An overview on μ Physics

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Outline

The role of μ in search for New Physics

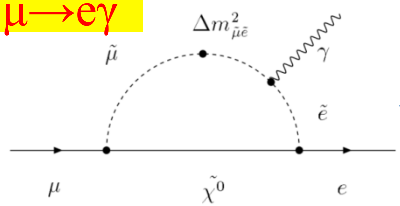
- Search for
  - Process forbidden in Standard Model (e.g. cLFV)
  - Process well predicted in SM (e.g. $(g-2)_\mu$)
- The experimental situation
  - $(g-2)_\mu$
  - The MEG project
  - The μ to e conversion experiments

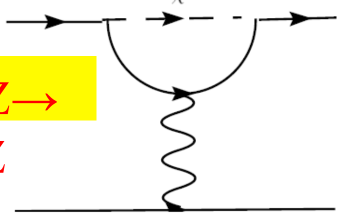
- Conclusions
- (Not intended nor possible to be full comprehensive)
- Credits to:
  - G. Cavoto, Y.Kuno, S. Mihara, D. Nicolo', N. Saito, Fermilabg-2, F. Renga, P. Paradisi and the others that I forgot

cLFV vs g-2, and EDM

- Contribution to EDM, MDM of leptons from diagonal elements of the slepton mass matrix
- LFV processes induced by off-diagonal terms (depend on how SUSY breaking is generated and what kinds of LFV interactions exist at the GUT scale)

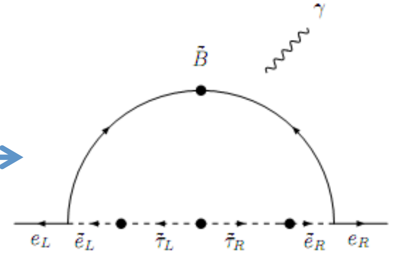
μ→eγ





μZ→ eZ

$$M^2_{\tilde{l}\tilde{l}} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

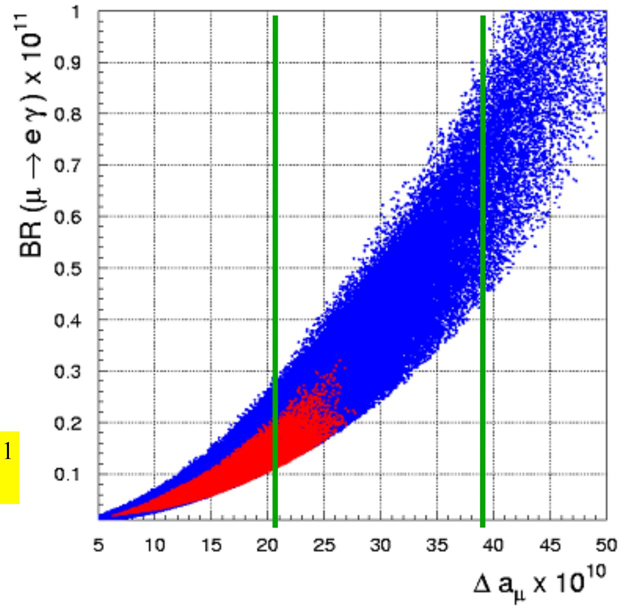


g-2 $\propto \Re(m^2_{\tilde{\mu}\tilde{\mu}})$

EDM $\propto \Im(m^2_{\tilde{\mu}\tilde{\mu}})$

- SUSY effect on g-2 ➔ deviations from SM predictions
- an experimental clue: E821 results

$$\Delta a_\mu \equiv a_\mu^{\exp} - a_\mu^{SM} = (297 \pm 79) \times 10^{-11}$$



$\Delta a_\mu \neq 0$ associated with SUSY

➔ $BR(\mu \to e\gamma) \geq 10^{-12}$

G.Isidori *et al.*

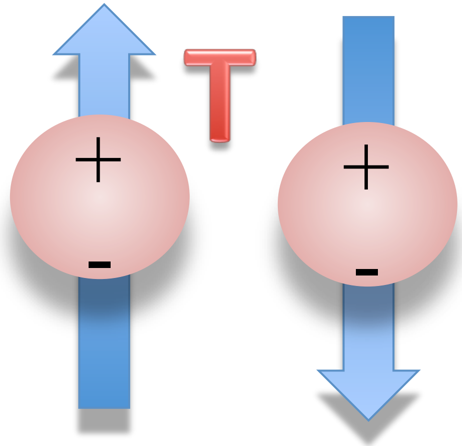
Phys. Rev. D75 (2007) 115019

➔ strong physics case

Particle Dipole Moments

- Magnetic and Electric Dipole Moments are related to Spin of the Particle: axial vector

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s} \qquad \vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}$$



$$a = \frac{g-2}{2}$$

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

MDM (Magnetic Dipole Moment)
Contains contributions from ALL PHYSICS!
- EW, QCD, and New Physics
⇒ precision test of the SM
⇒ the most precise determination of α_{EM} from electron g-2 (0.37 ppb)

EDM (Electric Dipole Moment)
If EDM nonzero, T is violated
⇒ CP violation in the lepton sector (under CPT)
⇒ leptogenesis?
⇒ Baryon Asymmetry in the Universe

Muon magnetic moment

- Magnetic moment and spin can be related as

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$$

$\vec{\mu}$: magnetic moment
$\vec{s}$: spin
g : gyromagnetic ratio

- Dirac equation predicts g=2 ⇨ a=0

$$\mu = (1+a)\left(\frac{e\hbar}{2m}\right) \qquad a = \frac{g-2}{2}$$

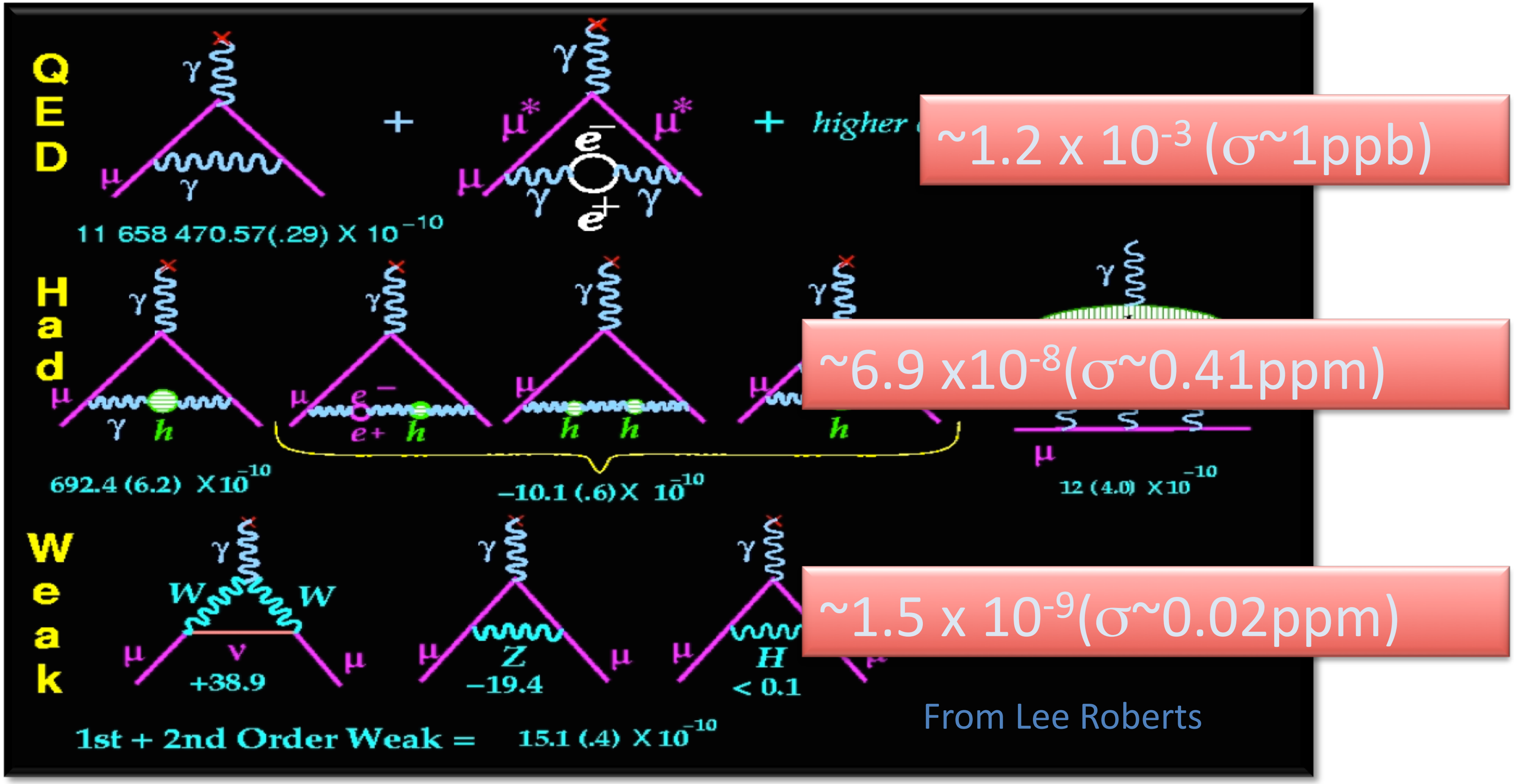
a=1.2e-3 for e, μ, ...
a=1.8 for proton

- Radiative corrections (including NEW PHYSICS) would make g≠2 ⇨ a≠0

$$\left(\frac{m_\mu}{m_e}\right)^2 \sim 40{,}000 \qquad \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 290$$

SM Contributions to a ≠0

- Any particle which couples to muon/photon would contribute : QED >> Hadron > Weak



Muon Spin precession

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$$\eta :\ d_\mu = \frac{\eta}{2}\left(\frac{e}{2m}\right) \text{ Electric Dipole Moment}$$

$$d_e = (6.9 \pm 7.4)\times 10^{-28}\, e\cdot\mathrm{cm}$$

Expected to be

$$d_\mu < (1.5 \pm 1.4)\times 10^{-25}\, e\cdot\mathrm{cm}$$

Measured to be

$$d_\mu = (0.0 \pm 0.9)\times 10^{-19}\, e\cdot\mathrm{cm}$$

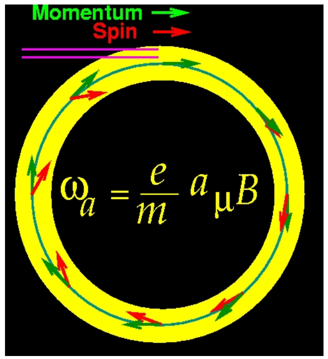
G.W.Benett et al. Phys.Rev.D80:052008,2009

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\gamma_{\text{magic}} = 29.3$$

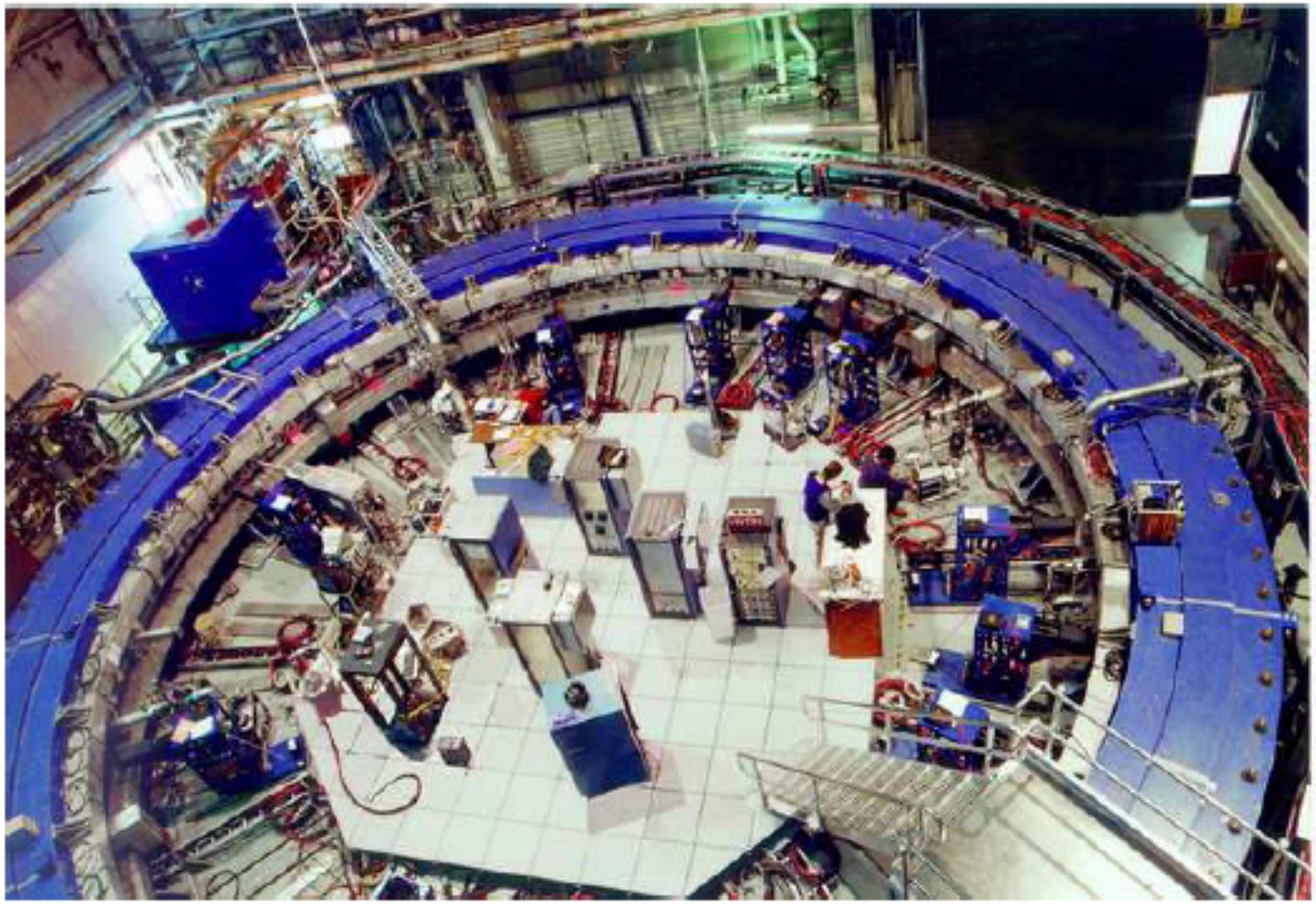
$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$



BNL E821

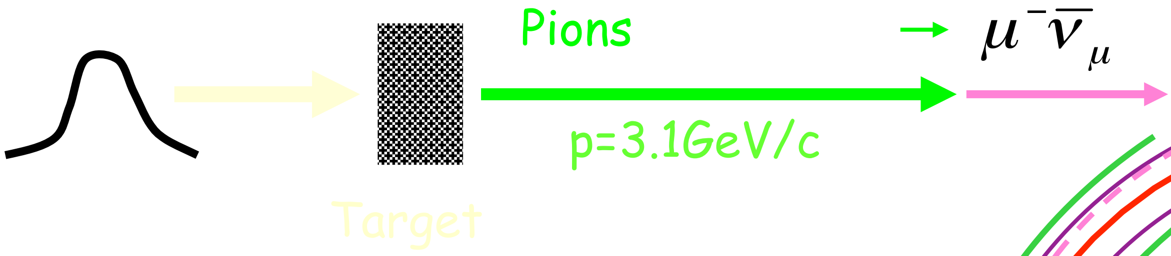
proposal to move to Fermilab

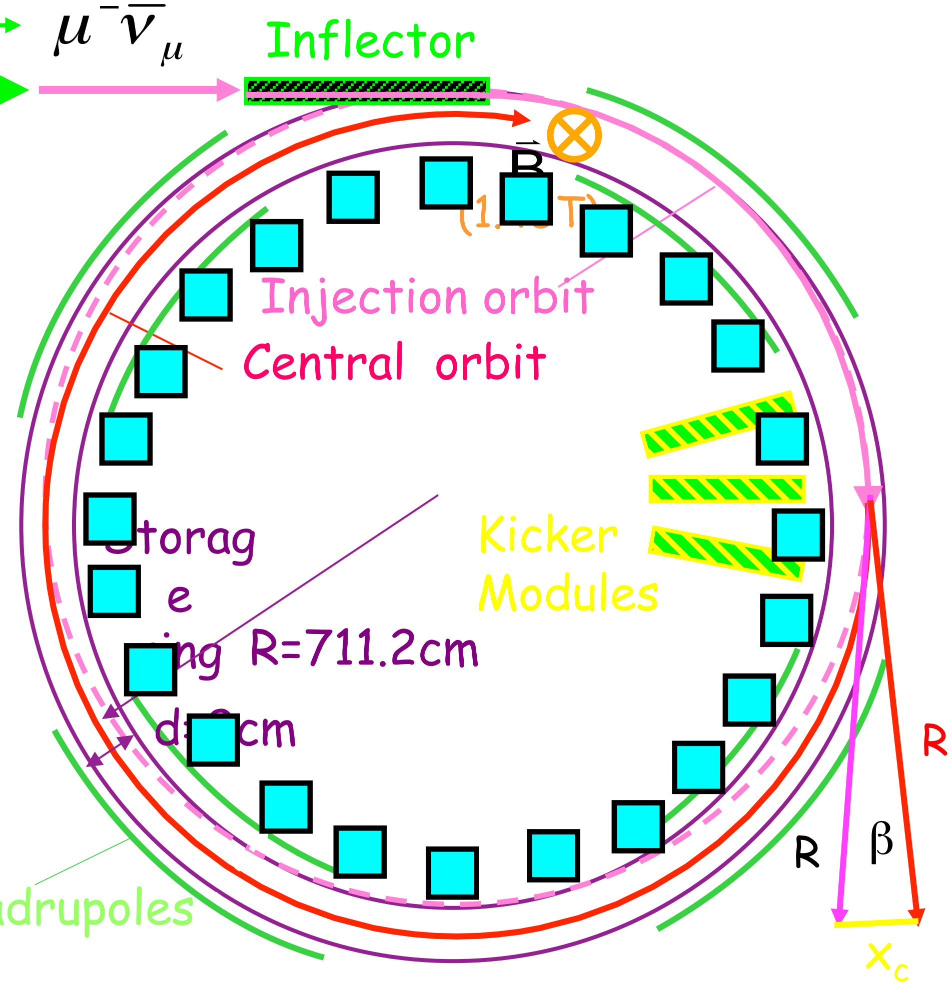


Experimental Technique: fill ring, count until all muons are gone; do it again

25ns bunch of
5 X 10^{12} protons
from AGS

$x_c \approx 77$ mm
$\beta \approx 10$ mrad
$B \cdot dl \approx 0.1$ Tm





- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

Electric Quadrupoles

(thanks to Q. Peng)

BNL, FNAL, and J-PARC

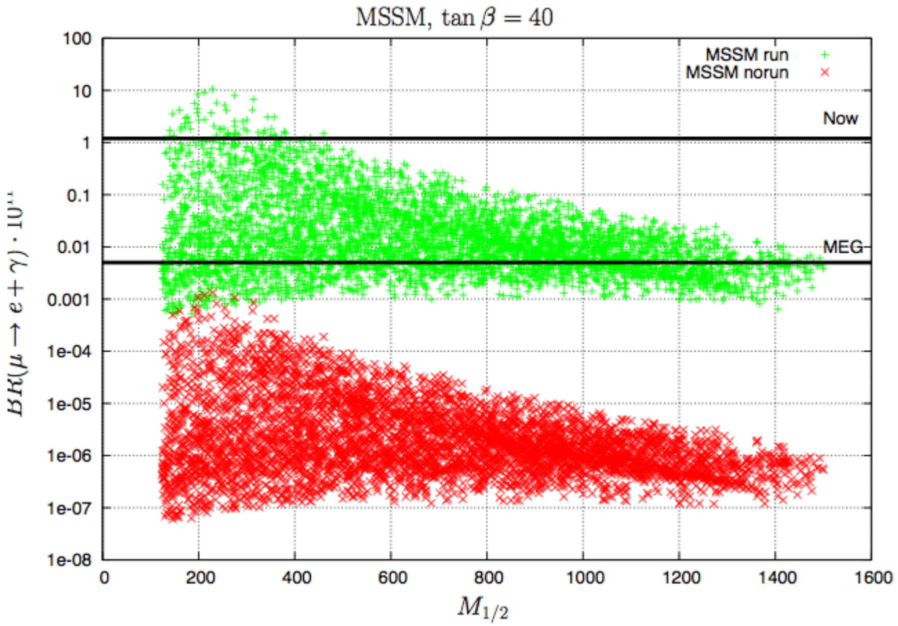
Done | Proposals with diff techniques | See K.Ishida WG3

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c (magic)		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

Lepton Flavor Violation of Charged Leptons

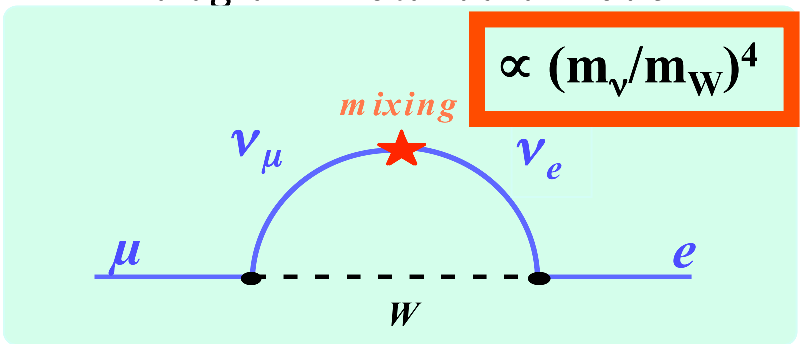
Contrary to the well established neutrino mixing the charged lepton one not observed yet

SO(10) SUSY GUT w/ see-saw
(Calibbi, Faccia, Masiero, Vempati '07)



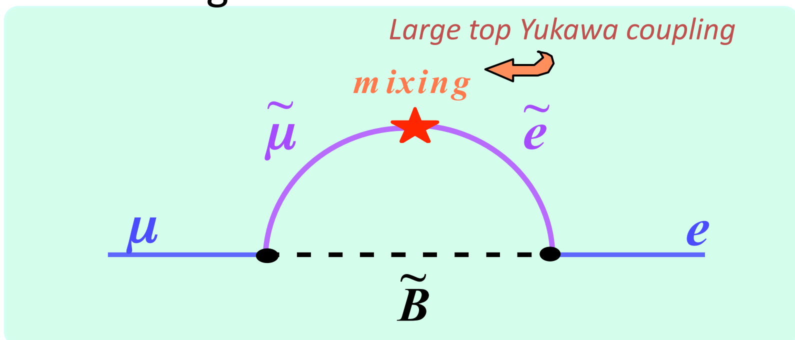
Discrimination power among models

LFV diagram in Standard Model



Very Small (10^{-52})

LFV diagram in SUSY



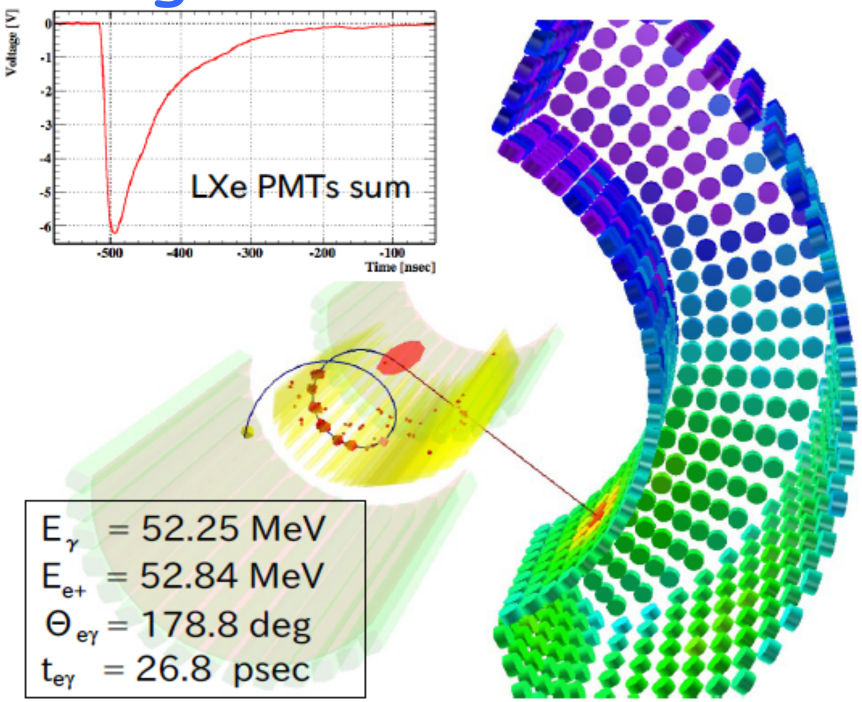
Sensitive to new Physics beyond the Standard Model

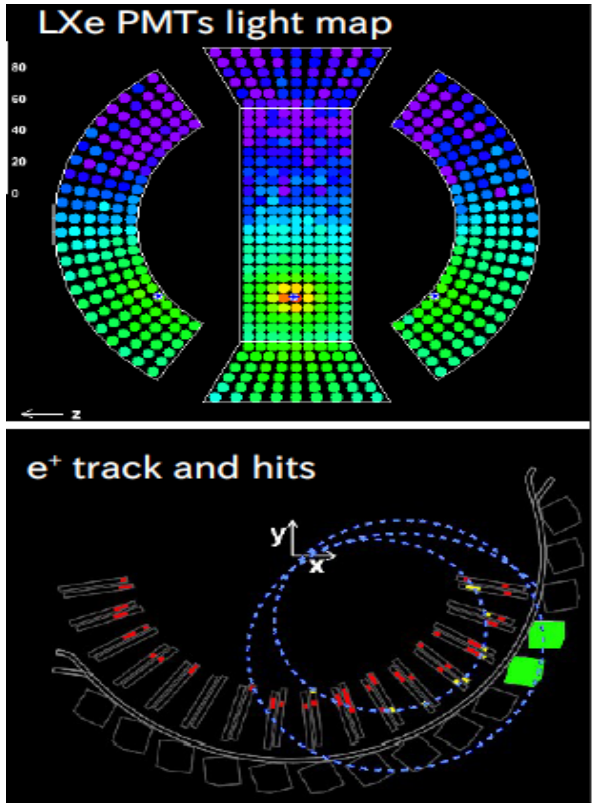
The MEG Experiment at PSI

See also H. Nishiguchi WG4 oct 21

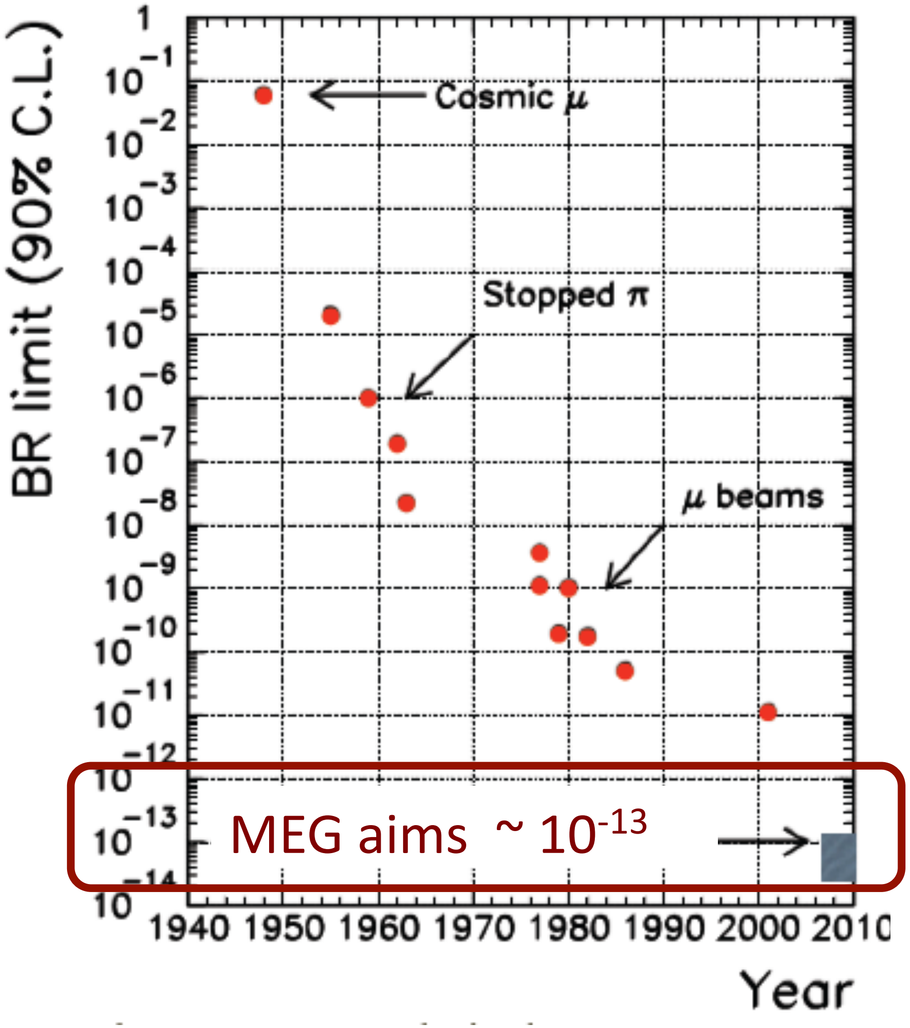
*The more intense DC μ beam in the world (up to 10^8 μ/s)
*The largest (800 l) Liquid Xenon Calorimeter for γ detection
* Dedicated e+ spectrometer with graded B field and high time resolution

A signal-like event





History

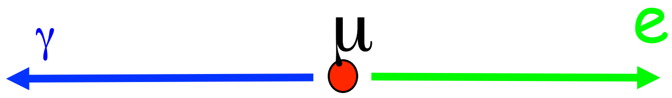


- 1947 – Hinks & Pontecorvo:
  - First limit;
- ~1960 the lack of a 10^{-4} signal ->existence of at least 2 neutrinos!
- 1977 - Van der Schaaf *et al.* (PSI) Depommier *et al.* (TRIUMF):
  - First experiments with muon beams.
- 1999 – MEGA (LANL):
  - Present best limit;
  - BR < 1.2 x 10^{-11} @ 90% C.L.

Experimental Signature

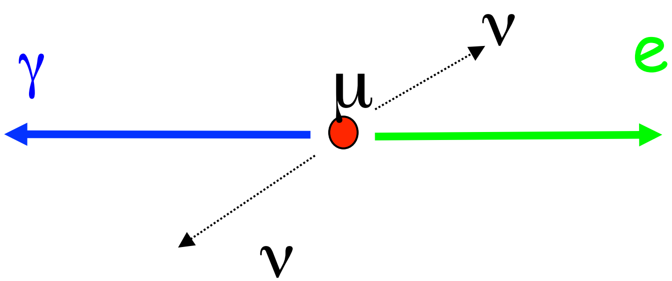
- To get 10^{-13} sensitivity:
  - high statistics;
  - high resolutions (energy, time, angle) for low background;

SIGNAL ∝ μ rate



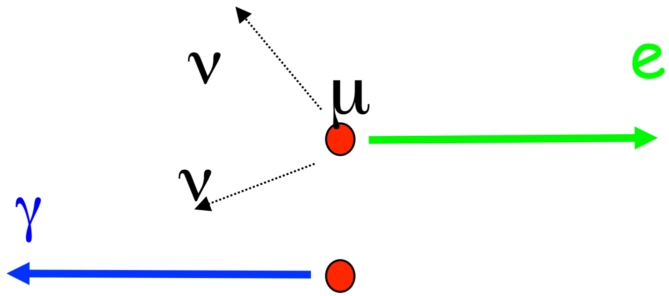
$E_\gamma = E_e = 52.8$ MeV,
$t_{e\gamma} = 180°$, $T_e - T_\gamma = 0$

RADIATIVE DECAY ∝ μ rate



DOMINANT

ACCIDENTAL ∝ (μ rate)²



$$\Gamma_{acc} \propto \Gamma_\mu^2 \cdot \delta E \cdot \delta T_{e\gamma} \cdot (\delta E_\gamma)^2 \cdot (\delta \Theta_{e\gamma})^2$$

Required Performances

BR ($\mu \to e\gamma$) ≈ 10^{-13} reachable

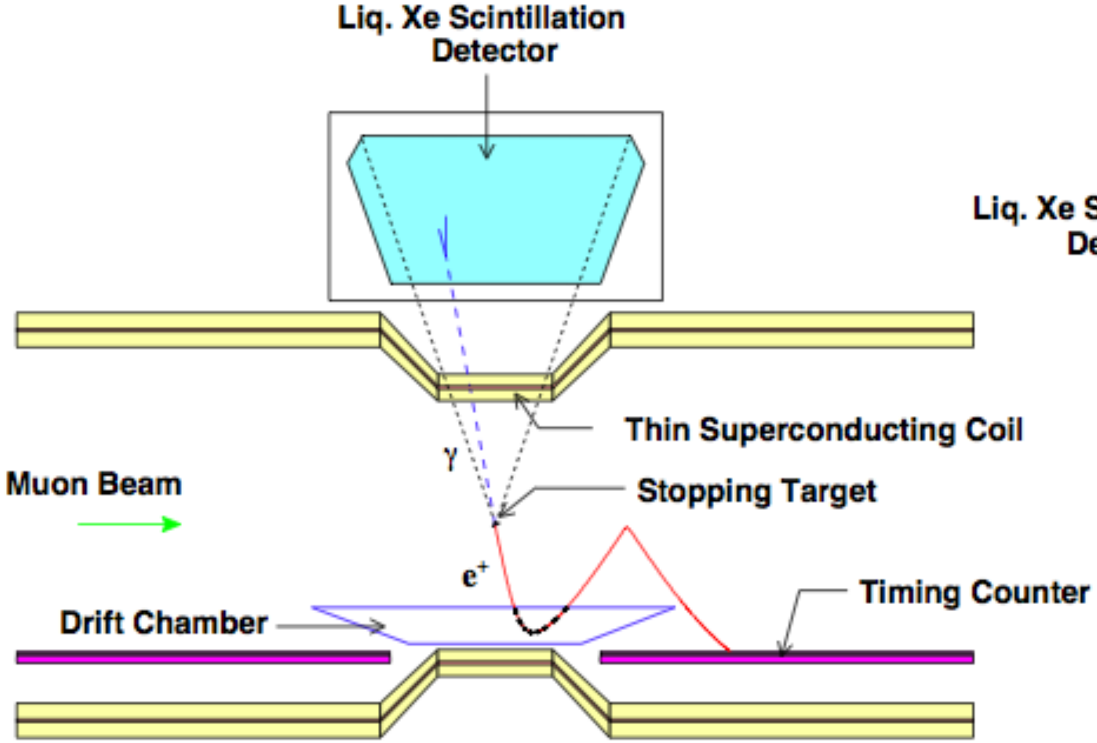
BRacc.b. ≈ 2 10^{-14} and BRphys.b. ≈ 0.1 BRacc.b. with the following resolutions

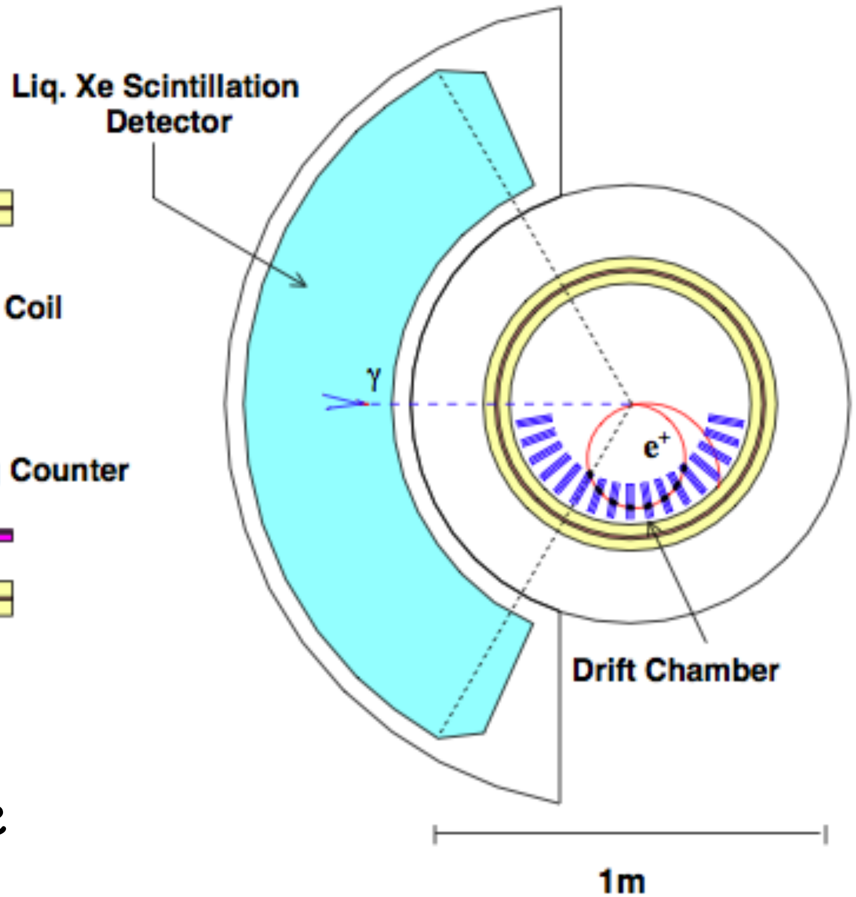
FWHM (applies to $\Delta E_e/E_e$, $\Delta E_\gamma/E_\gamma$, $\Delta t_{e\gamma}$, $\Delta\theta_{e\gamma}$)

Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5 x 10^5	100	3.6 x 10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2 x 10^5	100	1 x 10^{-9}
LANL	1979	8.8	8	1.9	37	2.4 x 10^5	6.4	1.7 x 10^{-10}
Crystal Box	1986	8	8	1.3	87	4 x 10^5	(6..9)	4.9 x 10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5 x 10^8	(6..7)	1.2 x 10^{-11}
MEG	2011	0.8	4	0.15	19	2.5 x 10^7	100	1 x 10^{-13}

Need of a DC muon beam

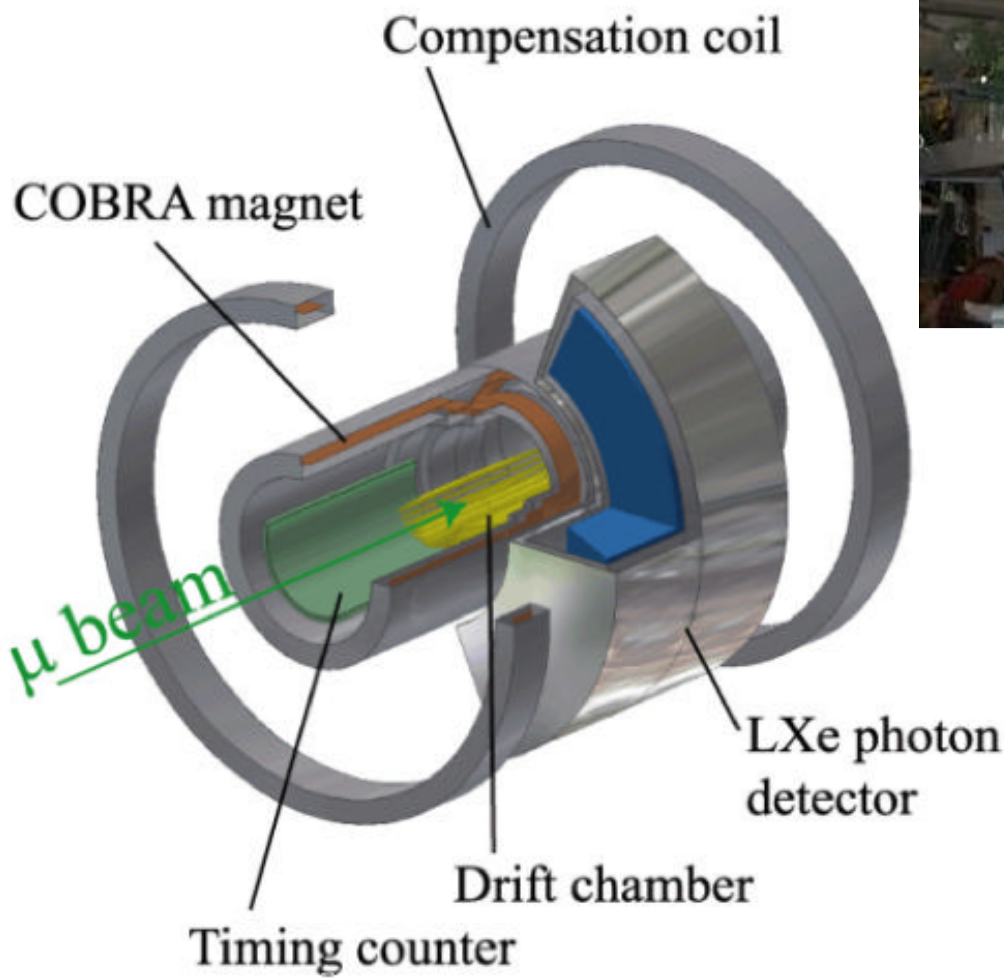
The MEG Experiment

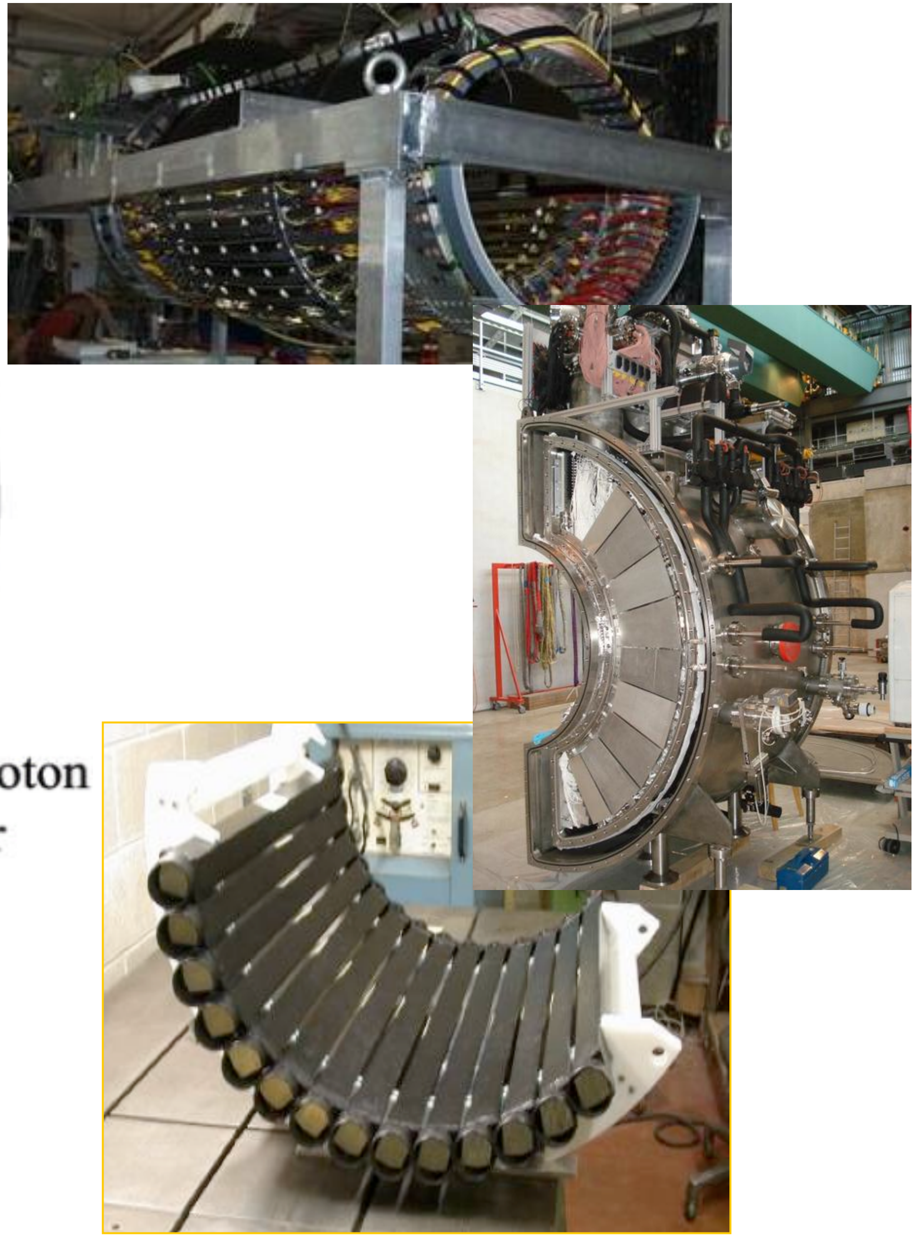




~ 10% geometrical acceptance

The MEG Experiment

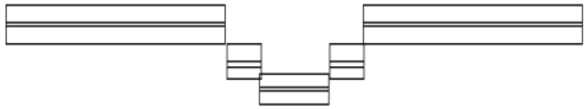


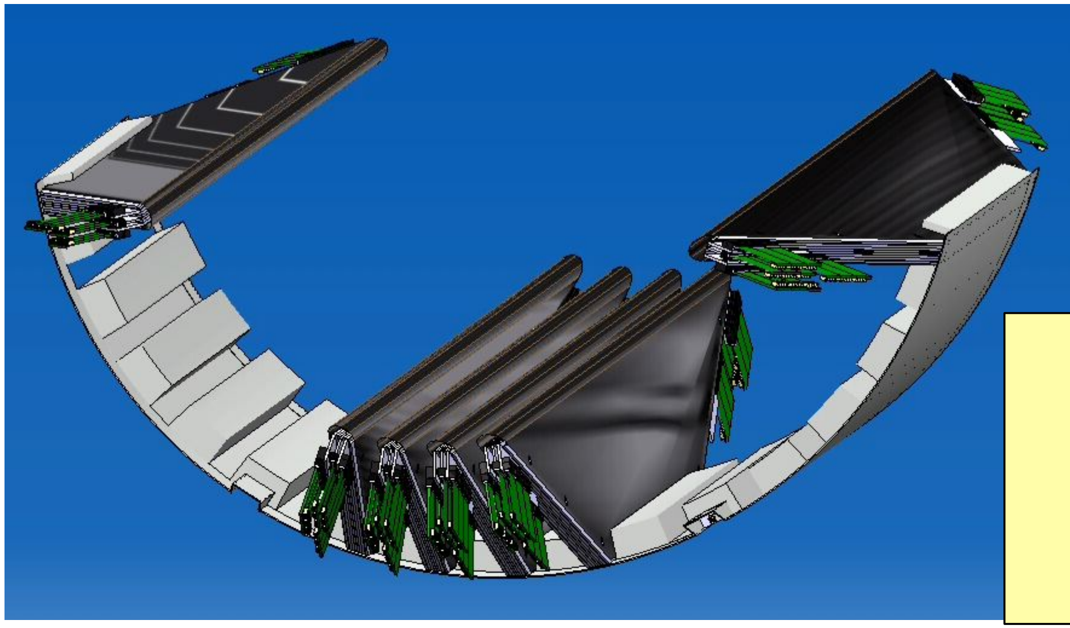


~60 physicists, 12 Institutions, 5 Countries
Italy, Japan, Russia, Switzerland, USA

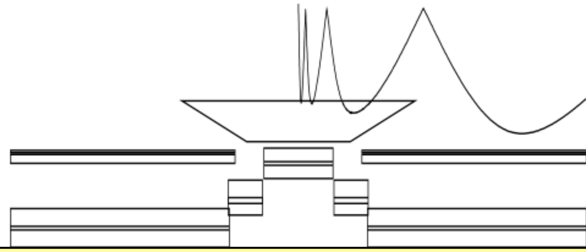
The Positron Spectrometer

- 16 low-mass *Drift Chambers* in a Helium atmosphere with a *graded magnetic field* :
  - very low total material budget (< 0.005 X_0);
  - fast expulsion of tracks from the spectrometer even at large polar angles.





Graded Field



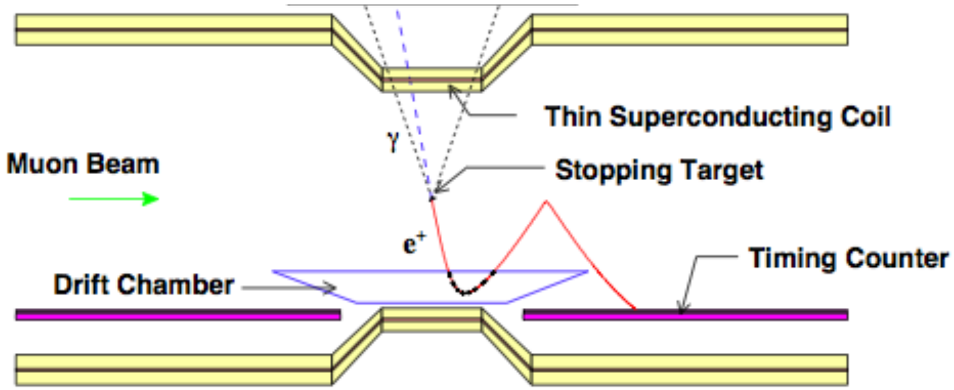
Design resolutions

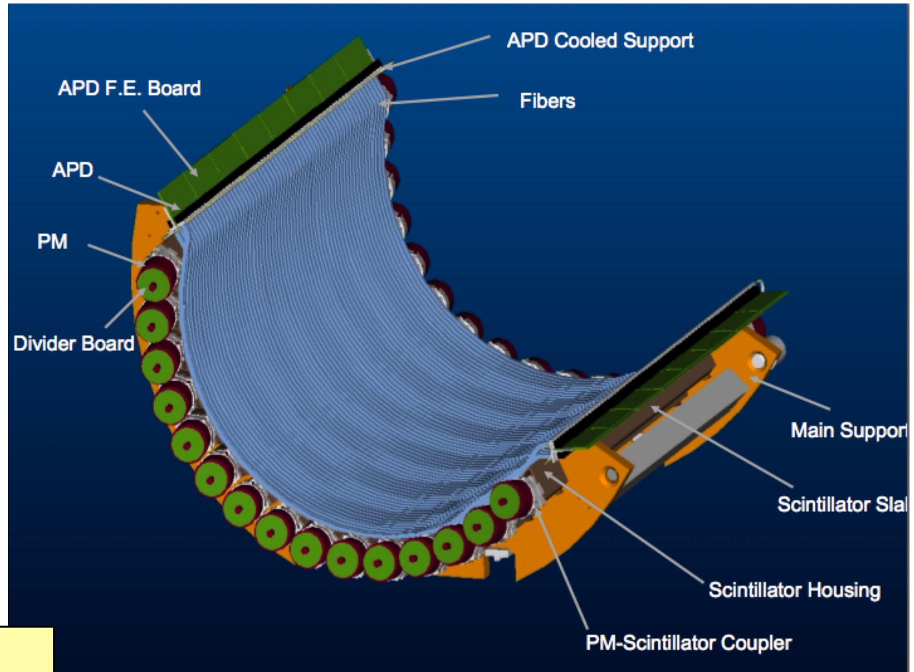
Momentum: 200 keV/c

Direction: 4.5 mrad

The Timing Counter

- 2 detectors (upstream & downstream) for precise positron timing and trigger;
- 15 plastic scintillating bars per detector read by PMTs:
  - timing
  - phi position
  - trigger
- 1 layer of scintillating fibers per detector, read by APDs:
  - z position
  - trigger

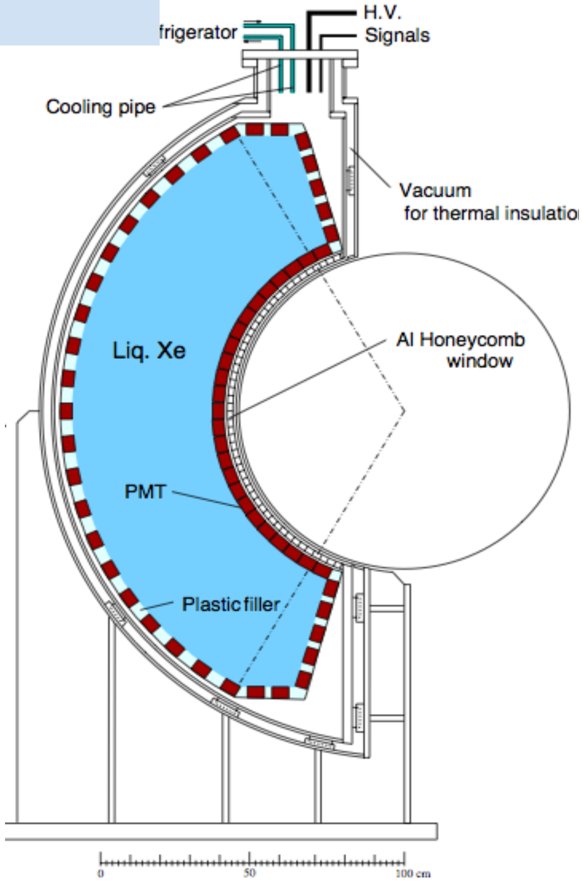




Design ResolutionTime: 45 ps

The LXe Calorimeter

- The largest LXe calorimeter in the world:
  - 800 liters;
- Fast response:
  - t = 4ns / 22ns / 45ns;
- Good light yield:
  - ~ 75% of NaI(Tl);
- Light collected by 846 PMTs.



Hamamatsu
R9288

Design RESOLUTIONS
Energy: 800 keV
Conversion Point: 2 - 4 mm
Time: 65 ps

Calibrations

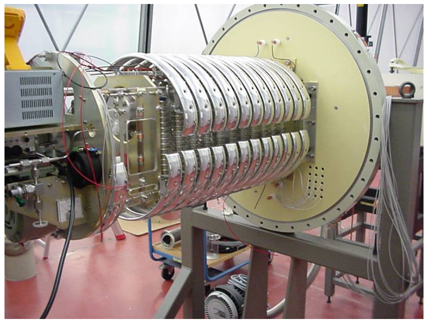
Charge Exchange (CEX)

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

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

high energy photons for XeC energy & relative time calibrations

Cockcroft-Walton accelerator



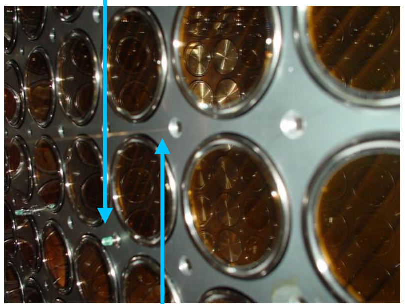
Protons on a Lithium Tetra-borate target

low-energy photons for XeC energy & relative time calibration

LED

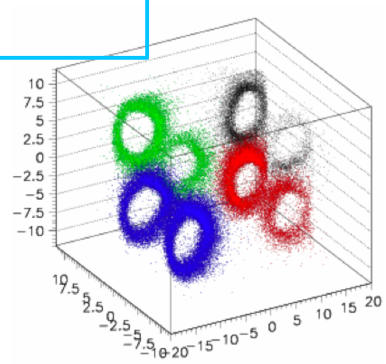
Installed inside the XeC

PMT gain calibration



a sources

Installed in wires inside the XeC



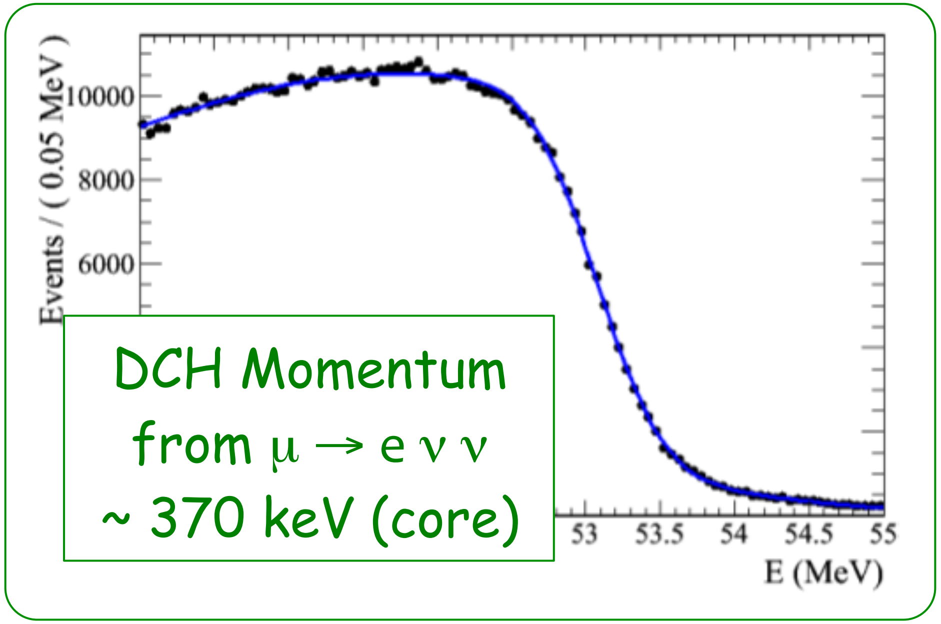
Calibration of Q.E., attenuation length, position

Resolutions (I)

CONTINUOUS IMPROVEMENTS

	2008	2009 (prelim.)
Gamma Energy	2% (core)	2% (core)
Gamma Timing	80 ps	> 67 ps
Gamma Position	5 / 6 mm	5 / 6 mm
e+ Momentum	1.6 %	0.74% (core)
e+ Timing	< 125 ps	< 95 ps
e+ Angle	10 / 18 mrad	7 / 11 mrad
m Decay Point	3.2 / 4.5 mm	2.3 / 2.8 mm
Gamma-e+ Time	148 ps	142 ps (core)
Gamma-e+ Angle	14 / 21 mrad	13 / 15 mrad

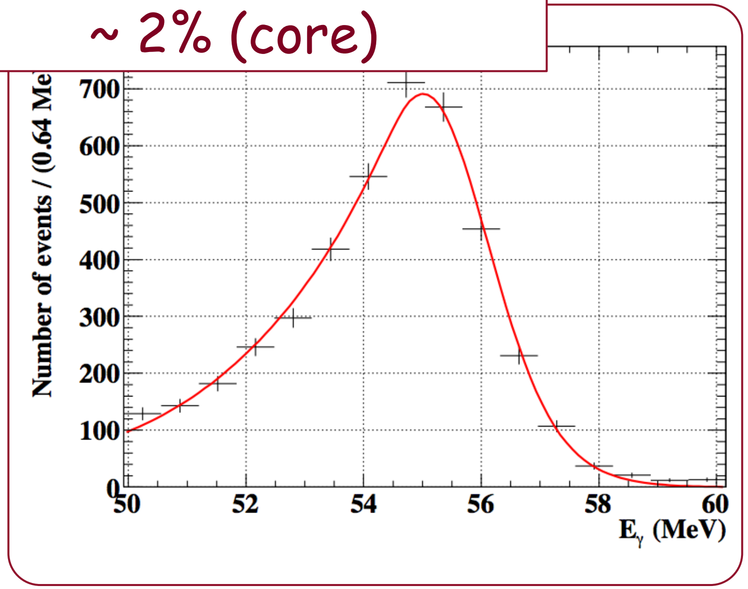
Resolutions (II)

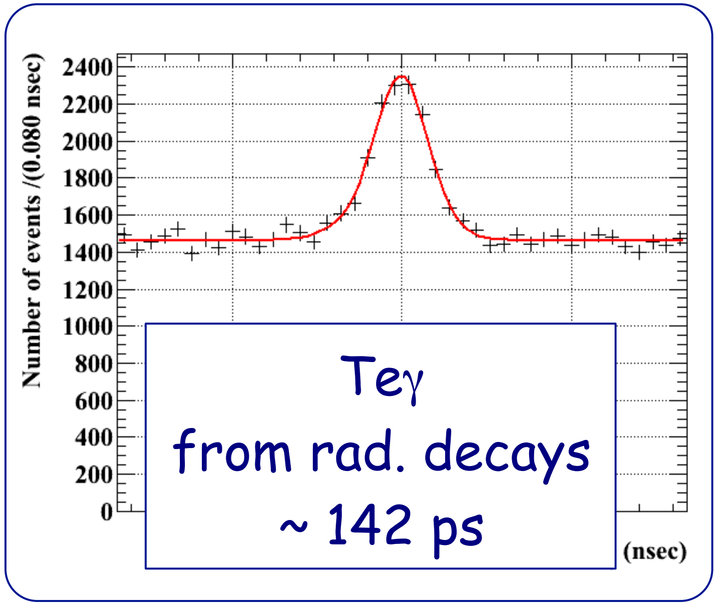


DCH Momentum
from $\mu \rightarrow e \nu \nu$
~ 370 keV (core)

From 2009 data

LXeCAL Energy
From charge exchange
~ 2% (core)



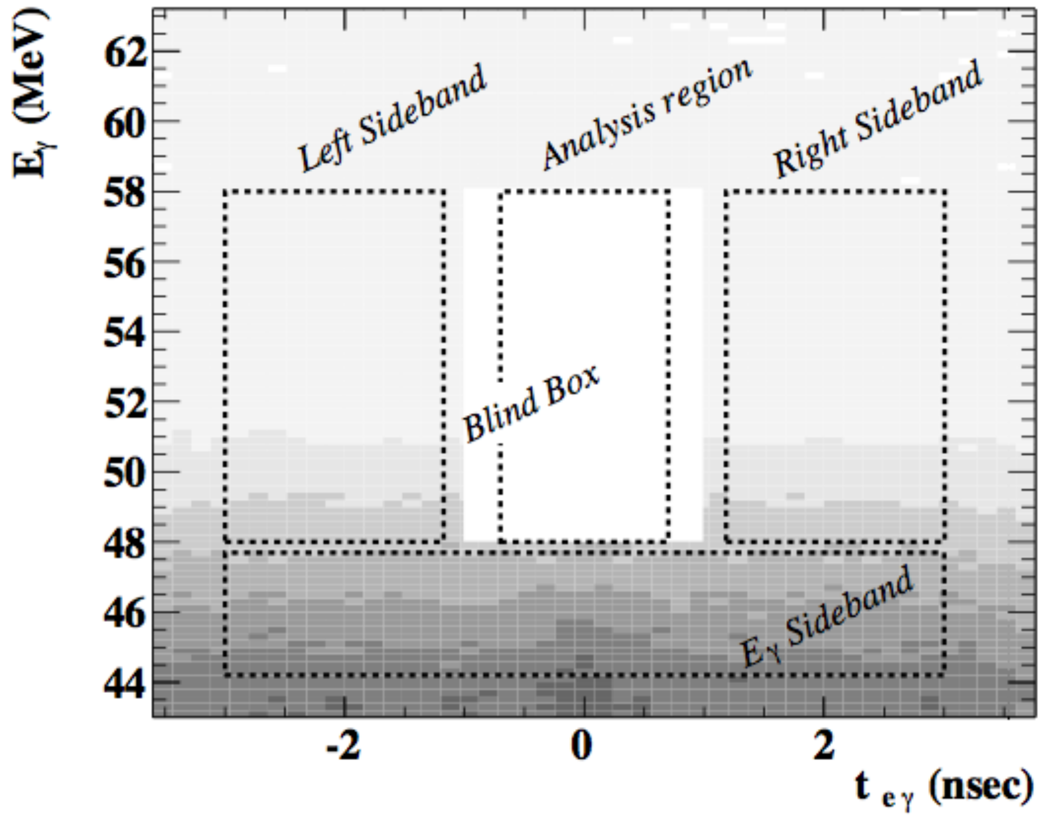


Teγ
from rad. decays
~ 142 ps

Analysis of 2009 Data

- Data Set-> 46 days of data taking   6.5 x 10^{13} stopped μ.

- *Blind analysis* :
  - development and optimizations based on sideband data;
- *Extended Maximum Likelihood* fit in 5 observables:
  - E_e, E_g, T_{eg}, y_{eg}, f_{eg}
- *Normalization* by counting the number of $\mu \to e\,\nu\,\nu$ decays.
  - Systematics cancel



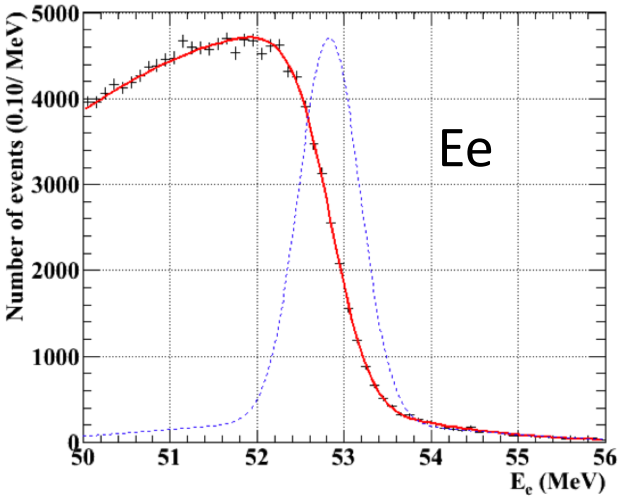
$$\frac{\mathcal{B}(\mu^+ \to e^+\gamma)}{\mathcal{B}(\mu^+ \to e^+\nu\bar{\nu})} =$$

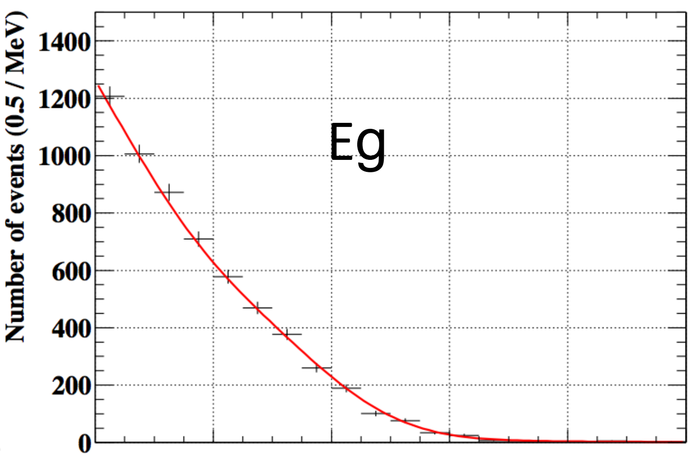
$$\frac{N_{\rm sig}}{N_{e\nu\bar{\nu}}} \times \frac{f^e_{e\nu\bar{\nu}}}{P \cdot \epsilon_{\rm pu}} \times \frac{\epsilon^{\rm trig}_{e\nu\bar{\nu}}}{\epsilon^{\rm trig}_{e\gamma}} \times \frac{\epsilon^{\rm DC}_{e\nu\bar{\nu}}}{\epsilon^{\rm DC}_{e\gamma}} \times \frac{1}{A^{\rm geo}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}} =$$

$$N_{\rm sig} \times (1.01 \pm 0.08) \times 10^{-12}.$$

Likelihood Analysis (I)

- Event-by-event PDFs:
  - Position dependence in the LXe;
  - two track quality categories;
- PDFs Modeled from sidebands and calibrations;
- Careful check for possible correlations;
- 3 different analysis frameworks for cross-checks.

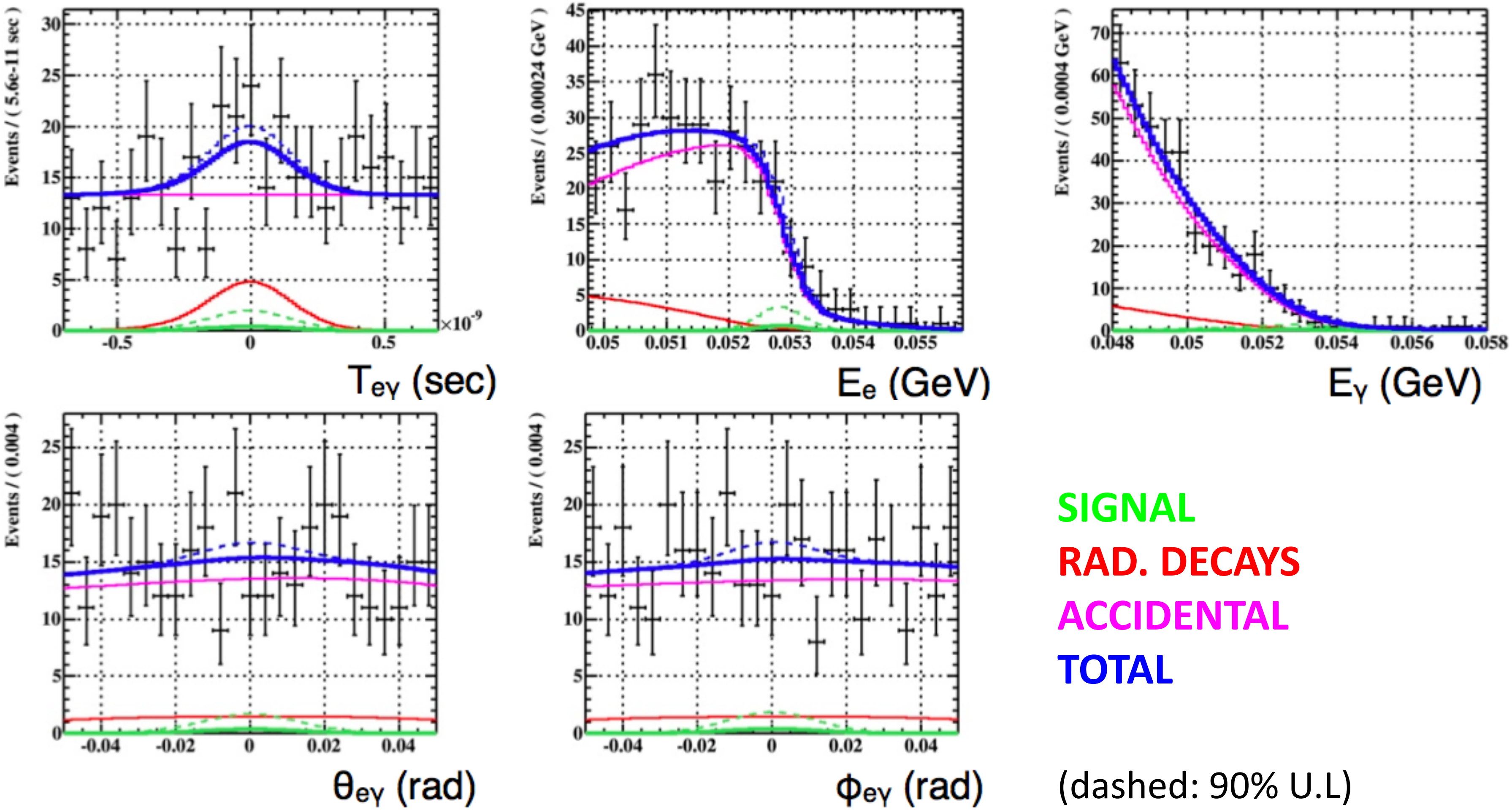




EXPECTED UL (from toy MC experiments) ~ 6.1×10^{-12}

Likelihood Analysis (II)

PRELIMINARY



(dashed: 90% U.L)

Best fit:

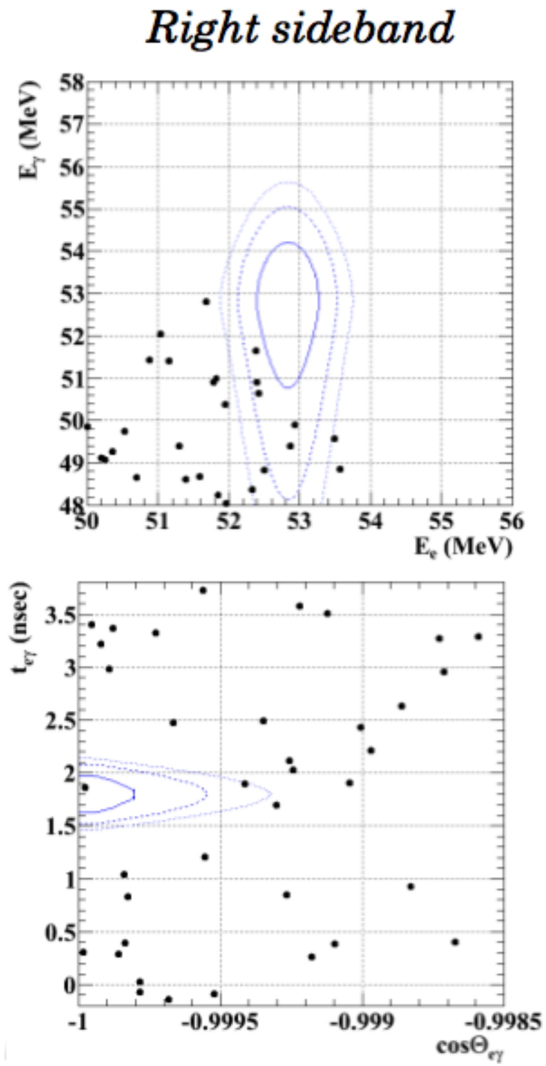
$N_S = 3.0$, $N_{RD} = 35^{+24}_{-22}$ (expected $N_{RD} = 32 \pm 2$)

$N_S < 14.5$ @ 90% C.L. (Feldman-Cousins)

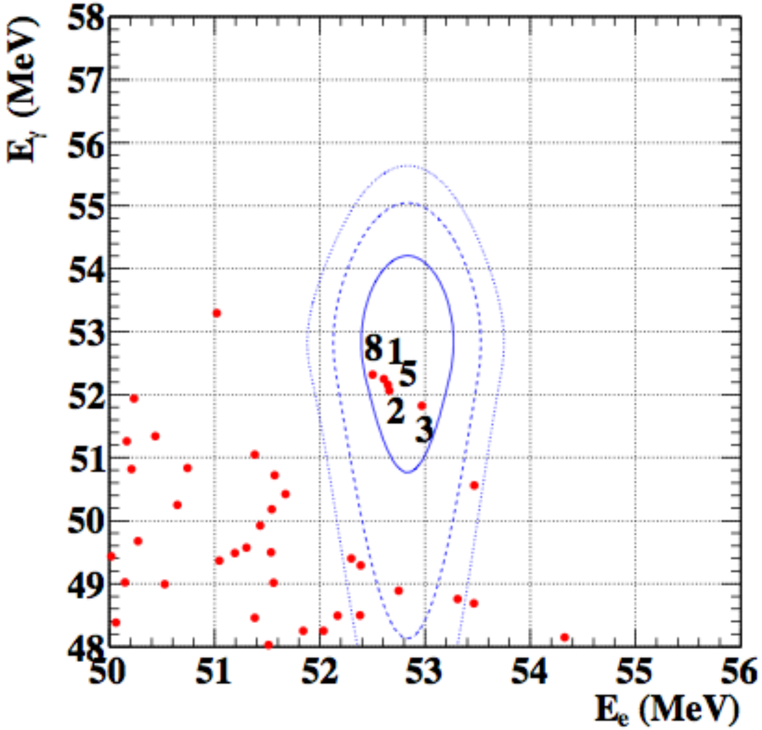
Control Samples

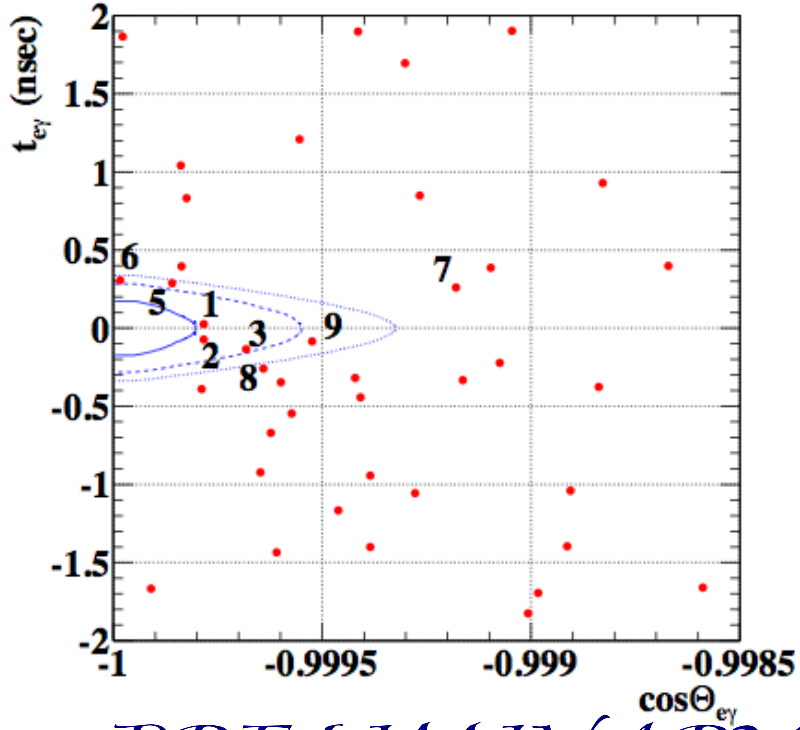
- The strategy is applied to the *Teγ sidebands* to check the consistency of the data description;
- Only accidental background is present:
  - both Signal and Rad. Decays should give zero yield;

Results are consistent with N_S = N_{RD} = 0 and with Toy MC expectations (fictitious ULs of $4 - 6 \times 10^{-12}$ are obtained)



Signal Region





PRELIMINARY

Contours are 2D signal PDF for 1s (39.3 %), 1.64s (74.2%) and 2s (86.5%) regions.
The numbered events are ranked according to the S/B likelihood ratio.

Systematics

- *Parameters are fluctuated* in the toy MC generation to include the systematics in the Feldman-Cousins procedure;.
- Large uncertainty on the angular PDFs due to reconstruction biases

PARAMETER	UNCERTAINTY
Normalization	8%
Eγ scale	0.4%
Eγ resolution	7%
Ee scale	50 keV
Ee resolution	15%
Teγ mean	15 ps
Teγ resolution	10%
Angle mean	7.5 mrad
Angle resolution	10%
Ee-ϕ correlation	50%

PRELIMINARY

Upper Limit

- From the U.L. on the number of signal events:
  - $N_S < 14.5$ @ 90% C.L.
- ... and the normalization factor:
  - $BR(\mu \rightarrow e\,\gamma) = N_S \times (1.01 \pm 0.08) \times 10^{-12}$
- ... we get the following U.L. on the Branching Ratio (syst. included):

PRELIMINARY

$$BR(\mu \rightarrow e\,\gamma) < 1.5 \times 10^{-11} \text{ @ 90\% C.L}$$

  - Looks different from estimated sensitivity
- No lower limit:
  - BR = 0 is within the 90% C.L. interval.

Next Steps

- MEG is taking data now (since August)
  - 2010 yield is x 3 2009 sample (stay tuned!)
  - Will help in understanding the preliminary results
- Meanwhile
  - Additional calibration tools
    - Monochromatic e+ beam for the spectrometer
    - 9 MeV γ-line induced by neutron generator in the LXe
- The MEG data taking will continue in 2011 and 2012
  - To reach an UL in the 10^{-13} range or
  - To make a great discovery!

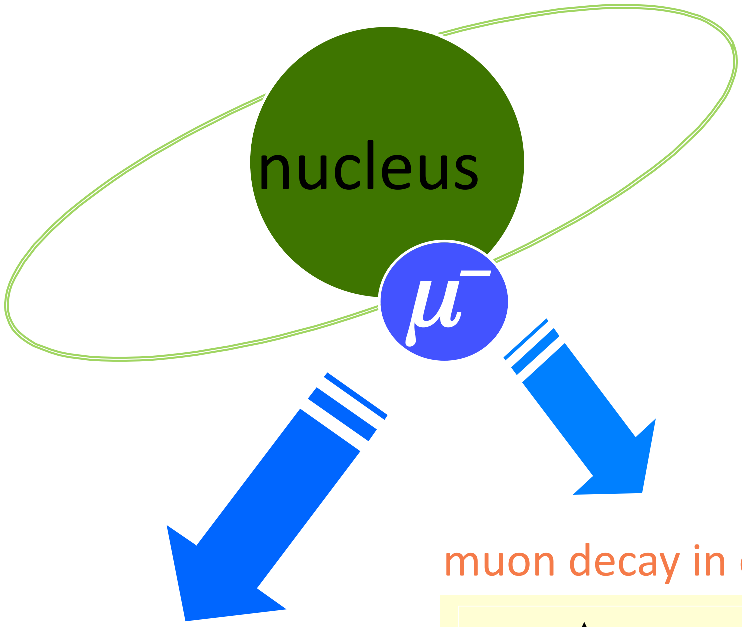
If they are roses…they will blossom

but if they are not and in any case there is an alternative…

What is μ-e Conversion ?

Y.Kuno WG4 Oct 21

1s state in a muonic atom



muon decay in orbit

$$\mu^- \lozenge \ e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \lozenge \ \nu_\mu + (A,Z-1)$$

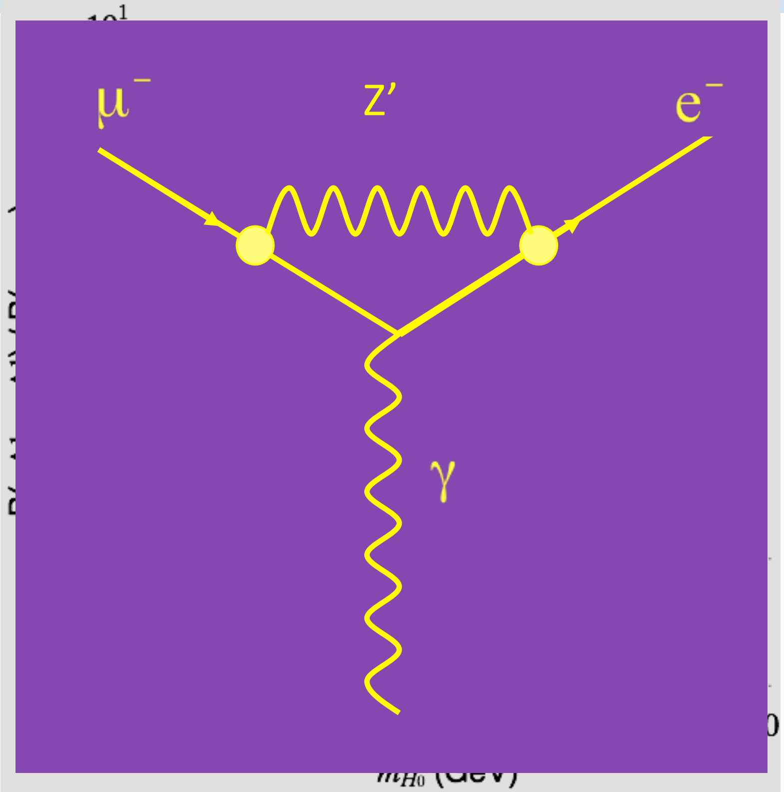
Neutrino-less muon nuclear capture (=μ-e conversion)

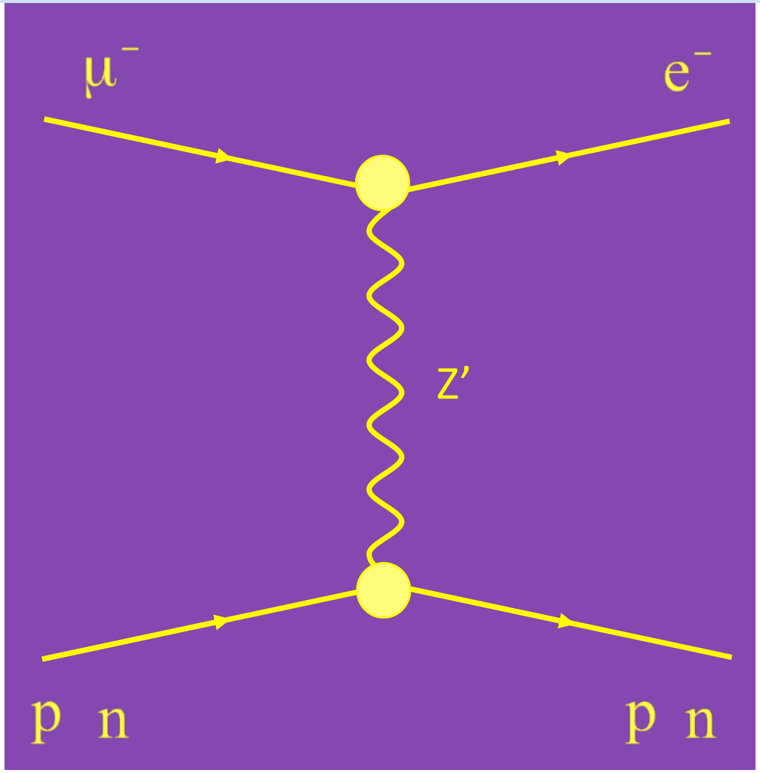
$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

lepton flavors changes by one unit

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

μ→eγ and μ-e conversion



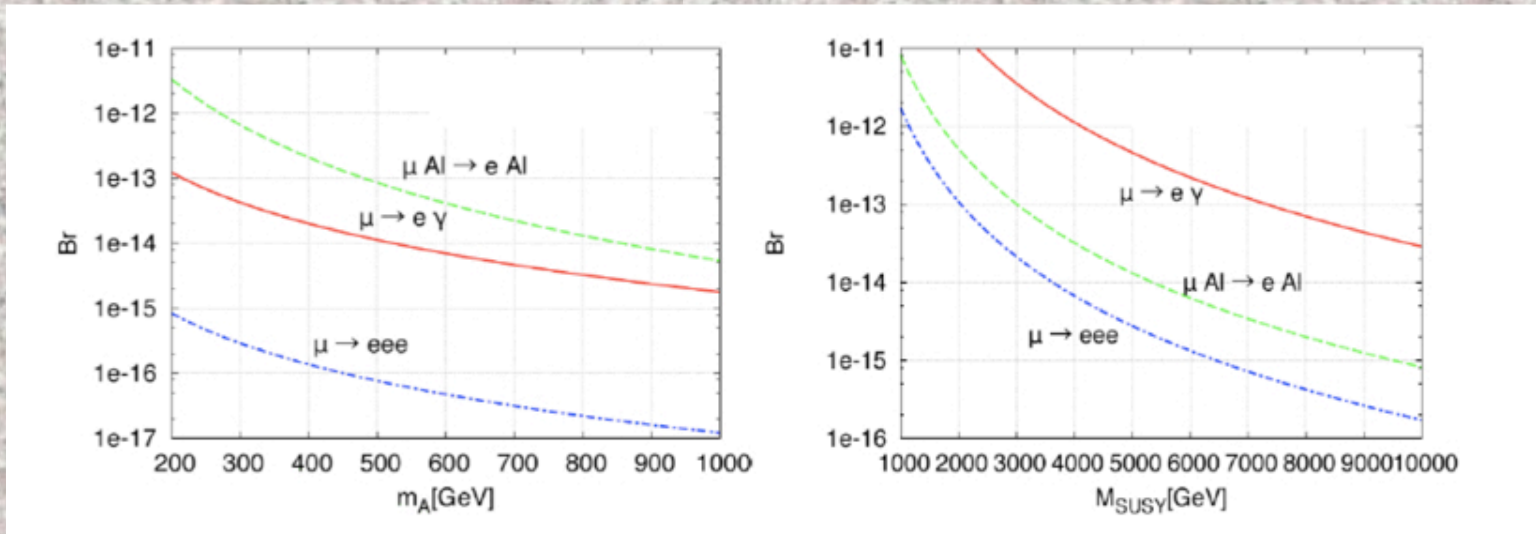


- If μ→eγ exits, μ-e conv must be
- Even if μ→eγ is not observed, μ-e conv may be
  - Loop vs Tree
  - Searches at LHC

$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$

μ→eγ and μ-e conversion

- Higgs exchange vs SUSY 1-loop



- Hisano et al. '10

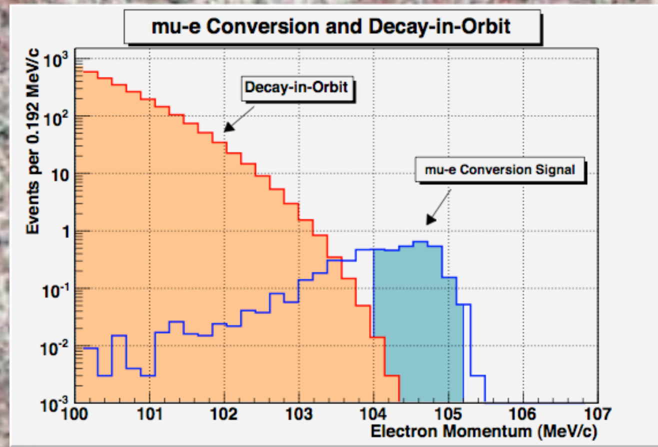
- Important to measure both μ→eγ and μ-e with similar sensitivity

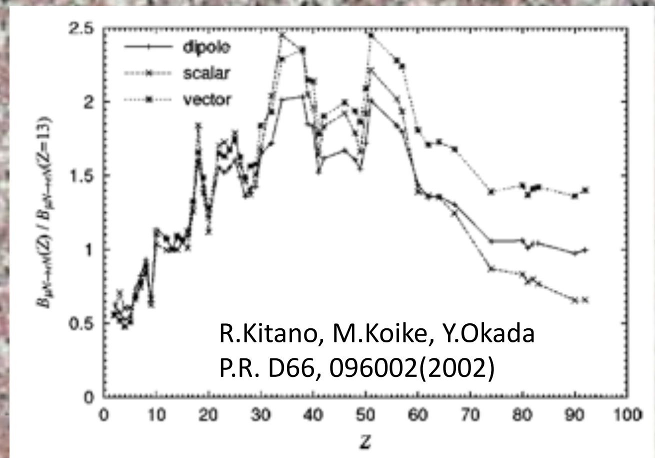
μ-e conversion signal

- $E_{\mu e} \sim m_\mu - B_\mu$
  - B_μ: binding energy of the 1s muonic atom

- Improvement of a muon beam is possible, both in purity (no pions) and in intensity (***thanks to muon collider R&D***). A higher beam intensity can be taken because of no accidentals.

- Potential to discriminate different models through studying the Z dependence



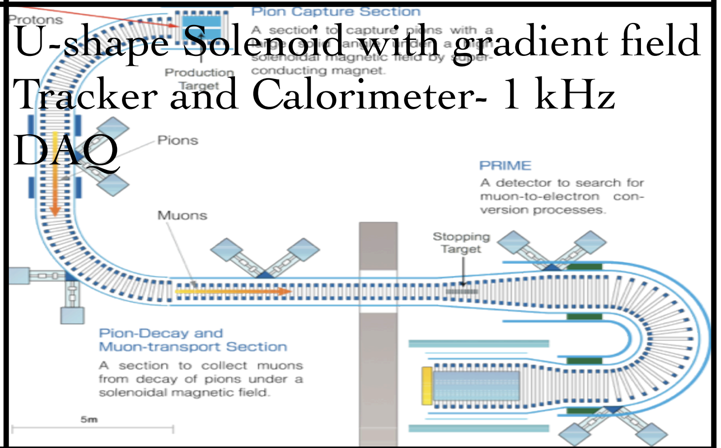


R.Kitano, M.Koike, Y.Okada
P.R. D66, 096002(2002)

History of μ-e conversion search

Year	Muon source	Target	Upper bound
1952	Cosmic rays	Cu, Sn	4×10^{-2}
1955	Nevis cycl.	Cu	5×10^{-4}
1961	Berkeley synchroc.	Cu	4×10^{-6}
1961-62	CERN synchroc.	Cu	2.2×10^{-7}
1972	Virginia SREL synchroc.	Cu	1.6×10^{-8}
1977	SIN	S	7×10^{-11}
1984	TRIUMF	Pb Ti	4.9×10^{-10} 4.6×10^{-12}
1992	PSI	Pb	4.6×10^{-11}
1993-97	(only in conference proc.)	Ti	6.1×10^{-13}
2006		Au	7×10^{-13}

Mu2e (Fermilab) vs COMET(J-Parc)

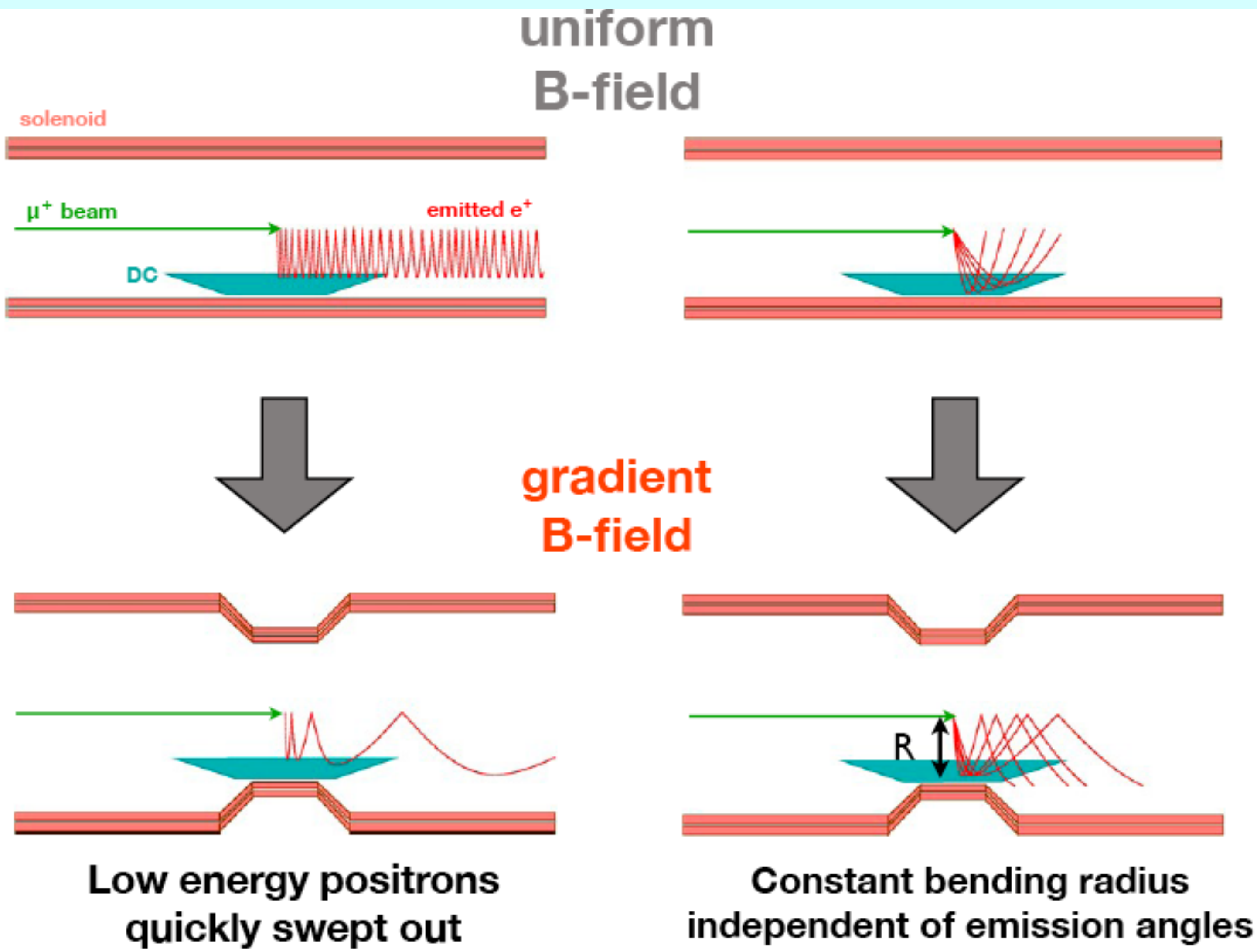
<table>
<tr><th></th><th>Mu2e</th><th>COMET</th></tr>
<tr><td>Proton Beam</td><td>8GeV, 20kW
bunch-bunch spacing 1.69 μsec
rebunching
Extinction: 10^{-9}</td><td>8GeV, 50kW
bunch-bunch spacing 1.18-1.76 μsec
empty buckets
Extinction: 10^{-9}</td></tr>
<tr><td>Mu Transport</td><td>S-shape Solenoid</td><td>U-shape solenoid</td></tr>
<tr><td>Detector</td><td>Straight Solenoid with gradient field
Tracker and Calorimeter – 500 kHz
DAQ
</td><td>U-shape Solenoid with gradient field
Tracker and Calorimeter- 1 kHz
DAQ

</td></tr>
<tr><td>Sensitivity
Approval status</td><td>SES: 2.5×10^{-17}
90% CL UL: 6×10^{-17}
CD-0 (of 4)</td><td>SES: 2.6×10^{-17}
90% CL UL: 6×10^{-17}
Stage 1 (of 2)</td></tr>
</table>

Conclusions

- Muon played an important role to establish the SM
- We believe that could be same in going beyond the SM
- Thanks to the intense muon beam described in this conference
- very well designed and conducted. Many thanks to the Organizers!

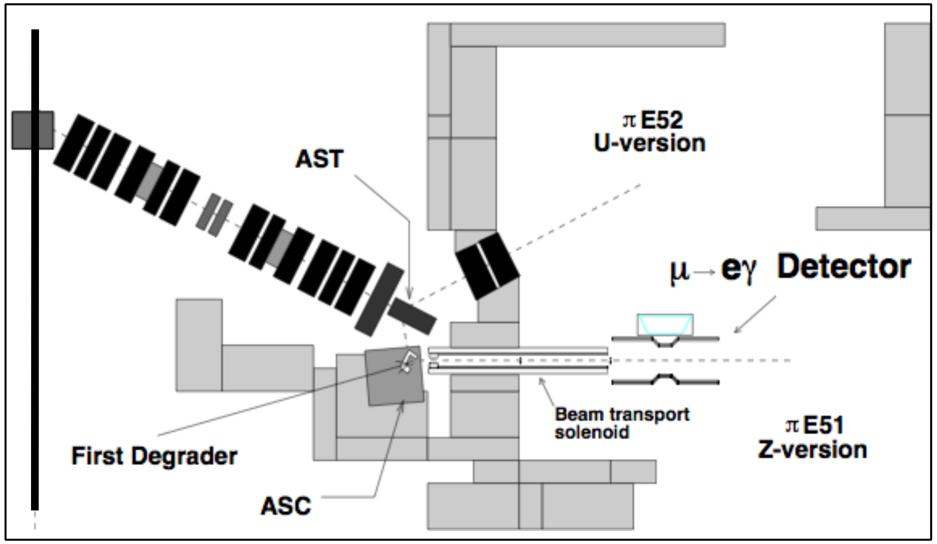
More slides

The Advantage of COBRA



The πE5 Beam @ PSI

- The most intense DC muon beam in the world:
  - up to 10^8 μ/s;
  - only 3 x 10^7 μ/s for the MEG running (reduced accidental rate);



Proton beam current	:	~ 2.2 mA
Muon production	:	from π decaying in target proton surface
Muon Momentum	:	28 MeV/c ± 3%

Data Sets

- 2008:
  - ... days of data taking
  - ~ ... stopped muons;
  - Sensitivity ~ 1.3×10^{-11} ;
  - BR(m → e g) < 2.8×10^{-11} *Nucl. Phys. B* ***834*** *(2010) 1*
- 2009:
  - Significant hardware upgrades (DCH, electronics);
  - 46 days of data taking;
  - ~ 6.5×10^{13} stopped muons.

Efficiencies

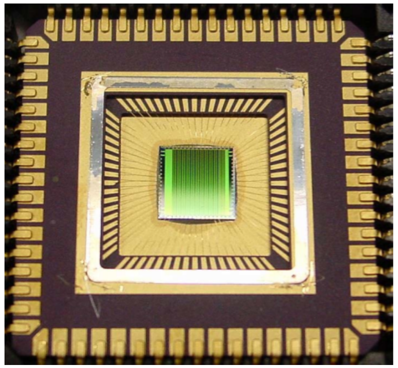
EFFICIENCIES

CONTRIBUTION	2008	2009
Gamma	63%	58%
Positron	14%	40%
Trigger	66%	84%
DAQ	62%	81%

DAQ & Trigger

- High accidental background rejection (~ 10^7) with ~100% signal efficiency required at the trigger level:
  - online determination of g energy, e – g timing and e – g collinearity (fully digital implementation);
  - ~ 5 – 10 Hz trigger rate during normal data acquisition;

- Very fast waveform digitalization (0.5 - 4.5 GHz) for offline analysis:
  - custom chip (Domino Ring Sampling, DRS) designed @ PSI;
  - 10 channels x 1024 bins per chip;
  - 40 ps time accuracy at 2.5 GHz.



Proposal for g-2@Fermilab

- Submitted to Fermilab PAC
  - Contact persons: Lee Roberts (Boston U)
    Dave Hertzog (UIUC)
  - Cost Estimate: ~$30 M (w/ contingency)
  - The PAC endorsed the experiment
  - Subject to DOE review in August