PbF2 calorimeter for the Muon g–2 experiment

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10/9/16

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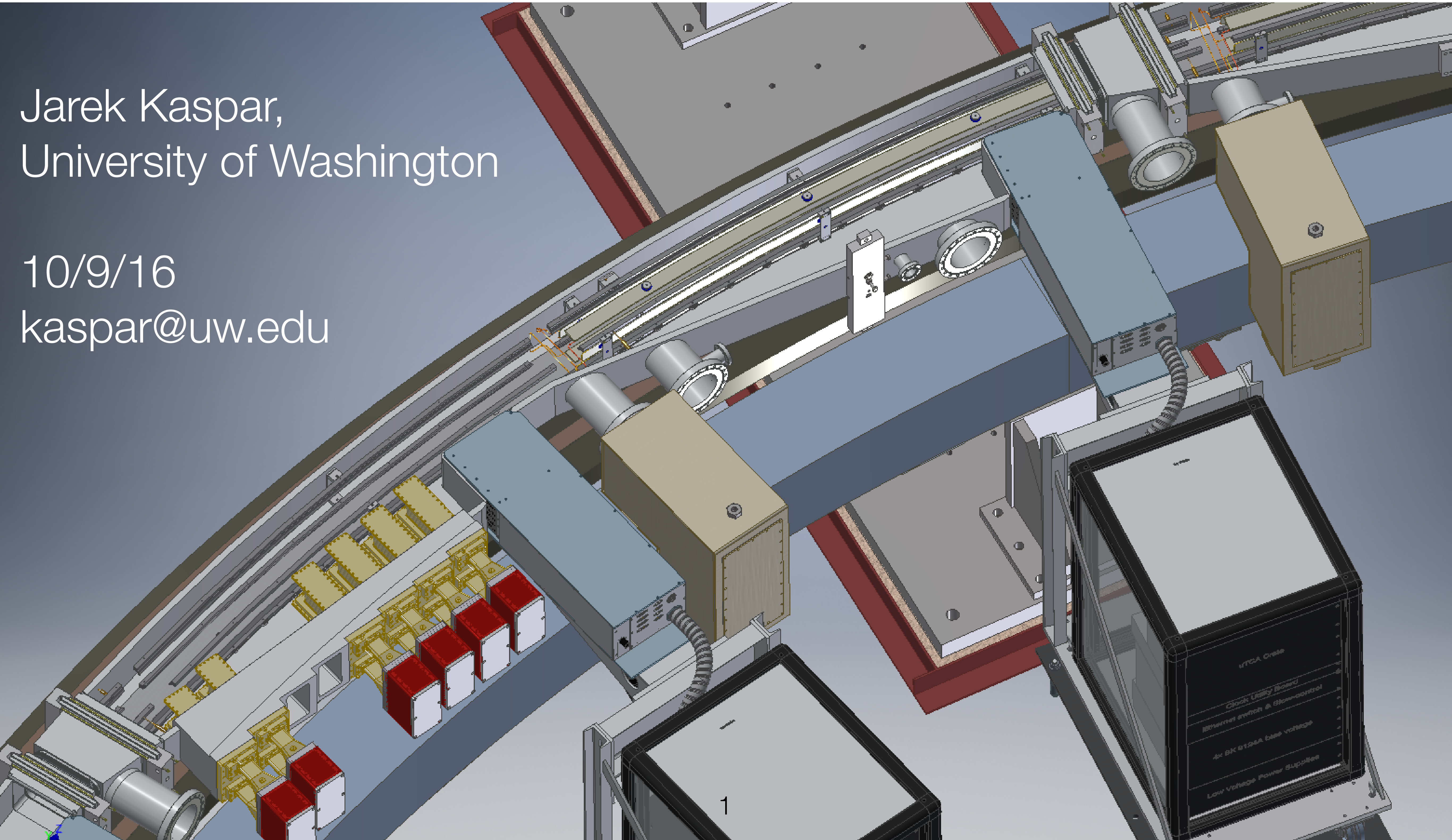
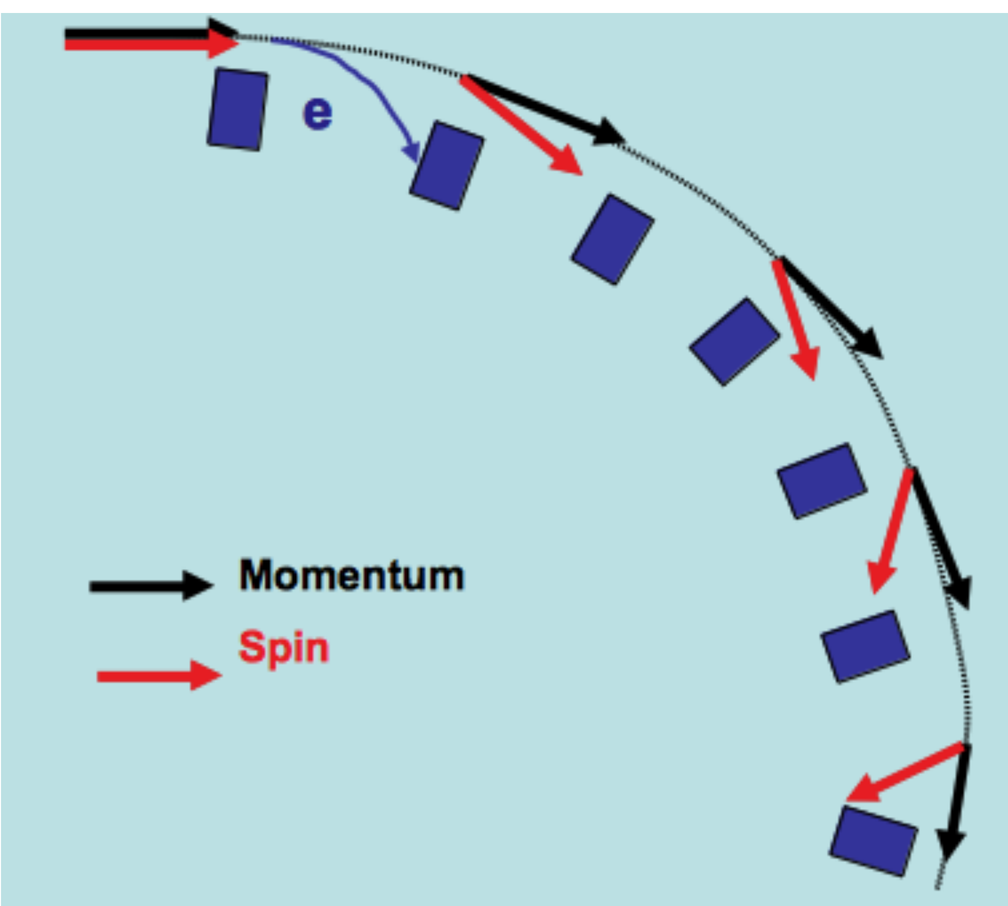
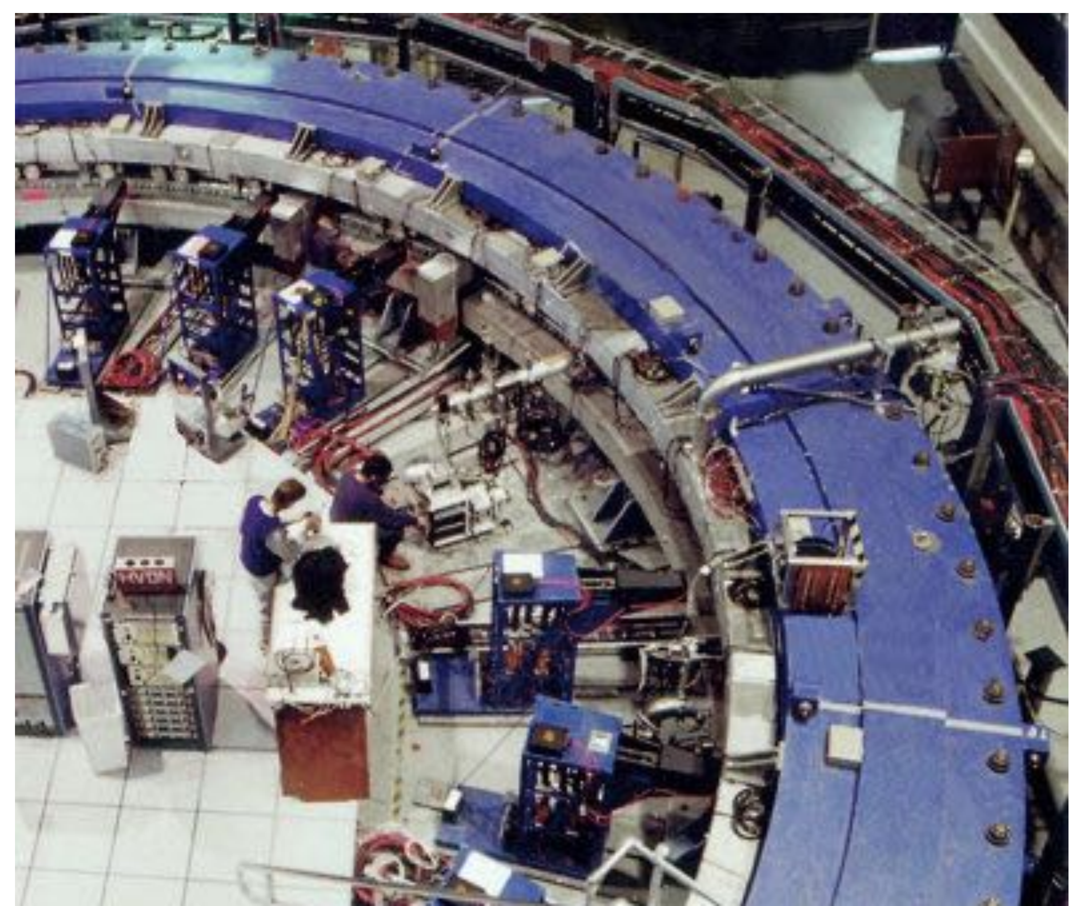


magnetic dipole moment of muon

- torque experienced in external magnetic field
- spin → intrinsic magnetic dipole moment
- experiment measures the anomalous part of magnetic dipole moment



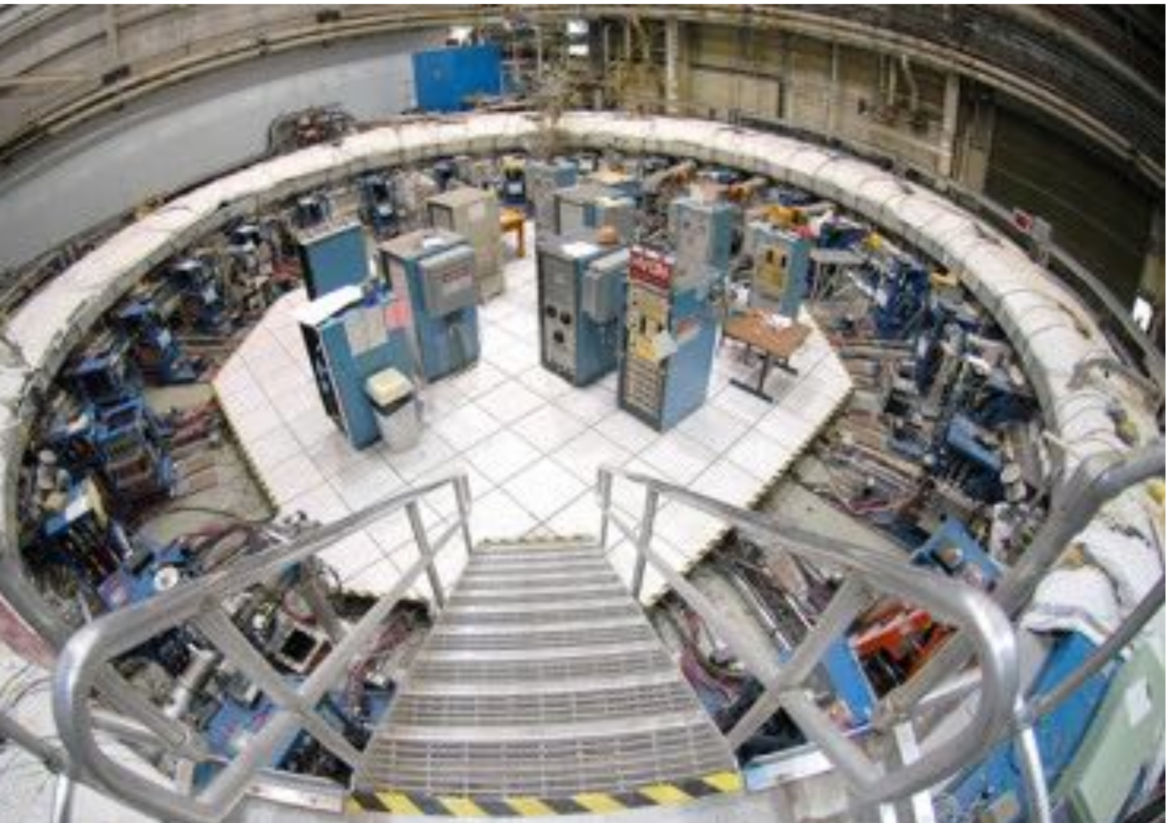


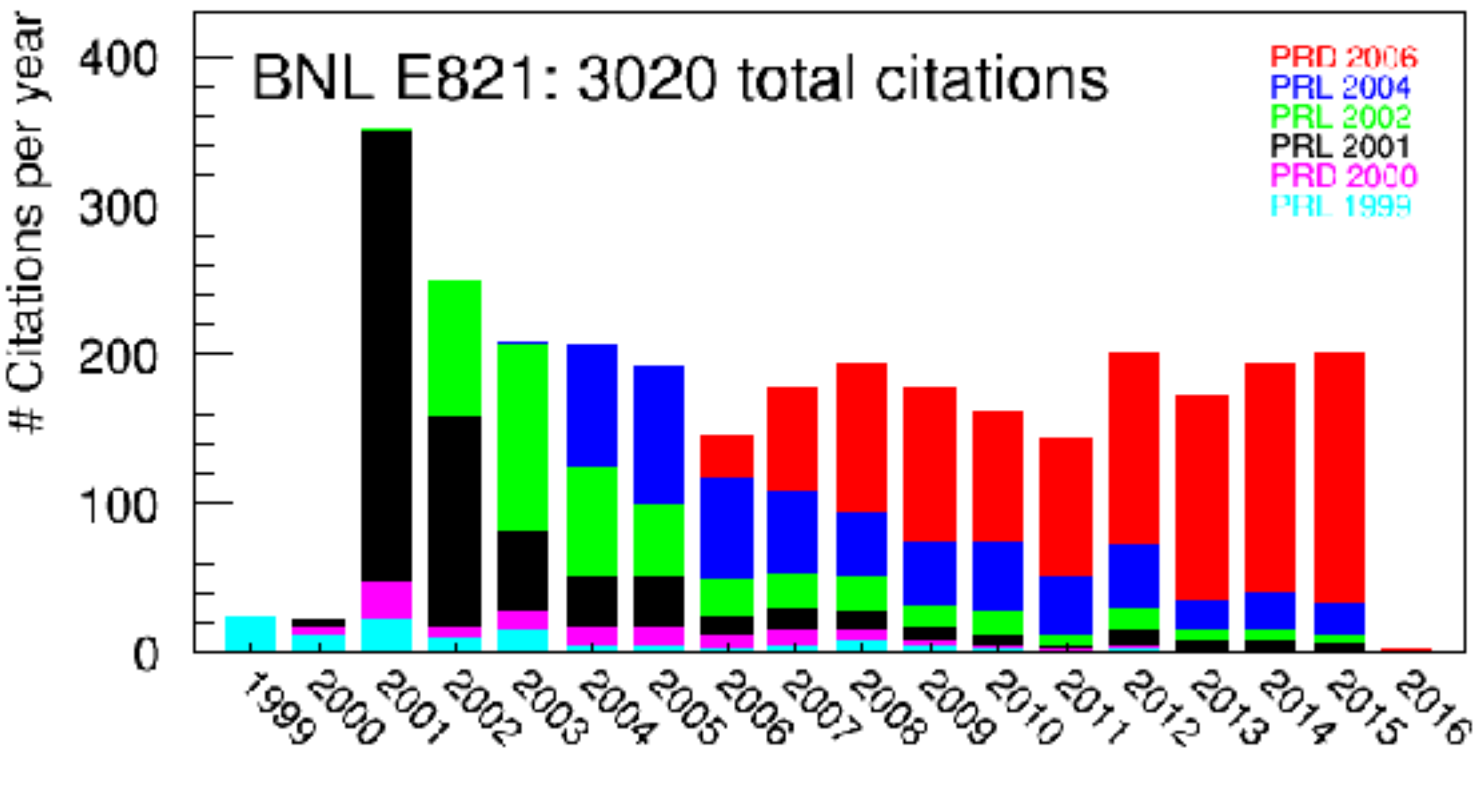
$g - 2$ experiment at BNL

E821 (1999 - 2006):

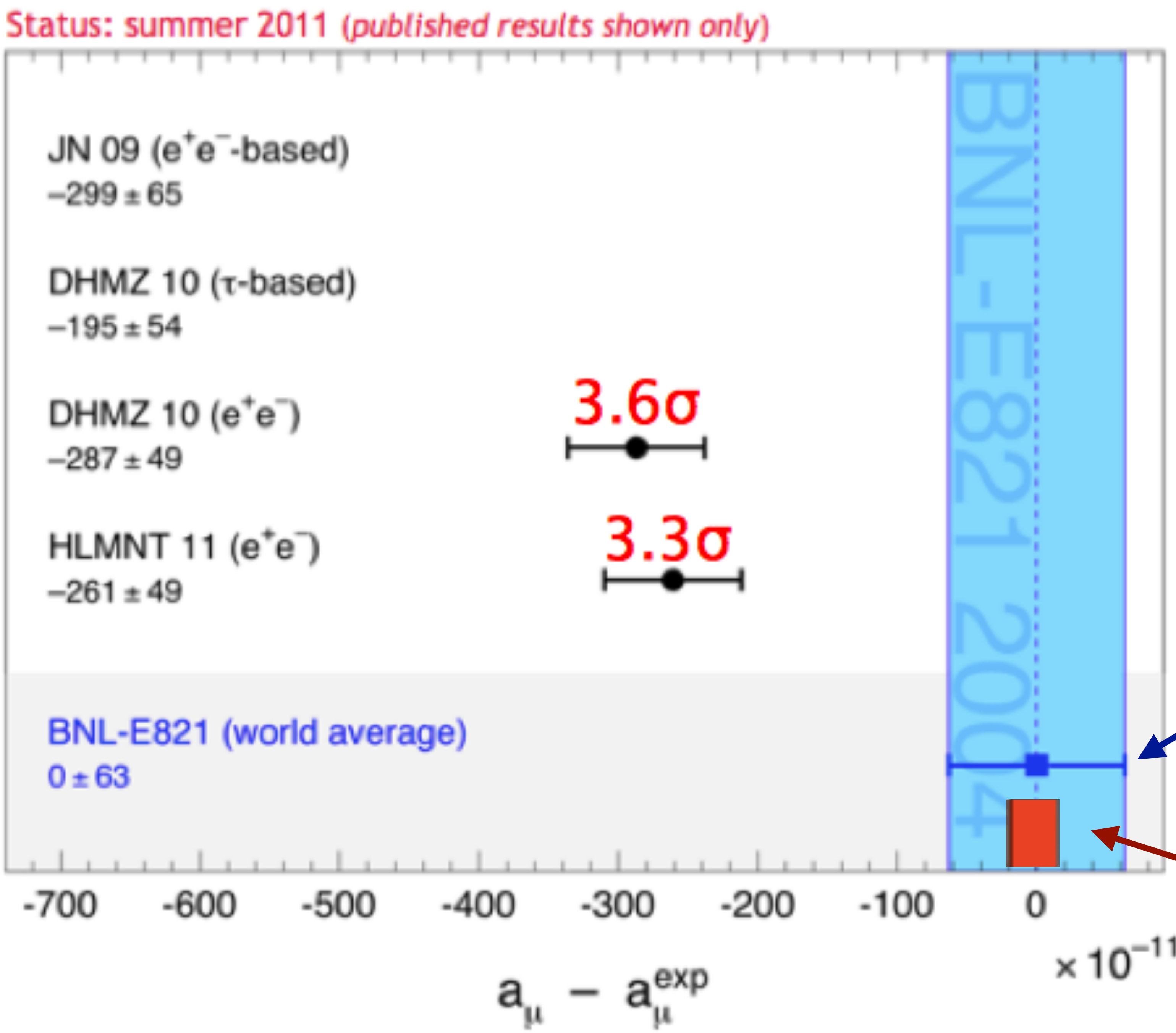
a_μ = 0.001 165 920 89 (63) (±0.54 ppm)

And a hint of New Physics ?





Standard Model prediction



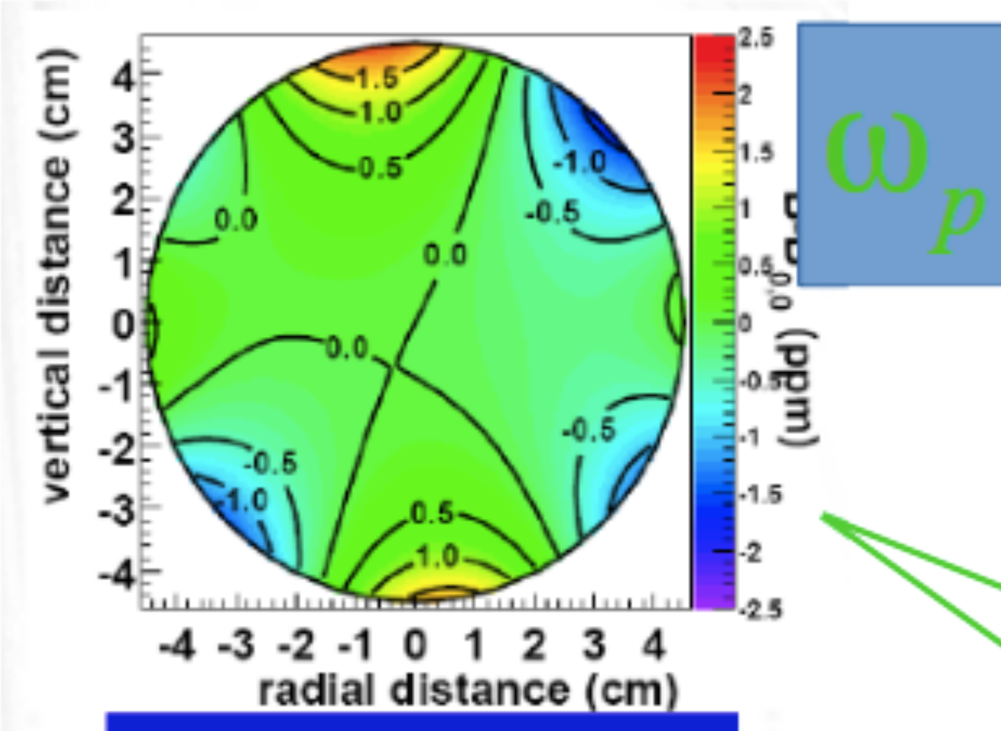
Experiment E821 at BNL

540 ppb uncertainty

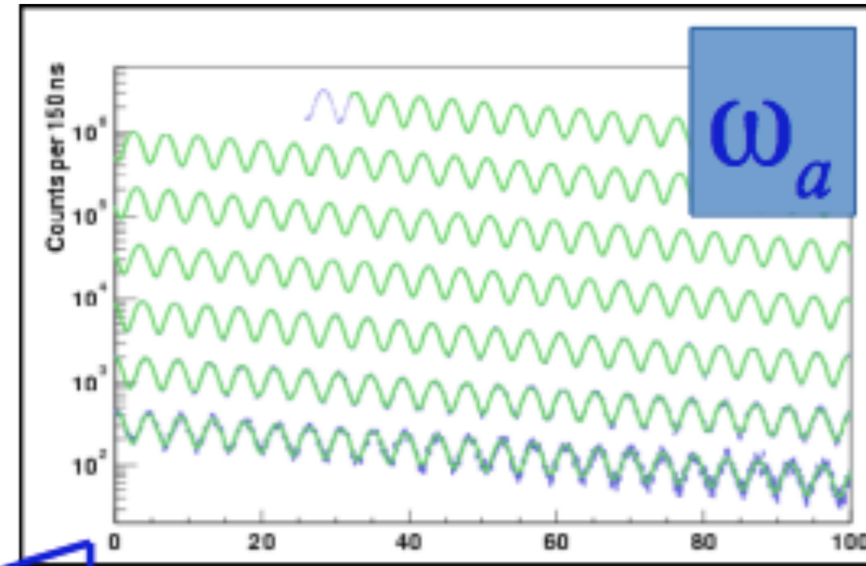
Muon g−2 exp. at FNAL

4 fold improvement

140 ppb uncertainty

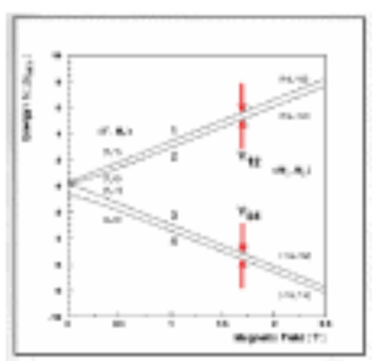


Our "Magnet"



Our conventional Detector, Electronics, and DAQ systems

$$a_\mu = \frac{\dfrac{\omega_a}{\omega_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\omega_p}}$$

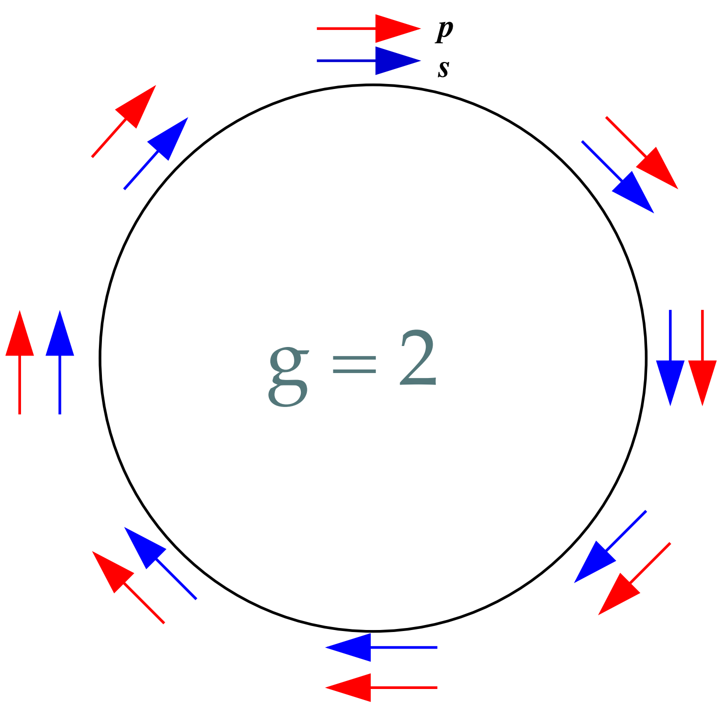


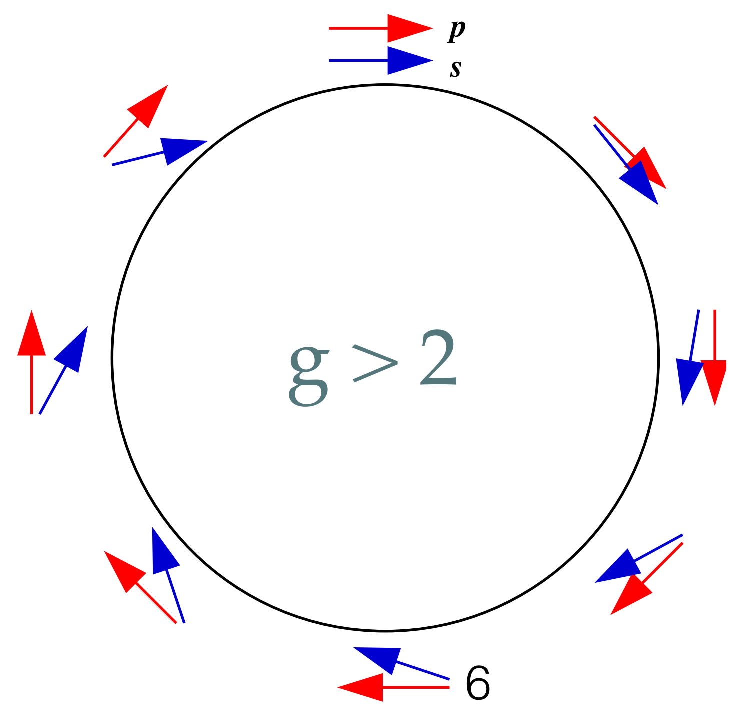
μ_μ/μ_p = 3.183 345 24(37) (120 ppb)
= *3.183 345 39(10) (31 ppb)*

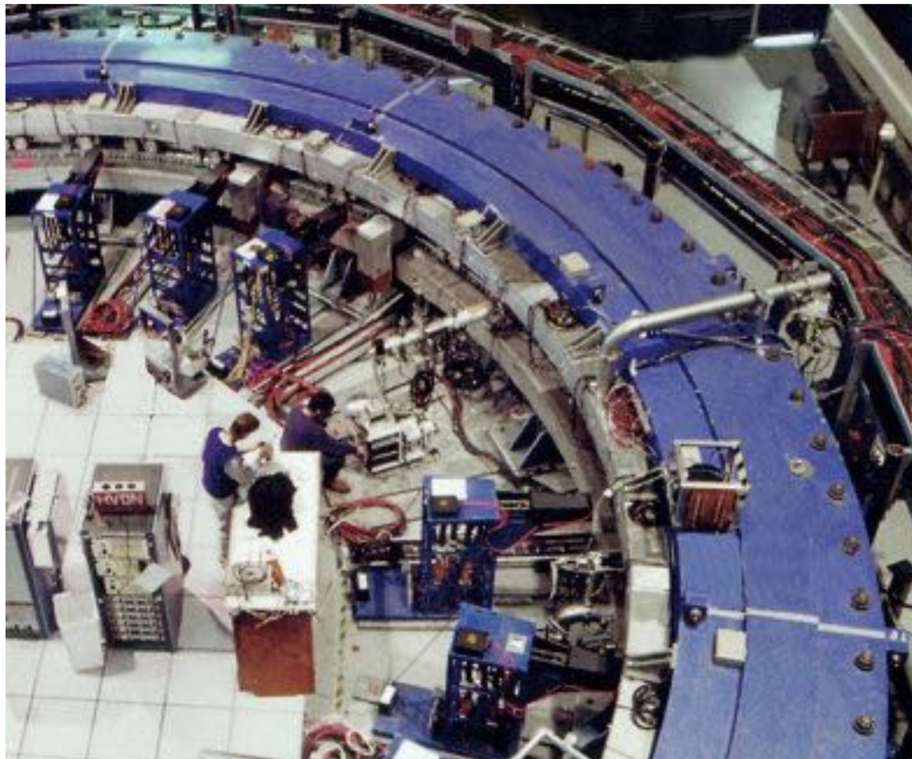
External Muonium Hyperfine Expt.

principles of ω_a measurement

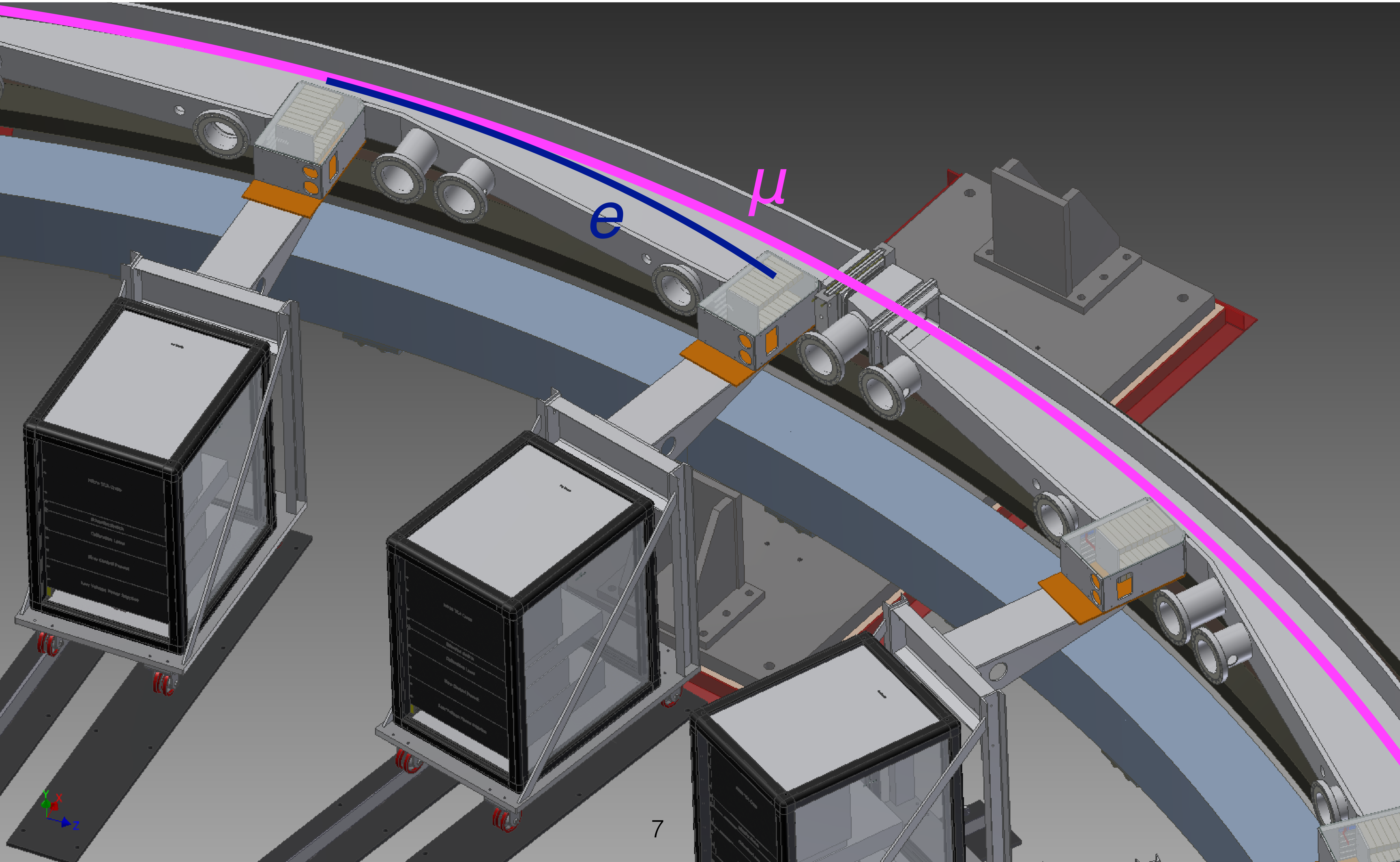
1. source of polarized muons (parity violating pion decay)
2. precession proportional only to the anomalous part of magnetic dipole moment *(g-2)*
3. magic momentum gets rid of $\beta \times E$ term
4. parity violating decay (positron reports on spin)
   Lorentz boost maps spin direction onto energy



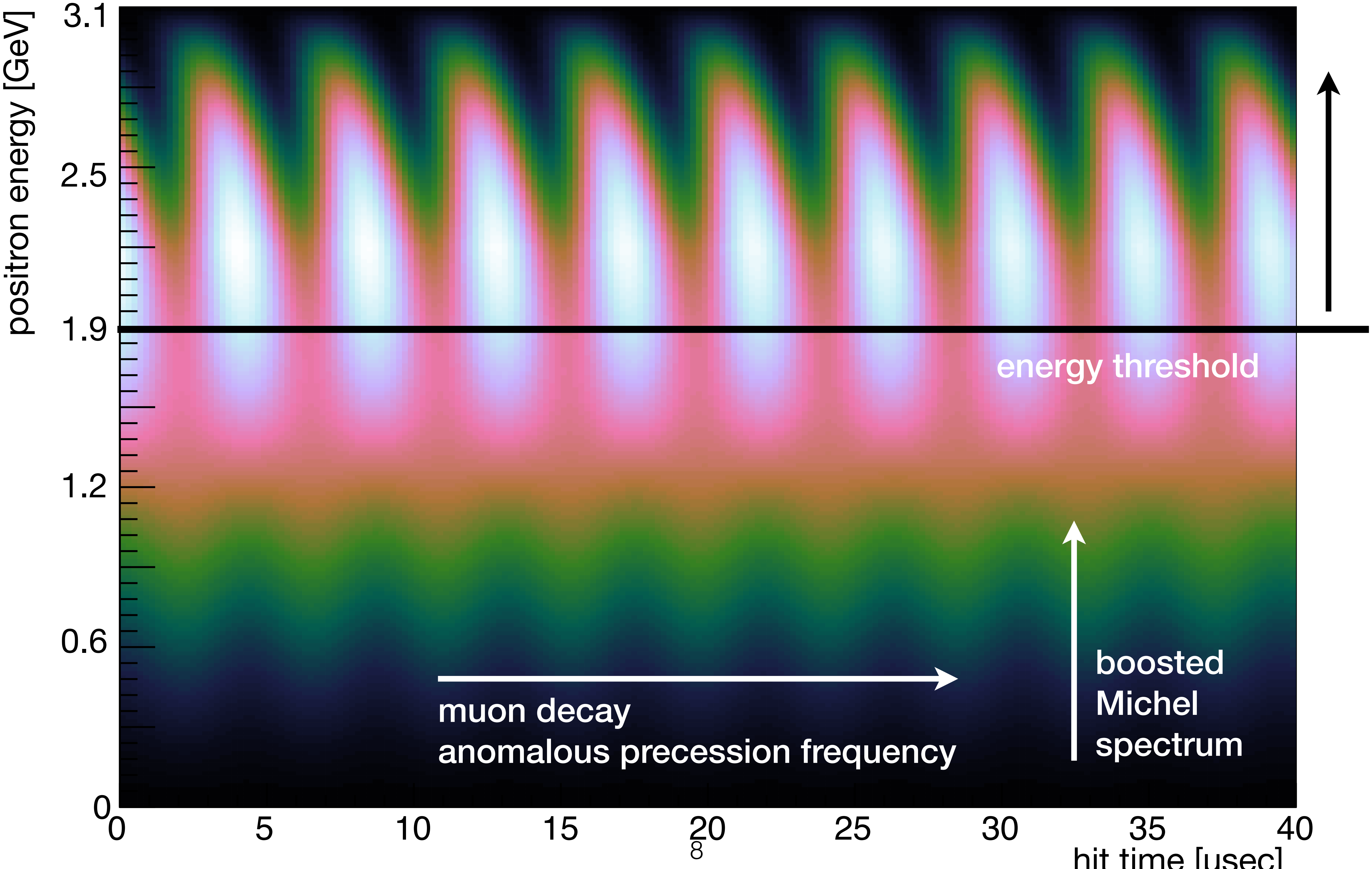


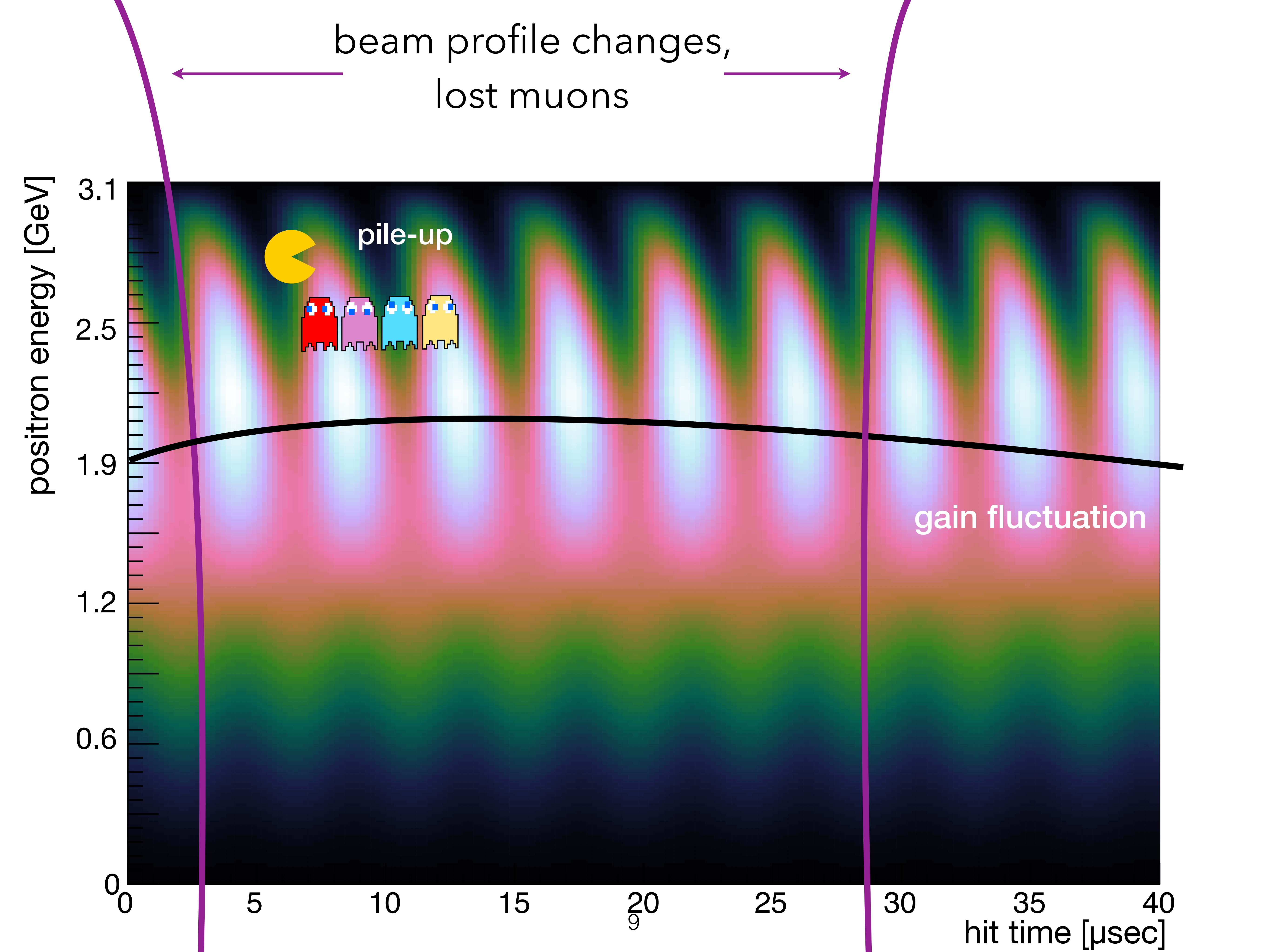


a lighthouse riding a carousel



what does a calorimeter see




beam profile changes,
lost muons
pile-up
gain fluctuation
positron energy [GeV]
3.1
2.5
1.9
1.2
0.6
0
0
5
10
15
20
25
30
35
40
hit time [μsec]

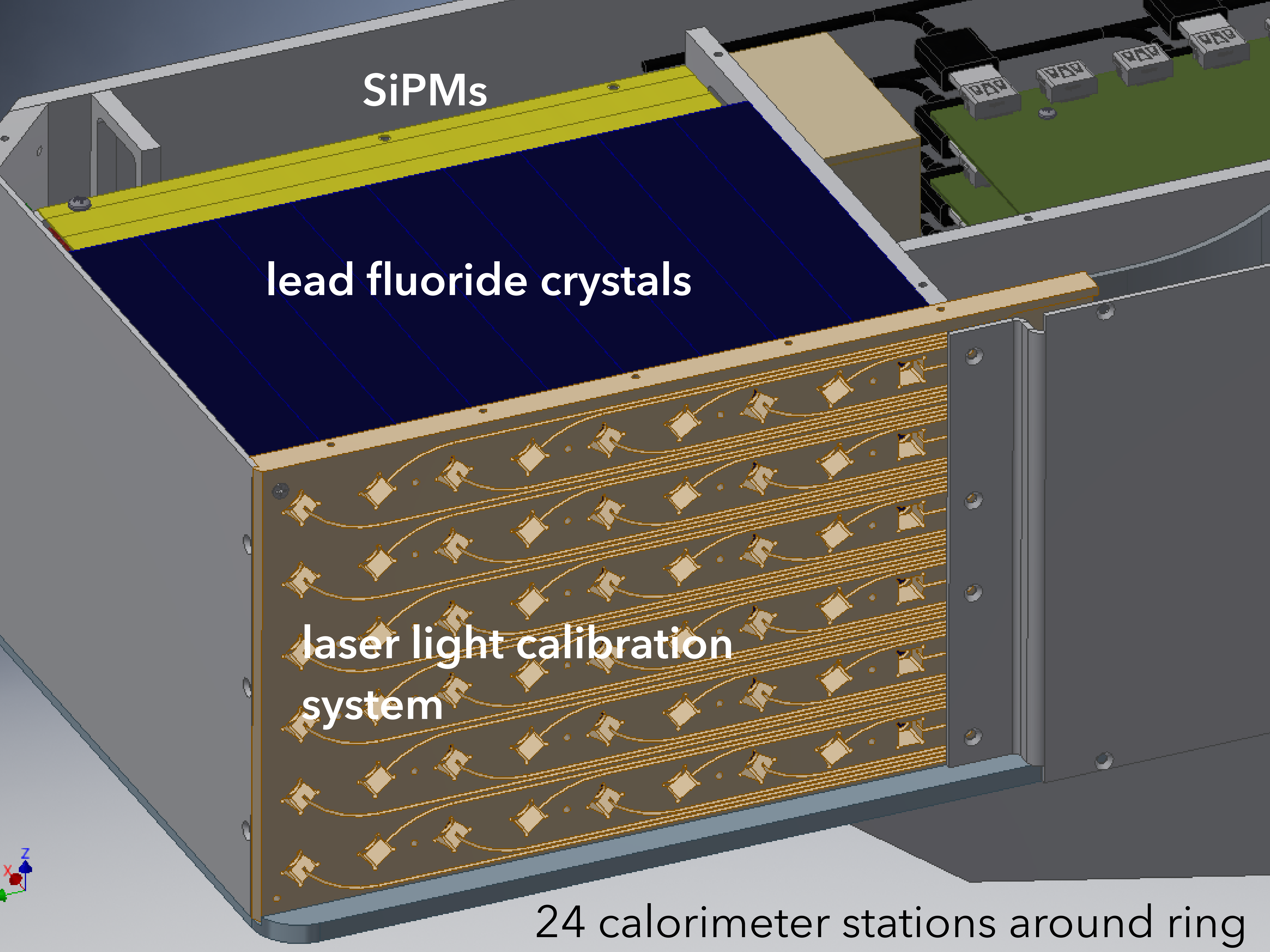
Calorimeter design goals

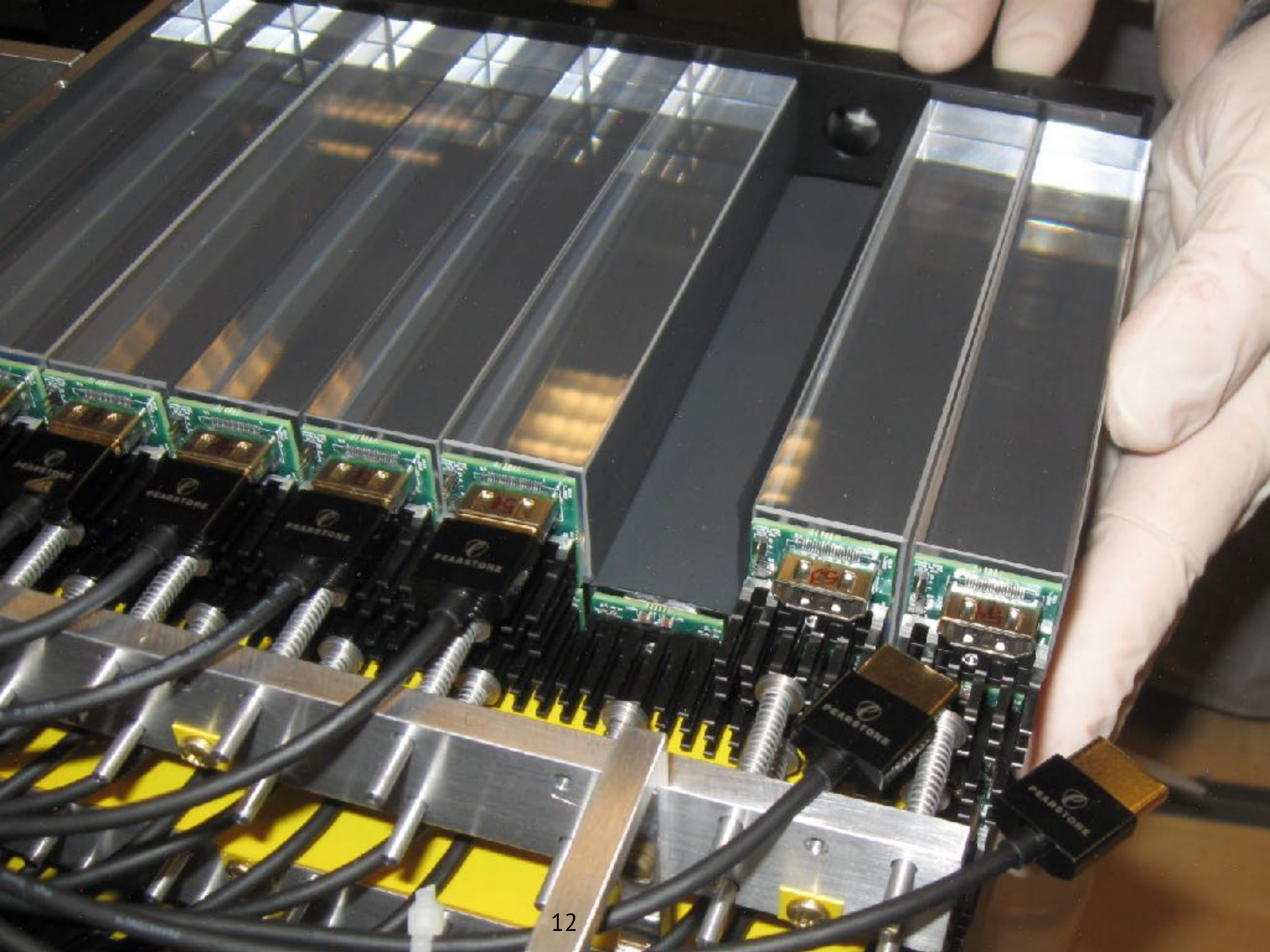
1. Positron **hit time** measurement with accuracy of (100 psec above 100 MeV)

2. **Deposited energy** measurement with resolution better than 5 % at 2 GeV

3. **Energy scale** (gain) **stability** in 1e−3 range, over the course of 700 μsec fill where rate varies by 1e4.

4. 100 % **pile-up separation** above 5 nsec, and 66 % below 5 nsec.

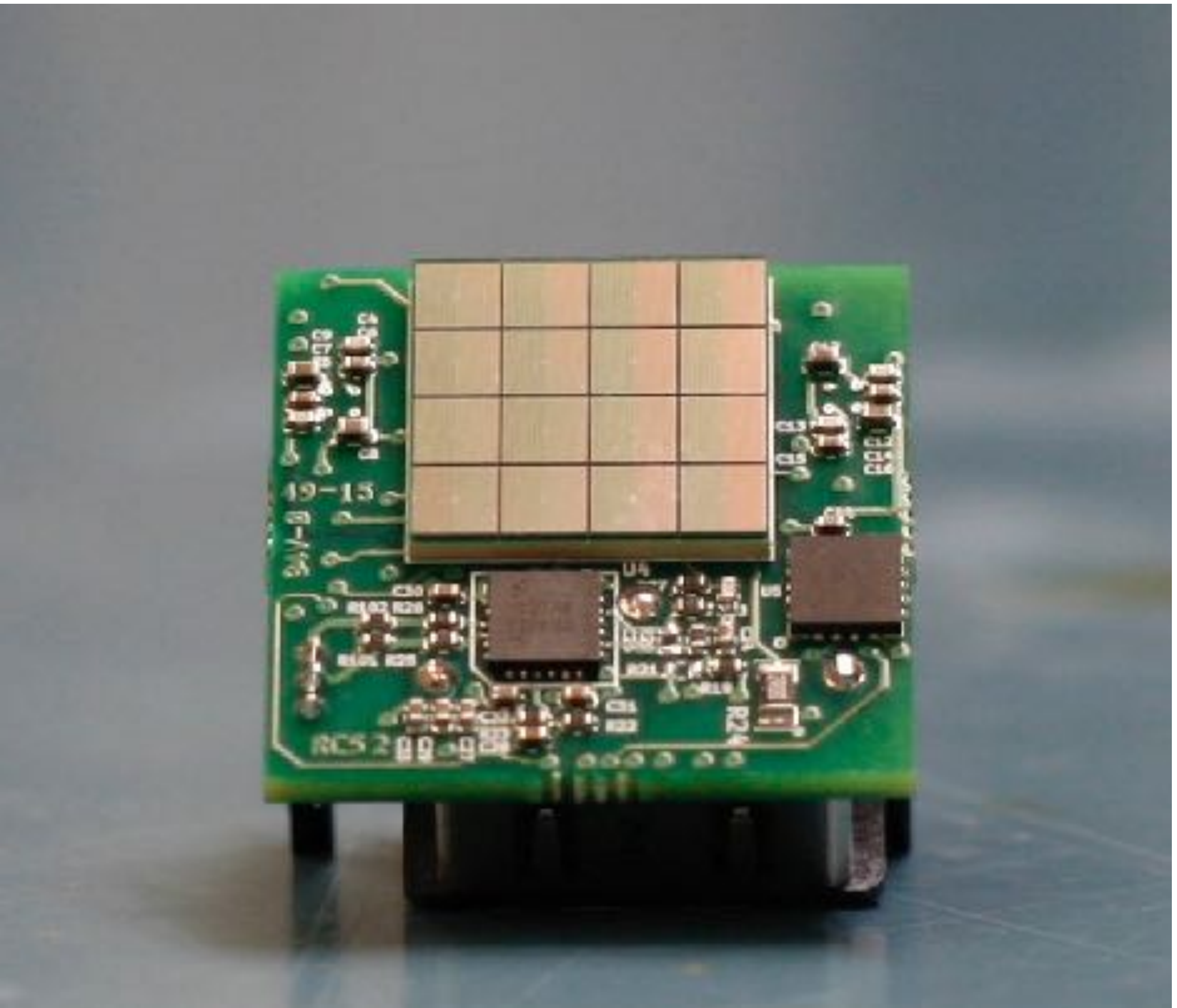

SiPMs
lead fluoride crystals
laser light calibration system
24 calorimeter stations around ring

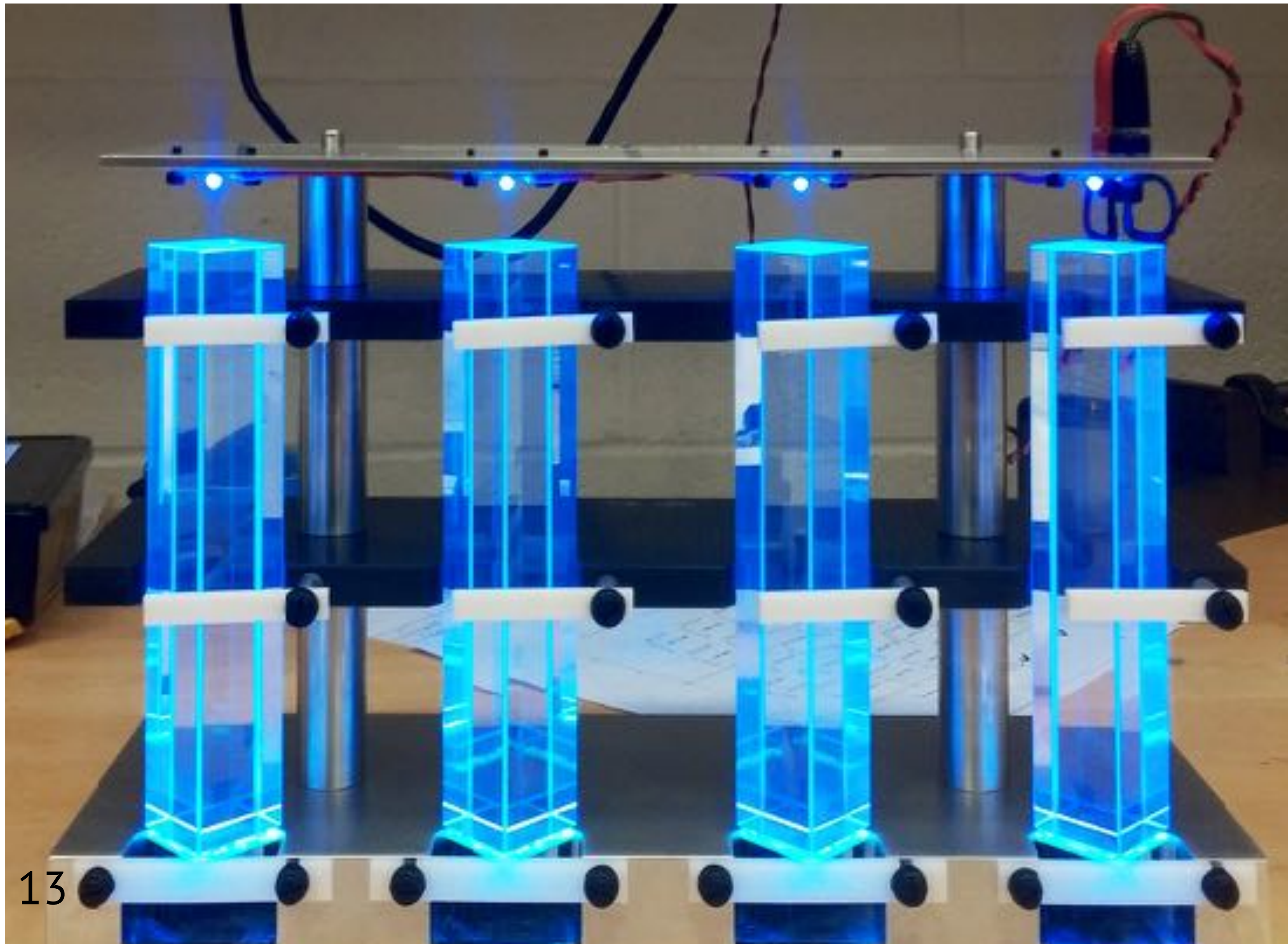

PEARSTONE

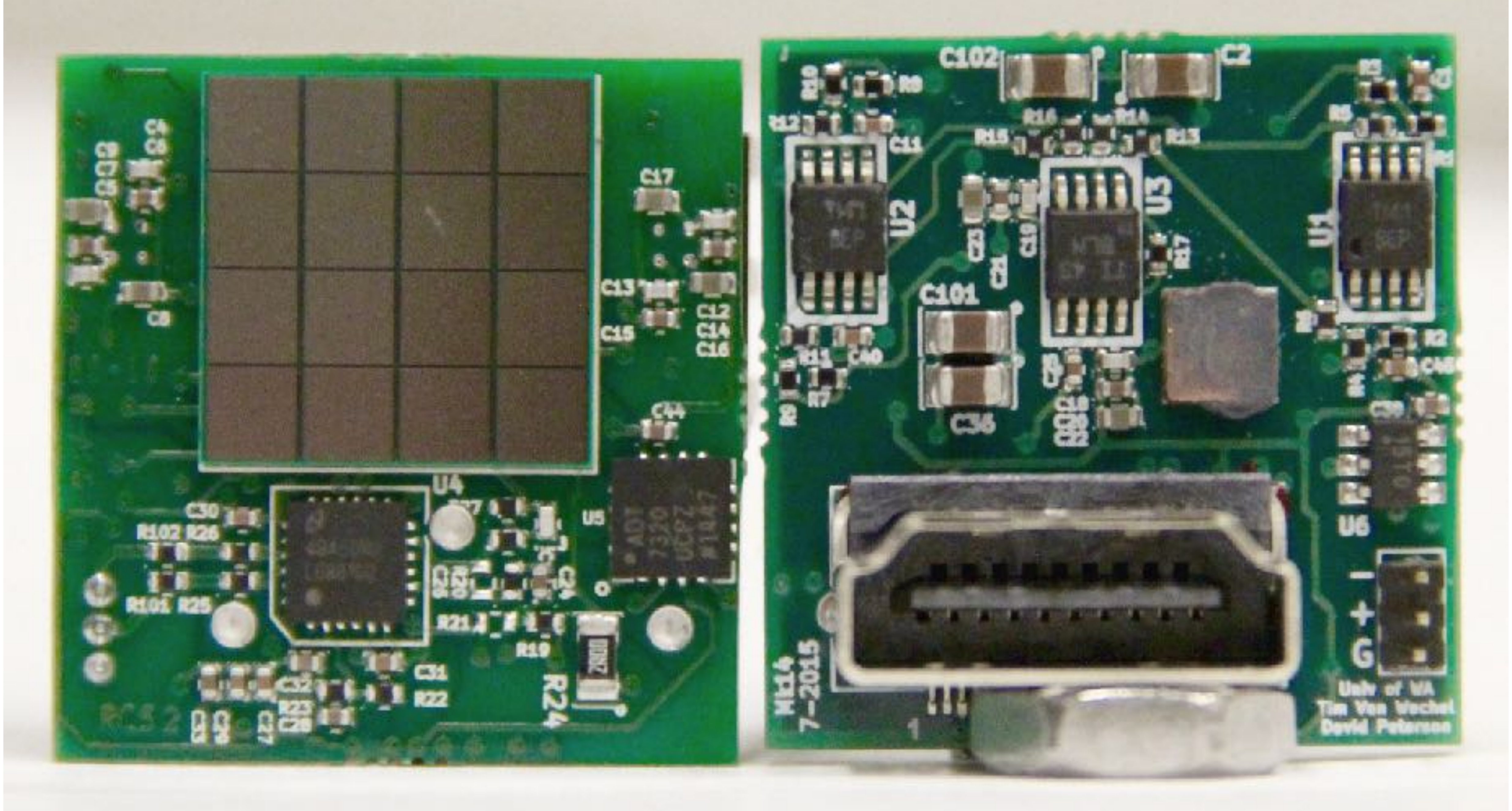
positron detection in calorimeter

PbF2 – pure Cherenkov radiator
SiPM – counts photons; magnetic field compatible

A.T. Fienberg, et al. Nucl.Instrum.Meth. A783 (2015) 12-21, arXiv:1412.5525







- based on a trans-impedance amplifier (no shunt resistor) PMT-like pulse shape
- programmable gain amplifier to equalize 1400 boards
- DC coupled differential signal to digitizers
- temperature sensor on board for offline gain calibration

custom made 800MHz digitizer

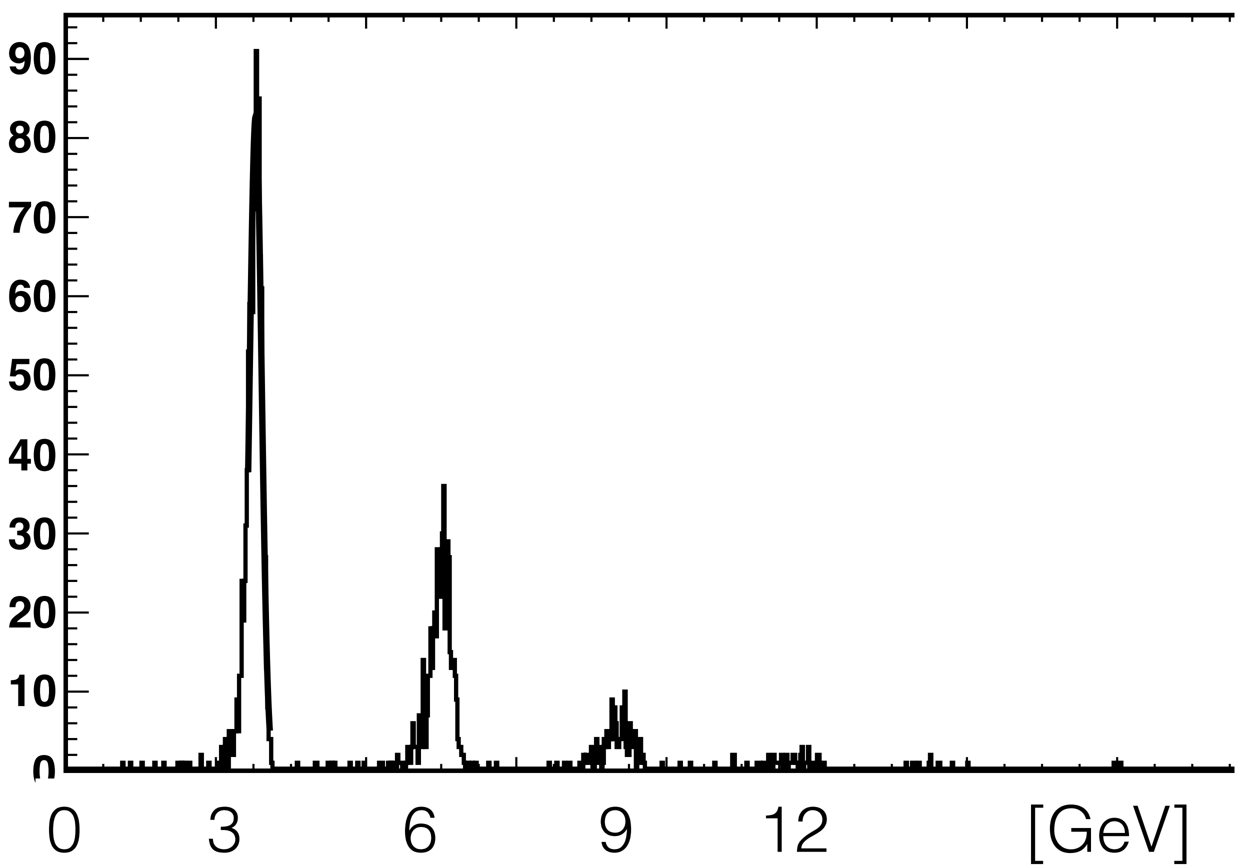
- 5ch, 800 MSpS
- 12 bit, TI ADS5401
- 1 V dynamic range
- <1 mV noise
- µTCA format

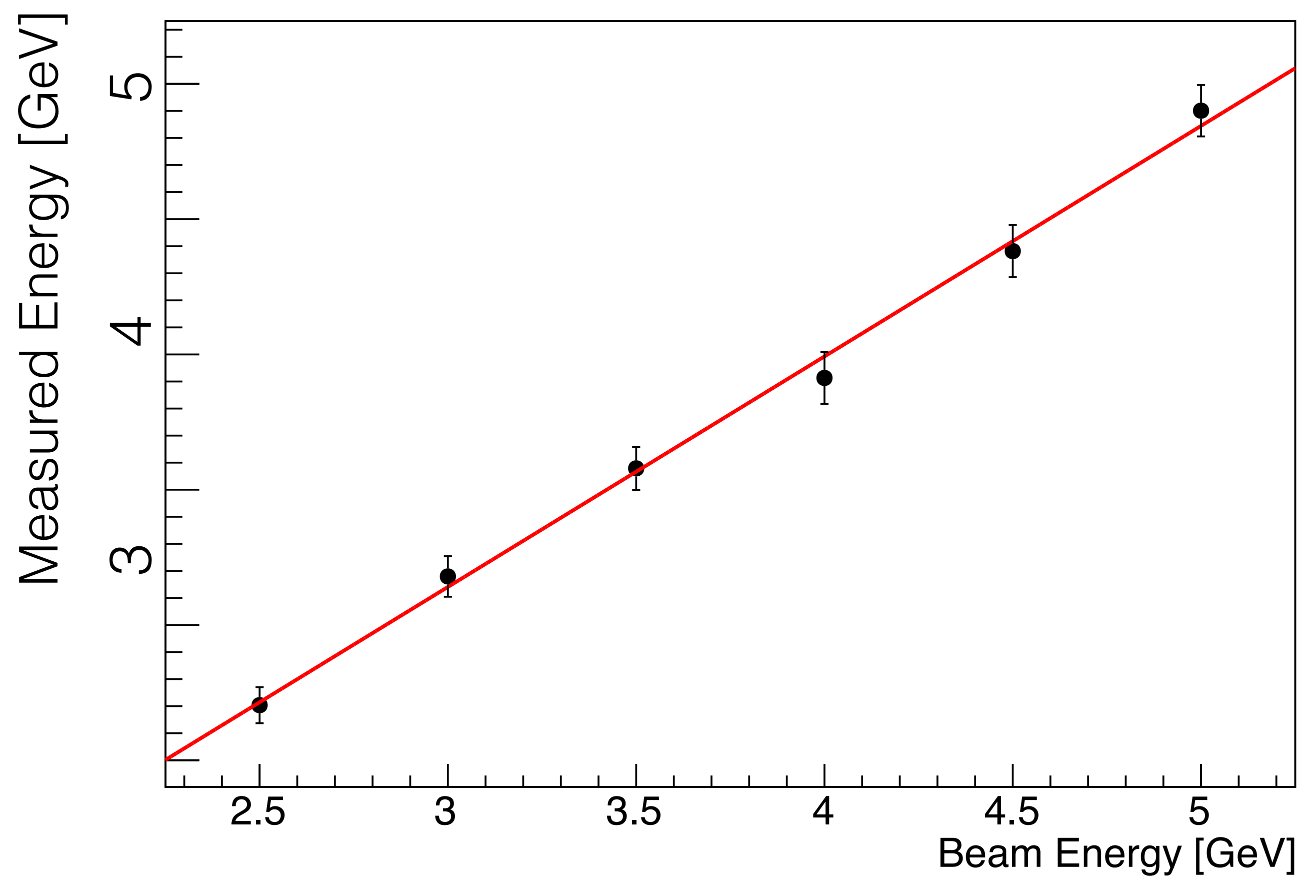
calorimeter at SLAC test beam

energy resolution 3% at 3GeV

both from data, and understanding of photo statistics and electronics contributions

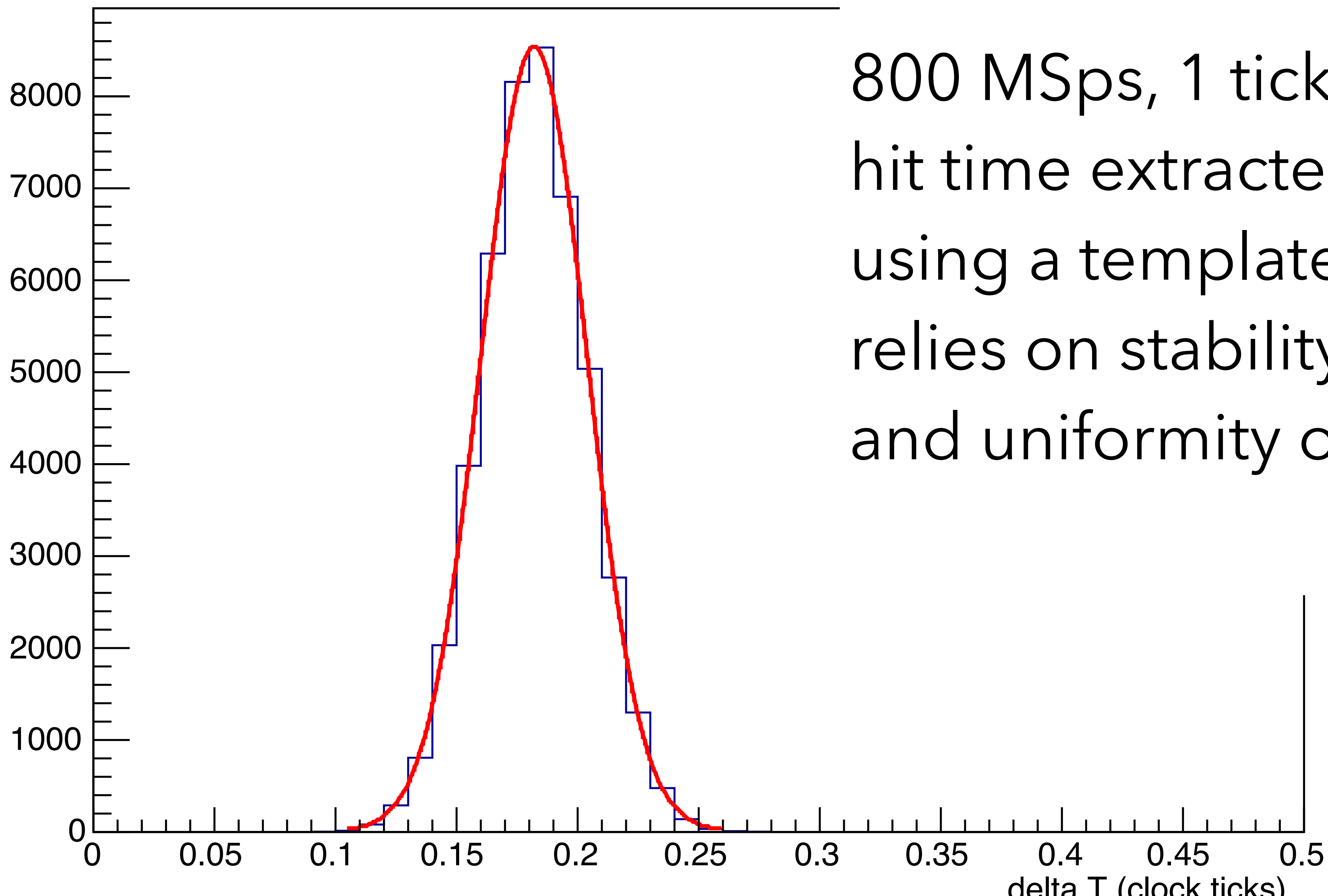
Poisson comb of hit energies, 3 GeV electron beam





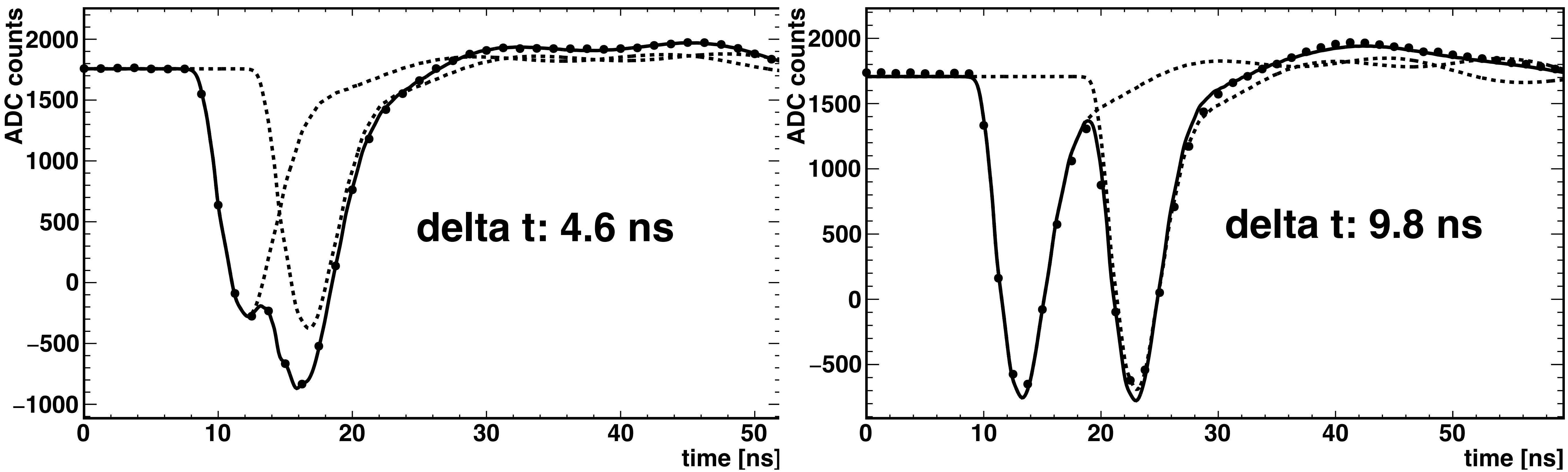
timing resolution 25ps at 3GeV

1. time differences within digitizer channels
2. time differences across channels



800 MSps, 1 tick is 1.25nsec
hit time extracted from leading edge
using a template fitter
relies on stability of pulse shape,
and uniformity of SiPM boards

pileup separation: double bunches 4.6 and 9.8 nsec separation

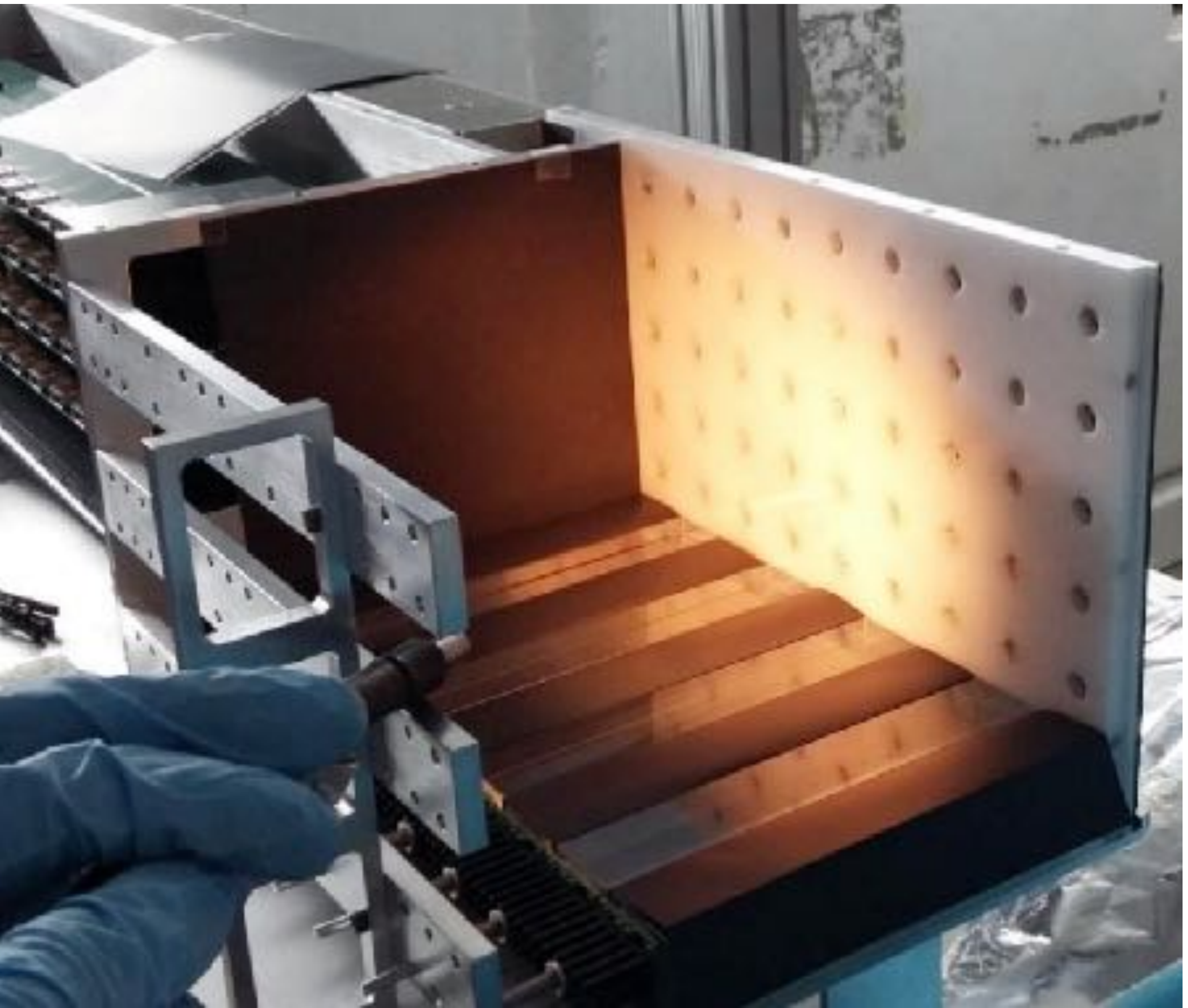


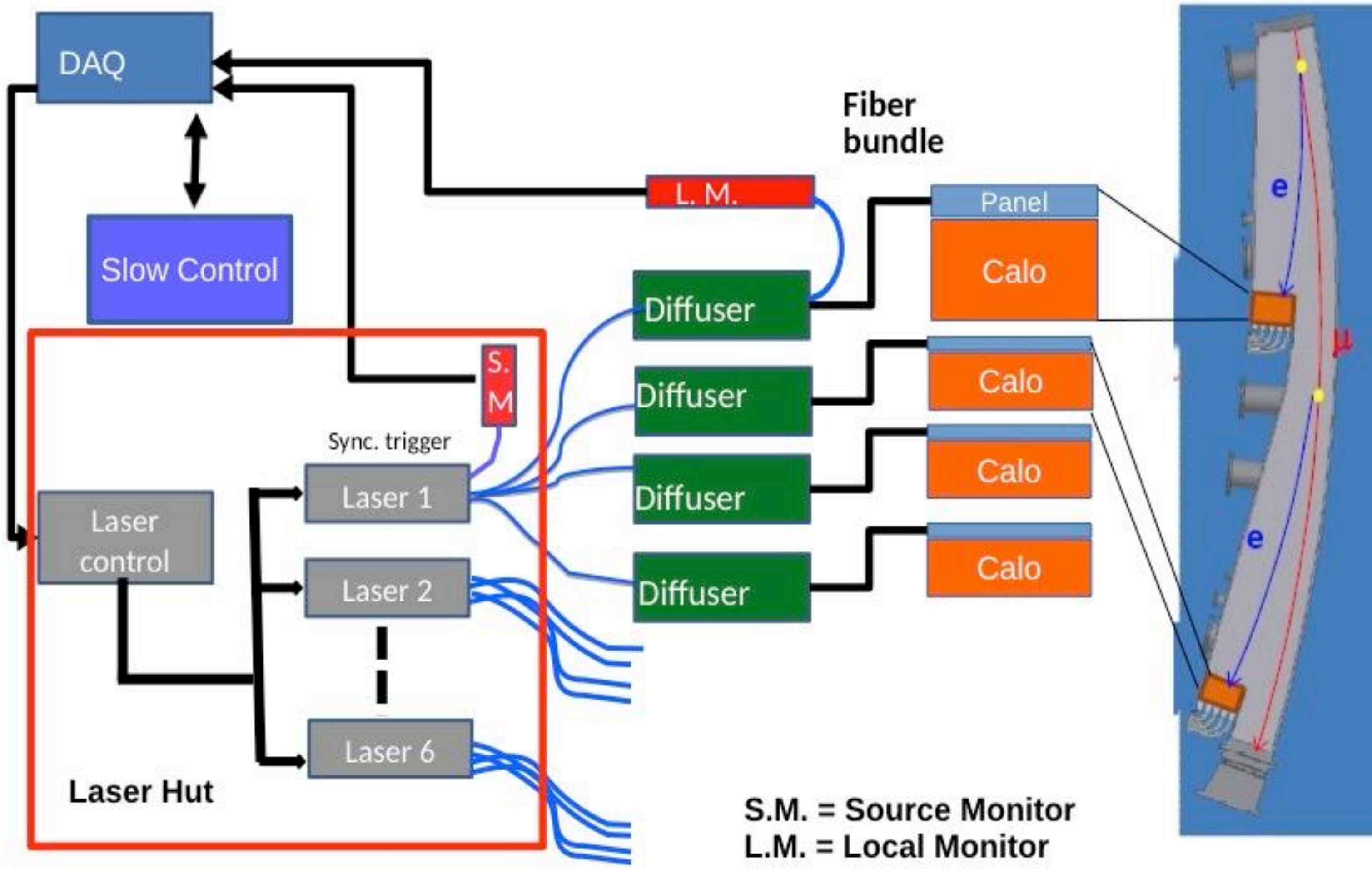
Pileup toolbox:

1. double-pulse fitter
2. spatial pattern of dep. energy
3. hit time pattern
4. pulse shape

laser calibration system

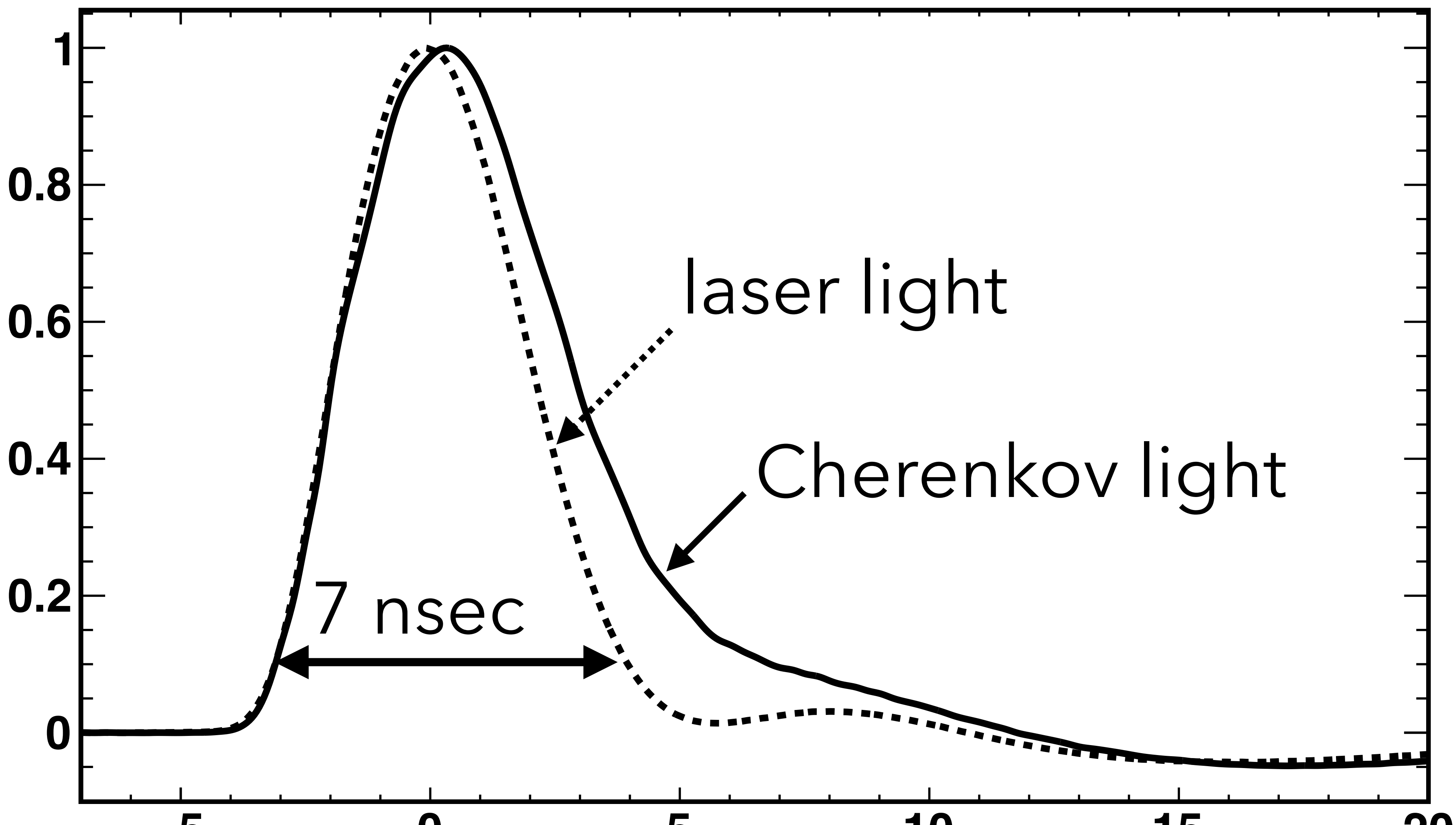
- gain stability of 0.04% in “offline” mode,
- 405 nm, *same pulse shape and delivery path as physics,*
- laser monitors with Am/NaI reference,
- and local calorimeter monitors





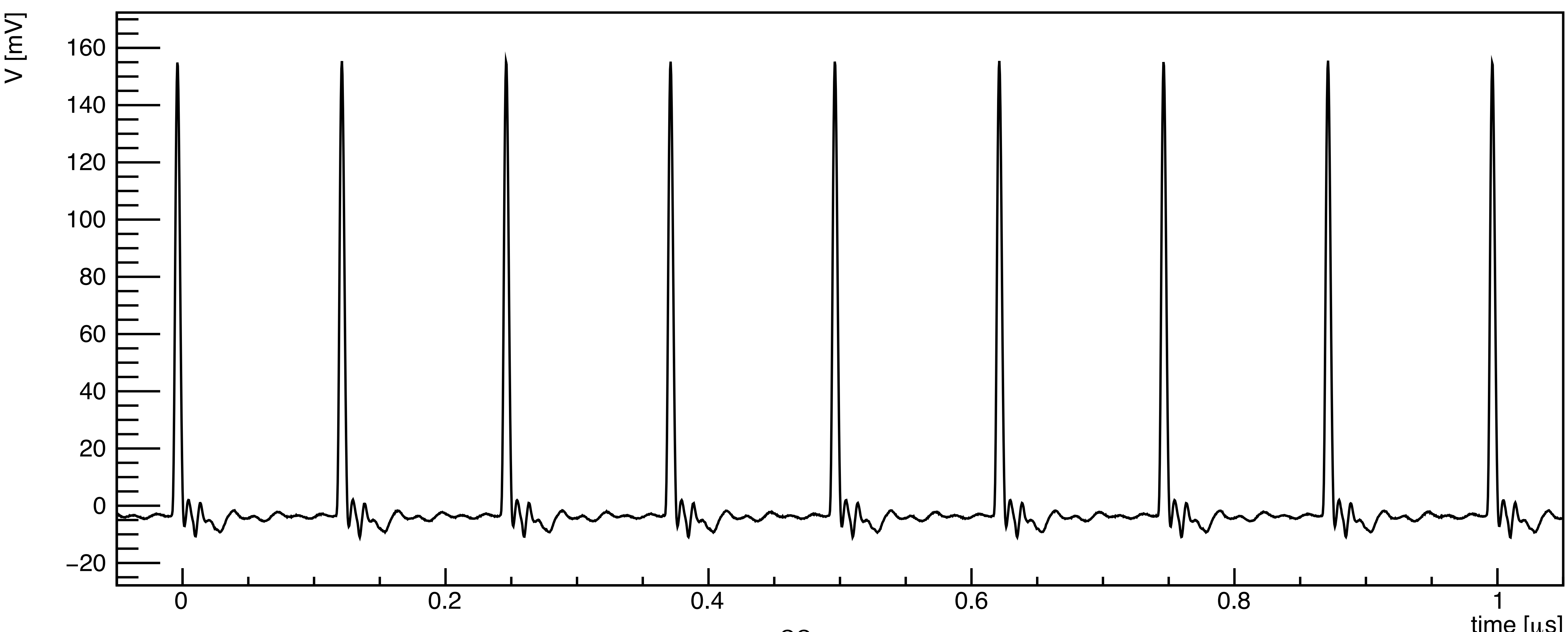
pulse shape comparison

crystals wrapped in black Tedlar,
to limit photon propagation to **total internal reflection only**



SiPMs are high rate tolerant

static load at 8 MHz,
desired qualities of bias voltage power supplies:
ability to maintain voltage, short transient response,
low resistance in series with load

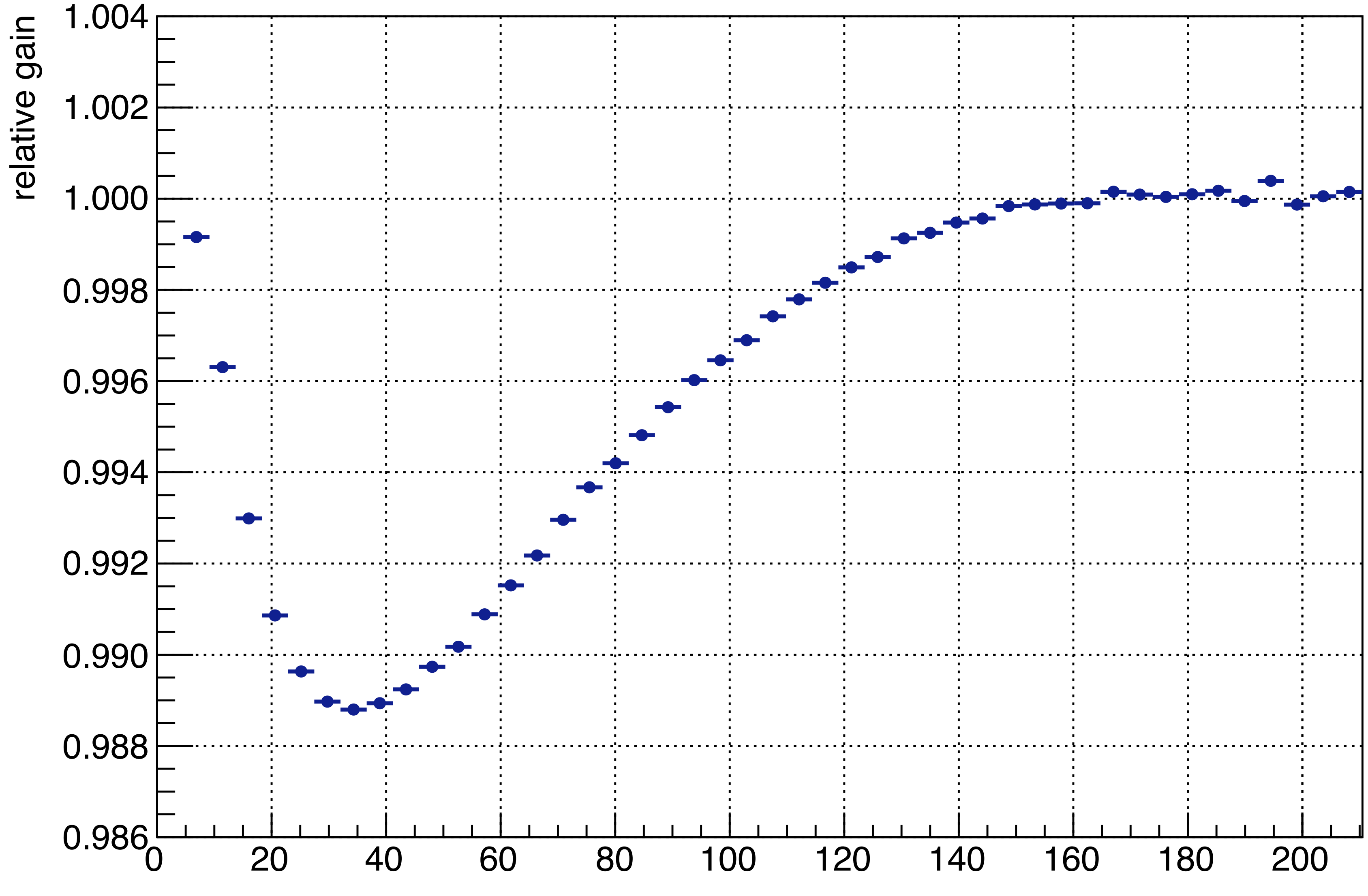


transient response on 10μsec scale

transient load: exp decay with 64μsec time constant, 1.5MHz (t=0)

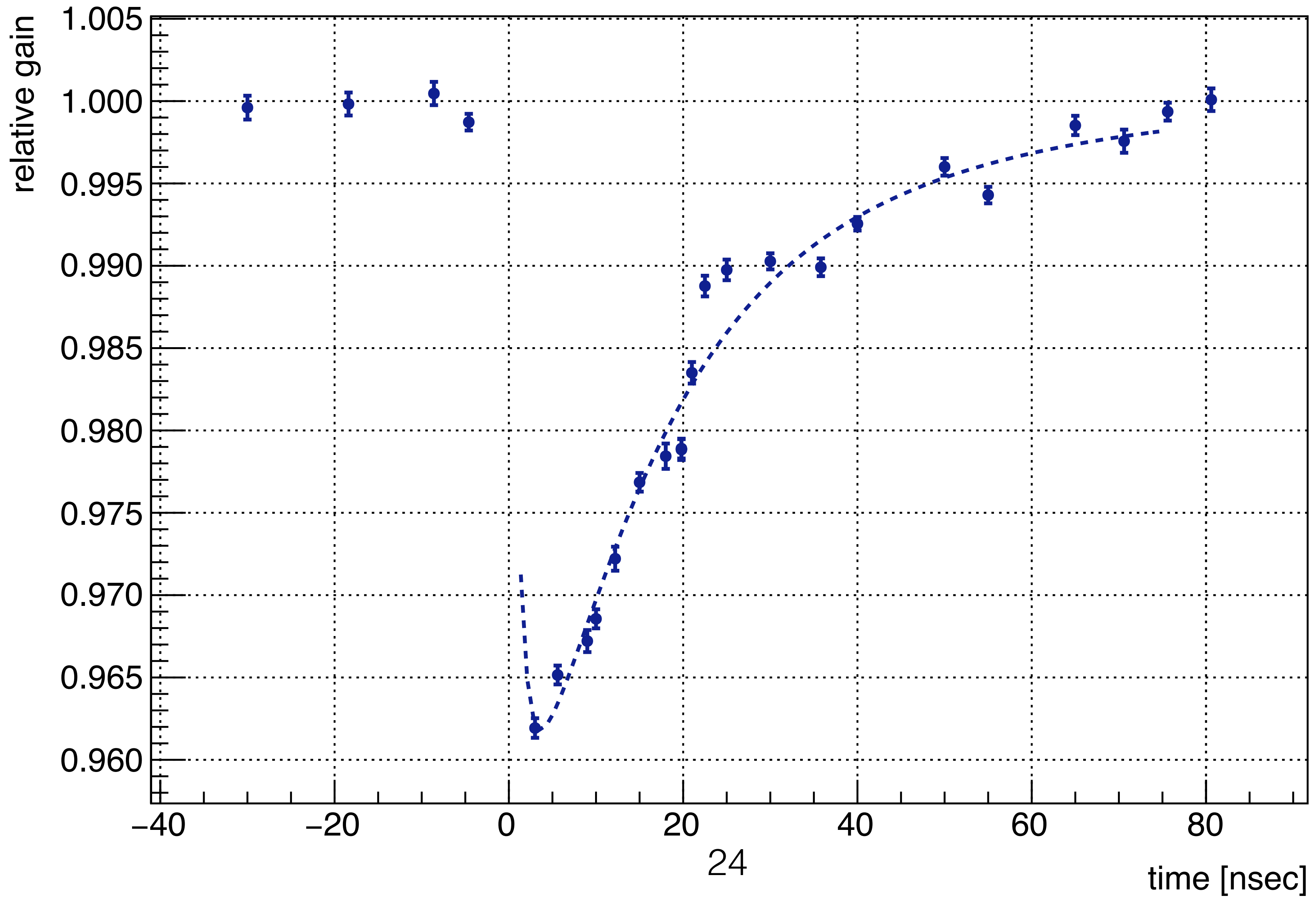
10 times more photons than Cerenkov light in a muon fill

BK1924A power supply, with 40μsec recovery time (mA load)



transient response on 10nsec scale

SiPM **preloaded with an LED** flash at t=0, **probed by a laser** pulse;
SiPM charge recovery from a local power supply on SiPM board.
Measurement matches SPICE simulation.



Muon g–2 calorimeter conclusions

Four fold improvement in determination of Muon g-2 requires new instrumentation.

Calorimeters are in production:
5ns FWHM pulses, 20ps timing, 3% at 3GeV energy resolution, pileup separation 4 nsec

Detector installation in ring begins in Fall 2016

First beam arrives in Spring 2017.

R&D opportunity for large-area low-photon readout

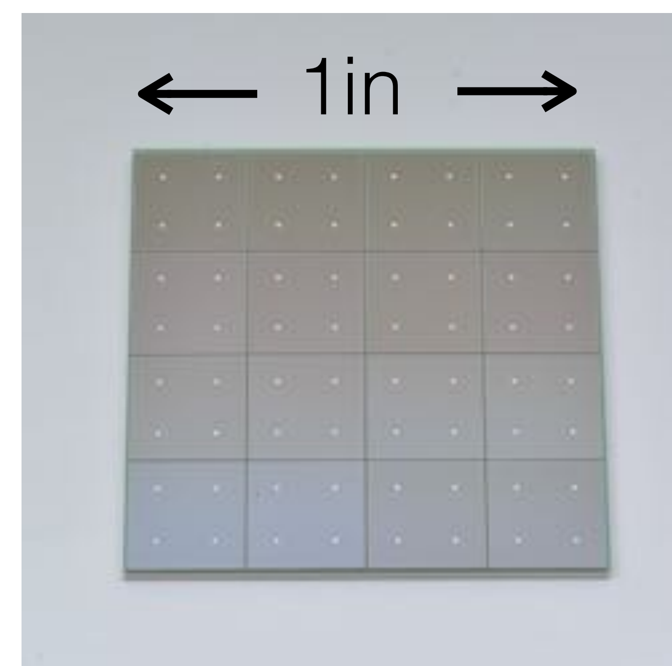
Large area SiPMs can do **both calorimetry and timing** at the same time.

- PMT-like pulse shape, high rate tolerant
- operate in strong magnetic fields
- low radioactivity, pressure and cryo friendly

Next step in evolution:

- larger area (~m^2, 100% geometry coverage)
- lower photon count (10's of photons)
- lower power
  (ASIC: gain stability and equalization, trigger logic)
- reach the dark-rate limit

NEXT, nEXO, MEG2, Mu2E, …



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