# The quest for μ->eγ and its experimental limiting factors at future high intensity muon beams


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in collaboration with

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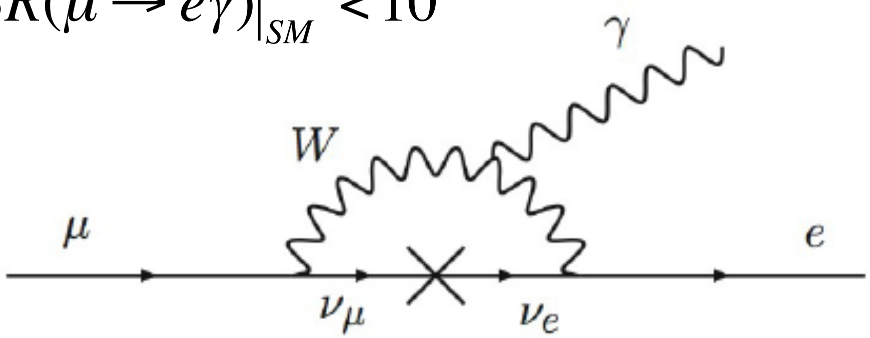
26th International Conference on Supersymmetry and Unification of Fundamental Interactions

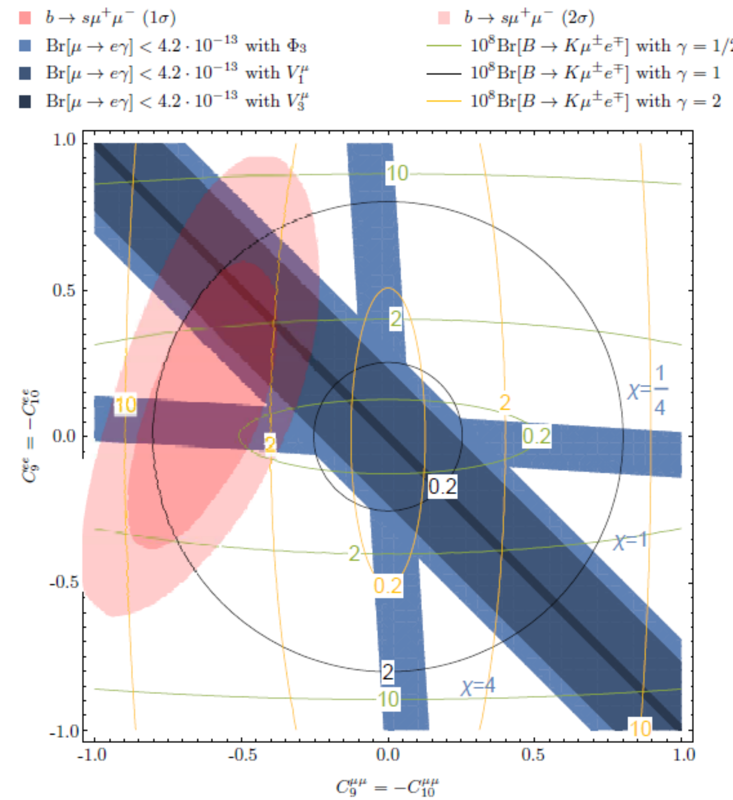
Barcelona, July 23-27, 2018

# Charged lepton flavor violation (cLFV)

- Allowed but unobservable in the Standard Model (with neutrino mass ≠0)

$$BR(\mu \to e\gamma)\big|_{SM} < 10^{-50}$$



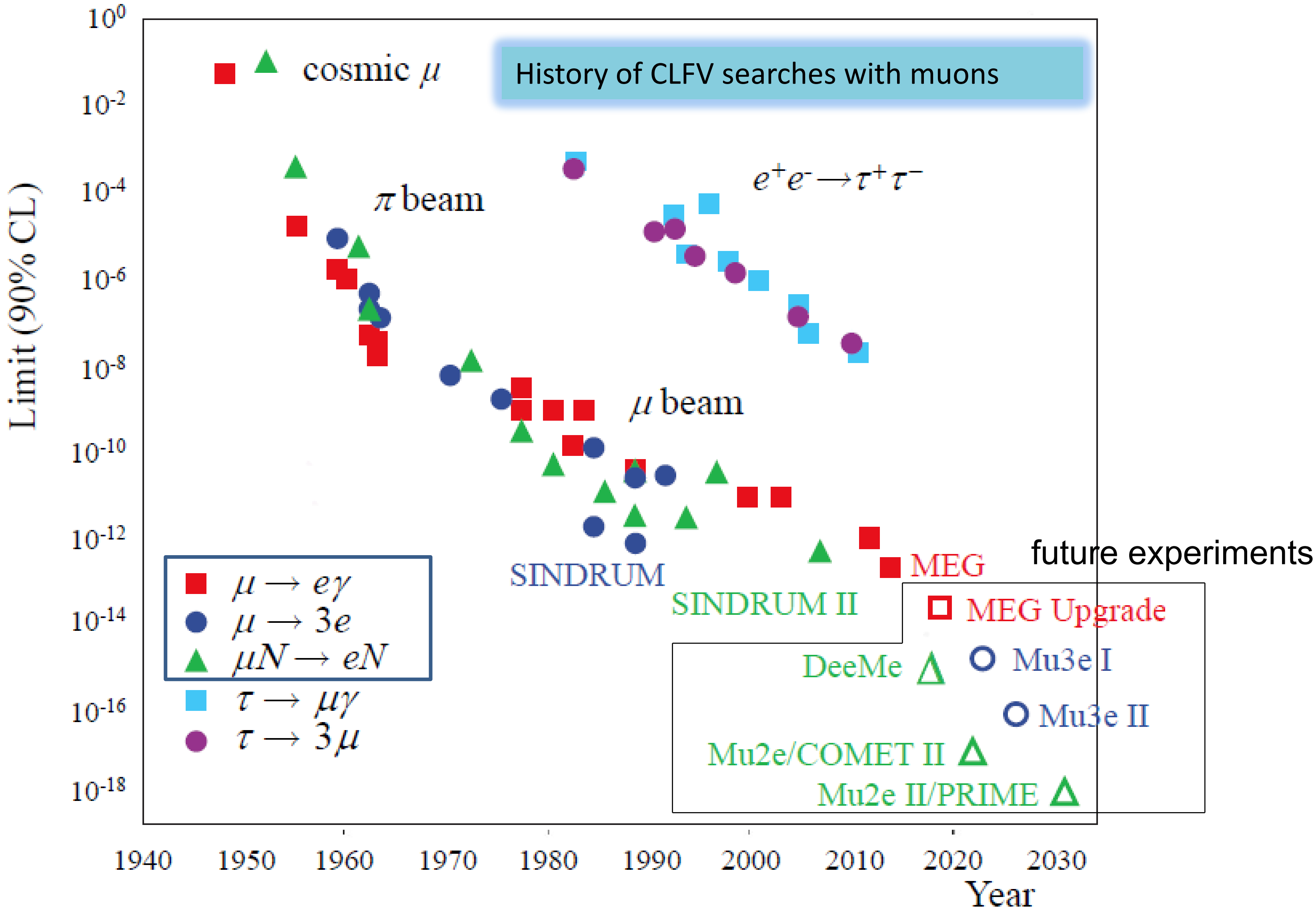




- Enanched, sometimes just below the experimental limit, in many New Physics models

Crivellin et. al.
arXiv:1706.08511

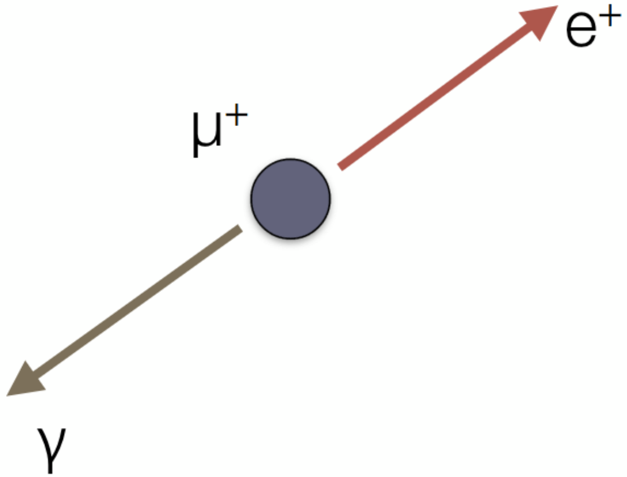
**Observation of cLFV is a clean signal of Physics beyond the Standard Model**

# History and future experiments



# Why $\mu \rightarrow e\gamma$

- Theoretically can be favored or disfavored vs other cLFV processes depending on the New Physics model
- Intense muon beams available:
  PSI presently: up to $10^8$ μ/s , future perspectives: $10^9$-$10^{10}$ μ/s
- Clean experimental signature
  (positive muon decays at rest)




Simultaneous back-to-back $e^+$ and γ with $E_\gamma = E_{e+} = 52.8$MeV

Discriminating variables:
$E_{e+}, E_\gamma, T_{e\gamma}, \Theta_{e\gamma}$

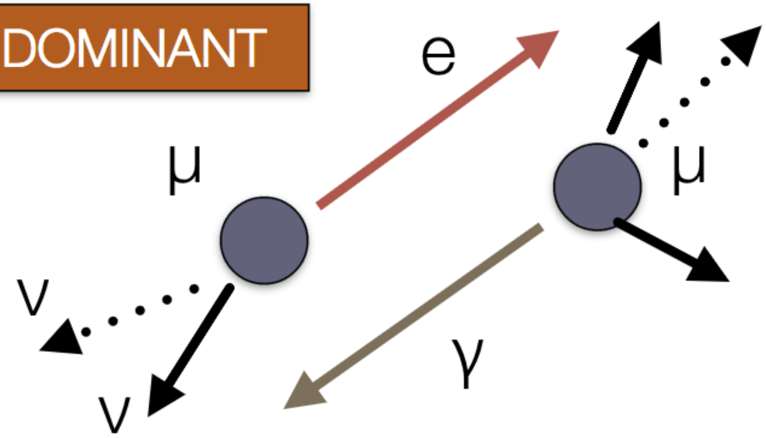
# $\mu \to e\gamma$ backgrounds

- ## Accidental background

  - Accidental coincidence of $e^+$ and $\gamma$:
  - Proportional to $\Gamma^2_\mu$ while signal proportional to $\Gamma_\mu$ ($\Gamma_\mu$= beam intensity)
  - Compromise between high signal and low background

Michel or radiative decay: μ->e(γ)νν

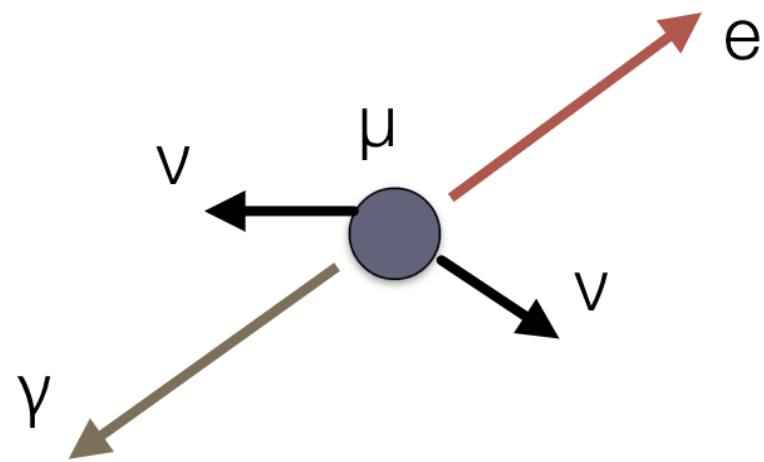
DOMINANT



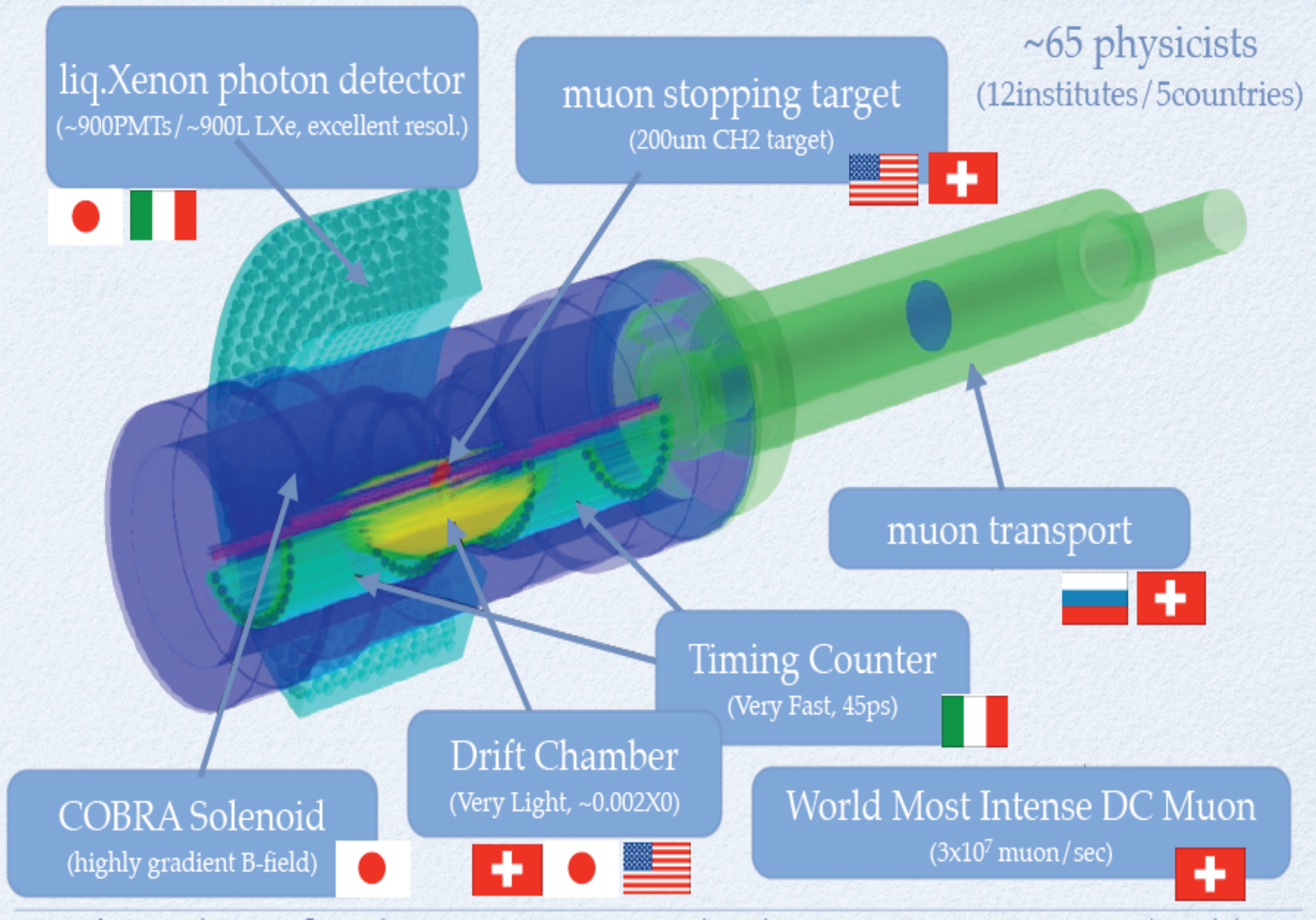

$$B_{acc} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta \Theta_{e\gamma})^2$$

- ## Radiative muon decay background

  - Proportional to $\Gamma_\mu$
  - Note: $e^+$ and γ simultaneous as for signal

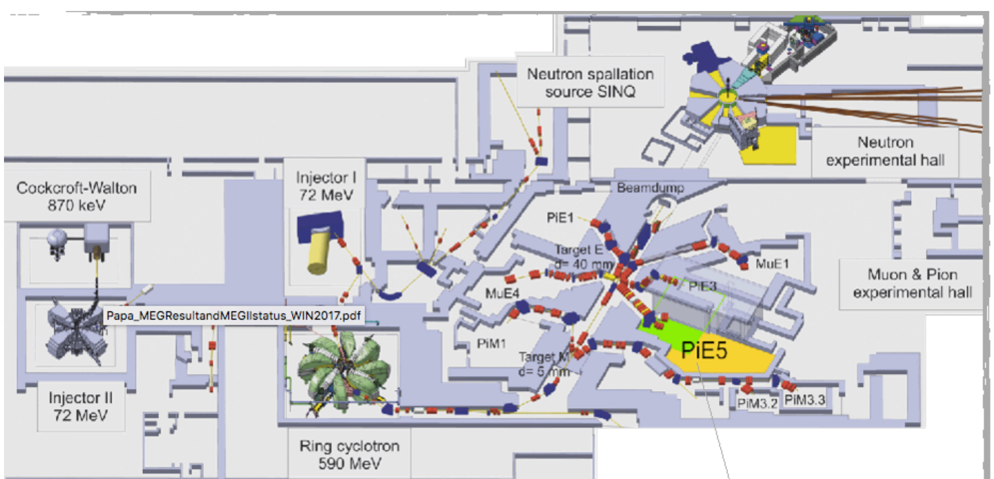


# The MEG experiment for μ→eγ search @PSI (Zurich)

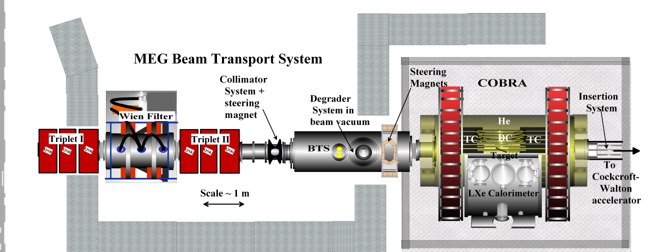


# PSI Muon beam

- Most intense continuous muon beam in the word
- Muons up to ~$10^8$ μ/s but MEG used only $3\times10^7$ to optimize the sensitivity
- Proton beam current: ~2.2mA
- Proton target: ~15% of protons stopped
  => pions=>sufrace muons (p=28MeV/c)
- Muons are stopped in a thin target inside the MEG detector

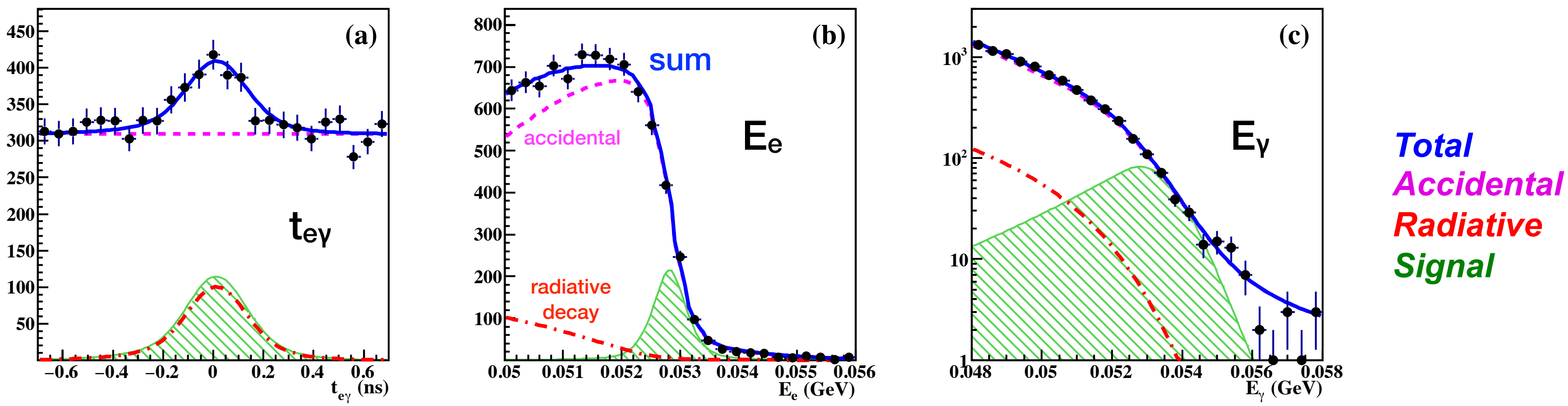


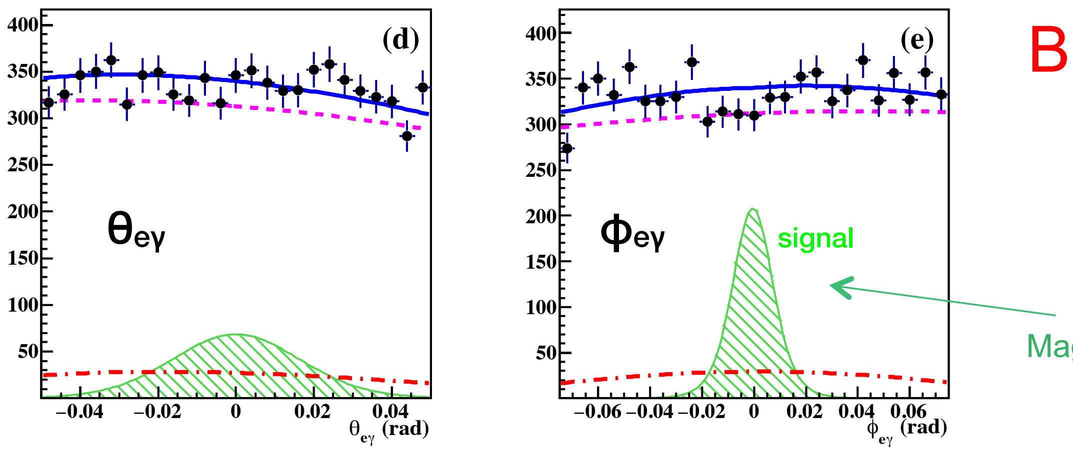

MEGII Experimental area



# MEG BR(μ→eγ) best word limit

- $7.5 \times 10^{14}$ stopped muons in 2009-2013
- 5 discriminating variables: $E_e$, $E_\gamma$, $T_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$
- likelihood analysis



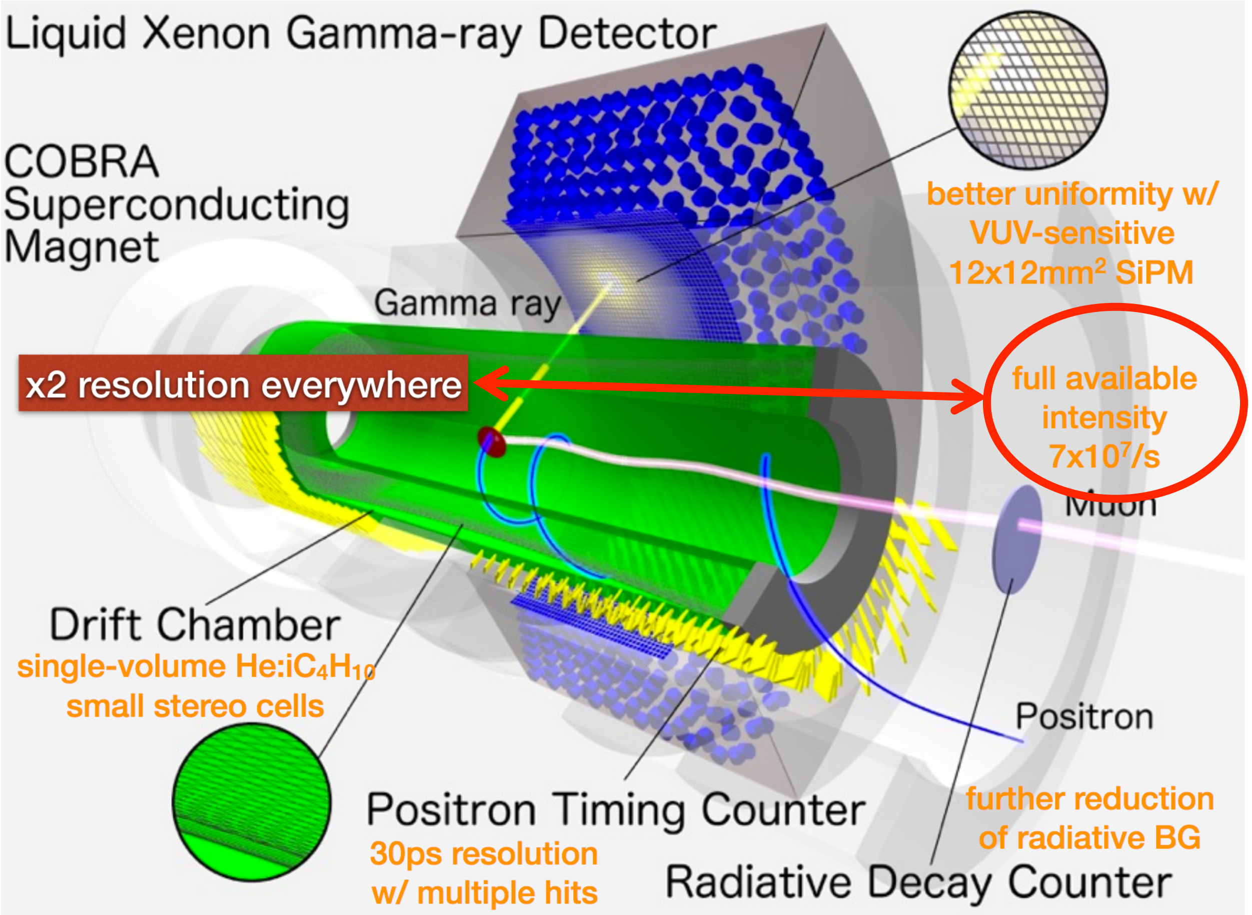

**BR (μ→eγ) < $4.2 \times 10^{-13}$ at 90% C.L.**

Eur.Phys.J.C76 (2016)

Magnified signal for illustrative purposes

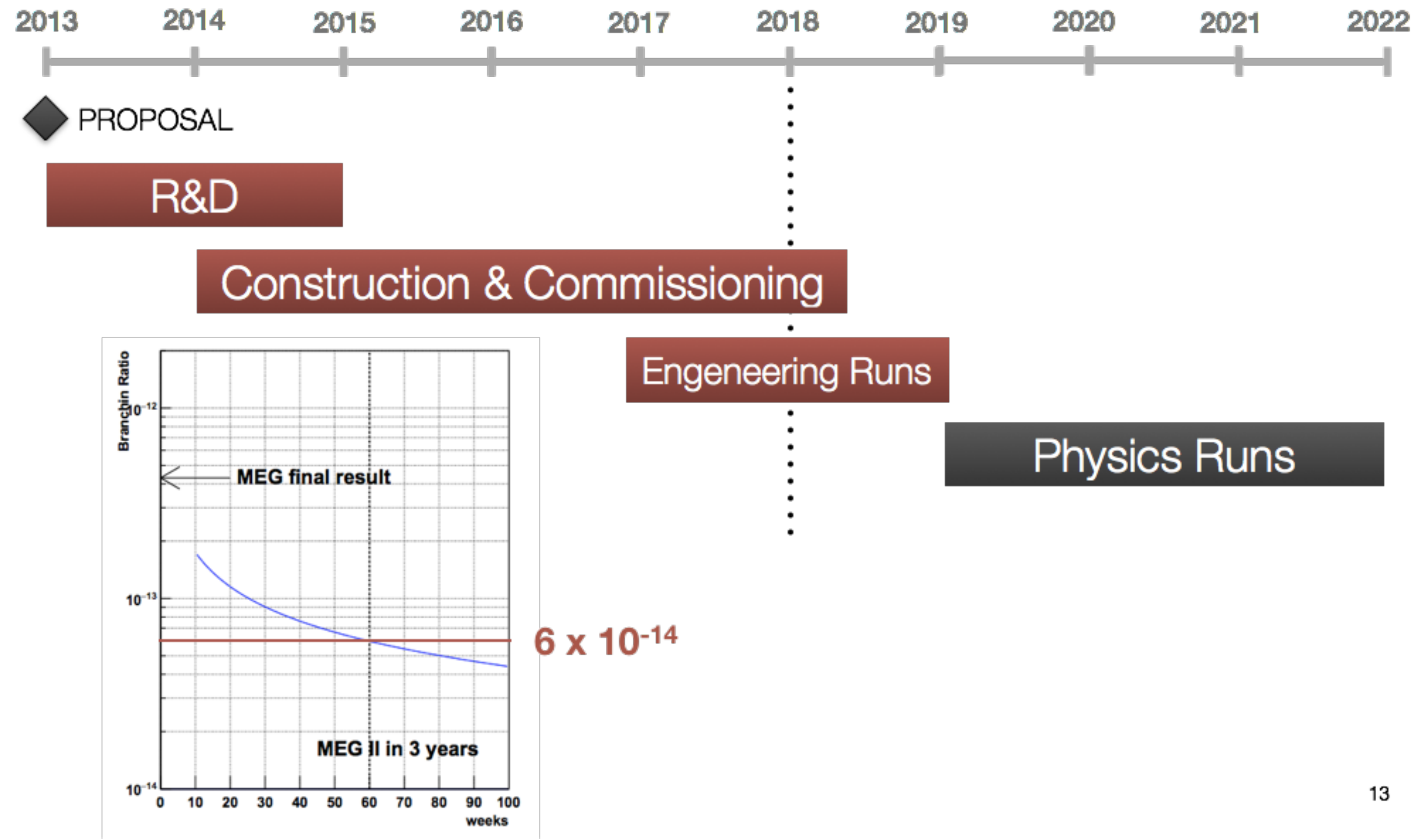
# Next: MEG upgrade: MEG-II

- Same detector concept as in MEG but better efficiency/resolution
- Increase beam intensity as much as allowed by accidental background




**optimized to enhance sensitivity (accidental background prop. to $I^2_{\mu}$)**

# MEG-II goals and schedule



What is the future of $\mu \to e\gamma$ searches?

(after MEGII)

G. Cavoto, A. Papa, F. Renga,
E. Ripiccini and **CV**

Eur. Phys. J. C (2018) **78**, 37

# Next generation of μ→eγ searches

- Activities around the world to increase the muon beam rate to $10^{9}$-$10^{10}$ muons/s
- Crucial to understand which factors will limit the sensitivity

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

$\Gamma_{\mu}$ = beam intensity

- For a given detector, there is no advantage in the increase of $\Gamma_{\mu}$ over a certain limit since at some point the sensitivity becomes constant (background dominated regime)

- MEGII, for example exploits $7\times10^{7}$ muon/s (available $10^{8}$ muon/s)

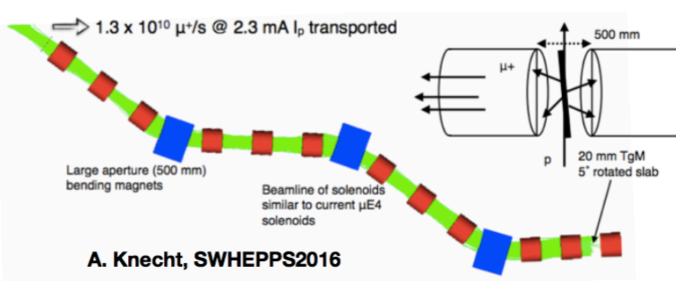
- New Projects: **HiMB@PSI, Music@RCNP**

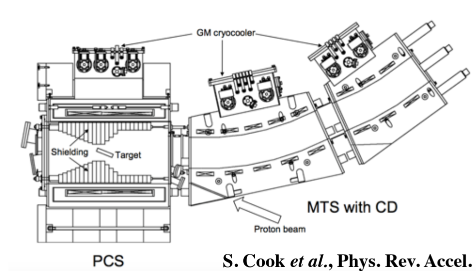
**HiMB Project @ PSI**

x4 μ capture eff.

x6 μ transport eff.

**$1.3 \times 10^{10}$ μ/s**




S. Cook *et al.*, Phys. Rev. Accel. Beams 20 (2017)

**MuSIC Project @ RCNP**

Thick production target

π capture solenoid

**$4 \times 10^{8}$ μ/s**

# Photon reconstruction

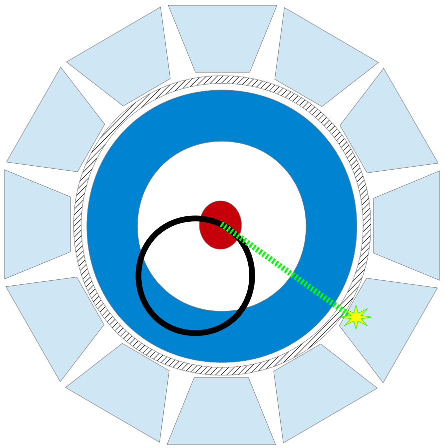
# Next generation of μ→eγ searches: photon reconstruction

- To reconstruct the photon two possible approaches:

### Calorimetric

- high efficiency, good resolution
- requirements:
  * high light yield
  * fast response

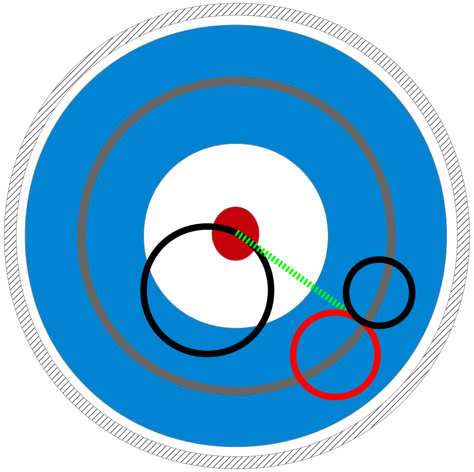
LaBr3(Ce) – a.k.a. Brillance :
our simulations and tests indicate
σ(E)~800keV σ(t)~30ps



### Photon conversion

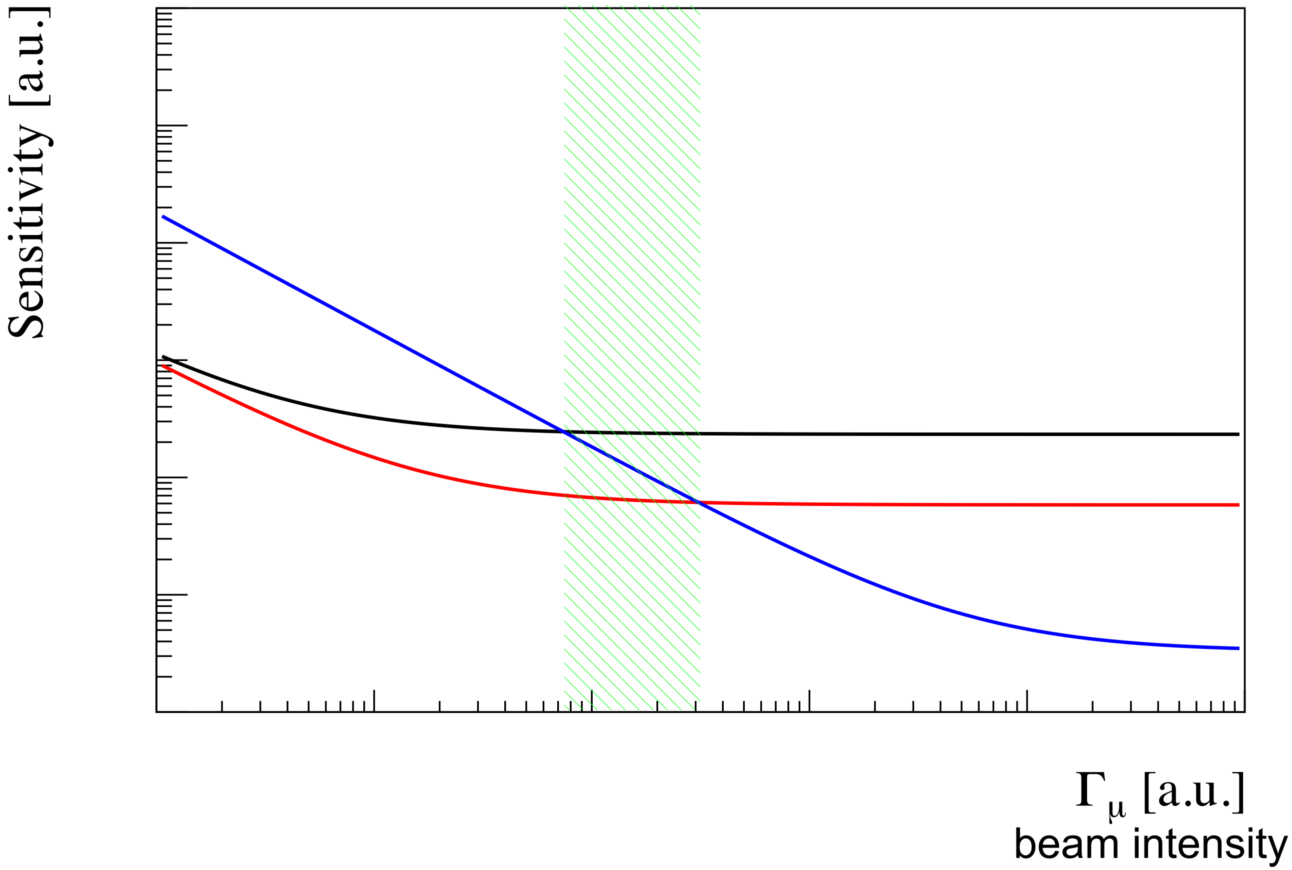
- low efficiency (%), extreme resolution
- photon direction

- requirements:
  * optimization of converter thickness
    (large Z materials like Pb,W)



# Calorimeter vs photon conversion

Sensitivity trend vs beam intensity
blue = pair conversion design
black = calorimeter design
red =  calorimeter design with x2 resolution



# Positron reconstruction

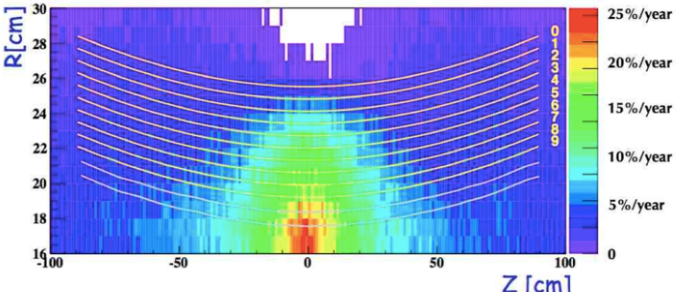
# Next generation of μ→eγ searches: positron reconstruction

- Tracking detectors in a magnetic field are the gold candidates: high efficiency, good resolution

- Need very light detector (MEGII~$10^{-3}X_0$) : positron reconstruction is ultimately limited by MS:

  - in the target & tracker-> angular resolution
  - in the tracker -> momentum resolution

- Silicon trackers are not competitive with gaseous detector in terms of resolution but could be the solution at very high rate




A. Baldini et al., MEG Upgrade Proposal, arXiv:1301:7225

expected aging in MEG-II DCH

# Photon-Positron timing

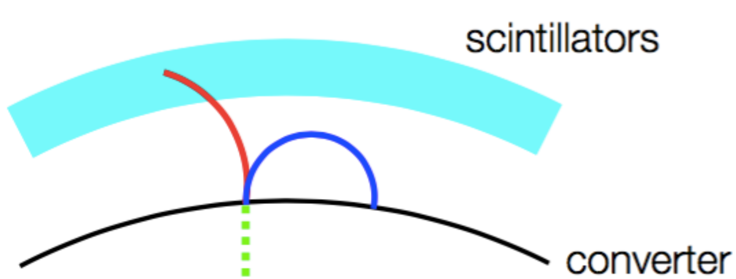
# Next generation of μ→eγ searches: relative time

- Timing plays a crucial role to avoid accidental coincidences

- Calorimetric approach: calorimeters+positron scintillating counters (MEG-II: $T_{e\gamma}$~80ps)

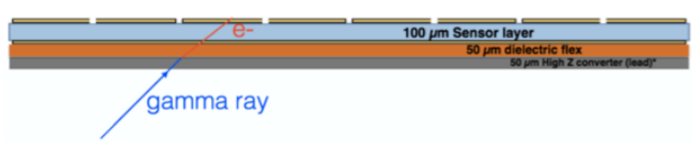
- Photon conversion approach: need to measure $e^+$ or $e^-$ time with a fast detector for photon timing

- Several conversion layers imply to have active material behind the converter




**FAST SILICON DETECTORS**

- R&D on going for PET application (**TT-PET**)




**M. Benoit et al., JINST 11 (2016) no. 03, P03011**

# Next generation of μ→eγ searches: possible scenarios

***CALORIMETRY*** (R&D with $LaBr_3(Ce)$)

| Variable | Resolution: *w/o vtx detector* | *w/ TPC vtx detector* conservative | *w/ TPC vtx detector* optimistic | *w/ silicon vtx detector* conservative | *w/ silicon vtx detector* optimistic |
|---|---|---|---|---|---|
| $\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad] | 7.3 / 6.2 | 6.1 / 4.8 | 3.5 / 3.8 | 8.0 / 7.4 | 6.3 / 6.9 |
| $T_{e\gamma}$ [ps] | | | 30 | | |
| $E_e$ [keV] | | | 100 | | |
| $E_\gamma$ [keV] | | | 850 | | |
| Efficiency [%] | | | 42% | | |

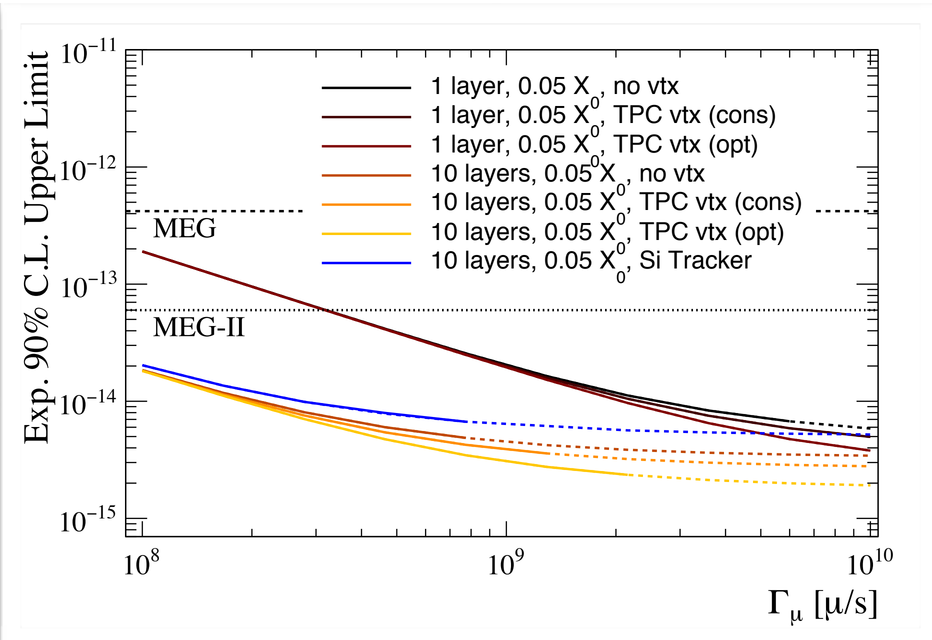
gaseous detector

***PHOTON CONVERSION***

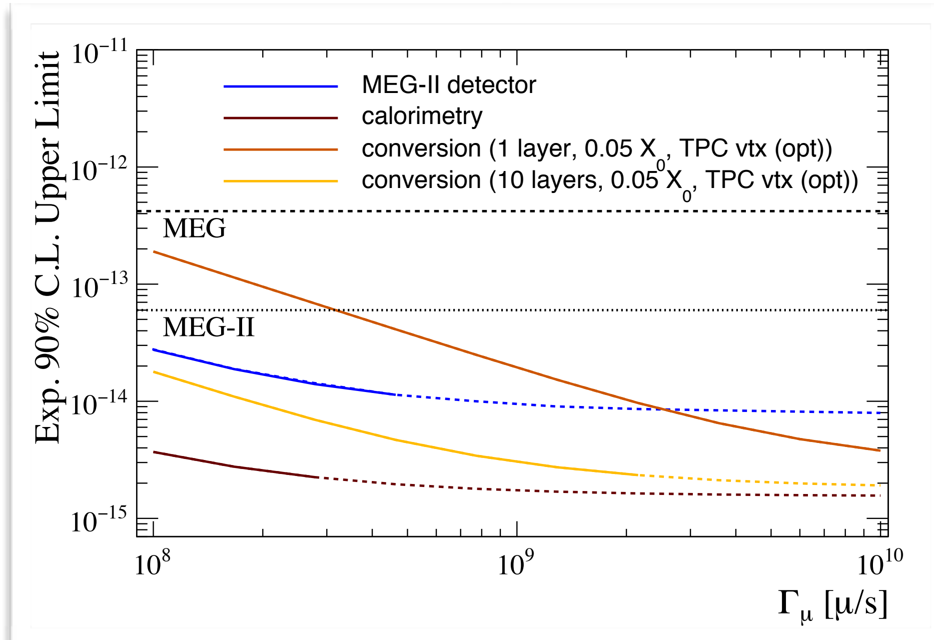
| Variable | Resolution: *w/o vtx detector* | *w/ TPC vtx detector* conservative | *w/ TPC vtx detector* optimistic | *w/ silicon vtx detector* conservative | *w/ silicon vtx detector* optimistic |
|---|---|---|---|---|---|
| $\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad] | 7.3 / 6.2 | 6.1 / 4.8 | 3.5 / 3.8 | 8.0 / 7.4 | 6.3 / 6.9 |
| $T_{e\gamma}$ [ps] | | | 50 | | |
| $E_e$ [keV] | | | 100 | | |
| $E_\gamma$ [keV] | | | 320 | | |
| Efficiency [%] | | | 1.2 **(1 LAYER, 0.05 $X_0$)** | | |

# Expected sensitivity (3years data taking)

## Photon conversion approach




## Photon conversion vs calorimetric approach




A few $10^{-15}$ level seems to be within reach for 3 years running at $10^{8}$ muon/s with calorimetry or $10^{9}$ muons/s with photon conversion

# Conclusion

- Search of μ→eγ decay continues
- Best word limit from MEG experiment

**BR (μ→eγ) < 4.2x $10^{-13}$ at 90% C.L.**

- MEG-II
  => expect a sensitivity of $4\times10^{-14}$ in 3 years

- What's next?

  - $10^{9}$-$10^{10}$ μ/s seems possible (HiMB,MUSIC..)
  - A few $10^{-15}$ level seems to be within reach for 3 years running at $10^{8}$ muon/s with calorimetry or $10^{9}$ muons/s with photon conversion approach (cheaper)
  - Further improvements require new detector concepts

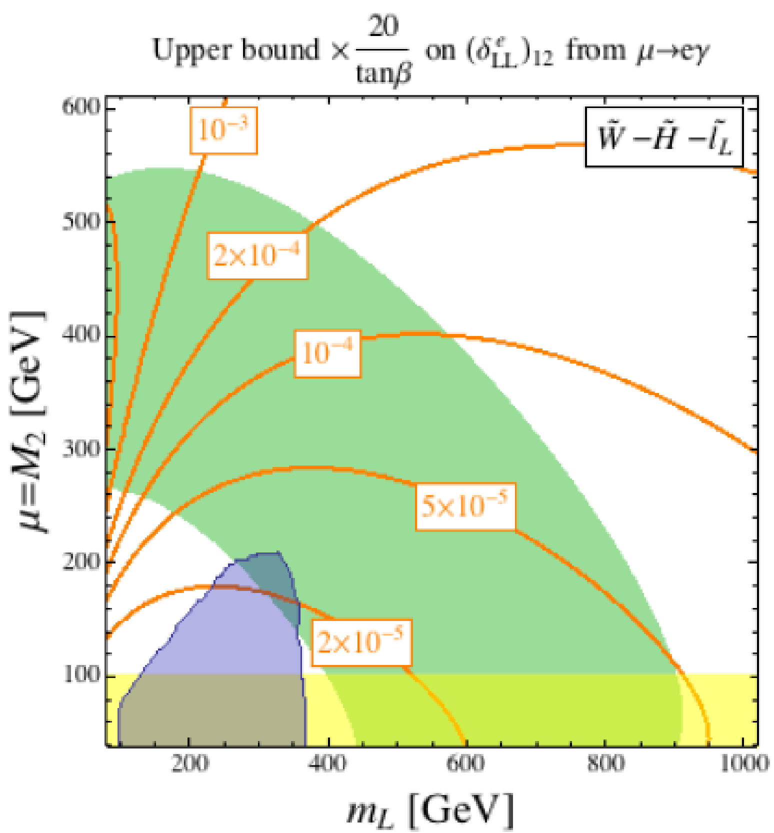
# Backup

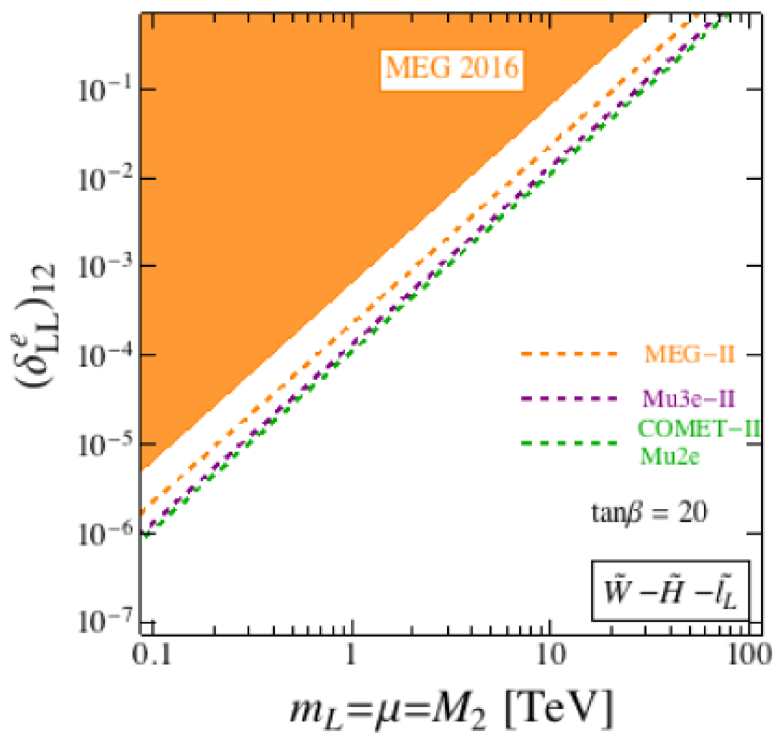
# Present CLFV limits

| Reaction | Present limit | C.L. | Experiment | Year |
|---|---|---|---|---|
| $\mu^+ \to e^+\gamma$ | $< 4.2 \times 10^{-13}$ | 90% | MEG at PSI | 2016 |
| $\mu^+ \to e^+e^-e^+$ | $< 1.0 \times 10^{-12}$ | 90% | SINDRUM | 1988 |
| $\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ † | $< 6.1 \times 10^{-13}$ | 90% | SINDRUM II | 1998 |
| $\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ † | $< 4.6 \times 10^{-11}$ | 90% | SINDRUM II | 1996 |
| $\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ † | $< 7.0 \times 10^{-13}$ | 90% | SINDRUM II | 2006 |
| $\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ † | $< 3.6 \times 10^{-11}$ | 90% | SINDRUM II | 1998 |
| $\mu^+e^- \to \mu^-e^+$ | $< 8.3 \times 10^{-11}$ | 90% | SINDRUM | 1999 |
| $\tau \to e\gamma$ | $< 3.3 \times 10^{-8}$ | 90% | BaBar | 2010 |
| $\tau \to \mu\gamma$ | $< 4.4 \times 10^{-8}$ | 90% | BaBar | 2010 |
| $\tau \to eee$ | $< 2.7 \times 10^{-8}$ | 90% | Belle | 2010 |
| $\tau \to \mu\mu\mu$ | $< 2.1 \times 10^{-8}$ | 90% | Belle | 2010 |
| $\tau \to \pi^0 e$ | $< 8.0 \times 10^{-8}$ | 90% | Belle | 2007 |
| $\tau \to \pi^0 \mu$ | $< 1.1 \times 10^{-7}$ | 90% | BaBar | 2007 |
| $\tau \to \rho^0 e$ | $< 1.8 \times 10^{-8}$ | 90% | Belle | 2011 |
| $\tau \to \rho^0 \mu$ | $< 1.2 \times 10^{-8}$ | 90% | Belle | 2011 |
| $\pi^0 \to \mu e$ | $< 3.6 \times 10^{-10}$ | 90% | KTeV | 2008 |
| $K_L^0 \to \mu e$ | $< 4.7 \times 10^{-12}$ | 90% | BNL E871 | 1998 |
| $K_L^0 \to \pi^0\mu^+e^-$ | $< 7.6 \times 10^{-11}$ | 90% | KTeV | 2008 |
| $K^+ \to \pi^+\mu^+e^-$ | $< 1.3 \times 10^{-11}$ | 90% | BNL E865 | 2005 |
| $J/\psi \to \mu e$ | $< 1.5 \times 10^{-7}$ | 90% | BESIII | 2013 |
| $J/\psi \to \tau e$ | $< 8.3 \times 10^{-6}$ | 90% | BESII | 2004 |
| $J/\psi \to \tau\mu$ | $< 2.0 \times 10^{-6}$ | 90% | BESII | 2004 |
| $B^0 \to \mu e$ | $< 2.8 \times 10^{-9}$ | 90% | LHCb | 2013 |
| $B^0 \to \tau e$ | $< 2.8 \times 10^{-5}$ | 90% | BaBar | 2008 |
| $B^0 \to \tau\mu$ | $< 2.2 \times 10^{-5}$ | 90% | BaBar | 2008 |
| $B \to K\mu e$ ‡ | $< 3.8 \times 10^{-8}$ | 90% | BaBar | 2006 |
| $B \to K^*\mu e$ ‡ | $< 5.1 \times 10^{-7}$ | 90% | BaBar | 2006 |
| $B^+ \to K^+\tau\mu$ | $< 4.8 \times 10^{-5}$ | 90% | BaBar | 2012 |
| $B^+ \to K^+\tau e$ | $< 3.0 \times 10^{-5}$ | 90% | BaBar | 2012 |
| $B_s^0 \to \mu e$ | $< 1.1 \times 10^{-8}$ | 90% | LHCb | 2013 |
| $\Upsilon(1s) \to \tau\mu$ | $< 6.0 \times 10^{-6}$ | 95% | CLEO | 2008 |
| $Z \to \mu e$ | $< 7.5 \times 10^{-7}$ | 95% | LHC ATLAS | 2014 |
| $Z \to \tau e$ | $< 9.8 \times 10^{-6}$ | 95% | LEP OPAL | 1995 |
| $Z \to \tau\mu$ | $< 1.2 \times 10^{-5}$ | 95% | LEP DELPHI | 1997 |
| $h \to e\mu$ | $< 3.5 \times 10^{-4}$ | 95% | LHC CMS | 2016 |
| $h \to \tau\mu$ | $< 2.5 \times 10^{-3}$ | 95% | LHC CMS | 2017 |
| $h \to \tau e$ | $< 6.1 \times 10^{-3}$ | 95% | LHC CMS | 2017 |

# Comparison with SUSY searches at LHC

$$(\delta_{\rm LL})_{ij} = \frac{(\Delta_{\rm LL})_{ij}}{\sqrt{(\tilde{m}^2_L)_{ii}(\tilde{m}^2_L)_{jj}}},$$

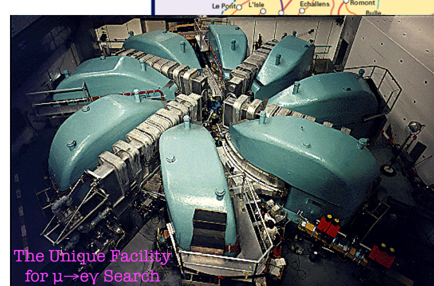



Calibbi, Signorelli, NC 2017

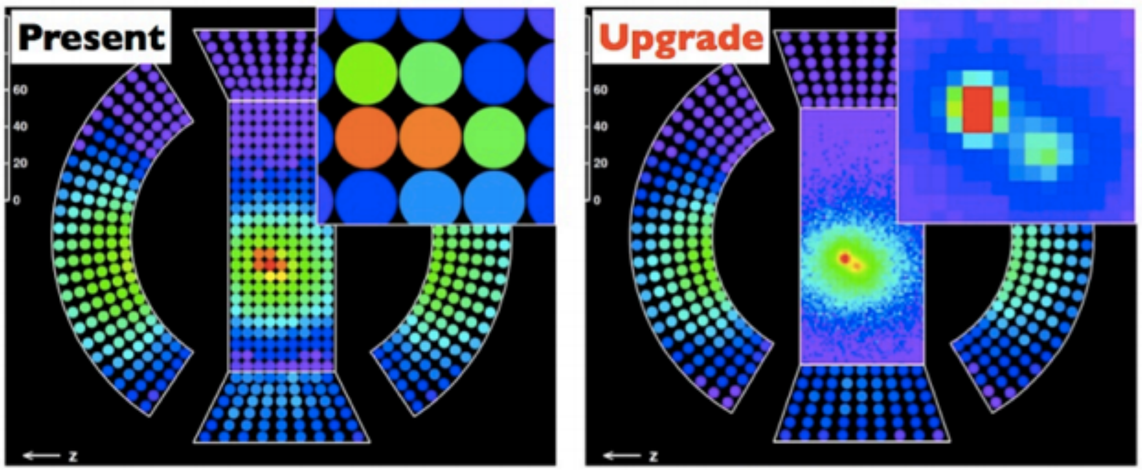
# The Paul Scherrer Institute
## Continuous muon beam up to few $10^8$ $\mu^+$/s

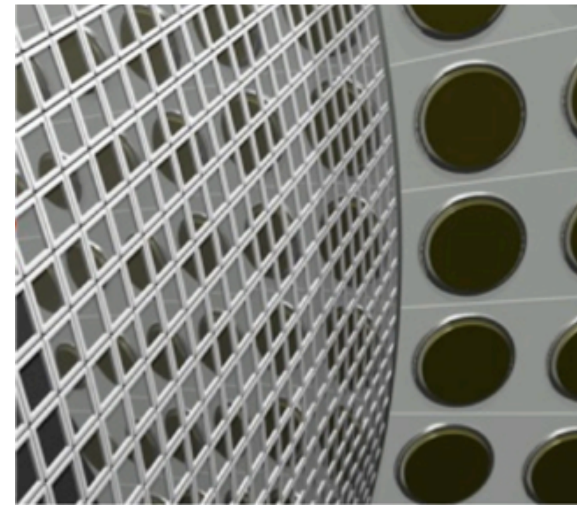
Multi-disciplinary lab:
- fundamental research, cancer therapy, muon and neutron sources
- protons from cyclotron ($D=15m$, $E_{proton}=590MeV$ $I=2.2mA$)

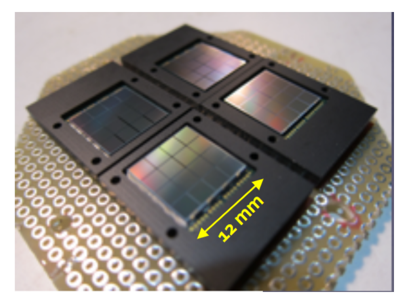
# MEG-II detector highlights: Liquid Xenon

Liquid Xenon Calorimeter with higher granularity in inner face:
=> better resolution, better pile-up rejection



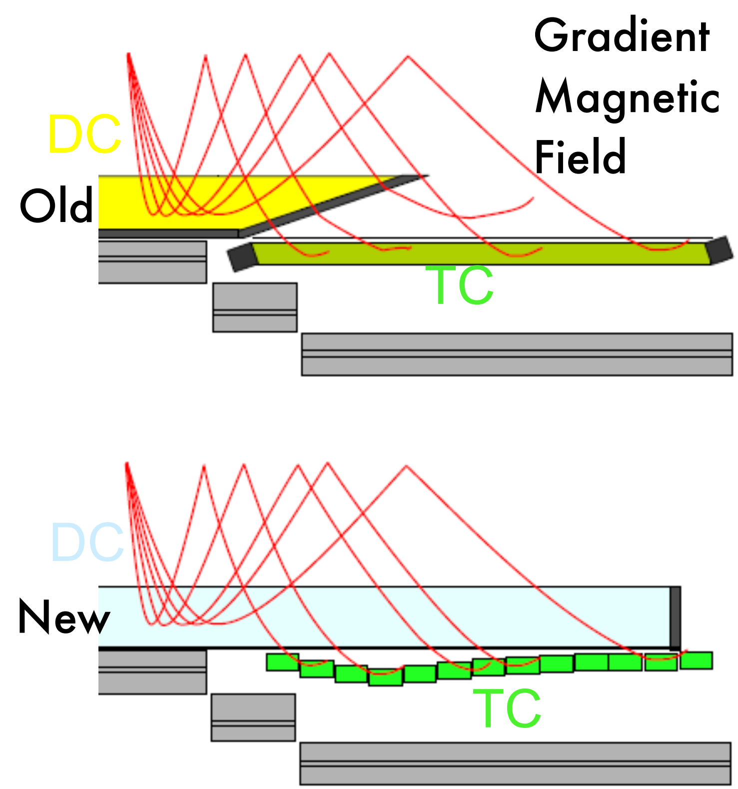
Large UV-ext SiPM



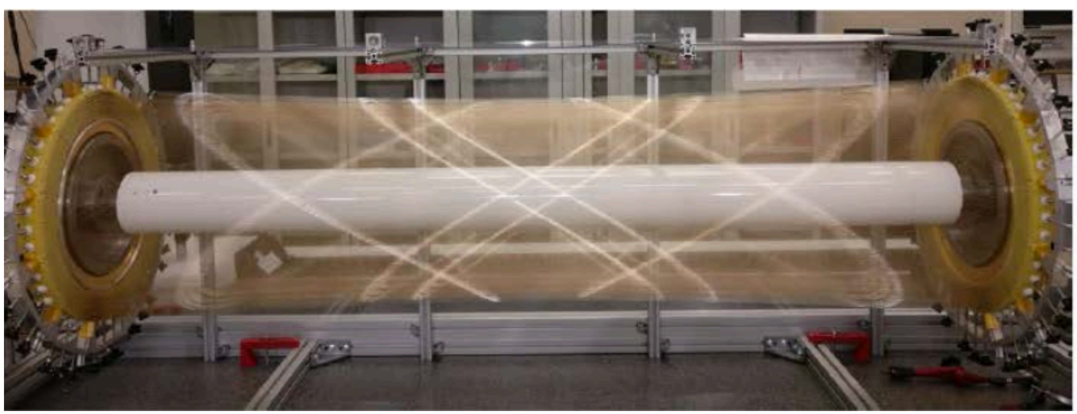

- Developed UV sensitive MPPC (vacuum UV 12x12mm$^2$ SiPM)
- Detector assembled, filled with LXe (commissioning on-going)

# MEG-II detector highlights: Drift Chamber

- Single volume drift chamber with 2π coverage
  - 2m long
  - 1300 sense wires
  - stereo angle (6°-8°)
  - low mass
  - high trasparency to TC
    (double signal efficiency)



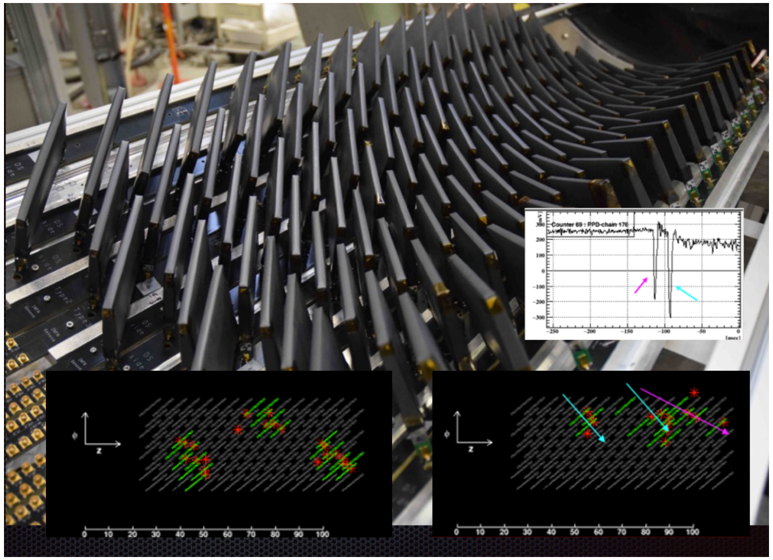

- On beam in fall 2018

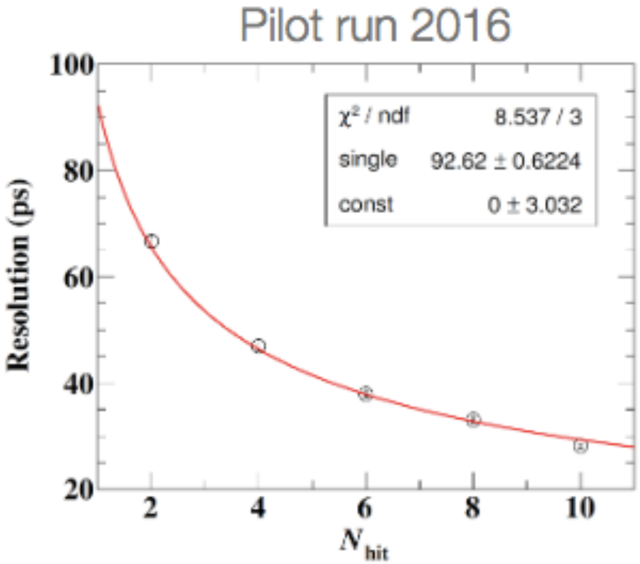


# MEG-II detector highlights: Timing Counter

- High granularity: 2 x 256 BC422 scintillator plates read by SiPM

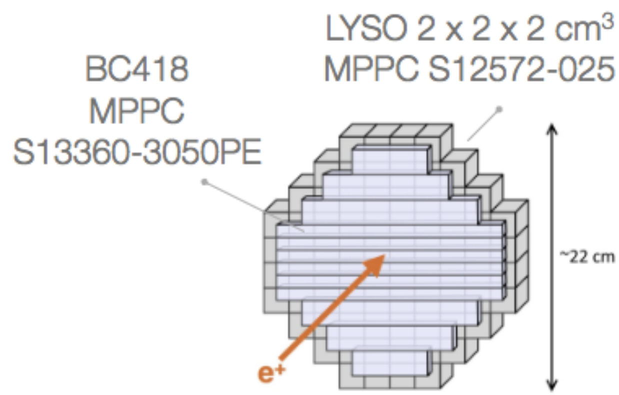
- improved timing resolution: 35ps (70ps in MEG)
- Assembly: completed
- Installation in COBRA in progress
- Full test during 2017 pre-engineering run
  (expected detector performances already confirmed in data)

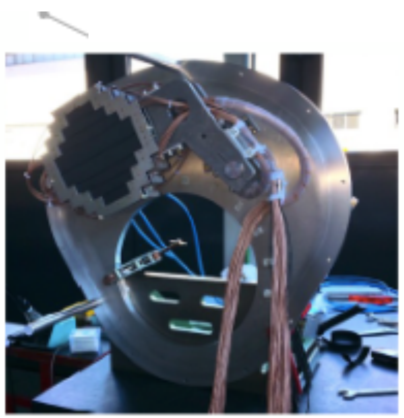


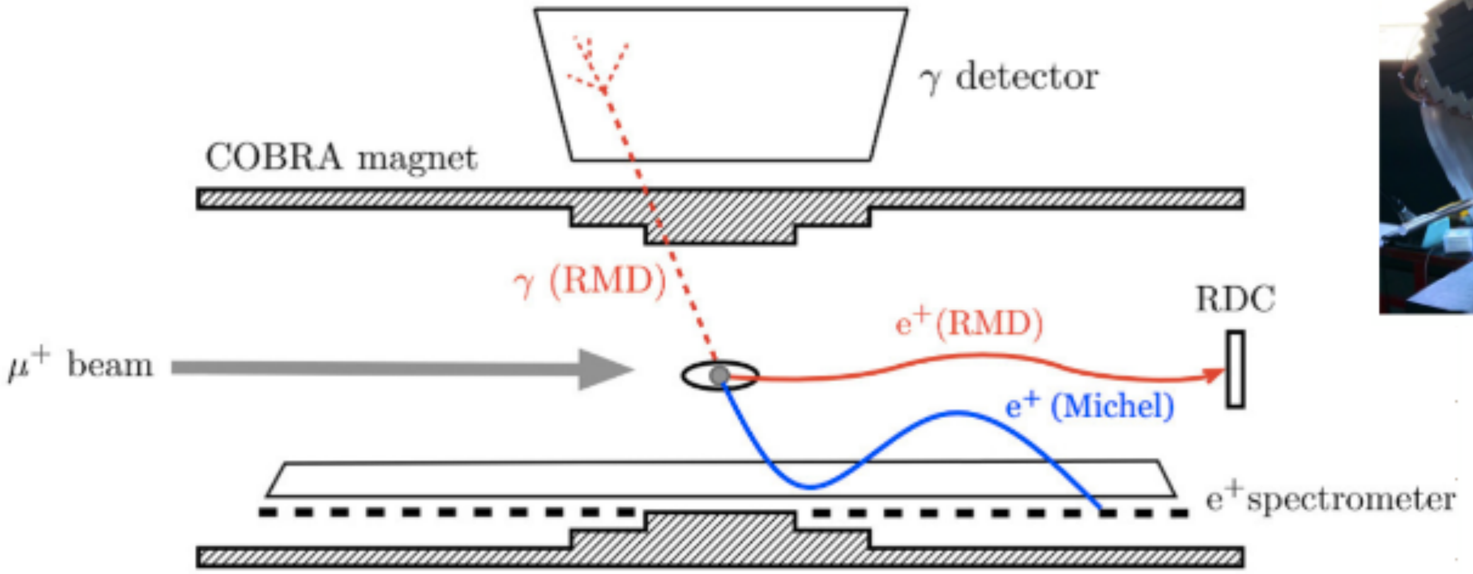


# MEG-II detector highlights: Radiative Decay Counter

- New auxiliary detector for background rejection purpose => improve sensitivity by 15%
- Commissioned during 2017 run
- Ready for 2018 pre-engineering run



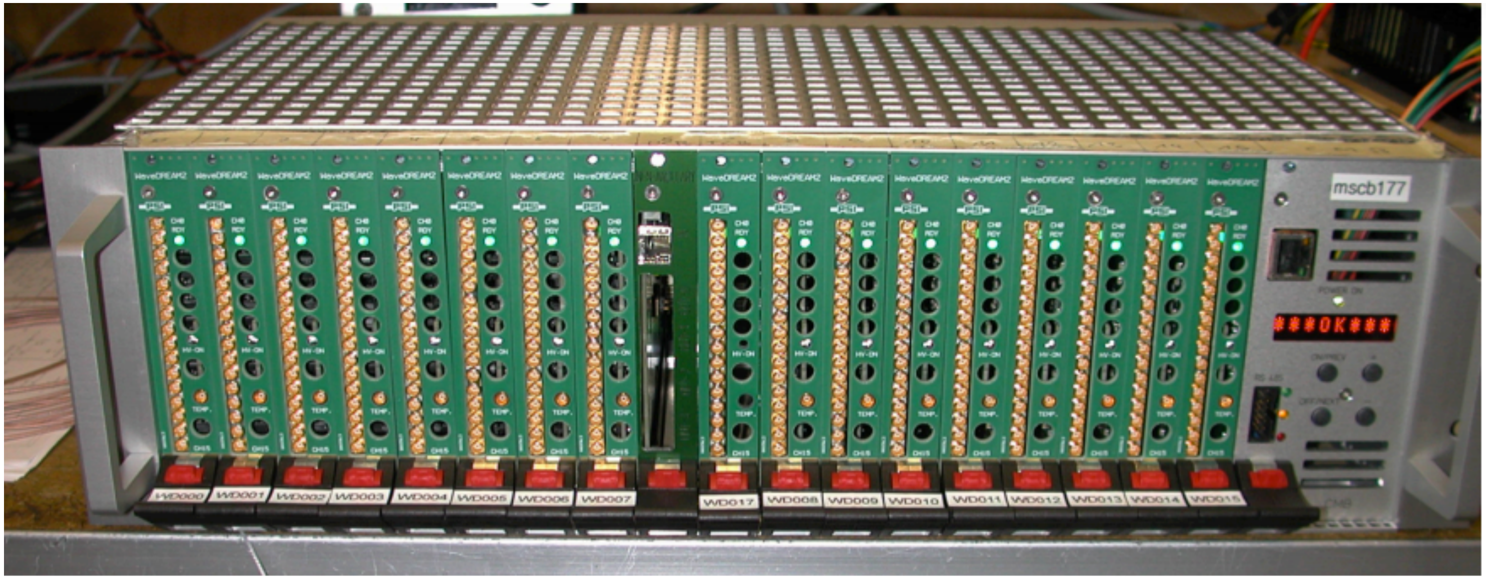


# MEG-II new trigger and DAQ system

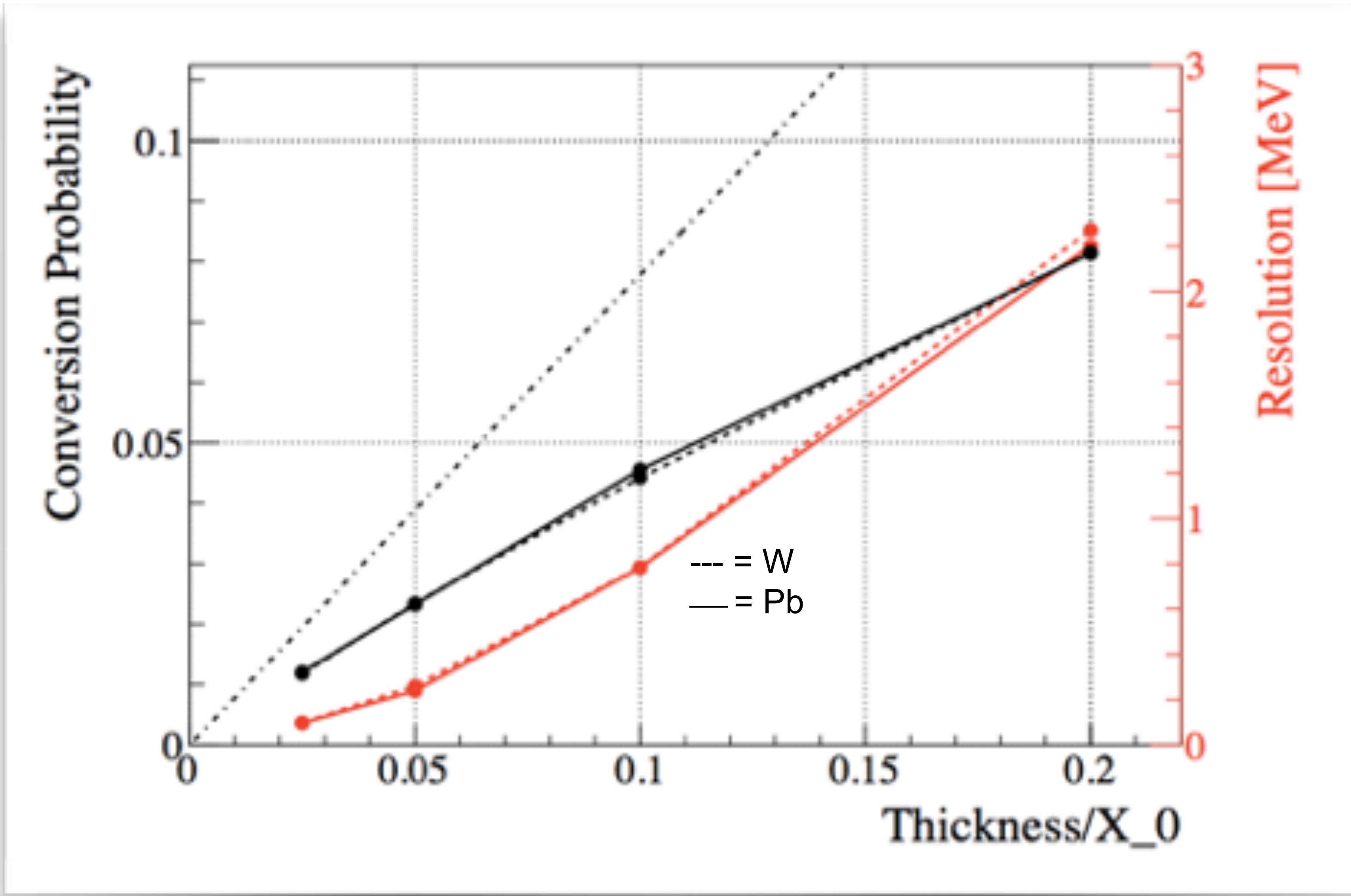
- New version of DRS (Wavedream) custom digitization board integrating both digitization, triggering and some HV

  - ~9000 channels (5GSPS)
  - 256 channels (1crate) tested during 2016 pre-engineering run
  - > 1000 channels available for the upcoming 2017 pre-engineering run

- Final production expected in winter 2018



# Photon reconstruction: limiting factors



# A tentative design with photon conversion