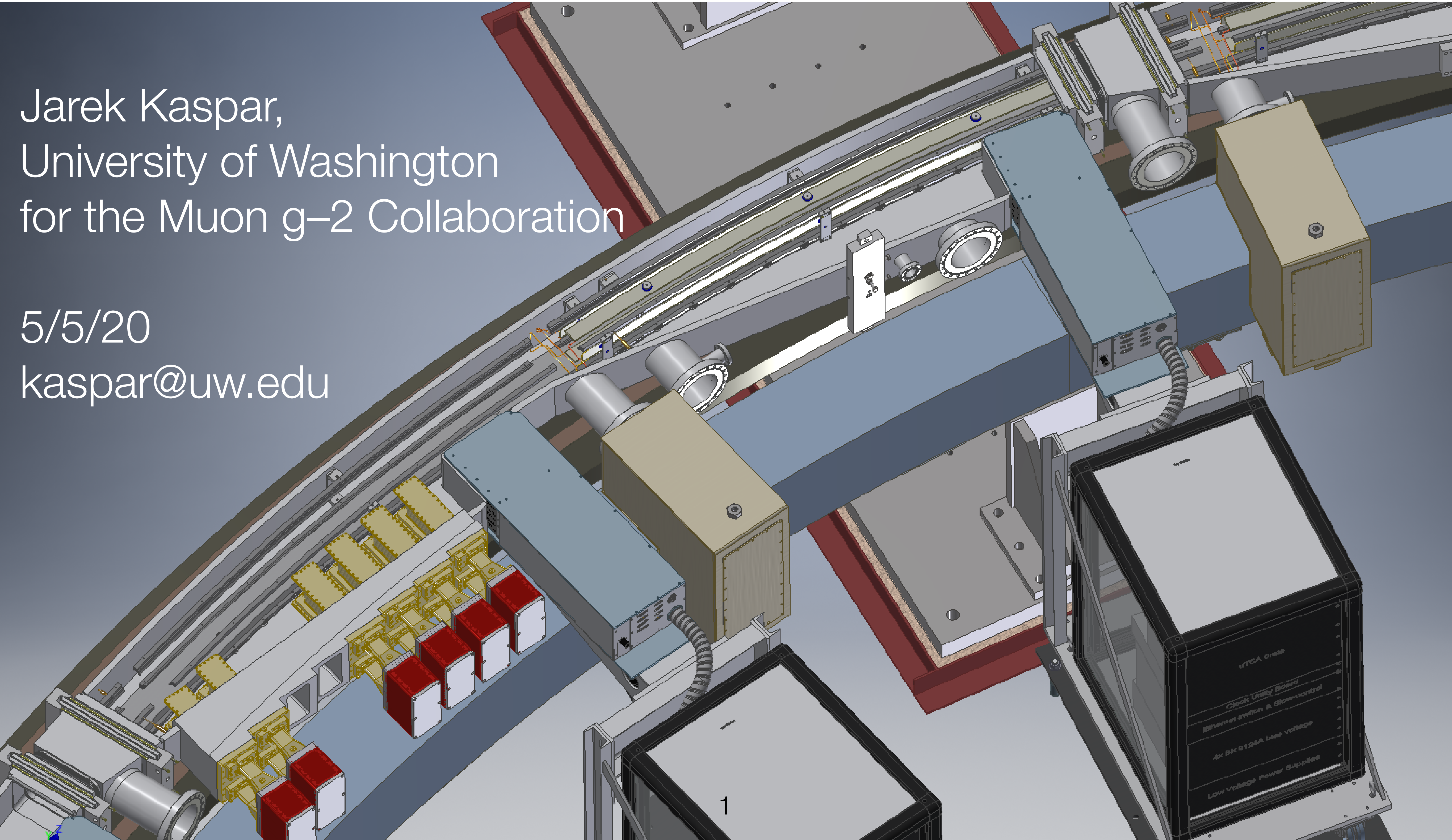
Muon g–2 experiment at Fermilab



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

5/5/20

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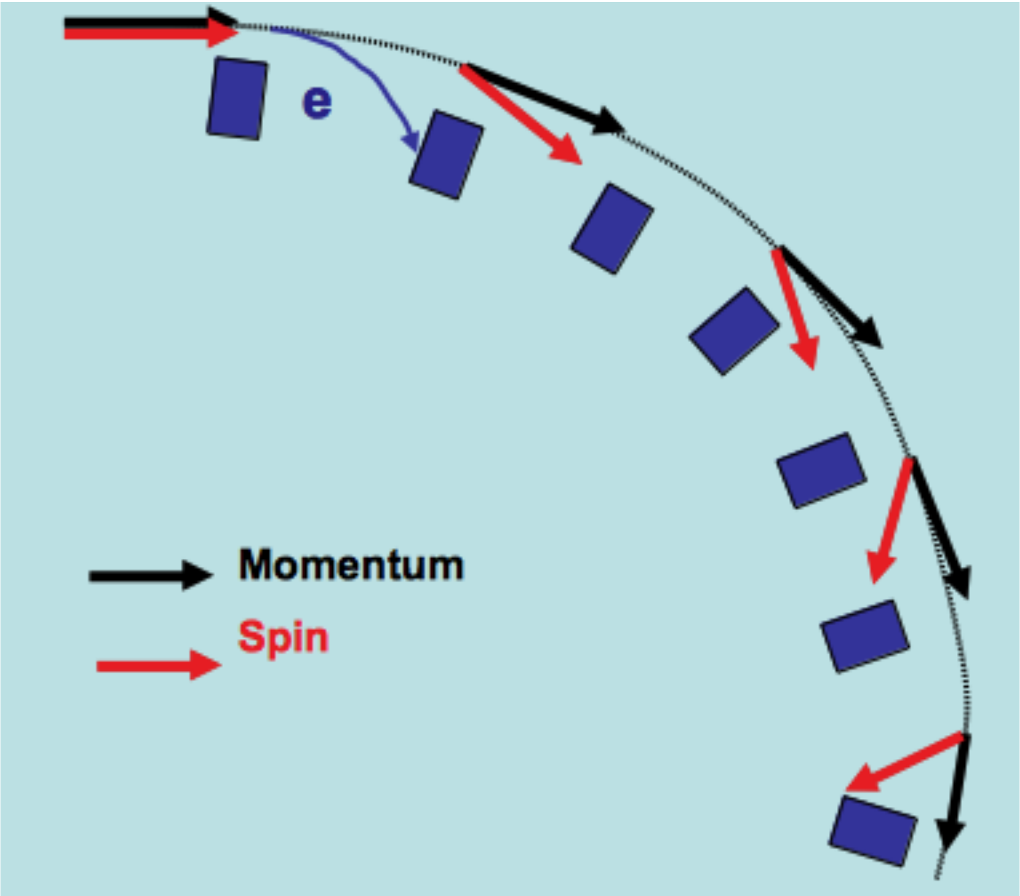
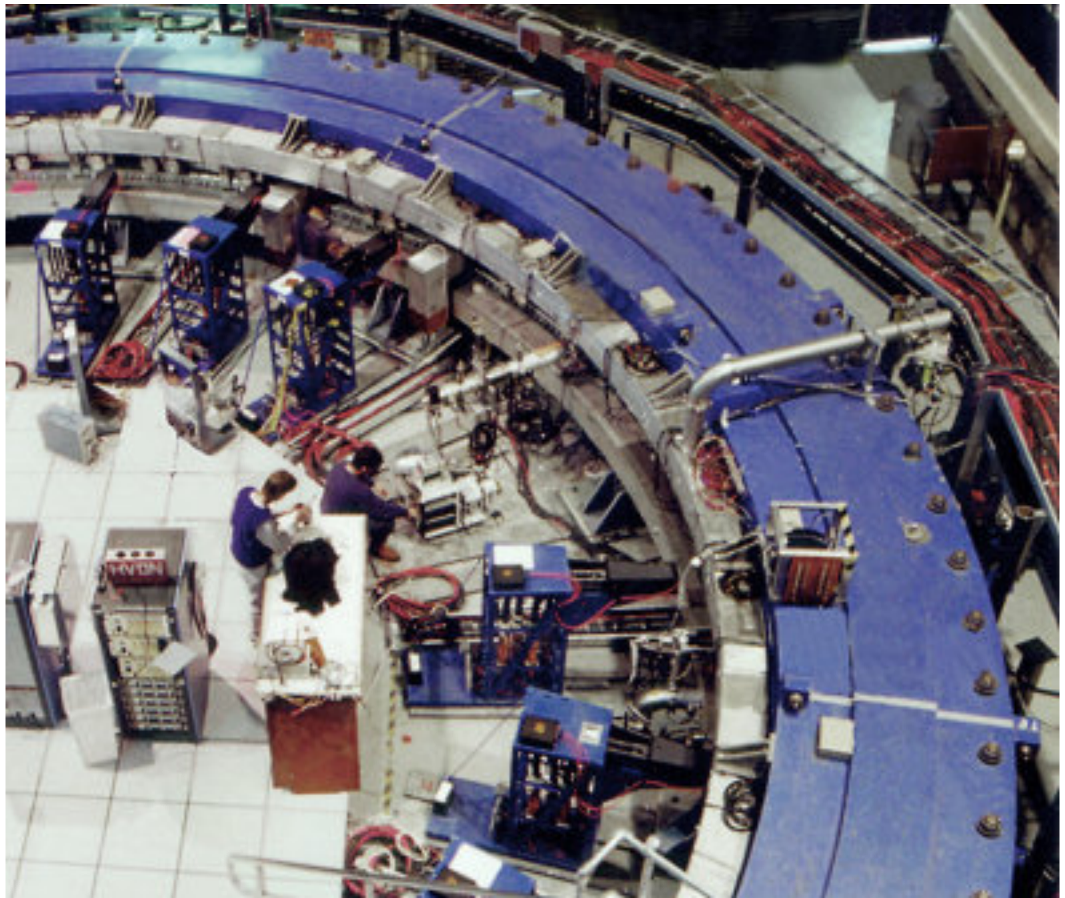
magnetic dipole moment of muon

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



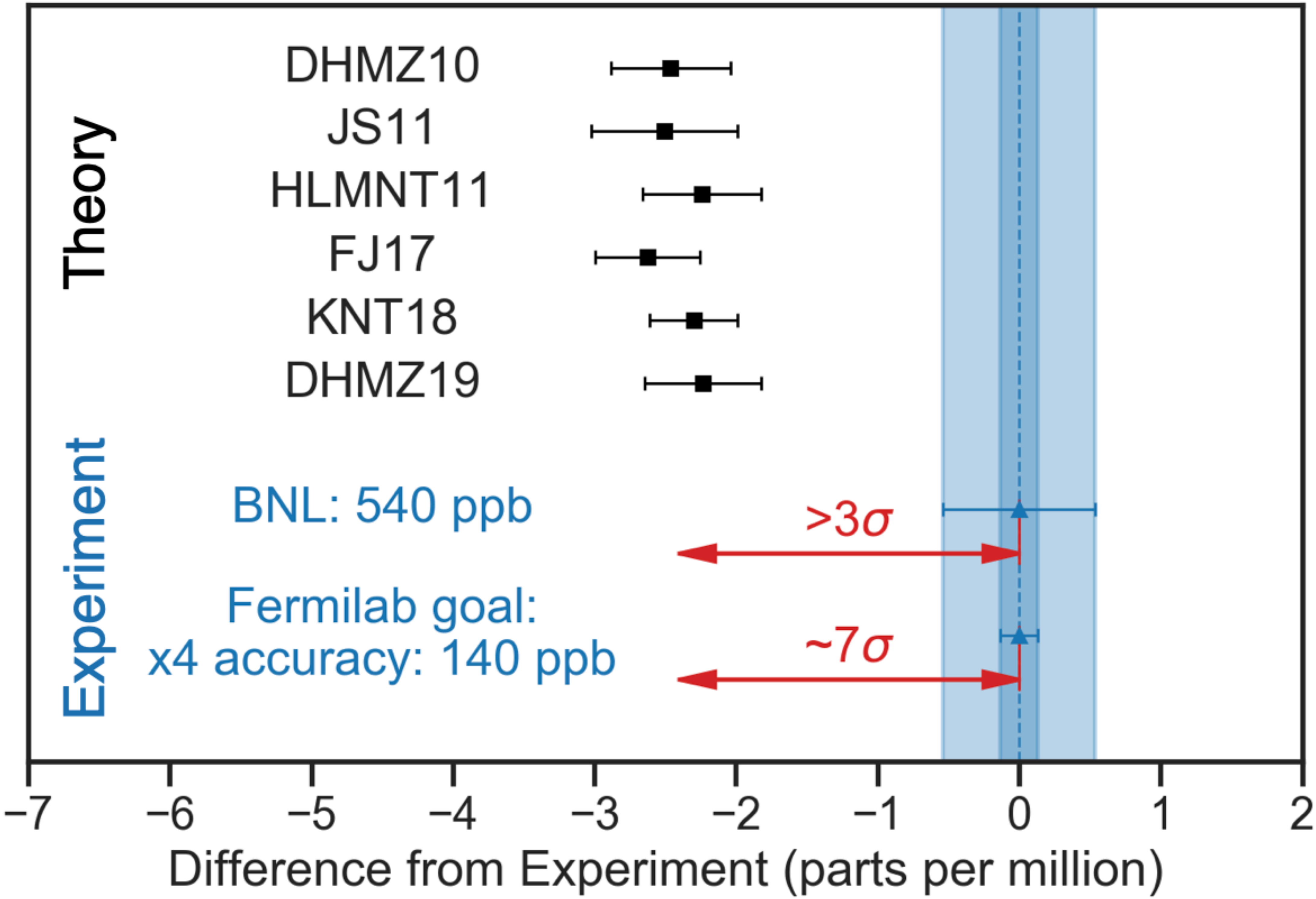


g – 2 experiment at BNL

E821 (1999 - 2006):
a_μ = 0.001 165 920 89 (63) (±0.54 ppm)
And a hint of New Physics ?

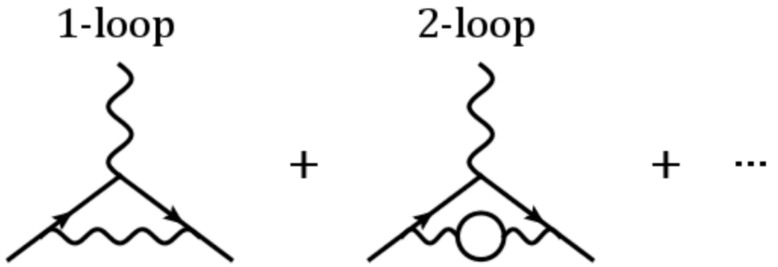
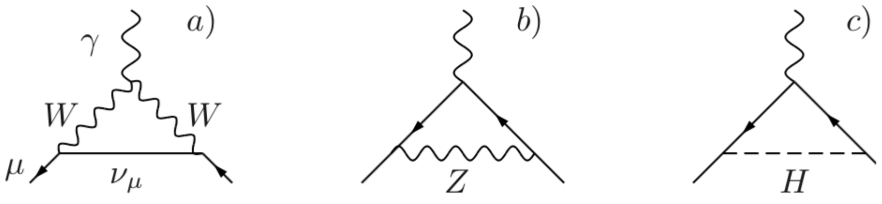
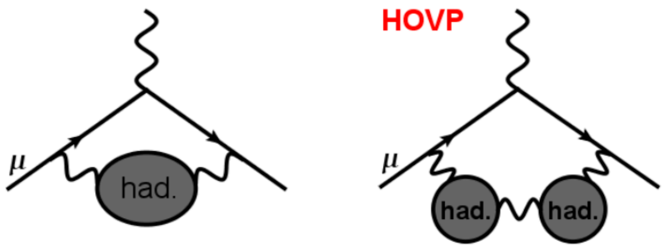
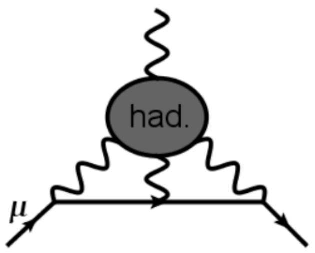
Figure 1.10: A picture from 1984 showing the attendees of the first collaboration meeting to develop BNL *g*-2 experiment. Standing from left: Gordon Danby, John Field, Francis Farley, Emilio Picasso, Frank Krienen. Kneeling from left: John Bailey, Vernon Hughes and Fred Combley.

Standard Model prediction



SM uncertainty dominated by hadronic terms

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

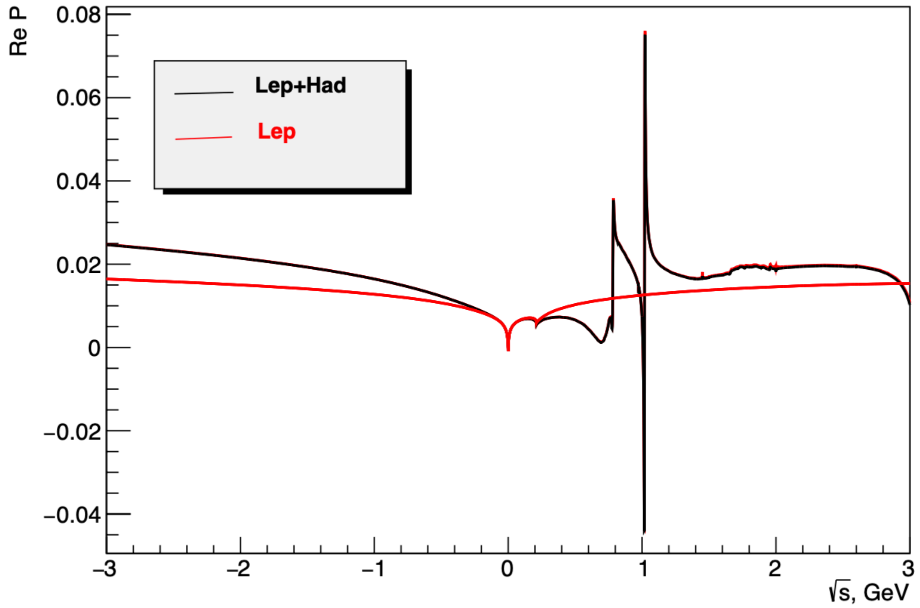
QED		Known to five-loop (12,672 diagrams)	99.99% of a_μ^{SM}	~0.001% of δa_μ^{SM}
EW		Known to two-loop (with m_H known)	0.0001% of a_μ^{SM}	~0.2% of δa_μ^{SM}
HVP		Non-perturbative (data input + lattice)	0.006% of a_μ^{SM}	~47% of δa_μ^{SM}
HLbL		Non-perturbative (data input + model/lattice)	0.0001% of a_μ^{SM}	~53% of δa_μ^{SM}
BSM		? ? ? ? ? ? ?		

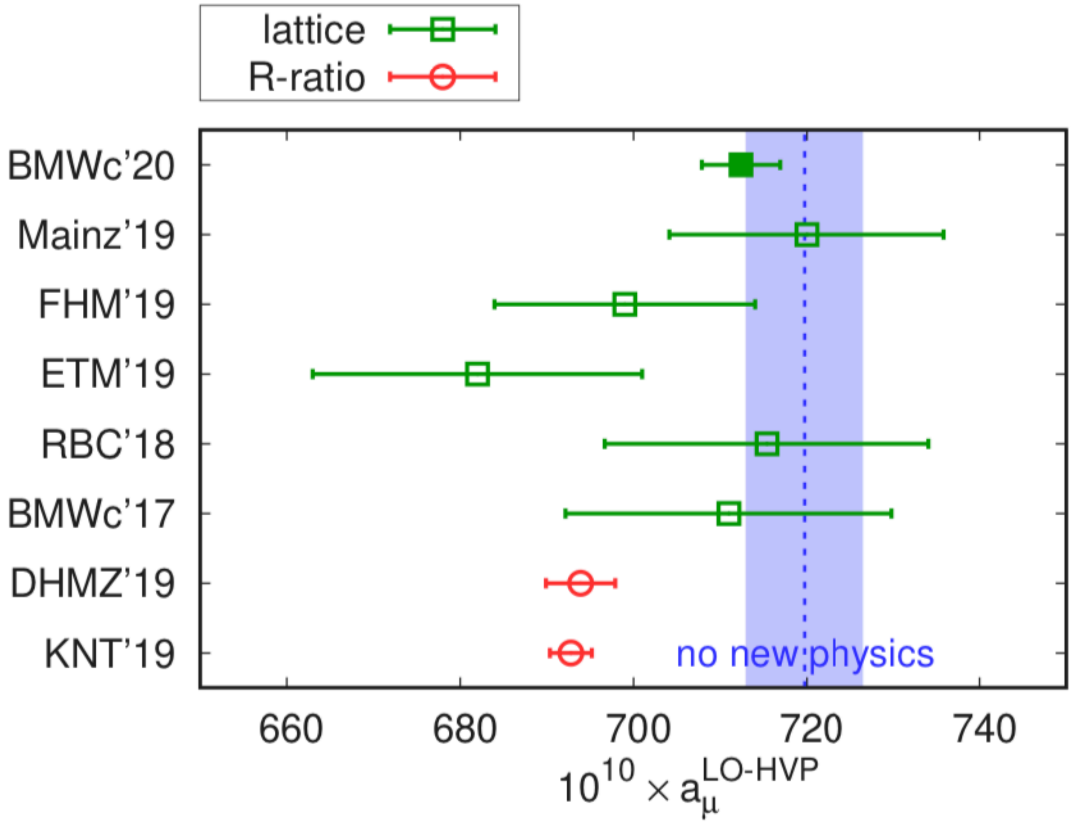
A. Keshavarzi

MUonE exp, and lattice for LOHVP

- MUonE is a novel way to measure the hadronic part of the photon vacuum polarization in the space-like region, using 150 GeV muons: μe -> μe
- the lattice caluculation is becoming competitive on LO HVP, too.

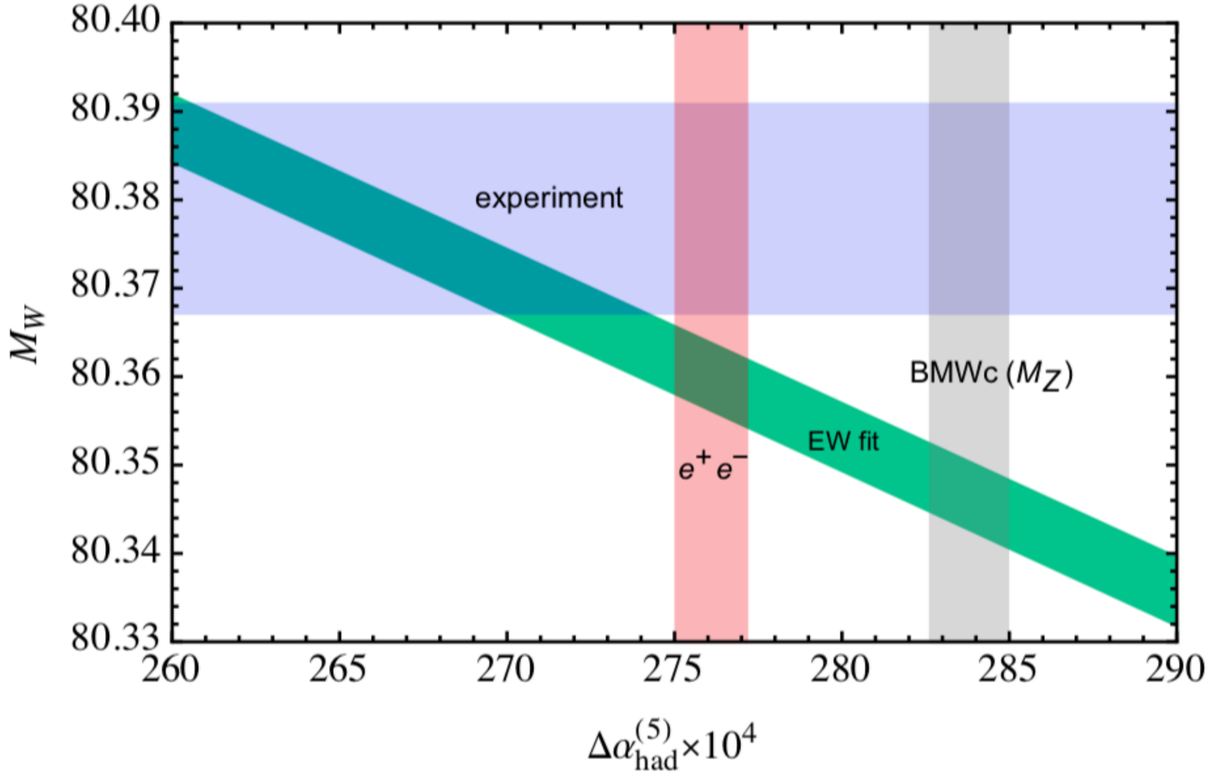
https://arxiv.org/abs/1811.11466





https://arxiv.org/abs/2002.12347

https://arxiv.org/abs/2003.04886

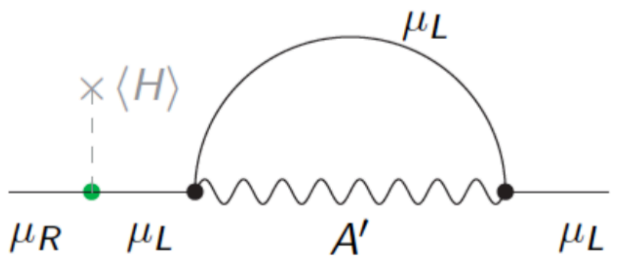


Many BSM candidates, no leader.

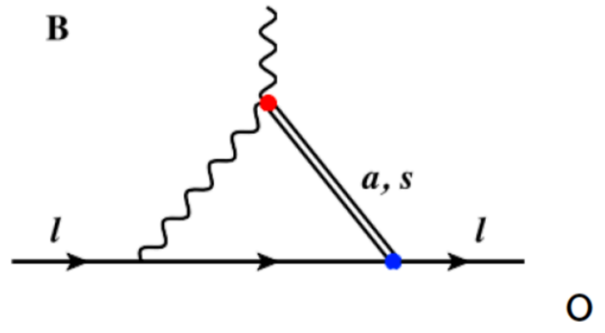
In general, possible theories to explain $g-2$ can be split into two scenarios:

Light new physics

- Dark photons → very specific model, only two parameters



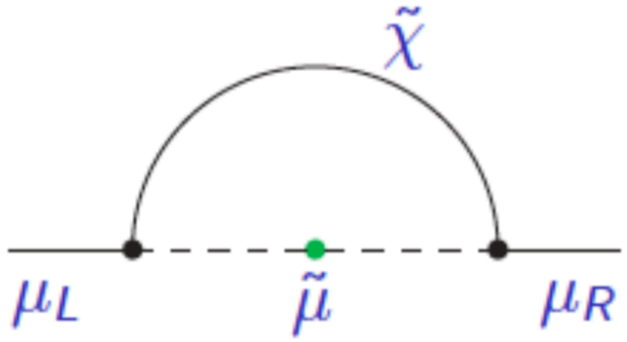
- Dark Z → tuned to resolve $g-2$
- Axion-like particles → must have very particular mass/coupling combinations



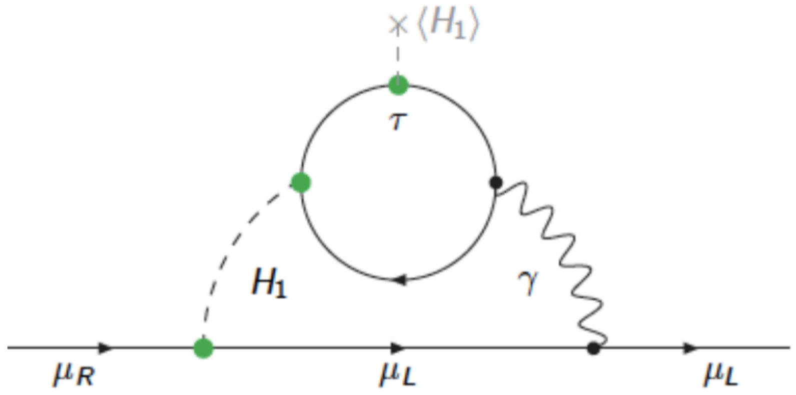
[Marciano, Masiero, Paradisi, Passera '16]

Heavy new physics

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

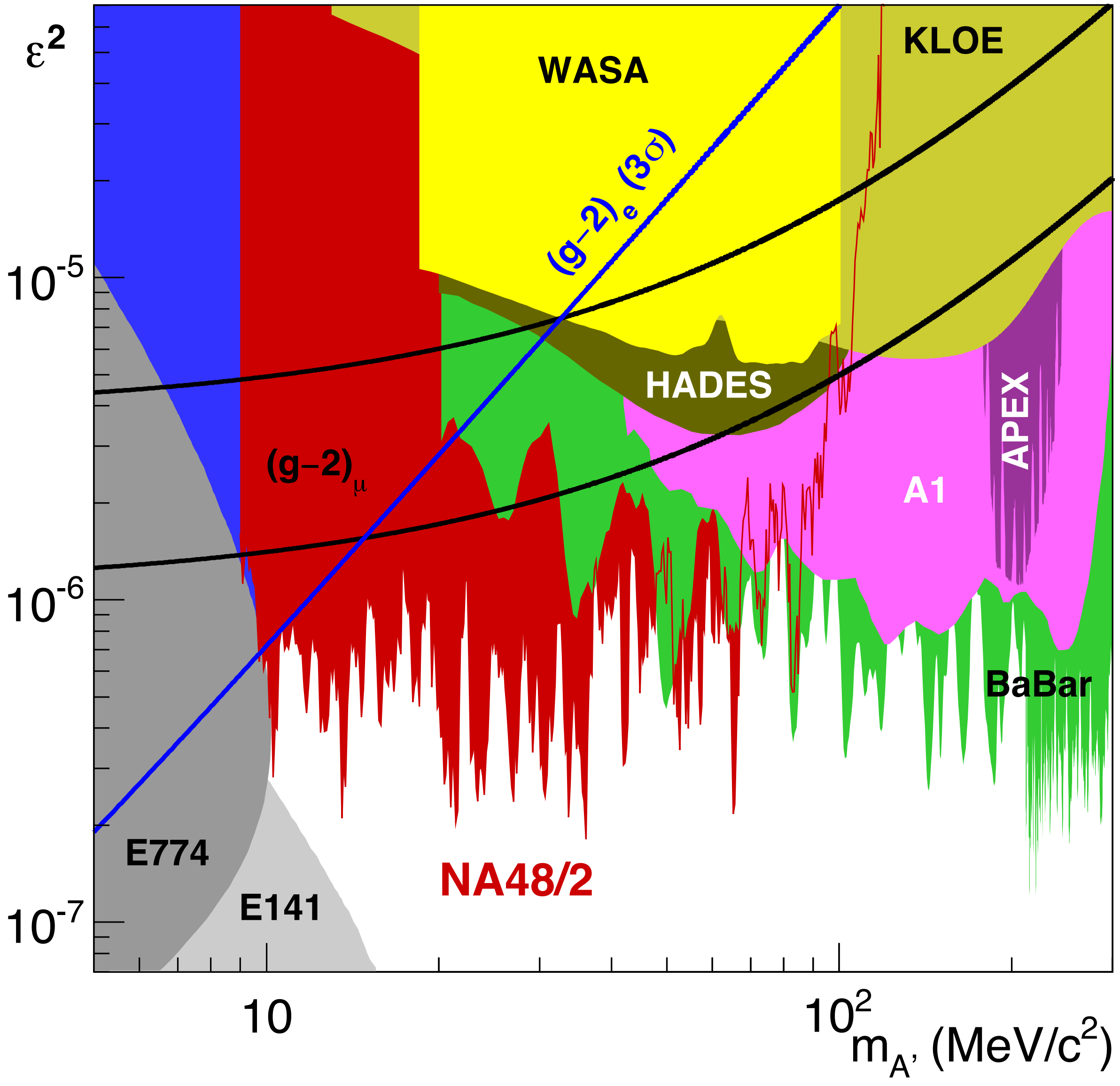


- Two-Higgs doublet models → can explain g-2 in very small, specific parameter region



D. Stoeckinger, via A. Keshavarzi

An example of difficulties any BSM candidate face



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

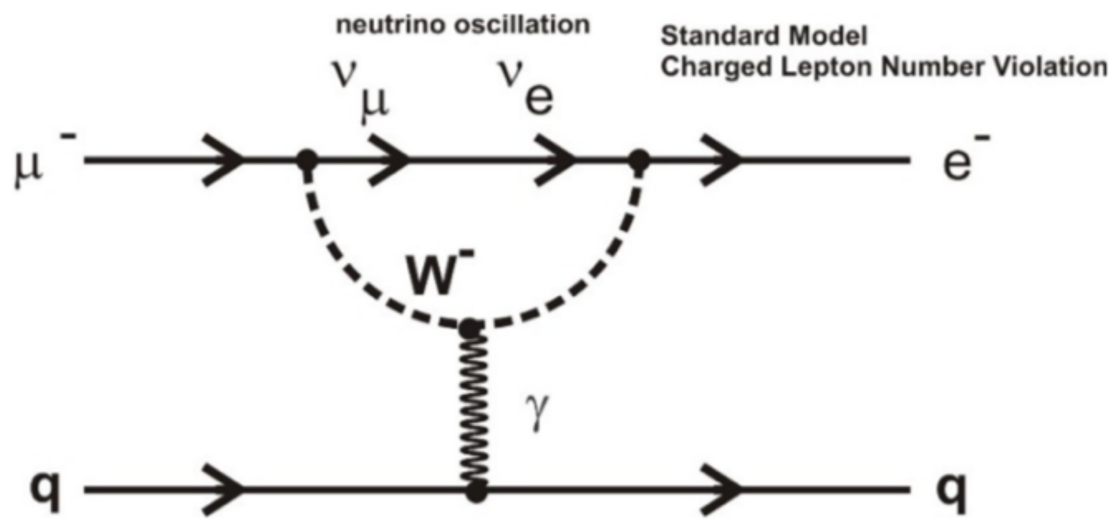
In 2018, Berkeley improved α measurement from Cs-133, and put tension on electron g-2.

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)

Alternative BSM search: charged lepton flavor violation

- Muon g-2 SM prediction is known extremely well
- Lepton flavor violation is observed in neutrinos
- Charged lepton flavor violation is a good candidate for BSM search
- SM contribution O(1e-50), neutrino mass is really small

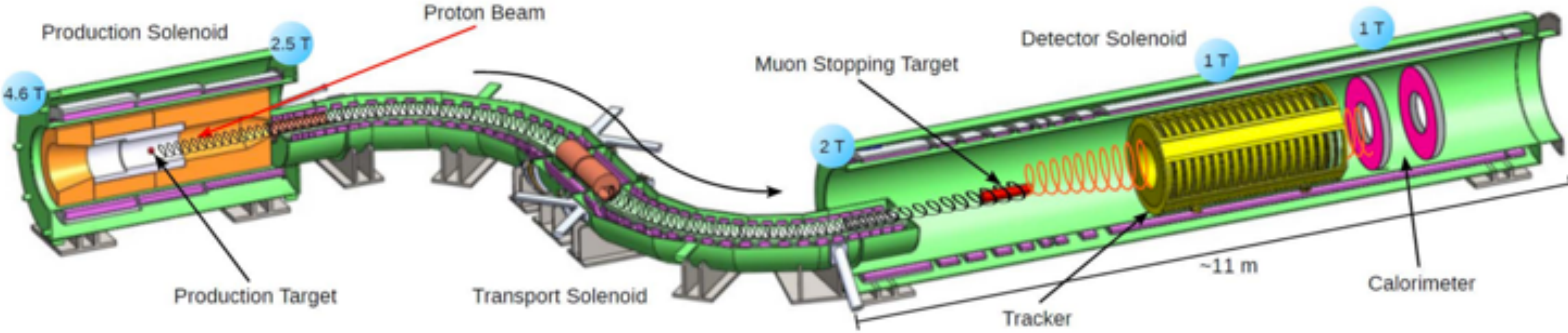


Mu2e experiment at Fermilab

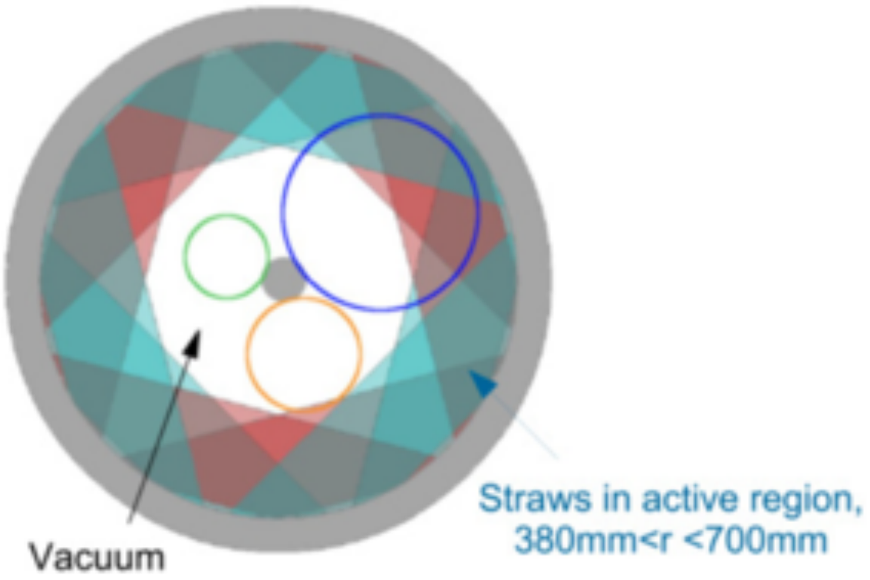
- Search for coherent conversion of muons to electrons in the field of a nucleus

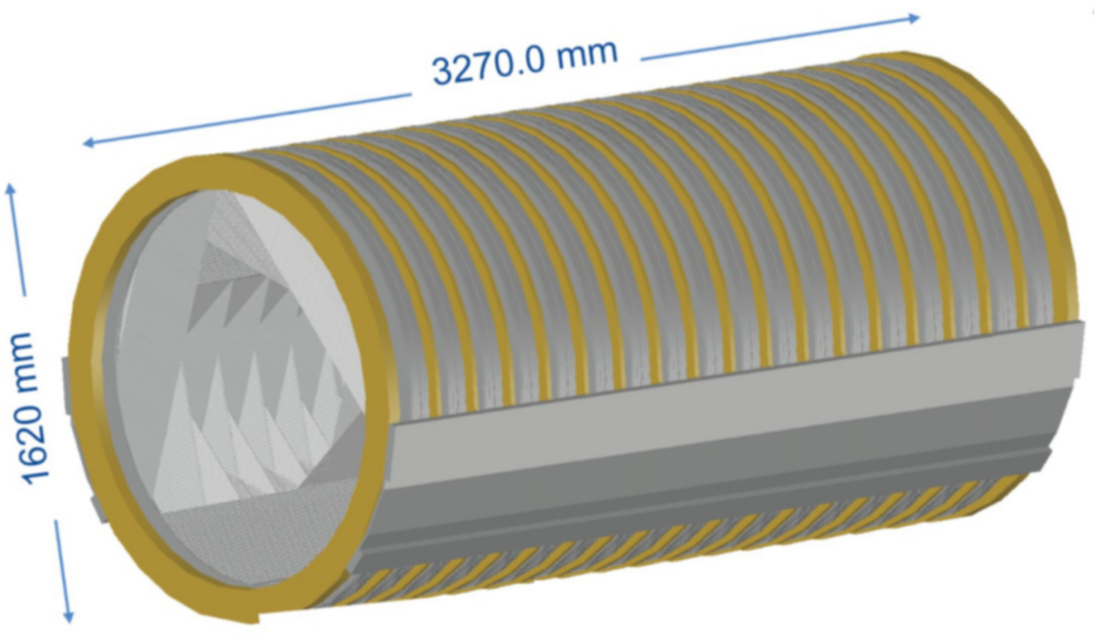
$$R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)}$$

- Goal is a sensitivity to branching ratios of 3e-17, 4 orders of magnitude improvement over the previous effort



Mu2e signal is 104.97MeV electrons





Key to the experiment is controlling backgrounds:

- beam related $\pi^- N \to \gamma N', \gamma \to e^+ e^-$
- cosmic ray $\mu^- \to e^- \nu_\mu \overline{\nu_e}$
- muon decay in orbit $\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$

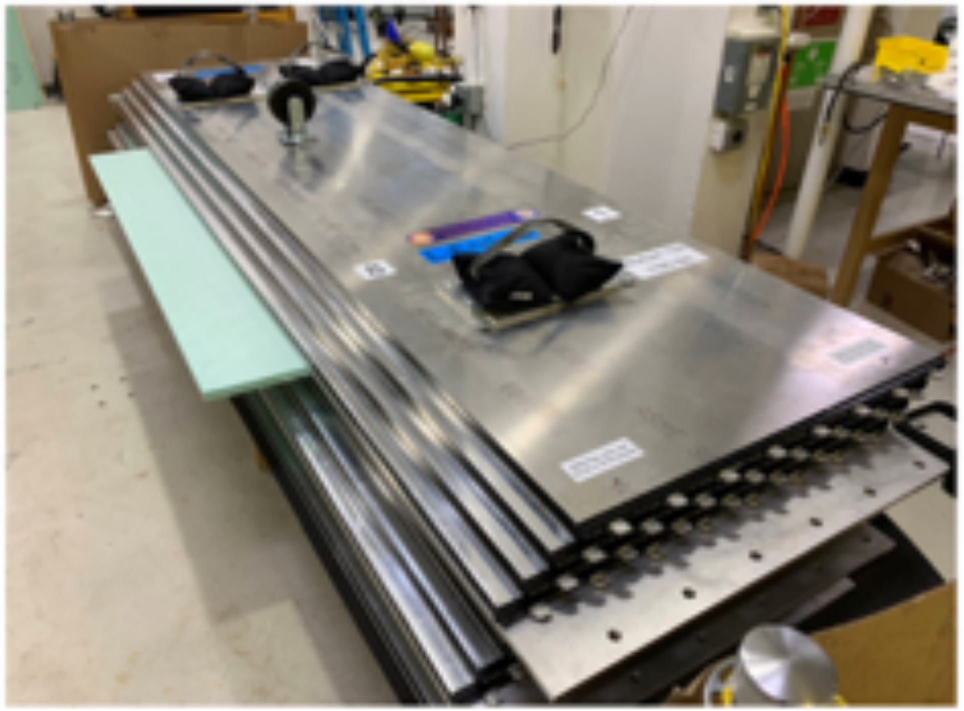
Mu2e schedule

- civil construction is complete
- experiment construction in progress
- installation and commissioning in 2021
- physics data taking in 2023

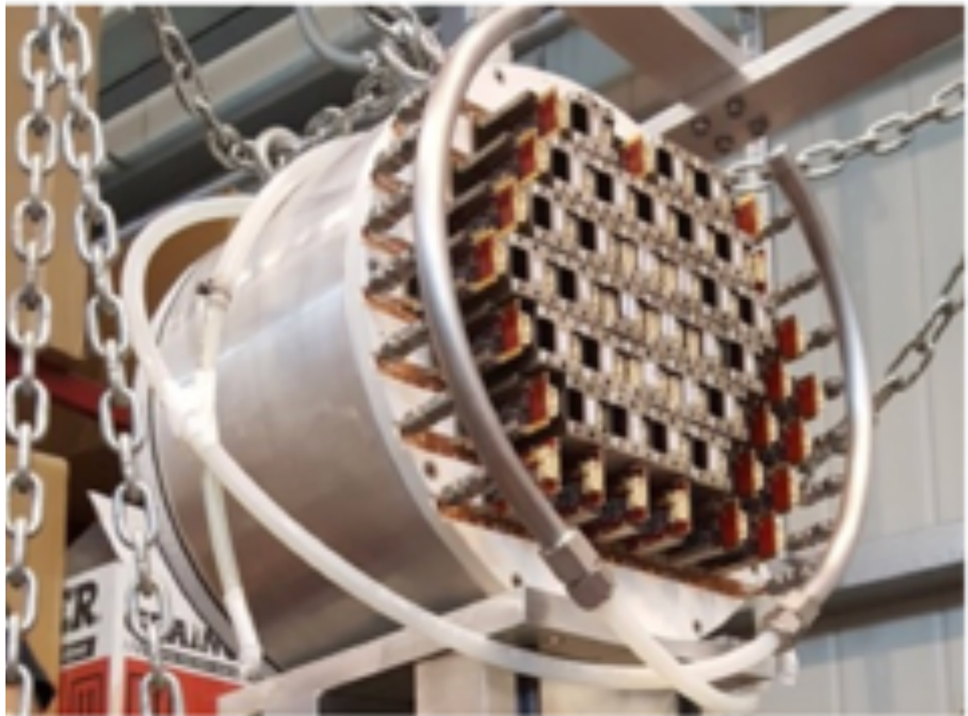
straw tracker plane

transport solenoids

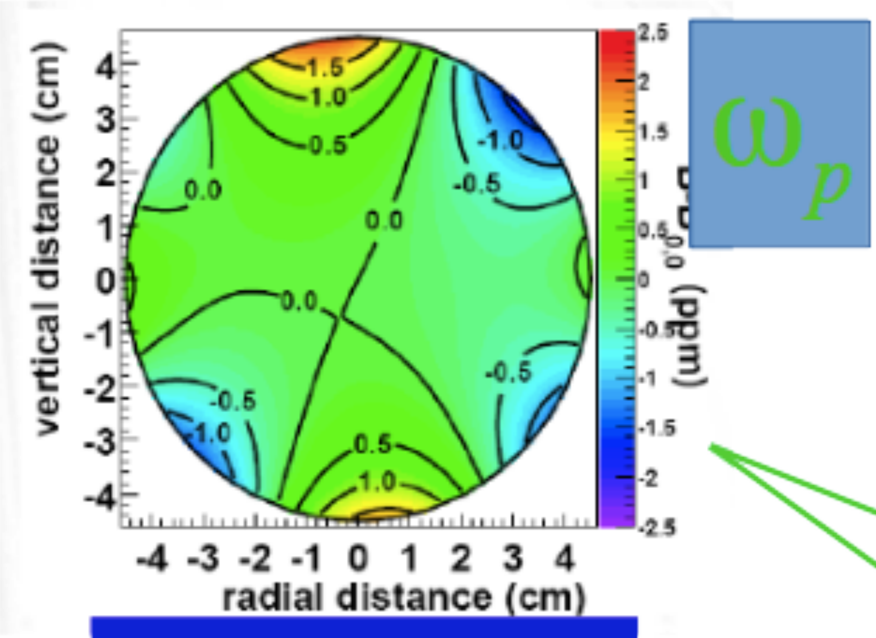
cosmic ray veto



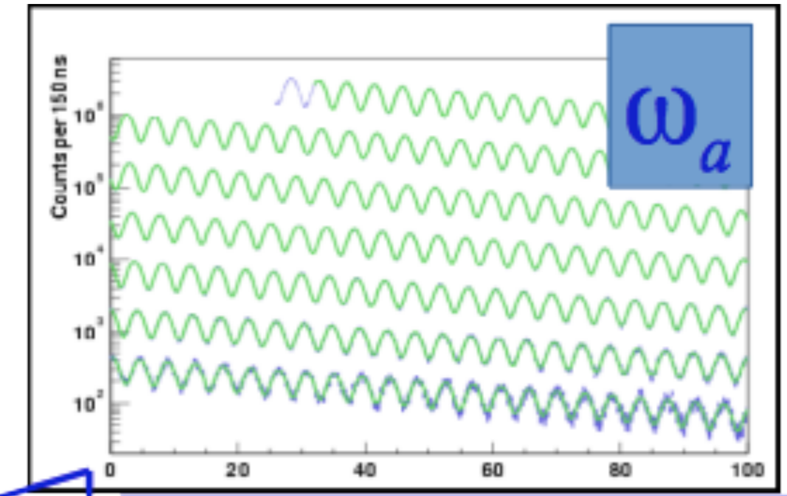
calorimeter prototype



Principles of Muon g-2 measurement

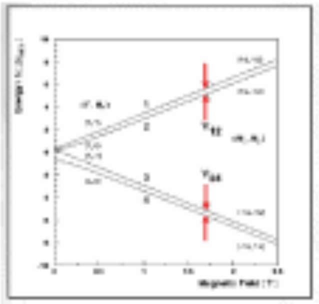


Our "Magnet"



Our conventional Detector, Electronics, and DAQ systems

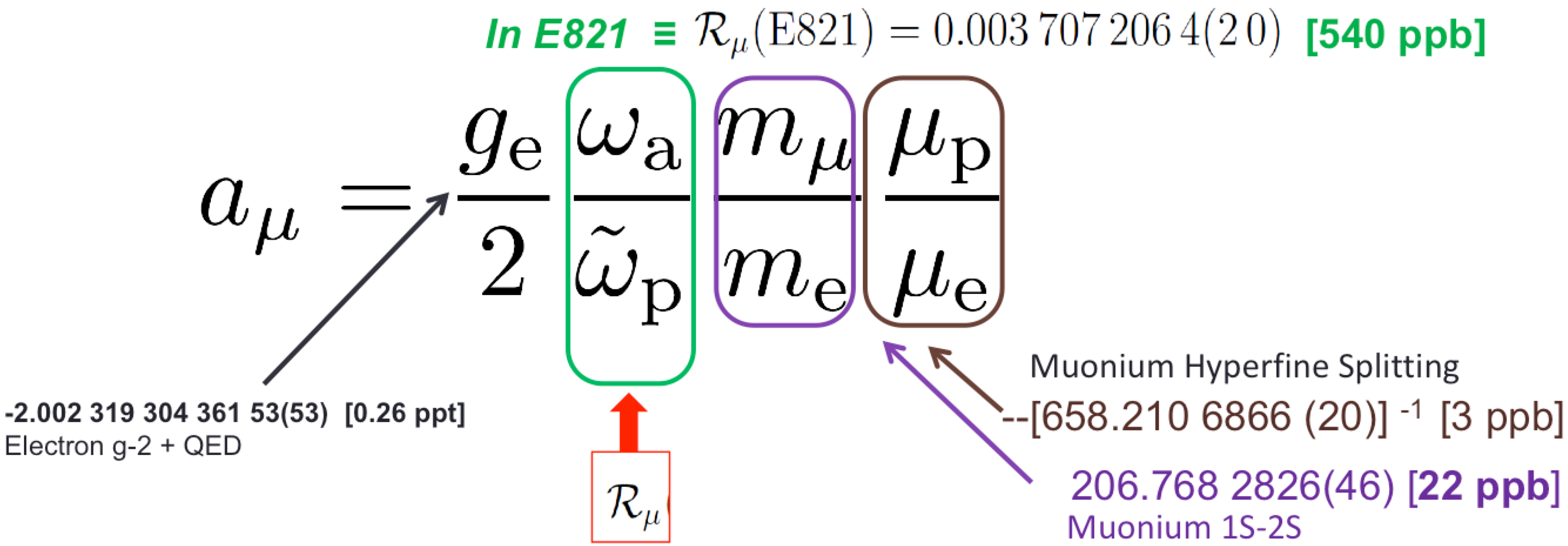
$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$



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]

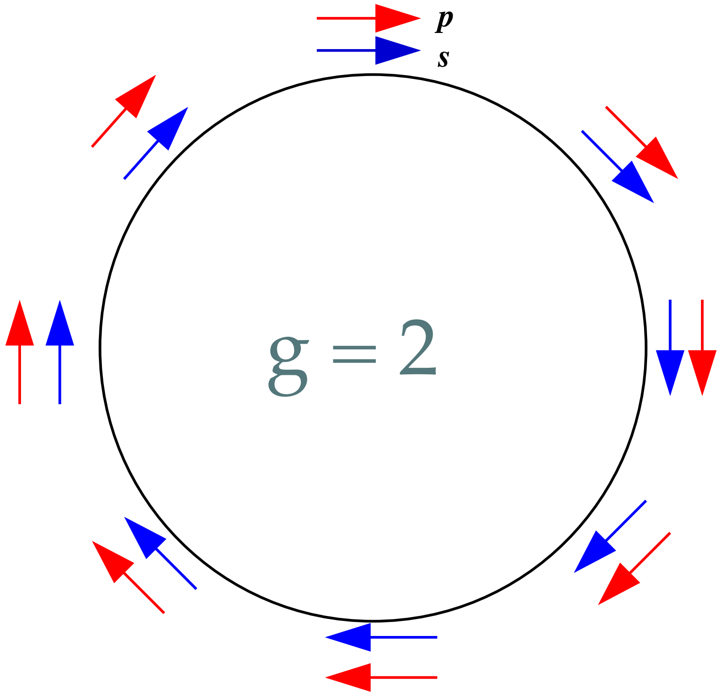
206.768 2826(46) [**22 ppb**]
Muonium 1S-2S

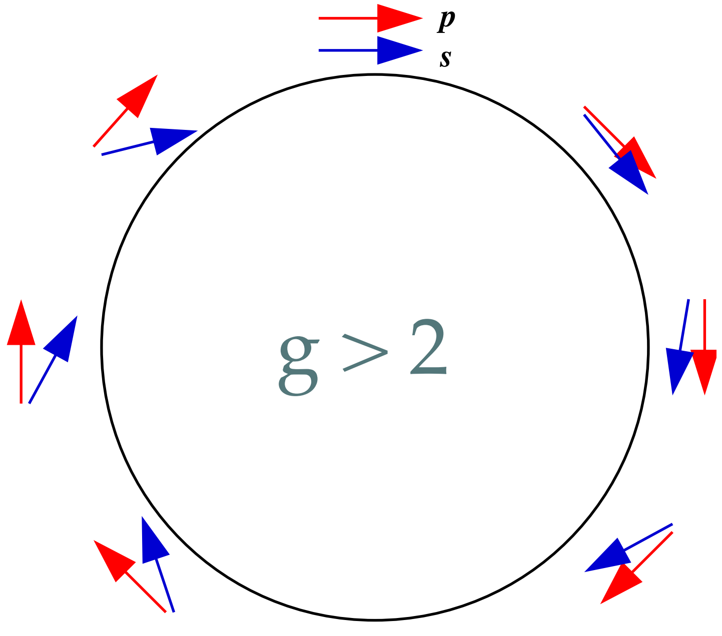
ω_{a} : Precession frequency

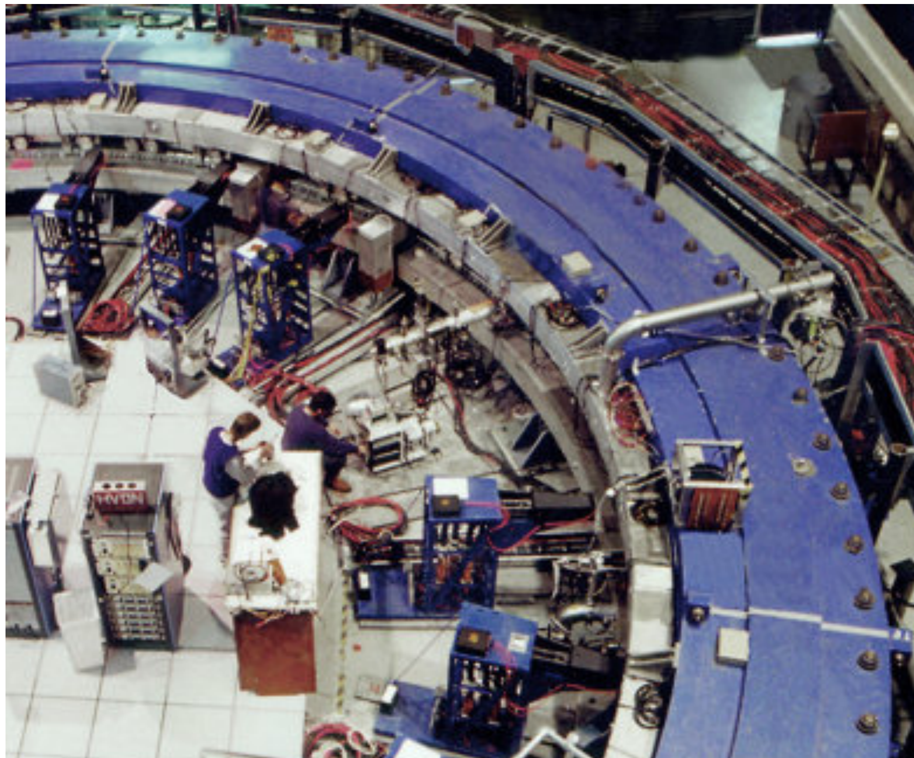
$\tilde{\omega}_{\mathrm{p}}$: Magnetic field (averaged, convoluted with muon distribution)

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



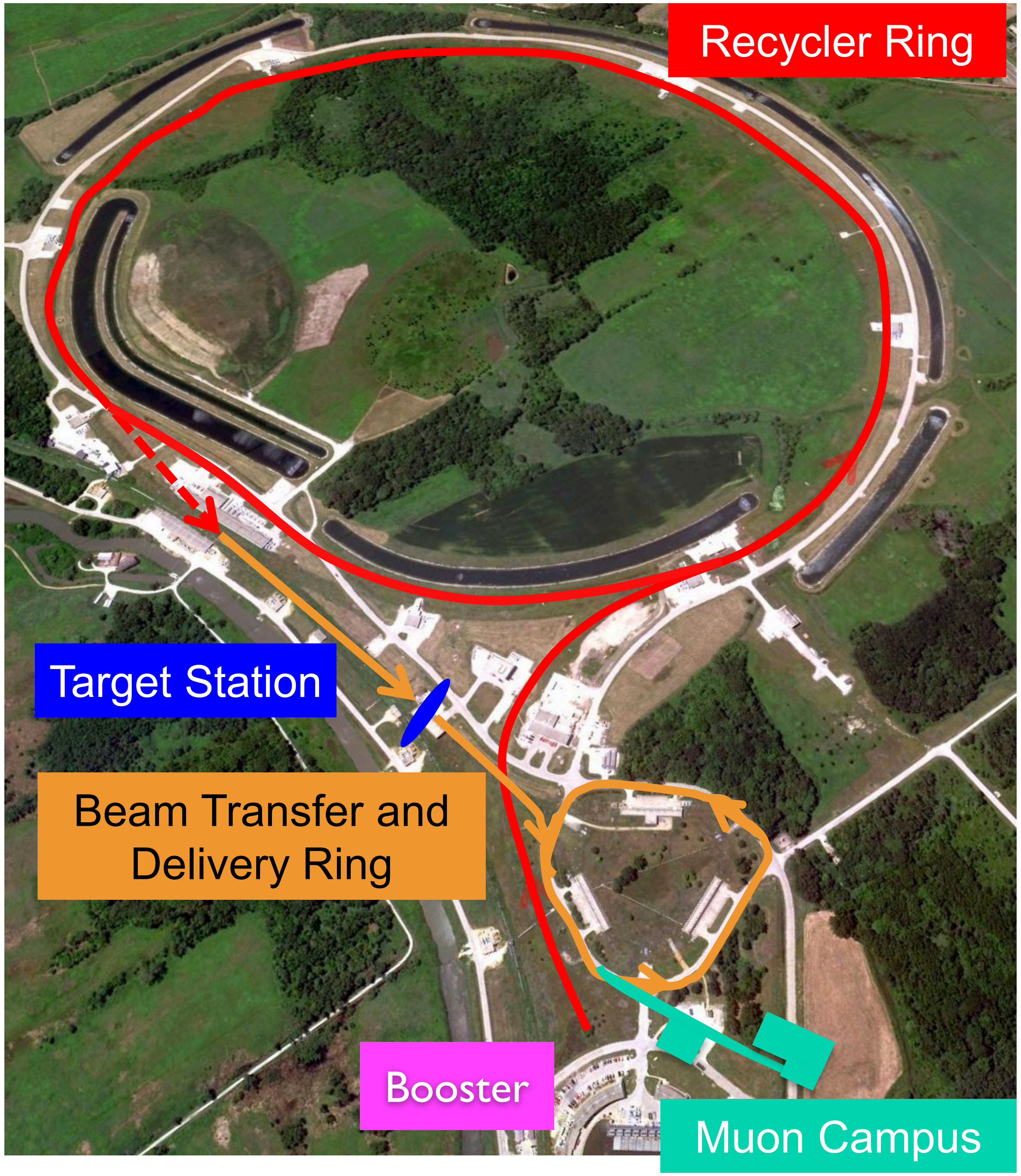




1. source of polarized muons

- 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



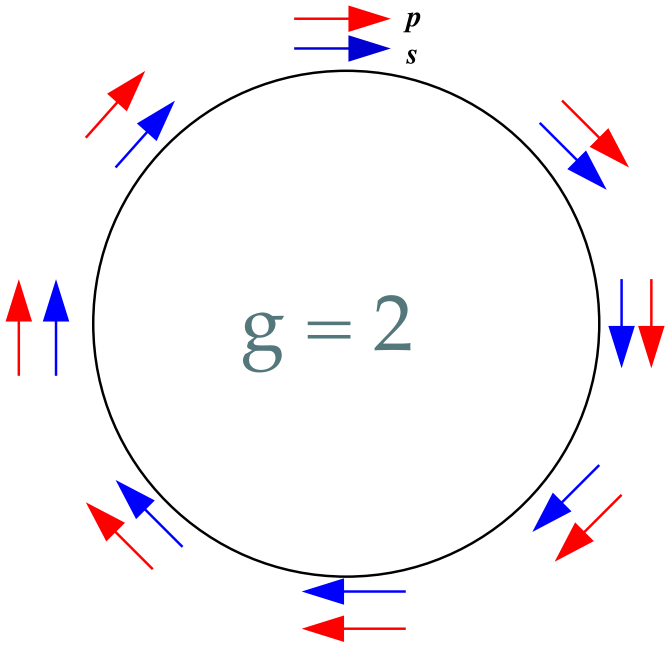
- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
 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

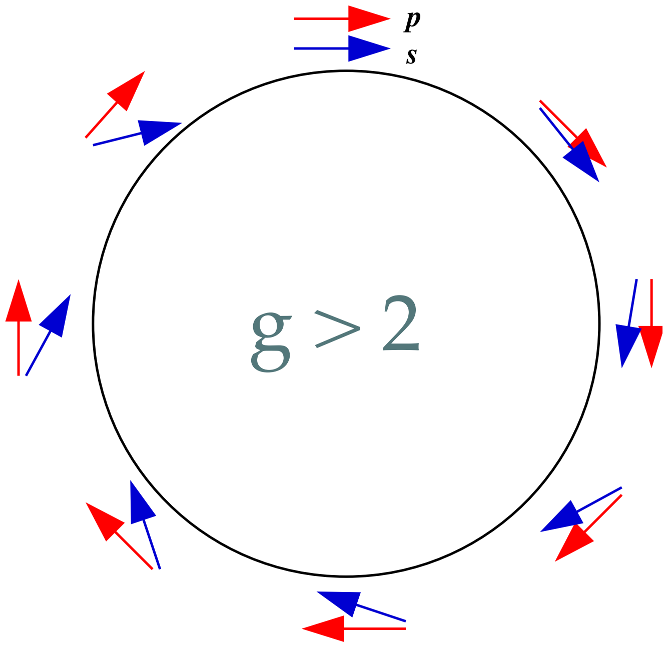
Talks by Diktys Stratakis, and Nathan Froemming

2. precession proportional to *g* – 2

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

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





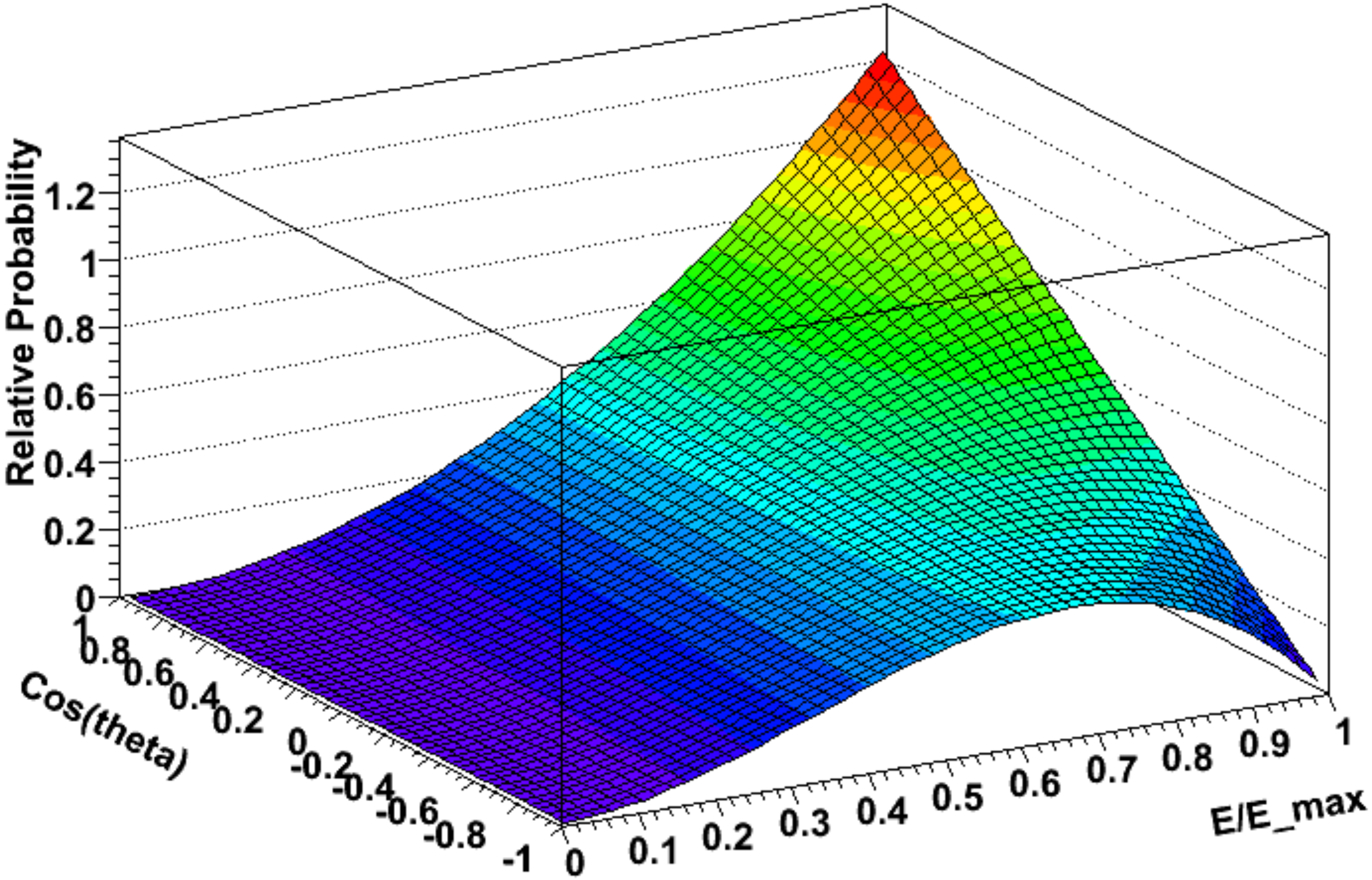
3. magic momentum

- electric quadrupole used for vertical focusing

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

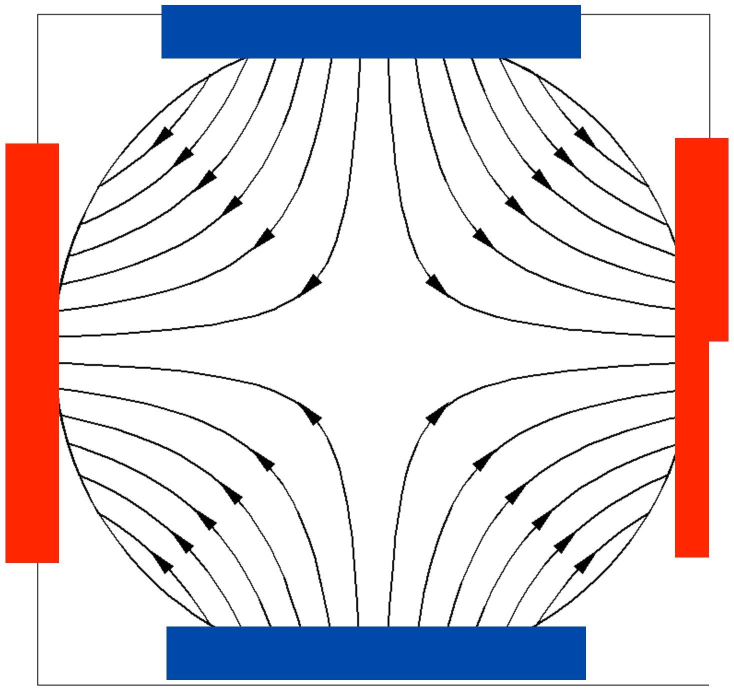
- select γ = 29.3, muon momentum 3.094 GeV
- design difference between FNAL and J-PARC

4. parity violating decay

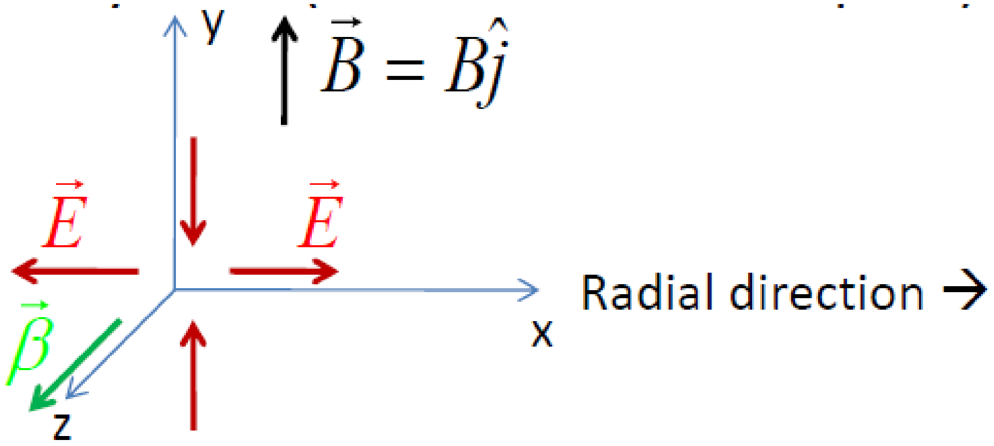


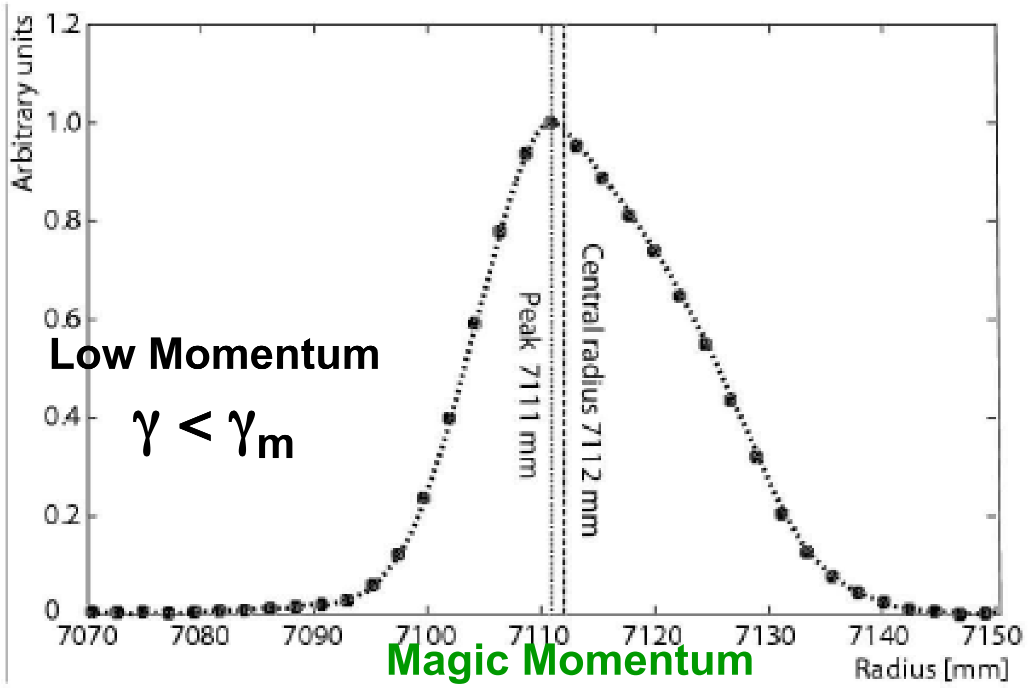
- muon -> electron and two neutrinos
- electron carries information on muon’s spin
- positron prefers spin direction
- electron would prefer opposite direction

systematics associated with focusing E-field



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





Low Momentum

$\gamma < \gamma_m$

Magic Momentum

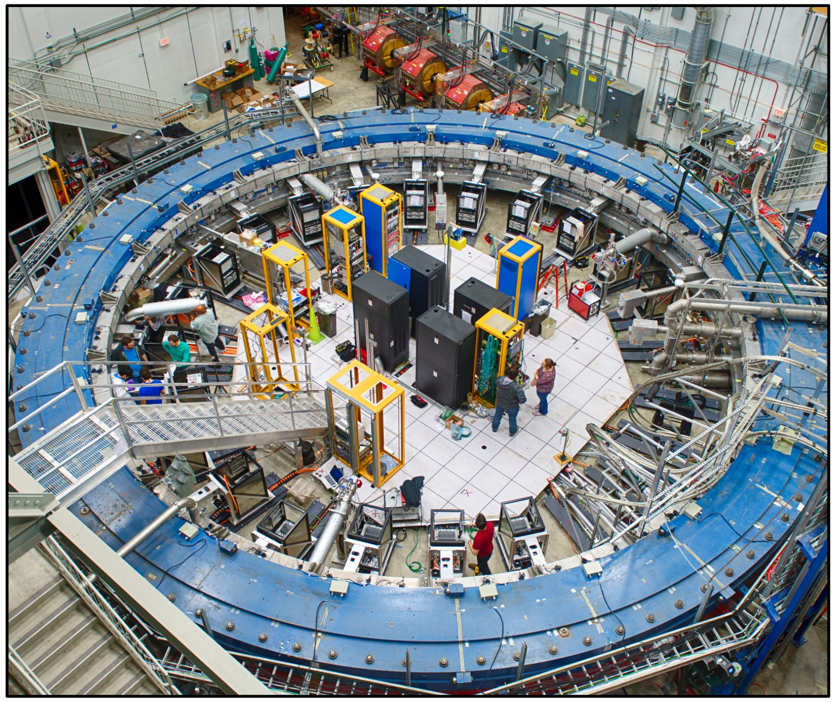
$\gamma \equiv \gamma_m$

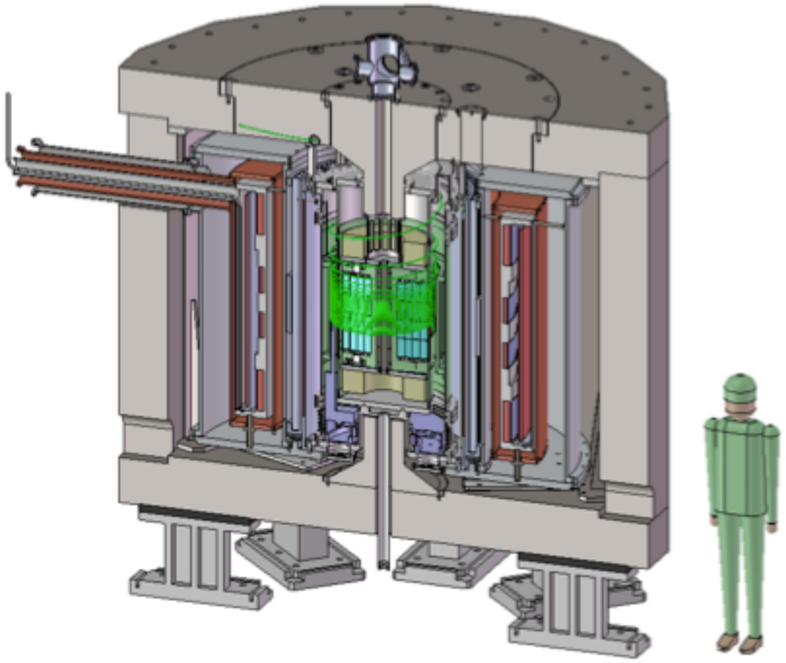
β x *E* and “γ” terms signs both flip depending on momentum

→ No cancellation

→ All off-momentum muons reduce effective a_μ

~0.5 ppm effect, net





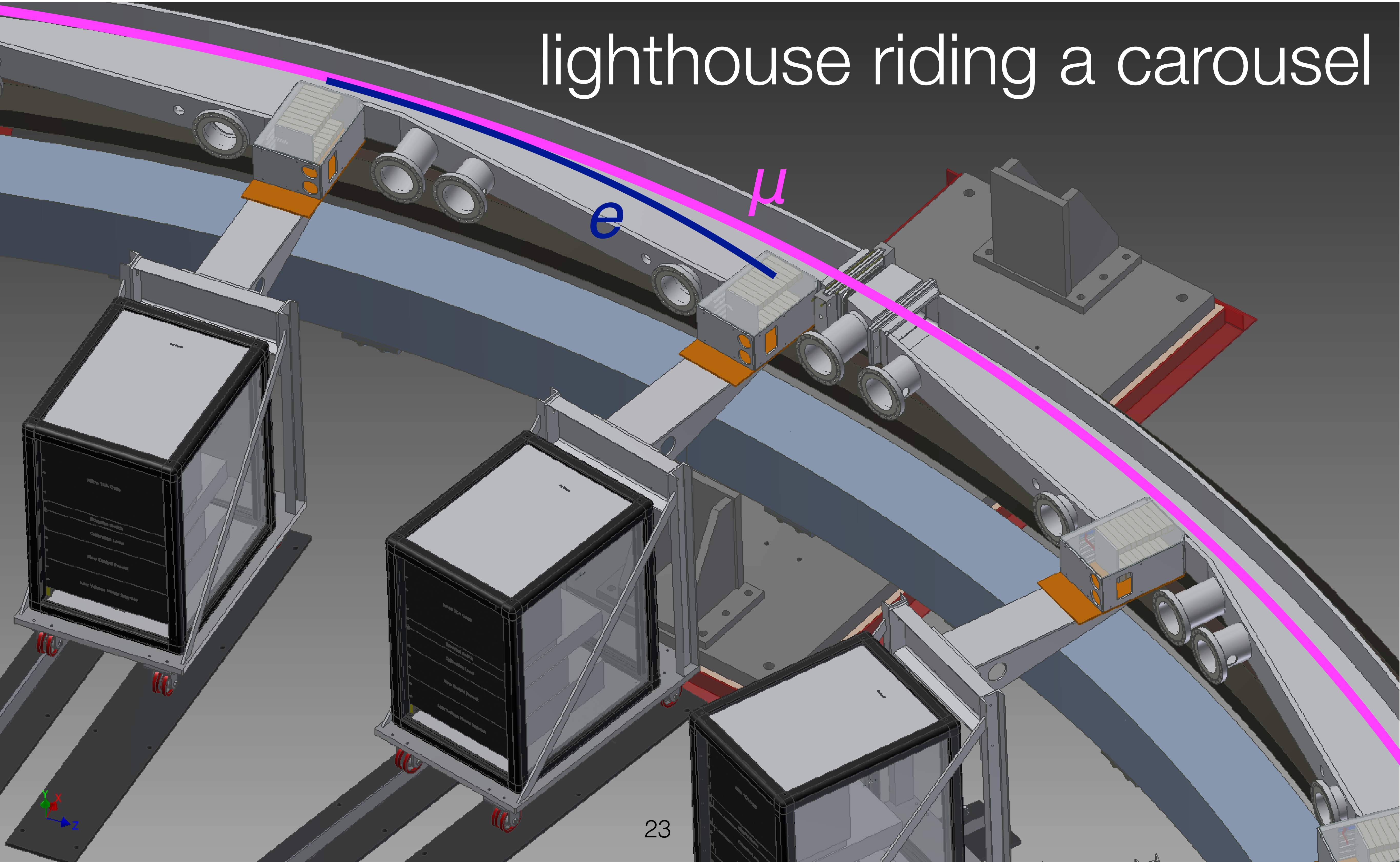
FNAL

- 7 m radius storage ring
- B = 1.45 T
- weak electric focusing
- high-rate 3 GeV/c beam
- spin polarization 97 %
- 100 ppb statistical uncertainty

J-PARC

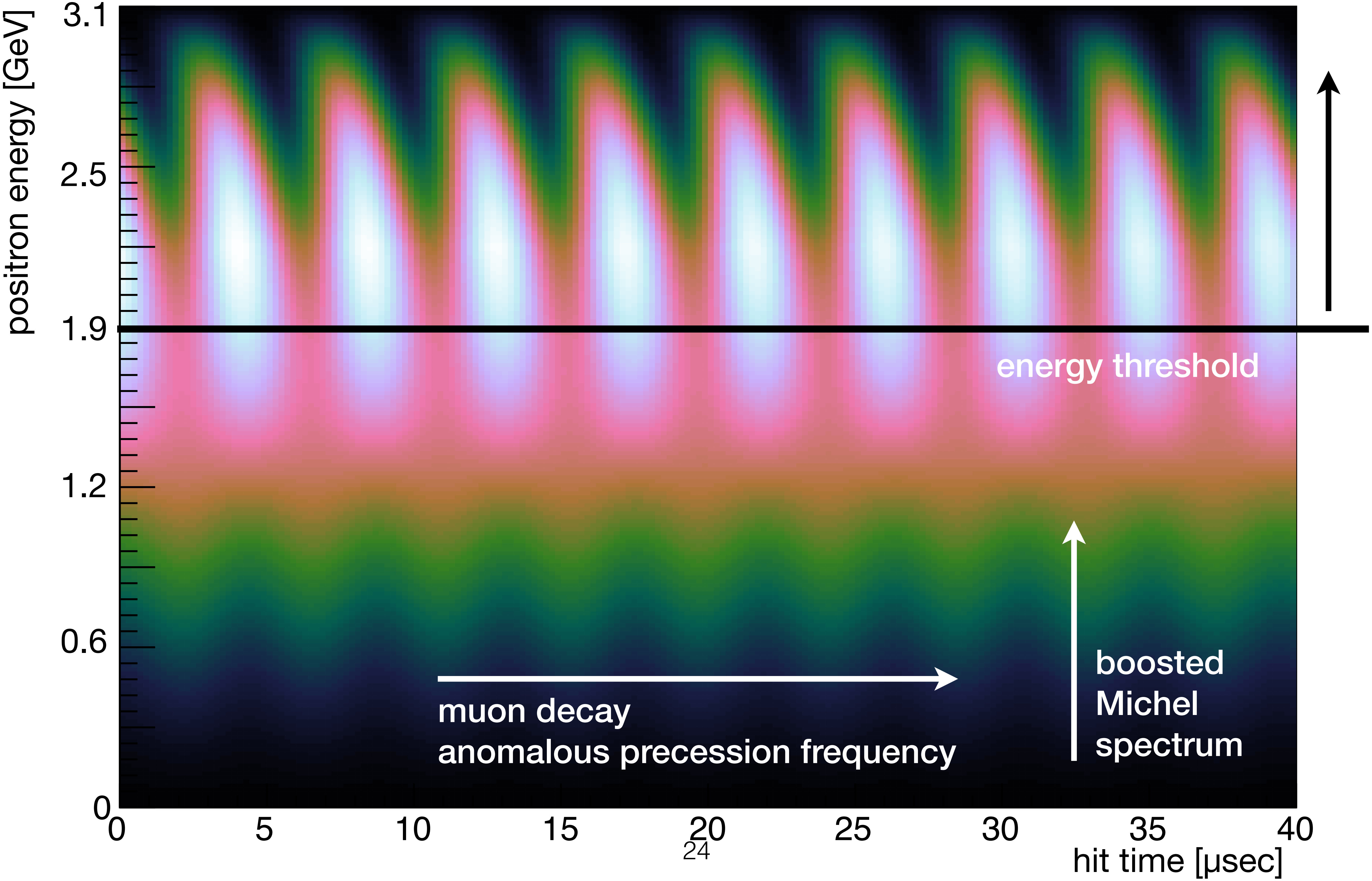
- 0.33 radius storage bottle
- B = 3 T
- no E -field, week mag. focusing
- 0.3 GeV/c beam
- spin polarization 50 %
- 400 ppb statistical uncertainty

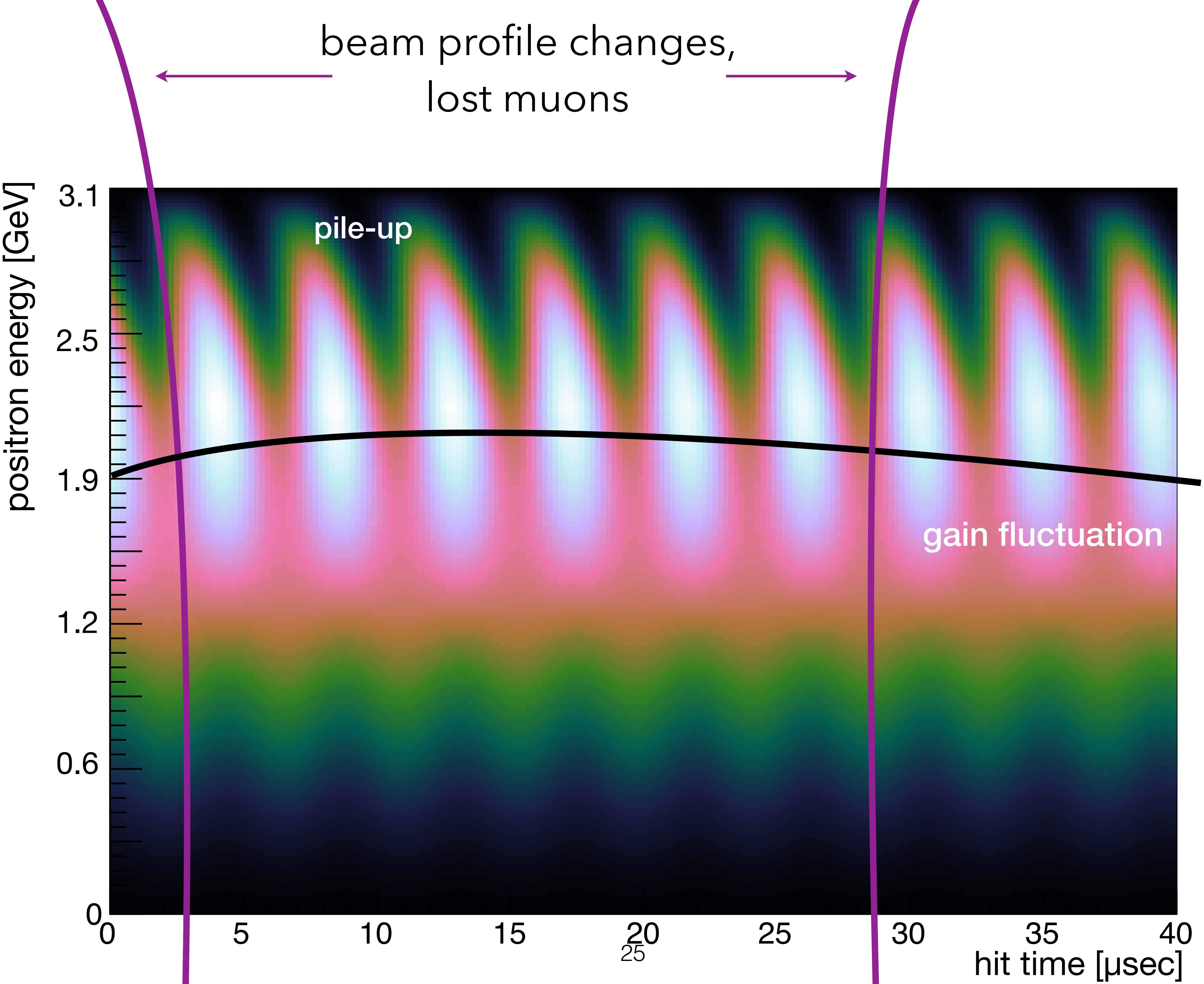
principles of positron detection at FNAL



lighthouse riding a carousel

what does a calorimeter see





beam profile changes,
lost muons

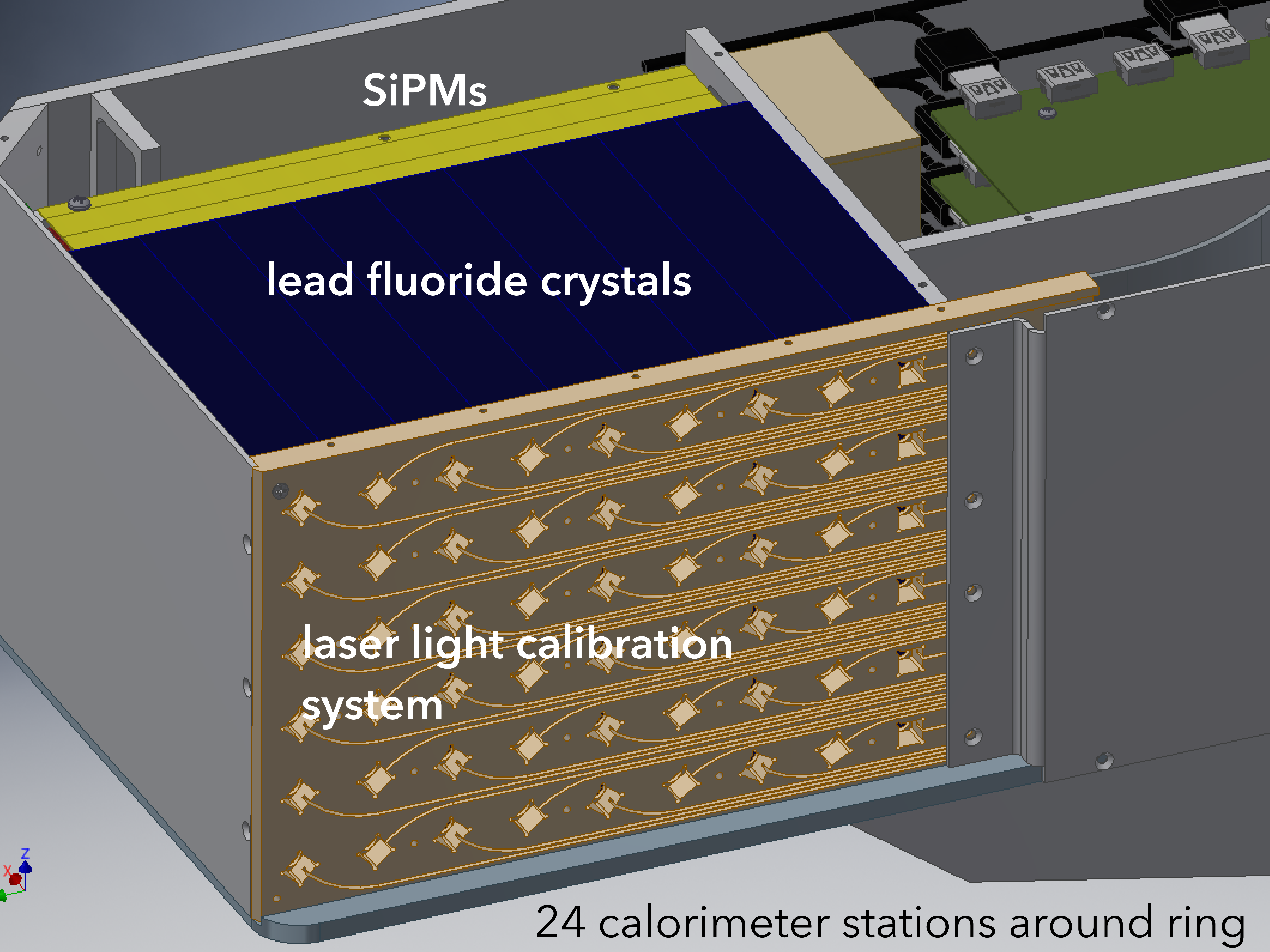
Calorimeter design goals

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.

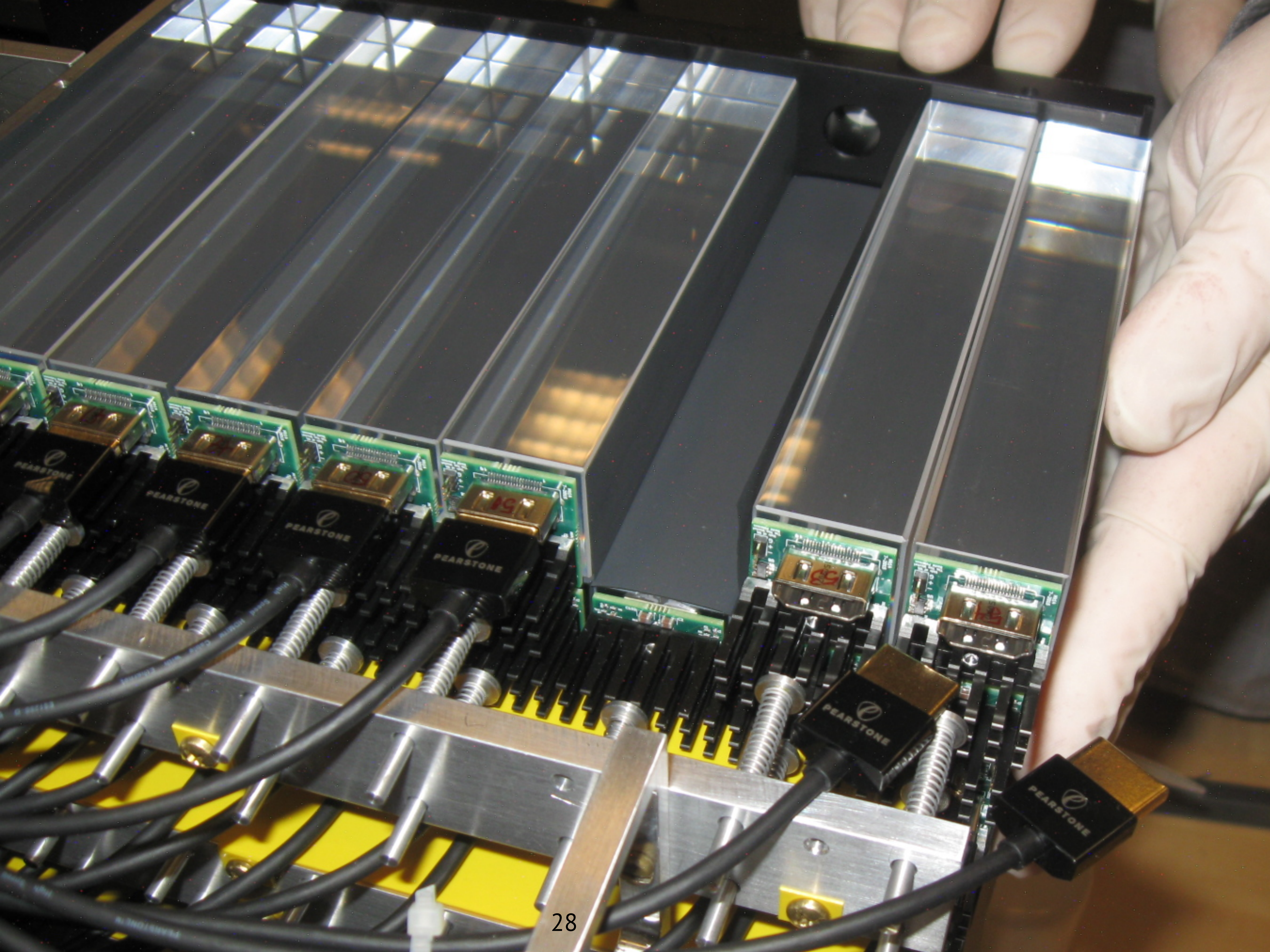
4. 100 % **pile-up separation** above 5 nsec, and 66 % below 5 nsec.


SiPMs

lead fluoride crystals

laser light calibration system

24 calorimeter stations around ring

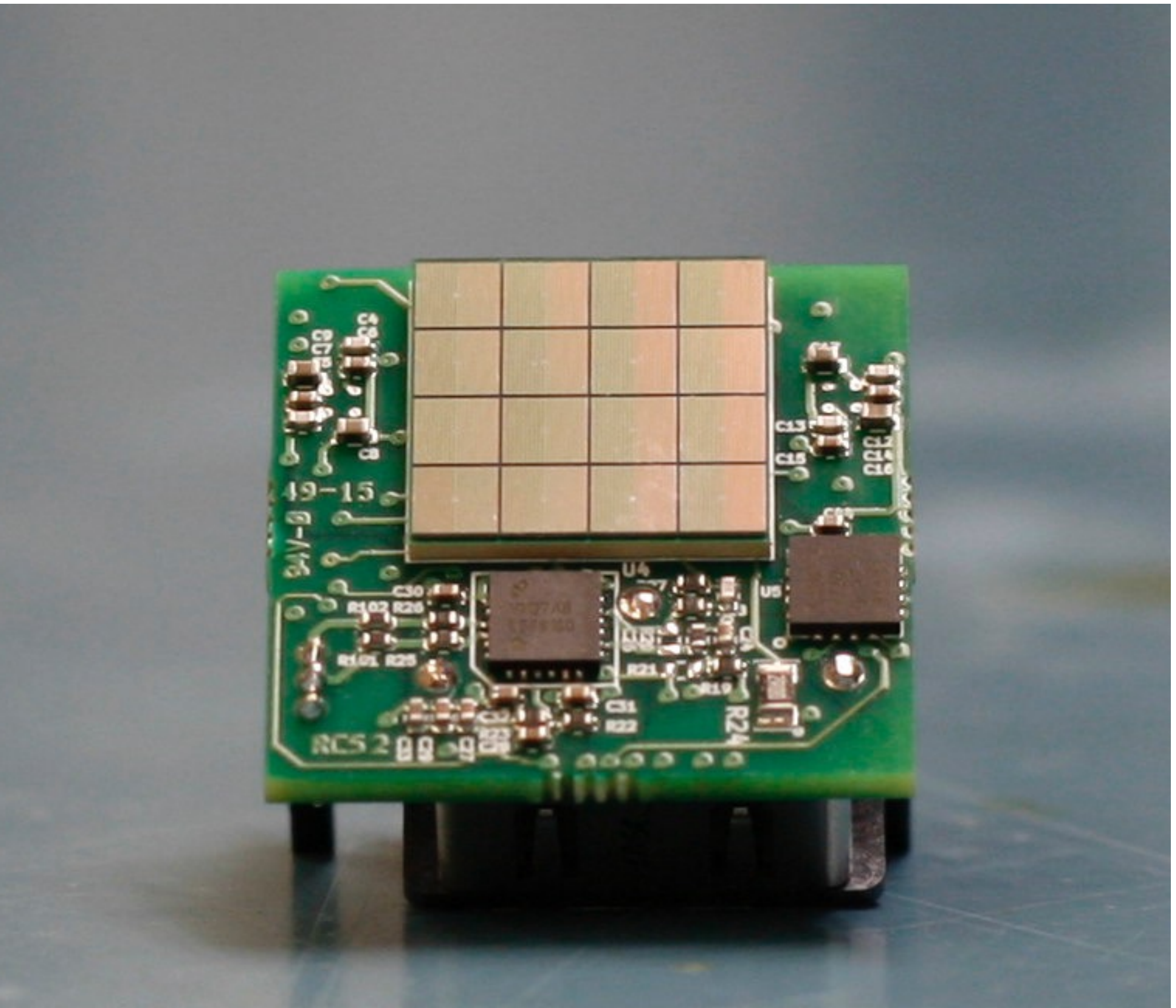

PEARSTONE
PEARSTONE
PEARSTONE
PEARSTONE
51
53
PEARSTONE
PEARSTONE

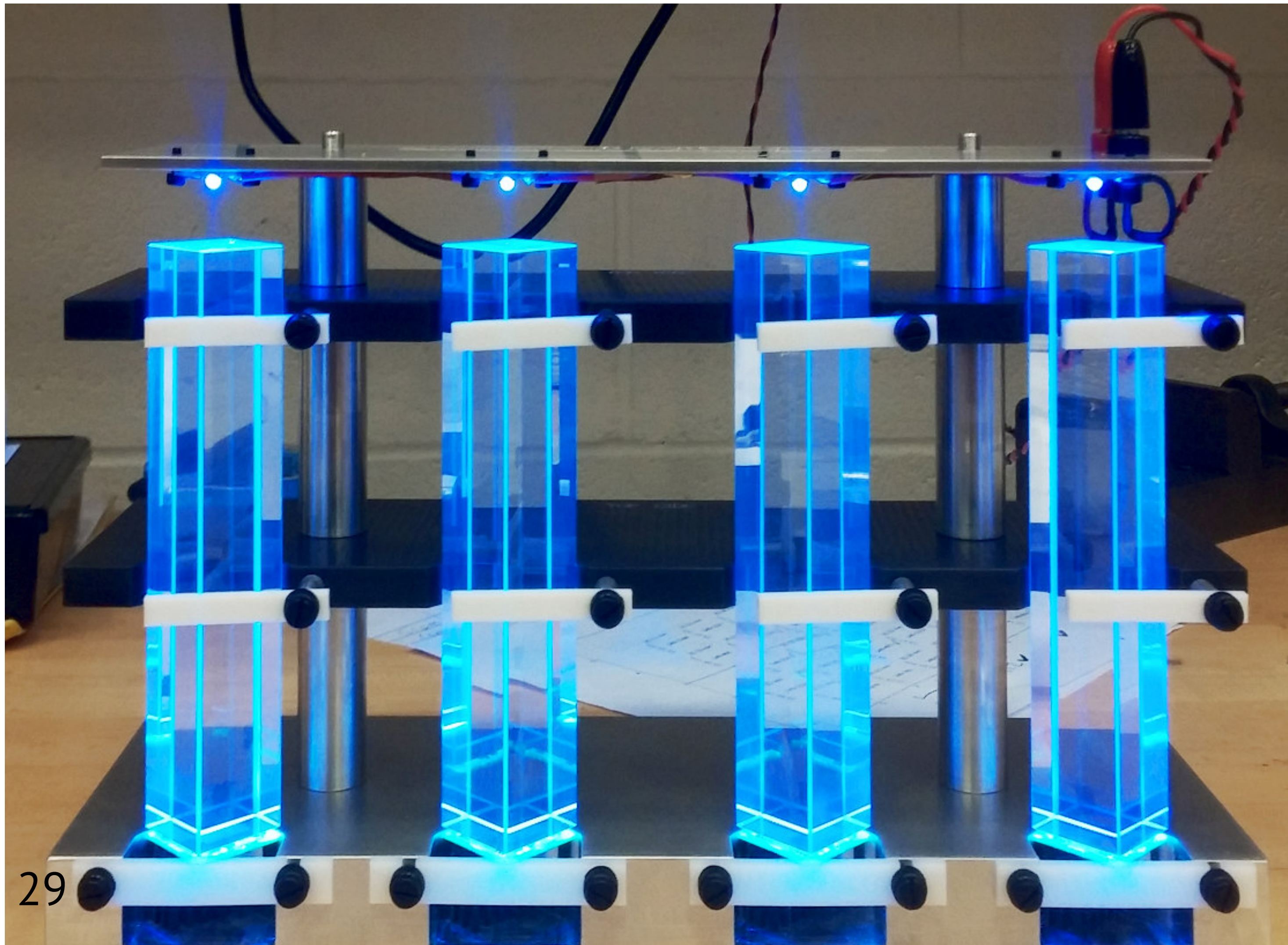
positron detection in calorimeter

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

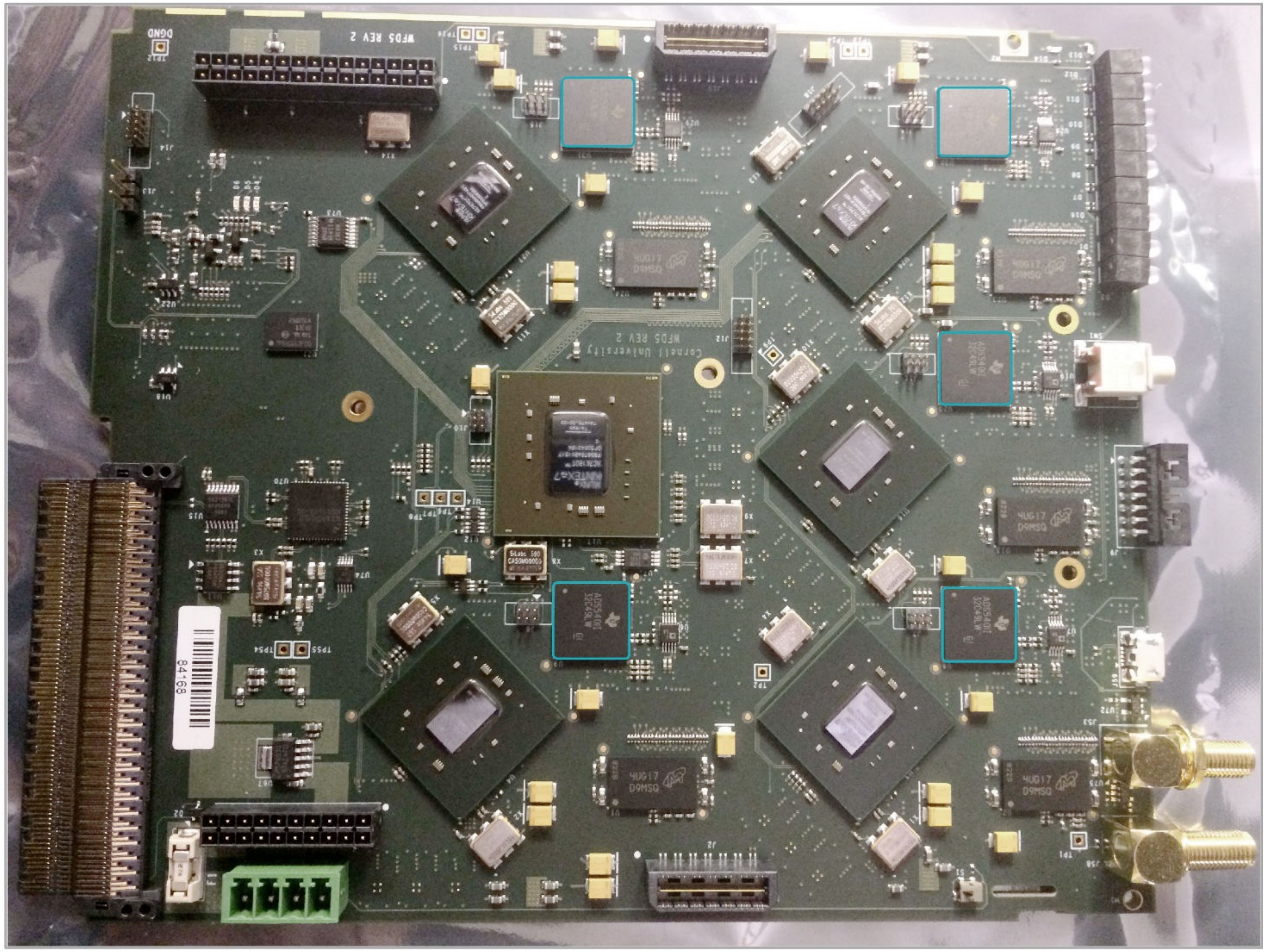




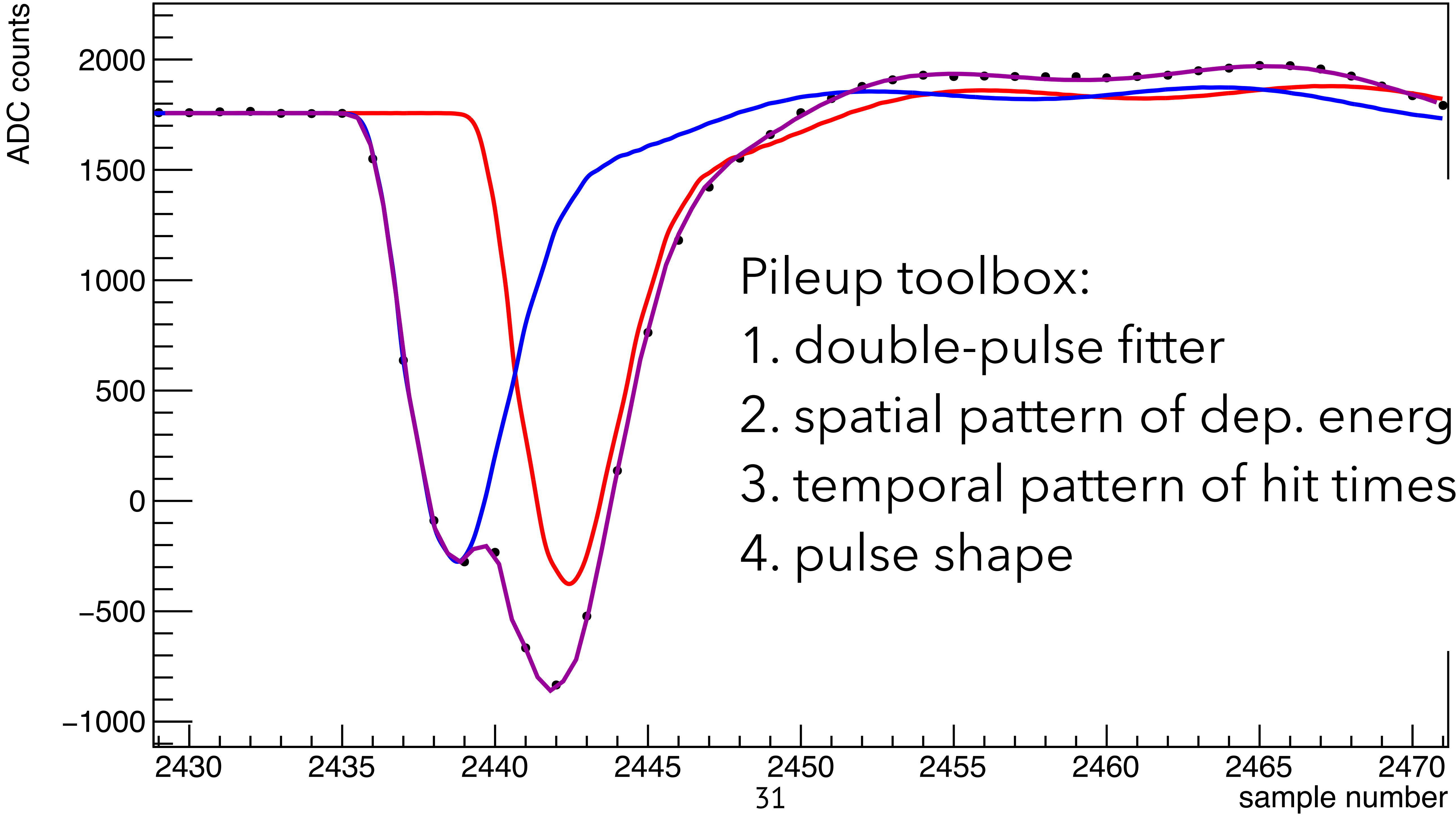
custom made 800MHz digitizer

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

- GPU data processing



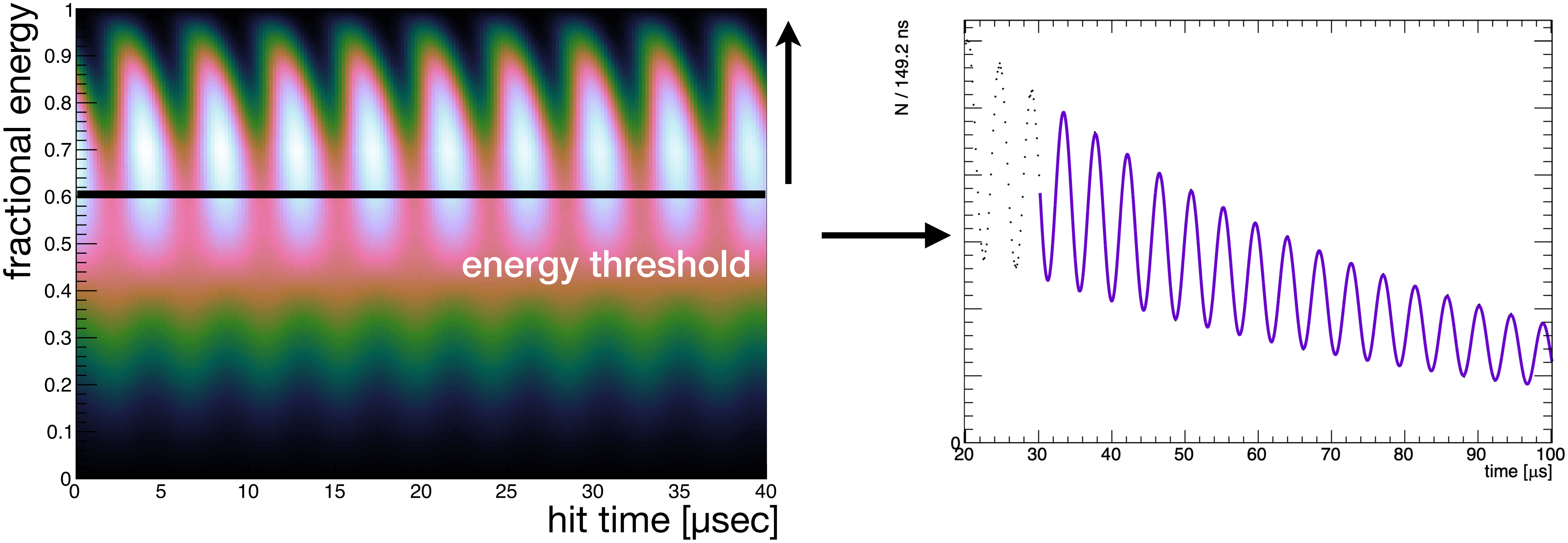
pileup separation: double bunches 4.5 nsec separation



Pileup toolbox:

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

a typical fit to calorimeter signal

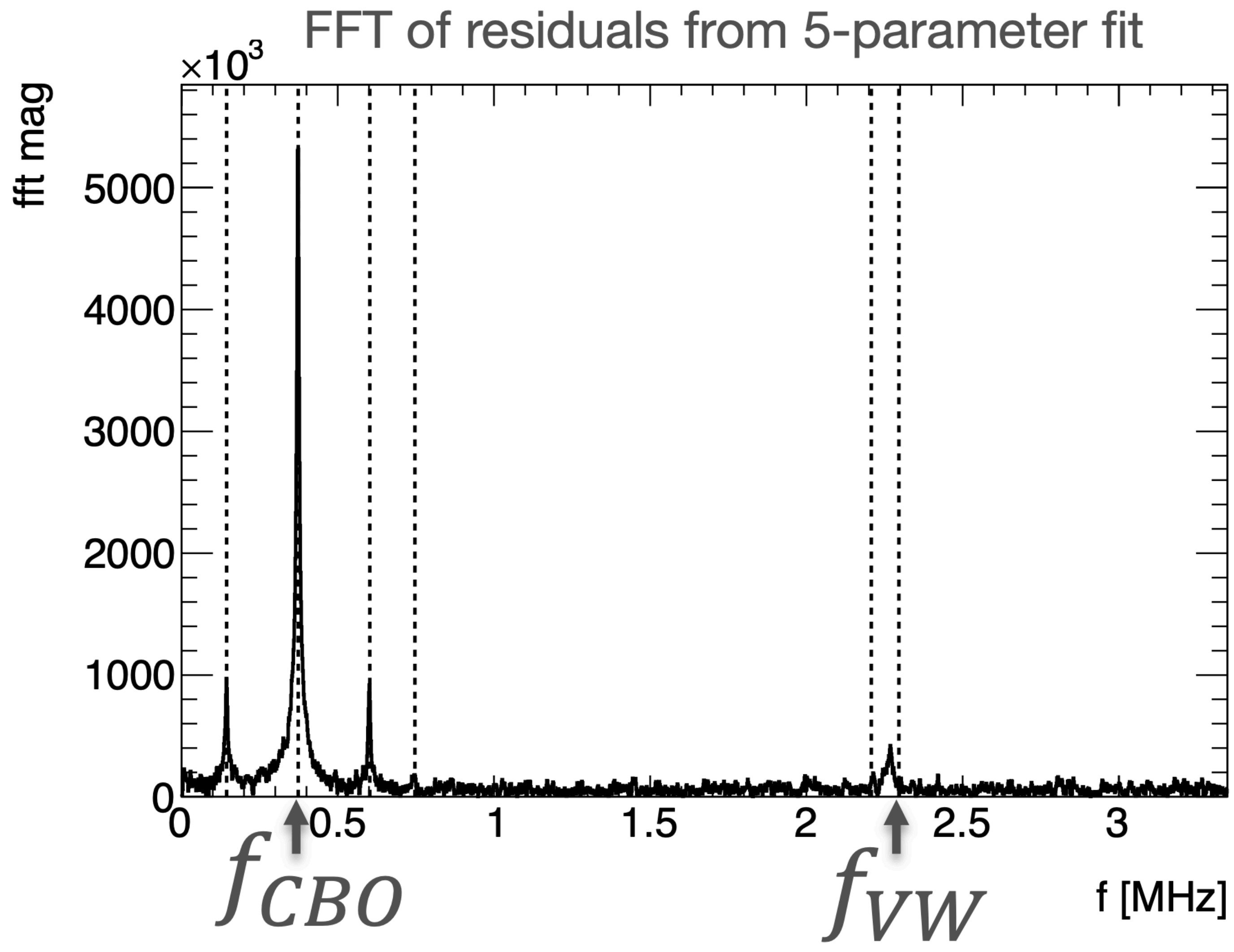


$$N\left(t\right) = N_0 \exp\left(-t/\gamma\tau_\mu\right)\left[1 + A\cos\left(\omega_{a,\mathrm{ref}}\left(1 + \Delta R + R\cdot 10^{-6}\right)t - \phi\right)\right]$$

The fit is double-blinded on the HW and SW levels.

including beam effects using trackers

- coherent beam motion
- lost muons that do not decay in storage volume
- beam injection

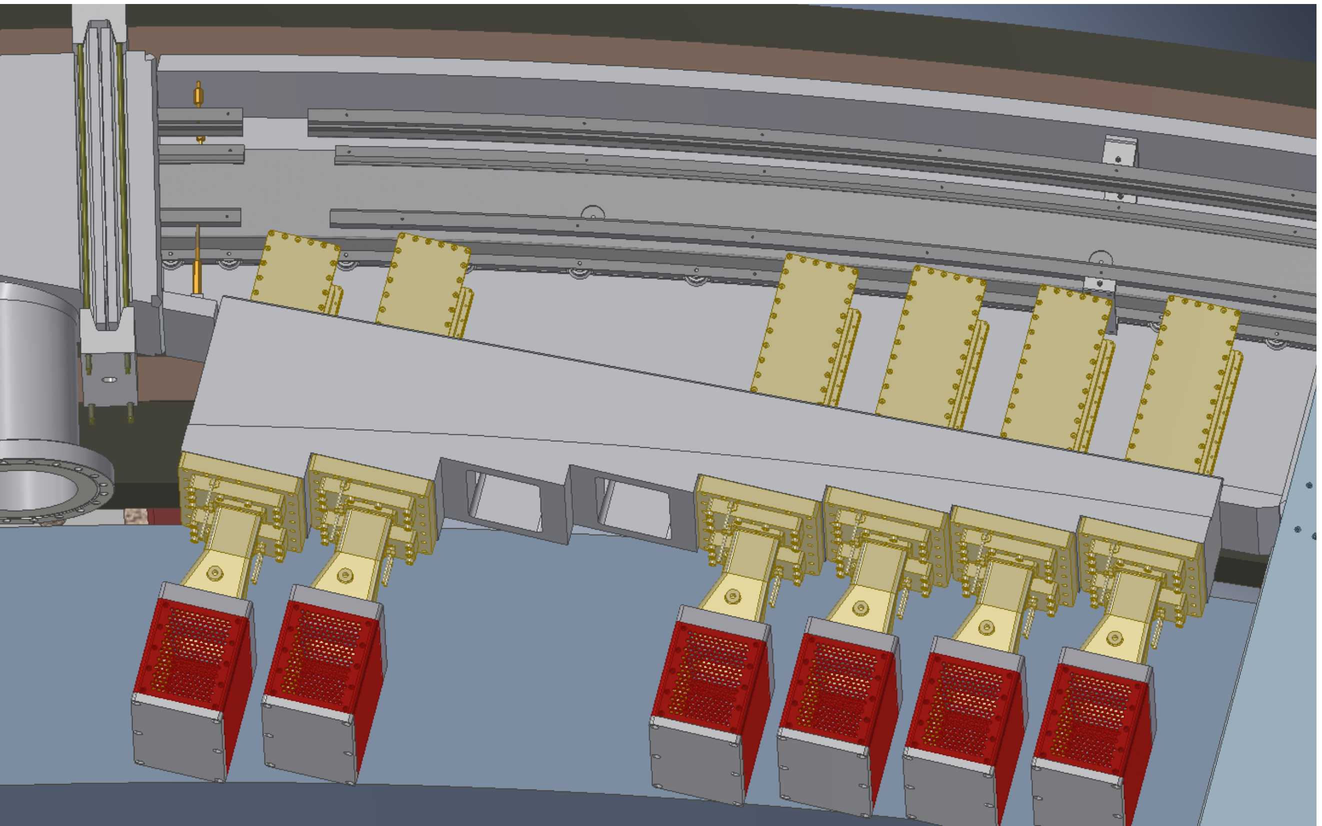


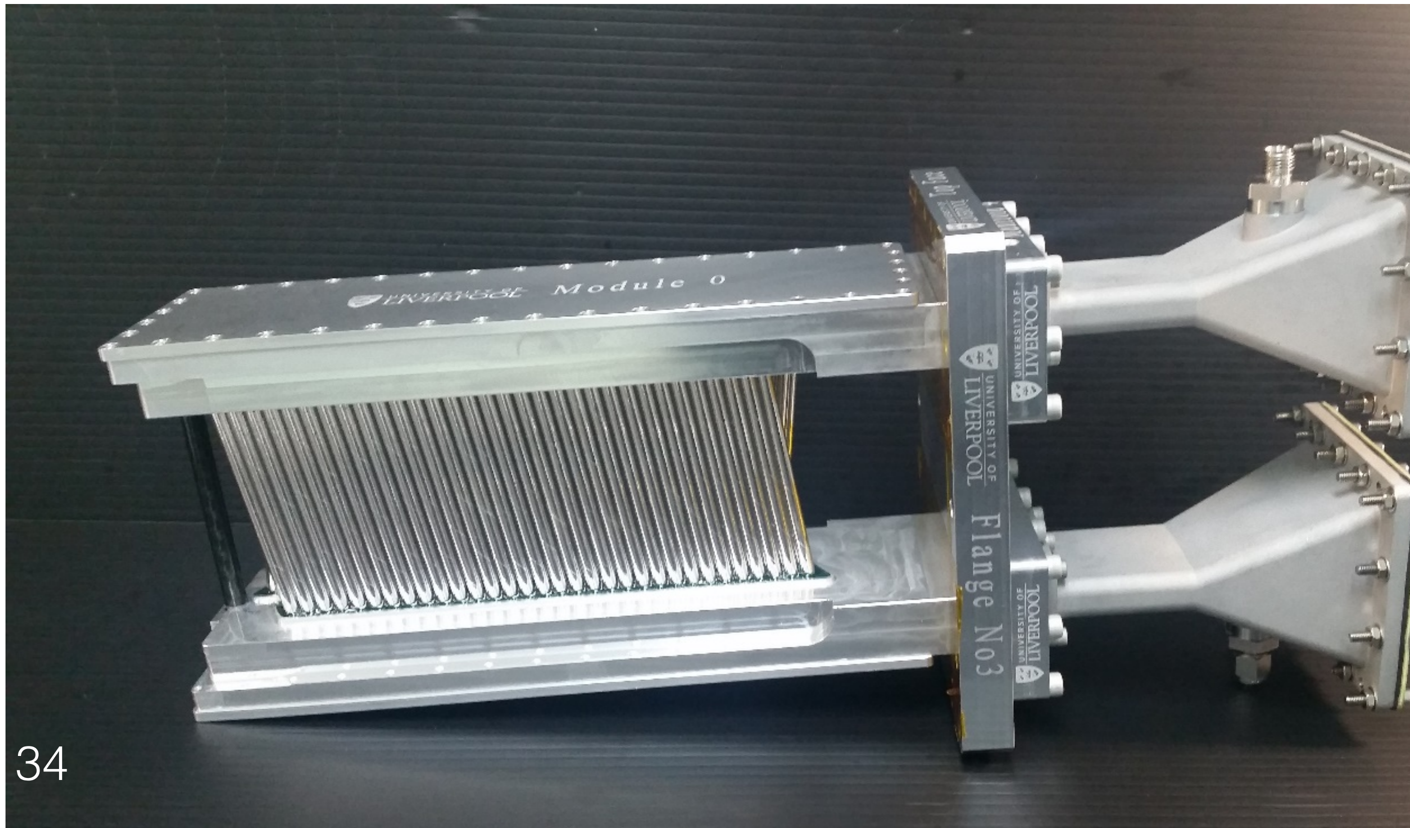
$$\boxed{N(t) = N_0\cdot\left(1 - K_{loss}\int_0^t e^{t'/\tau}L(t')\,\mathrm{d}t'\right)\cdot N_{CBO}(t)\cdot N_{VW}(t)\cdot e^{-t/\tau}\cdot[1 + A(t)\cos(\omega_a(R) - \phi(t))]}$$

Straw tracker design

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

Large azimuthal acceptance with low material (15μm Mylar)





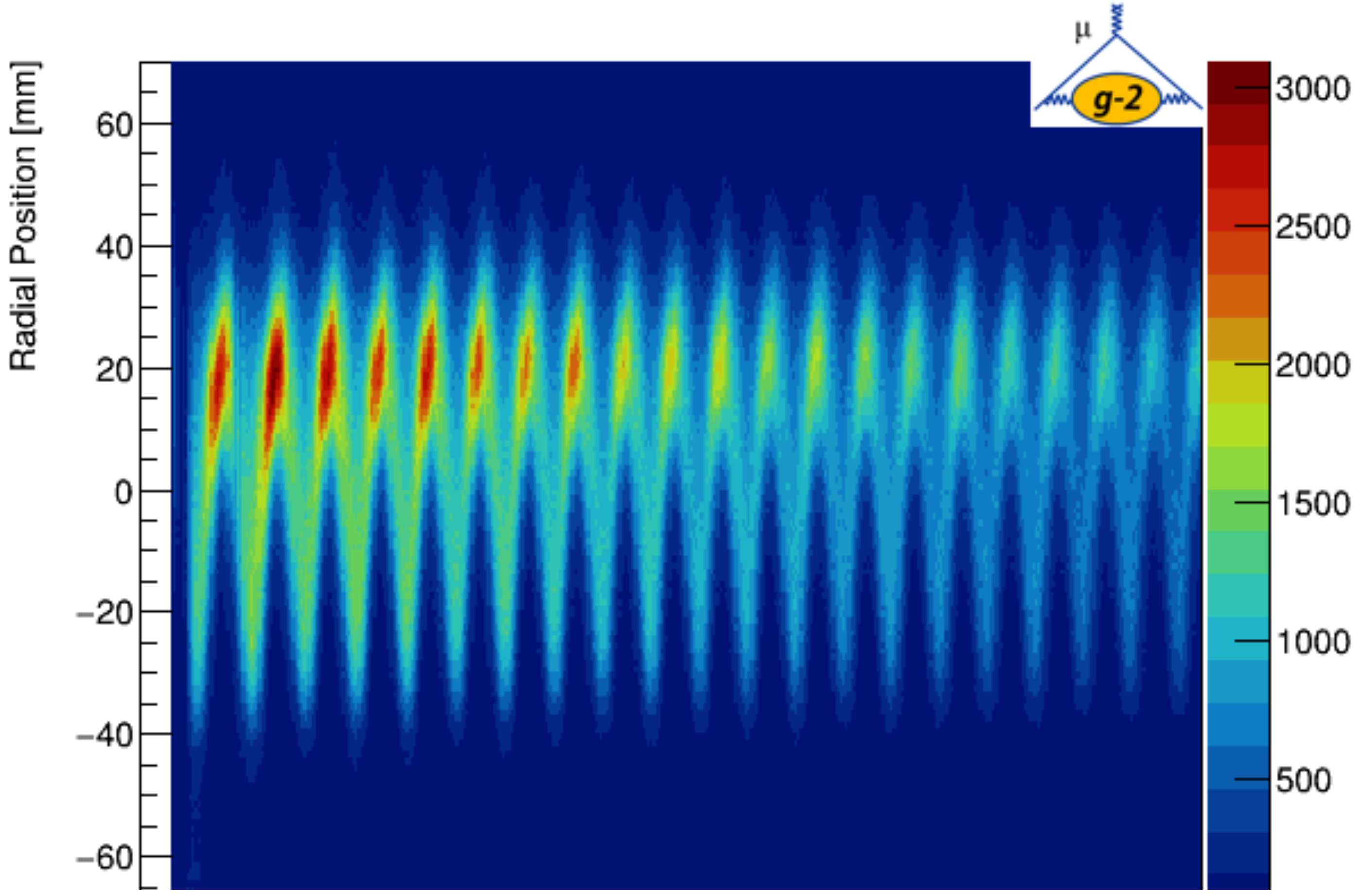
Swiss-knife of Muon *g*–2 experiment

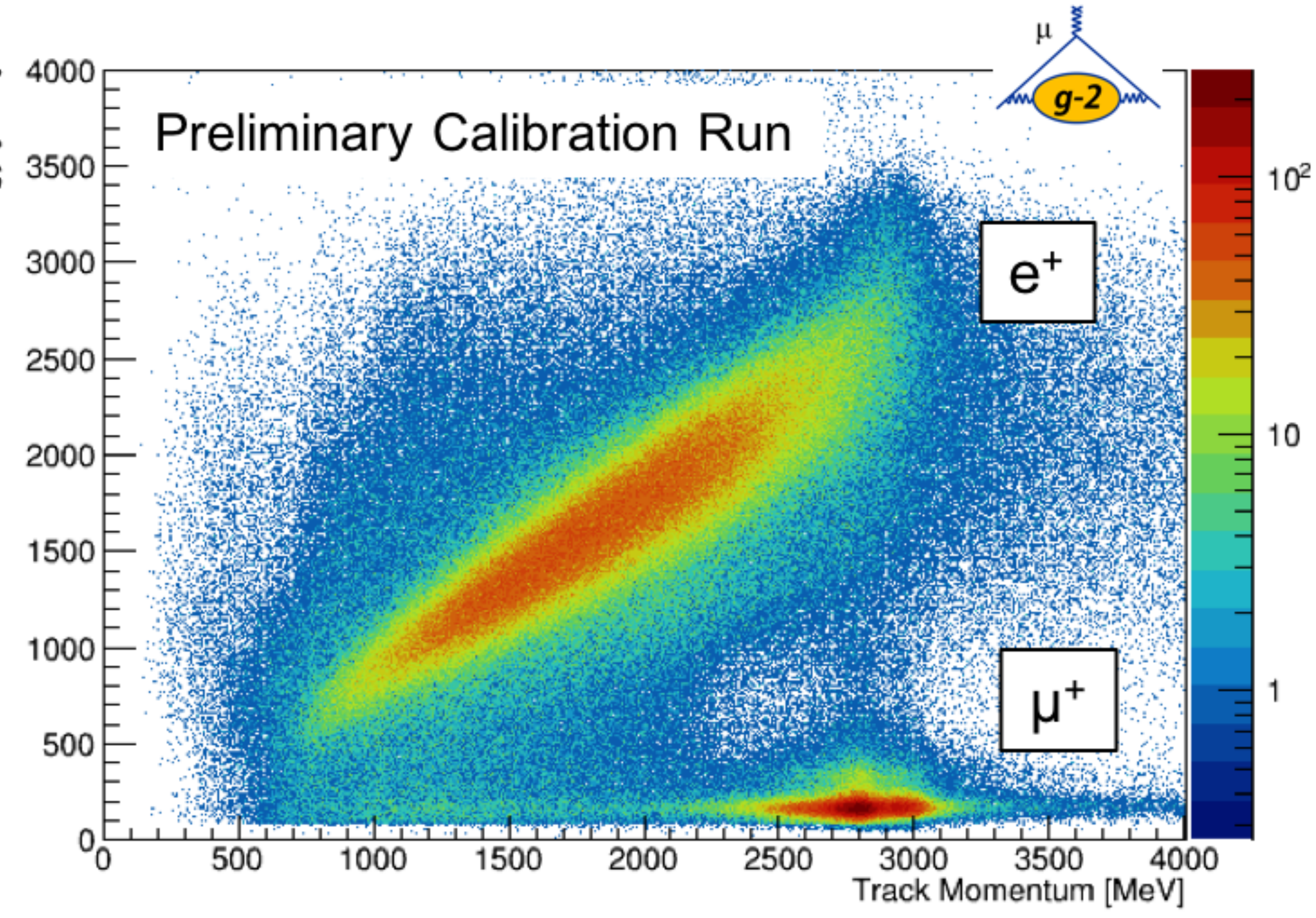
Measures stored **muon profile** and its time evolution.
Addresses **pile-up** systematics, measure positron momentum.
Detects **lost muons** escaping storage region.
Measures **vertical pitch** of decay positrons → EDM measurement.

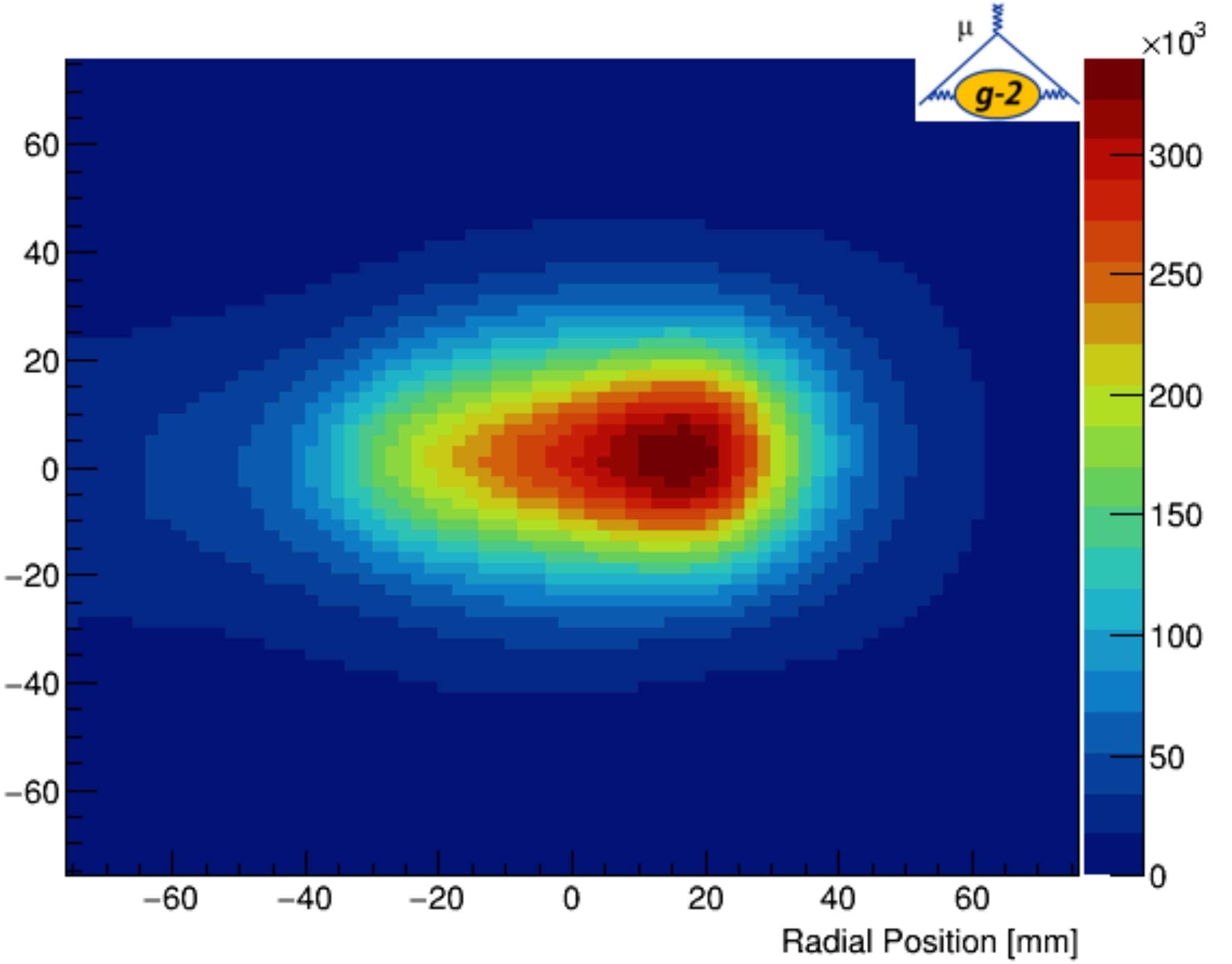
Determines area of **magnetic field map** seen by the muons
Limits the size or **radial and longitudinal** magnetic **fields**

Makes an independent measurement of **positron momentum.**

Excellent performance

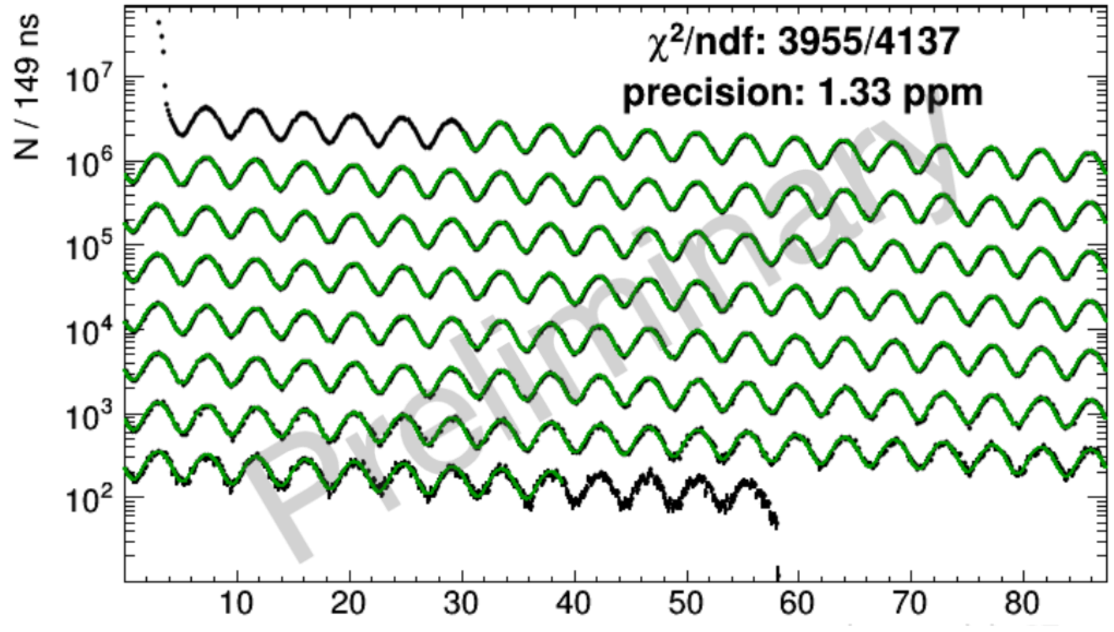




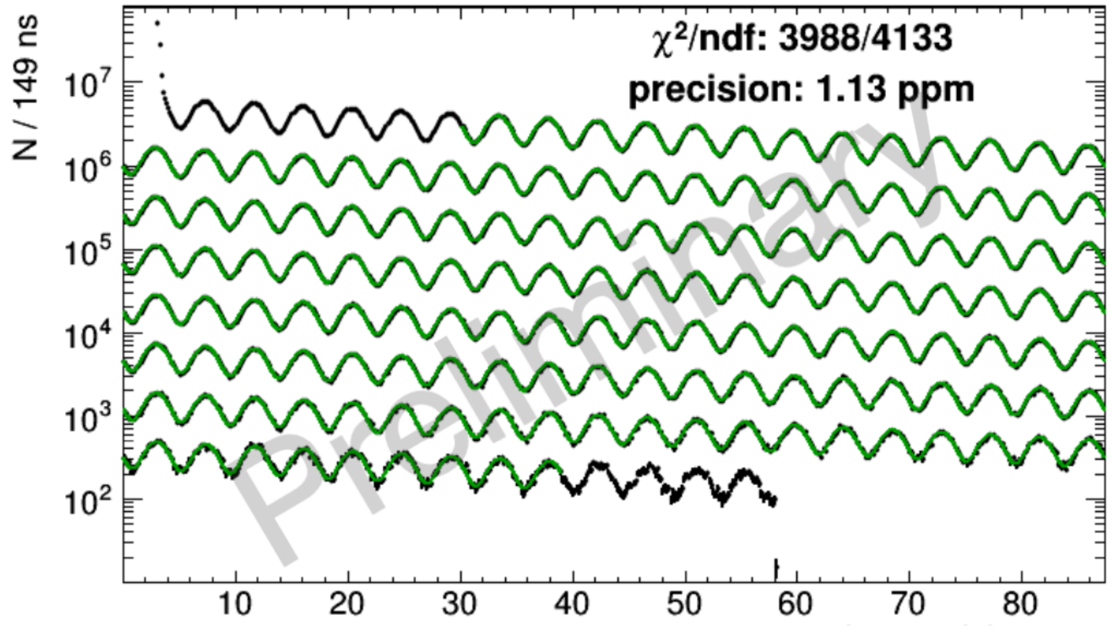


varying run conditions in Run1 dataset to better address systematics

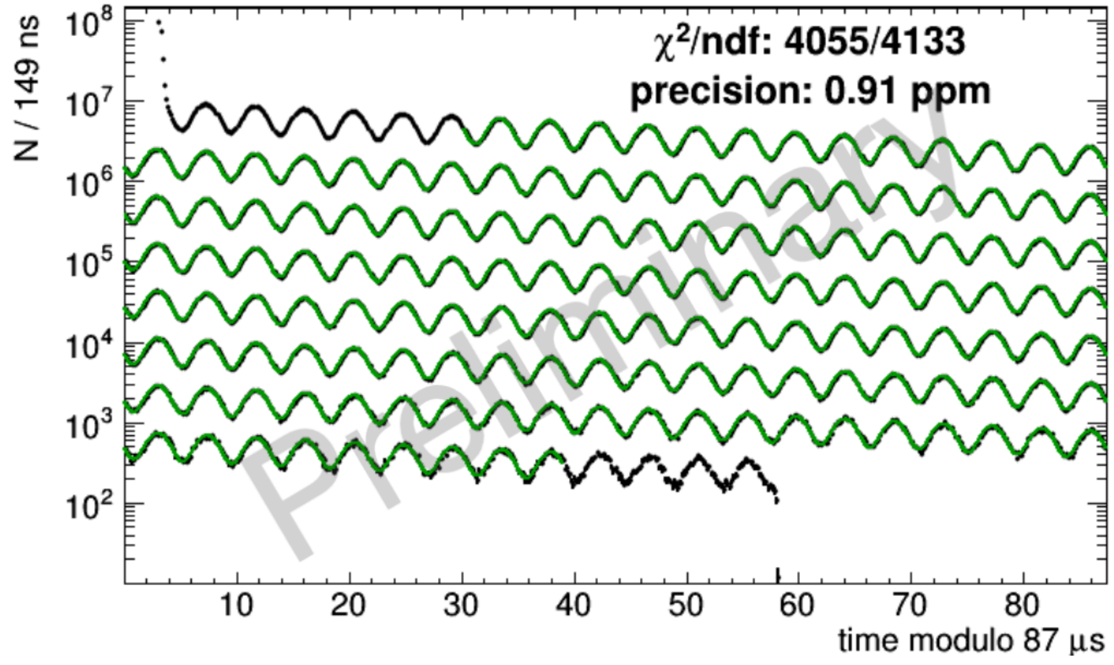
1a



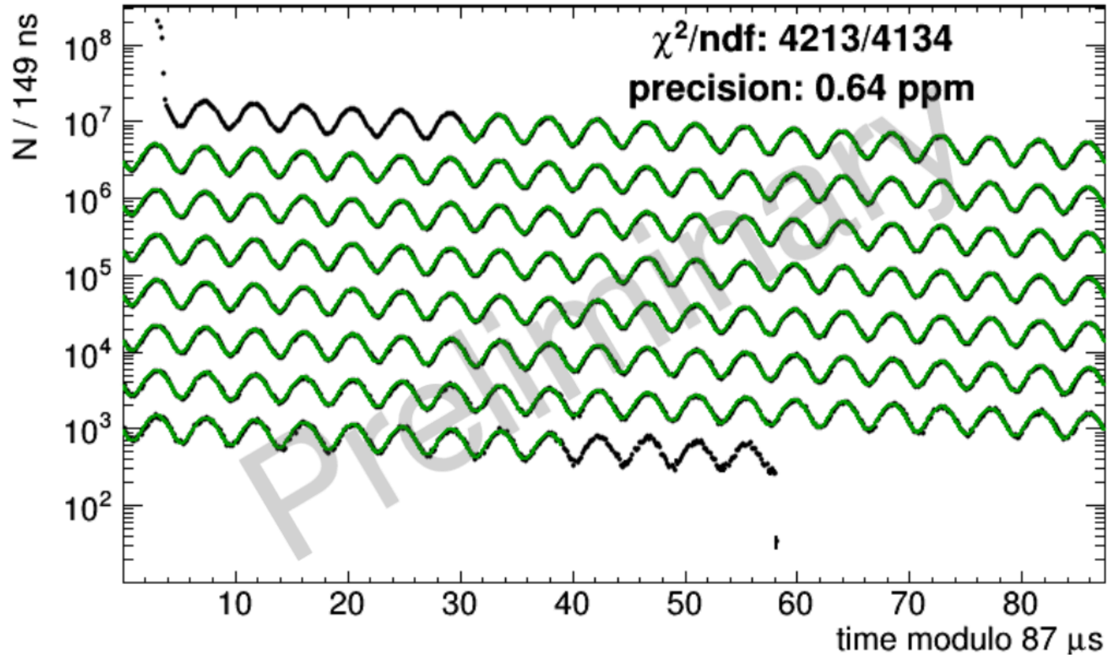
1b



1c

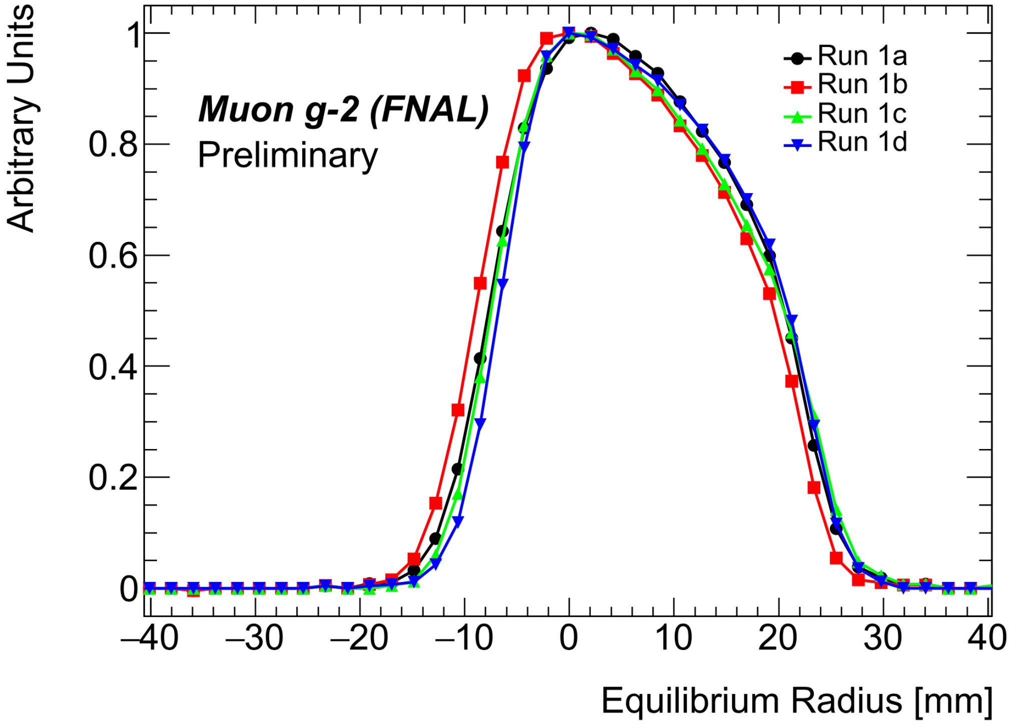


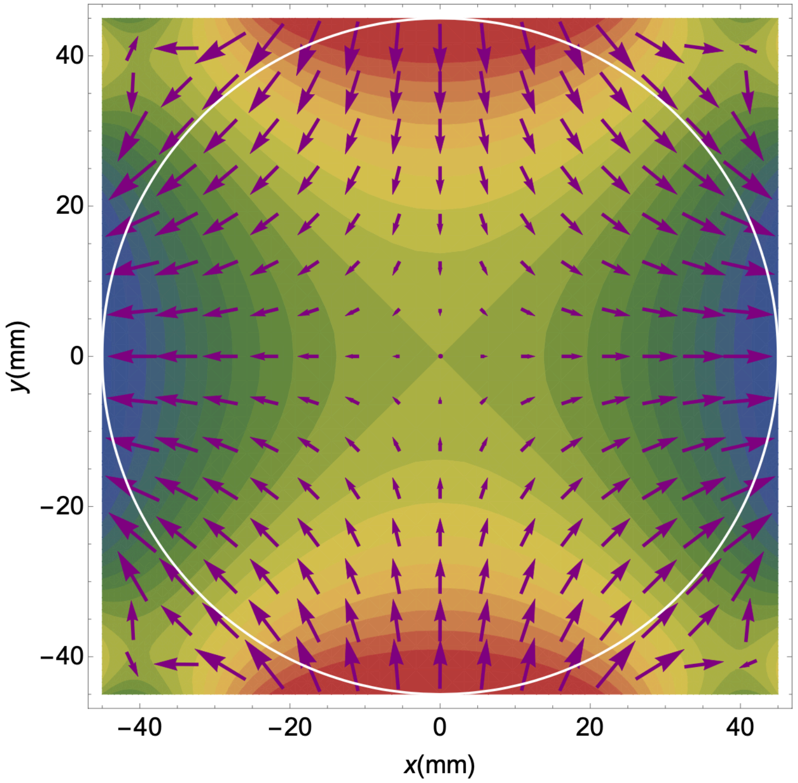
1d

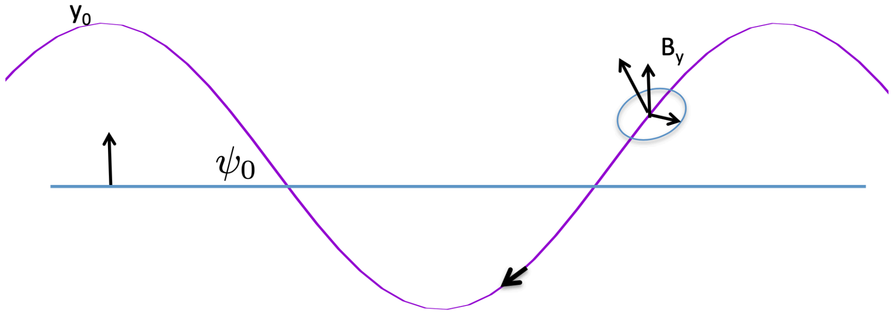


E-field and pitch corrections

- associated with $\vec{\beta}\times\vec{E}$ term in spin precession equation
- minimized but not avoided by choosing $a_\mu = \frac{1}{\gamma^2-1}$

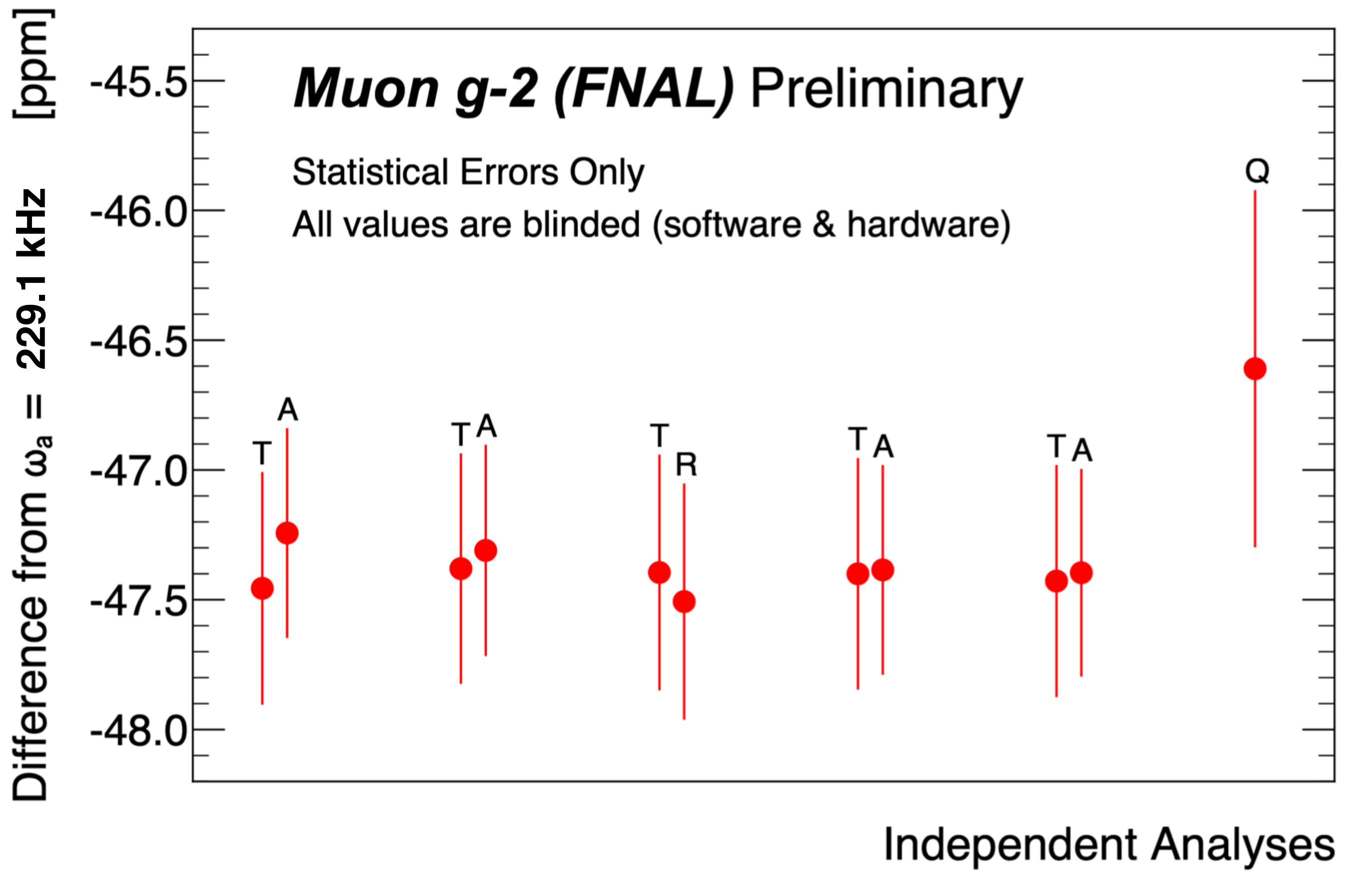






	Fourier Method	
Data Set	x_e (mm)	σ (mm)
Run 1a	6.09 ± 0.57	9.19 ± 0.36
Run 1b	4.89 ± 0.65	9.21 ± 0.36
Run 1c	6.34 ± 0.70	9.24 ± 0.36
Run 1d	6.67 ± 0.31	8.94 ± 0.25

Run1 spin precession freq analysis status



- 6 independent analysis
  2 reconstruction methods,
  3 pileup correction methods,
  4 fitting methods
- relative unblinding was encouraging
- total statistical error of Run1 is ~450 ppb
- method paper underway

Principle of g-2 experiment

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

$\mathcal{R}_\mu$

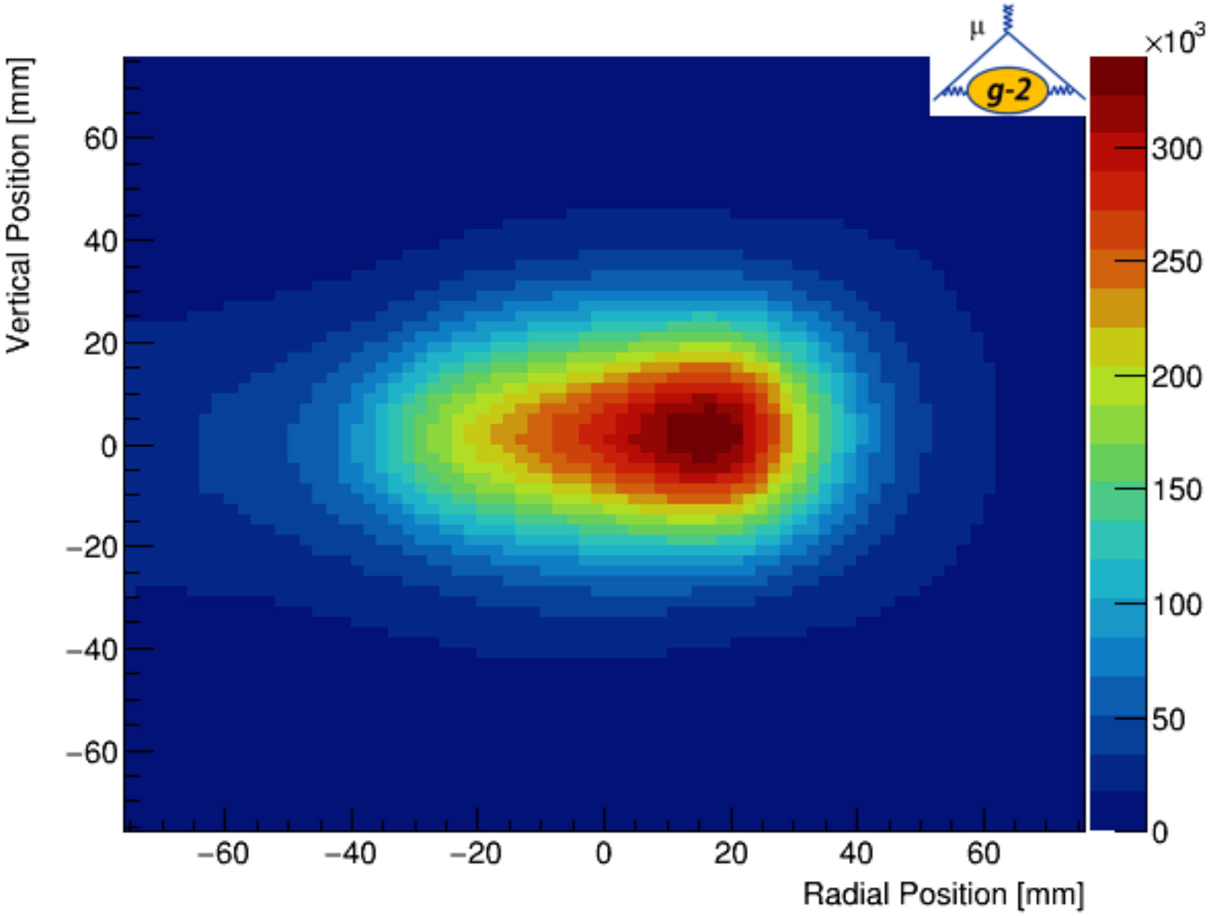
Muonium Hyperfine Splitting
--[658.210 6866 (20)] $^{-1}$ [3 ppb]

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

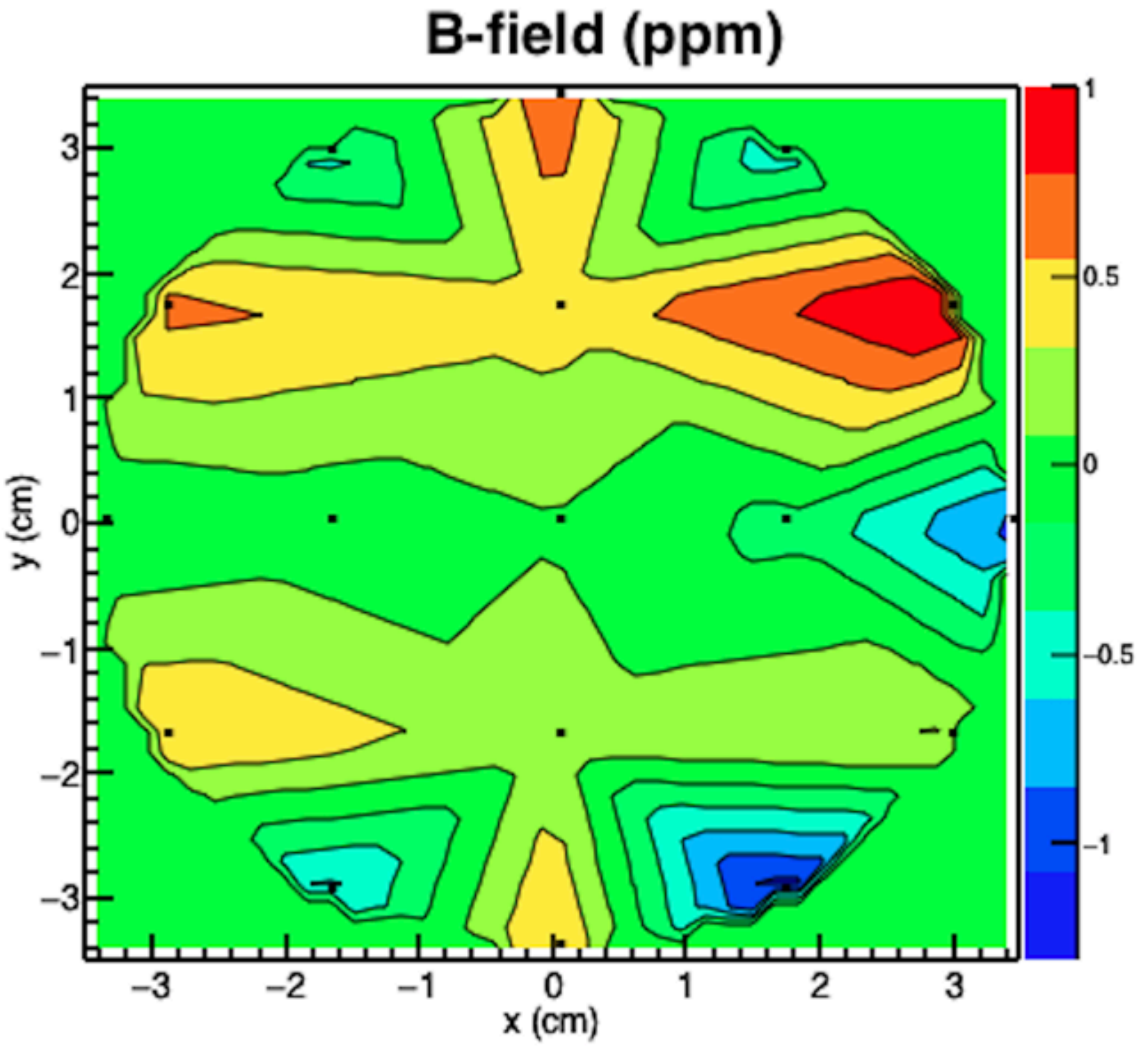
ω_a : Precession frequency

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

principles of ω_p measurement



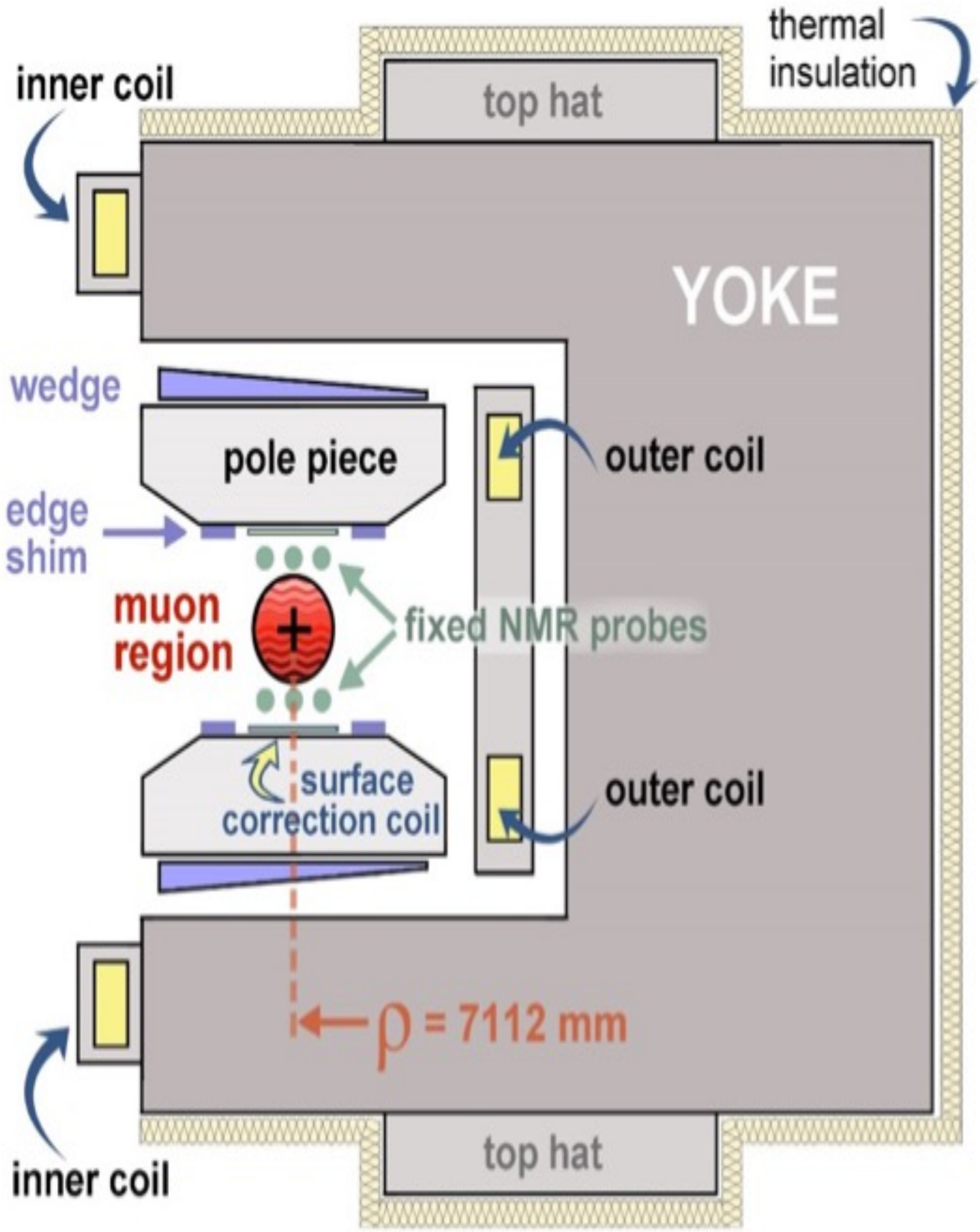
Larmor precession frequency of a free proton, measured where muons are stored, and when muons are stored



Field shimming

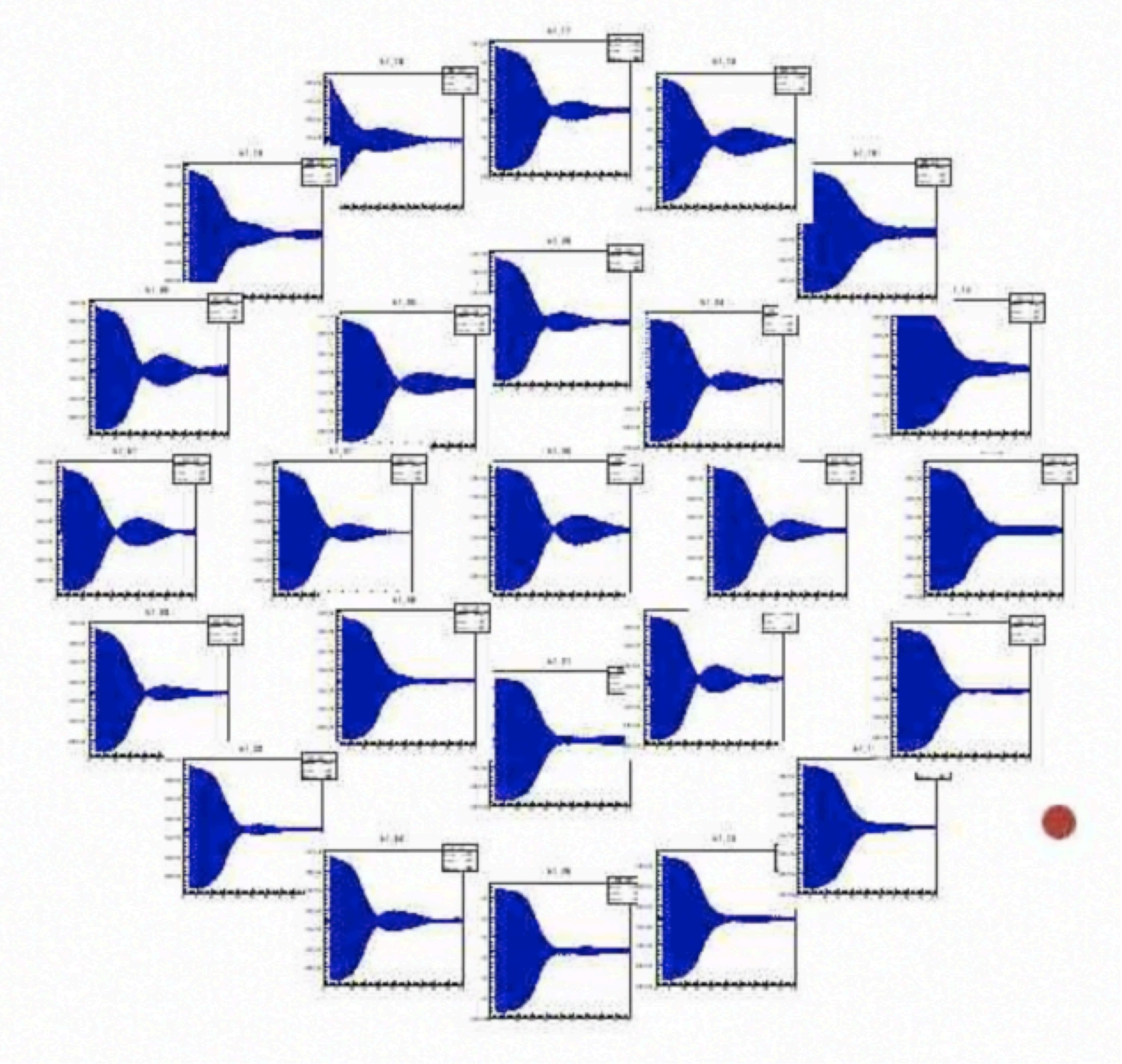
B=1.45 T (non-persistant)

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



g-2 Magnet in Cross Section

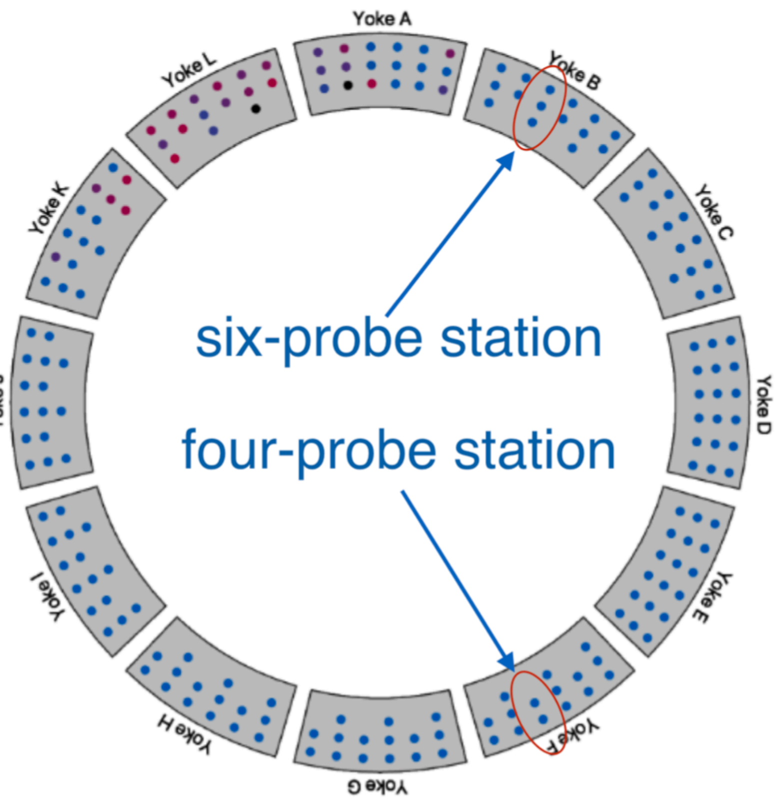
Field mapping trolley



- 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

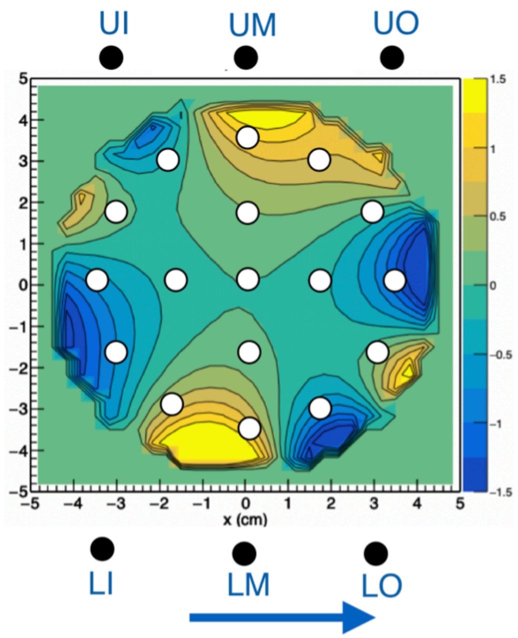
- 378 probes above and below the beam storage region
- Monitor the field in between trolley runs, when muons are stored



six-probe station

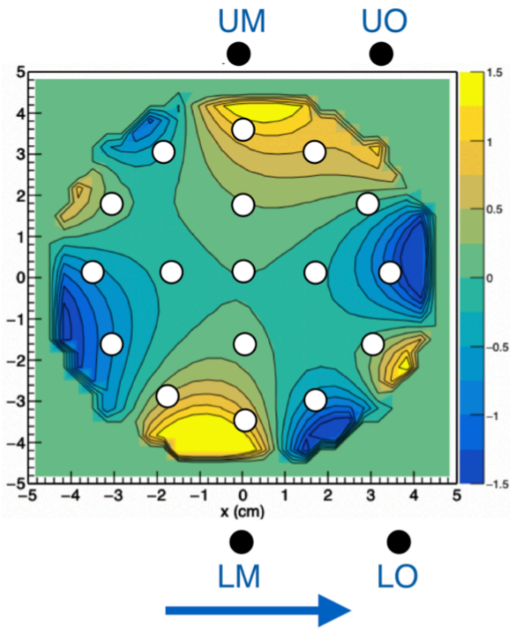
four-probe station

six-probe station

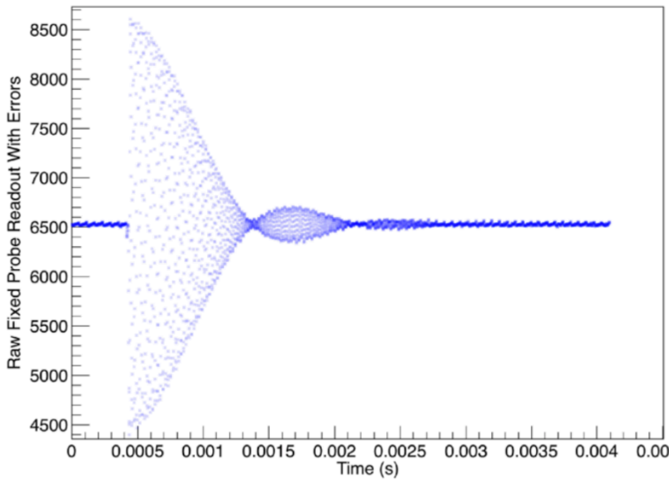


radially outwards

four-probe station



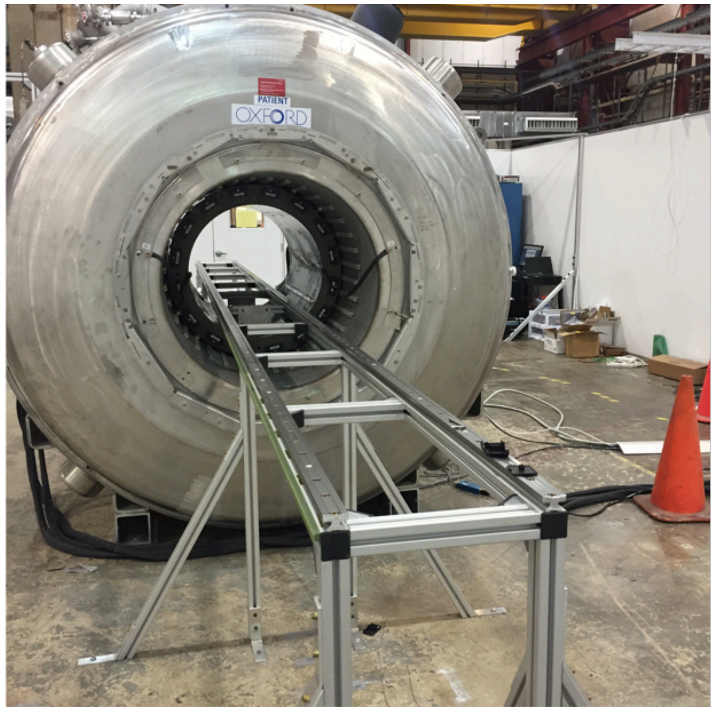
radially outwards

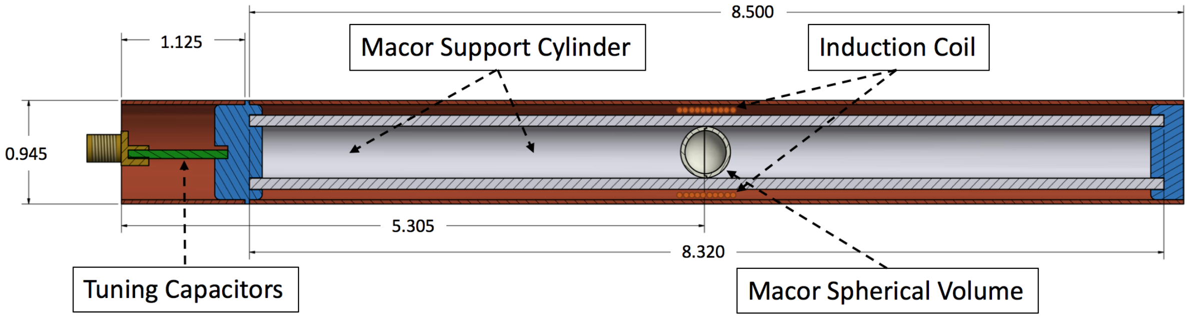


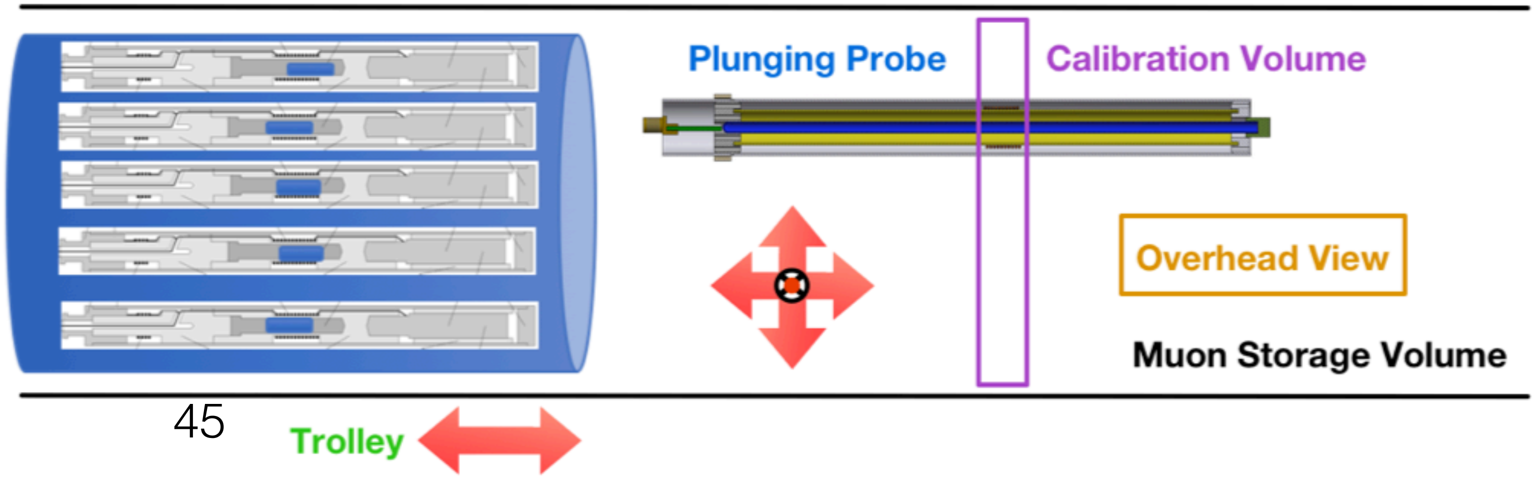
○ trolley probes ● fixed probes

Absolute field calibration

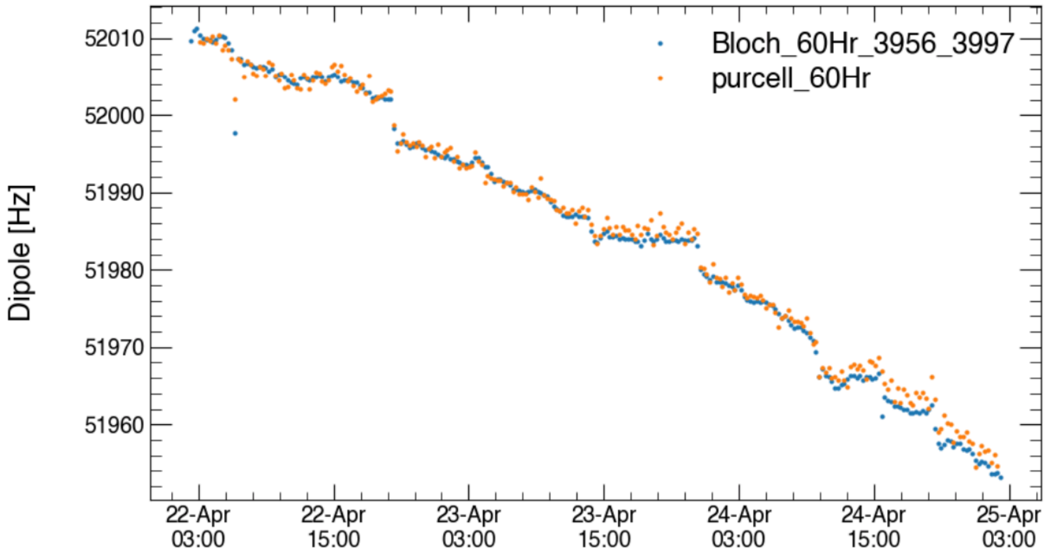
- precisely shimmed MRI magnet at ANL serving both FNAL and J-PARC
- absolute NMR probe designed to minimize systematics
- novel He3 probe cross-check
- plunging probe transfers the absolute calibration to trolley probes

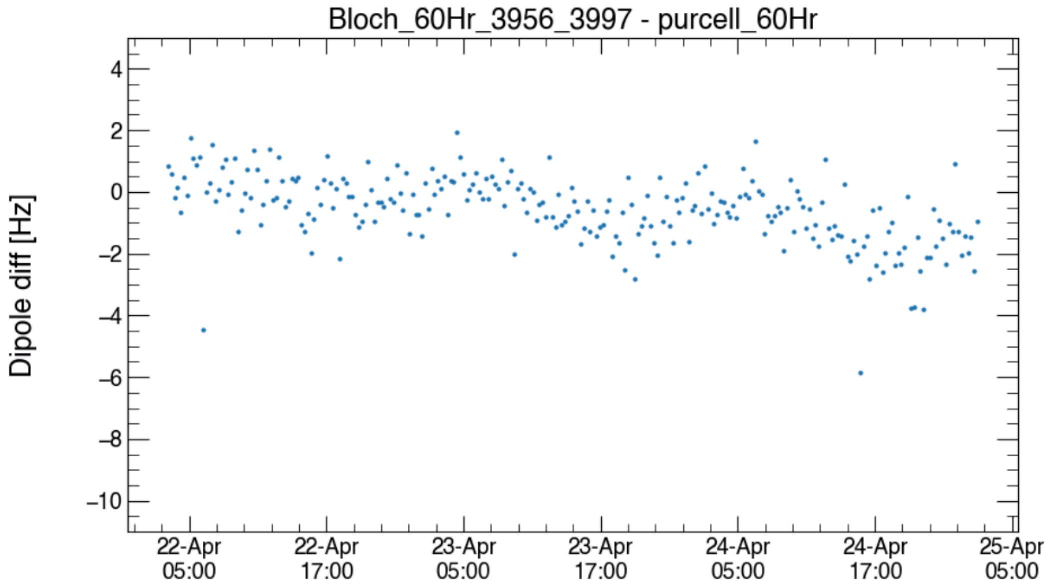






Run1 magnetic field analysis status

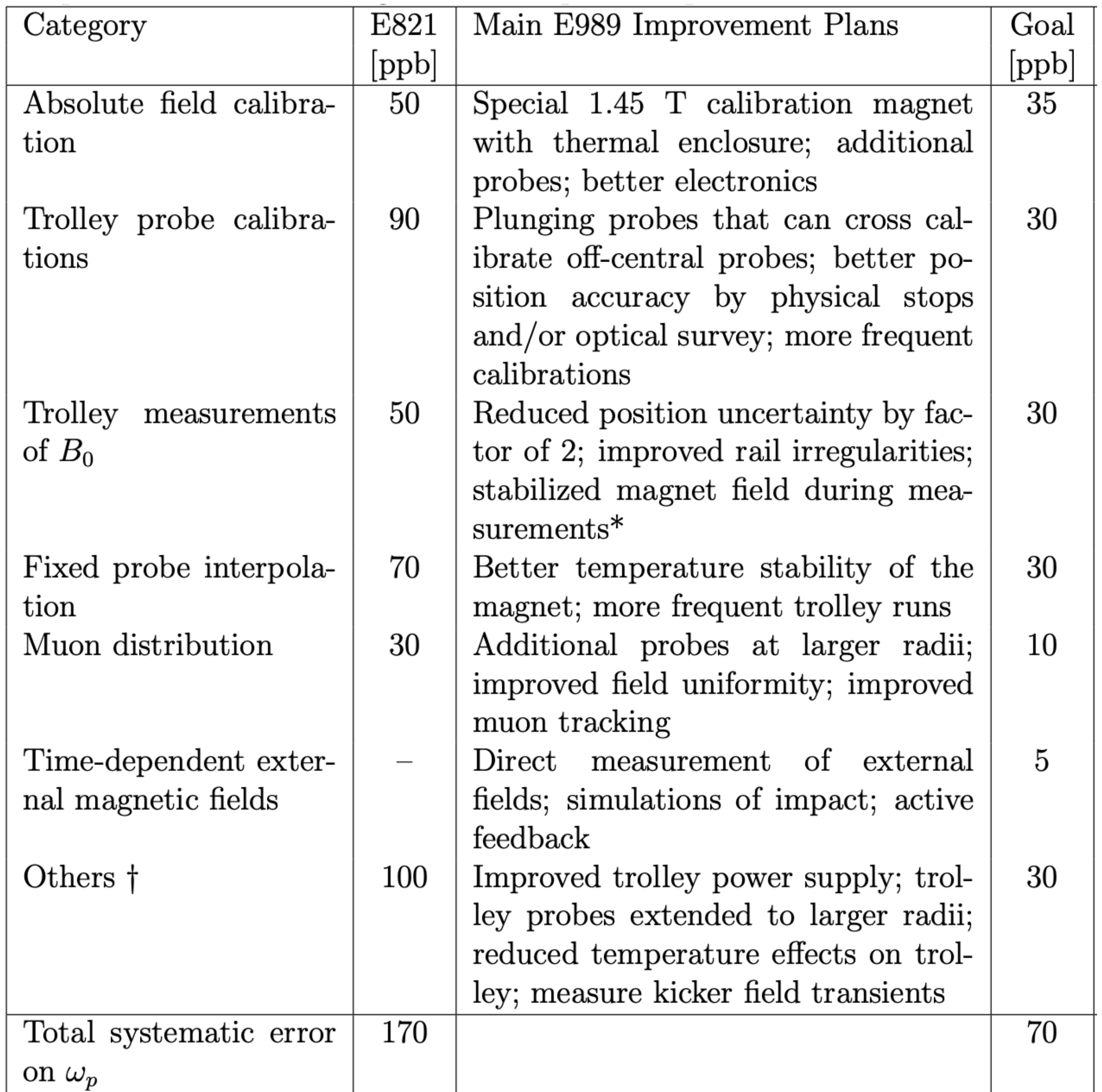




1 Hz = 16 ppb

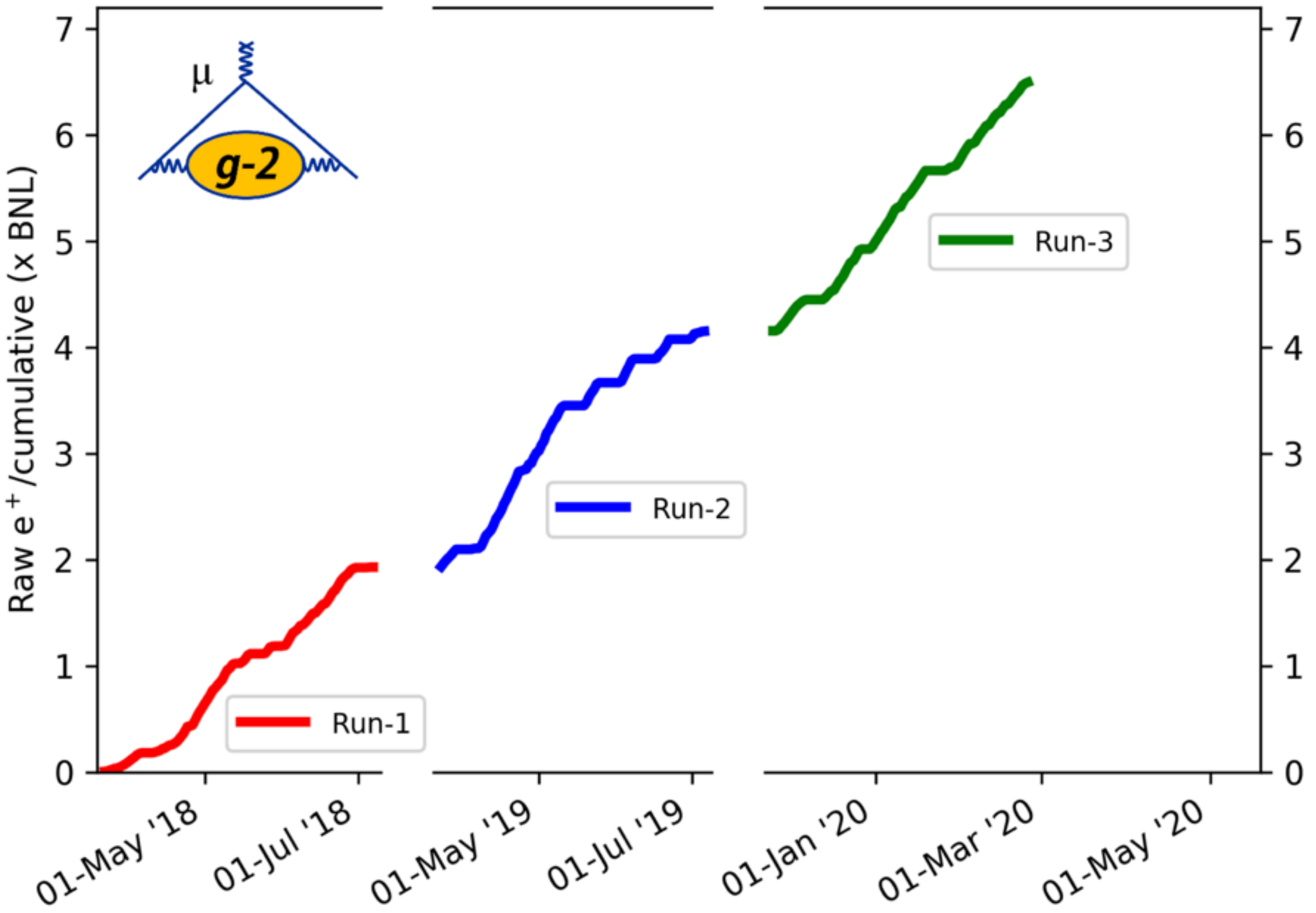
- 2 independent teams,
  2 different analysis

- on track to meet design goals



Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
Trolley probe calibrations	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30
Total systematic error on ω_p	170		70

Experiment status



- Run 3 ended
- 6.5x previous exp. on tape, ~5x BNL of physics quality data
- Run 1 analysis is almost complete
  statistical uncertainty ~450 ppb, systematics under control
- Run 2/3 data being processed
- Run 1 publication coming this year

Conclusions

- Muon g-2 experiment on track to collect 21x BNL, and the first publication coming really soon, with slightly better statistics than BNL.

- Mu2e experiment in construction to start data taking in 2023