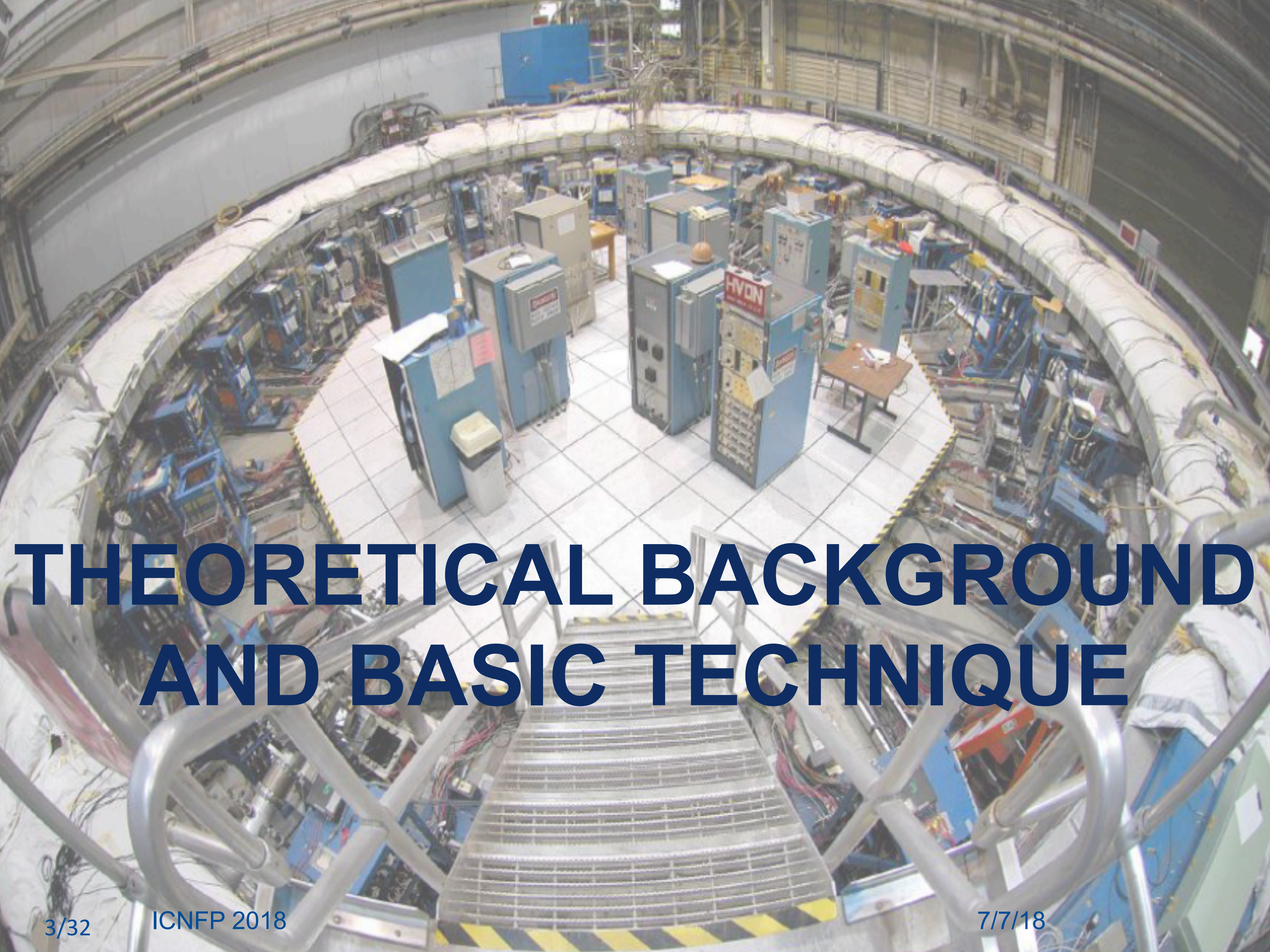
The current status the Fermilab Muon g-2 Experiment

Nandita Raha, INFN Pisa (on behalf the Muon g-2 Collaboration)
7th International Conference on New Frontiers in Physics (ICNFP 2018)

Outline

- Theoretical Background and Basic Technique
- Experimental Performance and Comparison with the current best measurement (E821 at BNL)
- Measurements and systematics
- Conclusion



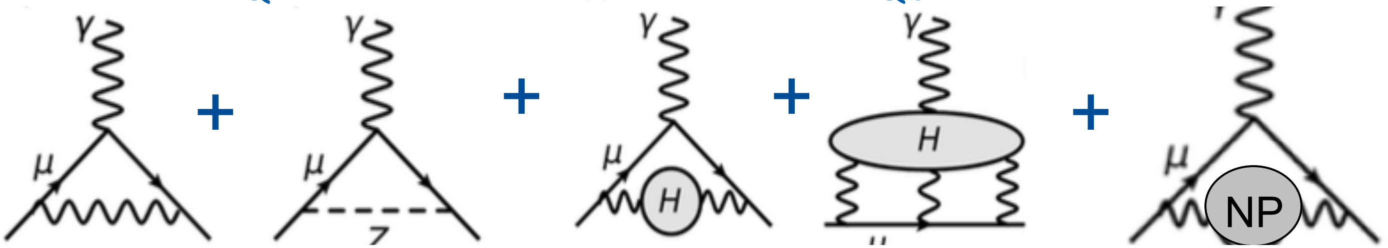
THEORETICAL BACKGROUND AND BASIC TECHNIQUE

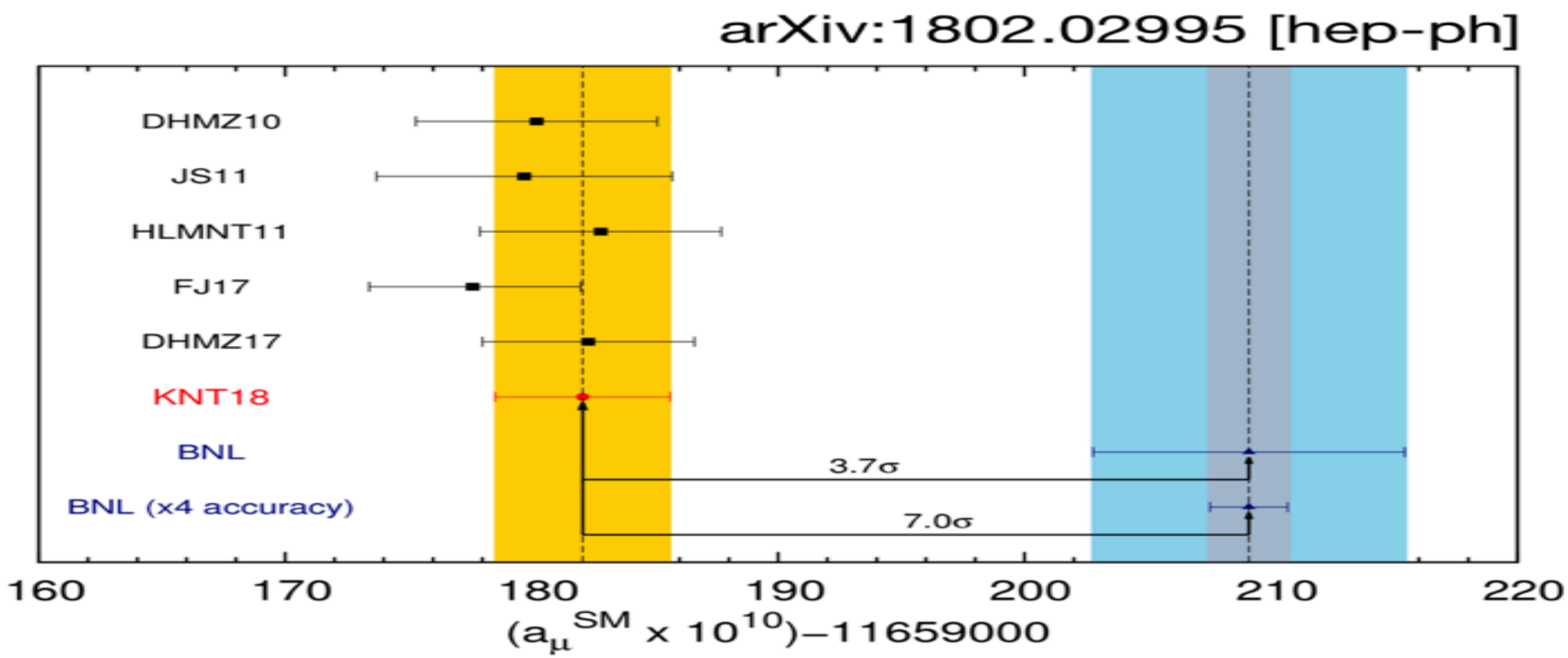
Muon g-2: The Basics

$$\vec{\mu} = g \frac{q}{2m} \vec{s}$$ with g = 2 for a tree level anomaly (Dirac)

$g = 2(\text{Dirac}) + O(10^{-3})_{QED} + O(10^{-9})_{EW} + O(10^{-7})_{QCD} + \text{NP (?)}$

$g_{SM} + g_{NP?}$:





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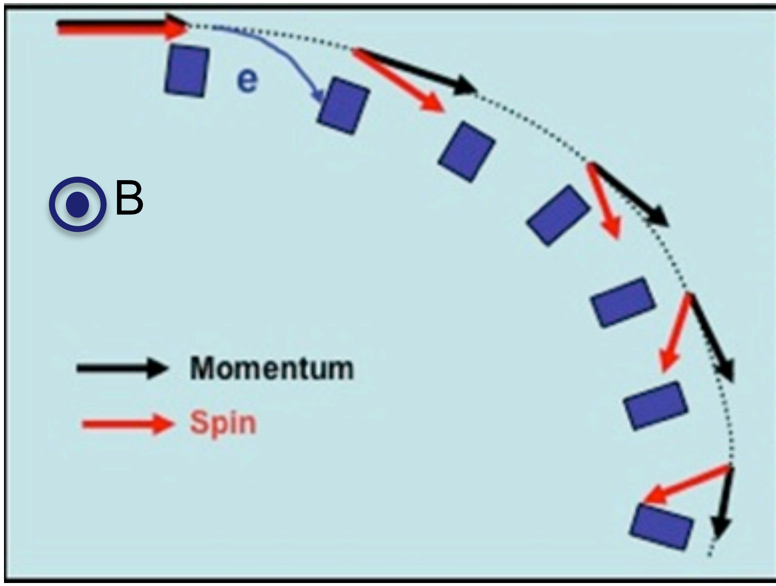

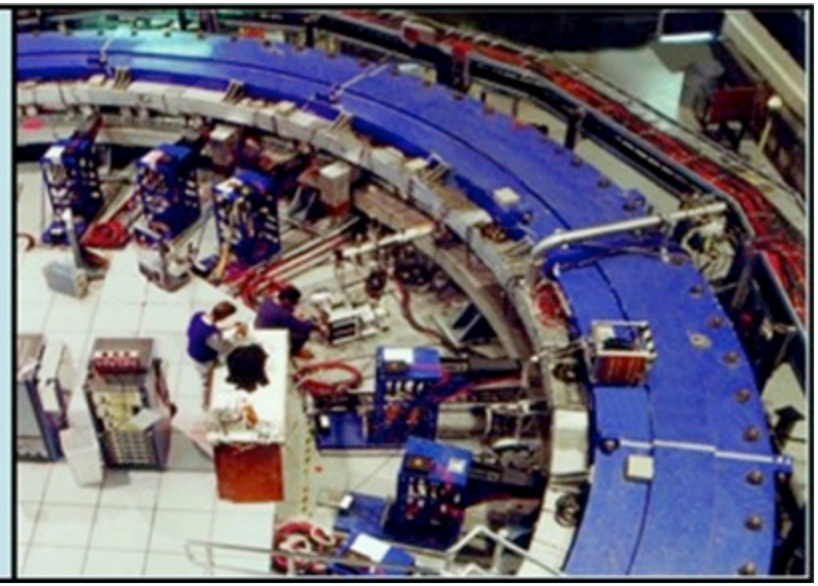

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

Magic p is at $\gamma = 29.3$

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

$$\omega_a = \omega_S - \omega_c = \frac{eB}{m}a_\mu$$

Muon g-2: The Basics

$$\vec{\mu} = g\frac{q}{2m}\vec{s}$$ with g = 2 for a tree level anomaly (Dirac)

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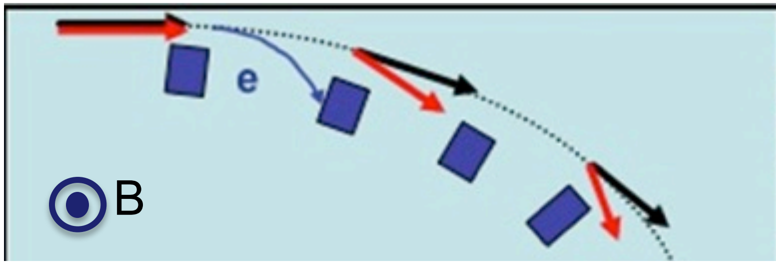
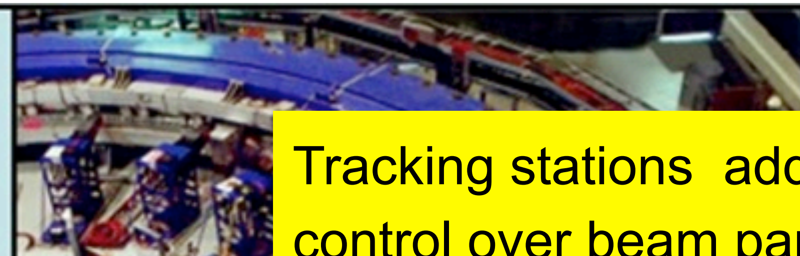
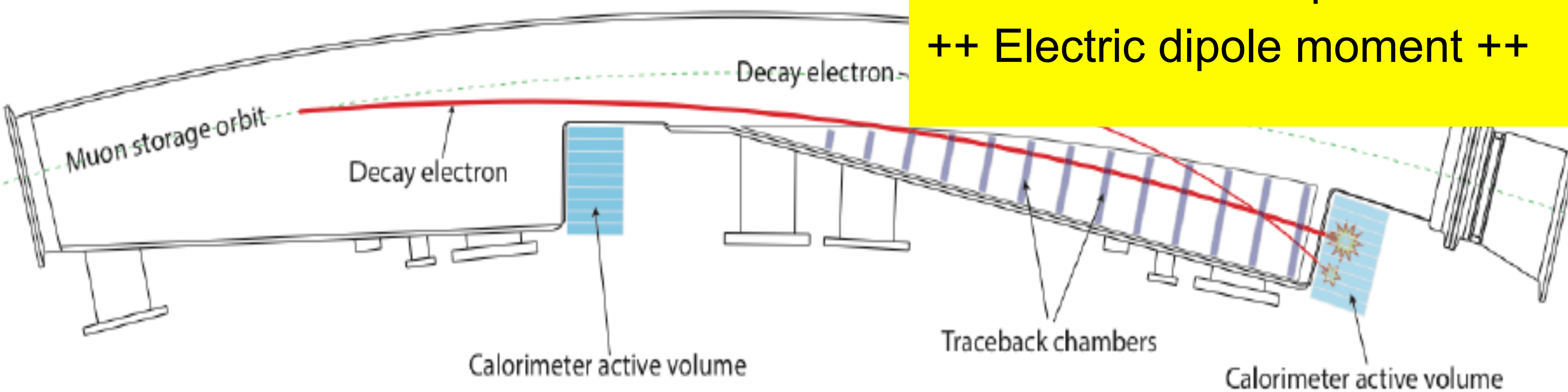




Tracking stations add much control over beam parameters

++ Electric dipole moment ++



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

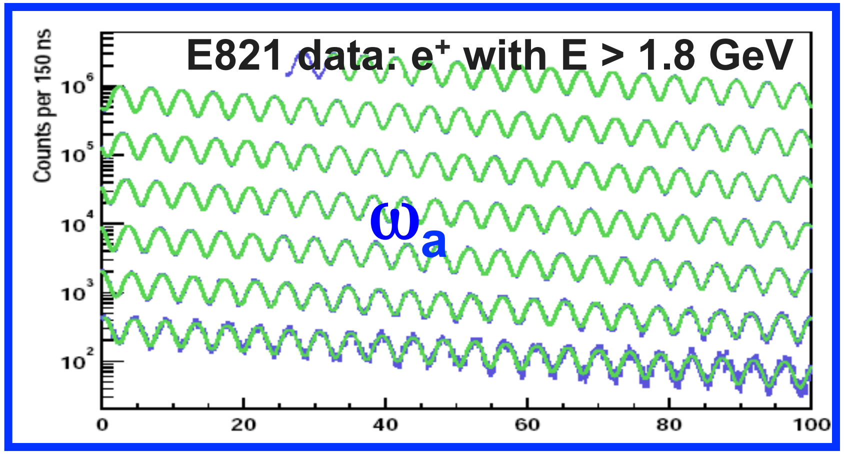
$$\omega_a = \omega_S - \omega_c = \frac{eB}{m}a_\mu$$

Muon anomalous moment measurement

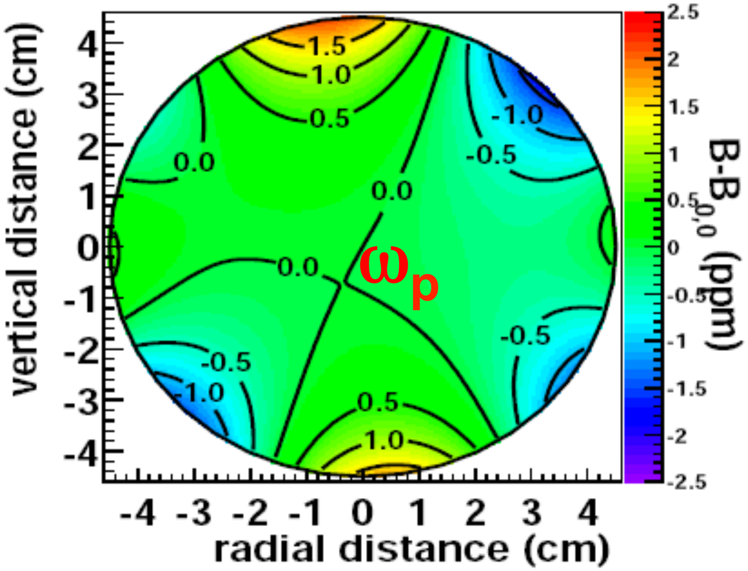
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Measure B → via NMR → recast a_μ in terms of proton precession frequency, ω_p (at B in its rest frame).

Muonic hyperfine experiment gives μ_μ/μ_p at ~26 ppb precision (ref. arXiv:1203.5425)



$$N(t) = N_0 e^{-t/\tau}\left(1 + A cos(\omega_a t + \phi)\right)$$

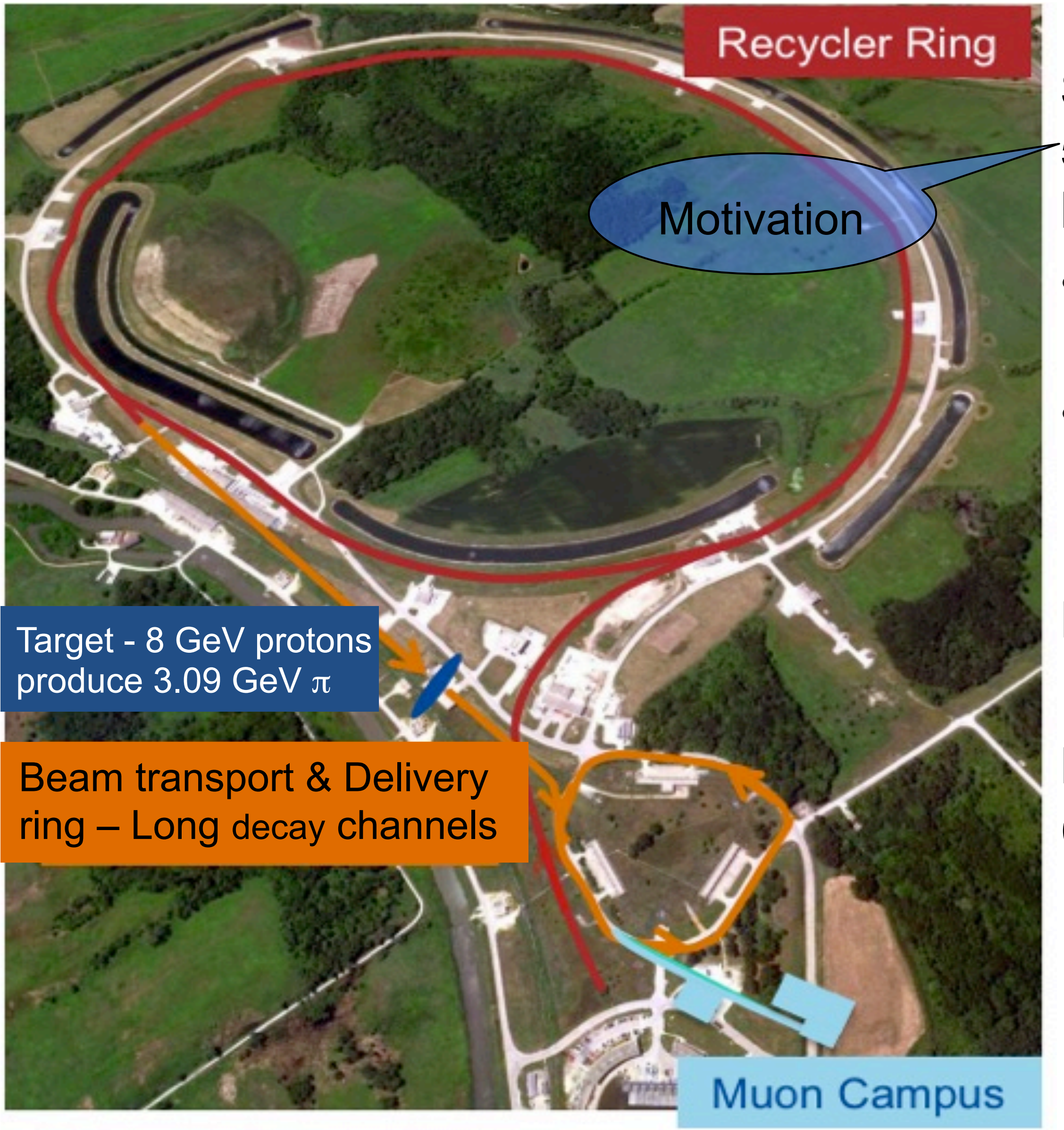


Positron spectrum gives distortions from

- Pileup, gain stability
- Beam Effects, Losses

THE EXPERIMENT – MUON BEAM PREPARATION, FOCUSING

Muon Beam Preparation for 21x BNL statistics



Statistical error improvement is: 540 ppb → 140 ppb (~21 x BNL). This requires:

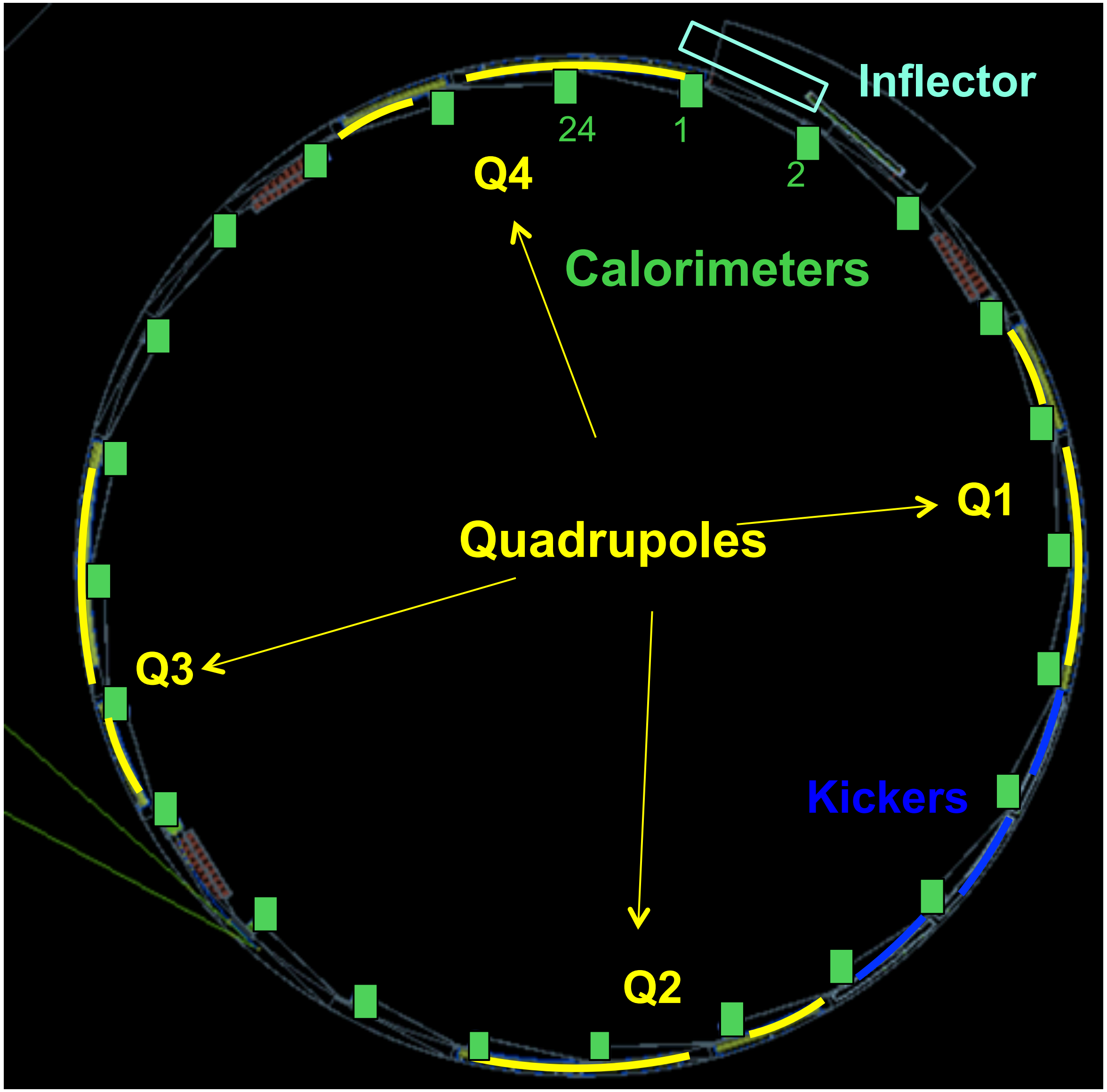
- Better p, π and μ separation with improved collection
- Delivery ring − eliminates background

Run Time: 18-24 months.

1 month engineering run 2017

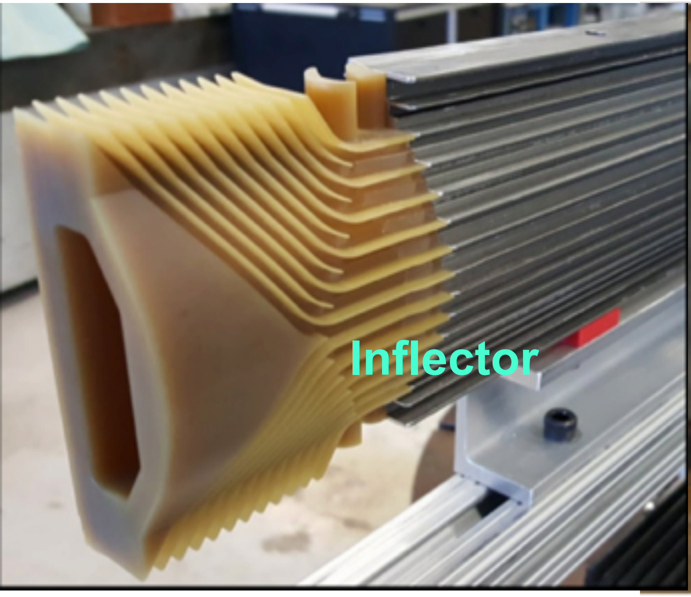
Production run 1 ended today (April to July 7th)

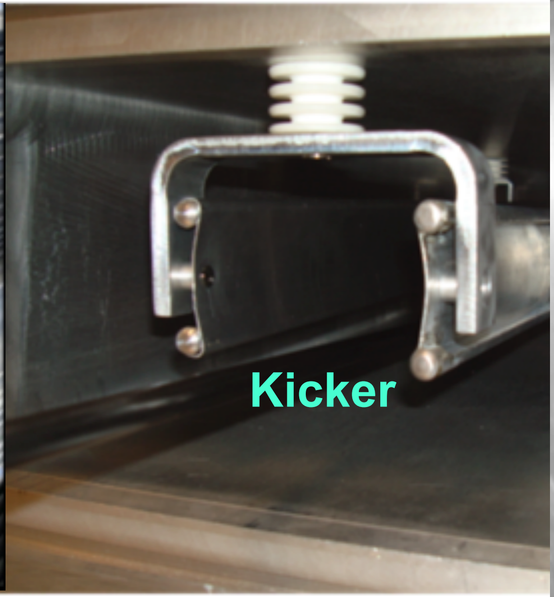
Muon Beam – Focusing in Storage Ring

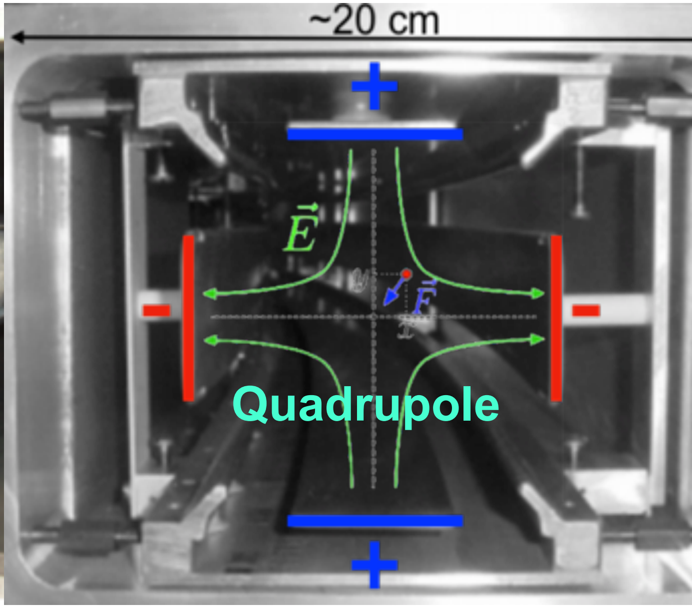


Muon Beam – Focusing in Storage Ring

- Inflector – Superconducting coil to cancel 1.45 T field of ring
- Kicker - pulsed magnet (~250 G peak) with vertical field, kicks the muons to the ideal orbit. Deflects by ~0.8 mrad
- Quadrupoles – Electrostatic quads for focusing of beam. Four Aluminium electrodes.

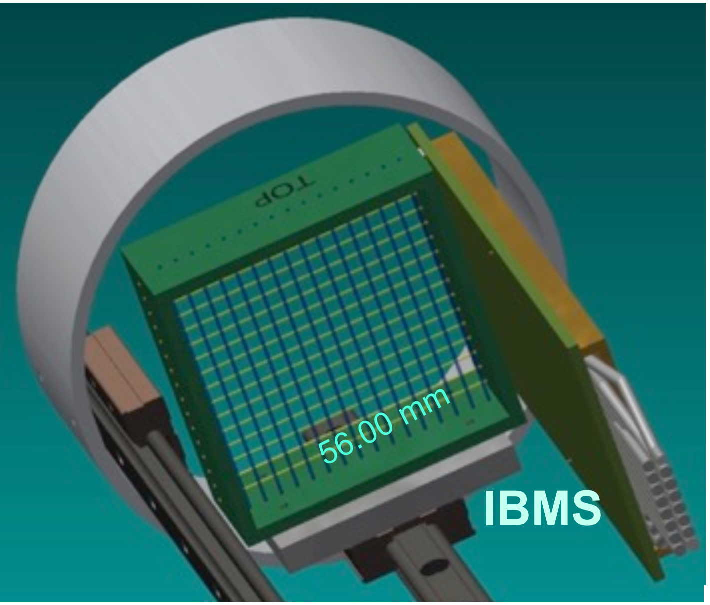


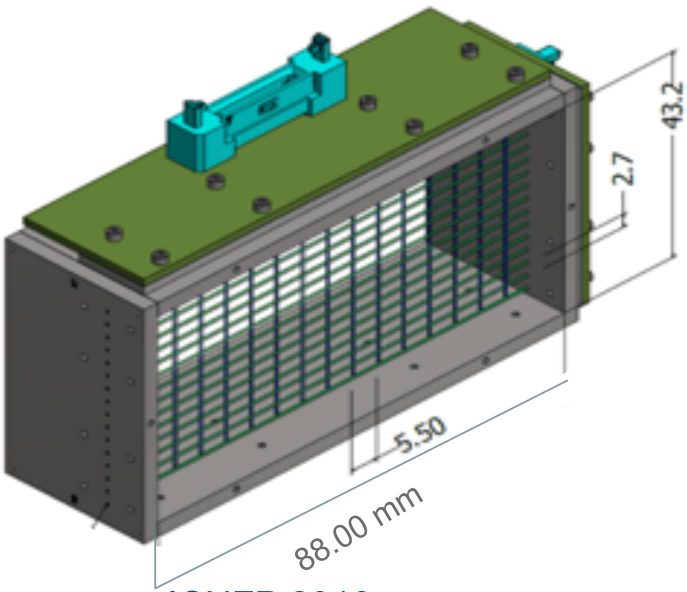


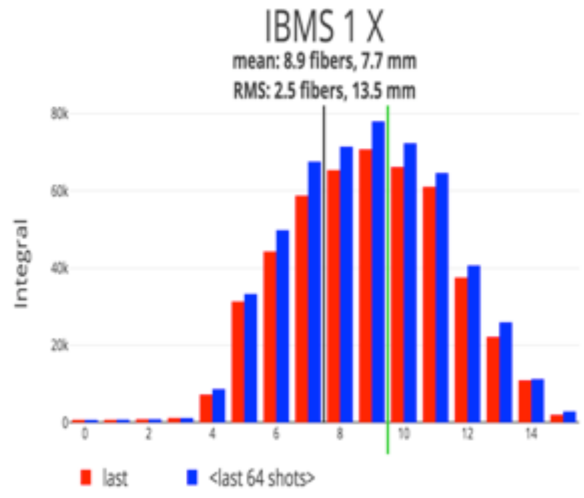


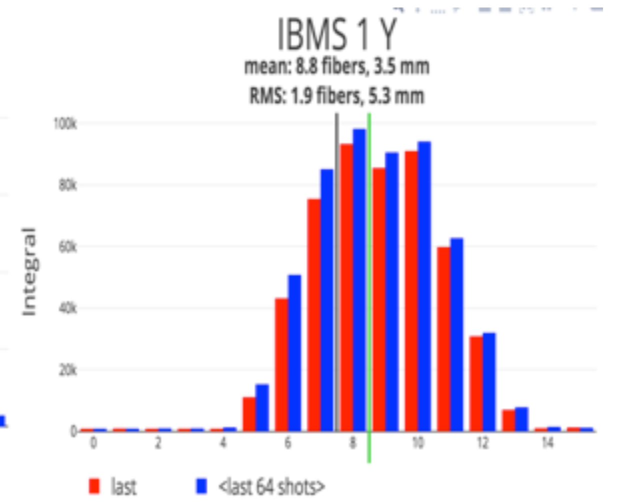
Inflector Beam Monitoring System

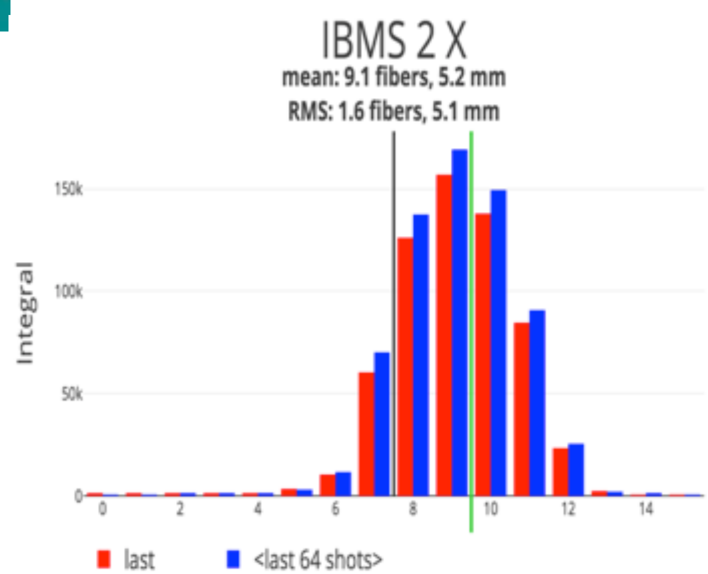
Scintillating-fibre (16 wires) beam profile monitors – Sample run

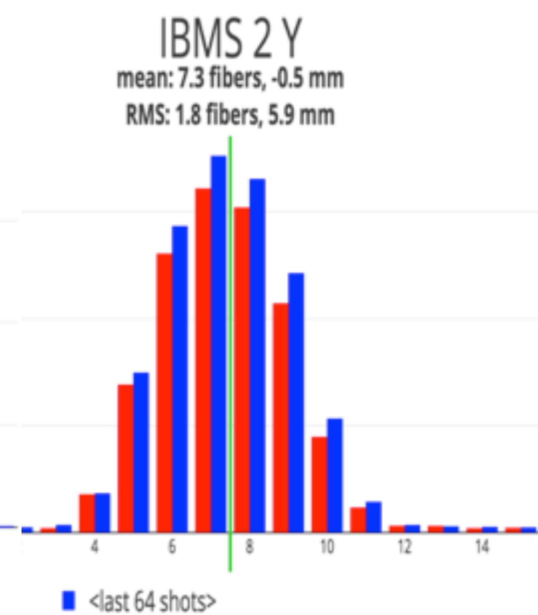




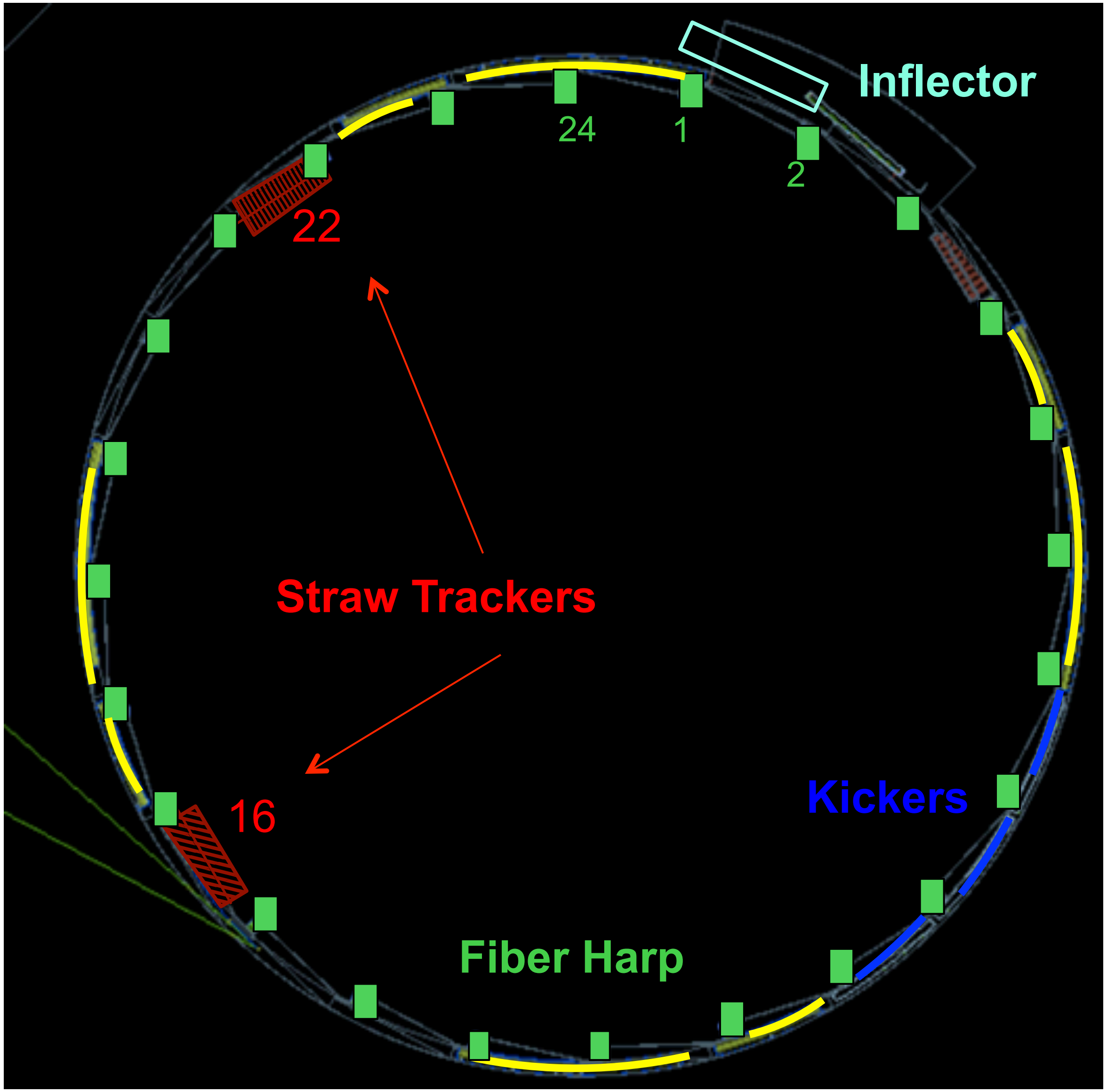






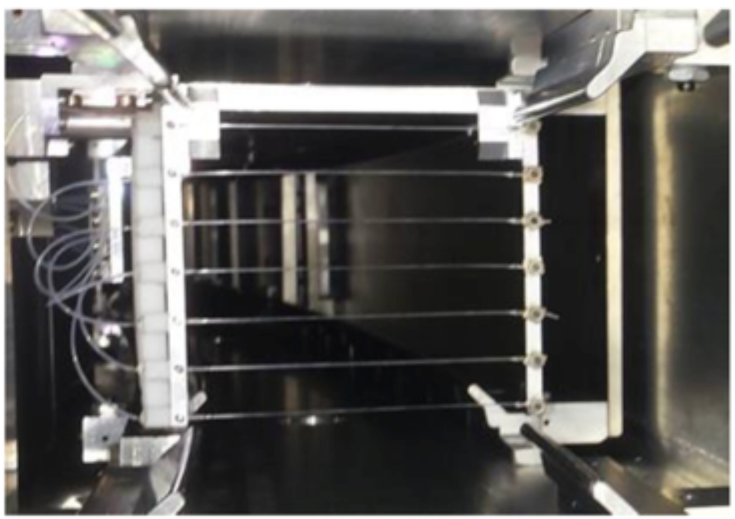


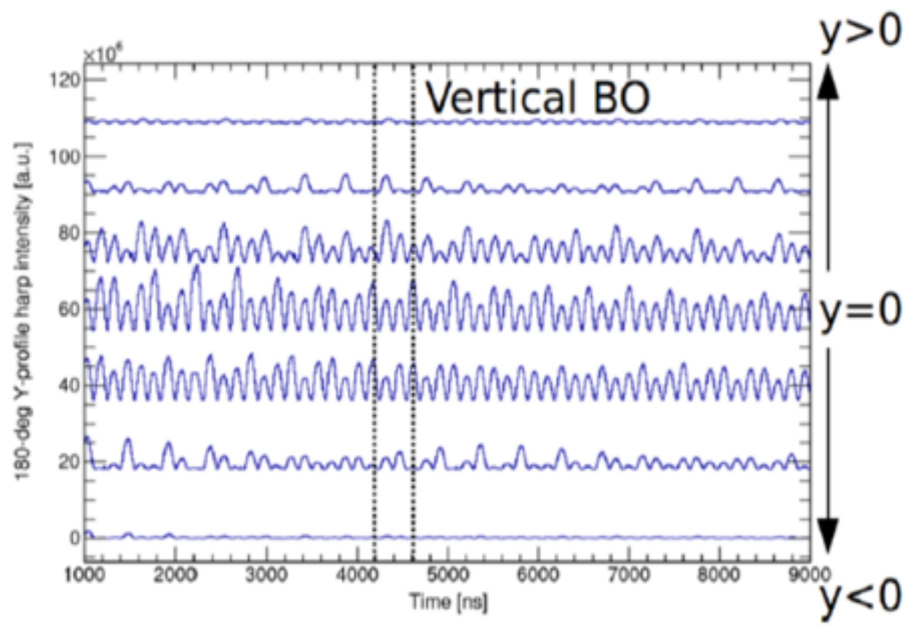
Further improvements and checks – Current run



Fiber Harps – Checking the beam in Current run

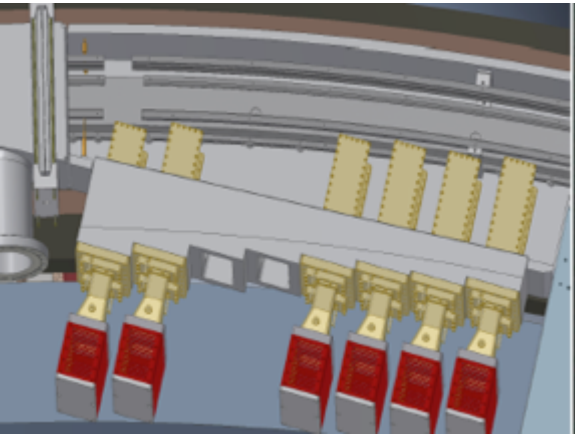
Used to study behaviour of the muon beam flux and the horizontal and vertical oscillatory effects of the beam due to electric field. Taken occasionally in between data taking (not during the runs as it is an obstacle to the beam).

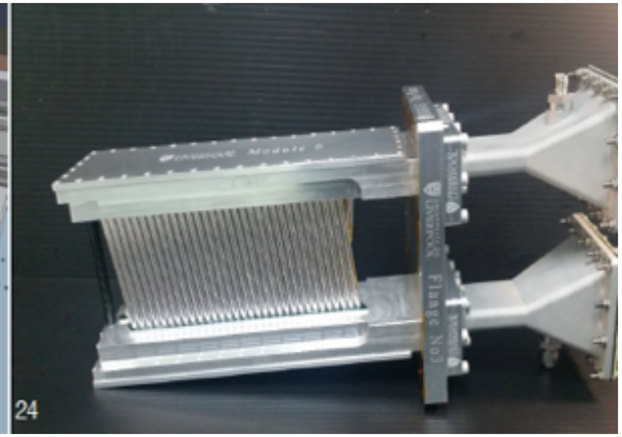


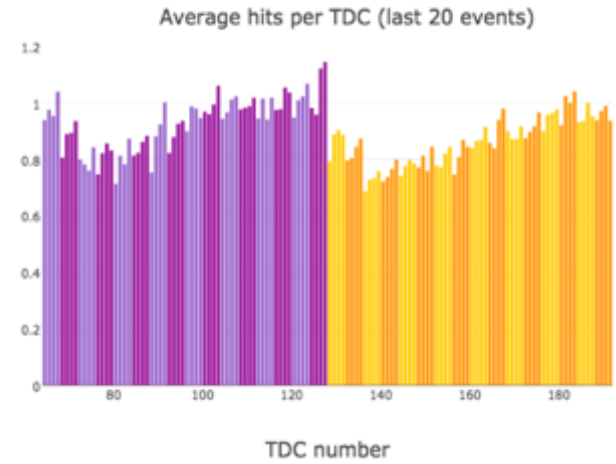


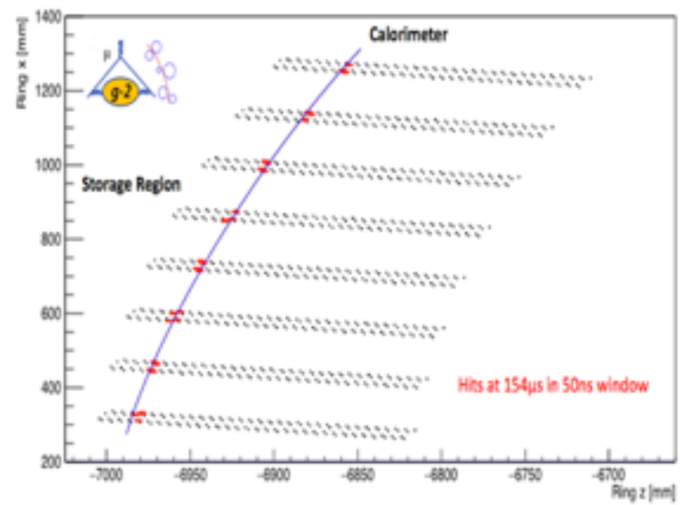
In–Vacuum Straw Trackers

2 Straw trackers installed in current run to reconstruct muon beam profile from e^+ tracks (8 modules each with 128 straws containing $Ar:CO_2$)









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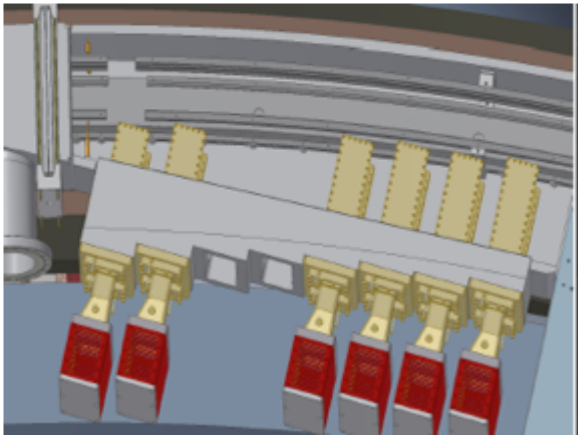
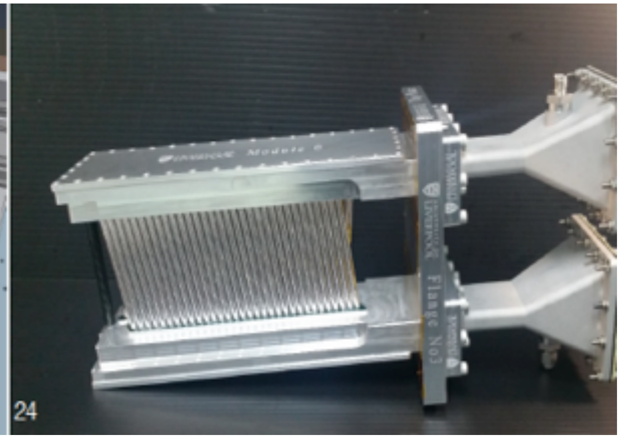
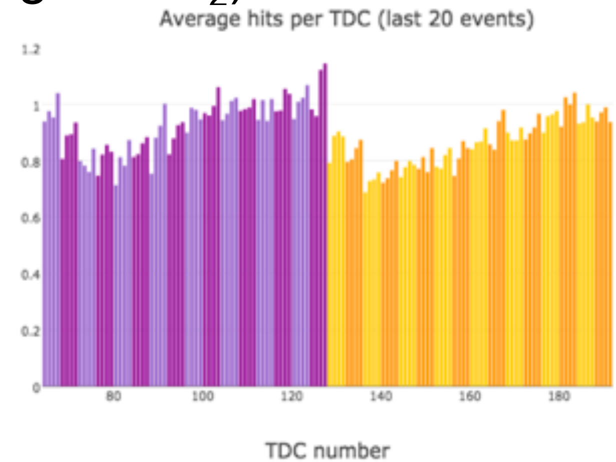
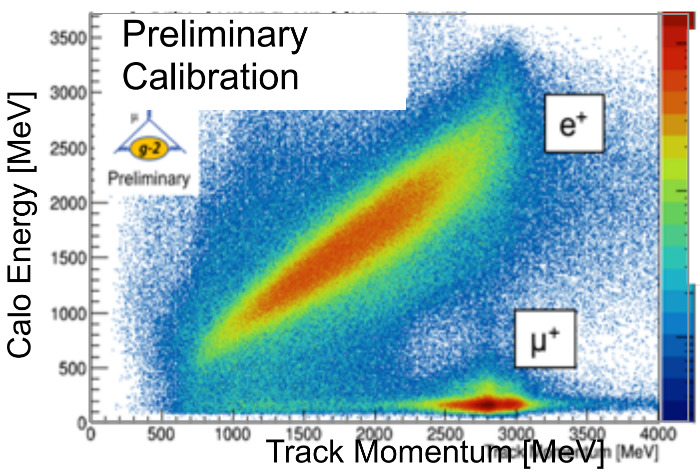
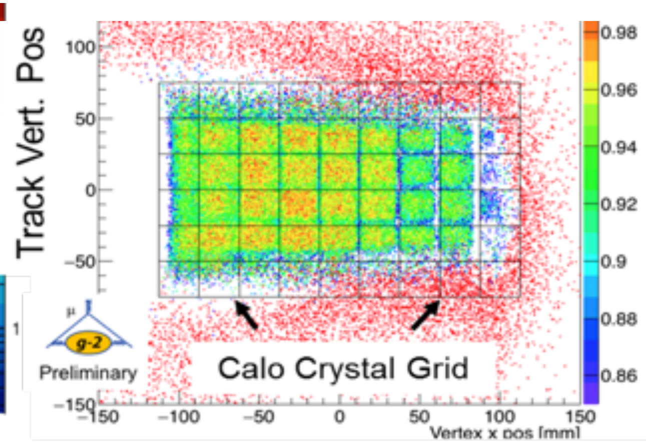


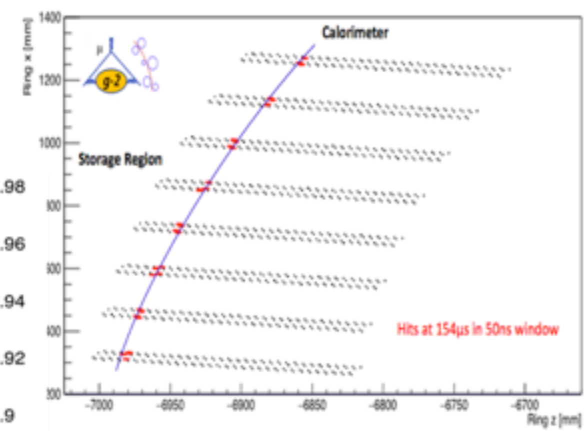




Trackers in combination with calos, show good particle discrimination (left) and imaging of calos (right)







THE EXPERIMENT – SYSTEMATIC IMPROVEMENTS

Systematic Improvements on ω_a

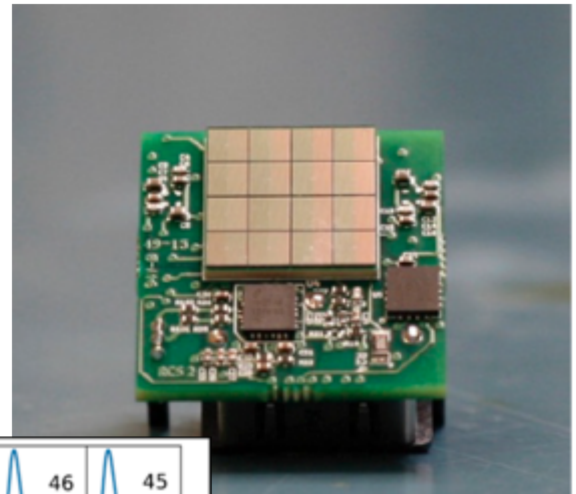
Systematics on ω_a 180 →70 ppb compared to E821. Achieved by:

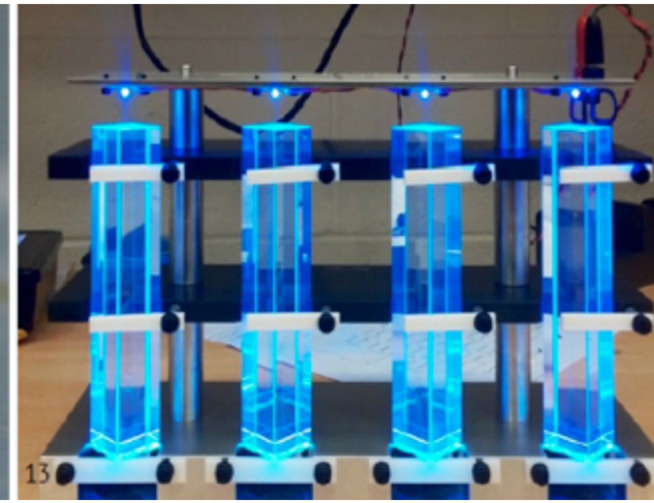
- Improved Calorimeters
- Much improved Laser control system
- New Straw Tracker (two installed in the current run)

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]	Key element:
Gain changes	120	Better laser calibration low-energy threshold	20	**Laser**
Pileup	80	Low-energy samples recorded calorimeter segmentation	40	Calo + Laser Calo + Laser
Lost muons	90	Better collimation in ring	20	
CBO	70	Higher n value (frequency) Better match of beamline to ring	< 30	Inflector + Kicker
E and pitch	50	Improved tracker Precise storage ring simulations	30	Tracker
Total	180	Quadrature sum	70	

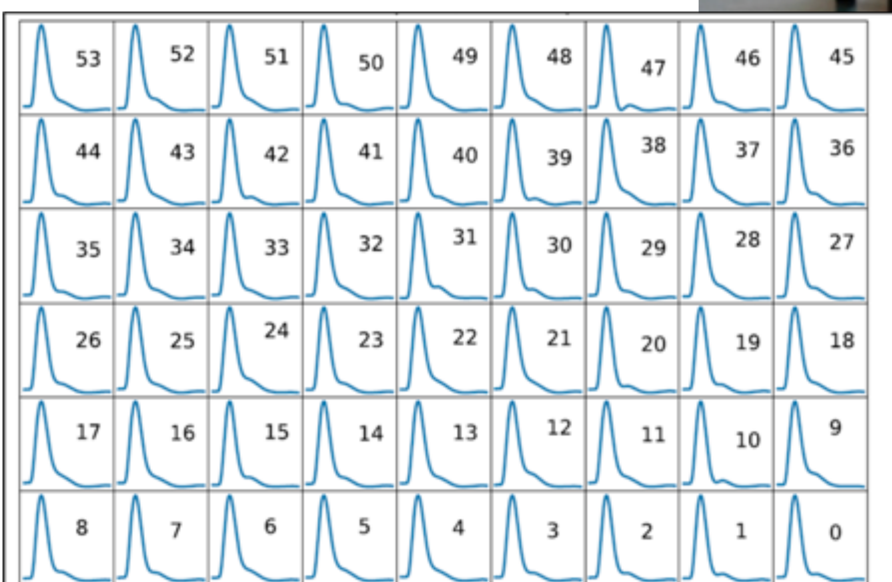
Calorimeters

- Employ 24 calorimeters to produce positron spectrum
- Each calorimeter is made up of 54(9x6) PbF_2 crystals with SiPMs (better in enduring the magnetic field) and read out by custom 800 MSPS waveform digitizers.





- Custom pulse shapes (templates) used for each crystal



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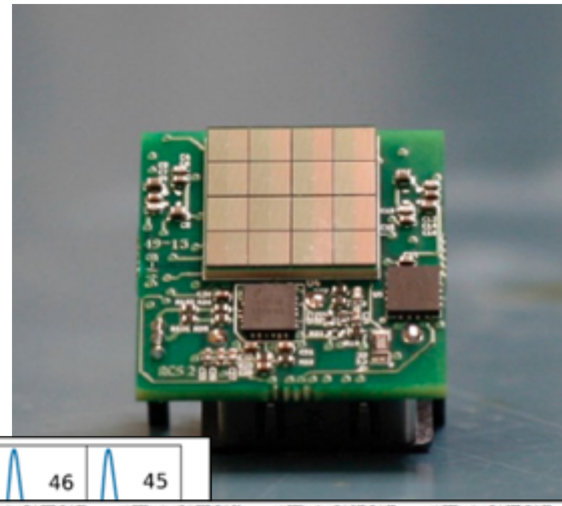

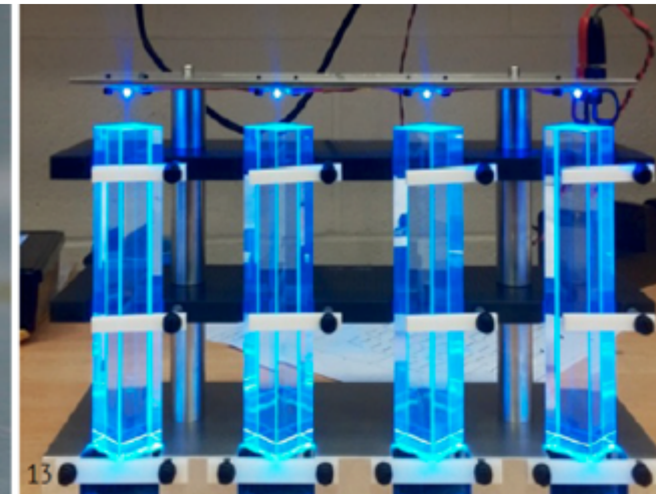

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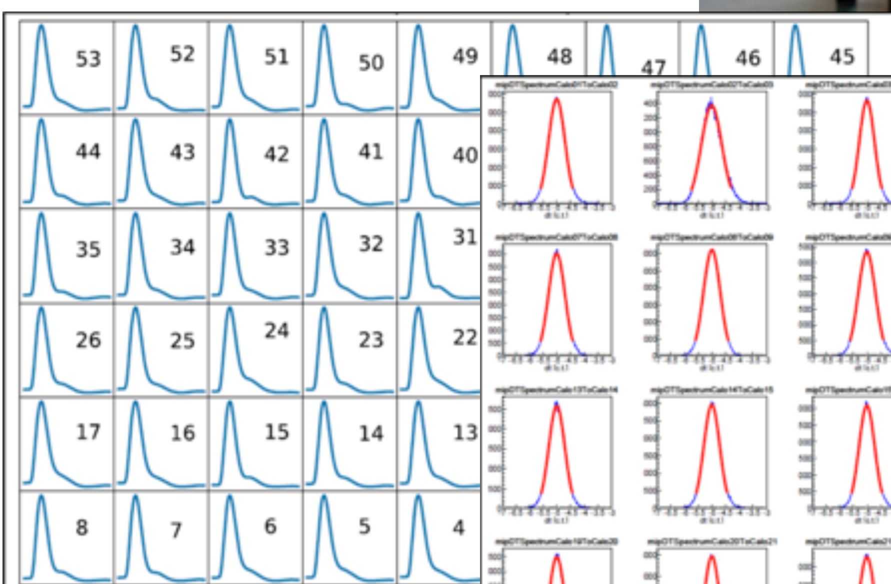
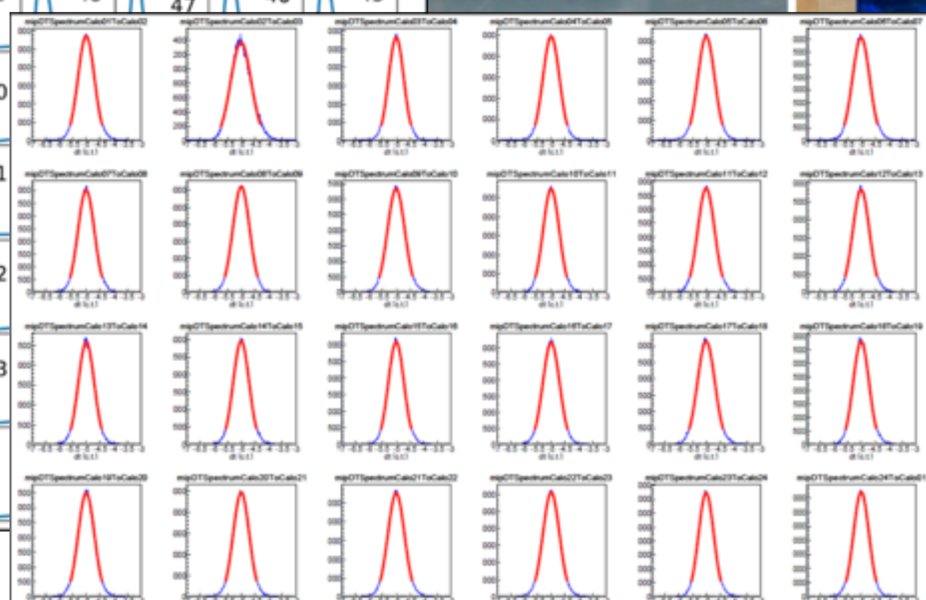
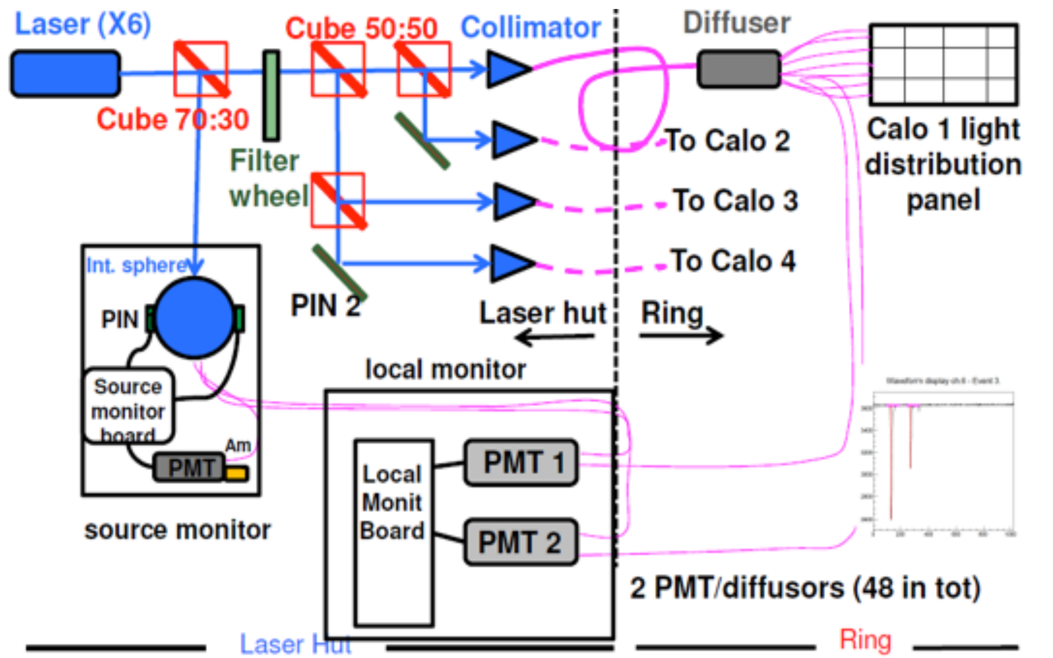




PbF_2 crystals provide excellent time resolution ~ 5 ps. Segmented (9x6) helps in better pileup protection.

Monitoring / Calibration of Calorimeter - Laser

- Laser calibration system – Laser light on calorimeters to calibrate them (use 6 laser heads).
- 6 SM (source monitor - 2 pin diodes + 1 PMT) to check and correct for laser light fluctuations.
- 24 LM (local monitors) that are used to check stability of the light distribution chain.

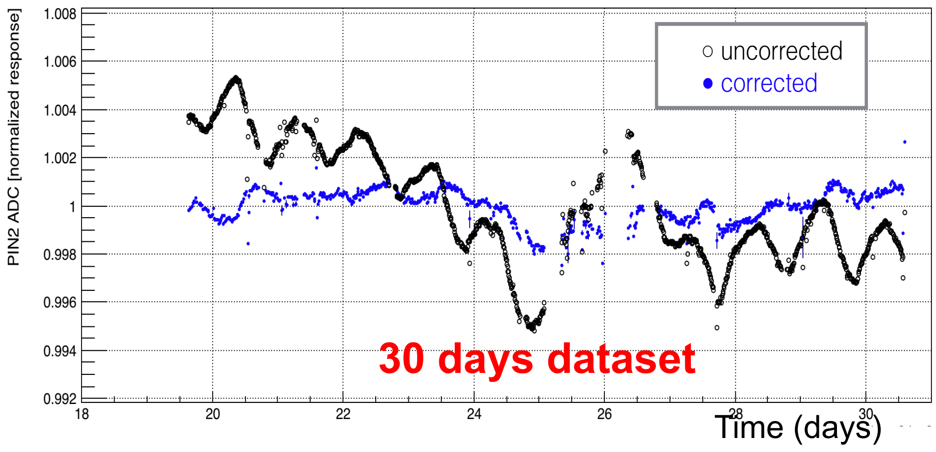


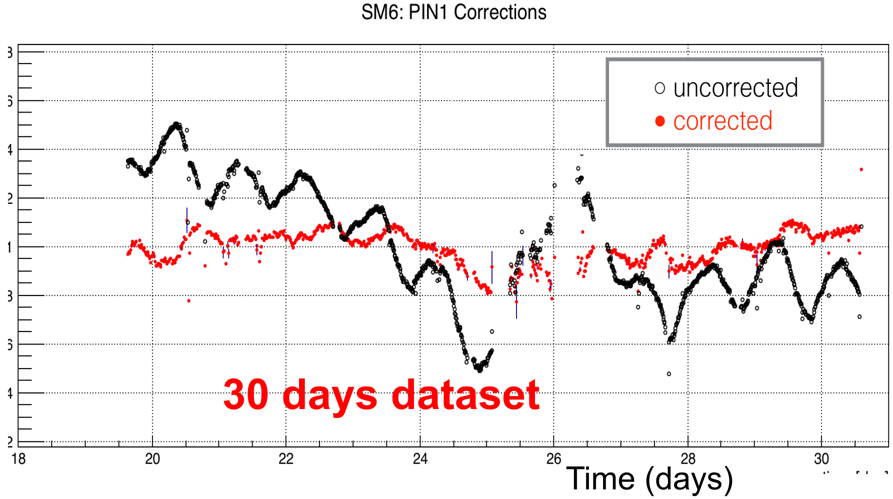
For calibration - Optical fibers carry laser shots to each of the 1296 calorimeter crystals. One laser head sends light to 4 calos as shown on the top fig.

Laser Monitoring System - Stability

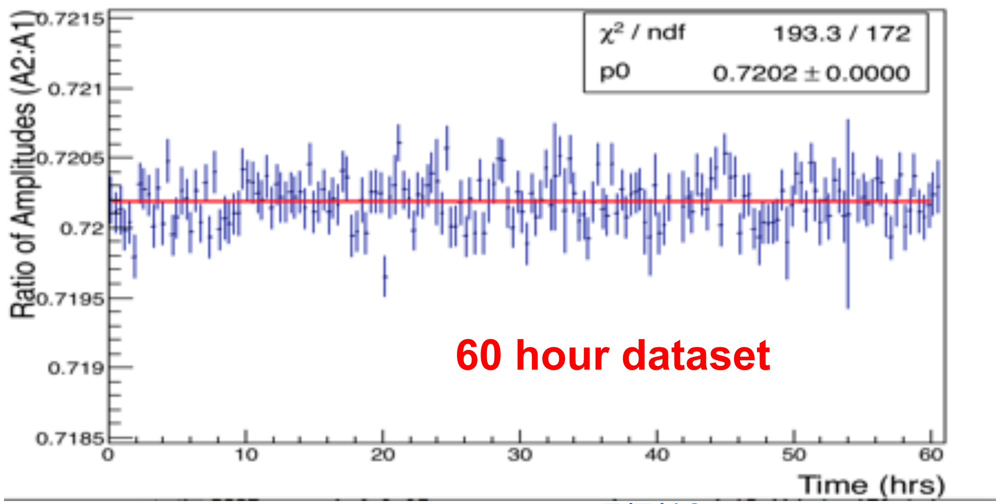
Timing and gain calibrations at the subpermil level requires the system to be very stable:

- Stability of SM after temperature correction ~10^{-4}



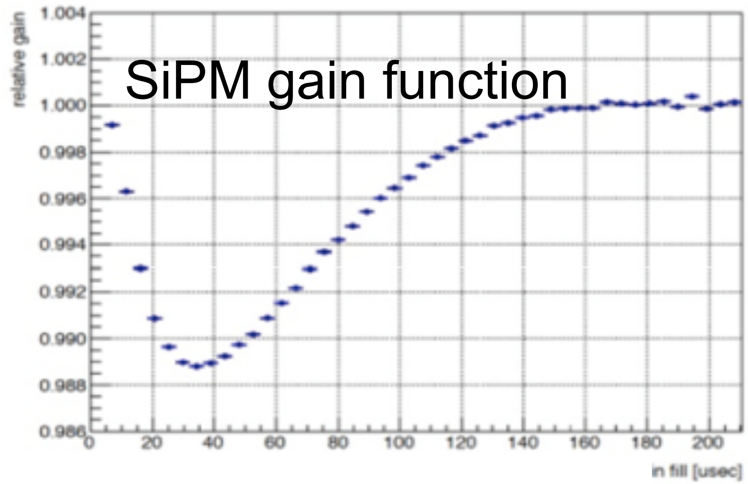


- Stability of laser light distribution chain after temperature correction ~10^{-4} (measured by LM)



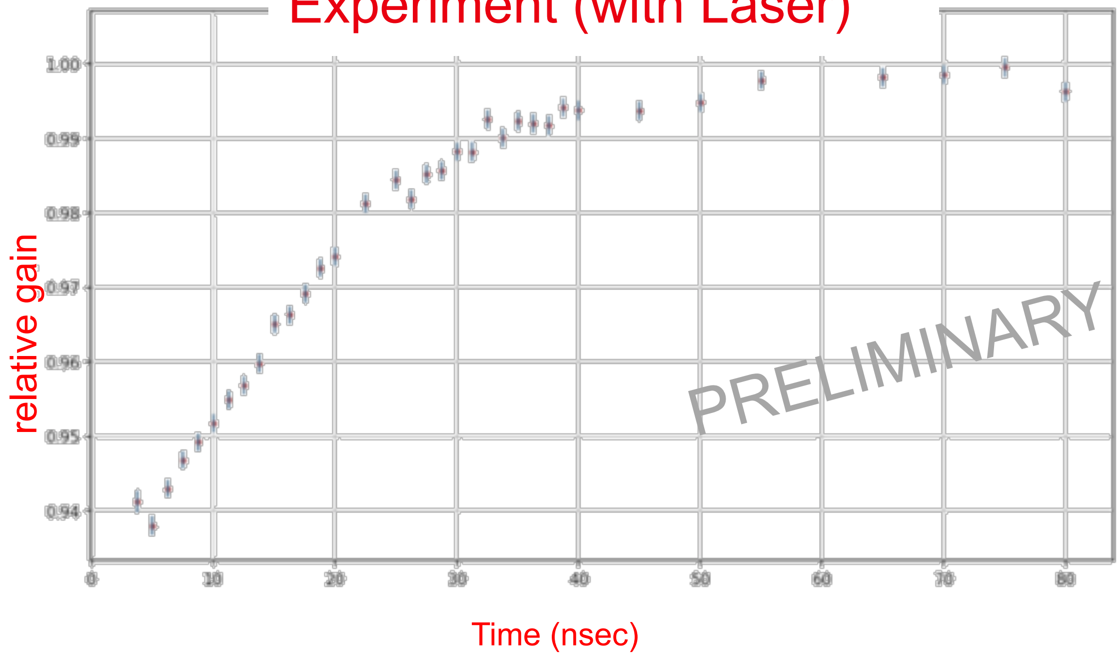
Monitoring / Calibration of Calorimeter - Laser

- Muon data taken in 700 μs fills.
- Gain of each SiPM crystal varies as shown on the right plot - calibrated using the laser system (simulation)
- An initial drop observed due to higher muon flux (flash in the beam) which stabilizes after 140 μs



Sample gain function from experimental data.

Experiment (with Laser)



Systematics in ω_p – Improvements

Systematics on ω_p 170 → 70 ppb compared to E821. Achieved by:

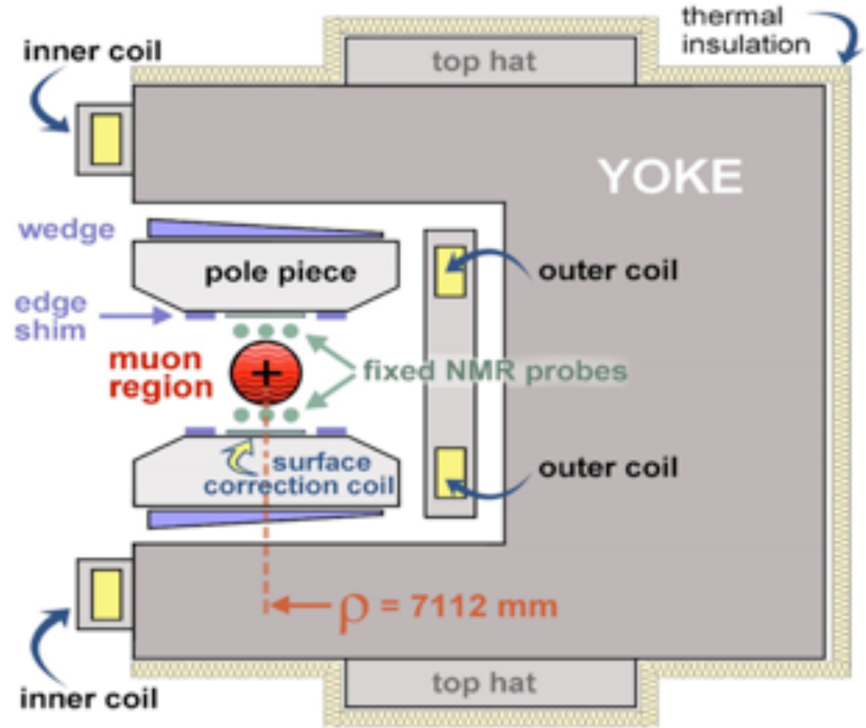
Error Source	Improvement Plan for E989
Absolute Field calibration	1.45 T calibration magnet with thermal enclosure (0.1^{o}C); additional probes; better electronics
Trolley probe calibrations	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops;
Trolley measurements of B_0	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements
Muon distribution	Additional probes at larger radii; improved field uniformity; improved muon tracking
Time – dependent external fields	Direct measurement of external fields; simulations of impact; active feedback
Others	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients

Improved shimming has a great effect on most systematics. Ex next slide. Using **iron lamination** in current run has made the magnetic field more uniform (about $\pm$ 21 ppb)

Magnetic Field Homogeneity / Upgrade – Current Run 1

- Iron shims removes quadrupole asymmetries.
- Top hats adjustments change the effective dipole moment.

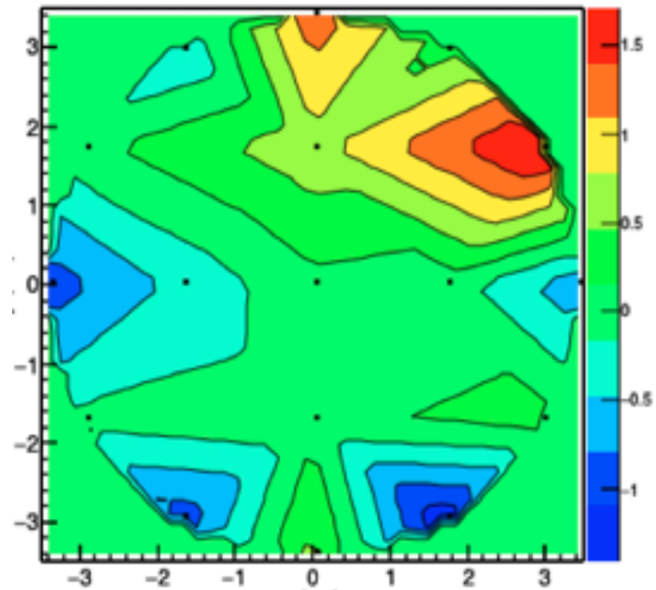
- Surface correction coils and **iron foils** – field more uniform.
- 378 Fixed probes at 72 locations around the ring
- Trolley calibrations
- 25+ trolley run for better field mapping
- Field stabilized to $\pm$ 21 ppb



g-2 Magnet in Cross Section

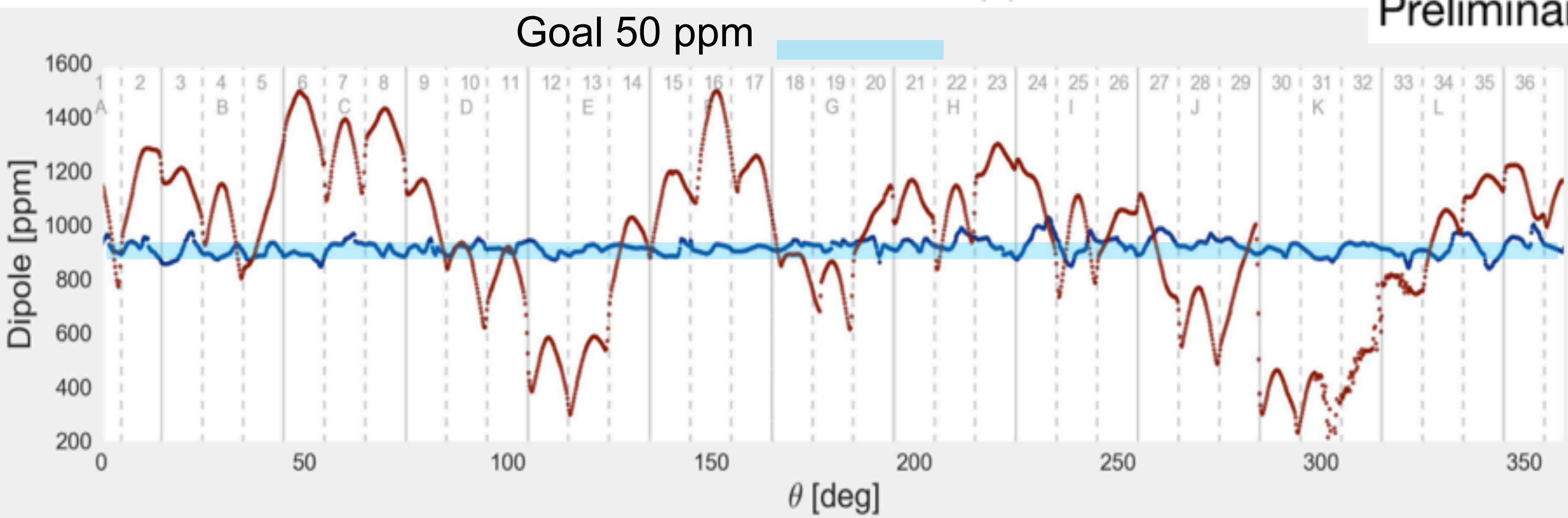
Magnetic Field Homogeneity / Upgrade – Current Run 1

Result of **iron foils** laminations, top hats, shimming etc. from the current run 1 data.



	Norm	Skew
Quad	0.50	0.76
Sext	-0.43	0.63
Octu	-0.07	0.35
Decu	0.23	0.08
Dipole	-0.0	

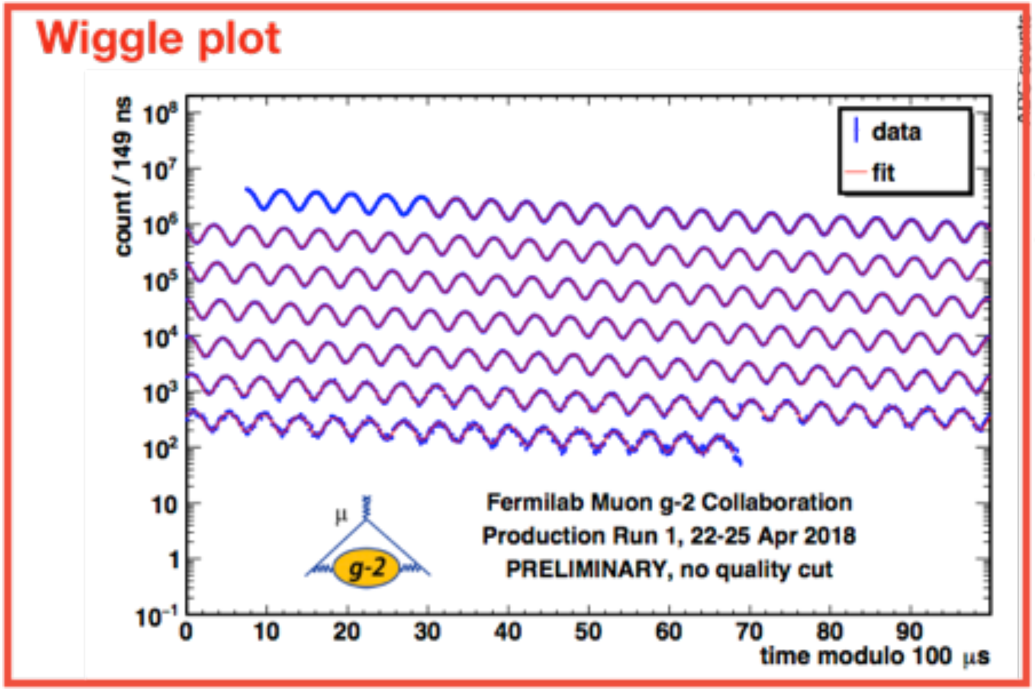
Preliminary

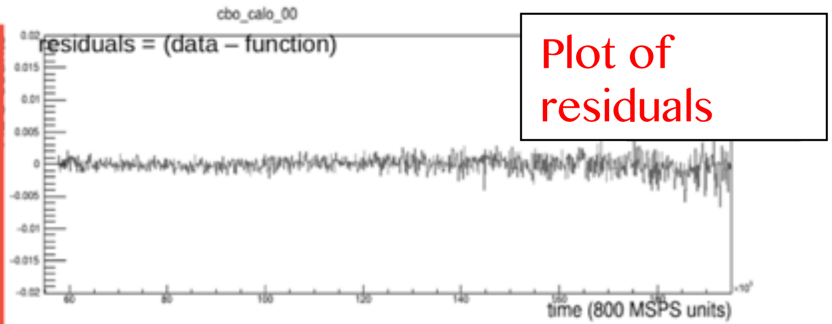


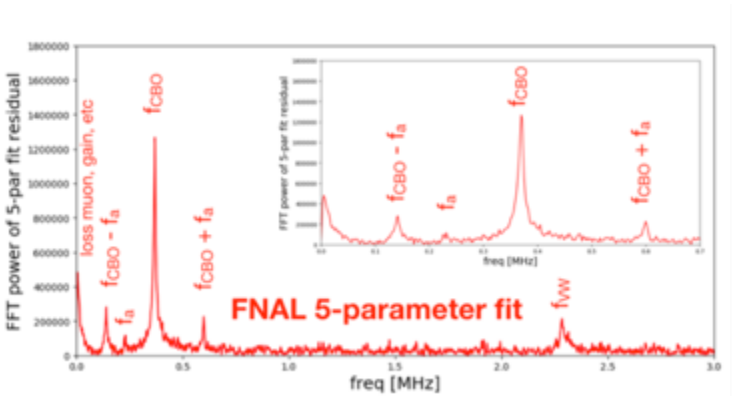
MEASUREMENTS AND SYSTEMATICS

Current run brief analysis status

- Several analysis using various method and at various places.
- Blind the analysis with an offset (in clock frequencies and data)
- Fitted the wiggle plot with T-method (distribution of decay e+ with time [T-mehtod] above a threshold frequency).
- Residues due to CBO (or other effects)

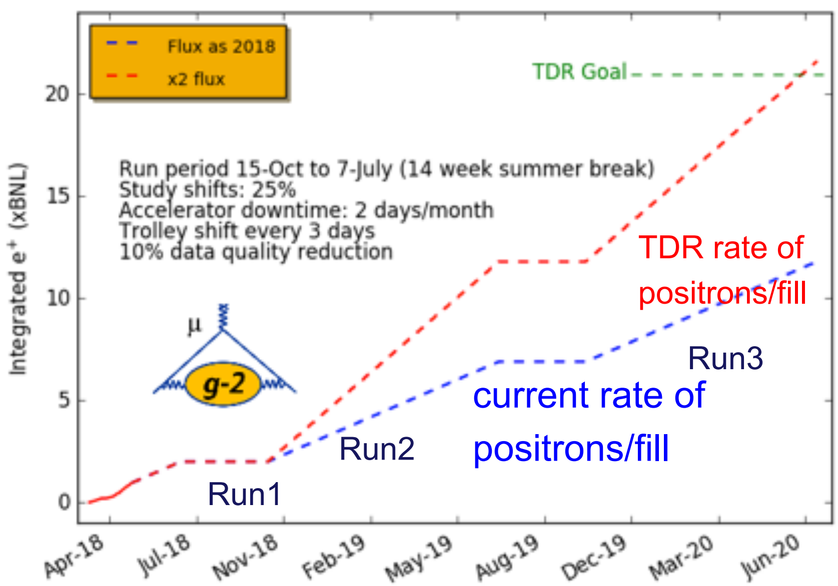


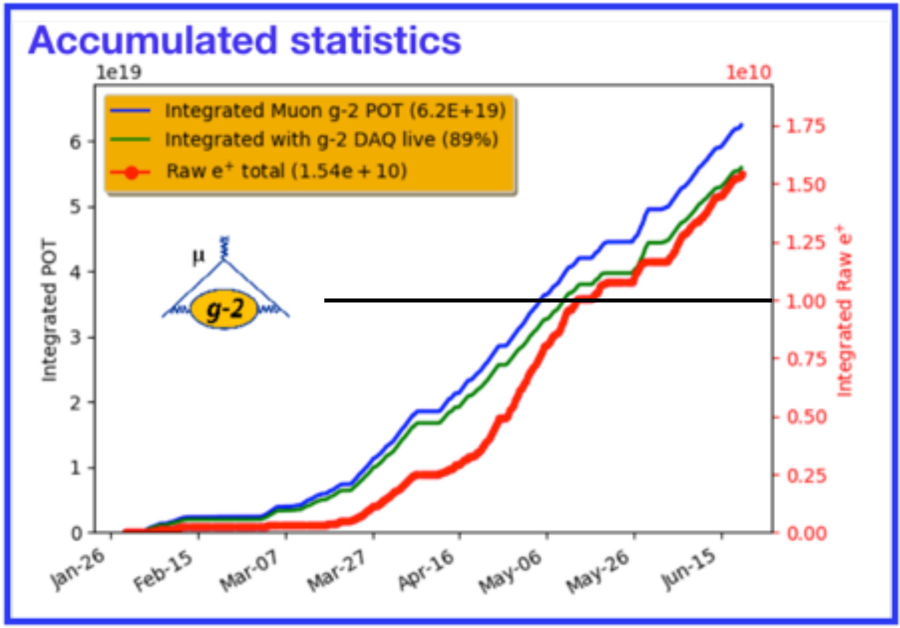




Summary and Outlook

- Systematic and performance improvements compared to BNL E821.
- Accumulated statistics 2.3 times BNL experiment and after quality cuts / reconstruction of data approx. = BNL.
- Improve by 2020 to 140 ppb in the measurement of a_{μ}.
- If the previous measure value of a_{μ} is correct, then we can have 7σ discrepancy from SM






EMMERT
Thank You!

Backup

The Fundamental Experimental Principle

- A more complete calculation which includes the effects of the focusing electrostatic field as well as a possible muon Electric Dipole Moment (EDM) :

Get a_μ

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

Magic $\gamma \sim 29.3$

EDM

Measure these

$$\vec{\omega}_{net} = \vec{\omega}_a + \vec{\omega}_{EDM}$$

- The magnetic field ***B*** is measured in terms of the *Larmor frequency of a free proton*
- A possible EDM would result in a *out of plane* precession term

More about cyclotron – electric field for focusing – why?

B and β should be perpendicular for 2nd term to vanish.
Thus, use quads to vertically focus beam and keep muon p parallel to cyclotron momentum.

$$\vec{\omega}_{diff} = \vec{\omega}_S - \vec{\omega}_C = -\frac{Qe}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

But the beam itself oscillates – CBO (coherent betatron oscillation) due to the slightly anomalies in focusing and cyclotron frequency itself. Horizontal component – is CBO and vertical is VM. These effects detected using fiber harps and reconstructing tracks away from the central orbit using straw trackers.

Systematics in ω_a – Accomplish these improvements

Error Source	Improvement Plan for E989
Gain Changes	Better **laser calibration**; low-energy threshold; temperature stability; eliminate hadronic flash
Pile up	Low-energy samples recorded; calorimeter segmentation; straw tracker to cross check
Lost Muons	Better collimation in ring; better tracking simulation/ measurements using straw tracker
CBO	Higher n value (frequency); Better matching of beamline to ring
E and pitch	Improved tracker; Precise storage ring simulations, better kick

For the engineering run many of these have been accomplished with a scope of much more improvement in the next data runs.

For example – improved laser calibration system, using 3 straw trackers instead of 1..

Backup - Field measurements

- 378 Fixed probes at 72 locations around the ring in alternate sets of 2 (at 7112 mm & 7142 mm) or 3 (at 7082, 7112 & 7142 mm)
- Special B calib runs to measure B using moving 17 probes on a trolley
- The above probes made of teflon and Al + Cu
- Absolute calibration of all these probes (as their materials can slightly perturb B) done using H_2O in pyrex (called abs calib probe)
- In specially well shimmed parts with high uniformity trolley probes need absolute calibration using plunging probes; help in cross calibrations too

Backup - Field measurements

- B_0 is the field at the center of the storage ring
- Value of wp is found by the weighted average of field weighted with muon distribution.
- In BNL, proton beam was extracted and muons were stored during the at-top of the cycle, with no effect on the g-2 measurement. But in E989, time-dependent magnetic fields from sources such as the Booster accelerator, and power lines could perturb the field in the storage ring at the ppb level. Error budget 5 ppb.