Search for the decay $\mu \rightarrow e\gamma$ in the MEG experiment

Yasuhiro NISHIMURA

(The University of Tokyo)

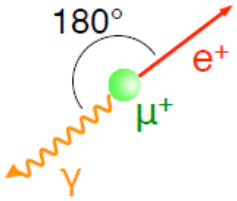
*on behalf of the **MEG collaboration***

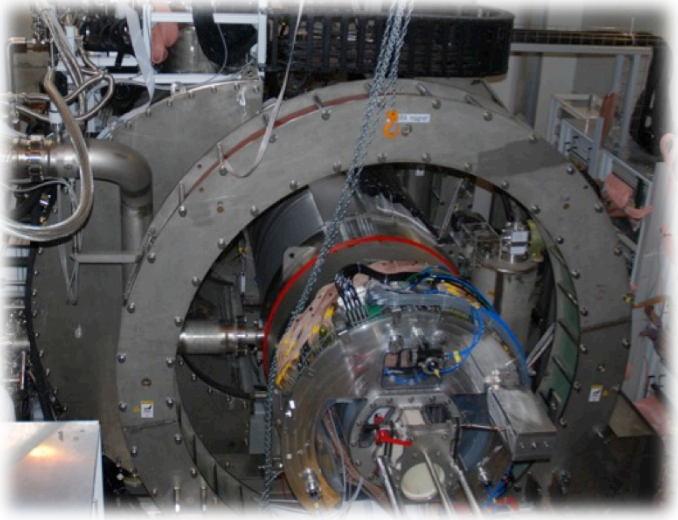
2nd International Conference on Particle Physics

23.June.2011

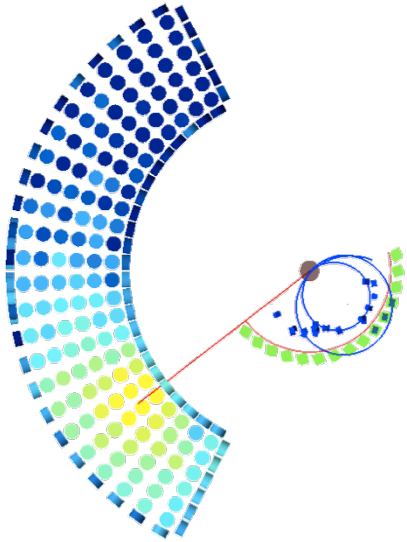
Contents

- $\mu \longrightarrow e\gamma$ and the MEG Experiment





- Detector in the MEG

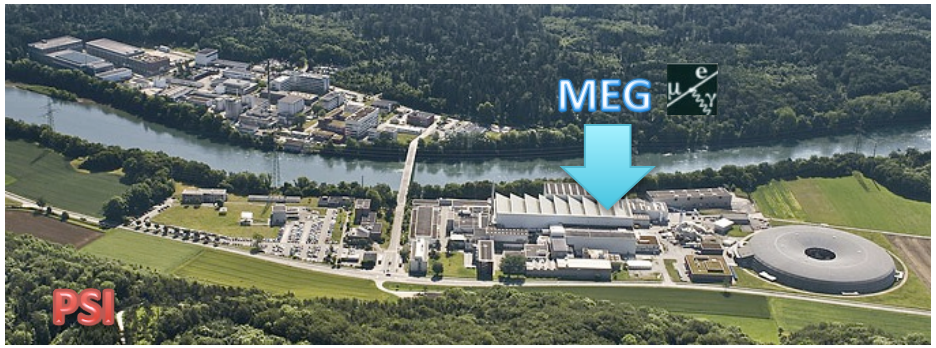


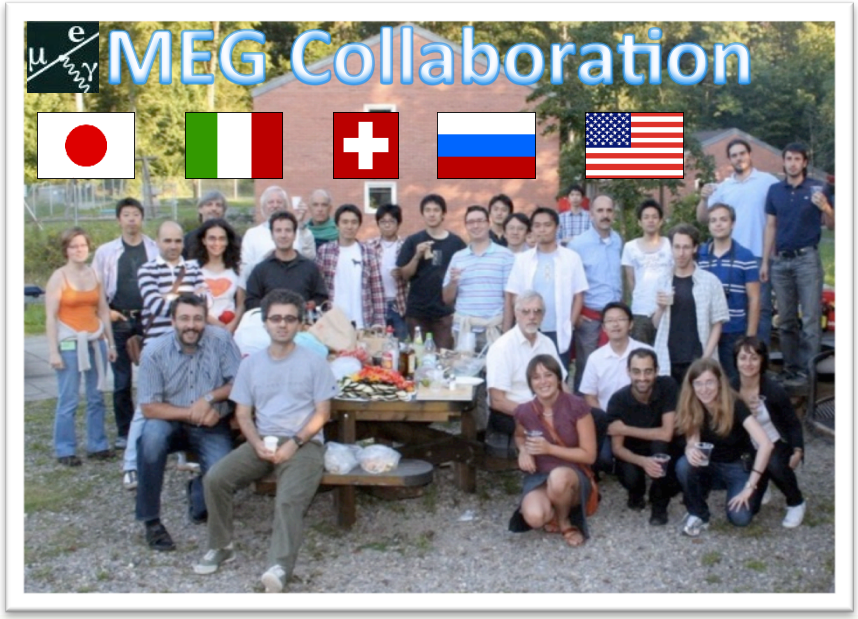
- Analysis

- Progress and Prospect

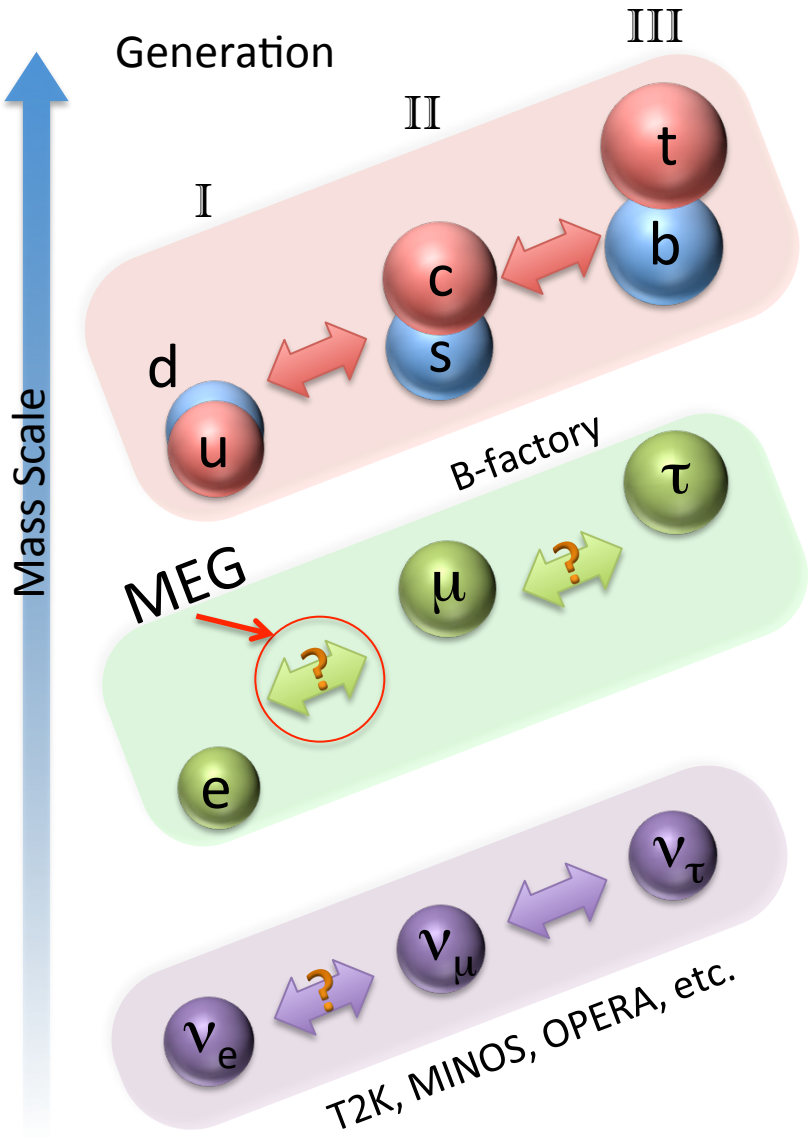
The MEG Experiment

- Search for the rare decay, $\mu^+ \longrightarrow e^+ \gamma$
  - Lepton flavor violation in charged lepton sector.
  - In 1999, the MEGA experiment set the upper limit (UL).
    - BR($\mu^+ \longrightarrow e^+ \gamma$) < 1.2×10^{-11} (90% C.L.)
  - Toward to $O(10^{-13})$
- About 60 researchers in 5 countries
- At Paul Sherrer Institut (PSI) in Switzerland





Flavor Mixing



Quarks

- Mixing via CKM matrix

Charged Leptons

- Not yet observed.
- Proof of new physics
  beyond the Standard Model

Neutrinos

- Mixing via MNS matrix
- Neutrino oscillation

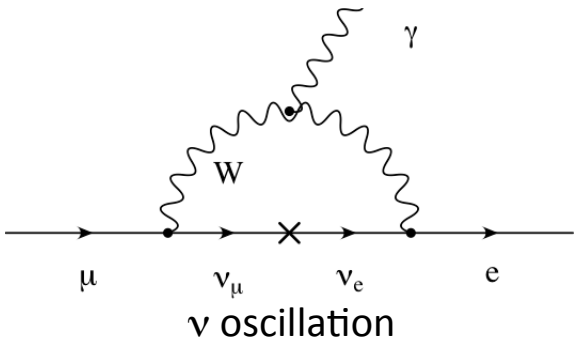
$\mu \rightarrow e\gamma$

- The SM + ν oscillation

$$BR = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^{*}_{\mu i} U_{ei} \frac{\Delta m^2_{\nu i1}}{M^2_W}\right|^2 \sim 10^{-55} - 10^{-45}$$

  - It is too small to be observed.

The Standard Model (SM)



ν oscillation

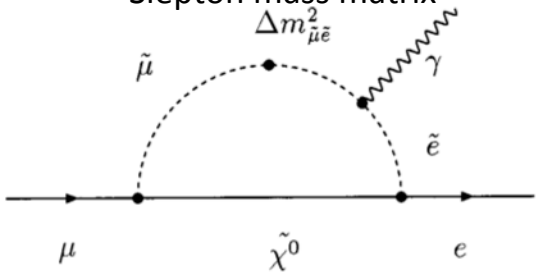
- SUSY GUT gives a large mixing in sleptons.

$$BR \sim 10^{-15} - 10^{-11} \longleftarrow \left|\frac{\Delta m^2_{\tilde{\mu}\tilde{e}}}{M^2_{SUSY}}\right|$$

  - Reaching the current limit.

SUSY – GUT

Slepton mass matrix



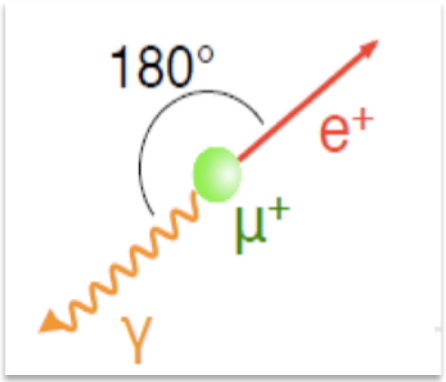
Many extensions of the SM predict $\mu \rightarrow e\gamma$ around the current upper limit $\sim 10^{-11}$.

– SUSY-GUT SO(10), $SU(5)_{RN}$, Higgs triplet, extra dimensions, etc.

⇨ $\mu \rightarrow e\gamma$ is a clear evidence beyond the SM.

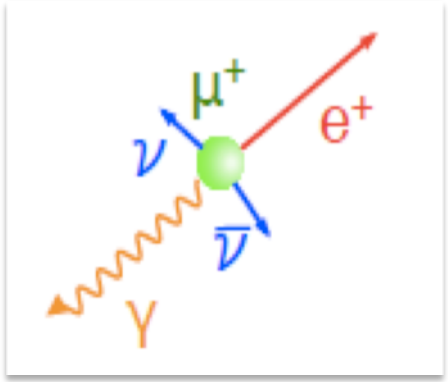
Signal and Background

Signal

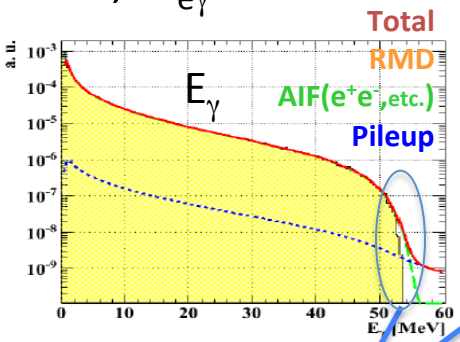


- $E_\gamma = E_e = 52.8$MeV, $t_{e\gamma} = 0$, $\Theta_{e\gamma} = 180°$
- BR < 1.2×10^{-11}
- MEG aims at $O(10^{-13})$

Prompt Background



- $t_{e\gamma} = 0$, $E_{\gamma,e} \sim 52.8$MeV $\pm\sigma$, $\Theta_{e\gamma} > 180° - \sigma$



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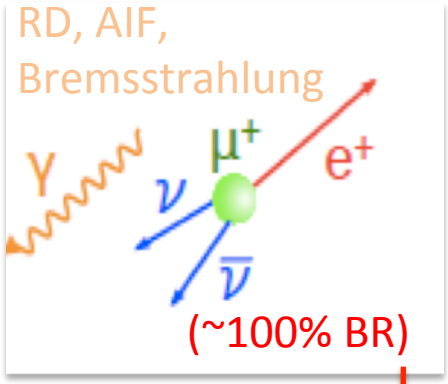
Accidental Background



- Dominant BG
- Beam rate and resolution limit

$B_{BG} \propto R_\mu \Delta t_{e\gamma} \Delta\theta_{e\gamma}^2 \Delta E_\gamma^2 \Delta E_e$

- Requirements
  - Intense muon source
  - High resolution
  - DC muon beam
  - High-rate e^+ tolerance

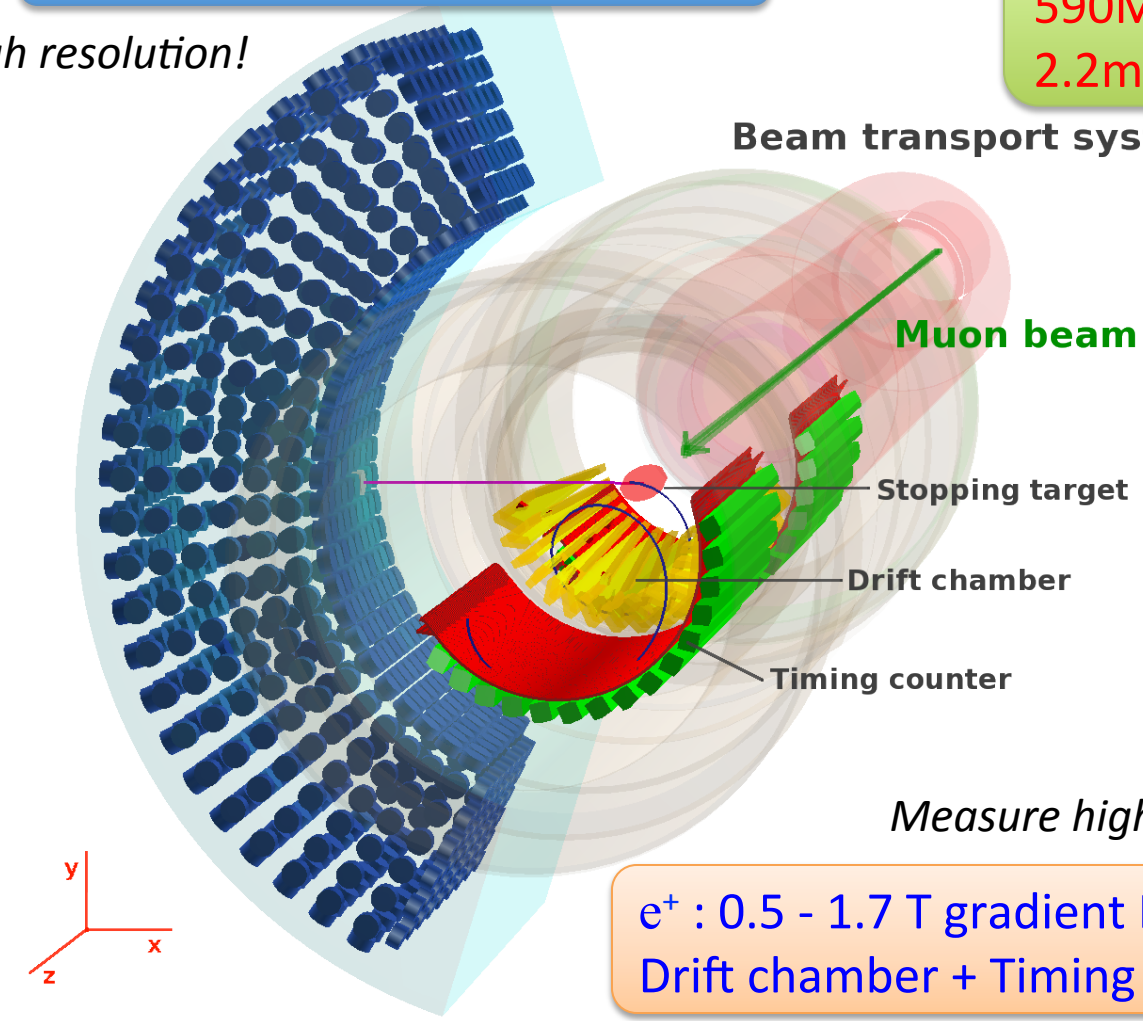
The MEG Detector

γ : 900L Liquid Xenon detector

High resolution!

μ^+ : DC Surface muon
590MeV Ring Cyclotron
2.2mA proton

Beam transport system *~3×10⁷ μ^+ / sec*

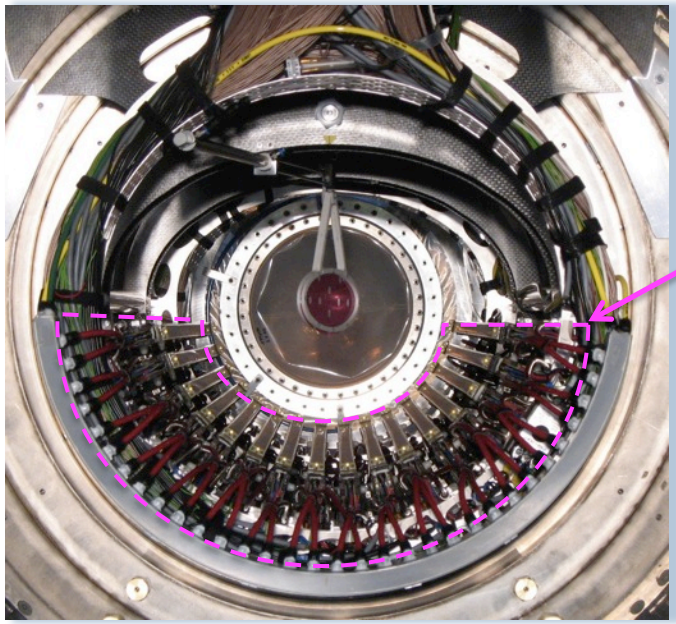


Measure high-rate e^+

e^+ : 0.5 - 1.7 T gradient B field +
Drift chamber + Timing counter

Positron Spectrometer

- COBRA spectrometer magnet
  - COnstant Bending RAdius
    to select momentum efficiently
  - e^+ is rapidly swept out to avoid pileups.



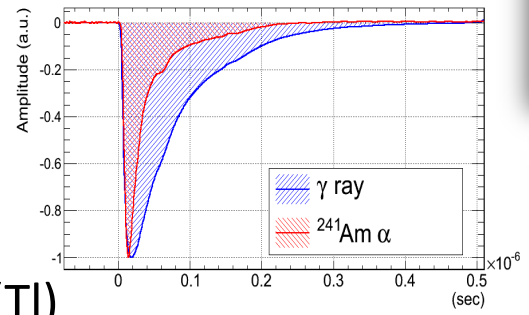
- Drift chamber
  - 16 modules radially aligned
    - Accept e^+ over 40 MeV/c
  - Determine R and Z position of e^+ tracking
    - $\sigma^*(E_e)$=0.74%, $\sigma^*(\phi)$, $\sigma(\theta)$=7.1, 11.2mrad
  - Low mass (2×10^{-3} X_0) to avoid AIF

* Core component

- Timing counter
  - Plastic counters measure e^+ timing
    at the end of track
  - A good timing resolution, 75ps in σ

Liquid Xenon Detector

- 900L liquid xenon to measure energy, time and position of γ-ray
  - Homogeneous, 11% Ω, $14X_0$ stopping power
  - Take all waveforms from 846 PMTs

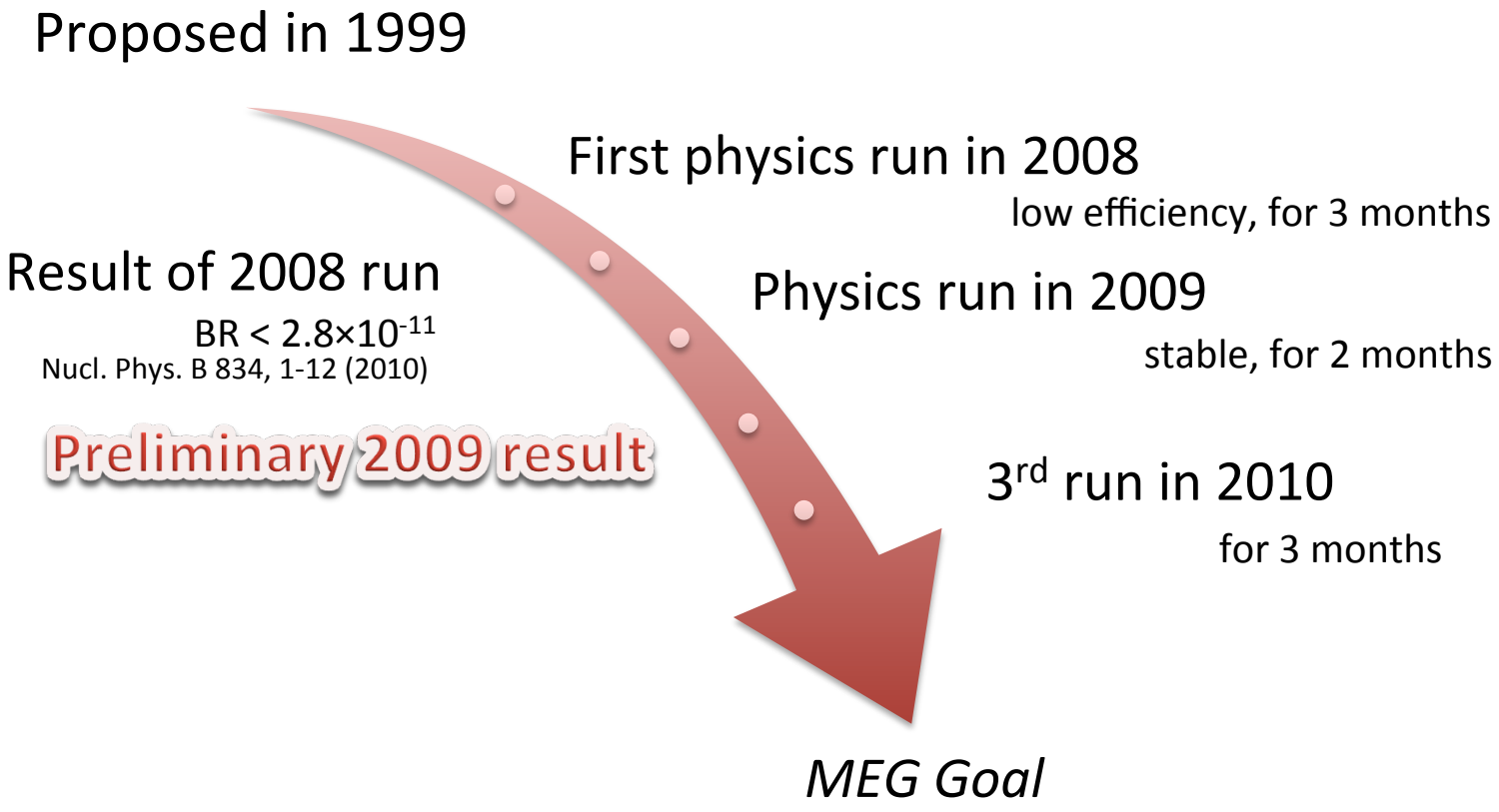


- Liquid xenon
  - Fast 45ns decay for γ ray
  - Particle separation
  - High light yield, 75% of NaI(Tl)
  - Strong stopping power, 2.8cm X_0

- Control
  - 165K stable cooling with pulse tube refrigerator
  - Gaseous / Liquid phase purification

- $\sigma_{upper}(E_\gamma)$ = 2.1% (depth>2cm),
  5mm in σ along transverse direction

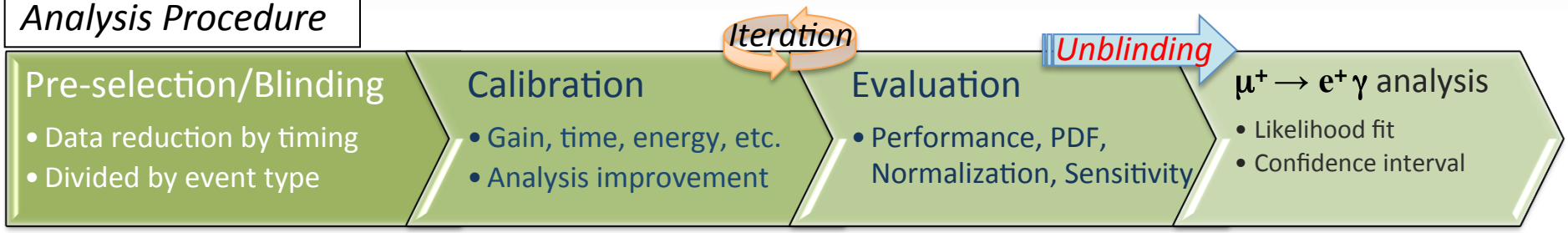
Analysis on 2009 Data



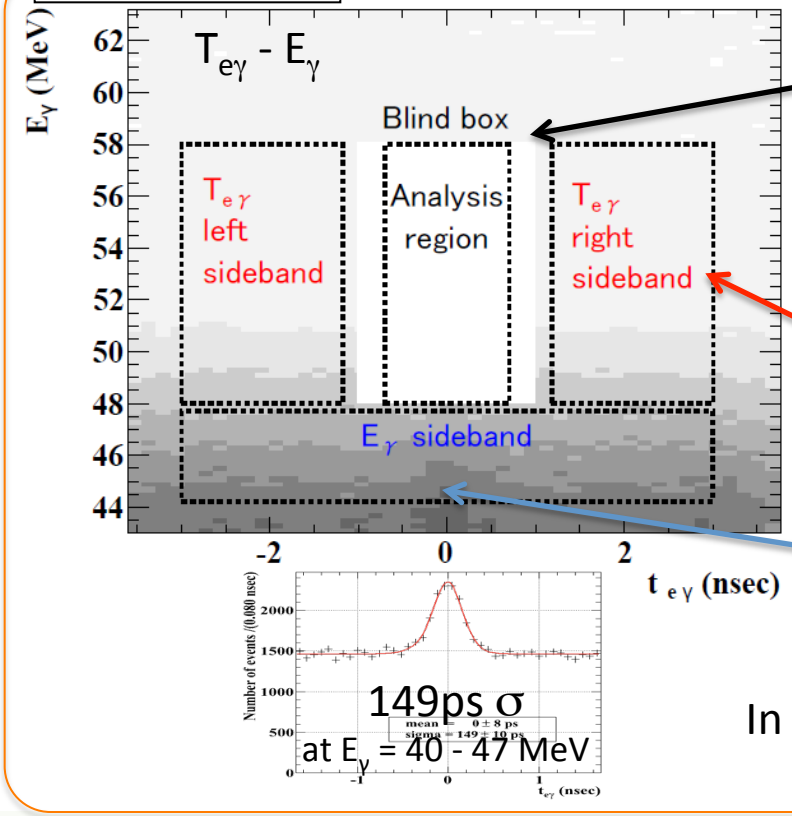
Preliminary result of 2009-year data is presented.

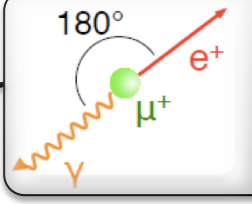
Analysis Strategy

Analysis Procedure



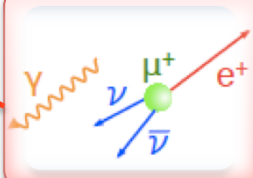
Physics Data





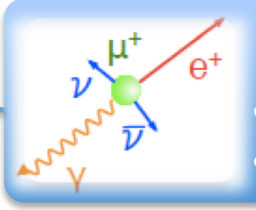
Blinded by E_γ , $t_{e\gamma}$ (±4.8MeV, ±1ns)

- Hidden until calibration and analysis are fixed.
- Analysis region for the maximum likelihood fit



$T_{e\gamma}$ sideband

- Accidental background estimation
- Sensitivity study



E_γ sideband

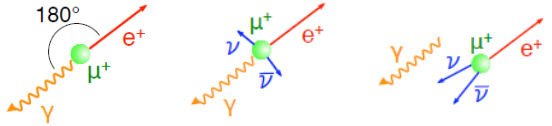
- Radiative muon decay estimation
- $T_{e\gamma}$ performance evaluation

In Eγ sideband data, clear μ → e νν γ peak was observed on the accidental background floor.

Likelihood Analysis

- Fit the number of signal and backgrounds (N_{sig}, N_{RD}, N_{Acc}).
  - $N=N_{sig}+N_{RD}+N_{Acc}$
  - N_{obs} : the number of events in the analysis region

$$L(N_{sig}, N_{RD}, N_{Acc}) = \frac{N^{N_{obs}} \exp(-N)}{N_{obs}!} \prod_{i}^{N_{obs}} \left(\frac{N_{sig}}{N} S_i + \frac{N_{RD}}{N} R_i + \frac{N_{Acc}}{N} B_i \right)$$

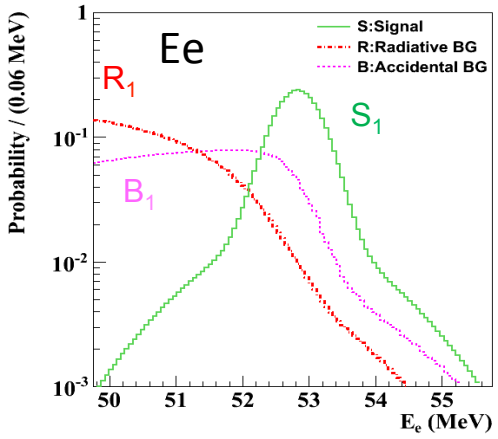


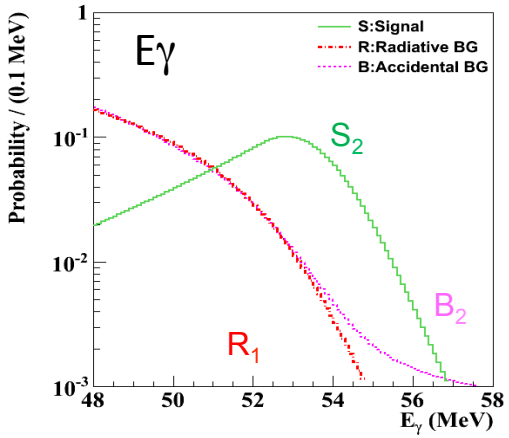
- S_i, R_i, B_i : Probability density function (PDF) of i-th event for **S**ignal ($\mu^+ \to e^+ \gamma$), **R**D ($\mu^+ \to e^+ \nu\nu \gamma$) and Accidental **B**ackground.
- Observables : (E_γ , E_e , $\theta_{e\gamma}$, $\phi_{e\gamma}$, $t_{e\gamma}$)

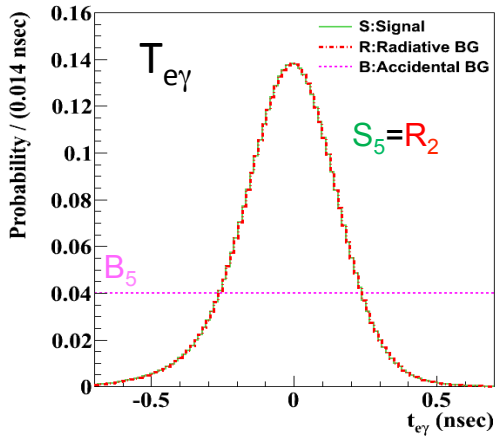
- Confidence region of N_{sig} is calculated by Feldman-Cousins method.
  - Toy MC uses PDFs for event generation.
- Independent other analysis tools confirmed a consistency.
  - Checked by Bayesian interface, constant PDF, BG constraint.

Probability Density Functions (PDFs)

- PDFs
  - Signal: $S = S_1(E_e)\, S_2(E_\gamma)\, S_3(\theta_{e\gamma})\, S_4(\phi_{e\gamma}|E_e)\, S_5(t_{e\gamma})$
  - Radiative decay BG: $R = R_1(E_e, E_\gamma, \theta_{e\gamma}, \phi_{e\gamma})\, R_2(t_{e\gamma})$
  - Accidental BG: $B = B_1(E_e)\, B_2(E_\gamma)\, B_3(\theta_{e\gamma})\, B_4(\phi_{e\gamma})\, B_5(t_{e\gamma})$
- Event-by-event construction by observables.
- Obtained from measured performance, actual background distributions.







S_1 : Multi-loop tracks
B_1 : $\mu^+ \to e^+\nu\bar{\nu}$

S_2 : Measured in $\pi^0 \to 2\gamma$
B_2 : $\mu^+ \to e^+\nu\bar{\nu}\gamma$ in $t_{e\gamma}$ sideband

S_5 : $\mu^+ \to e^+\nu\bar{\nu}\gamma$ in E_γ sideband
B_5 : Flat

- Relative angles : $S_{3,4}$ from e^+ / γ measured resolution, $B_{3,4}$ in $t_{e\gamma}$ sideband
- R_1 from signal PDF and RD correlations.

Normalization

- Relatively normalized to $\mu^+ \to e^+ \nu\bar{\nu}$ (~100%)
  - Counting e^+ during $\mu^+ \to e^+ \gamma$ data taking

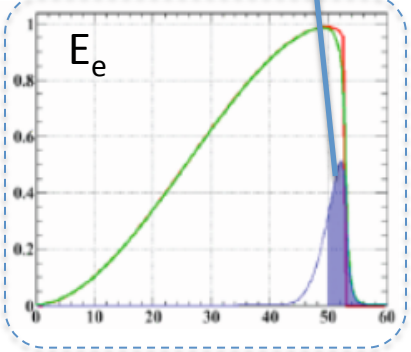
$$\frac{BR(\mu \to e\gamma)}{BR(\mu \to e\nu\bar{\nu})} = \frac{N_{sig}}{\left(N_{e\nu\bar{\nu}} \times P_{e\nu\bar{\nu}} / f^{e}_{e\nu\bar{\nu}}\right) / \left(\varepsilon^{Trig}_{e\nu\bar{\nu}} \times \varepsilon^{e}_{e\nu\bar{\nu}}\right)} \Big/ \left(\varepsilon^{Trig}_{e\gamma} \times \varepsilon^{e}_{e\gamma} \times A^{Geo}_{e\gamma} \times \varepsilon^{\gamma}_{e\gamma}\right)$$

~1

$\mu^+ \to e^+ \nu\bar{\nu}$

- Triggered 18k events.
- ~10^7 pre-scaling

Fraction & cut

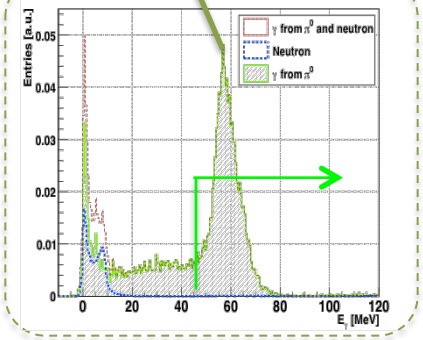


= O(1)

Positron efficiency is cancelled out.

E_γ from $\pi^0 \to \gamma\gamma$

γ detection efficiency



PRERIMINALY

$$BR(\mu \to e\gamma)/N_{sig} = (1.01 \pm 0.08) \times 10^{-12}$$

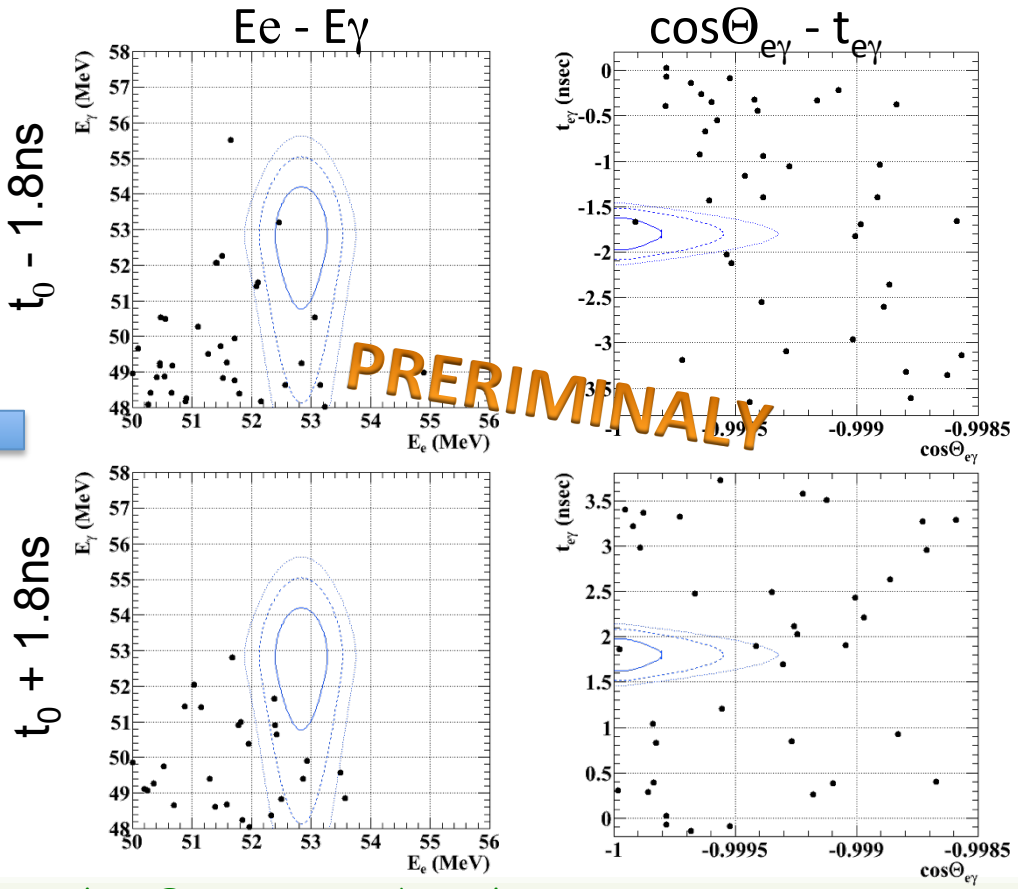
Sensitivity

- Sensitivity was estimated by toy-MC.
  - PDF base, Measured BG rate, Null-signal, 2009 statistics
  - $S_{2009} = 6.1 \times 10^{-12}$ in BR, average of ULs in many toy-experiments

- Obtained S_{2009} is lower than
  - $S_{2008} = 1.3 \times 10^{-11}$,
  - Limit by the MEGA, 1.2×10^{-11}.

- Check in $t_{e\gamma}$ sideband
  - Fit with $t_{e\gamma}$-sideband data.
  - Sensitivity in sideband
    $(4 - 6) \times 10^{-12}$
  - Confirmed consistency.

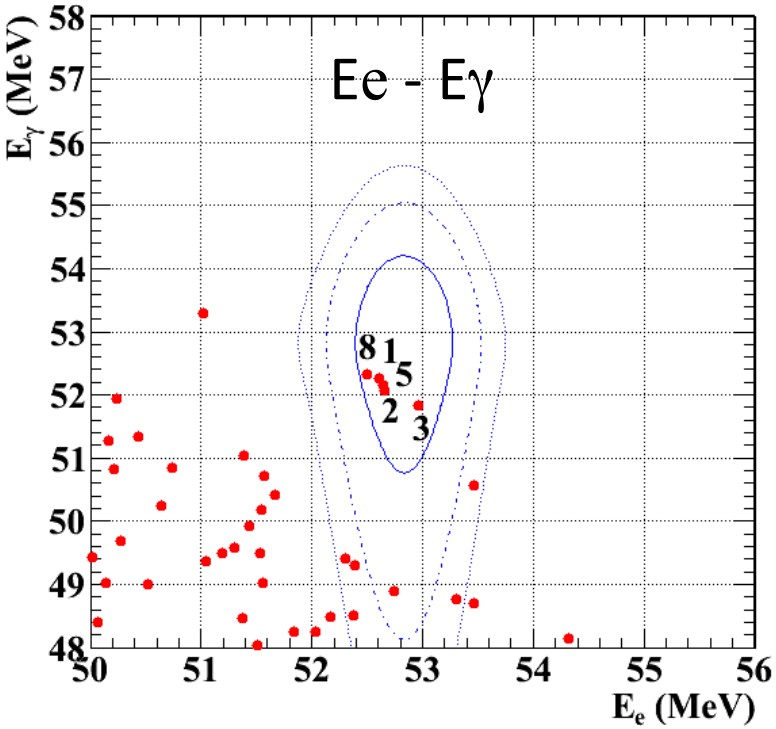
- Ready to open the blind box.

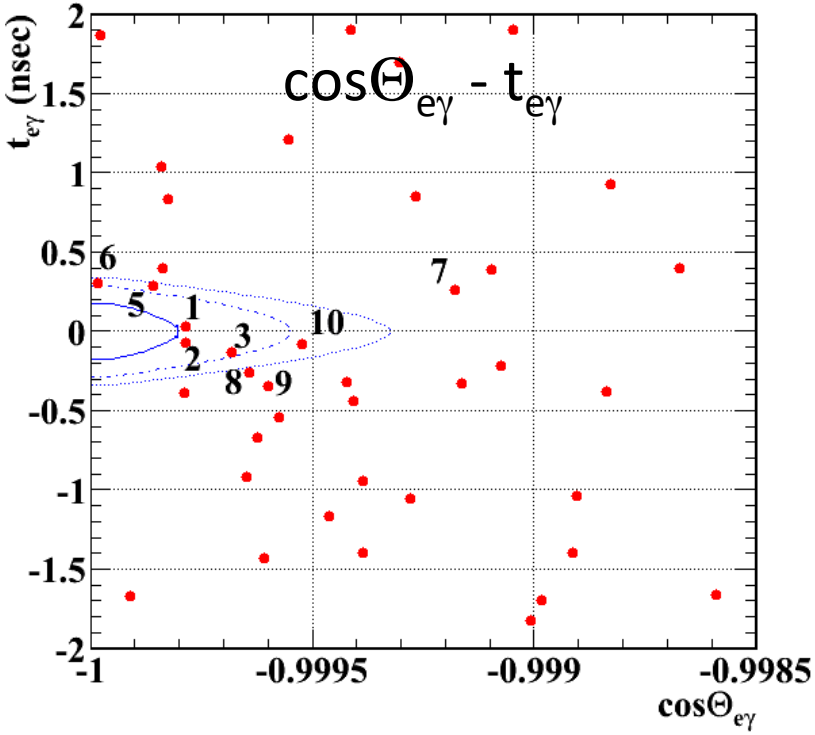


Event Distribution after Unblinding

- Open the blind region!

PRERIMINALY



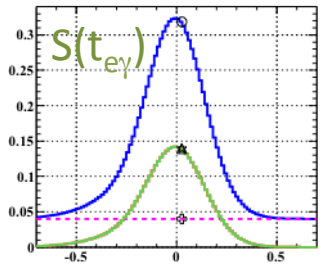


- The number shows the signal-like rank by S/(R+B).
- Contours by 1, 1.65, 2 σ in PDFs

Event Sample in the Blinded Region

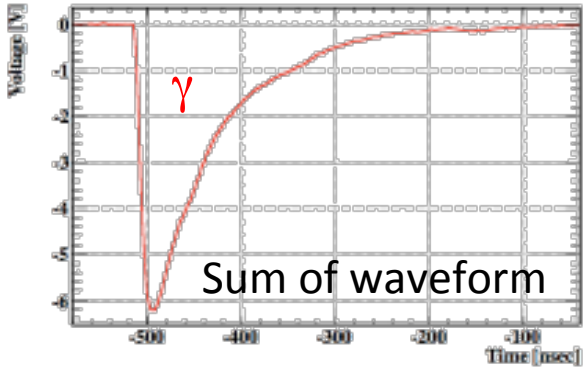
- Checked all blinded events. No mis-reconstruction was found.

The highly ranked event

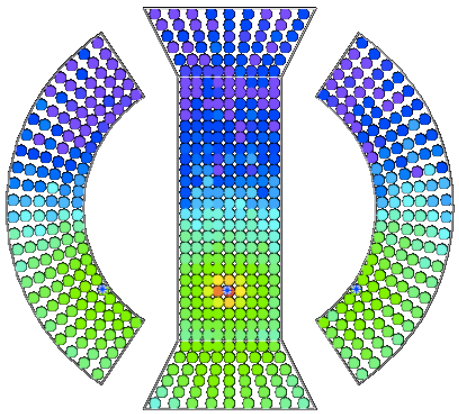


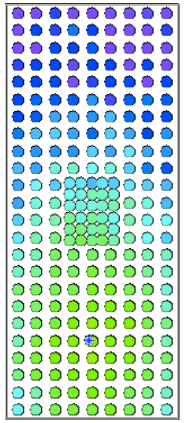
$t_{e\gamma}$ = 27 ps

No γ pileup
in the charge integration



No γ pileup
on the spatial light distribution

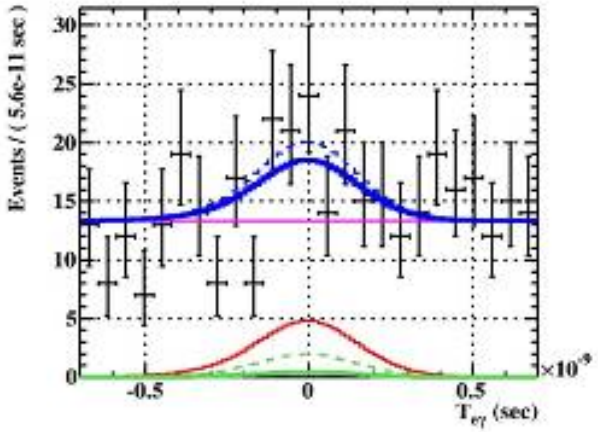




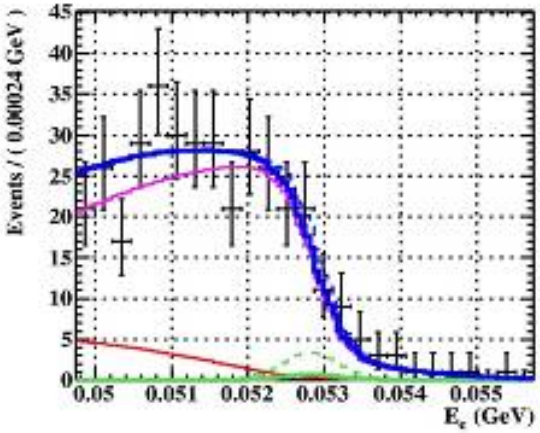
The Best Fit and Limit

PRERIMINALY

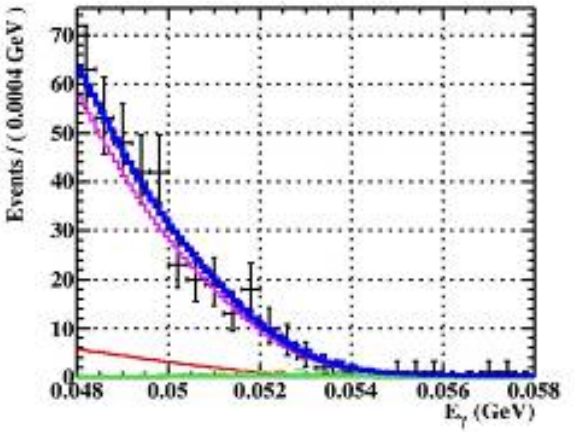
$T_{e\gamma}$ (ns)



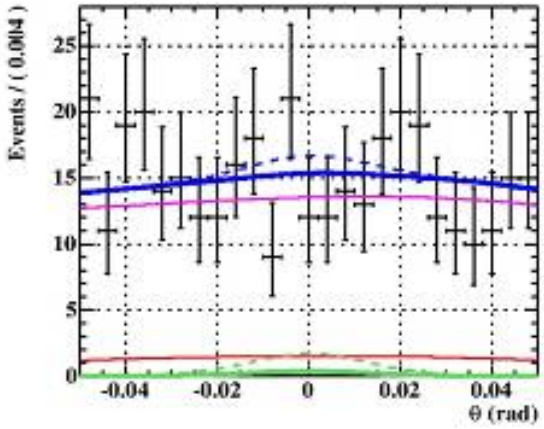
Ee (GeV)



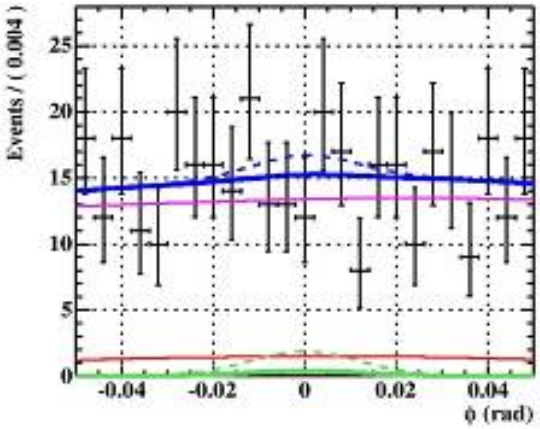
E_γ (GeV)



$\theta_{e\gamma}$ (rad)



$\Phi_{e\gamma}$ (rad)



Averaged PDF
Accidental BG, RD, Signal, Total

Dashed lines :
90% C.L. upper limit of N_{sig}

Best-fit $N_{sig} = 3.0$

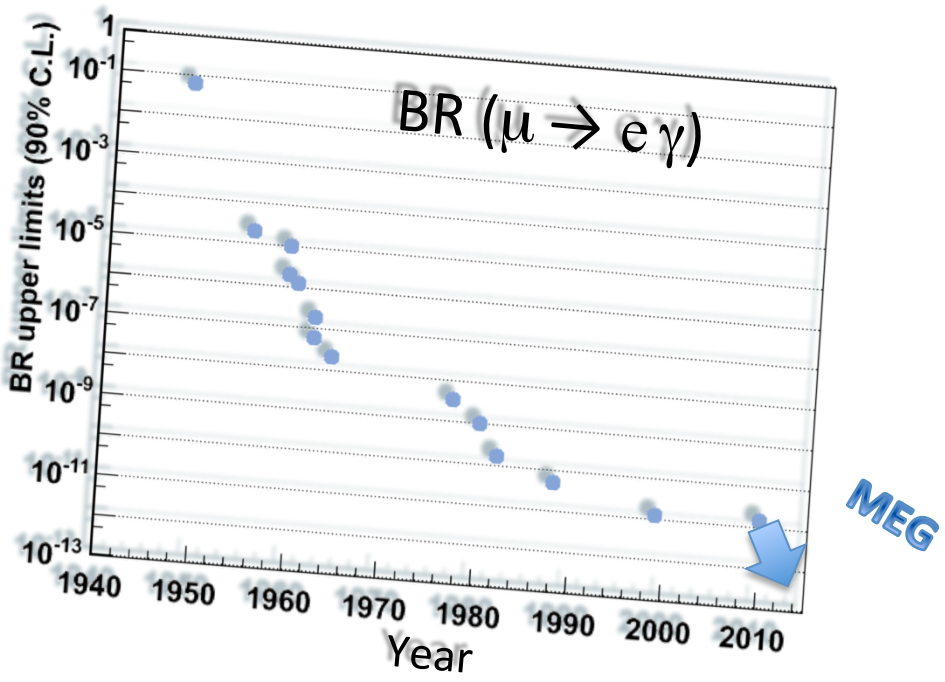
PRERIMINALY

$BR_{2009}(\mu^+ \to e^+ \gamma) < 1.5 \times 10^{-11}$ at 90% C.L.

Systematic errors are considered.
$N_{sig} = 0$ is still within 90% CL.

After 2009 preliminary result

PROGRESS FOR NEXT RESULT



Analysis Progress on 2009 Data

After the preliminary result

- Better understanding of **B-field** for e^+ tracking
  - Reduced systematics on B field
  - Took ϕ component into account ($B_\phi \sim 2\text{-}3 \times 10^{-3} \times B_z$)
- Investigation of **detector alignment**
  - Relative alignment with cosmic rays through both drift chamber and γ-ray detector
  - Alignment of γ-ray detector by Am-Be source or γ-ray through lead collimators

⇨ *Performance improved*

		Before	After
Better e^+ resolution	$\sigma^*(E_e)$ [%]	0.74	0.61
	$\sigma^*(\phi_e)$ [mrad]	7.4	6.1
	$\sigma\ (\theta_e)$ [mrad]	11.2	9.4
Lower Systematics	Sys. $\phi_{e\gamma}$[mrad]	7.5	3.2
	Sys. $\theta_{e\gamma}$[mrad]	7.5	3.1

* Core component

Understood major sources of systematic uncertainties

Analysis update

- BG estimation in sideband is more reliable.
  e.g.) 2009 preliminary : $N_{RD} = 32^{+2}_{-2}$ scaled from E_γ sideband, 35^{+24}_{-22} (1.65σ) in best fit
- Include constraint from BG rate measured in sideband in likelihood analysis
- Profile likelihood for confidence level calculation

2010 Data and Next Update

2010 Run

- New calibration systems
  - 9-MeV γ from neutron generator, Mott scattering target, etc.
- Better trigger / DAQ performance
  - 92 % direction match efficiency
- Three-month run from Aug. to Nov in 2010.
  - 2 times more statistics than 2009 data
  - Premature end by a problem of the beam transport solenoid.

Next BR Update

- We present the next result this summer, combining 2009 with 2010 data.
  - Three times statistics as much as 2009 data
  - With improved performance

Next Runs in 2011

- Hardware update
  - Multiple buffer readout
    - 84% → >95% live time
  - Z-tagging fiber counter for e^+ is ready
    - Online direction match becomes better.
  - New HV module reduced noise on chambers
    - Resolution will be improved.
  - BGO detector instead of NaI for $\pi^0 \rightarrow 2\gamma$ tagging
    - Efficient run and excellent γ tagging for γ calibration

- Long and stable run is expected.
  - Four-month physics run, from June or July to December

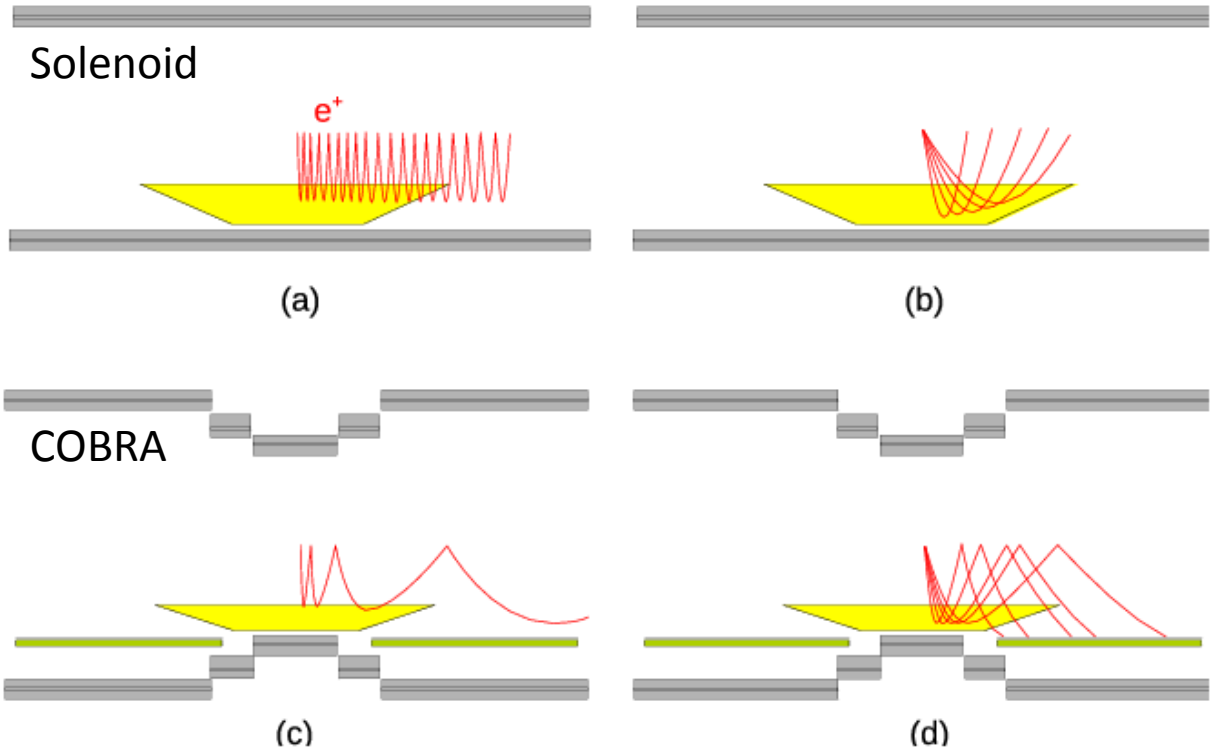
Summary

- The MEG experiment started in 2008 for the $\mu^+ \rightarrow e^+ \gamma$ search.
- Stably we took two-month data in 2009.
  - Sensitivity in 2009 is 6.1×10^{-12}.
  - Showed preliminary result, BR < 1.5×10^{-11} (90% C.L.)

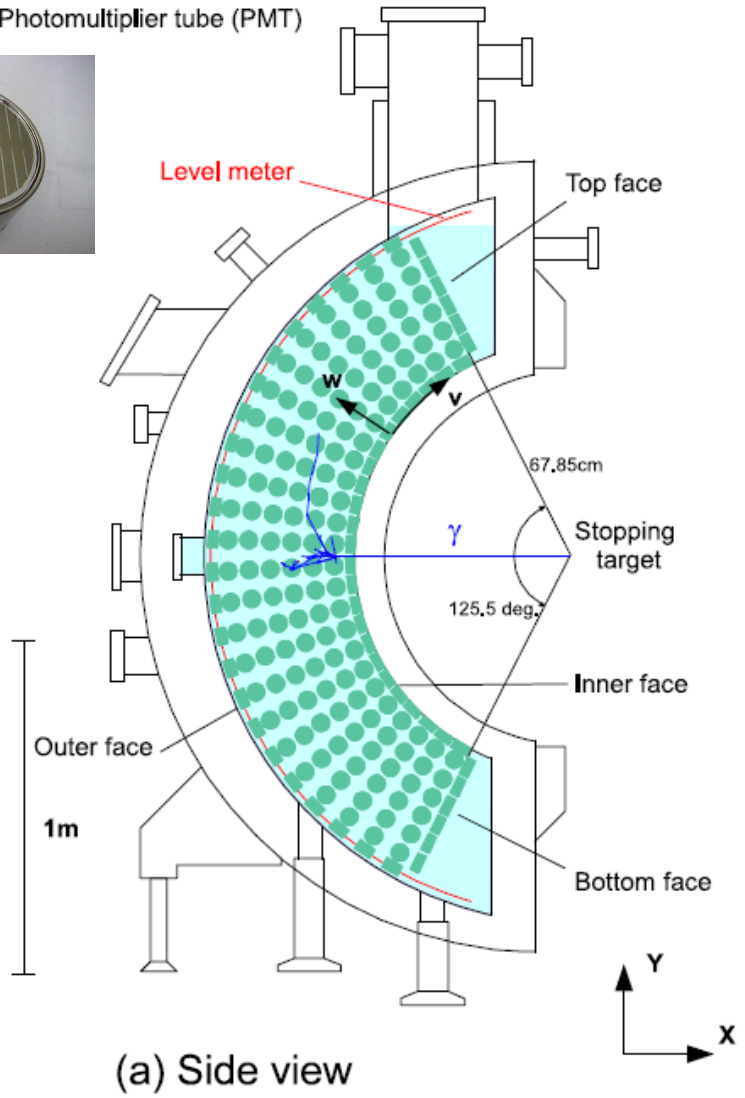
- 2010 data was successfully taken for three months.
  - As much as 2 × 2009 data.
- Next update comes this summer.
  - Combined 2009 and 2010 data with improvements.

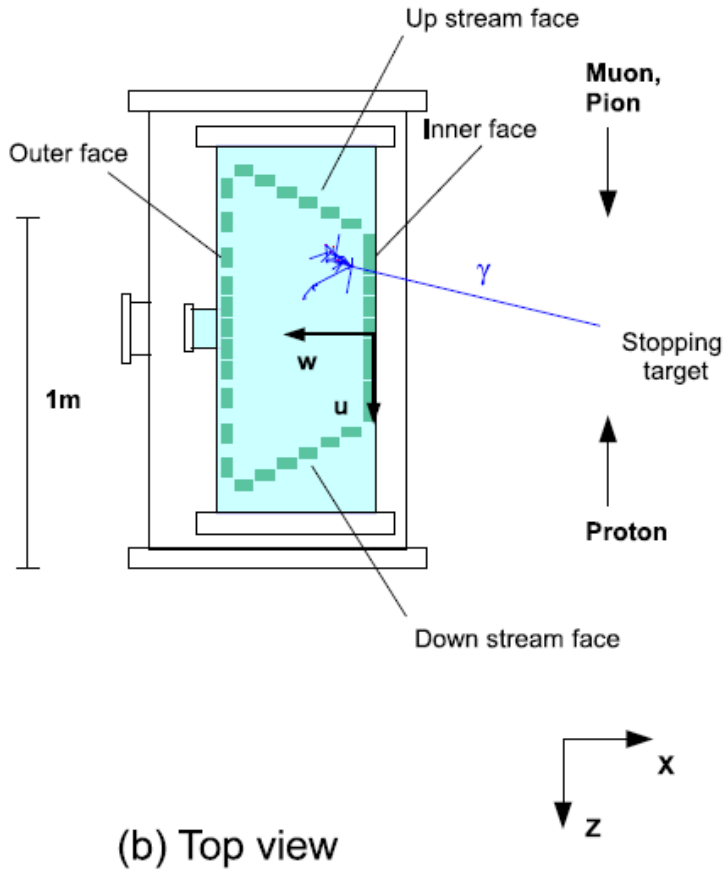
- Since 2011 the MEG will take a long run
  for a few years, toward to $O(10^{-13})$.

Positron track in the COBRA magnet



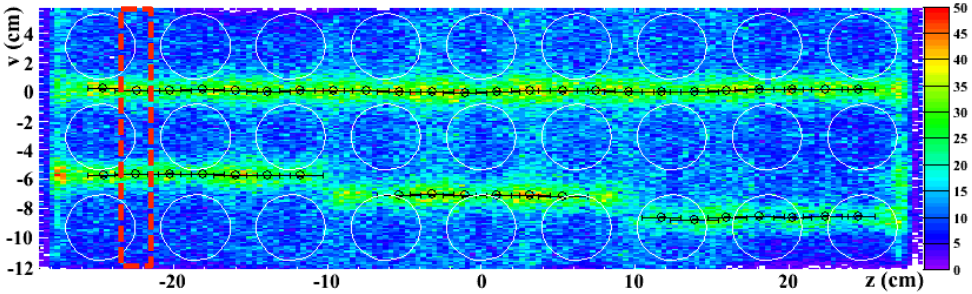
Liquid xenon detector

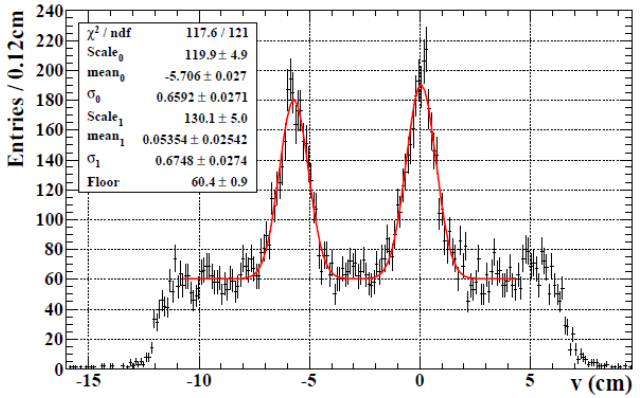




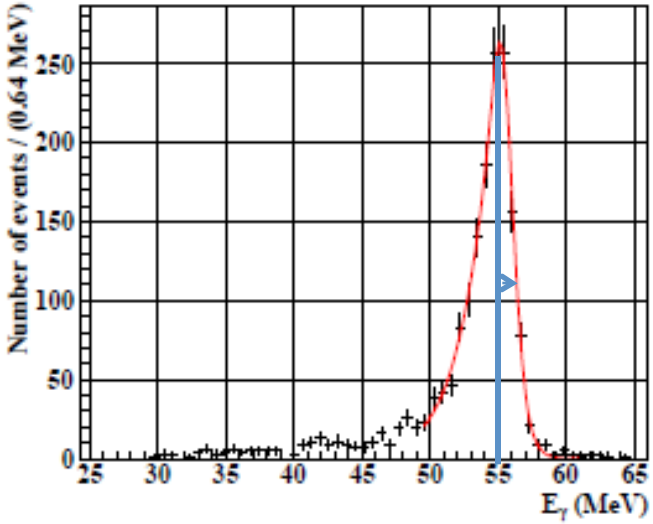
Performance of the liquid xenon detector

Position

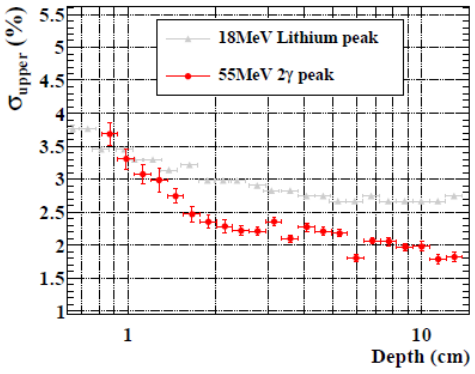


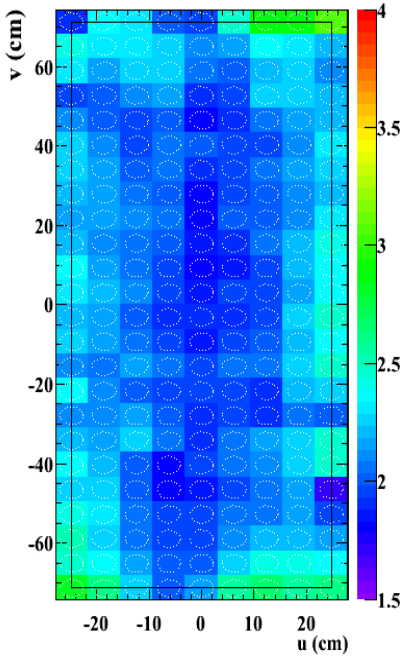


Energy



Energy resolution map





Systematic uncertainty and resolution

Resolutions in 2009 preliminary

σ_{E_γ} (%)	$\sigma_{(u,v,w)}$ (mm)	ϵ_γ	σ_{E_e} (%)	σ_{ϕ_e} (mrad)	σ_{θ_e} (mrad)	Vertex $\sigma_{Z,Y}$ (mm)	ϵ_e	$\sigma_{t_{e\gamma}}$ (ps)	ϵ_{trig}
2.1[1]	5, 6	0.58	0.74[2]	7.1[2]	11.2	3.4, 3.3	0.4	142[2]	0.84

[1] $w > 2$cm
[2] Core component

Systematic uncertainties in 2009 preliminary

E_γ	E_e	σE_e	$\theta_{e\gamma}$, $\phi_{e\gamma}$	$\sigma\theta_{e\gamma}$, $\sigma\phi_{e\gamma}$	$\delta E_e - \delta\phi_e$ correlation	$T_{e\gamma}$	$\sigma T_{e\gamma}$	Normalization
0.43%	50 keV	15%	7.5 mrad	10%	50%	15 ps	10%	9%

The best fit values in 2009 preliminary

$$(\hat{N}_{sig}, \hat{N}_{RD}, \hat{N}_{BG}) = (3.0^{+6.9}, 35^{+24}_{-22}, 332^{+38}_{-36})$$