Final Results of the MEG Experiment

and Status of MEG II

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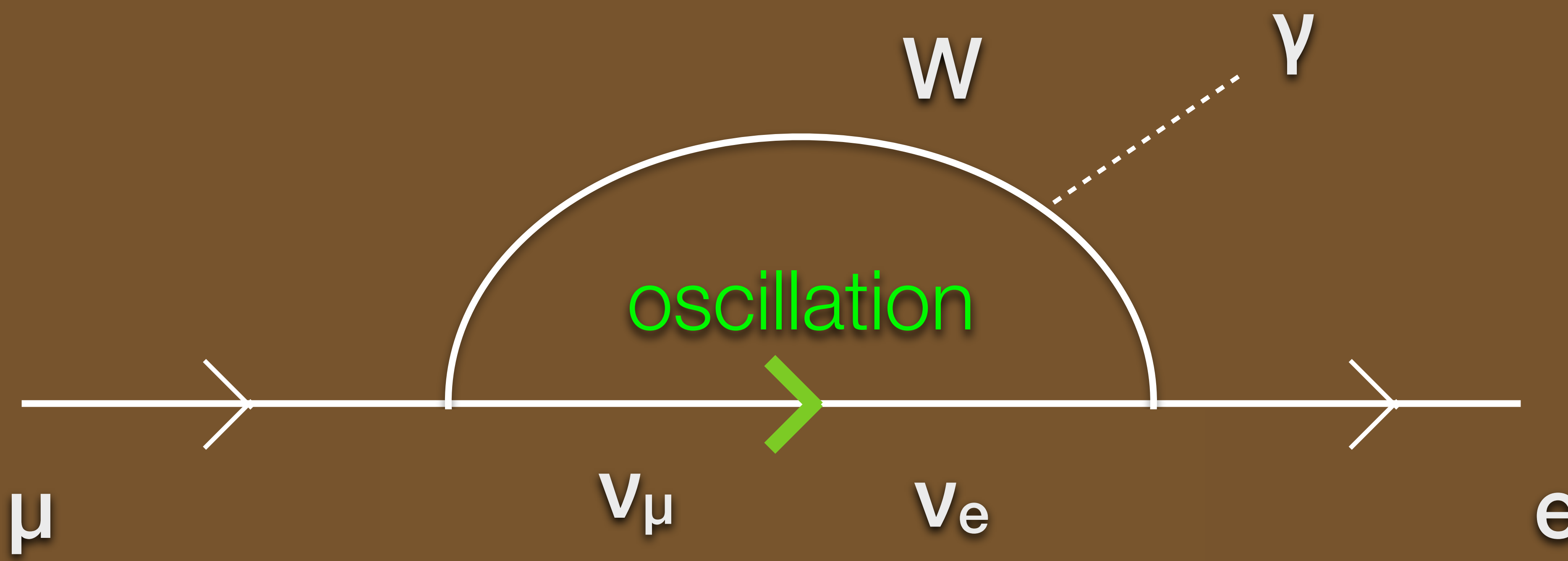
$\mu^+ \to e^+\gamma$ and ν oscillations

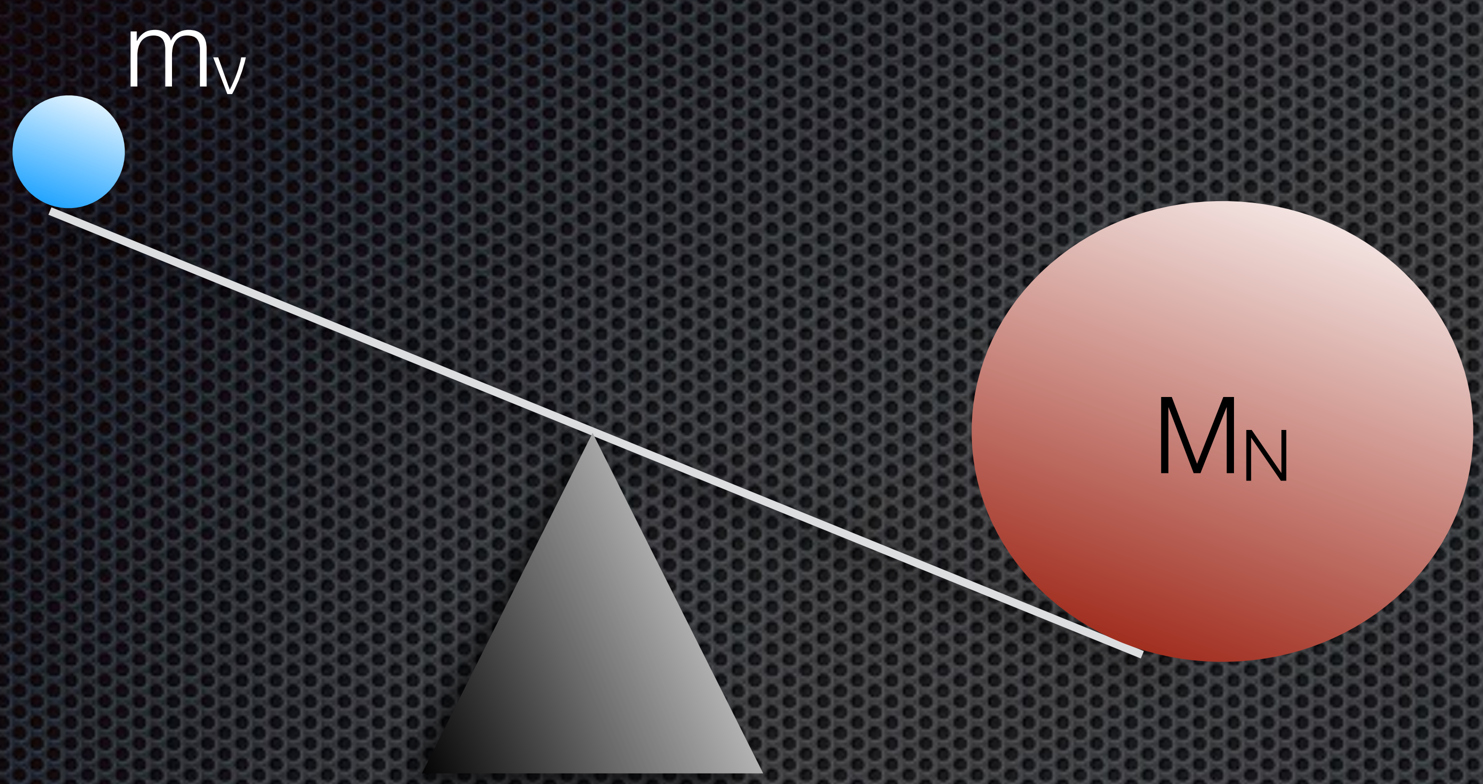
(Nobel prize 2015)



$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-50}$$

neutrinos are too light

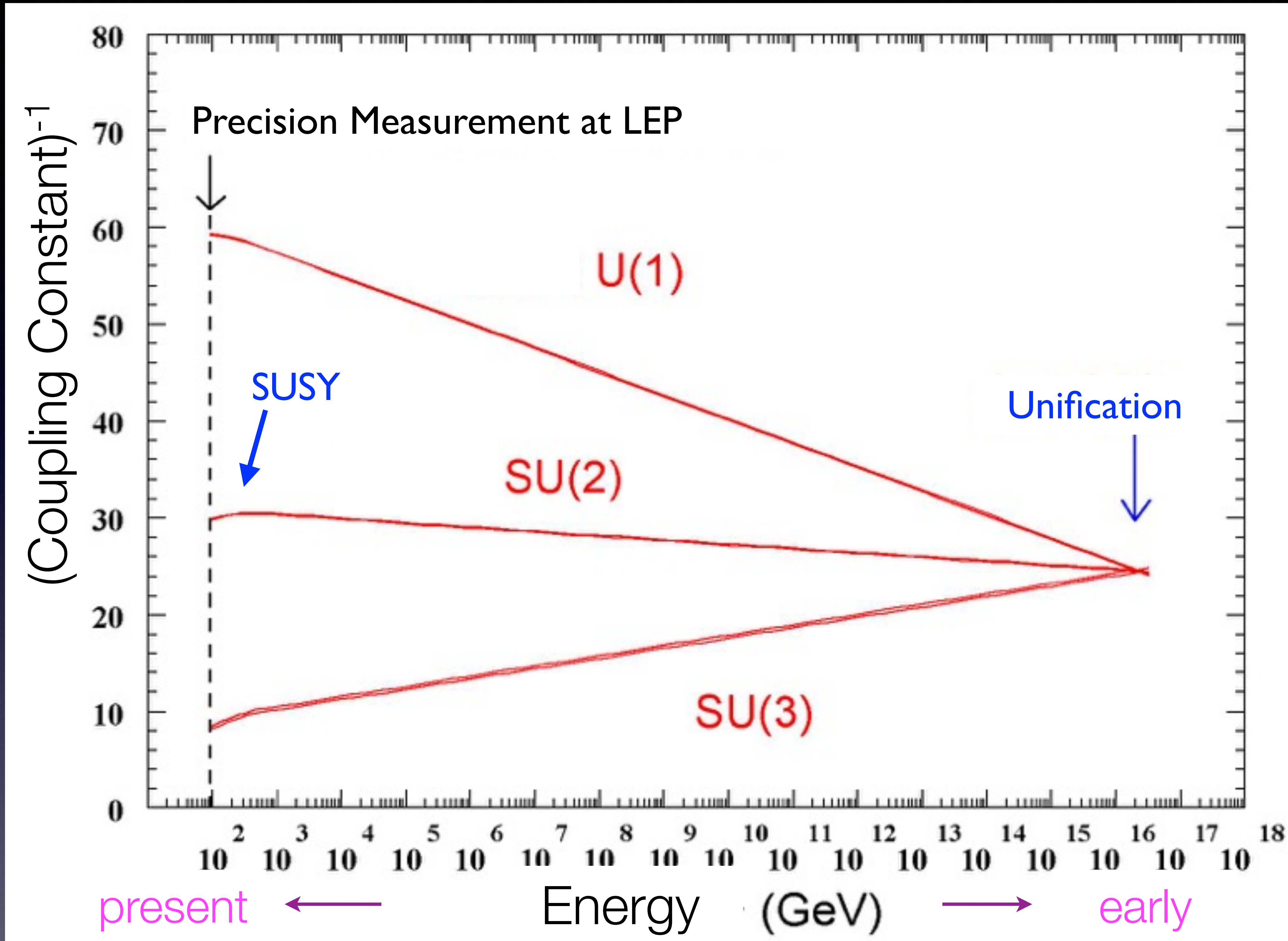
Very light neutrino masses may imply $\mu^+ \to e^+\gamma$



$$m_\nu = m_f^2 / M_N$$

m_f = mass of charged fermions

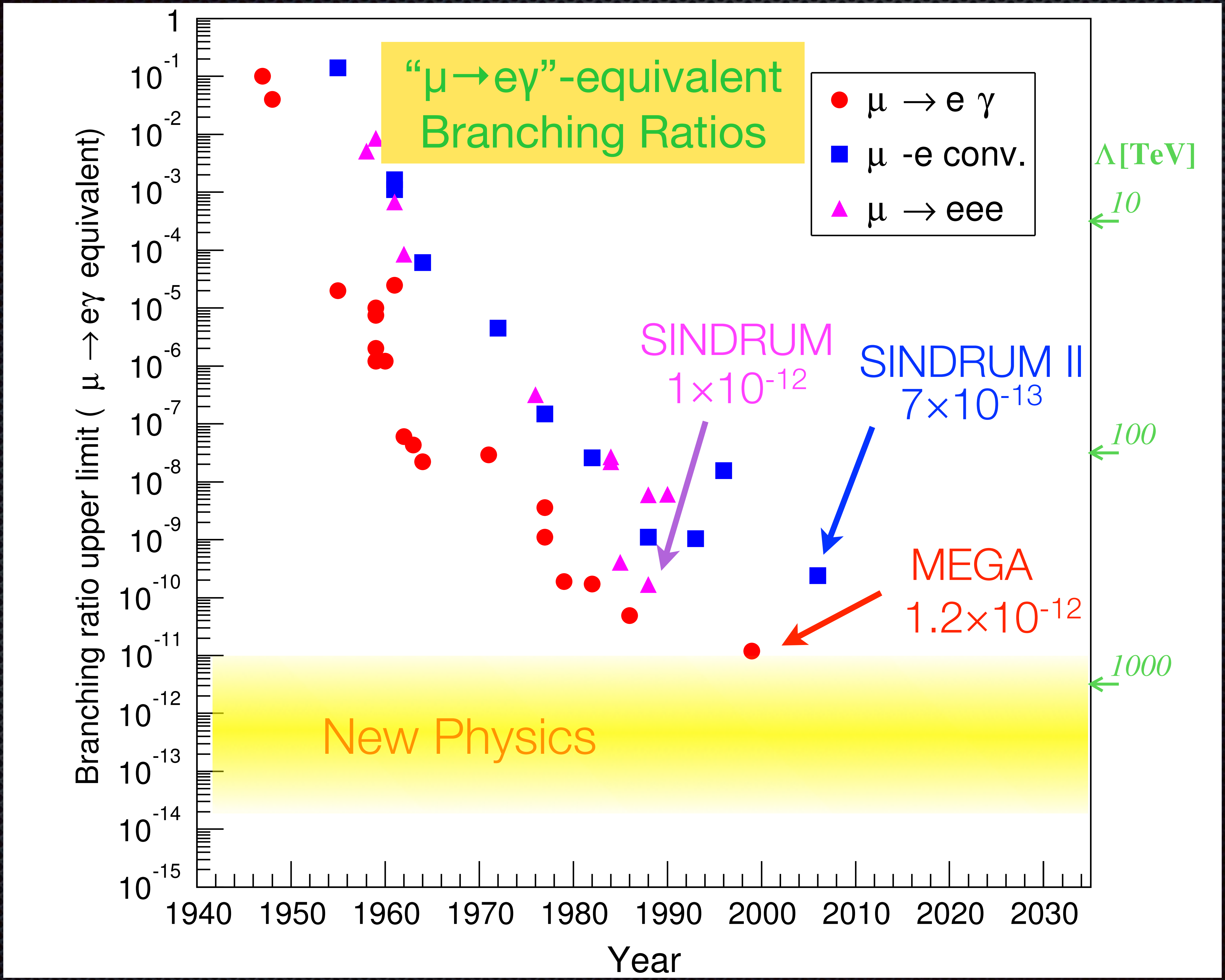
- See-saw mechanism
- Ultra-heavy majorana right-handed neutrino
  $M_N = 10^9 - 10^{12}$ GeV
  - GUT?
  - Leptogenesis?
  - $\mu^+ \to e^+\gamma \sim 10^{-12}$
    thru RGE evolution
    even if no flavor violation



SUSY Grand Unification

LFV grows through RGE to ~10^{-12}

Before MEG started:

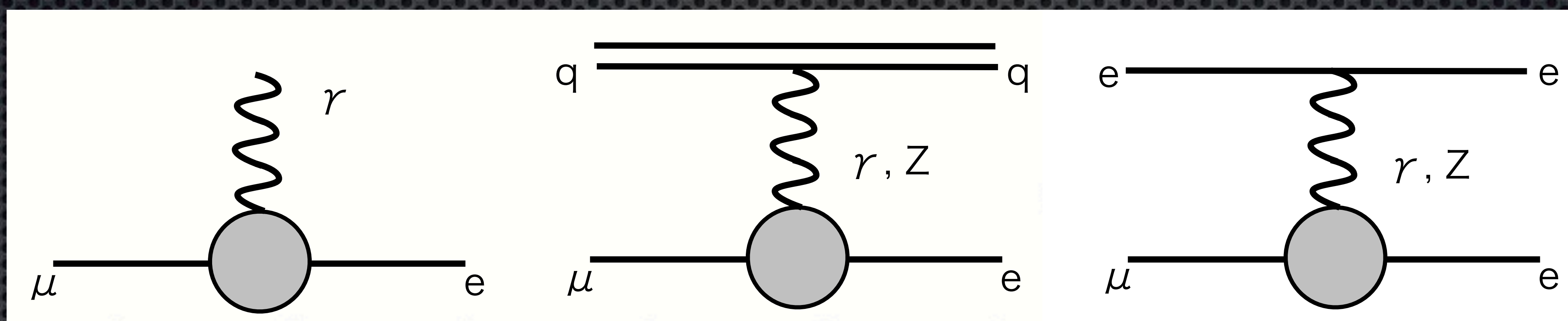


Muon cLFV Sensitivity Comparisons

$\mu \to e\gamma$ $\quad$ $\mu N \to eN$ $\quad$ $\mu \to 3e$

"dipole" dominant

(SUSY etc)



1 : 1/390 : 1/170

BR = 4×10^{-14} : 1×10^{-16} : 2×10^{-16}

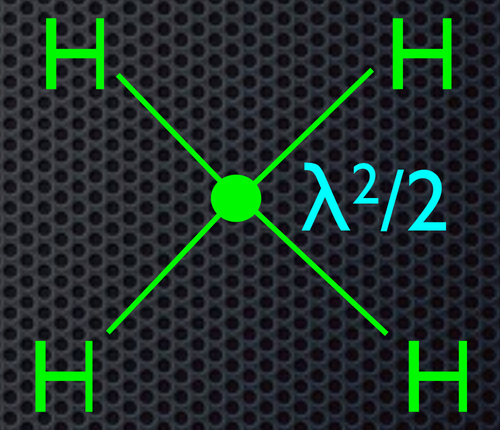
~MEG II goal $\quad$ for Al target

Recent Progress in Particle Physics

- Discovery of Higgs
  - Higgs is light（125GeV）

→ Higgs is likely to be elementary

→ Good prospects for GUT/seesaw



- Discovery of the third neutrino oscillation θ_{13}

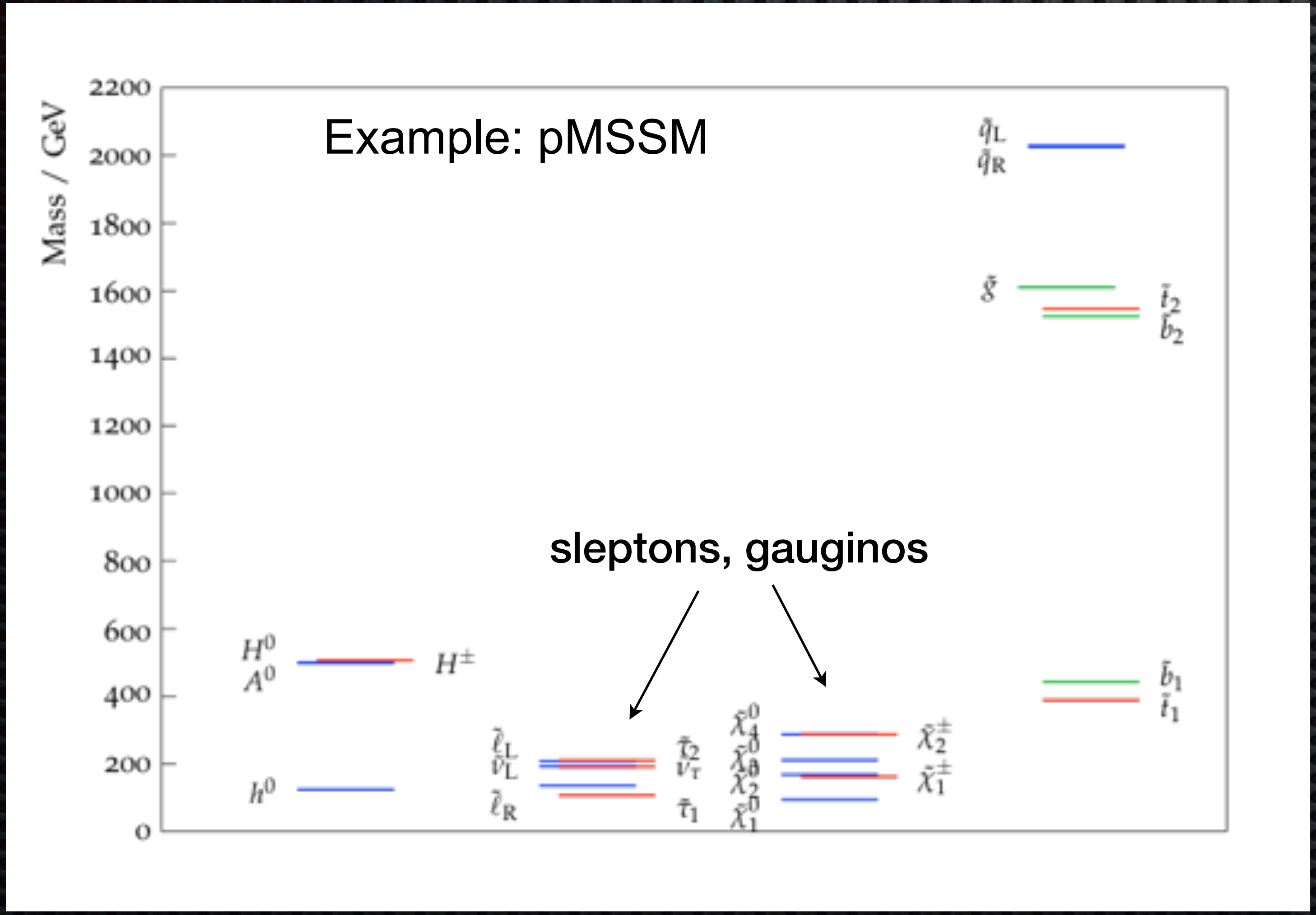
$M_H = \lambda\ v$

  - Mixing is large（θ_{13} ~9deg）

→ Larger BR($\mu \to e\gamma$) expected

Expectations even higher now for $\mu \to e\gamma$

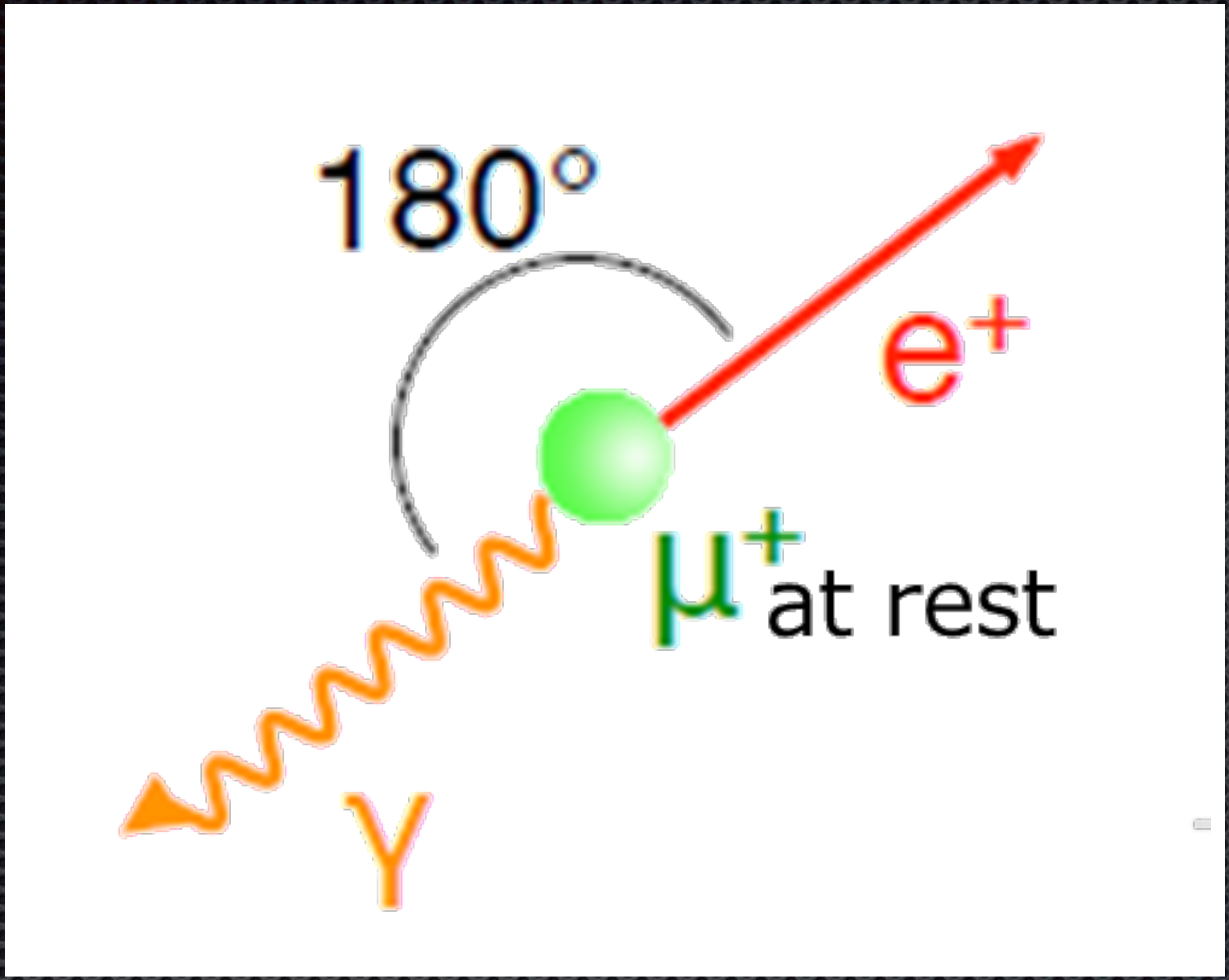
TeV scale physics strongly constrained by LHC ?



- Particles only electro-weakly interacting are NOT strongly constrained yet and thus may be lighter!

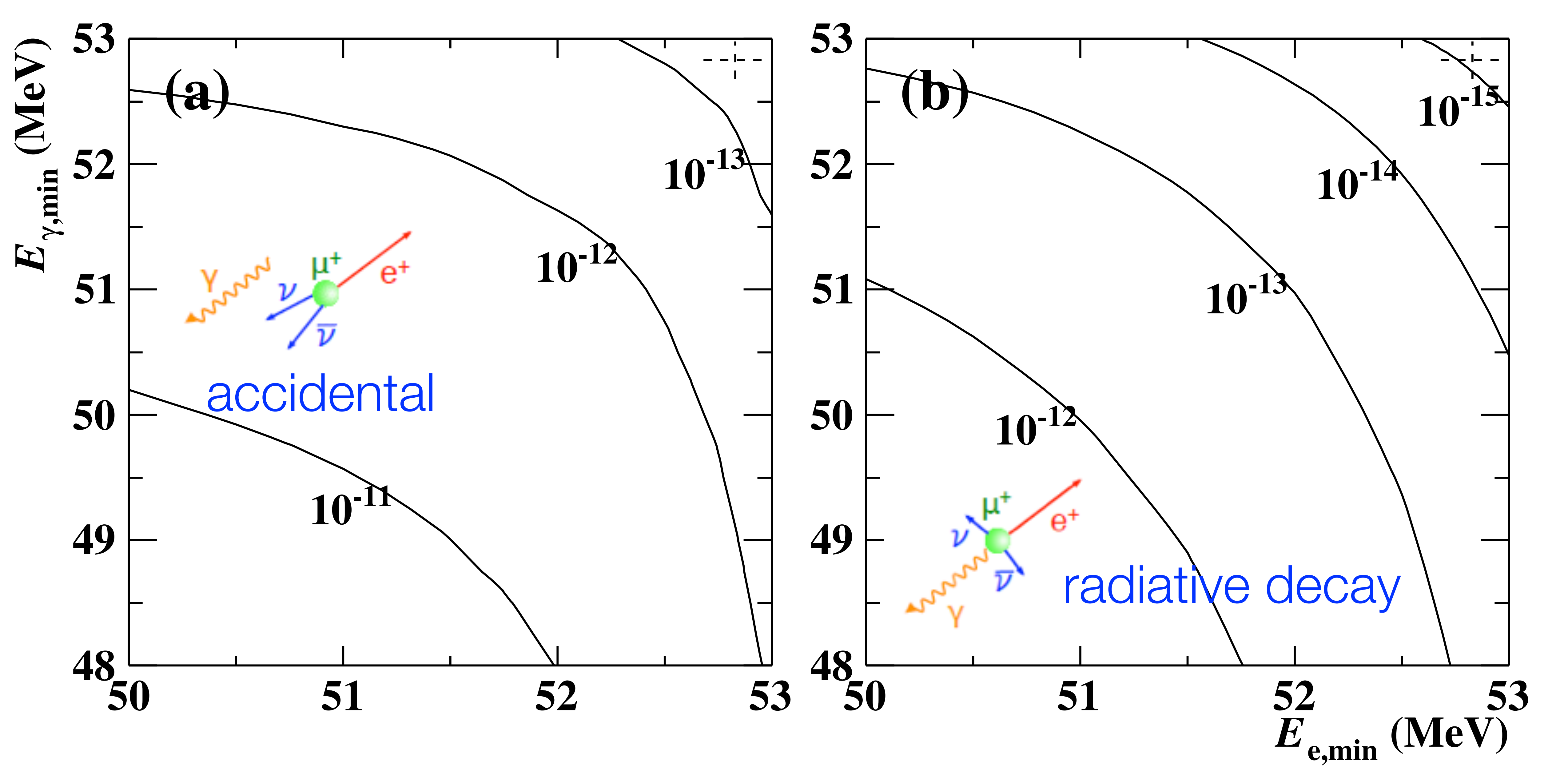
not necessarily **SUSY**

μ→eγ is Complementary & Synergetic to LHC



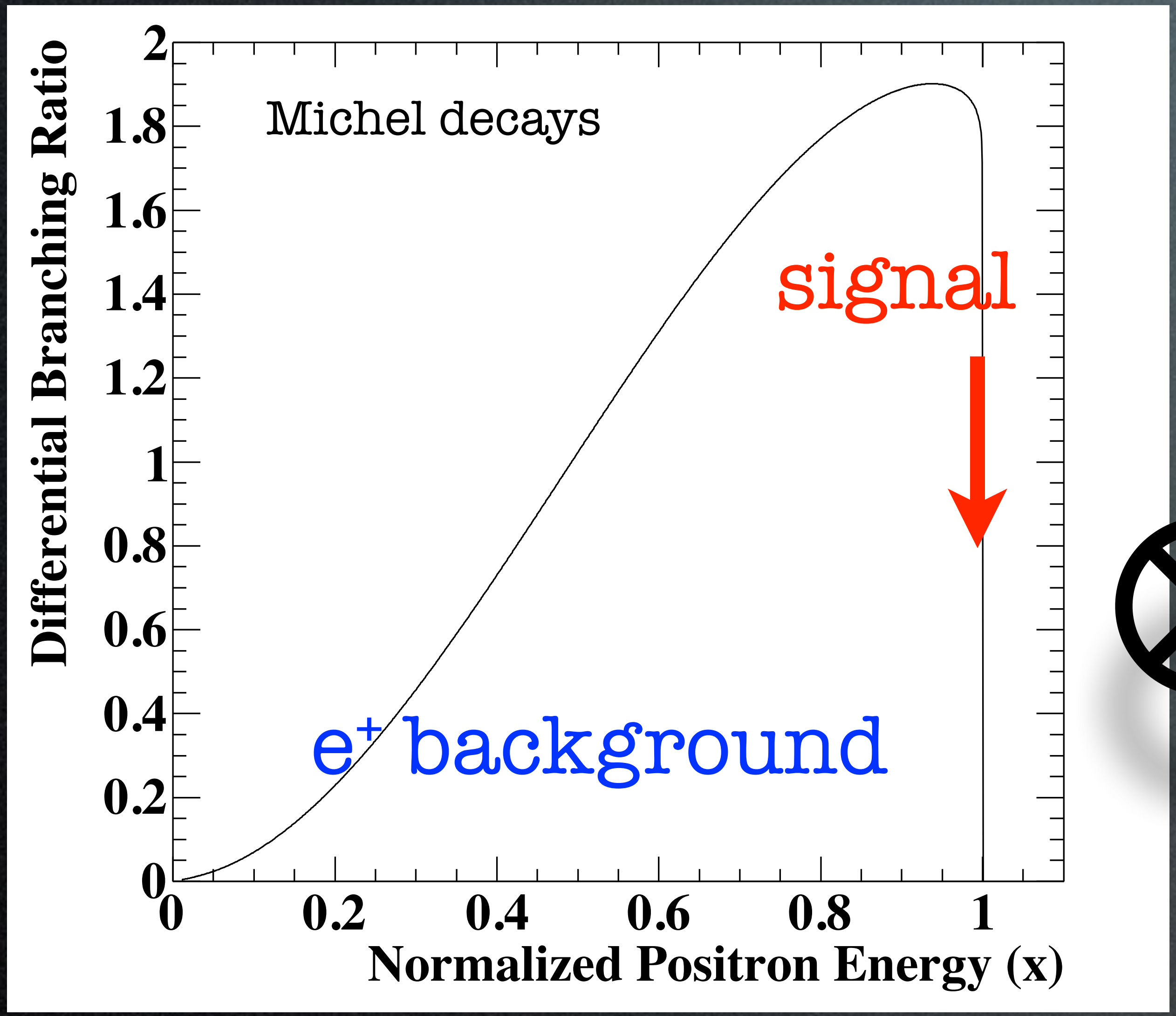
180°
e^+
$\mu^+_{\text{at rest}}$
γ

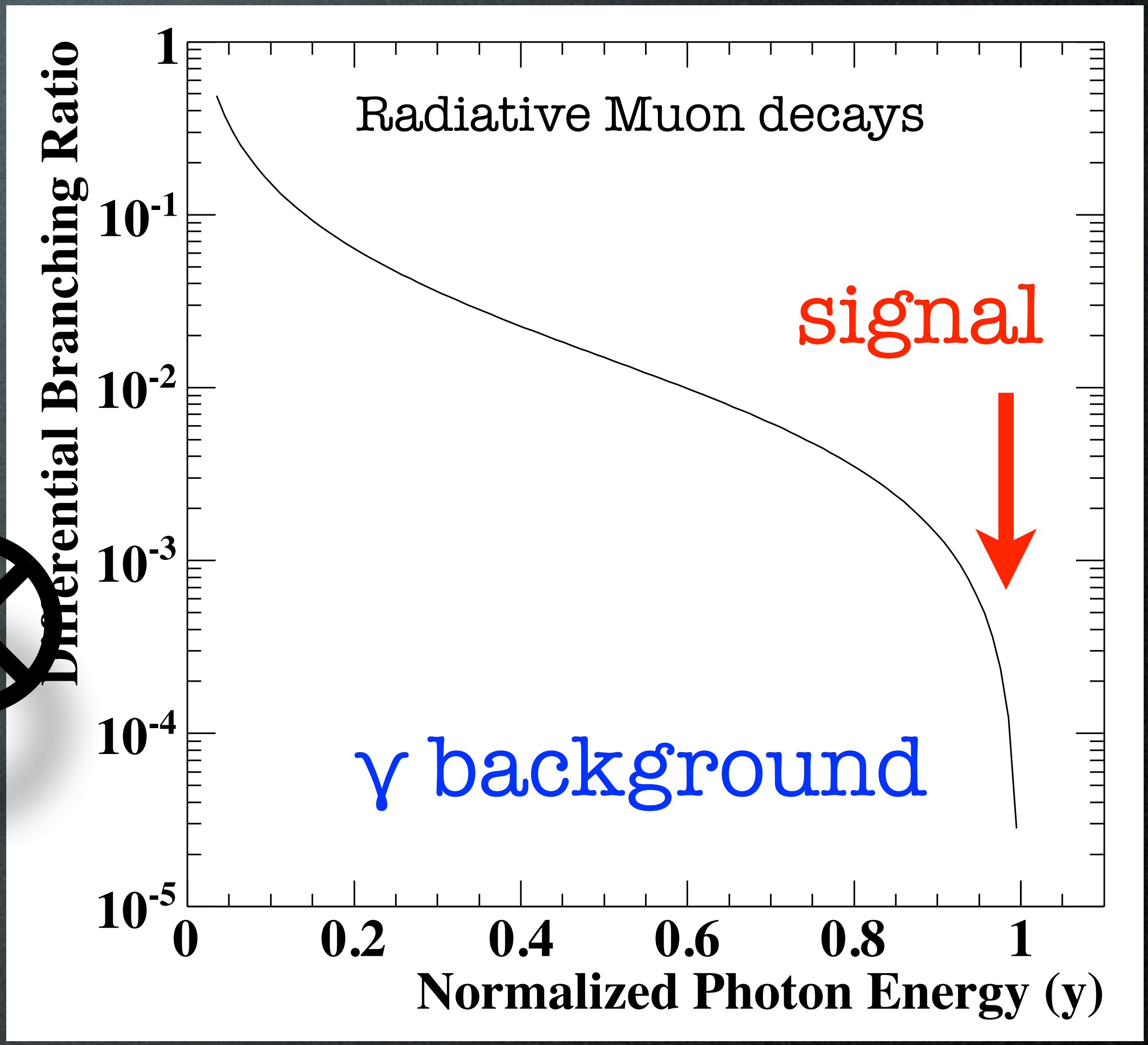
Background for μ⁺→e⁺γ



- Accidental BG are dominant for this high rate experiment

Dominant Background Is Accidental





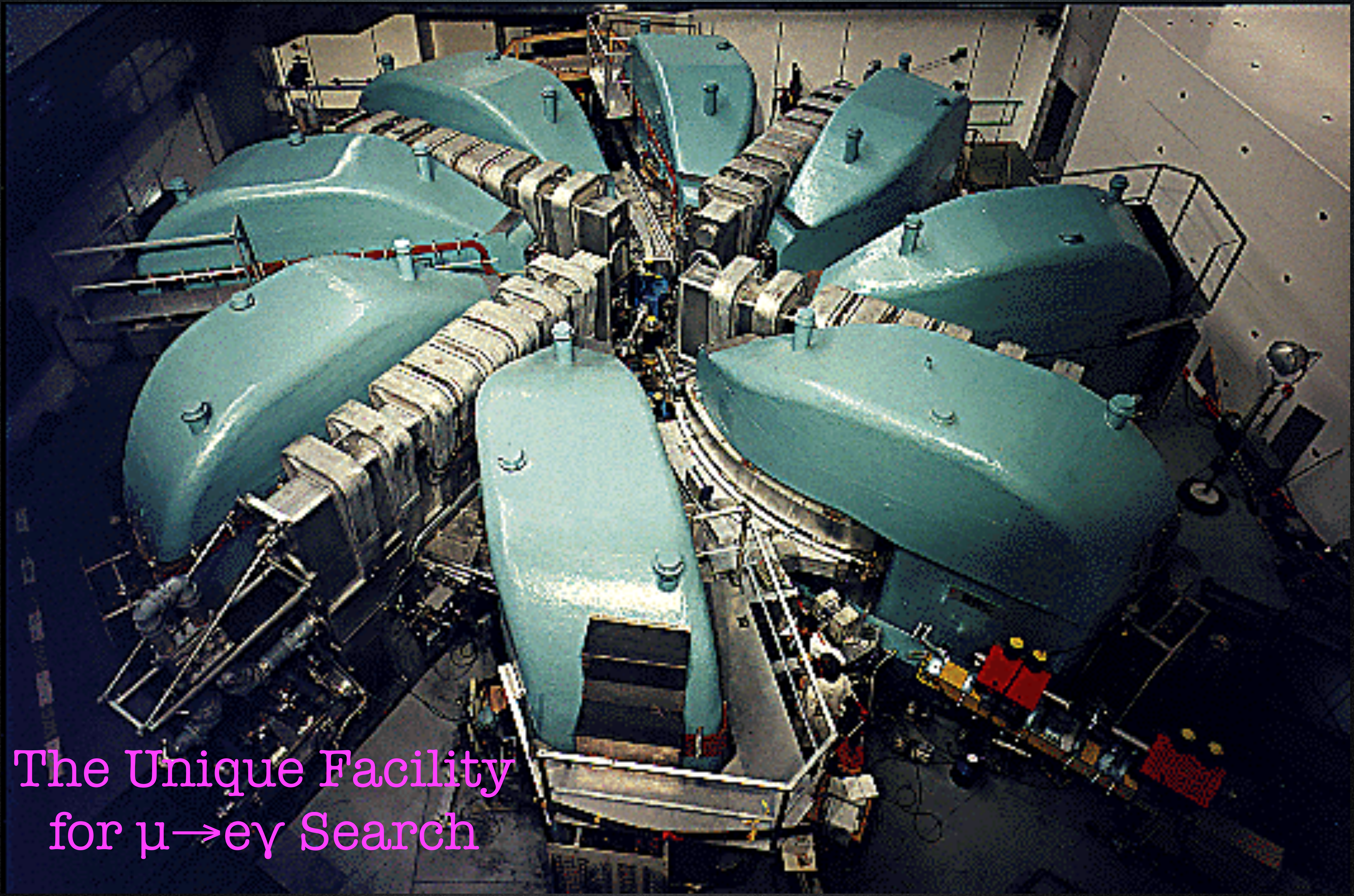
must manage high rate e^+

good γ resolution is most important !

➡ Gradient Magnetic Field Spectrometer

➡ Liquid Xenon Scintillation Detector

1.4MW Proton Cyclotron at PSI

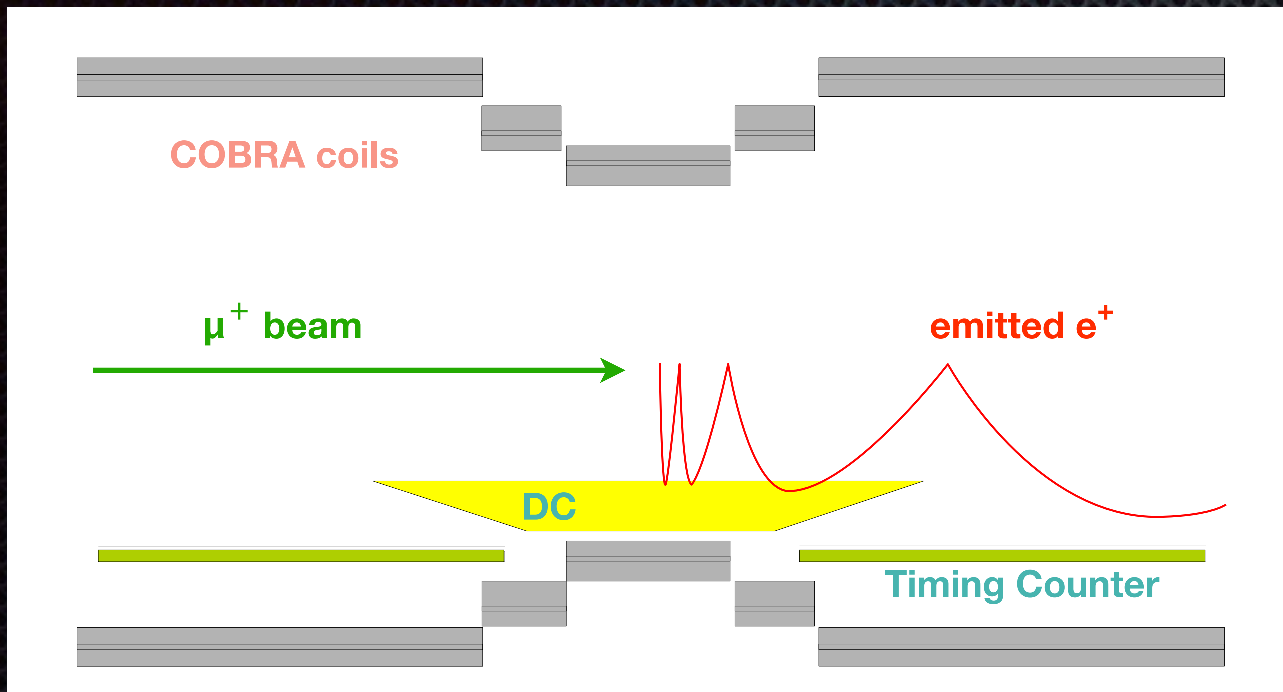


The Unique Facility
for $\mu \rightarrow e\gamma$ Search

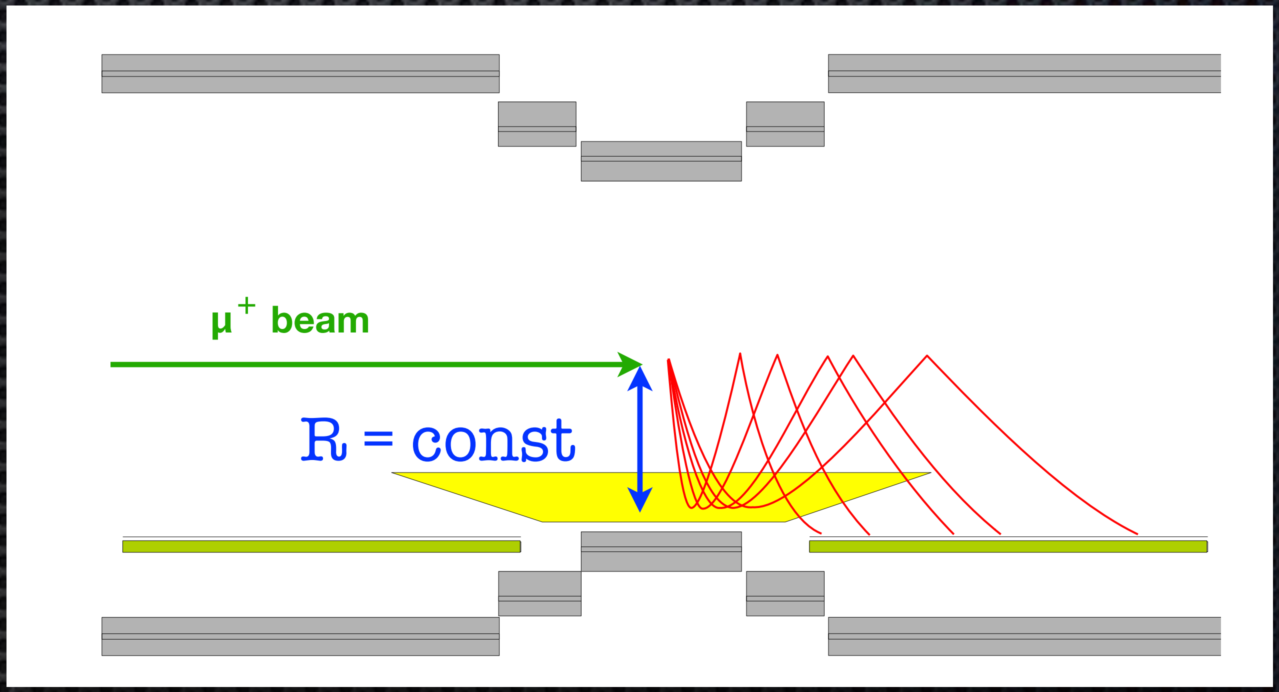
Provides world's most powerful DC muon beam $> 10^8$/sec

COBRA spectrometer with gradient B-field

(COnstant Bending RAdius)



Low energy positrons quickly swept out



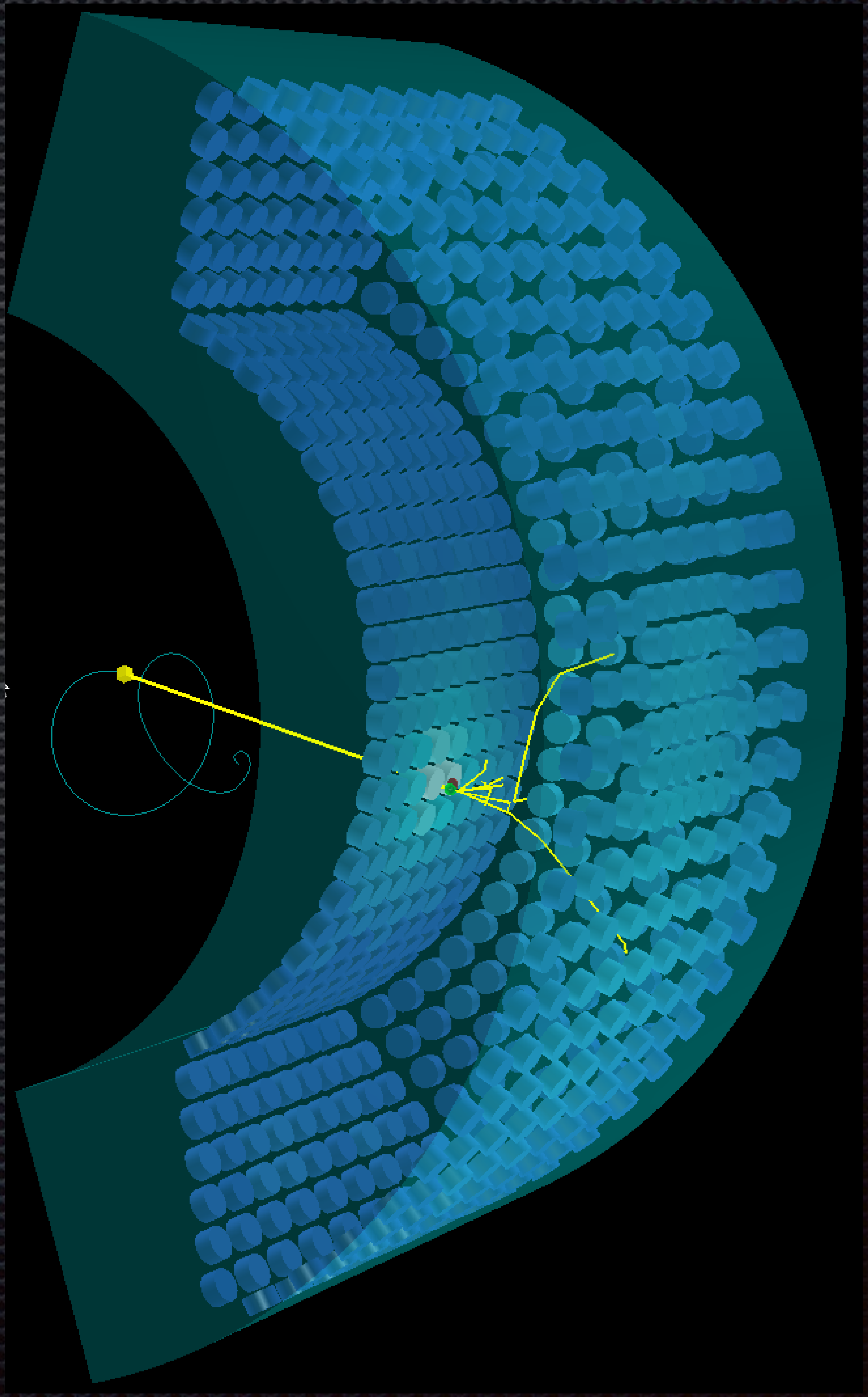
Constant bending radius independent of emission angles

“COBRA Concept” to manage high rate positrons

2.7t Liquid Xenon Photon Detector

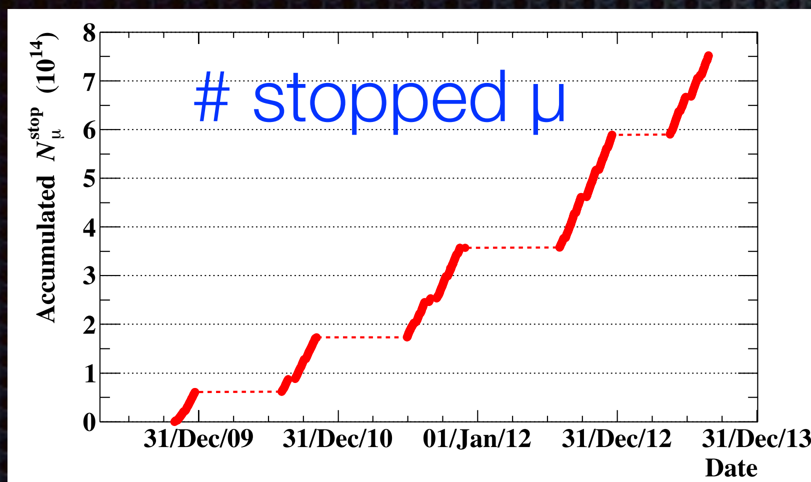
High resolution detector

- Scintillation light from 900 liter LXe is detected by 846 PMTs mounted on all surfaces and submerged in LXe
- Fast response & high light yield provide good resolutions of energy, time, & position
- Gas/liquid circulation system to purify xenon
    - Ultimate uniformity & purity unachievable by crystal calorimeter

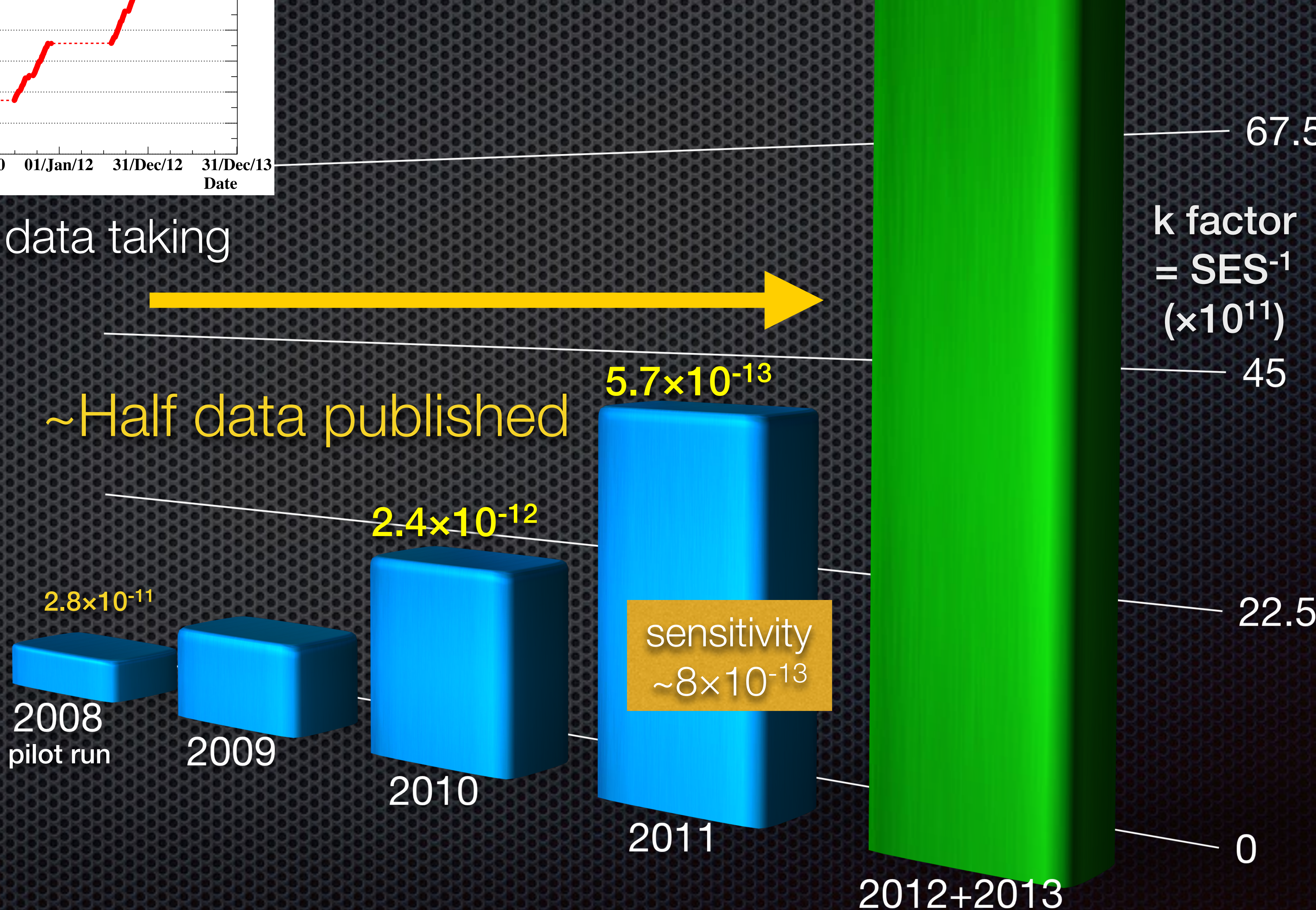


The Final MEG Data Analysis

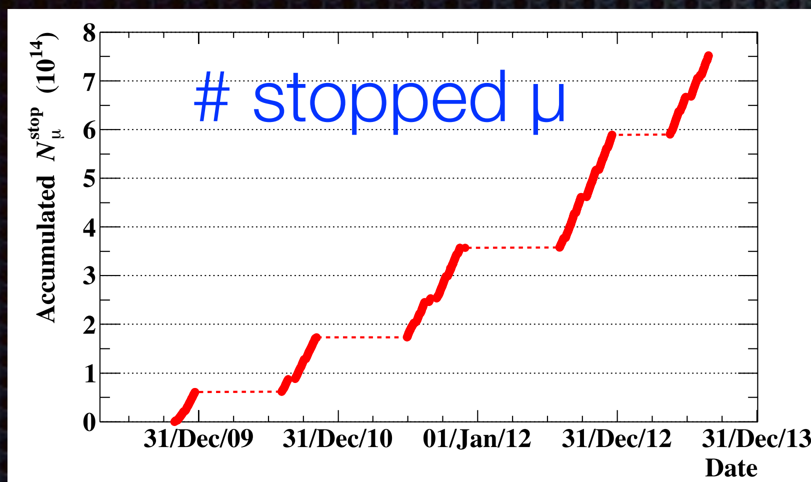
All MEG Data



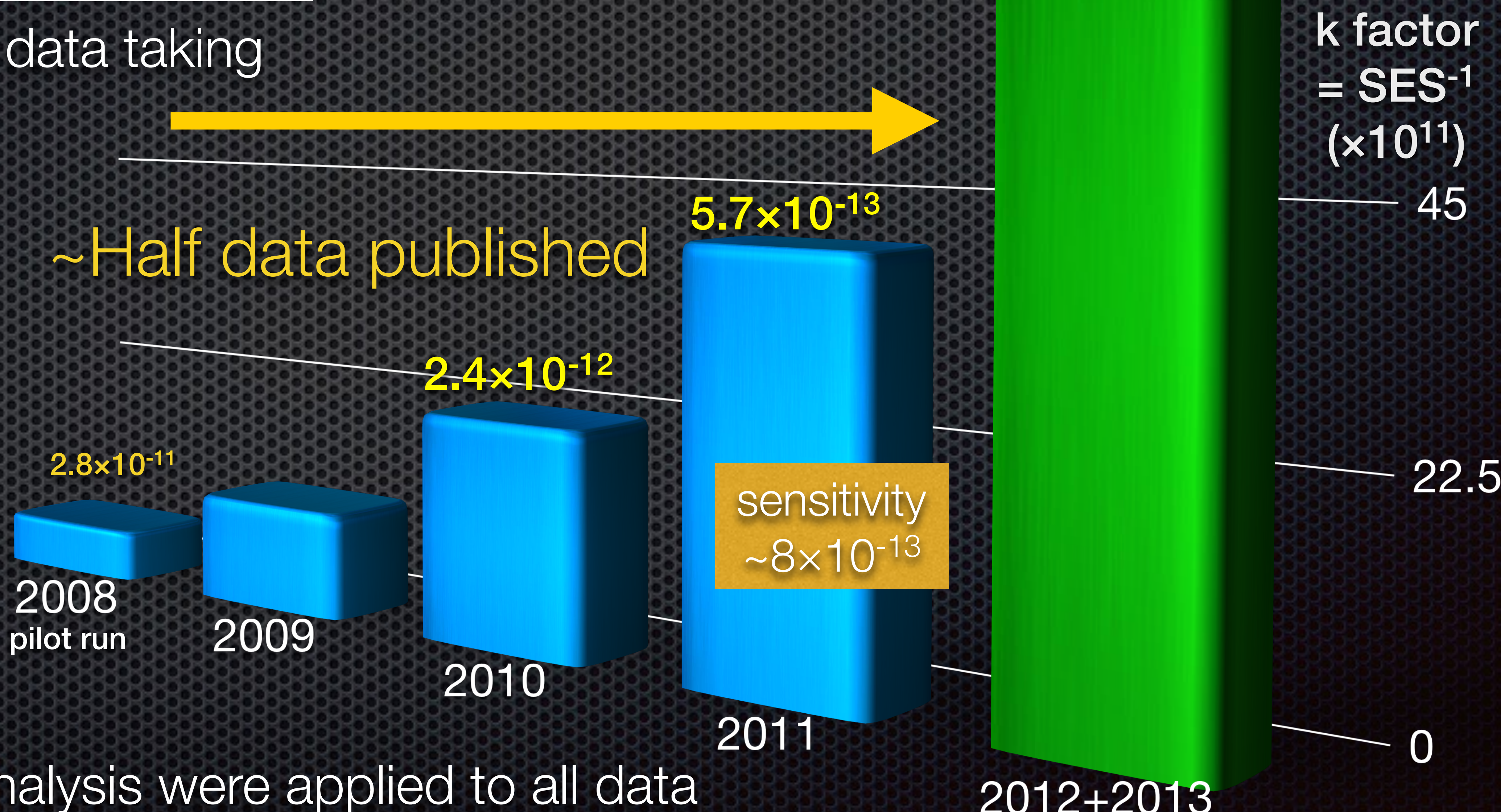
~4 years of data taking



All MEG Data



~4 years of data taking



Improved analysis were applied to all data

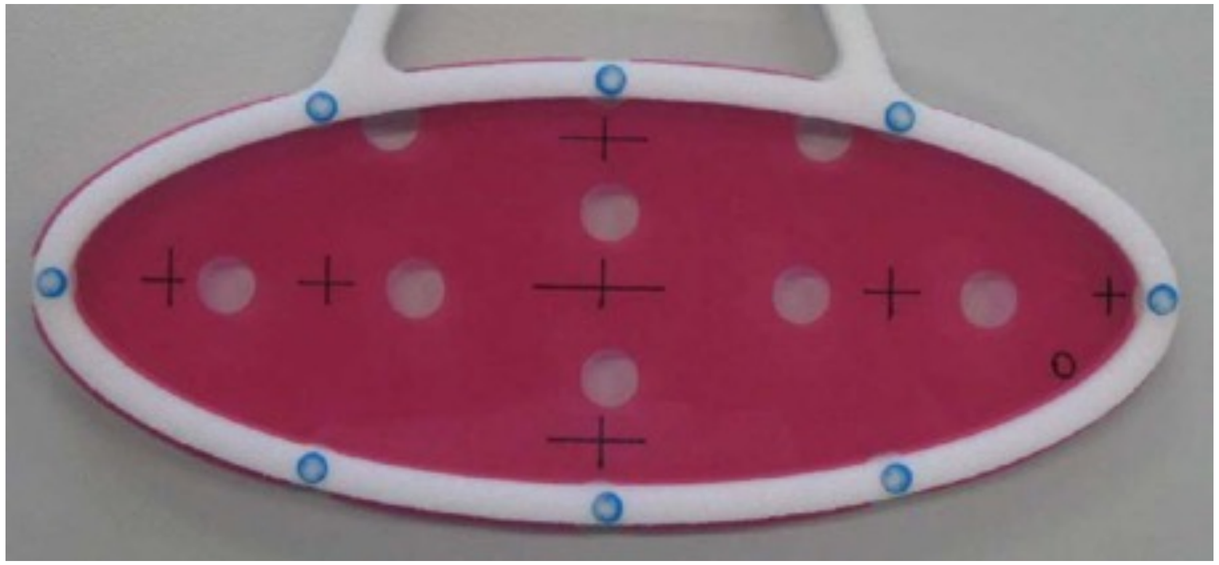
Issues & Improvements in $\mu^+ \to e^+\gamma$ Analysis

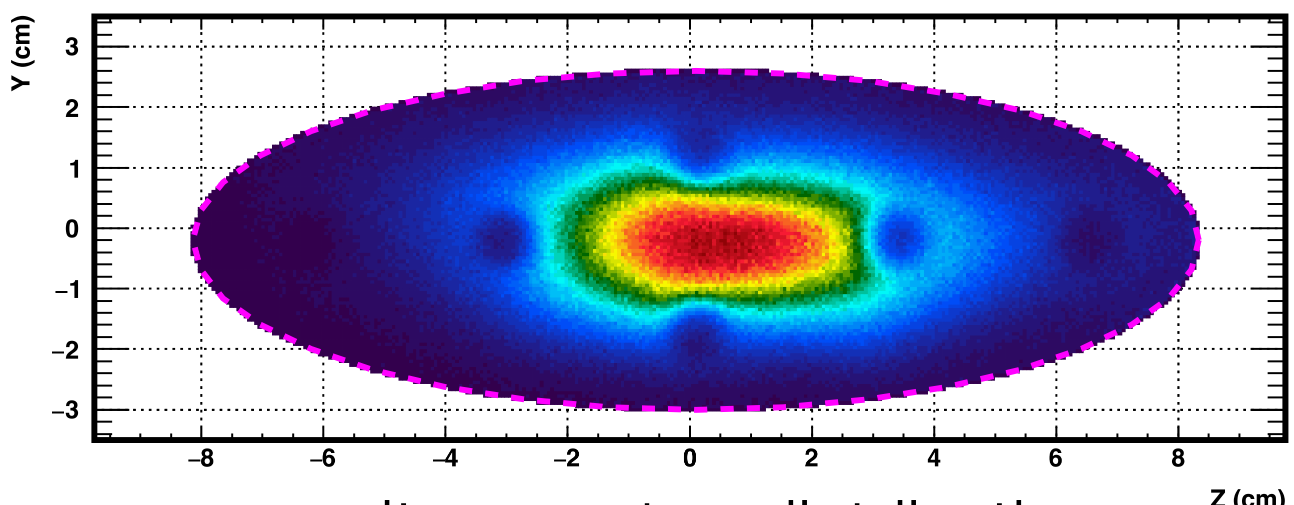
- Alignment of Muon Stopping Target
- Alignment of LXe Detector
- Rejection of Annihilation-of-Flight (AIF) Gamma-rays
- Recovery of Missing First Turns

Target Alignment

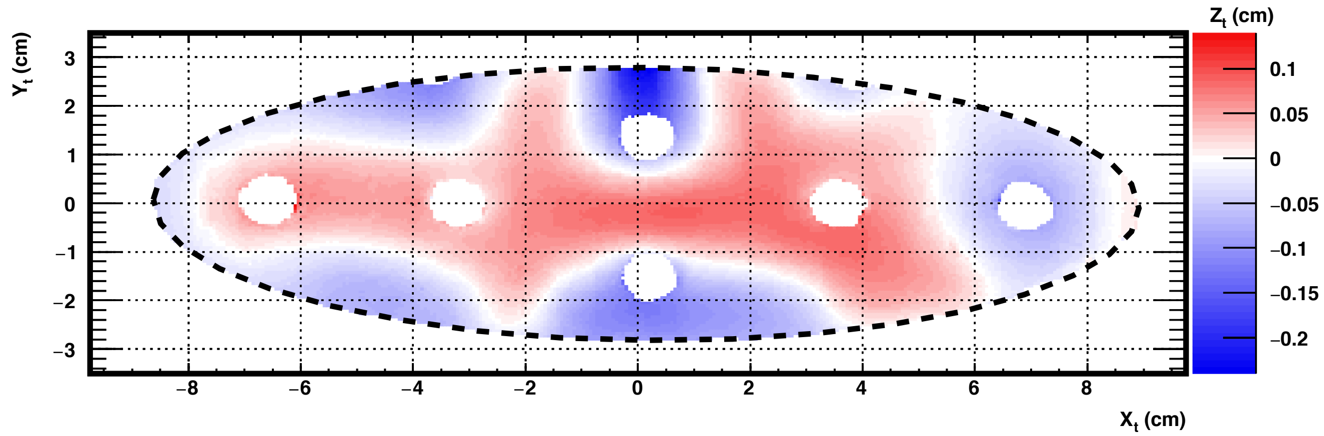
- Position & shape of the target are surveyed by
  - “hole” reconstruction
  - optical survey between the runs
- Non-planar deformation seems to have developed during the runs
- Effects not negligible for the 2012-13 runs
  - ~0.3 mm uncertainty
  - treated as nuisance parameters in likelihood analysis
- A few different target materials being studied for MEG II

~13% degradation in sensitivity



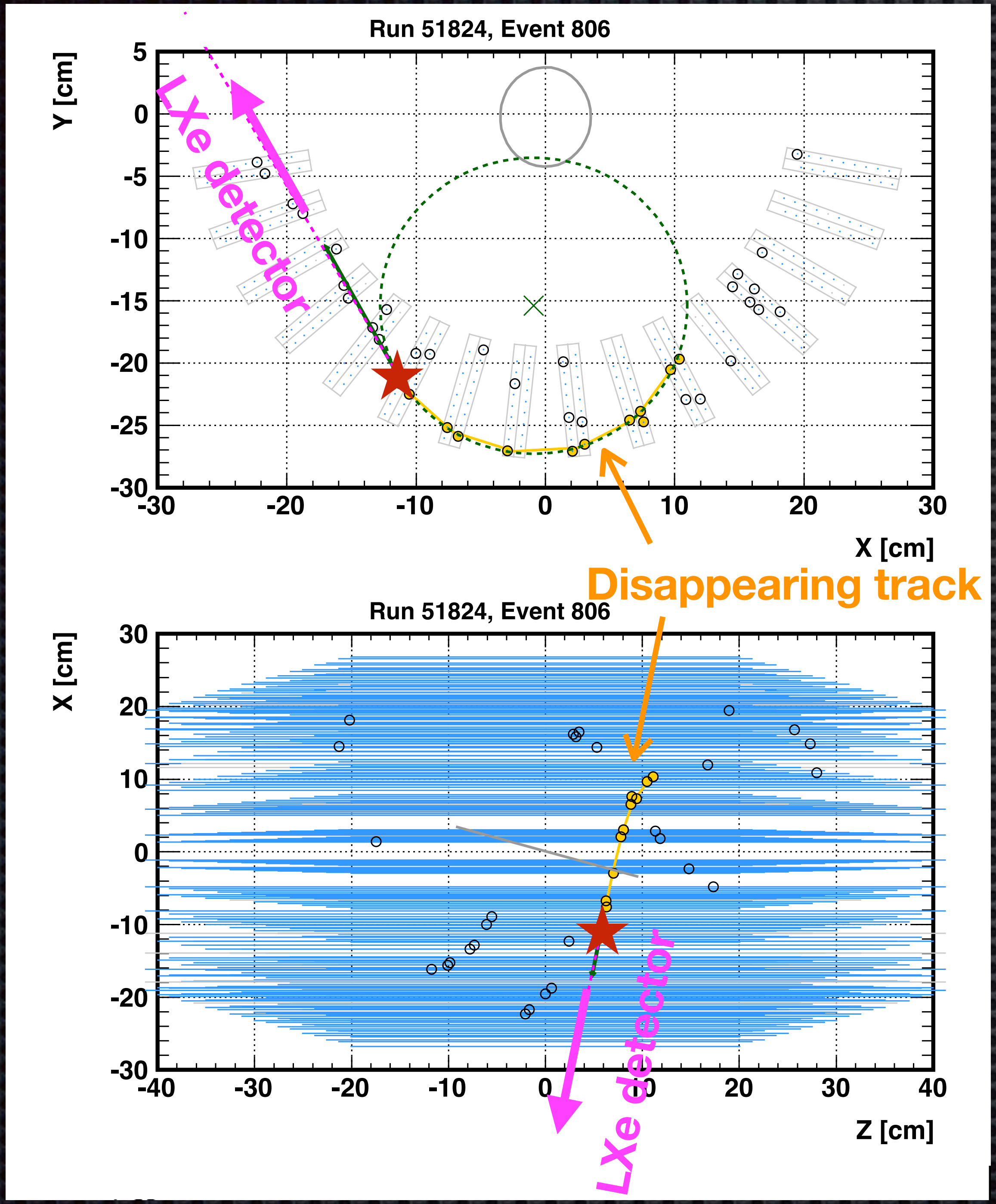


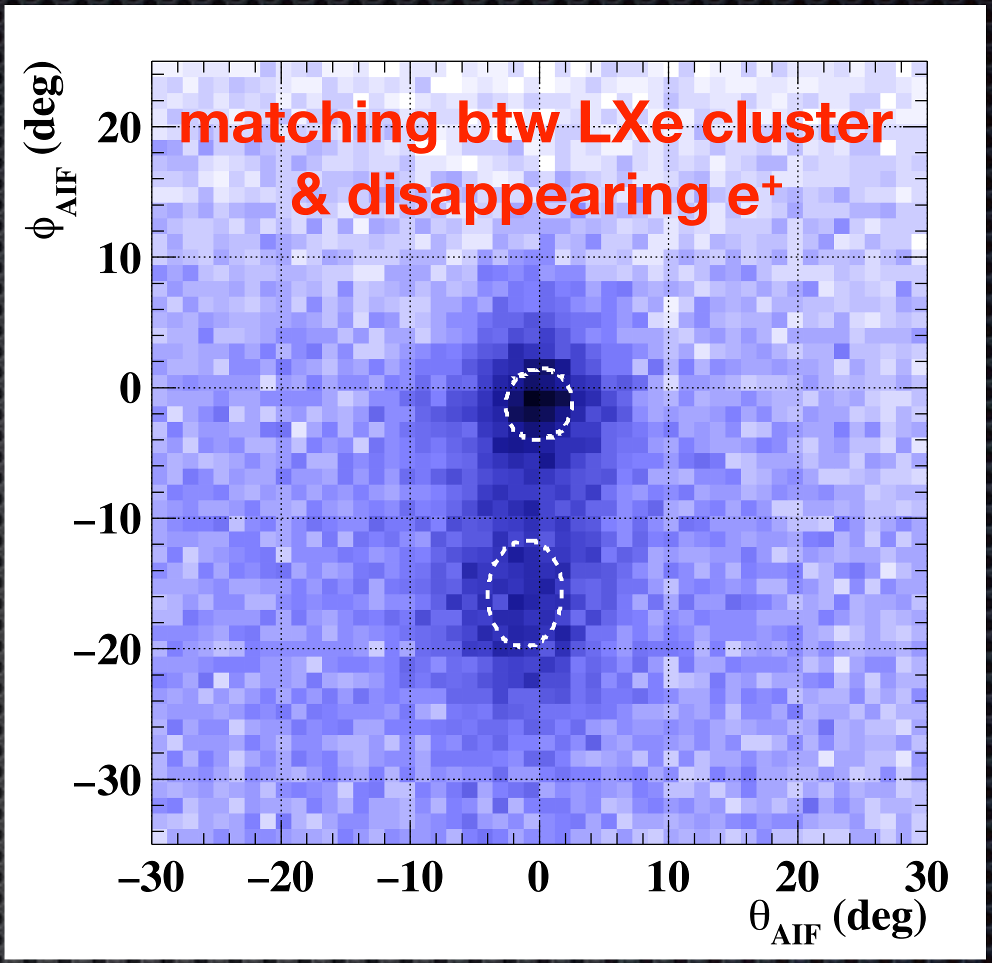
positron vertex distribution



deformation measured by 3D scanner

AIF Gamma-rays

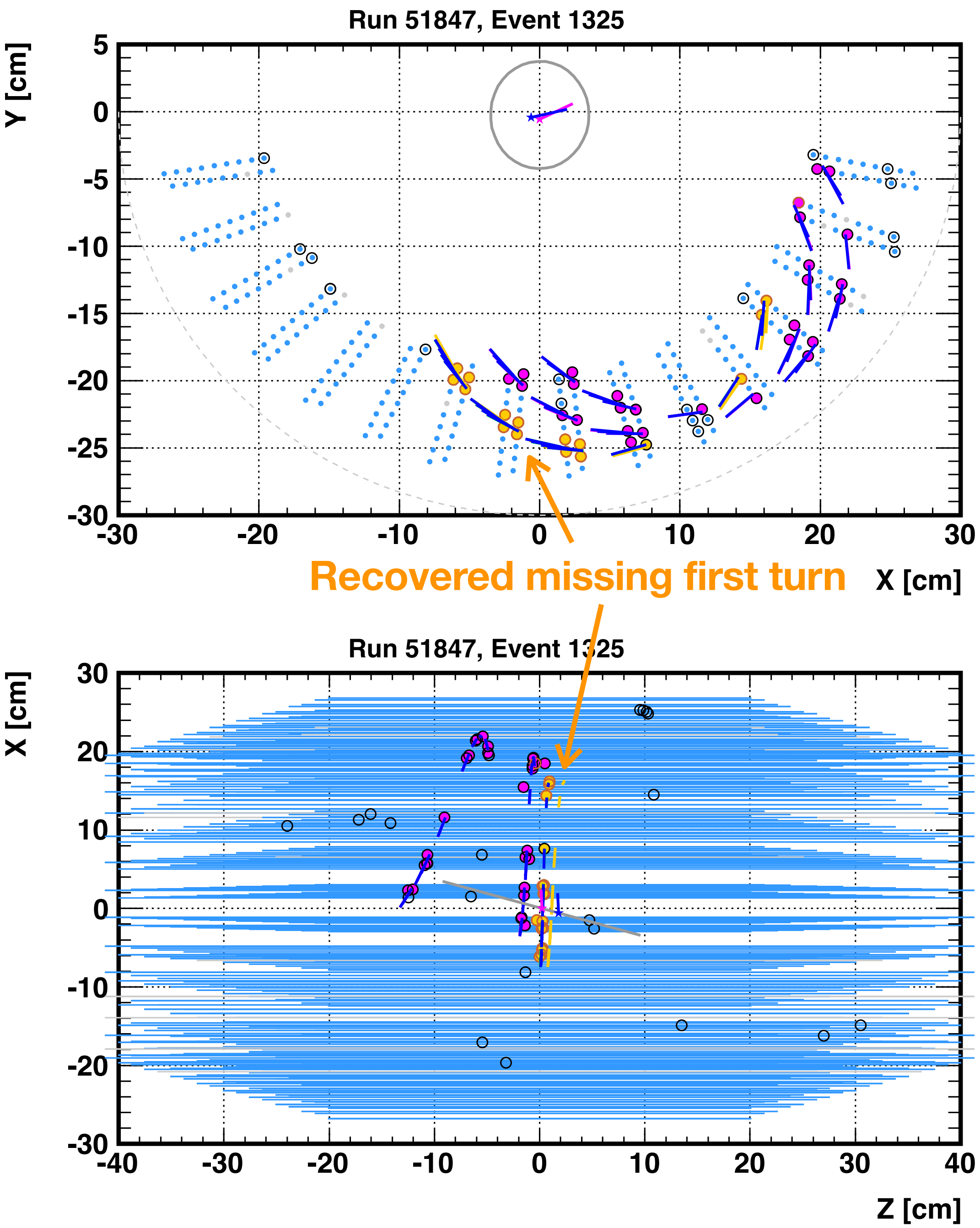




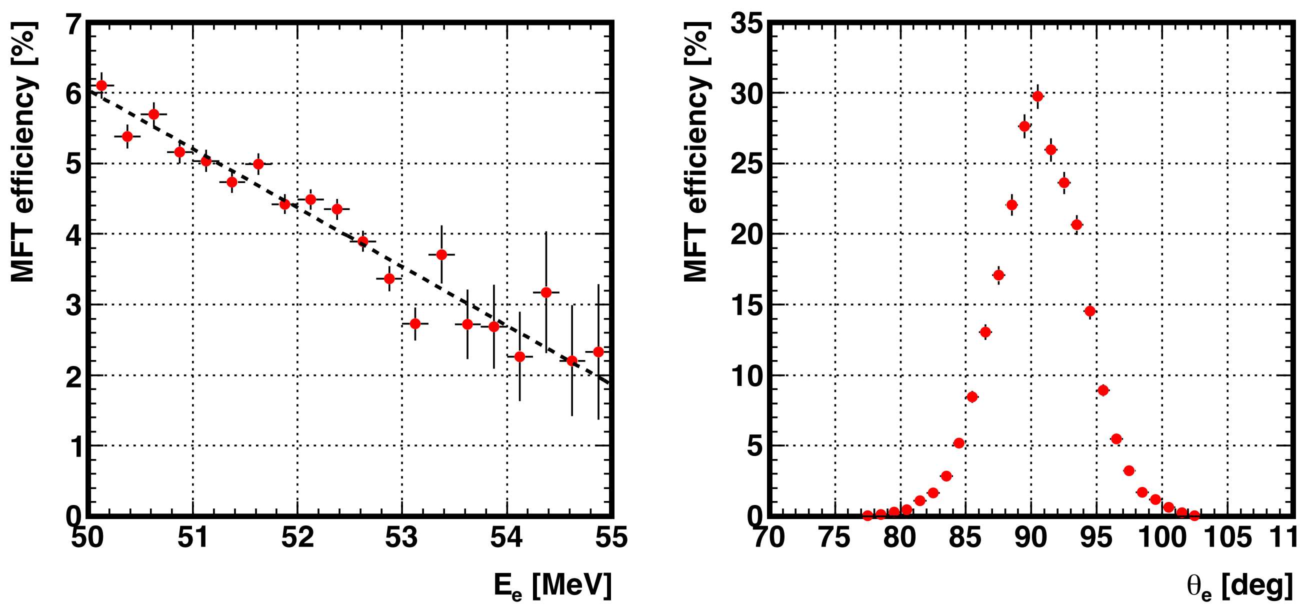
- Gamma-rays from e+ annihilation inside DC were identified & rejected
- overall BG rejection 1.9% signal inefficiency 1.1%

Missing 1st turn of e^+

- Possibility to miss the first turn in a multiple turn event
- Algorithm revised to recover missing first turn
  - Signal efficiency improved by ~4%



Efficiency of missing first turn recovery

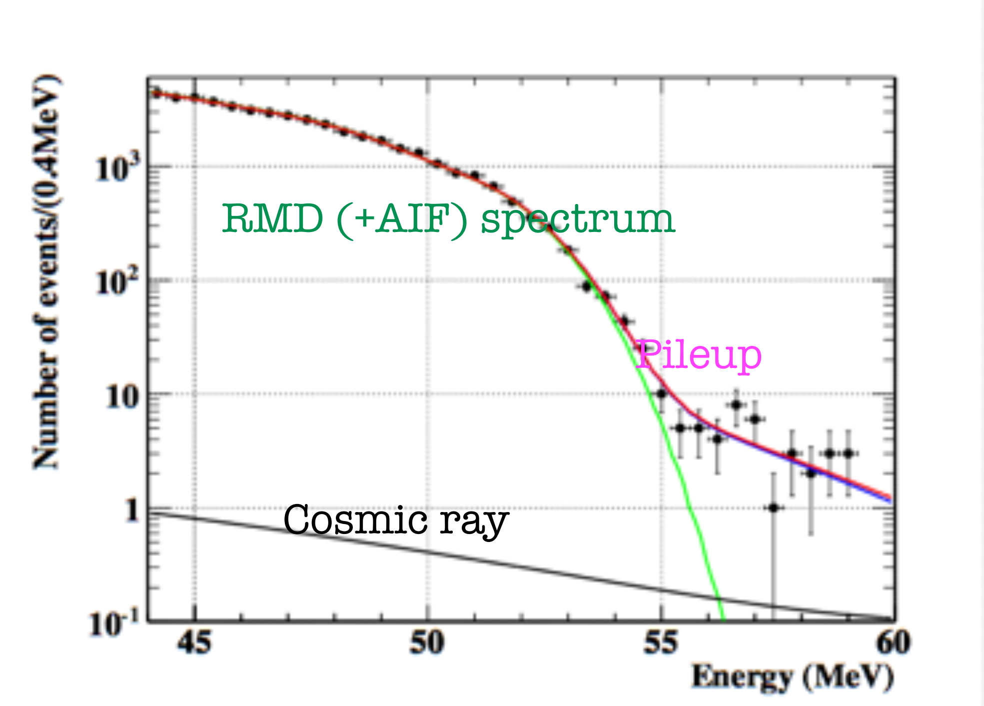


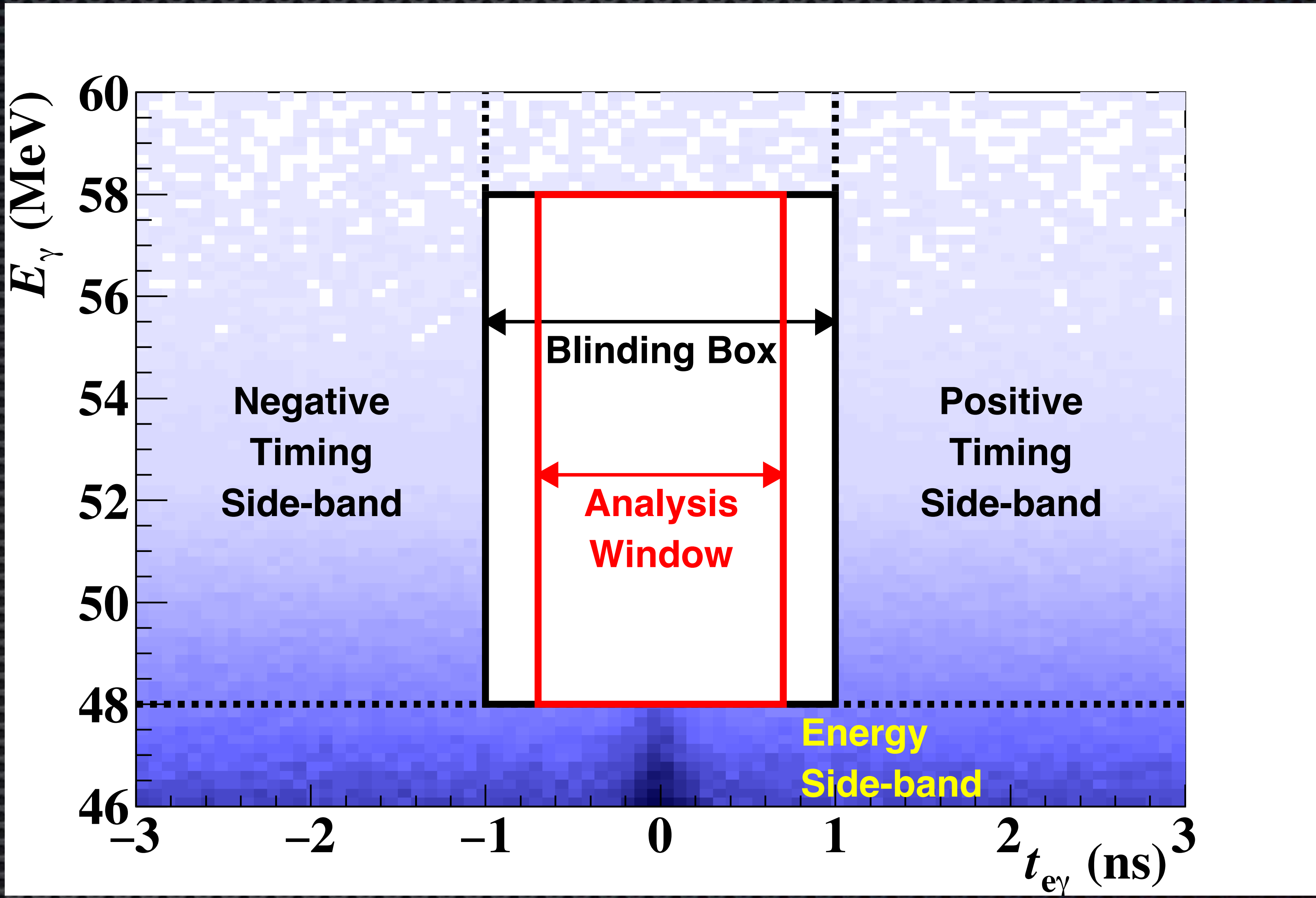
Blind & Likelihood Analysis

(Eγ, Ee, Teγ, θeγ, φeγ) → signal, acc BG, RD BG

Blind analysis

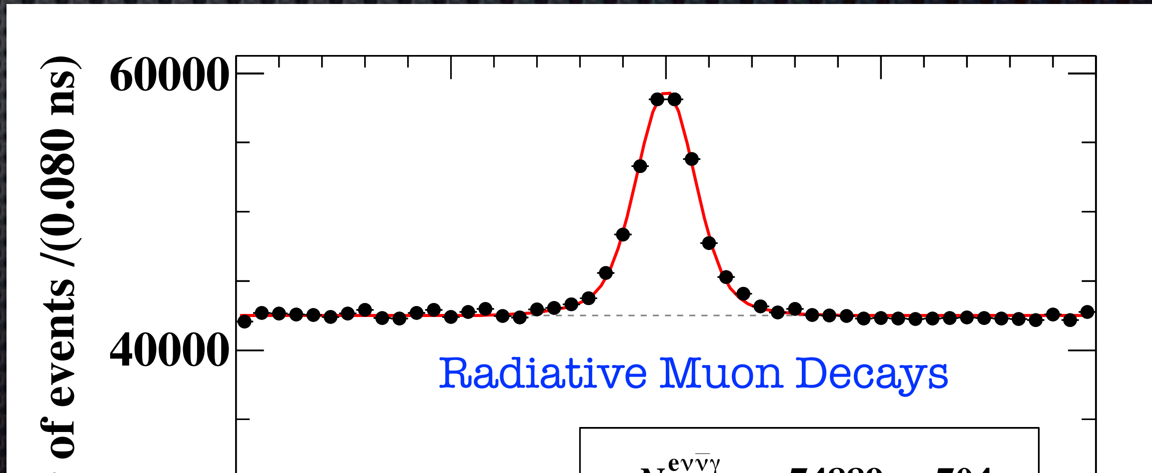
- Optimization of analysis and BG study are done in sidebands





PDFs from data

- accidental BG: side bands
- signal: measured resolution
- radiative BG: theory + resolution

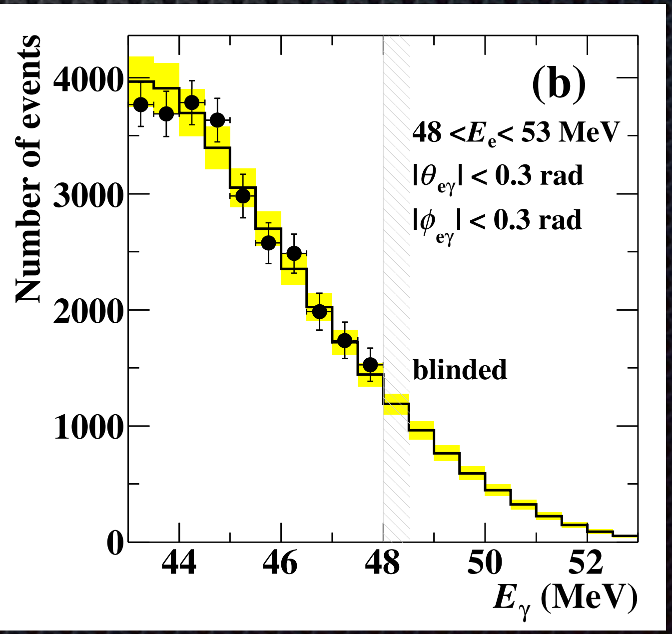


Maximum Likelihood Fit

- Fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering
  - Event-by-event PDFs for both e^+ & photons
  - Target alignment (**t**), N_{RMD} and N_{ACC} are treated as nuisance parameters and are profiled in the fit.

$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm ACC}, \mathbf{t}\right) = \frac{e^{-N}}{N_{\rm obs}!} C(N_{\rm RMD}, N_{\rm ACC}, \mathbf{t}) \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S(\mathbf{x}_i, \mathbf{t}) + N_{\rm RMD} R(\mathbf{x}_i) + N_{\rm ACC} A(\mathbf{x}_i)\right).$$

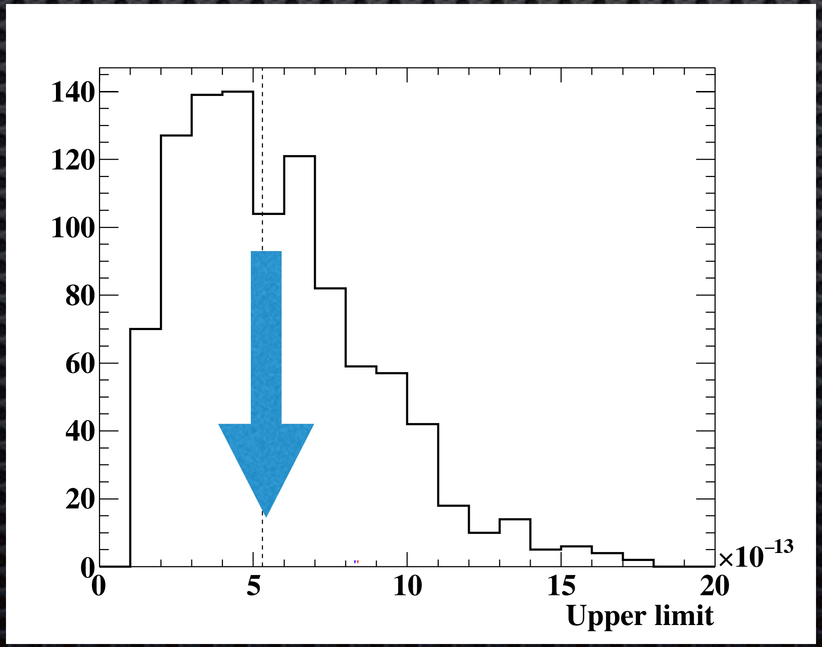
$x_i = (E\gamma, Ee, Te\gamma, \theta e\gamma, \phi e\gamma)$

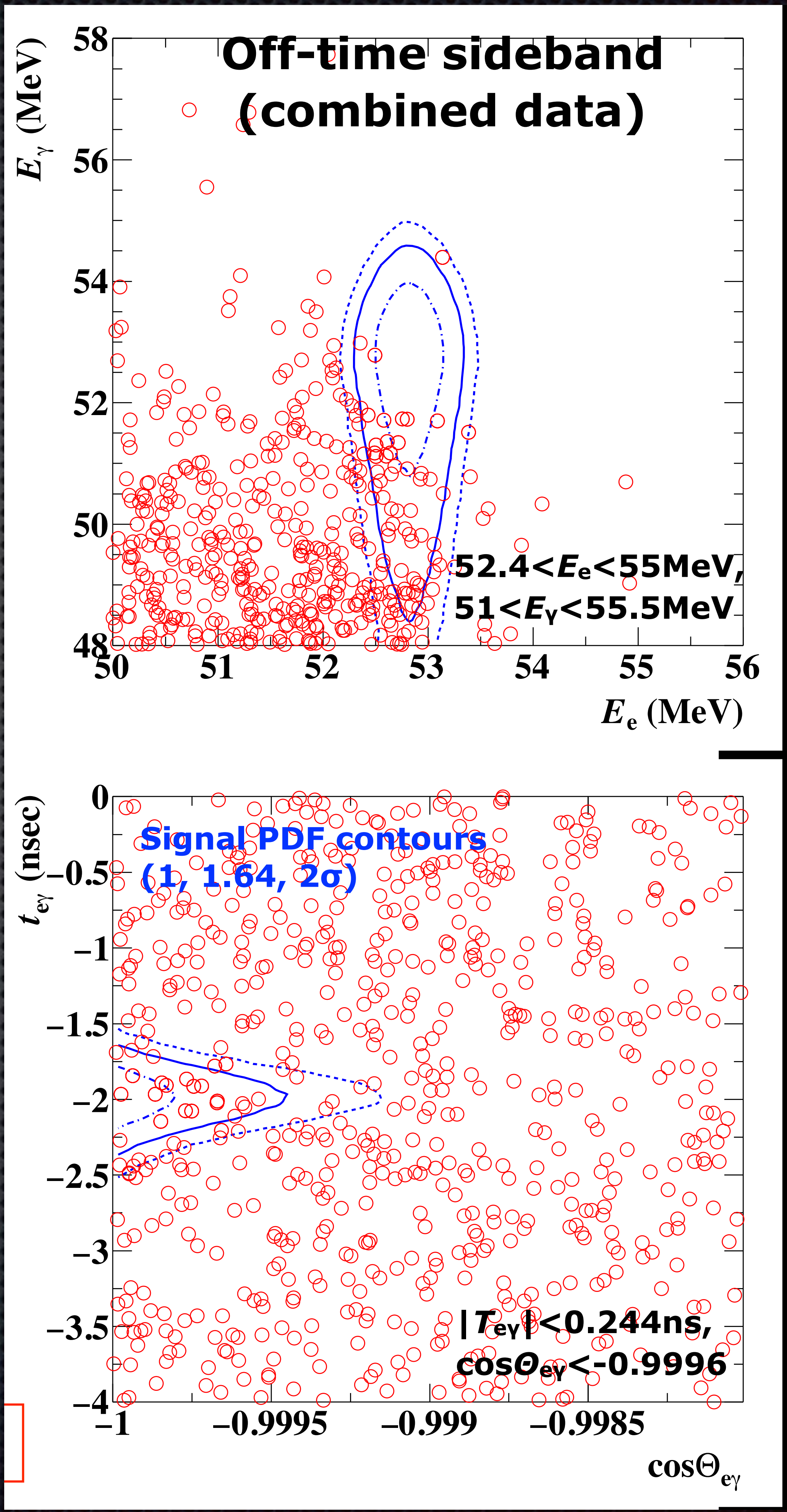


N_{RMD} evaluated from outside the blinded box

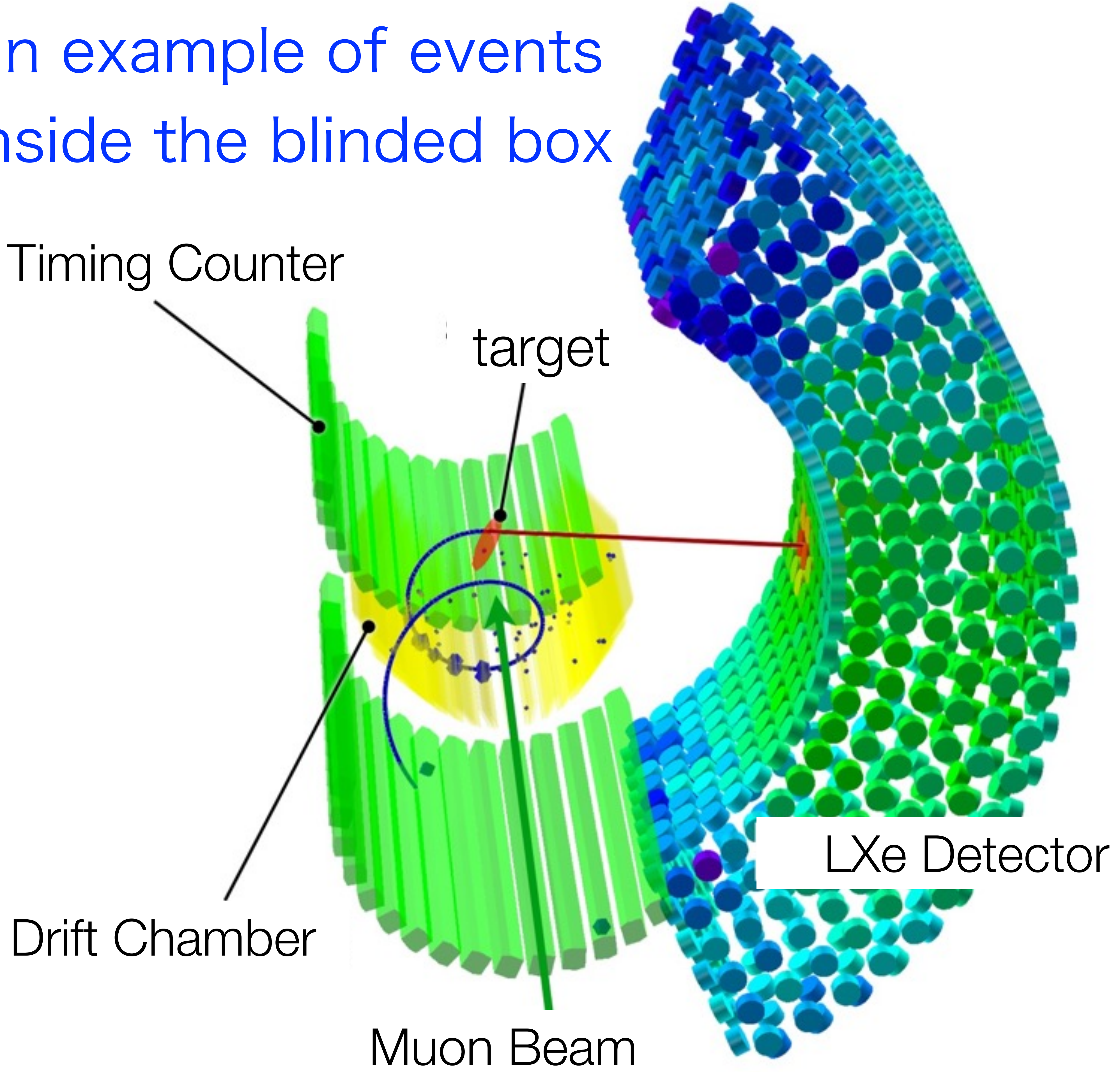
Sensitivity

- = average 90% CL Upper Limit w/ null-signal hypothesis
- Comparison w/ last publication of 2009-2011 data ~ Fine
- Checked by side-band data fits
- **~5.3×10^-13 for all data** (~8×10^-13 for 2009-2011 data)

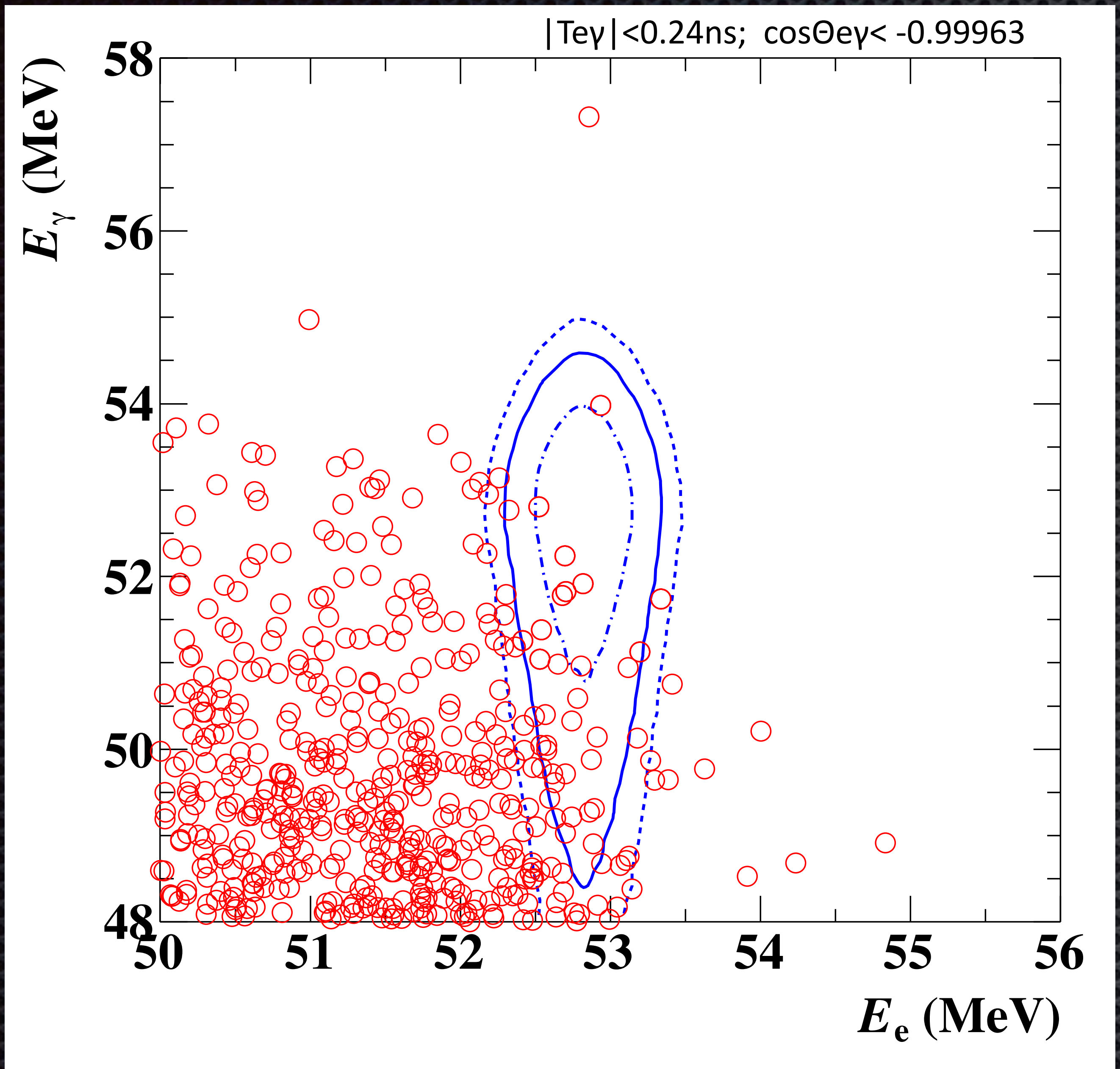


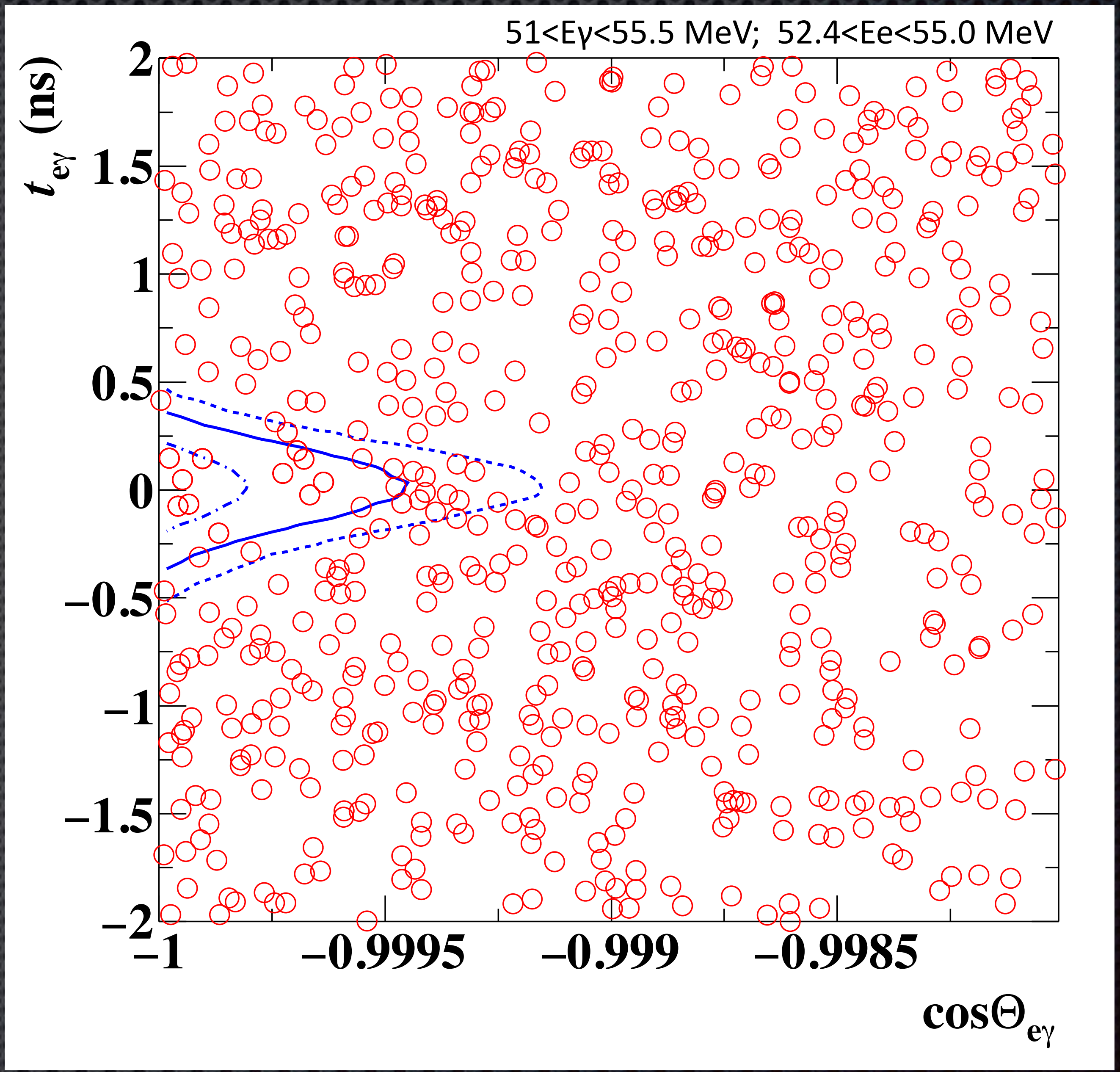


The Blinded Box was opened in December, 2015 an example of events inside the blinded box



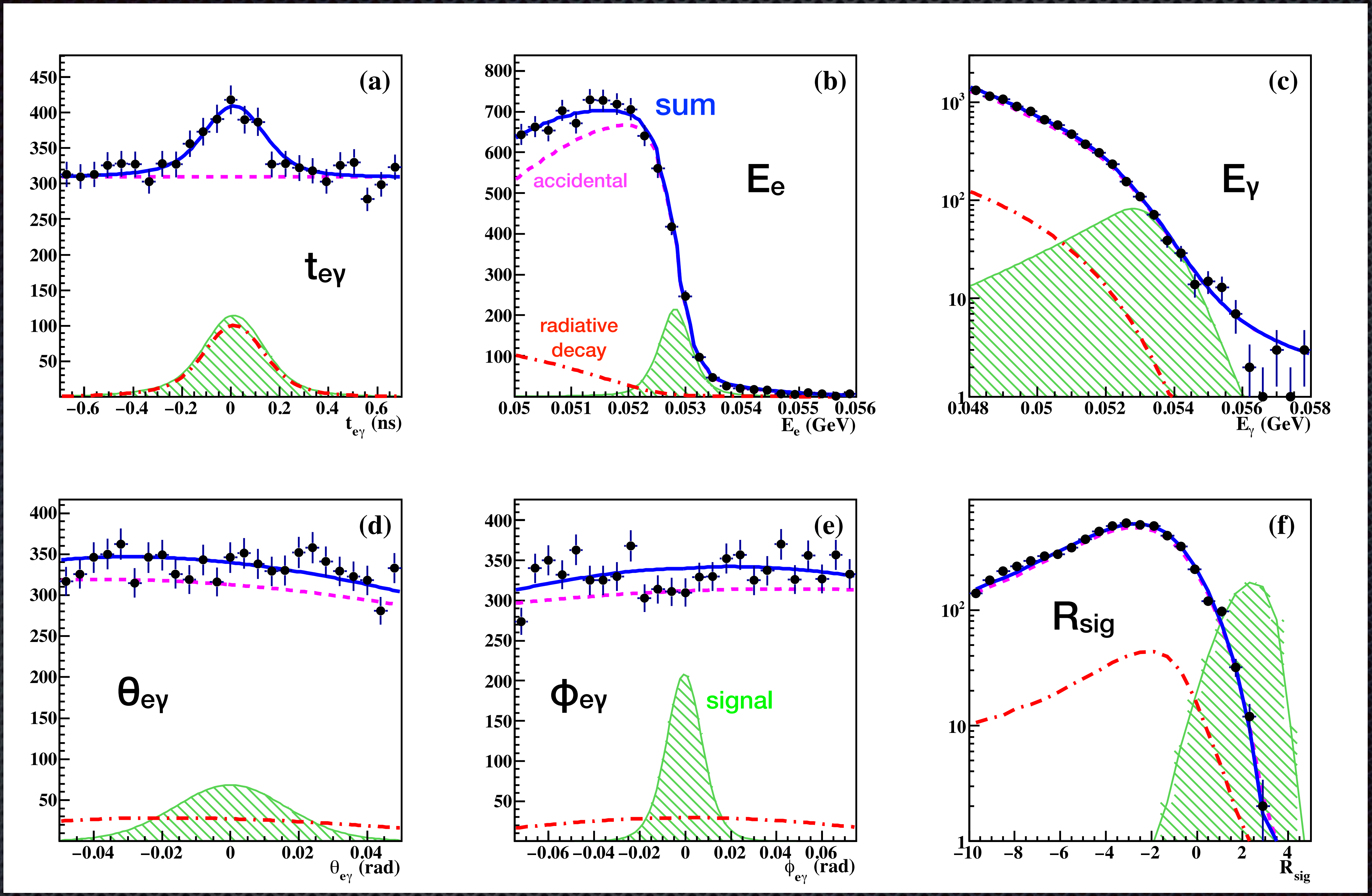
4D Event Distribution





signal contours of 1, 1.64, 2σ are shown

The Five Observables & R_{sig}

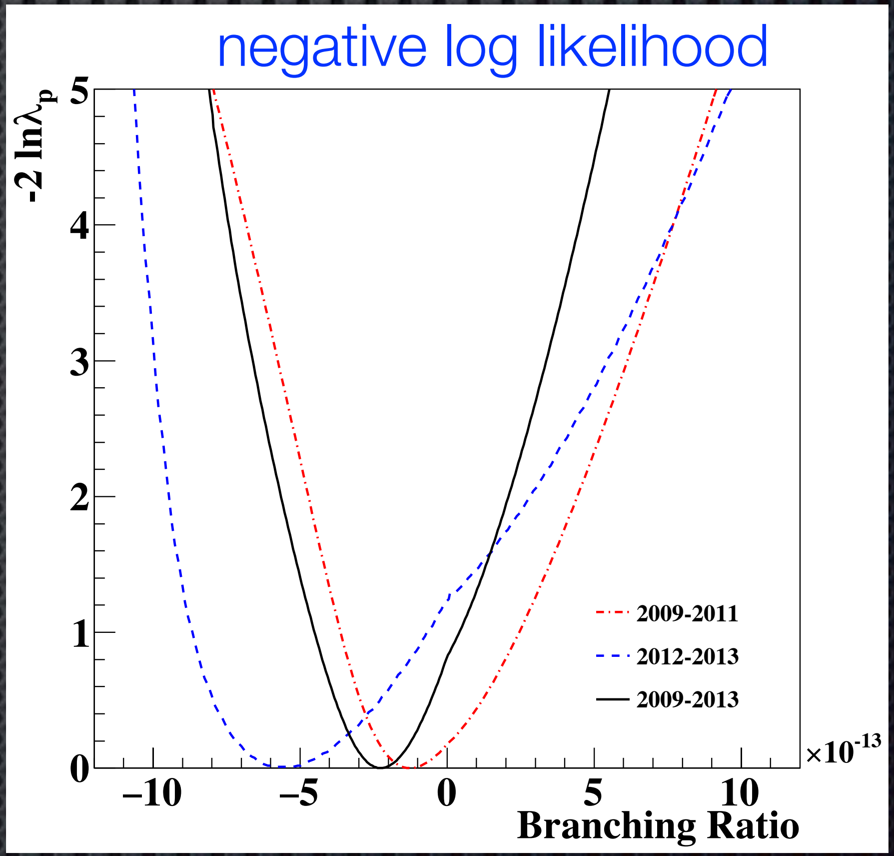


The best fitted likelihood function is shown. “Signal” in arbitrary scales.

$R_{sig} = \log_{10}(S / (f_R R + f_A A))$, where S=signal, R=radiative, A=accidental

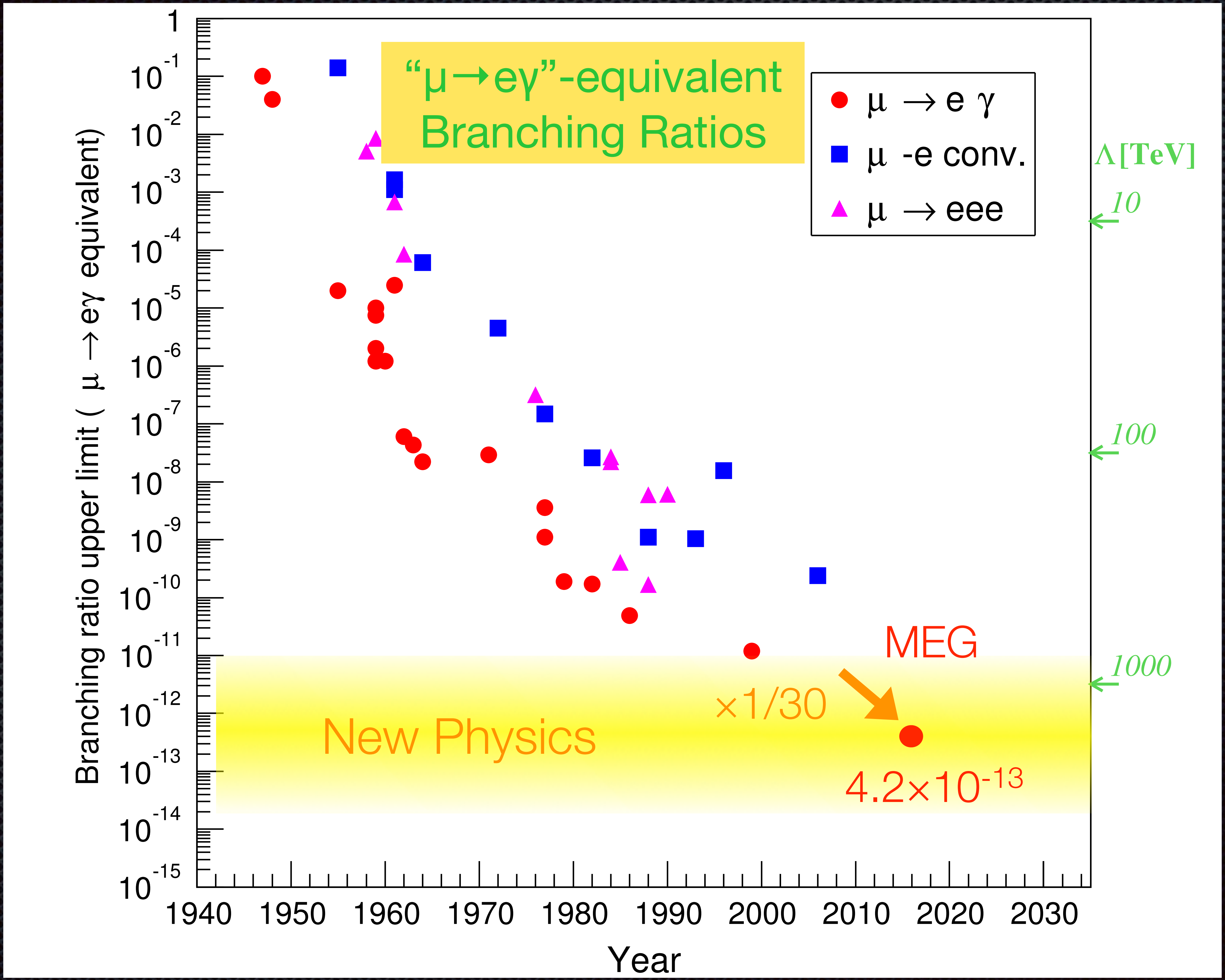
BR($\mu \rightarrow e\gamma$) < 4.2×10^{-13} @90%CL

Dataset	2009-11	2012-13	All
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



- Best fitted Branching Ratios and 90% C.L. Upper limits (in 10^{-13})

Final MEG Result:

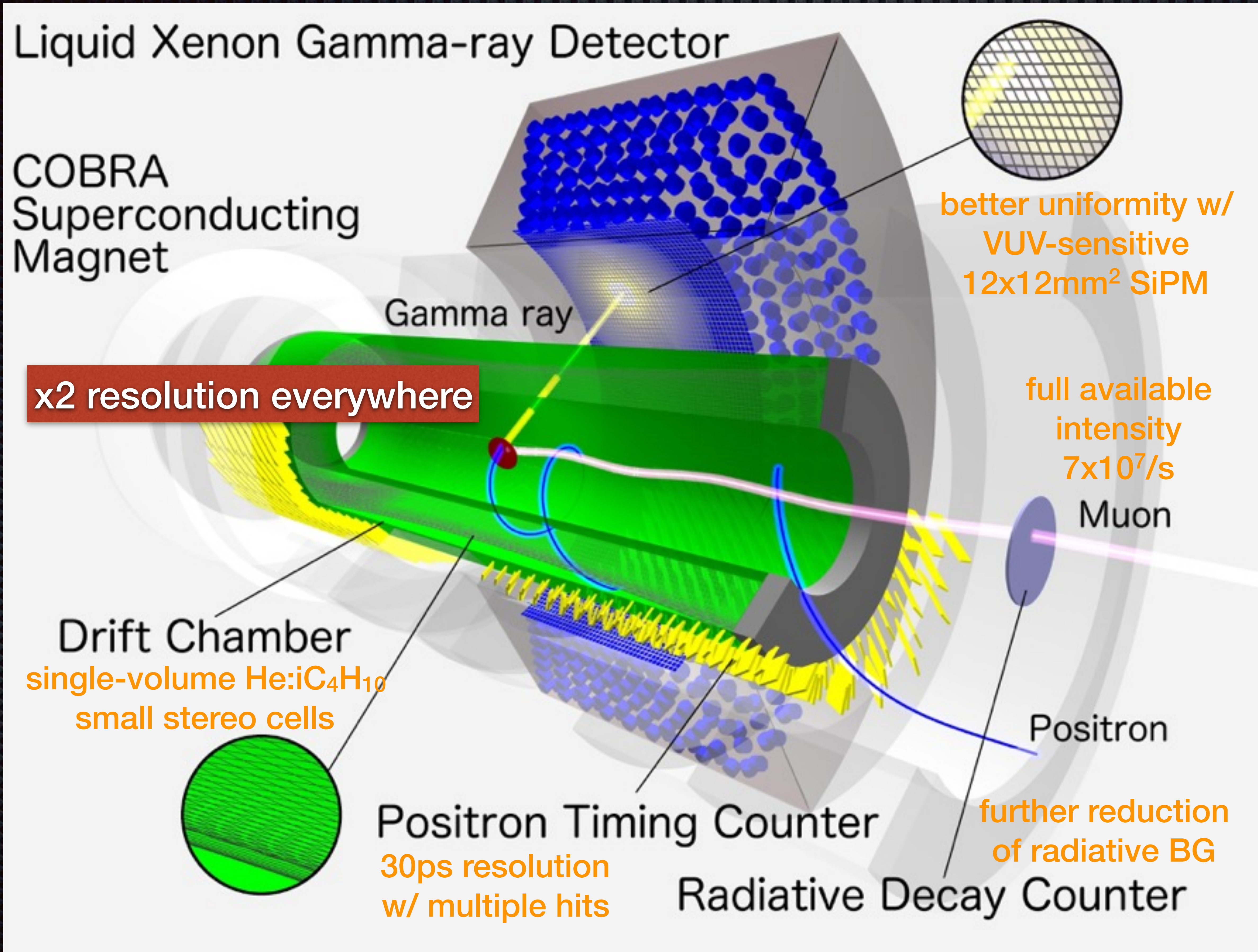


This is not the end !

Status of the Upgrade Experiment MEG II

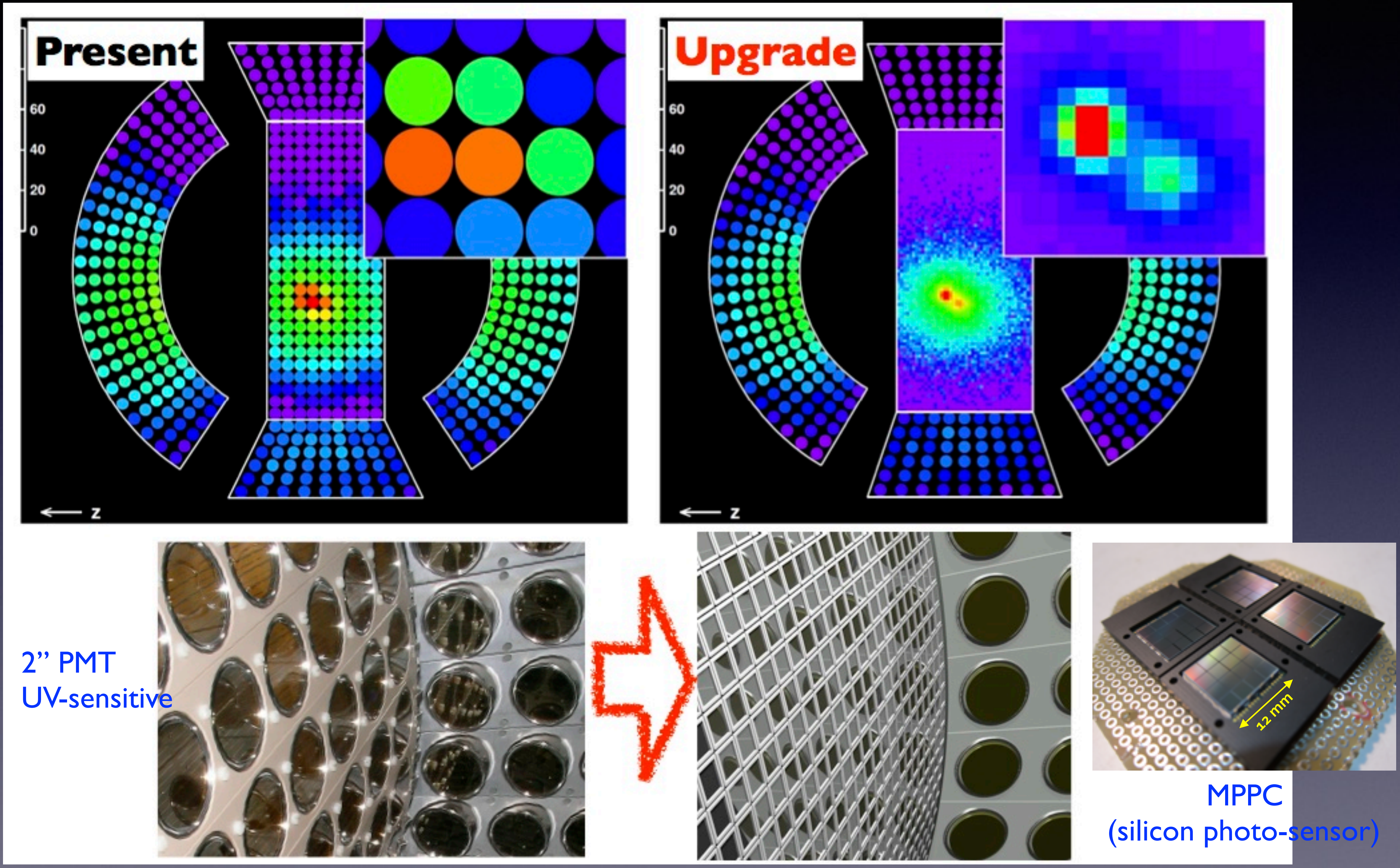
MEG II Experiment

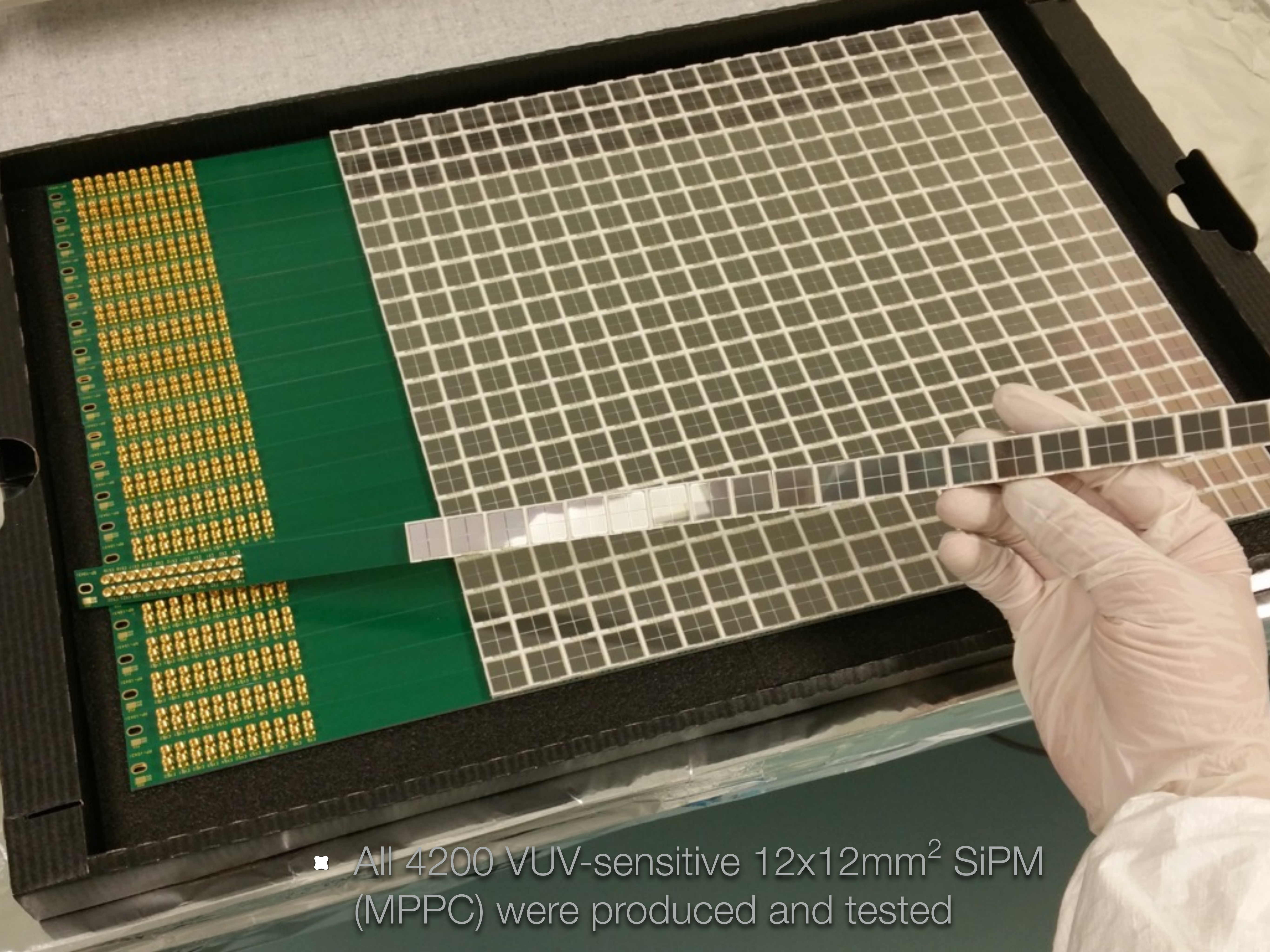
~4×10^{-14} sensitivity



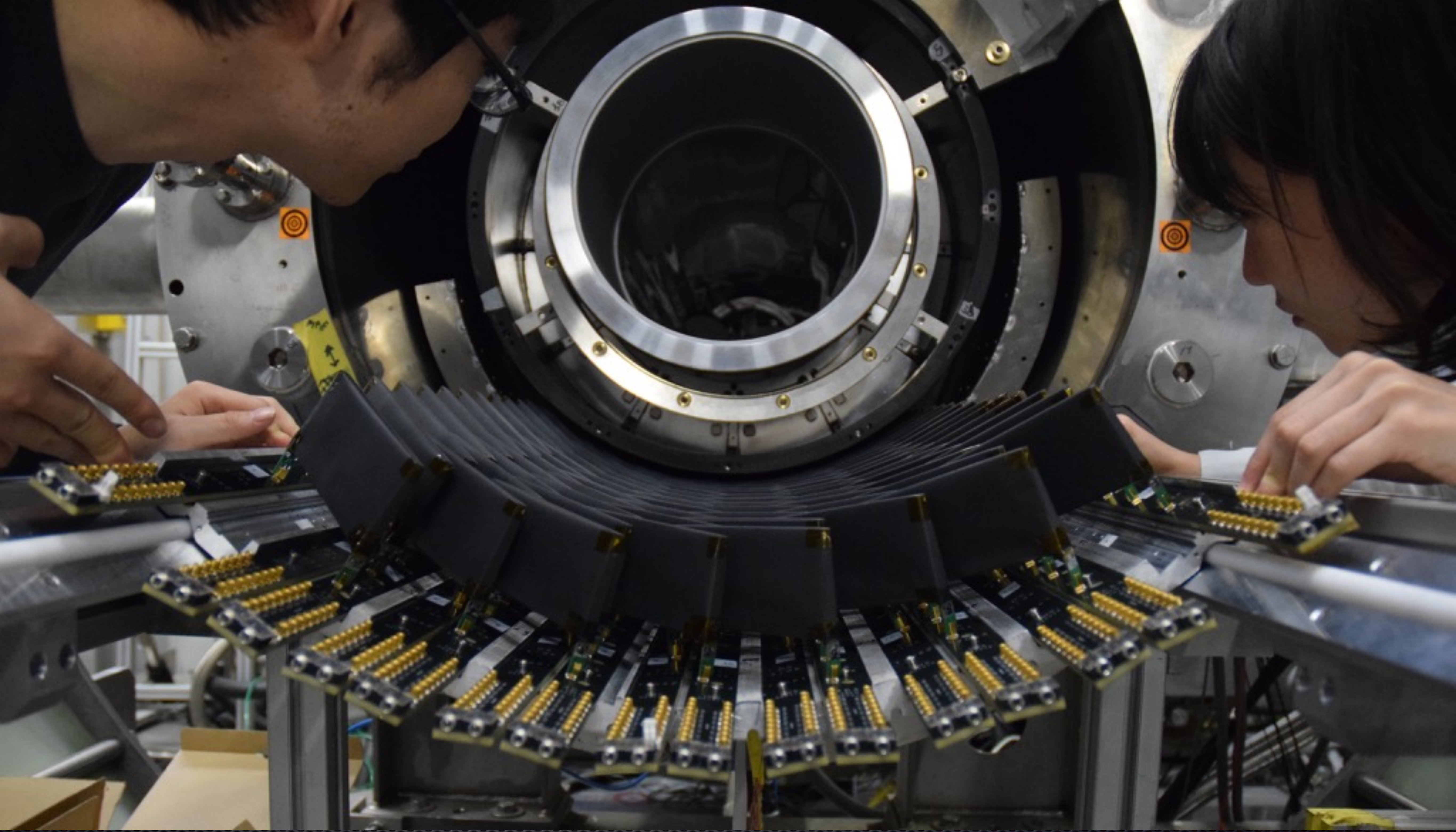
Upgraded LXe Photon Detector

improvements in energy & position resolutions by uniform precision 3D-imaging

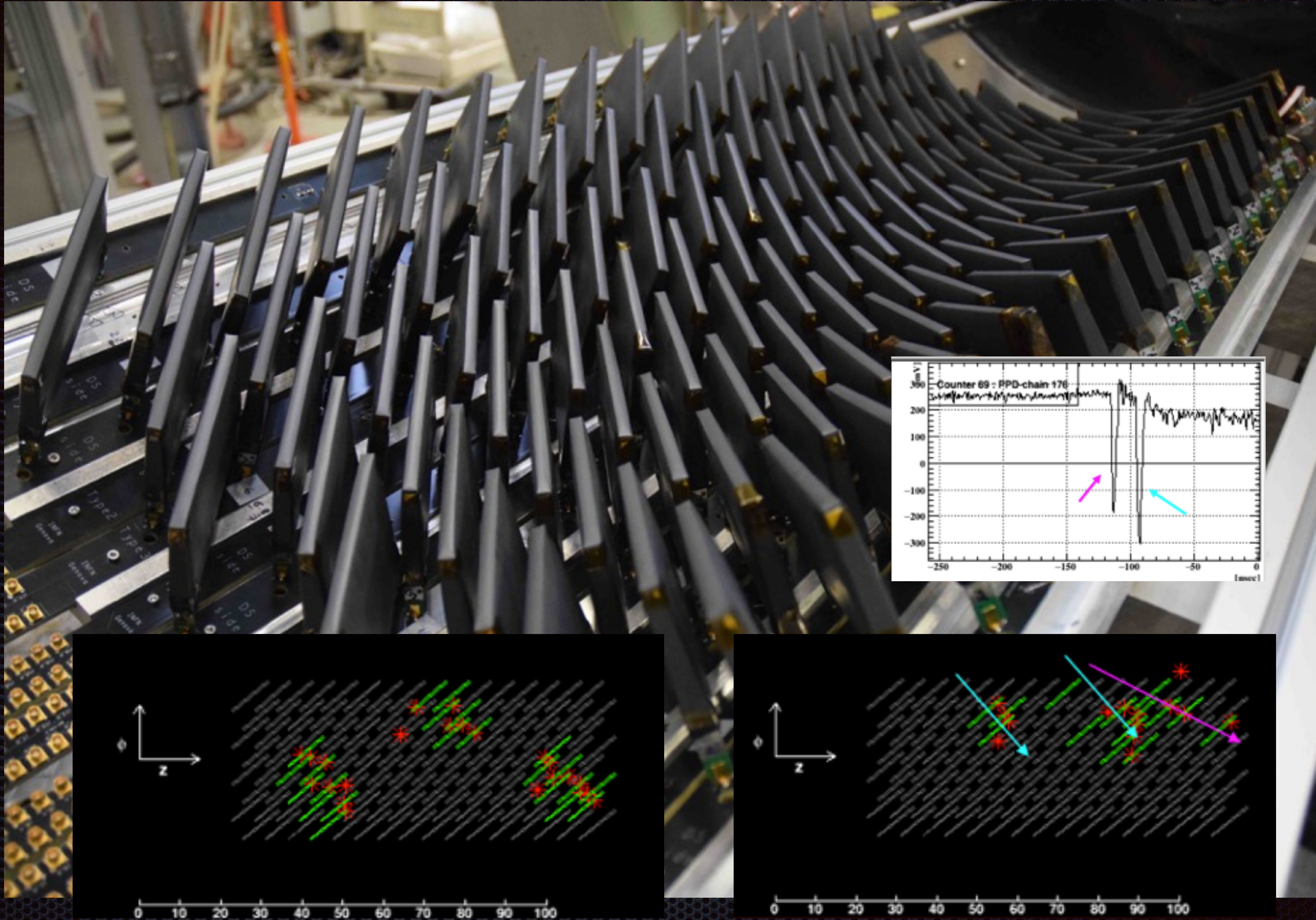




- All 4200 VUV-sensitive 12x12mm^2 SiPM (MPPC) were produced and tested



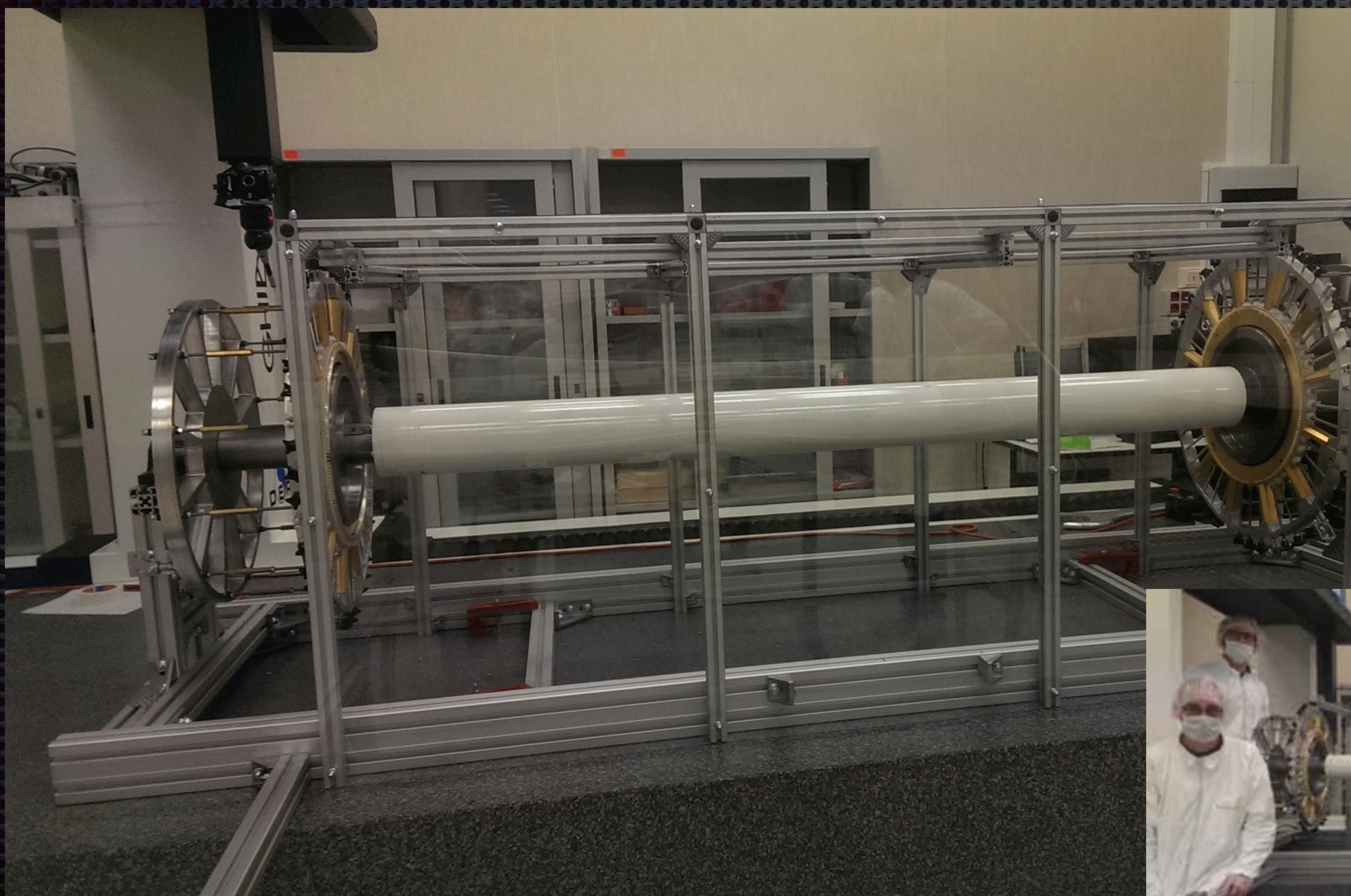
MEG II Timing Counter (half of downstream TC) installed & tested through full chain of trigger & DAQ electronics w/ Michel decays

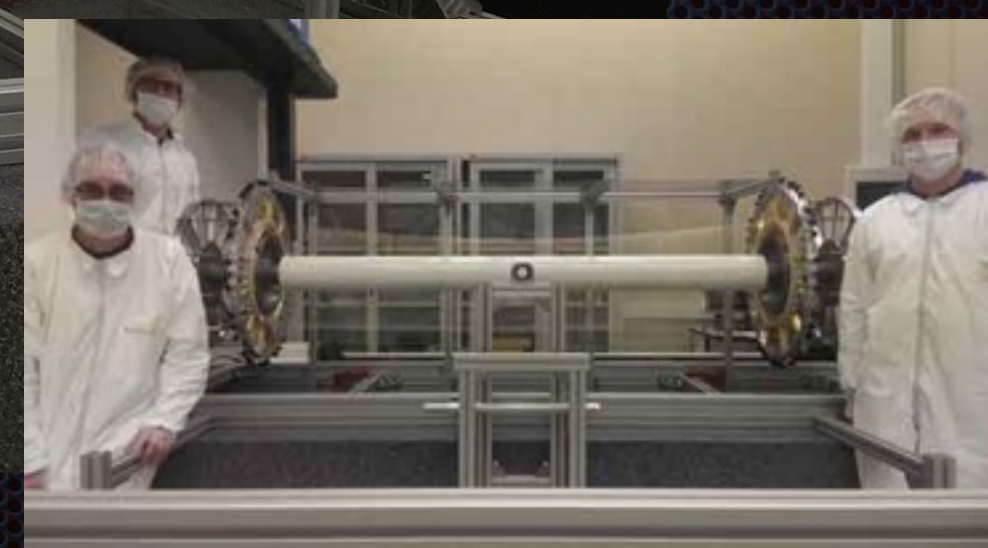


Counter 69 : PPD-chain 176
[mV]
300
200
100
0
-100
-200
-300
-250
-200
-150
-100
-50
0
[msec]
ϕ
z
0
10
20
30
40
50
60
70
80
90
100

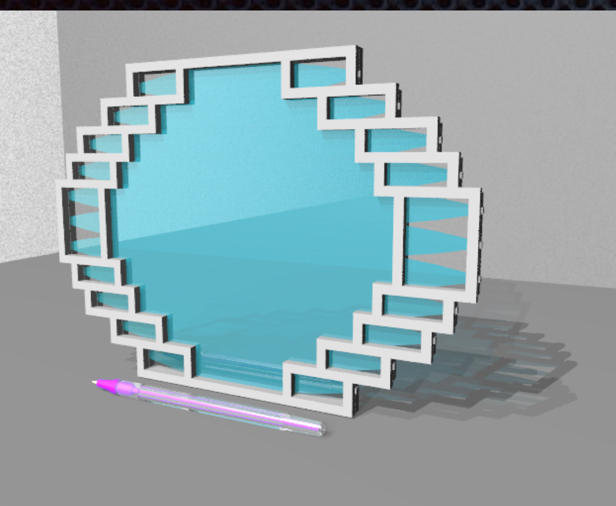
Drift Chamber

- Construction going on: wiring & assembly
- Expected to be delivered to PSI this fall for final tests toward the end of the year

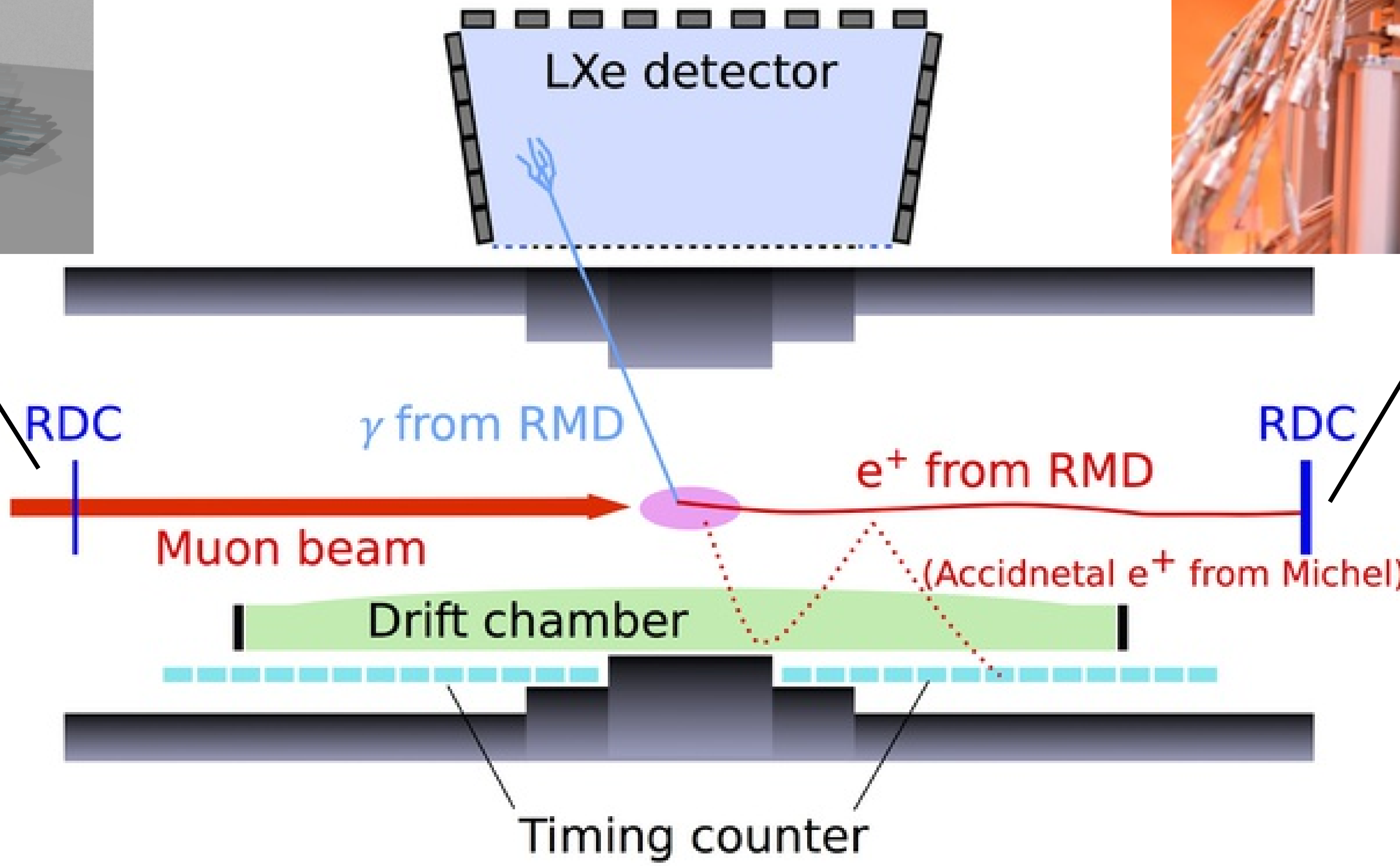


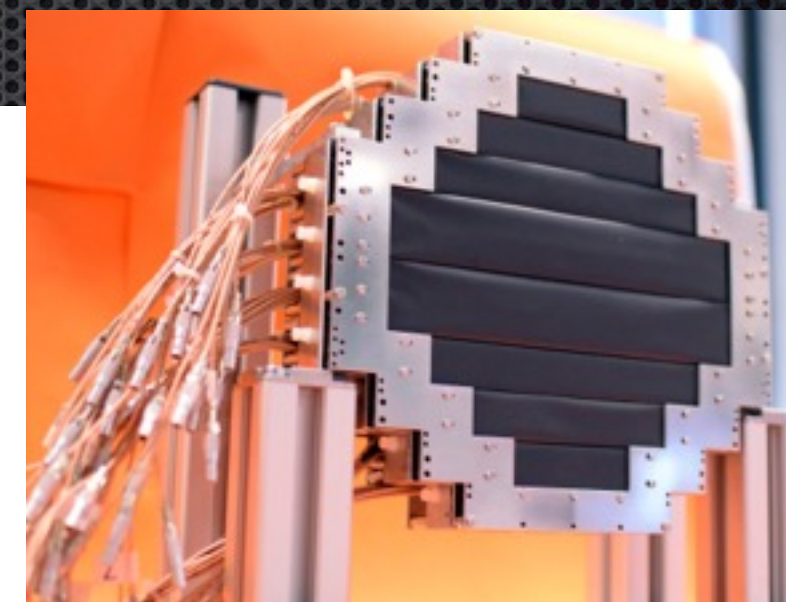


Radiative Decay Counter



successful
evaluation w/
beam



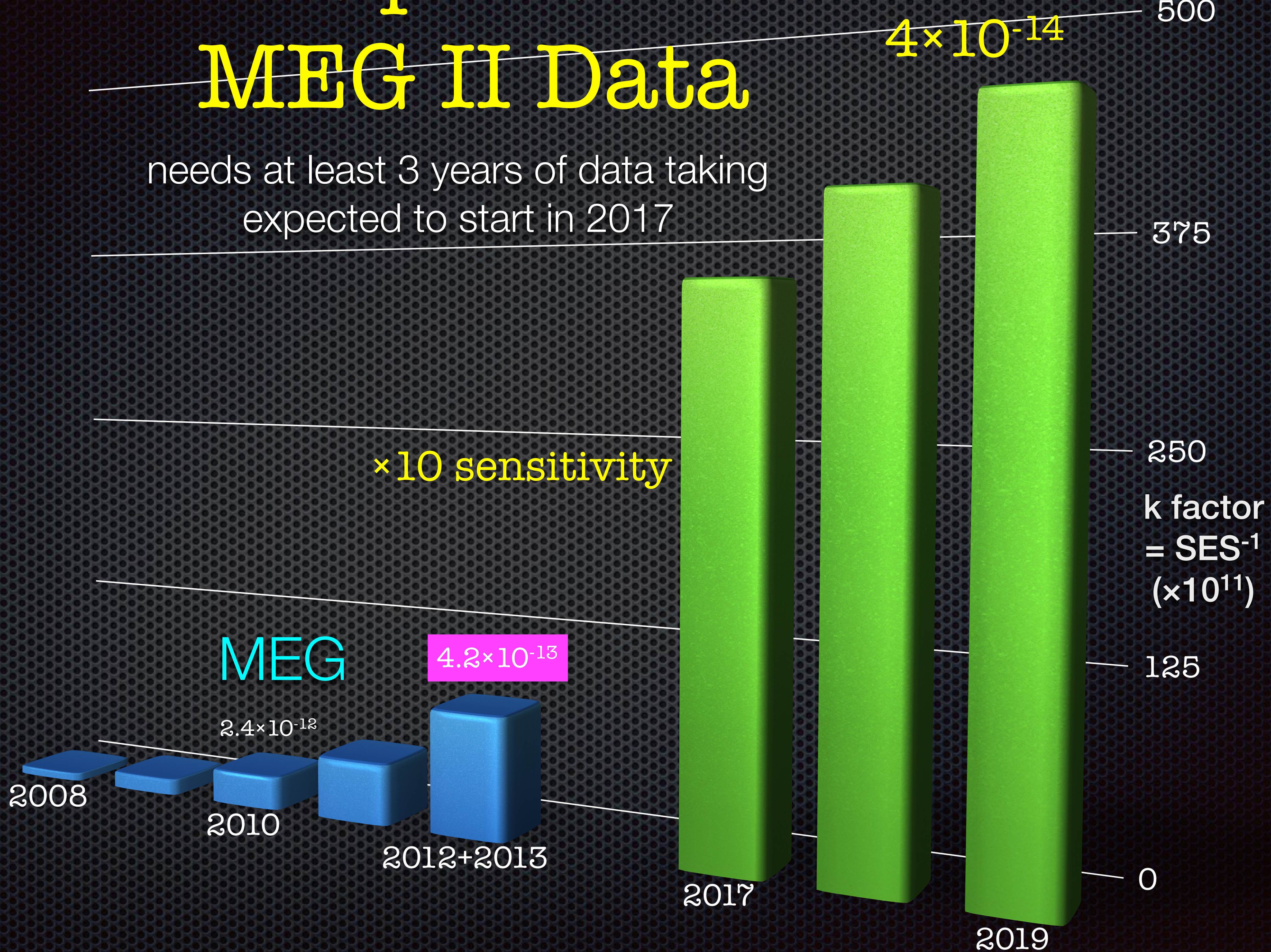


constructed
Ready!

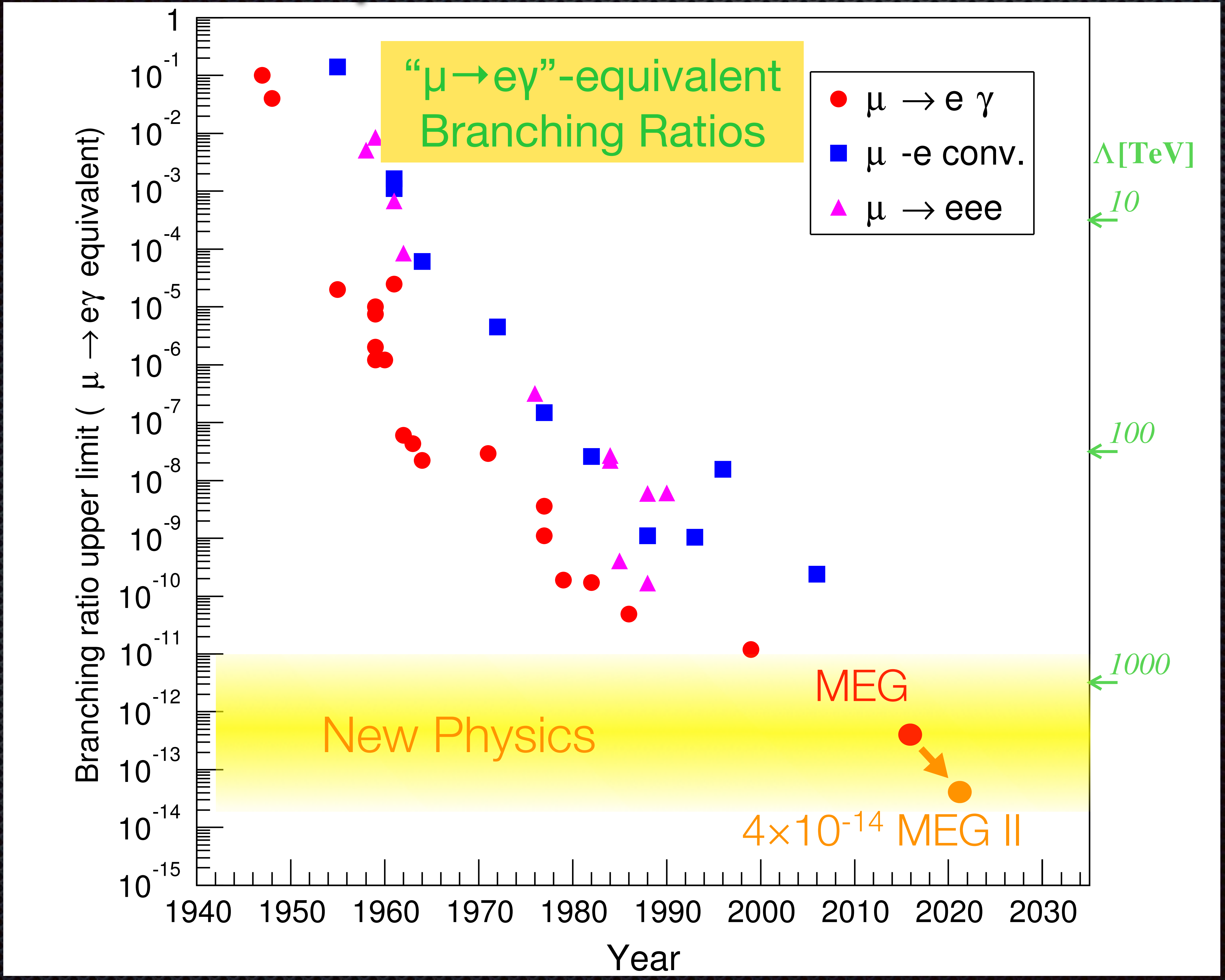
~28% sensitivity improvement by tagging gamma-rays from radiative decays

Prospects for MEG II Data

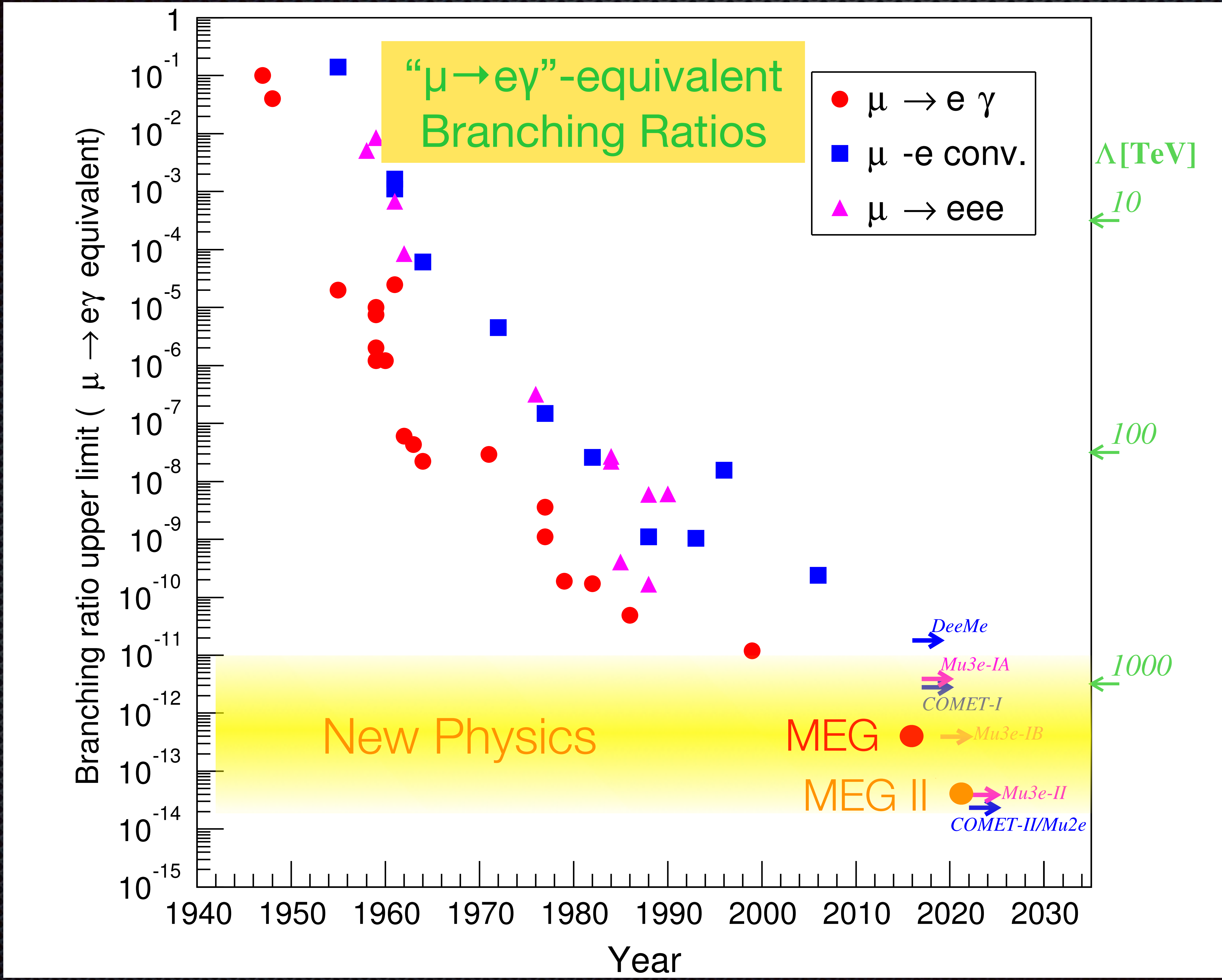
needs at least 3 years of data taking
expected to start in 2017



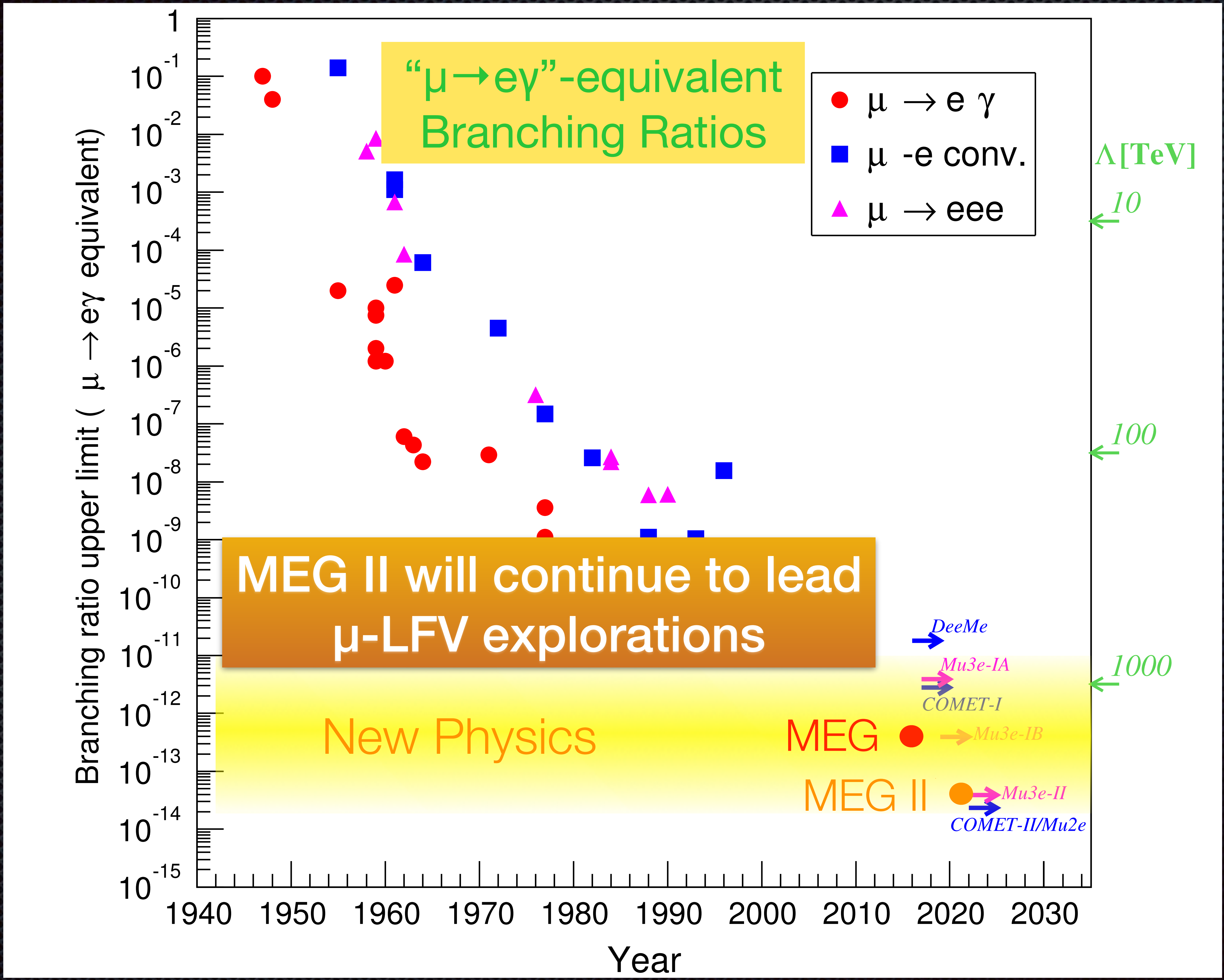
MEG II Expectation:



...followed by many others



...followed by many others



Summary

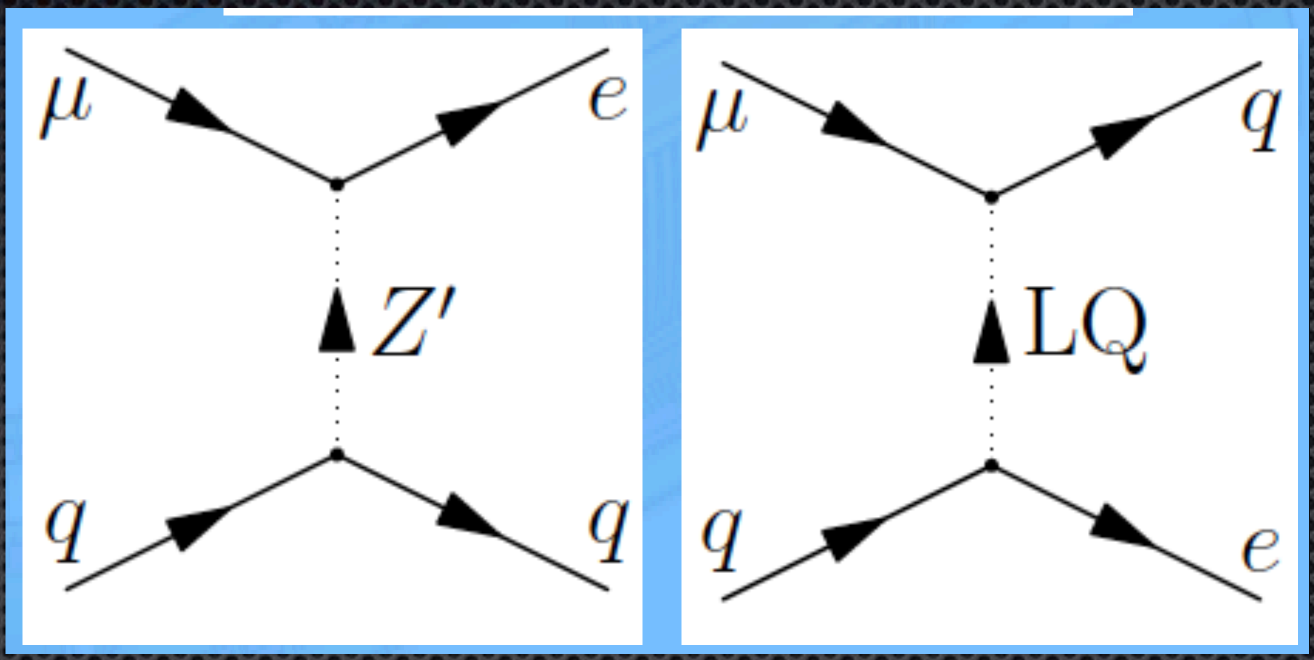
- No $\mu \to e\gamma$ event has been found yet.
- ~30× more stringent constraint than the previous experiment on possible new physics:
  $BR(\mu \to e\gamma) < 4.2\times10^{-13}$ @90% C.L.
- Preparation for MEG II well underway:
  expected to start in 2017 with 10× higher sensitivity $\sim 4\times10^{-14}$
- MEG II continues to lead charged lepton flavor violation searches in the coming years

The final result will be submitted to arXiv shortly

Also check our recent other publications:
"muon polarization", arXiv/1510.04743 (submitted to EPJC)
"radiative decay", EPJC 76(3), 108 pp.1-8

backup slides

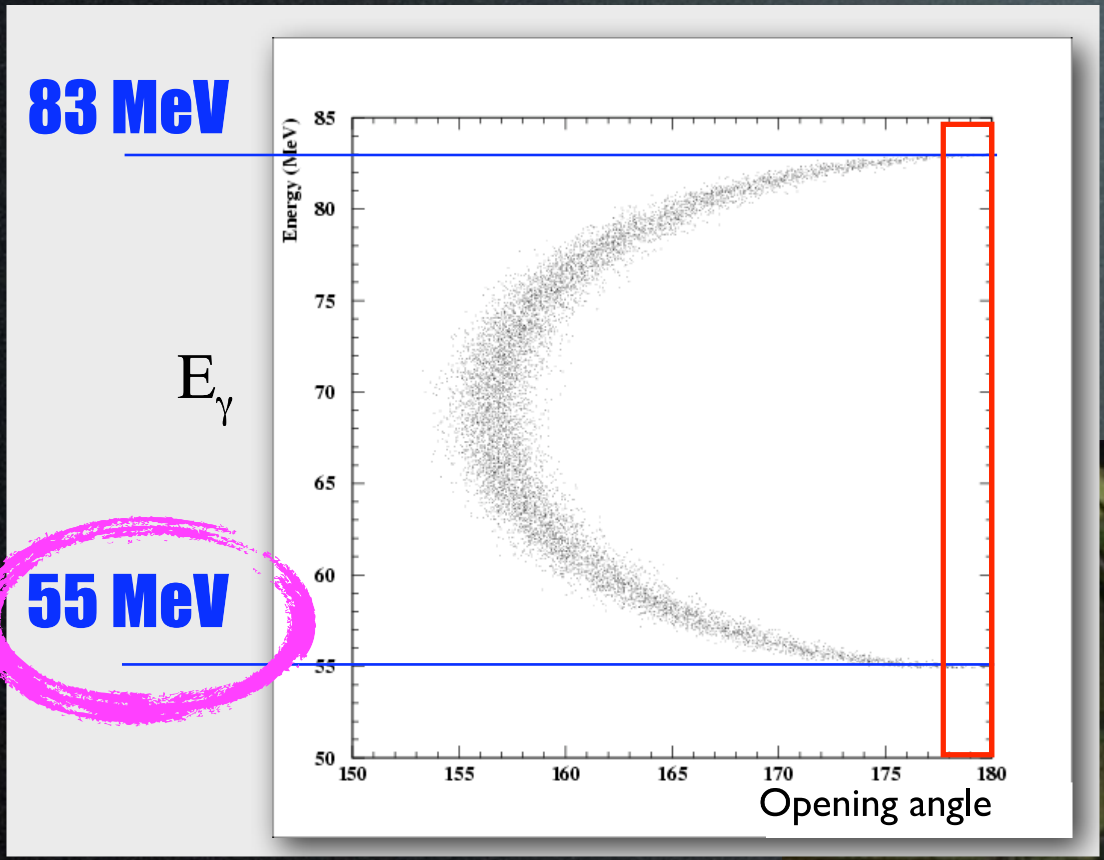
a caveat !



Some models have "four-fermion" *tree* terms which strongly enhance

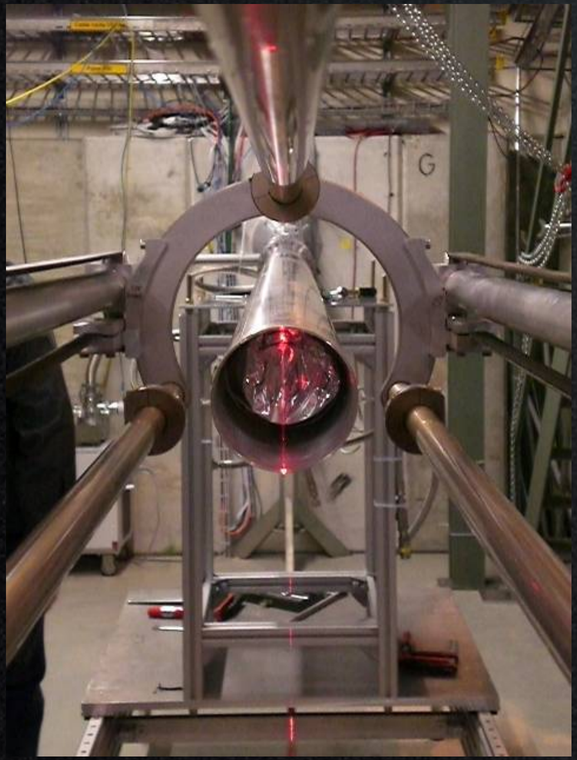
$\mu N \to eN$ $\quad\quad$ $\mu \to 3e$

Absolute γ Energy Calibration

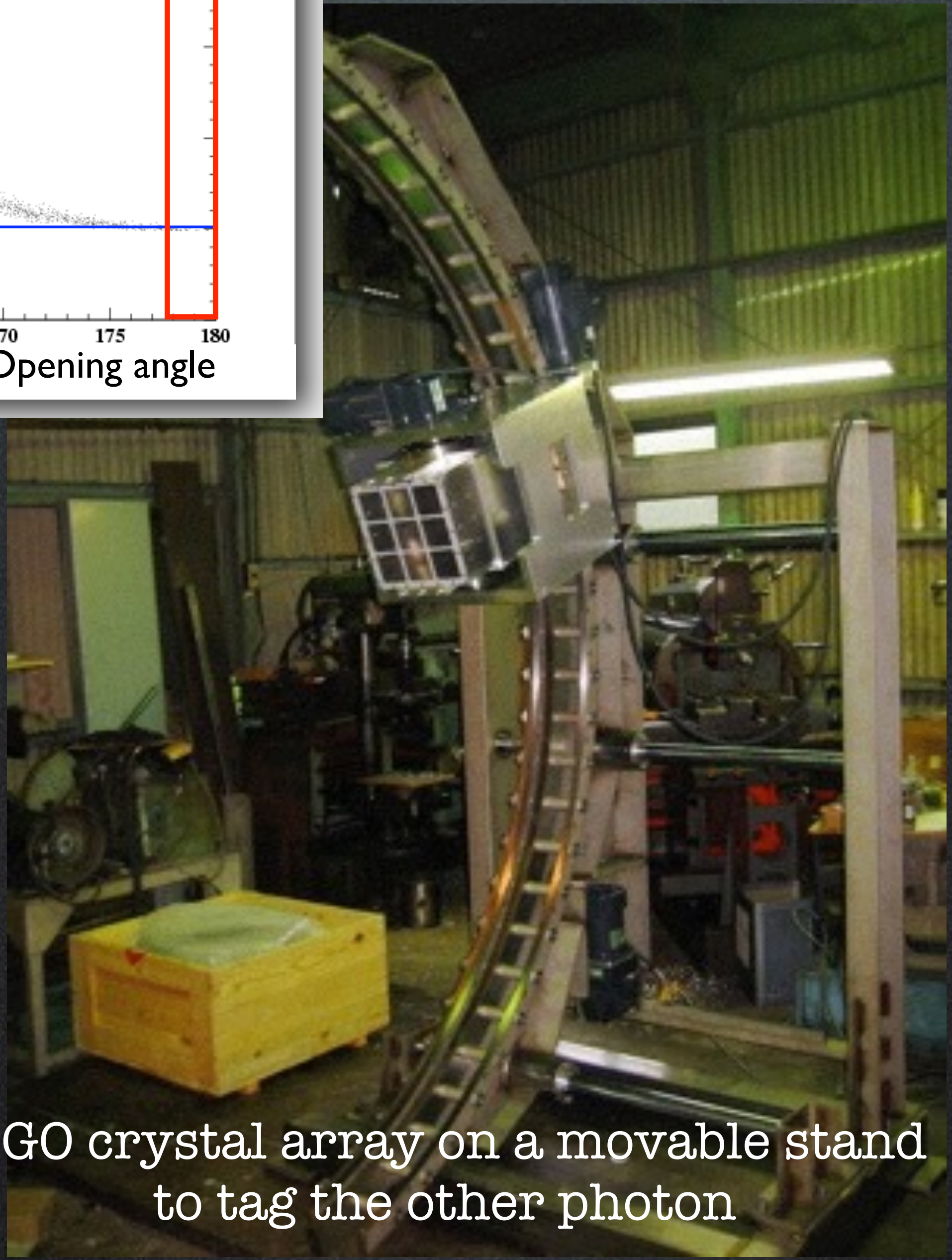


$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$

charge exchange reaction (CEX)

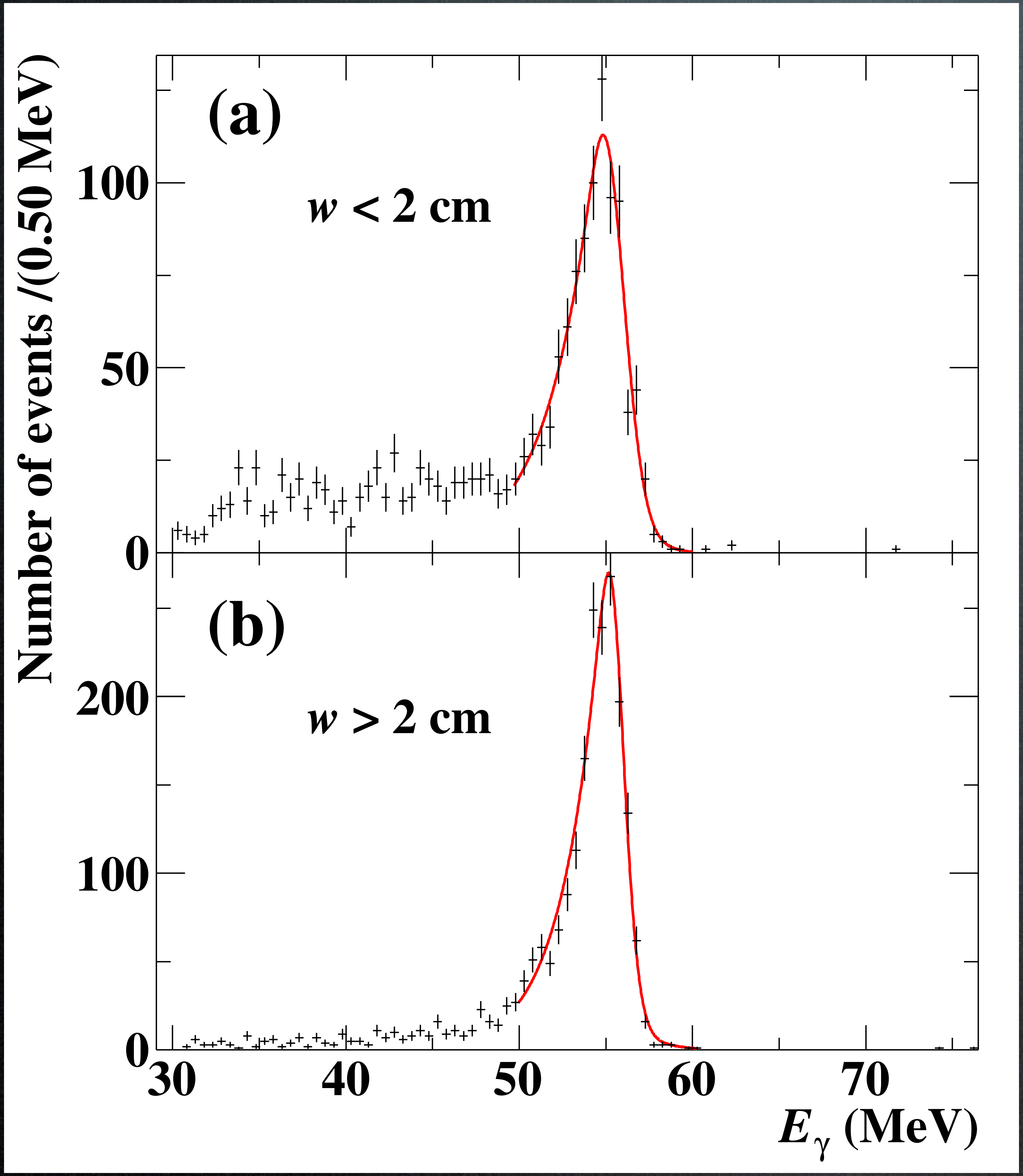


LH_2 target



BGO crystal array on a movable stand to tag the other photon

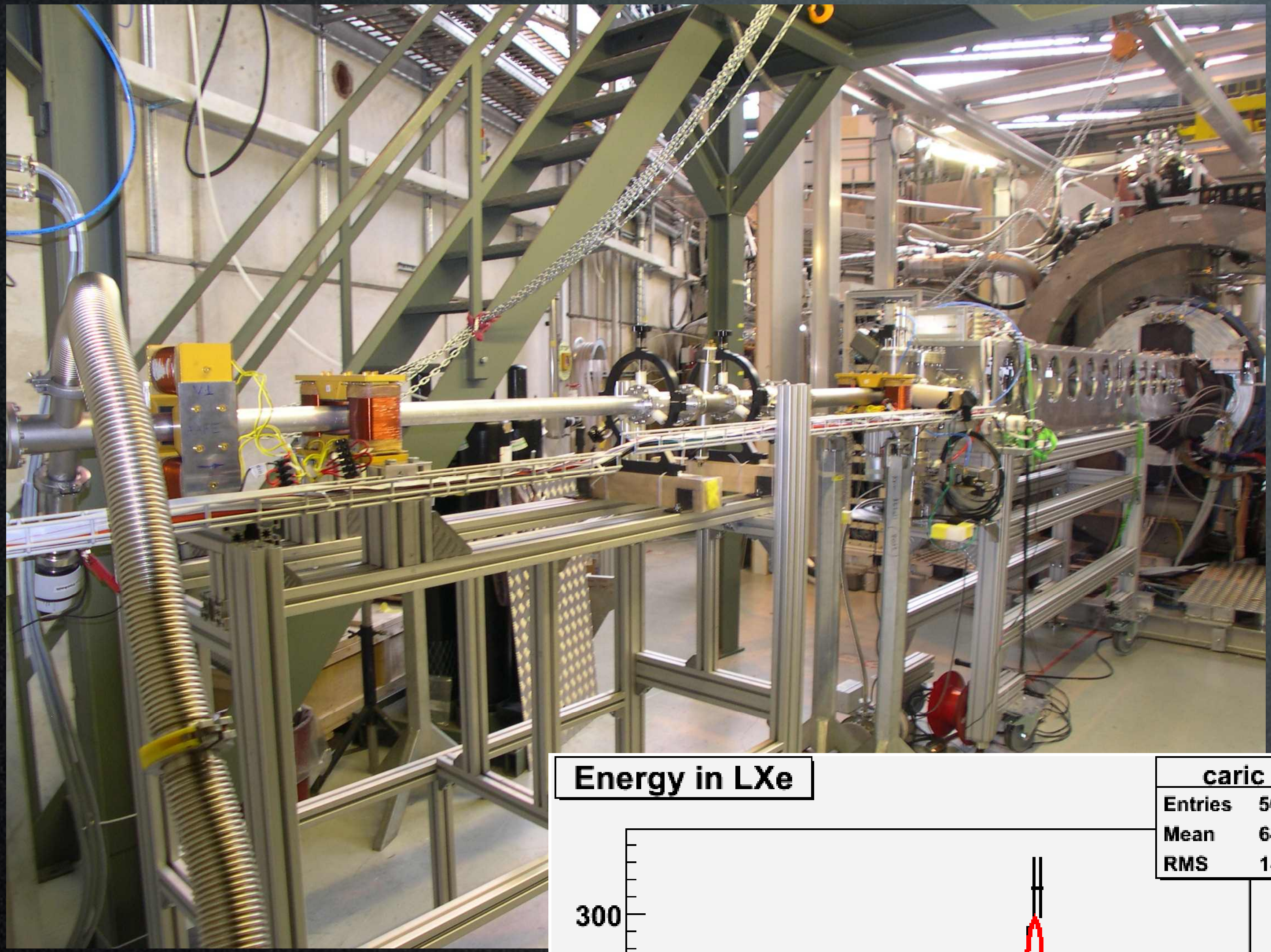
- negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180° provides monochromatic photons
- Dalitz decays were used to study positron-photon synchronization and time resolution



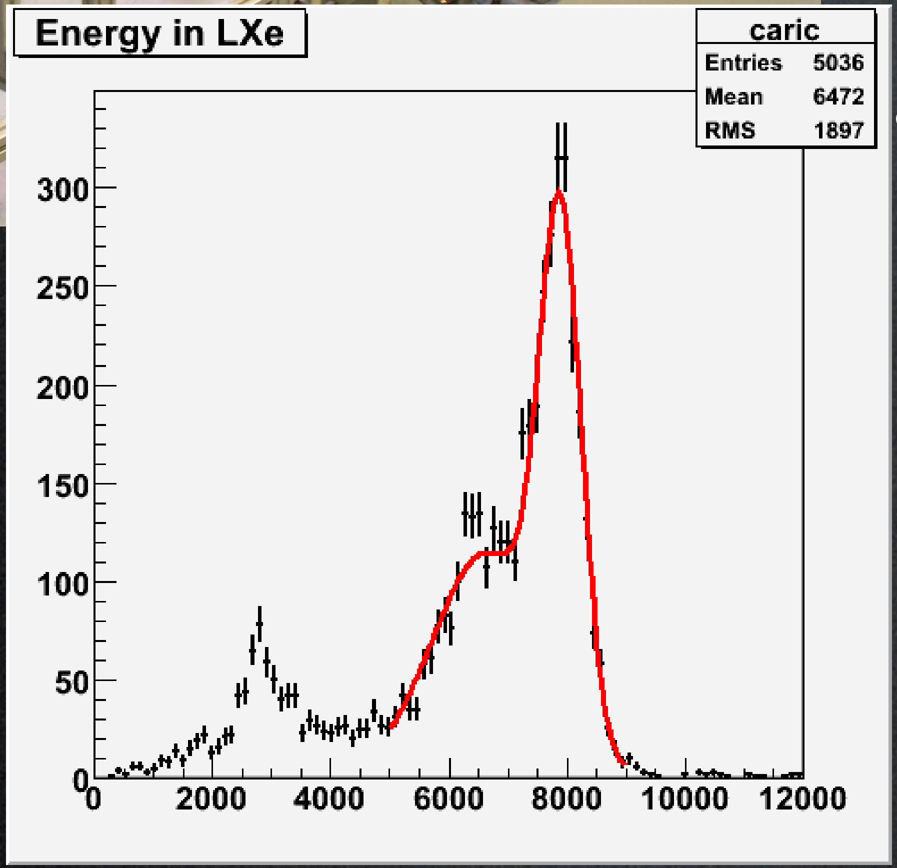
$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$

- Gamma ray energy
  - Signal PDF from the CEX calibration data
  - Accidental PDF from the side bands
  - Scale & resolutions verified by radiative decay spectrum
  - systematic uncertainty on energy scale: 0.3%

Monitor E_γ during Run



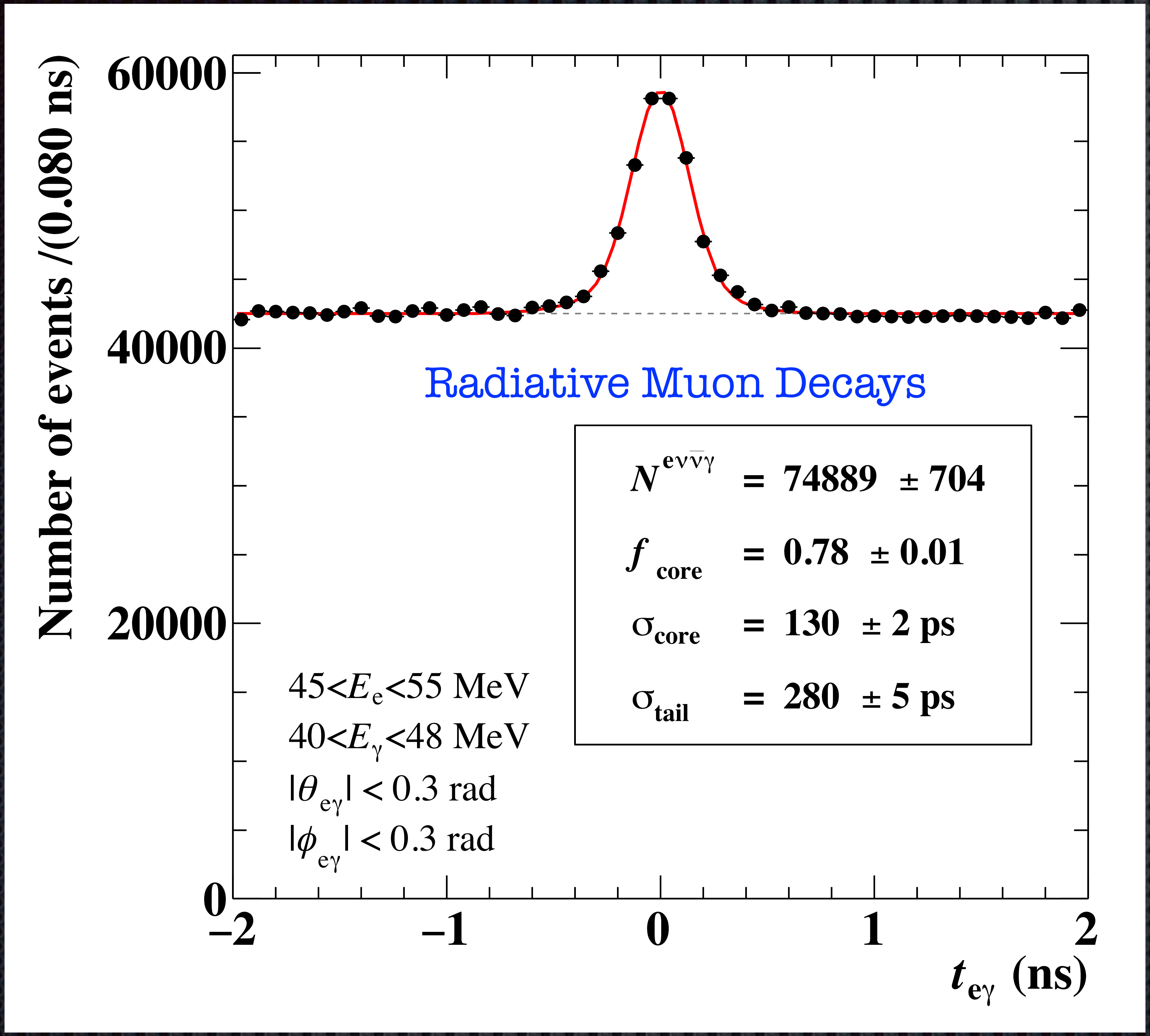
remotely extendable beam pipe of CW proton beam (downstream of muon beam line)



17.67MeV Li peak

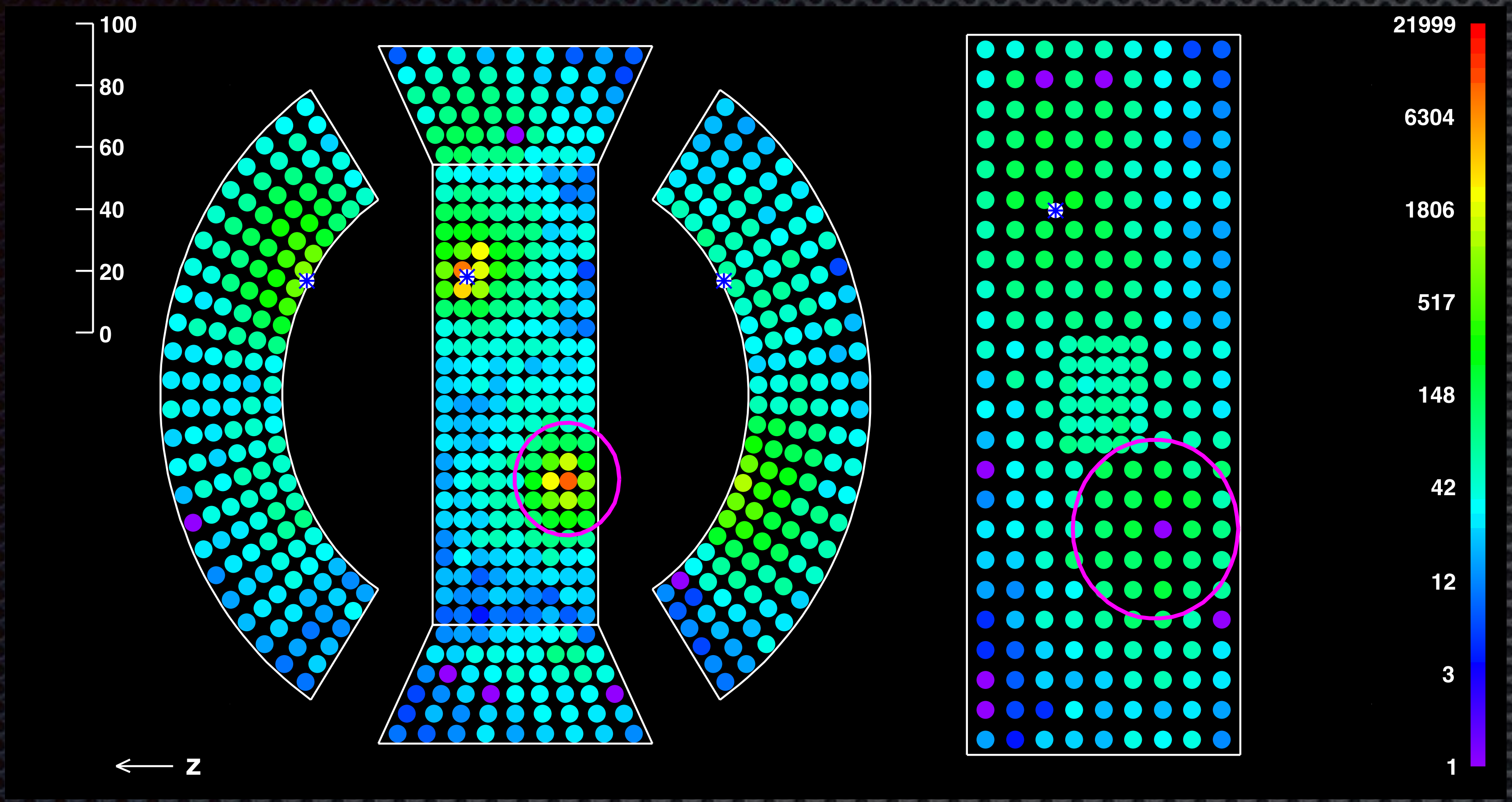
- sub-MeV proton beam from a dedicated Cockcroft-Walton accelerator are bombarded on $Li_2B_4O_7$ target.
- 17.67MeV from ^{7}Li
- 2 coincident photons (4.4, 11.6) MeV from ^{11}B: synchronization of LXe and TC
- Short runs 2-3 times a week

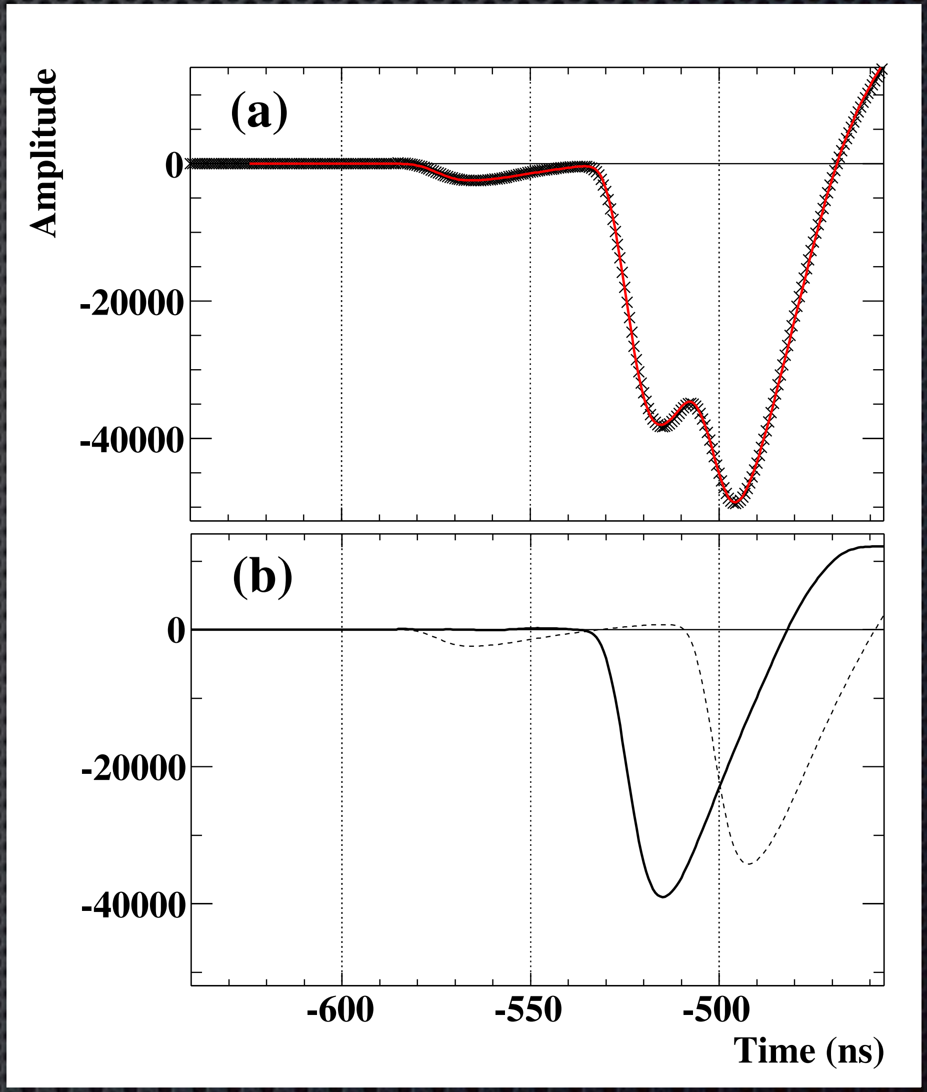
Positron - Photon Timing



- Positron time measured by TC and corrected by ToF (DC trajectory)
- LXe time corrected by ToF to the conversion point
- RMD peak in a normal physics run corrected by small energy dependence; stable < 20ps

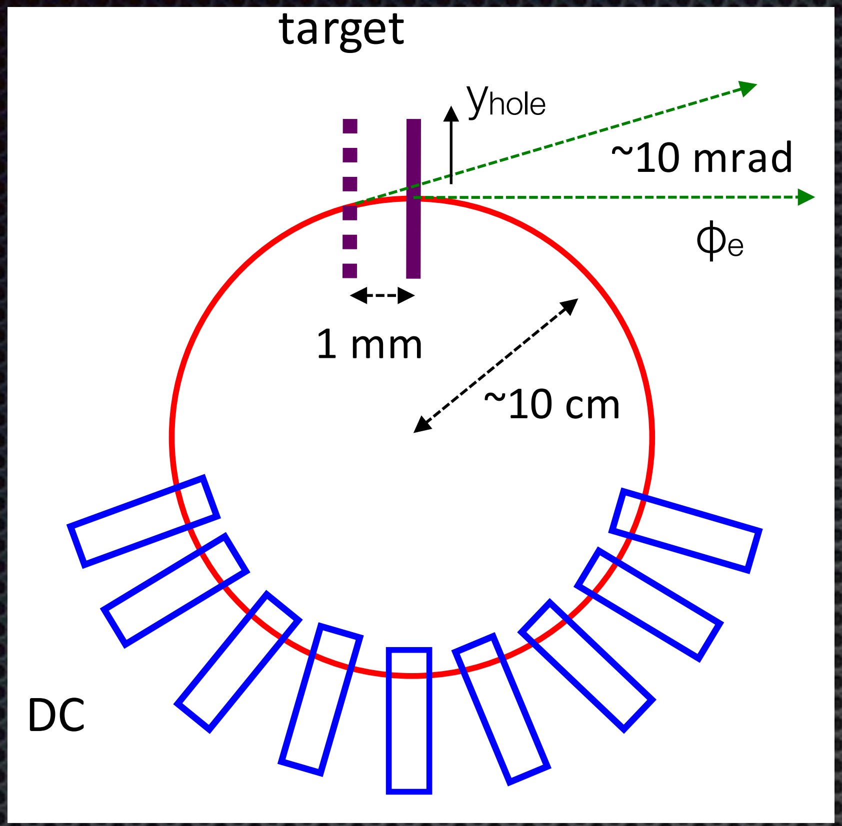
Pile-up Photon Removal

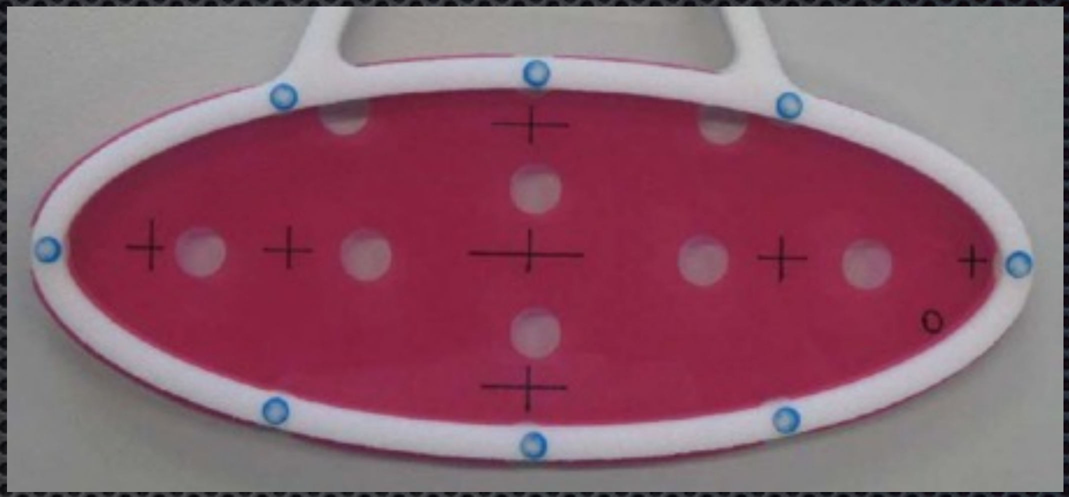


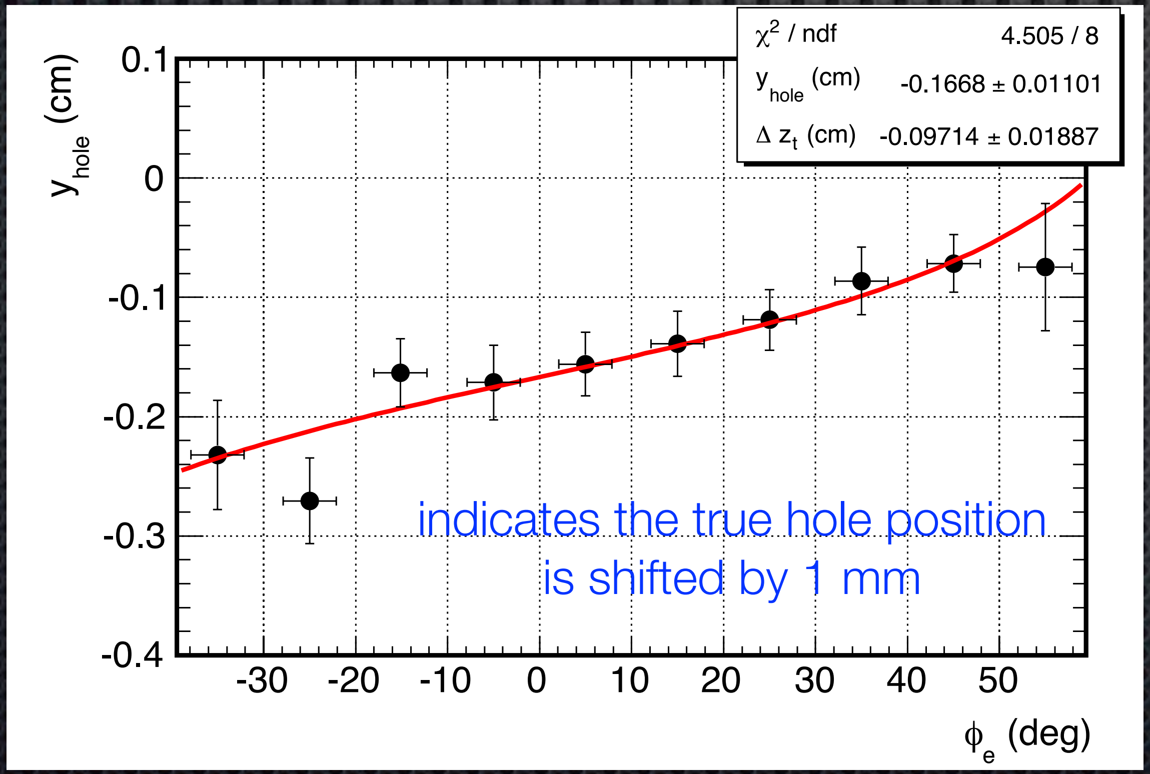


- Good position/timing resolutions enable to remove pile-up photons
- All the PMTs are read out by waveform digitizers (DRS)
- Events are not thrown away

Target Alignment by "Hole" Reconstruction







- The holes of the target are reconstructed by e^+ tracks.
- Displacement of the target manifests itself in dependence of the reconstructed hole position on e^+ angles.

Normalization

- Michel events & radiative decay events (RMD) were used to count total # of muon decays measured
- Some of the systematics on acceptance cancelled