The MEG/MEGII and Mu3e experiments at PSI

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on behalf of the MEG/MEGII and Mu3e collaborations

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- The world's most intense DC muon beam
- The MEG/MEGII experiment searching for the $\mu^+ \rightarrow e^+ \gamma$ decay
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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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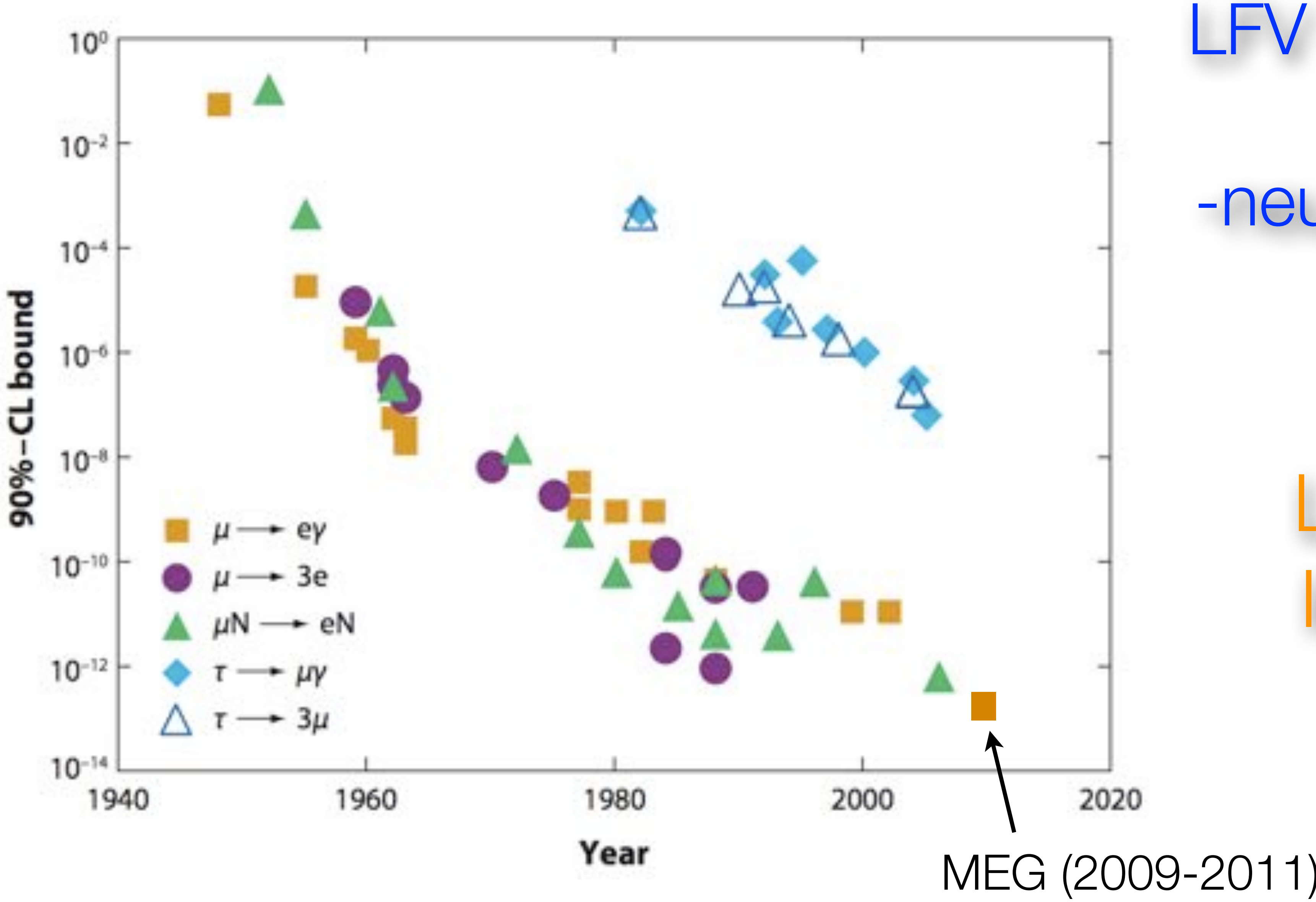
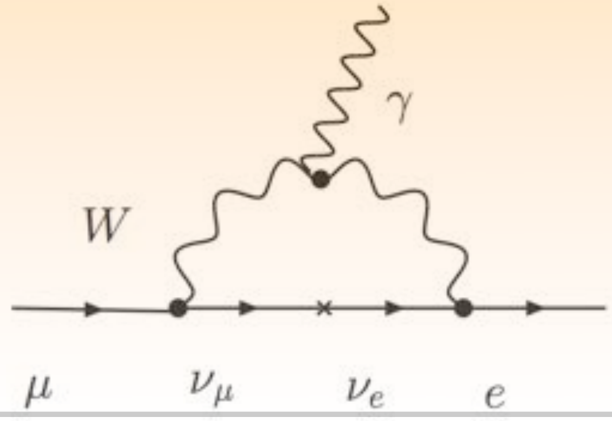


LFV of neutral leptons confirmed
-neutrino oscillations-

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)

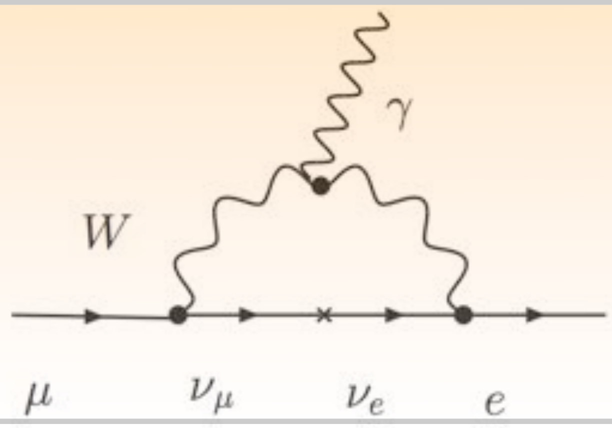
$$\Gamma(\mu \to e\gamma) = \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{\alpha}{2\pi} \sin^2 2\theta \, sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

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

too small to access experimentally

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

- Taking neutrino oscillations into account



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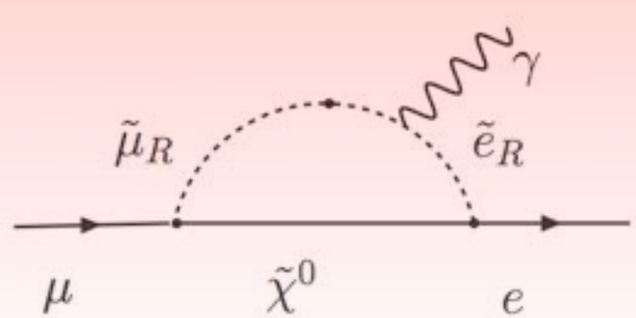
- Beyond SM theories such as SU(5) SUSY-GUT and SO(10) SUSY-GUT models predict measureble cLFV decay BR



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

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

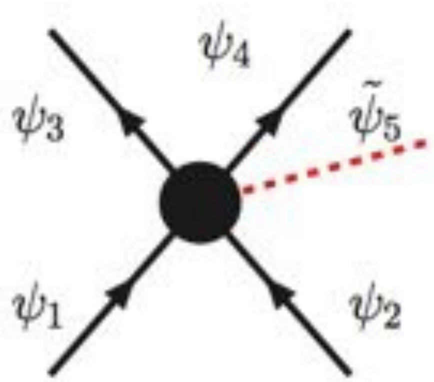
$$10^{-14} < B(\mu^+ \to e^+\gamma) < 10^{-11}$$

an experimental evidence: a clear signature of New Physics

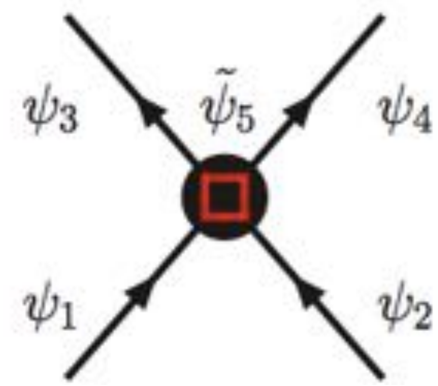
The role of low energy physics in the LHC era

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



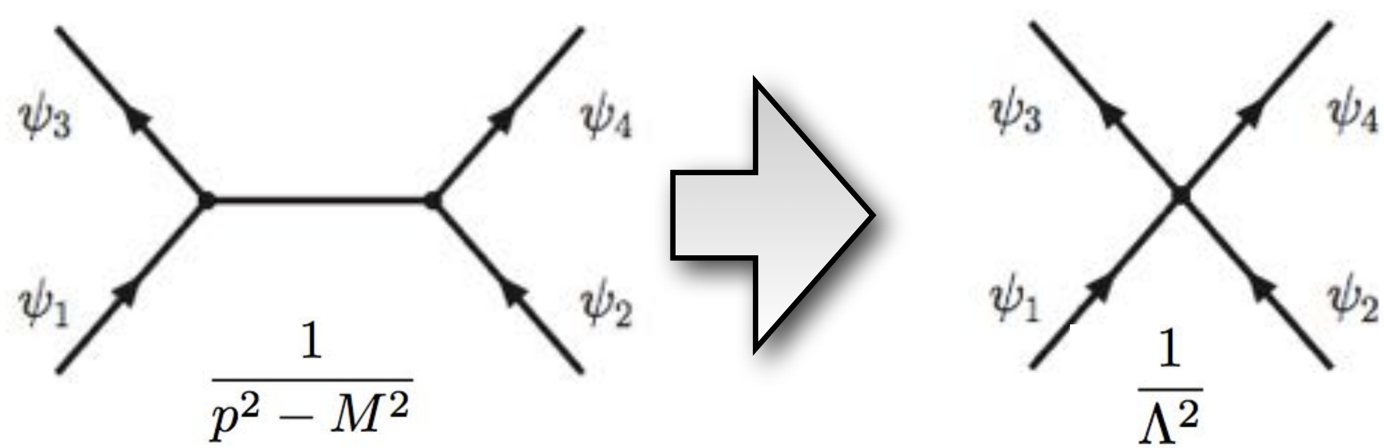
- Real BSM particles produced in the final state
- Energy frontier (LHC)



- 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

$\mu^+ \to e^+ \gamma$

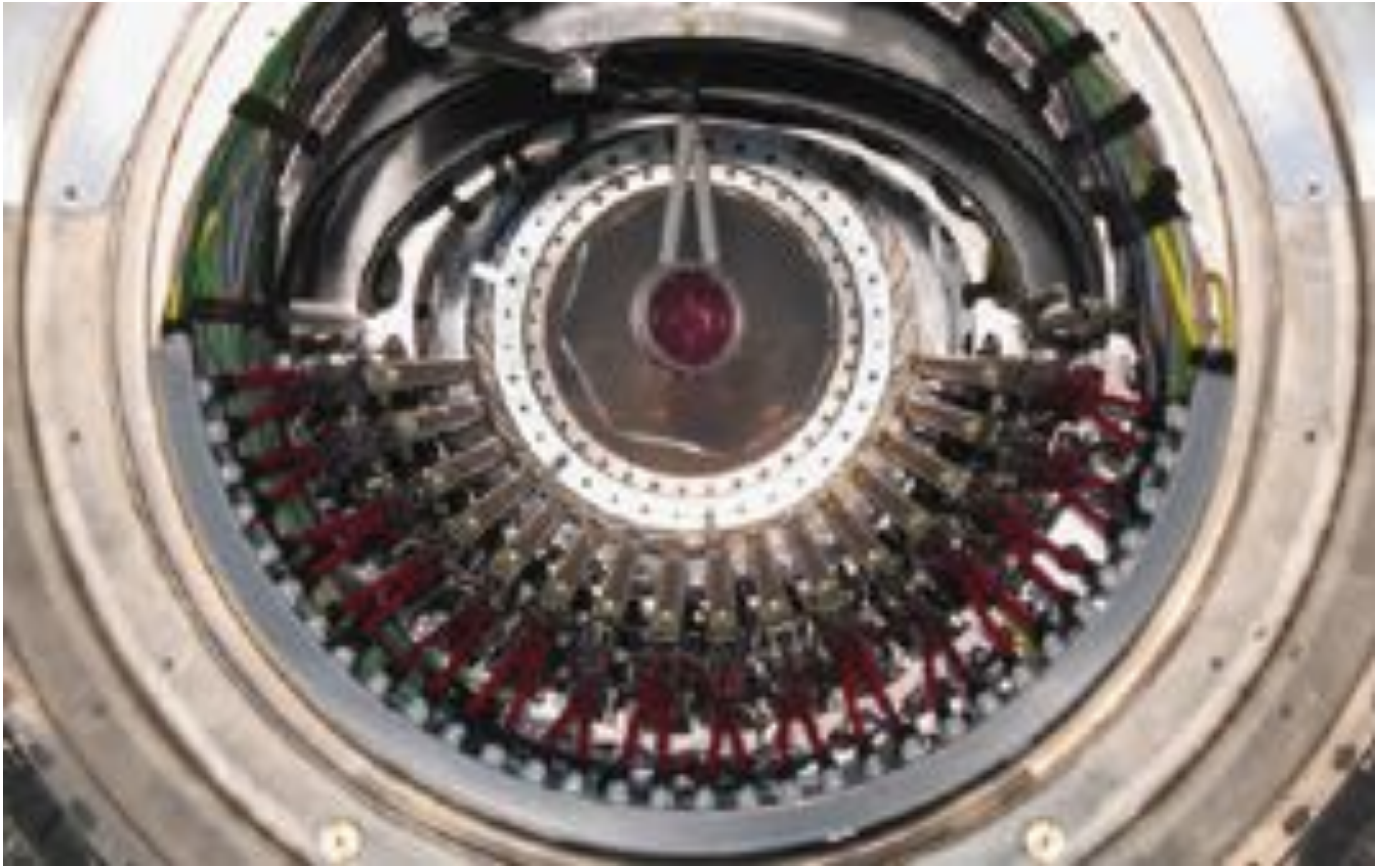
$\mu^+ \to e^+ e^+ e^-$

Favorite place: the Paul Scherrer Institute

- MEG/MEGII and Mu3e: looking for rare decays with coincident particles in the final state
- The best choice for a beam: the most intense continuous positive (surface) muon beam at low momentum (28 MeV/c)
  - **up to few x 10^8 muon/s**

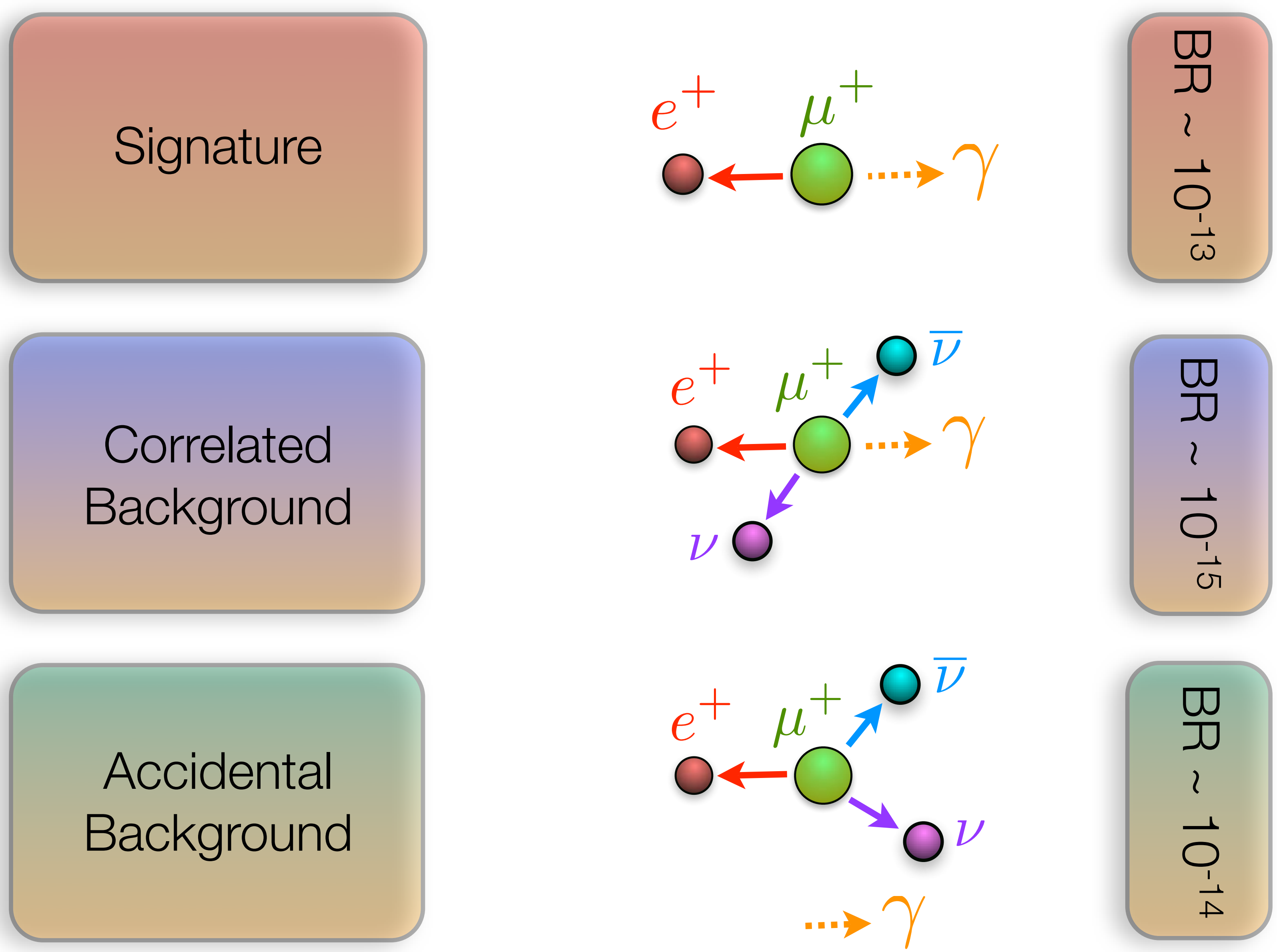
1.2 MW PROTON CYCLOTRON

The MEG/MEGII experiment



The MEG experiment

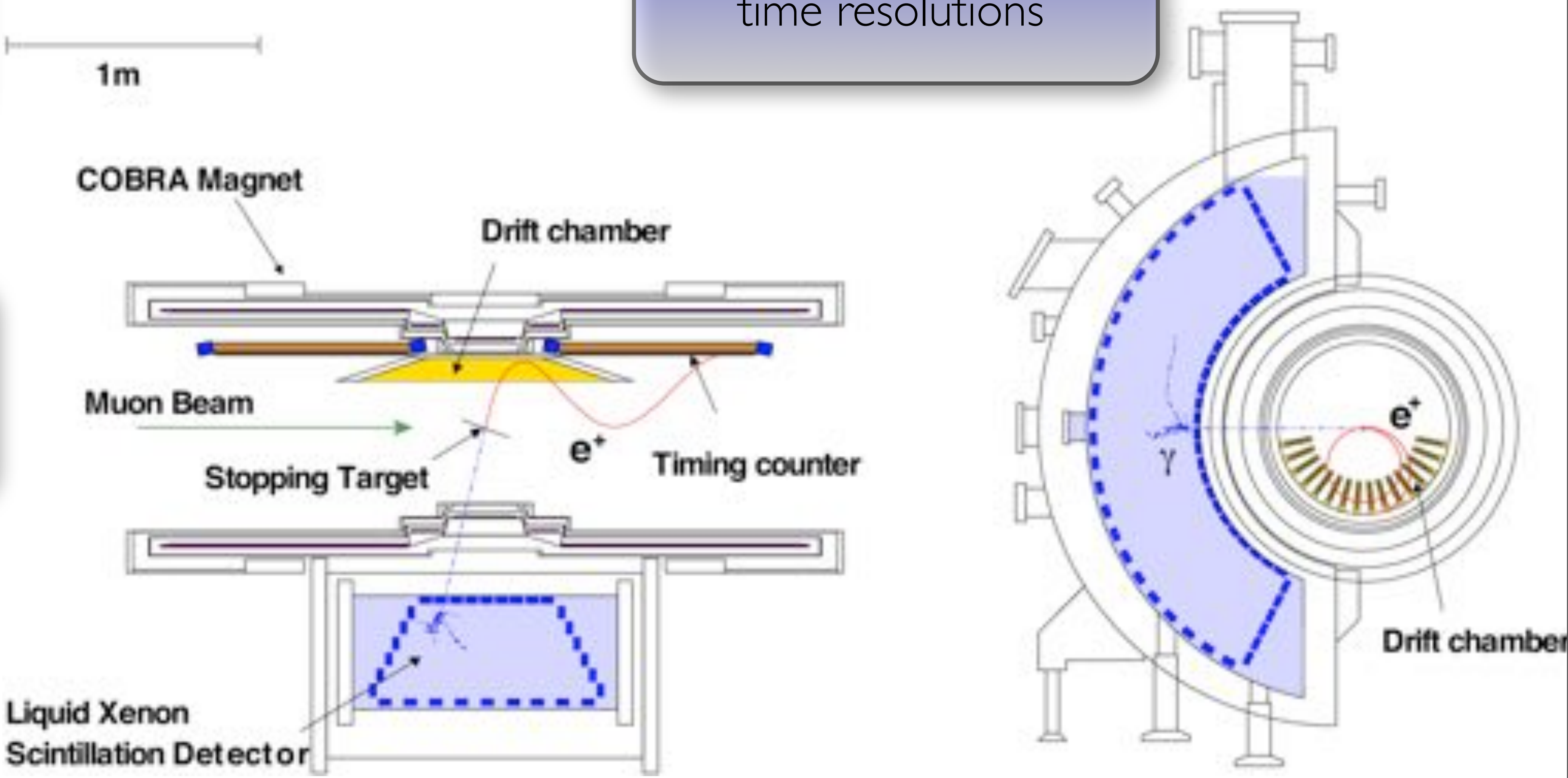
- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- **Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow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



Experimental set-up

The most intense DC muon beam

Gamma High energy and time resolutions



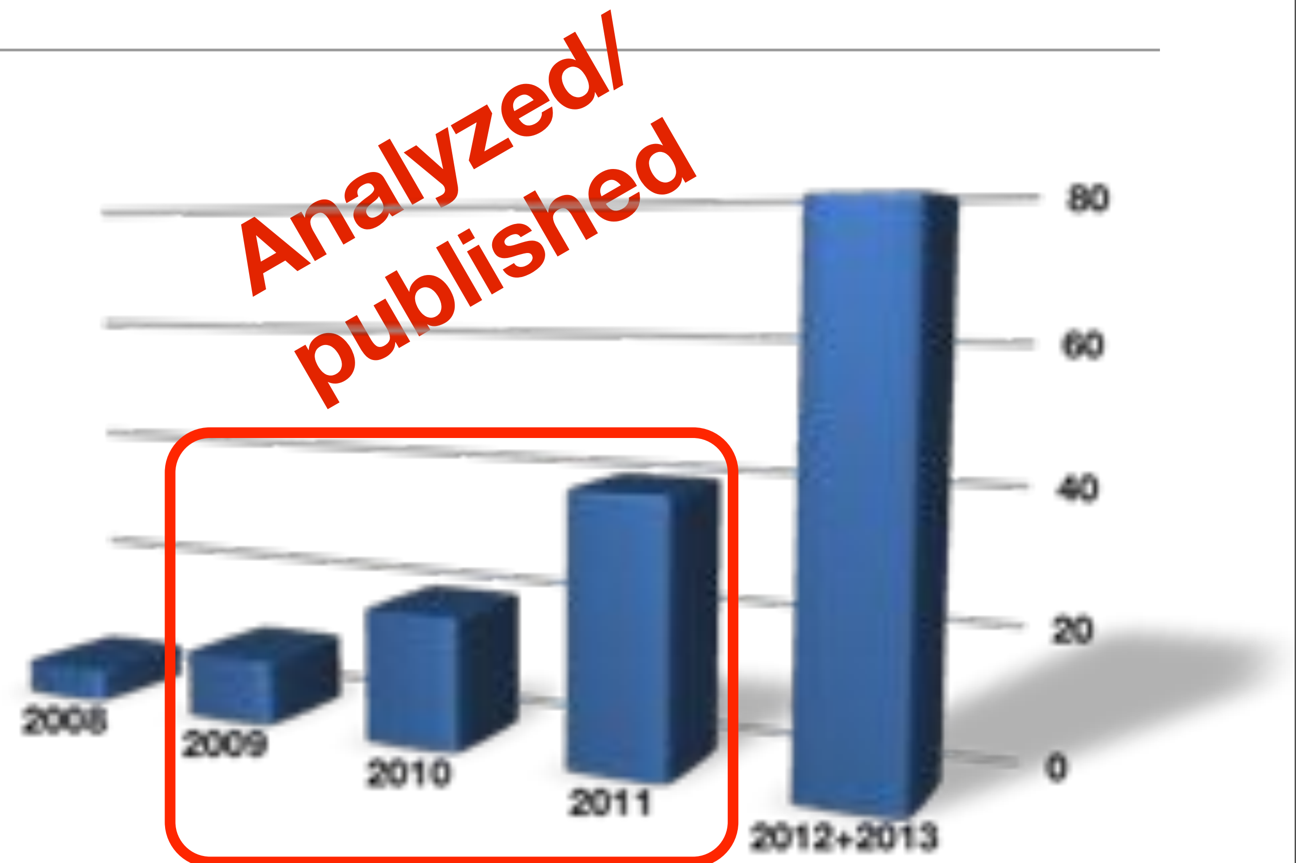
Positron Very precise momentum and time resolutions

High efficiency event selection and frequency signal digitization

Complementary calibration and monitoring methods

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

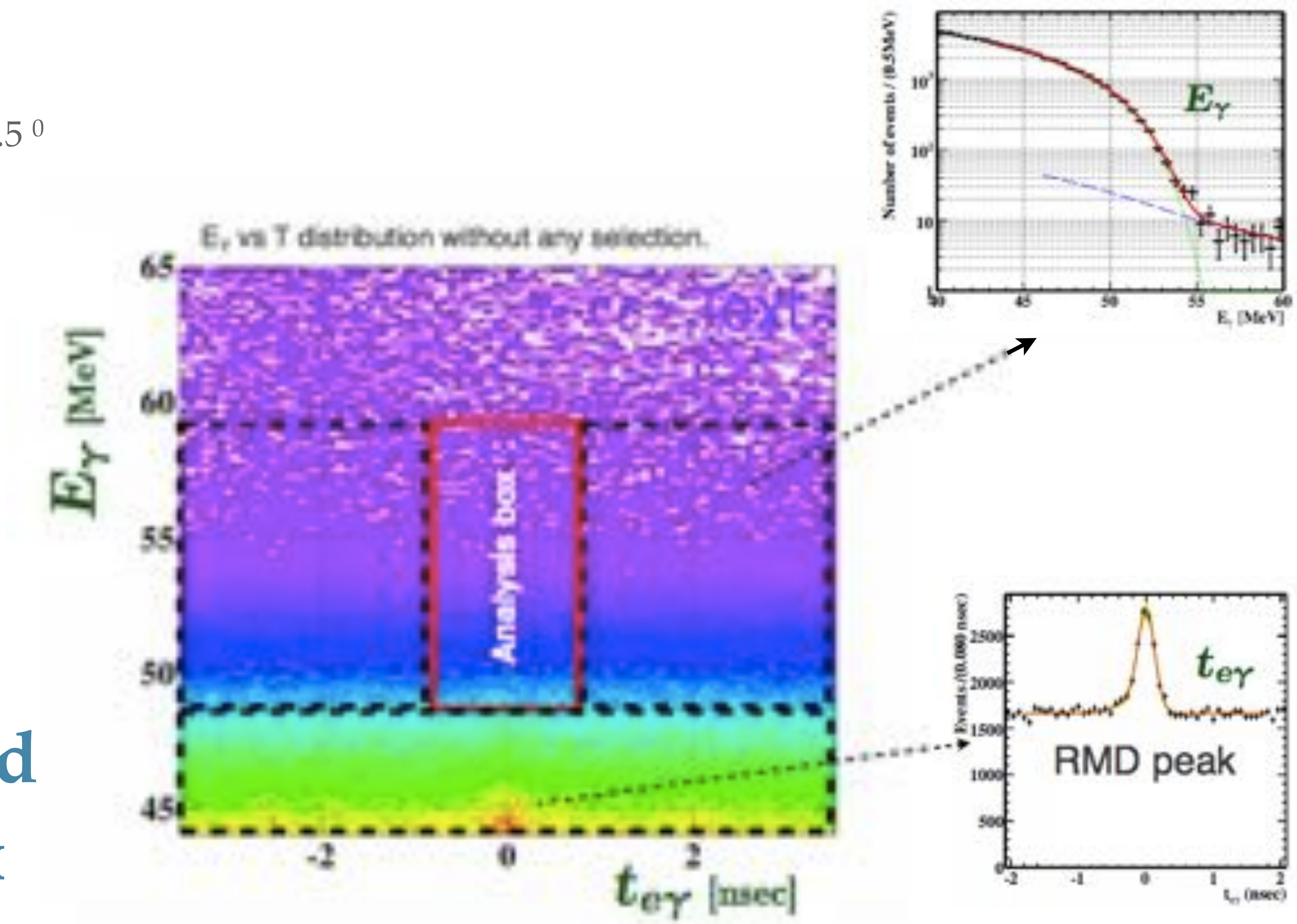
(~16% of the original sample)

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}

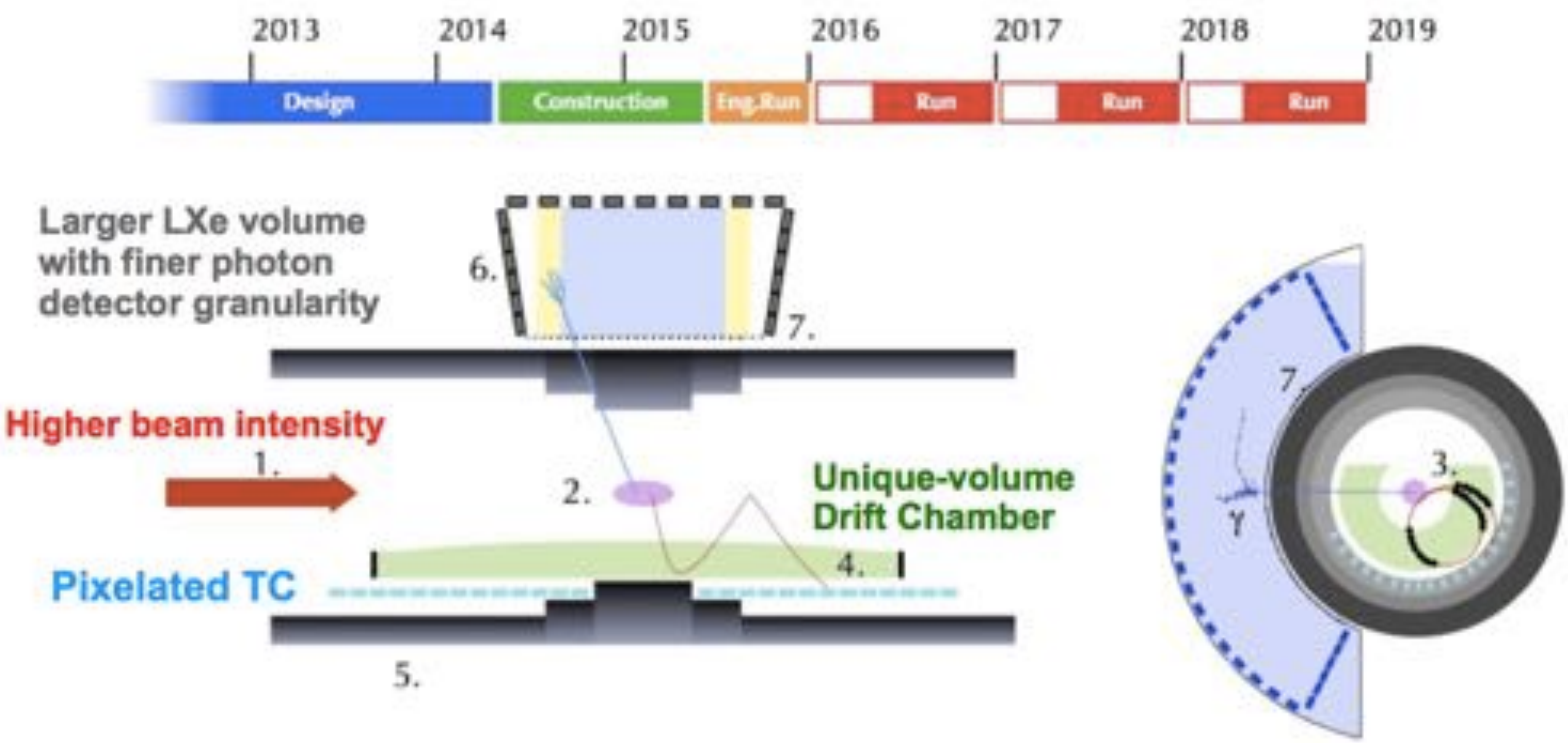
$B(\mu^+ \to e^+ \gamma) < 5.7 \times 10^{-13}$ (all combined data) *

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

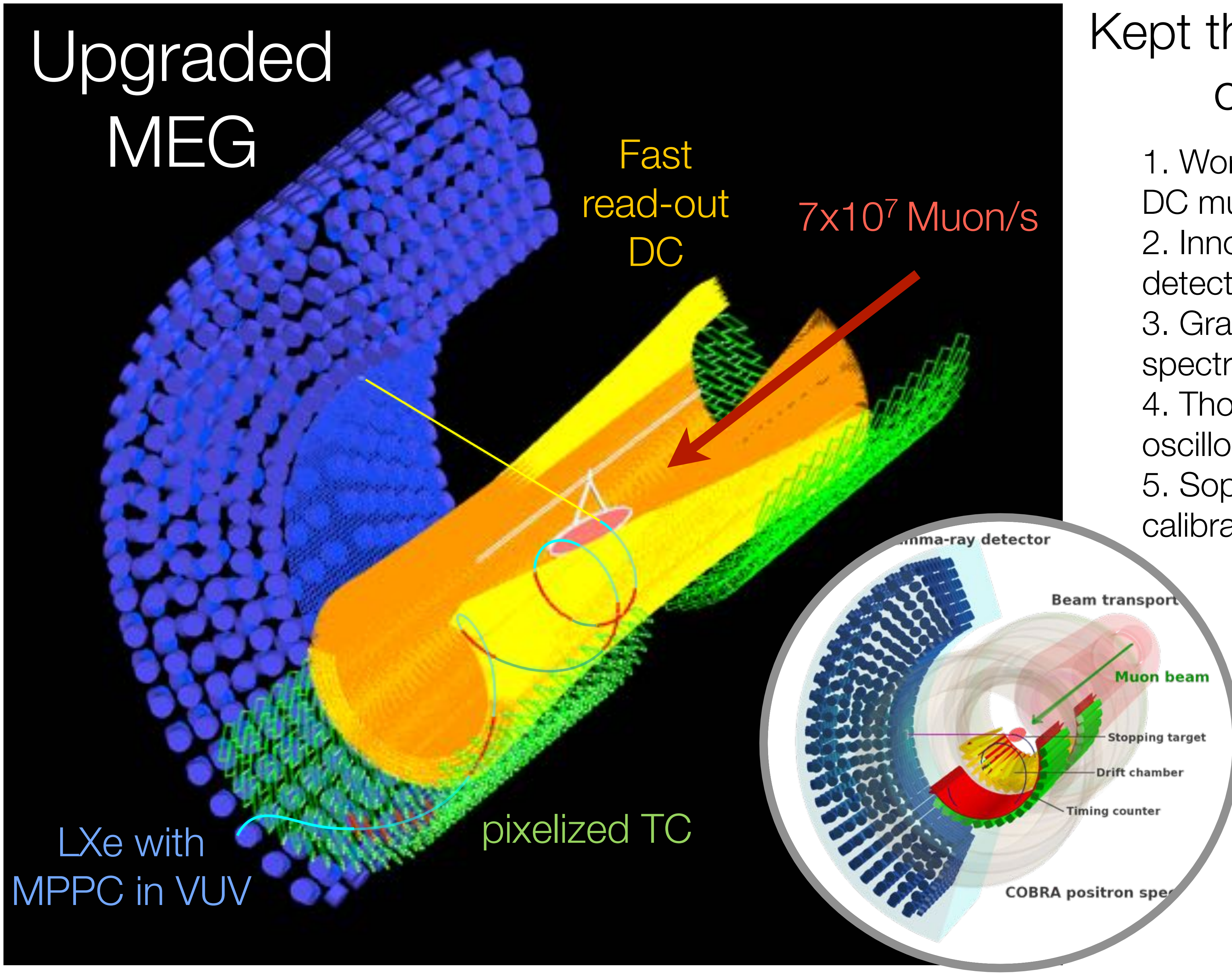
x20 more stringent than the MEGA experiment result
($B(\mu^+ \to e^+ \gamma) < 1.2 \times 10^{-11}$ -MEGA 2001)

MEGII

- 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



MEGII vs MEG

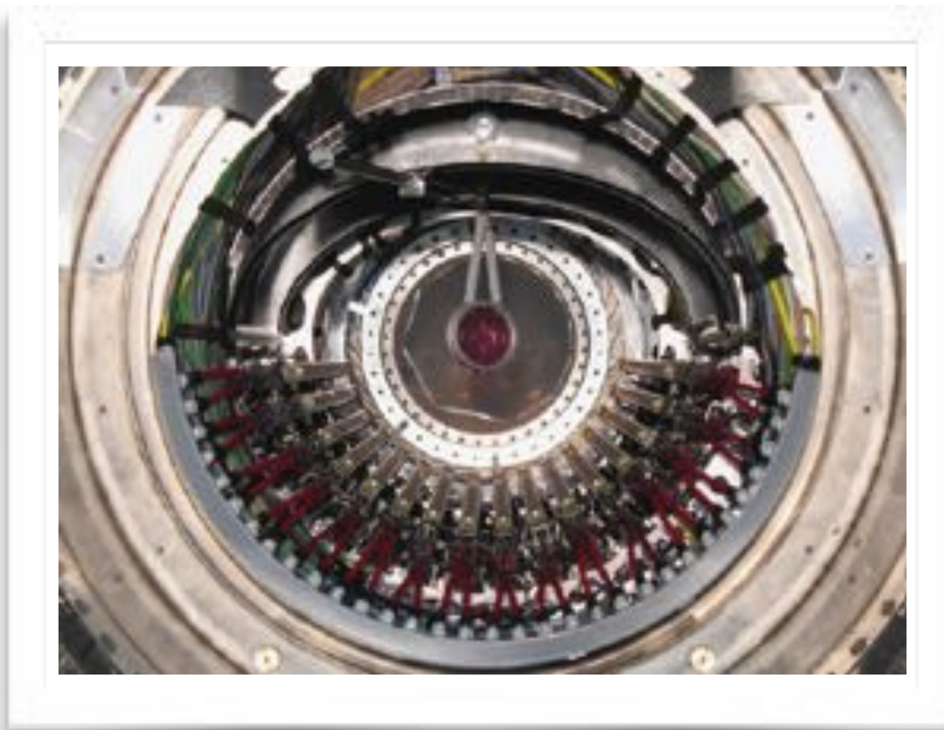


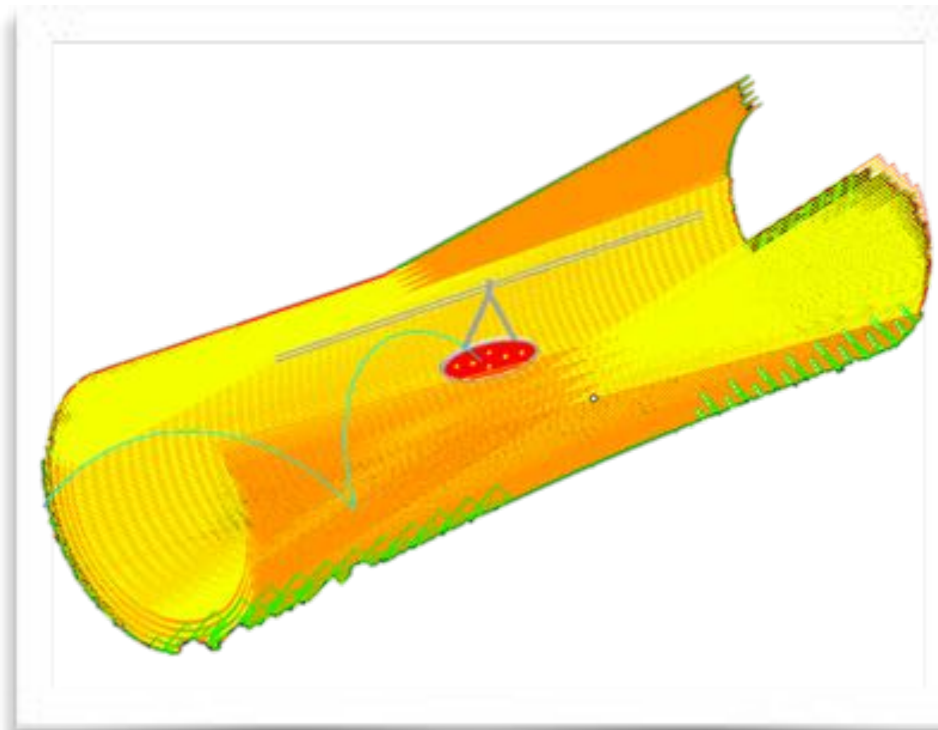
MEG Now

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

The new re-designed spectrometer: the single volume chamber

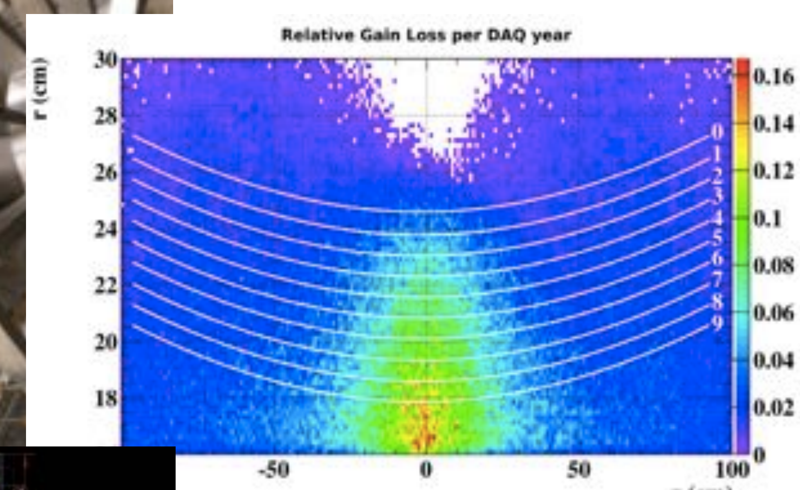


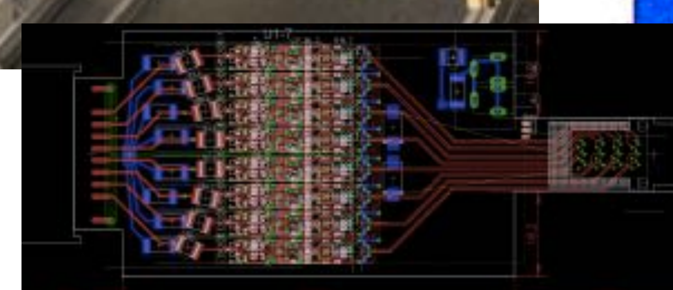


- High granularity/Increased number of hits per track
- Less material (helium:isobutane = 85:15, $2 \times 10^{-3} X_0$)
- High trasparency towards the TC

Resolutions	MEG	MEG II
p_e (keV)	306	130
ϑ_e(mrad)	9.4	5.3
φ_e(mrad)	8.7	4.8
e^+ efficiency (%)	40	88

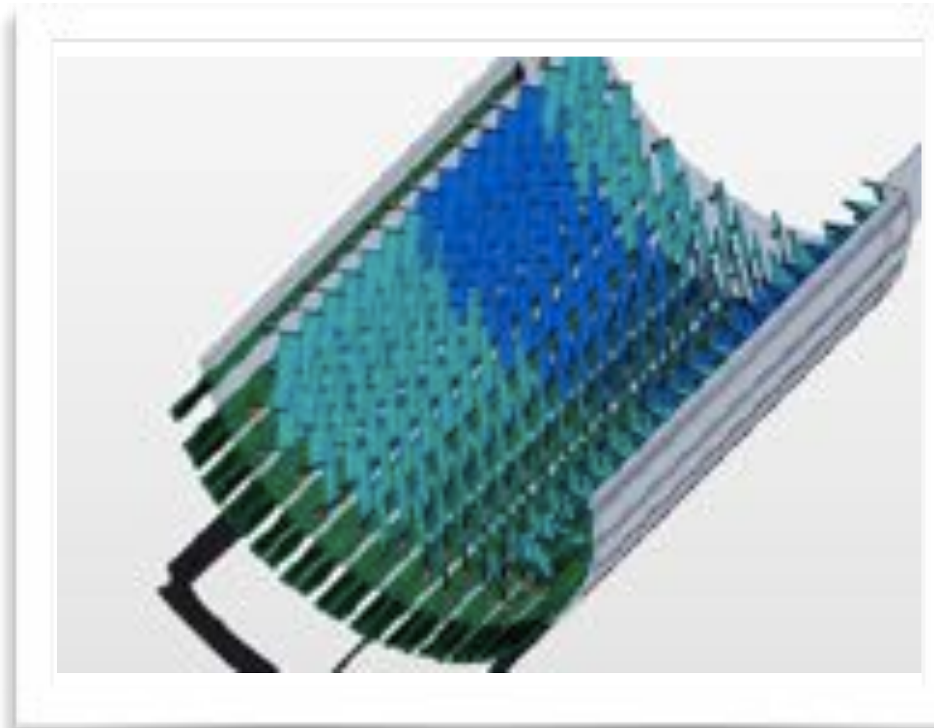
Ageing tests:





Front End Electronics: 3dB bandwidth around 1GHz

A new re-designed spectrometer: the pixelized Timing Counter

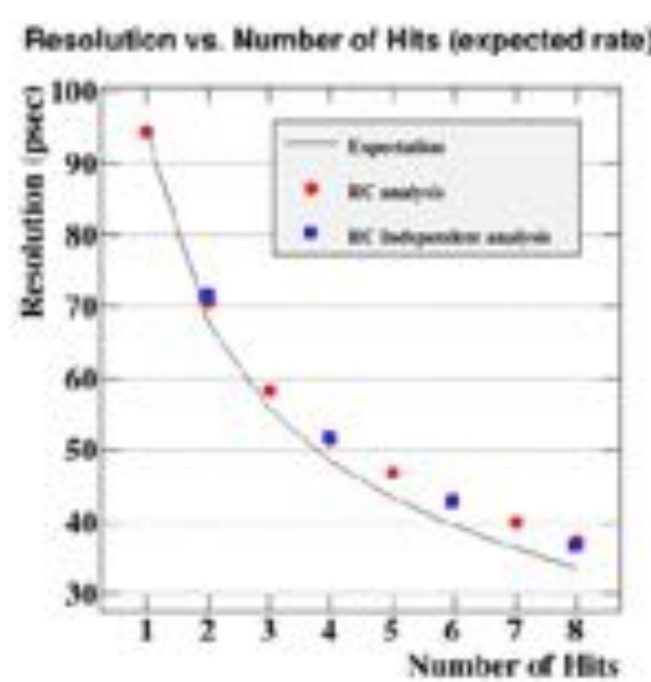


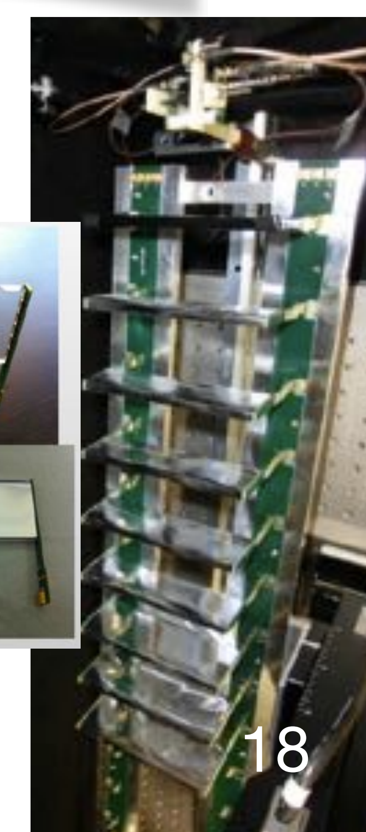
- Higher granularity: 2 x 256 of scintillator plates (120 x 50 x 5 mm^3) readout by SiPMs

- Improved timing resolution: from 70 ps to 35 ps

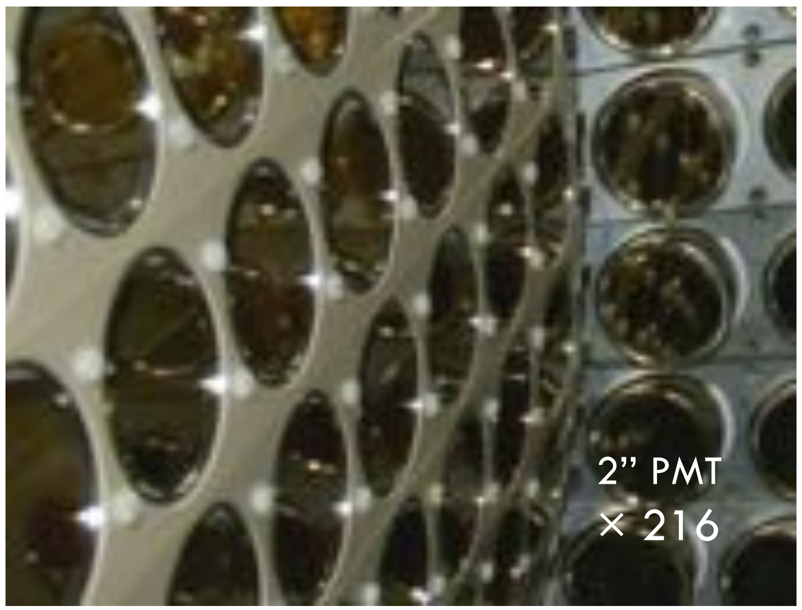
- Less multiple scattering and pile-up

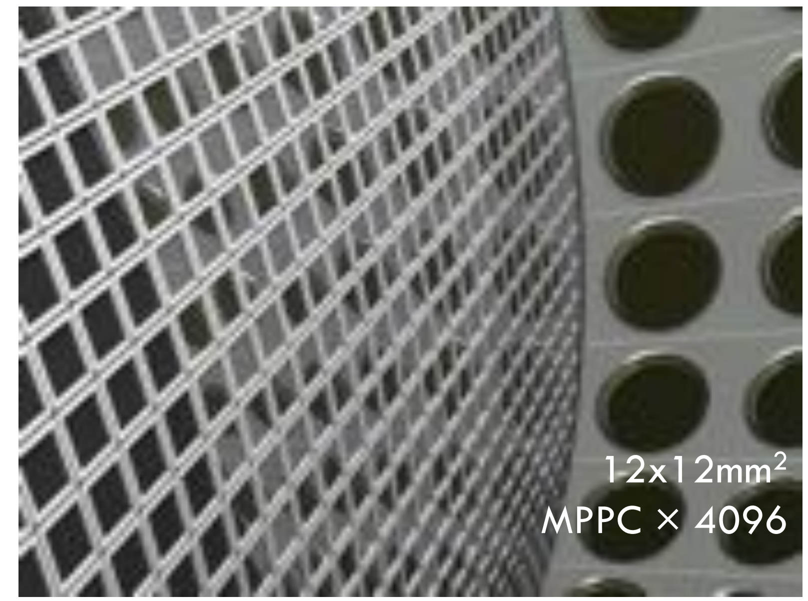
Timing resolution:
35 ps at the MEGII rate conditions



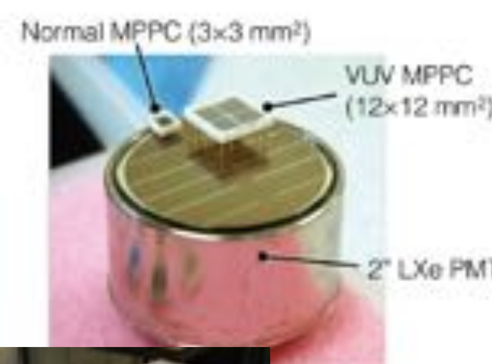


The upgraded Liquid Xenon calorimeter

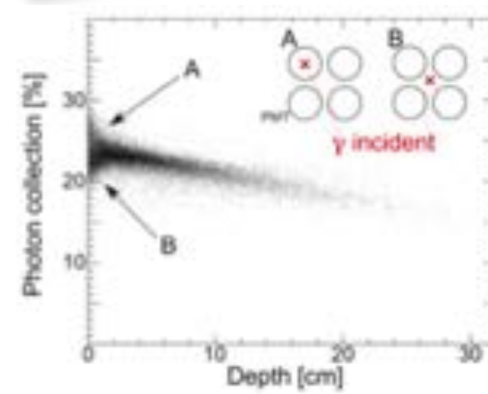


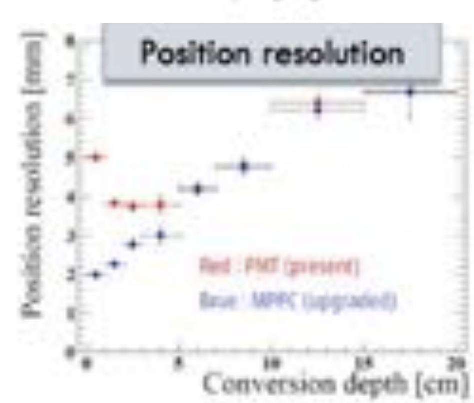


new R&D: VUV SiPM



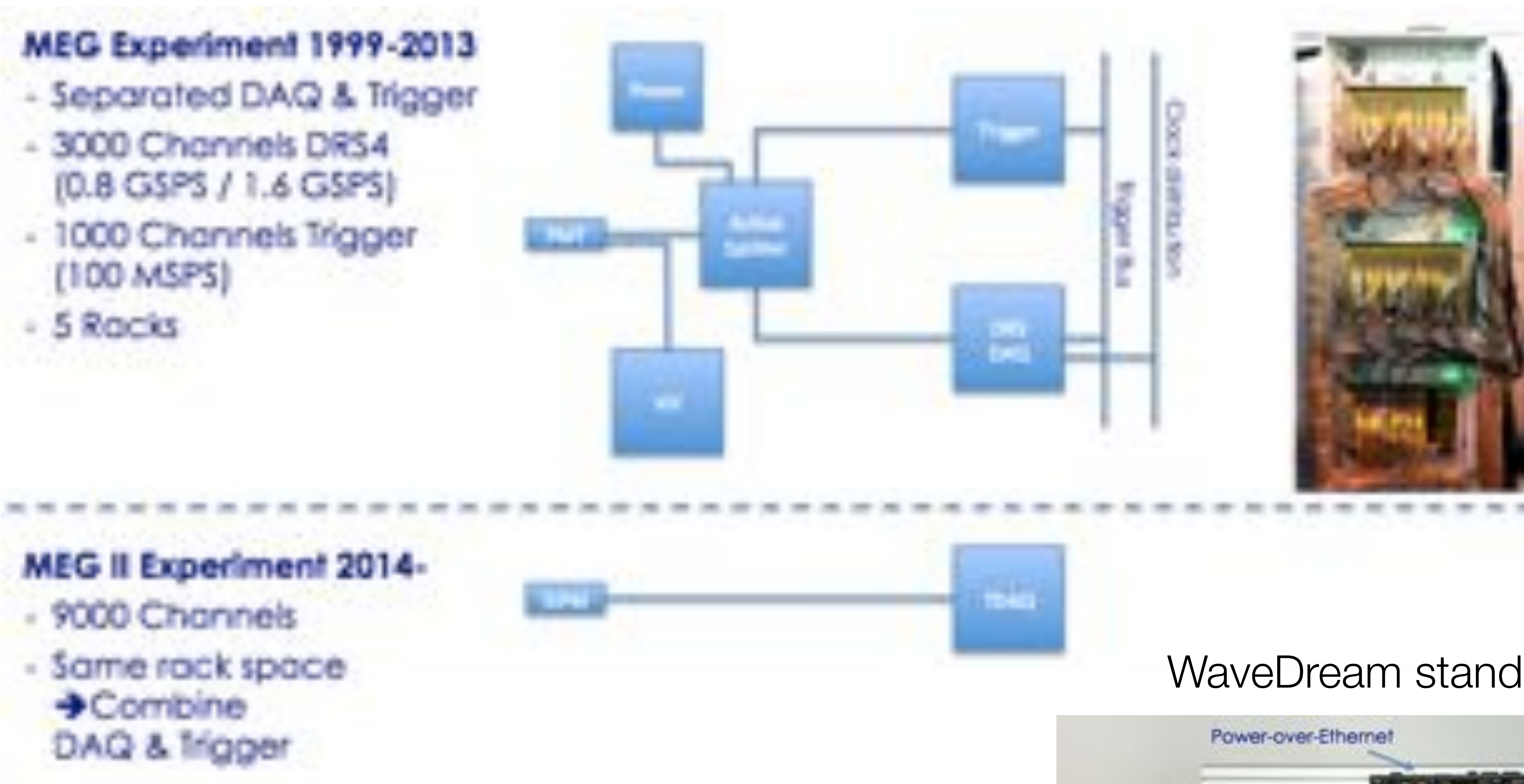
- High uniformity/Increased resolutions
- High pile-up rejection capability
- High acceptance and detection efficiency





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

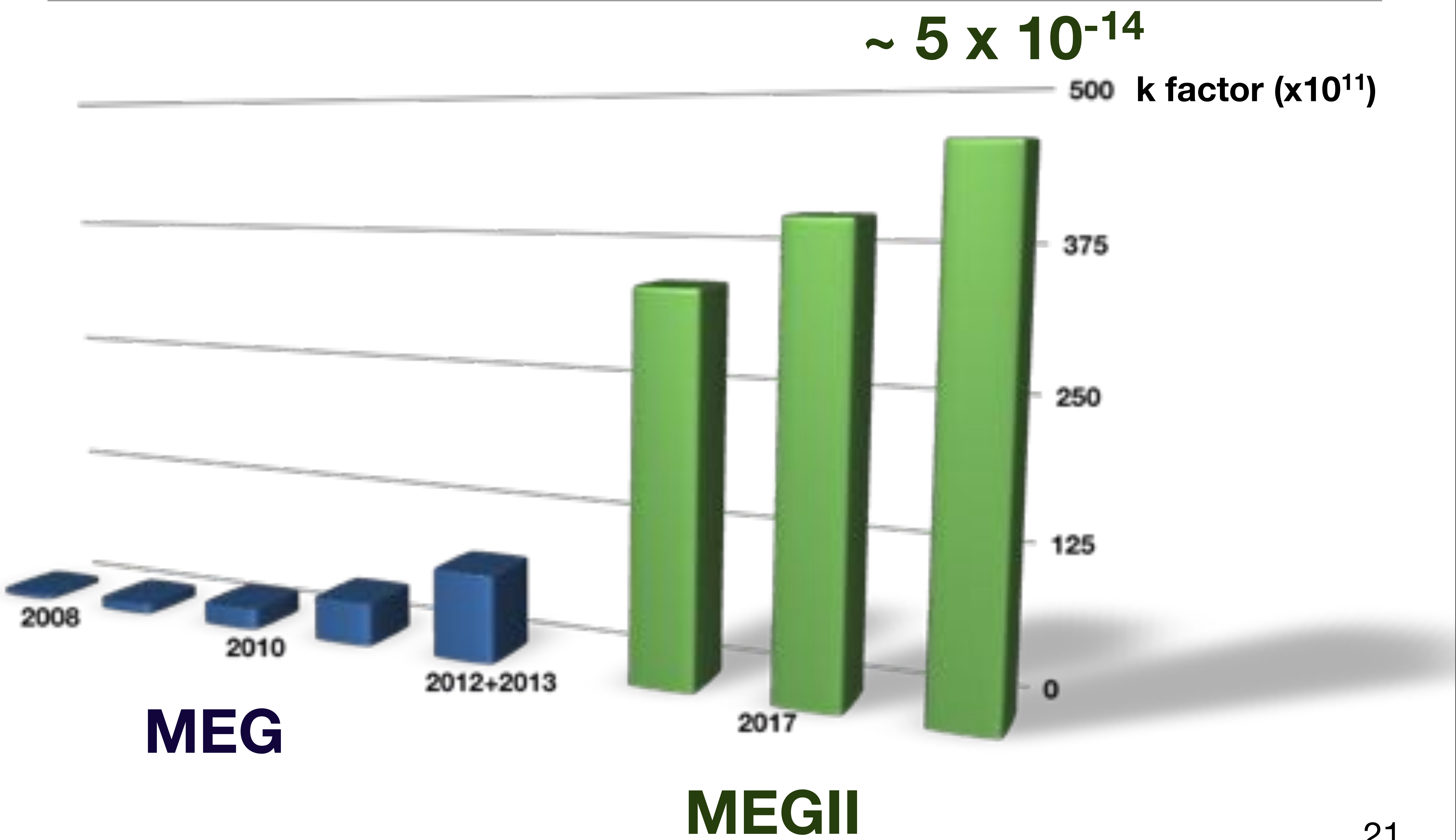
The new waveDAQ



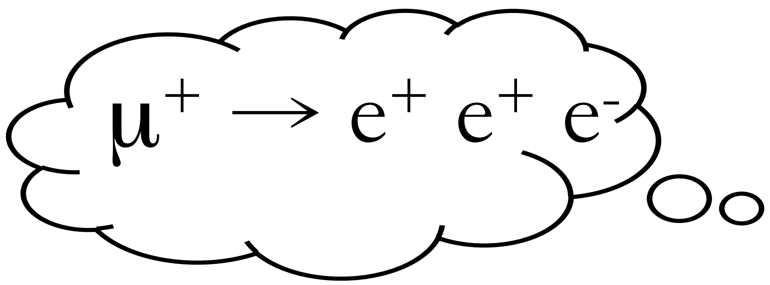
WaveDream standalone:

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

Where we will be



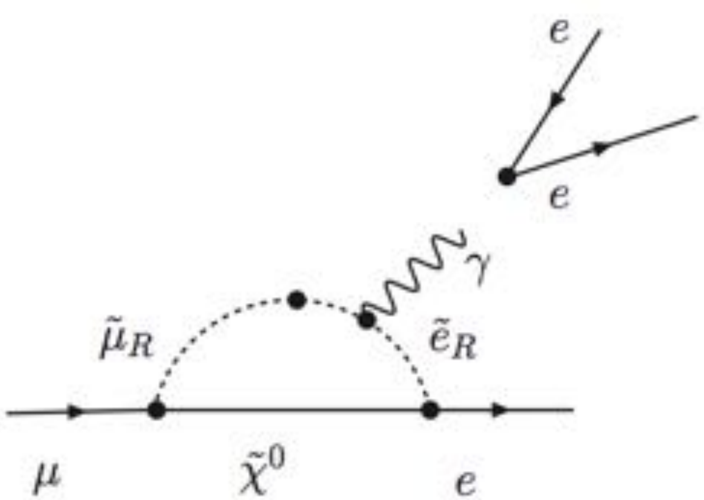
The Mu3e experiment

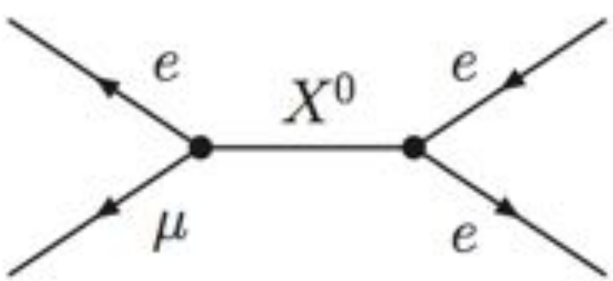


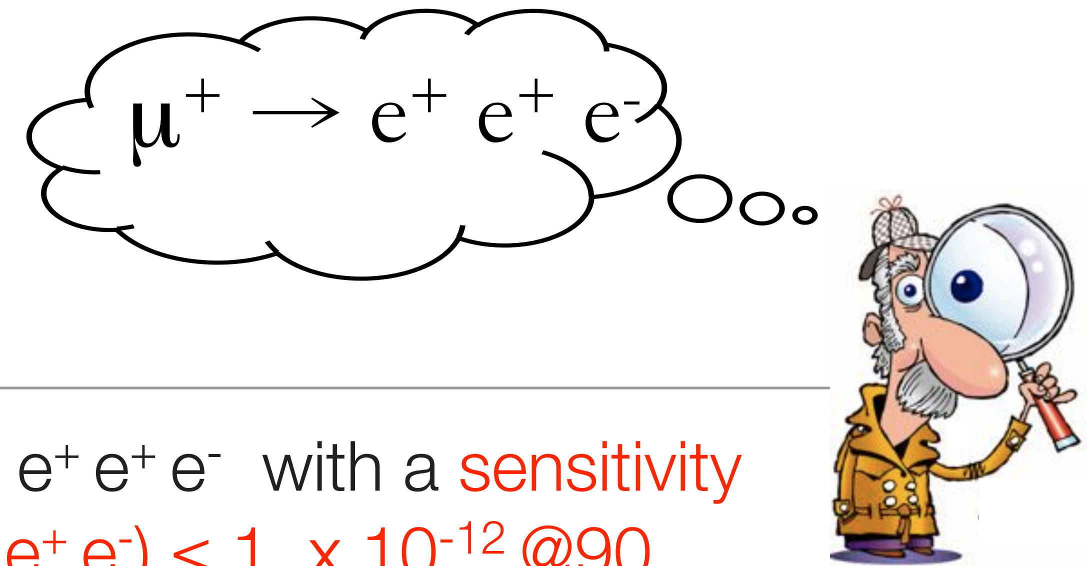
The Mu3e experiment

- The Mu3e experiment searches for $\mu^+ \rightarrow e^+ e^+ e^-$ and aims a sensitivity of ~10^{-16} (current best upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1. \times 10^{-12}$ @90 C.L. by the SINDRUM experiment)

$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\overline{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\overline{\mu}_R \gamma_\mu e_L \overline{f}\gamma^\mu f$$





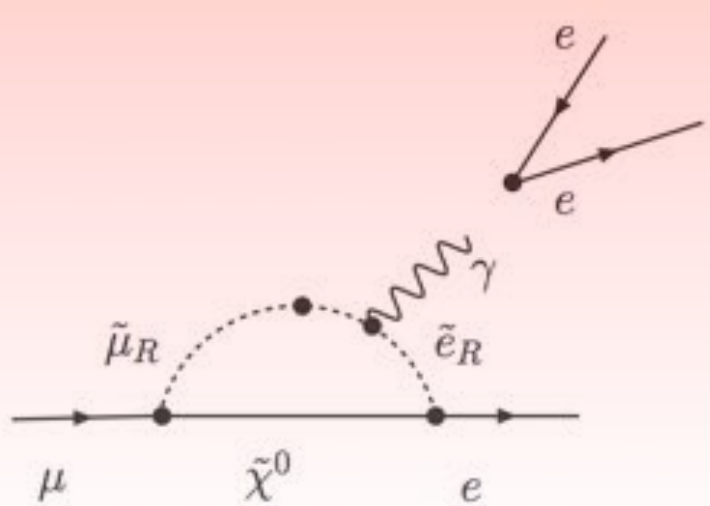


The Mu3e experiment

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-16}$ (current best upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1. \times 10^{-12}$ @90 C.L. by the SINDRUM experiment)

Case 1: dominant dipole coupling ($k \rightarrow 0$)

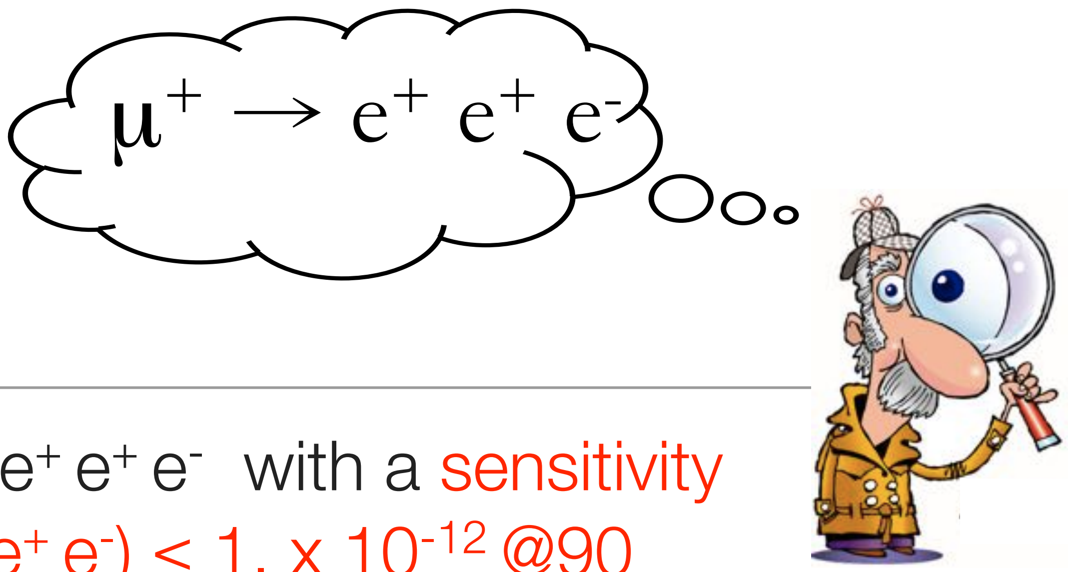
$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\bar{\mu}_R \gamma_\mu e_L \bar{f} \gamma^\mu f$$



$$\frac{BR(\mu^+ \rightarrow e^+ e^+ e^-)}{BR(\mu^+ \rightarrow e^+ \gamma)} \sim 0.006$$

$\mu^+ \rightarrow e^+ \gamma$ most sensitive channel!

The Mu3e experiment

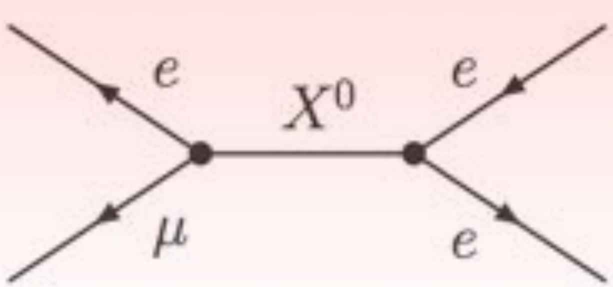


- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of ~10^{-16} (current best upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1. \times 10^{-12}$ @90 C.L. by the SINDRUM experiment)

Case 2: tree level interaction (k > 10)

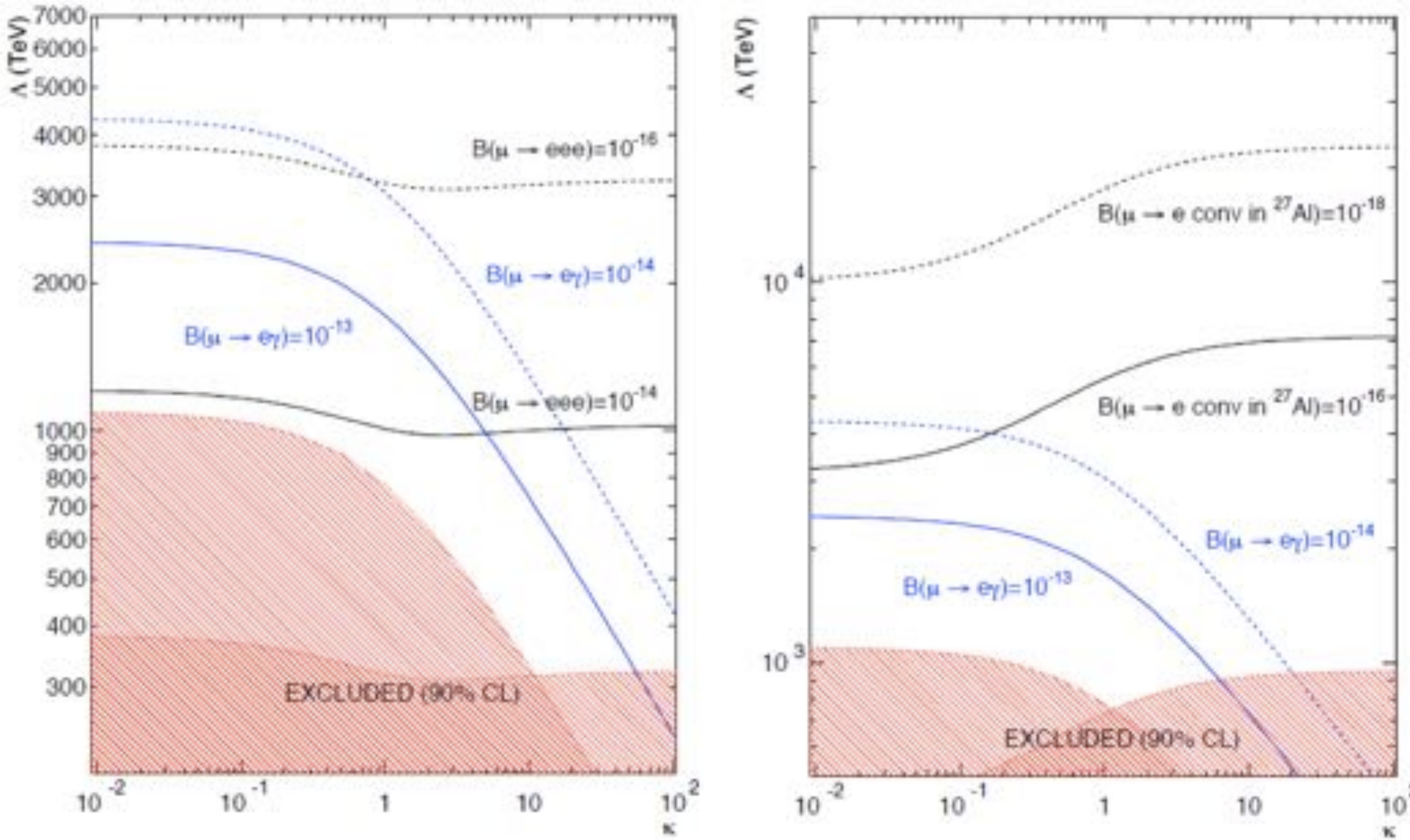
$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\overline{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\overline{\mu}_R \gamma_\mu e_L \overline{f} \gamma^\mu f$$

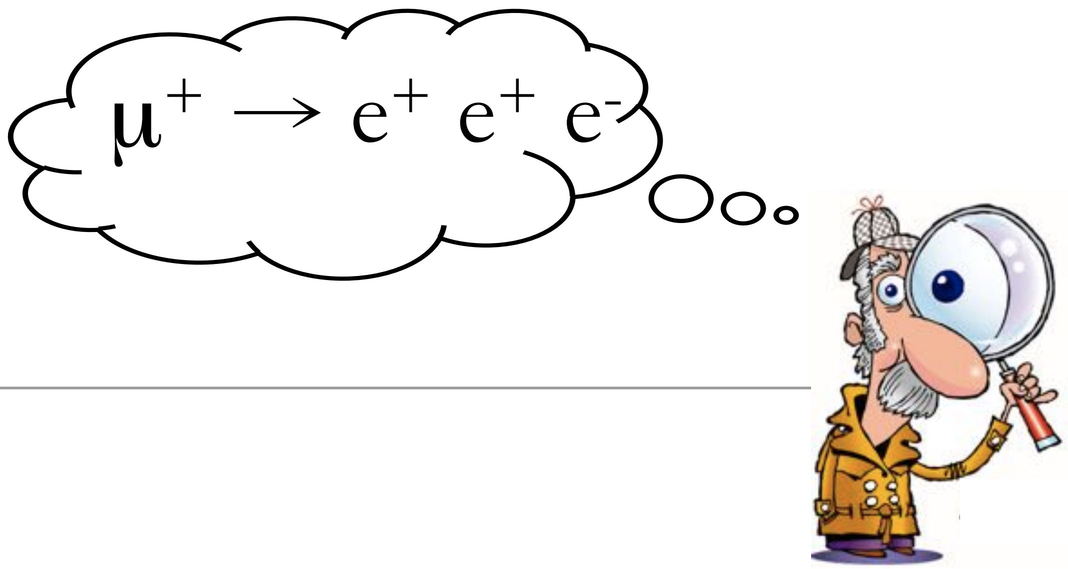
$$\frac{BR(\mu^+ \rightarrow e^+ e^+ e^-)}{BR(\mu^+ \rightarrow e^+ \gamma)} >> 1$$



tree level interaction accessible only via $\mu^+ \rightarrow e^+ e^+ e^-$!

cLFV search: complementry approch



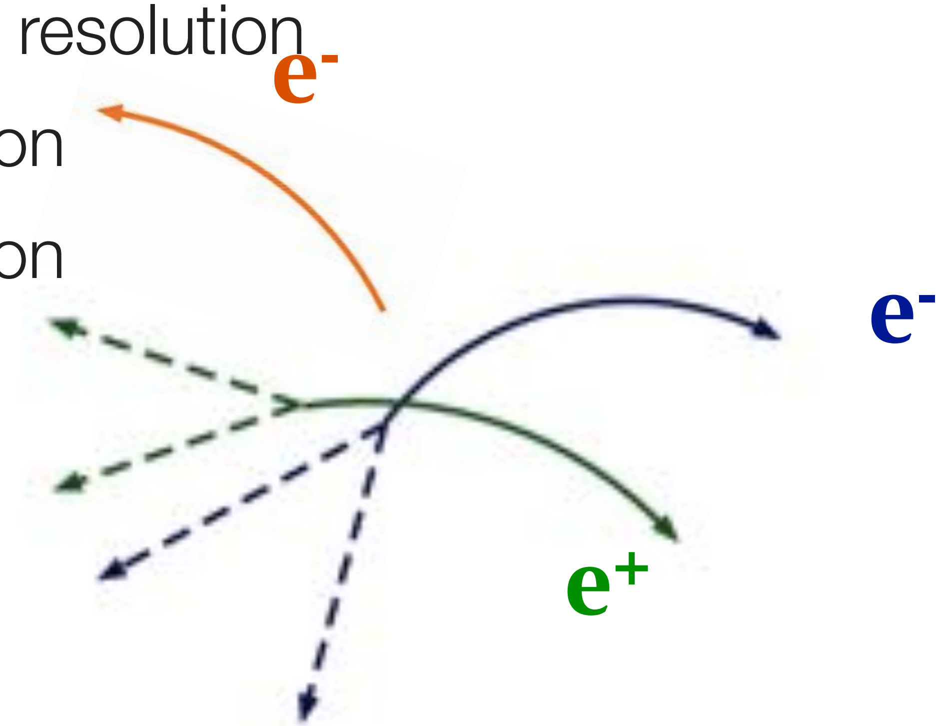


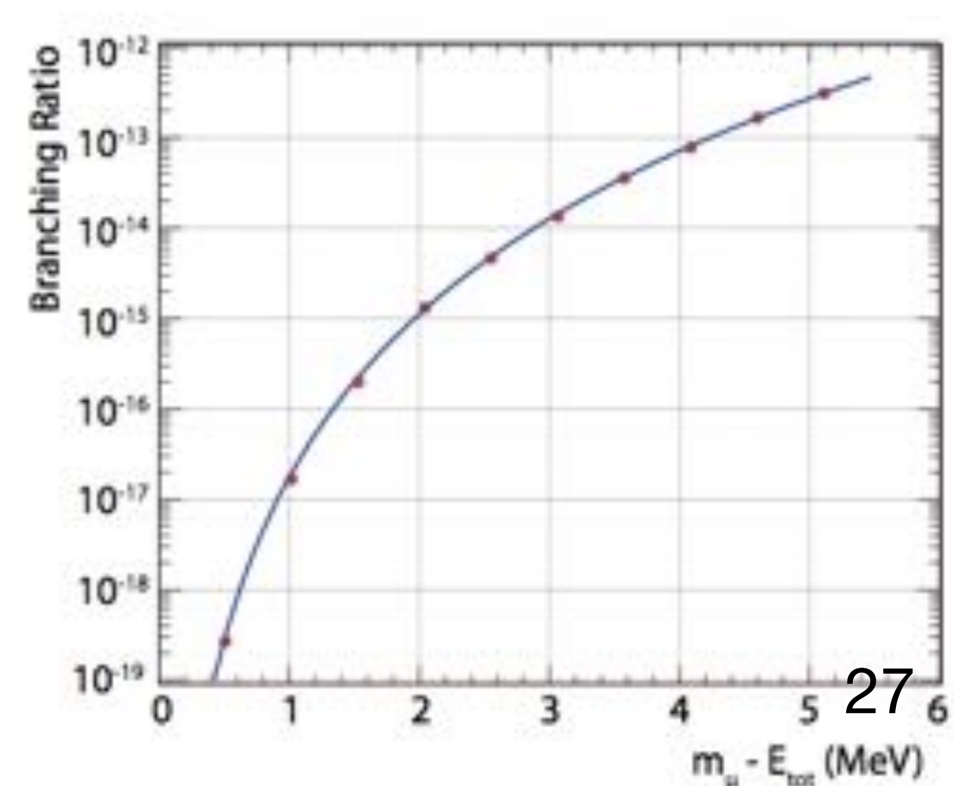
The Mu3e experiment

- The $\mu^+ \rightarrow e^+ e^+ e^-$ signature
  - 3 charged particle in the final state
  - no neutral particle in the final state allows for higher detector performances

- The $\mu^+ \rightarrow e^+ e^+ e^-$ main backgrounds
  - $\mu^+ \rightarrow e^+ e^+ e^- \nu \nu$
  - combinatorial e.g. $\mu^+ \rightarrow e^+ \nu \nu$, $\mu^+ \rightarrow e^+ \nu \nu, e^+ e^-$

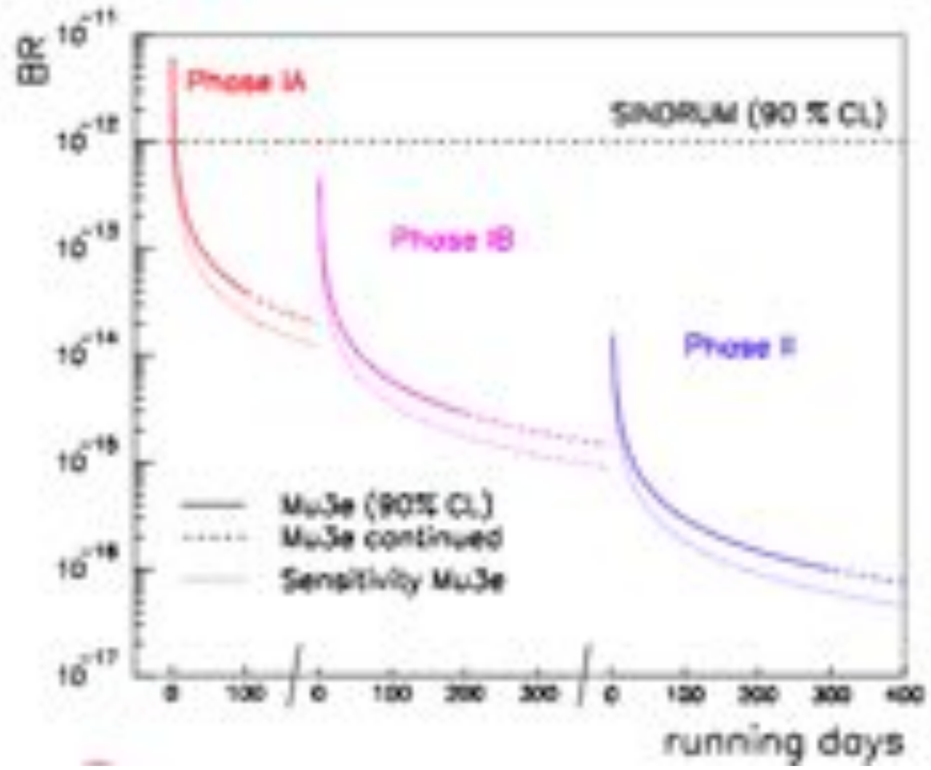
- Excellent momentun resolution
- Good vertex resolution
- Good timing resolution

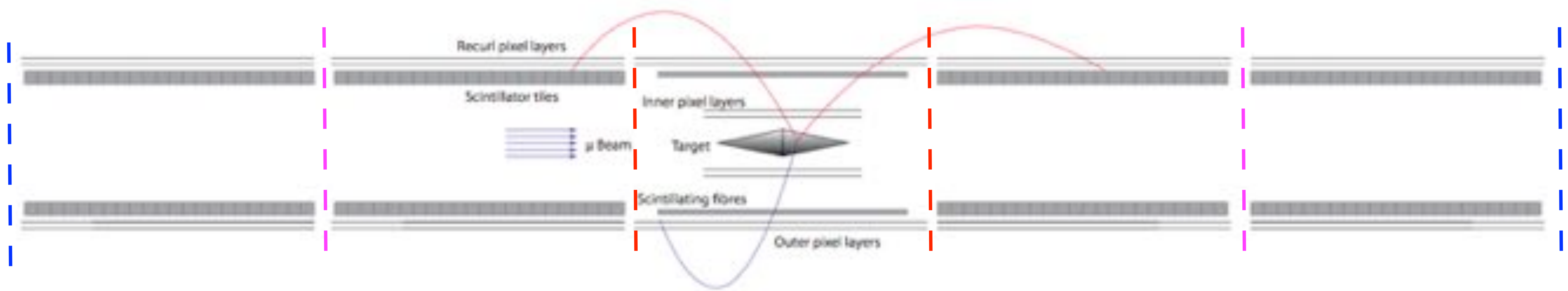




Mu3e staging approach

- Phase IA 201x (piE5 beam line: $O(10^7)$ mu/s)
- Phase IB 201x+1 (piE5 beam line: $O(10^8)$ mu/s)
- Phase II 202x (new beam line: $O(10^9)$ mu/s)

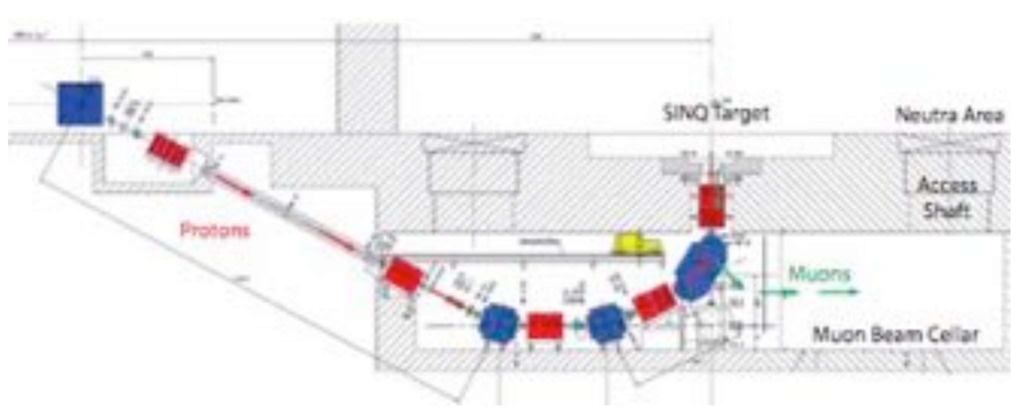


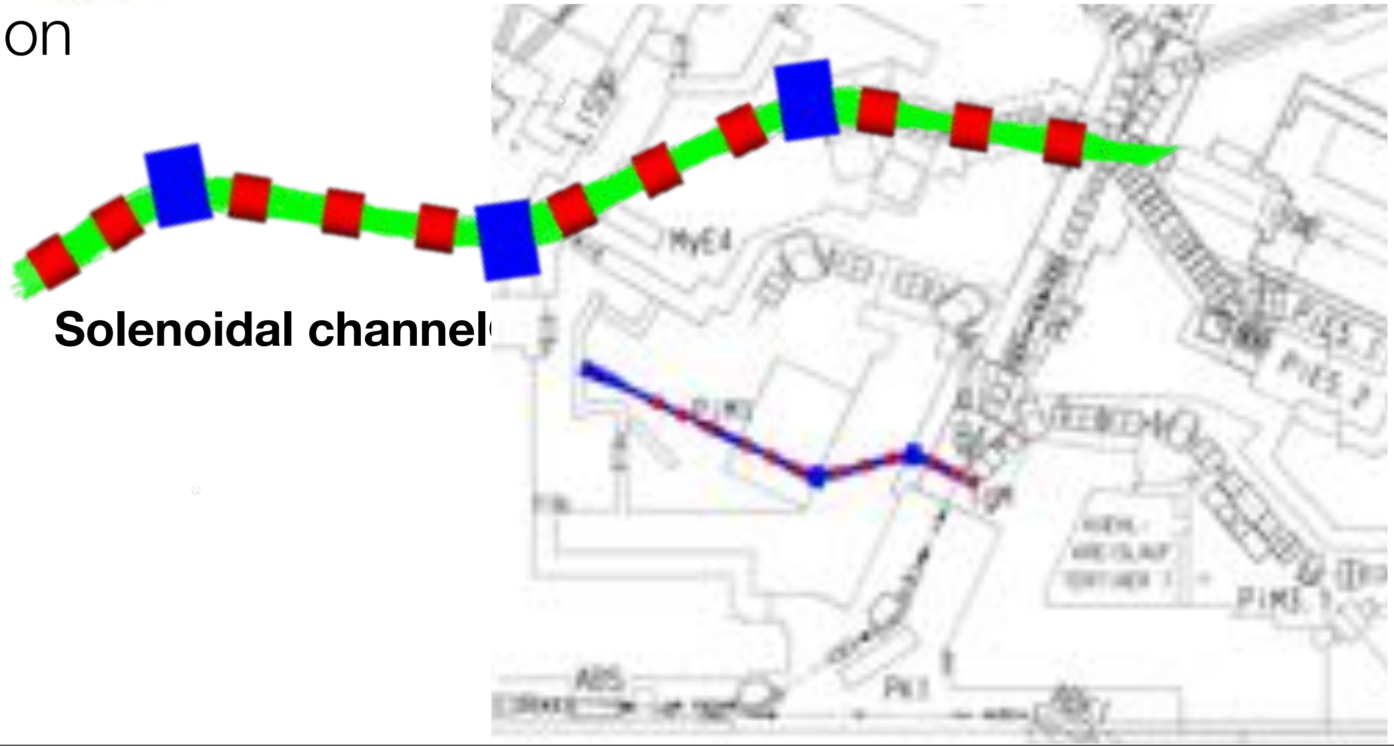


Feasibility study of a High Intensity Muon Beam (HIMB) line.

Aim: **$O(10^{10})$ mu/s**

HIMB@SINQ





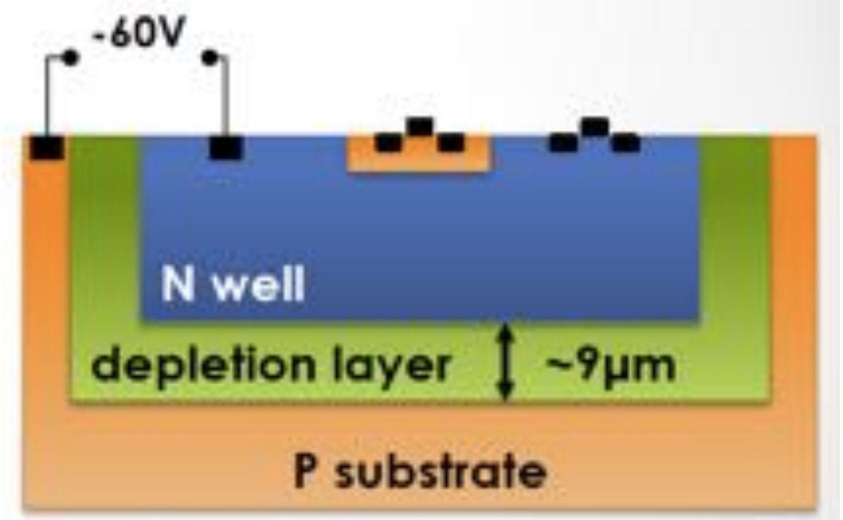
The compact muon beam line (CMBL)

- The MEGII and the phase IA and IB of Mu3e have similar beam requirements $O(10^8)$ mu/s, 28 MeV/c
- the CMBL allows both experiments to co-exist

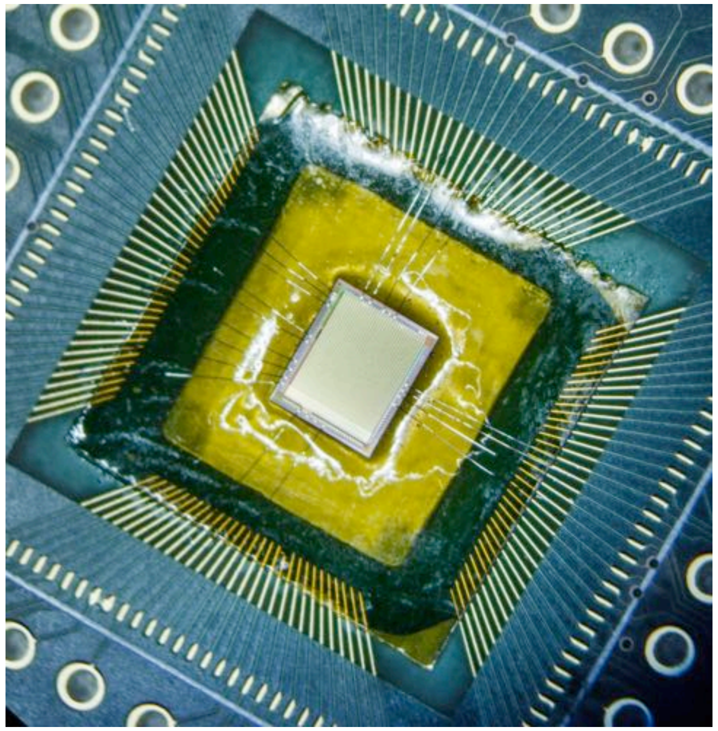
The compact muon beam line (CMBL)

The tracker detector: Mupix

- Based on the High Voltage Monolithic Active Pixel Sensors (HV-MAPs)
- HV-CMOS technology
- Reverserly biased ~60 V
    - fast charge collection via drift <1ns
    - thinned ~50 μm
- Integrated readout electronics
- 5 generation of prototype
    - Mupix 7 is the current version with all features of the final sensors
- Full detection efficiency (> 99%)
- High rate capability (> 1 MHz)
- Timing resolution < 17 ns

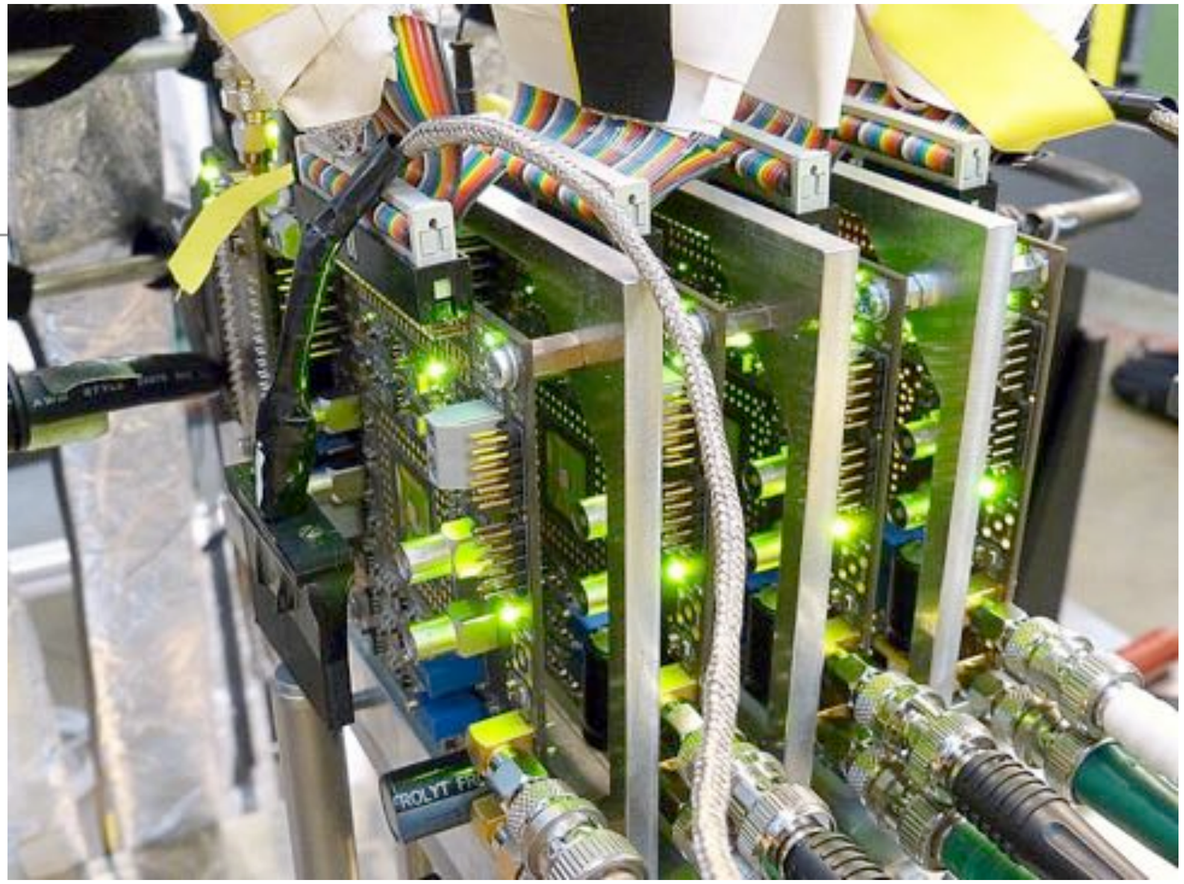


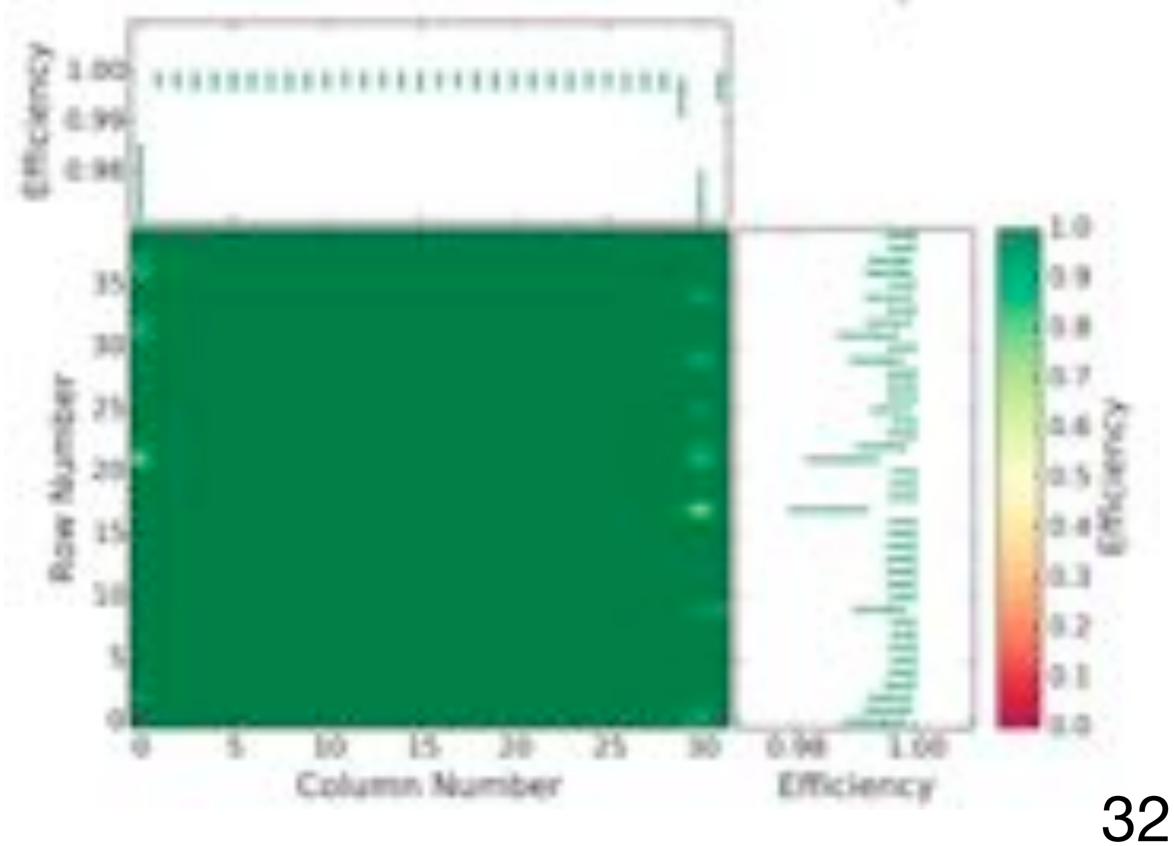
by Ivan Perić
I. Perić, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876



The tracker detector: Mupix

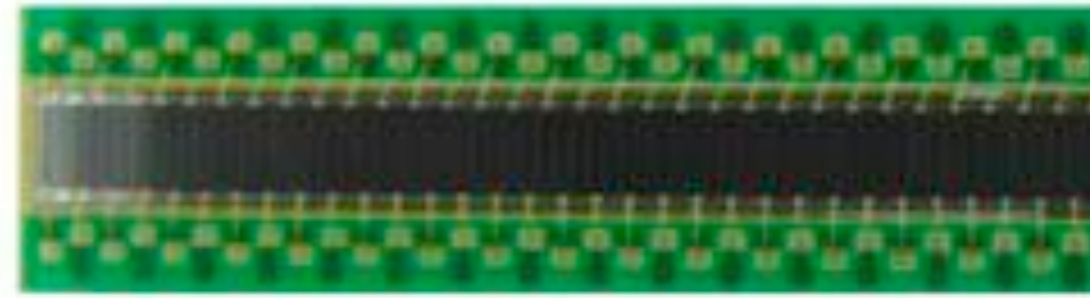
- Based on the High Voltage Monolithic Active Pixel Sensors (HV-MAPs)
- HV-CMOS technology
- Reverserly biased ~60 V
  - charge collection via drift
  - fast <1ns
  - thinning to ~50 μm
- Integrated readout electronics
- 5 generation of prototype
  - Mupix 7 is the current version with all features of the final sensors
- Full detection efficiency (> 99%)
- High rate capability (> 1 MHz)
- Timing resolution < 17 ns

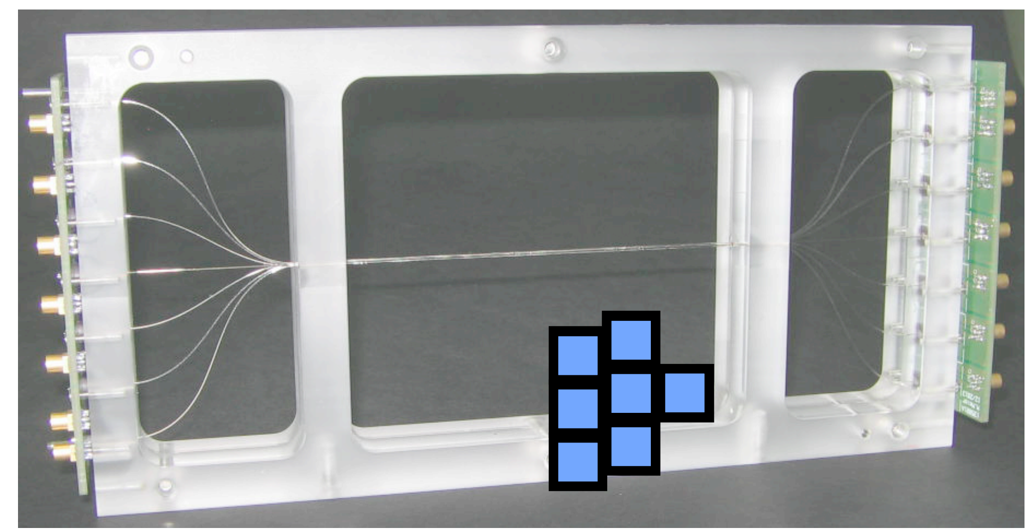


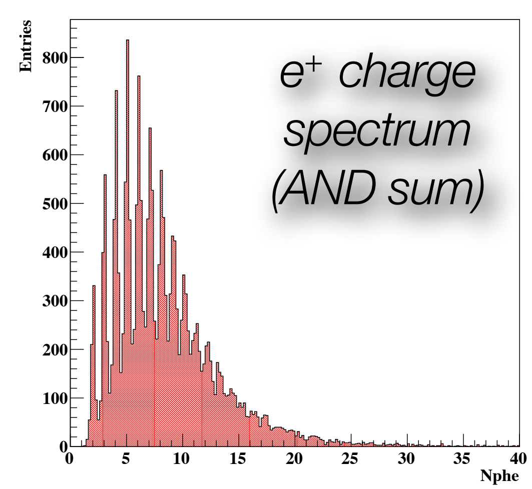


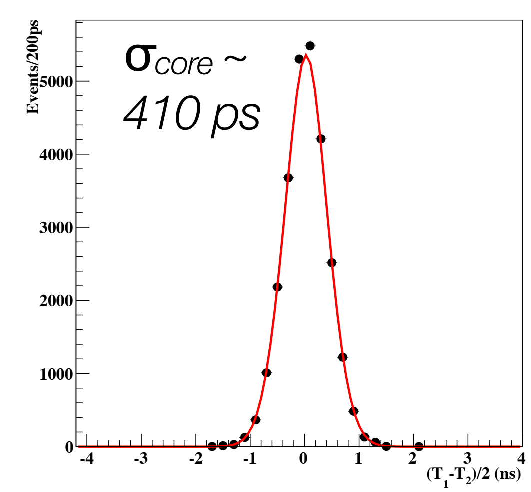
The timing detector: SciFi

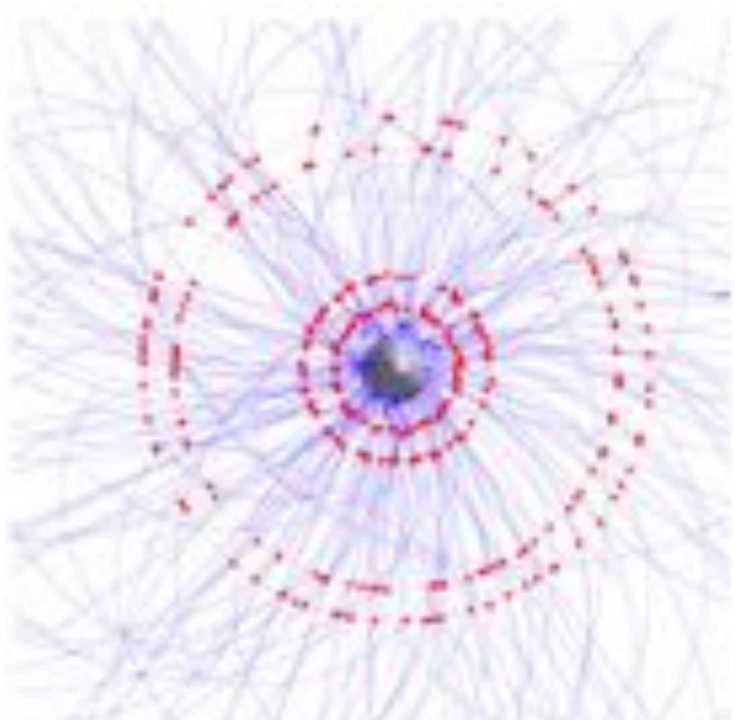
- Precise timing measurement is critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)



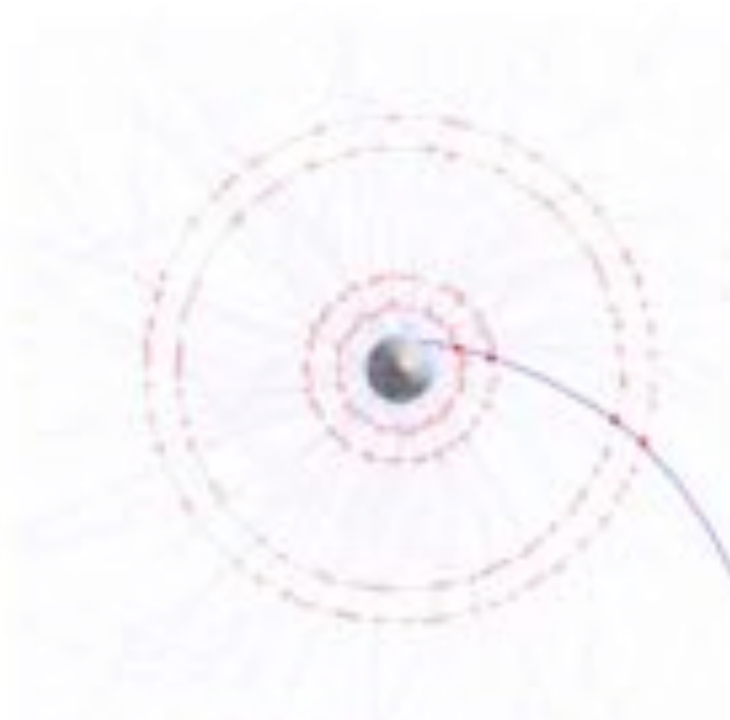






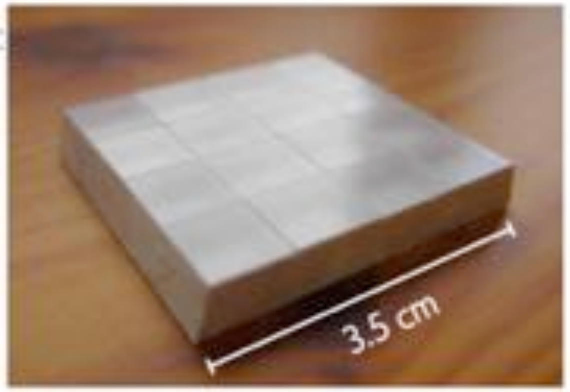


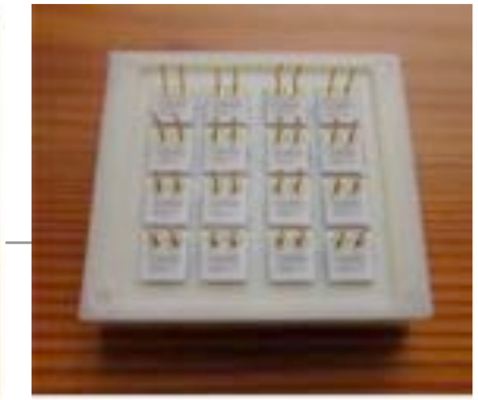
Pixels: O(50 ns)

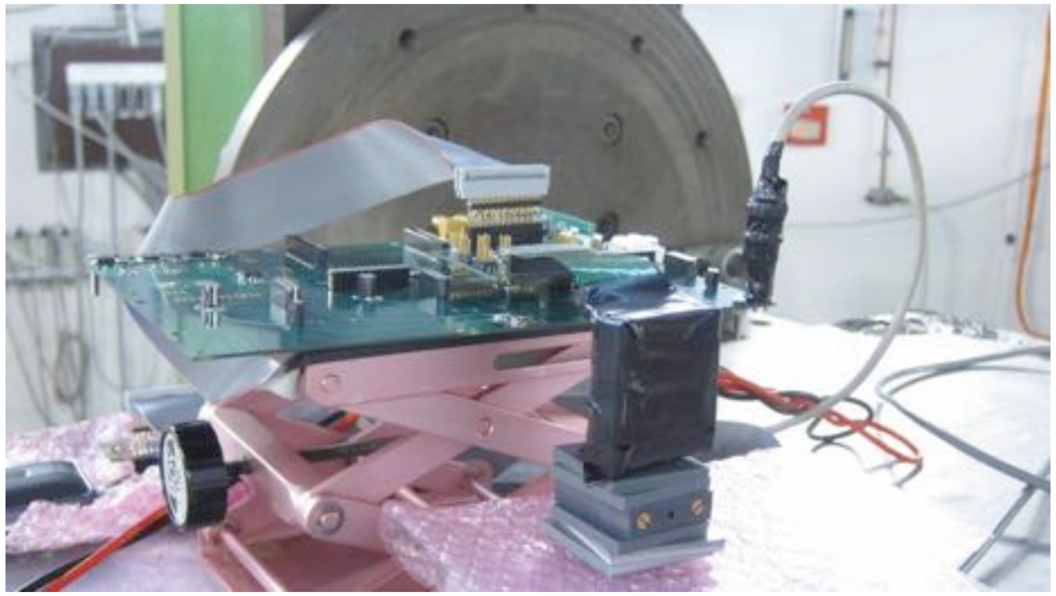


Scintillating fibres O(1 ns); Scintillating tiles O(100 ps)

The timing detector: Tiles







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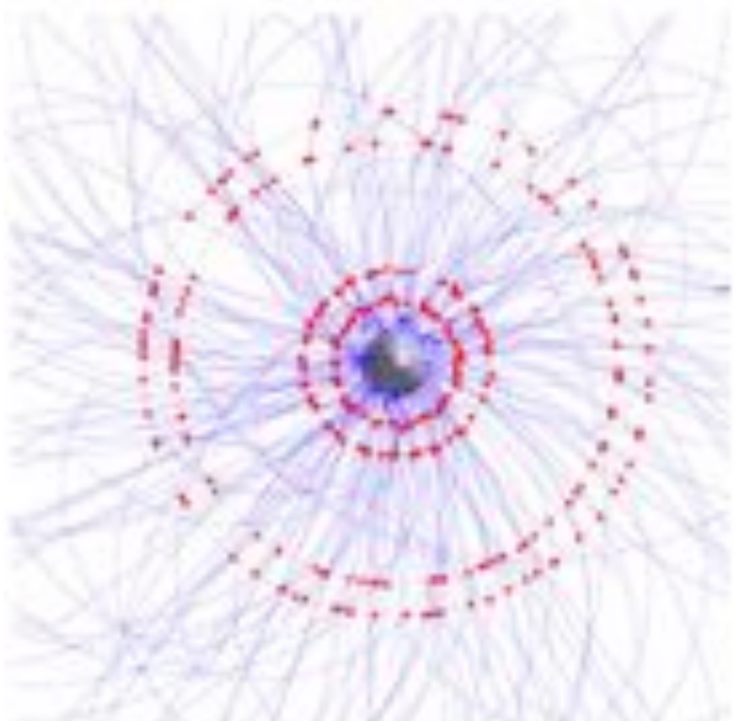
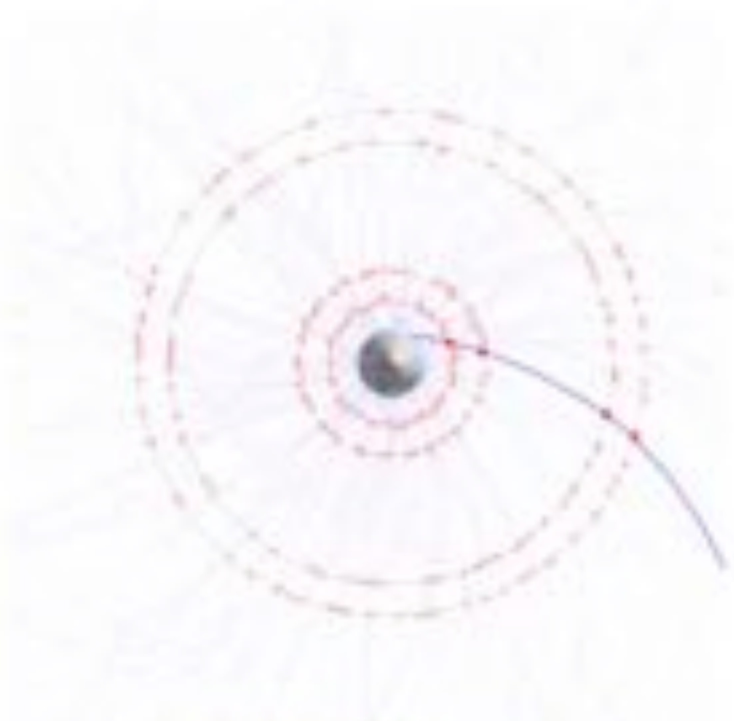
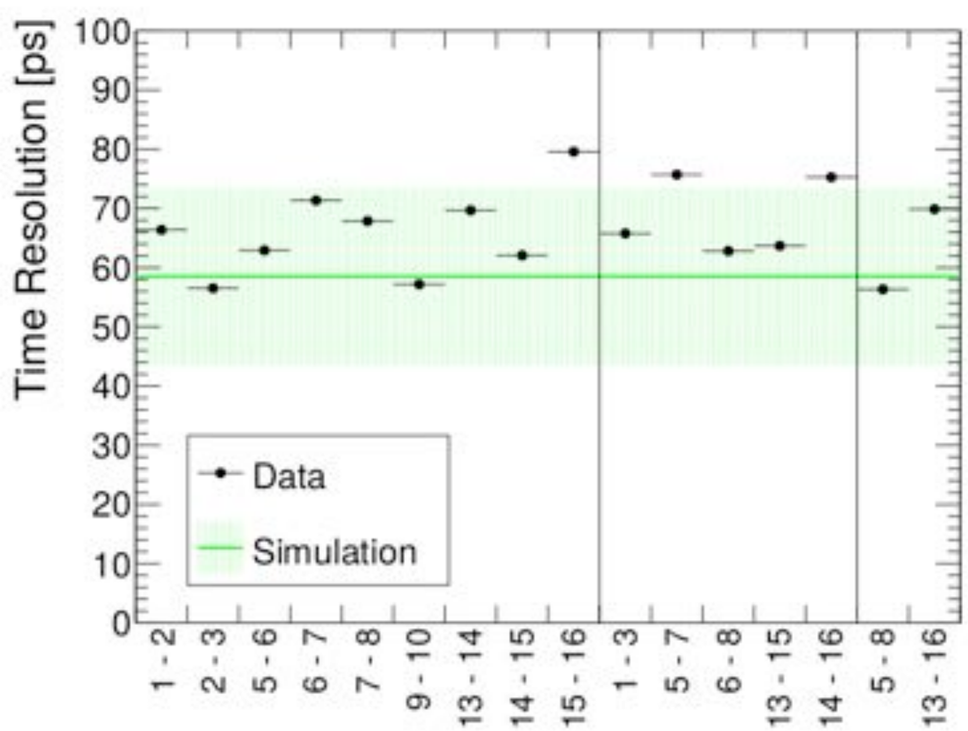


Pixels: O(50 ns)



Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)



Summary

- 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**

- 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}**

- Mu3e detector R&D in progress
  - an experiment completely based on new technologies
  - improved sensitivity on **$B(\mu^+ \rightarrow e^+ e^+ e^-)$** by 4 order of magnitude aiming at **few $\times 10^{-16}$**

Back-up

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

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

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

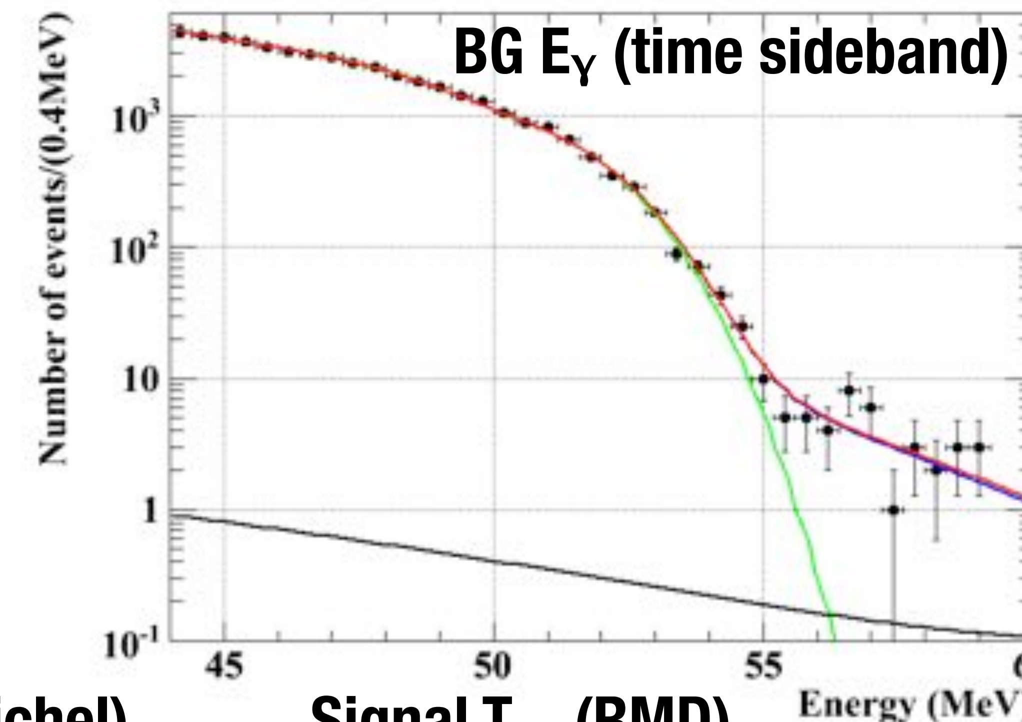
Probability Density Functions

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

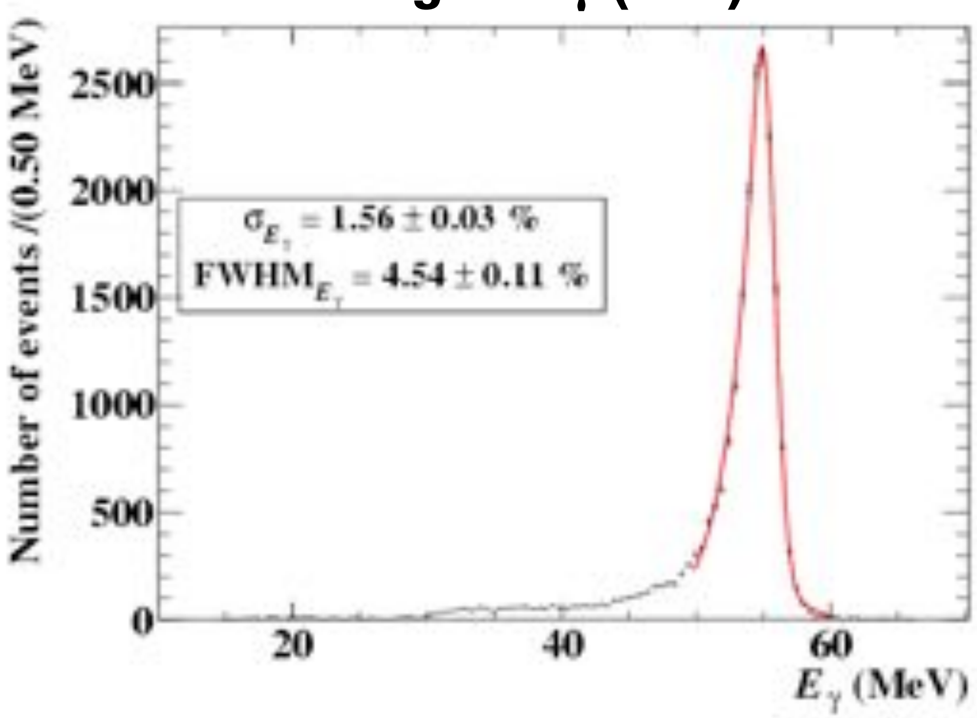
The signal PDF *S* is the product of the PDFs for Ee, θeγ, Φeγ,Teγ which are correlated variables, and the Eγ PDF

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

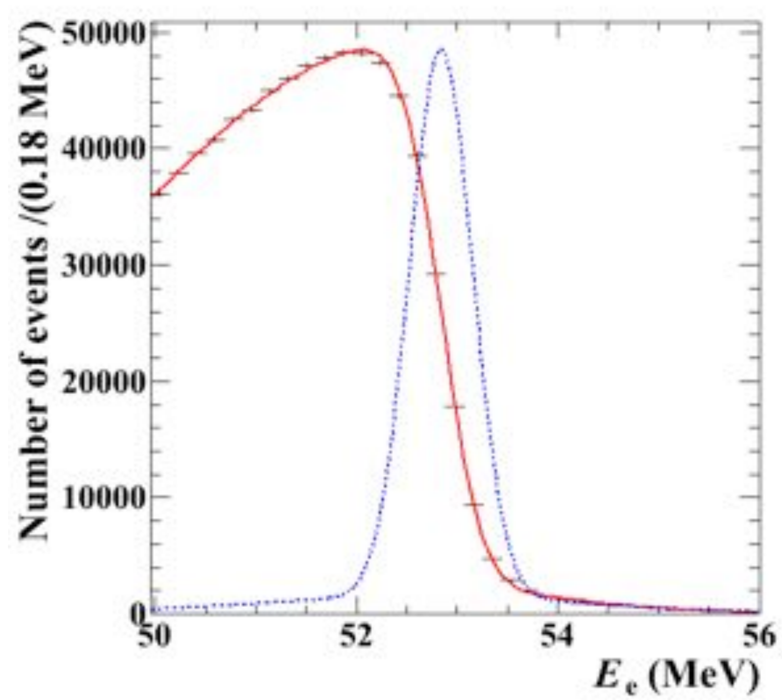
The BG PDF *B* is the product of the five PDFs, each of which is defined by the single background spectrum, precisely measured in the sidebands



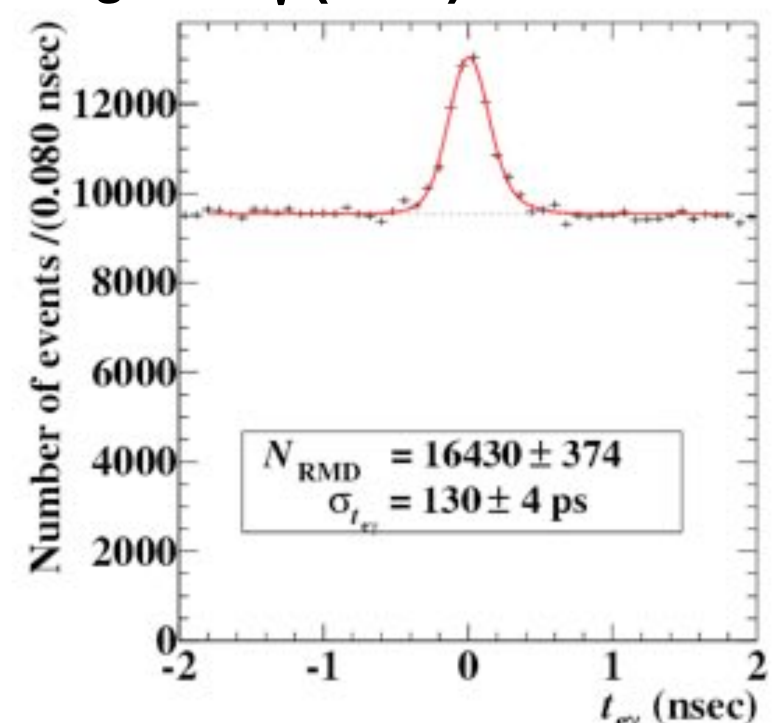
Signal Eγ (CEX)



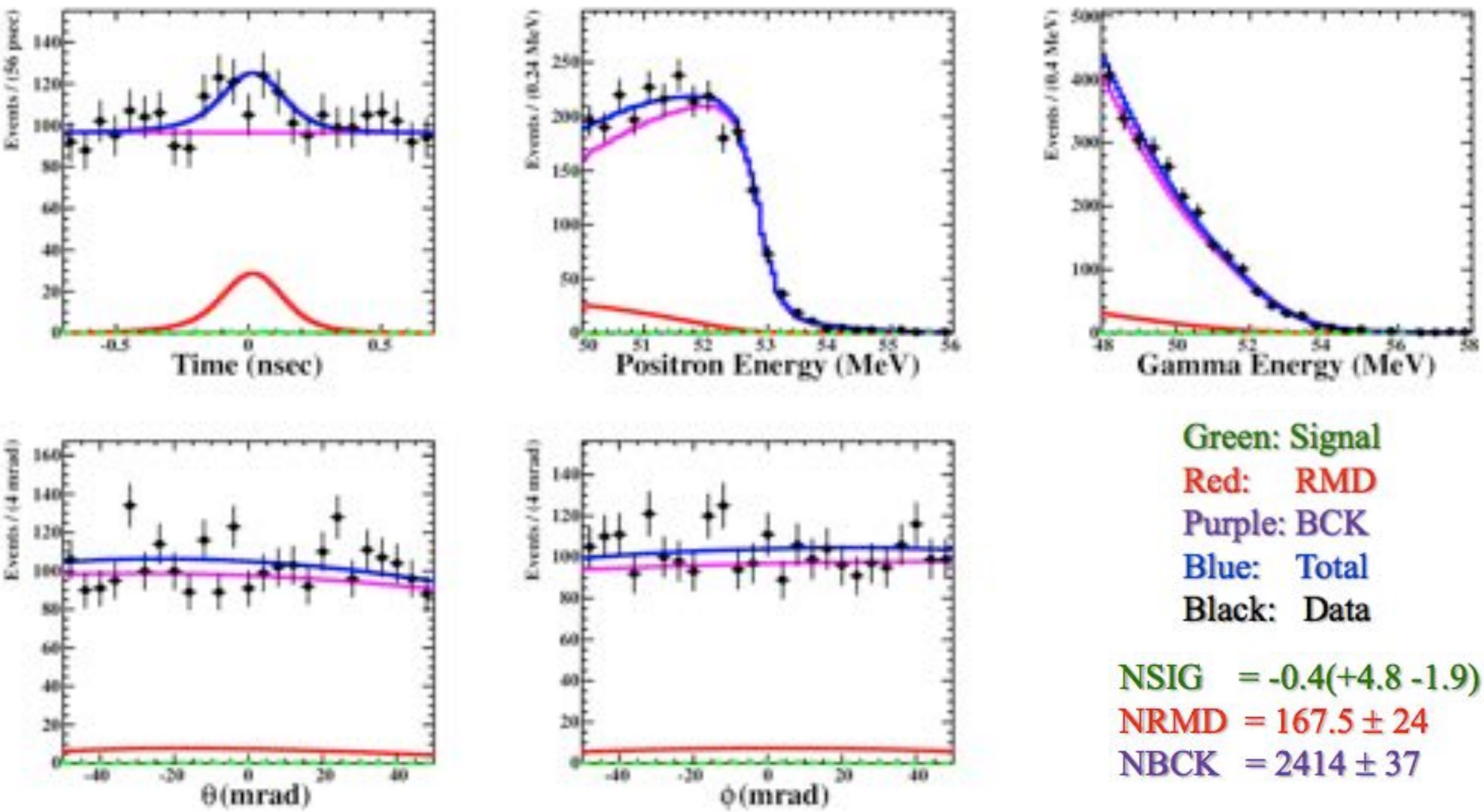
Signal Ee /BG (Michel)



Signal Teγ (RMD)

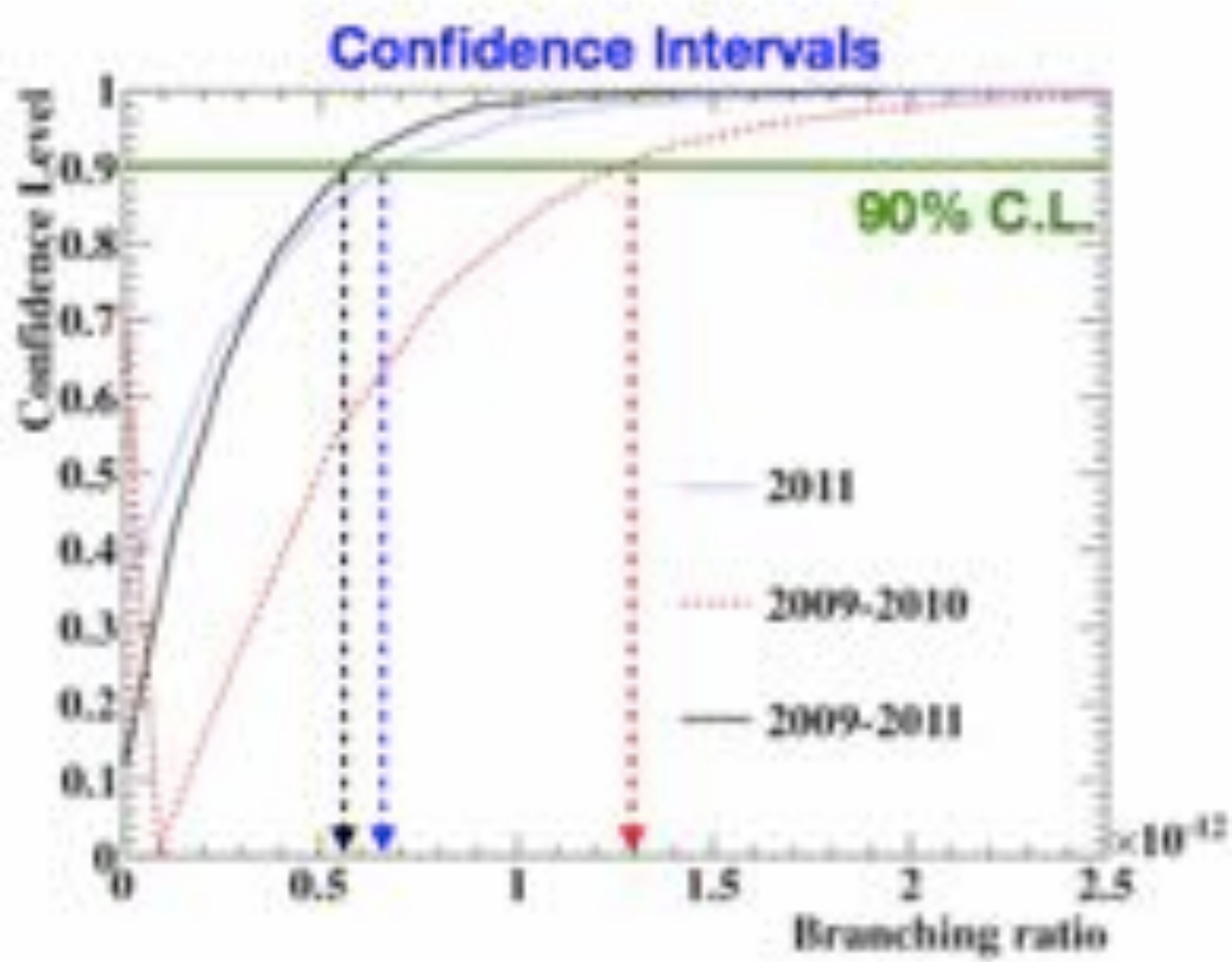


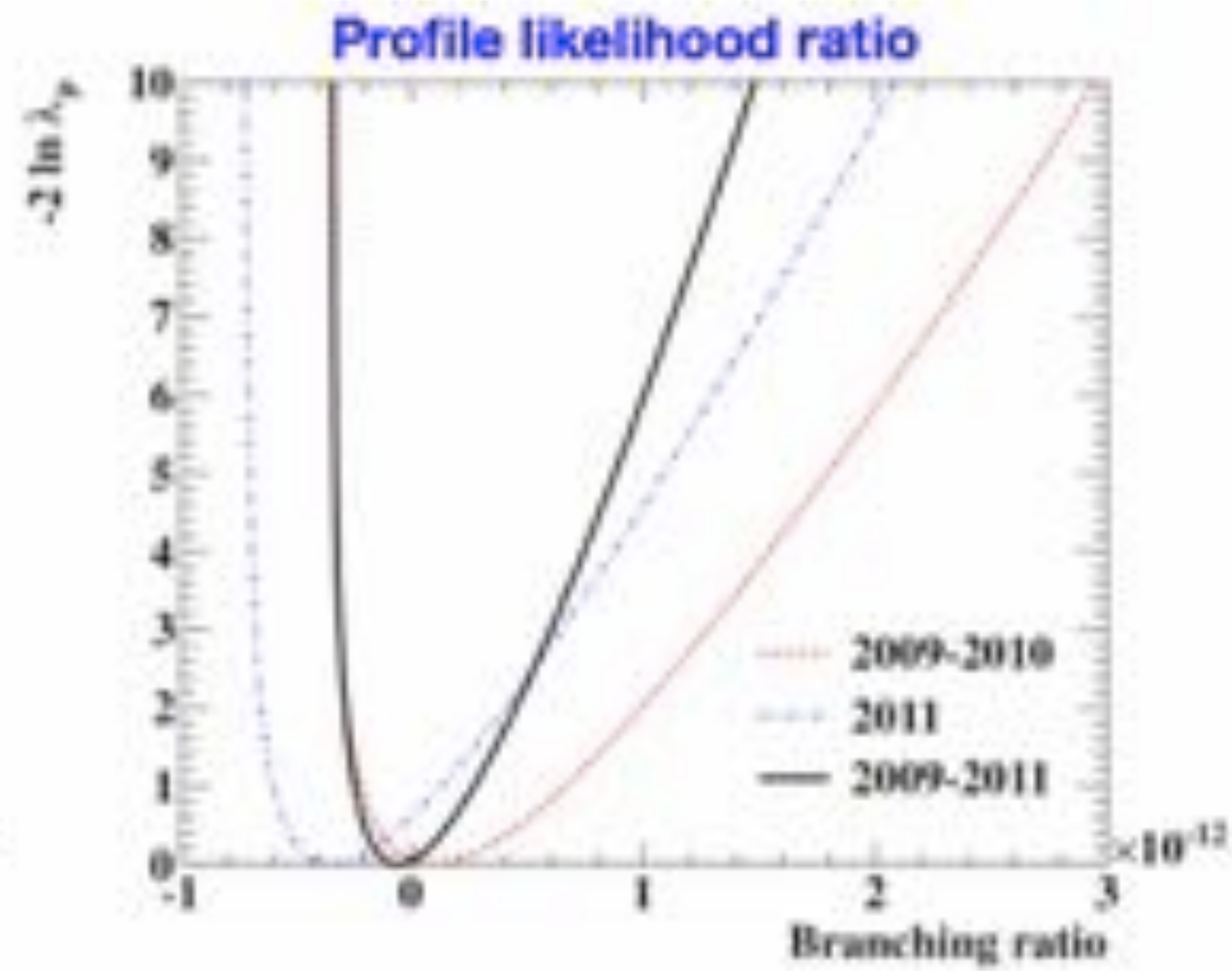
Likelihood Fit (2009-2011)



Confidence Interval

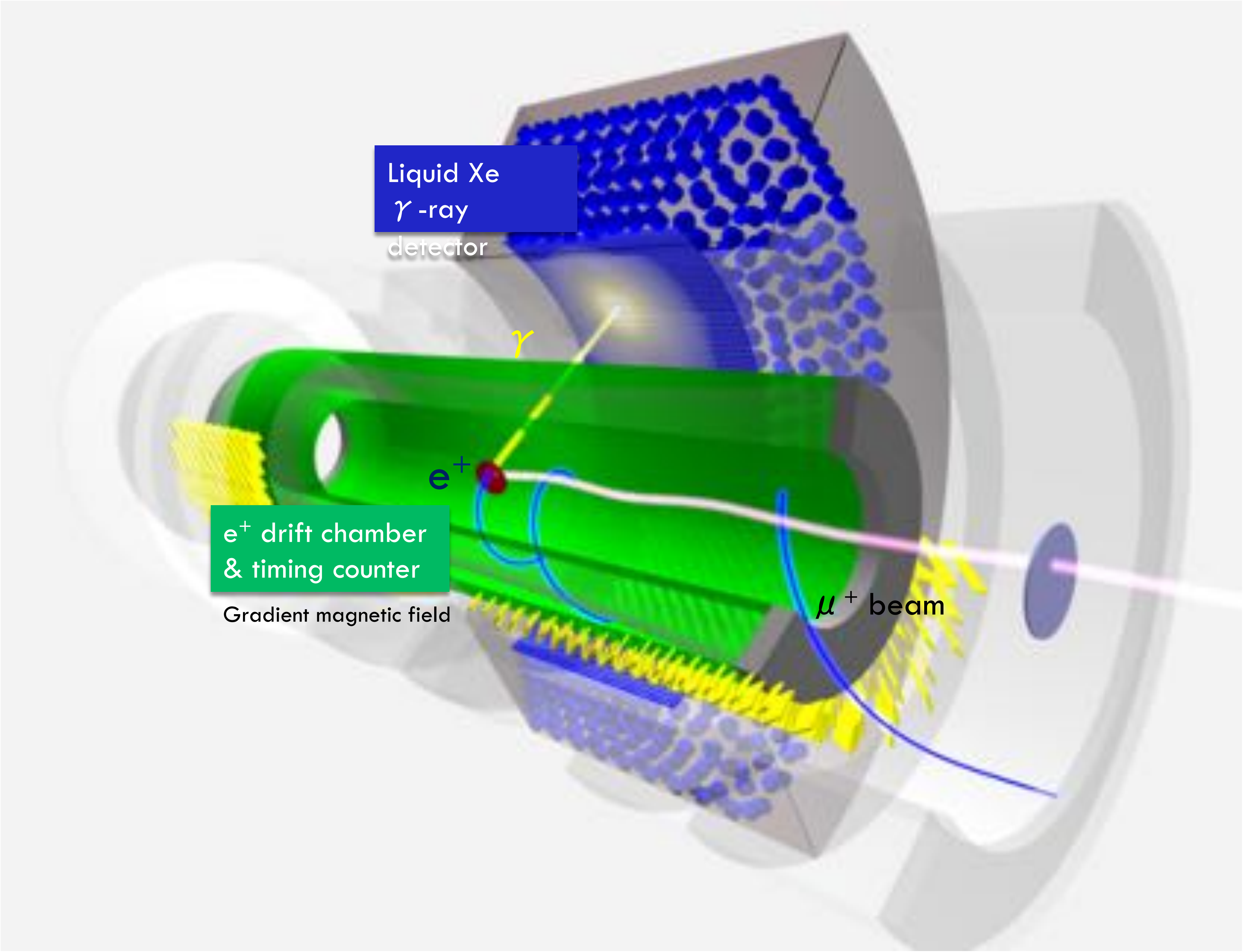
- Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering



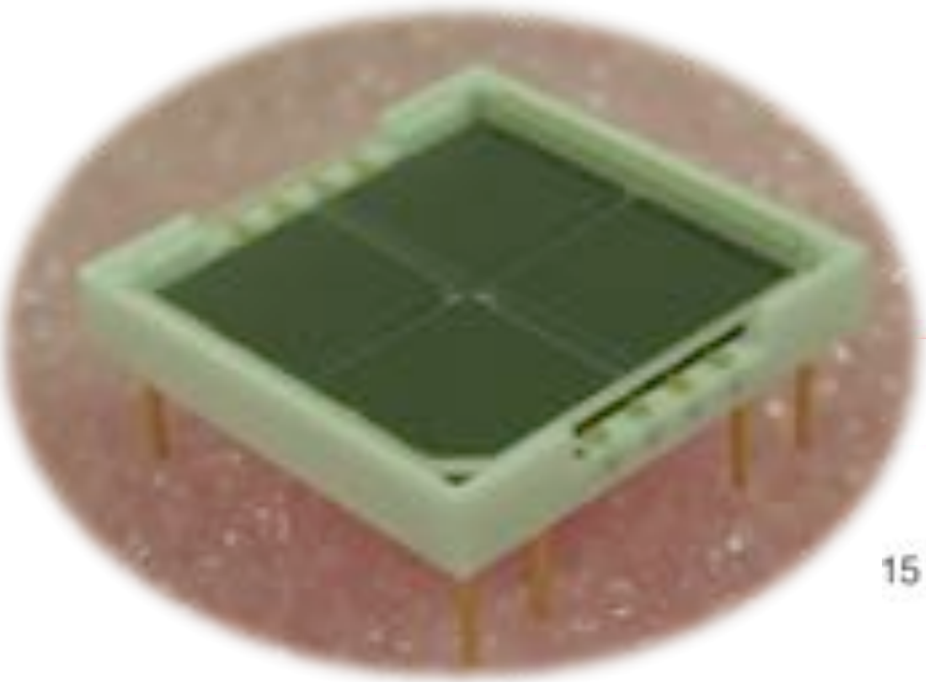


Consistent with null-signal hypotesis

The MEGII experiment - 3D view

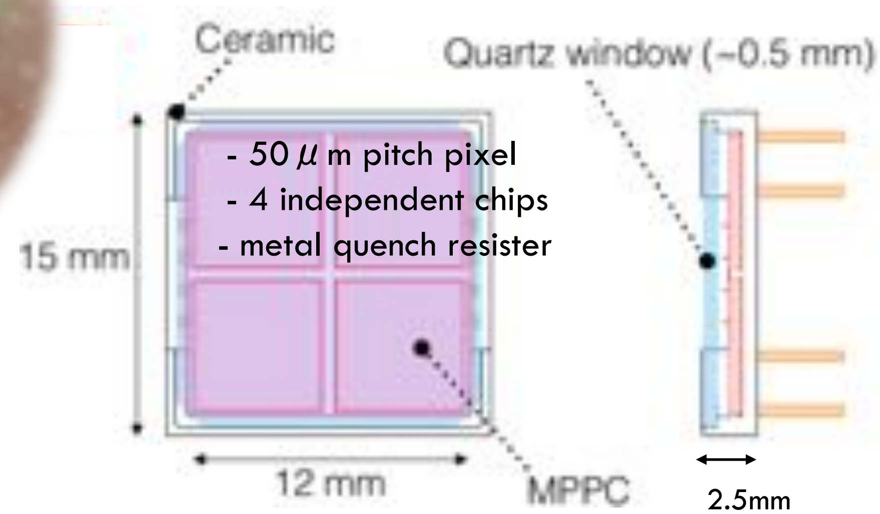


VUV-sensitive SiPM (MPPC using Hamamatsu convention)



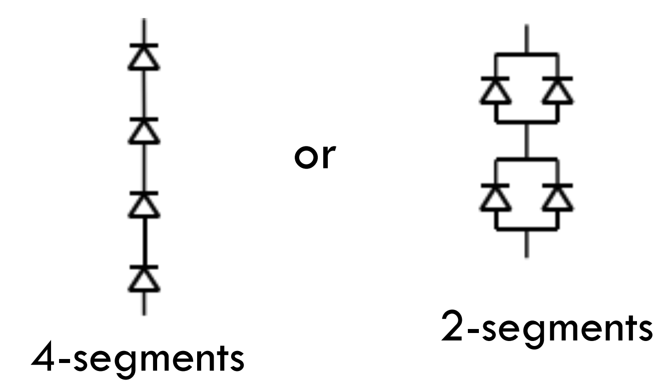
We have successfully developed **VUV-MPPC** in collaboration with Hamamatsu Photonics. K.K.

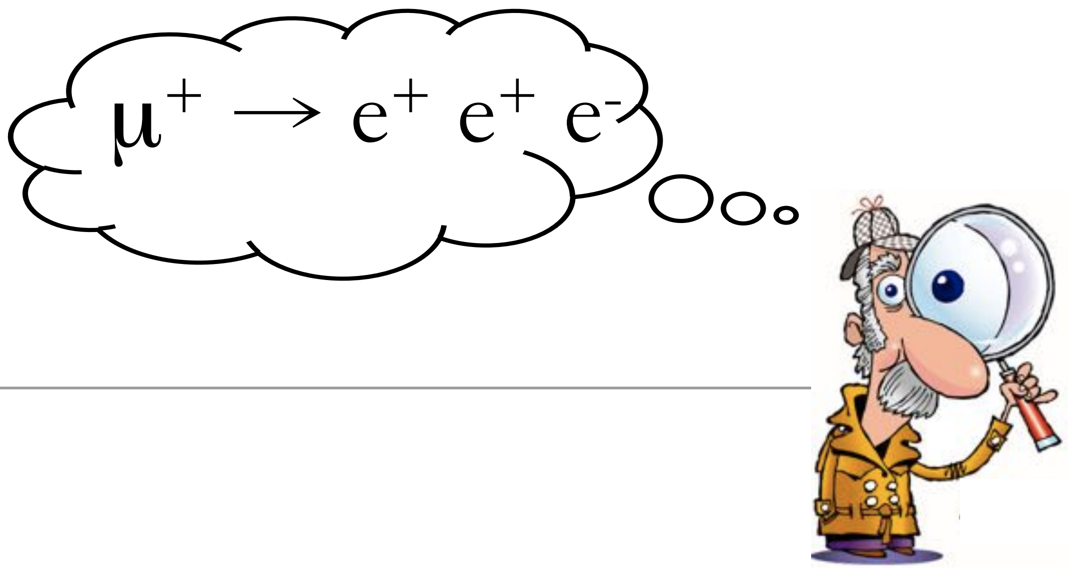
- **Sensitive to VUV-light**
  → Protection coating is removed, VUV-transparent quartz window is used for protection.



Hamamatsu S10943-3186(X)

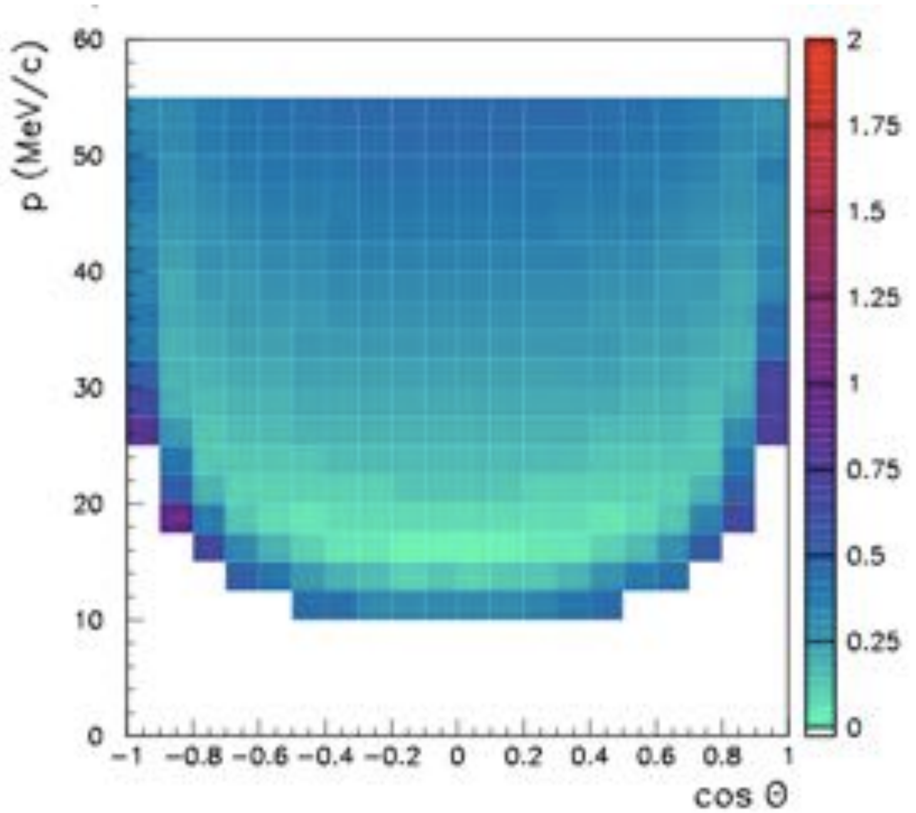
- **Large area (12x12 mm^2)**
  → signal tail become long due to large capacitance.
  →Reduce capacitance by connecting 4 chips in series.

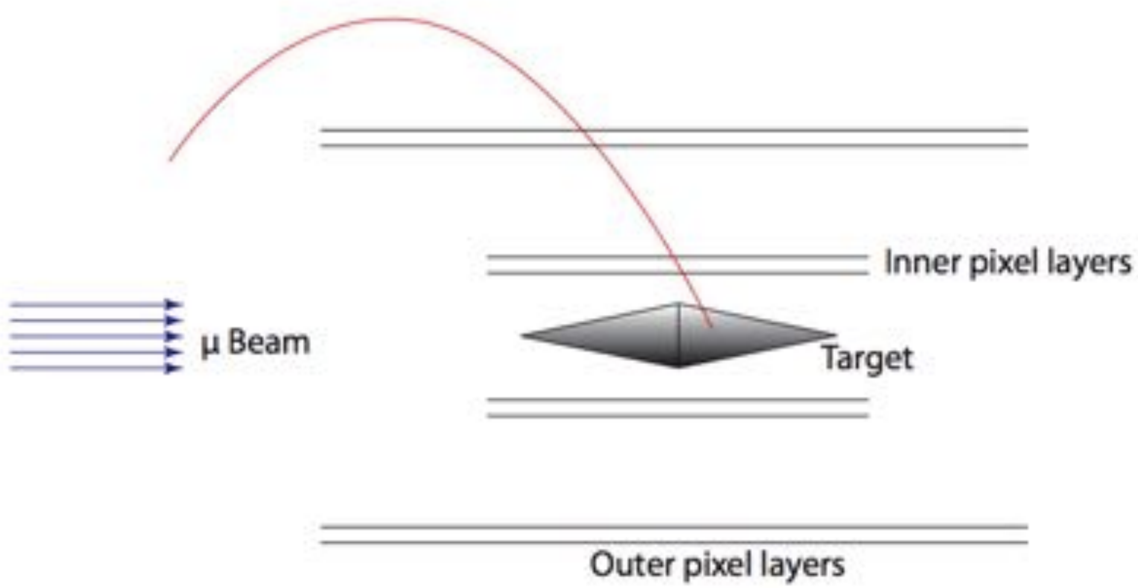




The Mu3e experiment

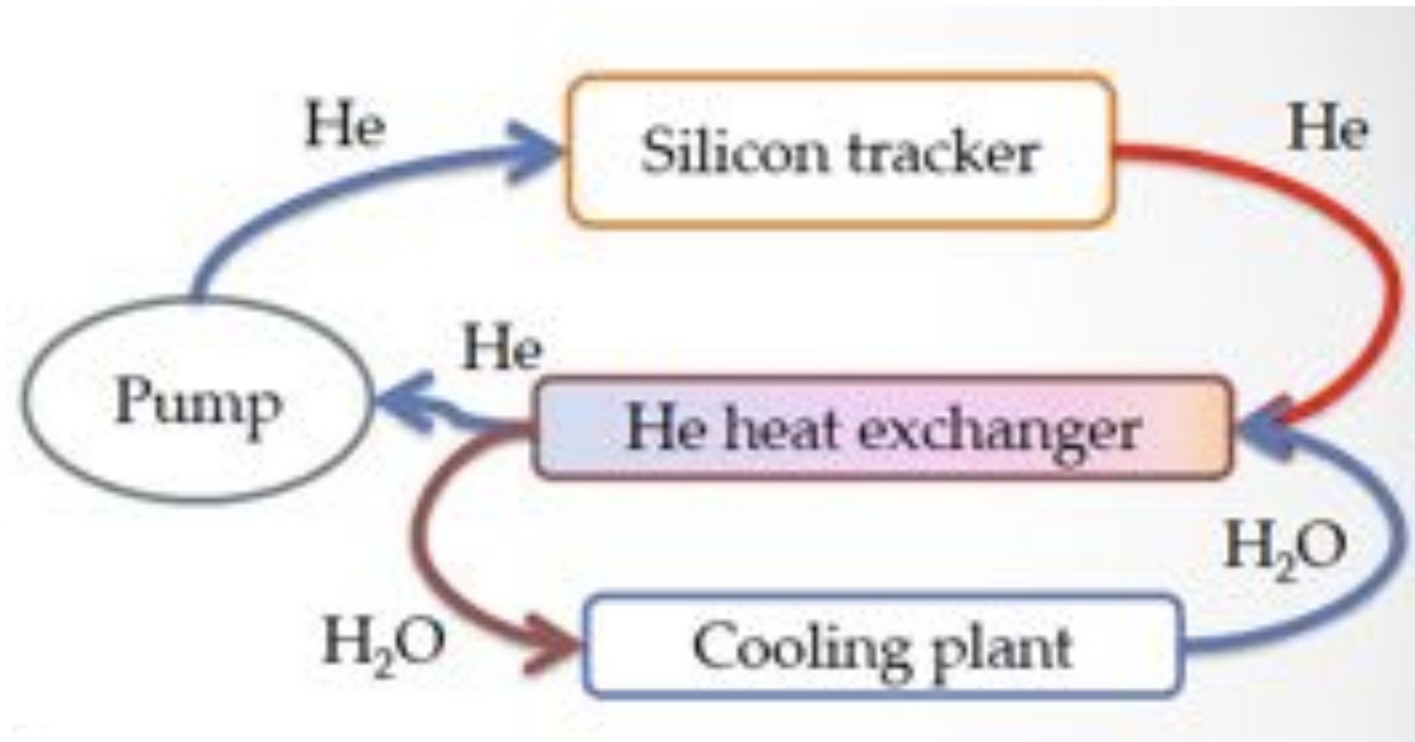
- Pixel dimension: 80 x 80 um^2
- Thinning to 50 um
- The sensor and read-out are integrated on the same device
- Momentum resolution < 0.5 MeV/c over a large phase space
- Vertex resolution < 200 um

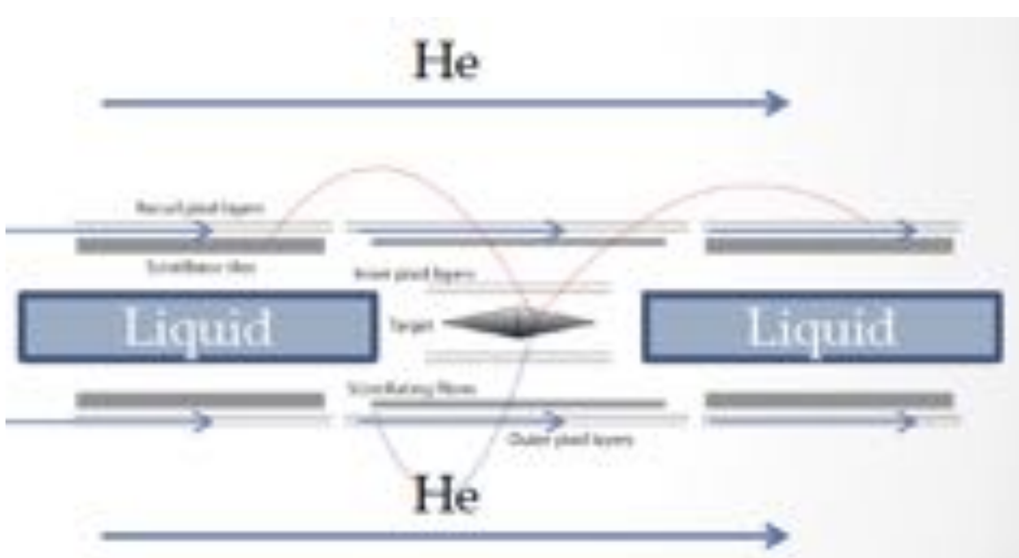


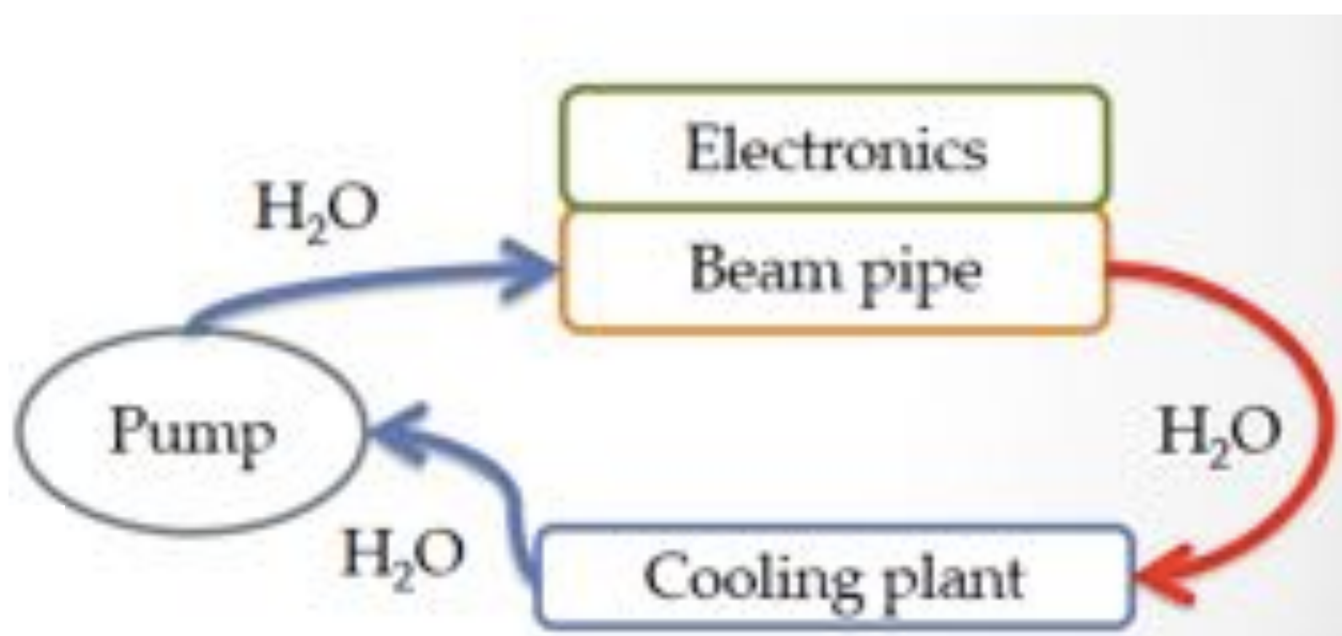


Cooling concept

- Gaseous He cooling
  - for silicon tracker
  - low radiation length
  - global flow
  - local direct cooling
- Liquid cooling
  - for readout electronics
  - integrated in beam-pipe

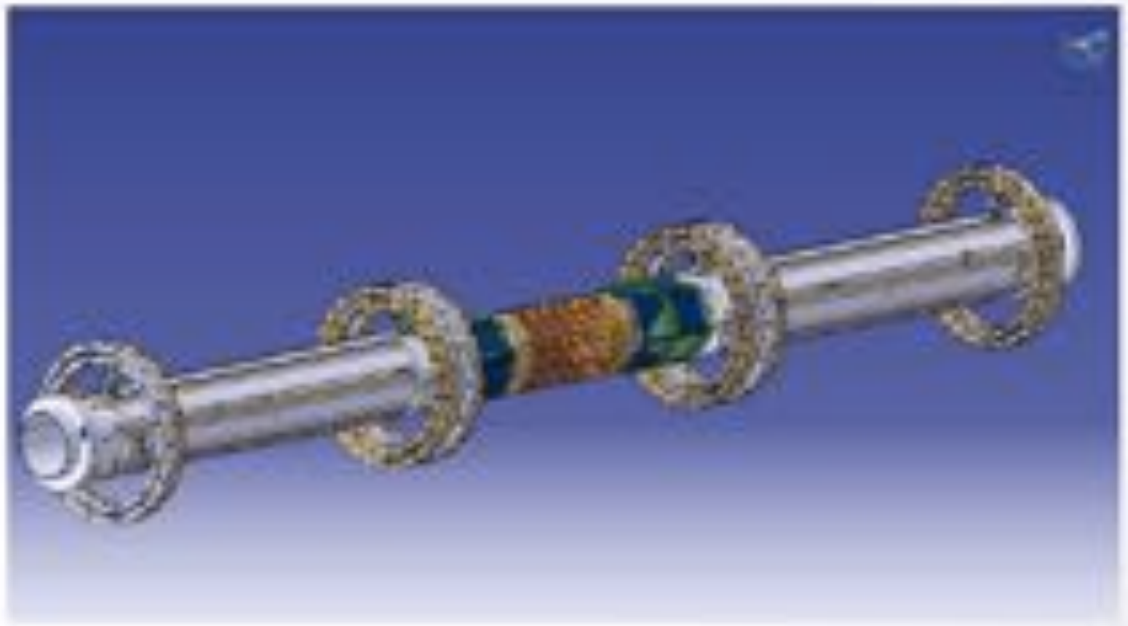






Beam Pipe

- Stainless steel pipe
  - Shields against background
- Mechanical support
  - Detectors attached to beam pipe
  - Via end rings
- Read-out PCBs attached
  - FPGAs mounted directly
  - Integrated cooling



Beam pipe design

Beam pipe supports detectors