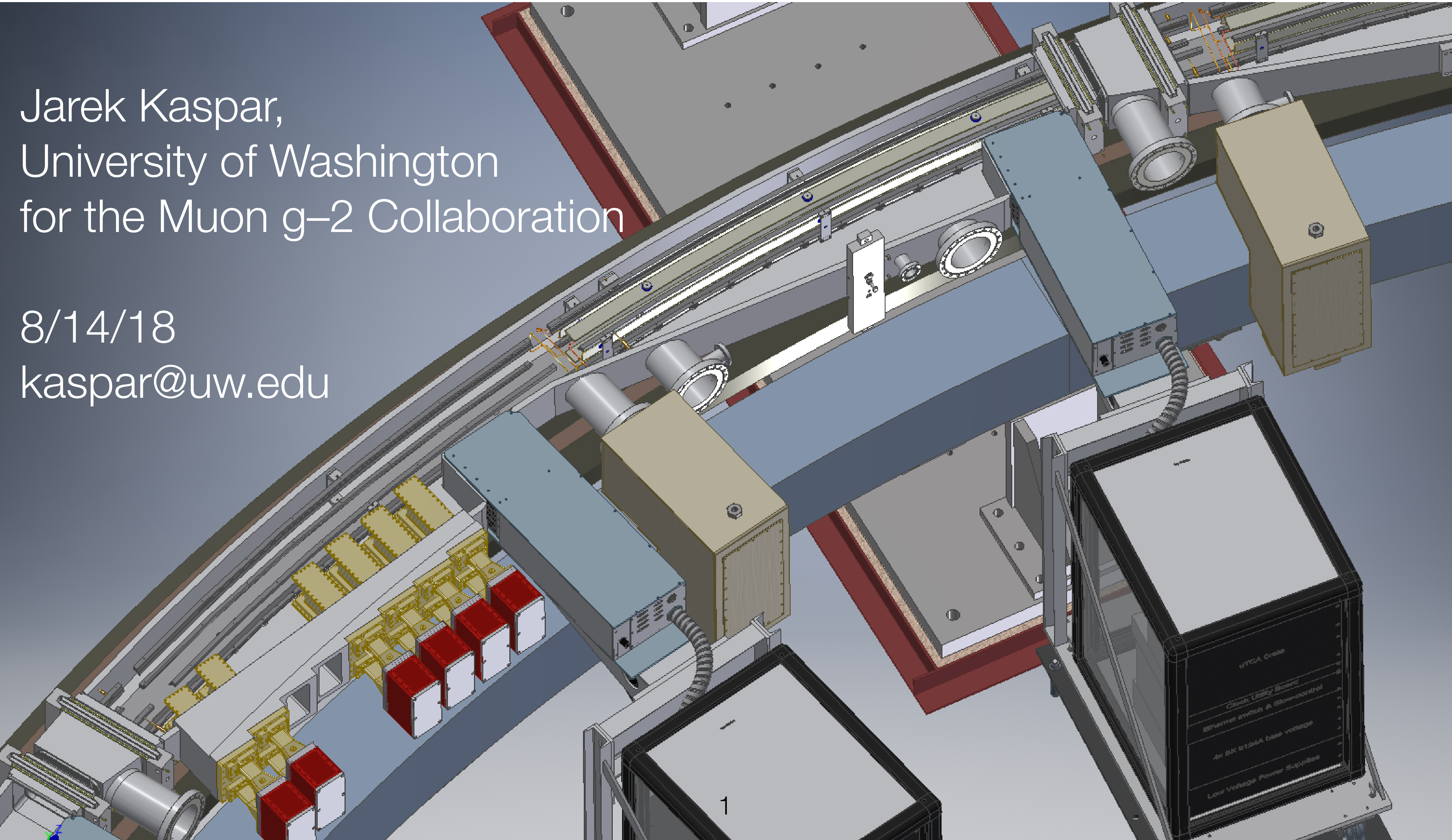
Muon g–2 experiment at Fermilab



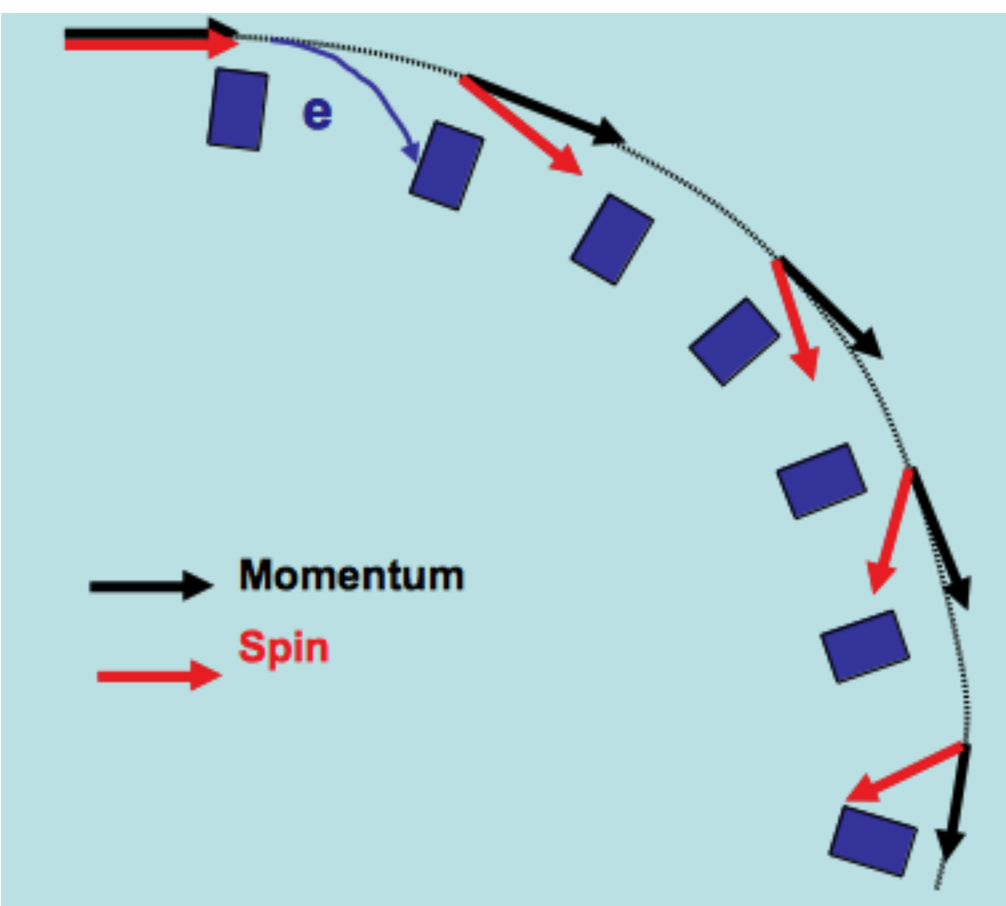
Jarek Kaspar,
University of Washington
for the Muon g–2 Collaboration

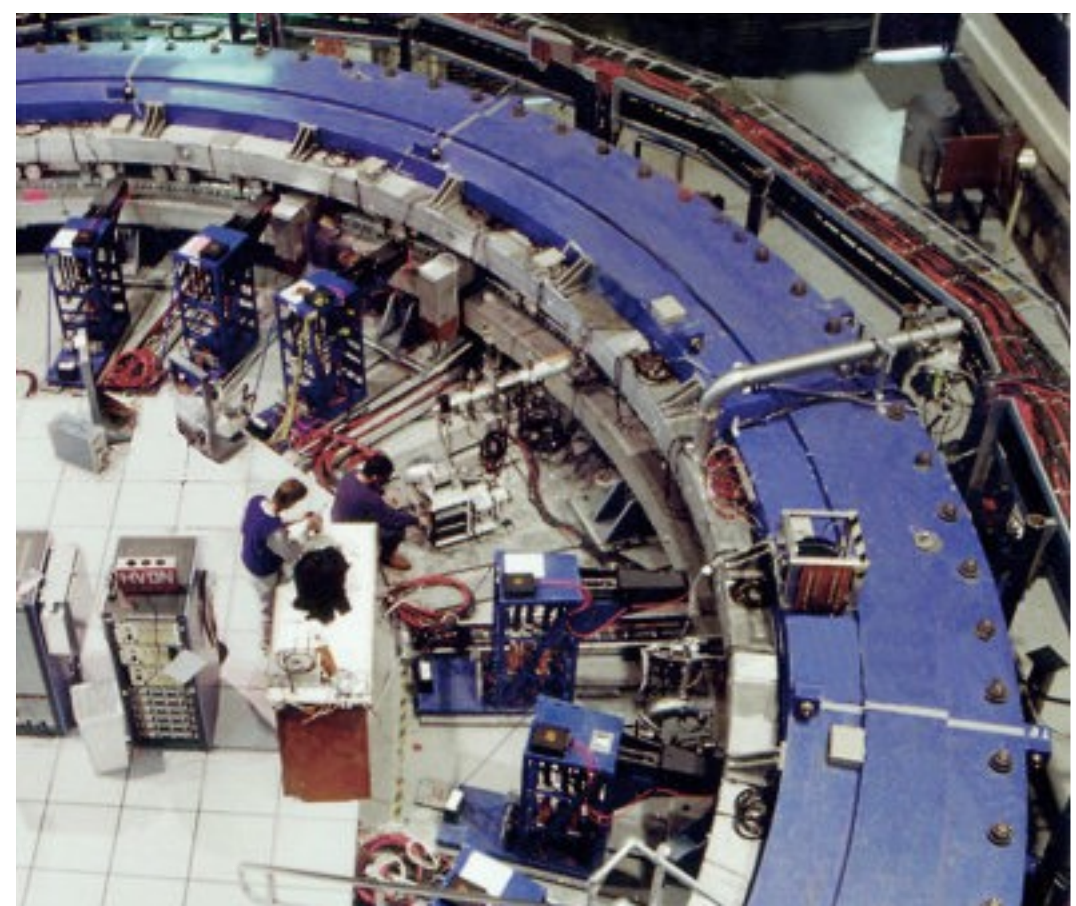
8/14/18

kaspar@uw.edu

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



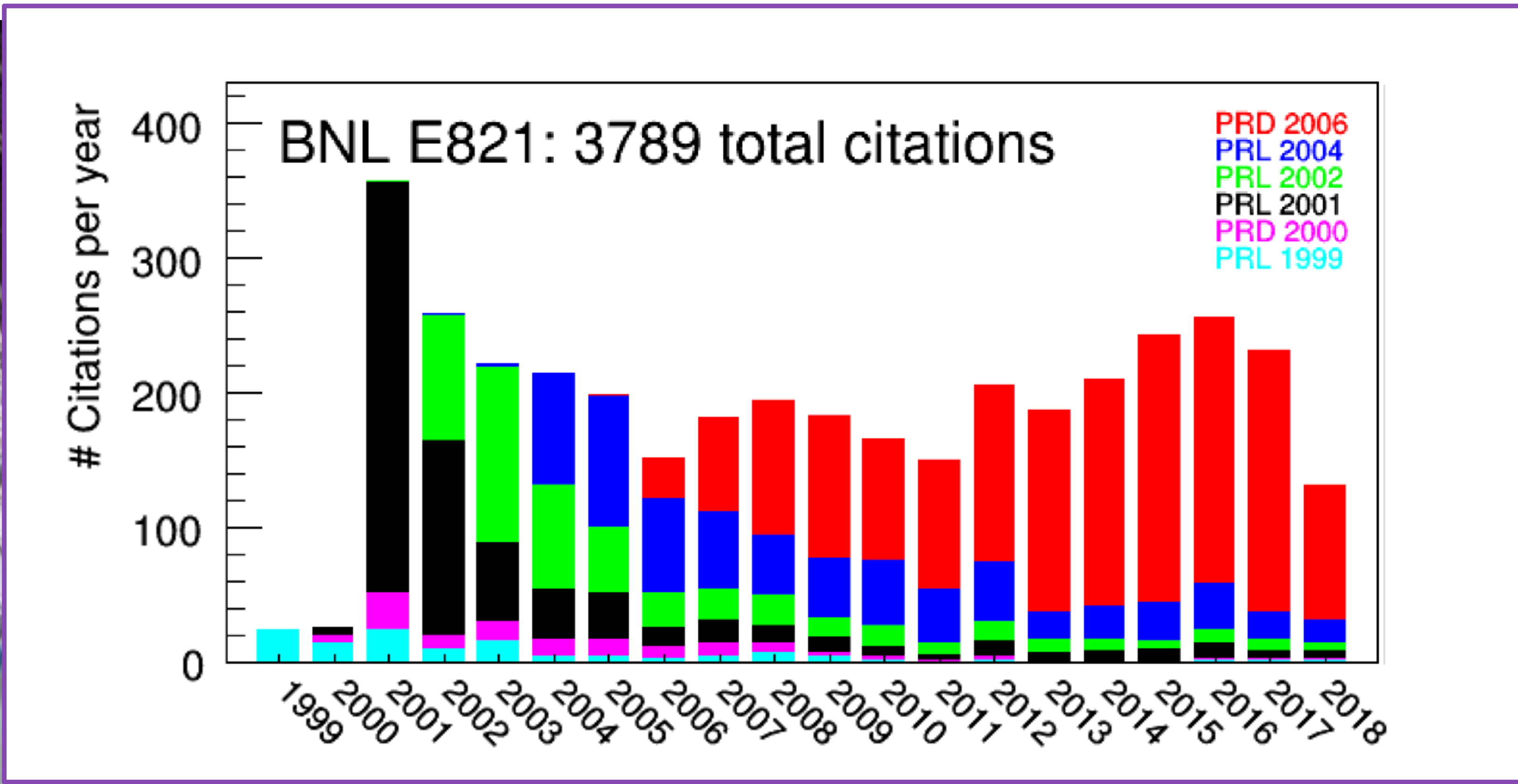


$g - 2$ experiment at BNL

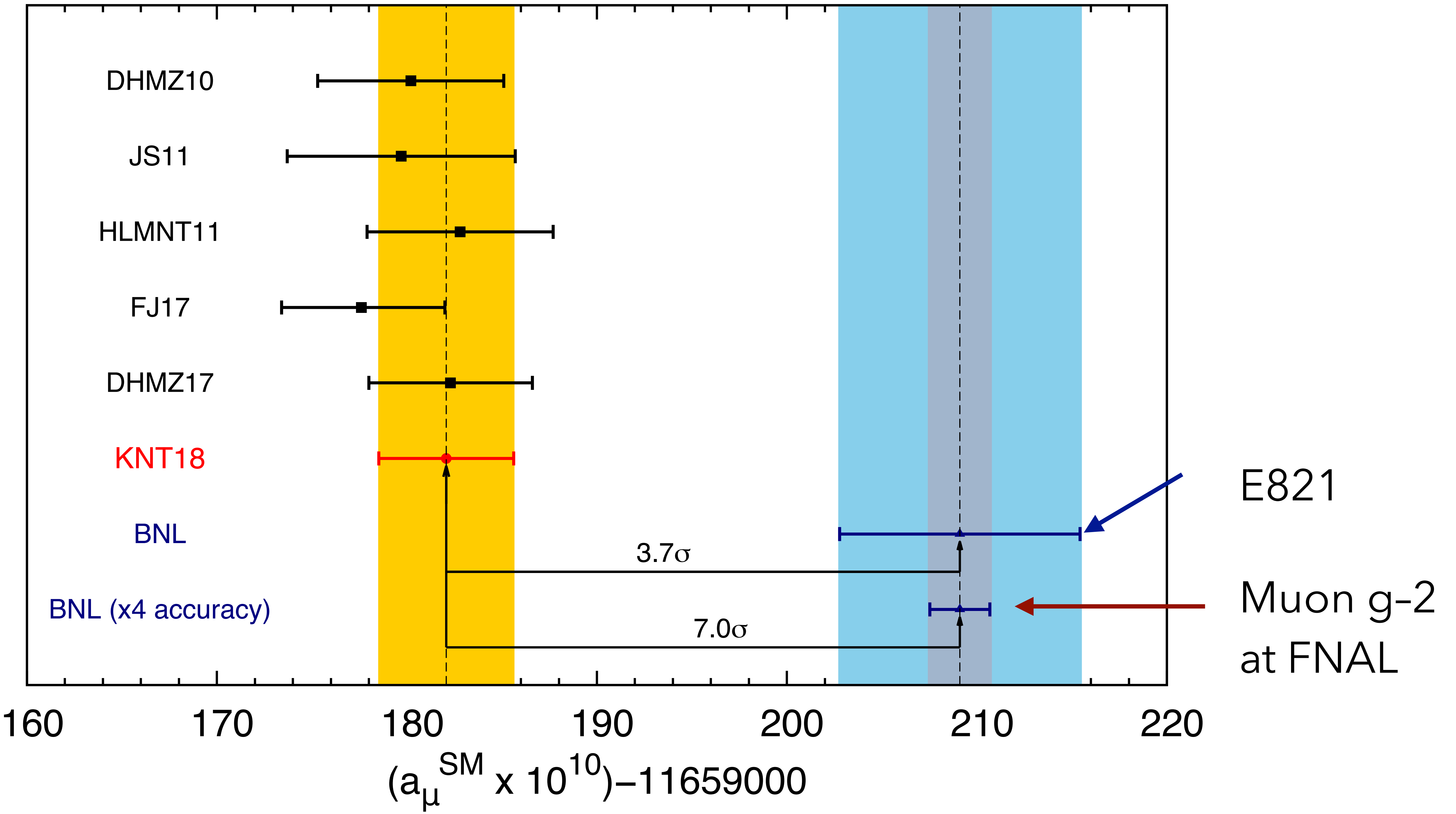
E821 (1999 - 2006):

$a_\mu = 0.001\ 165\ 920\ 89\ (63)$ (±0.54 ppm)

And a hint of New Physics ?



Standard Model prediction

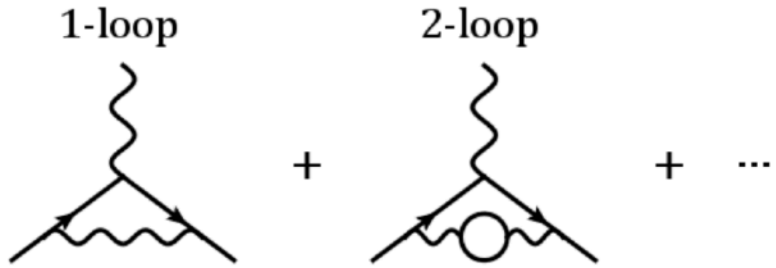


KNT18: Phys. Rev. D 97 (2018) 114025

SM uncertainty dominated by hadronic terms

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had, VP}} + a_\mu^{\text{had, LbL}} + a_\mu^{\text{BSM??}}$$

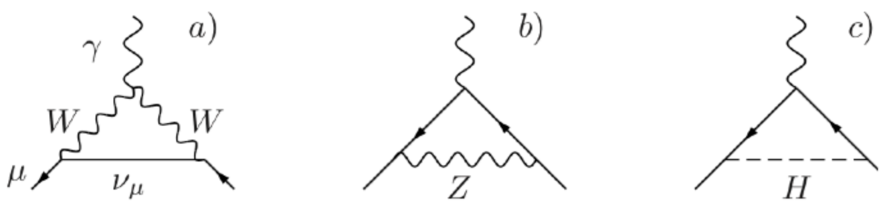
QED



Known to five-loop (12,672 diagrams)

99.99% of a_μ^{SM} ~0.001% of δa_μ^{SM}

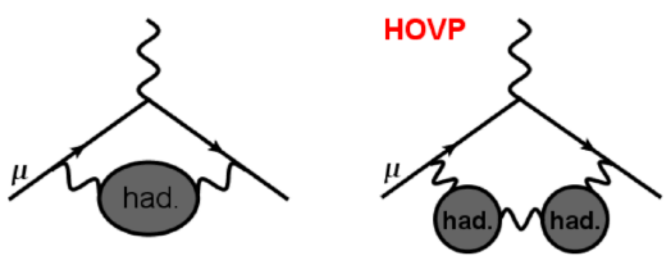
EW



Known to two-loop (with m_H known)

0.0001% of a_μ^{SM} ~0.2% of δa_μ^{SM}

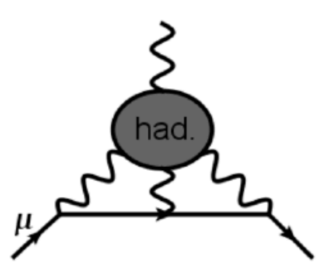
HVP



Non-perturbative (data input + lattice)

0.006% of a_μ^{SM} ~47% of δa_μ^{SM}

HLbL



Non-perturbative (data input + model/lattice)

0.0001% of a_μ^{SM} ~53% of δa_μ^{SM}

BSM

? ? ? ? ? ? ?

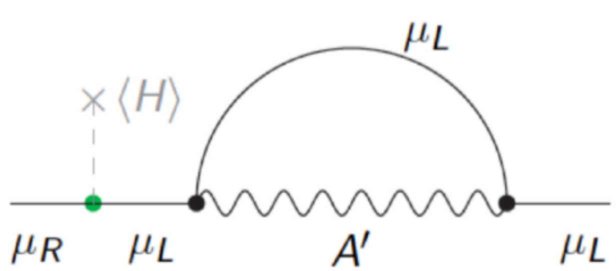
A. Keshavarzi

Many BSM candidates, no leader.

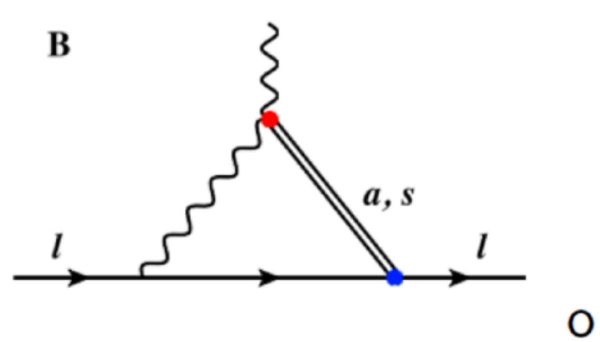
In general, possible theories to explain $g-2$ can be split into two scenarios:

Light new physics

- Dark photons $\rightarrow$ very specific model, only two parameters



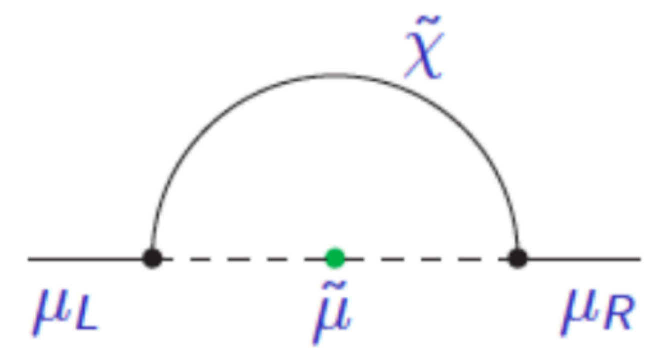
- Dark Z $\rightarrow$ tuned to resolve $g-2$
- Axion-like particles $\rightarrow$ must have very particular mass/coupling combinations



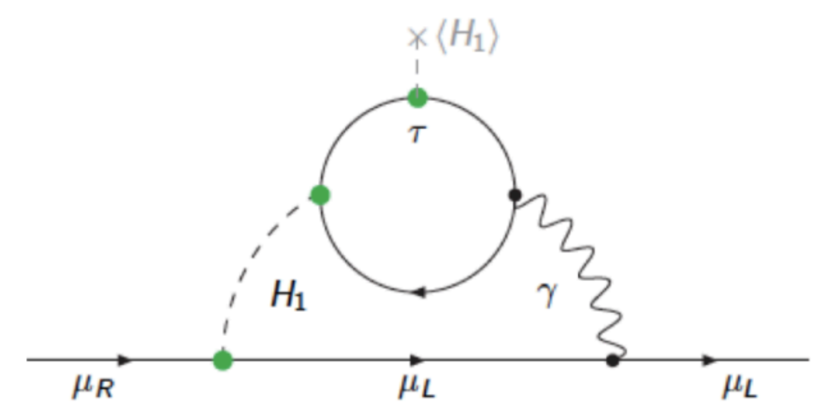
[Marciano, Masiero, Paradisi, Passera '16]

Heavy new physics

- SUSY $\rightarrow$ many scenarios which explain $g-2$ and which are not excluded

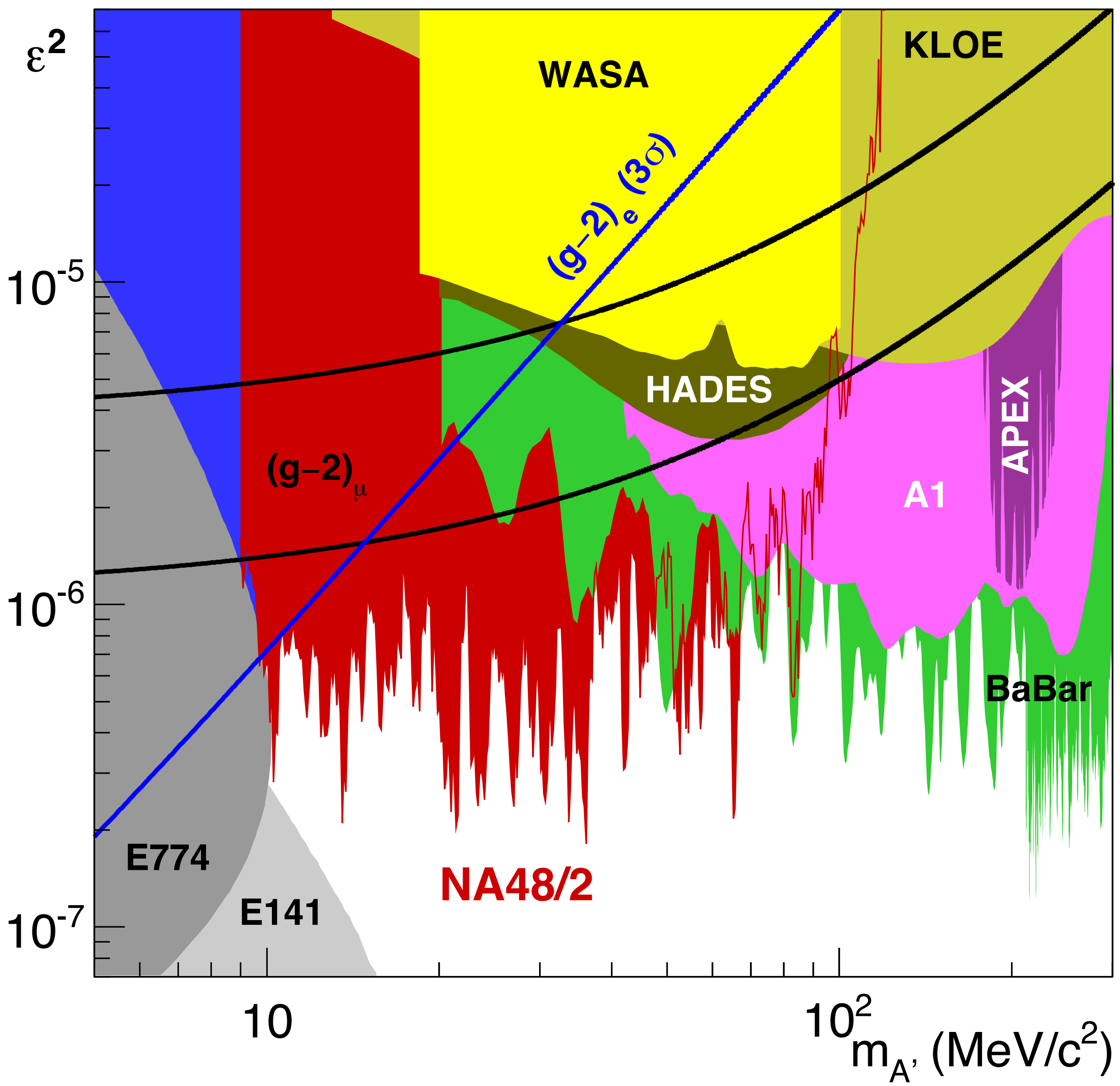


- Two-Higgs doublet models $\rightarrow$ can explain g-2 in very small, specific parameter region



D. Stoeckinger, via A. Keshavarzi

An example of difficulties any BSM candidate face



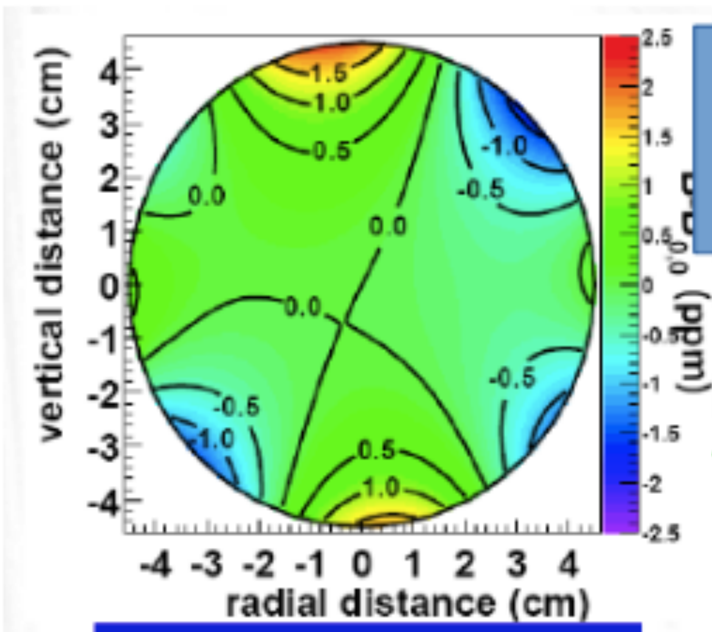
Dark photon (Z') limited by π0 decay, NA48/2, (2015).

In 2018, Berkeley improved α measurement from Cs-133, and put tension on electron g-2.

Muon g-2 and electron g-2 prefer opposite direction with respect to SM, the one prefers a vector, the other a pseudo-vector.

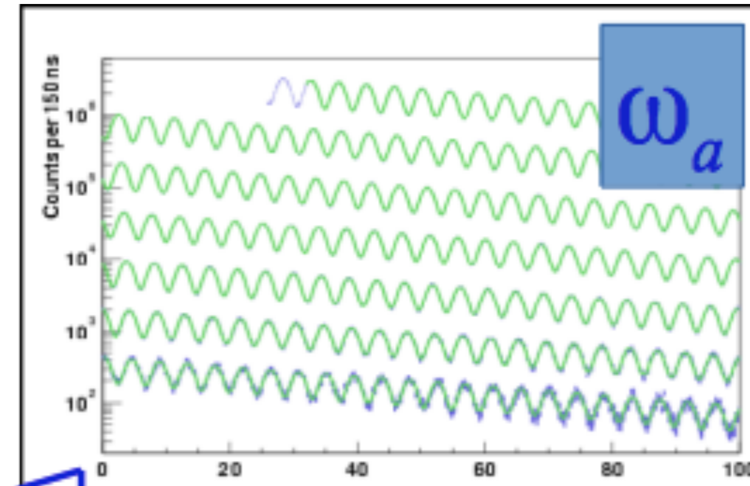
NA48/2: arXiv:1504.00607v2
Parker et al., Science 360, 191–195 (2018)

Principles Muon g-2 measurement



ω_p

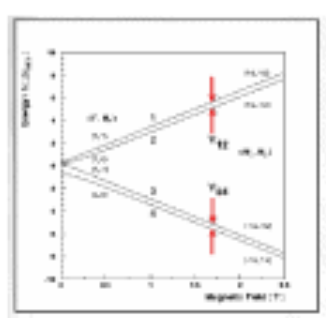
Our "Magnet"



ω_a

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.

and an alternative expression

In E821 **≡** $\mathcal{R}_\mu(\mathrm{E821}) = 0.003\,707\,206\,4(2\,0)$ **[540 ppb]**

$$a_\mu = \frac{g_\mathrm{e}}{2}\frac{\omega_\mathrm{a}}{\tilde{\omega}_\mathrm{p}}\frac{m_\mu}{m_\mathrm{e}}\frac{\mu_\mathrm{p}}{\mu_\mathrm{e}}$$

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

$\mathcal{R}_\mu$

Muonium Hyperfine Splitting
--[658.210 6866 (20)] $^{-1}$ [3 ppb]

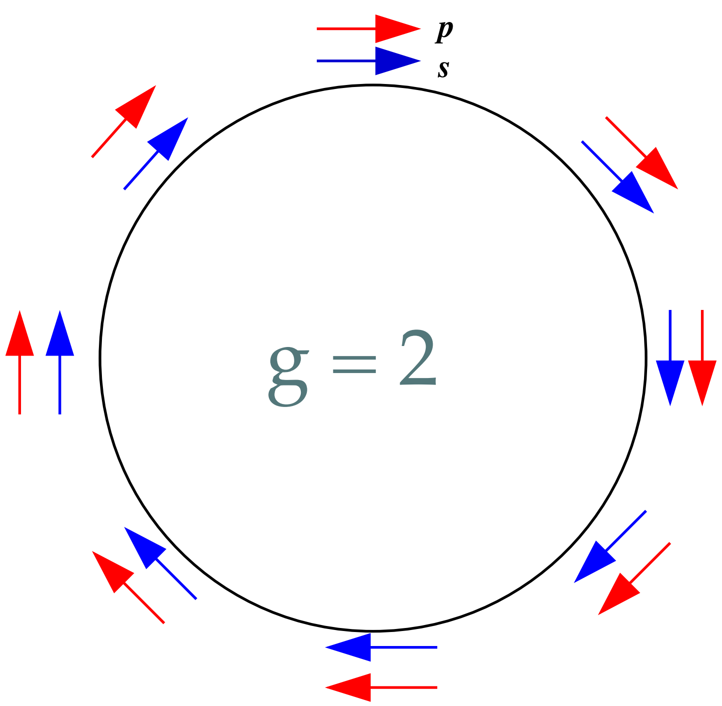
206.768 2826(46) **[22 ppb]**
Muonium 1S-2S

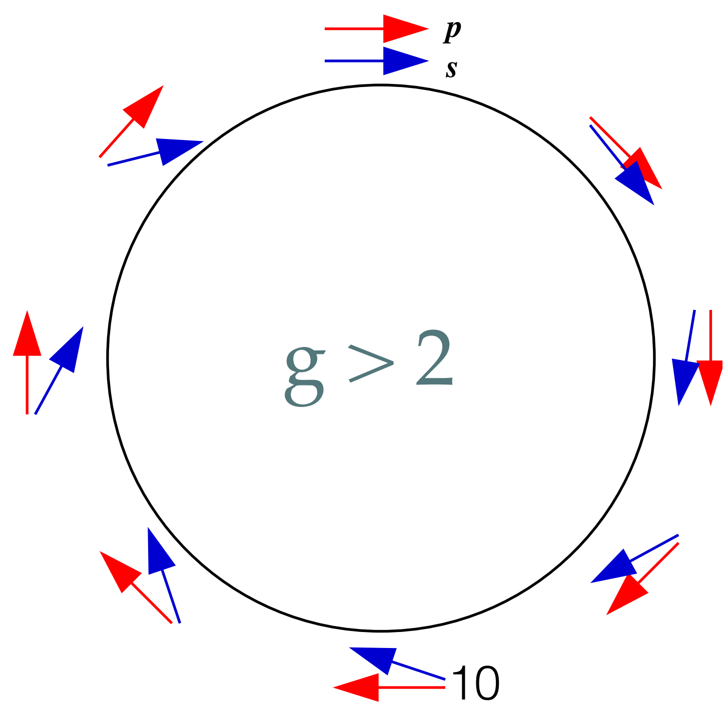
ω_a : Precession frequency

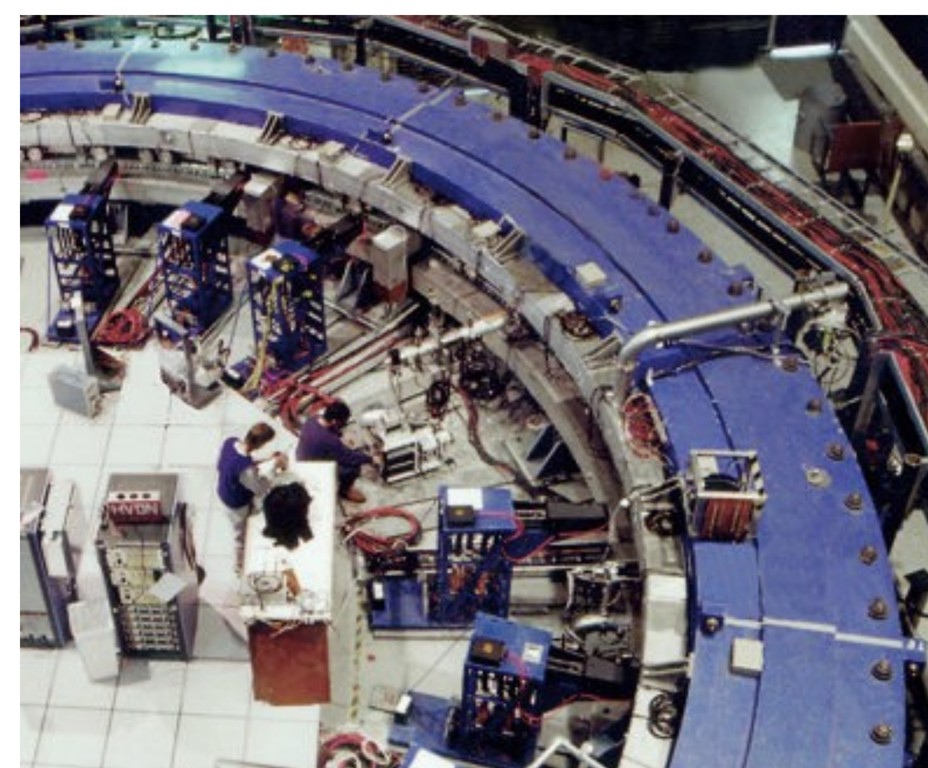
$\tilde{\omega}_p$: Magnetic field (averaged, convoluted with muon distribution)

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



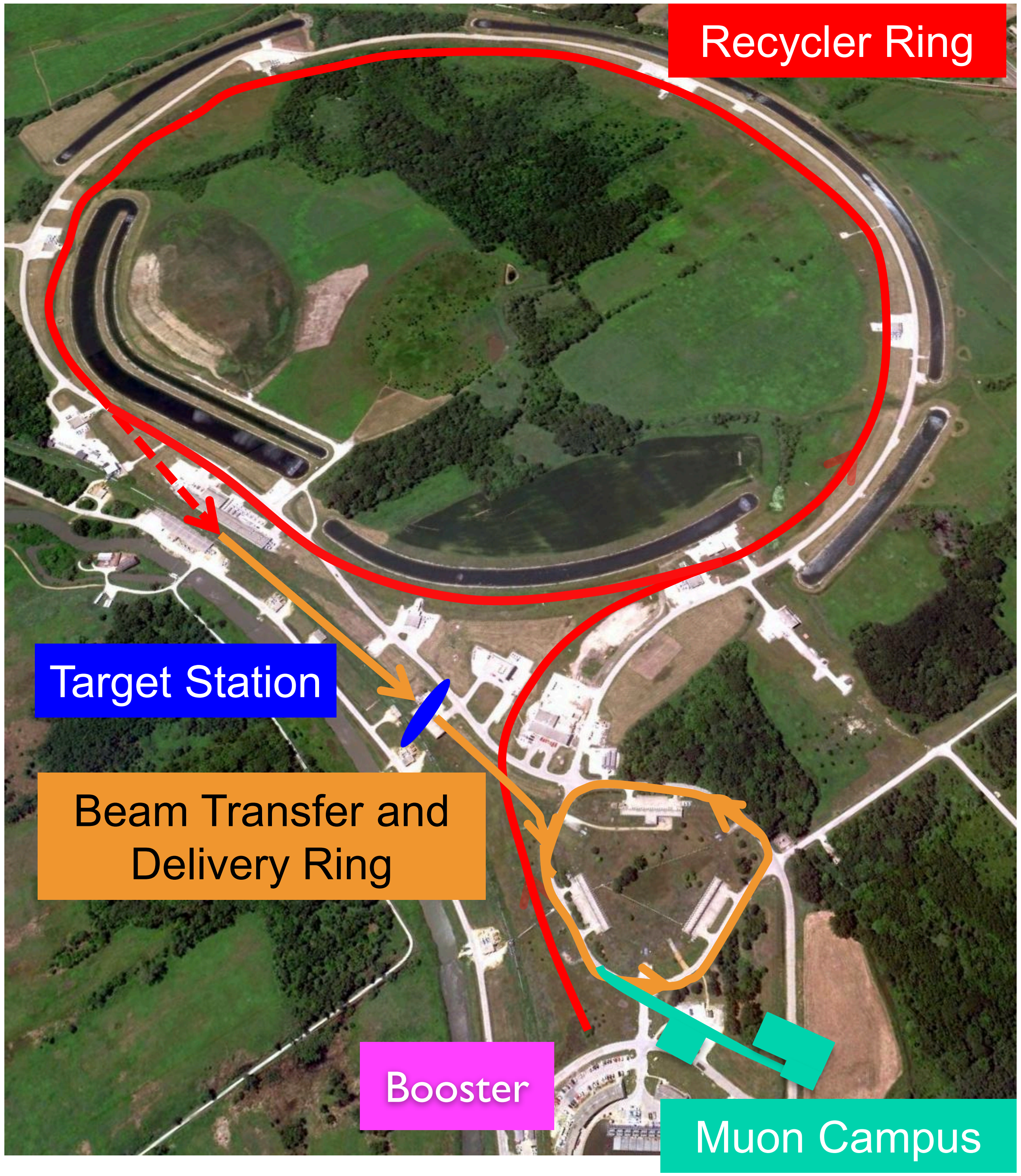




1. source of polarized muons

- pion decay into muon
- it’s parity violating decay
- spin prefers opposite direction to momentum
  (for positive pion)
- pions come from protons hitting Li target

1. source of polarized muons



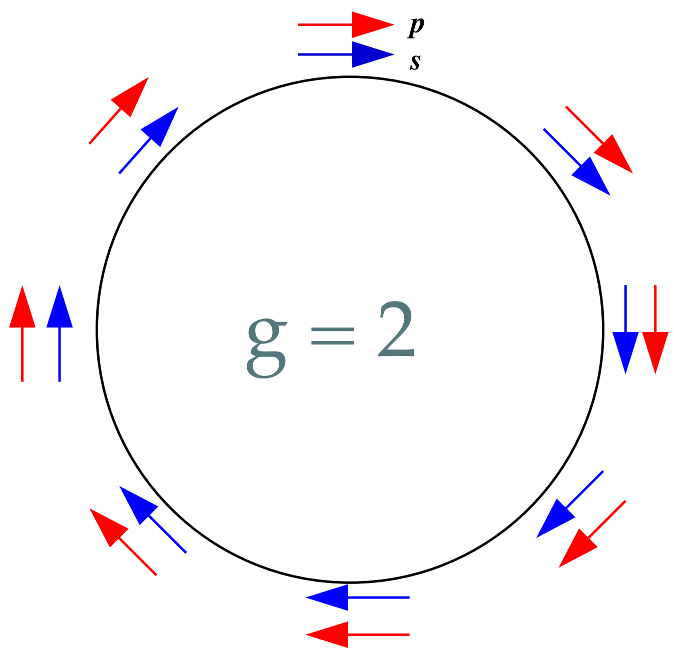
- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - Target to M2 to M3 to Delivery Ring
  - Proton removal
  - Extraction line (M4) to g-2 stub to ring in MC1 building

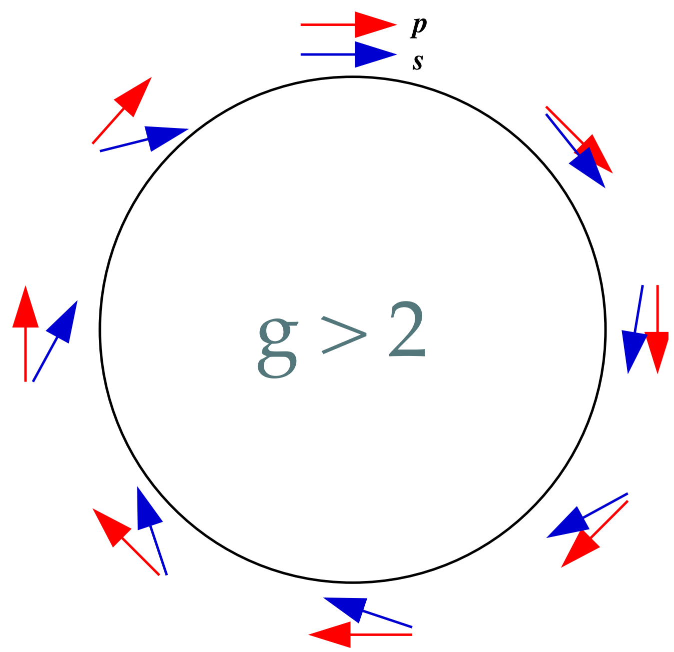
Talks by Diktys Stratakis, and Nathan Froemming

2. precession proportional to $g - 2$

$$\omega_C = \frac{eB}{mc\gamma} \qquad \omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$





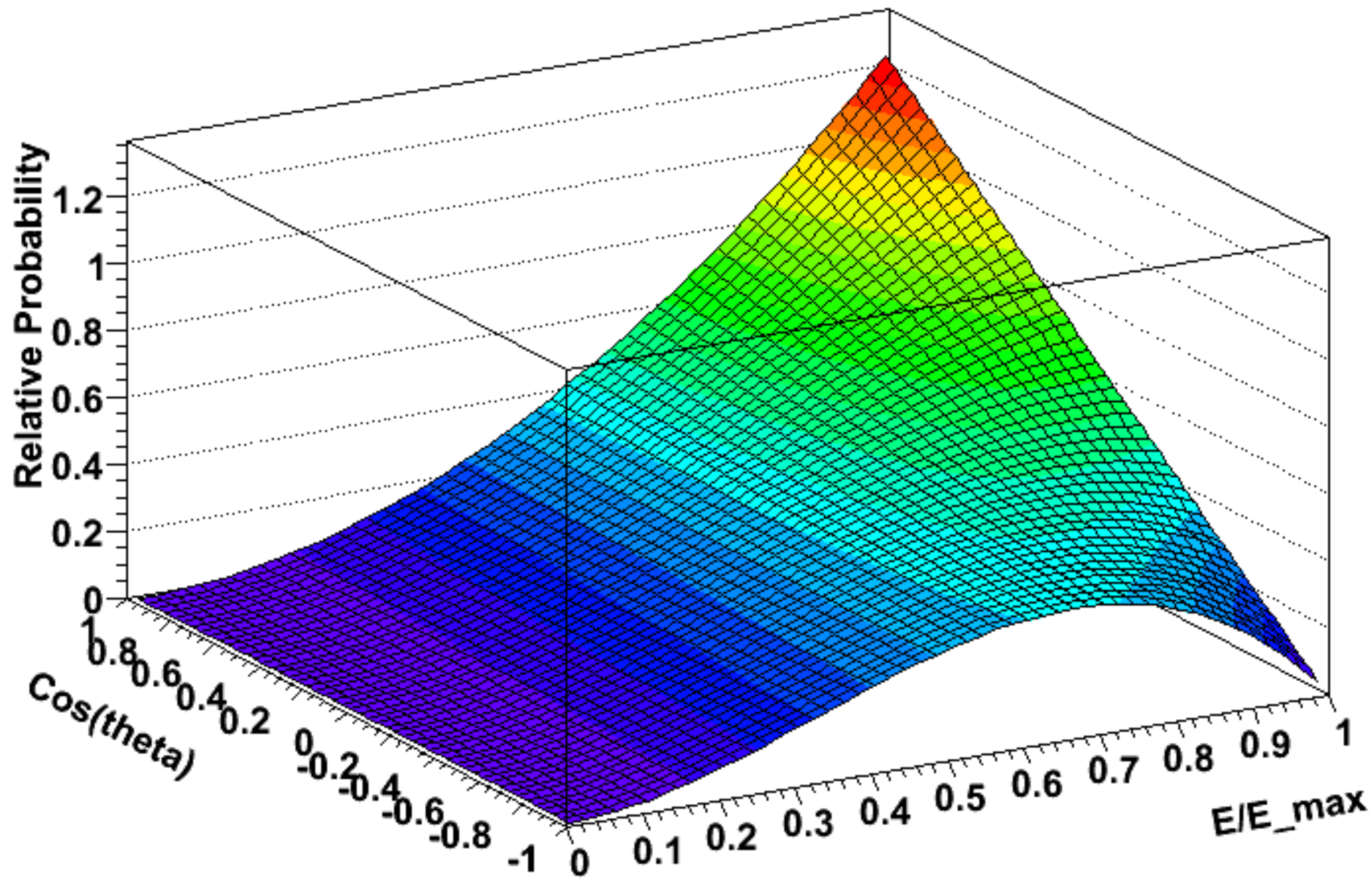
3. magic momentum

- electric quadrupole used for vertical focusing

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

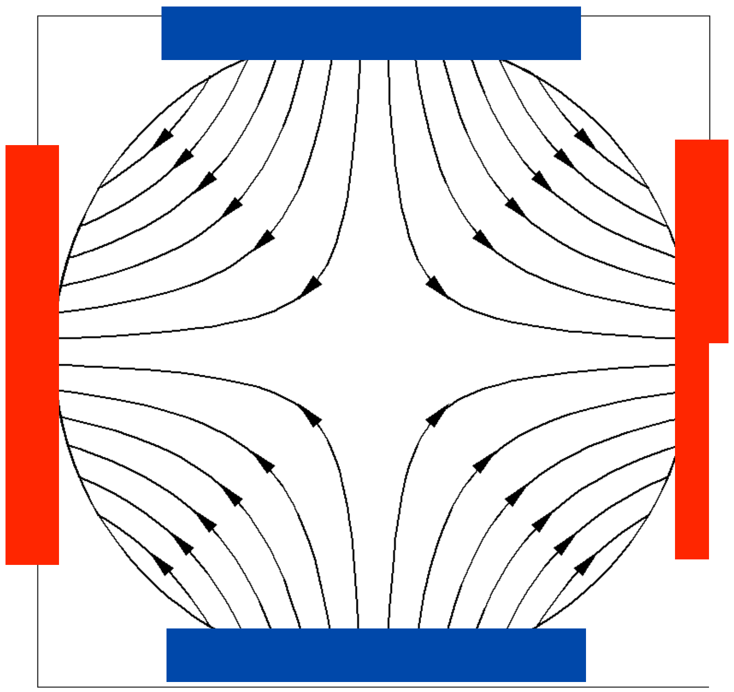
- select $\gamma = 29.3$, muon momentum 3.094 GeV
- design difference between FNAL and J-PARC

4. parity violating decay

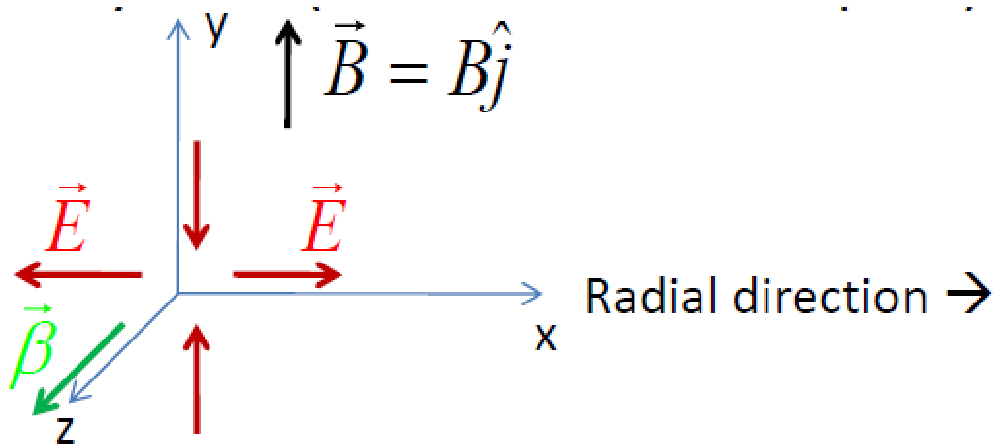


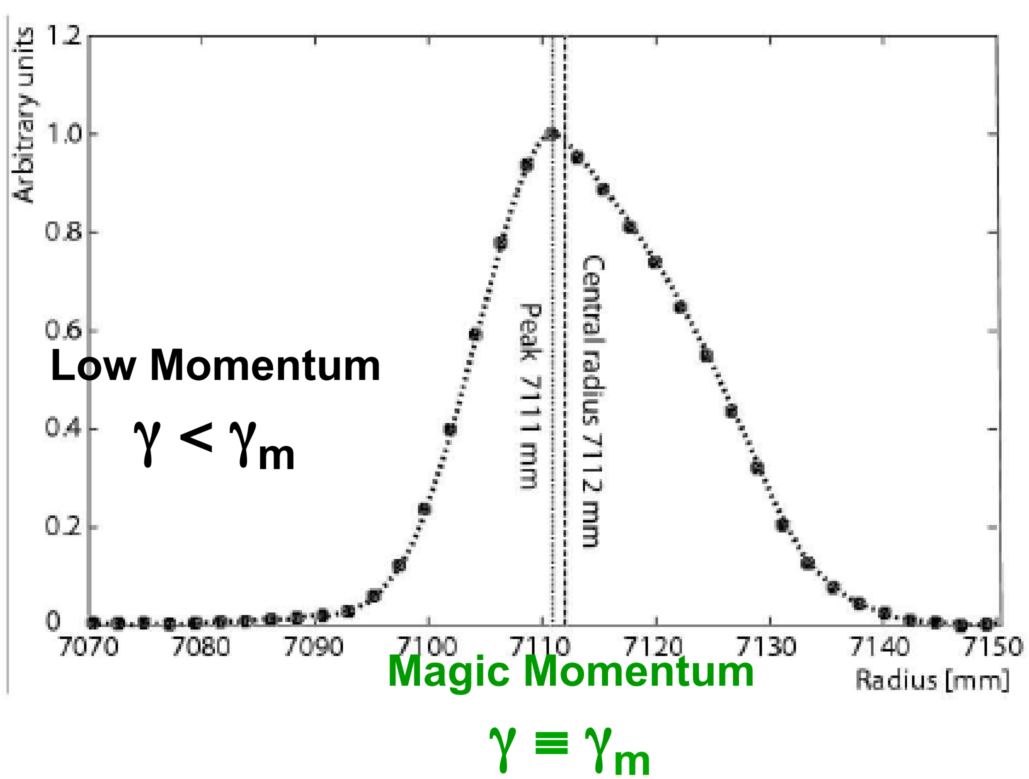
- muon -> electron and two neutrinos
- electron carries information on muon’s spin
- positron prefers spin direction
- electron would prefer opposite direction

systematics associated with focusing E-field



$$\vec{\omega} = -\frac{q}{m}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}\bullet\vec{B})\vec{\beta} + (-a_\mu + \frac{1}{\gamma^2-1})\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

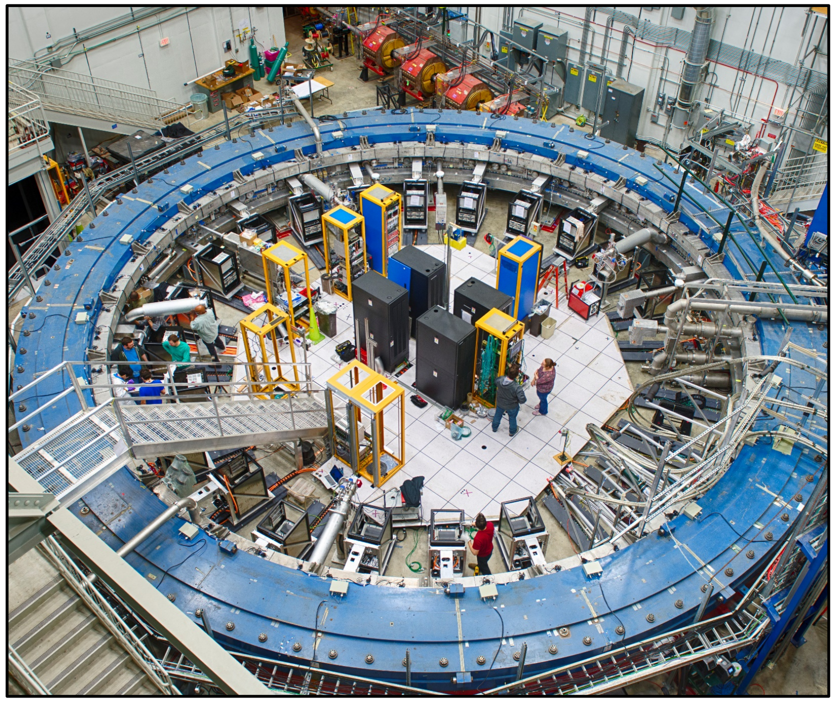


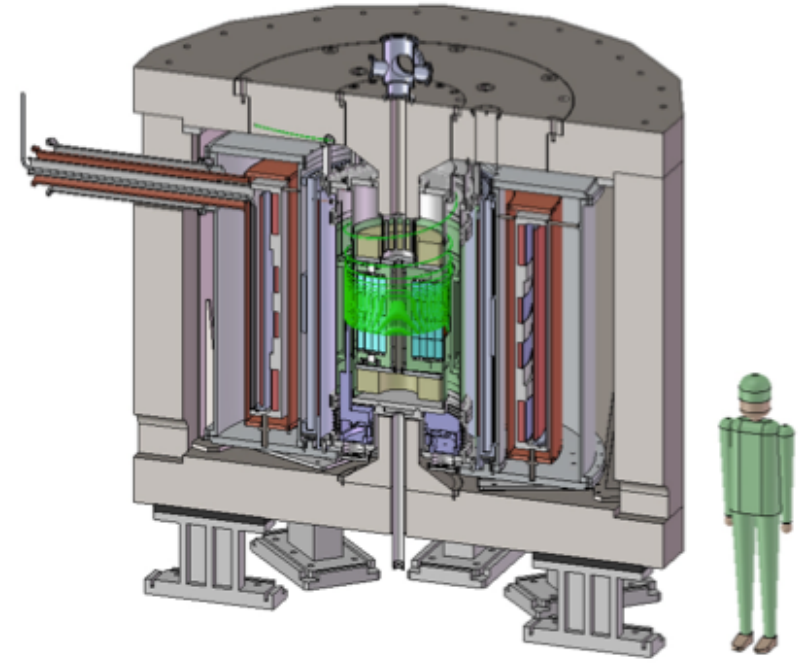


β x *E* and "γ" terms signs both flip depending on momentum

→ No cancellation
→ All off-momentum muons reduce effective a_μ

~0.5 ppm effect, net





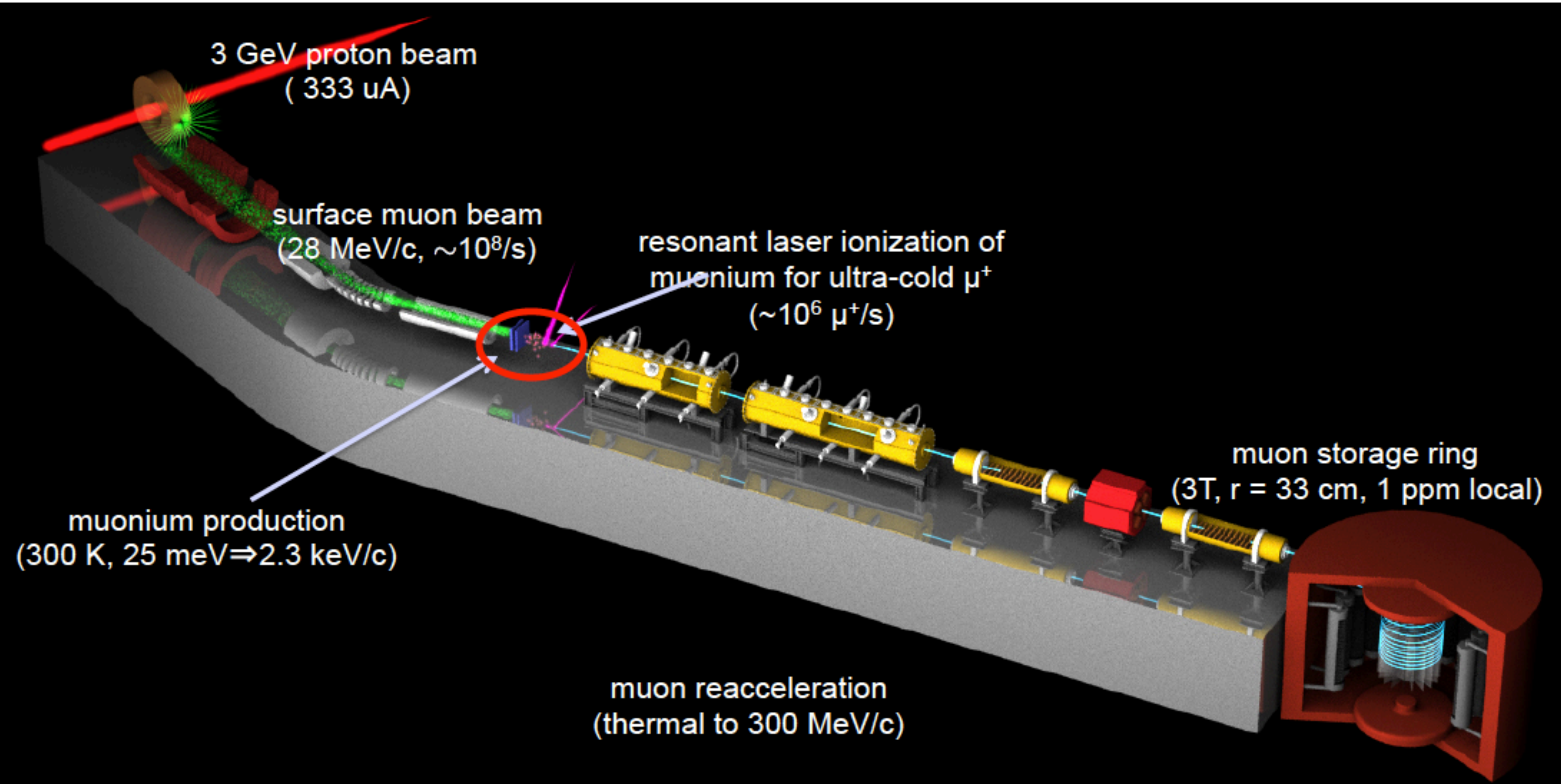
FNAL

- 7 m radius storage ring
- B = 1.45 T
- weak electric focusing
- high-rate 3 GeV/c beam
- spin polarization 97 %
- data taking 2018 - 2020
- 100 ppb by end of 2021

J-PARC

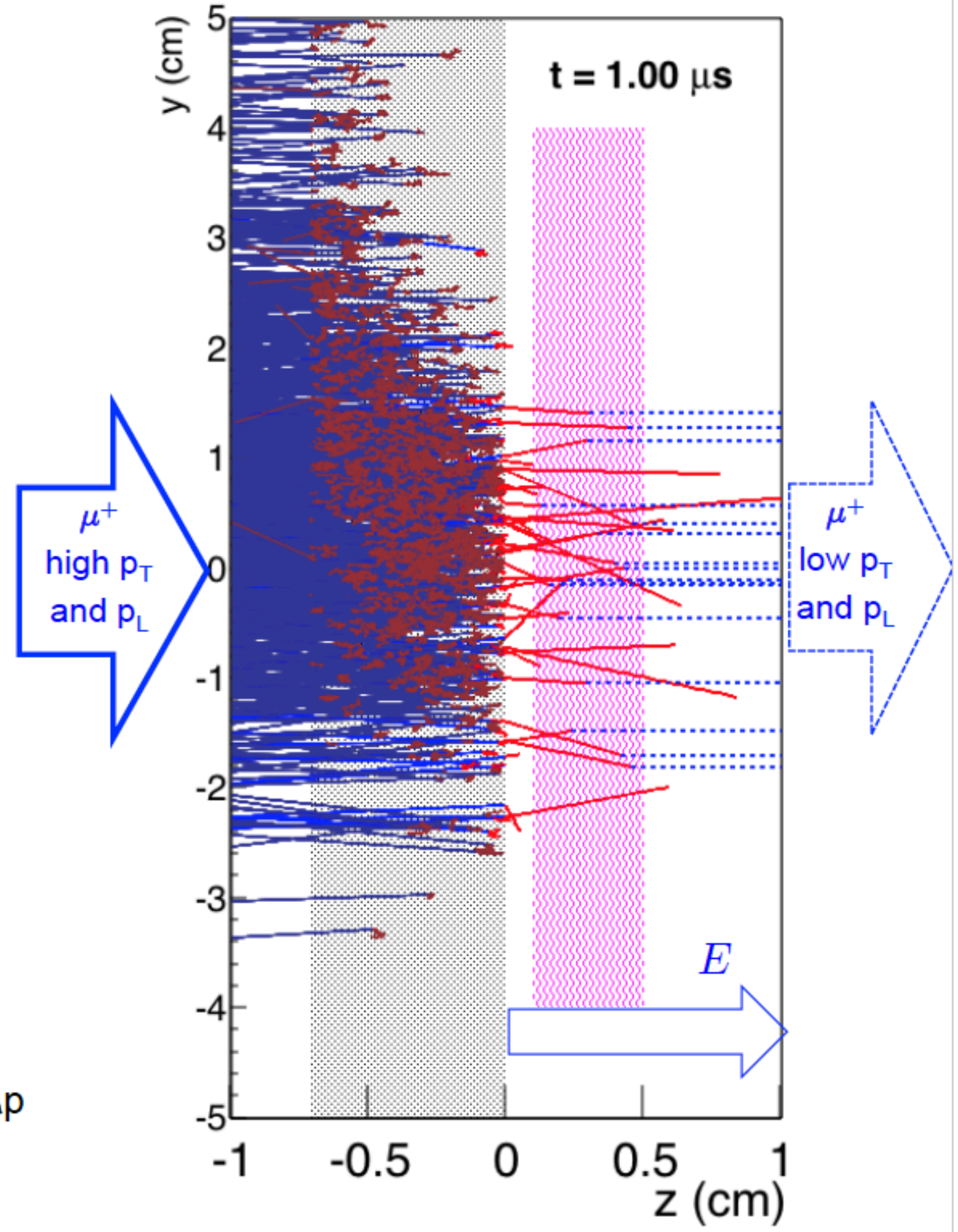
- 0.33 radius storage bottle
- B = 3 T
- no E -field, week mag. focusing
- 0.3 GeV/c beam
- spin polarization 50 %
- data taking 2020 - 2023
- 400 ppb by end of 2023

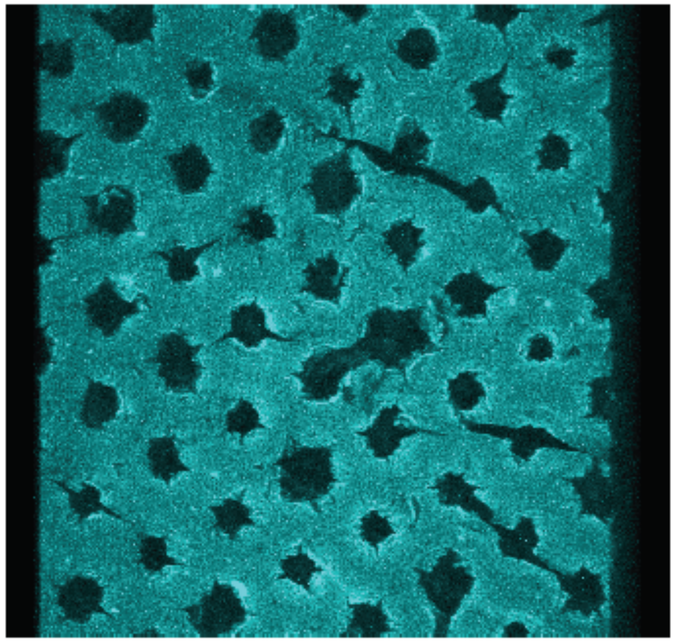
Schematics of J-PARC g-2 experiment

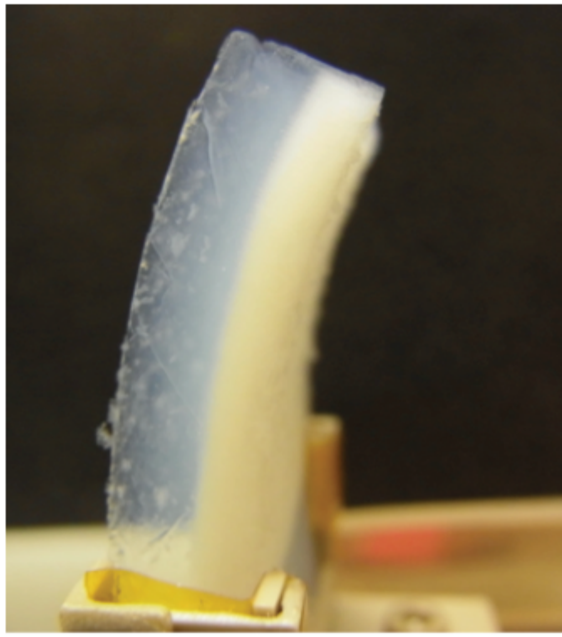


Aerogel target and muon production

- Surface muons
- Stop in target, form muonium
- Thermalize → ultra-cold source
- Diffusion into vacuum region
- Ionized
- Accelerated to 300 MeV/c
- Very low spread in p_T → contain muons without E-field → can choose different γ , choice of smaller radius

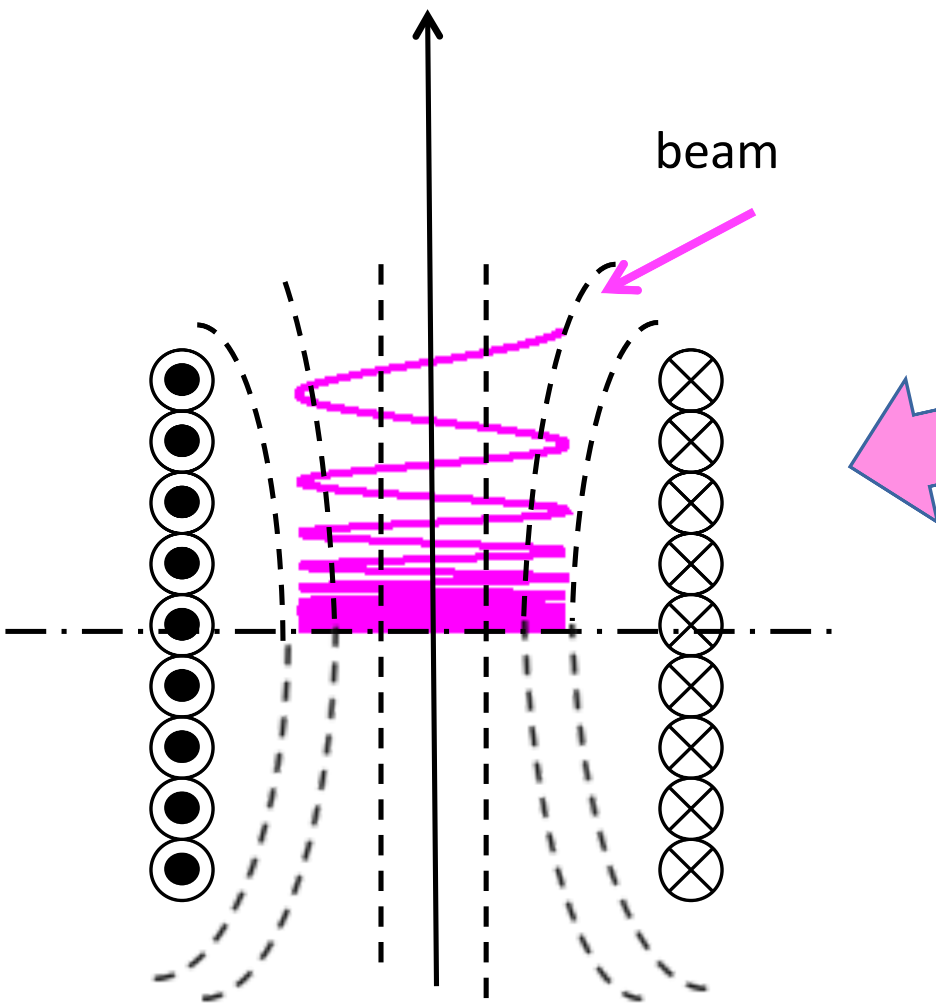


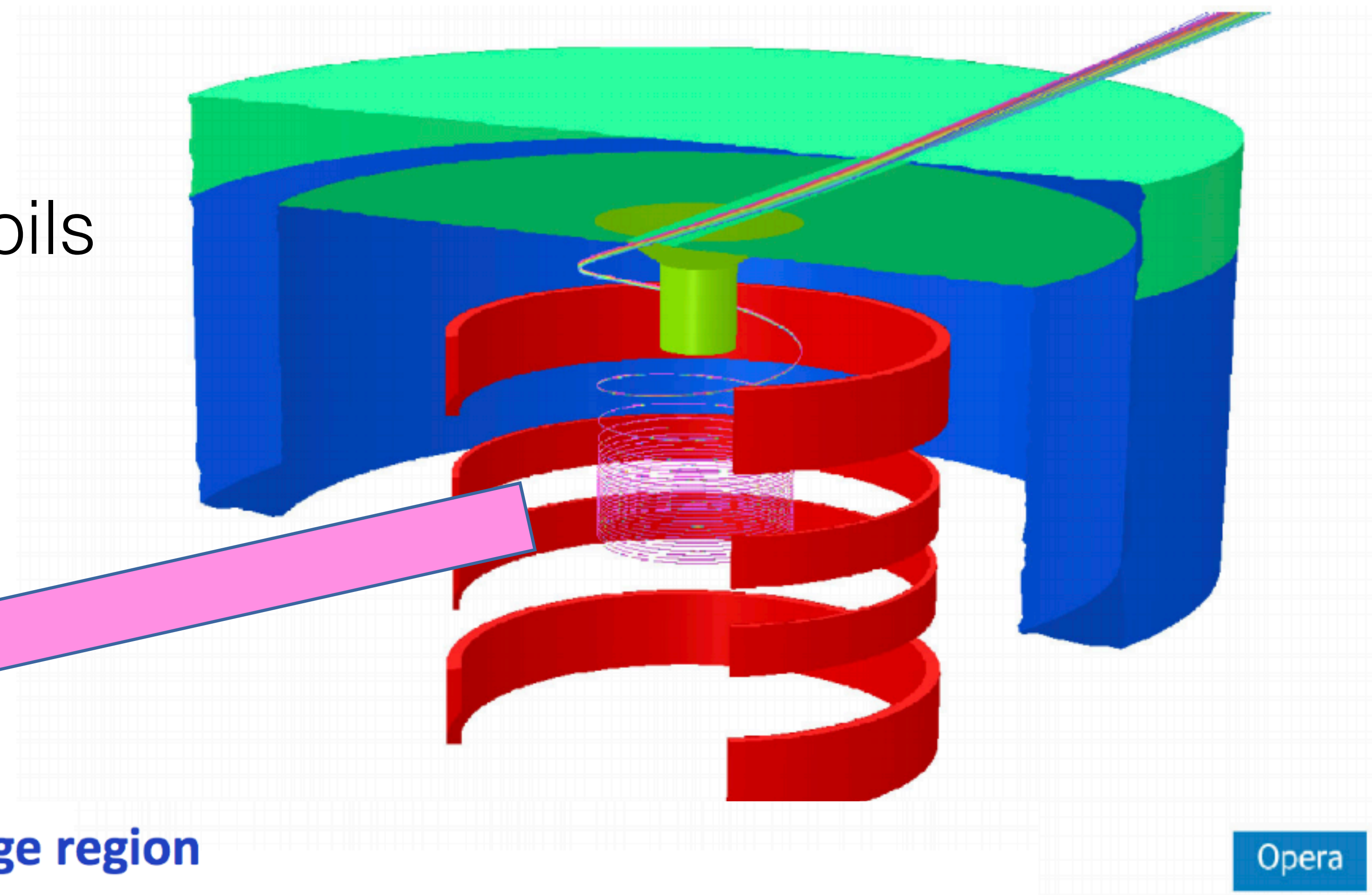




principles of muon storage at J-PARC

week magnetic focusing, and
vertical kick by anti-Helmholtz coils





Storage region

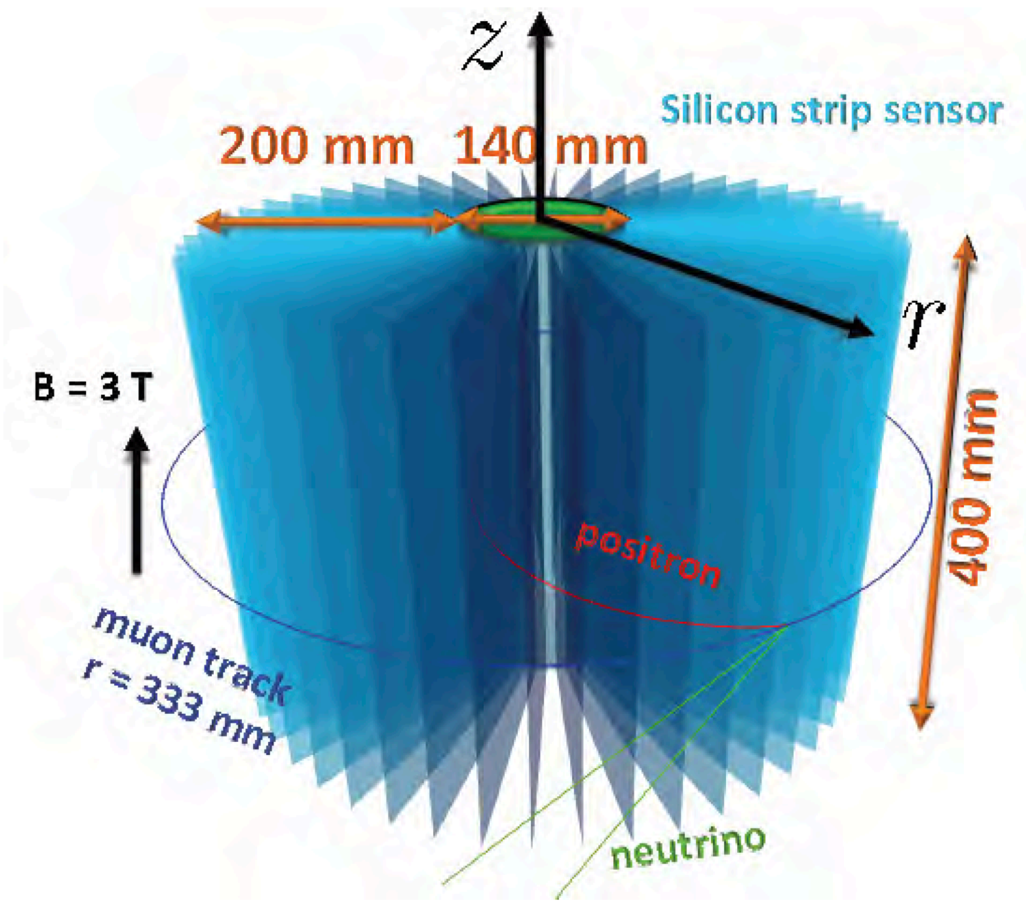
- **Field strength : 3 T**
- **Homogeneity: <1 ppm locally**
- **radius: 33.3 cm**
- **height: ±5 cm**

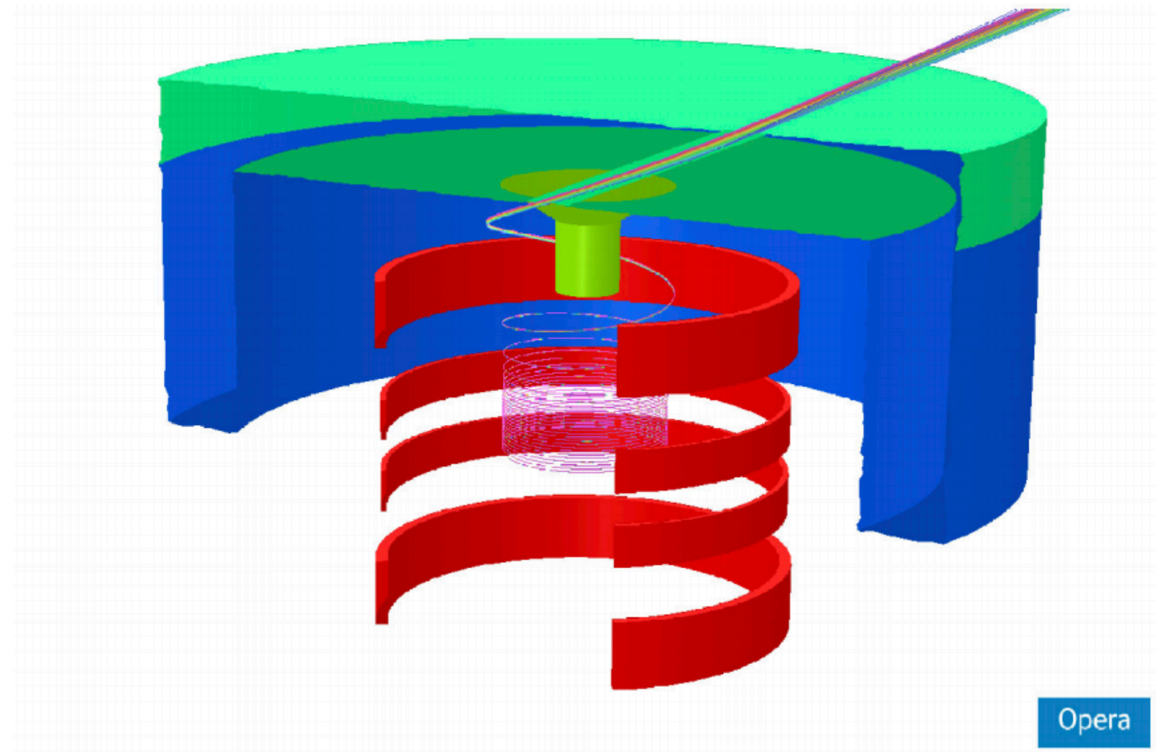
Injection region

- **B_r x B_z > 0**
- **B_r changes smoothly along the beam orbit**

Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

principles of positron detection at J-PARC

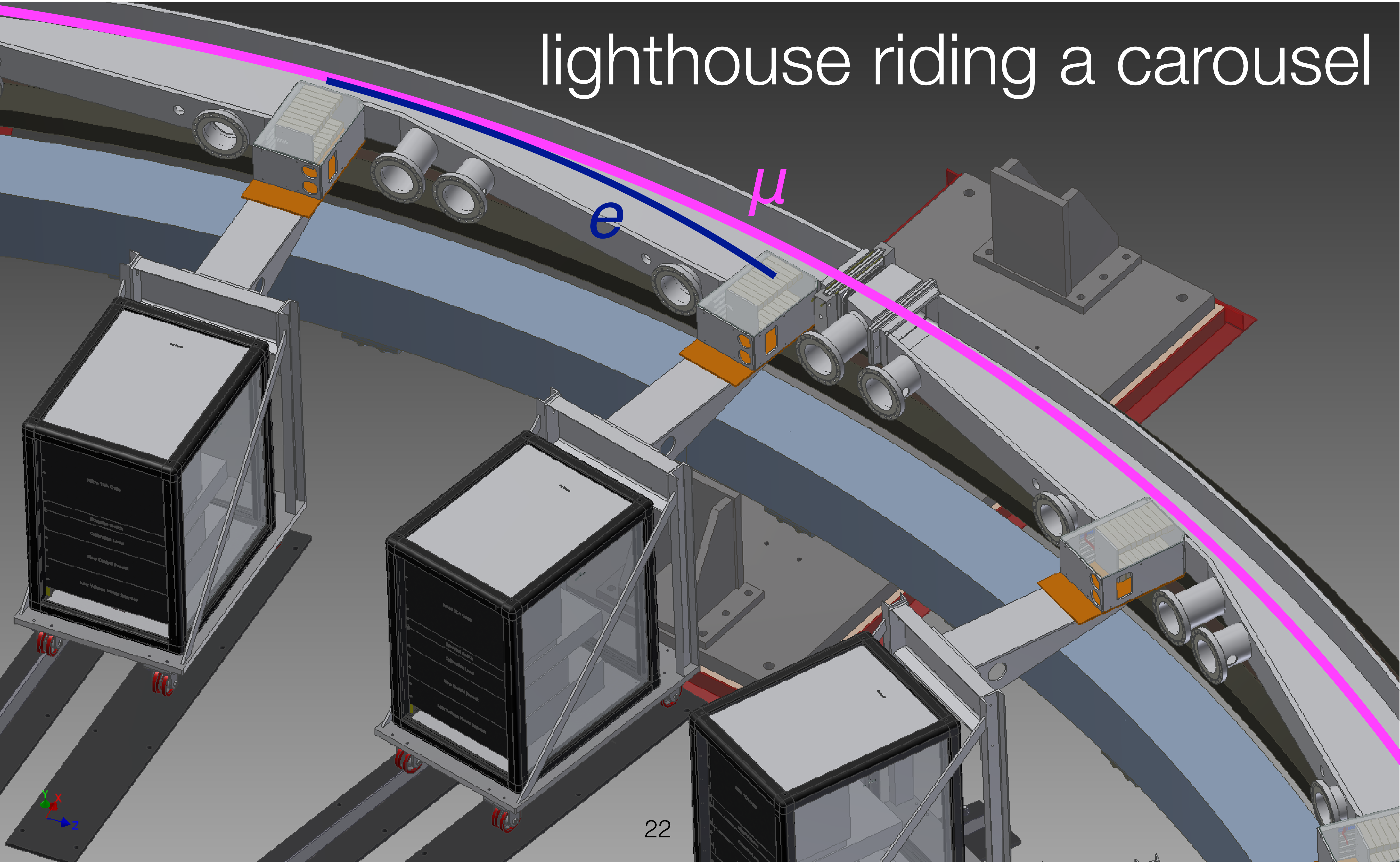




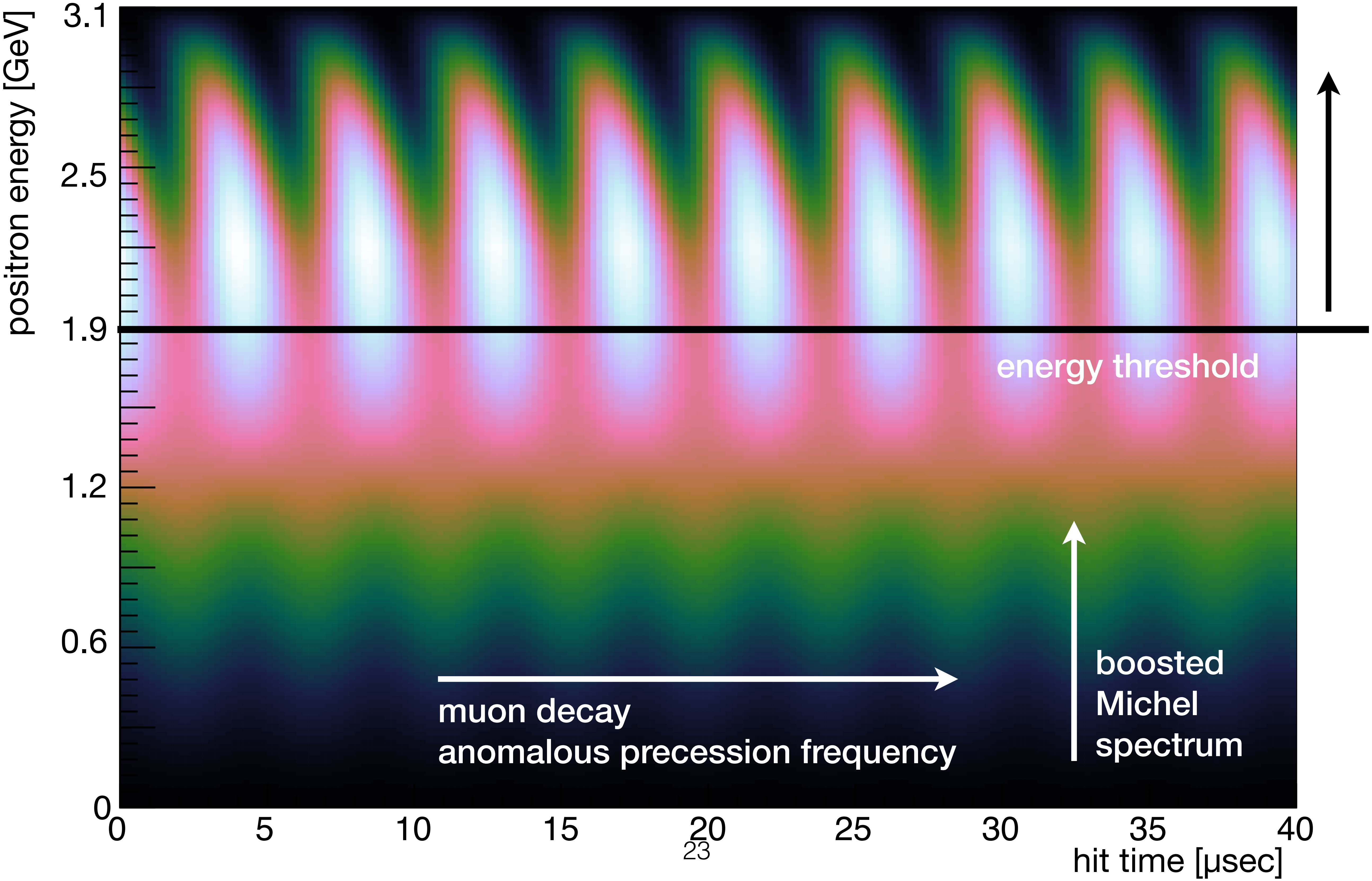
- **48 silicon tracking vanes inserted into the storage region.**
- **Radius = 70-270 mm**
- **Height = +/- 200 mm**
- **Segmentations allows for time tracking of the beam - reduces pileup effects.**

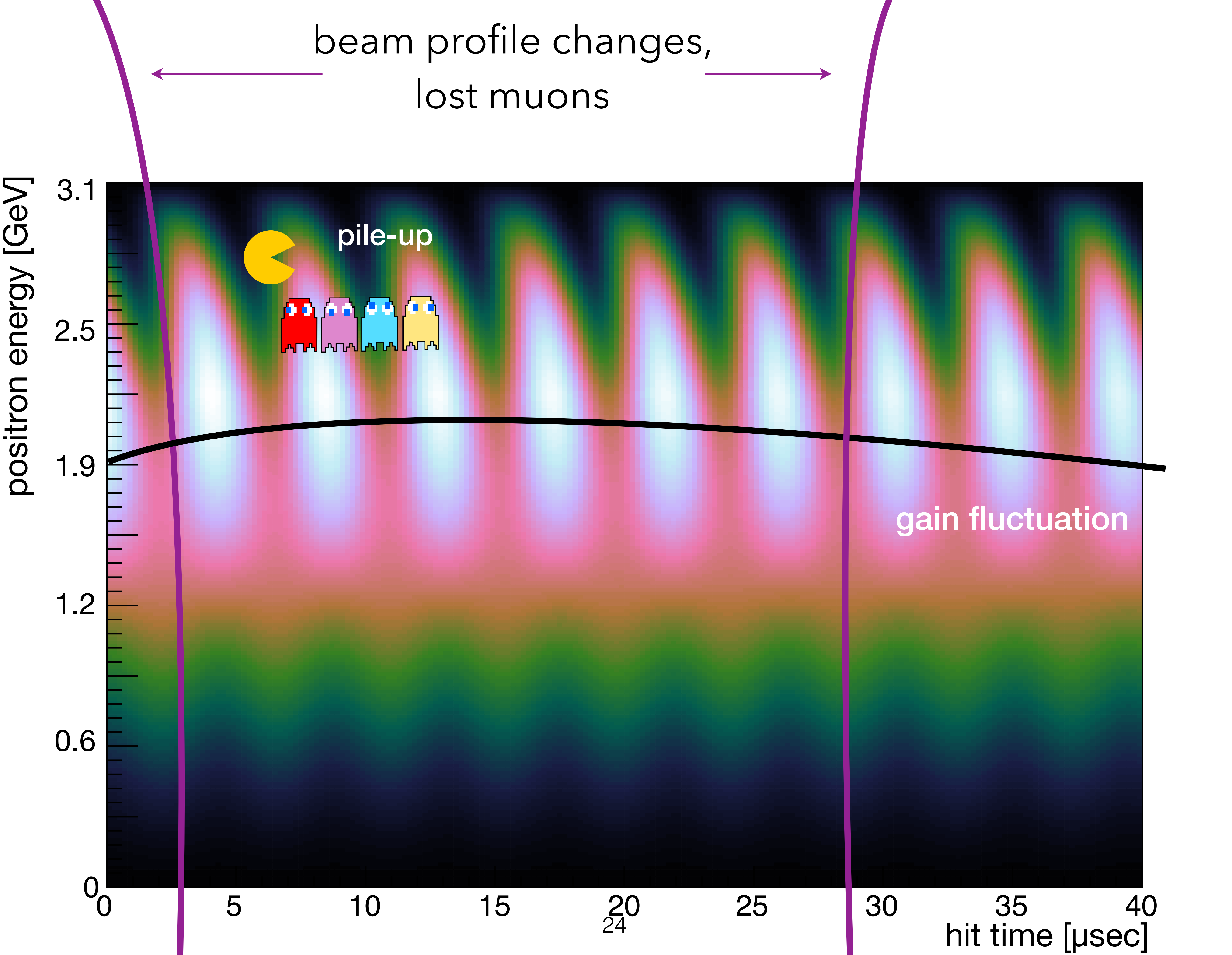
Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

principles of positron detection at FNAL



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]

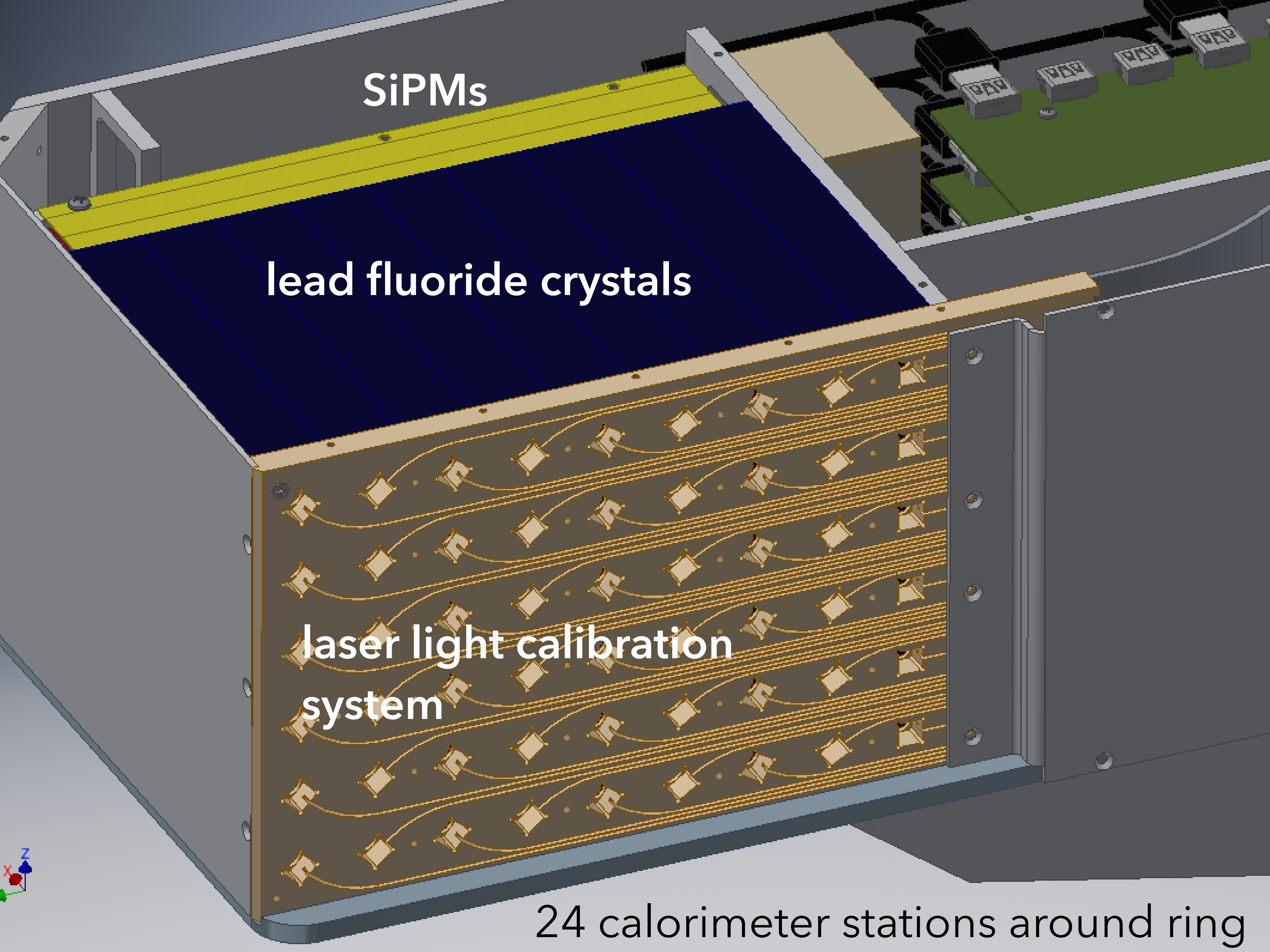
Calorimeter design goals

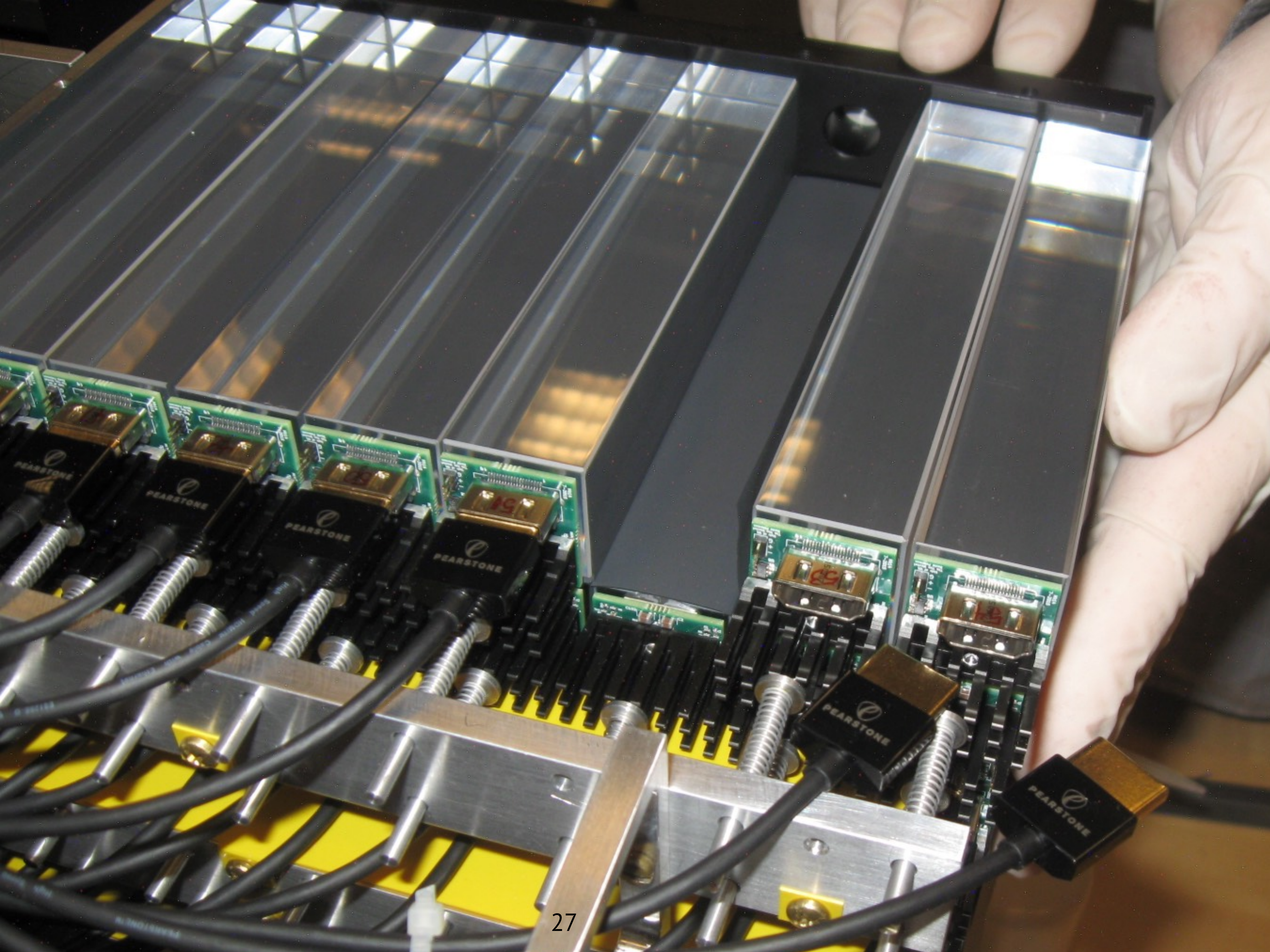
1. Positron **hit time** measurement with accuracy of (100 psec above 100 MeV)

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

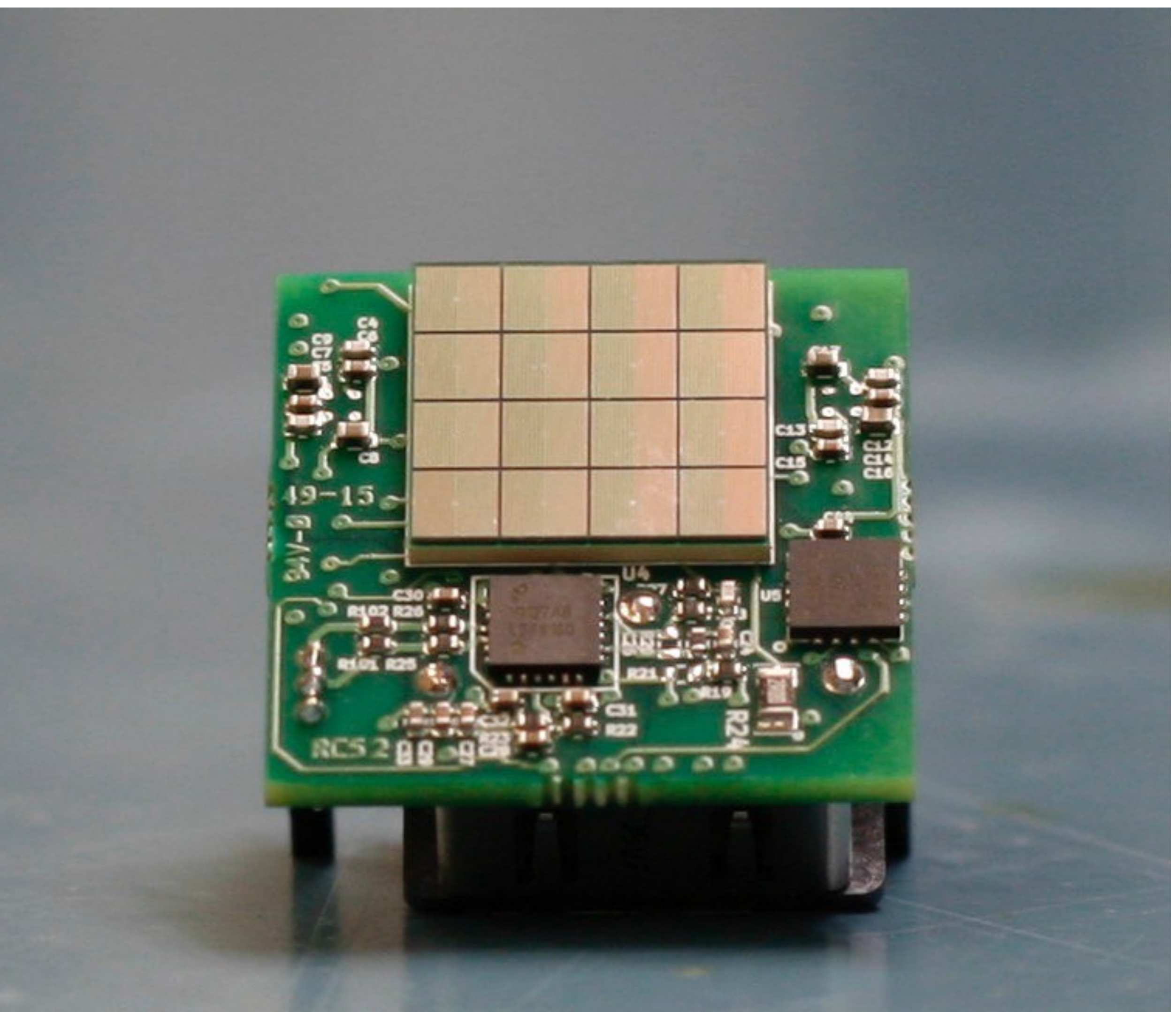

PEARSTONE

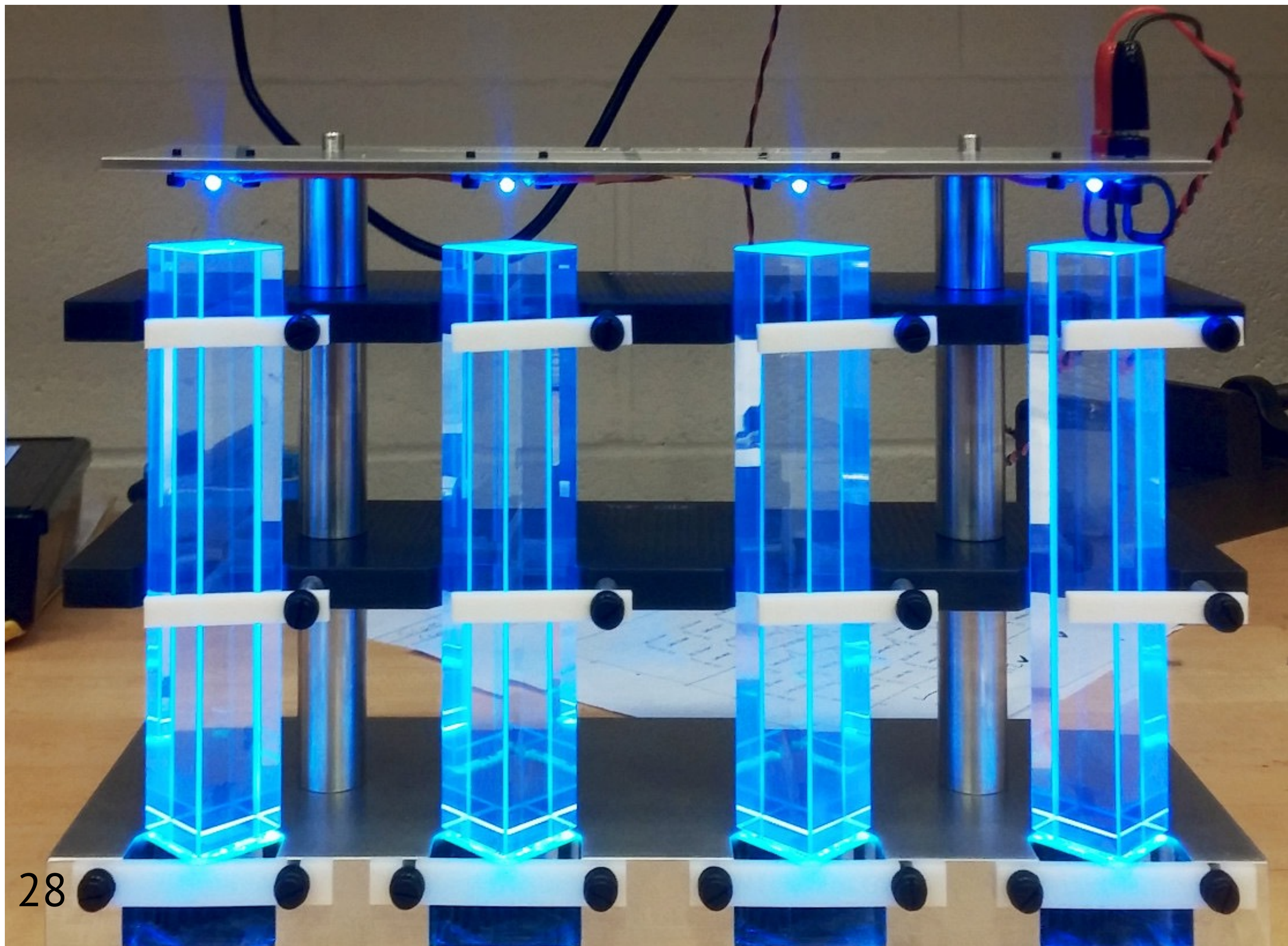
positron detection in calorimeter

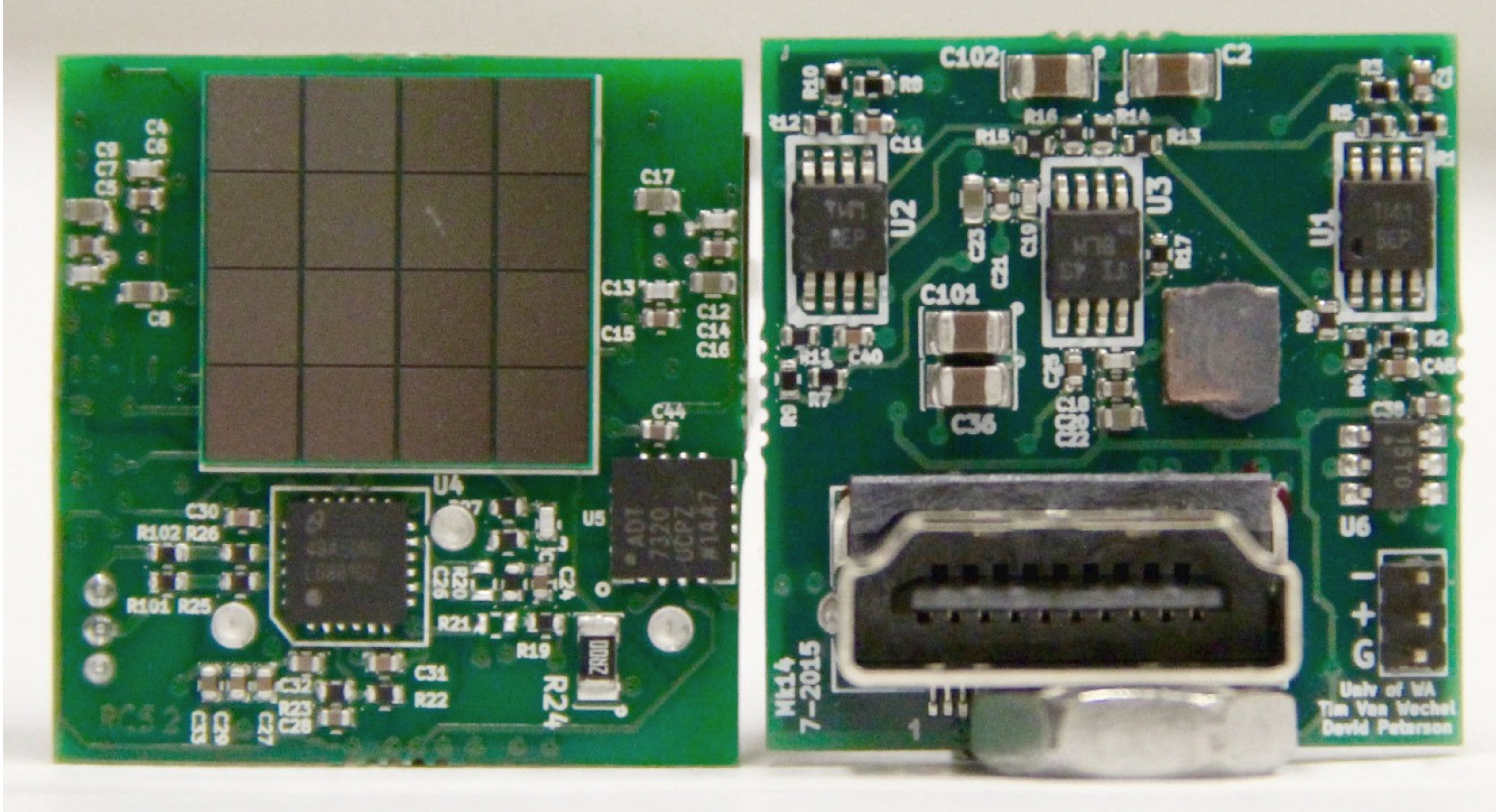
PbF2 – pure Cherenkov radiator

SiPM – counts photons; magnetic field compatible

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





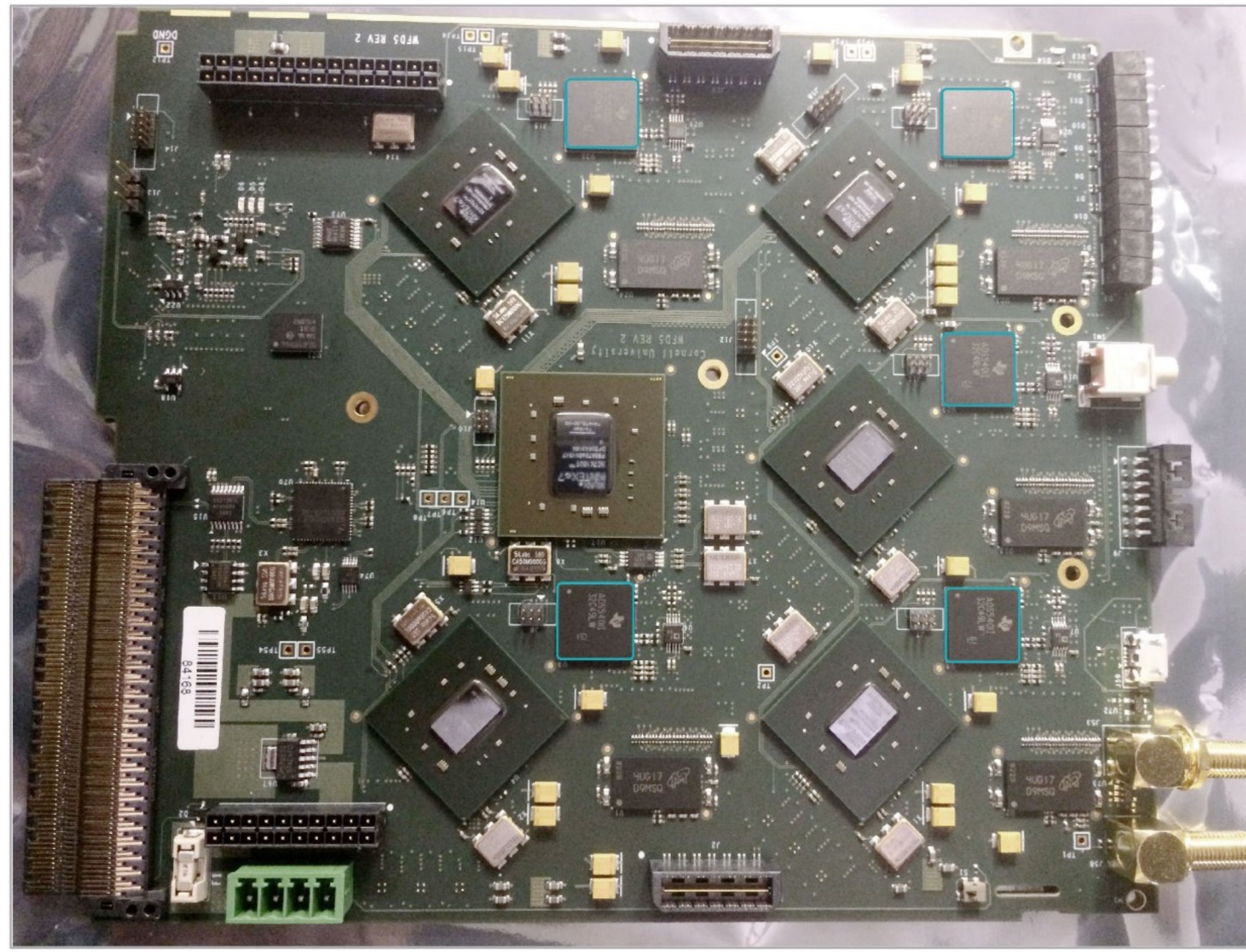


- based on a trans-impedance amplifier (no shunt resistor) PMT-like pulse shape
- programmable gain amplifier to equalize 1400 boards
- DC coupled differential signal to digitizers
- temperature sensor on board for offline gain calibration

custom made 800MHz digitizer

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

- GPU data processing

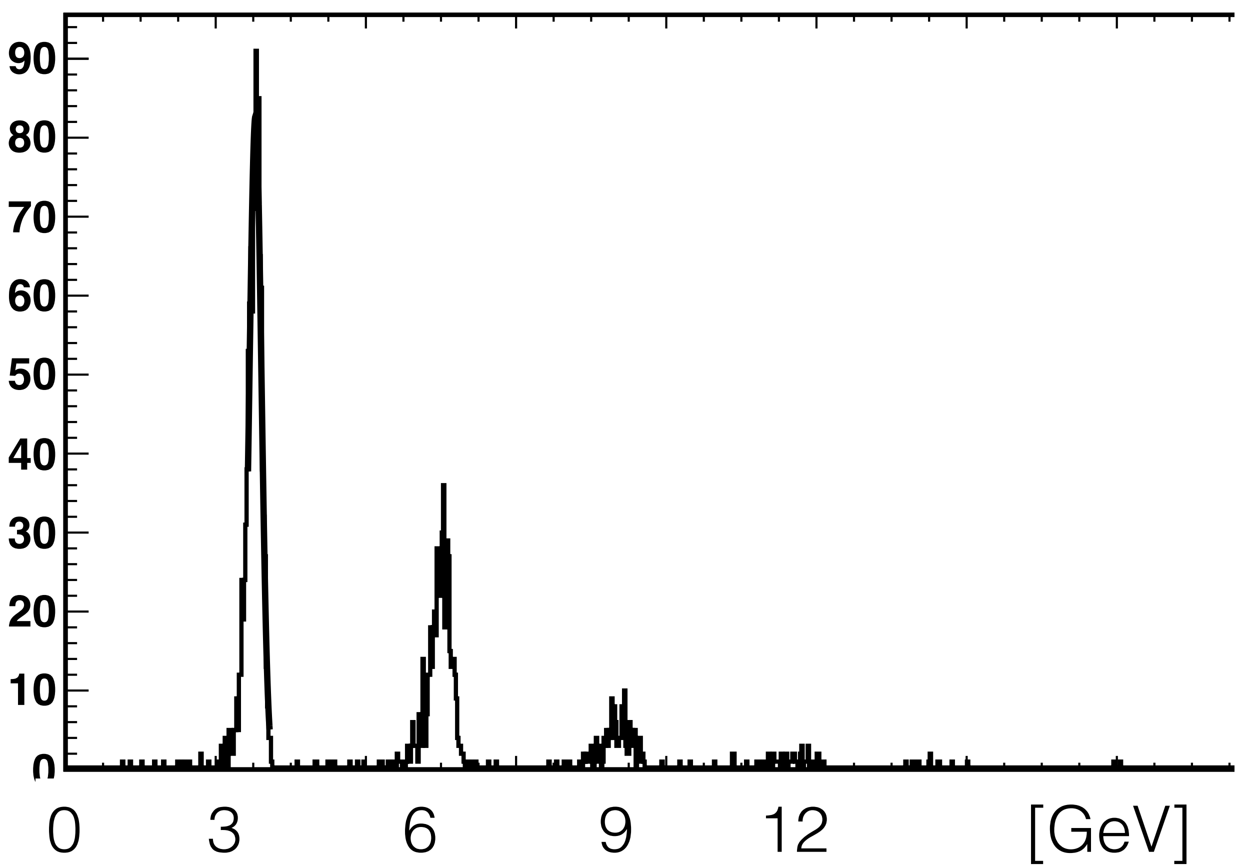


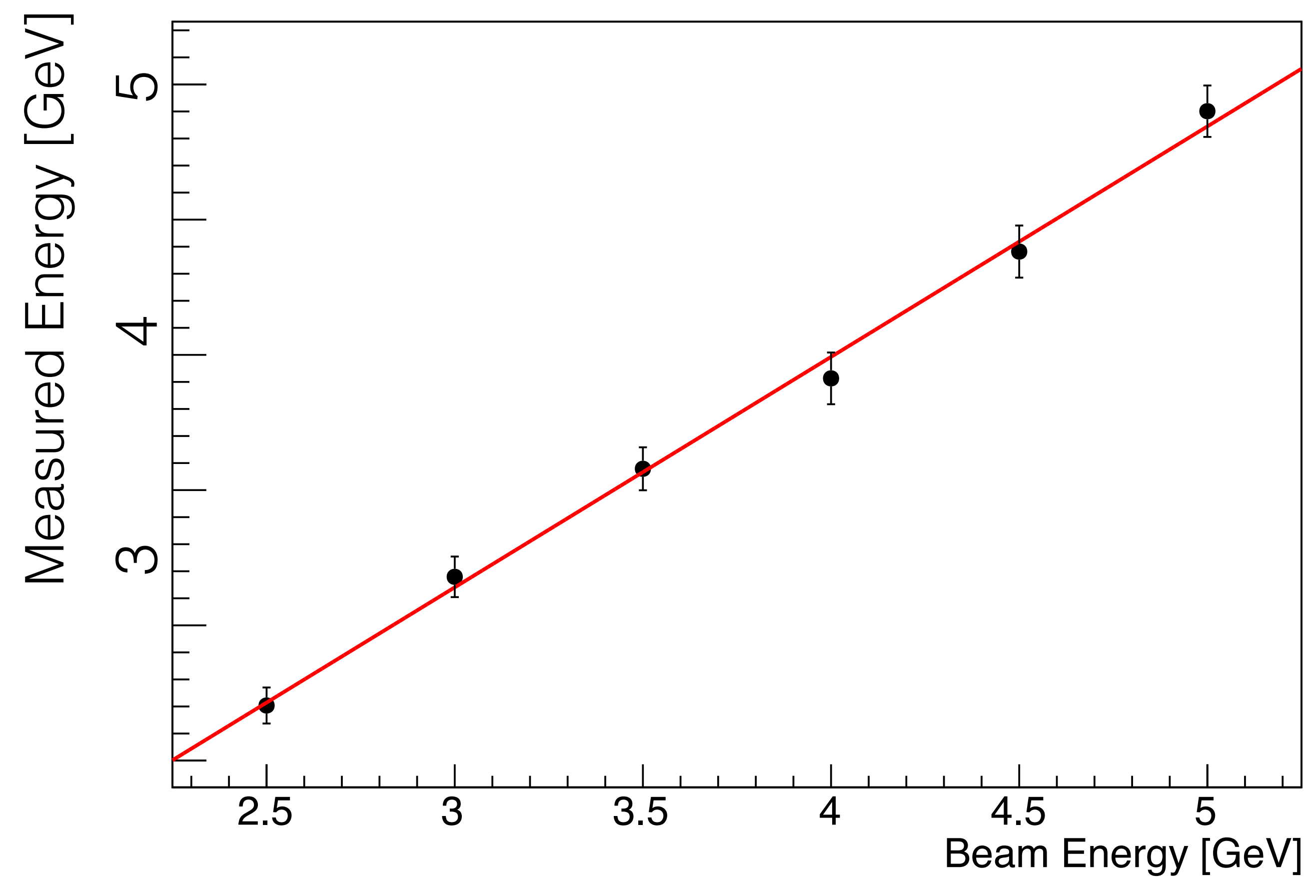
calorimeter at SLAC test beam

energy resolution 3% at 3GeV

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

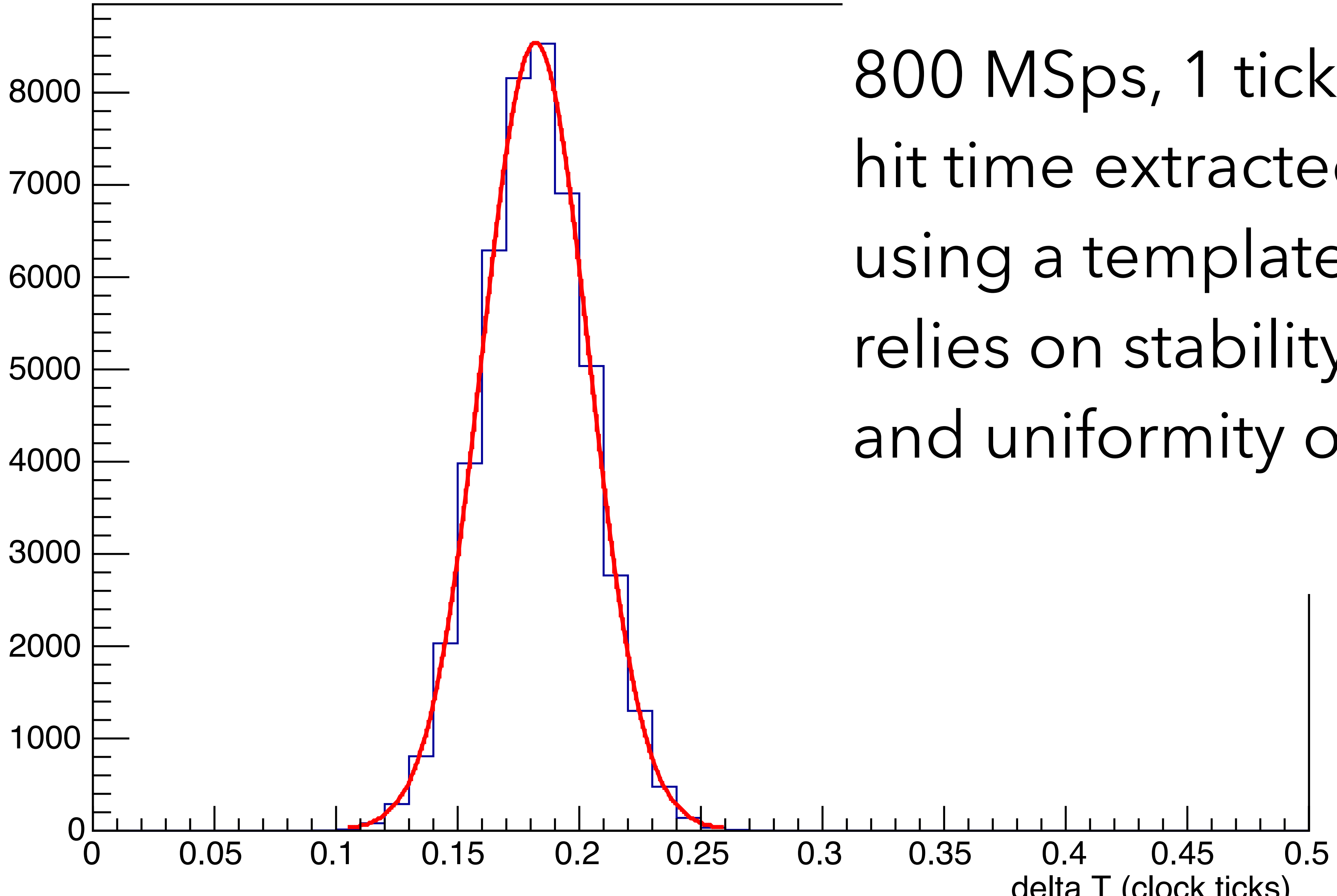
Poisson comb of hit energies, 3 GeV electron beam





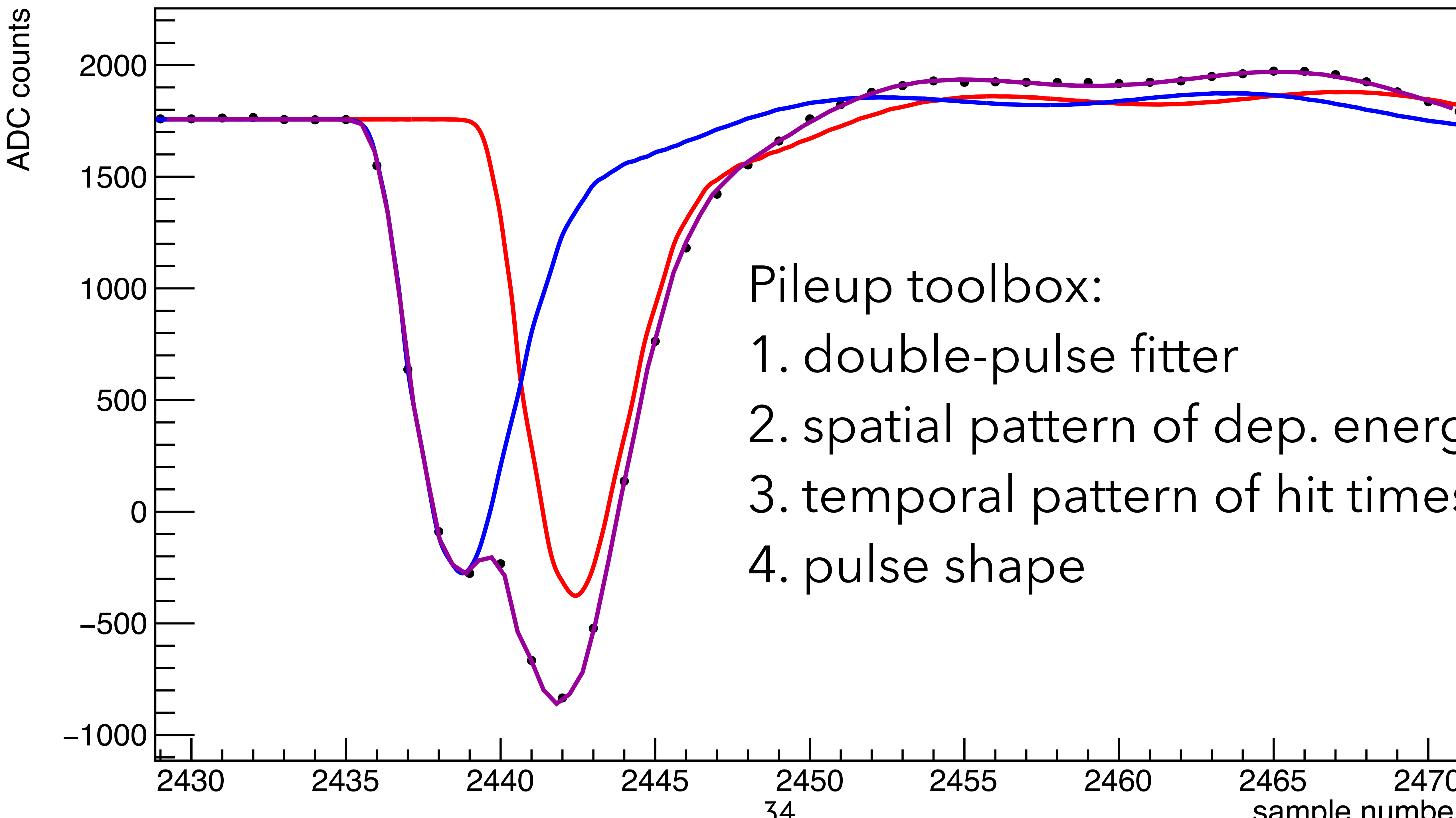
timing resolution 25ps at 3GeV

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 4.5 nsec separation

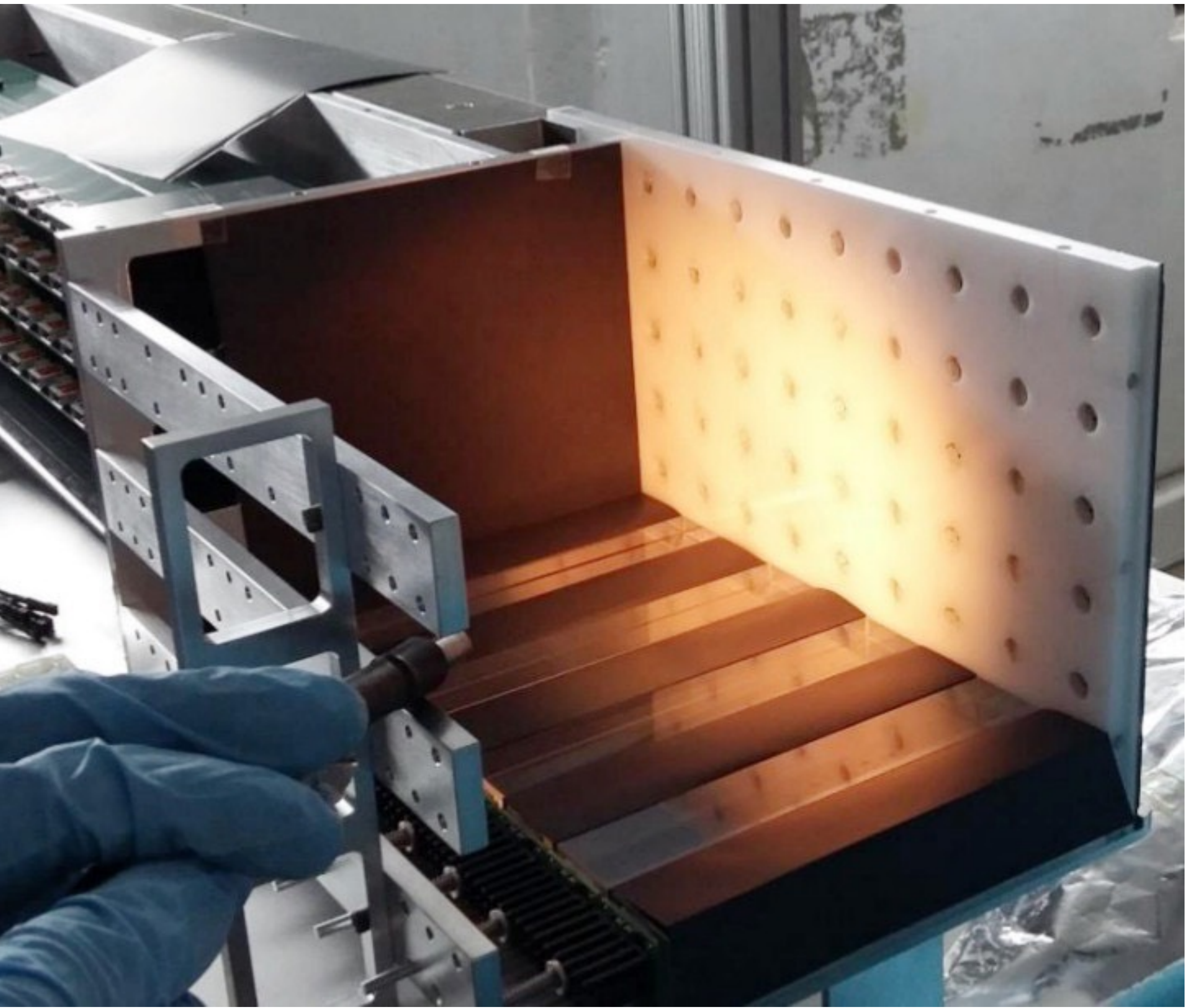


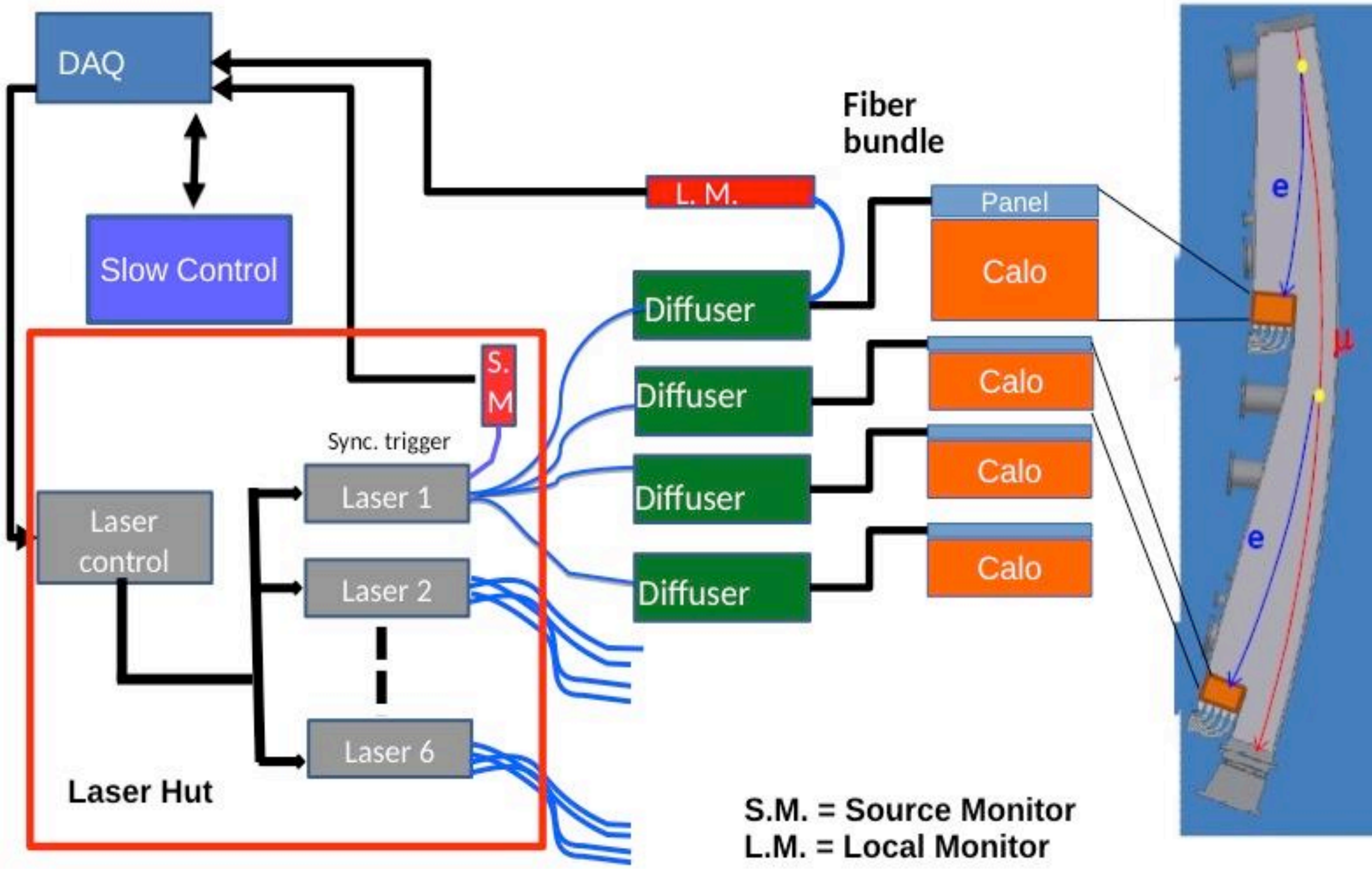
Pileup toolbox:

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

laser calibration system

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

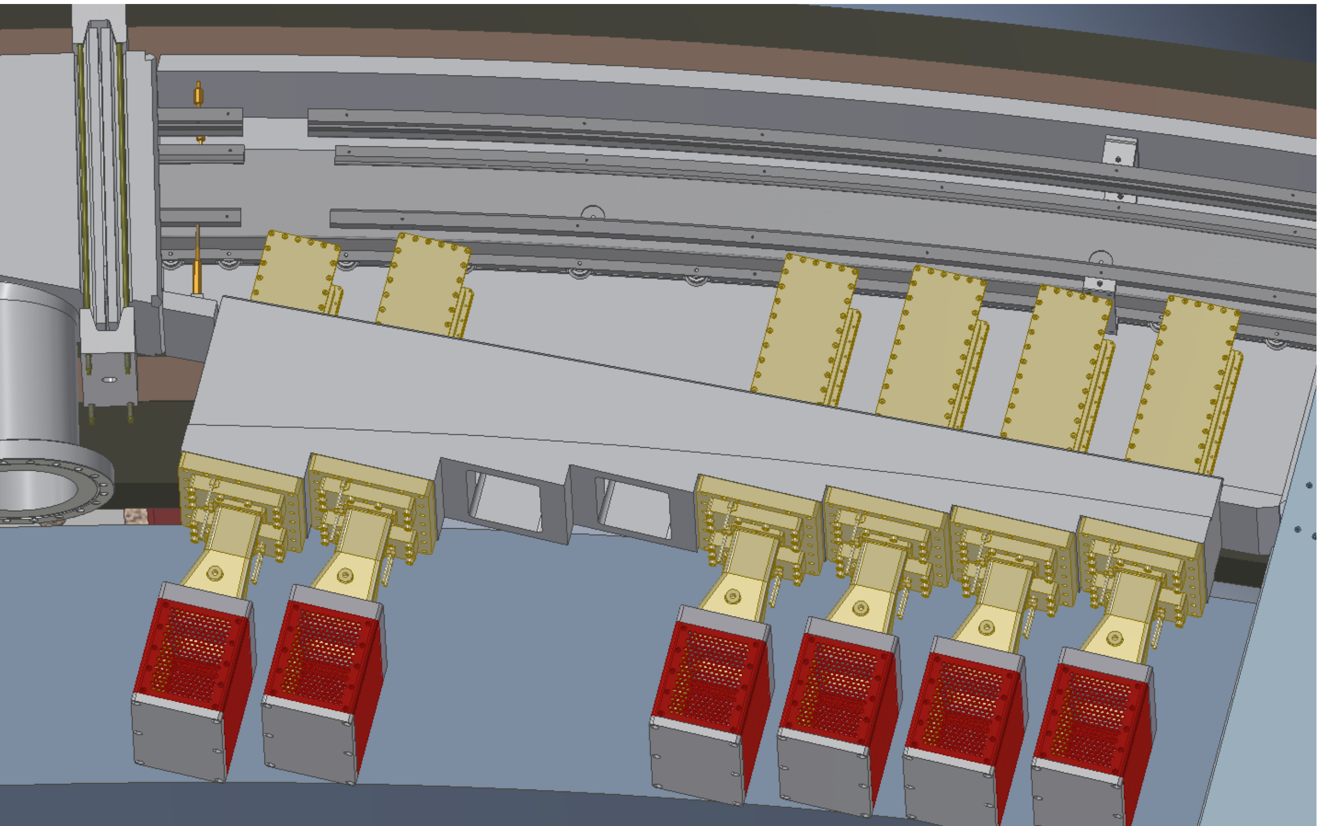


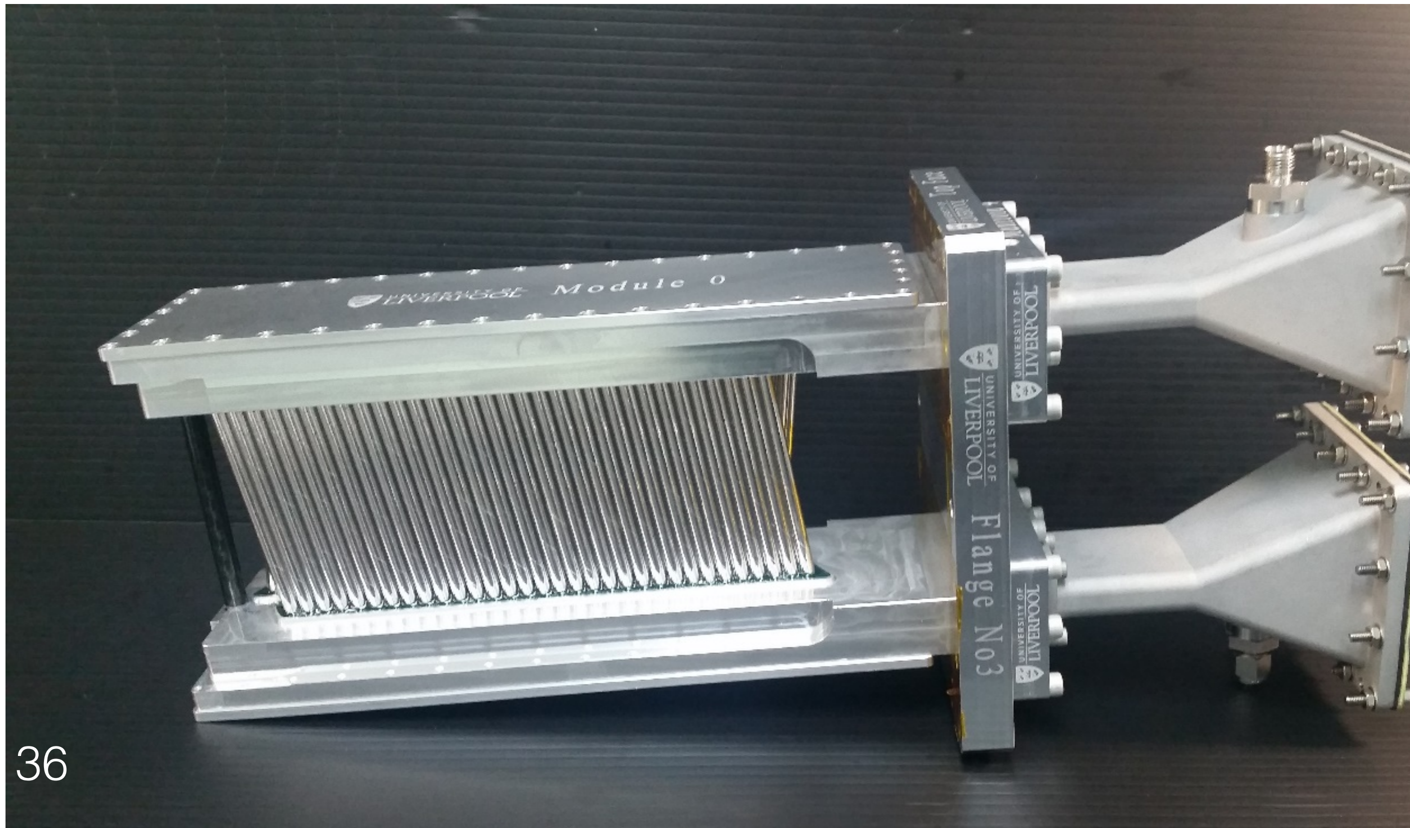


Straw tracker design

- At 3 points around ring,
- 8 modules per station
- high-gain Ar:Ethane

Large azimuthal acceptance with low material (15μm Mylar)





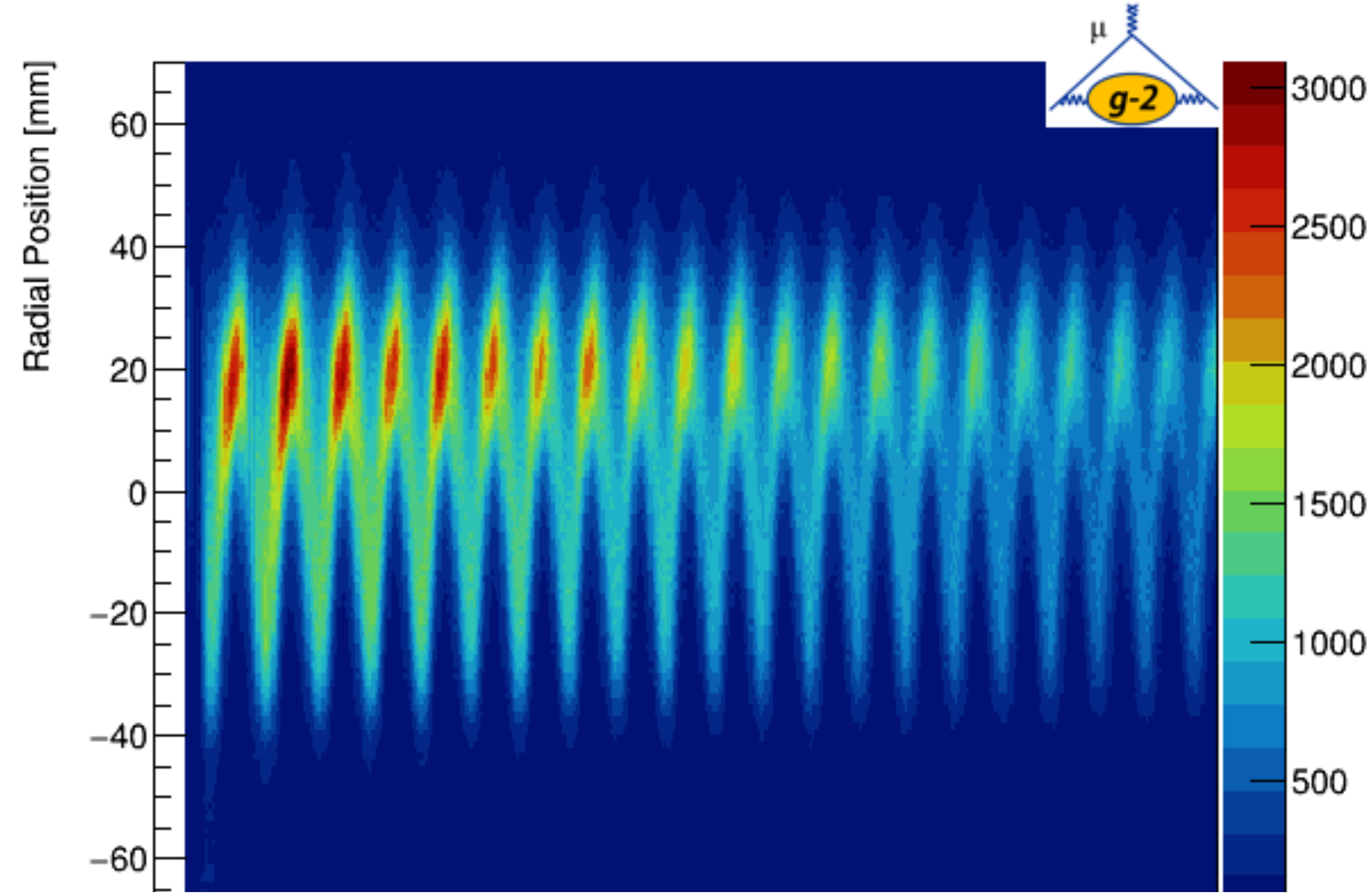
Swiss-knife of Muon *g*–2 experiment

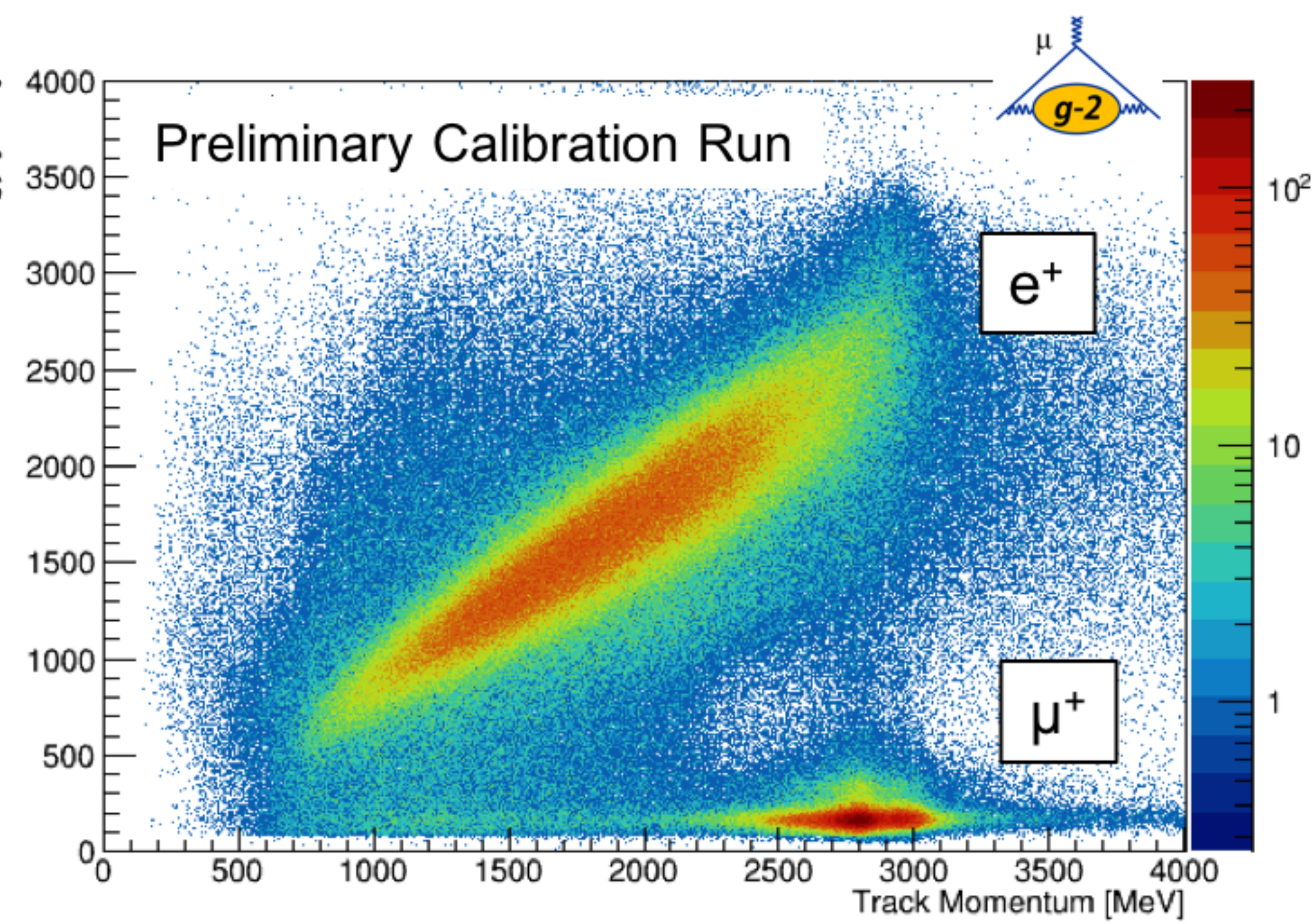
Measures stored muon profile and its time evolution.
Addresses pile-up systematics, measure positron momentum.
Detects lost muons escaping storage region.
Measures vertical pitch of decay positrons → EDM measurement.

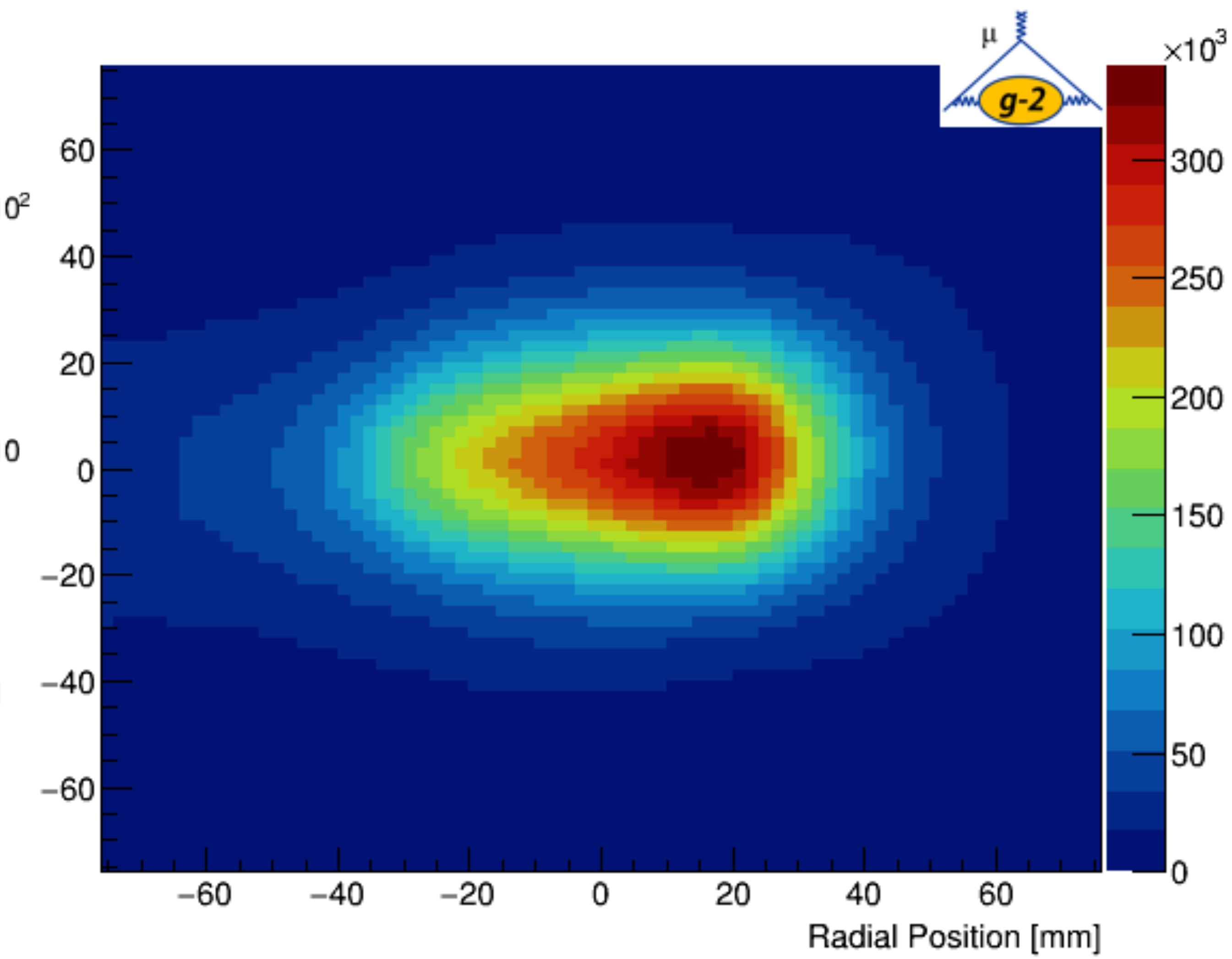
Determines area of magnetic field map seen by the muons
Limits the size or radial and longitudinal magnetic fields

Makes an independent measurement of positron momentum.

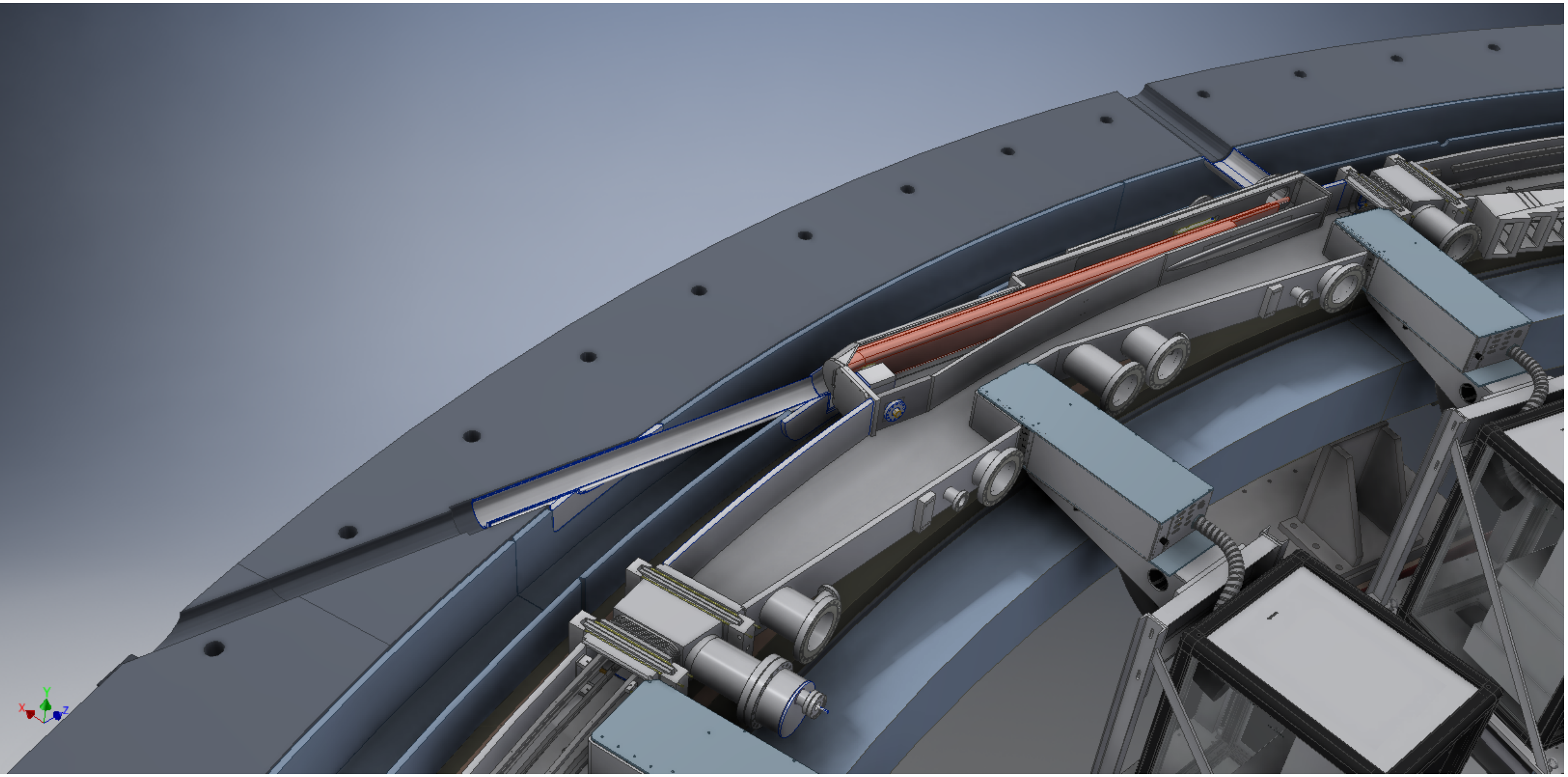
Excellent performance

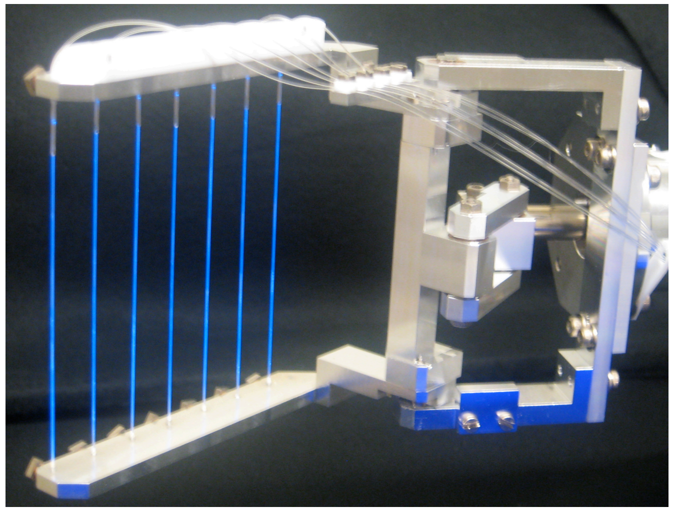


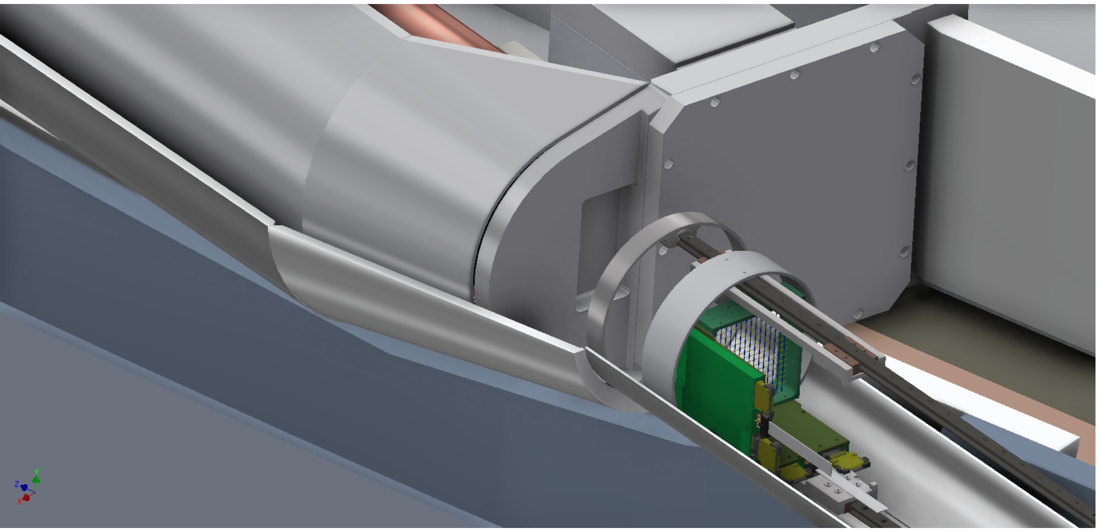


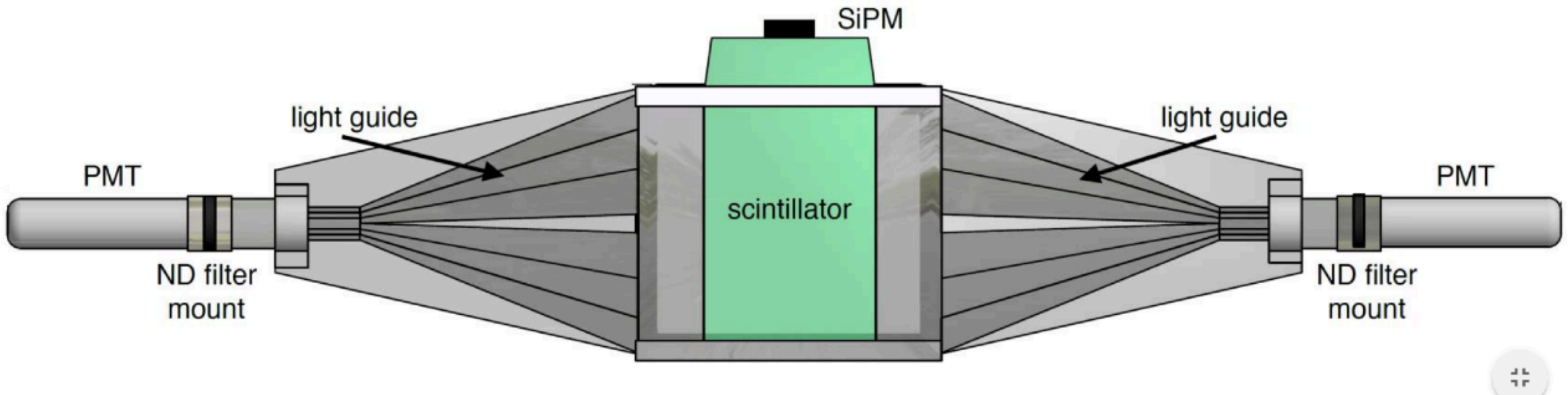


Entrance counters and destructive beam profile detectors characterize beam in redundant ways









Principle of g-2 experiment

In E821 $\equiv \mathcal{R}_\mu(\mathrm{E821}) = 0.003\,707\,206\,4(2\,0)$ **[540 ppb]**

$$a_\mu = \frac{g_e}{2}\boxed{\frac{\omega_a}{\tilde{\omega}_p}}\boxed{\frac{m_\mu}{m_e}}\boxed{\frac{\mu_p}{\mu_e}}$$

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

$\boxed{\mathcal{R}_\mu}$

Muonium Hyperfine Splitting
--[658.210 6866 (20)] $^{-1}$ [3 ppb]

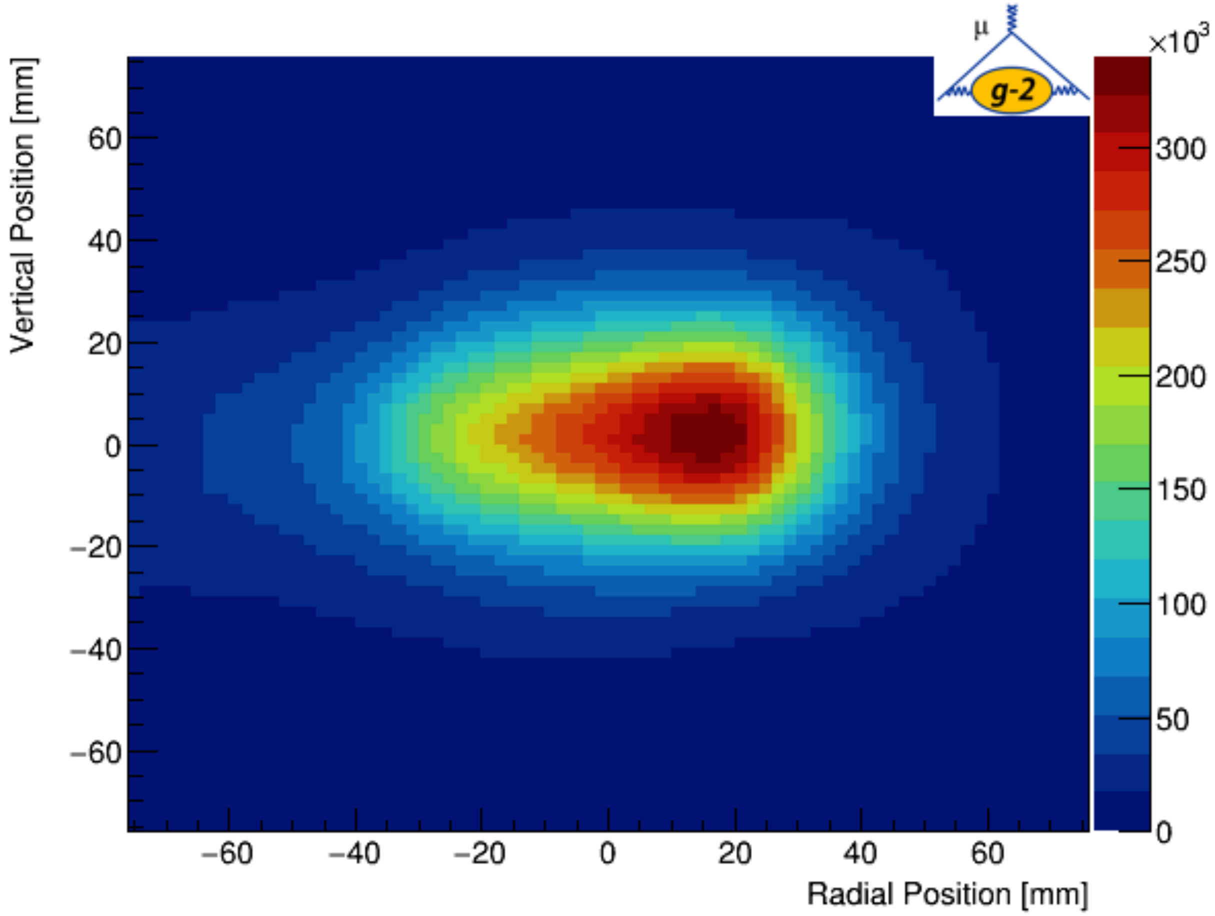
206.768 2826(46) **[22 ppb]**
Muonium 1S-2S

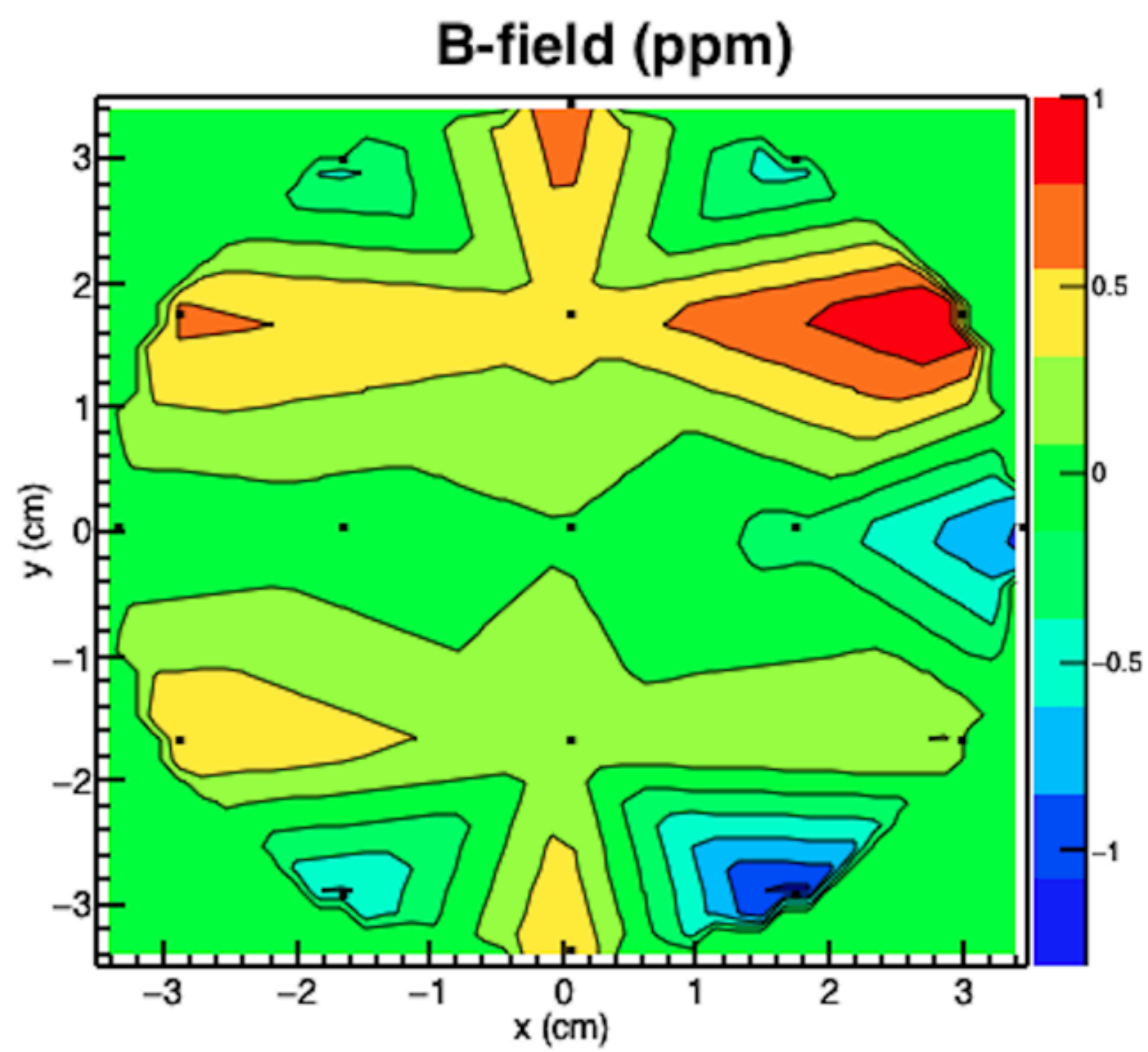
ω_a : Precession frequency

$\tilde{\omega}_p$: Magnetic field (averaged, convoluted with muon distribution)

principles of ω_p measurement

Larmor precession frequency of a free proton, measured where muons are stored, and when muons are stored

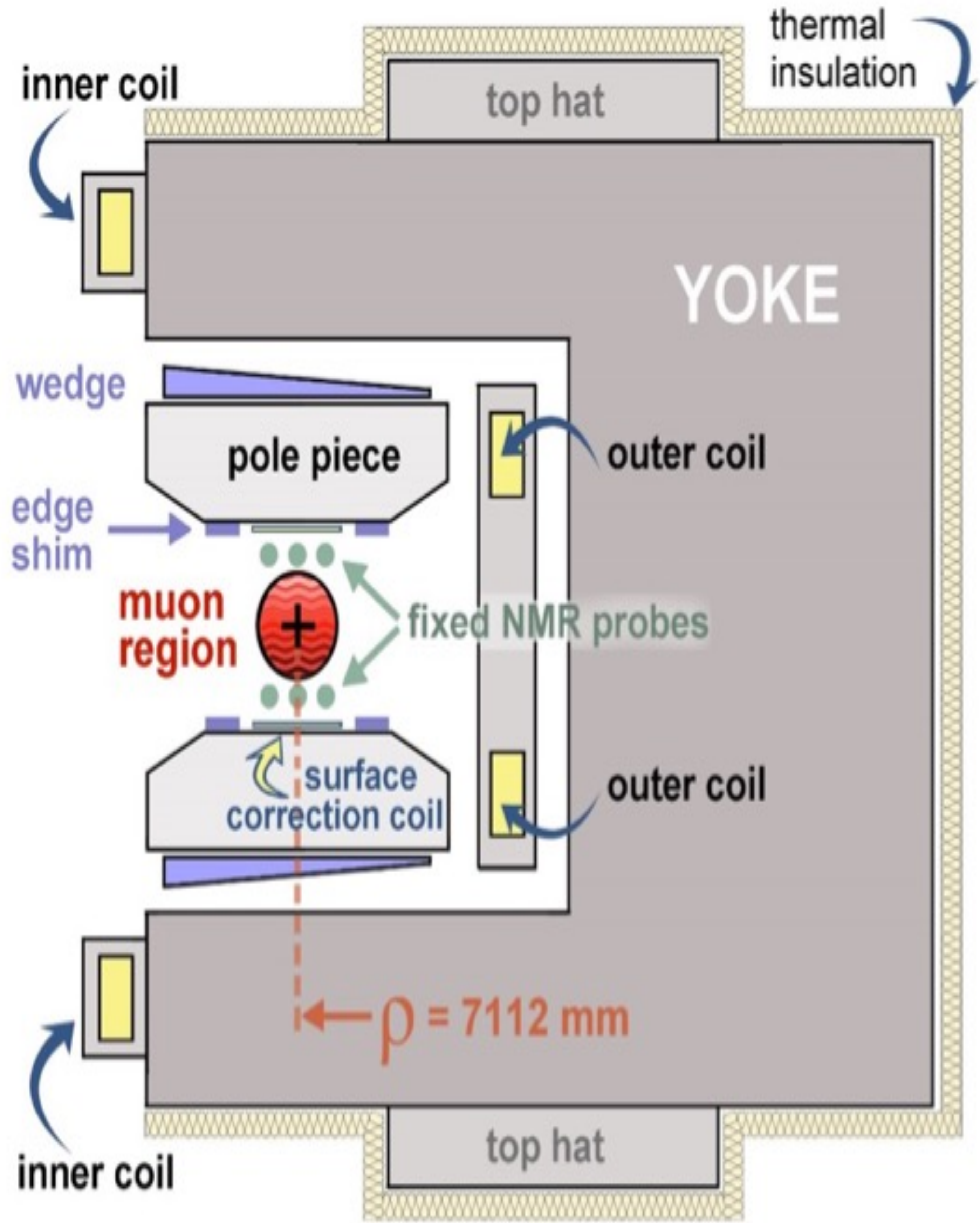




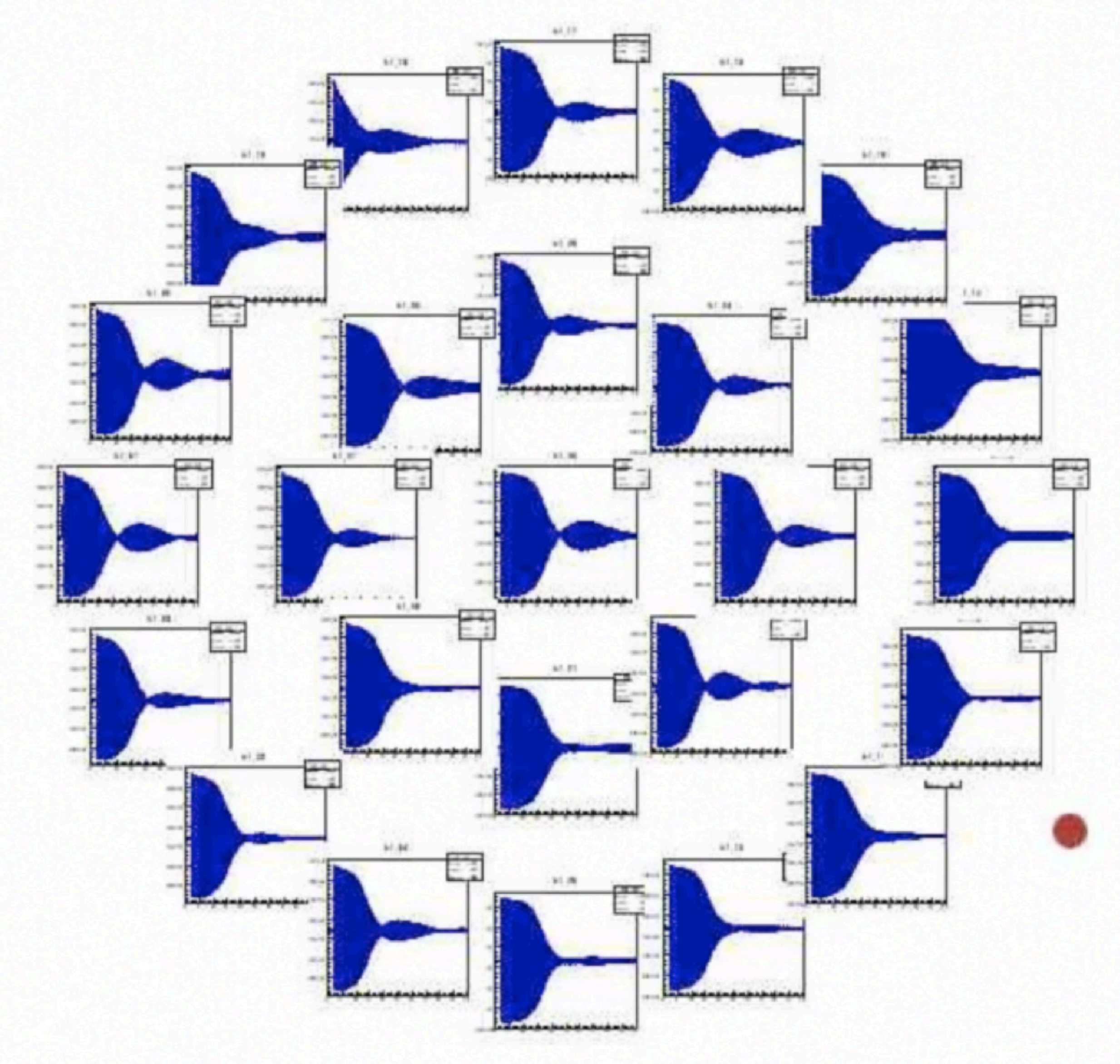
Field shimming

B=1.45 T (non-persistant)

- 48 top hats
- 864 wedge shims
- 144 edge shims
- 8424 laser cut iron foils
- 200 surface coils



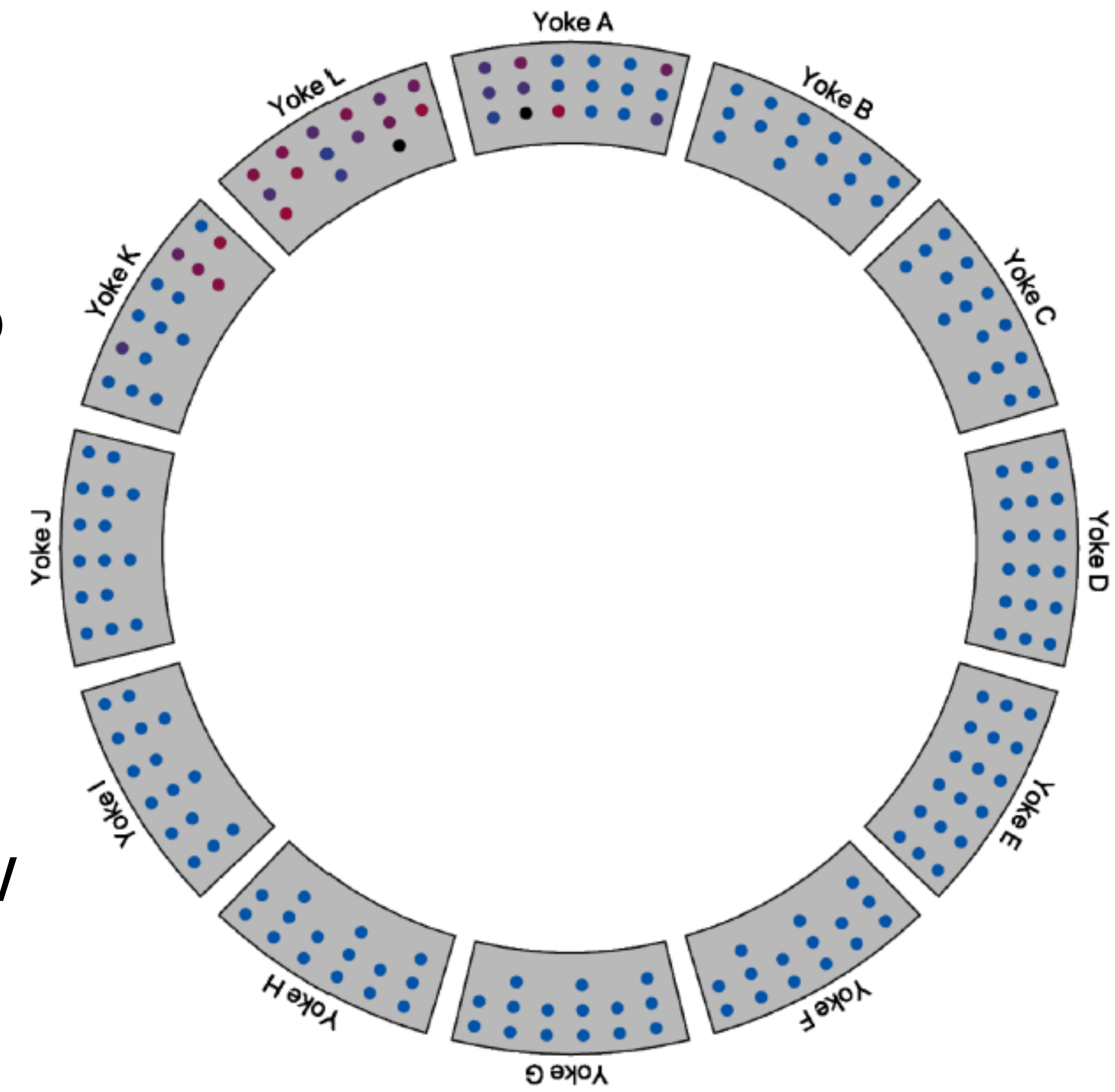
g-2 Magnet in Cross Section



Field mapping trolley

- 17 NMR probes
- two trolley runs per week
- measures field in the muon storage region
- when muons are not there

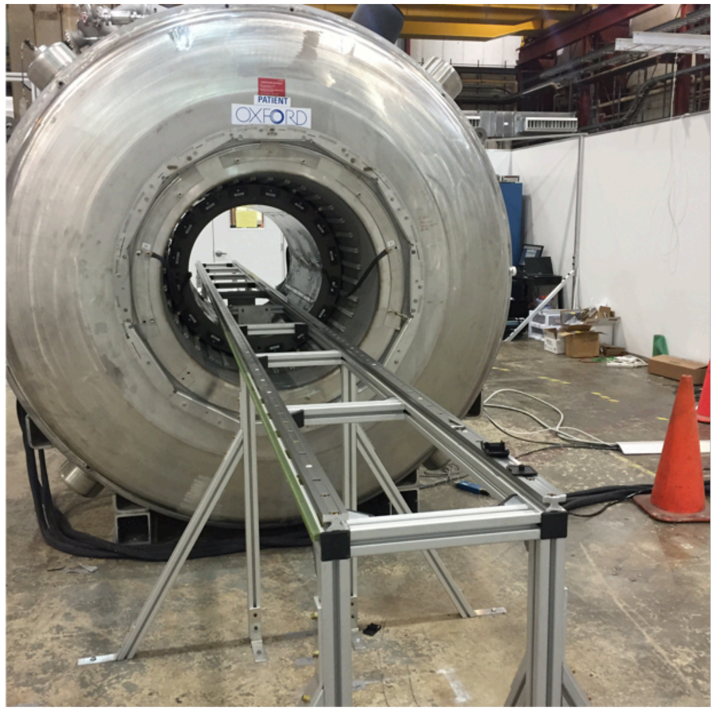
Field monitoring fixed NMR probes

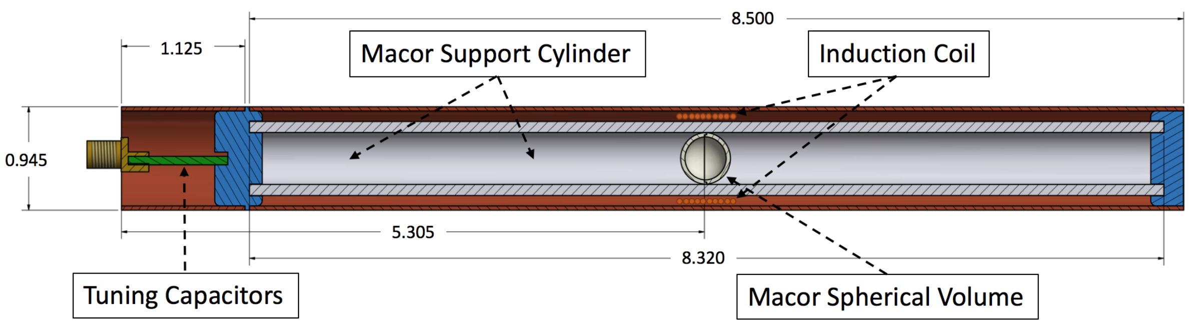


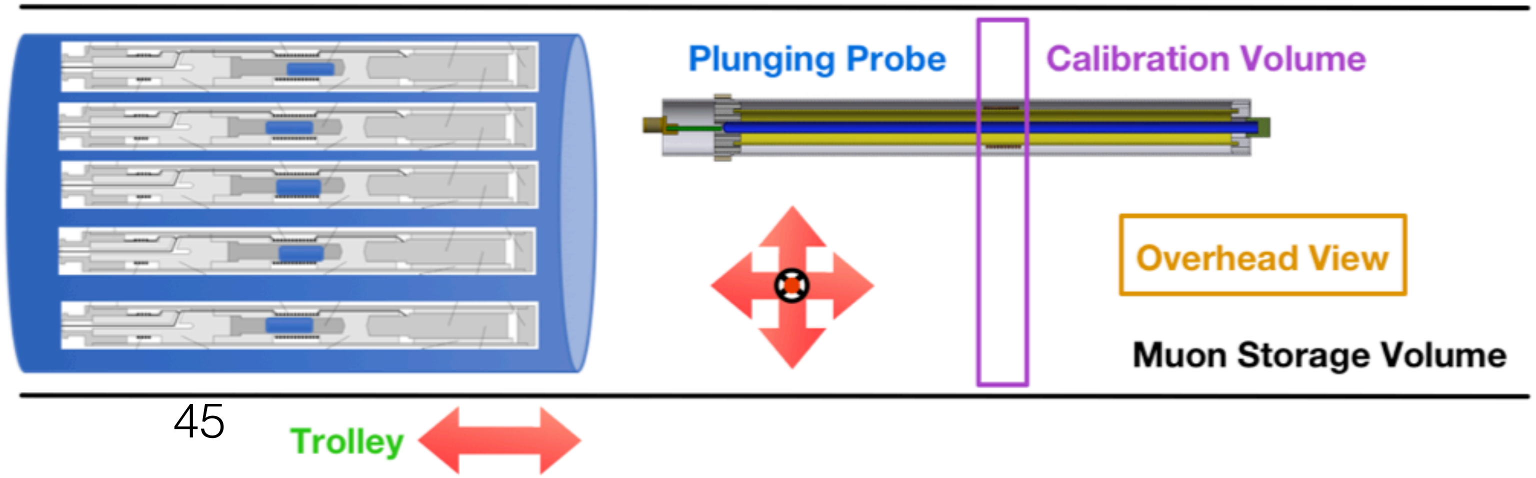
- 378 probes above and below storage region
- Monitor the field in between trolley runs, when muons are stored

Absolute field calibration

- precisely shimmed MRI magnet at ANL serving both FNAL and J-PARC
- absolute NMR probe designed to minimize systematics
- novel He3 probe cross-check
- plunging probe transfers the absolute calibration to trolley probes

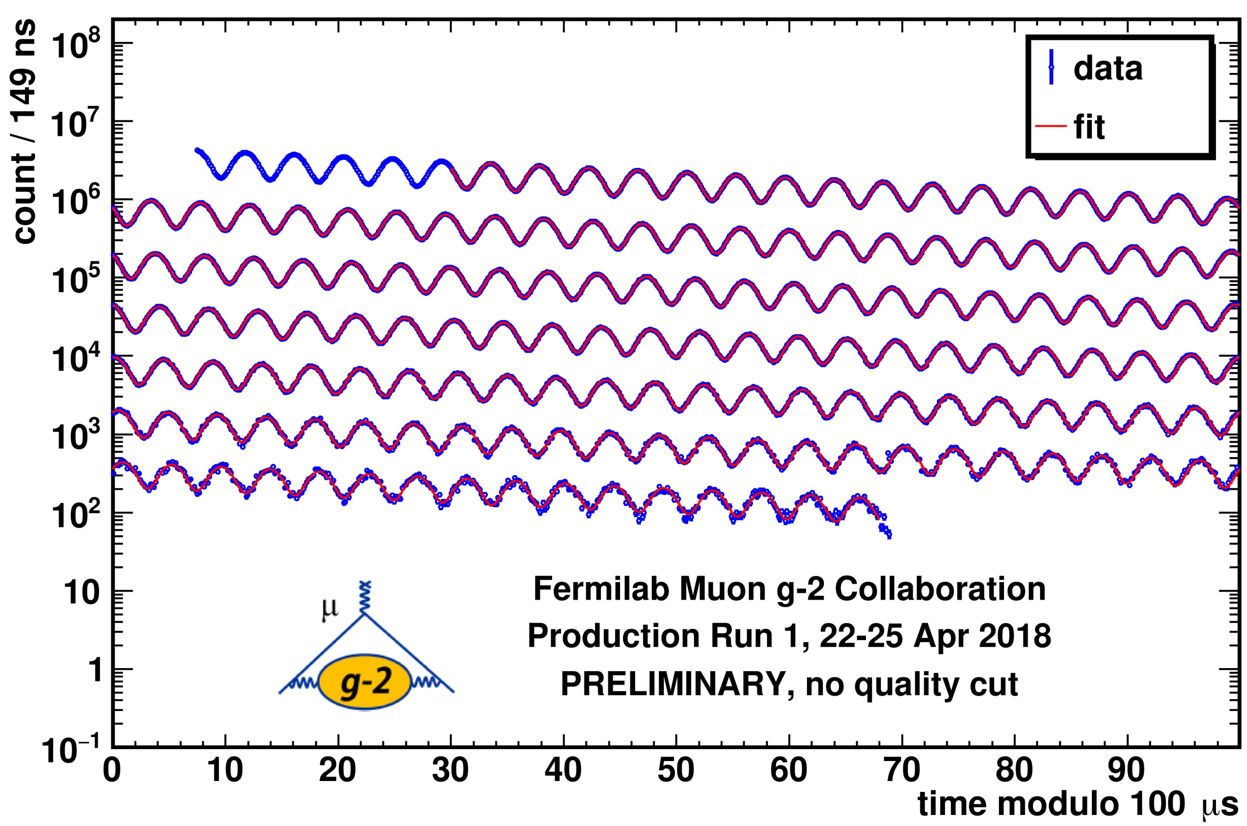


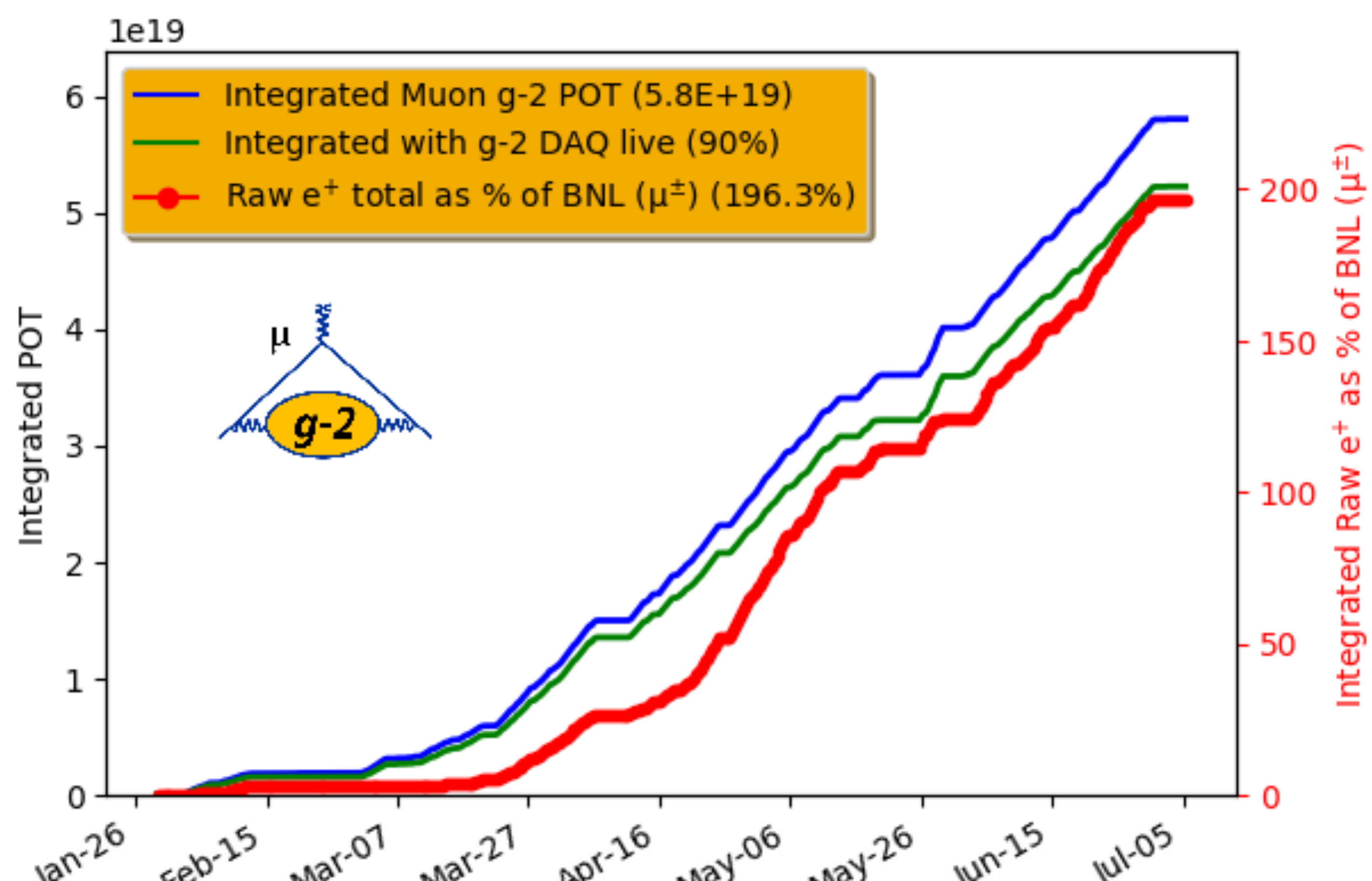




First physics run is successfully over.

- engineering run in Summer 2017
- commissioning run in Fall and Winter 2017
- first physics run from March to July 2018
- next physics run from November 2018 to July 2019





Summer upgrades are in progress

- improvements to *reliability* and uptime
  spark recovery, cryo recovery, DAQ uptime

- better *storage efficiency*
  ionization cooling,
  less material for beam to pass through

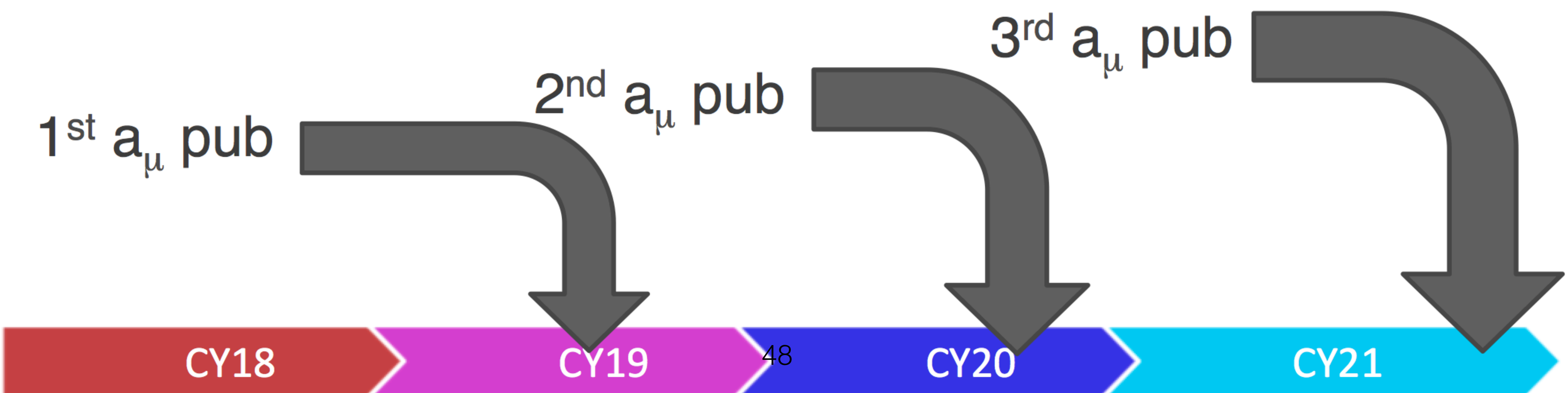
- better control over *systematics*
  improved kicker strength

publication plan

Planning on three generations of g-2 publications:

- 1-2 x BNL (~400 ppb) collected in FY18 and aiming for publication in 2019.
- 5-10 x BNL (~200 ppb) collected over FY18+FY19 with publication by end of 2020.
- 20+ x BNL (~140 ppb) collected by end of FY20 with final publication at end of 2021 or early 2022

Muon EDM and CPT/LV physics results in at least two generations.



Conclusions

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

First physics run is over collecting 1- 2 times BNL in rough data. Results will be published in 2019.

Summer upgrades are in progress.

Next physics run will collect 5 - 10 times BNL.

Thank you very much!