Lepton flavour violation experiments with muon beams

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On behalf of the MEG Collaboration

Tau/Charm Conference – 28th May 2013

Outline

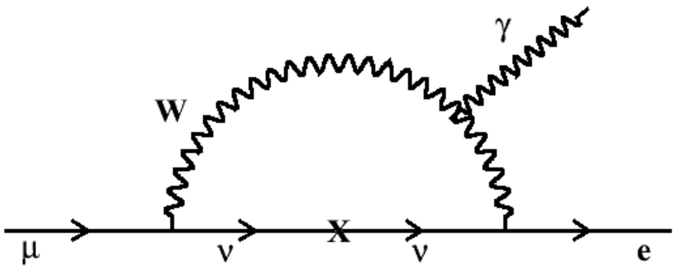
- Introduction to LFV (with muons);
- Why muons ?
- The historical channel: $\mu \longrightarrow e\gamma$
  - **Latest MEG results;**
  - **MEG upgrade.**
- $\mu \longrightarrow eee$: **Sindrum results, Mu3e**
- $\mu \longrightarrow e$ conversion: **Sindrum II, Mu2e, Comet/DeeMe**
- Other processes ($\mu^- A \rightarrow \mu^+ A$, rare K decays ..) not discussed;
- Perspectives with high intensity accelerators;
- Summary and conclusions.

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:



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

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

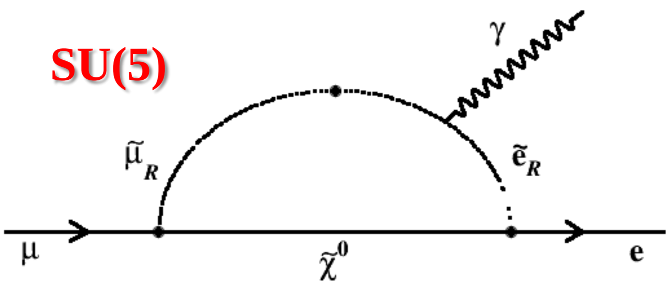
Experimentally not measurable !

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

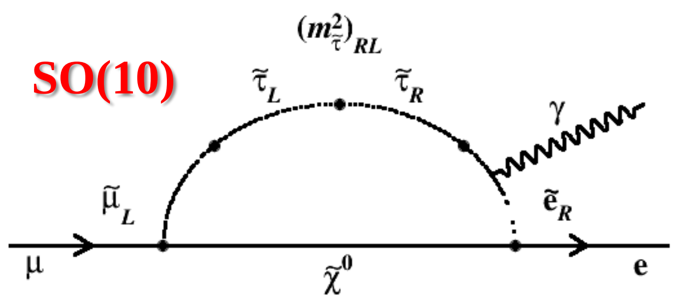
$$\approx 10^{-5}\,\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\bar{m}^2_{\tilde{\ell}}}\left(\frac{100\ \text{GeV}}{m_{\text{SUSY}}}\right)^4 \tan^2\beta$$

≈ 10^{-12}

SU(5)



SO(10)

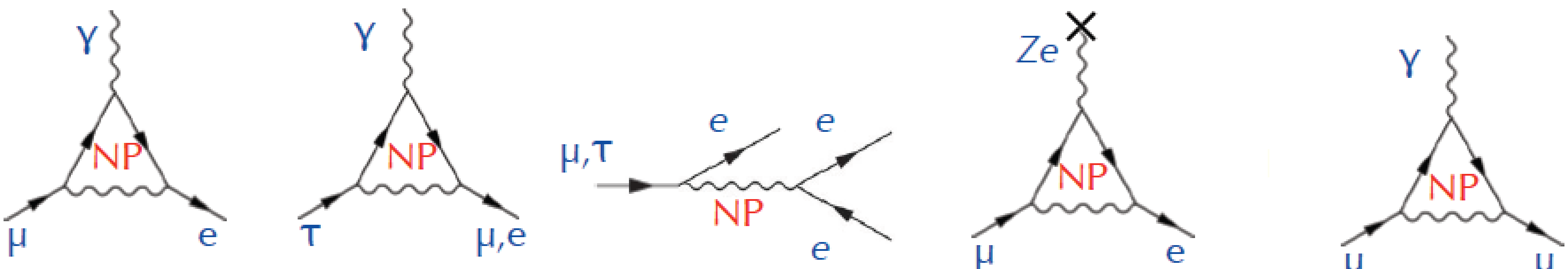


⇒ Observation of cLFV clear evidence for physics beyond SM

LFV 3)

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

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



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

μ, τ anomalous decays

μ → e conversion

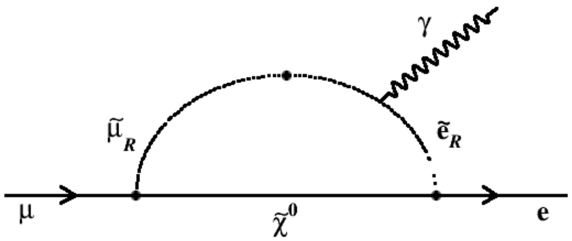
Anomalous magnetic moment

Why muons ?

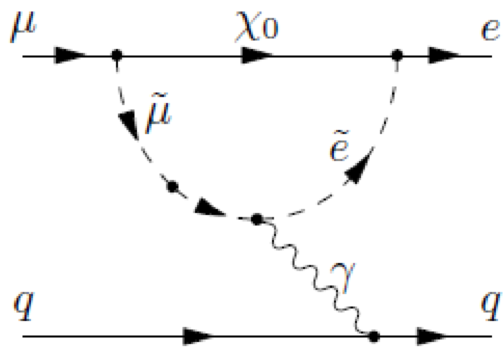
Muons are very sensitive probes to study Lepton Flavour Violation:

- **intense muon beams can be obtained at meson factories and proton accelerators (PSI, LAMPF, J-PARC, Fermilab ...);**
- **muon lifetime is rather long (2.2 μs);**
- **final states are very simple and can be precisely measured.**

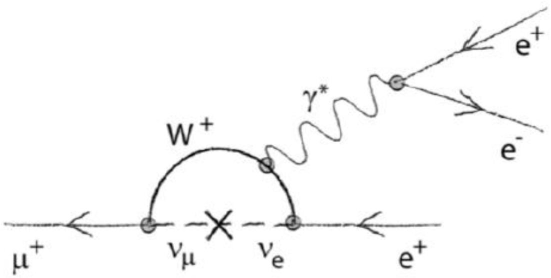
Multiple processes, several diagrams



Dipole μ → eγ

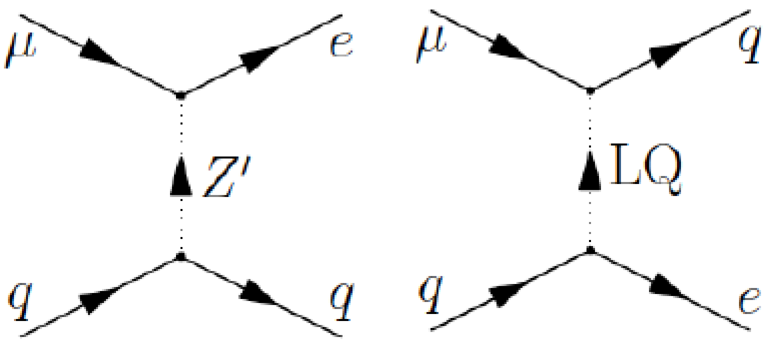


Dipole μ → e conversion

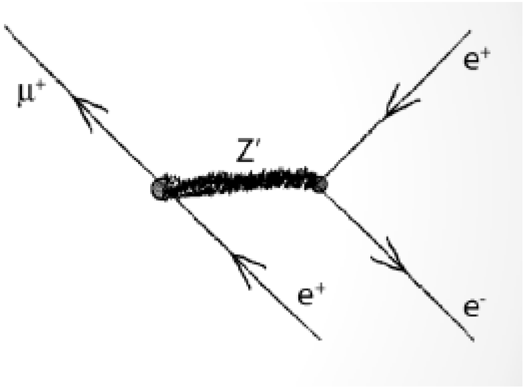


Dipole μ → eee

but also ...



Contact terms, μ → e conversion

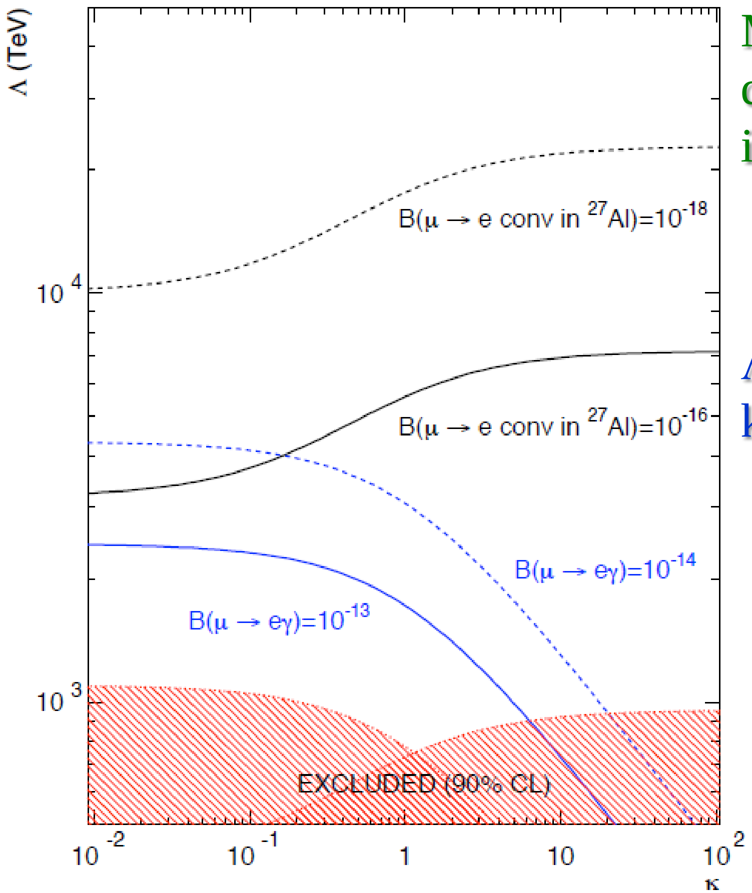


Contact term, μ → eee

And more ...

Sensitivity comparison 1)

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



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

Effective lagrangian

Magnetic dipole interaction

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

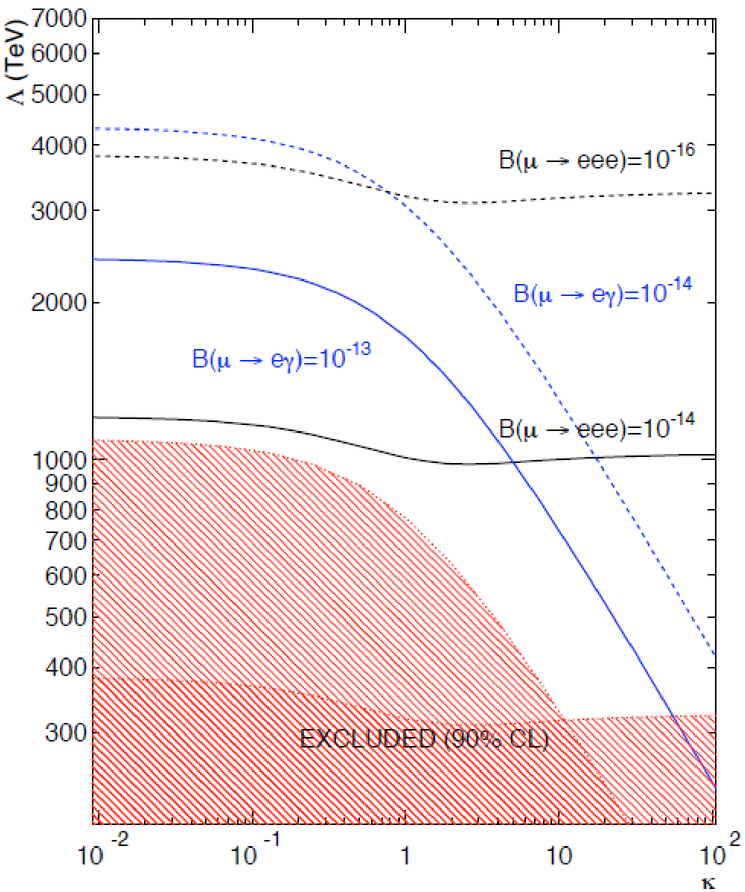
Four quark interaction

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

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

Sensitivity comparison 2)

$\mu \rightarrow e\gamma$ vs $\mu \rightarrow eee$



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Effective lagrangian

Magnetic dipole interaction

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

Four lepton interaction

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

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

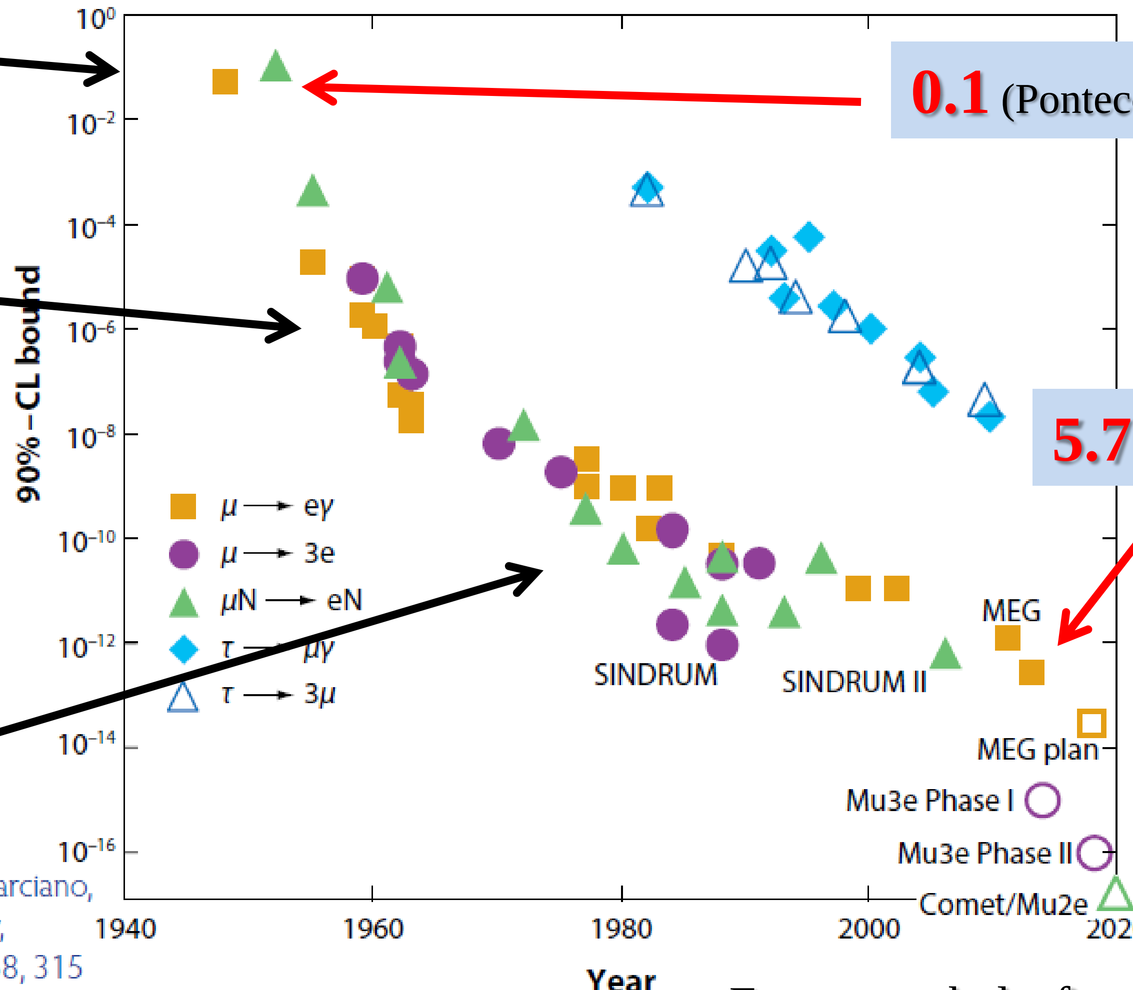
Needed all types of experiments

A 70 year history …

Cosmic μ's

Stopped π's

Muon beams



0.1 (Pontecorvo & Hincks,)

5.7×10^{-13}

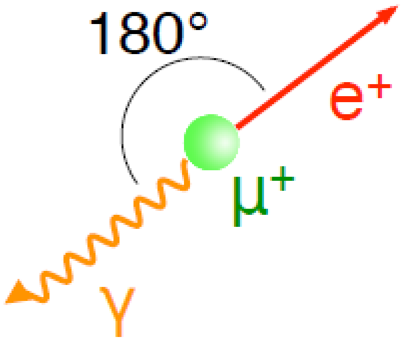
Gained twelve orders of magnitude !

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

Empty symbols: future experiments

The historical channel: $\mu \to e\gamma$

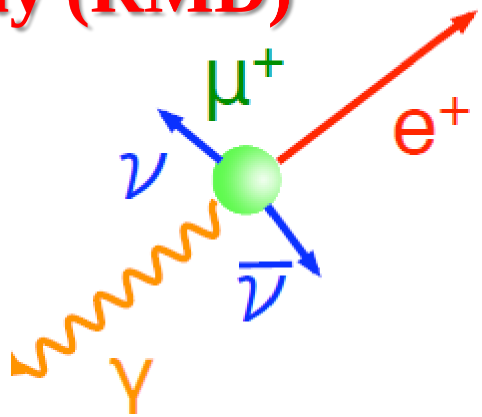
Signal



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

$T_e = T_\gamma$

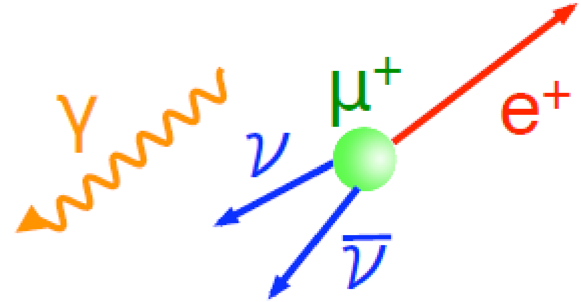
Radiative muon decay (RMD)



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

$T_e = T_\gamma$

Accidental Background (ACC)



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

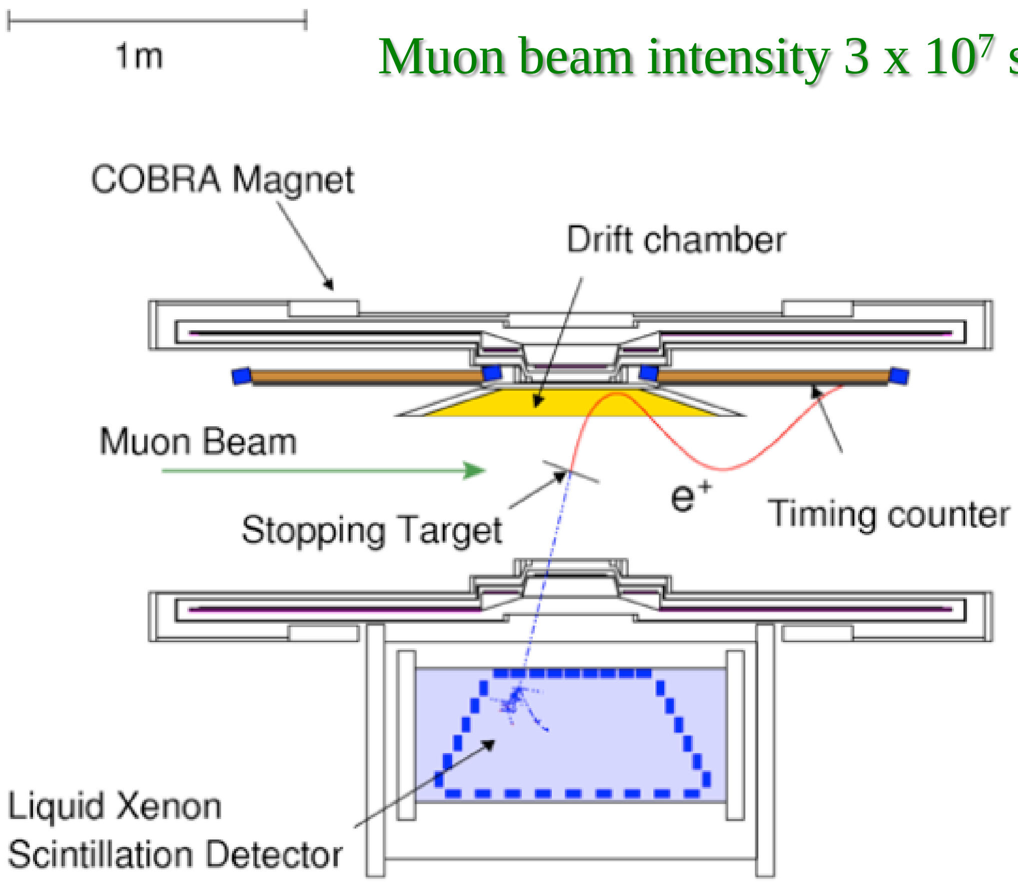
Random ΔT, $\Delta\Theta$, E_e, $E_\gamma < m_\mu/2$

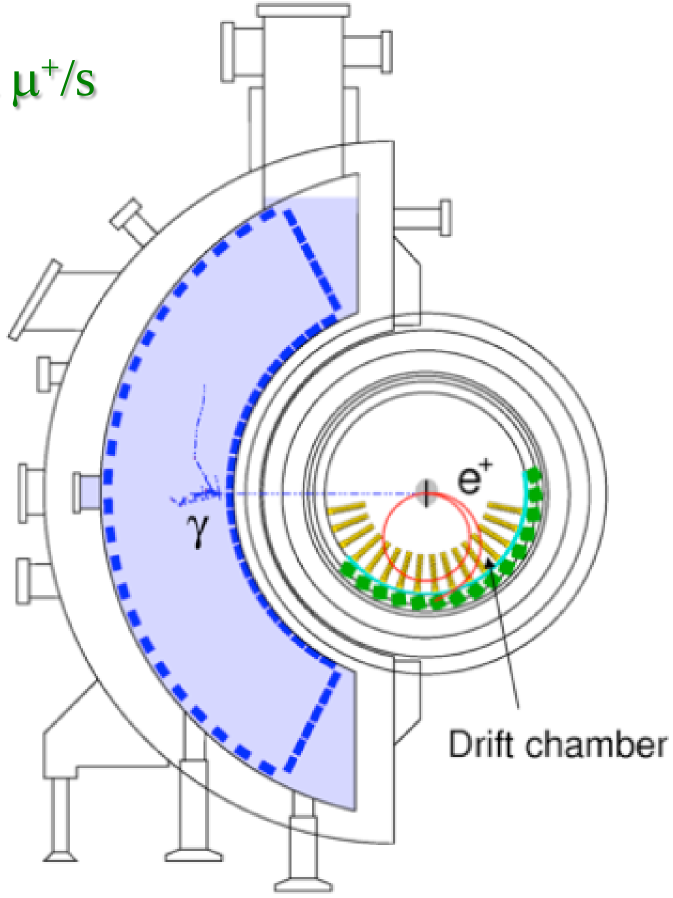
Signal, RMD $\propto R_\mu$, ACC $\propto R_\mu^{\ 2} \Rightarrow$

- **ACC is dominant**;
- needed **continuous beam** and **accurate choice of R_μ**;
- needed **high precision experiments.**

The MEG experiment @PSI

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





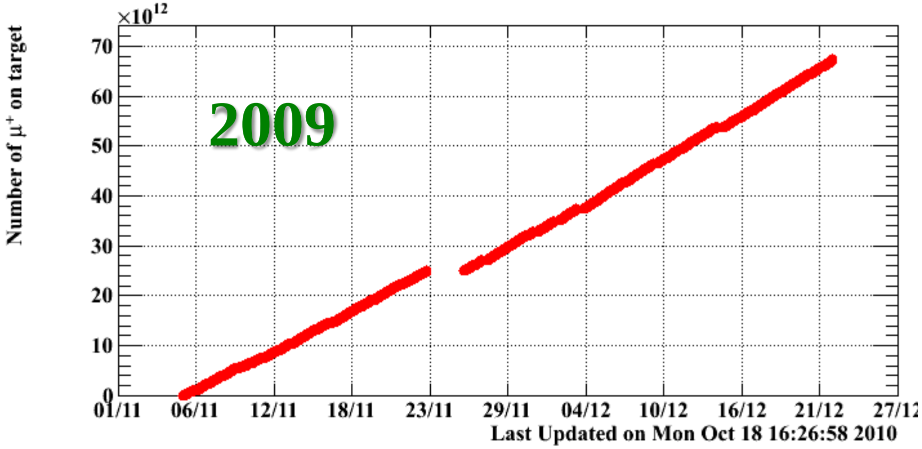
Eur. Phys. J. C **73** (2013) 2365

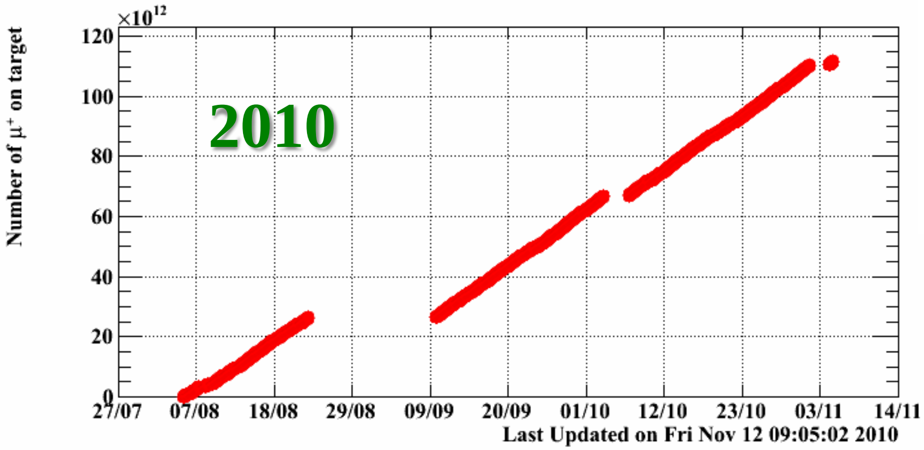
Latest MEG results

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

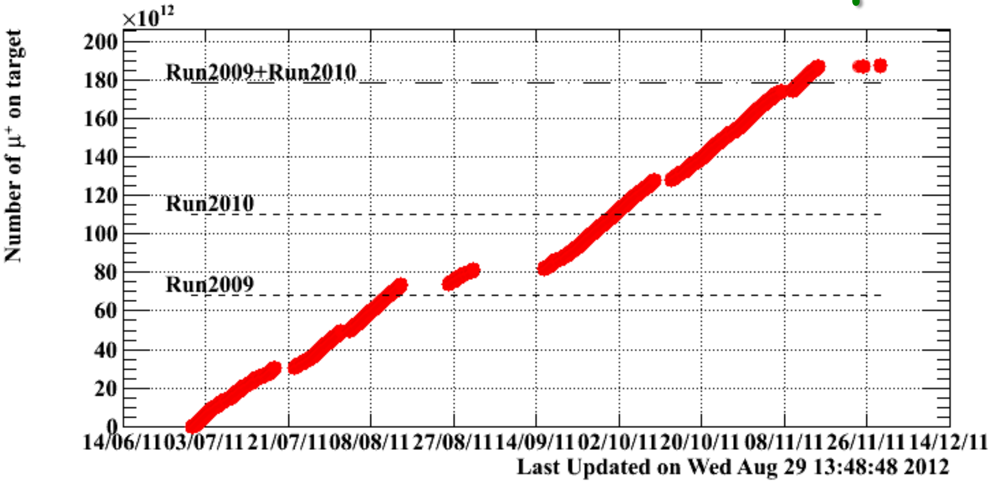
BR ($\mu \rightarrow e\gamma$) < 2.4 x 10^{-12} @90% C.L.

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





Added in 2011: **1.85 x 10^{14} μ^+**



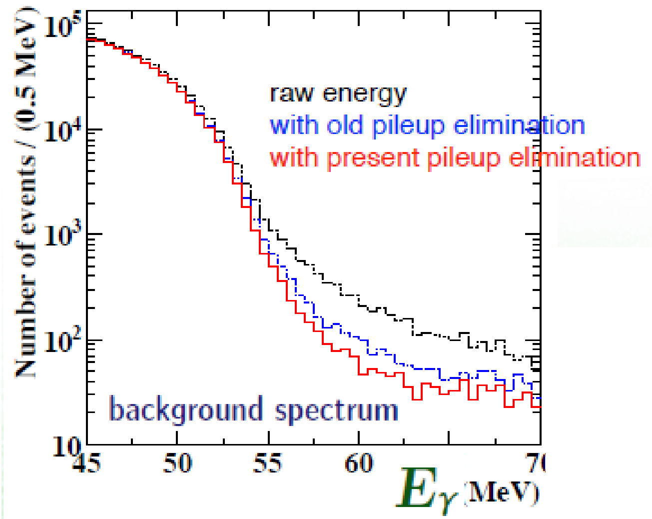
Total data sample: **3.6 x 10^{14} μ^+**

Reconstruction improvements

γ-side:

improved pile-up rejection method:

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



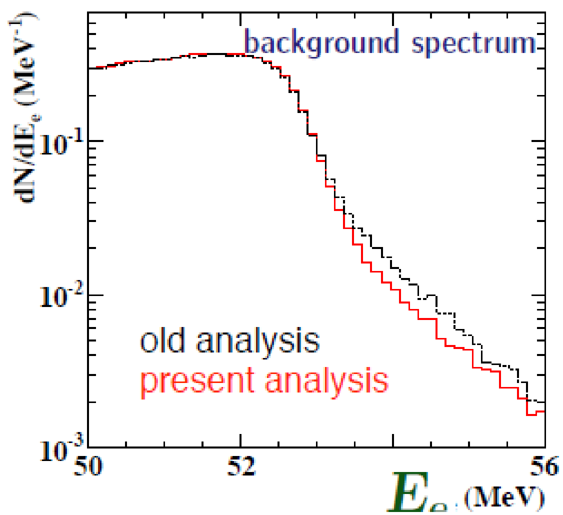
e^+-side:

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

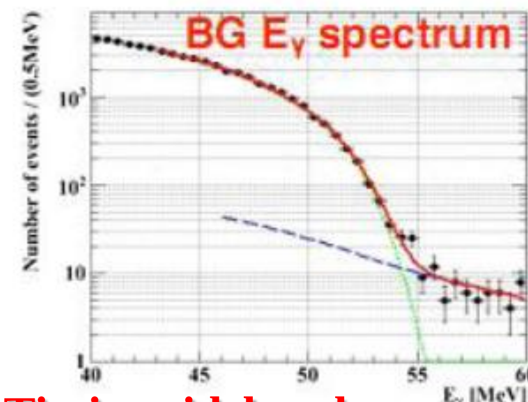


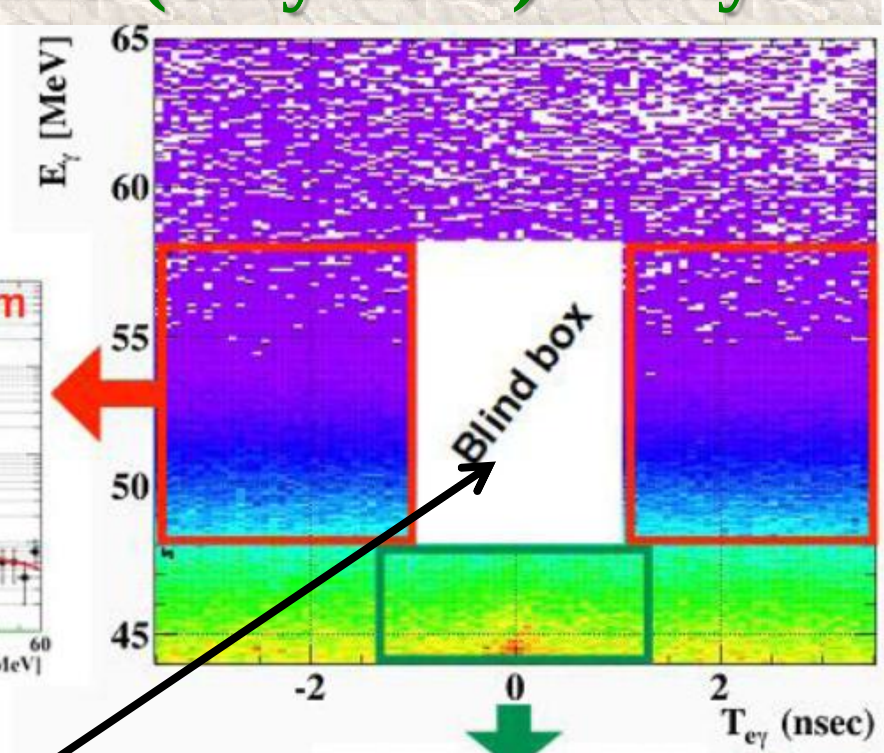
New algorithms applied to: - reanalyze 2009-2010 sample;
- process data collected in 2011

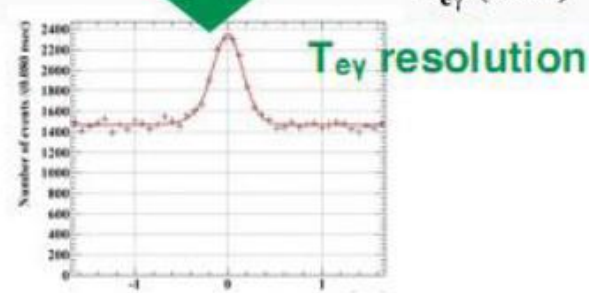
MEG analysis 1)

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 analysis 2)

- **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

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

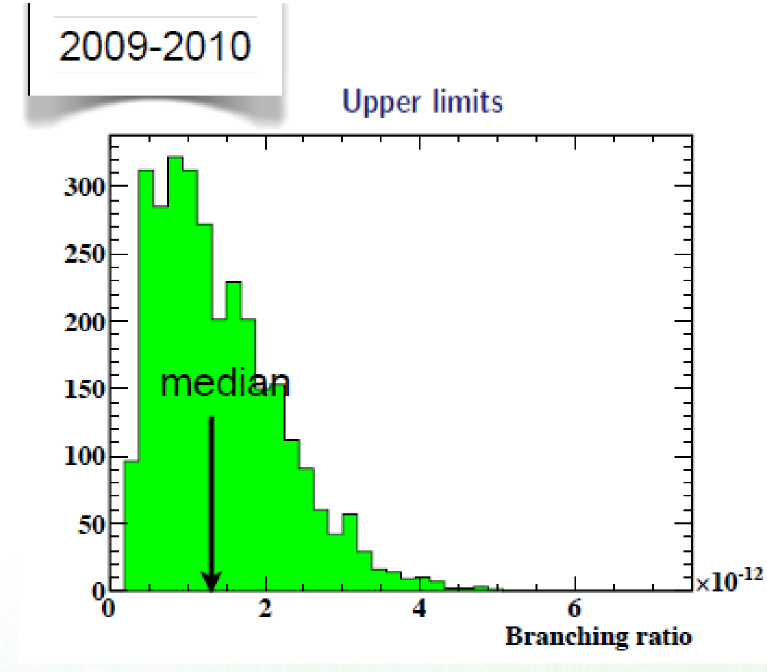
Background rate constraints

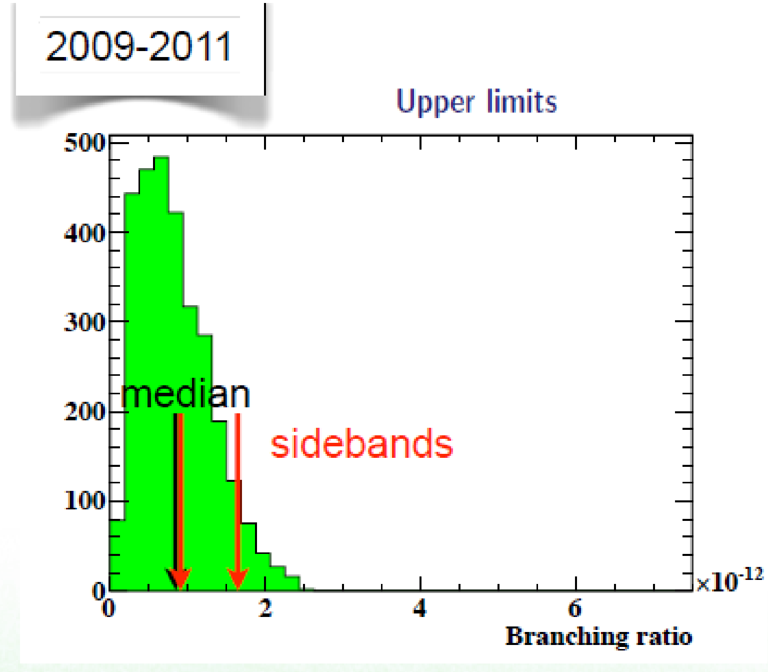
Signal
Radiative Bkg
Accidental Bkg

PDF= Probabilty Distribution Function

Sensitivity

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





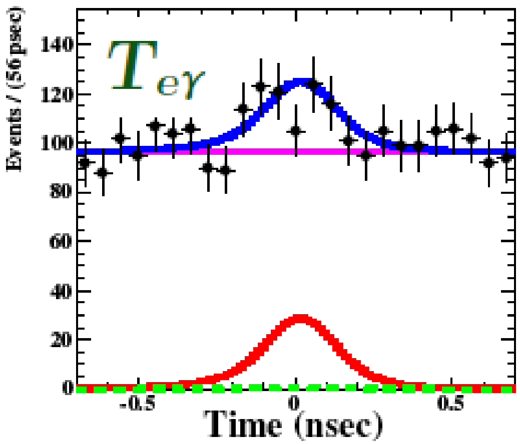
Median (**2009 - 2010**) = **1.30 x 10^{-12}** (1.6 x 10^{-12} in previous analysis, 20% improvement)

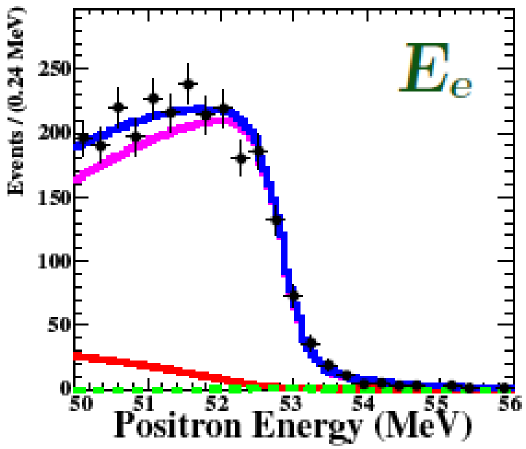
Median (**2009 - 2011**) = **7.7 x 10^{-13}**

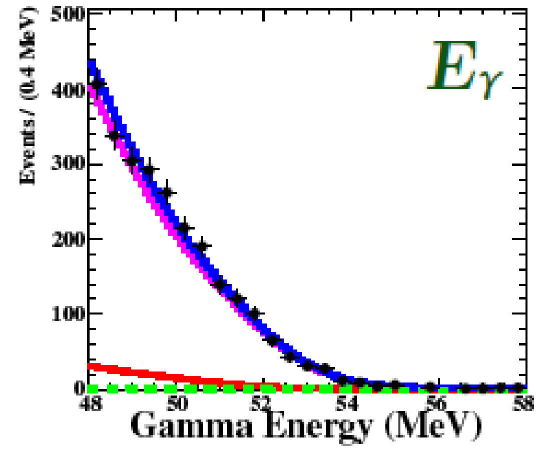
10^{-13} level reached !

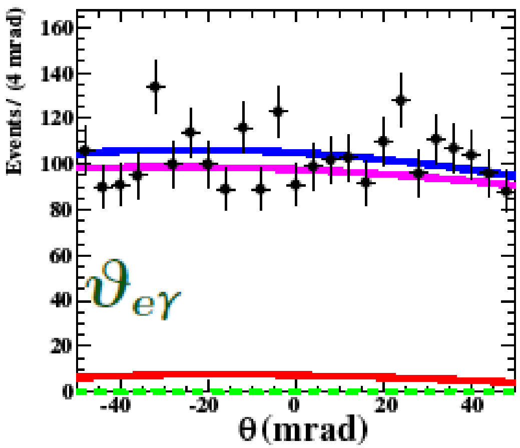
2009 - 2011 likelihood fit

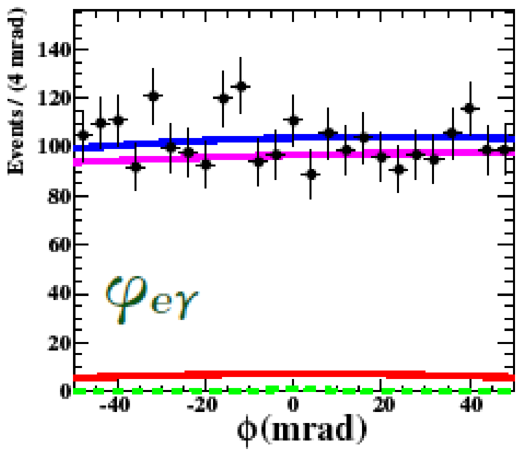
Unbinned maximum likelihood fit on $(E_e, E_\gamma, \Delta T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$











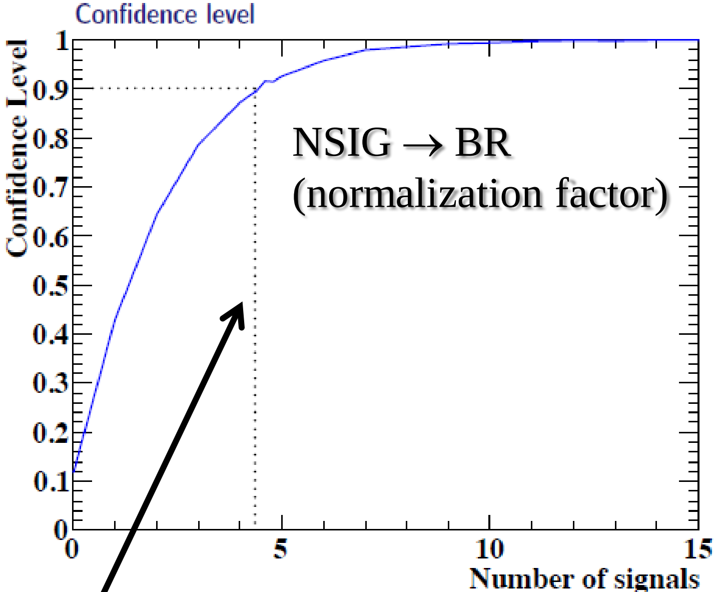
NSIG = -0.4(+4.8 -1.9)
NRMD = 167.5 ± 24
NBCK = 2414 ± 37

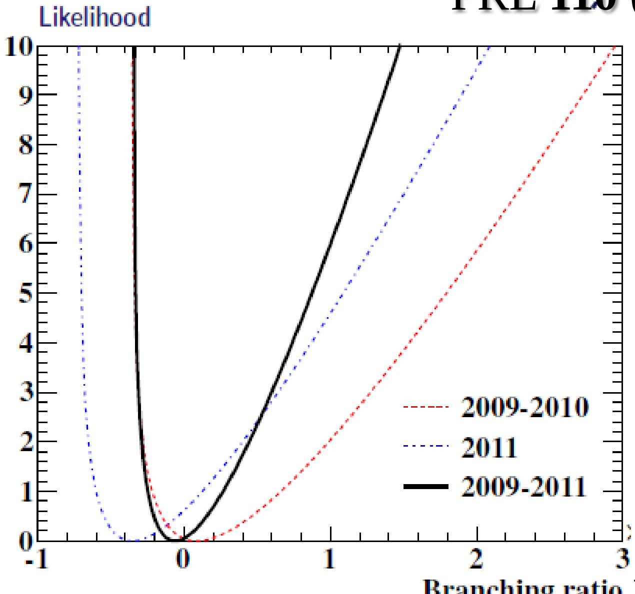
Green: Signal
Red: RMD
Purple: BCK
Blue: Total
Black: Data

Confidence level

Frequentistic analysis, Feldman-Cousins method

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





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

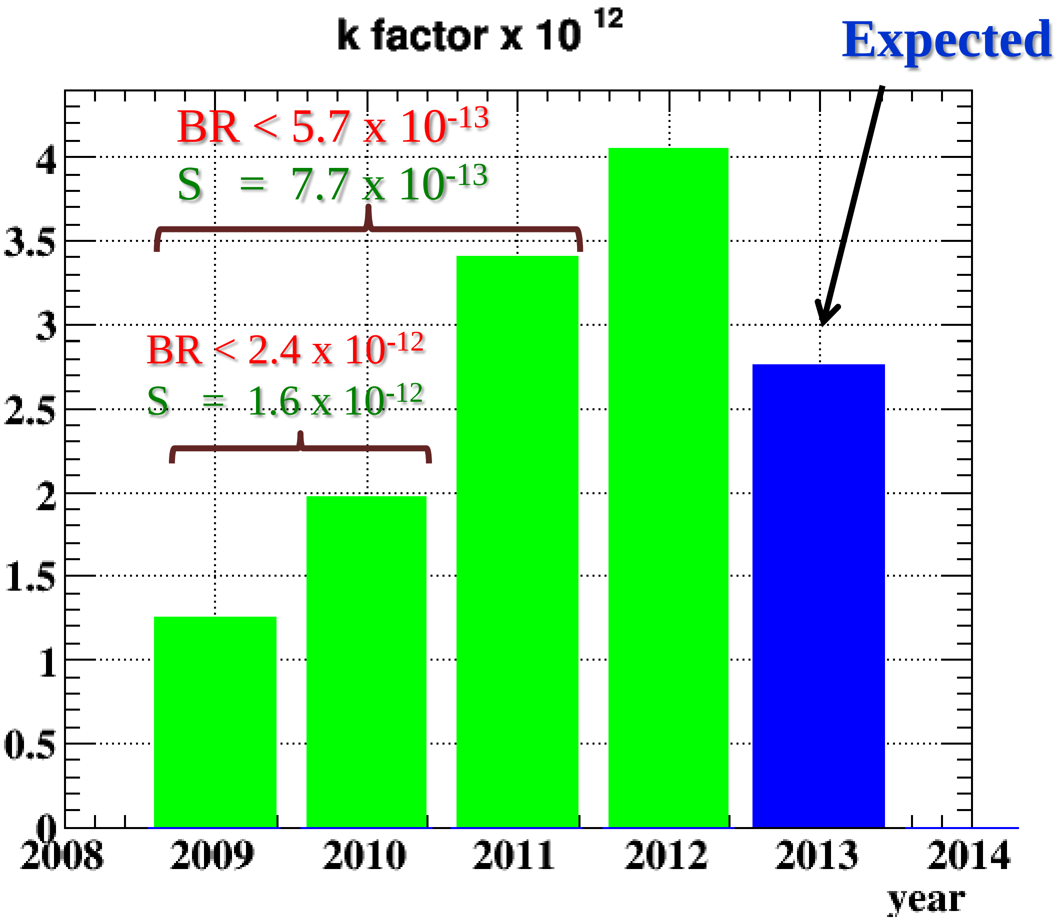
Data set	$\mathcal{B}_{\rm fit} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

Summary of all samples

Previous result: **2.4**; checked **statistical compatibility (31%).**

Final data and sensitivity

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

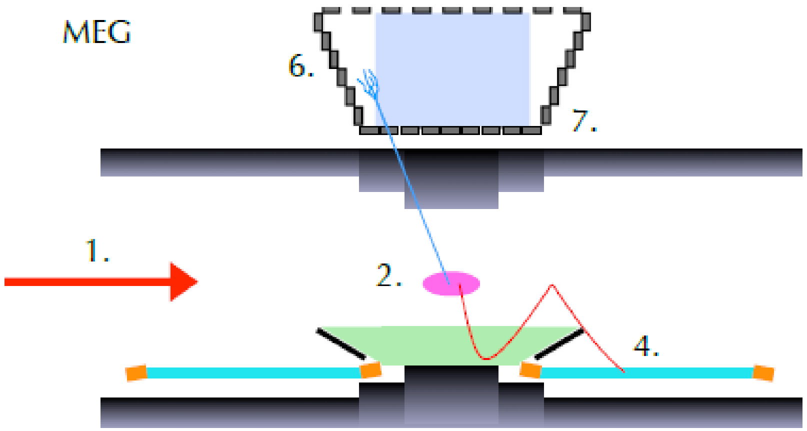


Estimated final sensitivity (toy MC)

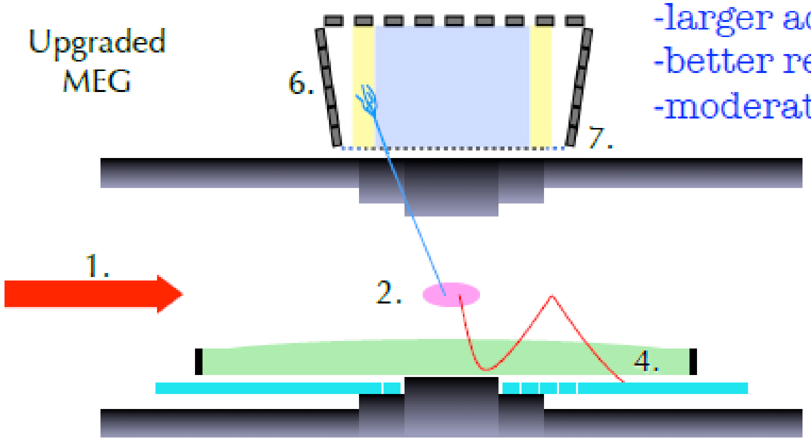
~ 5 x 10^{-13}

MEG Upgrade: introduction

MEG

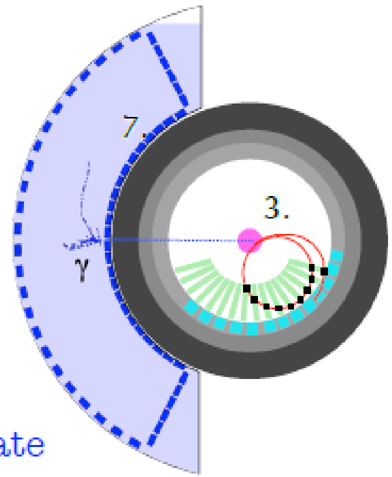


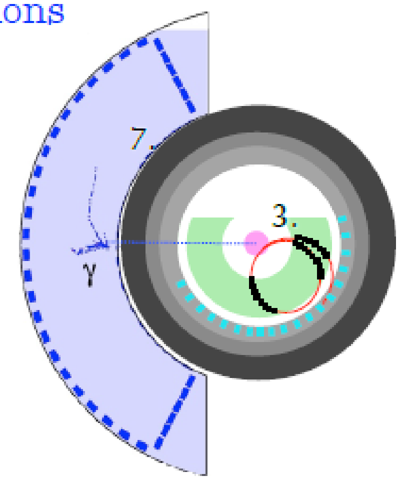
Upgraded MEG



-higher beam rate
-larger acceptance
-better resolutions
-moderate cost

upgrade design based on our long time experience



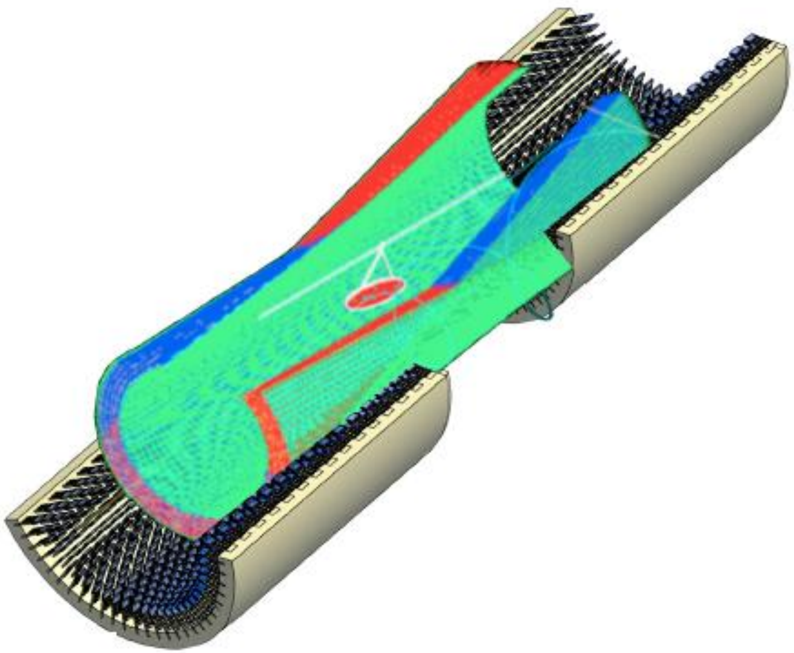


Proposal accepted by PSI

Ref. arXiv:1301.7225 [physics.ins-det]

MEG Upgrade: overview 1)

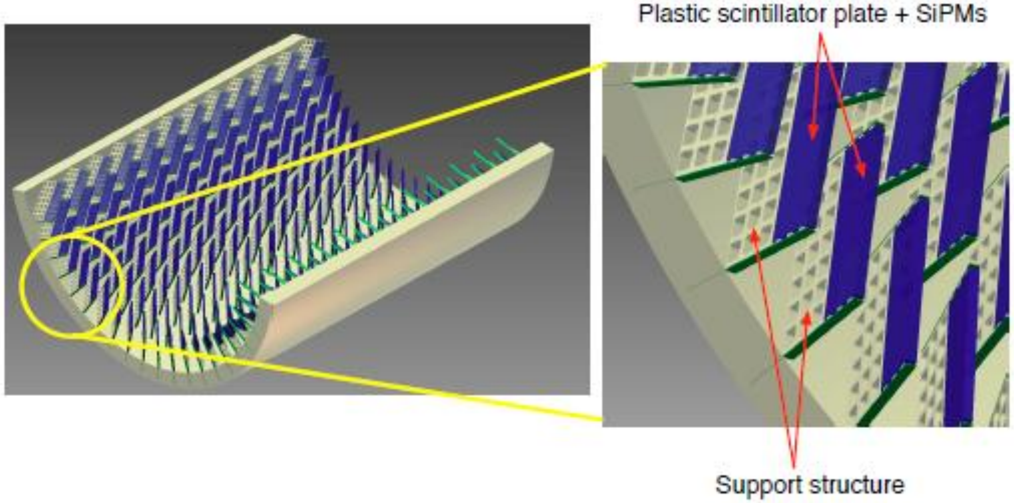
Increased beam intensity 3×10^7 μ/s → 7×10^7 μ/s.
Optimized target thickness and slant angle: 140 μm thickness, 15^o slant angle

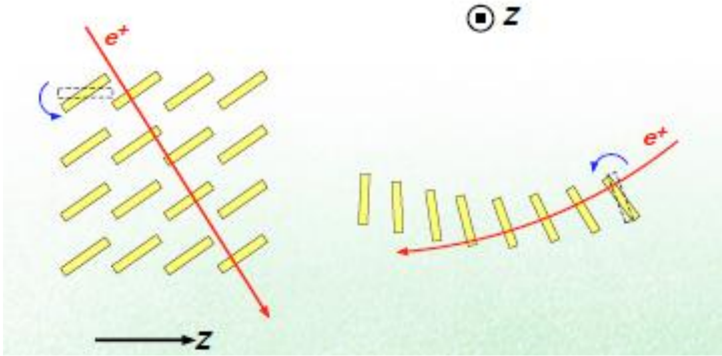


- **Unique volume cylindrical drift chamber;**
- He/Isobutane 90:10;
- ~ 1300 sense wires, ~ 7000 field+guard wires;
- High transparency (1.7×10^{-3} X_0);
- **Positron efficiency > 85%** (better coupling with TC, no extrapolation needed);
- Stereo view, $(7\div8)^o$ angle;
- **Hit resolution 120 μm;**
- Based on KLOE experience;
- Single hit resolution and gas aging effects verified on prototypes and test stations.

MEG Upgrade Overview 2)

Pixelated Timing Counter equipped with SiPM



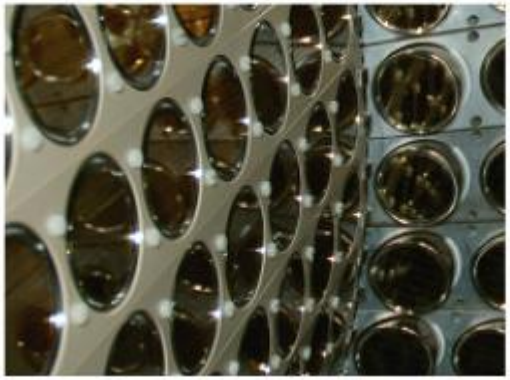


Improved resolution by multiple hits

Expected σ = 35 ps

(factor 2 better than present)

LXe detector: modifications in lateral faces & finer photon sensors at entrance face



(a) Present detector

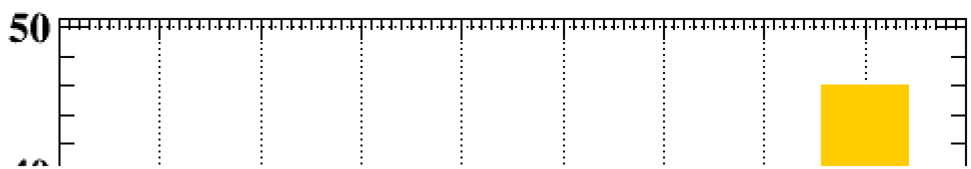
(b) Upgraded detector (CG)

12 x 12 mm^2 SiPM sensitive to LXe scintillation light. Development in progress.

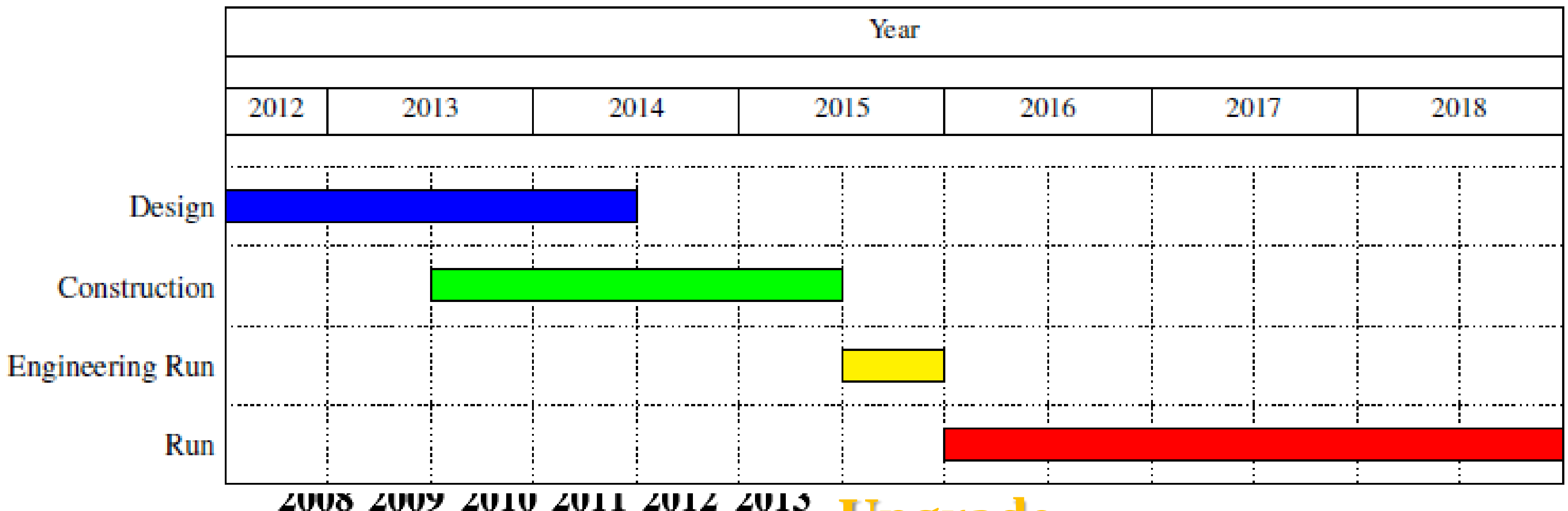
Expected a factor 2 better resolution in position and almost a factor 2 in energy.

MEG Upgrade: data and schedule

k factor x 10^{12}



Gantt chart 1: Overall MEG Upgrade Schedule



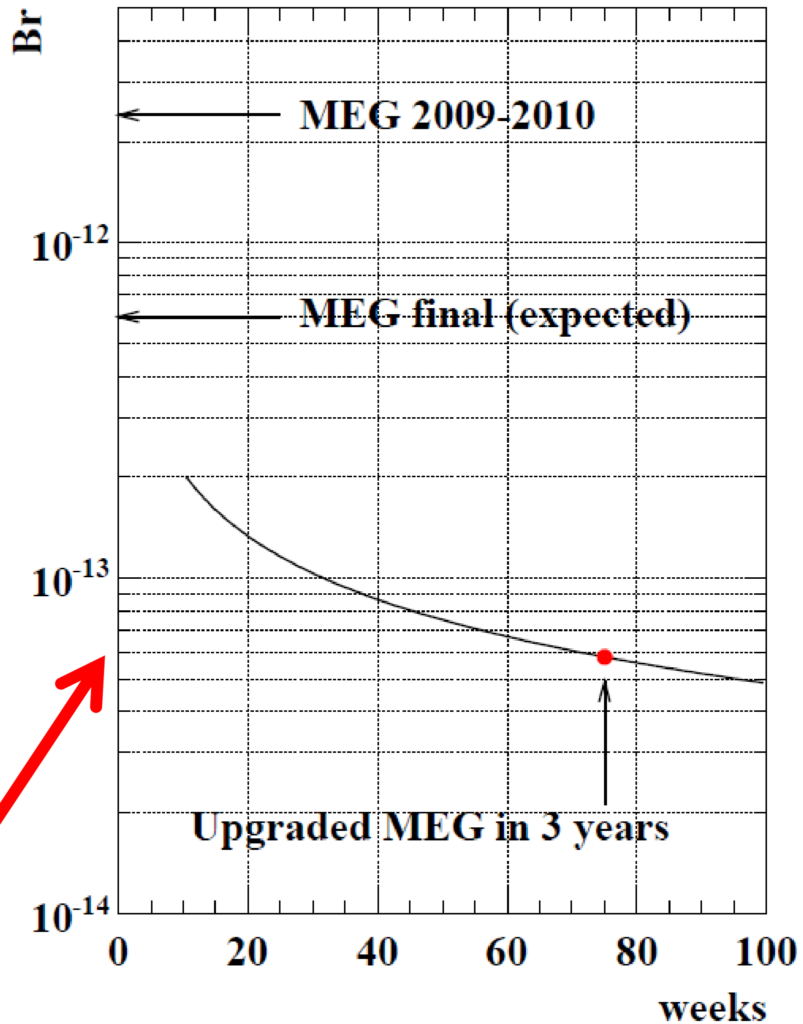
Upgrade

MEG Upgrade: sensitivity

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

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

Expected final sensitivity ~ 6 x 10^{-14}



$\mu \to eee$

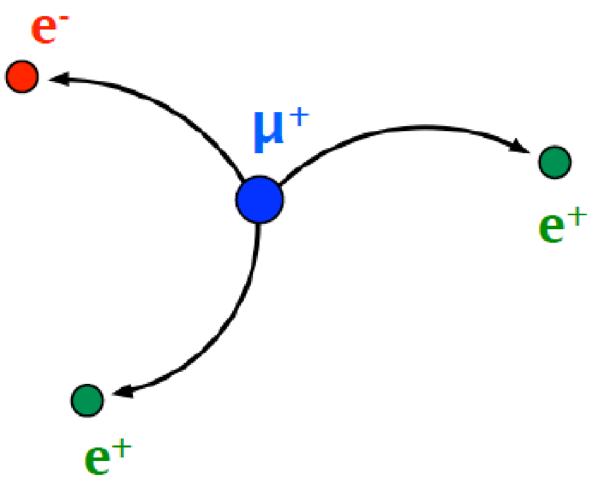
Present limit **BR($\mu \to eee$) < 10^{-12}**
(SINDRUM Coll., Nucl. Phys. **B260** (1985) 1)

Also limited by **accidental background** $\Rightarrow$ **continuous muon beam**
(Michel positron & e^+e^- pair from Bhabha scattering or γ conversion in detector)

Experimental advantage: no photons
$\to$ no e.m. calorimeter.

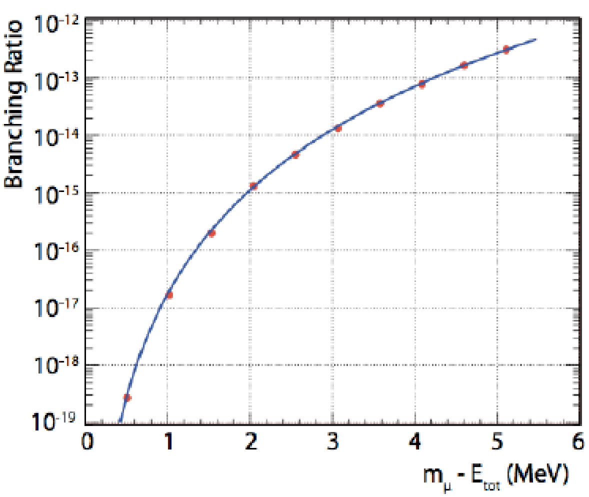
However: needed a large acceptance, large solid angle ($\sim 4\pi$) and low threshold spectrometer $\Rightarrow$ expected **very high rate** in tracking system
$\to$ dead time, trigger & pattern recognition problems.

$\mu \to eee$: signal vs bck



Signal: Total momentum zero (muon decaying at rest)
Total energy = m_μ
Time coincident tracks
Common vertex
Momentum of any particle ≤ $m_\mu/2$

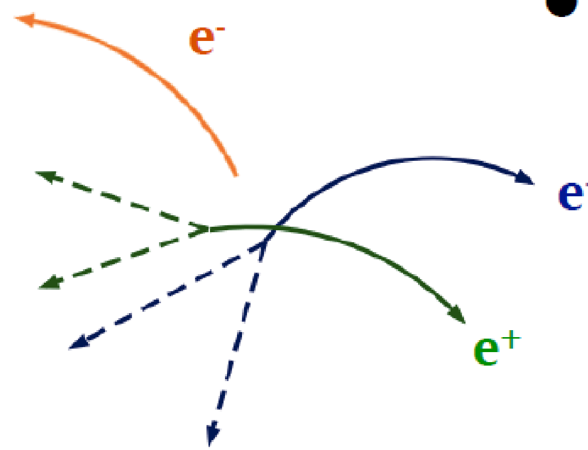
Backgrounds:



- $\mu \to eee\nu\nu$

Missing energy (ν)

Rejection:
momentum resolution

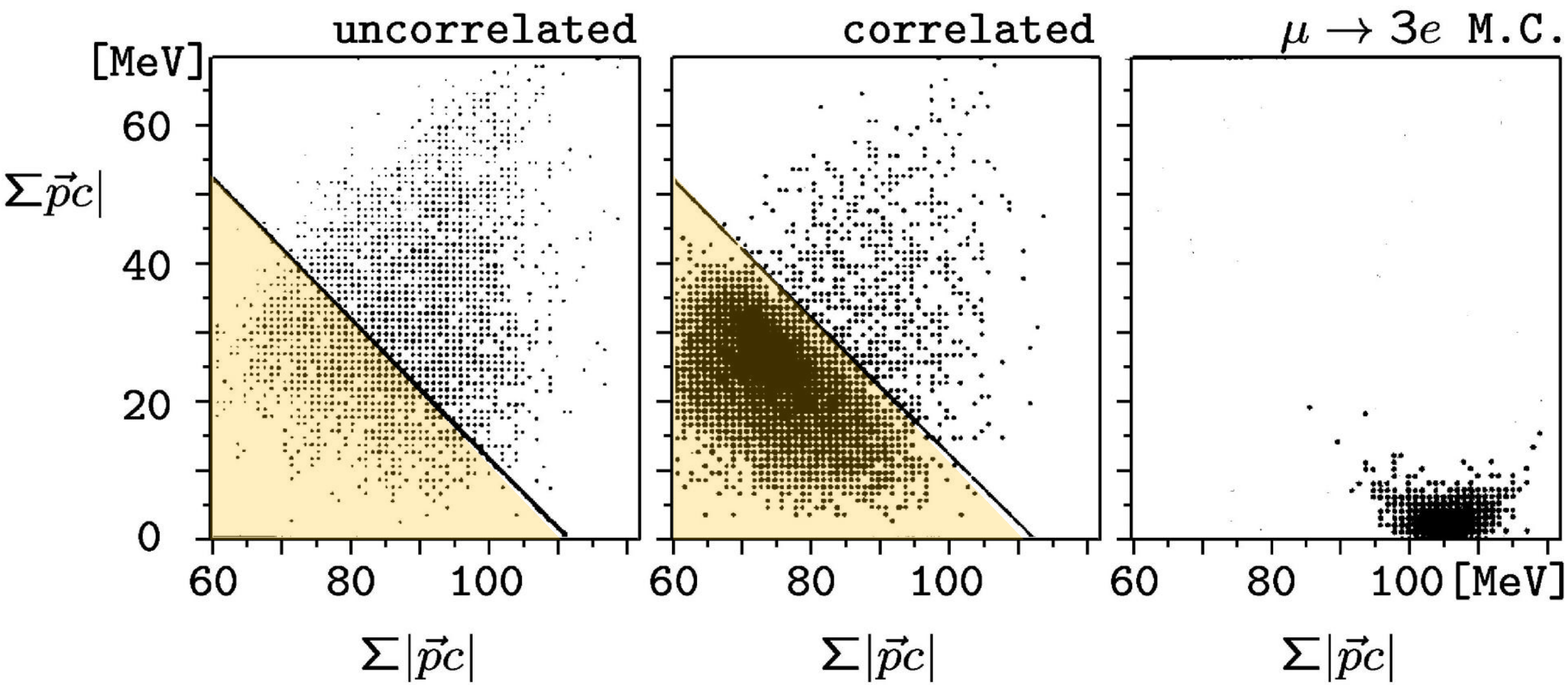


- Combinatorial

Positron from Michel decay + Dalitz pair

Rejection:
vertex & timing resolution

Sindrum result



Total momentum vs total energy for triplets of tracks satisfying kinematical constraints.
Correlated events: Δt and vertex matching; uncorrelated: random coincidences.
Diagonal line defines $\mu \to ee e \nu\nu$ allowed region.

BR < 1 x 10^{-12} 90% C.L.
(limited by stopping muon statistics)

The Mu3e experiment @PSI

Goal: reach **a sensitivity of 10^{-16}** (in two phases) **to $\mu \rightarrow 3e$ decay**

A big challenge:

- ❖ **improvement of four orders of magnitude over SINDRUM**;
- ❖ needed to collect **~ 10^{16} muon decays (~ 10^{9}/s)**

$\Downarrow$

intense continuous beam:- πE5 in first phase (~ 10^{8} μ/s)
- HIMB from Spallation Neutron Source in second phase (~10^{10} μ/s, in project, $\geq$ 2017)

- ❖ suppress **background at 10^{-16} level**

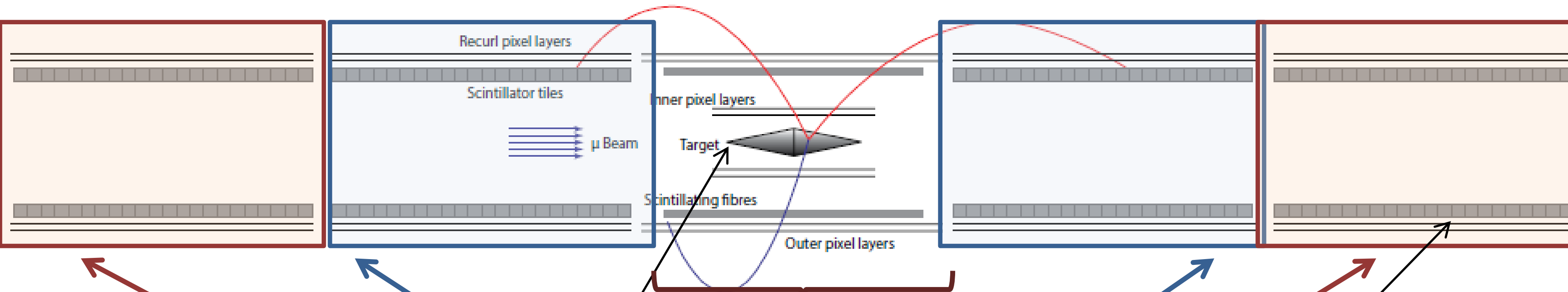
$\Downarrow$

refined experimental techniques: - excellent momentum resolution
- good timing and vertex resolution
- low material budget

Project approved in 2013.

Mu3e detector

1 T magnetic field, known with 10^{-4} precision

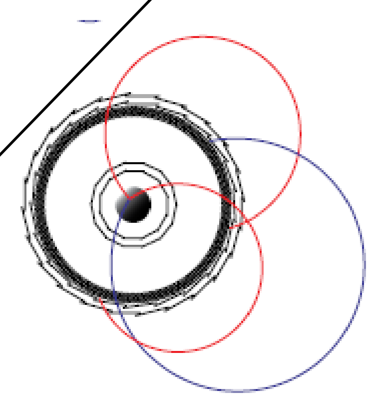


Phase IA, starting 2015
Sensitivity ~ 10^{-14}

Phase IB, 2016+
Sensitivity ~ 10^{-15}

Phase 2, 2017+
New beam line
Sensitivity ~ 10^{-16}

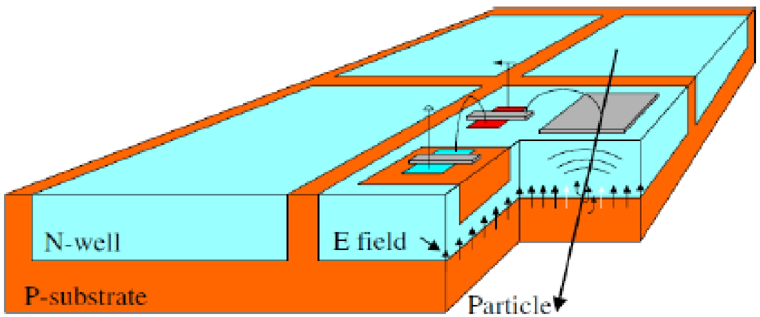
Double cone hollow target
- 0.06 X_0 along beam
- **Stopping efficiency 83%**



Recurl stations to **reduce MS effects** (dominant in σ_p)

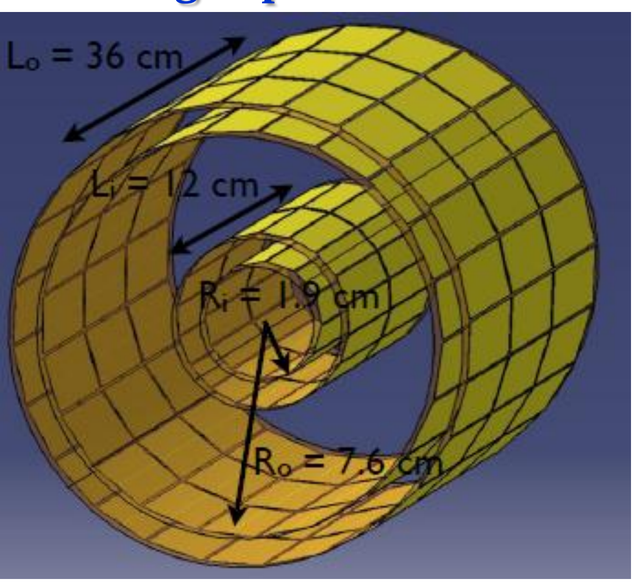
Mu3e detector elements 1)

Pixel sensors based on **HV-MAPS technology** (I. Peric, L. Fischer et al., NIM **A582** (2007) 876):



- integrated active sensors and readout;
- pixel size 80 x 80 μm^2 (base) x 50 μm (thickness)
- sensor size 2 x 2 cm^2
- light support structure
- $\sigma_{hit} \approx 30\ \mu m$ (MS: 150 μm), $\sigma_p < 0.5(0.7)$ MeV with (without) recurl stations
- power consumption 150 mW/cm^2 $\Rightarrow$ powerful cooling system needed (gaseous helium)

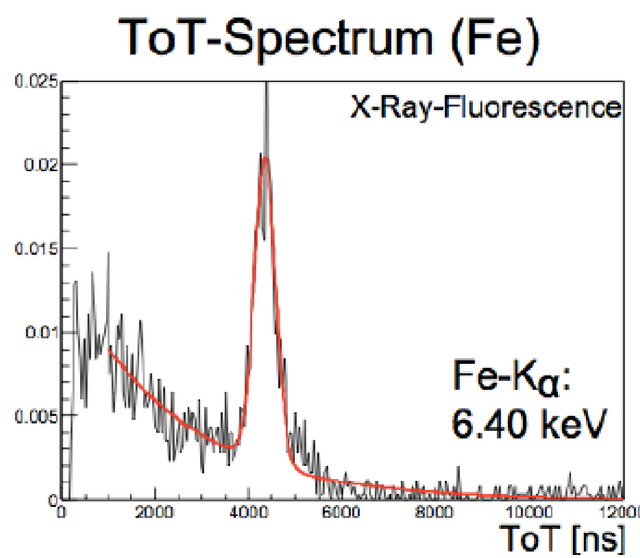
Drawing of pixel detector



Inner layer:
180 sensors

Outer layers:
4680 layers

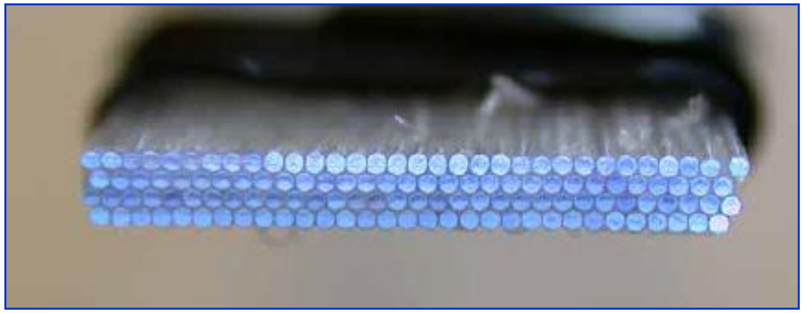
Total:
275M pixels



Energy Spectrum

SNR = (20÷40)

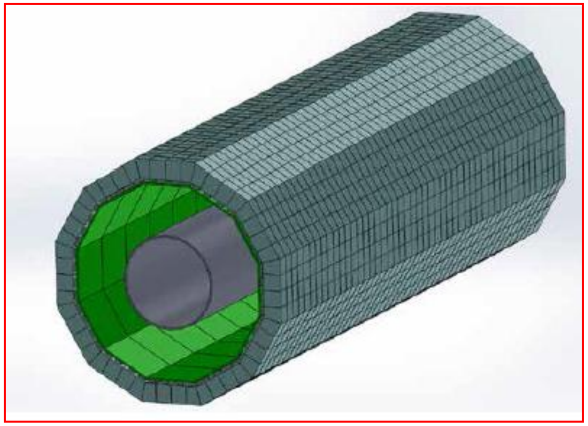
Mu3e detector elements 2)



Timing detectors:

1) 250 μm scintillating fibres + SiPM
   σ(ΔT) ~ 1 ns

2) ~ 1 cm³ scintillating tiles + SiPM
   σ(Δt) ~ 100 ps



Online filter farm:
50 PCs + Graphical Processing Units
to reduce data stream:

1Tb/s → 100 Mb/s

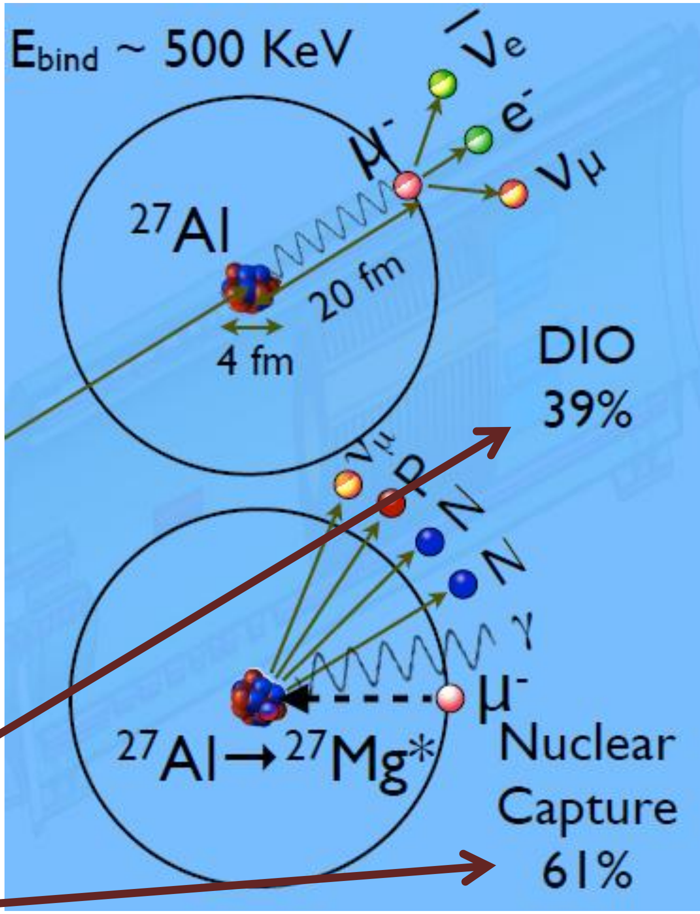
N. Berger, CLFV2013 Conference

$\mu^- \rightarrow e^-$ conversion

- Low energy **negative muons** stopped in material foils form muonic atoms.

- Three possible fates for the muon:
  - ❖ Nuclear capture;
  - ❖ Three body decay in orbit **(DIO)**;
  - ❖ **Coherent LFV decay** (extra factor of Z in rates).

- Muon lifetime in **Al ~ 0.86 μs**, in **Ti ~ 0.35 μs** (in vacuum: 2.2 μs).



Al fractions.

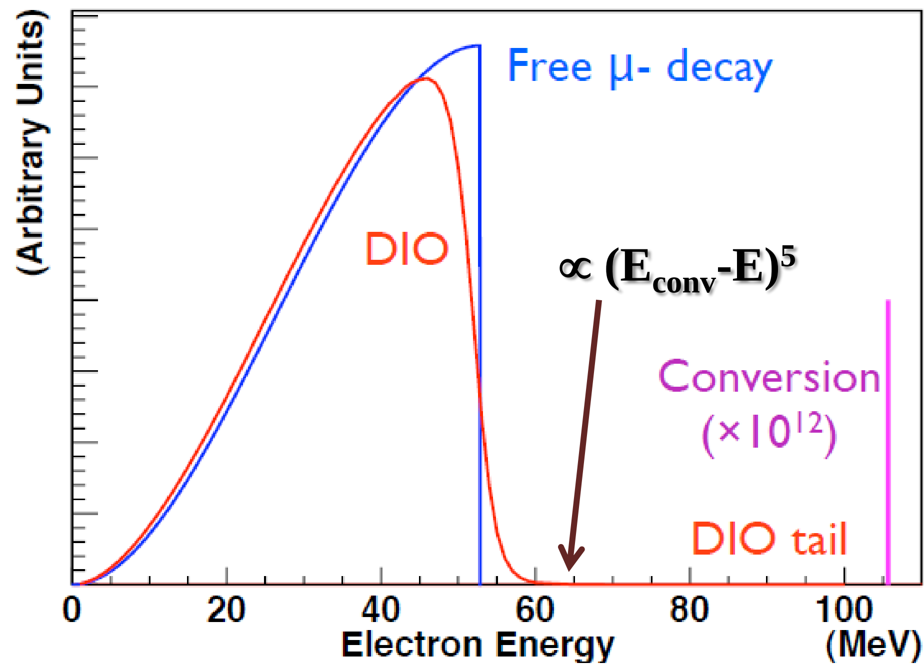
nuclear capture probability increases with Z

$\mu^- \rightarrow e^-$ conversion: signal vs bck

- Signal is a **single mono-energetic electron**:

$$E_{conv} = m_\mu - E_{bind} - E_{recoil} =$$

$$= 104.973 \text{ MeV for Al}$$

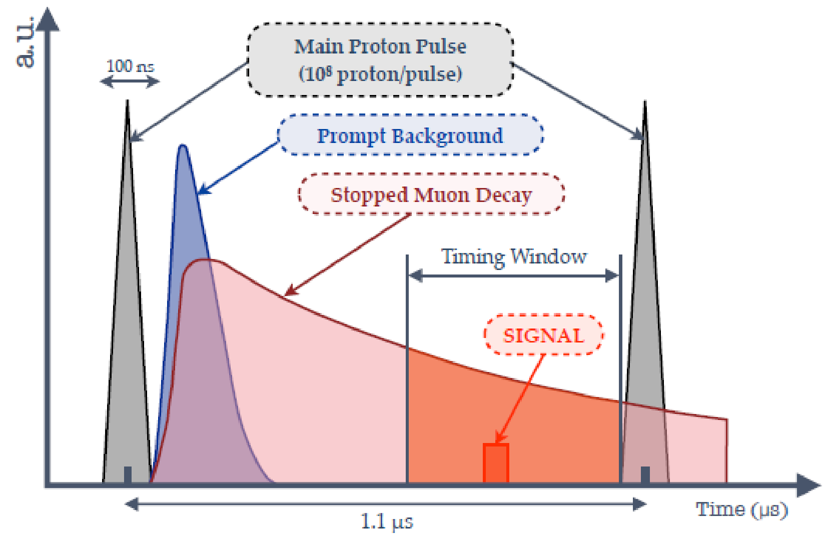


- Background:
  - muon **decay in orbit (DIO)**
  - muon/pion **radiative capture**
  - muons decaying in flight
  - cosmic rays …

Background reduction

1) Beam pulsing:

Muonic atoms have **some hundreds of ns lifetime τ** → use pulsed beam with **buckets << τ**, leave pions decay and **measure in a delayed time window**.



2) Extinction factor:

Protons arriving on target between the bunches can produce e^- or π in the signal timing window ⇒ **needed big extinction factor (~ 10^{-9})**

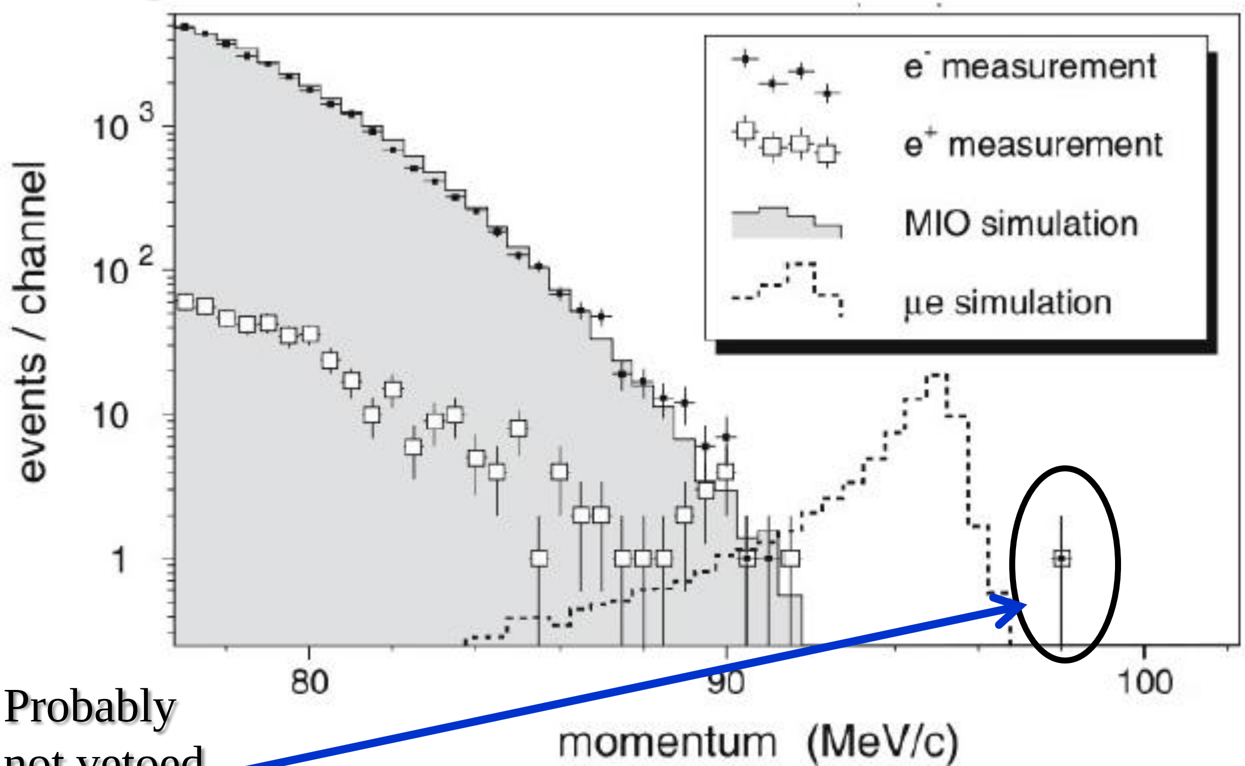
3) Beam quality:

- insert a **moderator** to **reduce the pion contamination**; a **10^6 reduction factor** obtained by SINDRUM II. **No more than 10^5 pions** may stop in target during the full measurement (**≤ 1** background event);
- select **a beam momentum < 70 MeV/c** to reduce energy of electrons from muons decaying in flight.

4) Cosmic ray muons: veto counter + signals in trackers, calorimeters …

Sindrum II results

Au target; DC beam



SINDRUM Plot

μ-e conversion in Au (Signal energy = 95 MeV)

Probably not vetoed cosmic ray

$R_{\mu e}(Ti) < 6.1 \times 10^{-13}$

PANIC 96 (C96-05-22)

$R_{\mu e}(Ti) < 4.3 \times 10^{-12}$

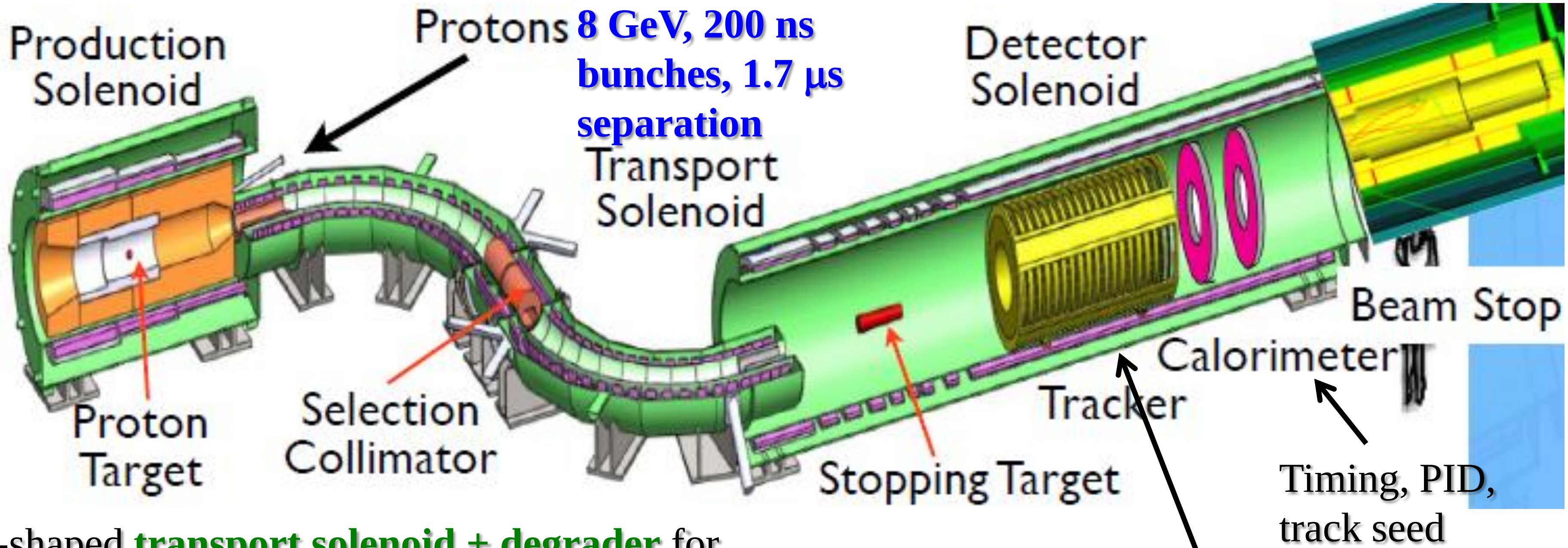
Phys.Lett. B317 (1993)

$R_{\mu e}(Au) < 7 \times 10^{-13}$

Eur.Phys.J. C47 (2006)

Future projects **(Mu2e & COMET)** aim to reach a **sensitivity ~ 5 x 10^{-17}**, an **improvement** by a factor **10^4** !

Mu2e experiment @ Fermilab



S-shaped **transport solenoid + degrader** for sign selection and antiprotons/neutral particles rejection.

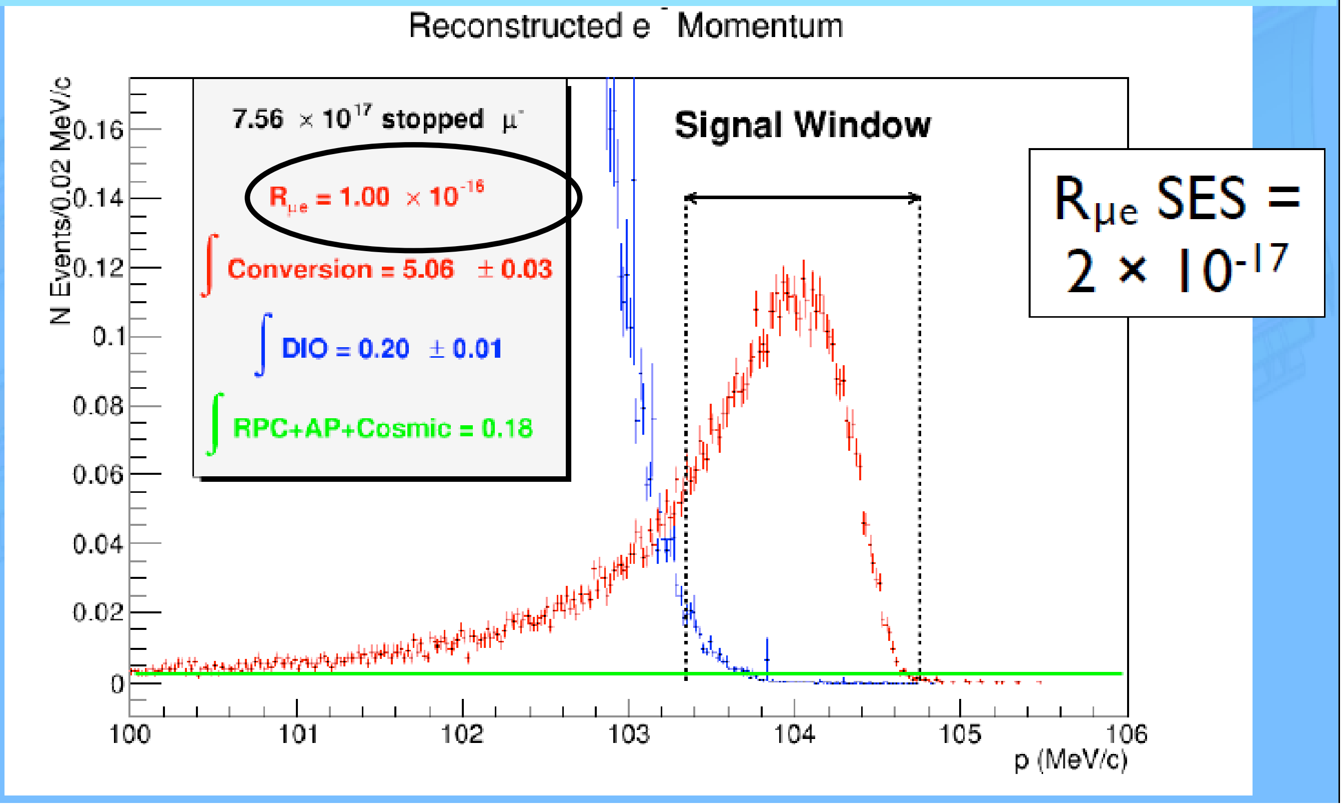
Beam extinction ~10^{-10} by a system of resonant AC dipoles (measured with Si telescope)

Derived from original MECO project at AGS.

Graded magnetic field ((1 ÷ 2) T) to select electrons with P > 90 MeV/c and recover backwards electrons.
Straw chamber tracker; expected resolution **≈1 MeV FWHM @100 MeV** (needed to control DIO background)

Mu2e sensitivity

Full G4 detector simulation, background overlay, reconstruction



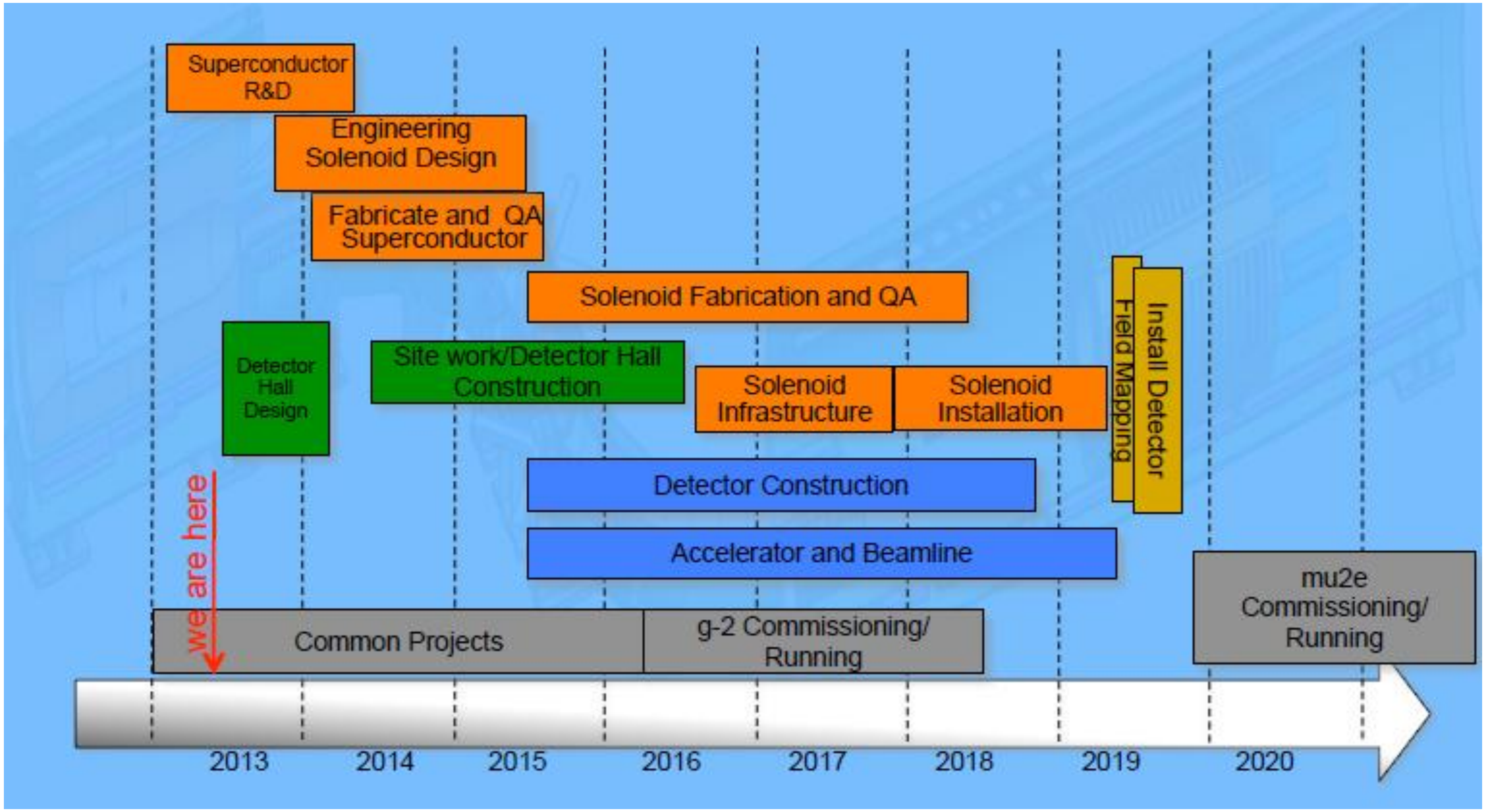
Used
1.2×10^{20} POT

Total BCK:
0.4 events

BR Sensitivity $\leq 6 \times 10^{-17}$

Designed to be **nearly background free**

Mu2e schedule



Data taking ≥ 2020

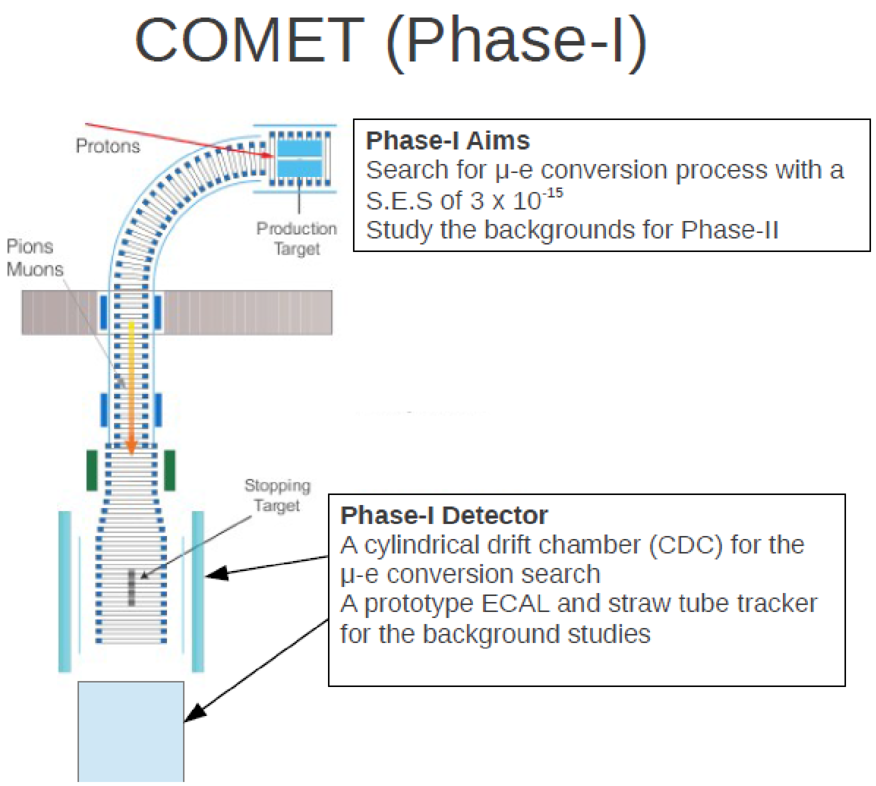
D. Brown, CLFV2013 Conference

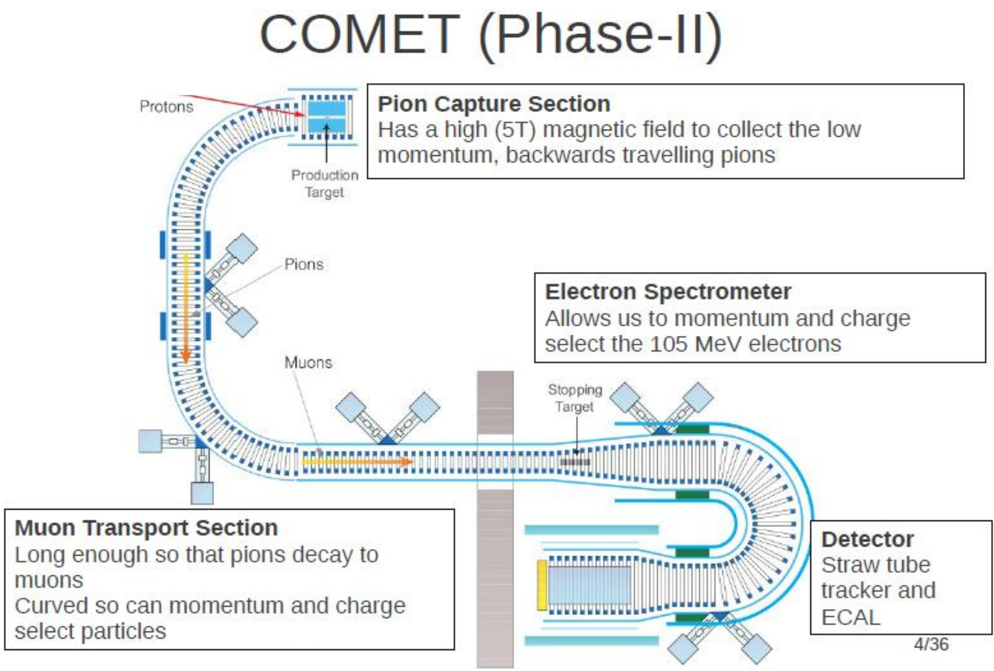
COMET experiment @J-PARC

Two-stages J-PARC program to $\mu \rightarrow e$ conversion at Hadron facility

Data taking 2016
SES = 3 x 10^{-15}

Data taking 2022
SES = 3 x 10^{-17}

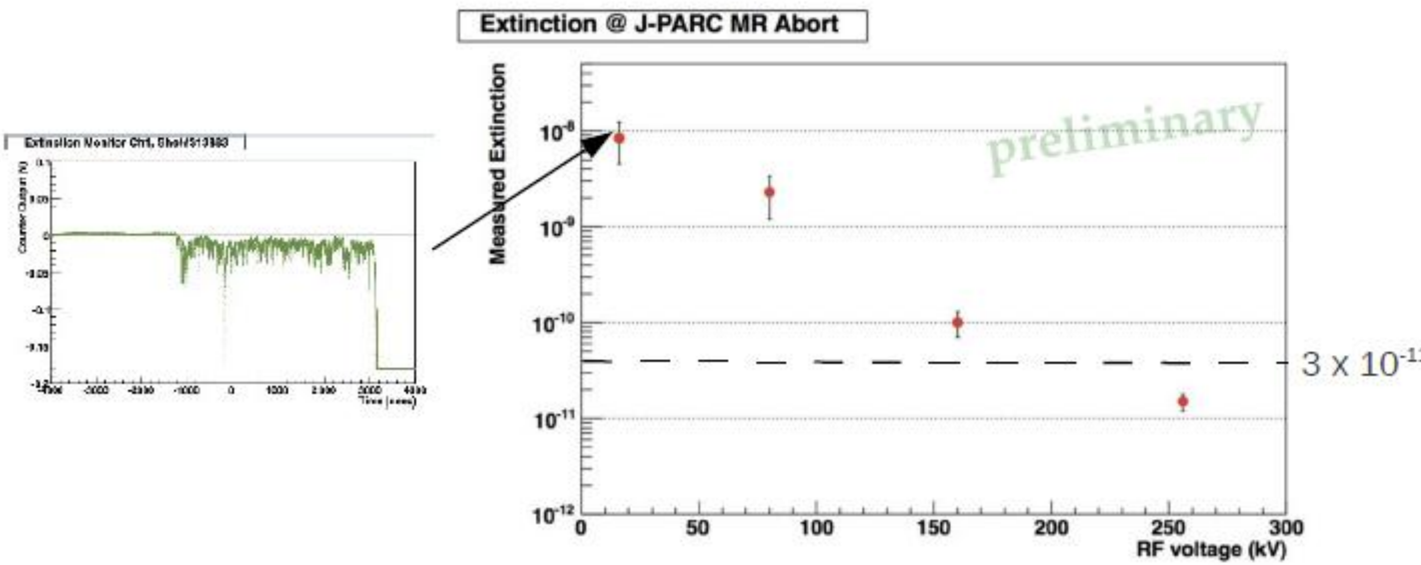




- Better muon selection
- Higher resolution detectors

Beam extinction @ J-Parc

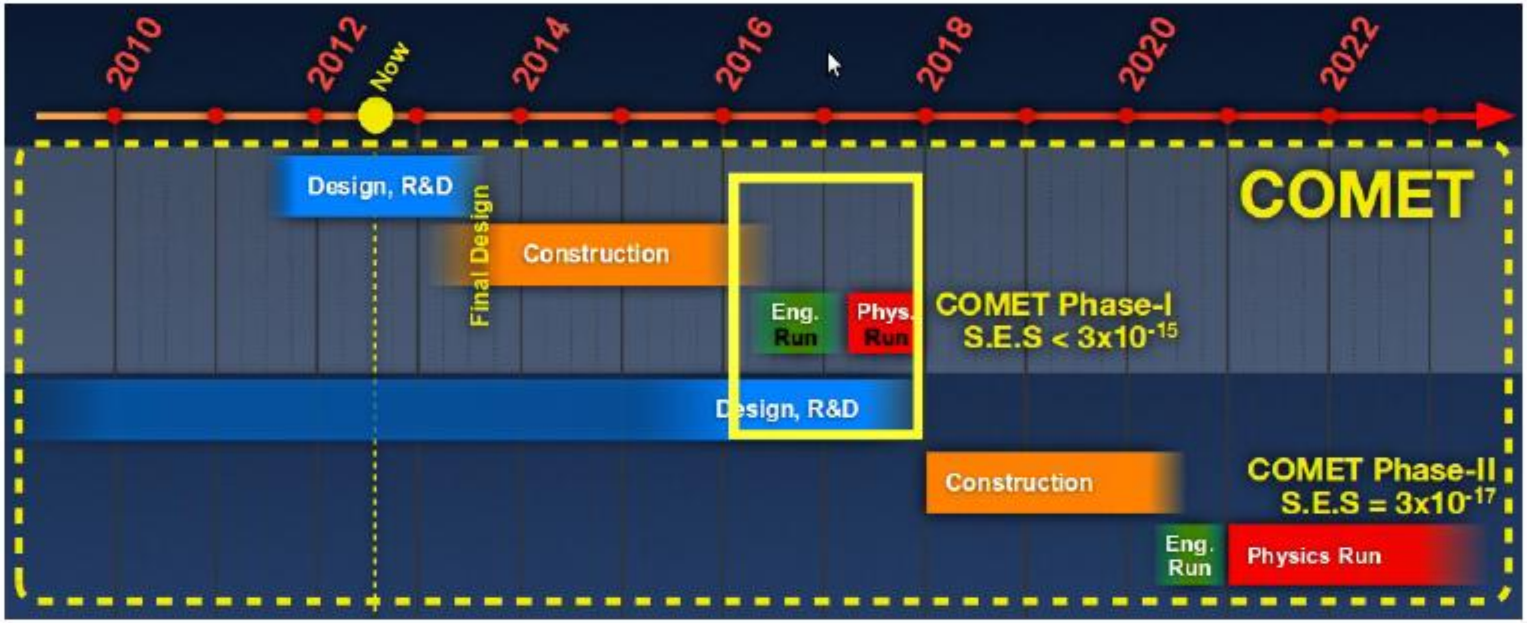
8 GeV proton beam; 3.2 kW/56 kW power (Phase I/Phase II)



Beam extinction goal 3 x 10^{-11}; reached on tests

A. Edmonds, CLFV2013 Conference

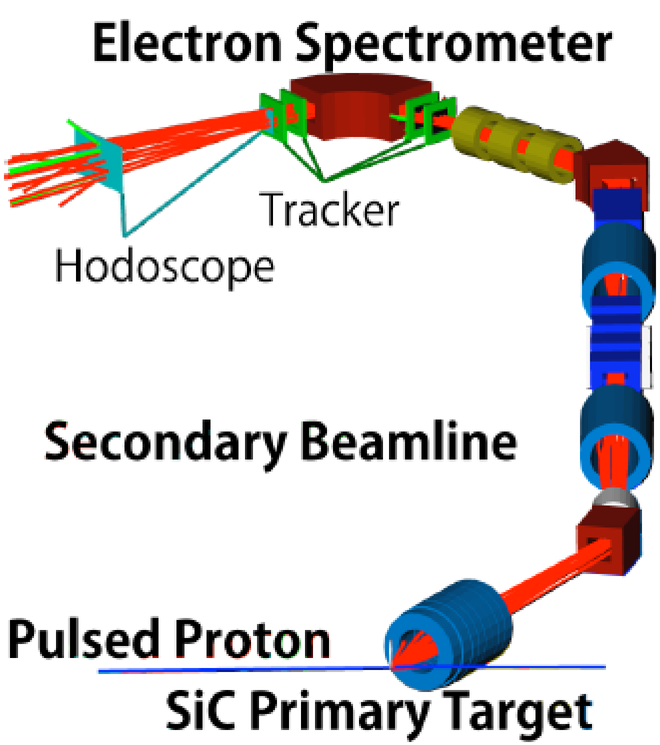
COMET schedule



DeeMe experiment @J-PARC MLF

MLF = **M**aterial and **L**ife science **F**acility **MUSE**

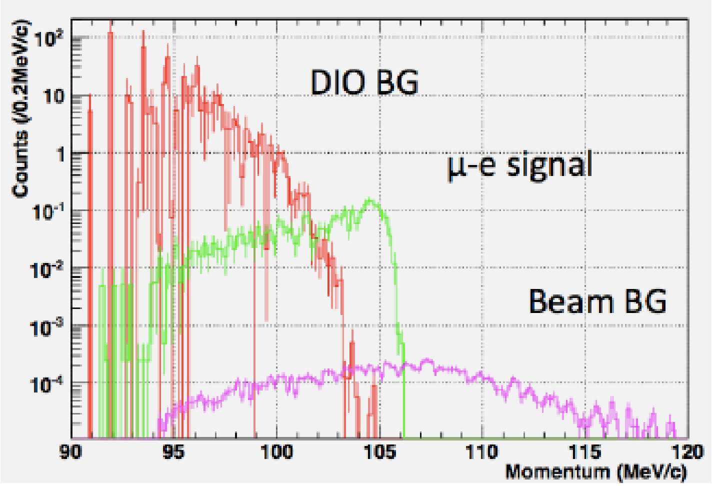
Search for $\mu \rightarrow e$ conversion with **10^{-14} sensitivity**
Data taking foreseen for **2015**



Assuming:

- T = 2 x 10^7 s
- Power 1 MW
- Δp = 0.5% FWHM

Sensitivity 2 x 10^{-14}



DIO B.G.	0.09
After proton B.G.	< 0.027 (0.05 90%C.L.)
Cosmic induced e	< 0.018 (MC stat. limited)
Cosmic induced μ	< 0.001
Radiative muon capture	< 0.0009

H. Natori, CLFV2013 Conference

Future perspectives 1)

Expected number of muons in one year available in future high intensity machines

Experiment	$\int I_\mu \, dt$	I_0/I_m	δT [ns]	ΔT [μs]	p_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- A \rightarrow e^- A$	10^{21}	$< 10^{-10}$	< 100	> 1	< 80	< 5
$\mu \rightarrow e\gamma$	10^{17}	n/a	n/a	n/a	< 30	< 10
$\mu \rightarrow eee$	10^{17}	n/a	n/a	n/a	< 30	< 10

Surface muons

n/a = continuous beam

Is it possible to **gain other orders of magnitude in sensitivity** in muon LFV experiments ?

Future perspectives 2)

$\mu \to e\gamma$, $\mu \to eee$

- Rate limited experiments
  (Accidental background $\propto (R_\mu)^2$)
- Rate increase is not enough; needed radical detector/target improvements.

With present technologies, **10^{-14} ($\mu \to e\gamma$)** and **10^{-16} ($\mu \to eee$)** represent tough experimental challenges.

$\mu \to e$ conversion

- Not rate limited
- Limiting factors:
  - Beam purity
  - Background control

ProjectX is supposed to supply 10x muons to Mu2e experiment.

Main concerns:

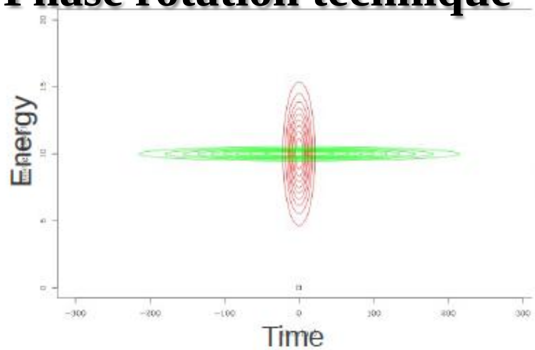
- target radiation shielding;
- DIO & RPC background < 1 event;
- Beam spread.

Beam spread reduction

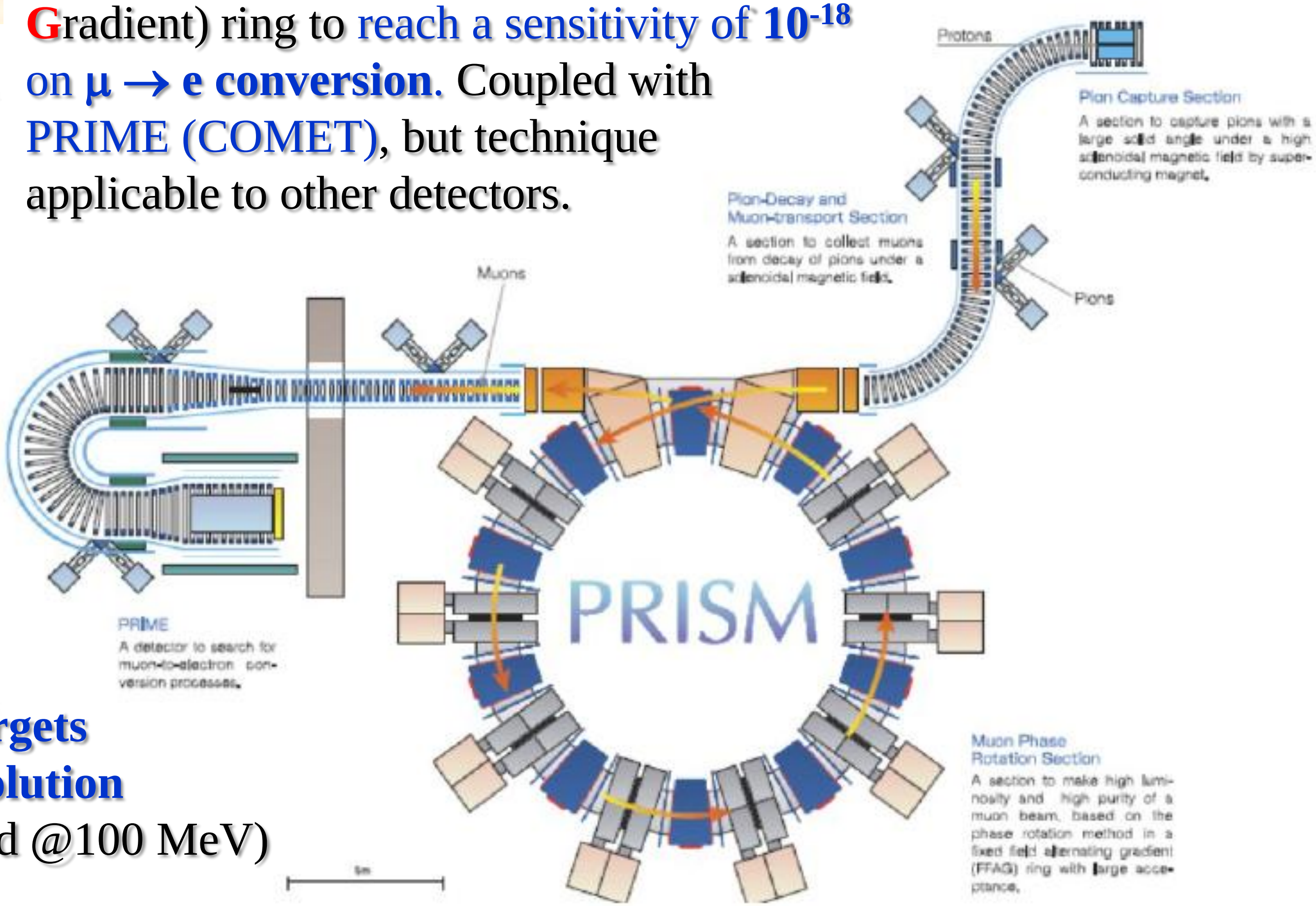
The PRISM Project

Use a **FFAG** (**F**ixed **F**ield **A**lternating **G**radient) ring to reach a sensitivity of **10^{-18}** on **$\mu \to e$ conversion**. Coupled with PRIME (COMET), but technique applicable to other detectors.

Phase rotation technique



Before phase rotation (red)
After phase rotation (green)



It allows to **use very thin targets**
to **improve momentum resolution**
(**≈ 350 keV FWHM** expected @100 MeV)

Summary and conclusions

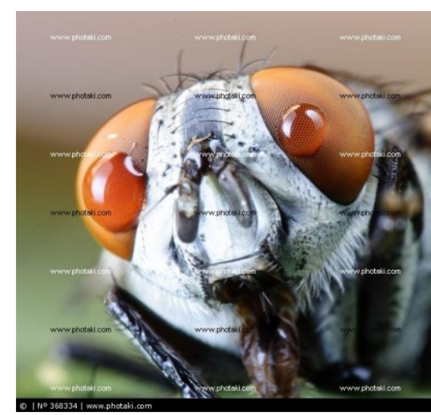
Muon beam experiments are **very sensitive tools to look for New Physics**.

Different kind of experiments under way or in preparation:

- **Best world limit on $\mu \to e\gamma$** set by MEG (**5.7×10^{-13}** @ 90% C.L.);
- **MEG upgrade** expected to **improve this result by a factor 10** in few years;
- **Mu3e experiment** aims to **improve $\mu \to eee$** limit by **4 orders of magnitude**;
- Experiments at Fermilab (**Mu2e**) and J-Parc (**COMET, DeeMe**) would also **improve the bound on $\mu \to e$ conversion** in nuclei by **a factor ~ 10^4**.

A "network" of **complementary searches**; **profound exploration of New Physics parameter space**.

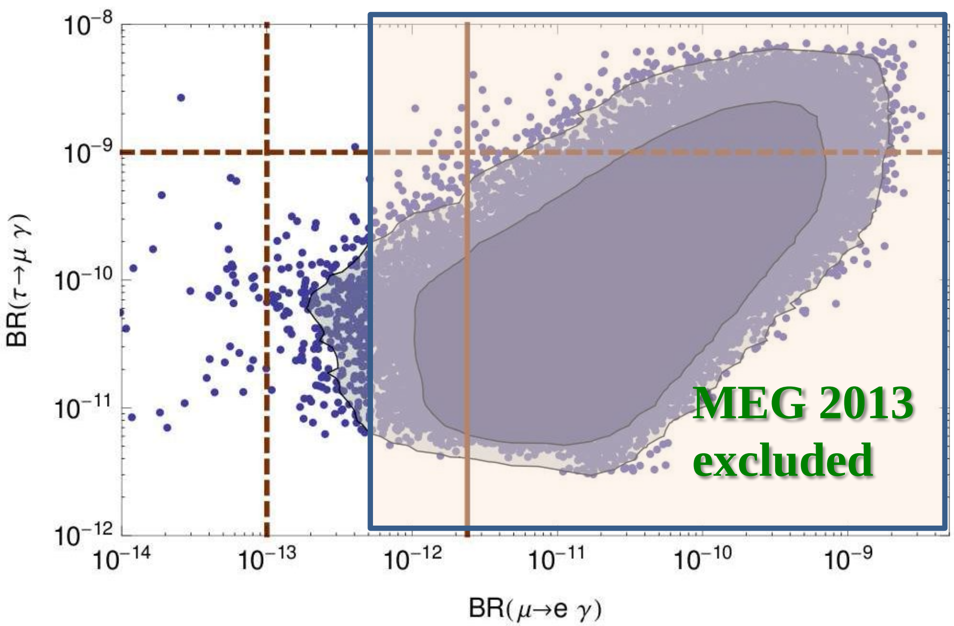
New Physics



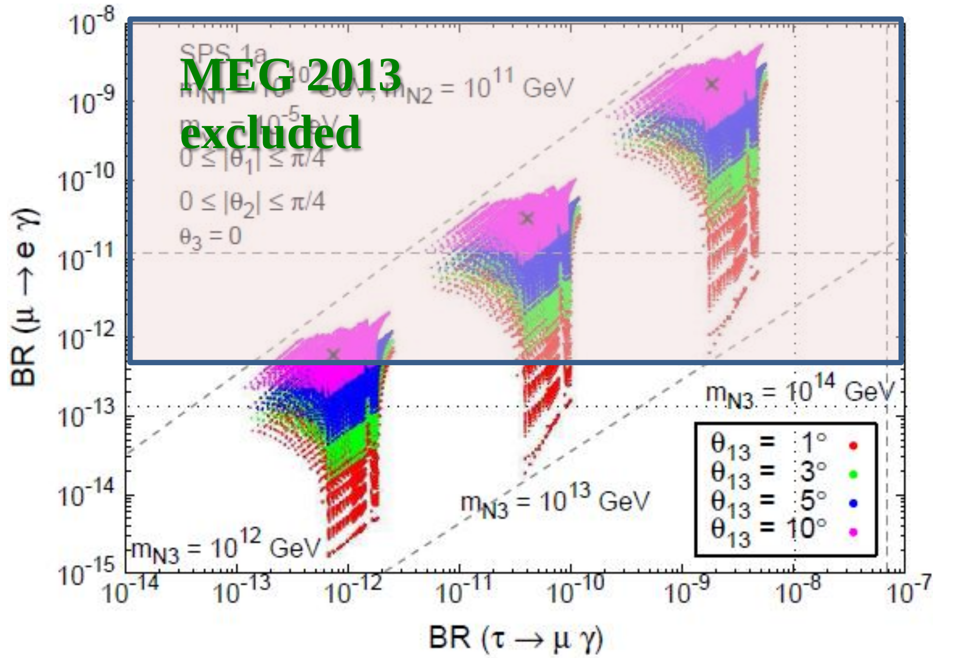
Backup

Muons vs taus

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



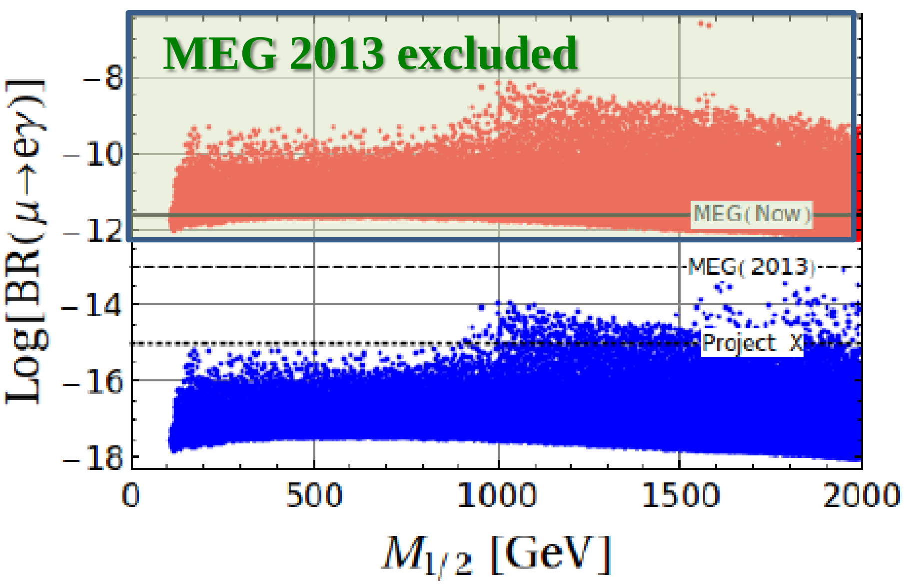
Antusch et al. JHEP **0611** (2006) 090

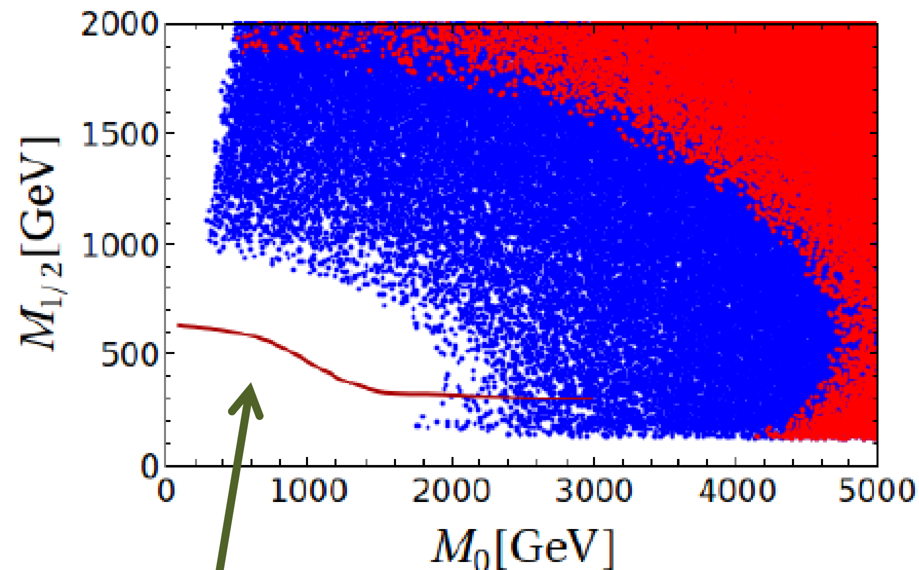


θ_{13} recently measured by Daya Bay, Reno, Double Chooz (7 ÷ 10^{o})

SUSY searches: indirect vs direct

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**

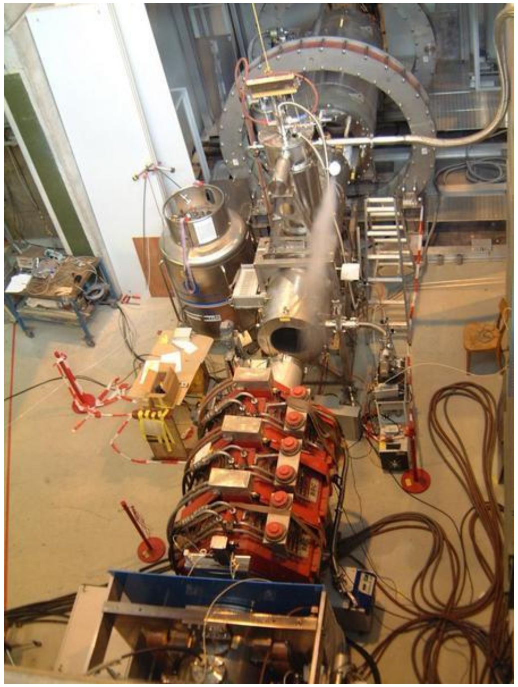
Models below this line excluded by direct LHC searches

The Paul Scherrer Institute (PSI)

- The **most powerful continuous machine** (proton cyclotron) in the world;
- **Proton energy 590 MeV**;
- **Power 1.2 MW**;
- **Nominal operational current 2.2 mA.**

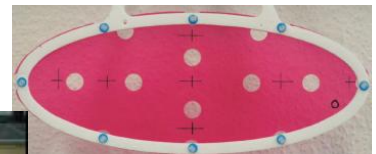
MEG beam line:

- Wien filter
- Beam transport solenoid
- Muon degrader



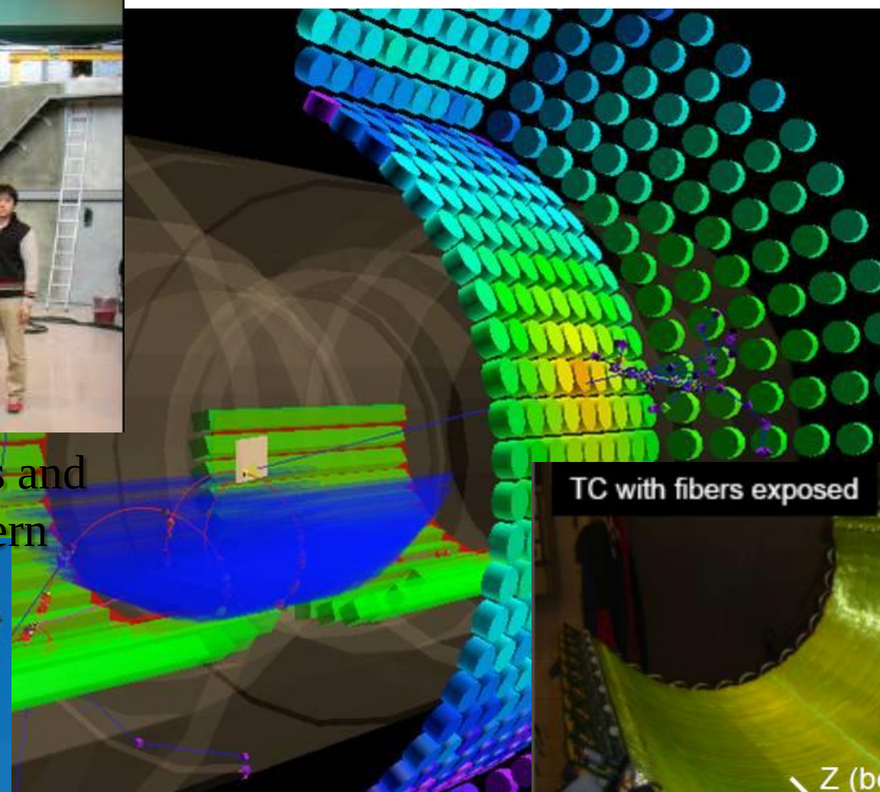
MEG detector components

Superconducting solenoid with gradient field (COBRA)

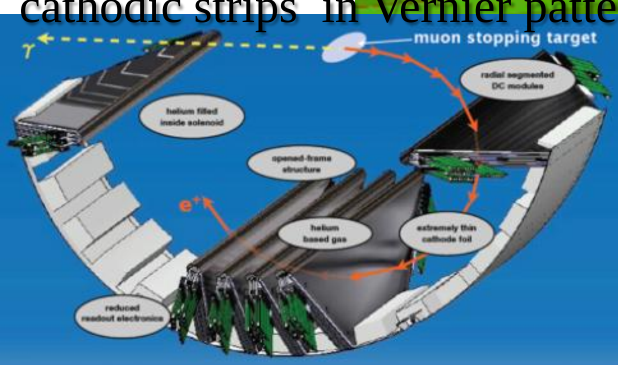


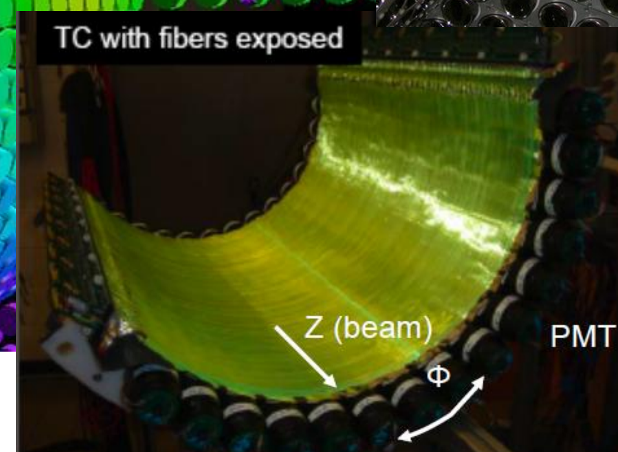
205 μm polyethylene target,20.5º slanted angle

900 l LXe detector
846 UV sensitive PMTs



16 this DCH with anodic wires and cathodic strips in Vernier pattern



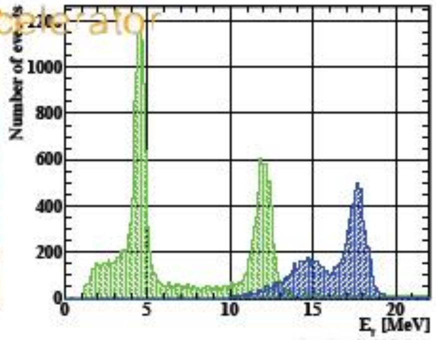


15 x 2 scintillator bars with fine mesh PMTs

MEG Calibration System

Detector Calibration

Proton Accelerator



Li(p,γ)Be

LiF target at COBRA center

17.6MeV γ

~daily calib.

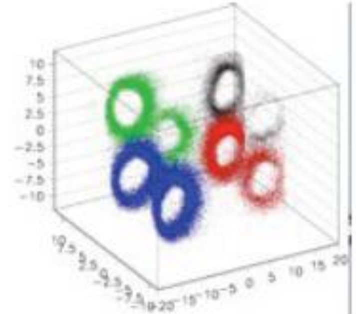
also for initial setup

Alpha on wires

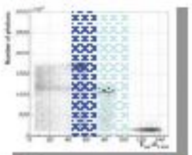
PMT QE & Att. L

Cold GXe

LXe



$\pi^0 \to \gamma\gamma$



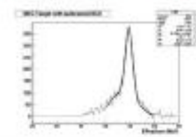
$\pi^- + p \to \pi^0 + n$

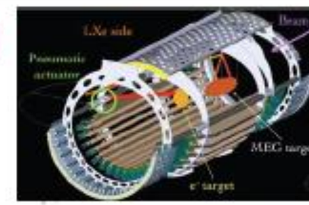
$\pi^0 \to \gamma\gamma$ (55MeV, 83MeV)

$\pi^- + p \to \gamma + n$ (129MeV)

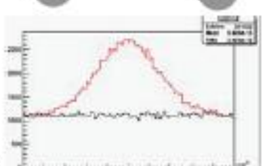
LH_2 target

Mott e+ scattering





μ radiative decay

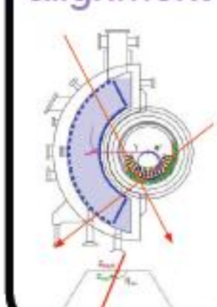


Lower beam intensity < 10^7

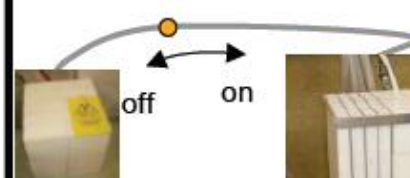
Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

Cosmic ray alignment

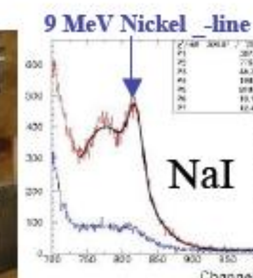


Nickel γ Generator



Illuminate Xe from the back

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



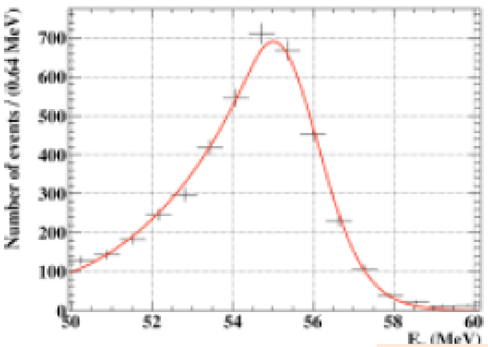
MEG performances

	2009	2010	2011	Note
Gamma E [%]	1.89	1.90	1.65	Effective sigma
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(u,v)6(w)	5(u,v)6(w)	5(u,v)6(w)	
Trigger/DAQ efficiency [%]	91/75	92/76	97/96	
Gamma efficiency [%]	63	63	63	π^0 sample
Positron efficiency [%]	43	36	36	From MC

Measured quantities are reported here

PDF's

55 MeV π^0 peak



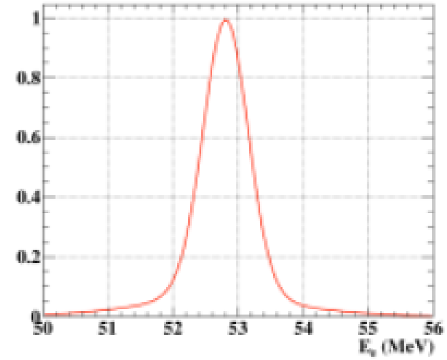
Gamma

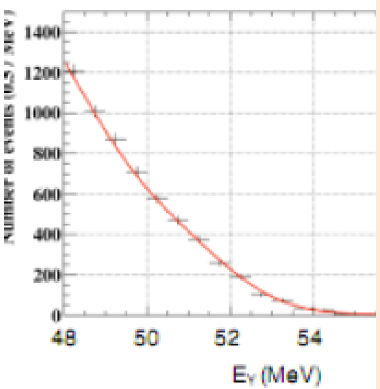
Signal PDF from 55MeV calibration gamma (π^0 decay)

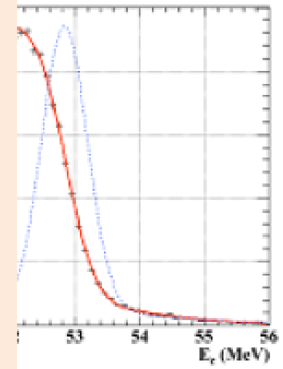
Positron

Signal PDF from measured resolution

Michel positrons





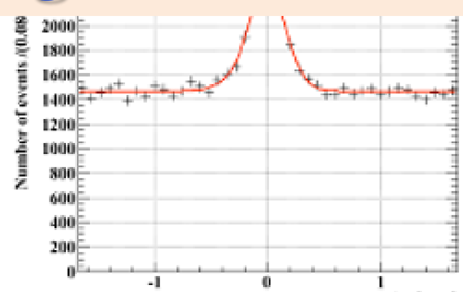


Two types of PDF's:

- Per-event (variable uncertainties)
- Constant with event categories

Results in agreement.

mostly in low energy part



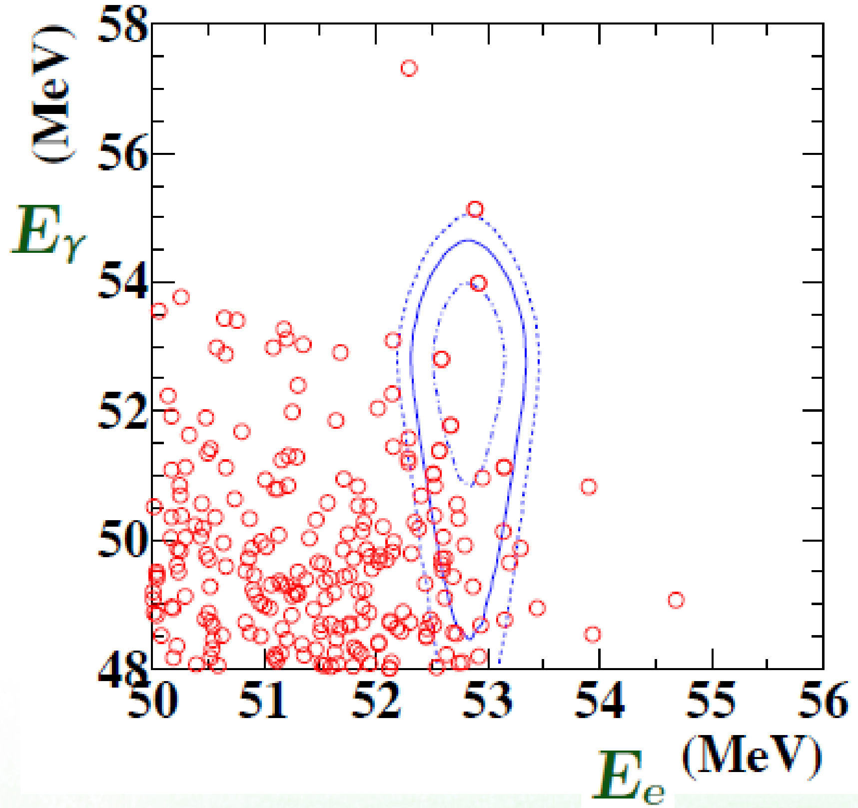
Relative time

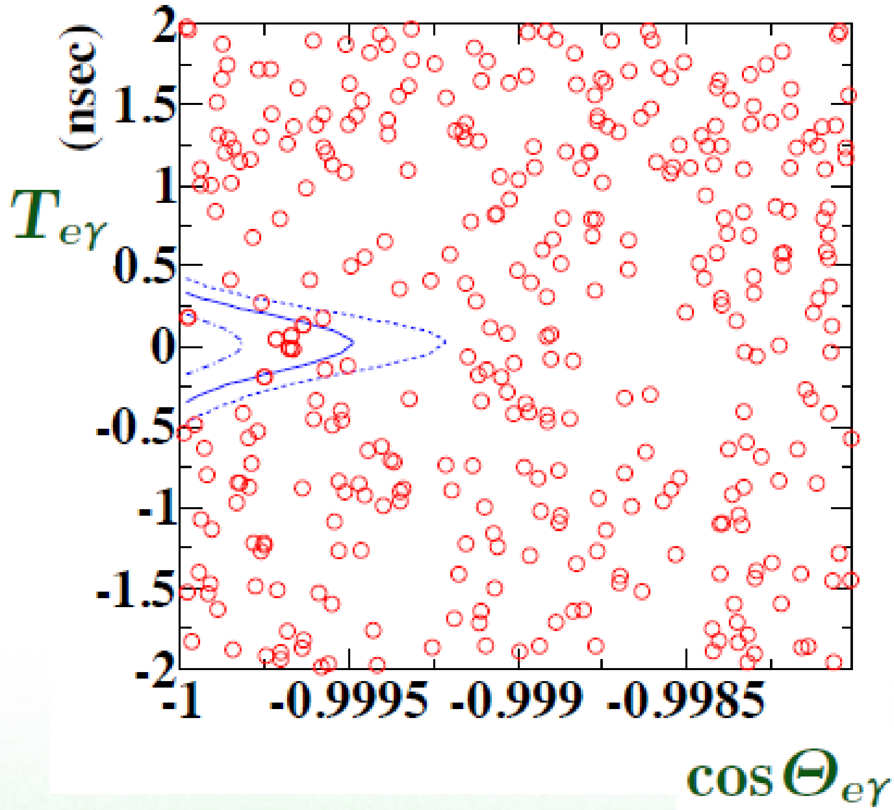
Signal PDF from measured RMD peak

Relative angle

From measured double turn tracks

Event distributions





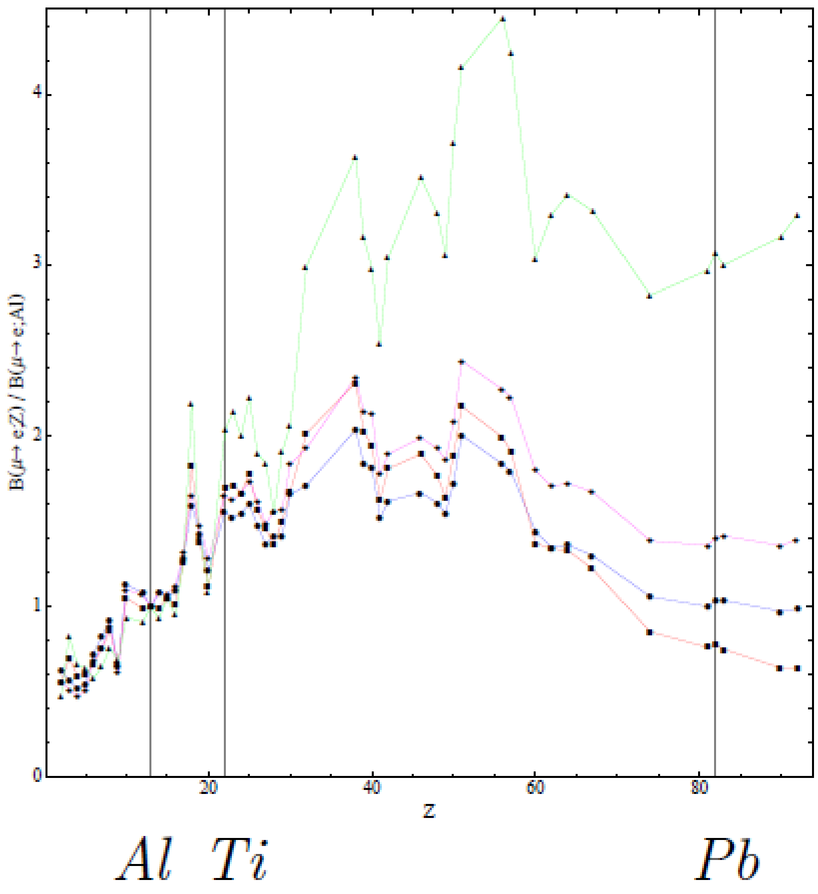
90% efficiency cut (74 for E_γ) on not-showed variables

No excess

Blue lines: 1, 1.5 & 2-σ levels

$\mu^- \rightarrow e^-$ conversion vs Z

Cirigliano, Kitano, Okada, Tuzon, 2009



Dependence of BR on nuclear charge

Theory uncertainties cancel in ratios