New Results from the MEG Experiment in the Search for $\mu^+ \rightarrow e^+\gamma$

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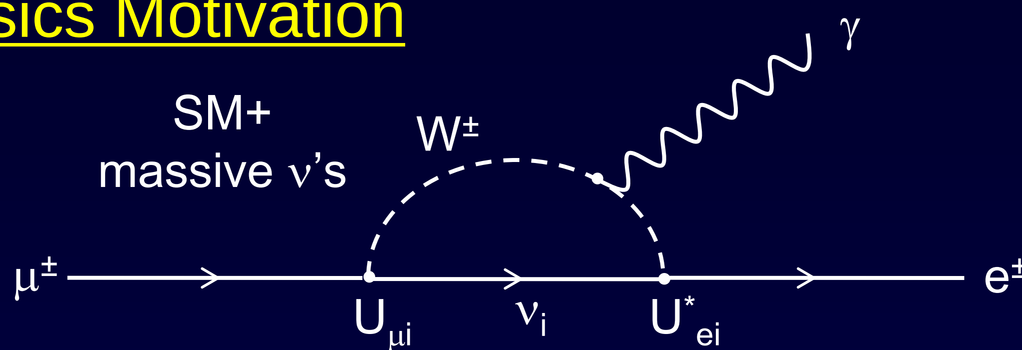
on behalf of the MEG collaboration

Talk Outline

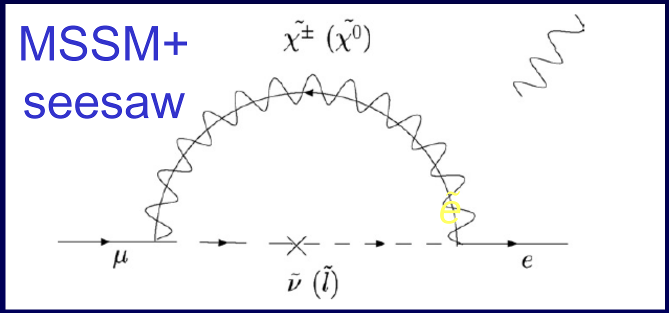
- Physics motivation
- MEG experiment
  - Event signatures
  - Hardware design
  - Timeline
- 2009 performance
- Analysis
  - Techniques
  - Results
  - Diagnostics
- Summary
- Future prospects

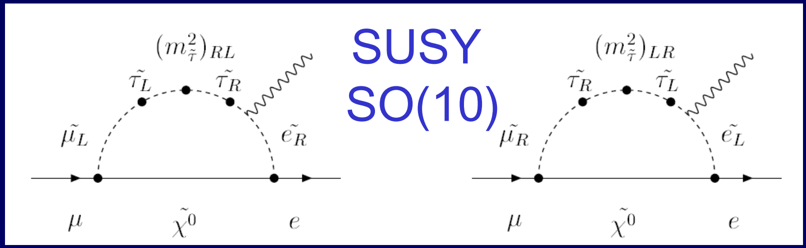
Physics Motivation

- nLFV has been studied by many experiments (e.g. SuperK, KamLAND, SNO) and implies the existence of CLFV at the level of at least BR($\mu \rightarrow e\gamma$)~10^{-54} without new physics
- CLFV has been elusive with a current U.L. of BR($\mu \rightarrow e\gamma$)<1.2 x 10^{-11}
- Predictions from many SUSY models lie close to the current limit (e.g. MSSM+seesaw, SUSY SO(10) GUT)
- Even in non-SUSY solutions to gauge hierarchy problem, $\mu \rightarrow e\gamma$ is generically present
  - Extended technicolor with non-universal gauge groups
  - Little Higgs
  - Extra dimensions
- MEG aims to reach ~ 10^{-13} sensitivity

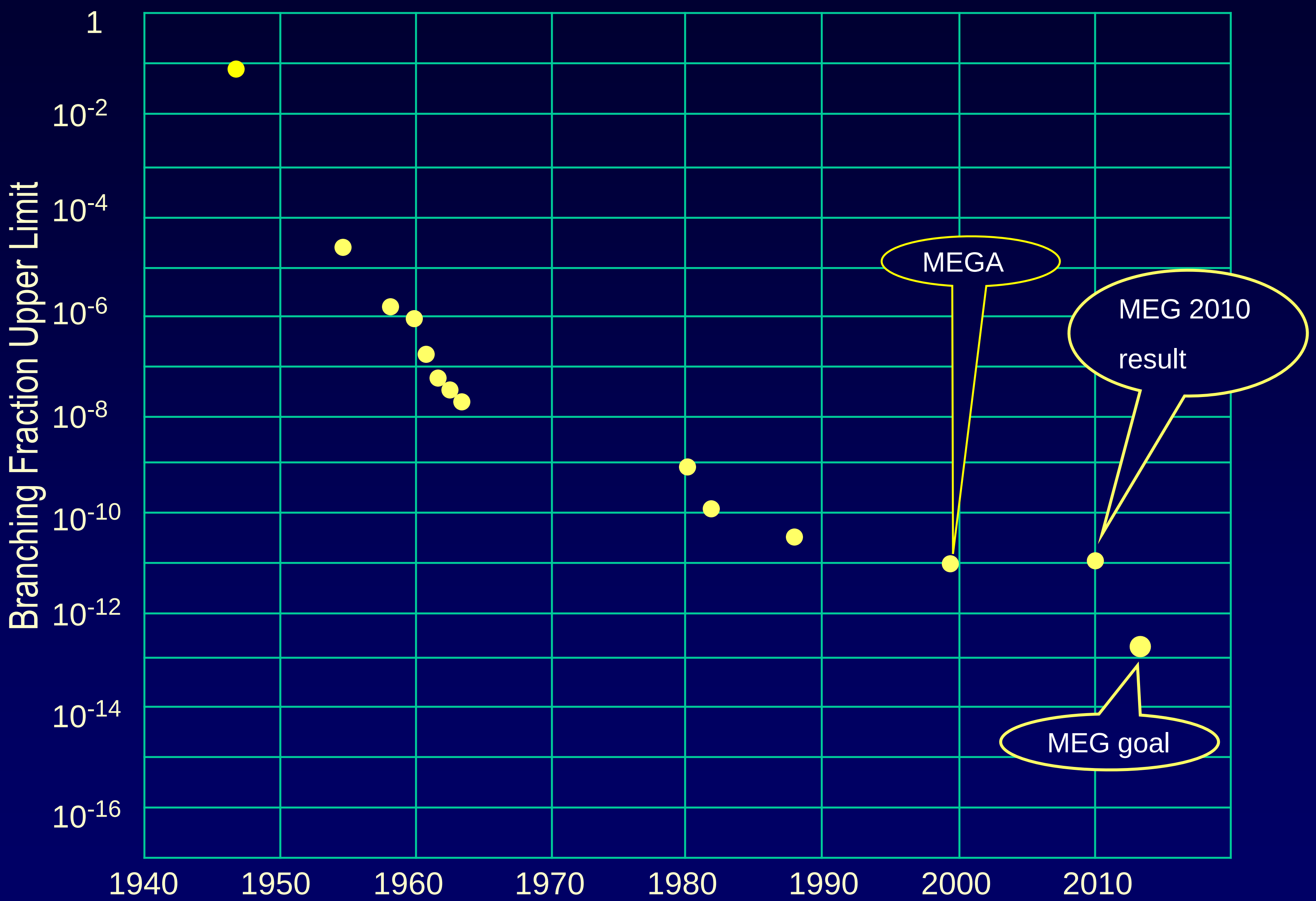


$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$



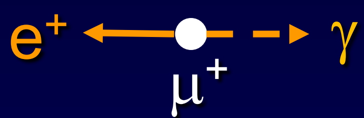


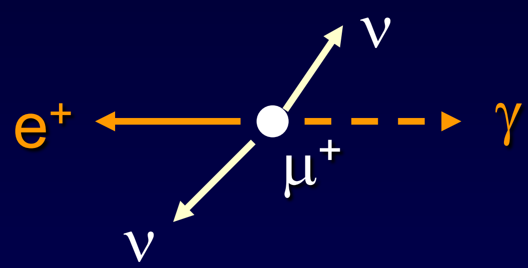
History of $\mu \rightarrow e\gamma$ Searches

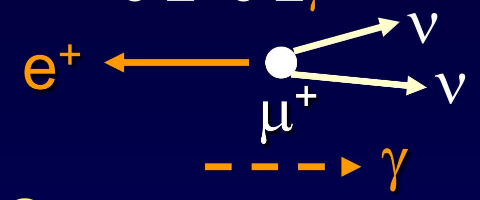


Signal and Background

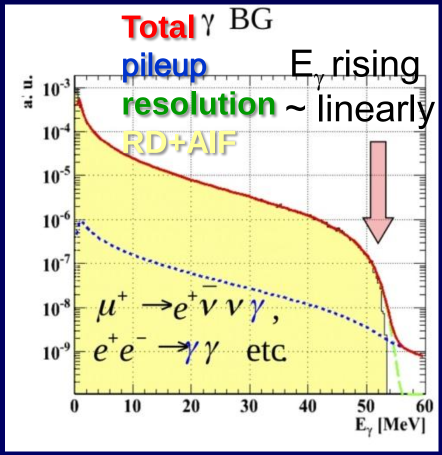
Signal	Radiative decay background	Accidental background
$\mu^+ \to e^+\gamma$	$\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$	$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ + $\mu^+ \to e^+\nu\nu\gamma$ or $e^+e^- \to \gamma\gamma$ or $e^+Z \to e^+Z\gamma$

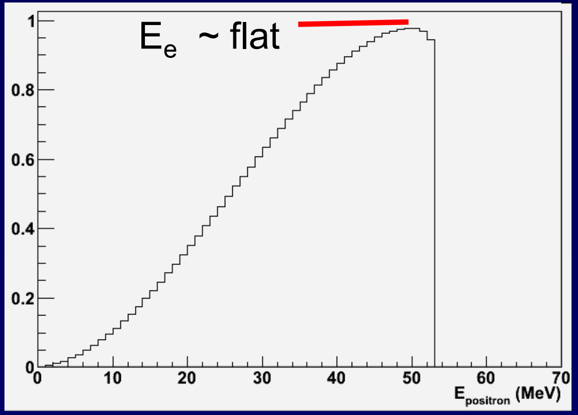






Signal	Radiative decay background	Accidental background
$\Theta_{e\gamma} = 180°$	$\Theta_{e\gamma}$ = any angle	$\Theta_{e\gamma}$ = random
$E_e \approx E_\gamma \approx 52.8$ MeV	$E_e, E_\gamma < 52.8$ MeV	$E_e, E_\gamma < 52.8$ MeV
$T_e = T_\gamma$	$T_e = T_\gamma$	$T_e - T_\gamma$ = random

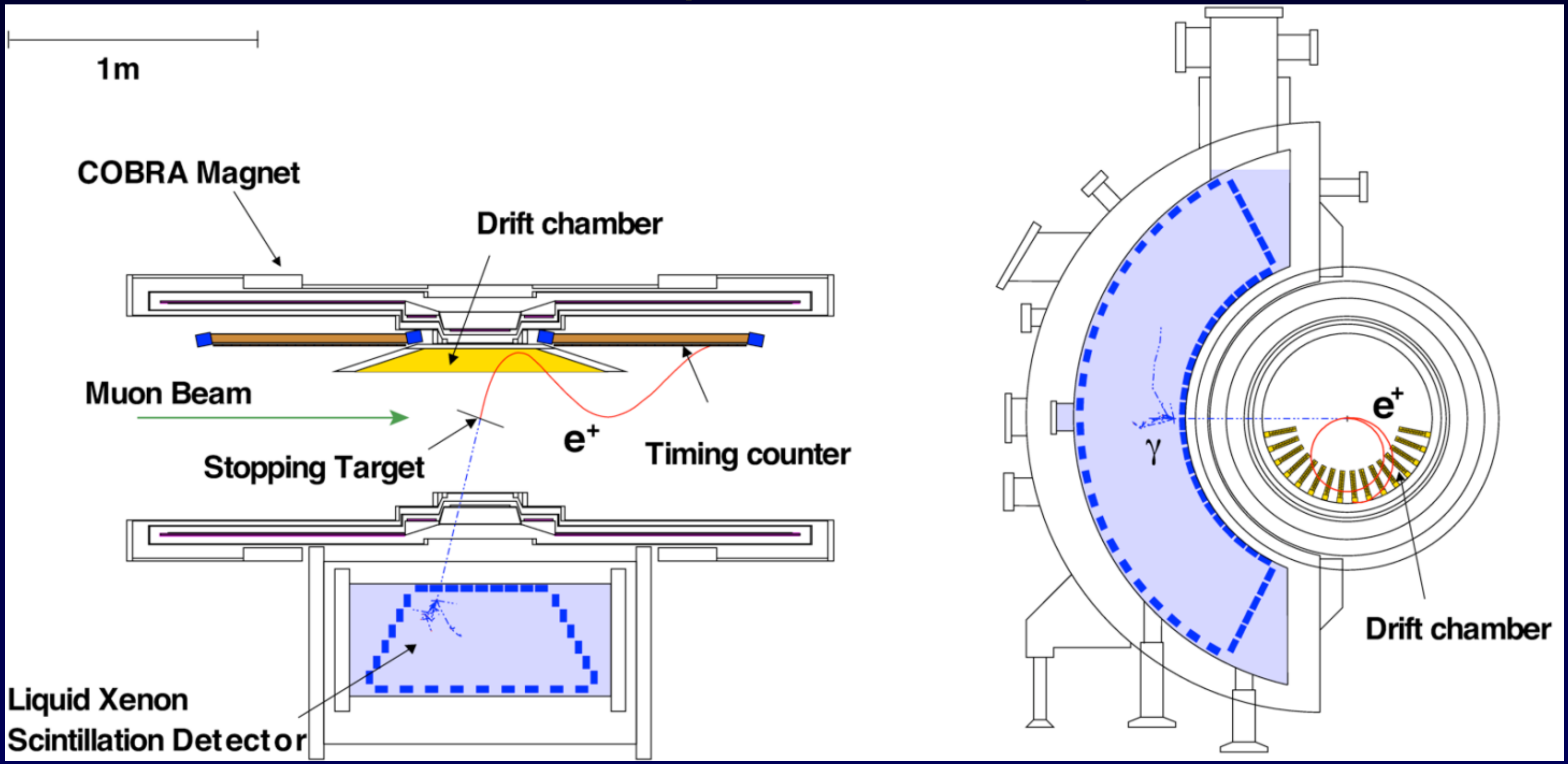




- Accidentals are dominant background at rates high enough to reach 10^{-13} sensitivity

- $N_{accidental}/N_\mu \propto \Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t_{e\gamma} \times (\Delta\theta_{e\gamma})^2 \times$ Rate

MEG Experiment Design



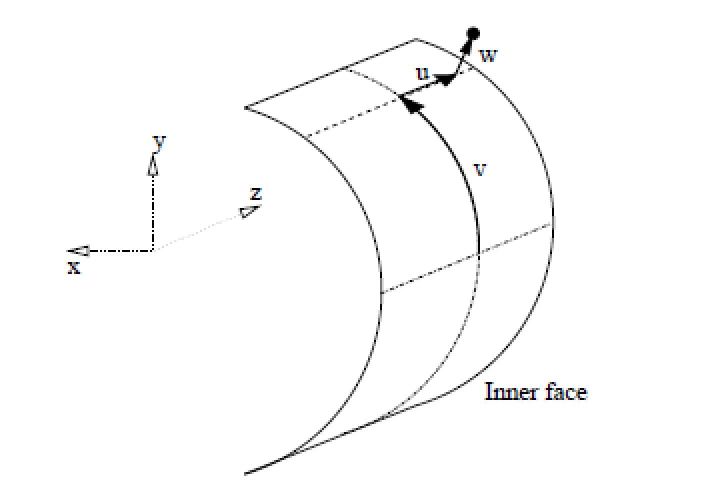
- ~ 3×10^7 μ^+/s beam incident on a thin, depolarizing stopping target
- Positron detection
  - Gradient B-field to sweep out e^+ quickly and keep bending radius constant
  - Low mass drift chambers to measure energy and emission angles
  - Timing counter with scintillating plastic for precise time measurement
- Photon detection
  - Energy, position, and time measured in a liquid xenon calorimeter
  - Fast response time, high light yield, high photocathode coverage

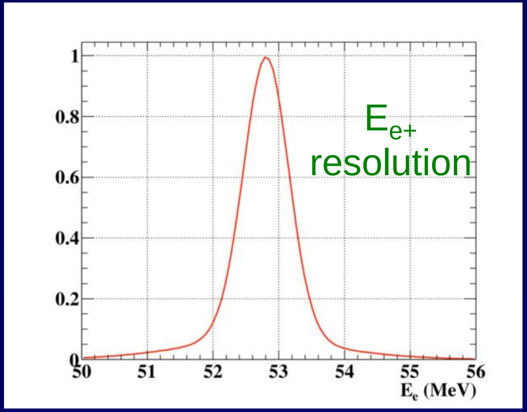
MEG Timeline: Past, Present, and Future

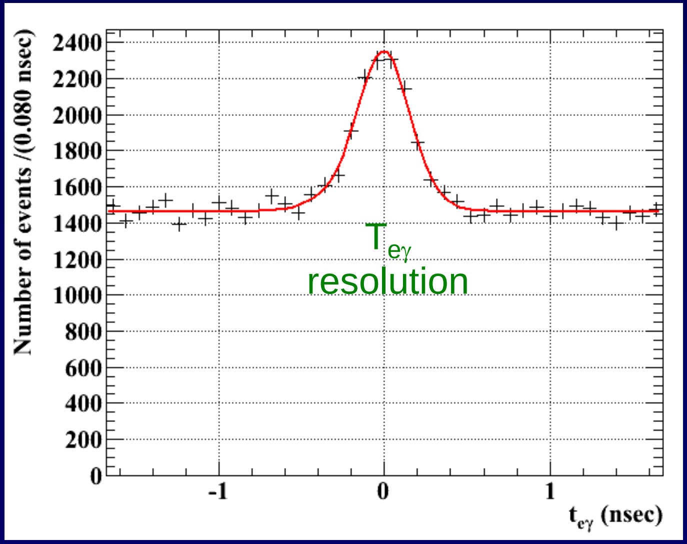
- 1998: Original LOI (PSI-RR-99-05)
- 2002: Proposal with a goal of 10^{-13} sensitivity
- 2007: (Nov-Dec): Engineering run
- 2008: (Sep-Dec): 1st physics run, some hardware problems leading to low efficiency and suboptimal resolutions
- 2009:
  - Analysis of 2008 data
    - Sensitivity = 1.3×10^{-11}
    - 90% CL UL = 2.8×10^{-11}
    - Nuclear Physics B, Volume 834, Issues 1-2, 21 July 2010, Pages 1-12
  - 2nd physics run (Nov-Dec)
    - Hardware upgrades
    - 43 days of data taking
    - 93 TB data taken (22.3M triggers)
- 2010:
  - Analysis of 2009 data (primary content of this talk)
  - 3rd physics run (starting July)
- 2011-2012: continue data taking

Detector & Reconstruction Performance

Quantity	Resolution(σ) or Efficiency
Photon energy (%)	2.1 (w > 2 cm)
Photon position (mm)	5(u,v) / 6(w)
e^+ momentum (%)	0.74 (core), 79% in core
e^+ angle (mrad)	7.4(φ core), 85% in core 11.2(θ)
Muon vertex position (mm) Correlated with and dominated by e^+ angle resolution	2.3 (R), 2.8 (Z)
Photon - e^+ timing (psec)	142 (core), 70% in core
Photon efficiency (%)	58
Trigger efficiency (%)	84

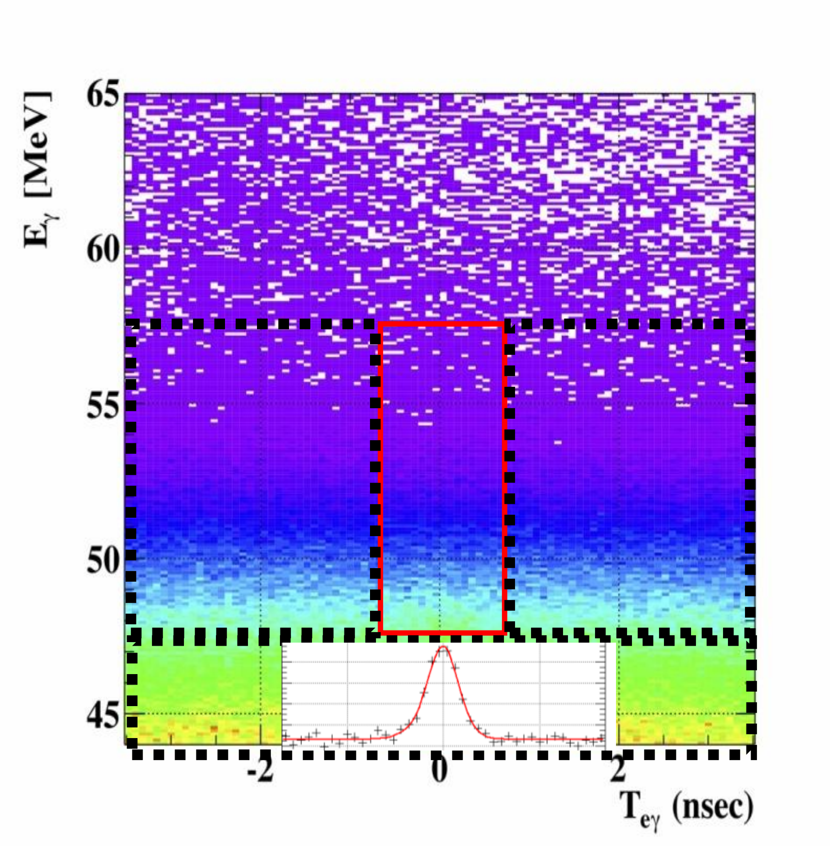






Blind Analysis Technique

- A rare decay search is very sensitive to the exact values of selection cuts
- If it is known which events satisfy cuts during analysis, 2 extreme cases of bias:
  - Cut to eliminate individual events, yielding better upper limit than justified
  - Cut to retain individual events, producing a signal where none is present
- MEG uses "Hidden Signal Box" technique (0.2% of data in signal box)
  - Signal-like events were hidden until selection cuts and PDFs were determined
    - $48 \leq E_\gamma \leq 58$ MeV
    - $| T_{e\gamma} | \leq 0.7$ ns
  - Sidebands adjacent to signal box (16% of data)
    - Can look at radiative decays for $E_\gamma \leq 48$ MeV
    - Can look at accidental photons in $| T_{e\gamma} | > 0.7$ ns



- Analysis Window (~ 10σ width)
  - $48 \leq E_\gamma \leq 58$ MeV
  - $| T_{e\gamma} | \leq 0.7$ ns
  - $|\varphi_{e\gamma}|$, $| \theta_{e\gamma} | \leq 50$ mrad (angles btw. reversed e+ and γ vectors)
  - $50 \leq E_e \leq 56$ MeV

Maximum Likelihood Analysis

- Fit for numbers of signal (N_{Sig}), radiative decay (N_{RD}), and accidental (N_{Acc}) events by maximizing an extended likelihood function

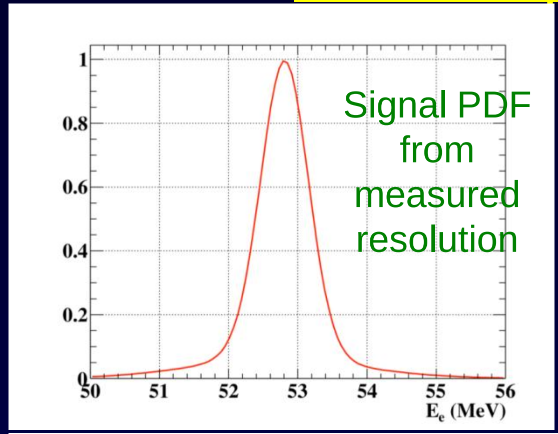
$$L(N_{Sig}, N_{RD}, N_{Acc}) = \frac{N^{N_{obs}} \exp(-N)}{N_{obs}!} \prod_{i=1}^{N_{obs}} \left[\frac{N_{Sig}}{N} S + \frac{N_{RD}}{N} R + \frac{N_{Acc}}{N} A \right]$$

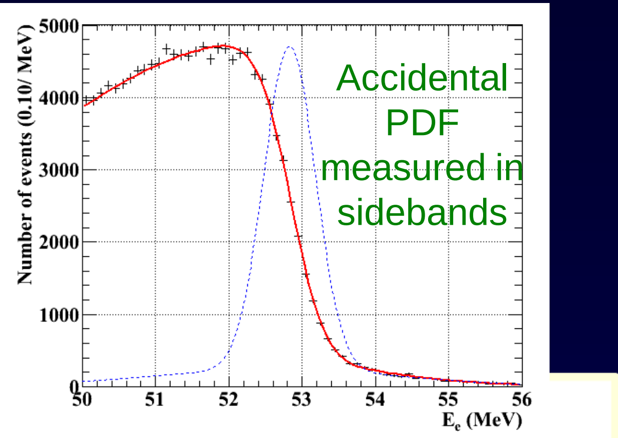
  - $N = N_{Sig} + N_{RD} + N_{Acc}$
  - Kinematic observables: E_e, E_γ, $T_{e\gamma}$, $\varphi_{e\gamma}$, $\theta_{e\gamma}$
- PDF procurement
  - Position dependent photon PDFs
  - Positron PDFs split into 2 classes of events based on event quality (fitting uncertainty, TIC-DCH projection agreement, etc.)
  - Most PDFs inferred from data
  - RD correlations obtained by convolving response functions with RD BR from theory
- Diagnostic checks
  - Checks with fits to events with $T_\gamma - T_e \neq 0$: expect no signal or radiative decay
  - Checks with fits to events with small E_γ: more RD events, no signal
  - Three independent likelihood analyses done to check systematic effects

- Normalization sample is a highly pre-scaled, simultaneous Michel e^+ sample: $BR(\mu \rightarrow e\gamma) = N_{Sig} / 1.0 \pm 0.1 \times 10^{12}$

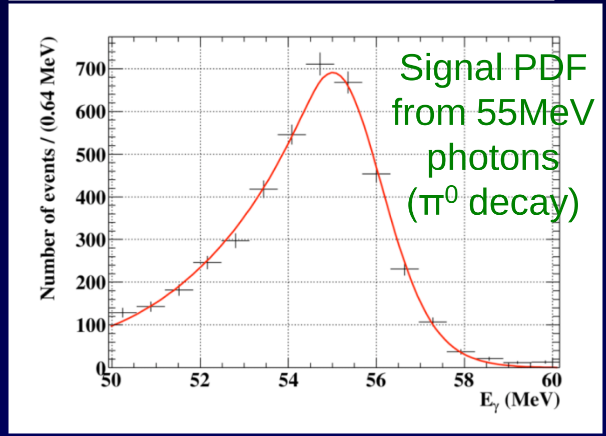
PDF shapes

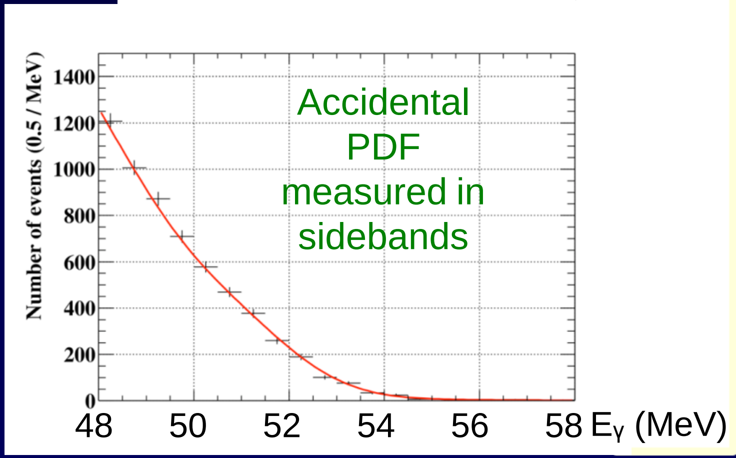
- Positron energy



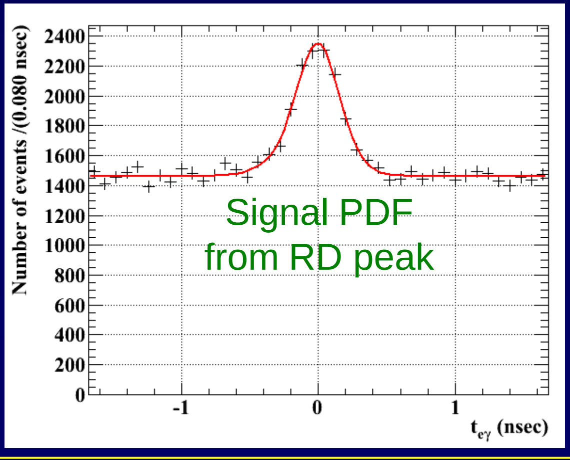


- Photon energy





- Relative time



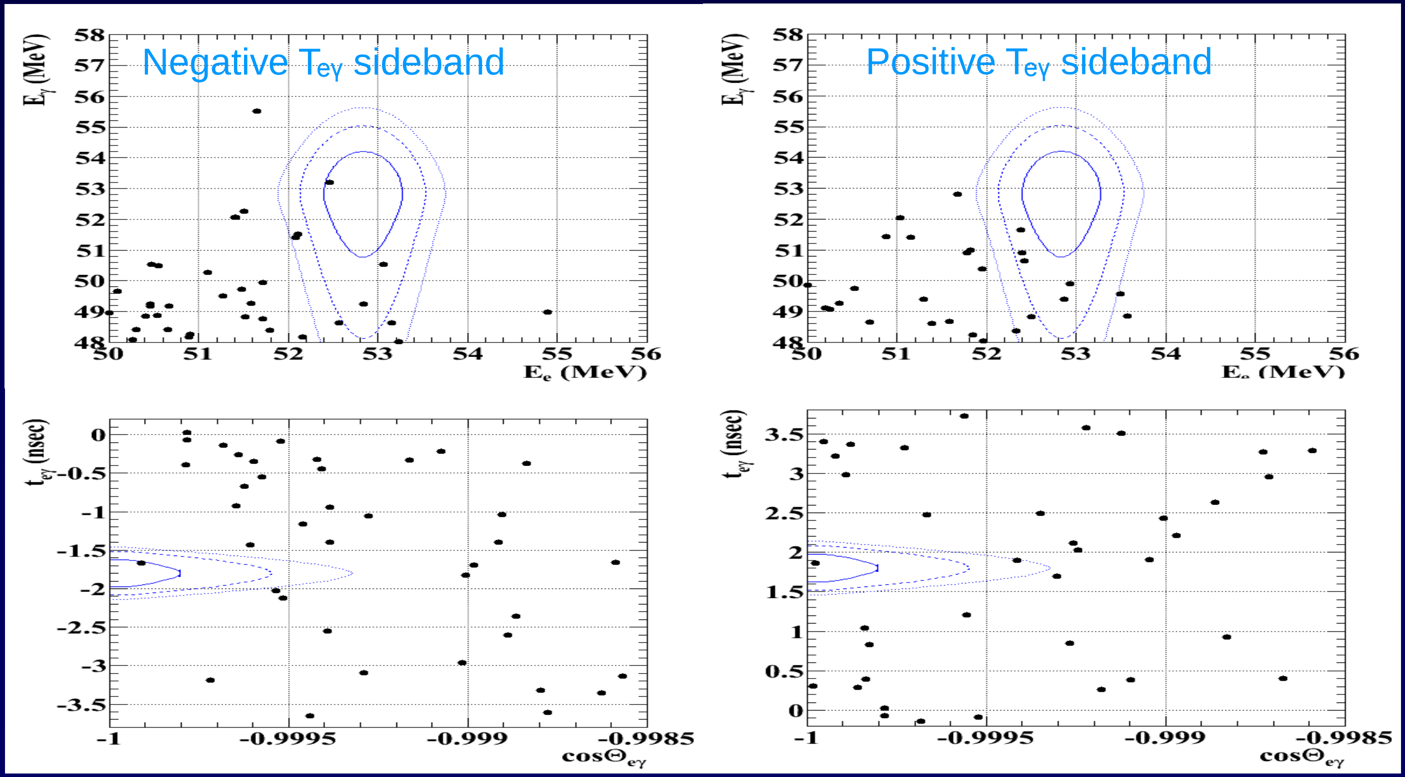
- Relative angle
  - Signal computed from measured position & and angle resolutions
  - Accidental from sidebands

Sensitivity Computation and Sideband Diagnostics

Preliminary

- Sensitivity Calculation
  - Set N_{Sig}=0 and N_{RD},N_{Acc}=best fit values from real data in analysis box
  - Generate many toy MC experiments according to PDFs and fit each one
  - Compute upper limit at 90% C.L. for each
  - Average 90% C.L. upper limit = 6.1×10^{-12}
- Sideband fits
  - Consistent with sensitivity estimate
  - $Br<4\sim6\times10^{-12}$ 90% CL
- MEGA result:

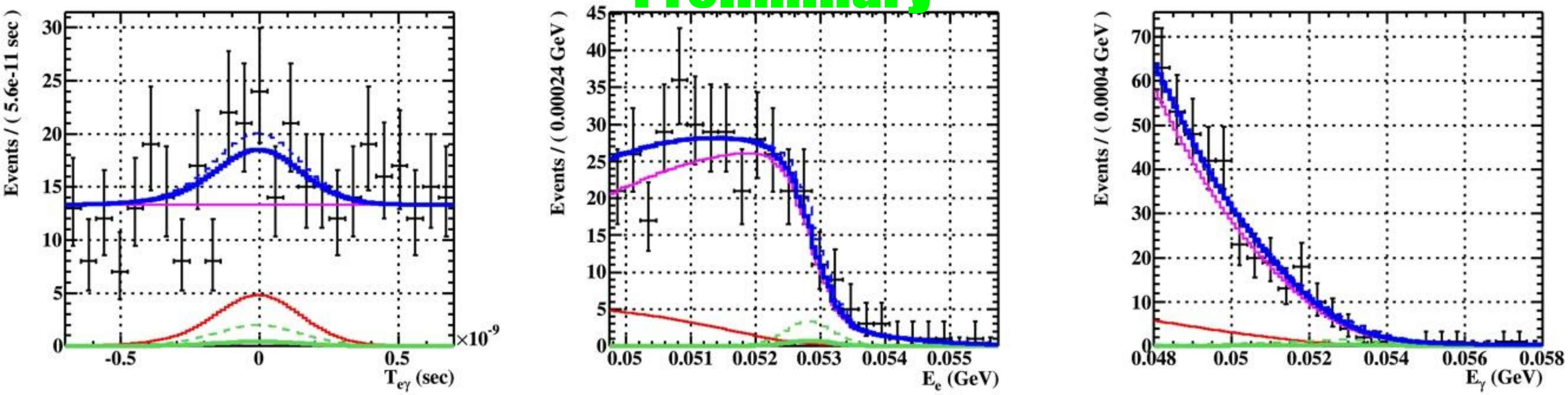
  $Br<12\times10^{-12}$



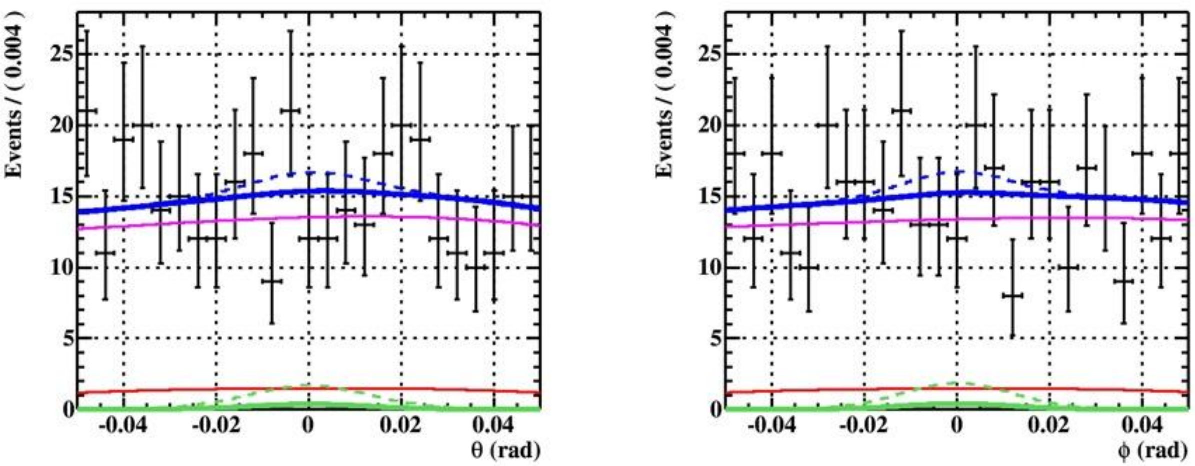
Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions. For each plot, cuts on each of the other 2 variables for roughly 90% windows are applied.

Results of Maximum Likelihood Fit

Preliminary



1D projections of the PDFs onto the kinematic observables



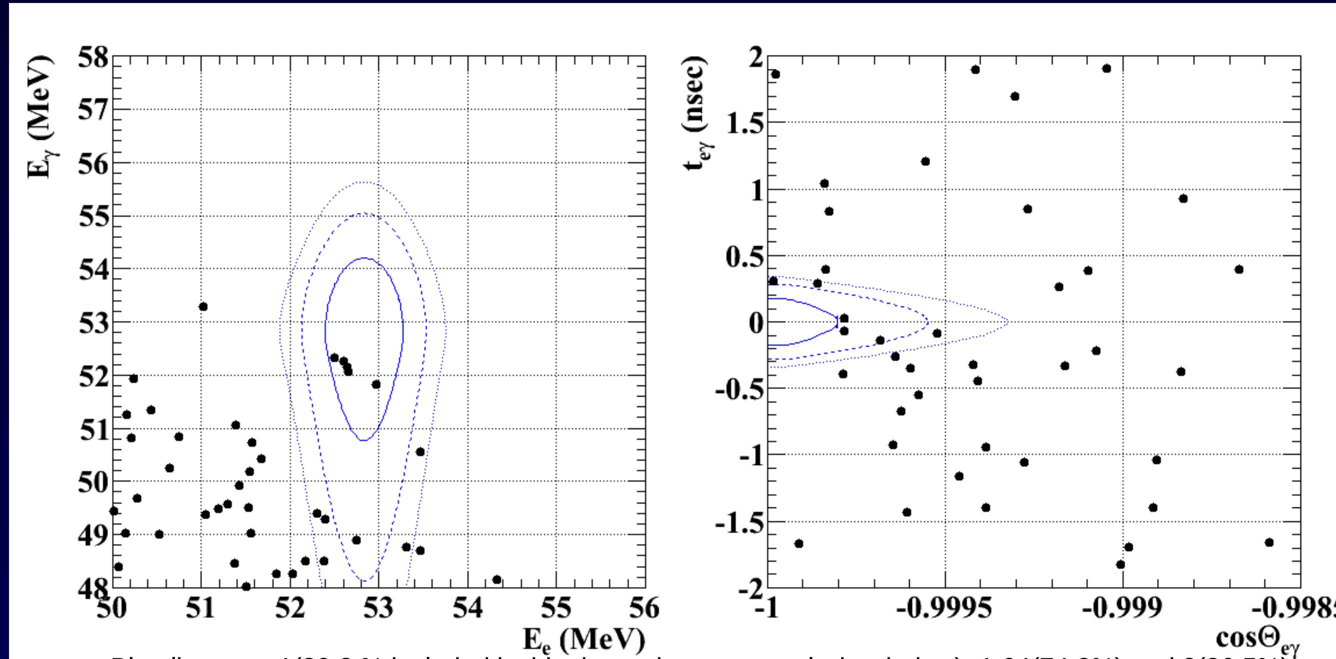
Accidental background
Radiative muon decay
Signal
Total

Dashed lines : 90% C.L. UL of Nsig

- Best fit values: N_{Sig}=3.0 and $N_{RD}=35^{+24}_{-22}$ (from sideband expect = 32±2)
- Nsig < 14.5 @ 90% C.L (N_{Sig}=0 is in 90% confidence region)
- Fitting was done by three groups with different parameterizations, analysis windows and statistical approaches, and confirmed to be consistent (Nsig best fit = 3.0-4.5, UL = 1.2-1.5×10^{-11})

Event Distributions of Kinematic Observables

- Check of kinematic variable distributions before and after selecting high quality positron tracks
- Selected by number of drift chamber (DC) hits, energy and angle fitting uncertainties, track fitting χ^2, r and z difference between timing counter hit and extrapolation of a track.
- Events near signal region persist



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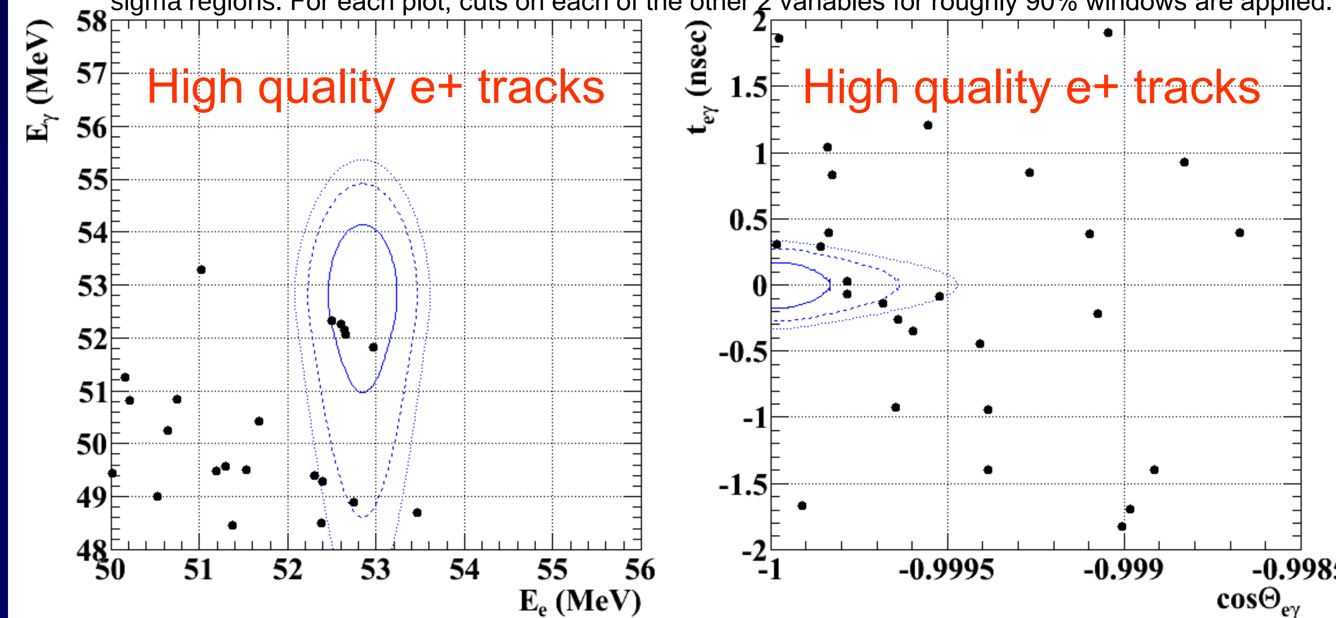
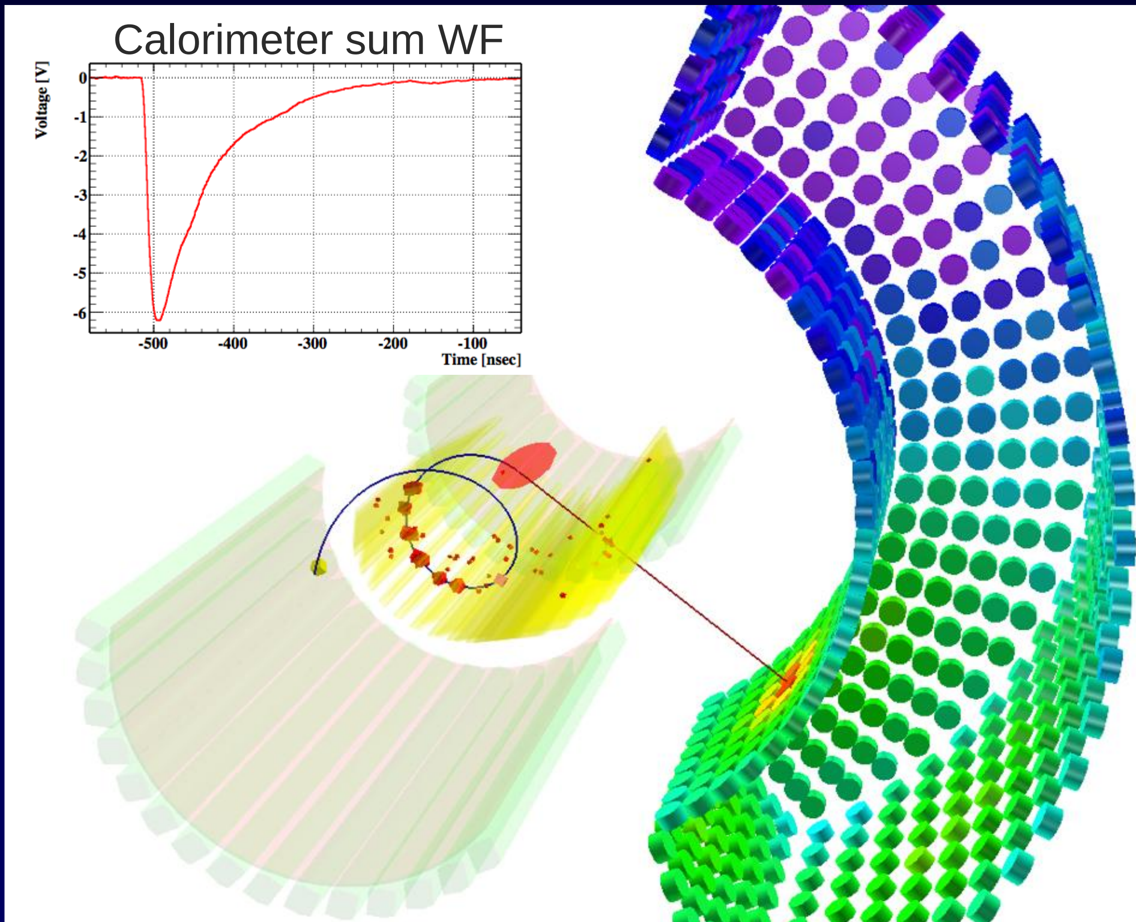
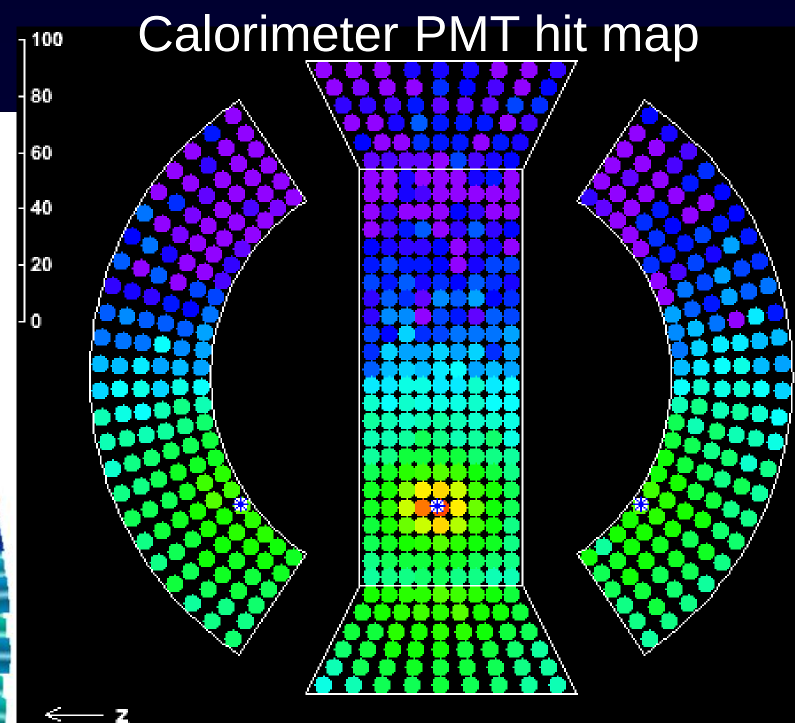
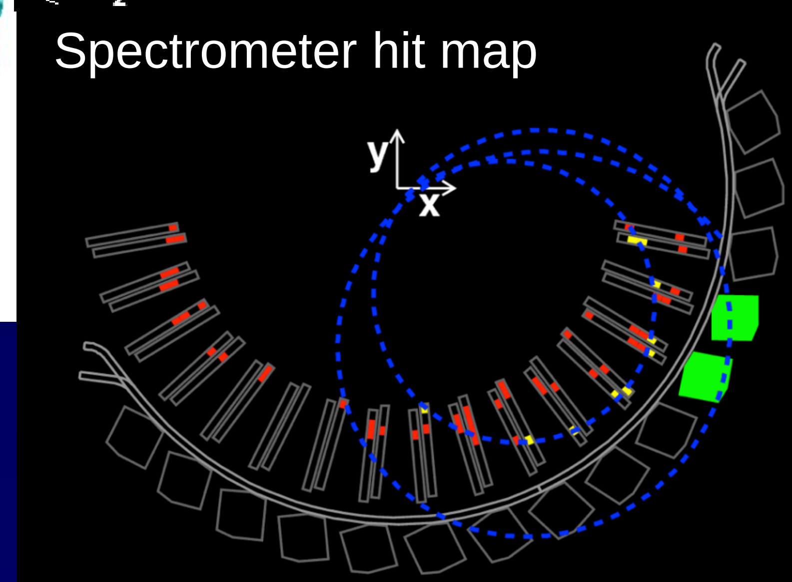


Candidate Event Checking

- Events with large signal likelihood are examined carefully







- Example of a signal-like event
  - E_{γ} = 52.25 MeV
  - E_{e+} = 52.84 MeV
  - $\Theta_{e\gamma}$ = 178.8 degrees
  - $T_{e\gamma}$ = 26.8 ps

Synopsis

- MEG acquired 2 months of data with stable detector operation in 2009
- Preliminary results
  - Estimated sensitivity: 6.1×10^{-12}
  - 90% C.L. includes $N_{Sig}=0$
  - 90% C.L. upper limit: 1.5×10^{-11}
  - Probability to get $N_{Sig} \geq 3.0$ from null hypothesis ~ 2-3%
- 2010 data collection in progress
  - 3 years of DAQ are anticipated to reach few **$\times 10^{-13}$** sensitivity
  - Can elucidate our result

Future Prospects

Resolution(σ) or Efficiency	2009	2010 (estimate)
Gamma Energy (%)	2.1(w>2cm)	1.5(w>2cm)
Gamma Timing (psec)	>67	68
Gamma Position (mm)	5(u,v) / 6(w)	←
Gamma Efficiency (%)	58	←
e^+ Momentum (%)	0.74(core)	0.7
e^+ Angle (mrad)	7.4(φ, core)/11.2(θ)	8(φ)/8(θ)
e^+ Efficiency (%)	40	←
e^+-gamma timing (psec)	142(core)	120
Muon Decay Point (mm)	2.3(R)/2.8(Z)	1.4(R)/2.5(Z)
Trigger efficiency (%)	84	94
Stopping Muon Rate (sec^{-1})	2.9×10^7(300μm)	3×10^7 (300μm)
DAQ time/Real time (days)	35/43	95/117
Sensitivity	6.1×10^{-12}	2.0×10^{-12}
BR upper limit (obtained)	1.5×10^{-11}	-

- 2010 data taking underway
- Foreseen improvements
  - Reduction of electronic noise in DCH waveforms
  - Potential for better understanding of e^+ spectrometer using monochromatic e^+s from Mott scattering
  - DRS4 timing improvements from hardware fine tuning
  - Use of TIC fibers to increase trigger efficiency
  - 2010 data will triple the statistics in 2009
  - Refinements in calorimeter analysis: $\sigma_E/E \rightarrow 1.5\%$

- Remember $N_{accidental}/N_\mu \propto \Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t_{e\gamma} \times (\Delta\theta_{e\gamma})^2 \times$ Rate

Back up slides

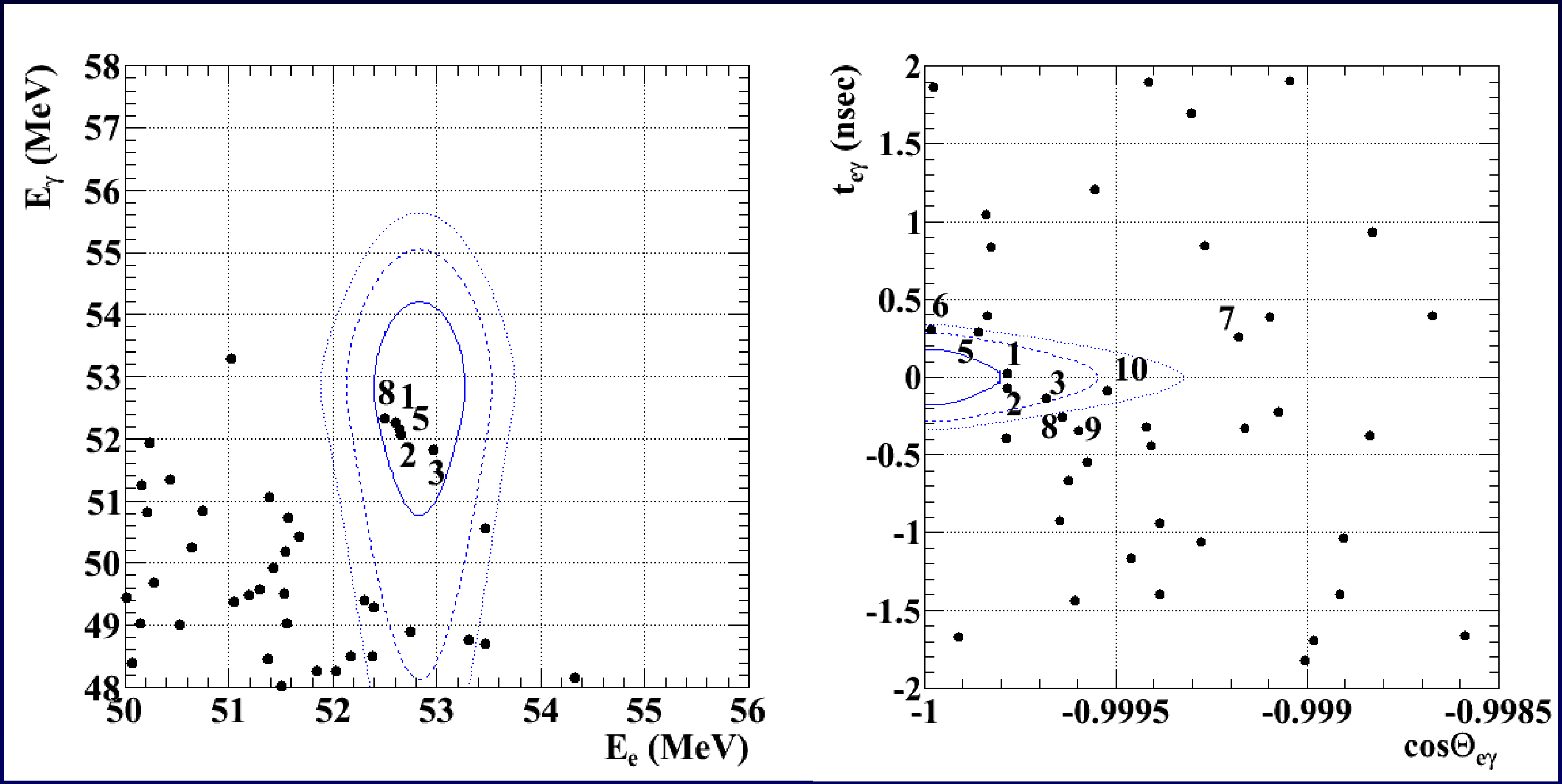
Normalization

- Result is normalized to the number of detected Michel decays, cancelling many sources of uncertainty
  - Positron acceptance + reconstruction efficiency is nearly identical, small correction for different momentum interval for the signal and Michel decays
- Most efficiencies or acceptances can be derived from data
- Photon reconstruction efficiency from MC, cross check with π^0 data: detect γ in NaI, measure probability of reconstructing opposite photon
- Signal trigger efficiency relies on MC

$B(\mu\to e\gamma) = B(\mu\to e\nu\nu)$	Michel branching fraction	known
X $N(\mu\to e\gamma)$	Number of signal events	counted
/ $N(\mu\to e\nu\nu)$	Number of Michel events	counted
/ $P(\mu\to e\nu\nu)$	prescale factor	known
X $f(\mu\to e\nu\nu)$	fraction of Michel > 50 MeV	calculated
X $G^e_{\mu\to e\nu\nu} / G^e_{\mu\to e\gamma}$	positron geometrical acceptance ratio	definition
X $R^e_{\mu\to e\nu\nu} / R^e_{\mu\to e\gamma}$	Positron acceptance+ reconstruction ratio	data
/ $G^{\gamma}:e^+$	Conditional geom. acceptance for photon	MC
/ R^{γ}	Photon reconstruction efficiency	MC (data check)
/ $Trig_{\mu\to e\nu\nu} / Trig_{\mu\to e\gamma}$	Trigger efficiency ratio	MC
/ $\varepsilon(\delta t)$	selection on photon-positron time	data
/ $\varepsilon(E_\gamma)$	selection on photon energy (in rec. eff)	data
/ $\varepsilon(E_e)$	selection on positron energy	data
/ ε(pileup, CR)	selection criteria for pileup, cosmic rays, etc	data estimate

$$B(\mu\to e\gamma) = 1.0 \times 10^{-12} \times N(\mu\to e\gamma)$$

Labeled Events



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For each plot, cuts on other two variables for roughly 90% windows are applied.

Numbers in figures are ranked by $L_{sig}/(L_{RMD}+L_{BG})$. Like-numbered dots in the right and the left figure are an identical event.