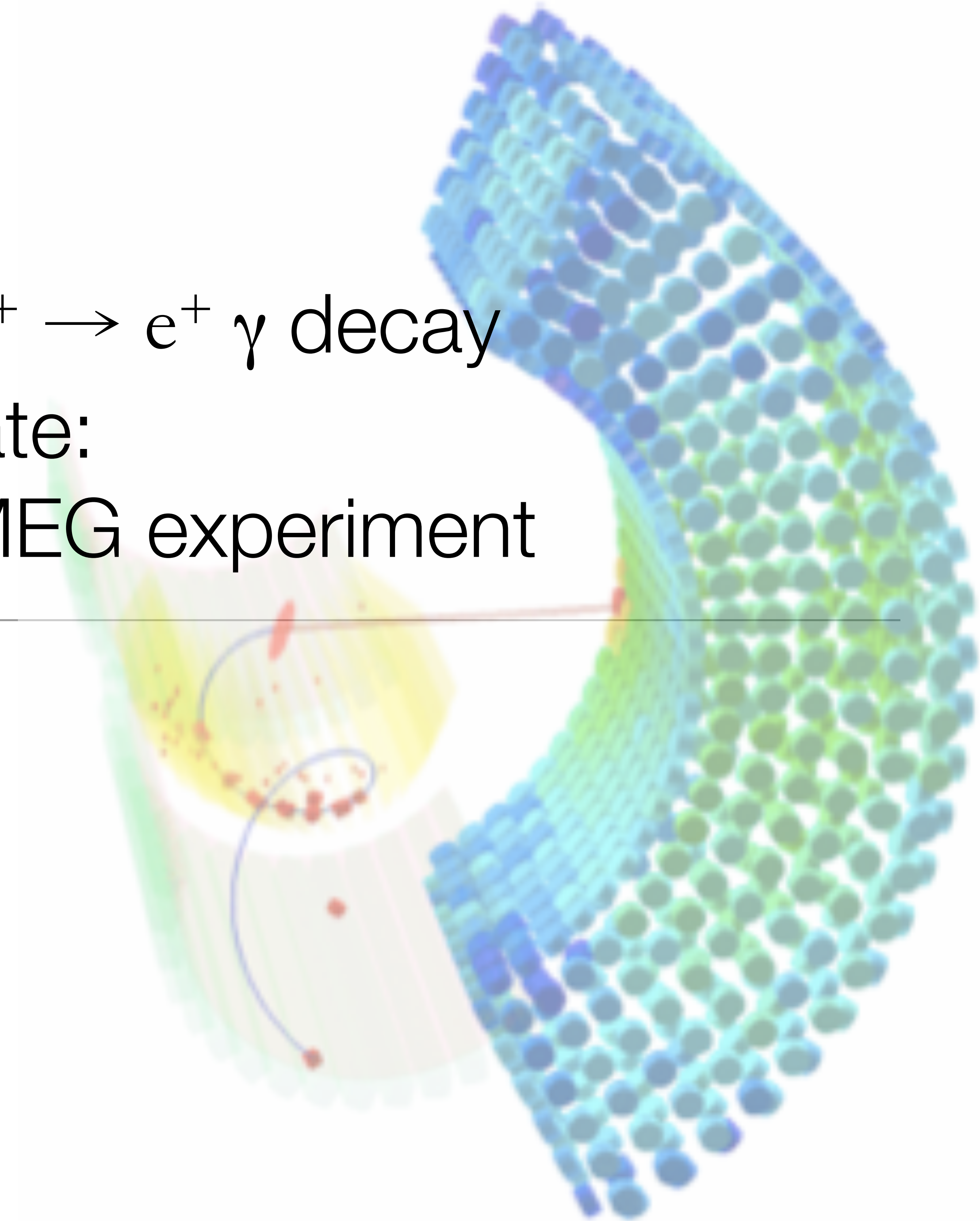
# The existence of the $\mu^+ \rightarrow e^+ \gamma$ decay from Pontecorvo up to date: a new constraint by the MEG experiment



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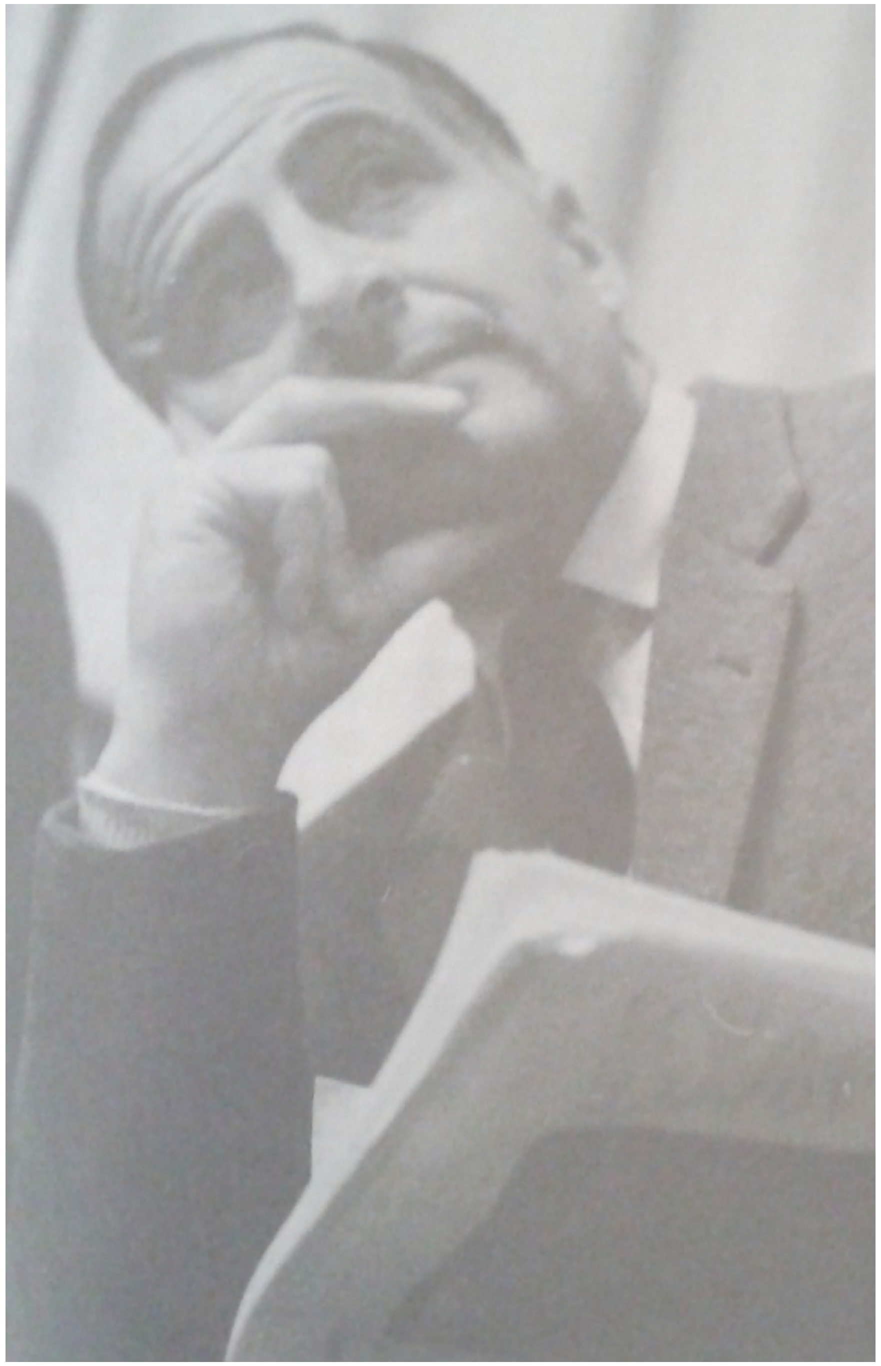
on behalf of MEG Collaboration

*August 22-28, 16th Lomonosov Conference 2013*
*Moscow University*

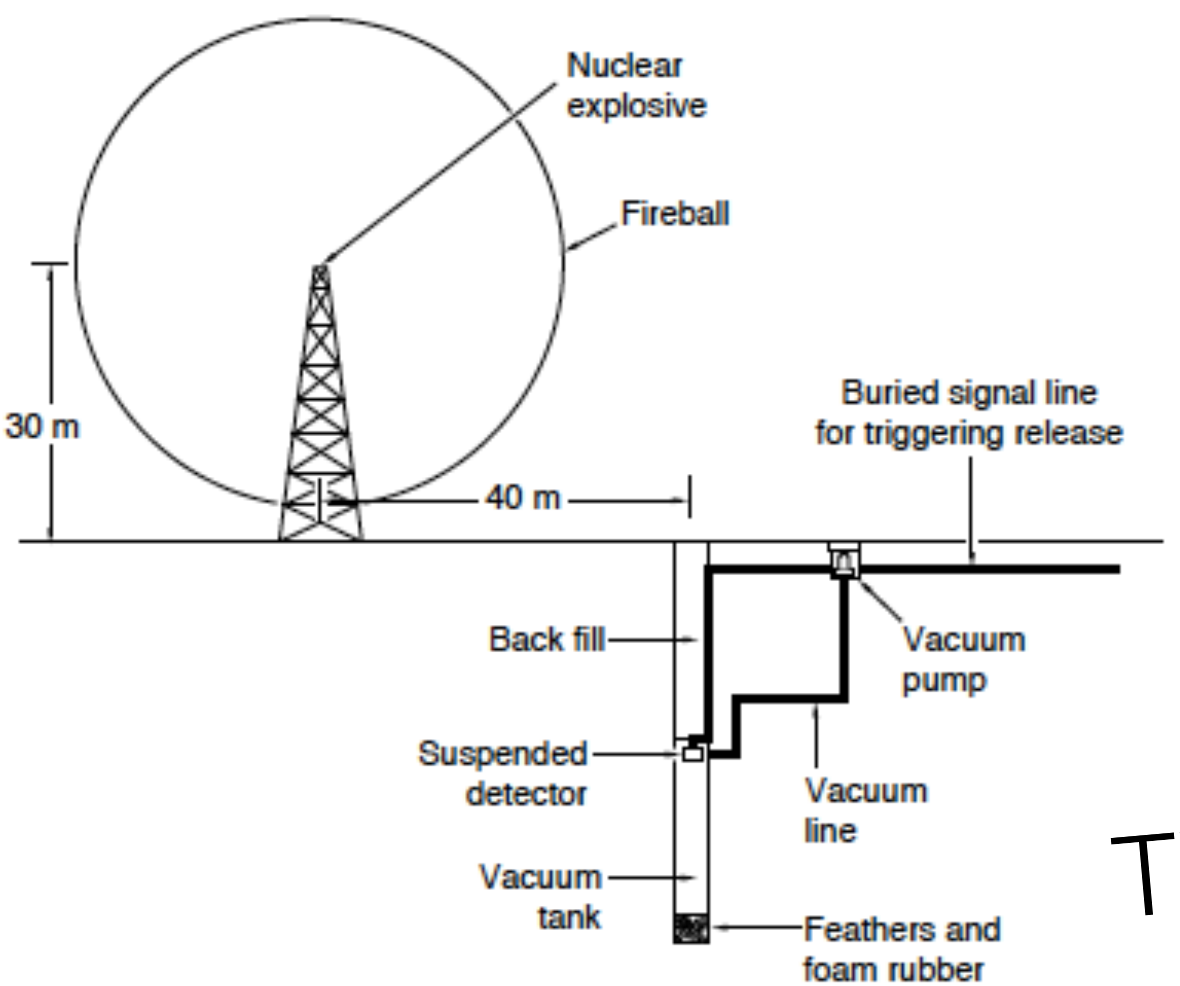
# Outlook

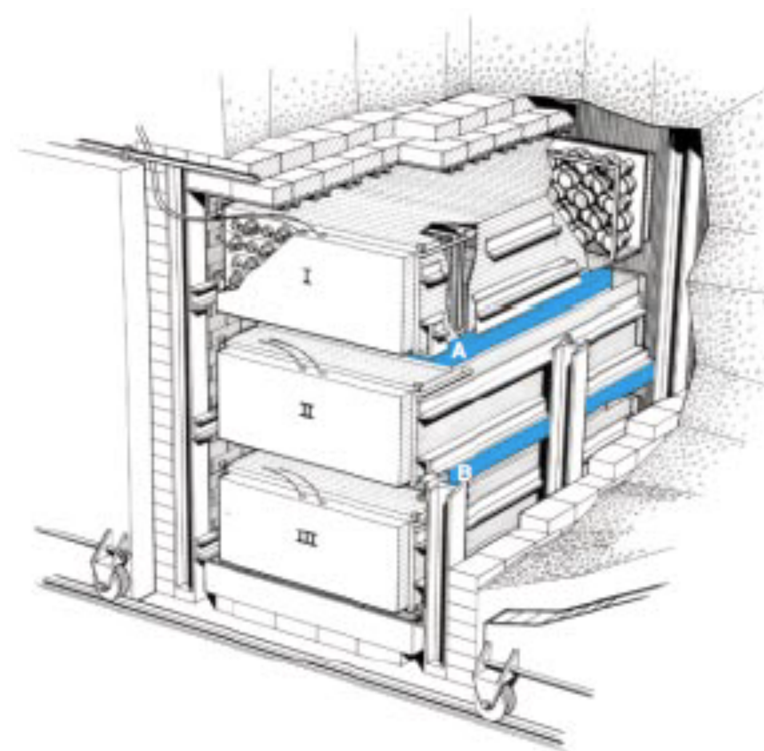
- **Introduction:**
  - a tribute to B. Pontecorvo “one of the founders of neutrino physics” (S.M. Bilenky)
- **The first muon decay search:**
  - E.P. Hincks and B. Pontecorvo
- **The (2013) latest result by the MEG experiment:**
  - a new upper limit on the $\mu^+ \to e^+ \gamma$ decay



# Tribute to B. Pontecorvo: The Neutrino sources

- High intensity Neutrino sources pointed out by B. Pontecorvo (when the widespread opinion was that it was pratically impossible to observe this particle)
  - The Reactors, the Sun and the irradiation of elements with neutrons in reactors
  - Antineutrinos from a reactor were detected in the mid-1950s (F. Raines and C. Cowan). F. Raines was awarded the Nobel prize for the discovery of the neutrino (1995)



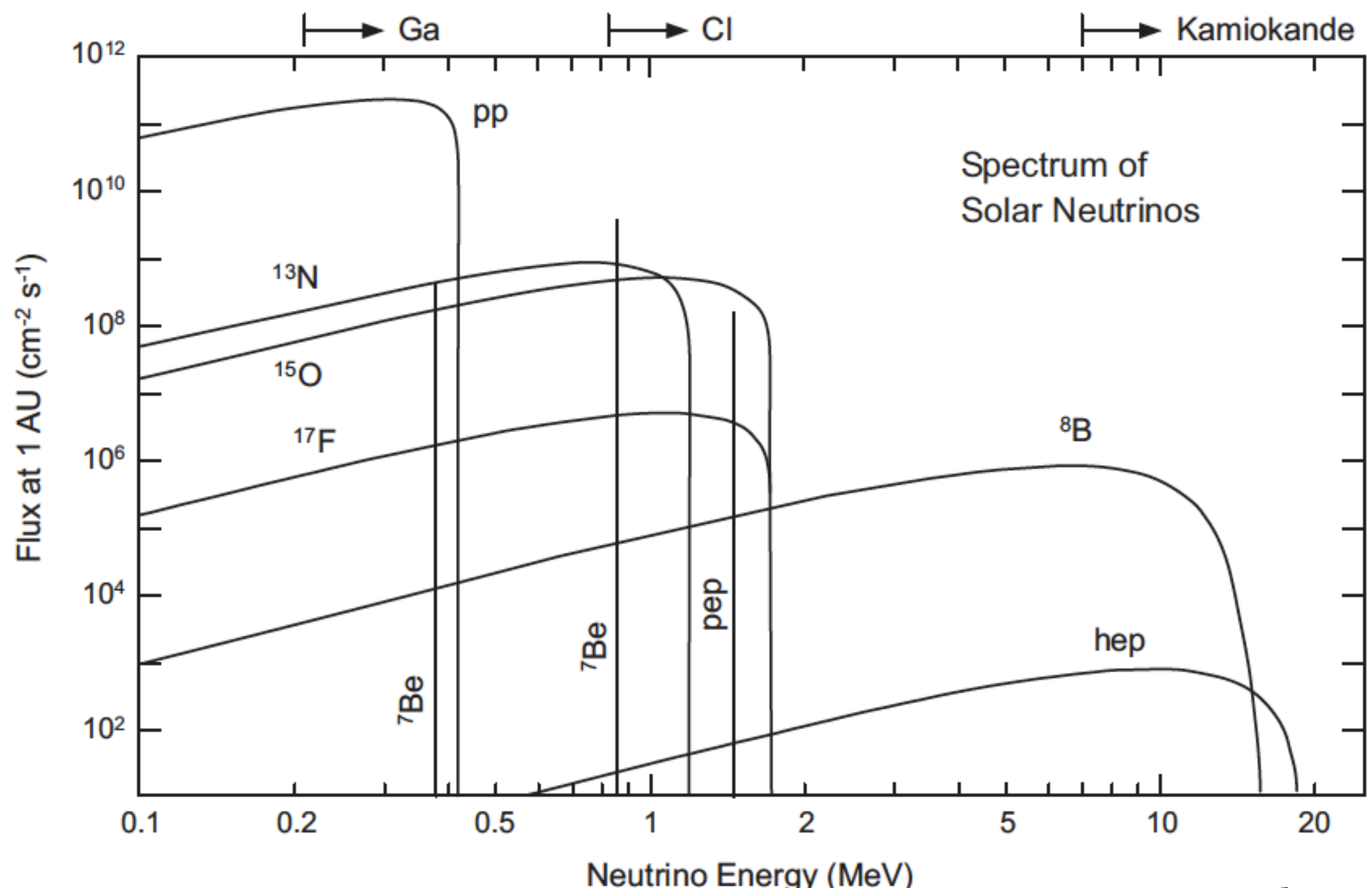




The Savannah River experiment

The first “neutrino” has been detected

Tribute to B. Pontecorvo: A way to detect Neutrinos

- The Detection: the radiochemical approach
  - The chlorine-argon method: $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ (Pontecorvo-Davis reaction)
  - Solar neutrino was detected applying this method (R. Davis et al.)

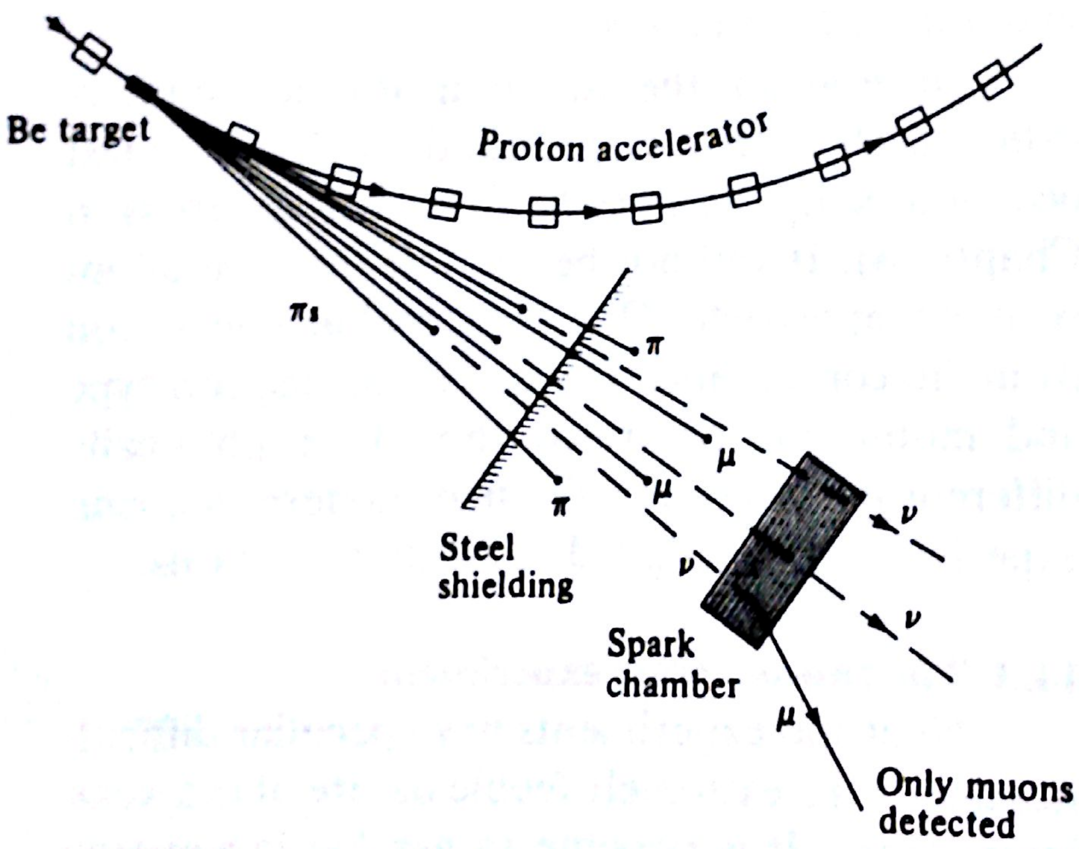




The neutrino astronomy is born

# The Neutrino flavour

- "Were the electron and the muon neutrinos different or identical particles?"
    - The B. Pontecorvo proposal was realized in Brookhaven (1962)
    - The electron and muon neutrinos were shown to be different particles
        - L. Lederman, J. Steinberger and M. Schwartz were awarded the Nobel Prize




The Neutrino physics at accelerators starts

Tribute to B. Pontecorvo: The Neutrino mass and mixing

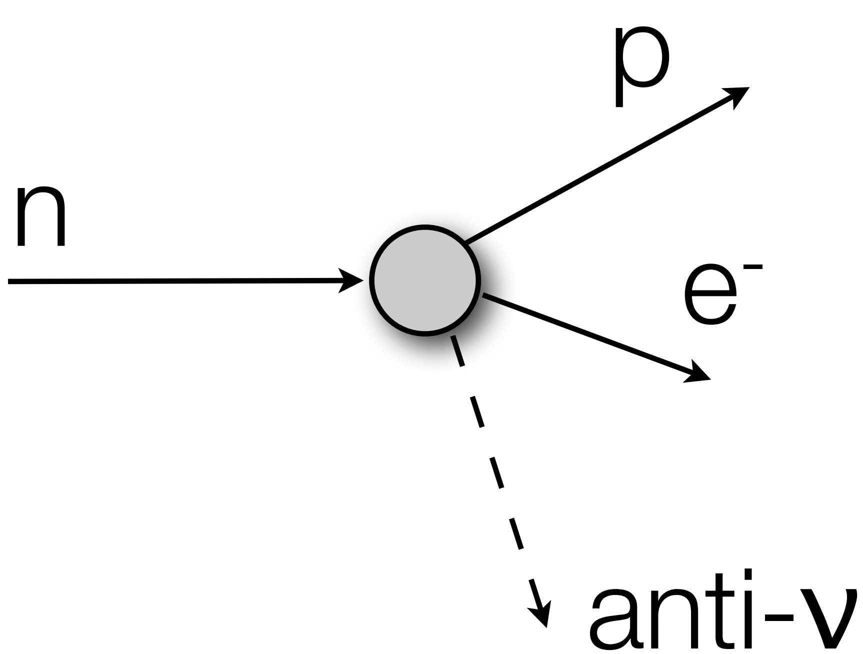
- The symmetry (analogy) in the interaction of hadrons and leptons: **B. Pontecorvo's leading idea**
- Anticipation of the neutrino oscillation, given the lepton-hadron symmetry ("a phenomenon similar to the oscillation of neutral kaons can exist in the world of leptons", B. Pontecorvo)
- B. Pontecorvo proposal to search for neutrino oscillation

$$\mathcal{P}_{\nu_l \to \nu_{l'}} = \quad |\langle \nu_{l'} | \nu_l \rangle|^2 = \left| \sum_i V_{li} V^*_{l'i} e^{-i(m_i^2/2E_i)/L} \right|^2 \neq 0$$


The Modern Neutrino physics appears

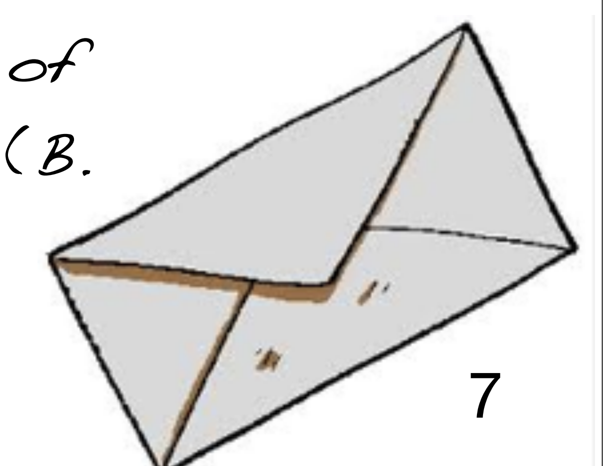
# The universality of the weak interaction

- B. Pontecorvo was the first to apprehend the profound analogy between the muon and the electron: the mu-e universality of the weak interaction
  - The weak interaction is an universal interaction including not only the beta-decay, but also processes such as muon absorption



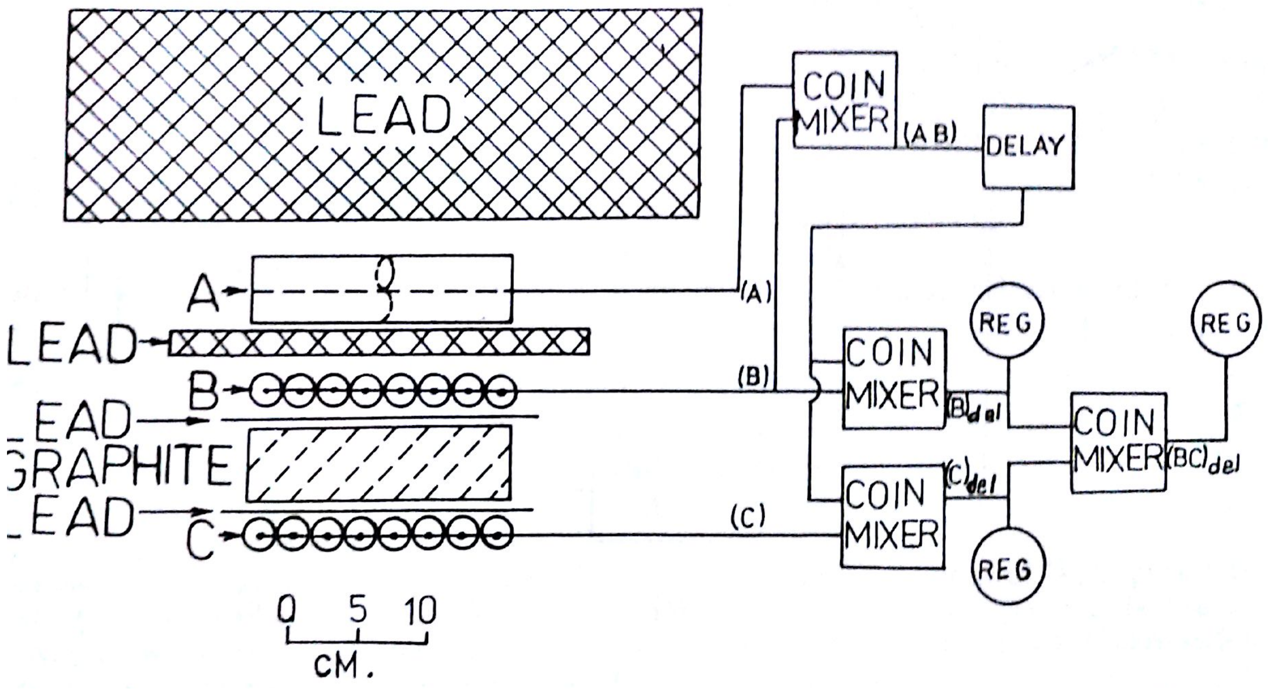

Letter to G. Wick, May 8th 1947

*" It can be deduced a similarity between beta processes and processes of absorption or emission of mesons, that, assuming that it is not coincidence, seems to be of fundamental character..." (B. Pontecorvo)*

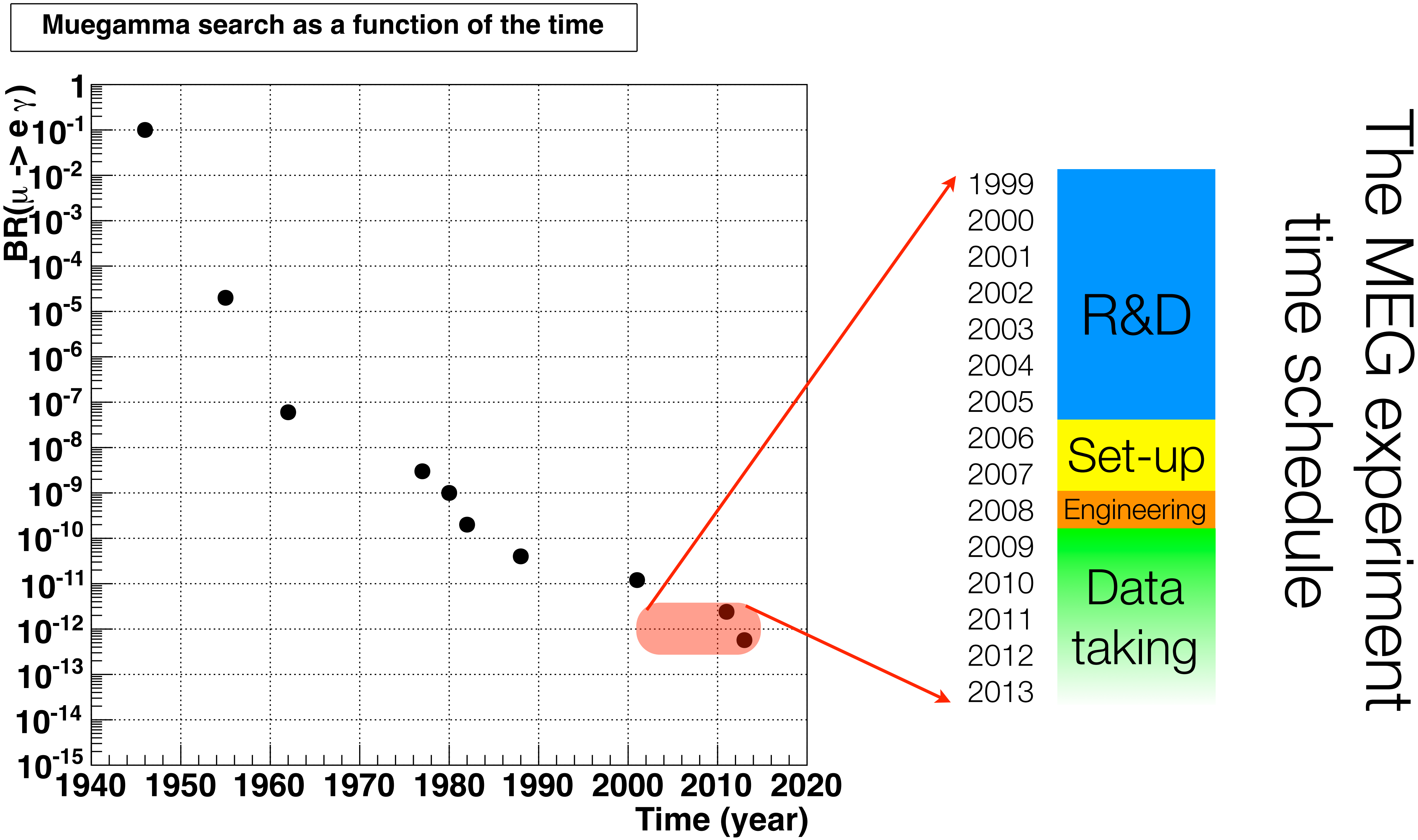


# The first muon decay search

- The Conversi-Pancini-Piccioni experiment proved the muon to be a weakly interacting particle
- What is known about this mysterious particle? Into what particles does the muon decay?
- By means of brilliant experiments B. Pontecorvo demonstrated that
  - the charged particle emitted in the muon decay is an electron
  - a muon decays into three particles
  - the decay of a muon into an electron and photon was not observed



# The $\mu^+ \to e^+ \gamma$ decay from B. Pontecorvo up to now




Why $\mu^+ \to e^+ \gamma$ decay search today?

# Lepton Flavour Violation of Charged Leptons (cLFV)

- Lepton flavour is preserved into the SM (“accidental” symmetry)
  - not related to the theory gauge structure
  - naturally violated in SM extensions


LFV of neutral leptons confirmed -neutrino oscillations-

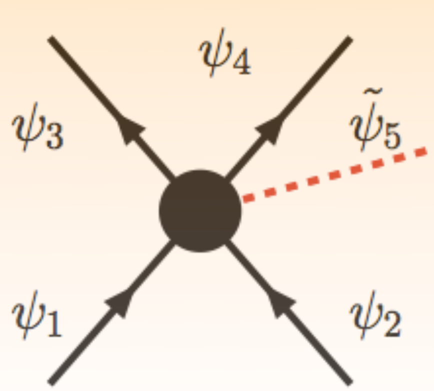
LFV of charged leptons not yet observed

(*)BSM = Beyond Standard Model

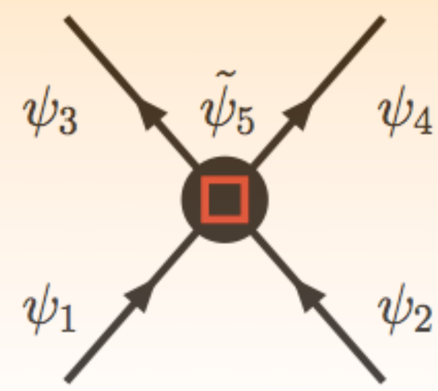
# The role of low energy physics in the LHC era

How can low energy experiments be sensitive to high-energy physics (BSM*)?

- Direct/indirect production of BSM particles



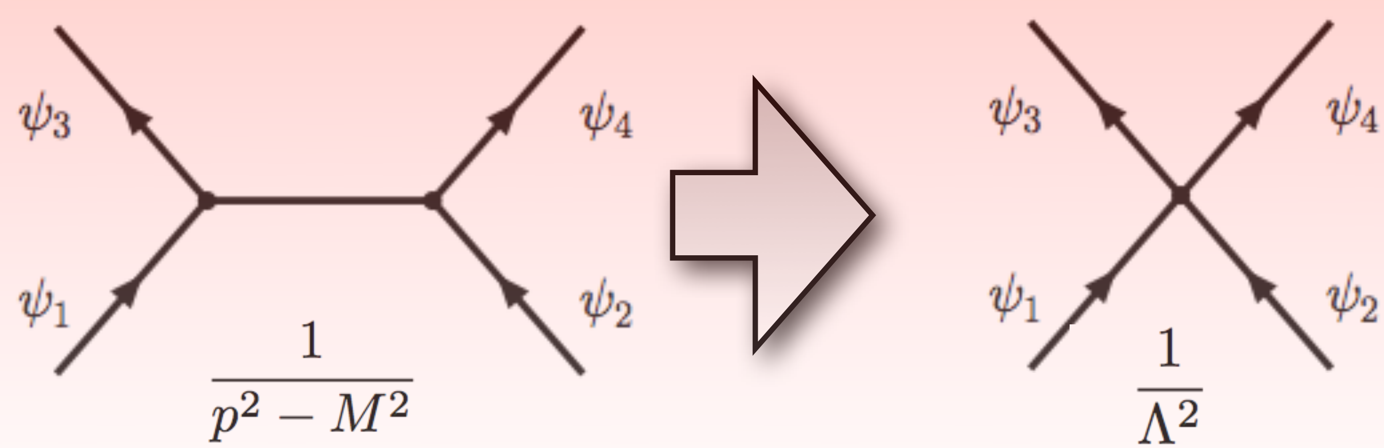

- Real BSM particles produced in the final state
- Energy frontier (LHC)




- Virtual BSM particles produced in loops
- Precision and intensity frontier

- Effective field theory approach

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

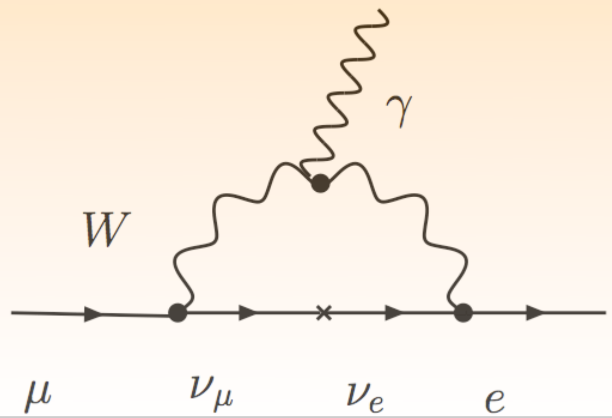



- $L_{eff}$ is in terms of inverse powers of heavy scale

[1] R. Barbieri, L. Hall and A. Strumia, Nucl. Phys. B 455 (1995) 219
[2] J. Hisano, D. Nomura and T. Yanagida, Phys. Lett. B 437 (1998) 351
[3] M. Raidal et al., Eur. Phys. J. C 57 (2008) 13
[4] G. Blankenburg et al., Eur. Phys. J. C 72 (2012) 2126

# The $\mu^+ \to e^+ \gamma$ decay

- Experimental evidence of neutrino oscillations




SM with massive neutrinos (Dirac)

$$\Gamma(\mu \to e\gamma) = \quad \approx \quad \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{\alpha}{2\pi} \sin^2 2\theta \, sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

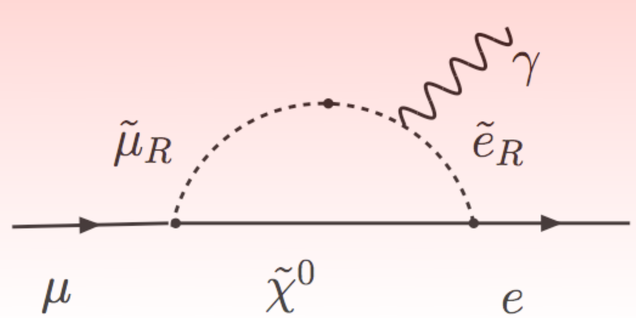
$$B(\mu^+ \to e^+\gamma) \approx 10^{-54}$$

- SU(5) SUSY-GUT and SO(10) SUSY-GUT models predict measureble LFV decay BR
- Null results
  - precise test of established model
  - rule out speculative models

$$\Gamma(l_1 \to l_2\gamma) = \frac{\alpha G_F^2 m_{l_1}^5}{2048\pi^4} (|D_R|^2 + |D_L|^2)$$

$$D_R = D_L \approx \frac{1}{G_F \Lambda^2}$$

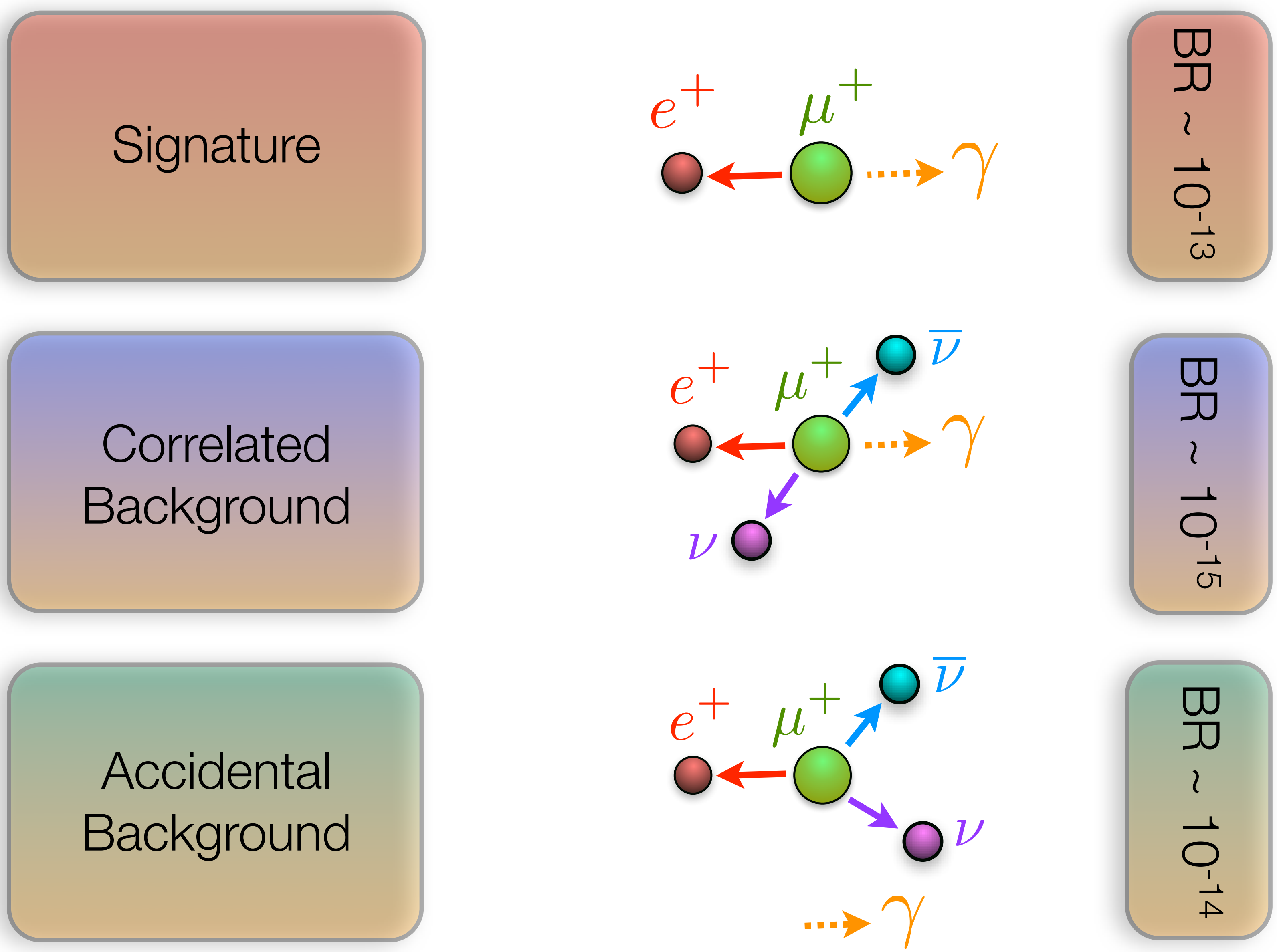
SU(5) SUSY-GUT o SO(10) SUSY-GUT




$$10^{-14} < B(\mu^+ \to e^+\gamma) < 10^{-11}$$

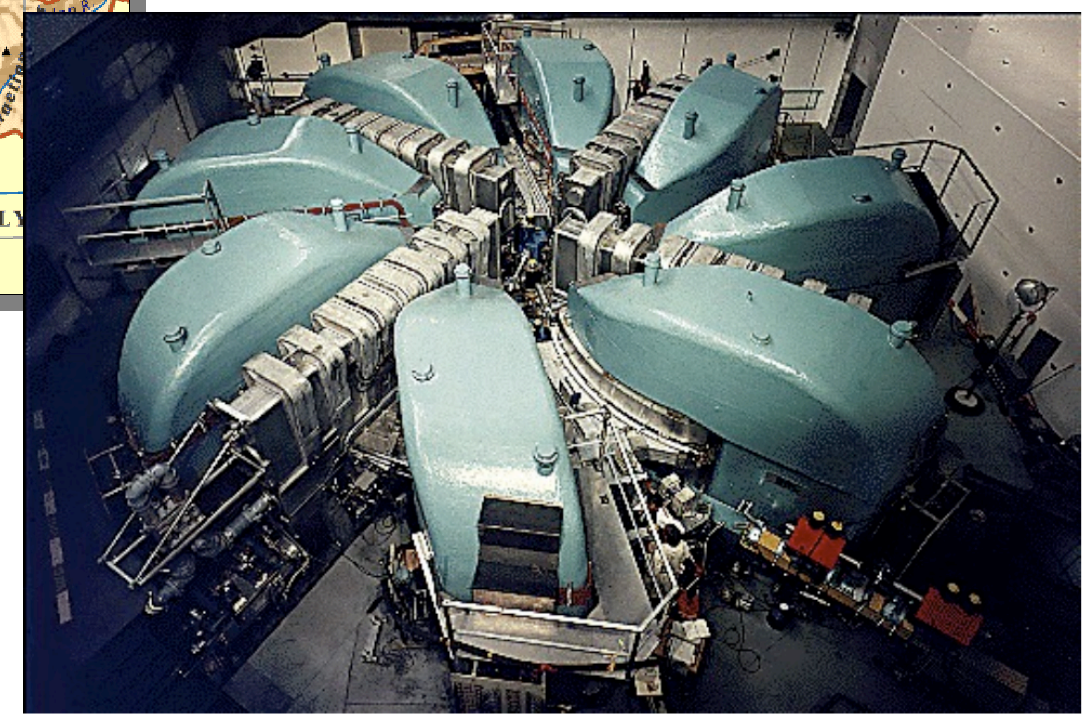
# The MEG experiment

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~$10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- **Five observables ($E_g$, $E_e$, $t_{eg}$, $\vartheta_{eg}$, $\phi_{eg}$) to characterize $\mu \rightarrow e\gamma$ events**



# Where: Paul Scherrer Institute


**1.2 MW PROTON CYCLOTRON**



- The most intense continuous positive (surface )muon beam at low momentum (28 MeV/c)
  - high sensitivity in a relative short time (few years)
  - accidental background undercontrol ($B_{acc} \sim R$)
  - low straggling and good identification of the decay region
  - muons stopped in a thin target ($CH_2$ thickness: 204 um)

(*) Eur. Phys. J. C (2013) 73:2365

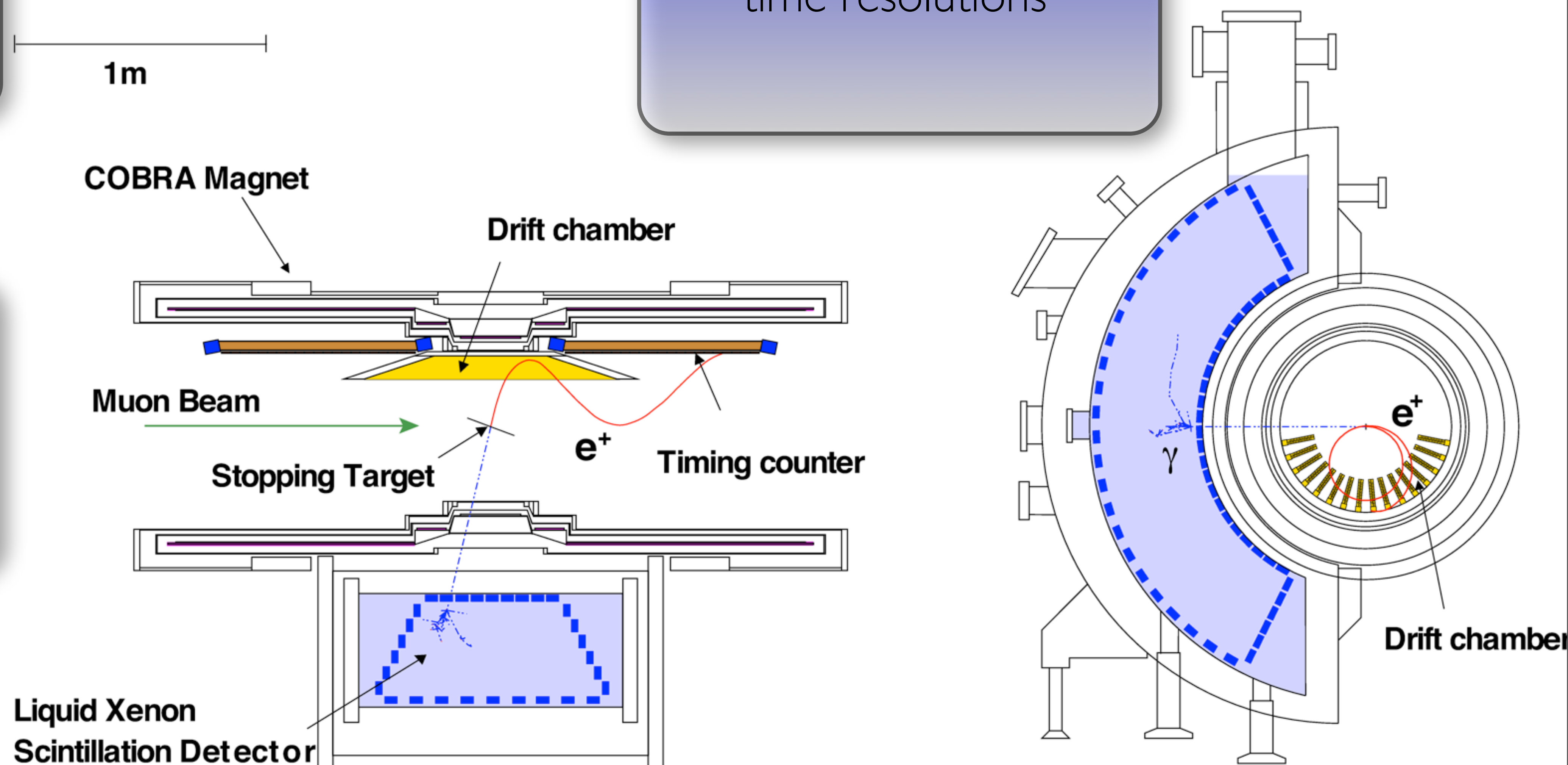
# Experimental set-up

The world most intense dc muon beam at PSI

**I = 3x $10^7$ muon/s**

High gamma energy and time resolutions

Very precise positron momentum and time resolutions



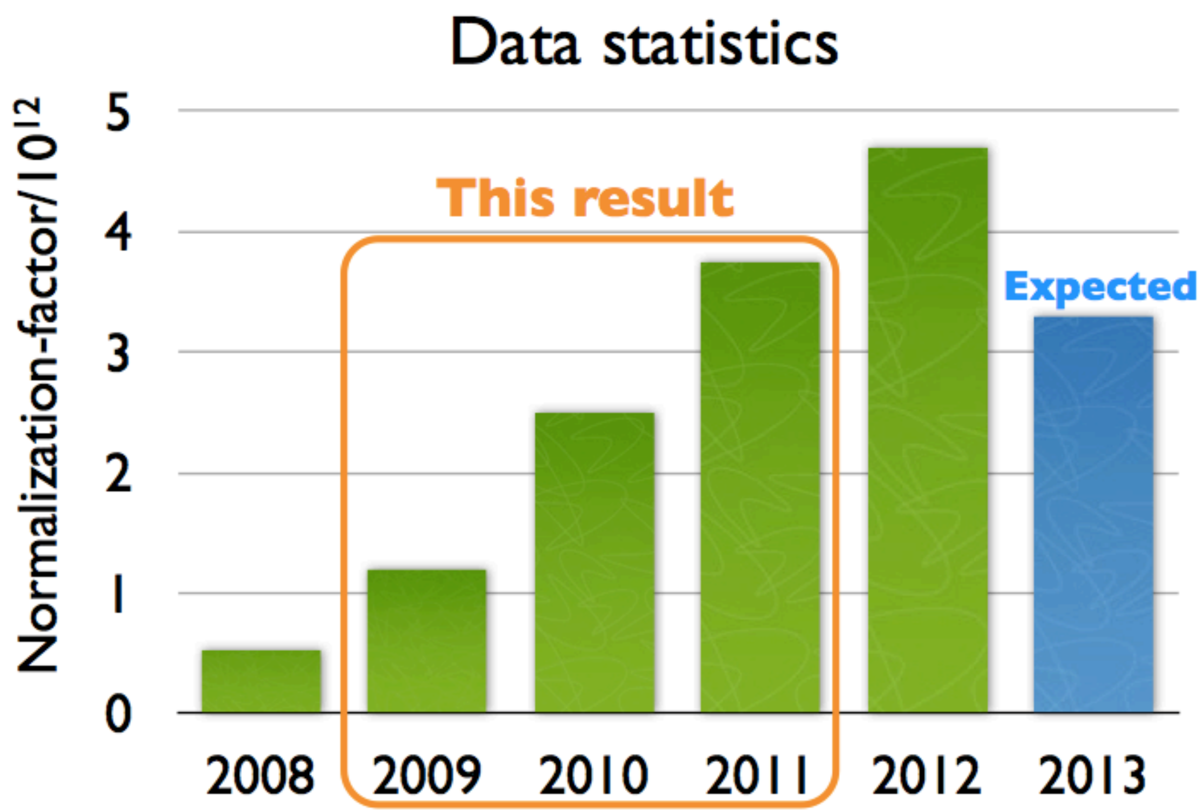

High efficiency event selection and frequency signal digitization

Complementary calibration and monitoring methods

# Detector performance and Data sample

New 2011

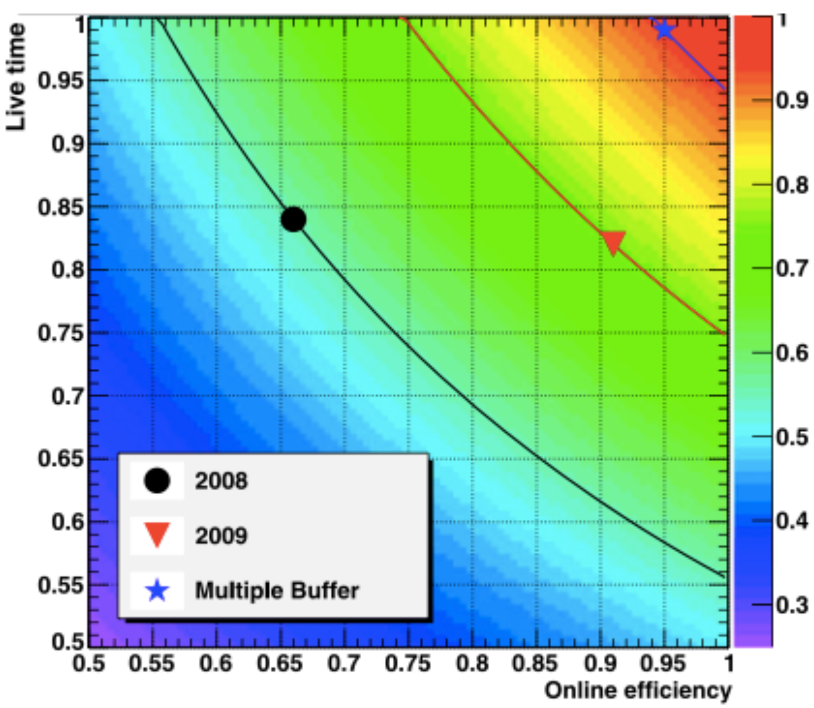
| | Resolutions (σ) |
|---|---|
| Gamma Energy (%) | 1.7(depth>2cm), 2.4 |
| Gamma Timing (psec) | 67 |
| Gamma Position (mm) | 5(u,v), 6(w) |
| Gamma Efficiency (%) | 63 |
| Positron Momentum (KeV) | 305 (core = 85%) |
| Positron Timing (psec) | 108 |
| Positron Angles (mrad) | 7.5 (Φ), 10.6 (θ) |
| Positron Efficiency (%) | 40 |
| Gamma-Positron Timing (psec) | 127 |
| Muon decay point (mm) | 1.9 (z), 1.3 (y) |

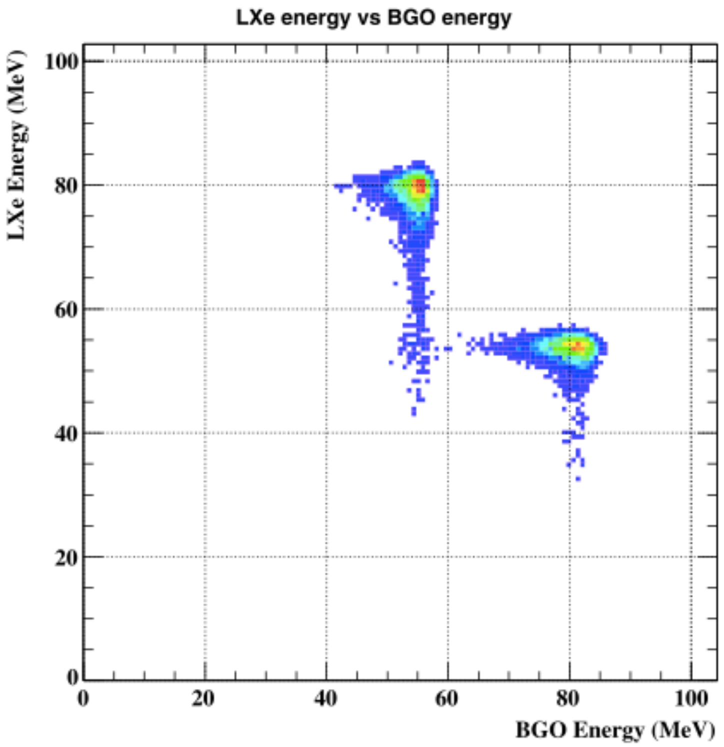



| | μ stopped | sensitivity |
|---|---|---|
| **2009+10** | $1.75 \times 10^{14}$ | $1.3 \times 10^{-12}$ |
| **2011** | $1.85 \times 10^{14}$ | $1.1 \times 10^{-12}$ |
| **2009+10+11** | $3.60 \times 10^{14}$ | $7.7 \times 10^{-13}$ |

# What's new in 2011

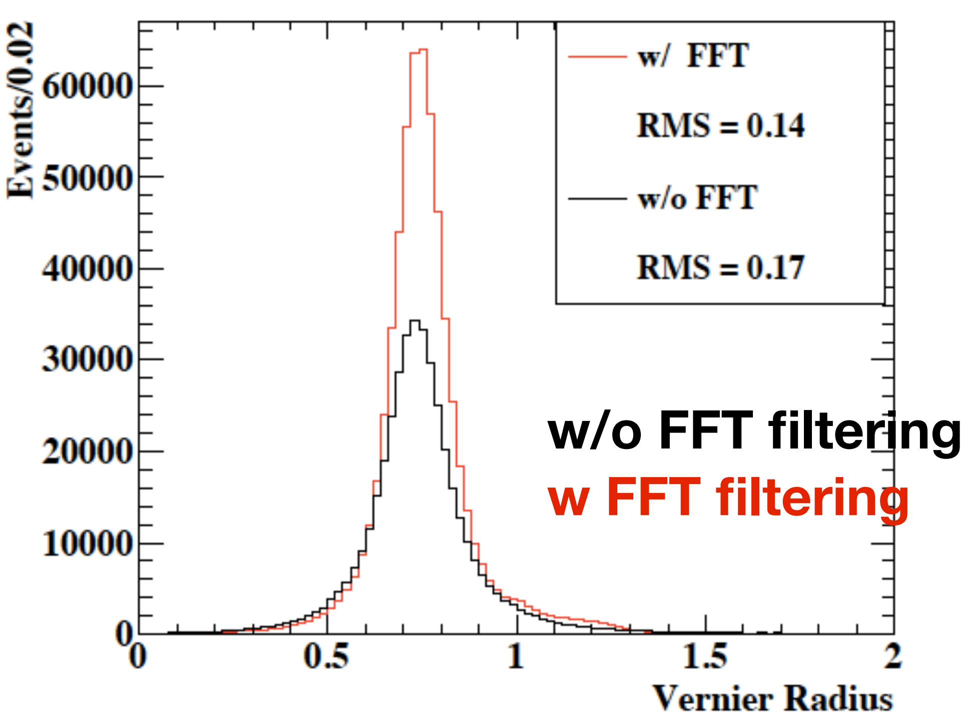
- Hardware improvements
  - **Improved** trigger and DAQ efficiency (Double buffer) (**ε ~95% ; livetime ~99%**)
  - **Improved** LXe calibration with CEX reaction ($\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow 2\gamma$) thanks to the higher BGO array (auxiliary) detector resolutions
  - **New** optical survey technique **with laser tracker**

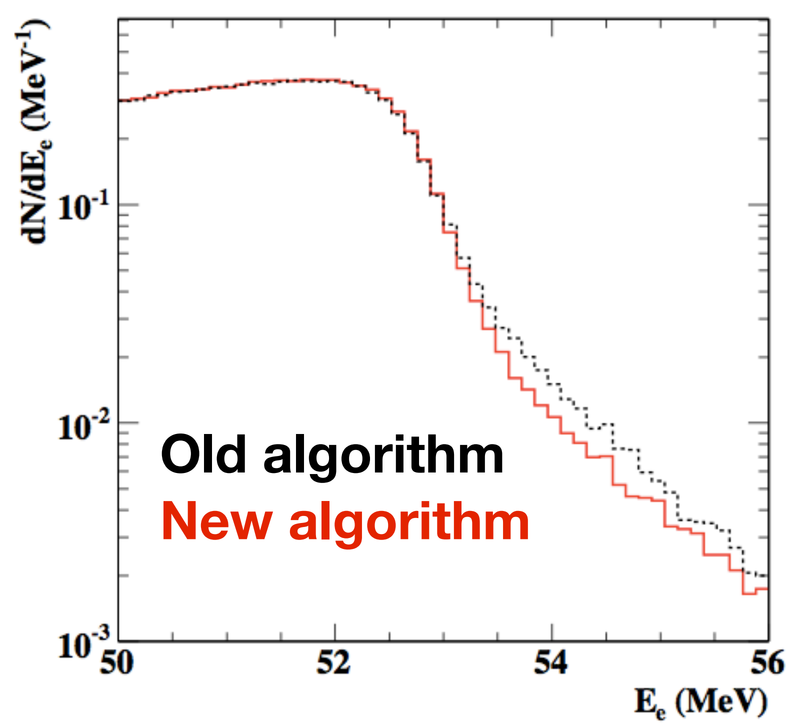


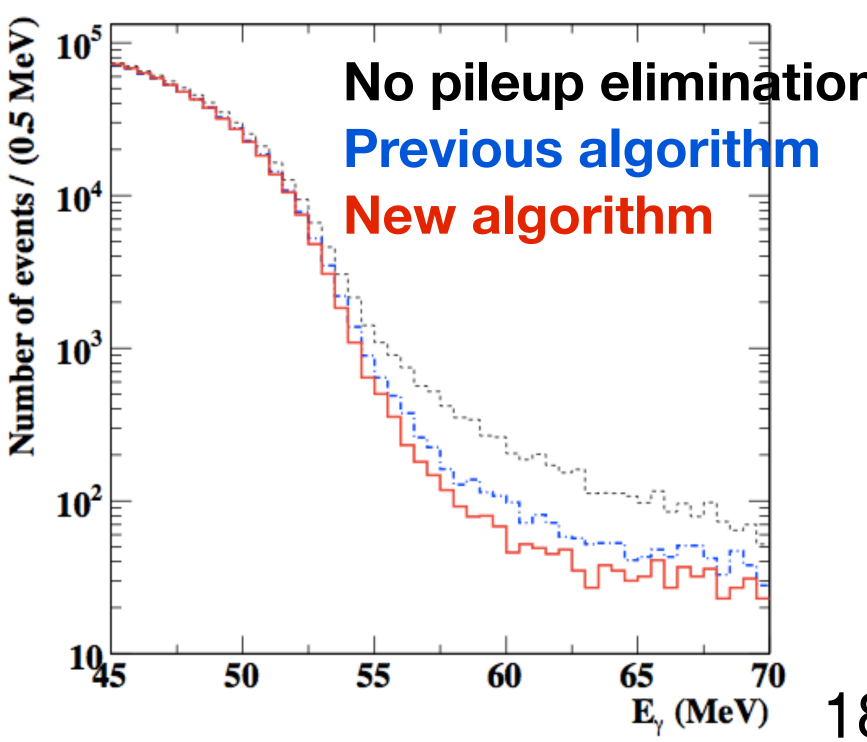




# What's new in 2011

- Software improvements
    - **Reduced** drift chamber noise **with FFT filtering** (**$\sigma(\Theta) < 10\%$**)
    - **New track fit** algorithm based on Kalman filter technique (**$\varepsilon > 7\%$**)
    - **Improved** pileup elimination algorithm in LXe detector (**$\varepsilon > 7\%$**)

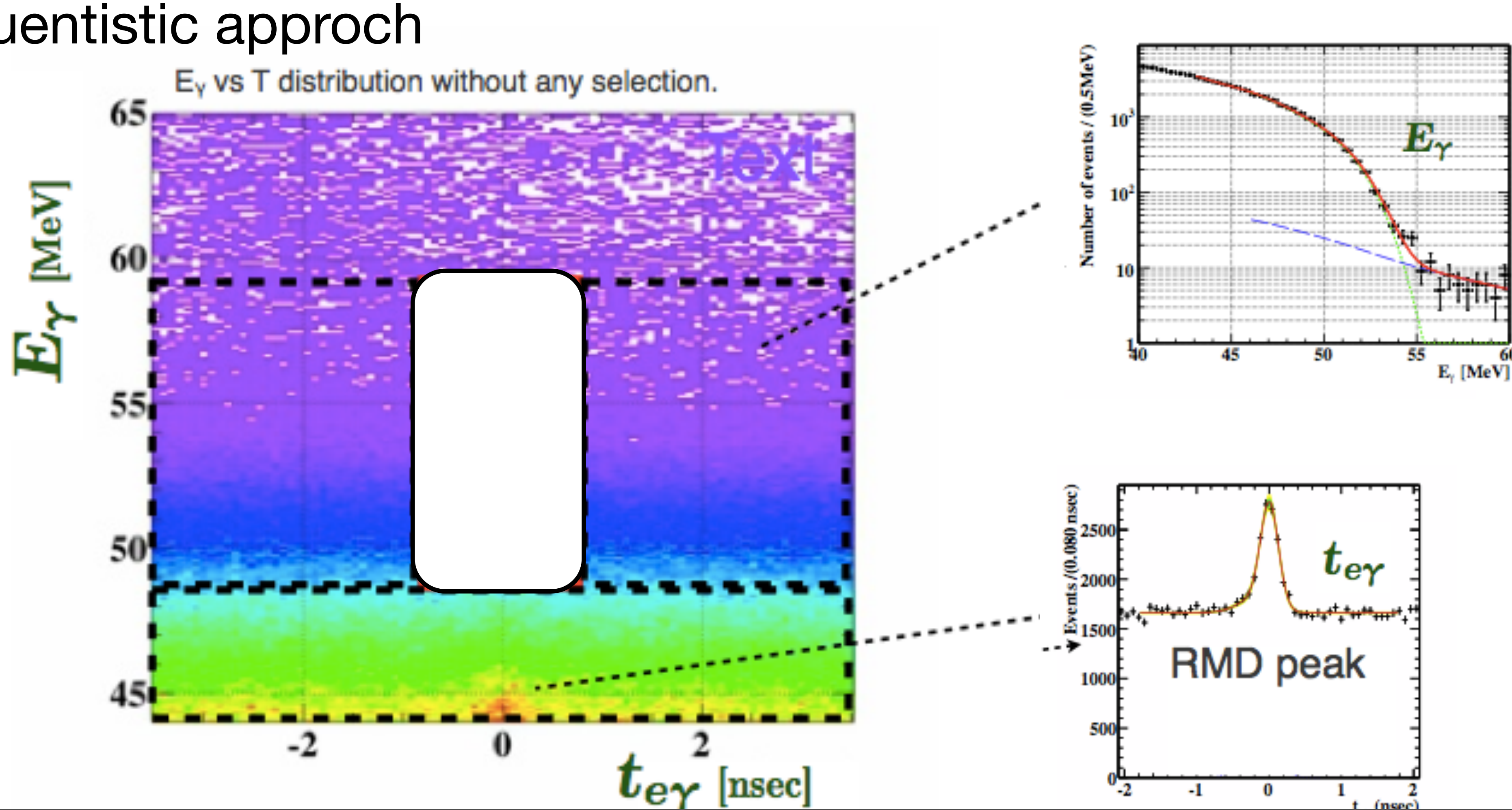


# Physics Analysis Overview and Event Selection

- Five observables **($E_g$, $E_e$, $t_{eg}$, $\vartheta_{eg}$, $\phi_{eg}$)** to characterize $\mu \to e\gamma$ events
- Event selection: Trigger selection ($E_g > 45$ MeV , $|\Delta t_{eg}| < 10$ ns, $|\Delta\phi| < 7.5^0$) + at least 1 reconstructed track
- Blind Analysis (Sideband, Blind box)
- Maximum likelihood to extract $N_{sig}$
- CL frequentistic approch



# Maximum Likelihood Analysis

- Analysis region: 48<Eγ<58MeV, 50<Ee<56MeV, |θeγ|<50mrad, |Φeγ|<50mrad, |Teγ|<0.7ns
- Maximum likelihood analysis to estimate # of signal
  - Event-by-event PDF
    - gamma: position dependent resolutions
    - positron: per-event error matrix from Kalman filter

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

- Confidence interval of $N_{\mathrm{sig}}$ (or B )
  - Frequentist approach with profile likelihood ratio ordering

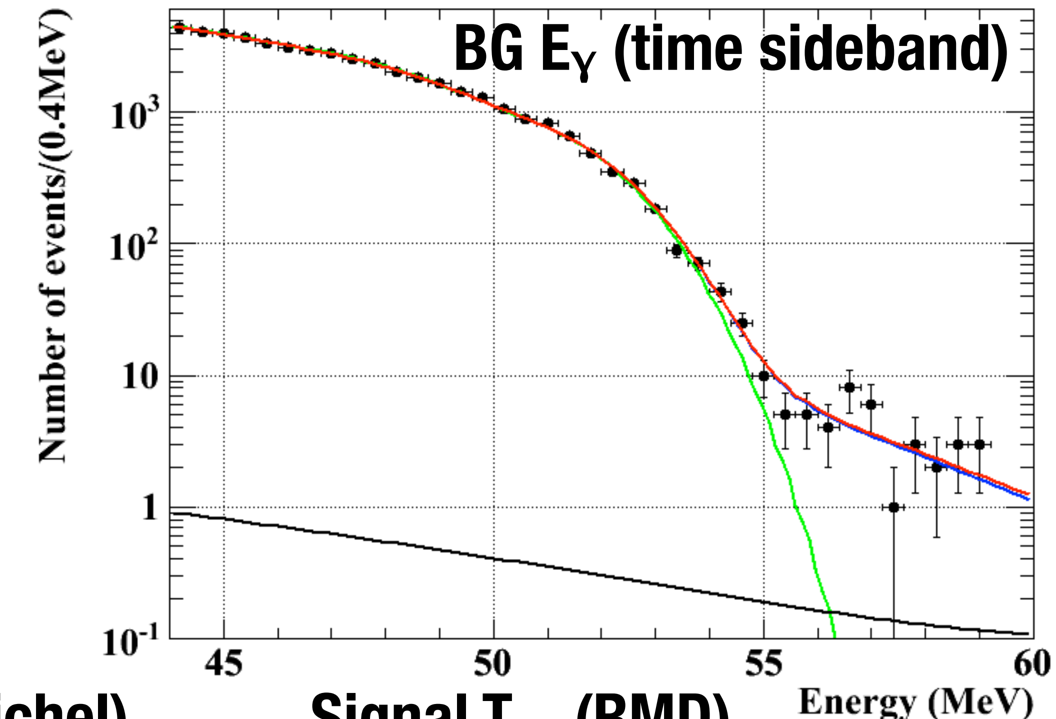
# Probability Density Functions

- **Probability density functions (PDF)** for likelihood function are mostly extracted from **data**

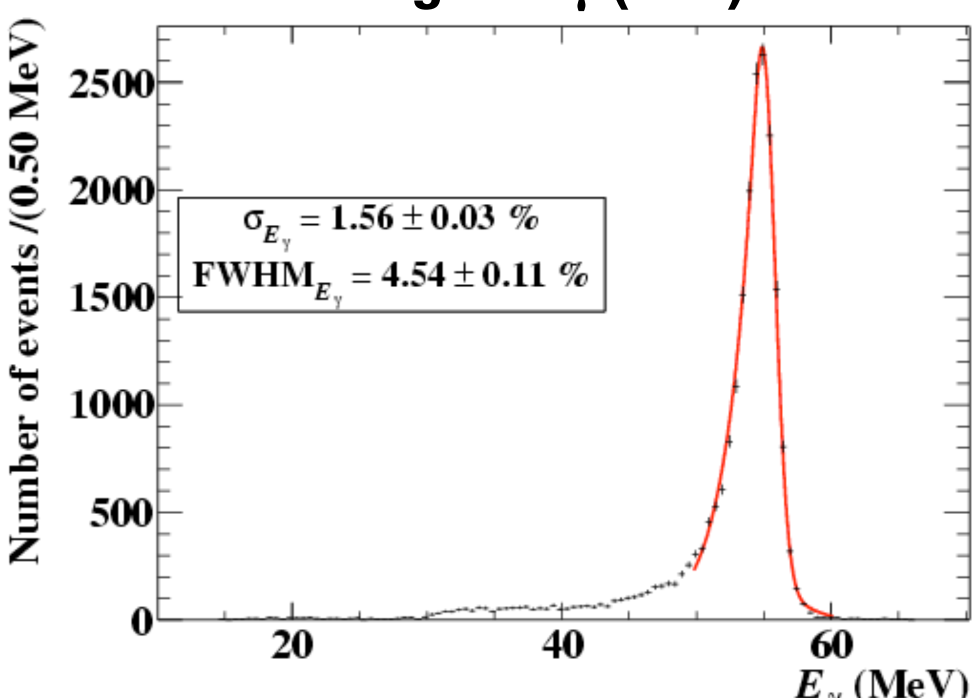
The signal PDF $S$ is the product of the PDFs for $E_e$, $\theta_{e\gamma}$, $\phi_{e\gamma}$, $T_{e\gamma}$ which are correlated variables, and the $E_\gamma$ PDF

The RMD PDF $R$ is the product of the same $T_{e\gamma}$ PDF as that of the signal and the PDF of the other four correlated observables, which is formed by folding the theoretical spectrum with the detector response functions

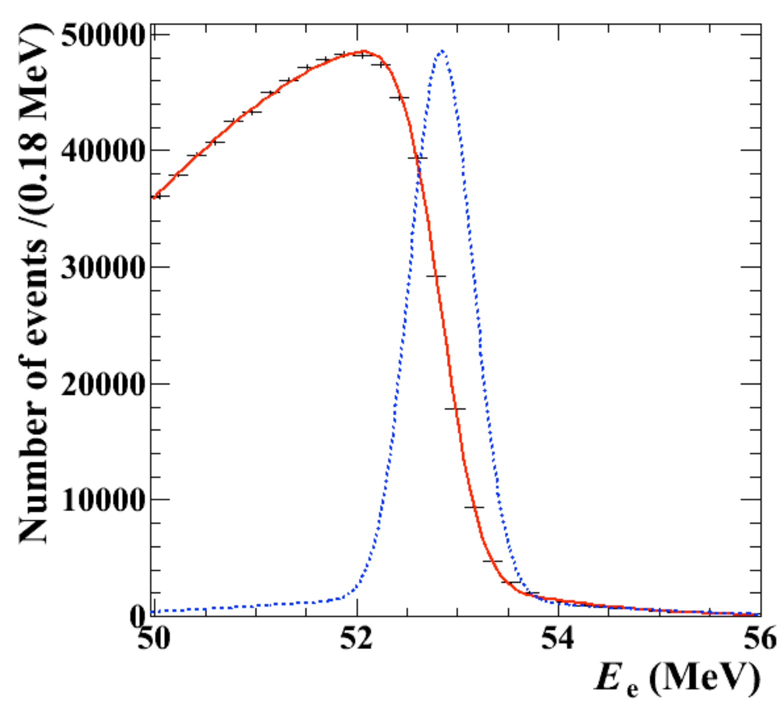
The BG PDF $B$ is the product of the five PDFs, each of which is defined by the single background spectrum, precisely measured in the sidebands



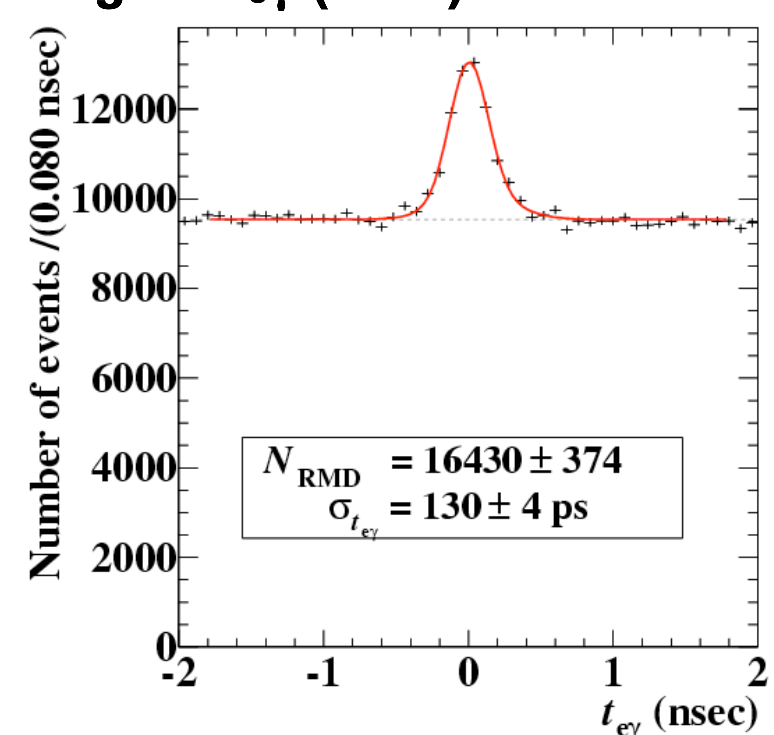

Signal Eγ (CEX)



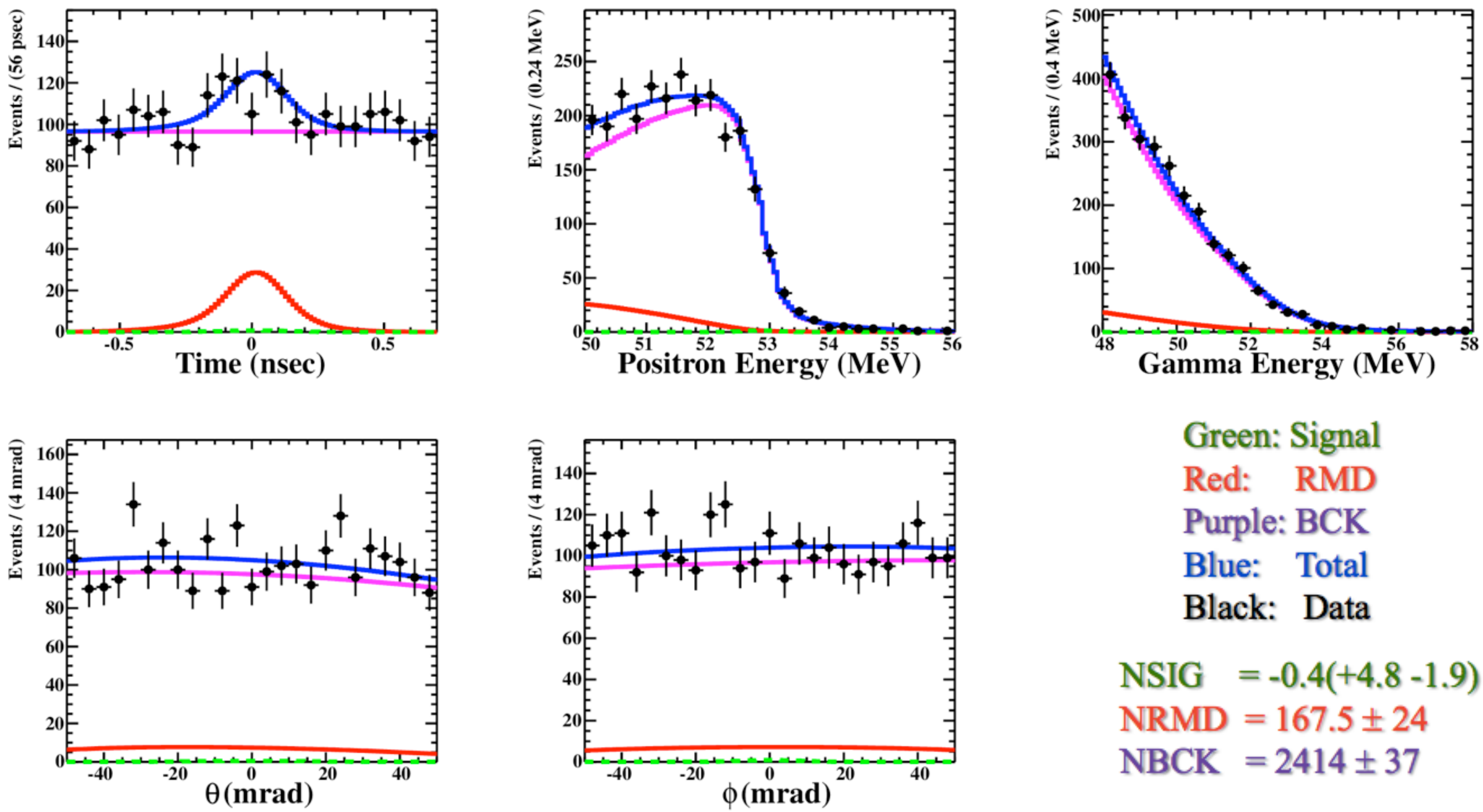

Signal Ee /BG (Michel)




Signal Teγ (RMD)



# Likelihood Fit (2009-2011)

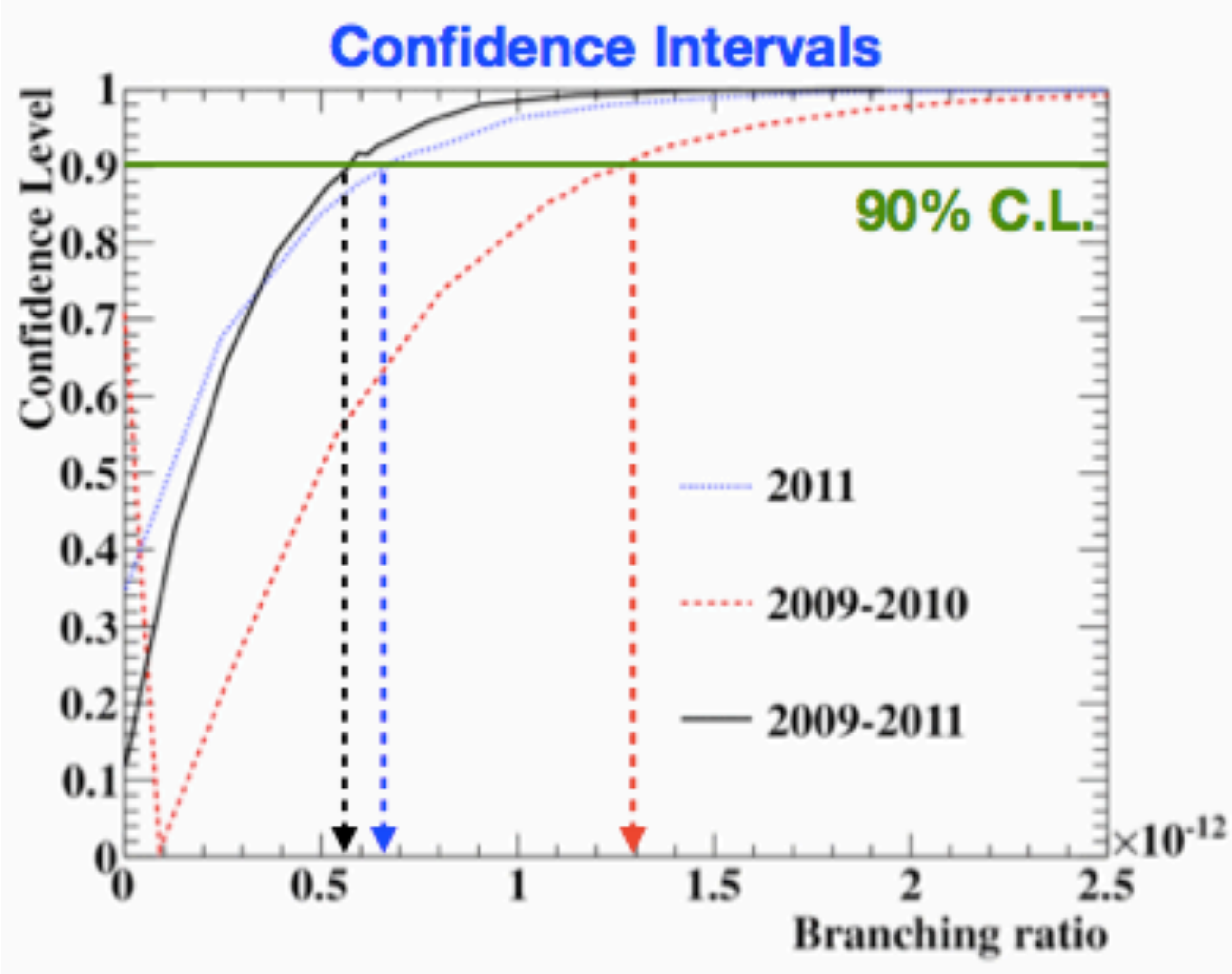


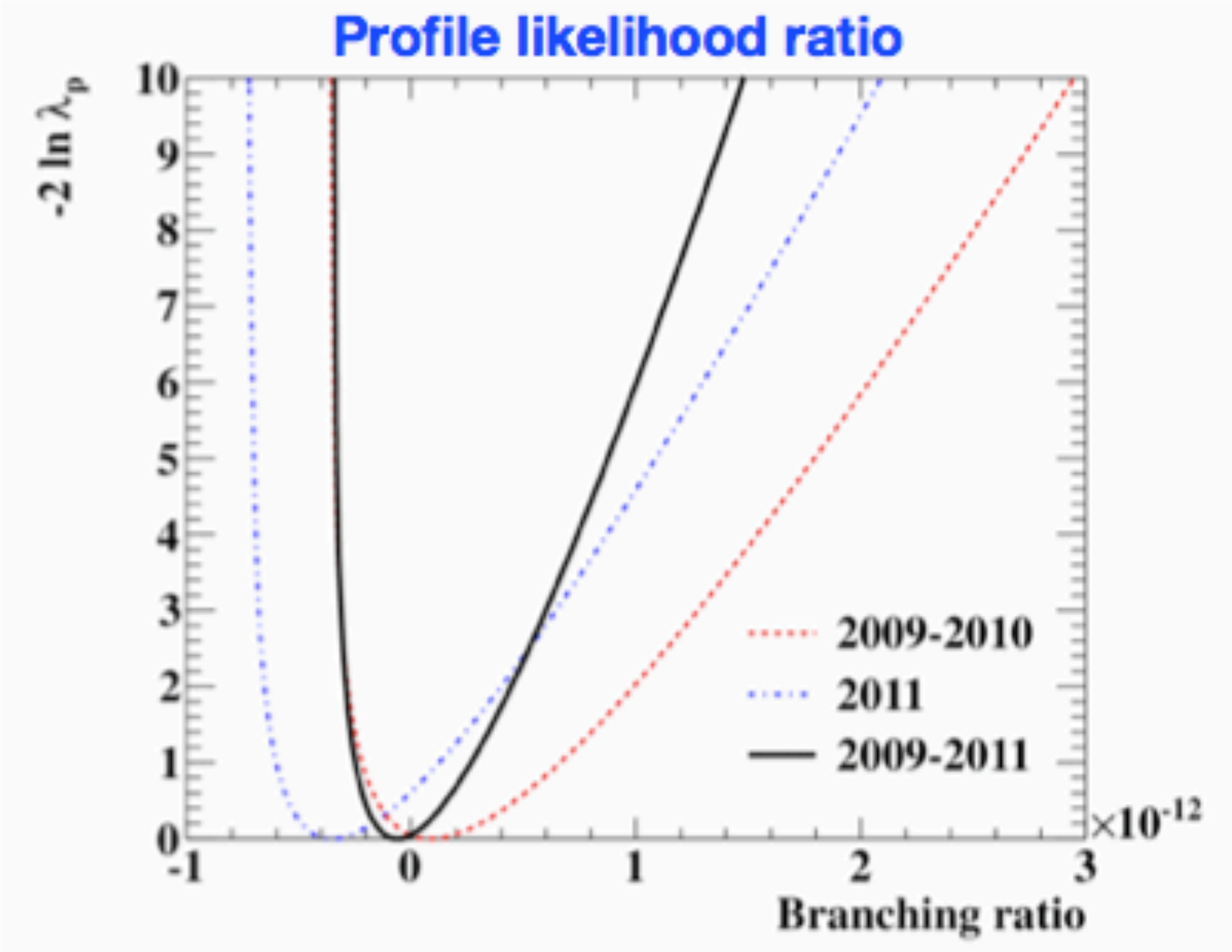

Green: Signal
Red: RMD
Purple: BCK
Blue: Total
Black: Data

NSIG = -0.4(+4.8 -1.9)
NRMD = 167.5 ± 24
NBCK = 2414 ± 37

# Confidence Interval

- Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering




**Consistent with null-signal hypotesis**

(*) Phy. Rev. Lett. 110, 201801 (2013)

# Summary of Results

(**) 90% C.L. upper limit averaged over pseudo-experiments based on null-signal hypothesis with expected rates of RMD and BG

| | Best fit | Upper Limit (90% C.L.) | Sensitivity ** |
|---|---|---|---|
| **2009+10** | $0.09 \times 10^{-12}$ | $1.3 \times 10^{-12}$ | $1.3 \times 10^{-12}$ |
| **2011** | $-0.35 \times 10^{-12}$ | $6.7 \times 10^{-13}$ | $1.1 \times 10^{-12}$ |
| **2009+10+11** | $-0.06 \times 10^{-12}$ | $5.7 \times 10^{-13}$ | $7.7 \times 10^{-13}$ |

**$B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}$ (all combined data) ***

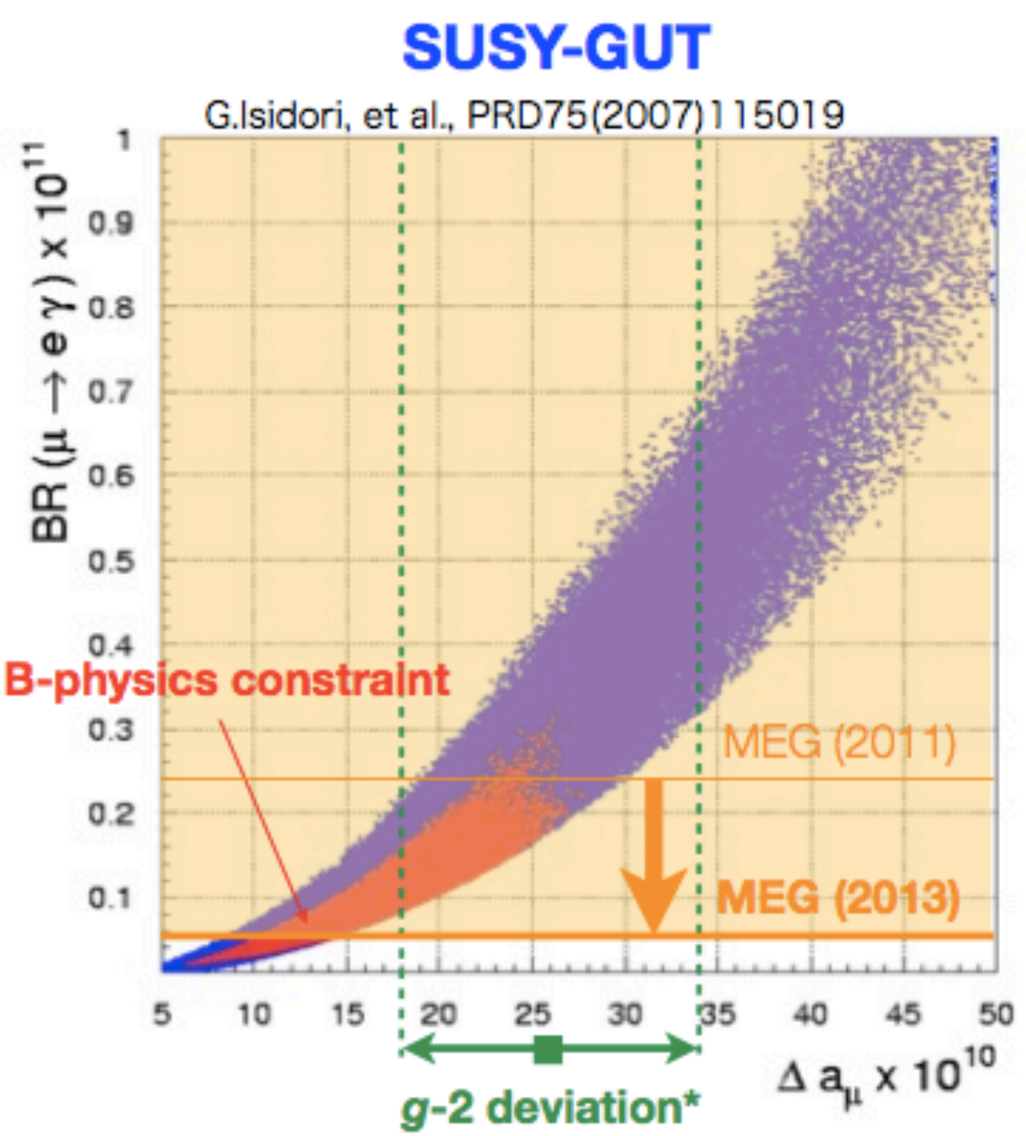
**x4 more stringent than the previous upper limit**

**($B(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$ -MEG 2009-10 )**

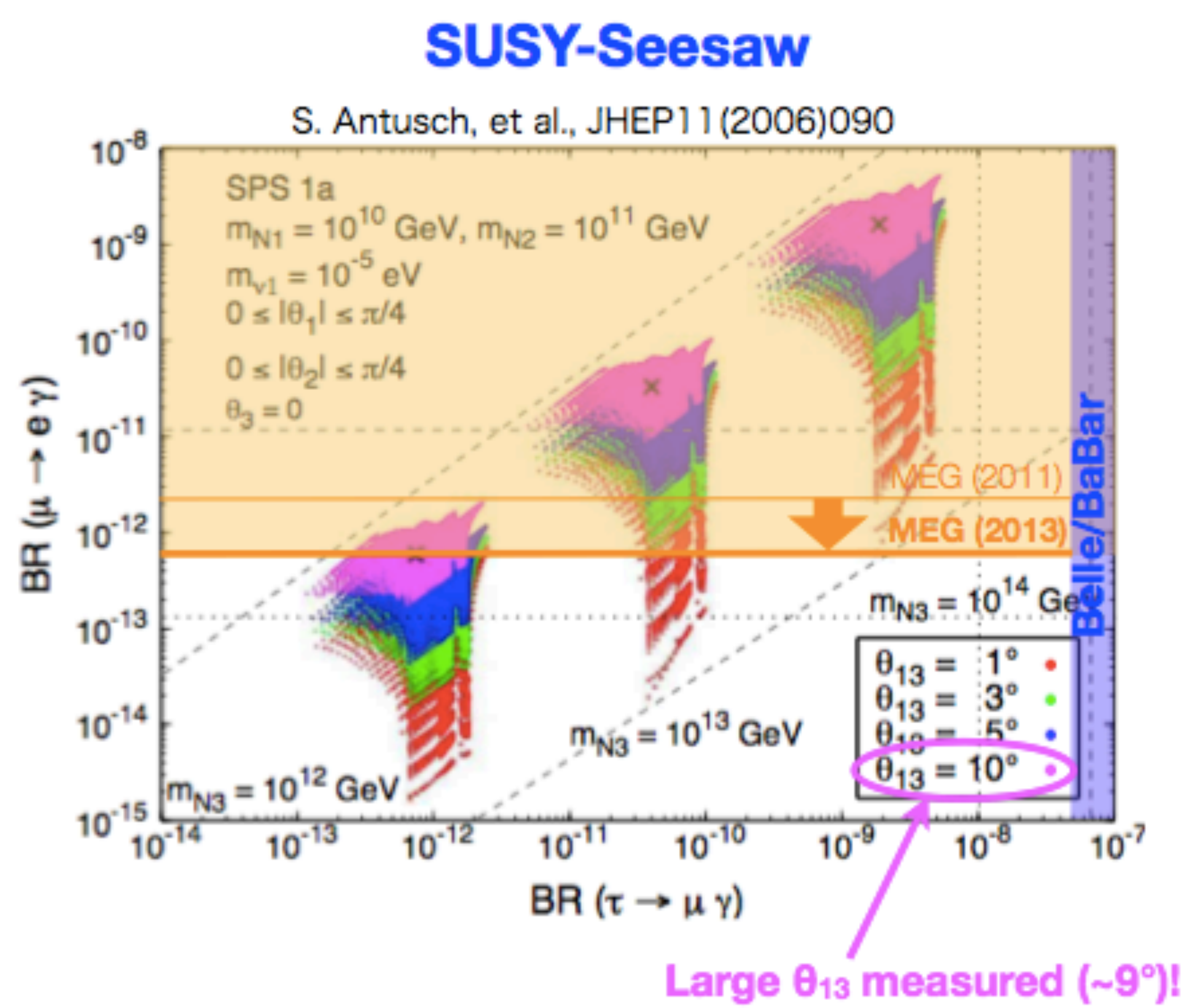
**x20 more stringent than the MEGA experiment result**

**($B(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11}$ -MEGA 2001 )**

# Impact on NP Models



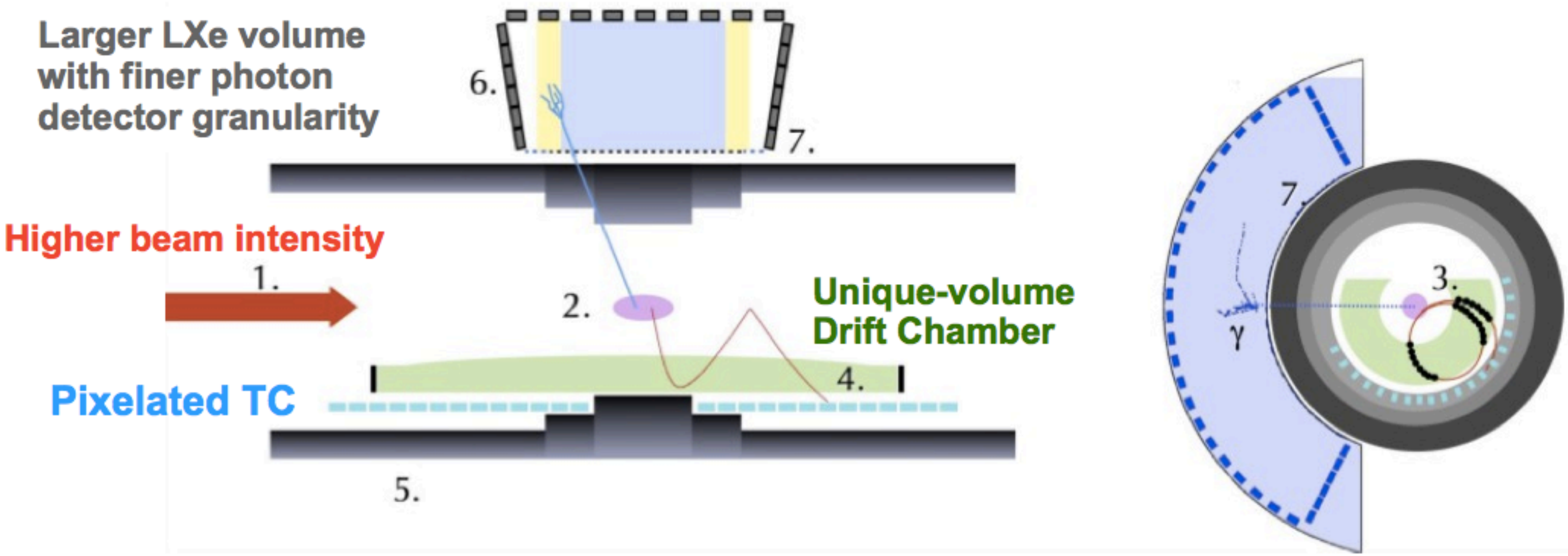

* $a_\mu$(EXP):PRD73(2006)072,
$a_\mu$(SM):Hagiwara et al., JPG38(2011)085003



(*) ArXiv:1301.7225.v2

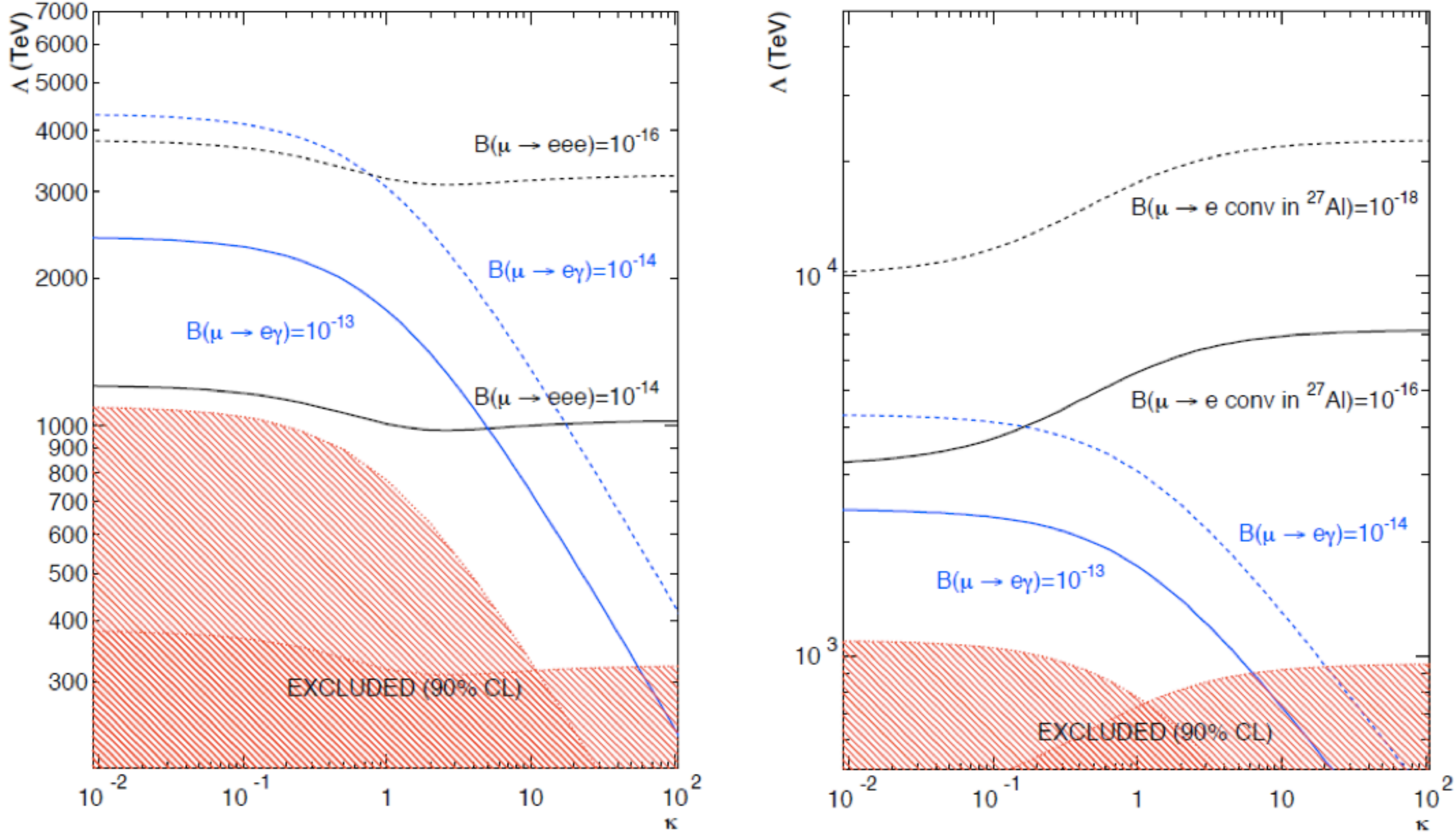
# Future Prospects

- An upgrade of MEG, aiming at a sensitivity improvement of one order of magnitude (**down to 5 x $10^{-14}$**) approved by PSI and funding agencies

(*) hep-ph:1303.4097

# $\mu^+ \to e^+ \gamma$ vs $\mu^+ \to e^+ e^+ e^-$ , N $\mu^- \to$ N $e^-$



# Summary

- MEG is searching for lepton flavor violating decay, $\mu^+ \rightarrow e^+ \gamma$, aiming at a sensitivity of **few x$10^{-13}$**
- Based on 2009-11 data set, the new upper limit on the branching ratio is

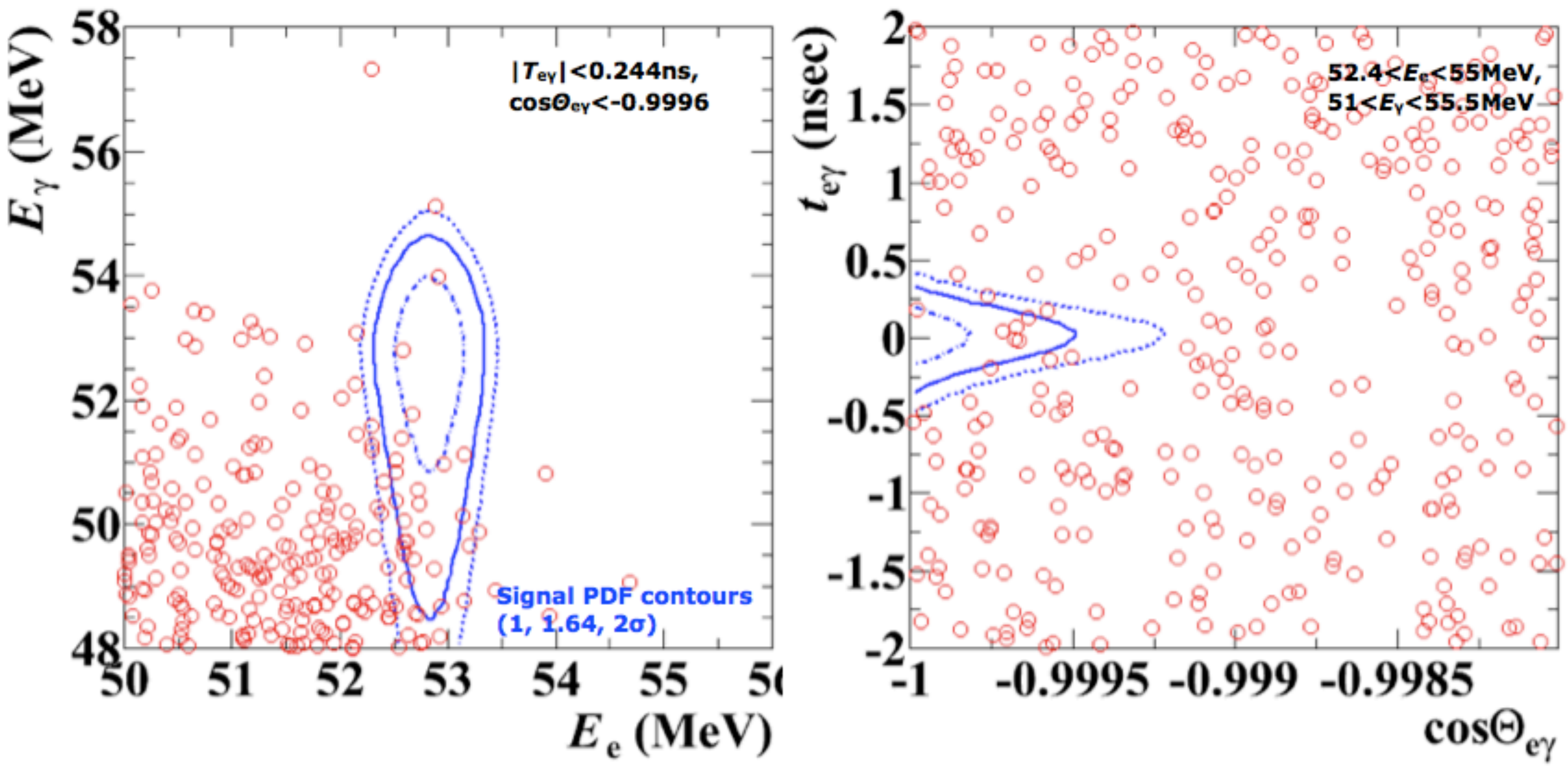
$$\mathbf{B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}}$$

- The data statistics is expected **to be doubled with** (2012-13 ) sample
- The MEG upgrade has been approved by the PSI committee in Jan. 2013 and is in progress
- Upgraded MEG with an ultimate sensitivity (**x10 higher than the current MEG**) is planned to start in 2016

# Back-up

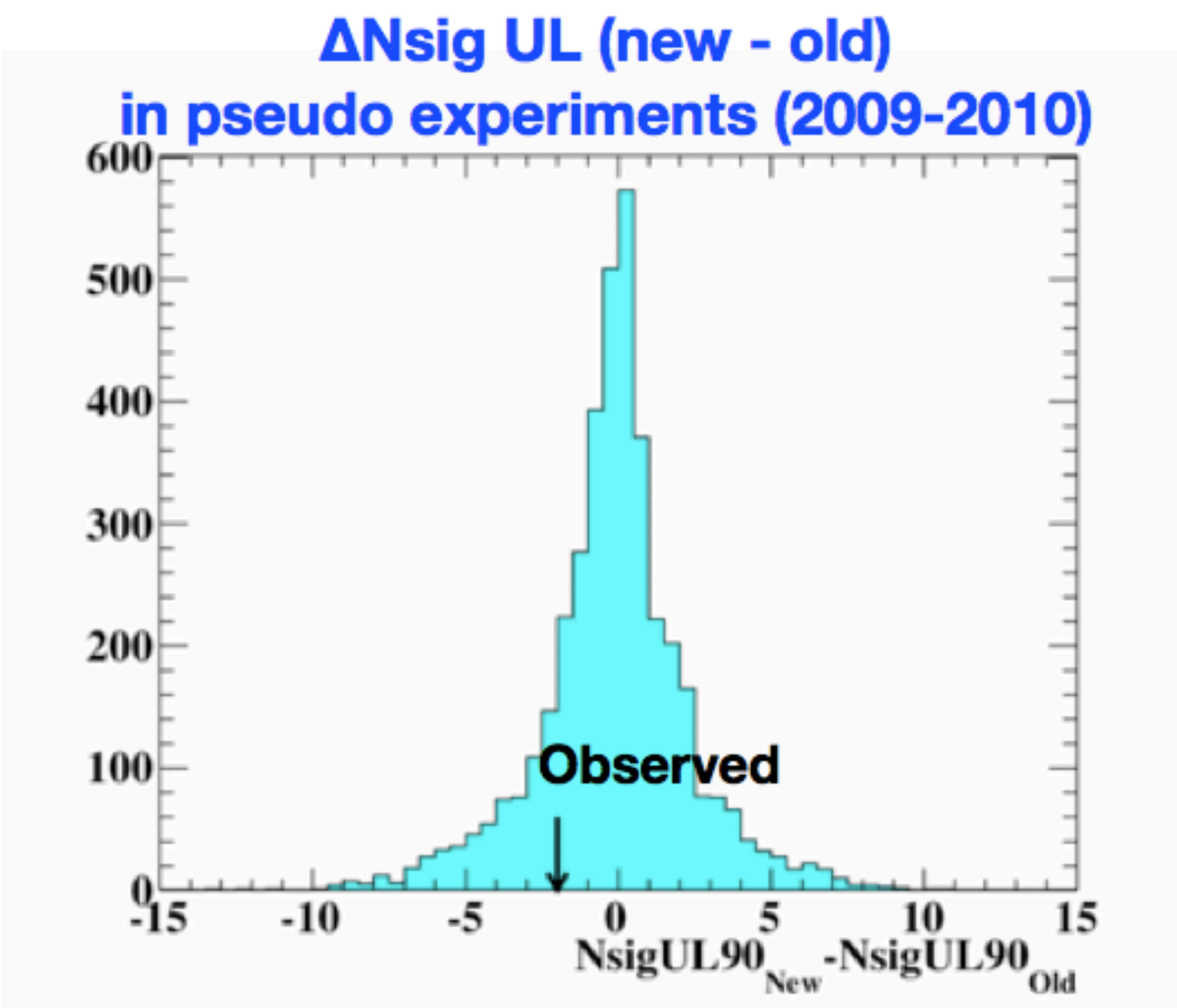
# Event Distribution

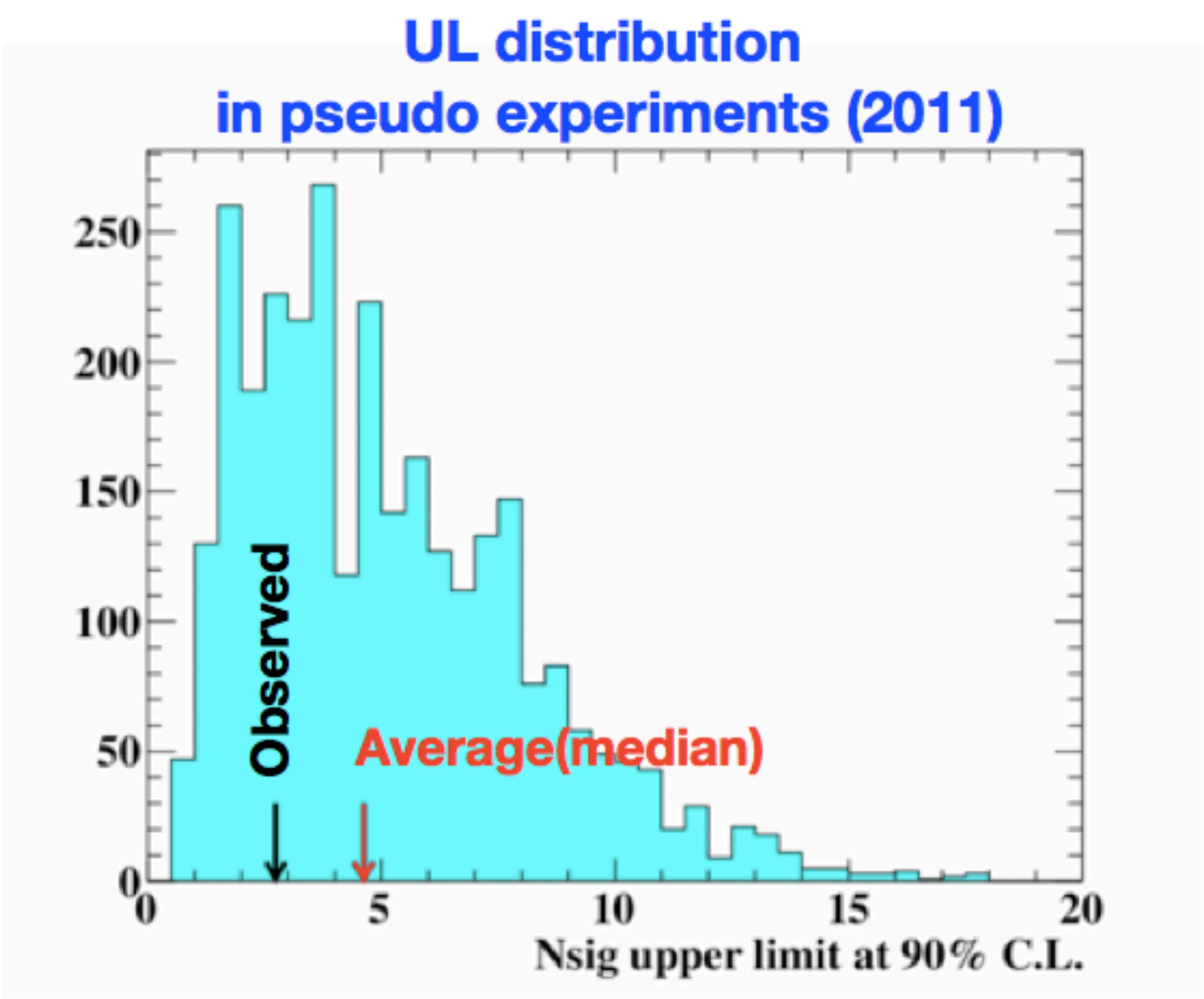
- All combined data (2009+10+11)



# Consistency Check

- Compatibility bw new/old analysis
- UL distribution

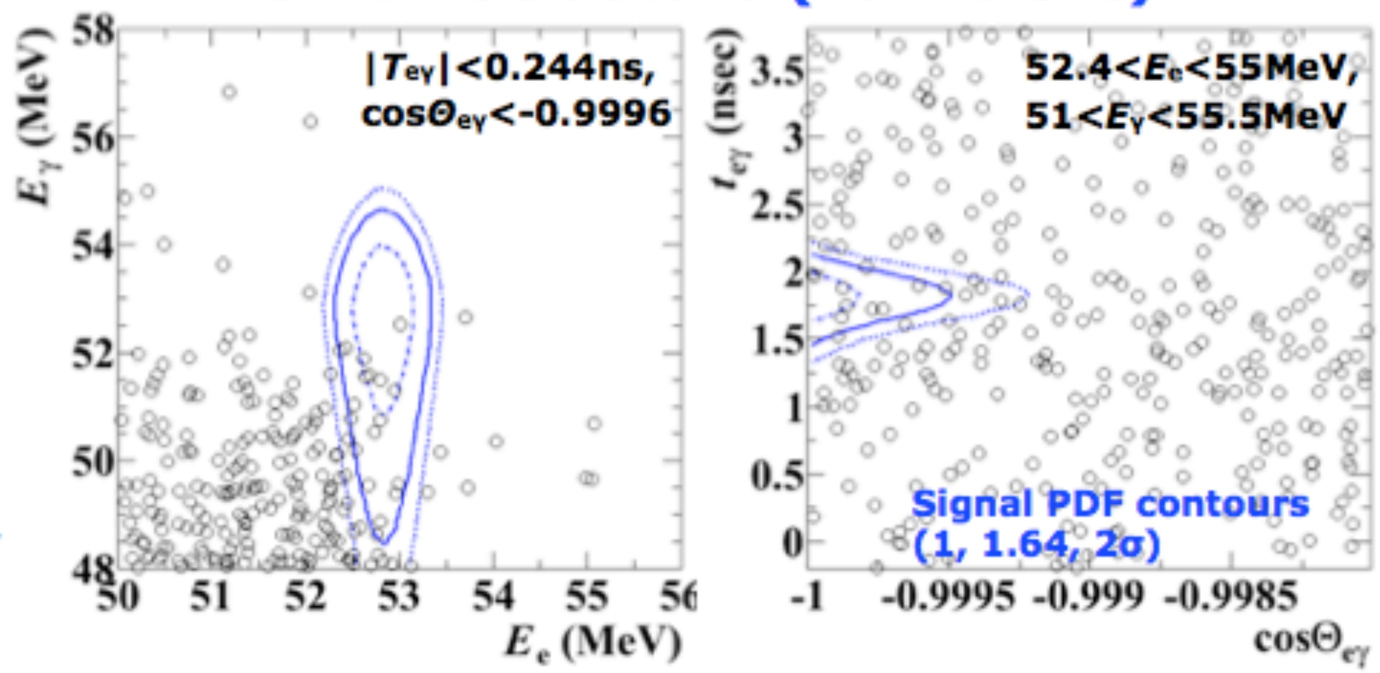


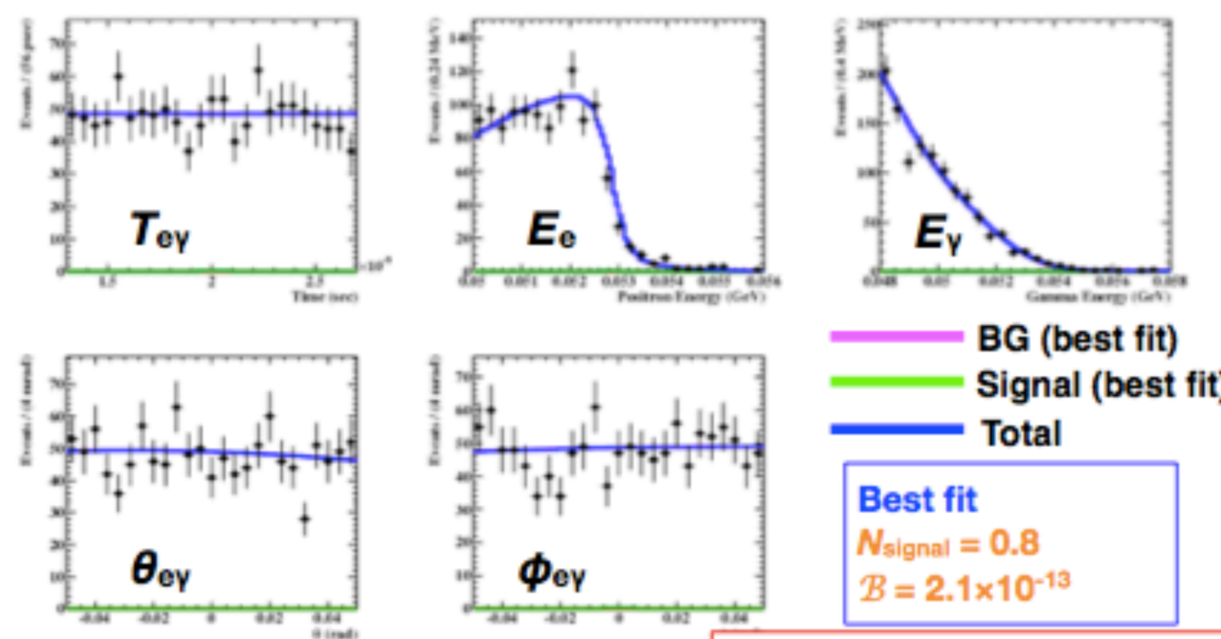



# Sideband Fit

- **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)**




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

# Normalization

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

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

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

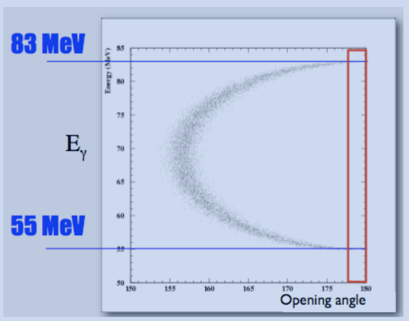
# Calibration methods

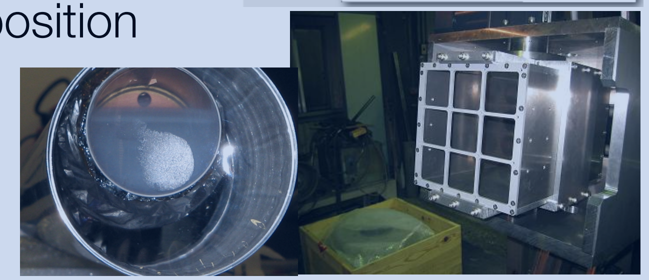
The only way to unsure that the required performances are reached and maintained during the time

## ---------------LXe-TC-------------------

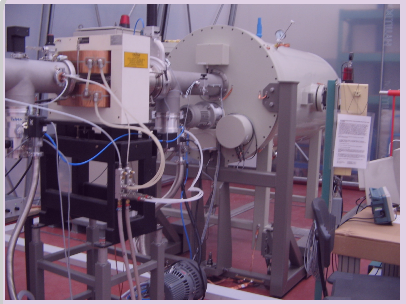
### CEX

γ resolutions:
- energy
- time
- position

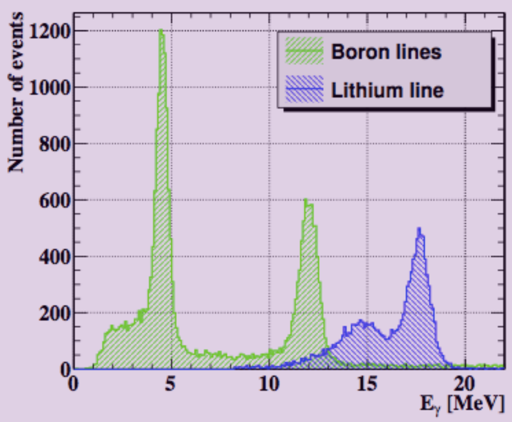


### CW

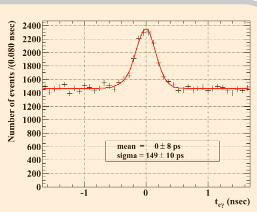


- LXe LY monitoring
- γ energy linearity
- γ energy resolution
- LXe uniformity
- LXe-TC timing



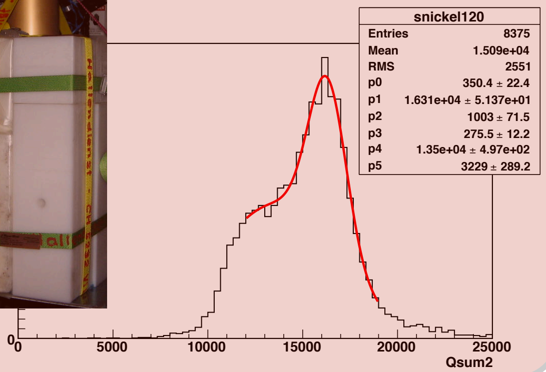

### RMD

- LXe-TC timing



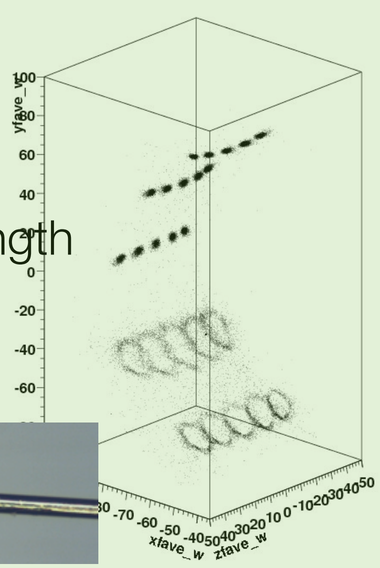
### NG

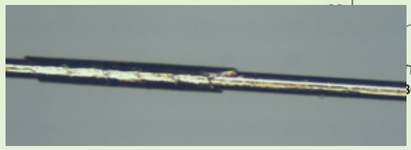
- LY monitoring
- Intercalibration beam on/off




### α

- PMT QE
- Absorption length
- LY monitoring



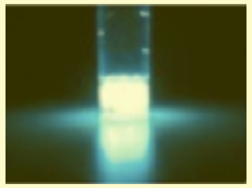



### AmBe

- LXe LY monitoring

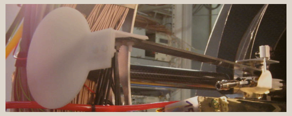
### LED

- PMT gain

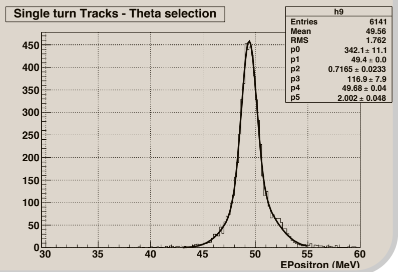


## -----DC-TC-----

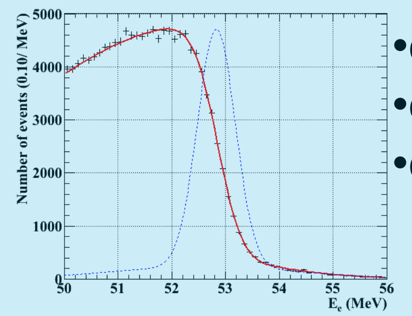
### Mott



- $e^+$ energy res.
- $e^+$ angular res.
- $e^+$ polarization
- DC acceptance
- DC alignment



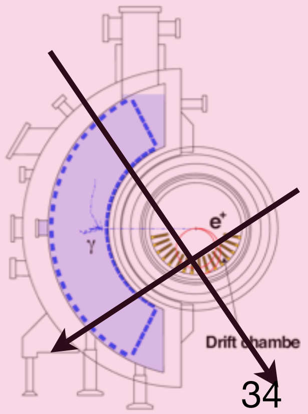

### Michel




- $e^+$ energy scale
- $e^+$ energy res.
- $e^+$ angular res.

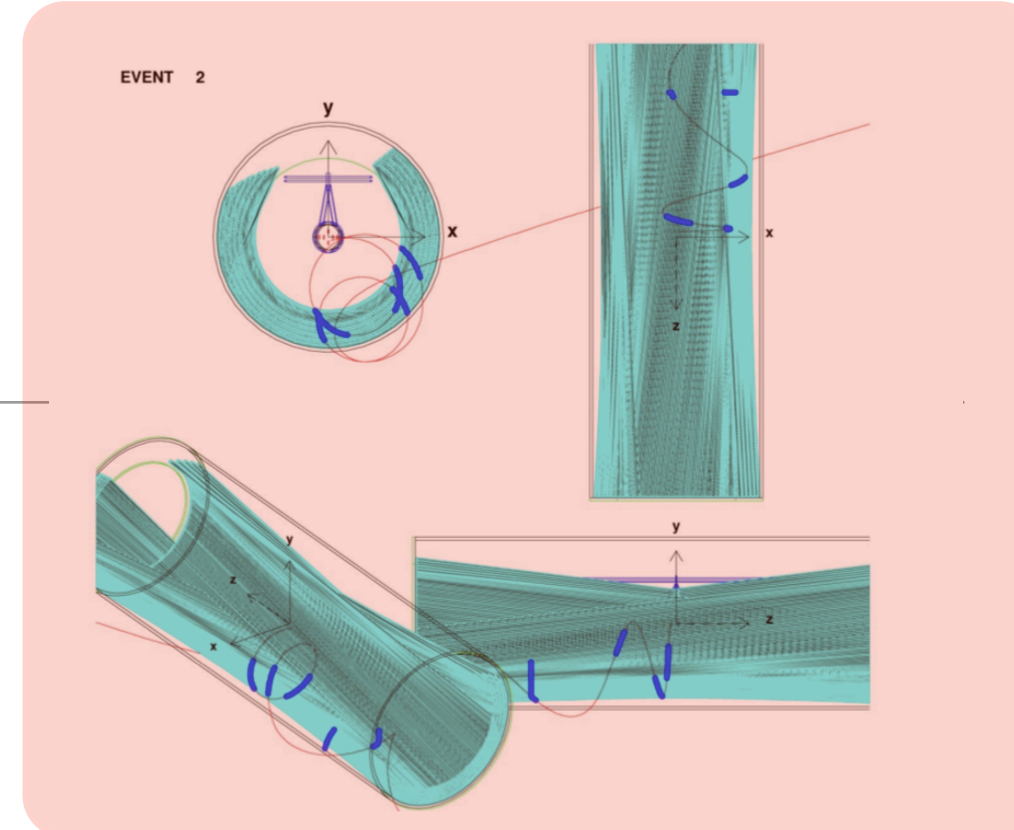
### Cosmic

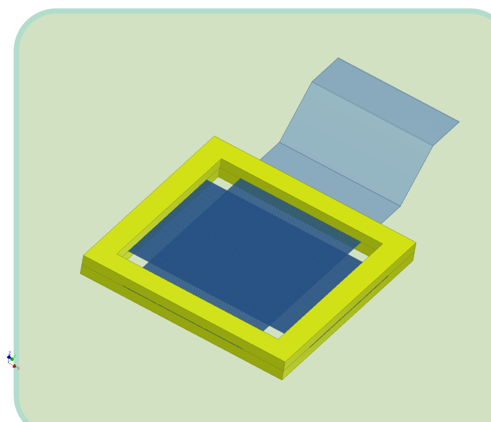
- LXe LY monitoring
- DC alignment

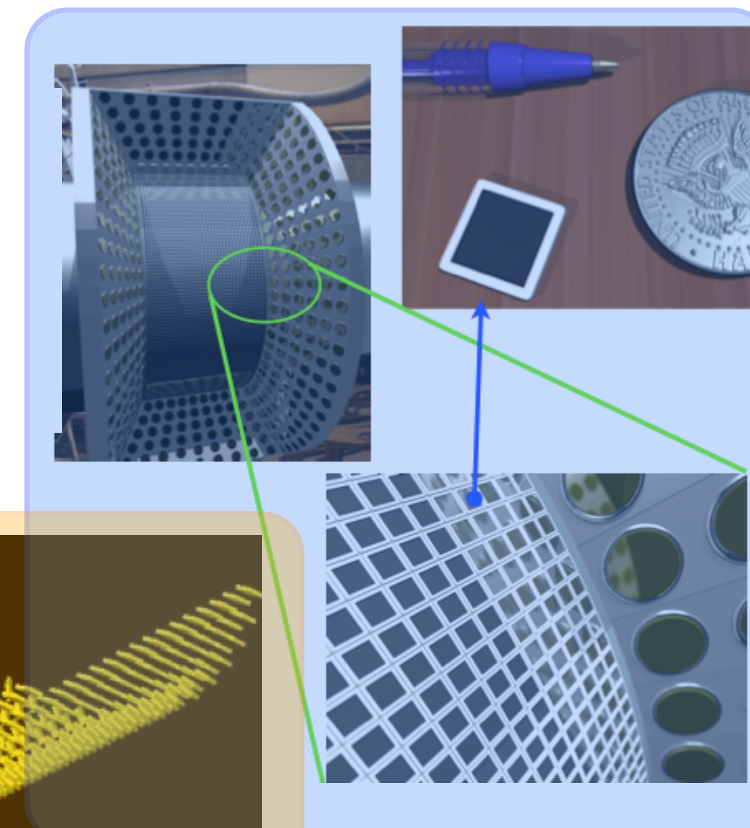


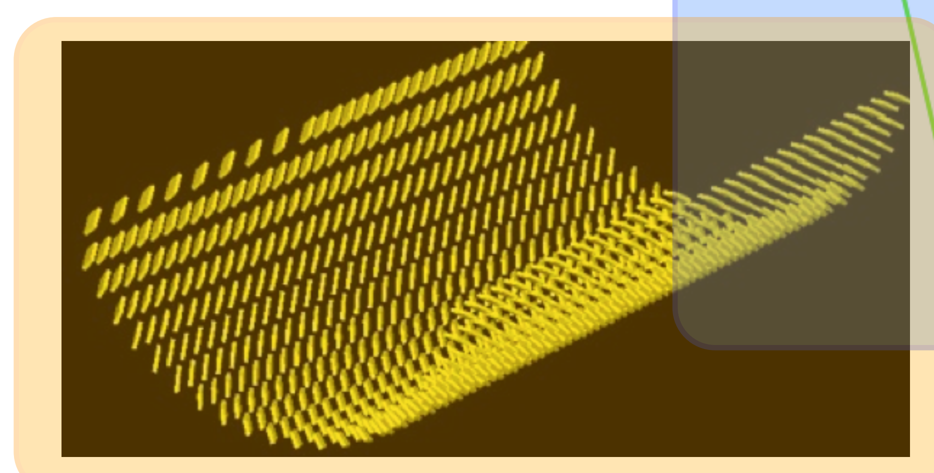
# MEG upgrade

- Unique volume gas chamber
  - Single hit resolution 50 ÷ 100 μm in r (250 μm)
  - Momentum resolution ~150 KeV (340 KeV)
  - Angular resolution ~5 mrad (7-11 mrad)
  - Trasparency towards TC ~80 % (40%)
- LXe detector upgrade with SiPM
  - Energy resolution ~1.3 (depth<3cm) (2.6%)
  - Position resolution ~2.5 mm (depth<3cm ) (5mm)
  - Detection efficiency ~75% (65%)
- Active target/SVT
  - Position resolution ~100 um (1-1.8 mm)
  - Momentum resolution ~100 KeV (340 KeV)
- Thin timing counter with SiPM
  - Timing resolution ~30 ps (70 ps)
- Higher beam intensity (a factor 3 more)
- Electronics upgrade







...to reach a sensitivity of $\sim 10^{-14}$