Searching For $\mu \rightarrow e\gamma$ with MEG and MEG-II

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On behalf of the MEG collaboration

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Marseille
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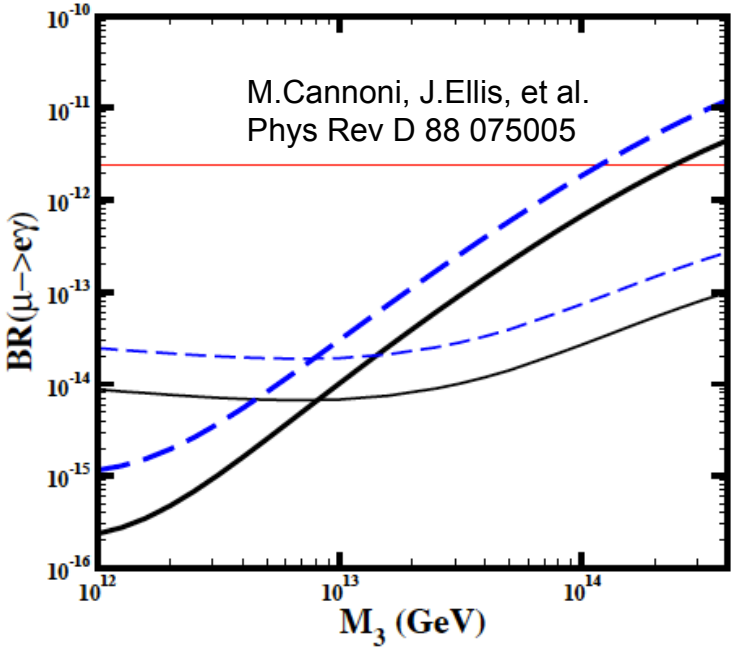
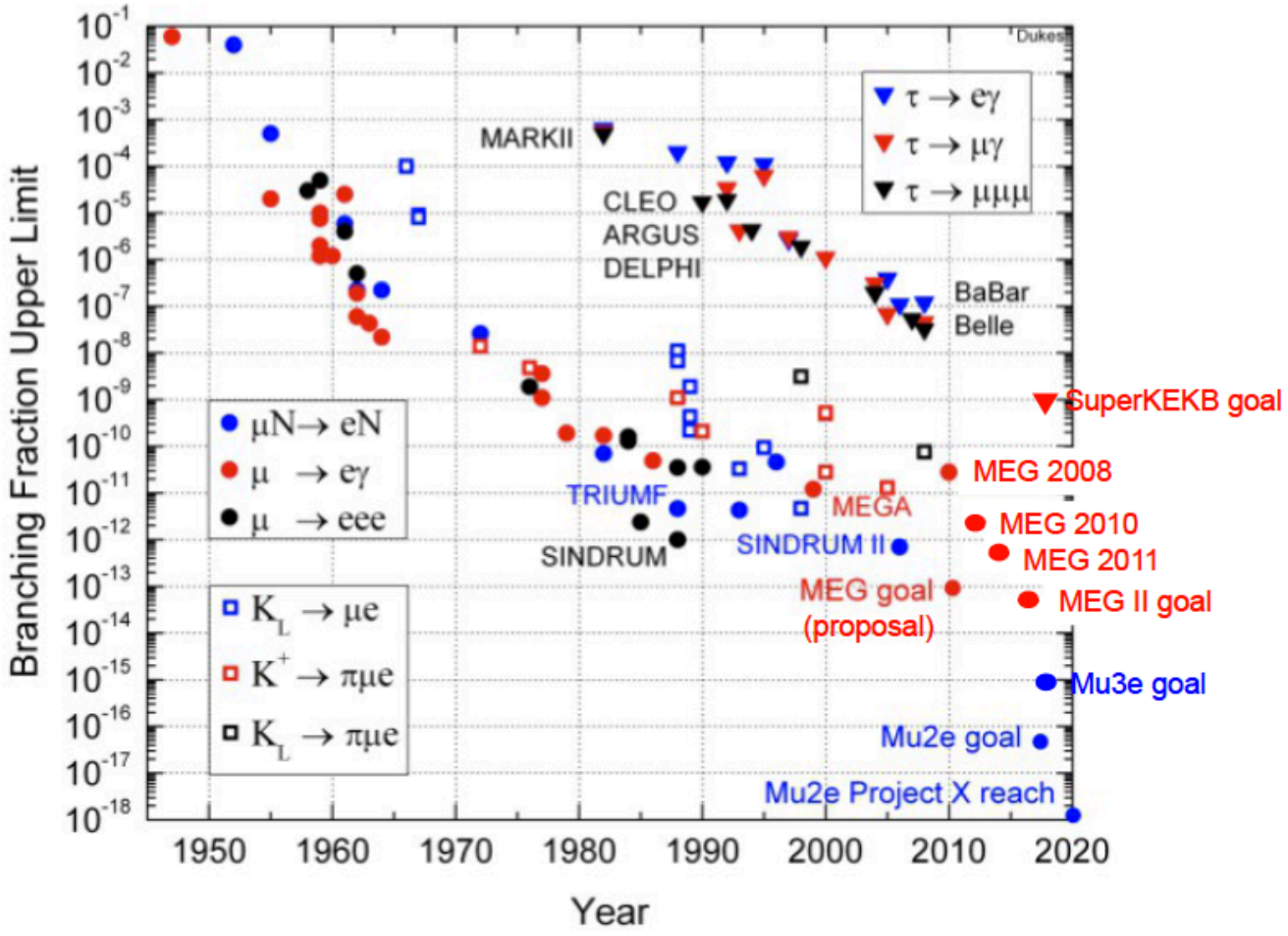
WHY $\mu \rightarrow e\gamma$?

- Standard Model prediction for BF $\propto (m_\nu/m_W)^4 < 10^{-55}$
  - not enough protons in the whole Universe to check this SM expectation…
- Current experimental limit (10^{-12}) close to *many* New Physics model predictions
- Clear two-body signal topology, background suppressed by better and better detectors.



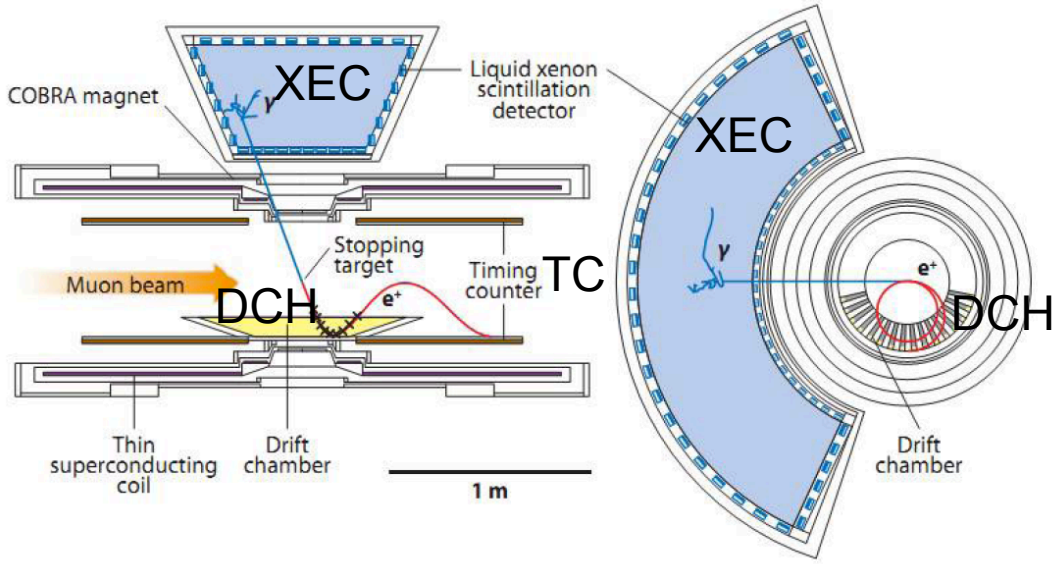
Heaviest Right Handed ν mass

A Long Story


Branching Fraction Upper Limit
Year
Dukes
MARKII
CLEO
ARGUS
DELPHI
BaBar
Belle
SuperKEKB goal
MEG 2008
MEG 2010
MEG 2011
MEG II goal
MEG goal
(proposal)
MEGA
TRIUMF
SINDRUM
SINDRUM II
Mu3e goal
Mu2e goal
Mu2e Project X reach
τ → eγ
τ → μγ
τ → μμμ
μN→ eN
μ → eγ
μ → eee
K_L → μe
K+ → πμe
K_L → πμe

The MEG Experiment

- **PSI** πE5 DC positive muons beam *J.~Adam et al., Eur.Phys.J. C 73 (2013) 2365*
  - $R_\mu = 3 \times 10^7$ stopped muon per second

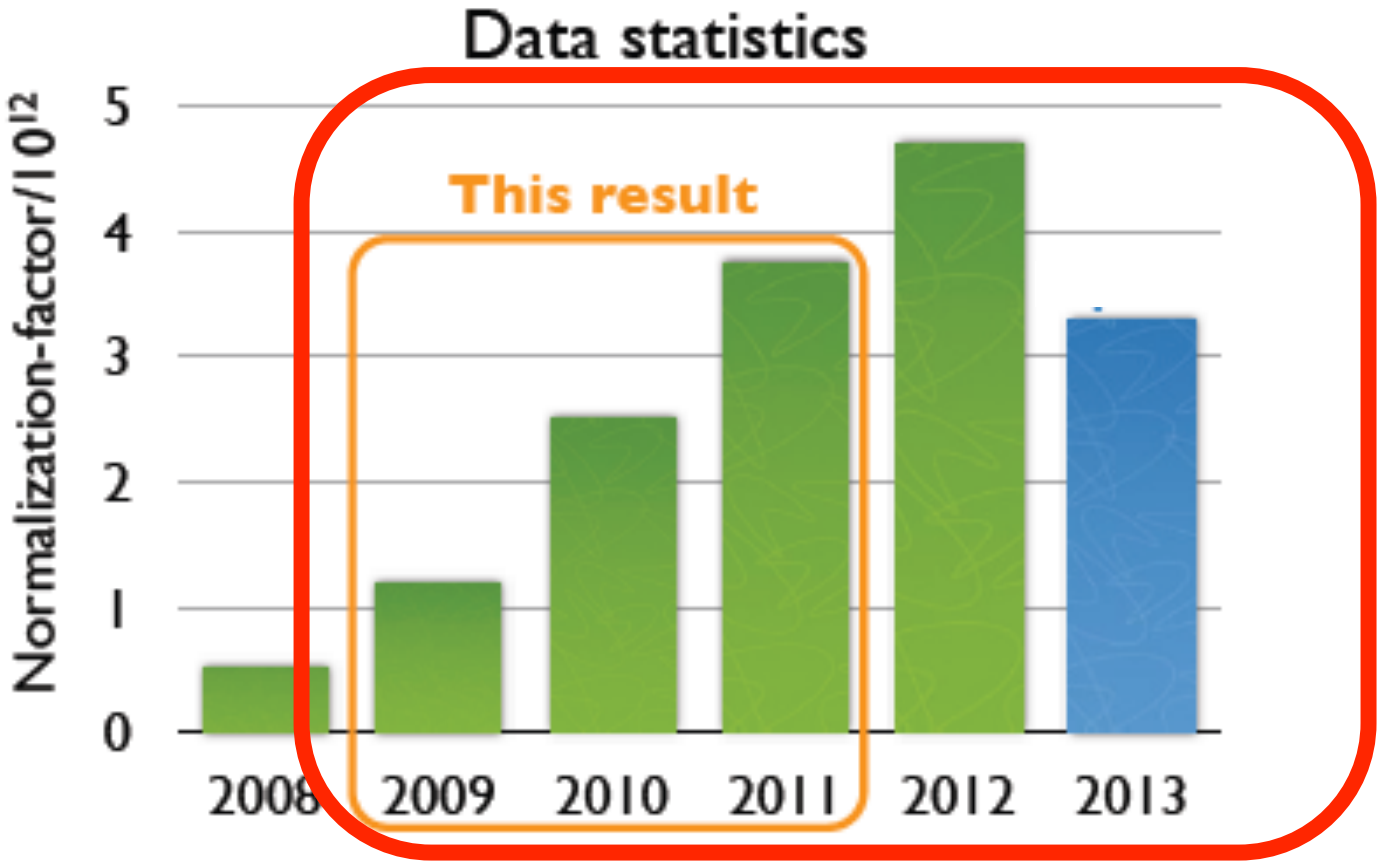


- 900L LXe photon detector
- Low mass drift ch. planes with fast scintillators in a gradient magnetic field

Optimized to detect photon with high efficiency and to sweep out Michel positron searching for the signal with an unprecedented resolution

MEG Datasets

Effective number of muons stopped on the target



New results to be released soon

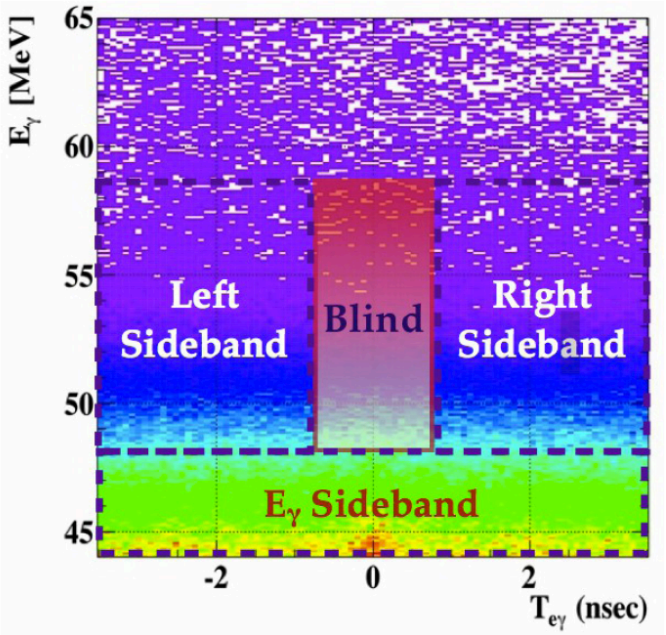
Analysis Overview

- Five observables
  - $E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \varphi_{e\gamma}$
- Signal [rate $\propto R_\mu$]
  - Muon at rest:
    - $E_\gamma = E_e = 52.8$ MeV
    - Back-to-back
    - $T_{e\gamma}=0$
- Backgrounds
  - Accidental coincidence [$\propto R_\mu^2$]
    - Michel e^+ & γ
      (γ from either RMD, e^+annihilation, or e^+Bremsstrahlung)
  - Radiative Michel Decay (RMD) [$\propto R_\mu$]
    - $T_{e\gamma}=0$ but x20 less than accindental

ANALYSIS region

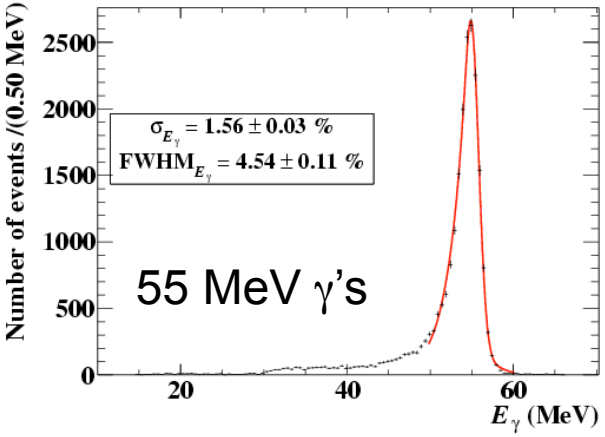
$48 < E_\gamma < 58$ MeV
$50 < E_e < 56$ MeV
$|T_{e\gamma}| < 0.7$ ns
$|\theta_{e\gamma}| < 50$ mrad
$|\varphi_{e\gamma}| < 50$ mrad

BLIND analysis



PDF DEFINITIONS

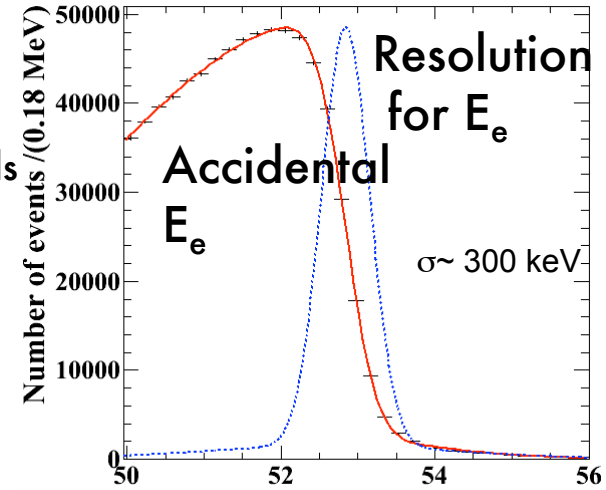
Resolution for E_γ



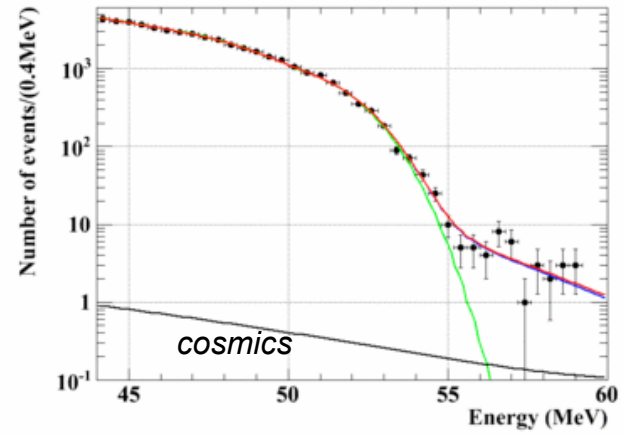
$\pi^- p \rightarrow \pi^0 n$

Selecting back to back photons

Michel spectrum in $T_{e\gamma}$ sidebands (fit to the edge)

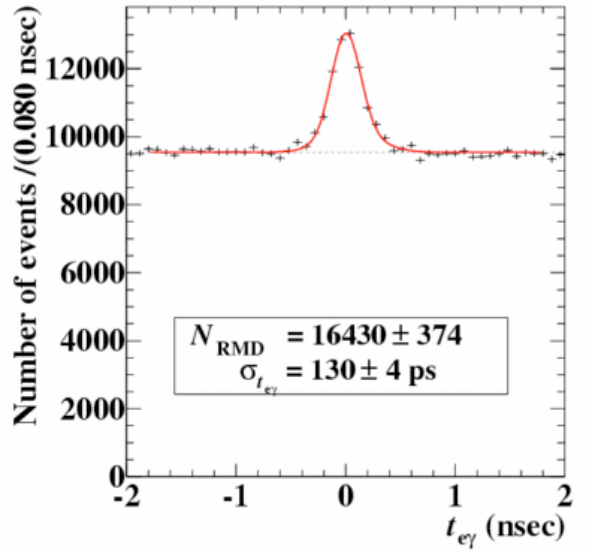


Accidental E_γ



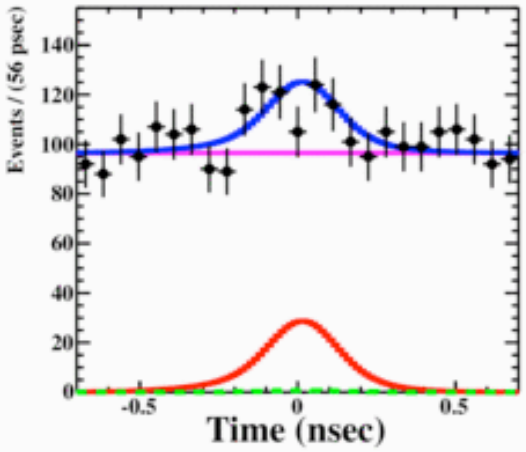
$T_{e\gamma}$ sidebands

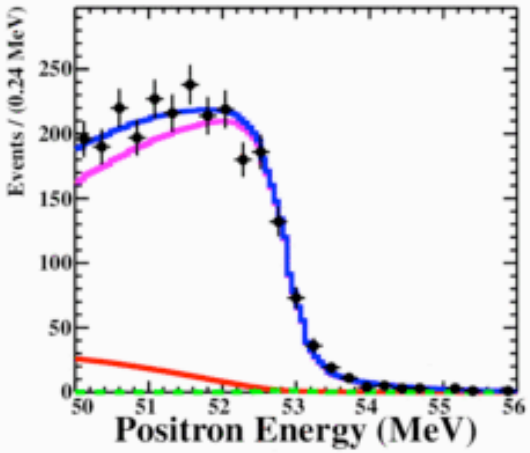
RMD in E_γ sidebands

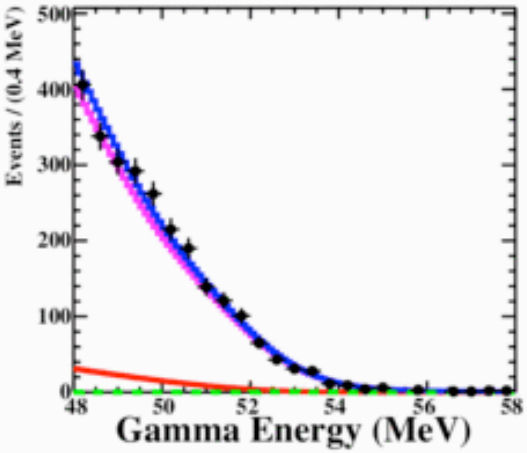


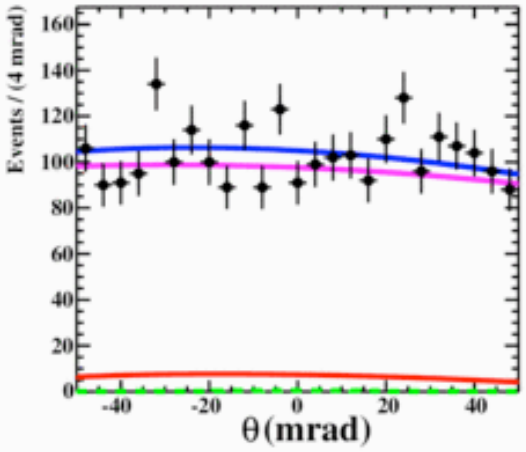
Positron angular and position resolution from double turn tracks

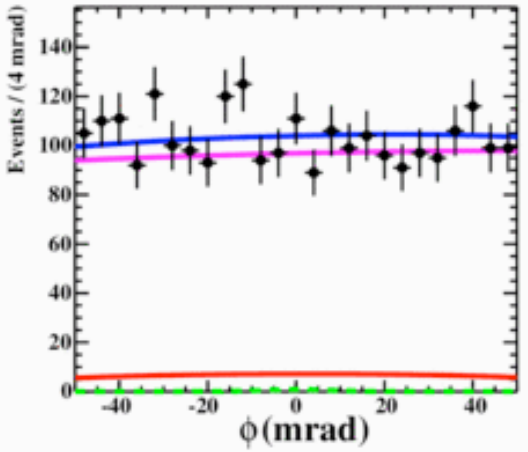
2009-2011 Results











S = - 0.4 +4.8 -1.9

A = 2413 ± 37

R = 167 ± 24

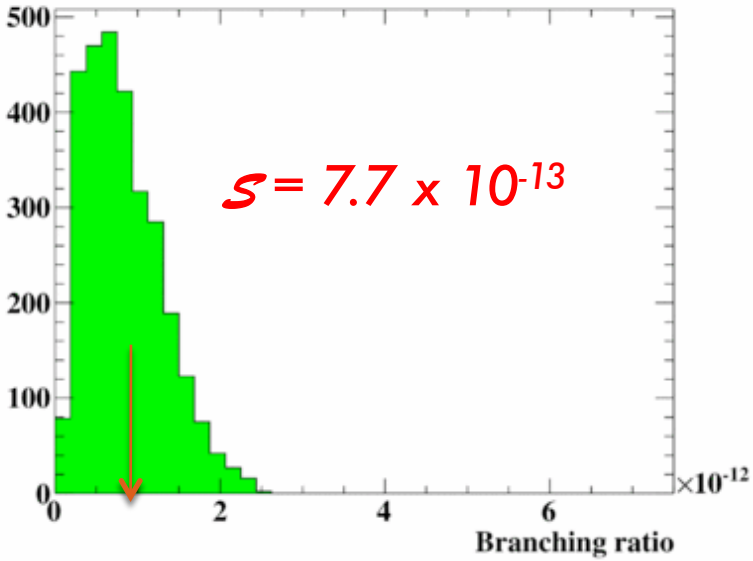
[MINOS errors]

CONFIDENCE INTERVALS

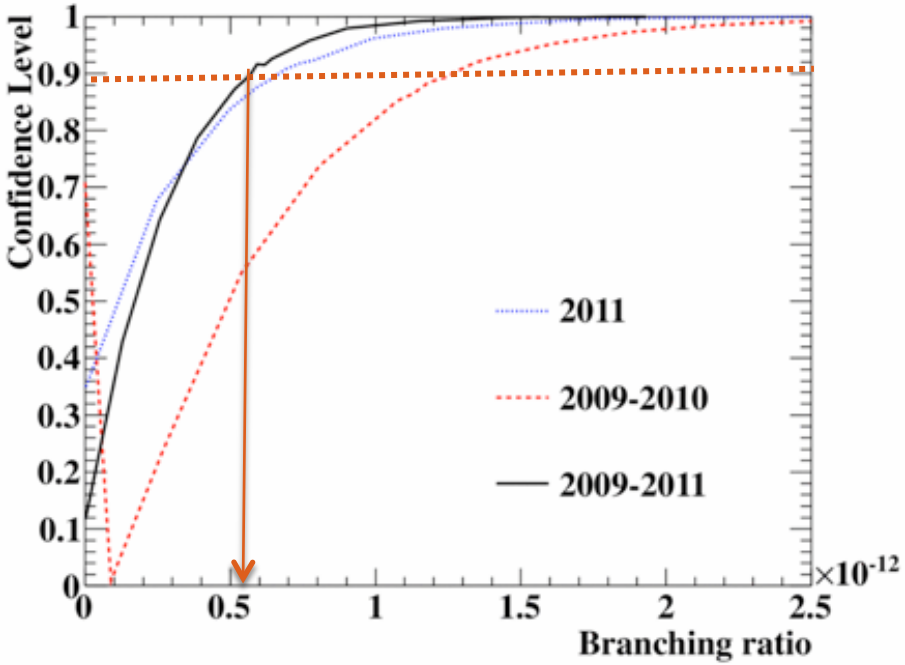
Frequentistic procedure based on the **profile likelihood ratio**

Sensitivity s

(Median of the upper limit distribution on ensemble of toy MC experiments)



$s = 7.7 \times 10^{-13}$



$BR(\mu \rightarrow e\,\gamma) < 5.7 \times 10^{-13}$

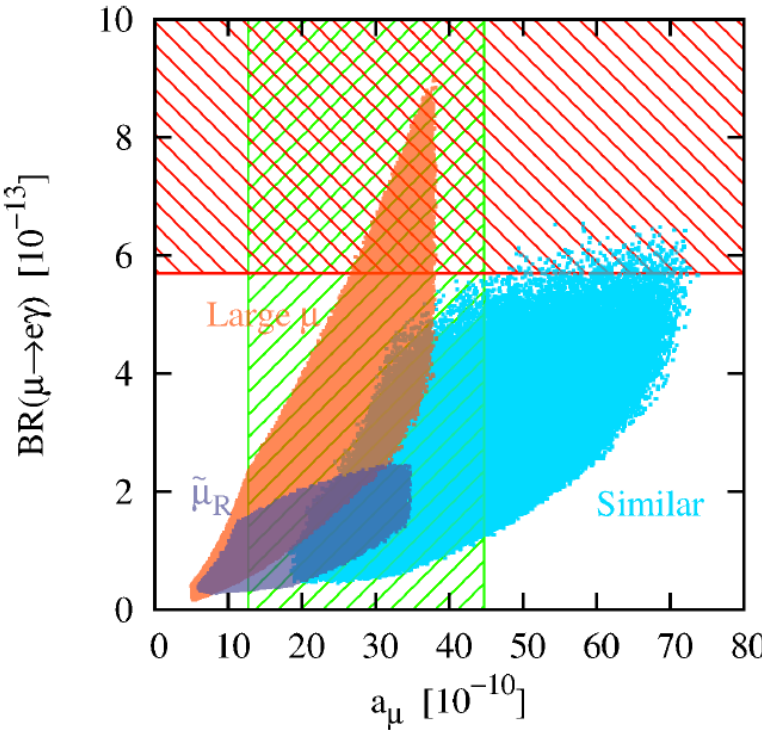
J.Adam et al., PRL 110 (20), 201801

Constraints on New Physics

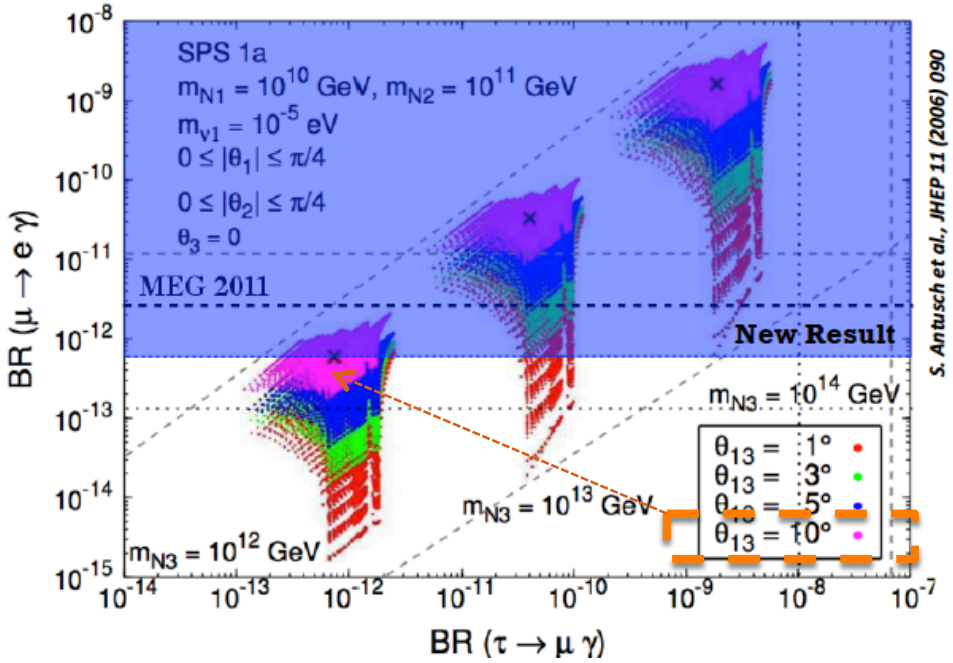
Four times more stringent constraint than previous result

Correlations in MSSM

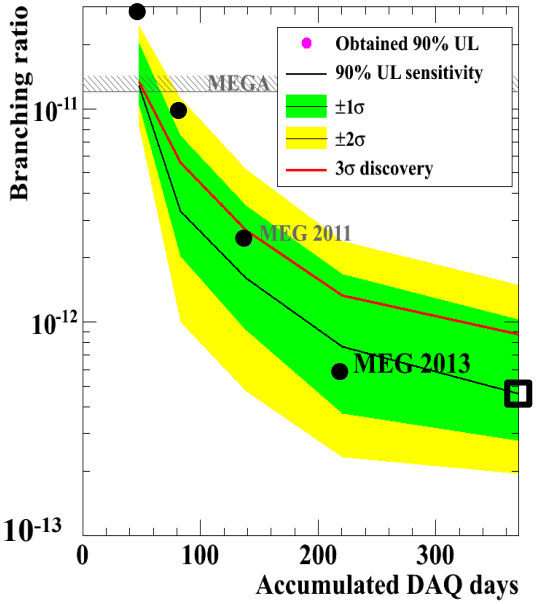
J.Kersten et.al. arXiv:1405.2972v1



SUSY and see-saw



OUTLOOK ON MEG



FINAL MEG results
will have a sensitivity

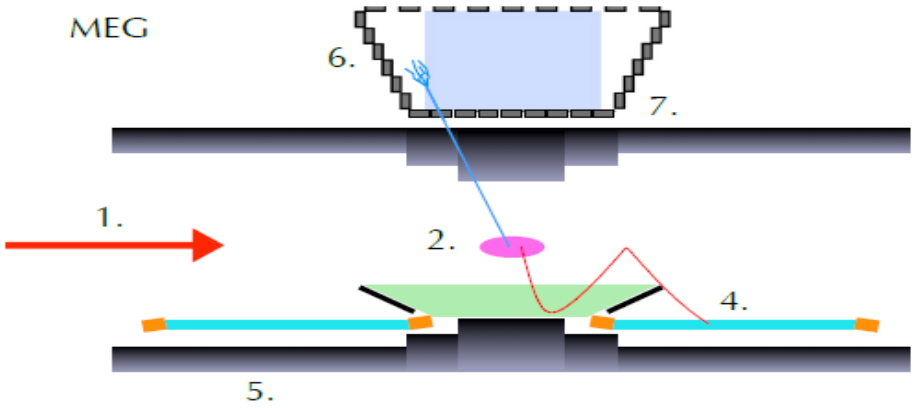
$\mathcal{S} = 5\ 10^{-13}$

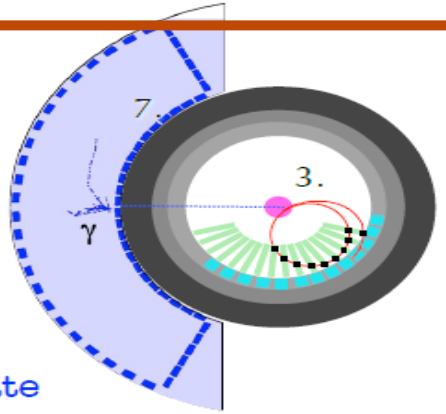
- Approaching the limit of current detector performance
  - $R_{ACC} \propto R_\mu^2 \cdot f_e \cdot f_\gamma \cdot \delta\omega/4\pi \cdot \delta t$
- BUT muon beam rate (R_μ) not fully exploited
- AND New Physics can show up at (any?) lower BF

MEG detector upgrade : MEG-II

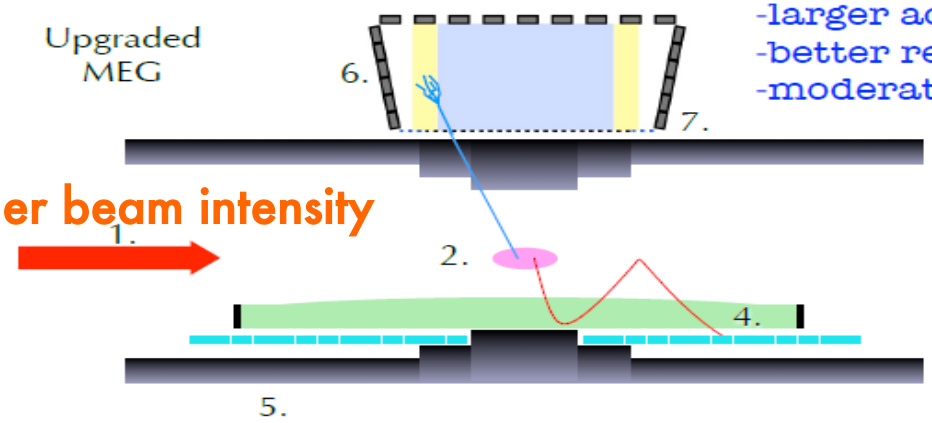
MEG-II CONCEPT

upgrade design based on
our long time experience

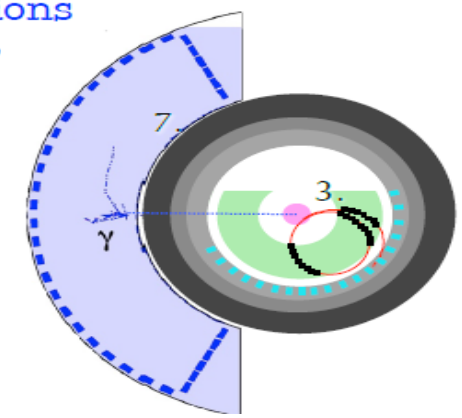




-higher beam rate
-larger acceptance
-better resolutions
-moderate cost



Higher beam intensity



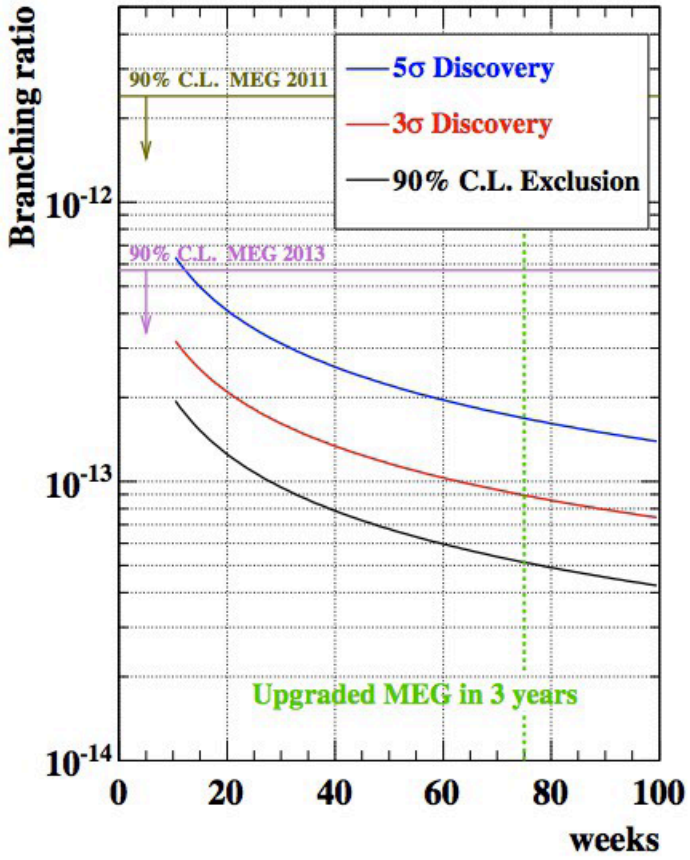
MEG Upgrade Proposal
(http://arxiv.org/abs/arXiv:1301.7225)

MEG-II GOALS

Expected beam rate : 7×10^7 μ/s

Expected performances

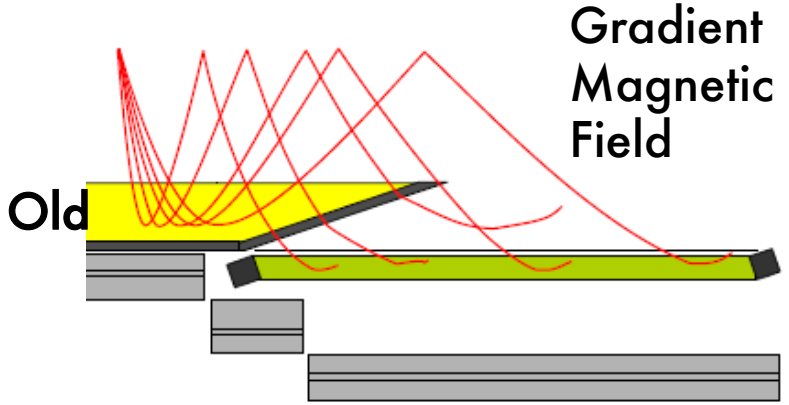
PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad) DCH res.	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+ DCH eff	40	88



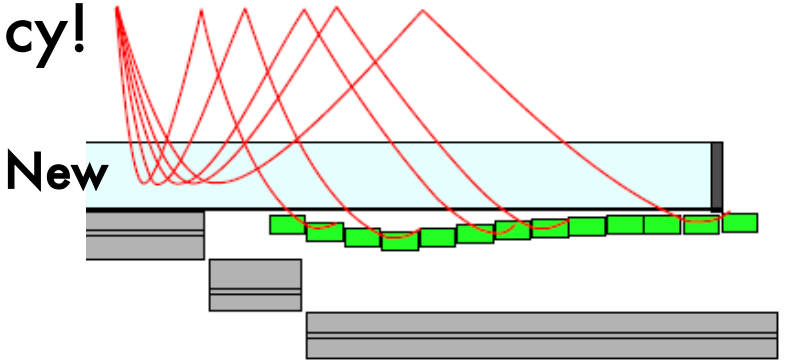
MEG-II Sensitivity: $5\ 10^{-14}$

New positron spectrometer

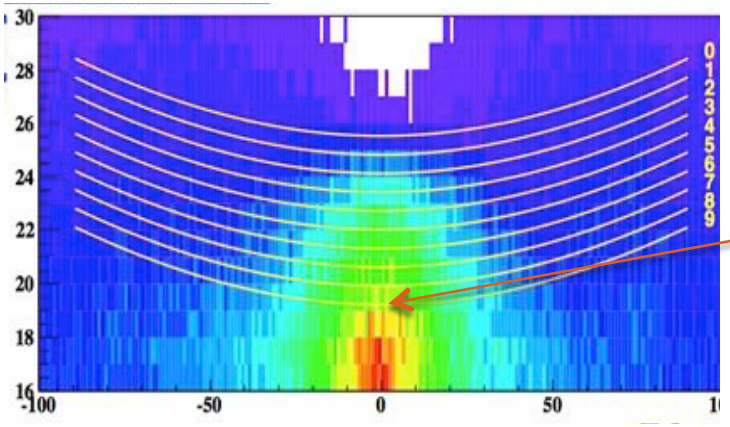
- Single volume 2π coverage drift chamber
- **2-m long, stereo wire, low mass chamber**
  - 1200 sense wires
  - 8° stereo angle (z reco.)
  - 1.7×10^{-3} X_0 per track



- **Higher transparency to timing counter**
  - Double the detection efficiency!
  - Precise reconstruction of path length (better timing resolution)



Tracker Requirements

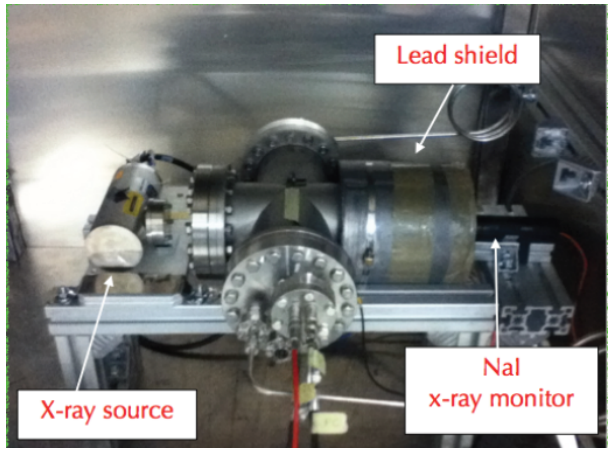


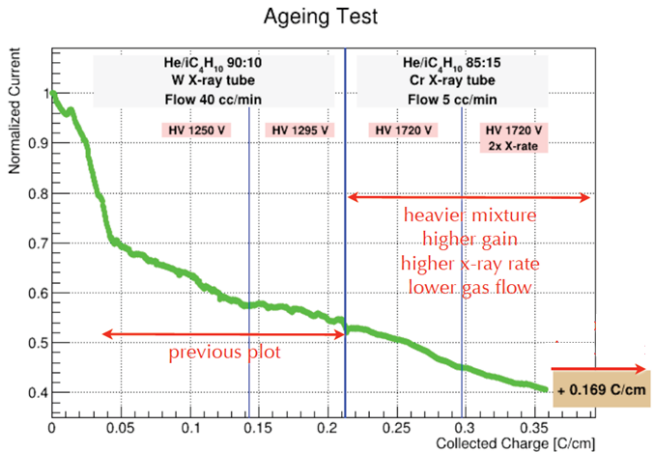
Instantaneous rate capability

Hit rate >30 kHz/cm^2
on the innermost wire @ 7x10^7 μ/s

Long term stability and ageing

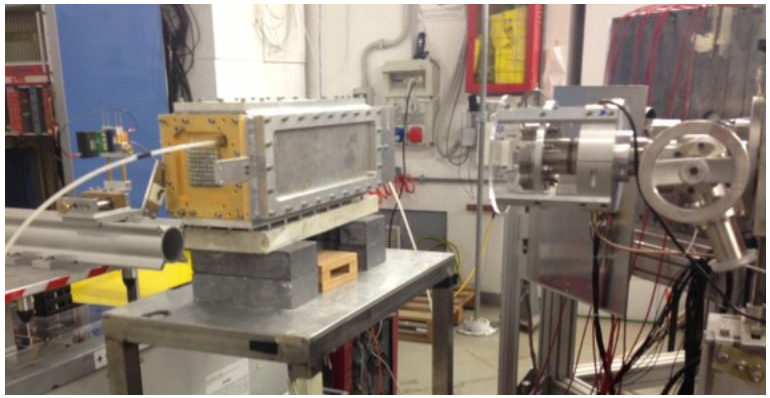
Test up to 0.5C/cm, no severe problem
Gain drop compensated by HV increase

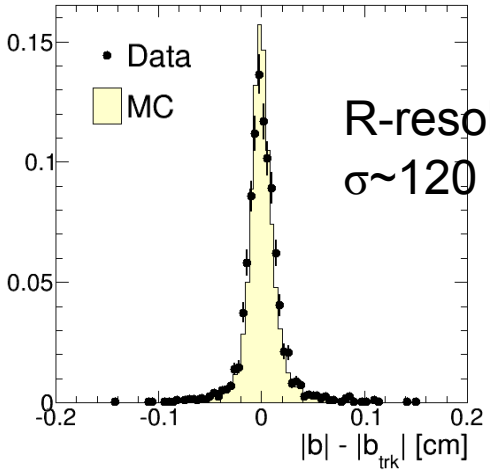




Prototyping DCH

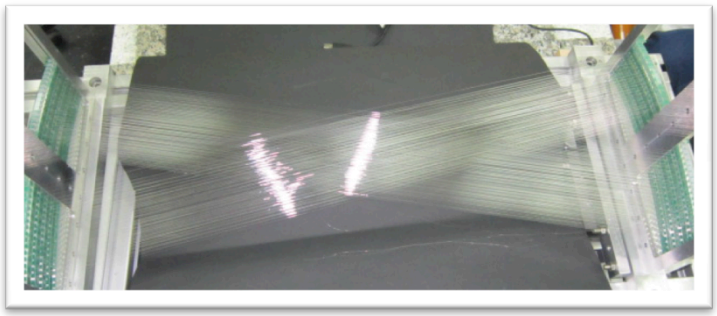
Test beam @ BTF Frascati





R-resolution
σ~120 μm

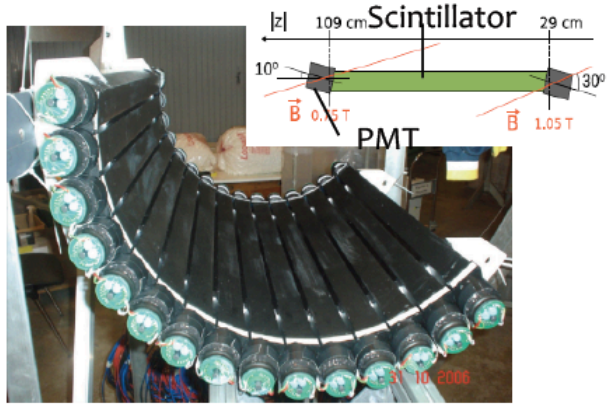
Full integration prototype



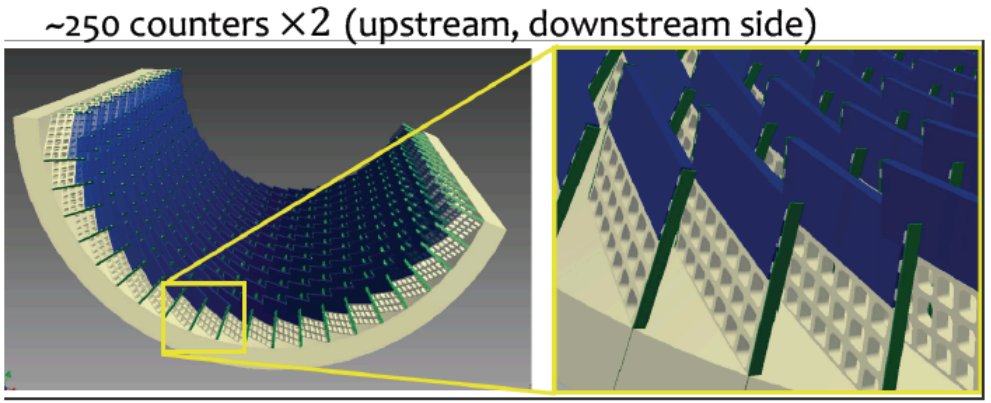
Stereo angle concept test

Full length prototype

New Positron Timing counter



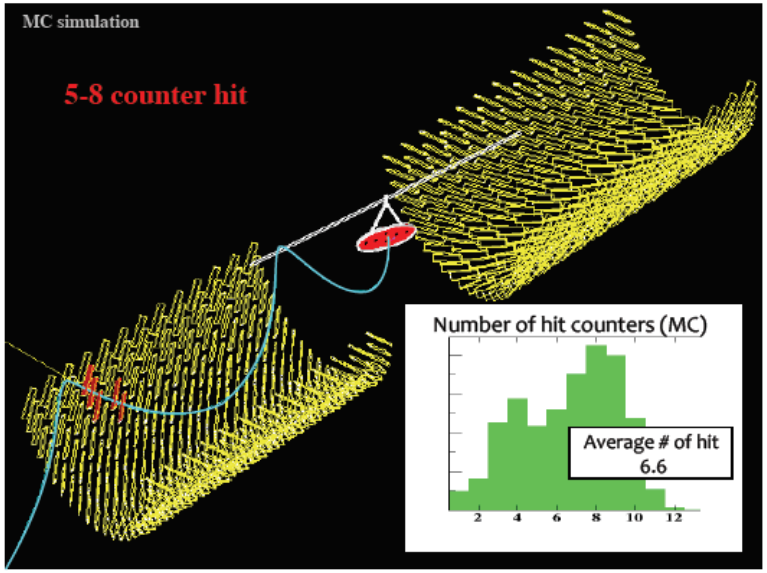
Present



Upgrade

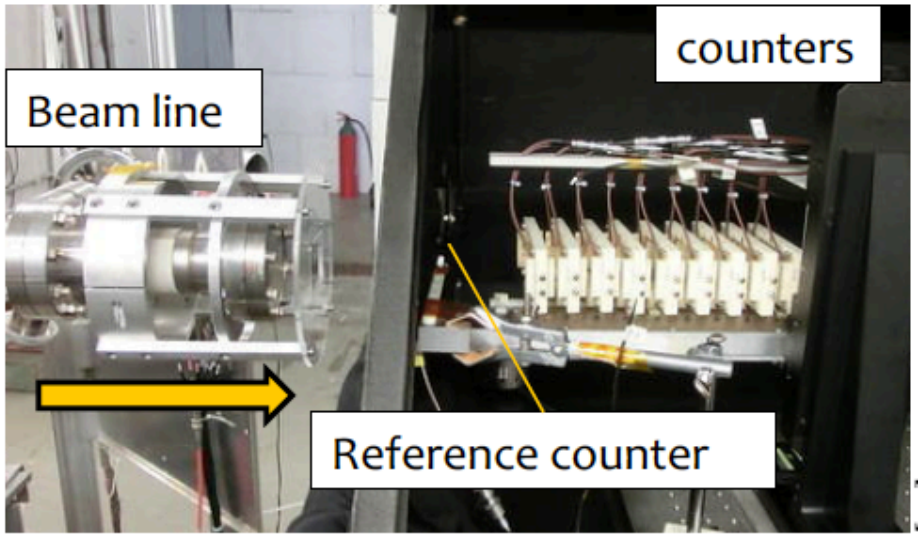
Pixelated detector

- 600 counters read out by SiPM
- Many time measurements per track
- Better geometry (pixel along track direction)
- Better handling of pile-up

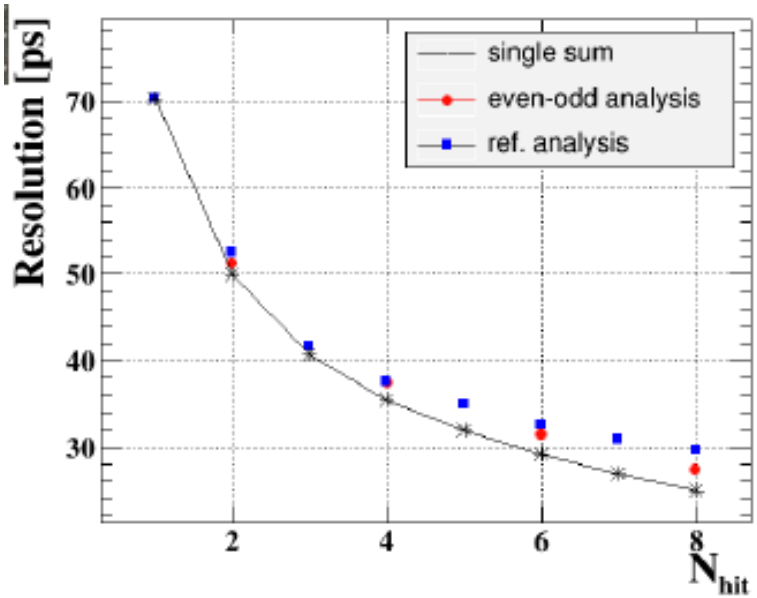


TC PROTOTYPING

Test at LNF BTF



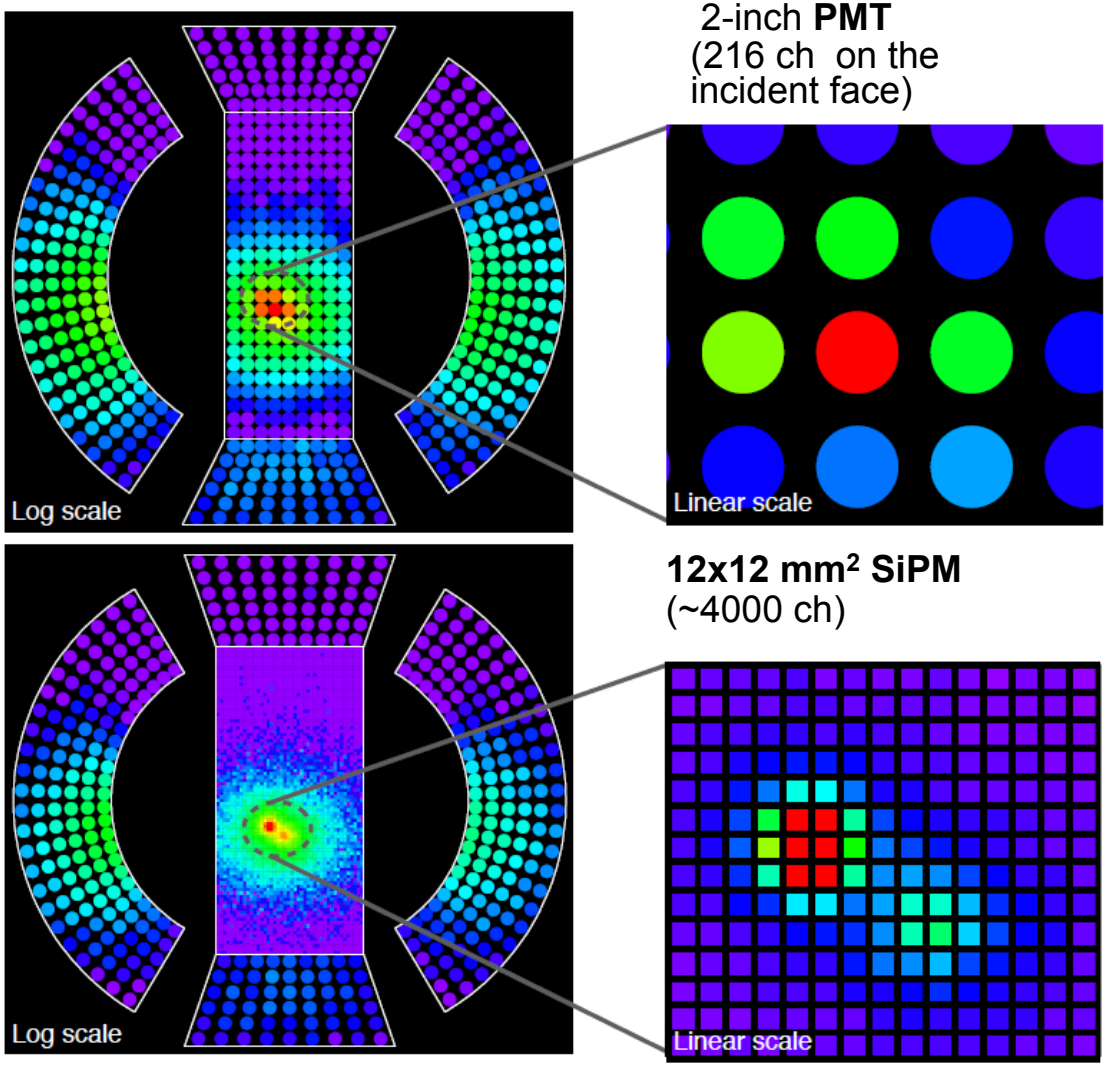
Single counter



Series of 5 SiPM reading a scintillator tile

Tim resolution < 40 ps achieved !

UPGRADED LXE DETECTOR

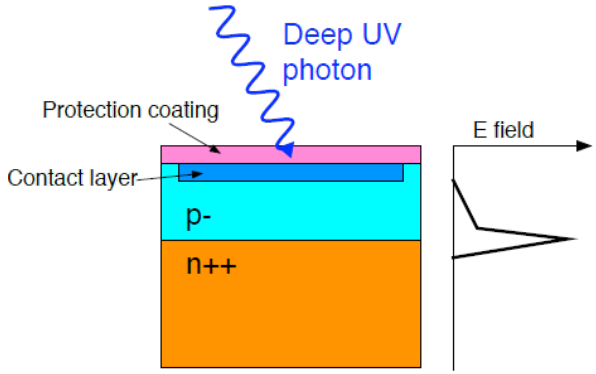


- Smaller devices
  - Better light collection
- PMT rearrangement
  - Better light containment

Better position and energy resolution for shallow events

New BIG SiPM

1. **VUV sensitive** : $\lambda \sim 175$ nm for LXe scint.
2. **large area** : 10x10 mm^2 → ~4000 channels
3. **fast** : large sensor shows long tail.
   Bad S/N, time resolution and pileup



Remove protective layer and use *quartz* protection!

Developed with Hamamatsu

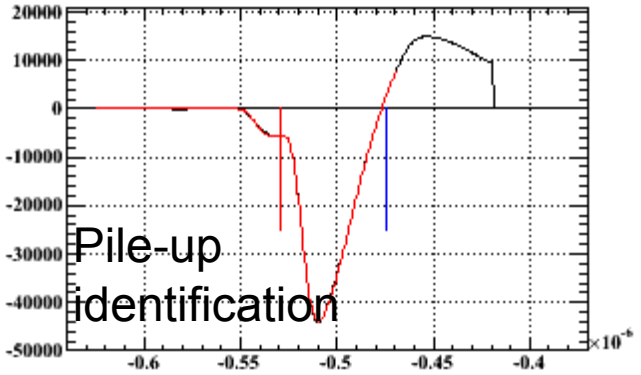
PDE > 15%

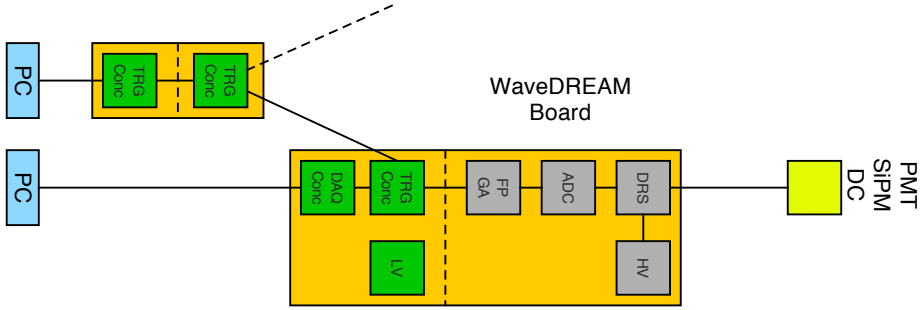
Short pulse shape
& good S/N
by adopting
a novel SiPM
connection method

New Electronics

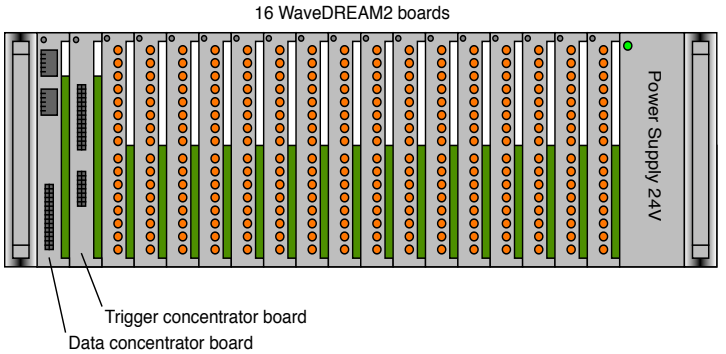
- Four times more channels
- Preserve full waveform recording

- multi-functional digitization board integrating both digitization and triggering





Compact system

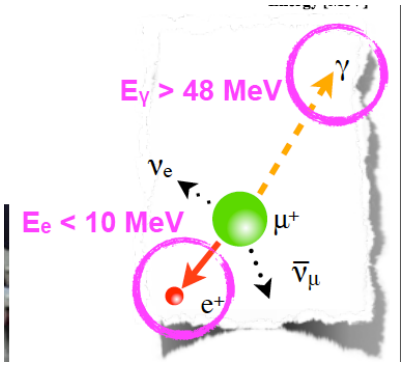


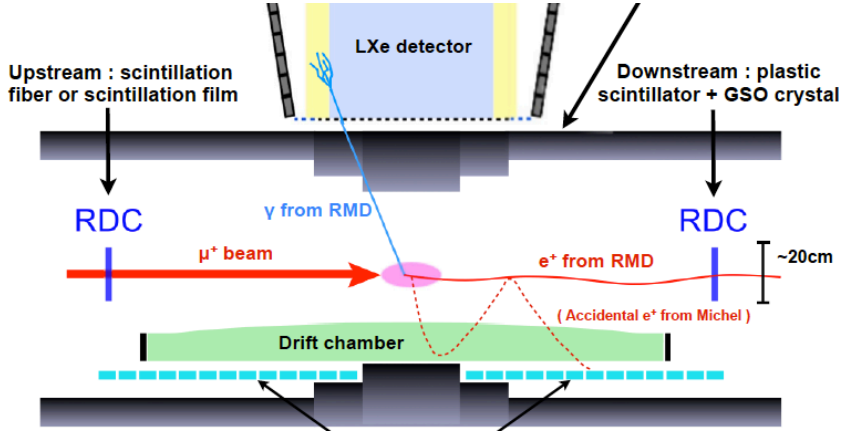
3U Eurocard with custom backplane

Design is going on, prototype available soon, will be used in test beams

Ancillary Devices

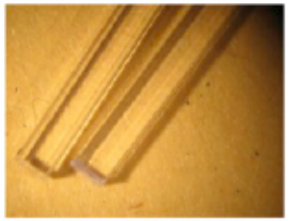
Radiative decay counter



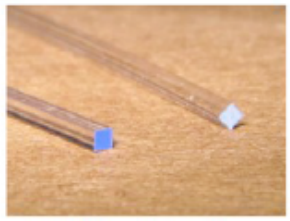


Active target

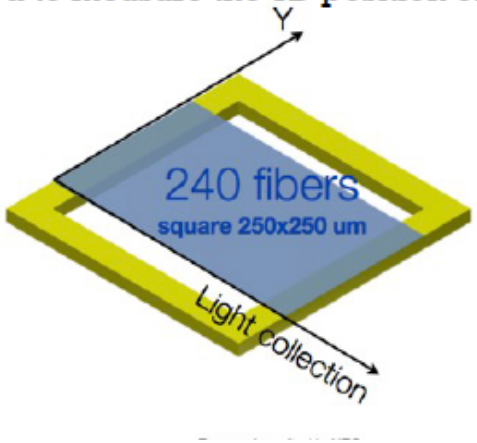
Active target using scintillation fibers is proposed to measure the 1D position of the emitted positrons
- Scintillation light will be read by SiPMs
- Efficiency is important key



Not polished and polished



Not Al and with 30nm Al deposit



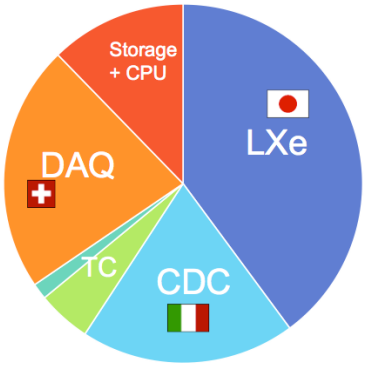
Not yet part of the MEG-II detector, but R&D well advanced.

MEG-II TIMELINE

arXiv:1301.7225

- A six year program
- Assuming exclusive use of PiE5 beam line at PSI during data-taking

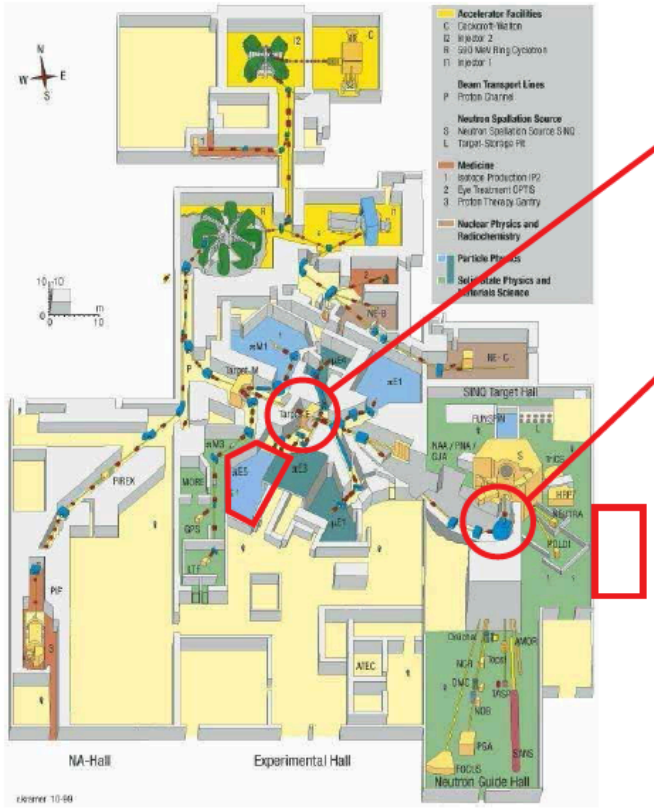
The upgrade program is fully funded (5.5 M$) and is proceeding in time



- Construction phase will start at the end of 2014/beginning 2015

Future plans at PSI

Muons from PSI



DC muon beams at PSI:

- πE5 beamline: ~ 10^8 muons/s
  (MEG experiment, Mu3e phase I)

Currently available

- SINQ (spallation neutron source) target could even provide
  ~ 5×10^{10} muons/s
  High intensity muon beamline (HIMB) proposal

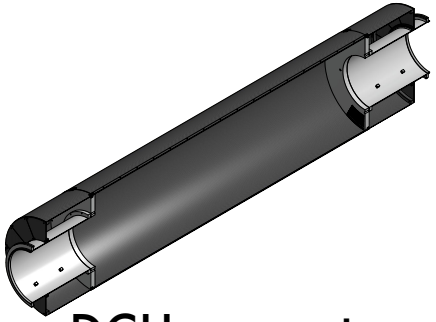
After 2017 (?)

- The $\mu \rightarrow eee$ experiment (final stage) requires 2×10^9 muons/s focused and collimated on a ~2 cm spot

Niklaus Berger – Lecce, May 2013 – Slide 23

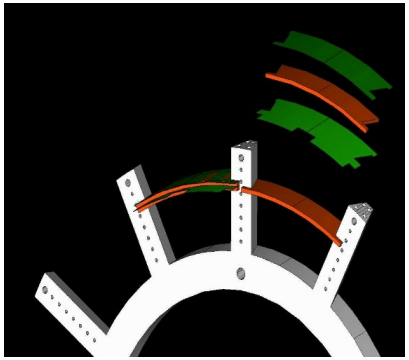
Status of the Upgrade

- DCH: test mounting procedure soon (wiring on PCB, PCB positioning,…) Start construction later this year



DCH support Structure

PCB on endcap



- XEC : beam test with 600 big SiPM reading LXe large prototype (beg. next year)
- TC: construct a realistic prototype and test it on beam (later this year)

Conclusions

- MEG at PSI has established a new constraint on the existence of the LFV $\mu \rightarrow e\gamma$ decay

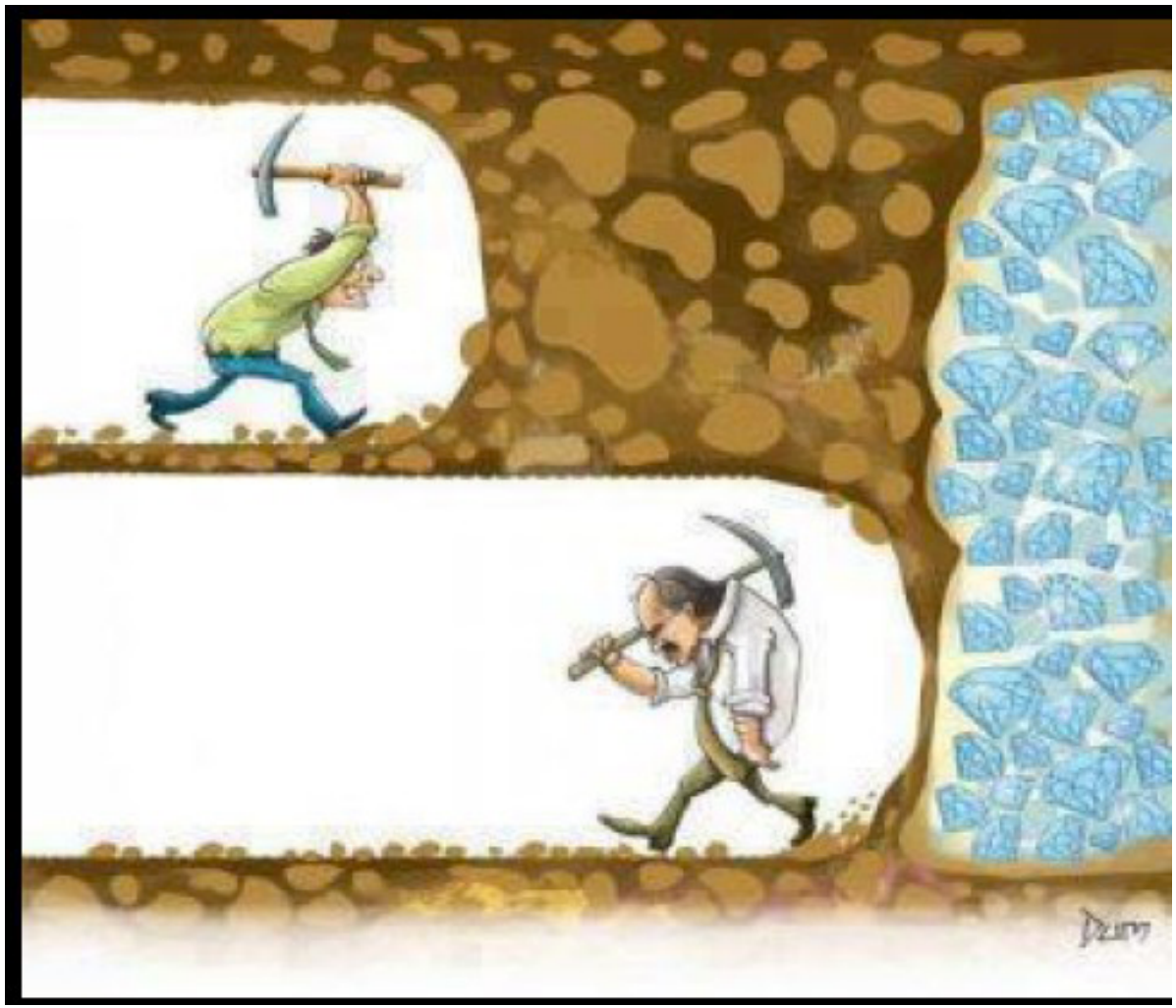
  $BR(\mu \rightarrow e\,\gamma) < 5.7 \times 10^{-13}$ at 90% C.L.

- The final MEG $\mathcal{S} = 5\ 10^{-13}$
  - Final results to be released soon

- MEG-II program is proceeding timely
  - Keep MEG basic design but improvement in all the subsystems, important upgrade of the positron spectrometer

- By 2018 ultimate sensitivity will be $\mathcal{S} = 5\ 10^{-14}$

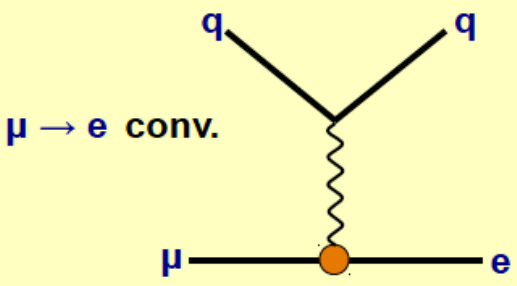
Never Give up...



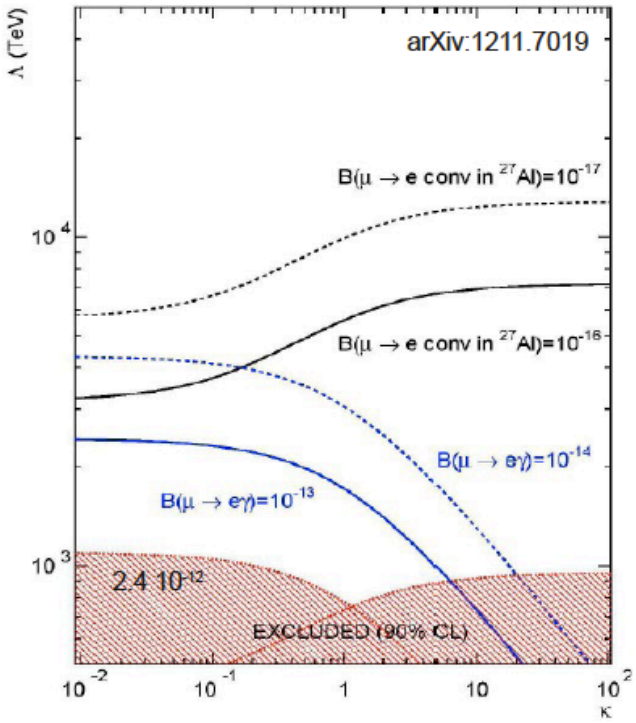
Back up slides

Model independently...

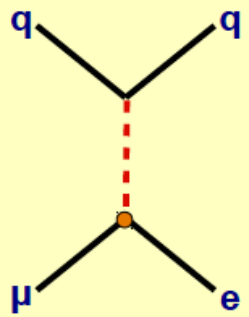
dipole couplings



$\kappa \to 0$



eμqq contact IA



$\kappa \to \infty$

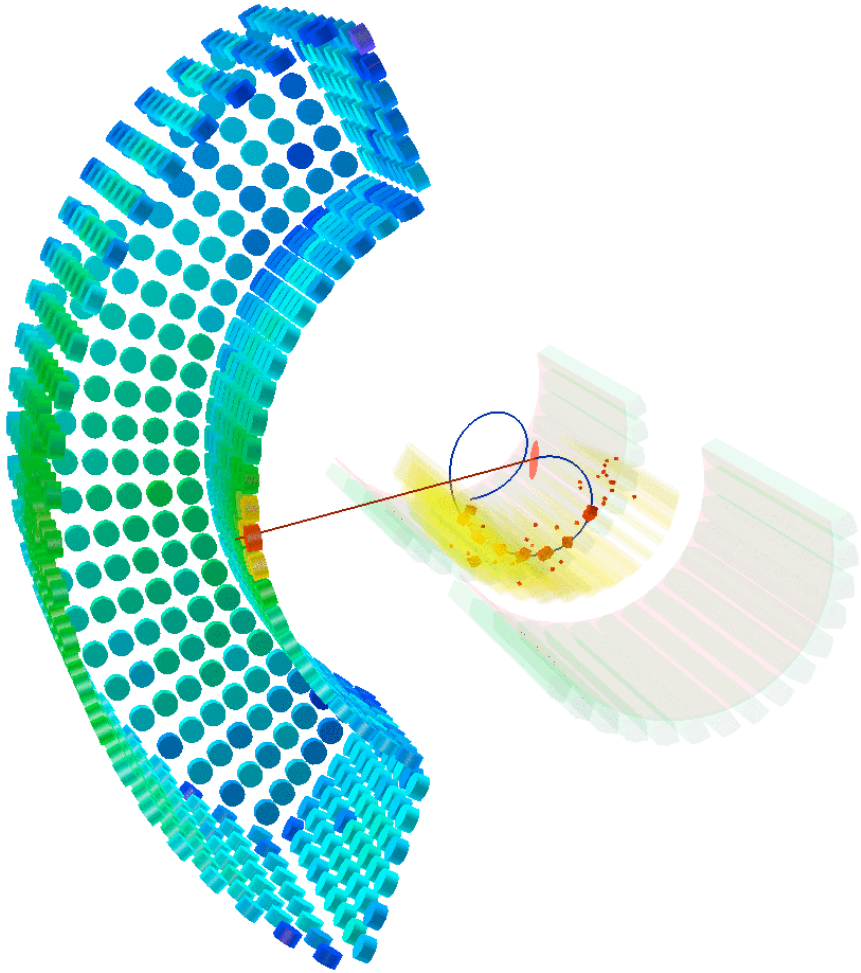
κ = model parameter

Λ = common effective mass scale

Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu,qq}$$

Event Display



MAX. LIKELIHOOD ANALYSIS

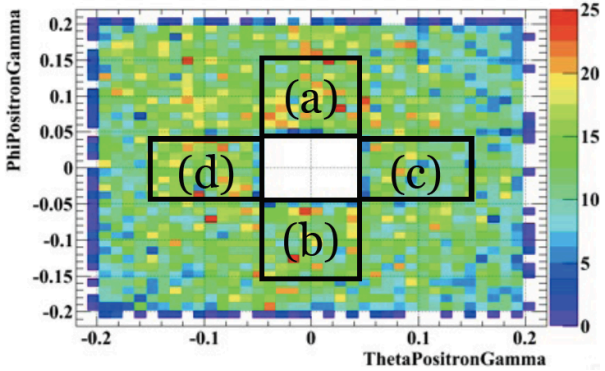
- Extended maximum likelihood analysis
  - Determine number of signal S in signal region
  - Constraints on background rate (Accidental [A] and radiative [R]) from sidebands
- Probability Density Function (PDF) from data
  - Resolution from sideband analysis or dedicated samples
  - Background PDF directly from sidebands!
  - Event-by-event resolution

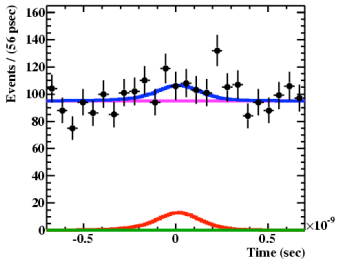
$$\mathcal{L}(\vec{x}_1,\ldots,\vec{x}_N,R_\diamond,A_\diamond|\hat{S},\hat{R},\hat{A}) = \frac{e^{-\hat{N}}}{N!} e^{-\frac{1}{2}\frac{(A_\diamond-\hat{A})^2}{\sigma_A^2}} e^{-\frac{1}{2}\frac{(R_\diamond-\hat{R})^2}{\sigma_R^2}} \prod_{i=1}^{N} \left(\hat{S}s(\vec{x}_i)+\hat{R}r(\vec{x}_i)+\hat{A}a(\vec{x}_i)\right)$$

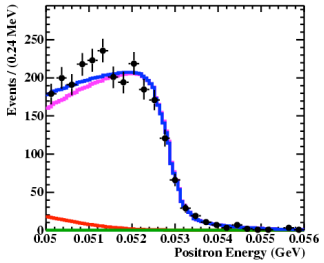
Fit to sideband

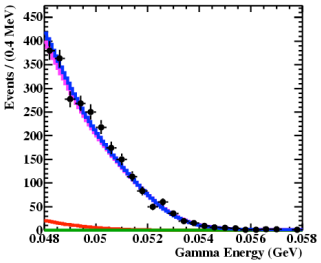
Fictitious analysis regions in the **sidebands of E_γ, $T_{e\gamma}$** and relative angles used as control samples

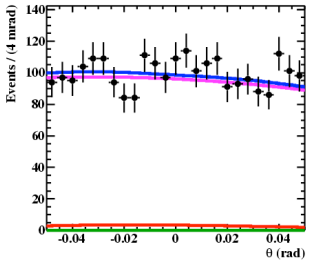
Angle sideband definition (events with $T_{e\gamma} \approx 0$)

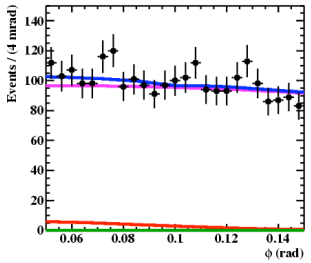






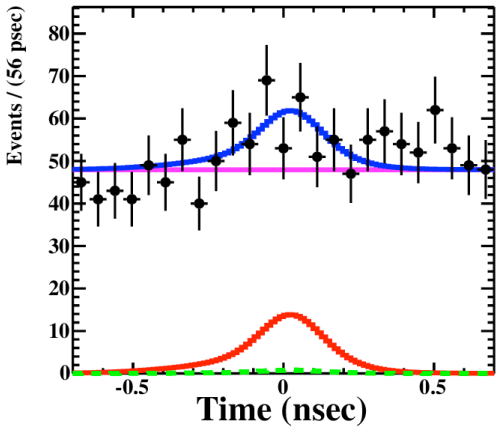


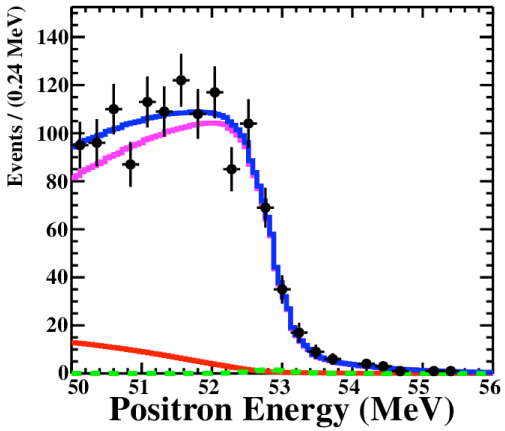


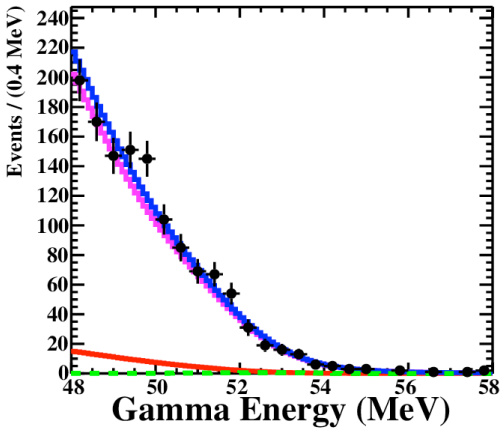


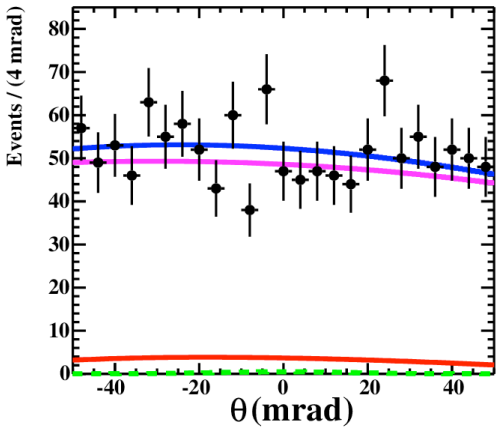
Limits consistent with toy MC studies

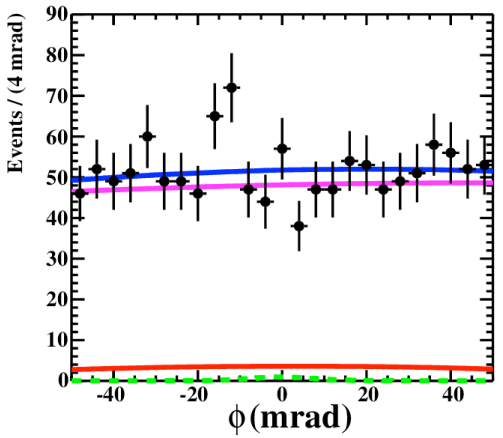
2009 & 2010 Results











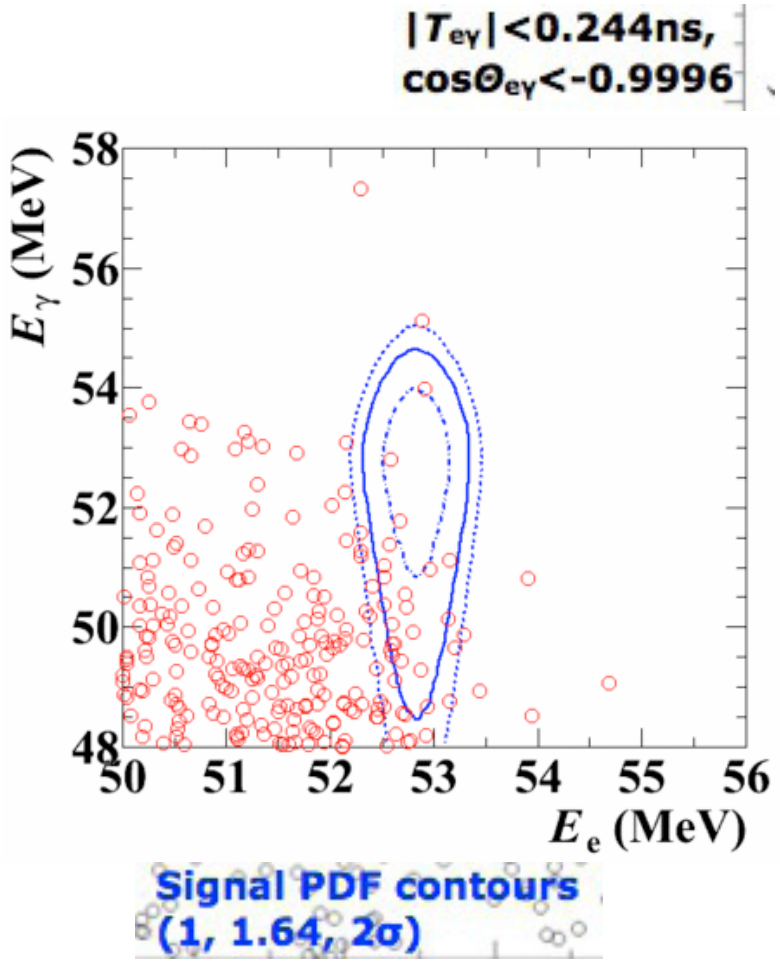
S = 0.3 +4.1 -1.5

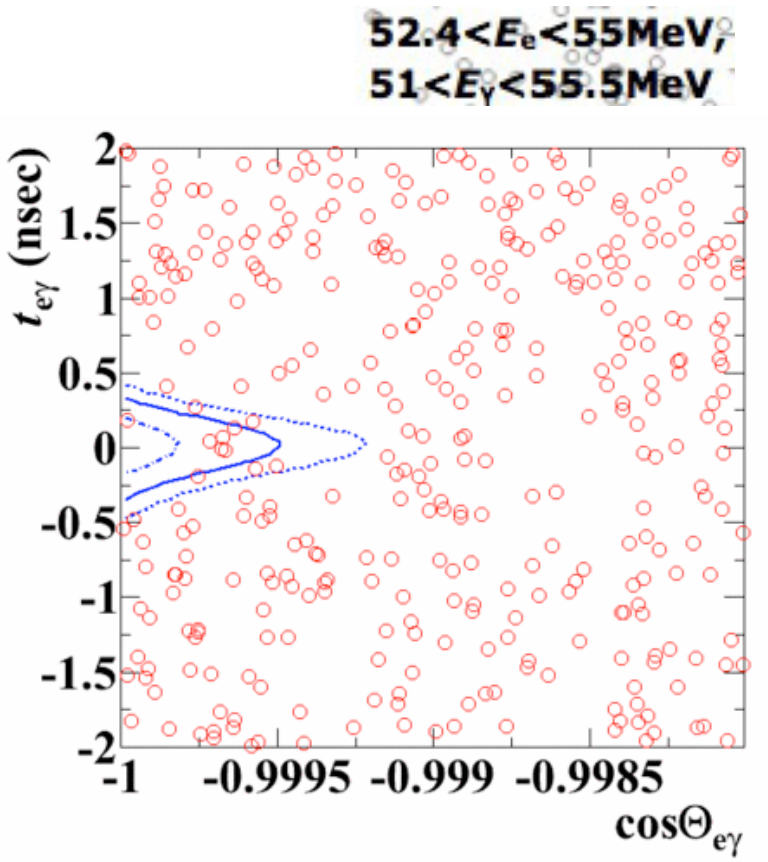
A = 1198± 26

R = 83± 13

[MINOS errors]

Distribution of events

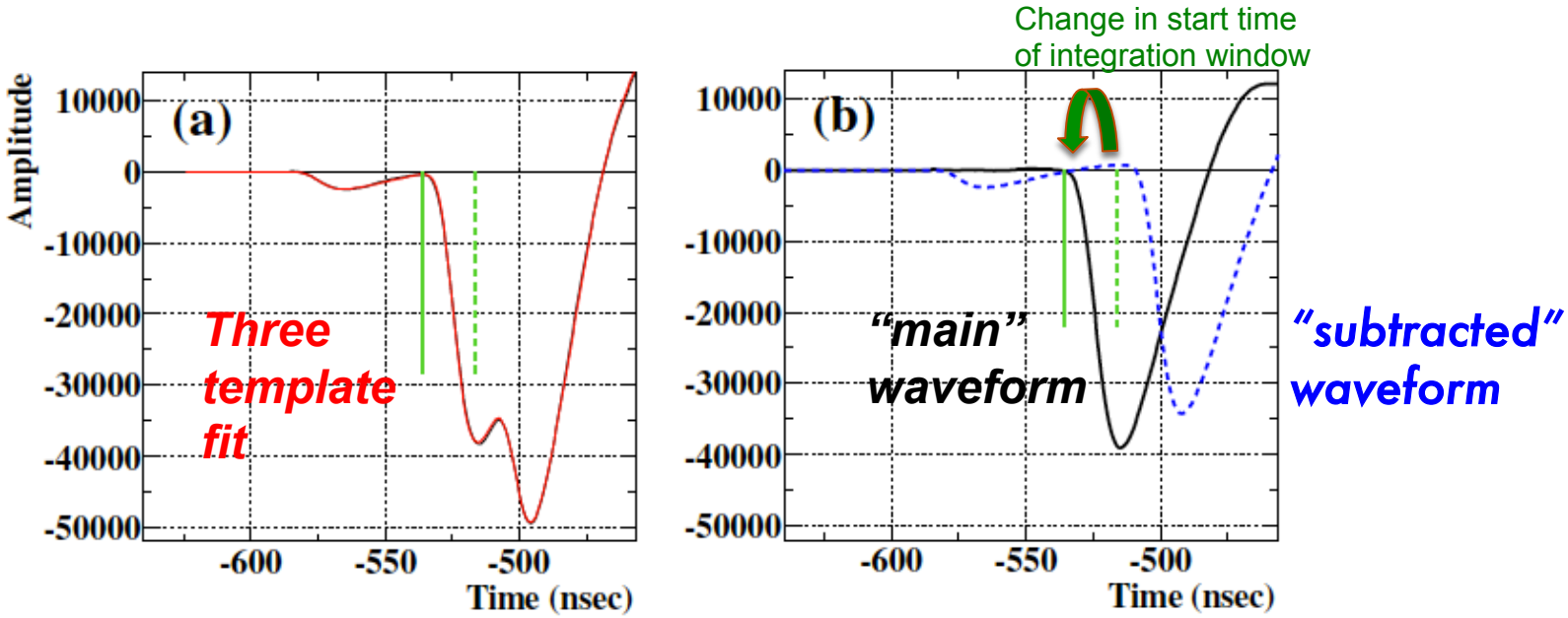




Signal PDF contours
(1, 1.64, 2σ)

XEC SumWaveform Analysis

- Meant to identify pile-up events and improve E_γ resolution
  - Light distribution in XEC not good enough
- Sum all the PMT (weighted) waveform
  - Based on time and position reconstruction
- Multi-template fit: main wf is the closest to event time



Crucial for high beam rate !

Summary of performances

	2009	2010	2011	Note
Gamma E [%]	1.89	1.90	1.65	Effective sigma
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(u,v)6(w)	5(u,v)6(w)	5(u,v)6(w)	
Trigger/DAQ efficiency [%]	91/75	92/76	97/96	
Gamma efficiency [%]	63	63	63	π^0 sample
Positron efficiency [%]	43	36	36	From MC

Measured quantities are reported here

Correlation and per-event event error included in the ML

"NORMALIZATION" FACTOR

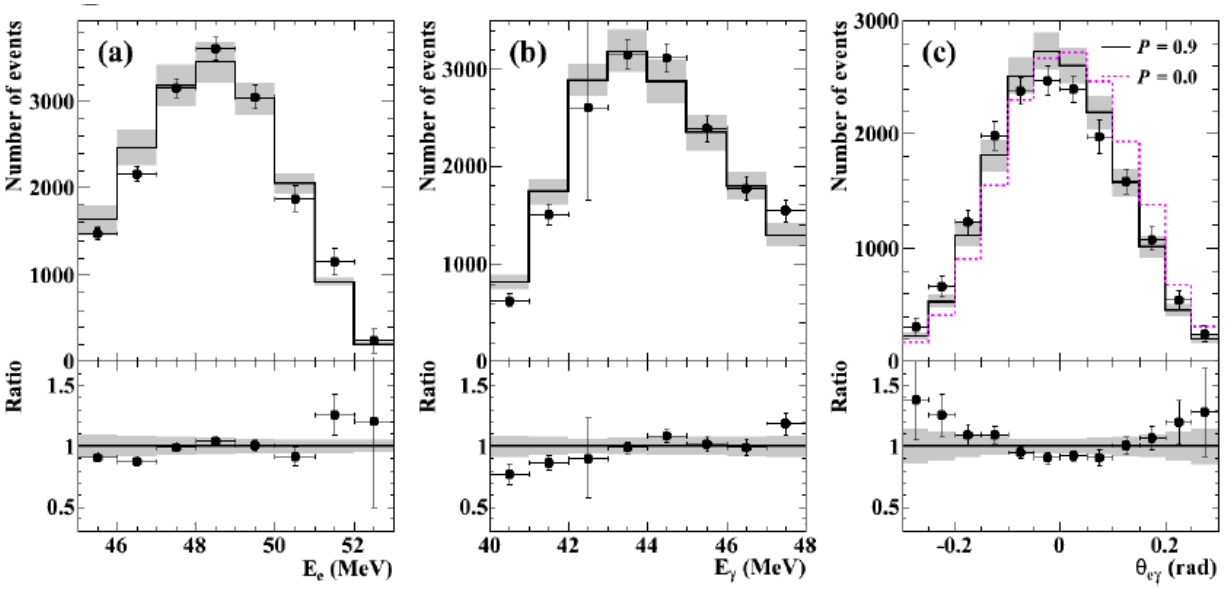
$$N_{e\gamma} = BR(\mu^+ \to e^+\gamma) \cdot k$$

TWO METHODS:

Count (prescaled) **Michel** positron – correcting for small difference with signal

Count **radiative** decays

Projected RMD distributions (2011 data)



	k (Michel) [10^{12}]
2009	**1.21± 0.07**
2010	**2.66 ± 0.13**
2011	**4.10 ± 0.20**

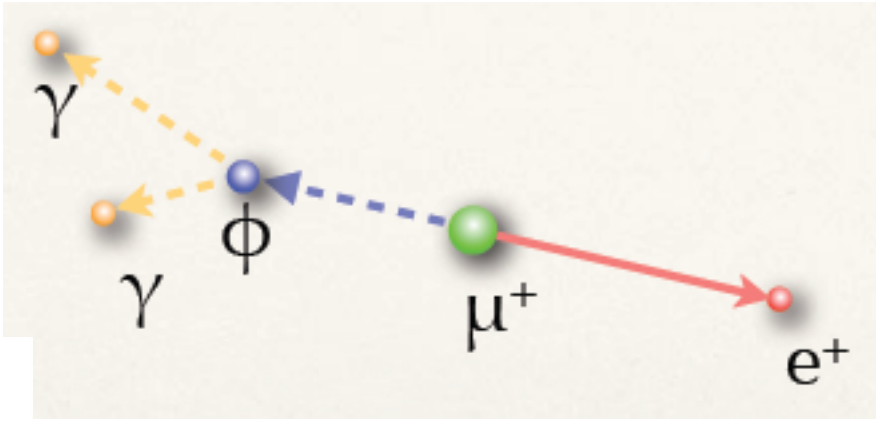
In 2011 data k(RMD) = 3.96 ± 0.24 10^{12}

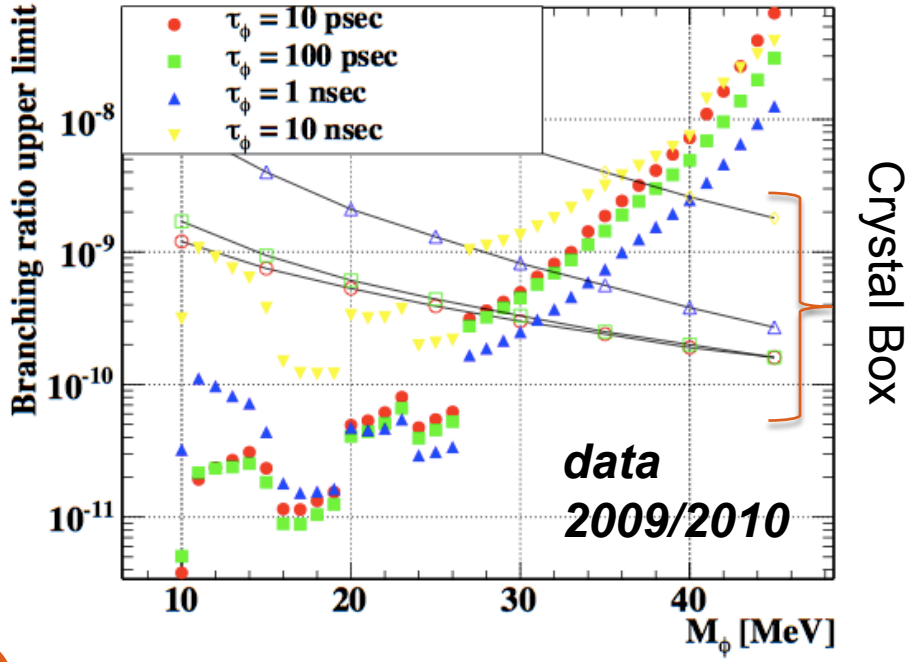
Other searches and measurement

- Measurement of RMD ($\mu \to e\nu\nu\gamma$) branching ratio and decay parameters
  - *Subject of a paper in preparation*
- Search for $\mu \to eJ$ *with* J *a (almost) massless particle [Majoron]*
  - *MEG could improve TWIST limit with full MEG stat*
- Search for $\mu \to eJ\gamma$
  - *Feasibility study on going (we could improve Crystalbox limit)*
- Muon polarization
  - *Measurement done, subject of a paper*
- Polarized muon lifetime in flight
  - *Exotic theory predicting a different value*
  - *Data without MEG target to be analyzed*

SEARCH FOR $\mu \to e$"ϕ", $\phi \to \gamma\gamma$

- Long lifetime, small mass resonance "ϕ"





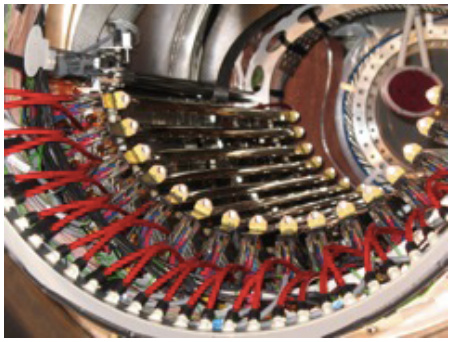
Crystal Box

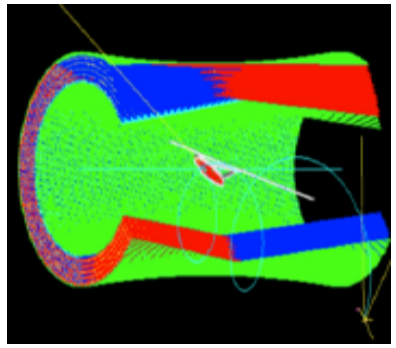
No signal at 90% CL

Full stat. (2009 to 2013) can improve it by a factor 3

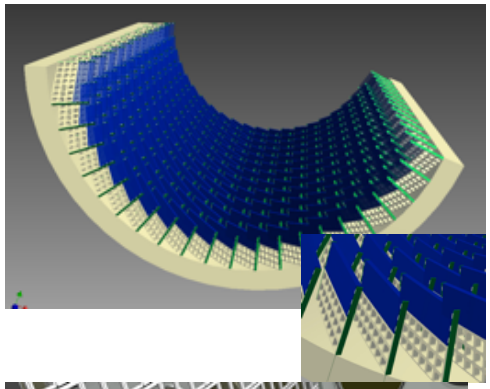
Upgrade Detectors

- Single volume DCH with stereo angle wires configuration





- Scintillator tiles TC with SiPM readout



- SiPM readout XEC with a larger sensitive volume
- Thinner target or active target