MEG実験におけるミュー粒子放射崩壊の測定と利用

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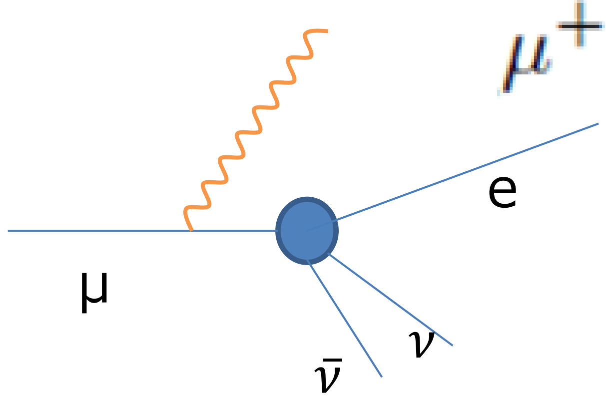
Introduction

- Studying radiative muon decay (RMD) is important and interesting
  - have to evaluate background rate for $\mu \to e\gamma$ search.
  - timing calibration tool.
  - internal check of analysis.
  - Michel parameters can be measured.

- We present result of the RMD analysis in the $\mu \to e\gamma$ search sample collected in 2009 & 2010.

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$$



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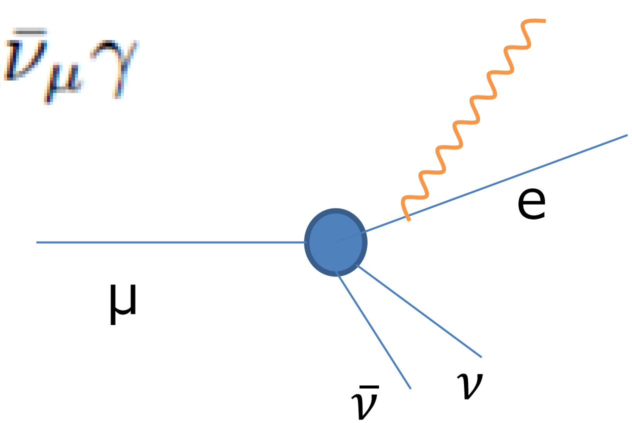
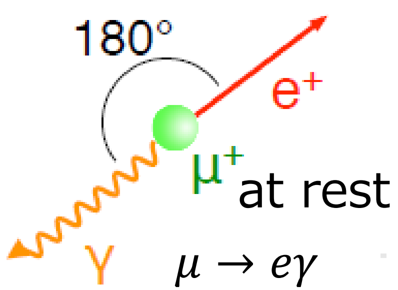
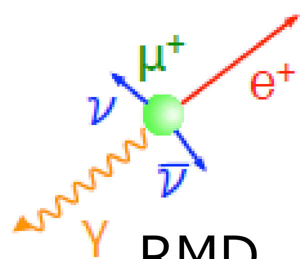


MEG experiment

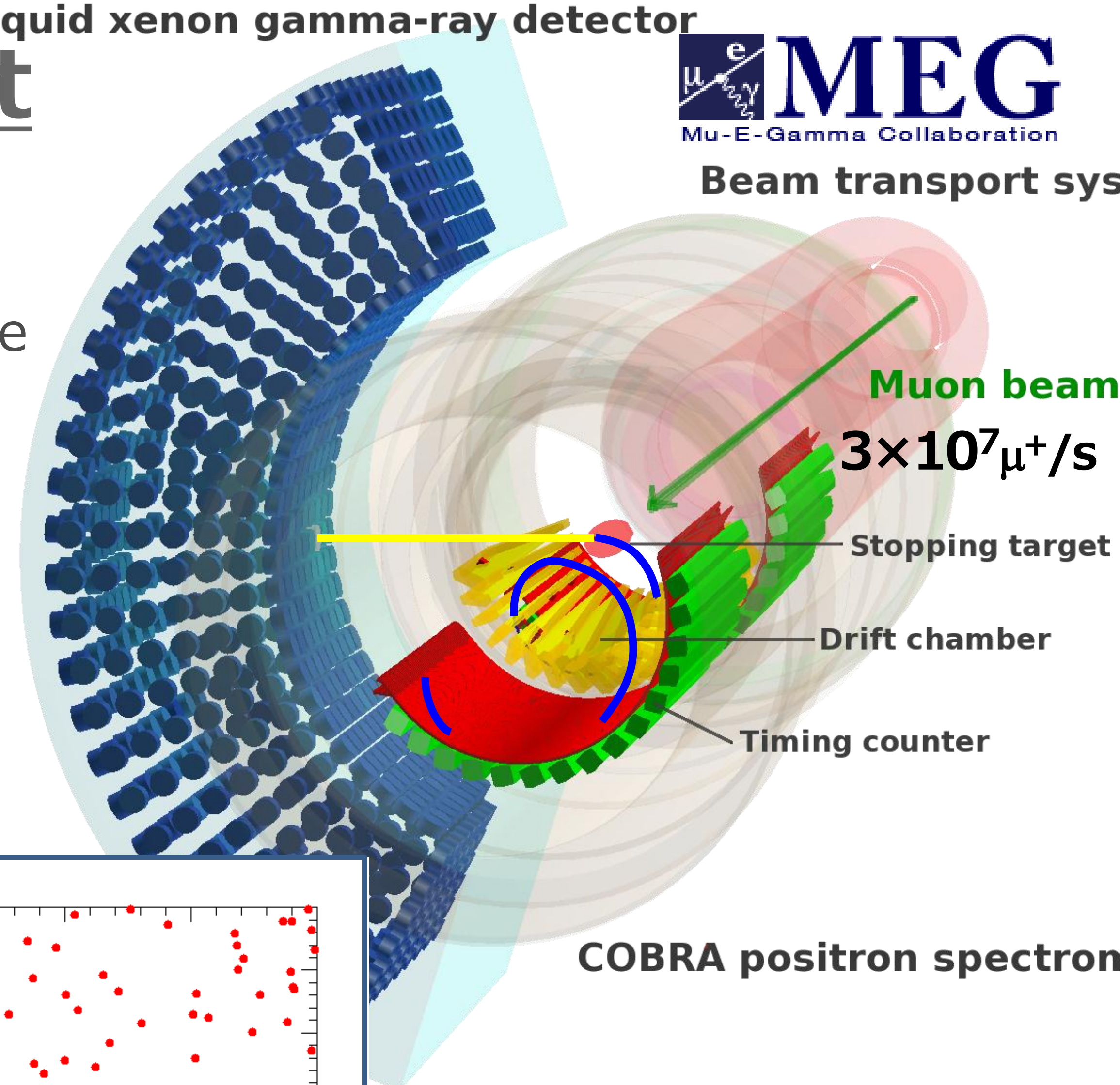
- Search for the lepton-flavor violating muon decay $\mu \to e\gamma$
  - Detectors, Beam, DAQ are all optimized to $\mu \to e\gamma$ detection

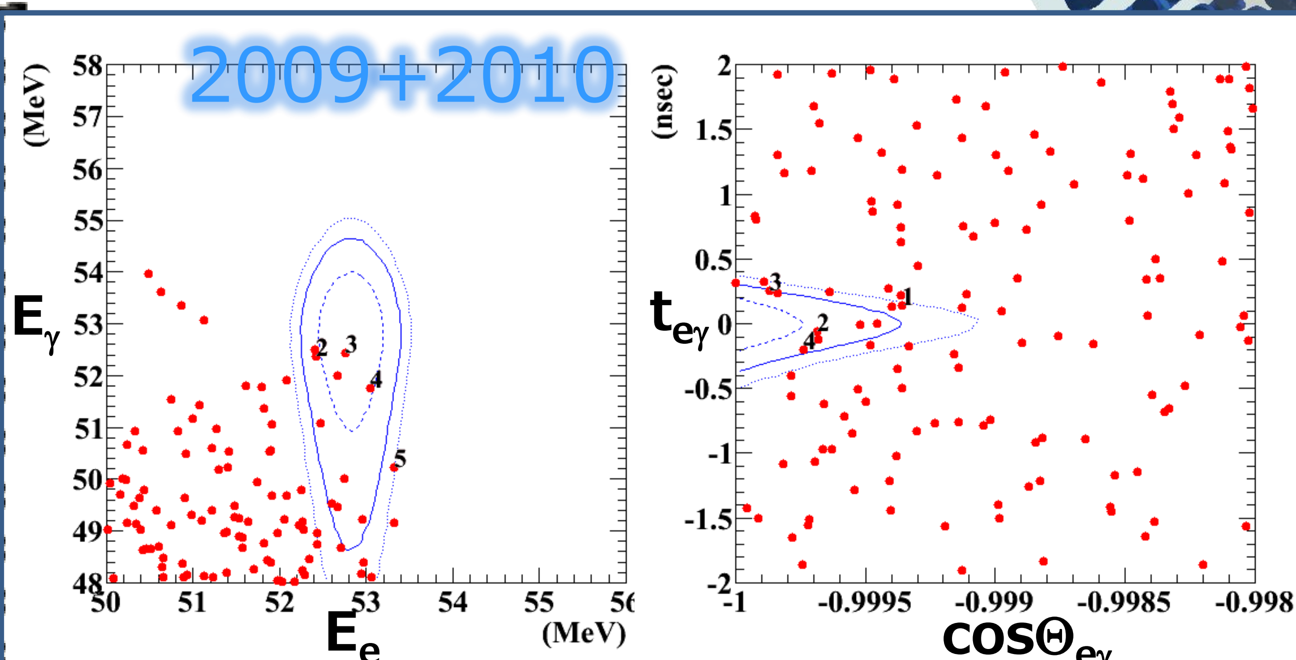


$\mu \to e\gamma$



RMD





(PRL **107**,171801(2011))

$\mathcal{B} < 2.4 \times 10^{-12}$

giving stringent constraint on new physics

Theory

- SM process RMD is explicitly & accurately calculated in electroweak theory.
- Differential BR of RMD in *V-A* structure can be written

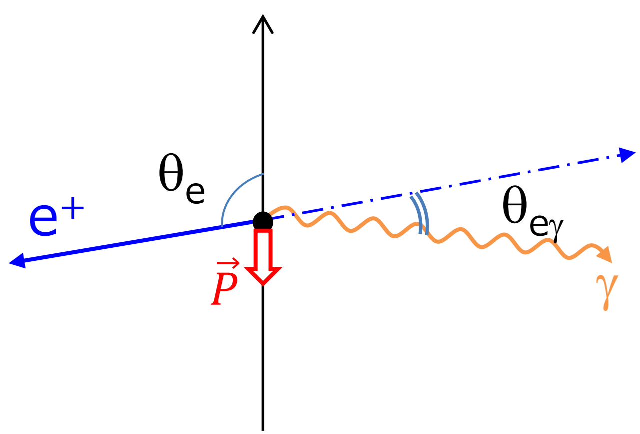
Y.Kuno and Y.Okada, Rev. Mod. Phys. 73, 151 (2001)

$$d\mathcal{B}(\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma) = \frac{\alpha}{64\pi^3}\beta dx \frac{dy}{y} d\Omega_e d\Omega_\gamma [F(x,y,d) + \beta P \cos\theta_e G(x,y,d) + P\cos\theta_\gamma H(x,y,d)],$$

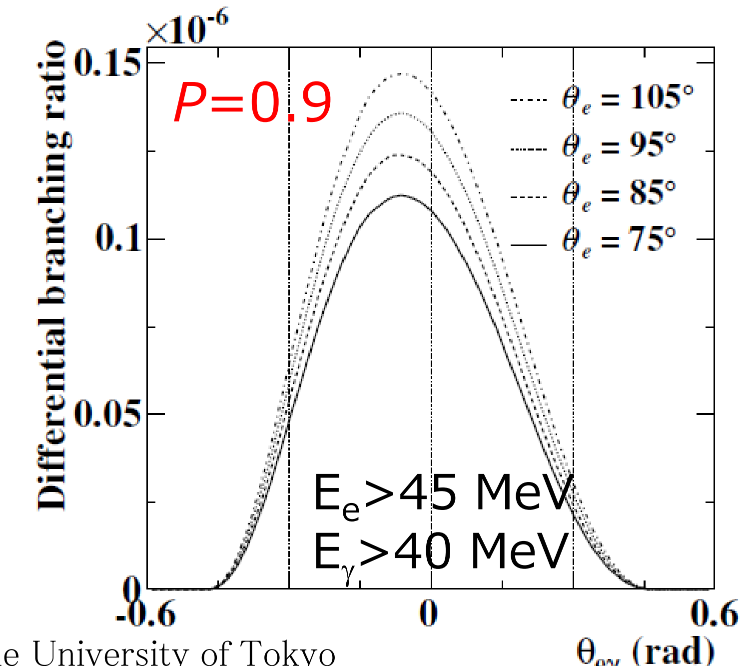
$x=2E_e/M_\mu$
$y=2E_\gamma/M_\mu$
$d=1-\beta\cos\Theta_{e\gamma}$

Polarization of muon

- Polarization of decaying muon in MEG target is preserved
  - Measured 0.89±0.04 with Michel spectrum.

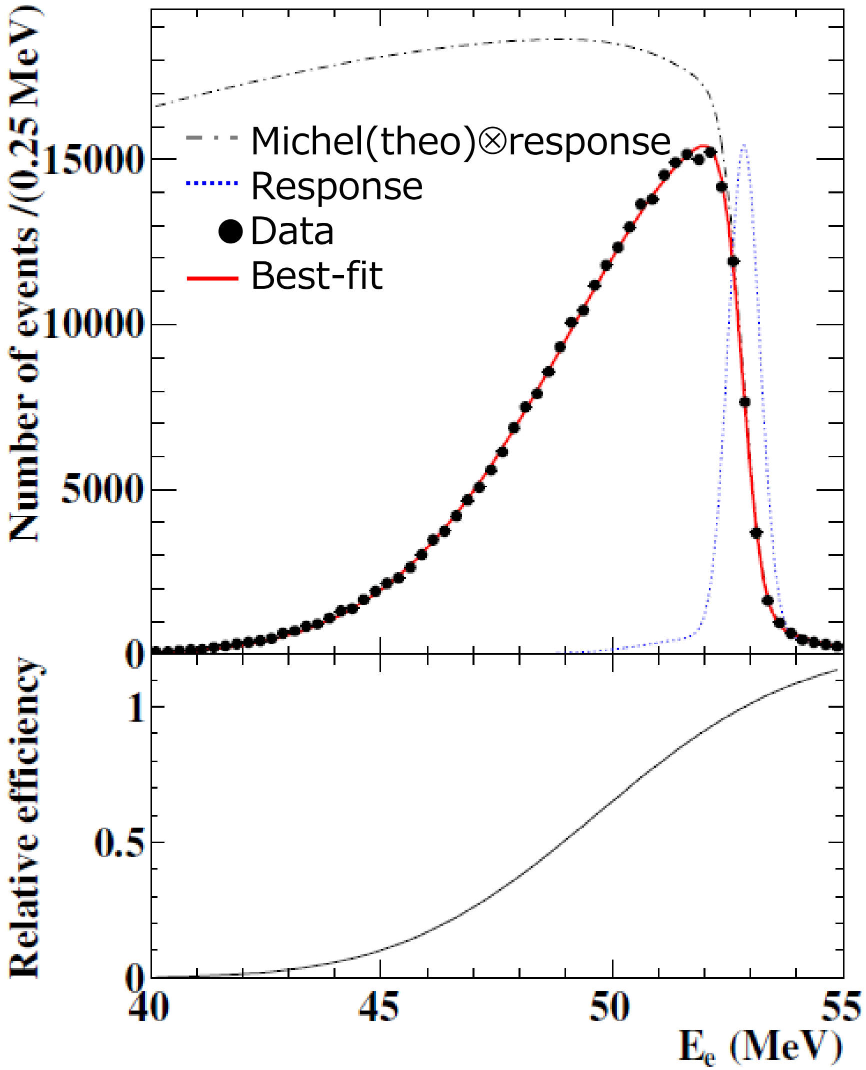


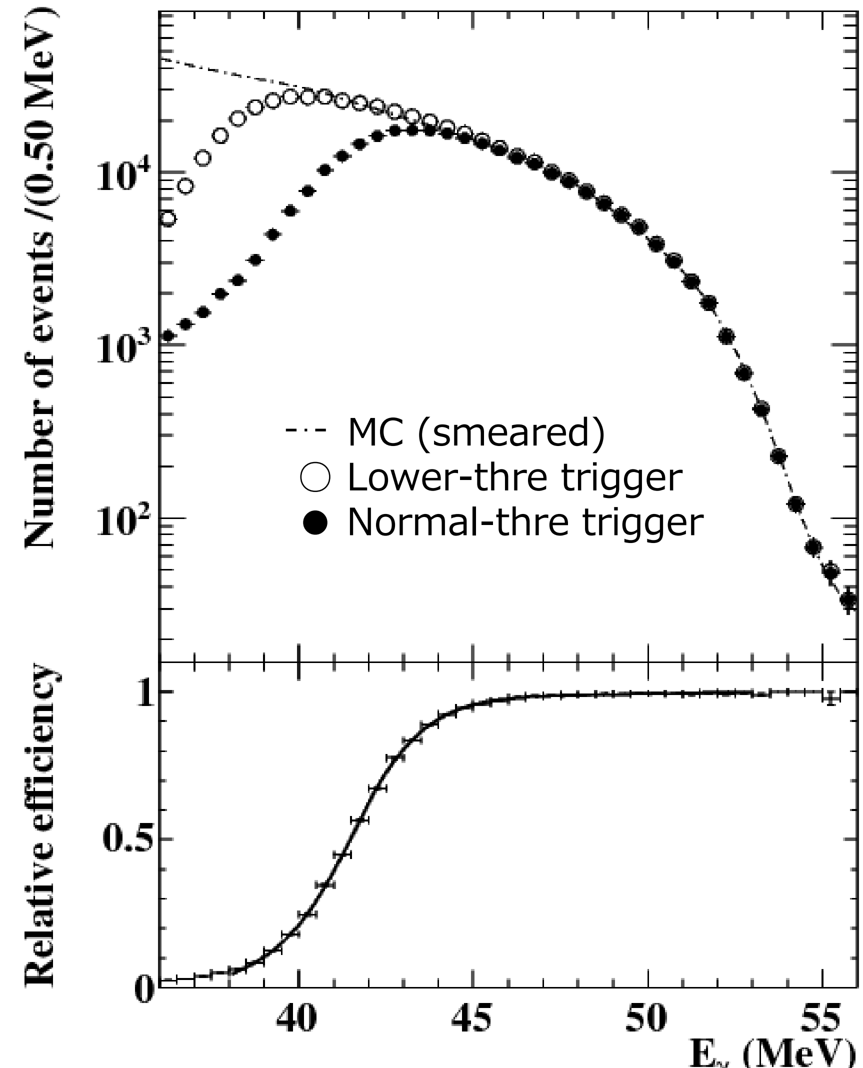
$$\theta_{e\gamma} = (\pi - \theta_e) - \theta_\gamma$$

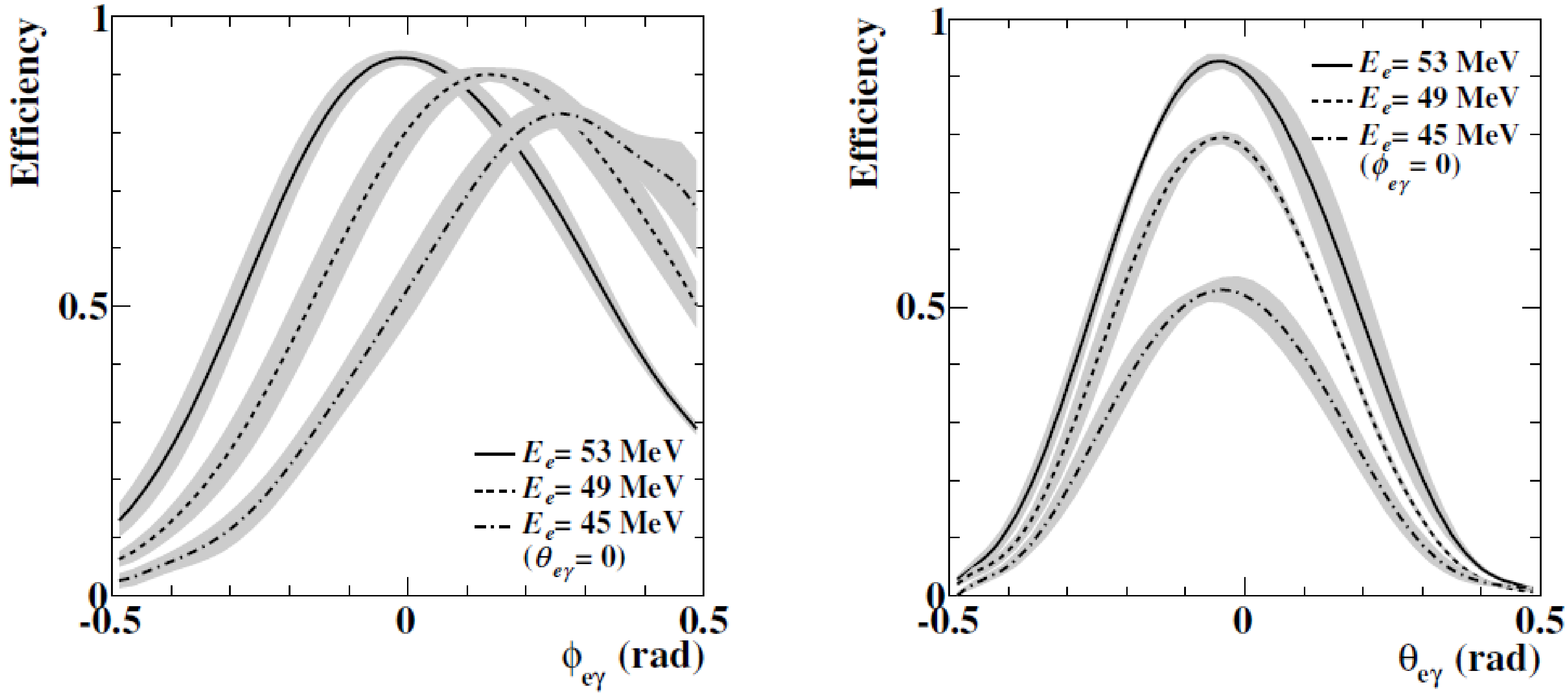


MEG acceptance & efficiency

- MEG setup limits the phase space able to be measured.



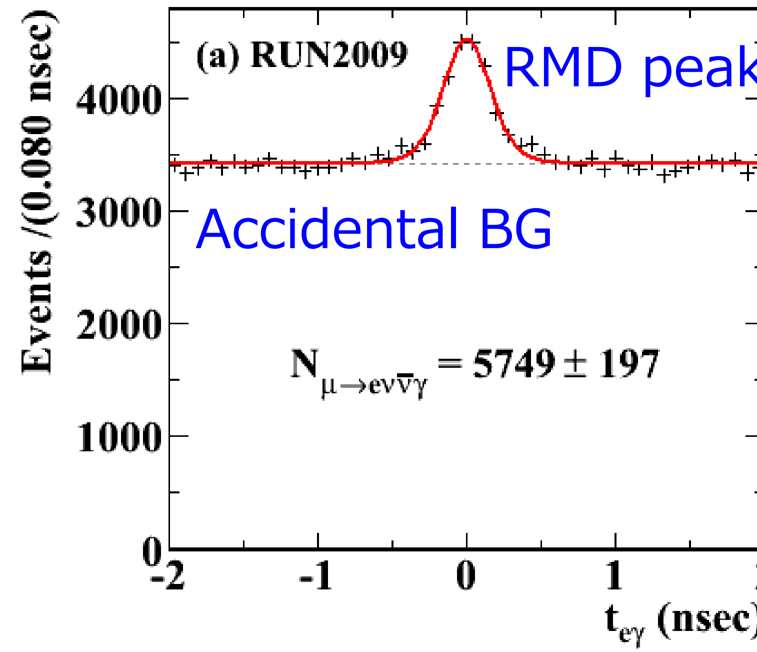


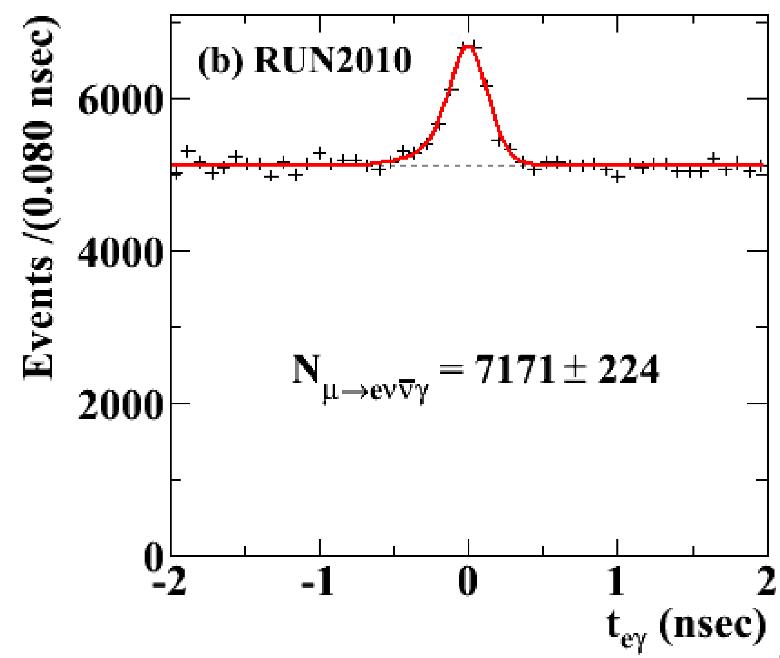


- Direction-match in trigger also deforms RMD spectrum
  - Angle efficiency depends on E_e
  - Calculate efficiency table based on MC, and check with measured distribution of accidental background.

Counting RMD events

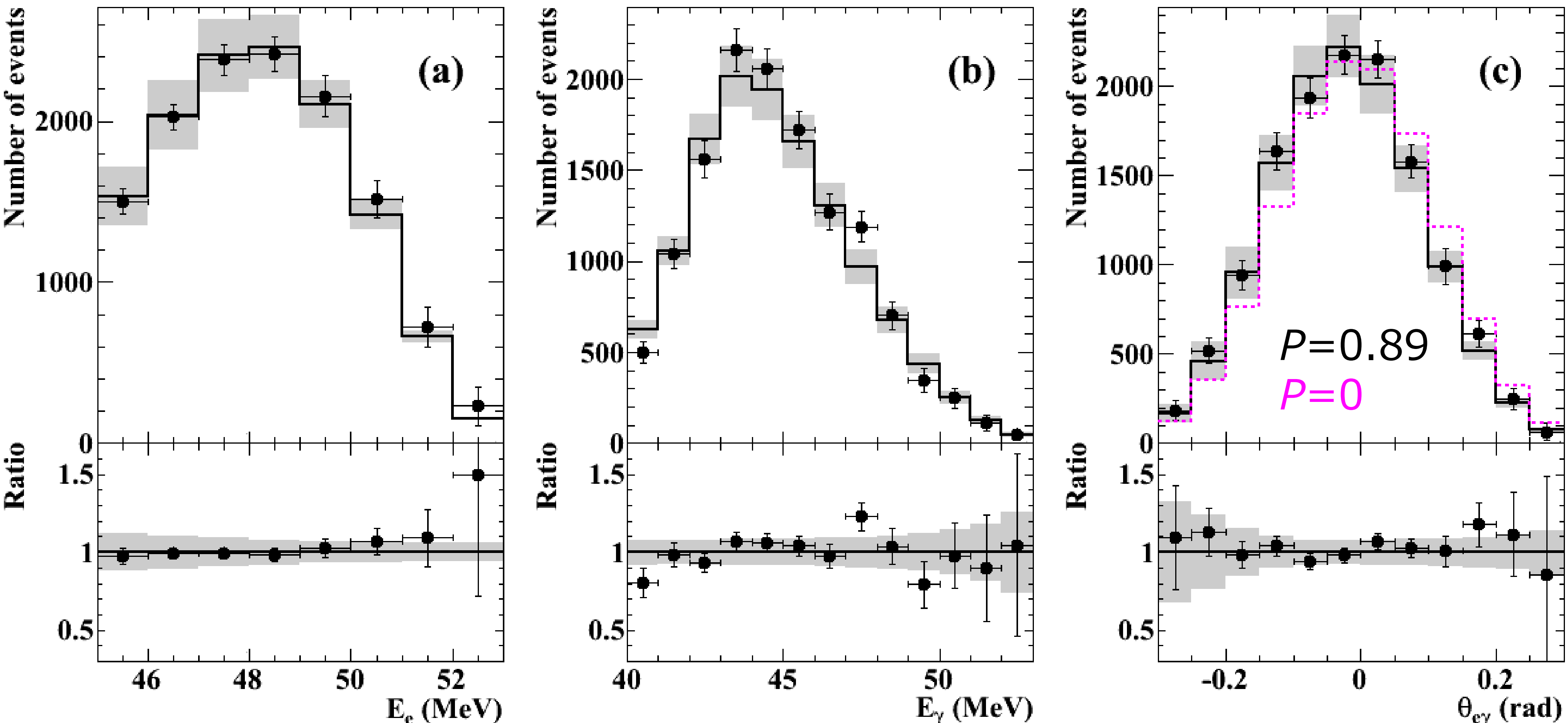
- Event selection
  - Tracking quality (uncert, χ^2) of track fitting (Kalman filter)
  - Matching with TC hits in space & time
  - Originating at target
  - Cosmic-ray cut in LXe
  - They are identical to those for $\mu \to e\gamma$ search
- Measure number of RMD with fit to time distribution
  - no assumption on energy and angle distribution
  - high timing resolution of MEG enables it





Projected Distributions

- 2009+2010
- BG are subtracted



Normalized to Michel positrons
Gray bands show systematic (diagonal elements)

BR measurement

- measure BR of RMD for possible largest window: E_e>45, E_γ>40 MeV
- Fit to time distribution

  45 < E_e < 53 MeV
  40 < E_γ < 53 MeV
  $|\theta_{e\gamma}|$ < 0.3 rad
  $|\phi_{e\gamma}|$ < 0.3 rad

  - N^{obs}= 12920±299 event
- Normalization to Michel
  - in pre-scaled unbiased trigger

$$\mathcal{B}(\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma) = \frac{N_{e\nu\bar{\nu}\gamma}}{N_\mu \cdot \epsilon_{e\nu\bar{\nu}\gamma}} = \frac{N_{e\nu\bar{\nu}\gamma}}{N_{e\nu\bar{\nu}} \cdot p \cdot (1/f) \cdot (\epsilon_{e\nu\bar{\nu}\gamma}/\epsilon_{e\nu\bar{\nu}})},$$

uncertainties

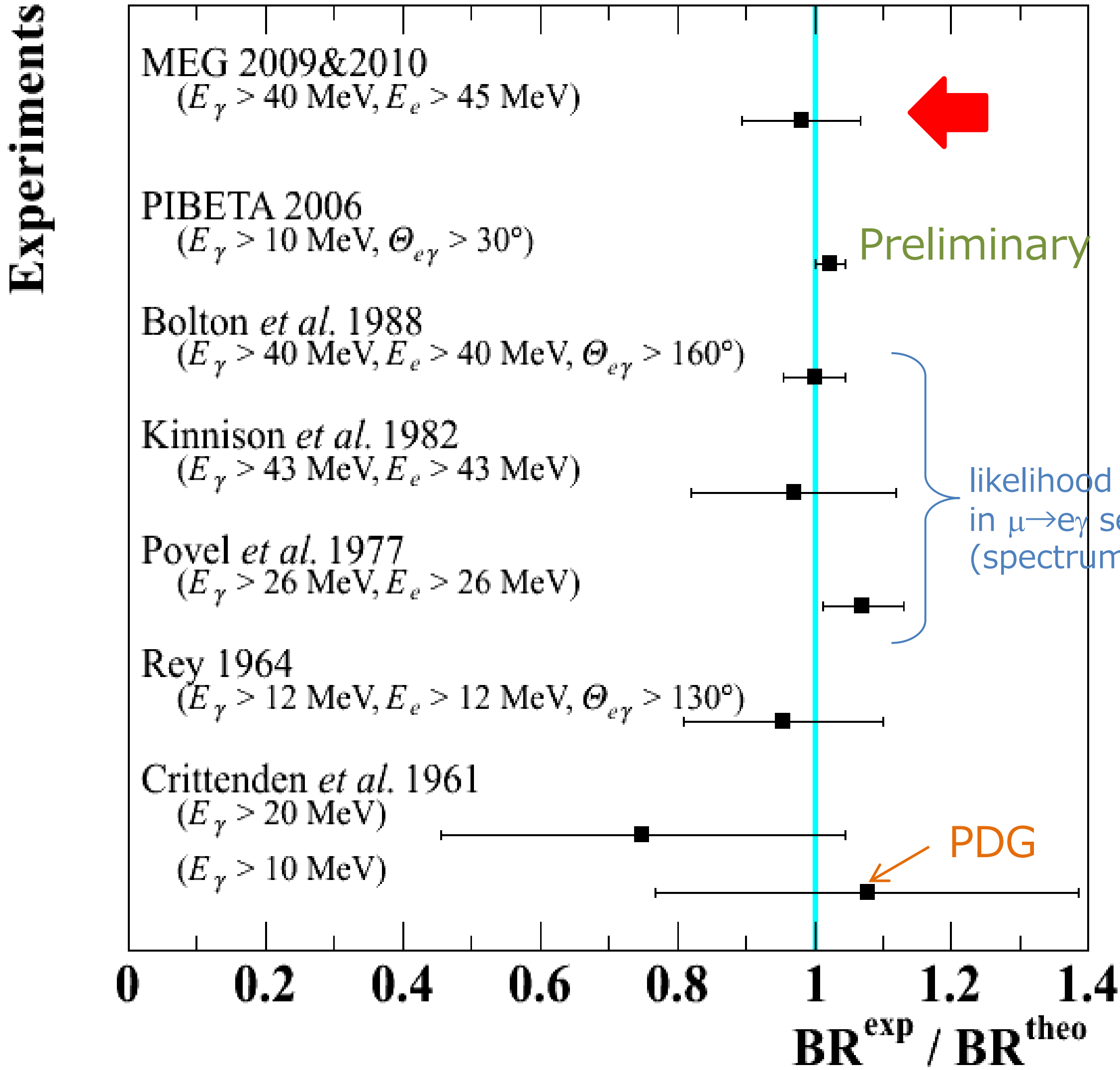
Source	(%)
Photon energy scale	3.4
Photon response & efficiency curve	2.1
Positron response & efficiency curve	6.1
Time response	0.5
Angle response	< 0.1
Angle matching efficiency	1.2
Angle dependence of efficiency	0.6
Muon polarization	< 0.1
Absolute photon efficiency	2.5
Absolute trigger efficiency	1.0
Michel normalization	2.8
Total systematic	8.5
Statistical	2.3
Total (added in quadrature)	8.8

$$\mathcal{B}(\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma) = (6.03 \pm 0.14 \pm 0.53) \times 10^{-8}$$

$$\text{for} \quad (E_e > 45, E_\gamma > 40 \text{ MeV}),$$

Comparisons

MEG
Mu-E-Gamma Collaboration



- Ratio to theory (SM)

$$\mathcal{B}^{SM}(\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma) = 6.15 \times 10^{-8}$$

$$BR^{exp}/BR^{theo} = 0.98 \pm 0.09$$

No definition of 'total' BR
(infrared divergent)
BR in limited phase space

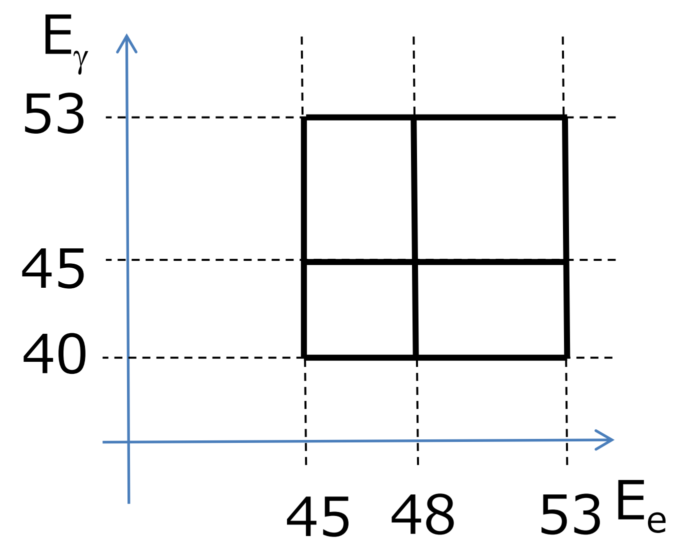
$\Gamma(e^- \bar{\nu}_e \nu_\mu \gamma)/\Gamma_{total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.014 ±0.004		CRITTENDEN	61	CNTR	γ KE > 10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	862	BOGART	67	CNTR	γ KE > 14.5 MeV
0.0033±0.0013		CRITTENDEN	61	CNTR	γ KE > 20 MeV
	27	ASHKIN	59	CNTR	

Spectrum analysis

- Compare spectrum shape with theory
- Extract {polarization, normalization} from RMD

- Fit distribution in multi dimensions
  - binned fit
  - $(E_e, E_\gamma, \theta_{e\gamma})$ = 2x2x6, total 24 bins
    - bins in $\theta_{e\gamma}$ for polarization measurement



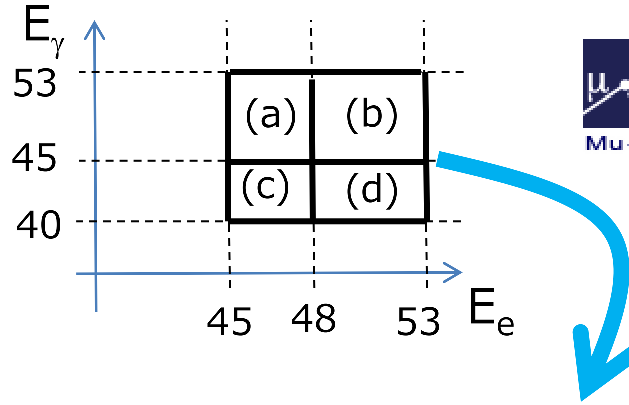
- To incorporate correlations of systematic uncertainties among bins, covariance (error) matrix should be used
- Chi-square definition

$$\chi^2(P_\mu, \alpha) = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(N_i^{obs} - N_i^{cal}\right)\left(V^{-1}\right)_{ij}\left(N_j^{obs} - N_j^{cal}\right)$$

$$N_i^{cal} = B_i\left(P_\mu\right) \cdot \epsilon_i \cdot \alpha N_\mu$$

(α : normalization scale parameter)

Fit result



- no constraint on pol nor norm

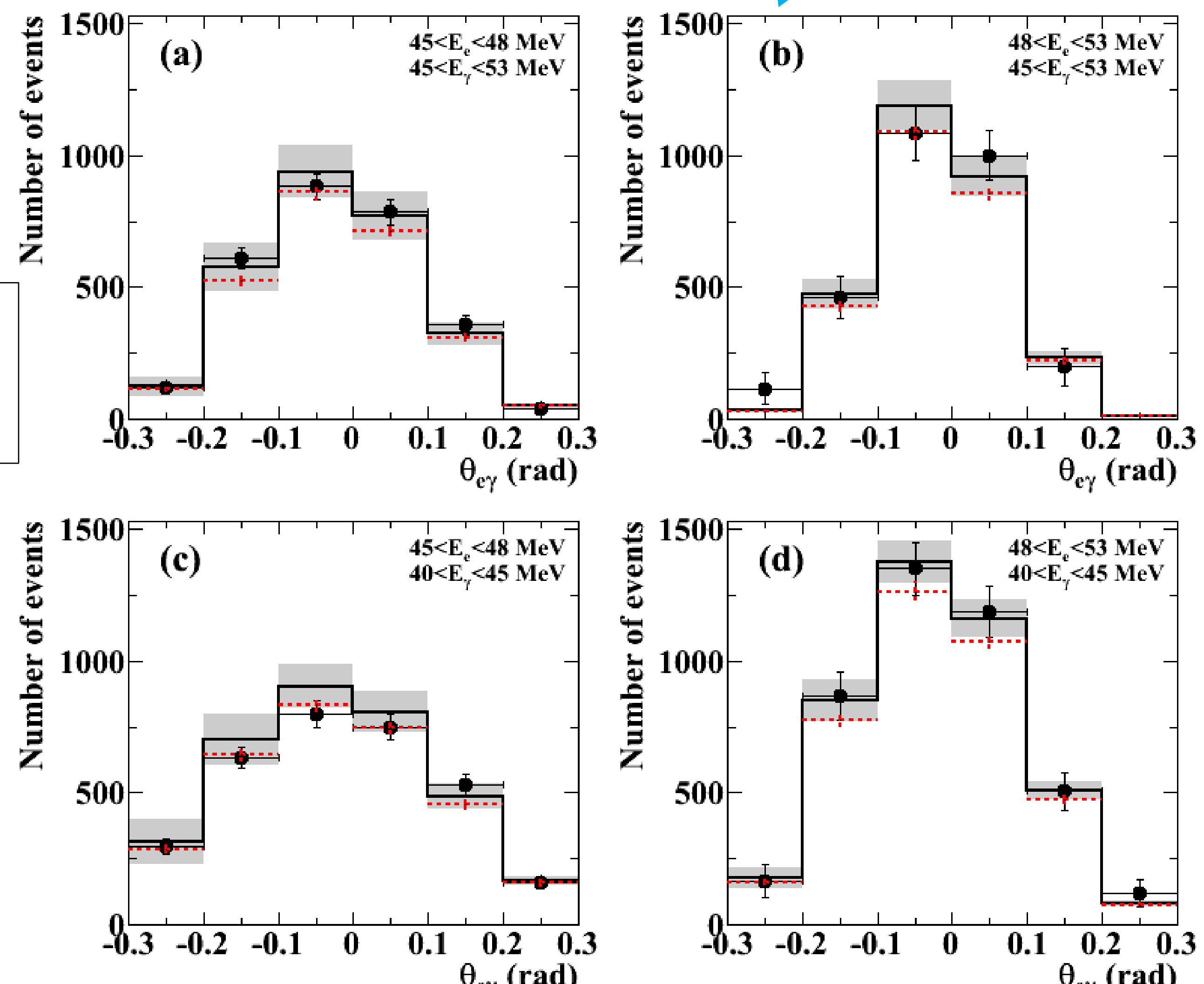
Chi2 / NDF = 11.9 / 22
= 0.541

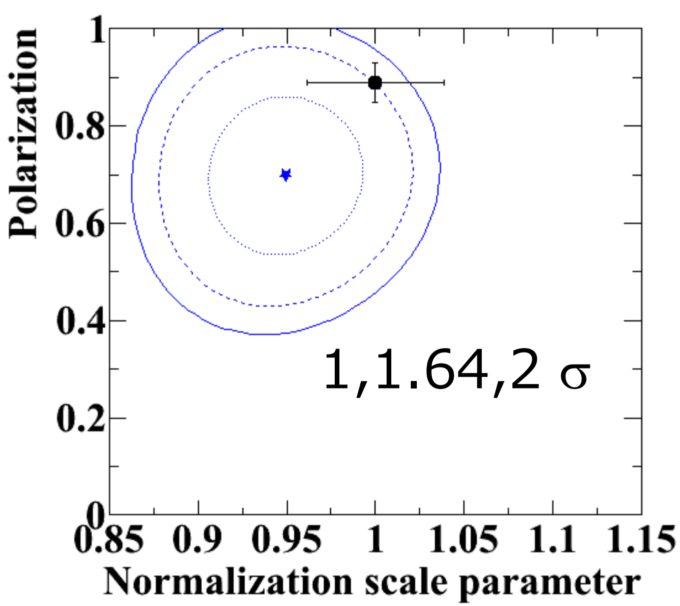
Pol 0.70 ± 0.16

Norm 0.95 ± 0.044

measured value with Michel
Pol 0.89 ± 0.04
Norm 1±0.04

□predicted
□best fit





Discussions

MEG
Mu-E-Gamma Collaboration

- Impact on $\mu \to e\gamma$ search
  - Powerful internal check of the experiment
    - (calibration, resolutions, efficiencies, normalization, etc.)
  - Estimated N_{RMD} in $\mu \to e\gamma$ search before unblinding, and used it in the likelihood as a constraint.
  - Provides a good normalization channel
    - Systematics are independent of Michel channel
- Branching ratio measurement
  - Measurement for largest phase space was given by old experiment (1961)
  - Most precise one has been given by recent result from PIBETA experiment (still preliminary?)
  - **MEG** gives one for the most stringent window (close to kinematical edge)
    - Relevant to the background in $\mu \to e\gamma$ search
    - The most sensitive to the deviation from SM
    - Require huge amount of muon decays and precise detectors to measure tiny BR.
- Furthermore, RMD from polarized muon decay
  - No measurement so far. MEG is a unique experiment.
  - Provides a possibility of measuring an unmeasured Michel parameter.

RMD rate and parameters

- In general, RMD rate can be written as (Fronsdal&Ueberall, Phys.Rev.**113**-2(1959)654),

$$BR(\mu^+ \to \bar{\nu}_\mu e^+ \nu_e \gamma) = \boldsymbol{F} + \left(1 - \tfrac{4}{3}\rho\right)\boldsymbol{I} + \bar{\eta}\boldsymbol{L}$$
$$+P_\mu \xi \left\{\beta \cos\theta_e \left[\boldsymbol{G} - \tfrac{1}{3}\left(1 - \tfrac{4}{3}\delta\right)\boldsymbol{J} + \kappa \boldsymbol{M}\right] + \cos\theta_\gamma \left[\boldsymbol{H} - \tfrac{1}{3}\left(1 - \tfrac{4}{3}\delta\right)\boldsymbol{K} + \kappa \boldsymbol{N}\right]\right\}$$

- ***F,G,H,I,J,K,L,M,N*** are function of (x, y, $\Theta_{e\gamma}$)
  - In V-A, only ***F,G,H*** terms remain.
  - If no polarization, only ***F,I,L*** terms remain.
- ρ, δ, ξ are Michel parameters which can be determined by normal Michel decay measurements.
- $\bar{\eta}, \kappa$ are the new Michel parameters which can only be determined by RMD
  - $\bar{\eta}$: spectrum shape
    - $\bar{\eta} = \left(|g^V_{RL}|^2 + |g^V_{LR}|^2\right) + \frac{1}{8}\left(|g^S_{LR} + 2g^T_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2\right) + 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right) \geq 0.$
  - κ : asymmetry in polarized muon decay
  - If assume $\rho = \delta = {}^3/_4, \xi = 1$,
    - $\bar{\eta} = \kappa = {}^1/_4(1 - \xi'),\ 0 \leq \bar{\eta} = \kappa \leq {}^1/_2$
    - equivalent to the longitudinal polarization of positron in muon decay

	V-A
ρ	¾
δ	¾
ξ	1
ξ'	1
$\bar{\eta}$	0
κ	0

Current status

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$\overline{\eta}$ PARAMETER

$(V-A)$ theory predicts $\overline{\eta} = 0$. $\overline{\eta}$ affects spectrum of radiative muon decay.

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.02 ±0.08 OUR AVERAGE					
−0.014±0.090	EICHENBER...	84	ELEC	+	ρ free
+0.09 ±0.14	BOGART	67	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.035±0.098	EICHENBER...	84	ELEC	+	ρ=0.75 assumed

previous μ→eγ experiment @ SIN (PSI)

- recent measurement by PIBETA
  - preliminary result in a dissertation & some conf. proceedings.
    - $\bar{\eta} = -0.084 \pm 0.050 \pm 0.034 \quad (\rho = 0.75)$
    - $\bar{\eta} < 0.033\ (68\%\ C.L.)$
  - They are going to finalize result & publish it by the summer 2012

- No measurement of κ parameter

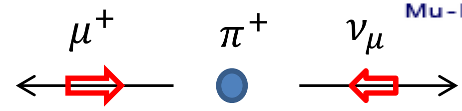
Conclusion

MEG Mu-E-Gamma Collaboration

- Analyzed RMD from polarized muon decay in MEG data
- Measure BR for MEG acceptance range
  - BR(E_e>45,E_γ>40MeV) = $(6.03\pm0.14\pm0.53)\times10^{-8}$
  - BR^{exp}/BR^{theo} = 0.98 ± 0.09
  - Good agreement with SM
- Spectrum analysis (fit)
  - Good agreement with SM ($\chi2$/NDF = 11.9/22)
  - Extract polarization and normalization
    - RMD only : Polarization : 0.70 ± 0.16
      Normalziation factor: 0.95 ± 0.043 (relative to one from Michel)
    - Consistent result with prediction
      - less powerfull for polarization measurement
      - Normalization uncertainty goes down to 4%

- Possibility of measuring Michel parameters. Next step.

Polarization

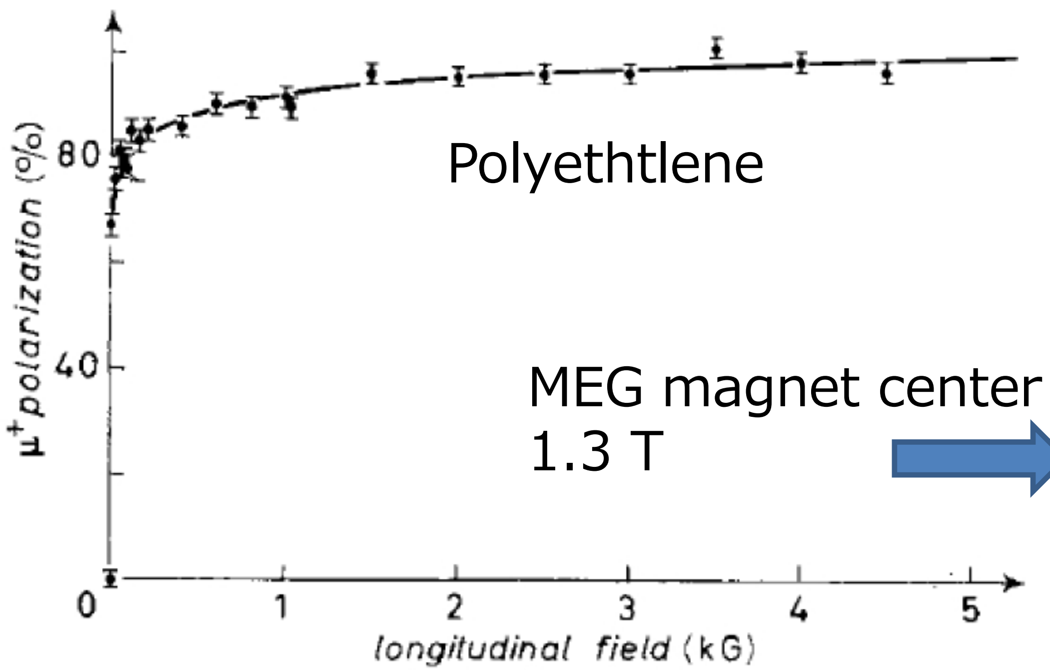


- surface muons are fully polarized
- depolarization effects
  - beam angular acceptance : 2.5%
  - multiple scattering in production target : <0.5%
  - contribution from ‘cloud muon’: 4.5%
  - E-field in beamline (separator): 0.7%
  - In plastic target (moderation, muonium formation): 3%

TABLE I. – *Values of muon residual polarization at zero field for various ta*

Aluminium	(100.2 ± 2) %
Carbon	(100.0 ± 2) %
Calcium	(99.0 ± 2) %
Freon 11	(79.5 ± 3) %
Freon 13	(78.5 ± 3.5) %
Polyethylene	(67.1 ± 2) %
Teflon	(62.0 ± 2) %
Emulsion	(35.8 ± 2) %
Scintillator	(20.4 ± 2) %
Sulphur	(10.0 ± 3) %

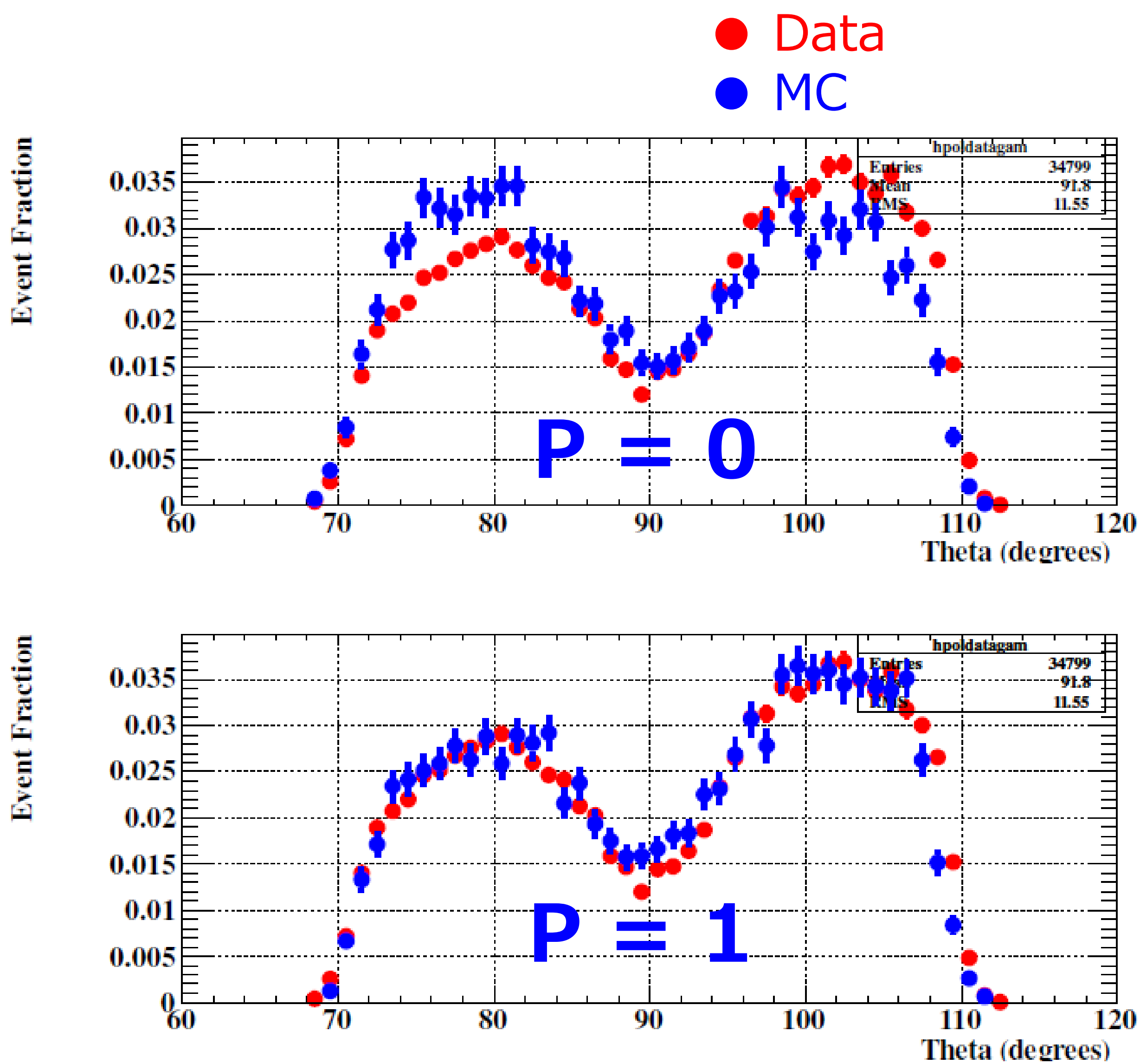
A.Buhler et al. Nouvo Cimento **39**, 824 (1965)



A.Buhler et al. Nouvo Cimento **39**, 812 (1965)

Polarization measurement

- Measure polarization from angular distribution of Michel positrons
- Two-dimensional fit to E_e vs θ_e distribution gives P = 0.90±0.04



Radiative correction to RMD

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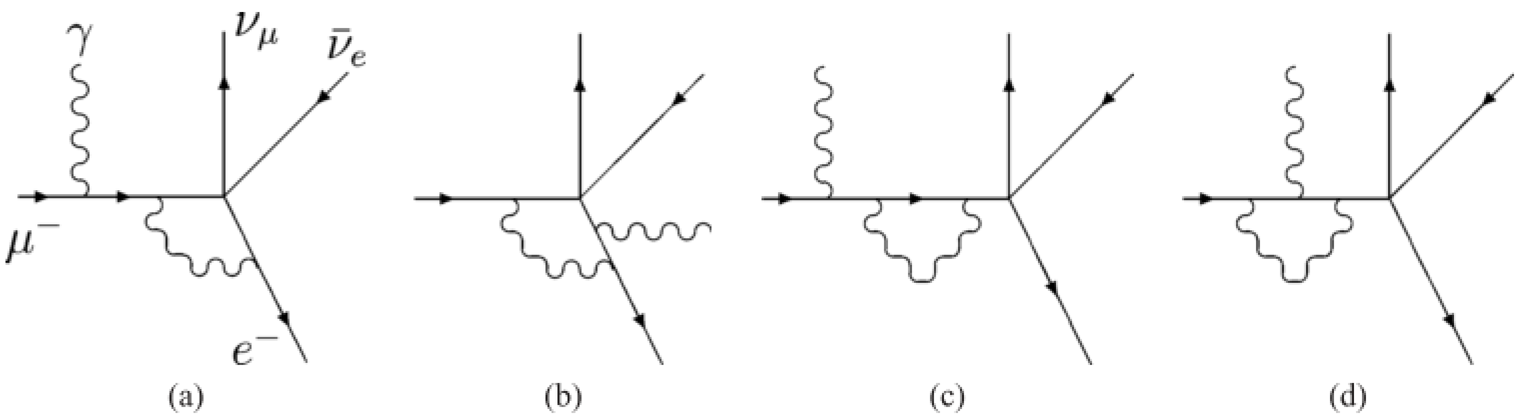


\+ real (soft or hard) photon emission

Fig. 1. Types of Feynman diagrams for radiative muon decay with one-loop RC.

- papers
  - "Radiative corrections to background of m→eg decay", A.B.Arbuzov et al., Phys. Lett. B 432, 421-426 (1998)
  - "One-loop corrections to radiative muon decay", A.B.Arbuzov et al., Phys. Lett. B 597, 285-290 (2004)
- Now under evaluation for MEG case

Table 1
Numerical estimates for the corrections δ_1 and $\delta_{SV\gamma}$ versus $\sigma_1, \sigma_2, \theta, \xi$

$10^2\sigma_1$	$10^2\sigma_2$	$10^2\theta$	$10^2\delta_1$			$10^2\delta_{SV\gamma}$		
			$\xi=0$	$\xi=0.5$	$\xi=-0.5$	$\xi=0$	$\xi=0.5$	$\xi=-0.5$
1.0	1.0	1.0	−1.2	−1.0	−1.3	−10.5	−10.7	−10.3
3.0	3.0	3.0	−3.7	−3.0	−4.0	−8.3	−8.5	−8.1
5.0	5.0	5.0	−6.1	−5.0	−6.7	−7.2	−7.5	−7.1
6.0	6.0	3.0	−10.0	−8.6	−10.8	−6.6	−6.9	−6.5
3.0	3.0	5.9	4.4	3.8	4.9	−13.1	−13.2	−13.0
4.0	4.0	3.0	−6.0	−5.0	−6.5	−7.5	−7.8	−7.4

Chisquare

- Define chisquare

$$\chi^2(P_\mu,\alpha) = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(N_i^{obs} - N_i^{cal}\right)(V^{-1})_{ij}\left(N_j^{obs} - N_j^{cal}\right)$$

$$N_i^{cal} = B_i\left(P_\mu\right)\cdot\epsilon_i\cdot\alpha N_\mu$$

(α : normalization scale parameter)

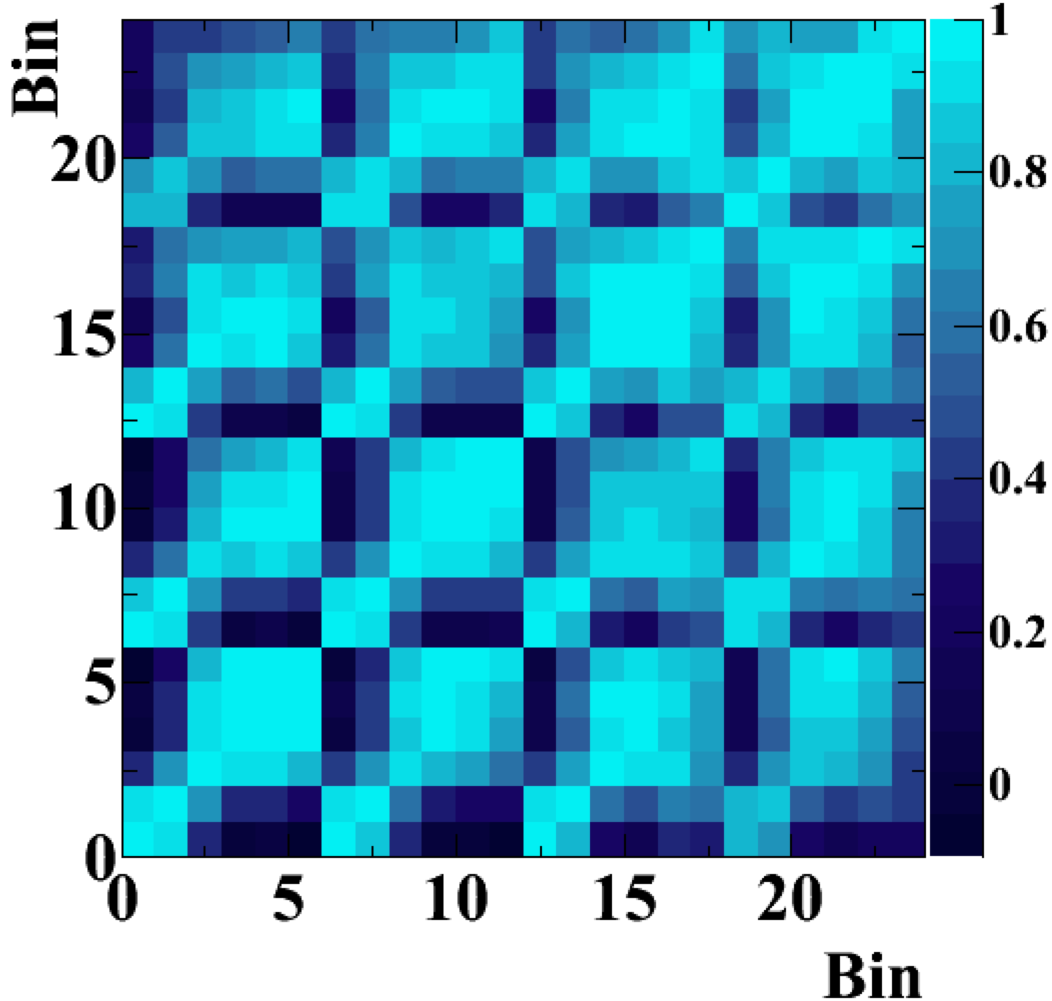
$V = V_{stat} + \sum V_{sys}$: covariance matrix

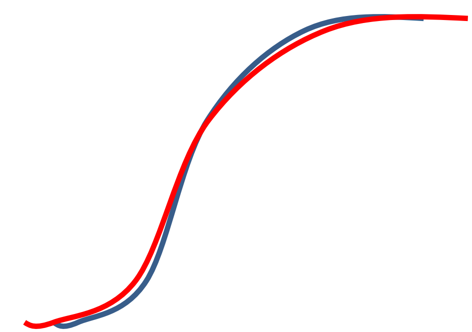
- See the deviation of N_i^{cal} when each systematic parameter is varied by 1 standard deviation.

$$V_{stat} = \begin{pmatrix} \sigma_1^2 & 0 & \cdots \\ & \sigma_2^2 & \\ & & \end{pmatrix} \qquad V_{sys} = \begin{pmatrix} \delta_1\delta_1 & \delta_1\delta_2 & \cdots \\ & \delta_2\delta_2 & \\ & & \end{pmatrix}$$

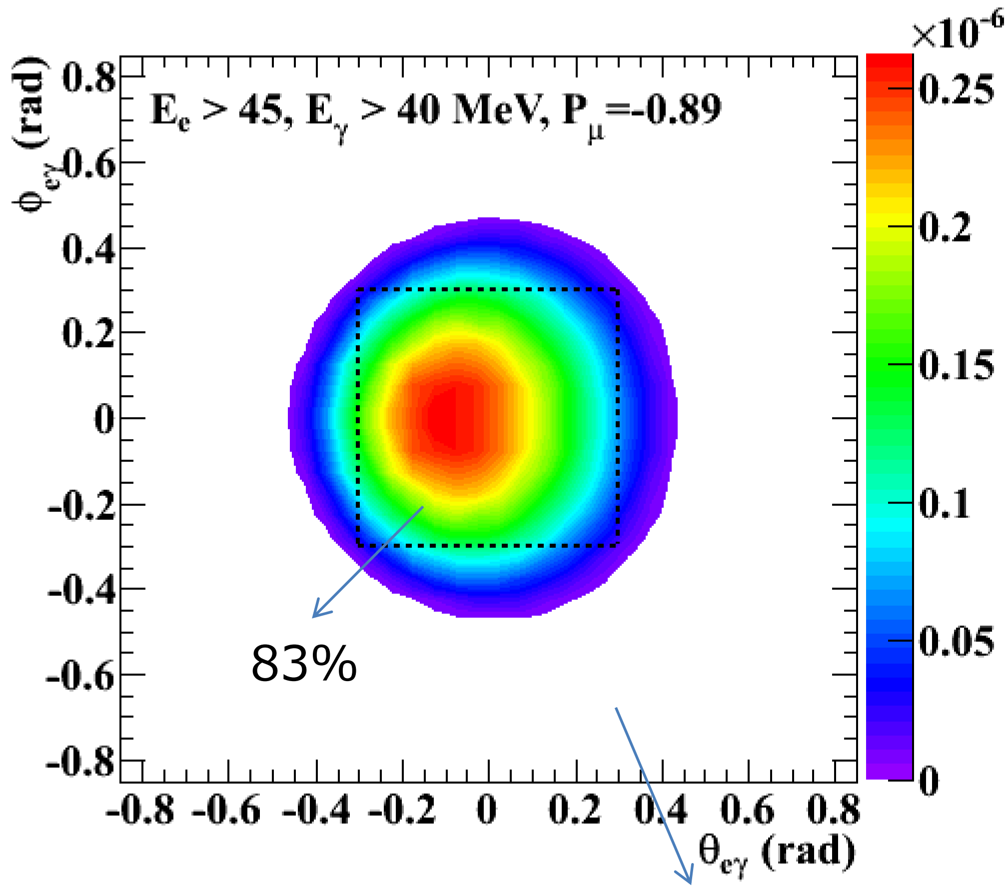
Error matrix

- correlation matrix





- For the energy range, $\pi - \Theta_{e\gamma} < 0.048$ rad is allowed.



Not allowed by momentum conservation

Fit result 2

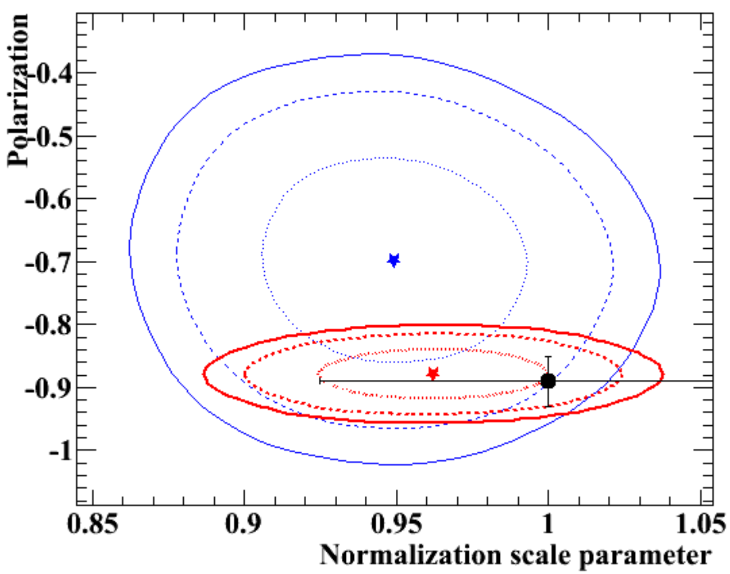
- Constrain pol & norm

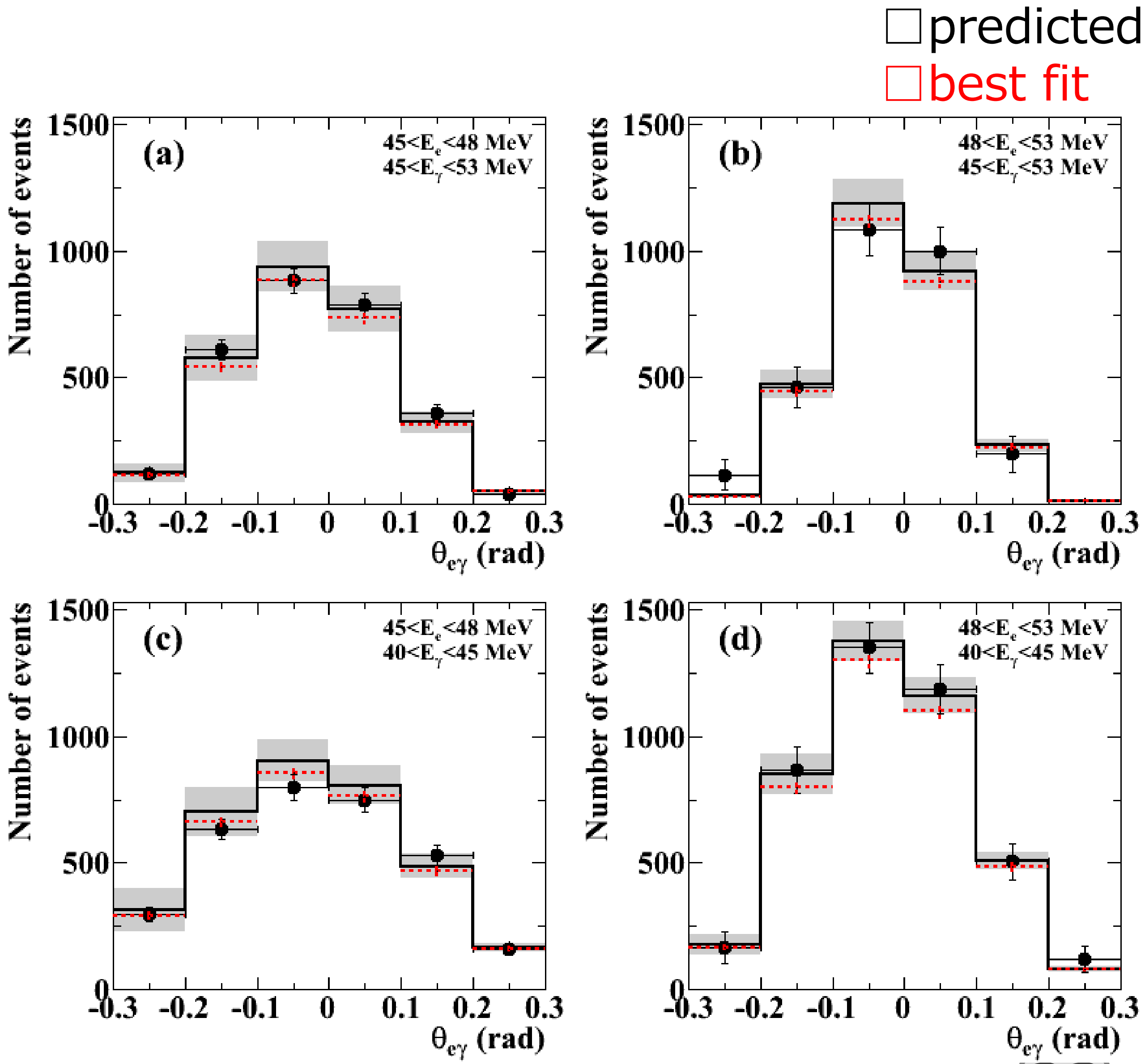
Pol -0.88+- 0.04

Norm 0.96 +- 0.038

Chi2 / NDF = 13.6 / 22

= 0.617





From previous studies

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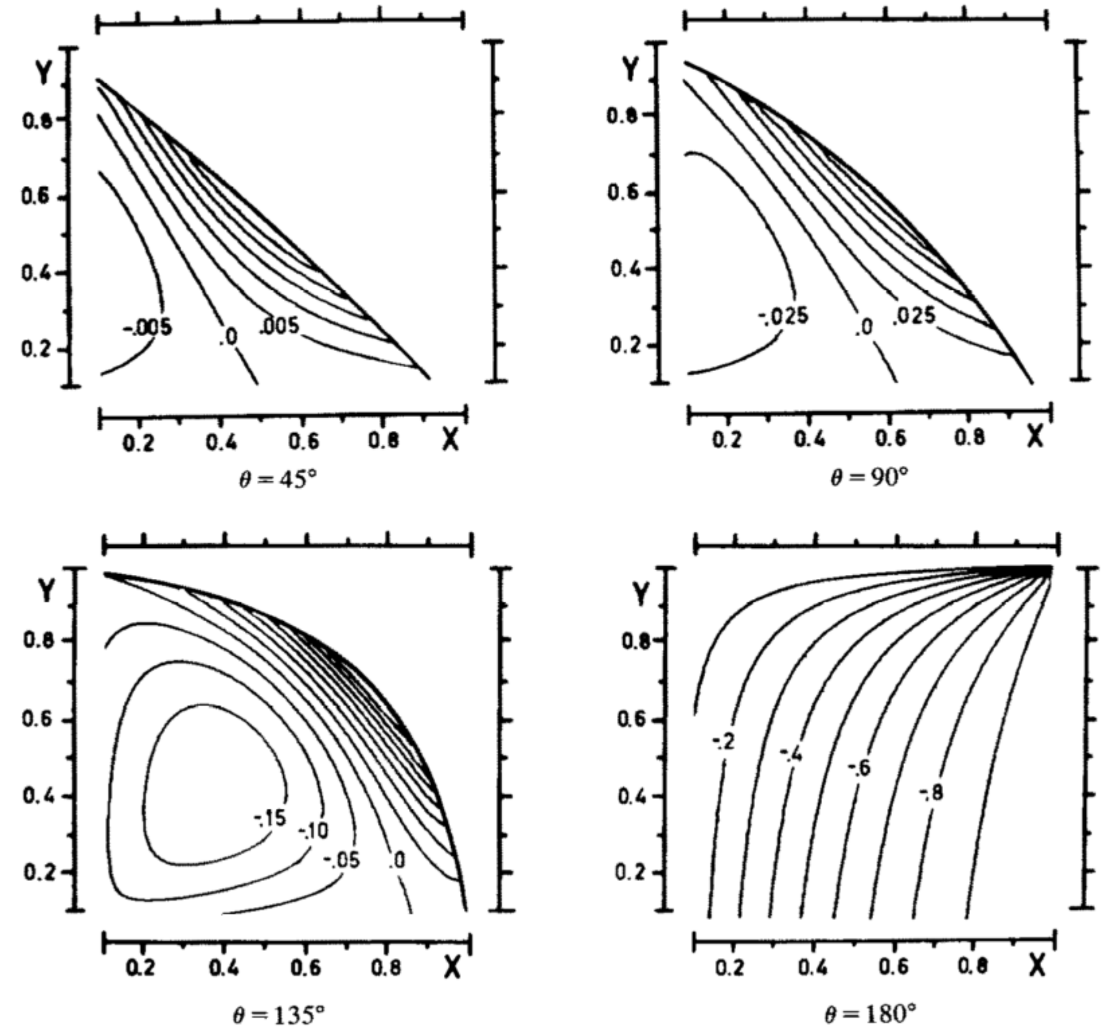
> $BR(\mu^+ \to \bar{\nu}_\mu e^+ \nu_e \gamma) = \boldsymbol{F} + \left(1 - \frac{4}{3}\rho\right)\boldsymbol{I} + \bar{\eta}\boldsymbol{L}$
>
> ~~$+P_\mu \xi \{\beta \cos\theta_e [\boldsymbol{G} - \frac{1}{3}(1 - \frac{4}{3}\delta)\boldsymbol{J} + \kappa \boldsymbol{M}] + \cos\theta_\gamma [\boldsymbol{H} - \frac{1}{3}(1 - \frac{4}{3}\delta)\boldsymbol{K} + \kappa \boldsymbol{N}]\}$~~

- ***(L/F)*(x,y)** plot show the 'sensitivity' of $\bar{\eta}$ measurement.
  - the closer to back-to-back and the higher x, the larger contribution of L term relative to SM (F term).
  - Of course, the statistics also decrease as closing to kinematic edge.
  - MEG data is suitable
    - High statistics data for back-to-back & large x.

W.Eichenberger et al. Nucl. Phys **A412** (1984) 523



Michel parameters in PDG

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ρ PARAMETER

$(V-A)$ theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7503 ±0.0004 OUR AVERAGE						
$0.75014 \pm 0.00017 \pm 0.00045$		[30] MACDONALD	08	TWST	+	Surface μ^+
$0.75080 \pm 0.00032 \pm 0.00100$	6G	[31] MUSSER	05	TWST	+	Surface μ^+
0.7518 ± 0.0026		DERENZO	69	RVUE		

δ PARAMETER

$(V-A)$ theory predicts $\delta = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7504 ±0.0006 OUR AVERAGE						
$0.75067 \pm 0.00030 \pm 0.00067$		MACDONALD	08	TWST	+	Surface μ^+
$0.74964 \pm 0.00066 \pm 0.00112$	6G	GAPONENKO	05	TWST	+	surface μ^+
$0.7486 \pm 0.0026 \pm 0.0028$		[38] BALKE	88	SPEC	+	Surface μ^+'s

$|(\xi \text{ PARAMETER})\times(\mu \text{ LONGITUDINAL POLARIZATION})|$

$(V-A)$ theory predicts $\xi = 1$, longitudinal polarization $= 1$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0007±0.0035 OUR AVERAGE						
$1.0003 \pm 0.0006 \pm 0.0038$		JAMIESON	06	TWST	+	surface μ^+ beam
$1.0027 \pm 0.0079 \pm 0.0030$		BELTRAMI	87	CNTR		SIN, π decay in flight

$\xi' =$ LONGITUDINAL POLARIZATION OF e^+

$(V-A)$ theory predicts the longitudinal polarization $= \pm 1$ for $e^\pm$, respectively. We have flipped the sign for e^- so our programs can average.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00 ±0.04 OUR AVERAGE						
0.998 ± 0.045	1M	BURKARD	85	CNTR	+	Bhabha + annihil
0.89 ± 0.28	29k	SCHWARTZ	67	OSPK	−	Moller scattering
0.94 ± 0.38		BLOOM	64	CNTR	+	Brems. transmiss.
1.04 ± 0.18		DUCLOS	64	CNTR	+	Bhabha scattering
1.05 ± 0.30		BUHLER	63	CNTR	+	Annihilation

Normal Michel parameters are measured very precisely by dedicated experiments.

No chance to improve with MEG data