Latest results of the MEG experiment

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On behalf of the MEG Collaboration

EPS-HEP Conference, Stockholm, 18-24 July 2013

Outline

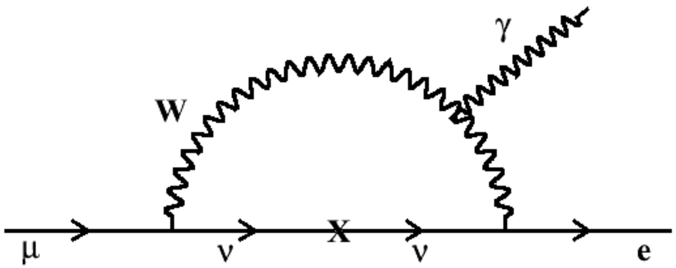
- Lepton Flavour Violation **(LFV)**
- The MEG Experiment
- Re-analysis of 2009/2010 Data
- Analysis of 2011 Data and combined results
- Impact on Beyond Standard Model Physics **(BSM)**
- Summary and Perspectives

LFV 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**) $\Rightarrow$ needed to **extend the standard model by including neutrino masses and coupling between flavours**.
- **cLFV indicates non conservation of lepton flavour in processes involving charged leptons**.

LFV 2)

Including neutrino masses and oscillations in SM:



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

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2 \approx 10^{-54}$$

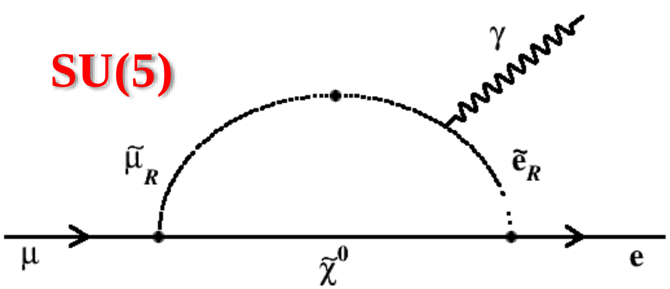
Experimentally not measurable !

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

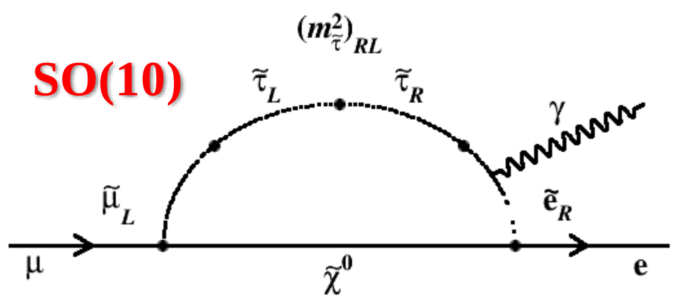
$$\approx 10^{-5} \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\bar{m}^2_{\tilde{\ell}}} \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}}\right)^4 \tan^2\beta$$

$\approx 10^{-12}$

SU(5)



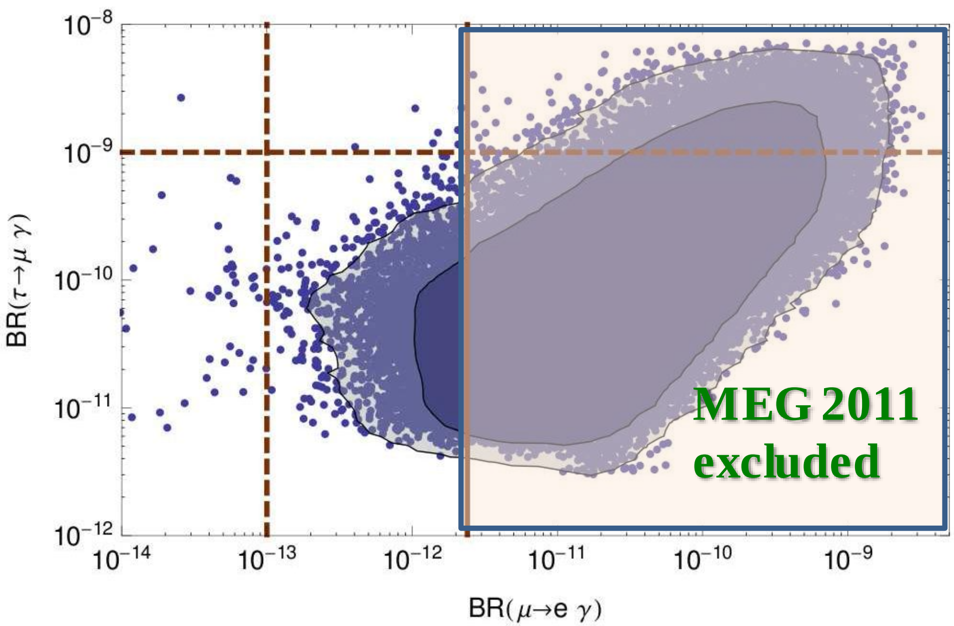
SO(10)



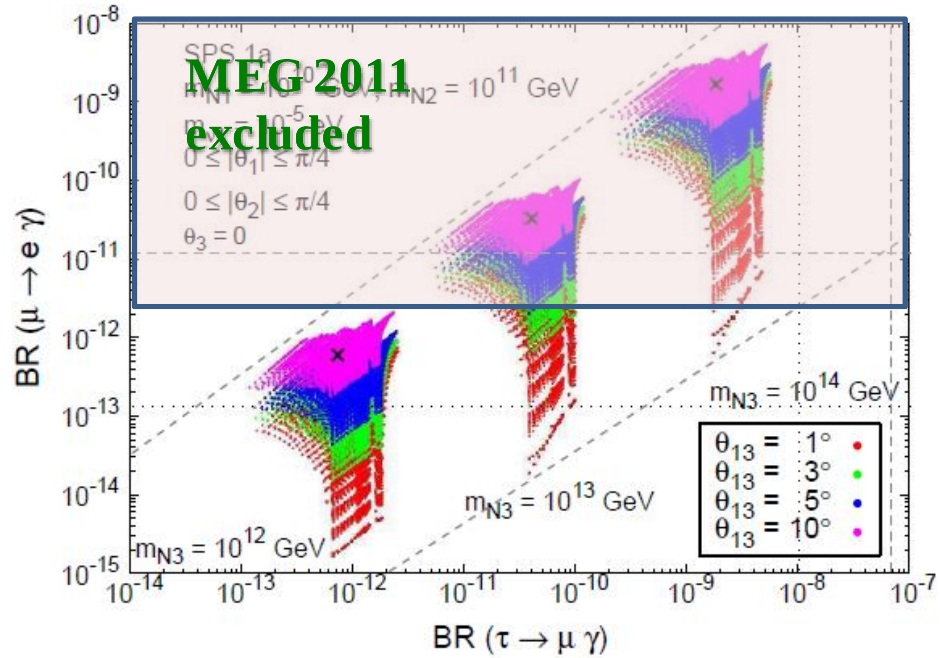
⇒ **Observation of cLFV clear evidence for physics beyond SM**

$\tau \to \mu\gamma$ vs $\mu \to e\gamma$ < 2013

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



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



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

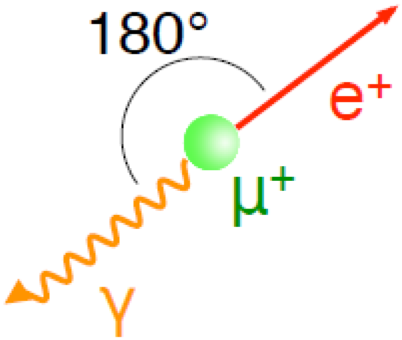
θ_{13} recently measured by Daya Bay, Reno, Double Chooz ... ($7 \div 10^o$)

The MEG Experiment

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

Signal and background

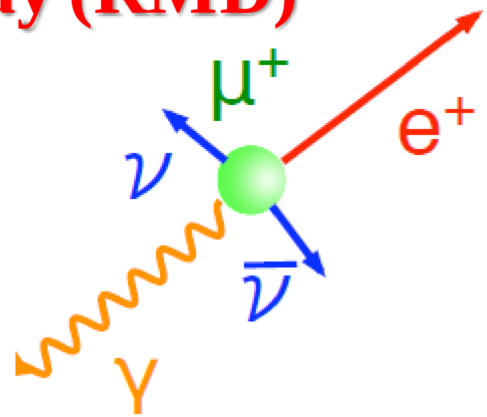
Signal



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

$T_e = T_\gamma$

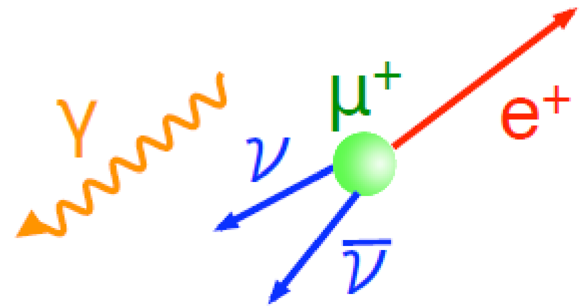
Radiative muon decay (RMD)



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

$T_e = T_\gamma$

Accidental Background (ACC)



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

Random $\Delta T, \Delta\Theta, E_e, E_\gamma < m_\mu/2$

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

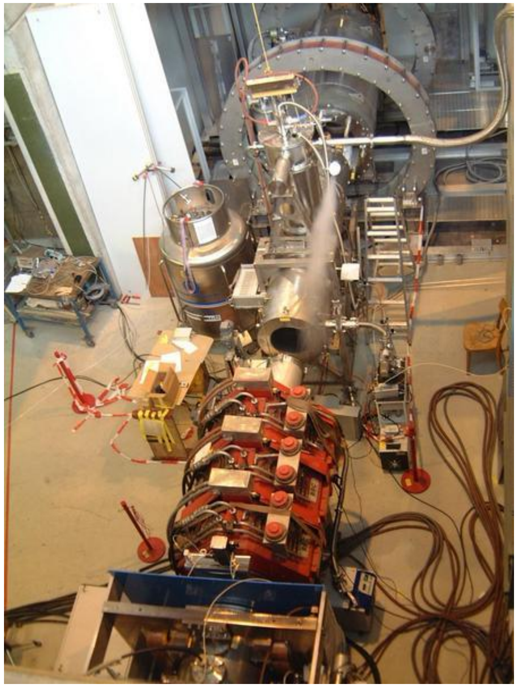
- **ACC is dominant (x 10 RMD in signal region)**;
- needed **continuous beam** and **accurate choice of** R_μ;
- needed **high precision experiments.**

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.**

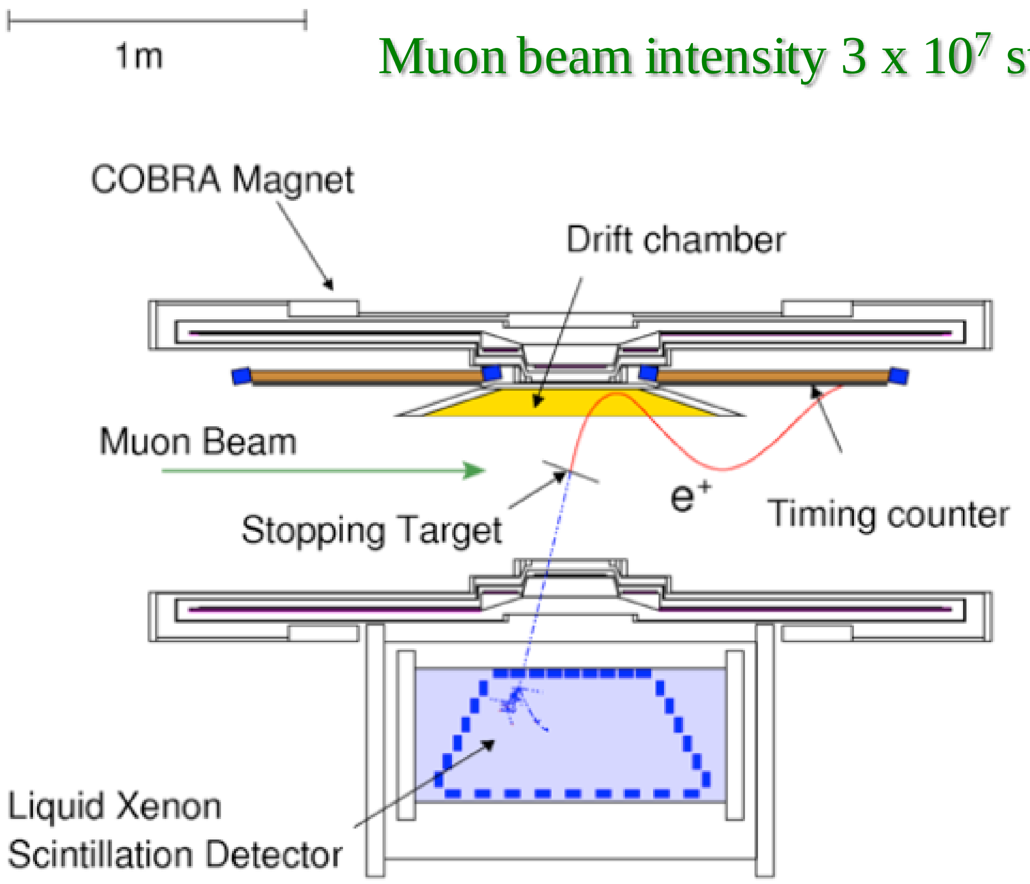
MEG beam line (πE5 secondary muon line):

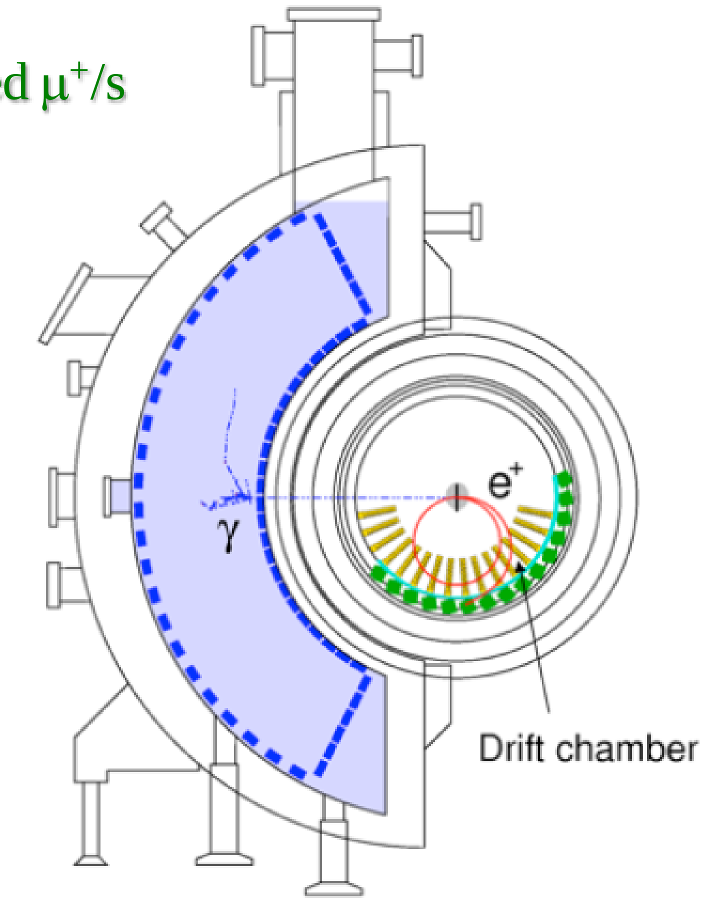
- Wien filter
- Beam transport solenoid (BTS)
- Muon degrader
- 2-d beam spot on target: ~ (1 x 1) cm^2



Detector layout

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





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

Summary of MEG performances

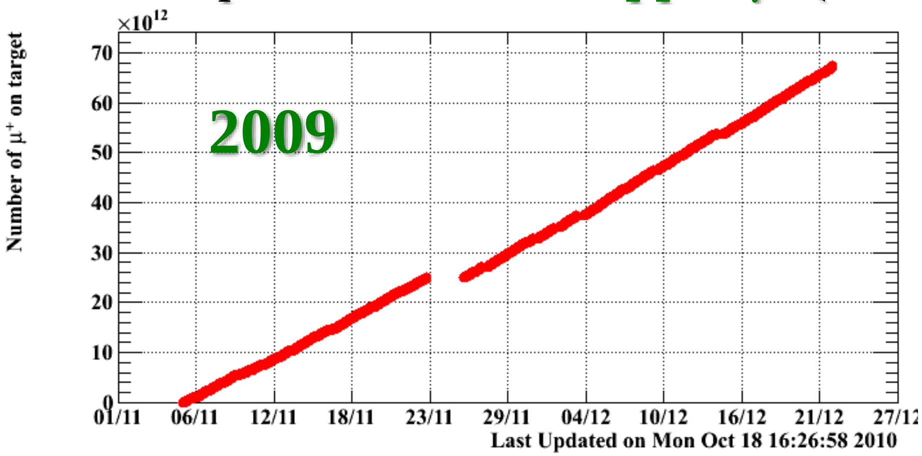
	2009	2010	2011	Note
Gamma E [%]	1.89	1.90	1.65	Effective sigma (averaged on event depth)
Relative timing $T_{e\gamma}$ [ps]	160	130	140	RMD with E_γ < 48 MeV
Positron E [keV]	306 (86%)	306 (85%)	304 (86%)	Michel edge, core resolution
Positron θ [mrad]	9.4	10.4	10.6	Double turn
Positron ϕ at zero [mrad]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

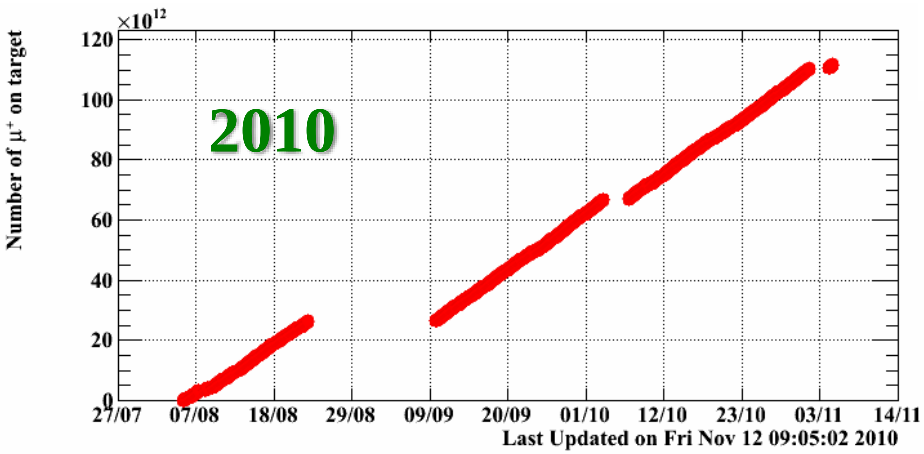
MEG data sample

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

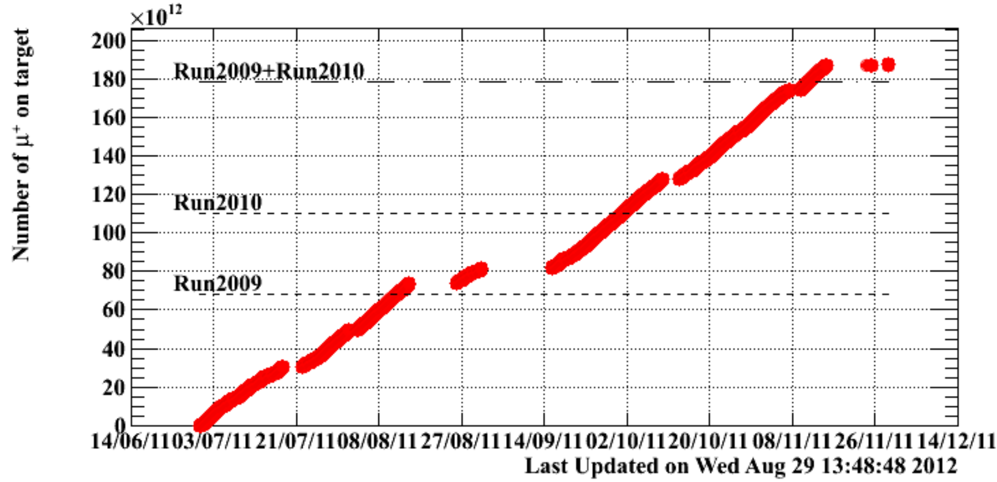
BR ($\mu \to e\gamma$) < 2.4 x 10^{-12} @90% C.L.

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^+**

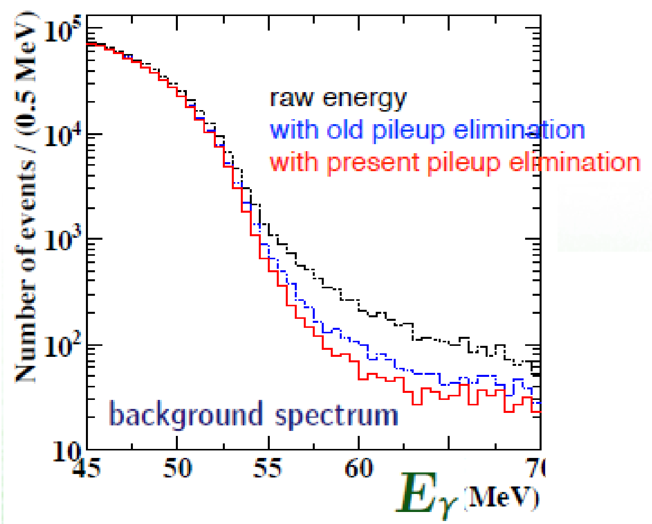
Hardware improvements in 2011:
- NaI replaced by BGO for π^0 measurements
- Laser tracker system for DCH/target alignment
- Multiple buffer readout

Reconstruction improvements

γ-side:

improved pile-up rejection method:

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



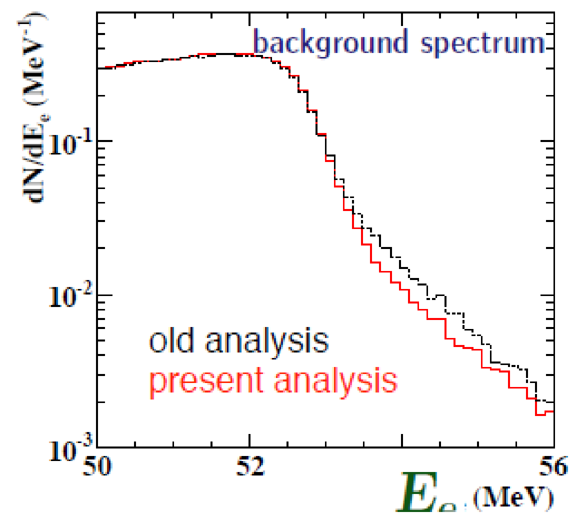
e^+-side:

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

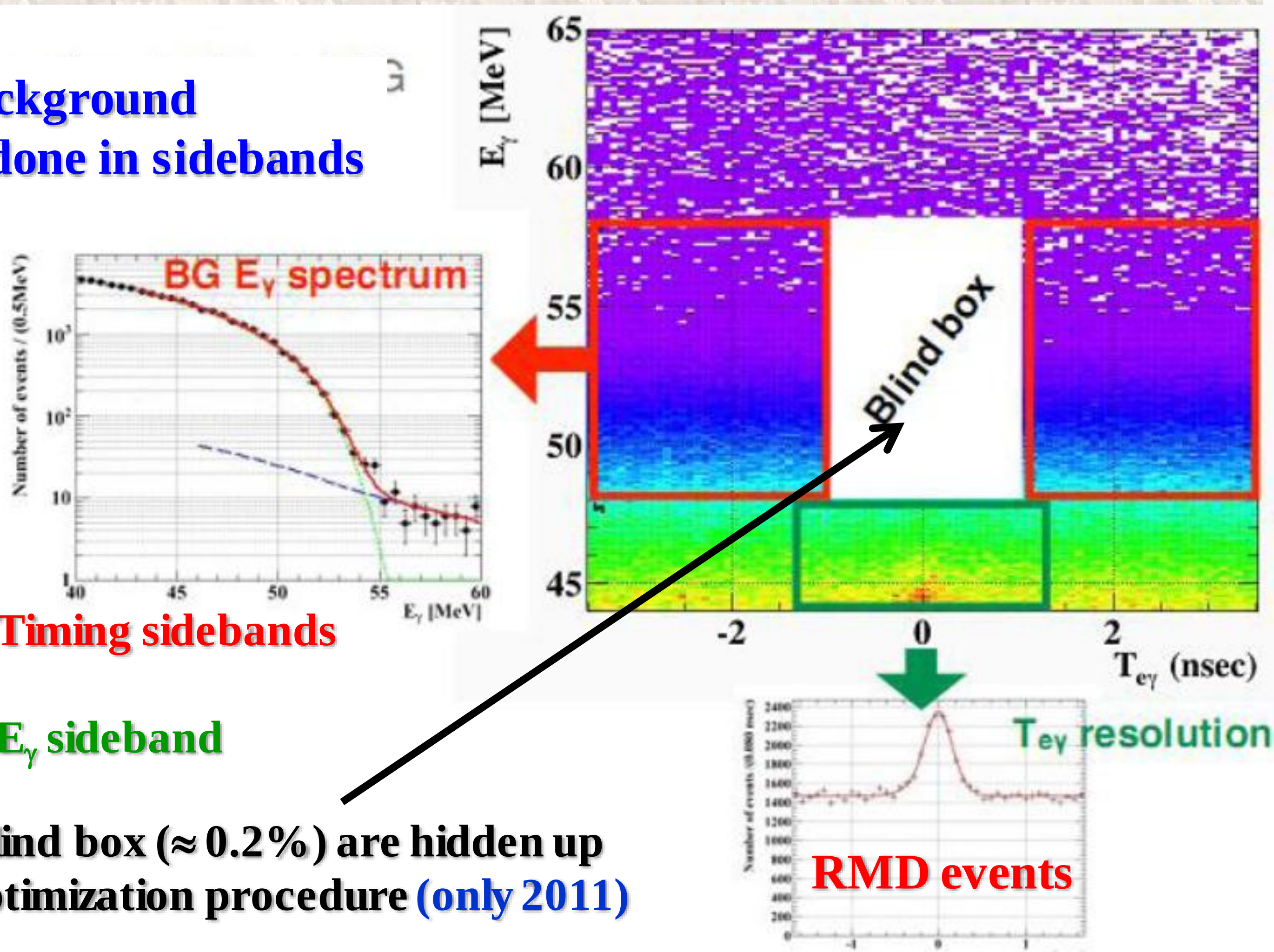


New algorithms applied to: - reanalyze 2009-2010 sample;
- process data collected in 2011

MEG 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)

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

Most dangerous background is measured !

Likelihood function

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

PDFs

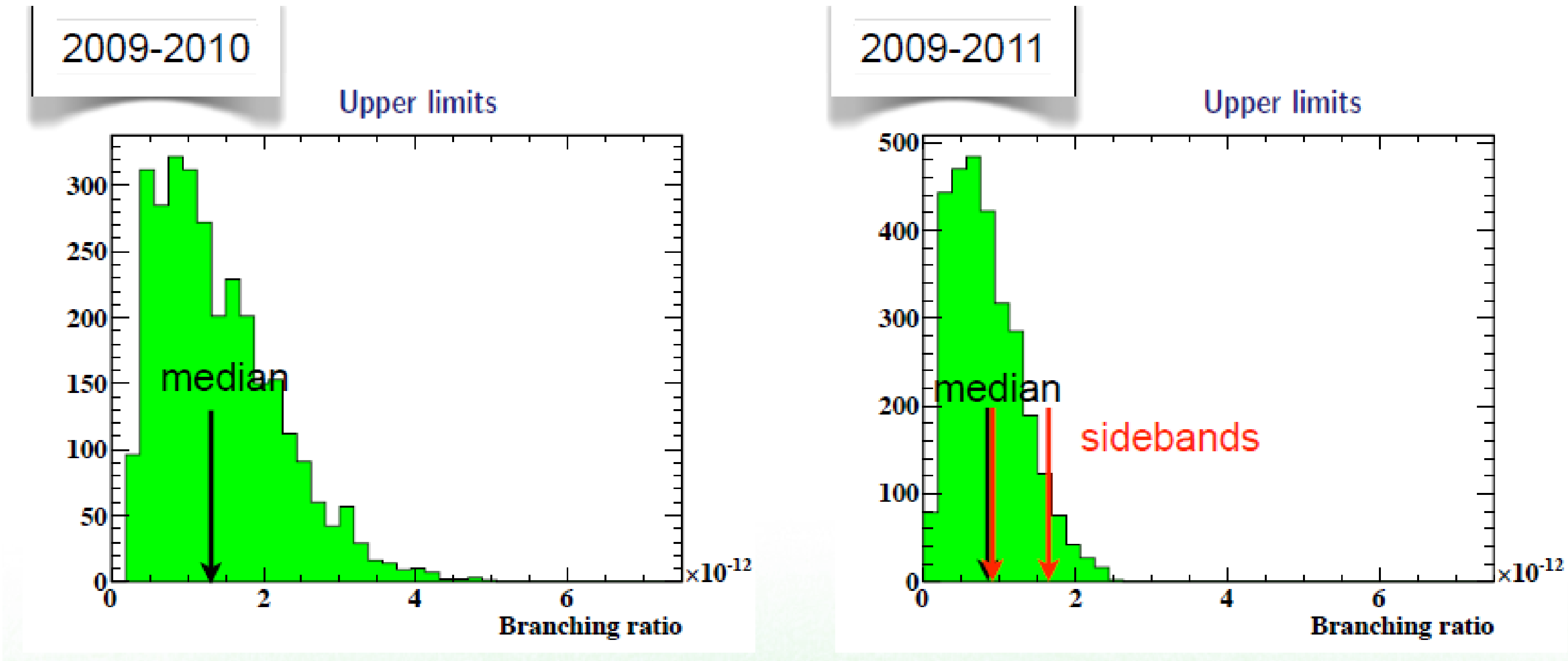
Background rate constraints

PDF= Probabilty Distribution Function

Signal
Radiative Bkg
Accidental Bkg

Sensitivity

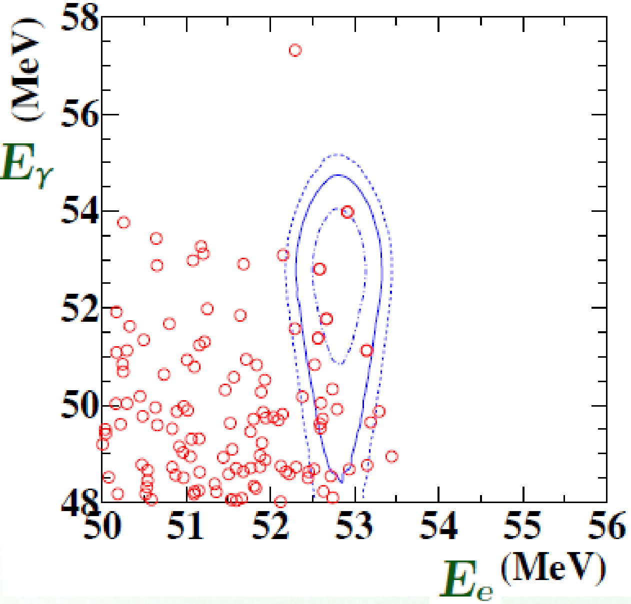
Median upper bound of a sample of **toy MC experiments** generated with **zero signal hypothesis** using the measured background pdf's.

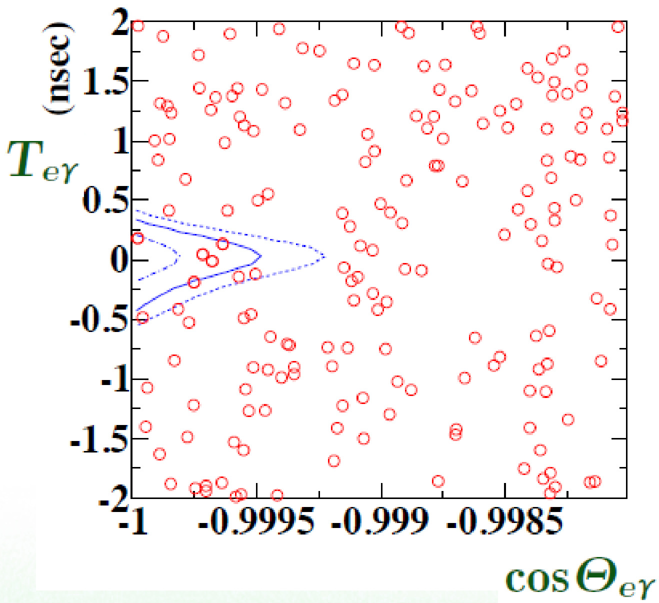


Median (2009 - 2010) = 1.30 x 10^{-12} (1.6 x 10^{-12} in previous analysis, 20% improvement)
Median (2009 - 2011) = 7.7 x 10^{-13}

10^{-13} level reached !

Re-analysis of 2009-2010





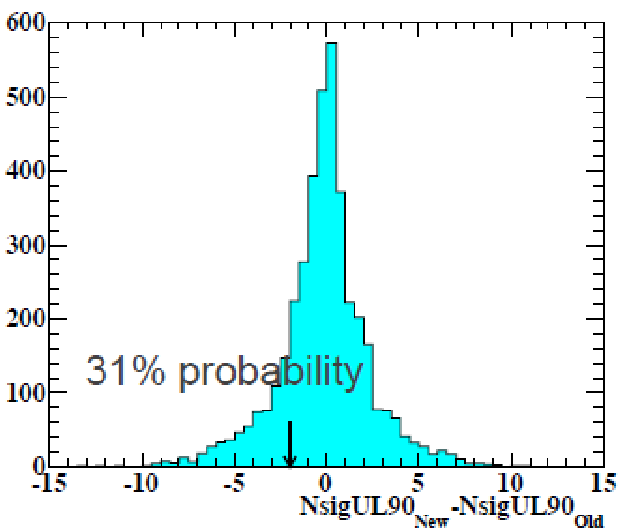
Event distributions; cuts on not shown variables

Signal PDF contours at 39.3, 74.2, 86.5%

No excess found

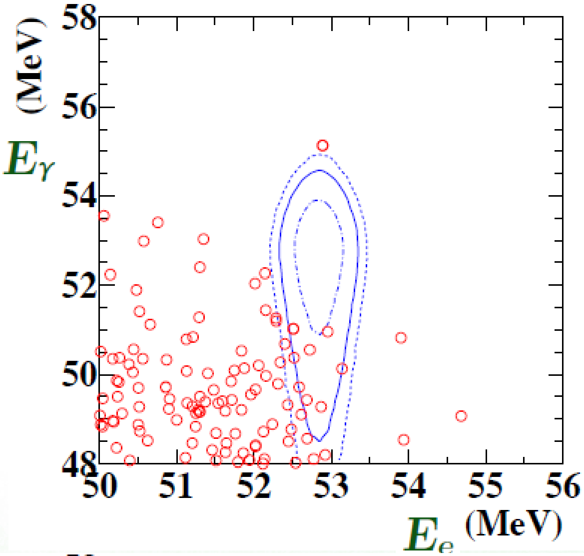
⇓

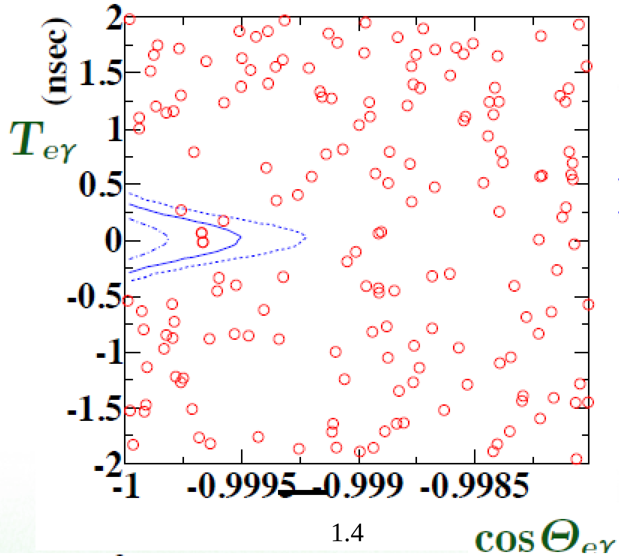
NSIG Best = 0.3 (+4.1, -1.5)



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

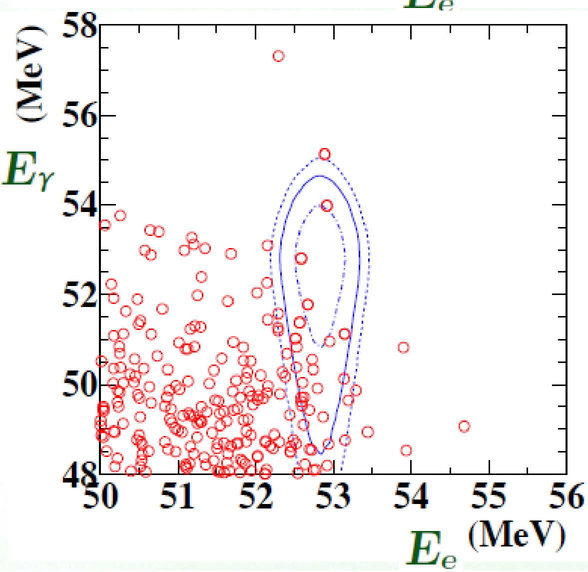
2011 and 2009-2011 analysis

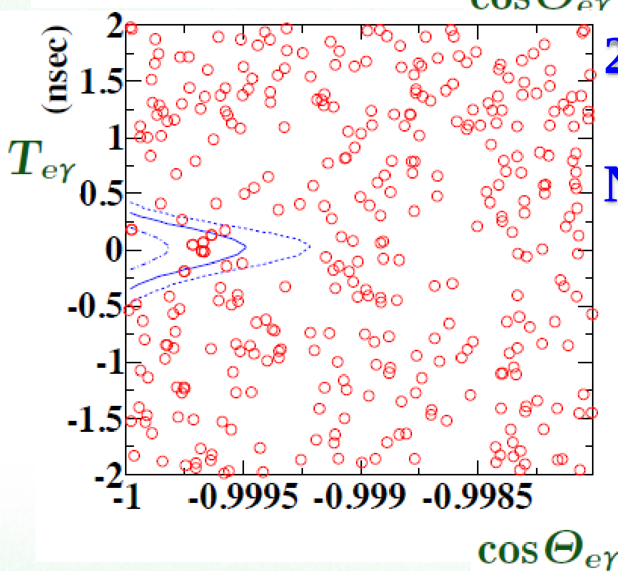




2011 data only

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





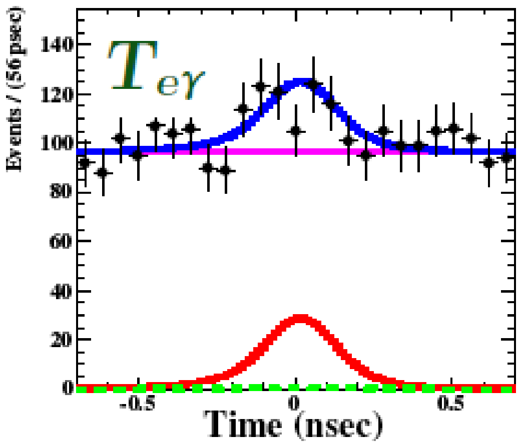
2009-2011 data

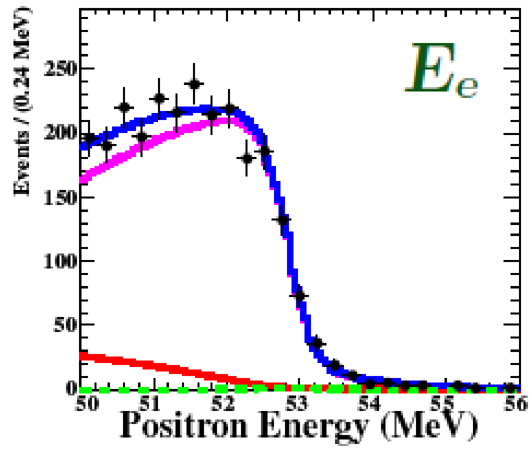
NSIG Best = -0.4 (+4.8, -1.9)

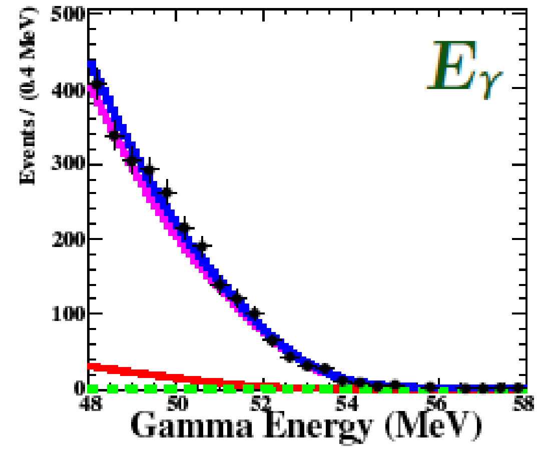
No excess observed in all samples

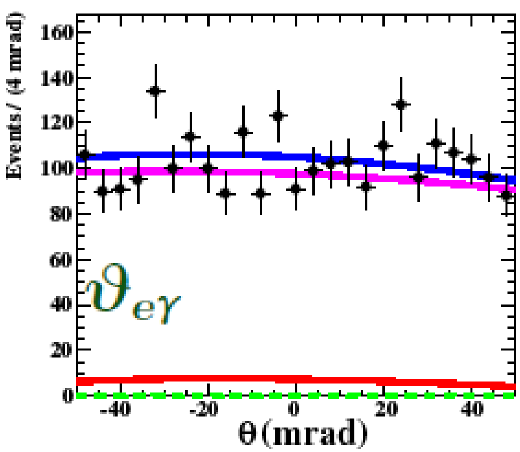
2009-2011 likelihood fit

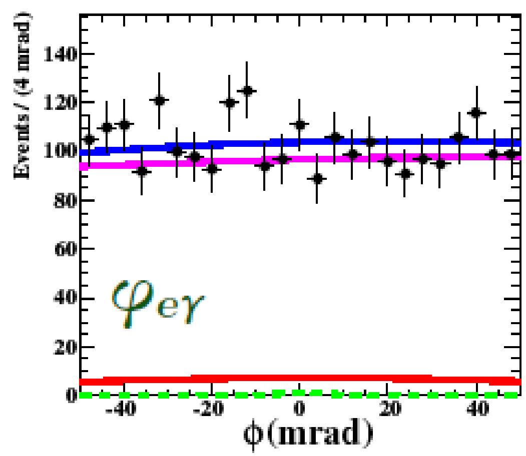
Unbinned maximum likelihood fit on $(E_e, E_\gamma, \Delta T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$











NSIG = -0.4(+4.8 -1.9)

NRMD = 167.5 ± 24

NBCK = 2414 ± 37

Green: Signal

Red: RMD

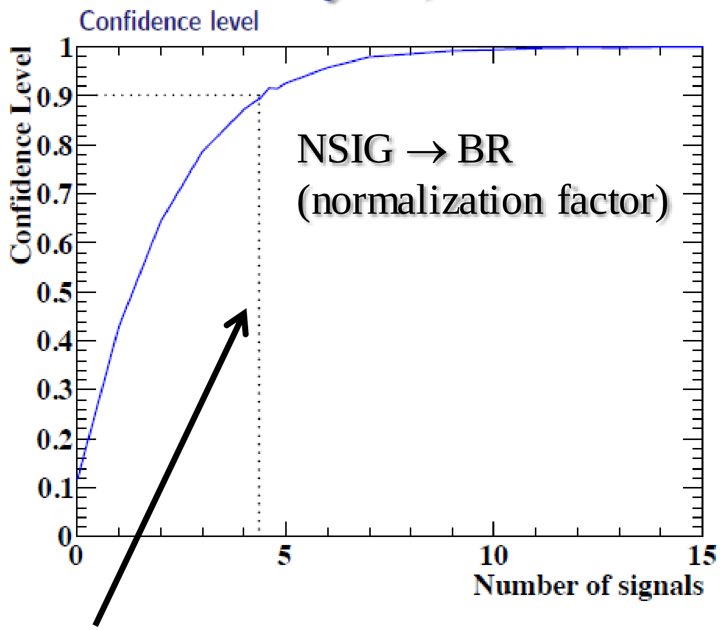
Purple: BCK

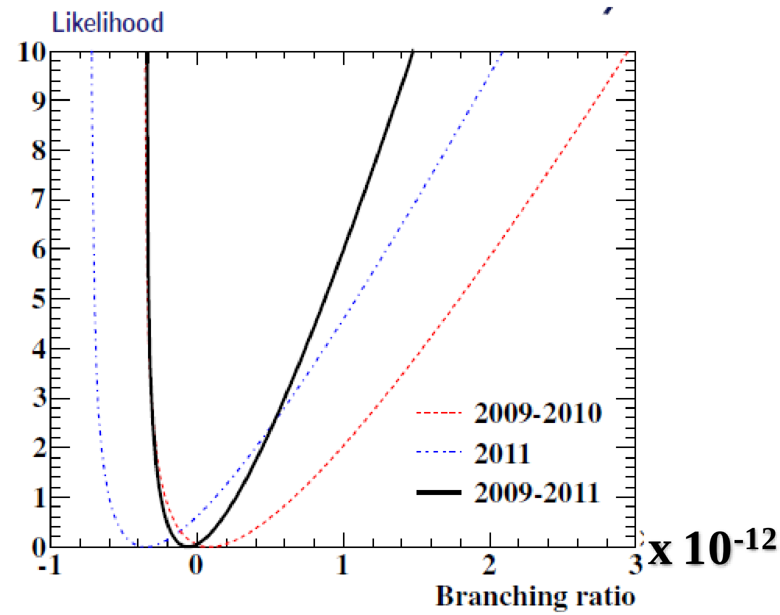
Blue: Total

Black: Data

Confidence level

Frequentistic analysis, Feldman-Cousins method





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

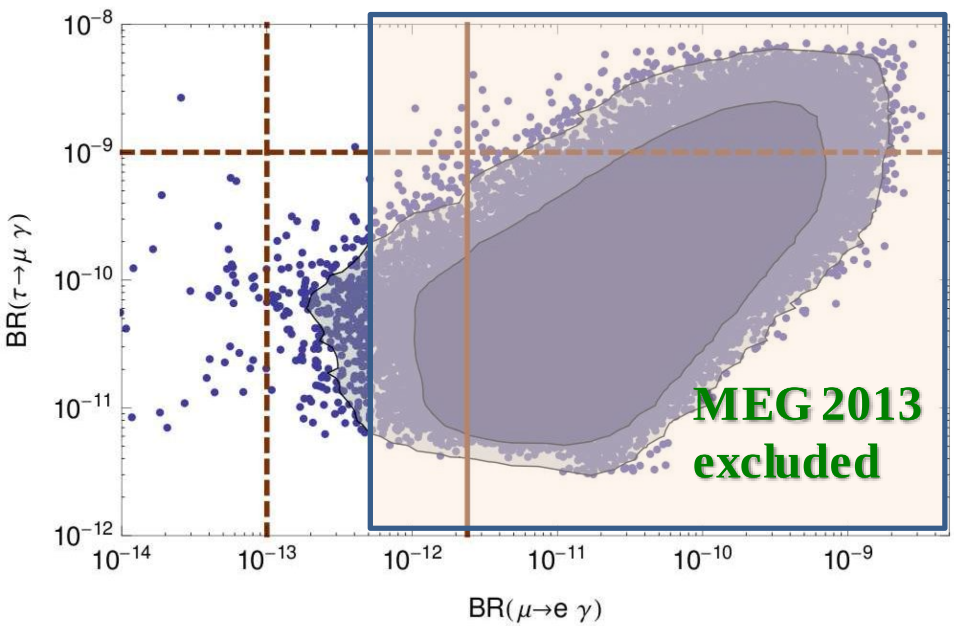
Data set	$\mathcal{B}_{\rm fit} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

Summary of all samples

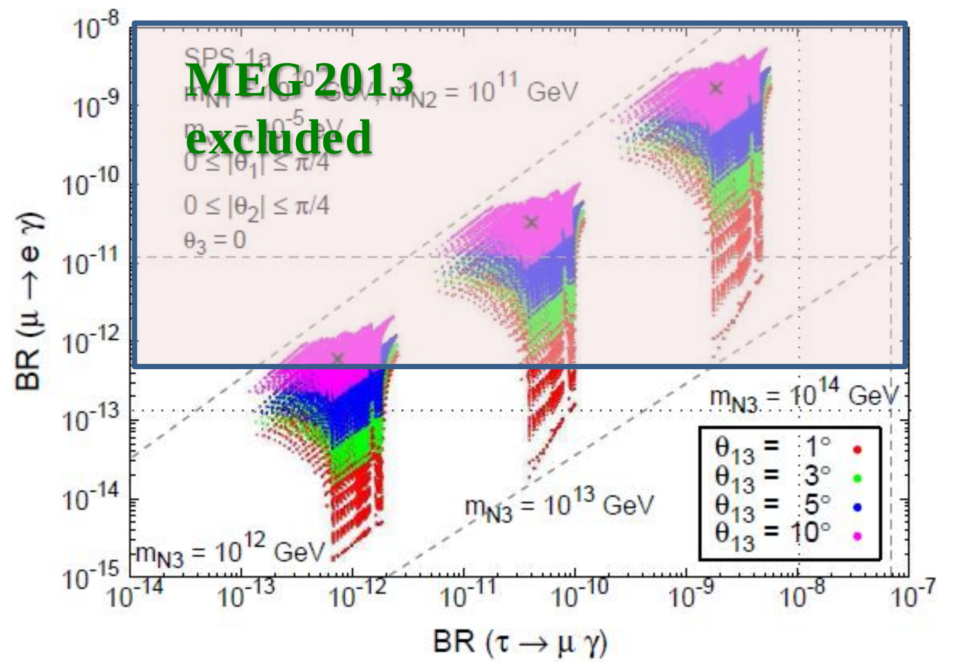
Result published in PRL **110** (2013) 201801

$\tau \to \mu\gamma$ vs $\mu \to e\gamma$ NOW

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



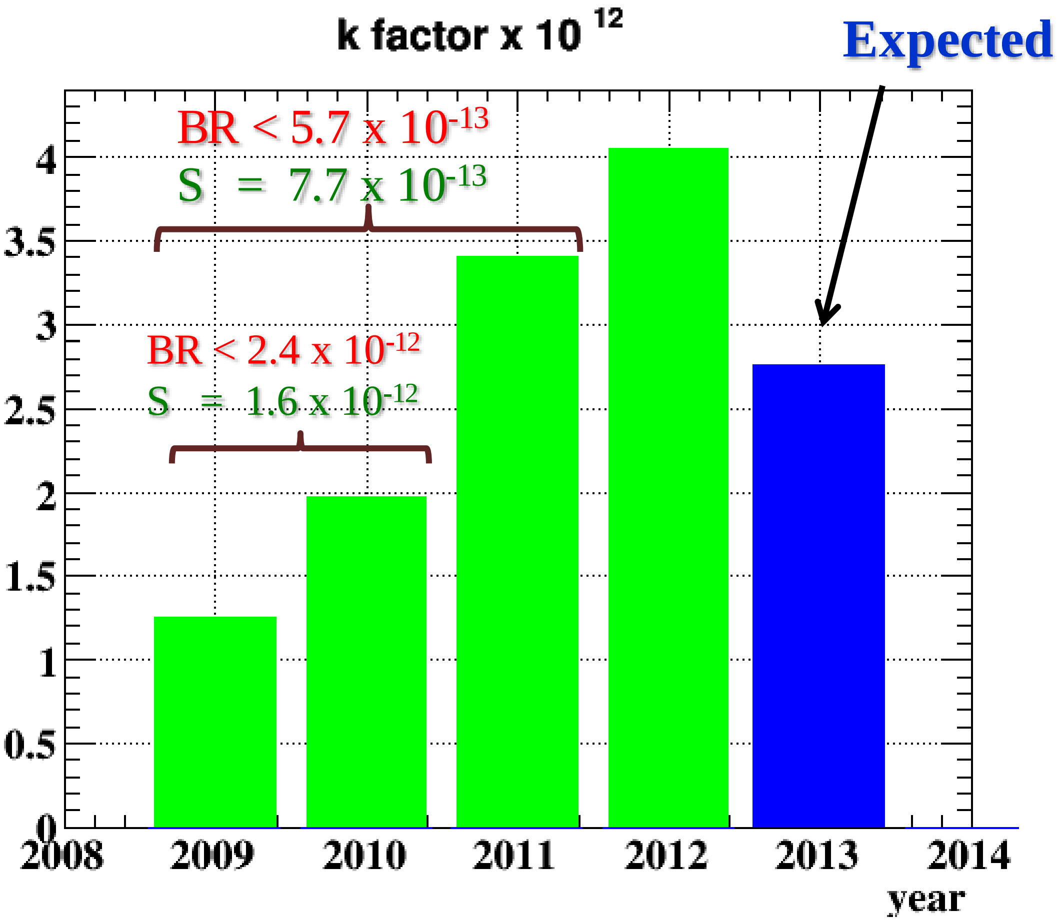
Antusch et al. JHEP **0611** (2006) 090



θ_{13} recently measured by Daya Bay, Reno, Double Chooz ... ($7 \div 10^o$)

Final data and sensitivity

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



(2012 + 2013) ≈ (2009 + 2010 + 2011)

⇒ **Double statistics !**

Estimated final sensitivity (toy MC)

~ 5 x 10^{-13}

Summary and Perspectives

- The MEG experiment analyzed data collected in the years 2009-2011, corresponding to a total sample of 3.6 x 10^{14} μ^+ stopped on target.
- No excess was found ⇒ MEG established **a new upper limit** on **BR($\mu^+ \to e^+\gamma$) < 5.7 x 10^{-13}** (90% C.L.):
  - 4 times better than previous MEG limit (MEG 2011)
  - 20 times better than pre-MEG limit (MEGA, 2001)

  Sensitivity was 7.7 x 10^{-13} (negative fluctuation observed);
- Data acquisition will end on late summer 2013;
- Data collected in 2012+2013 will double the statistics ⇒ **expected final sensitivity 5 x 10^{-13}**.

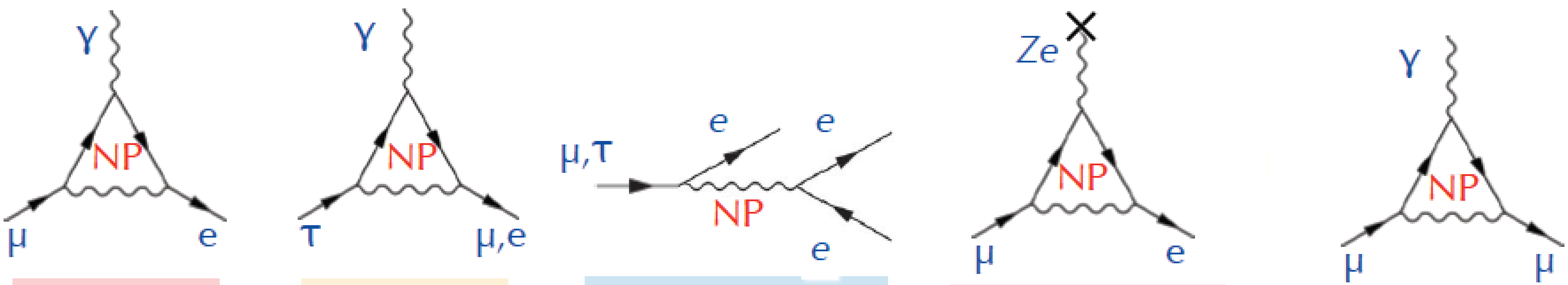
Detector upgrade proposal approved ⇒ see Y. Uchiyama talk !

Backup slides

LFV 3)

Several LFV processes, sensitive to **New Physics (NP)** through

"new" lepton-lepton coupling $y_{ij}\bar{\ell}_i F^{\mu\nu} \ell_j \sigma_{\mu\nu}$



$\mu \rightarrow e\gamma$	$\tau \rightarrow \mu\gamma$ $\tau \rightarrow e\gamma$	$\mu \rightarrow eee$	$\mu^- \mathcal{N} \rightarrow e^- \mathcal{N}$	$(g-2)_\mu$

μ,τ anomalous decays

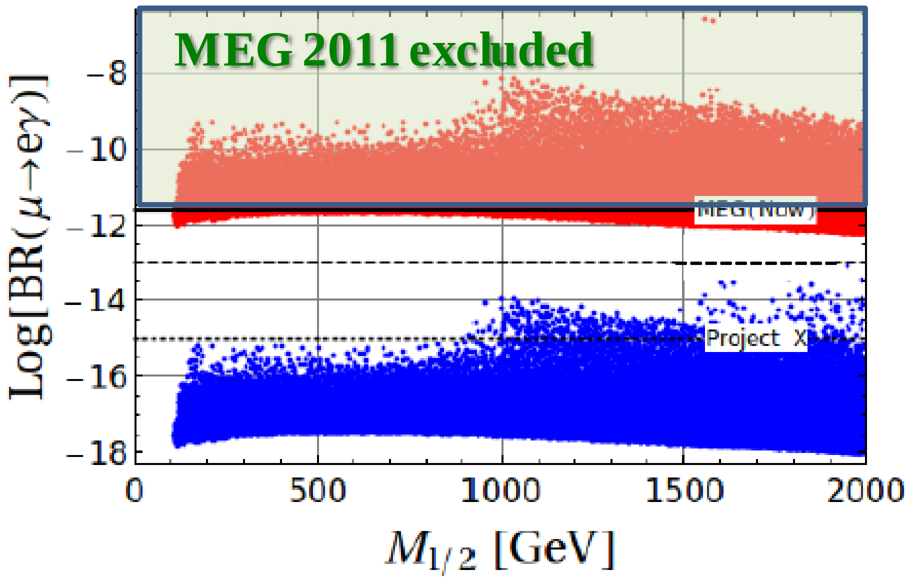
μ → e conversion

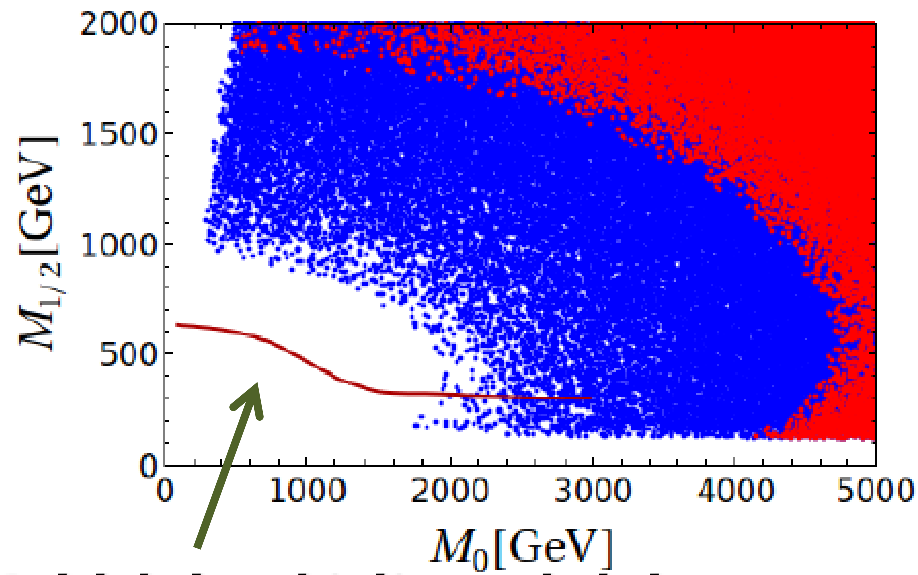
Anomalous magnetic moment

Indirect vs direct searches < 2013

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

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





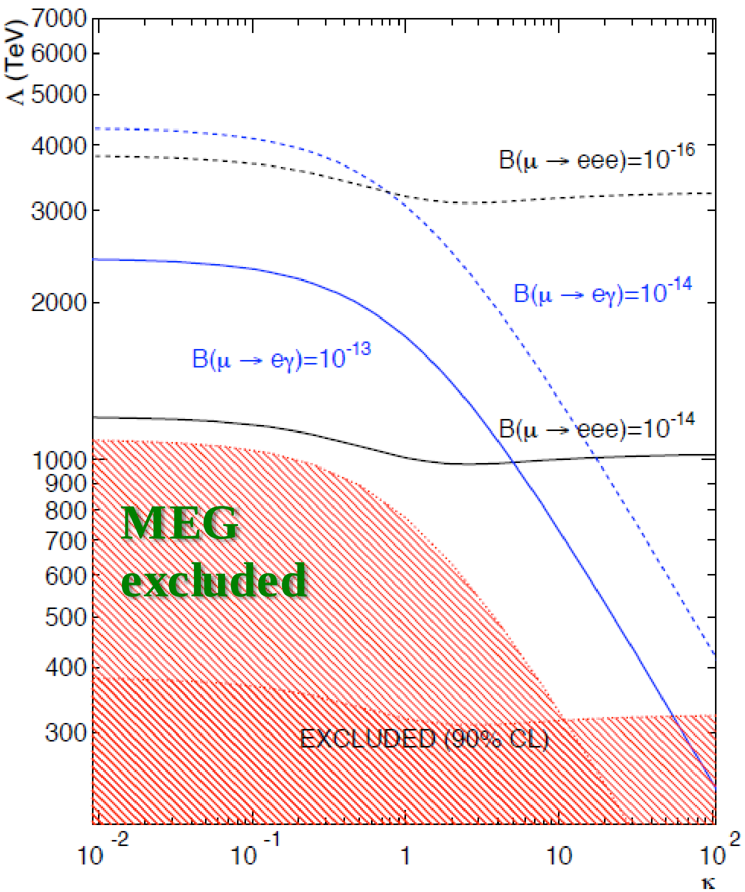
Models below this line excluded
by direct LHC searches

mSUGRA, tan β = 10, U_{e3} = 0.11
Red points: mixing based on **PMNS**
Blue points: mixing based on **CKM**

Models compatible with MEG 2011result

Sensitivity of different experiments 2)

$\mu \to e\gamma$ vs $\mu \to eee$



A. de Gouvea & P. Vogel, hep-ph 1303.4097

Effective lagrangian

Magnetic dipole interaction

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

Four lepton interaction

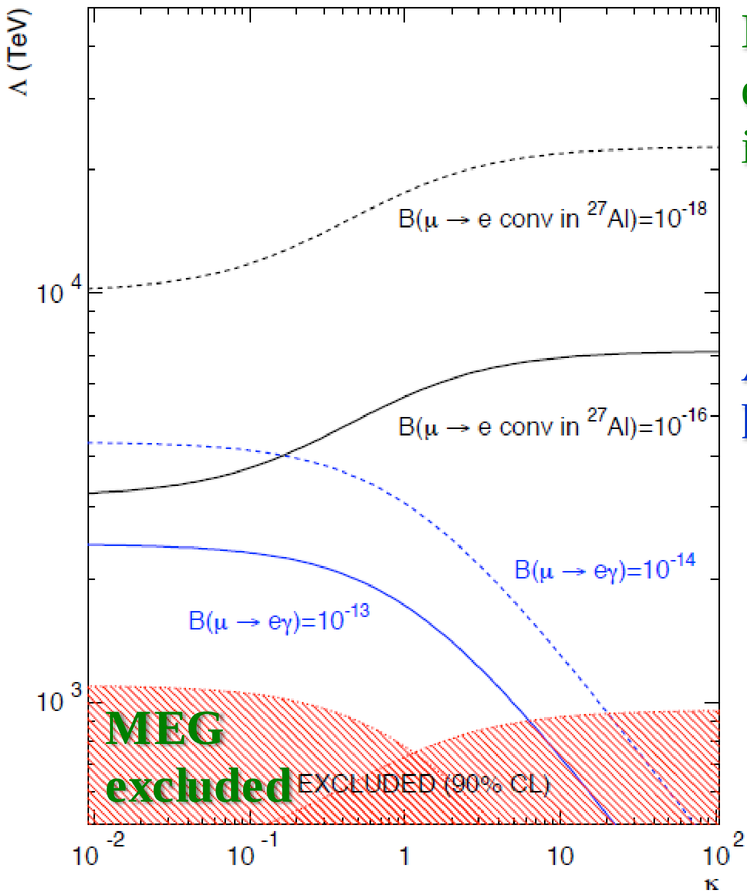
Λ = New Physics scale
k = Relative weight of two terms

A $\mu \to e\gamma$ experiment with sensitivity of ~ 10^{-14} is competitive with a $\mu \to eee$ experiment with sensitivity ~ 10^{-16} for $k \leq 1$; for large k, only $\mu \to eee$ survives.

Needed all types of experiments

Sensitivity of different experiments 1)

$\mu \to e\gamma$ vs $\mu \to e$ conversion



A. de Gouvea & P. Vogel, hep-ph 1303.4097

Effective lagrangian

Magnetic dipole interaction

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

$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c.\,.$$

Four quark interaction

Λ = New Physics scale
k = Relative weight of two terms

A $\mu \to e\gamma$ experiment with sensitivity of ~ 10^{-14} is competitive with a $\mu \to e$ experiment with sensitivity ~ 10^{-16} for **k < 1**; for **k >> 1** $\mu \to e\gamma$ sensitivity drops and **$\mu \to e$ conversion is the unique sensitive process**.

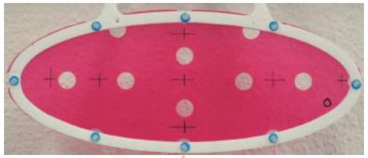

Part of
The MEG collaboration
Total ≈ 60 physicists
Tokyo U.
Waseda U.
KEK
INFN & U Pisa
INFN & U Roma
INFN & U Genova
INFN & U Pavia
INFN & U Lecce
PSI
UCIrvine
JINR Dubna
BINP Novosibirsk
8

MEG detector components 1)

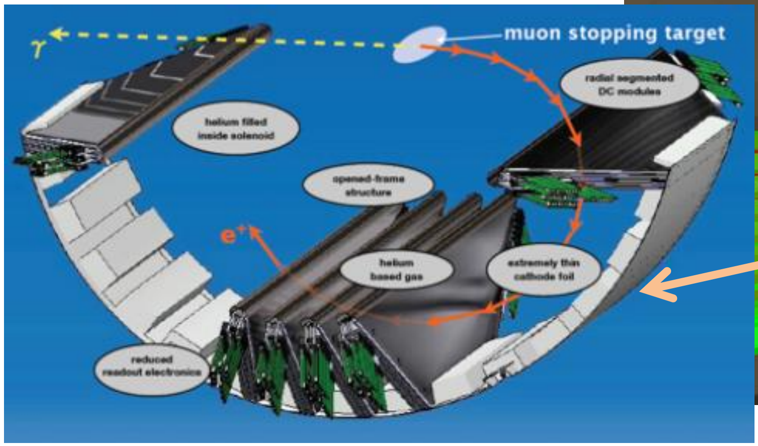
Superconducting solenoid with gradient field (**COBRA**)

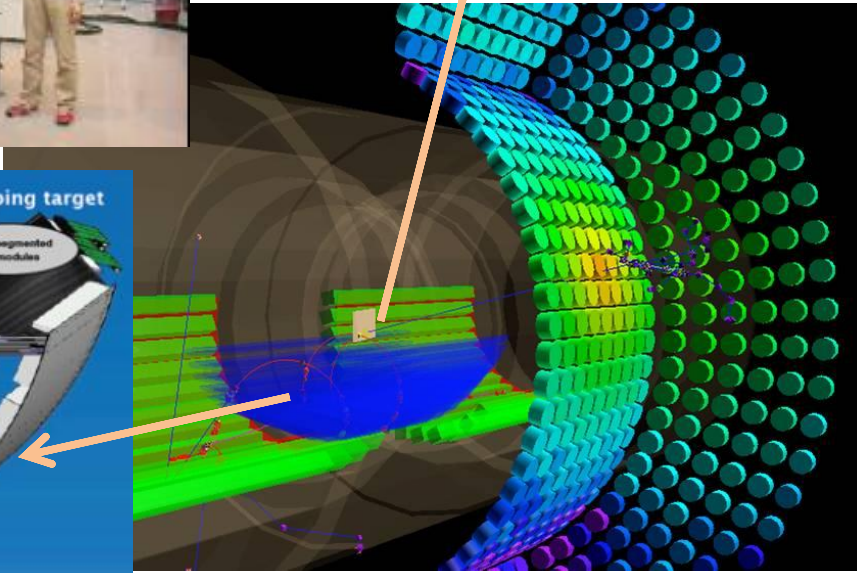
Sweeps out low P_z positrons.
Bending radius independent of θ emission angle.

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



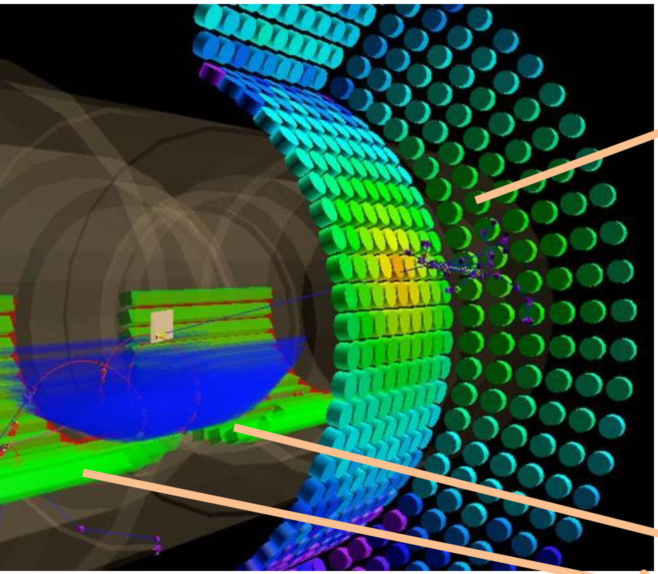
16 DCH with staggered anodic wires and cathodic strips in Vernier pattern.
Gas mixture
$He:C_2H_6$ =50:50

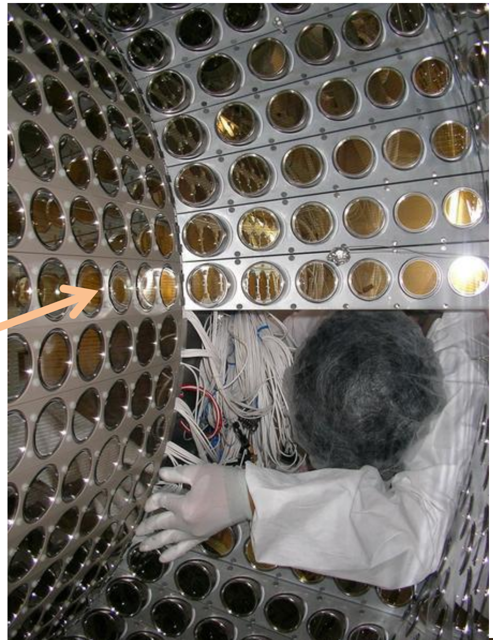




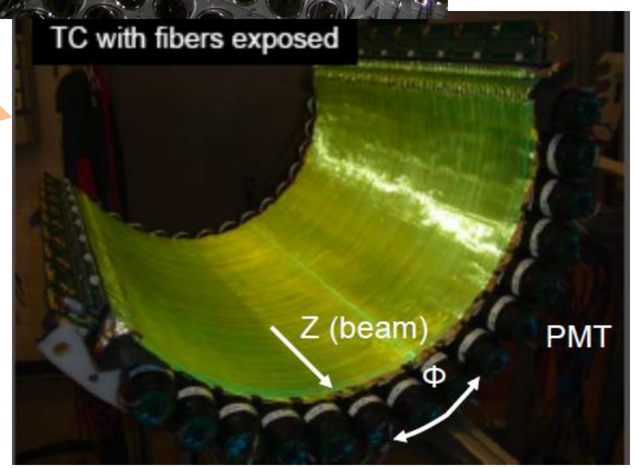
Positron momentum vector measurement.

MEG detector components 2)



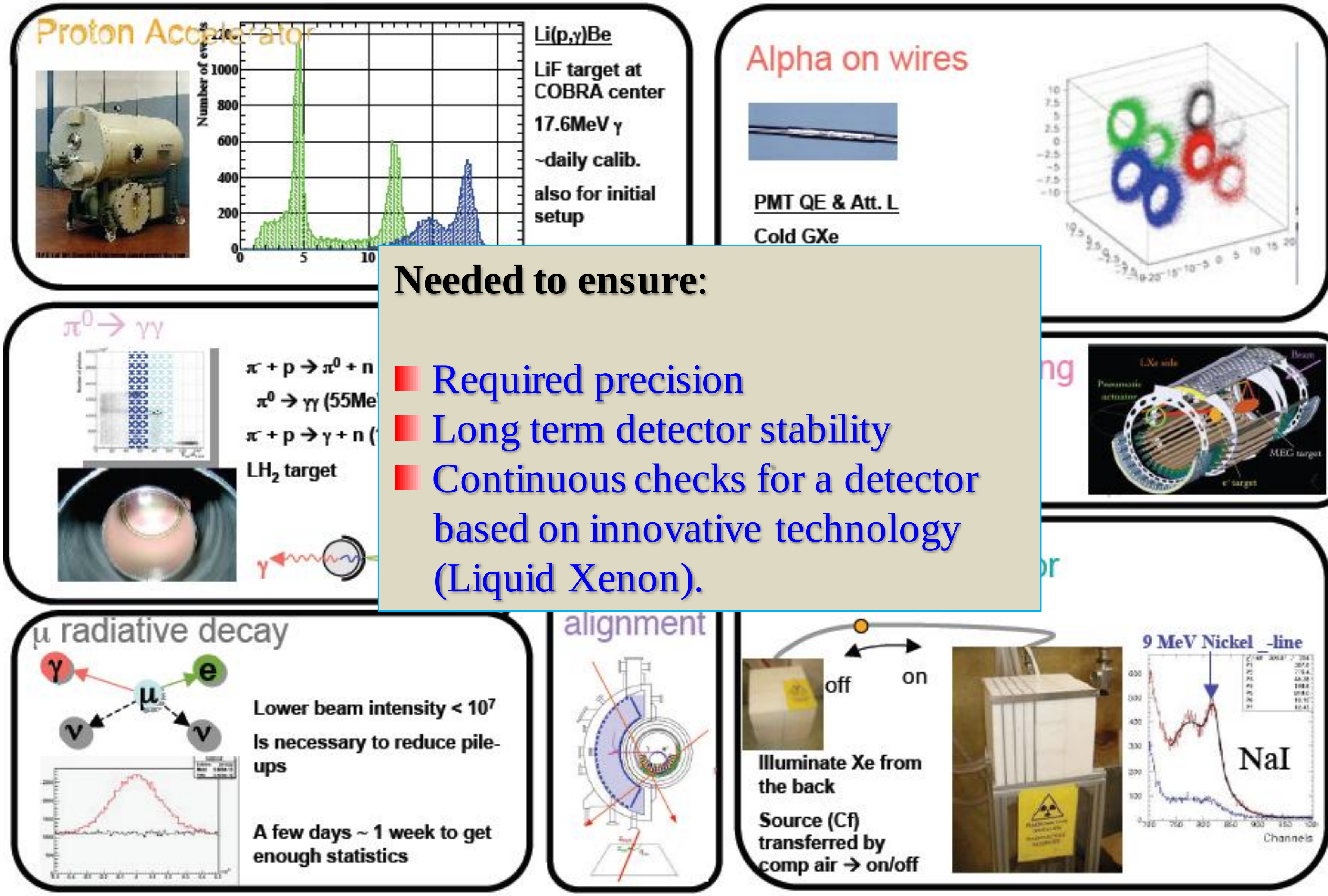


900 l Liquid Xenon detector
846 UV sensitive PMTs
Light yield ≈ **0.8 NaI**.
Fast timing response (**45 ns**)
$\Delta\Omega/4\pi \approx 0.12$
Photon energy, timing and interaction point measurement.



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

Overview of calibration system



Needed to ensure:

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

Trigger and electronics

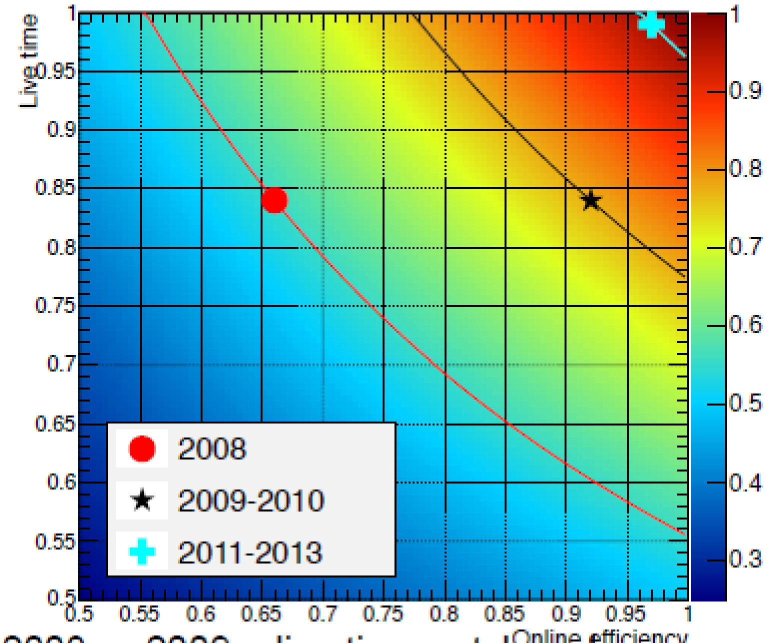
- **Trigger**

  FPGA based system
  designed to reduce the trigger rate by using fast estimates:

  γ-energy: → 2×10^3 Hz
  $e^+\gamma$ timing → 100 Hz
  $e^+\gamma$ direction → **10 Hz**

  Signal efficiency > 95%
  Live Time fraction 99%

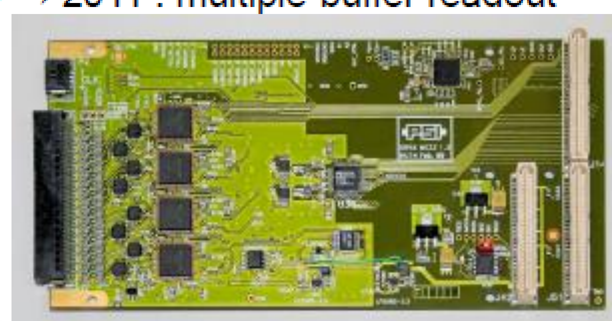
Live time - online efficiency plane



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

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

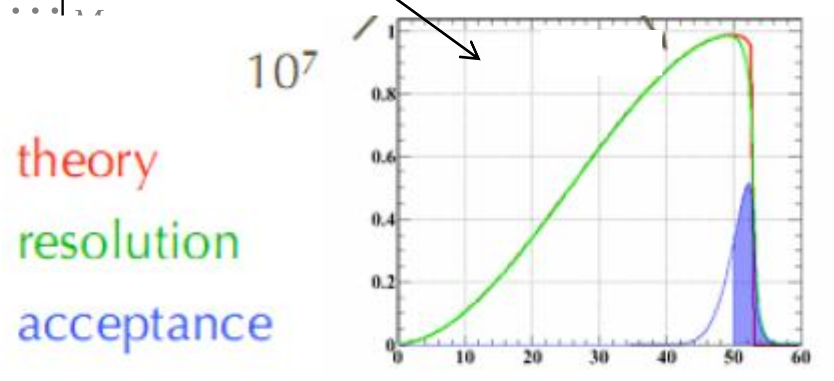
where:

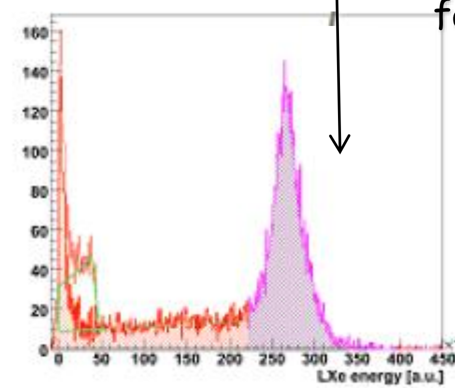
$$k \equiv N_{e\nu\nu} \times \left[\frac{f_S}{f_M}\right] \times \left[\frac{\varepsilon(TRG=0\,|\,e^+\gamma)}{\varepsilon(TRG=22\,|\,track \cap e^+_m \cap TC)}\right] \times A(\gamma\,|\,track)\cdot\varepsilon(\gamma)\cdot Psc(22)$$

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

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

10^7 pre-scaling factor



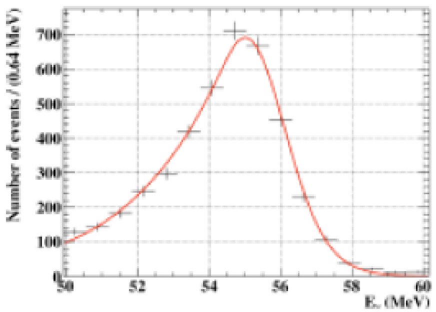


TRG = 22: Michel events trigger (only DCH track required)

TRG = 0: MEG events trigger

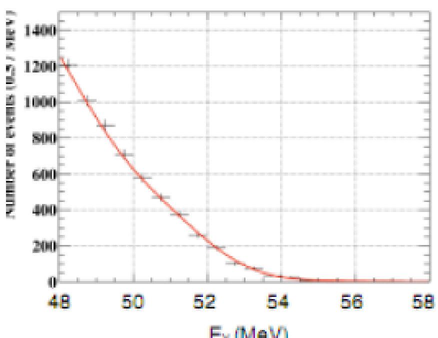
PDF's

55 MeV π^0 peak



Gamma

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



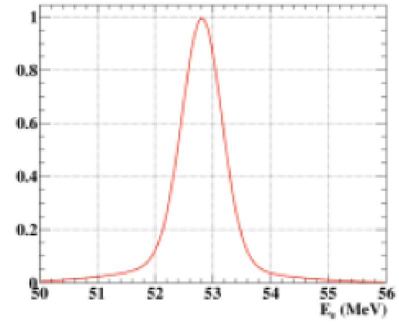
BG measured in sideband

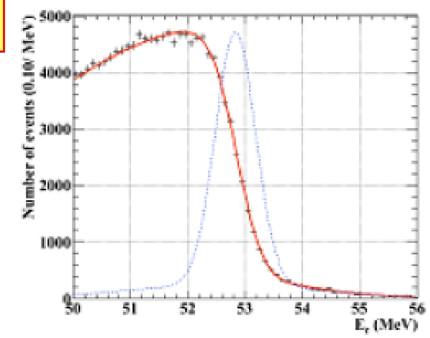
Positron

Signal PDF from measured resolution

- Michel positrons
- Mott scattering device

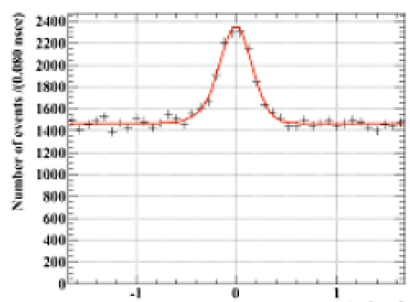
BG measured in sideband





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

RMD peak mostly in low energy part



Relative time

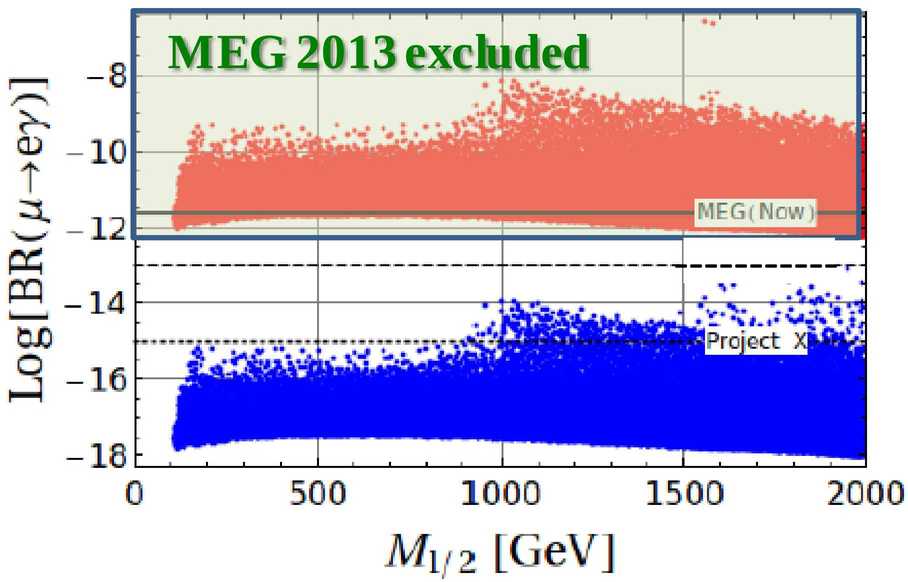
Signal PDF from measured RMD peak

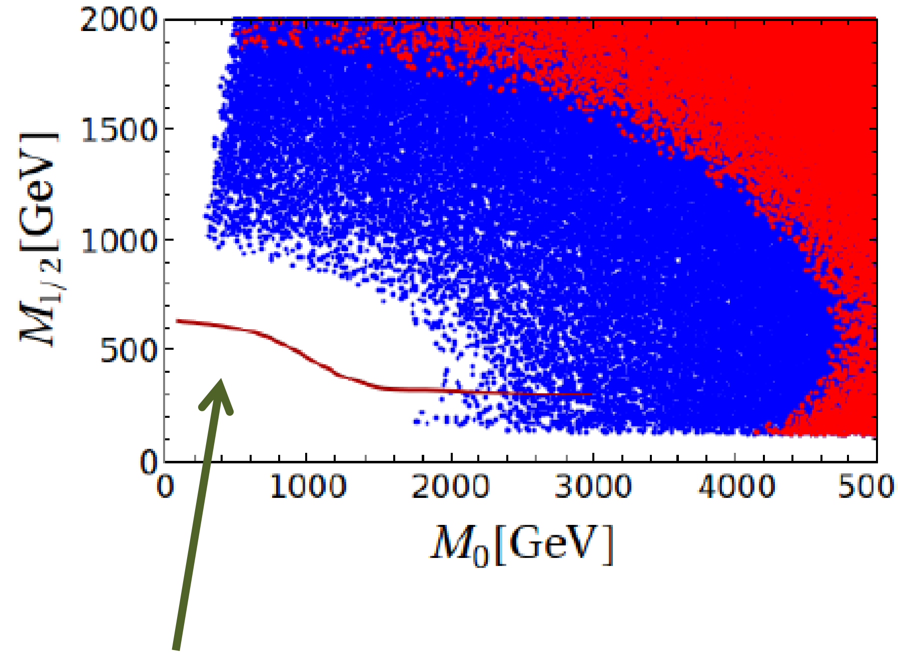
Relative angle

From measured double turn tracks

Indirect vs direct searches NOW

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





mSUGRA, tan β = 10, U_{e3} = 0.11
Red points: mixing based on **PMNS**
Blue points: mixing based on **CKM**

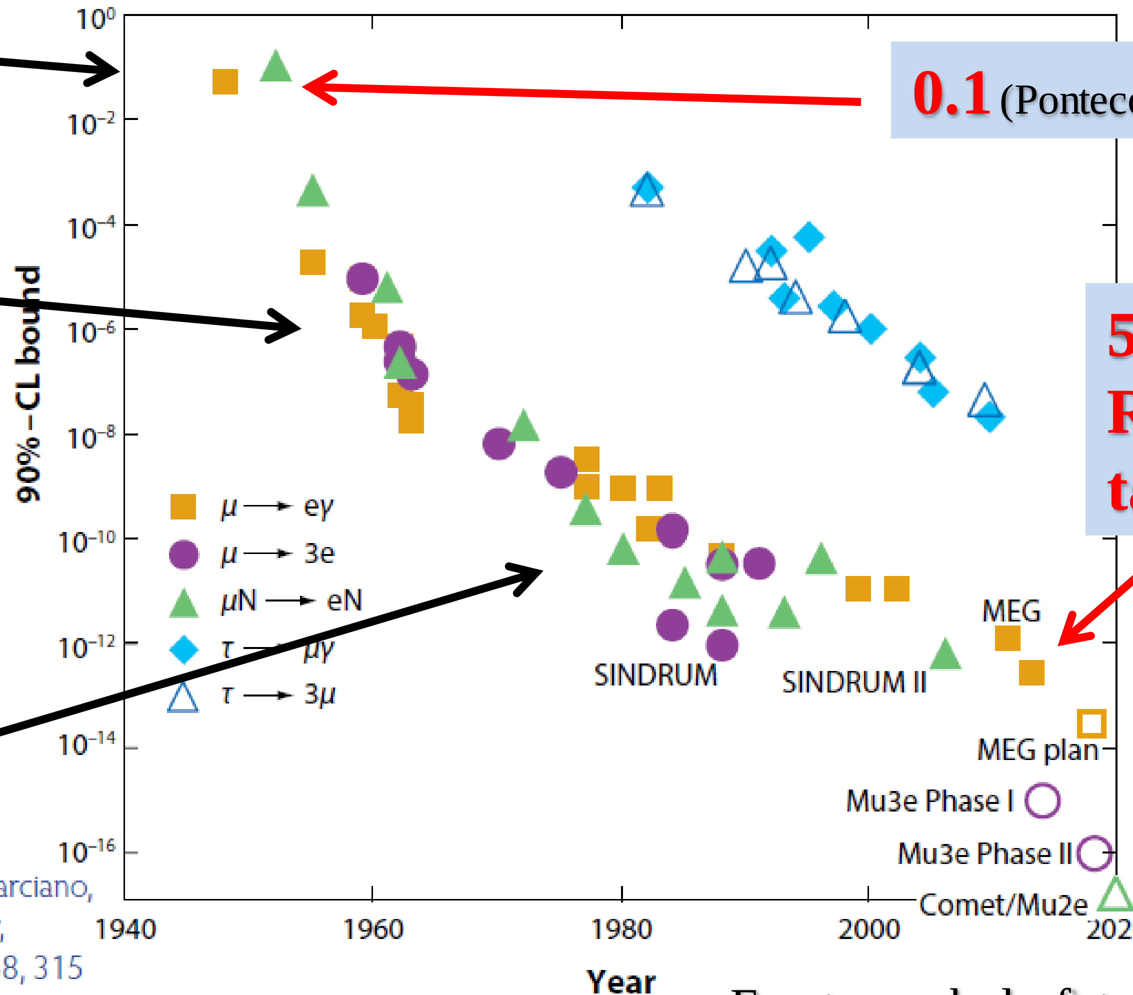
Models below this line excluded
by direct LHC searches

A 70 year history ..

Cosmic μ's

Stopped π's

Muon beams



0.1 (Pontecorvo & Hincks,)

5.7 x 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