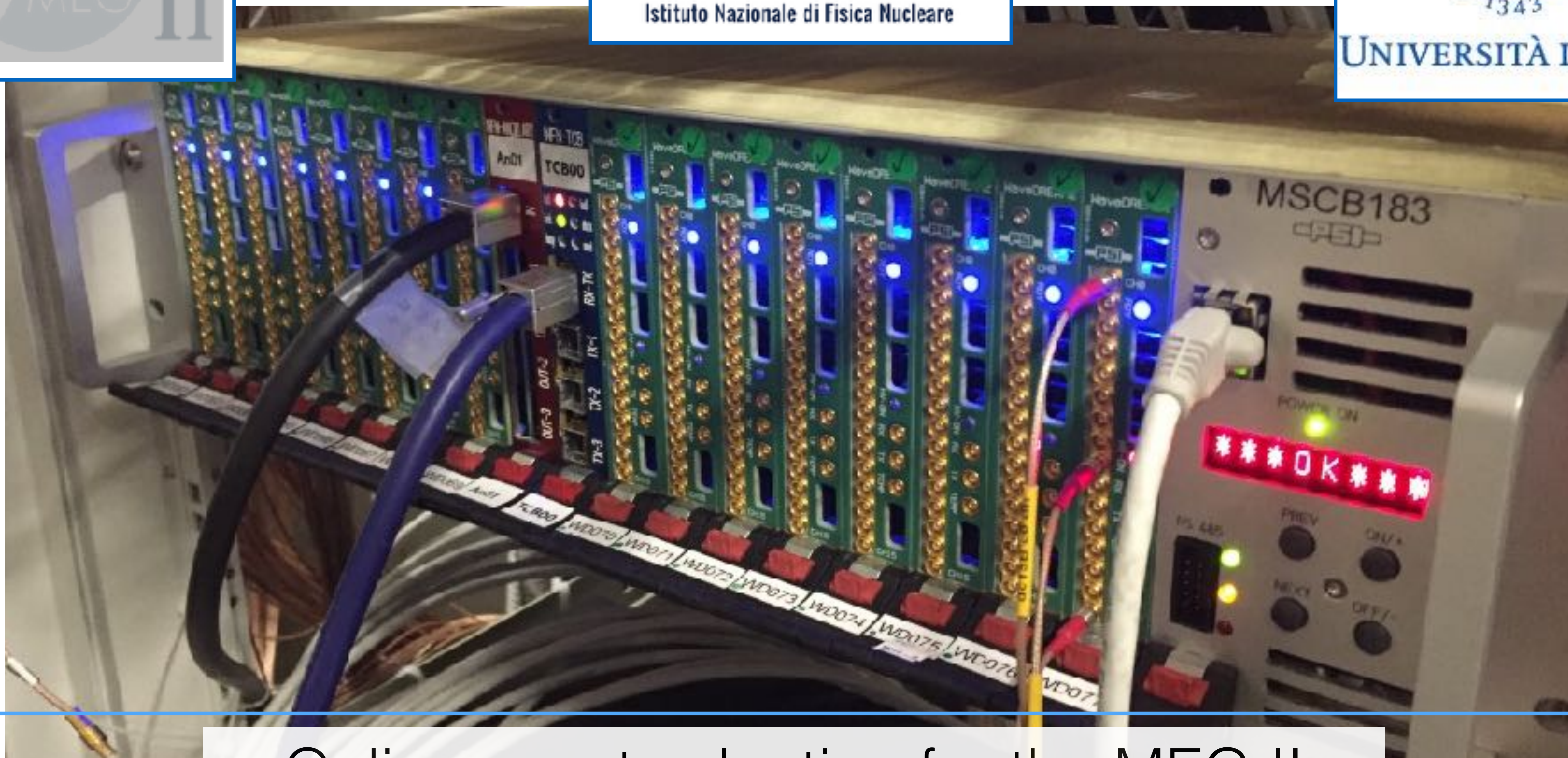
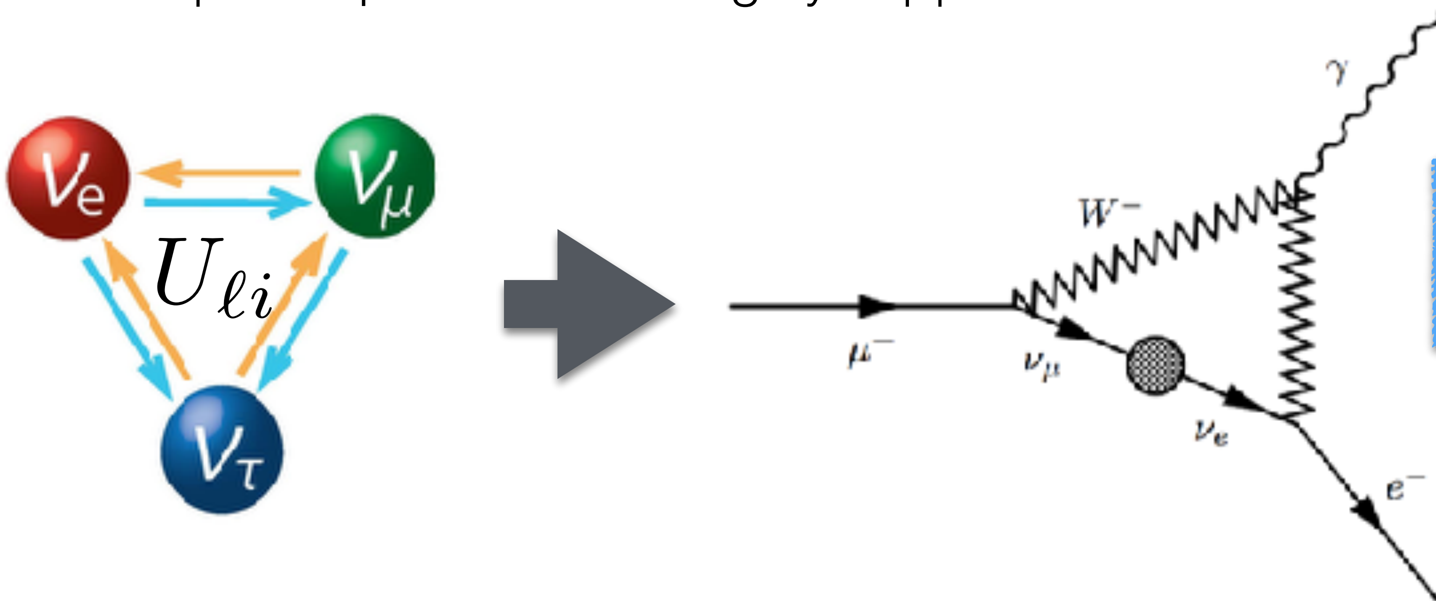


Online event selection for the MEG II Experiment

Marco Francesconi
on the behalf of MEGII collaboration
2nd year Ph.D. seminar - Pisa 22/10/2018

The μ⁺→e⁺γ decay

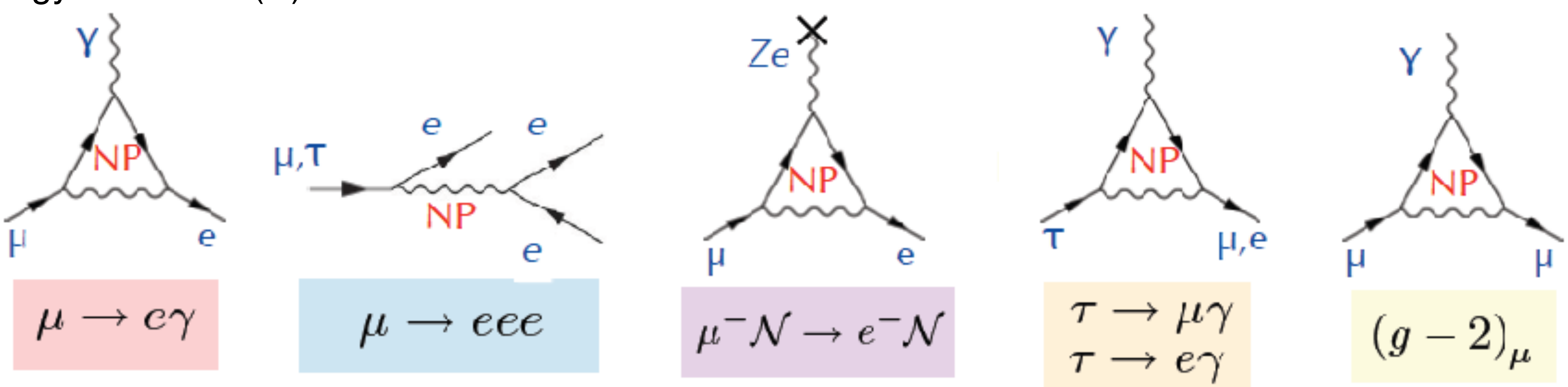
- The decay is **forbidden for conservation of lepton flavor** in Standard Model
- However lepton flavor is violated by the neutrino oscillations → Mixing in lepton sector
  - So μ⁺→e⁺γ exists but is highly suppressed in massive-neutrino SM modifications



$$\mathcal{B}(\mu \to e\gamma) \propto \left| \sum_{i,j=1,2,3} U^*_{\mu i} U_{ej} \frac{\Delta m^2_{ij}}{m^2_W} \right|^2 \approx 10^{-54}$$

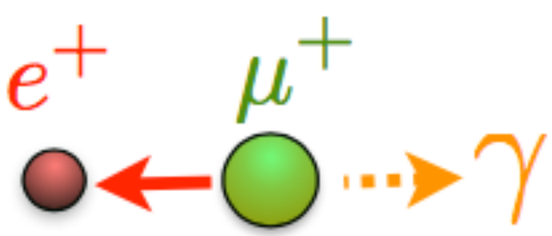
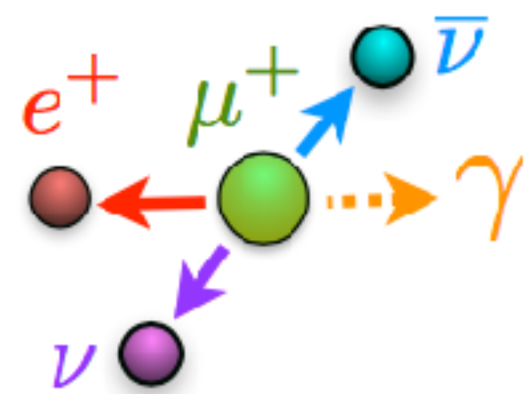
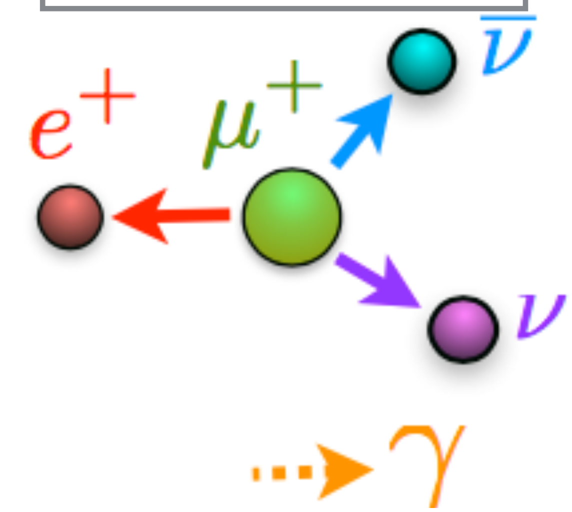
SM contribution negligible

- Loop process, can get contributions from **Beyond SM Physics**
- Synergy with other (C)LFV searches



MEG | Mu3e | Mu2e, COMET | Belle II | Gminus2

Signal and Backgrounds

Signal	Irreducible Background:	Accidental Background:
		
$E_\gamma = 52.8$ MeV	$E_\gamma < 52.8$ MeV	$E_\gamma < 52.8$ MeV
$E_{e^+} = 52.8$ MeV	$E_{e^+} < 52.8$ MeV	$E_{e^+} < 52.8$ MeV
$\Theta_{e\gamma} = 180°$	$\Theta_{e\gamma} < 180°$	$\Theta_{e\gamma} < 180°$
$T_{e\gamma} = 0$ s	$T_{e\gamma} = 0$ s	$T_{e\gamma} \Rightarrow$ flat

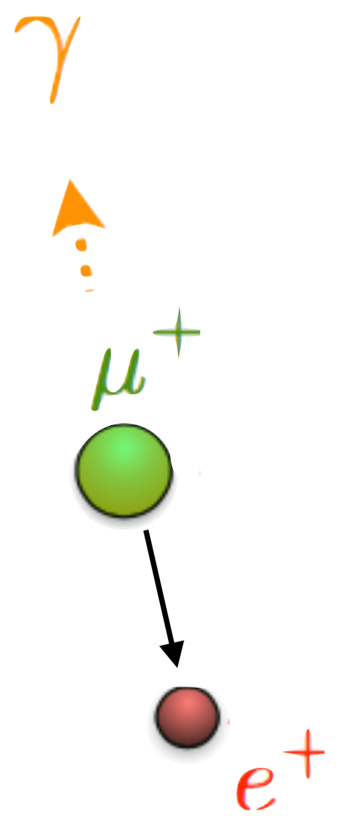
Photon from: RMD, AIF, Bremsstrahlung

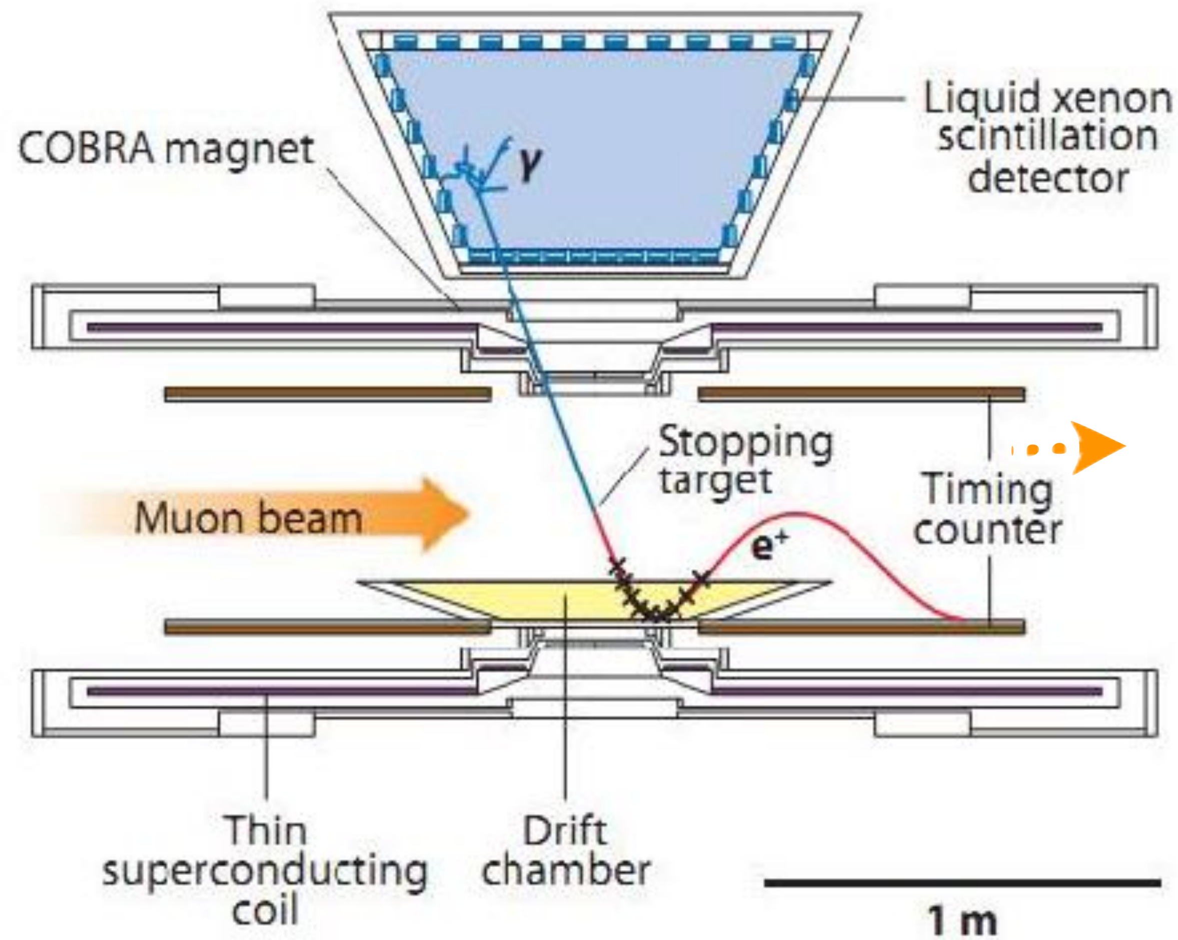
$$R_{Rad} = R_\mu \mathcal{B}(\mu \to e\nu\bar{\nu}\gamma | \Delta E_\gamma, \Delta E_e, \Delta\Theta_{e\gamma})$$

$$R_{Acc} \approx R_\mu^2 \cdot \Delta E_e \cdot \Delta E_\gamma^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

Dominating for high muon rates R_μ

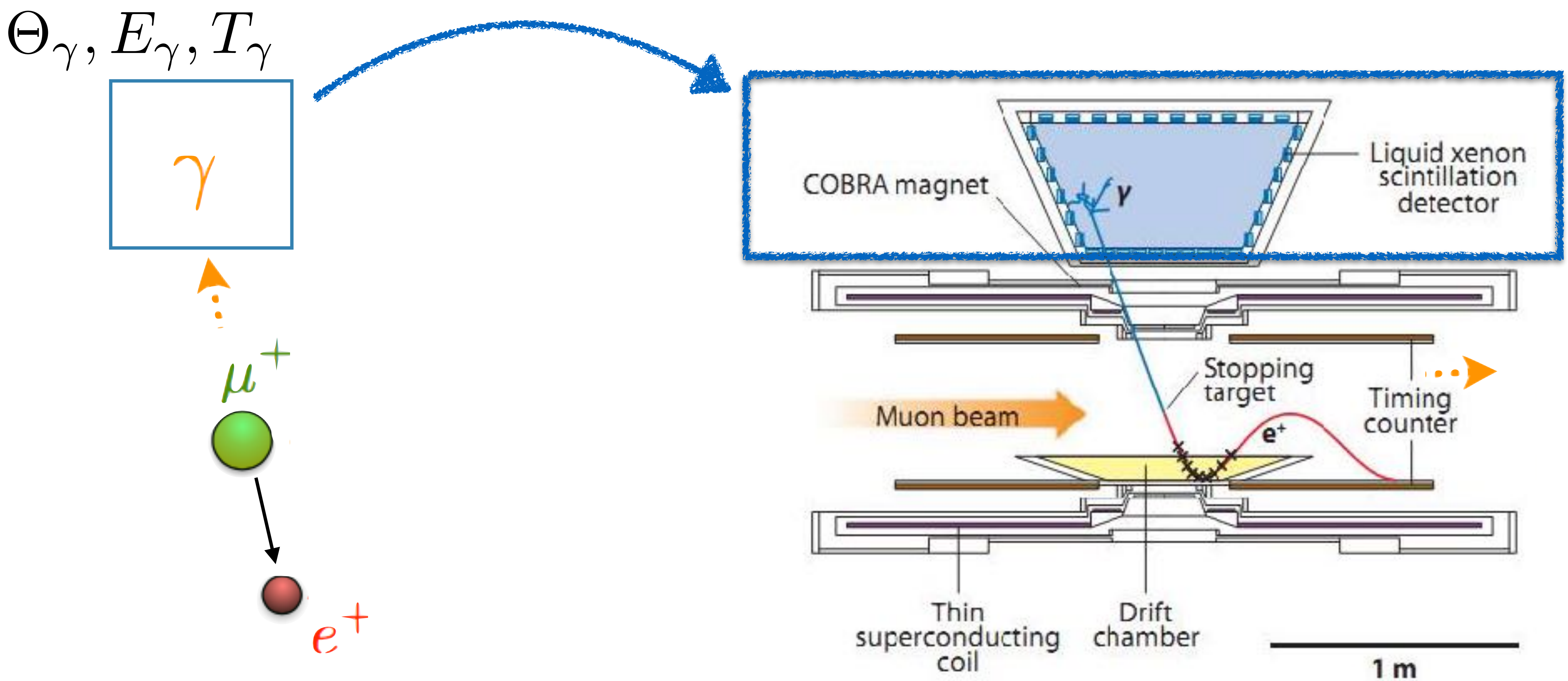
MEG detection strategy





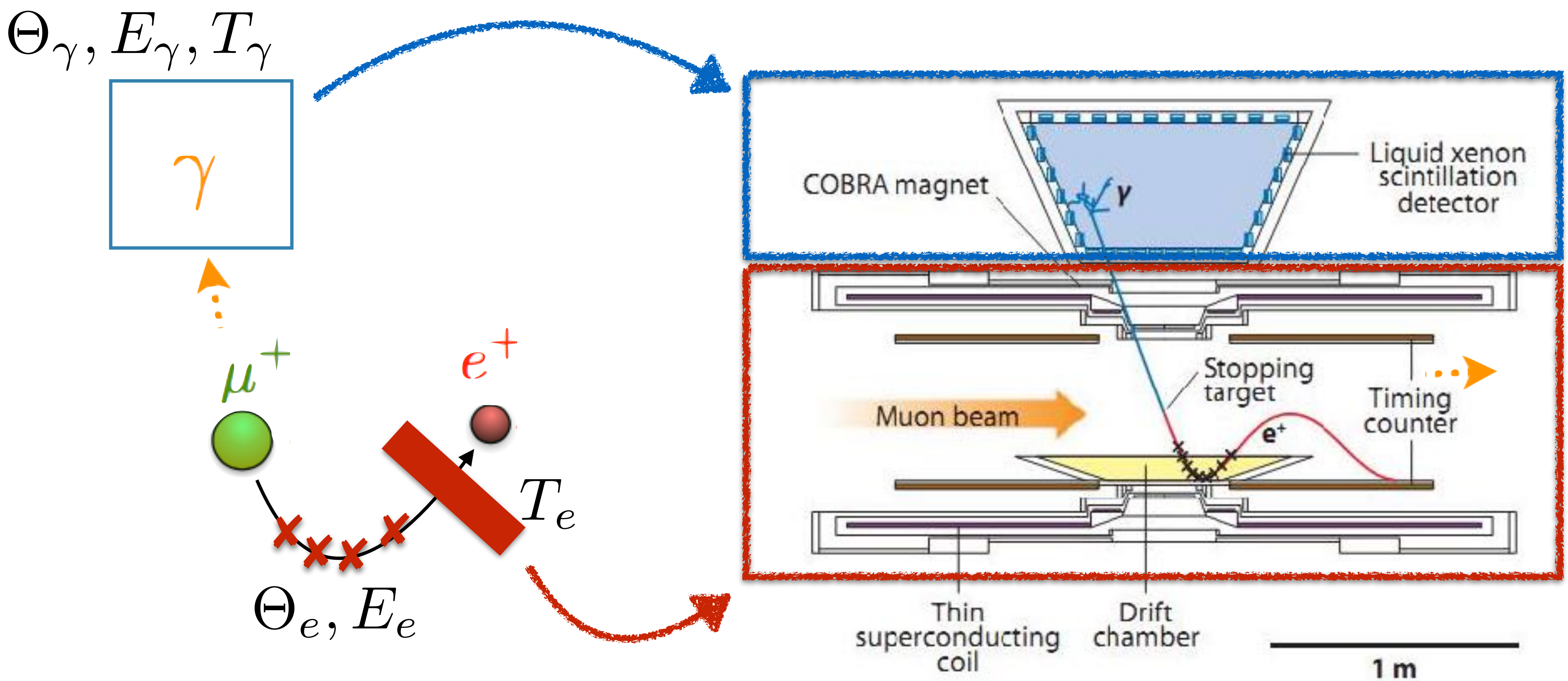
- **Stop muon** at center of experiment→ High intensity continuous muon beam needed (7x10^7 mu/s @ Paul Scherrer Institut)

MEG detection strategy



- **Stop muon** at center of experiment→ High intensity continuous muon beam needed (7x10^7 mu/s @ Paul Scherrer Institut)
- **Liquid Xenon detector** (scintillation calorimeter) to reconstruct gamma variables

MEG detection strategy



- **Stop muon** at center of experiment→ High intensity continuous muon beam needed (7x10^7 mu/s @ Paul Scherrer Institut)
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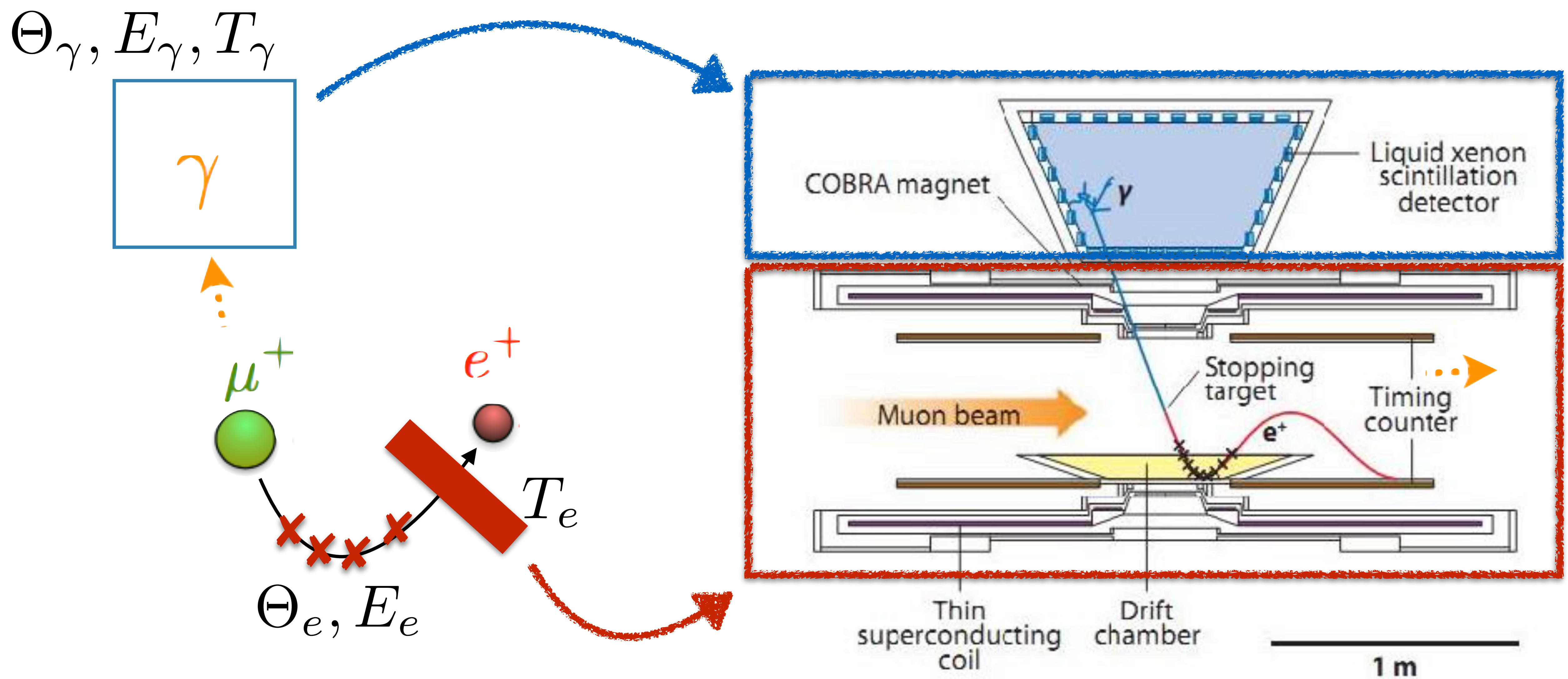
- **Magnetic Spectrometer** (drift chamber + TOF) to detect the positron

MEG detection strategy



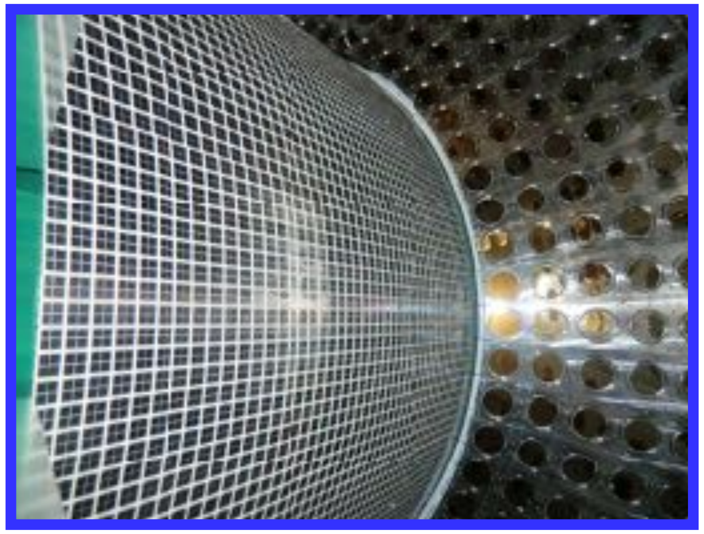
- **Stop muon** at center of experiment→ High intensity continuous muon beam needed (7x10[7] mu/s @ Paul Scherrer Institut)
- **Liquid Xenon detector** (scintillation calorimeter) to reconstruct gamma variables
- **Magnetic Spectrometer** (drift chamber + TOF) to detect the positron
- Dedicated online event selection and offline full-waveform analysis (chip DRS4)

$$\mathcal{B}(\mu^+ \to e^+ + \gamma) \leq 4.2 \times 10^{-13} \ (90\% \ CL)$$

From MEG I to MEG II

LXe

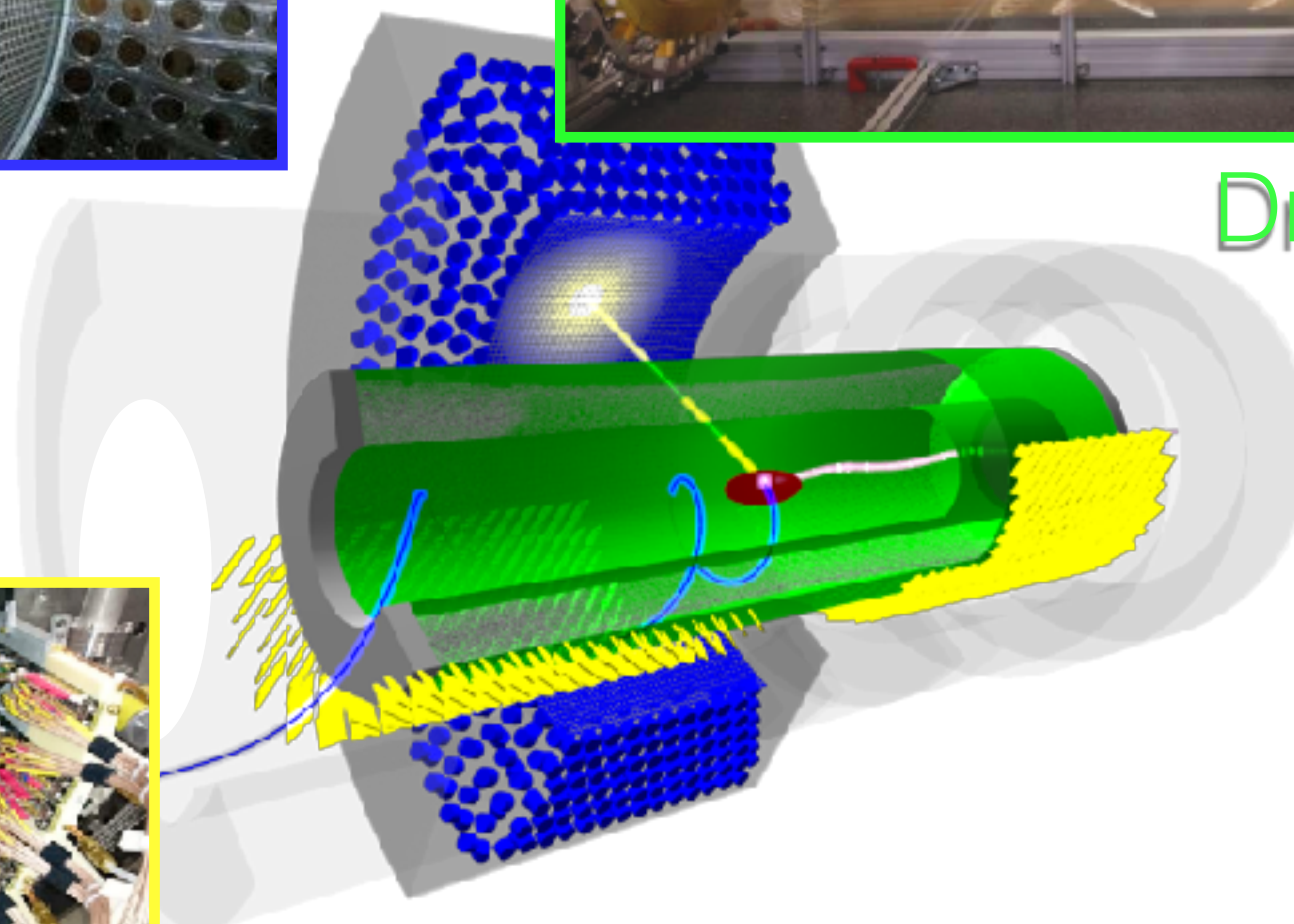
Scintillation Detector
4092 **SiPMs**
+ 668 **PMTs**



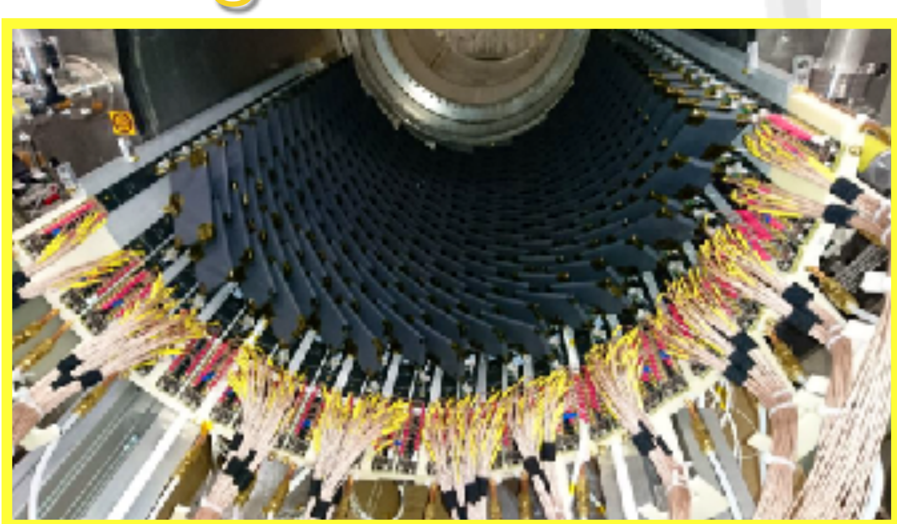
Measure:
E_γ ~(1%)
Θ_γ ~(2 cm) @ r=68cm
T_γ ~(70ps)

Drift Chamber

1728 square **drift cells**
Measure electron track with ~110um resolution:
E_e ~(130 KeV),
Θ_e ~(5 mrad)



Timing Counter



1024 **plastic scintillator** tiles with SiPMs double-readout. Measure: T_e ~(30ps)

Very good charge and time measurement on **heterogeneous detector technologies** while handling an high pileup environment:
How much a 8000 channel oscilloscope?

Evolution of Trigger and DAQ

MEG **DAQ** and **Trigger** systems:

- GSPS sampling by DRS4 ASIC
- Parallel 100MHz sampling for triggering

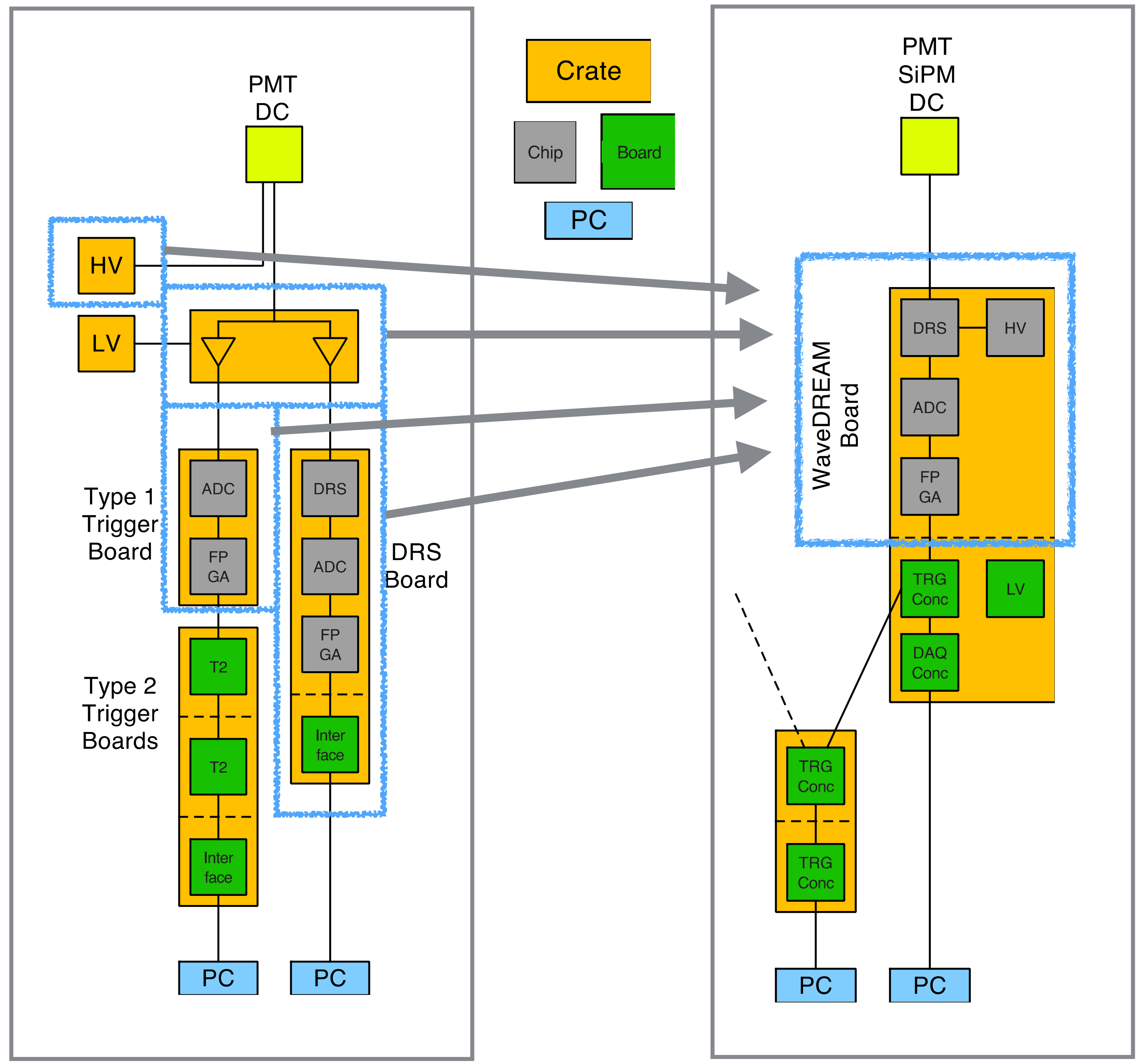
VME readout

↓

Fully integrated Trigger and DRS sampling:

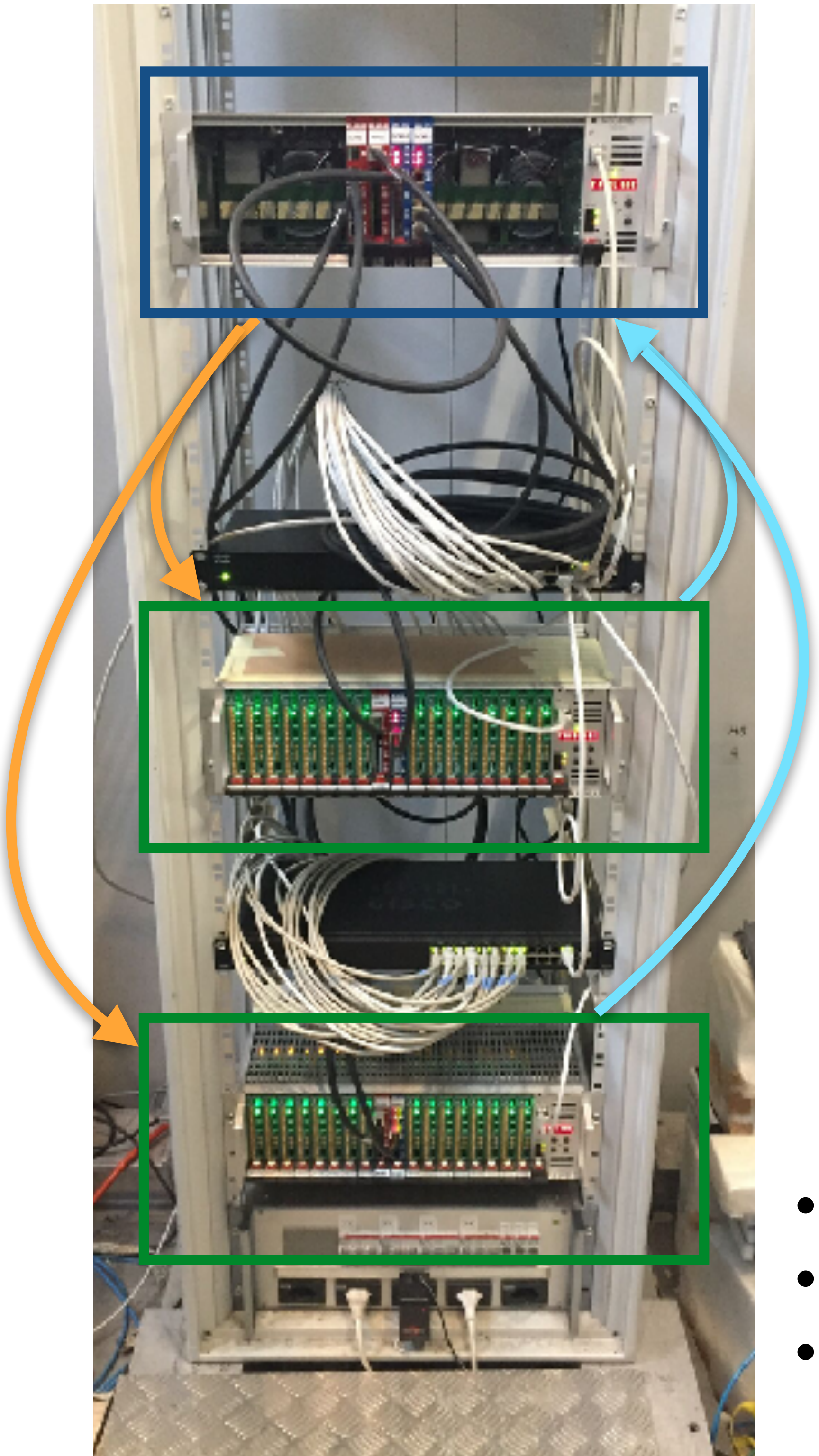
WaveDAQ system

- fit MEG II in the same rack space
  - no more signal splitting
  - SiPM biasing by the frontend card
- scale up to 16384 channels
- GbE Readout



Old Trigger + DAQ Systems New WaveDAQ System

Trigger Data Flow in new system



- Grown from 1 to 6 crates

Signals are connected to **WaveDREAM Boards**

↓

Assembly of digital output within each crate

↓

Trigger information (80 MSPS waveform + analog discriminator state) are streamed to **Trigger Crate**

↓

Trigger is sent back to stop **WaveDREAMs** for event readout

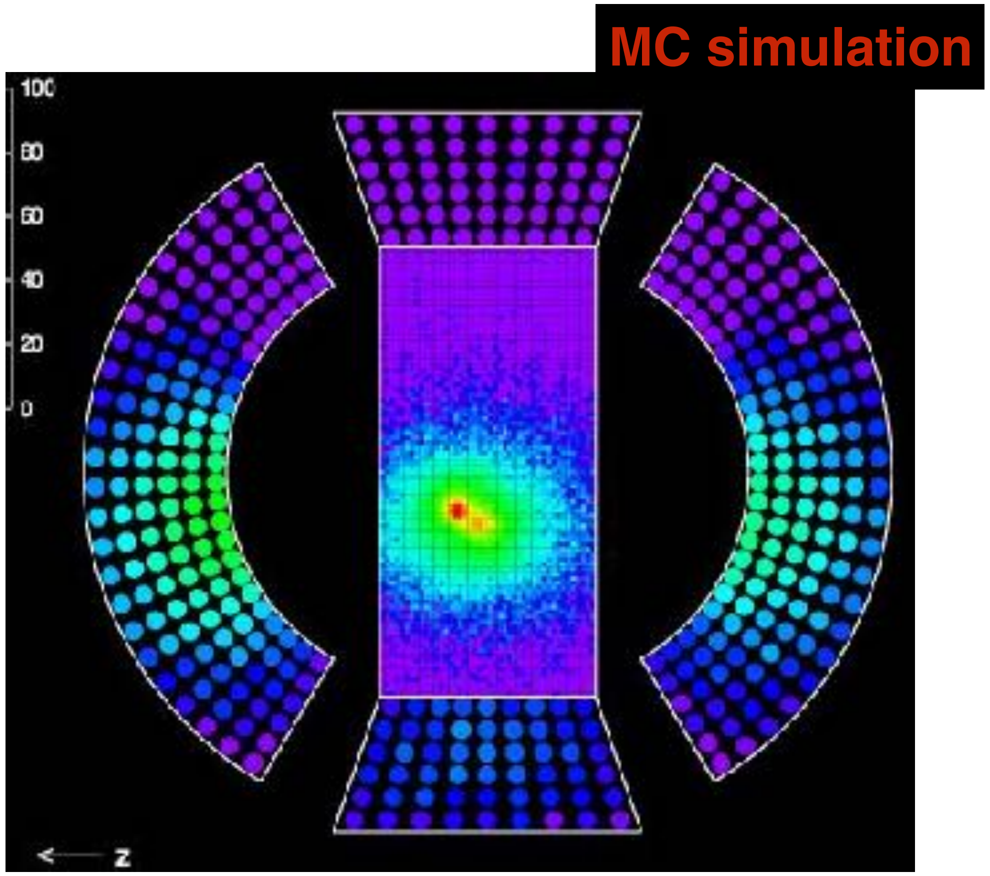
- Installed and tested with **Timing Counter** and **LXe** detectors
- Fully integrated in the MEG **MIDAS DAQ** software.
- Overall **latency** constrained by readout DRS4 chip: $\frac{1024}{f_{\mathrm{Sample}}}$
  - To operate at 2 GSPS: 512 ns maximum latency

Online trigger variables

$$R_{Acc} \approx R_{\mu}^2 \cdot \Delta E_e \cdot \Delta E_{\gamma}^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

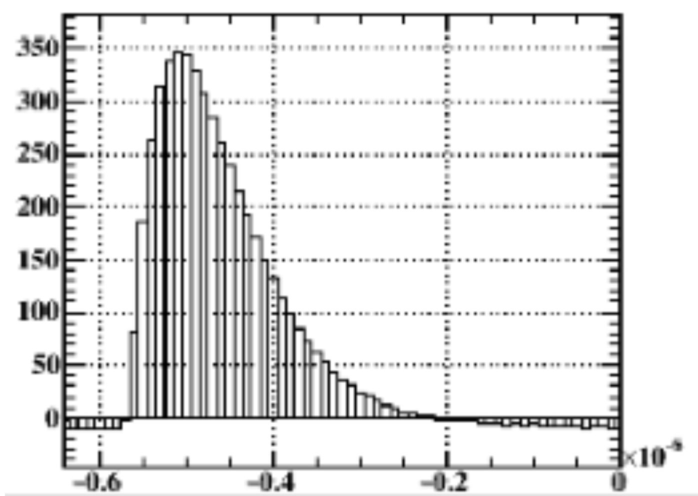
Very important: quadratic in accidental background

LXe detector

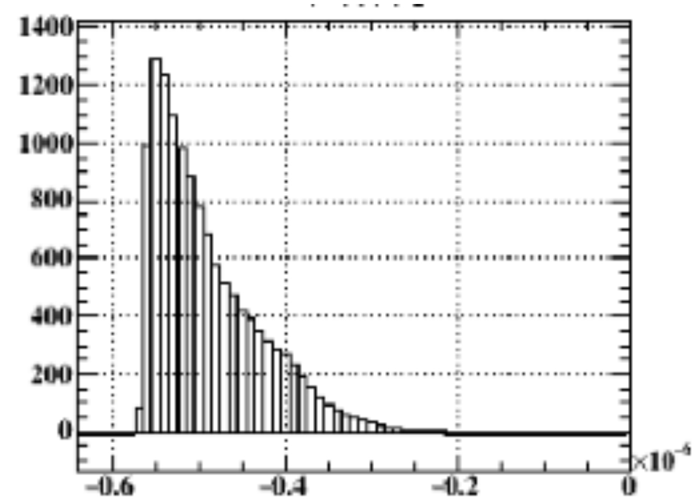


Weighted sum of the amplitude of LXe sensors
→ avoid waveform integration
(requires time to integrate the tail)

SiPM Waveform



PMT Waveform



Weights will be tuned for:

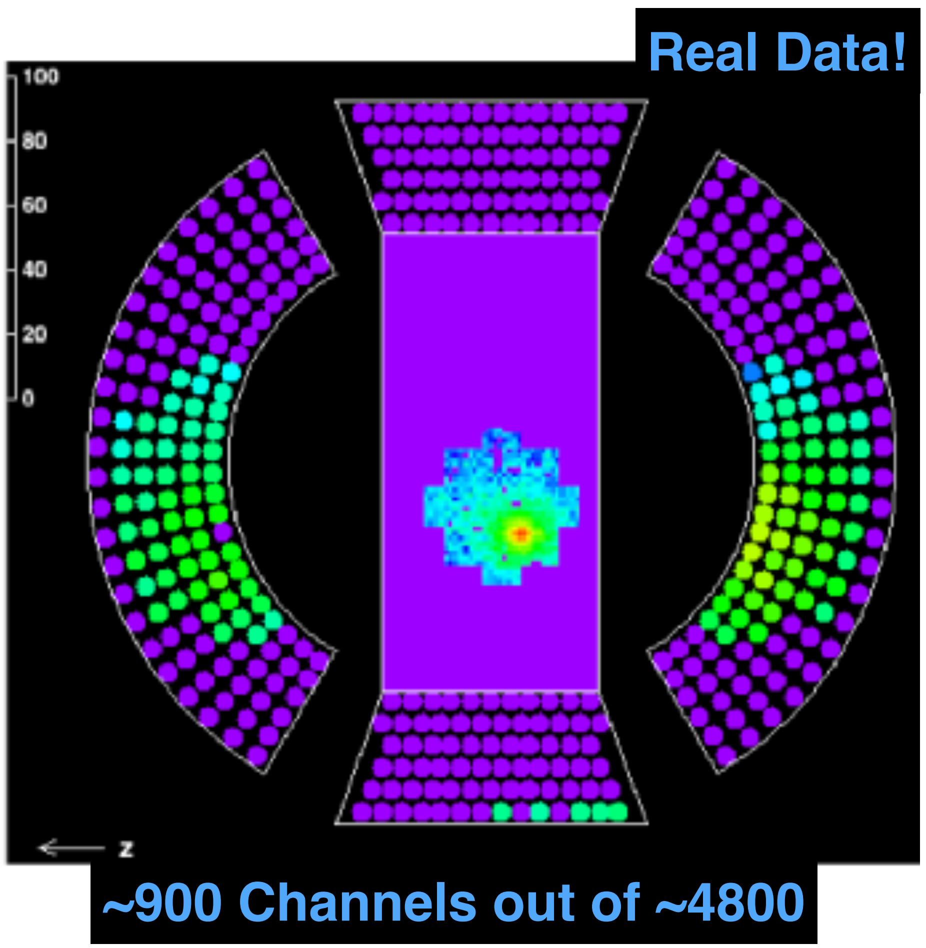
- sensor gain variations
- local ratio of sensitive area to dead material
- pulse shape difference

Online trigger variables

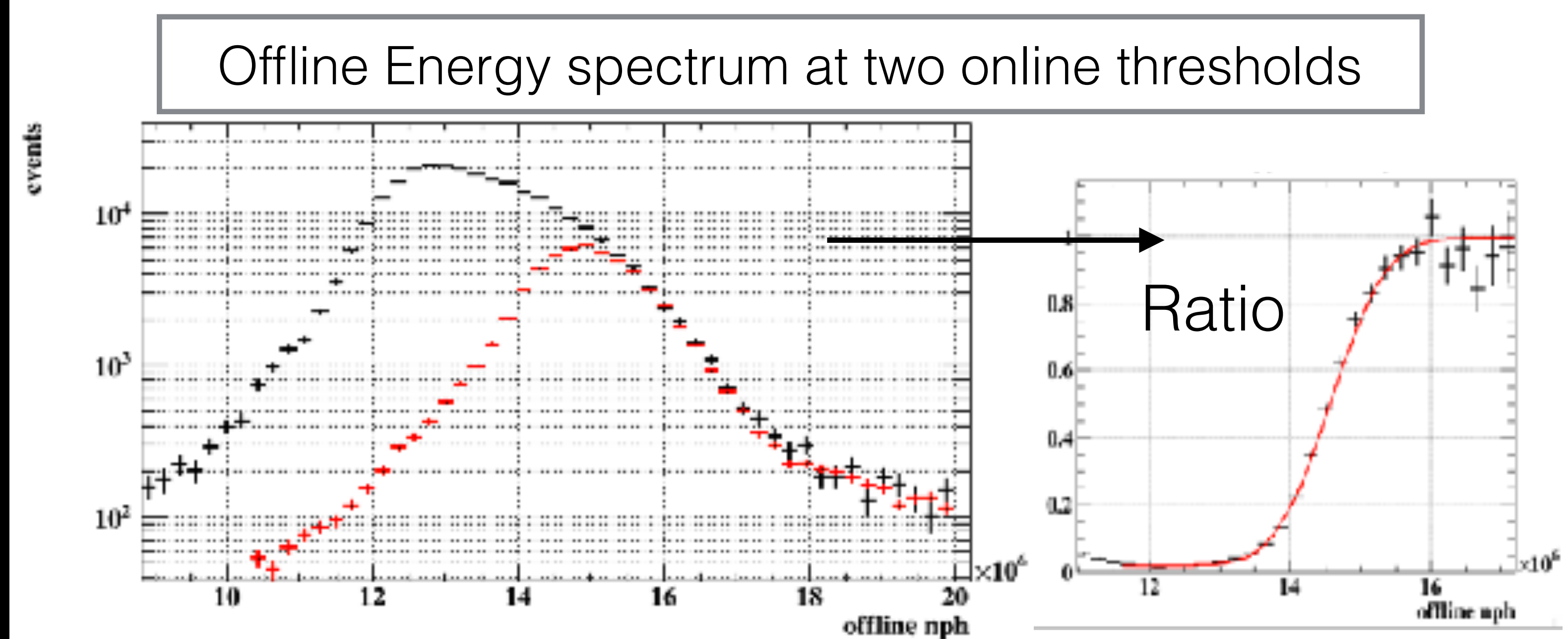
$$R_{Acc} \approx R_{\mu}^2 \cdot \Delta E_e \cdot \Delta E_{\gamma}^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

Complete trigger **sum**, **calibration**, **threshold** and **veto** with overall latency of 700ns

LXe detector



Preliminary test with limited number of channels



4% resolution at threshold level

Limited by

- shower fluctuations due to missing channels,
- weights not set,
- noise

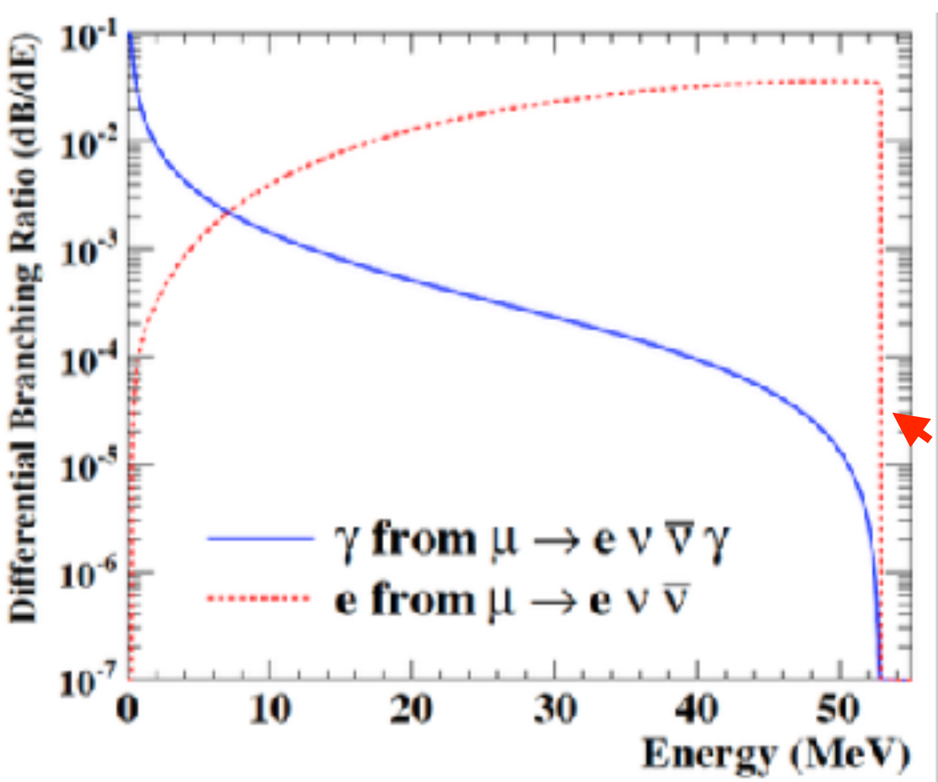
Online trigger variables

$$R_{Acc} \approx R_{\mu}^2 \cdot \Delta E_e \cdot \Delta E_{\gamma}^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

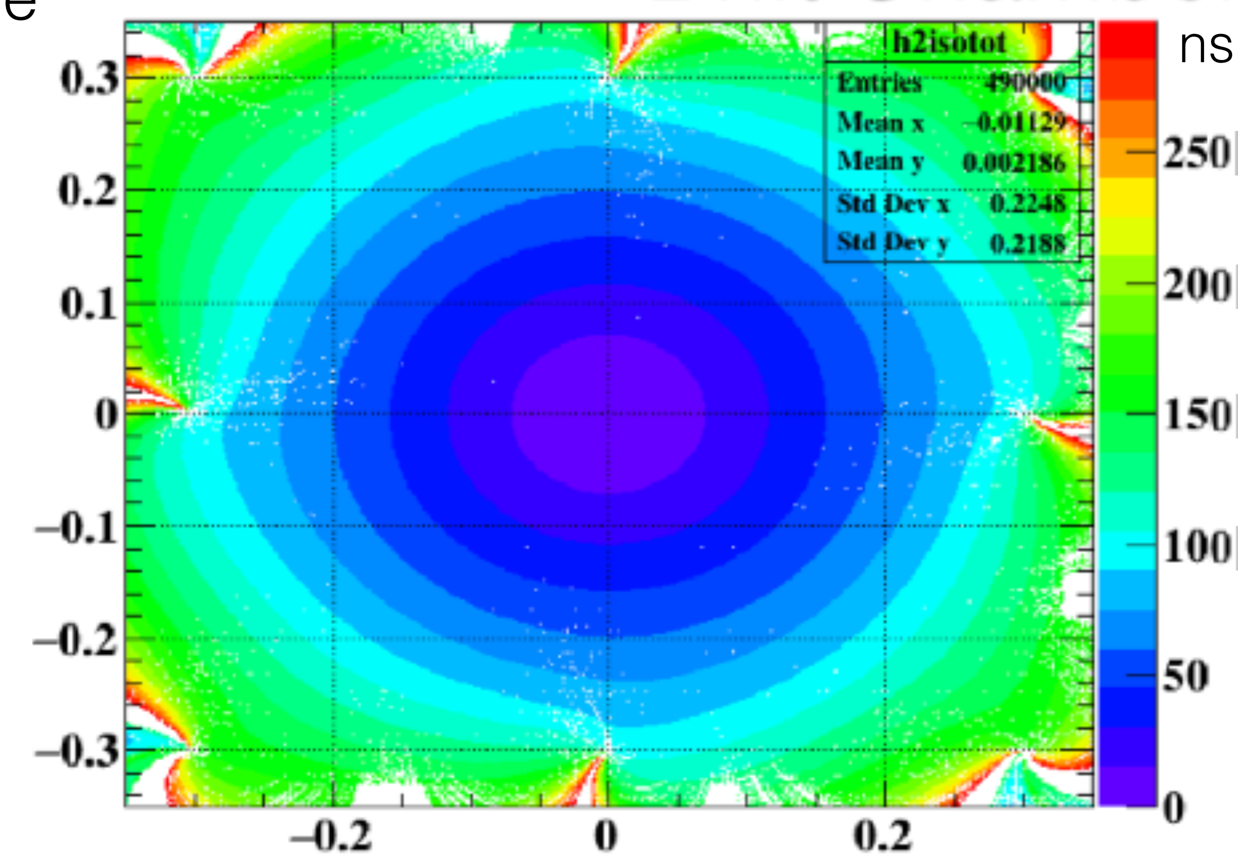
Pulse formation in Drift Chamber takes time

Up to **150 ns** to be added on top of the computation latency

Impossible to track the helix in 400 ns



Drift Chamber



- Positrons from muon decays tends to be at high energy
  - Positron spectrometer has a non uniform magnetic field to swipe low energy positrons

Very loose energy cut, starting from 35-40 MeV

Online trigger variables

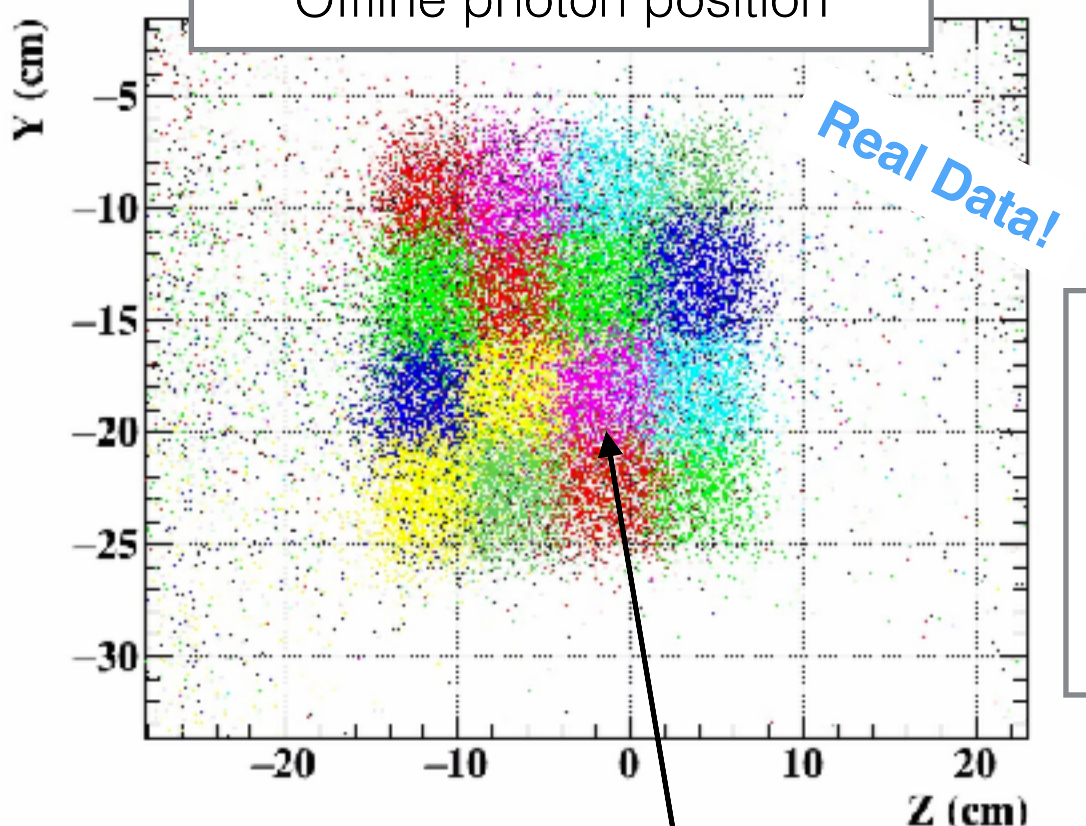
$$R_{Acc} \approx R_\mu^2 \cdot \Delta E_e \cdot \Delta E_\gamma^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

Rely only on LXe reconstruction and hit on Timing Counter

LXe detector
Timing Counter
~~Drift Chamber~~

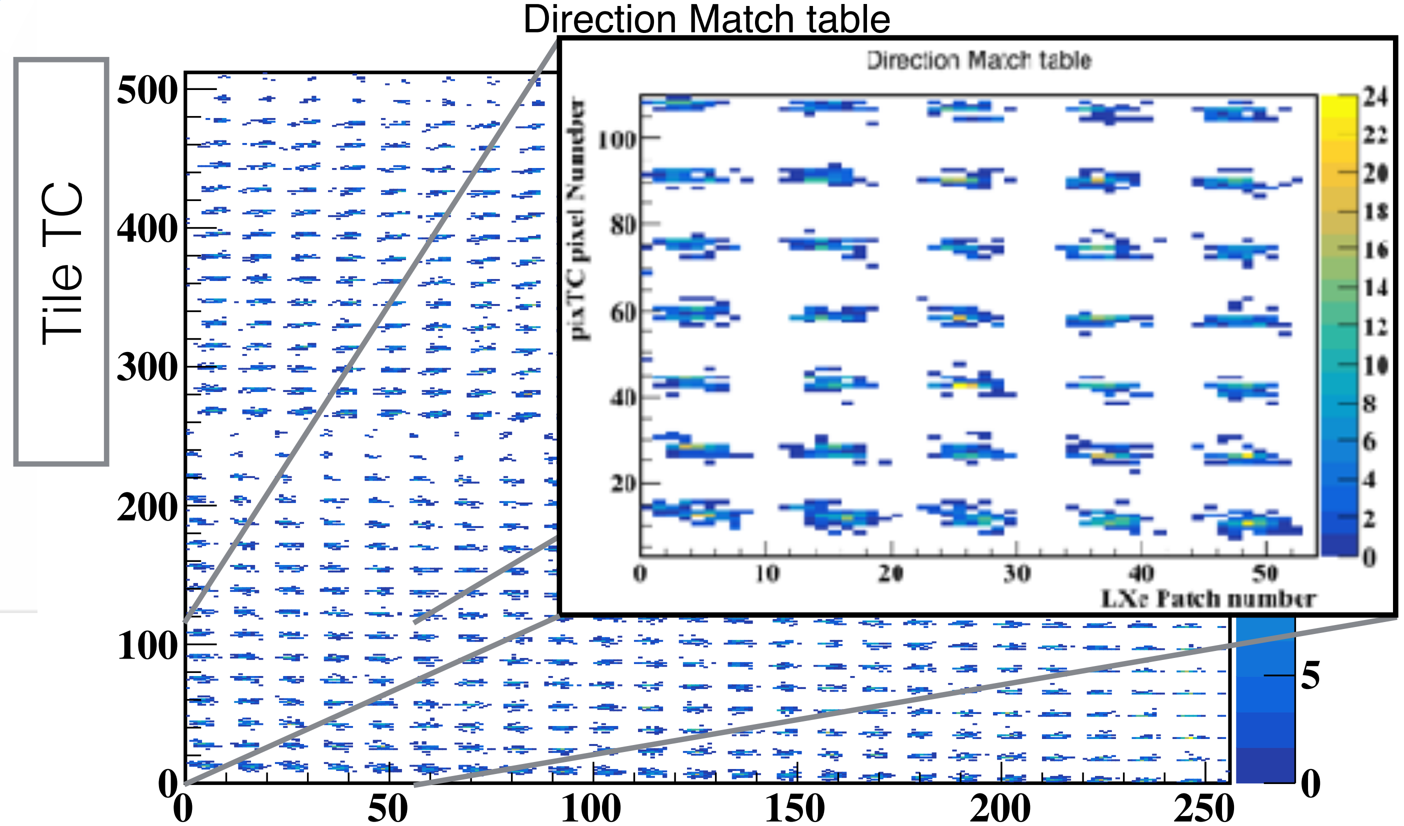
1. Search Max on the inner face

Offline photon position



Reduce combinatorial:
group channels in 4x4 "Patches"

2. Check is consistent with TC hit **assuming signal positrons** (Lookup Table from MC)



Online photon position

Online trigger variables

$$R_{Acc} \approx R_{\mu}^2 \cdot \Delta E_e \cdot \Delta E_{\gamma}^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

LXe detector

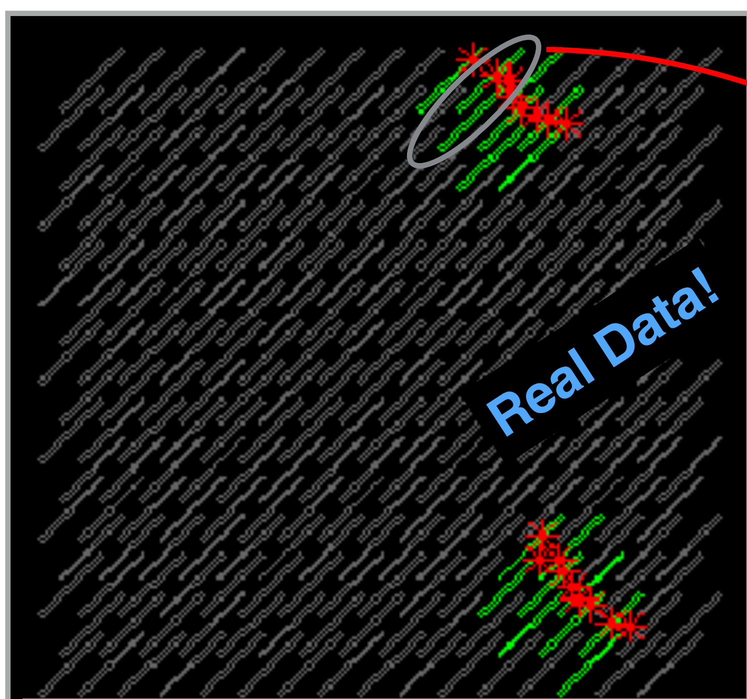
Timing Counter

Check time difference between LXe Patches and TC Tiles

Exploit fast **analog discriminators**: 640 MHz refresh rate → σ_{Tile}= 320ps

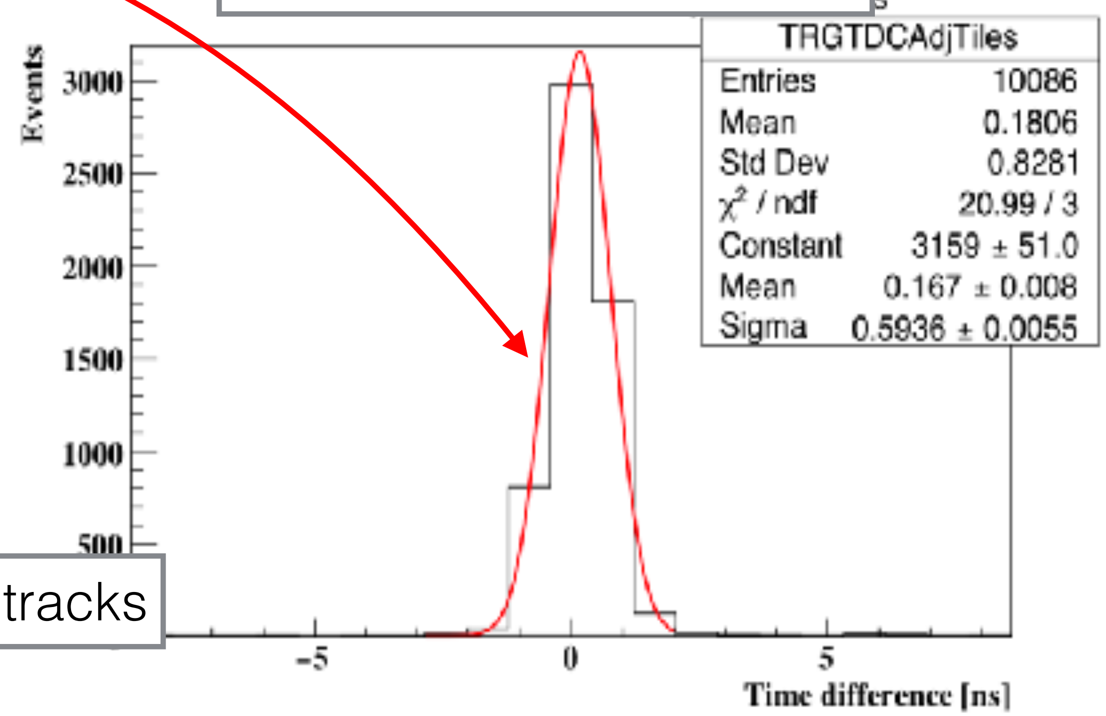
Checked by compared recorded time by two nearby tiles → σ_{Tile}= 420ps

Similar studies for averaging 16 channels in LXe Patch in progress



Offline-reconstructed positron tracks

Online time difference



Final selection limited by possibility to correct for track length:
only gain in tail cut

What is missing

E_γ Photon energy

- Optimize weights
- Study noise filtering

$\Theta_{e\gamma}$ Emission angle

- Reconstruction of TC hit position

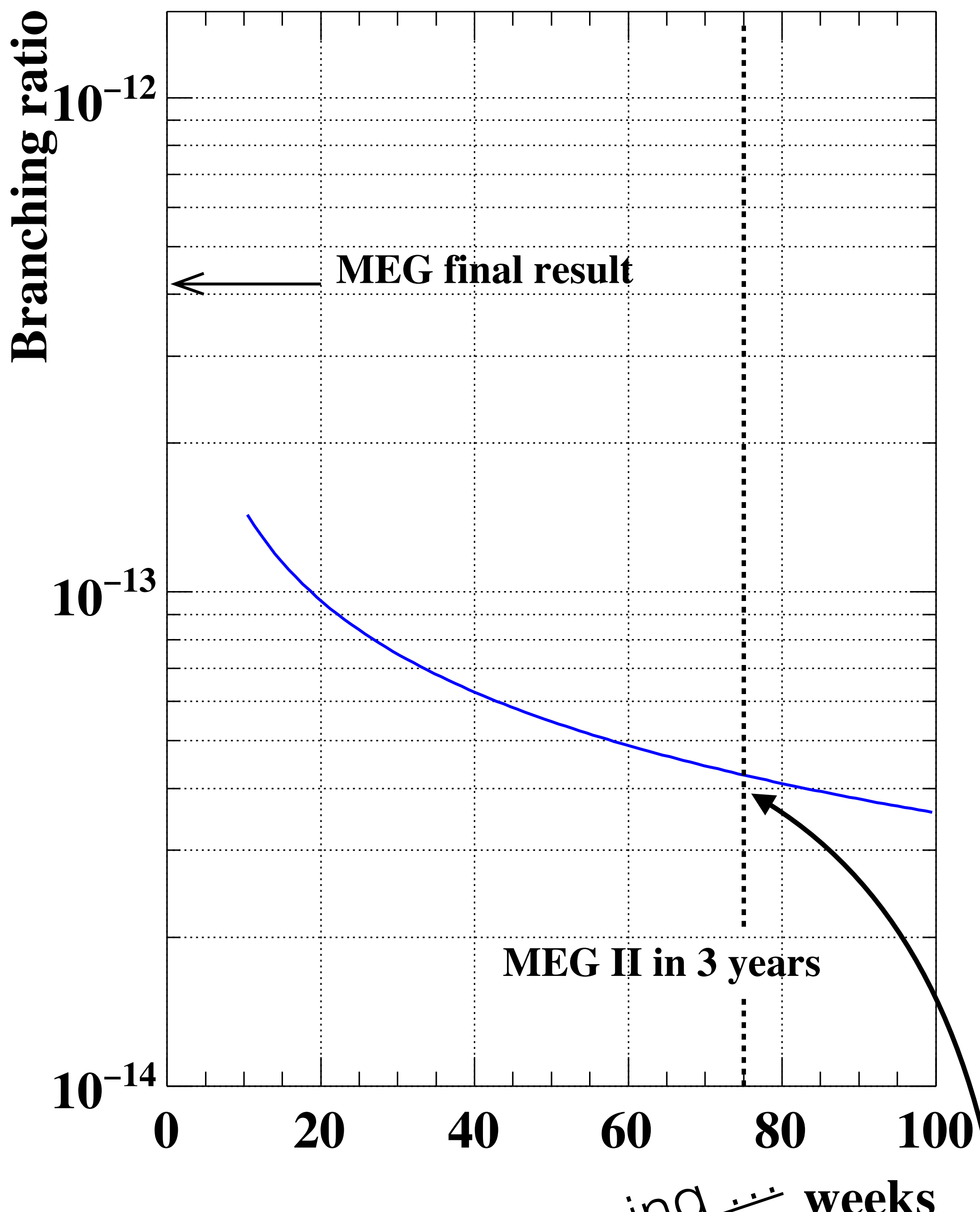
$T_{e\gamma}$ Relative time

- Time extraction from single channel timing
- Add time information to $\Theta_{e\gamma}$

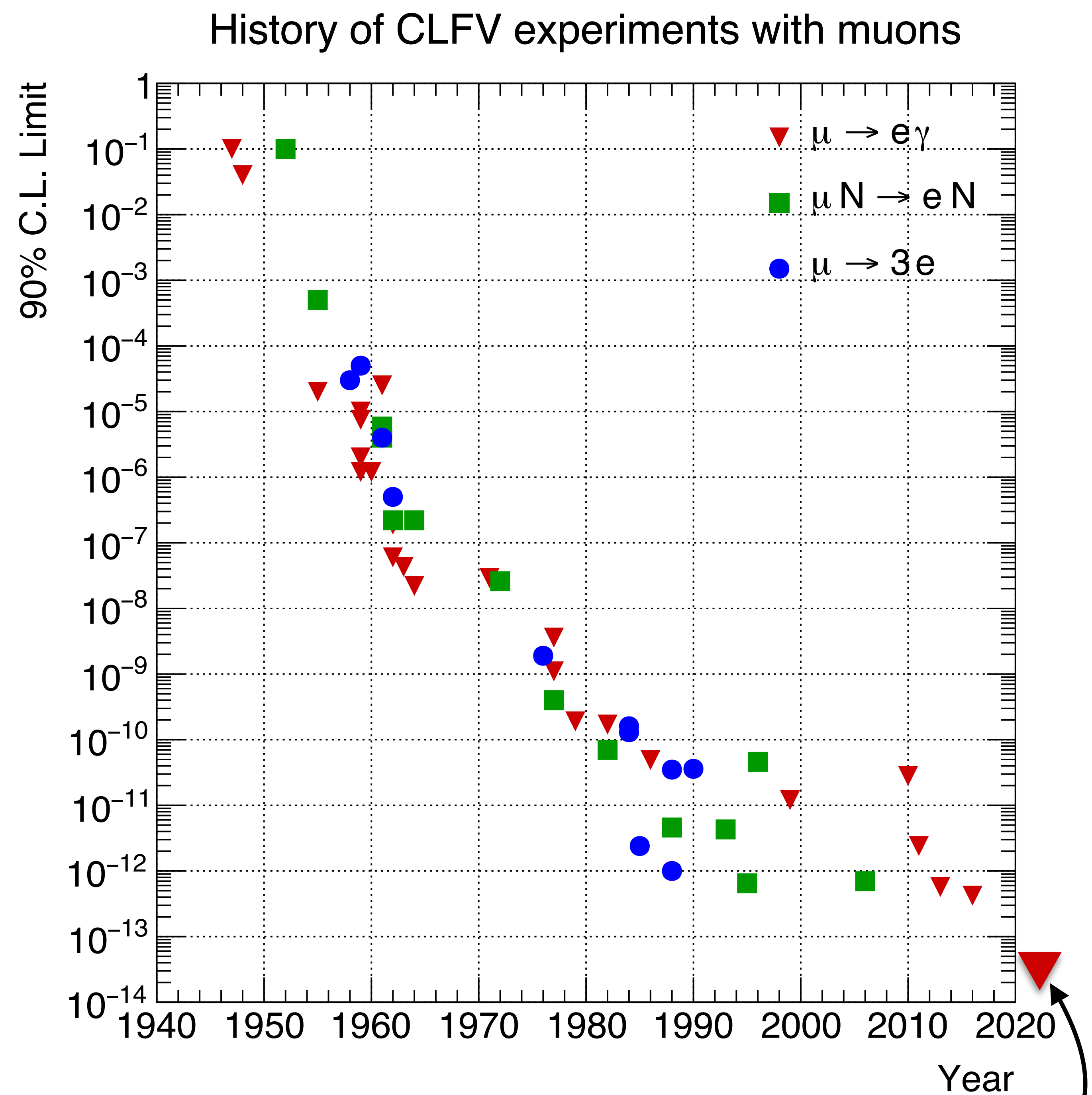
- Final system integration with Data Concentrator Board and online computing
  - Needed to achieve goal DAQ speed (~1Hz → ~1kHz)
- Offline Analysis tools
  - To monitor of selection efficiency

1 month Pre-Engineering run this Fall
Long Engineering run next year

Prospectives



after next-year commissioning …



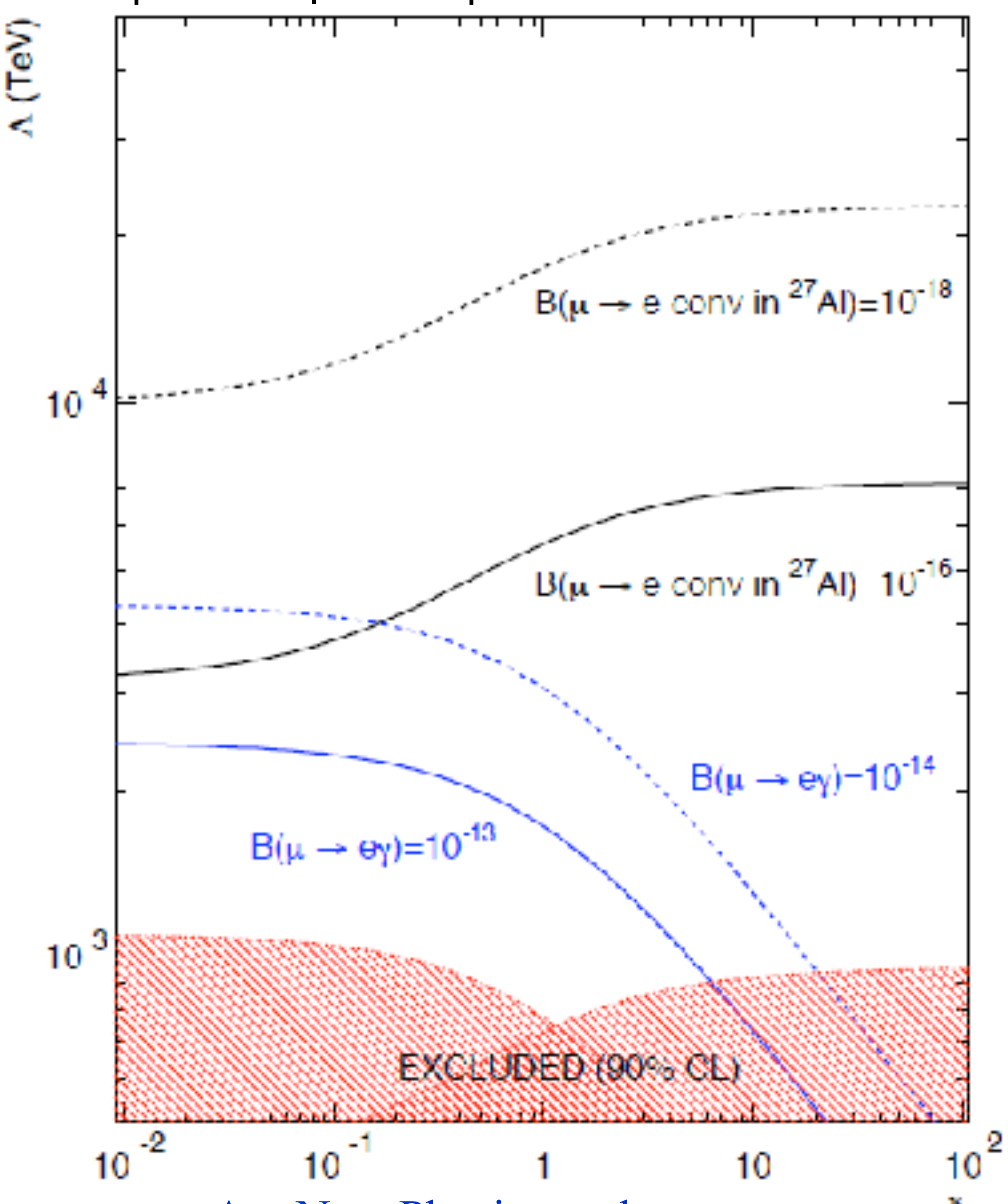
take **this** sensitivity expectation,
and, in three years, add a limit **here**.
Or discover something new…

Backup

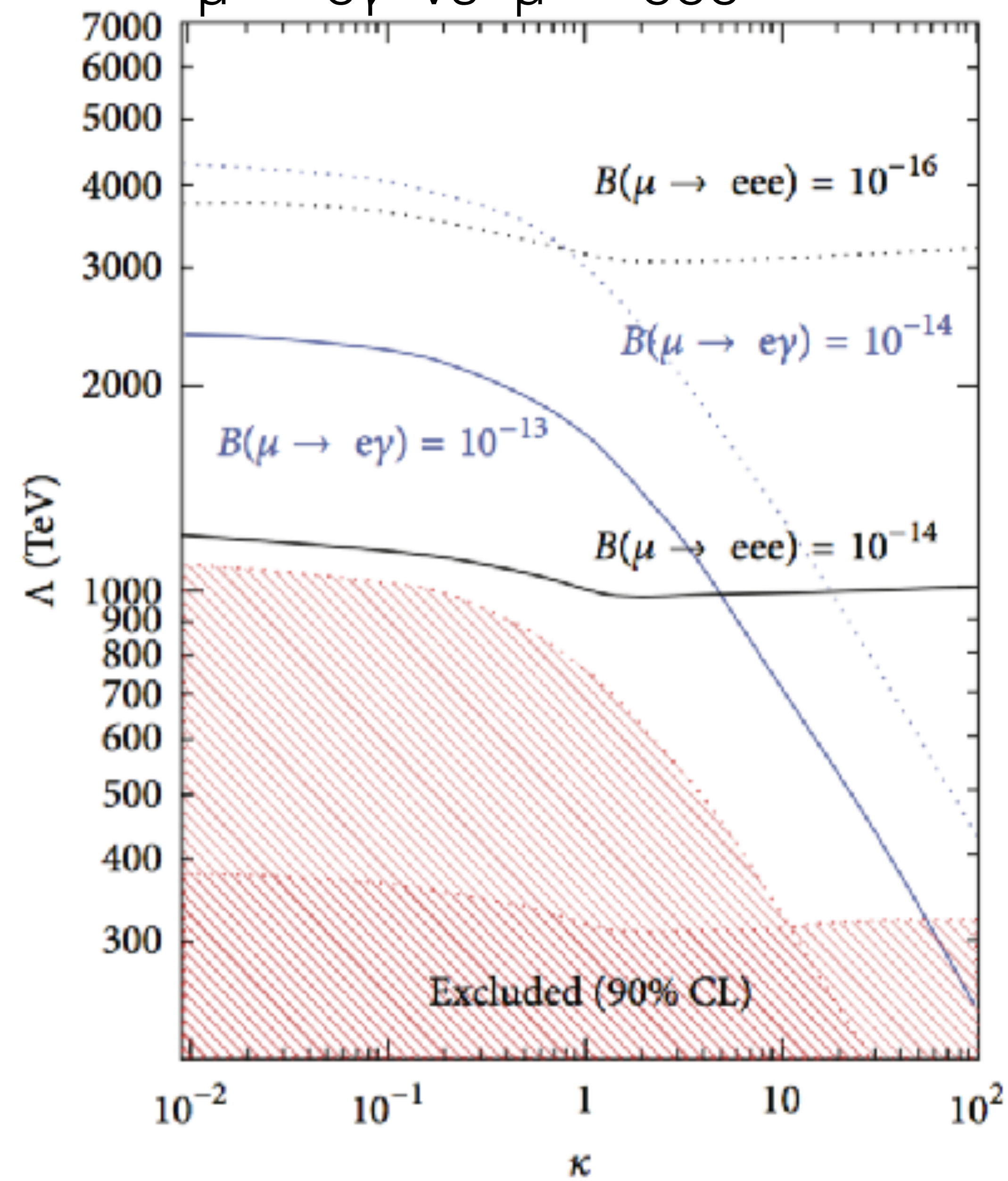
SUSY sensitivity

A. de Gouvea & P. Vogel, hep-ph 1303.4097

μ → eγ vs μ → e conversion



μ → eγ vs μ → eee

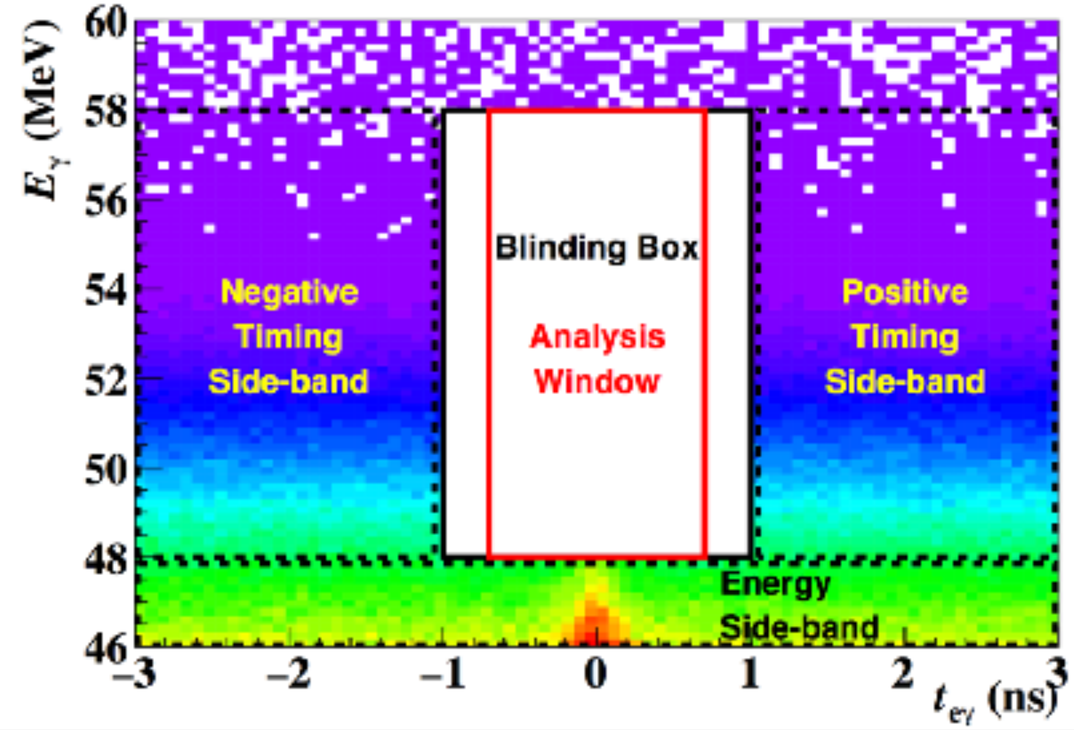


Λ = New Physics scale

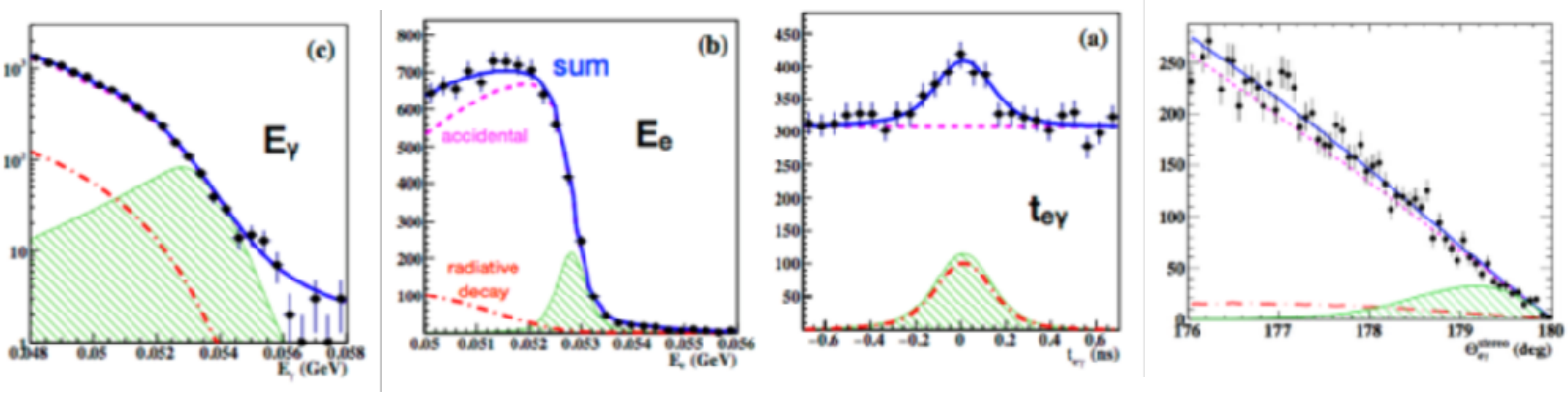
k = Relative weight of two terms

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\bar{\mu_R}\sigma^{\mu\nu}e_L\ F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\bar{\mu_L}\gamma^\mu e_L(\bar{U_L}\gamma_\mu U_L + \bar{D_L}\gamma_\mu D_L)$$

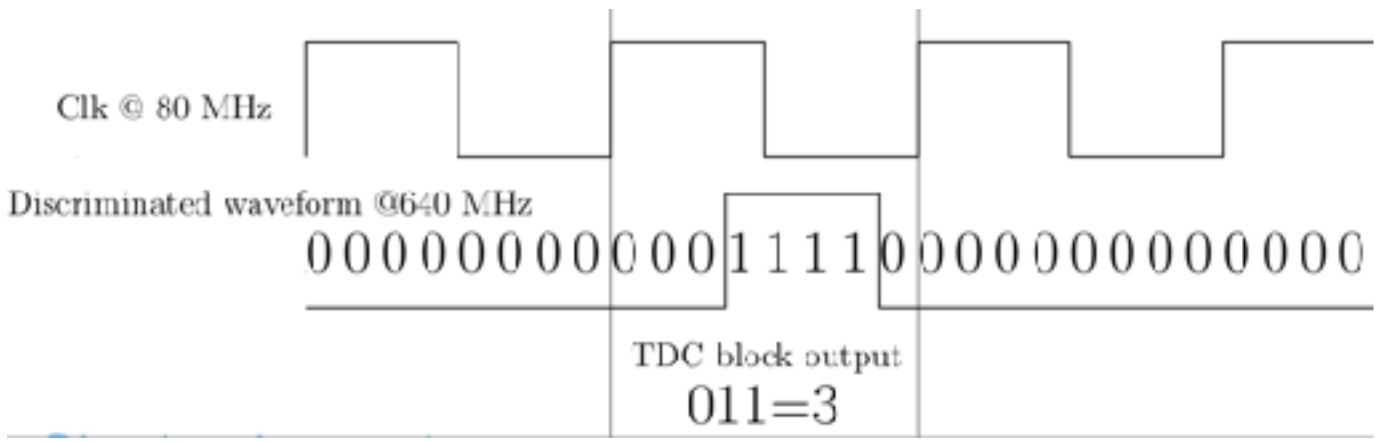
MEG Analysis



Similar expected for MEG II (with improved resolutions)



Trigger Time resolution



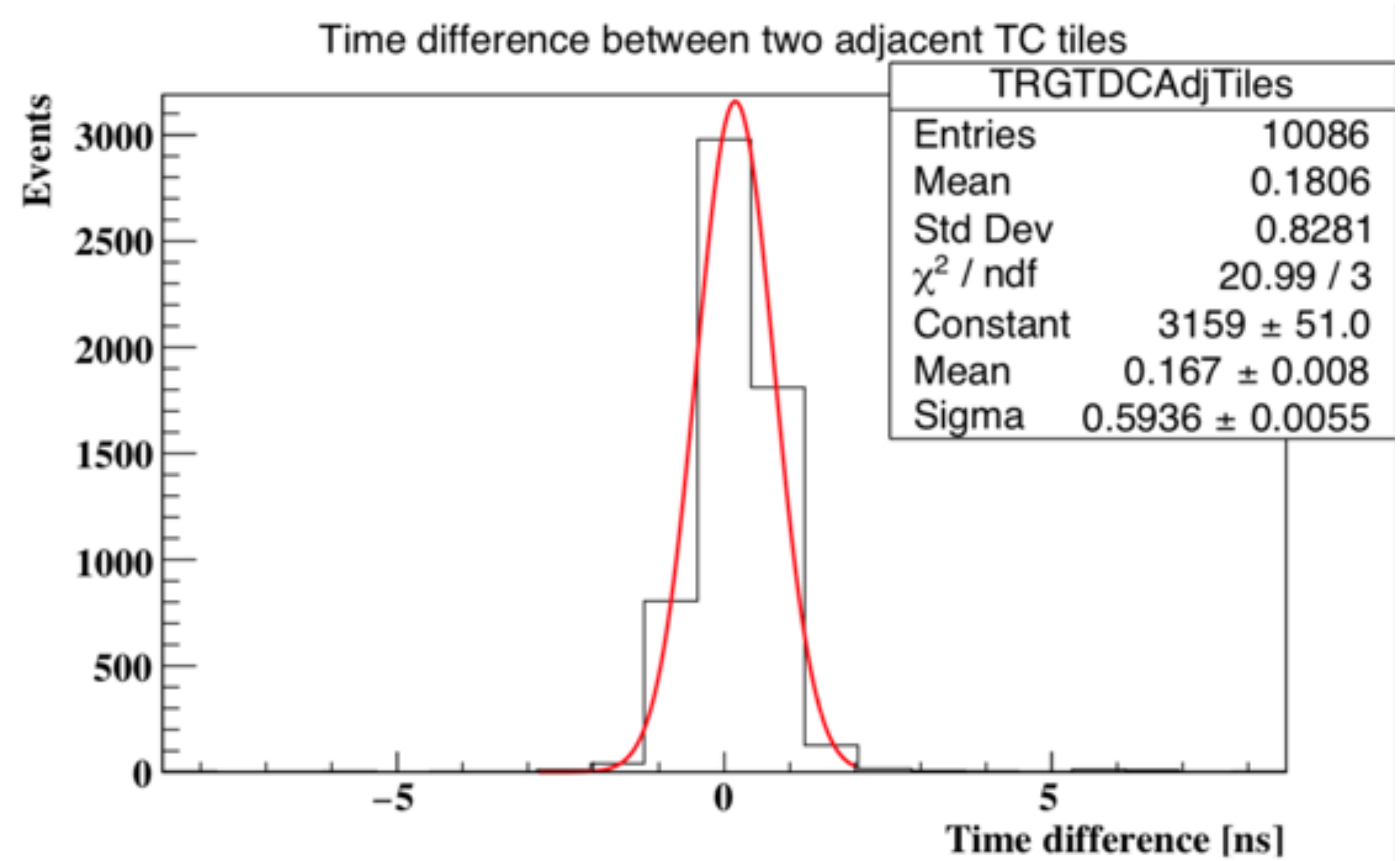
The same 640MHz clock used for data serialization can be used for fast sampling of the analog input

8 sample bit “waveform” each clock cycle

than encoded in the FPGA

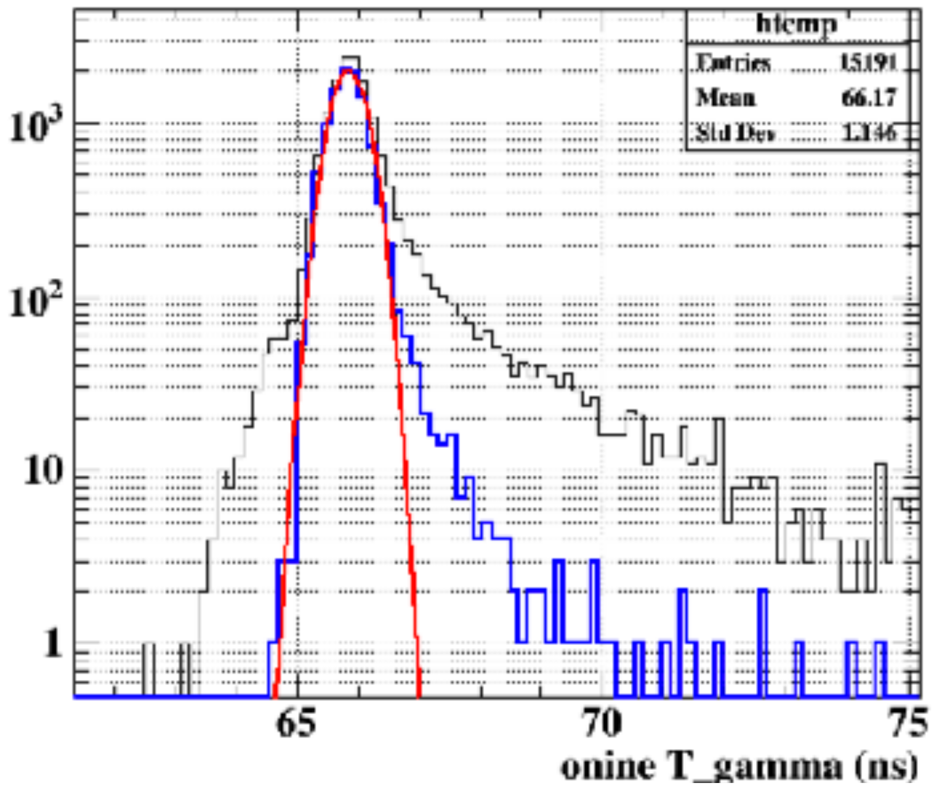
1,56ns / sqrt(12) rms resolution each channel

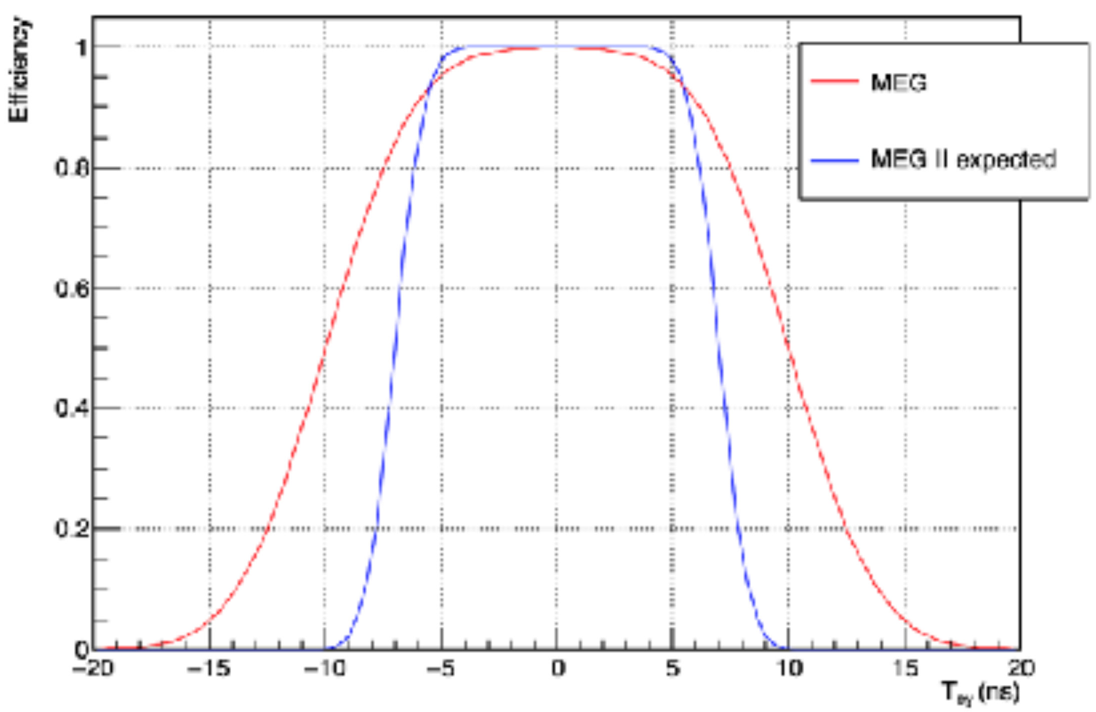
In TC Test Run:
single tile resolution ~415 ps (320 ps intrinsic electronics contribution)



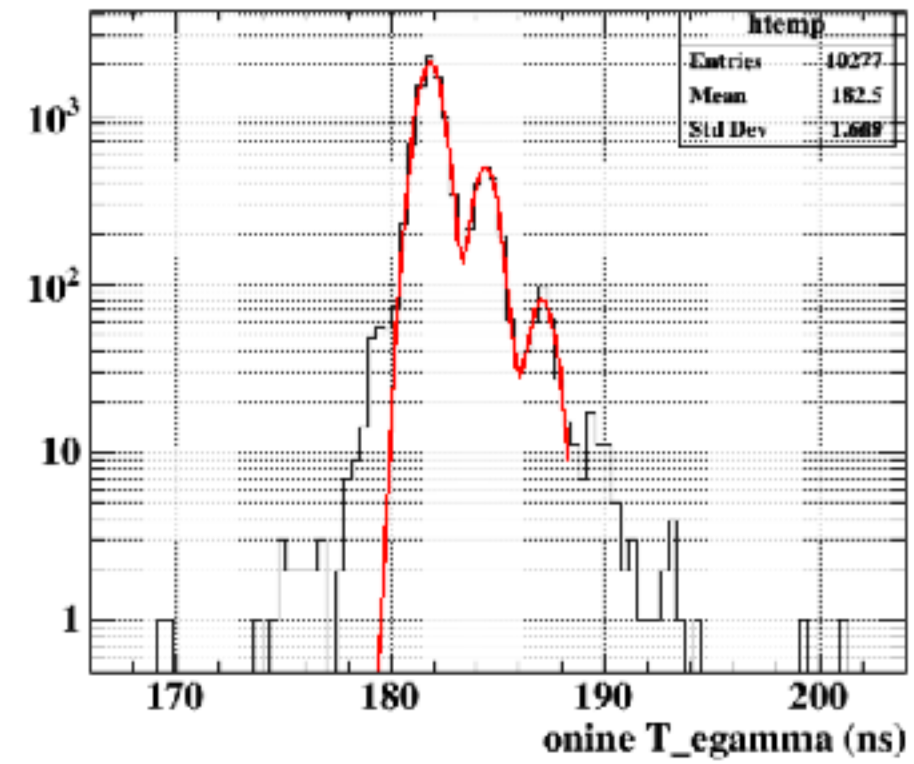
Online Gamma Time

Online T_gamma from MC





Online T_egamma from MC

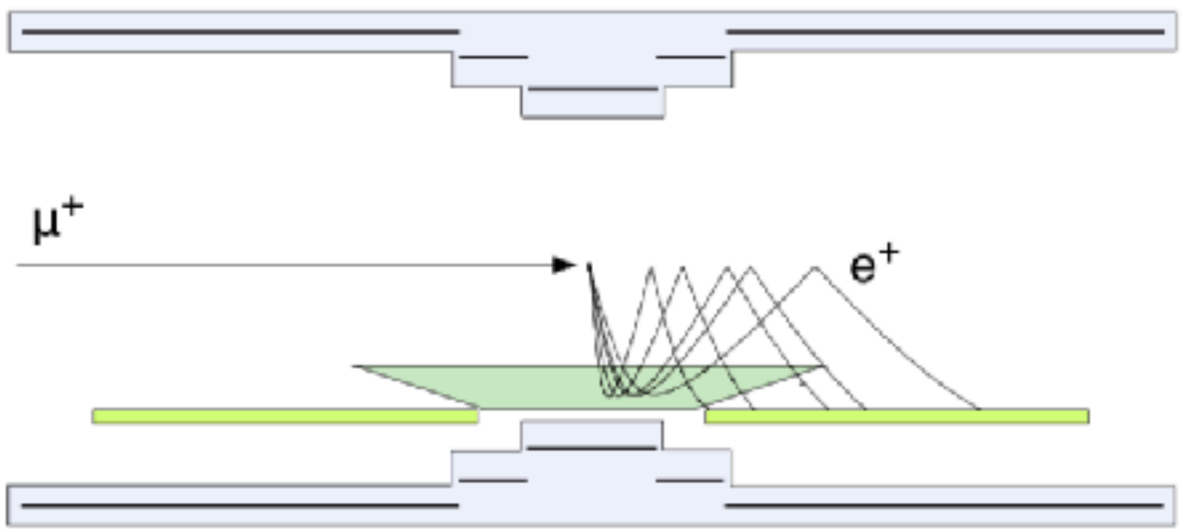


Equally spaced peaks:

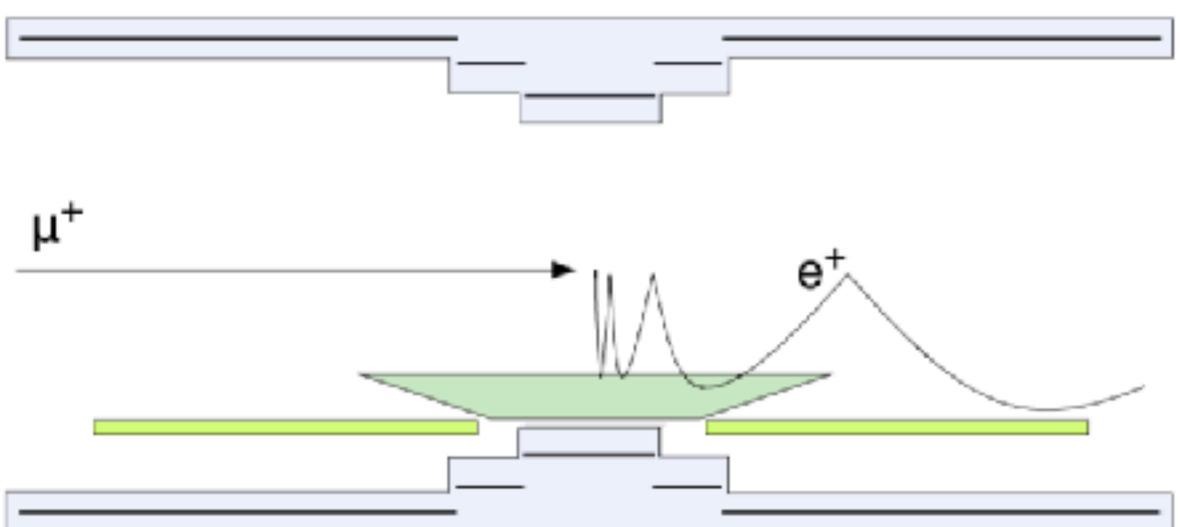
1,2,3 turns in the drift chamber volume by ~2.5ns

impossible to discriminate without drift chamber information (and tracking)

CoBRa



Cobra

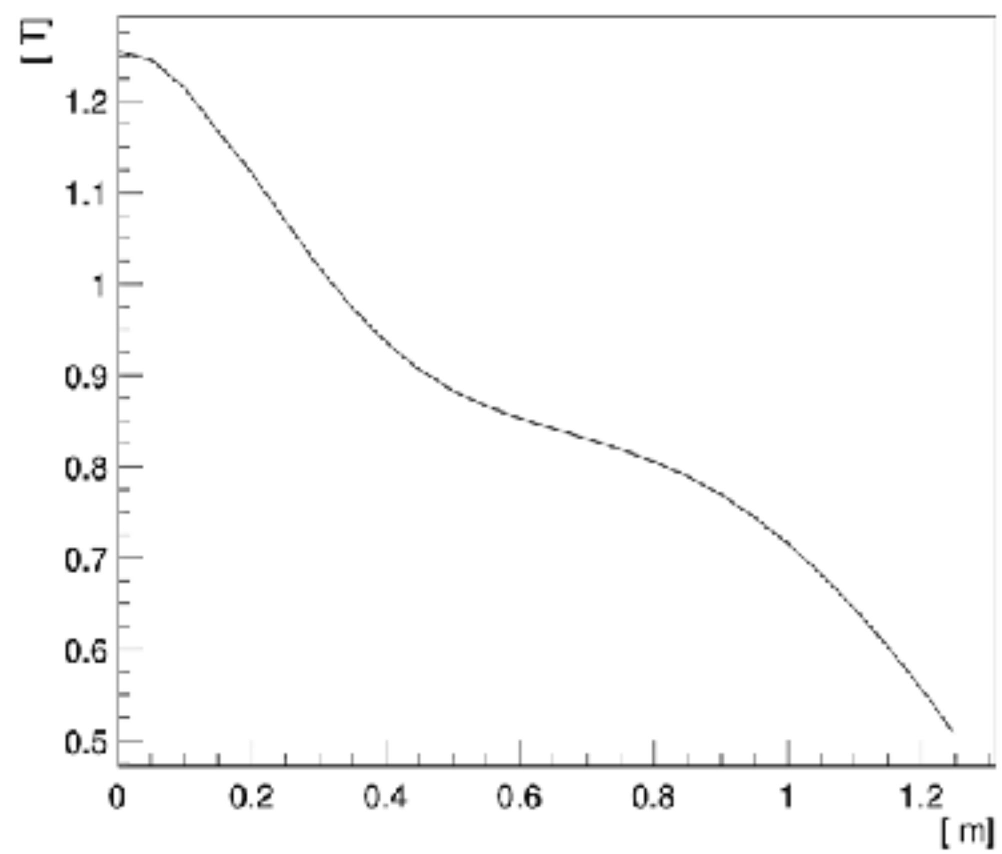


Solenoid

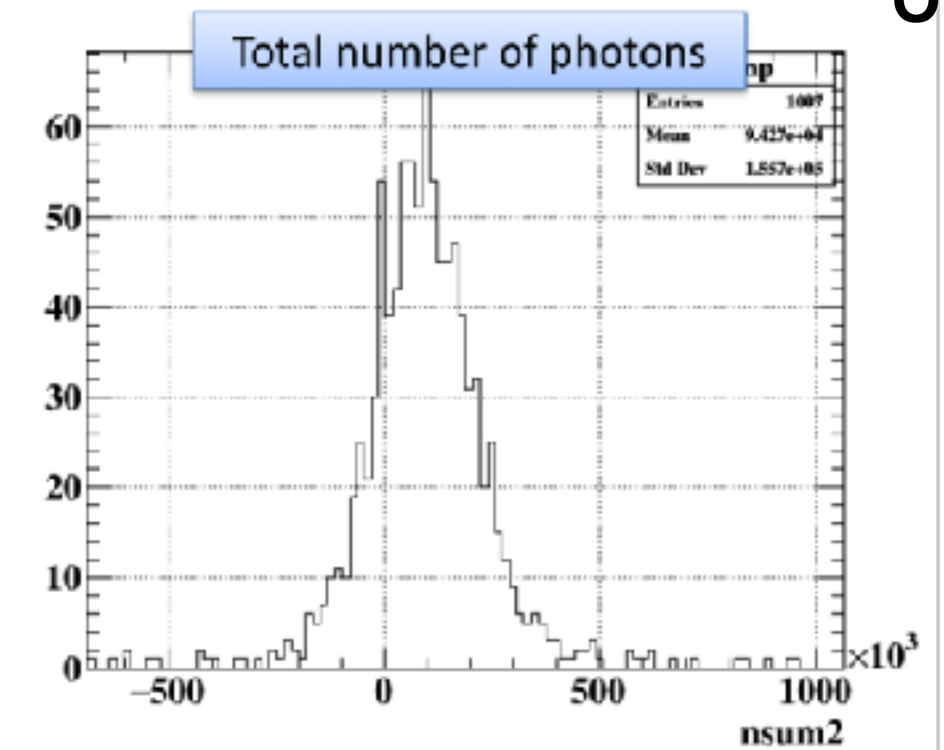
Constant Bending Radius

particle in acceptance have a banding radius proportional to the energy

➡ not to the parallel component of momentum

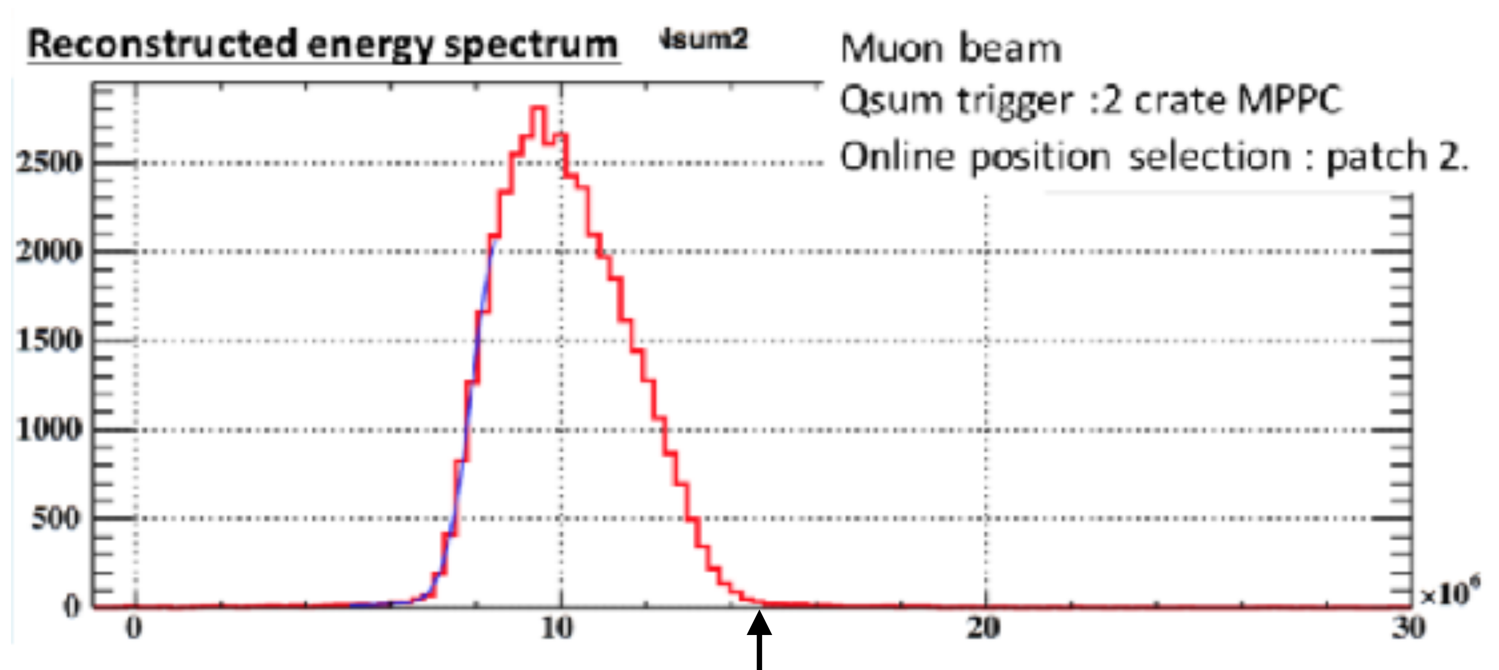


Liquid Xenon Noise

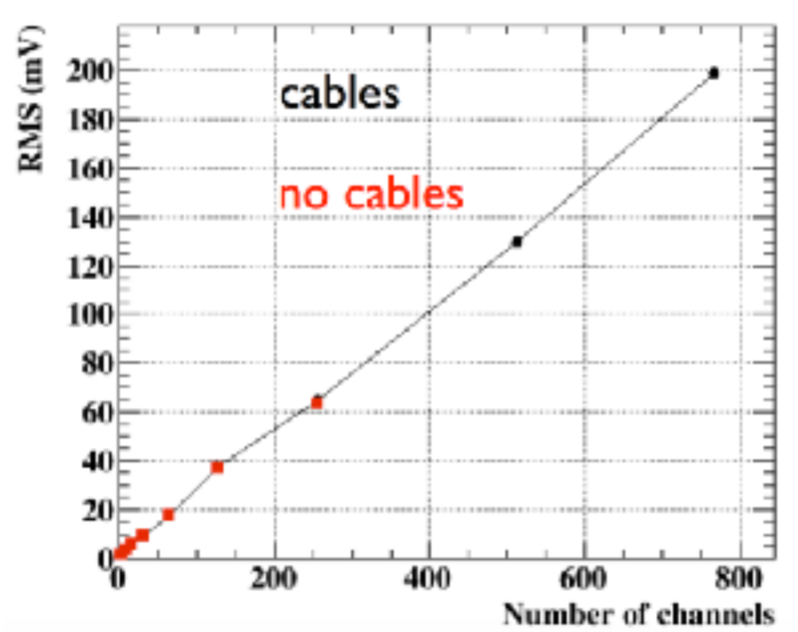


ph.e for pedestal RMS =1.5 10^5

Offline energy



Radiative Muon endpoint = 1.3 10^7 ph.e.

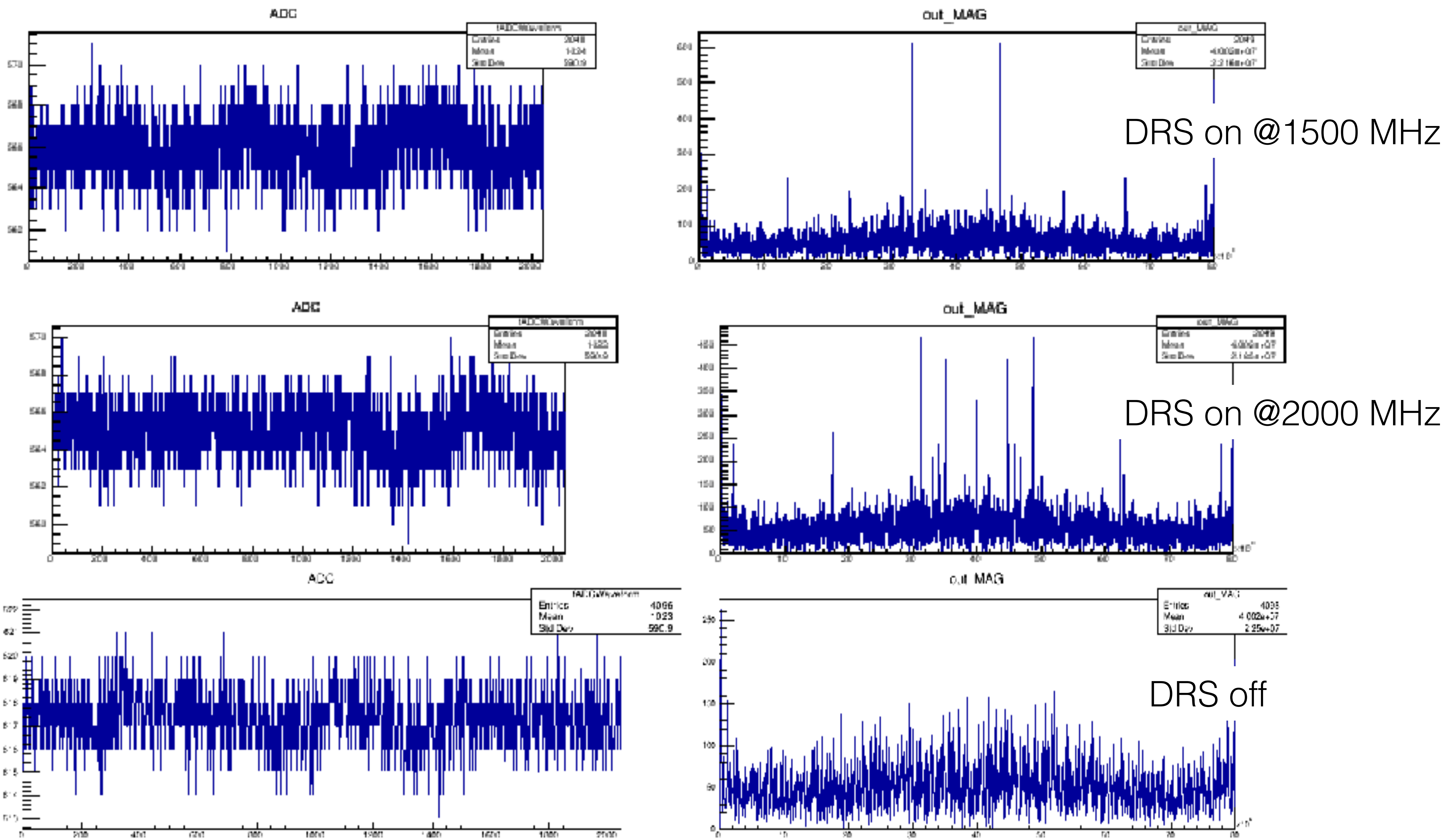


Online pulse amplitude

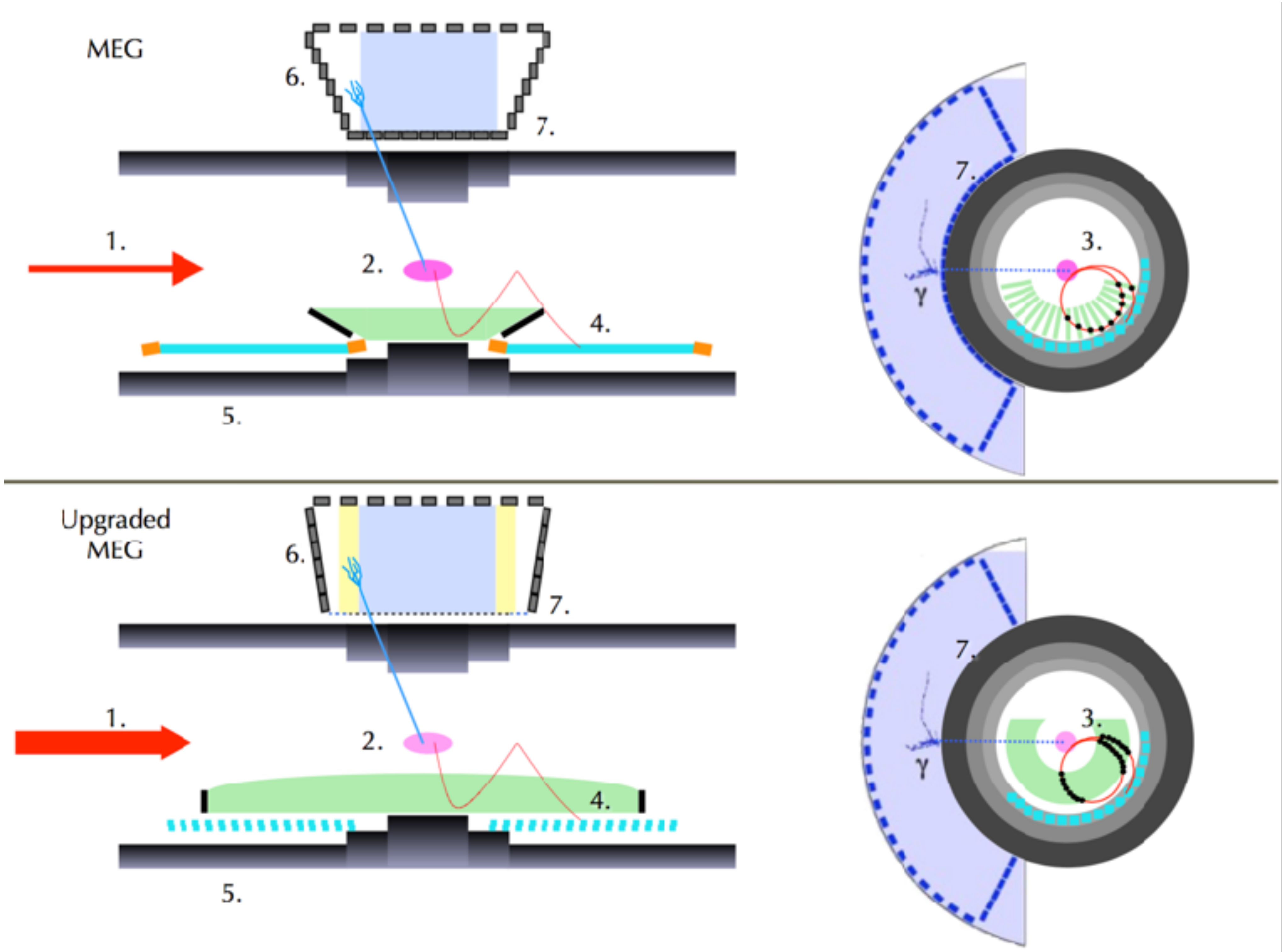
RMS of pedestal scales linearly instead of sqrt(N)

Evidence of correlated noise

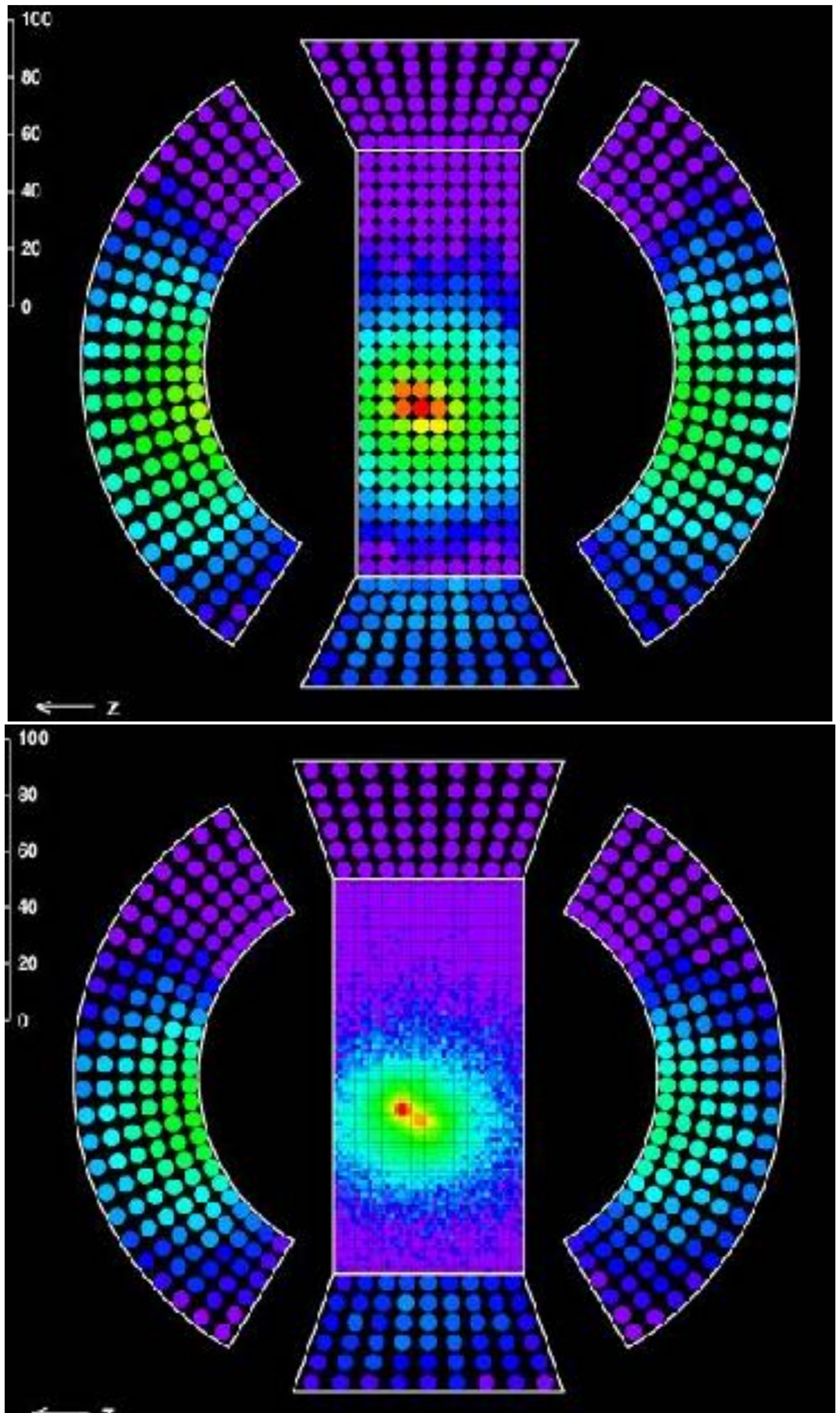
Online Noise

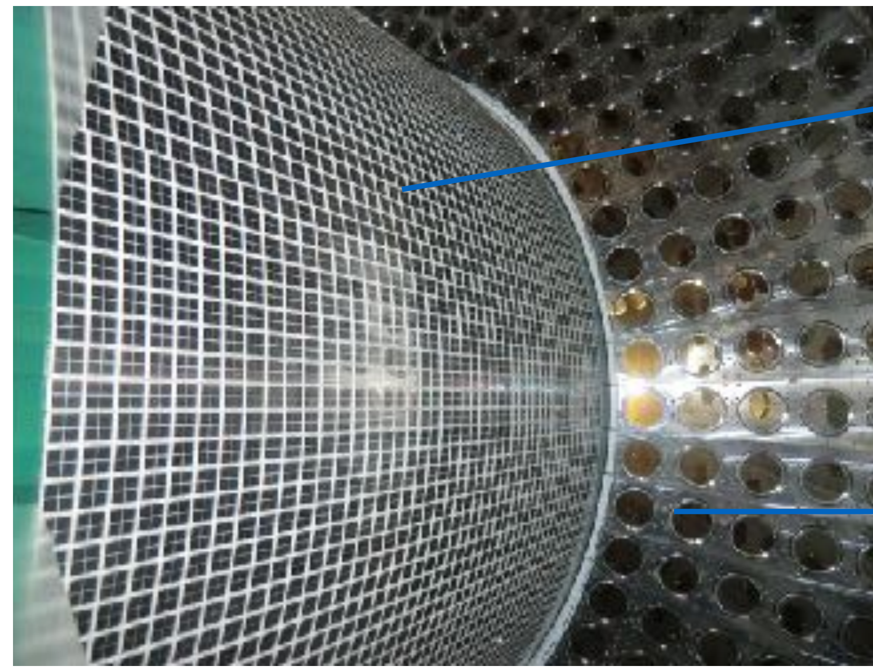


MEG - MEG II



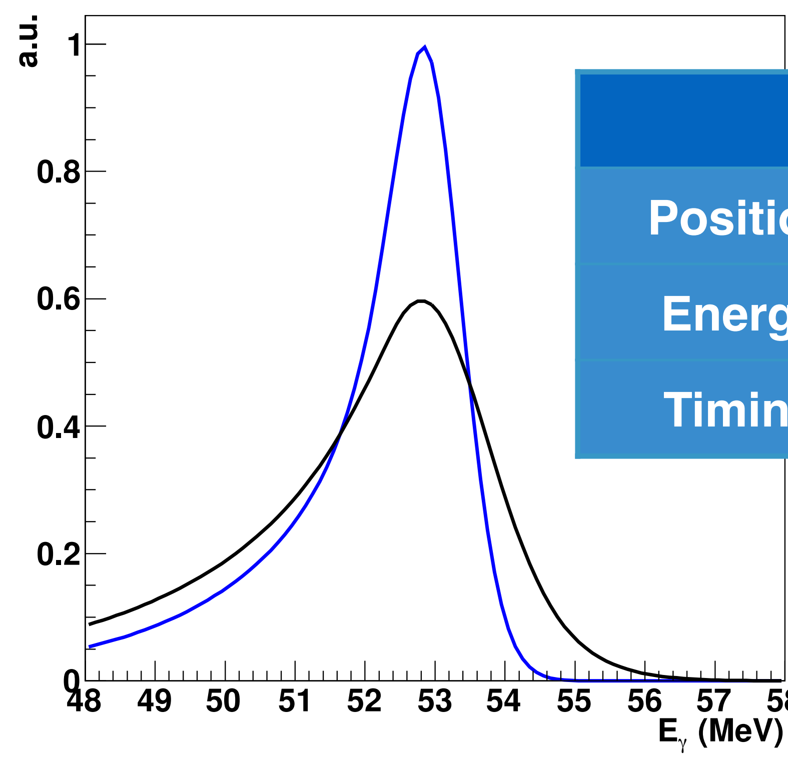
The LXe detector





4092 UV SiPM
12mmx12mm

optimized positions of the remaining 688 PMT

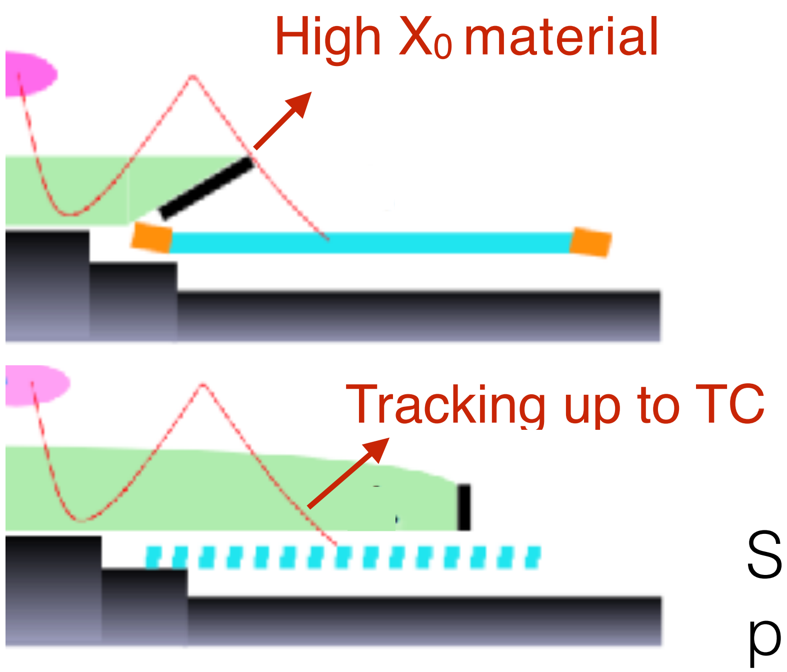


	MEG	MEG II
Position	5 mm	2.4 mm
Energy	2.4%-1.7%	1%
Timing	67 ps	60ps

Detector installed:

Beam test in 2017, noise optimization in progress

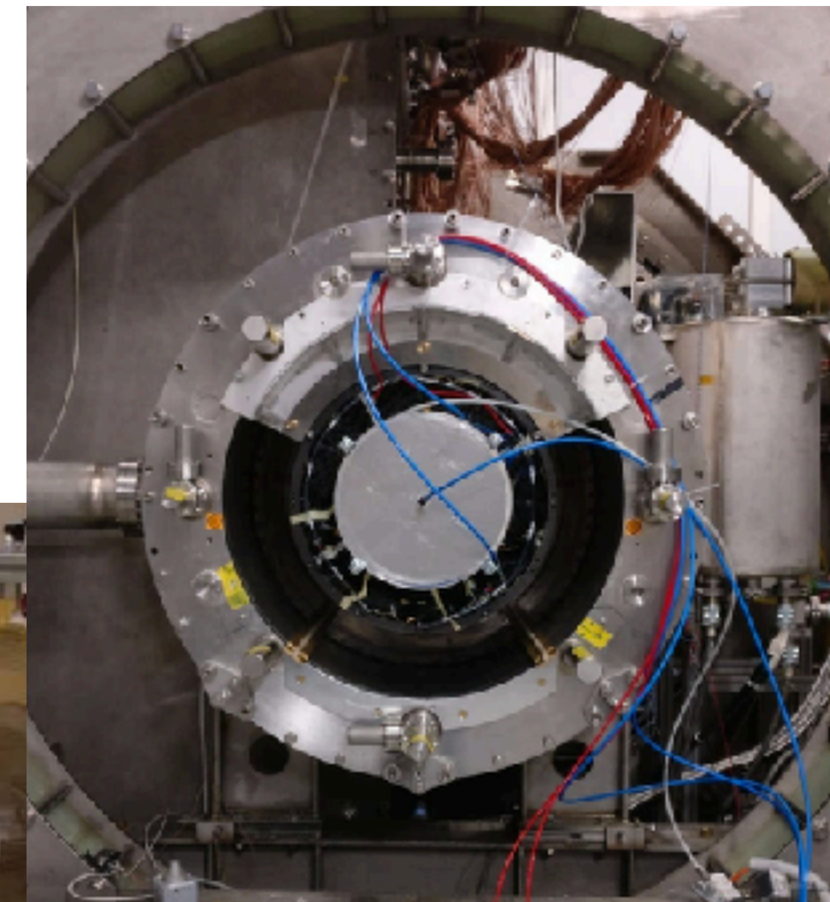
Cylindrical Drift Chamber

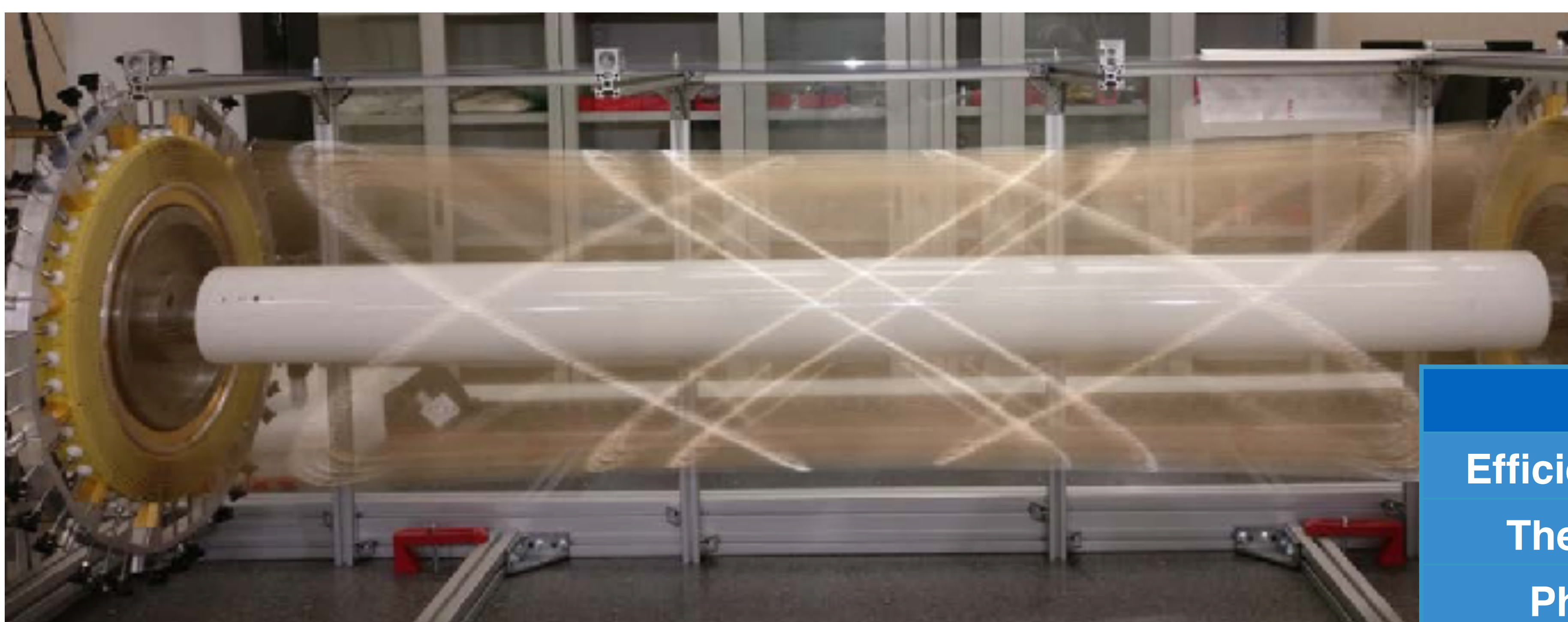


- Single volume stereo drift chamber with He:Isobutane
- 1.5 10^{-3} X_0 per turn
- Drift cells 6mm x 6mm to cope with pileup (PCB-based construction)
- ~65 hits per track (MEG: ~12)

Recently installed:

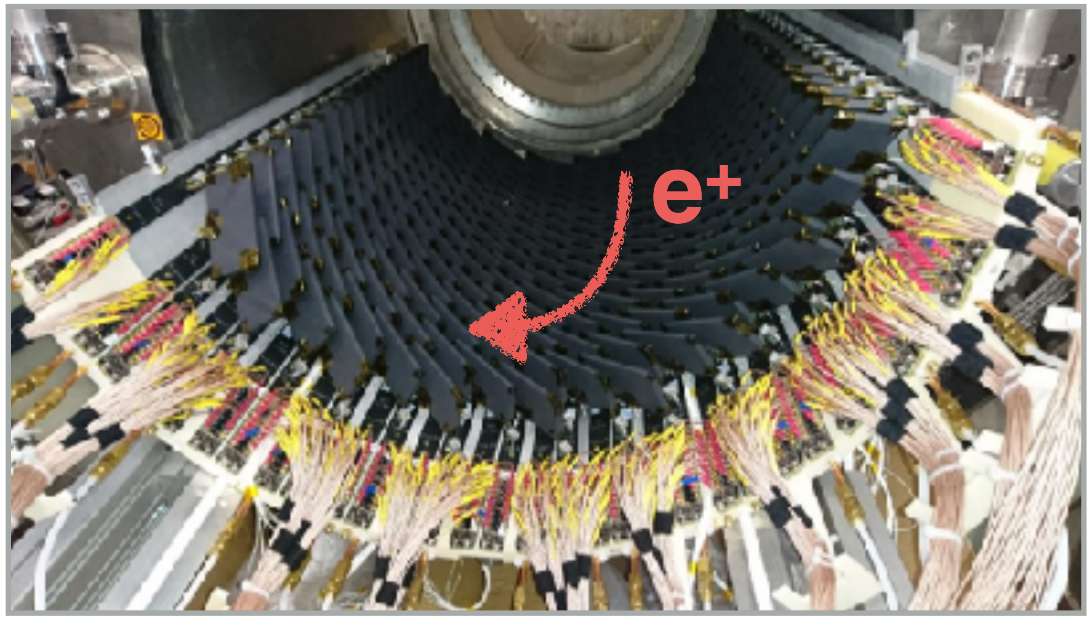
Service connection in progress, preliminary measurements by end of this year

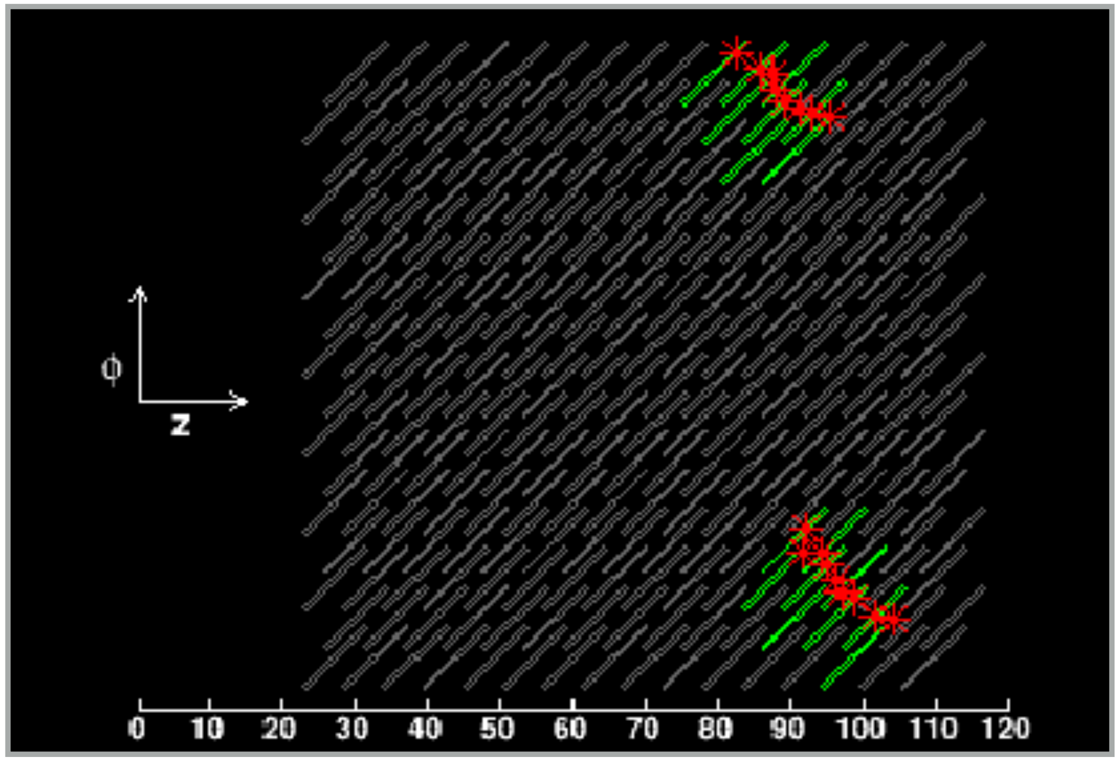




	MEG	MEG II
Efficiency	29%	70%
Theta	9.4 mrad	5.3 mrad
Phi	8.7 mrad	3.7 mrad
Energy	306 keV	130 keV

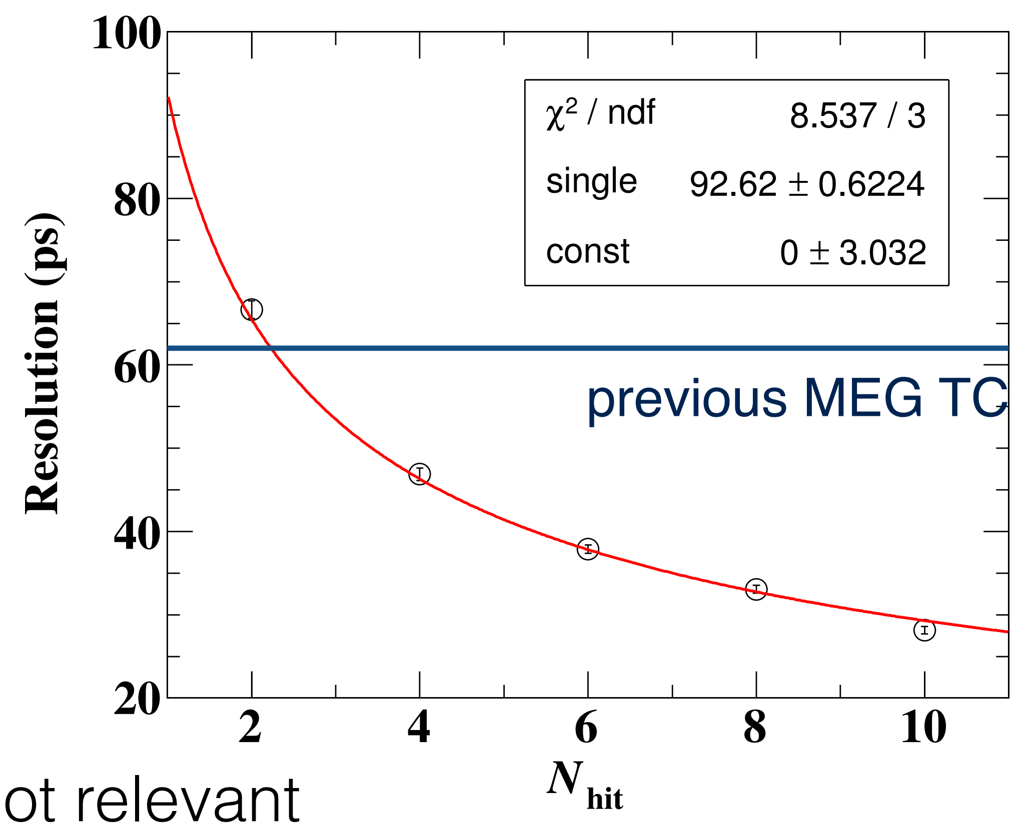
MEG II Timing Counter beam test





Tested with final detector and **full MEG II beam intensity** (8 10^8 μ/s):

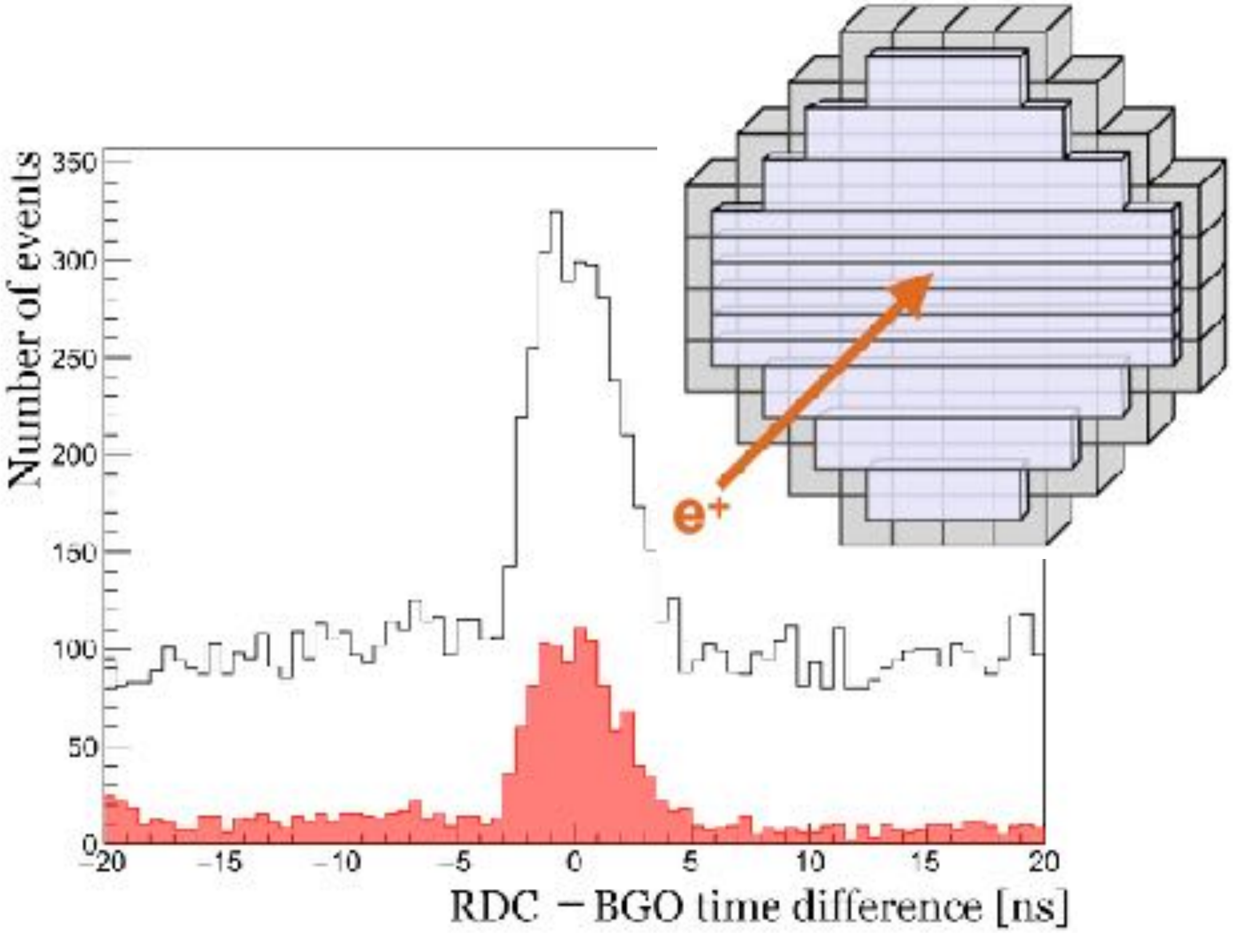
- 256 scintillating tiles, **512 readout chn.** (two crate system)
- 2 Auxiliary Laser chn. for monitoring
- Trigger on single tile (coincidence of two tile channels) select **positron tracks**

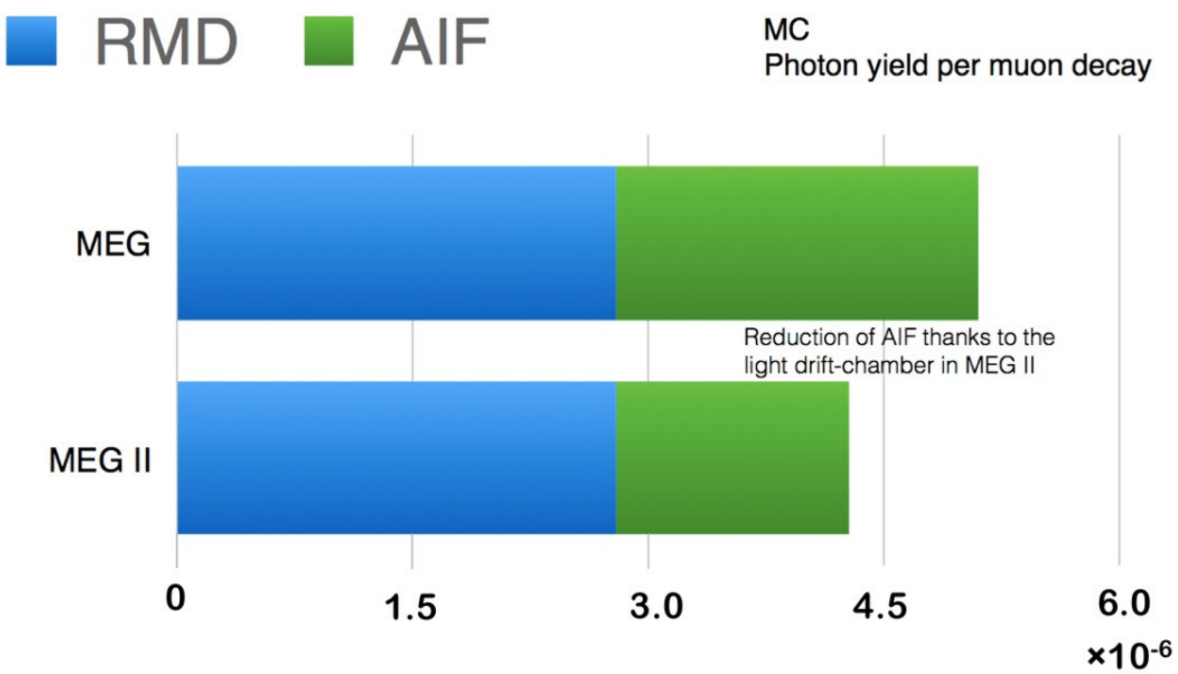


Offline DRS4 analysis: Time resolution scales as **square root** of hit multiplicity with electronic contribution on the order of 10ps/chn

↳ Electronic contribution not relevant

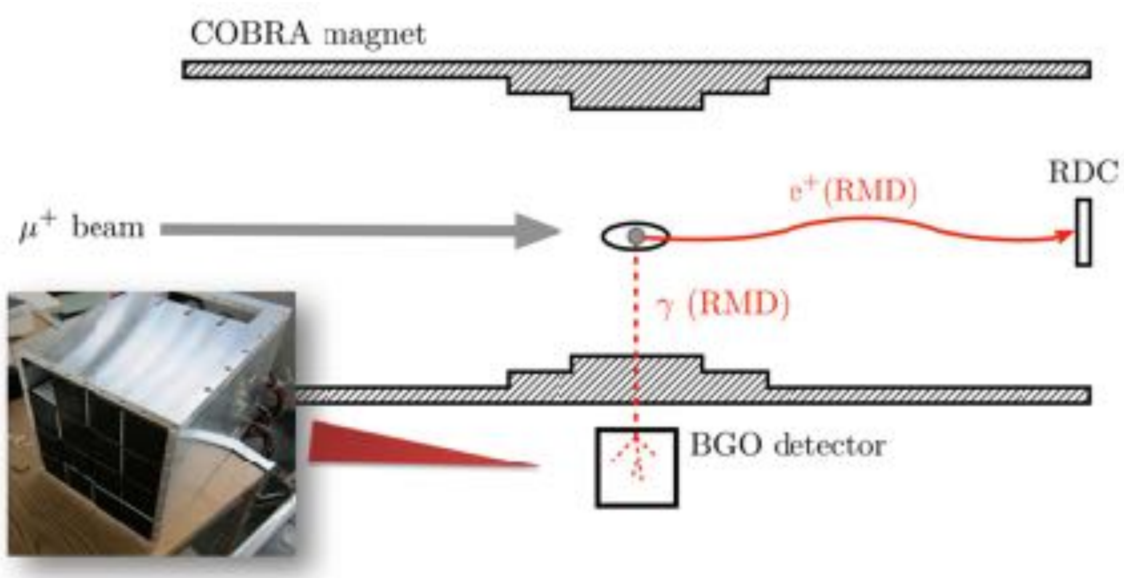
RDC





Detector Completed

- Plastic Scintillators + LYSO
- Tag events with low energy positrons, possibly with high energy photons
- veto in search for $\mu \rightarrow e\gamma$

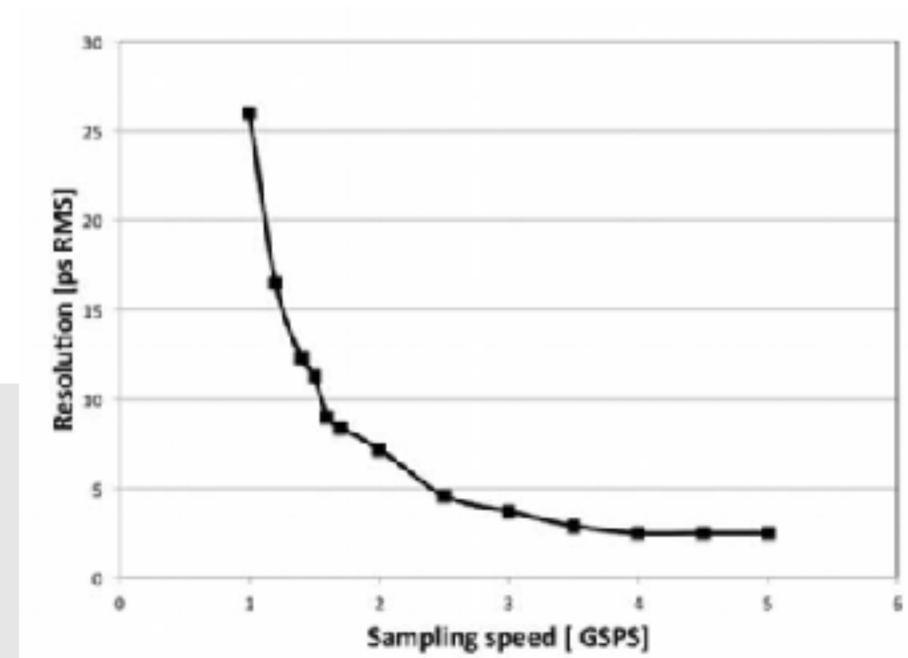


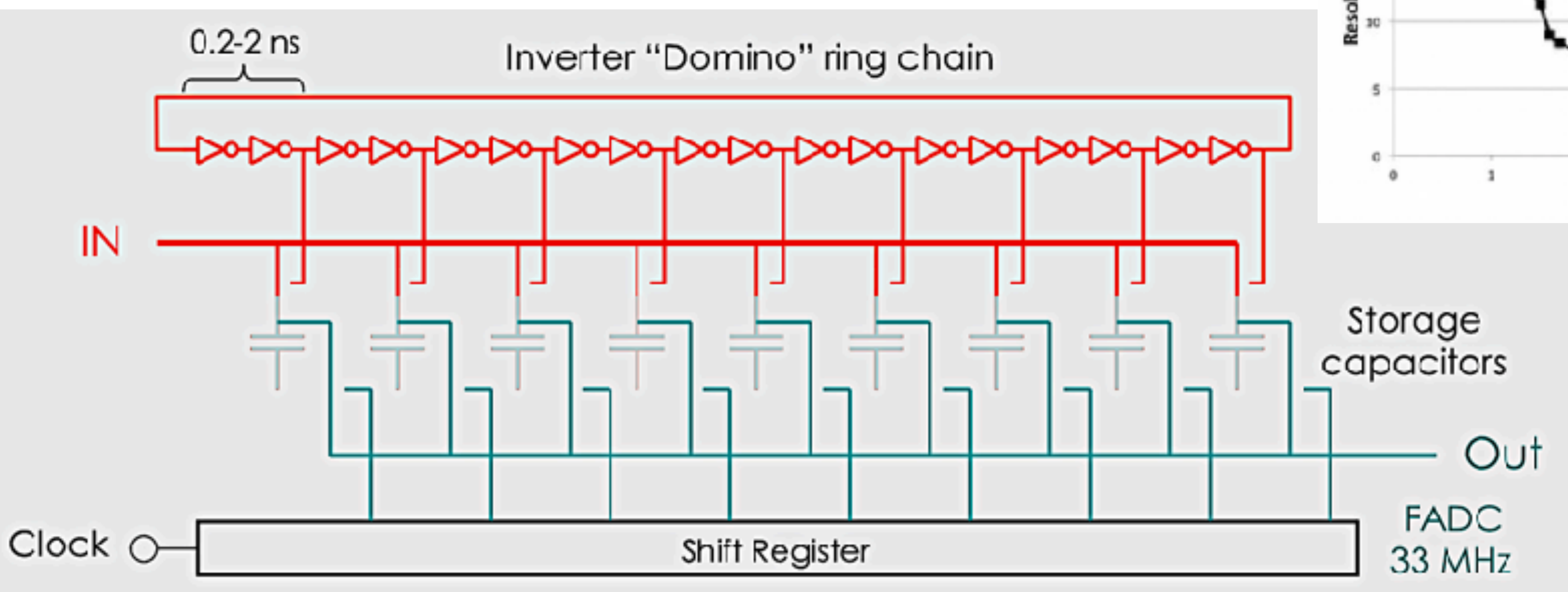
DRS 4 Digitizer

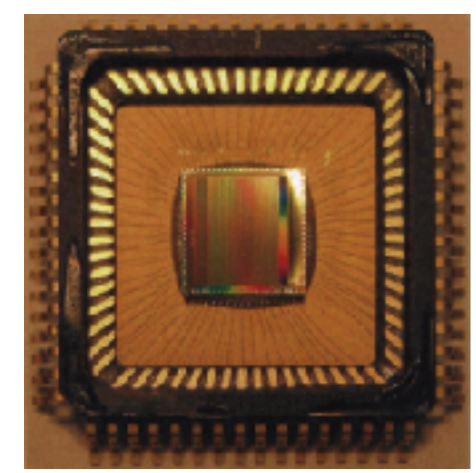
Analog switched capacitor array: analog memory with a depth of 1024 sampling cells
Developed at PSI for the MEG experiment, perform a "**sliding window**" sampling

500MSPS ↔ 5GSPS sampling speed

8 analog channels + 1 clock-dedicated channel







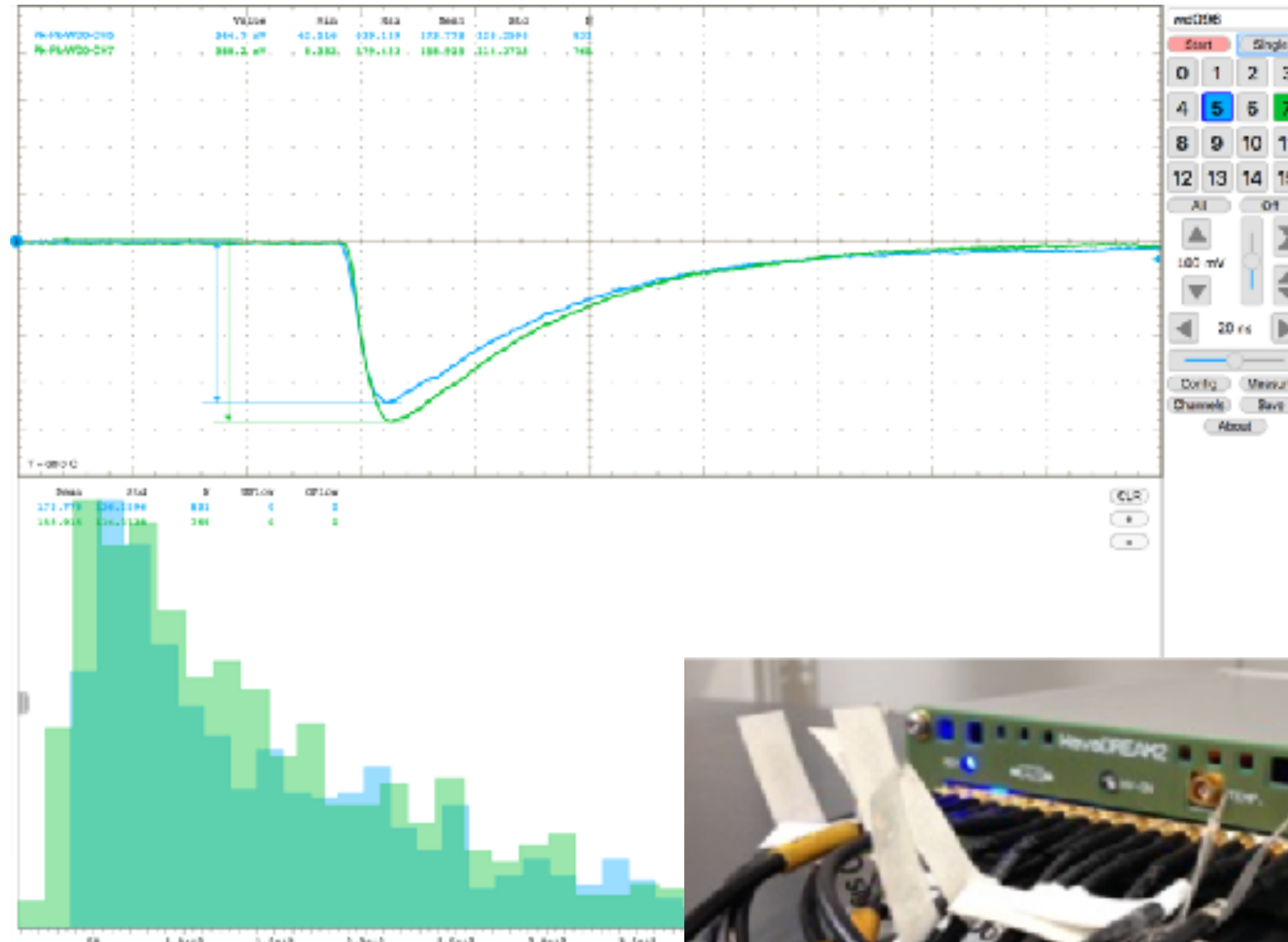
External trigger needed before data in signal cell is overwritten
→ 512ns maximum trigger latency at 2GSPS

Single board DAQ

Single board **DAQ** software developed by PSI.
HTML5-Ajax web interface working at 60 fps with online Histogramming

Server software using Mongoose C/C++ Framework
- Easy low level calls for fast DAQ operations:
- Single executable with no need of dedicated http server

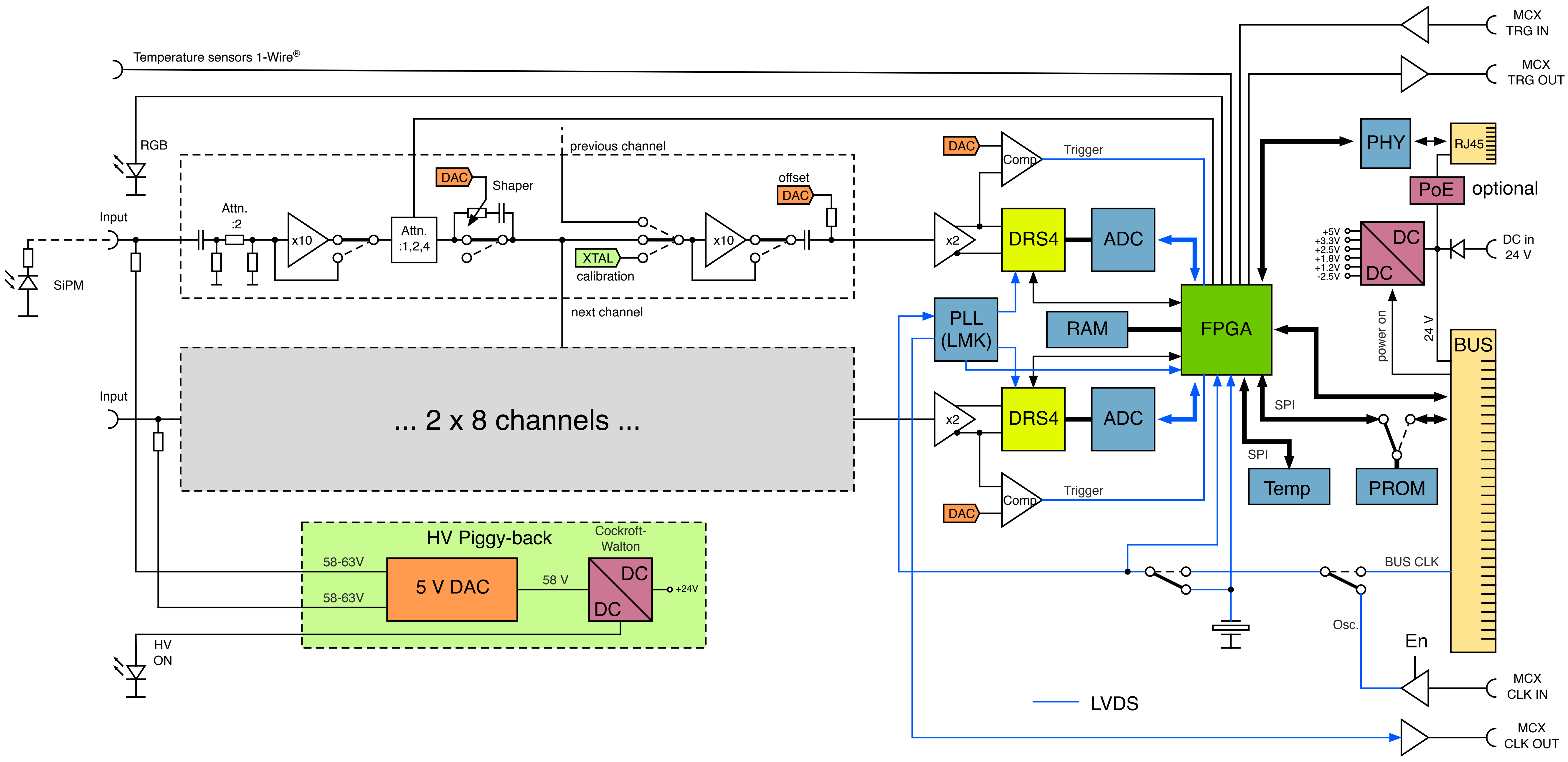
Wide use within and outside MEG II collaboration for small scale **prototype tests** and fast **signal checks**



Fully working demo: http://elog.psi.ch/scope

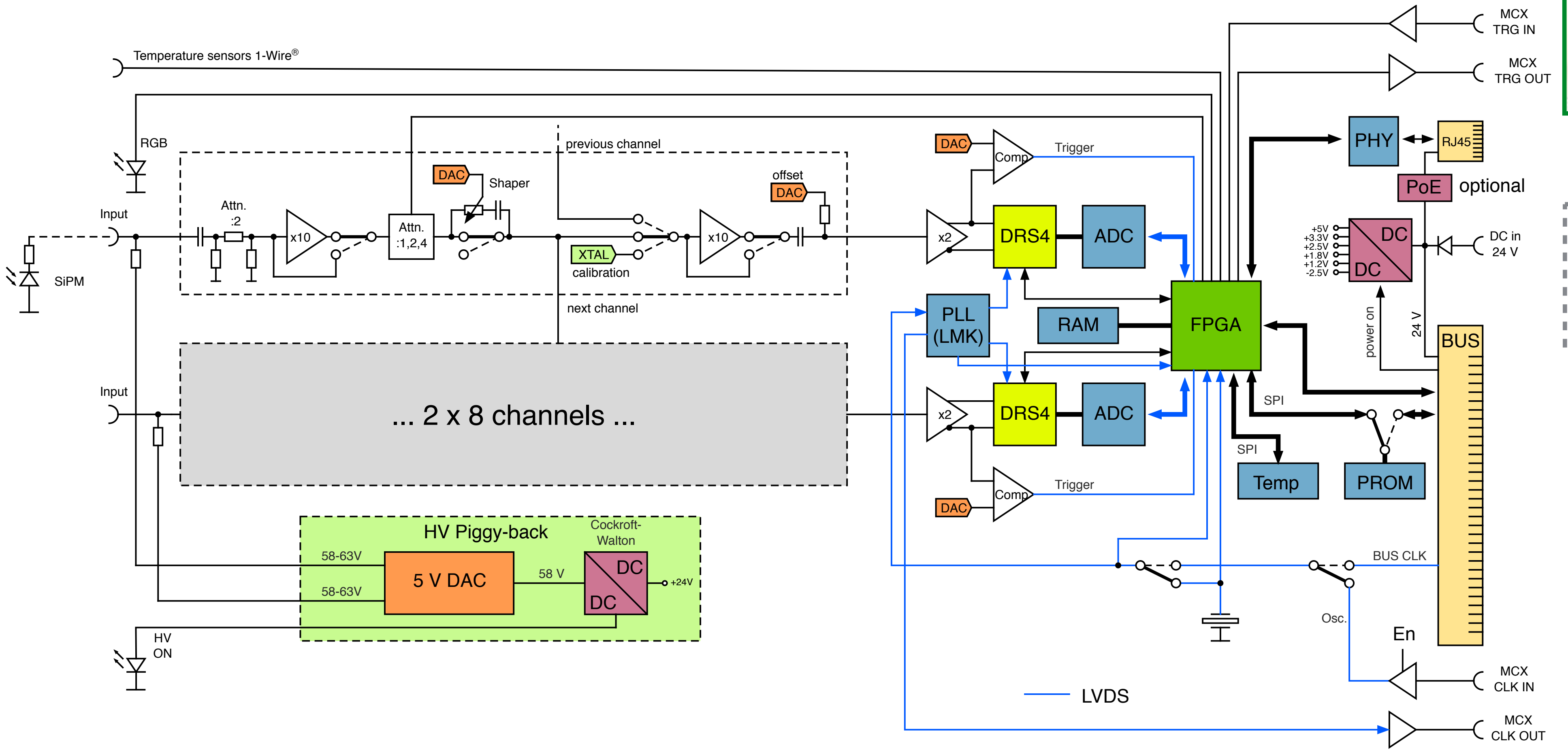
See poster #388 “Web-based Real Time Monitoring with HTML5” by Stefan Ritt

WaveDREAM Block Schematic



WaveDREAM board

WaveDREAM:
16 ch **D**rs4 **REA**dout **M**odule
Waveform digitizer with two **DRS4** each with 80MSPS **ADC** for fast readout and parallel trigger sampling



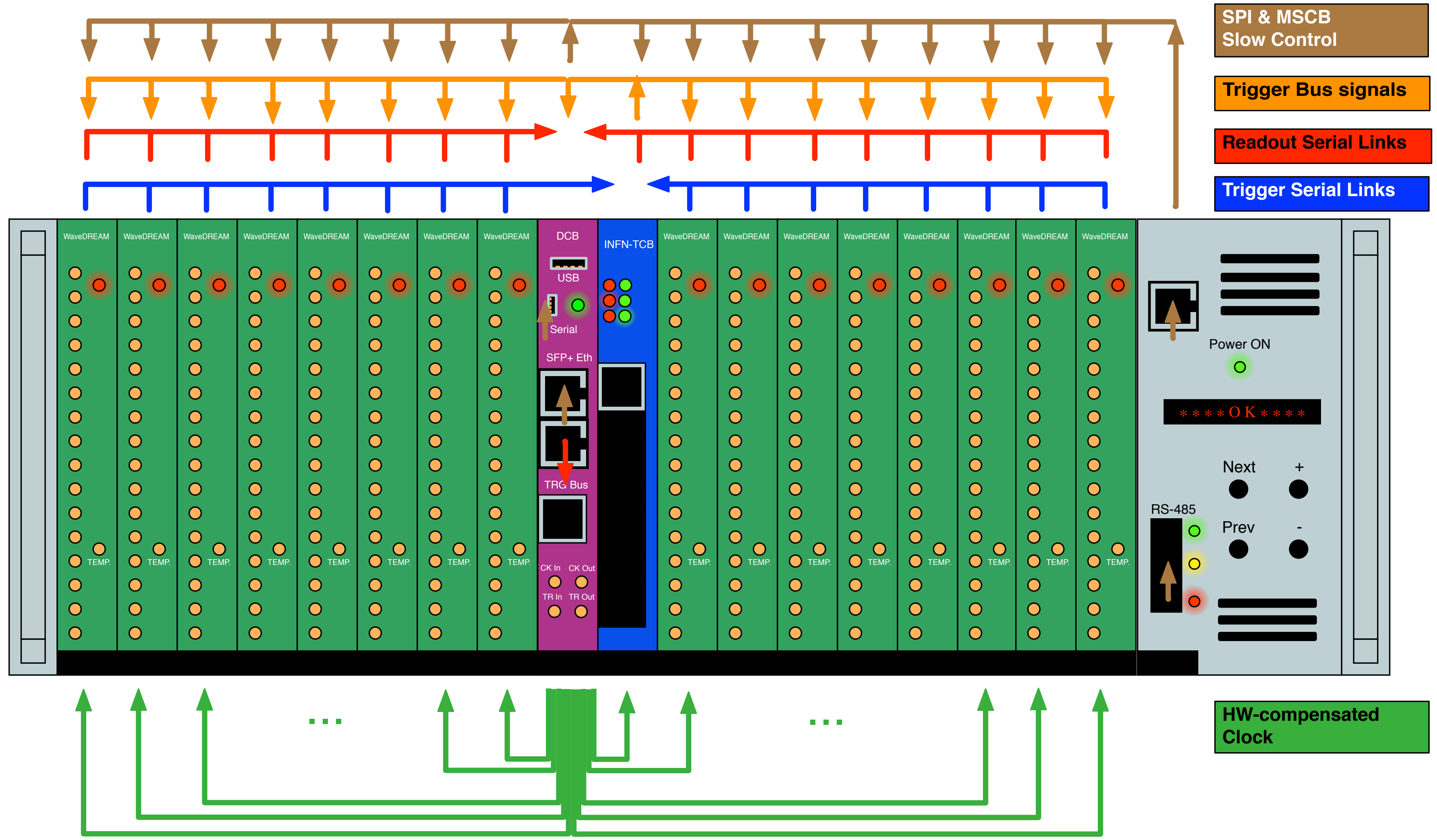
Selectable frontend **gain** and **PZC** intensity

Additional fast analog comparator for online pulse timing (450 ps rms limited by current FPGA firmware)

Piggy-back **HV module** up to 240V for SiPM arrays with integrated current readout

Can work in crate or standalone for 16ch tabletop DAQ with **Gb Ethernet** readout

Medium-size system



Up to 16 WaveDREAMs fit in a **custom** designed **3U crate** (256 channels) with hardware compensated **Clock distribution** and shared LVDS **Trigger signal**.
Crate management board with **M**IDAS **S**low **C**ontrol **B**us node and **SPI interface** to boards.

Trigger combination by means of Kintex 7 **T**rigger **C**oncentrator FPGA **B**oard **TCB** using low latency **serial links**, up to 64 trigger lines involving **charge** and **time** algorithms.

Shared **readout** through **10Gb** interfaces on Zynq 7 SoC in the **D**ata **C**oncentrator **B**oard **DCB**

Bigger systems

Bigger systems?

↓

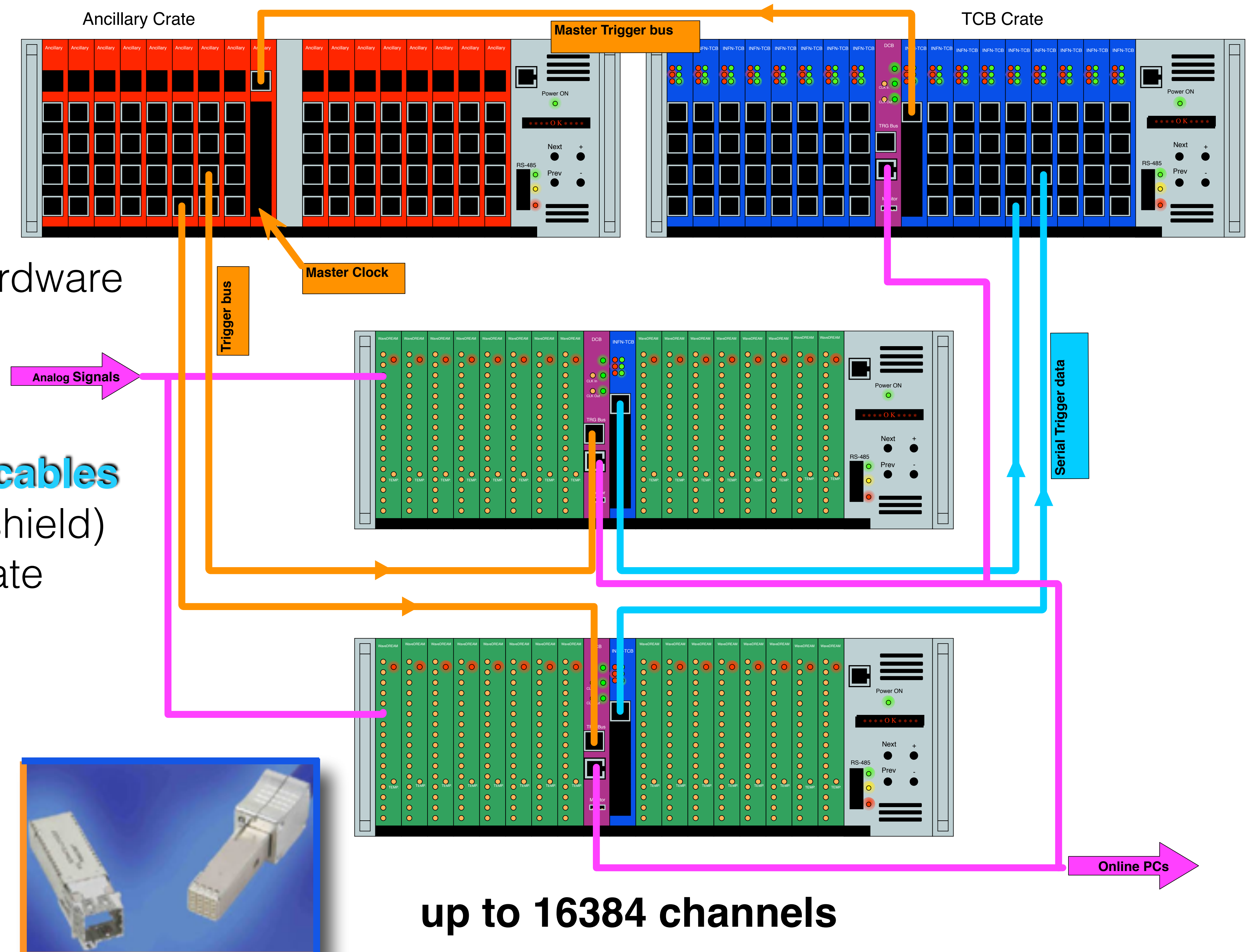
Additional aggregation layers by TCBs using High Speed LVDS cables

↳Reuse existing hardware when possible

- 16:1 inside crate
- 4:1 through **trigger cables**
- (FCI Densishield)
- 16:1 inside trigger crate

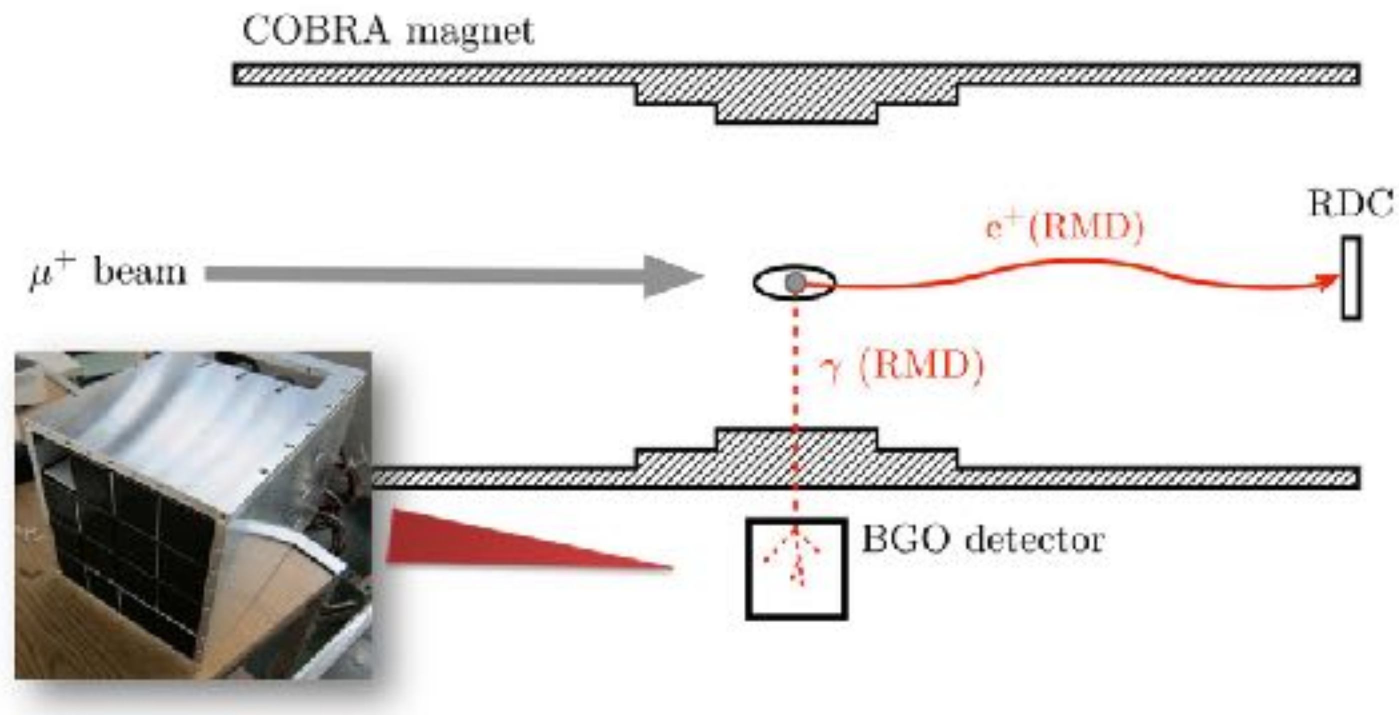
The **Ancillary** system distributes **trigger** and **clock signals** through the system

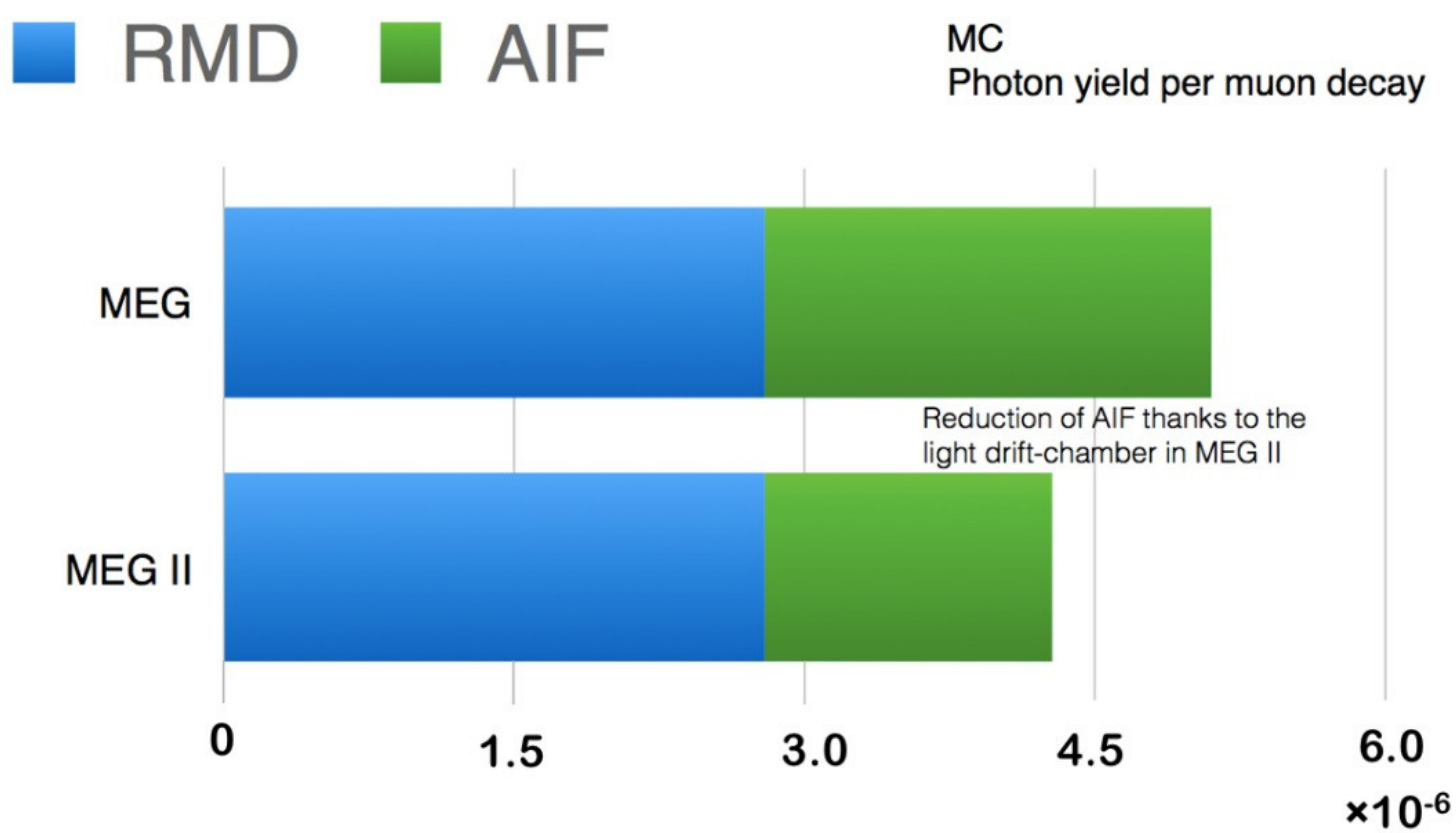
<10ps jitter on clock



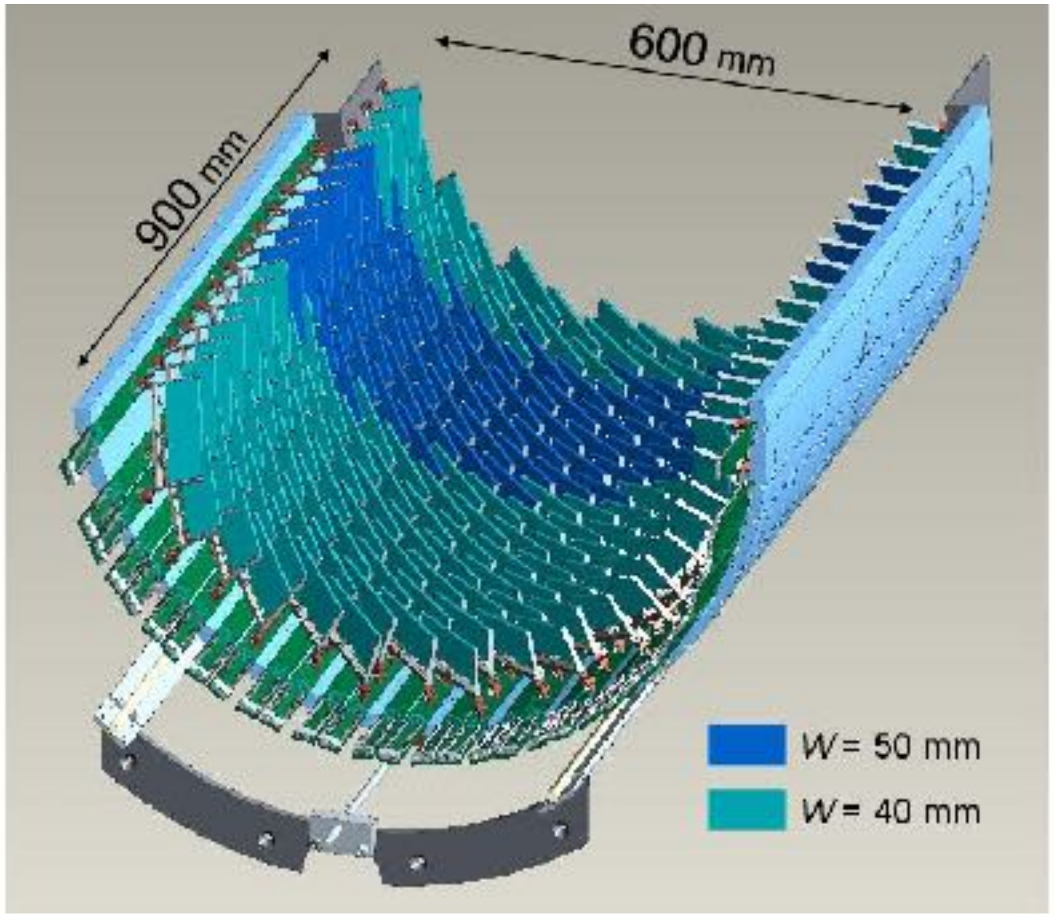
up to 16384 channels

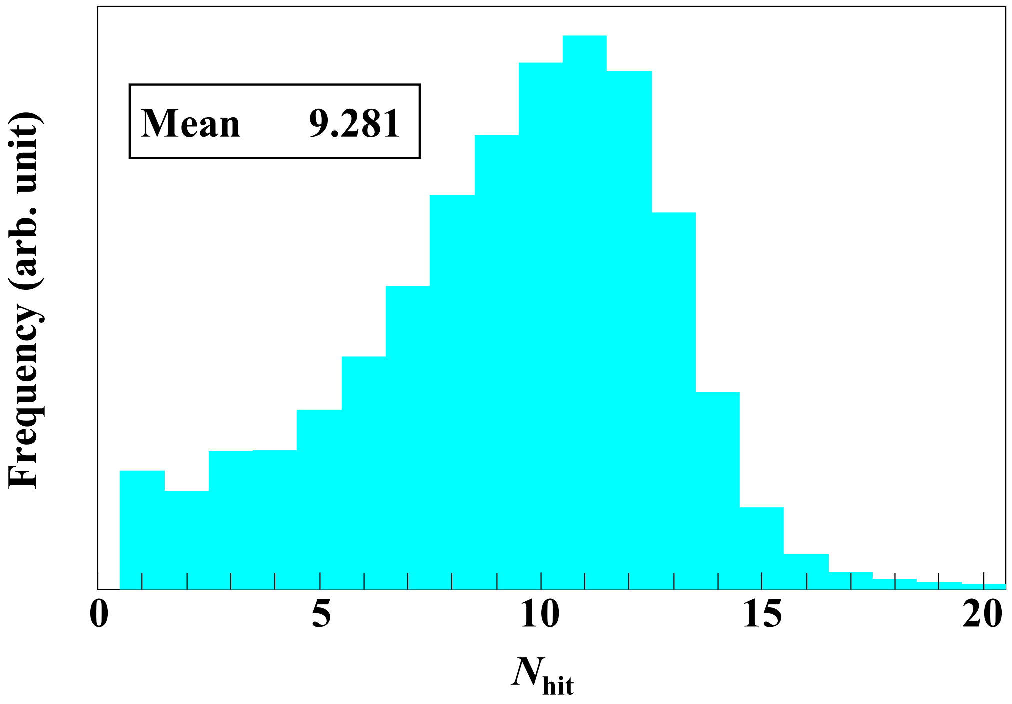
Radiative decay counter

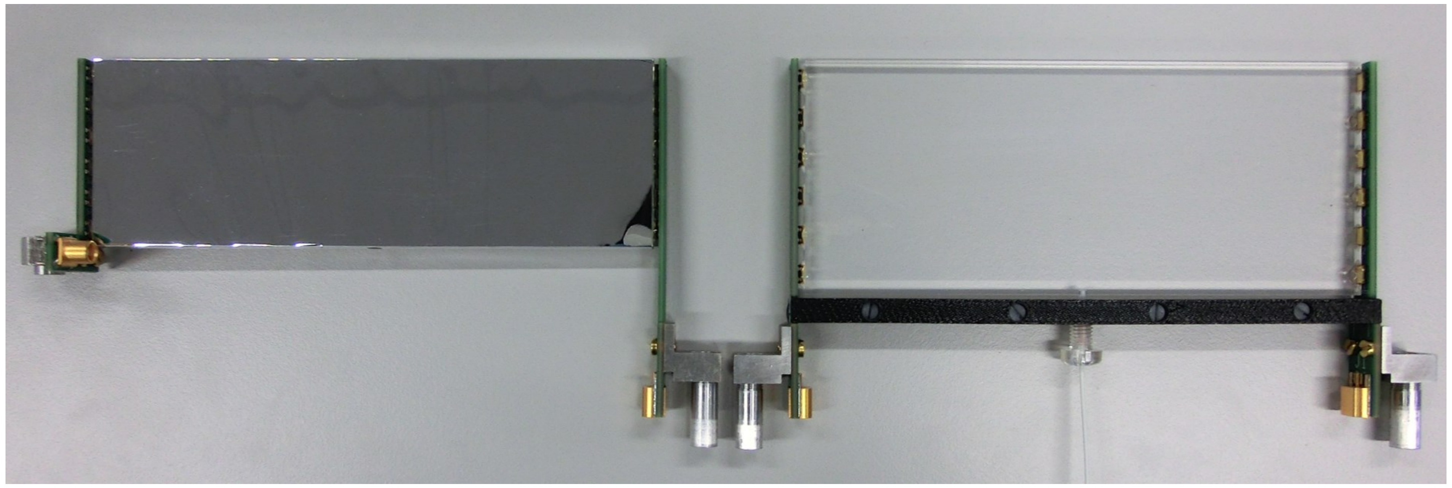


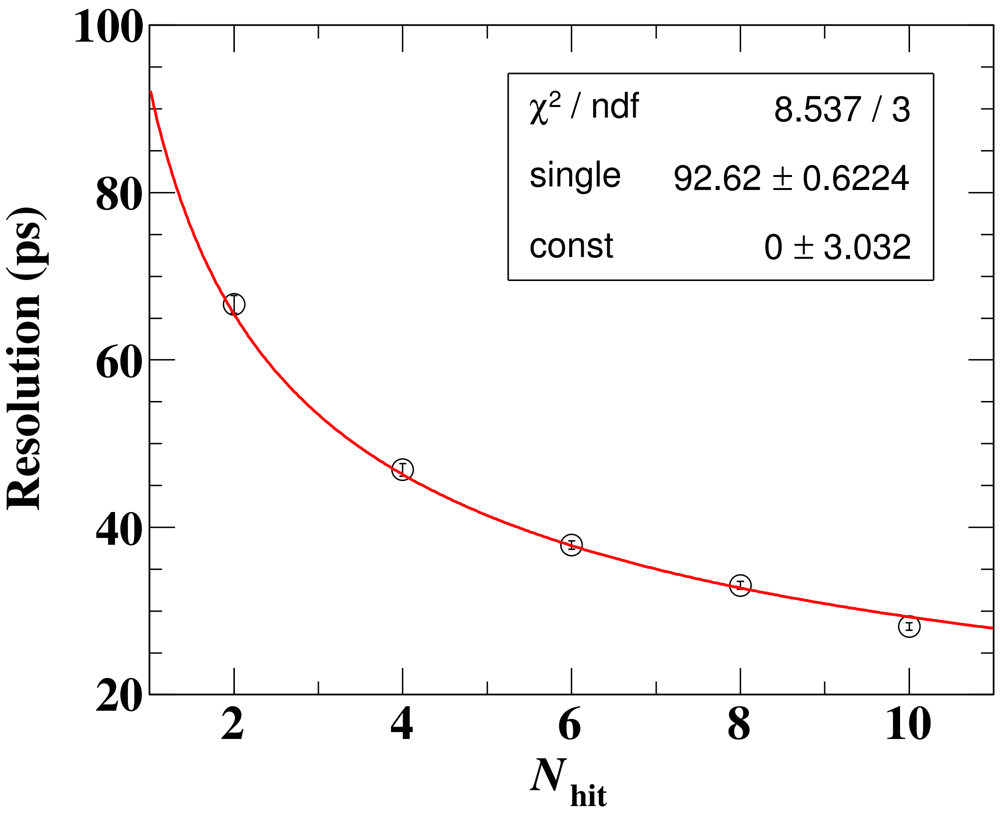


TC Multiplicity

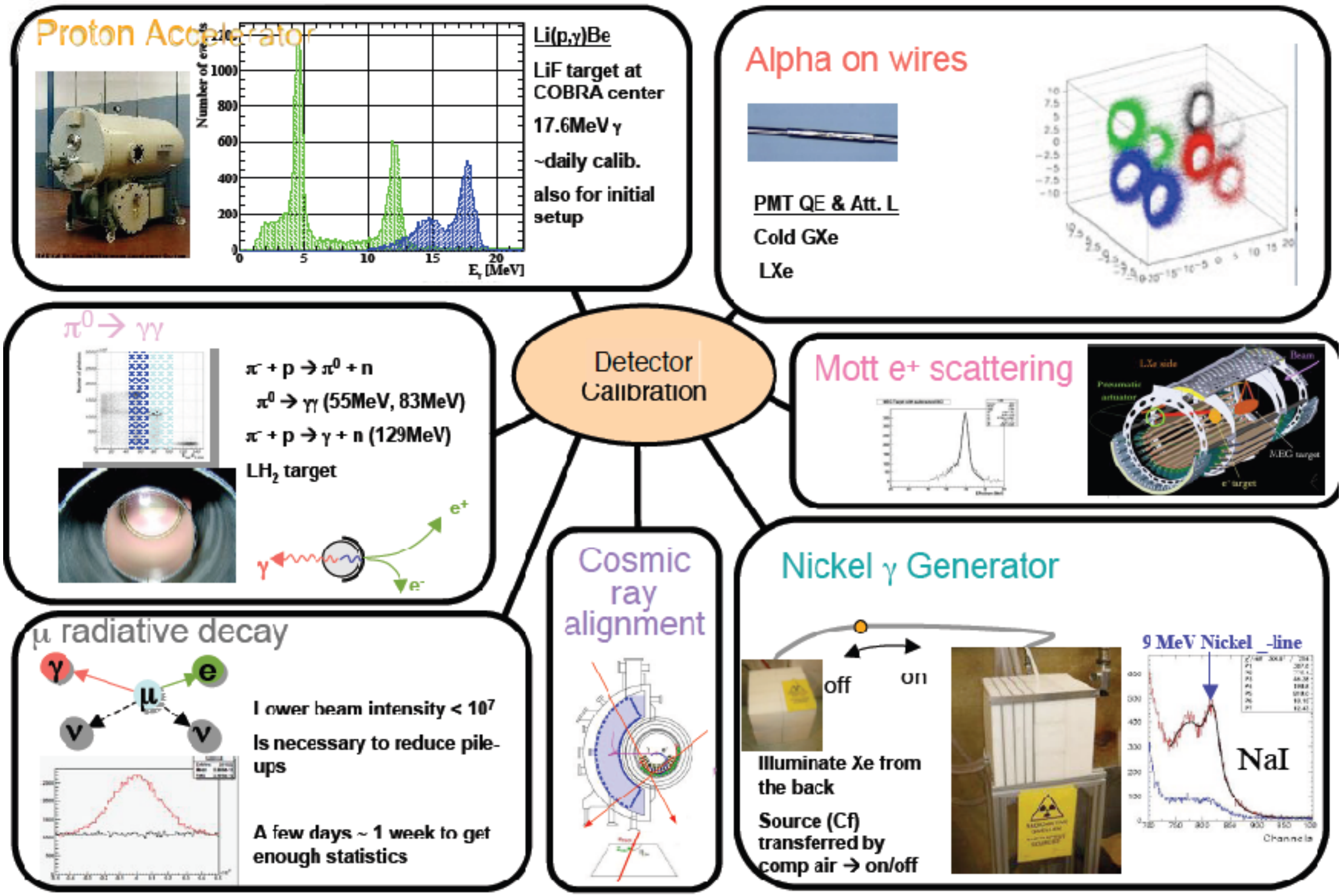






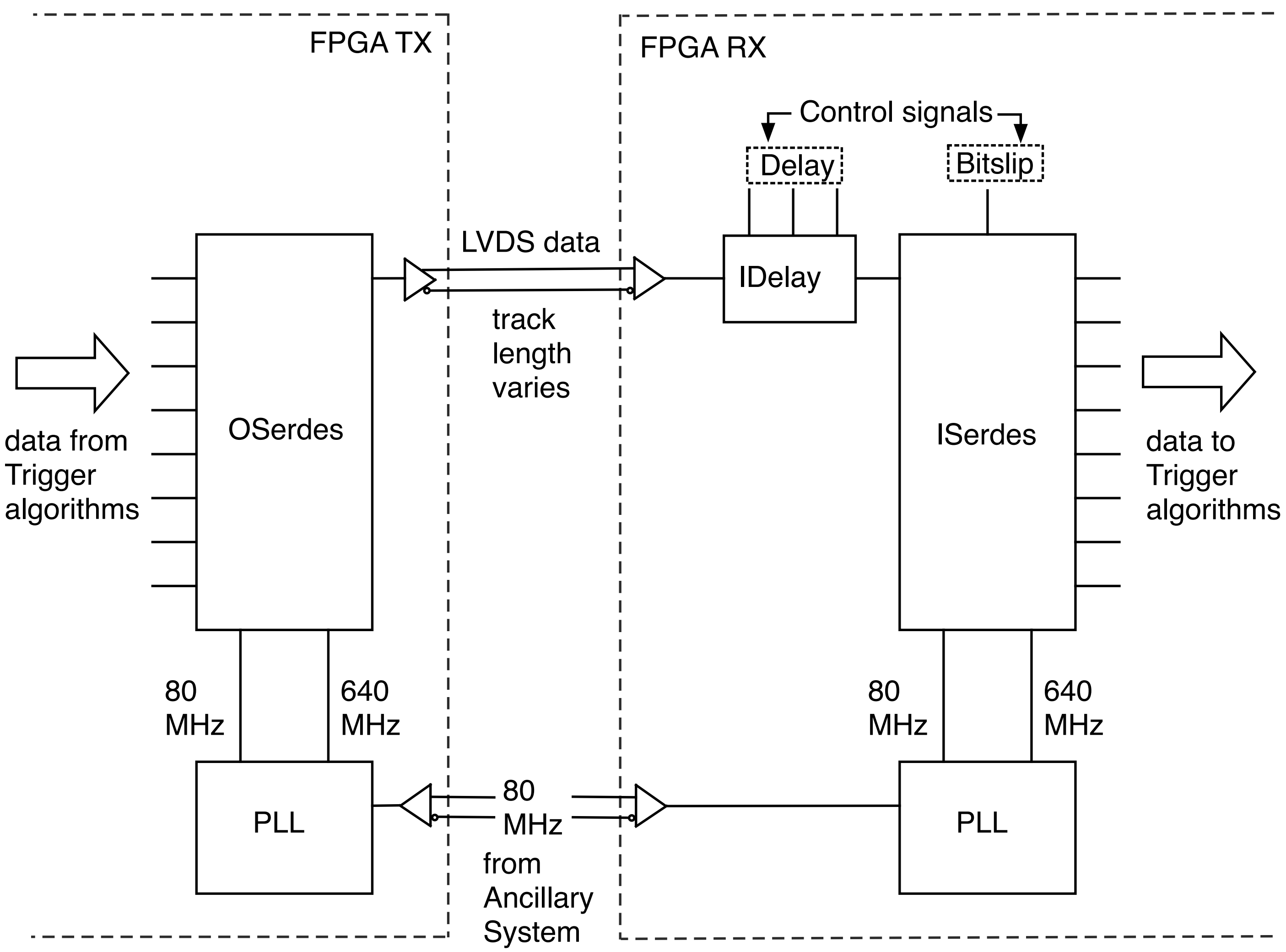


Calibrations

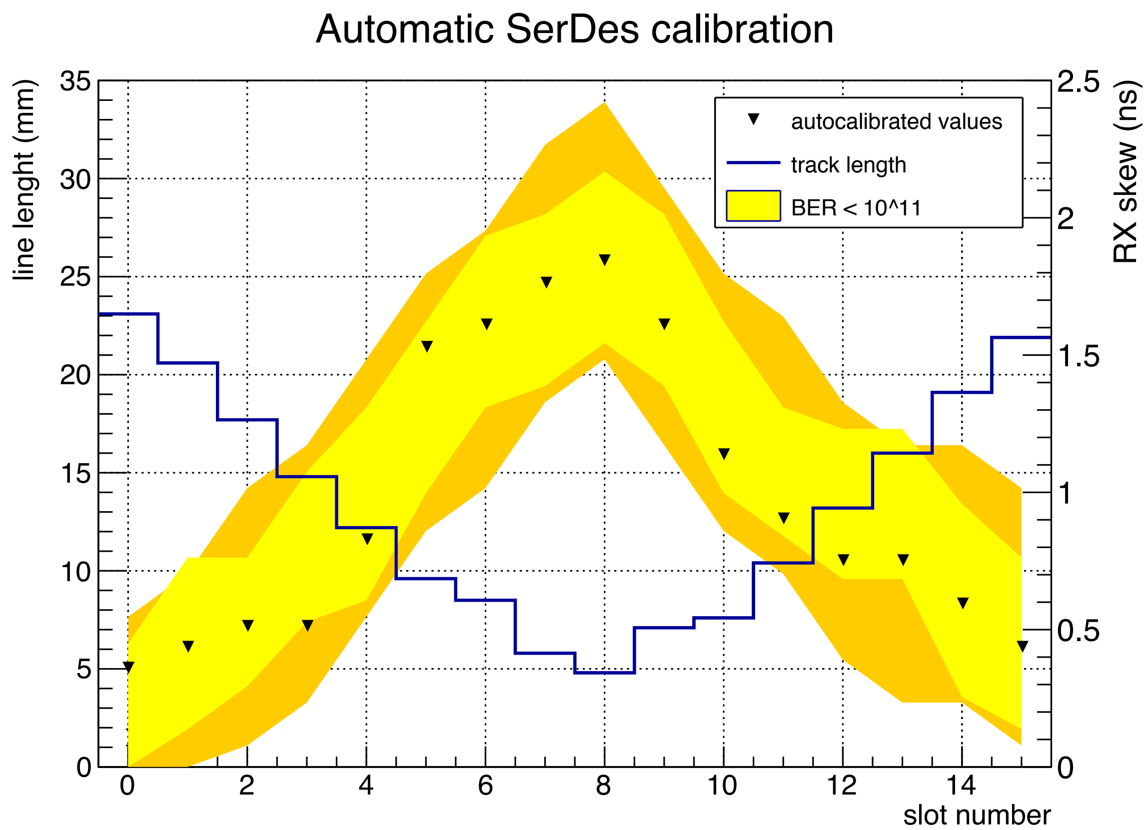


Trigger Links

Low latency serial connection are mandatory to keep a low latency trigger



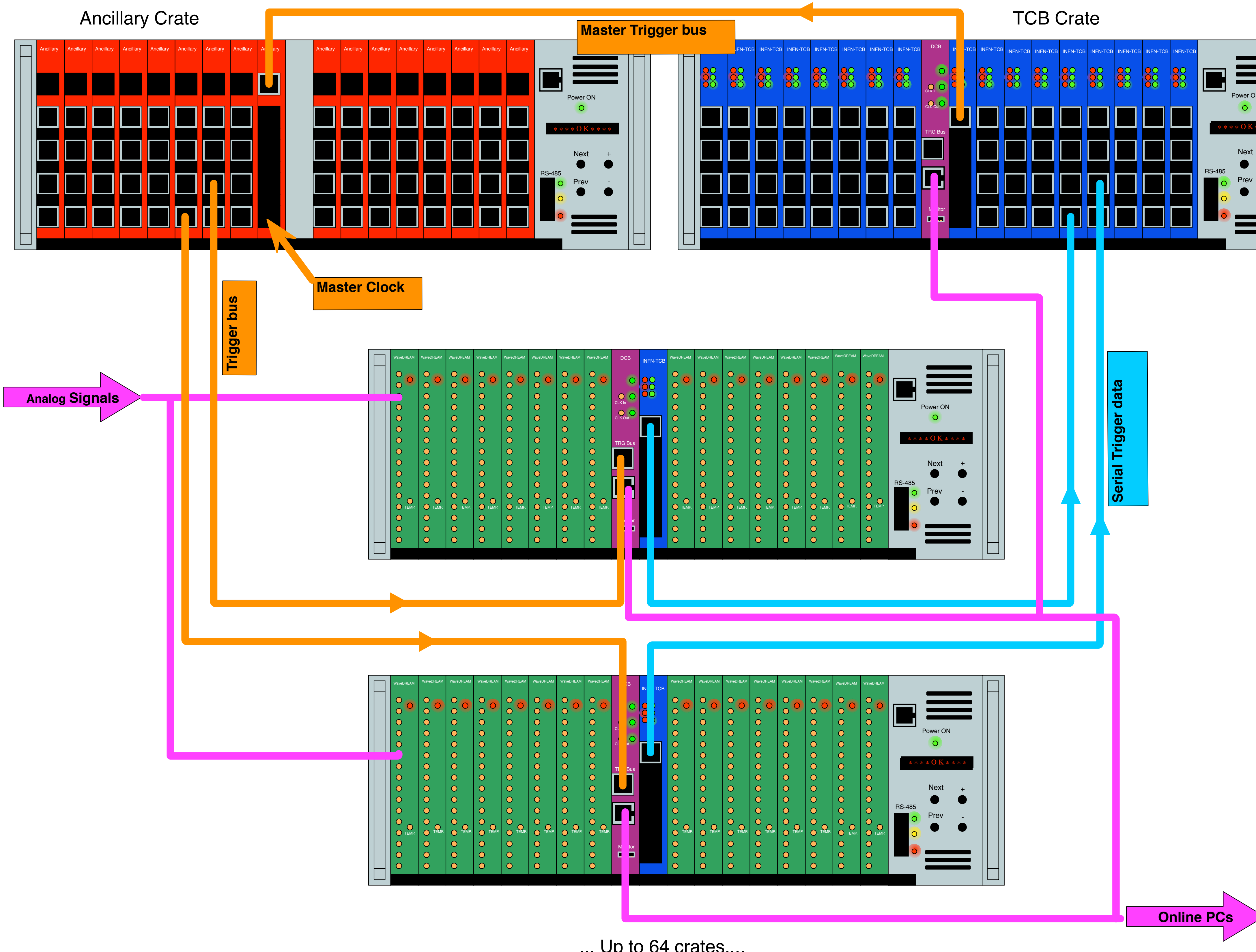
8 links each with a serialization ratio of 8 = 64 bit/clock



Serial links have been implemented using ISerdes/Oserdes primitive by Xilinx

MultiGigabit GTX transceiver have been discarded due to the high intrinsic latency

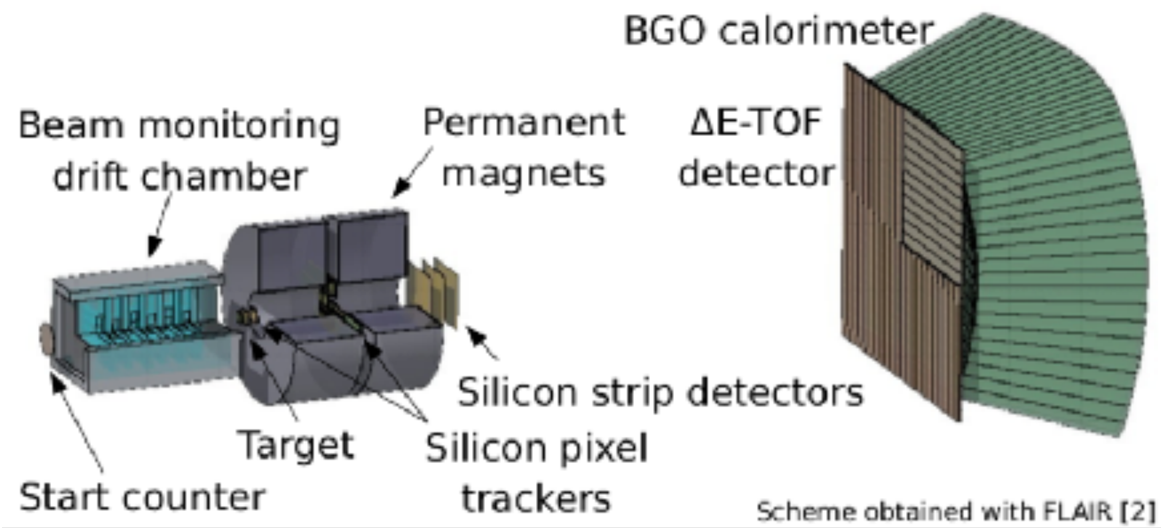
System

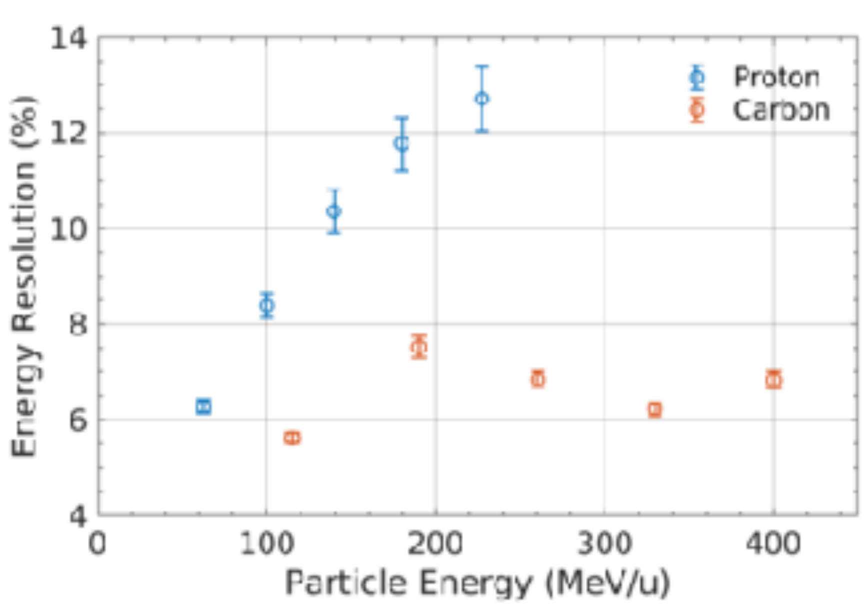


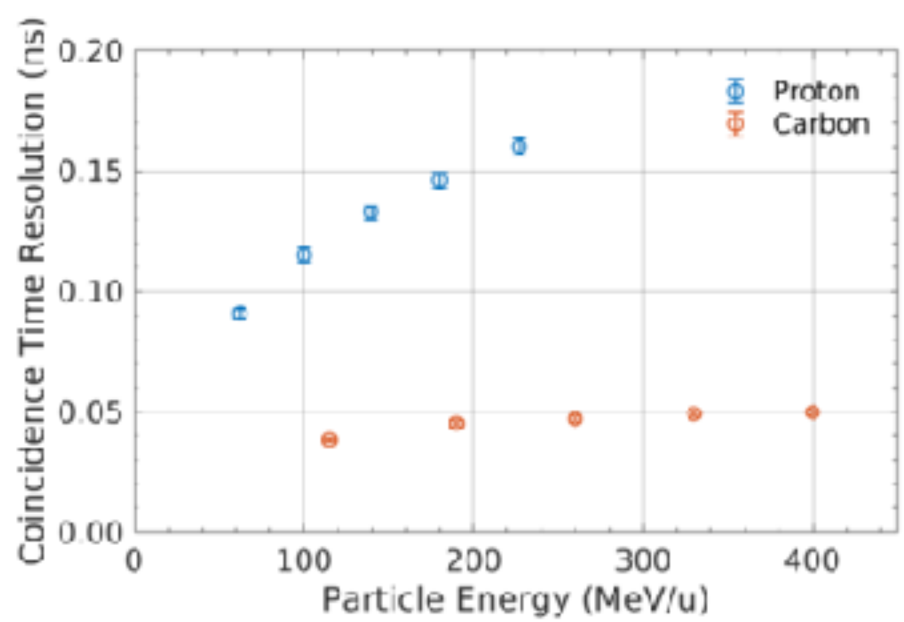
Ancillary Crate
TCB Crate
Master Trigger bus
Master Clock
Trigger bus
Analog Signals
Serial Trigger data
Online PCs
... Up to 64 crates....

Applications outside MEG II

FragmentatiOn Of Target







Prototype bars tested on beam at CNAO (IT) with standalone WaveDREAM board

Measuring ion **fragmentation** cross sections for proton therapy simulation improvement

Single crate WaveDAQ has been selected to readout ΔE-TOF detector (good time and charge resolutions needed)

44 Plastic Scintillator bars 2x0.3x44 mm with **SiPM** readout at both edges

\+

Start counter (to be defined)

Very high trigger ~kHz
Mandatory Data suppression