NUFACT 15 RIO DE JANEIRO BRAZIL AUGUST 10-15

The MEGII experiments at PSI

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on behalf of the MEGII collaboration

PAUL SCHERRER INSTITUT PSI

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- Introduction
- The MEGII experiment searching for the $\mu^+ \rightarrow e^+ \gamma$ decay

Lepton Flavour Violation of Charged Leptons (cLFV)

- Lepton flavour is preserved in the SM ("accidental" symmetry)
  - not related to the theory gauge
  - naturally violated in SM extentions

LFV of neutral leptons confirmed
-neutrino oscillations-

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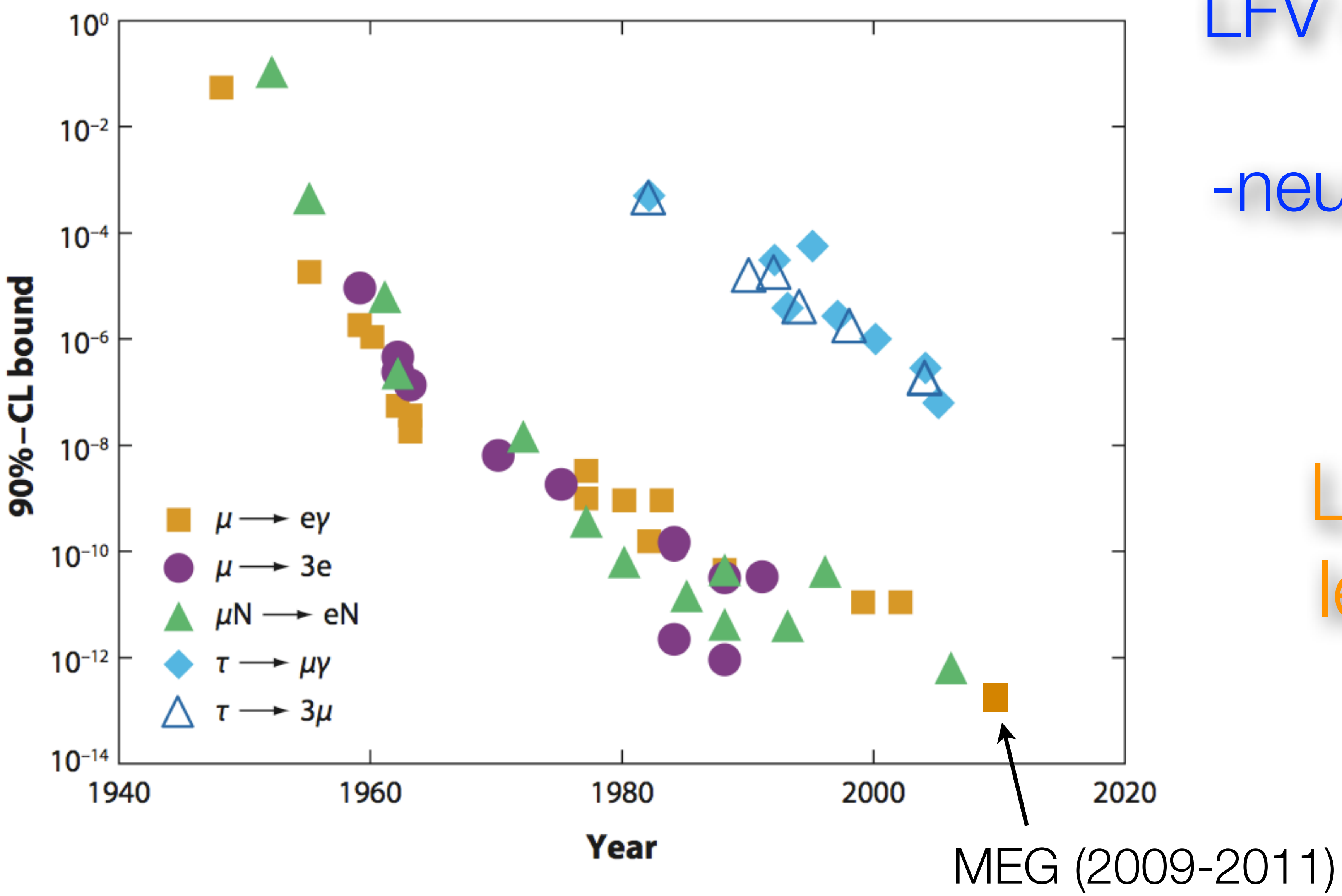
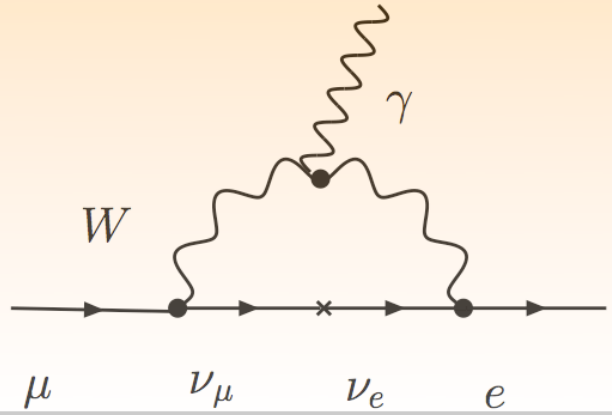


LFV of neutral leptons confirmed -neutrino oscillations-

LFV of charged leptons not yet observed

The $\mu^+ \to e^+ \gamma$ decay as an example

- Taking neutrino oscillations into account



SM with massive neutrinos (Dirac)

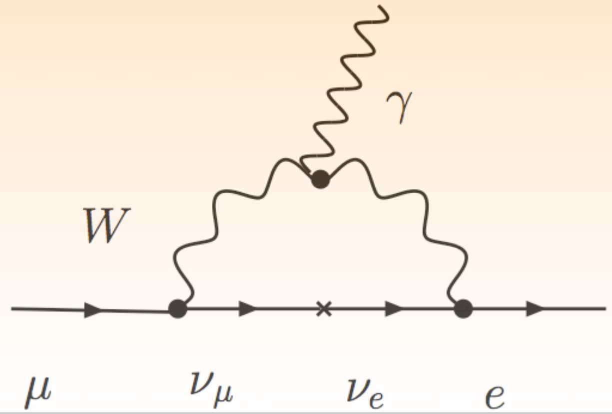
$$\Gamma(\mu \to e\gamma) = \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{\alpha}{2\pi} \sin^2 2\theta \, sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$B(\mu^+ \to e^+\gamma) \approx 10^{-54}$$

too small to access experimentally

The $\mu^+ \to e^+ \gamma$ decay as an example

- Taking neutrino oscillations into account



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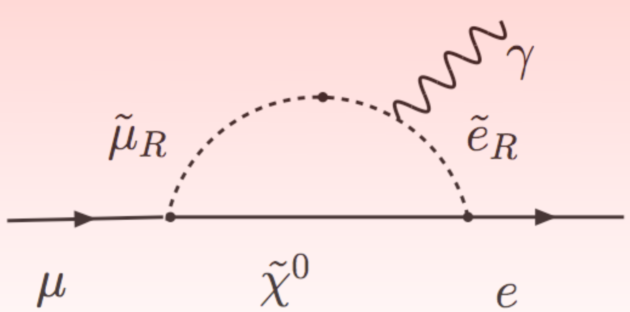
- Beyond SM theories such as SU(5) SUSY-GUT and SO(10) SUSY-GUT models predict measureble cLFV decay BR



SU(5) SUSY-GUT or SO(10) SUSY-GUT

$$\Gamma(l_1 \to l_2\gamma) = \frac{\alpha G_F^2 m_{l_1}^5}{2048\pi^4}(|D_R|^2 + |D_L|^2)$$

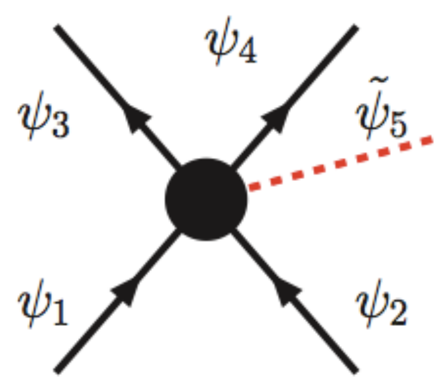
$$10^{-14} < B(\mu^+ \to e^+\gamma) < 10^{-11}$$

an experimental evidence: a clear signature of New Physics

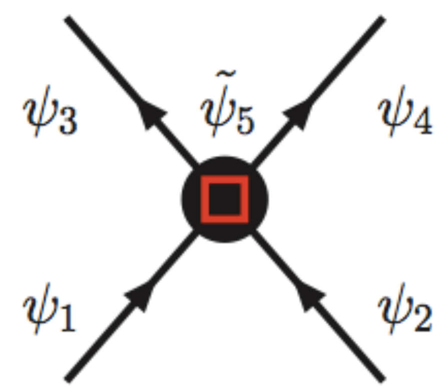
The role of low energy physics in the LHC era

Rare decay searches as a complementary way to unveil BSM physics and explore much higher energy scale w.r.t. what can be done at the high-energy frontiers

- Direct/indirect production of BSM particles



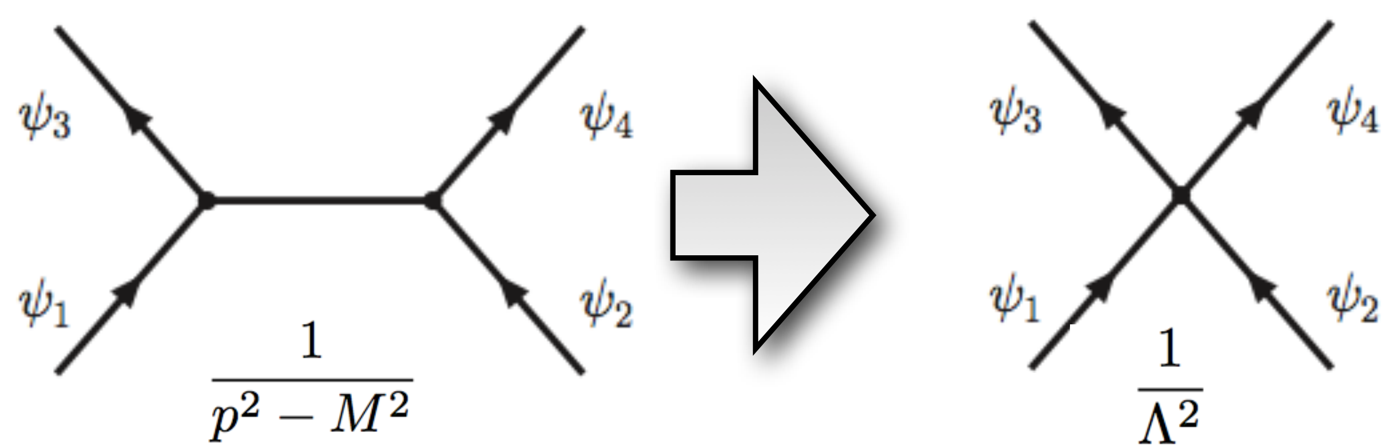
- Real BSM particles produced in the final state
- Energy frontier (LHC)



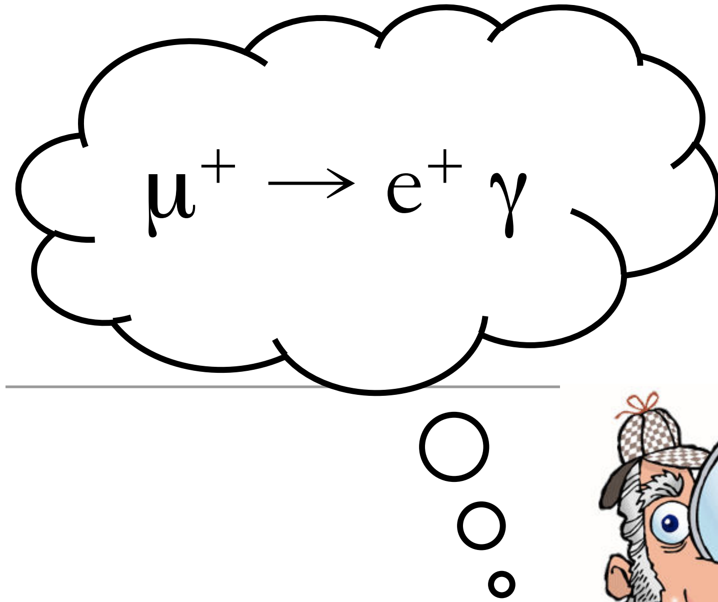
- Virtual BSM particles produced in loops
- Precision and intensity frontier

- Effective field theory approach

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

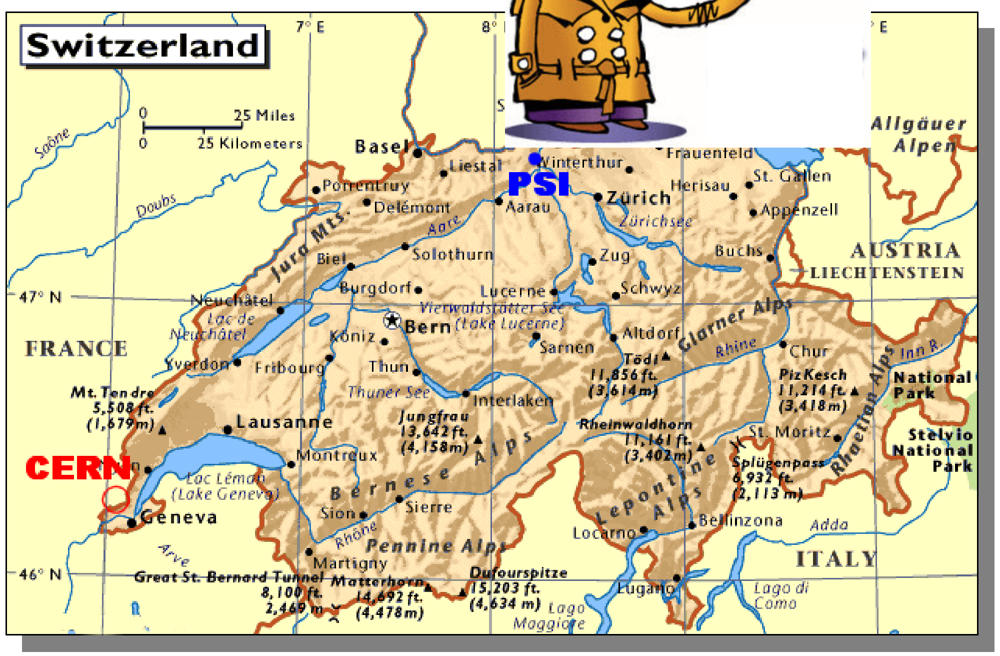


- L_{eff} is in terms of inverse powers of heavy scale



Favorite place: the Paul Scherrer Institute

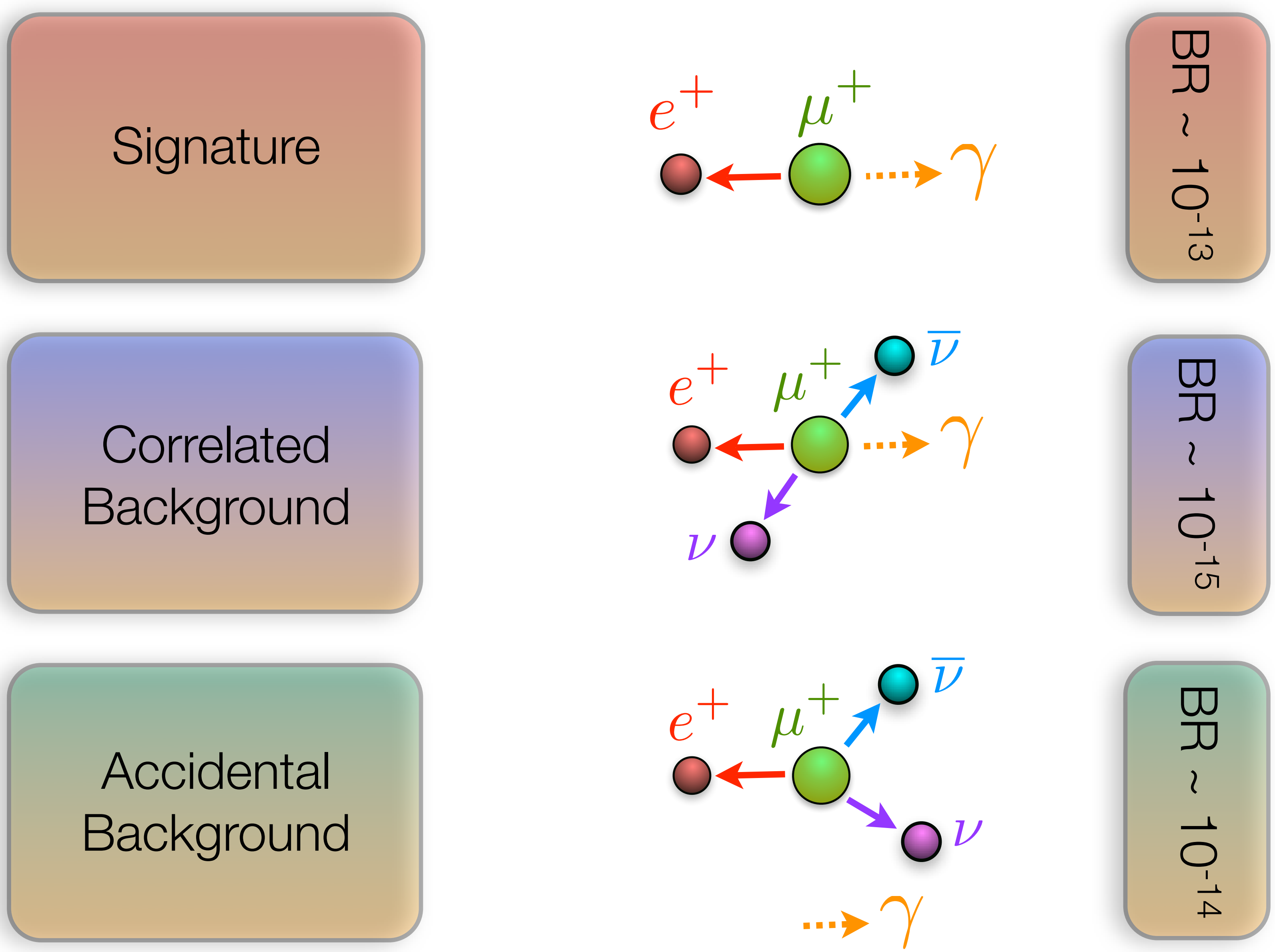
- The most intense continuous positive (surface) muon beam at low momentum (28 MeV/c)
  - **up to few x 10^8 muon/s**
- The best choice for experiments like MEGII looking for rare decays with coincident particles in the final state



1.2 MW PROTON CYCLOTRON

The MEG experiment

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- **Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events**

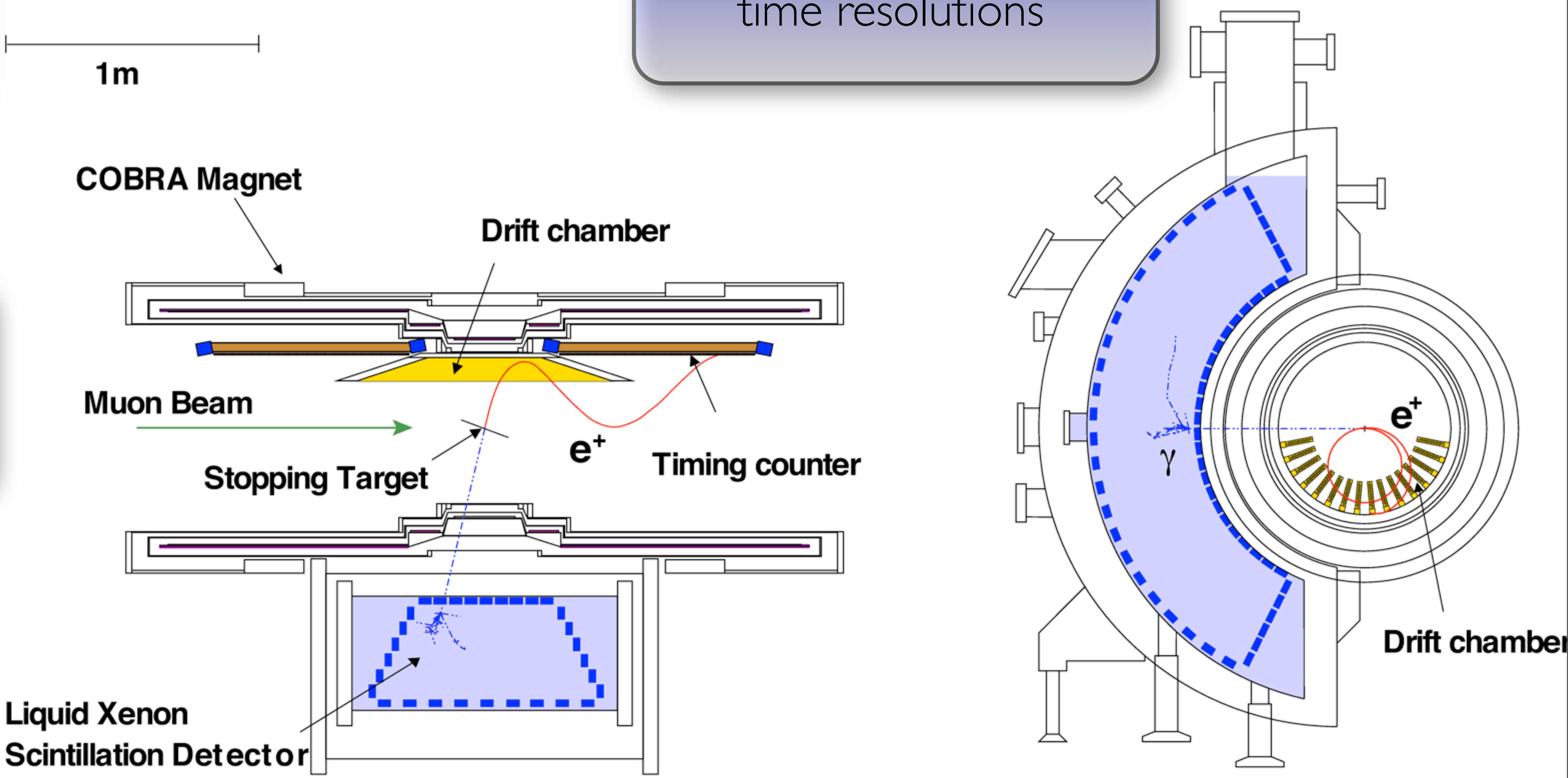


Experimental set-up

The most intense DC muon beam

Positron Very precise momentum and time resolutions

Gamma High energy and time resolutions



High efficiency event selection and frequency signal digitization

Complementary calibration and monitoring methods

How the sensitivy can be pushed down?

high statistics

- More sensitive to the signal...

$$\text{SES} = \frac{1}{R \times T \times A_g \times \boldsymbol{\varepsilon}(e^+) \times \boldsymbol{\varepsilon}\,(\text{gamma}) \times \boldsymbol{\varepsilon}(\text{TRG}) \times \boldsymbol{\varepsilon}(\text{sel})}$$

beam rate
acquisition time
geometrical acceptance
detector efficiency
selection efficiency

high resolutions

- More effective on rejecting the background...

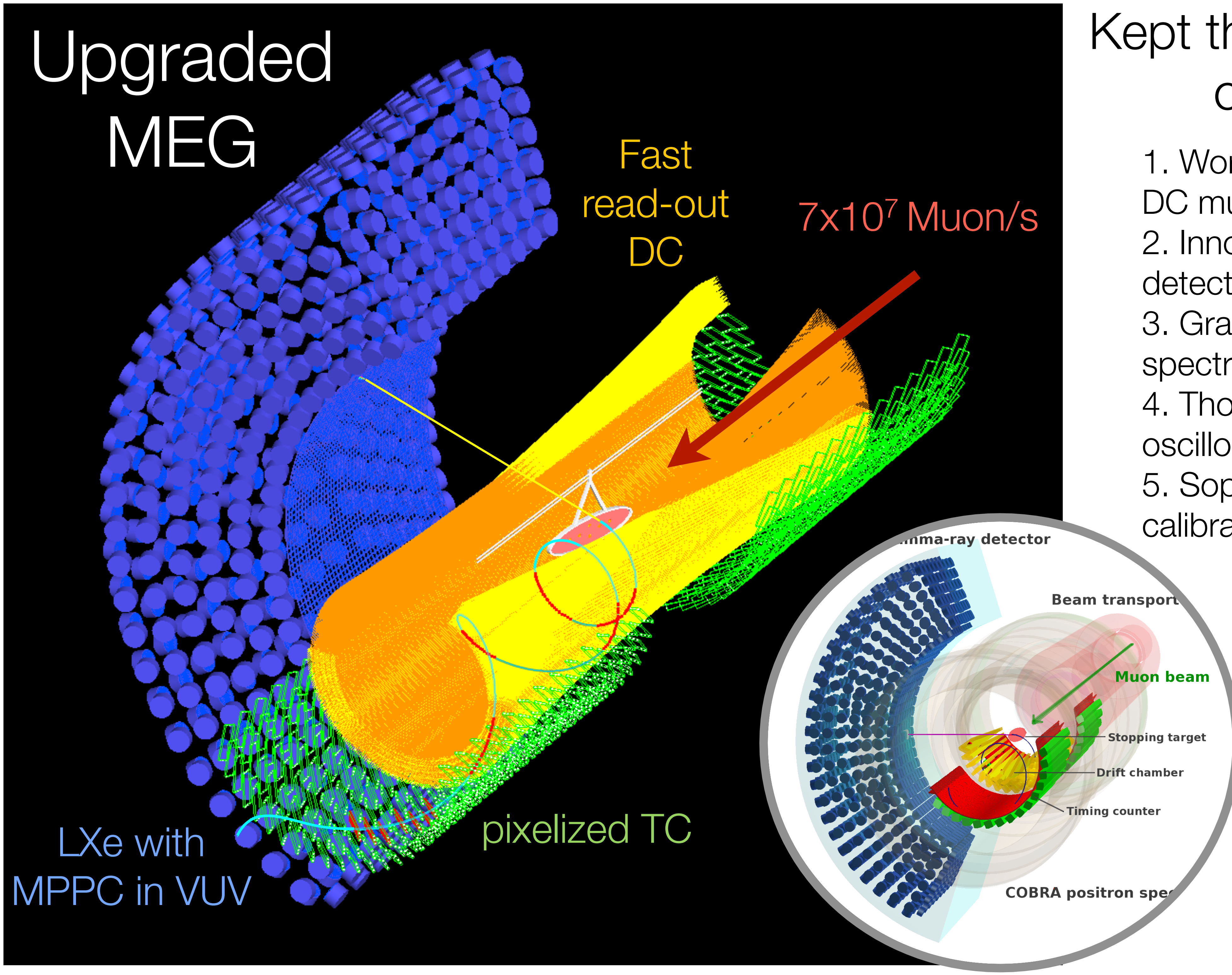
$$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2$$

momentum resolution
Energy resolution
Relative timing resolution
Relative angular resolution

Towards and upgrade

- Higher beam intensity $7x10^7$ mu/s ($3x10^7$ mu/s)
  - all detector should be able to sustain that rate
- Higher detector efficiency
  - Chamber trasparency towards TC 80% (40%)
  - LXe detector 75% (65%)
- Better signal selection and background rejection
  - higher resolution
  - pile-up rejection

MEGII vs MEG



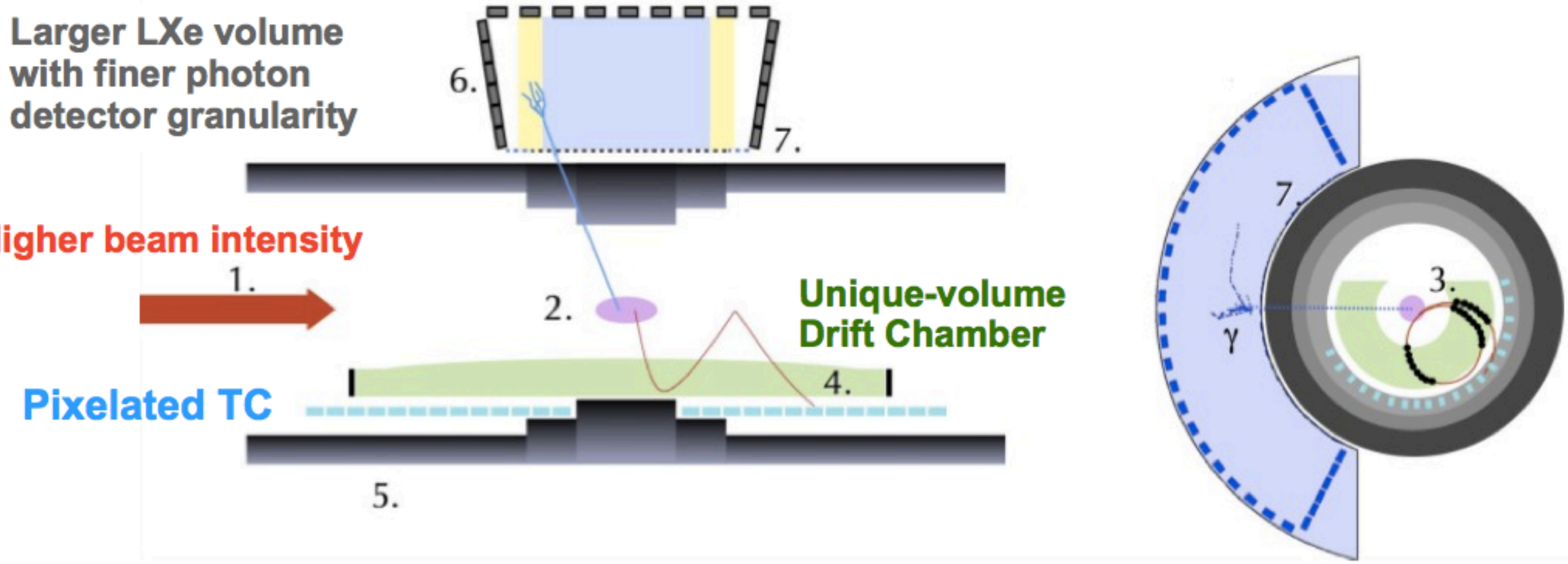
Kept the key elements of MEG

1. World's most intense DC muon beam @ PSI
2. Innovative LXe γ-ray detector
3. Gradient B-field e^+-spectrometer
4. Thousends virtual oscilloscopes (DAQ)
5. Sophisticated calibration methods

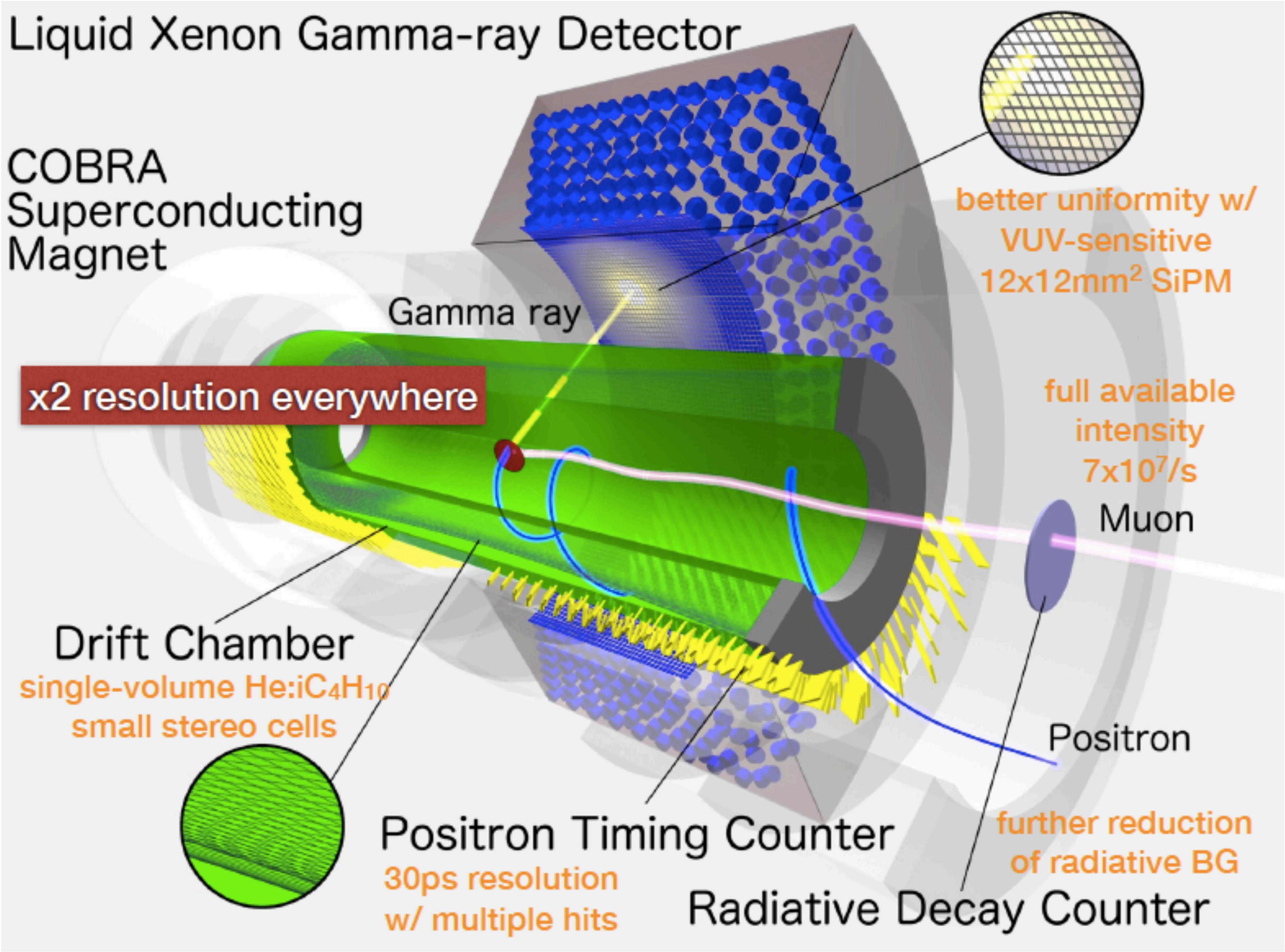
MEG Now

The MEGII experiment

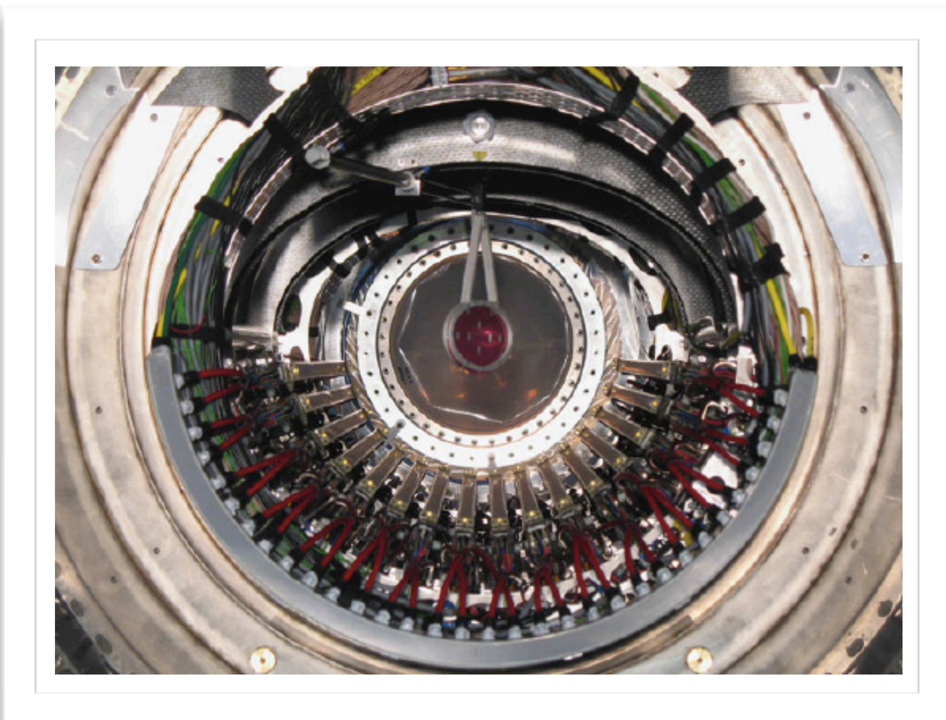
- An upgrade of MEG, aiming at a sensitivity improvement of one order of magnitude (**down to 5 x 10^{-14}**) approved by PSI and funding agencies is ongoing

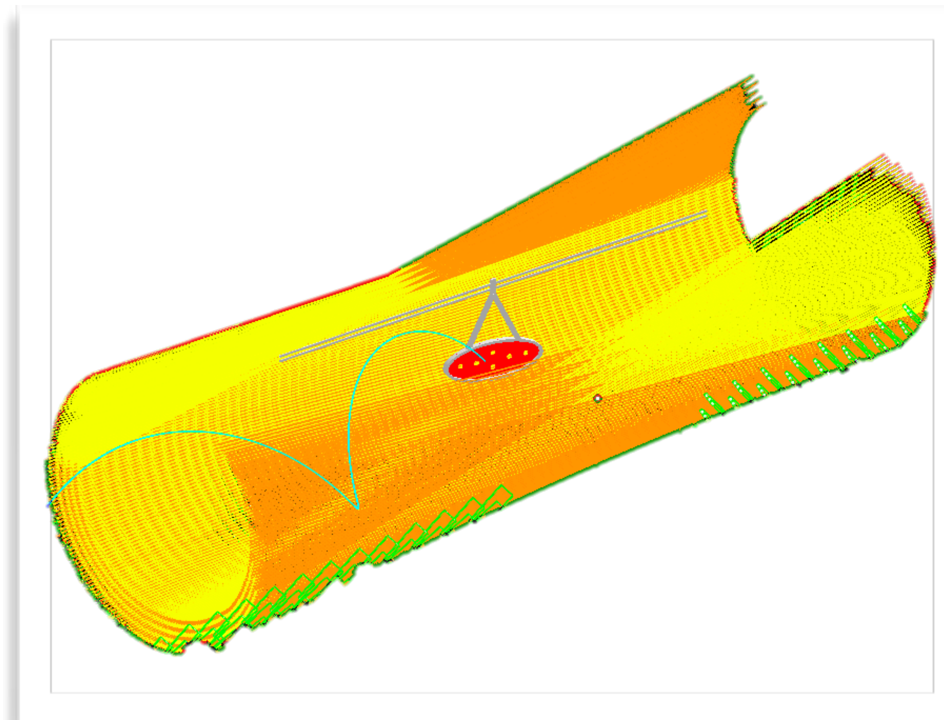


The MEGII experiment -3D view



The new re-designed spectrometer: the single volume chamber

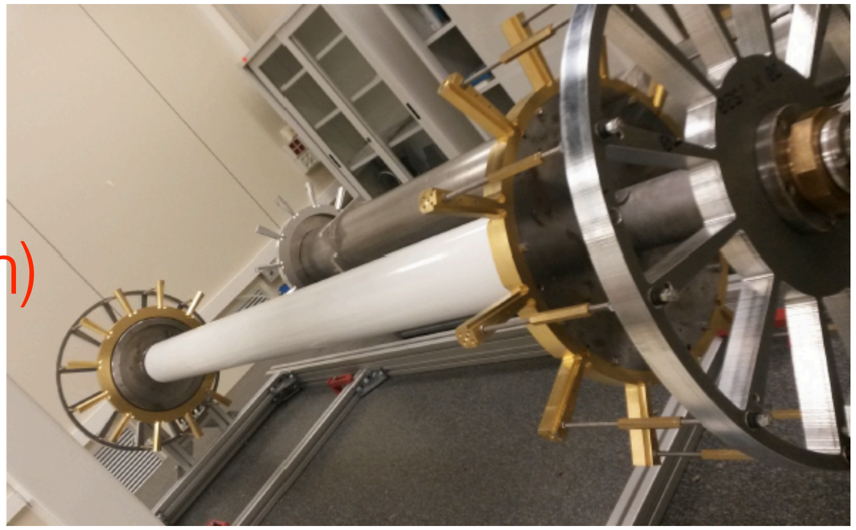




- High granularity/Increased number of hits per track
- Less material (helium:isobutane = 85:15, $2\text{x}10^{-3}\, X_0$)
    - better momentum and angular resolutions
- High trasparency towards the TC

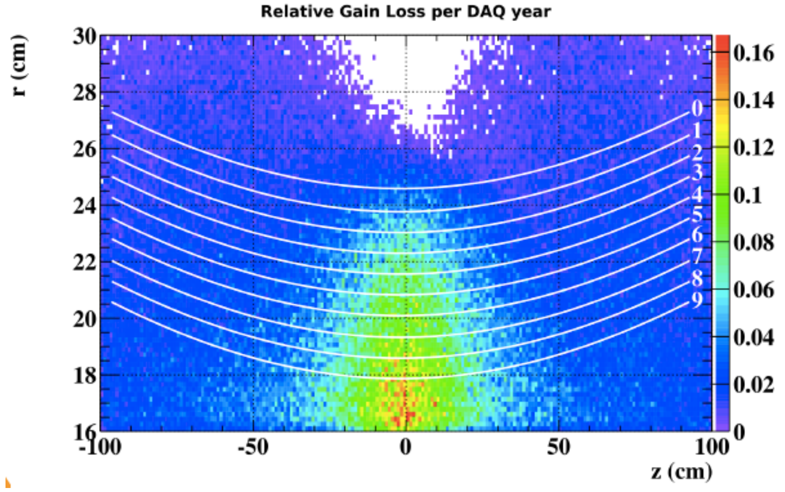
The new re-designed spectrometer: the single volume chamber (in numbers)

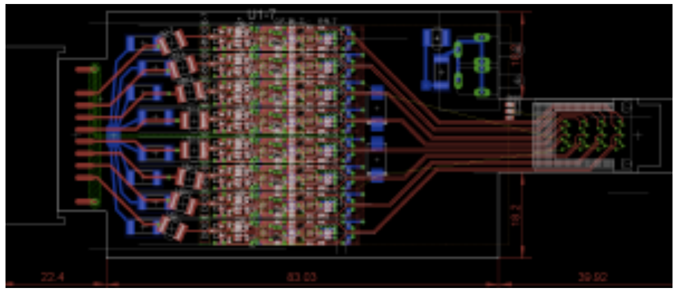
- Positron momentum and direction measurement



- Unique volume gas chamber
  - Single hit resolution 50 ÷ 100 μm in r (250 μm)
  - Momentum resolution ~130 KeV (310 KeV)
  - Angular resolution ~5 mrad (8-11 mrad)
  - Trasparency towards TC ~80 % (40%)
- Target (default solution)
  - Thinner passive target 140 um (205 um)

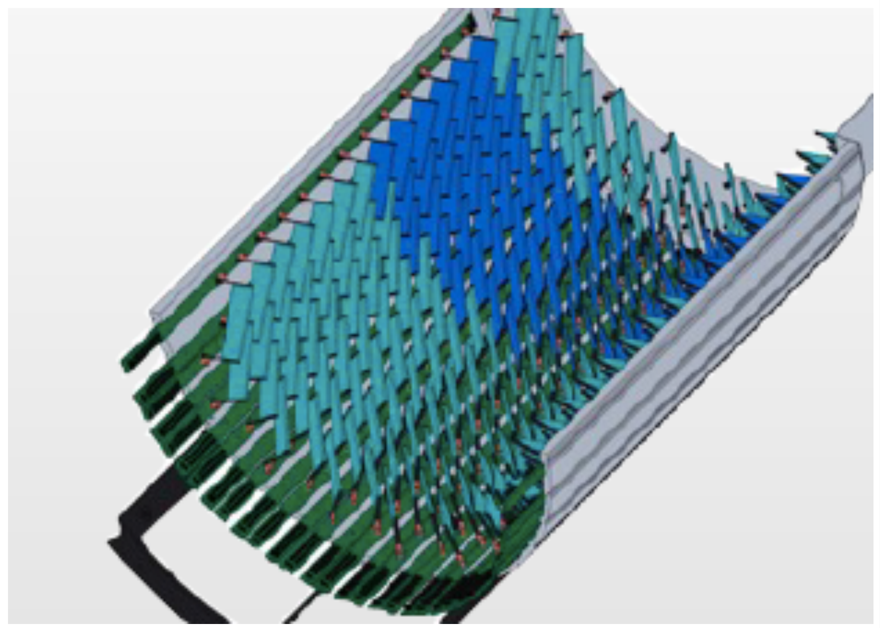
Ageing tests:





Front End Electronics: 3dB bandwidth around 1GHz

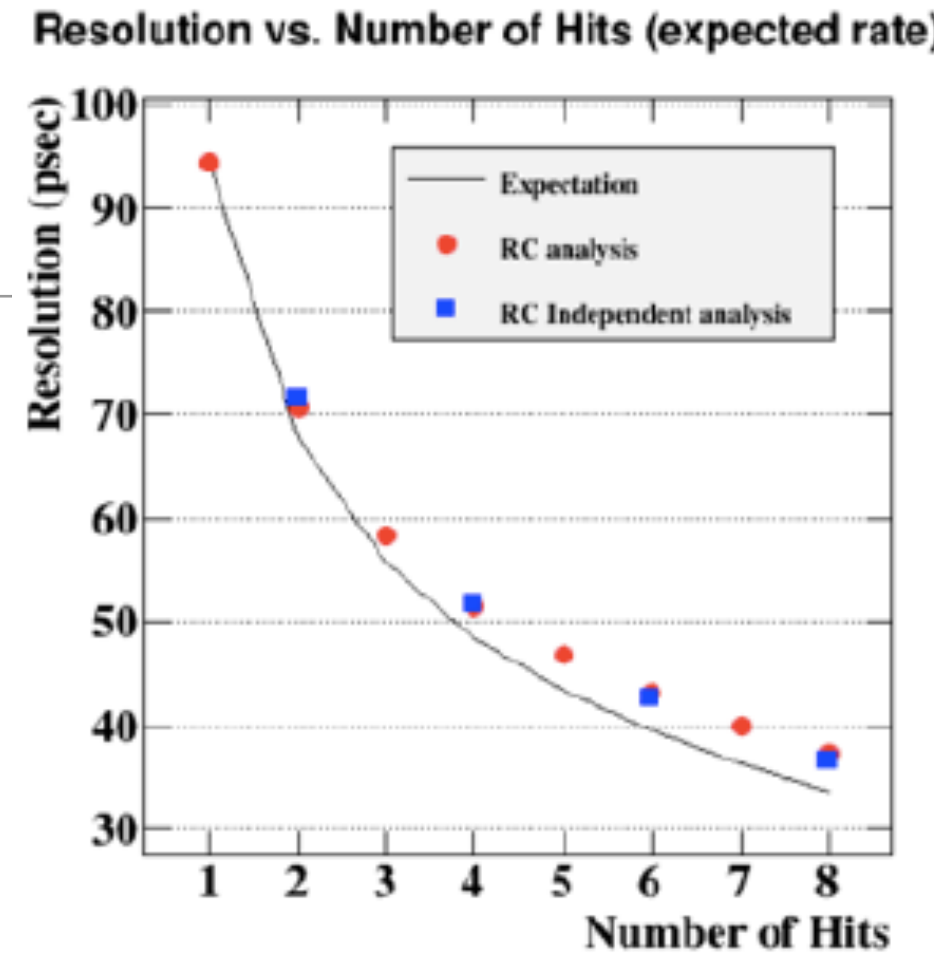
A new re-designed spectrometer: the pixelized Timing Counter

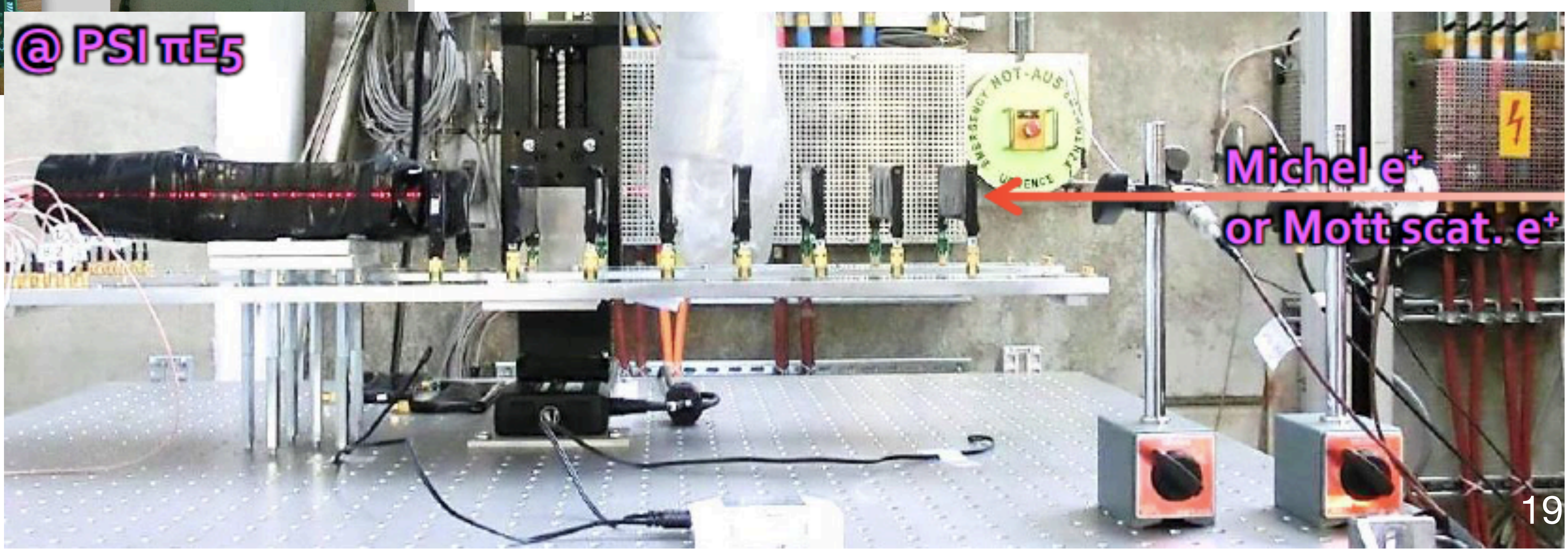


- Higher granularity: 2 x 256 of scintillator plates (120 x 50 x 5 mm^3) readout by SiPMs
- Improved timing resolution (with multiple hits): from 70 ps to 35 ps
- Less multiple scattering and pile-up

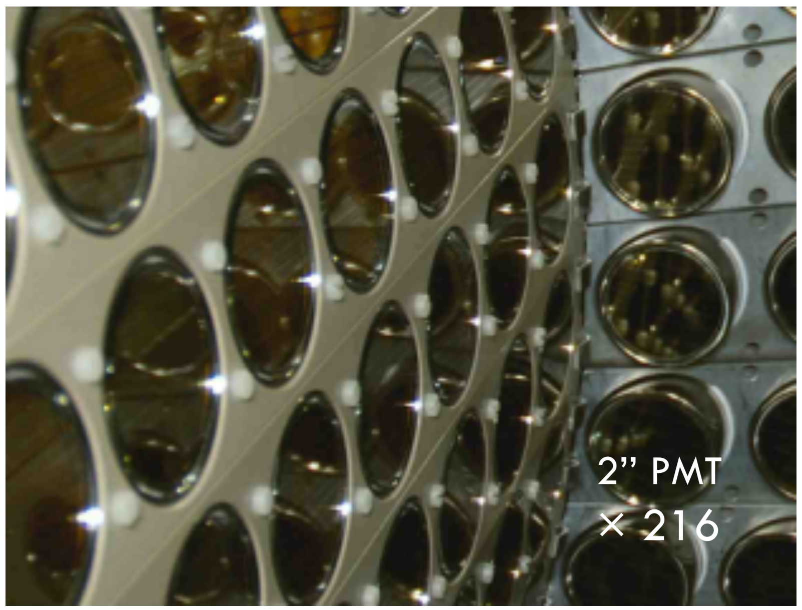
A new re-designed spectrometer: the pixelized Timing Counter (in numbers)

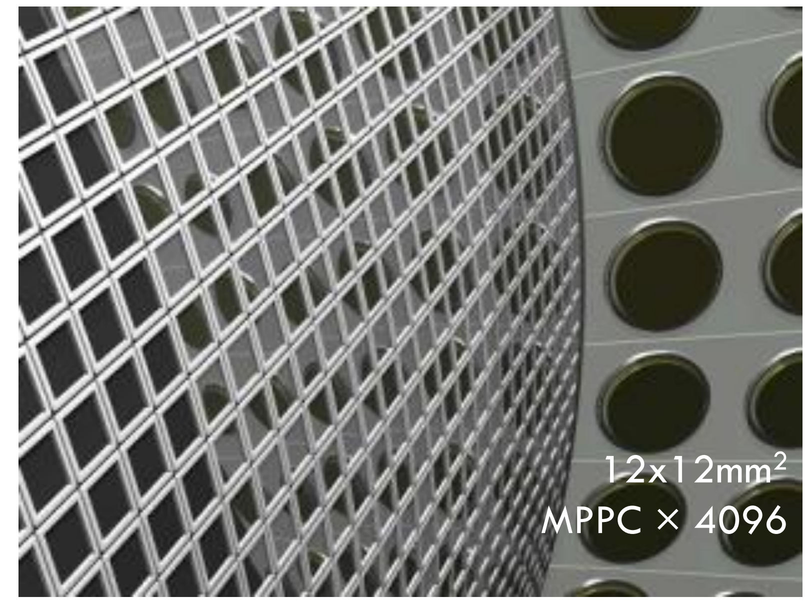
Timing resolution:
35 ps at the MEGII rate conditions





The upgraded Liquid Xenon calorimeter





- Replacement of the inner face PMT (2") with SiPM (12x12 mm^2)
  - Higher granularity and uniformity
    - Increased energy, timing and position resolutions
  - Higher pile-up rejection capability
  - Higher detection efficiency
- Increased acceptance

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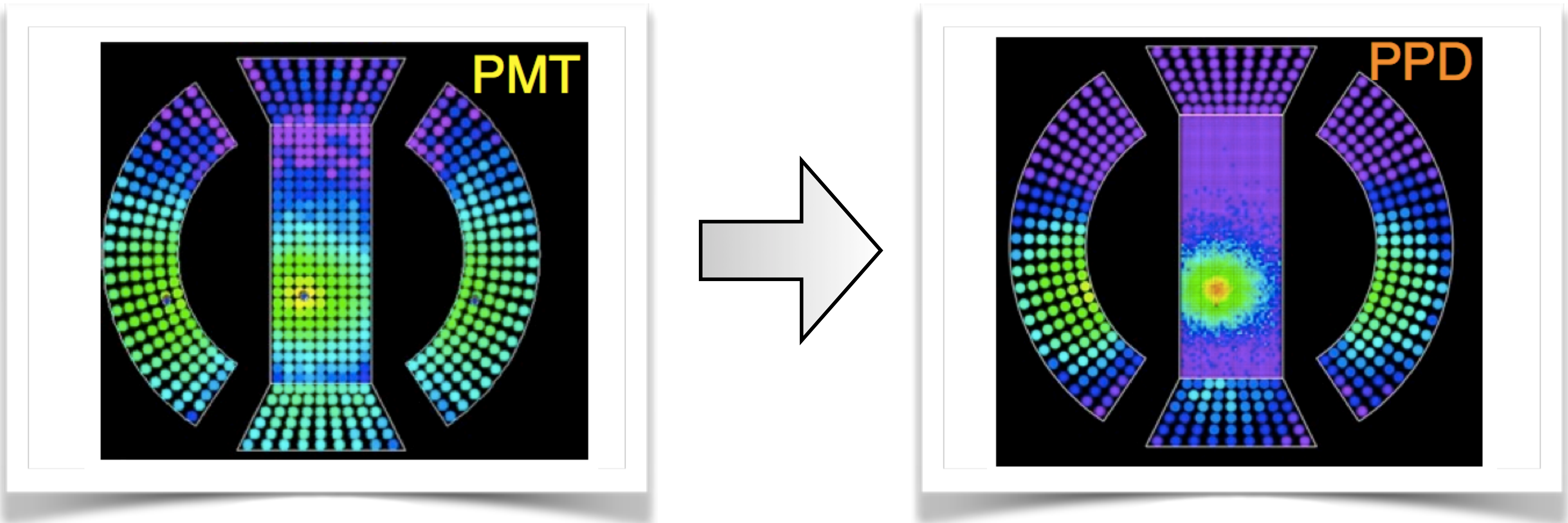

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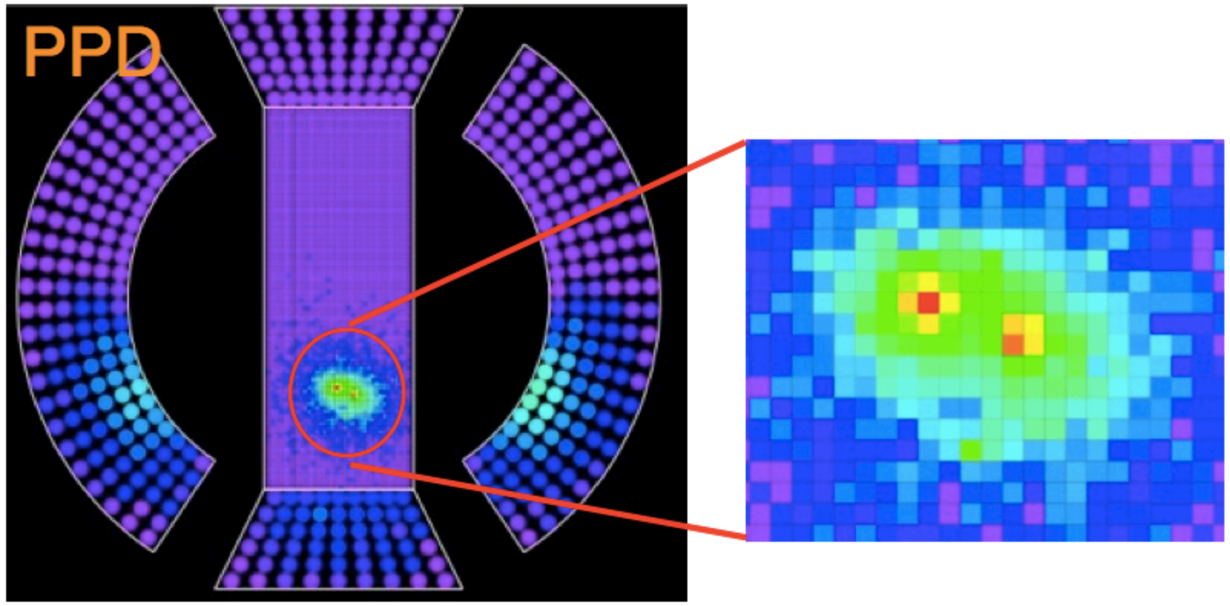
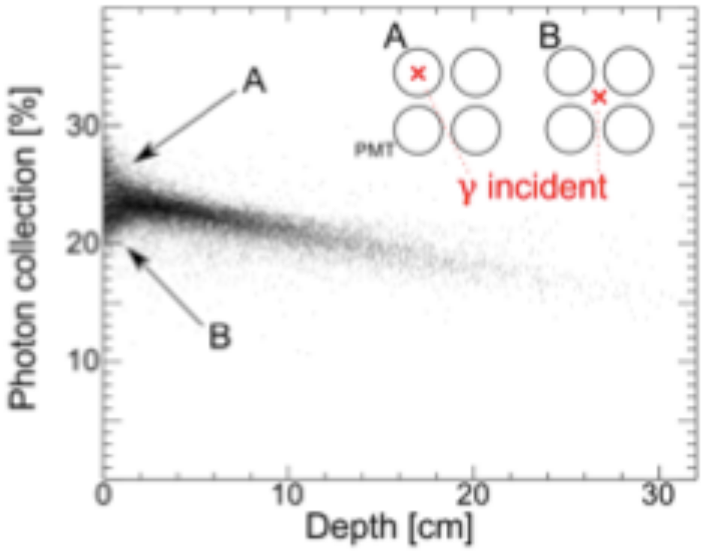
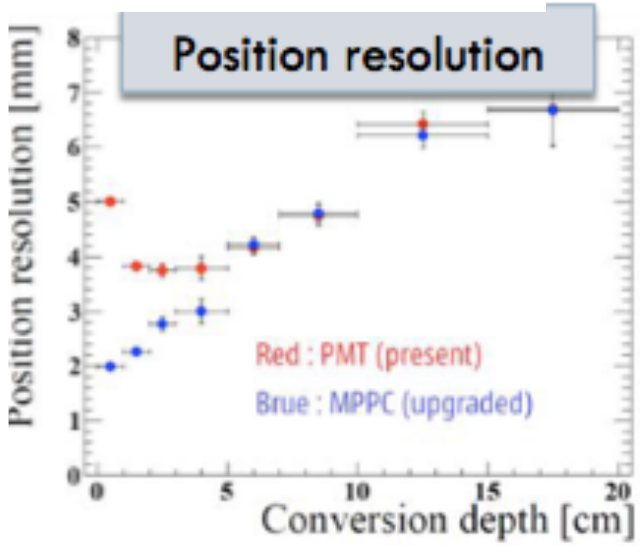
The upgraded Liquid Xenon calorimeter (in numbers)

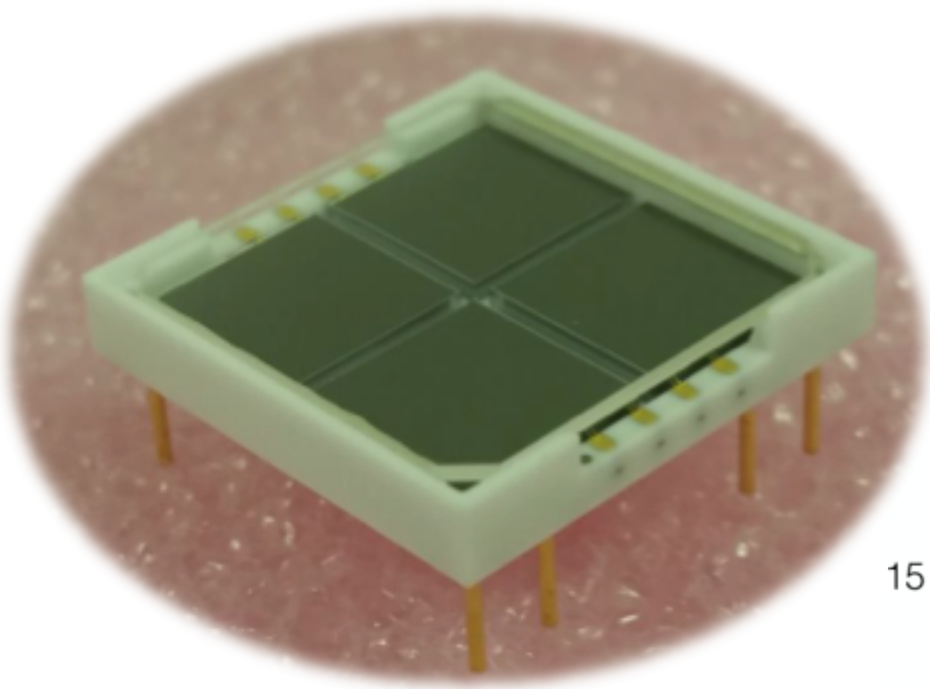
Resolution	MEGI	MEGII
u (mm)	5	2.4
v (mm)	5	2.2
w (mm)	6	3.1
E_γ (w<2cm)	2.4%	1.1%
E_γ (w>2cm)	1.7%	1.0%
t_γ (ps)	67	60





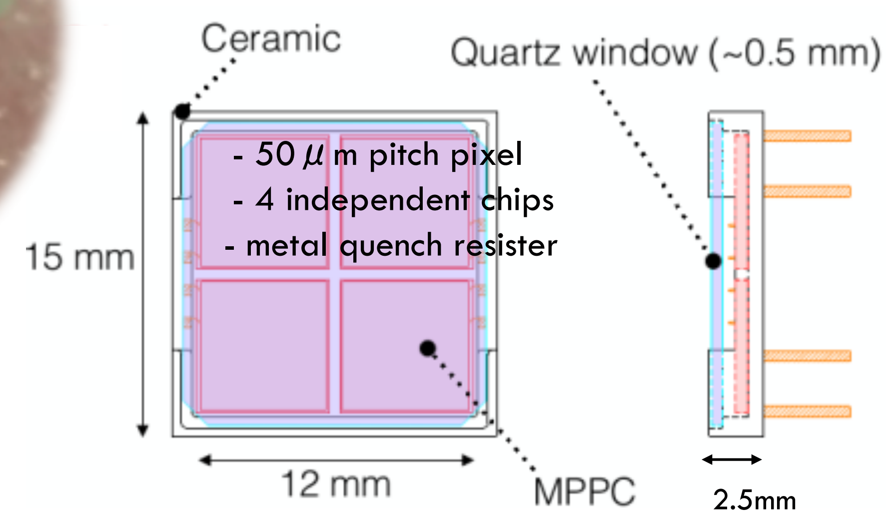


R&D in collaboration with Hamamatsu: VUV-sensitive SiPM (MPPC using Hamamatsu convention)



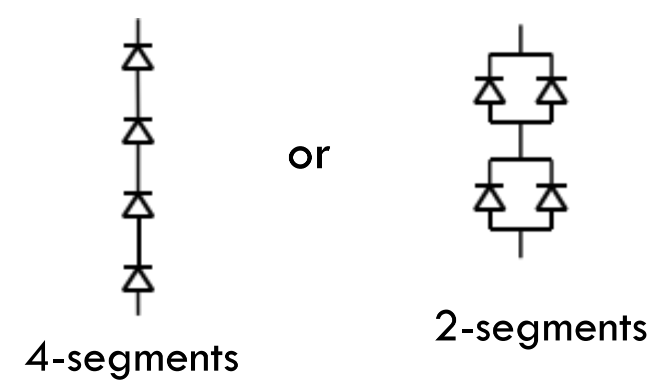
We have successfully developed **VUV-MPPC** in collaboration with Hamamatsu Photonics. K.K.

- **Sensitive to VUV-light**
  → Protection coating is removed, VUV-transparent quartz window is used for protection.



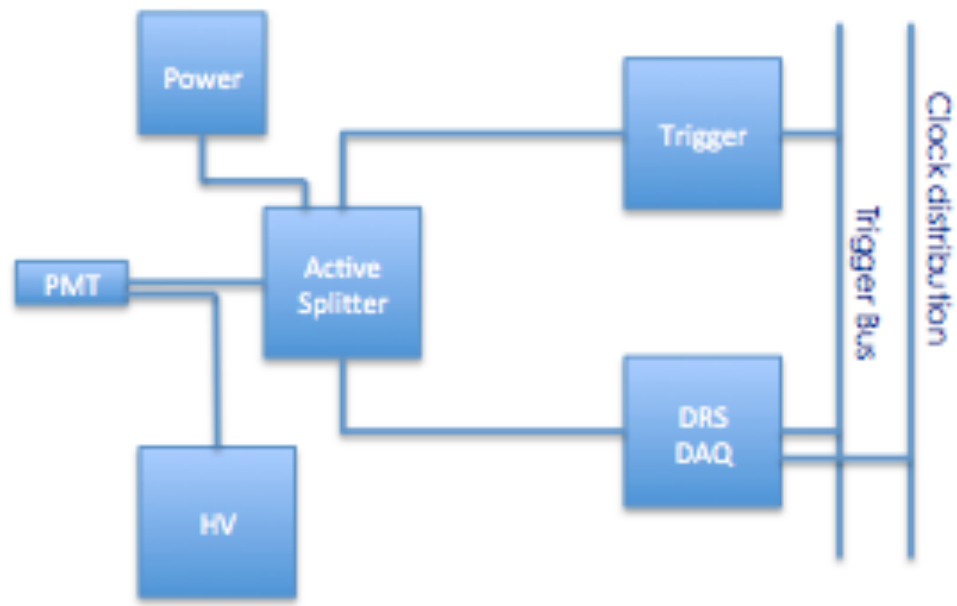
Hamamatsu S10943-3186(X)

- **Large area (12x12 mm^2)**
  → signal tail become long due to large capacitance.
  →Reduce capacitance by connecting 4 chips in series.



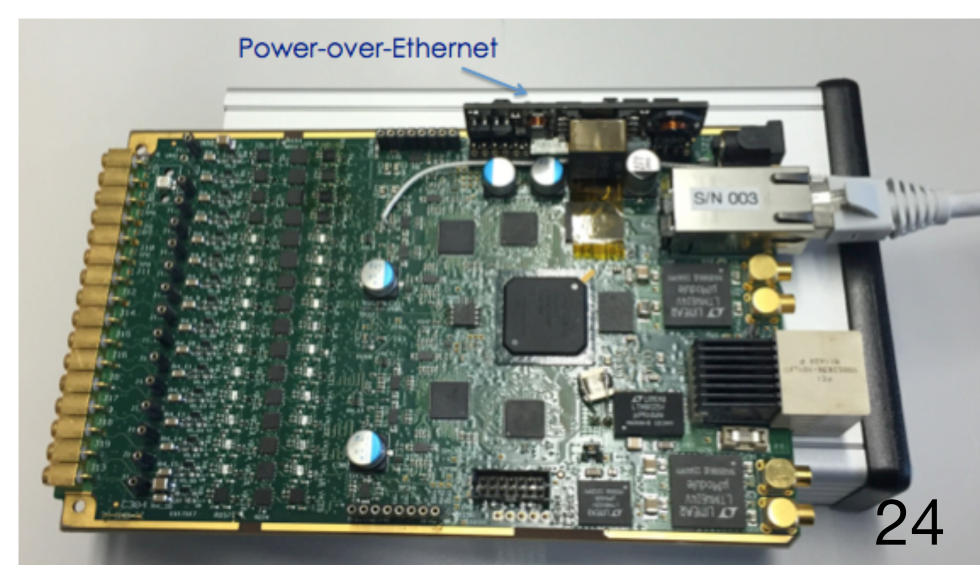
The new waveDAQ

MEG Experiment 1999-2013
- Separated DAQ & Trigger
- 3000 Channels DRS4 (0.8 GSPS / 1.6 GSPS)
- 1000 Channels Trigger (100 MSPS)
- 5 Racks



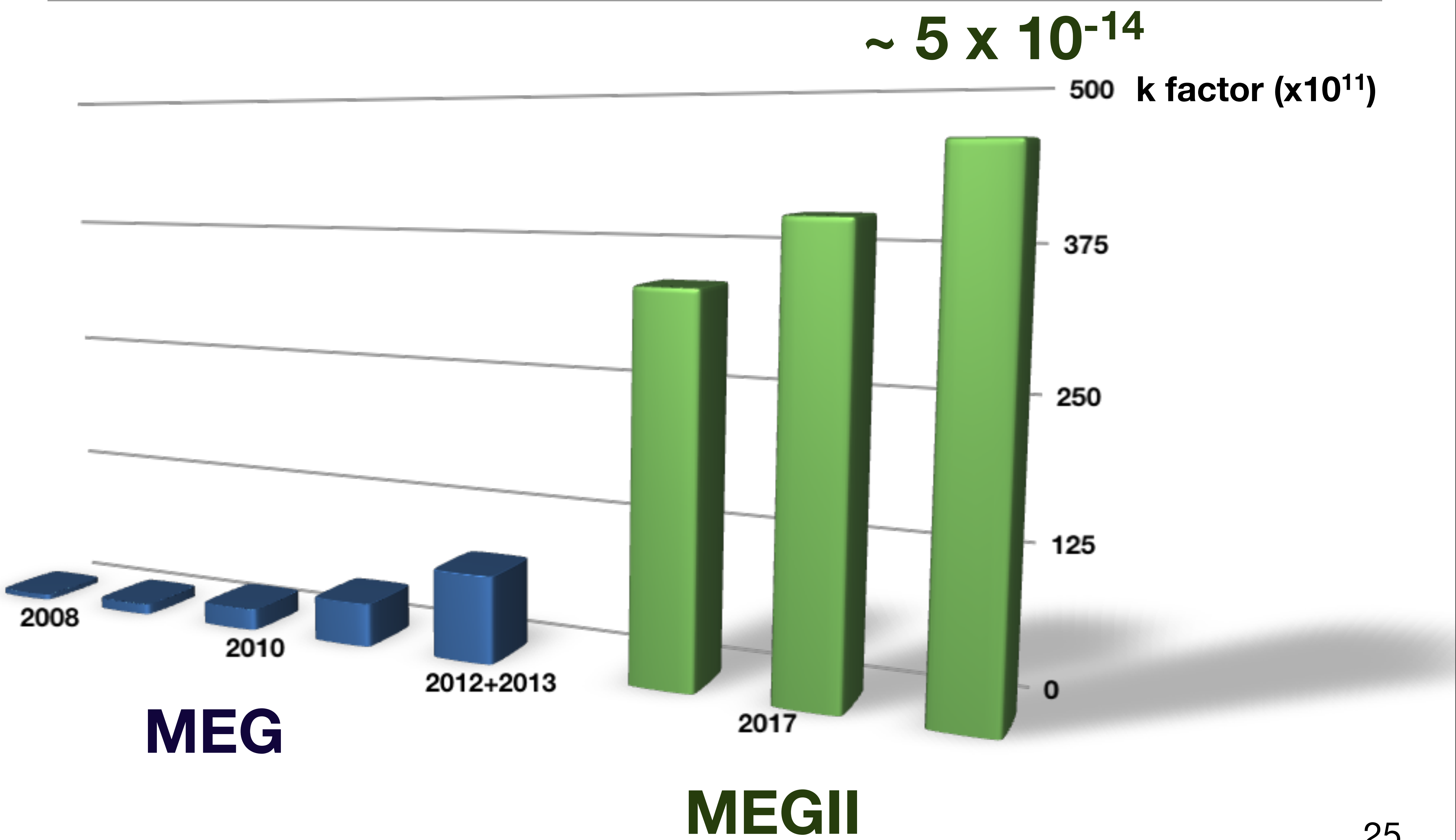
MEG II Experiment 2014-
- 9000 Channels
- Same rack space
  ➔Combine DAQ & Trigger

WaveDream standalone:

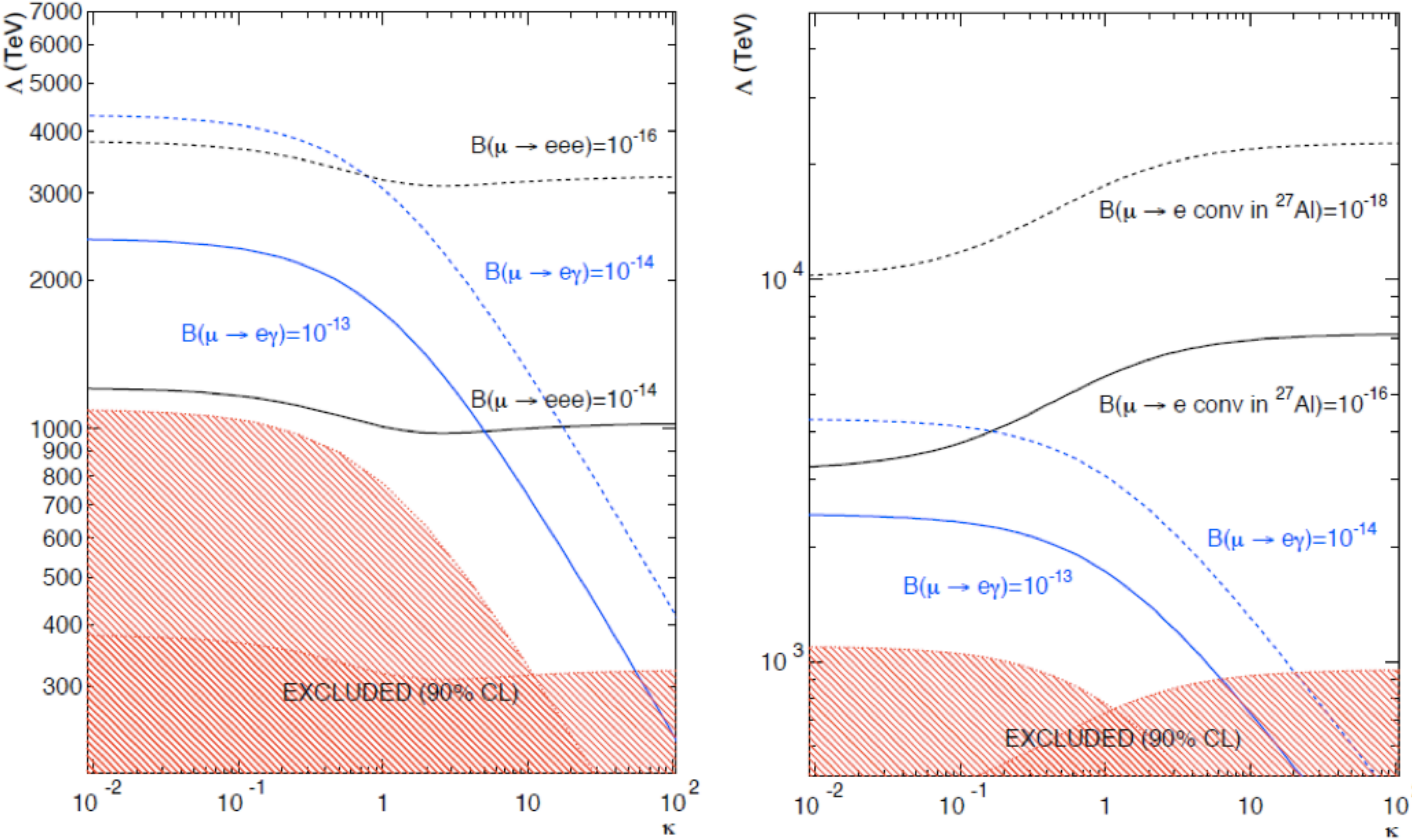


- Based on the DRS4 chip
- Waveform Sampling: 5 GS/s
- SiPM power supply included

Where we will be



cLFV search: complementry approch



Summary

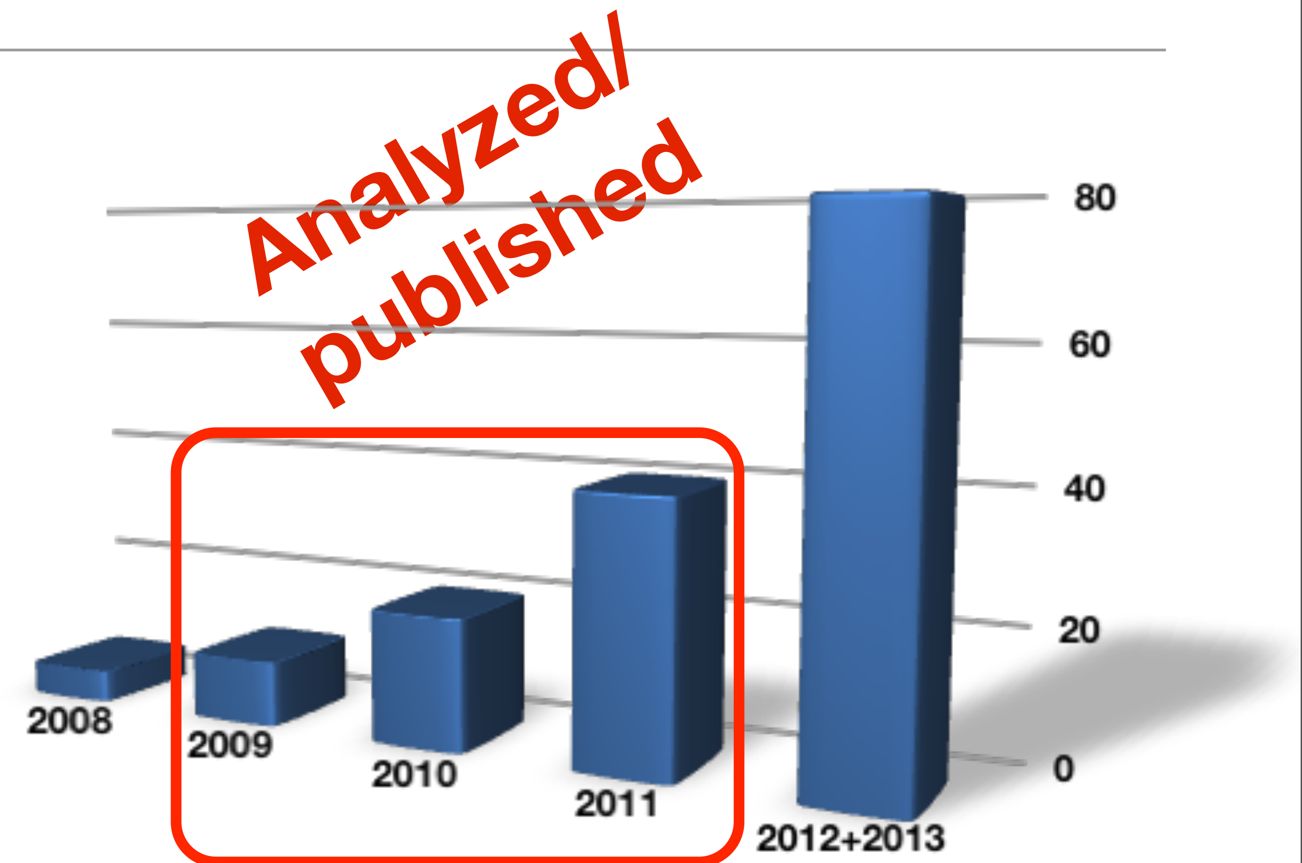
- MEG completed successfully
  - data sample 2009-2011: best upper limit of any particle decay
    $B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}$
  - data sample 2009-2013: final result just around the corner
- MEGII preparation in good shape
  - improved sensitivity by a factor of 10 reaching **5×10^{-14}**

- Unique DC muon beam at PSI
  - high intensity **$O(10^8)$ muon$^+$/s**
  - feasibility studies ongoing to increase it, aiming at **$O(10^{10})$ muon$^+$/s**

Back-up

Detector performance and Data sample

	Resolutions (σ)
Gamma Energy (%)	1.7(depth>2cm), 2.4
Gamma Timing (psec)	67
Gamma Position (mm)	5(u,v), 6(w)
Gamma Efficiency (%)	63
Positron Momentum (KeV)	305 (core = 85%)
Positron Timing (psec)	108
Positron Angles (mrad)	7.5 (Φ), 10.6 (θ)
Positron Efficiency (%)	40
Gamma-Positron Timing (psec)	127
Muon decay point (mm)	1.9 (z), 1.3 (y)



	μ stopped	sensitivity
2009+10	1.75×10^{14}	1.3×10^{-12}
2011	1.85×10^{14}	1.1×10^{-12}
2009+10+11	3.60×10^{14}	7.7×10^{-13}

Event selection

trigger MEG

$E_g > 40$ MeV & $|\Delta t_{eg}| < 10$ ns & $|\Delta\varphi| < 7.5^0$

pre-selected events

Al least 1 reconstructed track on DCHs

short relative time between LXe-TC

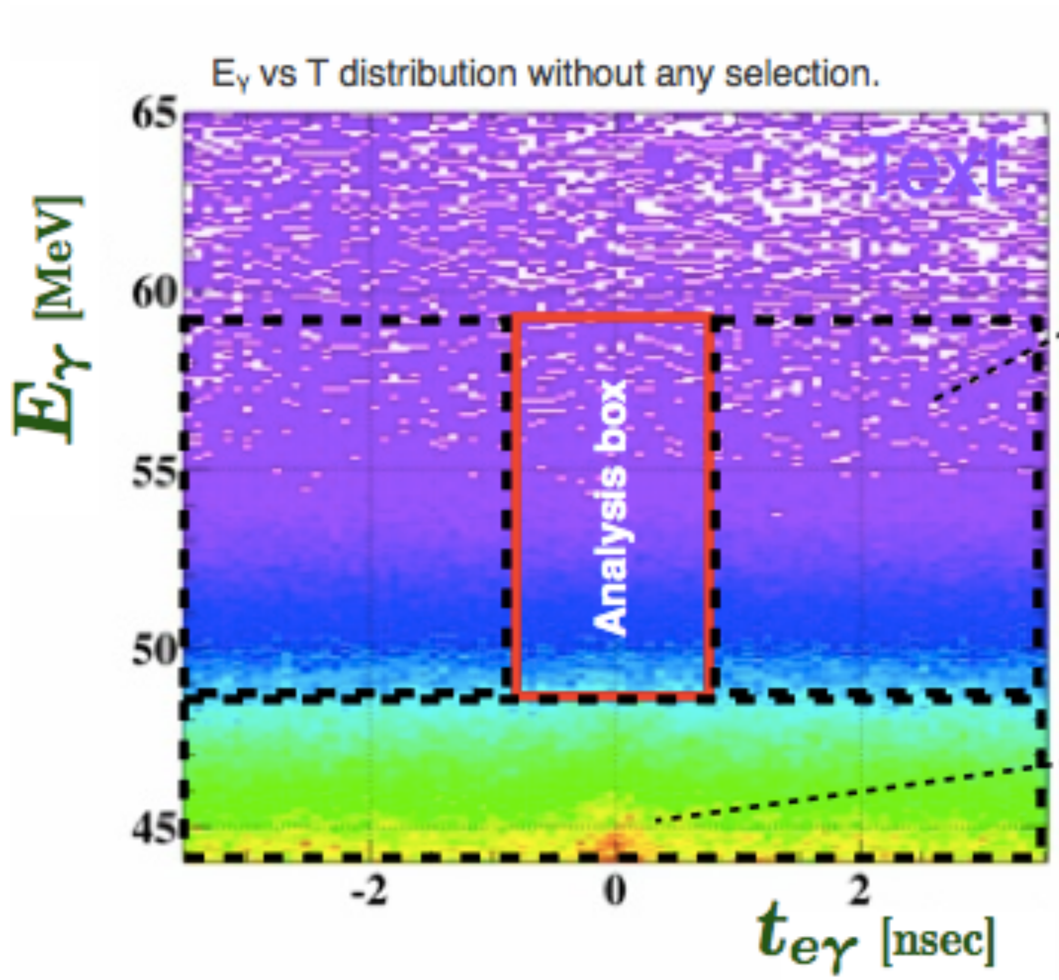
(~16% of the original sample)

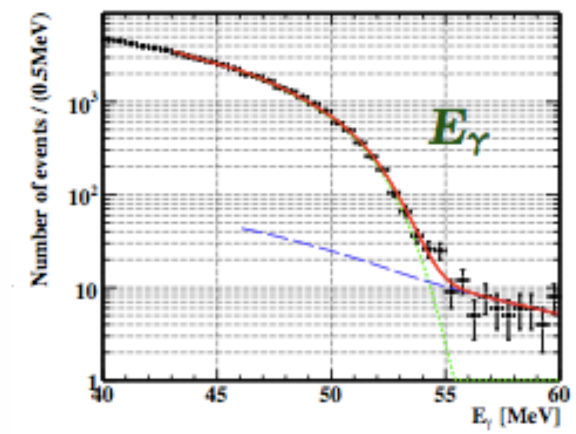
Side-boxes

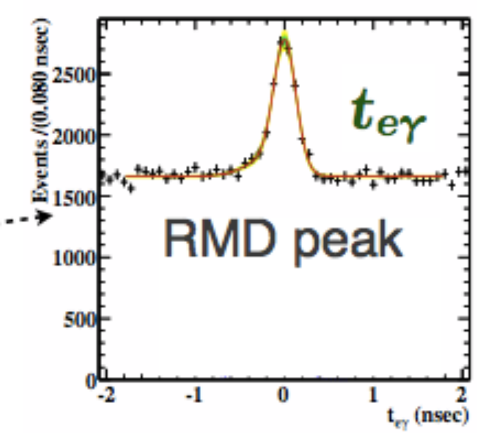
to study the background and to optimize the algorithm

Blind box

hidden events







RMD: radiative michel decay

$\mu^+ \rightarrow e^+ \nu\nu\gamma$

Phy. Rev. Lett. 110, 201801 (2013)

Summary of Results

(**) 90% C.L. upper limit averaged over pseudo-experiments based on null-signal hypothesis with expected rates of RMD and BG

	Best fit	**Upper Limit (90% C.L.)**	**Sensitivity** **
2009+10	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009+10+11	-0.06×10^{-12}	5.7×10^{-13}	7.7×10^{-13}

$B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}$ (all combined data) *

x4 more stringent than the previous upper limit
($B(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$ -MEG 2009-10)

x20 more stringent than the MEGA experiment result
($B(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11}$ -MEGA 2001)

Maximum Likelihood Analysis

- Analysis region: $48<E_\gamma<58$MeV, $50<E_e<56$MeV, $|\theta_{e\gamma}|<50$mrad, $|\Phi_{e\gamma}|<50$mrad, $|T_{e\gamma}|<0.7$ns
- Maximum likelihood analysis to estimate # of signal
  - Event-by-event PDF
    - gamma: position dependent resolutions
    - positron: per-event error matrix from Kalman filter

$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) = \frac{e^{-N}}{N_{\rm obs}!} e^{-\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{2\sigma^2_{\rm RMD}}} e^{-\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{2\sigma^2_{\rm BG}}} \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S(\vec{x}_i) + N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i)\right)$$

- Confidence interval of N_{sig} (or B)
  - Frequentist approach with profile likelihood ratio ordering

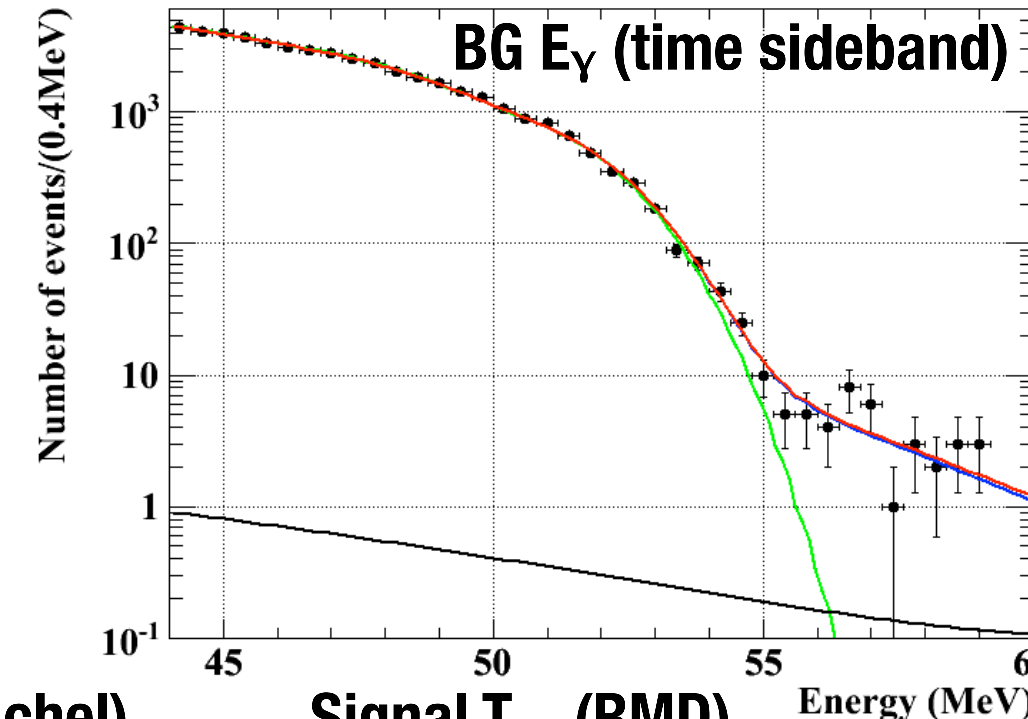
Probability Density Functions

- **Probability density functions (PDF)** for likelihood function are mostly extracted from **data**

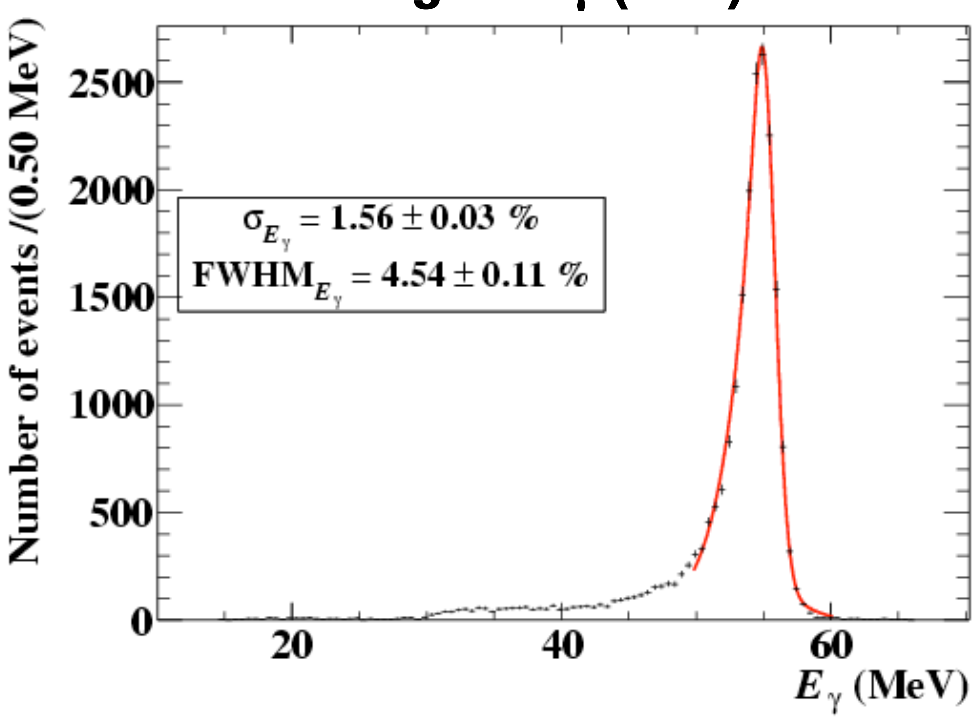
The signal PDF *S* is the product of the PDFs for Ee, θeγ, Φeγ,Teγ which are correlated variables, and the Eγ PDF

The RMD PDF *R* is the product of the same Teγ PDF as that of the signal and the PDF of the other four correlated observables, which is formed by folding the theoretical spectrum with the detector response functions

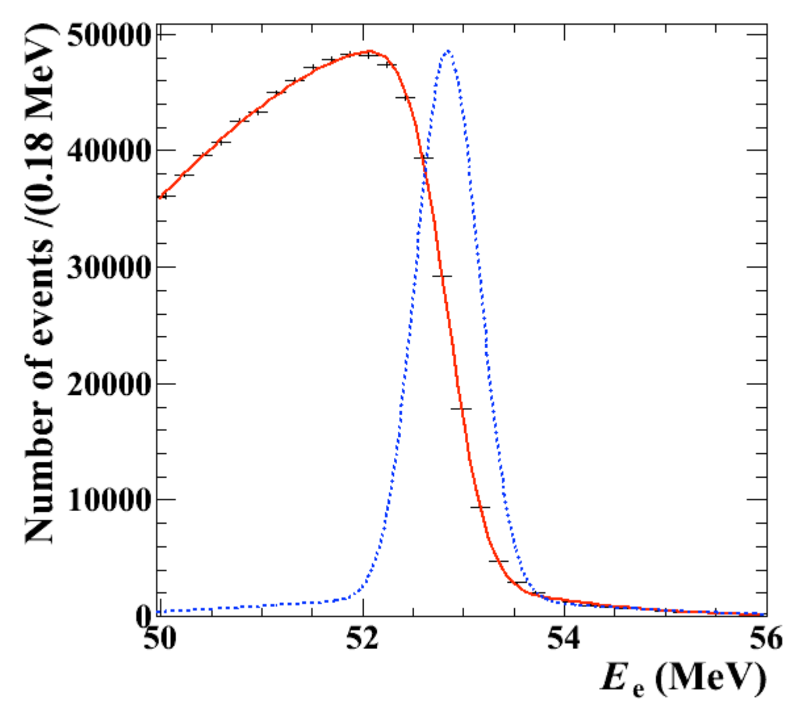
The BG PDF *B* is the product of the five PDFs, each of which is defined by the single background spectrum, precisely measured in the sidebands



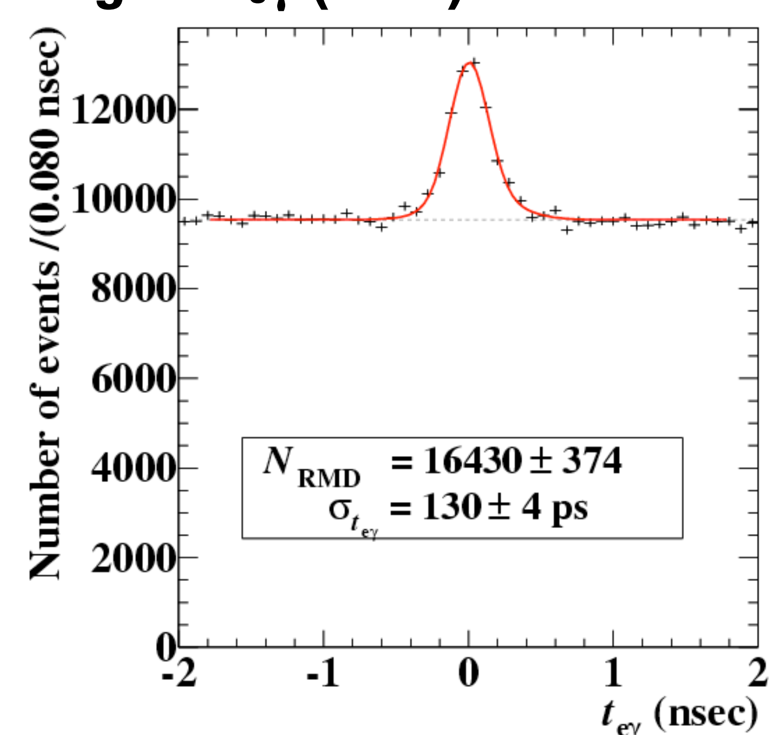
Signal Eγ (CEX)



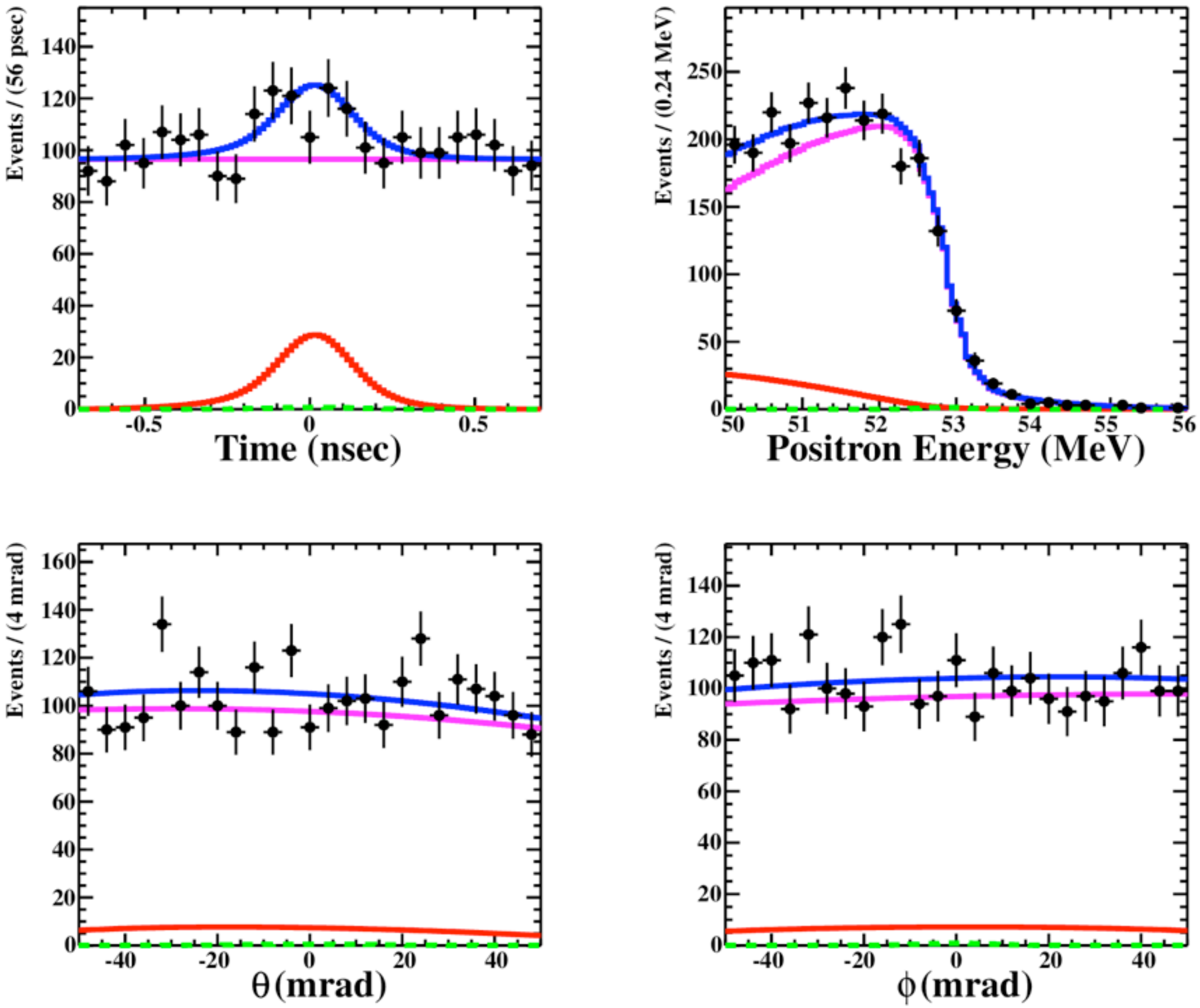
Signal Ee /BG (Michel)



Signal Teγ (RMD)



Likelihood Fit (2009-2011)

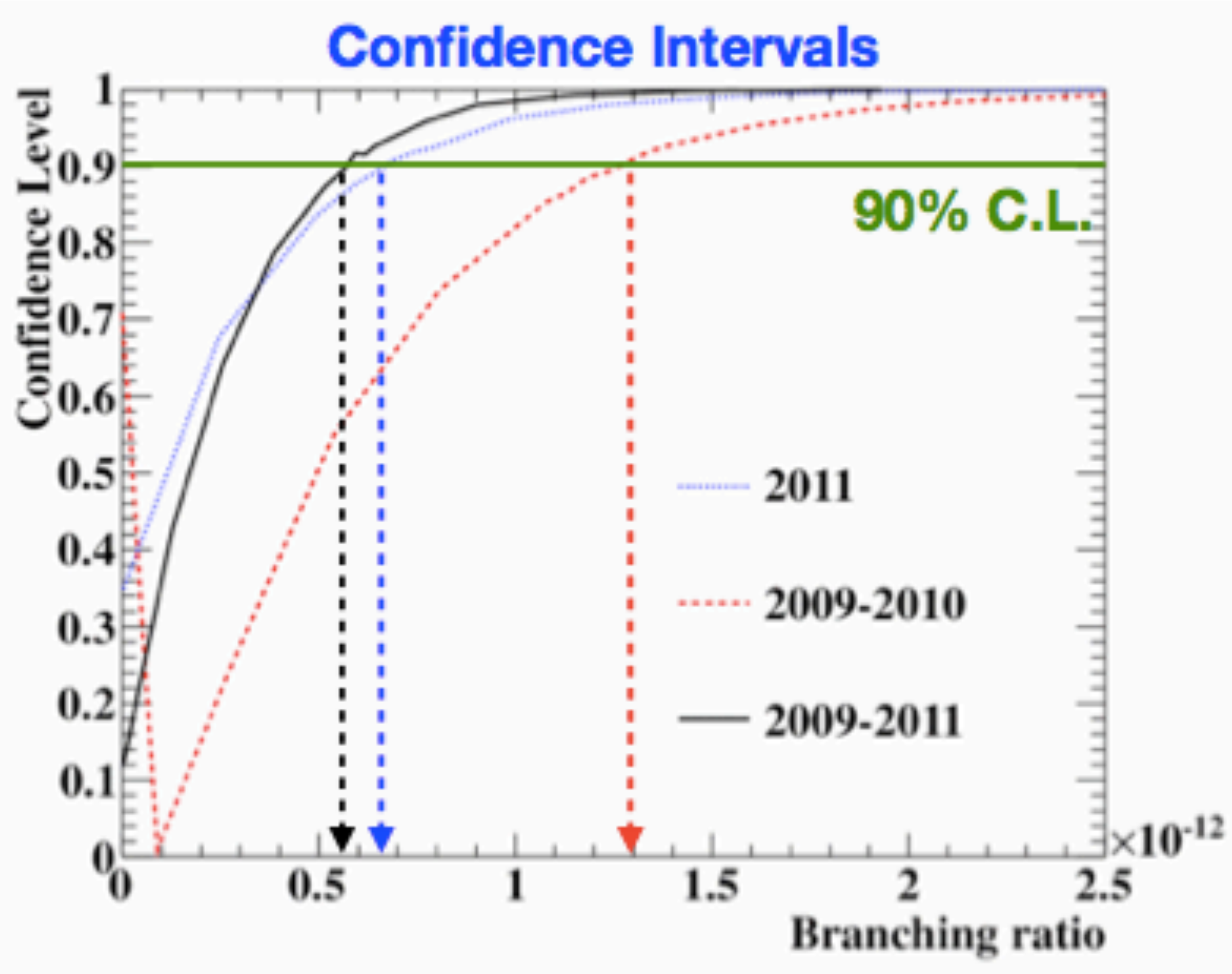


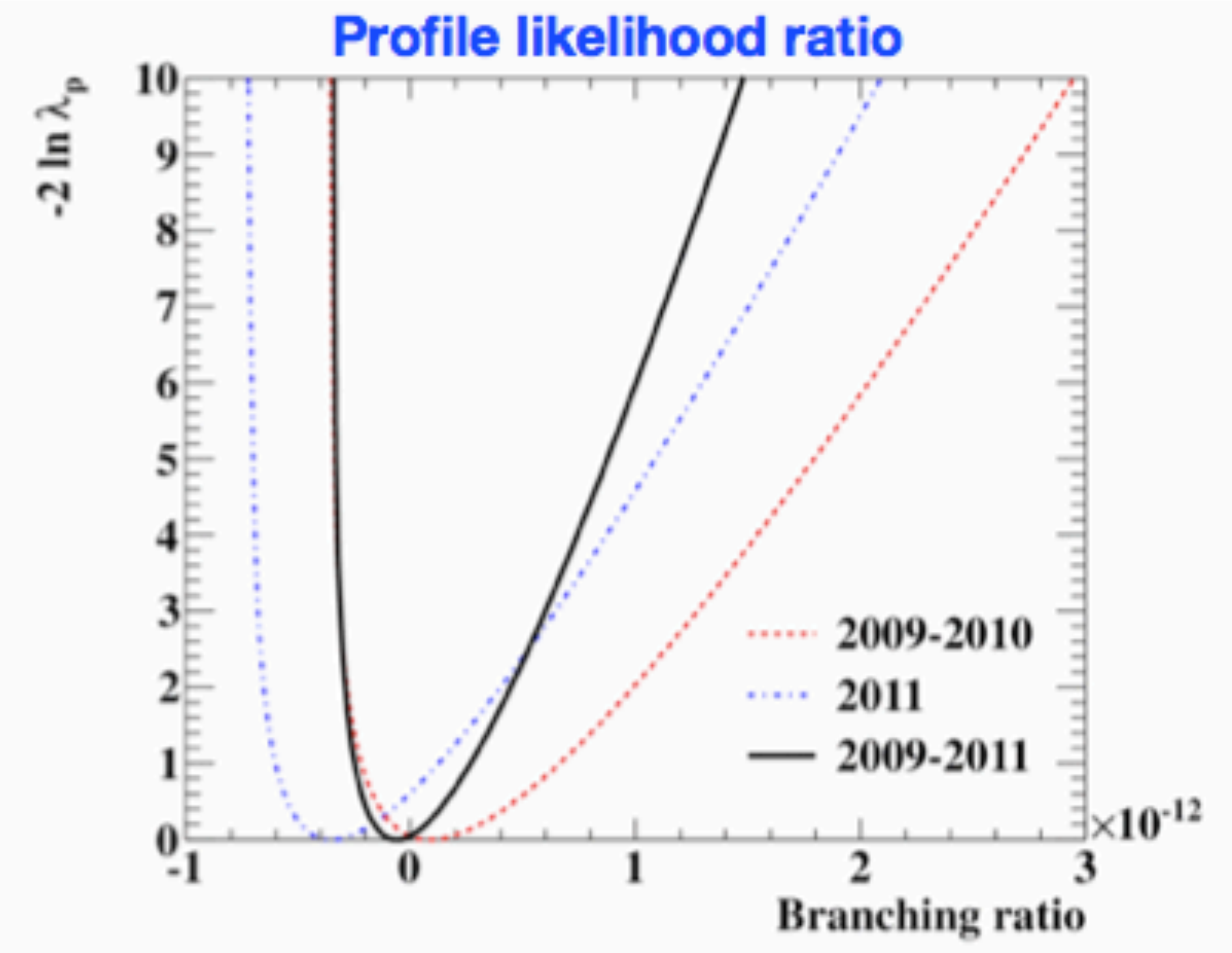
Green: Signal
Red: RMD
Purple: BCK
Blue: Total
Black: Data

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

Confidence Interval

- Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering





Consistent with null-signal hypotesis