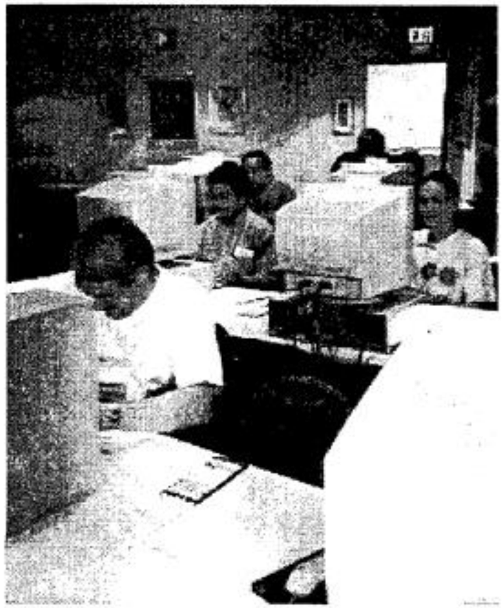
Stefan Ritt, Paul Scherrer Institute, Switzerland

# FUTURE OF cLFV USING MUONS
# - a technological approach

# Predicting the Future

## 11th Real Time Conference, Santa Fe, NM, 1999
## What will dominate the future of DAQ?



- PCs for Data Acquisition
- Linux as Operating System
- Java for DAQ programming

→ 66% success rate

interest. I hope everyone enjoyed the panel presentations and discussions by Bob Downing, Sandro Vascotto and Stefan Ritt, dynamically moderated by Wolfgang von Rueden.

# Agenda

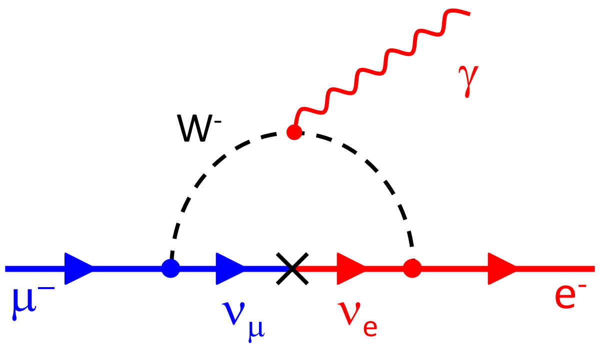
- Introduction to cLFV experiments
- Technical requirements
- Current and future solutions
  - Muon beams
  - Calorimetry
  - Tracking
  - Timing
  - (Crate standards)
  - Data visualization

# Why is cLFV so interesting?

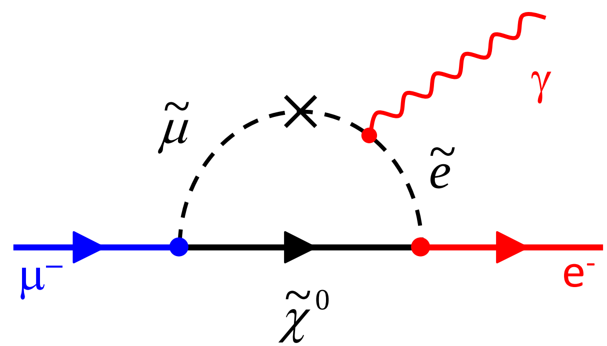
- New physics can be explored through virtual loops in low energy high precision experiments, reach O(100 TeV)
- While cLFV is forbidden in SM, it is possible on most SM extensions

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

Standard Model




SUSY



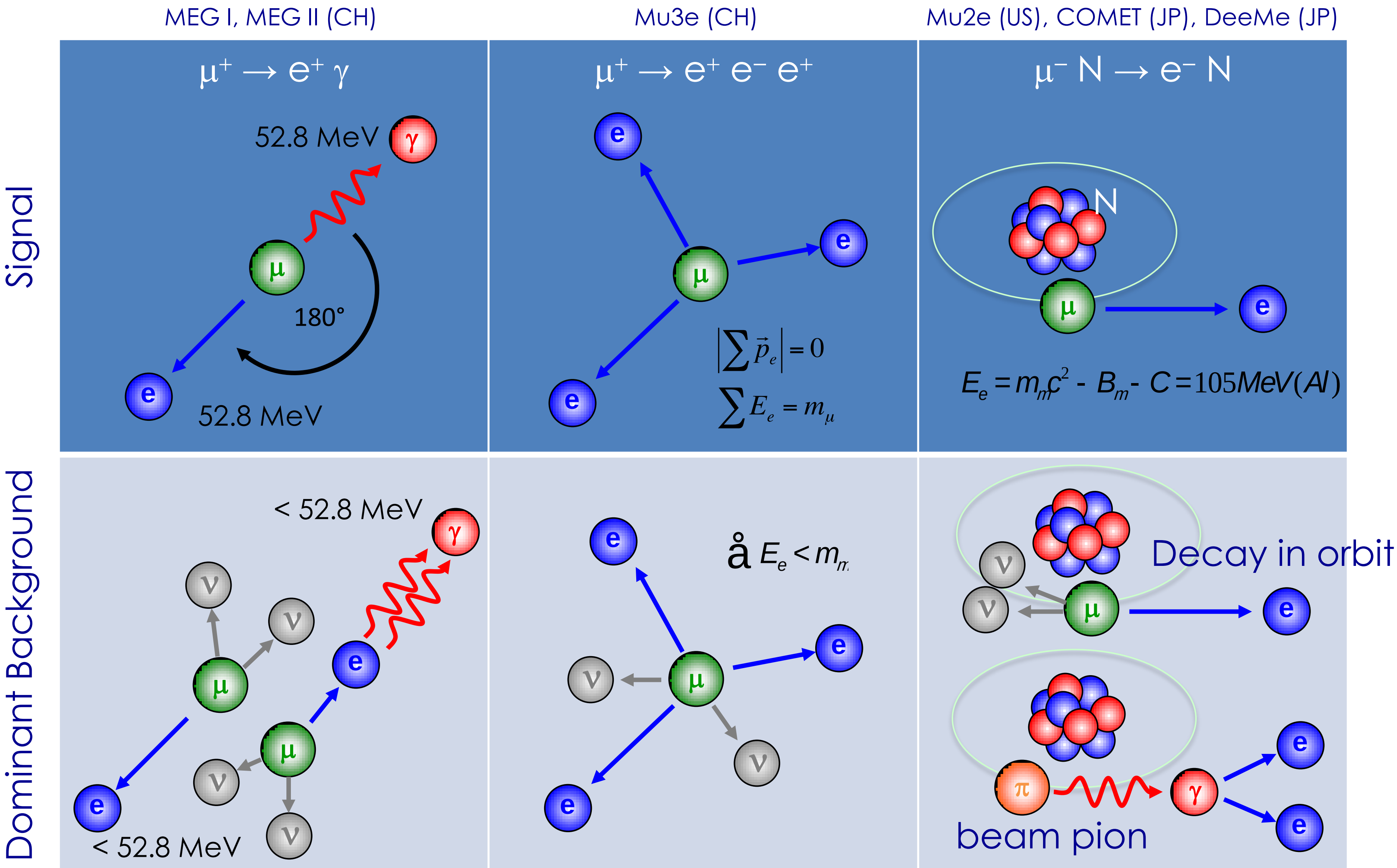

$$BR(m^+ \rightarrow e^+ g)\big|_{SM} \propto \frac{m_u^4}{m_W^4} \approx 10^{-54}$$

$$BR(\mu^+ \rightarrow e^+\gamma)\big|_{SUSY} \approx 10^{-5} \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\overline{m}^2_{\tilde{l}}} \left(\frac{100GeV}{m_{SUSY}}\right)^4 \tan^2\beta \approx 10^{-12} \cdots 10^{-14}$$

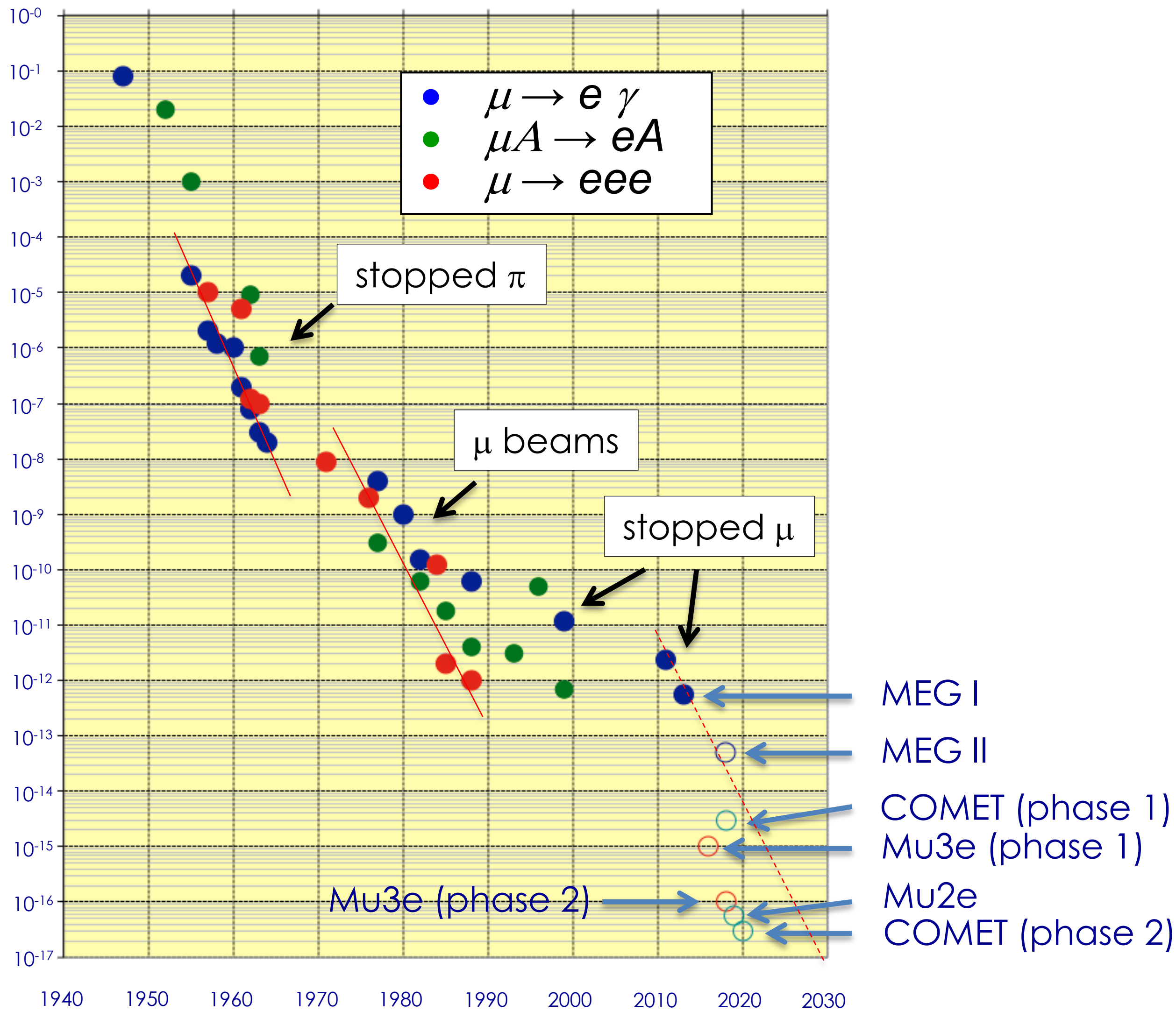
Experimental limit: BR($\mu^+ \rightarrow e^+\gamma$) < 5.7 x $10^{-13}$

MEG collaboration, PRL 110 (2013) 201801

# cLFV with muons



# History of cLFV experiments



# Requirements for cLFV experiments

- Muon beam
  - $10^{-17}$ sensitivity requires $>10^{17}$ muons per year
  - stopping target (low mass)
  - pulsed vs. DC beam
- Gamma detector ($\mu^+ \rightarrow e^+ \gamma$)
  - Good efficiency (solid angle)
  - Good resolutions in energy, position and time
- Positron/Electron detector
  - Good position resolution for momentum, tracking, vertexing
  - Good time resolution

20 – 100 MeV

# Muon Beams

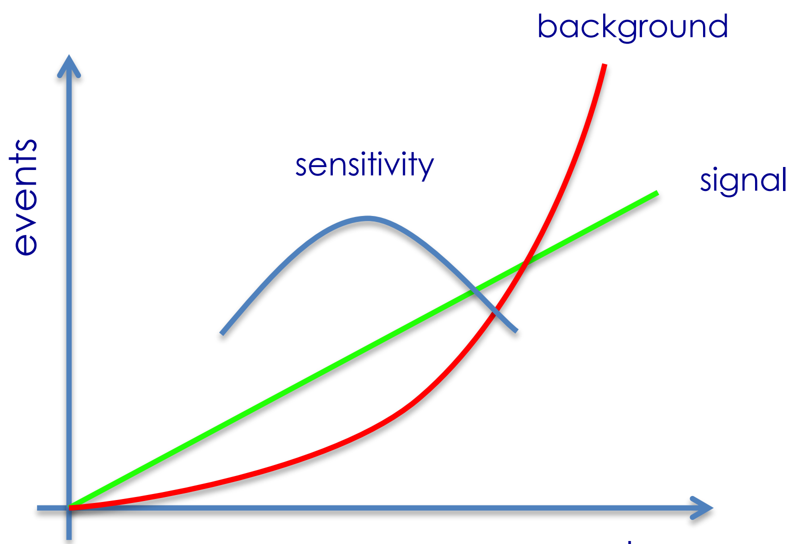
# Pulsed vs. DC muon beam

**Coincidence experiments**

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

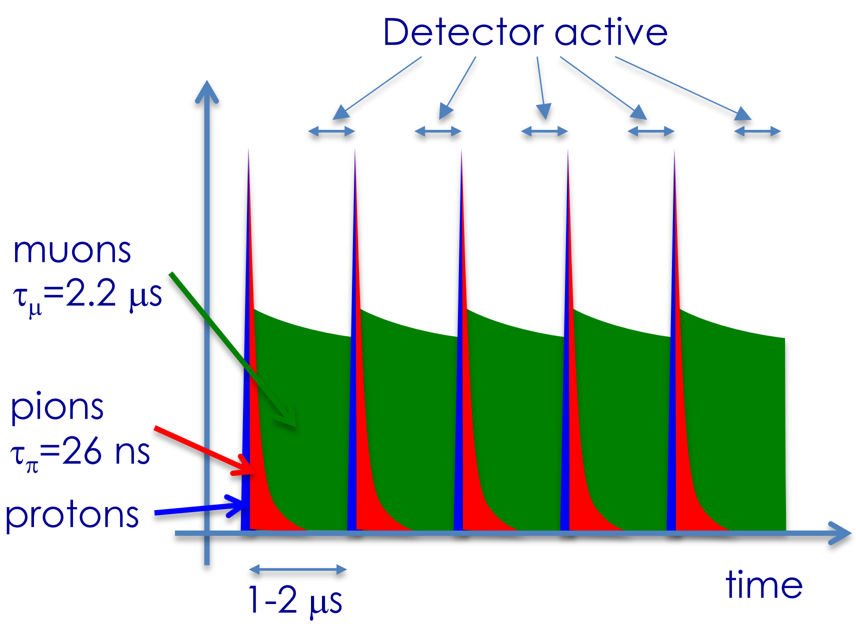
$\mu^+ \rightarrow e^+ e^- e^+$

- Limited by accidental background
- $R_{bck} \propto R\mu^2$
- DC muon beam is best




**μ – e conversion**

- Limited by pions in beam
- Contamination $<10^{-17}$
- Only possible with pulsed beam



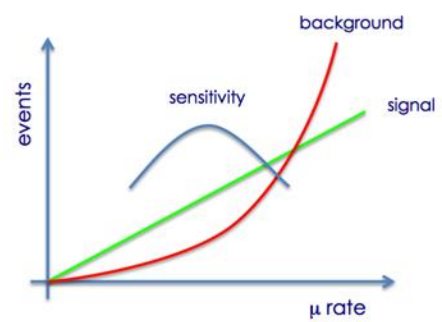
# Current and planned muon beams

running
planned

| Laboratory | Beam line | DC rate [Hz] | Pulsed rate [Hz] |
|---|---|---|---|
| PSI (CH)<br>0.59 GeV / 1.3 MW | LEMS | $4 \cdot 10^{8}$ ($\mu^{+}$) | |
| | $\pi$E5 | $1.6 \cdot 10^{8}$ ($\mu^{+}$) | |
| | HiMB | $1 \cdot 10^{10}$ ($\mu^{+}$) (>2018) | |
| J-PARC (JP)<br>3 GeV / 210 kW<br>(planned 1 MW) | MUSE D-line | | $3 \cdot 10^{7}$ ($\mu^{+}$) |
| | MUSE U-line | | $6.4 \cdot 10^{7}$ ($\mu^{+}$) |
| 8 GeV / 56 kW | COMET | | $1 \cdot 10^{11}$ ($\mu^{-}$) (2020) |
| 8 GeV / 300 kW | PRISM/PRIME | | $10^{11}$-$10^{12}$ ($\mu^{-}$) (>2020) |
| FNAL (USA) | | | |
| 8 GeV / 25 kW | Mu2e | | $5 \cdot 10^{10}$ ($\mu^{-}$) (2020) |
| 0.8 GeV / 100 kW | PIP-II | | $2 \cdot 10^{12}$ ($\mu^{-}$) (> 2022) |
| TRIUMF (CA)<br>0.5 GeV / 75 kW | M20 | $2 \cdot 10^{6}$ ($\mu^{+}$) | |
| RAL-ISIS (UK)<br>0.5 GeV / 75 kW | RIKEN-RAL | | $1.5 \cdot 10^{6}$ ($\mu^{+}$) |
| KEK (JP)<br>0.5 GeV / 2.5 kW | Dai Omega | | $4 \cdot 10^{5}$ ($\mu^{+}$) |
| RCNP Osaka (JP)<br>0.4 GeV / 400 W | MUSIC | | $10^{4} – 10^{5}$ ($\mu^{+}/\mu^{-}$) (2016) |
| DUBNA (RU)<br>0.66 GeV / 1.6 kW | Phasatron | | $3 \cdot 10^{4}$ ($\mu^{+}$) |

# Beam requirements

| Experiment | Optimal rate | Possible rate |
| --- | --- | --- |
| MEG I | $3 \cdot 10^7$ | $1 \cdot 10^8$ |
| MEG II | $7 \cdot 10^7$ | $1 \cdot 10^8$ |
| Mu3e Phase I | $1 \cdot 10^8$ | $1 \cdot 10^8$ |
| Mu3e Phase II | $> 10^9$ | $1 \cdot 10^{10}$ (>2018) |
| Mu2e | $5 \cdot 10^{10}$ | $5 \cdot 10^{10}$ (2020) |
| COMET Phase I | $1.3 \cdot 10^9$ | $1.3 \cdot 10^9$ (2018/19) |
| COMET Phase II | $1 \cdot 10^{12}$ | $1 \cdot 10^{11}$ (>2020) |

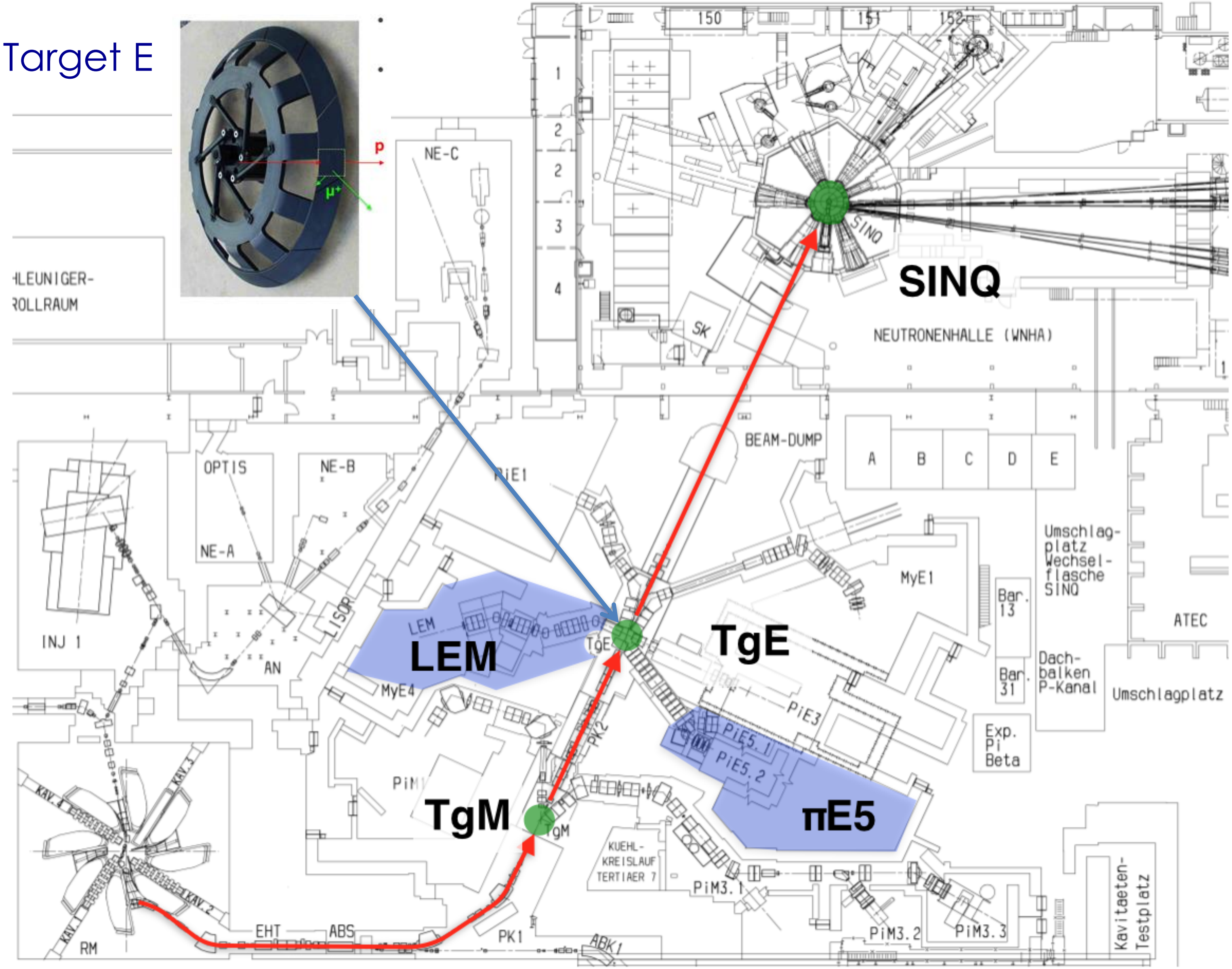



Long term future:

- More muons
- More muons
- More muons

# PSI Beam Lines

Target E

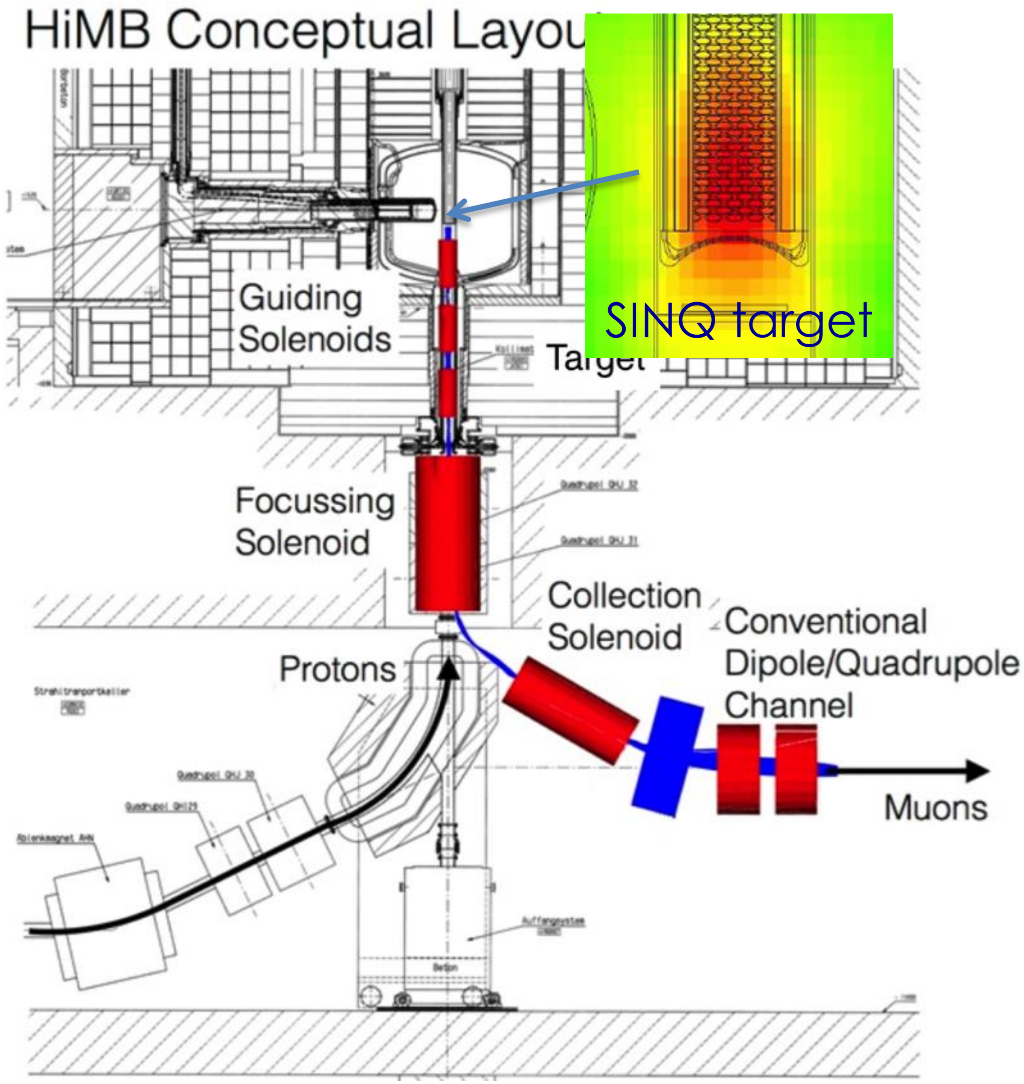


# HiMB @ SINQ target

- Muons transported opposite of proton beam in a solenoidal channel
- Capture large solid angle of full proton beam
- First estimates > $10^{10}$ $\mu$ / s

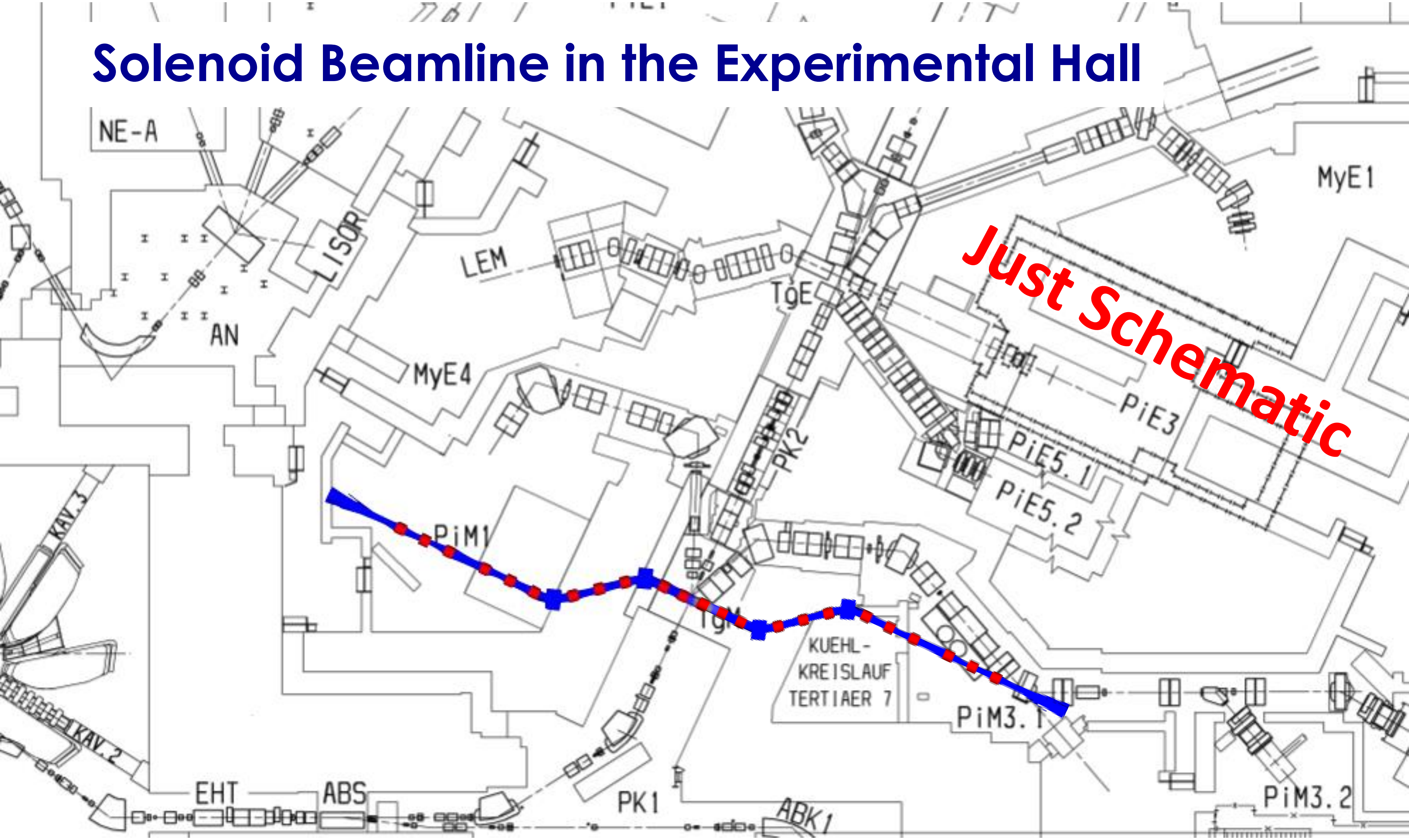
- Problems:
  - SINQ moderator tank imposes severe constraints
  - Source collection too low without significant SINQ redesign (impractical)

  → given up



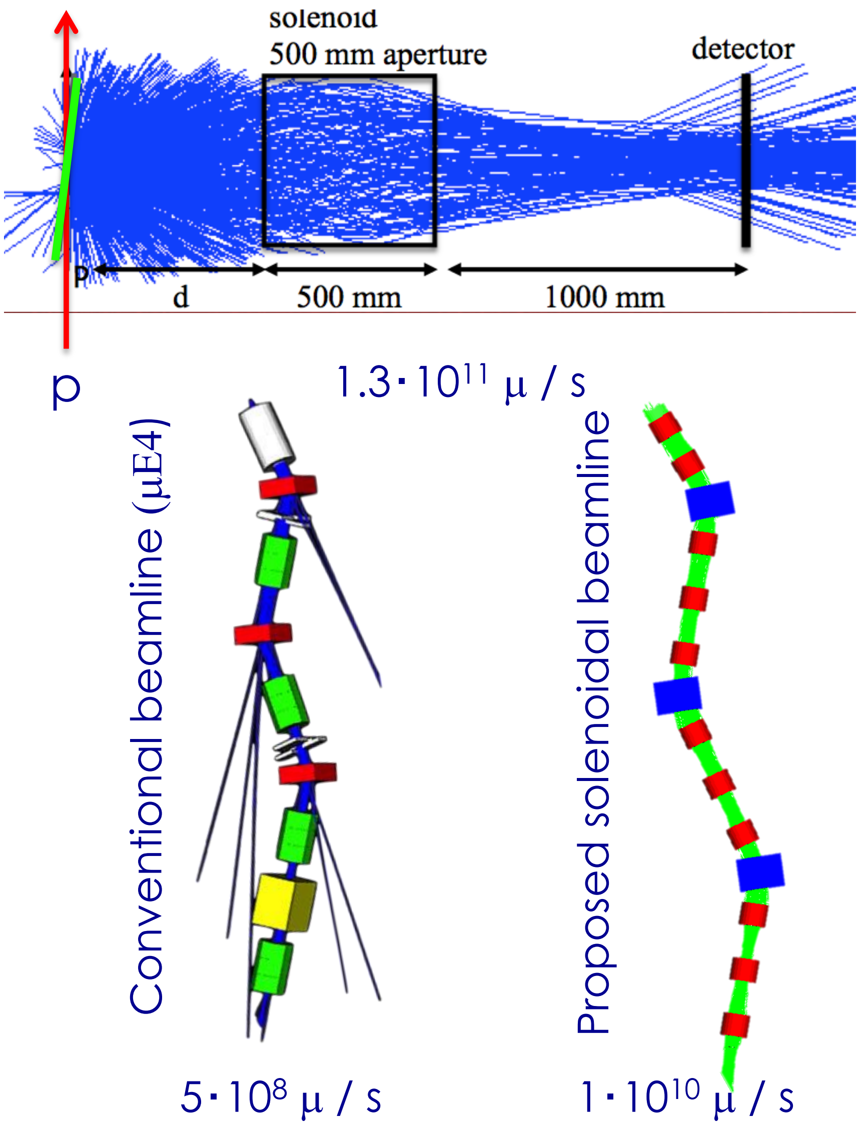
# HiMB @ EH

## Solenoid Beamline in the Experimental Hall



# HiMB @ EH details

- Feasibility study started 2014
- Preliminary conclusions:
  - A new 20 mm rotated graphite target seems optimal for muon production
  - A capture solenoid (0.5 T) at d = 250 mm can catch $1.5 \cdot 10^{10}$ μ / s
  - A solenoidal beam line can transport ~$1 \cdot 10^{10}$ μ / s
  - minor impact on other PSI beam lines
- Final conclusion by the end of this year, design will probably follow



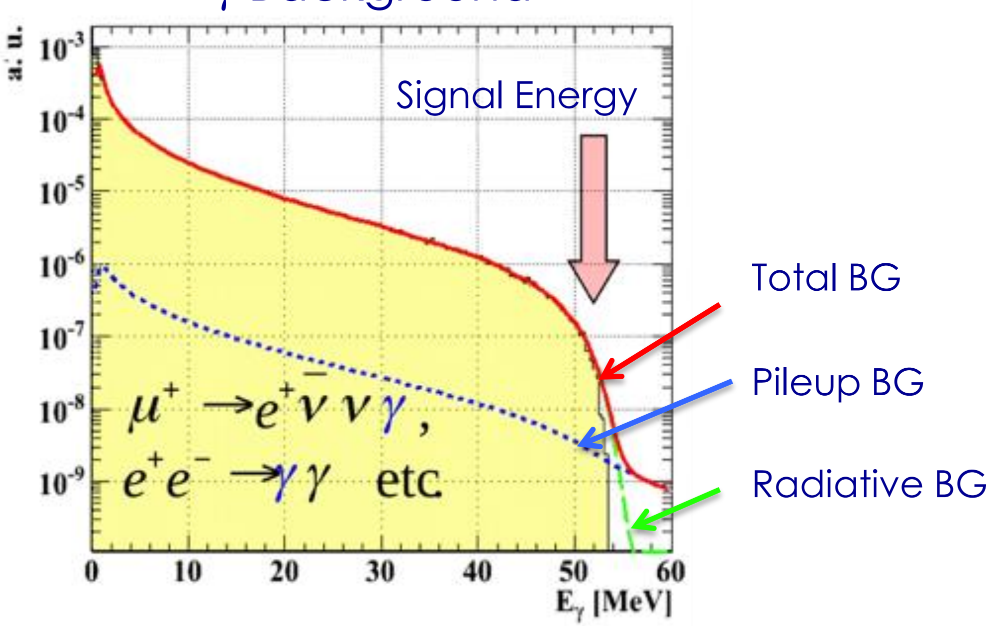
# Calorimetry

# Requirements for photon detector

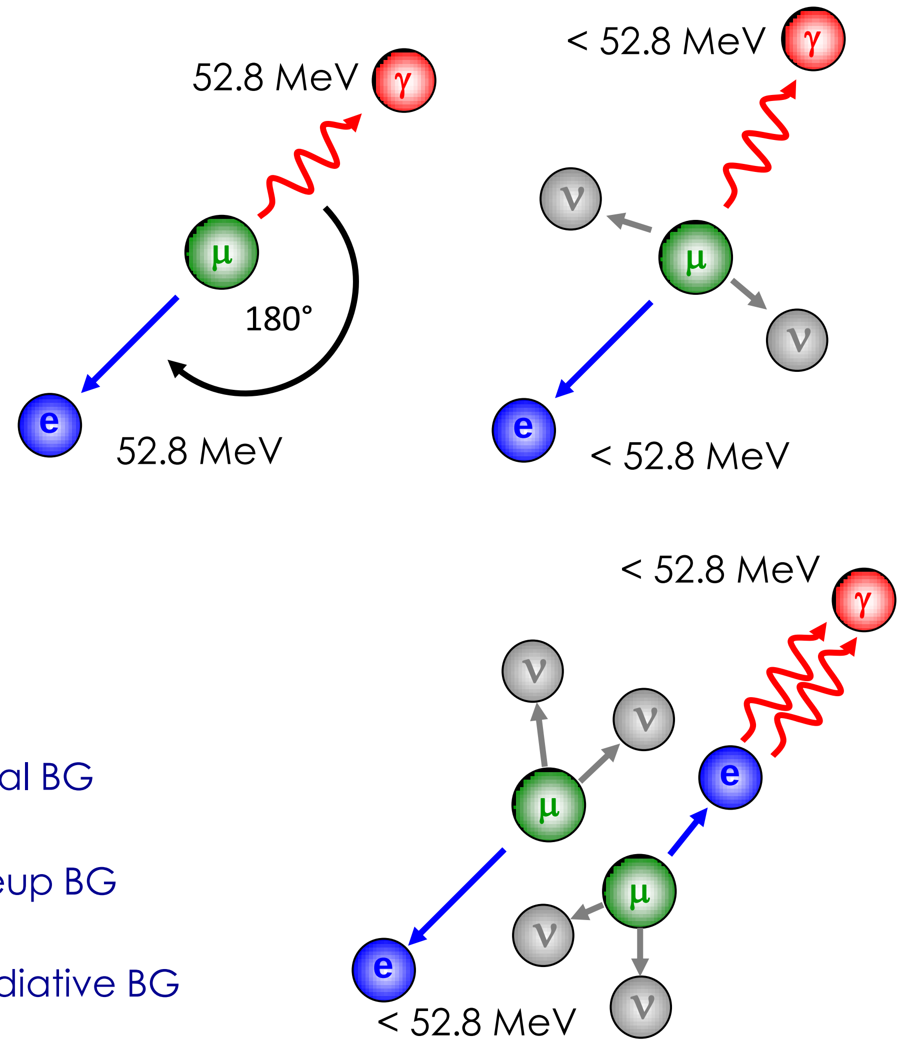
- Good efficiency (high Z)
- Large solid angle
- Good energy resolution
- Good position resolution
- Good time resolution

$$R_{acc} \propto R_{\mu}^{2} \cdot (\Delta\theta)^{2} \cdot (\Delta E_{\gamma})^{2} \cdot \Delta t \cdot \Delta E_{e}$$

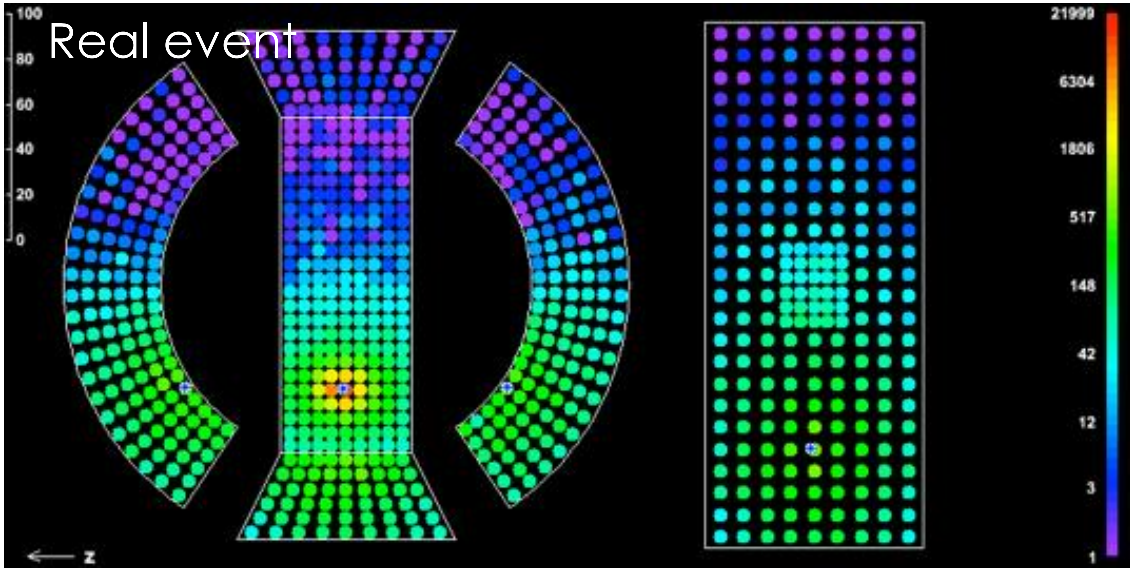
## γ Background

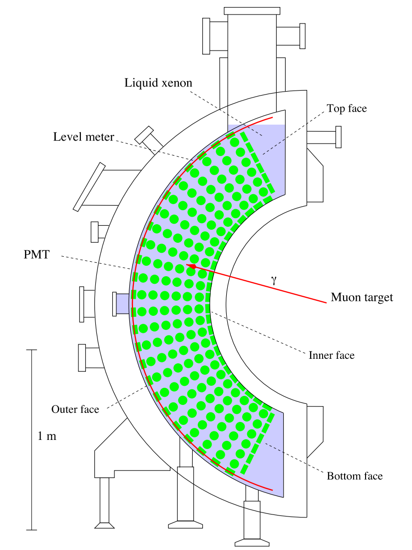


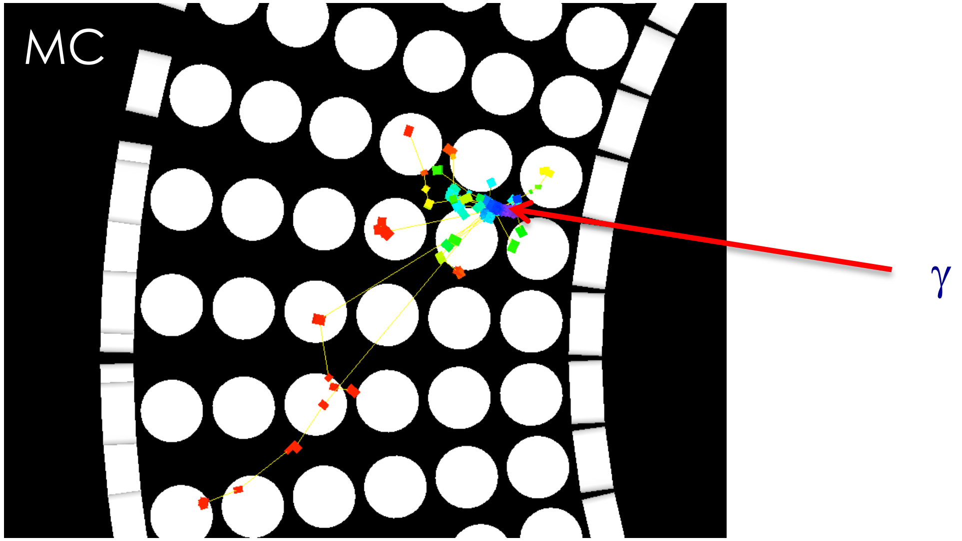

Radiative Decay

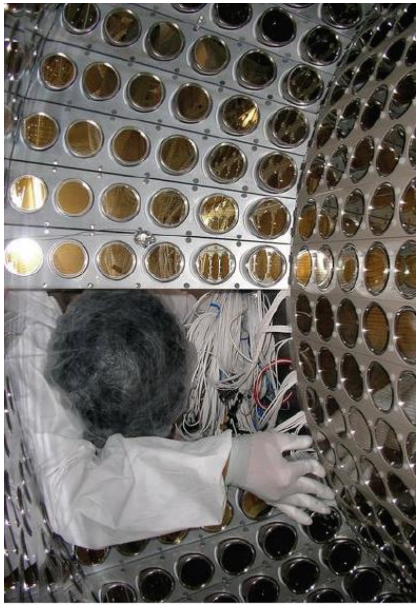


# Calorimetry MEG I



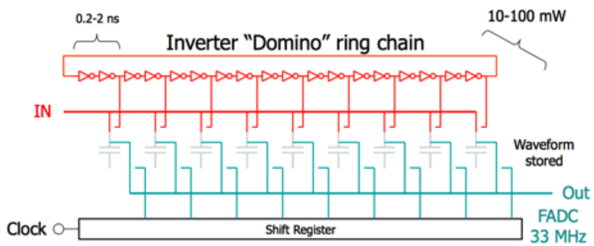



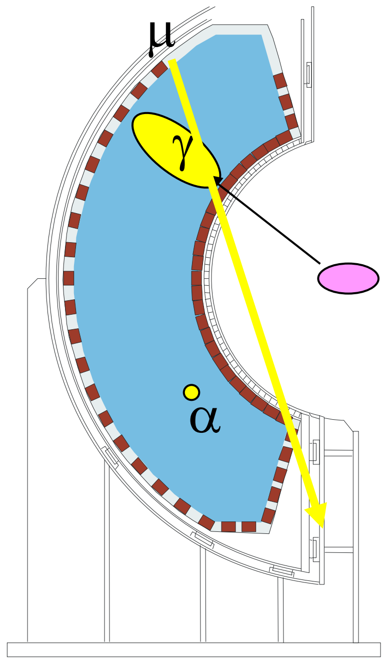



# Calorimeter waveforms

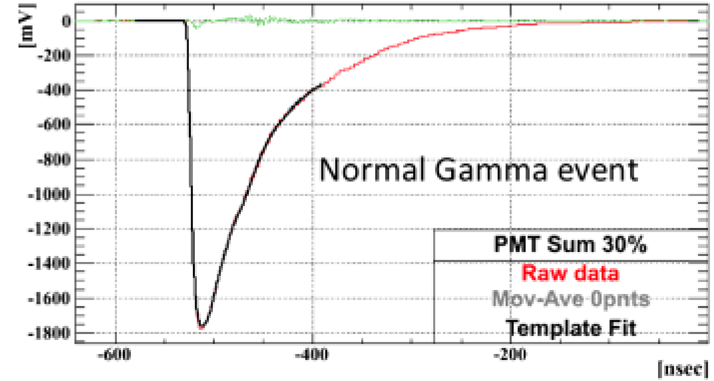
DRS4 Chip: 5 GSPS / 11.5 bits



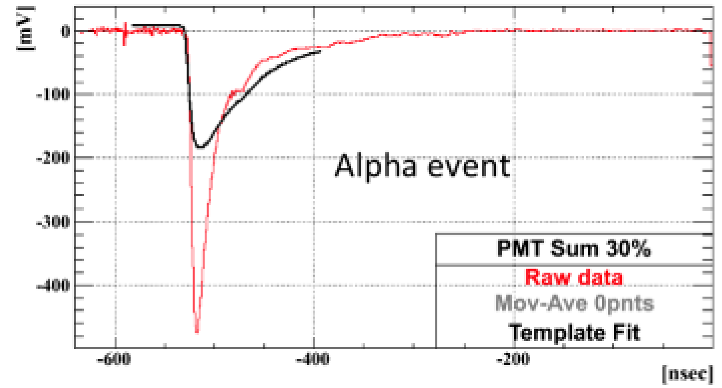

900 channels



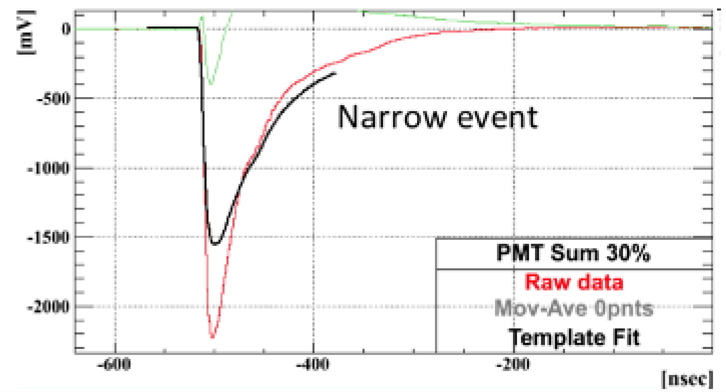

γ



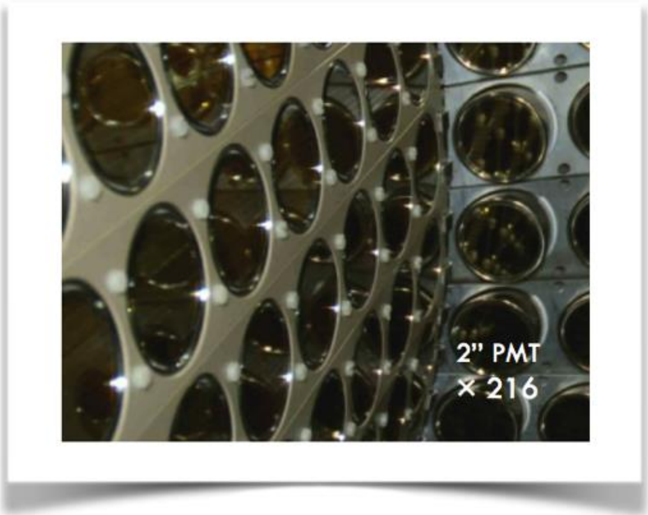

α

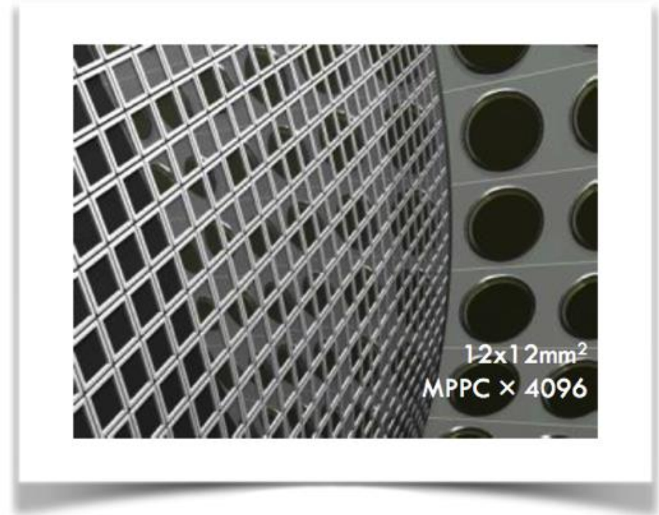



μ

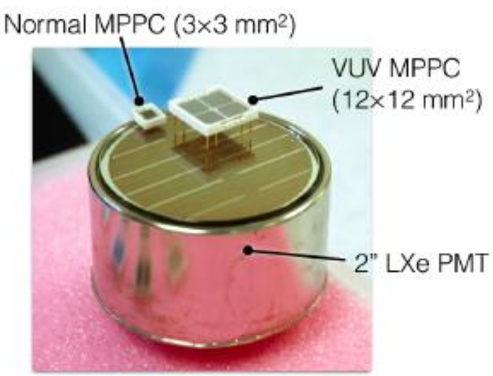


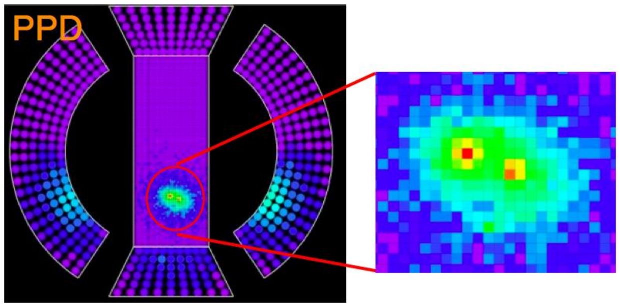
# Calorimetry MEG II




New Hamamatsu VUV SiPM

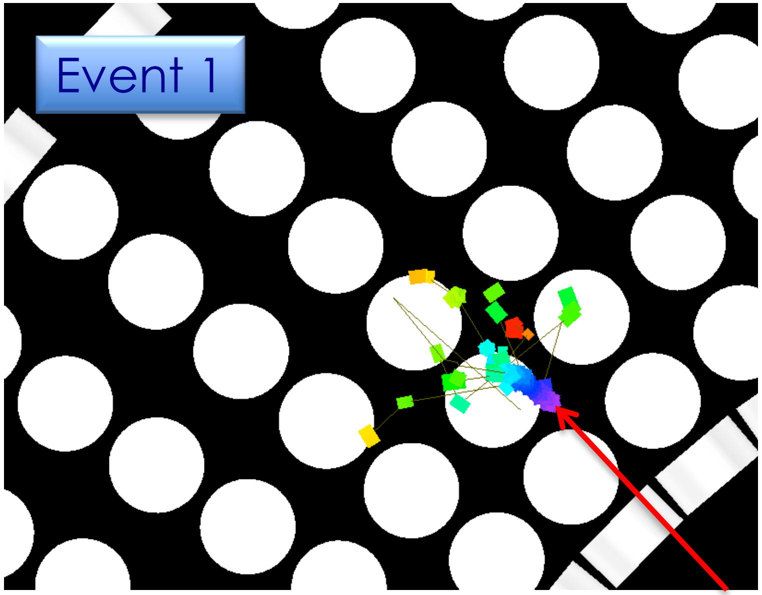


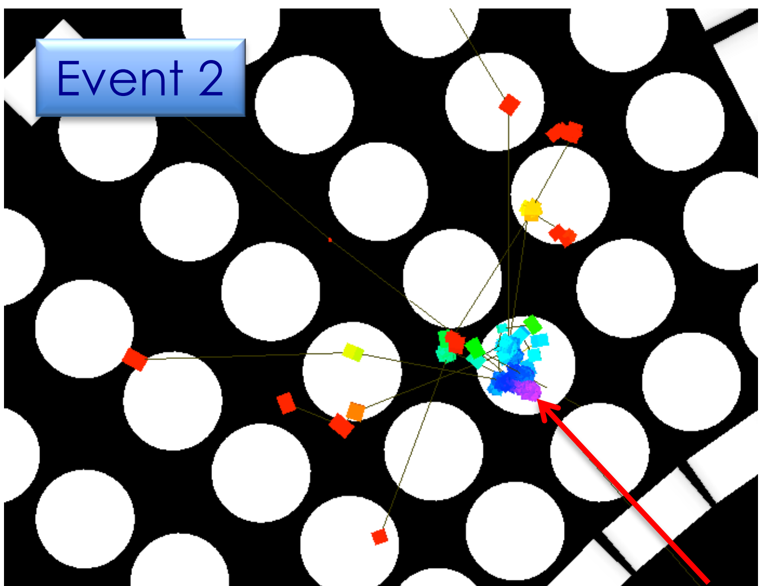



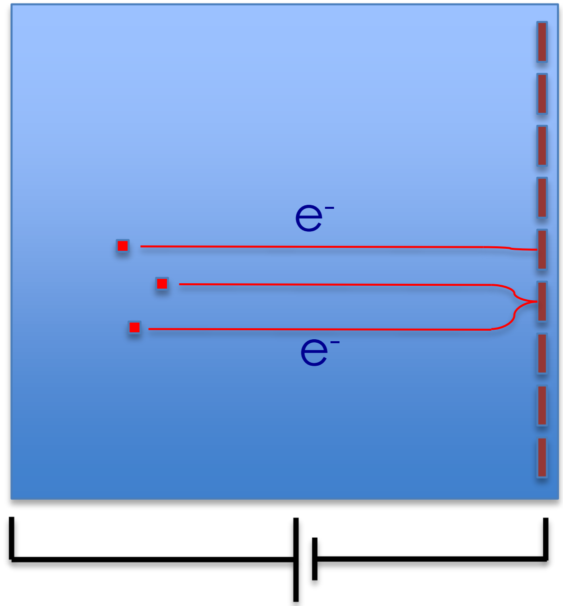

| Resolution | MEG I | MEG II |
|---|---|---|
| x (mm) | 5 | 2.4 |
| y (mm) | 5 | 2.2 |
| z (mm) | 6 | 3.1 |
| $E_\gamma$ (z<2cm) | 2.4% | 1.1% |
| $E_\gamma$ (z>2cm) | 1.7% | 1.0% |
| $t_\gamma$ (ps) | 67 | 60 |

Tomorrow: Calorimetry
Ryu Sawada: "Noble liquid calorimetry"

# Future calorimetry

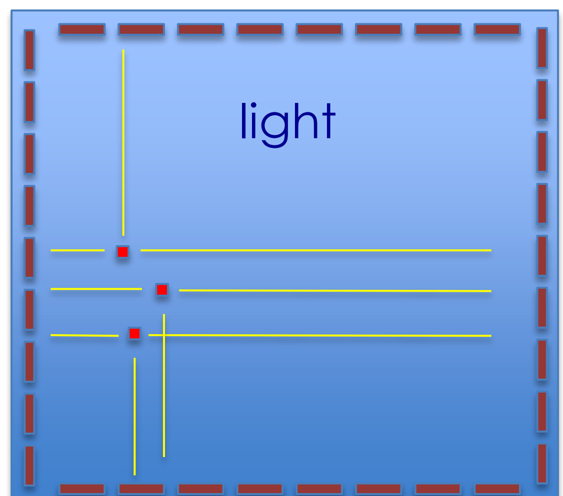



TPC
- use only primary e⁻
- use pixel amplifiers with ultra low noise (< 4e, R. Horisberger, PSI, priv.comm.)

G. Signorelli (Pisa): FOXFIRE project




Optical TPC
- use light and TOF with ~ps resolution to reconstruct full shower

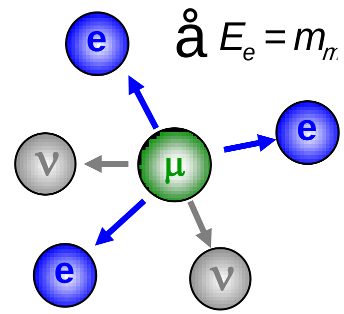
Tomorrow: Photodetectors
Eric Oberla: "Optical TPC"

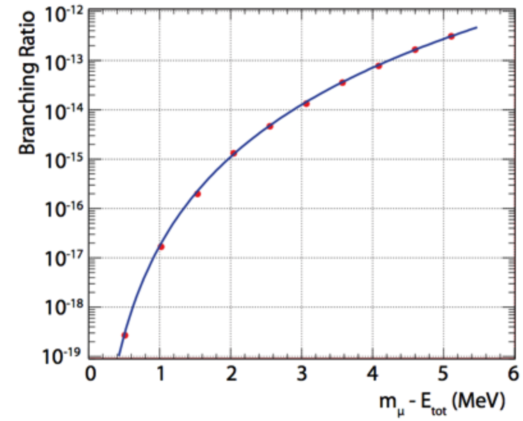
# Tracking

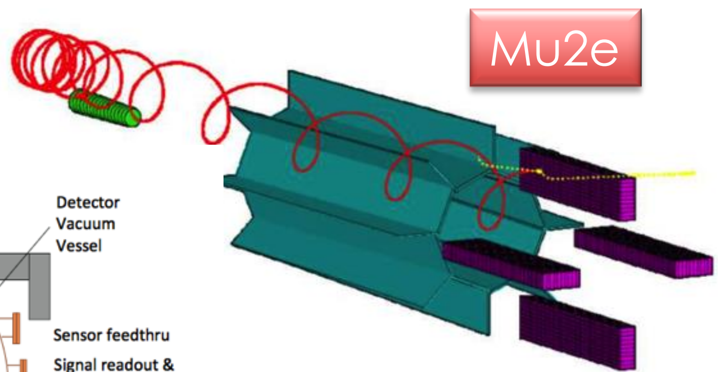
# Requirements for charged particle detection

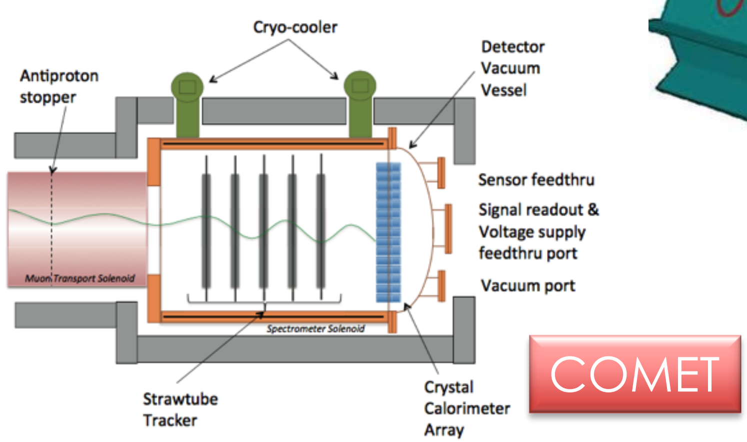
$\mu^+ \rightarrow e^+ e^- e^+ \nu \nu$

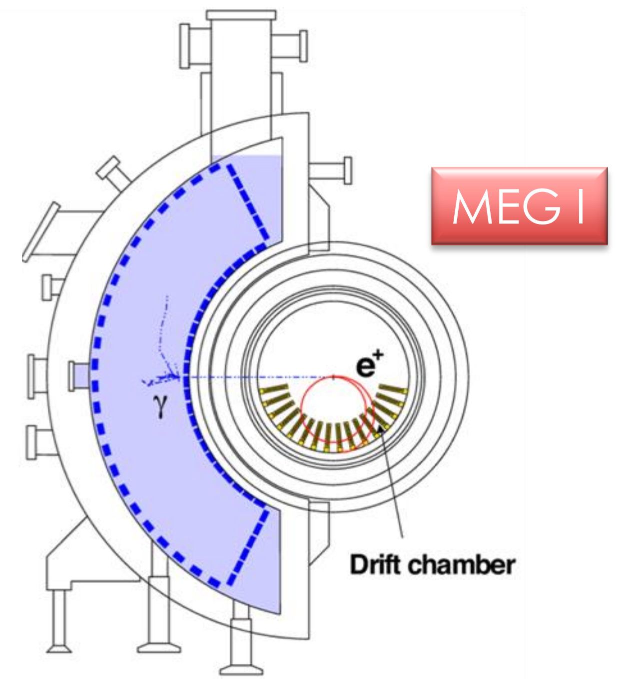
- High efficiency and acceptance
- High rate capability ($10^8$-$10^{11}$ hits/s)
- High energy resolution
  - Magnetic spectrometer O(1T)
    → good position resolution O(100 μm)
    → ultra **low mass** to reduce multiple scattering
  - EM calorimeter (time, trigger)



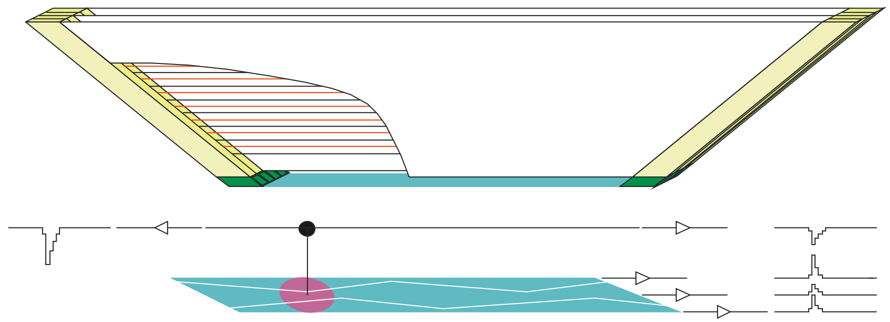



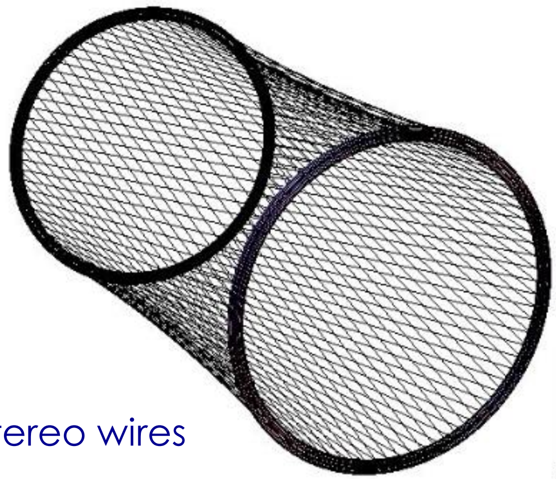
# Tracking with DCs and Straws

MEG I

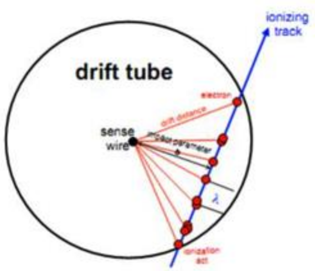


$\sigma_R = 210\ \mu m$
$\sigma_Z = 800\ \mu m$

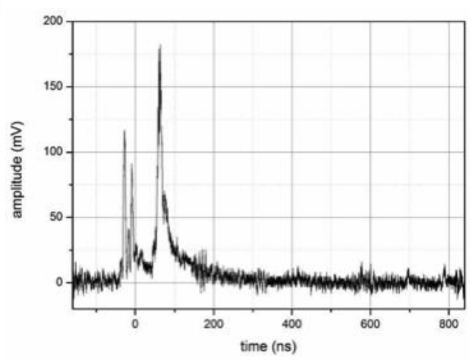
MEG II



Stereo wires



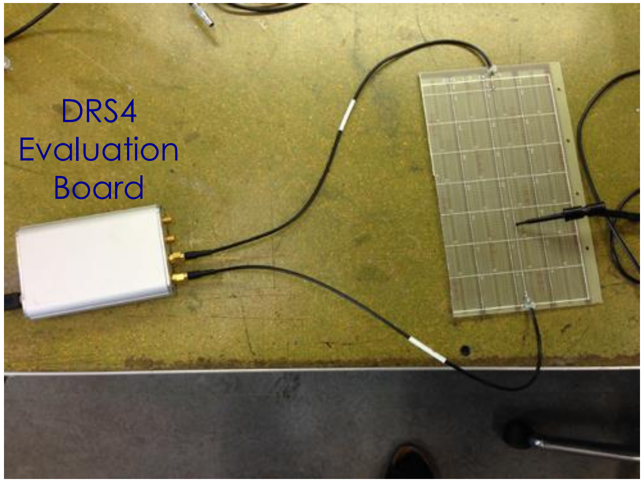

Cluster counting

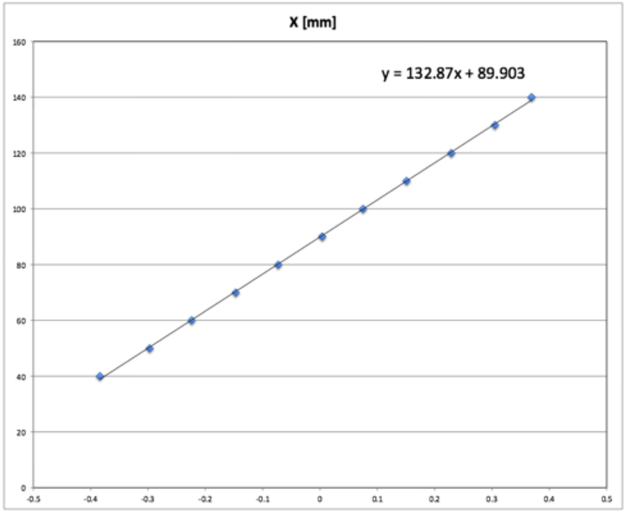


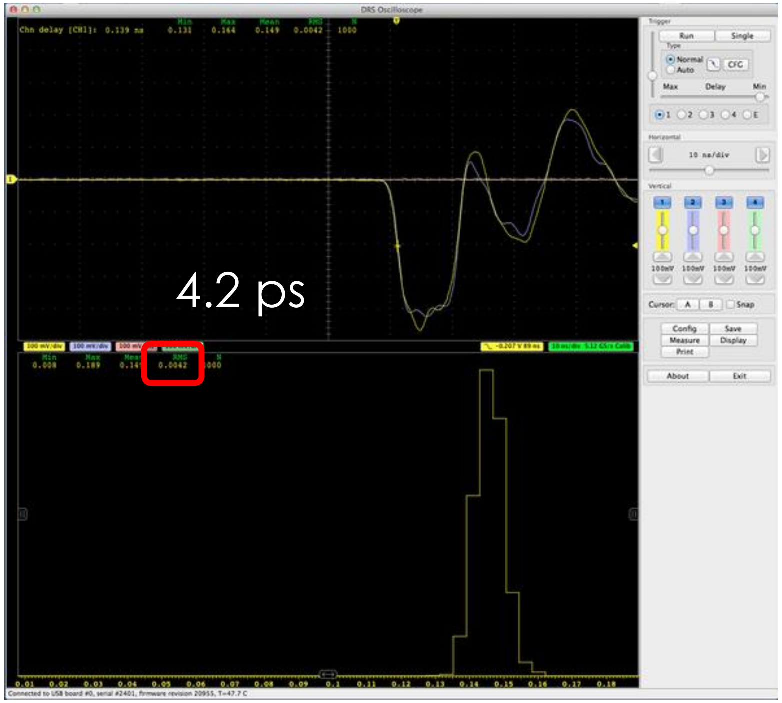

$\sigma_R = 120\ \mu m$
$\sigma_Z = 170\ \mu m$

# New idea: "Wire-TOF"

- Charge division along a wire (DC/Straw) gives ~2 cm resolution
- Measuring TOF with new electronics should be much better!



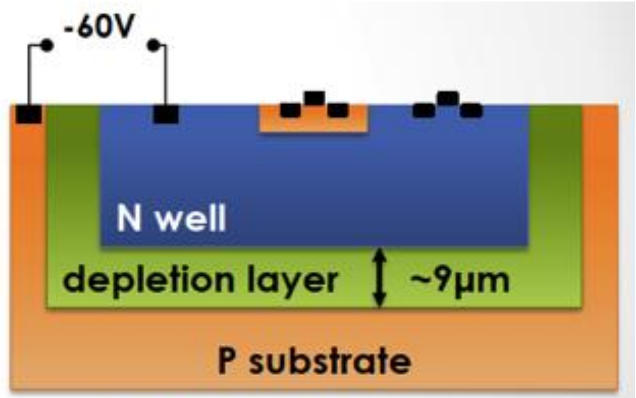

Speed$^{-1}$: 7.5 ps / mm
Resolution: 560 μm

Tomorrow: Tracking & Vertex
Anatoly Ronzin: "Fast Timing"

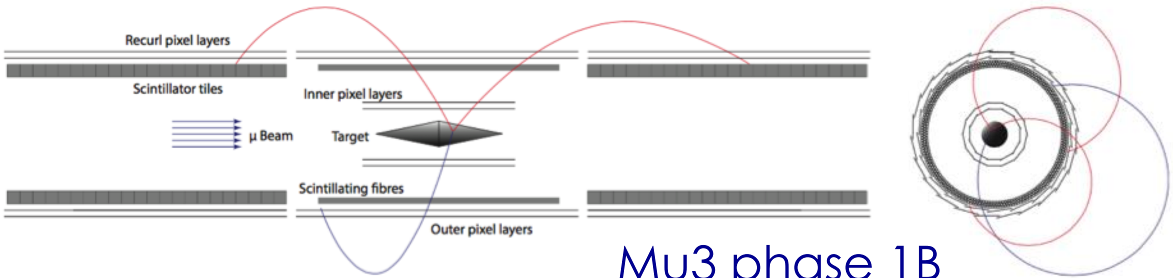
# Tracking with HV-MAPS

- High Voltage Monolithic Active Pixel Sensors (HV-MAPS)
- Reverse biased ~60 V
  - fast charge collection < 1ns
  - can be thinned to ~50 μm !
  - standard HV CMOS technology: ~1000 $ / 8" wafer (3.2 $ / cm$^2$ vs. 100 $ / cm$^2$ for hybrid pixels)
- Prototypes successfully tested for Mu3e experiment
  - 80 μm x 80 μm pixels
  - > 99% efficiency
  - timing resolution <17 ns
  - hit rate capability > 1 MHz / cm$^2$
  - $X/X_0$ = 0.1% including frame, flex print, …

→ attractive replacement for gas detectors! (minus cooling problem)




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

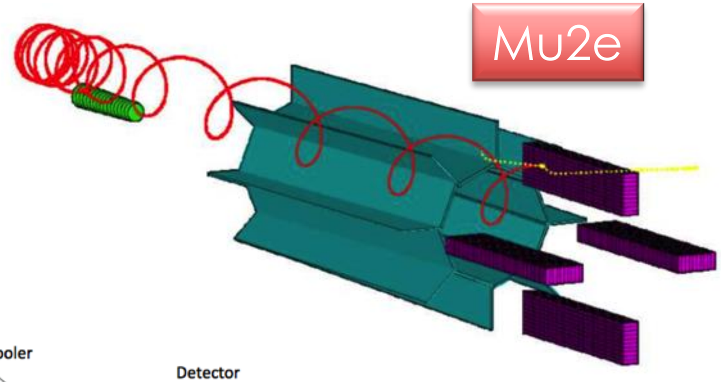


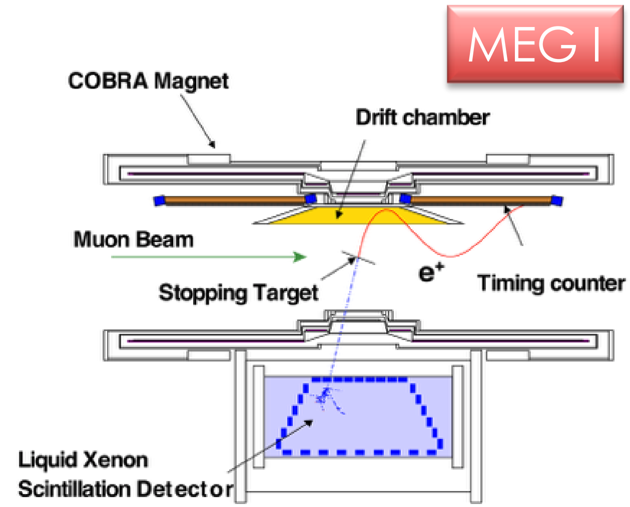

Mu3 phase 1B

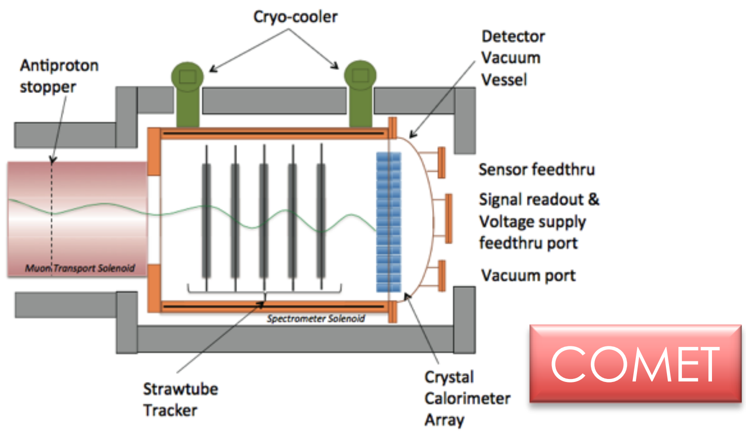
50 μm thin silicon wafer

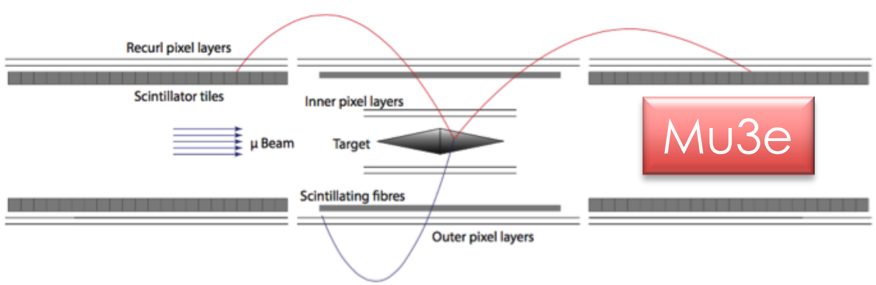
# Can’t we make that simpler?

- Gas detectors for low mass and good resolution
- Scintillation detectors for good timing and triggering



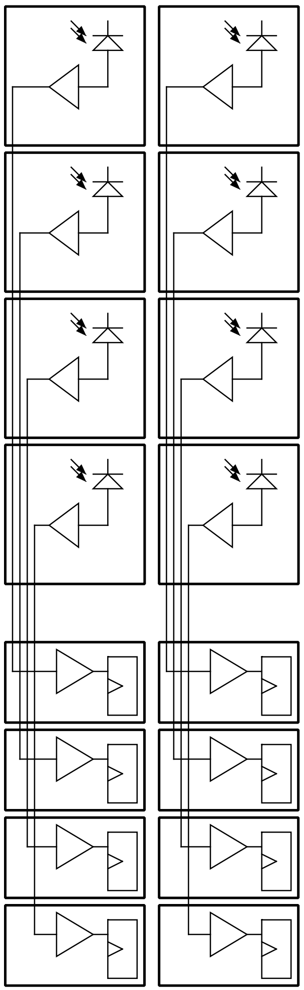



# HVMAPS + TDC

## Current Mu3e MUPIX

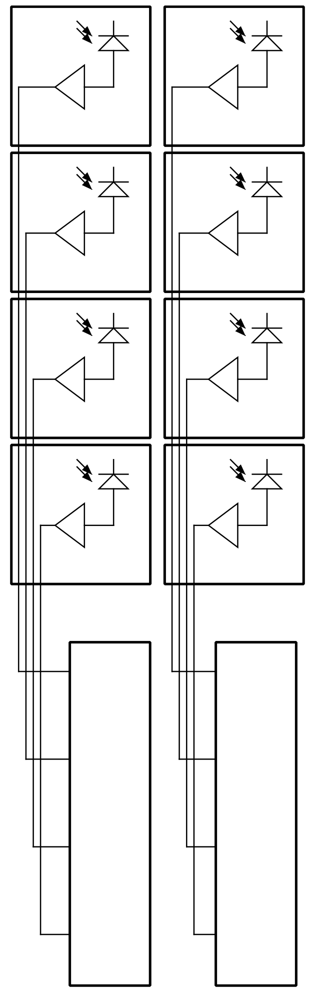


Pixel

Latch

50 ns frames

## HVMAPS+TDC

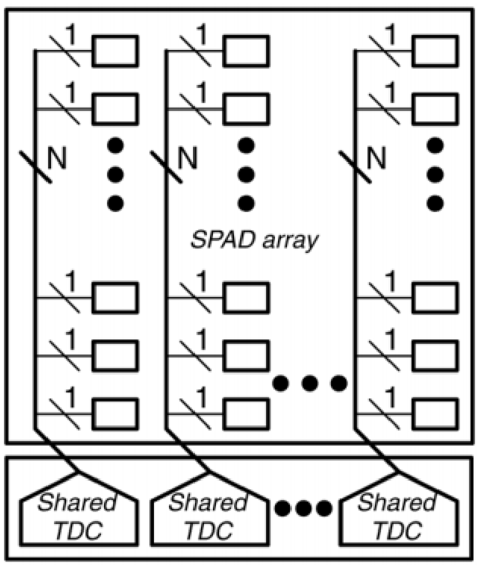


Pixel

TDC

~ 100 ps resolution

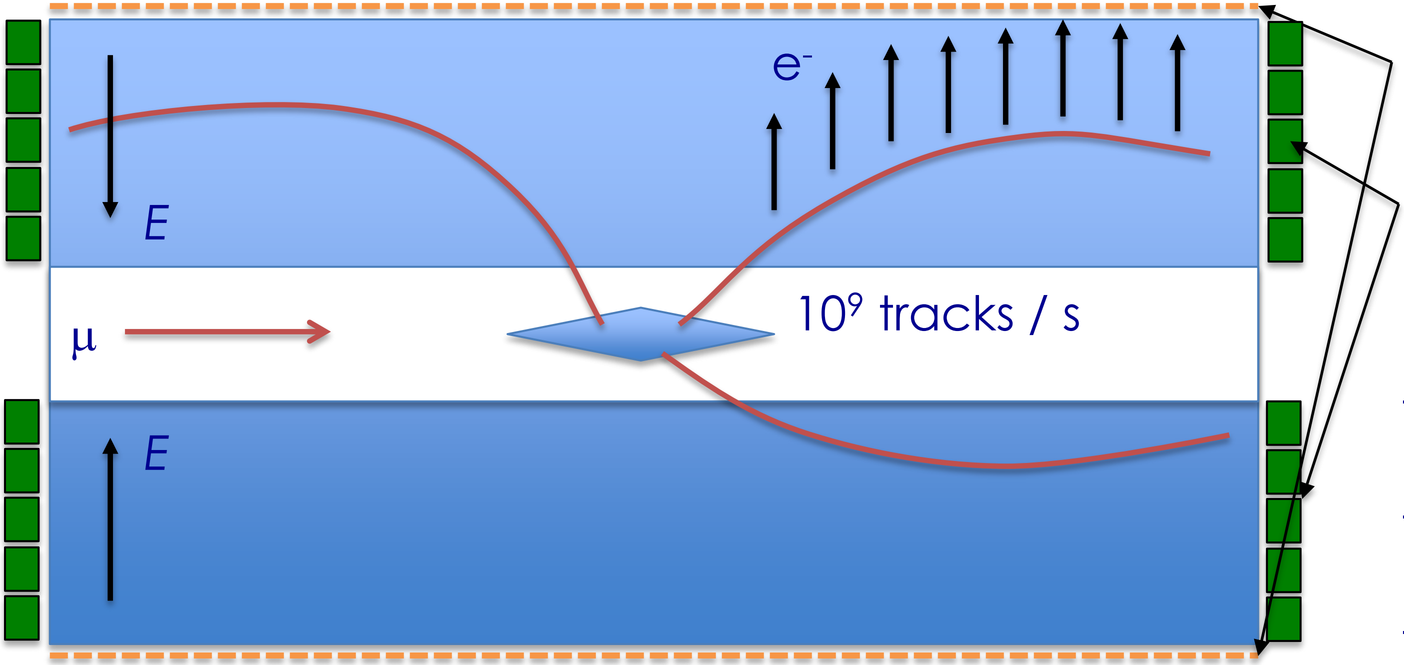
50 ps TDC resolution has been demonstrated with SiPMs:



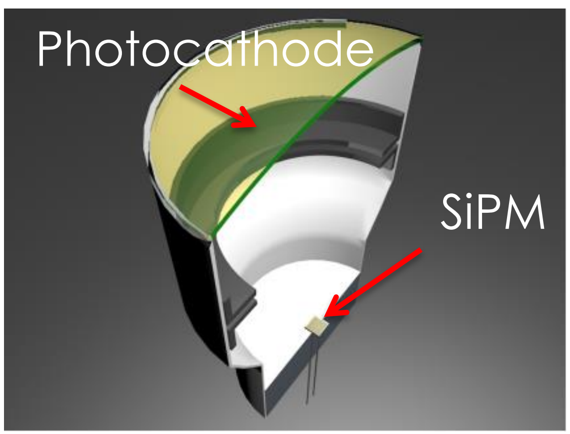

*Column-parallel TDC*

S. Mandai et al.,
IEEE TNS 61 (2014) 44
(Delft University, the Netherlands)

# TPC for cLFV experiments




R. Horisberger, PSI:
- excellent energy resolution
- tracking at high rate
- problem: ageing




VSiPMT (Hamamatsu)

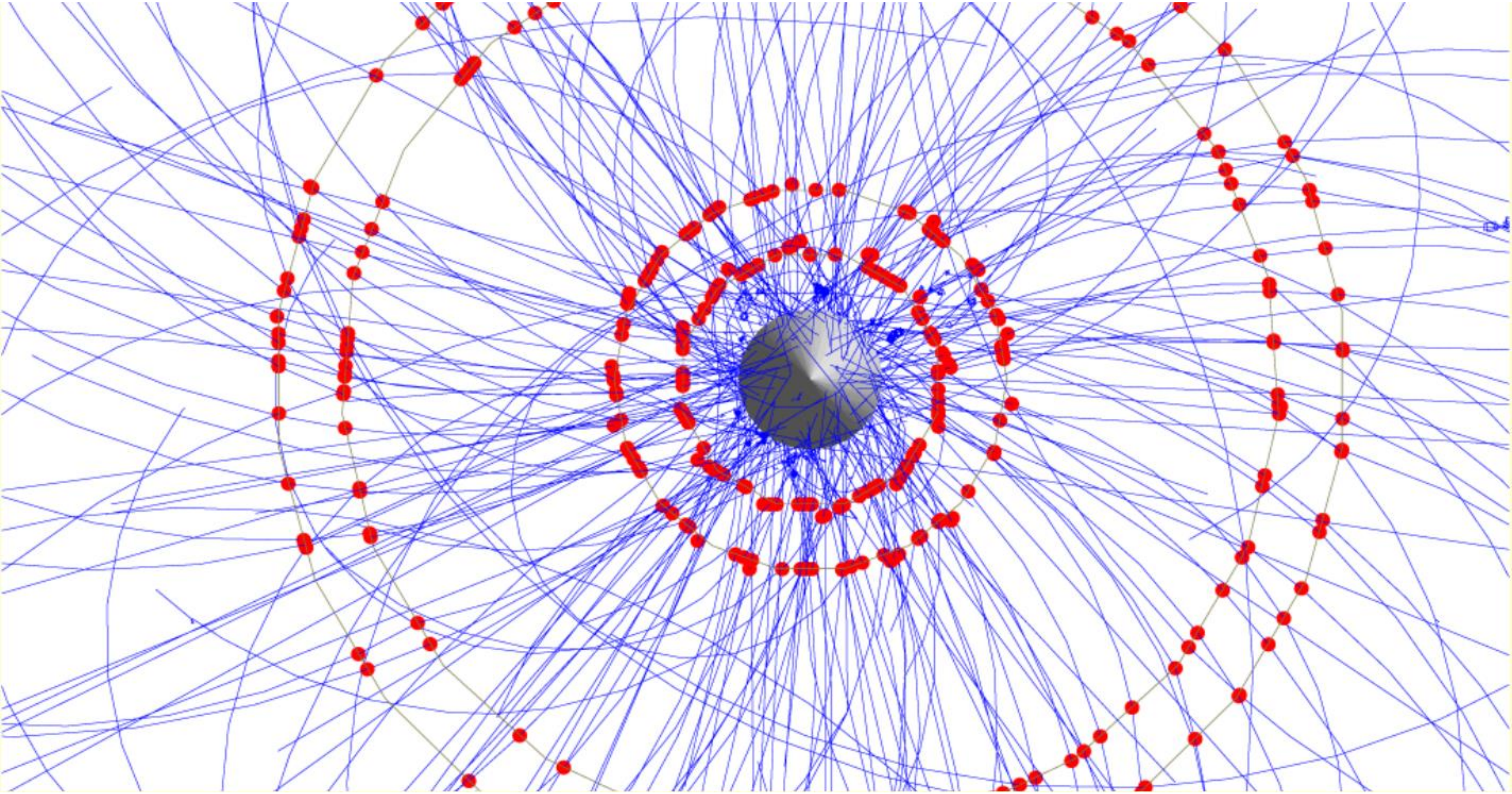
- No gas gain (ageing!)
- VSiPMT can directly detect $e^-$ @ 3 keV (less with reduced $SiO_2$ layer)
- QE = 100% · fill factor, 100 ps timing

G. Barbarino et al, arXiv:1407.2805

# Timing

# Timing requirements for Mu3e

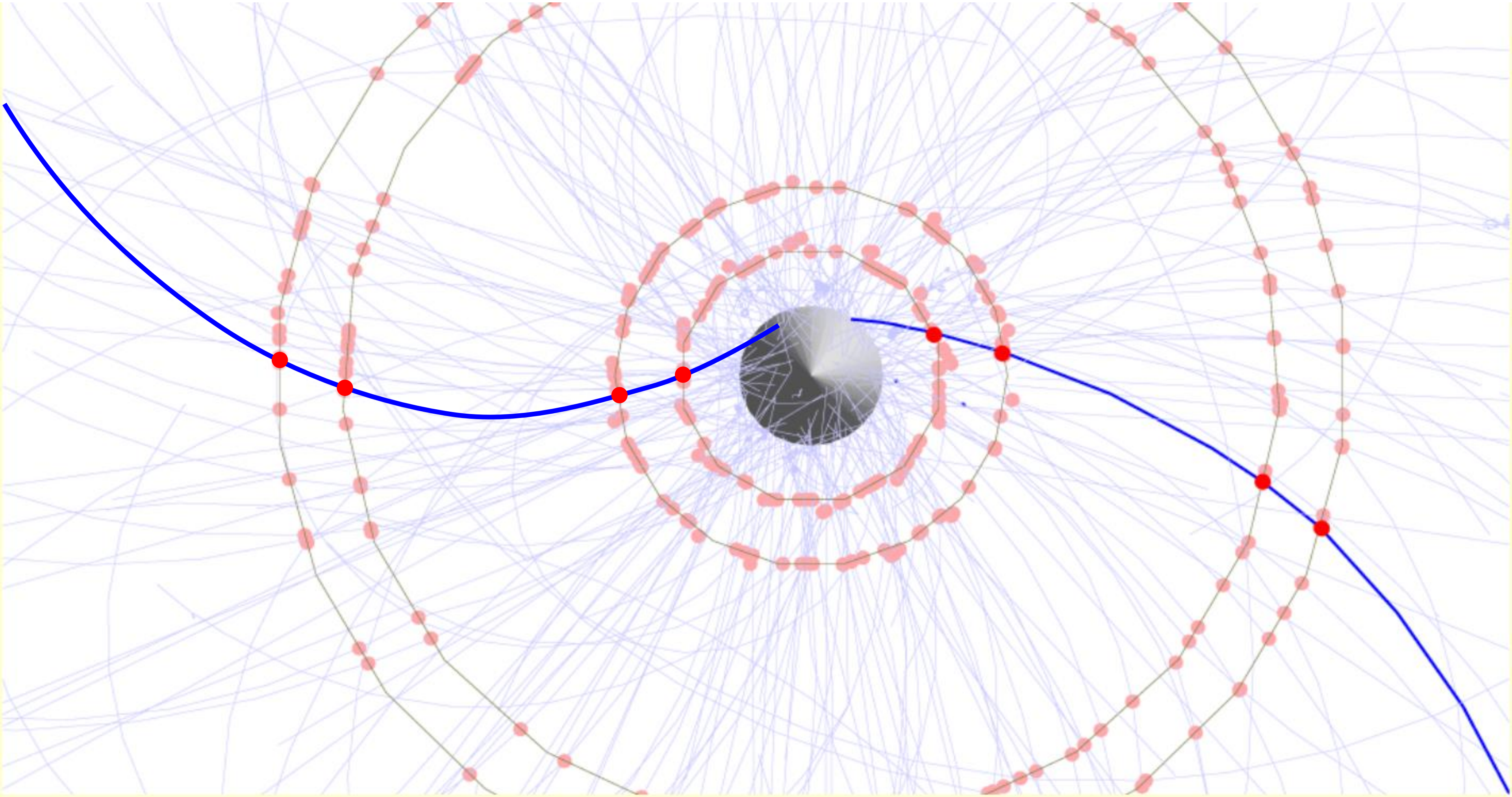
2 x $10^9$ $\mu$ stops/s, 50 ns frame rate



100 $\mu$ decays

# Timing requirements for Mu3e

2 x $10^9$ $\mu$ stops/s, 50 ns frame rate



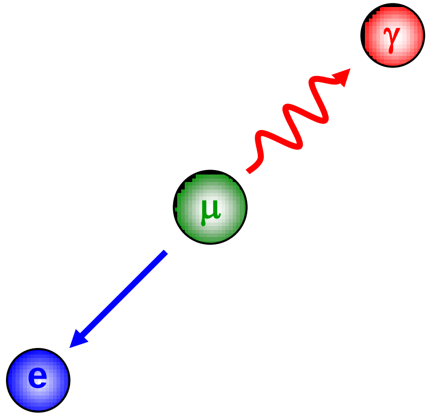
Additional time detector (<1ns): 2 $\mu$ decays

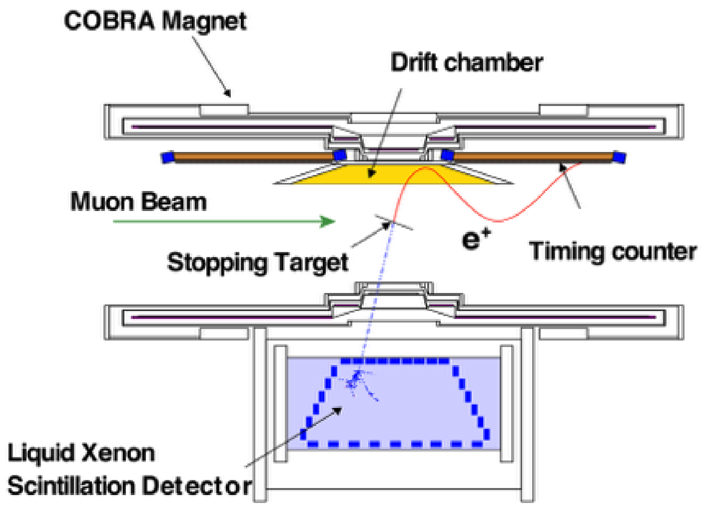
# Timing requirements for MEG

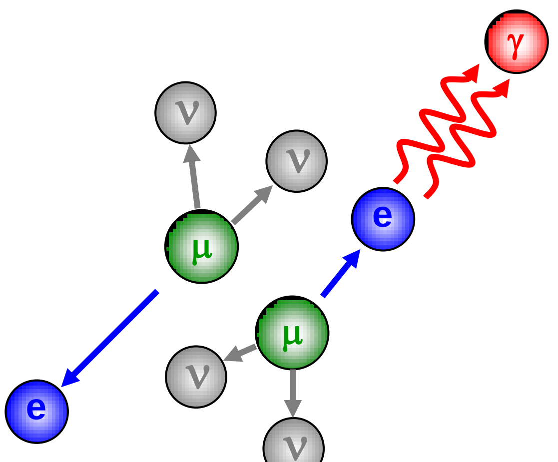
- Limited by accidental background
- Timing can help to separate signals from background
- $\gamma$ time from LXe calorimeter
- $e^+$ time from dedicated timing counter

| Resolution (ps) | MEG I | MEG II |
|---|---|---|
| $\Delta t_\gamma$ | 67 | 60 |
| $\Delta t_e$ | 107 | 35 |
| $\Delta t_{e\text{-}\gamma}$ | 127 | 84 |

All values in sigma!

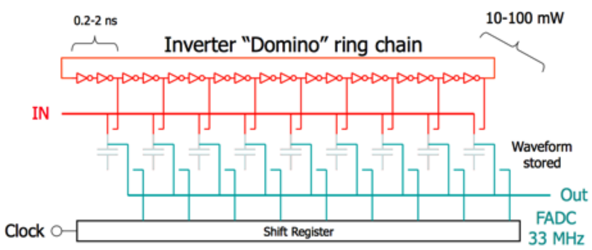


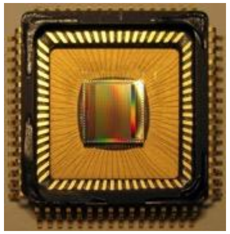



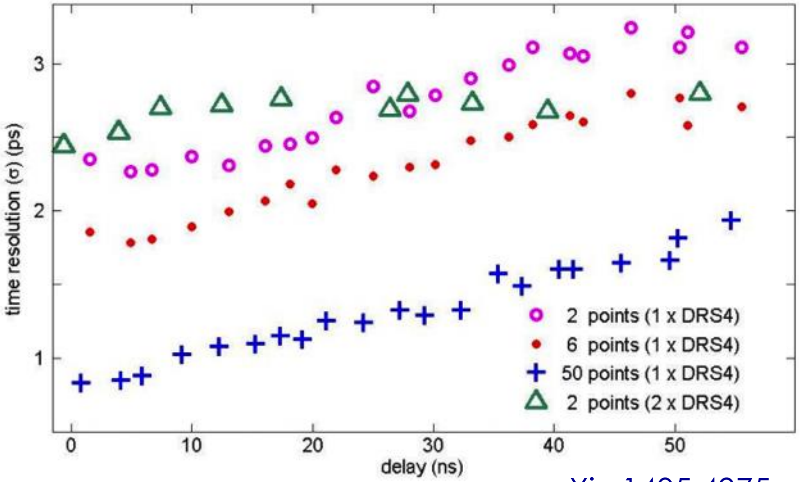
# Electronics for timing

- Switched capacitor array chips give excellent timing:
  - PSEC4 (Chicago): **9 ps**, DRS4 (PSI): **1.4 ps**
- TDC follow up:
  - TDC130 (CERN): **2.4 ps**, SAMPIC (Saclay): **6.5 ps**
- Precision clock distribution possible
  - MEG I: **20 ps**, MEG II: **5 ps**



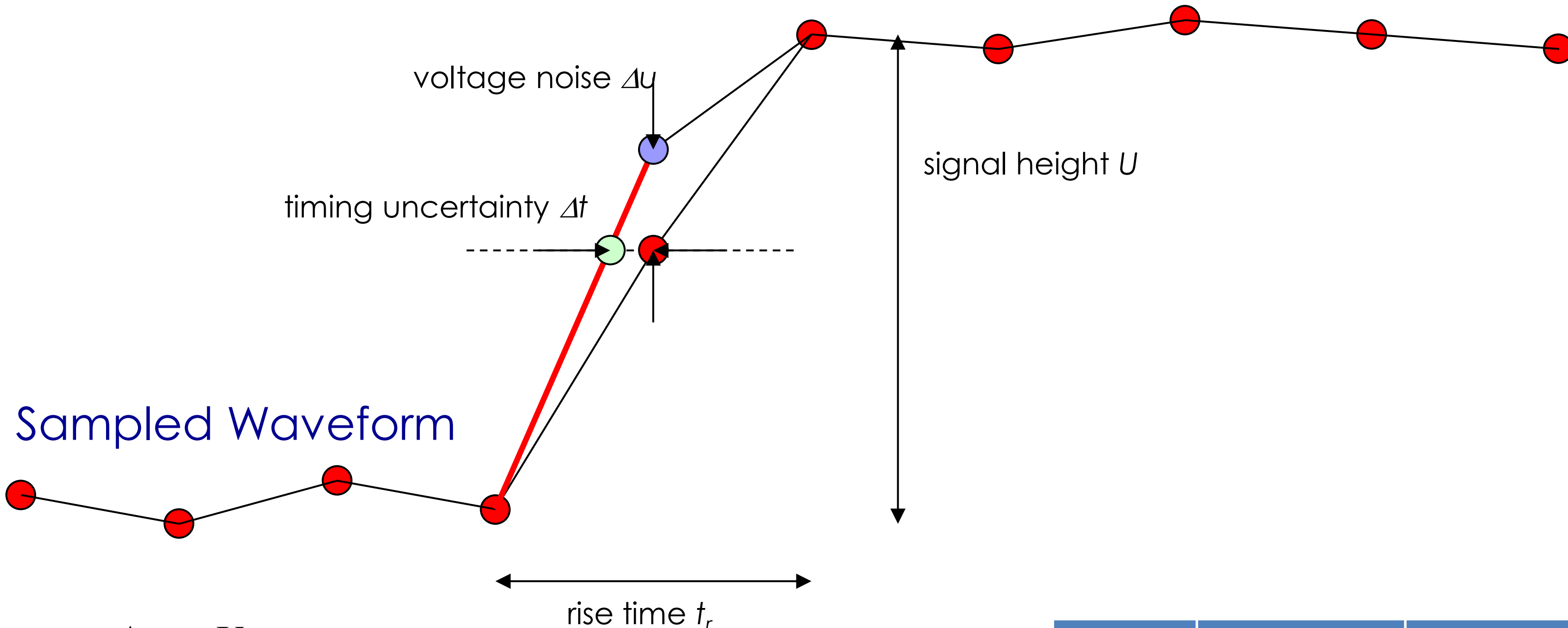



DRS4




arXiv:1405.4975

# Timing limitation




$$\frac{\Delta u}{\Delta t} = \frac{U}{t_r}$$

$$t_r \approx \frac{1}{3 f_{3dB}}$$

$$\Delta t = \frac{\Delta u}{U} \cdot t_r = \frac{\Delta u}{U\sqrt{n}} \cdot t_r = \frac{\Delta u}{U} \cdot \frac{t_r}{\sqrt{t_r \cdot f_s}} = \frac{\Delta u}{U} \cdot \frac{\sqrt{t_r}}{\sqrt{f_s}} = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

number of samples on slope only for waveform digitizing

$SNR^{-1}$

Sampling speed

Analog bandwidth

*Simplified estimation!*

| | Today | NG |
|---|---|---|
| U | 100 mV | 100 mV |
| Δu | 1 mV | 1 mV |
| $f_s$ | 2 GSPS | 10 GSPS |
| $f_{3dB}$ | 300 MHz | 3 GHz |
| Δt | ~ 10 ps | 1 ps |

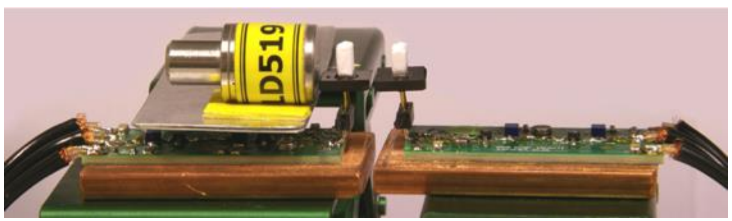
# Timing resolution with SiPMs

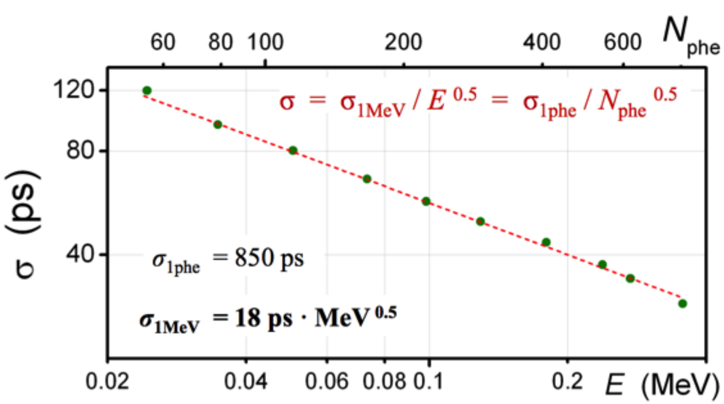
A. Stoykov et. al. (PSI): NIM A695 (2012) 202

- Timing method: CF (20%)
- SiPM: MPPC S10362-33-050 (3·3 mm²)
- Scintillator: BC422 (3·3·2 mm²)

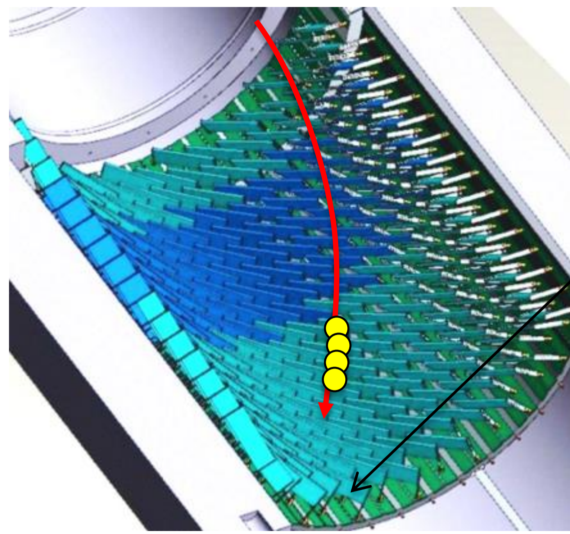
$$Dt \approx 20\,ps \cdot \frac{1}{\sqrt{k \cdot E[MeV]}}$$

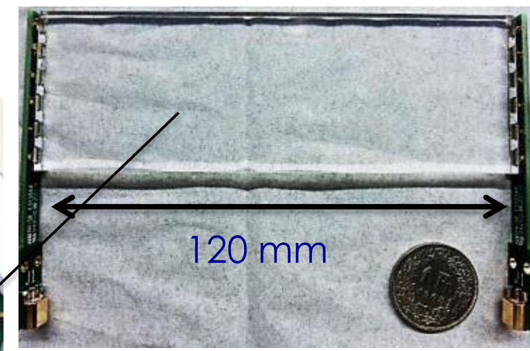
fill factor area SiPM / area Scint.




MEG II timing counter





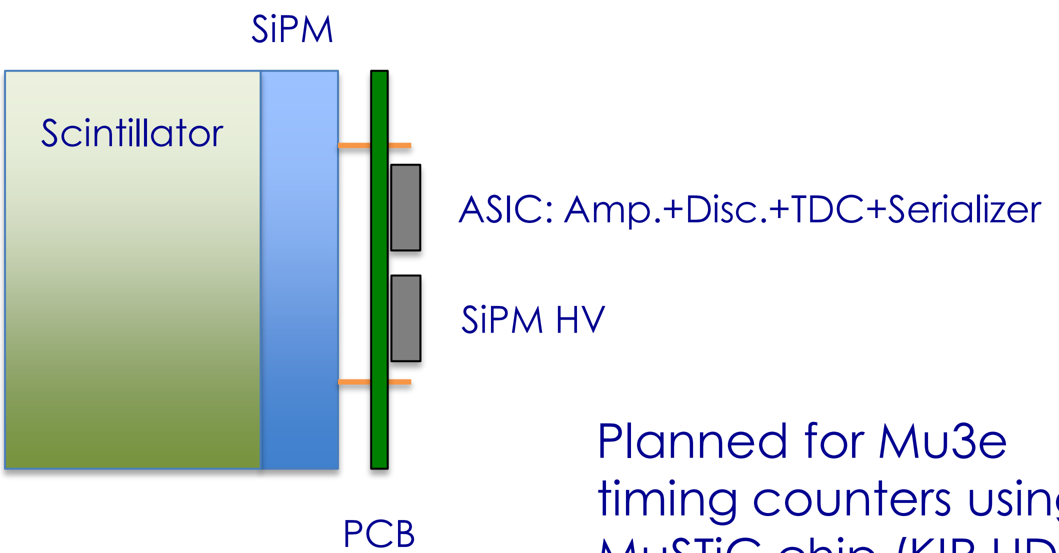

6 SiPMs in series

| | |
|---|---|
| Expected (point source) | Δt=(1.14·20ps) / √ (0.135·0.9 MeV)= 65 ps |
| Measured (uniform illumination) | 75 ps |
| Hit position error | ~40 ps |

# Road to better timing

- Aim for complete coverage (k=1)
- Reduce counter size
  (increases channel count □)
- Integrate readout electronics into detector (avoid long cables)

MEG

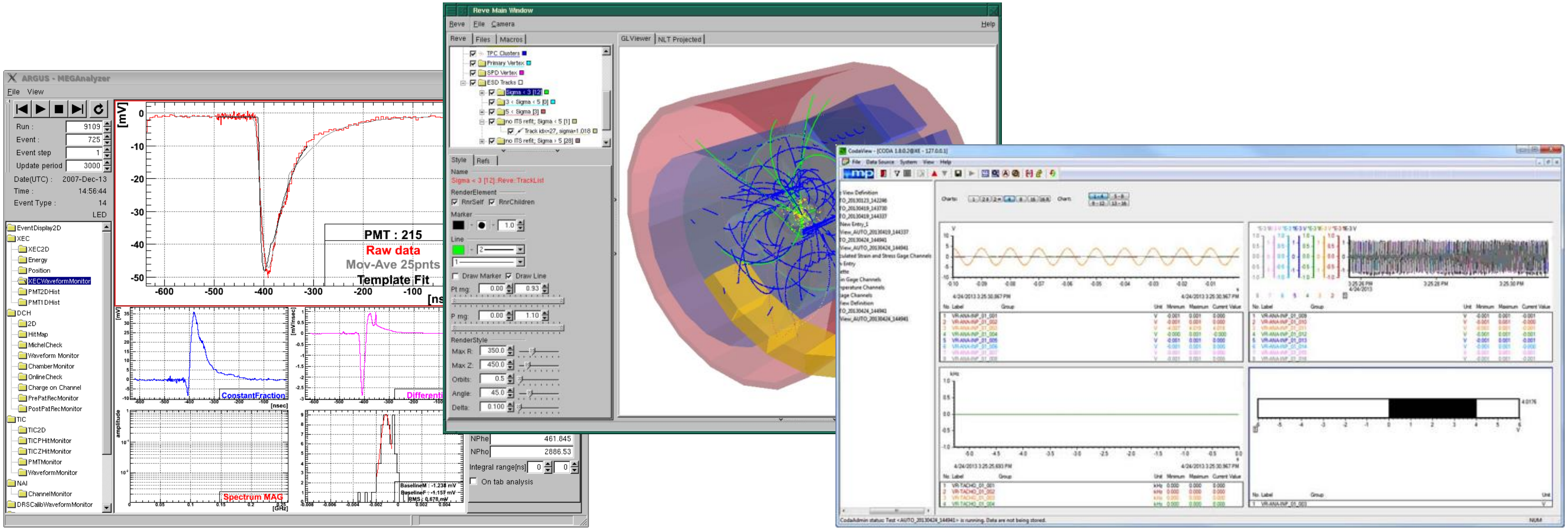



Planned for Mu3e timing counters using MuSTiC chip (KIP HD)

# Data Visualization

# Experimental Data Visualization

- The traditional way
  - Dedicated programs (ROOT, Qt, TCL/TK, …)
  - Must be compiled for different OS
  - Require certain libraries to be installed
  - No smartphone support



# A new opportunity

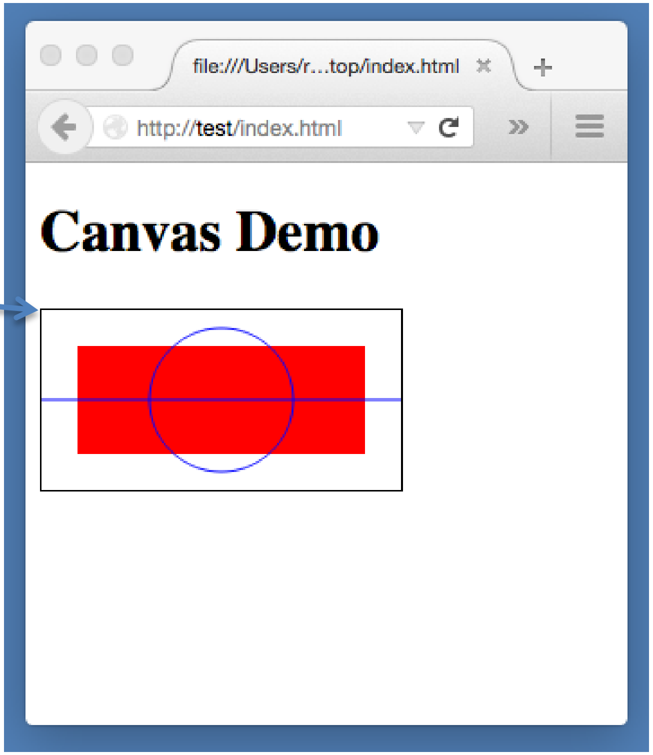

HTML5 – CSS3 – JavaScript – JSON

# Canvas Object

HTML

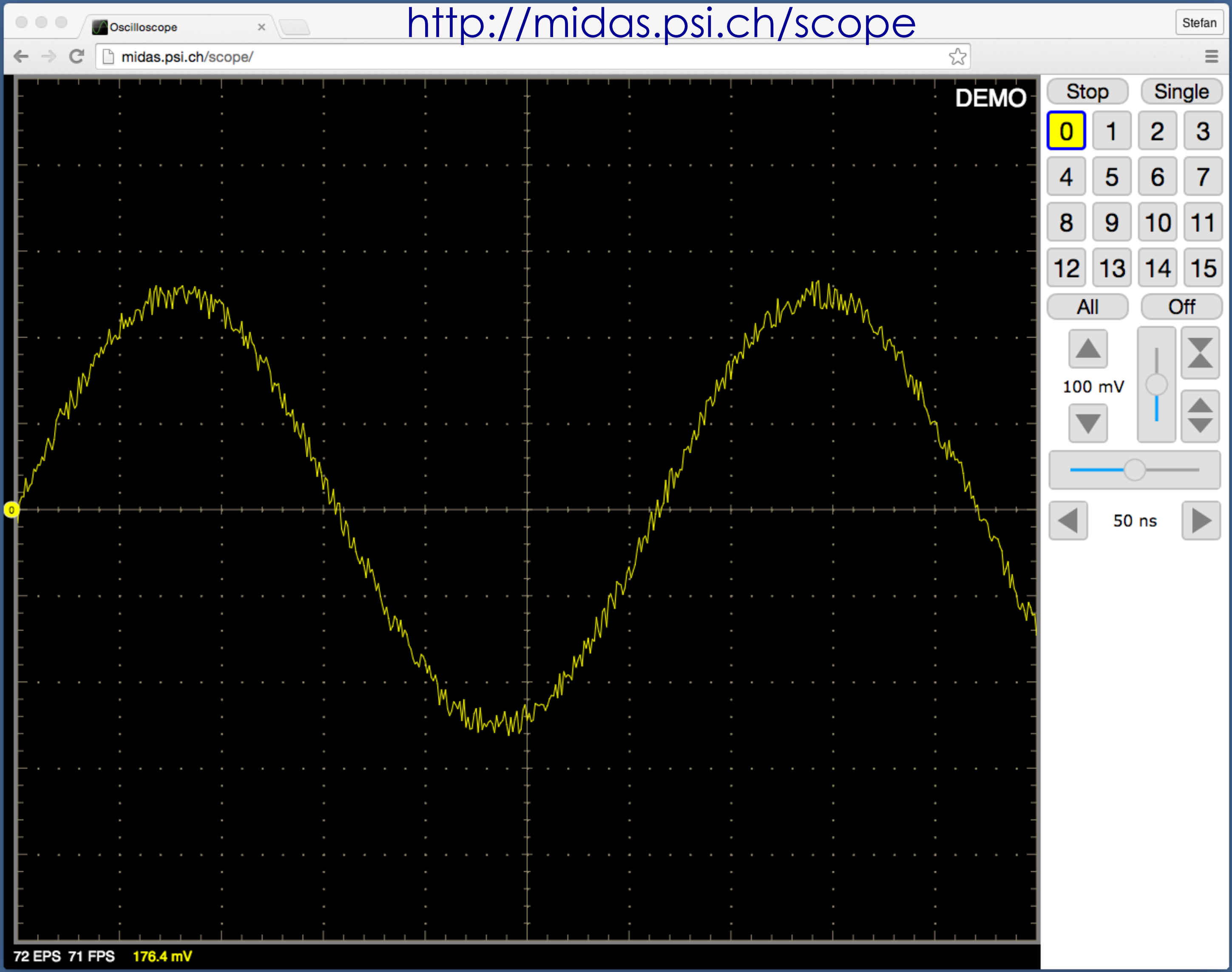
JavaScript

```
<!DOCTYPE html>
<html>
<body>
<h1>Canvas Demo</h1>

<canvas id=“myCanvas” width=“200”
height=“100” style=“border:1 px solid
black”>
</canvas>

<script>
var c = document.getElementById(“myCanvas”);
var ctx = c.getContext(“2d”);
ctx.fillStyle = “red”;
ctx.fillRect(20,20,160,60);
ctx.strokeStyle = “blue”;
ctx.moveTo(0,50);
ctx.lineTo(200,50);
ctx.stroke();
ctx.beginPath();
ctx.arc(100,50,40,0,2*Math.PI);
ctx.stroke();
</script>

</body>
</html>
```

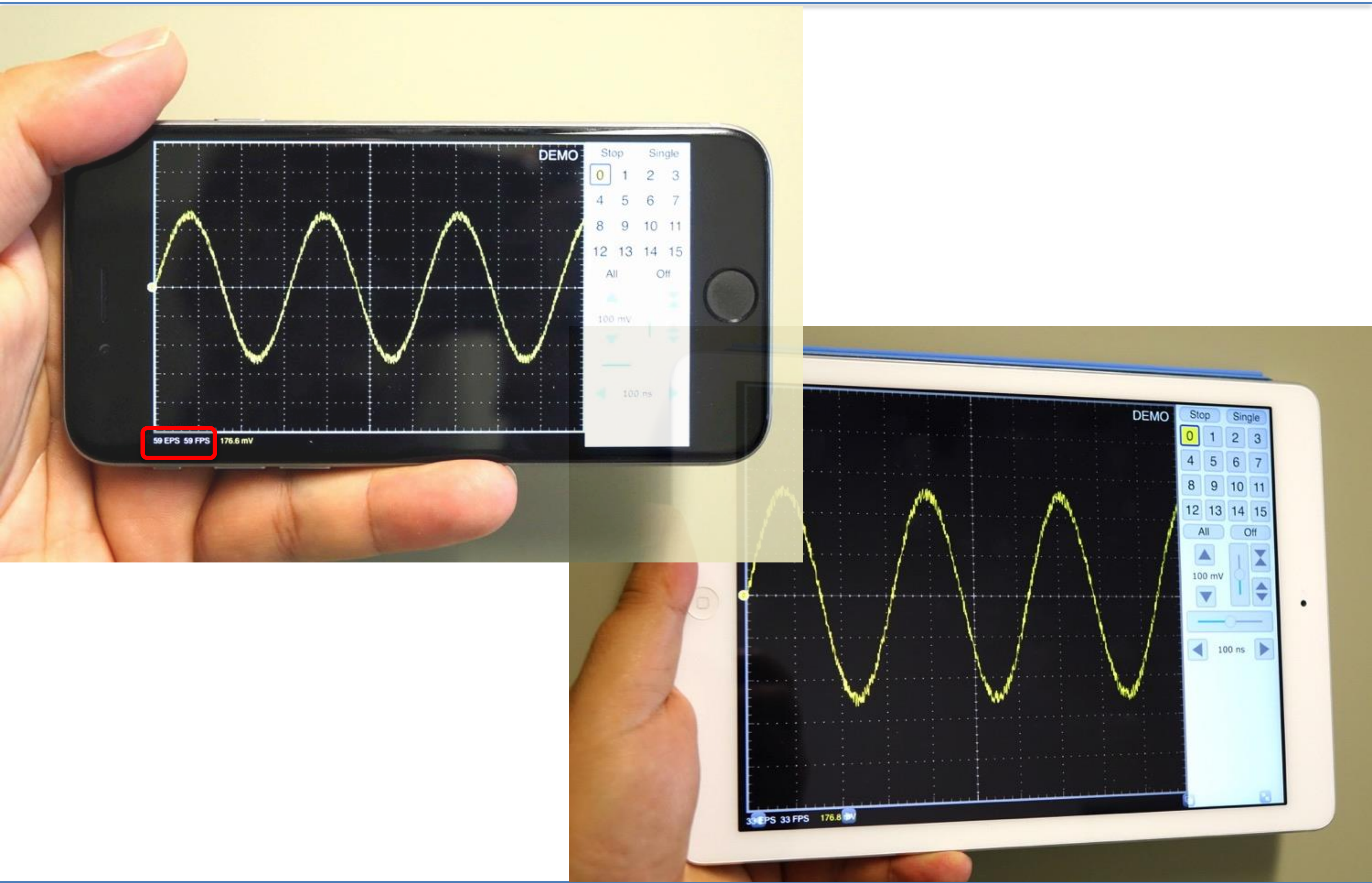


# DRS4 Web Oscilloscope

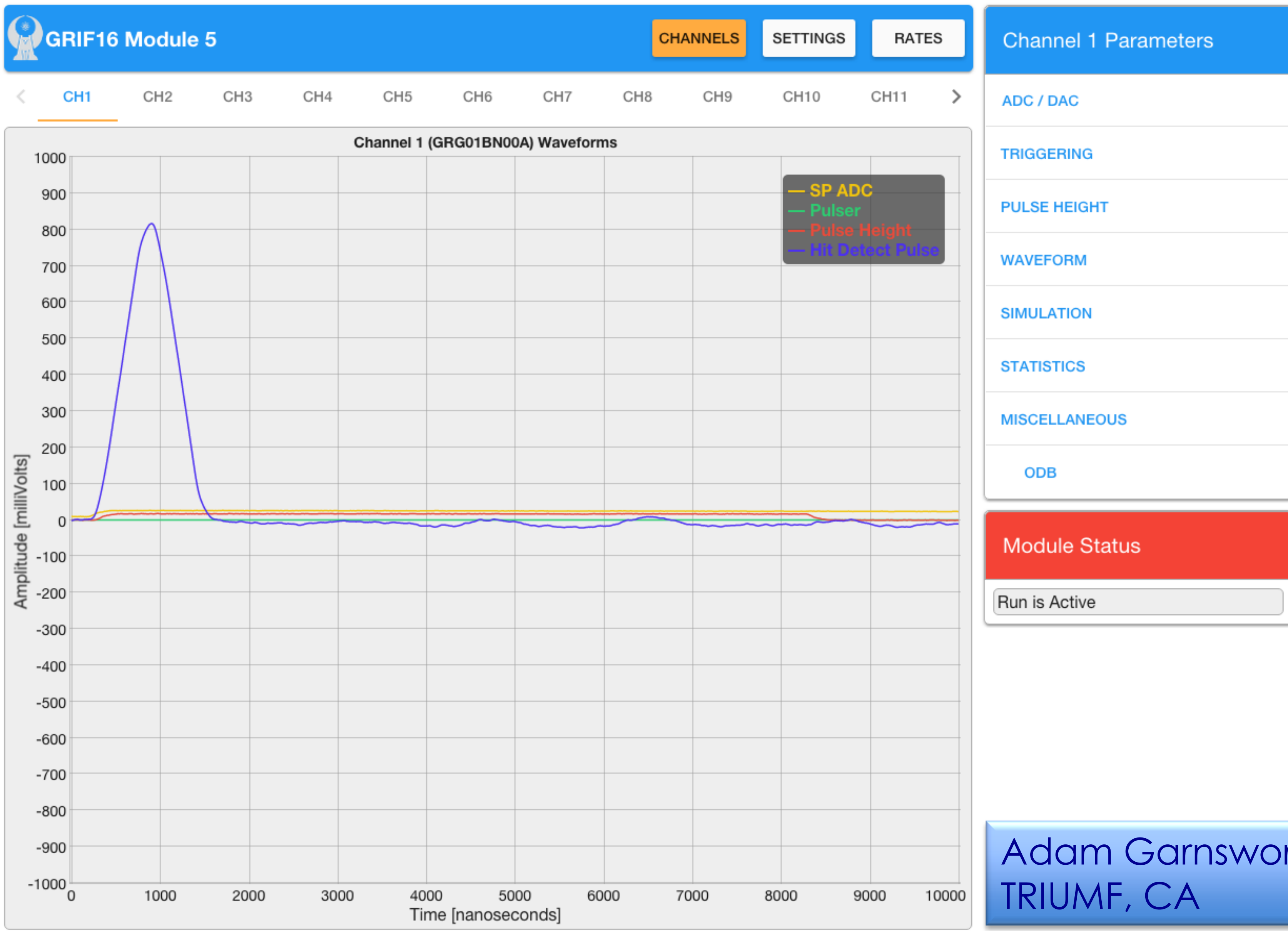
http://midas.psi.ch/scope



# Smartphone and Tablet

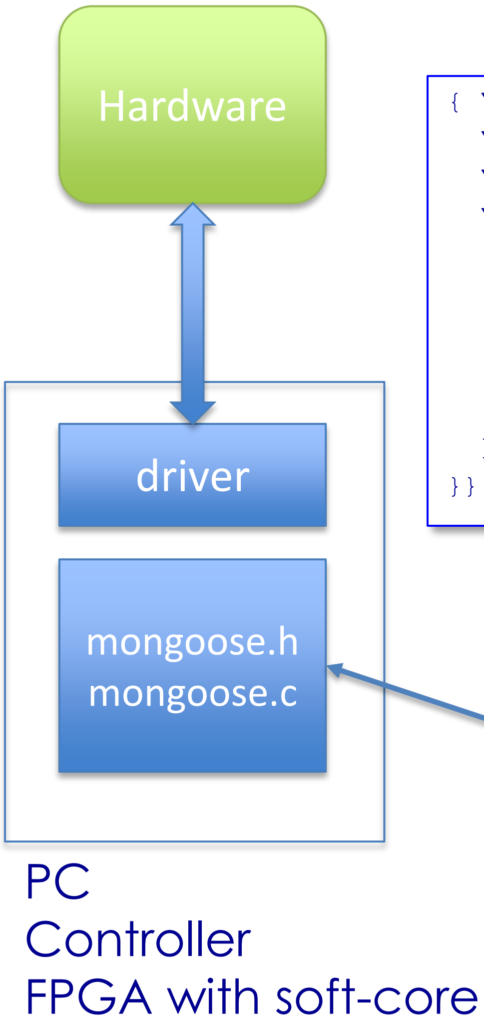


# Another Display




Adam Garnsworthy, TRIUMF, CA

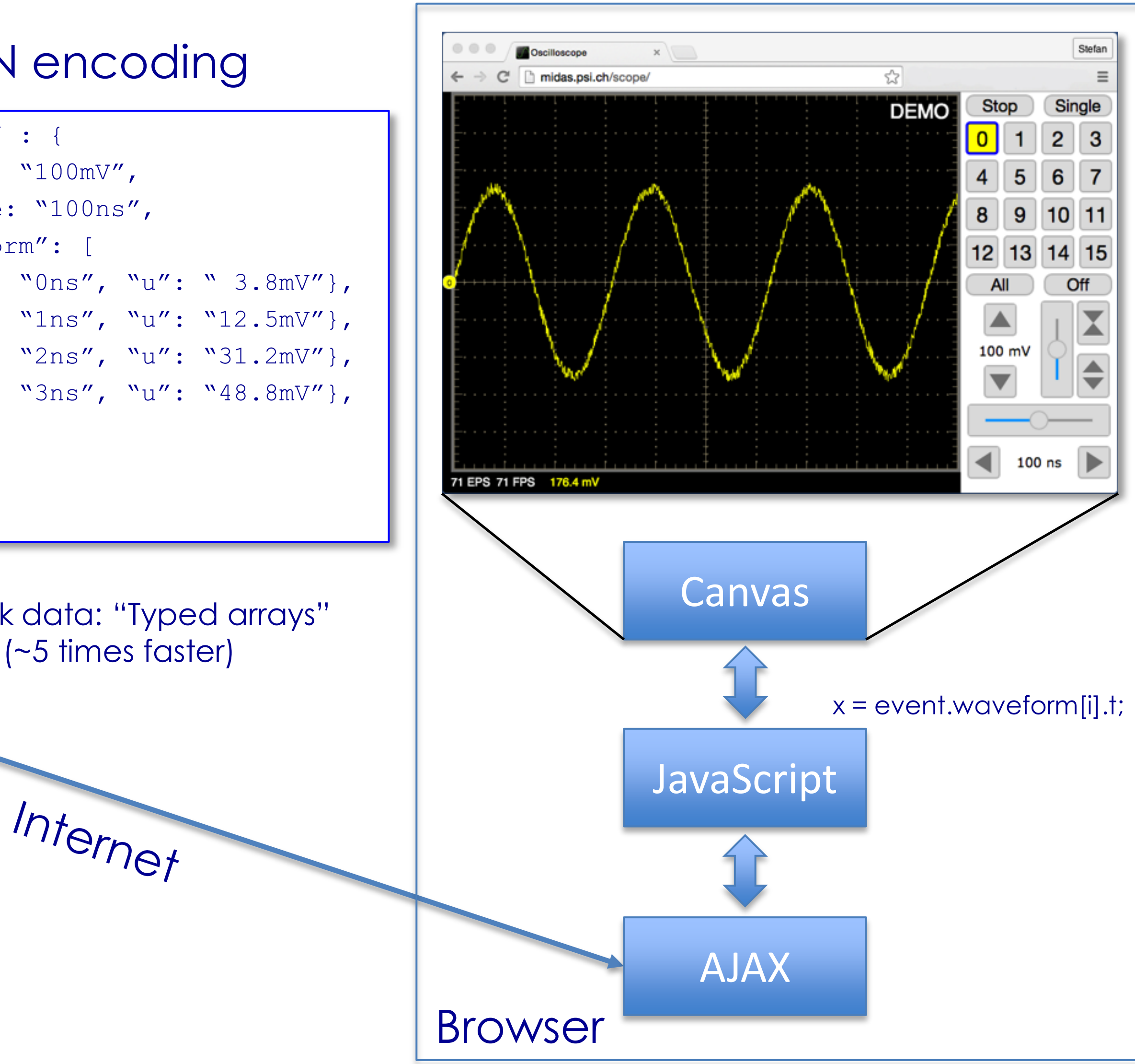
# Data Transport




## JSON encoding

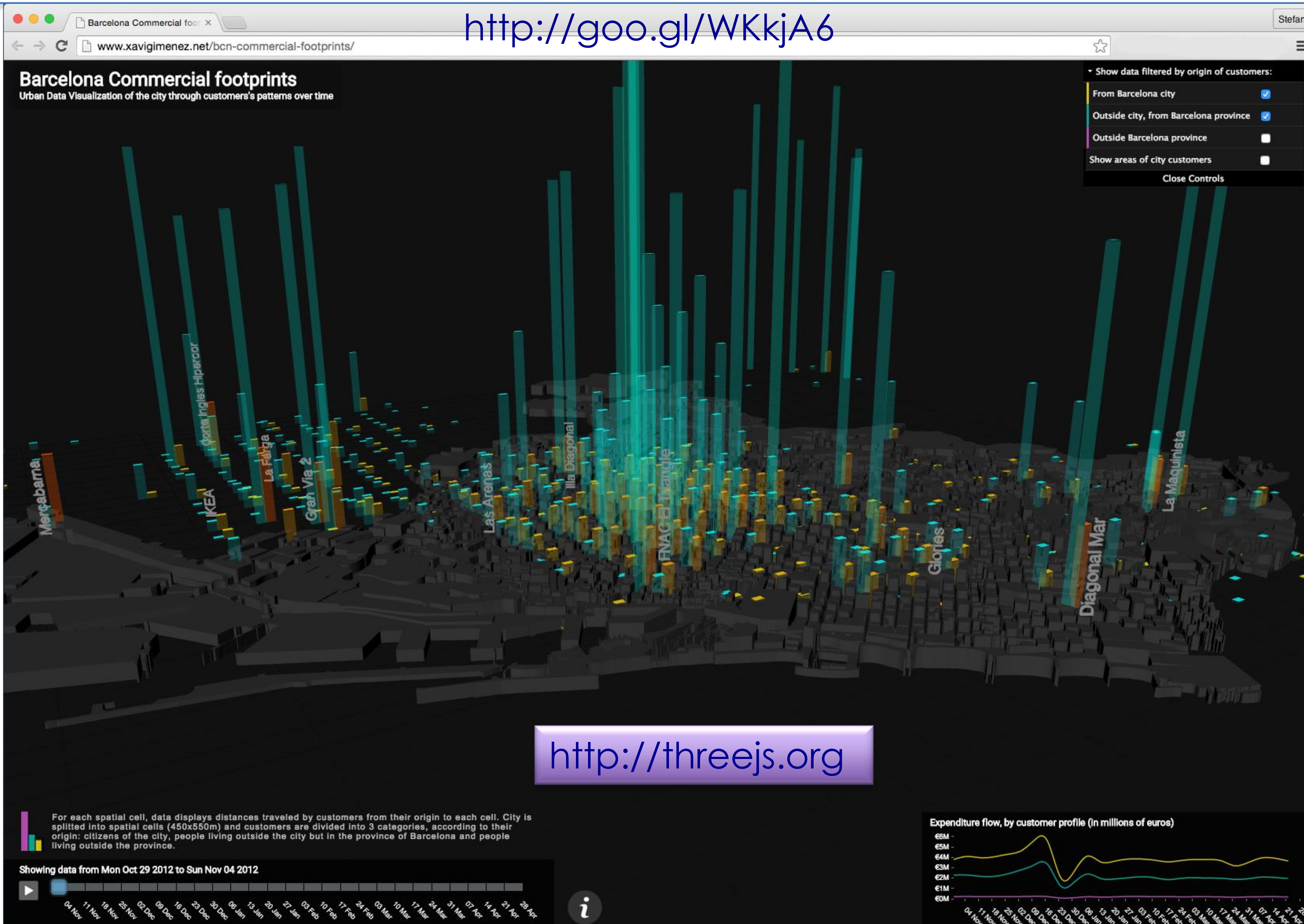
```
{ "event" : {
  "scale: "100mV",
  "tscale: "100ns",
  "waveform": [
    {"t": "0ns", "u": " 3.8mV"},
    {"t": "1ns", "u": "12.5mV"},
    {"t": "2ns", "u": "31.2mV"},
    {"t": "3ns", "u": "48.8mV"},
    …
  ]
}}
```

For bulk data: "Typed arrays"
(~5 times faster)



# 3D Canvas

http://goo.gl/WKkjA6




http://threejs.org

# Future of visualization

- Experiment data can be displayed on any browser (soon)
  - HTML5 is standardized through W3C
  - No software to install, no libraries required
  - Central updates of software
  - Only raw (binary) data needs to be transferred (as opposed to remote desktop applications)
  - Perfect for remote monitoring and control
  - Easy to learn (Scope took me one week from scratch)
- Web server can be incorporated into any web device ("Internet of Things (IoT)")

# Conclusions

- Learn HTML5
- Try wire-TOF if you use gas detectors
- Invest in HV-MAPS technology
- Work on electronics-on-detector integration

- Have more exchange in technical sectors between cLFV experiments

Thanks to: Satoshi Mihara, Ryu Sawada, Alexey Stoykov, Peter-Raymond Kettle, Zachary Hodge, Felix Berg, Roland Horisberger, André Schöning, Nik Berger, …

# Spare Slides

# Crate Standards

# Bus/Crate Standards

- Current standards lack functionality or are expensive
  - ps clock distribution
  - trigger distribution
  - complicated shelf management
  - typical 1 k$ per (empty) slot 6 HE
- For MEG II, we developed our own standard
  - stackable without dead space
  - dual star gigabit link topology
  - system-wide clock (ps jitter) and triggering
  - program all (!) FPGAs through shelf manager
  - crate high voltage for SiPMs
  - cost 125 $ per slot 3 HE

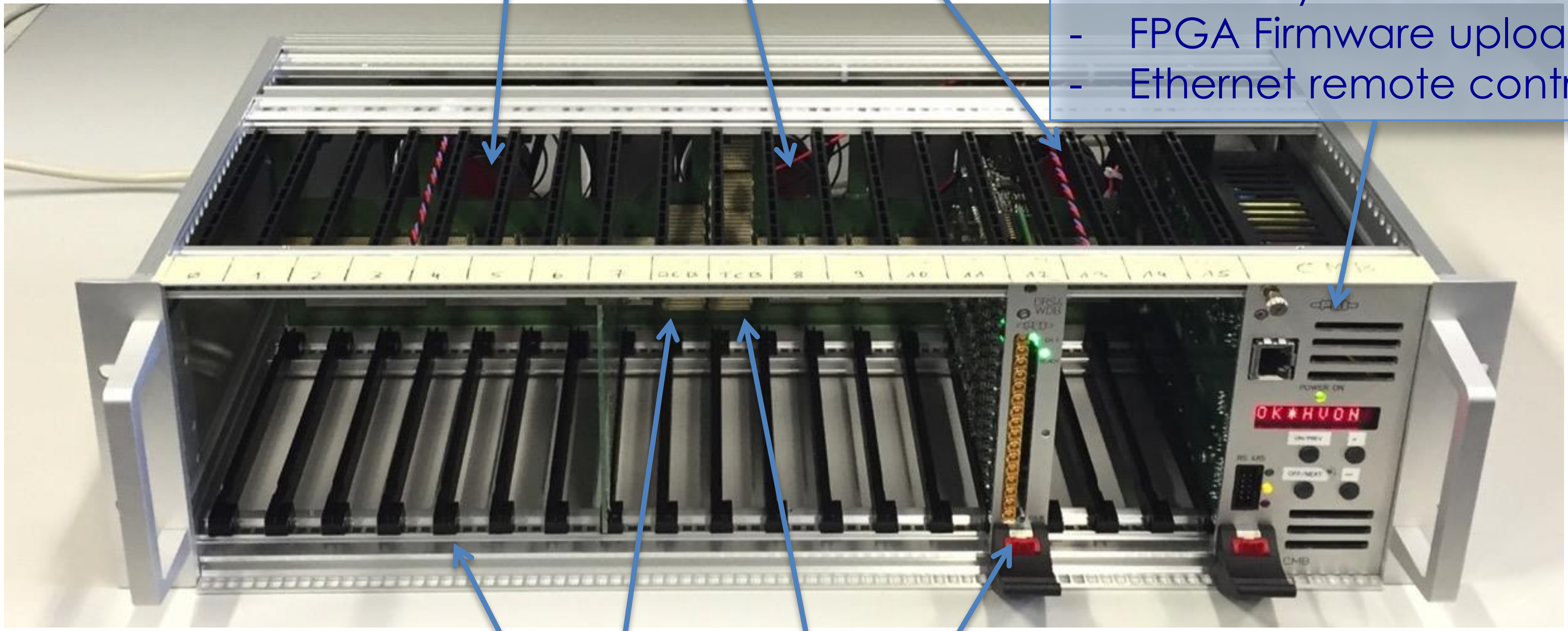
*A personal view from a crazy physicist*

Tomorrow: Markus Joos:
Crate standards at CERN

# WaveDAQ System

Fans blow from back to front

**C**rate **M**anagement **B**oard
- Power supply 24V / 300W
- Fan / Temp. control
- Power cycle each slot
- FPGA Firmware upload
- Ethernet remote control

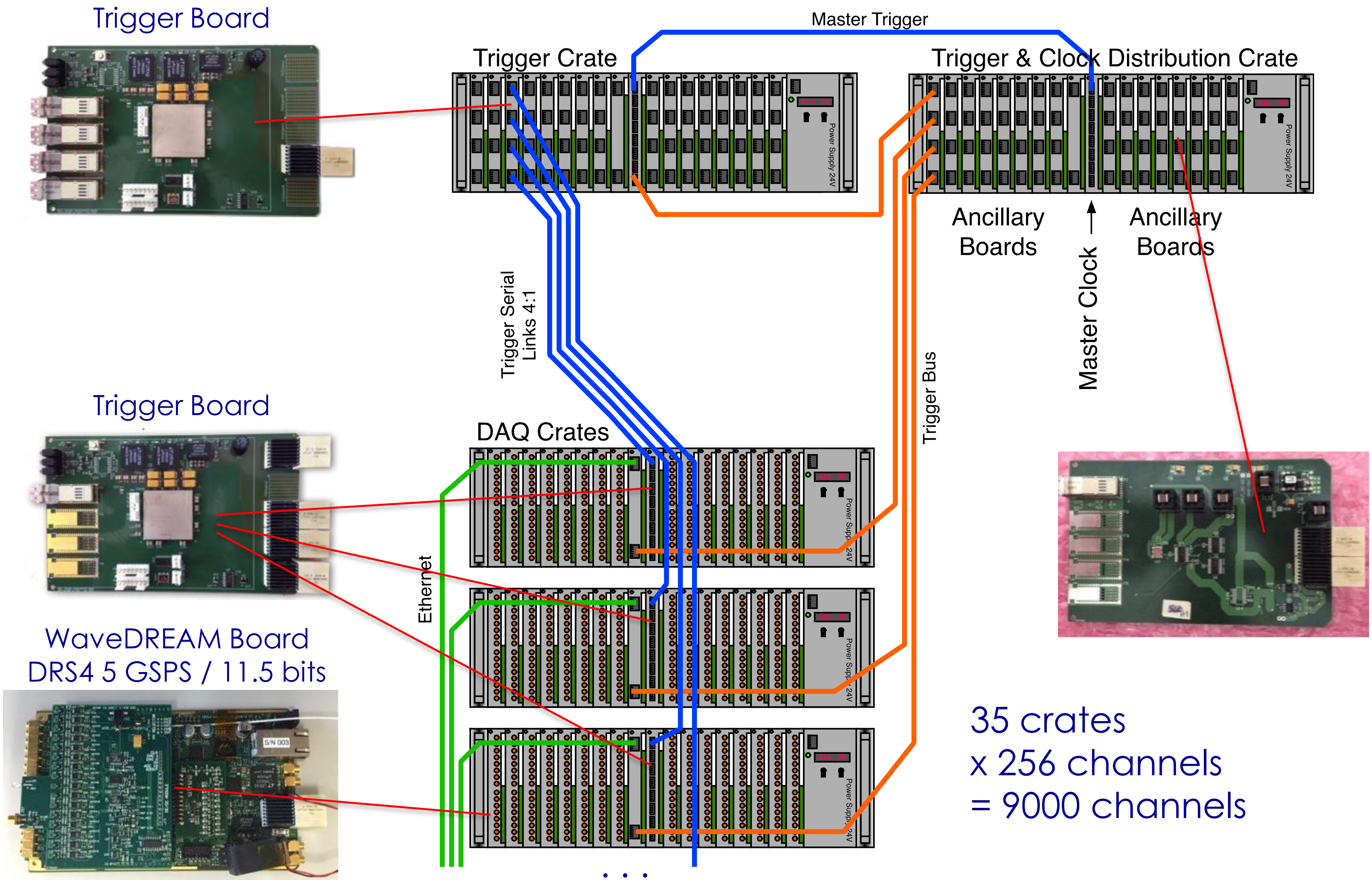



**D**ata **C**oncentrator **B**oard

**T**rigger **C**oncentrator **B**oard

16 WaveDREAM boards
(256 channels)

# MEG II System




35 crates
x 256 channels
= 9000 channels