Searching for the LFV decay $\mu \to e\gamma$ with MEG and MEG-II

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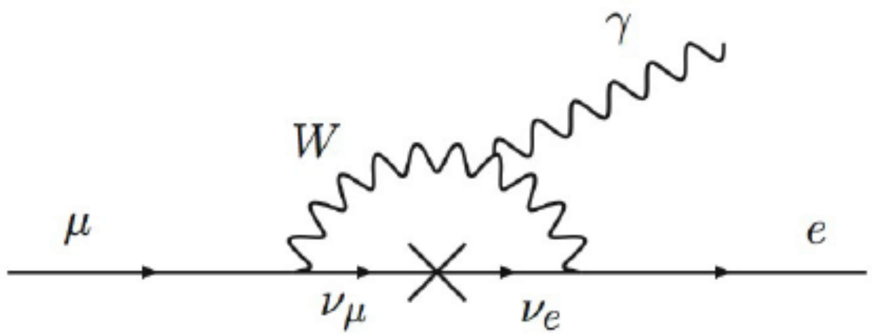
on behalf of the MEG collaboration

4th workshop on flavour symmetries and consequences in accelerators and cosmology

University of Sussex 17-21 June 2014

Why μ→eγ? - theory

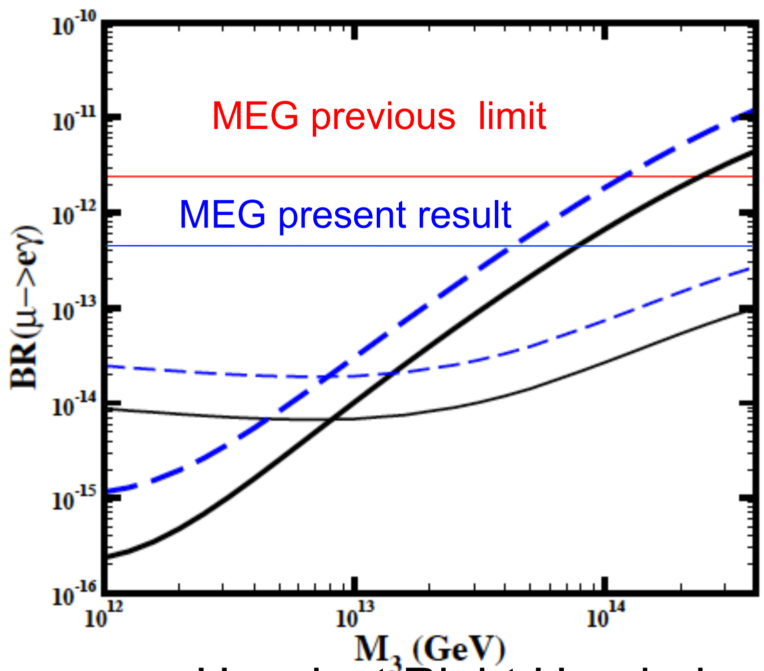
- As for other charged lepton flavor violating decays: allowed but unobservable in the Standard Model (SM)



$$BR(\mu \to e\gamma)\big|_{SM} < 10^{-50}$$

M.Cannoni, J.Ellis, et al.
Phys Rev D 88 075005

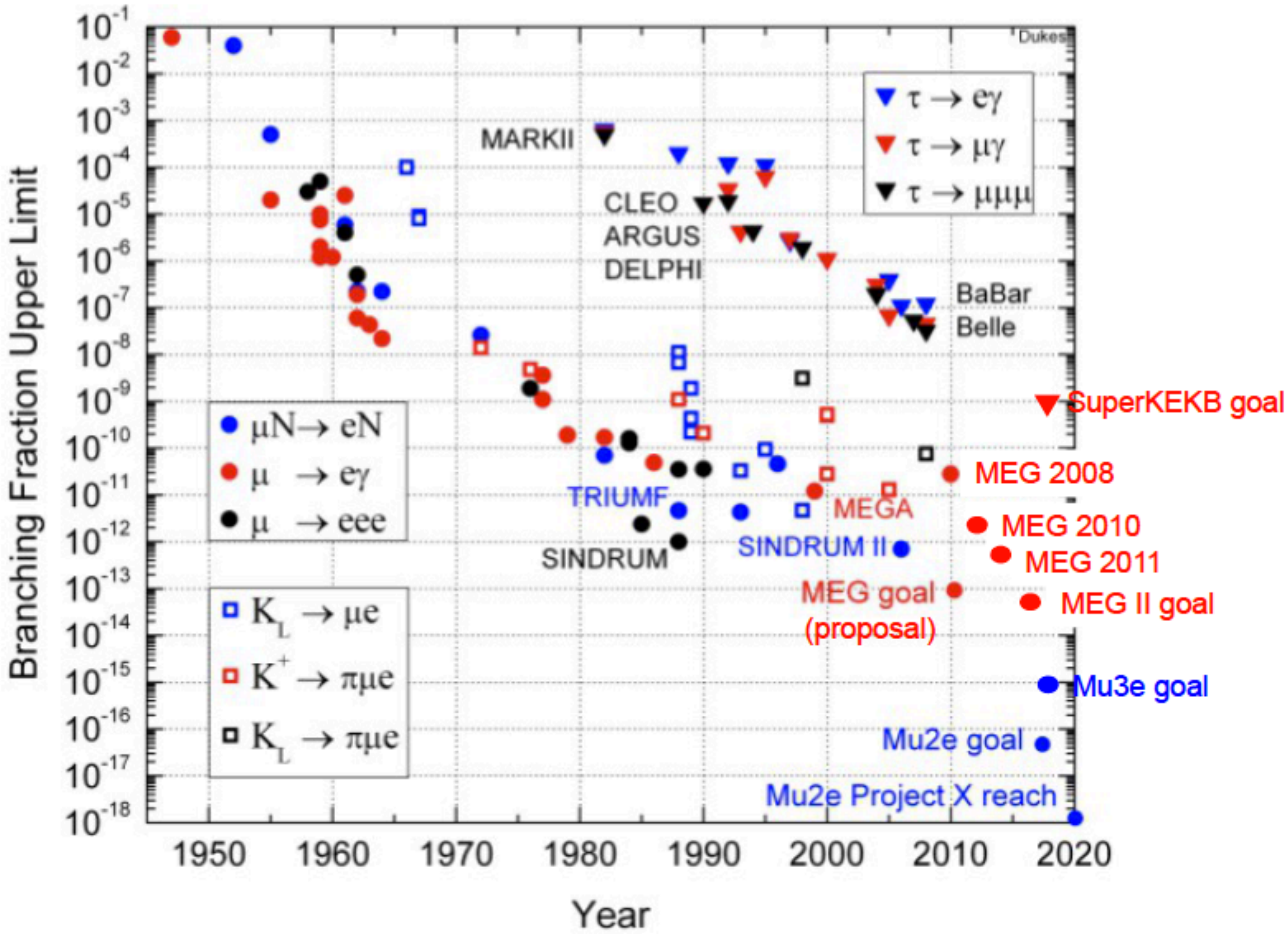
- Enanched (sometimes just below experimental limit) in many New Physics Model



Heaviest Right Handed
ν mass

Observation of μ→eγ is Physics beyond SM

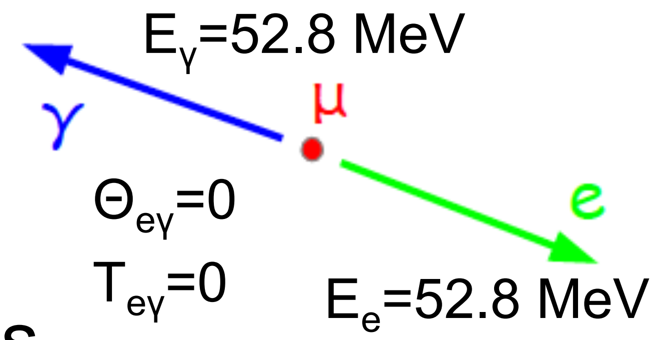
A long quest


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

Why μ→eγ? - experiment

- Intense muon beams available
- Clear two-body signature
  (muon decays at rest)
- Very good experimental resolutions
  are needed to suppress backgrounds

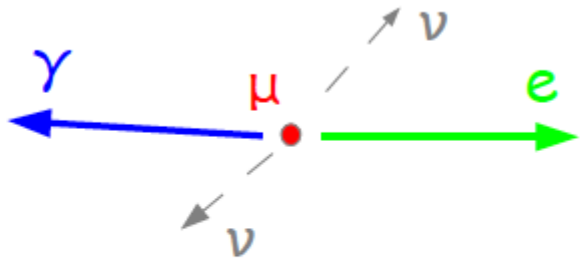
SIGNAL



ACCIDENTAL BACKGROUND

Rate goes with square of beam intensity

RADIATIVE MUON DECAY

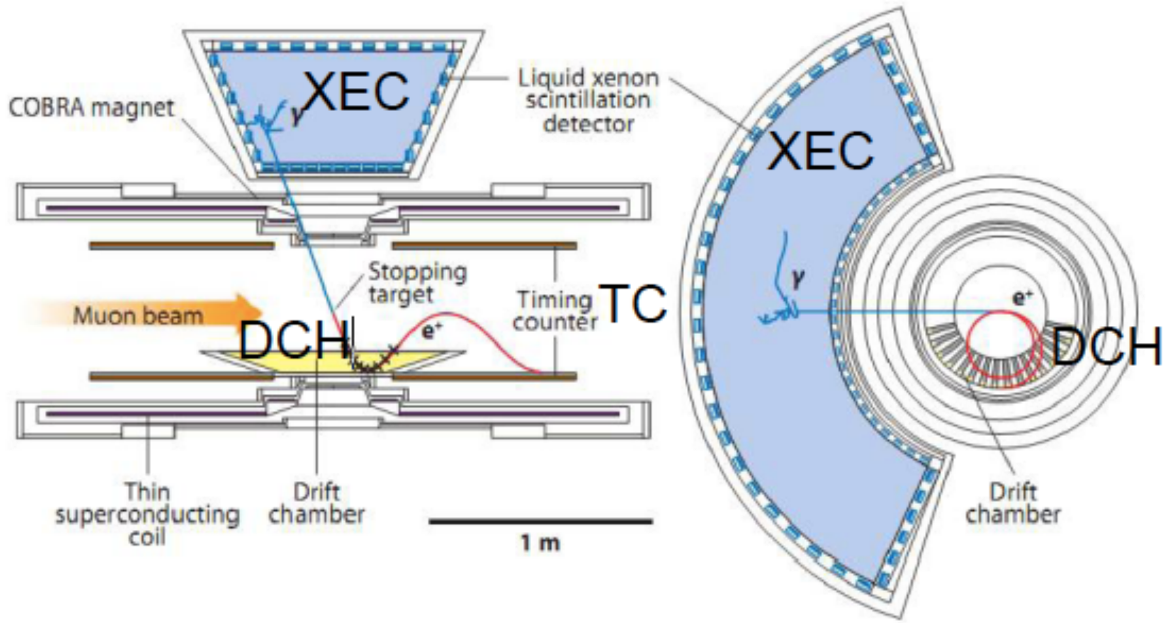


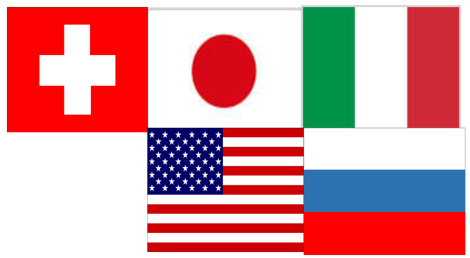
The MEG experiment

J. Adam et al., Eur.Phys.J. C 73(2013) 2365

- Paul Scherrer Institut: most intense muon beam in the world up to 10^8 μ^+/s ($3x10^7$ μ^+/s used)

- 900l liquid Xe detector
- Low mass drift chambers planes with fast scintillators in a gradient magnetic field

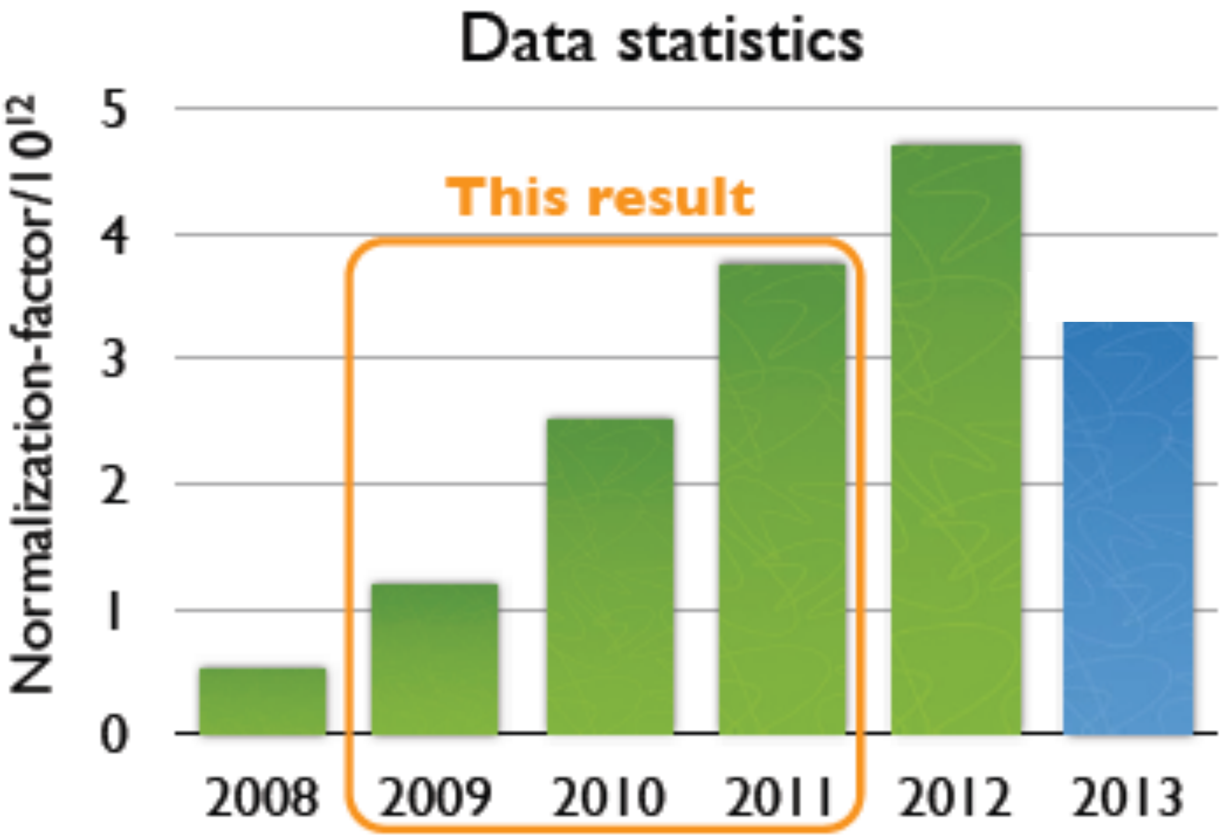




MEG Datasets

- New results on full data set will be released soon

Effective number of muons stopped on target

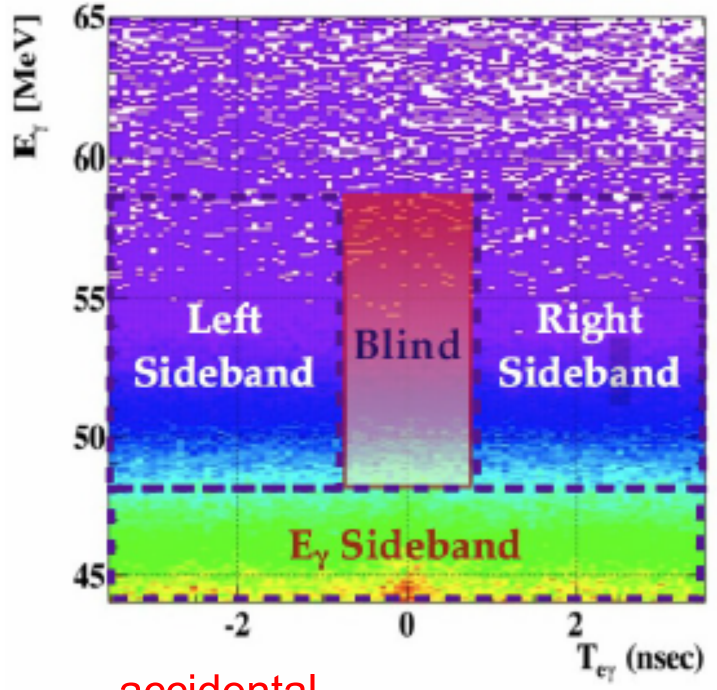


Analysis strategy

- Blind-box likelihood analysis strategy

- Observables: $E_{e+}, E_\gamma, \theta_{e\gamma}, \varphi_{e\gamma}, T_{e\gamma}$
  (energies, relative angle and time)

- Careful treatment of correlations



constrained from sideband

accidental

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

signal

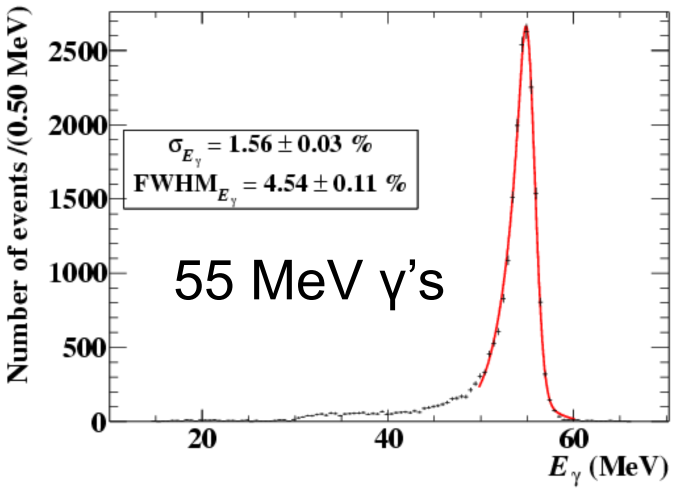
radiative

- Signal and radiative decay PDF by combining the results of the calibration procedures

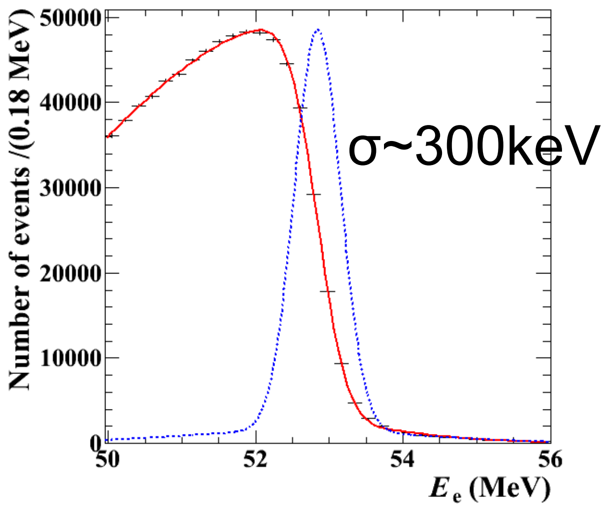
- Accidental background PDF from data sidebands

PDF definitions

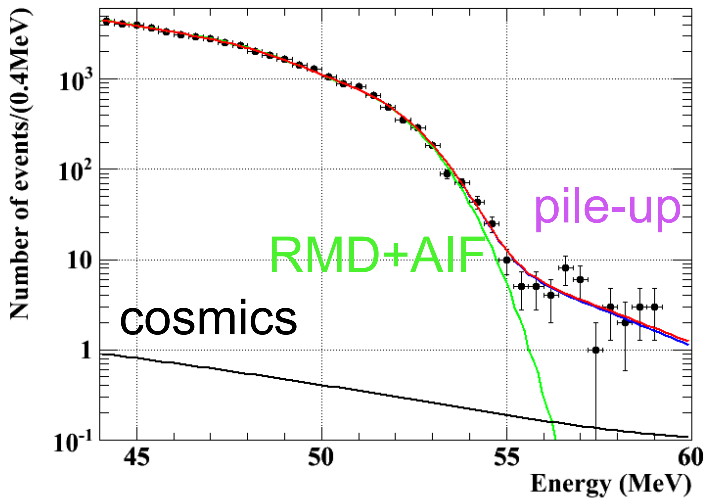
E_γ signal from CEX calibration ($\pi^- p \rightarrow \pi^0 n$)



E_e signal (fit to the edge) and accidental background from Michel spectrum

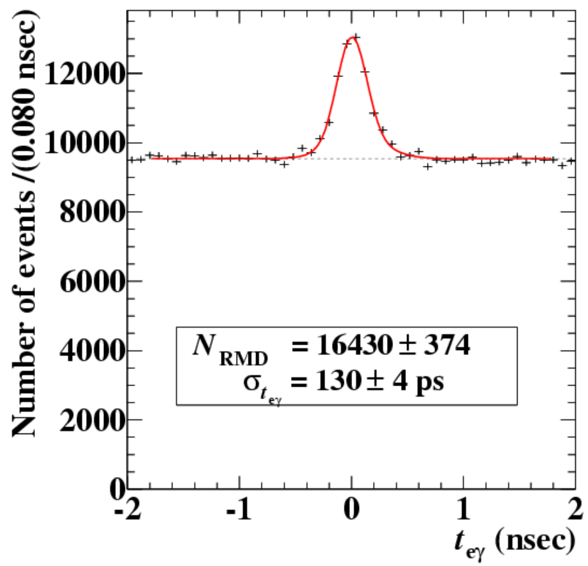


E_γ accidental background from data sidebands



$T_{e\gamma}$ from radiative decays in sidebands

Positron angular and position resolution from double turn tracks

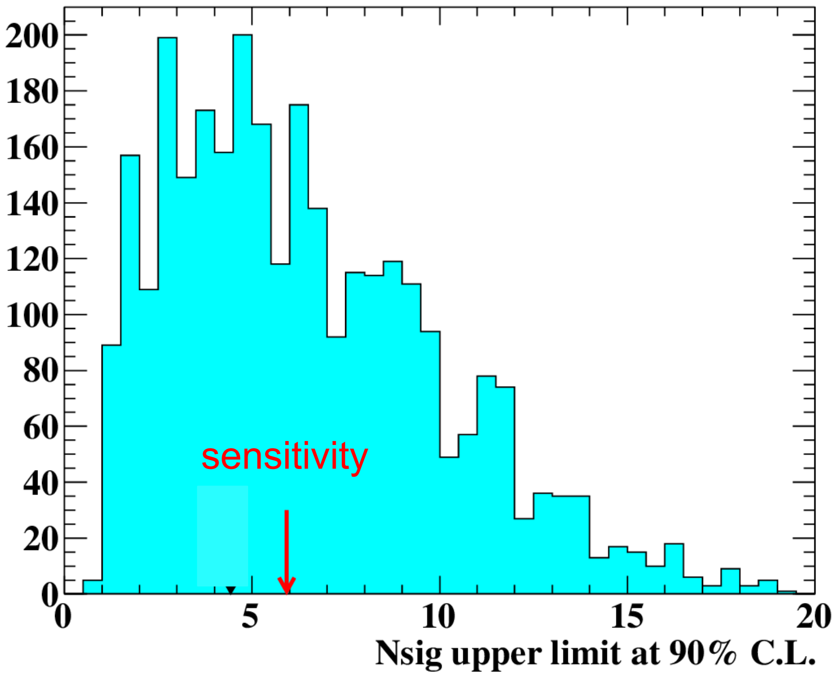


Statistical approach and sensitivity

Confidence intervals from a frequentistic procedure based on the profile likelihood ratio

$$\lambda_p(N_{SIG}) = \frac{\max_{N_{RMD},N_{ACC}} \mathcal{L}(N_{SIG}, N_{RMD}, N_{ACC})}{\max_{N_{SIG},N_{RMD},N_{ACC}} \mathcal{L}(N_{SIG}, N_{RMD}, N_{ACC})}$$

2009-2011 sensitivity

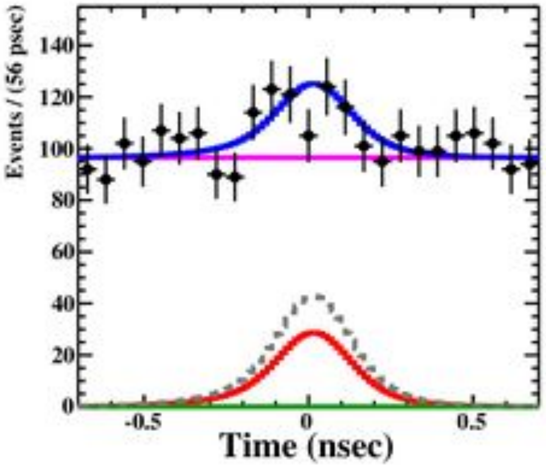


Sensitivity: median of upper limits from an ensamble of toy MC experiments (checked on data-sidebands)

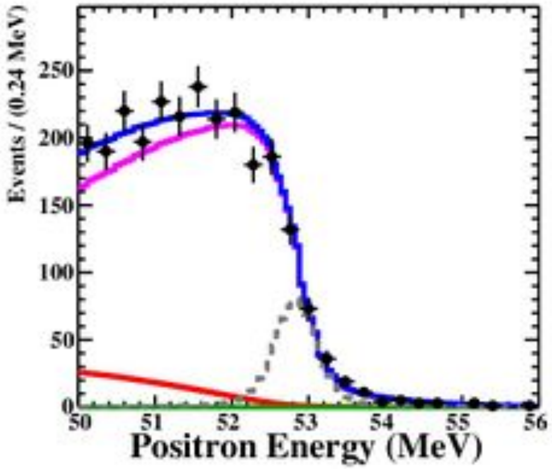
Branching ratio sensitivity: 7.7×10^{-13}

2009-2011 likelihood fit result

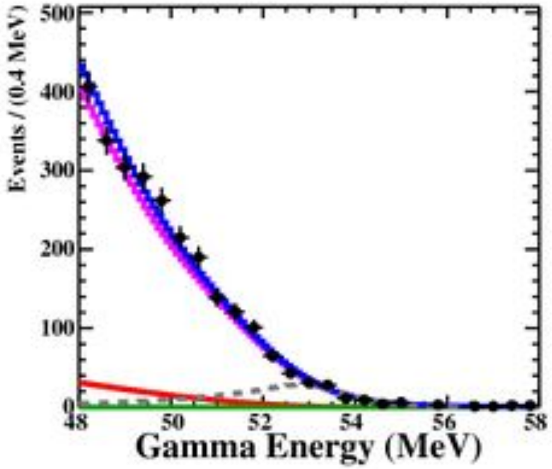
$T_{e\gamma}$

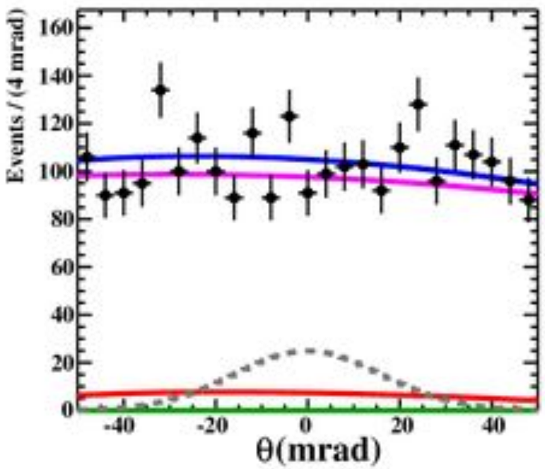


E_e

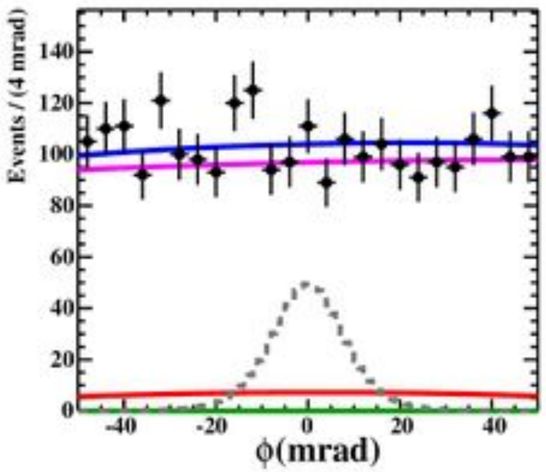


E_γ





$\theta_{e\gamma}$



$\varphi_{e\gamma}$

Signal=$-0.4^{+4.8}_{-1.9}$

Accidental=2414±37

Radiative=168±24

dotted line =pdfs for 250 signal events (for explicative purposes)

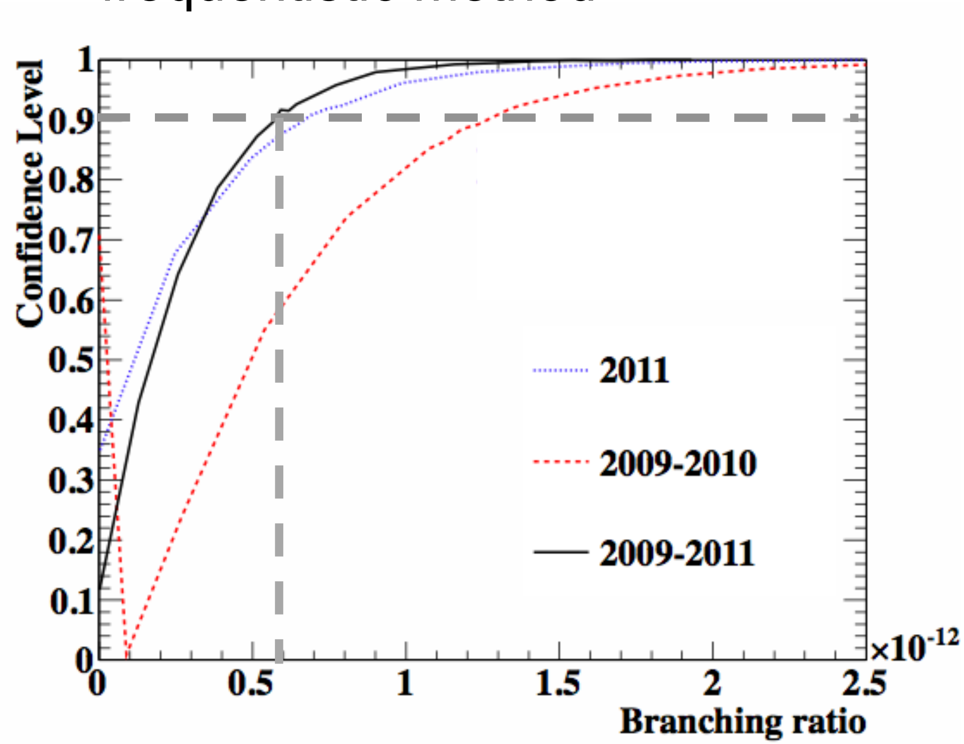
Physics results

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

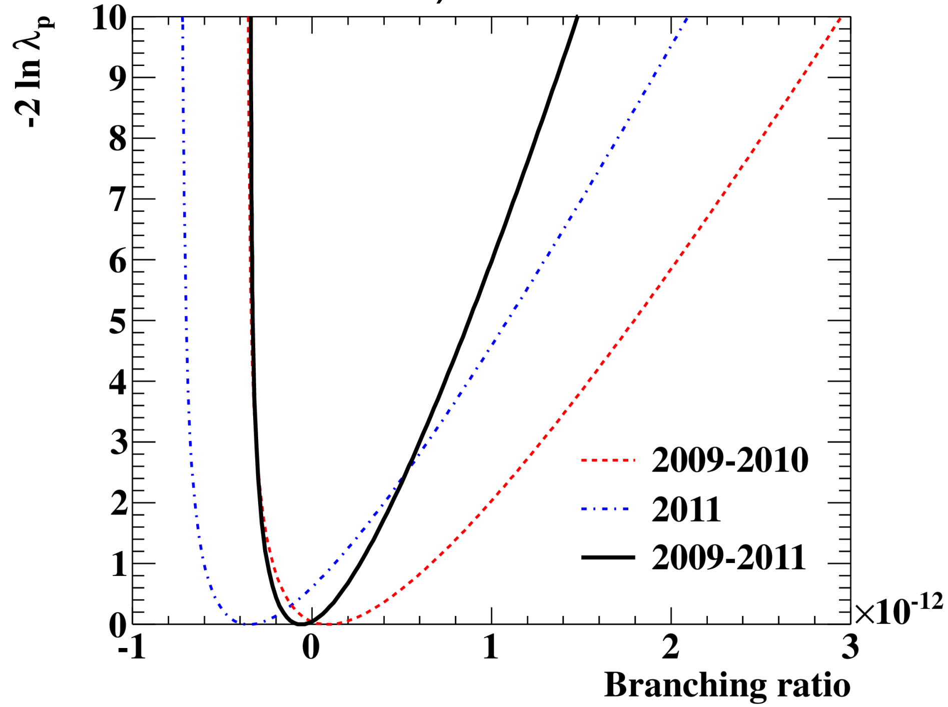
including systematics

PRL 110,201801(2013)

Confidence levels from the frequentistic method



Profile likelihood curves
(note that these curves are not used to derive the U.L.)

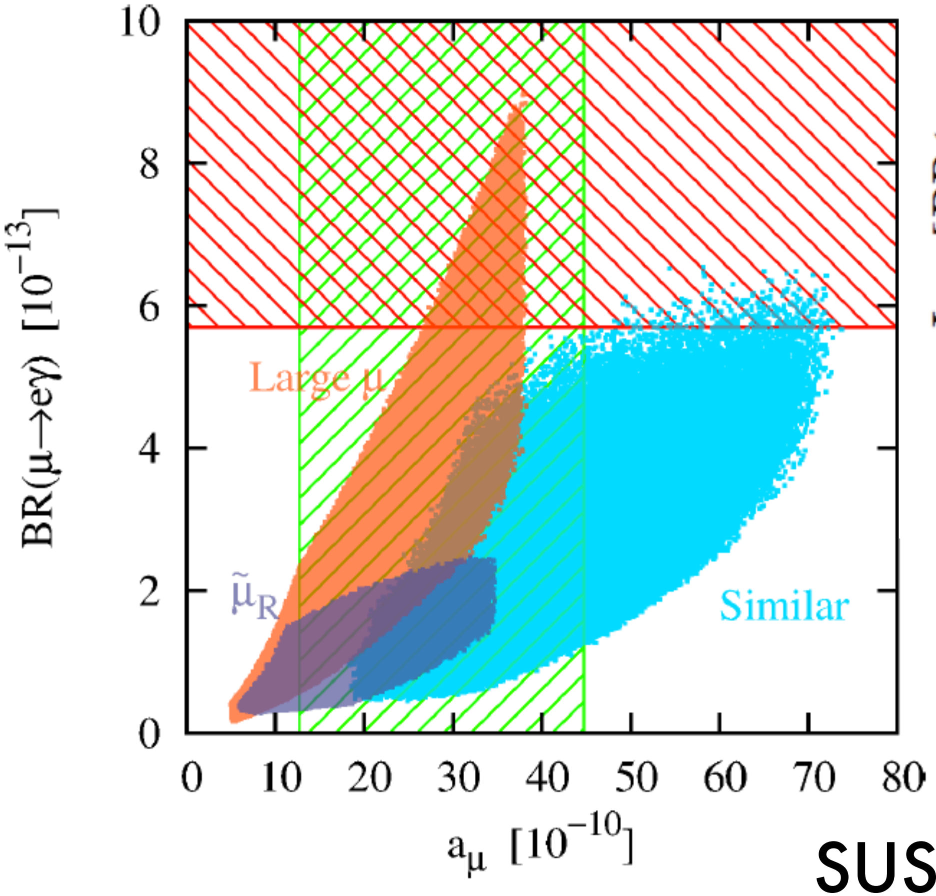


Normalization from the number of Michel decays and radiative decays

Constraints on new Physics

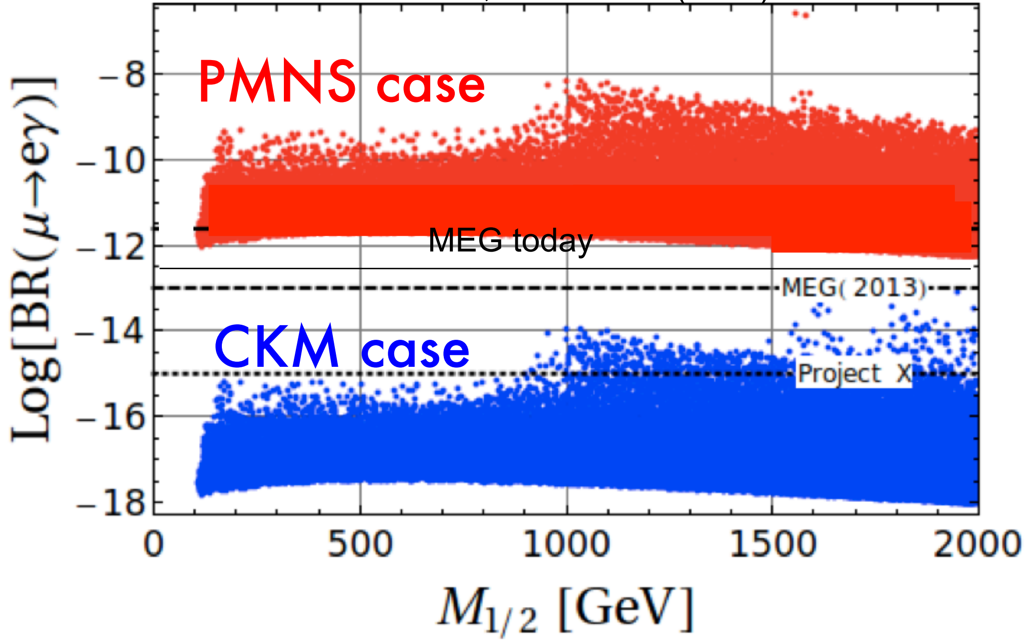
Correlations in MSSM

J.Kersten et.al. arXiv:1405.2972v1

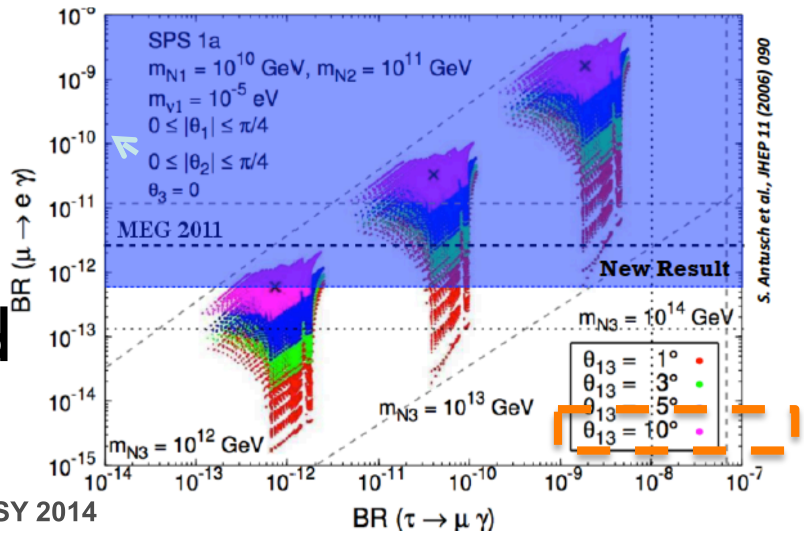


SSM type-I see-saw SO(10)

Calibbi et al., JHEP 1211 (2012) 040



SUSY and see-saw

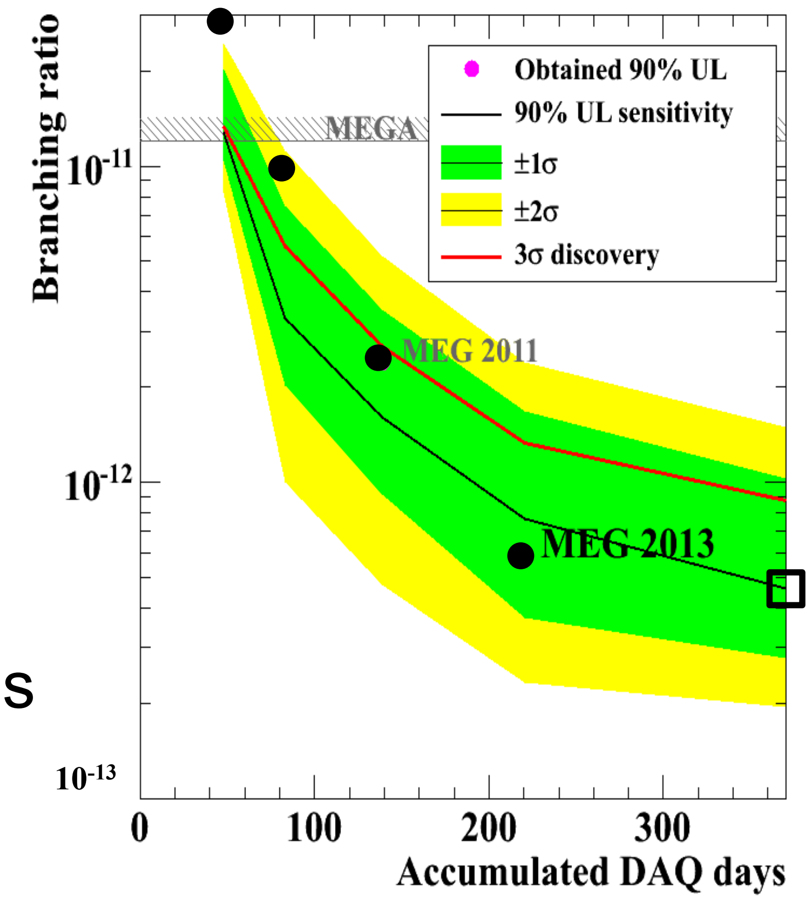


Outlook

- Current MEG result improves by a factor four previous result

- Final MEG sensitivity: ~5x10^{-13}

- We are approaching the limit of the current detector performances while the available beam rate is not fully exploited

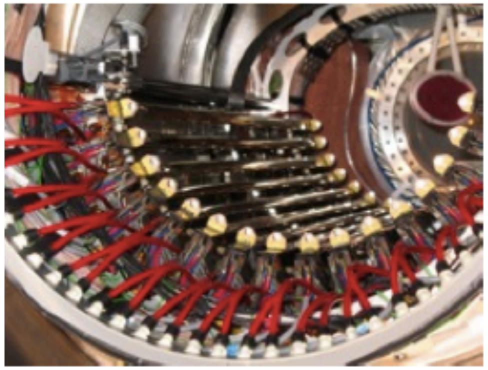


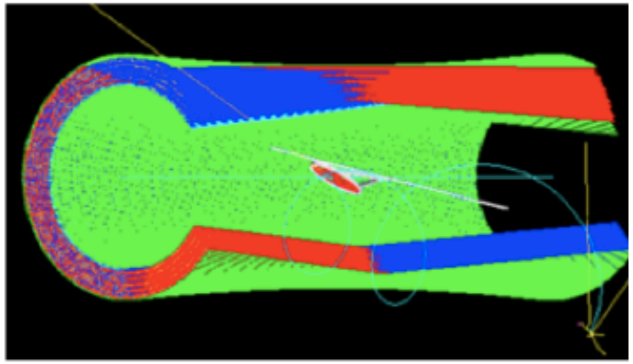
MEG detector upgrade: MEG-II

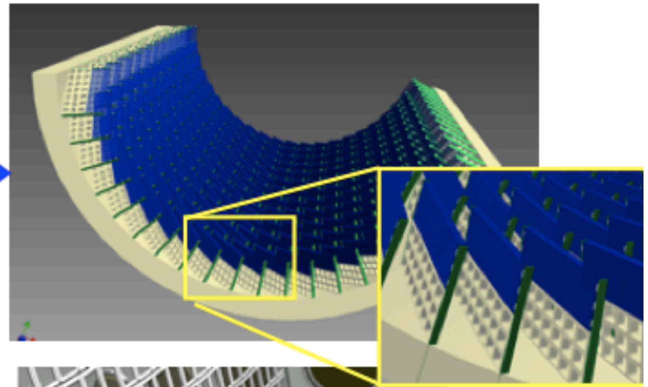
MEG-II concept

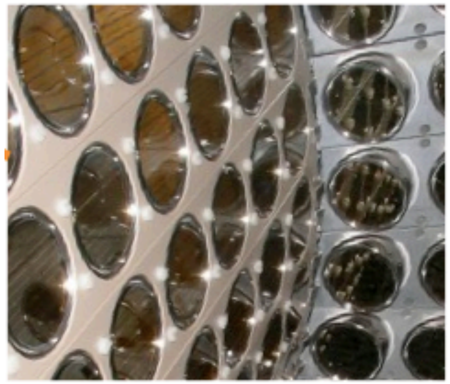
- Upgraded items

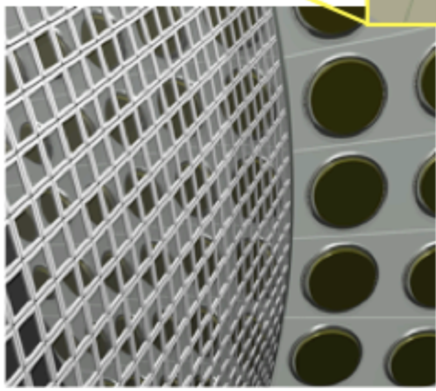
  - Higher μ intensity
  - Single volume drift chamber with stereo angle wire configuration
  - Pixelated timing counter with SiPM readout
  - LXe detector with SiPM readout
  - Thinner target
  - New readout electronics







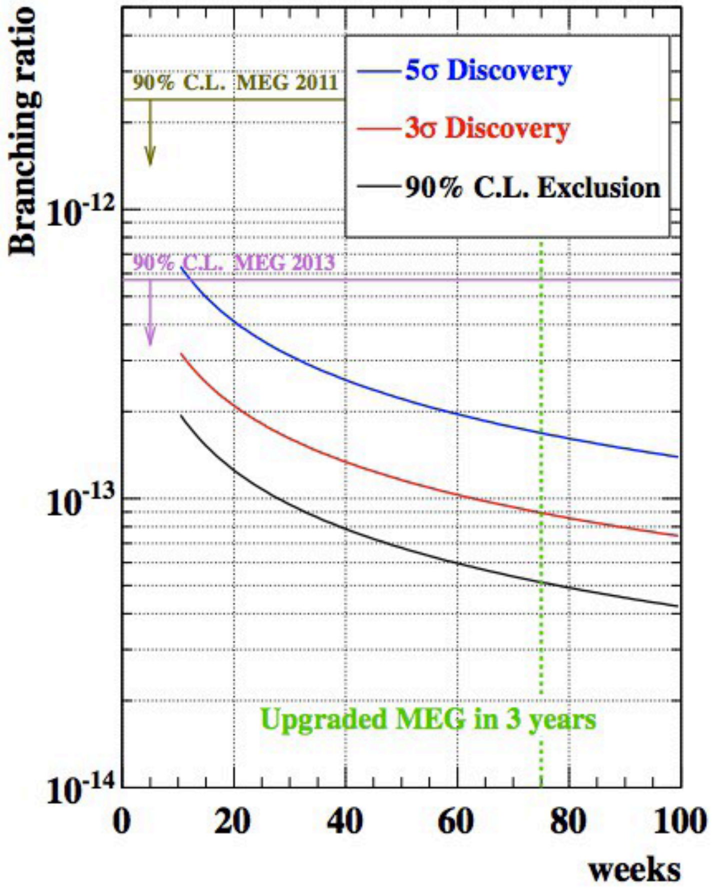




MEG-II goals

Beam rate 7×10^7 μ/s

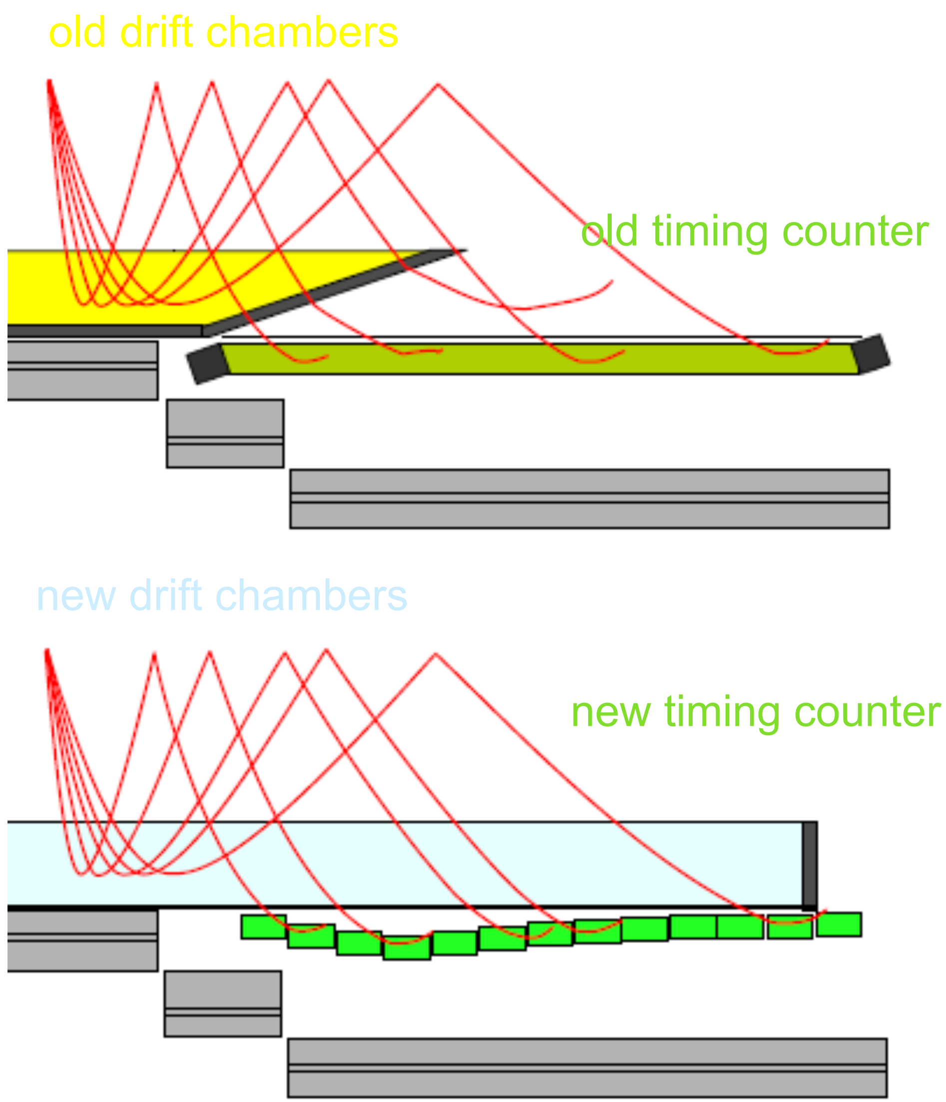
PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency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



MEG upgrade timeline

New position spectrometer

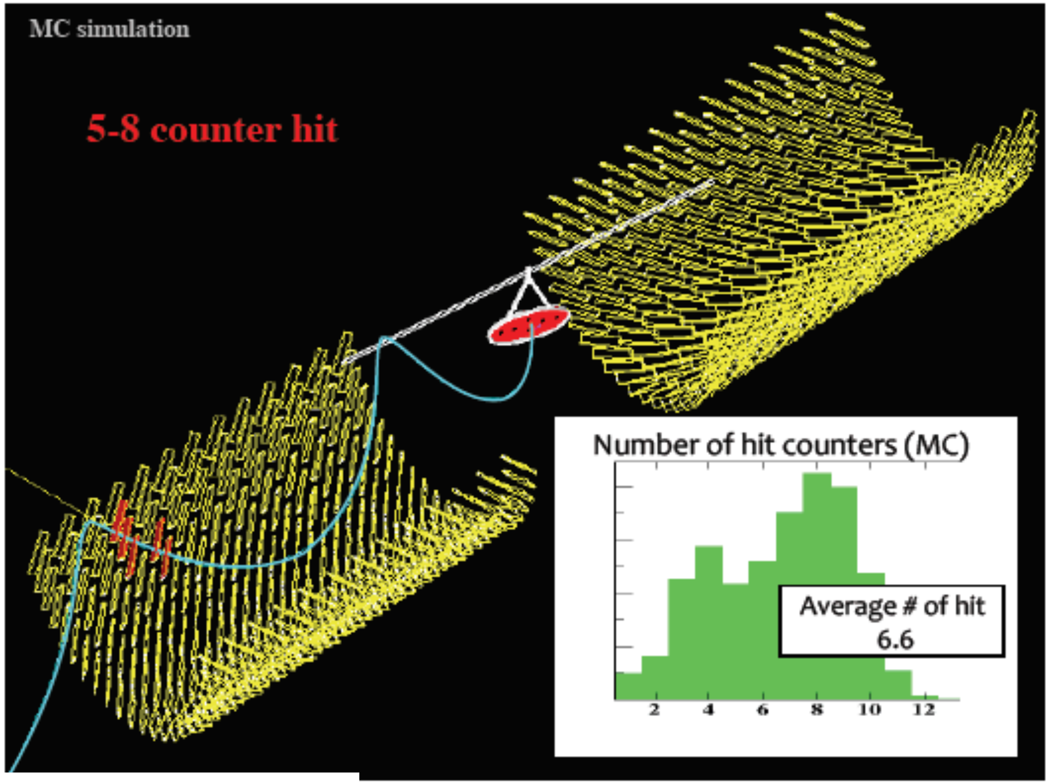
- Single volume 2π coverage drift chamber
  - 2m long, stereo wire, low mass
  - 1200 sense wires
  - 8^{o} stereo angle
  - high transparency to timing counter
  - high rate capability

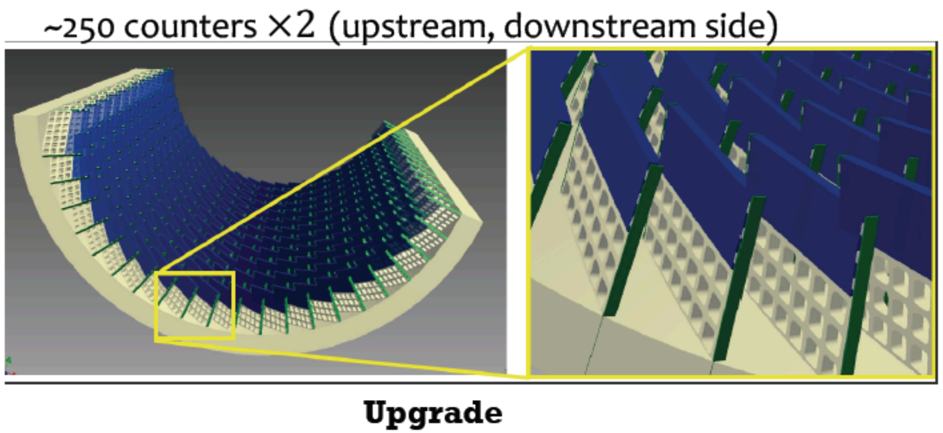


New timing counter

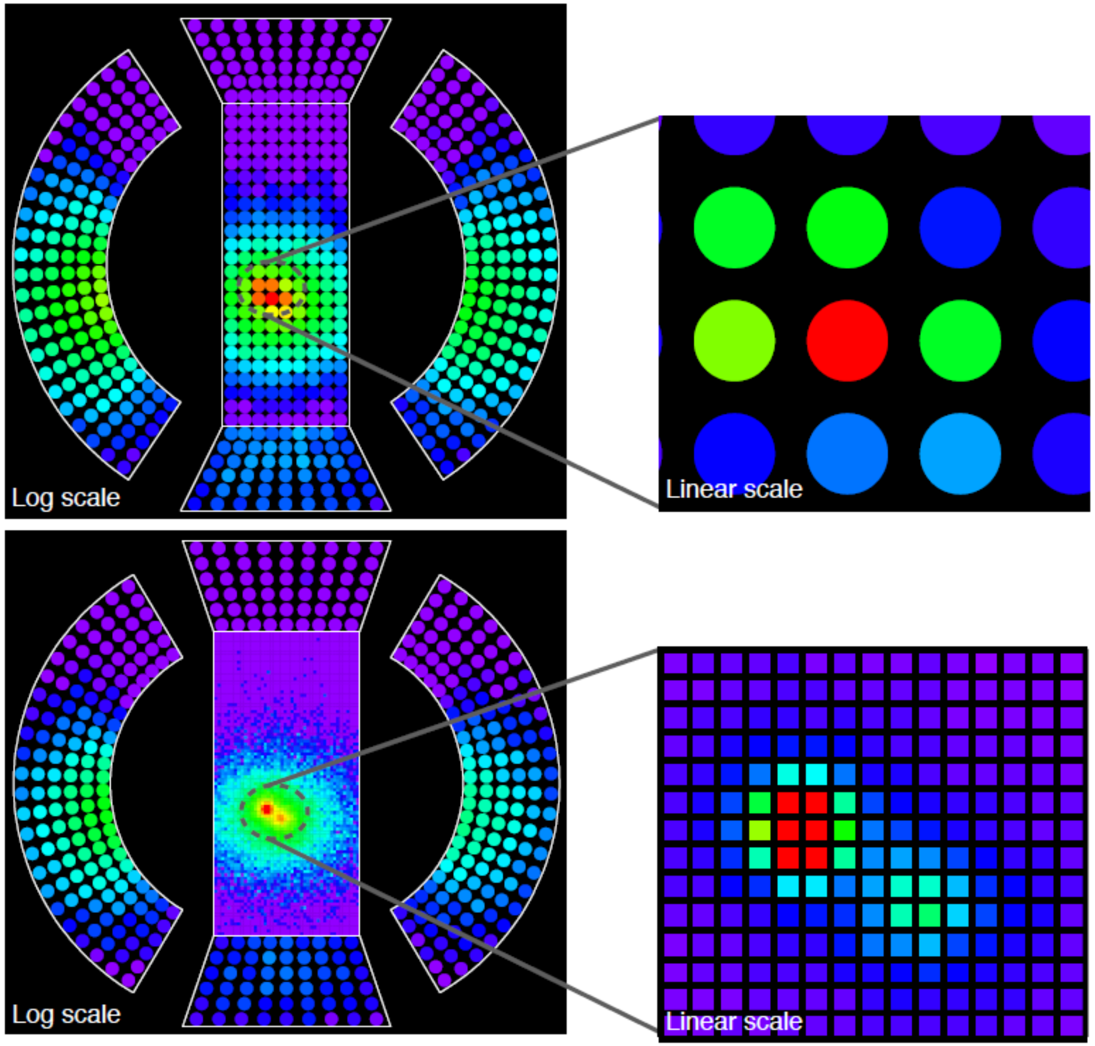
- Pixelated detector

- 600 counters read out by SiPM
- many time measurements per track





New LXe detector



- Smaller readout devices

=> better light collection

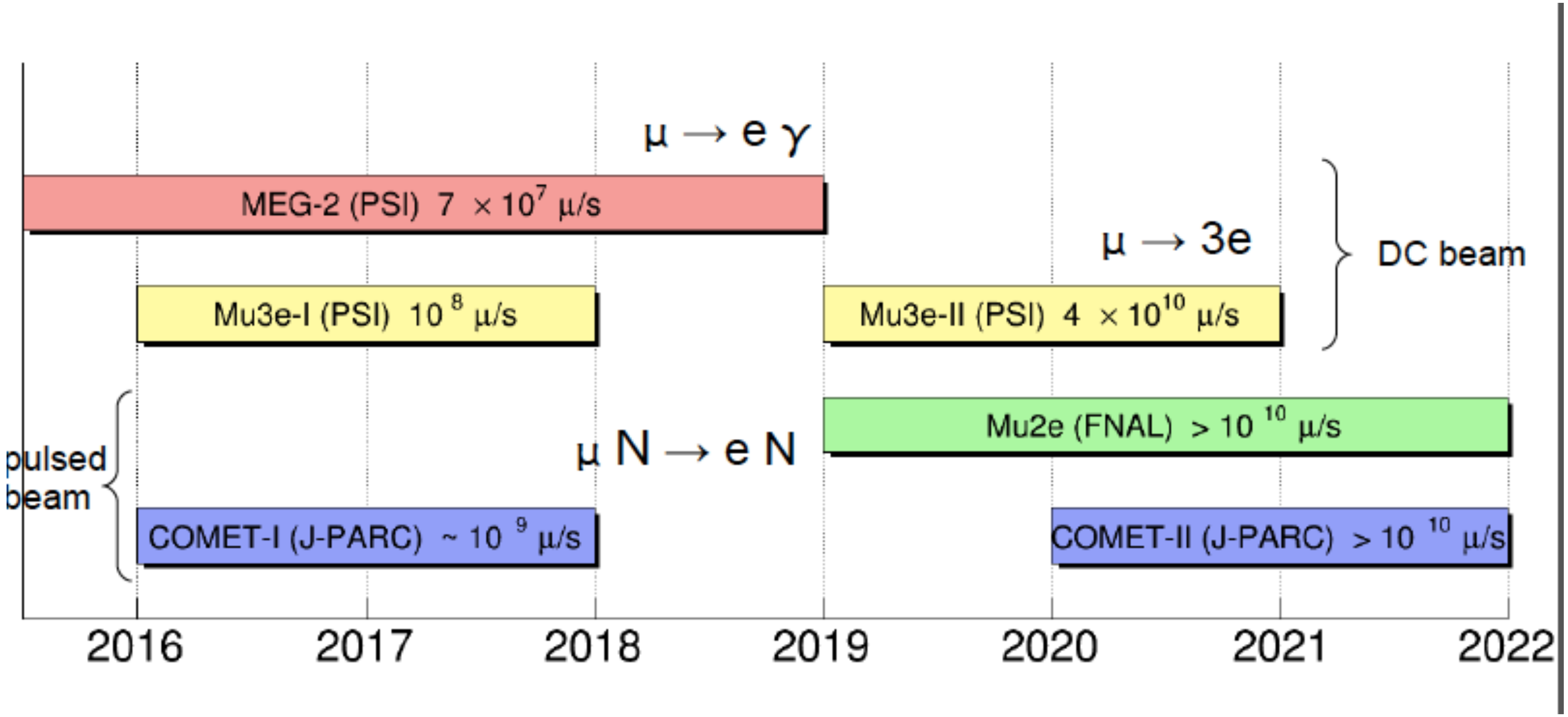
- Different devices rearrangements

=> better light containment

- New VUV sensitive large area SiPM

In the next decade

- MEG-II μ→eγ: goal sensitivity $5x10^{-14}$
- mu2e, COMET μN→eN: goal sensitivity 10^{-16}-10^{-18}
- Mu3e μ→eee: 10^{-15} 10^{-16}



Conclusions

- MEG at PSI established a new constraint on the existence of the LFV μ→eγ decay:

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

- Final MEG sensitivity: $5\text{x}10^{-13}$

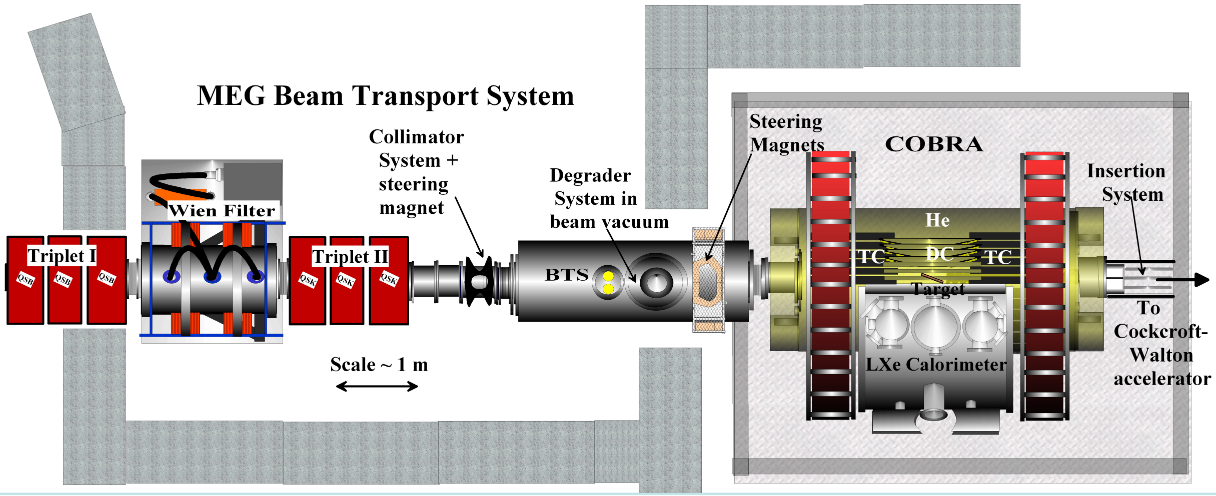
- MEG-II program fully funded is proceeding timely
  - Keep MEG basic design but important upgrades of all the subsystems

- MEG-II 2018 ultimate sensitivity: $\sim 5\text{x}10^{-14}$

Backup

The muon beam: why PSI?

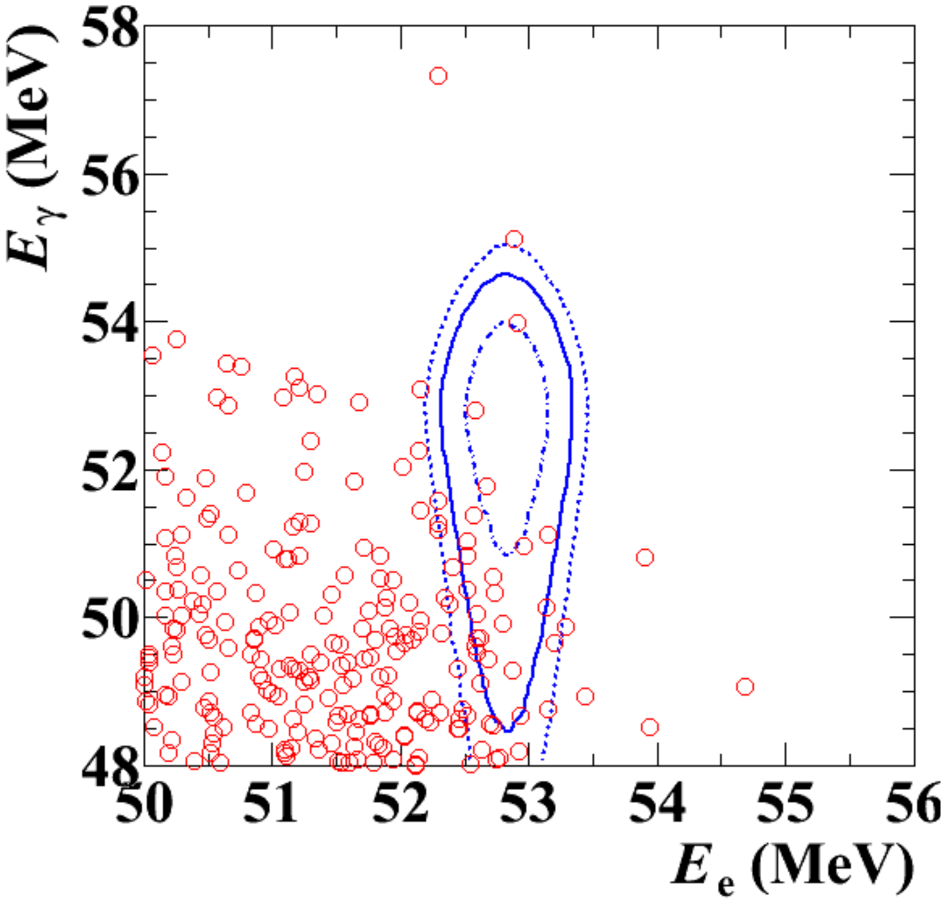
- Most intense continuous muon beam in the world
- Up to ~10^8 μ^+/s: only 3×10^7 μ^+/s used for MEG to optimize the sensitivity



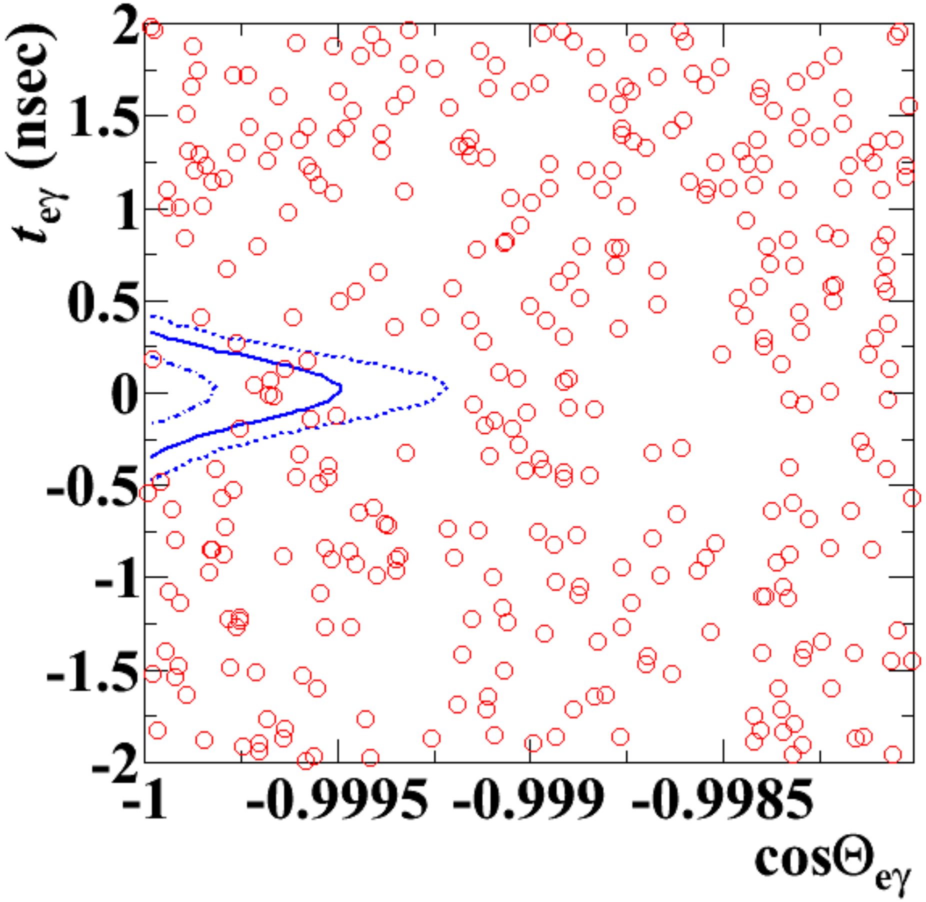
Proton beam current	: ~2.2mA
Muon production	: from π decaying on the production target surface
Muon central momentum	: 28 MeV/c
Δp/p	: 5% (full-width)

2009-2011 event distribution

$|T_{e\gamma}|<0.244$ns; $\cos\Theta_{e\gamma}<-0.9996$



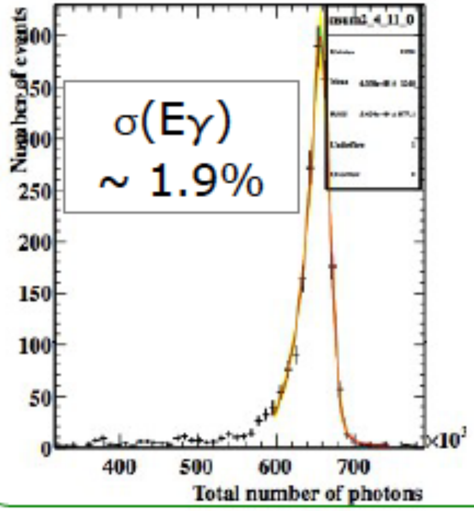
51 < E_γ <55 MeV; 52.4 E_e<55 MeV



contours: 1σ,1.64σ,2σ

Calibrations

Charge Exchange (CEX)



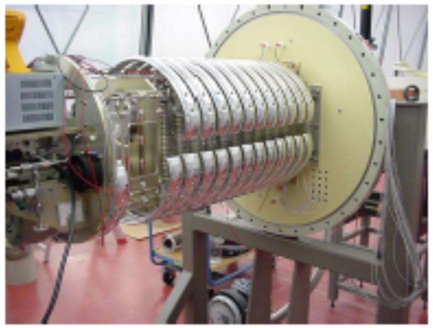
~ monochromatic γ @ 55 MeV from…

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

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

…by selecting back-to-back γ's

Cockcroft-Walton accelerator

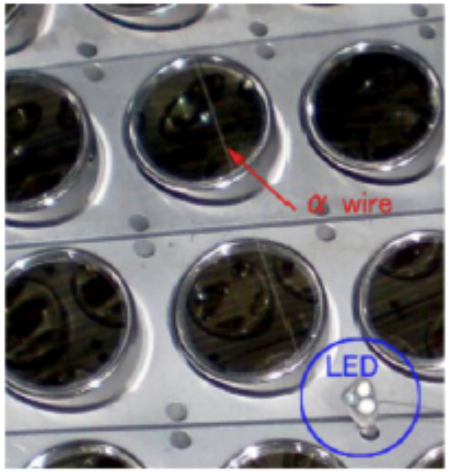


Protons on a Lithium Tetra-borate target

bi-weekly monitoring of calorimeter's energy scale

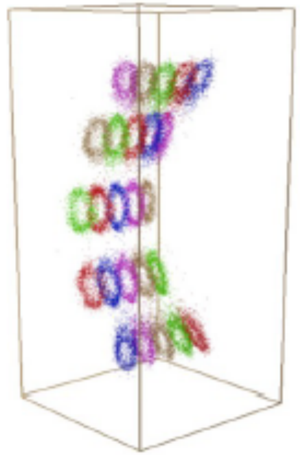
LEDs

Installed inside the XeC



α sources

Installed in wires inside the XeC



bi-weekly calibration of PMT quantum efficiencies and gains

New: pulsed neutron generator: 9 MeV photons

Performances

TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade

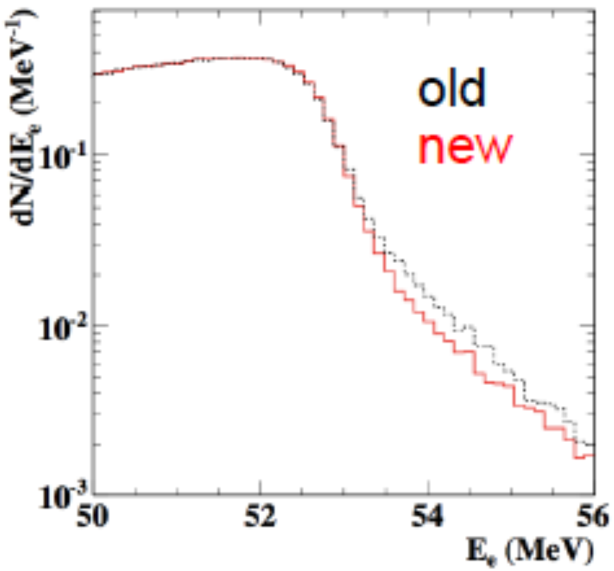
PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency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

muon rate	3.3×10^7/sec	7×10^7/sec

New Kalman filter

- New Kalman filter procedure:

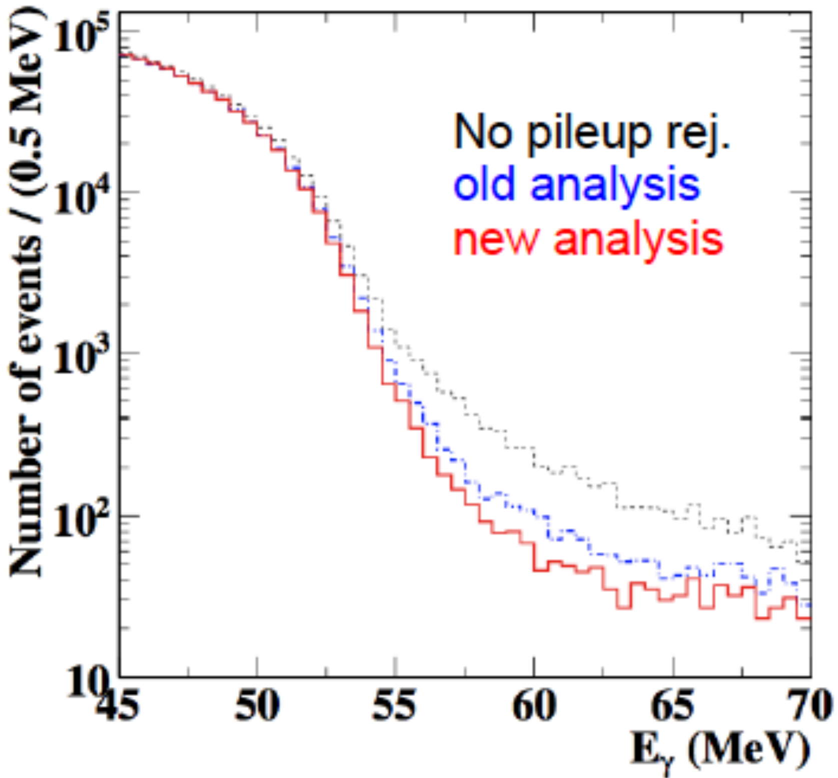
  - 7% increase in tracking efficiency
  - smaller resolution tails
  - per event estimate of track uncertainties parameters used in the likelihood analysis (10% increase of sensitivity)



New photon pile-up rejection

- New analysis of the Liquid Xenon waveforms to reject pile-up of photons

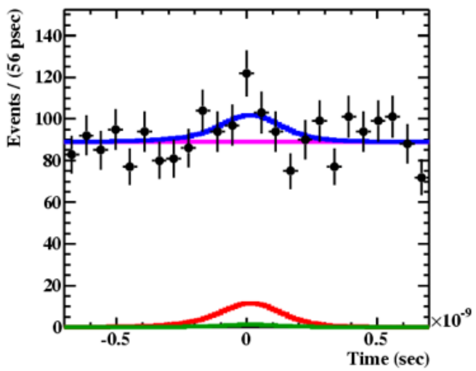
  - 7% increase in photon detection efficiency
  - suppressed rate of unrecognized pile-up events

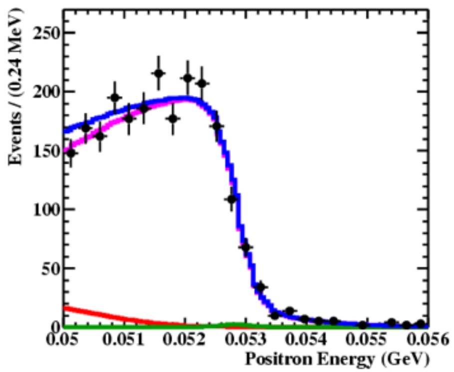


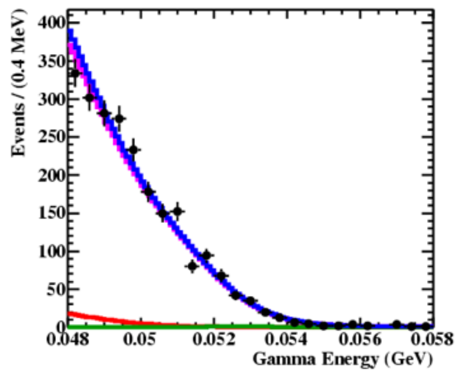
Control samples

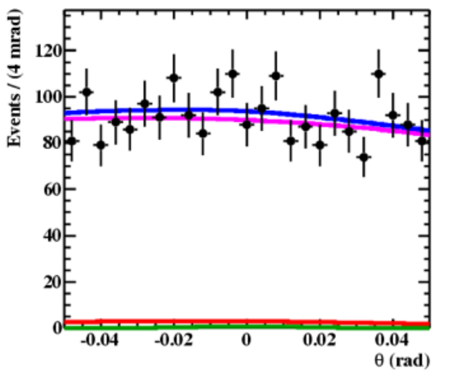
- Fictitious analysis regions
  in the sidebands of E_γ, $T_{e\gamma}$ and angular

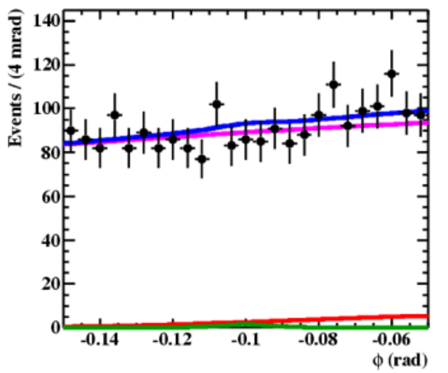
Example: phi negative sideband -150mrad<$\varphi_{e\gamma}$<50mrad











	Best fit	Error (MINOS 1.645σ)
N_{sig}	+2.8	+5.7−3.0
N_{RMD}	+34.0	+5.4−5.4
N_{BG}	+1098.1	+24.9−24.9

Systematic errors

Table 16: Relative contributions of uncertainties to upper limit of $\mathcal{B}$.

Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.11
E_γ scale	0.07
E_e bias	0.06
$t_{e\gamma}$ signal shape	0.06
$t_{e\gamma}$ center	0.05
Normalization	0.04
E_γ signal shape	0.03
E_γ BG shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.03
γ angle resolution (u_γ, v_γ, w_γ)	0.03
E_e BG shape	0.01
E_e signal shape	0.01
Angle BG shape	0.00
Total	0.25

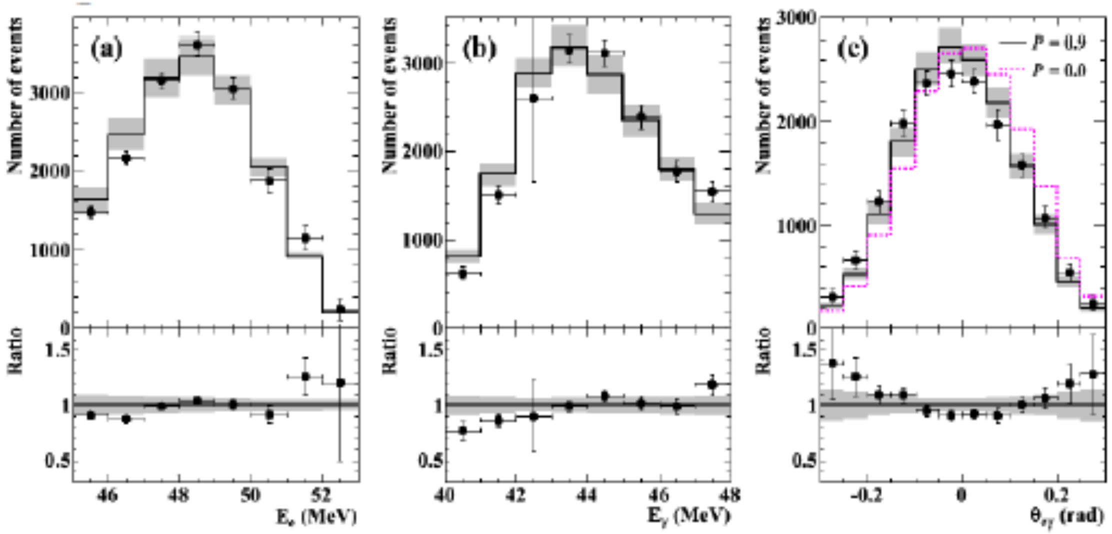
Normalization

Two methods:

- Count (prescaled) Michel positron (correcting for small differences 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}