MEG, $\mu \to e\gamma$ Search at Paul Scherrer Institute

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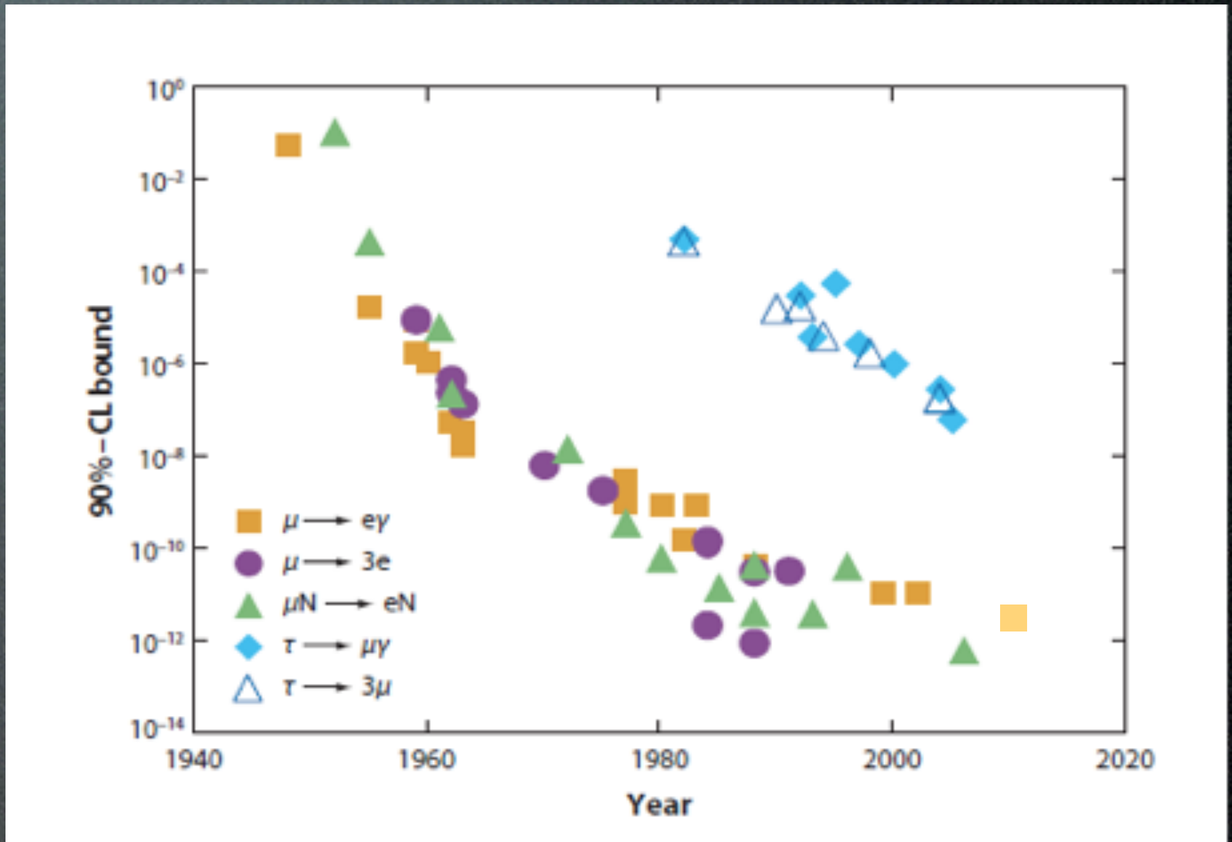
on behalf of the MEG collaboration

Outline

- Introduction
- MEG, μ→eγ search at PSI
  - Experiment method
  - 2009 & 2010 result
  - 2011 run and future prospect
- Future cLFV experiments
- Summary

cLFV search

- Long history since its discovery
- Different motivation at different age



Annu. Ref. Nucl. Part. Sci. 2008. 58:315-41
W. J. Marciano, T.Mori, and J. M. Roney

cLFV search

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. Hincks and B. Pontecorvo
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada

December 9, 1947

THE meson decay process which is identified by a mean life of 2.2 microseconds[1] has been usually thought of as consisting of the emission of an electron and a single neutrino, as suggested by the well-known Yukawa explanation of the ordinary beta-process in nuclei. However, the Yukawa theory is at variance with the results of the experiment of Conversi, Pancini, and Piccioni,[2] and since there remains no strong justification for the electron-neutrino hypothesis,[3] a direct experiment to test an alternative hypothesis—*that the decay process consists of the emission of an electron and a photon, each of about 50 Mev*—has been performed.

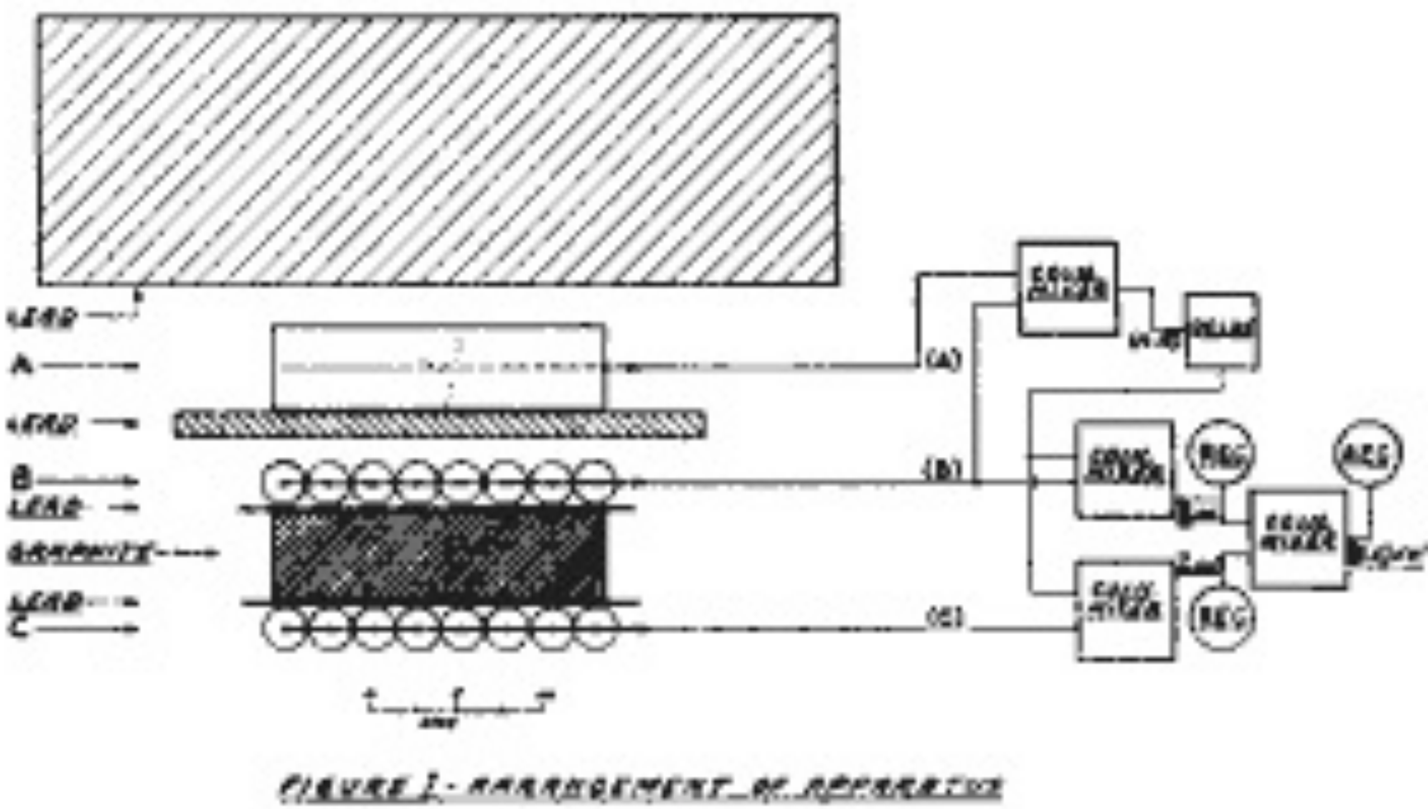


FIG. 1. Arrangement of apparatus.

MEG

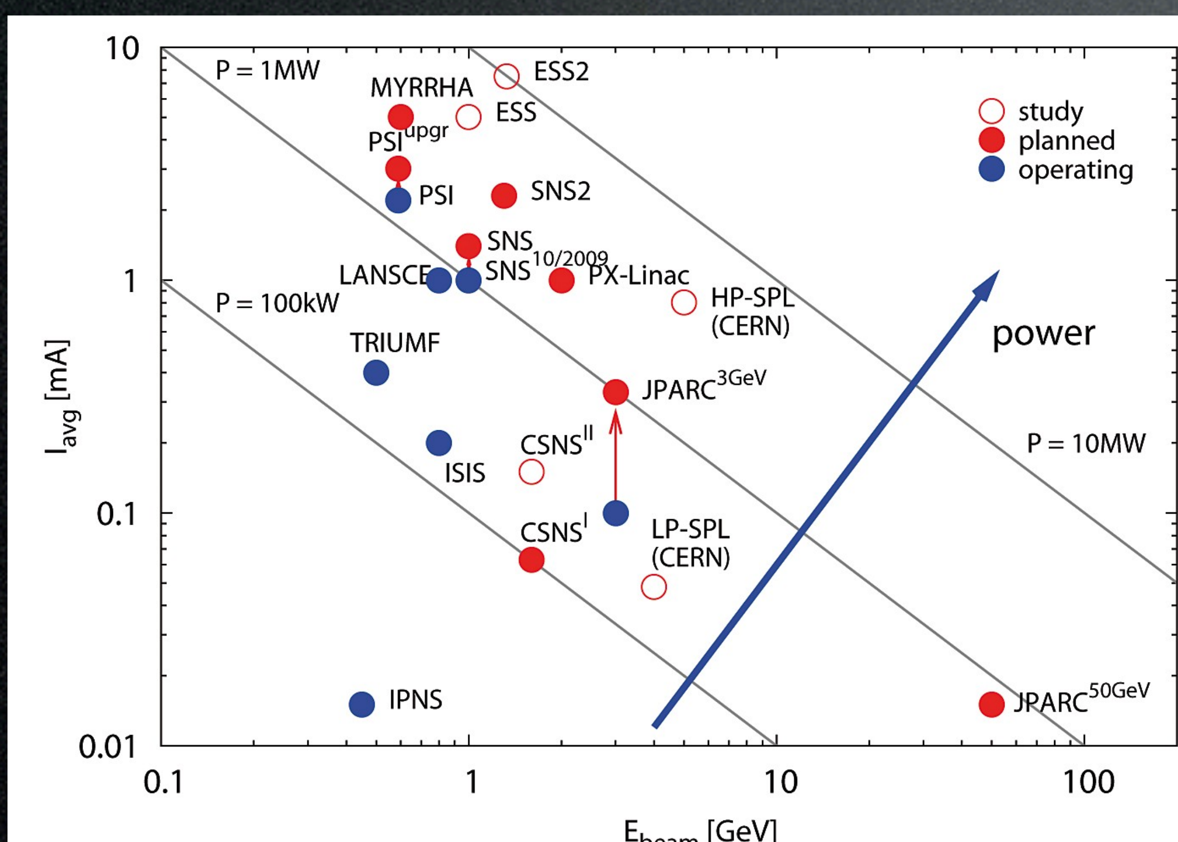
$\mu \rightarrow e\gamma$ Search at PSI

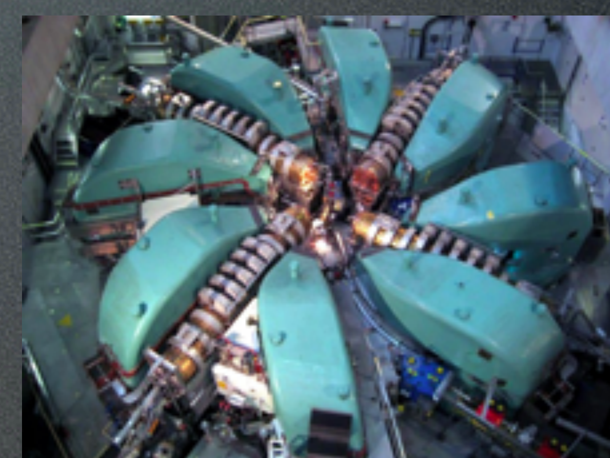
MEG History

1999		Proposal
		...
2007	Dec.	Engineering run
2008	Sep.-Dec.	1st physics data acquisition
2009		Analysis of 2008 data
		Hardware upgrade
	Nov.-Dec.	2nd physics data acquisition
	Dec.-	Analysis of 2009 data
2010	Jul.-Dec.	3rd physics data acquisition
2011	Jun.-Dec.	4th physics data acquisitio

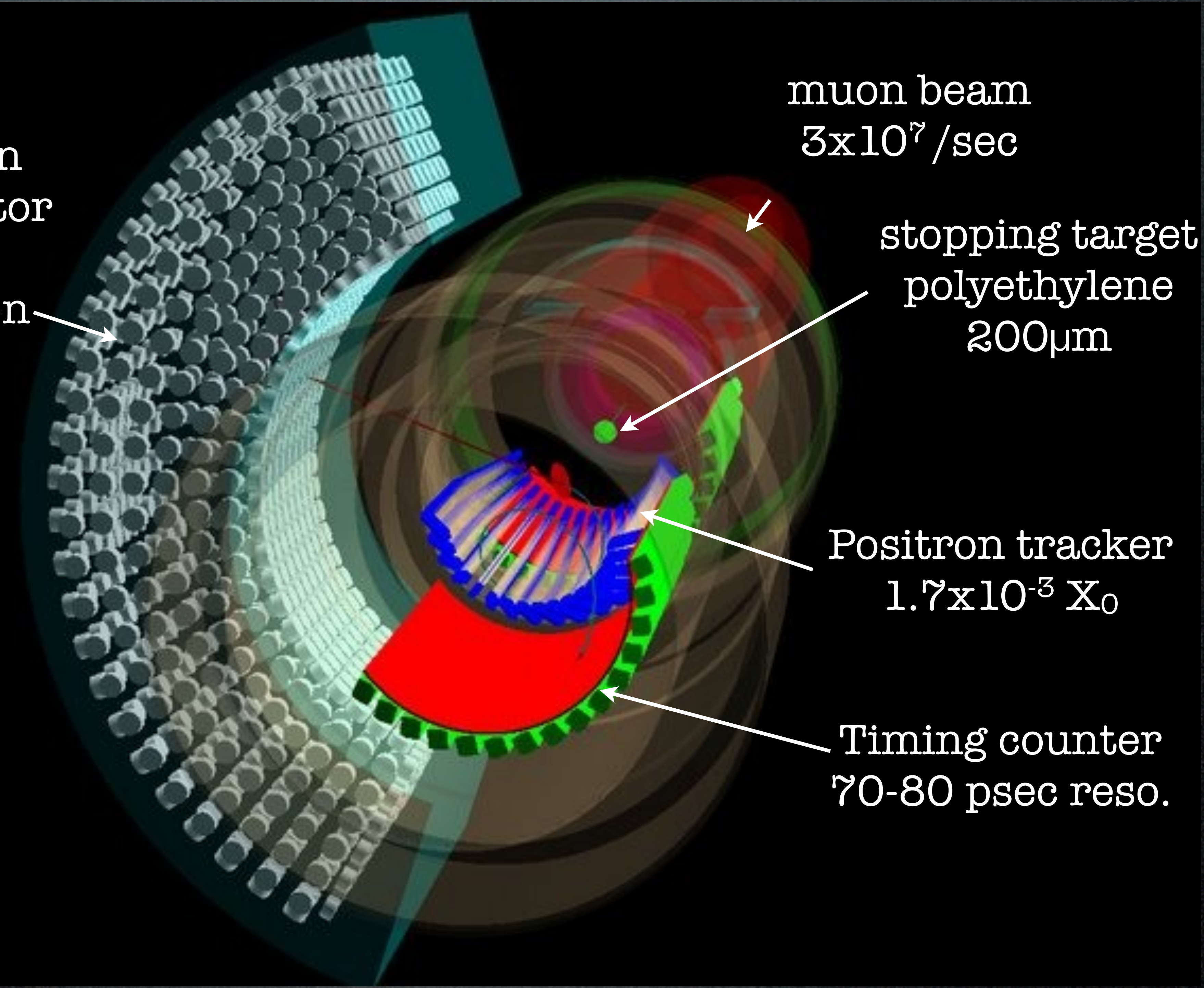
Paul Scherrer Institut Cycrotron

- Proton Energy 590MeV
- Beam current >2.0mA DC
- Time btw pulses 19.75 nsec



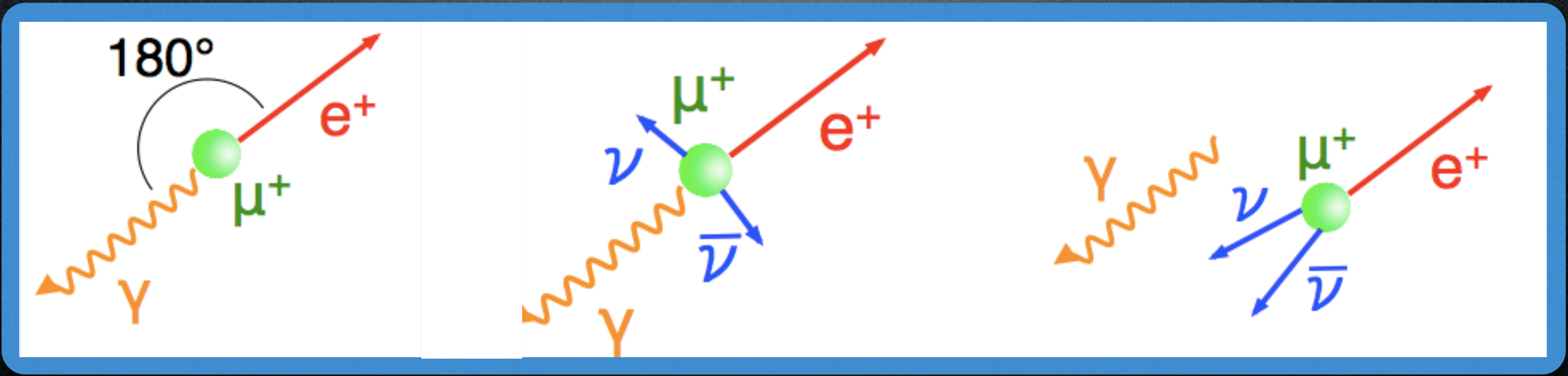


MEG Detector



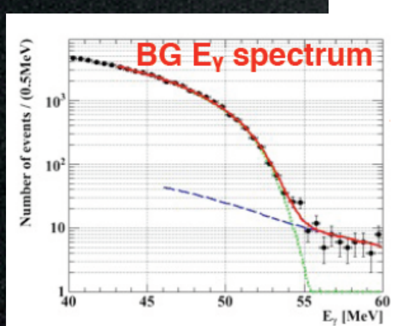
- 日本
- Schweiz
- Italia
- U.S.
- Россия

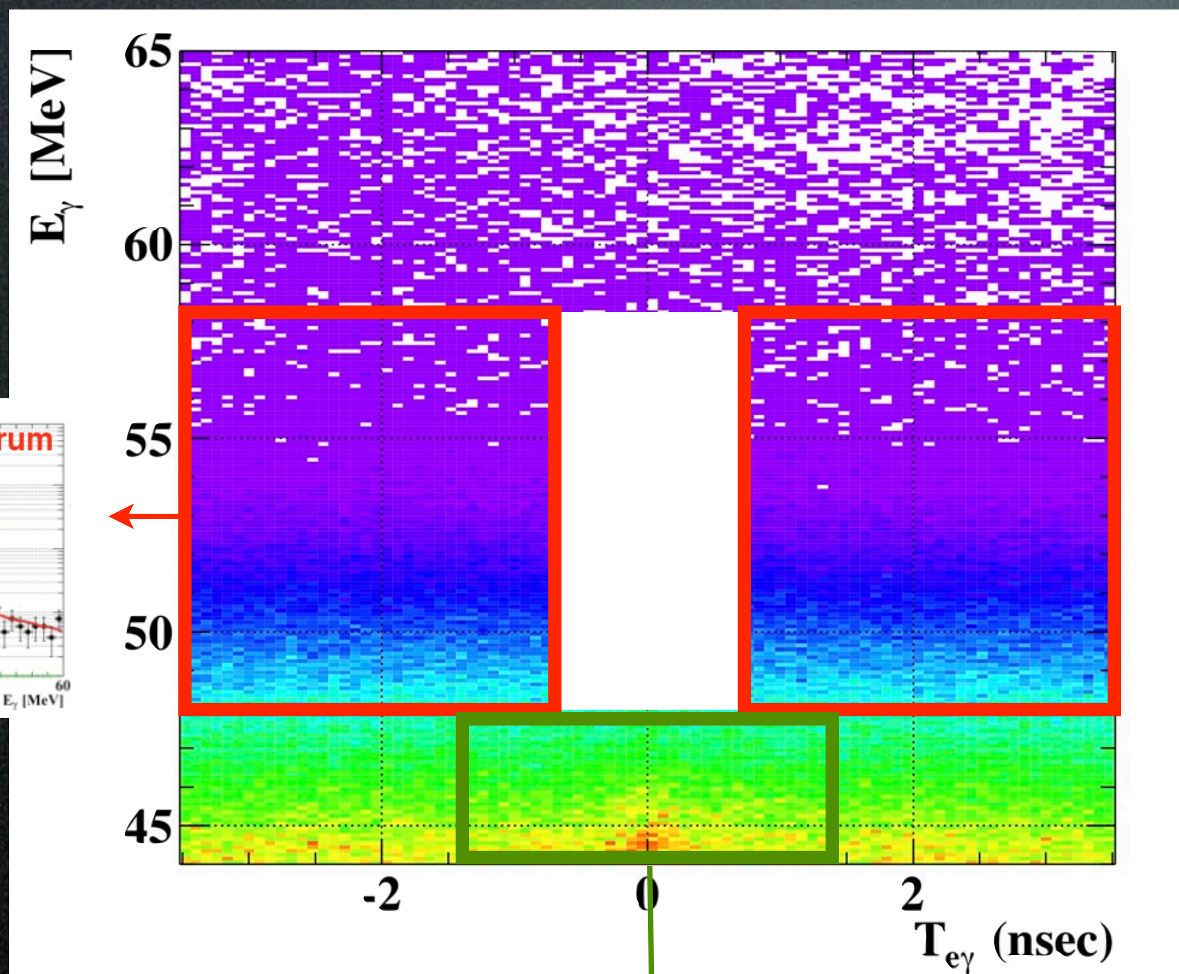
Signal and Background



- Signal
  - Gamma and positron with 52.8MeV
  - Back to back
  - Time coincidence
- Prompt background - Radiative muon decay
  - Gamma and positron < 52.8MeV
  - Any angle < 180°
  - Time coincidence
- Accidental background
  - Gamma and positron < 52.8MeV
  - Any angle
  - Random

MEG Data Analysis





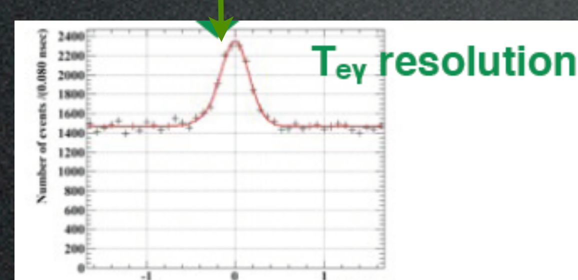
Analysis box (~10σ width)

$48 \leq E_\gamma \leq 58$ MeV

$50 \leq E_e \leq 56$ MeV

$|T_{e\gamma}| \leq 0.7$ ns

$|\phi_{e\gamma}|, |\theta_{e\gamma}| \leq 50$ mrad



- Blind Analysis
- Calibration, BG study using side band data
- PDF

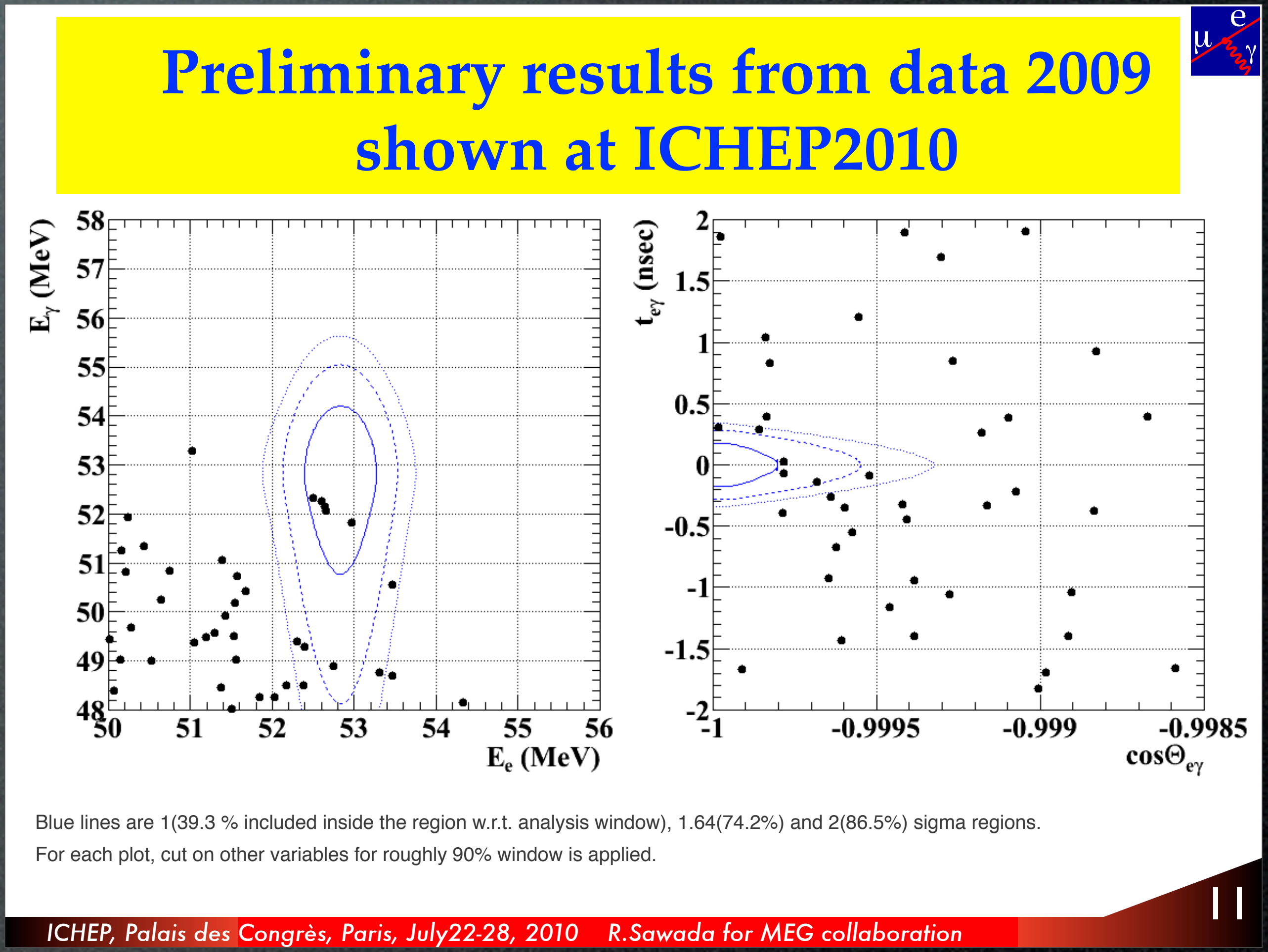
MEG Data Analysis

- Maximum likelihood analysis to extract N_{signal}
  - Three event types: signal, radiative μ decay (RMD), accidental BG
  - Observables x_i: E_γ, E_e, $T_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$
  - Fit parameters: N_{signal}, N_{RMD}, N_{BG}
- Probability Density Function (PDF) is evaluated (mostly) from data
  - Signal: measured detector response function
  - RMD: theoretical spectrum convoluted with detector response
  - BG: BG spectrum measured in side-bands

$$L(N_{sig}, N_{RMD}, N_{BG}) = \frac{N^{N_{obs}} e^{-N}}{N_{obs}!} \prod_{i=1}^{N_{obs}} \left[\frac{N_{sig}}{N} S + \frac{N_{RMD}}{N} R + \frac{N_{BG}}{N} B \right]$$

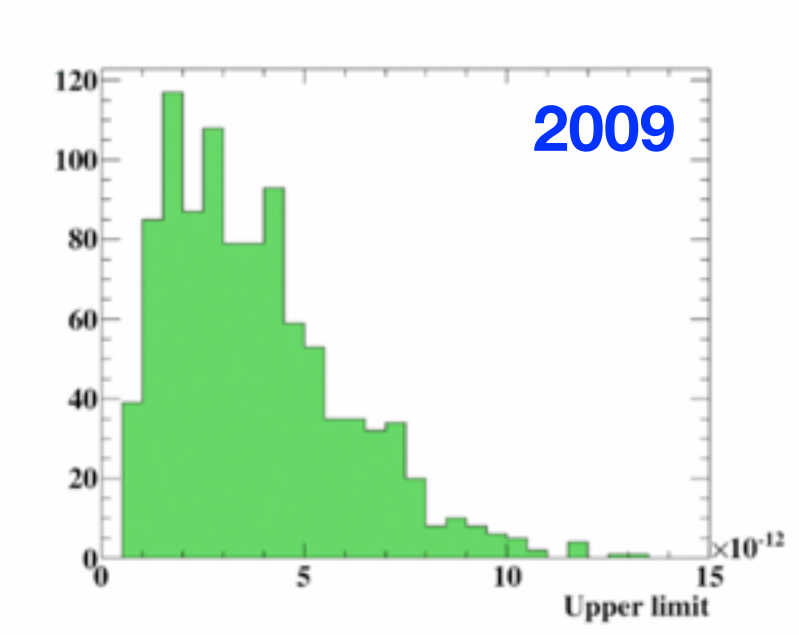
MEG 2009 Result
presented at ICHEP 2010

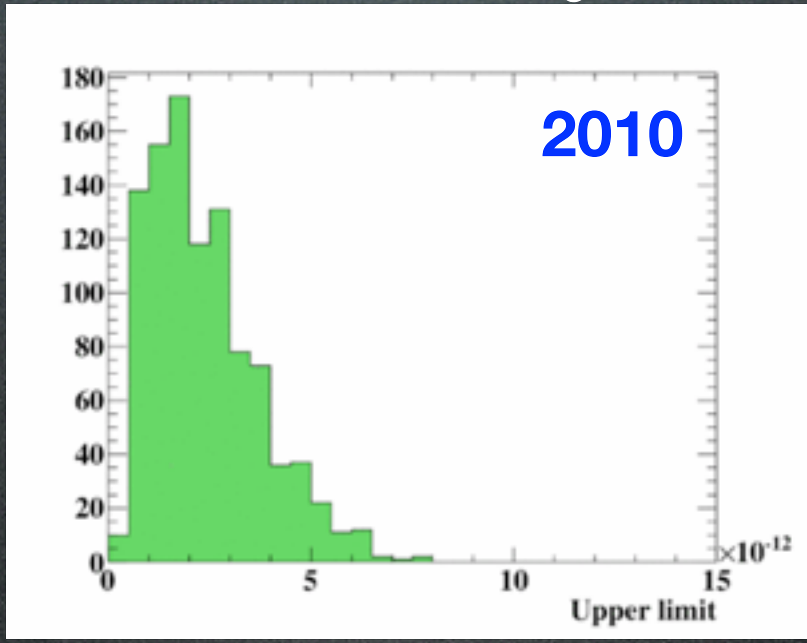
- Preliminary 2009 result with a small excess shown at ICHEP 2010
- Analysis updates including new data (run2010)
    - Data 2010 (data statistics = 2 × data 2009)
    - Improve detector alignment
    - More detailed implementation of correlations in positron observables
    - Improve magnetic field map
    - Improve likelihood analysis tool
- New result from analysis on combined data sample for run 2009+2010 was published in Oct.'11.

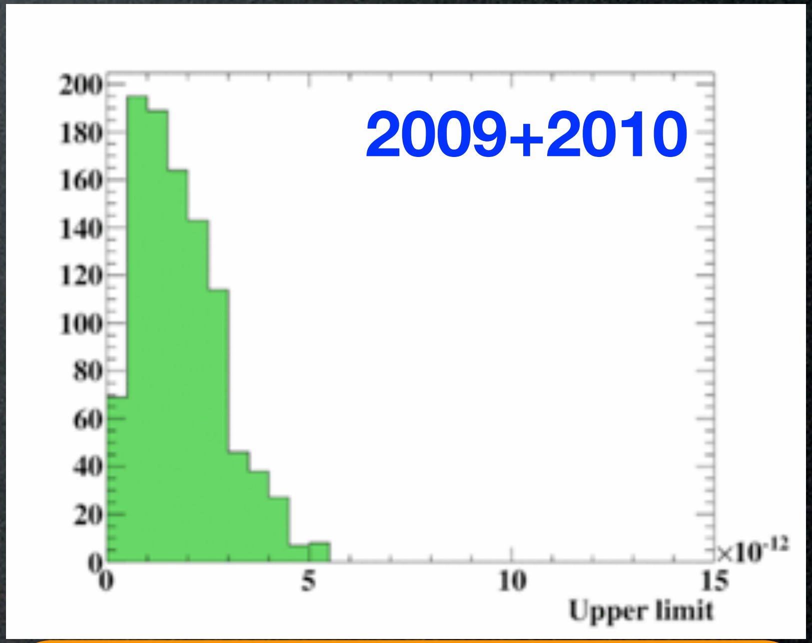


Sensitivity (data 2009+2010)

- **Sensitivity**
  - Upper limit averaged over an ensemble of many toy MC experiments with BG only hypothesis with BG rate measured in side-bands
  - Consistent with side-band data analysis result



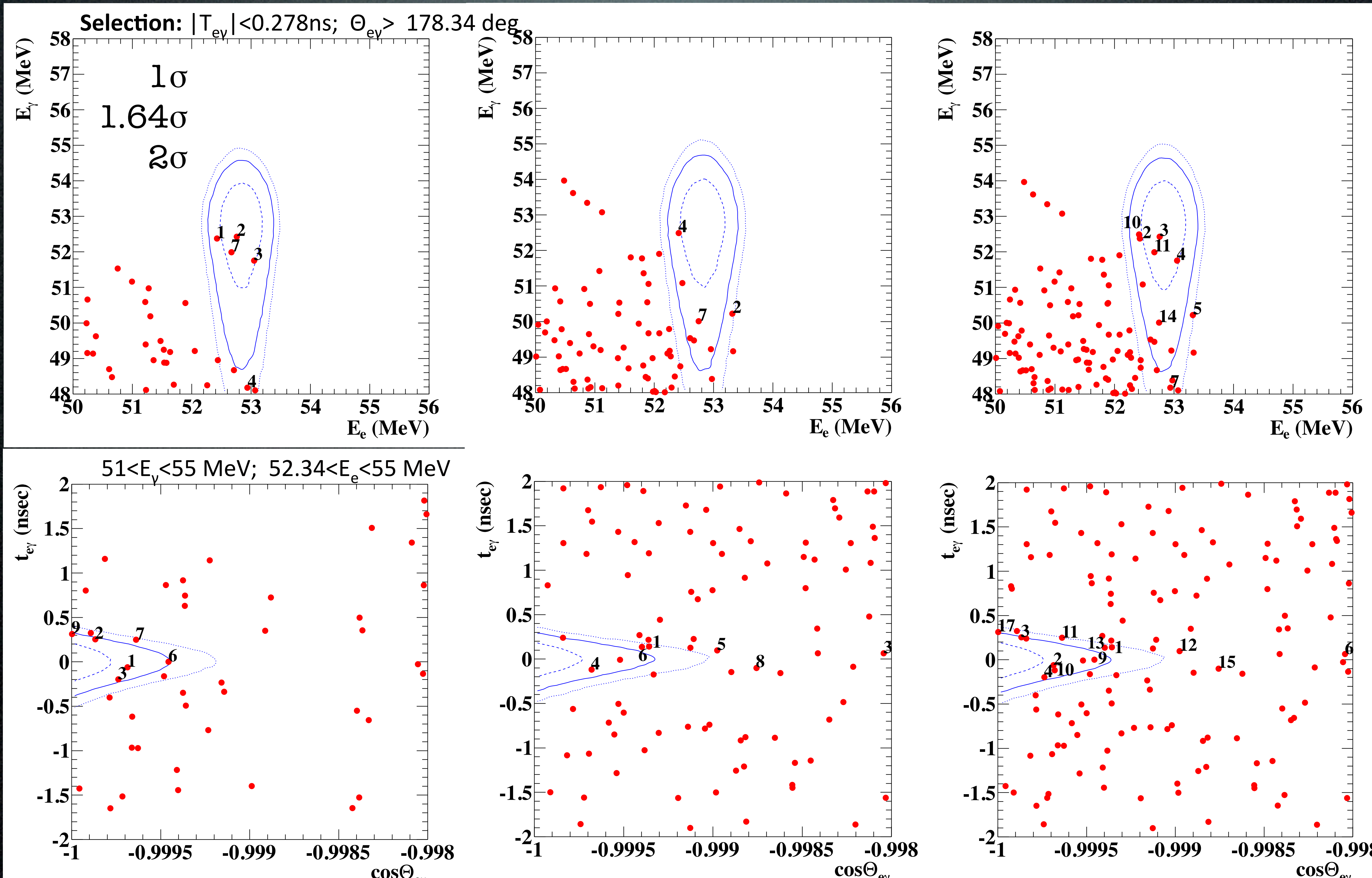




$\mathcal{B} = 3.3\times10^{-12}$ (median) $\mathcal{B} = 2.2\times10^{-12}$ (median) $\mathcal{B} = 1.6\times10^{-12}$ (median)

Sensitivity(2009+2010) is ×8 better than previous best upper limit ($B<1.2\times10^{-11}$ (90%C.L.) MEGA 1999)

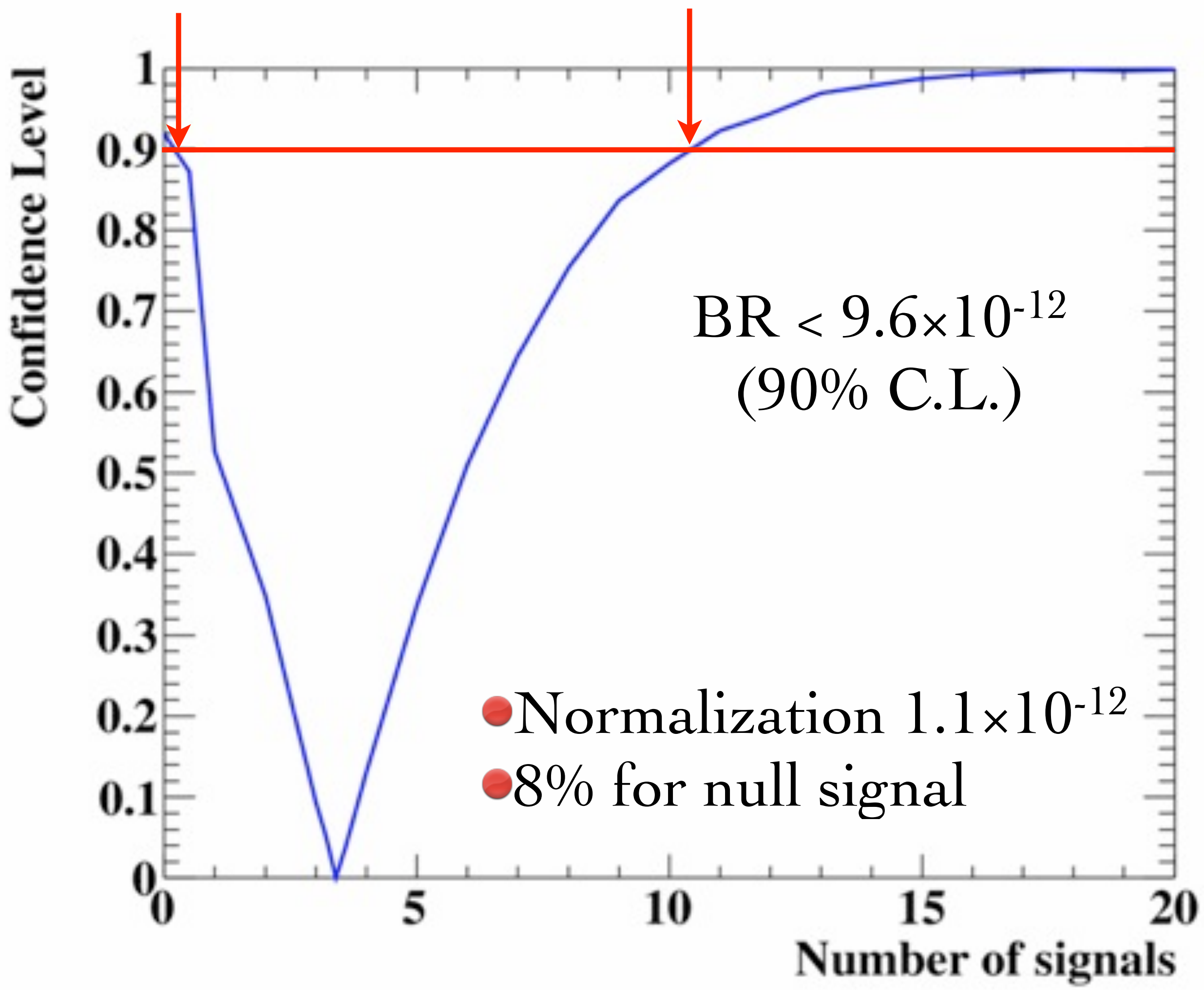
2009 2010 2009+2010



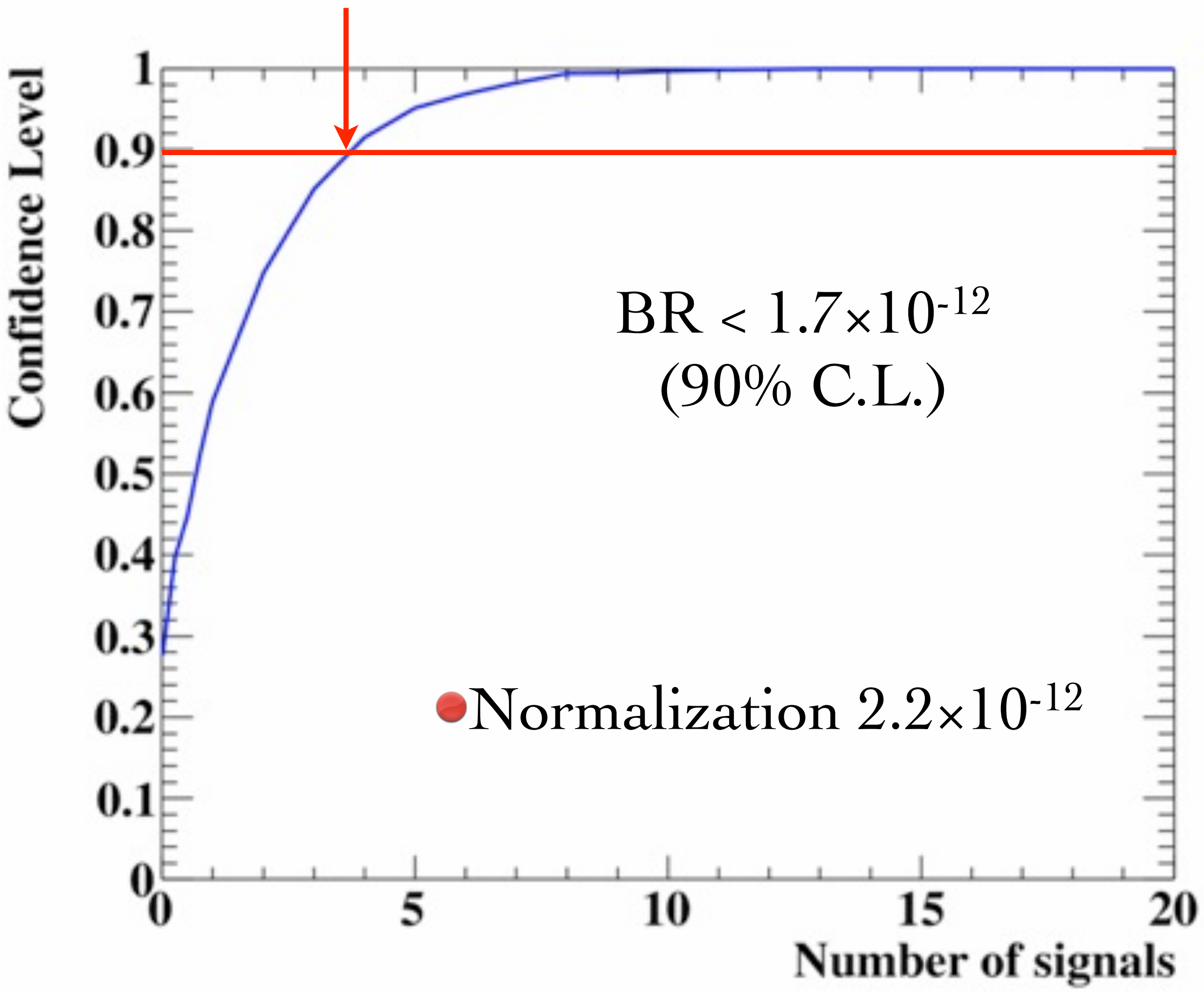
Just for reference, not used in the analysis

Confidence Level Curves

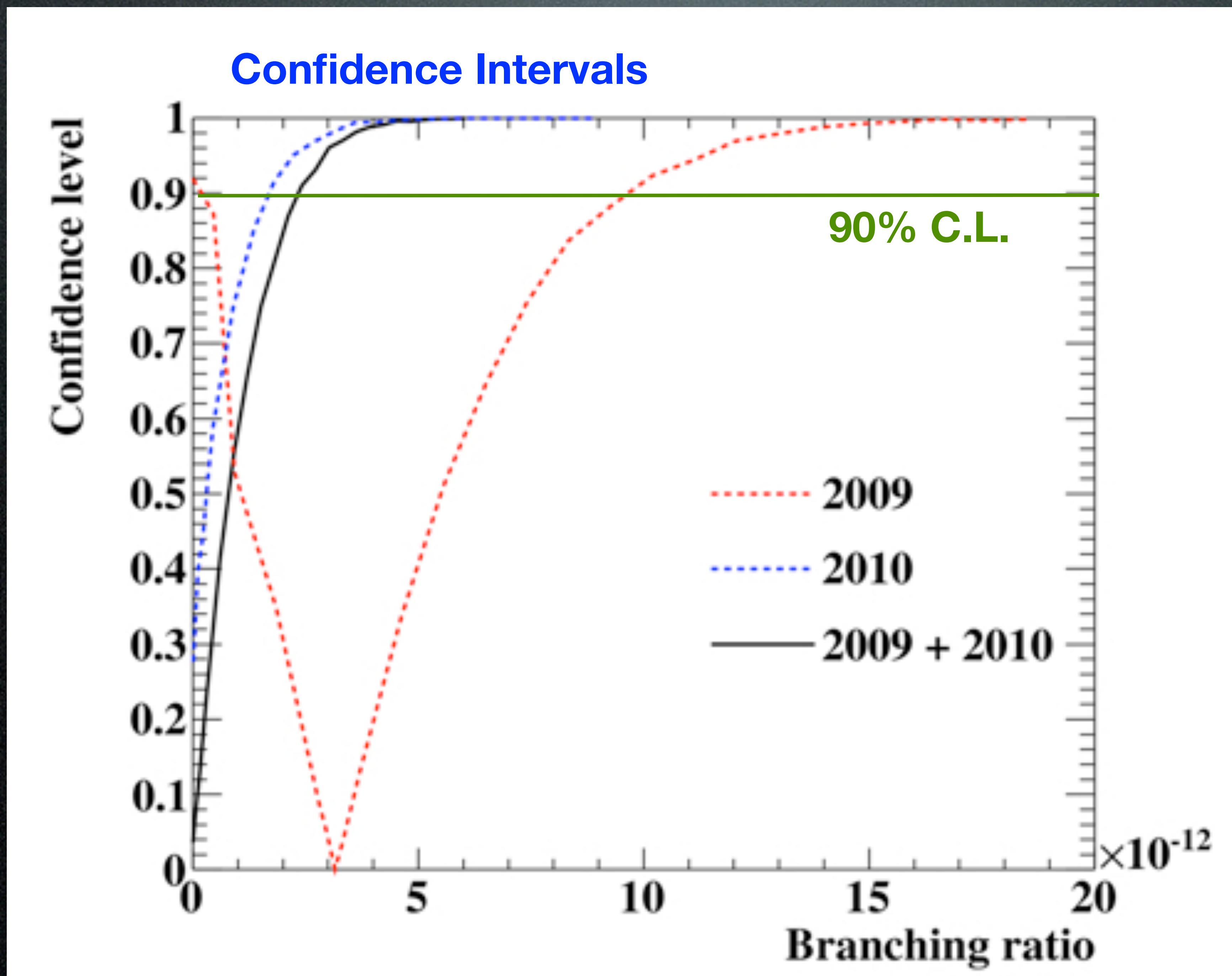
2009



2010



Combined Result



宇宙の始まりを説明する「大統一理論」の証明に向け、東京大学を中心とする国際チームが進める実験の中間結果が報告された。「ミュー粒子」という素粒子が壊れる、大統一理論が予測する未知の現象を探したが、現時点では発見に至らなかった。さらに2年間、探索を継続する。

宇宙誕生示す「大統一理論」

裏付け現象なお未発見

東大が中間報告
探索は継続

研究チームが探すのは、電子と似た性質をもつミュー粒子が壊れて電子とガンマ線になる現象。標準理論では起こり得ないが、大統一理論では数千億から10兆分の1程度の確率で起こるとされる。スイスにある実験施設を使い、過去の研究の5倍にあたる5千億個のミュー粒子を作り出して観測した。

予備実験で「兆候」が見つかり期待が高まっていたが、崩壊現象は結局見つからなかった。実験を率いる東大の森俊則教授は「かなりがっかりした」と打ち明ける。今後、2年ほどデータを集め、10兆個のミュー粒子を観測して発見に挑む。

もし崩壊が見つからなければ、素粒子物理学を支える理論は再構築を余儀なくされ、宇宙誕生の謎も説明できなくなる。

▼**大統一理論** 素粒子物理学の基礎である標準理論を発展させ、新たな素粒子の存在などを考慮に入れて提唱された理論。自然界の4つの力のうち重力を除く3つが元は1つだったとする。約137億年前に宇宙が誕生した直後に急膨張する「インフレーション」を起こしてビッグバン（大爆発）に至ったとする説の基礎になっている。

New Result Summary

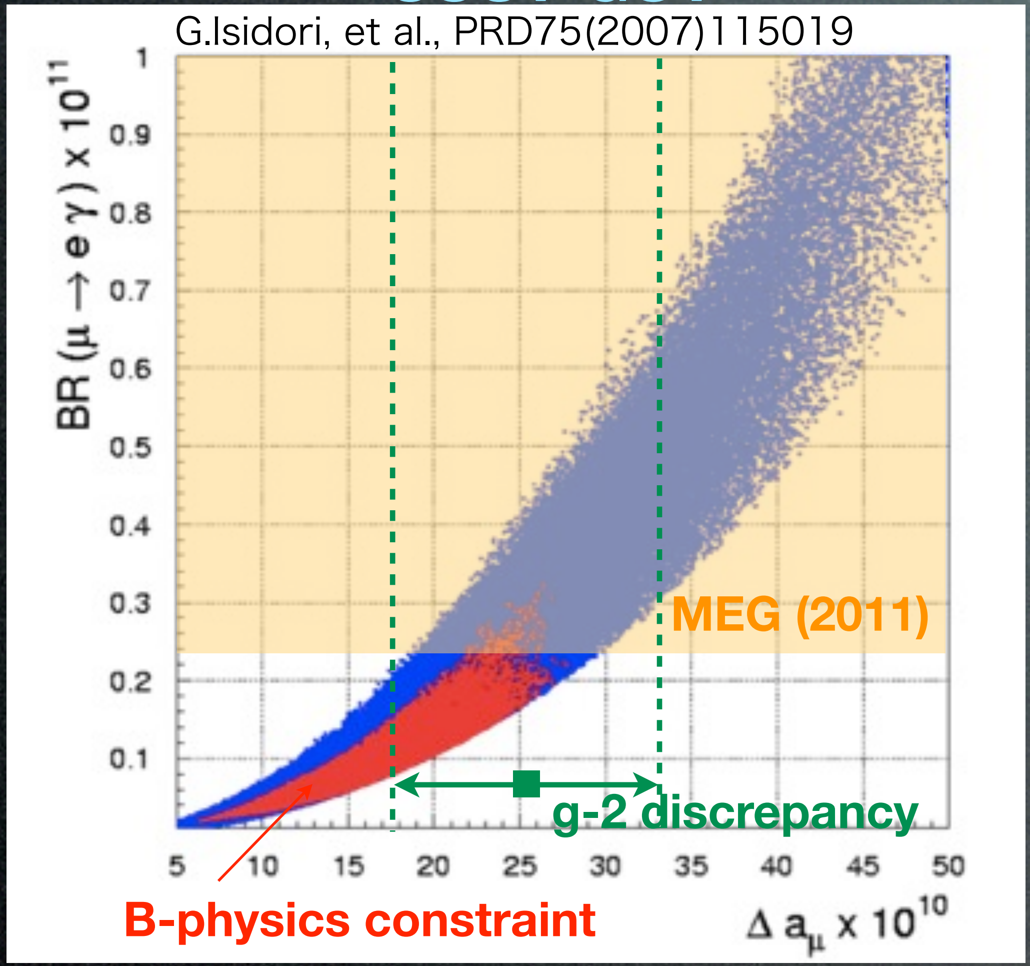
Data set	B_{fit}	Sensitivity	LL	UL
2009	3.2×10^{-12}	3.3×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-12}	2.2×10^{-12}	-	1.7×10^{-12}
2009+2010	-1.5×10^{-12}	1.6×10^{-12}	-	2.4×10^{-12}

- New limit: $Br(\mu\rightarrow e\gamma) < 2.4\text{x}10^{-12}$ @ 90% C.L.
- 5 times more stringent than the previous MEGA limit ($Br < 1.2\text{x}10^{-11}$)
- Published in PRL 107, 171801 (2010)

MEG Constrains NP

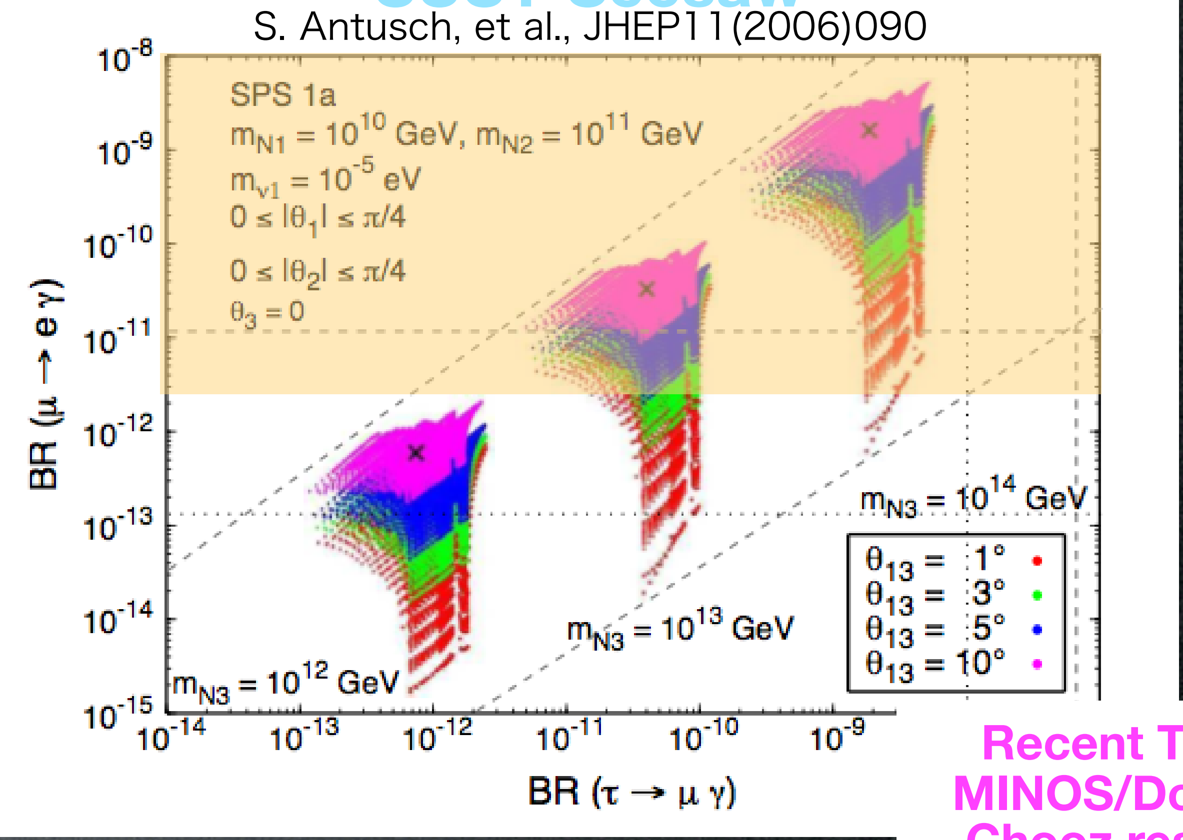
SUSY-GUT

G.Isidori, et al., PRD75(2007)115019



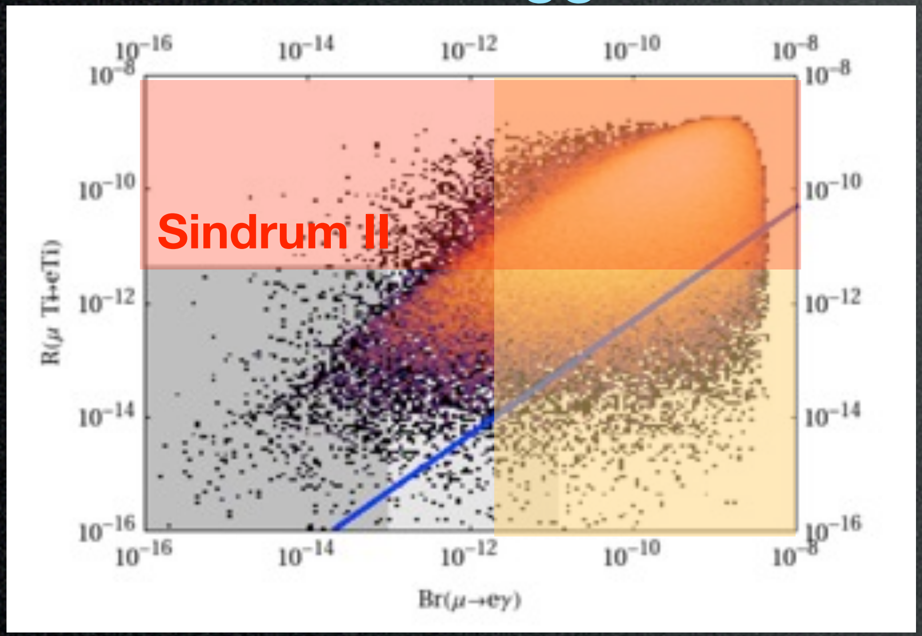
SUSY-Seesaw

S. Antusch, et al., JHEP11(2006)090



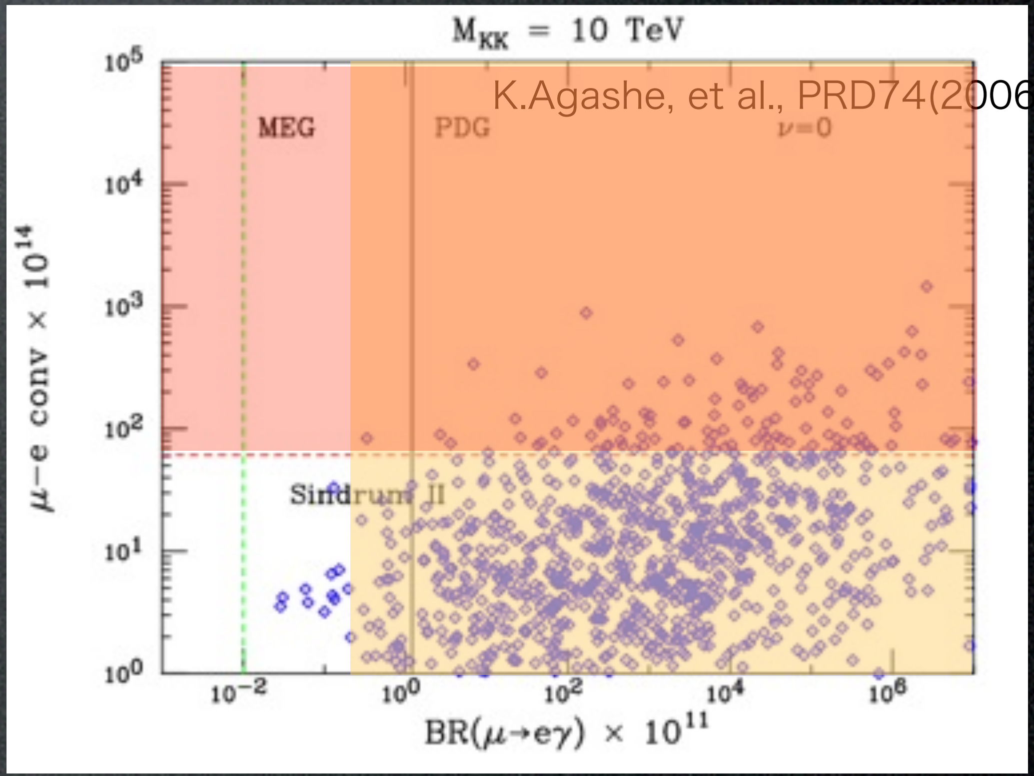
Recent T2K/ MINOS/Double Chooz results favors large θ_{13}!

Little Higgs



M.Blanke et al., Acta Phys.Polon.B41(2010)657

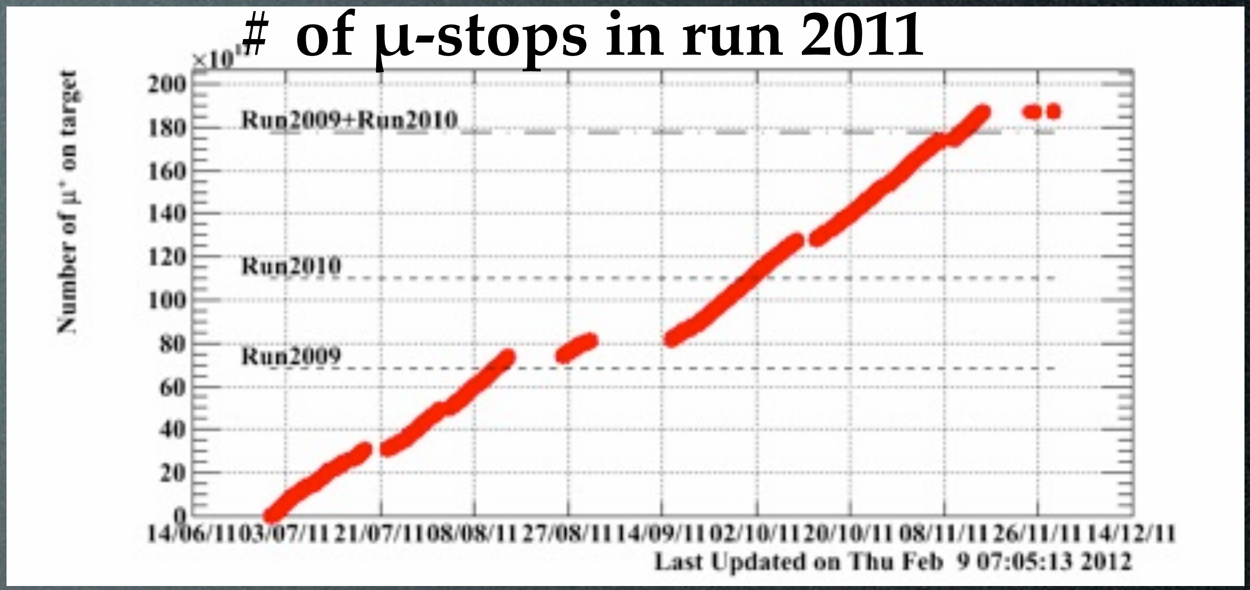
Extra dimensions



2011 Run
and
Future Prospect

2011 Data

- Successful!
- Data statistics doubled !!

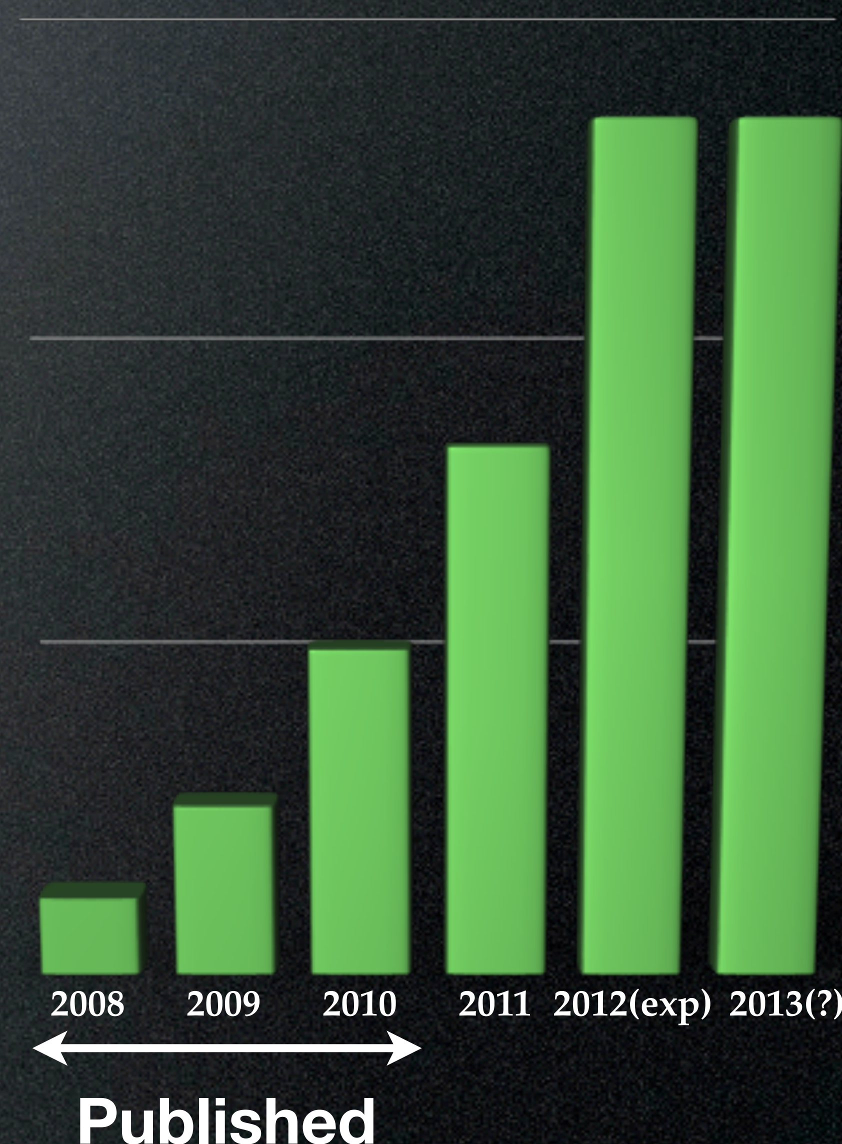


	2009	2010	2011(prelim)
Gamma energy(%)	1.9% (w>2cm)	1.9% (w>2cm)	1.7% (w>2cm)
Gamma position(mm)	5 (u,v) / 6 (w)	5 (u,v) / 6 (w)	←
Positron momentum (%)	0.59 (core 80%)	0.61 (core 79%)	0.61 (core 86%)
Positron angle (mrad)	6.7 (φ, core), 9.4 (θ)	7.2 (φ, core), 11.0 (θ)	6.5 (φ, core), 10.8 (θ)
Vertex position (mm)	1.5 (Z), 1.1 (Y)	2.0 (Z), 1.1 (Y)	1.9 (Z), 1.0 (Y)
Gamma-positron timing (ps)	146 (core)	126 (core)	133
Gamma efficiency (%)	58	59	←
Trigger efficiency (%)	91	92	95
Data statistics (k-factor)	1.1×10^{12}	2.1×10^{12}	3.4×10^{12}

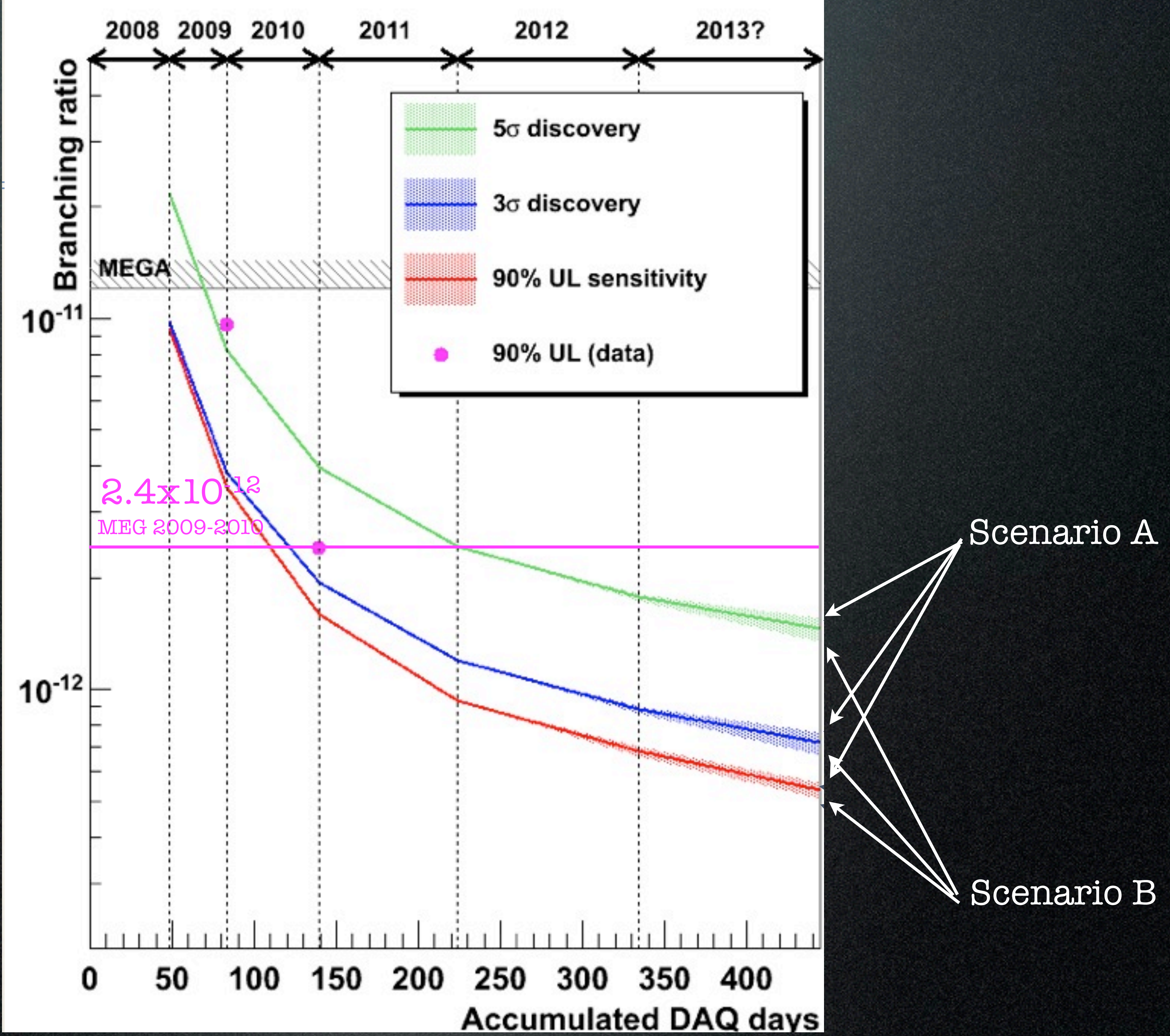
Sensitivity Prospect

- Run 2012 in preparation
- Explorer O(10^{-13}) with 2011+2012 data
- BG is starting to limit the sensitivity improvement → Detector upgrade!

	Scenario A	Scenario B
Gamma energy (%)	1.7% (w>2cm)	1.5 % (w>2cm)
Gamma position (mm)	5 (u,v) / 6 (w)	←
Positron momentum	0.59 (core 80%)	←
Positron angle (mrad)	6.7 (ϕ, core), 9.4 (θ)	←
Vertex position (mm)	1.5 (Z), 1.1 (Y)	←
Gamma-positron timing	126 (core)	←
Gamma efficiency (%)	59	←
Trigger efficiency (%)	95	←
Data statistics (k-factor)	3.4×10^{12} (2011) 5.3×10^{12} (2012) 5.7×10^{12} (2013)	← ← 6.4×10^{12} (2013)

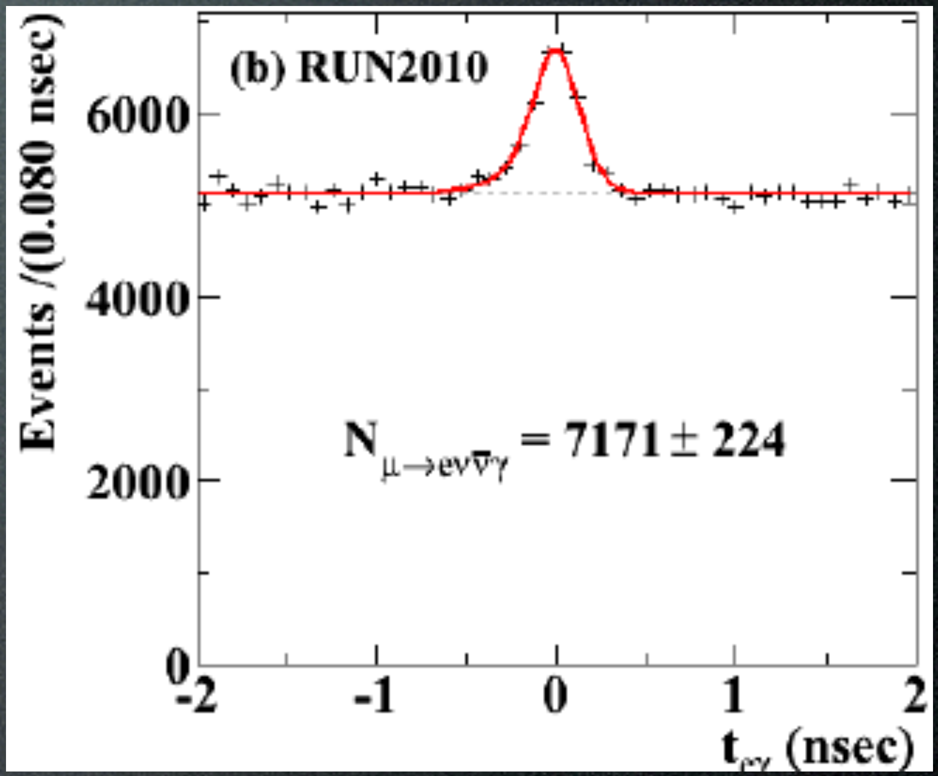


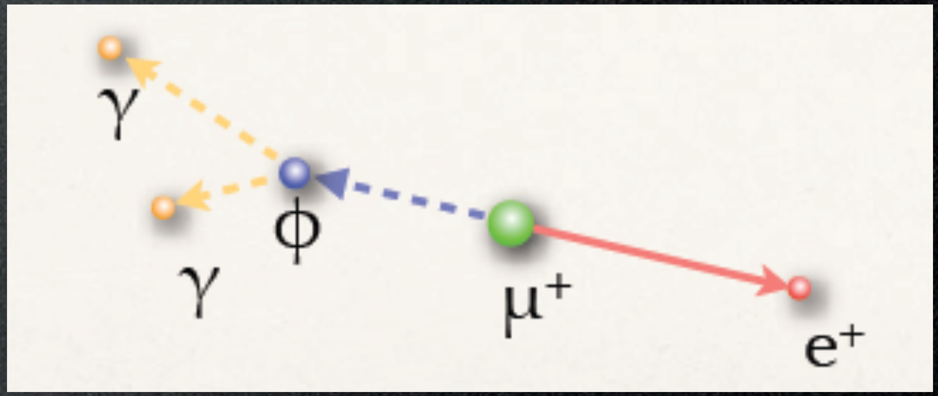
Sensitivity Prospect



Spin-off Physics

- Measurement of Radiative Muon Decay branching ratio and decay parameters, published soon
- Exotic physics searches
  - Search for muon decay mediated by pseudo-scaler particle, published soon
  - Search for muon decay with massless Majoron, analysis in progress





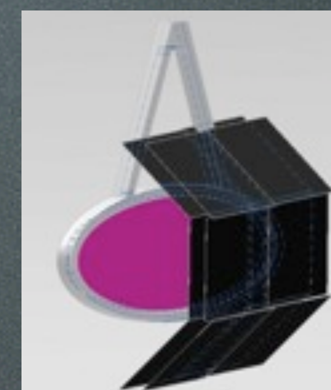
$$\mu^+ \to E^+ + J$$

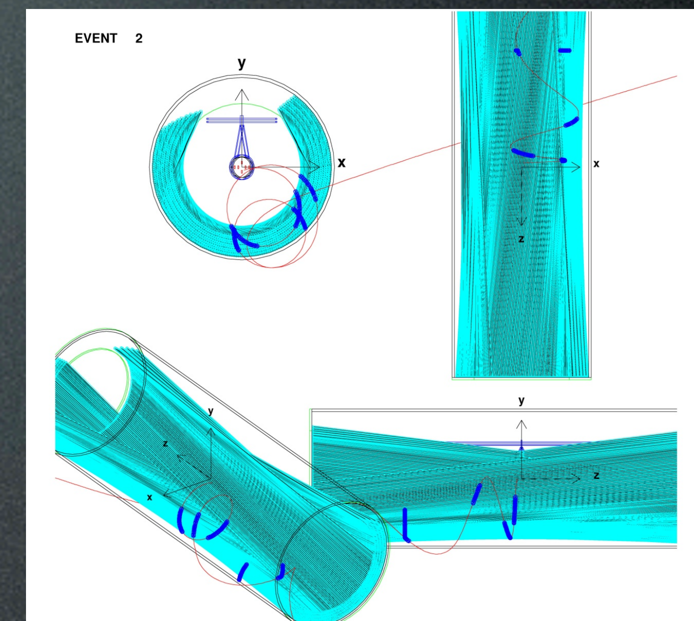
Future Plan

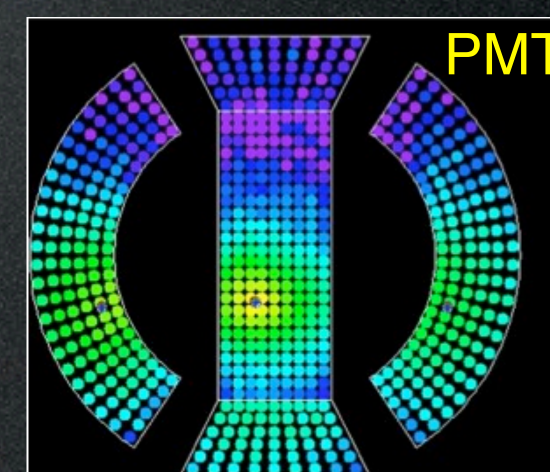
- PSI will certainly stay the best place to perform $\mu \rightarrow e\gamma$ search in next decade
- Limited by accidental pile-ups
    - Need to improve resolutions
- MEG collaboration considers
    - Electron tracker upgrade
    - Photon detector upgrade
    - Vertex detector installation

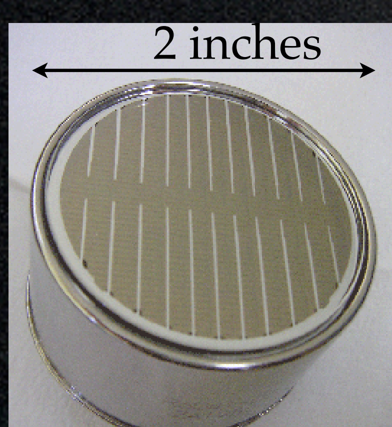
MEG Upgrade Plan

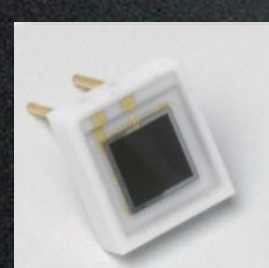
- Positron tracker
  - Wire chamber
    - Single volume
    - Stereo or transverse wires configurations
  - Thin scintillator tracker
  - Silicon vertex detector
- Photon detector
  - Replace current photon sensors (2 inch PMT)
    - PPD or PMT (1 inch)
  - Higher granularity and better coverage
    - Better Energy Resolution and Pile-up rejection

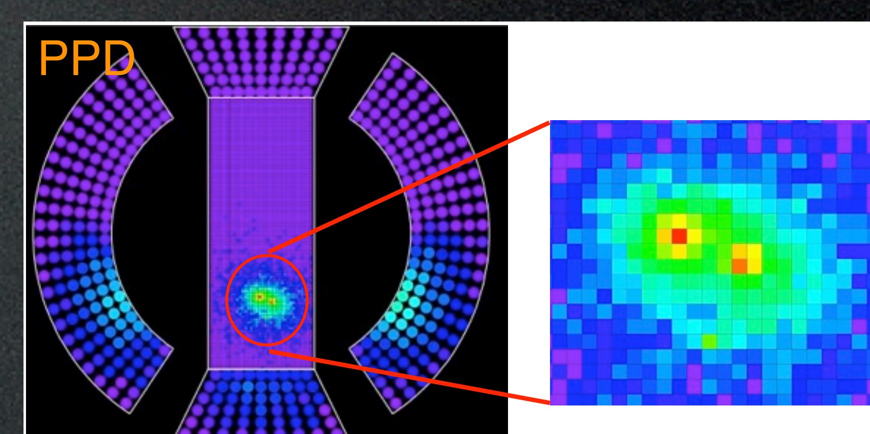










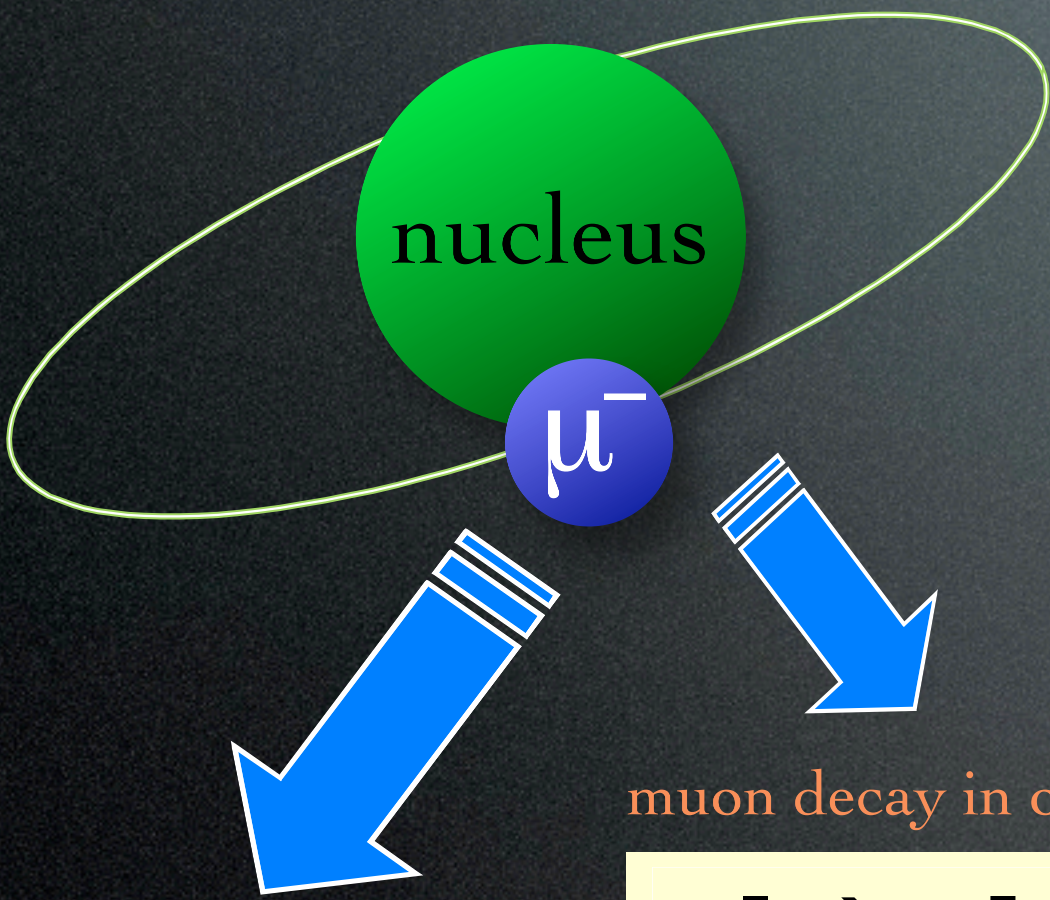


Future cLFV experiments using μ

- μ-e conversion searches
  - DeeMe & COMET at J-PARC
  - Mu2e at FNAL
- μ→eee searches
  - LoI at PSI

μ-e Conversion Searches

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

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

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

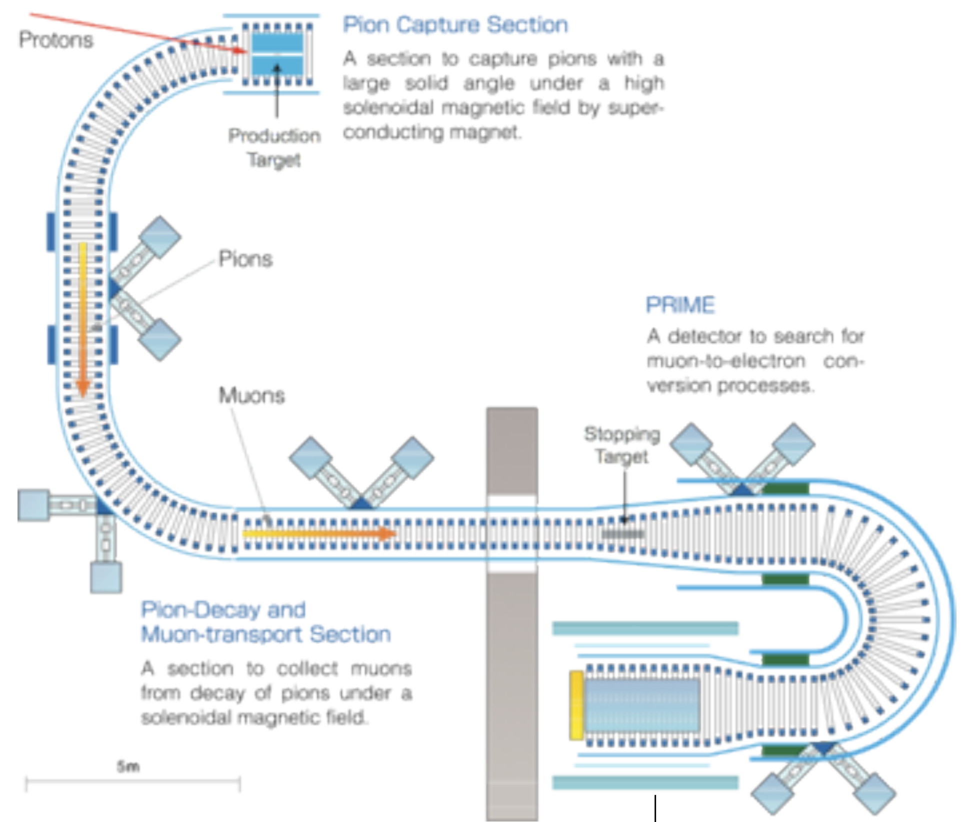
lepton flavours changes by one unit

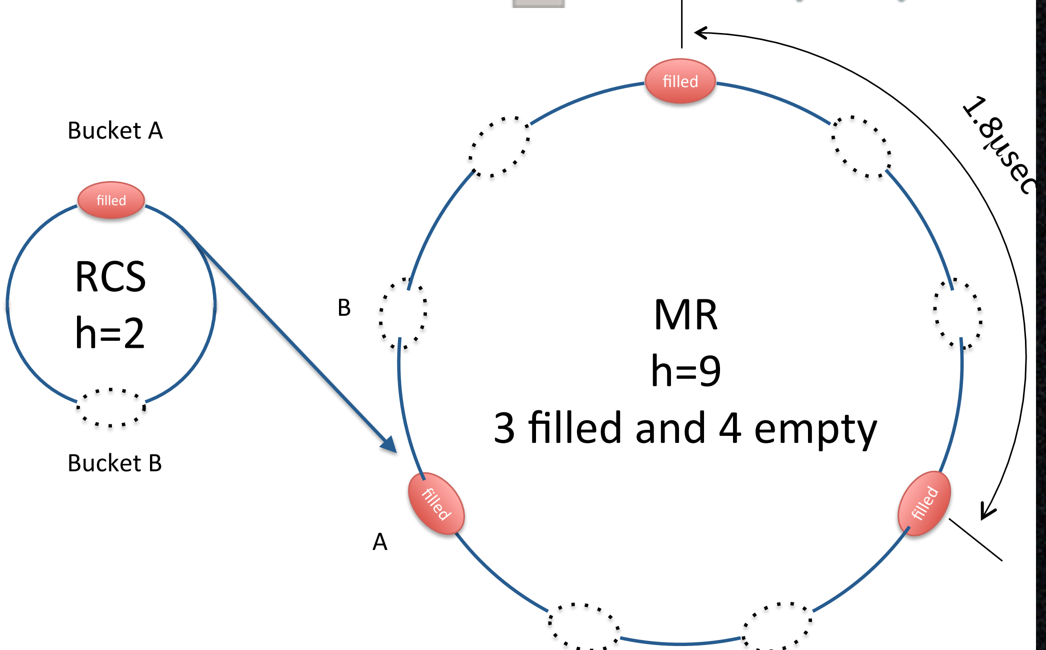
- $E_{\mu e} \sim m_\mu - B_\mu$
  - B_μ: binding energy of the 1s muonic atom

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

COMET at J-PARC

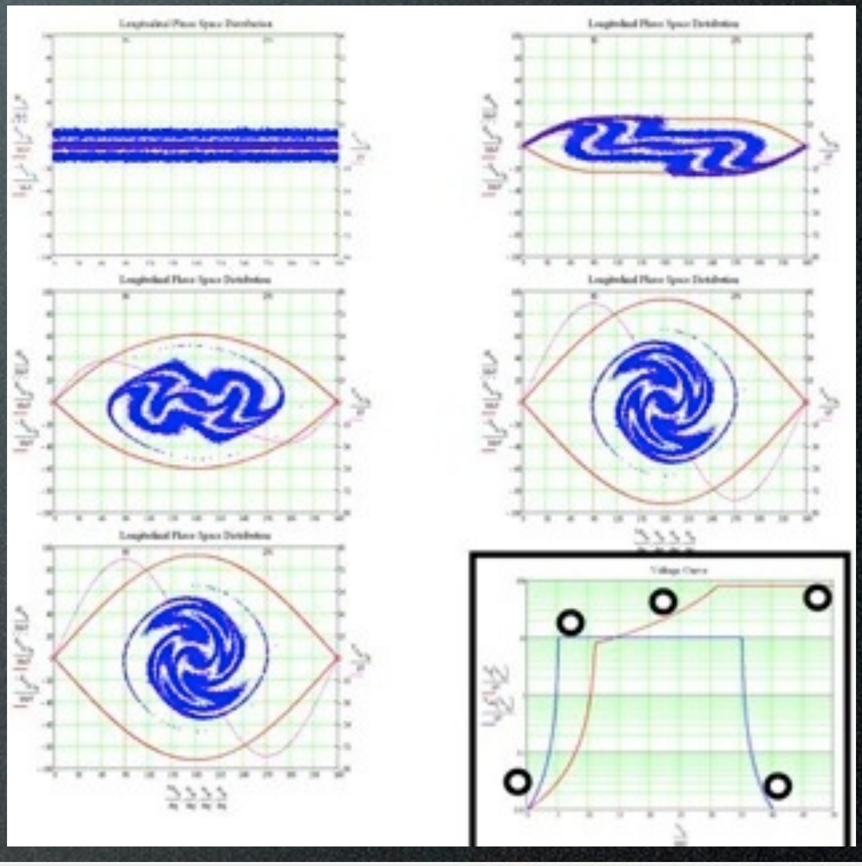
- **Target S.E.S. 2.6×10^{-17}**
- Pulsed proton beam at J-PARC
  - Insert empty buckets for necessary pulse-pulse width
  - bunched-slow extraction
- pion production target in a solenoid magnet
- Muon transport & electron momentum analysis using C-shape solenoids
  - smaller detector hit rate
  - need compensating vertical field
- Tracker and calorimeter to measure electrons
- Recently staging plan showed up. The collaboration is making an effort to start physics DAQ as early as possible under this.

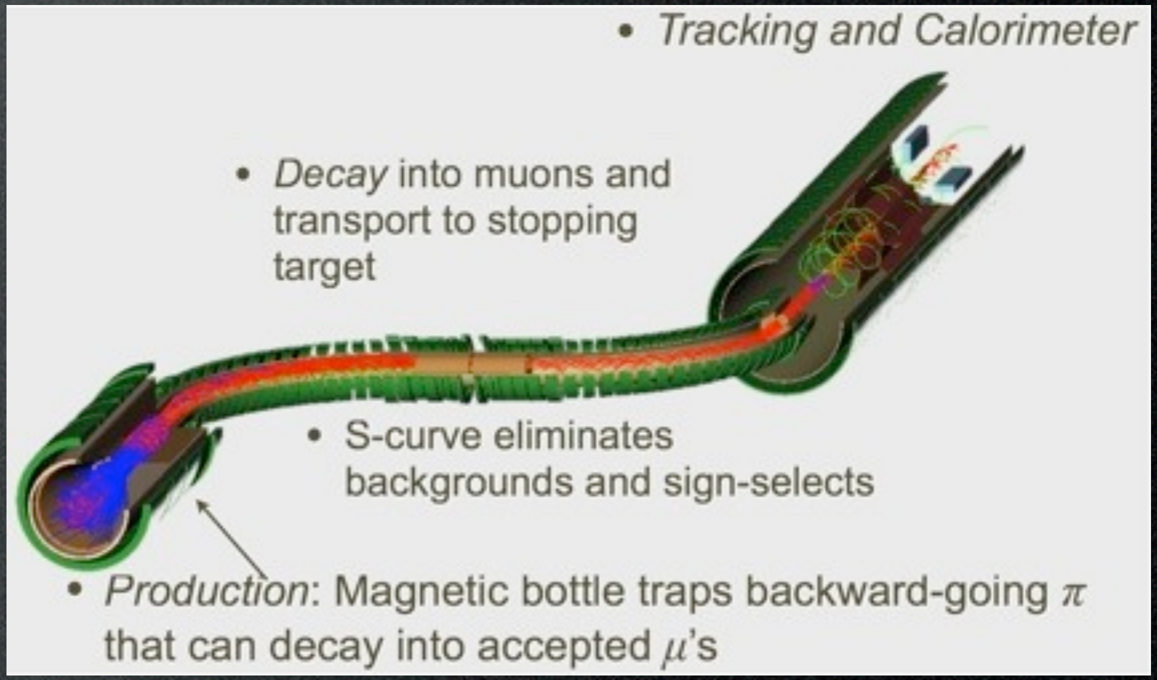




Mu2e at FNAL

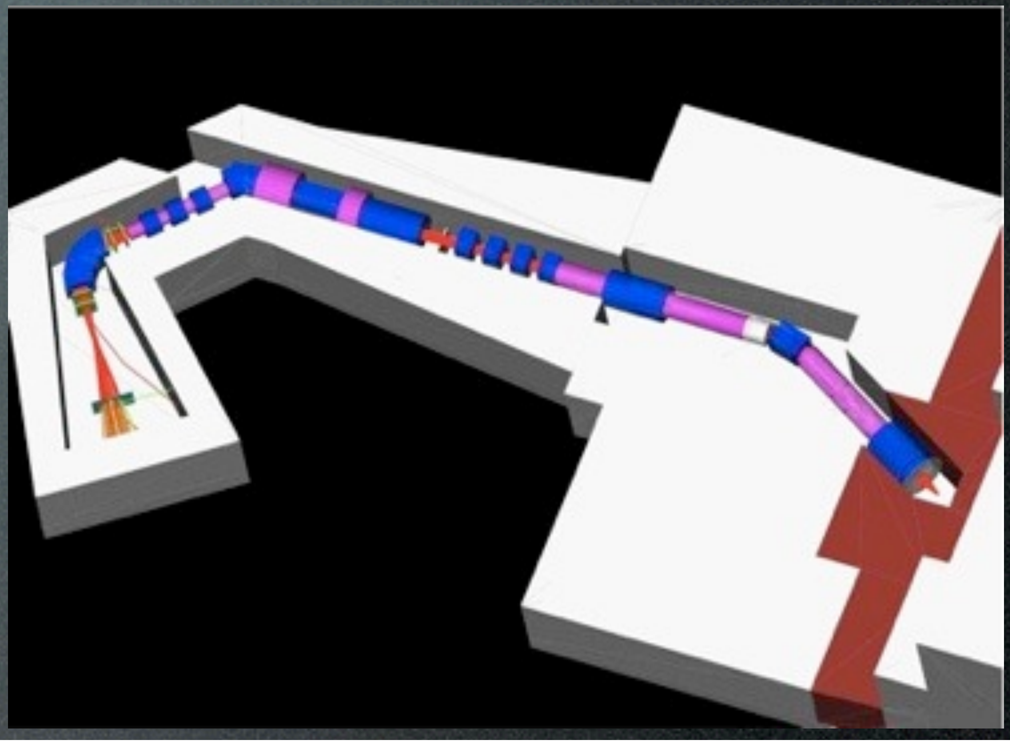
- **Target S.E.S. 2×10^{-17}**
- uses the antiproton accumulator/ debuncher rings to manipulate proton beam bunches
- No interference with NOvA experiment
  - Mu2e uses beam NOvA can't
- pion production target in a solenoid magnet
- S-shape muon transport to eliminate BG and sign-select
- Tracker and calorimeter to measure electrons

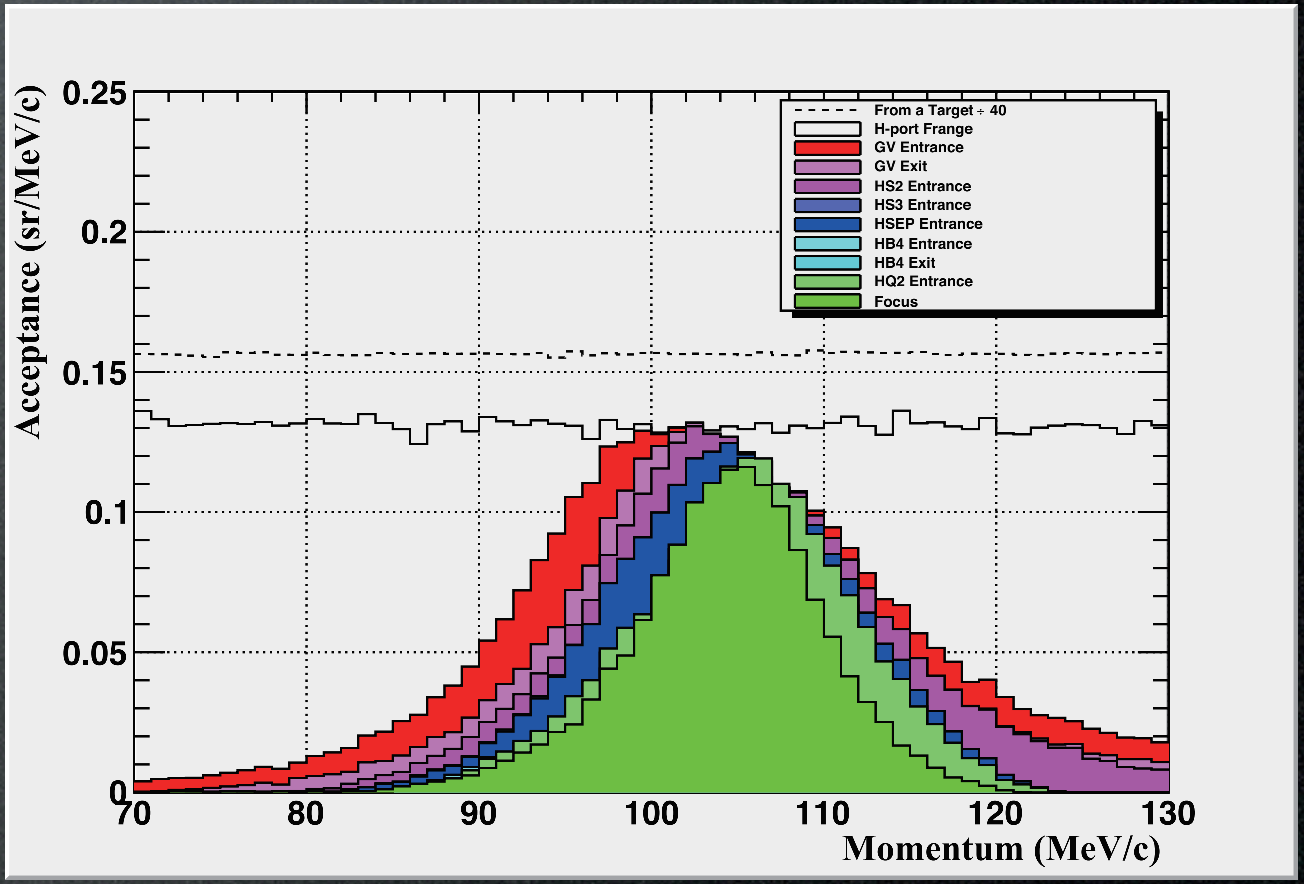




and DeeMe at J-PARC

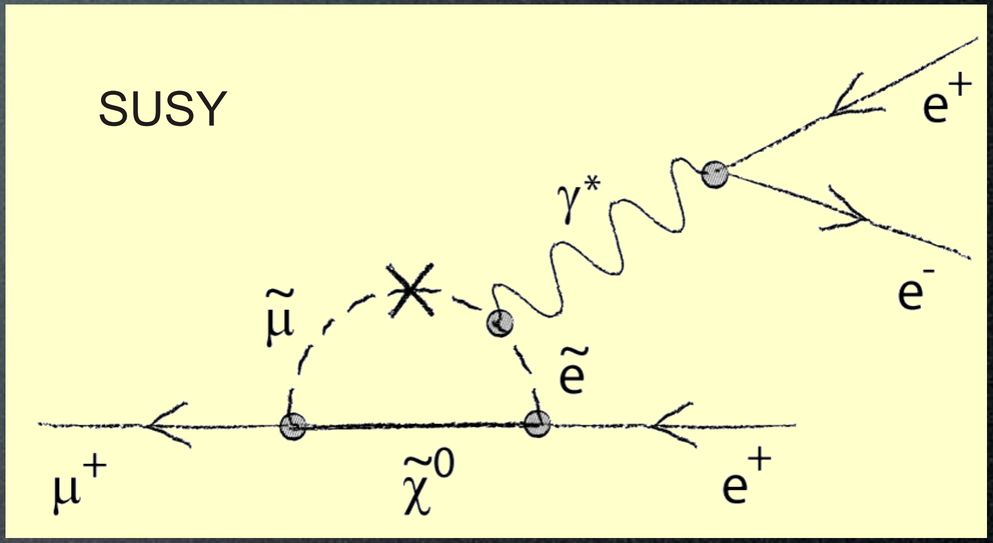
- **mu-e conversion search at J-PARC with a S.E.S. of 10^{-14}**
- Primary proton beam from RCS
  - 3GeV, 1MW
- Pion production target as a muon stopping target
- Beam line as a spectrometer
  - Kicker magnets to remove prompt background
- Multi-purpose beam line for DeeMe, HFS, g-2/EDM is under construction

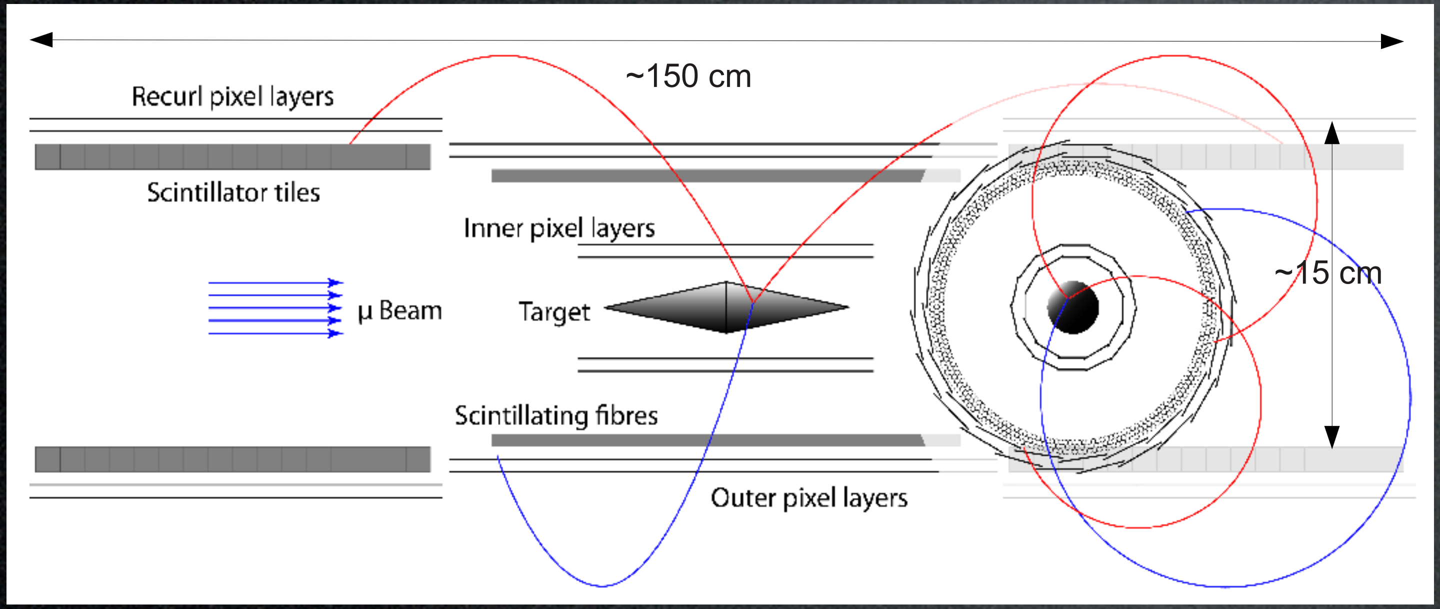


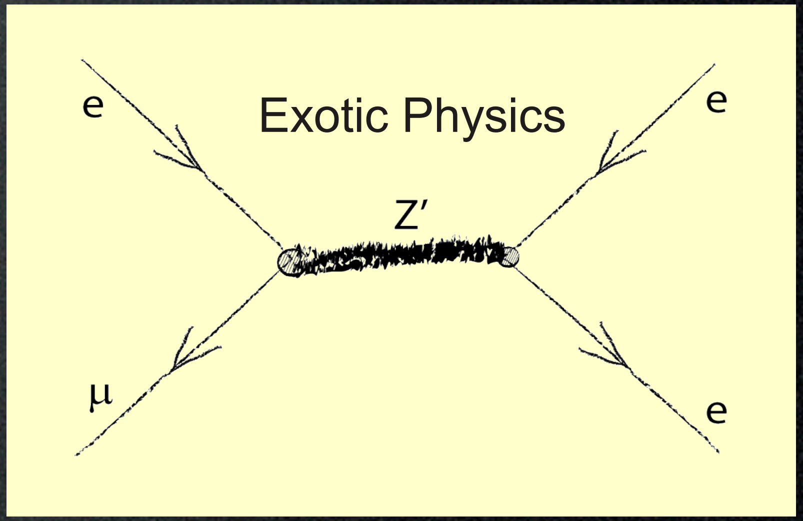


μ→eee Search at PSI

- Plan to search for μ→eee using PSI muon beam
  - SINDRUM limit in 1988 1.0×10^{-12}
  - **Target sensitivity 10^{-16}**
- Thin pixel silicon tracker and scintillating fiber timing counter
- LoI presented at PSI Users' meeting in Feb/2012
  - Proposal foreseen in 2013







Summary

- MEG updated the BR($\mu \rightarrow e\gamma$) upper limit 2.4×10^{-12} at 90% C.L.
- 2011 data analysis in progress
- More data in 2012 to explorer the branching ratio region of $O(10^{-13})$
- Detector upgrade R&D in progress
    - aiming at sensitivity of $O(10^{-14})$
- New cLFV experiments using μ are in preparation