Search for charged-lepton-flavor-violation in rare muon decays

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on behalf of the MEG collaboration

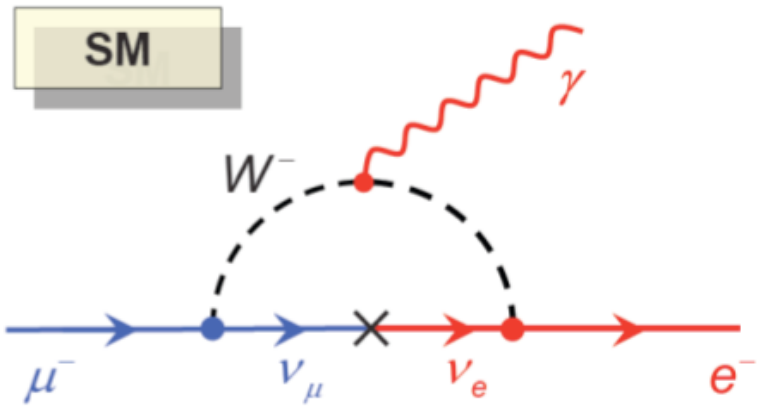
The XI International Conference on Heavy Quarks and Leptons
Praga June 11-15 2012

Outline

- Charged lepton flavor violation (cLFV) and new physics
- History of cLFV searches
- The Mu3e proposal ($\mu^+ \rightarrow e^+ e^+ e^-$)
- The MEG experiment ($\mu^+ \rightarrow e^+ \gamma$)
- MEG results
- Future perspectives

Charged LFV and new physics

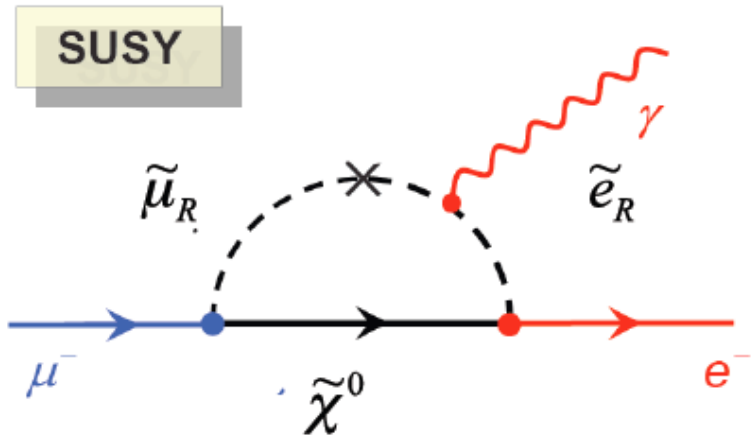
- Standard Model (SM) with ν mass and oscillation:



Charged LFV very small

$$BR(\mu \to e\gamma)\big|_{SM} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-54}$$

- Beyond Standard Model e.g. SUSY



Charged LFV can be largely enhanced, in some models just below the experimental limit ($<2.4\cdot10^{-12}$ @90%C.L. MEG)

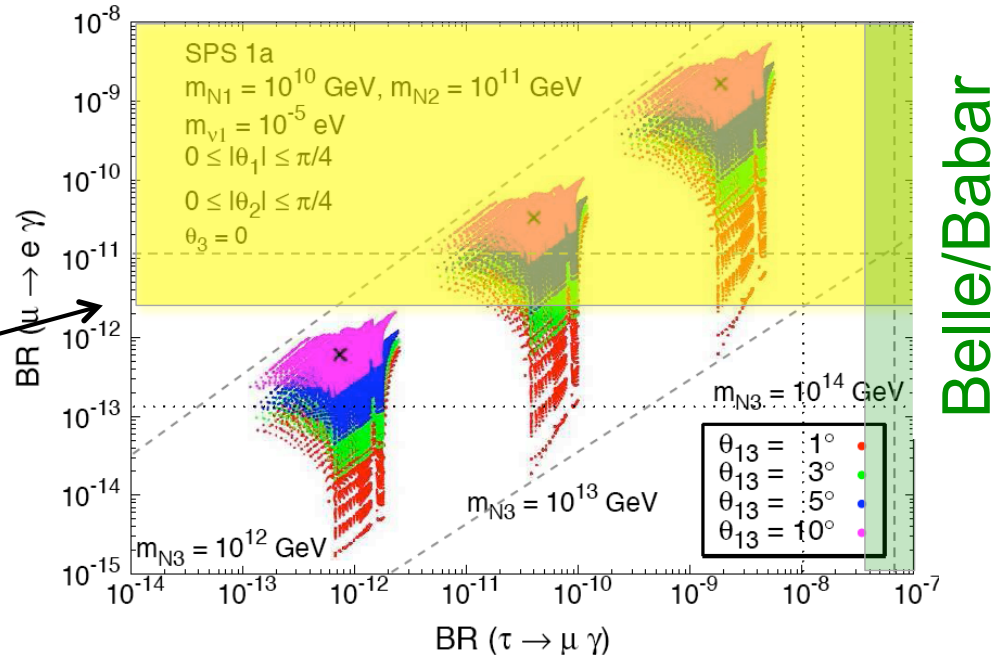
Observation of charged LFV is Physics beyond SM (no SM background)

Some examples

- SUSY-Seesaw

Antusch et al., JHEP11(2006)090

MEG 2010
$\theta_{13} \sim 9^o$

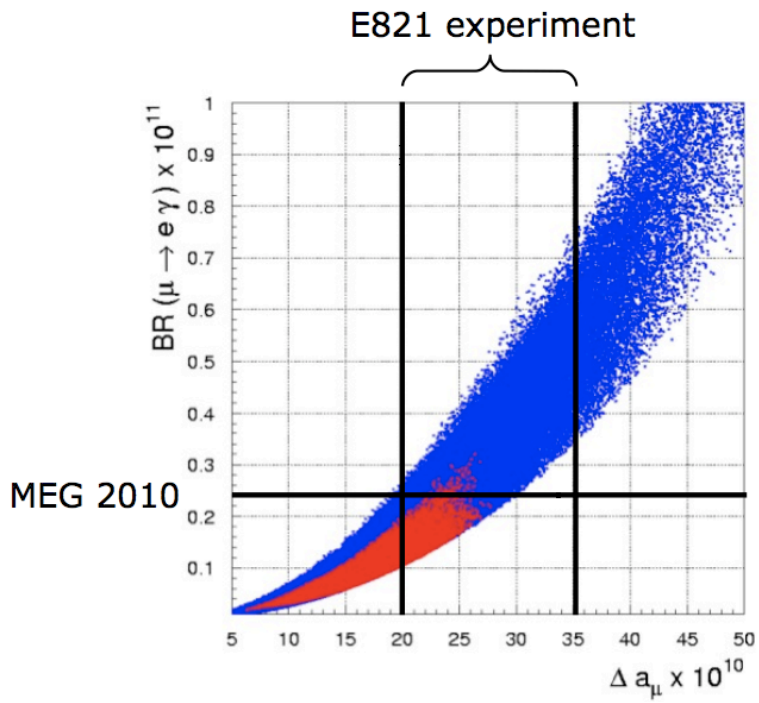


Belle/Babar

- Muon g-2

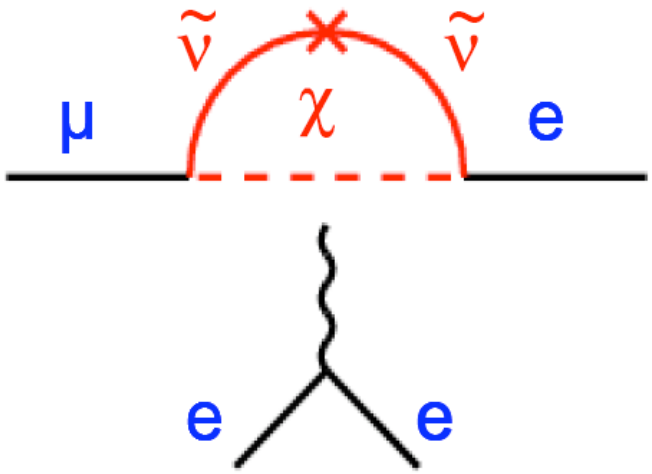
Connection with g_μ-2, predicts signal in MEG accessible region

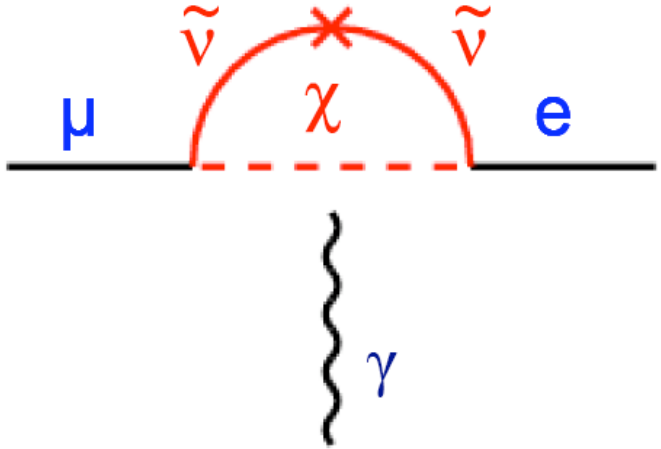
Isidori *et al.*, Phys.Rev.D75 (2007) 115019



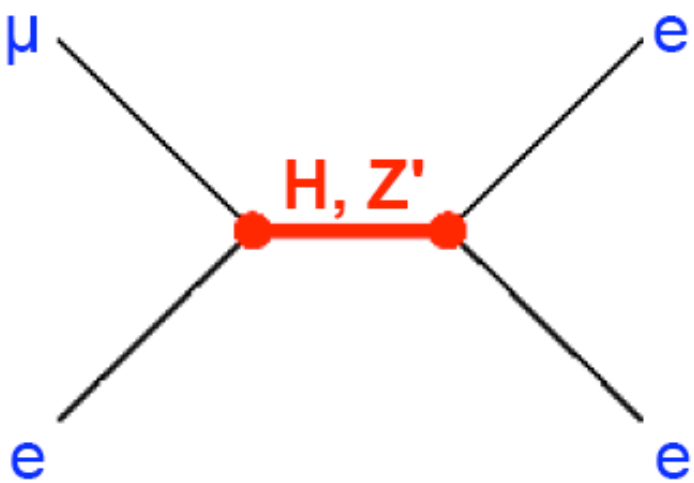
μ→eγ vs μ→3e

- Loop diagram



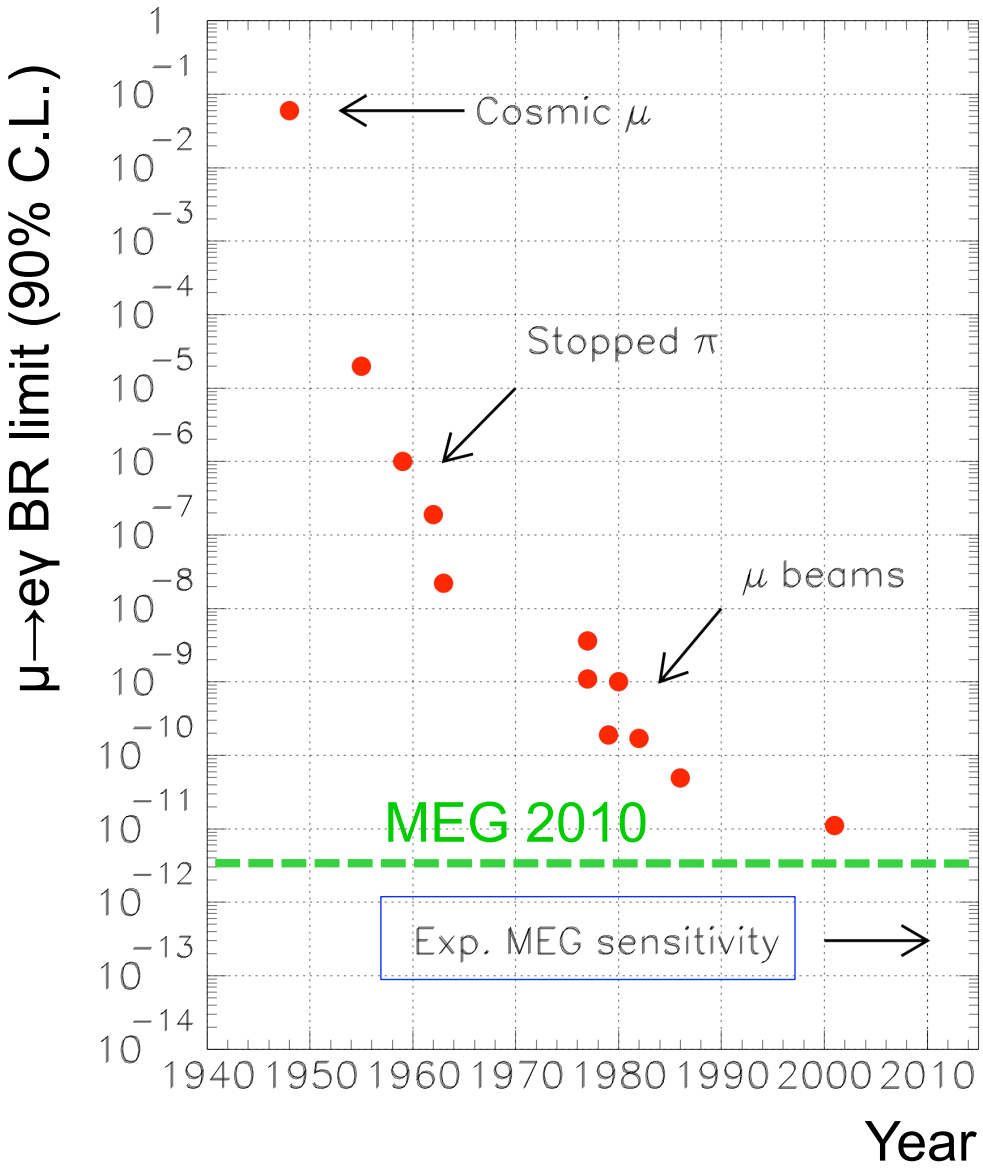


- Tree diagram



μ→3e loop diagram suppressed but sensitive to possible additional diagrams

A long search



Improvements due to better sources and detector resolutions

MEG (original) goal:
=> sensitivity of ~10^{-13}

μ→3e best limit:
Sindrum 1988
BR(μ→3e)<10^{-12} (90%C.L.)
Mu3e goal:
sensitivity of ~10^{-16}

The location: PSI lab

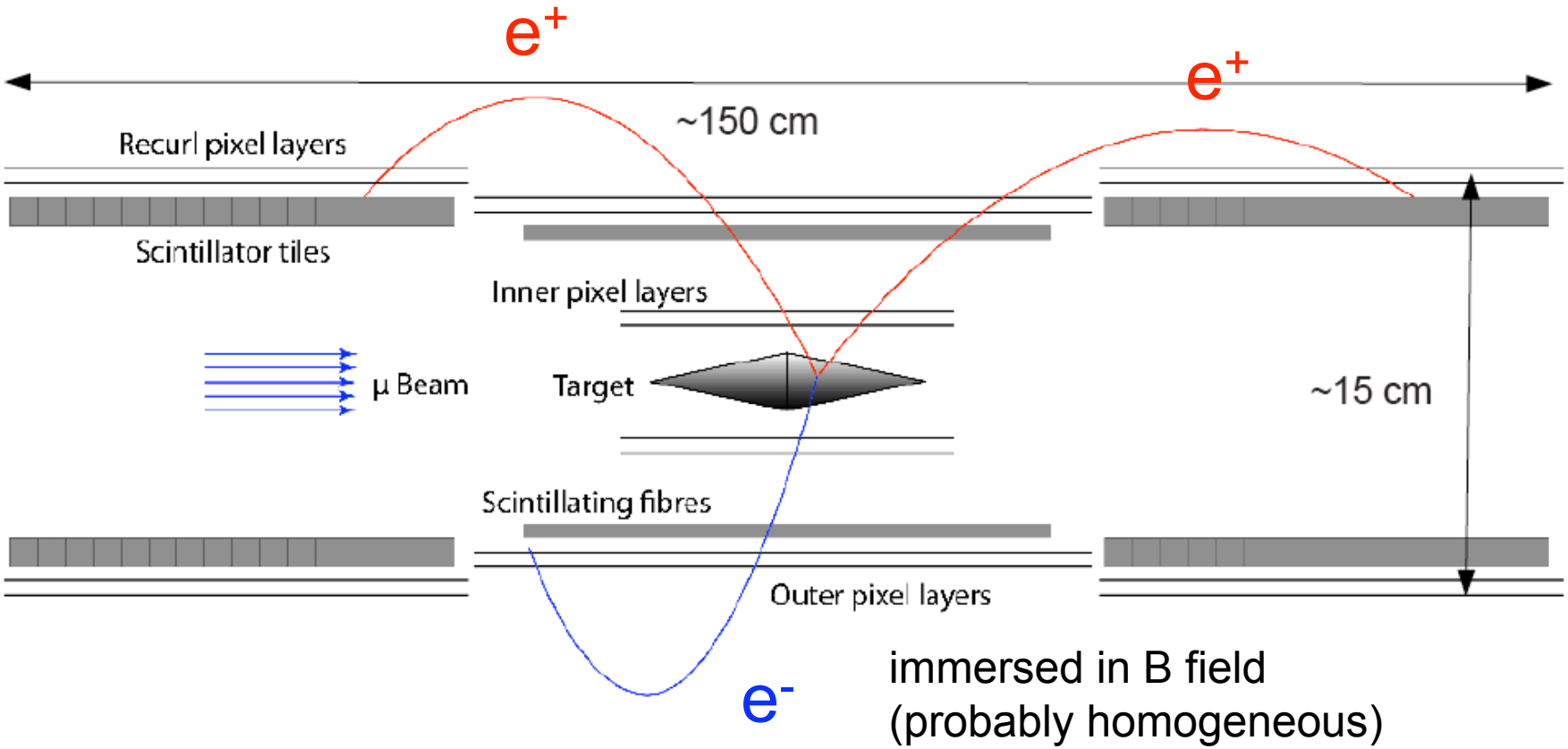
The Paul Scherrer Institute

Continuous muon beam up to $2x10^8$ μ^+/s

Multi-disciplinary lab:

- fundamental research, cancer therapy, muon and neutron sources
- protons from cyclotron (D=15m, E_{proton}=590MeV I=2.2mA)

The Mu3e baseline design



- Tracker: Silicon pixel sensors

- Scintillating fibers and tiles
  - Unambigous assigment of silicon hits

The Mu3e timeline

- The collaboration presented a letter of intent to PSI in february 2012

- A detailed resarch proposal will be presented to PSI in early 2013

  - 2 phases are forseen

    - Phase 1: Run with present or little upgraded PSI muon beam: $2x10^8$ μ/s sufficient to reach sensitivity of 10^{-15} in 3 years 2014-2017
    - Phase 2: $2x10^9$ μ/s needed to reach ultimate goal (significant upgrade of PSI muon beam line needed) > 2017

Letter of Intent for an Experiment to Search for the Decay $\mu \to eee$

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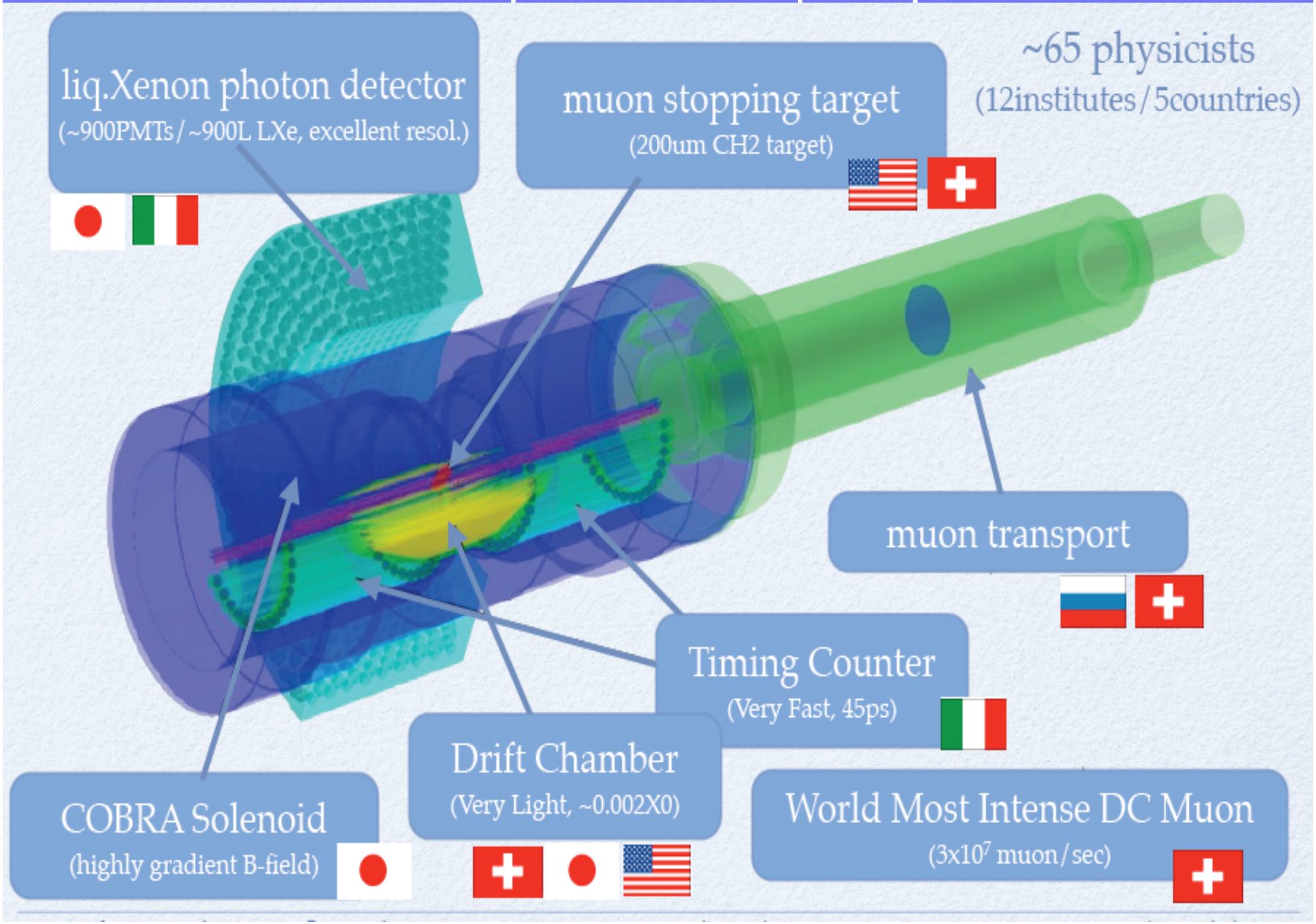
M. Hildebrandt, P.-R. Kettle, A. Papa, S. Ritt
Paul Scherrer Institut, Villigen

G. Dissertori, Ch. Grab, R. Wallny
Eidgenössiche Technische Hochschule Zürich, Zürich

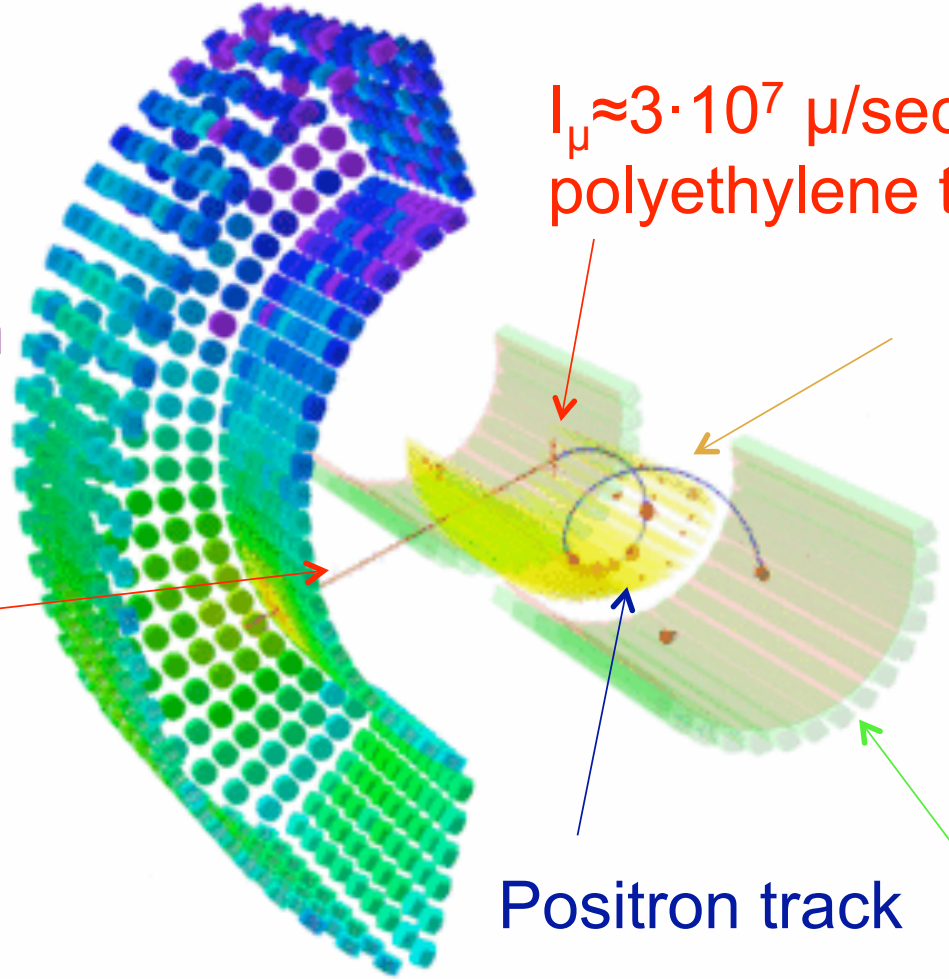
P. Robmann, U. Straumann
Universität Zürich, Zürich

January 23rd, 2012

The MEG experiment for μ→eγ search



Detector concept: search for μ→eγ



Signal: simultaneous back-to-back μ and γ with $E_\gamma = E_{e+} = 52.8$MeV

Backgrounds:

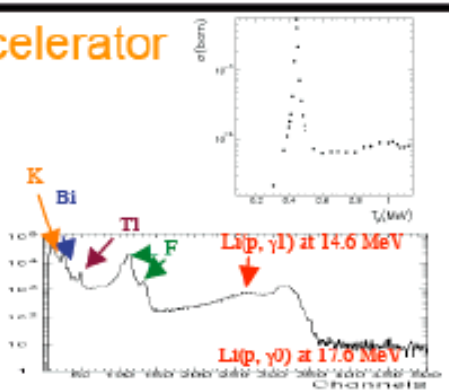
1) Accidental: e^+ from Michel muon decay and a γ (dominant)

2) Radiative muon decay

Calibrations

Xenon Calibration

Proton Accelerator



Li(p,γ)Be

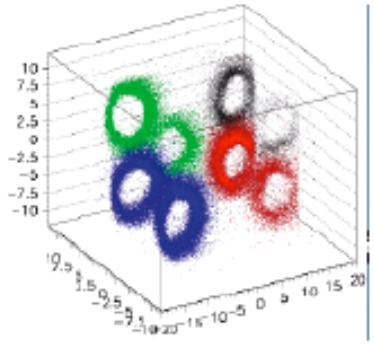
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

Alpha on wires

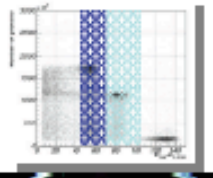


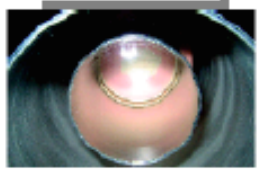
PMT QE & Att. L

Cold GXe

LXe

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



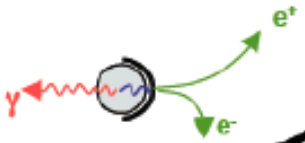


π^- + p → π^0 + n

π^0 → γγ (55MeV, 83MeV)

π^- + p → γ + n (129MeV)

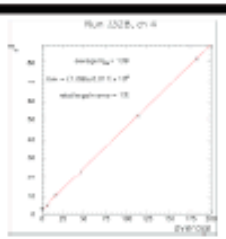
LH_2 target

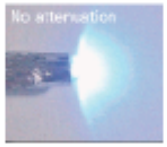


LED

PMT Gain

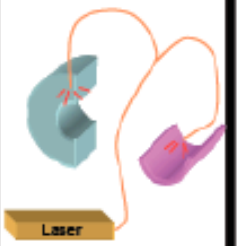
Higher V with light att.



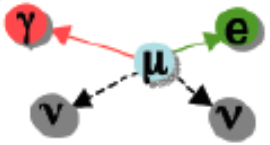


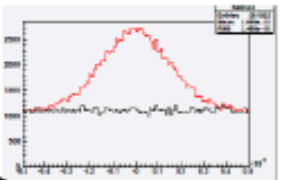
Laser

relative timing calib.



μ radiative decay





Lower beam intensity < 10^7

Is necessary to reduce pile-ups

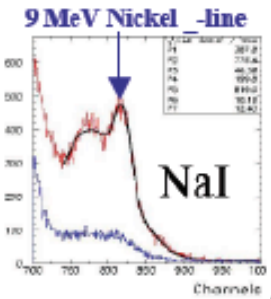
A few days ~ 1 week to get enough statistics

Nickel γ Generator

off on

Illuminate Xe from the back

Source (Cf) transferred by comp air → on/off

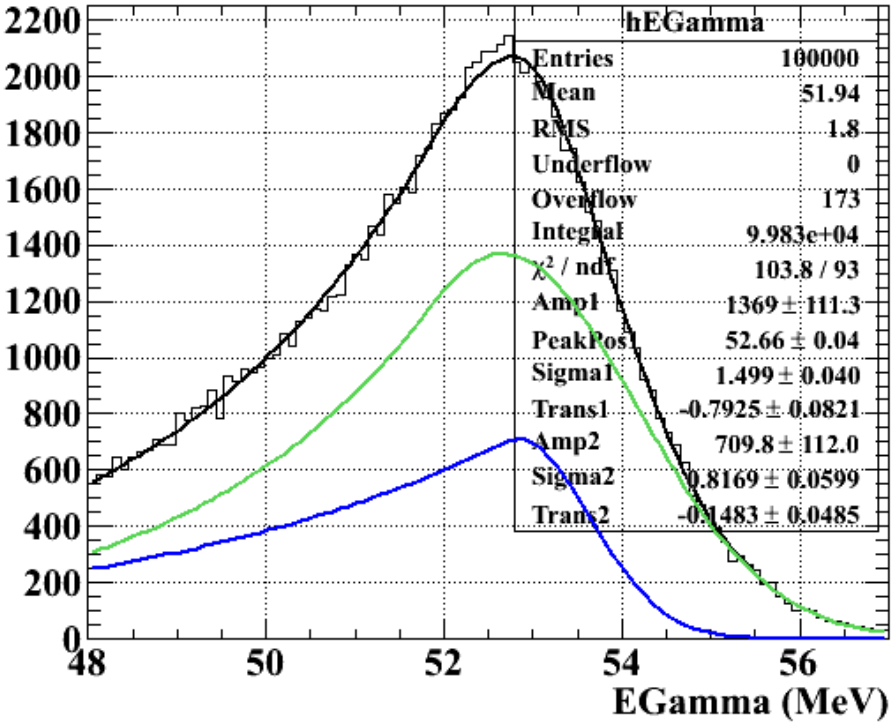


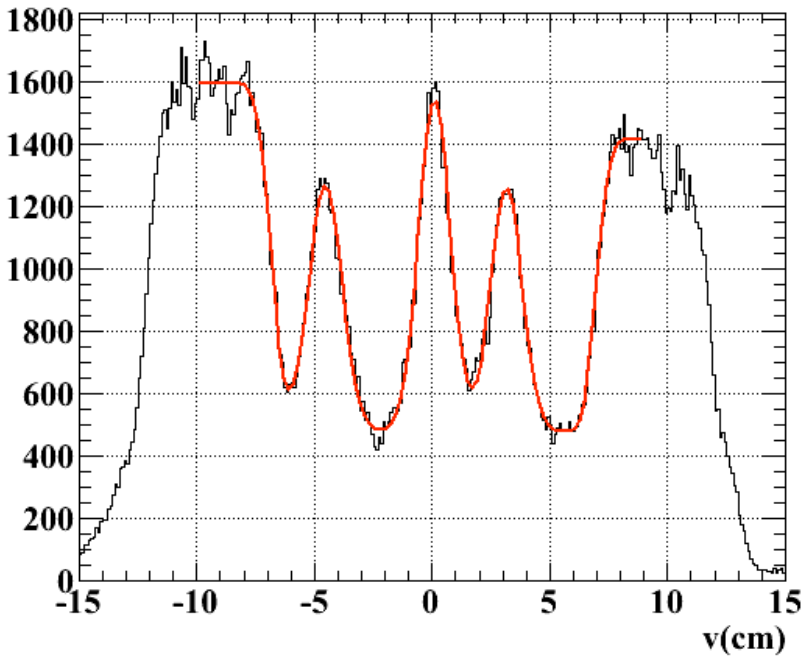
Detector performances: Calorimeter

Performances from special charge-exchange- run

γ energy from $\pi^0 \rightarrow \gamma\gamma$ decays with back-to-back photons: $\sigma_{right}(E_\gamma)$=1.9%

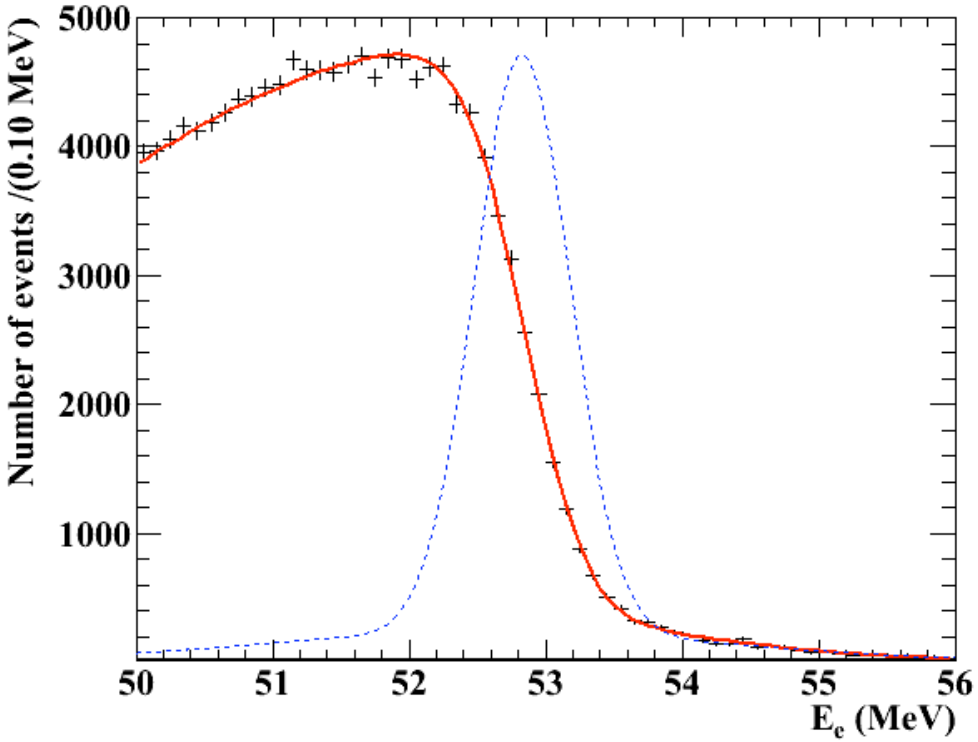
γ position resolution: 5-6 mm using collimator





Detector performances: Drift chamber and timing

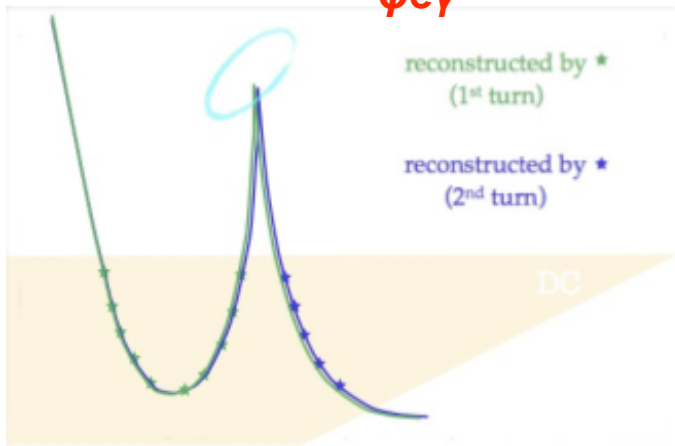
e^+ energy resolution: ~330keV from Michel decays



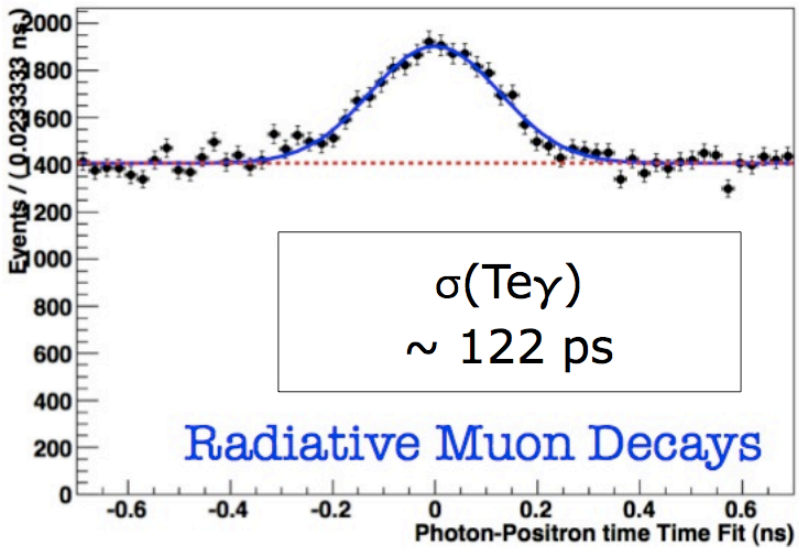
angular resolution from different segments of same track

$\sigma_{\theta e\gamma}$ = *17.1 mrad*

$\sigma_{\varphi e\gamma}$ = *14.0 mrad*



relative time resolution: 122ps from radiative decay spectrum



Data Samples

Muons on target:

2009: 0.7×10^{14} preliminary result @LP2010

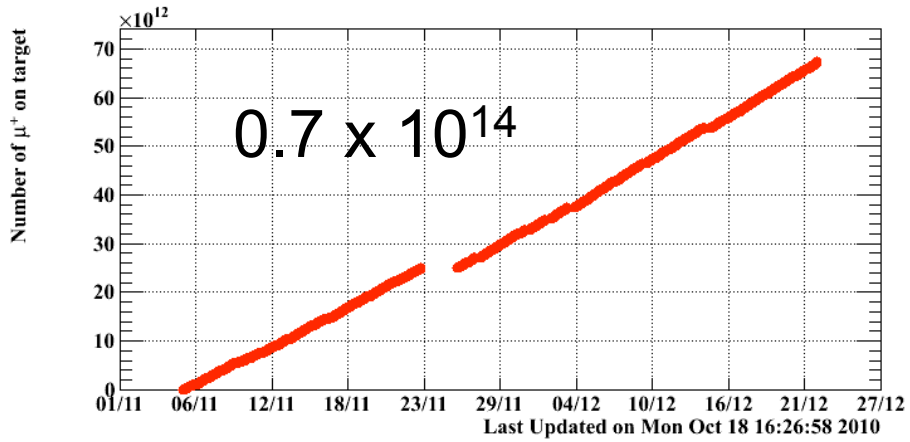
2009+2010: 1.8×10^{14} **PRL 107,171801 (2011)**

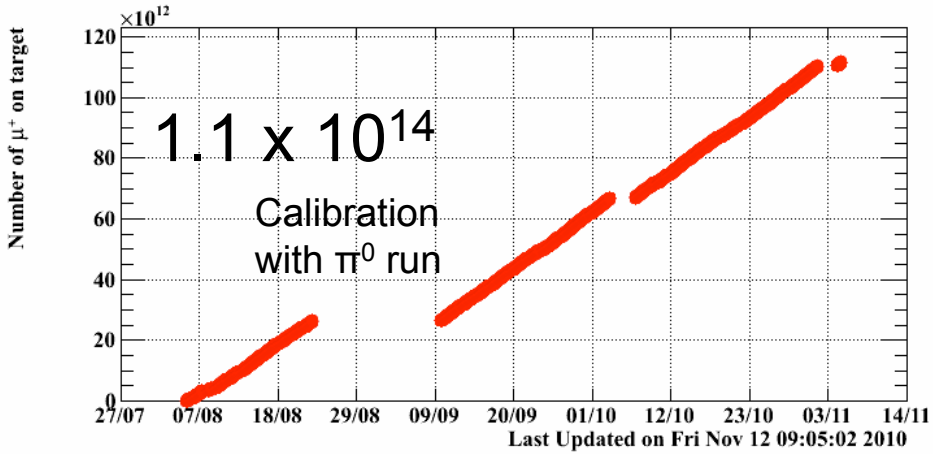
2009

35 days DAQ time
Stable conditions

2010

56 days DAQ time
Improve electronic timing
Slightly worse DC conditions





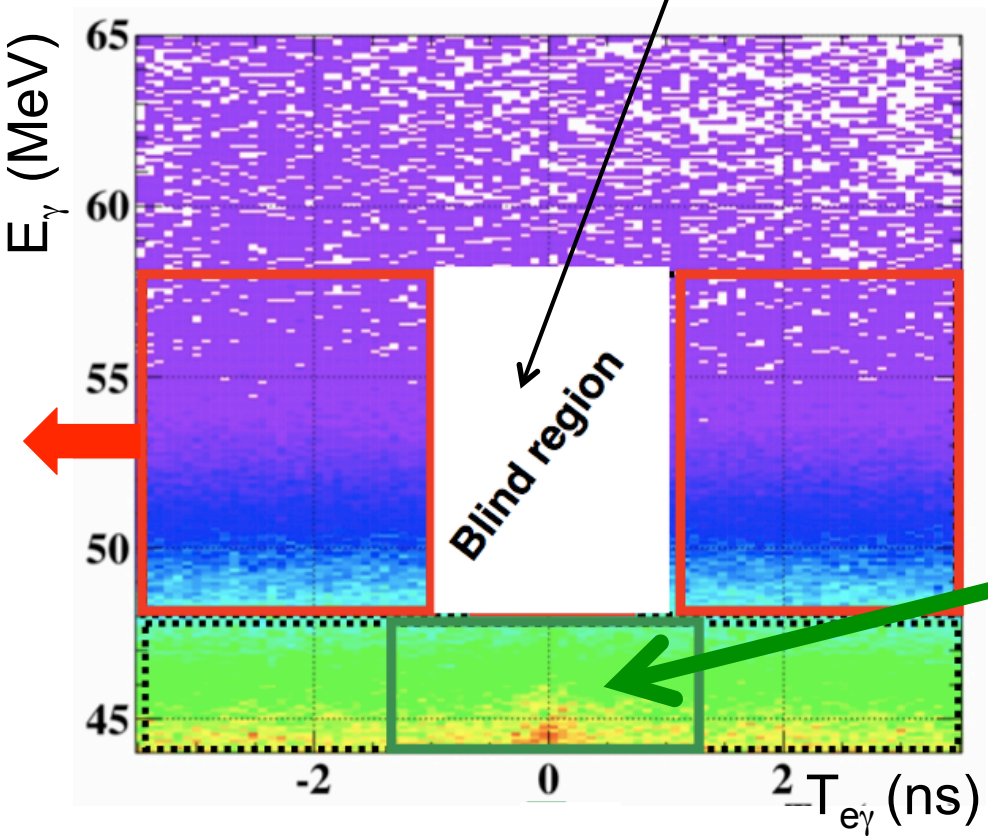
Analysis strategy

- Blind-box likelihood analysis strategy
- Observables: $E_{e+}, E_\gamma, \theta_{e\gamma}, \varphi_{e\gamma}, T_{e\gamma}$

$$\vec{x} = \begin{pmatrix} E_\gamma & : \text{Gamma energy} \\ E_e & : \text{Positron energy} \\ t_{e\gamma} & : \text{Time difference} \\ \vartheta_{e\gamma} & : \vartheta \text{ angle difference} \\ \varphi_{e\gamma} & : \varphi \text{ angle difference} \end{pmatrix}$$

Blind box, signal is expected here, kept hidden until analysis is defined

Sideband: accidental background



Radiative Decay background ($T_{e\gamma}$=0 as signal)

Analysis strategy

- Likelihood function

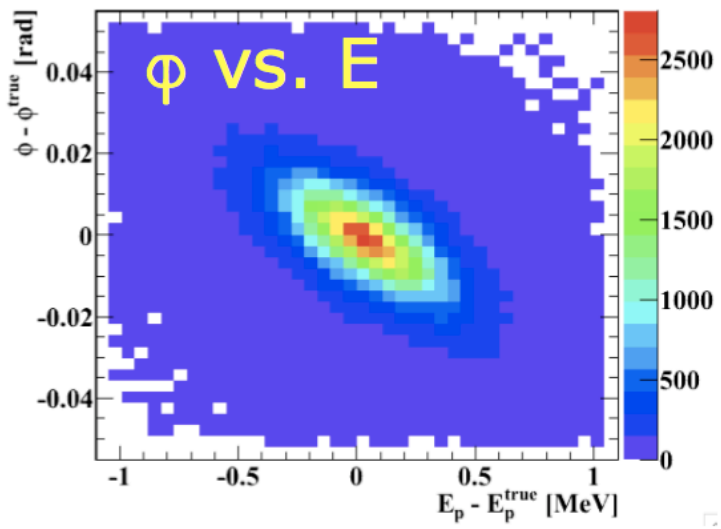
$$\mathcal{L}(\vec{x}_1,\ldots,\vec{x}_N,R_\diamond,A_\diamond|\hat{S},\hat{R},\hat{A}) = \frac{e^{-\hat{N}}}{N!} e^{-\frac{1}{2}\frac{(A_\diamond-\hat{A})^2}{\sigma_A^2}} e^{-\frac{1}{2}\frac{(R_\diamond-\hat{R})^2}{\sigma_R^2}} \prod_{i=1}^{N} \left(\hat{S}s(\vec{x}_i)+\hat{R}r(\vec{x}_i)+\hat{A}a(\vec{x}_i)\right)$$

- Accidental pdfs fully defined from data sidebands:
  - very solid determination of the dominant background

- Signal and radiative decay pdfs by combining results of calibration

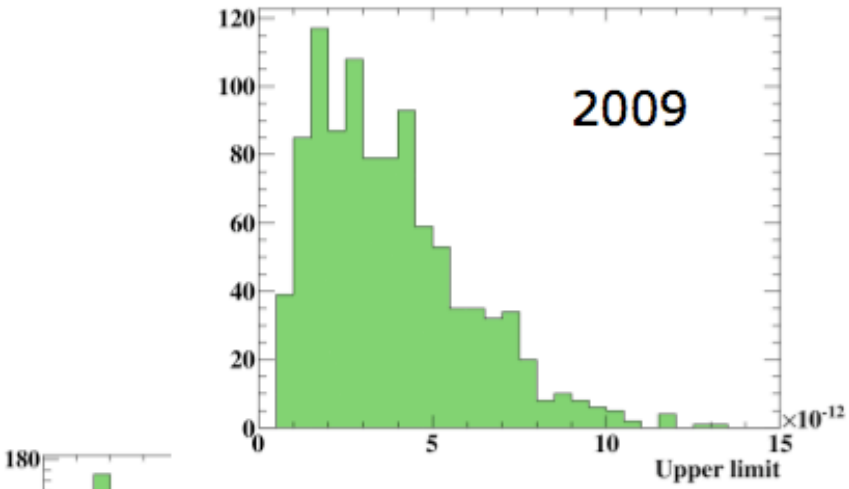
- Correlations between kinematic variables taken into account

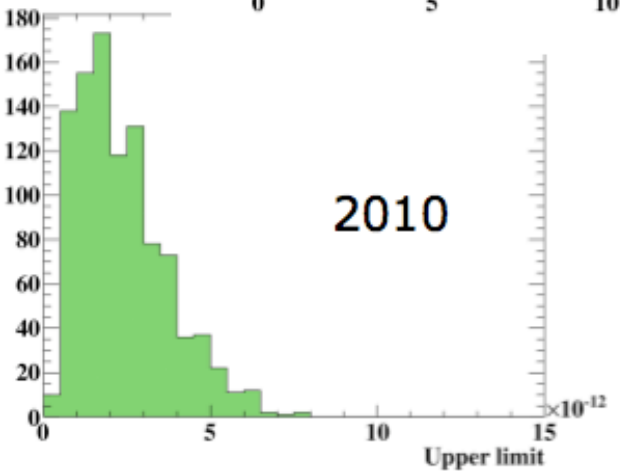
- Normalization from Michel decays

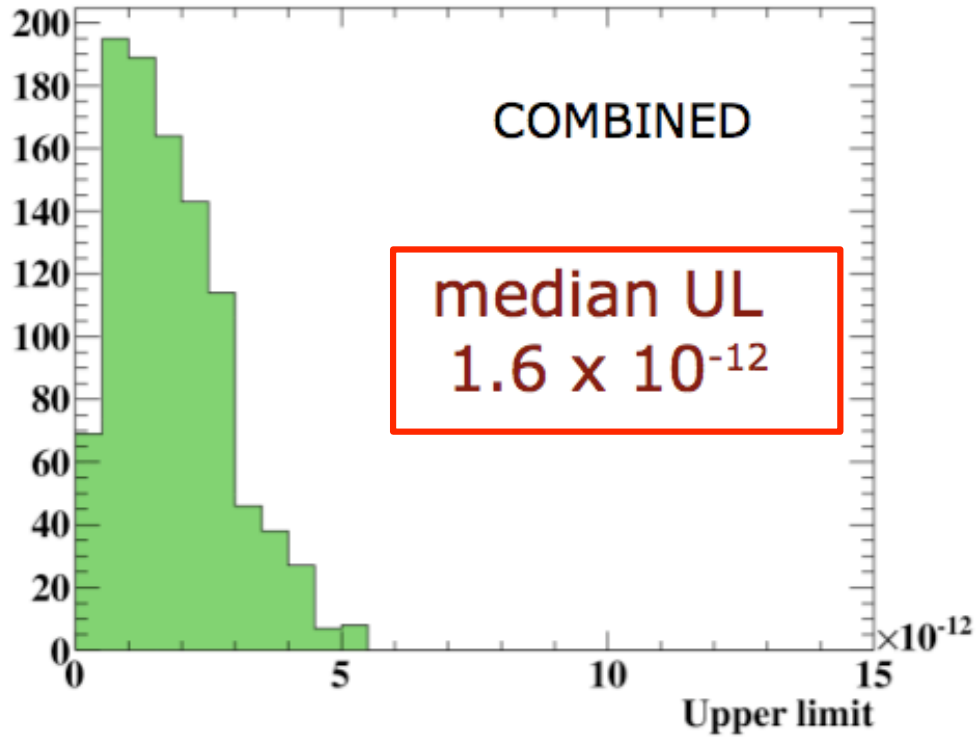


Sensitivity from toy Monte Carlo

- Upper limit obtained with toy MC samples with no signal
- Include systematic effects







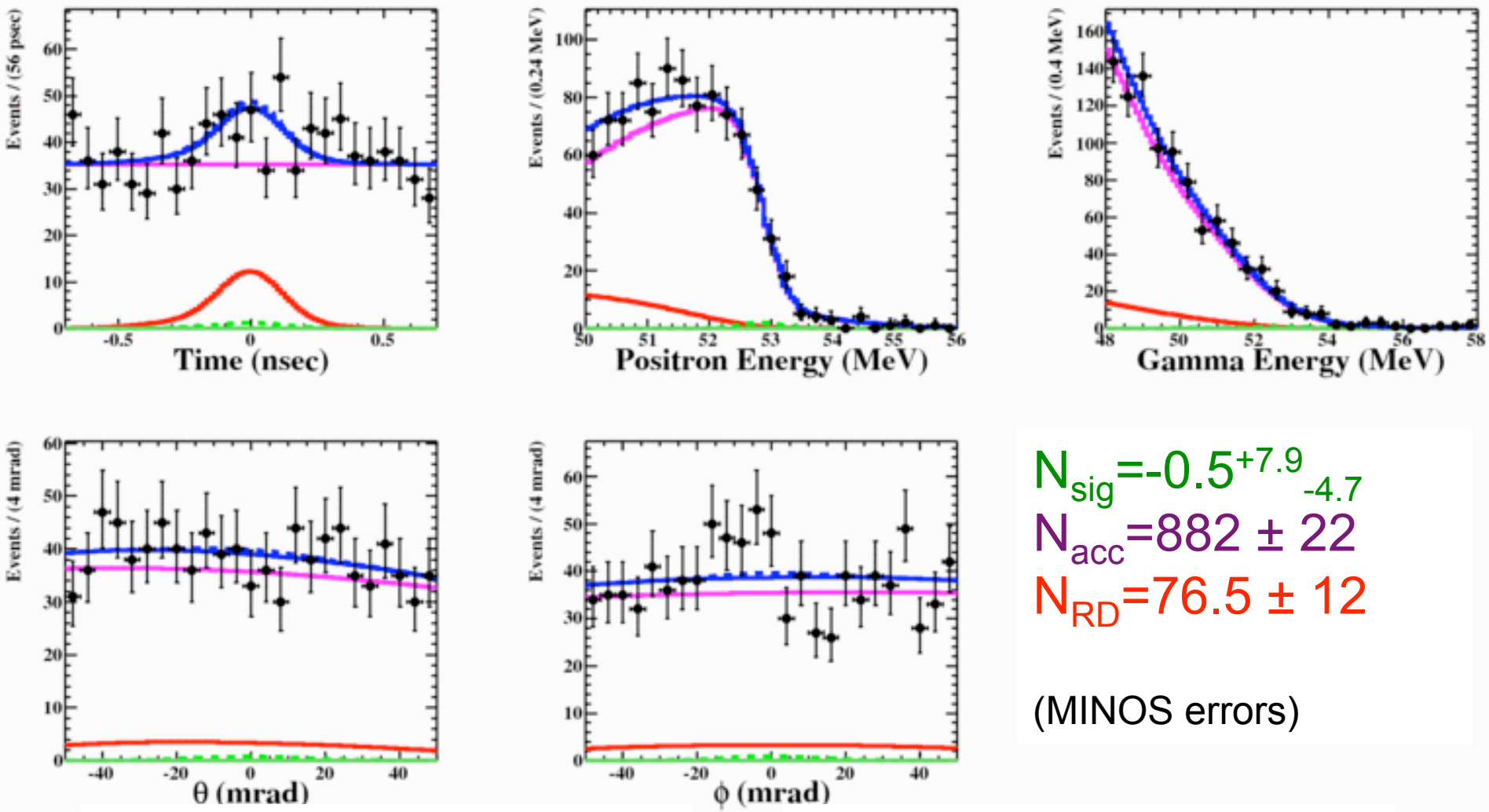
Result 2009+2010

Total
Accidental
Radiative
Signal

$BR(\mu \rightarrow e\,\gamma) < 2.4 \times 10^{-12}$

Phys. Rev. Lett. 107 (2011) 171801

Syst. uncertainty
(in total 2% of UL)
- relative angle offsets
- correlation in e+ variables
- normalization



$N_{sig} = -0.5^{+7.9}_{-4.7}$

$N_{acc} = 882 \pm 22$

$N_{RD} = 76.5 \pm 12$

(MINOS errors)

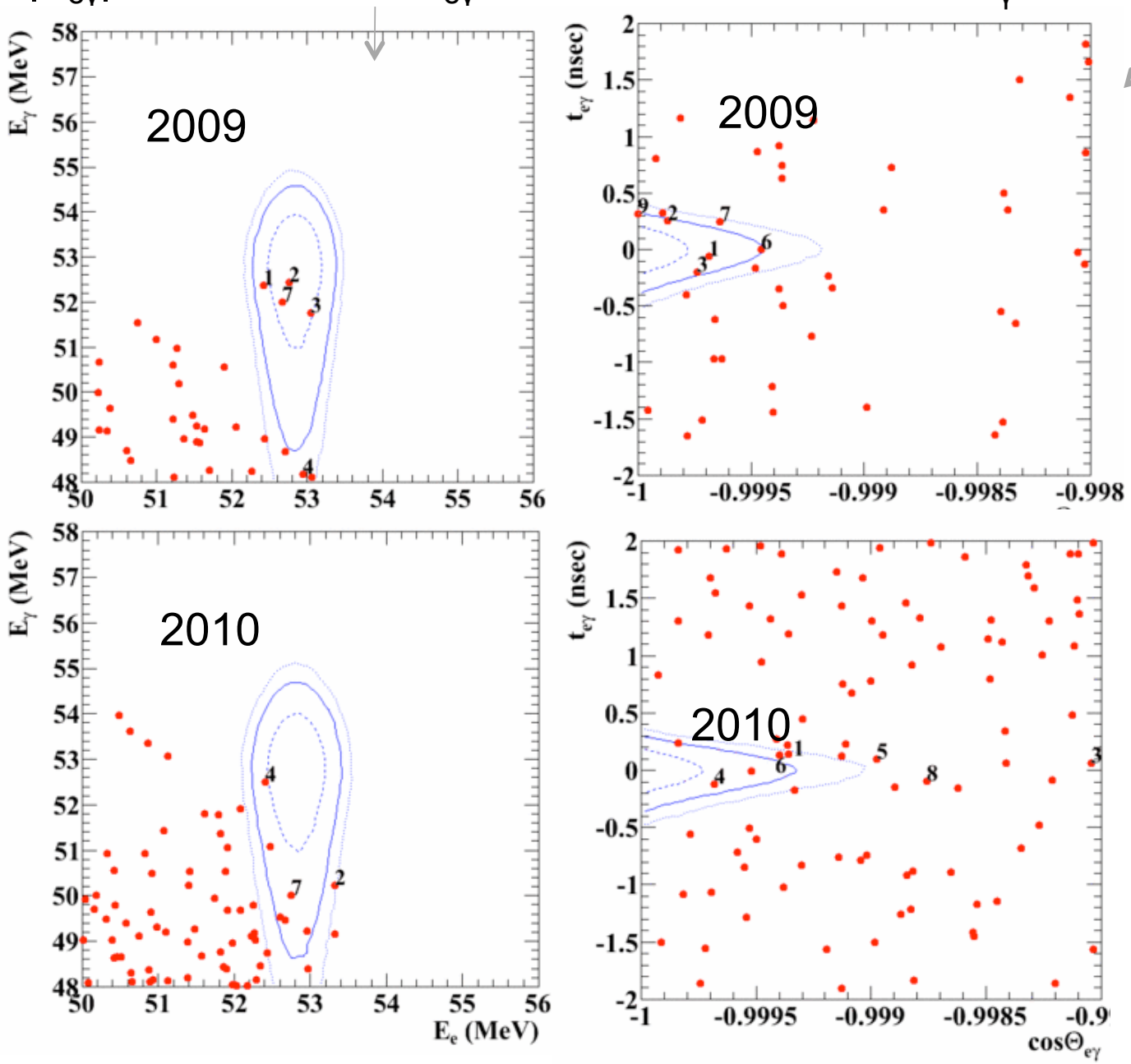
2009: N_{sig}(best fit) = 3.4

2010: N_{sig}(best fit) = -2.2

Event distribution

$|T_{e\gamma}|<0.278$ns; $\cos\Theta_{e\gamma}<0.9996$

$51<E_\gamma<55$ MeV; $52.34<E_e<55$ MeV



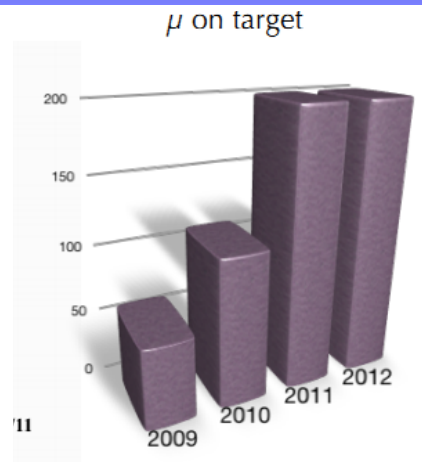
1, 1.64, 2 σ contours

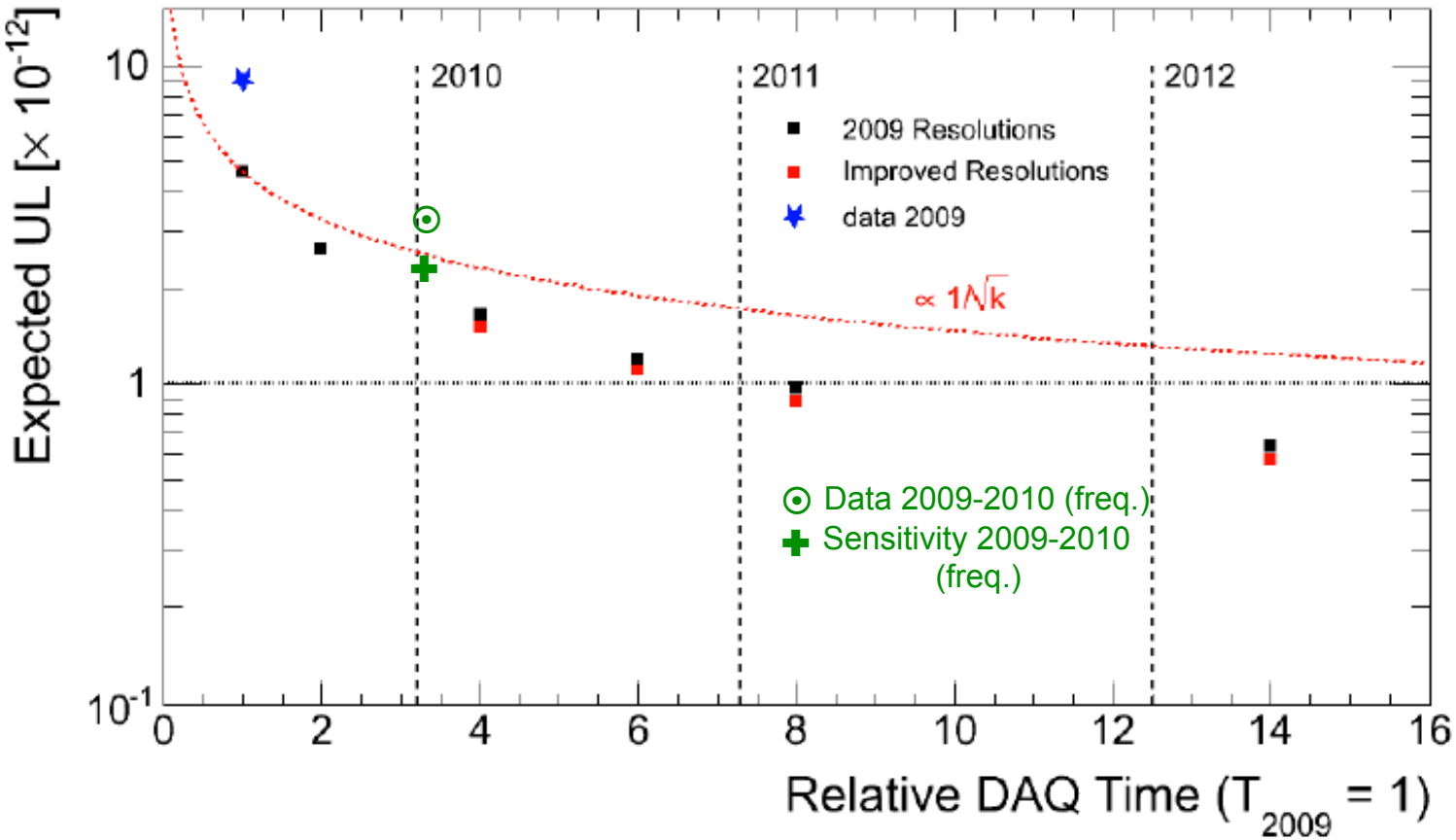
Ranking of variables according to

$$R_{sig} = Log_{10}\left(\frac{L_{sig}}{0.1L_{RMD} + 0.9L_{BG}}\right)$$

Perspectives

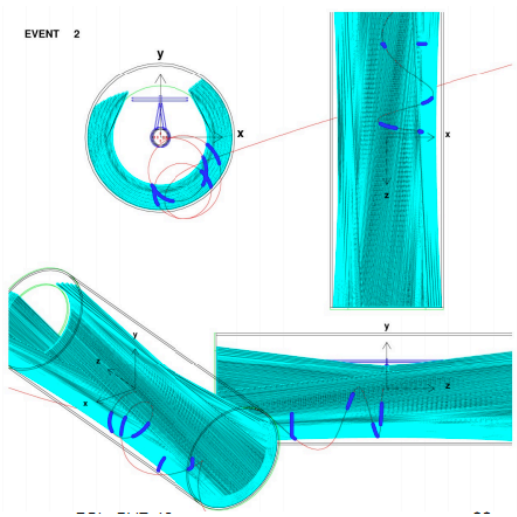
- About to add 2011 data
- 2012 run will start in 1 month
- Plan to reach ~5×10^{-13}
- Intrinsic limit: accidental background





Toward an upgrade of MEG

- The collaboration is considering possible upgrades to improve sensitivity by one order of magnitude (5×10^{-14})



- New Drift Chamber system
  cylinidrical DC, a la Kloe,
  possibly with cluster timing capabilities
- Replacement of inner face PMTs of calorimeter with smaller ones or MPPC
- Active target with scintillating fibers
- Other solutions are also under study (e.g. new Timing counter with scintillating tiles)

- Timescale: 2 years RD + 2-3 years of running

Conclusion

- No evidence of $\mu \rightarrow e\gamma$ signal in MEG dataset (so far)
  - 2009+2010 result improves by factor 5 previous best limit by MEGA experiment

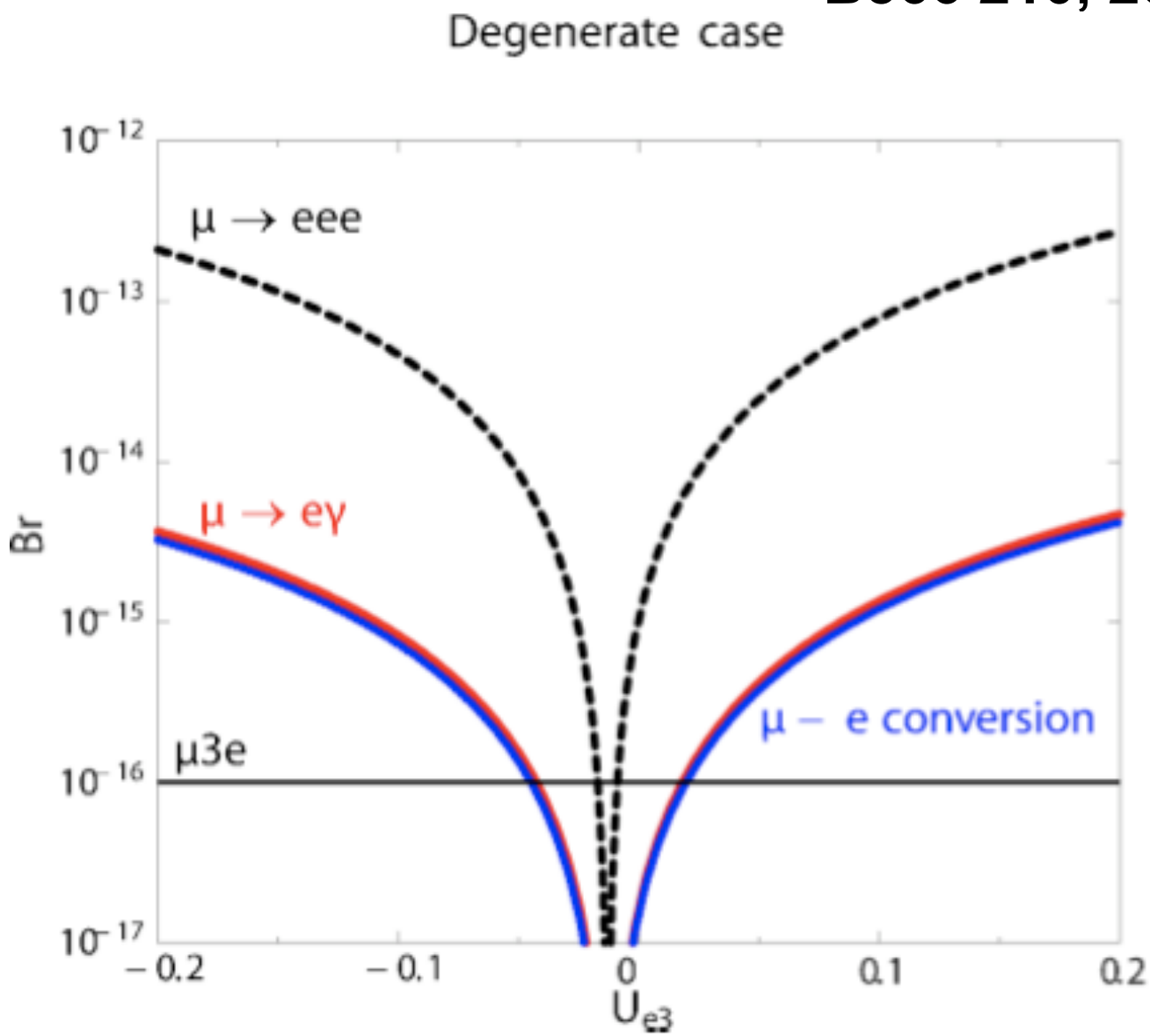
- $BR(\mu \rightarrow e\gamma) < 2.4 \times 10^{-12}$ @ 90% CL
  - We will improve sensitivity by end of 2012, hopefully will reach 5×10^{-13}
  - MEG is considering upgrade to reach 5×10^{-14} (timescale 2014-2015 for data-taking)

- Proposal for new $\mu \rightarrow eee$ experiment to be presented at PSI in early 2013 aims at sensitivity of $\sim 10^{-16}$
  - experiment timescale (if approved): 2014-2017 (phase1) and >2017 (phase 2)

Backup

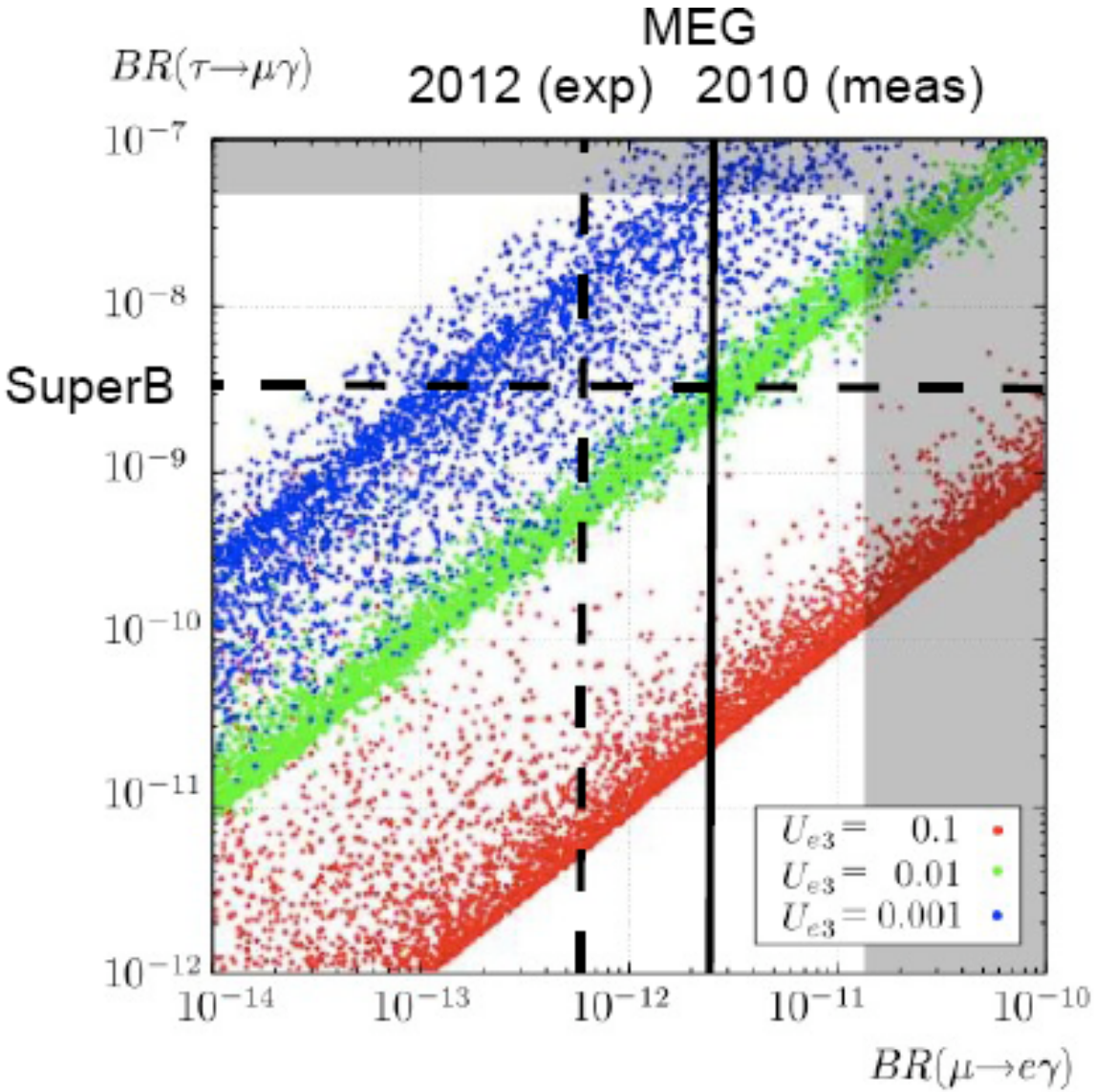
Example: triple Higgs model

M.Kakizaki et al., Phys.Lett.
B566 210, 2003



Example: τ and μ

SUSY SU(5) with right-handed neutrino
(Hisano, Nagai, Paradisi, Shimizu '09)



MEG Detector performances

	2009	2010
Gamma E [σ_R,w>2cm – 63%]	1.9%	1.9%
Relative timing $T_{e\gamma}$(RMD)	150ps	130ps
Positron E [Michel edge]	330 keV(82% core)	330 keV (79% core)
Positronθ	9.4 mrad	11.0 mrad
Positron ϕ [at zero]	6.7 mrad	7.2 mrad
PositronZ/Y	1.5/1.1(core)mm	2.0/1.1(core)mm
Gamma position	5(u,v)6(w) mm	5(u,v)6(w) mm
Trigger efficiency	91%	92%
Gamma efficiency	58%	59%
Positron efficiency	40%	34%

Normalization

The BR is normalized to the number of Michel decays

- Positron only trigger acquired in parallel with μ→eγ trigger
- Correction factors take into account photon efficiency and acceptance
- Kinematical and trigger difference between signal and Michel
- Cross-check with muon radiative decay measurement

$$\mathrm{BR}(\mu^+ \to e^+\gamma) = \frac{N_{\mathrm{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{\mathrm{trig}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{trig}}_{e\gamma}} \times \frac{A^{\mathrm{TC}}_{e\nu\bar{\nu}}}{A^{\mathrm{TC}}_{e\gamma}} \times \frac{\epsilon^{\mathrm{DCH}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{DCH}}_{e\gamma}} \times \frac{1}{A^{\mathrm{g}}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}$$

$$k = \frac{N_{sig}}{Ne\nu\bar{\nu}} = 1.03(2.22) \times 10^{12}$$ for 2009(2010)

error=9%

Systematic errors

Evaluated by toy MC procedure

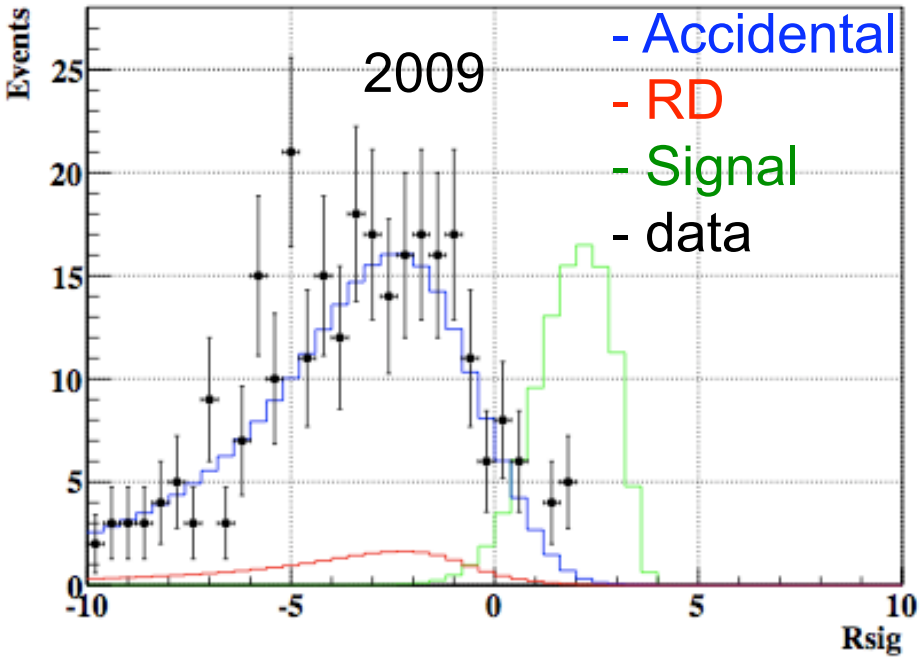
RMS of variation of likelihood ratio profile on toy MC experiments

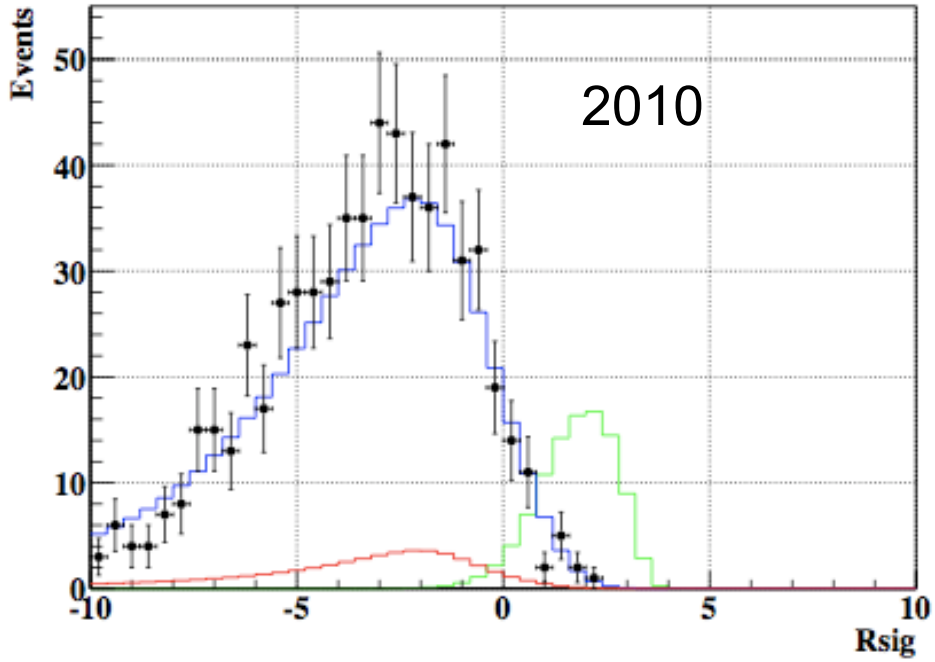
Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.16
Normalization	0.13
E_γ scale	0.07
E_e bias, core and tail	0.06
$t_{e\gamma}$ center	0.06
E_γ BG shape	0.04
E_γ signal shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.02
γ angle resolution (u_γ, v_γ, w_γ)	0.02
E_e BG shape	0.02
E_e signal shape	0.01

Cut analysis

Use variable R that includes all the information

$$R_{sig} = Log_{10}\left(\frac{L_{sig}}{0.1L_{RMD} + 0.9L_{BG}}\right)$$



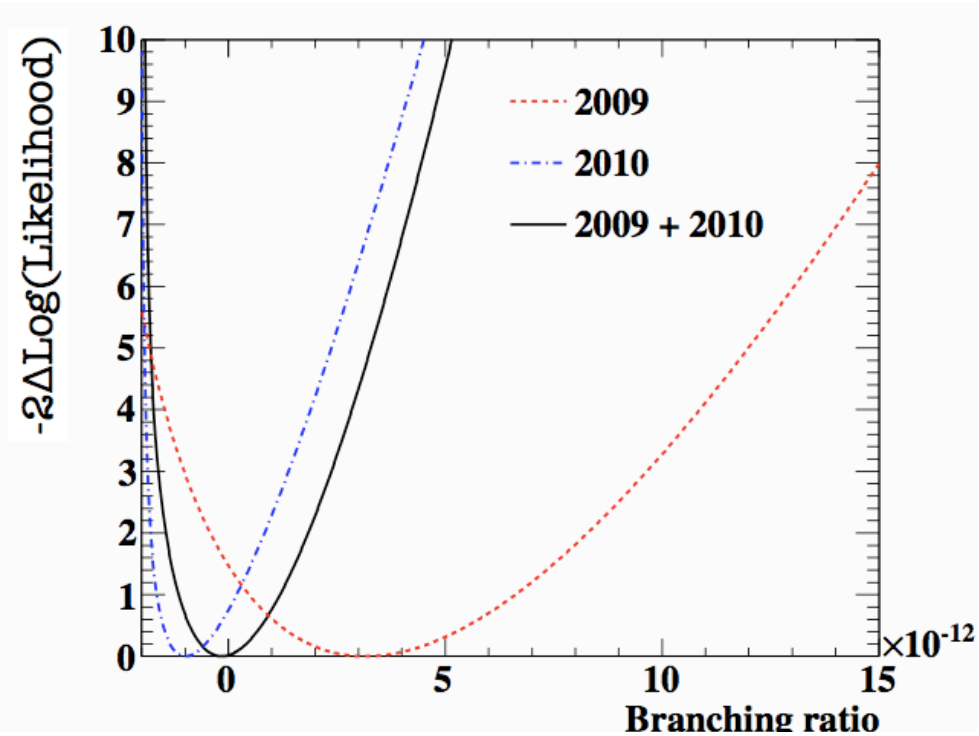


Year	Cut in R_{sig}	$B_{exp,tot}$	N_{obs}	Sensitivity	Upper Limit
2009	1.66	1.1	3	5.0×10^{-12}	9.5×10^{-12}
2010	1.72	2.1	1	3.3×10^{-12}	2.0×10^{-12}
Combined	1.84	2.3	3	2.4×10^{-12}	3.0×10^{-12}

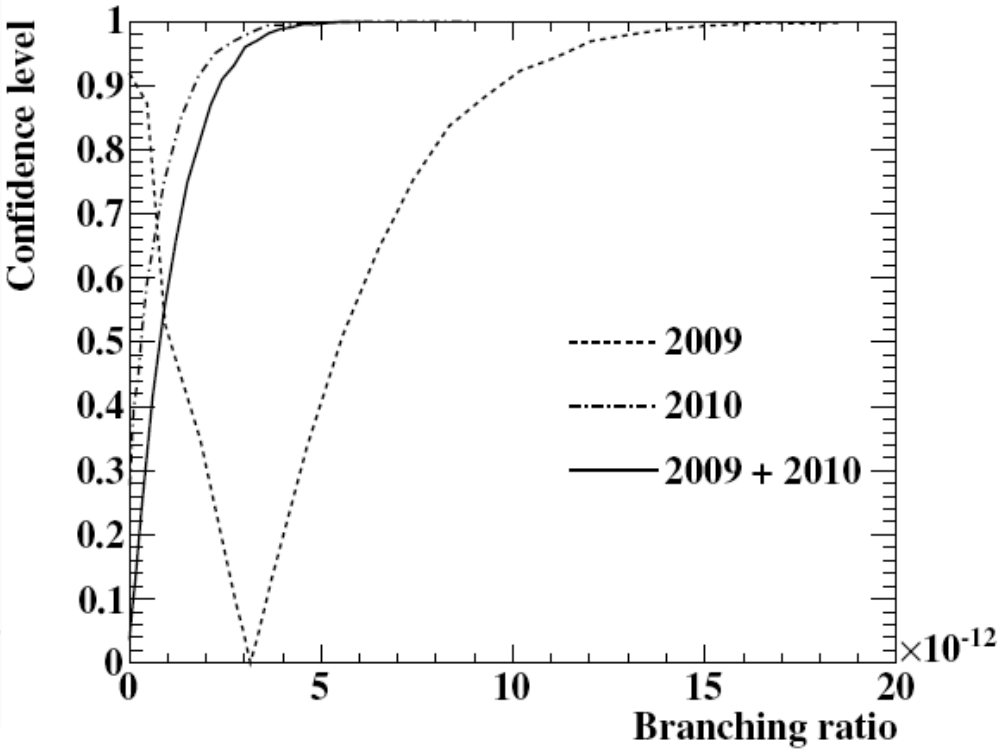
Upper limit on BR(μ→eγ)

BR(μ→eγ) < 2.4x10^{-12} @90% CL

Likelihood profile curves



Confidence Level



2009 UL: 9.6x10^{-12} 2010 UL: 1.7x10^{-12}