The MEG experiment results and upgrade proposal

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On behalf of the MEG Collaboration

ICNFP, Kolymbari, Creta, 04 September 2013

Outline

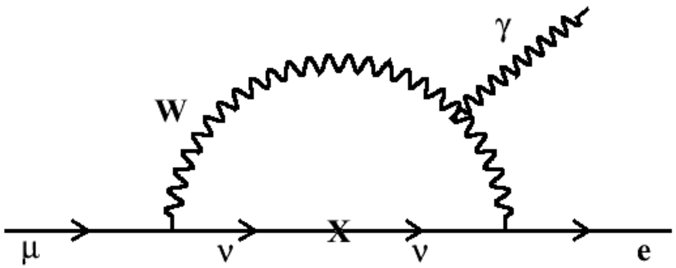
- Charged Lepton Flavour Violation **(CLFV)** as BSM probe
- Signal and Background
- The MEG Detector
- Analysis of 2011 Data and results with 2009-2011 sample
- Perspectives
- Upgrade design

cLFV 1)

- In the **SM of electroweak interactions**, leptons are grouped in doublets and there is **no space for transitions where the lepton flavour is not conserved**.
- However, **lepton flavour is experimentally violated** in neutral sector (**neutrino oscillations**) ⇒ **extension the Standard Model by including neutrino masses and coupling between flavours**.
- **cLFV indicates non conservation of lepton flavour in processes involving charged leptons**.

cLFV 2)

Including neutrino masses and oscillations in SM:



$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \quad \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \quad \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

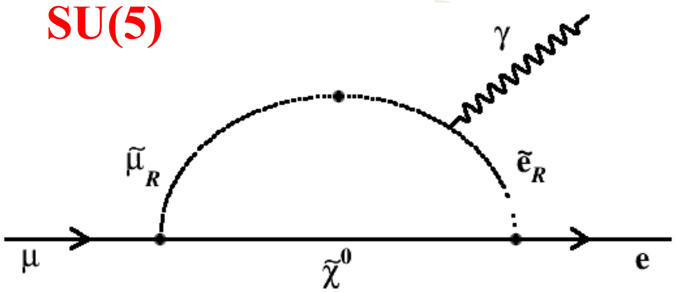
$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3}\frac{3\alpha}{32\pi}\left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2 \quad \approx 10^{-50}$$

Experimentally unmeasurable !

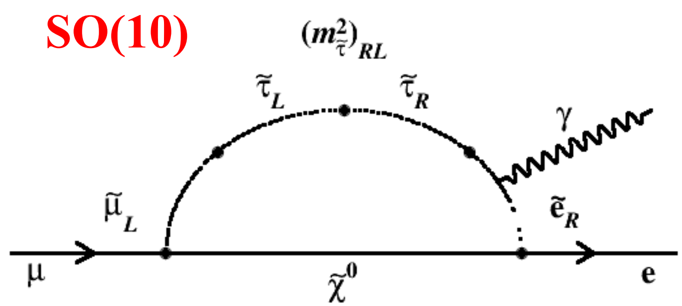
Large rate enhancement in some SM extensions ⇒ predicted rates experimentally accessible ! (Barbieri, Masiero, Ellis, Hisano ..)

$$\approx 10^{-5}\,\frac{\Delta m^2_{\%\%}}{\bar{m}^2_{\%}}\left(\frac{100\text{ GeV}}{m_{\text{SUSY}}}\right)^4 \tan^2\beta \quad \approx 10^{-12}$$

SU(5)



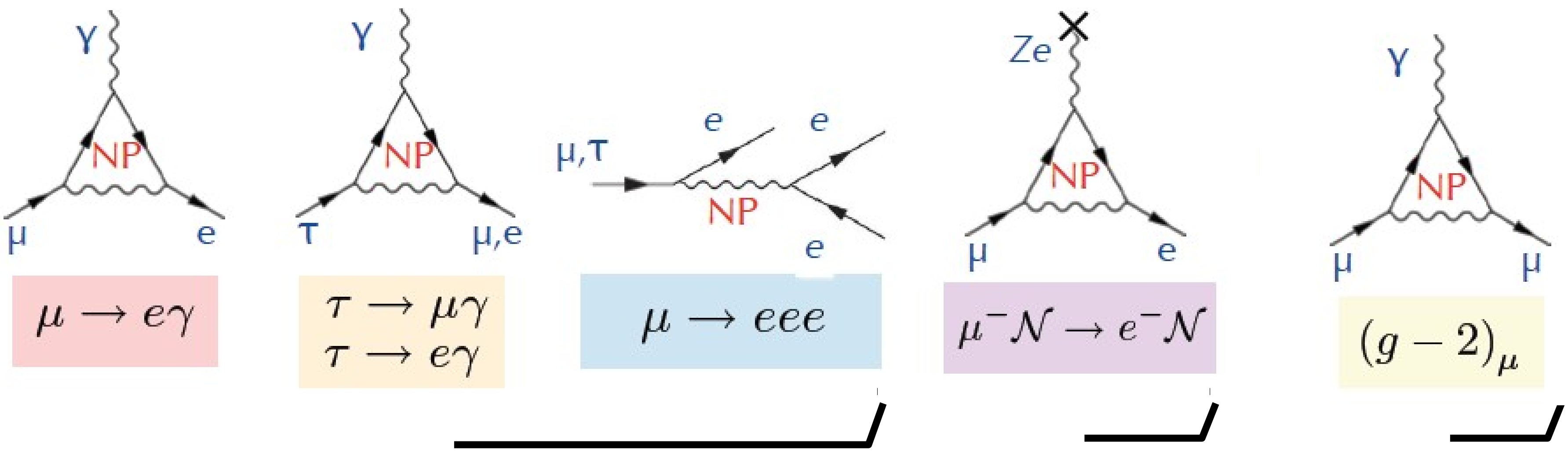
SO(10)



⇒ **cLFV unambiguous evidence for physics beyond SM**

LFV 3)

Several cLFV processes, sensitive to **New Physics (NP)**



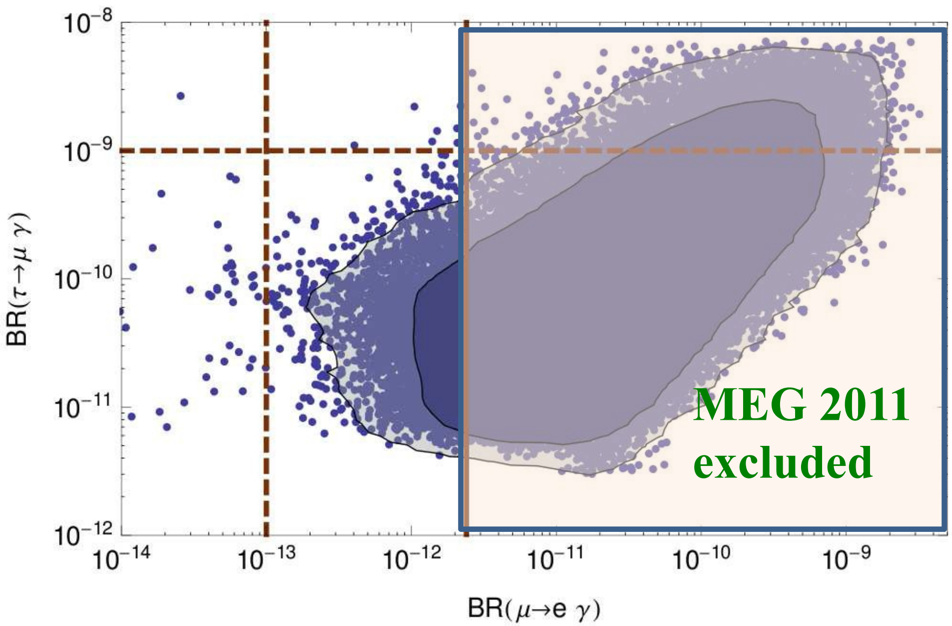
μ,τ anomalous decays

μ → e conversion

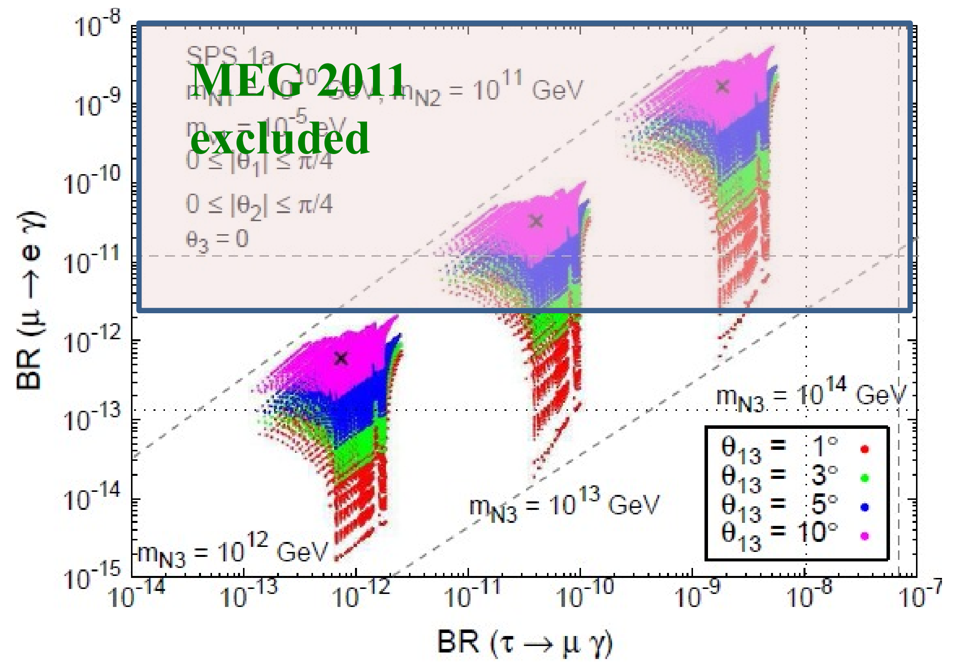
Anomalous magnetic moment

$\tau \rightarrow \mu\gamma$ vs $\mu \rightarrow e\gamma$: < 2013

Blankenburg et al. Eur.Phys.J. **C72** (2012) 2126



Antusch et al. JHEP **0611** (2006) 090



MEG 2011 = PRL **107** (2011) 181201

θ_{13} recently measured by Daya Bay, Reno, Double Chooz (7 ÷ 10º)

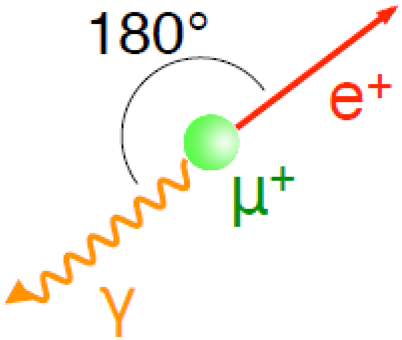
The MEG Experiment

Goal: search for $\mu^+ \rightarrow e^+ \gamma$ decay with a sensitivity on BR $\leq 10^{-13}$


Part of
The MEG collaboration
Koshiba Hall
Total ≈ 60 physicists
KEK
Tokyo U.
Waseda U.
KEK
INFN & U Pisa
INFN & U Roma
INFN & U Genova
INFN & U Pavia
INFN & U Lecce
PSI
UCIrvine
JINR Dubna
BINP Novosibirsk

Signal and background

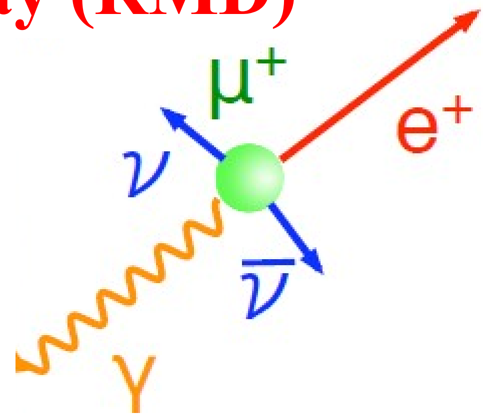
Signal



$E_e = E_\gamma = 52.8$ **MeV** $= m_{\mu/2}$

$T_e = T_\gamma$

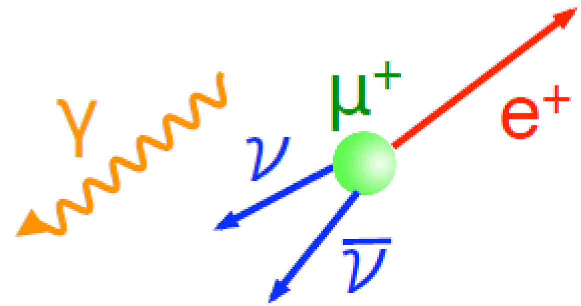
Radiative muon decay (RMD)



$E_e, E_\gamma < m_{\mu/2}$

$T_e = T_\gamma$

Accidental Background (ACC)



e^+ from Michel decay, γ from RMD, e^+e^- annihilation ..

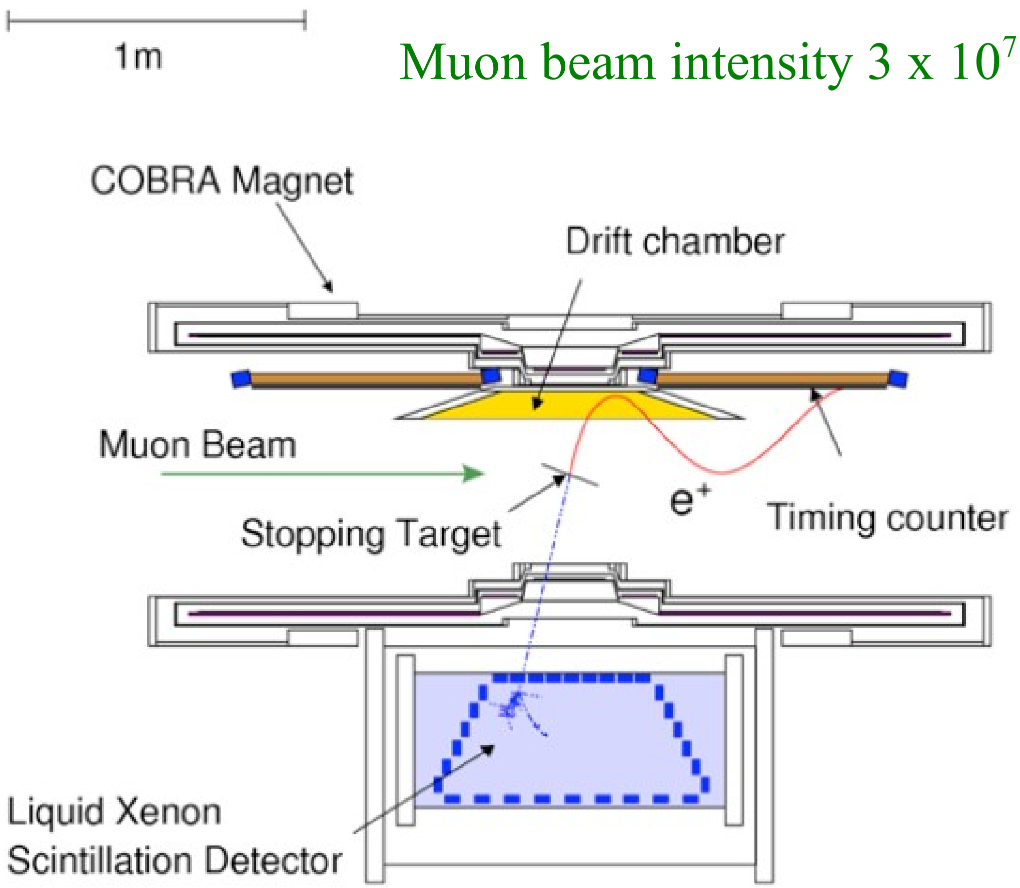
Random ΔT, $\Delta\Theta$, E_e, $E_\gamma < m_{\mu/2}$

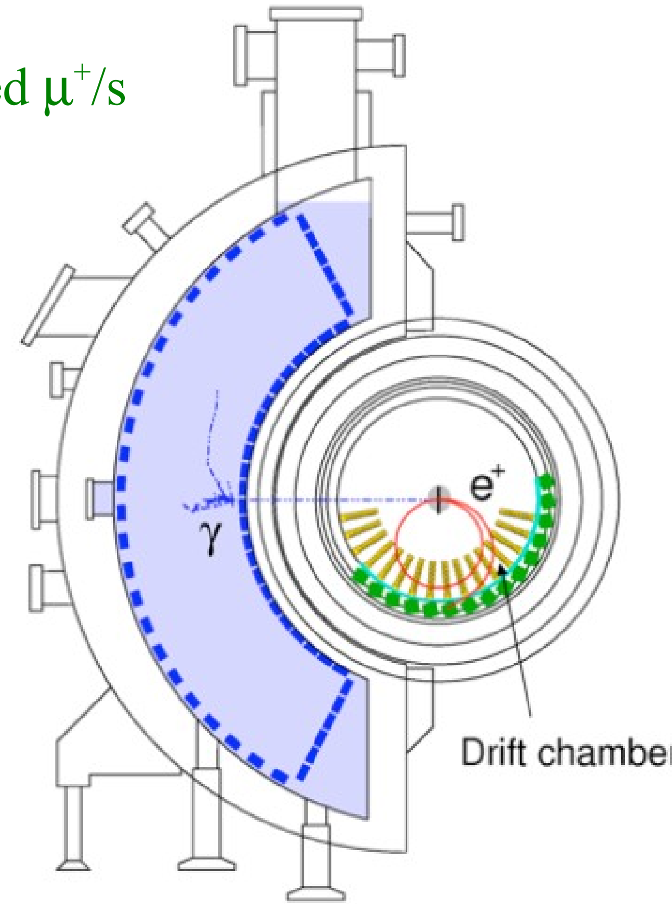
Signal, RMD $\propto R_\mu$, ACC $\propto R_\mu^2$ $\Rightarrow$

- **ACC is dominant (10 larger than RMD in signal region)**;
- needed **continuous beam** and **accurate choice of R_μ**;
- needed **high precision experiments.**

Detector layout

Muon beam intensity 3 x 10^7 stopped μ^+/s





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

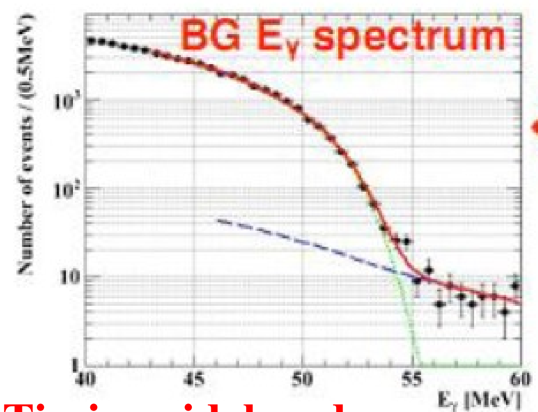
Summary of MEG performances

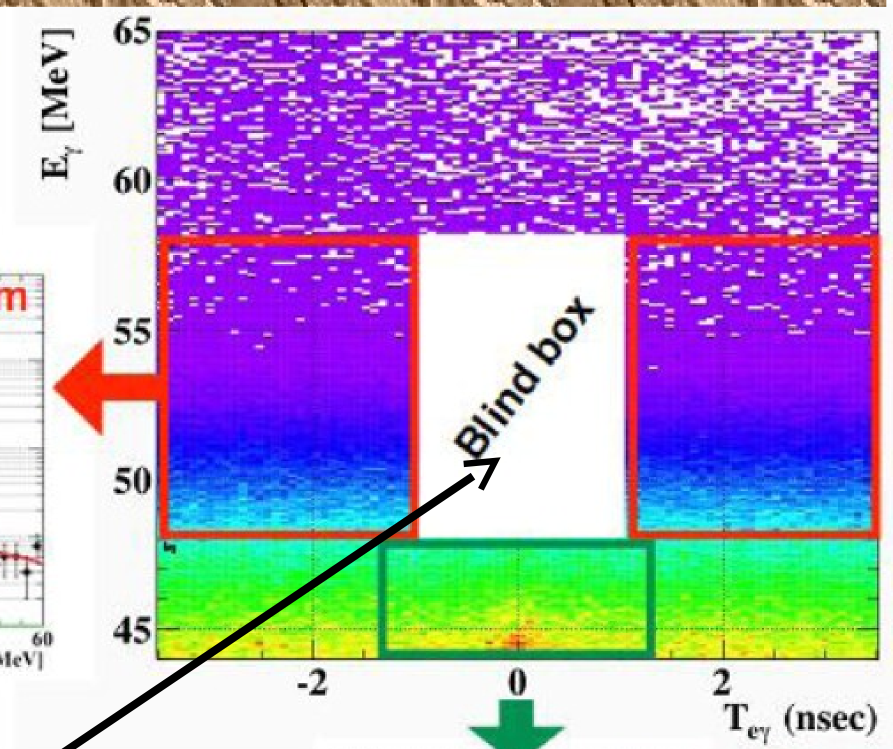
	2009	2010	2011	Note
Gamma E [%]	1.89	1.90	1.65	Effective sigma (averaged on event depth)
Relative timing $T_{e\gamma}$ [ps]	160	130	140	RMD with $E\gamma < 48$ MeV
Positron E [keV]	306 (86%)	306 (85%)	304 (86%)	Michel edge, core resolution
Positron θ [mrad]	9.4	10.4	10.6	Double turn
Positron φ at zero [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)	π0 measurement with lead collimators
Trigger/DAQ efficiency [%]	91/75	92/76	97/96	
Gamma efficiency [%]	63	63	63	π0 sample
Positron efficiency [%]	43	36	36	From MC

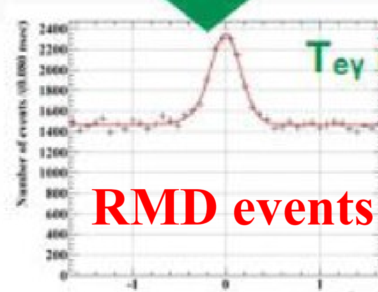
MEG analysis

Likelihood + Blind (only 2011) analysis

Signal and background optimization done in sidebands







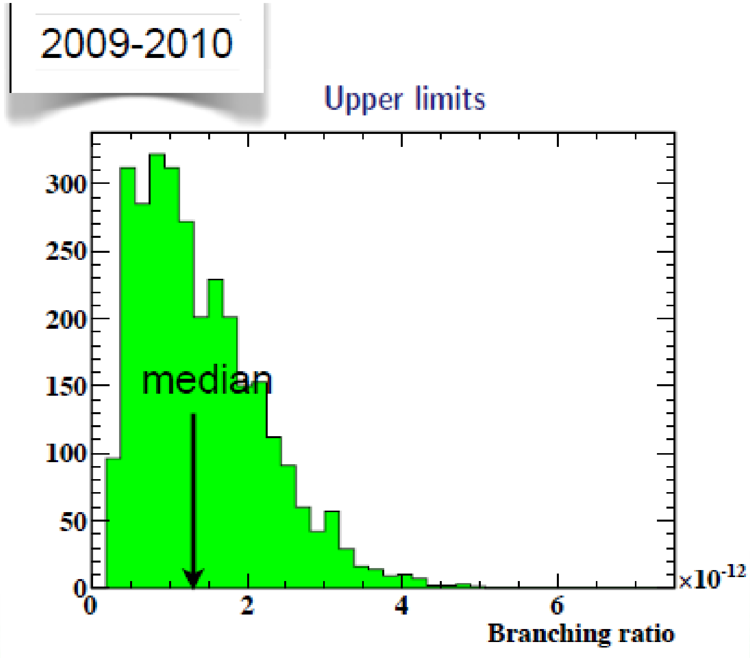
Timing sidebands

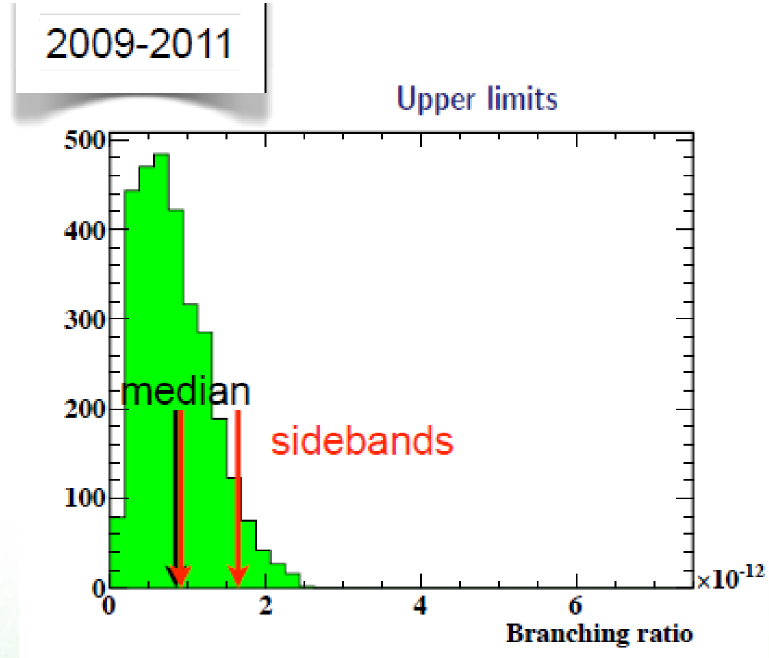
E_γ sideband

Events in the blind box (≈ 0.2%) are hidden up to the end of optimization procedure (only 2011)

Sensitivity

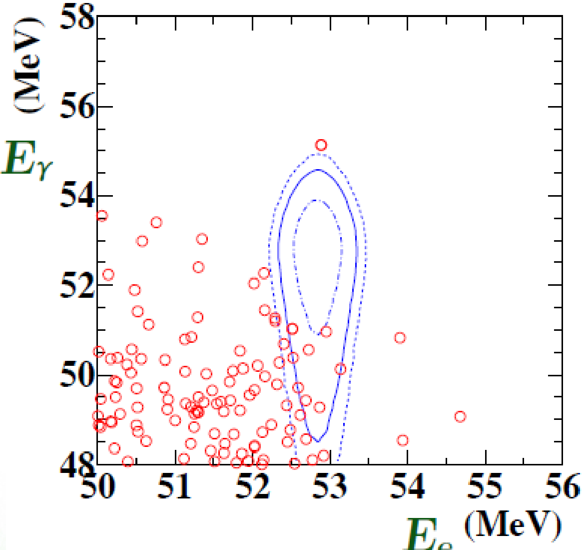
Median upper bound of a sample of **toy MC experiments** generated with **zero signal hypothesis** using the measured background pdf's.

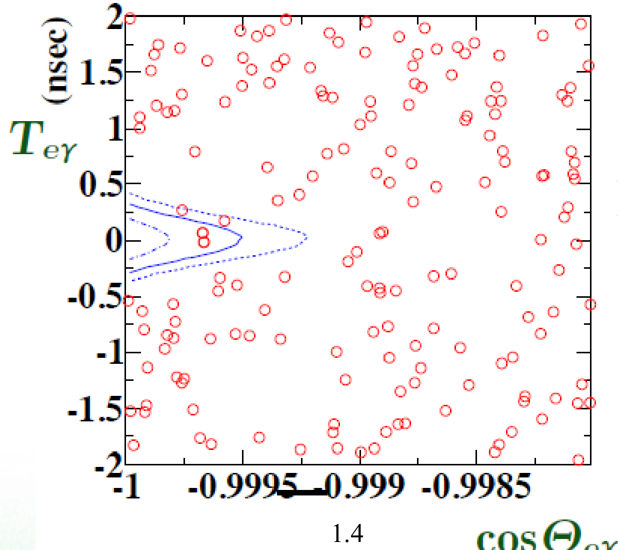




Median (**2009 - 2010**) = **1.30 x 10^{-12}**)
Median (**2009 - 2011**) = **7.7 x 10^{-13}**

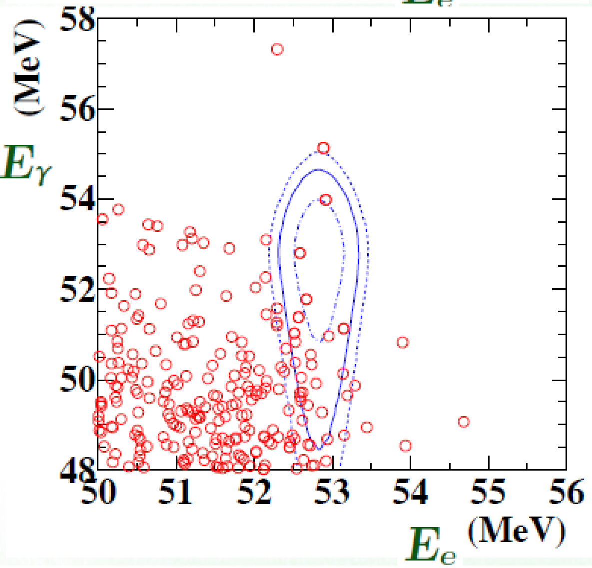
2011 and 2009-2011 analysis

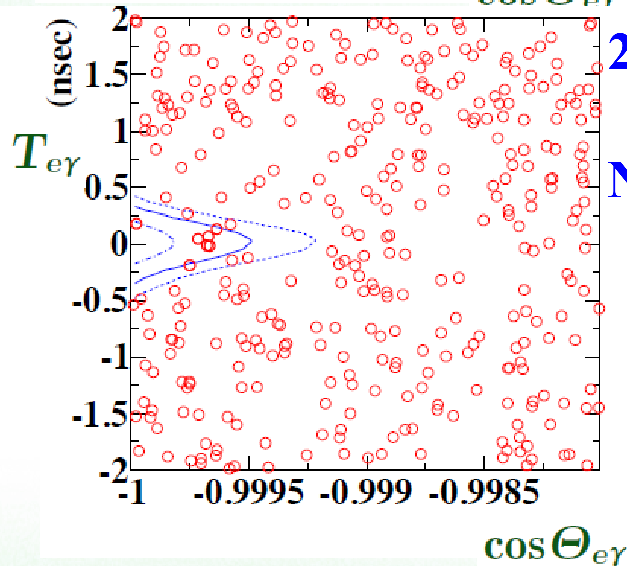




2011 data only

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





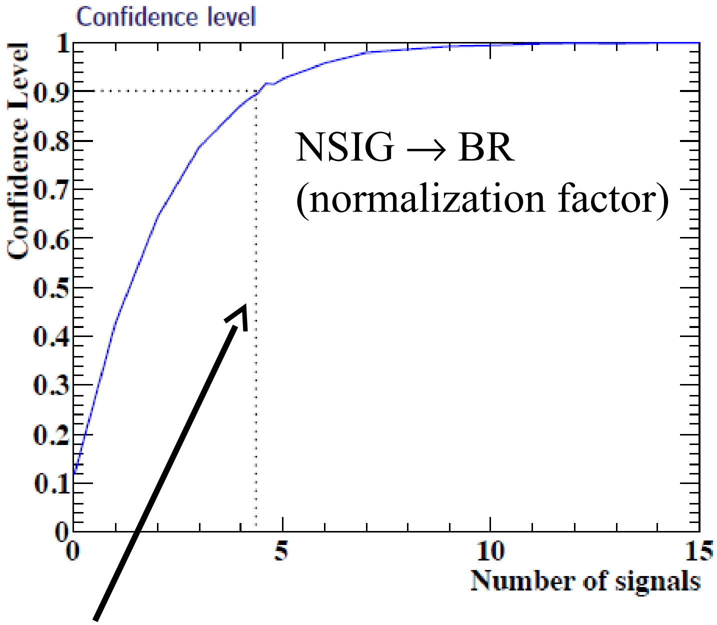
2009-2011 data

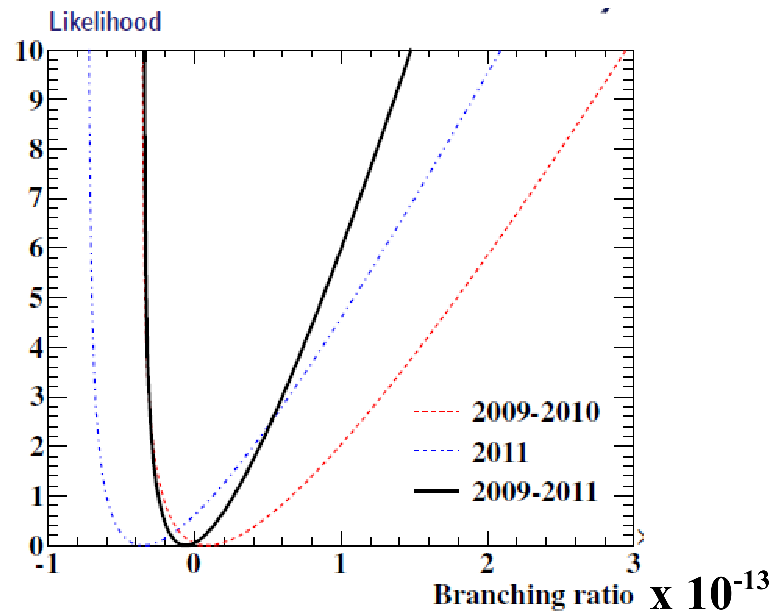
NSIG Best = -0.4 (+4.8, -1.9)

No excess observed in all samples

Confidence level

Frequentistic analysis, Feldman-Cousins method





BR ($\mu \rightarrow e\gamma$) < 5.7 x 10^{-13} (90% C.L.) **factor 4 improvement !**

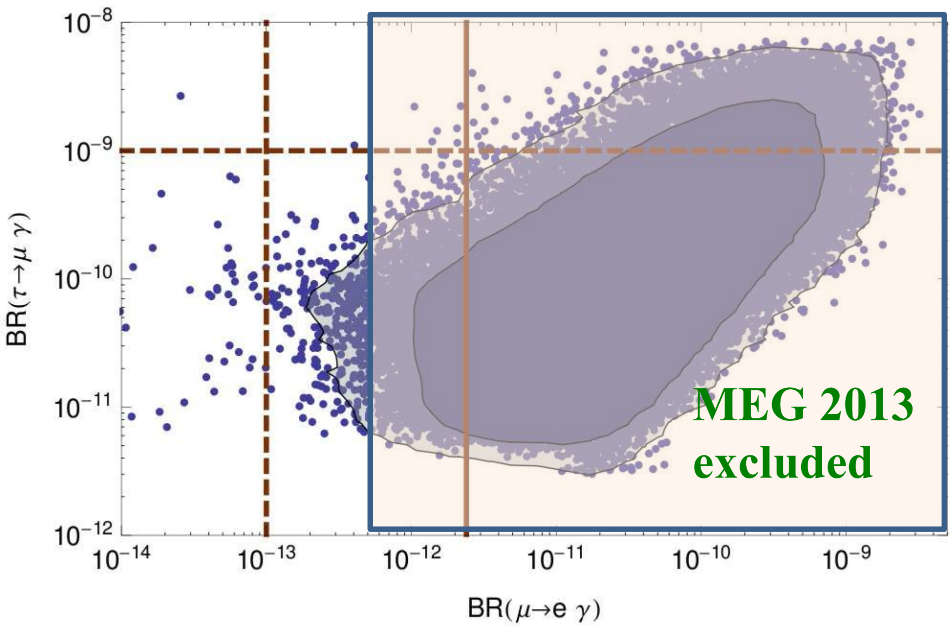
Data set	$\mathcal{B}_{\rm fit} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

Summary of all samples

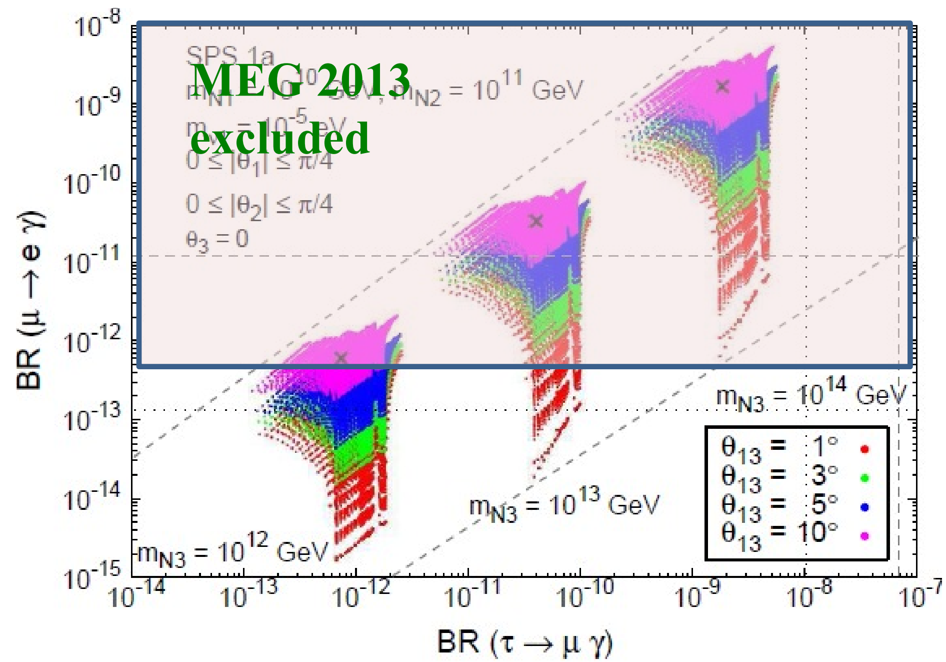
Result published in PRL **110** (2013) 201801

τ →μγ vs μ→eγ: now

Blankenburg et al. Eur.Phys.J. **C72** (2012) 2126



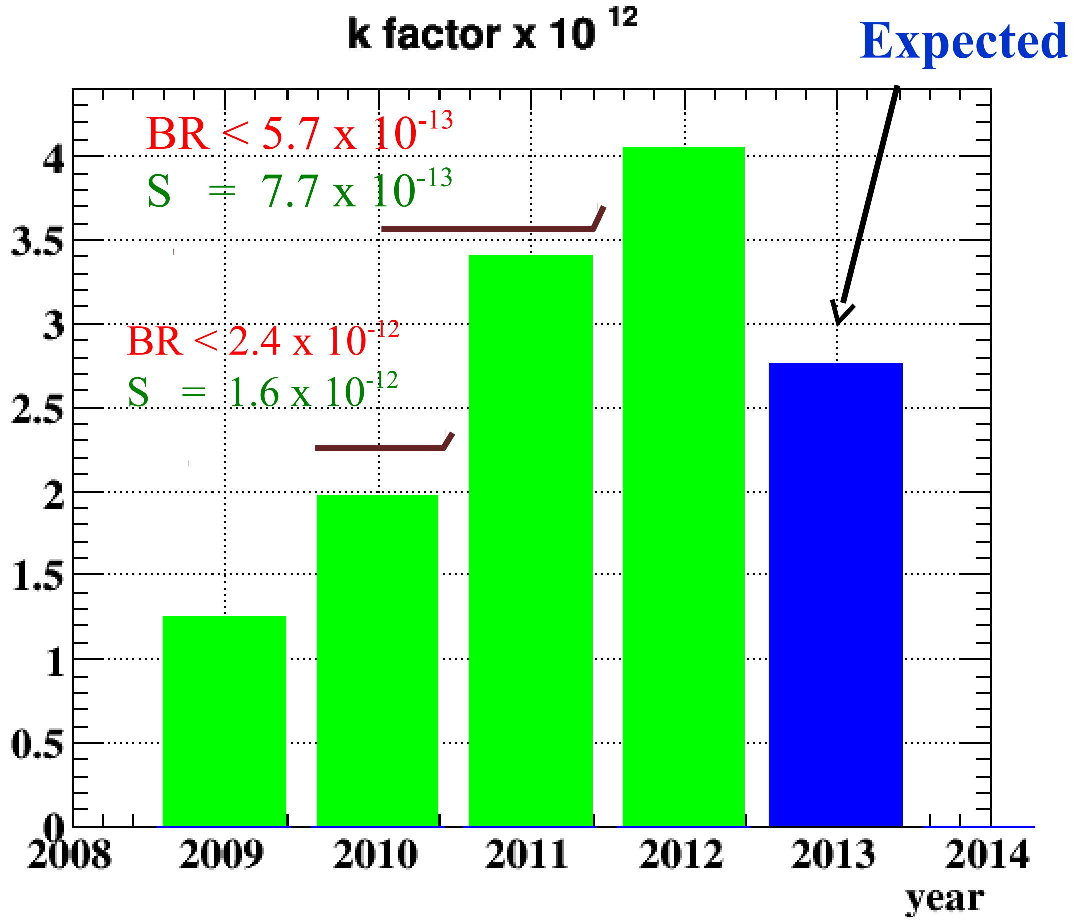
Antusch et al. JHEP **0611** (2006) 090



θ_{13} recently measured by Daya Bay, Reno, Double Chooz (7 ÷ 10°)

Final data and sensitivity

Number of $\mu^+ \rightarrow e^+\gamma$ events = **(k factor) x BR ($\mu^+ \rightarrow e^+\gamma$)**

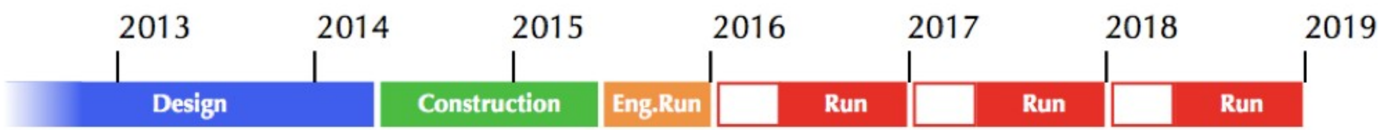


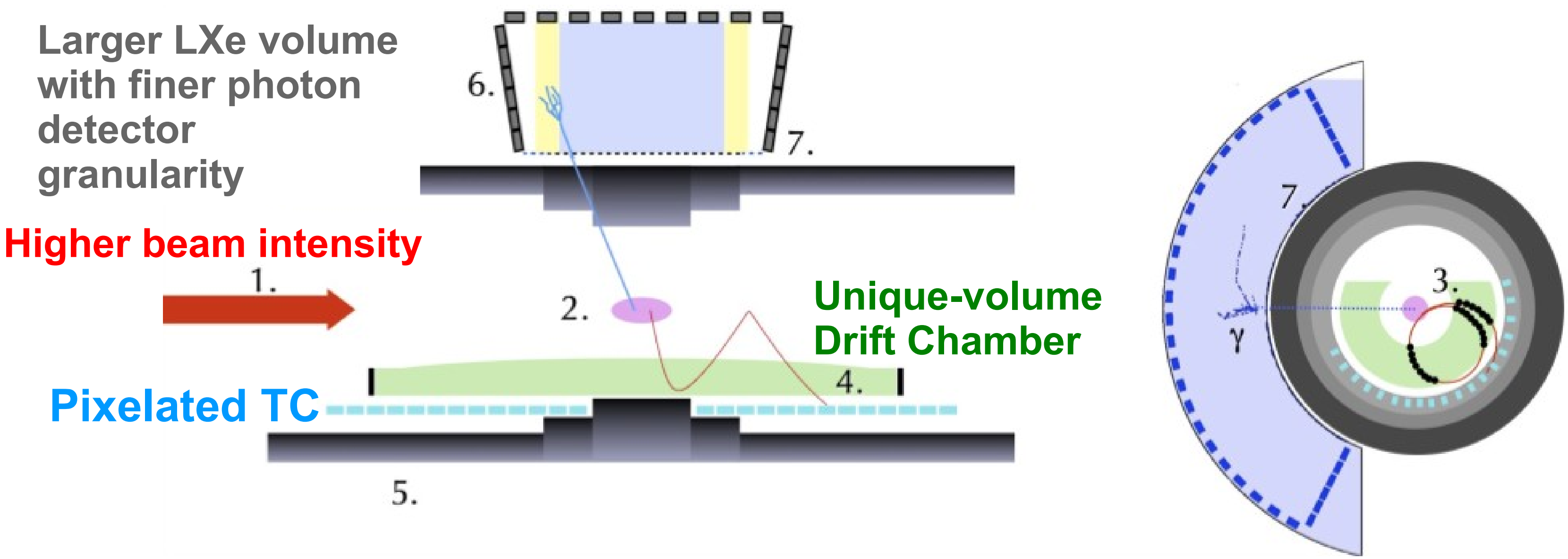
Estimated final sensitivity (toy MC)

~ 5×10^{-13}

The MEG Upgrade (arXiv:1301.7225)

- A MEG upgrade, aiming at a sensitivity improvement of **one order of magnitude** (~5 x 10^{-14}) is under design;
- Strong endorsement by the PSI Scientific Committee, and funding agencies in Japan and Italy.





Drift Chamber Design

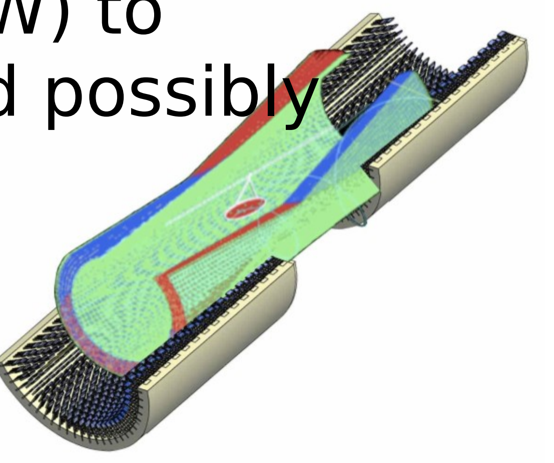
- Unique-volume drift chamber with **stereo wires** and helium-isobutane gas admixture, to replace the current system of 16 independent chambers;

MAIN IMPROVEMENTS

- Longer tracking region with finer granularity;
- Lower material budget (30% less X_0);
- Faster readout electronics (~ GHz BW) to improve the drift time resolution and possibly identify single ionization cluster;

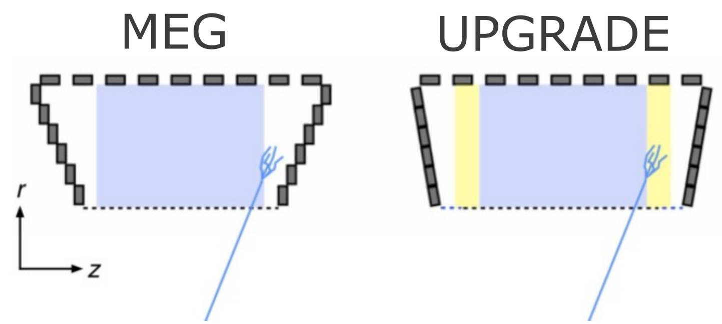
$\sigma(XY) \sim 120\ \mu m$ $\Rightarrow$ $\sigma(p) \sim 130$ keV

$\sigma(Z) \sim 900\ \mu m$ $\quad$ $\sigma(\psi,\phi) \sim 5$ mrad



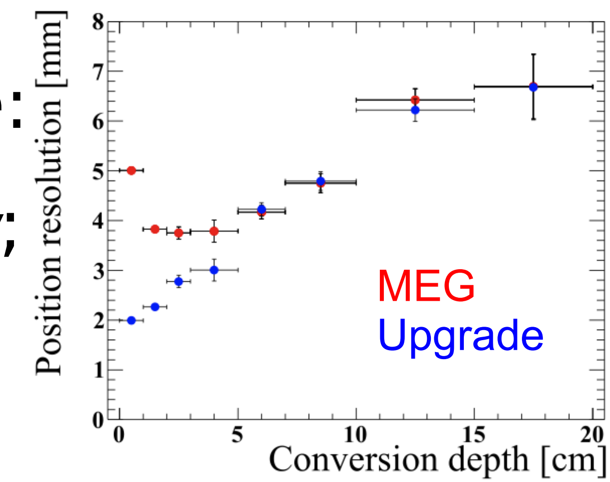
LXe Detector Design

- Silicon Photomultipliers (SiPM) to replace PMTs in the inner face;
- New geometry for side faces



MAIN IMPROVEMENTS

- Larger fiducial volume;
- Finer granularity in the inner face:
  - better resolutions for shallow γ;
- Better control of reflexions in the lateral faces.



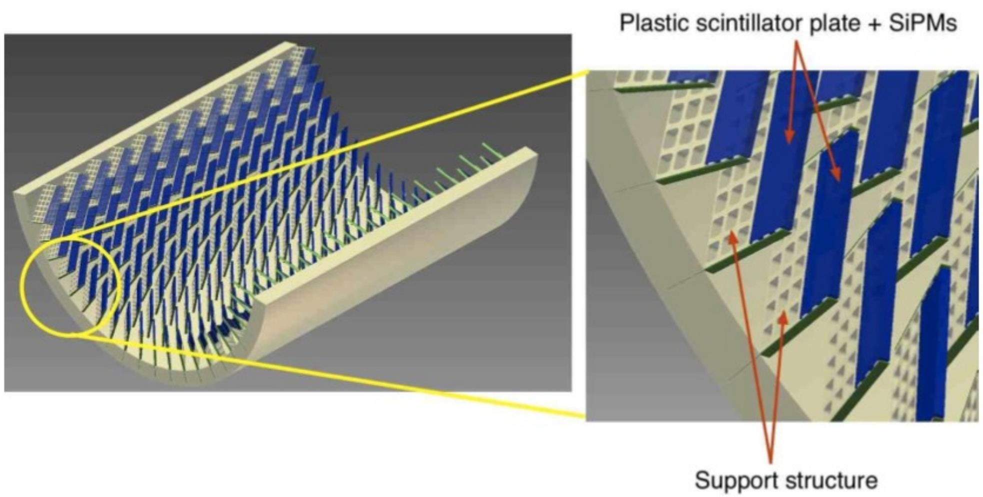
$\sigma(E_\gamma) \sim 1\%$ $\sigma(\text{position}) \sim 2\ (5)$ mm in x,y (z)

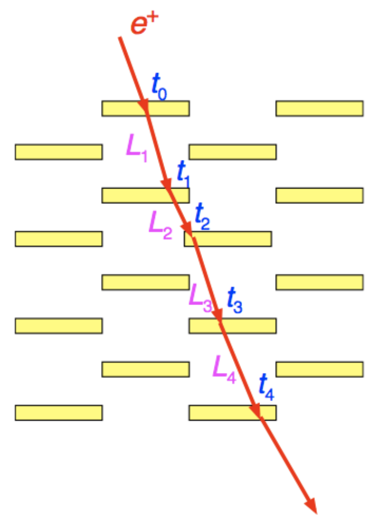
Timing Counter Design

- *Pixelated TC*:~500–800 scintillating tiles, read out by SiPM, to replace the 30 bars of the present TC

MAIN IMPROVEMENTS

- Better time resolution and multiple time measurements for the same positr
- Higher rate tolerance.

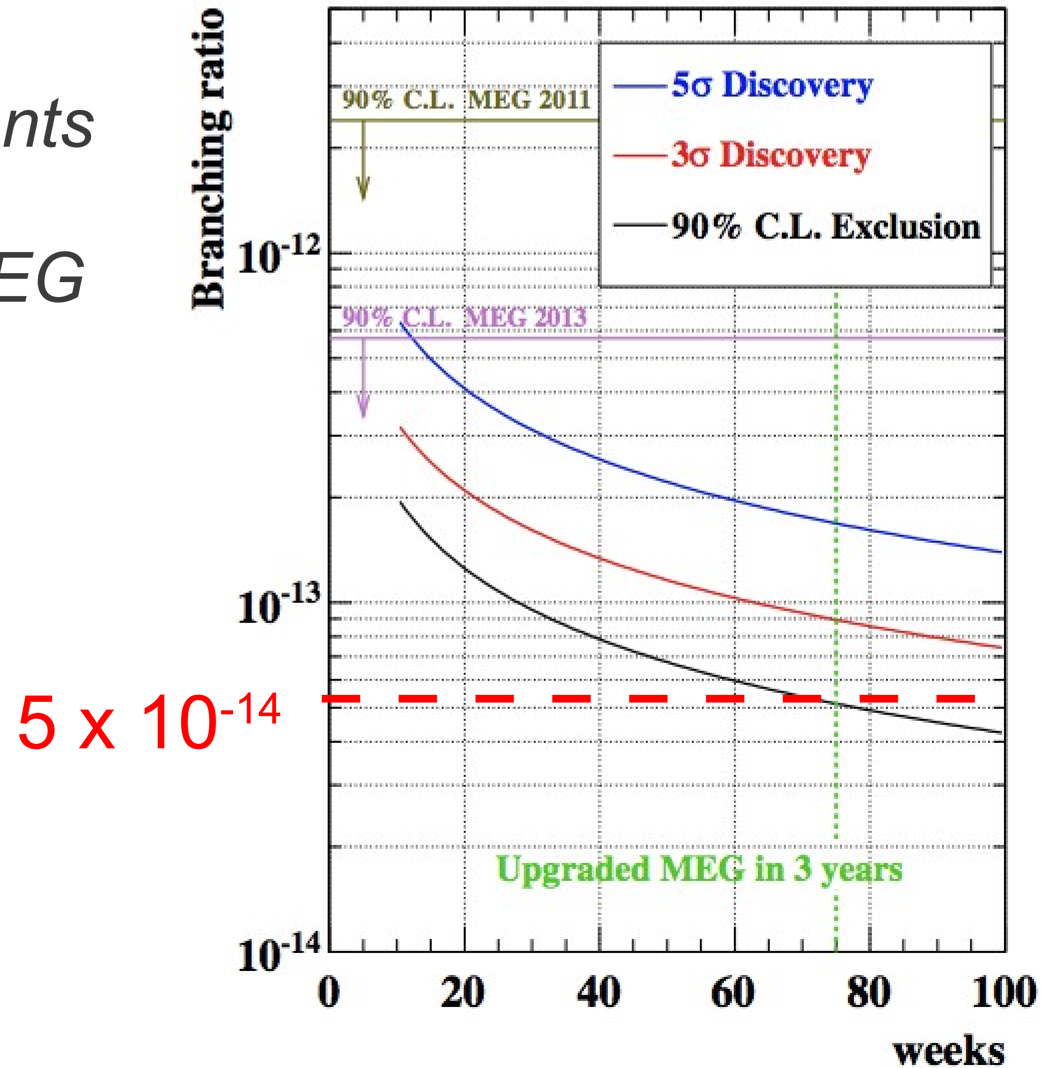




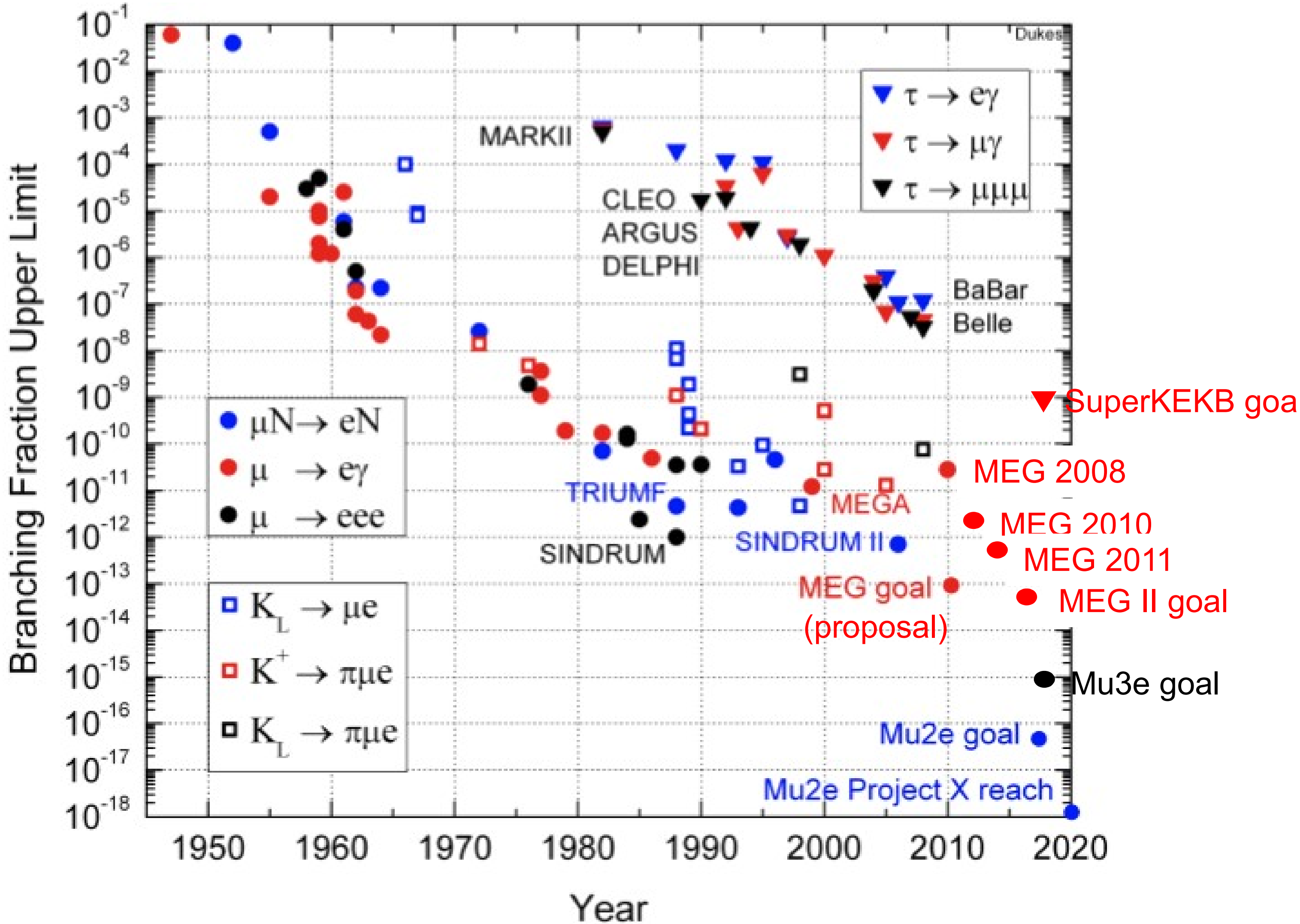
$$\sigma^2_{\text{overall}} = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter-pixel}}}{N_{\text{hit}}} + \sigma^2_{\text{MS}}(N_{\text{hit}})$$

Projected Sensitivity

From Toy MC experiments including all relevant features observed in MEG data and upgrade simulations (event-dependent resolutions, correlations, etc.).



History of searches for LFV



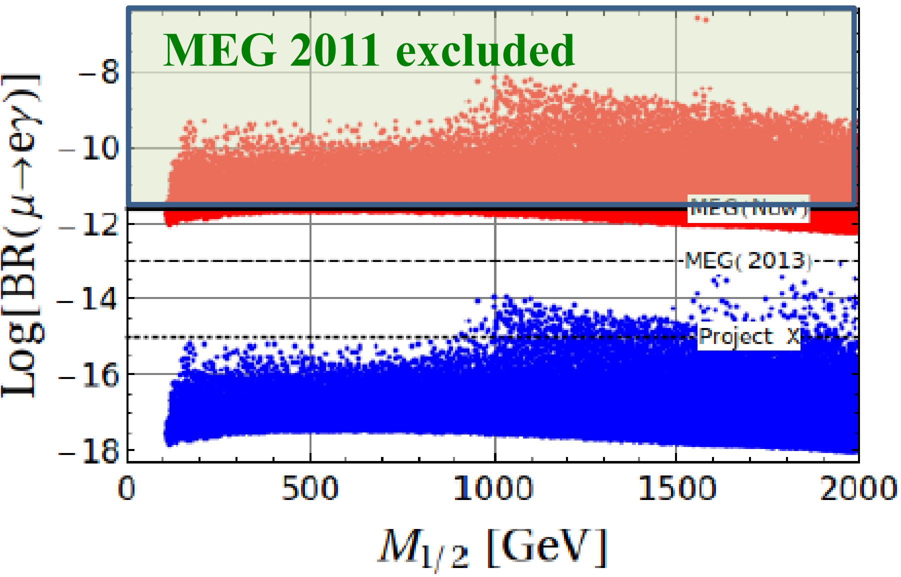
E. C. Dukes, TAU2010

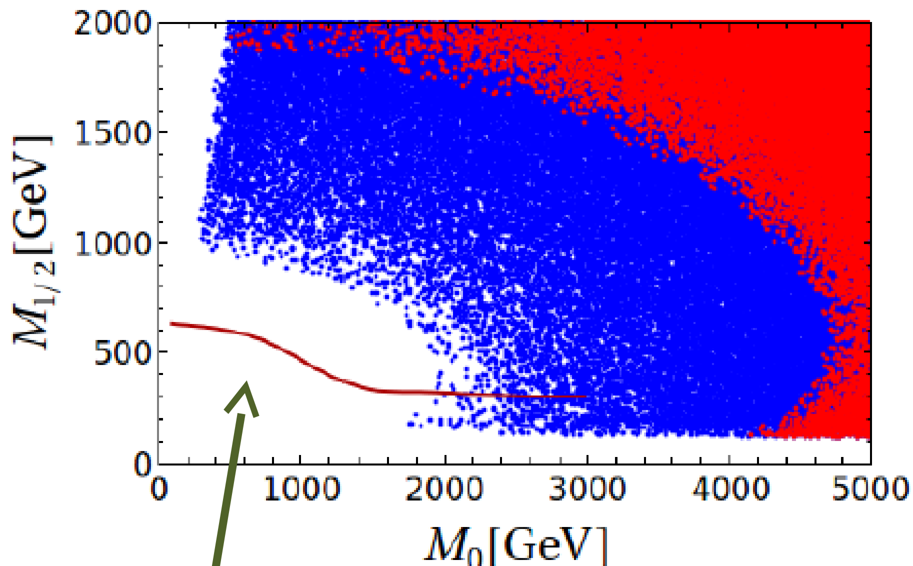
Backup slides

Indirect vs direct searches: < 2013

L. Calibbi et al., JHEP **1211** (2012) 040

MEG 2011 = PRL **107** (2011) 181201





mSUGRA, tan β = 10, U_{e3} = 0.11

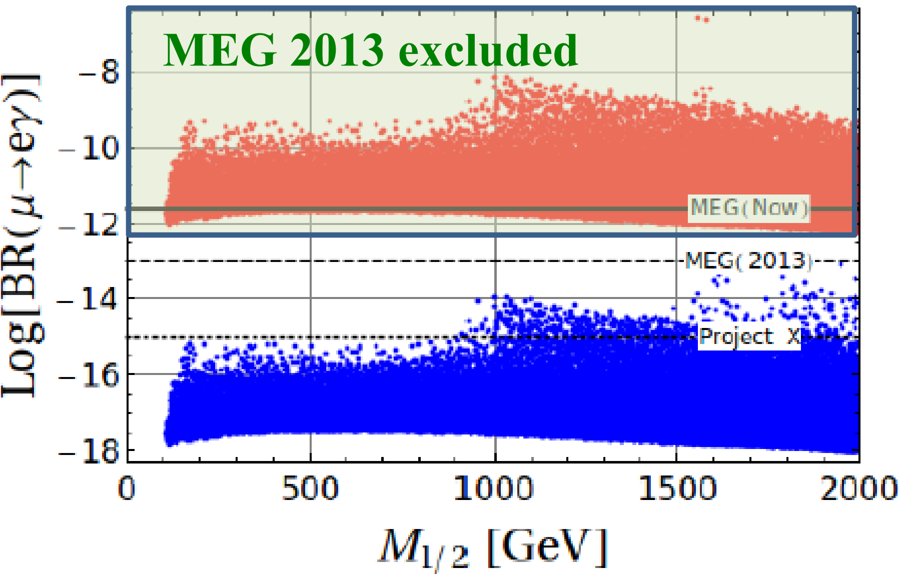
Red points: mixing based on **PMNS**

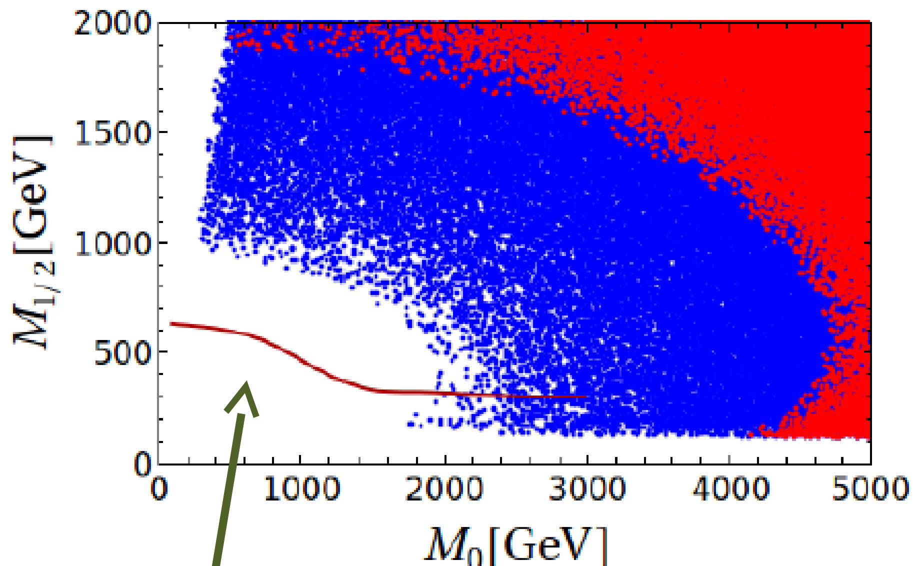
Blue points: mixing based on **CKM**

Models below this line excluded by direct LHC searches

Indirect vs direct searches: now

L. Calibbi et al., JHEP **1211** (2012) 040





mSUGRA, tan β = 10, U_{e3} = 0.11

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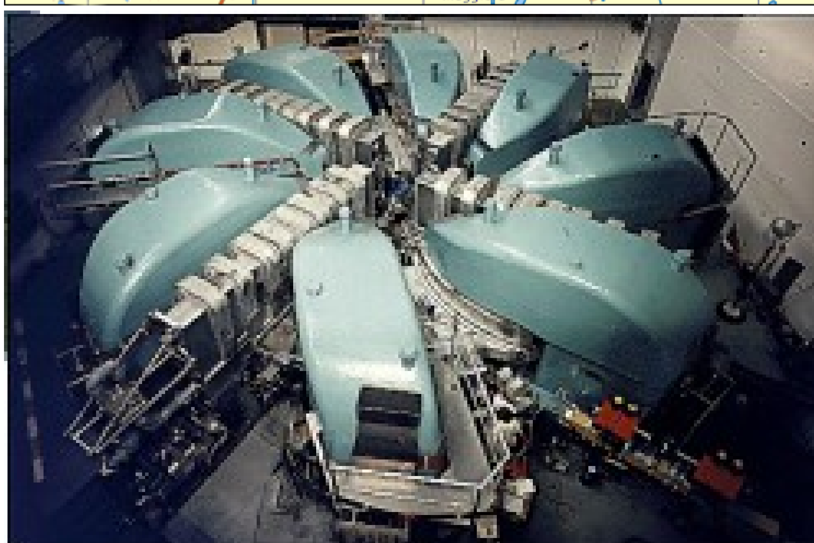
Models below this line excluded by direct LHC searches

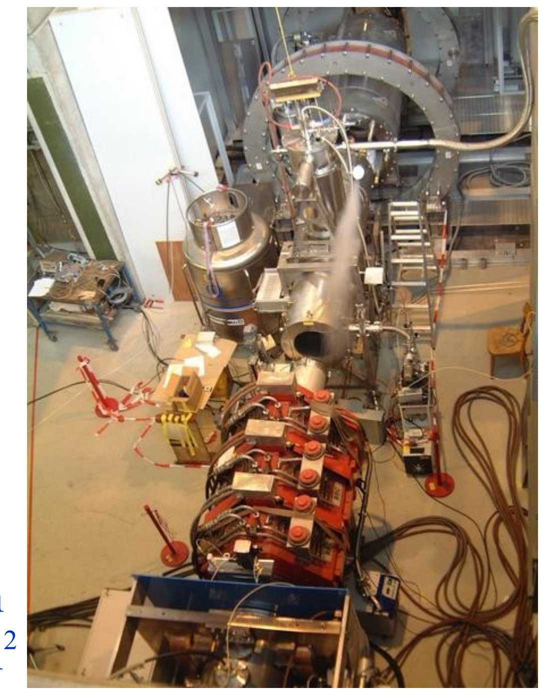
The Paul Scherrer Institute (PSI)



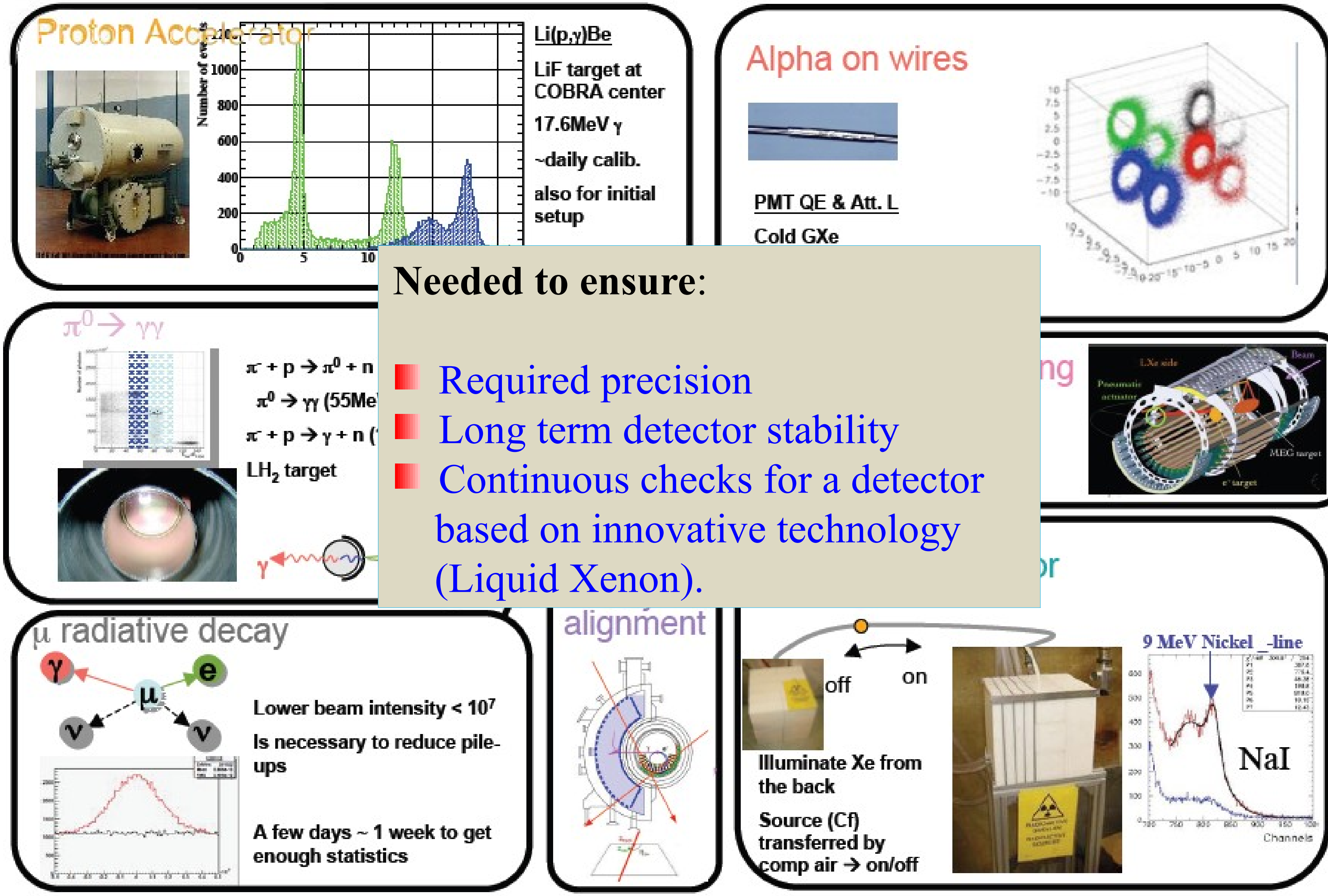
- The **most powerful continuous machine** (proton cyclotron) in the world;
- **Proton energy 590 MeV**;
- **Power 1.4 MW**;
- **Nominal operational current 2.2 mA**.

MEG beam line (πE5 secondary muon line):

- Wien filter
- Beam transport solenoid (BTS)
- Muon degrader
- 2-d beam spot on target: < 1 x 1 cm^2



Overview of calibration system



Needed to ensure:

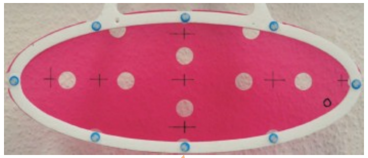
- Required precision
- Long term detector stability
- Continuous checks for a detector based on innovative technology (Liquid Xenon).

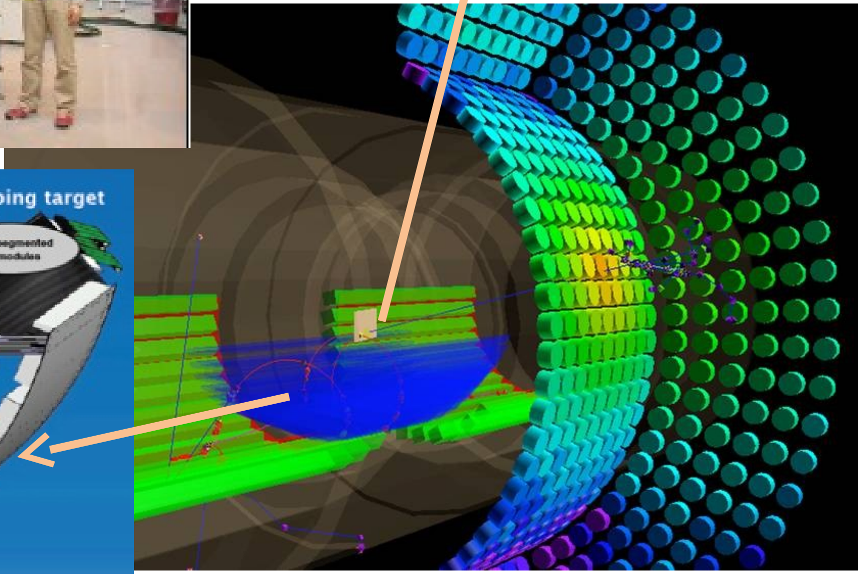
MEG detector components 1)

Superconducting solenoid with gradient field (**COBRA**)

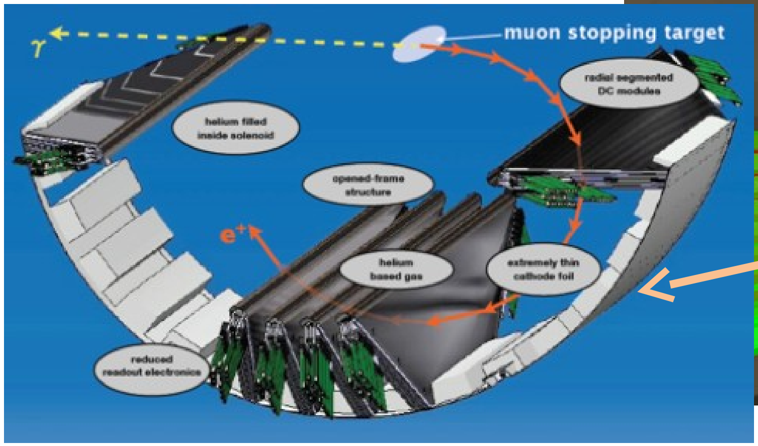
Sweeps out low Pz positrons.
Bending radius independent of θ emission angle.

205 μm polyethylene target, 20.5° slanted angle, stopping efficiency 82%



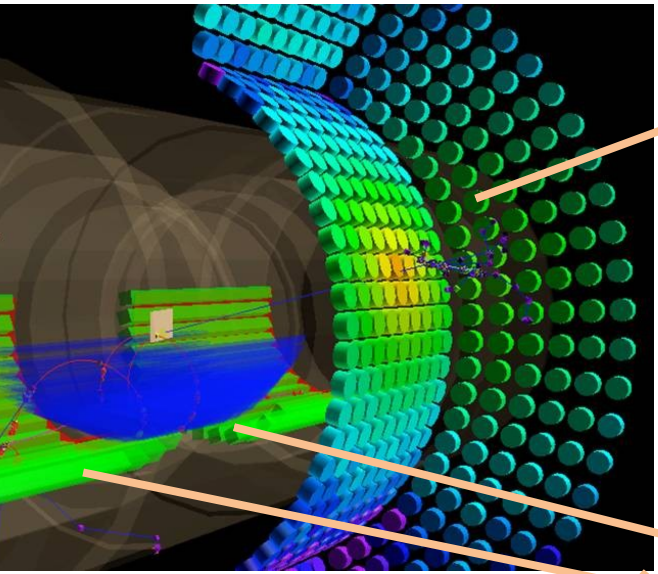


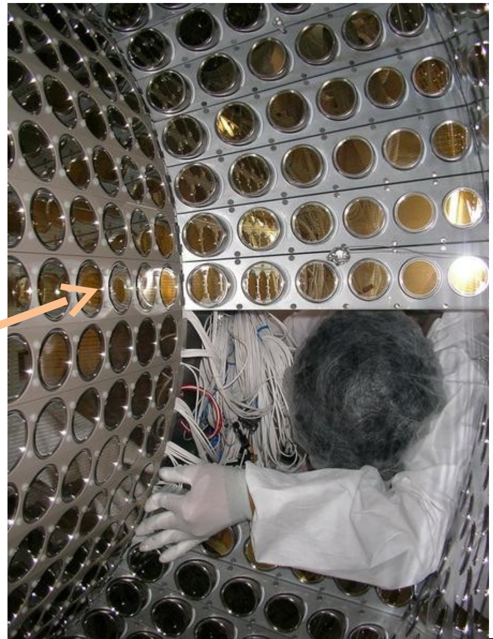
16 DCH with staggered anodic wires and cathodic strips in Vernier pattern.
Gas mixture
He:C2H6 =50:50



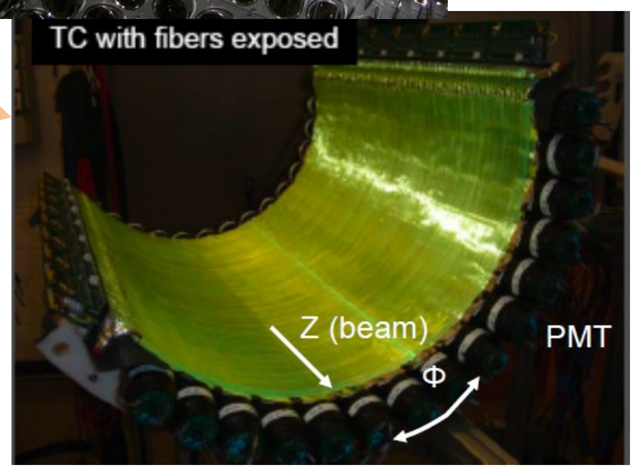
Positron momentum vector measurement.

MEG detector components 2)





900 l Liquid Xenon detector
846 UV sensitive PMTs
Light yield **≈ 0.8 NaI**.
Fast timing response (**45 ns**)
$\Delta\Omega/4\pi \approx 0.12$
Photon energy, timing and interaction point measurement.

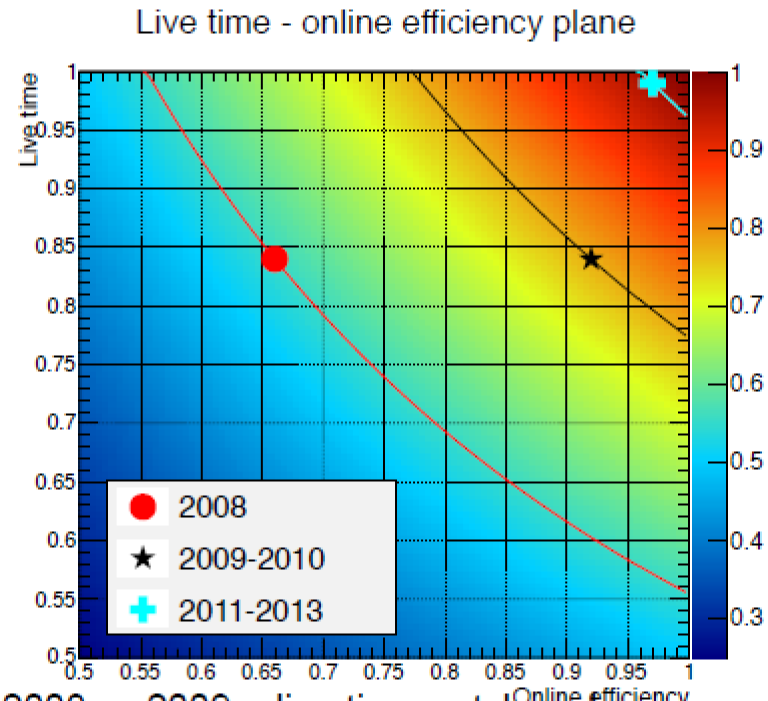


15 x 2 scintillator bars with fine mesh PMTs at both ends.
Positron timing measurement.

Trigger and electronics

- **Trigger**

  FPGA based system
  designed to reduce the trigger rate by using fast estimates:
  γ-energy: → 2 x 103 Hz
  e+γ timing → 100 Hz
  e+γ direction → **10 Hz**
  Signal efficiency > 95%
  Live Time fraction 99%



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

- Readout

  DRS digitizer chip developed at PSI
  Maximum sampling speed 5 GHz, used in MEG **0.8 and 1.6 GHz**.
  12 bit voltage digitization

Normalization

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

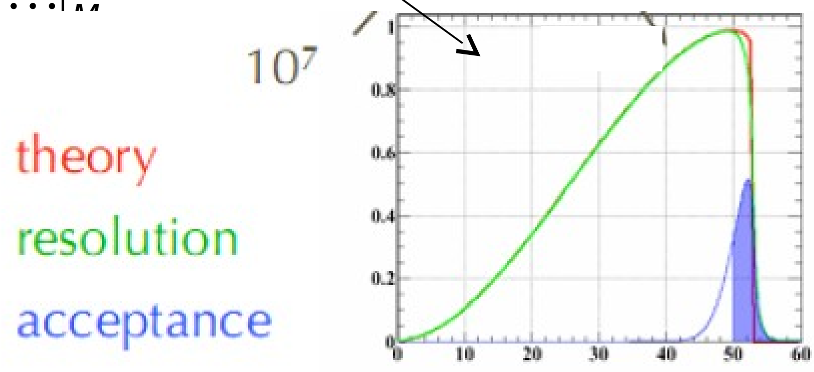
where:

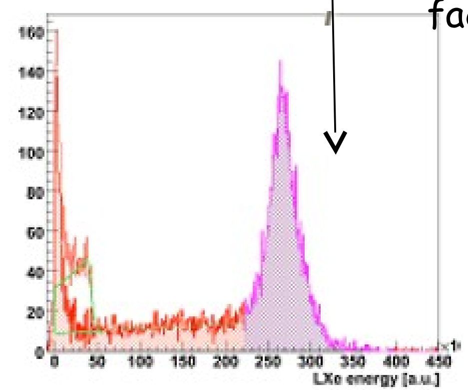
$$k \equiv N_{e\nu\nu} \times \left[\frac{f_S}{f_M}\right] \times \left[\frac{\varepsilon(TRG=0 \mid e^+\gamma)}{\varepsilon(TRG=22 \mid track \cap e^+_m \cap TC)}\right] \times A(\gamma \mid track) \cdot \varepsilon(\gamma) \cdot Psc(22)$$

$$f_S \equiv A(DC) \cdot \varepsilon(track, p_e > 50\,\text{MeV} \mid DC) \cdot \varepsilon(TC \mid p_e > 50\,\text{MeV})\big|_S$$

$$f_M \equiv \ldots\big|_M$$

10^7 pre-scaling factor





TRG = 22: Michel events trigger (only DCH track required)

TRG = 0: MEG events trigger

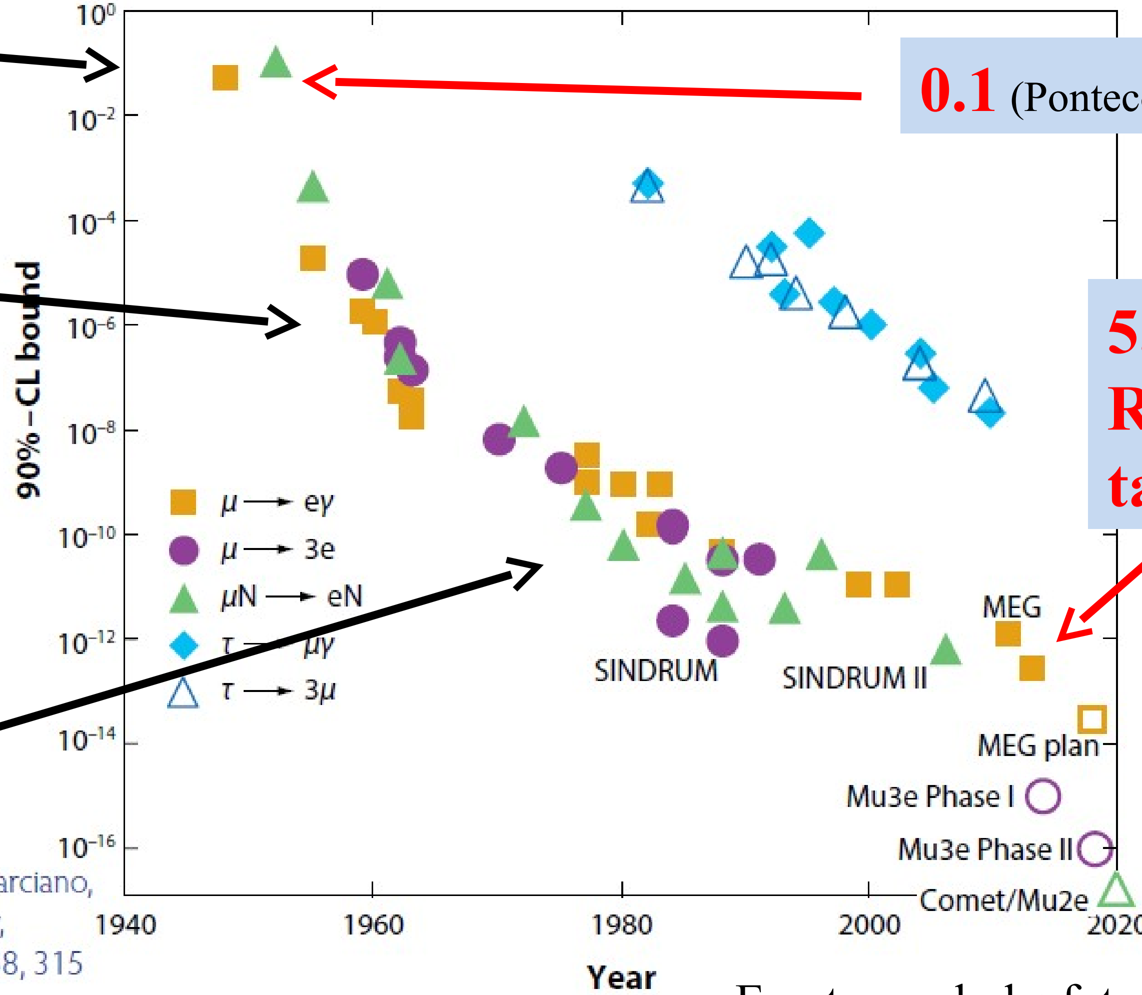
A 70 year history ..

Cosmic μ's

Stopped π's

Muon beams

0.1 (Pontecorvo & Hincks,)



5.7×10^{-13} Result in this talk (2013)

Gained twelve orders of magnitude !

(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

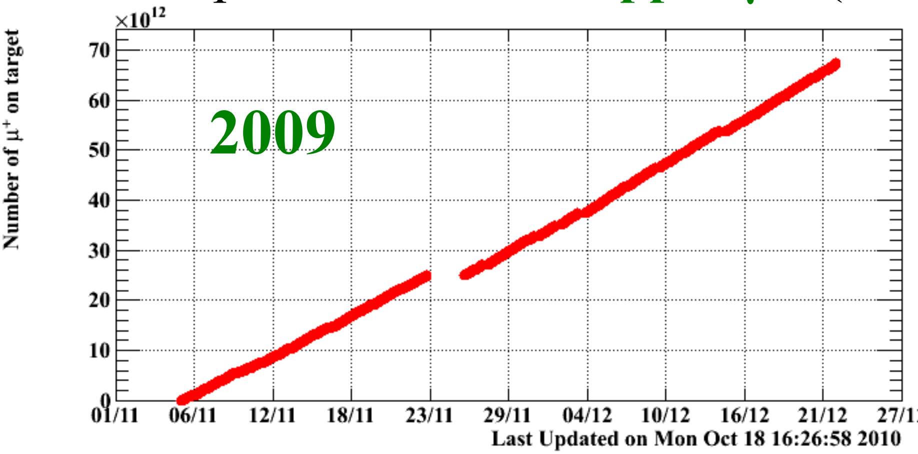
Empty symbols: future experiments

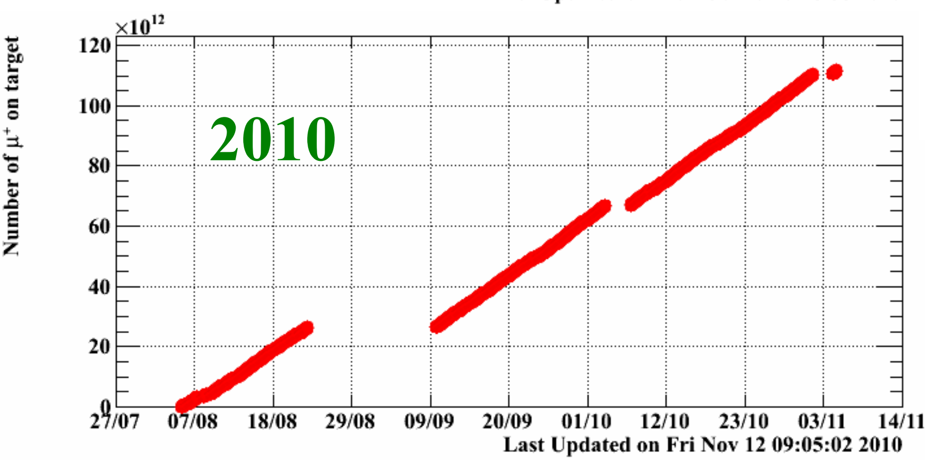
MEG data sample

Previous result:
(PRL **107** (2011) 181201)

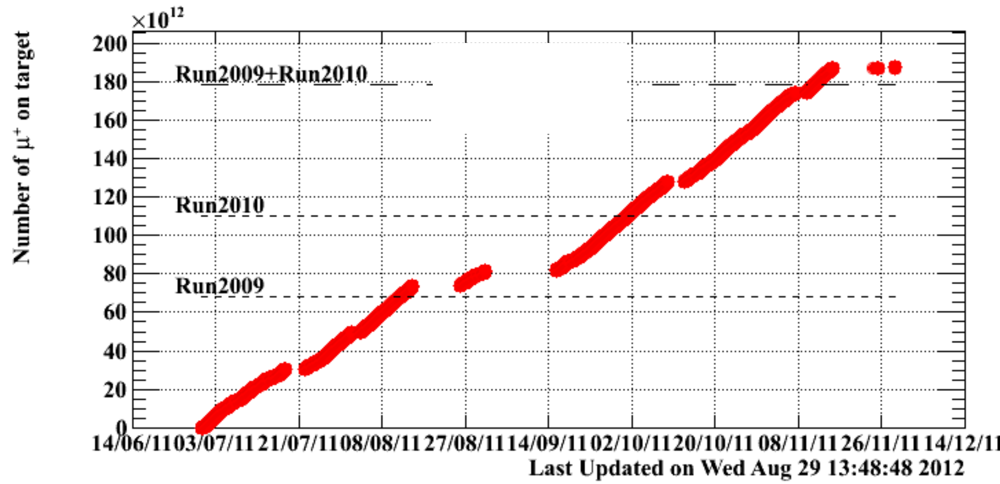
BR (μ → eγ) < 2.4 x 10^{-12} @90% C.L.

Data sample: **1.75 x 10^{14} stopped μ+** (2009 + 2010)





Added in 2011: **1.85 x 10^{14} μ+**



Total data sample: **3.6 x 10^{14} μ^+**

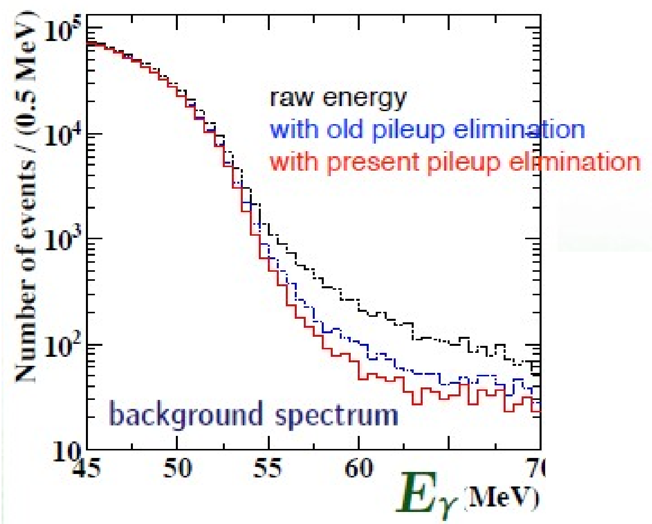
Hardware improvements in 2011:
- NaI replaced by BGO for π^0 measurements
- Laser tracker system for DCH/target alignment

Reconstruction improvements

γ-side:

improved pile-up rejection method:

- ❑ reduced high energy tail
- ❑ 7% higher signal efficiency



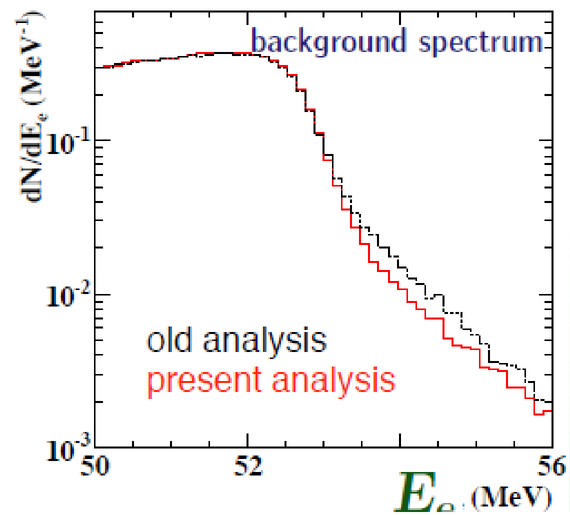
e⁺-side:

FFT offline noise reduction

- ❑ few % better angle resolution
- ❑ 6% higher signal efficiency

New track fitter (Kalman filter)

- ❑ reduced high energy tail
- ❑ 7% higher signal efficiency



New algorithms applied to: - reanalyze 2009-2010 sample;
- process data collected in 2011

MEG likelihood analysis

- **Maximum likelihood analysis** to extract N_{signal}
  - Observables: E_γ, E_e, $T_{e\gamma}$, $\theta_{e\gamma}$, $\Phi_{e\gamma}$
  - **PDFs are formed mostly from data.**
    - **Signal**: Measured resolutions
    - **Accidental BG** : Measured spectrum in sidebands
    - **RMD**: Theoretical spectrum smeared by detector resolutions
- Different likelihood analyses performed to check systematics
  - **PDF**: Event-by-event PDF, different PDFs according to tracking quality, averaged PDF

The most dangerous bck is measured !

Likelihood function

PDFs

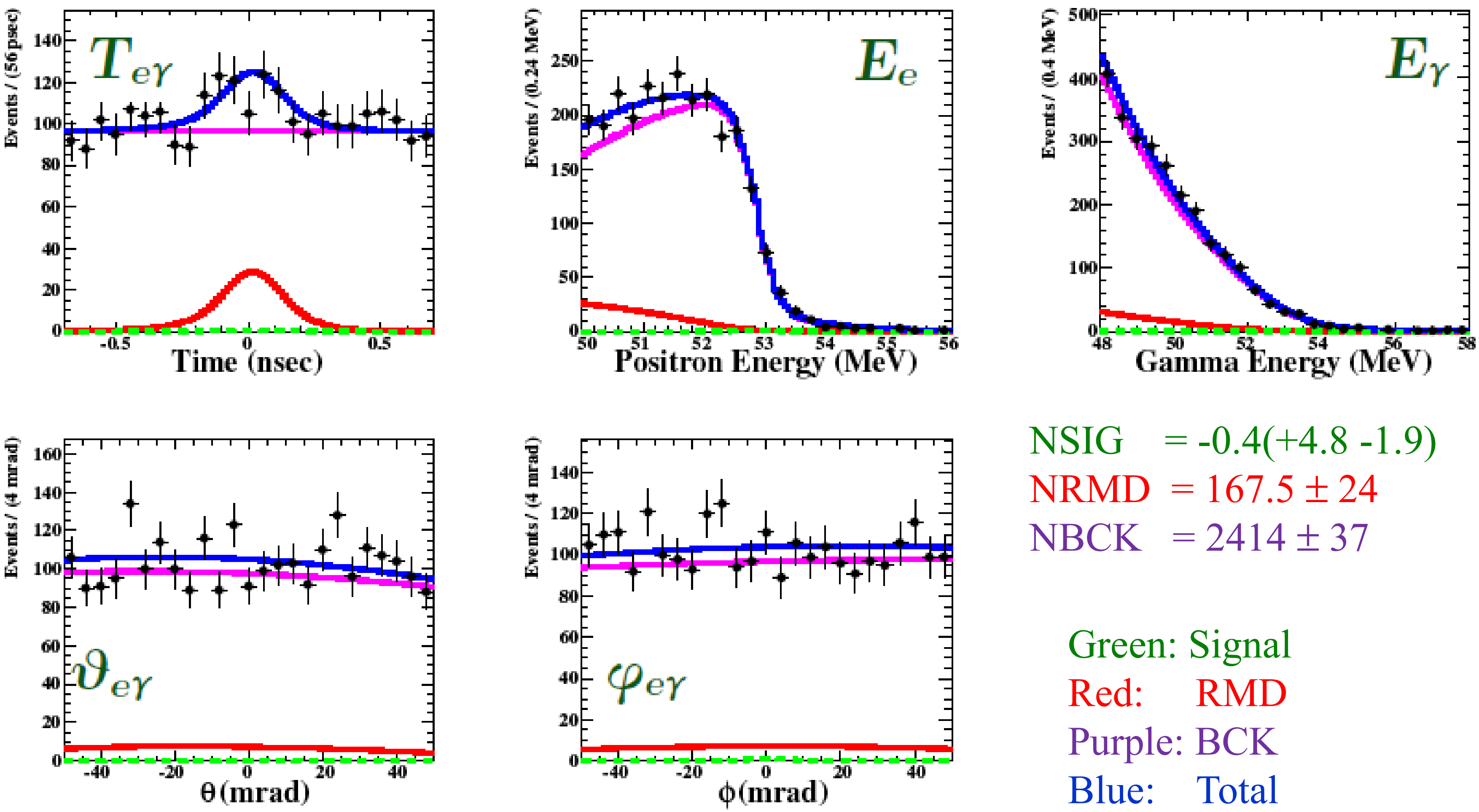
$$\mathcal{L}(\vec{x}_1,\ldots,\vec{x}_N,R_\diamond,A_\diamond|\hat{S},\hat{R},\hat{A}) = \frac{e^{-\hat{N}}}{N!} e^{-\frac{1}{2}\frac{(A_\diamond-\hat{A})^2}{\sigma_A^2}} e^{-\frac{1}{2}\frac{(R_\diamond-\hat{R})^2}{\sigma_R^2}} \prod_{i=1}^{N} \left(\hat{S}s(\vec{x}_i)+\hat{R}r(\vec{x}_i)+\hat{A}a(\vec{x}_i)\right)$$

Background rate constraints

Signal
Radiative Bkg
Accidental Bkg

PDF= Probabilty Distribution Function

2009 - 2011 likelihood fit



NSIG = -0.4(+4.8 -1.9)

NRMD = 167.5 ± 24

NBCK = 2414 ± 37

Green: Signal

Red: RMD

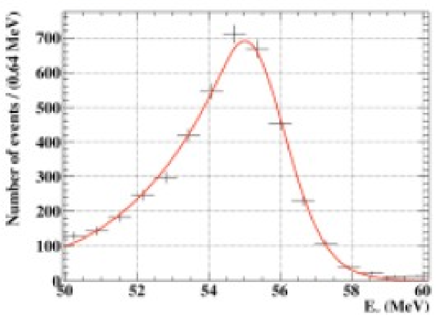
Purple: BCK

Blue: Total

Black: Data

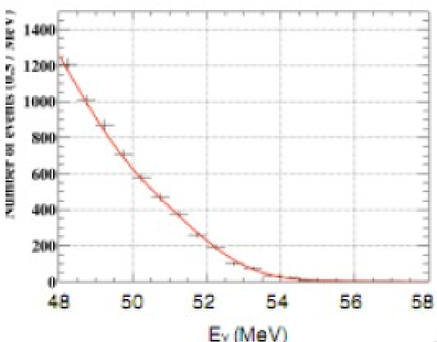
PDF's

55 MeV π^0 peak



Gamma

Signal PDF from 55MeV calibration gamma (π^0 decay)



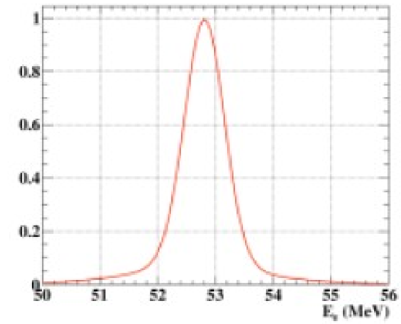
BG measured in sideband

Positron

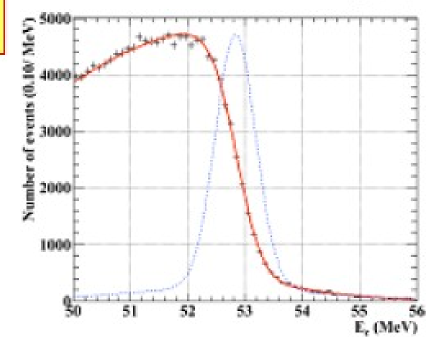
Signal PDF from measured resolution

Michel positrons

Mott scattering device

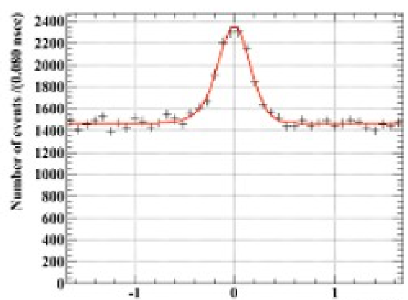


BG measured in sideband



Per-event error matrix for positron introduced in 2011. **Improvement of 10 % in analysis sensitivity**.

RMD peak mostly in low energy part



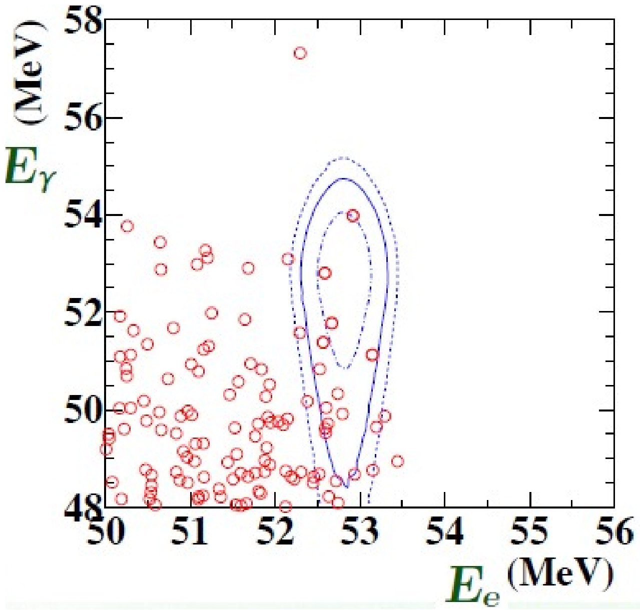
Relative time

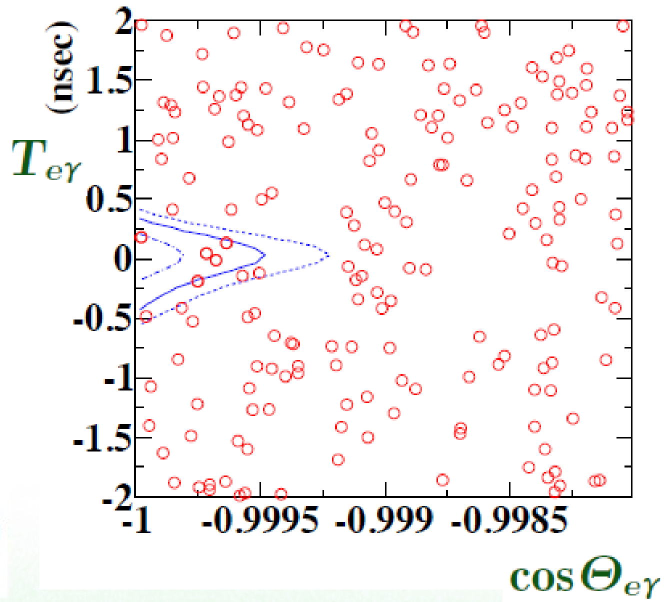
Signal PDF from measured RMD peak

Relative angle

From measured double turn tracks

Re-analysis of 2009-2010





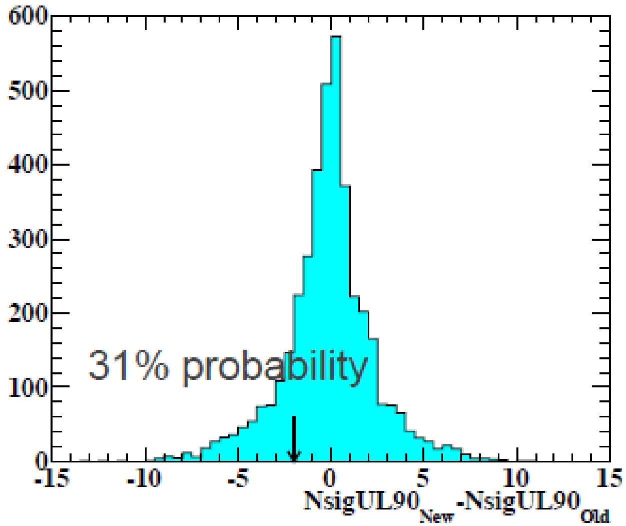
Event distributions; cuts on not shown variables

Signal PDF contours at 39.3, 74.2, 86.5%

No excess found

⇓

NSIG Best = 0.3 (+4.1, -1.5)



Comparison with previous analysis:
UL changed because of different reconstruction algorithms.
Statistical compatibility checked with toy MC: **31% probability.**