New Result from MEG Experiment

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on behalf of MEG collaboration

Rencontres de Moriond EW 2013, La Thuile, Italy
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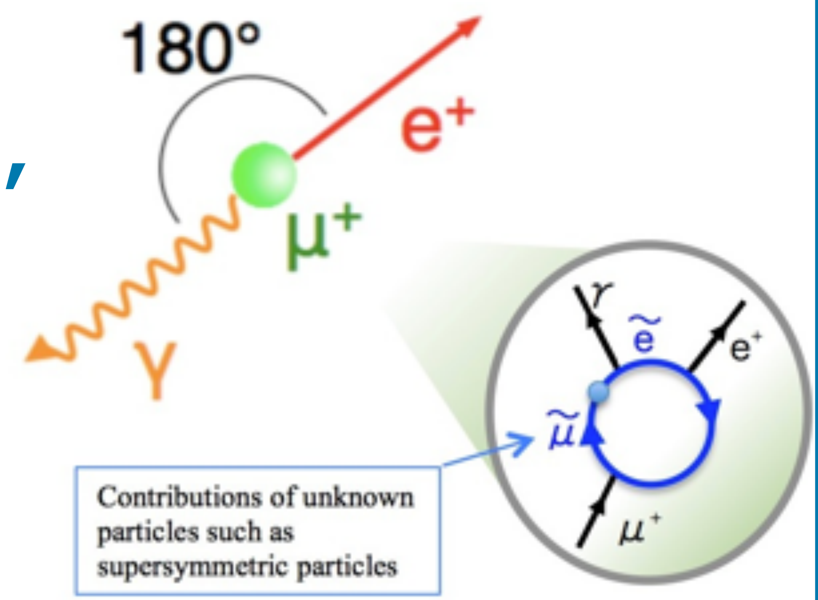
$\mu \to e\gamma$

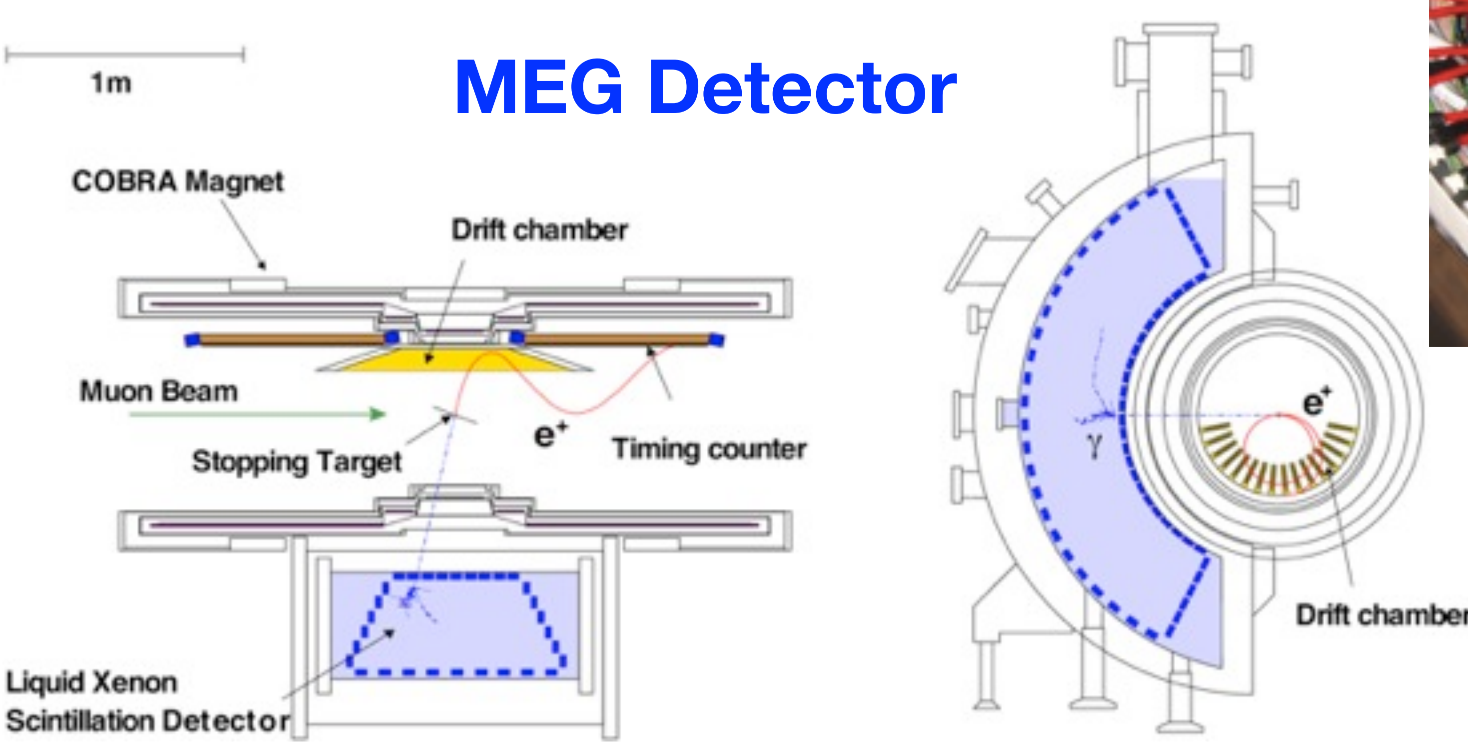
- **MEG searches for lepton flavor violating decay $\mu \to e\gamma$ with an unprecedented sensitivity.**
- **Why to look for $\mu \to e\gamma$?**
  - **Possible to occur even within standard model but at immeasurably small rate due to small neutrino mass**
  - **Many well-motivated models of BSM physics predict measurable rate just below present experimental limit ($\mathcal{B} < 2.4 \times 10^{-12}$, MEG in 2011).**
  - **If discovered, it would be an unambiguous evidence of BSM physics!**

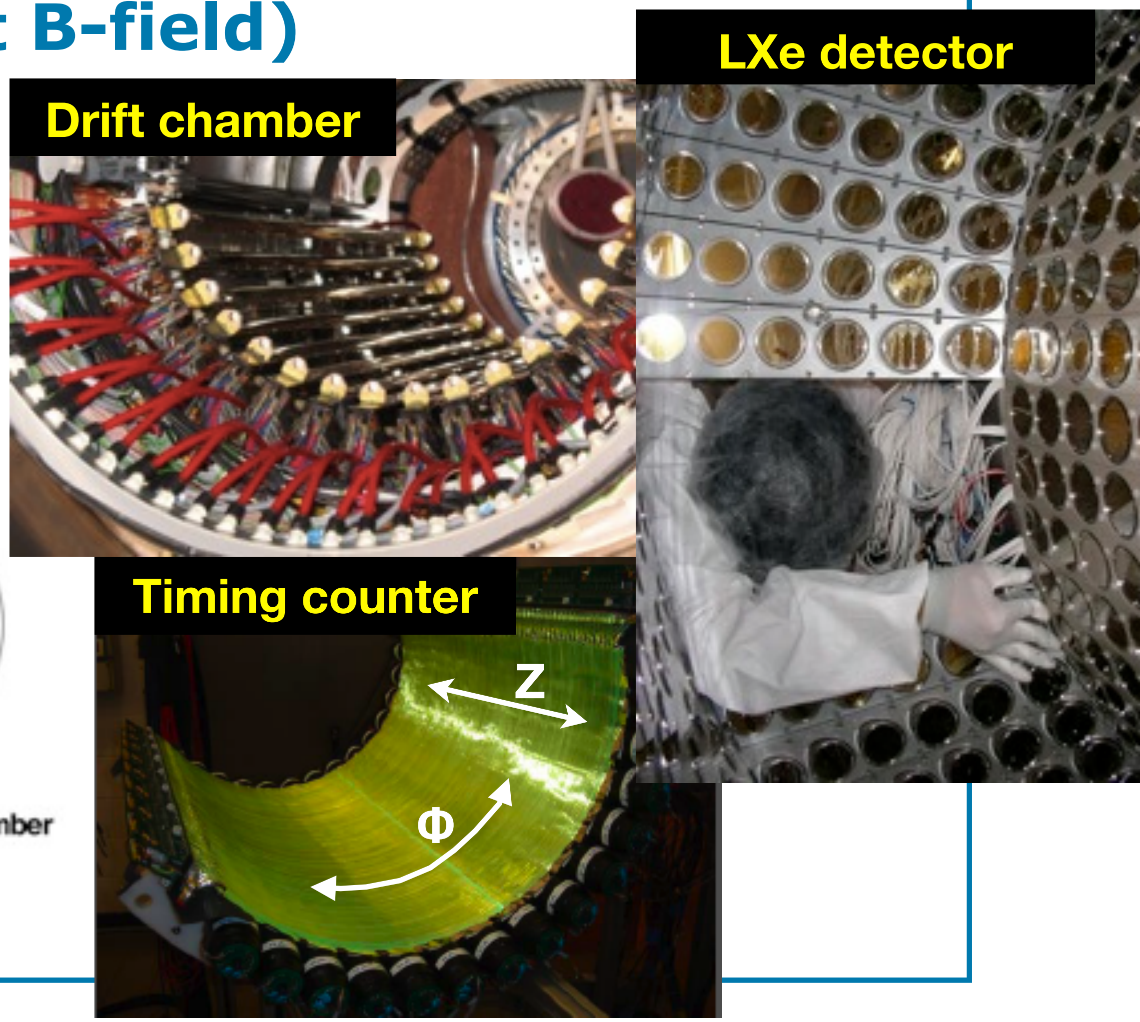


MEG Experiment

- World's most intense μ^+ beam at Paul Scherrer Institute (PSI) (3×10^7 μ^+/sec at MEG)
- Detectors
  - 900L LXe γ-ray detector with PMT readout
  - Positron spectrometer (low-mass drift chamber system +fast timing counter in gradient B-field)

MEG Detector

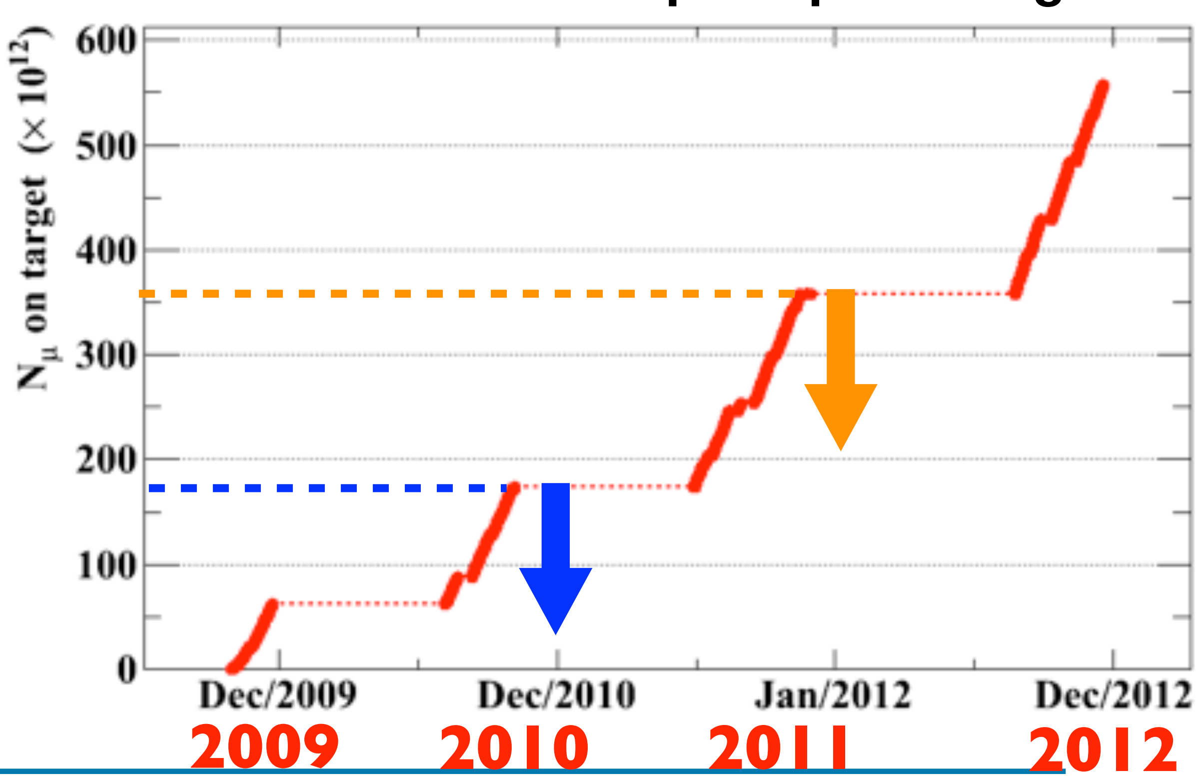




MEG History

- 1999: Approved at PSI
- -2007: Detector construction/commissioning/ engineering run
- 2008: DAQ started
- 2011: Published analysis result with 2009-2010 dataset (1.65×10^{14} μ^+/s)
  - $\mathcal{B} < 2.4\times10^{-12}$ (90% C.L.) (x5 more stringent than previous experiment)
- 2013: New result (this work)
  - Combined analysis of data 2009-2011 (3.6×10^{14} μ^+/s)
  - Improved analysis
    - 2009-2010 are also re-analyzed.

Accumulated # of μ^+ stops on target



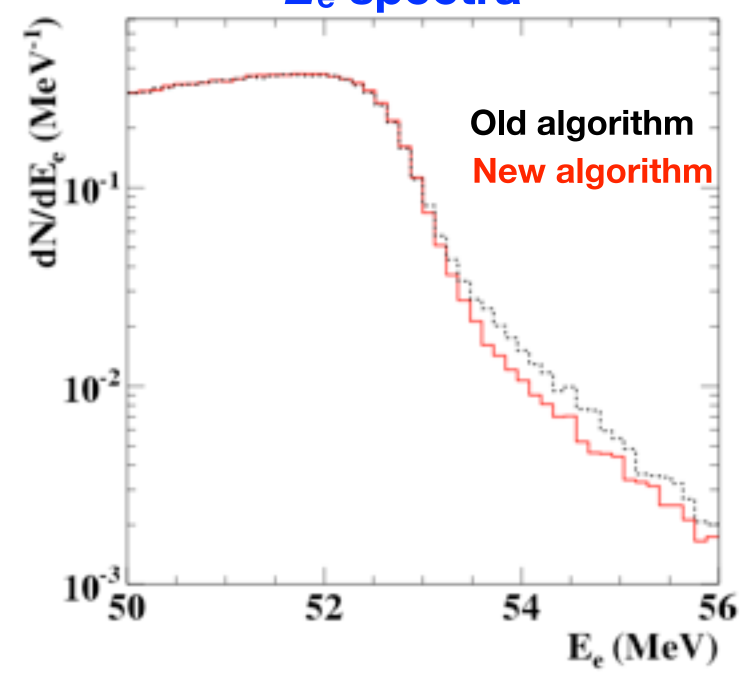
What's New in This Work

- Hardware improvements in run 2011
  - Higher resolution BGO array detector introduced in LXe energy calibration with CEX reaction ($\pi^+ p \to n\pi^0$, $\pi^0 \to 2\gamma$)
  - New optical survey technique with laser tracker
- New data and new analysis with improved algorithms
  - Reduced drift chamber noise with FFT filtering
    - Angular resolution improved by <10%
  - Totally revised track fit algorithm based on Kalman filter technique
    - Reduced tail in response function, 7% better efficiency, per-event error matrix introduced to likelihood analysis
  - Improved pileup elimination algorithm in LXe γ-detector
    - Less pileup, 7% better efficiency

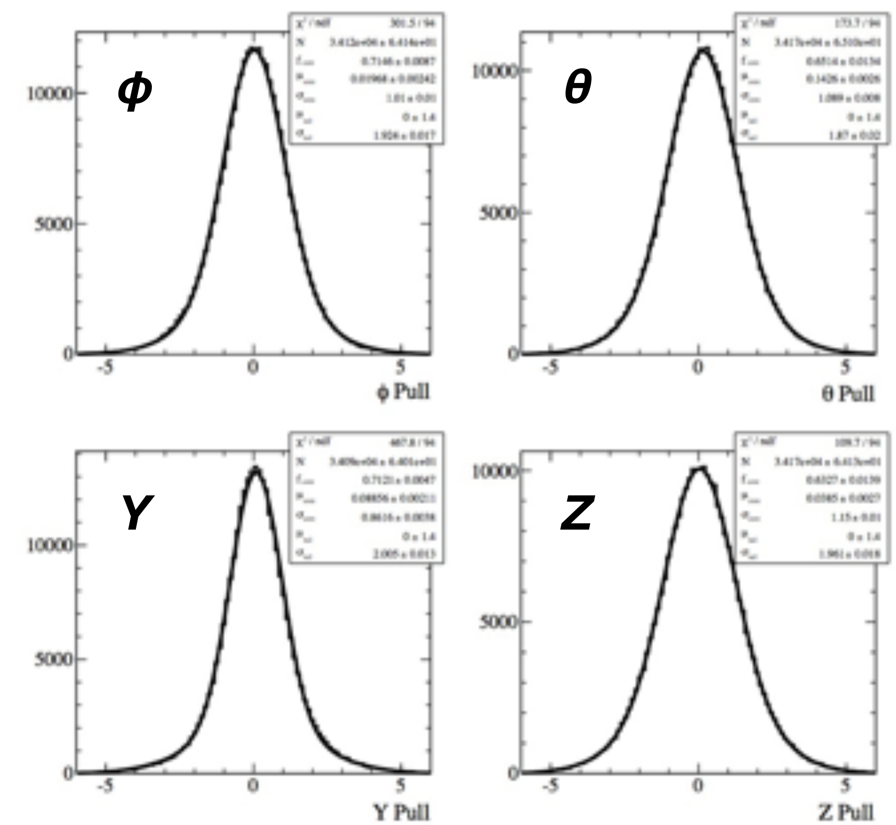
Track Fit wit Kalman Filter

- Improved track fit algorithm with **new Kalman filter**
  - Better modeling for hit with GEANE
  - Better modeling for detector materials
  - **Reduced tail and improved efficiency (7%)**
- **Per-event error matrix** provided by Kalman filter is incorporated in likelihood analysis
  - **Sensitivity is improved by about 10%.**

E_e spectra



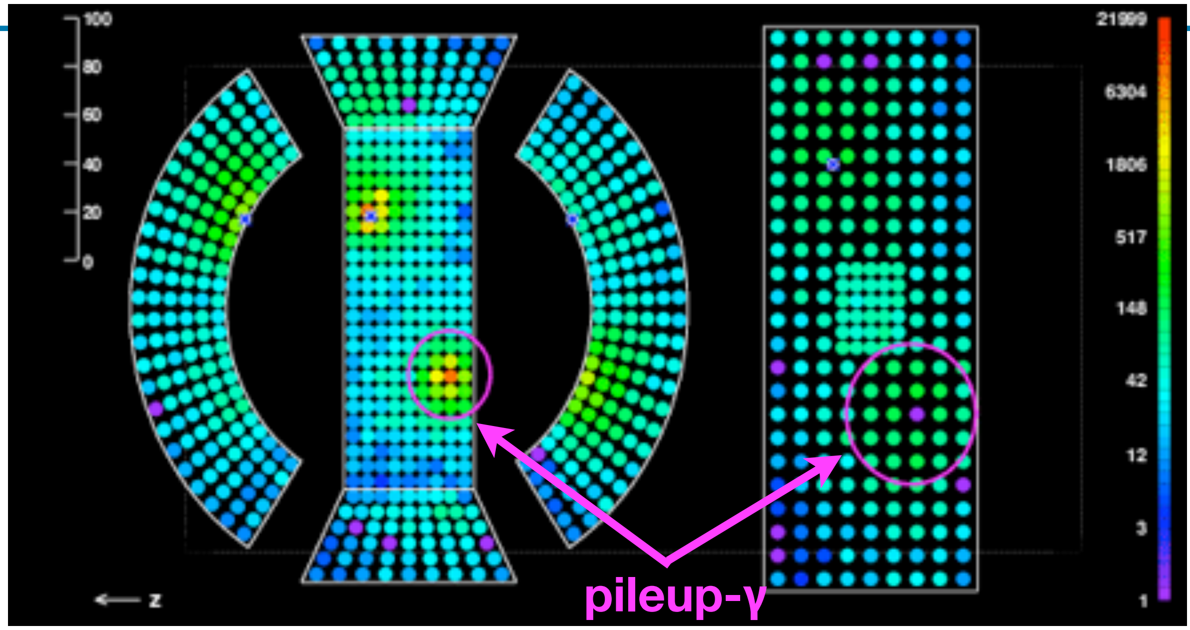
Pull distribution: $(x-x_{true})/\sigma_x$



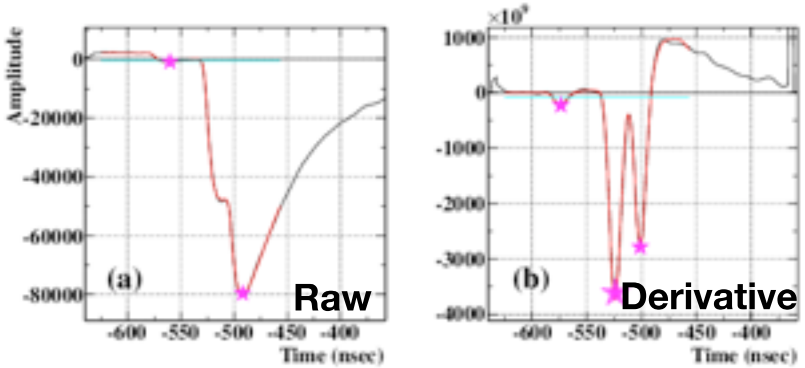
Pileup Elimination

- **15% probability of multiple BG γ-ray pileup at 3×10^{7} μ^{+}/sec.**
- **Pileup events are NOT discarded by removing pileup-γ.**
- **Pileup-γ is identified and removed by using**
  - **Pattern in PMT light distribution**
  - **PMT waveform ←Improved with detailed waveform analysis**
- **Efficiency improved by 7% in new analysis**

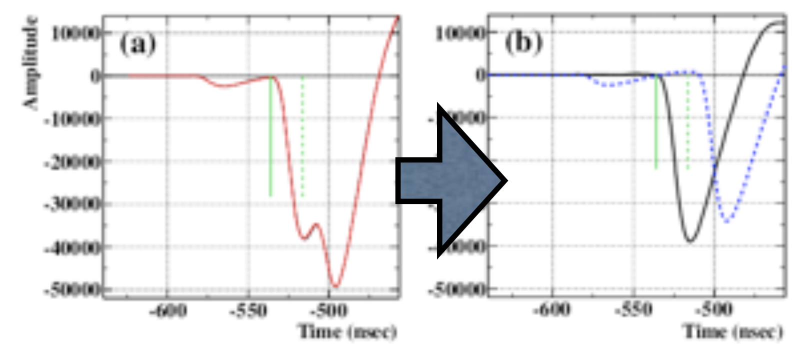
LXe γ-detector event display



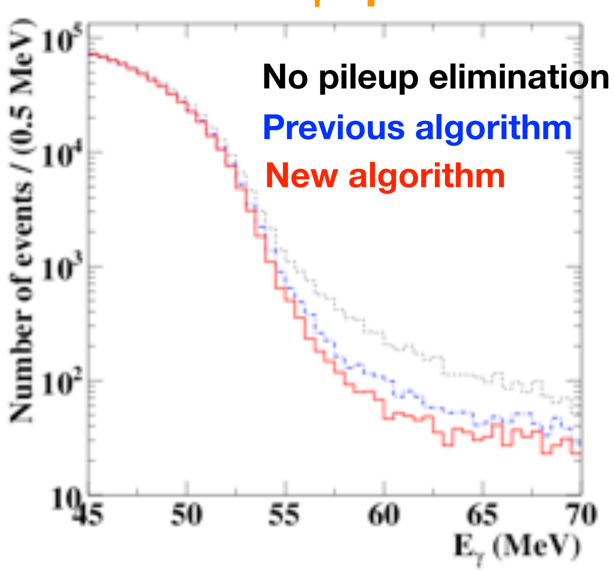
Peak search in waveform



Removal of pileups with template fit

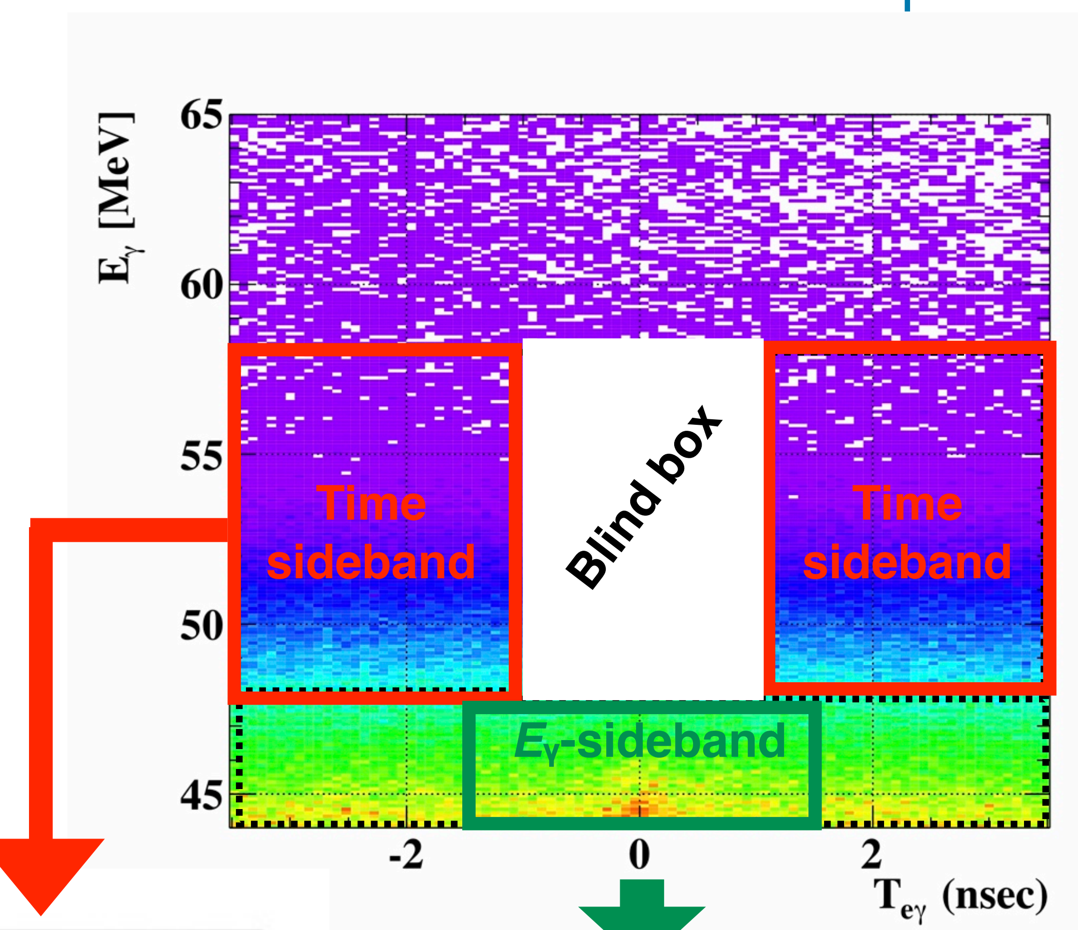


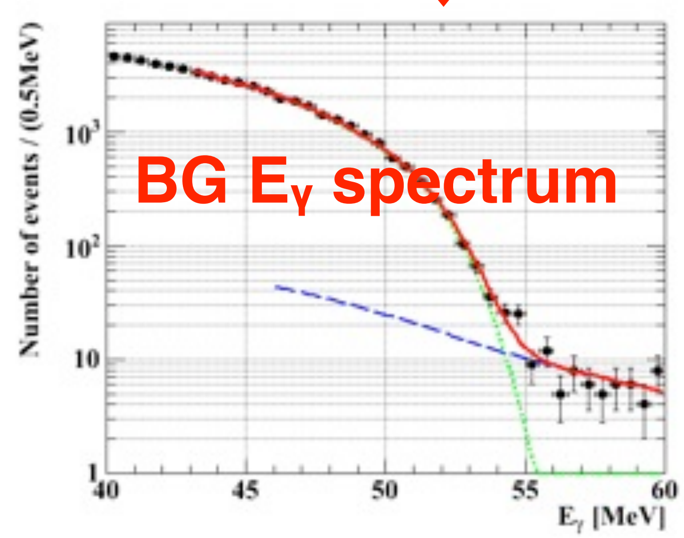
BG E_γ spectra

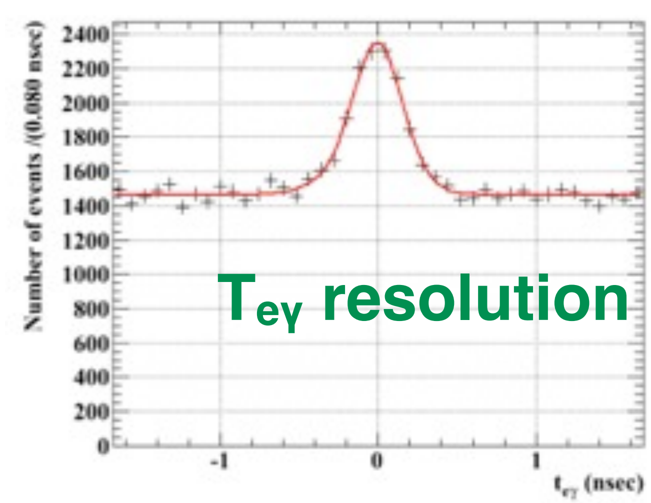


Physics Analysis Overview

- Five observables (E_e, E_γ, $\theta_{e\gamma}$, $\Phi_{e\gamma}$, $T_{e\gamma}$) to characterize $\mu \to e\gamma$ event
  - Back-to-back ($\theta_{e\gamma}=\Phi_{e\gamma}=0$)
  - Monoenergetic ($E_e=E_\gamma=52.8\text{MeV}(=m_\mu/2)$)
  - Coincident ($T_{e\gamma}=0$)
- Predominant BG: accidental overlap bw/ Michel e^+ and γ (AIF, RMD, brems.)
- Maximum likelihood analysis to extract N_{sig}
- Blind analysis procedure applied to new data in 2011







Maximum Likelihood Analysis

- Maximum likelihood analysis to estimate # of signal
  - Analysis region
    - $48<E_\gamma<58$MeV, $50<E_e<56$MeV, $|\theta_{e\gamma}|<50$mrad, $|\phi_{e\gamma}|<50$mrad, $|T_{e\gamma}|<0.7$ns
  - Event-by-event PDF
    - γ: position dependent resolutions
    - e: per-event error matrix from Kalman filter ← New

Signal PDF RMD* PDF BG** PDF

$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{e^{-N}}{N_{\rm obs}!} e^{-\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{2\sigma_{\rm RMD}^2}} e^{-\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{2\sigma_{\rm BG}^2}} \prod_{i=1}^{N_{\rm obs}} (N_{\rm sig} S(\vec{x}_i) + N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i))$$

$$\vec{x}_i = (E_e, E_\gamma, \theta_{e\gamma}, \phi_{e\gamma}, T_{e\gamma})$$

- Confidence interval of $N_{\rm sig}$ (or $\mathcal{B}$)
  - Frequentist approach with profile likelihood ratio ordering
  - $N_{\rm RMD}$, $N_{\rm BG}$ treated as nuisance parameters

$$\lambda_p(N_{\rm sig}) = \frac{\mathcal{L}(N_{\rm sig}, \hat{\hat{N}}_{\rm RMD}(N_{\rm sig}), \hat{\hat{N}}_{\rm BG}(N_{\rm sig}))}{\mathcal{L}(\hat{N}_{\rm sig}, \hat{N}_{\rm RMD}, \hat{N}_{\rm BG})}$$

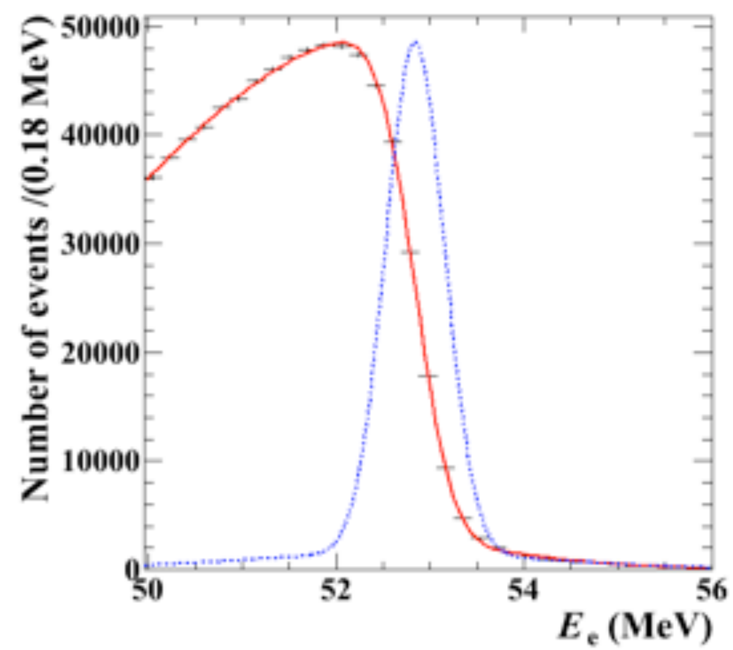
* RMD: radiative muon decay

** BG: accidental background

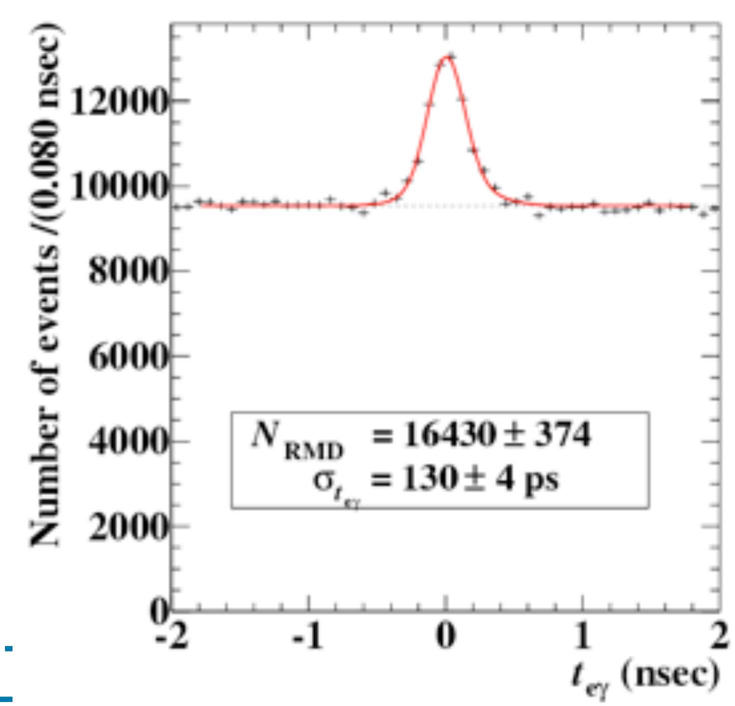
PDF

- Probability density functions (PDFs) for likelihood function are mostly extracted from data.
  - **Signal**: detector response function
  - **RMD**: Theoretical spectrum smeared by detector response
  - **BG**: Single BG spectrum measured at sidebands

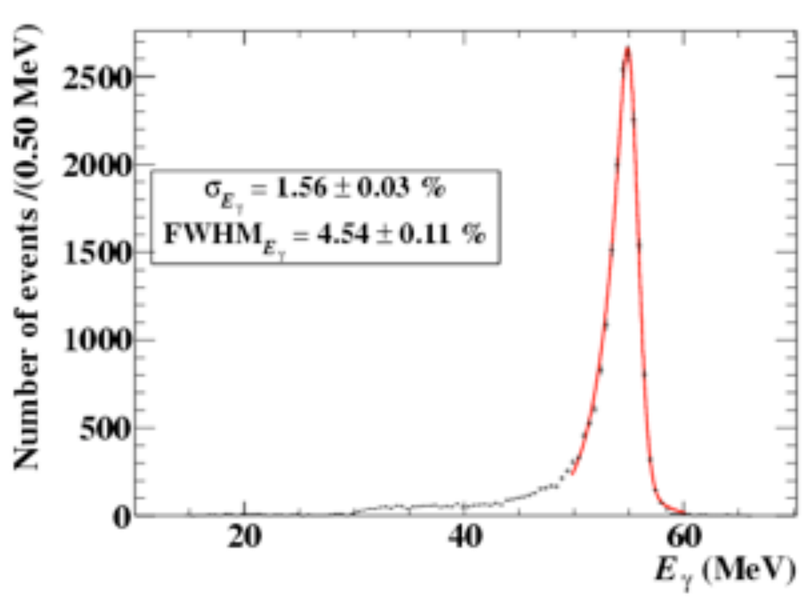
Signal/BG E_e (Michel spectrum)



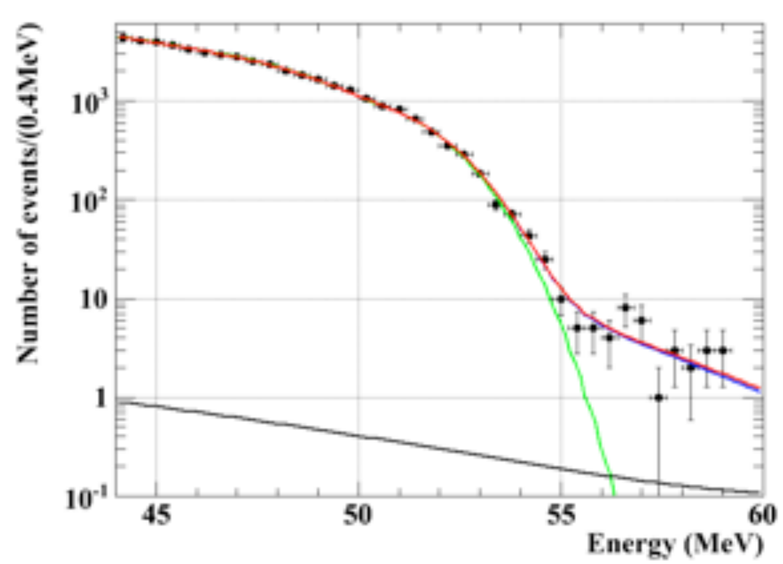
Signal $T_{e\gamma}$
(RMD peak in E_γ-sideband)



Signal E_γ (55MeV-γ from π^0-decay)



BG E_γ (time sideband)



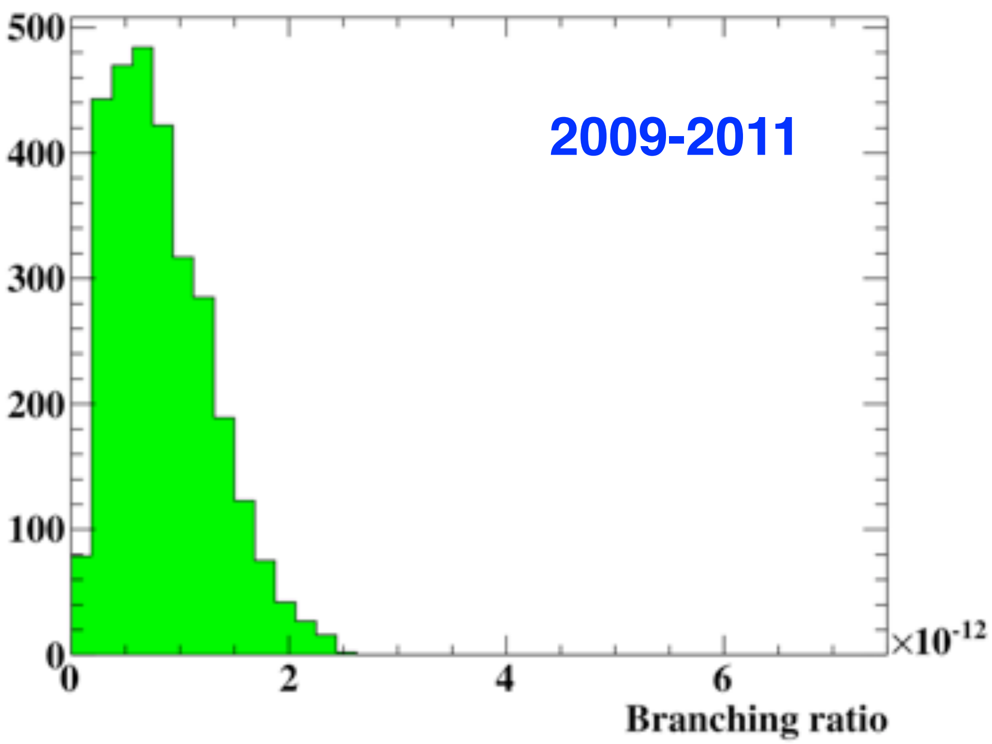
Sensitivity

- **Sensitivity**: 90% C.L. upper limit averaged over pseudo-experiments based on null-signal hypothesis with expected rates of RMD and BG.
- **~20% improvement** in total with new algorithms
- **MEG has started exploring $\mathcal{B}$ ~10^{-13} region!**

	μ^+ stops	Sensitivity
2009-2010	1.75×10^{14}	1.3×10^{-12}*
2011	1.85×10^{14}	1.1×10^{-12}
2009-2011	3.60×10^{14}	7.7×10^{-13}

* 1.6×10^{-12} in previous analysis

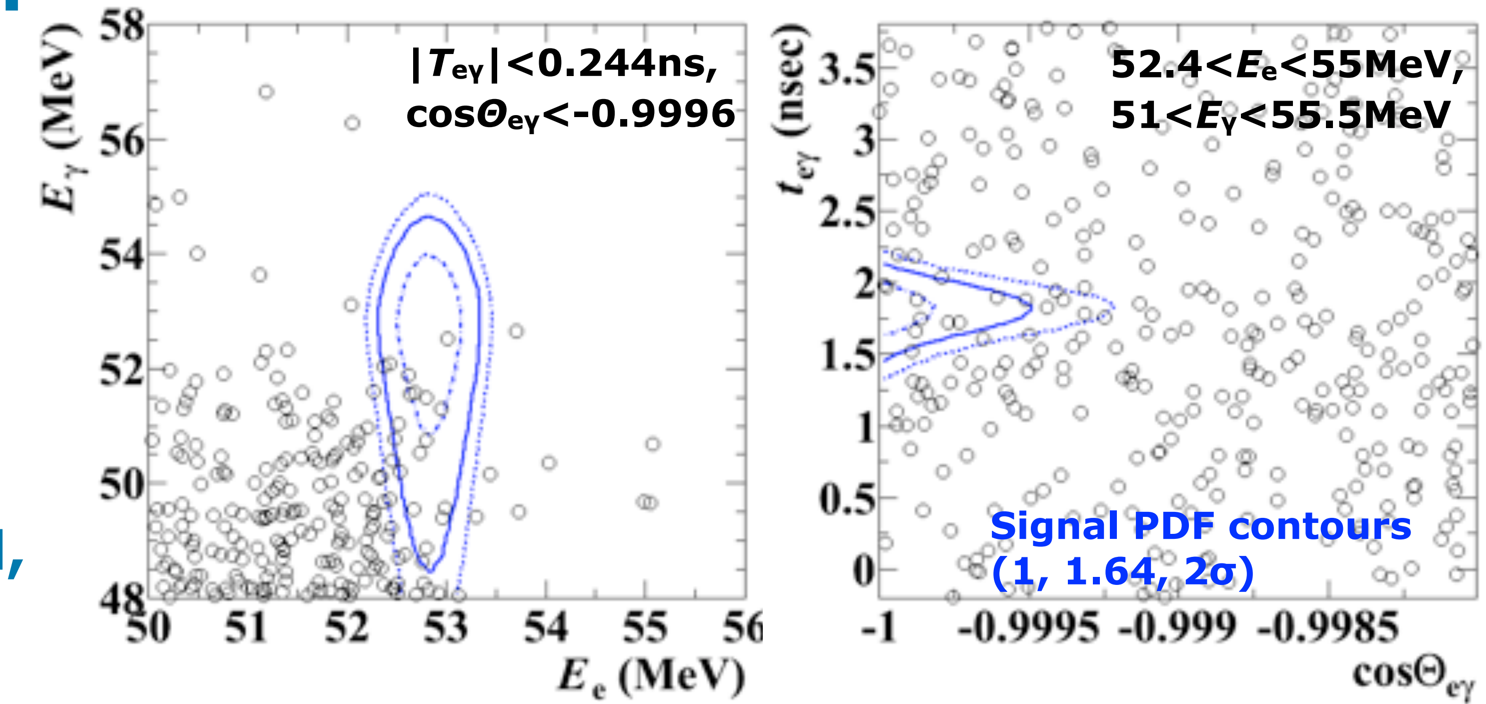
Distribution of 90%UL in pseudo exp.

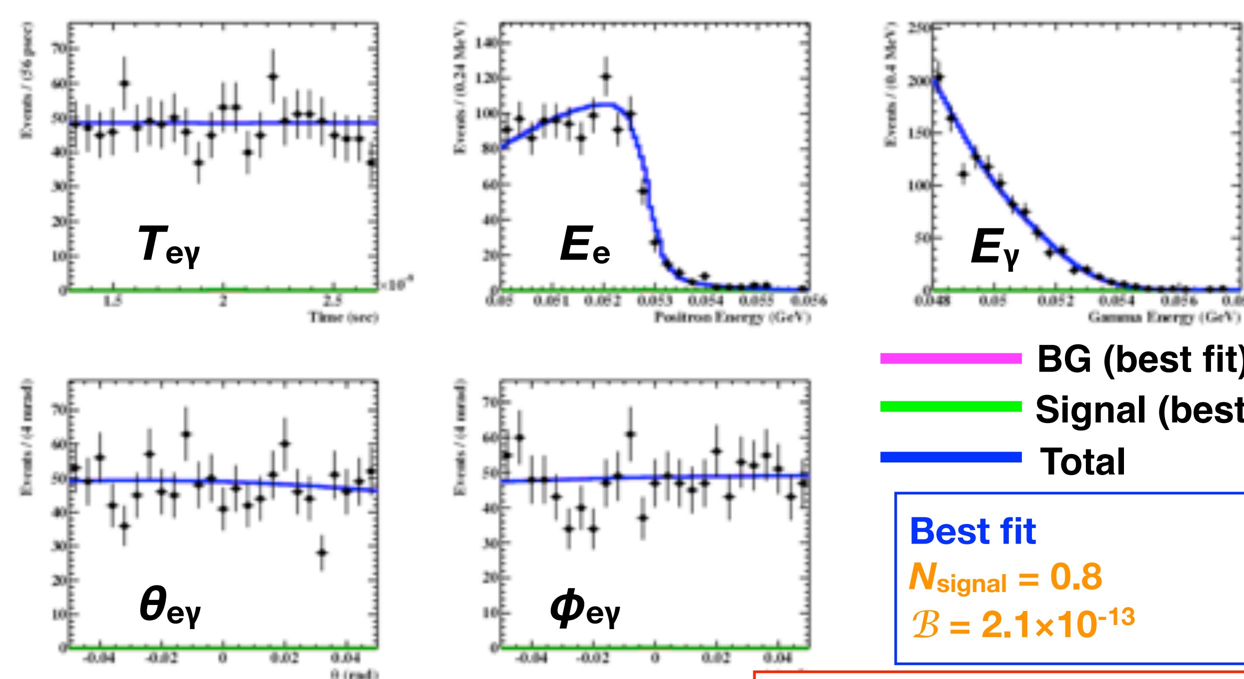


Sideband Fit

- Likelihood analyses in fictitious analysis regions in sidebands.
  - **Off-time sideband**
    $1.3<|T_{e\gamma}|<2.7$ns
  - **Off-angle sideband**
    $50<|\theta_{e\gamma}|(|\phi_{e\gamma}|)<150$mrad,
    $|T_{e\gamma}|<0.7$ns
- **Observed upper limits are consistent with sensitivity.**

Off-time sideband (2011 alone)





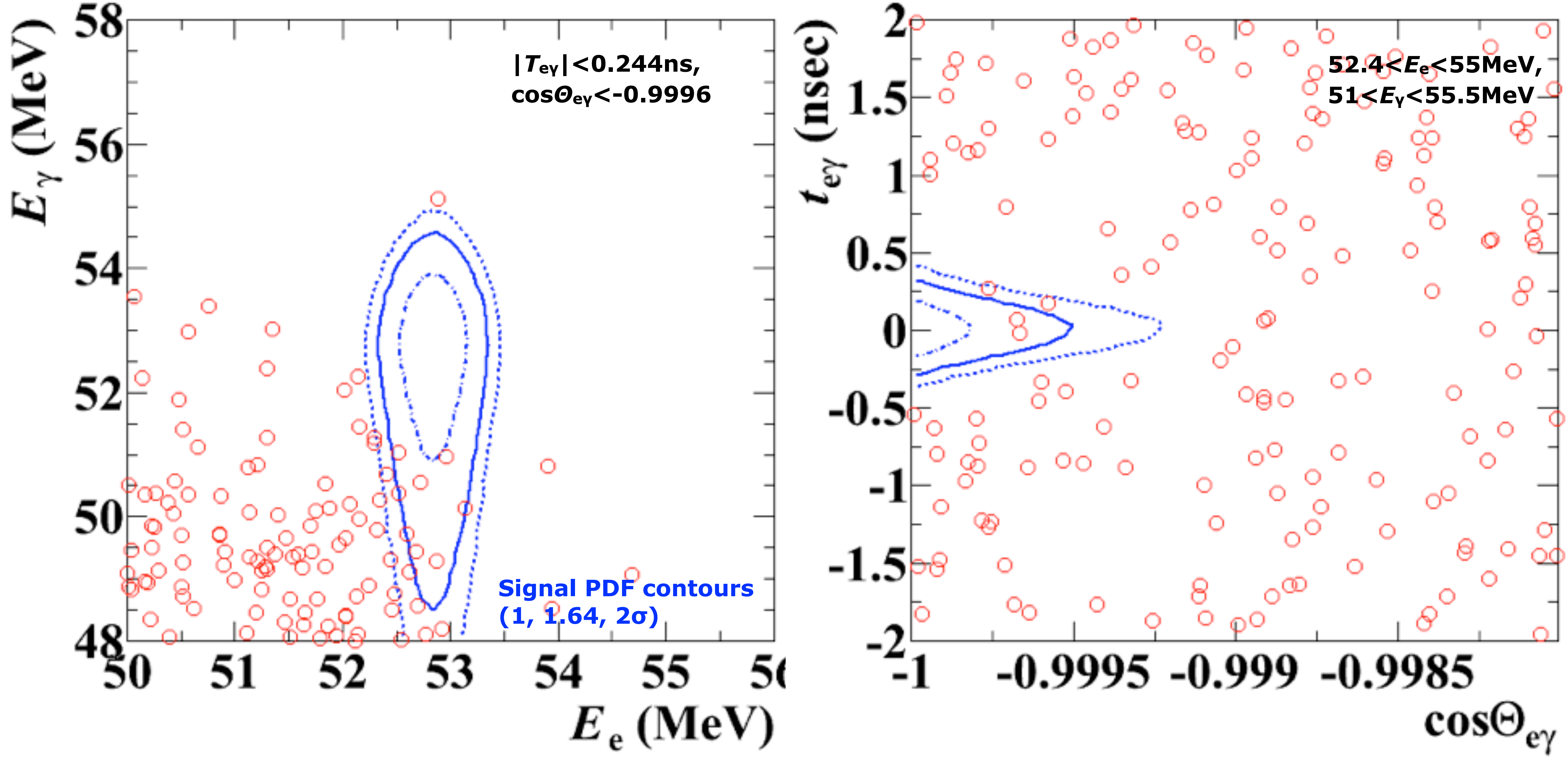
BG (best fit)
Signal (best fit)
Total

Best fit
$N_{signal} = 0.8$
$\mathcal{B} = 2.1\times10^{-13}$

$\mathcal{B}<1.4\times10^{-12}$ (90%C.L.)

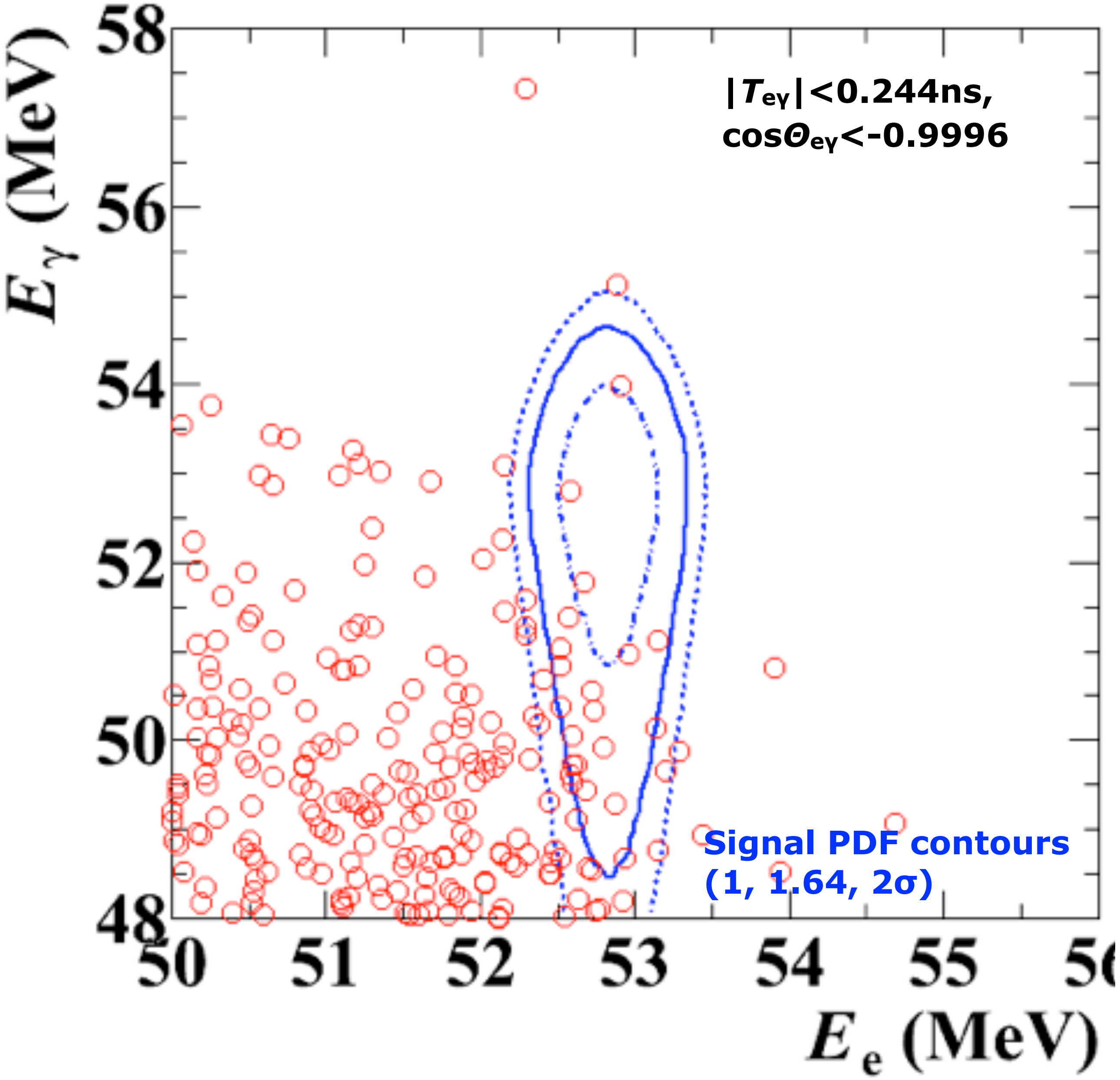
Event Distribution

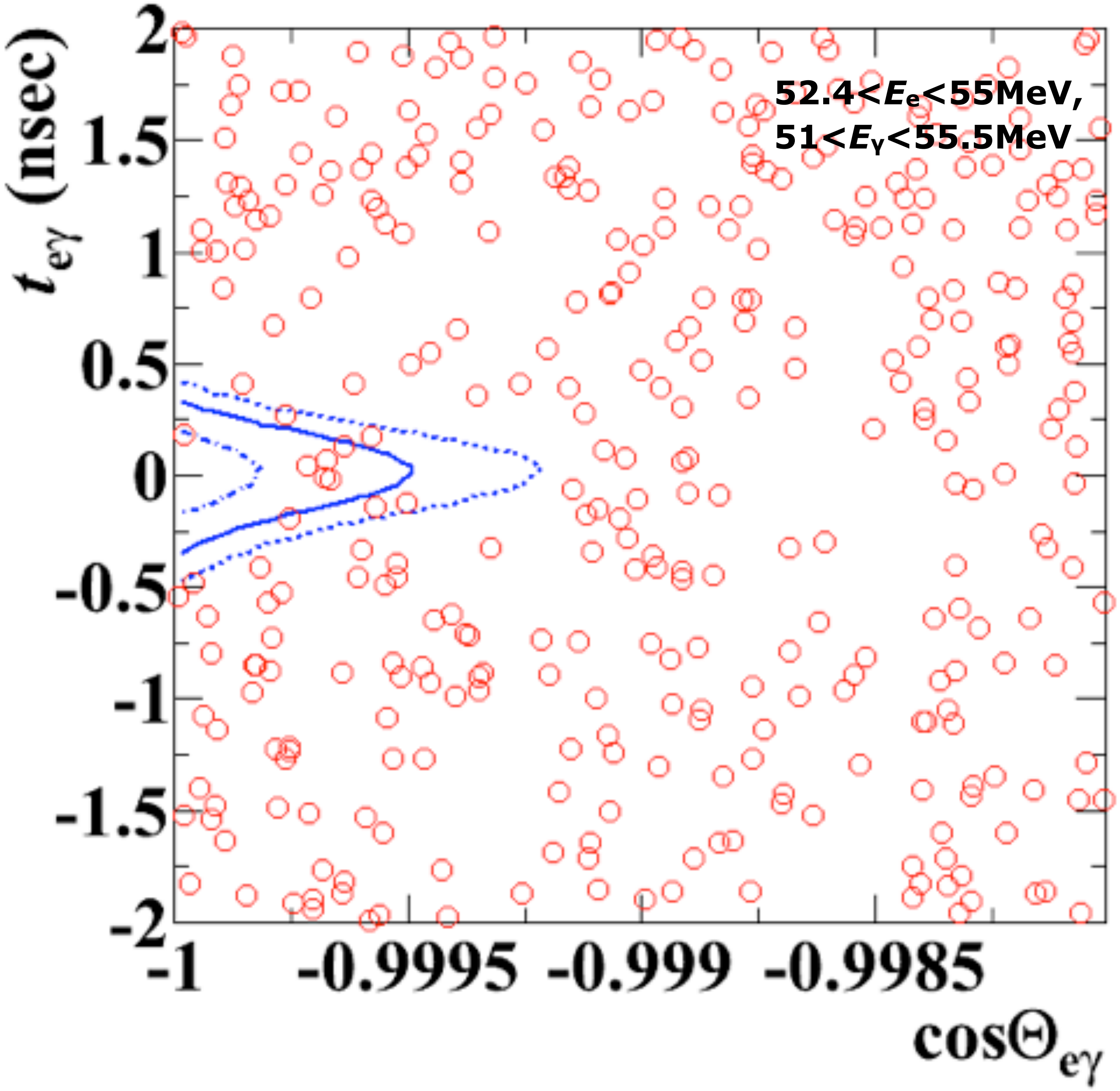
- 2011 alone



Event Distribution

- 2009-2011 all combined

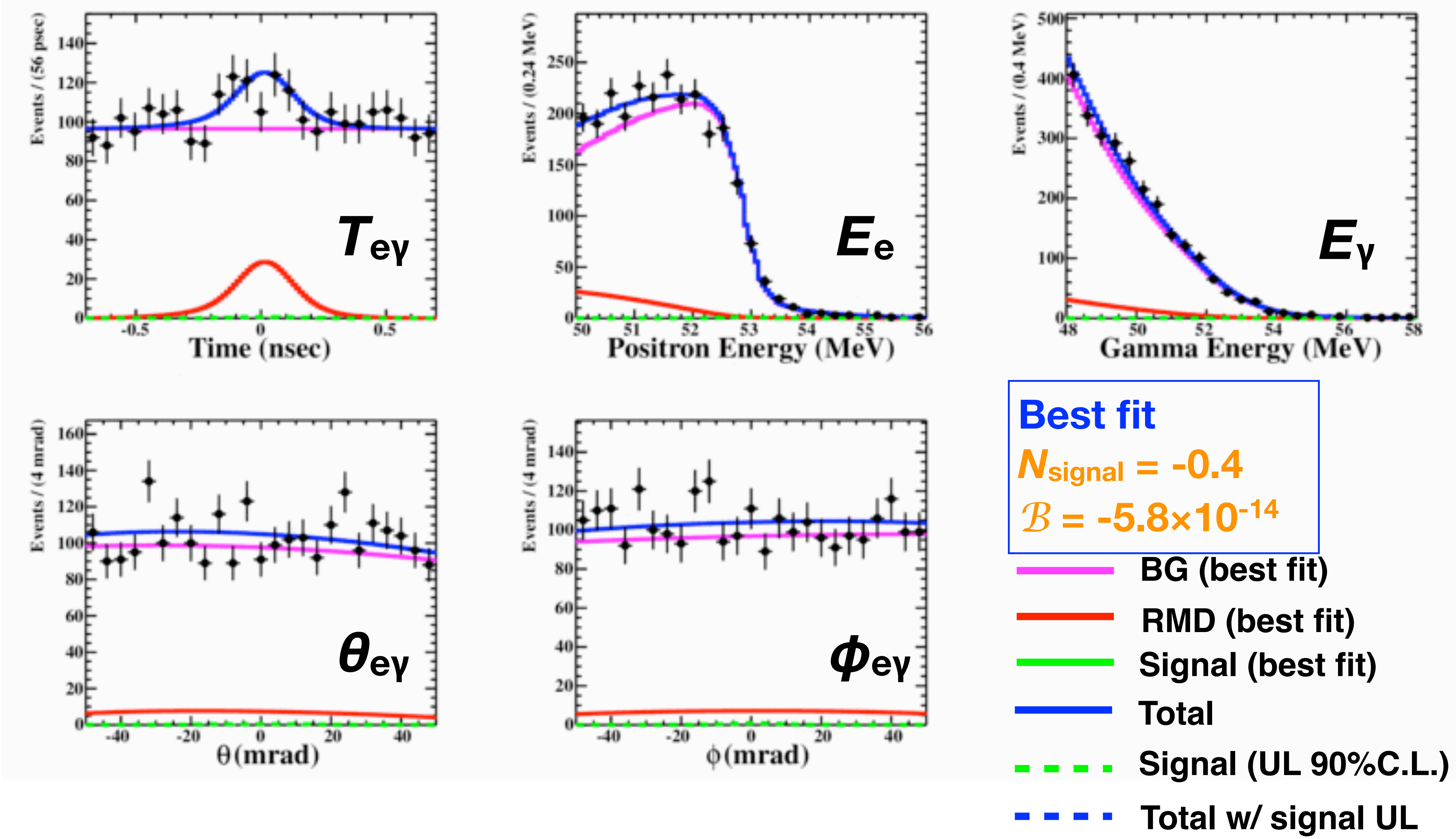




Likelihood Fit

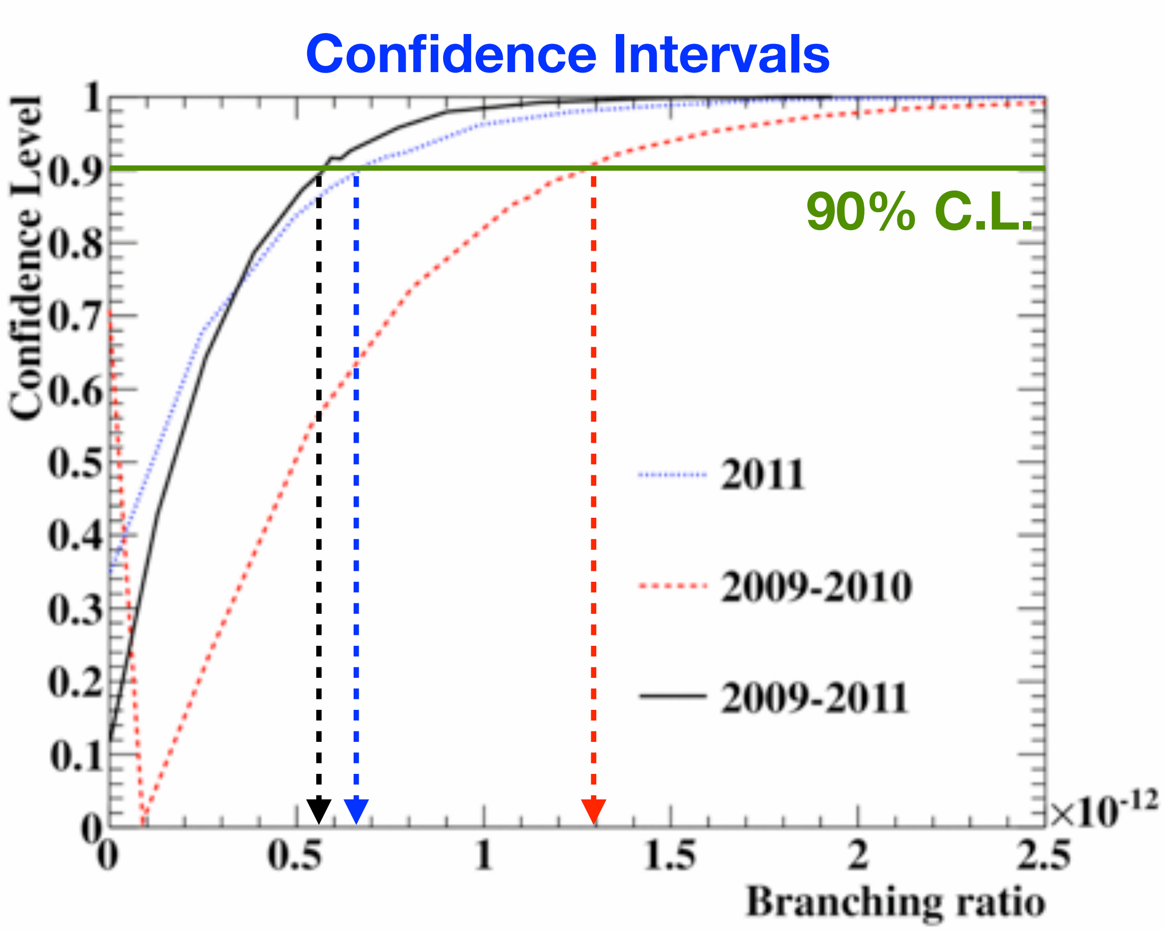
- **No excess over expected background is observed in analyzed dataset.**

Projection of fitted likelihood function (2009-2011 all combined)

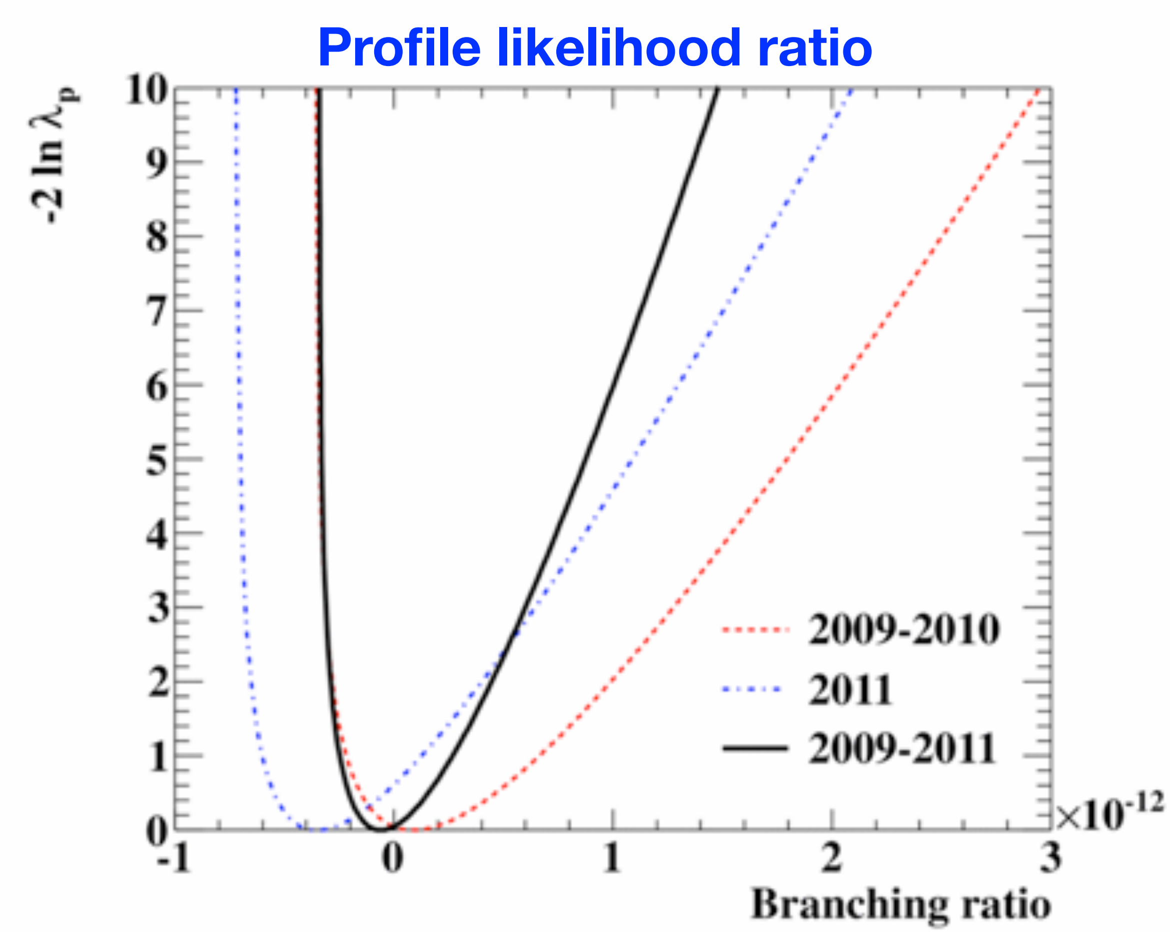


Confidence Interval

- Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering
- Consistent with null-signal hypothesis



CL curve: Allowed region of branching ratio can be read at given confidence level.



N.B. likelihood curves are not directly used in confidence interval calculation

Likelihood Analysis Summary

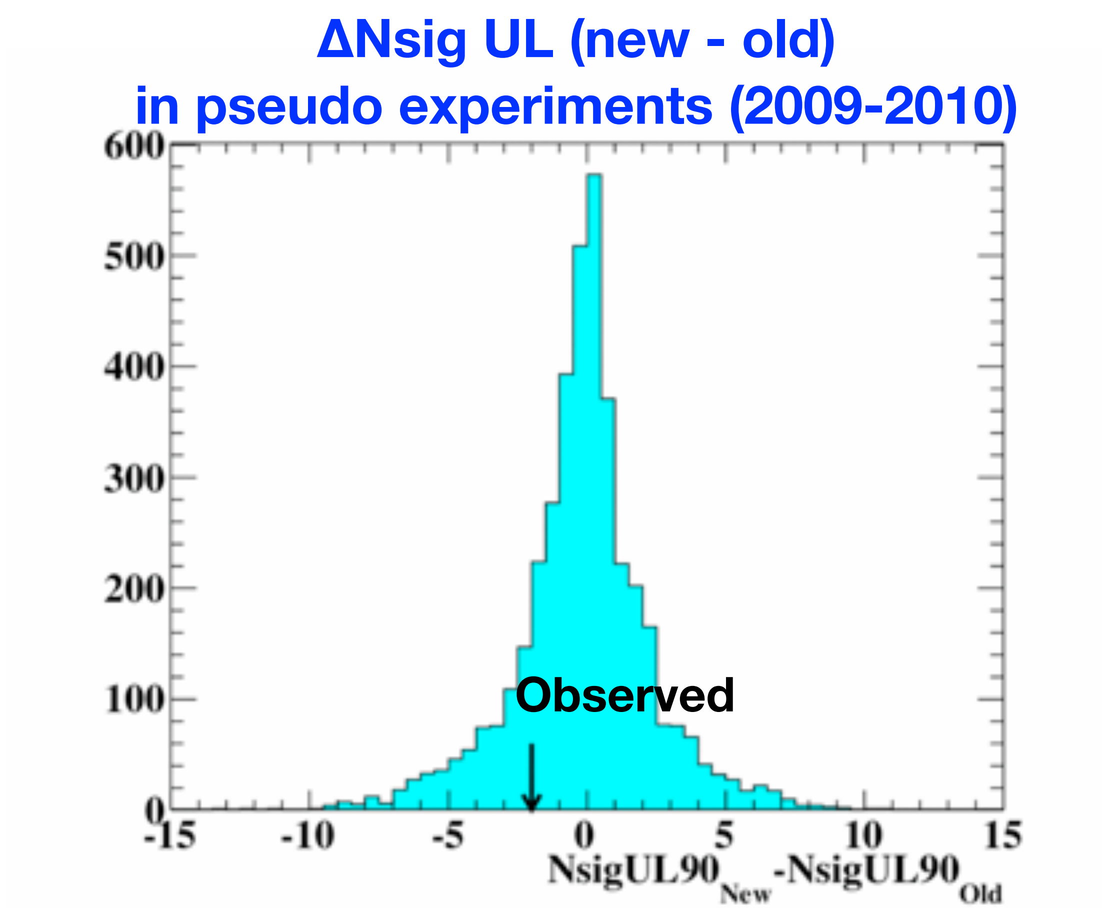
Fit results on branching ratio

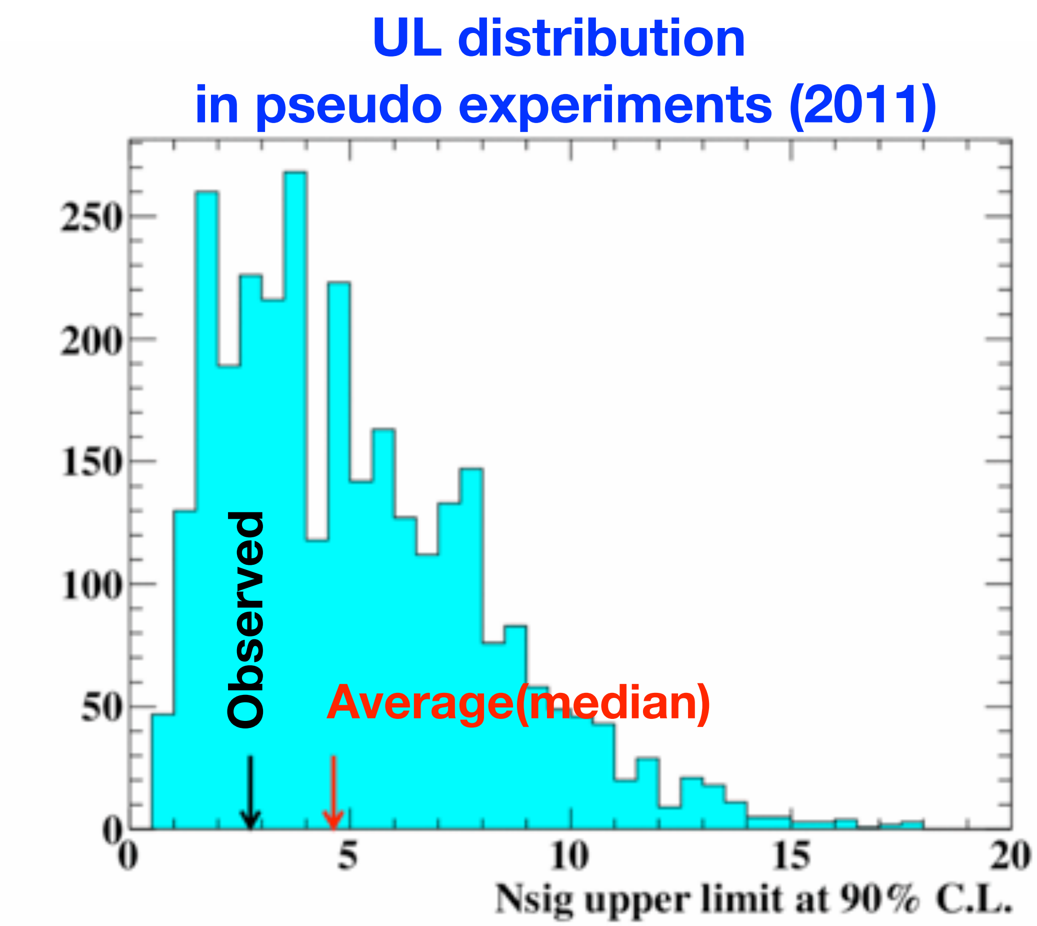
	Best fit	Upper limit (90% C.L.)	Sensitivity
2009-2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	$\boxed{5.7\times10^{-13}}$	7.7×10^{-13}

- **Upper limit from all combined dataset:**
  - **$\mathcal{B}<5.7\times10^{-13}$ (90%C.L.)**
- **×4 more stringent than the present upper limit**

Consistency Check

- Compatibility bw/ new and old analyses: 31%
- Probability to observe UL equal or lower than observed in 2011: 24%





Quality Check

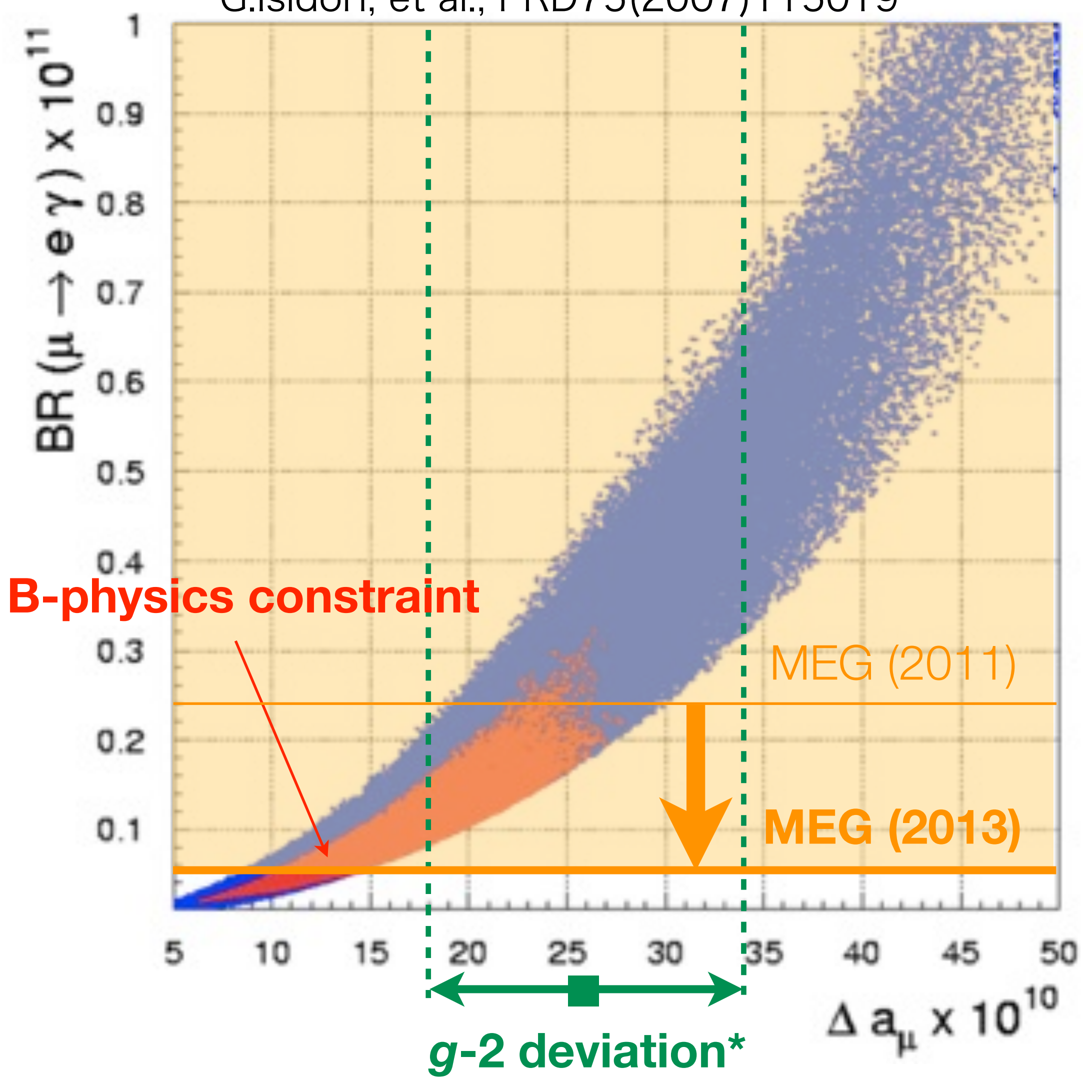
- N_{BG} and N_{RMD} are estimated in likelihood fit without imposing constraints from the rates expected from the time- and E_{γ}-sideband measurements
- The estimates are in good agreement with the expectation.
- Validated our estimation on BG an RMD at sidebands

	Best Fit	Expected
BG	2411±57	2415±25
RMD	163±32	169±17

Constraints on BSM Physics

SUSY-GUT

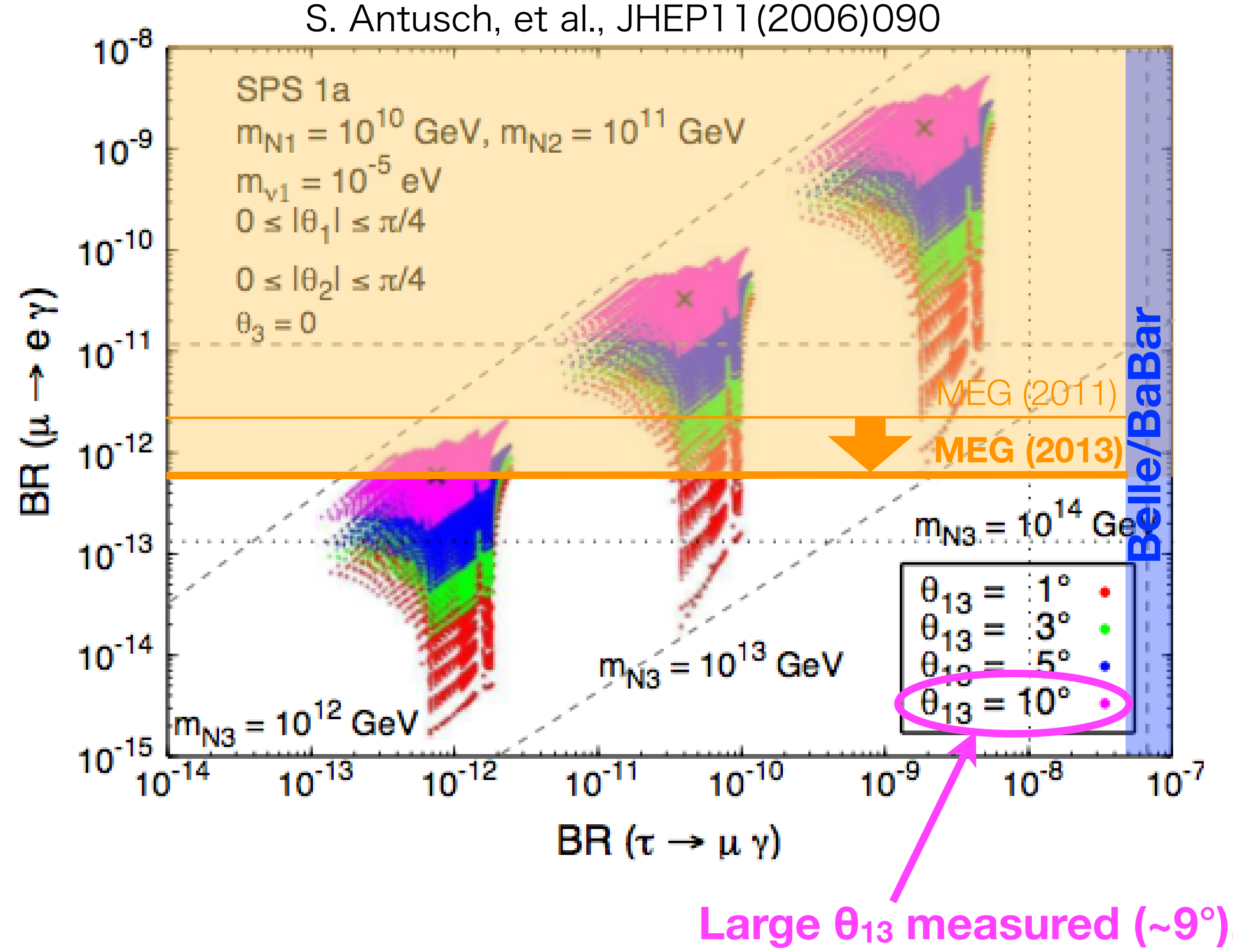
G.Isidori, et al., PRD75(2007)115019



* a_μ(EXP):PRD73(2006)072,
a_μ(SM):Hagiwara et al., JPG38(2011)085003

SUSY-Seesaw

S. Antusch, et al., JHEP11(2006)090



For More Details

arXiv:1303.0754 (submitted to Phys. Rev. Lett.)

New constraint on the existence of the $\mu^+ \to e^+\gamma$ decay

J. Adam,[1,2] X. Bai,[3] A. M. Baldini[a],[4] E. Baracchini,[3,5,6] C. Bemporad[ab],[4] G. Boca[ab],[7] P. W. Cattaneo[a],[7] G. Cavoto[a],[8] F. Cei[ab],[4] C. Cerri[a],[4] A. de Bari[ab],[7] M. De Gerone[ab],[9] T. Doke,[10] S. Dussoni[a],[4] J. Egger,[1] K. Fratini[ab],[9] Y. Fujii,[3] L. Galli[a],[1,4] G. Gallucci[ab],[4] F. Gatti[ab],[9] B. Golden,[6] M. Grassi[a],[4] A. Graziosi,[8] D. N. Grigoriev,[11] T. Haruyama,[5] M. Hildebrandt,[1] Y. Hisamatsu,[3] F. Ignatov,[11] T. Iwamoto,[3] D. Kaneko,[3] P.-R. Kettle,[1] B. I. Khazin,[11] N. Khomotov,[11] O. Kiselev,[1] A. Korenchenko,[12] N. Kravchuk,[12] G. Lim,[6] A. Maki,[5] S. Mihara,[5] W. Molzon,[6] T. Mori,[3] D. Mzavia,[12] R. Nardò,[7] H. Natori,[5,3,1] D. Nicolò[ab],[4] H. Nishiguchi,[5] Y. Nishimura,[3] W. Ootani,[3] M. Panareo[ab],[13] A. Papa,[1] R. Pazzi[ab],[4] G. Piredda[a],[8] A. Popov,[11] F. Renga[a],[8,1] E. Ripiccini,[8] S. Ritt,[1] M. Rossella[a],[7] R. Sawada,[3] F. Sergiampietri[a],[4] G. Signorelli[a],[4] S. Suzuki,[10] F. Tenchini[ab],[4] C. Topchyan,[6] Y. Uchiyama,[3,1] R. Valle[ab],[9] C. Voena[a],[8] F. Xiao,[6] S. Yamada,[5] A. Yamamoto,[5] S. Yamashita,[3] Z. You,[6] Yu. V. Yudin,[11] and D. Zanello[a8]

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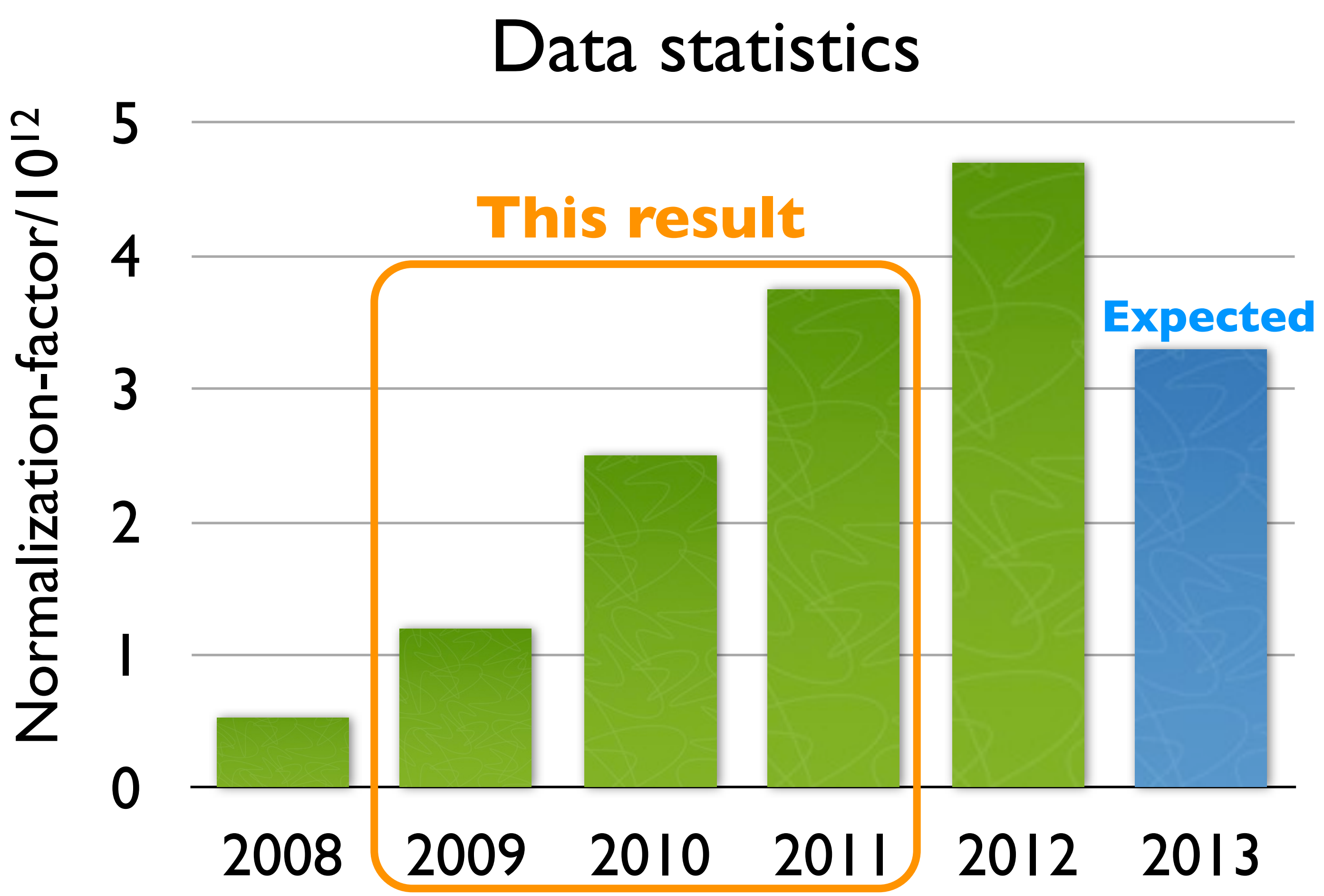
(Dated: March 4, 2013)

The analysis of a combined dataset, totaling 3.6×10^{14} stopped muons on target, in the search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ is presented. The data collected by the MEG experiment at the Paul Scherrer Institut show no excess of events compared to background expectations and yield a new upper limit on the branching ratio of this decay of 5.7×10^{-13} (90% confidence level). This represents a four times more stringent limit than the previous world best limit set by MEG.

Prospects

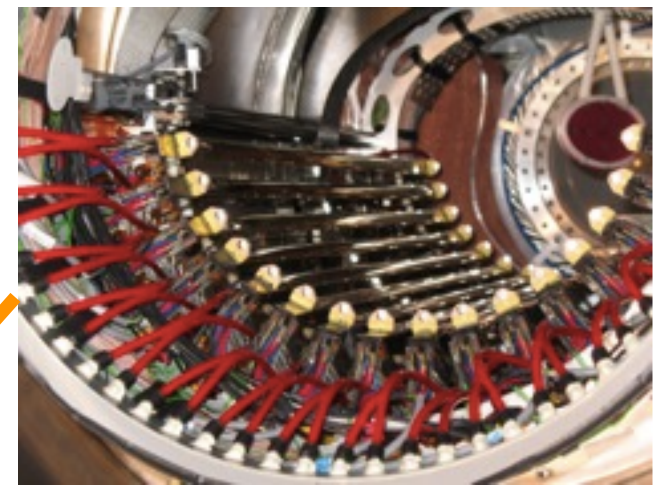
- MEG will continue DAQ till summer in 2013.
- Data statistics will be doubled with 2012+2013(expected).

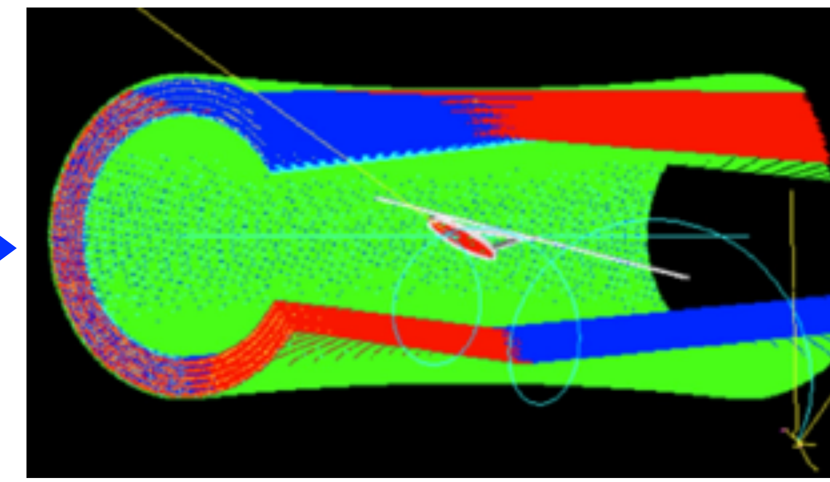


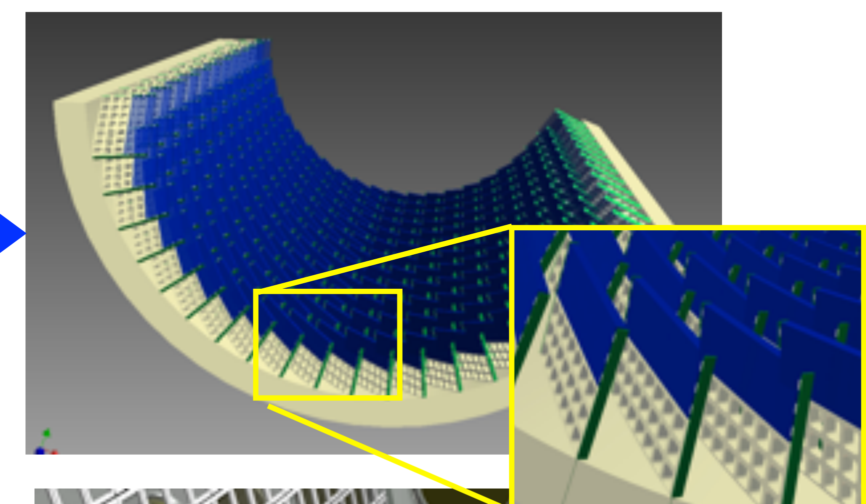
- But this is not the end of the story...

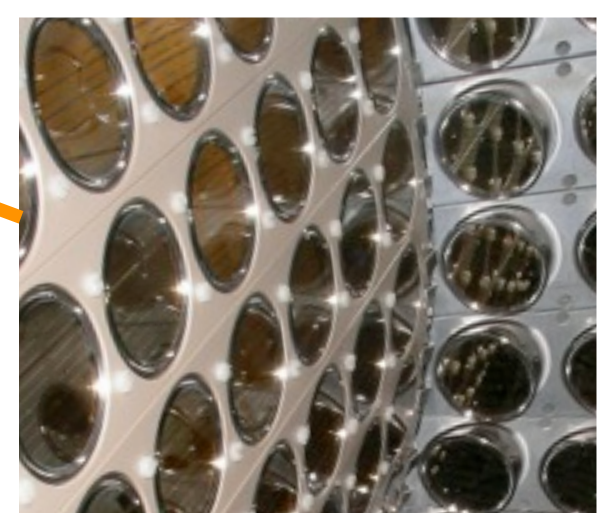
MEG Upgrade

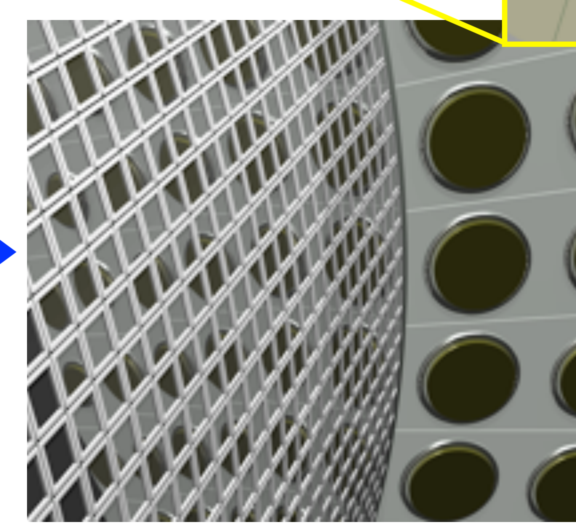
- **MEG upgrade proposal approved at PSI in Jan. 2013**
- **Upgraded items**
  - Higher μ intensity
  - Single volume drift chamber with stereo angle wire configuration
  - Pixelated timing counter with SiPM readout
  - LXe detector with SiPM readout
  - Thinner target











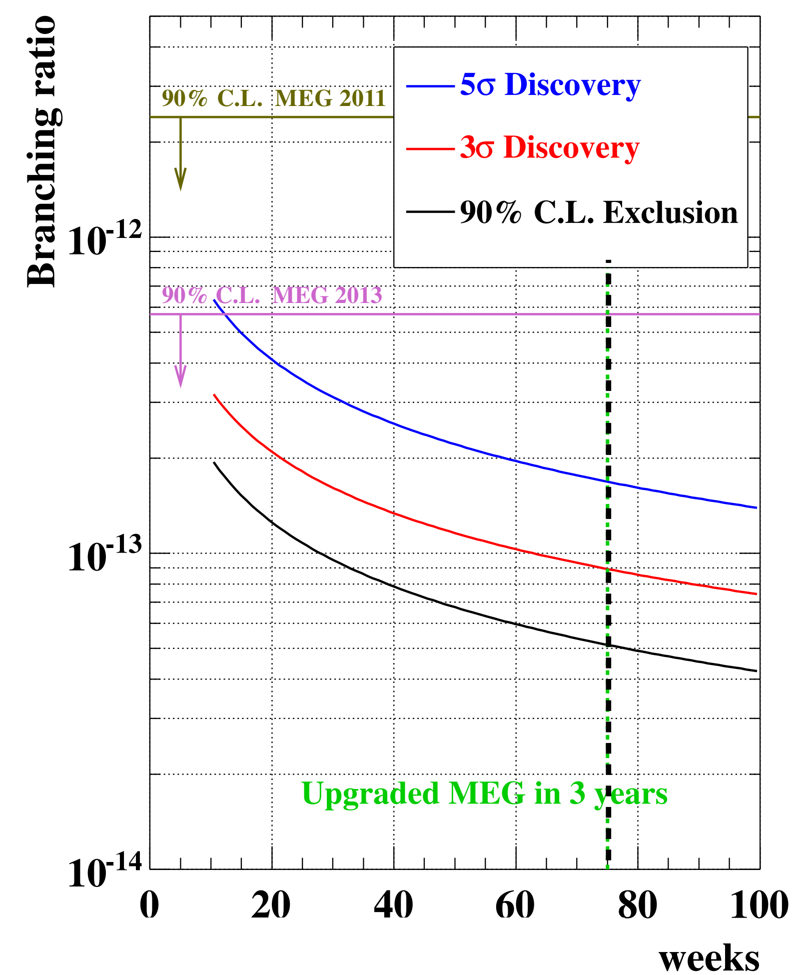
MEG Upgrade

- **Upgraded MEG** is expected to explore down to $\mathcal{B}\sim 5\times10^{-14}$ in three years!
  - **×10 improvement** w.r.t. current MEG
- More details in arXiv:1301.7225

Expected performance

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

Projected sensitivity



MEG upgrade timeline

Summary

- MEG has searched for lepton flavor violating decay, $\mu \to e\gamma$, with combined data sample for 2009-2011.
- The events observed in the dataset is found to be consistent with null-signal hypothesis.
- Established ×4 more stringent upper limit on branching ratio
  - $\mathcal{B}(\mu^+ \to e^+\gamma) < 5.7\times10^{-13}$ (90% C.L.)
- The data statistics is expected to be doubled by summer 2013.
- MEG upgrade program has been approved by the PSI committee in Jan. 2013.
- Upgraded MEG with an ultimate sensitivity (×10 higher than current MEG) is planned to start in 2016.

Thank You for Your Attention!

MEG collaboration

~60 physicists from 12 institutes from 5 countries

Backup Slides

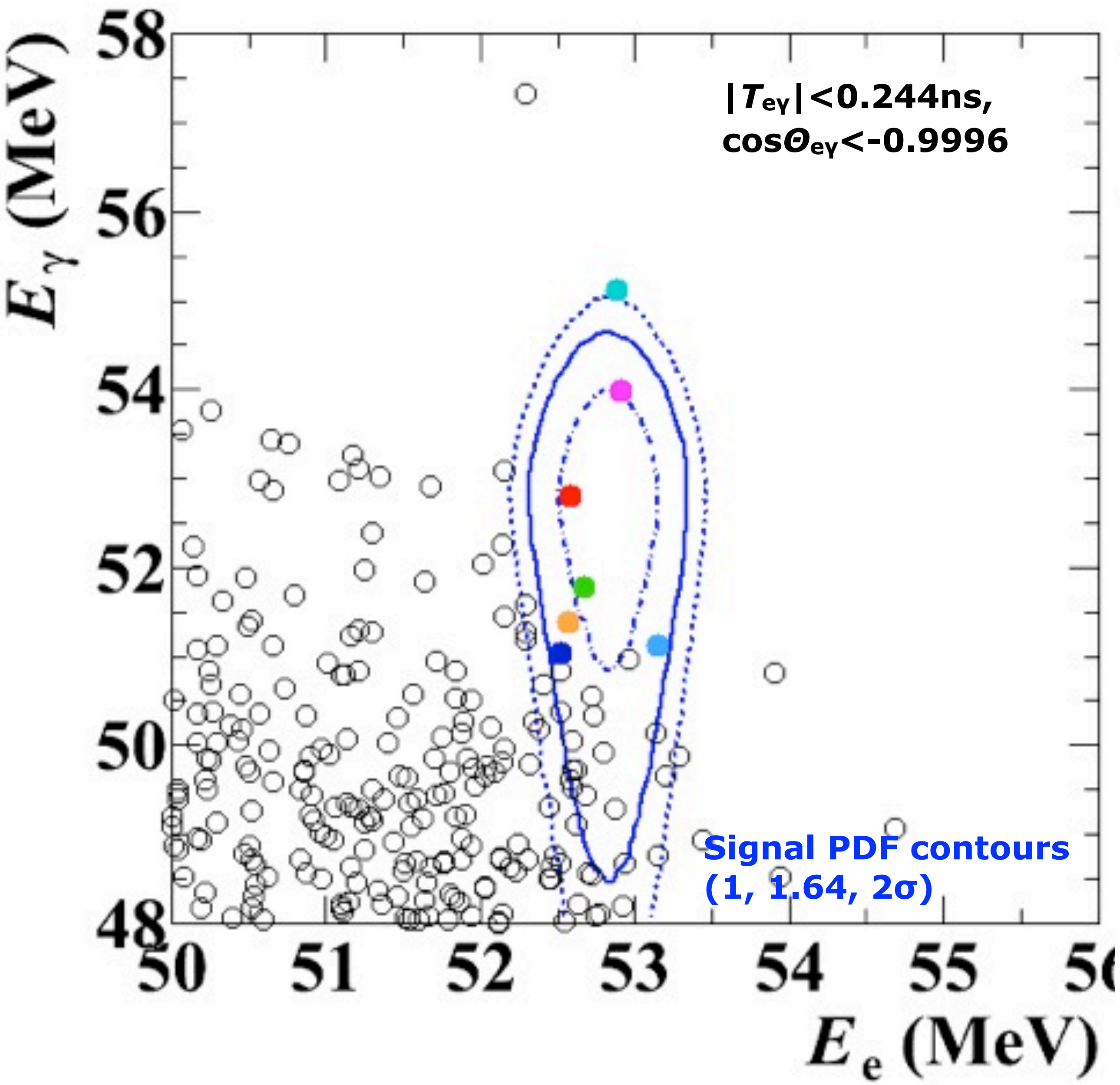
Normalization

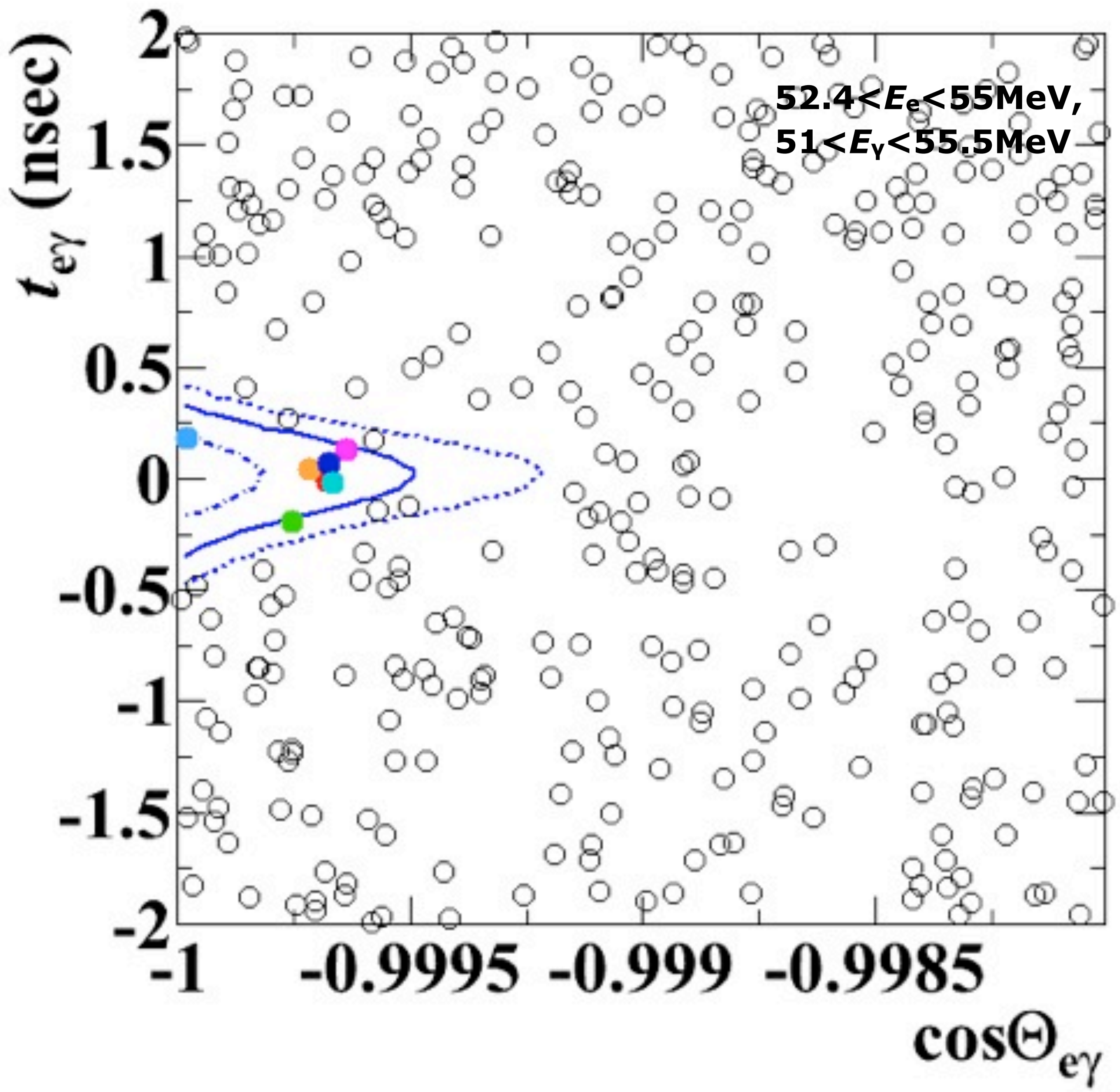
- Normalization to translate N_{sig} into $\mathcal{B}$
  - Two independent methods
    - Michel positrons counted with dedicated trigger
    - RMD rate observed at E_γ-sideband
- Combined estimate results in 4% uncertainty

$$
\begin{aligned}
N_{sig} &= N_\mu \times \boxed{Br_{e\gamma}} \times \tau_{e\gamma} \times \epsilon^{trig}_{e\gamma} \times G^{DC}_{e\gamma} \times A^{TC}_{e\gamma} \times \epsilon^{DC}_{e\gamma} \times A^{LXe}_{e\gamma} \times \epsilon^{LXe}_{e\gamma} \\
N_{e\nu\bar{\nu}} &= N_\mu \times Br_{e\nu\bar{\nu}} \times \tau_{e\nu\bar{\nu}} \times \epsilon^{trig}_{e\nu\bar{\nu}} \times G^{DC}_{e\nu\bar{\nu}} \times A^{TC}_{e\nu\bar{\nu}} \times \epsilon^{DC}_{e\nu\bar{\nu}} \times f^{E}_{e\nu\bar{\nu}} \times P
\end{aligned}
$$

$$
\mathrm{BR}(\mu^+ \to e^+\gamma) = \frac{N_{\mathrm{signal}}}{N_{e\nu\bar{\nu}}} \times \frac{f^{E}_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{\mathrm{trig}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{trig}}_{e\gamma}} \times \frac{A^{\mathrm{TC}}_{e\nu\bar{\nu}}}{A^{\mathrm{TC}}_{e\gamma}} \times \frac{\epsilon^{\mathrm{DCH}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{DCH}}_{e\gamma}} \times \frac{1}{A^{\mathrm{g}}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}
$$

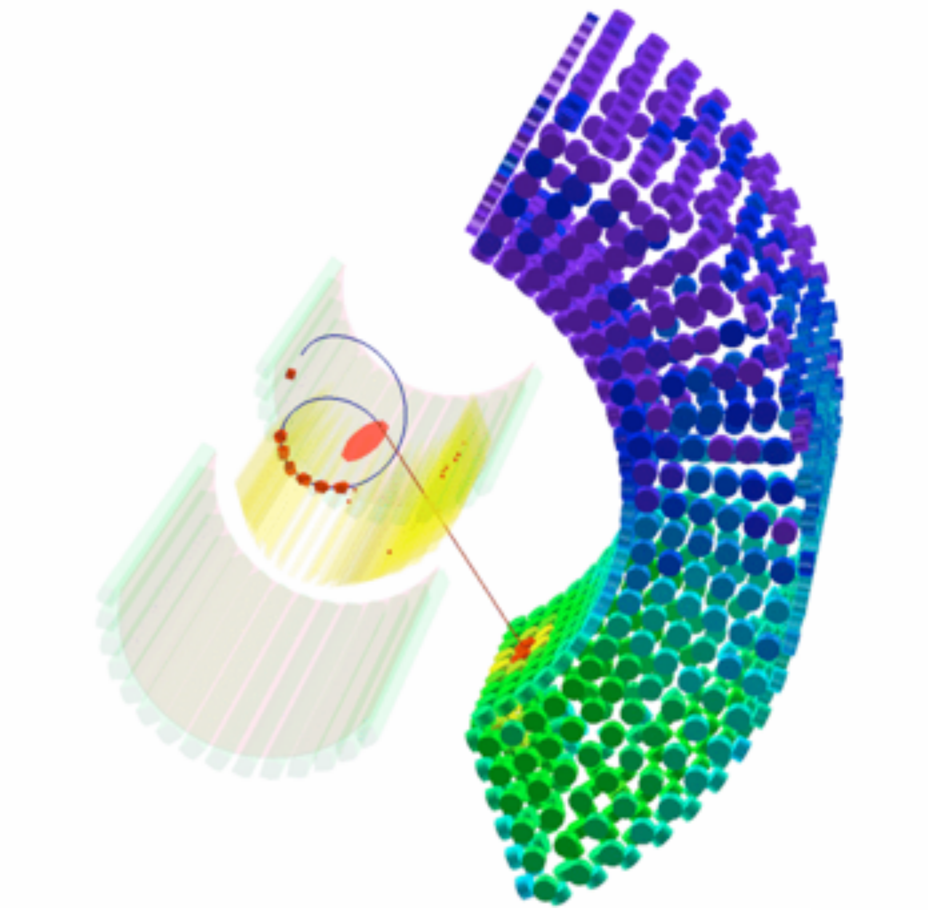
Event Distribution



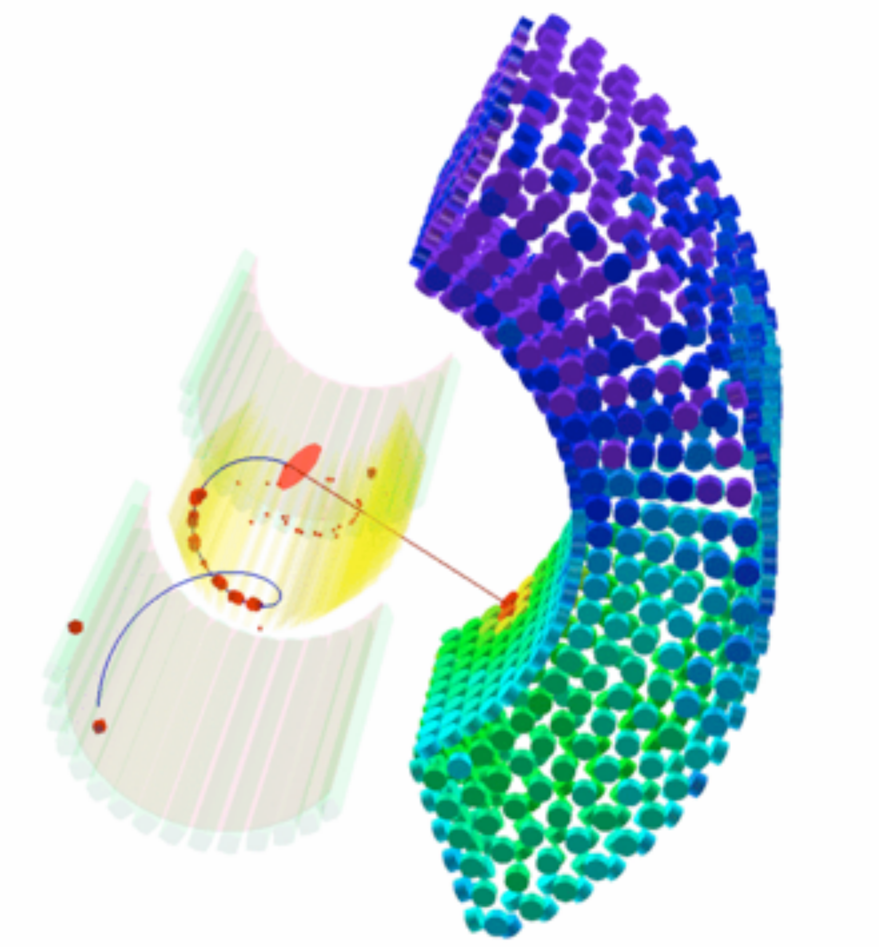


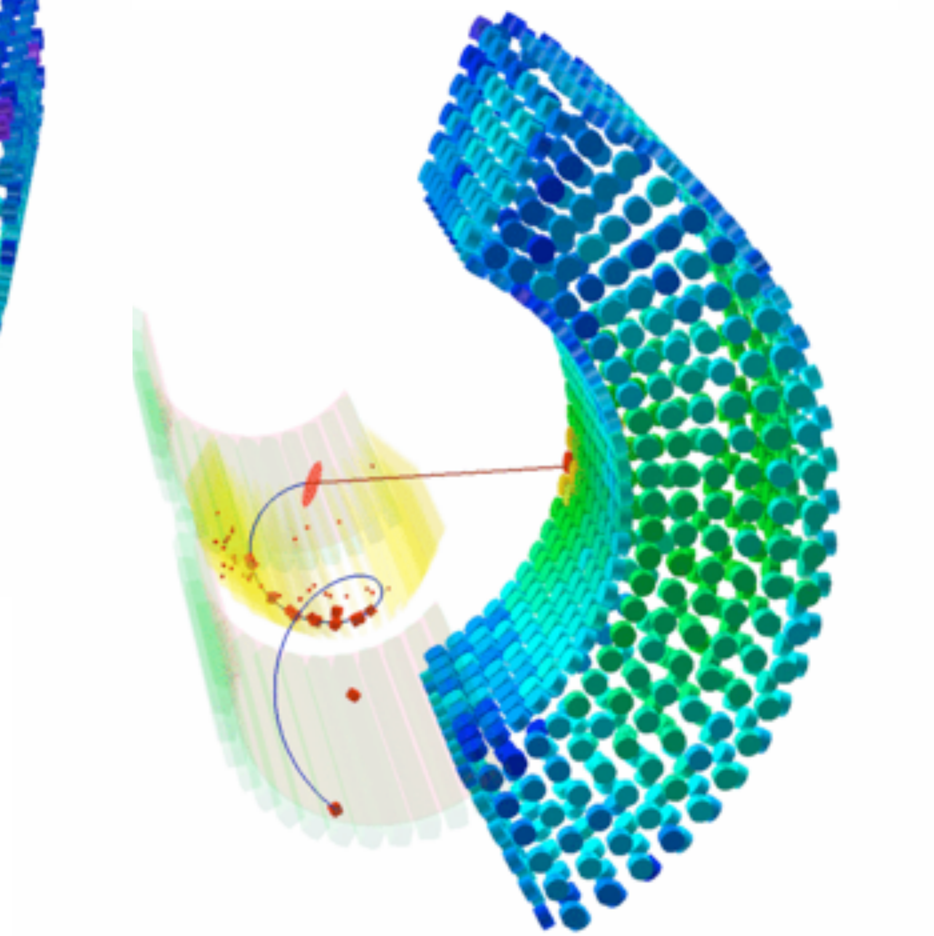
A Collection of Observed Events

Run:102907 Event:559
(E_{γ}=50.27MeV, E_{e}=52.34MeV, $T_{e\gamma}$=-78.7ps, $\Phi_{e\gamma}$=17.83mrad, $\theta_{e\gamma}$=7.77mrad)



Run:100452 Event:1878
(E_{γ}=49.27MeV, E_{e}=52.87MeV, $T_{e\gamma}$=-9.3ps, $\Phi_{e\gamma}$=17.51mrad, $\theta_{e\gamma}$=-10.65mrad)





Run:123579 Event:1318
(E_{γ}=55.13MeV, E_{e}=52.89MeV, $T_{e\gamma}$=-14.9ps, $\Phi_{e\gamma}$=5.58mrad, $\theta_{e\gamma}$=-25.27mrad)

Systematics

- **Systematic uncertainties of PDF parameters and normalization are taken into account by fluctuating PDFs in confidence interval calculation.**
- **The effect of systematic uncertainties is only 1% change in upper limit.**

Effect on UL (change in ΔNLL)

Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.11
E_γ scale	0.07
E_e bias	0.06
$t_{e\gamma}$ signal shape	0.06
$t_{e\gamma}$ center	0.05
Normalization	0.04
E_γ signal shape	0.03
E_γ BG shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.03
γ angle resolution (u_γ, v_γ, w_γ)	0.03
E_e BG shape	0.01
E_e signal shape	0.01
Angle BG shape	0.00
Total	0.25