Search for Charged Lepton Flavour Violation with the MEG and MEG II experiments

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on behalf of the MEG collaboration

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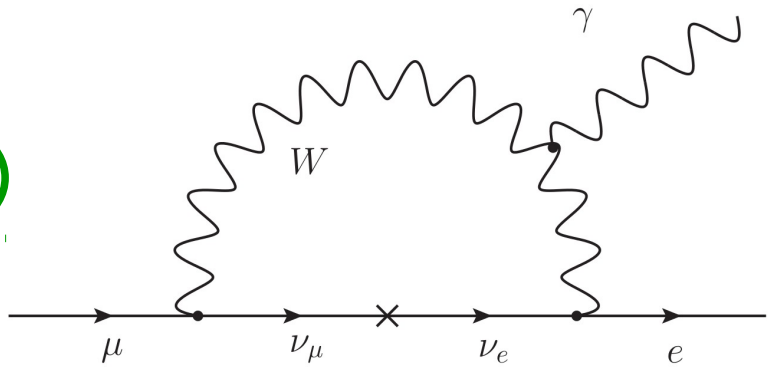
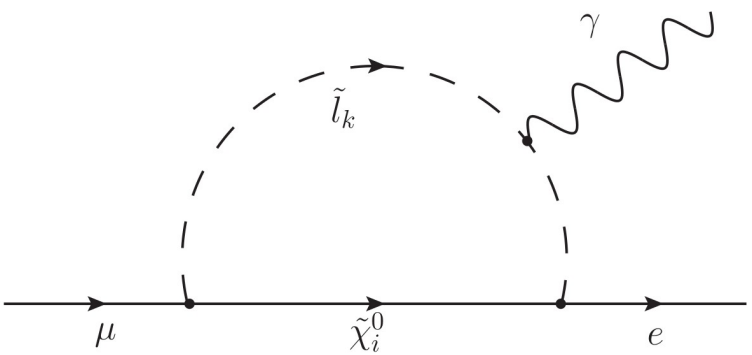
Charged Lepton Flavour Violation

Minimal Standard Model does not admit Lepton Flavour changing processes.
A non-null though **negligible** amplitude results from **neutrino oscillations**.

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



Many new physics scenarios predict an **enhanced probability**, through **mixing** between new particles of the theory.



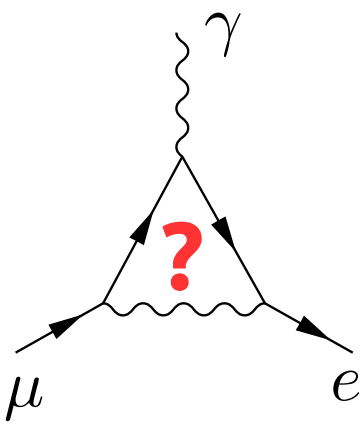
The existence of new physics at high energy scale may result in

$$\mathcal{B} \sim 10^{-14} \div 10^{-12}$$

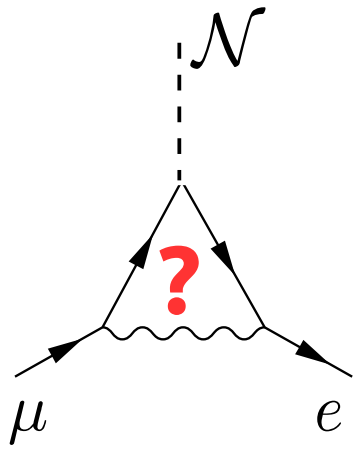
free from SM background!

CLFV channels

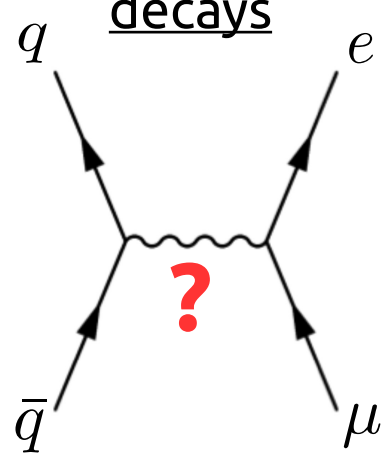
Lepton decays



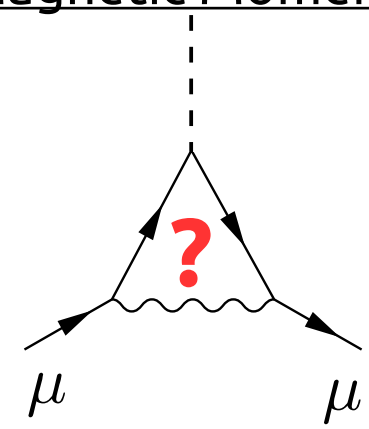
μ-e conversion

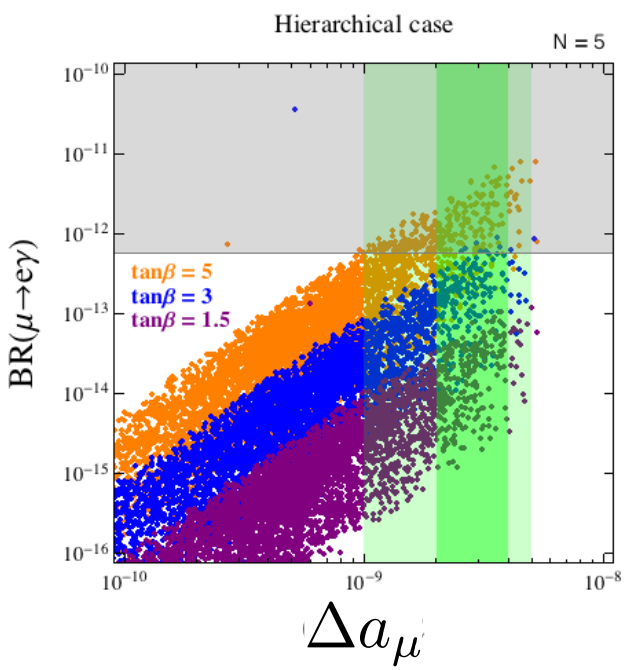


Meson (or Higgs) decays



(Anomalous Magnetic Moment)





Calibbi et al, ArXiv e-prints (2014),1408.0754

Look out for discrepancies on lepton couplings at Hadron Colliders!

$$R_K^{\mu e} = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)} \qquad \mathcal{B}(h \to \mu\tau)$$

$$\mathcal{B}(B \to K^*\mu\mu)$$

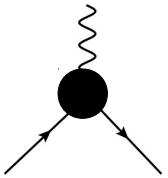
LHCb collab., Phys.Rev.Lett. 113 (2014) 151601
CMS collab., Phys.Lett. B 749 (2015) 337
LHCb collab., Phys.Rev.Lett. 111 (2013) 191801

Muon channels

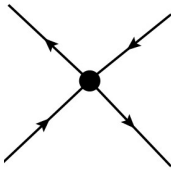
Due to the **extremely-low** accessible **branching ratios**, CLFV muon channels can strongly **constrain** new physics models and scales.

Model independent Lagrangian:

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



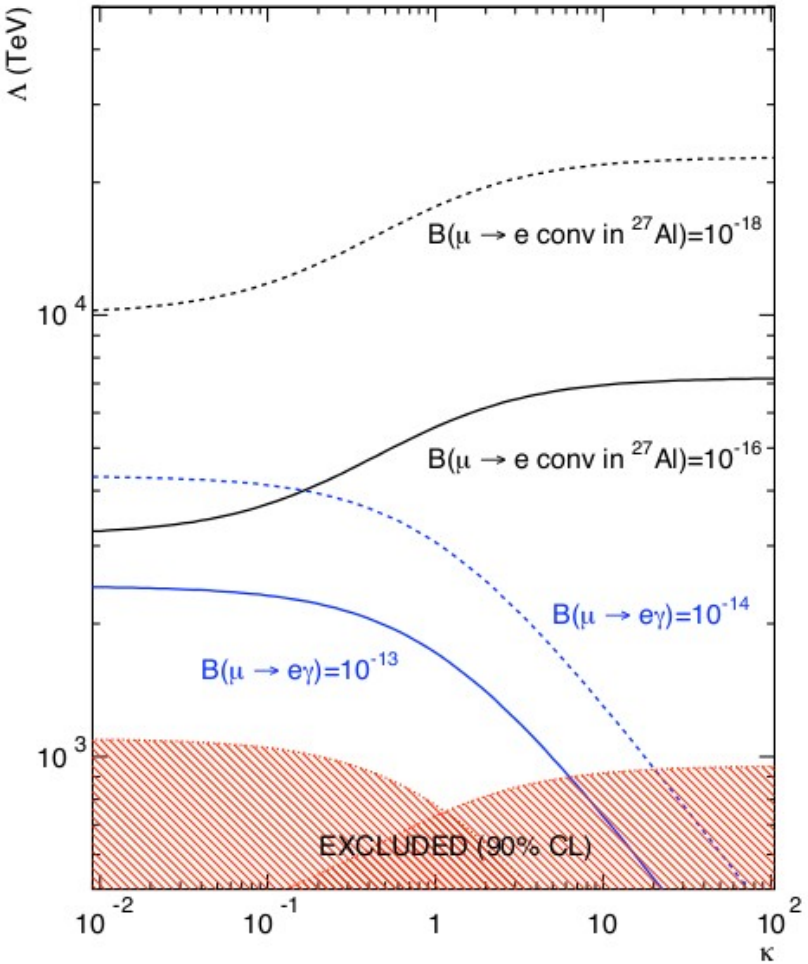
$$+ \quad \frac{\kappa}{(\kappa+1)\Lambda^2} \times$$



Dipole term (*e.g.* SUSY)	Contact term (*e.g.* Z', LQ)
$\mu \to e\gamma$	

$$\mu \to eee$$

$$\mu - e \text{ conversion}$$



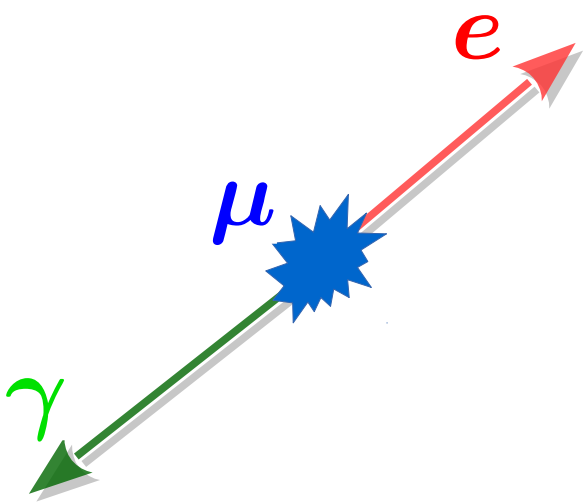
de Gouvea et Vogel, *ArXiv e-prints (2013), 1303.4097*

Sensitive to high-mass New Physics!

The MEG experiment

Search for the Lepton Flavour Violating process $\mu \to e\gamma$

The $\mu \to e\gamma$ decay



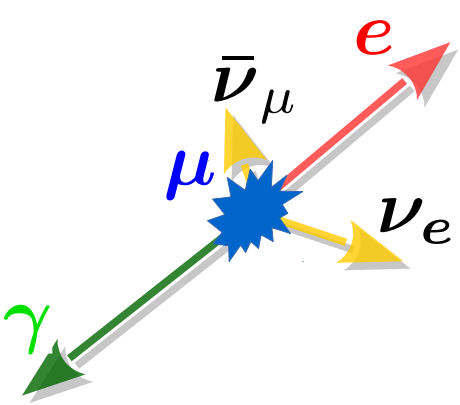
Clear kinematic signature (at rest):

1) $E_\gamma = m_\mu/2$
2) $E_e = m_\mu/2$
3) $\Theta_{e\gamma} = 180°$
4) $t_{e\gamma} = 0$

$\propto R_\mu$

with two sources of background:

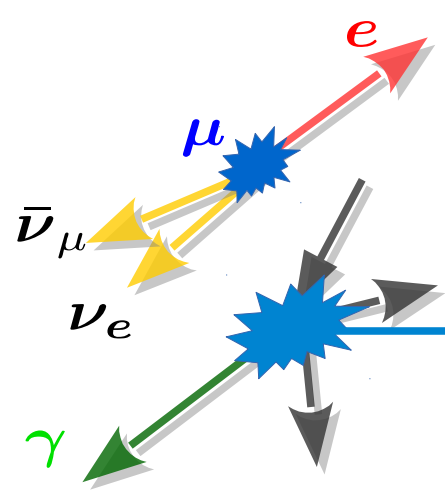
Radiative Muon Decay



1) $E_\gamma \lesssim m_\mu/2$
2) $E_e \lesssim m_\mu/2$
3) $\Theta_{e\gamma} \lesssim 180°$
4) $t_{e\gamma} = 0$

$\propto R_\mu$

Accidental Background

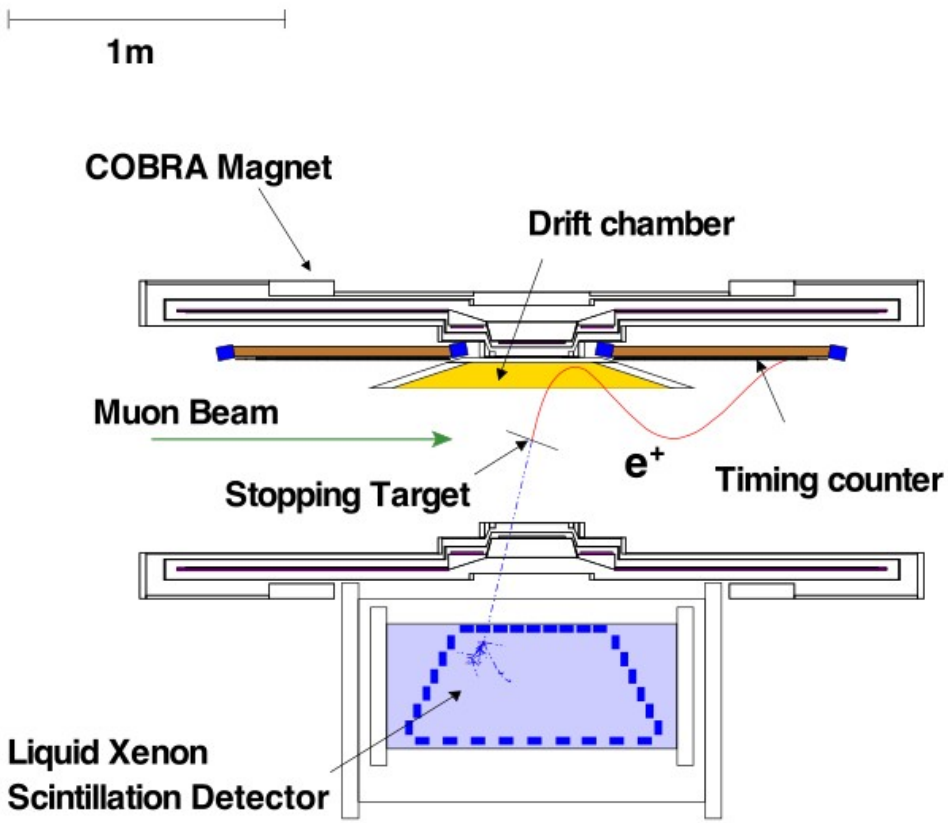


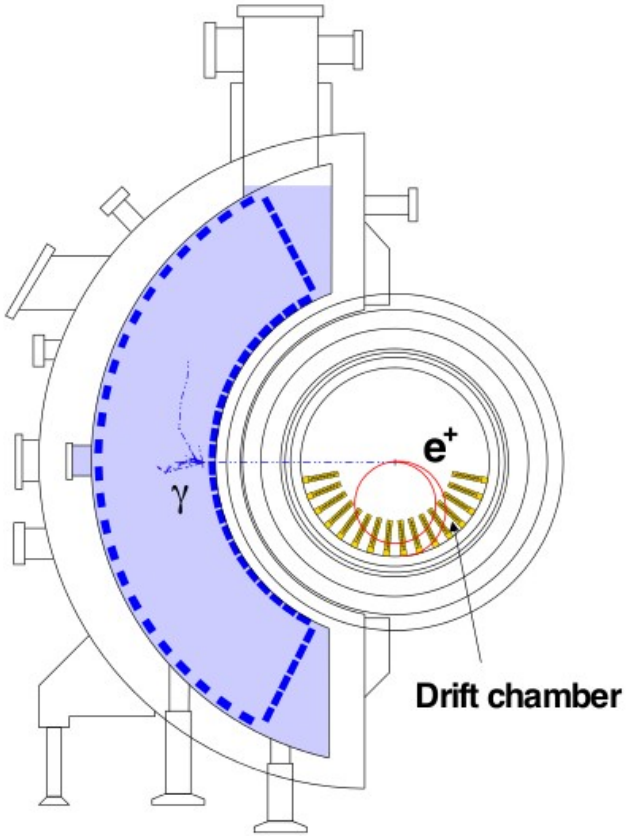
$\propto R_\mu^2$

$$\begin{cases} \mu^+ \to e^+ \bar{\nu}_\mu \nu_e \gamma \\ e^+ e^- \to \gamma\gamma \\ e^+ N \to e^+ N \gamma \end{cases}$$

The MEG apparatus

Tailored to take advantage of the well-defined kinematics



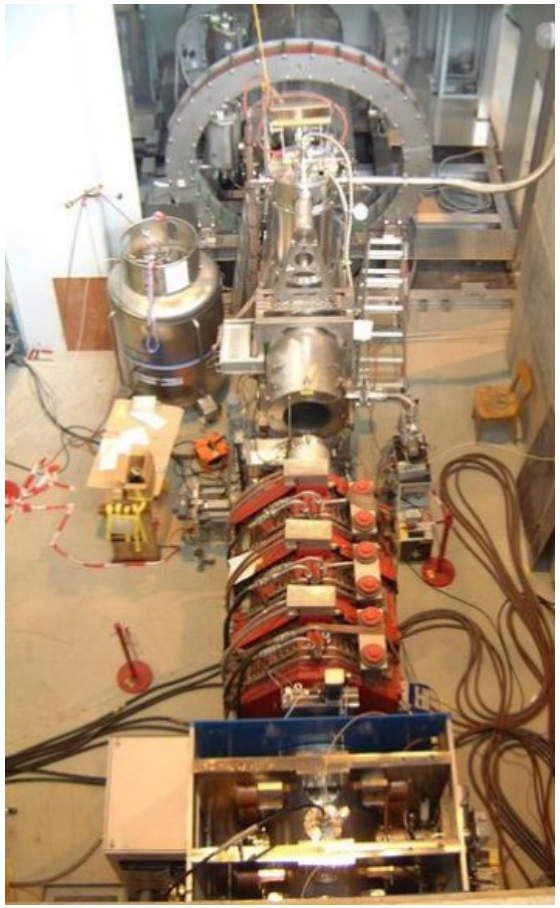


Adam et al., Eur.Phys.J.,2013, C73:2365

- Positive muons stopped in a thin polyethylene target
- Positrons are detected by a spectrometer immersed in a non-uniform magnetic field
- Photons are detected by a liquid Xenon calorimeter

The MEG apparatus

μ

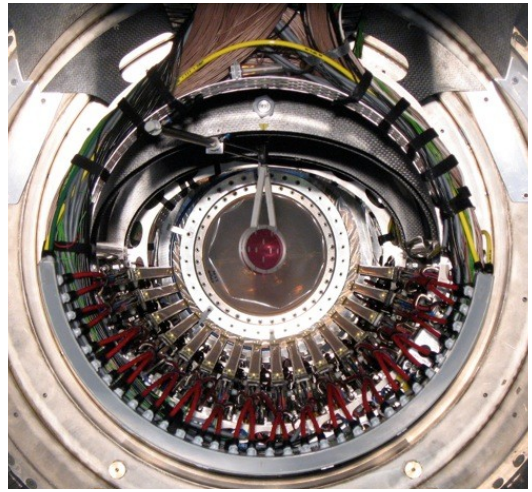


from PSI πE5 beam line

$$3 \times 10^7 \mu^+/s$$

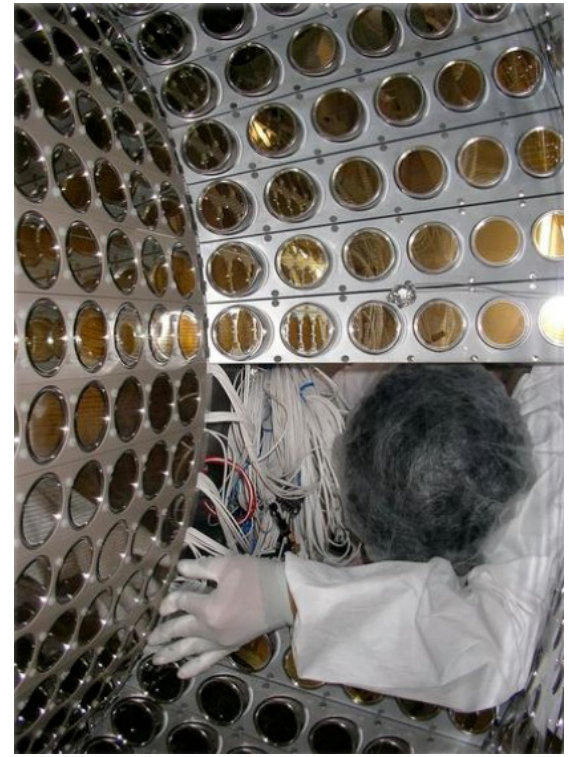
$$p = 29\,\mathrm{MeV}/c$$

e



- 16 drift chamber modules
- 15 plastic bars + scintillating fibres for timing

γ



- fast: τ's $= 4/22/45$ ns
- high Light Yield $LY \sim 0.8\, LY_{\mathrm{NaI}}$
- Short Radiation Length $X_0 = 2.77$ cm

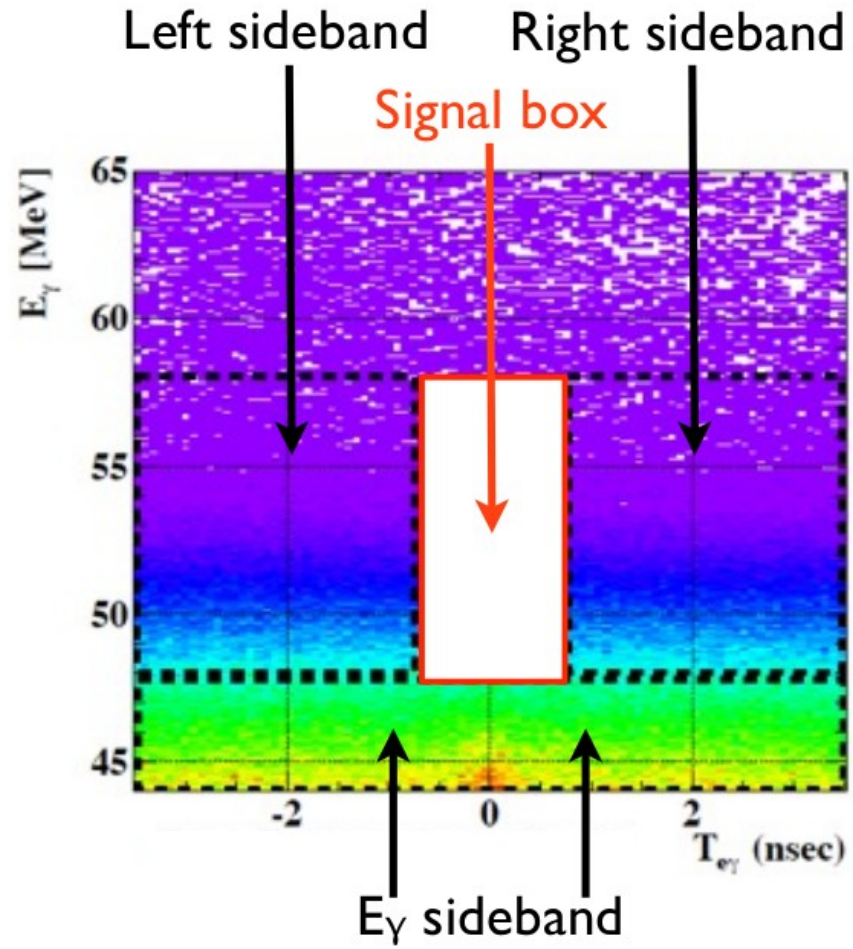
Analysis strategy

- Events described by 5 variables:

$$\vec{x} = (E_\gamma,\, E_e,\, t_{e\gamma},\, \vartheta_{e\gamma},\, \varphi_{e\gamma})$$

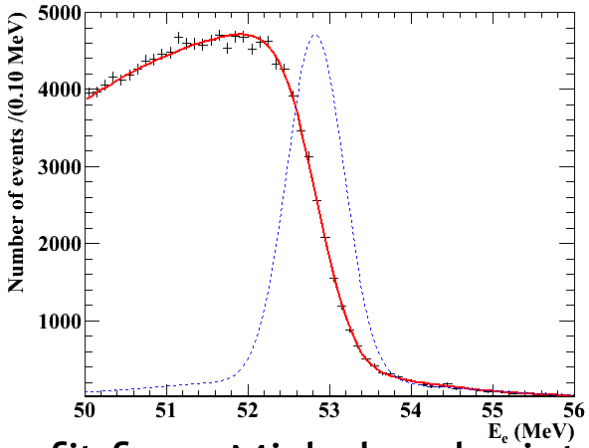
- Probability Density Functions (PDFs) for signal and backgrounds are determined starting from data **outside the signal box**.

- Two-fold use of sidebands
  - Evaluation of PDFs.
  - Estimate of the background events entering the signal box.



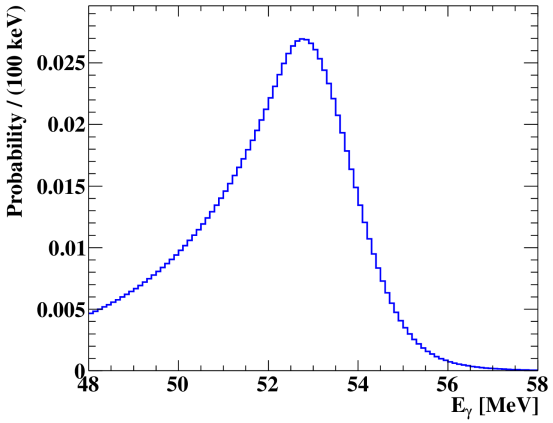
Probability density functions

Positron Energy



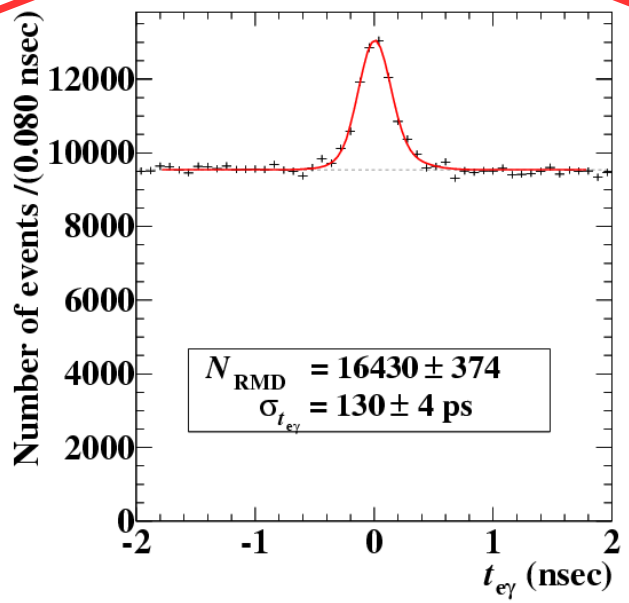
fit from Michel endpoint left/right sidebands

Photon Energy



fit from 55 MeV calibration

Relative Time

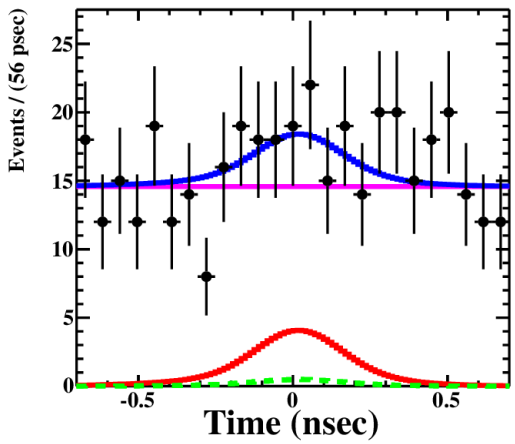


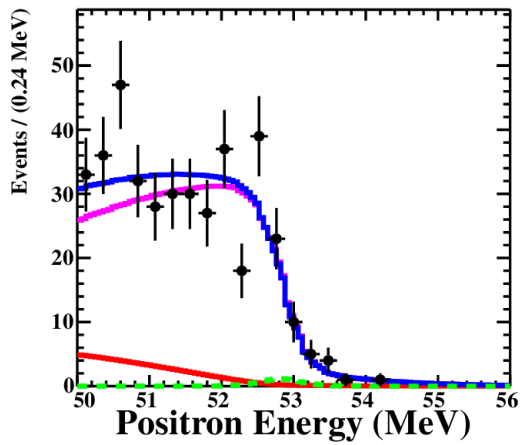
from lower sideband

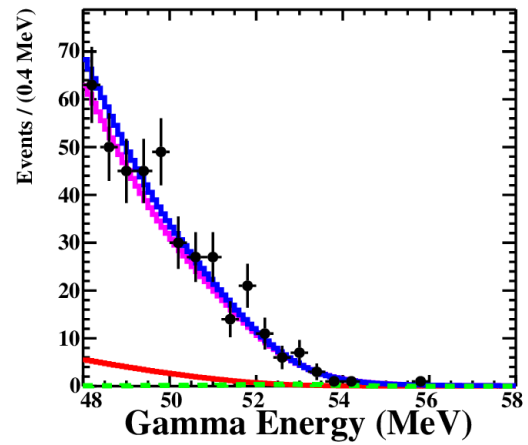
Likelihood fit

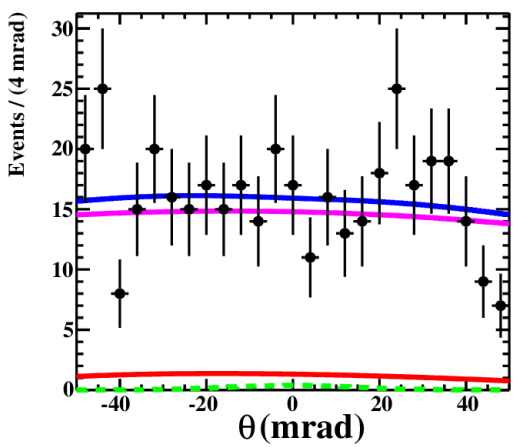
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm ACC}) = \frac{e^{-N}}{N_{\rm obs}!} \prod_{i=1}^{N_{\rm obs}} \left[N_{\rm sig}\, S(\vec{x}_i) + N_{\rm RMD}\, R(\vec{x}_i) + N_{\rm ACC}\, B(\vec{x}_i) \right]$$

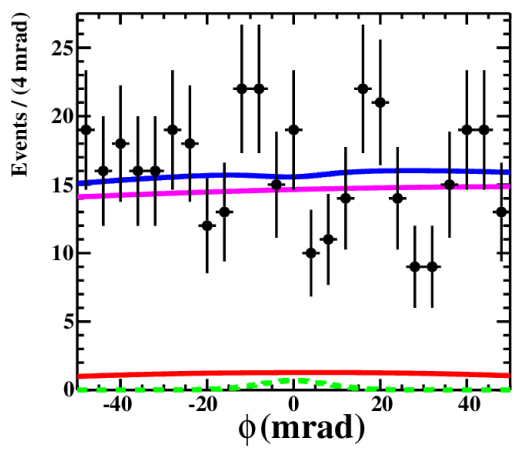
$$\exp\left[-\frac{(N_{\rm RMD} - \langle N_{\rm RMD} \rangle)^2}{2\sigma^2_{\rm RMD}} \right] \exp\left[-\frac{(N_{\rm ACC} - \langle N_{\rm ACC} \rangle)^2}{2\sigma^2_{\rm ACC}} \right]$$











from this fit we get

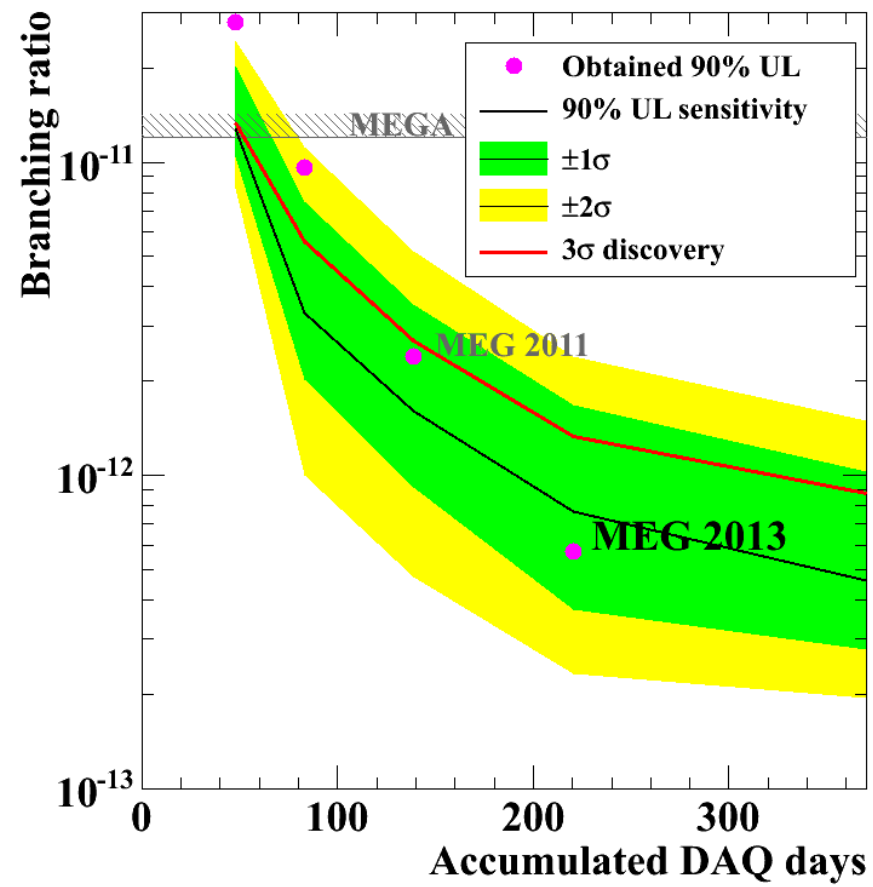
Branching ratio

1) **Normalization**: obtained from Michel and radiative decays.
2) **Confidence interval** calculated with Feldman & Cousins approach with profile likelihood ratio ordering.

with half of the collected statistics:

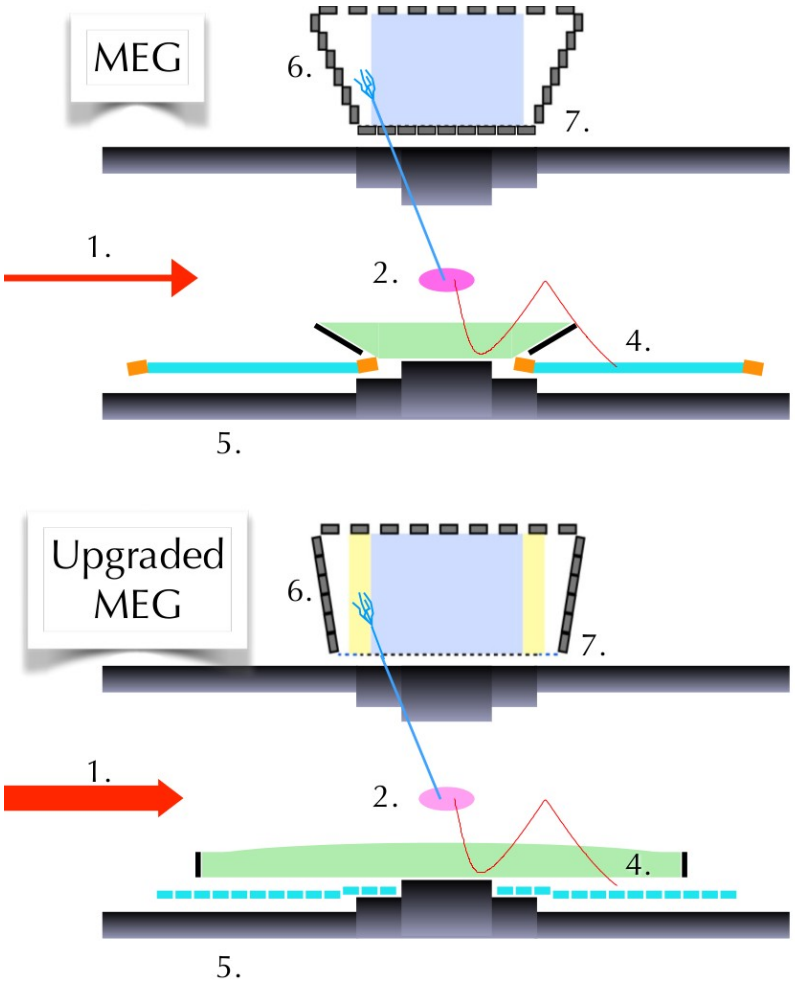
$$\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$$
$$@\,90\%\ \text{C.L.}$$

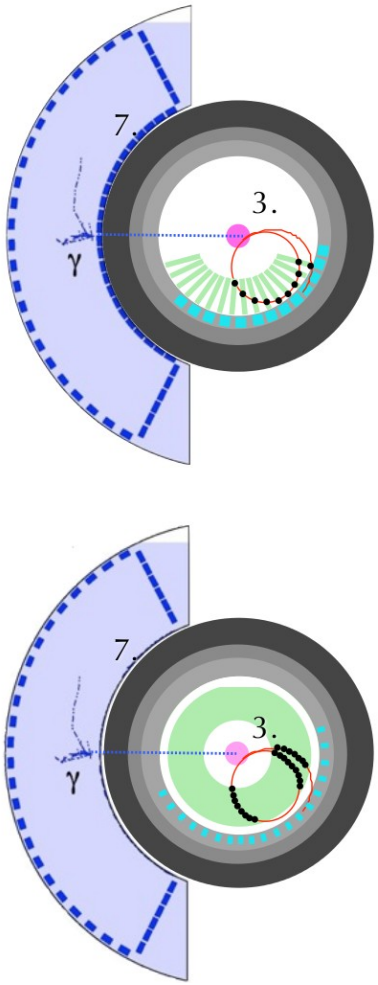
Adam et al., Phys. Rev. Lett., (2013) 110:201801



Final result from the MEG data set will be released in a few weeks, with an expected sensitivity of ~ 4×10^{-13} thanks to the **double statistics** and **improvements on analysis**.

MEG upgrade





1. Higher Muon Rate
⇐ better detector resolutions

2. Less energetic muons
⇒ thinner target

3. New tracker with higher resolution

4. Improved matching between drift chamber and timing counter

5. New timing counter.

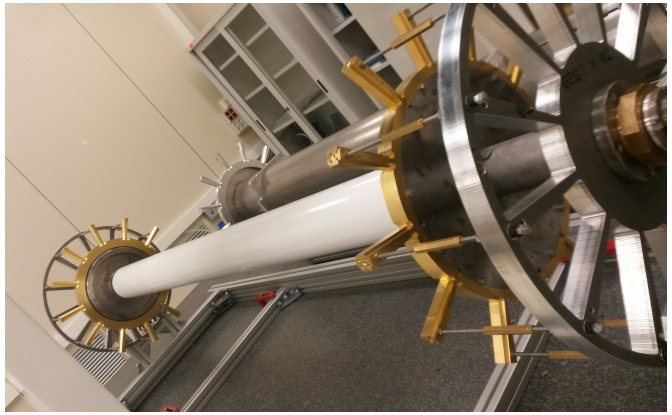
6. Larger XEC acceptance

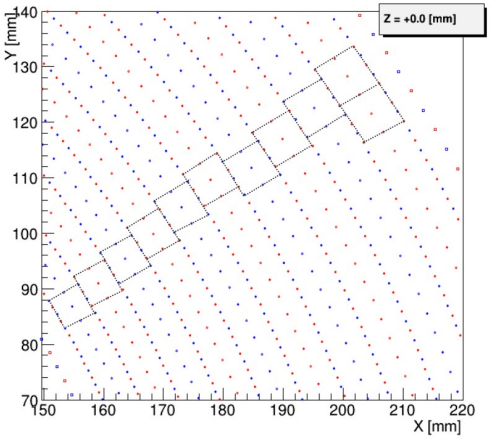
7. Better XEC scintillation light collection

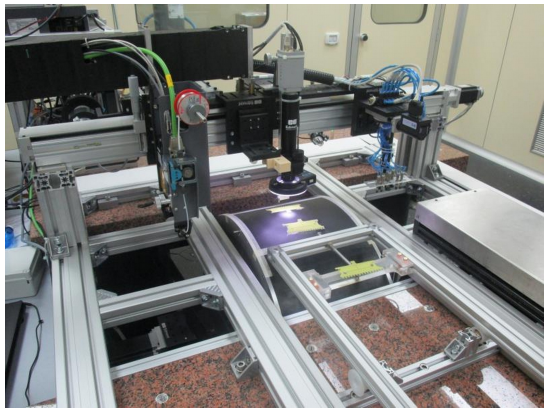
Baldini et al., ArXiv e-prints (2013), 1301.7225.

A new drift chamber

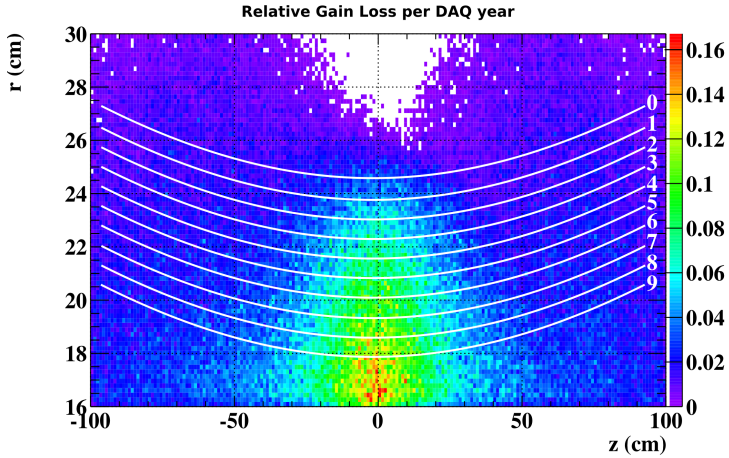
A new single-volume cylindrical drift chamber is under construction.



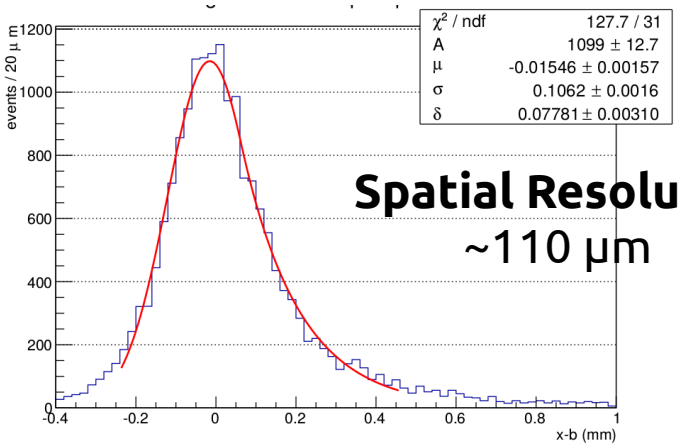




- 10 layers with wires at stereo angles ±7°÷8°.
- Drift cells with approximately squared shape 7x7 mm^2 (**high granularity**).
- Low mass gas mixture with helium and isobutane 85:15 (**high transparency**).
- Semi-automatic wiring robot with laser soldering tool developed for wiring >10000 wires.



Radiation hardness measured in laboratory tests



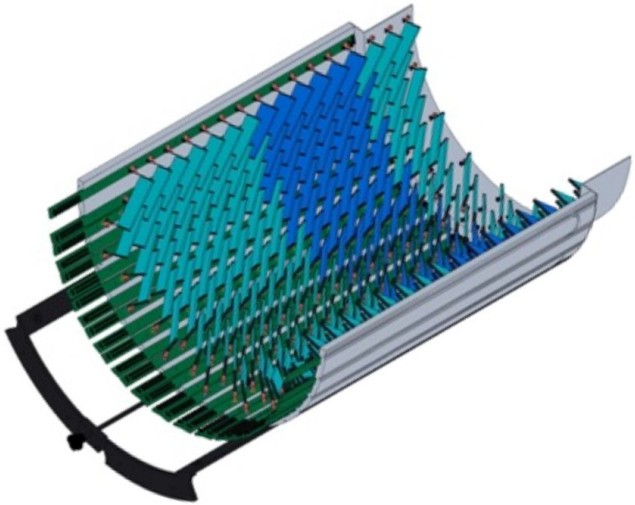
Spatial Resolution ~110 μm

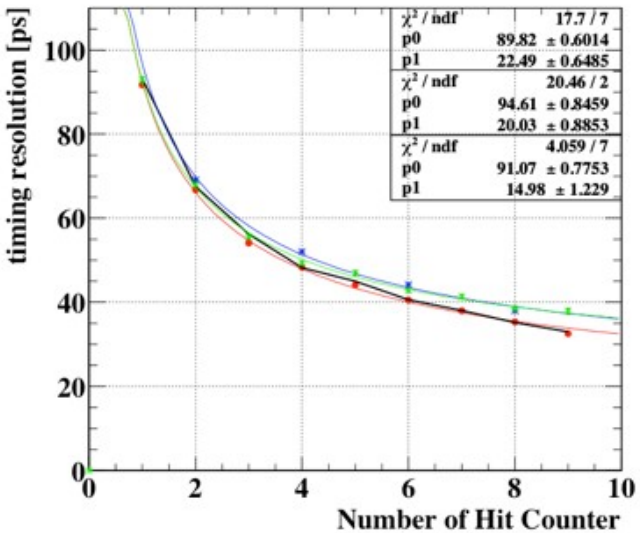
The new timing counters

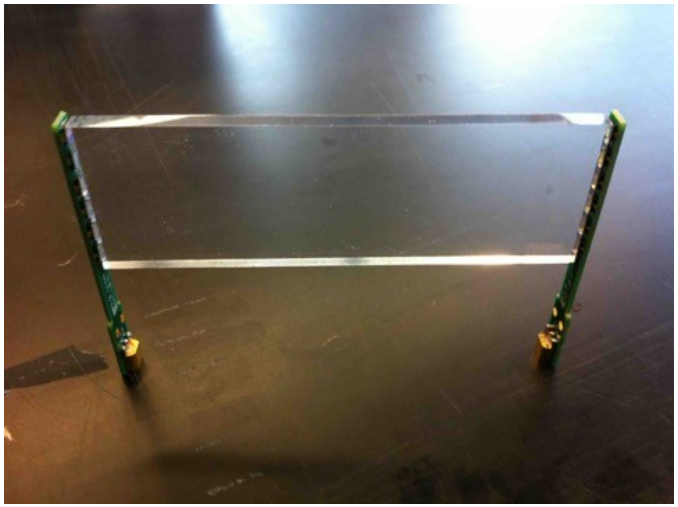
Good single pixel resolution is improved with **multiple hits** down to **35 ps**.

Each timing counter consists of 256 scintillator plates, read-out by 6 SiPMs.

- **Transparency**: thin scintillators for smaller multiple scattering contribution.
- **Segmentation**: less pile-up at even higher beam intensity.



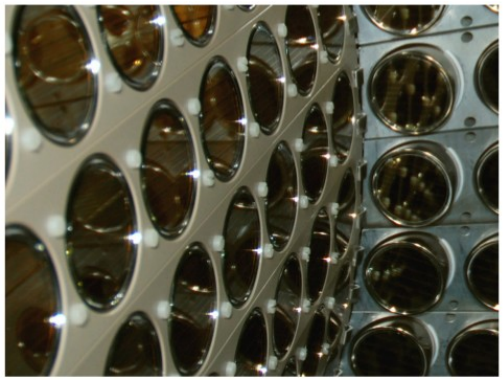




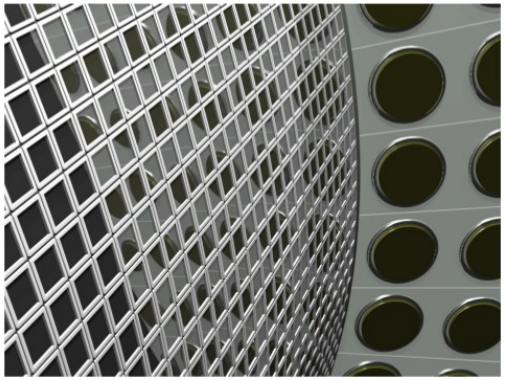
The upgraded LXe detector

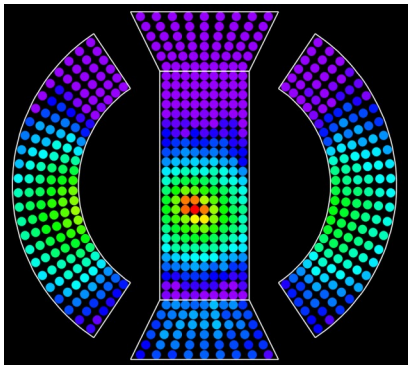
Replacement of the photosensors in the front face and rearrangement of those in the lateral faces.

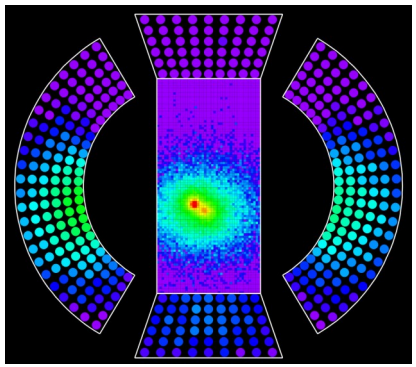
2'' PMTs

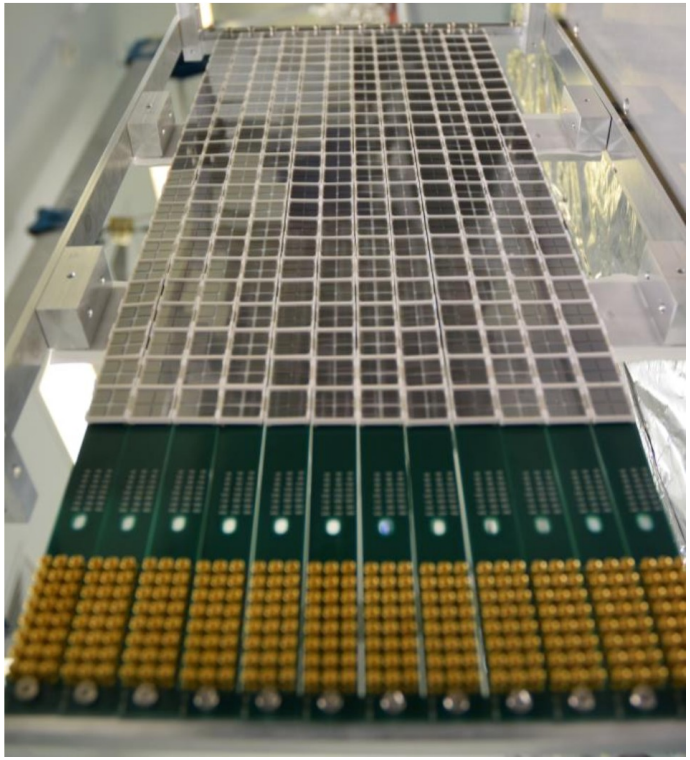


12x12mm^2 MPPCs





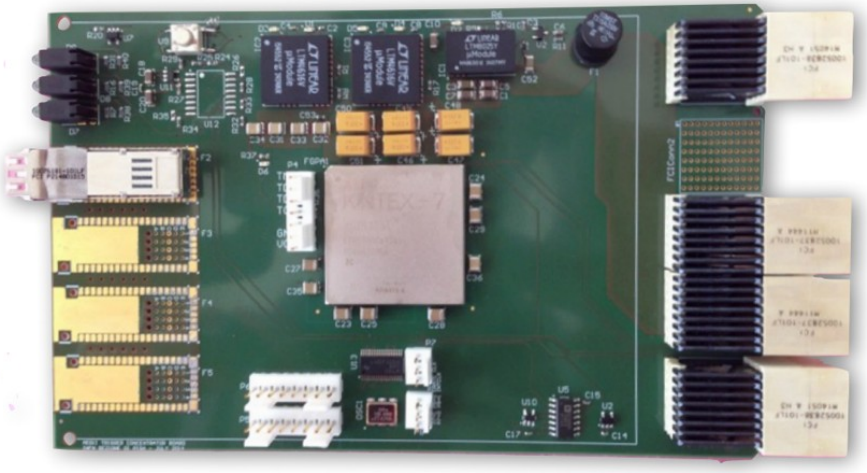


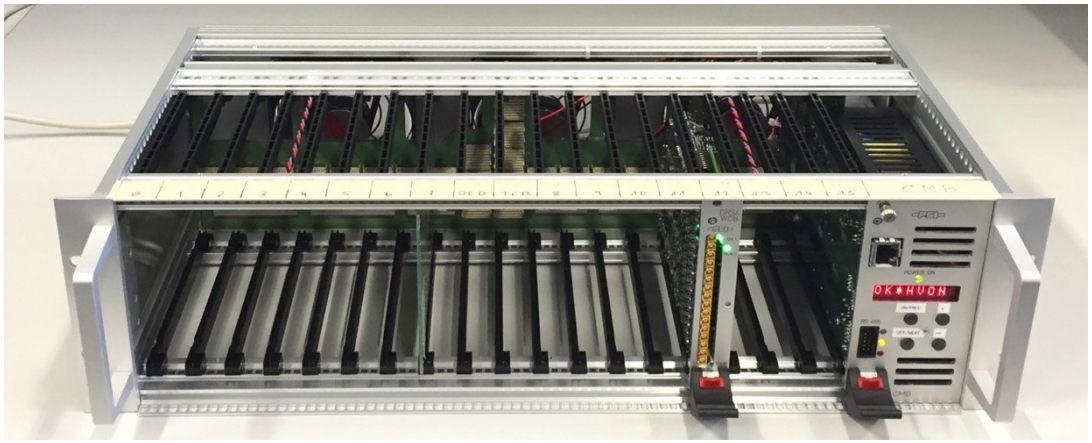


Trigger and DAQ

Custom system based on:

- 1-GHz waveform digitizers (**DRS chips**) for pile up rejection.
- **FPGAs** for online processing.





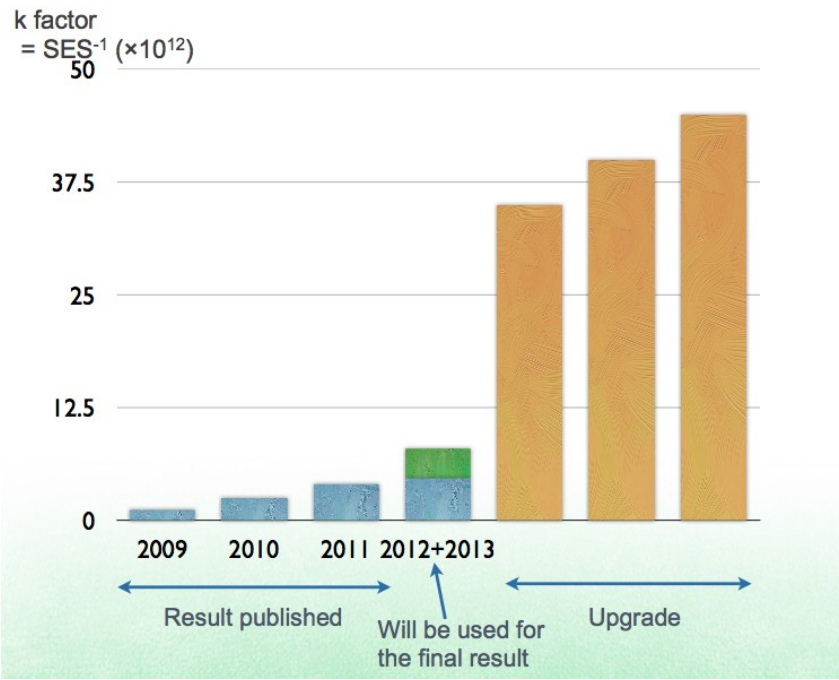
Resolution improvements

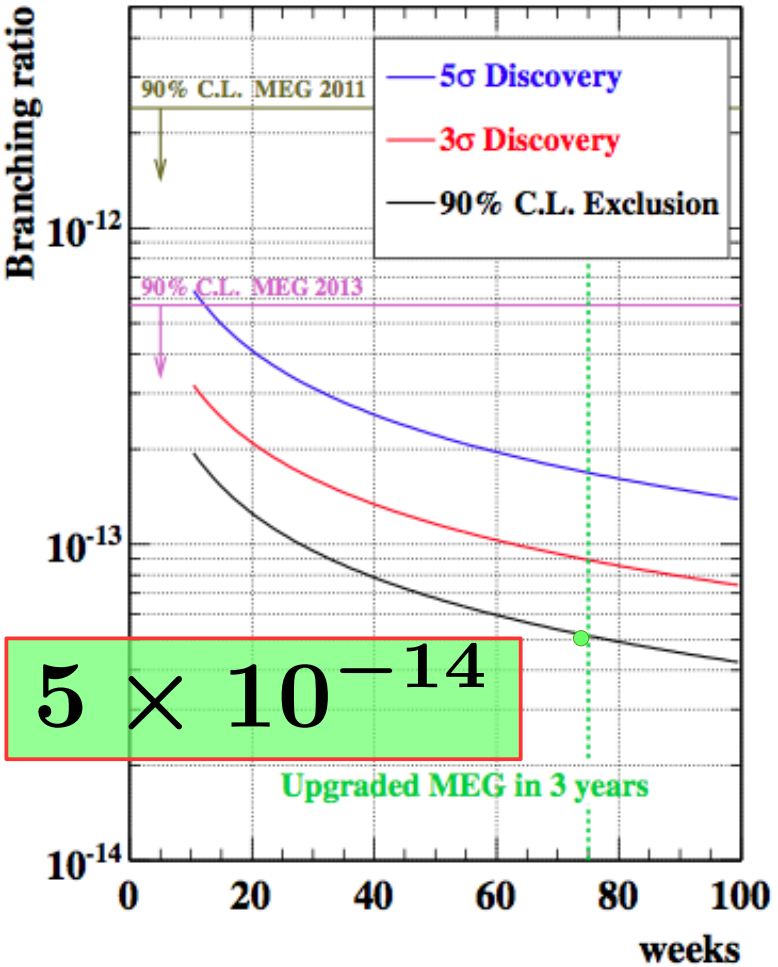
All the resolutions on the kinematic variables are improved by about a **factor 2** !

Variable	MEG	MEG2
$\Delta E_\gamma(\%)$	1.7	1.0
γ position (mm)	$5(u,v)$, $6(w)$	$2.6(u)$, $2.2(v)$, $5(w)$
ΔP_e (keV)	306	130
e^+ angle (mrad)	$7(\varphi_e)$, $9.4(\vartheta_e)$	$5.3(\varphi_e)$, $3.7(\vartheta_e)$
$\Delta t_{e\gamma}$ (ps)	122	84
e^+ efficiency (%)	40	88
γ efficiency (%)	63	69
trigger efficient(%)	~ 99	~ 99

MEG2 expected sensitivity

- 3 DAQ years estimated
- ~10x in stopped muons
- Schedule ongoing

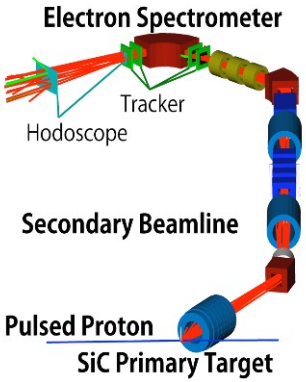




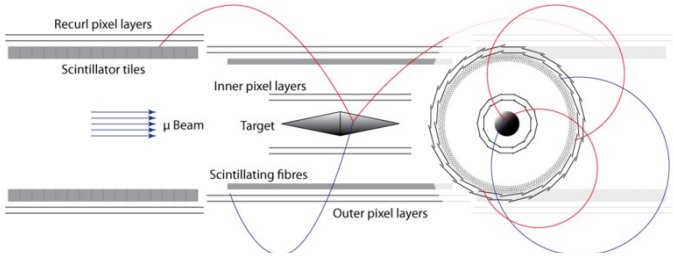
Conclusions

- **Charged Lepton Flavour Violation** experiments represent a powerful tool to investigate new physics scenarios **with no SM background**.
- Combined measurements on CLFV processes can significantly **constrain** new physics at **high energy scales**.
- The MEG experiment has recently set **the most stringent limit** on CLFV physics scenarios.
- Next year **MEG2** will start data taking with the goal of improving MEG results by an **order of magnitude**.

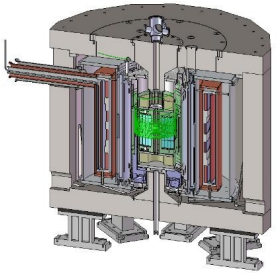
In the next decade…



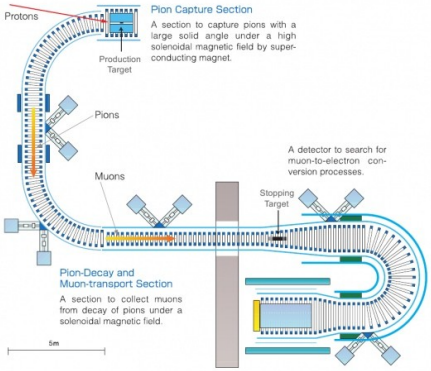
DeeMee DAQ



Mu3e DAQ



J-PARC g-2 DAQ

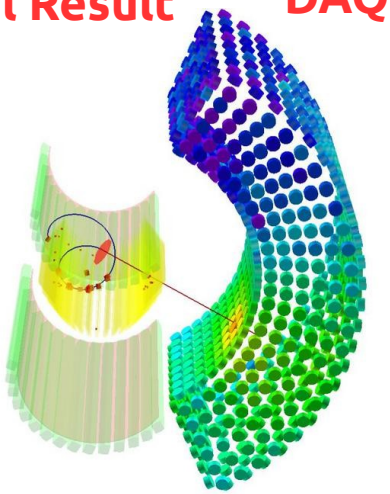


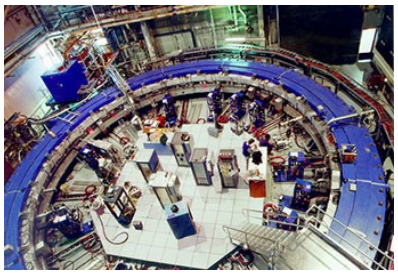
COMET-II DAQ

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

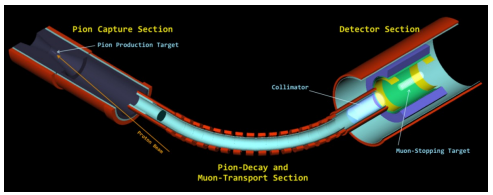
MEG Final Result

MEG2 DAQ



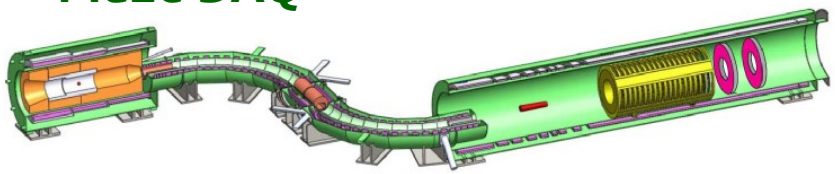


FNAL g-2 DAQ



COMET-I DAQ

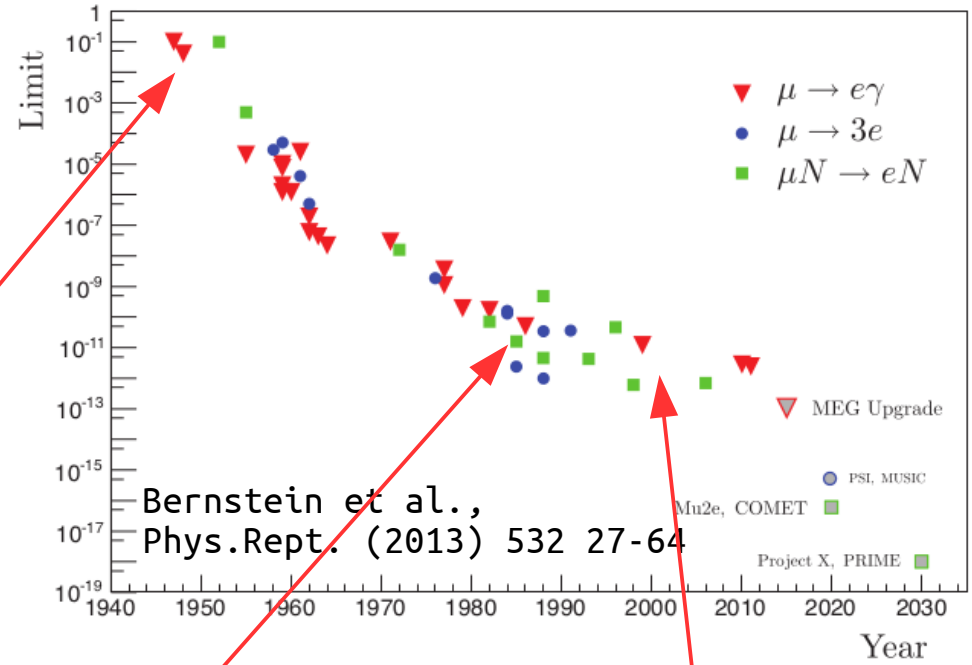
Mu2e DAQ



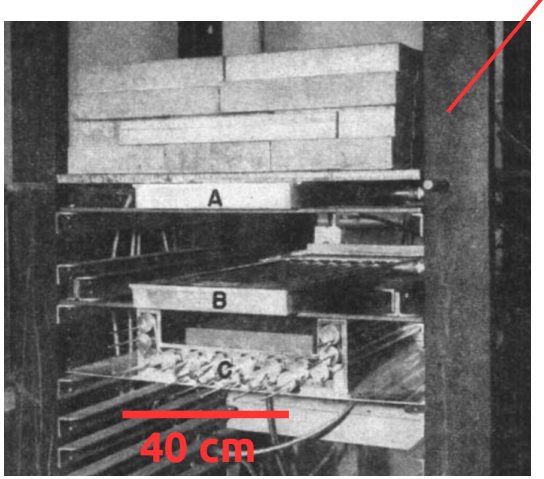
Spare Slides

“Table-top”experiments

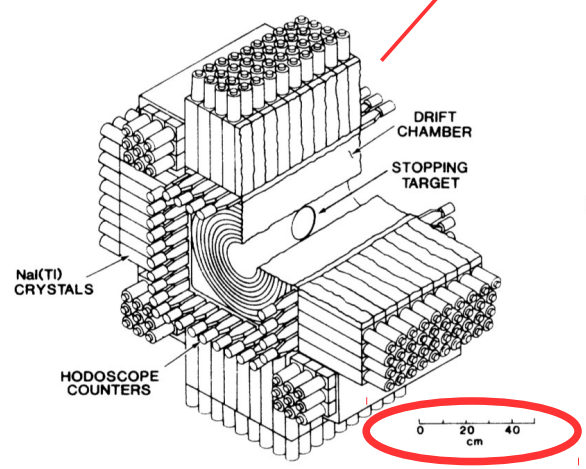
- Dedicated experiments
- A long road in beam and detector technology improvements



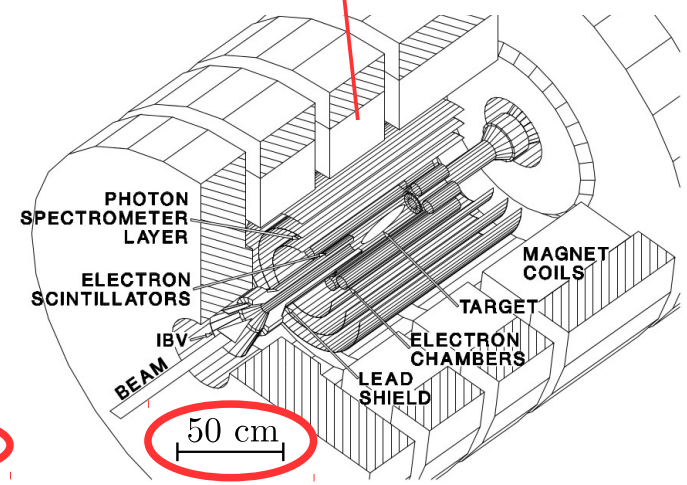
Experiments looking for $\mu \to e\gamma$



Hincks-Pontecorvo 1948



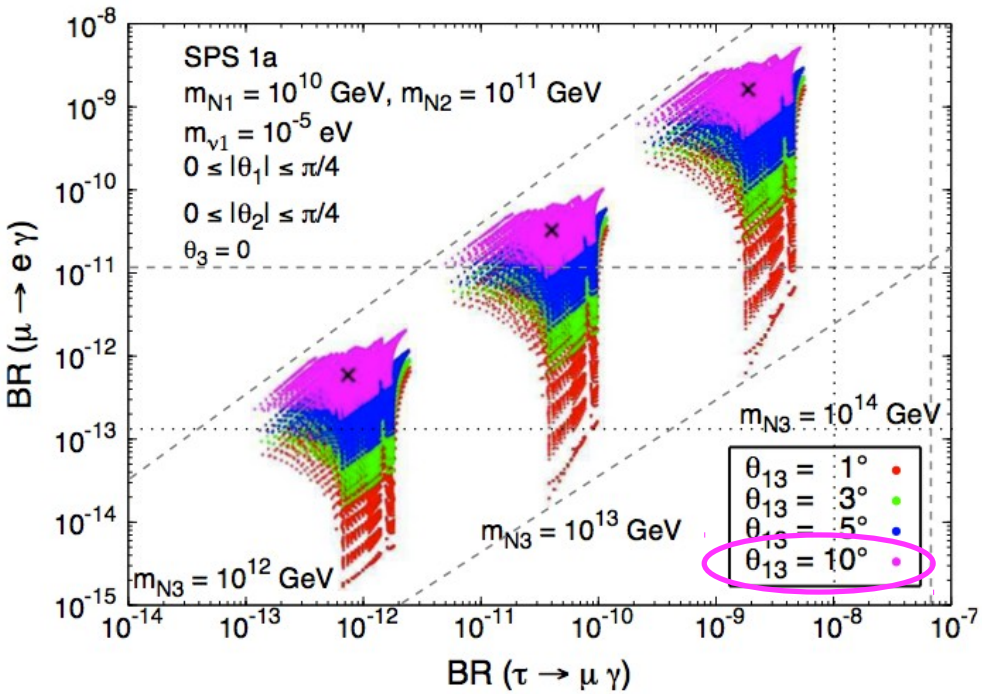
Crystal-Box 1988

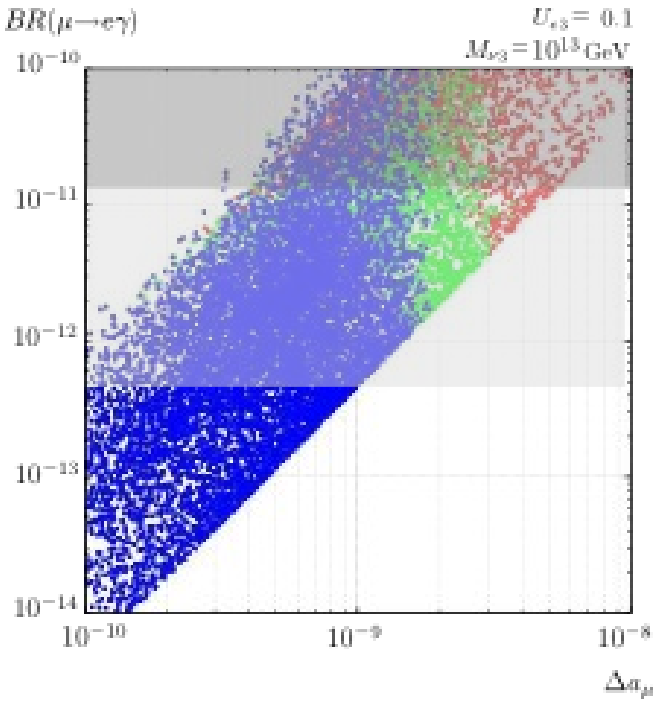


MEGA 1999

Probes to New Physics

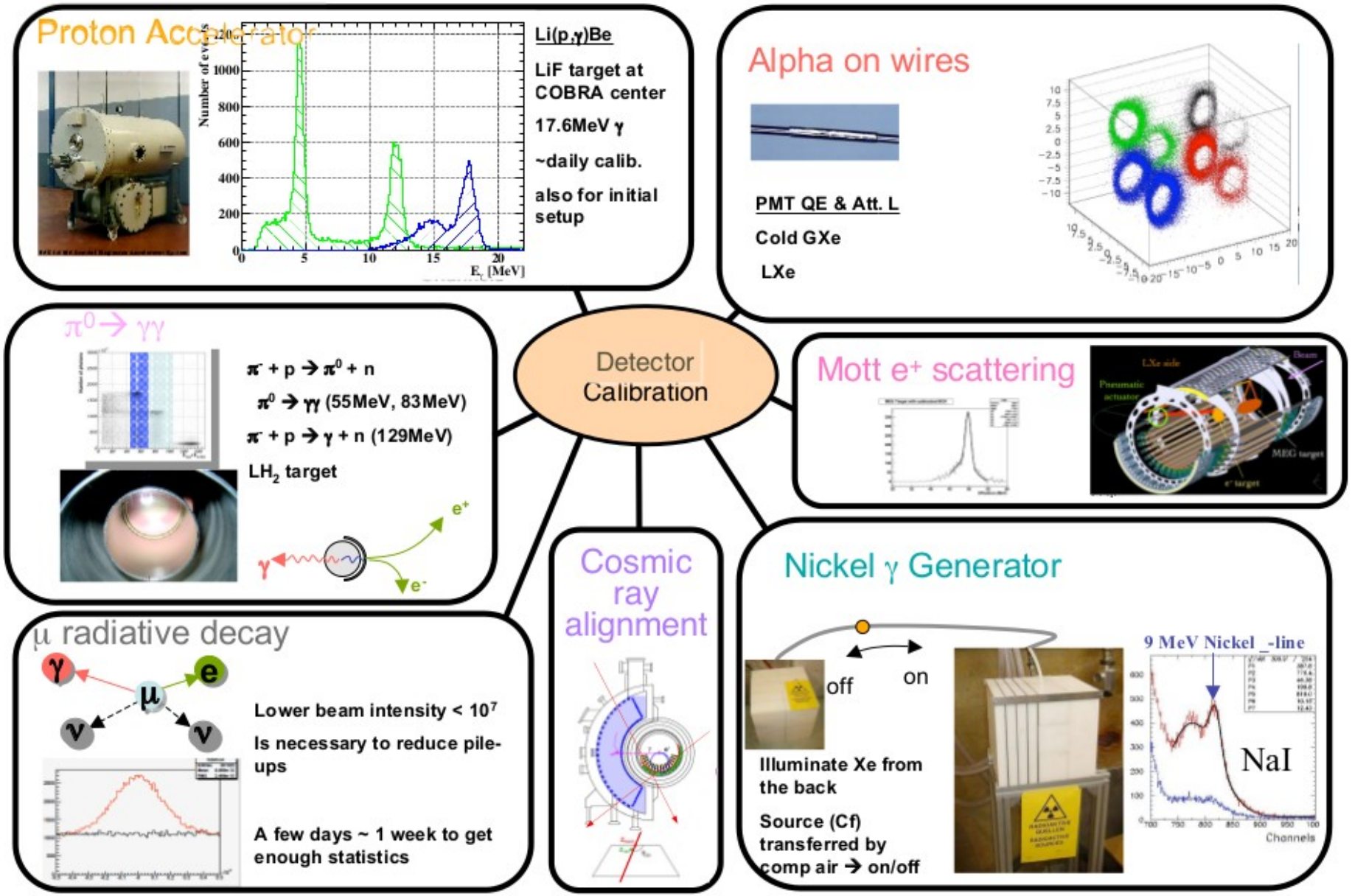
Between the different processes **tight connections** are envisaged in several models





Antusch et al.,JHEP (2006),0611:090
Hisano et al., JHEP (2009),0912:030

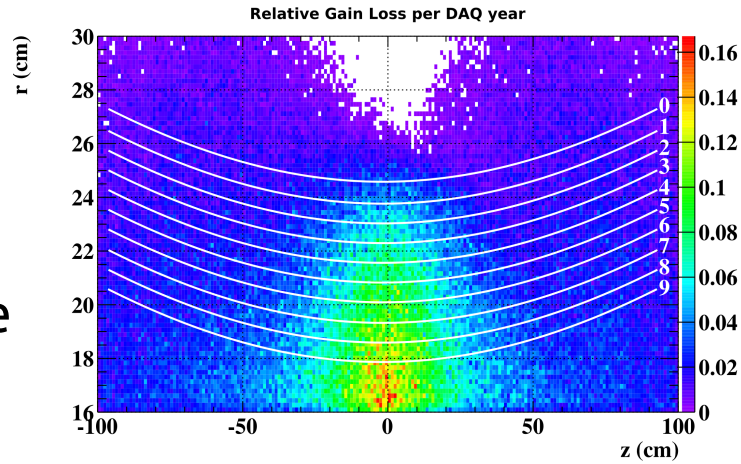
Detector calibrations

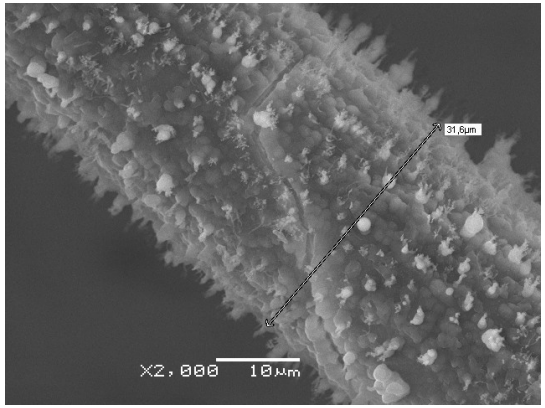


A new drift chamber

Radiation hardness

Laboratory tests showed that the expected accumulated charge of **0.5 C/cm** correspond to a gain loss of **~50%** in the whole data taking period in the hottest portion.





Performance

In low-mass gas mixtures spatial resolution is limited by poor **ionisation statistics**.

- Tests on small prototypes showed a single-hit resolution of ~**110 µm**.
- The high-bandwidth (1 GHz) electronic chain allows for the improvement of such results by means of the **cluster timing** technique.