PAUL SCHERRER INSTITUT

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

In search of $\mu \to e\gamma$: The final result from MEG

New Trends in High Energy Physics 2016

Giada Rutar
Paul Scherrer Institute & ETH Zurich, Switzerland
on behalf of the MEG Collaboration

The Role of cLFV

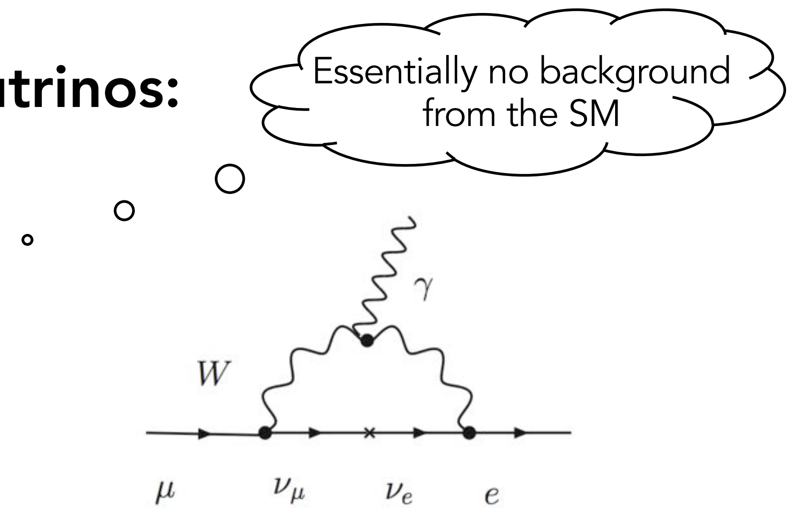
The Standard Model: A very successful theory, but a lot of questions remain unanswered...
Dark matter, gravity, matter-antimatter asymmetry, number of generations, ...

Lepton Flavor Violation

- Observed in the neutral sector (neutrino oscillations)
- Not observed in the **charged** sector – „accidental" symmetry, no gauge-theoretical motivation!

Standard Model with massive neutrinos:

$$\mathcal{B}(\mu^+ \to e^+\gamma) \ll 10^{-50}$$

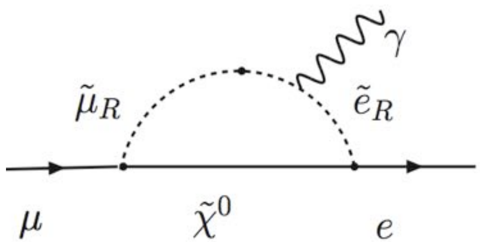


The Role of cLFV

A cLFV signal would be clear evidence for new physics

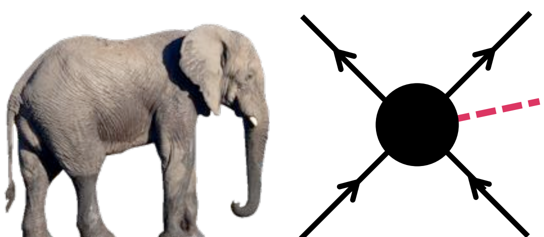
And if we don't observe it: Constrain new physics models

Many new physics models (SUSY, GUT models,…) predict
B >> O(10^{-50})



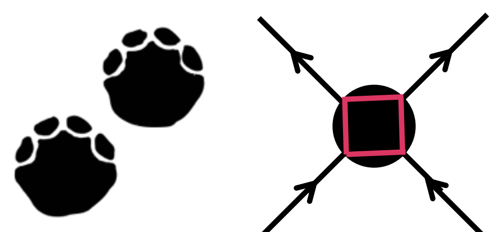
cLFV searches are a highly sensitive tool to new physics up to a very a high mass scale

Energy Frontier



Real BSM particles

Precision & Intensity Frontier



Virtual BSM particles

cLFV with Muons

"Golden Channels"

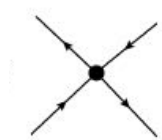
$\mu \to e\gamma$

$\mu \to eee$

$\mu N \to eN$

complementary searches

dipole term
(e.g. SUSY)



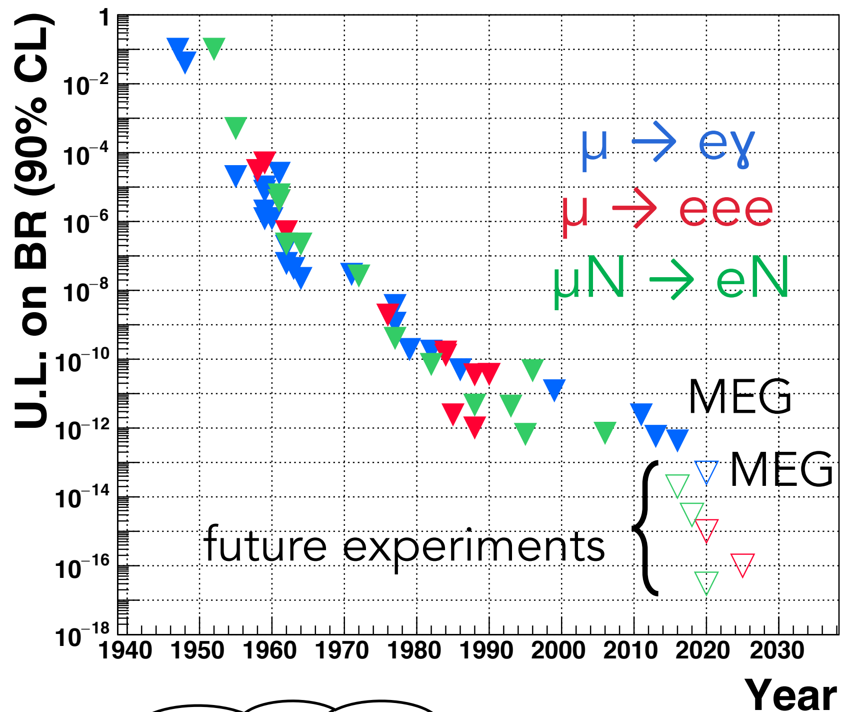
contact term
(e.g. Z', LQ)

$\mu \to e\gamma$

$\mu \to eee$

$\mu N \to eN$

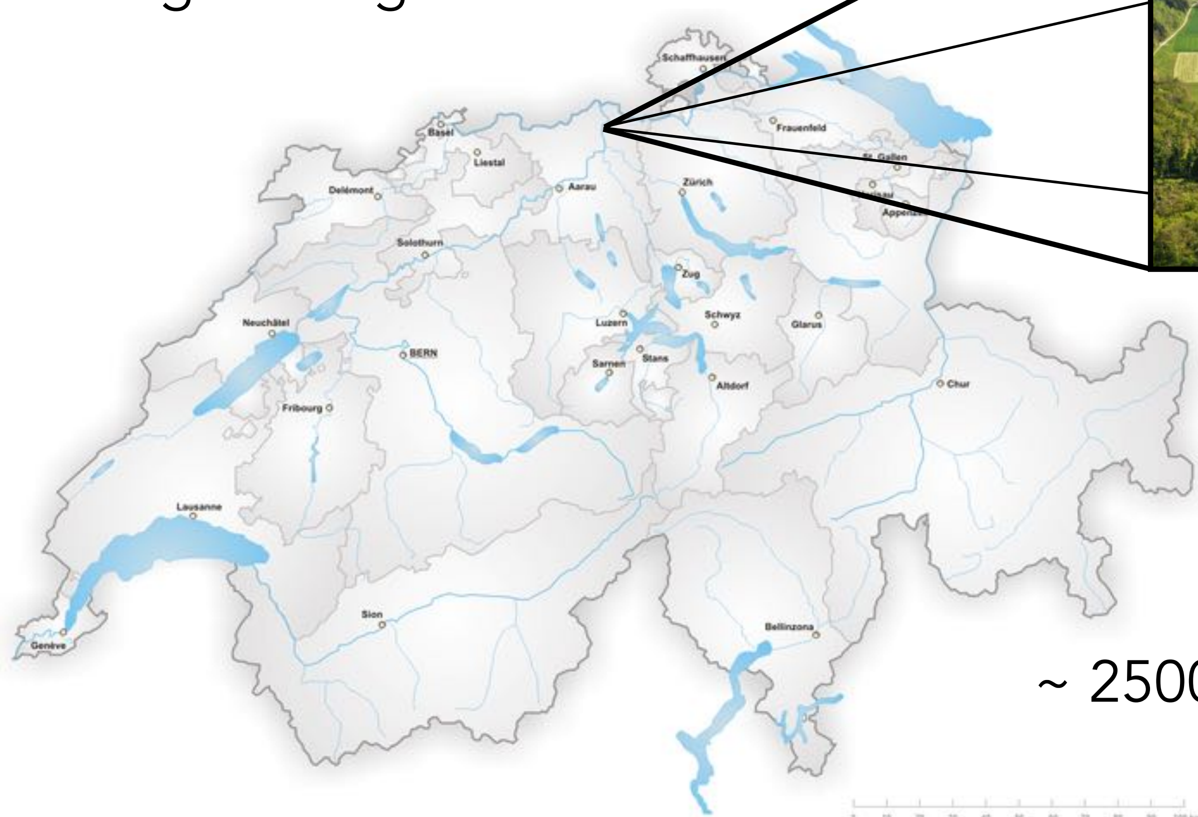
μ available in large quantities at dedicated accelerators



cLFV is also sensitive to the **structure** of the NP

The Paul Scherrer Institute

Largest National Research Institute for Natural and Engineering Sciences



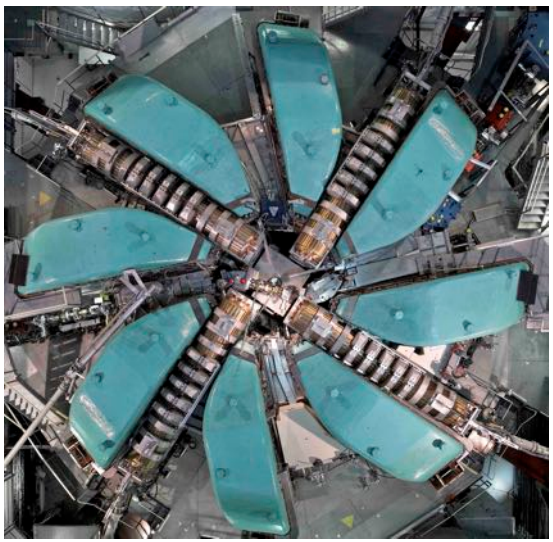
Picture credits: Paul Scherrer Institut

~ 2000 employees

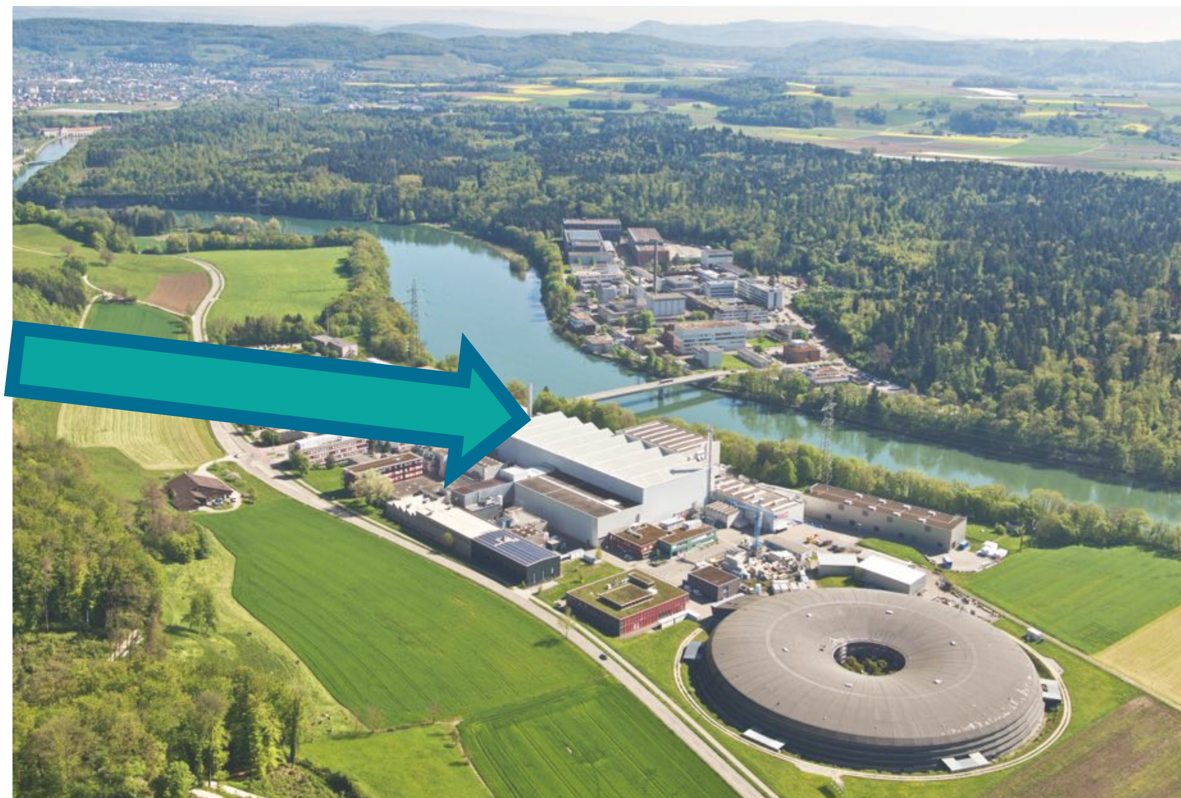
~ 2500 users/ year from all around the world

cLFV Experiments at PSI

World's most intense continuous muon beams
O(10^8) μ/sec ➔ a unique place for cLFV searches!



High Intensity Proton Accelerator facility:
590 MeV proton energy
2.3 mA proton current
1.4 MW power



Picture credits: Paul Scherrer Institut

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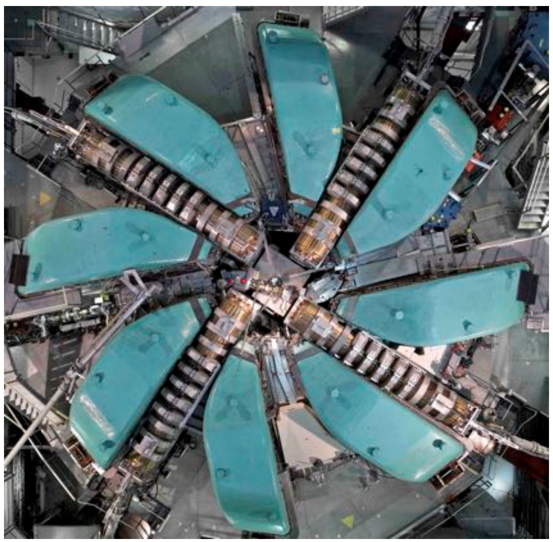

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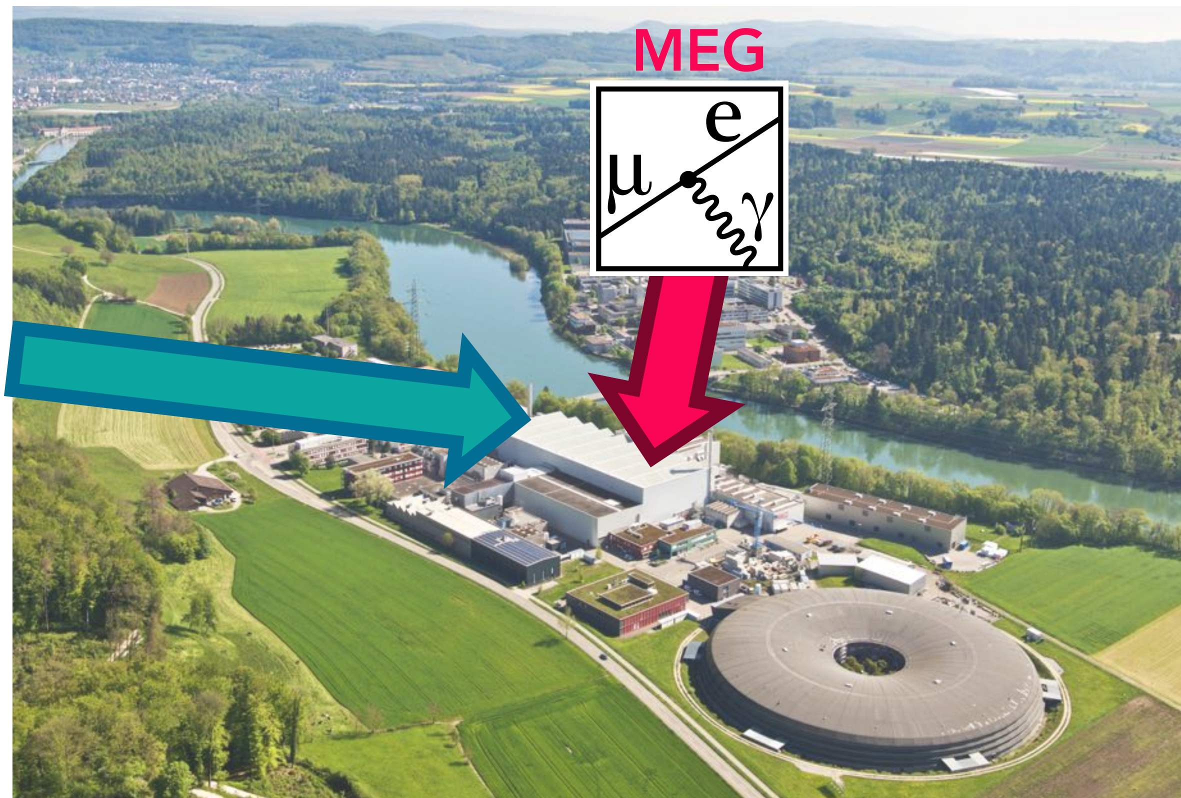


 Picture credits: Paul Scherrer Institut

The MEG Collaboration

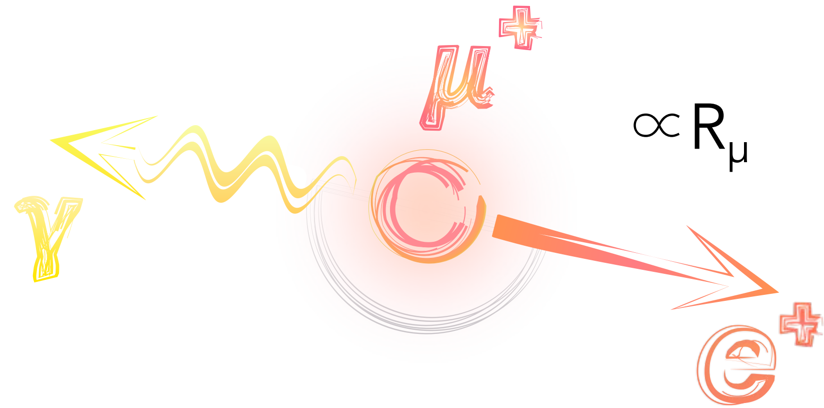
~70 physicists from 5 countries

The $\mu \rightarrow e^{+}\gamma$ decay

Signal Signature

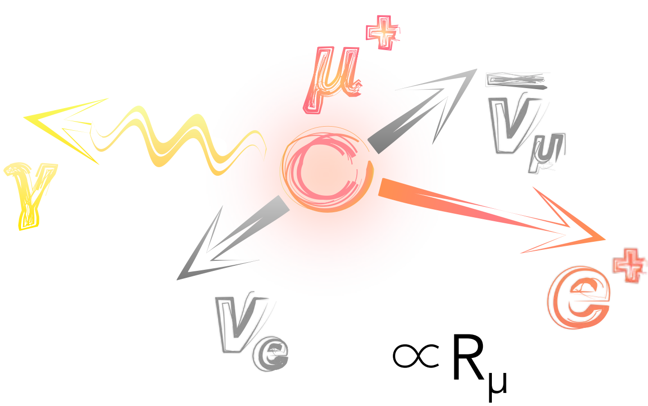
2-body-decay with e^{+} and γ

- back-to-back ($\Theta_{e\gamma} = 0$)
- time-coincident ($t_{e\gamma} = 0$)
- monochromatic ($E_{\gamma} = E_{e+} = 52.8$ MeV)

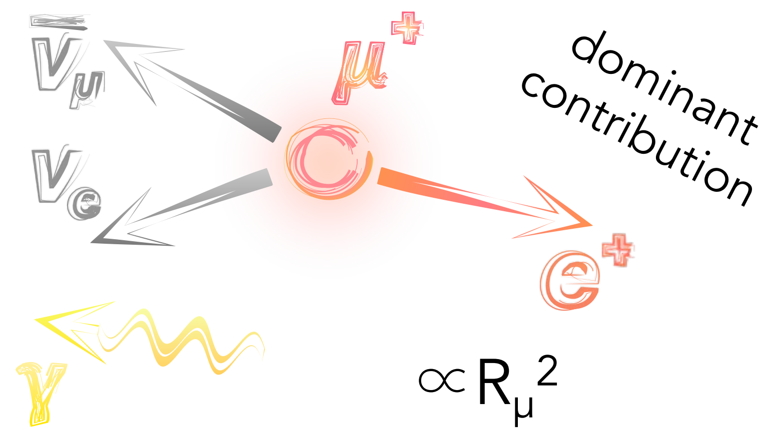


Backgrounds

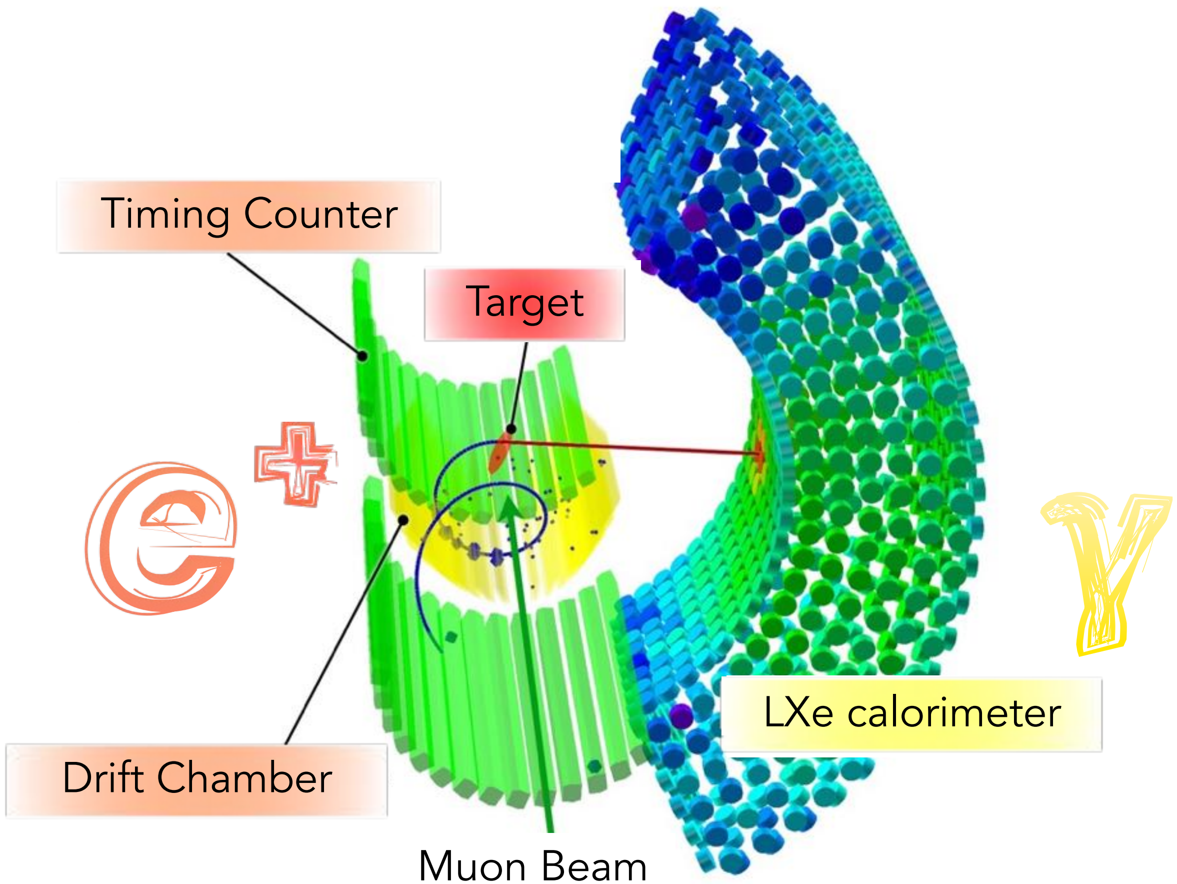
Radiative Muon Decay



Accidentals



The MEG Experiment



Beamline and Target

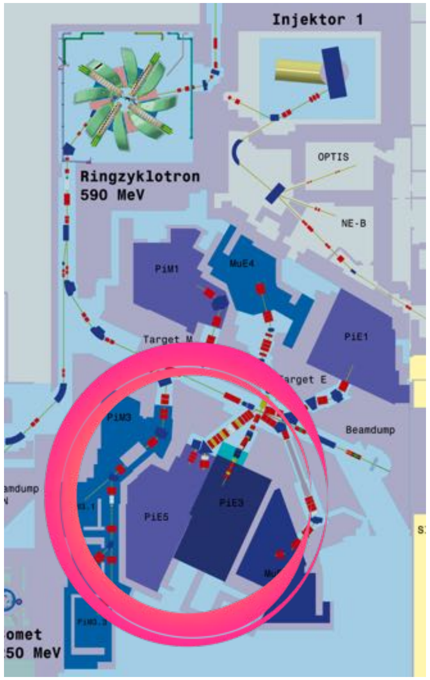
Surface Muons

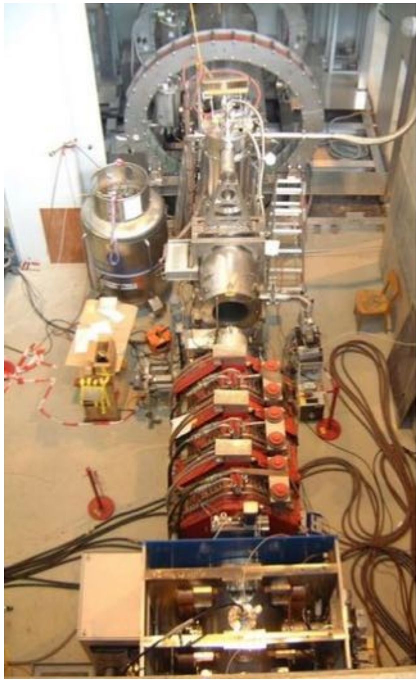
πE5 beamline @ PSI:

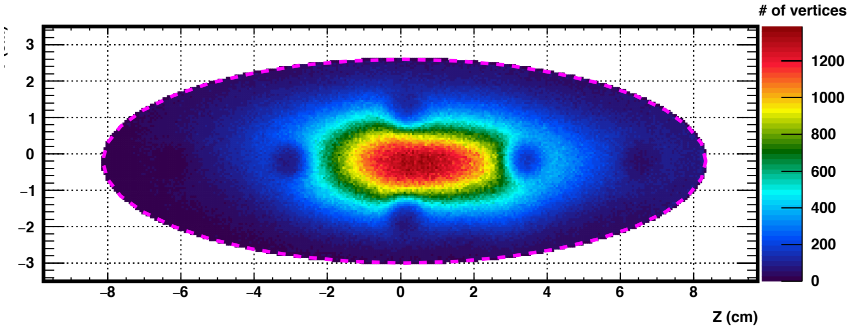
- $3 \times 10^7\ \mu^+/s$
- Low momentum p = 29 MeV/c
- Small momentum spread O(10%)

Muon Stopping Target

- Polyethylene-polyester sandwich
- 205 μm thickness, slanted at ~70°
- Holes and crossmarks for target alignment





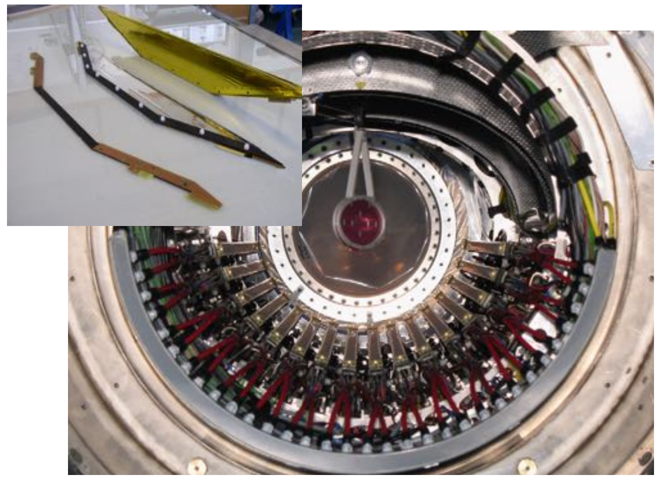


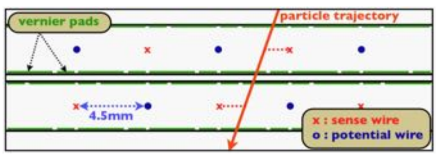
The Positron Spectrometer

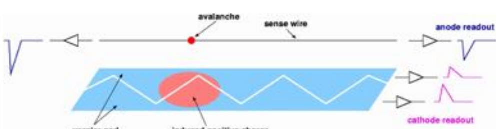
Drift Chamber

Tracking:

- 16 modules
- Low mass ($0.2\%\ X_0$)







Timing Counter

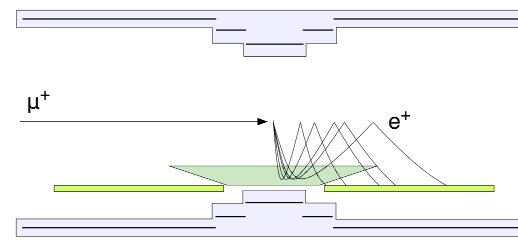
e^+ timing:

- 30 scintillating plastic bars coupled to PMTs

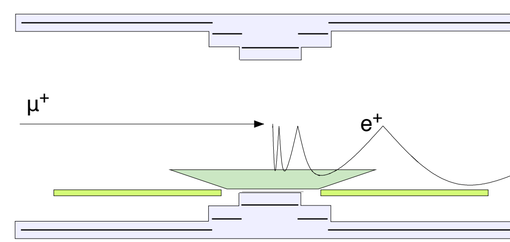
COBRA magnet

Gradient magnetic field:

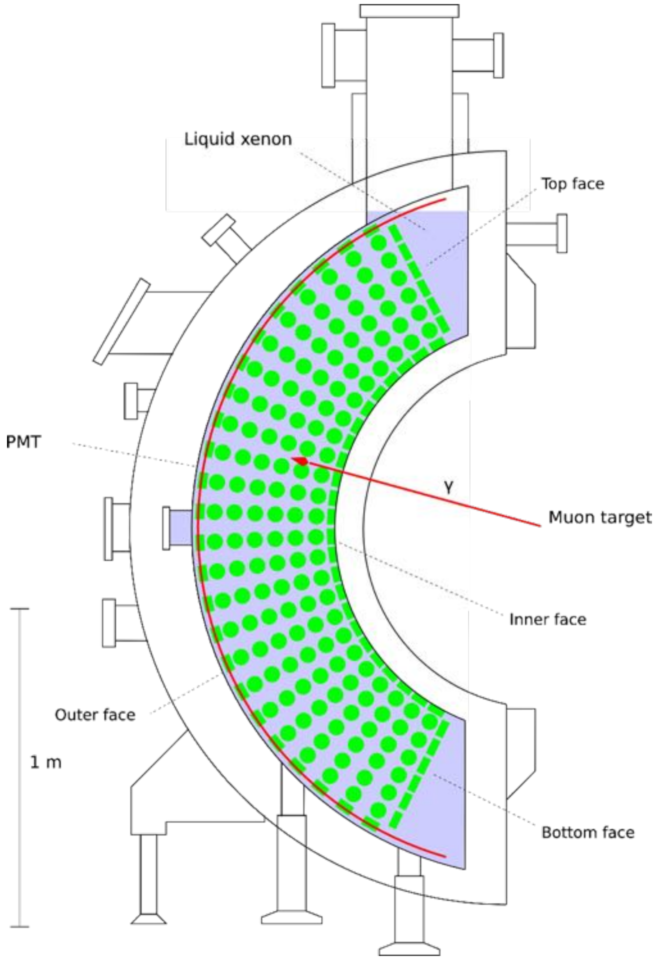
- **Co**nstant proj. **b**ending **ra**dius → selection of high momentum e^+



- e^+ emitted at cosθ~0 quickly swept away



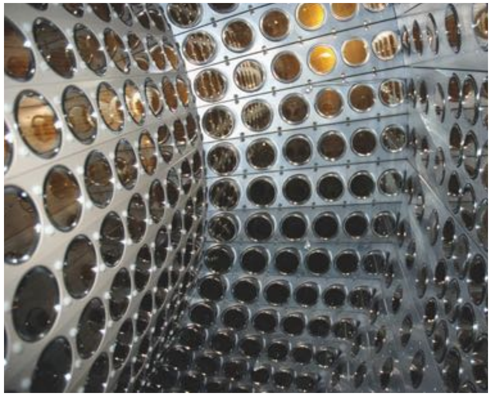
The LXe Calorimeter

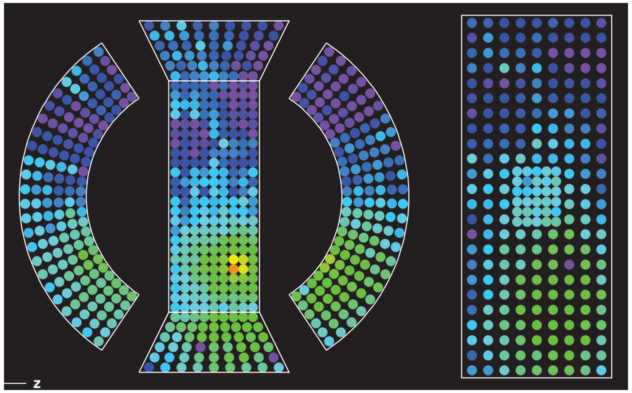


900 l liquid Xe viewed by ~ 850 PMTs covering ~ 11% solid angle

Liquid xenon:

- Efficient detection medium for γ-rays (high Z, dense, short X_0)
- Fast scintillation (τ = 4/22/45 ns)
- High light yield (~ 0.8 NaI)
- Good homogeneity





The MEG Experiment

Experimental Resolutions

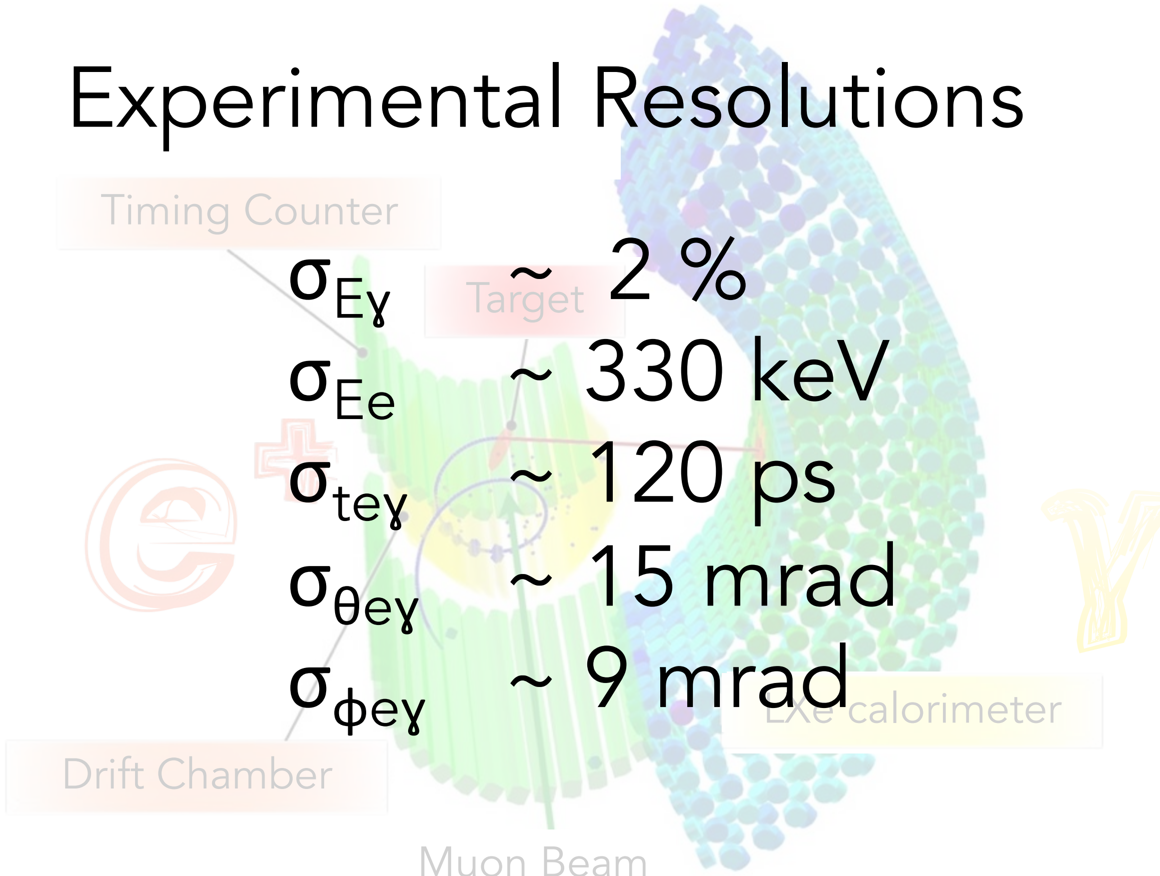
$\sigma_{E\gamma}$ ~ 2 %

σ_{Ee} ~ 330 keV

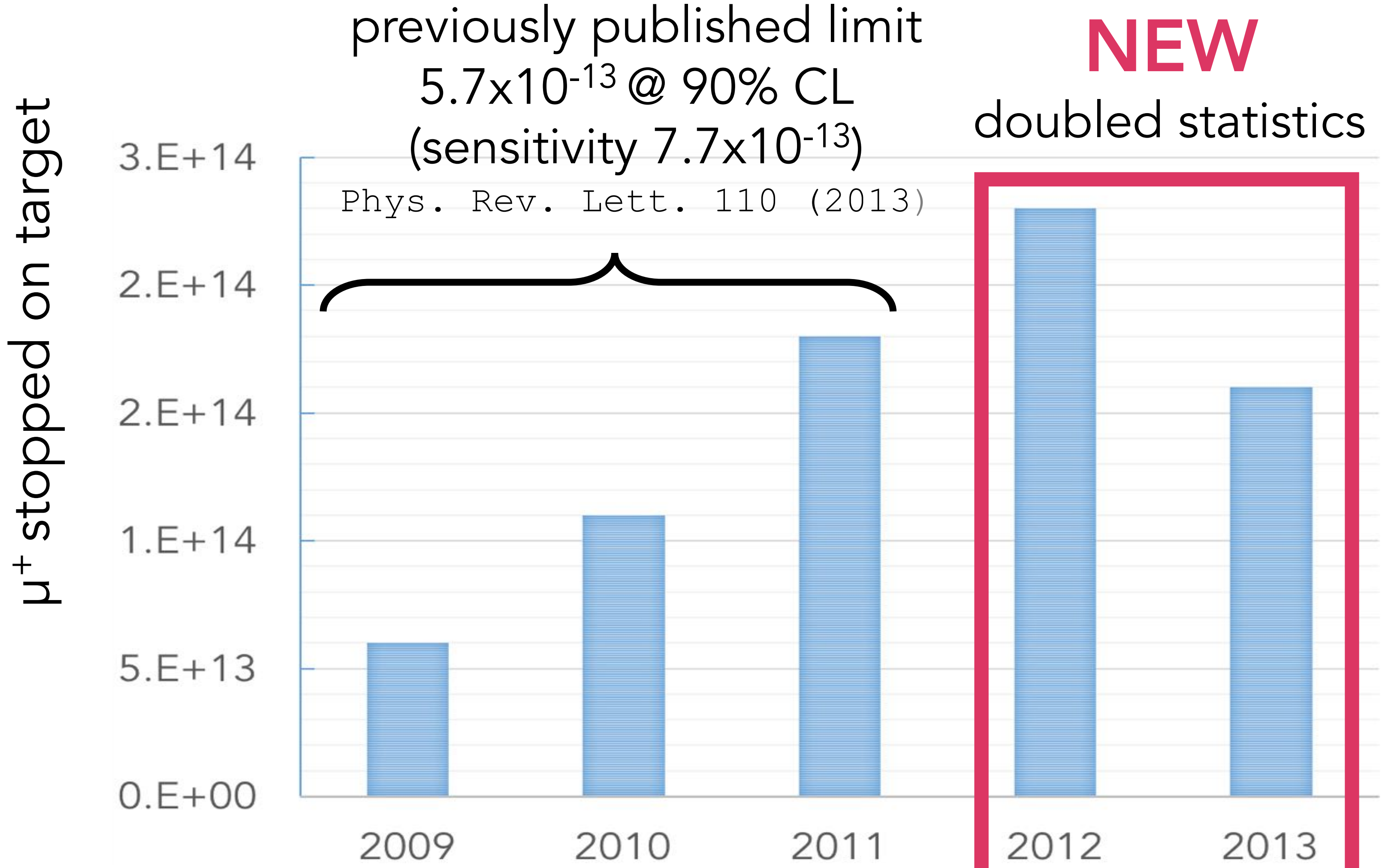
$\sigma_{te\gamma}$ ~ 120 ps

$\sigma_{\theta e\gamma}$ ~ 15 mrad

$\sigma_{\phi e\gamma}$ ~ 9 mrad



Full MEG Dataset



Analysis Strategy

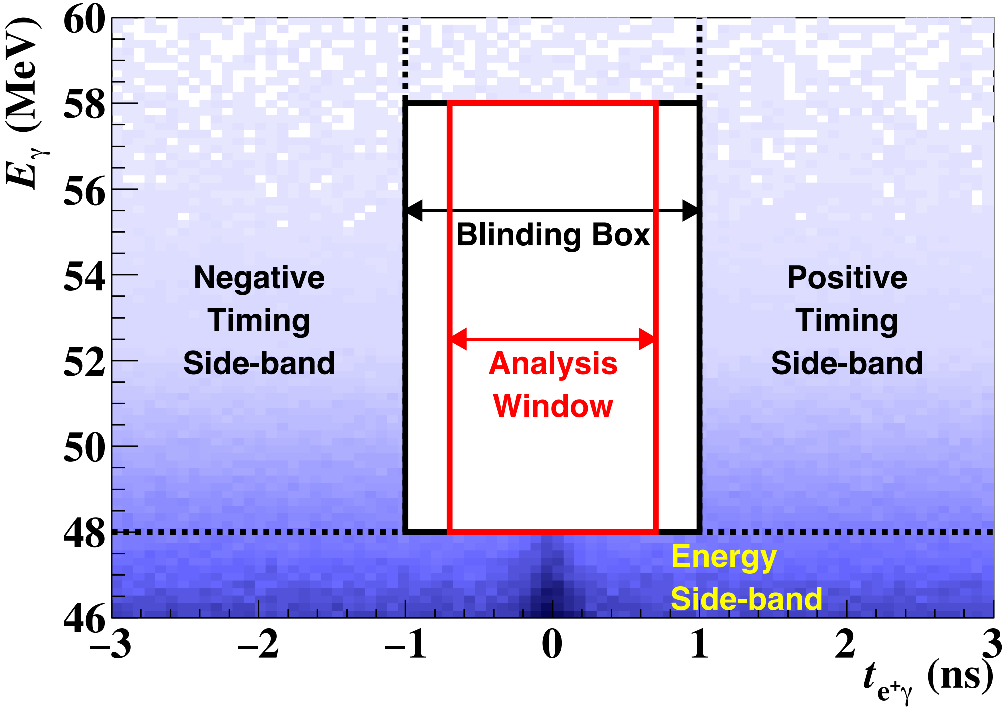
How do you get a rare decay's branching ratio (or an upper limit thereof)?

- ⇨ Estimate the number of signal events N_{sig} observed in the data by Maximum Likelihood Analysis
- ⇨ Normalize by the total number of muon decays k measured during the experiment's life time

$$B(\mu^+ \to e^+\gamma) \equiv \frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma_{total}} = \frac{N_{sig}}{k}$$

Analysis Strategy

To avoid experimenter bias: Blind analysis



Blinding Box

~ 5-20 x resolutions

$48 \text{ MeV} < E_\gamma < 58 \text{ MeV}$

$50 \text{ MeV} < E_e < 56 \text{ MeV}$

$|t_{e\gamma}| < 0.7 \text{ ns}$

$|\theta_{e\gamma}| < 50 \text{ mrad}$

$|\phi_{e\gamma}| < 75 \text{ mrad}$

Estimation of N_{sig}

(Extended) likelihood function for MEG:

interesting parameter

nuisance parameters

constraints on nuisance par.

$$\mathcal{L}(N_{sig}, N_{RMD}, N_{acc}, \mathbf{t}) = \frac{e^{-N}}{N_{obs}!} \times C(N_{RMD}, N_{acc}, \mathbf{t})$$

$$\times \prod_{i=1}^{N_{obs}} \left(N_{sig} \cdot S(\mathbf{x_i}, \mathbf{t}) + N_{RMD} \cdot R(\mathbf{x_i}) + N_{acc} \cdot A(\mathbf{x_i})\right)$$

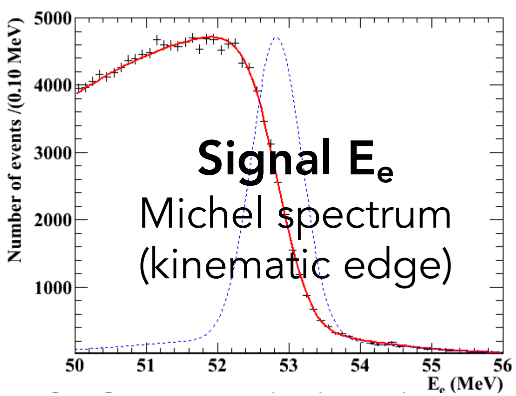
PDFs for the signal, RMD and accidental background

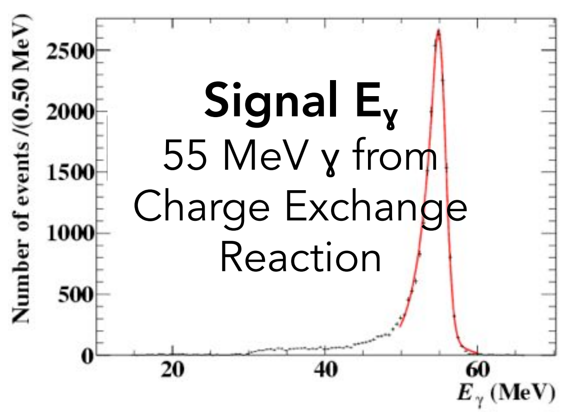
with $x_i = (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})_i$ and $N = N_{sig} + N_{RMD} + N_{acc}$

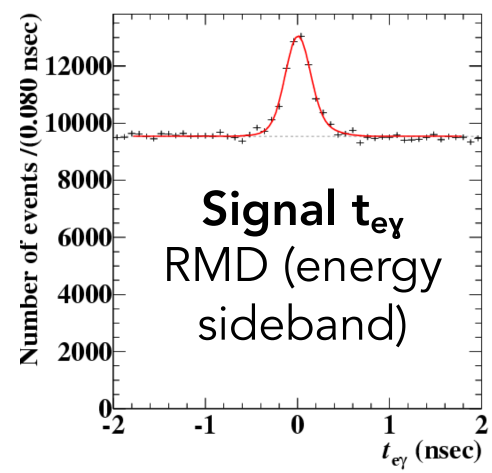
Estimation of N_{sig}

PDFs extracted mostly from data:

- **Signal:** Measured detector response
- **RMD:** Theoretical spectrum folded with detector response
- **Accidentals:** Sidebands







Event-by-event PDFs

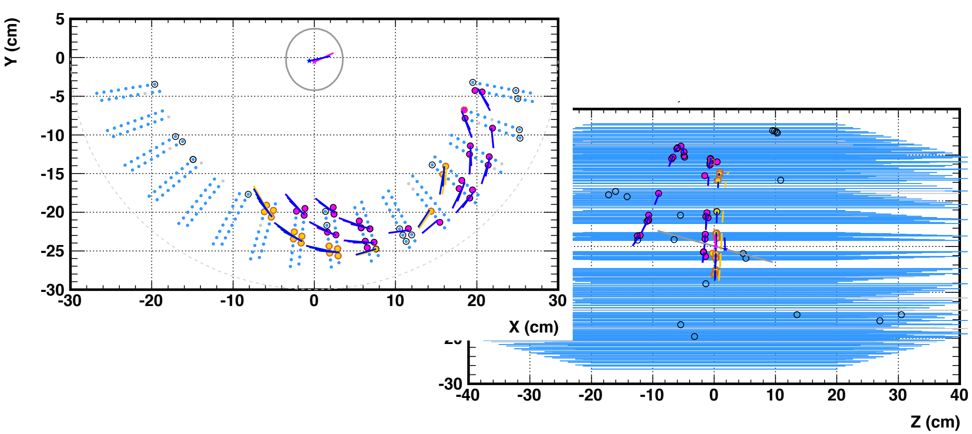
- Positron: Per event error matrix from Kalman filter
- Gamma: Position dependent resolutions

Analysis Improvements

Missing Turn Recovery

Previously: Sometimes missed a part of the trajectory of **"multi-turn-tracks"** → wrong muon decay point, time, e^+ momentum

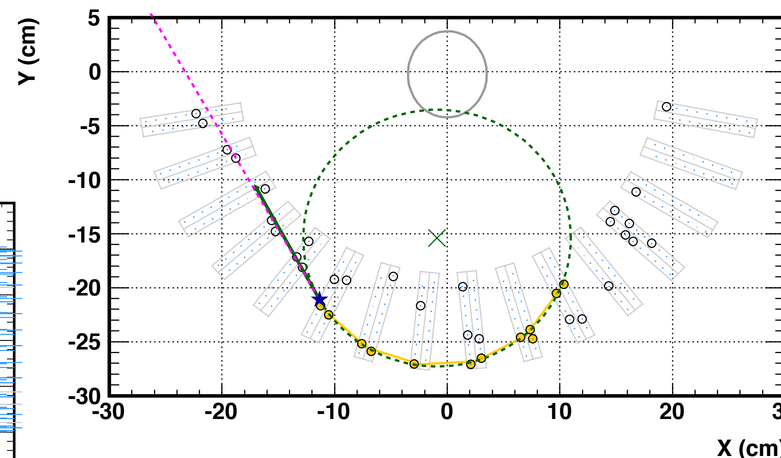
Now: Additional algorithm to identify missing turm tracks and refit them → **4% increase in signal detection efficiency**



Identification of AIF

Identify and reject photon background caused by **annihliation-in-flight** of the e^+ inside the DCH

Overall background rejection ~ 2%



Target Alignment

$\mathcal{L}\left(N_{sig}, N_{RMD}, N_{acc}, \mathbf{t}\right)$ nuisance parameter related to target

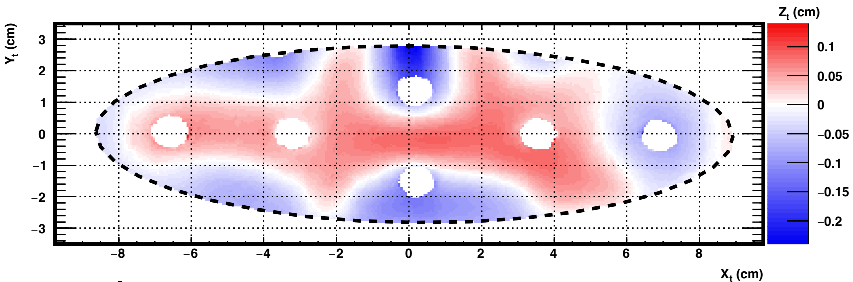
Target Alignment

$$\mathcal{L}\left(N_{sig}, N_{RMD}, N_{acc}, \mathbf{t}\right)$$

nuisance parameter related to target

Target position and shape surveyed by

- optical survey
- reconstruction of holes



laser scanner imagine at the end of 2013

↓

Observed increasing **target aplanarity** with time

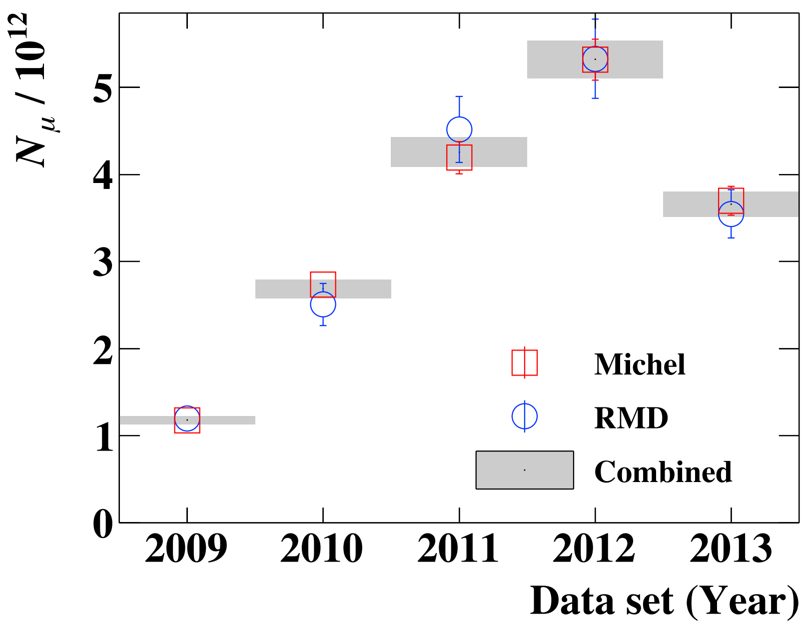
- Treated as nuisance parameter
- Dominant systematic uncertainty: Degradation of the sensitivity by 13% on average

Normalization

No. of effectively measured muon decays

$$B(\mu^+ \to e^+\gamma) \equiv \frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma_{total}} = \frac{N_{sig}}{k}$$

with $k = N_\mu \times \langle A \times \varepsilon \rangle_{e\gamma}$



Two independent samples:

- Michel decay

$$k = \frac{N_{Michel}}{\mathcal{B}_{Michel}} \times \frac{\langle A \times e \rangle_{e\gamma}}{\langle A \times e \rangle_{Michel}}$$

- RMD decay

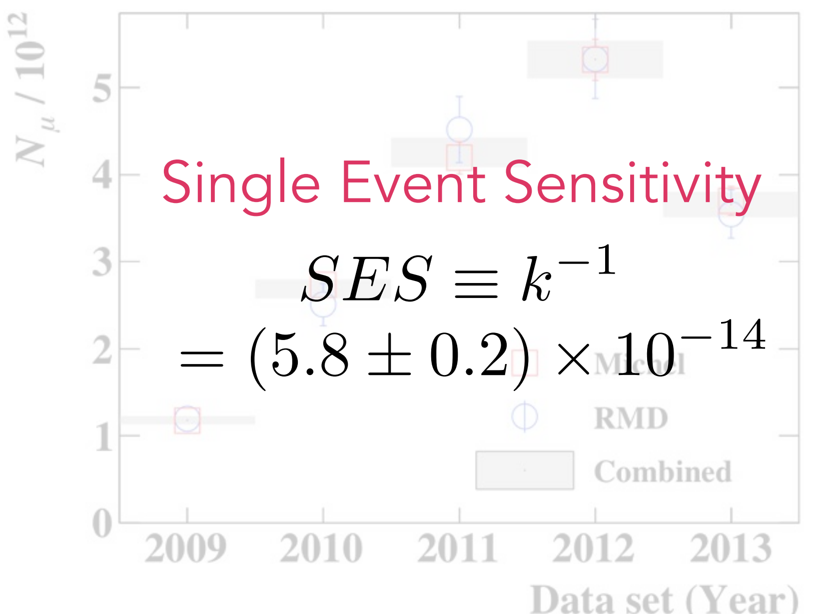
$$k = \frac{N_{RMD}}{\mathcal{B}_{RMD}} \times \frac{\langle A \times e \rangle_{e\gamma}}{\langle A \times e \rangle_{RMD}}$$

Normalization

No. of effectively measured muon decays

$$B(\mu^+ \rightarrow e^+\gamma) \equiv \frac{\Gamma(\mu^+ \rightarrow e^+\gamma)}{\Gamma_{total}} = \frac{N_{sig}}{k}$$

with $k = N_\mu \times \langle A \times \varepsilon \rangle_{e\gamma}$



Single Event Sensitivity

$$SES \equiv k^{-1}$$
$$= (5.8 \pm 0.2) \times 10^{-14}$$

Two independent samples:

- Michel decay

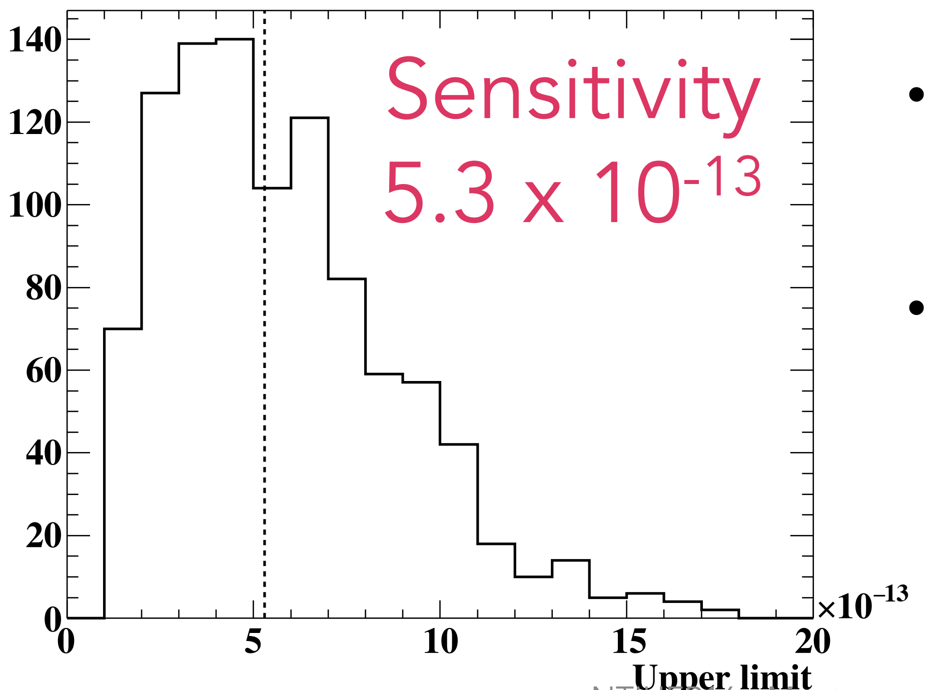
$$k = \frac{N_{Michel}}{\mathcal{B}_{Michel}} \times \frac{(A \times e)_{e\gamma}}{(A \times e)_{Michel}}$$

- RMD decay

$$k = \frac{N_{RMD}}{\mathcal{B}_{RMD}} \times \frac{(A \times e)_{e\gamma}}{(A \times e)_{RMD}}$$

Sensitivity

- Compute the upper limit at 90% CL for many pseudo-experiments assuming the null-signal hypothesis
- Sensitivity ≡ above distribution's median

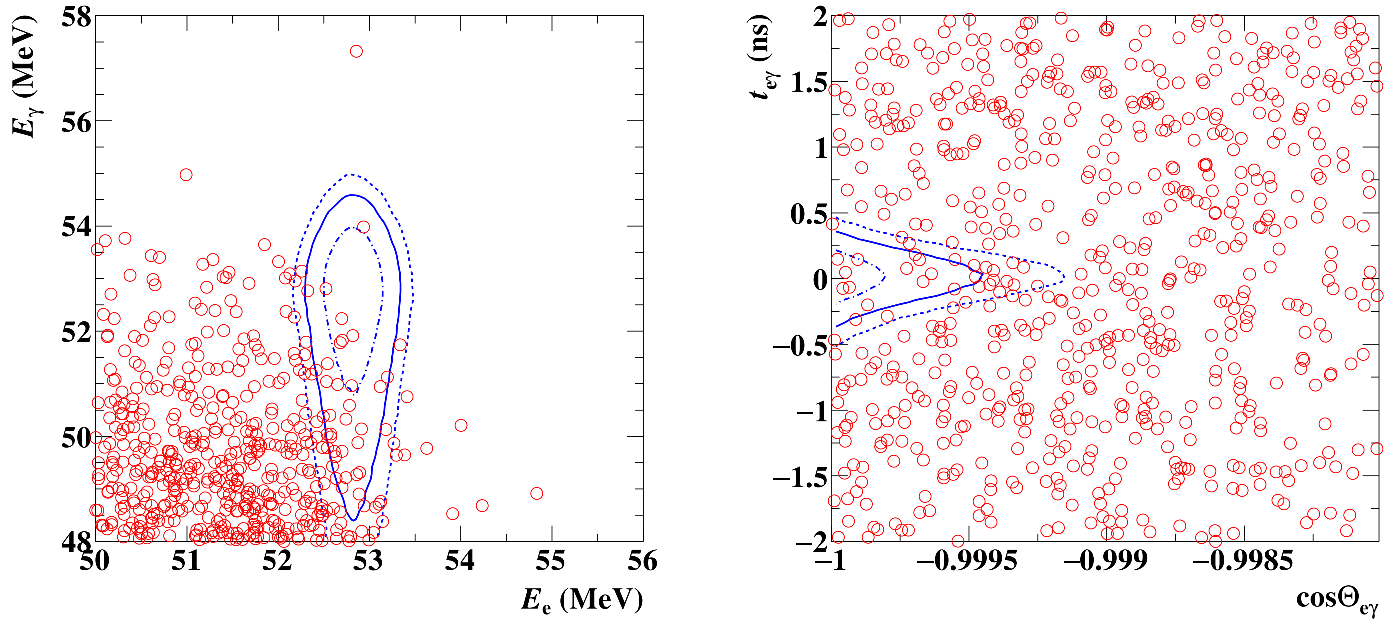


- RMD and accidental bg rates as estimated from sidebands
- Includes systematic uncertainties (average contribution ~14%)

Event Distributions

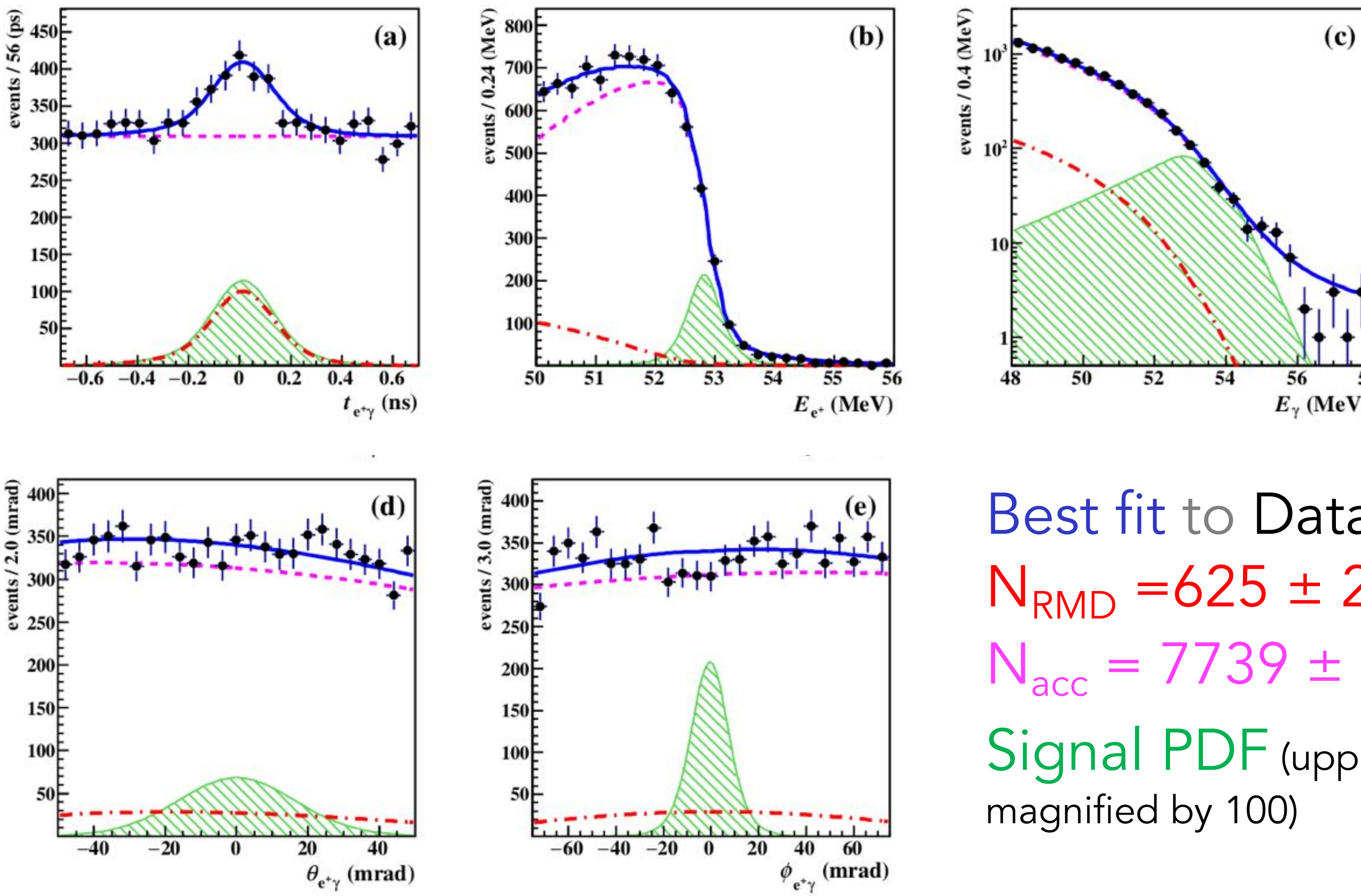
Opening the Blinding Box: 8344 events

No signal excess found



1σ, 1.64σ, 2σ signal PDF contours

Likelihood Fit



Best fit to Data

N_{RMD} =625 ± 28

N_{acc} = 7739 ± 38

Signal PDF (upper limit magnified by 100)

Final MEG Result

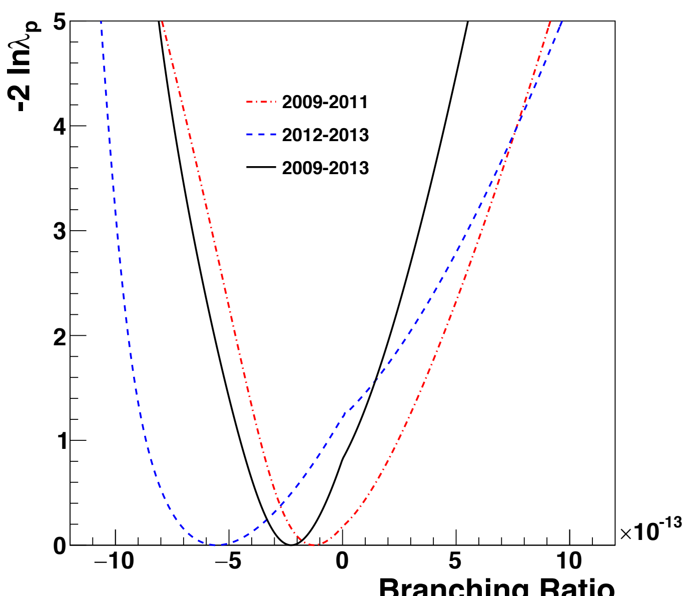
Upper limit on the branching ratio

Confidence interval calculated with Feldman & Cousins approach with profile likelihood ratio ordering

30 times better limit than MEGA (1999)!

$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13} \text{ @ 90\% C.L.}$$

Eur. Phys. J. C (2016) 76:434



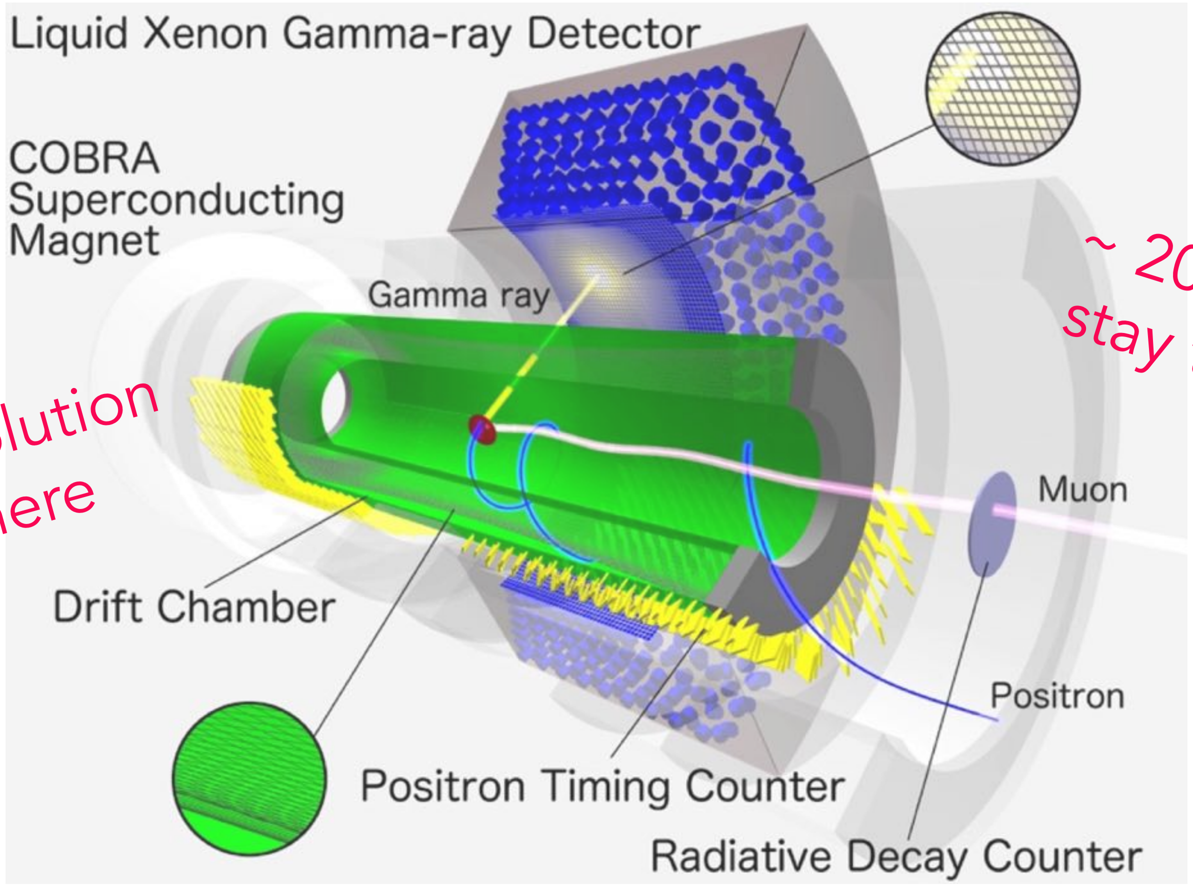
Full data set 2009-2013 ≙ 7.5×10^{14} μ^+ stopped on target

Systematic uncertainties:

- Target alignment: 5%
- Other sources: <1%

The MEGII Experiment

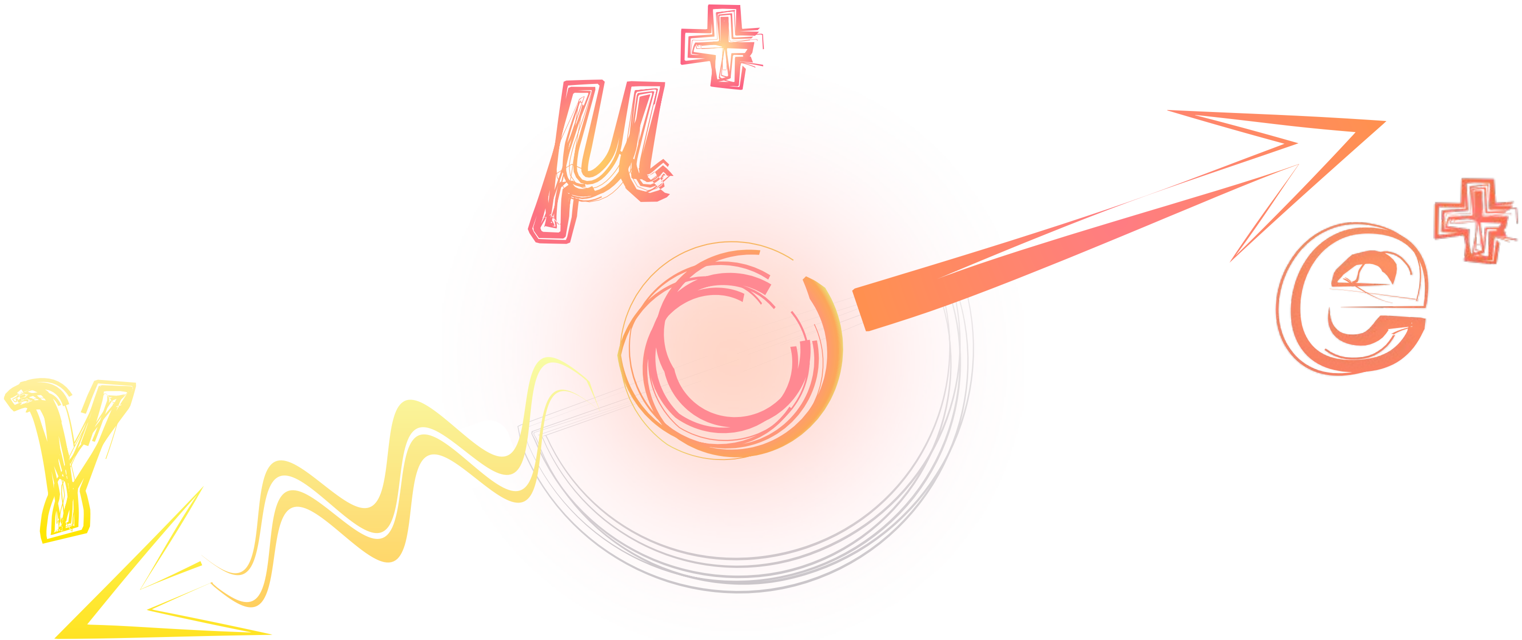
Sensitivity goal ≈ 5 x10^{-14}



ca. x 2 resolution everywhere

~ 2017-2020
stay tuned...

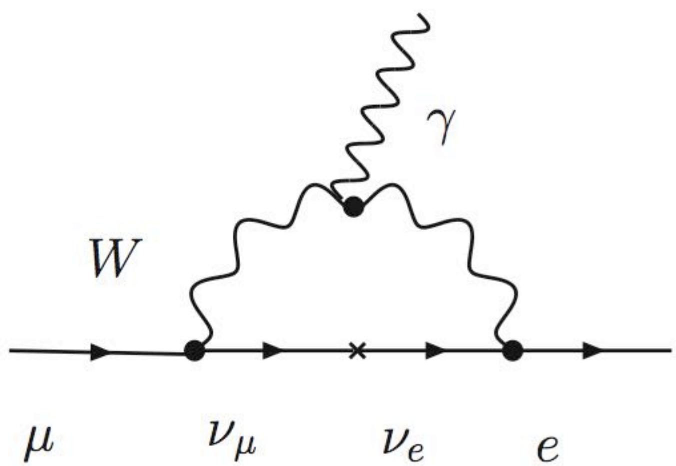
Backup



The Role of cLFV

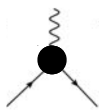
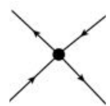
Standard Model with massive neutrinos:

$$B(\mu^+ \to e^+\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$



The Role of cLFV

Kappa-Plot

$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$  $+ \frac{\kappa}{(\kappa+1)\Lambda^2} \times$ 

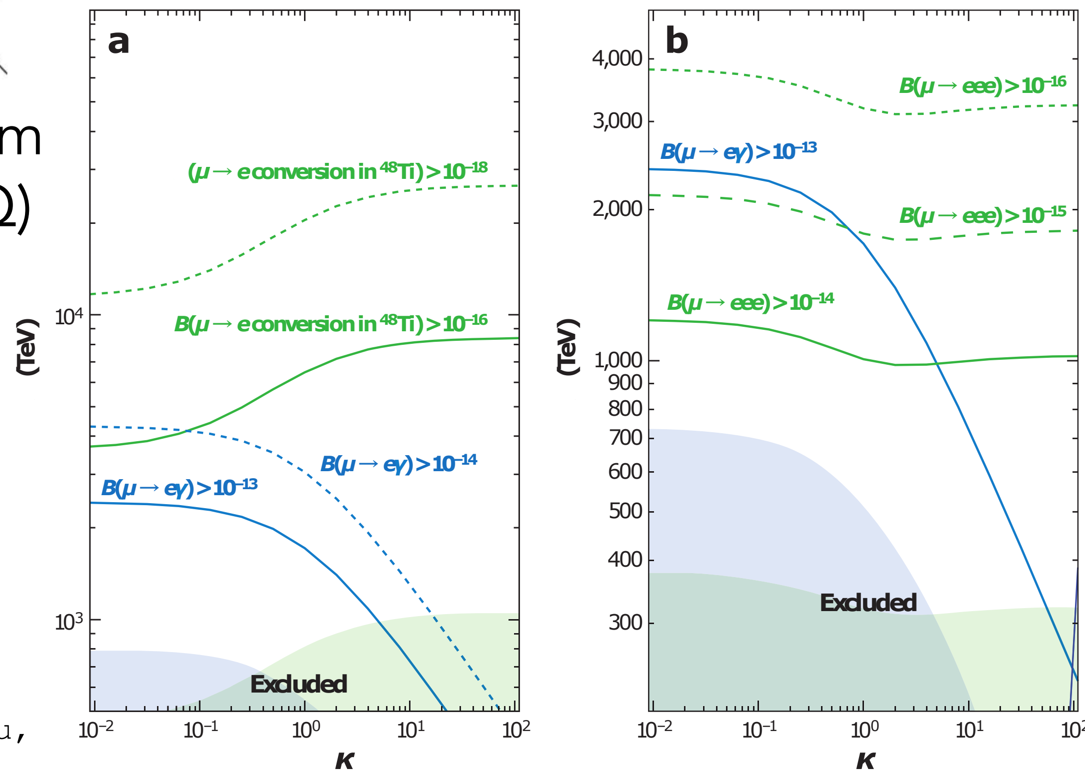
dipole term (e.g. SUSY)

contact term (e.g. Z′, LQ)

μ → eγ

μ → eee

μN → eN

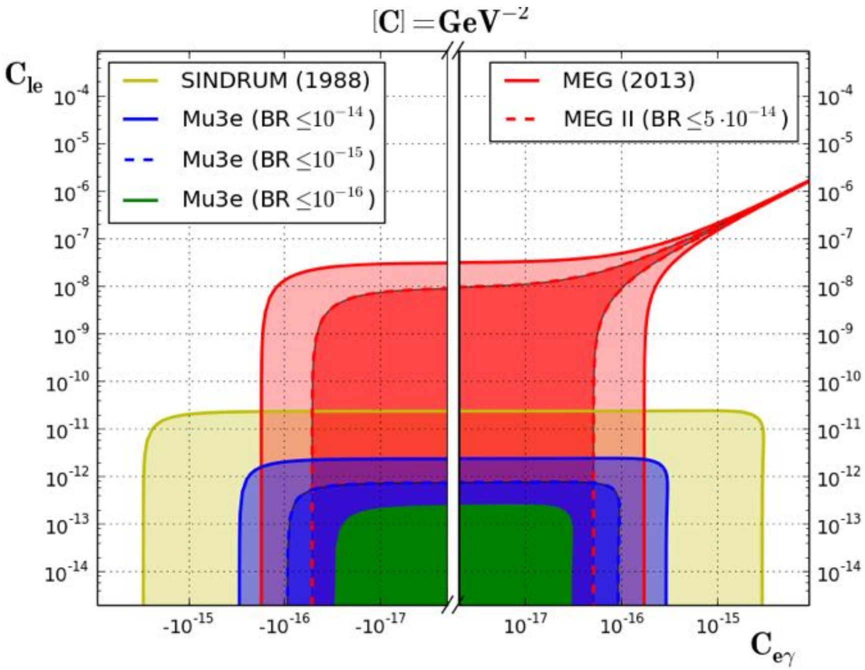


A. De Gouvêa et N. Saulidou, Ann. Rev. Nucl. Part. Sci. (2010) **60**:513

The Role of cLFV

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$



Allows to combine constraints from low energy experiments with LFV searches at high energies

G.M. Pruna and A. Signer arXiV:1511.04421v1

G.M. Pruna and A. Signer JHEP 10 (2014) 014

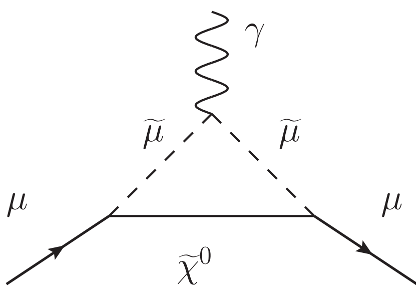
cLFV Limits

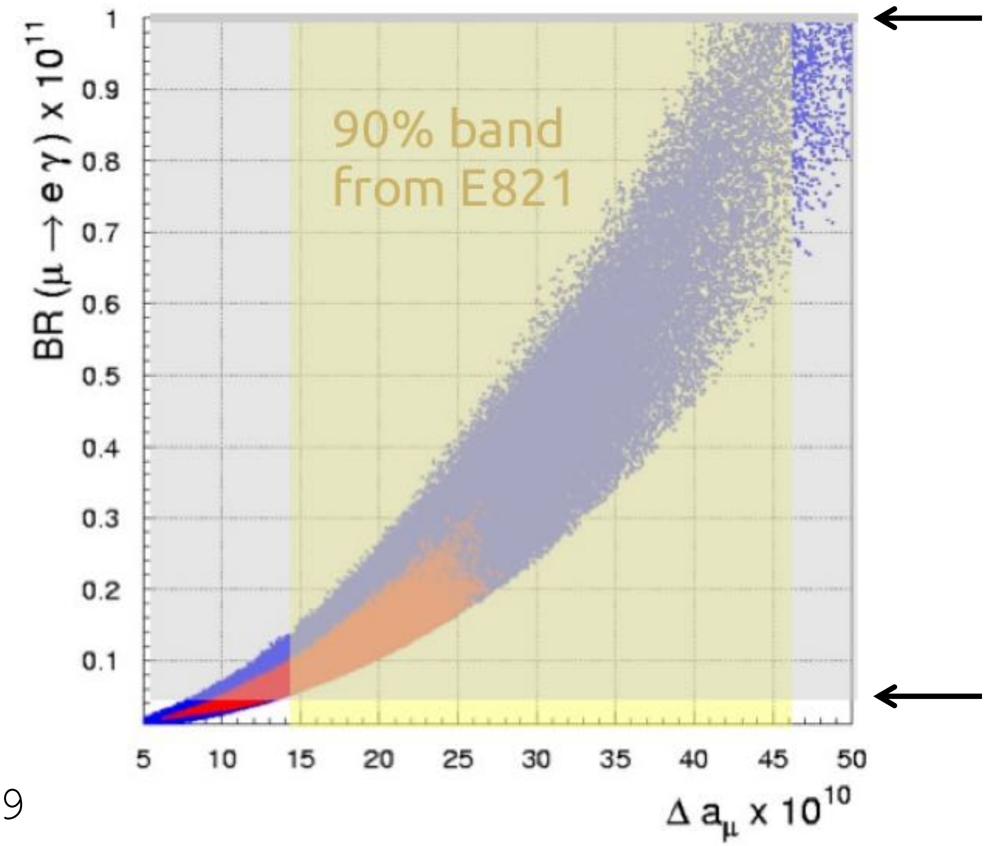
MUONIC AND TAUONIC LFV TRANSITIONS - A SELECTION

- BR($\mu \to 3e$)$< 1.0 \times 10^{-12}$ at the 90% C.L.
  SINDRUM Collaboration, Nucl. Phys. B **299** (1988) 1;
- BR($\mu \to \gamma + e$)$< 4.2 \times 10^{-13}$ at the 90% C.L.
  MEG Collaboration, Eur. Phys. J. C **76** (2016) 434;
- BR($Z \to e + \mu$)$< 7.5 \times 10^{-7}$ at the 95% C.L.
  ATLAS Collaboration, Phys. Rev. D **90** (2014) 072010;

- BR($\tau \to 3e$)$< 2.1 \times 10^{-8}$ at the 90% C.L.
  BELL Collaboration, Phys. Lett. B **687** (2010) 139-143;
- BR($\tau \to \gamma + \mu$)$< 4.4 \times 10^{-8}$ at the 90% C.L.
  BaBar Collaboration, Phys. Rev. Lett. **104** (2010) 021802;
- BR($Z \to \tau + \mu$)$< 1.2 \times 10^{-5}$ at the 95% C.L.
  DELPHI Collaboration, Z. Phys. C **73** (1997) 243-251;
- BR($H \to \tau + \mu$)$< 1.8 \times 10^{-2}$ at the 90% C.L.
  ATLAS/CMS Collaboration, arXiv:1508.03372/arXiv:1502.07400.

The relationship between $\mu \to e\gamma$ and $(g\text{-}2)_\mu$





MEGA (1999)

MEG (2016)

Isidori et al., Phys. Rev. D (2007) 75:115019

Calibration Methods

Mott Scatttered e^+ Beam
Monochromatic beam $E_e \approx 52$ MeV
DCH alignment and performance

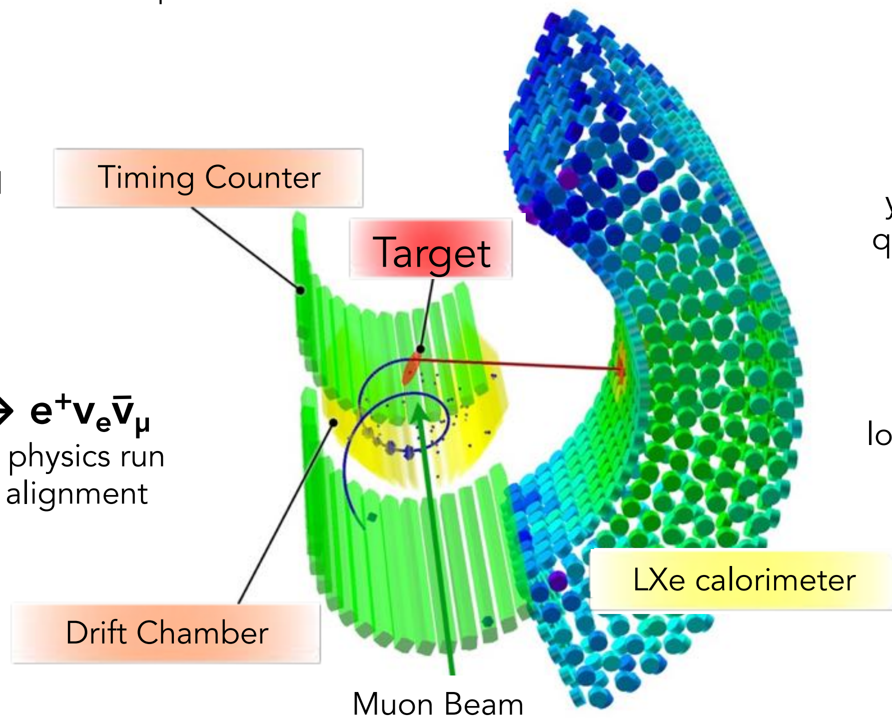
Cockcroft-Walton Accelerator
$E\gamma$ = 14.8,17.6 MeV from Li(p,γ)Be
time-conicident $E\gamma$ = 4.4, 11.6 MeV from B(p,γγ)C

Cosmic Rays
relative alignment LXe – DCH
alignment DCH system
TC calibration

^{241}Am-sources
α of 5.5 MeV
transparency and light
yield of the Lxe, relative
quantum PMT efficiciency

Michel positrons $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
continuously collected during physics run
DCH detector response and alignment

Neutron Generator
9 MeV Ni line
low energy γ-rays simultaneously
with the beam



LED
PMT gains

Radiative Muon Decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$
zero position of the relative timing

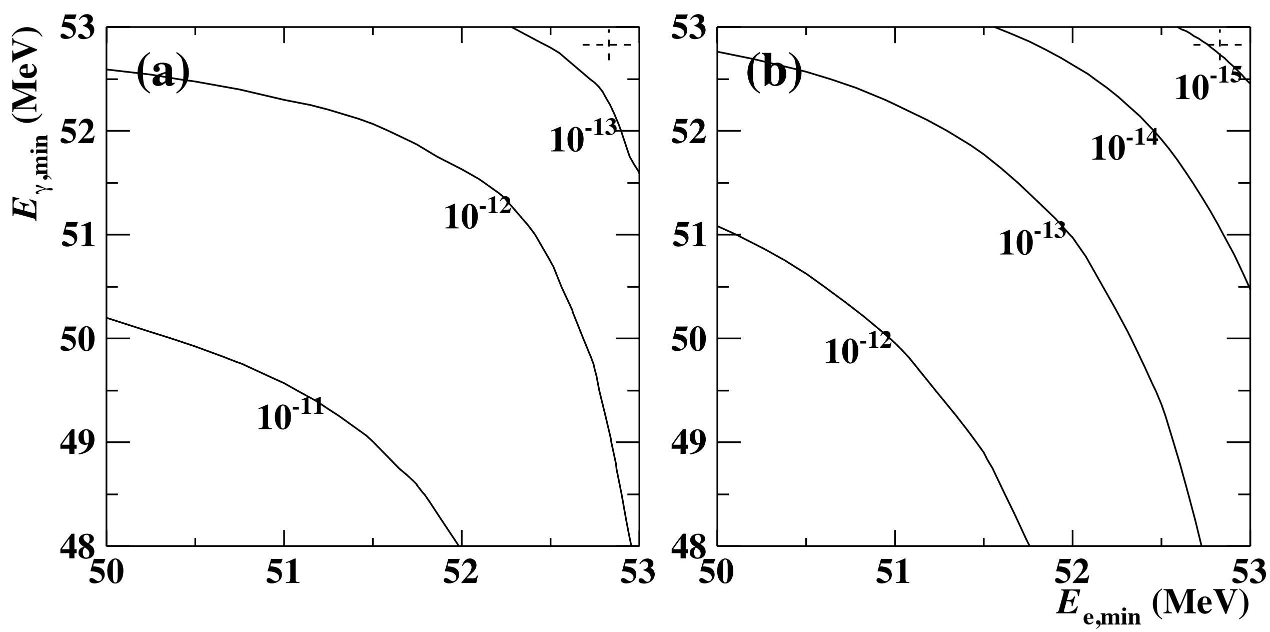
Charge Exchange Reaction
70.5 MeV/c negative pion beam on LH_2 target
$\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow \gamma\gamma$ 55 MeV, 83 MeV

RMD and Accidental BG

Effective branching ratios

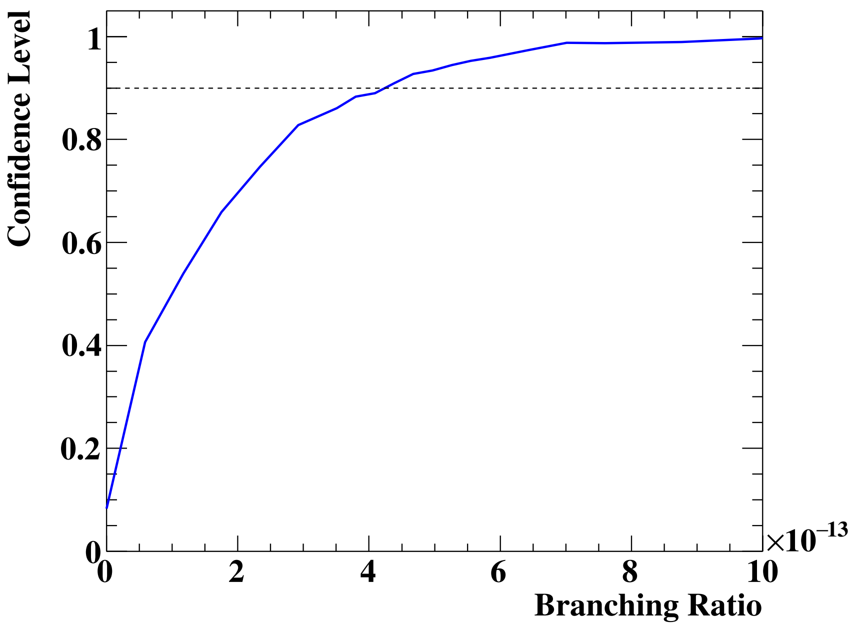
$E_{\gamma,min} < E_\gamma < 53.5$ MeV $|t_{e\gamma}| < 0.24$ ns

$E_{e,min} < E_e < 53.5$ MeV $|\cos\Theta_{e\gamma}| < -0.9996$ (~178°)



Confidence Interval

Cwith Feldman & Cousins approach with profile likelihood ratio ordering



Profile likelihood

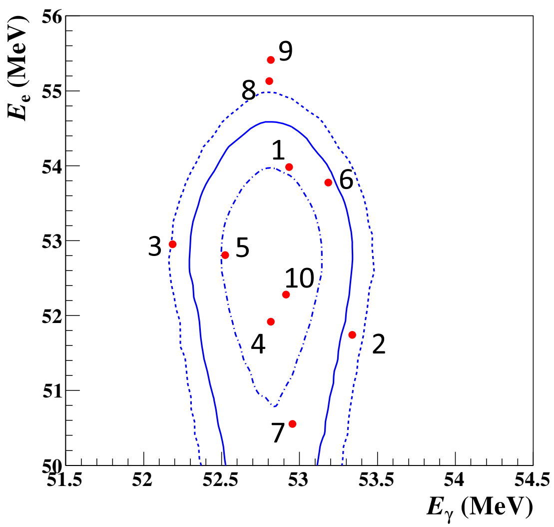
$$\lambda_p(N_{\mathrm{sig}}) = \begin{cases} \dfrac{\mathcal{L}(N_{\mathrm{sig}},\hat{\hat{\boldsymbol{\theta}}}(N_{\mathrm{sig}}))}{\mathcal{L}(0,\hat{\hat{\boldsymbol{\theta}}}(0))} & \text{if } \hat{N}_{\mathrm{sig}} < 0 \\ \dfrac{\mathcal{L}(N_{\mathrm{sig}},\hat{\hat{\boldsymbol{\theta}}}(N_{\mathrm{sig}}))}{\mathcal{L}(\hat{N}_{\mathrm{sig}},\hat{\boldsymbol{\theta}})} & \text{if } \hat{N}_{\mathrm{sig}} \geq 0, \end{cases}$$

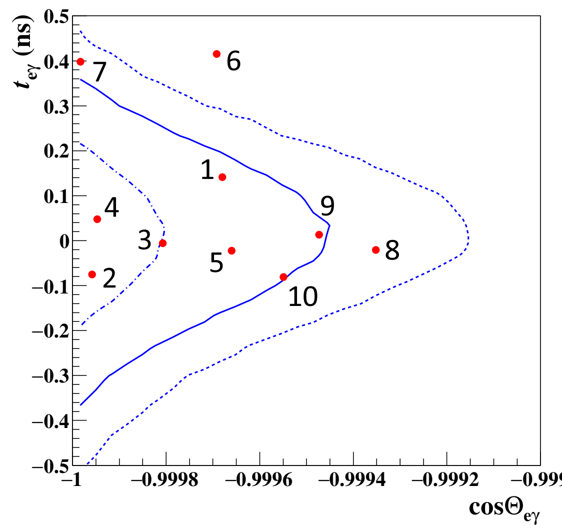
Test statistics

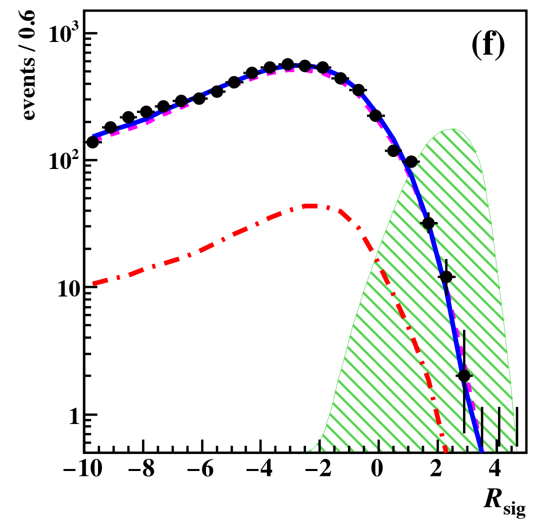
$$q(N_{\mathrm{sig}}) = -2\ln\lambda(N_{\mathrm{sig}})$$

Top Ten Signal-Like Events

$$R_{\mathrm{sig}} = \log_{10}\left(\frac{S(\boldsymbol{x}_i)}{f_R R(\boldsymbol{x}_i) + f_A A(\boldsymbol{x}_i)}\right)$$



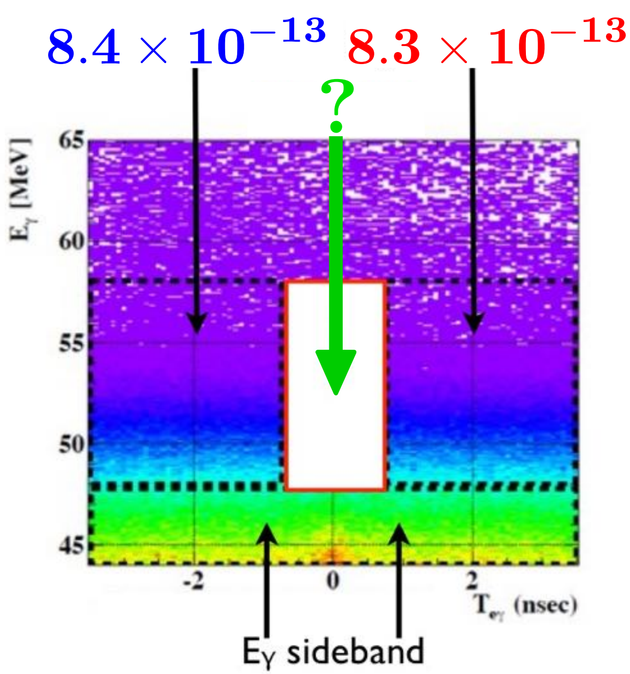


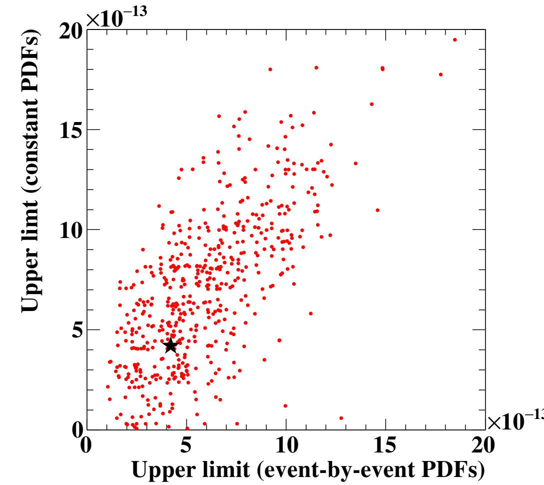


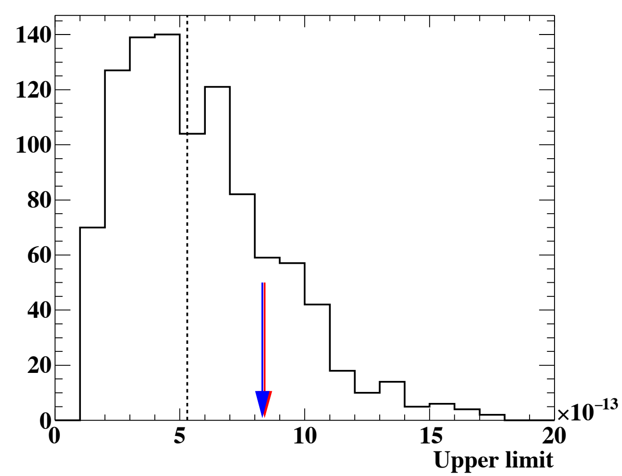
See also https://meg.web.psi.ch/docs/theses/kaneko_phd_final.pdf

Additional Checks

- Fitting without constraint
- Fictitious analysis window centered at $t_{e\gamma} = \pm 2$ ns
- Analysis with constant PDFs







Sensitivites and Limits for different years

dataset	2009–2011	2012–2013	2009-2013
$\mathcal{B}_{\text{fit}} \times 10^{13}$	−1.3	−5.5	−2.2
$\mathcal{B}_{90} \times 10^{13}$	6.1	7.9	4.2
$\mathcal{S}_{90} \times 10^{13}$	8.0	8.2	5.3