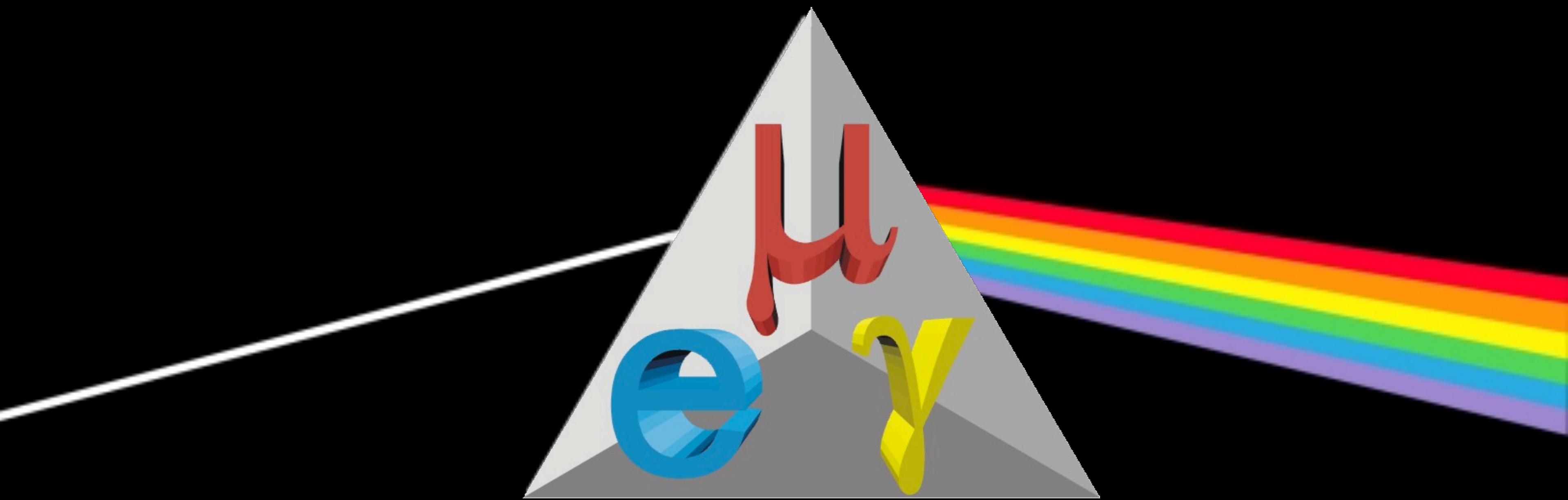
A glance beyond the Standard Model: the MEG experiment



S. Dussoni
PSIPSI ’13
sep. 9-12, 2013

MEG's "5W" rule (outline)

WHY?

- role of $\mu \to e\gamma$ and Lepton Flavor phenomena as a tool to explore New Physics (in brief)

WHO?

- "the MEG experiment, I suppose": a tiny collaboration of ~60 researchers from Italy, Japan, Russia, USA and Switzerland

WHERE?

- At Paul Scherrer Institut, with the most intense DC muon beam worldwide

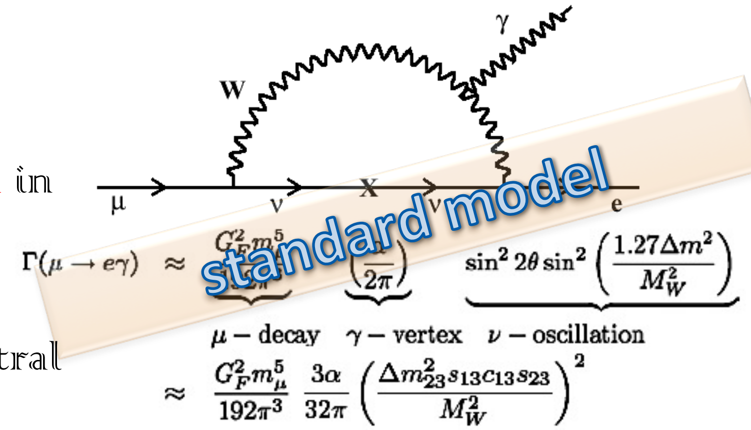
WHAT?

- signal, backgrounds and experimental challenges, final results

WHEN?

- now and future, constraining even further NP with MEG_II

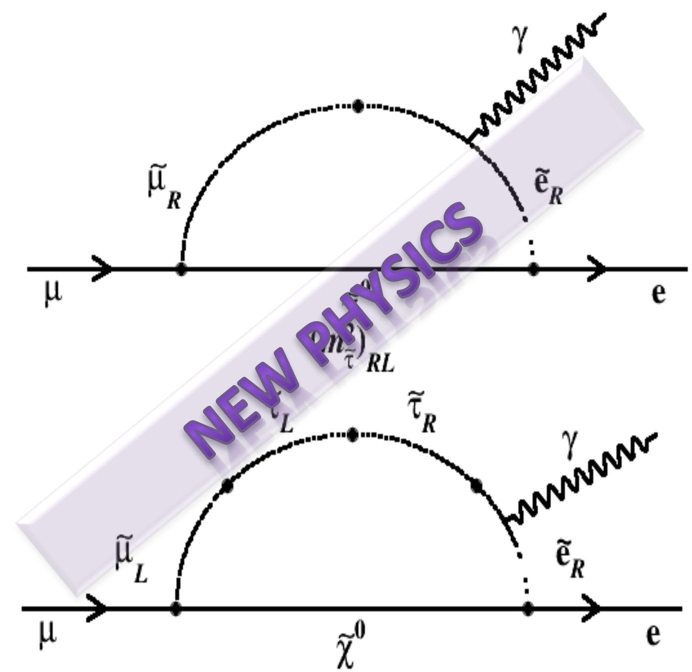
μ→eγ: a tool for New Physics



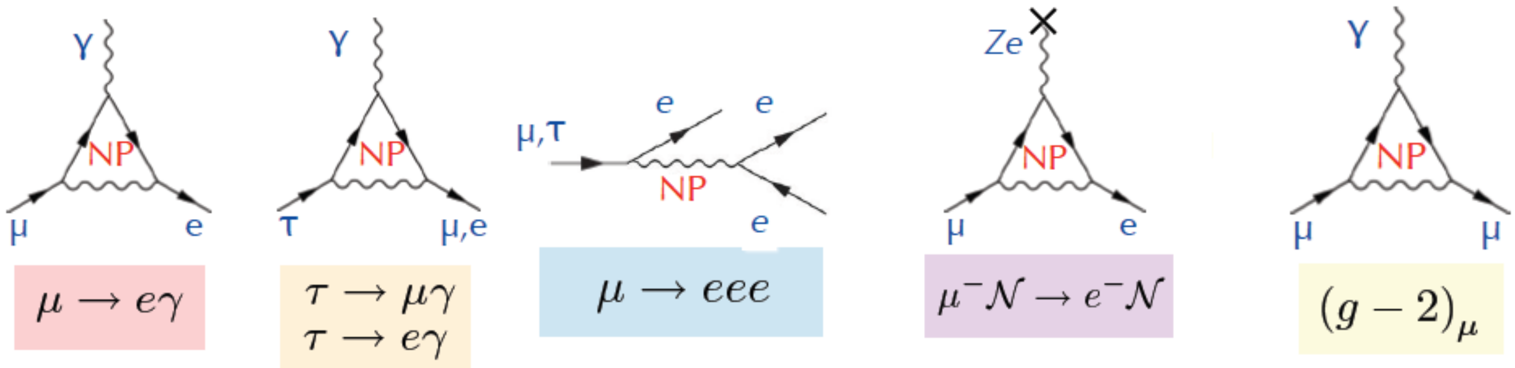
Lepton Flavor Violation (LFV) is strictly forbidden in "original" SM with vanishing ν masses

- modified SM to account for ν oscillations (neutral LFV process): μ→eγ (and all charged LFV processes) still heavily suppressed, $\mathcal{BR}_{\mu\to e\gamma} \sim 10^{-50}$

- in proposed extensions of SM, charged LFV is enhanced: μ→eγ rises up to (hardly) detectable levels $\mathcal{BR}_{\mu\to e\gamma} \sim 10^{-15} \div 10^{-11}$
  - hints on lepton sector, non-SM dark matter candidates and cosmology problems through lepton number violation;
  - μ→eγ and other cLFV processes can test "new Physics" happening at an energy scale far out of LHC capability;
  - μ→eγ is the cleanest channel;
  - this remains a tough challenge for experimenters.



μ→eγ and cLFV-mates



In the muon sector cLFV can be observed in:

- μ→eγ, no neutrinos emitted (analog processes **τ→μγ** and **τ→eγ**)
- μ→eee muon to three electrons
- μ N→ e N muon conversion in nuclei
- anomalous muon magnetic moment

All of them can be modeled with a general effective Lagrangian of the form:

$$\mathcal{L}_{\rm CLFV} \;=\; \frac{m_\mu}{(\kappa+1)\Lambda^2}\,\bar{\mu}_R \sigma_{\mu\nu} e_L\, F^{\mu\nu} \;+\; h.c.$$

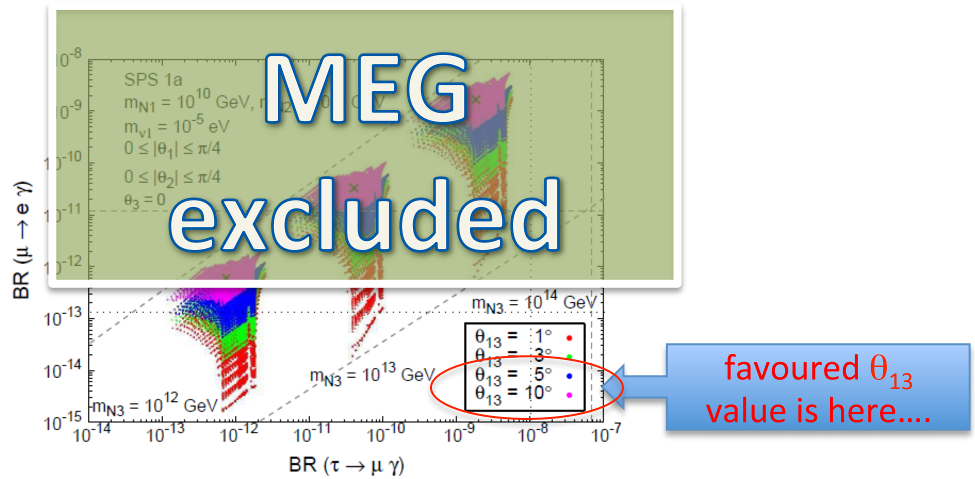
SPOILER!

This representation has some implications, as we will see…

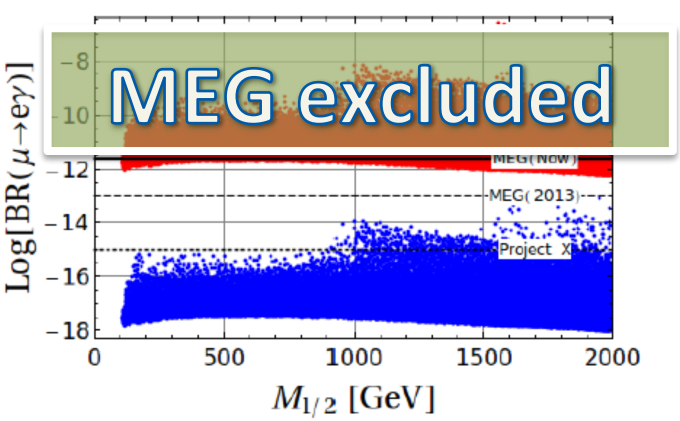
μ→eγ and cLFV-mates

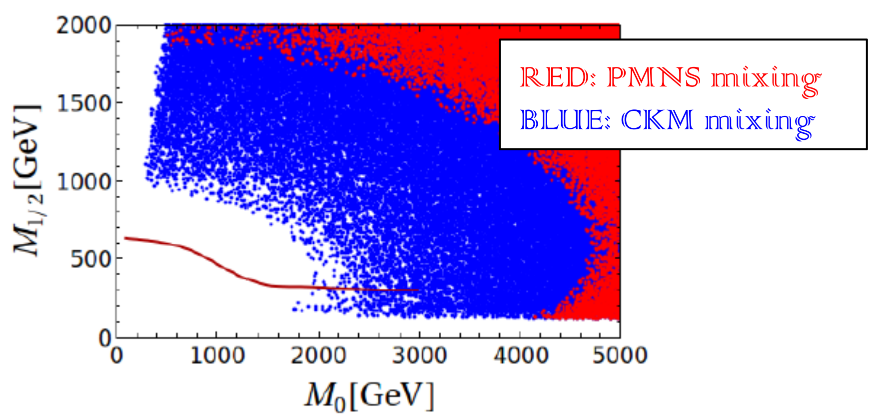
MEG already eroded place for Beyond Standard Model theories

Especially, one can notice that with the best estimate for θ13 from recent neutrino oscillation experiments (Daya Bay, DoubleChooz…), the μ cLFV is favoured against τ channels!



Furthermore, MEG (and cLFV searches) are an ideal complement to LHC measurements looking for BSM effects, capable to explore higher energy region





MEG keywords

- High rate (rare events, large statistics…)
  - most intense continuous Muon Beam in the world (PSI)
  - stringent trigger/DAQ requirements
- Light and precise (lowest background possible)
  - light target, light Drift Chambers for positron tracking with minimum multiple scattering
  - thin magnet for reduced gamma interaction probability (high efficiency)
- Reliable over long time multi-year data-taking
  - Several calibration and monitoring methods
- Innovative detectors with outstanding performances
  - Liquid Xenon calorimeter,
  - Drift Chambers,
  - high-speed digitizers (DRS),
  - COBRA magnet,
  - high resolution time measurements in magnetic field
- Optimized for looking at the $\mu \to e\gamma$ channel
- Small (~60 researchers involved, from many countries)

The MEG crew

The experimental method

$\mu \rightarrow e\gamma$ signature: photon and positron simultaneously emitted back-to-back and with equal energies in Center-Of-Mass system (μ decays at rest)

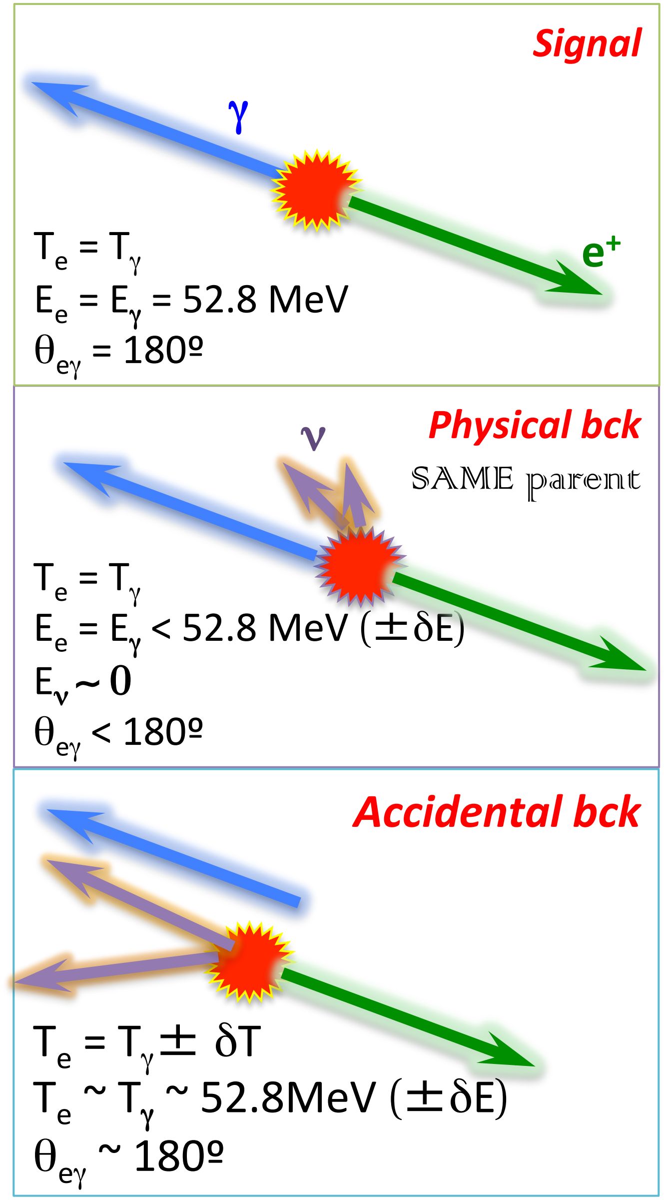
signal will be hindered by a huge background:

- "physics": $\mu \rightarrow e\nu\nu\gamma$ radiative decay with "end-point" γ and e and low energy ν's
- "accidental": e and γ from different sources but with compatible kinematics to the $\mu \rightarrow e\gamma$ one
- in our conditions $\mathcal{BR}_{phys} \sim 0.1\ \mathcal{BR}_{acc}$ (dominant)

$$\mathcal{BR}_{(acc)} \sim (R_\mu)^2\ (\delta E_\gamma)^2\ \delta E_{pos}\ \delta t\ (\delta\omega)^2$$

✓ squared rate dependence

✓ crucial dependence on detector resolutions

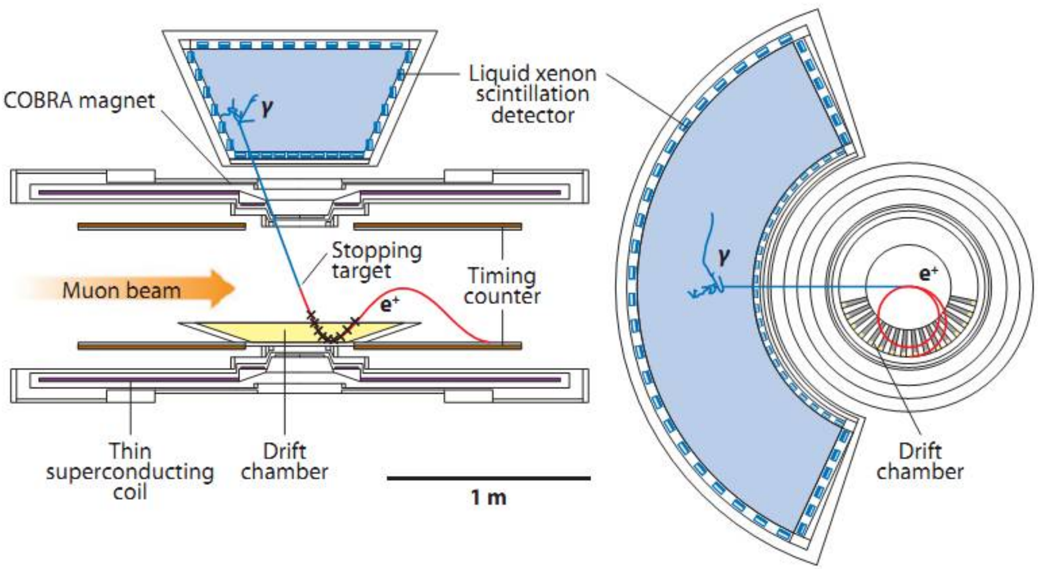


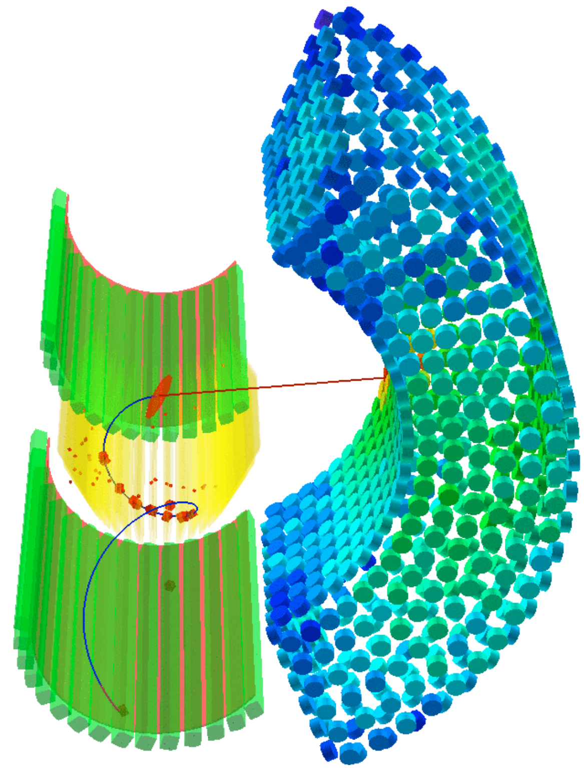
A MEG overview

Muons are stopped in a THIN polyethilene TARGET from which a positron and a photon emerge.

The positron is bent in the COBRA magnetic field and detected with the positron tracker (DRIFT CHAMBERS, 16 modules) and the time detector (TIMING COUNTER: 2 sectors with 15 scintillator bars each).

The photon escapes COBRA and is detected in the LXE Calorimeter, a C-shaped 880 liters vessel equipped with 848 PMTs.

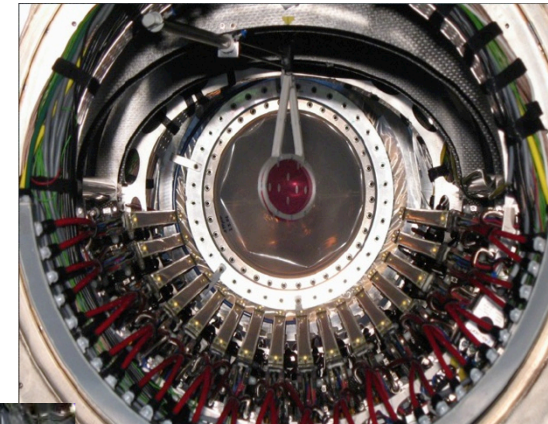




Detector Paper:

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

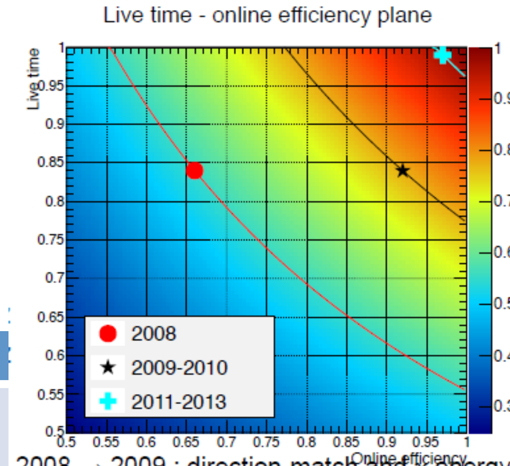
MEG montage pics ☺



Winning the challenge

We have several constraints for the MEG detector given the extreme rarity of the searched events:

- high statistics, need for detector efficiency and huge μ stop rate $R\mu = 3\times10^{7}$ μ/s
- accidental bck rejection: ultimate resolutions
- trigger system and algorithms capable of selecting interesting events online with high live time and efficiency (total trigger rate ~10 Hz, from 2011 livetime is ~99%)

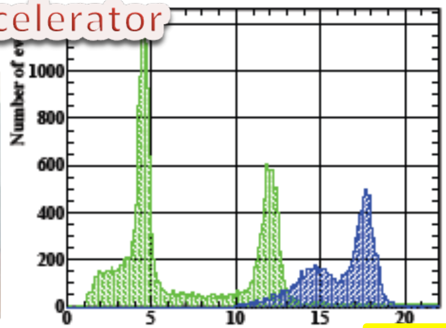


2008 → 2009 : direction-match and γ energy resolution improvement
2010 → 2011 : multiple-buffer readout

	2009	2010	2011	Note
Gamma E [%]	1.89	1.90	1.65	Effective sigma (averaged on event depth)
Relative timing $T_{e\gamma}$ [ps]	160	130	140	RMD with $E_\gamma < 48$ MeV
Positron E [keV]	306 (86%)	306 (85%)	304 (86%)	Michel edge, core resolution
Positron θ [mrad]	9.4	10.4	10.6	Double turn
Positron ϕ at zero [mrad]	8.7	9.5	9.8	Double turn
Positron Z/Y [mm]	2.4/1.2	3.0/1.2	3.1/1.3	Double turn, Y core resolution
Gamma position [mm]	5 (transvers) 6 (depth)	5 (transverse) 6 (depth)	5 (transverse) 6 (depth)	π^0 measurement with lead collimators
Trigger/DAQ efficiency [%]	91/75	92/76	97/96	
Gamma efficiency [%]	63	63	63	π^0 sample
Positron efficiency [%]	43	36	36	From MC

Calibrate at a glance

Proton Accelerator



protons on light elements(Li, F): exothermic reaction with emitted γs

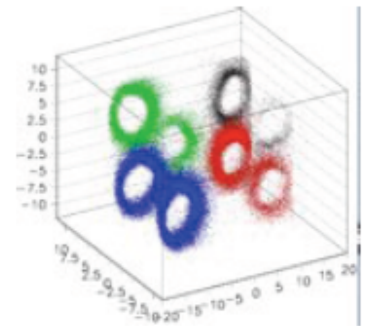
energies: 4.4, 11.7, 17.6 MeV
- ✓ energy calibration and monitoring
- ✓ start-up trigger threshold setting

Daily calibration

Alpha on wires

Am sources, 5 MeV
- ✓ PMT QE study
- ✓ Xe purity monitor

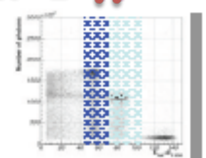
Daily calibration

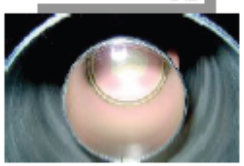


We need to
- ✧ ensure a stable operation throughout the whole data taking period which is split in more years
- ✧ set up the detector at the beginning
- ✧ validate the energy scale and time response

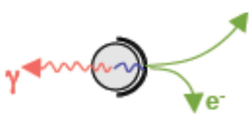
we developed several different calibration methods to do this.

$\pi^0 \rightarrow \gamma\gamma$

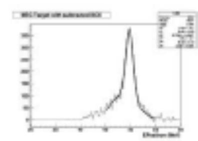


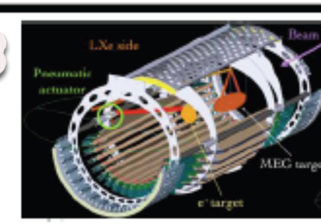


$\pi^- + p \rightarrow \pi^0 + n$
$\pi^0\ \gamma\gamma$ (55 & 83 MeV)
- ✓ dedicated LH_2 target and beamline setup
- ✓ once every year, ~2 weeks
- ✓ possibility to exploit also Dalitz decays and pair production

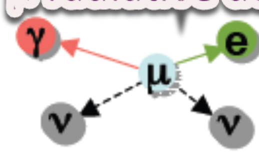


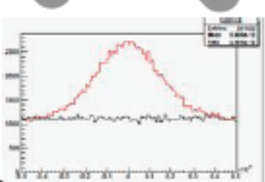
Mott e+ scattering





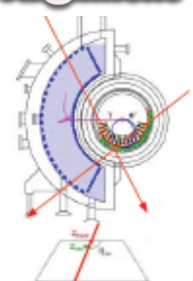
μ radiative decay



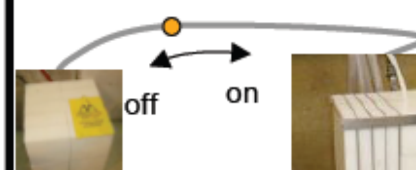


Once a year, with lower beam intensity
- ✓ avoid pile up
- ✓ study of signal/background PDFs
- ✓ time calibration
- ✓ by-product: study of Radiative muon decay

Cosmic ray Alignment

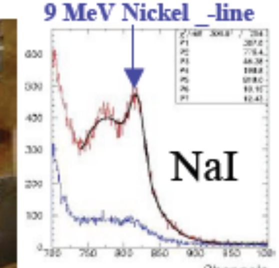


Nickel γ Generator

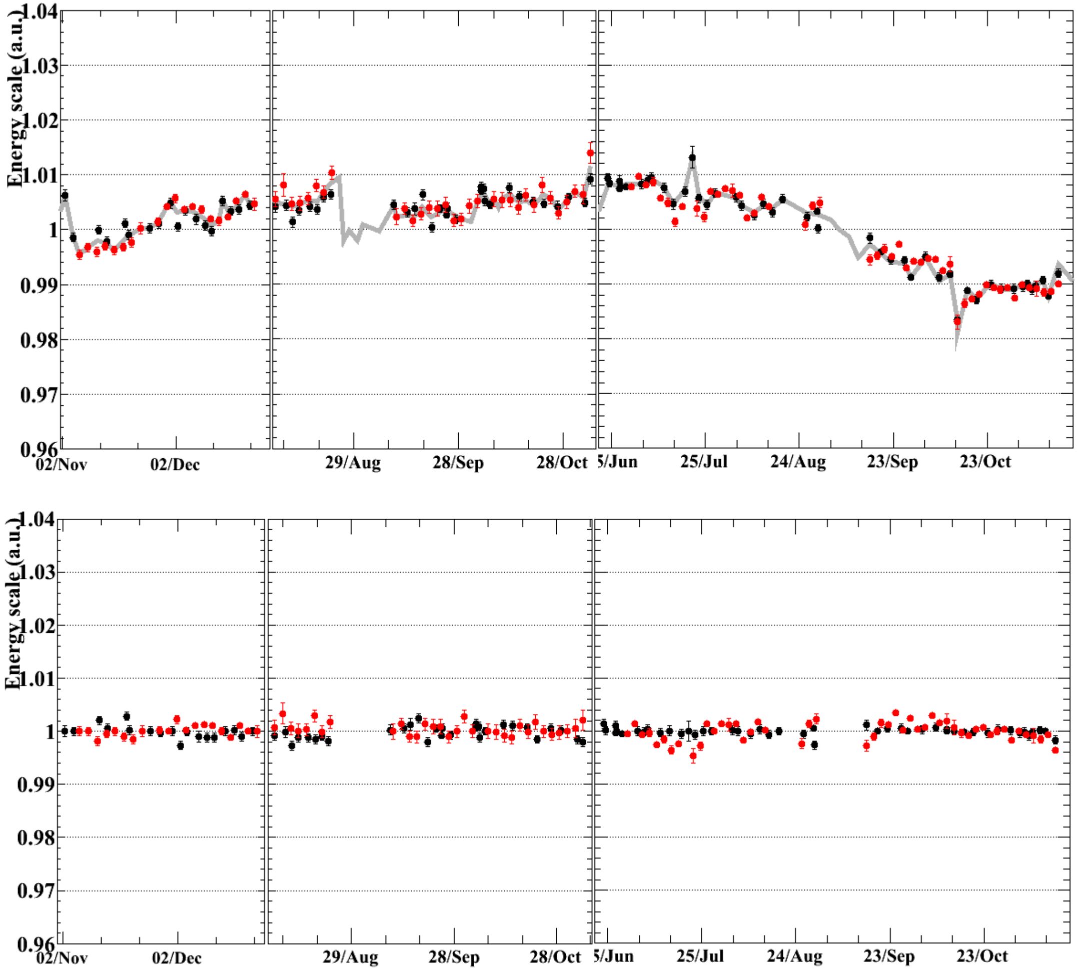


9 MeV γ on Xe, from back side
- ✓ switchable by moving the source with compressed air system

9 MeV Nickel -line



Calibrations: effects!



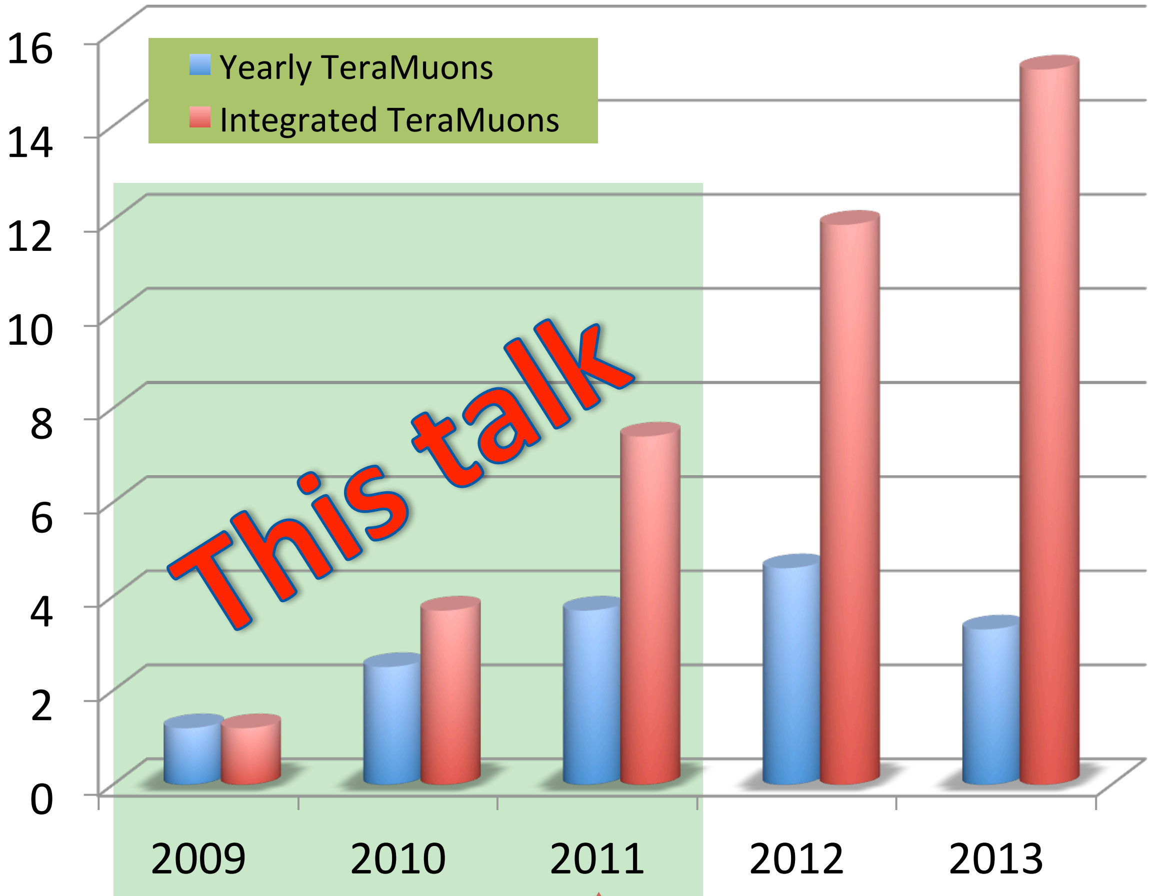
Reconstructed energy scale in the LXe detector before and after the correction evaluated from periodic calibration

Final stability is within 0.2% to be compared with energy resolution of 1,6÷1,9%

RED: RMD edge estimate

Black: CW data

muon counting



precise estimate of DETECTED MUONS from the TOTAL STOPPED MUONS:

- normalization of the final results
- estimate of full detector efficiency

obtained with smart use of cross-efficiencies (TC|DC) combined with the flexible trigger setup

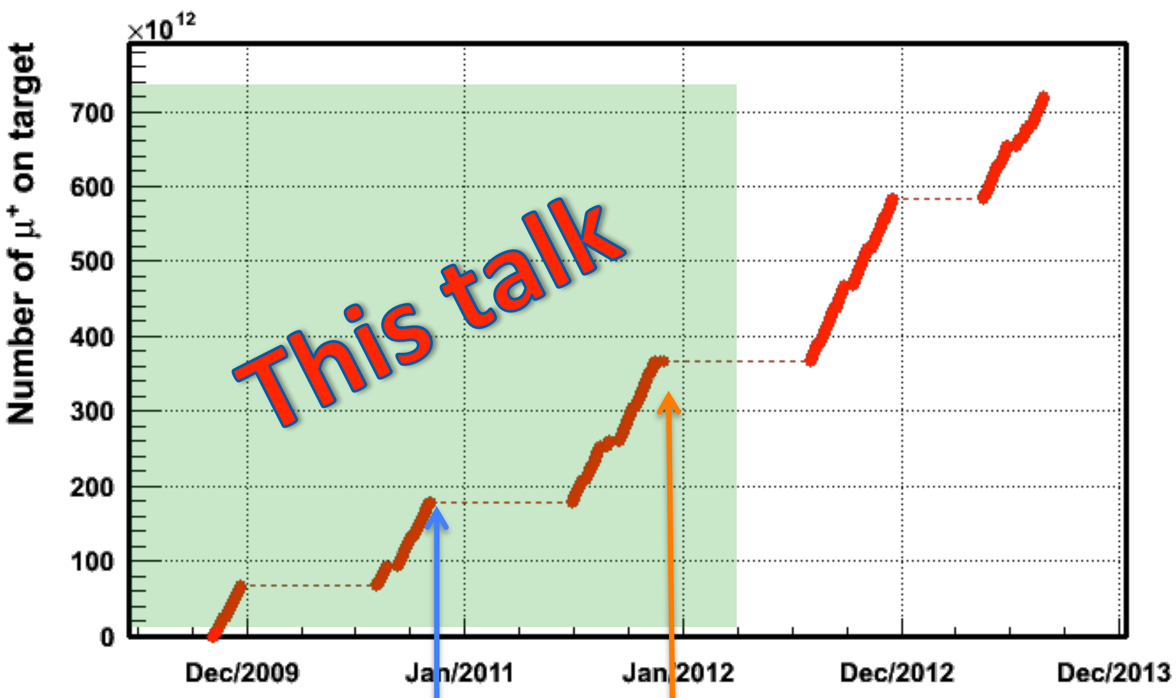
every data set is circa doubling the preceding

End of MEG Data-taking: Aug. 28th, 2013

1/2 of the full data taken still to be analyzed

This talk: up to 2011

muon ~~counting~~ stopping



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End of MEG Data-taking: Aug. 28th, 2013

1/2 of the full data taken still to be analyzed

Analysis of 2009 - 2010 data:
PRL 107 (2011) 171801
$\mathrm{Br}(\mu^+ \to e^+\gamma) < 2.4 \cdot 10^{-12}$ (90% CL)

Analysis of 2009 - 2011 data:
PRL 110 (2013) 201801

Data Analysis

In order to combine the 5 observables:

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

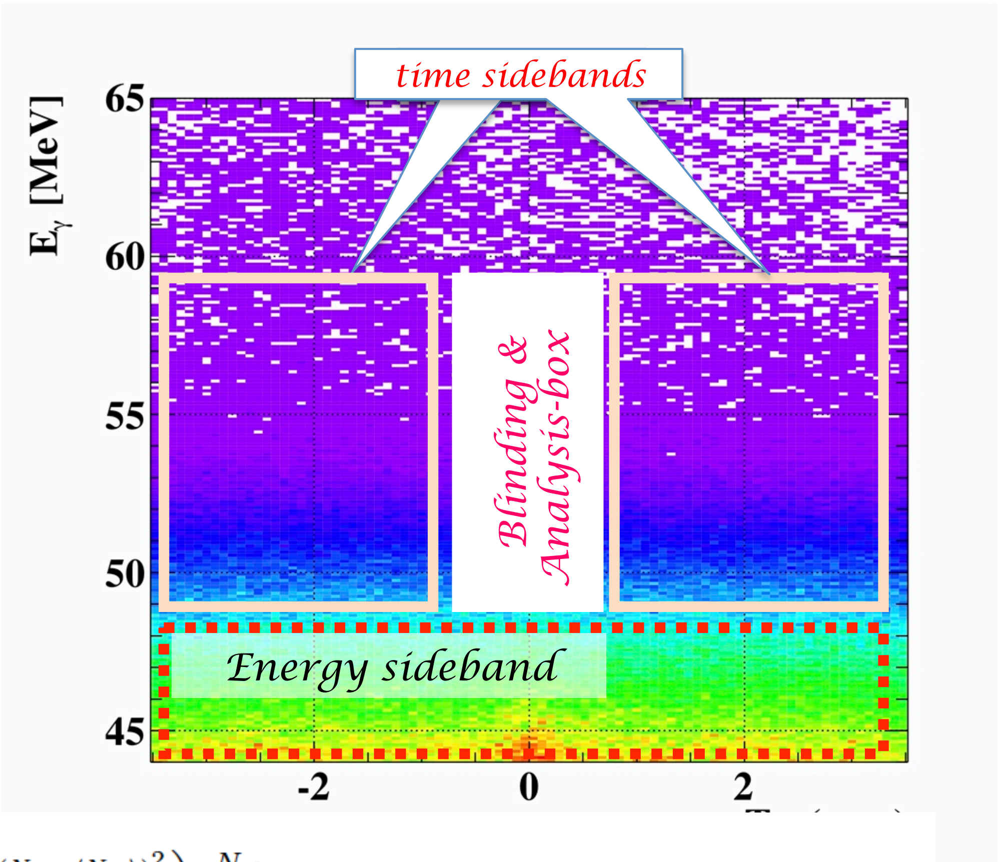
we used a Blind Box approach to extract all useful information before looking at the rare events searched.

The Blind Box definition was based on the photon energy and the relative positron-photon time. The analysis was developed on events outside the BB and the obtained resolutions were used to give Probability Density Functions for signal-like events (d-functions for all observables, convoluted with detector respons).

A Maximum Likelihood fit, to determine

- ✓ number of signal events N_{sig}
- ✓ number of radiative N_R m->eννγ
- ✓ number of accidental N_A bck

expected in the blind box, is then performed:



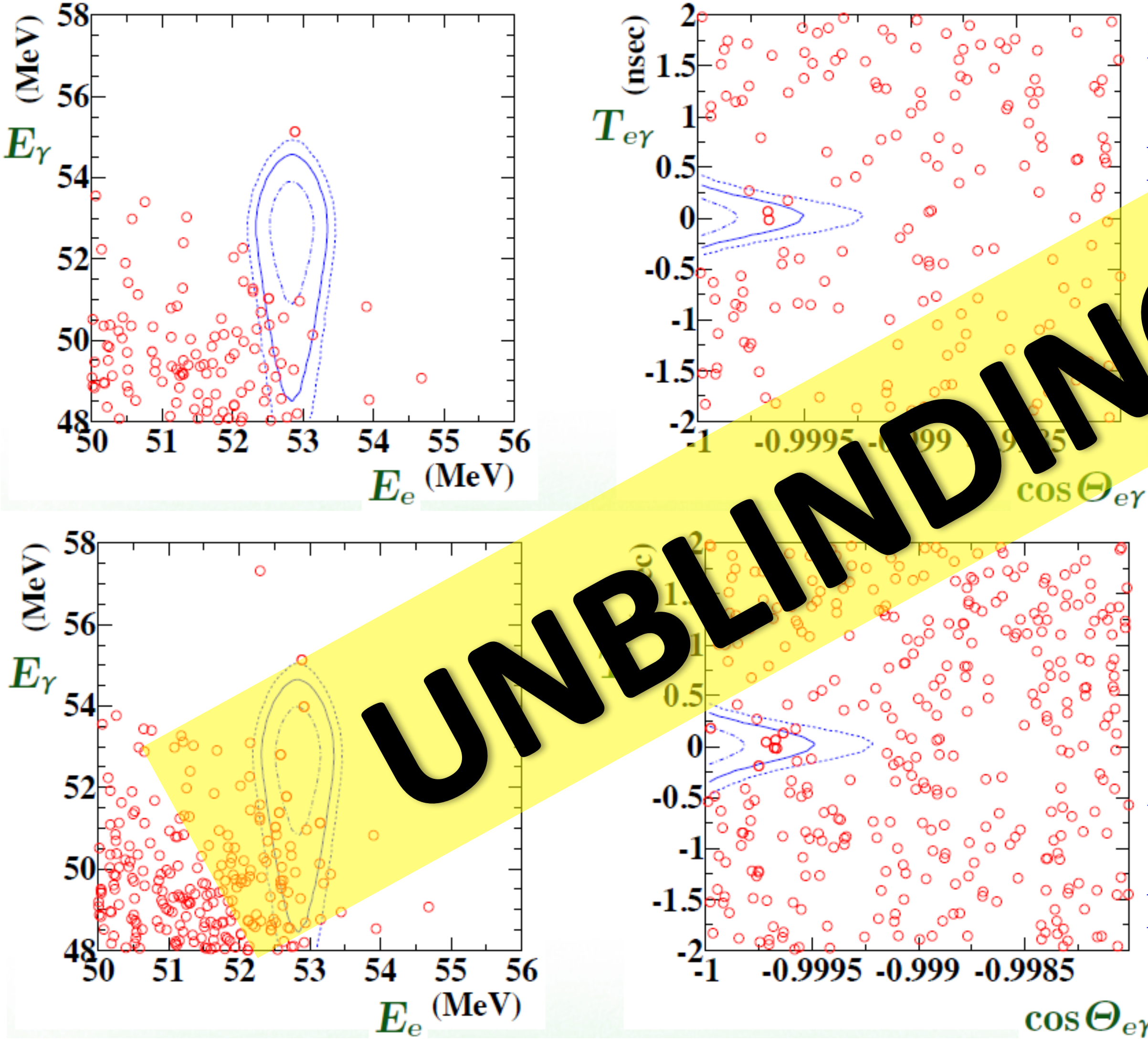
$$\mathcal{L}(N_{\rm sig}, N_{\rm R}, N_{\rm A}) = \frac{e^{-N}}{N_{\rm obs}!}\, e^{-\left(\frac{(N_{\rm R}-\langle N_{\rm R}\rangle)^2}{2\sigma_{\rm R}^2}+\frac{(N_{\rm A}-\langle N_{\rm A}\rangle)^2}{2\sigma_{\rm A}^2}\right)} \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig}\, S(\vec{x}_i) + N_{\rm R}\,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

normalization

S, R, A: PDFs for different event types


UNBLINDING!!!

Opening the Blinding Box



2011 data only

NSIG Best = -1.4 (+3.8, -1.3)

Event distributions; cuts on not shown variables

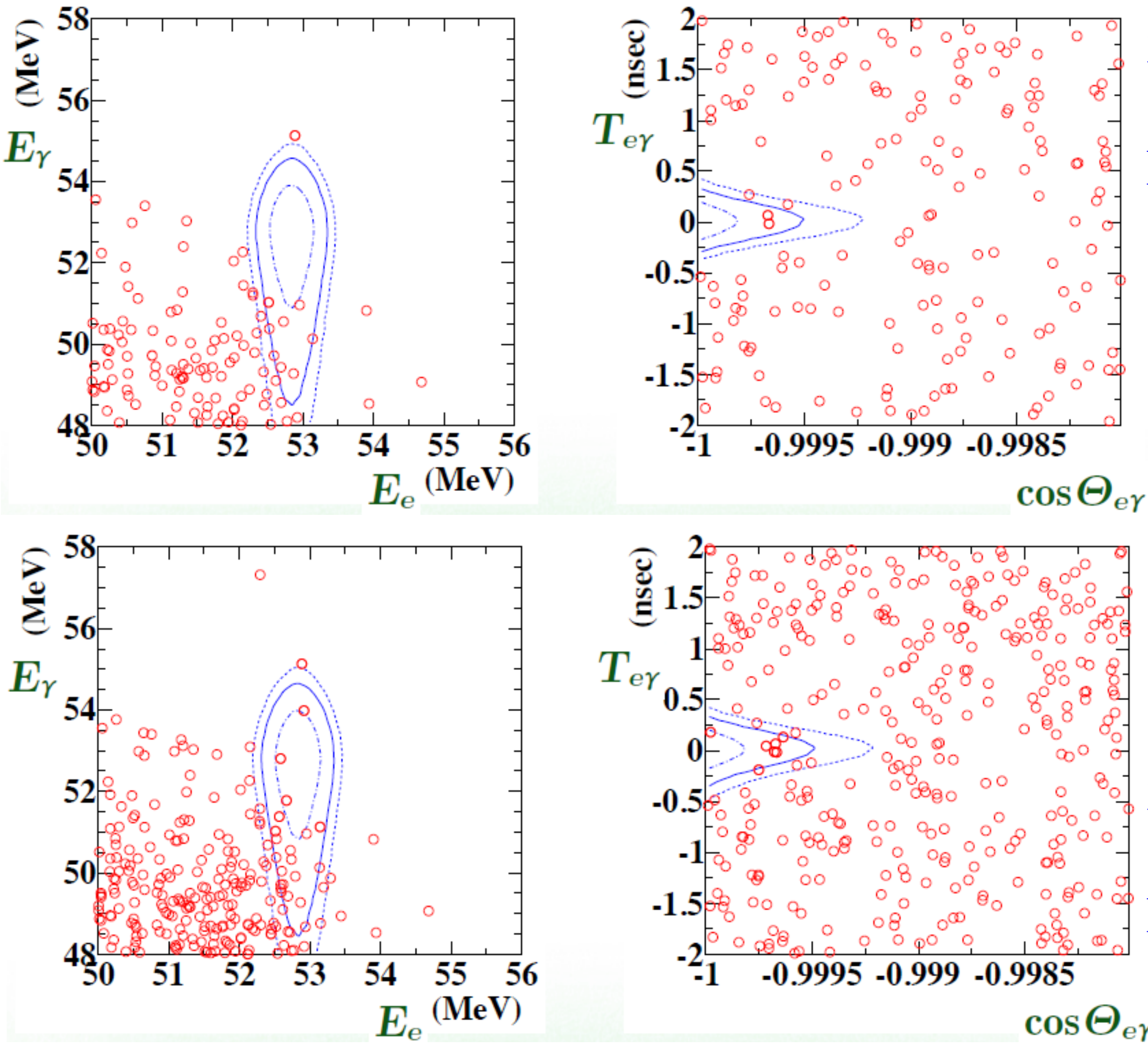
Signal PDF contours at 39.3, 74.2, 86.5%

No excess found

2009-2011 data

NSIG Best = -0.4 (+4.8, -1.9)

Opening the Blinding Box



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Event distributions; cuts on not shown variables

Signal PDF contours at 39.3, 74.2, 86.5%

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2009-2011 data

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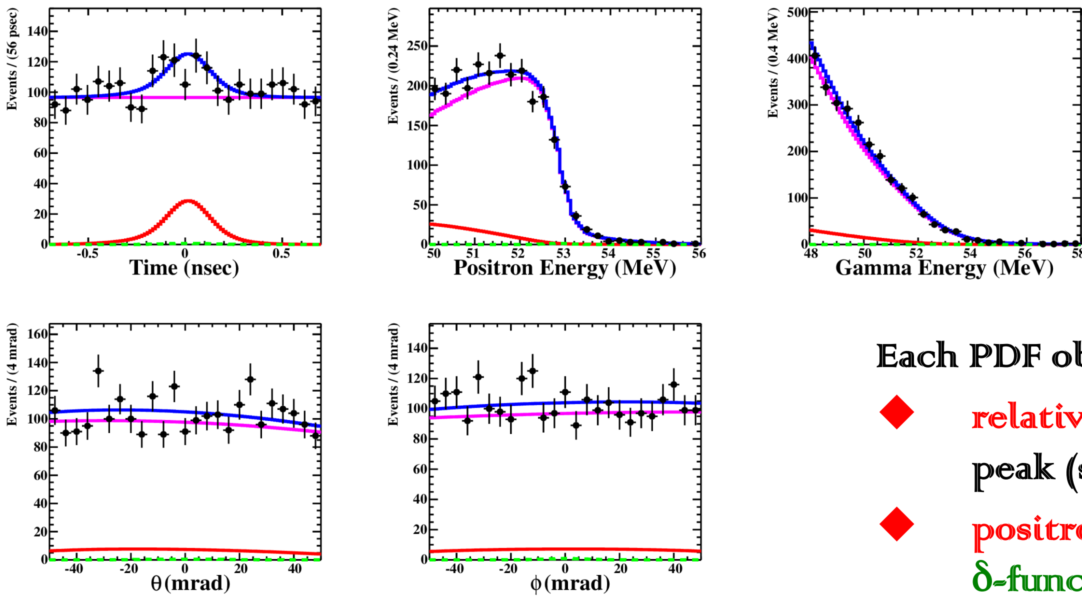
PDFs and Likelihood Fit



FIT Results

NSIG = -0.4(+4.8 -1.9)
NRMD = 167.5 ± 24
NBCK = 2414 ± 37
NOBS = 2574

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

Each PDF obtained from different processes:

- relative time: fit of Radiative Muon Decay peak (scaled for different photon energy)
- positron energy: fit of Michel Edge for BCK, δ-function convoluted with experimental resolution for signal (Mott scattering and double turn method)
- gamma energy: Background spectrum from time sidebands, Radiative Muon Decay theoretical shape, detector response to π^0 55 MeV Photon (signal)
- relative angles from double turns tracks in spectrometer
- Sideband Fit before the unblinding to estimate expected number of bck events

Result: a new Upper Limit

A factor 20 better than pre-MEG limit (MEGA 2002), 4 times better than MEG 2009-2010

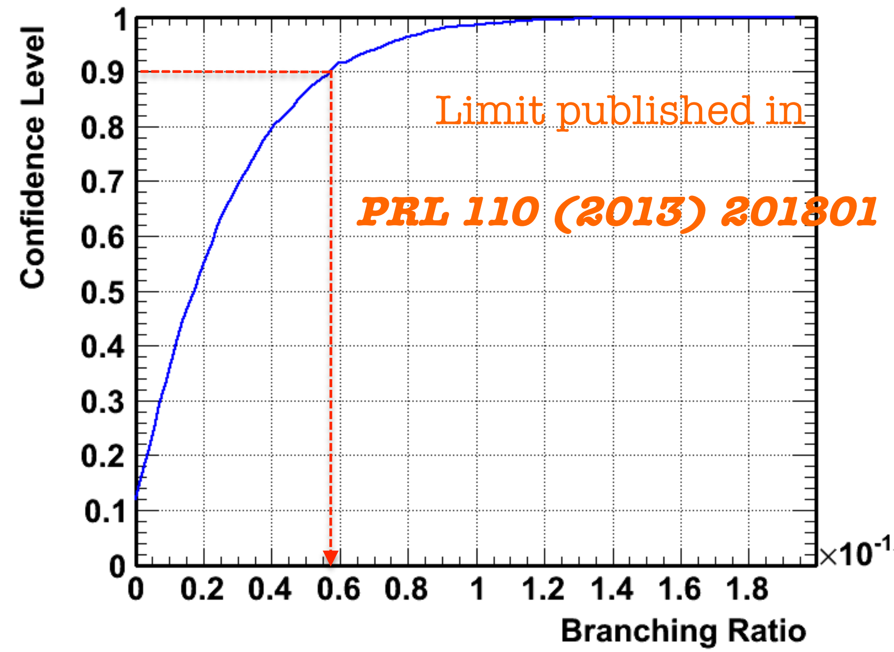
Slightly better than the expected sensitivity (7.7×10^{-13}) evaluated with Toy MC

Confidence interval of N_{sig} evaluated in a Feldman-Cousins fashion taking into account PDF uncertainties and fluctuations of signal and background.

Normalization: through the use of independent unbiased trigger on reference events (Michel decays) we can estimate total number of detected muons by applying the same cuts. A comparison with RMD data shows consistent values for the k-factor..

BR = Nunmber of events / total number of muons

$$\mathrm{Br}(\mu^+ \to \mathrm{e}^+\gamma) \; < \; 5.7 \cdot 10^{-13} \; (90\,\%\ \mathrm{C.L.})$$



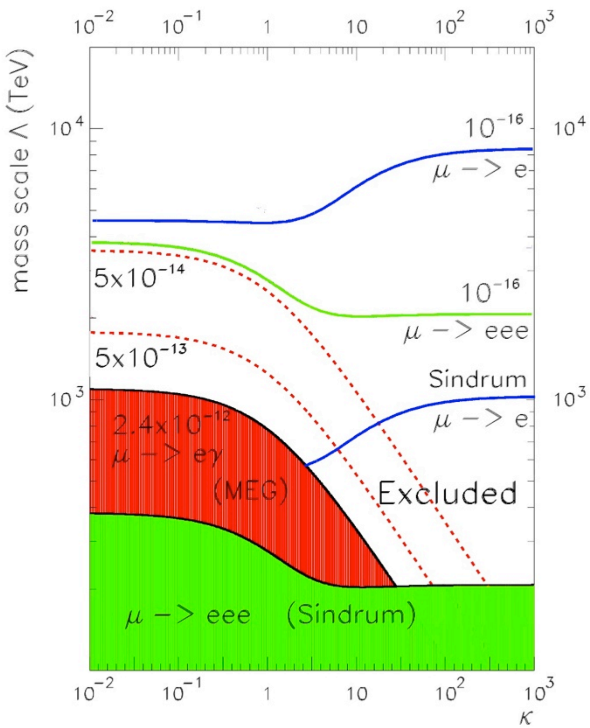
$$\lambda_{\mathrm{p}}(N_{\mathrm{sig}}) = \frac{\mathcal{L}(N_{\mathrm{sig}}, \hat{\hat{N}}_{\mathrm{R}}(N_{\mathrm{sig}}), \hat{\hat{N}}_{\mathrm{A}}(N_{\mathrm{sig}}))}{\mathcal{L}(\hat{N}_{\mathrm{sig}}, \hat{N}_{\mathrm{R}}, \hat{N}_{\mathrm{A}})}$$

Next: why a MEG upgrade?

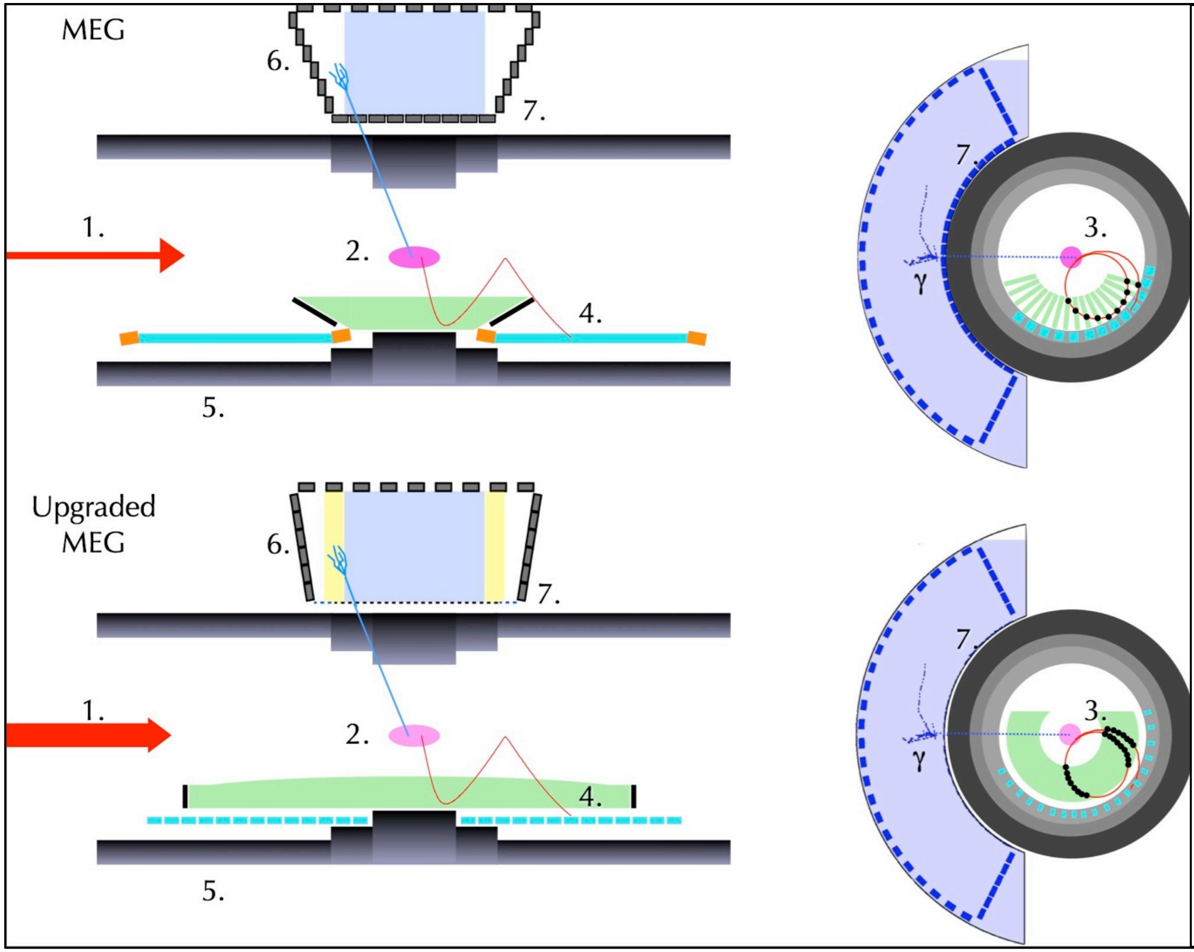
- MEG saturates its sensitivity with 2013 run
- interesting to go further by another order of magnitude
- needed a re-design of the detector to gain this (MEG is limited by current performances)
- quick process: we identified weak points of MEG detector and our expertise allows to implement modifications "easily"
- short time scale compared to other cLFV experiments
- competitive tool for New Physics for low values of k in the "effective Lagrangian":

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\,\bar{\mu}_R\sigma_{\mu\nu}e_L\,F^{\mu\nu} + h.c.$$

- as already stated, growing interest is pinned on the $\mu \to e\gamma$ decay by large θ_{13} value



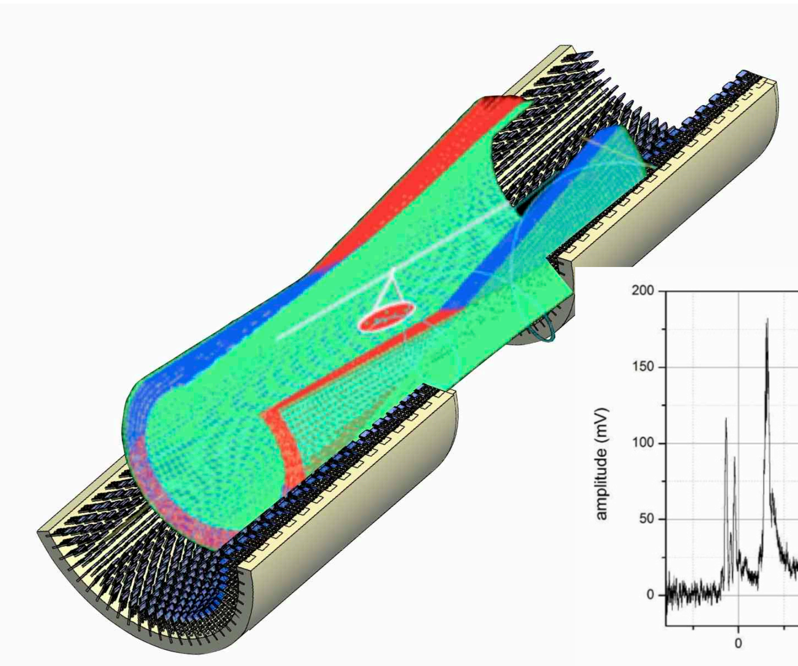
Upgrade concept

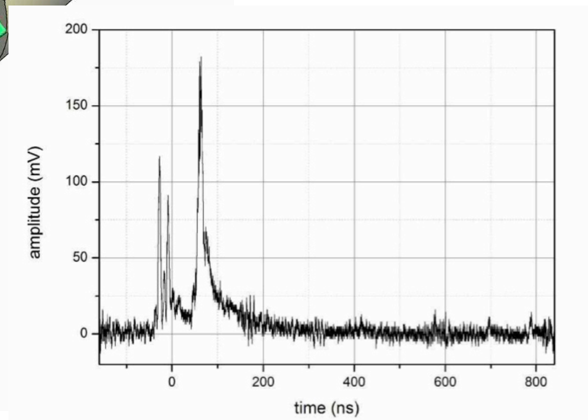


MEG_UP is going to implement several improvement in the experimental apparatus:

1. higher beam rate (more statistic)
2. thinner target (less background)
3. more points for a better track reconstruction (improve positron resolutions)
4. shorter path from last DC point to Timing Counter (time resolution)
5. segmented Timing Counter, for better matching with DC volume and multi-hit exploitation
6. different Calorimeter shape within the existing cryostat
7. finer inner face granularity with new readout devices (SiPM) for better energy reconstruction and pile-up rejection

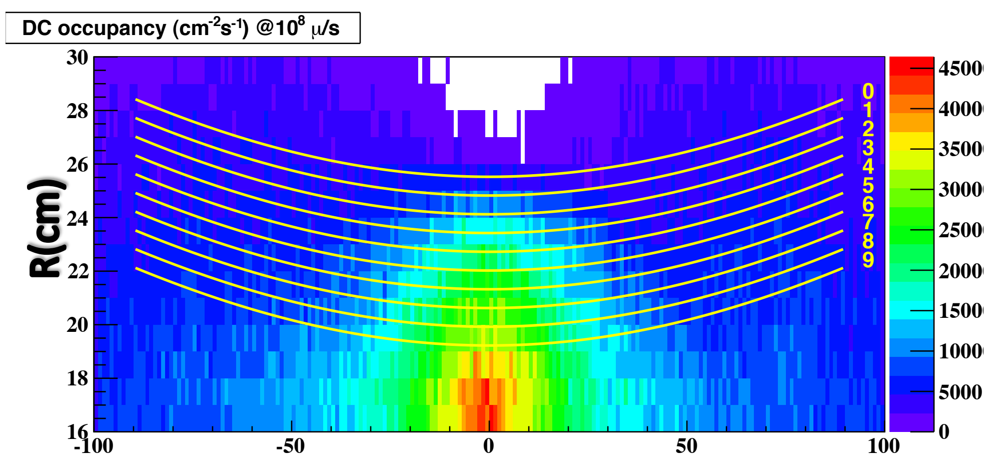
DC upgrade

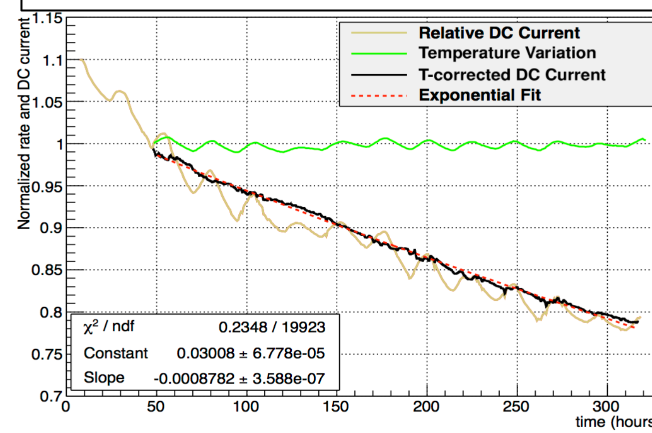




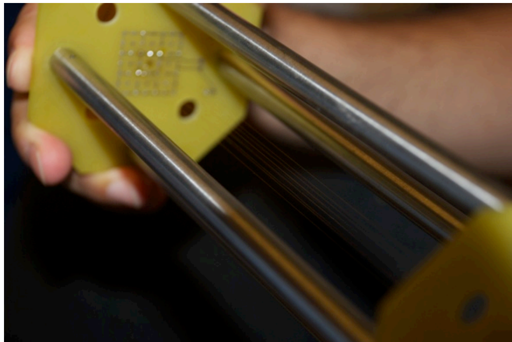
A unique cylindrical volume, with stereo wires

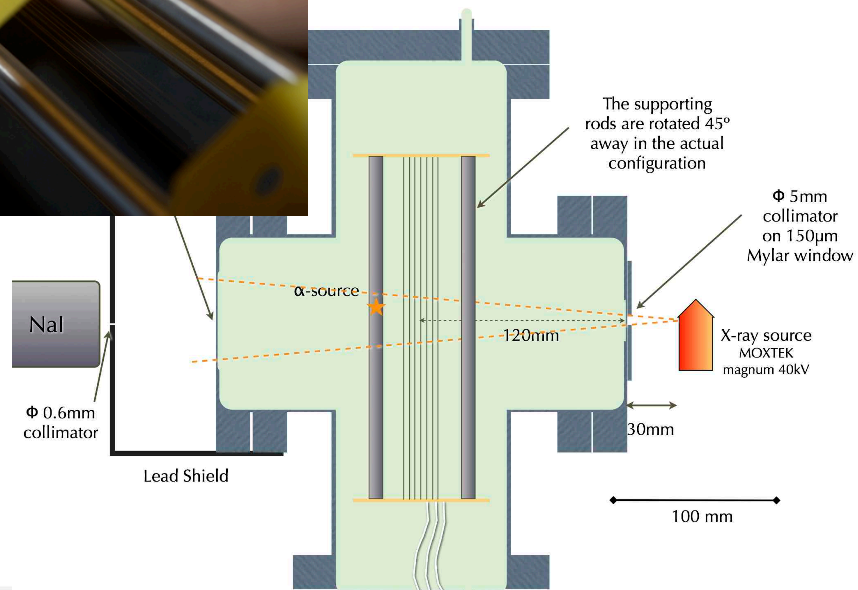
- full active volume, less dead layers giving multiple scattering problems
- extends closer to the target for better vertex reconstruction
- high bandwidth readout with fast counting gas: possibility to exploit Cluster Counting and Timing for better single-hit performances
- higher rate means severe constraints on central wires: demonstration of a 3 years operation for the worst case (inner cell, central position) by means of an accelerated ageing test



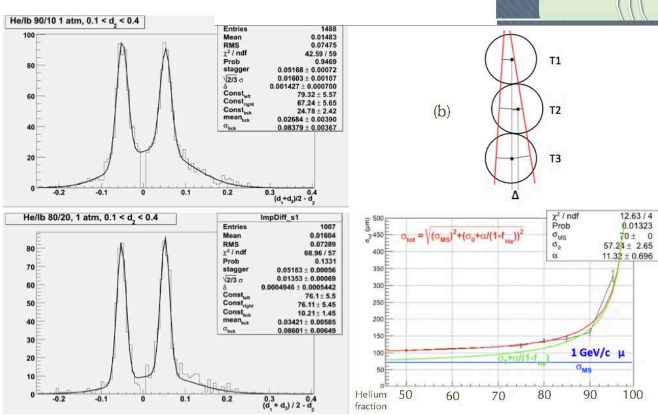


DC R&D examples





Ageing



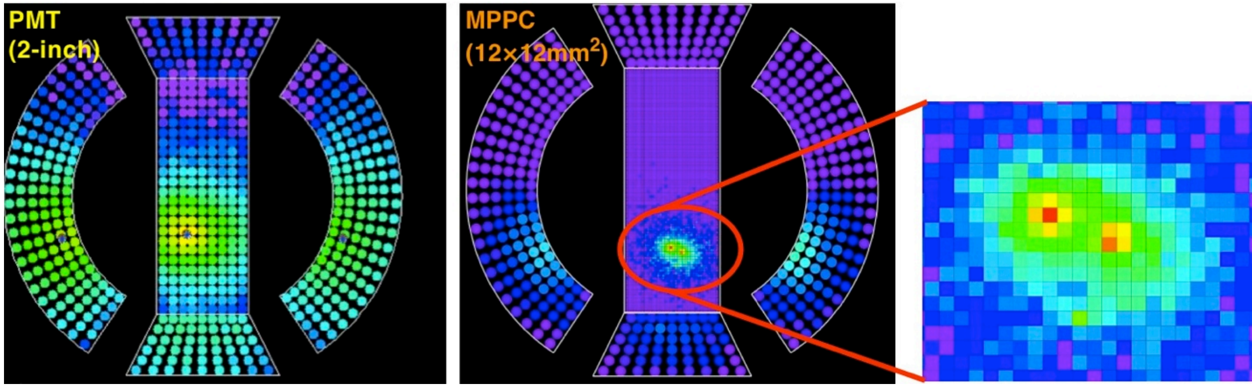
(a) (c)

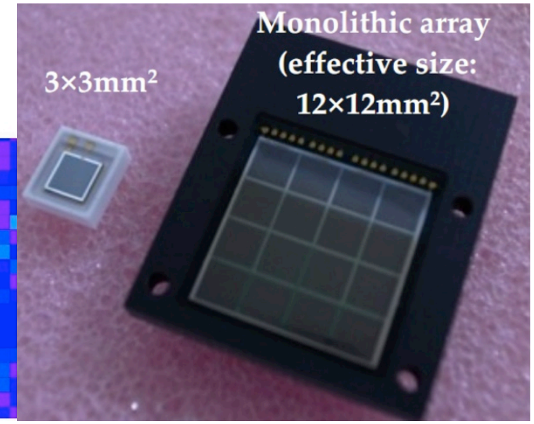
Three-tube

different prototypes prepared, each dedicated to different studies:

- Long prototype for signal/noise issues and wiring testes
- small prototype with a single cell for ageing measurements
- three-tube and three-cells configuration for hit resolution
- dedicated preamplifier developed for the upgraded detector
- facility for high precison tracking (Cosmic Ray telescope) for detector resolution and alignment procedures studies

XEC upgrade



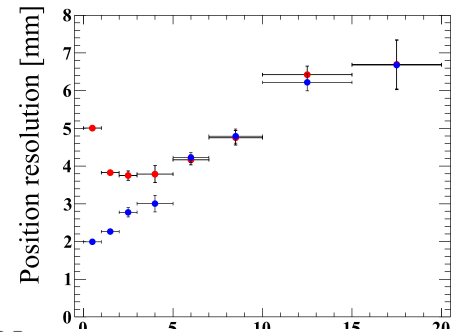


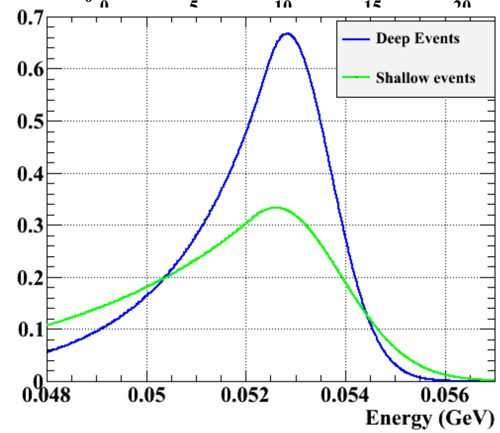
In the existing calorimeter, due to 2" size of PMTs:

- ✧ spatially close photons cannot be disentangled: residual Pile-up
- ✧ poorer energy resolution for shallow events (conversion depth < 3 cm)
- ✧ limit on conversion point resolution (angular matching)

Main imrovement:

- ✧ substitute inner face PMT with $12x12mm^2$ SiPMs/G-APDs/MPPCs (name depends on brand!)
- ✧ R&D for VUV detection, after-pulsing and linearity issues, mechanical coupling to the structure, feedthroughs….





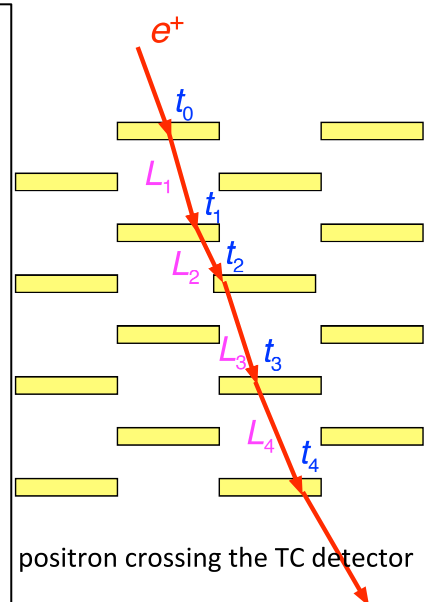
TC upgrade

Positron timing limited by:

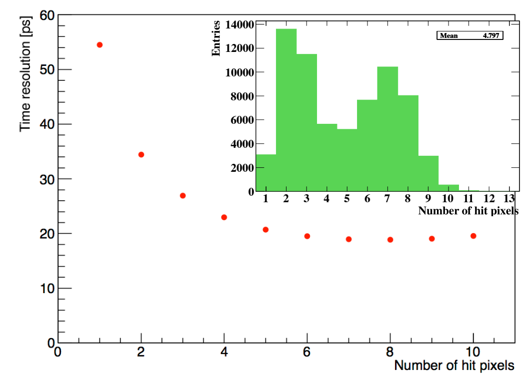
- ✧ Long path from the last tracker point to the TC, with much material (structures, cabling, gas system, DC PCB)
- ✧ large thickness of TC bars needed for photo-statistic to limit PMT jitter contribution: large energy loss of positrons with path fluctuation

furthermore, with the new tracker, the room for TC is smaller

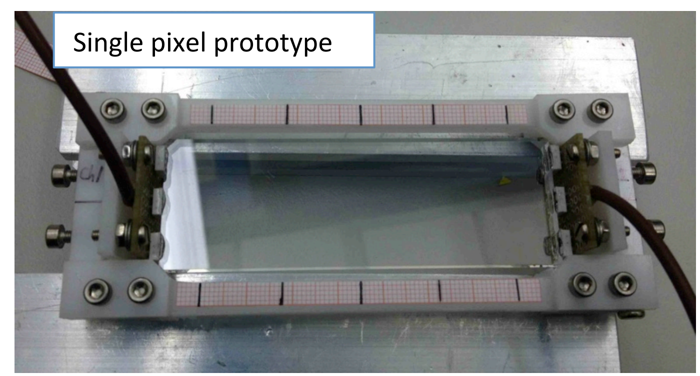
- ✧ solution: replace large bars (4x4x80 cm³) with small scintillator counters read out with SIPM
- ✧ possible to use multiple hit lowering the time resolution thanks to high multiplicity
- ✧ optimize the orientation of each pixel independently
- ✧ the TC structure is just outside the tracking volume!



positron crossing the TC detector



Time resolution scaling with the number of hit pixels


Single pixel prototype

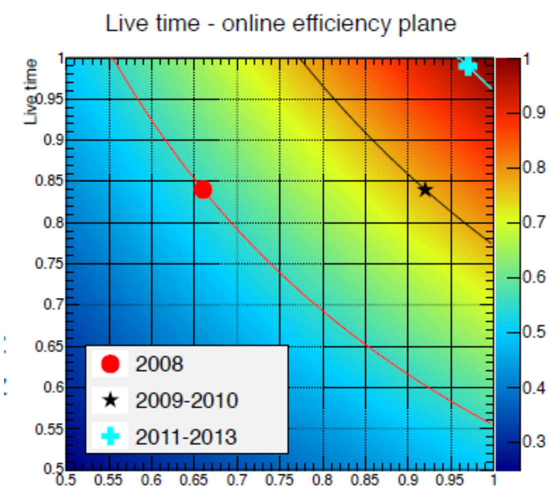
A new DAQ

For a continuous beam experiment, there is a livetime to online selection efficiency tradeoff

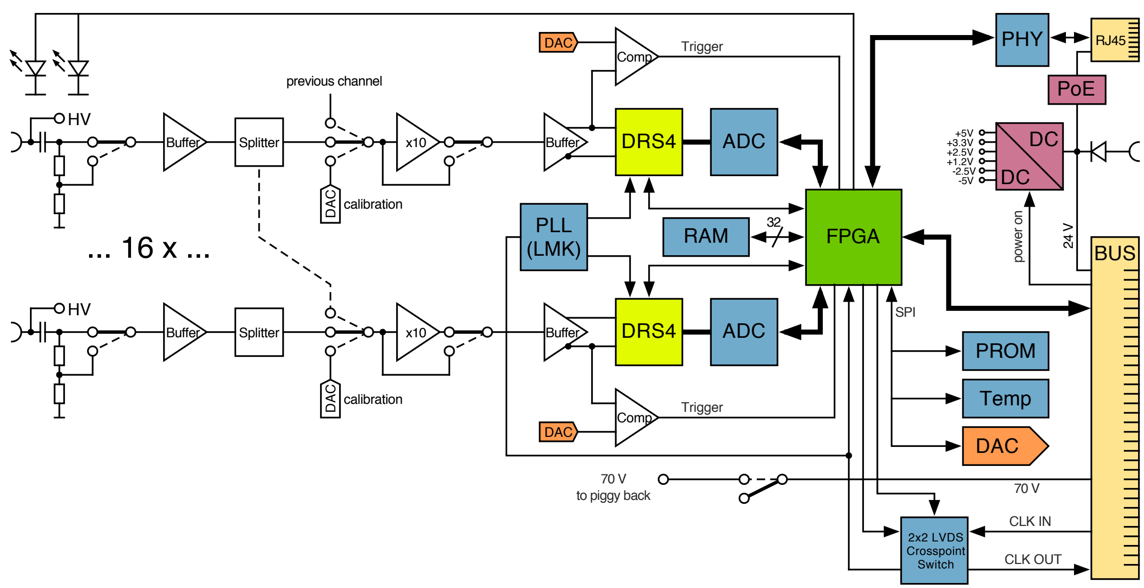
- solved in MEG for the current beam intensity: up to 99% live time with >95% efficiency
- not sufficient in MEG_UP due to higher beam rate
- moreover, MEG_UP has an higher number of channels to be acquired

Need to rethink the DAQ structure

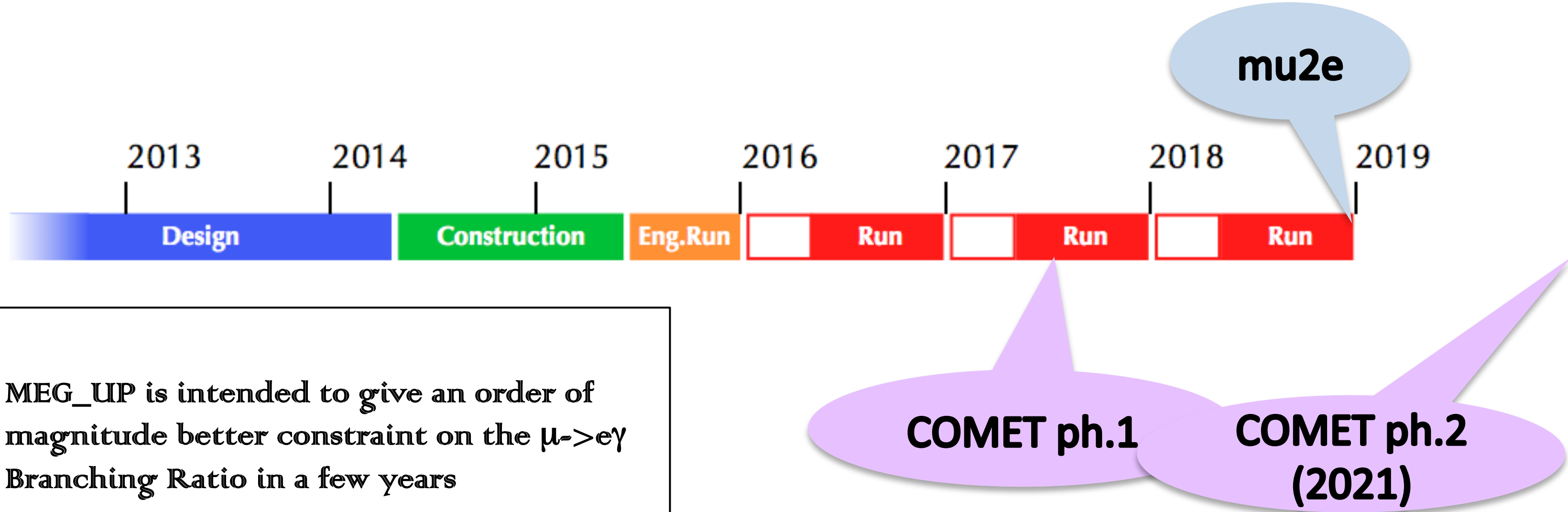
- digitizer: DRS sampling chip developed at PSI, working up to 5 GHz
- existing trigger system: dedicated boards with 100 MS/s sampling speed and FPGA processing of trigger algorithms
- a bottleneck is the limited communication speed between the two class of boards
- Our solution: have one type of board capable of handling complex trigger decisions: the WAVEDREAM concept



2008 → 2009 : direction-match and γ energy resolution improvement
2010 → 2011 : multiple-buffer readout



Synthesizing MEG_UP



MEG_UP is intended to give an order of magnitude better constraint on the μ->eγ Branching Ratio in a few years

- re-design of full detector based on existing know-how
- new concept for DAQ: board with integrated high-speed digitizer and trigger
- fast R&D process (3 years study and construiction, 3 years data taking)
- to be compared with ambitions and timescales of other muon-based Lepton Flavor searches e.g. mu2e, Comet…

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

In conclusion…

The MEG experiment had a successful run in the period 2009-2013, with a total number of ~ 1.5 x 10^{13} accumulated muons.

The current best limit, using only 2009-2011 data, is already 20 times better than the previous limit from MEGA and 4 times better than the first released MEG limit.

With the current detector there is no room to improve the limit with further data taking after 2013: so we envisage an upgrade:

- new positron tracker and time detector
- modification of the photon detector
- major improvements in the DAQ system
- higher beam intensity

The upgrade will be able to detect the $\mu \rightarrow e\gamma$ decay with an order of magnitude better sensitivity in a timely fashion.

THANK YOU FOR THE ATTENTION!

spares

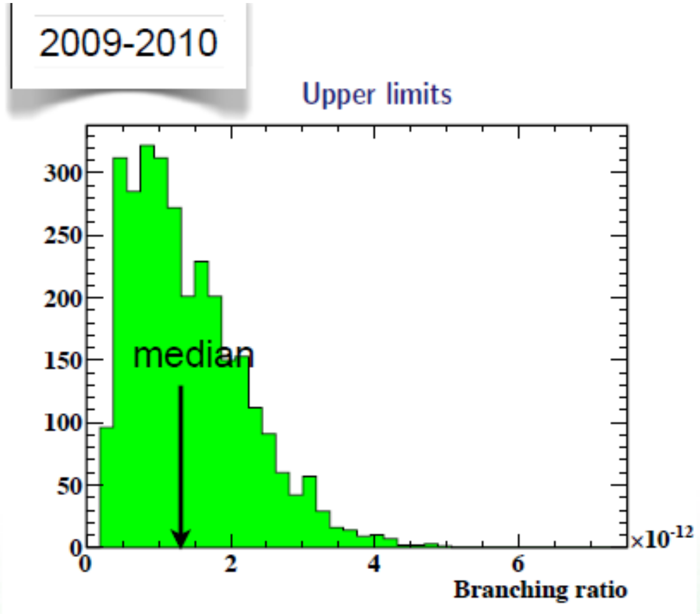
sensitivity

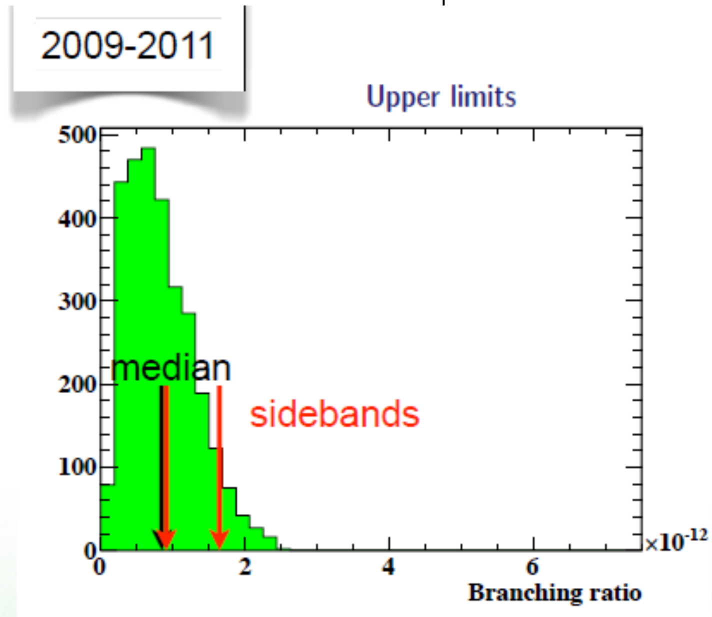
MEG Sensitivity:

Toy MC produced starting from the measured background PDFs + null signal hypothesis

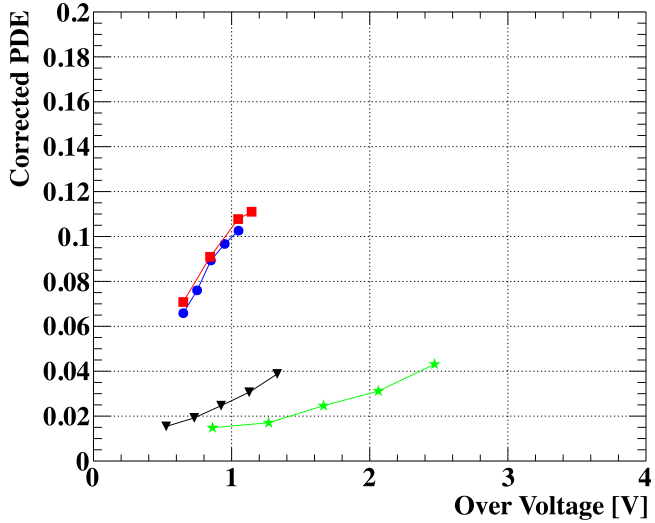
Distribution of “measured” Branching Ratio Upper Limits (i.e. background fluctuations)

The sensitivity is defined as the median of this distribution

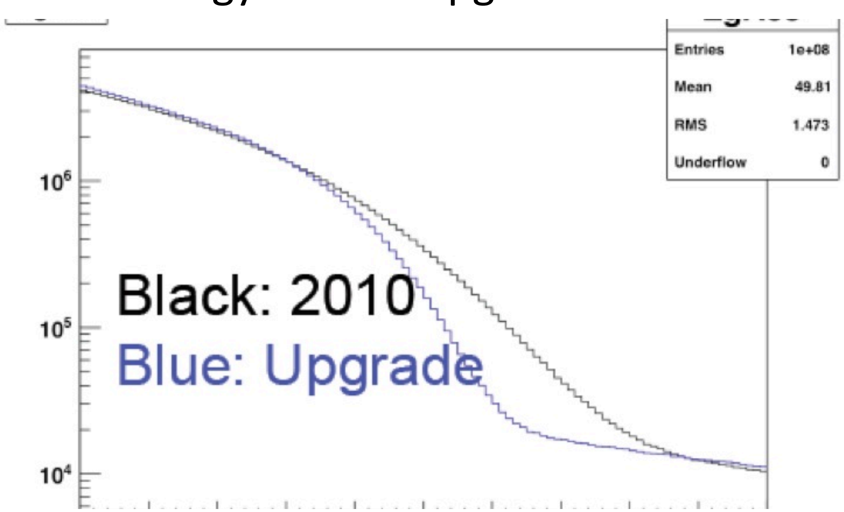


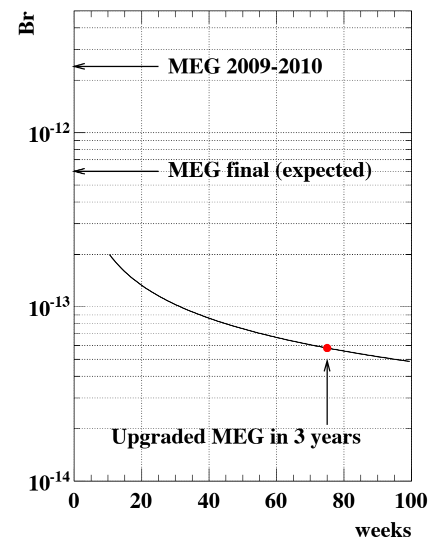


photon detector upgrade



top: Photon Detection Efficiency for SIPMs
bottom: gamma energy PDF for upgraded XEC





final MEG sensitivity
vs MEGUP