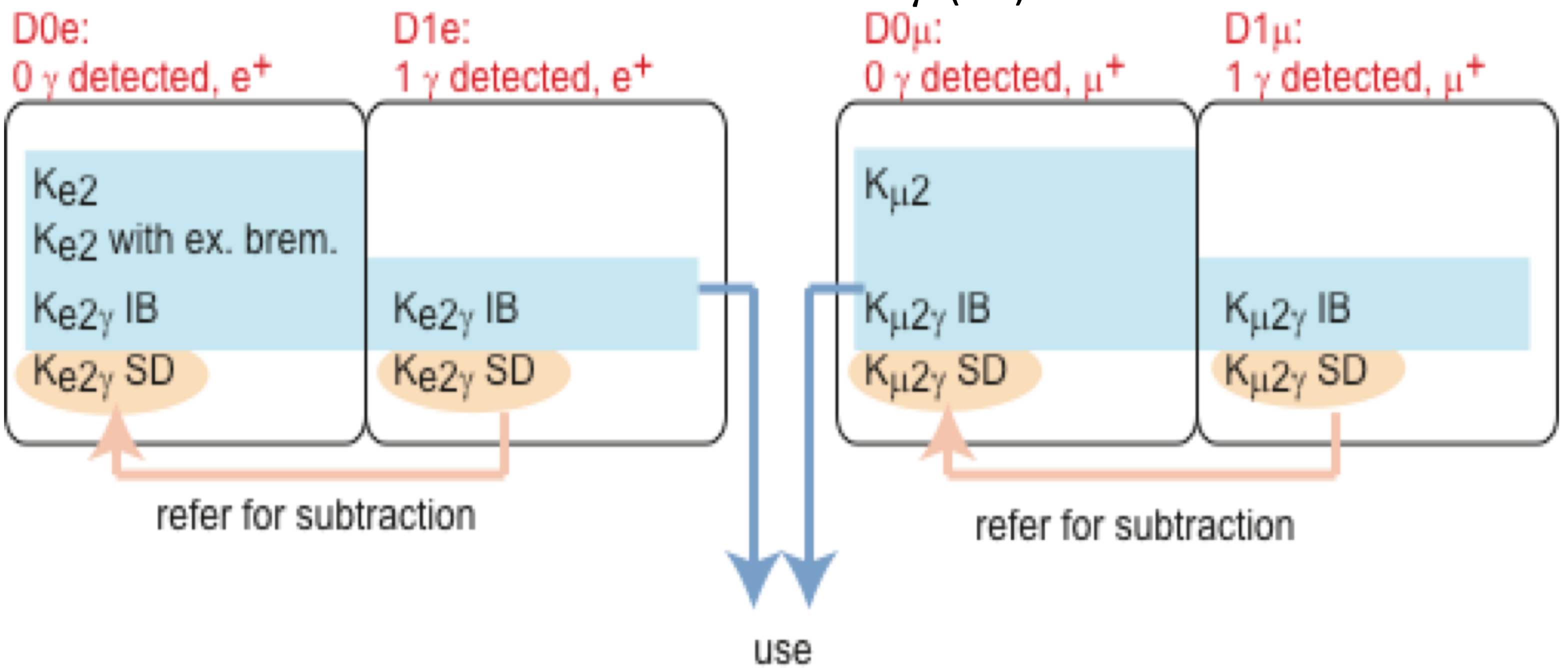
e+ momentum spectrum



JPS2018.3
23pK606-11

1. Introduction (1)

Subtraction of $Kl2\gamma$ (SD)



- $K_{e2\gamma}$ = IB + SD : SD is a background which have to be subtracted
- The SD branching ratio and form factor can be determined for the estimation of background fraction

$$\Gamma_1(k_{e2\gamma}) = \frac{N\left(K_{e2\gamma}^{(0\gamma)}\right)}{N\left(K_{e2}^{(0\gamma)}\right)} \frac{\Omega\left(K_{e2}^{(0\gamma)}\right)}{\Omega\left(K_{e2\gamma}^{(0\gamma)}\right)} \Gamma(k_{e2}) \qquad \Gamma_2(k_{e2\gamma}) = \frac{N\left(K_{e2\gamma}^{(1\gamma)}\right)}{N\left(K_{e2}^{(0\gamma)}\right)} \frac{\Omega\left(K_{e2}^{(0\gamma)}\right)}{\Omega\left(K_{e2\gamma}^{(1\gamma)}\right)} \Gamma(k_{e2})$$

- We will publish the results after careful estimation of systematic uncertainties

2. Introduction (2)

$K_{e2\gamma}$ amplitudes

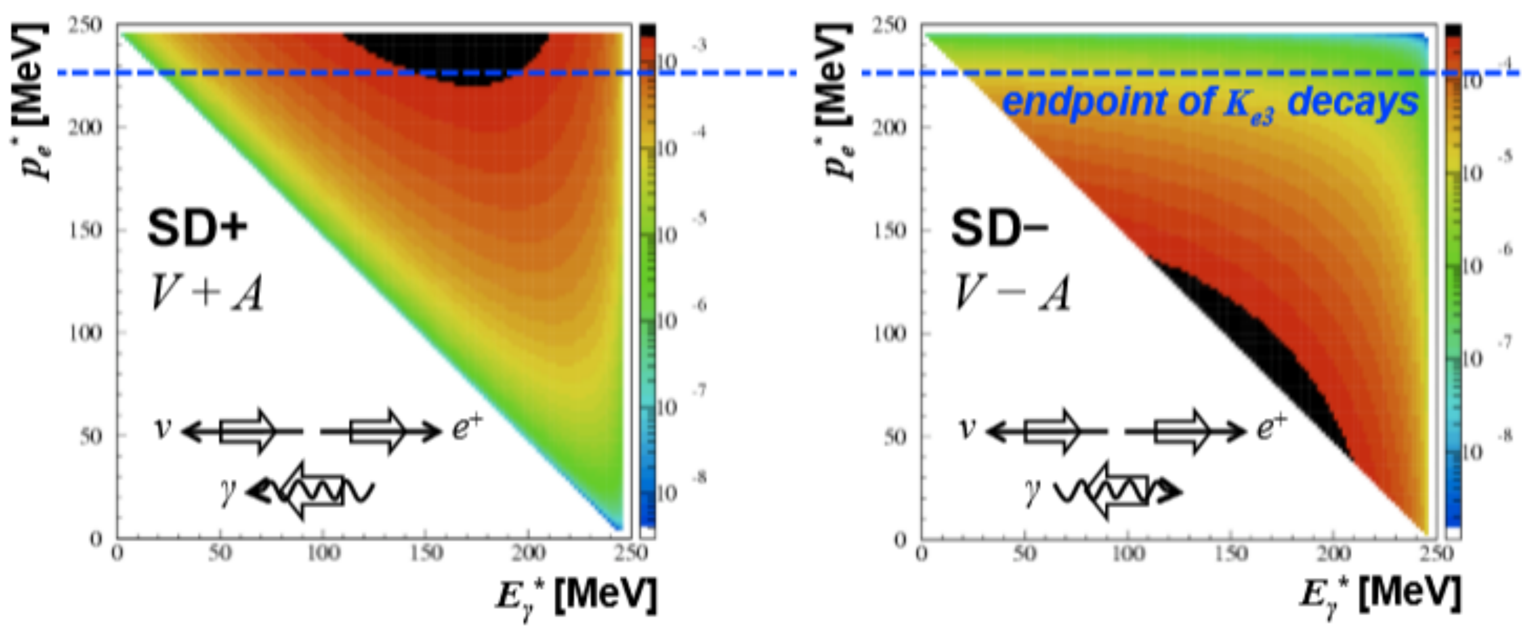
negligible

$$\frac{d\Gamma(K \to e\nu\gamma)}{dx\,dy} = \rho_{\mathrm{IB}}(x,y) + \rho_{\mathrm{SD}}(x,y) + \rho_{\mathrm{INT}}(x,y)$$

$$x = 2E_\gamma^* / m_K$$
$$y = 2E_e^* / m_K$$

$$\rho_{\mathrm{SD}}(x,y) = \frac{G_F^2 |V_{us}|^2 \alpha}{64\pi^2} m_K^5 \left((V+A)^2 f_{\mathrm{SD+}}(x,y) + (V-A)^2 f_{\mathrm{SD-}}(x,y) \right)$$

V, A: effective vector and axial couplings



2. Introduction (2)

$K_{e2\gamma}$: Theoretical predictions for SD

1. ChPT(Chiral Perturbation Theory) at O(p^4) $p^2 = m_K^2(1-x)$.

No dependence on γ energy
$V \approx 0.0945$
$A \approx 0.0425$

Bijnens, Ecker, Gasser '93

2. ChPT at O(p^6)

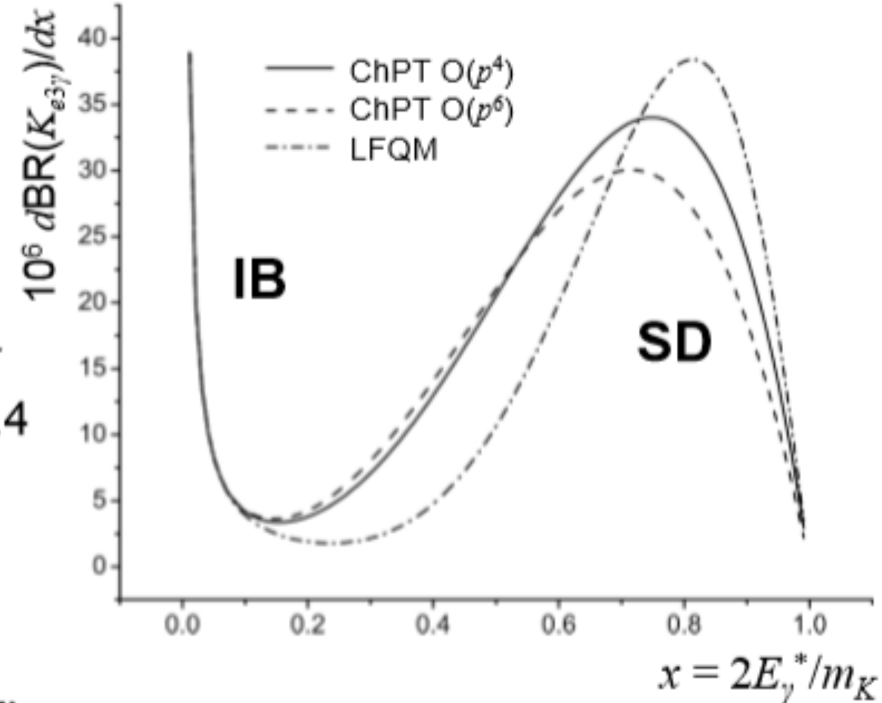
Linear energy dependence for V
$V \approx 0.082[1 + \lambda(1-x)]$ with $\lambda \approx 0.4$
$A \approx 0.034$

Ametller, Bijnens, Bramon, Cornet '93
Geng, Ho, Wu '04
Chen, Geng, Lih '08

3. Light Front Quark Model (LFQM)

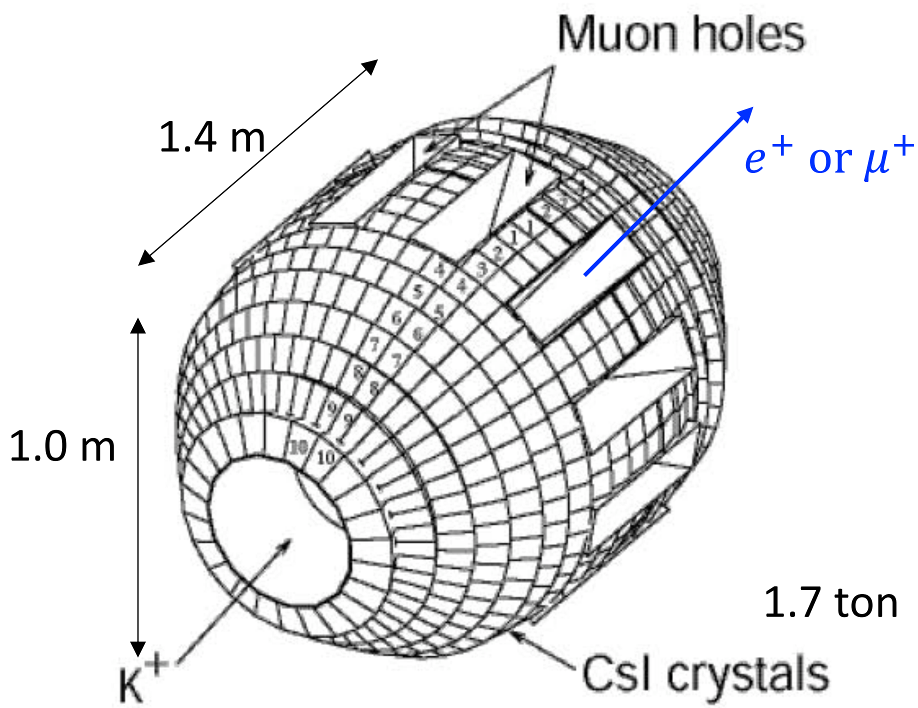
Non-trivial x dependence
$V = A = 0$ at $x = 0$ or $t = t_{max} = m_K^2$

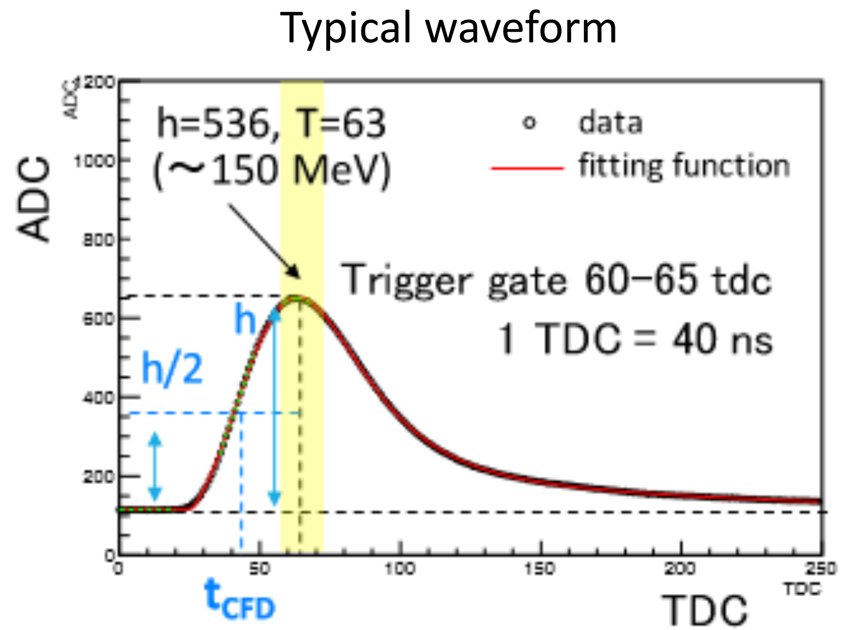
Chen, Geng, Lih '08



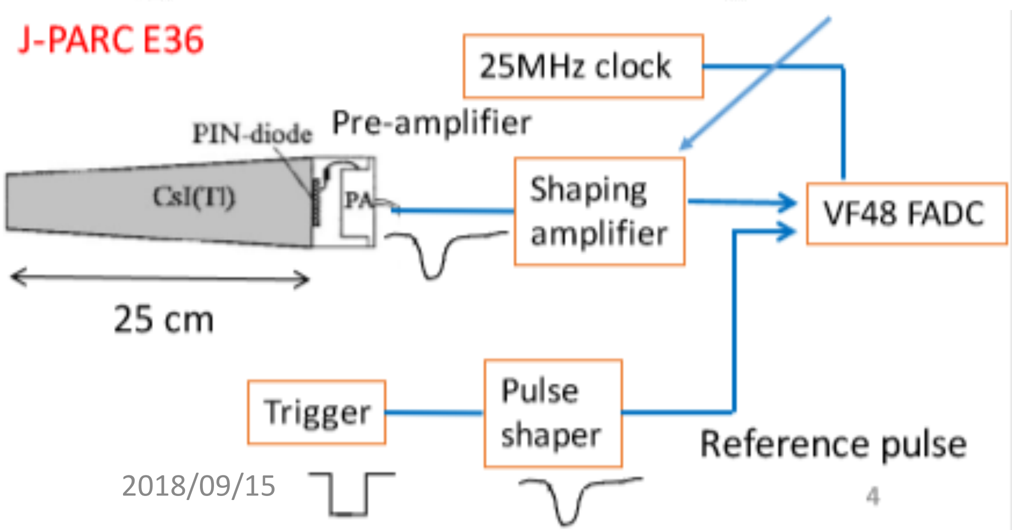
$$\rho_{SD}(x,y) = \frac{G_F^2|V_{us}|^2\alpha}{64\pi^2} m_K^5\left((V+A)^2 f_{SD+}(x,y)\right)$$

3. CsI(Tl) calorimeter & γ detection



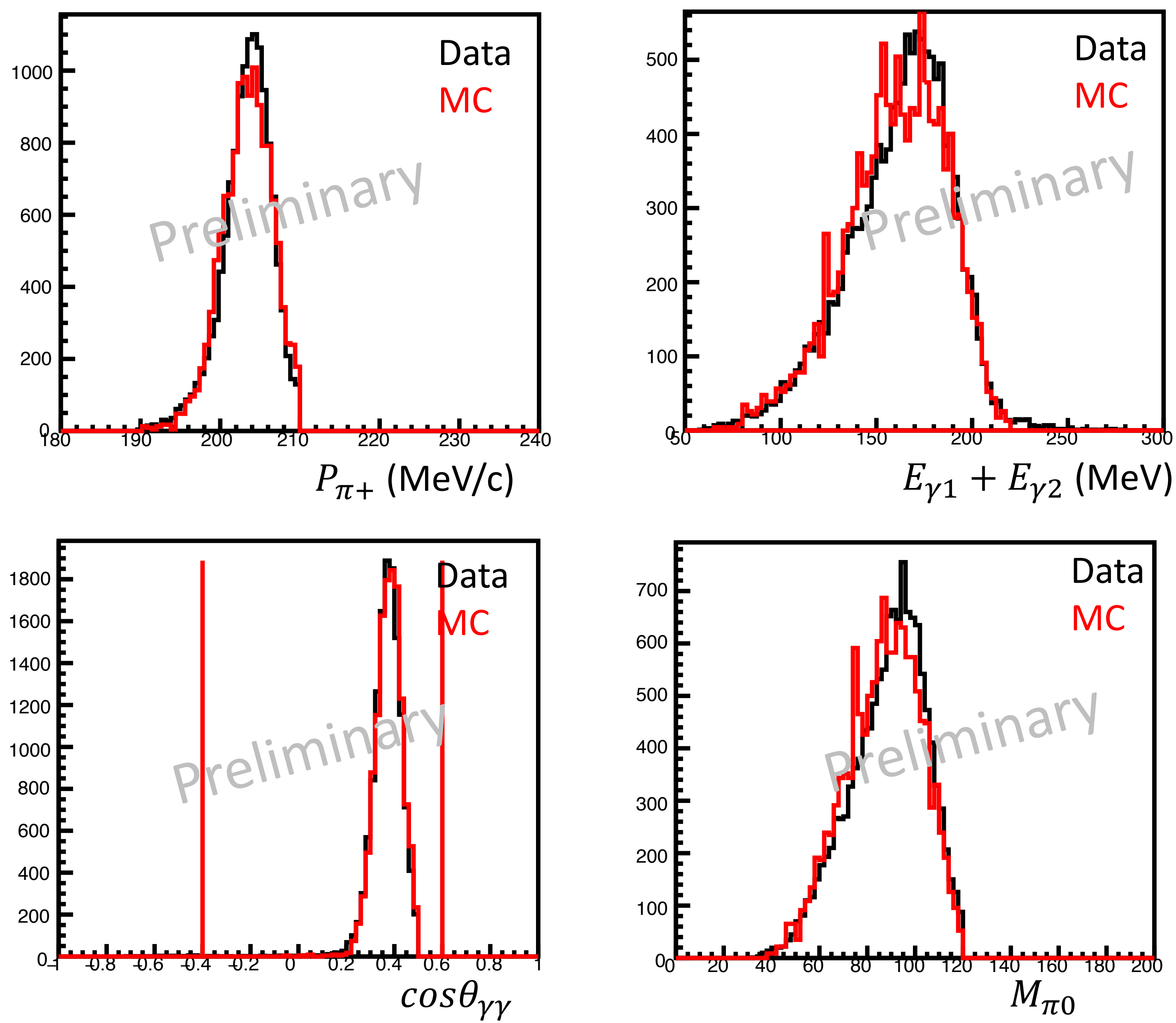


JPS 2017.9 19pK34-7

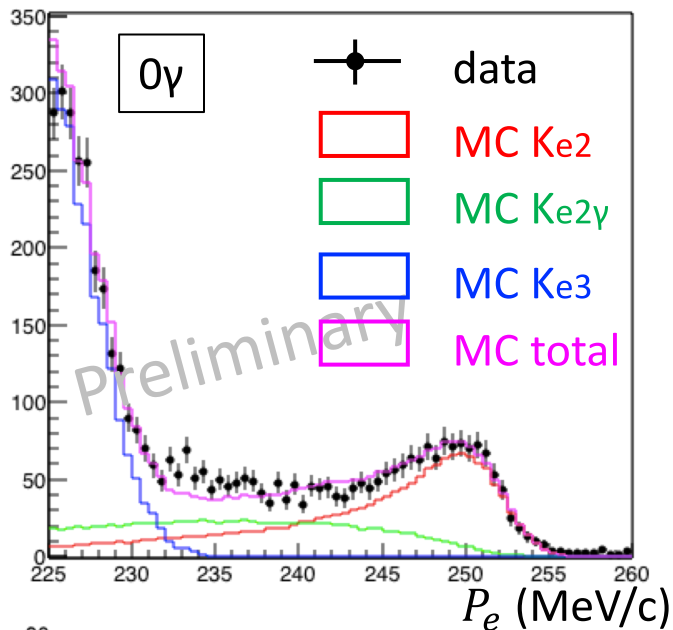


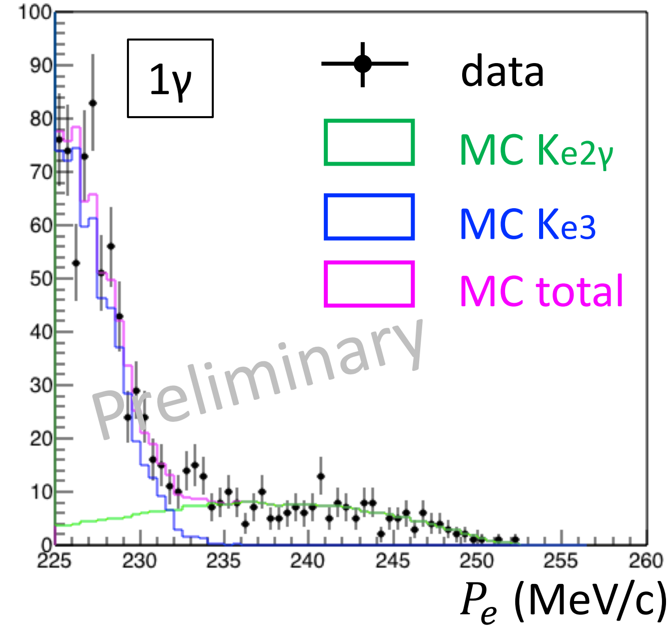
- CsI(Tl) module: 768
- Total weight：1.7 ton
- Acceptance: 75%
- PIN photodiode readout
- Amplifier time constant ~1 μsec
- 25 MHz FADC wave record

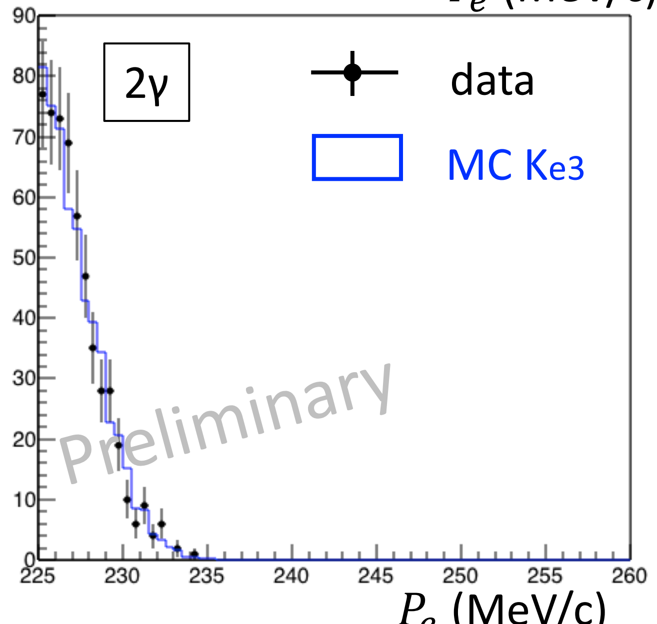
4. CsI(Tl) performance check using $K_{\pi 2}$ $(K^+ \rightarrow \pi^+ \pi^0)$



5. e+ momentum spectra in E36

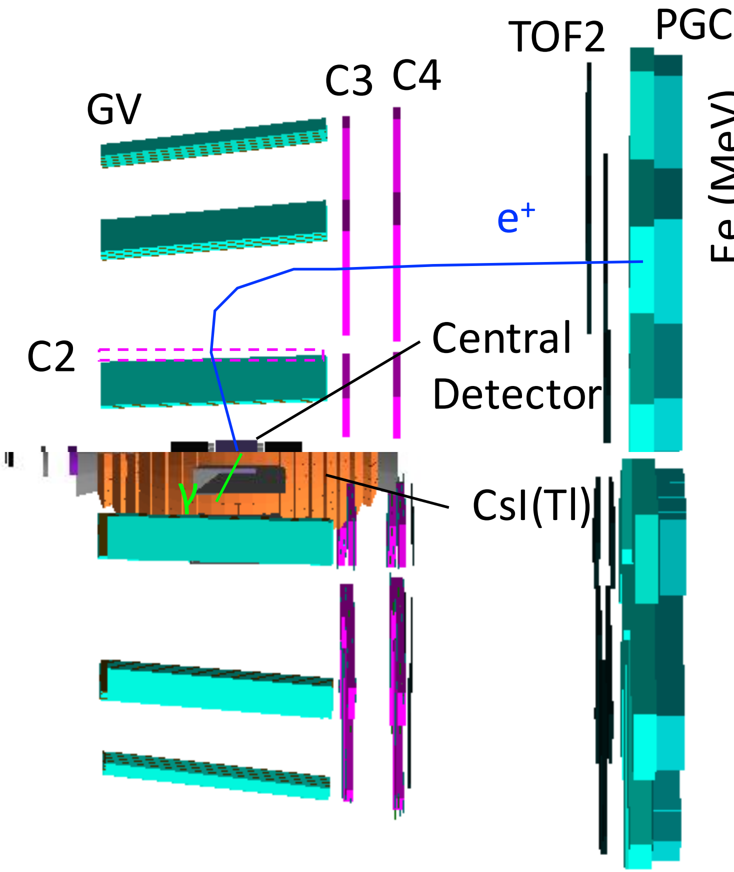




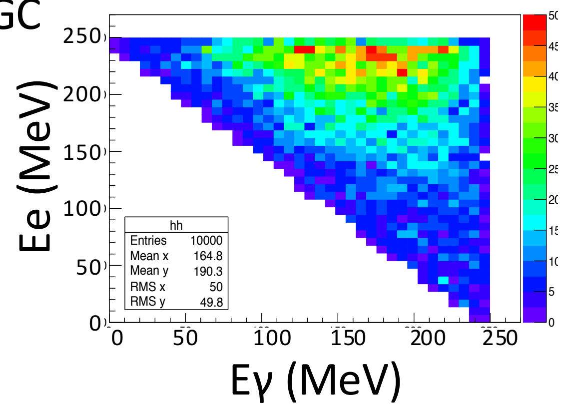


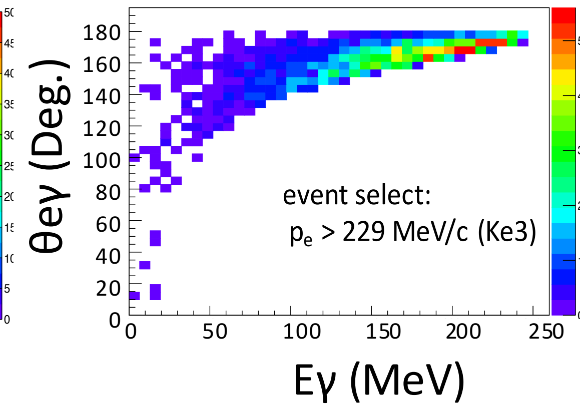
MC Ke2γ model is ChPT(p^6).
V_0=0.083, A_0=0.034, λ=0.4

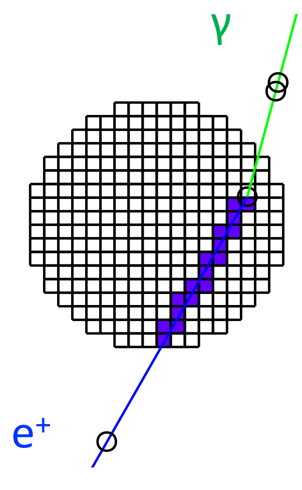
6. Form factor determination for $K_{e2\gamma}$

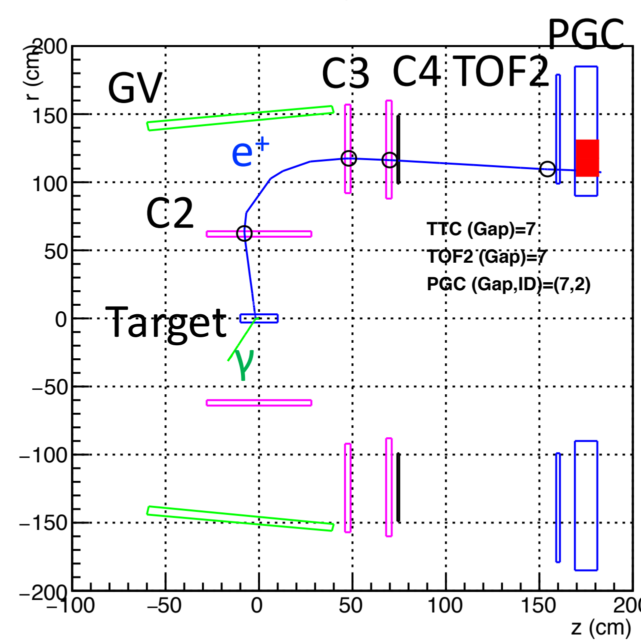


particle energy & momentum vector at birth

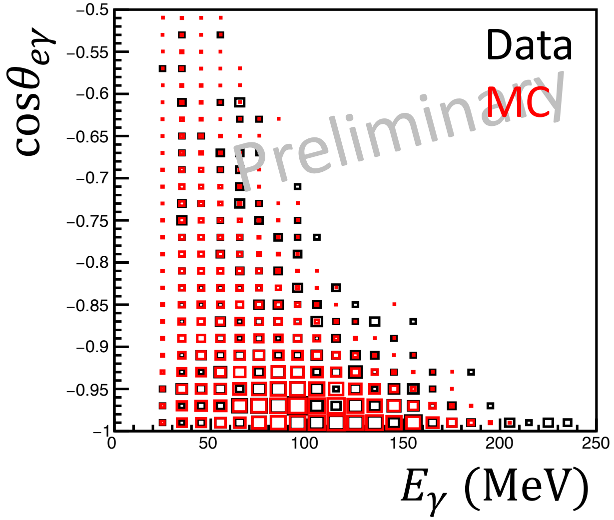


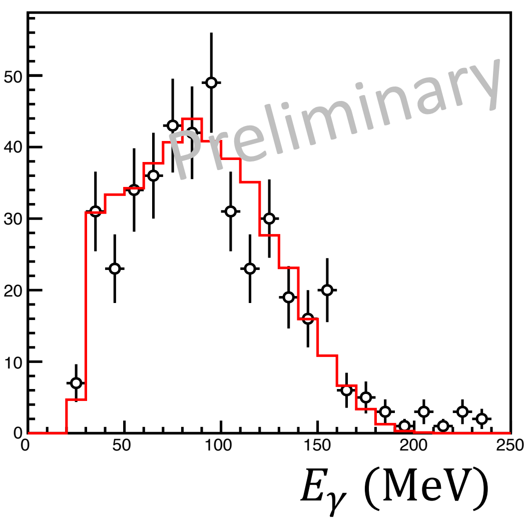


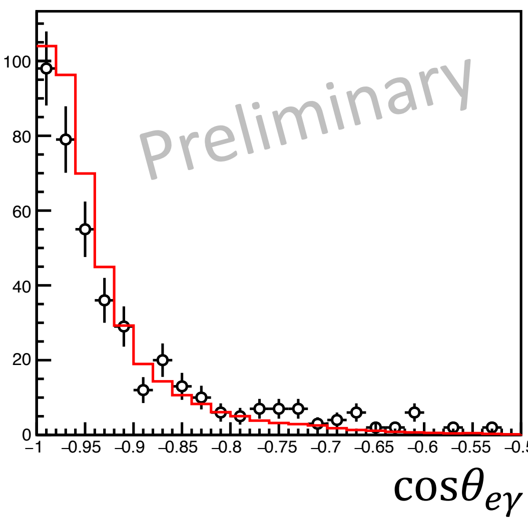


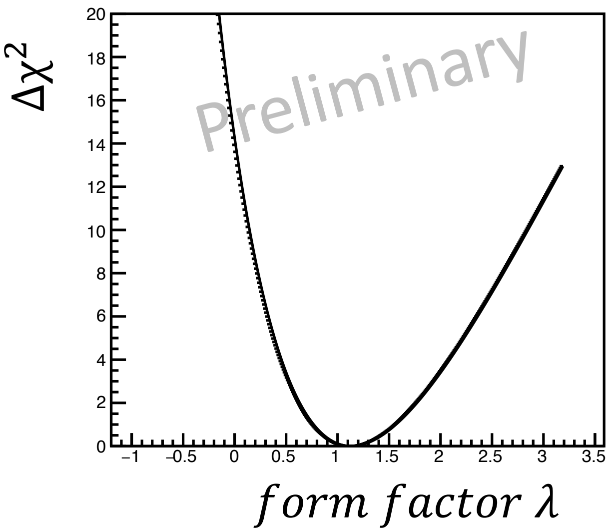


6. Form factor determination for $K_{e2\gamma}$







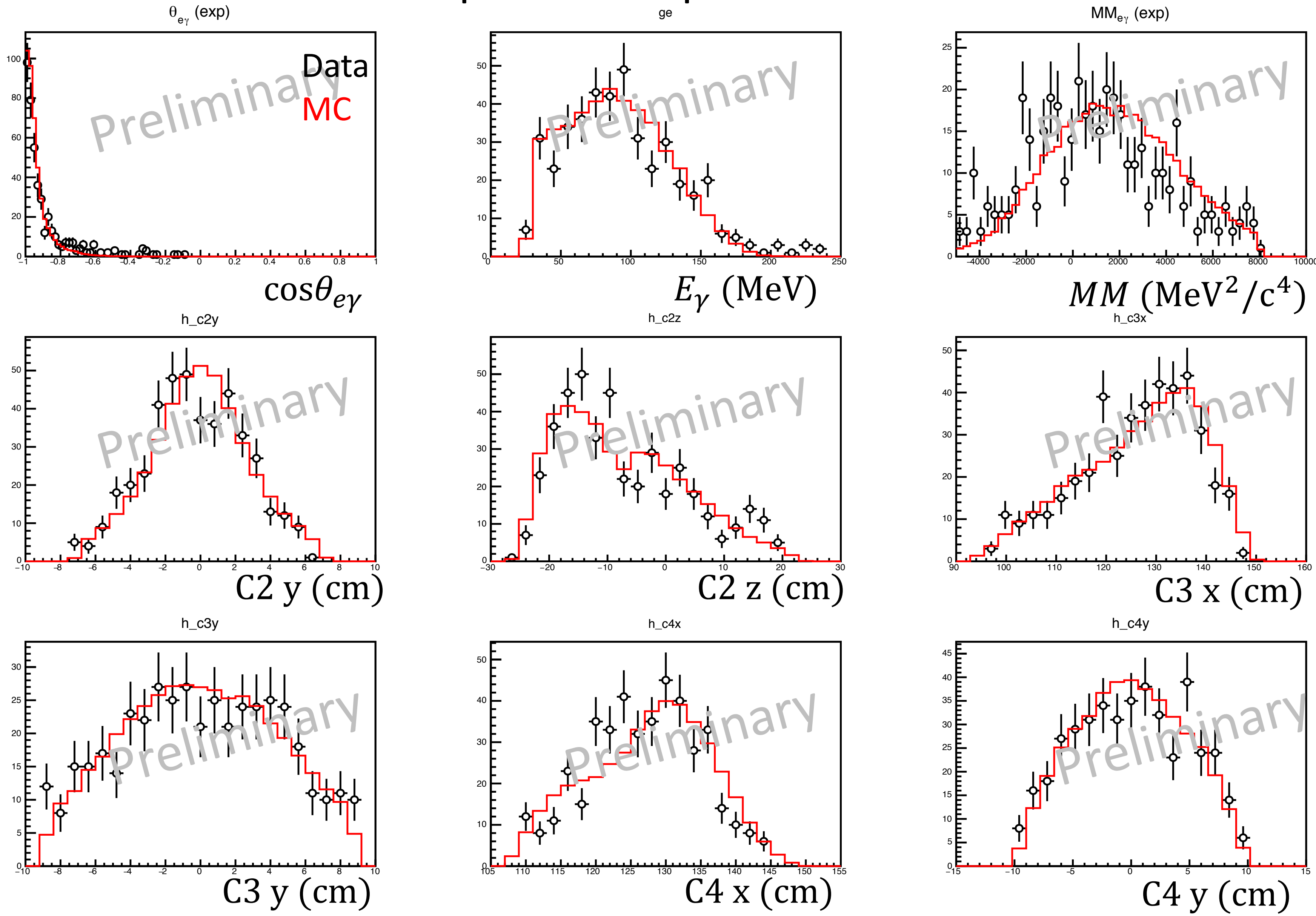


$\chi^2_{\mathrm{min}}/\mathrm{ndof} = 395/142$

Fitted $\lambda = 1.13^{+0.44}_{-0.37}$(stat)

6. Form factor determination for $K_{e2\gamma}$

Other profile comparison with MC



7. Summary

- $K_{e2\gamma}$ is an important background for R_K determination.
- The CsI performance was checked using $K_{\pi2}$.
- e+ spectra with 0γ, 1γ, and 2γ was consistent with MC K_{e2}, K_{e3}, and $K_{e2\gamma}$.
- Form factor $K_{e2\gamma}$ was determined preliminary.
- Next prospection

  Branching ratio $\Gamma(k_{e2\gamma})$ determination carefully

  Systematic uncertainty estimation

  $k_{e2\gamma}$ subtraction for R_K determination

TRECK – E36 Collaboration

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CANADA

University of British Columbia
Department of Physics and Astronomy
TRIUMF

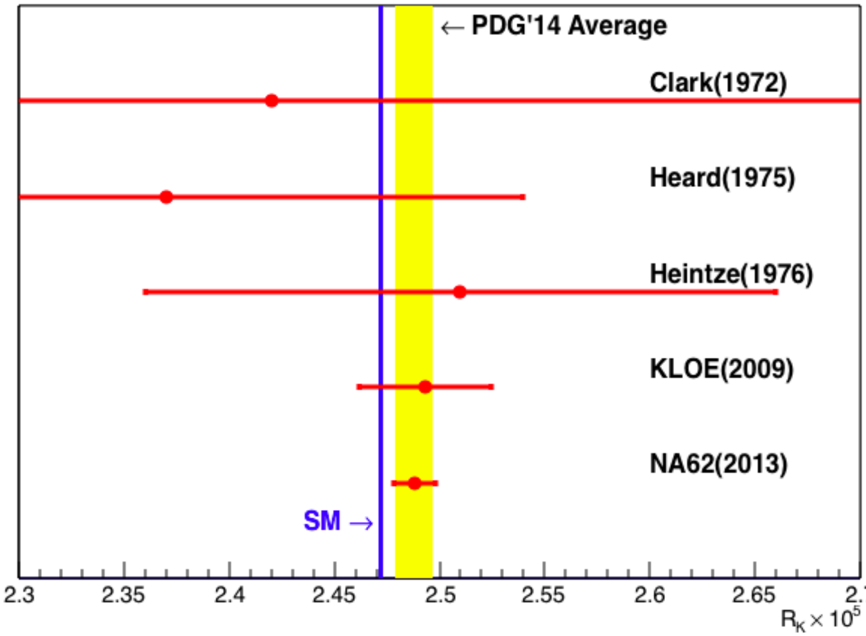
RUSSIA

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

Backup

1. Introduction

J-PARC E36 Experiment: Search for Lepton Universality Violation to measure $\Gamma(K^+ \to e^+\nu_e)/\,\Gamma(K^+ \to \mu^+\nu_\mu)$ using stopped positive kaon



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

radiative correction

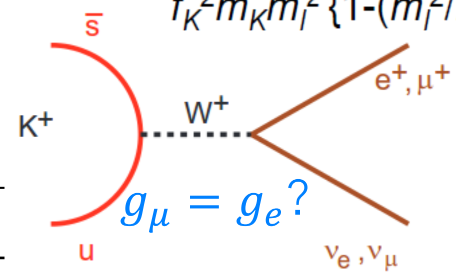
helicity suppression

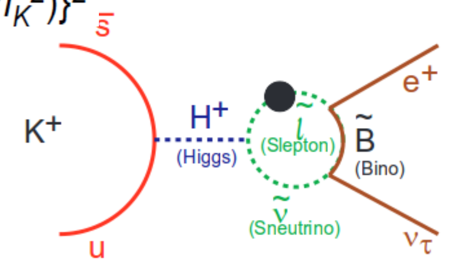
	$R_K \times 10^5$	$\Delta R_K/R_K$
KLOE(2009)	$2.493 \pm 0.025 \pm 0.019$ (stat) (sys)	1.26%
NA62(2013)	$2.488 \pm 0.007 \pm 0.007$ (stat) (sys)	0.40%
SM	2.477 ± 0.001	0.04%
Initial goal of E36		0.25%

$K^+ \to l^+\nu_l$

$\Gamma(K_{l2}) = g_l^2\,(G^2/8\pi)\, f_K^2 m_K m_l^2\,\{1-(m_l^2/m_K^2)\}^2$

Candidate Model: MSSM with LFV





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

$$\sim R_K^{SM}(1 + 0.013_{\max})$$

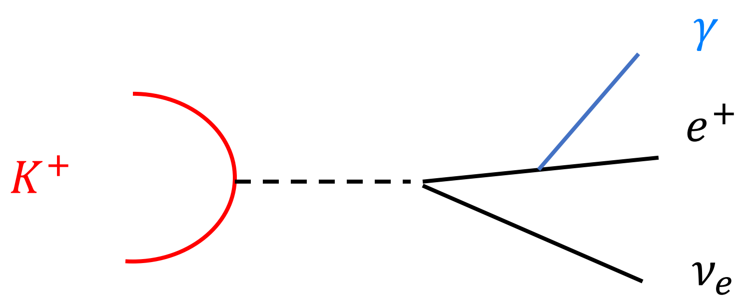
Phys. Rev. D **74**

1. Introduction

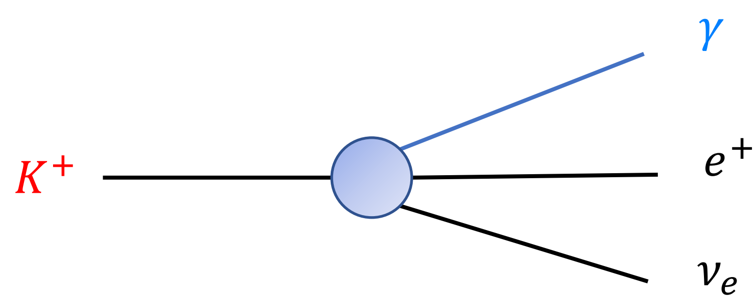
Main background: radiative decay to $K^+ \to e^+\nu_e\gamma$

$$R_K = \frac{\Gamma(K_{e2}) + \Gamma(K_{e2\gamma}(IB))}{\Gamma(K_{\mu2}) + \Gamma(K_{\mu2\gamma}(IB))}$$

Γ(Ke2) ~ 1.6×10^{-5}
Γ(Ke2γ(SD)) ~ 9.4×10^{-6}
From PDG



Internal Bremsstrahlung (IB)



Structure Dependent (SD)

Monte Carlo simulation

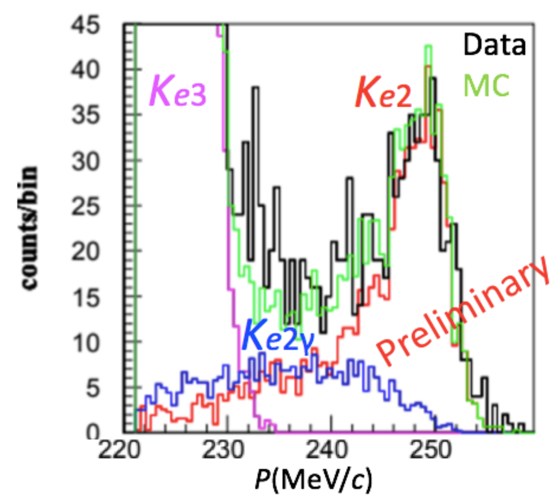
MC-IB

MC-SD

MC-SD

MC-IB

e+ momentum spectrum



2. $K^+ \to e^+\nu\gamma$ (SD) in ChPT(Chiral Perturbation Theory)

arXiv:hep-ph/9208204v1 4 Aug 1992

$K^+ \to e^+\nu\gamma$ Dalitz Density

$$\frac{d^2\Gamma}{dx\,dy} = \frac{m_K^5}{64\pi^2}\alpha G_F^2 \sin^2\theta_c (1-z) A(x,y),$$

$$x = 2E_\gamma/m_K$$
$$y = 2E_e/m_K$$
$$r_e = m_e^2/m_K^2.$$
$$z = (x+y-1-r_e)/x$$

$$A(x,y) = A_{IB}(x,y) + A_{SD^+}(x,y) + A_{SD^-}(x,y) + A_{INT^+}(x,y) + A_{INT^-}(x,y),$$

$$A_{IB}(x,y) = \frac{4r_e|F_K|^2}{m_K^2 z x^2}\left[x^2 + 2(1-r_e)\left(1-x-\frac{r_e}{z}\right)\right],$$

$$A_{SD^+}(x,y) = |F_V+F_A|^2 \frac{x^2 z^2}{1-z}\left(1-x-\frac{r_e}{z}\right),$$

This is a domination!

$$A_{SD^-}(x,y) = |F_V-F_A|^2 x^2 (y-z),$$

$$A_{INT^+}(x,y) = -\frac{4r_e}{m_K} Re[F_K(F_V+F_A)^*]\left(1-x-\frac{r_e}{z}\right),$$

$$A_{INT^-}(x,y) = \frac{4r_e}{m_K} Re[F_K(F_V-F_A)^*]\frac{1-y+z}{\lambda}.$$

2. $K^+ \to e^+\nu\gamma$ (SD) in ChPT(Chiral Perturbation Theory)

arXiv:hep-ph/9208204v1 4 Aug 1992

$$A_{SD^+}(x,y) = |F_V + F_A|^2 \frac{x^2 z^2}{1-z}\left(1 - x - \frac{r_e}{z}\right)$$

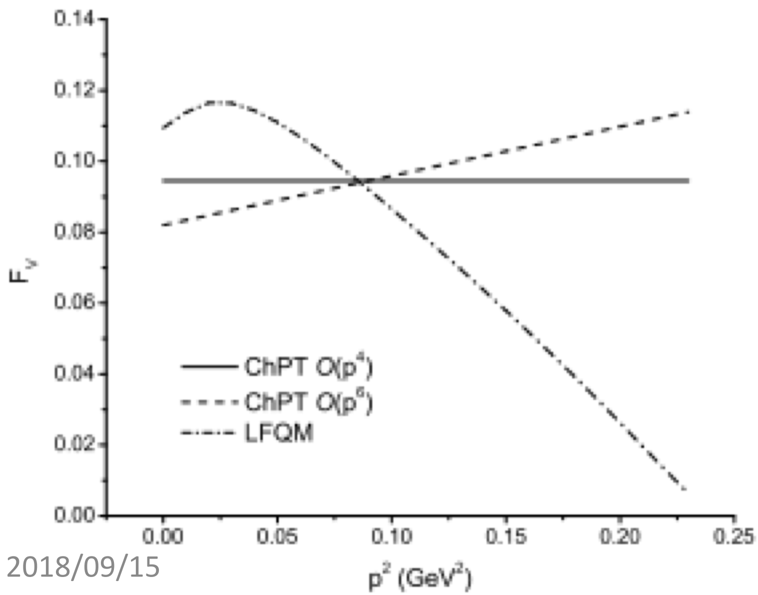
Model	$F_V(0)$	$F_A(0)$
ChPT at $O(p^4)$	0.0945	0.0425
ChPT of $O(p^6)$	0.082	0.034
LFQM.	0.106	0.036

$F_{V,A} = F_{V,A}(p^2)$

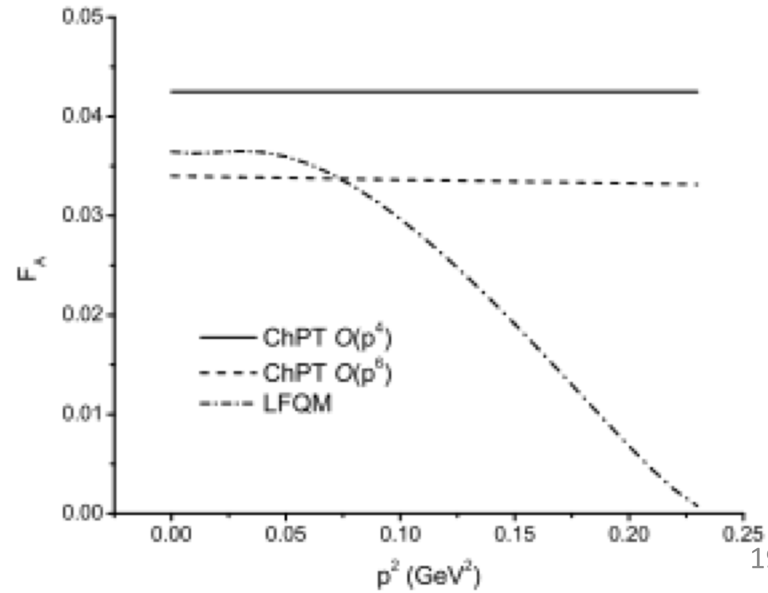
ChPT O(p⁶): $F_V = F_V(0)\big(1 + \lambda(1-x)\big), F_A = F_A(0)$

$\lambda \sim 0.4$ and $F_V(0) + F_A(0) = 0.125$ were published by KLOE group (2009).

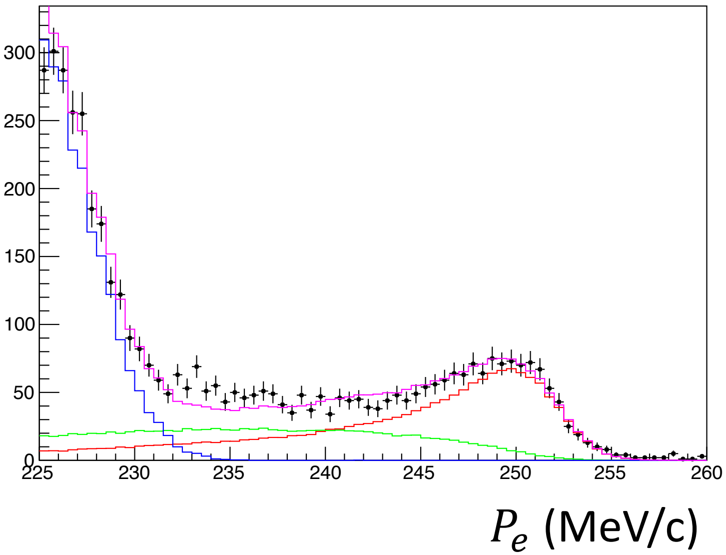
F_V

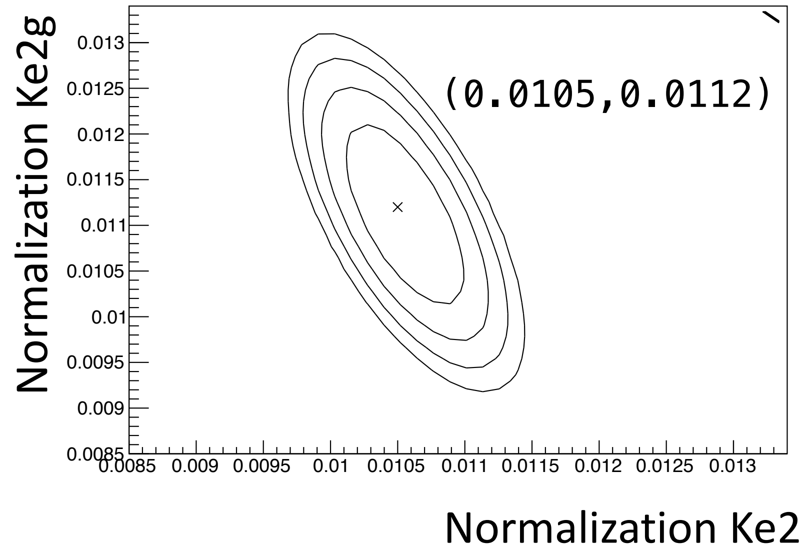


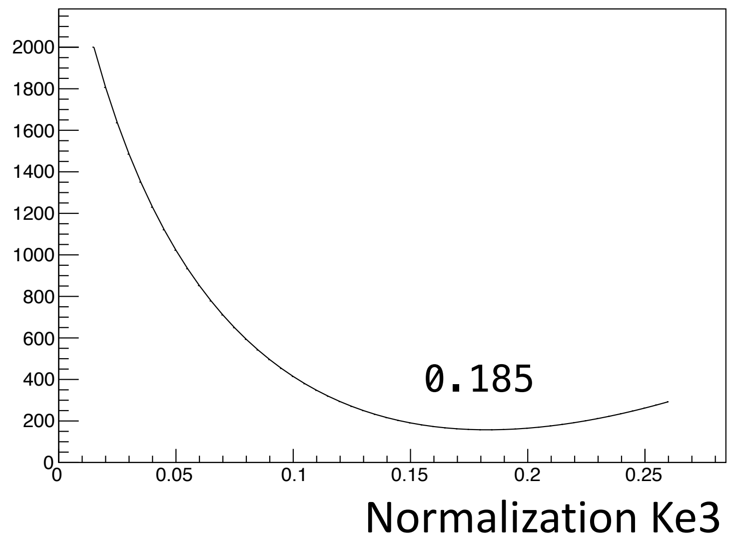
F_A



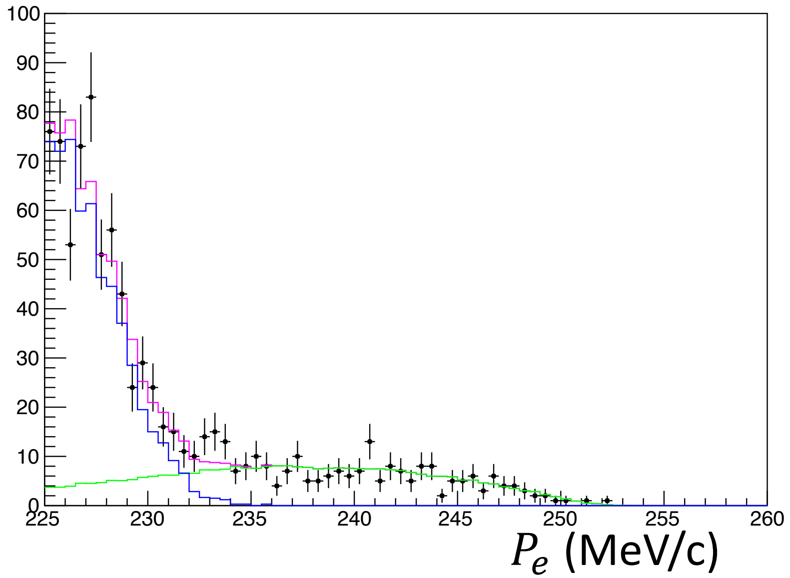
e+ momentum spectra 0γ
Normalization factor

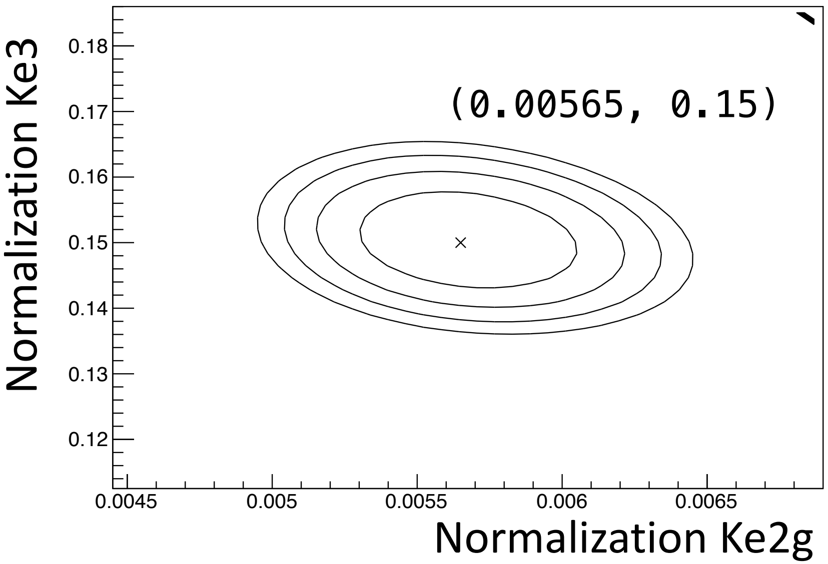




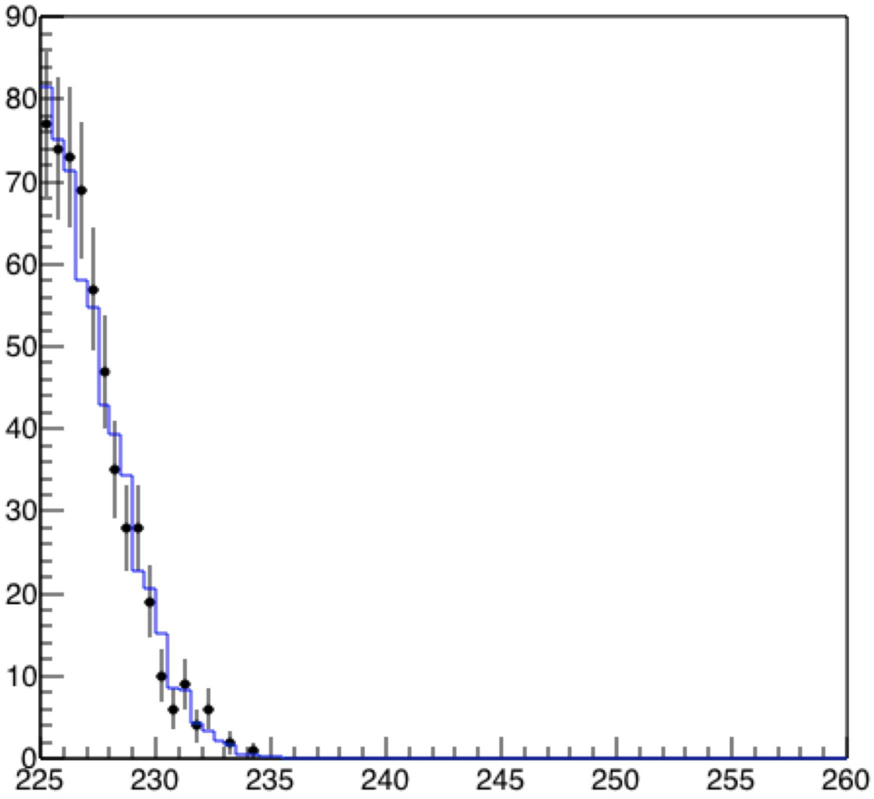


e+ momentum spectra 1γ
Normalization factor





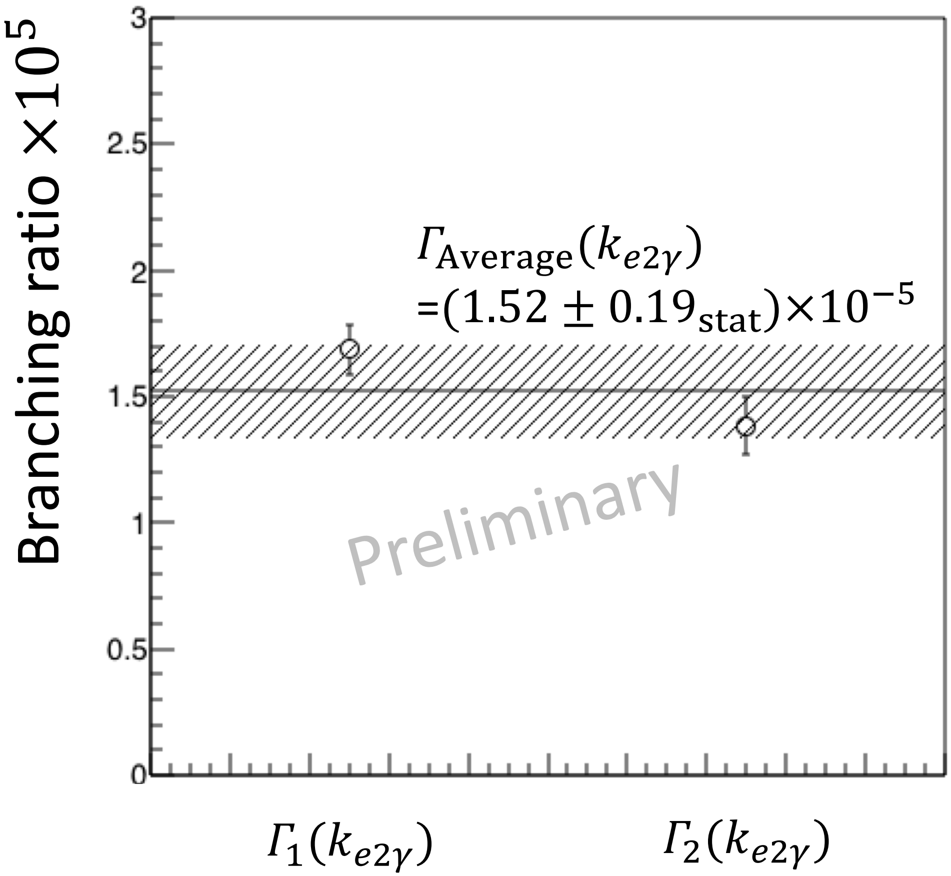
e+ momentum spectra 2γ
Normalization factor



P_e (MeV/c)

Normalization factor
0.13

6. Ke2γ branching ratio



$$\Gamma_1(k_{e2\gamma}) = \frac{N\left(K_{e2\gamma}^{(0\gamma)}\right)}{N\left(K_{e2}^{(0\gamma)}\right)} \frac{\Omega\left(K_{e2}^{(0\gamma)}\right)}{\Omega\left(K_{e2\gamma}^{(0\gamma)}\right)} \Gamma(k_{e2})$$

$$= (1.69 \pm 0.10_{\mathrm{stat}})\times 10^{-5}$$

$$\Gamma_2(k_{e2\gamma}) = \frac{N\left(K_{e2\gamma}^{(1\gamma)}\right)}{N\left(K_{e2}^{(0\gamma)}\right)} \frac{\Omega\left(K_{e2}^{(0\gamma)}\right)}{\Omega\left(K_{e2\gamma}^{(1\gamma)}\right)} \Gamma(k_{e2})$$

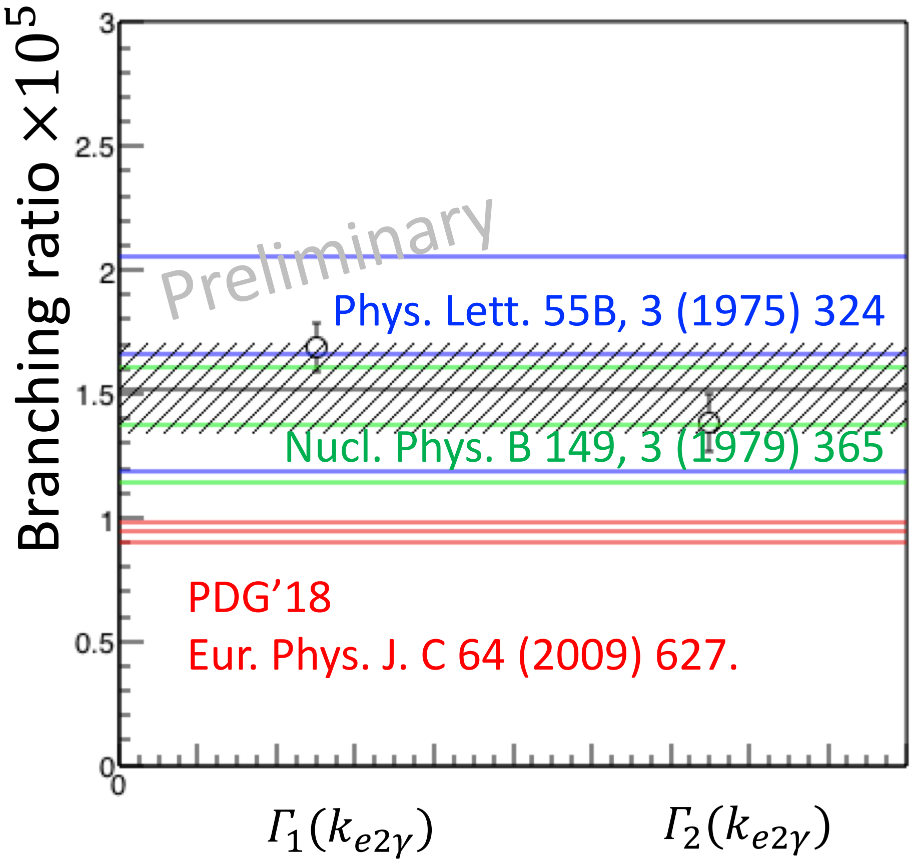
$$= (1.38 \pm 0.11_{\mathrm{stat}})\times 10^{-5}$$

$$\Gamma(k_{e2}) = (1.582 \pm 0.007)\times 10^{-5}$$

Next prospection :

Comparison with $\Gamma(k_{e3})$

$K_{e2\gamma}$ branching ratio



$$\Gamma_1(k_{e2\gamma}) = \frac{N\left(K_{e2\gamma}^{(0\gamma)}\right)}{N\left(K_{e2}^{(0\gamma)}\right)} \frac{\Omega\left(K_{e2}^{(0\gamma)}\right)}{\Omega\left(K_{e2\gamma}^{(0\gamma)}\right)} \Gamma(k_{e2})$$

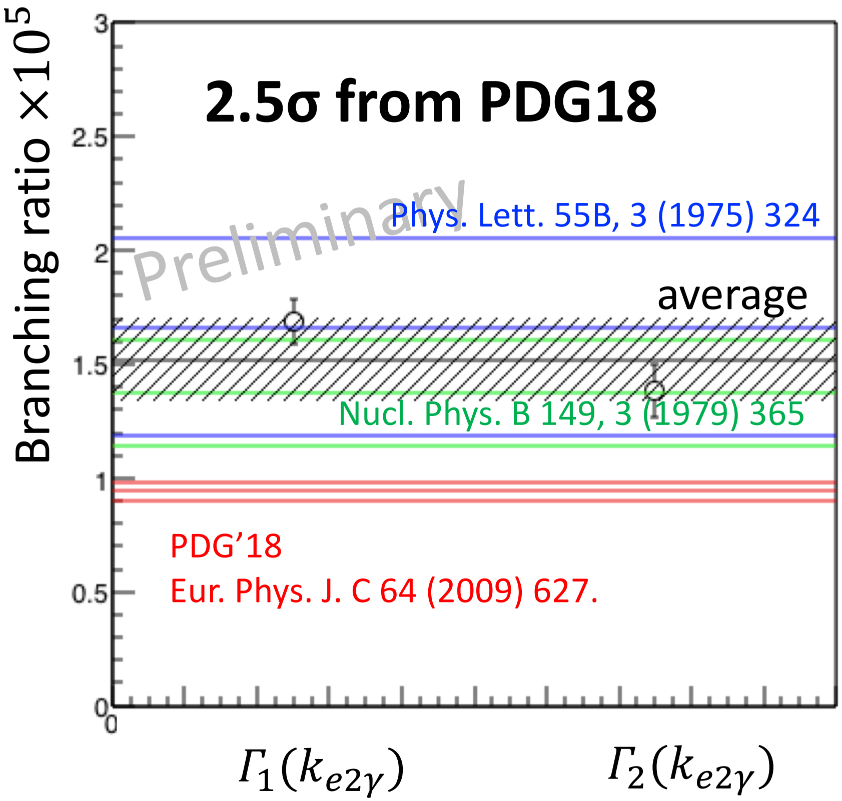
$$= (1.69 \pm 0.10_{\mathrm{stat}})\times 10^{-5}$$

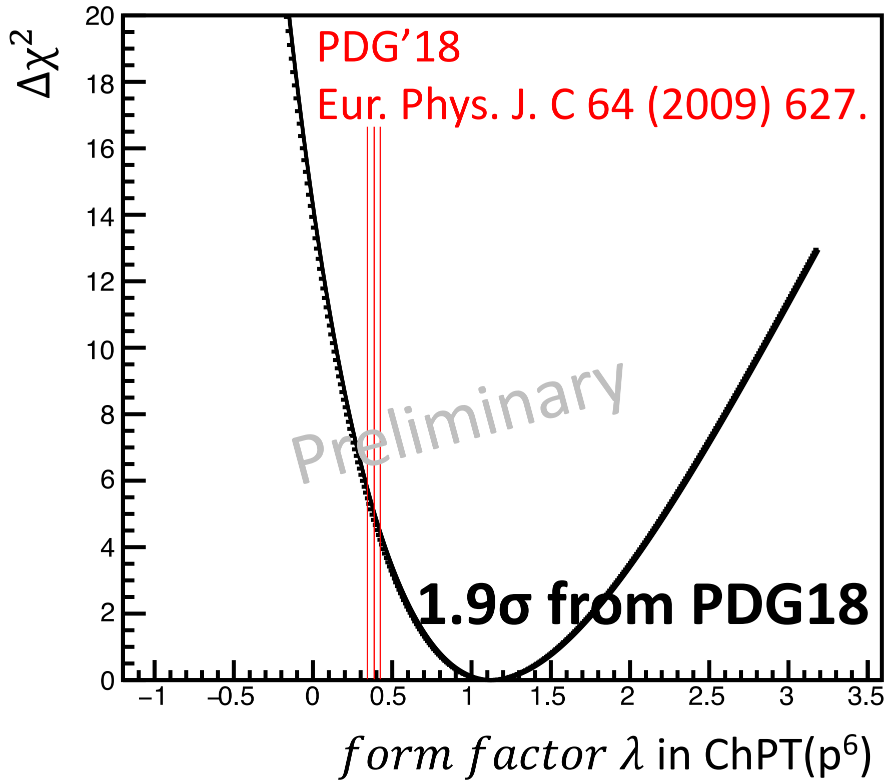
$$\Gamma_2(k_{e2\gamma}) = \frac{N\left(K_{e2\gamma}^{(1\gamma)}\right)}{N\left(K_{e2}^{(0\gamma)}\right)} \frac{\Omega\left(K_{e2}^{(0\gamma)}\right)}{\Omega\left(K_{e2\gamma}^{(1\gamma)}\right)} \Gamma(k_{e2})$$

$$= (1.38 \pm 0.11_{\mathrm{stat}})\times 10^{-5}$$

$$\Gamma(k_{e2}) = (1.582 \pm 0.007)\times 10^{-5}$$

Ke2γ branching ratio





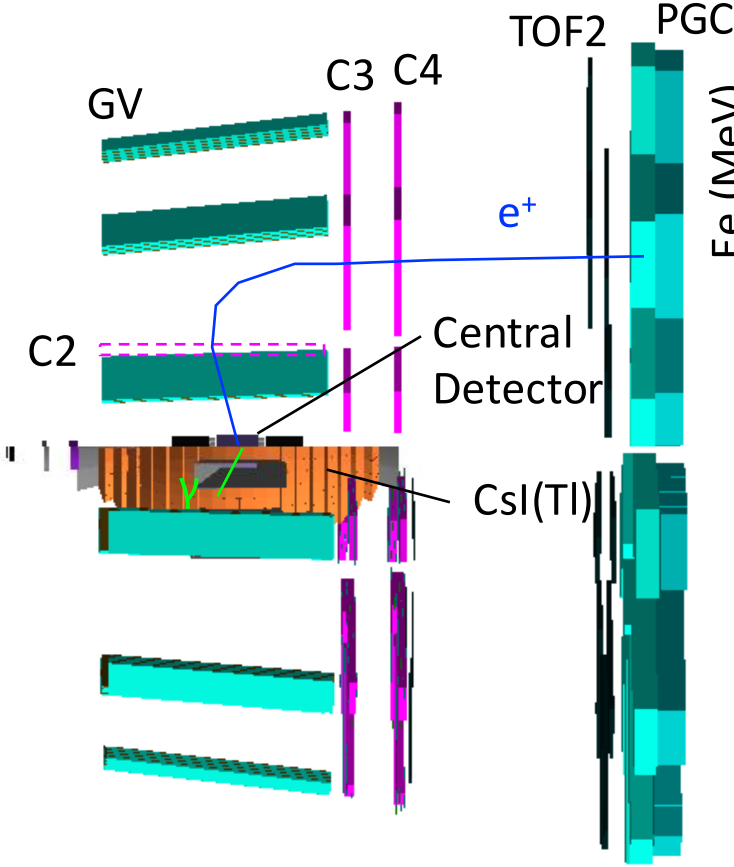
6. Discussion & Prospection

Systematic uncertainty

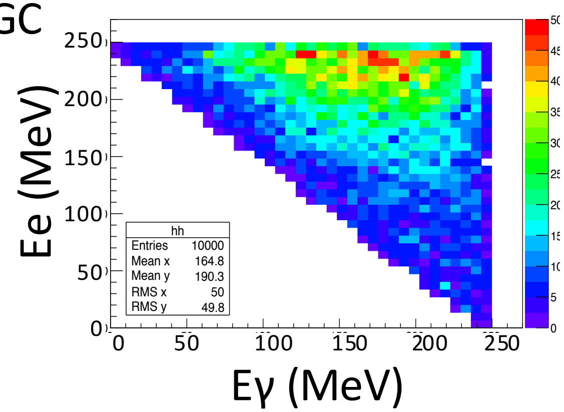
Branching ratio	sigma
Ke2 branching ratio	0.44%
Threshold determination	Not yet
Spectrometer acceptance	Not yet

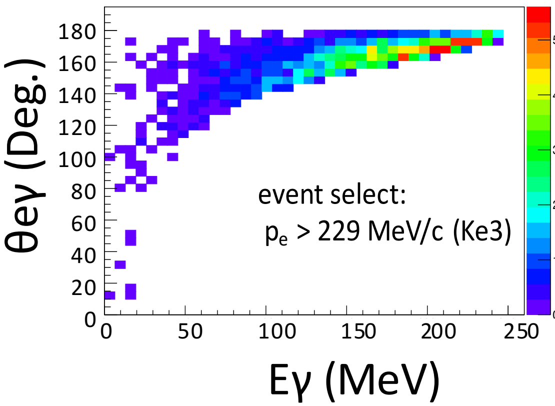
Form factor λ	(90%CL)
CsI gain calibration	2.65%
Detector arraignment	Not yet
	Not yet

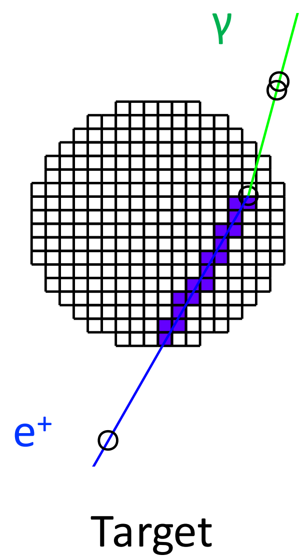
モンテカルロシミュレーション by GEANT4
Ke2 γ（SD） Event

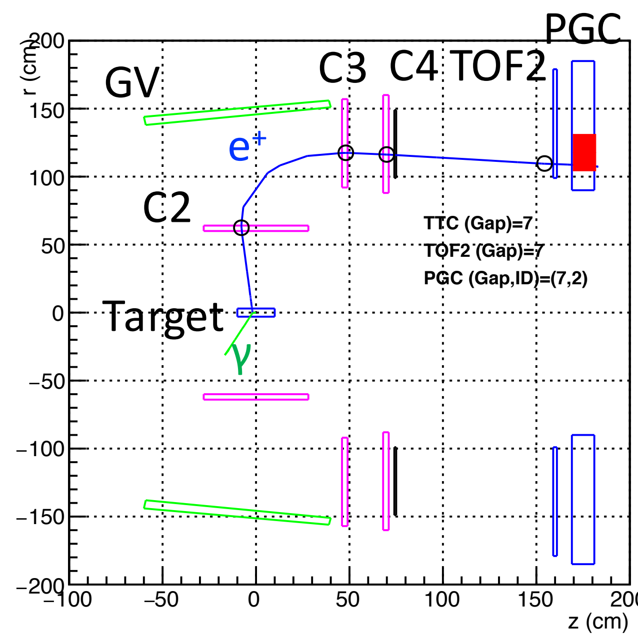


Kl2γ Decay Channel Form Factor λ = 0.38 [1]



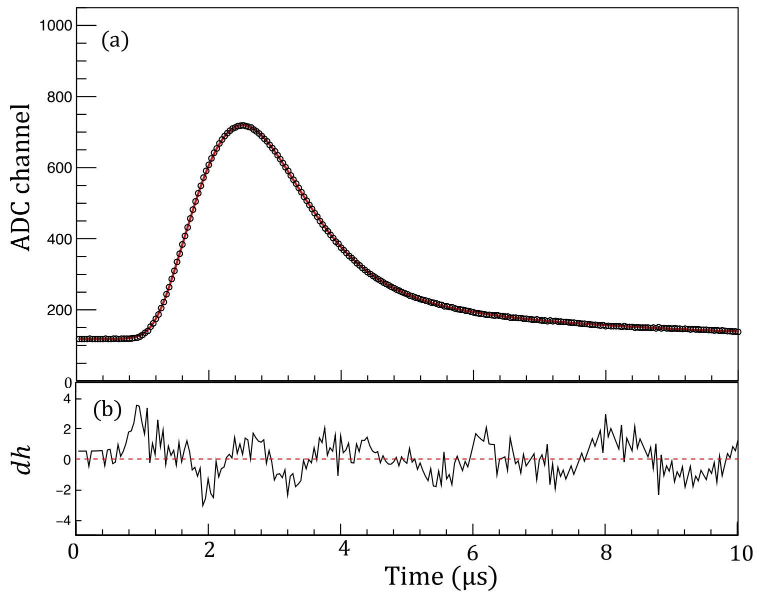






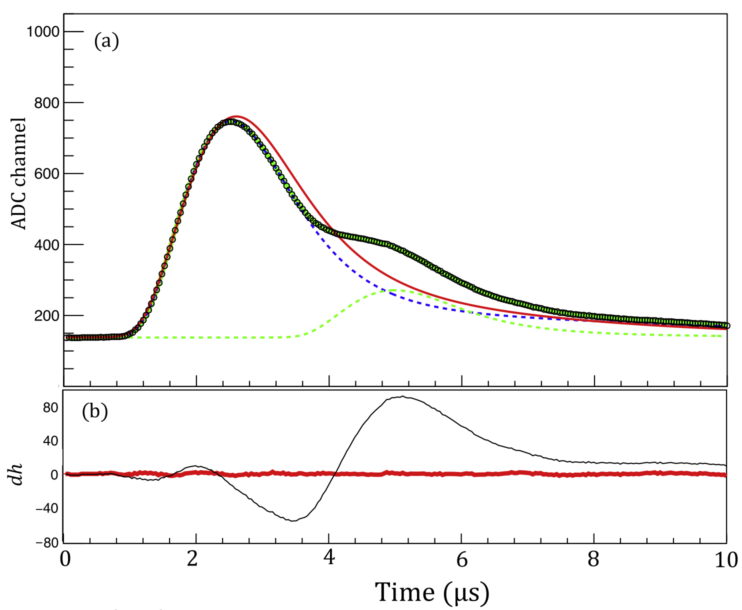
[1] F. Ambrosino et al., EPJ C64 627.

Waveform model function



$$f(t) = \frac{A}{1 - \exp\{-(t-\tau_0)/\lambda\}} \cdot Freq\left(\frac{t-\tau_0-d}{\mu}\right) \cdot \left\{ \frac{t-\tau_0}{\tau_1} \exp\left(1 - \frac{t-\tau_0}{\tau_1}\right) + \varepsilon \frac{t-\tau_0}{\tau_2} \exp\left(1 - \frac{t-\tau_0}{\tau_2}\right) \right\},$$

$$Freq(x) = \frac{1}{\sqrt{2}} \int_{\infty}^{x} exp(-t^2/2)dt.$$



Energy & time resolution

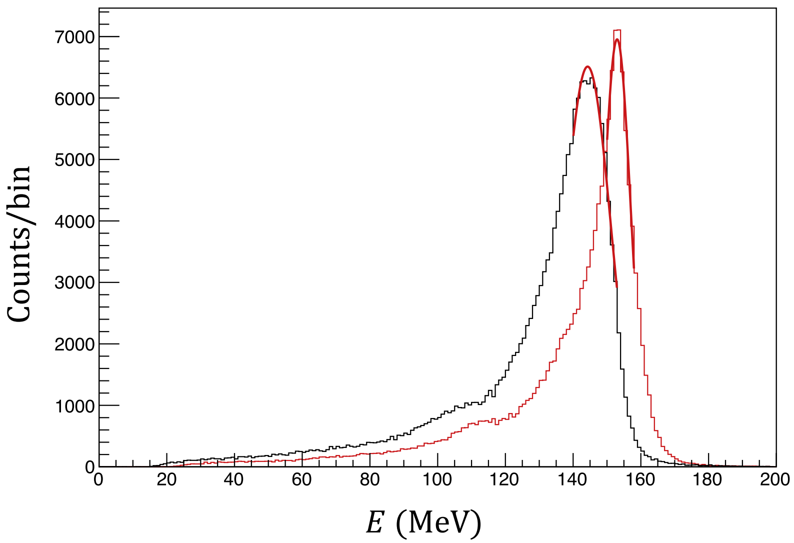


Fig. 6. The calibrated energy spectra obtained using the $K^+ \to \mu^+\nu_\mu$ decays. The red spectrum includes a correction for the energy loss in the target. The red lines are the fitting results assuming a Gaussian function. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

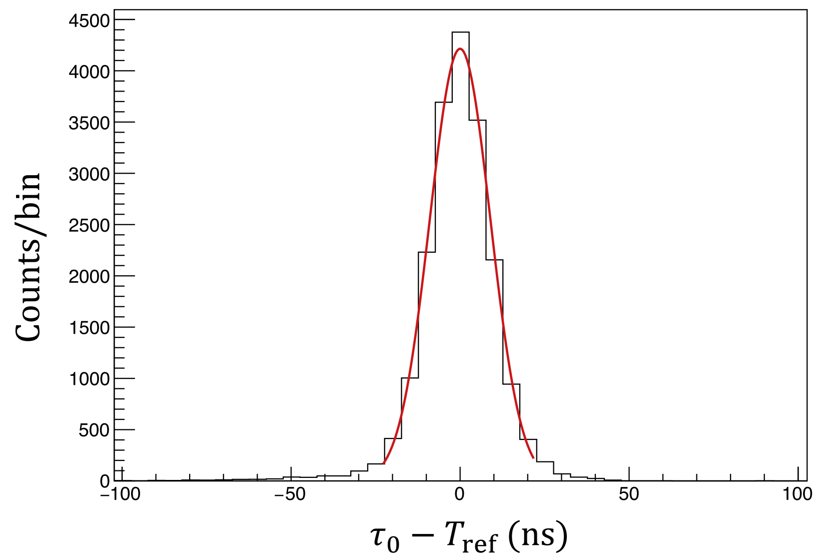


Fig. 7. The μ^+ timing distribution corrected for T_{ref} ($\tau_0 - T_{\mathrm{ref}}$). The timing resolution was determined to be $\sigma = 10.7 \pm 0.1$ ns. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

H. Ito et al., NIM A 901 (2018) 1.