Muon g-2 experiment at Fermilab.

International workshop on flavor changing and conserving processes, Sept. 7-9, 2017.

Tim Gorringe, University of Kentucky,
on behalf of muon g-2 collaboration

Muon g-2 experiment at Fermilab.

- **US Universities**
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Kentucky
  - Massachusetts
  - Michigan
  - Michigan State
  - Mississippi
  - Northern Illinois University
  - Northwestern
  - Regis
  - Virginia
  - Washington
  - York College
- **National Labs**
  - Argonne
  - Brookhaven
  - Fermilab

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

Netherlands:
- Groningen

Germany:
- Dresden

Russia:
- Dubna
- Novosibirsk

United Kingdom

University College London

Liverpool

Oxford

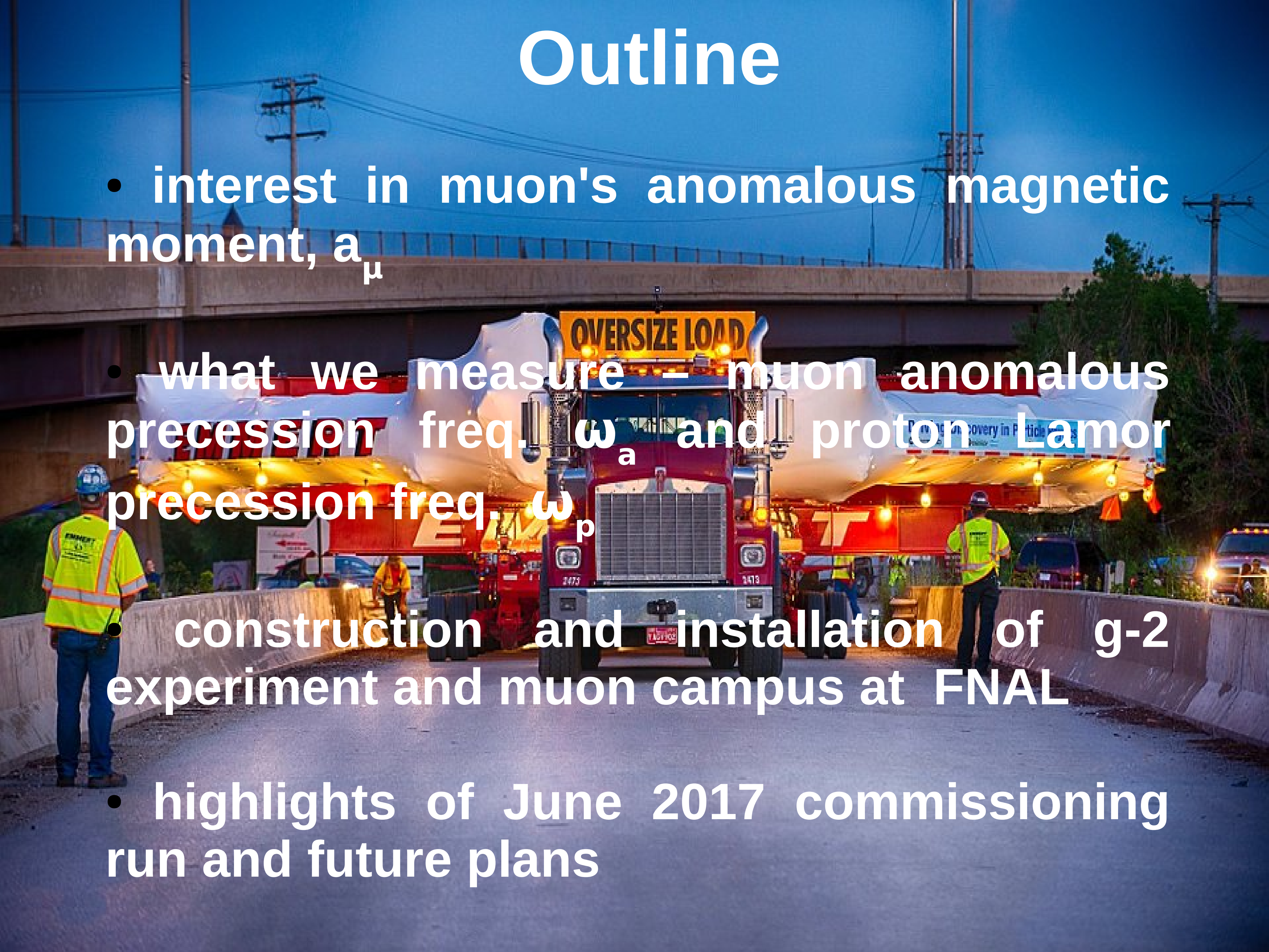
Korea

KAIST

~33 institution,
~150 members

D.W. Hertzog, C. Polly,
co-spokesperson

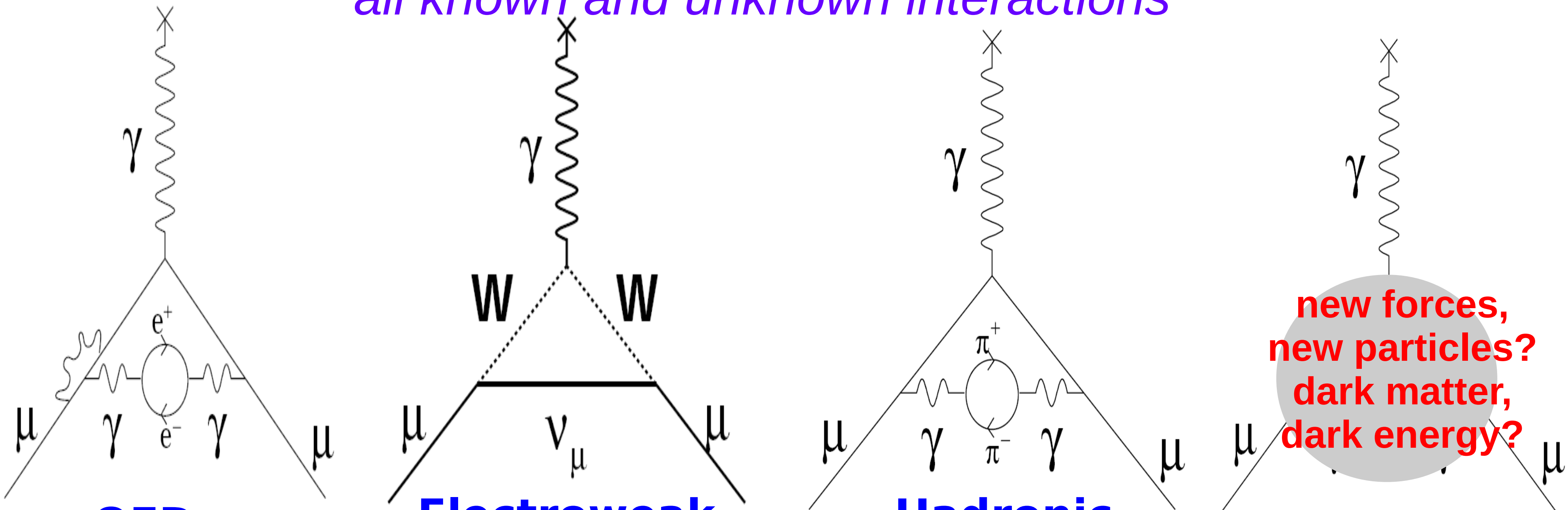
Outline



- interest in muon's anomalous magnetic moment, a_μ
- what we measure – muon anomalous precession freq. ω_a and proton Lamor precession freq. ω_p
- construction and installation of g-2 experiment and muon campus at FNAL
- highlights of June 2017 commissioning run and future plans

Interest in muon anomaly, $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Strong} + a_\mu^{Weak} + a_\mu^{NP}$

magnetic moment is dressed by quantum fluctuations from all known and unknown interactions



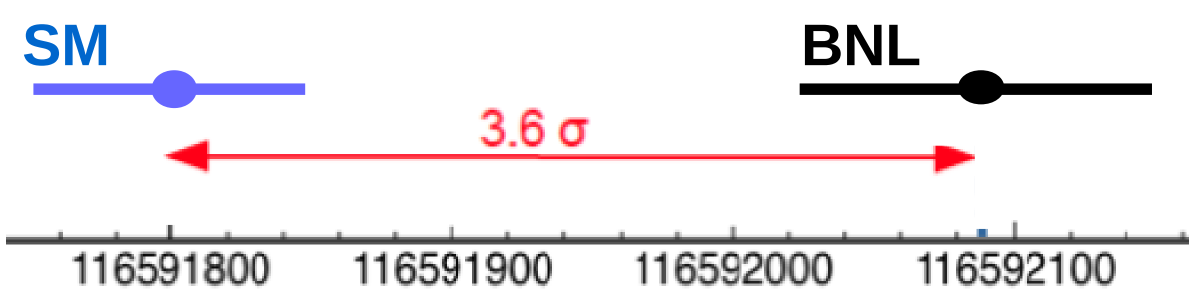
QED | **Electroweak** | **Hadronic**

a_μ^{QED} = 116 584 719.0 (0.1)

a_μ^{EW} = 154 (1)

a_μ^{Had} = 6983 (44)

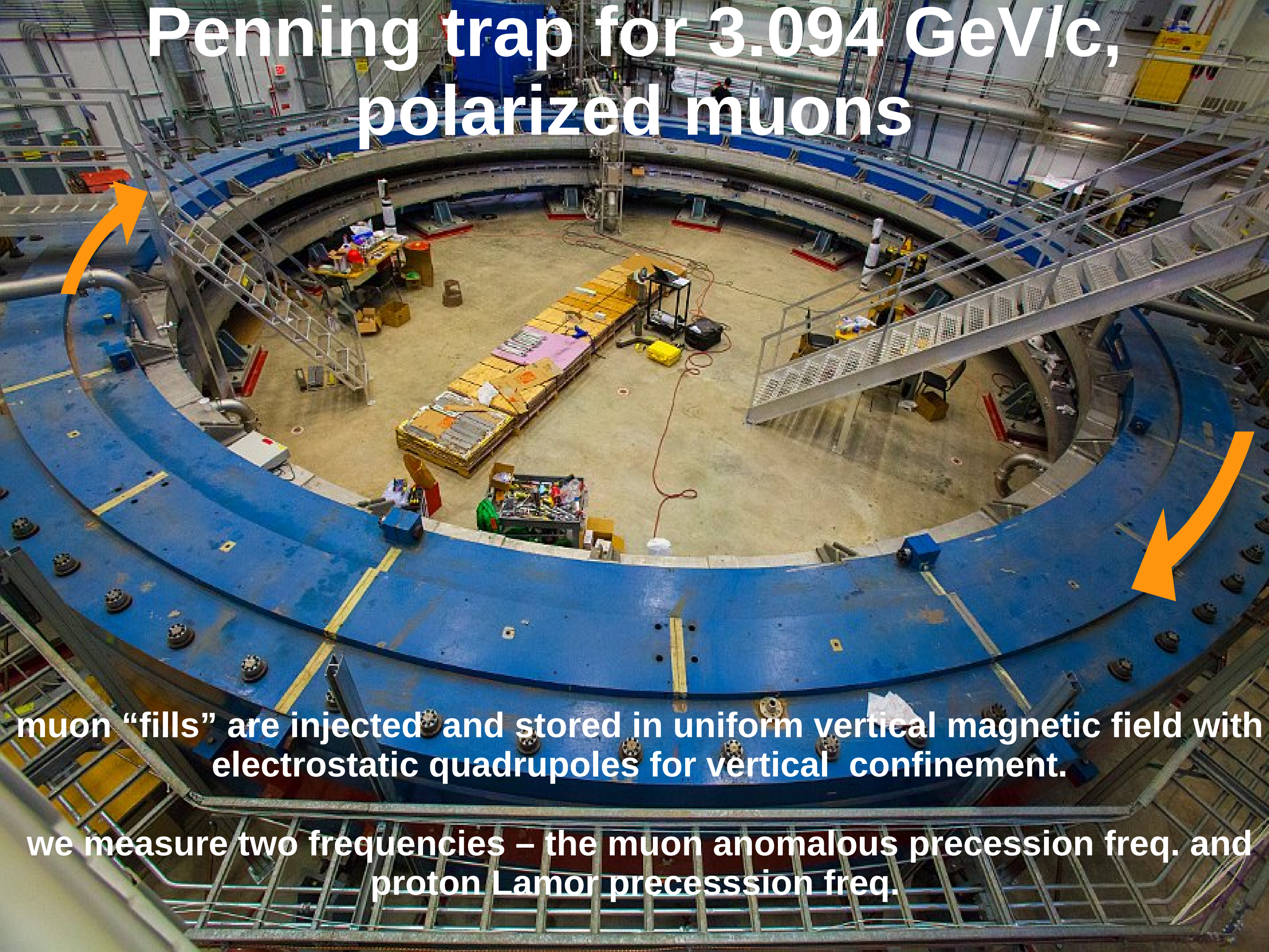
$\times 10^{-11}$



a_μ $\times 10^{-11}$

15-year, persistent discrepancy

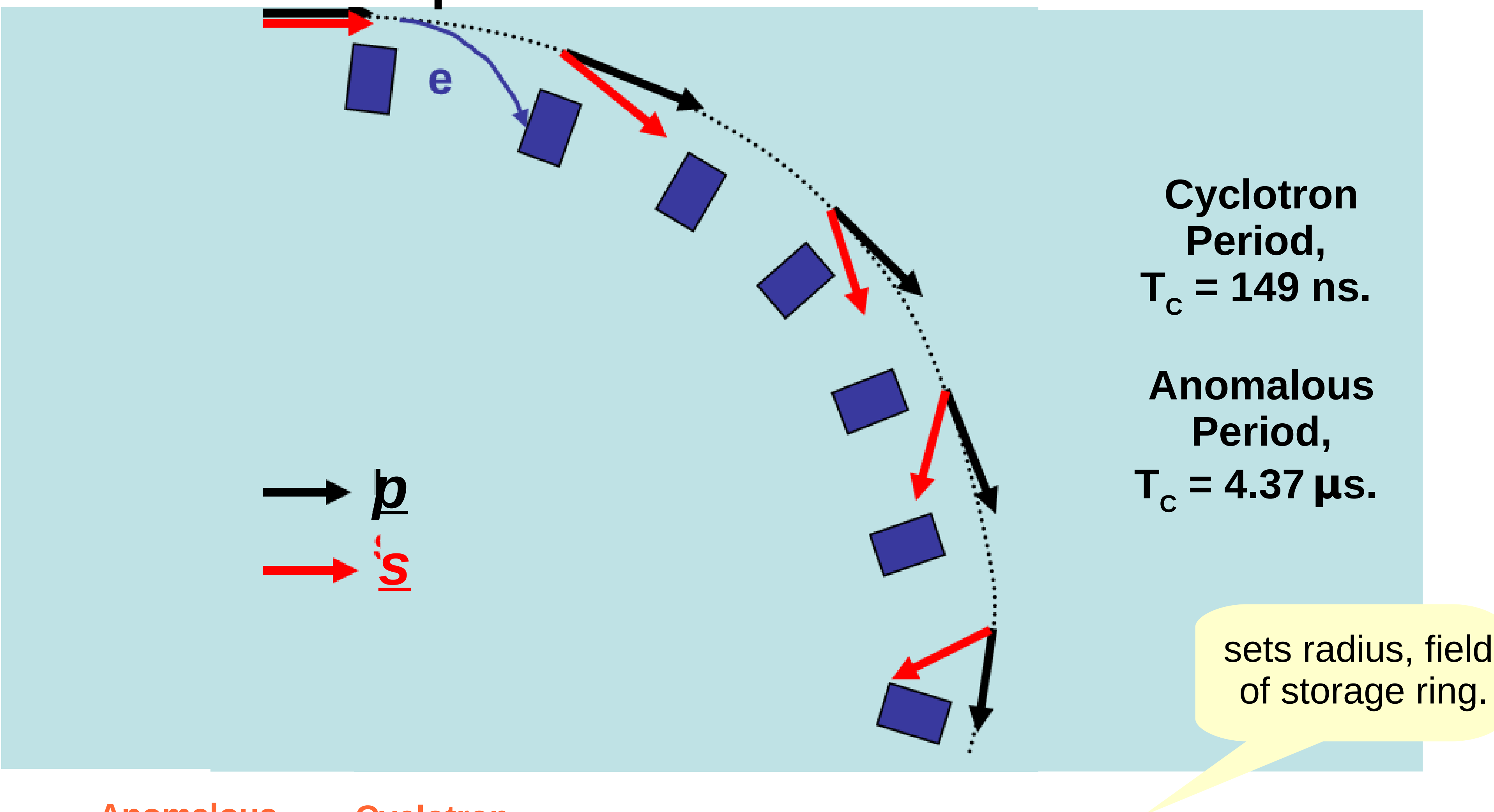
Penning trap for 3.094 GeV/c, polarized muons



muon “fills” are injected and stored in uniform vertical magnetic field with electrostatic quadrupoles for vertical confinement.

we measure two frequencies – the muon anomalous precession freq. and proton Lamor precesssion freq.

Penning trap for 3.094 GeV/c, polarized muons.



Anomalous freq.

Cyclotron freq.

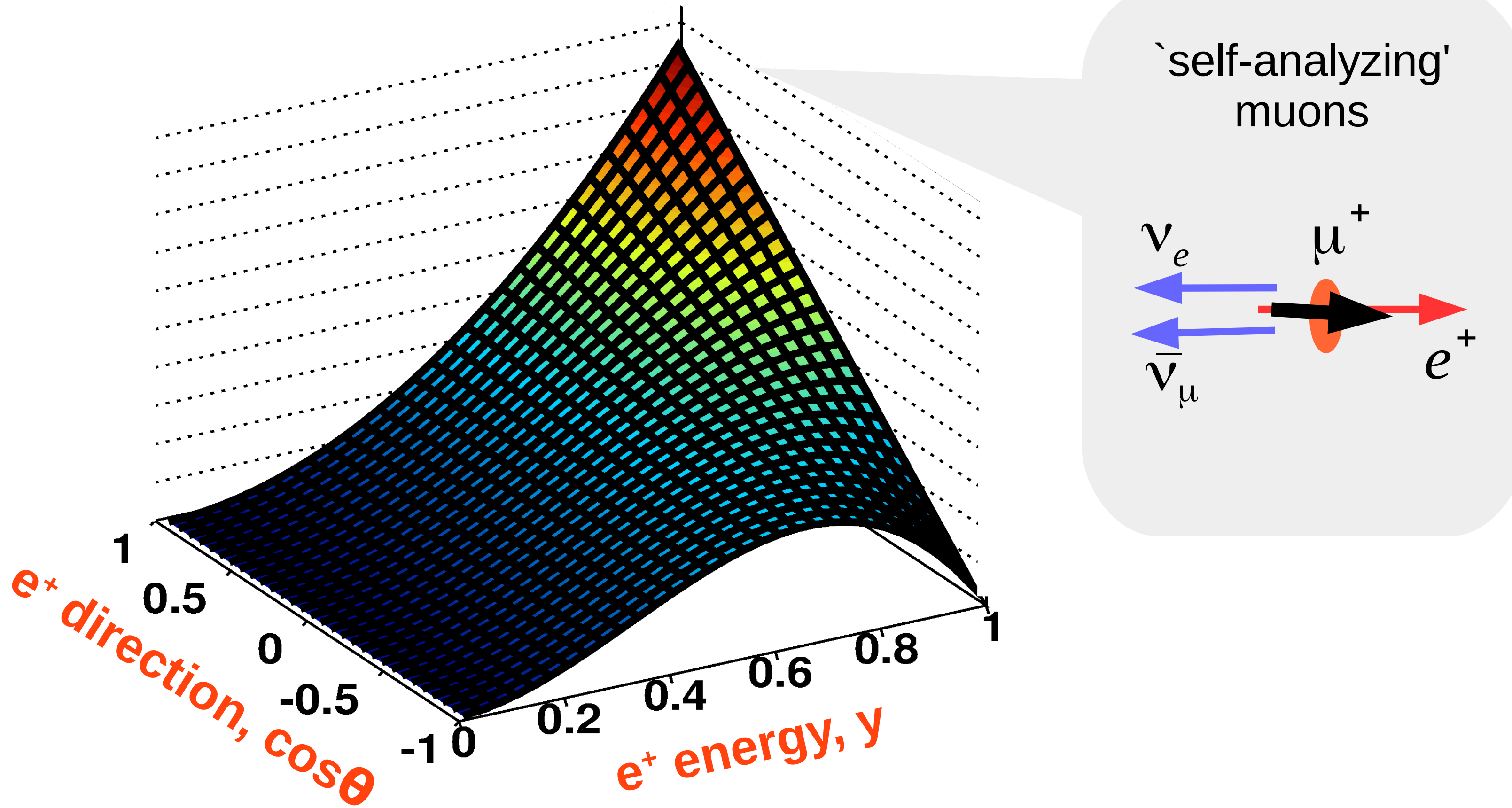
γ = 29.3

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta}\, x\, \vec{E}}{c} \right]$$

Lamor freq.

~0

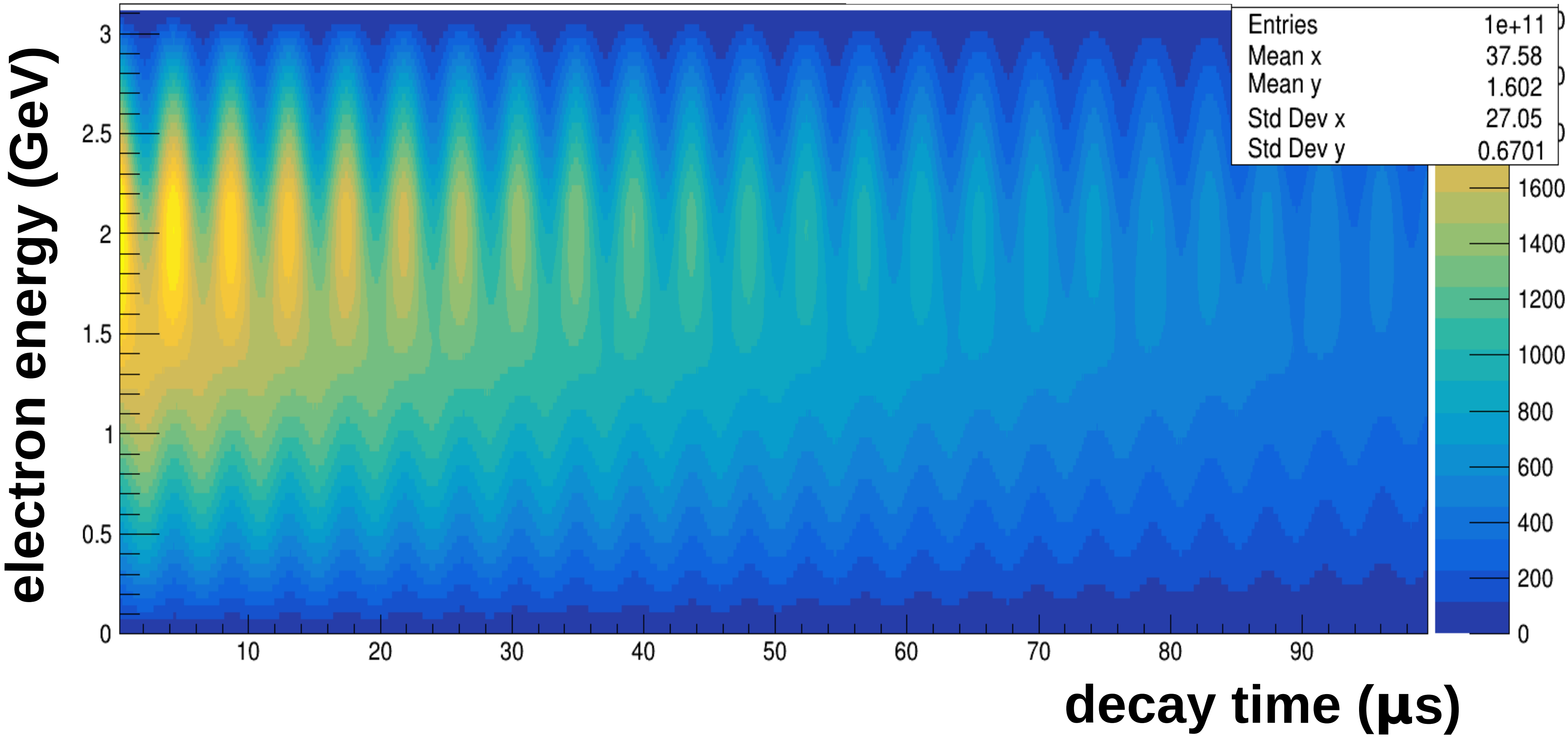
Self-analyzing muons, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$



• relativistic boost from μ to lab frame yields higher energy positrons when emitted along **μ-direction**

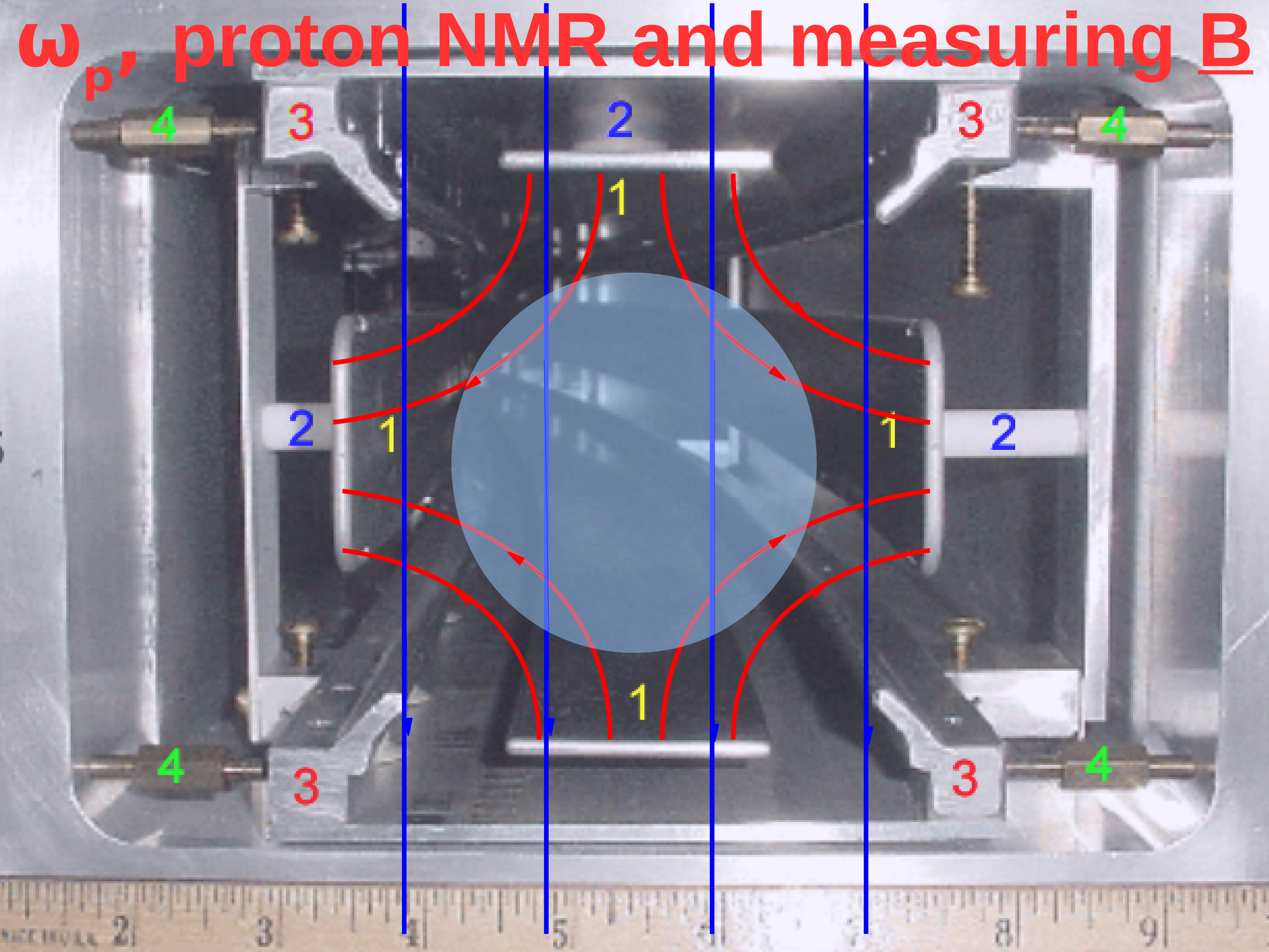
• relativistic boost from μ to lab frame yields lower energy positrons when emitted opposite **μ-direction**

Self-analyzing muons, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

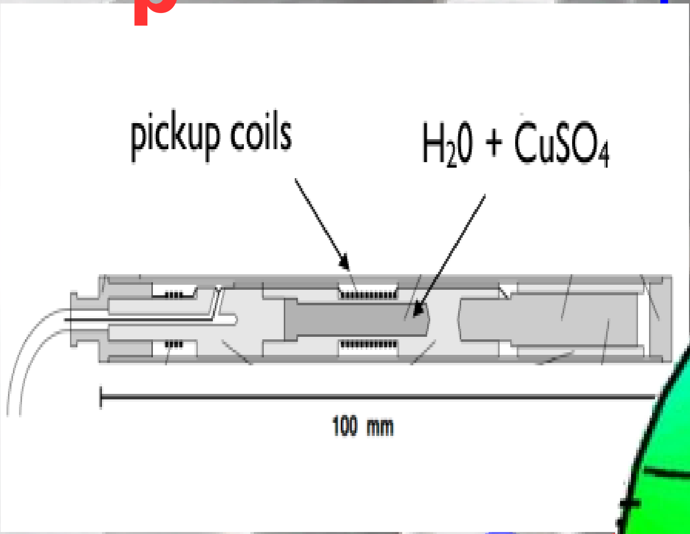


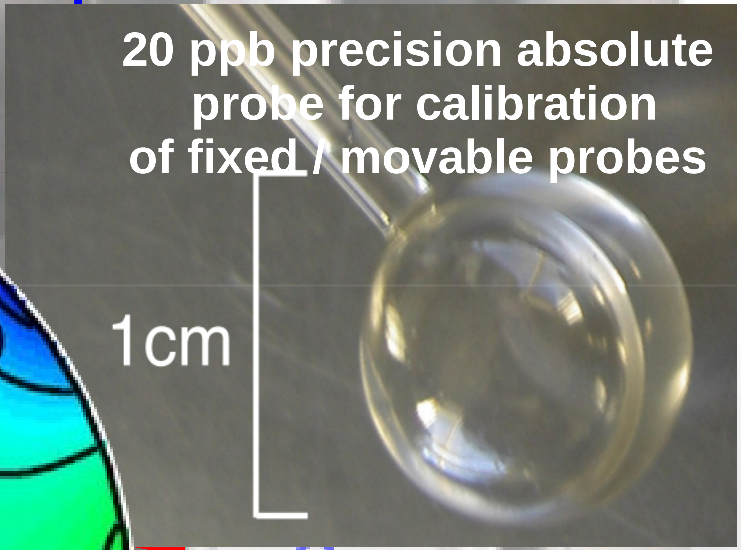
- number of high energy e^+s wiggles with freq. ω_a
- energy deposited by all e^+s wiggles with freq. ω_a

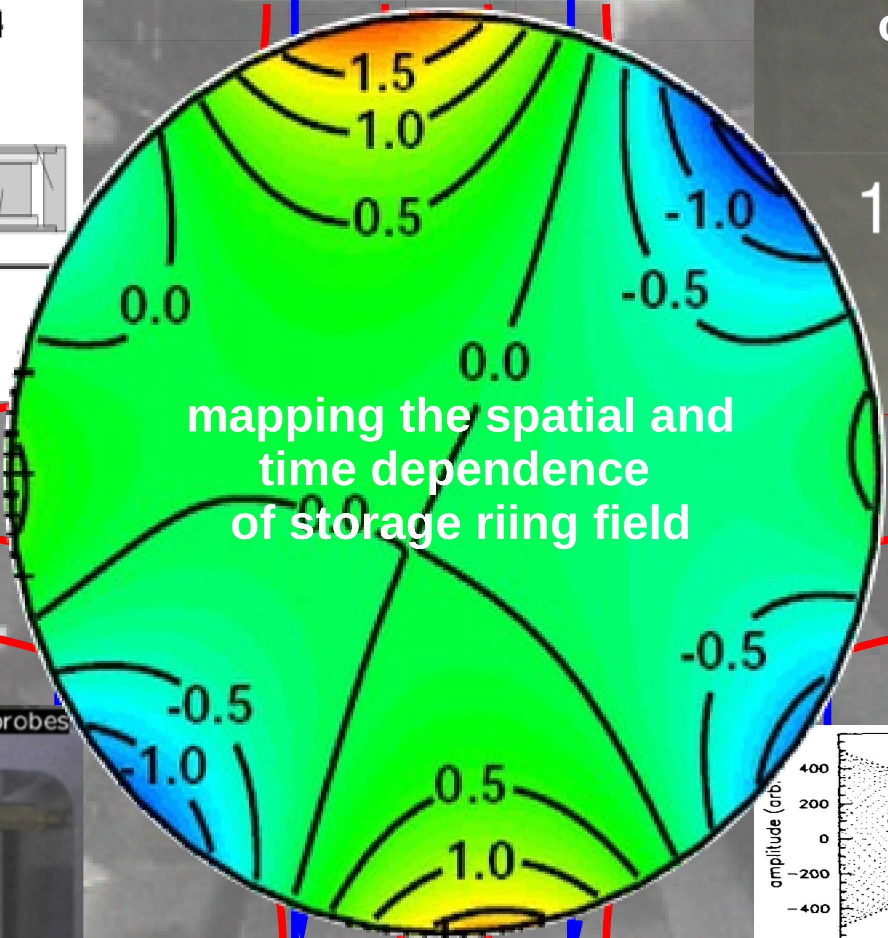
ω_p, proton NMR and measuring B

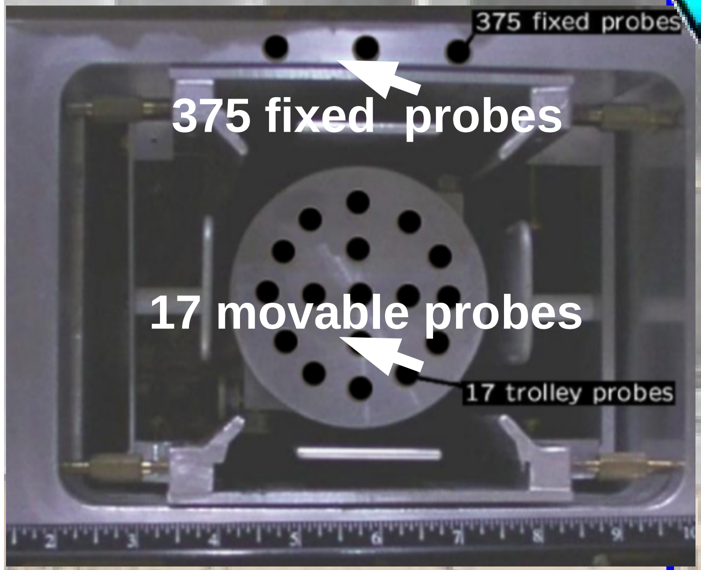


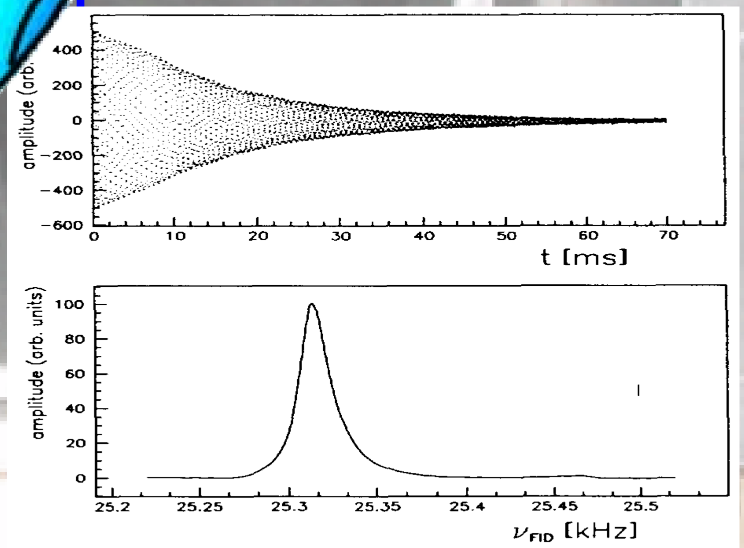
ω_p, proton NMR and measuring $\underline{B}$



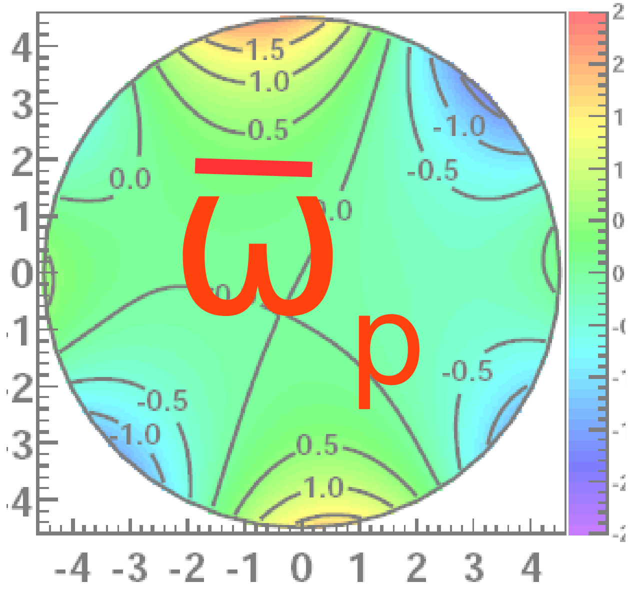






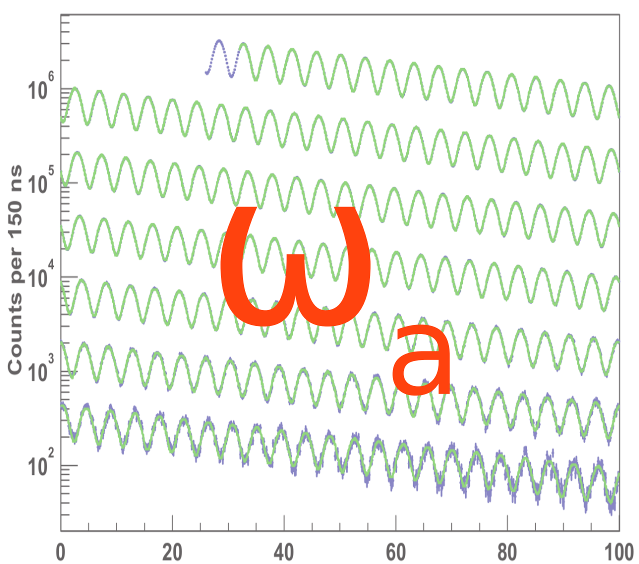


Extracting the anomaly a_μ from ω_μ, ω_p



$$a_\mu = \frac{\omega_a / \overline{\omega}_p}{\mu_\mu / \mu_p - \omega_a / \overline{\omega}_p}$$

26 ppb, from muonium hyperfine experiment



From BNL expt. to FNAL expt.

- **0.54ppm ➡ 0.14 ppm in a_μ**
- **x21 statistics of decay e's**
- **x2 reduction (to 0.07 ppm) in ω_a, ω_p systematic errors**

From big move to first data

summer 2013,


Wisconsin
Michigan
Toronto
Map
Sat
Ohio
Indiana
Indianapolis
Columbus
Pennsylvania
Philadelphia
Maryland
West Virginia
New Jersey
Rhode Island
Connecticut
Missouri
Kentucky
Virginia
North Carolina
Charlotte
Arkansas
Atlanta
South Carolina
Alabama
Georgia
Louisiana
Tampa
Gulf of Mexico
The Bahamas
Imagery ©2013 TerraMetrics, Map data ©2013 Google, INEG

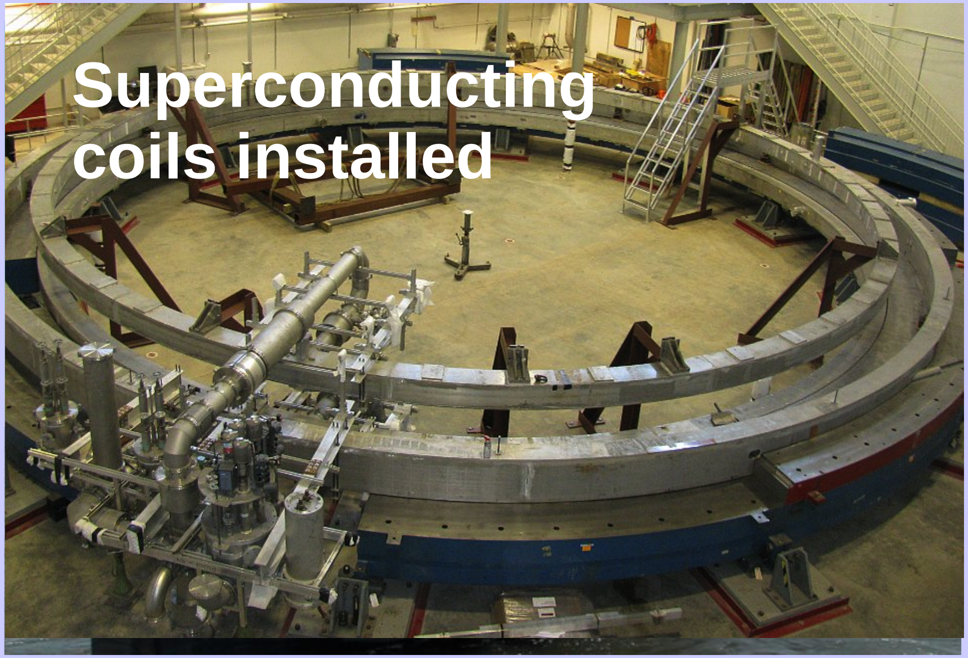

Muon g-2
EMMERT


TRIDENT


OVERSIZE LOAD
EMMERT
Driving Discovery in Particle Physics

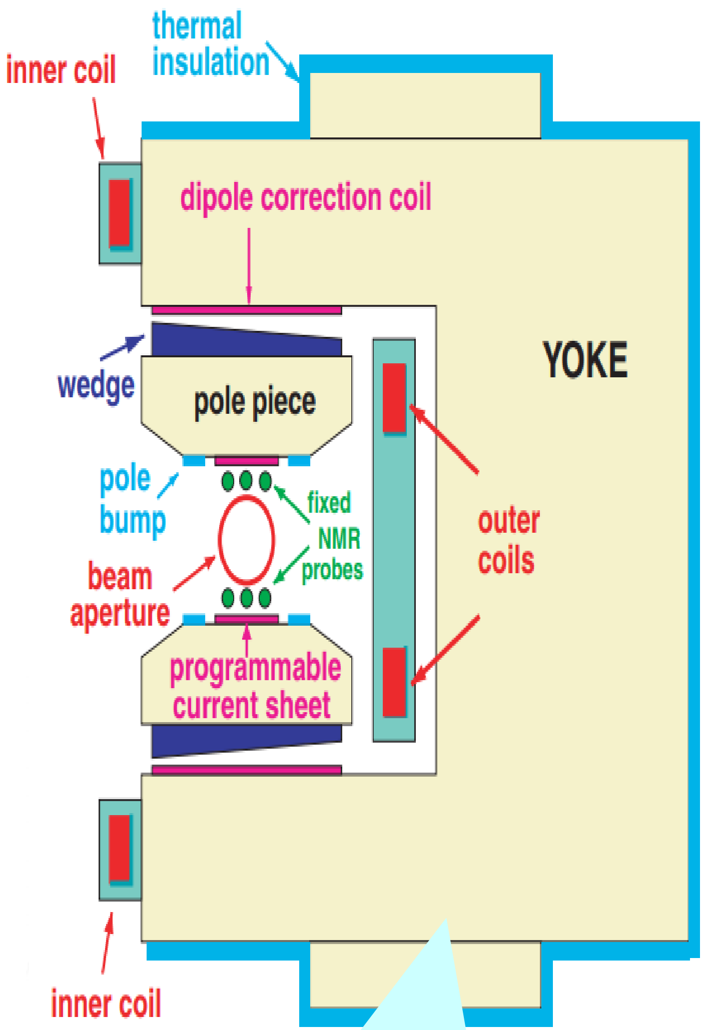

2013-14

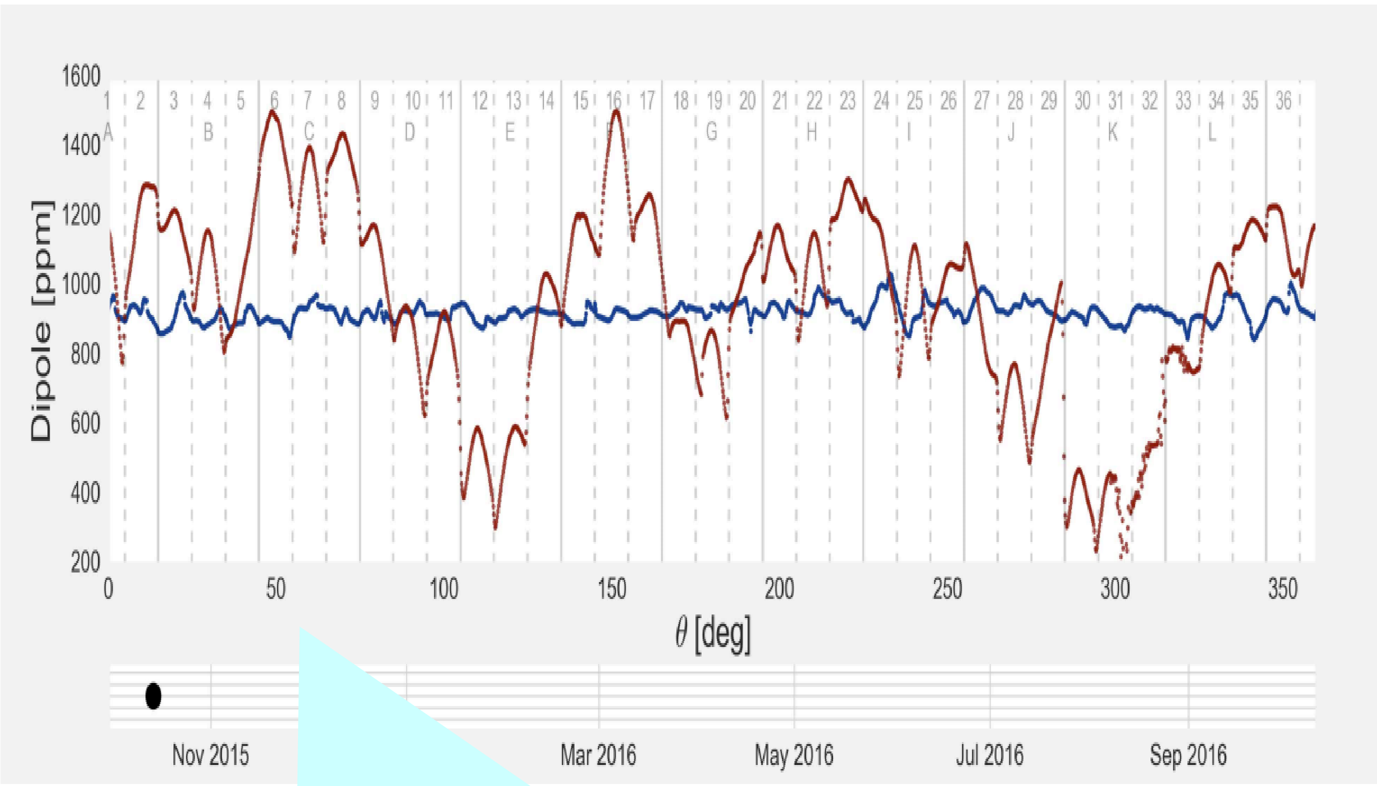

Bottom yoke installed


Superconducting
coils installed


Top yoke installed

Magnet shimming

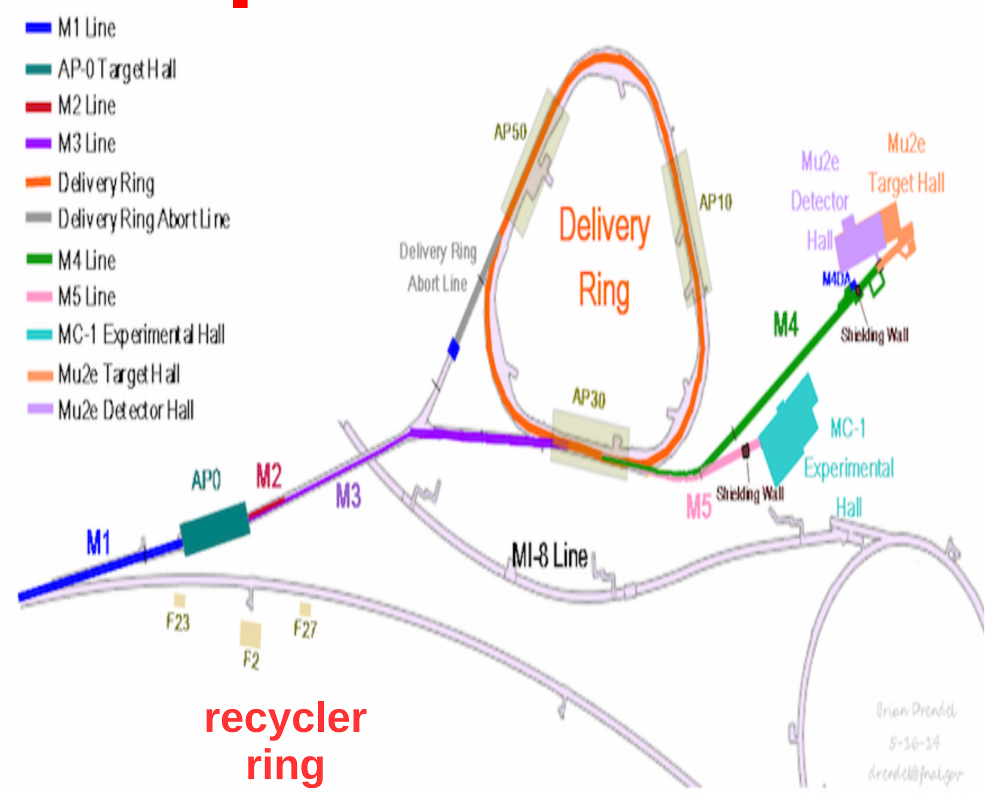




large number of shimming tools

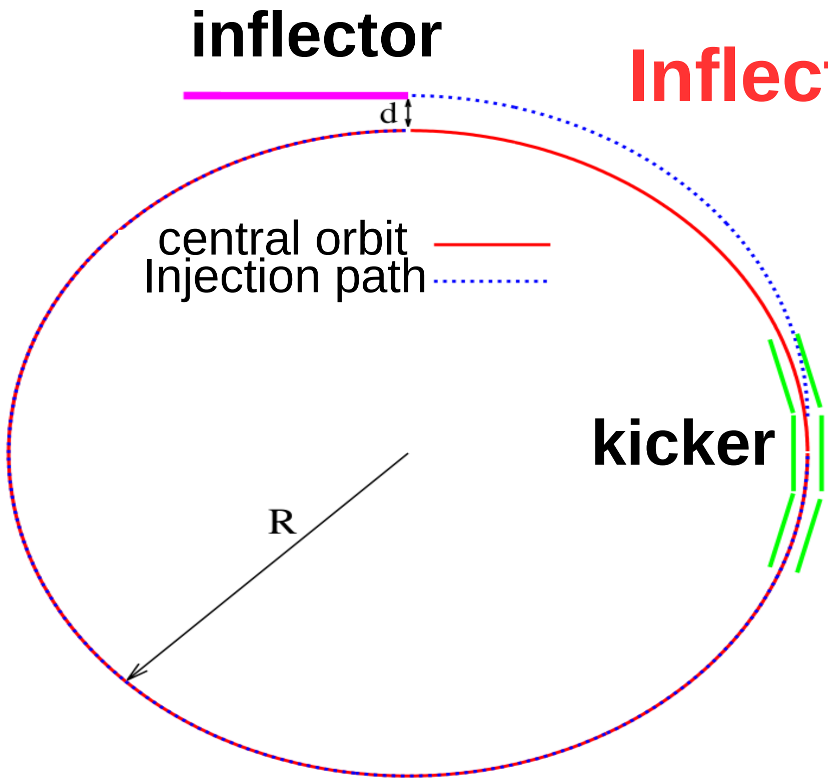
ω_a is determined by average magnetic field seen by stored muon distribution **so** work hard to minimize longitudinal / transverse inhomogeneities

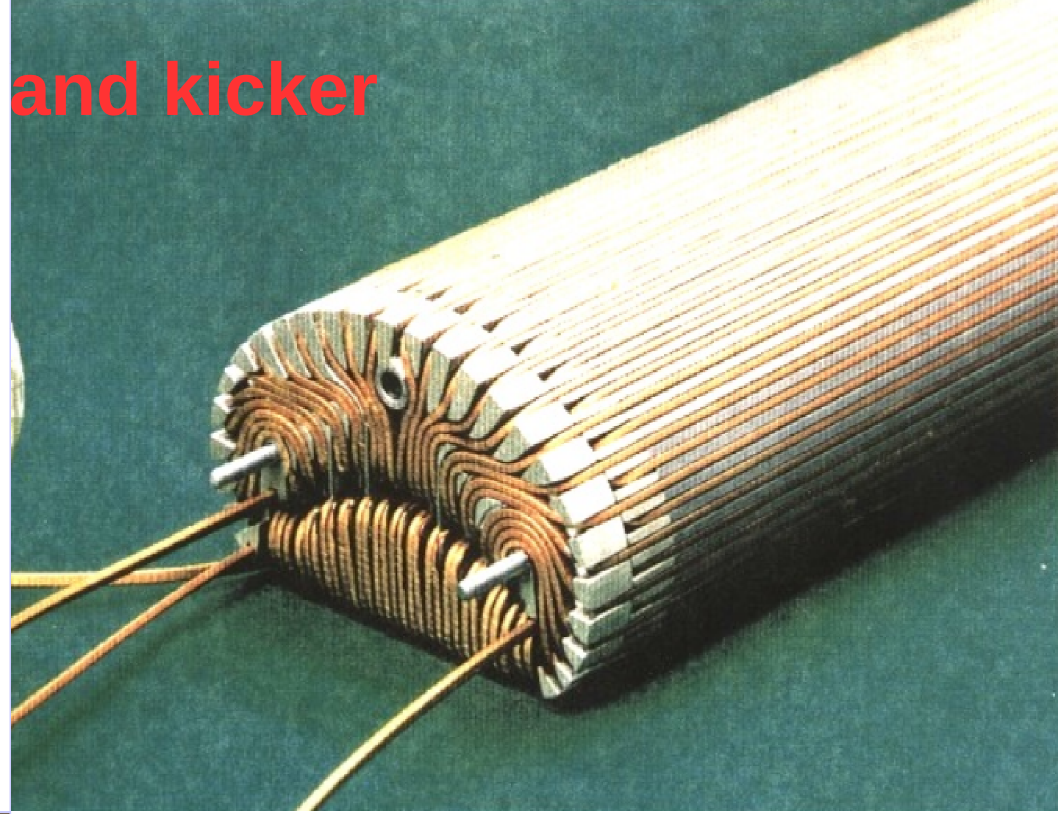
Muon Campus

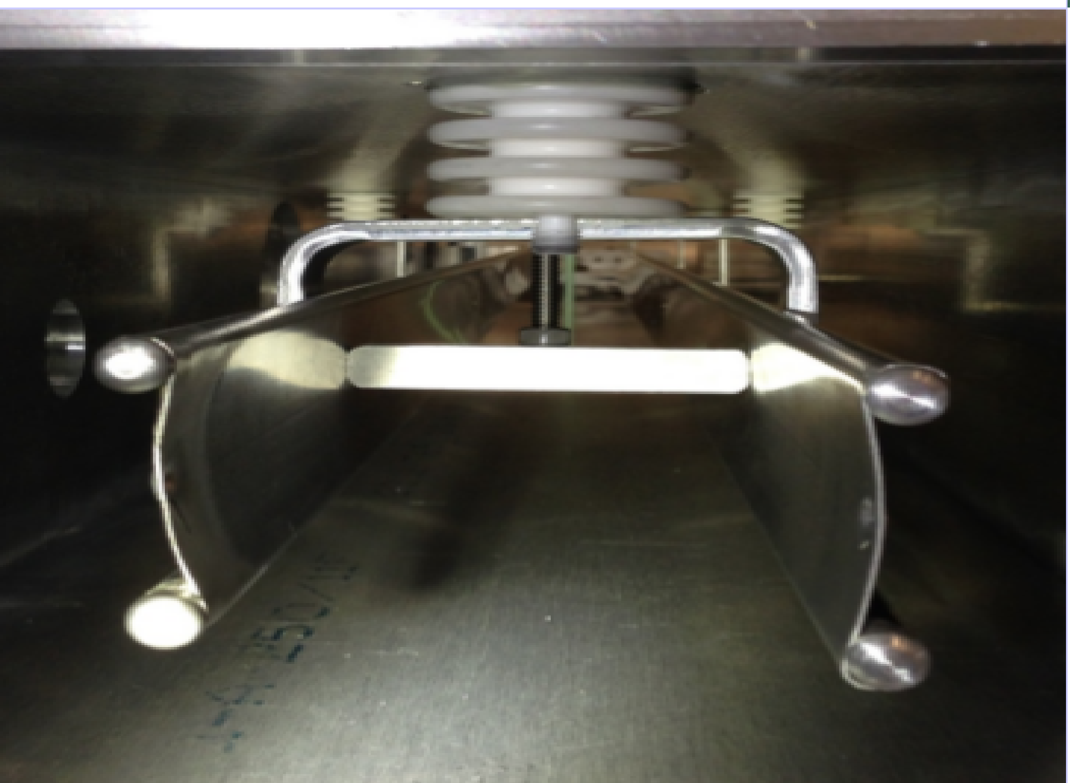


- 8 GeV protons to recycler ring for rebunching
- extracted bunch and strike the π-production target
- decay of π's to polarized μ's in decay line
- Injection into delivery ring for μ, π, p separation
- Muons extracted to g-2 storage ring

Inflector and kicker



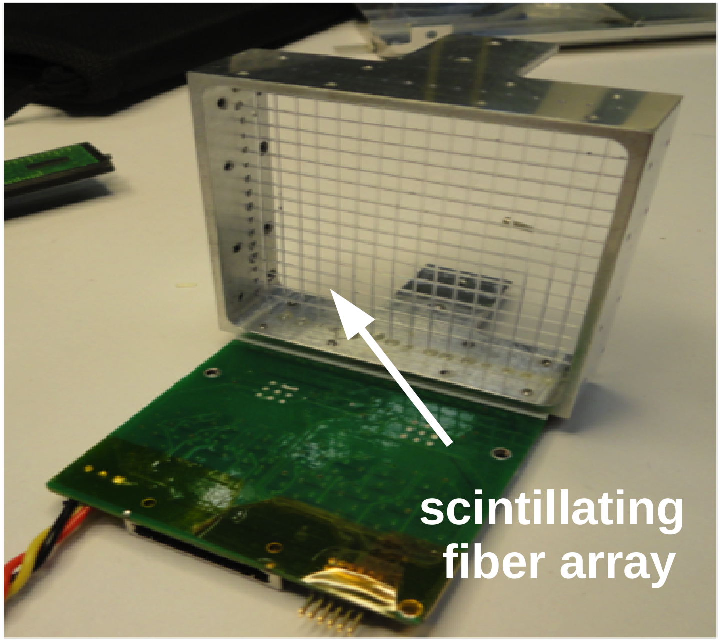


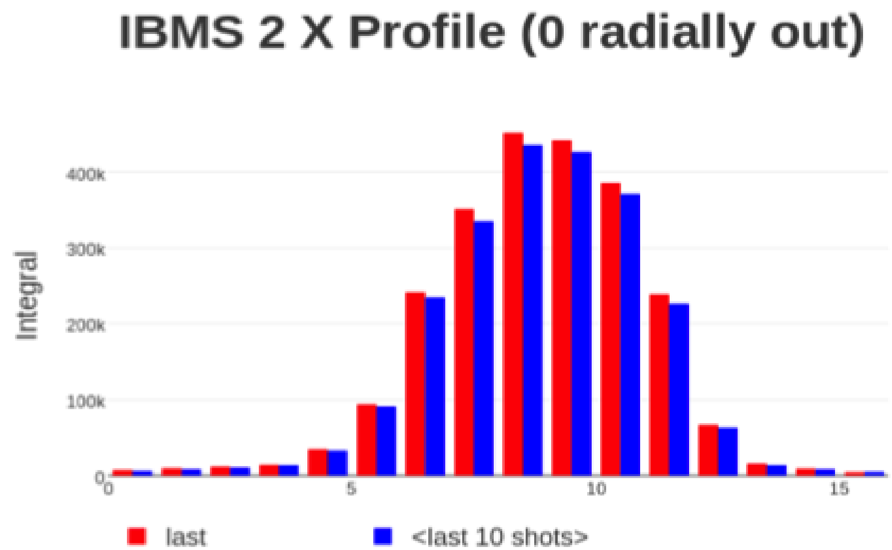


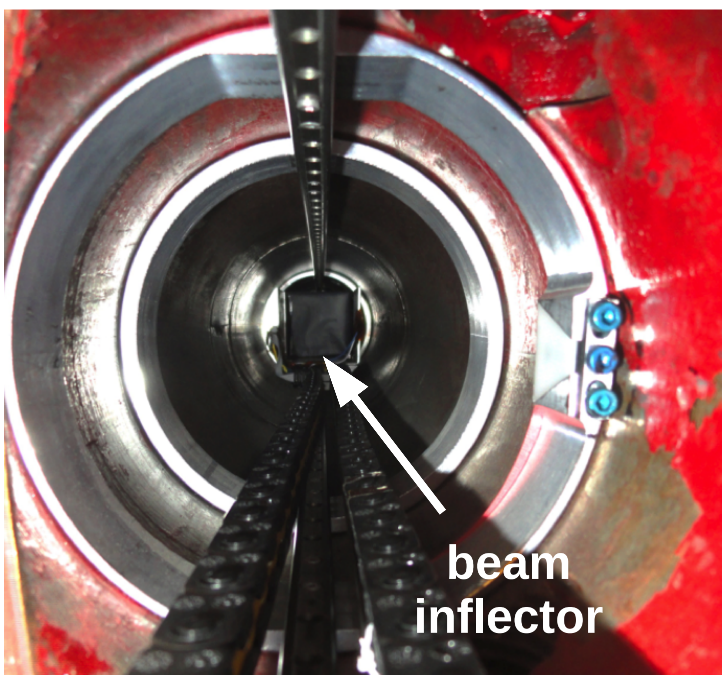
- inflector null's storage ring 1.5T field in beamline entrance using superconducting double cosine theta coil.

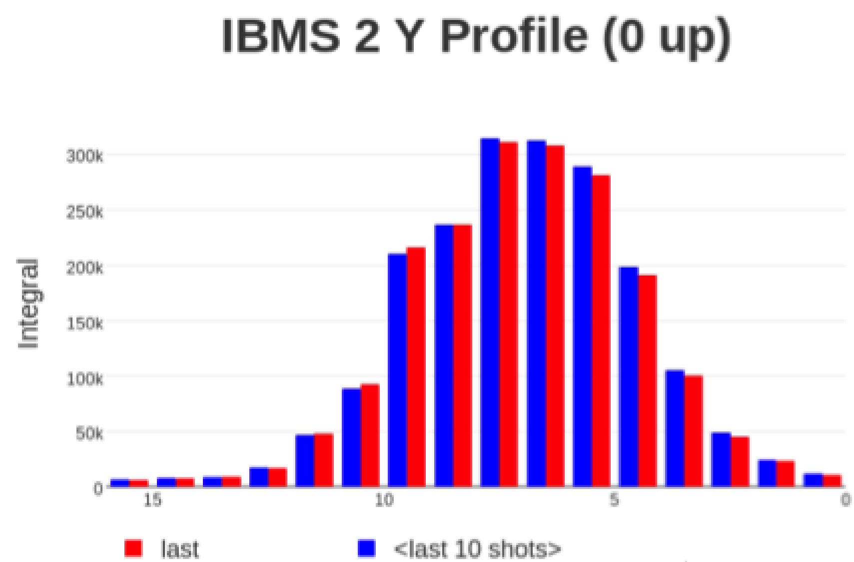
- kicker displaces the injected beam by ~0.8 mrad to place on storage ring's central orbit.

Scintillating-fiber beam profile monitor – June 2017 commissioning run

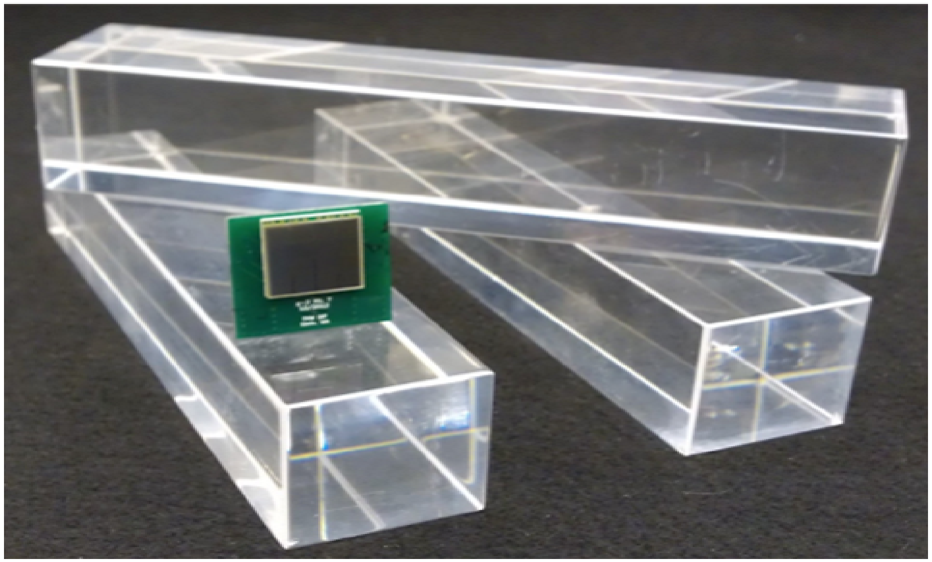


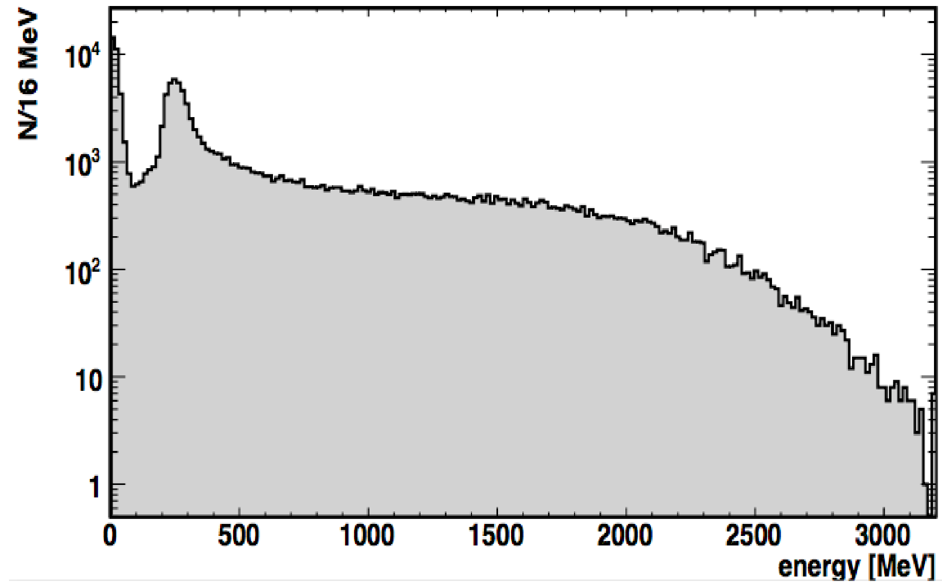


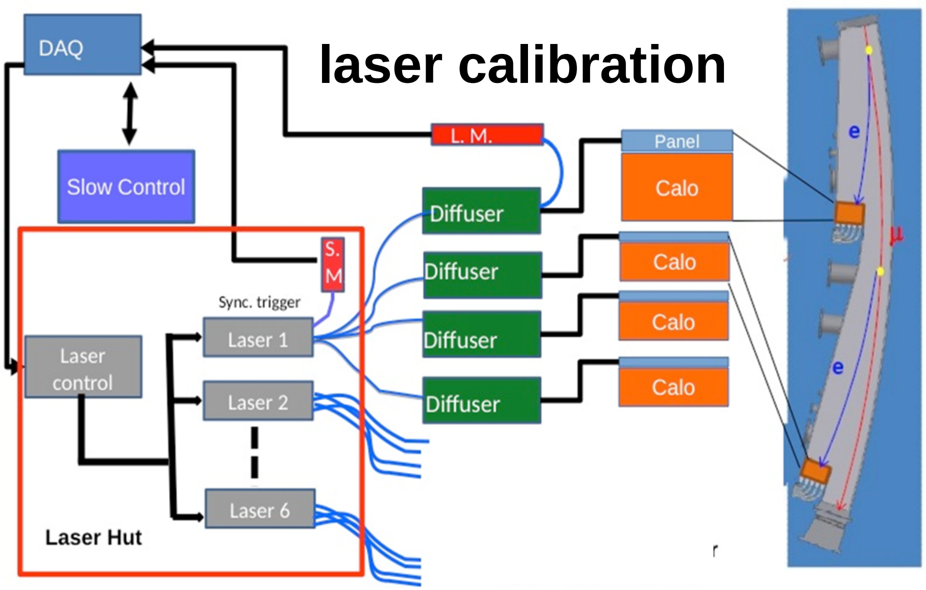


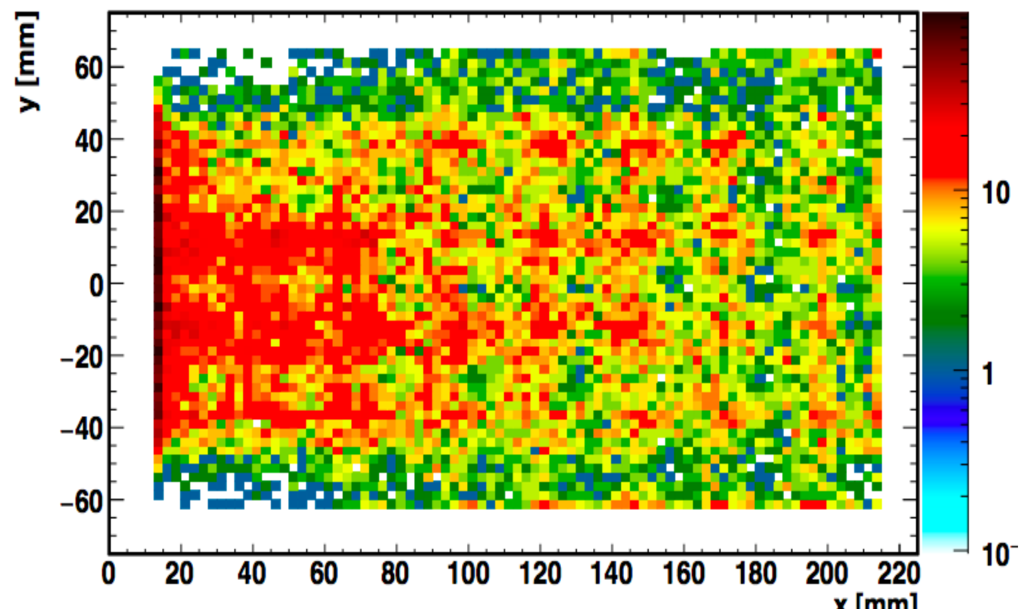


Twenty four, segmented PbF_2 calorimeters – June 2017 commissioning run

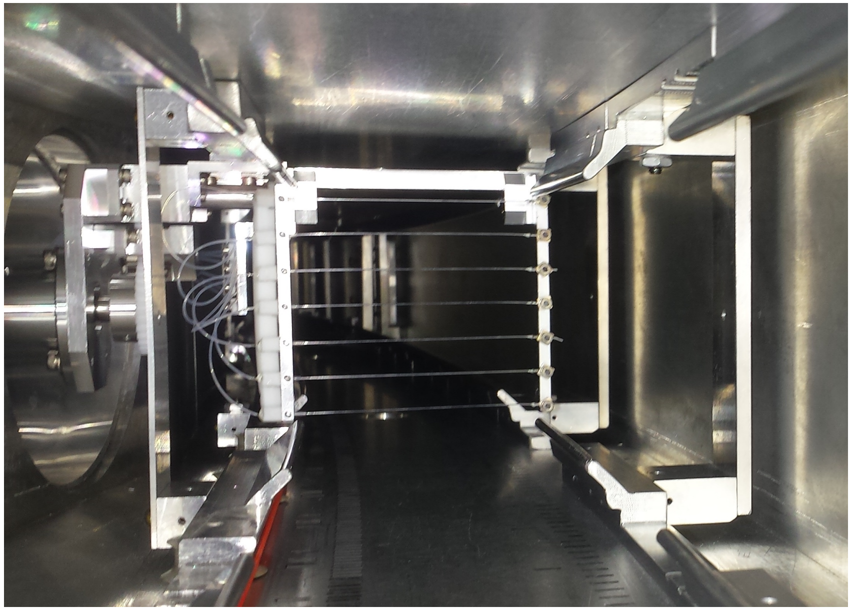


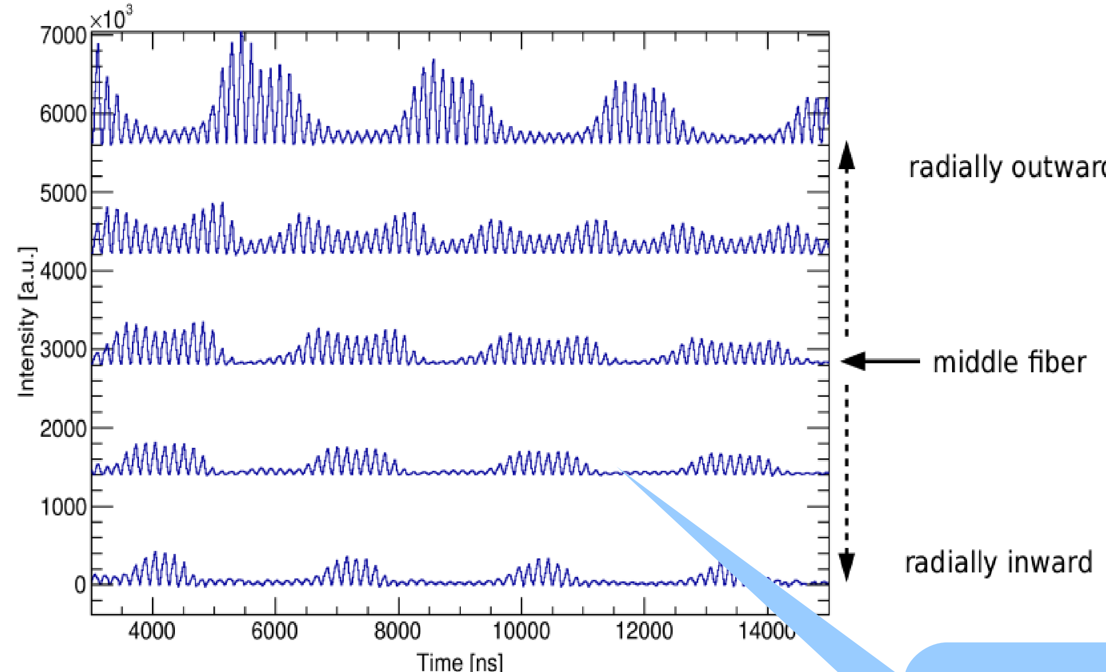




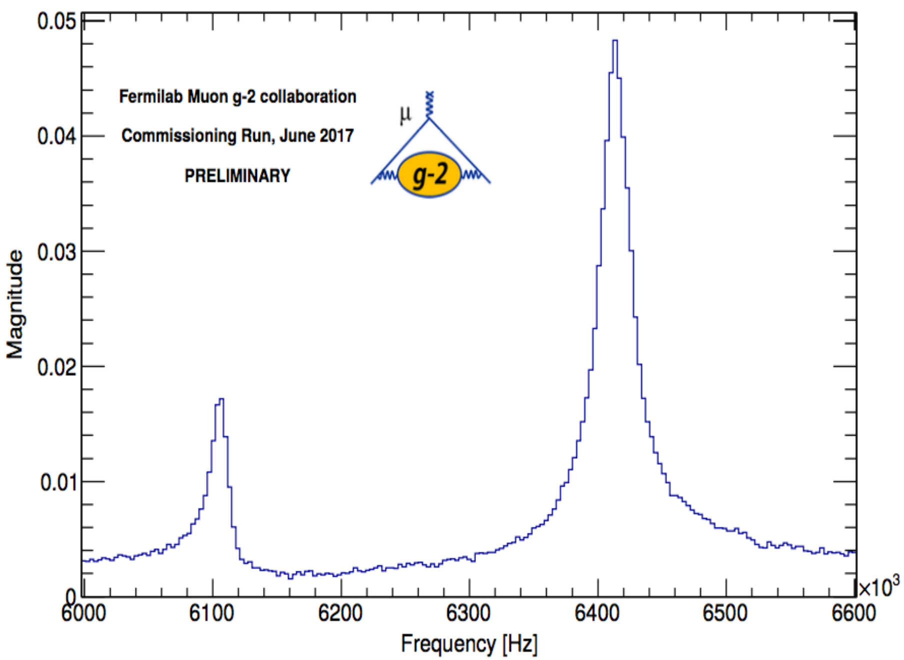


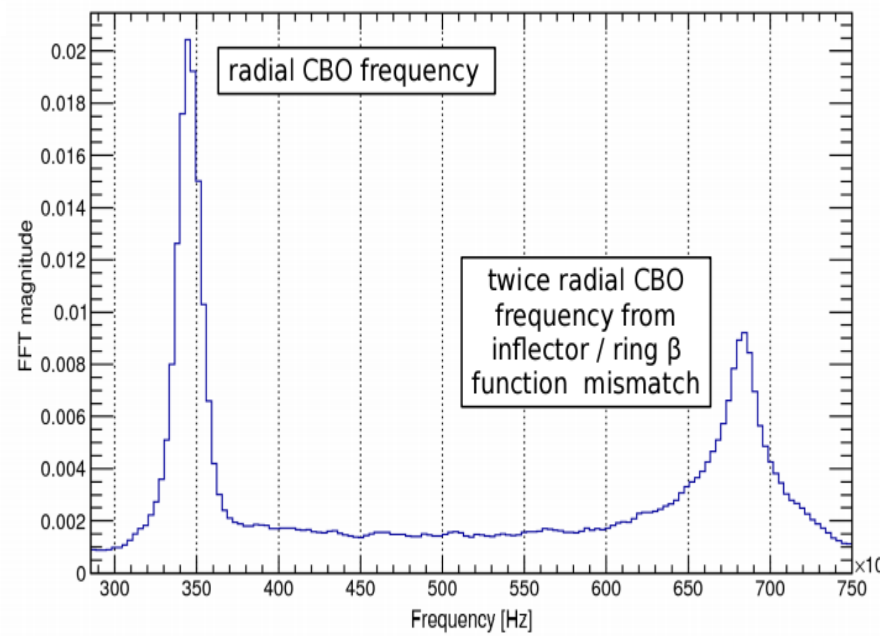
Horizontal / vertical, in-vacuum scintillating fiber arrays – June 2017 commissioning run



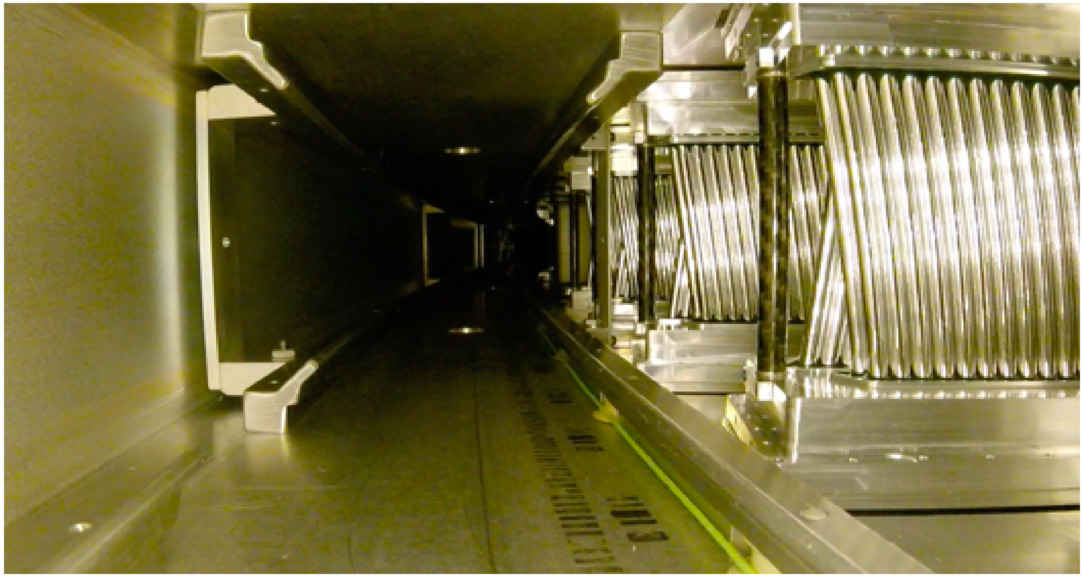


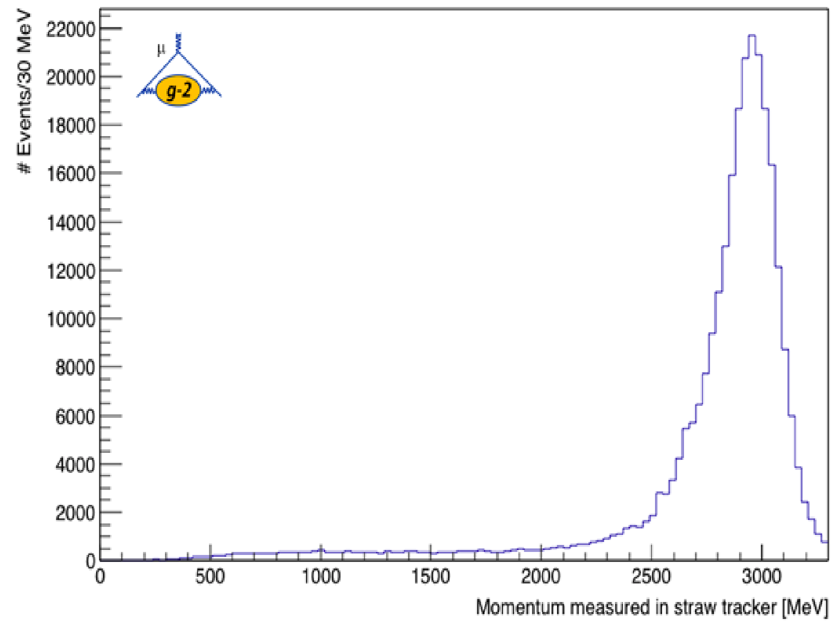
note ω_c, ω_{CBO}

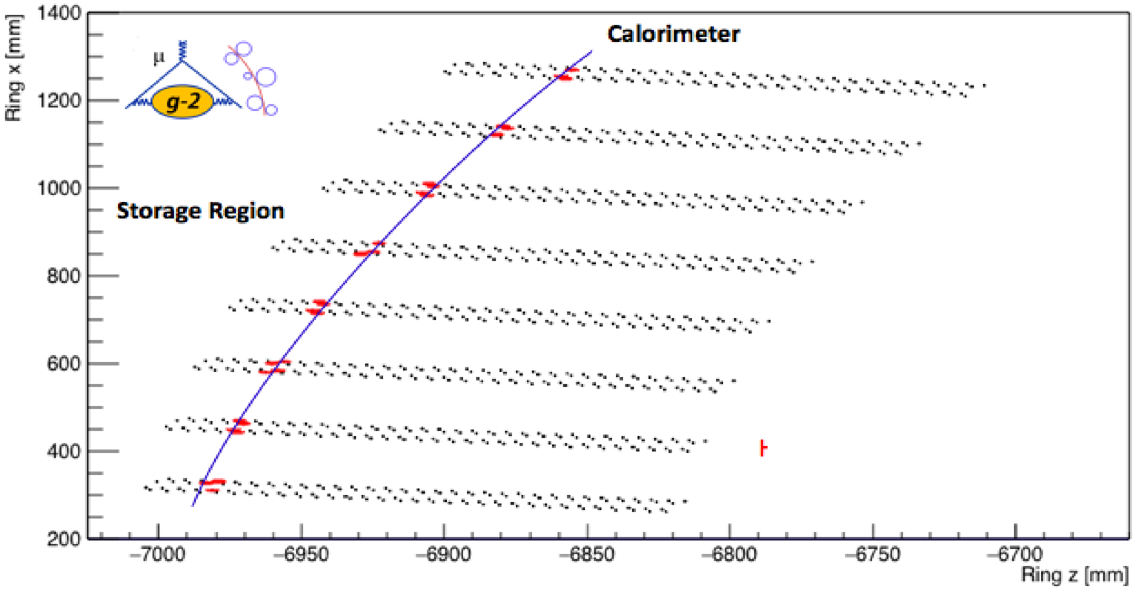


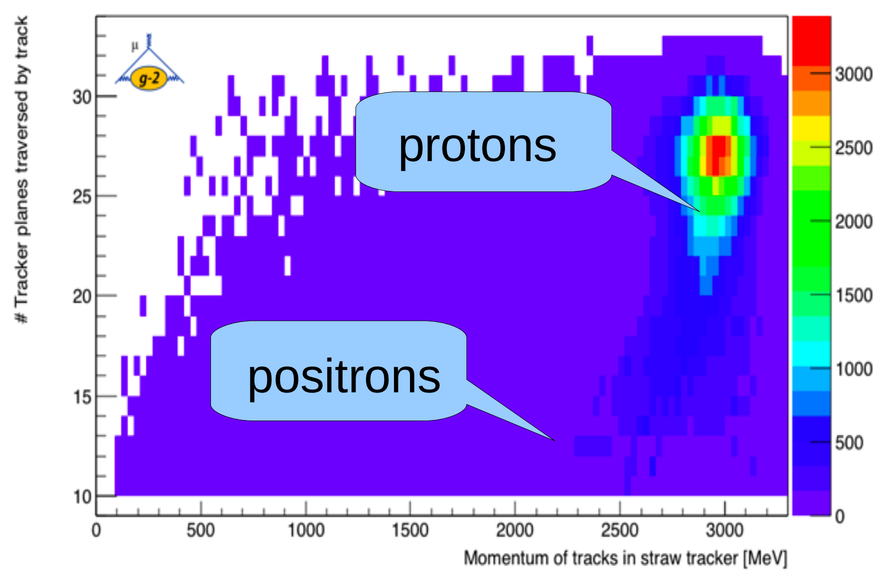


In-vacuum, straw tube arrays for positron detection – June 2017 commissioning run

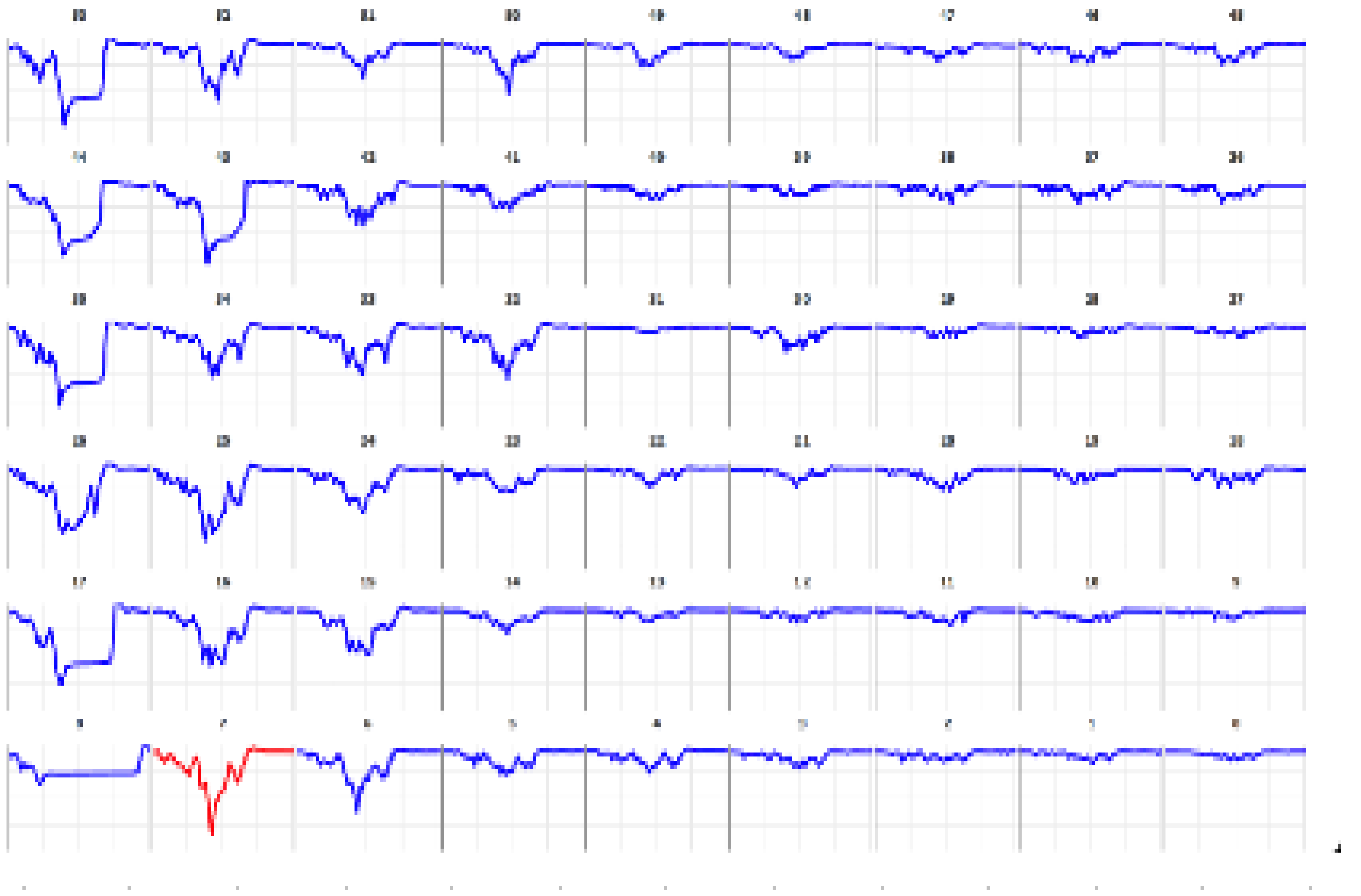




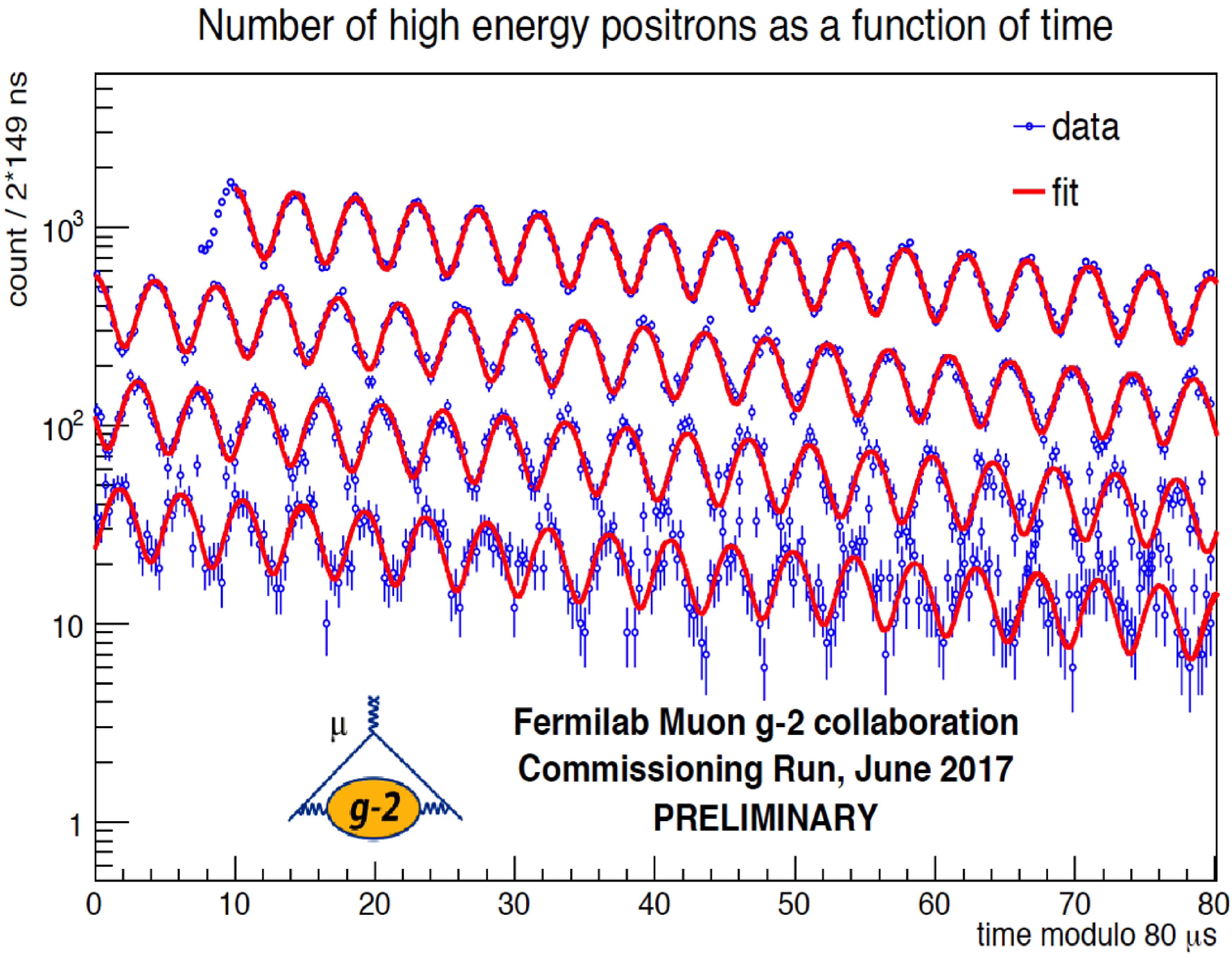




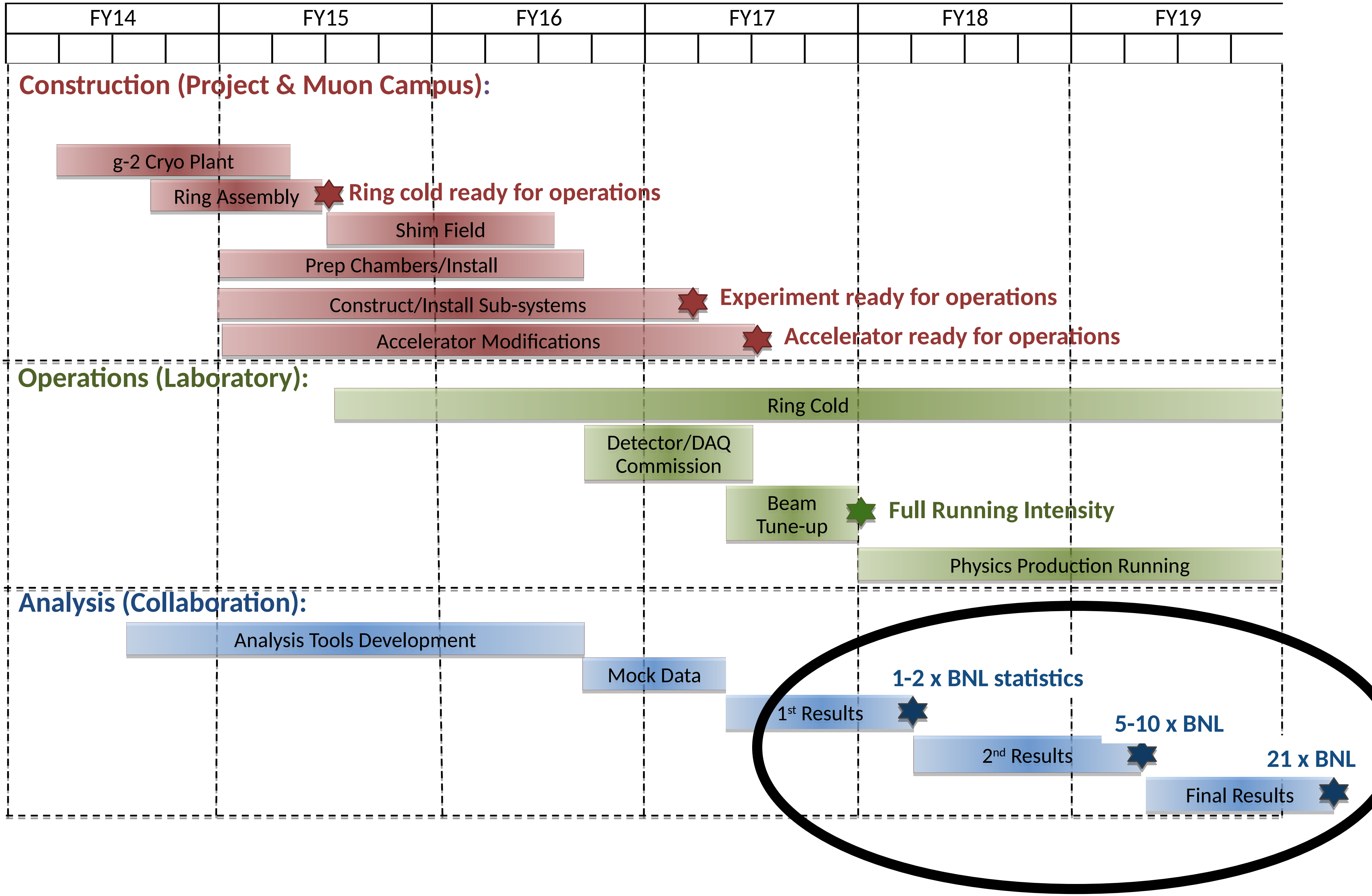
First fill – May 23, 2017 commissioning run



Wiggle plot – June 2017 commissioning run



Schedule


FY14
FY15
FY16
FY17
FY18
FY19
Construction (Project & Muon Campus):
g-2 Cryo Plant
Ring Assembly
Ring cold ready for operations
Shim Field
Prep Chambers/Install
Construct/Install Sub-systems
Experiment ready for operations
Accelerator Modifications
Accelerator ready for operations
Operations (Laboratory):
Ring Cold
Detector/DAQ Commission
Beam Tune-up
Full Running Intensity
Physics Production Running
Analysis (Collaboration):
Analysis Tools Development
Mock Data
1-2 x BNL statistics
1st Results
5-10 x BNL
2nd Results
21 x BNL
Final Results

Extras.

Physical frequency	Variable	Expression	Frequency	Period
Anomalous precession	f_a	$\frac{e}{2\pi m} a_\mu B$	0.23 MHz	4.37 μs
Cyclotron	f_c	$\frac{v}{2\pi R_0}$	6.71 MHz	149 ns
Horizontal betatron	f_x	$\sqrt{1-n} f_c$	6.23 MHz	160 ns
Vertical betatron	f_y	$\sqrt{n} f_c$	2.48 MHz	402 ns
Horizontal CBO	f_{CBO}	$f_c - f_x$	0.48 MHz	2.10 μs
Vertical waist	f_{VW}	$f_c - 2f_y$	1.74 MHz	0.57 μs

Statistics

Item	Estimate
Protons per fill on target	10^{12} p
Positive-charged secondaries with $dp/p = \pm 2\%$	4.8×10^7
π^+ fraction of secondaries	0.48
π^+ flux entering FODO decay line	$> 2 \times 10^7$
Pion decay to muons in 220 m of M2/M3 line	0.72
Muon capture fraction with $dp/p < \pm 0.5\%$	0.0036
Muon survive decay 1800 m to storage ring	0.90
Muons flux at inflector entrance (per fill)	4.7×10^4
Transmission and storage using $(dp/p)_\mu = \pm 0.5\%$	0.10 ± 0.04
Stored muons per fill	$(4.7 \pm 1.9) \times 10^3$
Positrons accepted per fill (factors 0.15 x 0.63)	444 ± 180
Number of fills for 1.8 $\times 10^{11}$ events	$(4.1 \pm 1.7) \times 10^8$ fills
Time to collect statistics	(13 ± 5) months
Beam-on commissioning	2 months
Dedicated systematic studies periods	2 months
Net running time required	17 ± 5 months

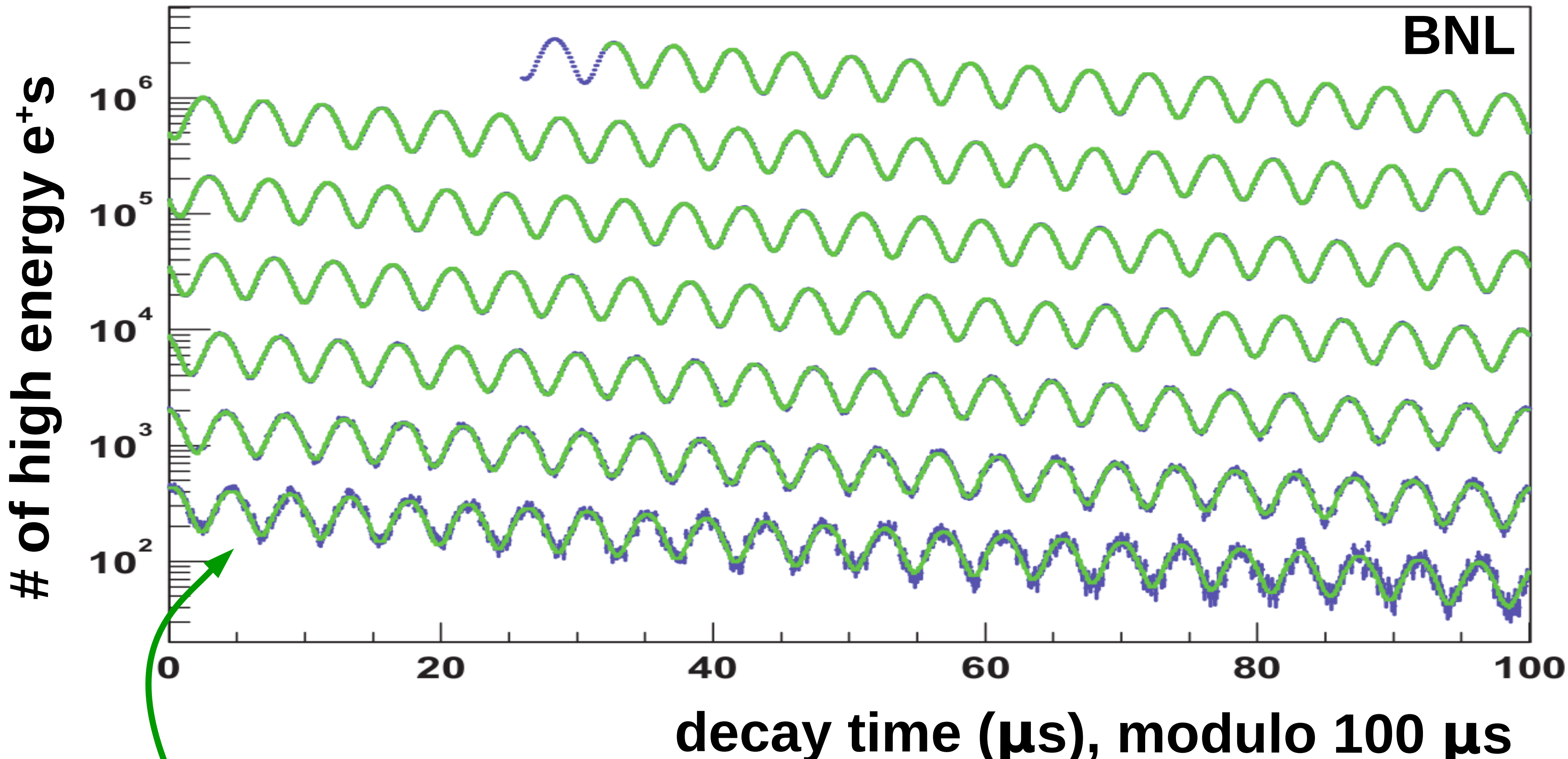
ω_a systematics.

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

ω_p systematics.

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

BNL E821



$$\frac{dN}{dt} = N_o e^{-t/\tau}\left[1 + A\cos\left(\omega_a t + \varphi\right)\right]$$