Latest results from the MEG experiment

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on behalf of MEG Collaboration

ICEPP, the University of Tokyo
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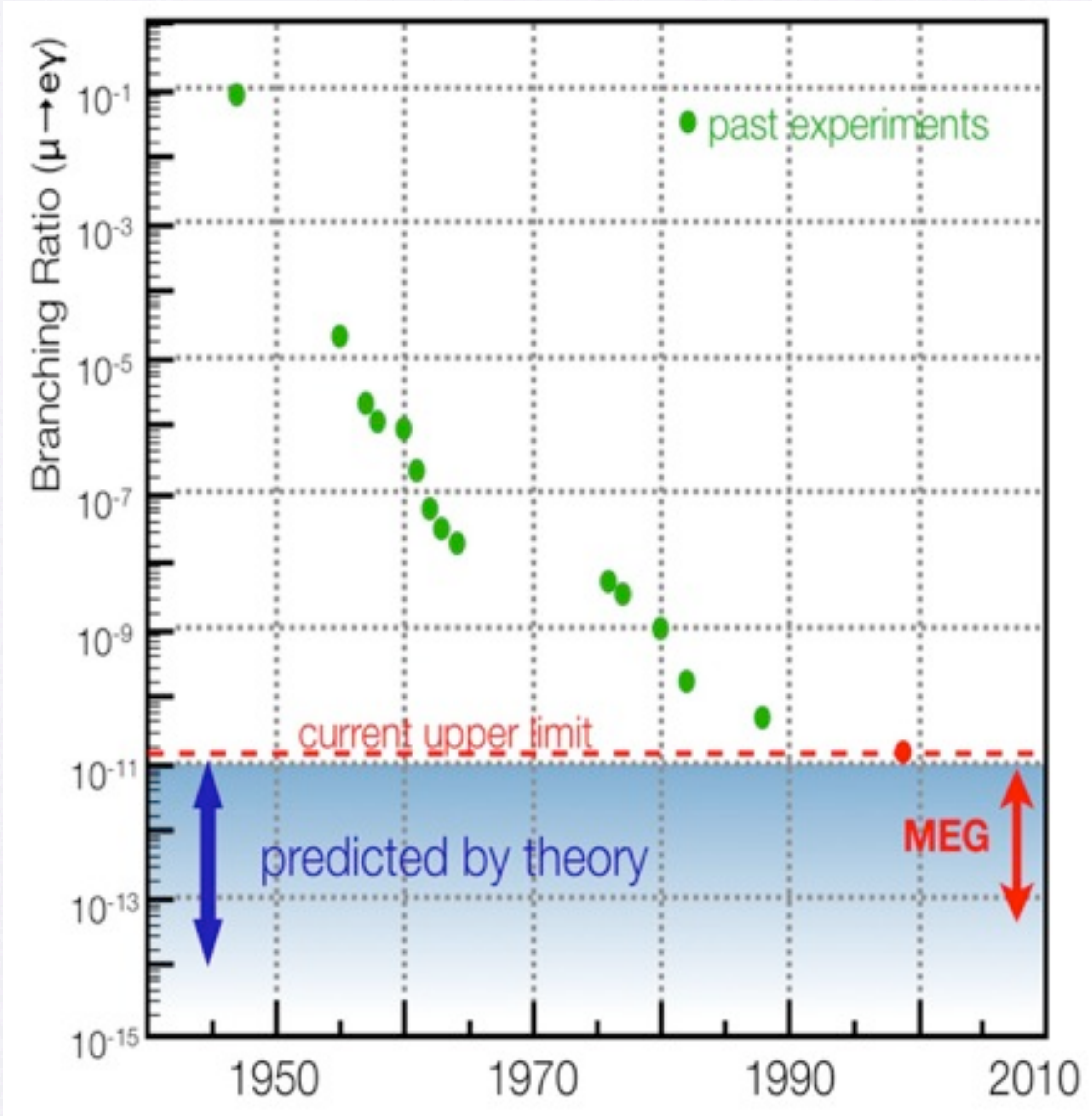
Outline

- μ→eγ search
- MEG experiment
- Detector performance
- Physics analysis
- Results in 2009+2010
- Other physics
- Prospects

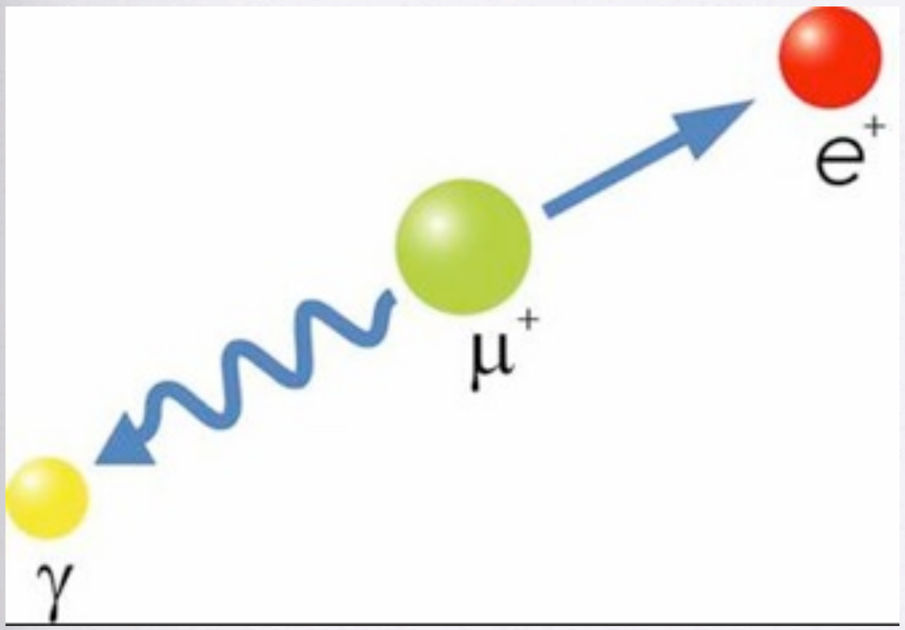
μ→eγ search

- Lepton flavor violating decay
- In neutrino sector, this is violated via neutrino oscillation. In charged sector, there is no observation yet
- Expectation of branching ratio with SM + neutrino mass < 10^{-50}
- New physics (SUSY-GUT, SUSY-seesaw, ...) predict large branching ratio below 10^{-11}



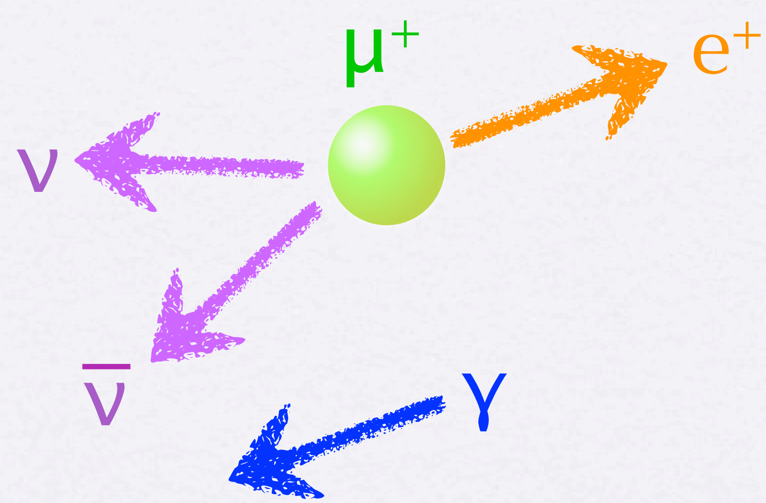
Signal & Background

Signal



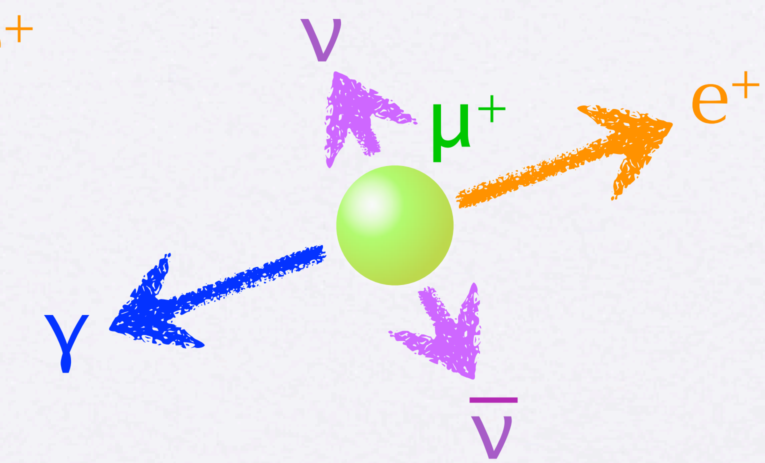
- μ^+ decay at rest
- Clear two body decay in final state
- $E_e, E_\gamma = 52.8\mathrm{MeV}$
- $T_e = T_\gamma$
- back-to-back ($\theta_{e\gamma}=180°$)

Accidental background



- dominant for us
- Michel e^+ + random γ from RMD/AIF

Radiative muon decay background

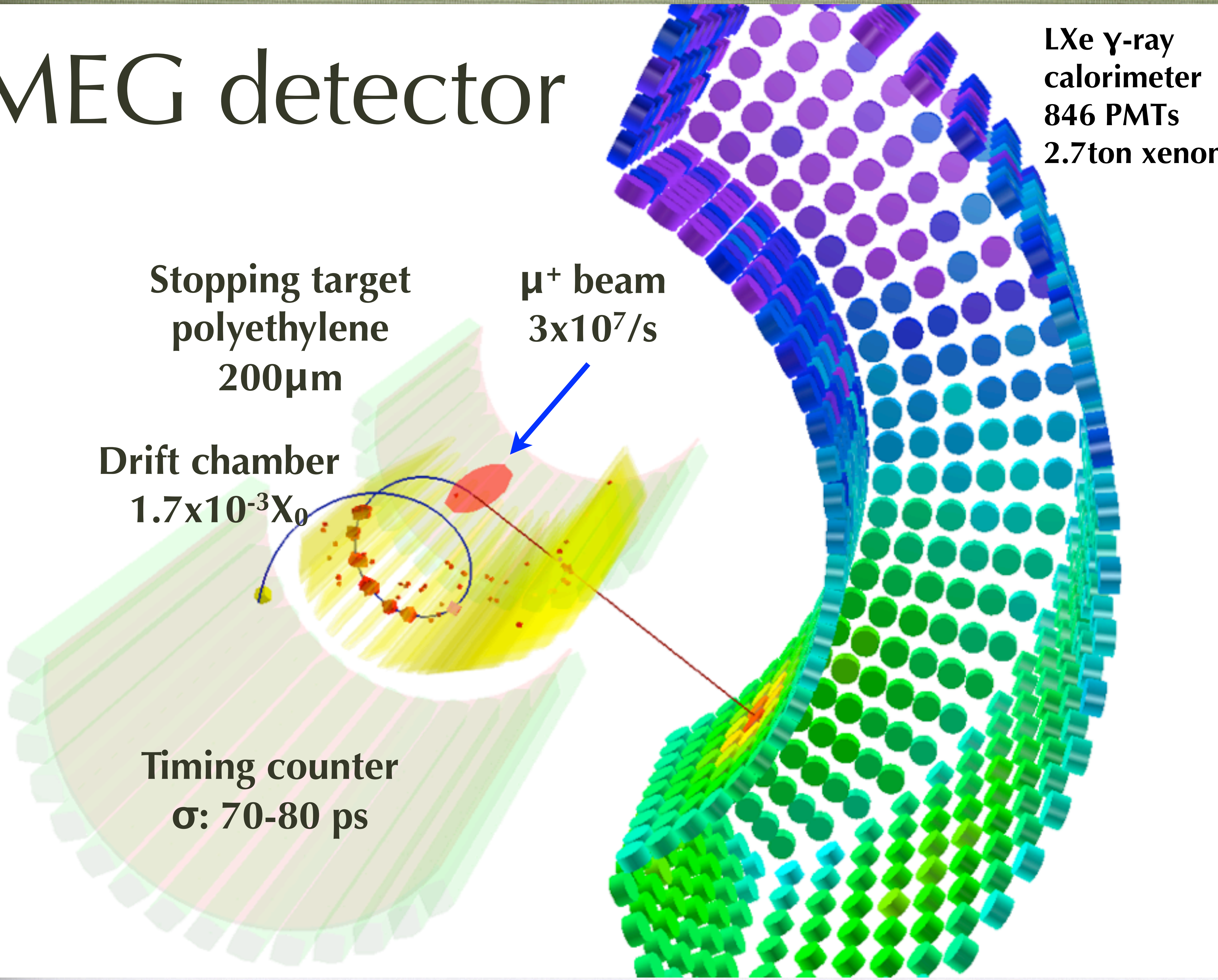


- timing coincident

MEG experiment

- Requirements
  - Intense μ^+ beam
  - e+ tracking in high rate environment
  - Good energy, position, and timing measurements

MEG detector

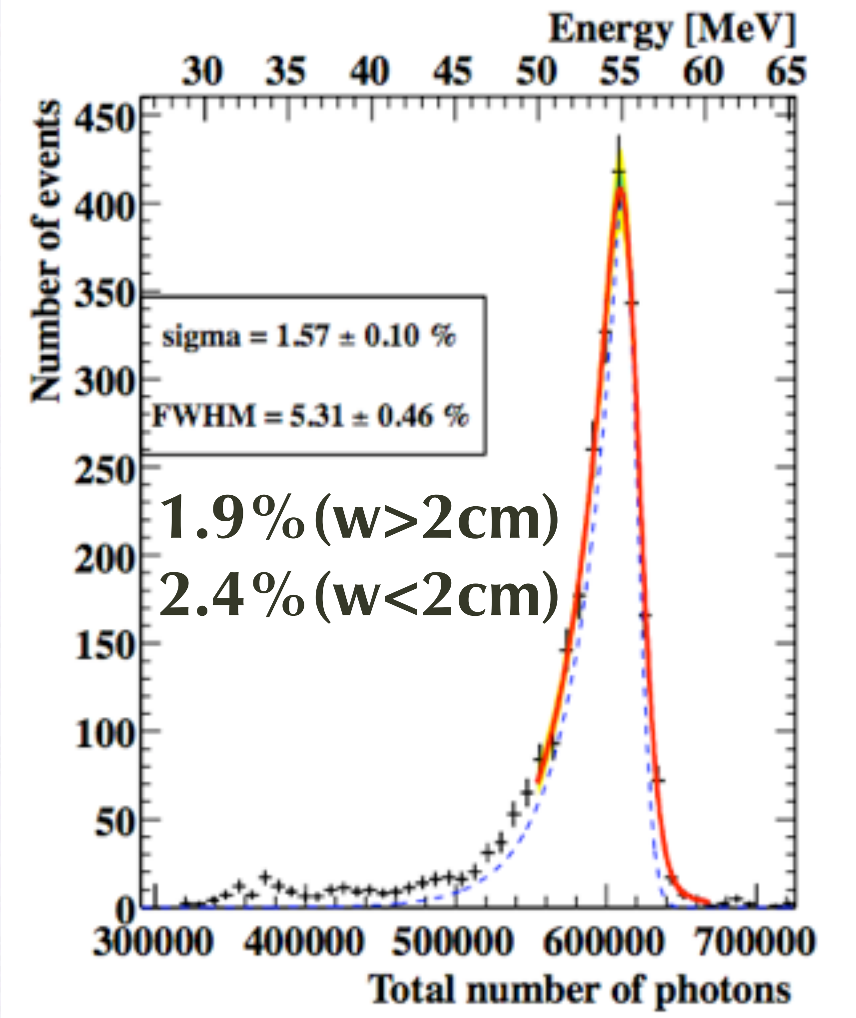


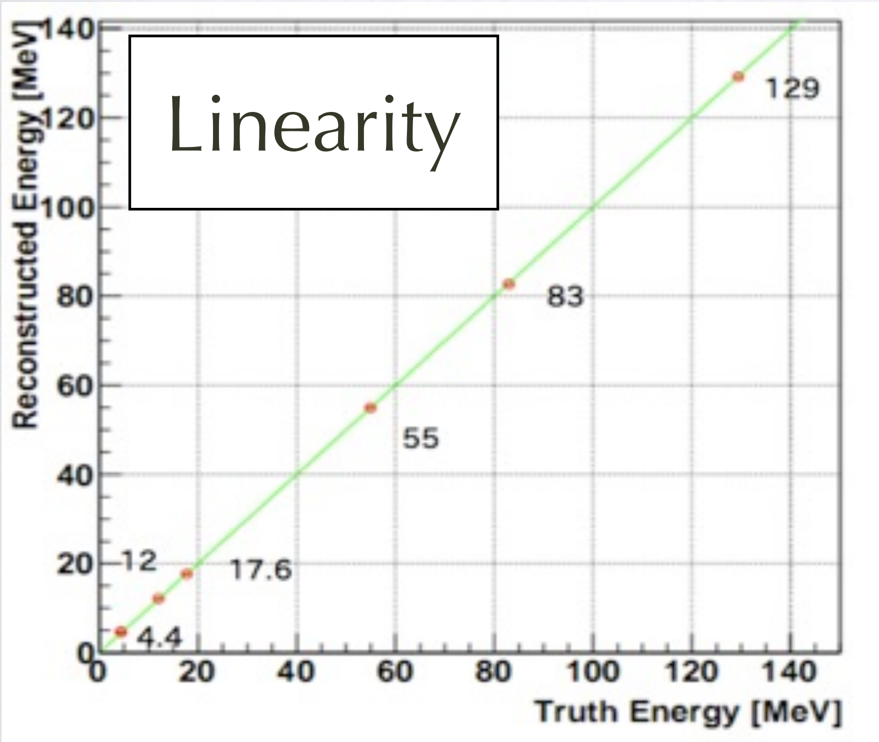
MEG status

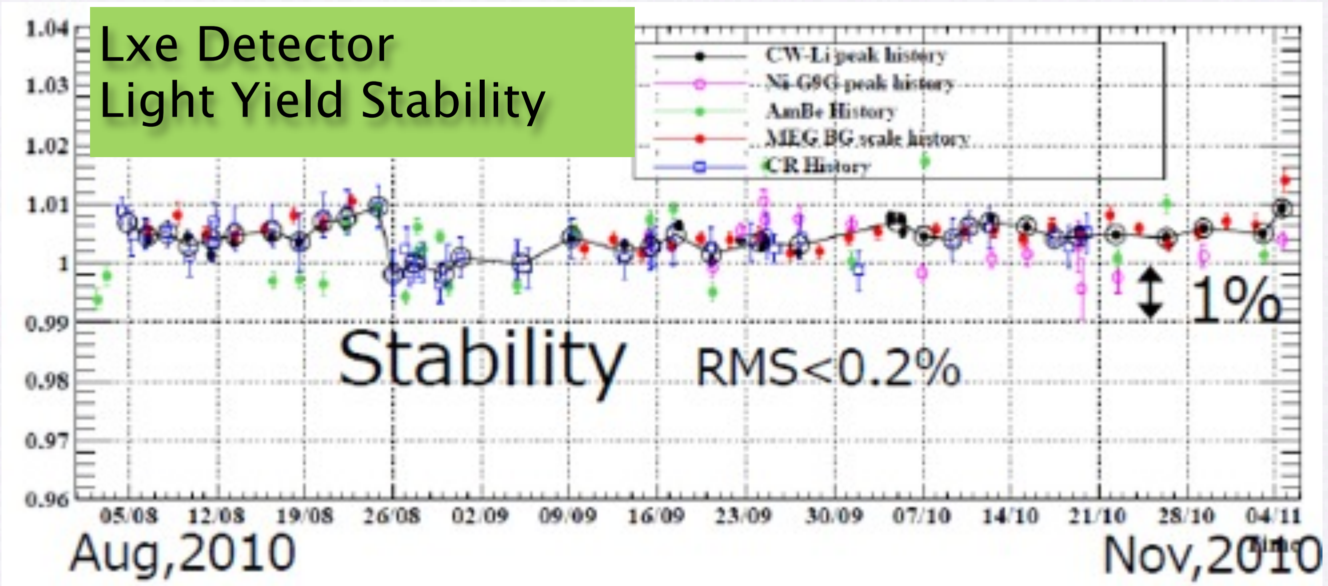
- 1999 : Proposal
- 2007 : Engineering run
- Physics data taking
  - 2008 Sep-Dec published in Nucl.Phys.B834 1
  - 2009 Nov-Dec Preliminary result was presented in ICHEP2010
  - 2010 Aug-Oct **2009 + 2010 combined results (today's topic)**
  - 2011 Jul-Nov   is being analyzed

Detector performance(γ)

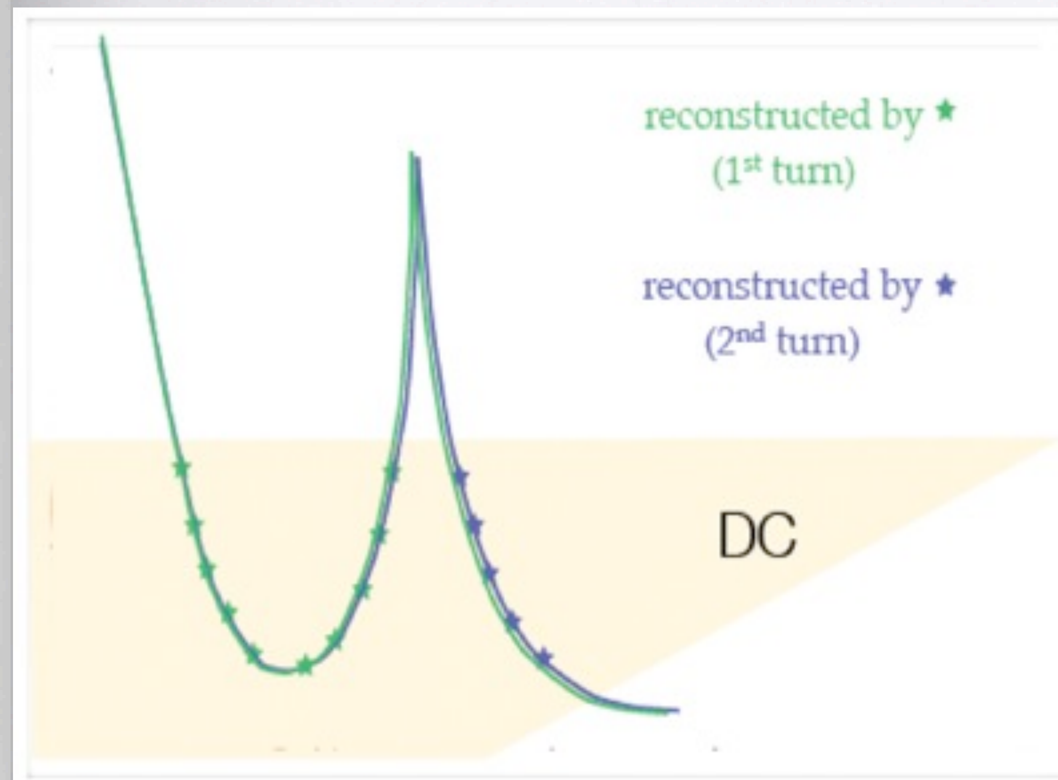
- $\pi^- p \to \pi^0 n$, $\pi^0 \to 2\gamma$
  - back-to-back 55, 83MeV 2γs are suitable calibration for signal γ
- Various calibration methods are established to calibrate and monitor the detector condition
  - γ : CW Li(17.6MeV), Ni(9MeV), CW Boron(4.4,12MeV)
  - ^{241}Am α (QE, light yield), LED (PMT gain)



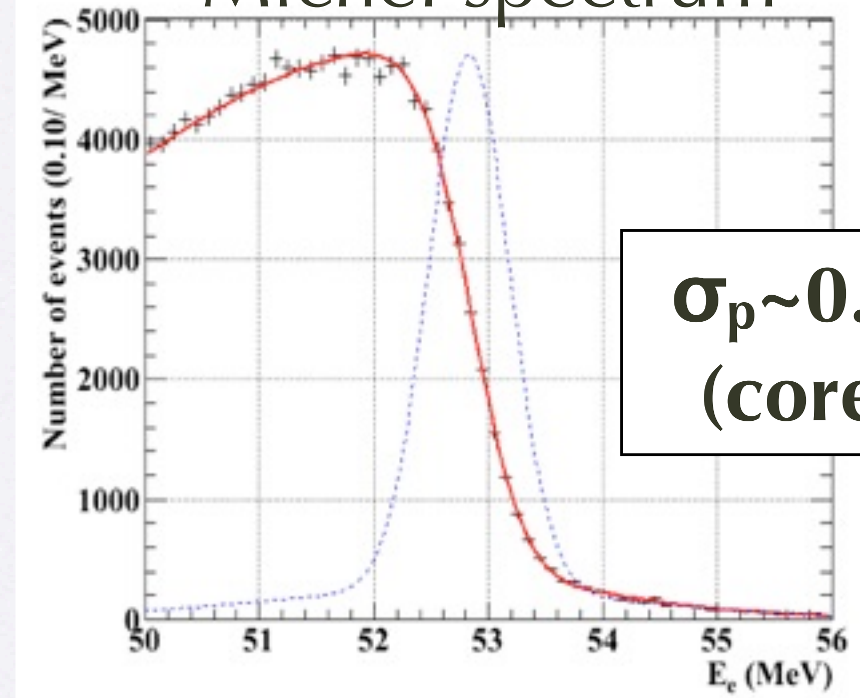




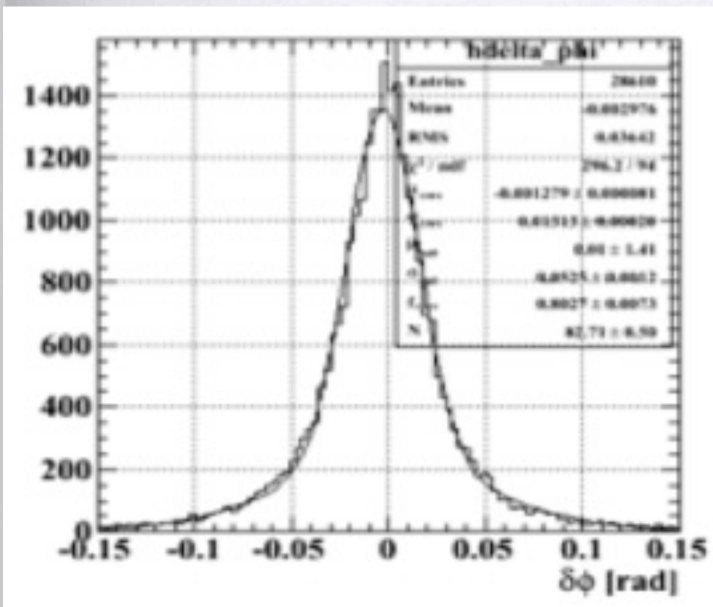
Detector performance (e^+)

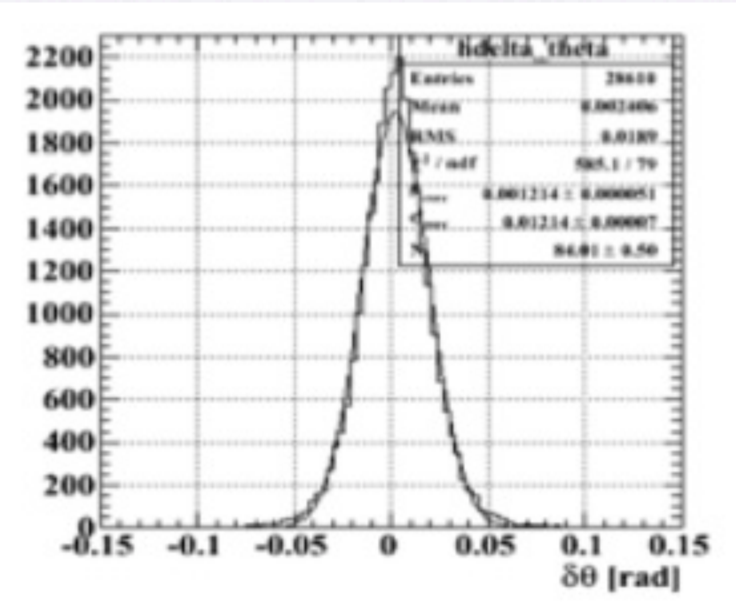


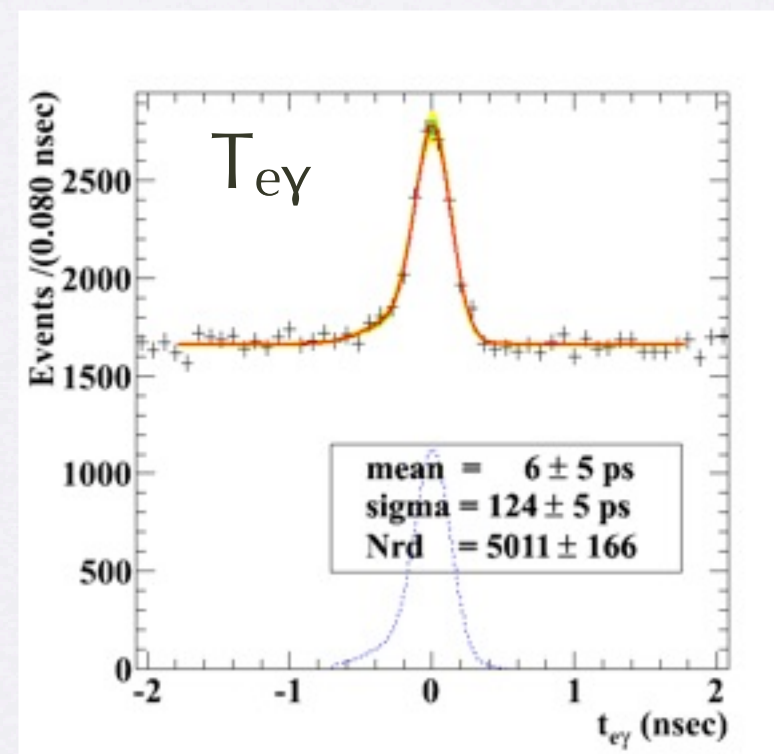
Michel spectrum



σ_p~0.32MeV
(core 79%)





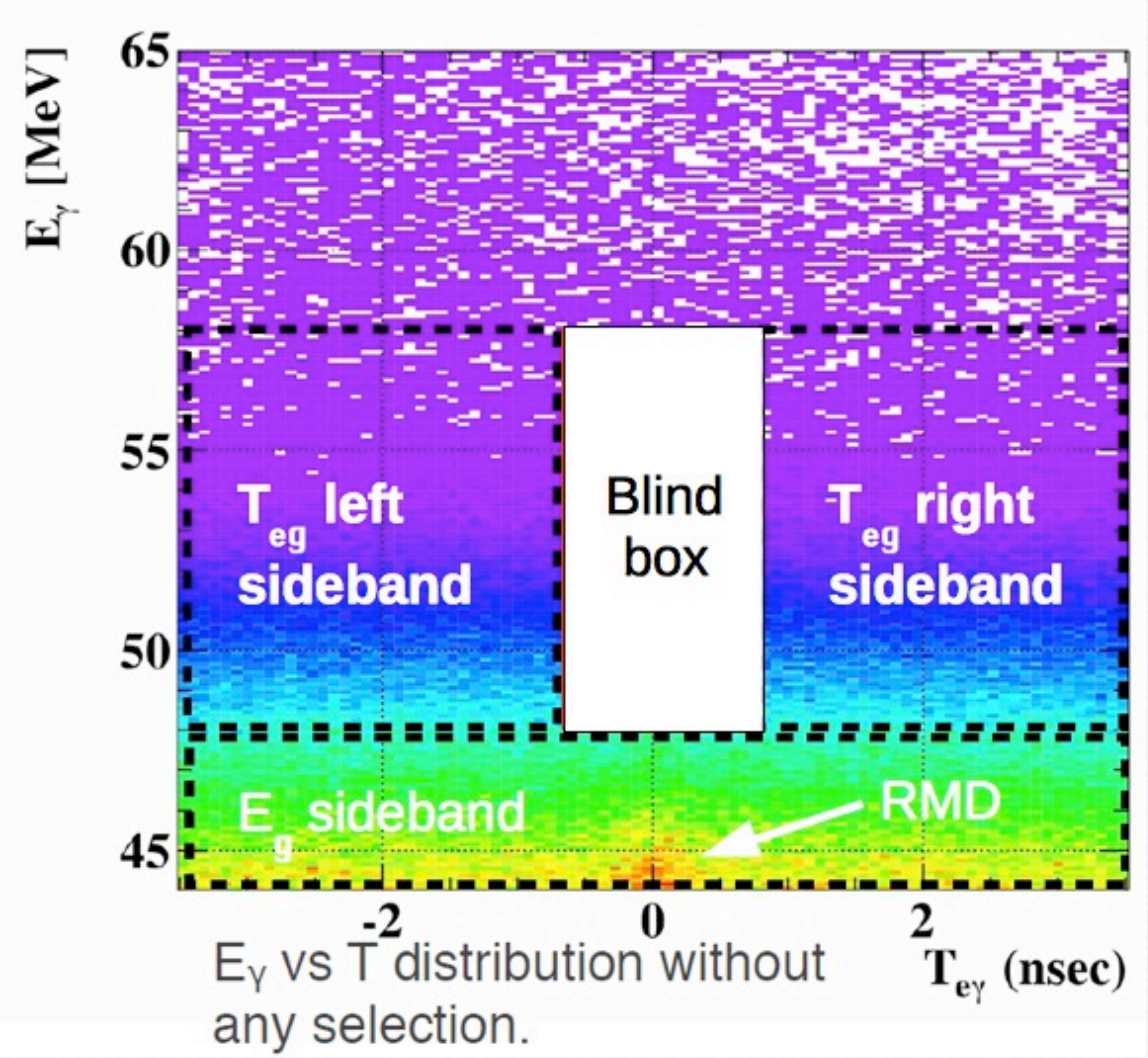


e^+ angle(θ)
~ 11.0mrad

e^+ angle (φ)
~7.2mrad

Analysis

- Blind analysis
  - ($T_{e\gamma}$, E_γ)
  - calibration, BG estimation, performance evaluation can be done outside the box
- Accidental background study -timing sideband data
- RMD study - E_γ sideband data



Likelihood analysis

$$\mathcal{L}(\vec{x}_1,\ldots,\vec{x}_N,R_\diamond,A_\diamond|\hat{S},\hat{R},\hat{A})=\frac{e^{-\hat{N}}}{N!}e^{-\frac{1}{2}\frac{(A_\diamond-\hat{A})^2}{\sigma_A^2}}e^{-\frac{1}{2}\frac{(R_\diamond-\hat{R})^2}{\sigma_R^2}}\prod_{i=1}^{N}\left(\hat{S}s(\vec{x}_i)+\hat{R}r(\vec{x}_i)+\hat{A}a(\vec{x}_i)\right)$$

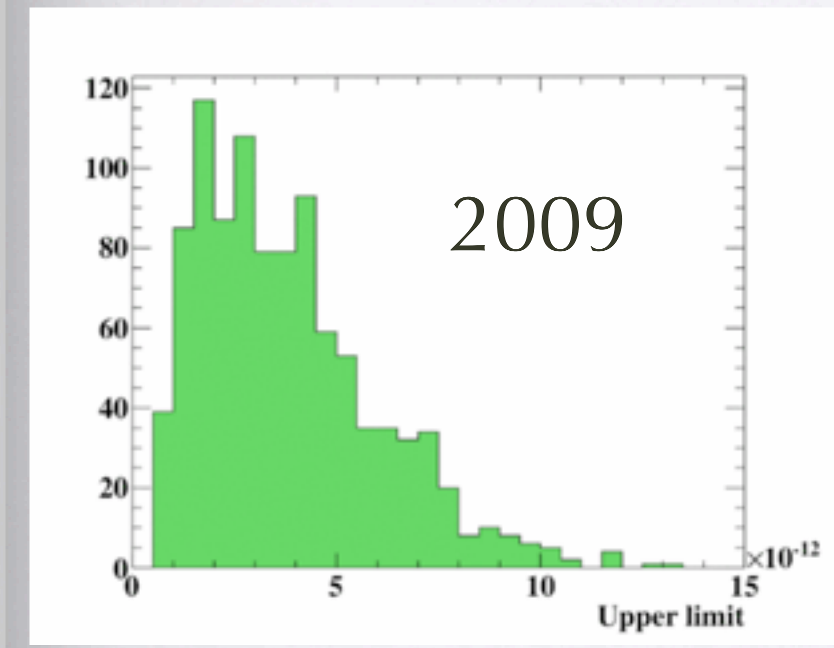
PDFs

Background rate constraints

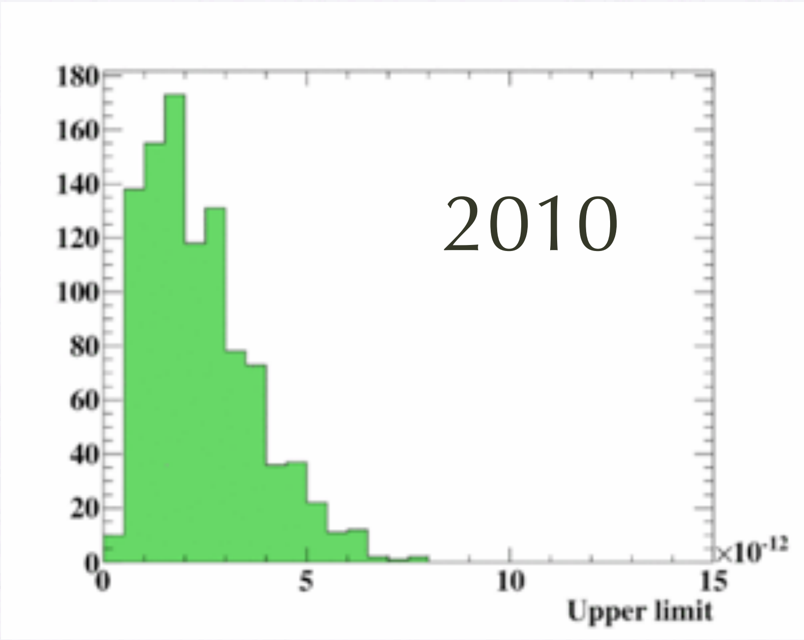
- Fully frequentist approach (Feldman-Cousins) with profile likelihood ratio ordering
- Extended maximum likelihood fit
  - Observables : E_γ, E_e, $T_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$
  - Fit parameters : N_{signal}(S), N_{RMD}(R), N_{BG}(B)
- PDF is evaluated (mostly) from data
  - Background : spectrum measured in sideband data
  - RMD : theoretical spectrum convoluted with detector response
  - Signal : measured detector response function

Sensitivity

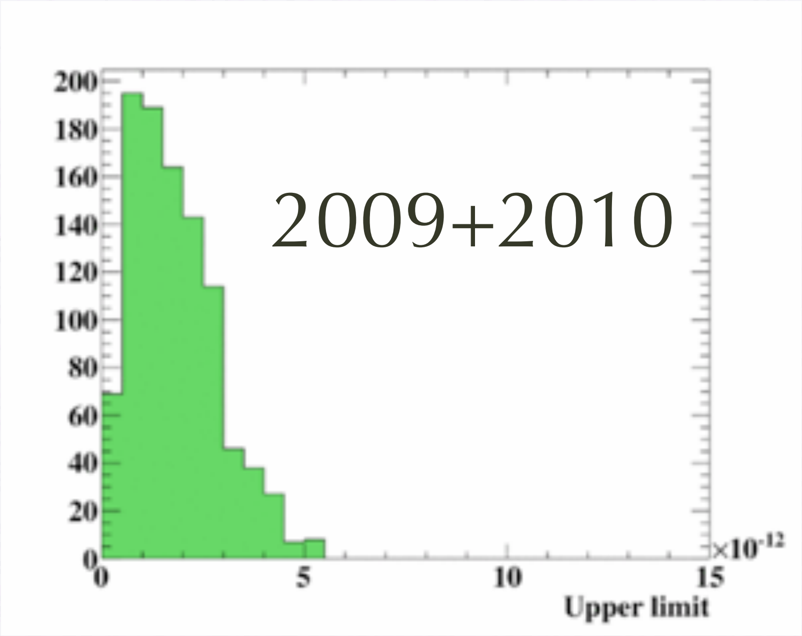
- 90% C.L. upper limit averaged over an ensemble of many toy PC experiments with BG only hypothesis with BG rate measured in side-bands.



Br=3.3x10^{-12}



Br=2.2x10^{-12}

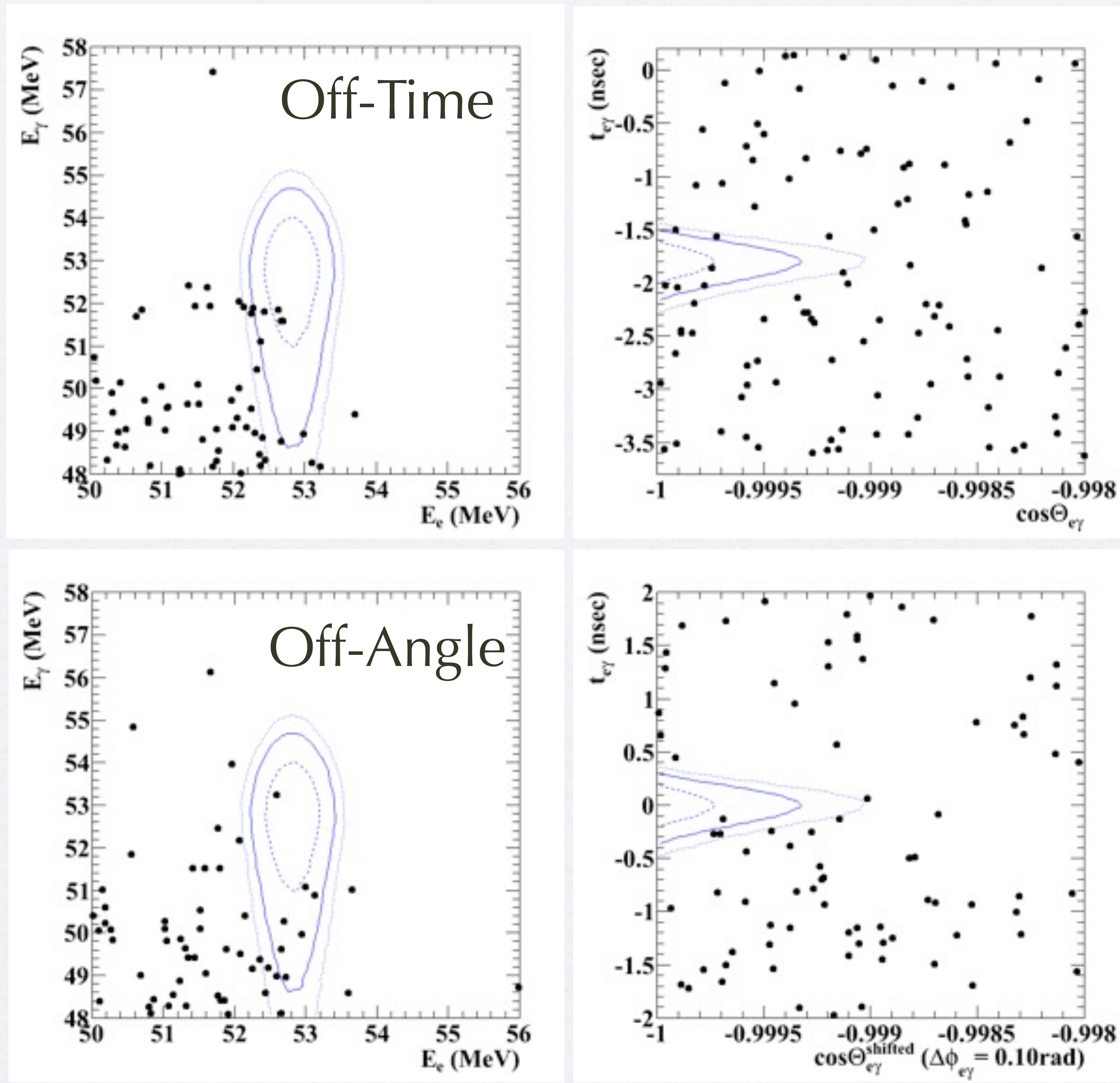


Br=1.6x10^{-12}

- Combined 2009 + 2010 Sensitivity - 1.6 x 10^{-12}
  is 8x better than previous best upper limit (Br<1.2x10^{-11} (90%C.L.) MEGA 1999)

Sideband Analysis

- Same analysis performed in sideband data before unblinding
    - $T_{e\gamma}$ sideband (off-time)
    - Angle sideband (off-angle)
- Observed branching ratio upper limits consistent with sensitivity
- Ready to open the blind box.

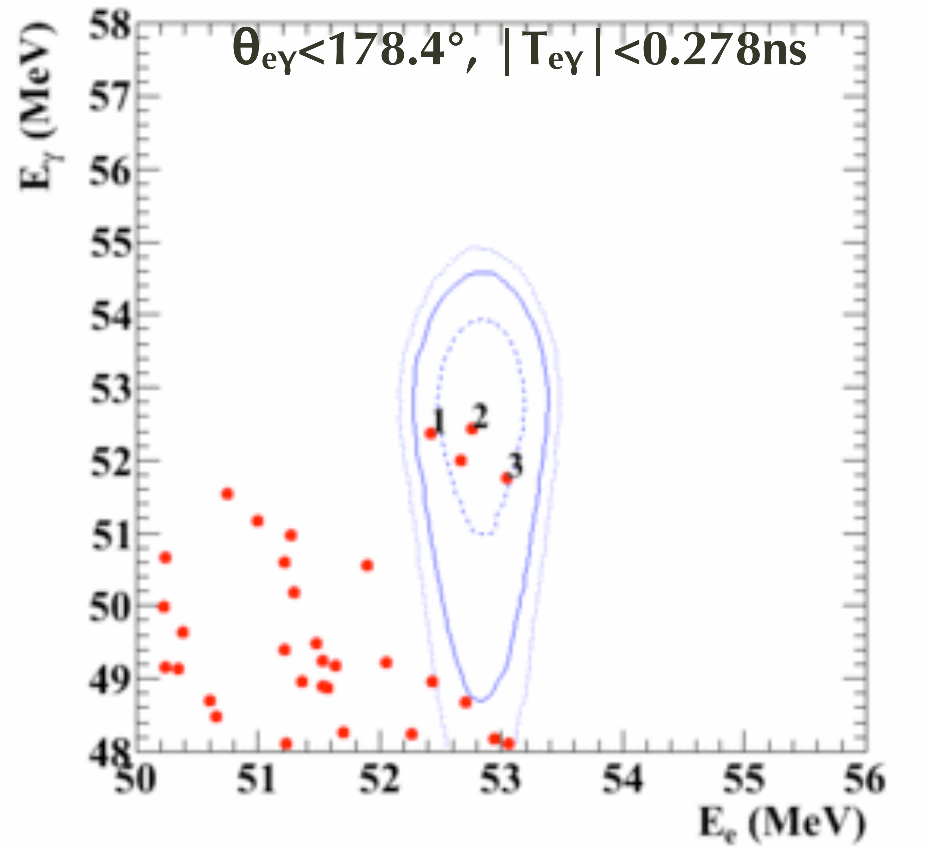


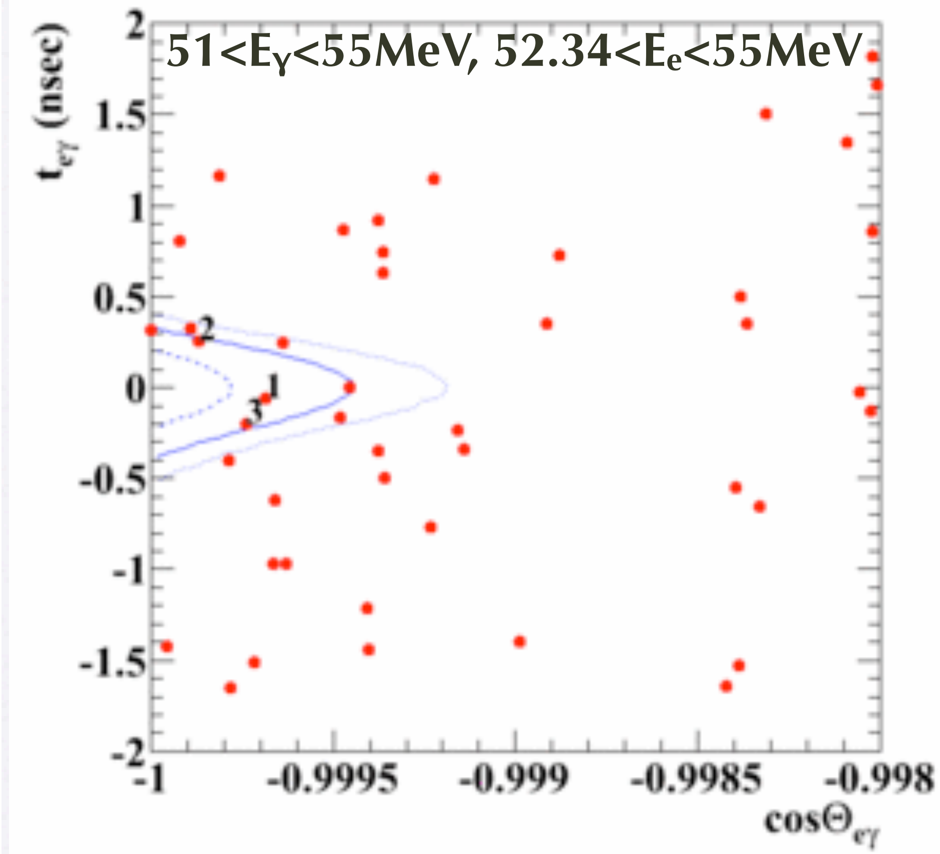
Blue curves: PDF contour (1,1.64,2-σ)
Selection
(E_e-E_γ:$\theta_{e\gamma}$<178.4°, |$T_{e\gamma}$|<0.278ns
($\cos\theta_{e\gamma}$-$T_{e\gamma}$): 51<E_γ<55MeV, 52.34<E_e<55MeV

N.B. : These plots are just for reference, not used in the analysis

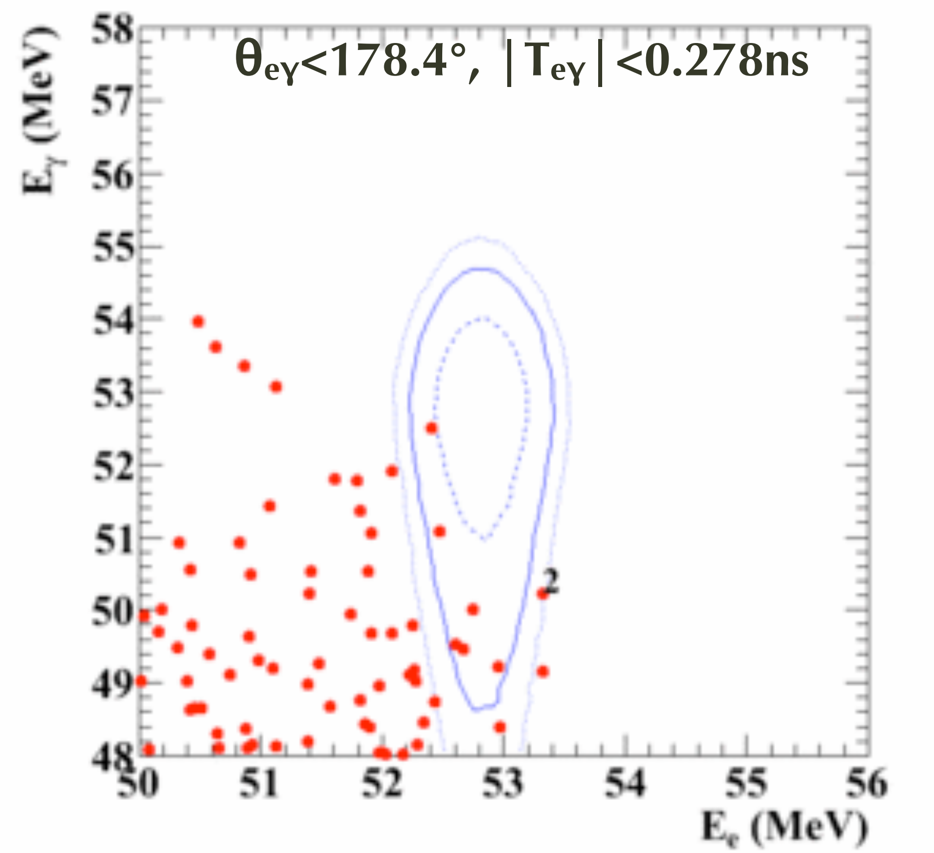
Event distribution in 2009 and 2010

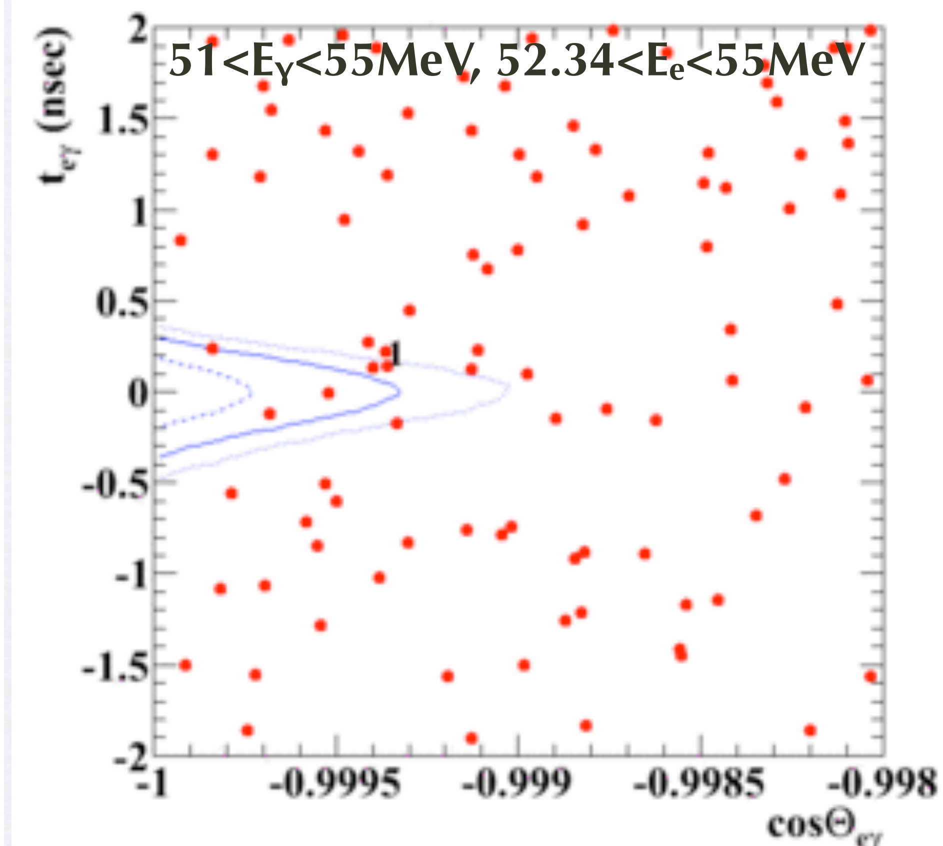
2009





2010



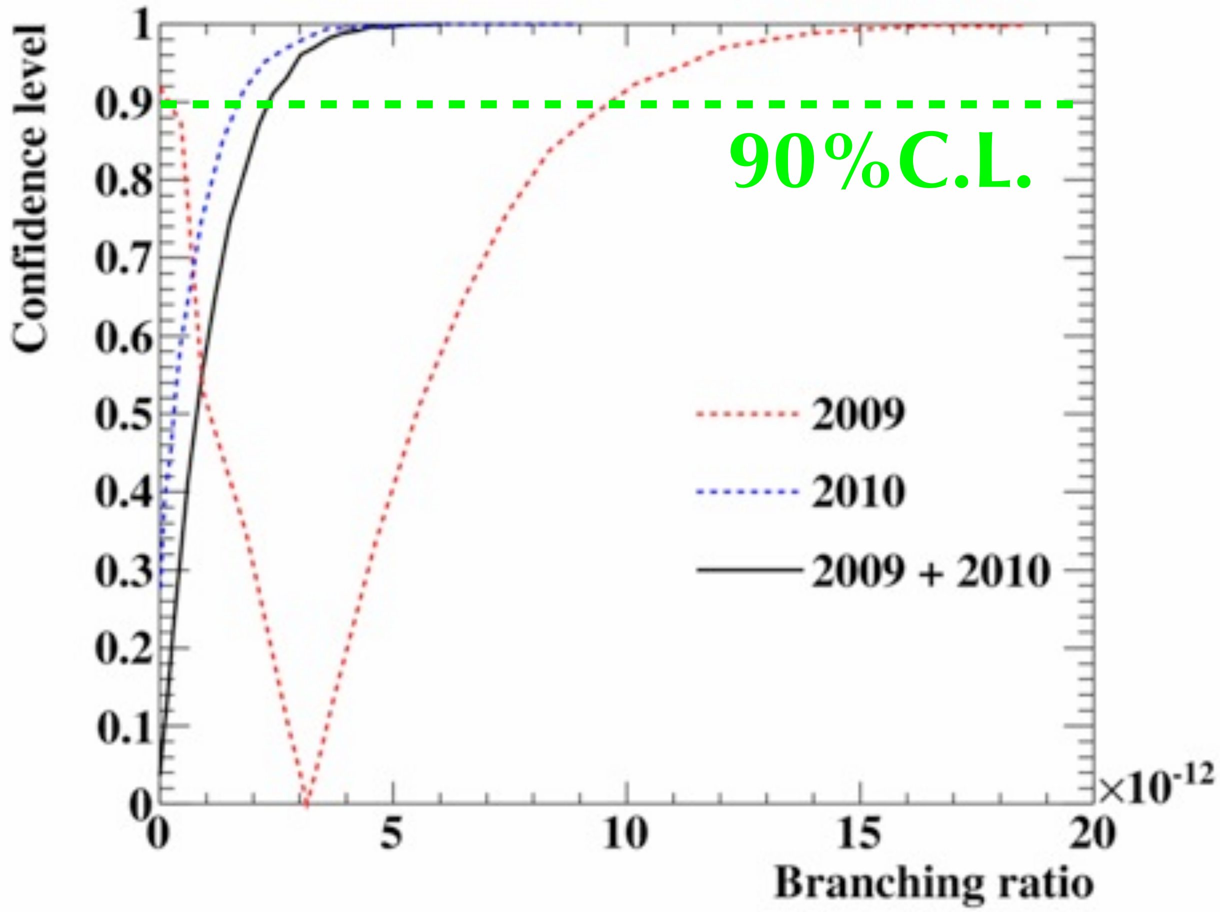


- Blue curves : signal PDF contour (1, 1.64, 2-σ)
- Events with highest signal likelihood (S/(0.1R+0.9B)) are numbered.
- These plots are just for reference, not used in the analysis

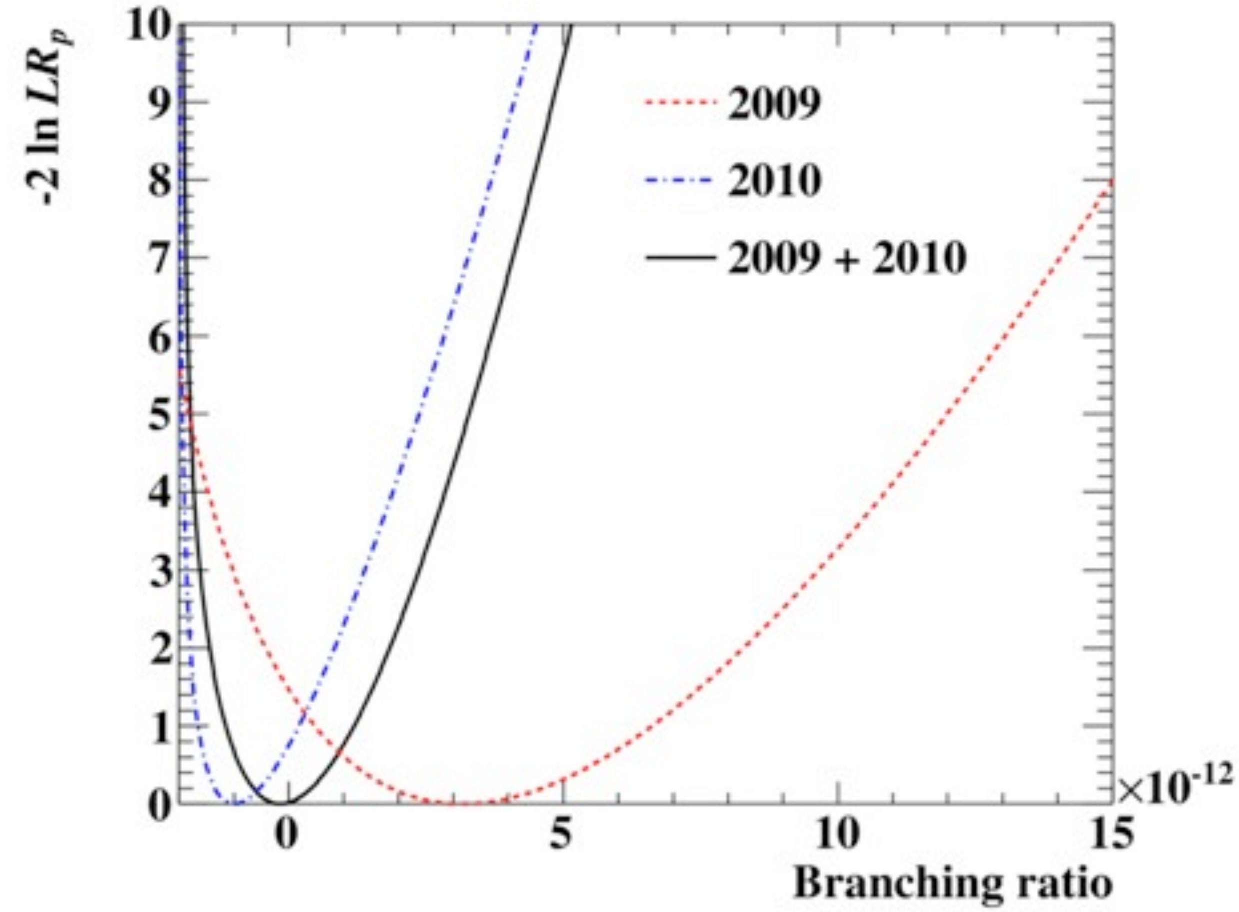
Confidence interval in 2009 and 2010

- Confidence interval calculated with Feldman-Cousins method + profile likelihood ordering
- Run2009 marginally excludes B = 0, but the significance is not high. (p-value~8%)
- Compatibility between 2009 and 2010 ~15%

Confidence Intervals



Profile likelihood ratio



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

Likelihood curves are not directly used in confidence interval calculation

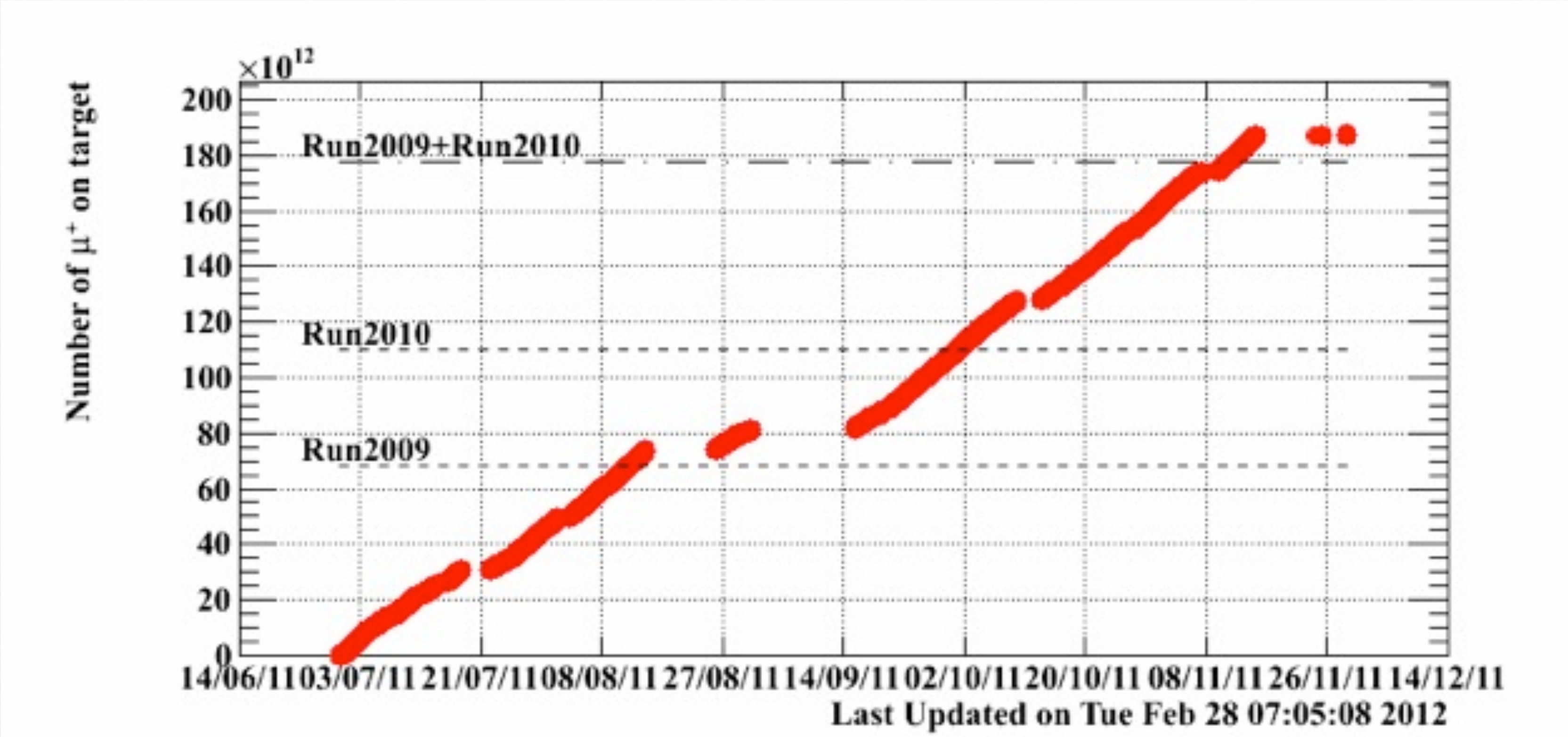
New result

Data set	Best fit	Sensitivity	LL(90%CL)	UL(90%CL)
2009	3.2×10^{-12}	3.3×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-12}	2.2×10^{-12}	--	1.7×10^{-12}
2009+2010	-1.5×10^{-12}	1.6×10^{-12}	--	2.4×10^{-12}

- New upper limit : $B(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$ (90%C.L.)
    - x5 more stringent than previous limit ($B < 1.2 \times 10^{-11}$, MEGA 1999)
    - Published in Oct. 2011 (Phys. Rev. Lett. 107, 171801(2011))

Run 2011

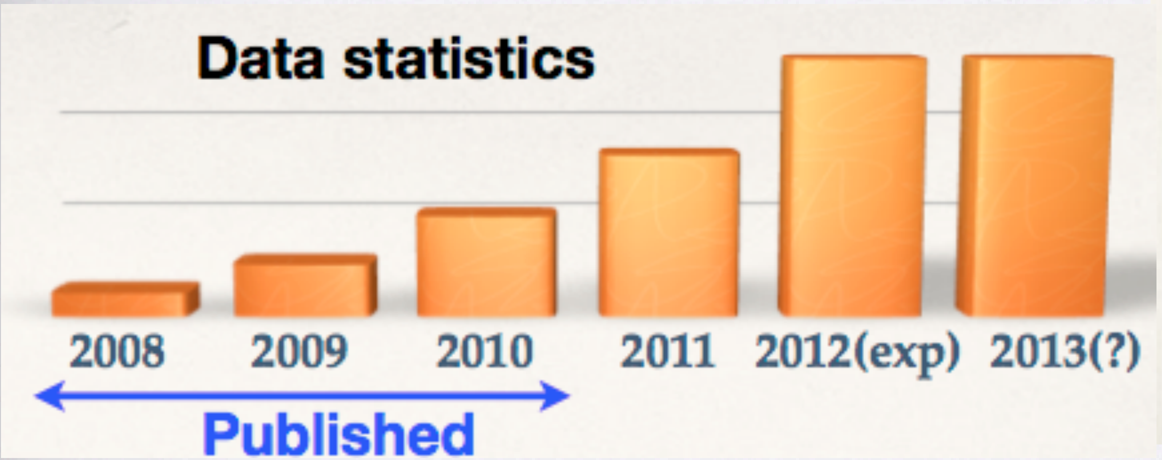
- Data statistics doubled.
- Analysis on data 2011 is in a good shape
- Detector performance (preliminary) already comparable to previous years

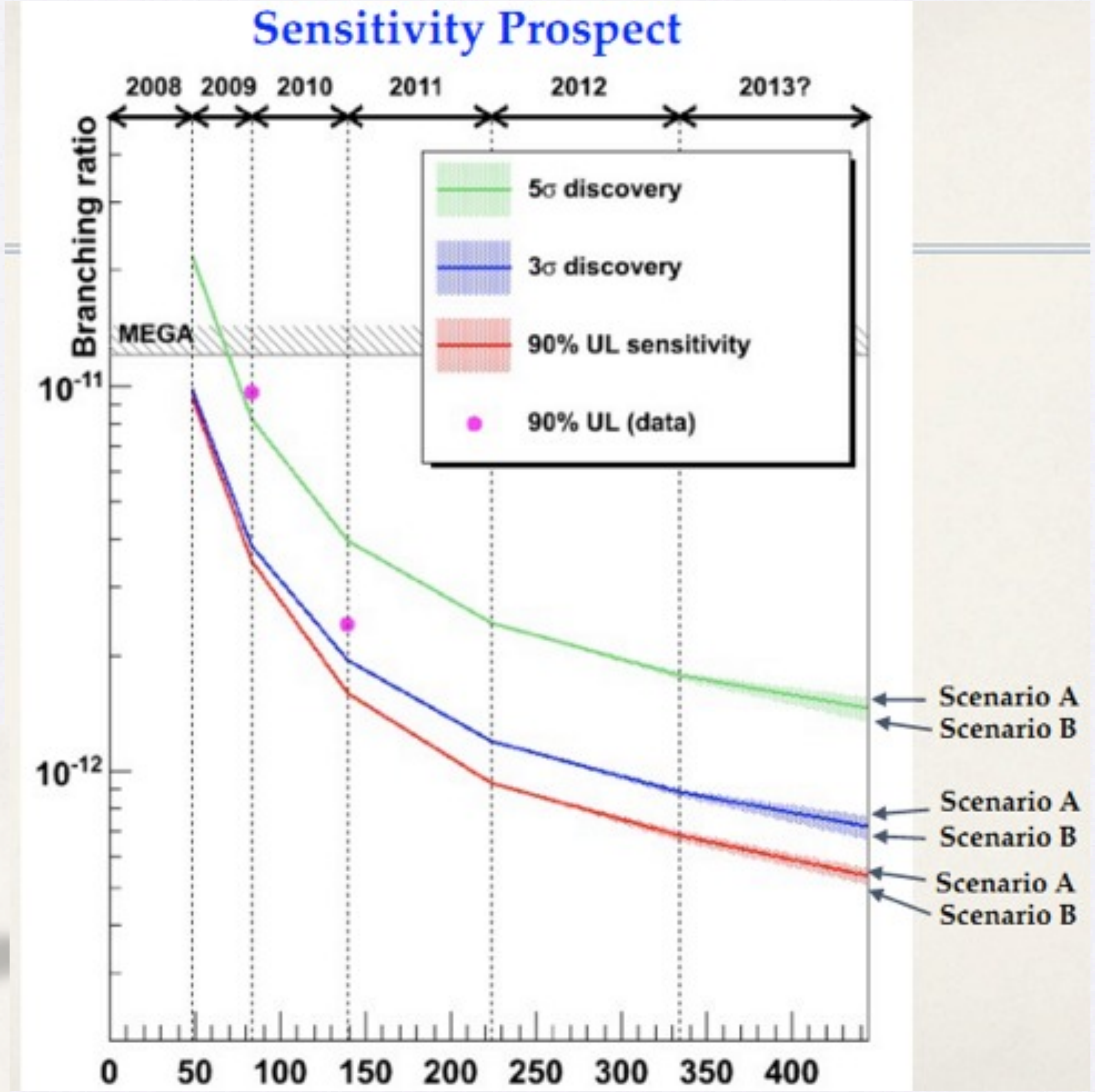


	2009	2010	2011(preliminary)
Gamma energy (%)	1.9% (w>2cm)	1.9% (w>2cm)	1.7% (w>2cm)
Gamma position (mm)	5 (u,v) / 6 (w)	5 (u,v) / 6 (w)	←
Positron momentum (%)	0.59 (core 80%)	0.61 (core 79%)	0.61 (core 86%)
Positron angle (mrad)	6.7 (Φ,core), 9.4 (θ)	7.2 (Φ,core), 11.0 (θ)	6.5 (Φ,core), 10.8 (θ)
Vertex position (mm)	1.5 (Z), 1.1(Y)	2.0 (Z), 1.1(Y)	1.9 (Z), 1.0(Y)
Gamma-positron timing (ps)	146 (core)	126 (core)	133
Gamma efficiency (%)	58	59	←
Trigger efficiency (%)	91	92	95
Data statistics (k-factor)	1.1×10^{12}	2.1×10^{12}	3.4×10^{12}

Prospects

- Run 2012 in preparation
- Explorer O(10^{-13}) with 2011+2012 data
- BG is starting to limit the sensitivity improvement -> Detector upgrade

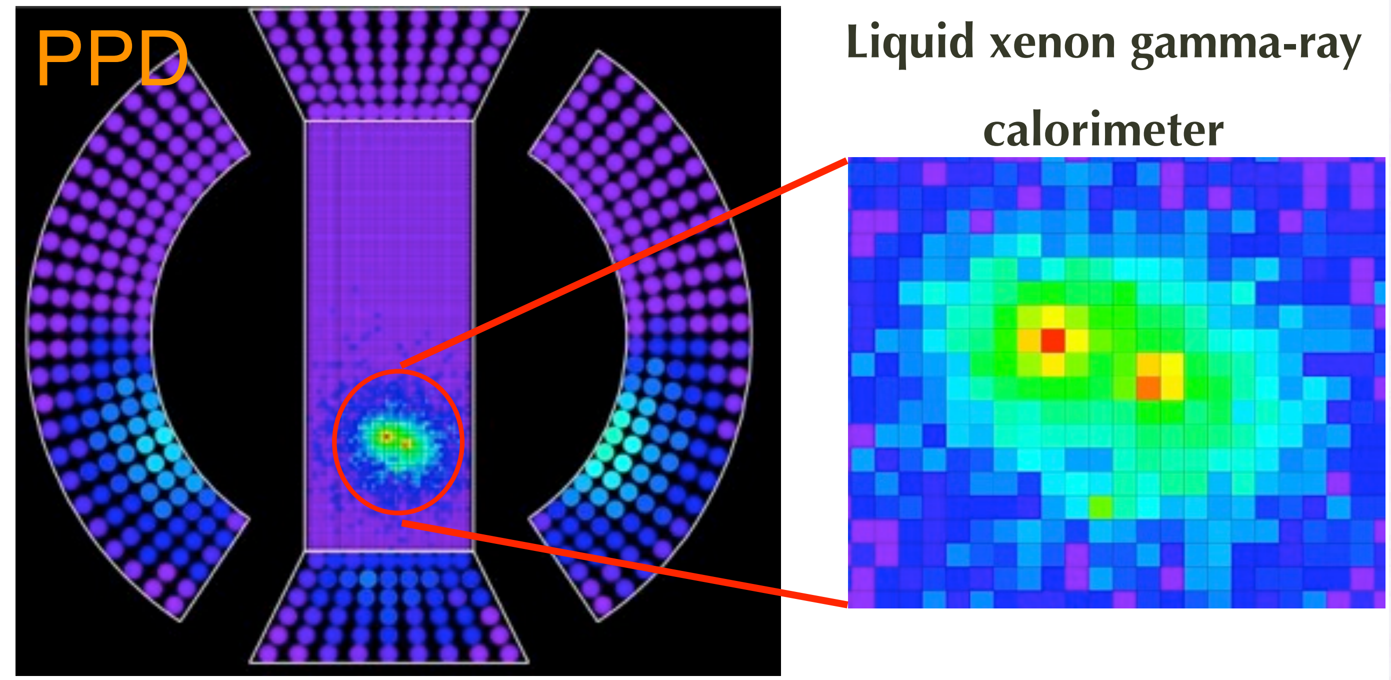




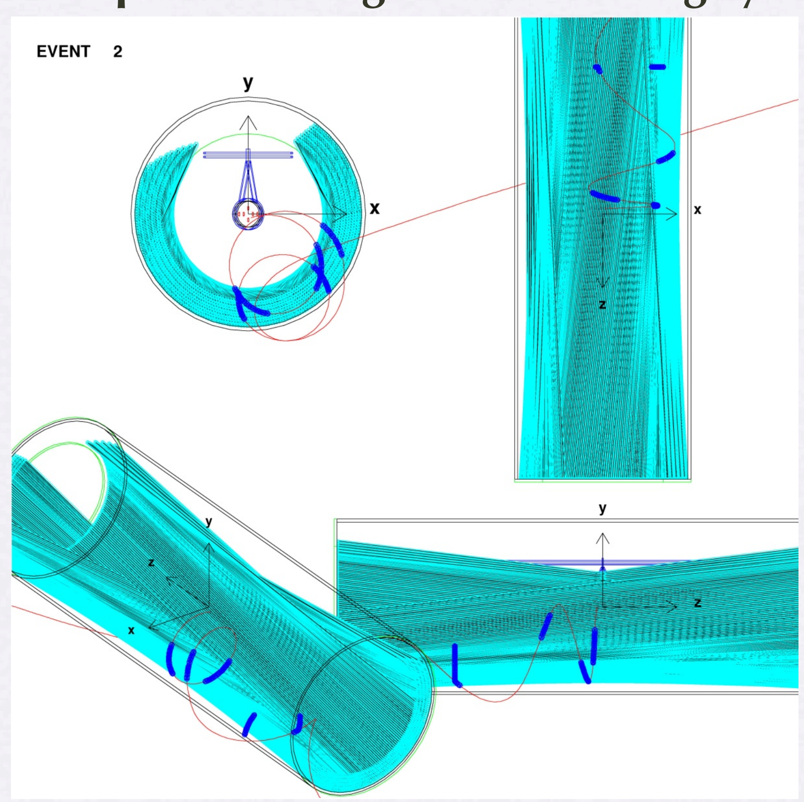
Detector upgrade

- Upgrade of MEG experiment under consideration, aiming at sensitivity ~O(10^{-14})
    - Higher beam intensity(10^8 μ^+/s, already possible at PSI)
- R&D have started based on various ideas on new detectors
    - LXe detector with smaller photo-sensors(PPD, PMTs, ...)
    - Unique-volume gaseous tracking system
    - Thin silicon vertex tracker
    - Active target
    - Tracker with scintillating thin sheets
    - ...

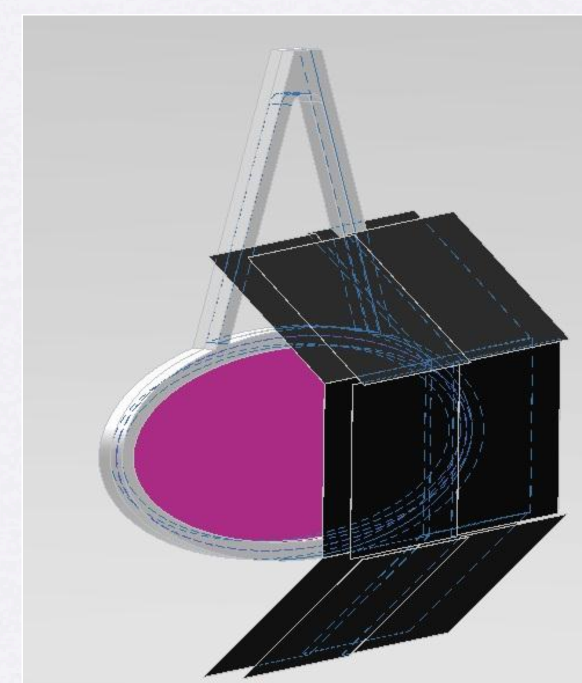
Liquid xenon gamma-ray calorimeter



Unique-volume gaseous tracking system

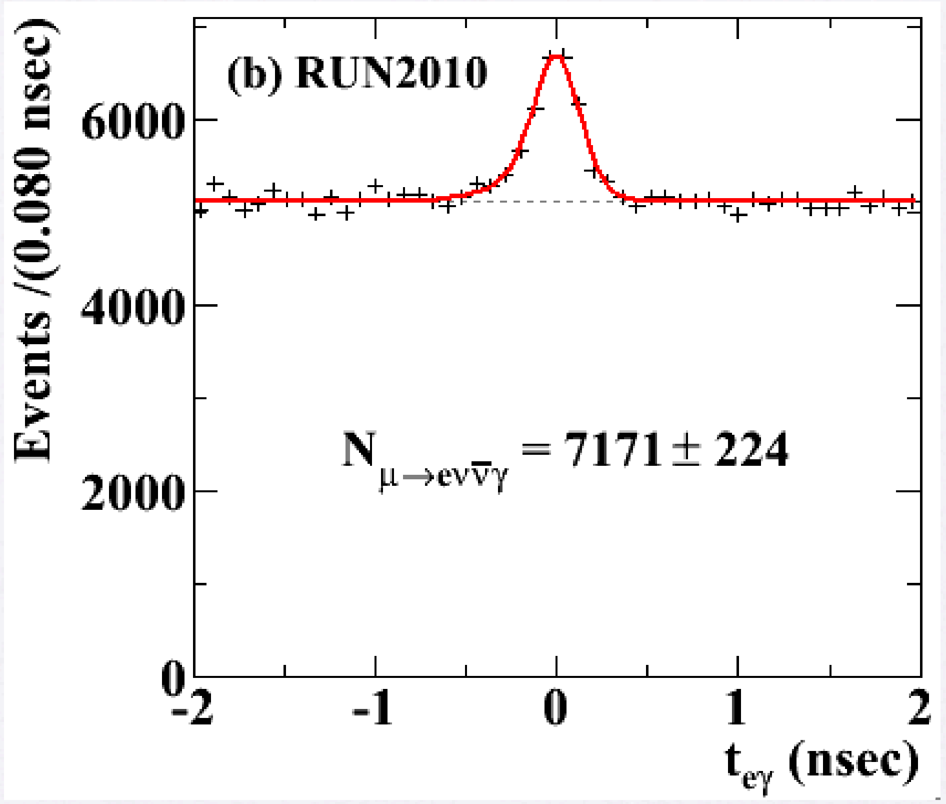


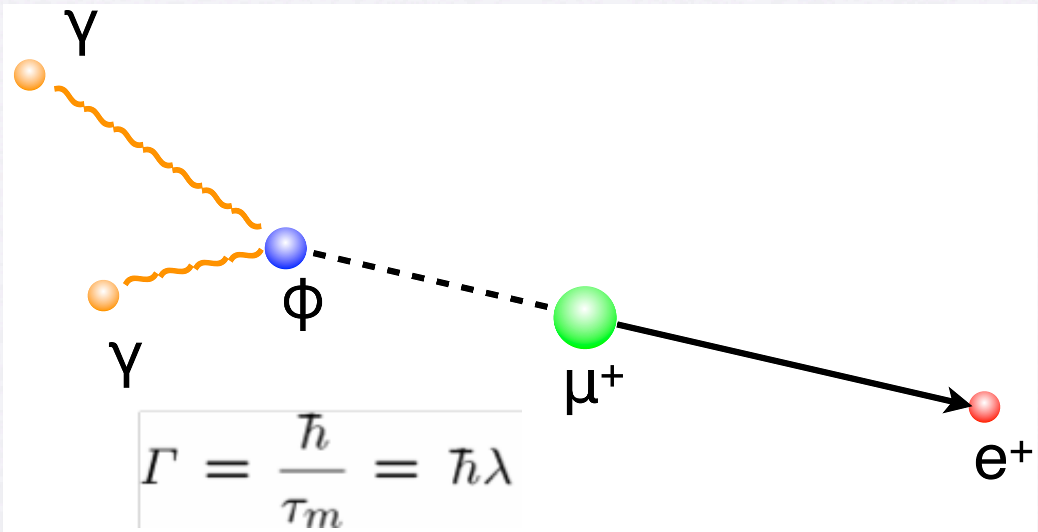
Silicon vertex tracker



Other physics in MEG

- Measurement of radiative muon decay (RMD) branching ratio and Michel parameters
- Exotic physics searches
  - Search for muon decay mediated by light pseudo-scalar particle, $\mu^+ \rightarrow e^+\varphi$, $\varphi \rightarrow \gamma\gamma$
  - Search for muon decay with massless Majoron, $\mu \rightarrow e^+J$

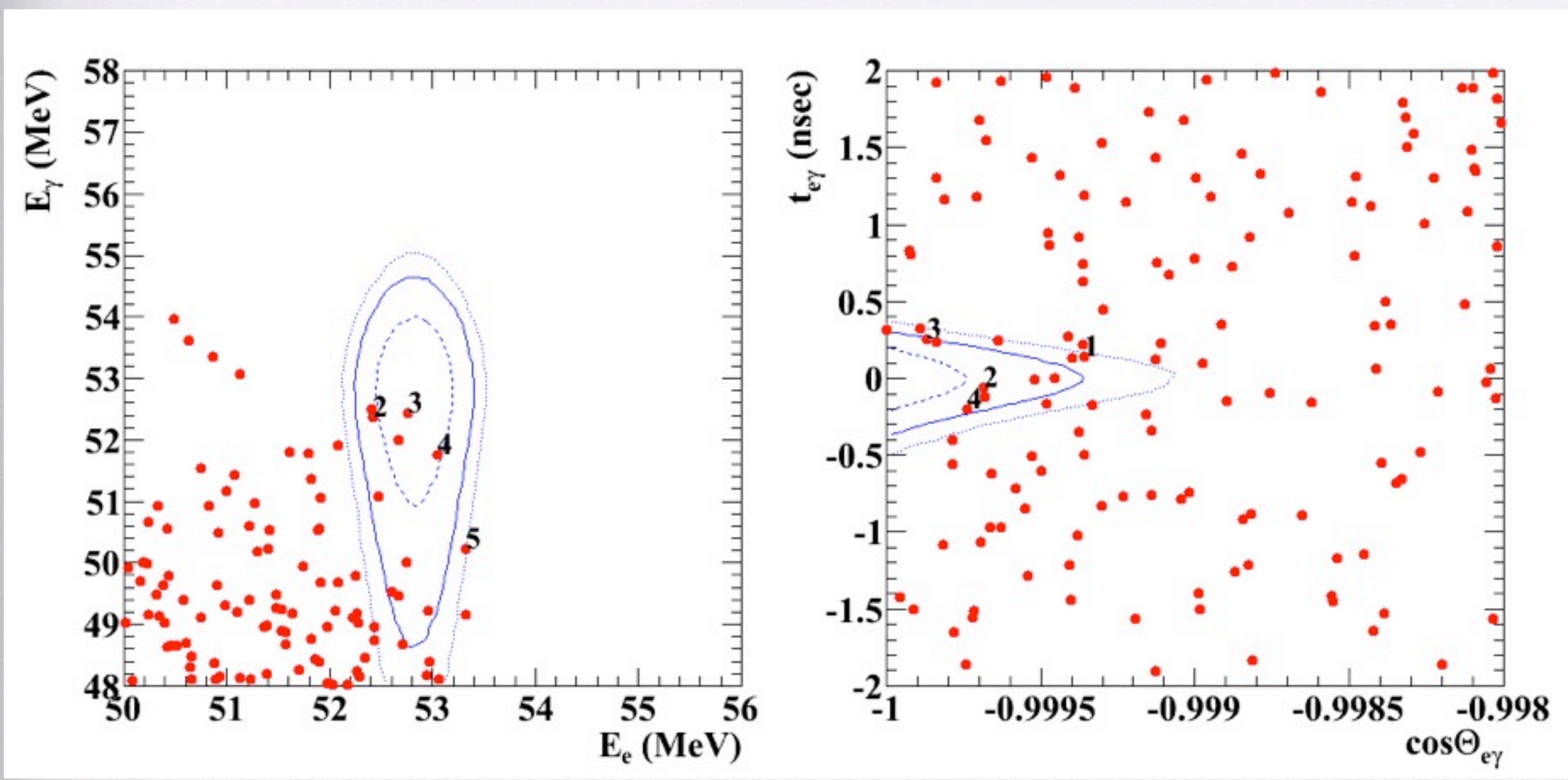




Summary

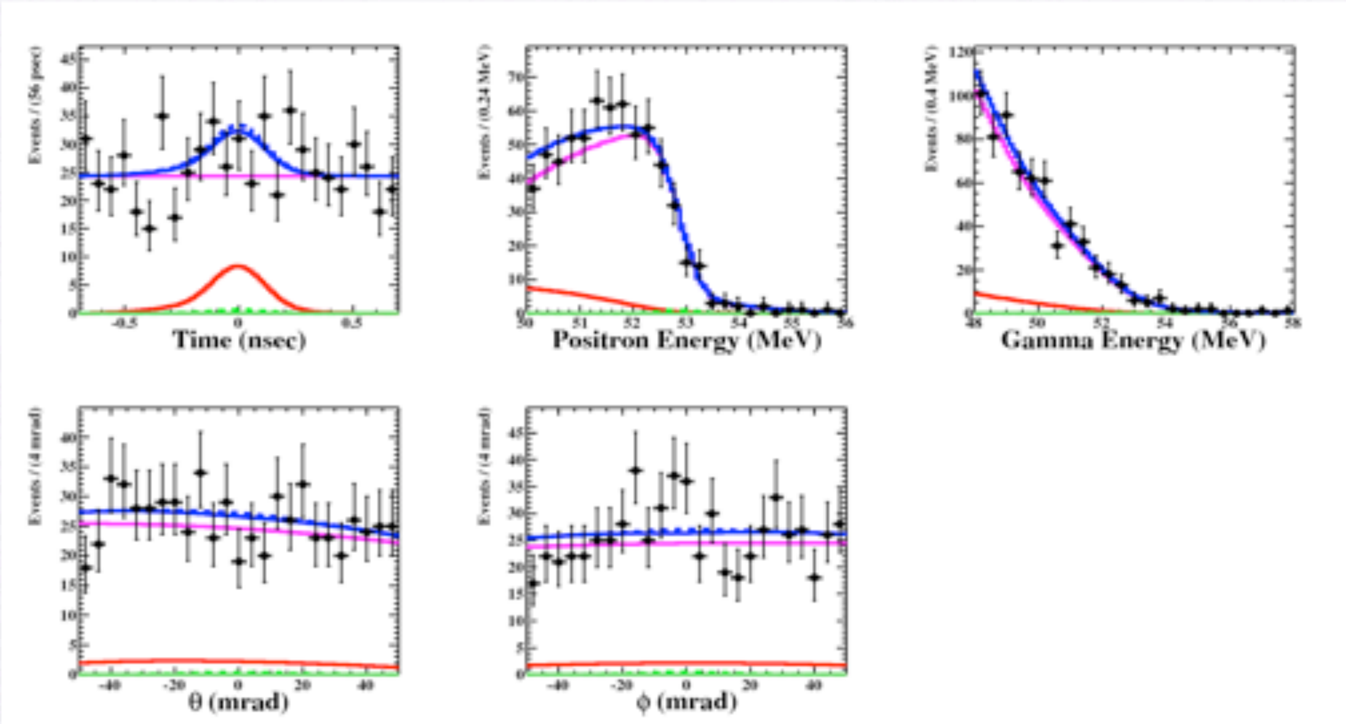
- MEG updated the BR($\mu \rightarrow e\gamma$) upper limit 2.4×10^{-12} at 90% C.L.
- 2011 data analysis is in progress
- More data in 2012 to explorer the branching ratio region of $O(10^{-13})$
- Detector upgrade R&D in progress
  - aiming at sensitivity of $O(10^{-14})$

Event distribution in 2009+2010



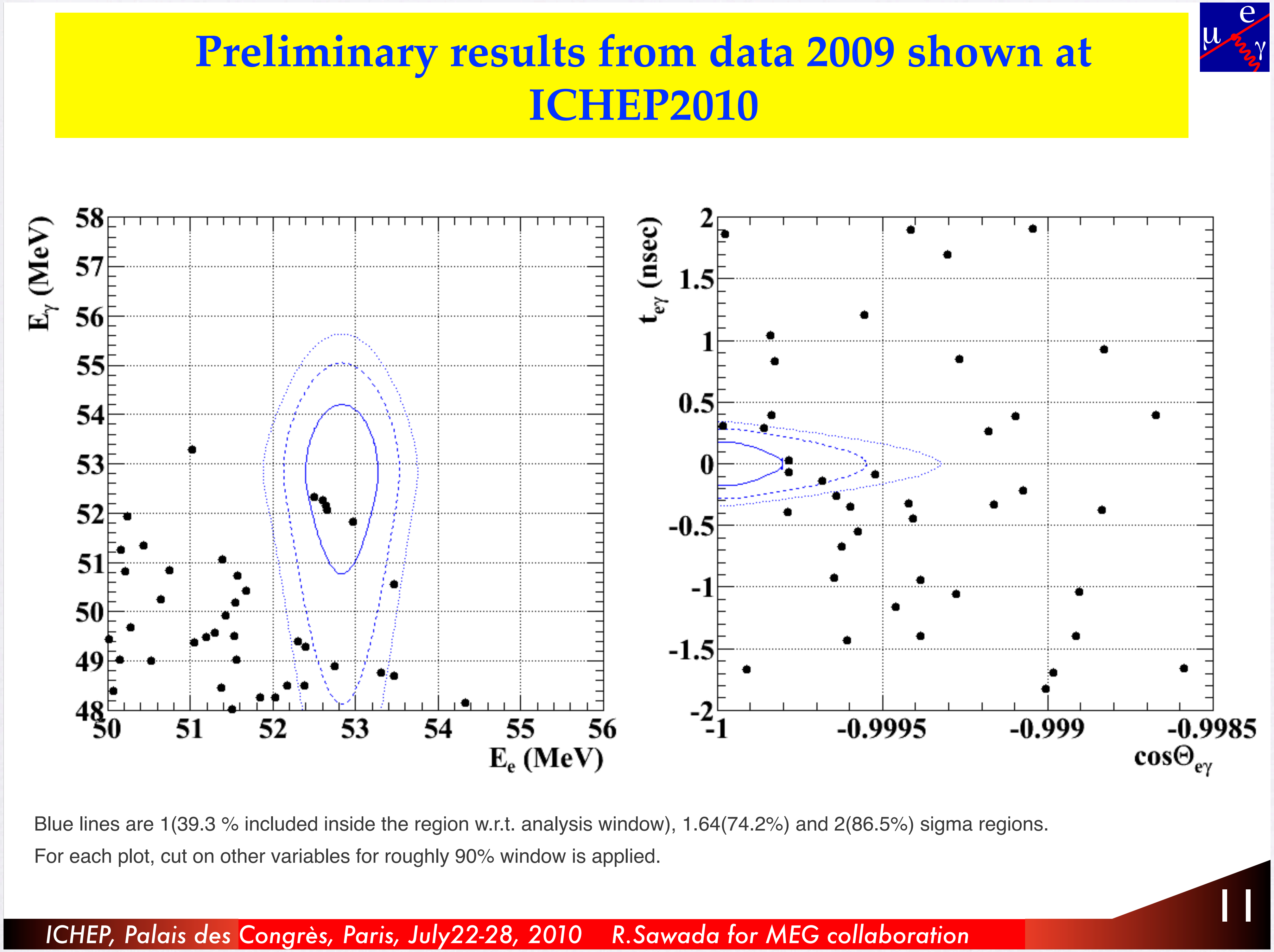
- Blue curves : Signal PDF contour (1, 1.64, 2σ)
- Selection : 51<EGamma<55MeV, 52.34<EPositron<55MeV, $\cos\theta_{e\gamma}$<-0.9996

Likelihood fit



ICHEP2010 result

- Preliminary result on data 2009 was presented in ICHEP2010 showing a small excess

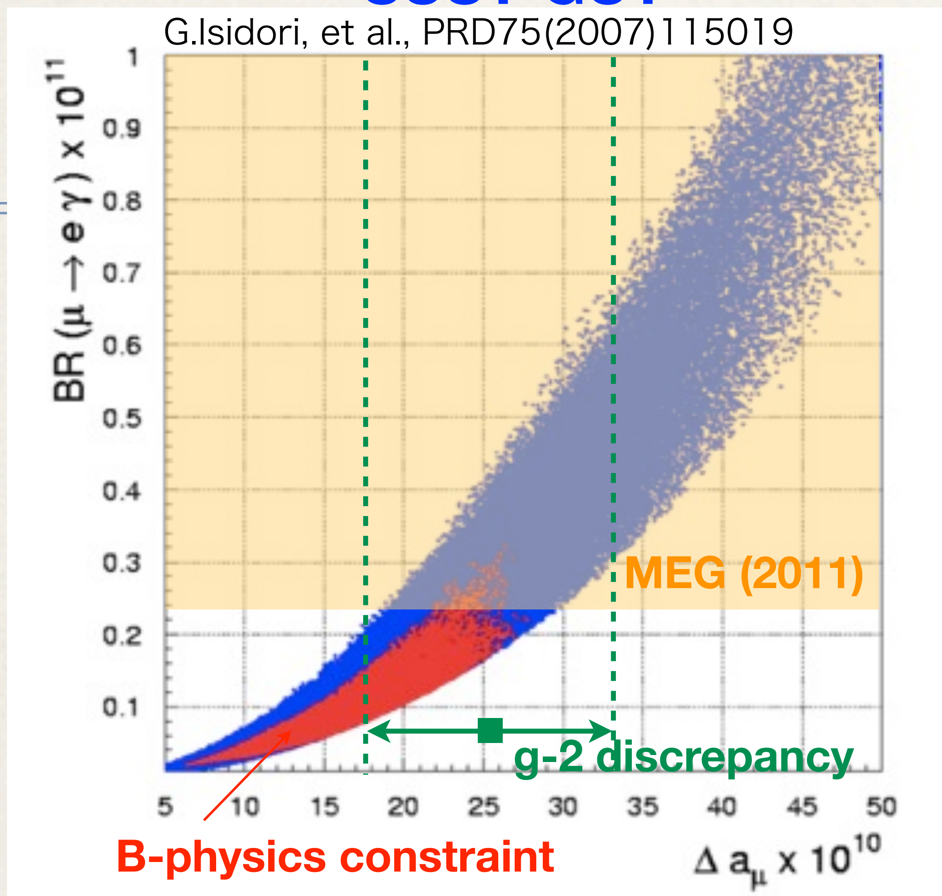


Updates from ICHEP2010 result

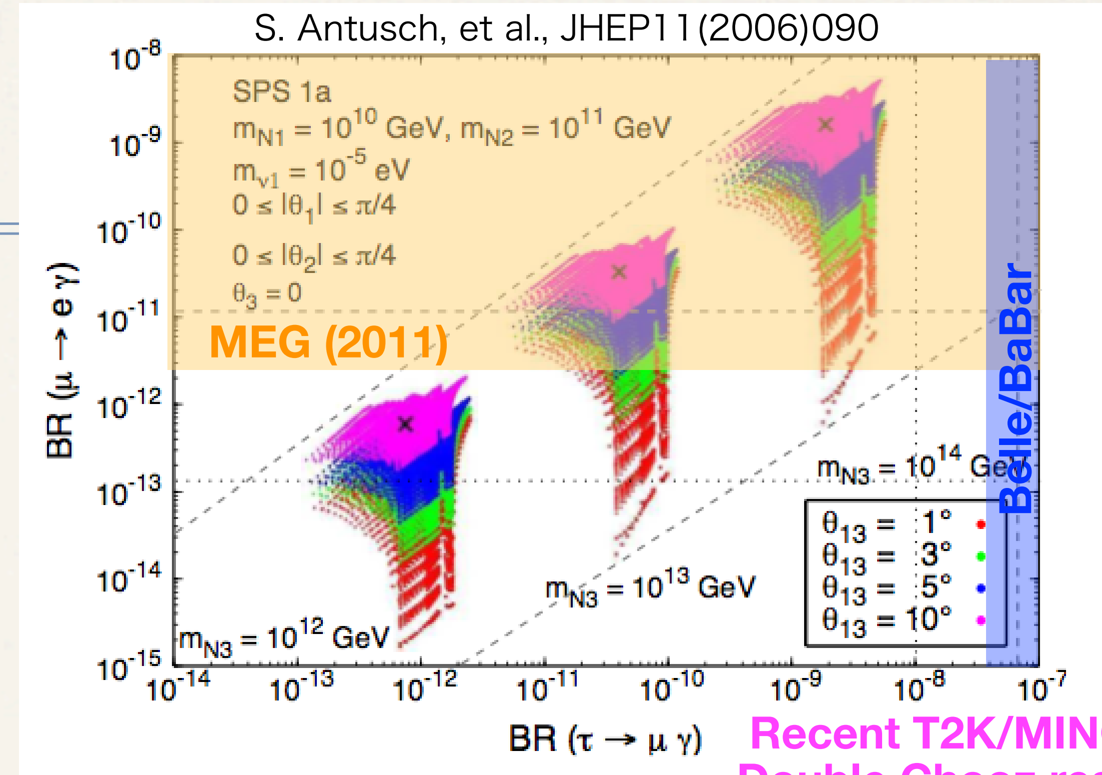
- Updates with new data (from run2010) and new analysis
  - Data 2010 (data statistics = 2xdata 2009)
  - Improve detector alignment
  - More detailed implementation of correlations in positron observables
  - Improve magnetic field map
  - Improve likelihood analysis tool

MEG Constrains New Physics

SUSY-GUT

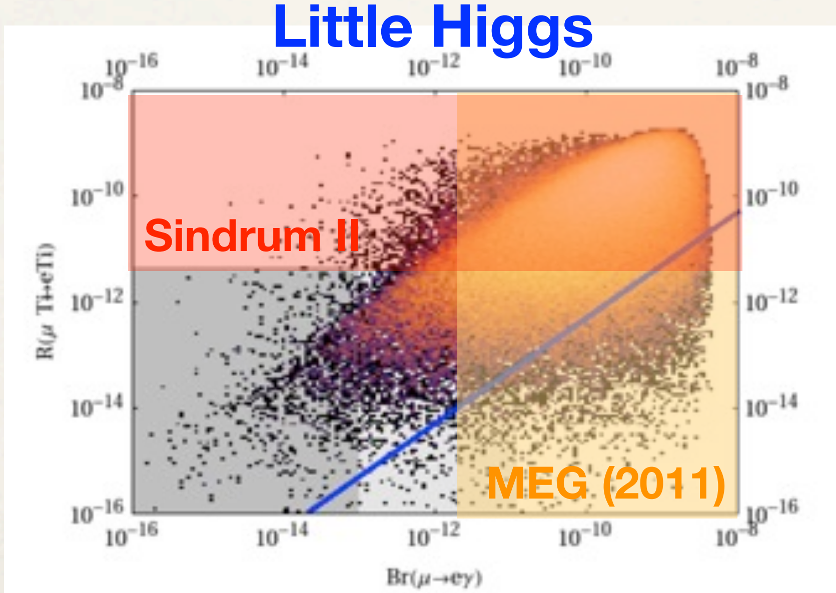


SUSY-Seesaw



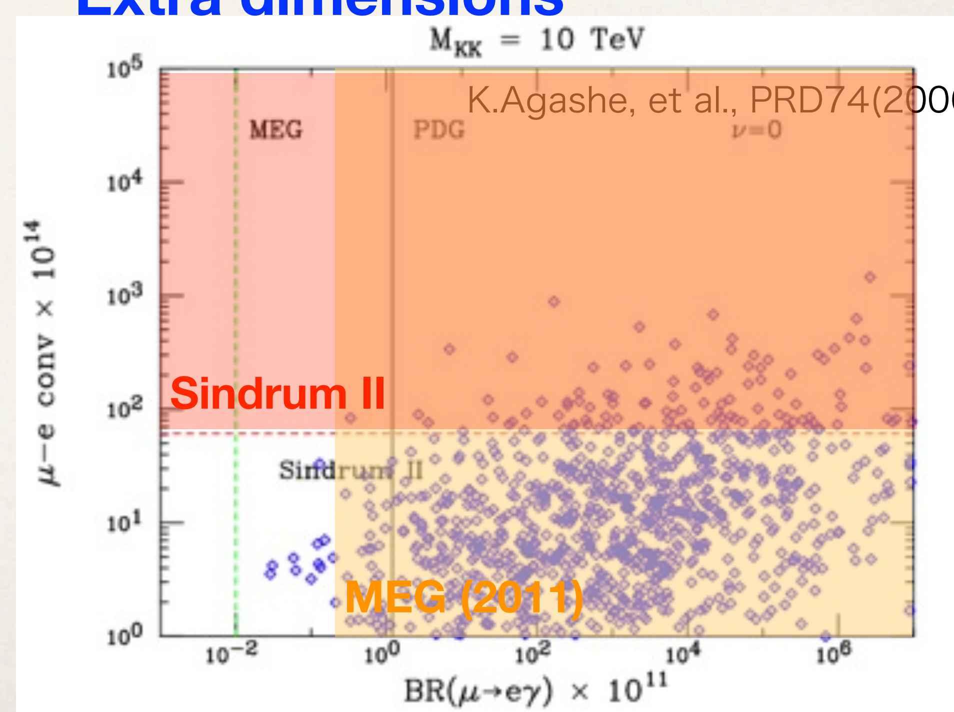
Recent T2K/MINOS/ Double Chooz results favors large θ_{13}!

Little Higgs



M.Blanke et al., Acta Phys.Polon.B41(2010)657

Extra dimensions



Run 2011

- All sub-detectors operational with reasonable performance for whole period
  - New DC HV-system (reduced noise)
  - New DC alignment system
  - More efficient LXe calibration (CEX with new BGO detector)
  - Slow LXe light yield degradation (well monitored and corrected)
  - Higher DAQ efficiency with multi-buffer scheme
  - DAQ had to stop in beg-Nov due to damage of cryo-plant caused by power outage.
- Data statistics doubled. run2011 ~ (run2009+run2010)

Run2012

- Increased beam intensity is planned (x1.15, ~3.5×10^{7} μ^{+} stops/s)
- Some improvements in resolutions and efficiencies anticipated

Likelihood analysis

- Fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering

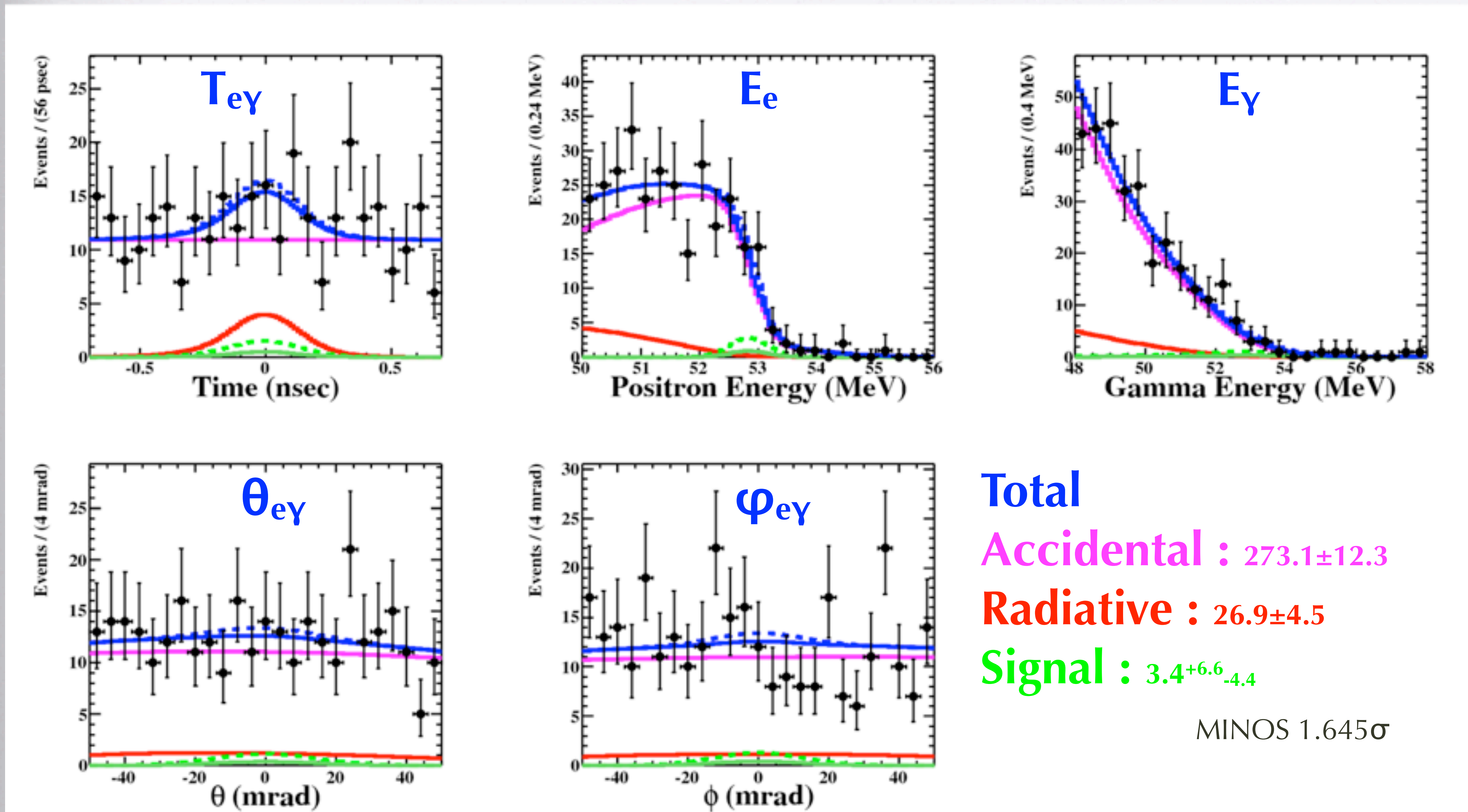
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{e^{-N}}{N_{\rm obs}!} e^{-[(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2/2\sigma^2_{\rm RMD}]}$$

$$\times\ e^{-[(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2/2\sigma^2_{\rm BG}]} \prod_{i=1}^{N_{\rm obs}} [N_{\rm sig} S(\vec{x}_i)$$

$$+ N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i)], \qquad \vec{x}_i = \{E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}\}$$

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

Likelihood Fit 2009

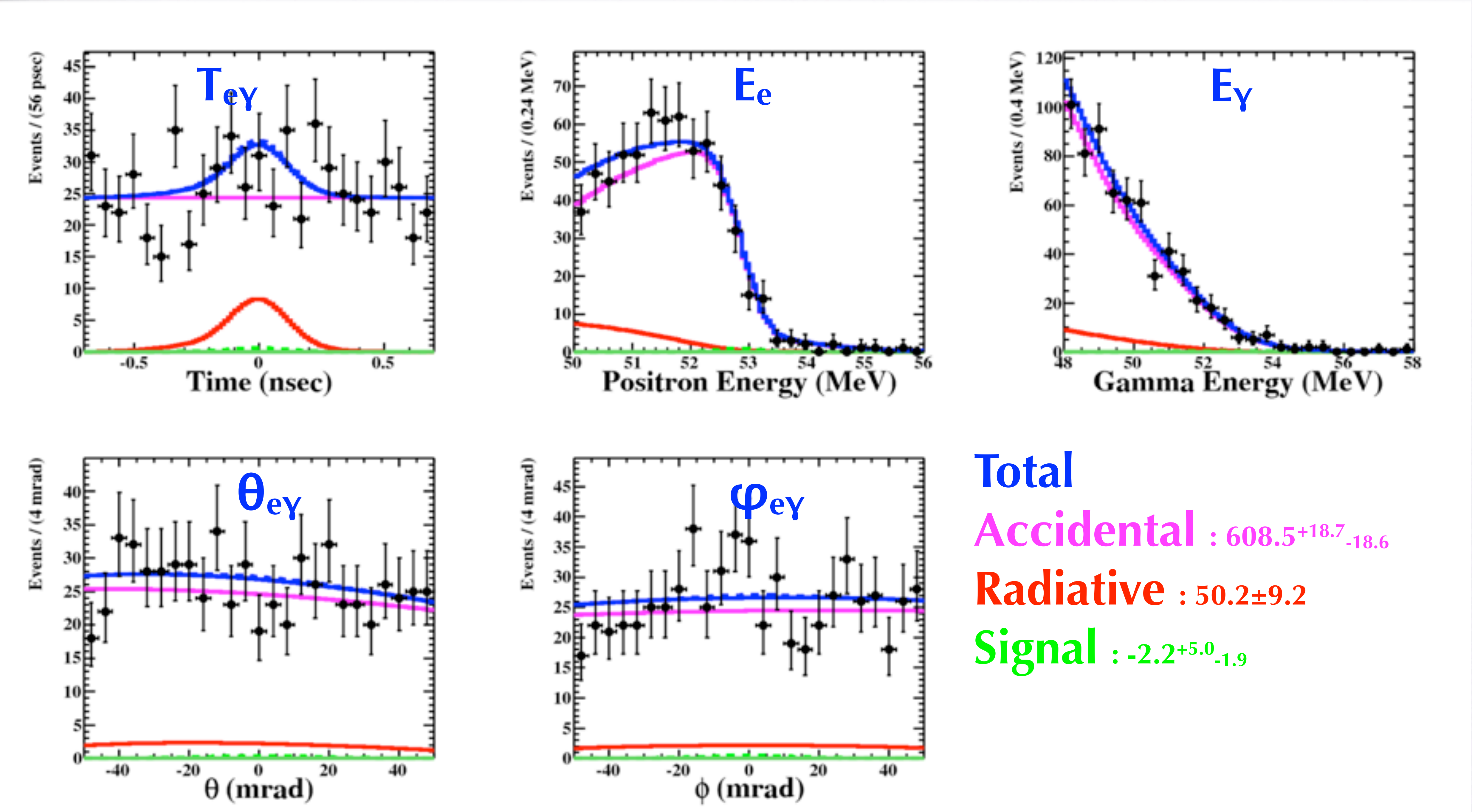


Solid lines correspond to the best fit, and dashed lines correspond to 90% upper limit of number of signals

Without physics constraint : N_{signal} is allowed to be negative in the fitting

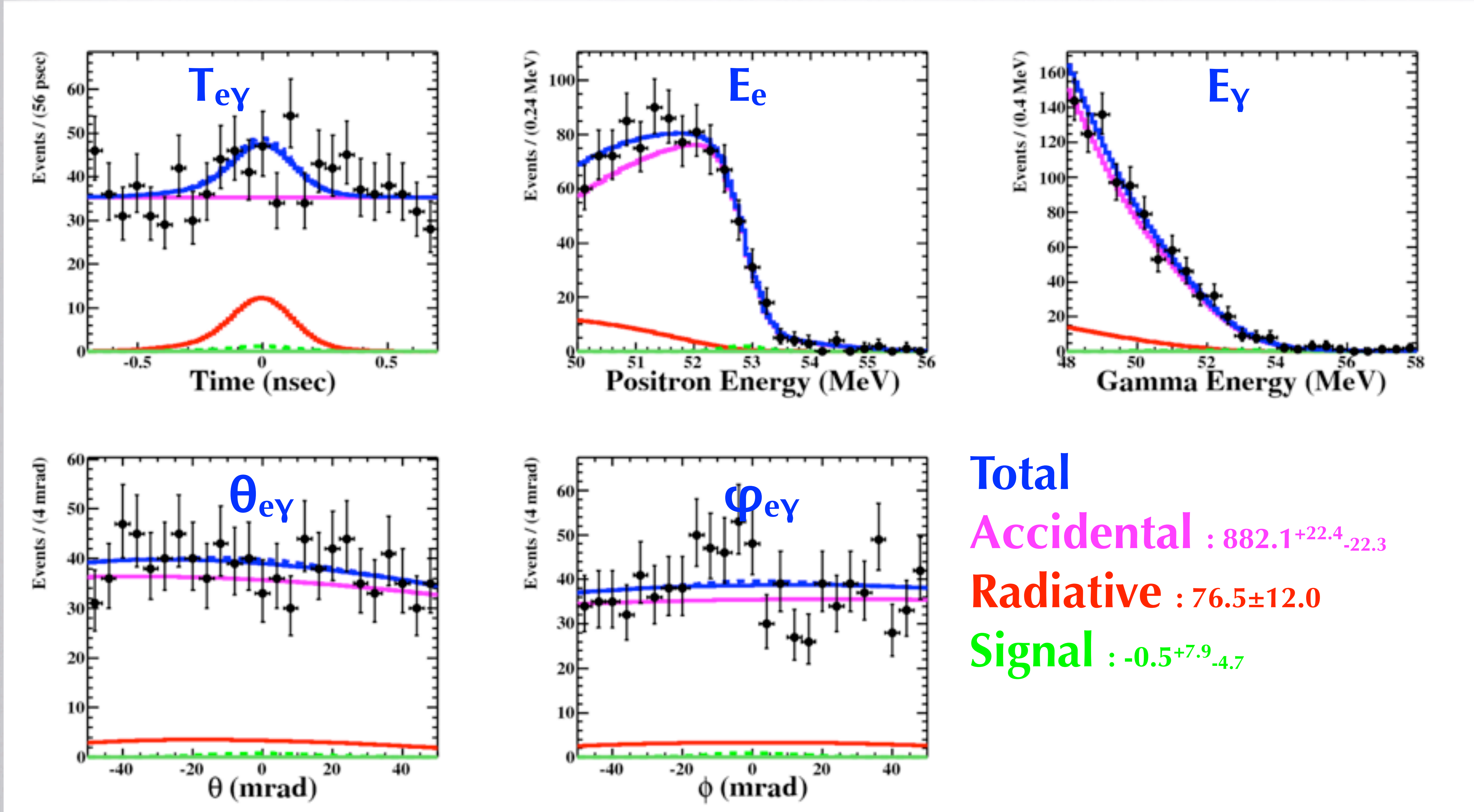
Gaussian constraints from sideband: $\langle N_{RMD} \rangle = 27.2 \pm 2.8$, $\langle N_{BG} \rangle = 270.9 \pm 8.3$

Likelihood Fit 2010



Solid lines correspond to the best fit, and dashed lines correspond to 90% upper limit of number of signals
Without physics constraint : N_{signal} is allowed to be negative in the fitting
Gaussian constraints from sideband: $\langle N_{RMD}\rangle$=52.2±6.0, $\langle N_{BG}\rangle$=610.8±12.6

2009+2010 Likelihood Fit



Solid lines correspond to the best fit, and dashed lines correspond to 90% upper limit of number of signals
Without physics constraint : N_{signal} is allowed to be negative in the fitting
Gaussian constraints from sideband: $\langle N_{RMD} \rangle = 79.4 \pm 7.9$, $\langle N_{BG} \rangle = 881.7 \pm 15.1$

Systematics

- Method to incorporate systematics
  - Uncertainties for N_{RMD} and N_{BG} : Profiling
  - Other systematics : Smearing likelihood ratio distribution simulated for the pseudo-experiments in the computation of the confidence intervals, by fluctuating PDF parameters according to their uncertainties.
- Size of effect of systematics : ~ 2% shift in UL
  - Largest contributions come from uncertainties of
    - Offsets of the relative angles
    - Correlations in the positron observables
    - Normalization

Search for $\mu^+ \to e^+\varphi$, $\varphi \to \gamma\gamma$

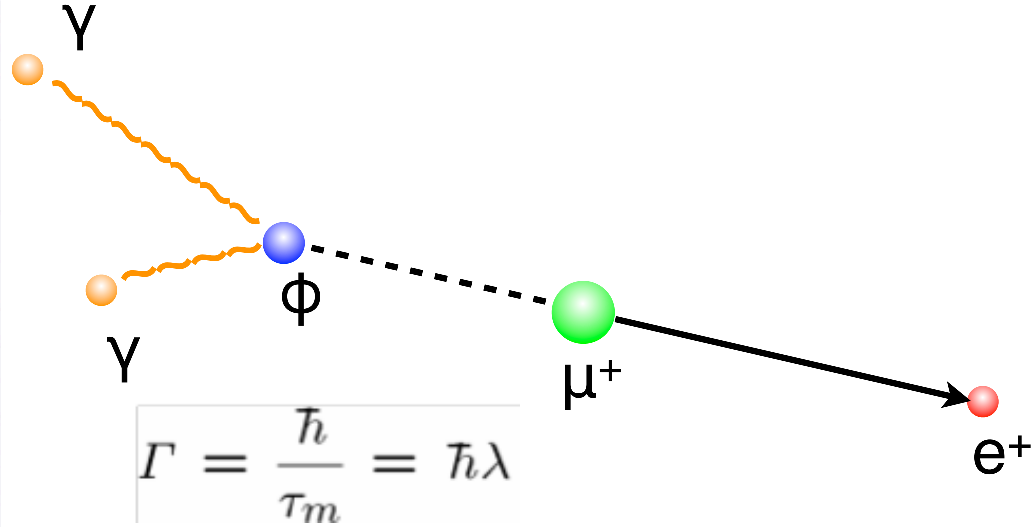
- Search for muon decay mediate by very light pseudo scalar particle

- $\mu^+ \to e^+\varphi$, $\varphi \to \gamma\gamma$ is not yet searched

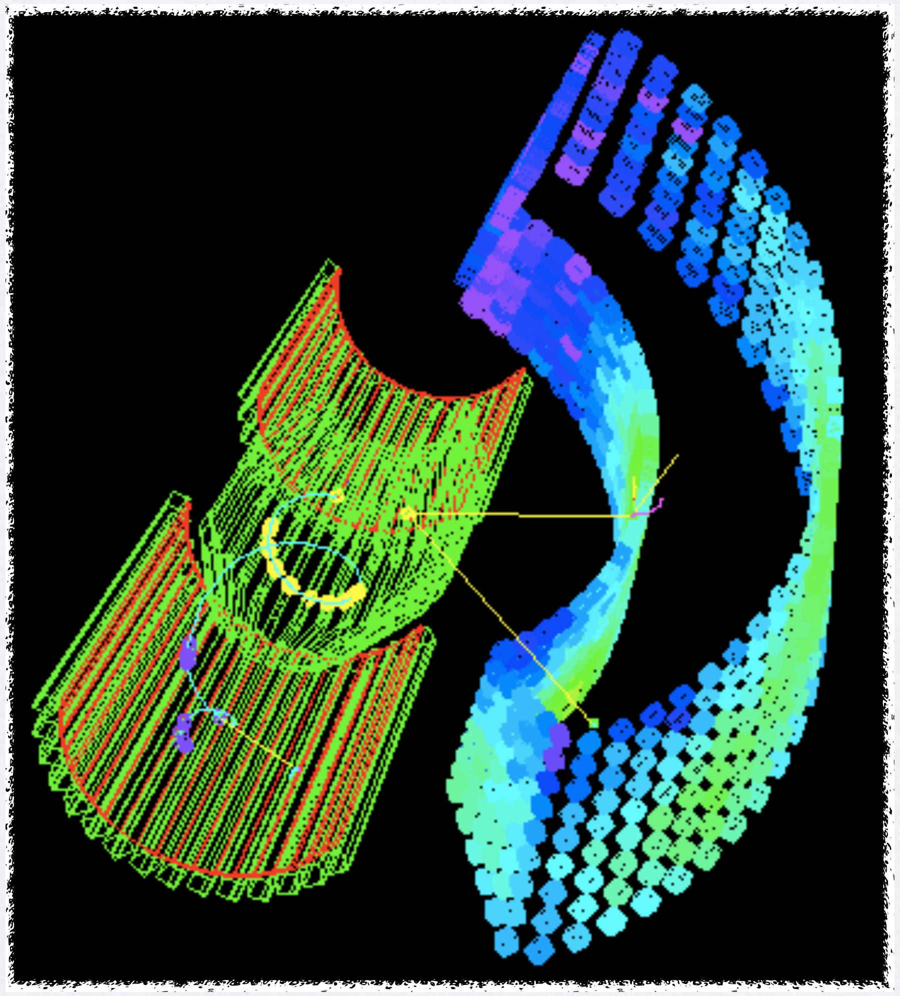
    - Leptophobic case is possible, coupling to ee is small and only decay into $\gamma\gamma$

    - Phys. Rev. D72, 117701(2005)

- Preliminary result from analysis on data 2009+2010 shows branching ratio UL of $O(10^{-11}\text{-}10^{-10})$ depending on M_φ



Event Example(MC, M_φ=20MeV)



Search for $\mu^+ \rightarrow e^+ J$

- Possibility to search using MEG data for two-body muon decay with Majoron, $\mu^+ \rightarrow e^+ J$

$$\frac{d\Gamma(\mu \to eJ)}{dcos\theta} = \frac{m_\mu}{64\pi} |O^{ccp}_{L\mu eJ}|^2 (1 \pm P_\mu cos\theta)$$

M. Hirch et al.,
Phys. Rev. D80, 055023(2009)

- Potentially complementary to accelerator search

- Previous search by TWIST
  - BR($\mu^+ \rightarrow e^+ J$) $<6.7 \times 10^{-5}$@90%C.L.(for A=-1)

MC