
THE UNIVERSITY OF TOKYO

Flavor Physics

# Charged lepton: results and future prospects

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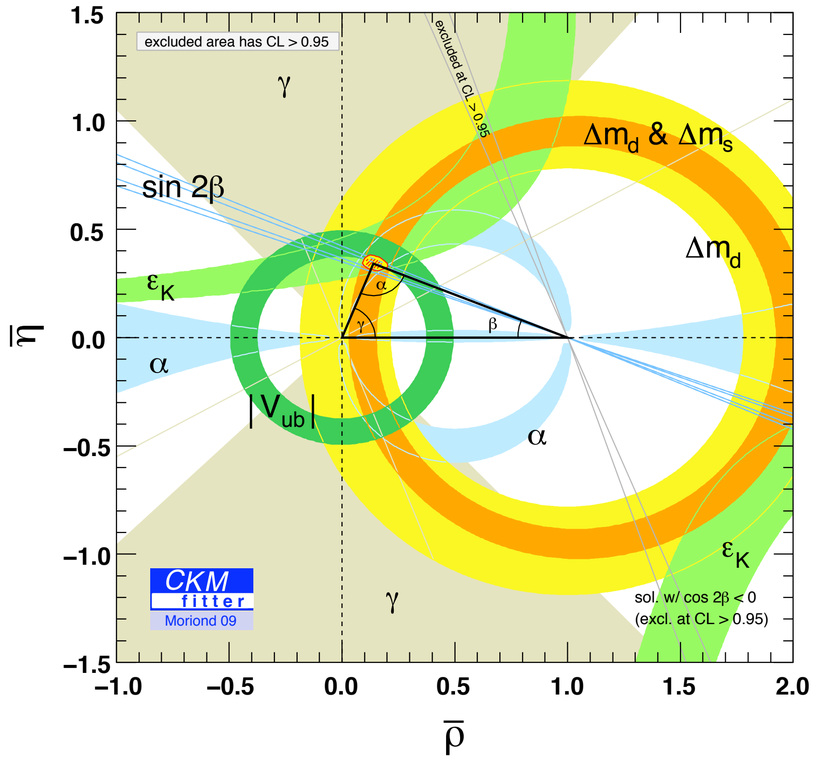
ICEPP, the University of Tokyo

Aug. 9, 2016
ICHEP2016

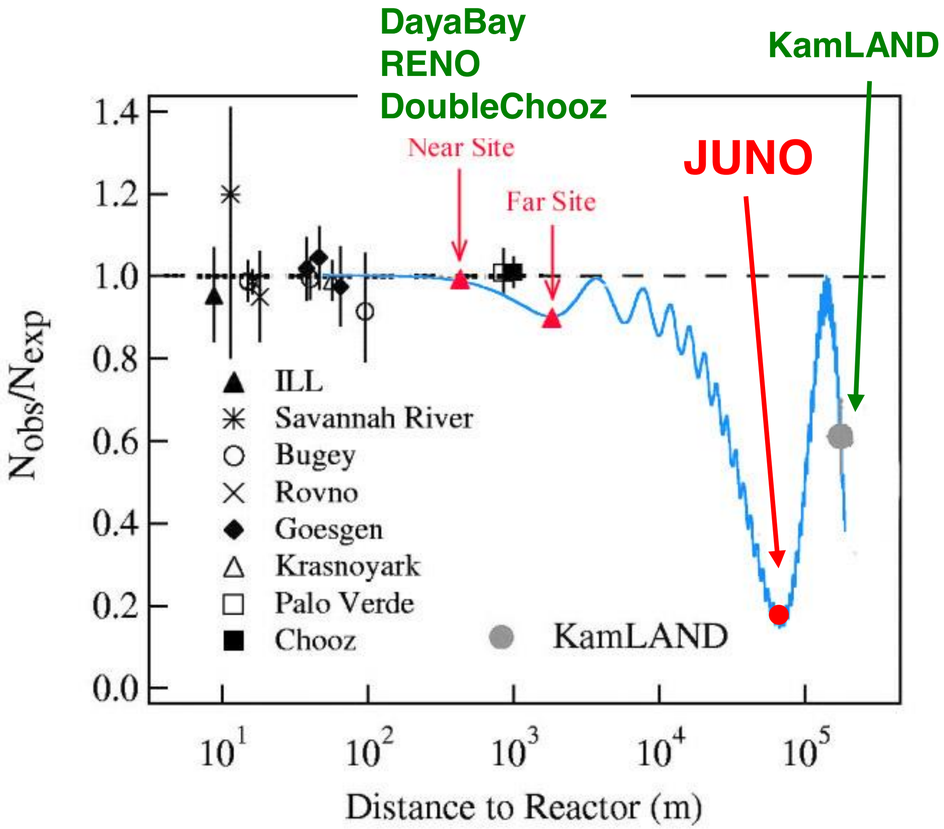
# Now we know that



## Quarks mix




## Neutrinos oscillate

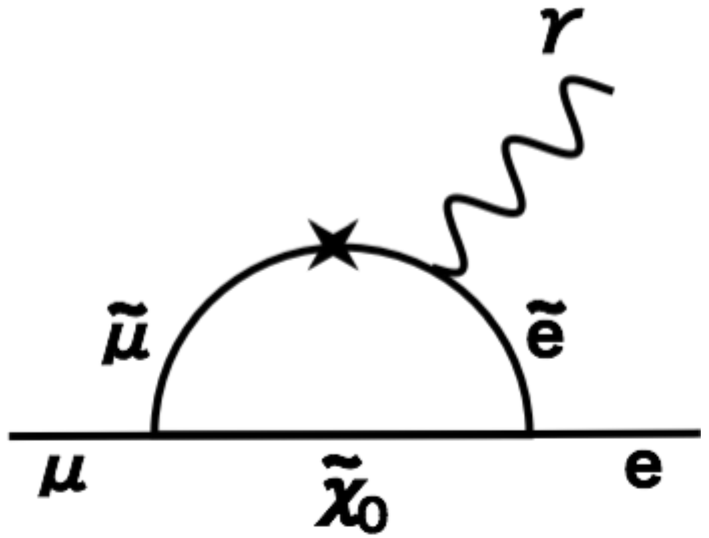



**How about charged leptons ?**

# charged lepton flavor violation (cLFV)



- In the SM, the charged lepton flavor is conserved
  - cLFV have not been observed
  - cLFV in SM through ν-oscillations is very tiny
- In many new theories beyond the SM (e.g. SUSY-GUT, SUSY-seesaw, extra-dimension…), the charged lepton flavor is naturally violated
  - Predicted branching ratios of cLFV rare decays are sizable !!
- Any observations of cLFV will be unambiguous evidences of new physics (NP)
- Complementary to direct searches at LHC
  - Sensitive to higher NP masses
  - color-less new particles are not constrained very much



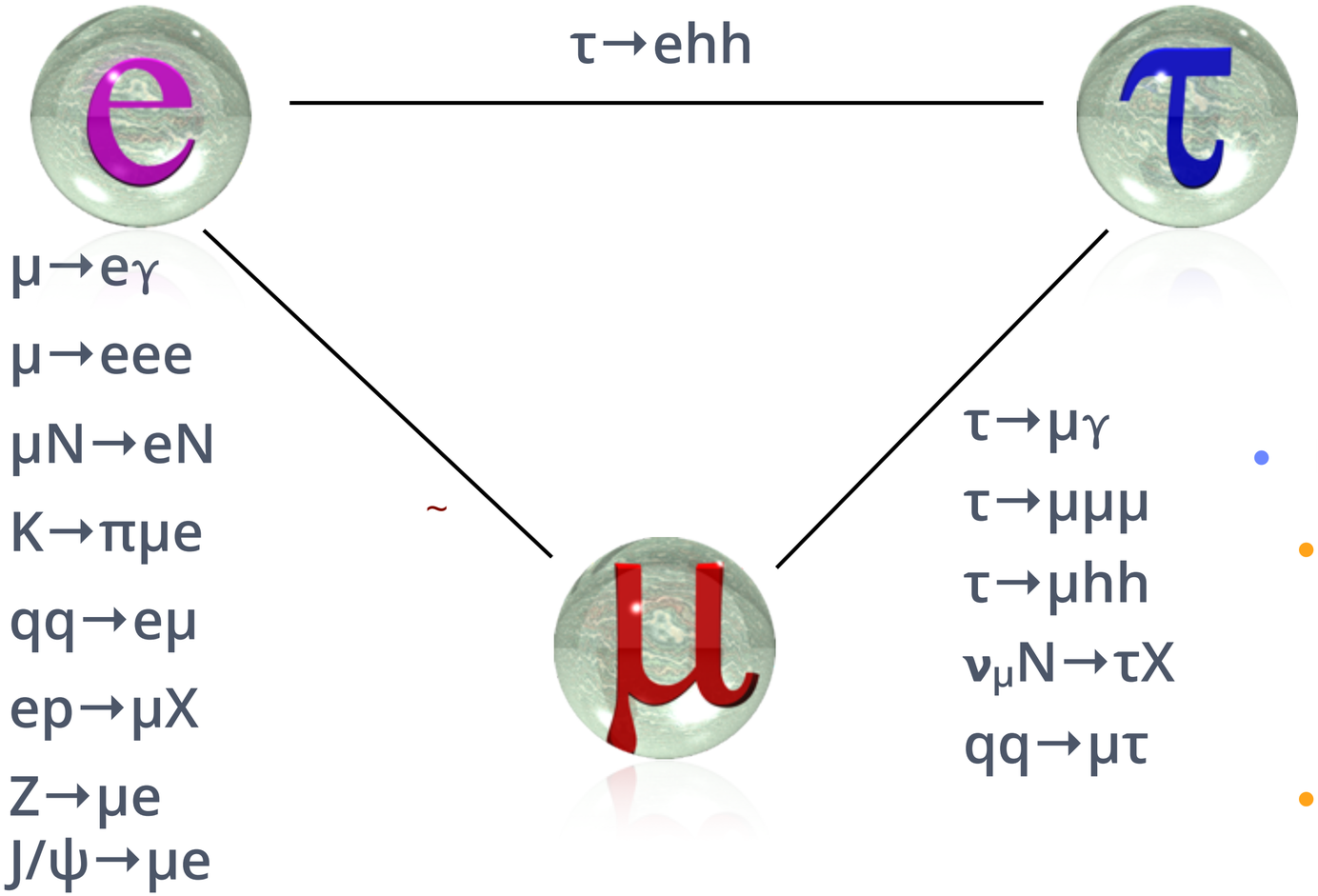
# Hints of new physics in charged lepton sector



- **Muon g-2 : 3.6 σ difference from the SM value (BNL E821)**
  - Next generation experiments at Fermilab (first result in FY2017—2018) and J-PARC
- **Proton radius puzzle : 7 σ difference between ep and μp (CREMA@PSI)**
  - e-μ universality violation ?
  - New results expected from CREMA, MUSE, PRad, MAMI
- **B-physics**
  - $B \to D\tau\nu$ vs $B \to D\mu\nu$ : 3.9 σ difference from SM
  - $b \to s$ flavor anomalies
    - BR($B^+ \to K^+\mu\mu$) / BR($B^+ \to K^+ee$), BR($B_s \to \phi\mu\mu$), $B \to K^*\phi\mu\mu$ angular analysis
- **$H \to \mu\tau$: CMS observed with 2.4 σ significance in Run 1 data**

# cLFV search channels






- **Muon channels are "Golden"**
  - High intensity muon source available
    - $O(10^8)$ μ/sec @PSI, $O(10^{11})$ μ/sec in next generation experiments
  - Low background

# The cLFV Wheel

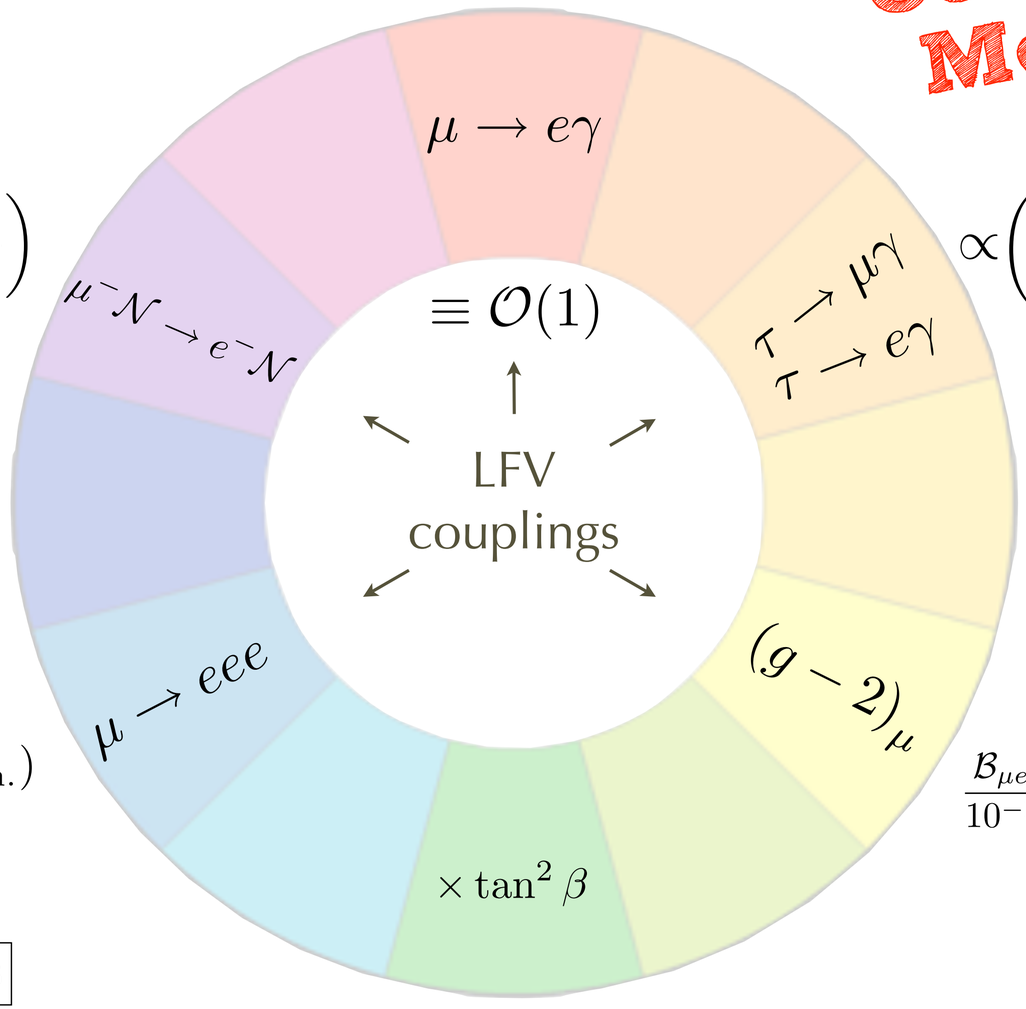


If the “dipole” interaction is dominant.

Common Models

**1/390**
for AL target

$$\propto \left(\frac{Z\alpha}{\pi}\right)$$




$$\propto \left(\frac{m_\tau}{m_\mu}\right)^{2\div 4}$$

**O(10²)—O(10⁵)**

**1/170**

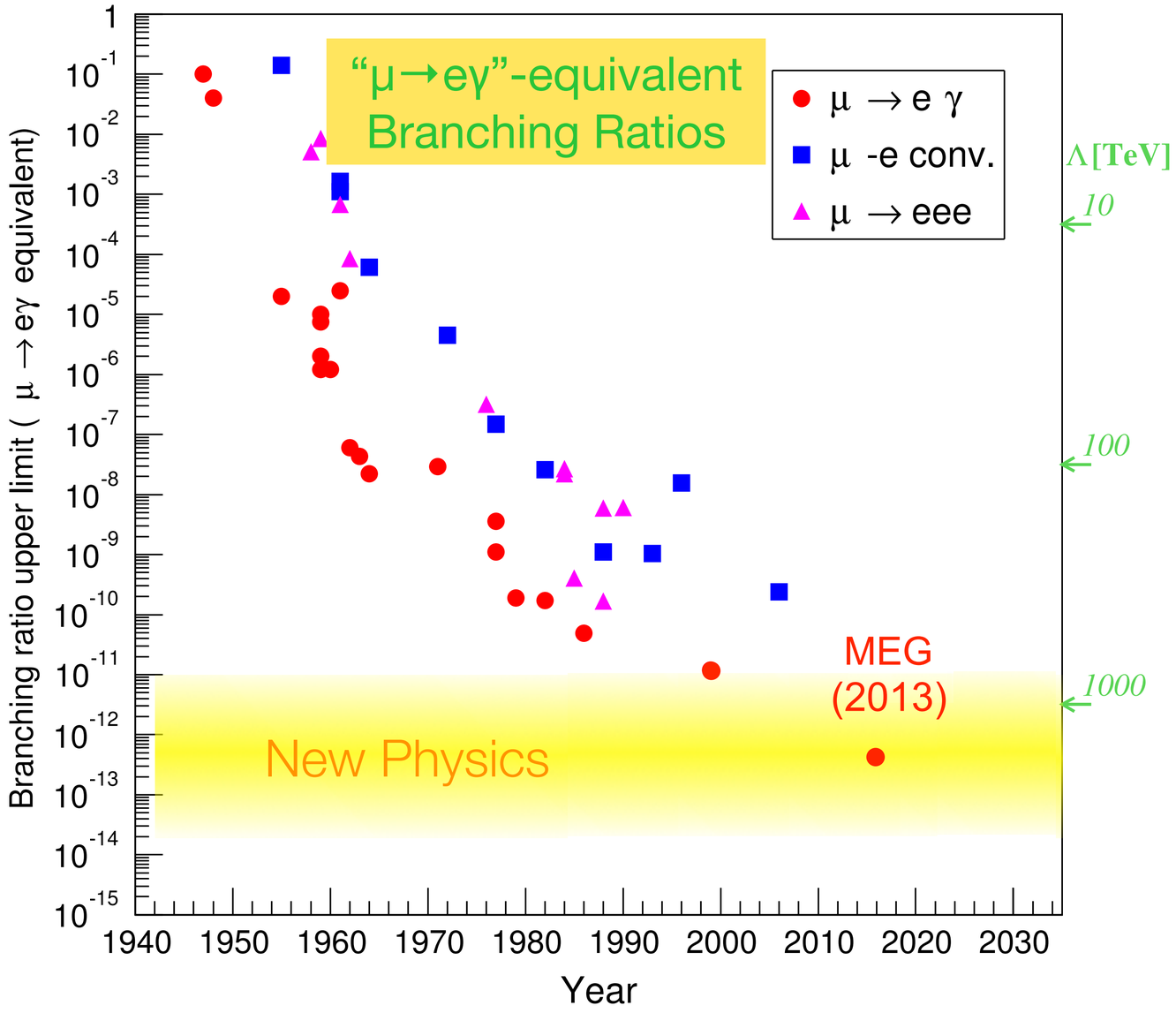
$$\propto (\alpha_{\mathrm{e.m.}})$$

$$\frac{\mathcal{B}_{\mu e\gamma}}{10^{-12}} \propto \left(\frac{\Delta a_\mu}{10^{-9}}\right)^2$$

G.Signorelli, FPCP2013

# μ cLFV history and status





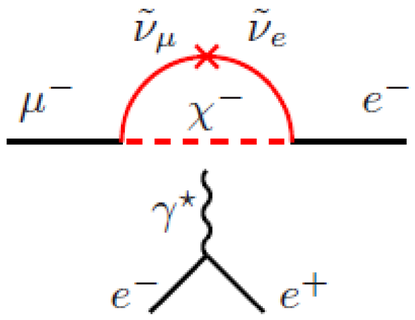

Sensitivity of the searches are already predicted region by BSM theories

# cLFV : Correlations

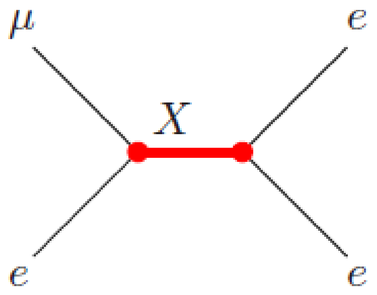


| ratio | LHT | MSSM (dipole) | MSSM (Higgs) |
|---|---|---|---|
| $\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$ | $0.02 \ldots 1$ | $\sim 6 \cdot 10^{-3}$ | $\sim 6 \cdot 10^{-3}$ |
| $\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$ | $0.04 \ldots 0.4$ | $\sim 1 \cdot 10^{-2}$ | $\sim 1 \cdot 10^{-2}$ |
| $\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$ | $0.04 \ldots 0.4$ | $\sim 2 \cdot 10^{-3}$ | $0.06 \ldots 0.1$ |
| $\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$ | $0.04 \ldots 0.3$ | $\sim 2 \cdot 10^{-3}$ | $0.02 \ldots 0.04$ |
| $\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$ | $0.04 \ldots 0.3$ | $\sim 1 \cdot 10^{-2}$ | $\sim 1 \cdot 10^{-2}$ |
| $\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$ | $0.8 \ldots 2.0$ | $\sim 5$ | $0.3 \ldots 0.5$ |
| $\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$ | $0.7 \ldots 1.6$ | $\sim 0.2$ | $5 \ldots 10$ |
| $\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$ | $10^{-3} \ldots 10^{2}$ | $\sim 5 \cdot 10^{-3}$ | $0.08 \ldots 0.15$ |

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




dipole coupling




four-fermion interaction through a boson (H, Z'...)

**New physics can be discriminated from the correlations in searches**

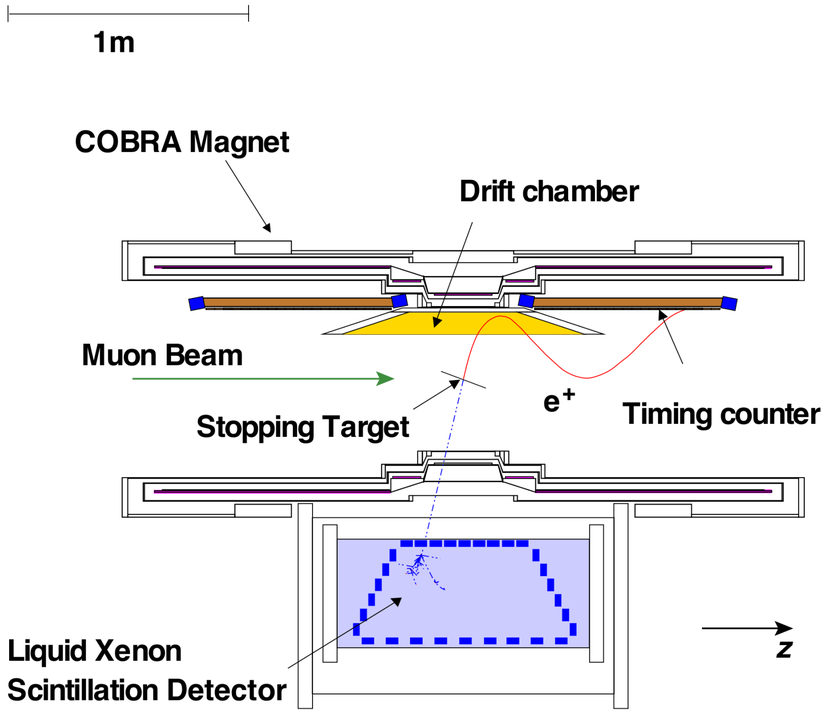
# $\mu \rightarrow e\gamma$ : MEG

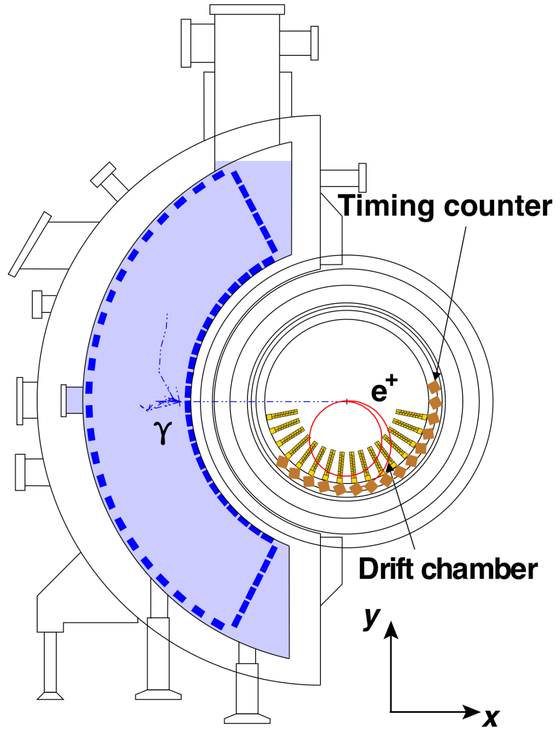


- Searching for cLFV decay $\mu^+ \rightarrow e^+\gamma$
- Most intense DC $\mu^+$ beam, $3\times10^7$ $\mu$/sec @ PSI, Switzerland
- Detector
  - Photon : Largest LXe photon detector
  - Positron : gradient B-field, Ultra light drift chamber, high resolution $e^+$ timing counter
- Data taking in 2008-2013
- Previous result with 2009-2011 dataset
  - Br UL : $5.7\times10^{-13}$ (90%CL)

*PRL, 110 201801 (2013)*

- Analysis of full data completed



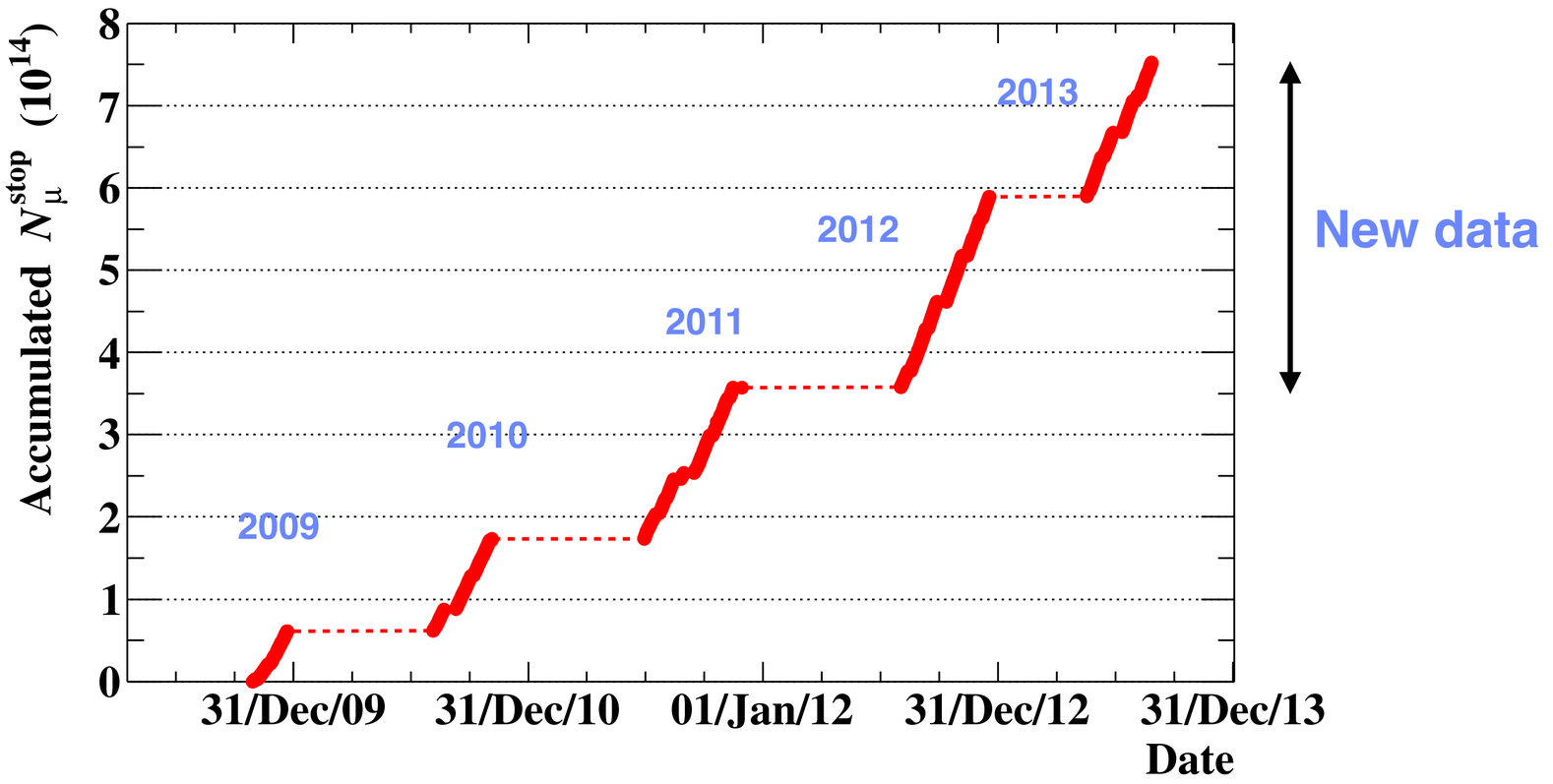
# MEG : Analysis with full data



- Full data : Double the data statistics
- All data (including 2009-2012) were analyzed with improved analysis
  - Target alignment
  - Positron missing first turn analysis
  - AIF event veto
  - Photon-detector alignment
- 90%CL UL Sensitivity

  **$5.3\times10^{-13}$ for full data**

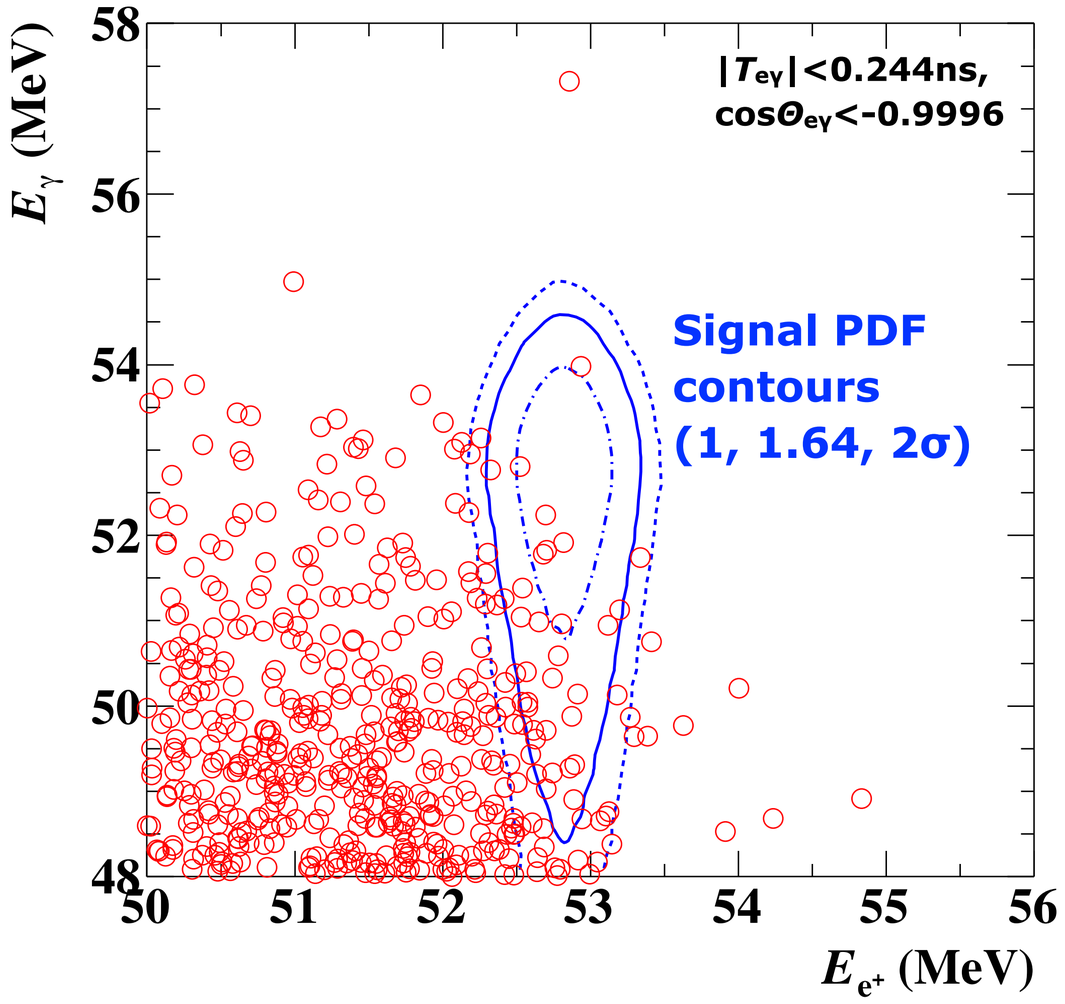
  ($8.0\times10^{-13}$ for 2009-2011 data)

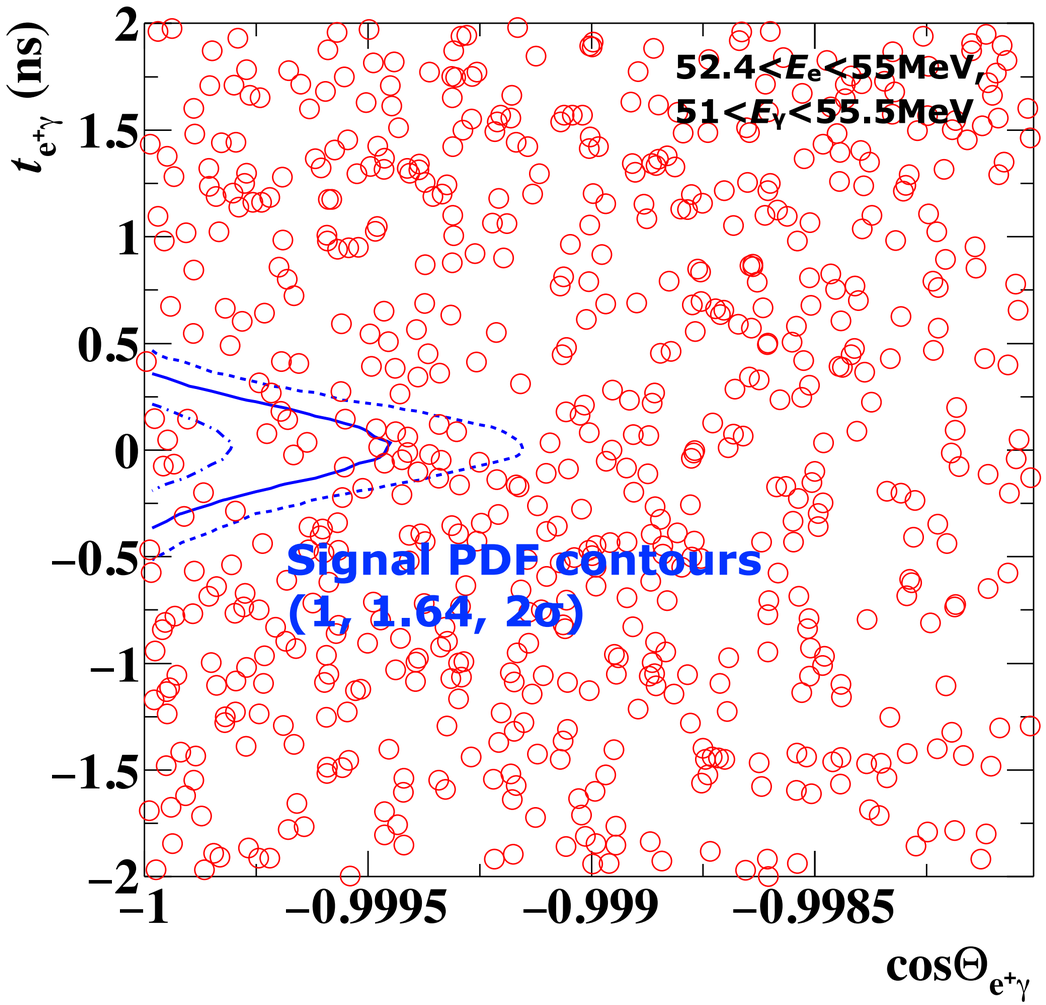


# MEG : event distribution



No visible excess in signal region

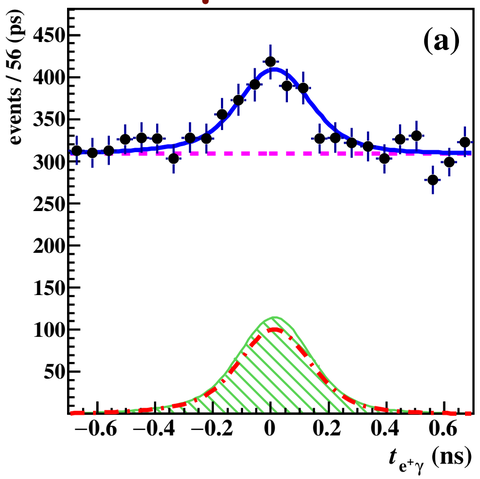


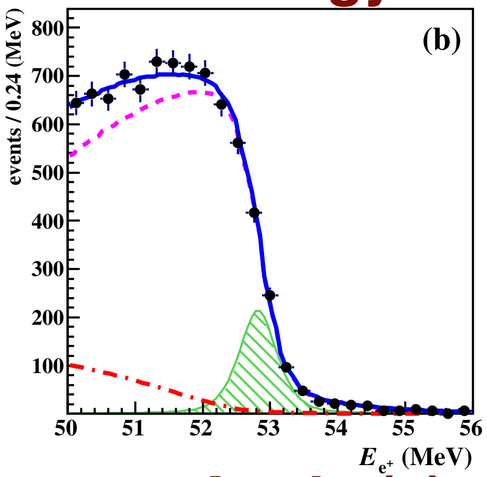
# MEG : Fit on the full data



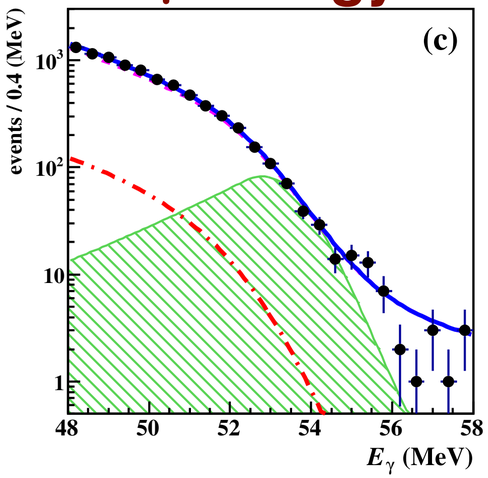
## $e^+\gamma$ Time




## $e^+$ Energy

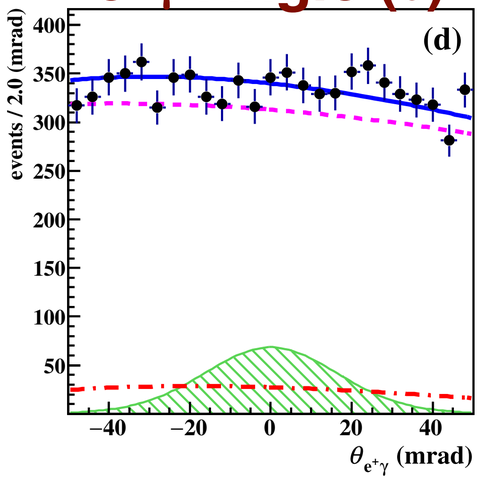



## $\gamma$ Energy

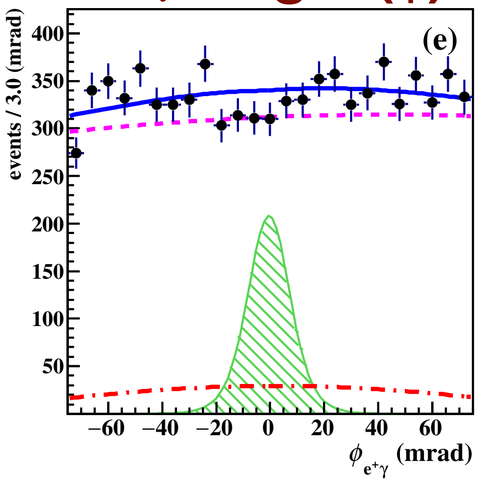



Accidental BG
RMD
100× signal upper limit

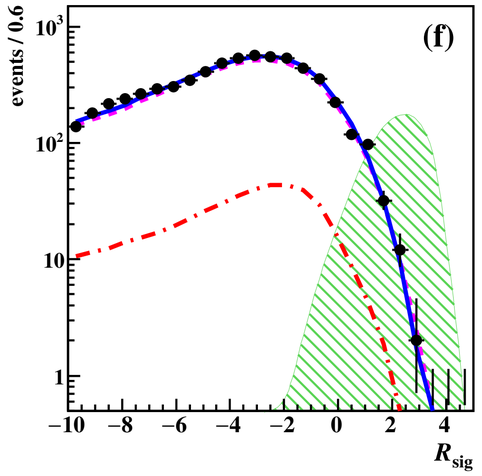
## $e^+\gamma$ Angle ($\theta$)




## $e^+\gamma$ Angle ($\varphi$)




## Relative signal likelihood




→ signal-like

**Data consistent with BG PDF**

# Final result of MEG



No excess was found and the new UL was set

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13} \text{ @ 90\% C.L.}$$

arXiv:1605.05081
ready for publication from EPJC

**×30 more stringent than the previous experiment**

| (×10$^{-13}$) | 2009-2011 data | 2012-2013 data | All combined |
|---|---|---|---|
| **Best Fit** | -1.3 | -5.5 | -2.2 |
| **90% CL Upper limit** | 6.1 | 7.9 | **4.2** |
| **Sensitivity** | 8.0 | 8.2 | **5.3** |

Previous limit with 2009-2011 dataset : 5.7×10$^{-13}$

UL : Feldman-cousins with profile-likelihood ratio ordering

Systematic uncertainties

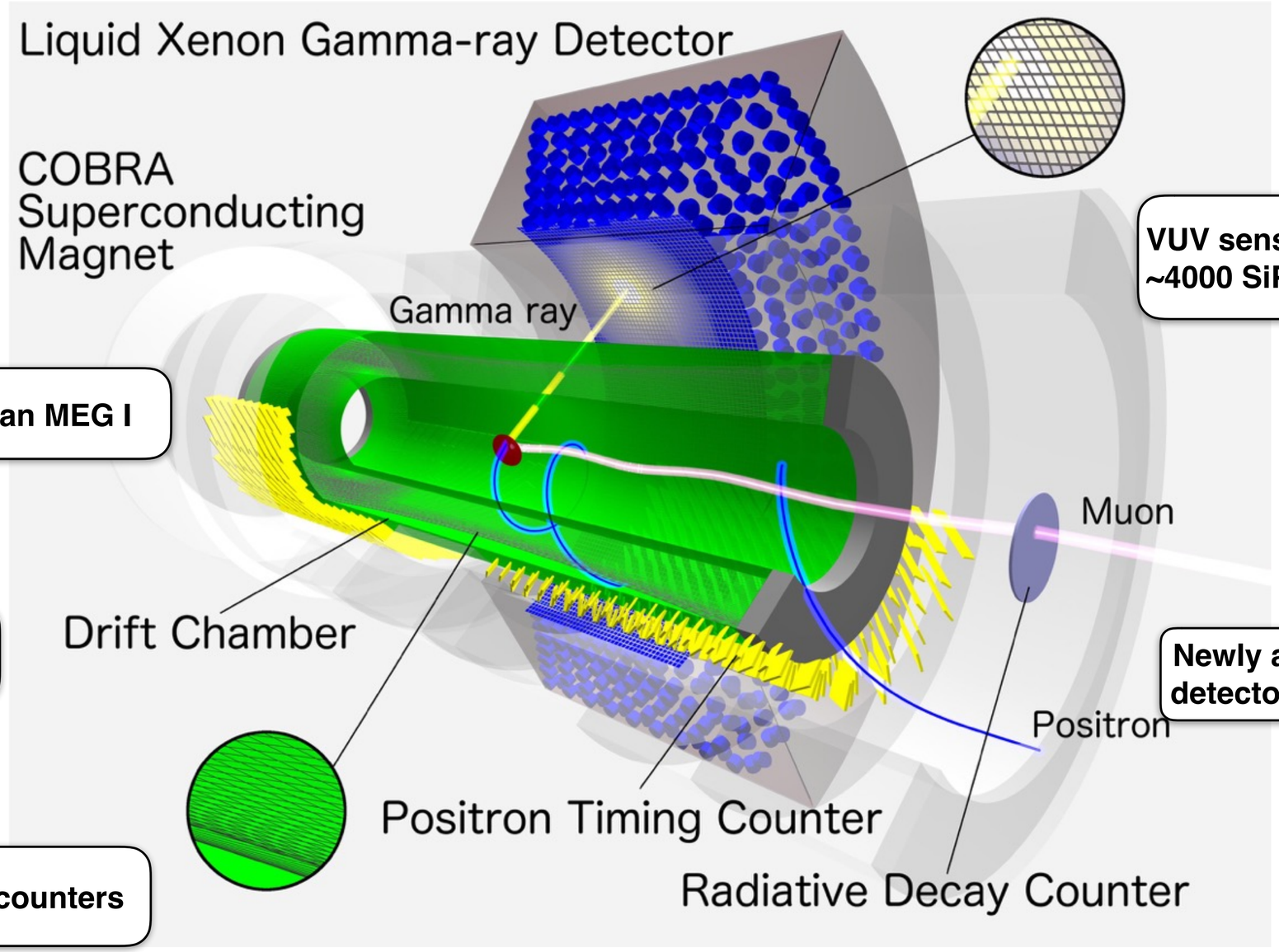
UL increase by

- 5% by target position/shape uncertainties
- <1% by other systematic uncertainties

# Future : MEG II

## Upgrades for 10 times higher sensitivity






**Beam intensity >2 higher than MEG I**

**VUV sensitive SiPMs**
**~4000 SiPM in the detector**

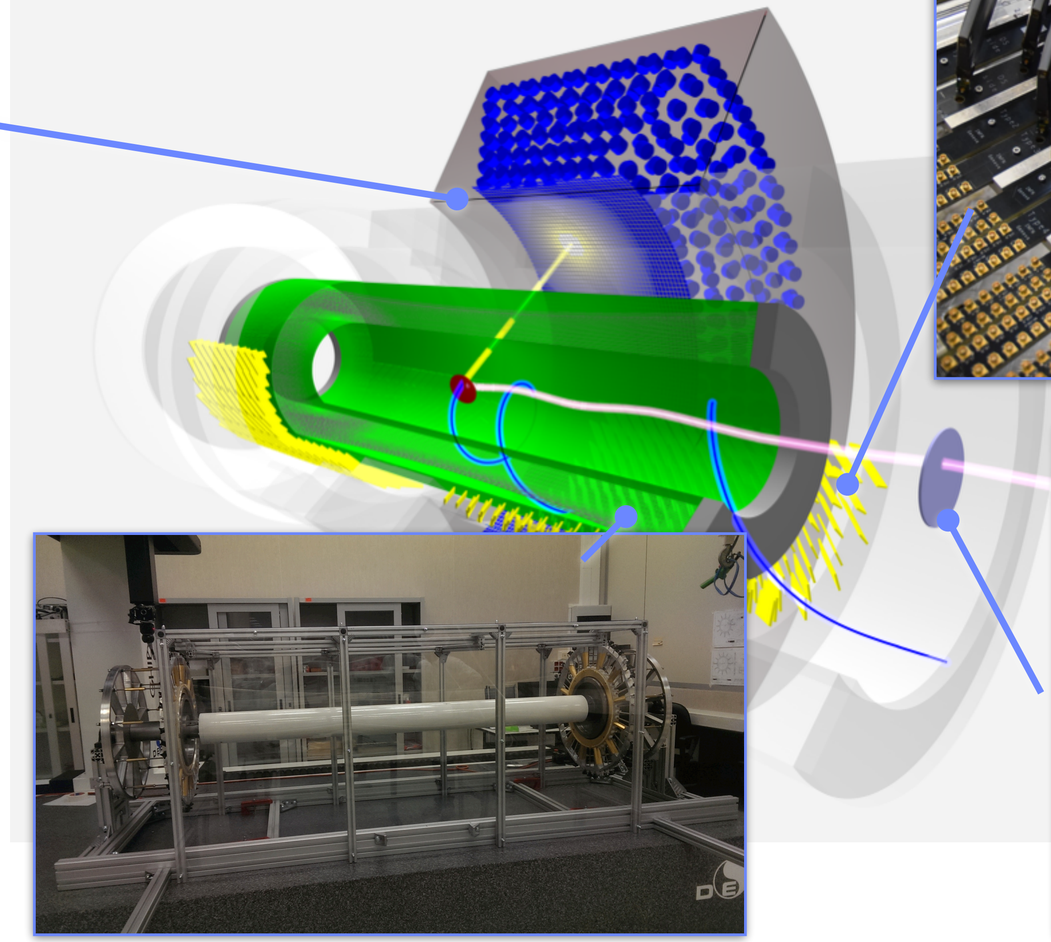
**Single volume, stereo wire chamber**

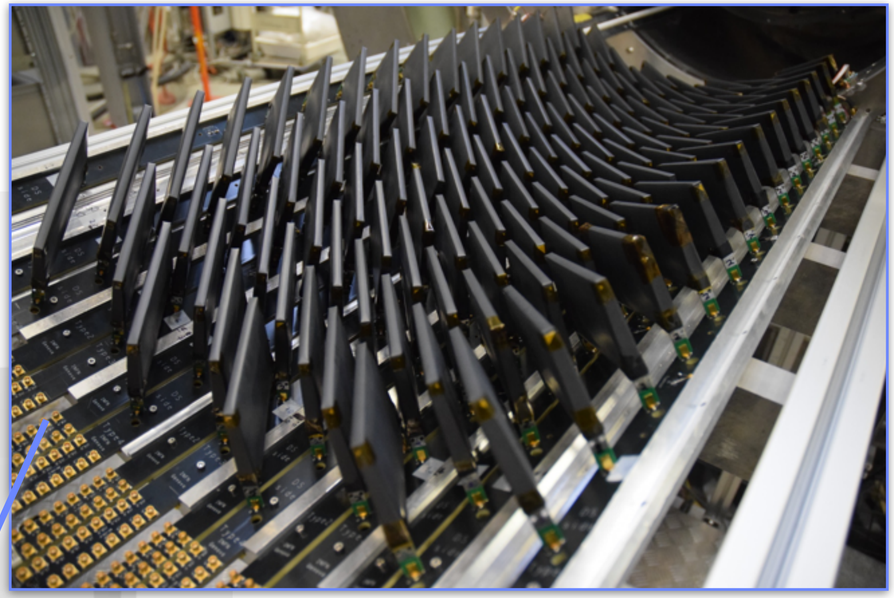
**Newly added $e^+$ detector for BG veto**

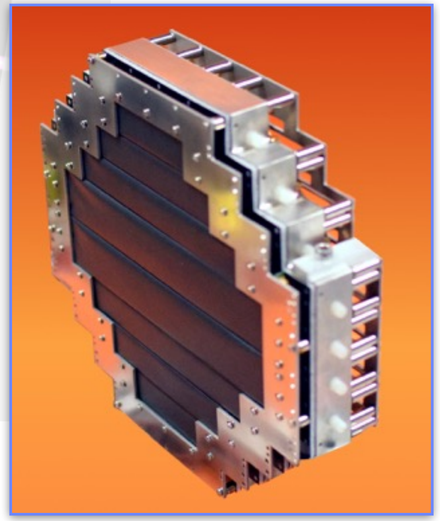
**highly segmented plastic counters**

# Future : MEG II



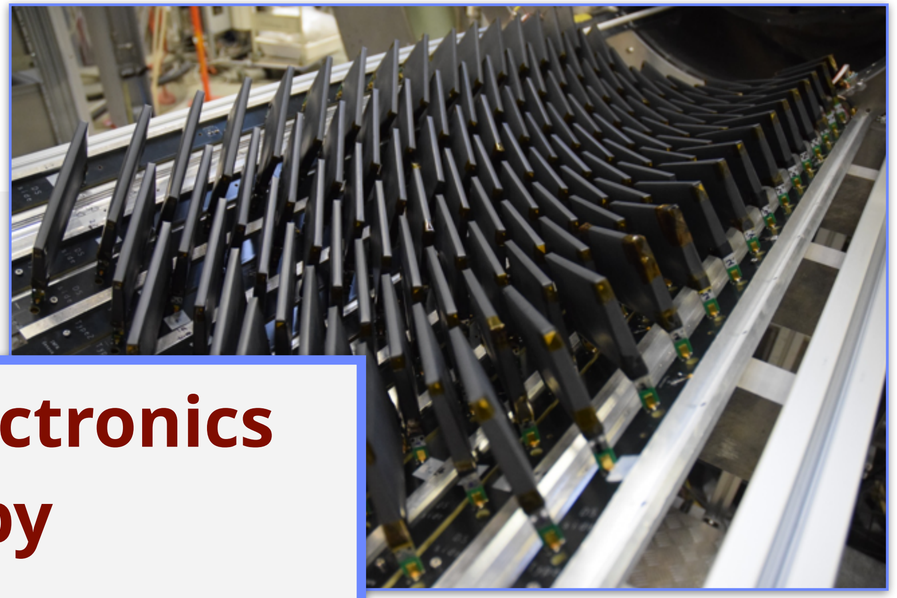


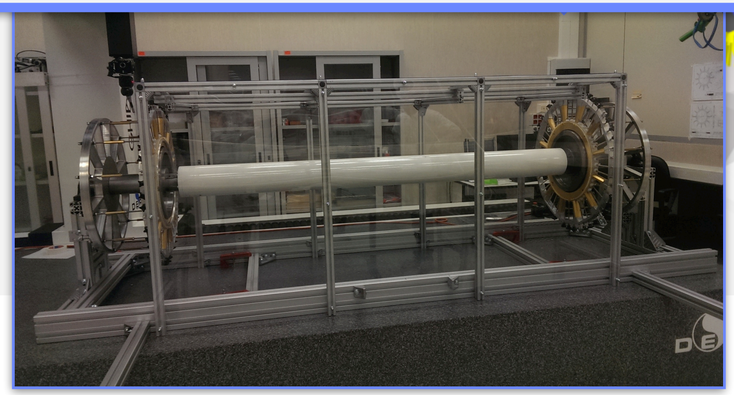




# Future : MEG II





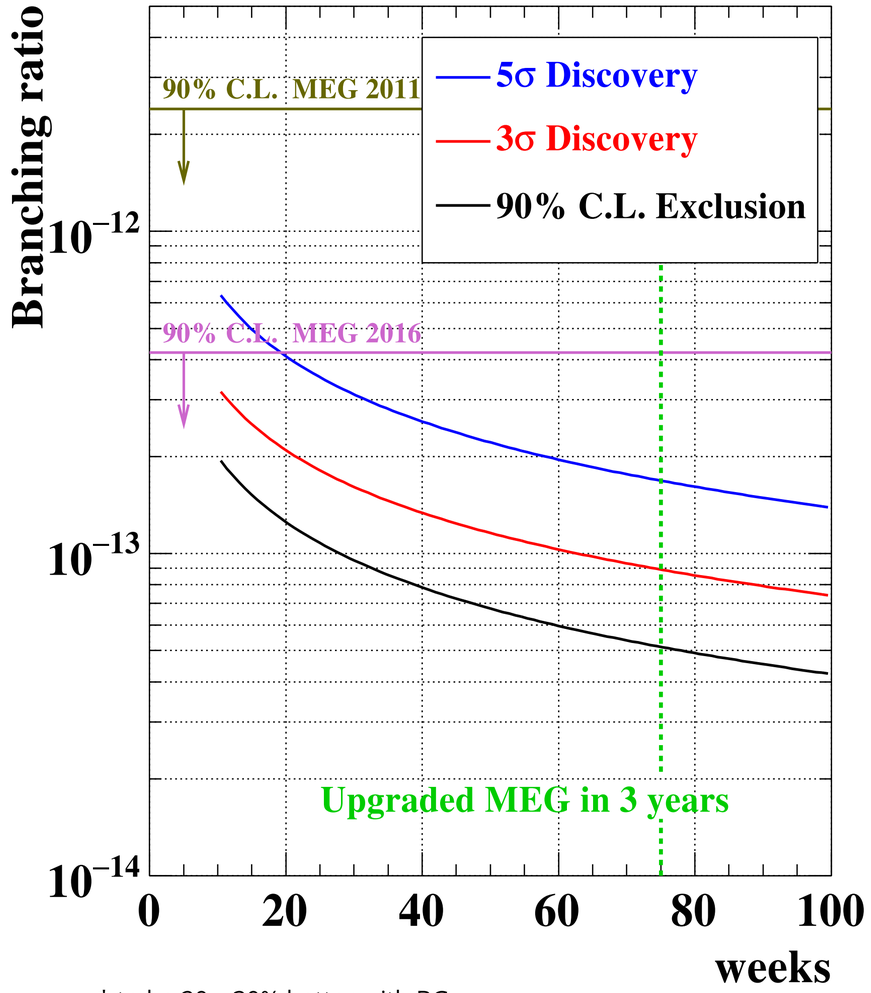


**The detector and the TDAQ electronics production will be completed by Autumn 2017**
**Engineering run followed by physics run.**

# MEG II physics reach

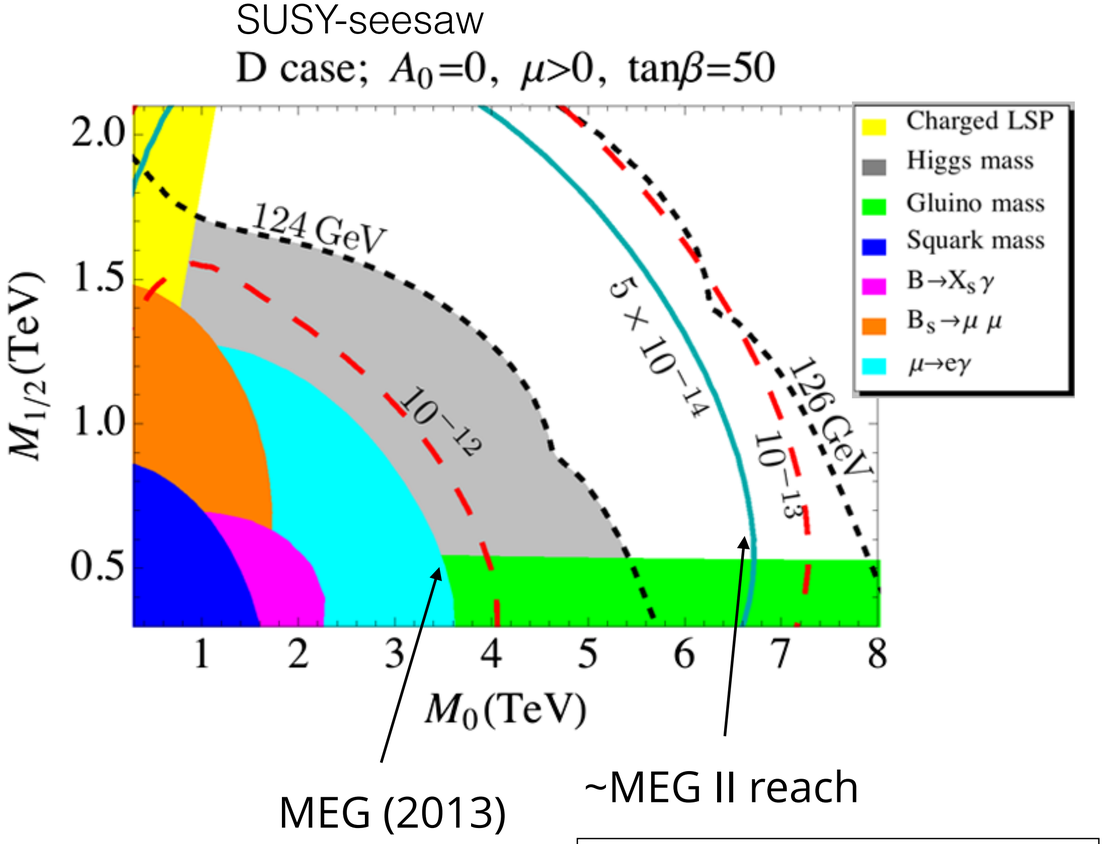


Projected sensitivity *




* to be 20—30% better with BG reduction by additional detector (RDC)

**MEG II sensitivity will reach the MEG limit in a couple of months**
**10 times higher sensitivity with 3 years of data**




Phys. Rev. D 91, 033007 (2015)

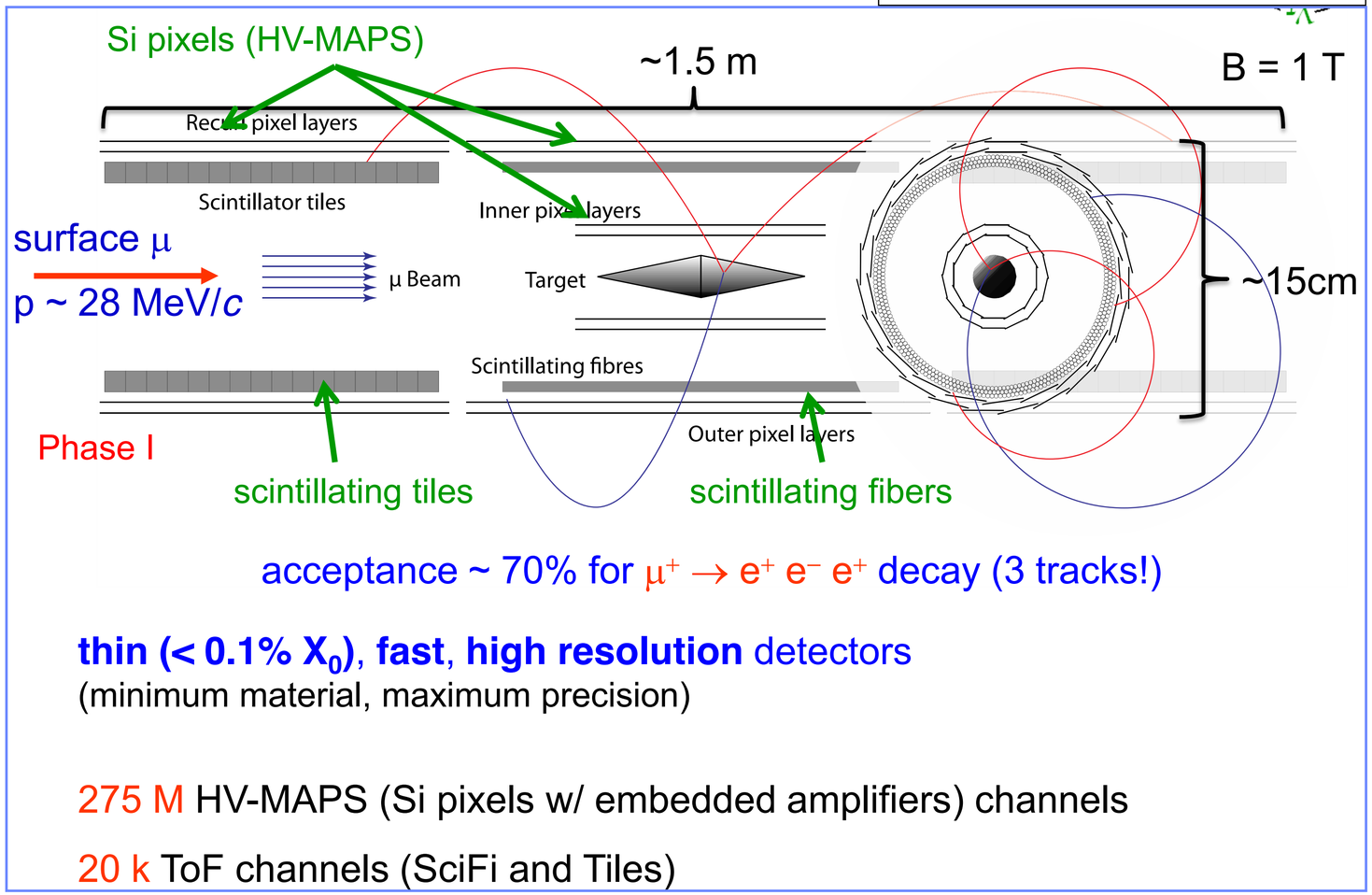
# μ→eee : Mu3e @ PSI

current limit : $1.0\times10^{-12}$ (SINDRUM, 1988)



- Stage I (2018–2020), BR < **$10^{-15}$**
- Stage II (> 2020), BR < **$10^{-16}$**

Alessandro Bravar, ICHEP2016

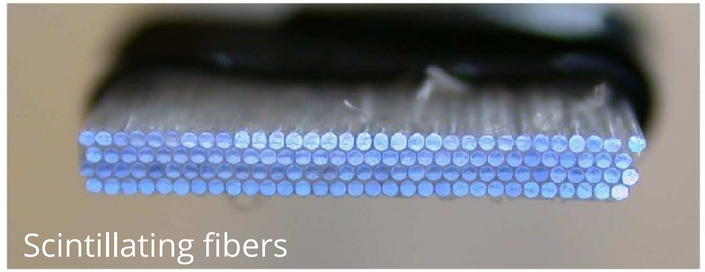


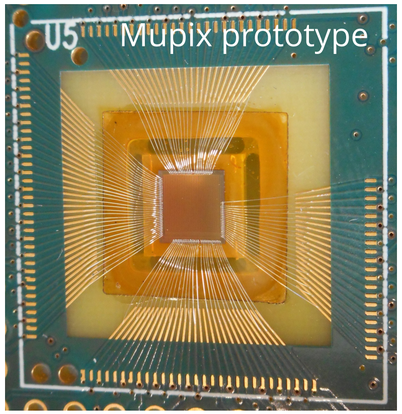

acceptance ~ 70% for $\mu^+ \rightarrow e^+ e^- e^+$ decay (3 tracks!)

**thin (< 0.1% $X_0$)**, **fast**, **high resolution** detectors
(minimum material, maximum precision)

275 M HV-MAPS (Si pixels w/ embedded amplifiers) channels

20 k ToF channels (SciFi and Tiles)

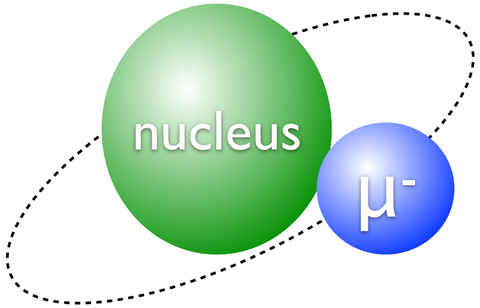



# μ→e conversion

current limit : $7\times10^{-13}$ (SINDRUM II)

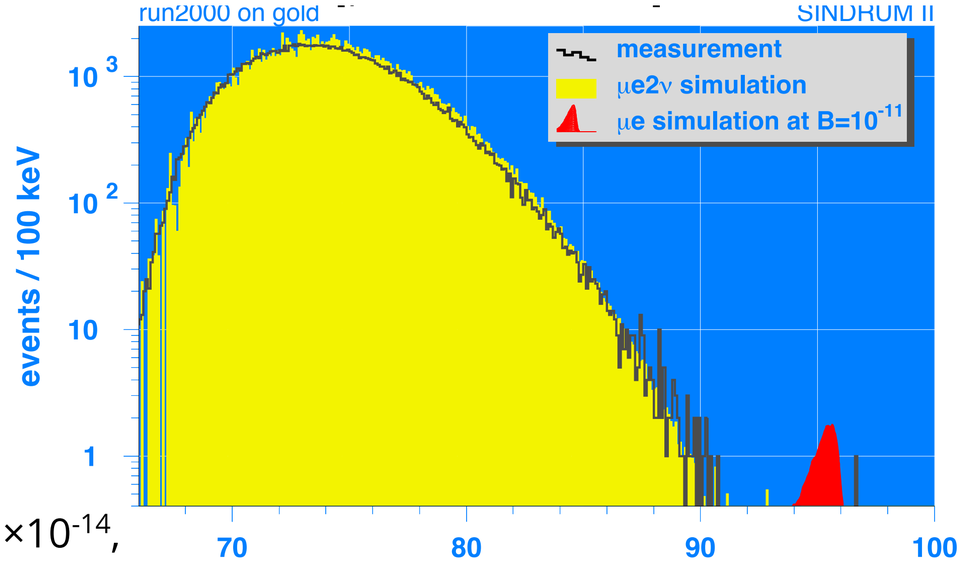


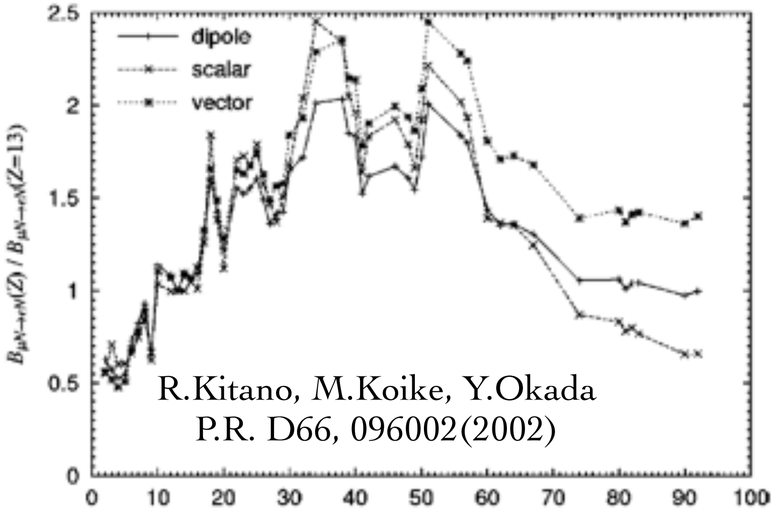



$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

| | Background | Challenge |
|---|---|---|
| μ→eγ | accidental | Detector resolution |
| μN→eN | beam, cosmic ray | Beam quality |

No accidental BG → high beam intensity




Experiments:

- COMET @ J-PARC
- Mu2E @ Fermilab
- DeeMe @ J-PARC $1.2\times10^{-13}$—$2.1\times10^{-14}$, will start after beam line complete in Japanese FY2016

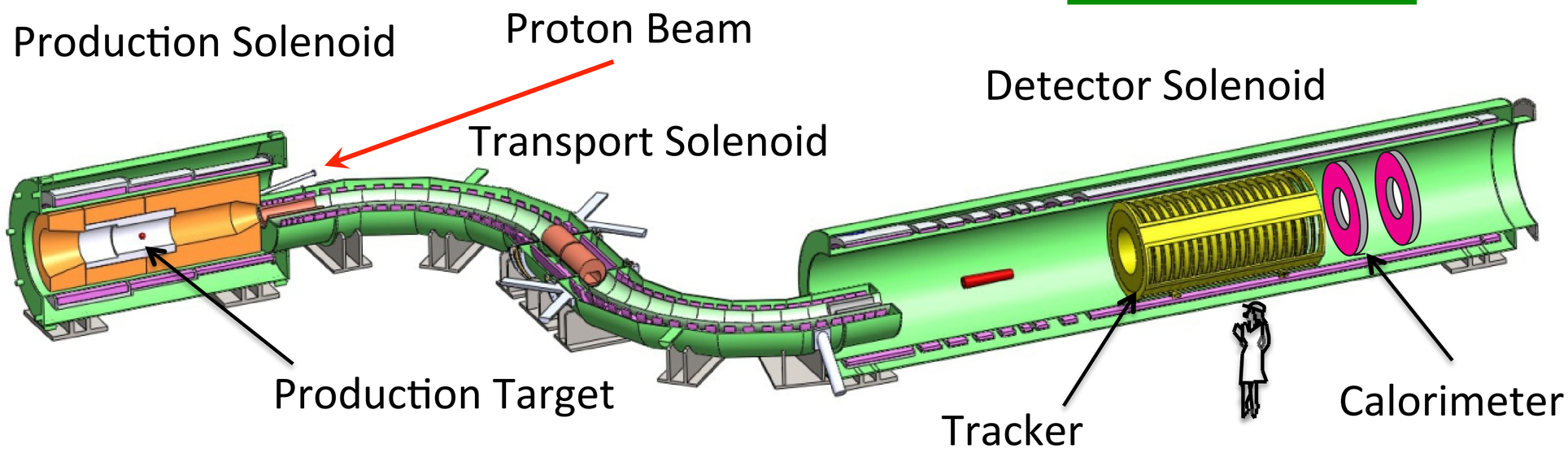
signal rate depends on the target material
→ Discriminate physics model

# Mu2e @ Fermilab

current limit : $7\times10^{-13}$ (SINDRUM II)



Cosmic Ray Veto not shown



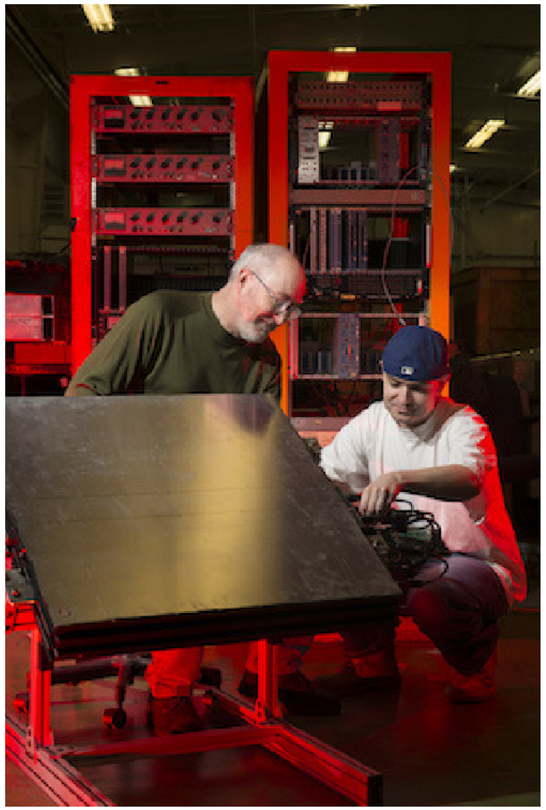

- Target single event sensitivity: $2.6\times10^{-17}$
- Fully funded
- Construction ongoing
- Physics data taking expected to start in ~2021

# Mu2e @ Fermilab



Prototype detectors

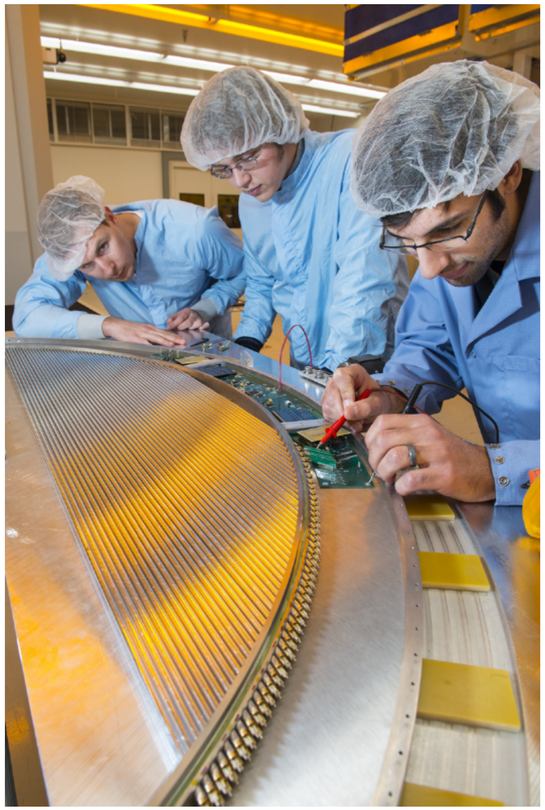
CRV



Transport solenoid

Calorimeter


Tracker

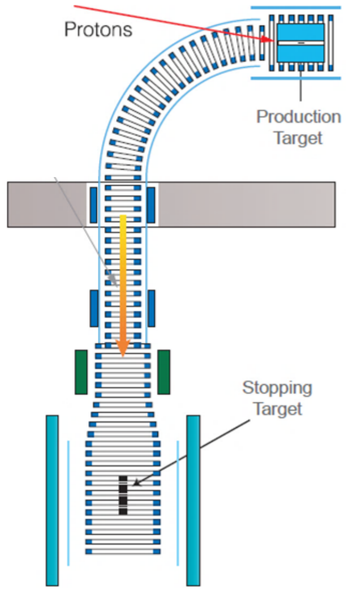


# COMET @ J-PARC

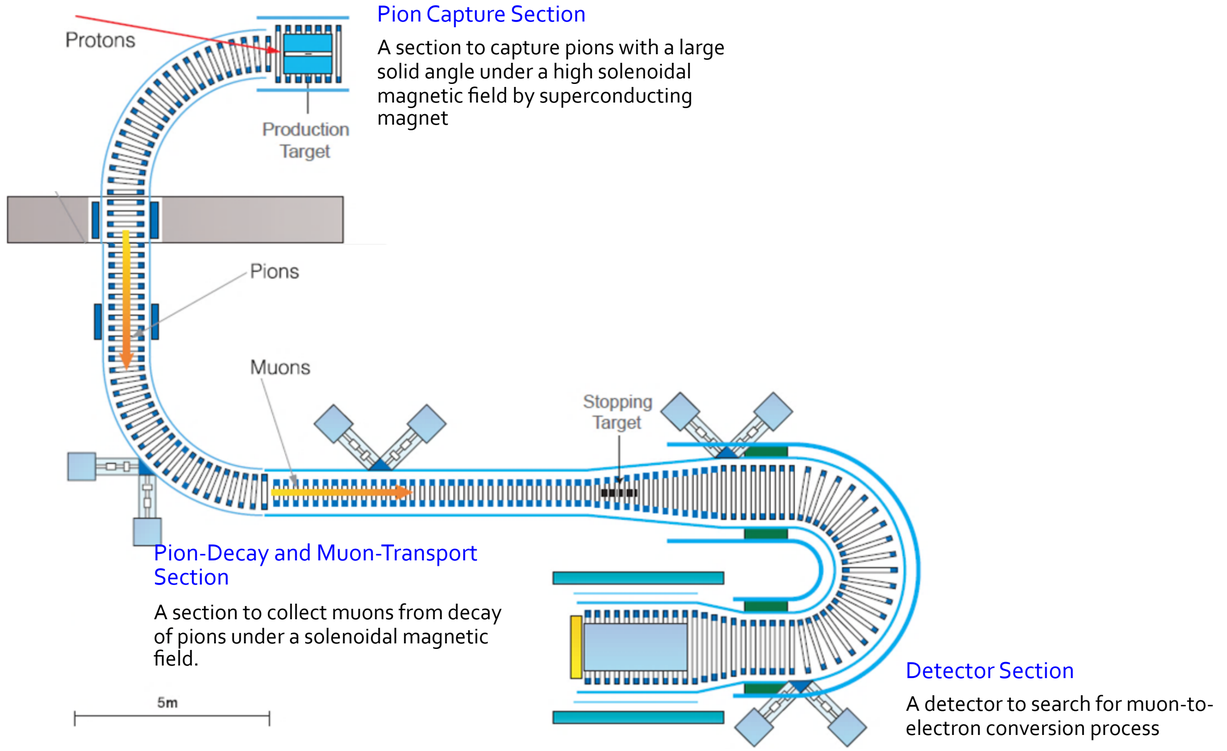
current limit : $7\times10^{-13}$ (SINDRUM II)



## Phase I




## Phase II



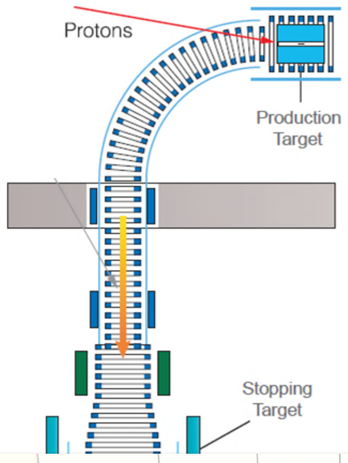

- **Phase I (C-shaped muon solenoid, muon target in the detector), 2018 or 2019**
  - Single event sensitivity: **$3.1\times10^{-15}$**
- **Phase II (Full apparatus shown above), 2021**
  - Single event sensitivity: **$2.5\times10^{-17}$**

# COMET @ J-PARC

current limit : $7\times10^{-13}$ (SINDRUM II)



## Phase I

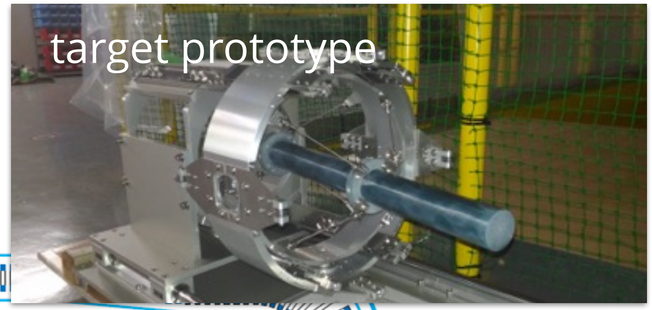


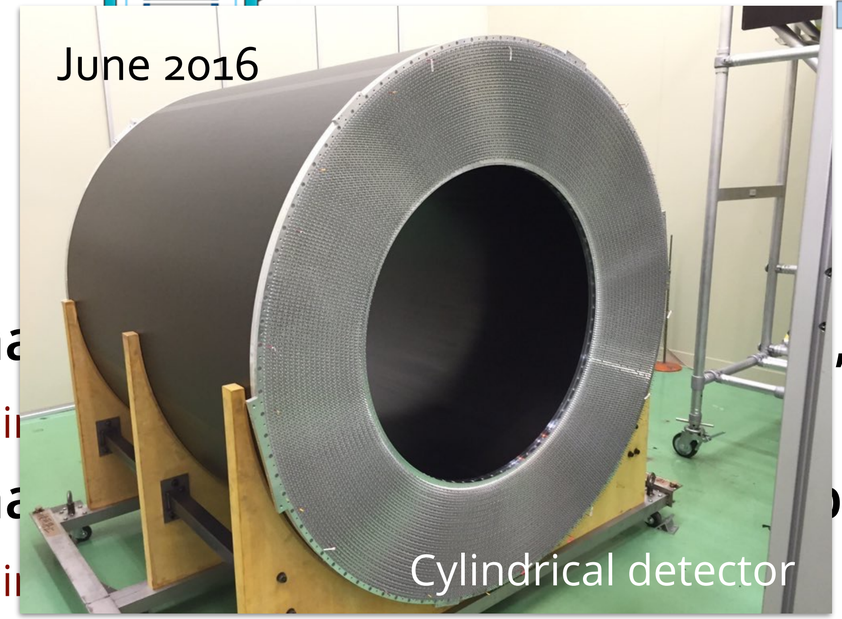


## Phase II

ure Section

o capture pions with a large
under a high solenoidal
field by superconducting

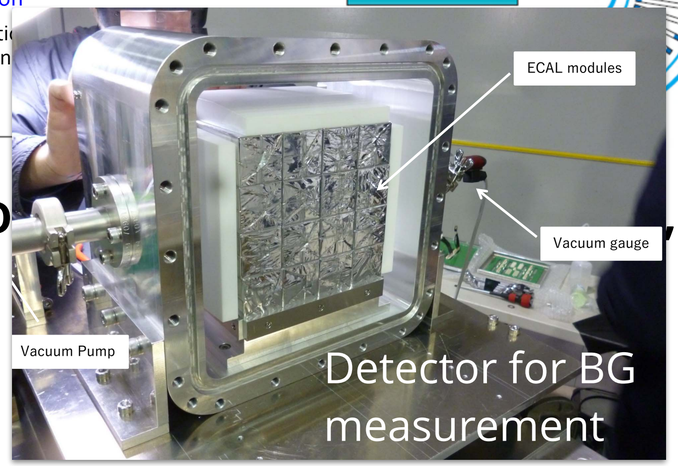



Pion-Decay and Muon-Transport Section

A secti
of pion
field.

5m




Detector Section

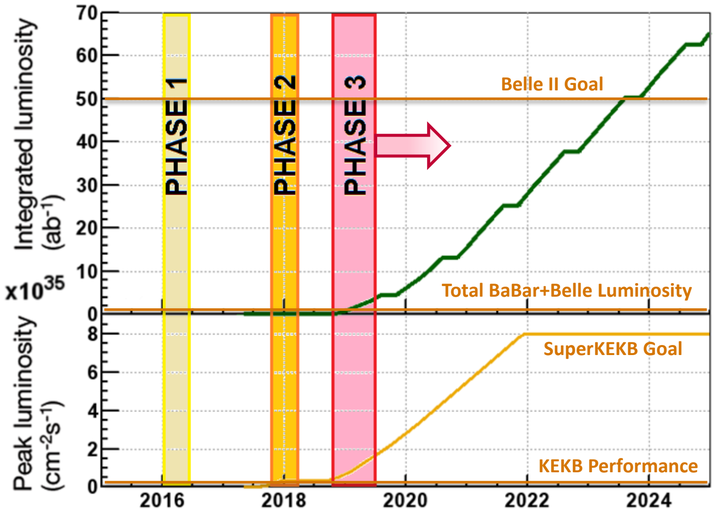
A detector to search for muon-to-electron conversion process

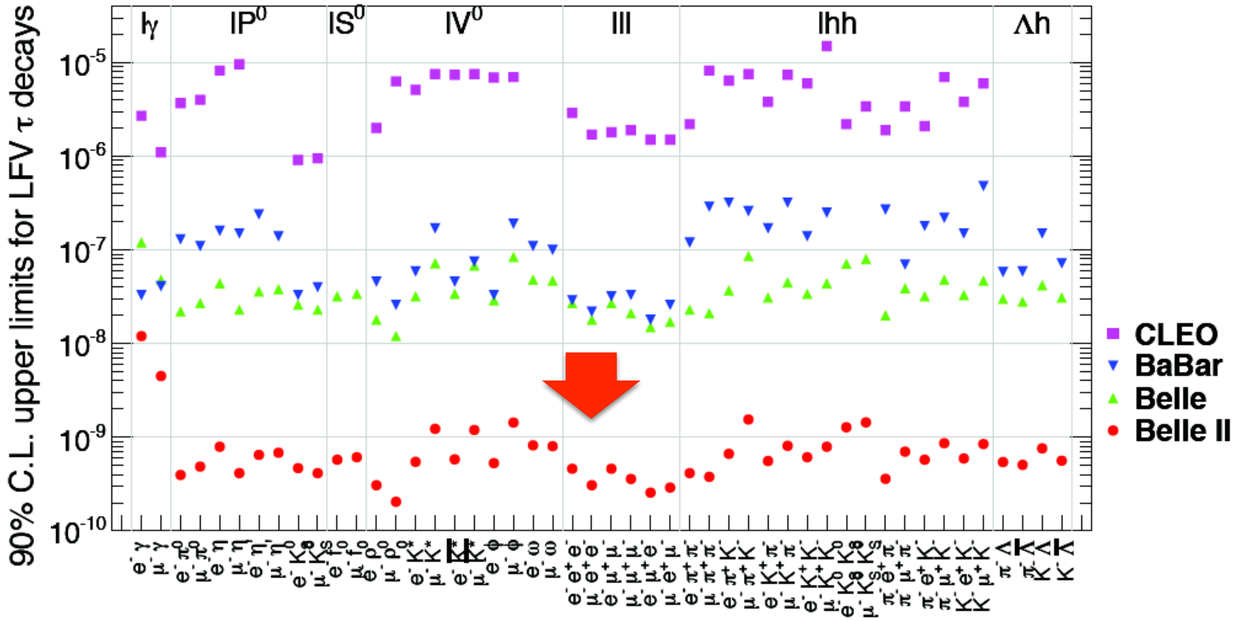
- Pha , muo , 2018 or 2019
  - Si
- Pha ove),
  - Si

# τ cLFV



- **NP prediction of BR is O($10^{-7}$–$10^{-10}$)**
- **Belle and Babar searches for ~50 channels of rare decays in tau pairs of O($10^{9}$)**
  - No excess of events
  - Upper limits in O($10^{-8}$)
- **Belle II**
  - Accelerator upgrade is finished
  - Full physics run expected to start in 2019
  - 50 $ab^{-1}$ by 2023—2024
  - Expected sensitivity O($10^{-9}$–$10^{-10}$)

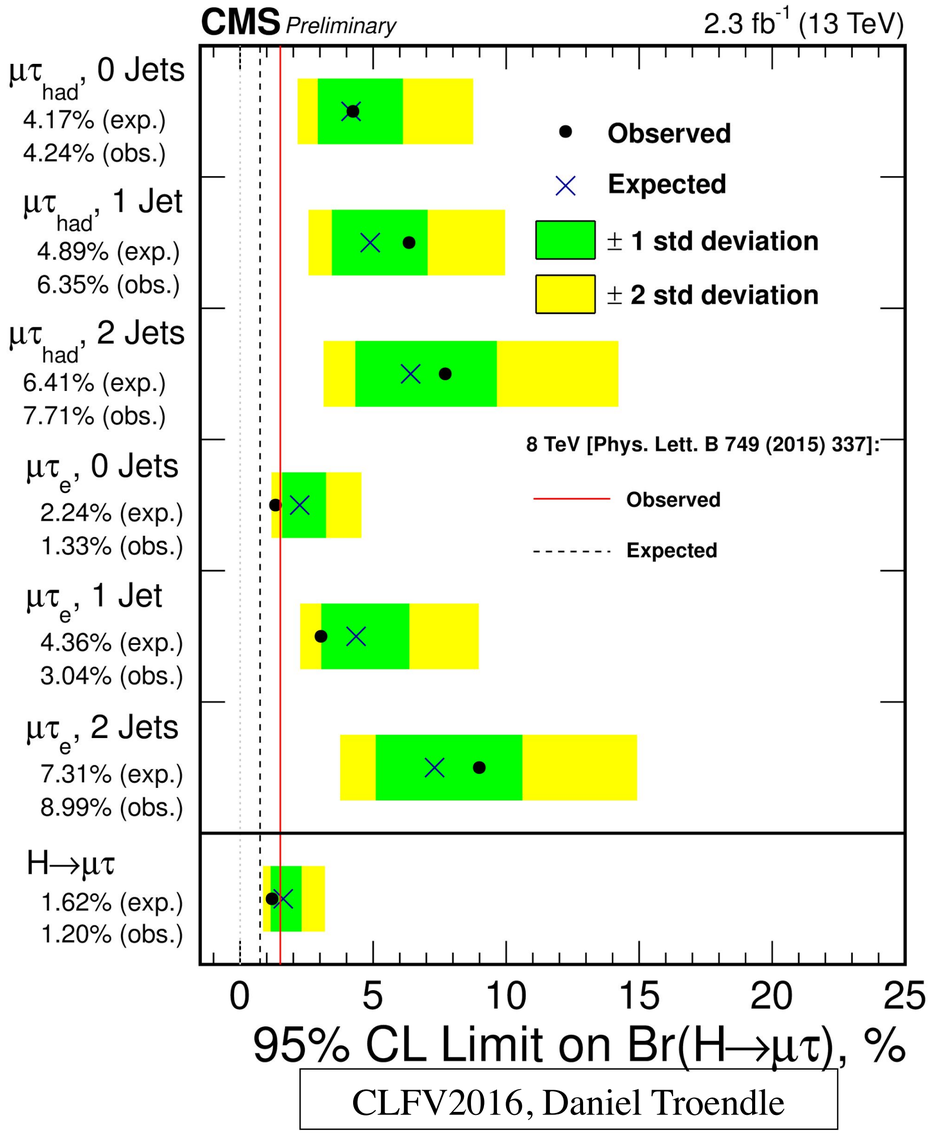


# cLFV searches at LHC

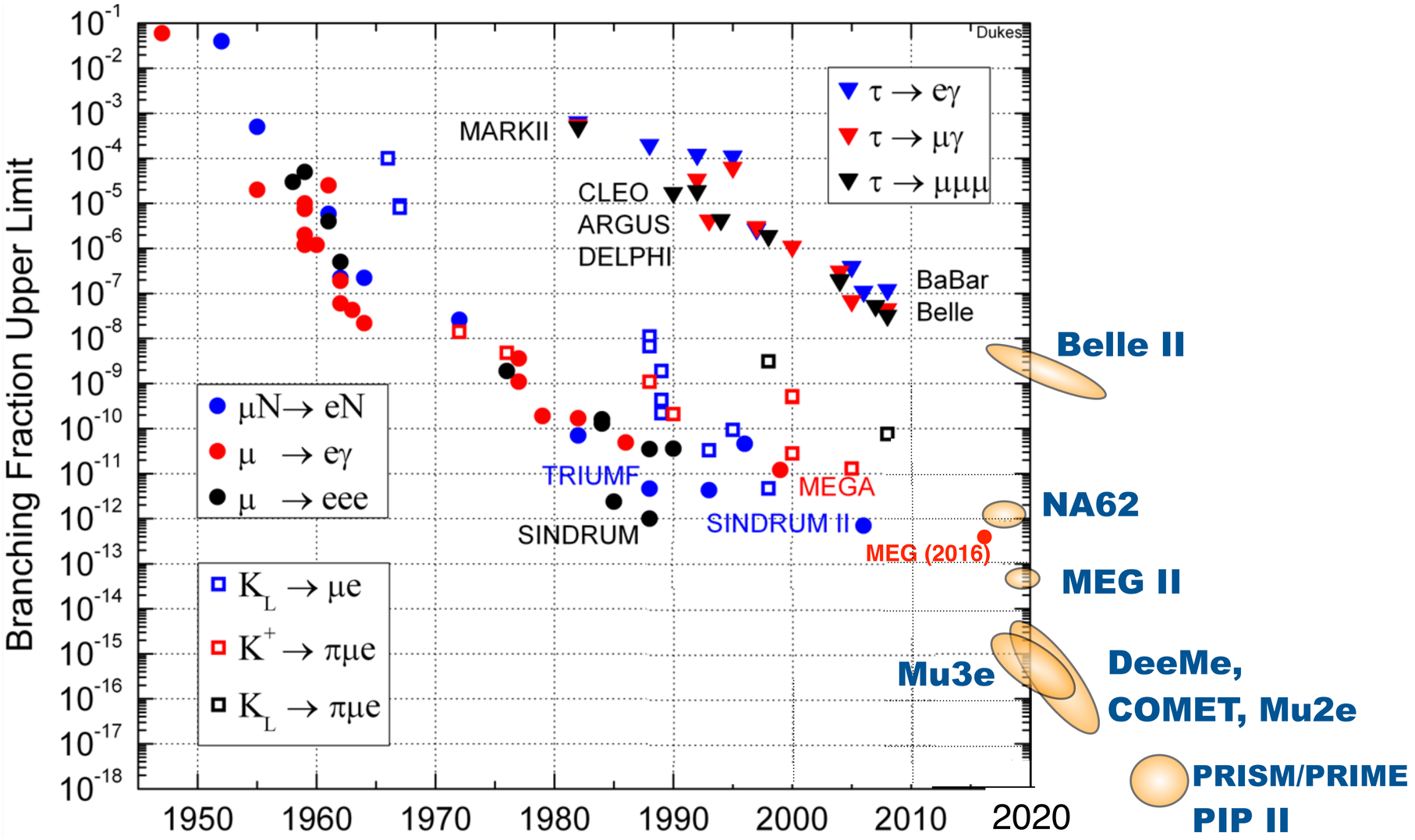


- cLFV searches through decays of SM particles and new particles
- H→μτ
  - 8 TeV data
    - best fit Br=0.84±0.39% (2.4σ excess) in CMS
    - no excess in ATLAS (Br < 1.43%)
  - 13 TeV data
    - no excess in CMS so far
    - Br < 1.2% (8 TeV best-fit value is not rejected)
- No excess over the SM is seen so far in other channels (Atlas, CMS and LHCb)
- Much more data coming in Run 2 and beyond



# Prospects




Branching Fraction Upper Limit
Dukes
MARKII
CLEO
ARGUS
DELPHI
BaBar
Belle
TRIUMF
MEGA
SINDRUM
SINDRUM II
MEG (2016)
τ → eγ
τ → μγ
τ → μμμ
μN→ eN
μ → eγ
μ → eee
K_L → μe
K+ → πμe
K_L → πμe
Belle II
NA62
MEG II
Mu3e
DeeMe,
COMET, Mu2e
PRISM/PRIME
PIP II
1950
1960
1970
1980
1990
2000
2010
2020

# Conclusions



- Charged lepton flavor experiments are powerful probes into new physics
- Many near-future experiments in the U.S., Europe and Asia have high potential to discover new physics in the next decade
- It is important to measure many channels for discriminating new physics

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- Many near-future experiments in the U.S., Europe and Asia have high potential to discover new physics in the next decade
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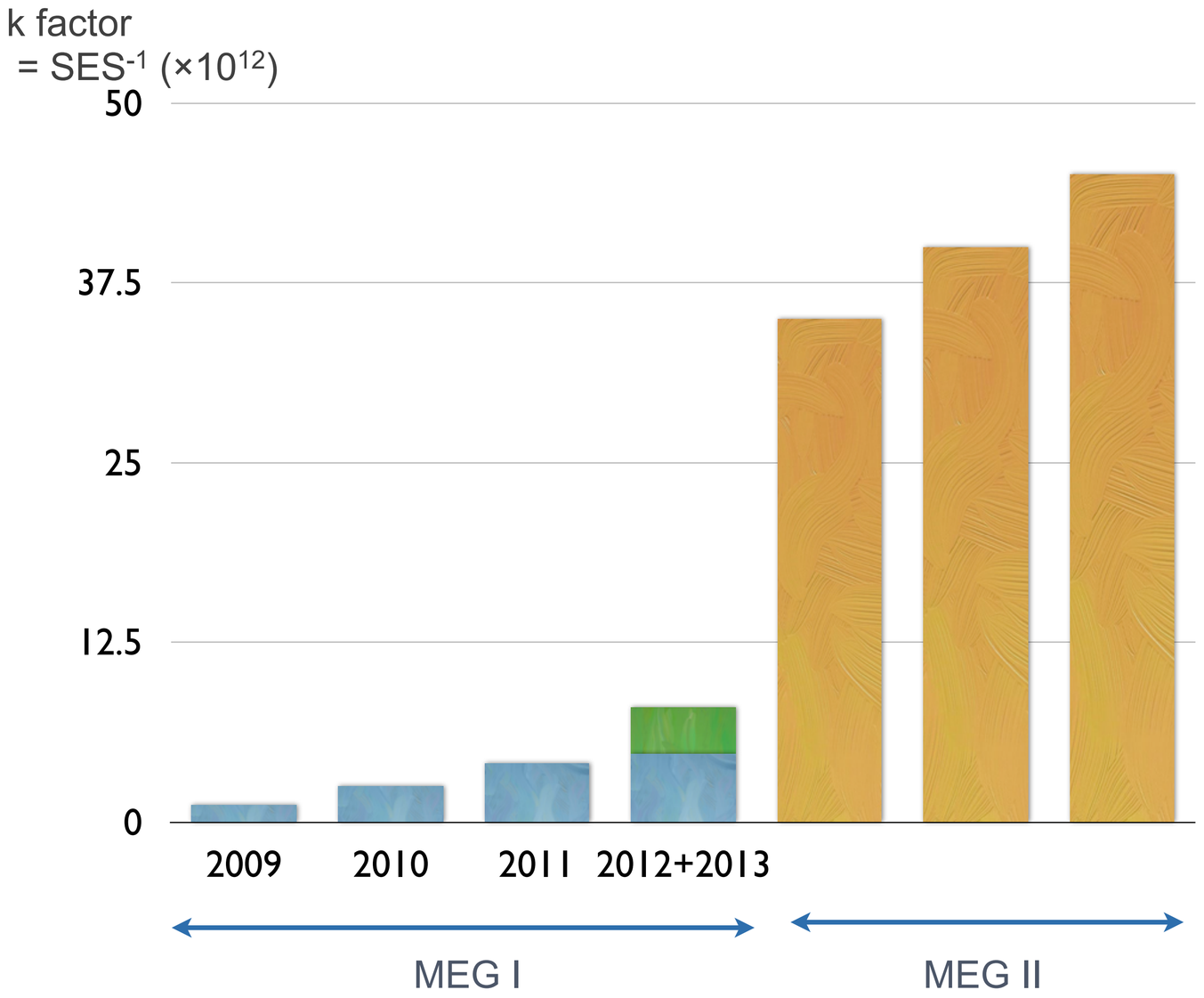
**Big surprises may be hiding where we haven't seen deeply enough yet**

# Backup

# MEG II Data Statistics





# MEG II expected performances

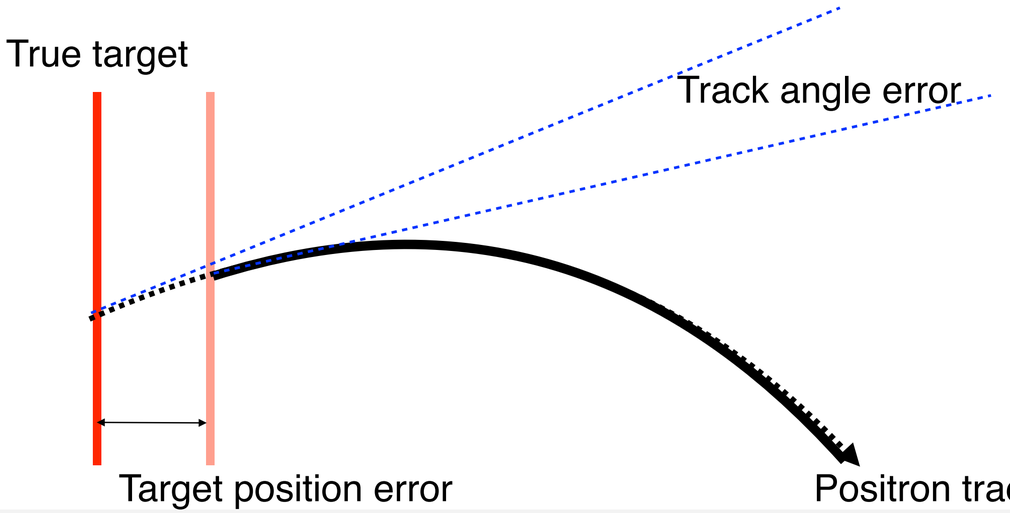


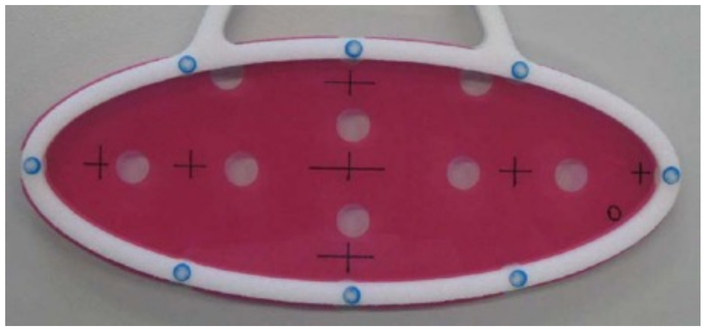
| **PDF parameters** | Present MEG | Upgrade scenario |
|---|---|---|
| $e^+$ energy (keV) | 306 (core) | 130 |
| $e^+$ $\theta$ (mrad) | 9.4 | 5.3 |
| $e^+$ $\phi$ (mrad) | 8.7 | 3.7 |
| $e^+$ vertex (mm) $Z/Y$(core) | 2.4 / 1.2 | 1.6 / 0.7 |
| $\gamma$ energy (%) ($w$ <2 cm)/($w$ >2 cm) | 2.4 / 1.7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

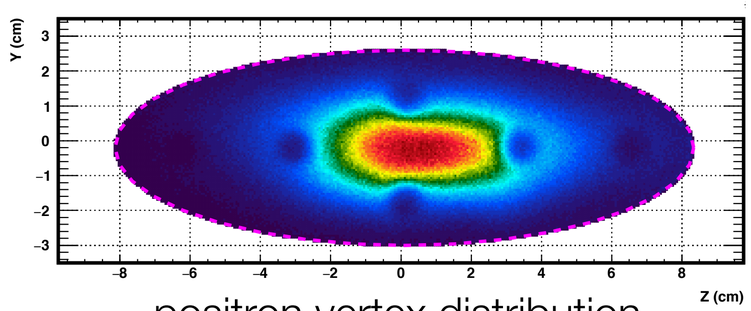
# MEG : Target uncertainty



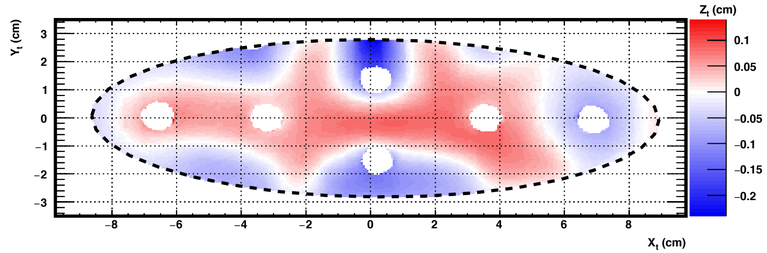
- The target position and shape are measured by
  - Optical survey of cross marks
  - Positron data : hole position reconstruction
    - Approximation as paraboloid
  - 3D scanner
- The position uncertainty (0.3—0.5 mm) and the deformation uncertainty (difference of the two measurements) included as a systematic uncertainty as nuisance parameter.
  - e.g. 0.5 mm position error ~ 4 mrad error in the eγ angle






positron vertex distribution




deformation measured by 3D scanner

**13% degradation in sensitivity**

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

After A. de Gouvêa, P. Vogel, arXiv:1303.4097