The Fermilab muon g-2 straw tracking detectors and the muon EDM measurement

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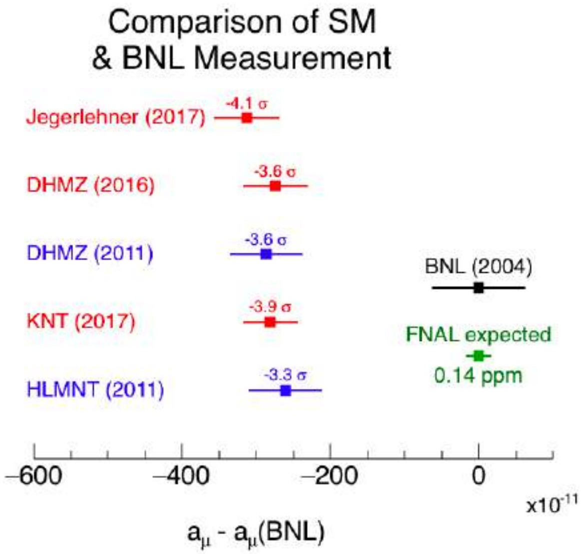
The new g-2 experiment at Fermilab

The new g-2 experiment at Fermilab aims to measure the muon g-2 to a precision of 140ppb (a factor 4 improvement on the previous experiment at Brookhaven)

Why?

The BNL measurement differs from the theoretical prediction by ~3.5σ.



Is this :

- A mistake in the theory
- A sign of new physics
- A mistake / statistical fluctuation in the experiment

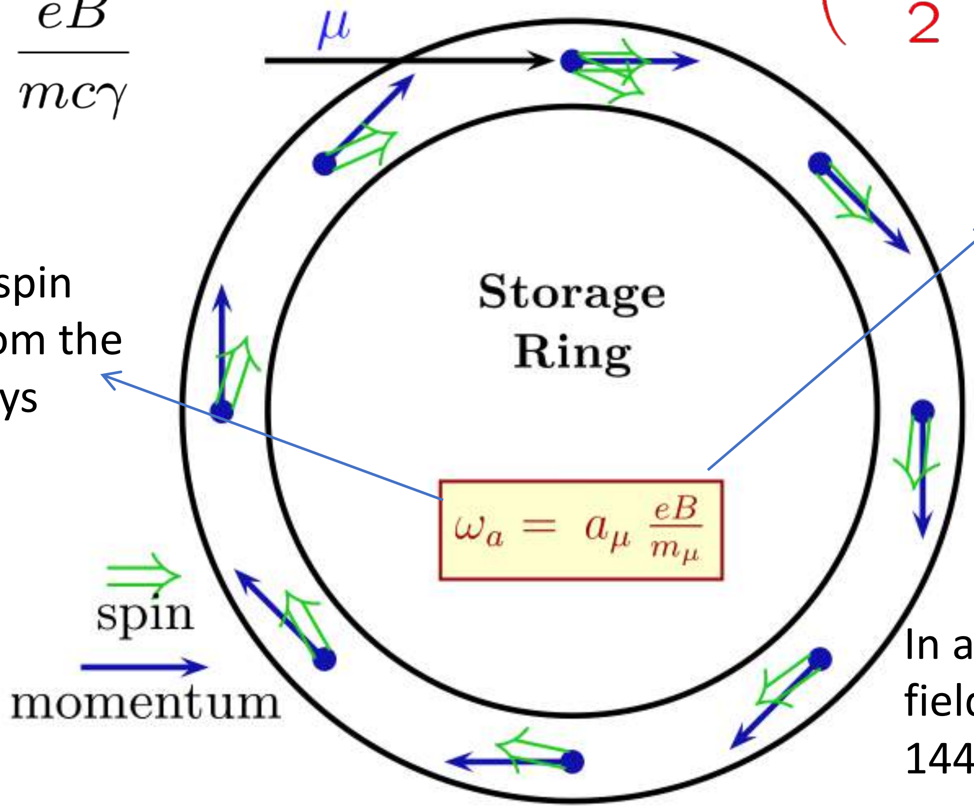
How?

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

$$\omega_C = \frac{eB}{mc\gamma}$$

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

Measure the spin precession from the positron decays



Measure the magnetic field in the ring

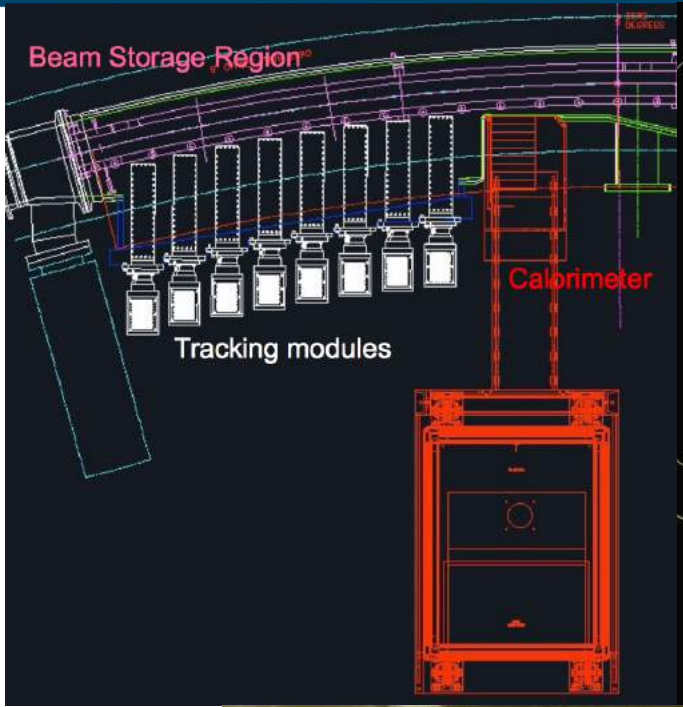
In a 1.5 T magnetic field the spin rotates in 144ns and the momentum in 149ns

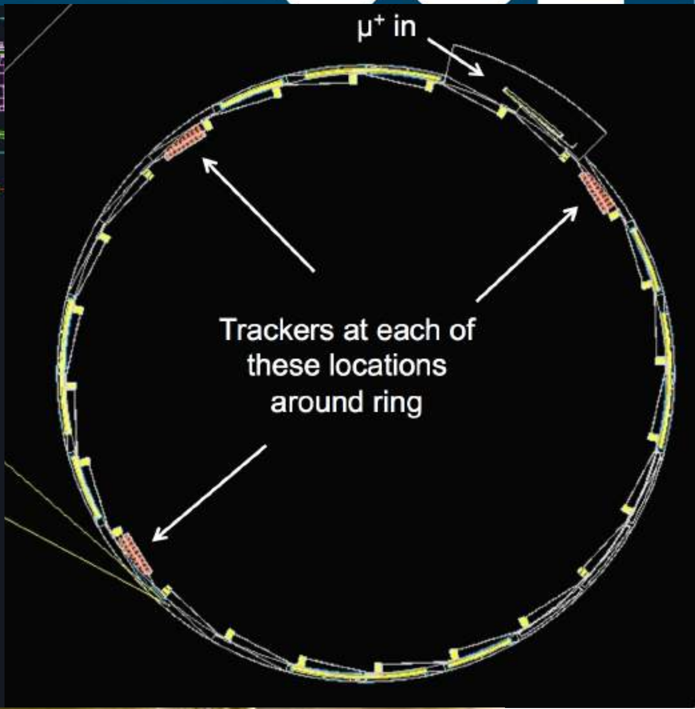
The straw tracking detectors

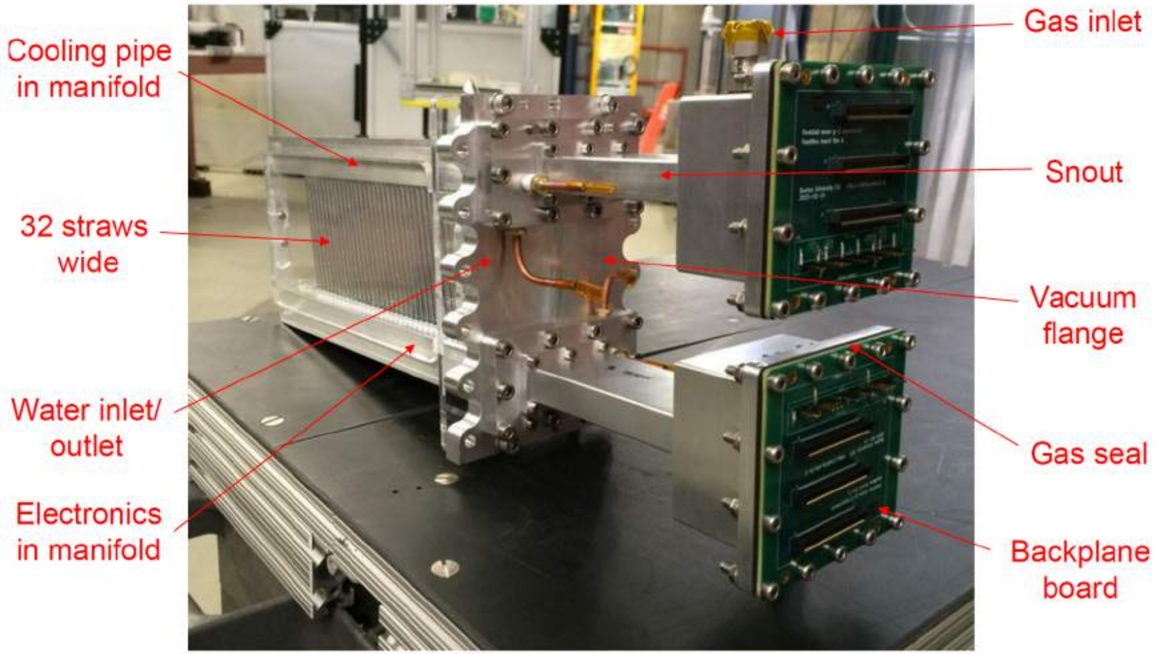
The straw tracking detectors are located at the 3 "empty" locations around the ring

Each tracker consists of 8 modules placed as close to the storage ring as possible for maximum acceptance

Each module consists of 4 layers of 32 straws, 2 layers in each view with each view at a 7.5 degree angle from vertical



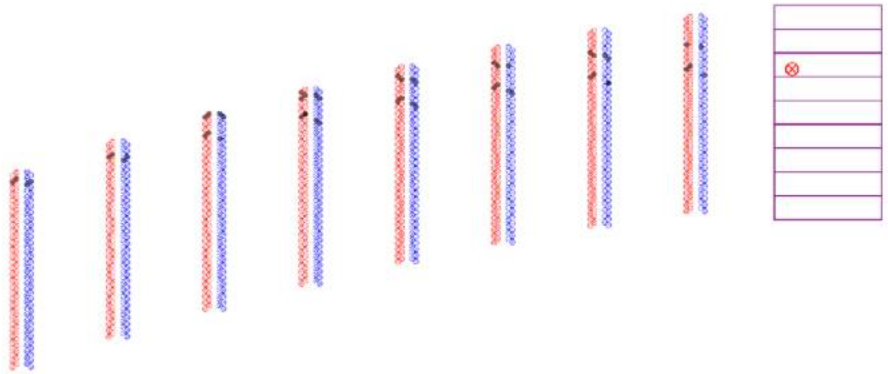




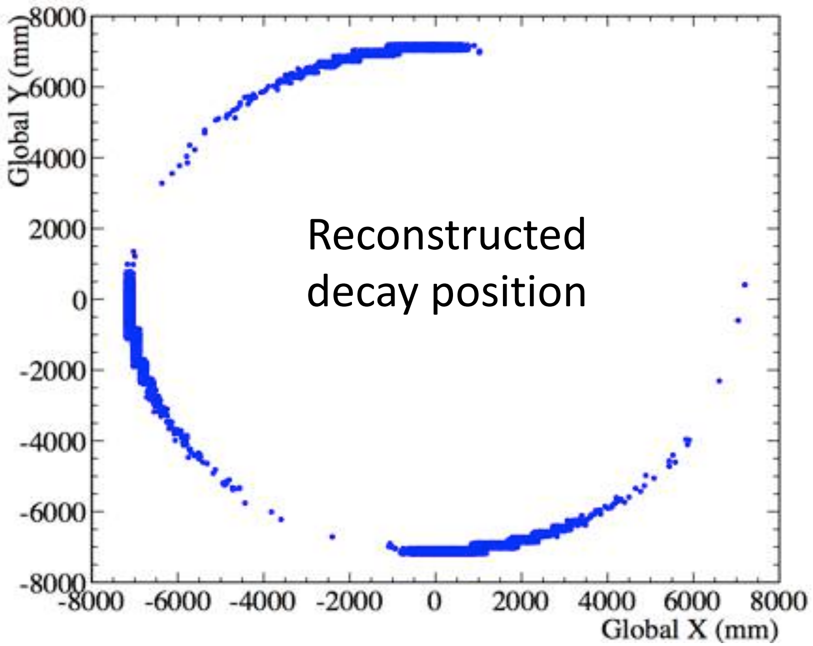
The straw tracking detectors

What do we aim to do with the trackers in the g-2 experiment?

- **Measure the beam profile in multiple locations around the ring as a function of time to validate our model of beam dynamics**
    - Momentum spread of the beam
    - Muon spatial distribution
    - Position and width of CBO modulations



- **Calibration and acceptance of the calorimeters**
    - Calorimeter gain
    - Authenticate pile up
    - Identify lost muons



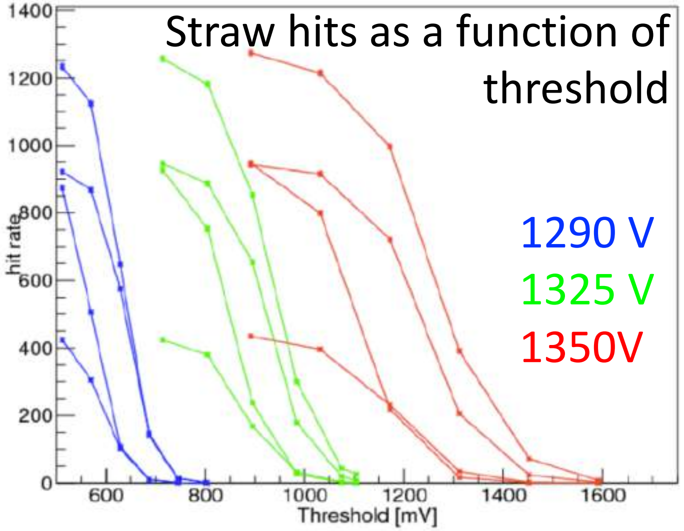
- **Look for a vertical tilt in the precession plane**
    - Indicative of a radial component to the magnetic field
    - Set a limit on a muon Electric Dipole Moment

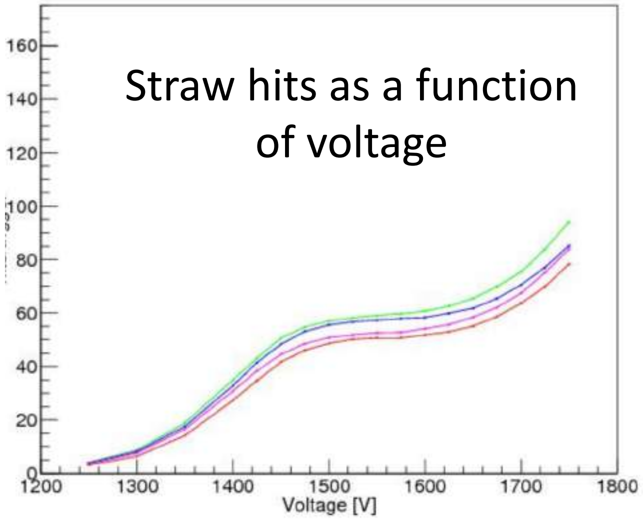
The straw tracking detectors

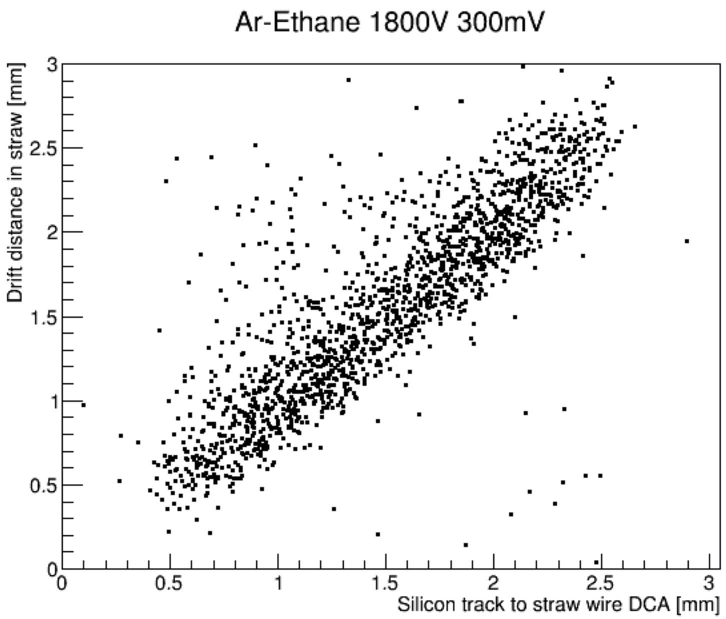
The tracker modules are built in Liverpool and then tested and installed at Fermilab

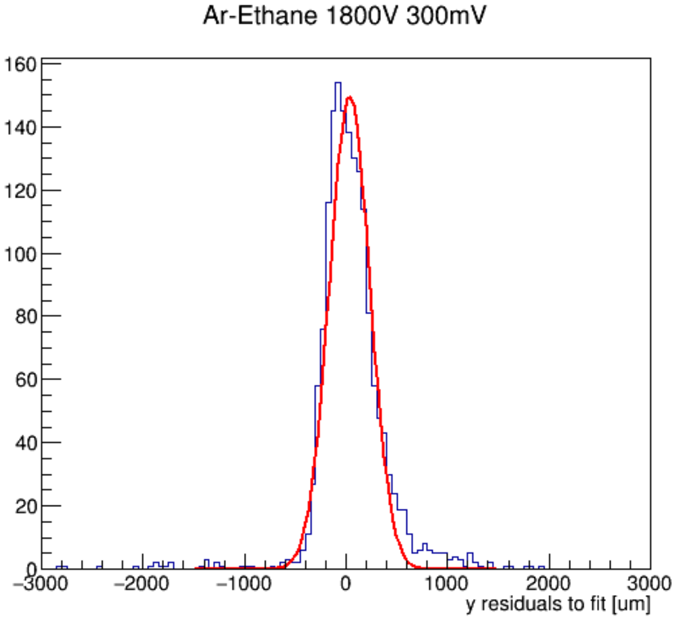
Each module goes through vacuum testing, straw characterisation and cosmic testing before being placed in the ring

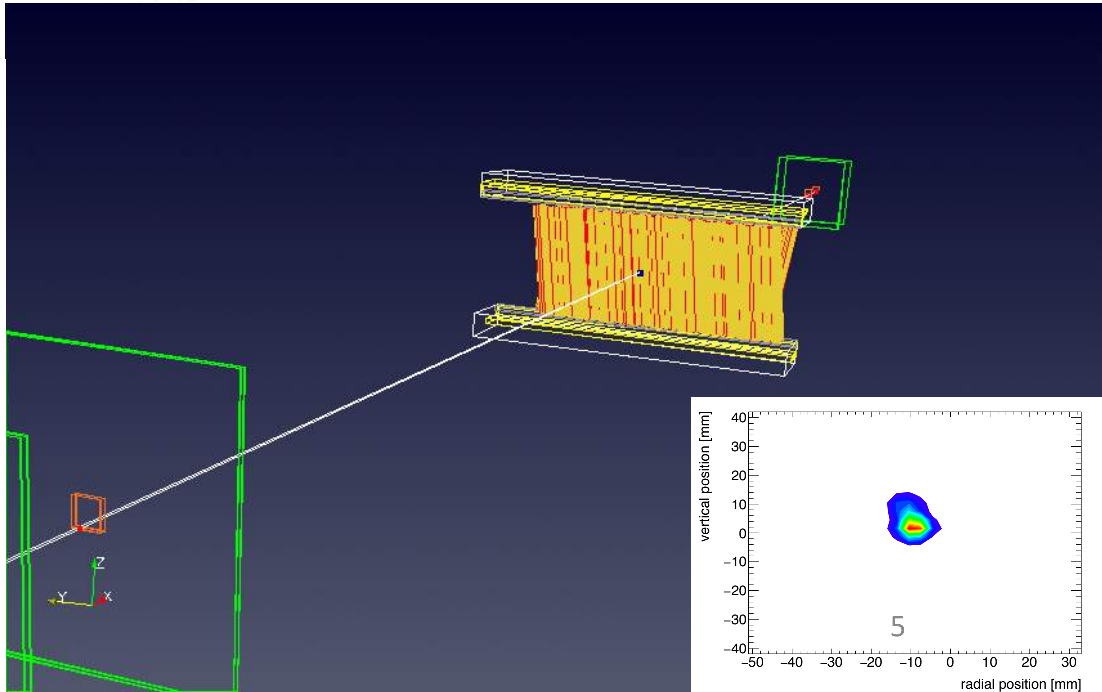
A tracker test beam at Fermilab a couple of years ago showed that the trackers can provide a **radial resolution of 100µm**





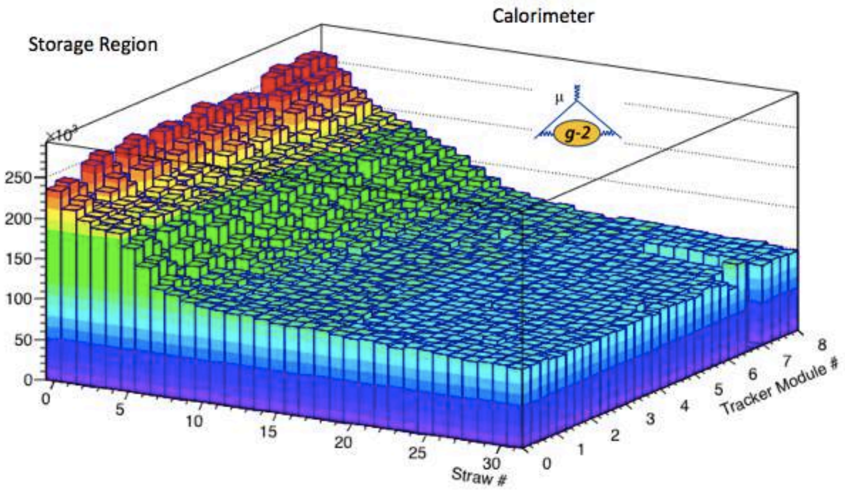






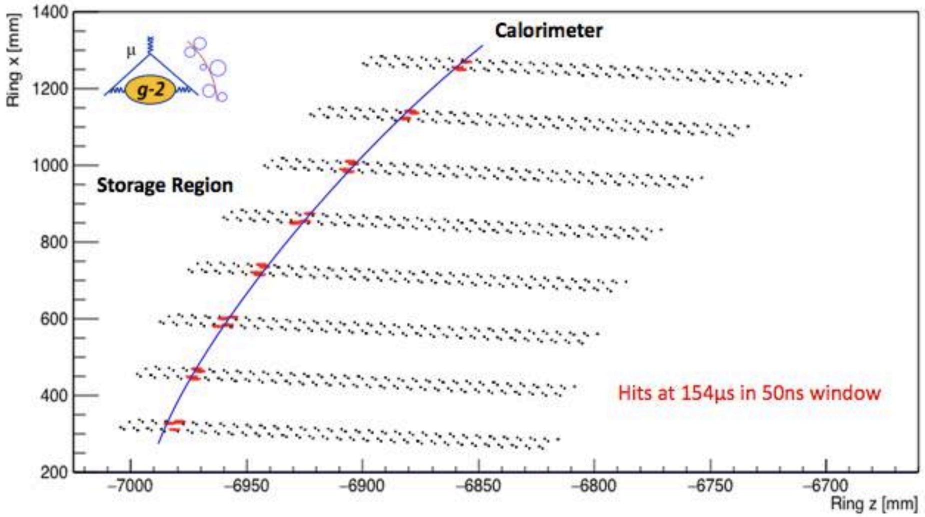
The straw tracking detectors

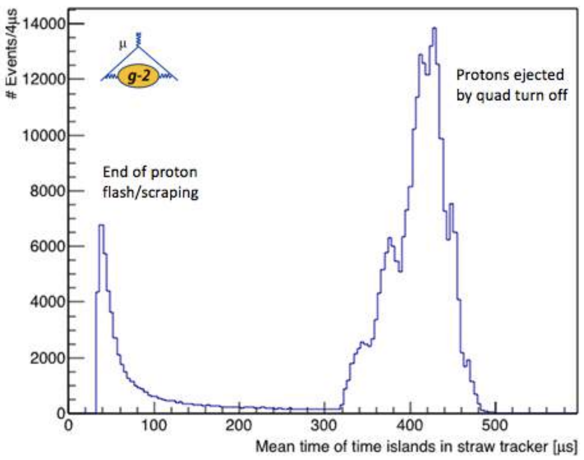
The g-2 experiment has just come to the end of a successful commissioning run and is ready to take data starting in November

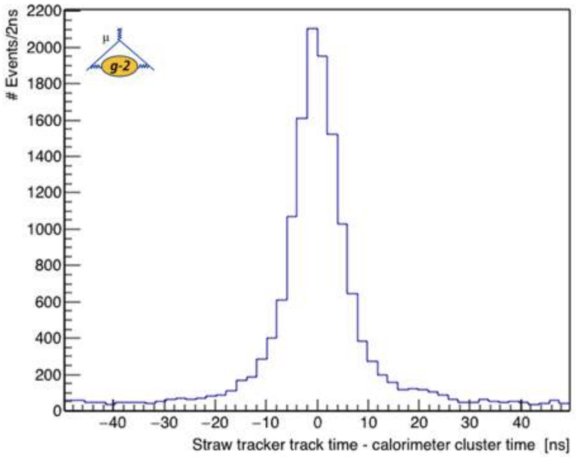


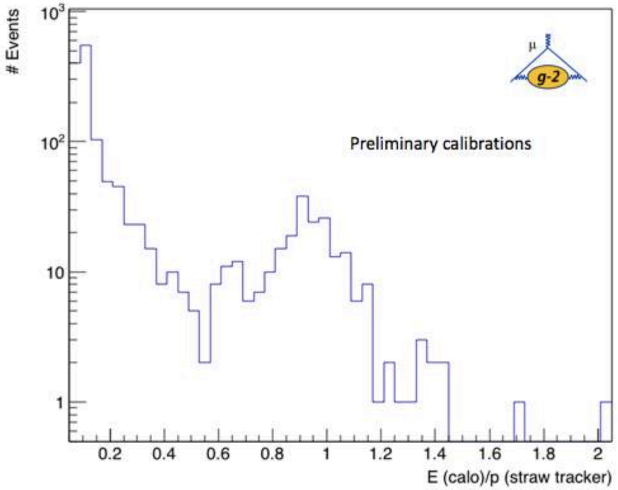
Initial basic analyses of the data show the expected results :

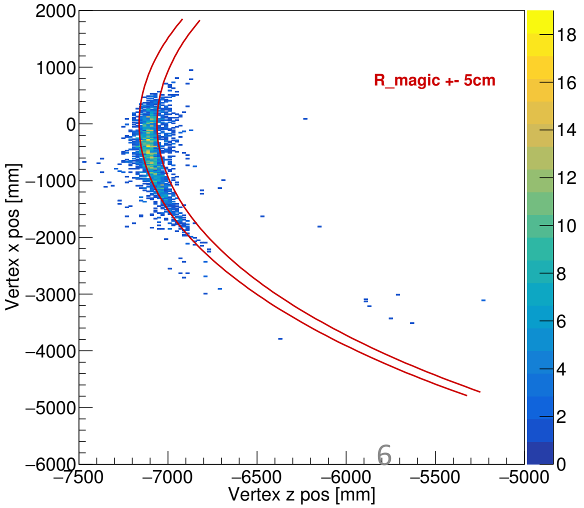
- Highest occupancy in the straws closest to the beam
- A matching between the straw and calorimeter hit times
- Flash at beam injection and protons when the quads turn off











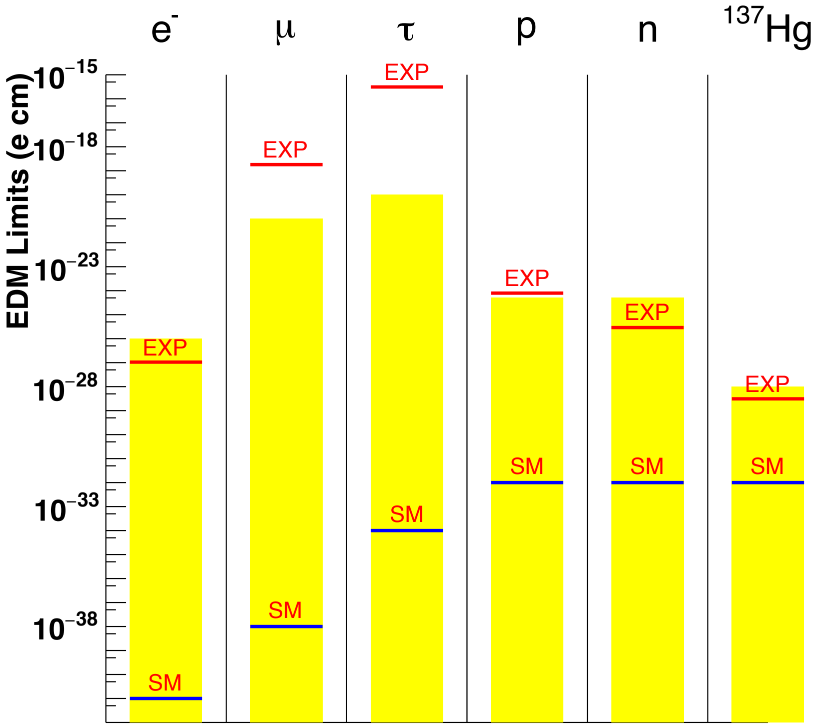
The muon EDM – why?

The g-2 experiment at Fermilab can also look for a potential muon EDM – something the trackers are useful for

Fundamental particles can also have an EDM defined by an equation similar to the MDM:

$$\vec{d} = \eta \frac{Qe}{2mc}\vec{s} \qquad \vec{\mu} = g\frac{e}{2mc}\vec{s}$$

Defined by the Hamiltonian: $H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$



Provides an additional source of CP violation

	E	B	μ or d
P	-	+	+
C	-	-	-
T	+	-	-

Standard scaling :

$$\frac{d_\mu}{d_e} \sim \frac{m_\mu}{m_e}$$

d_e limits imply d_μ scale of 10^{-25} e•cm

But some BSM models predict non-standard scalings (quadratic or even cubic)

The muon is a unique opportunity to search for an EDM in the 2nd generation

The muon EDM – how?

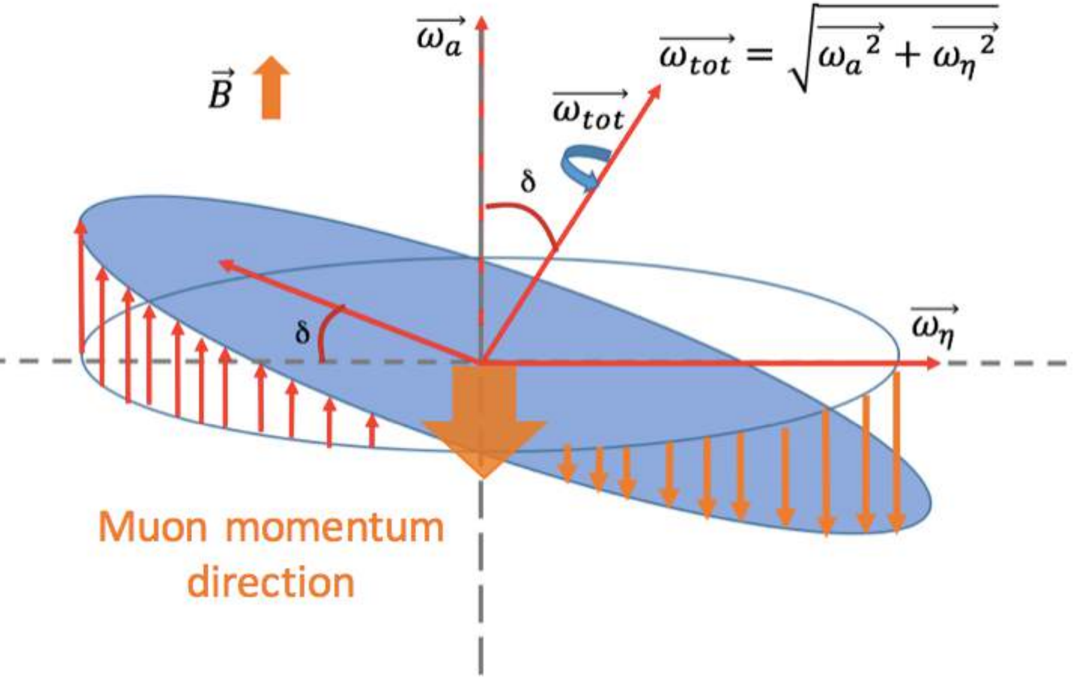
If an EDM is present the spin equation is modified to:

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = -\overbrace{\frac{Qe}{m}\left[a\vec{B} - \cancel{\left(a-\frac{1}{\gamma^2-1}\right)}\frac{\vec{\beta}\times\vec{E}}{c}\right]}^{\text{MDM}} \overbrace{-\eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c}+\boxed{\vec{\beta}\times\vec{B}}\right]}^{\text{EDM}}$$

Run at the "magic momentum"

$\gamma_{magic} = 29.3$, $p_{magic} = 3.094$ GeV

Dominant term



An EDM tilts the precession plane towards the centre of the ring

→ Vertical oscillation (π/2 out of phase)

$$\omega_{a\eta} = \sqrt{\omega_a^2 + \omega_\eta^2} \qquad \delta = \tan^{-1}\left(\frac{\eta\beta}{2a}\right)$$

Assuming the motional field dominates we expect tilt of ~mrad for d_μ ~10^{-19}

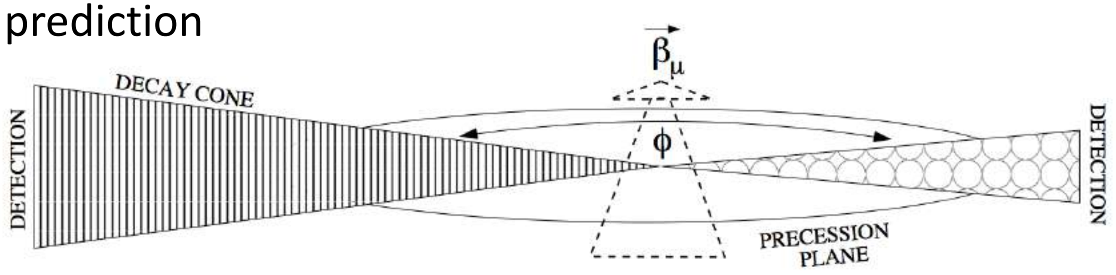
An EDM also increases the precession frequency

The muon EDM at BNL

Several methods were used to measure the EDM at the g-2 experiment at BNL (E821)

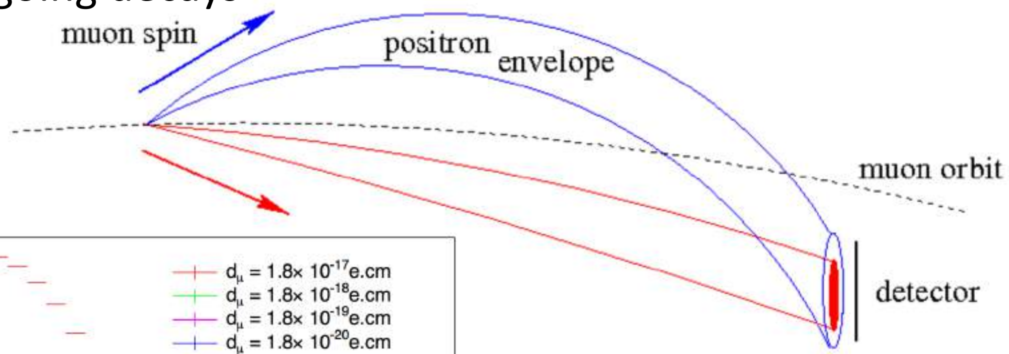
The EDM can be measured

- **Indirectly** by comparing the measured value of ω_a to the SM prediction
- **Directly** by looking for a tilt in the precession plane

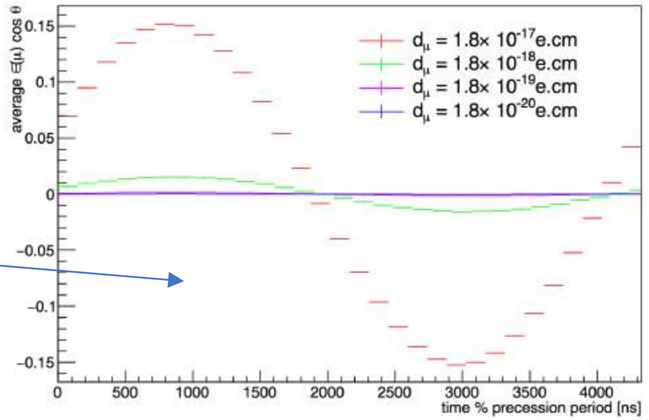


For the direct method 3 techniques were used at E821:

- **Phase as a function of vertical position**
  - Due to the difference in phase between inward and outward going decays
  - Systematics dominated
  - Provides a useful cross check



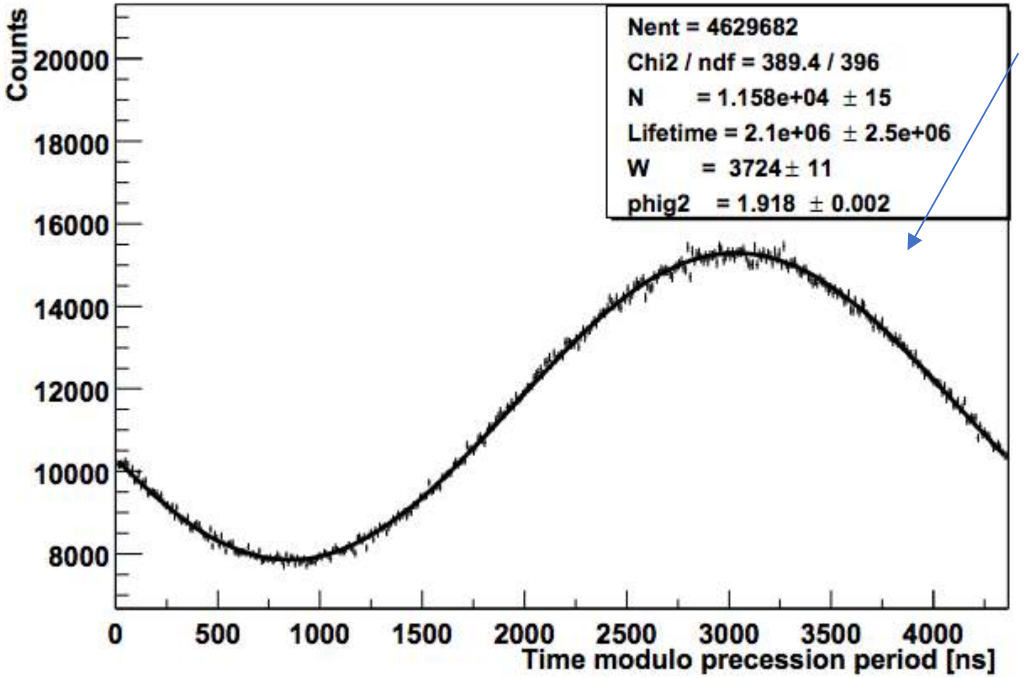
- **Vertical position oscillation as a function of time**
  - Expect this to vary if the precession plane is tilted
  - Must account for the natural breathing of the beam
  - Again systematics dominated



- **Vertical decay angle oscillation as a function of time**
  - Statistics dominated
  - Easiest improvement at E989

Vertical decay angle oscillations

Look for an oscillation in the vertical decay angle of the positrons



Plot the number oscillation as a function of time modulo the precession period

Minimises period disturbances at other frequencies

Use the period calculated from the ω_a fit

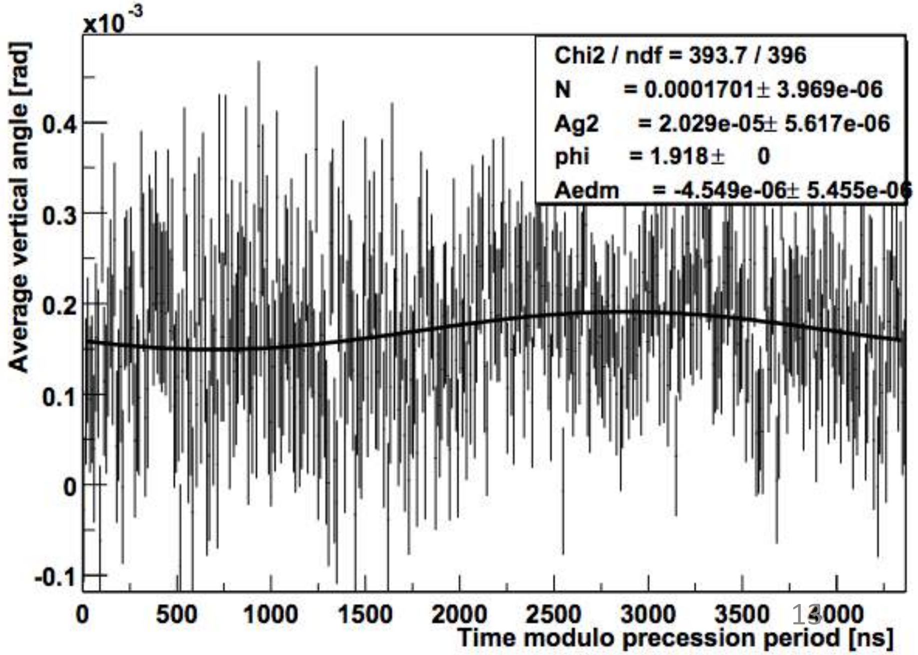
Fit to calculate the phase : $N(t) = e^{-t/\tau_e}\left(N_0 + W\cos(\omega t + \boxed{\Phi})\right)$

Plot the average vertical decay angle as a function of time modulo the precession period

Fit (fix phase from above):

$$\theta(t) = M + A_\mu \cos(\omega t + \Phi) + A_{EDM}\sin(\omega t + \Phi)$$

EDM oscillation comes in π/2 out of phase from the MDM



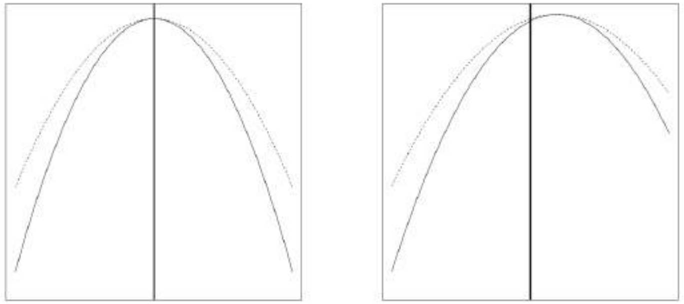
Vertical decay angle systematics

Consider the main systematic errors at the previous experiment and how these can be improved on at the new experiment

Radial Magnetic field:

Would cause a tilt in the precession plane

$$\vec{\omega}_a = -\frac{Qe}{m} a\vec{B}$$



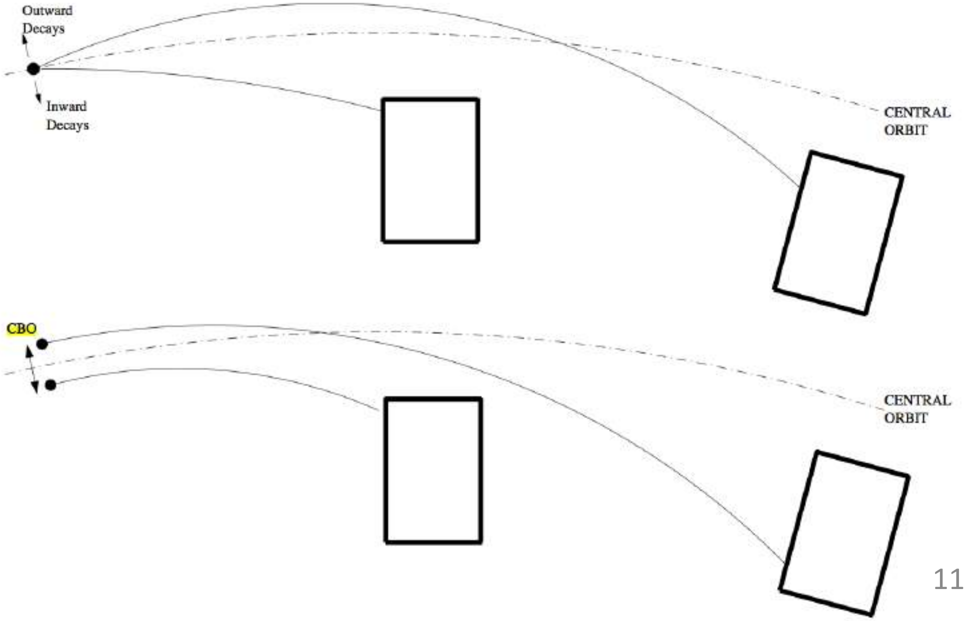
Systematic error	Vertical oscillation amplitude (μrad lab)	Precession plane tilt (mrad)	False EDM generated 10^{-19} ($e\cdot$ cm)
Radial field	0.13	0.04	0.045
Acceptance coupling	0.3	0.09	0.1
Horizontal CBO	0.3	0.09	0.1
Number oscillation phase fit	0.01	0.003	0.0034
Precession period	0.01	0.003	0.0034
Totals	0.44	0.13	0.14

Detector acceptance:

Inward going positrons travel a shorter distance than outward going positrons

$\longrightarrow$ narrower beam spread

Horizontal CBO oscillations



Phase or period errors:

Could mix the number oscillation into the EDM phase

E821:

Oscillation amplitude : $(-0.1 \pm 4.4) \times 10^{-6}$ rad

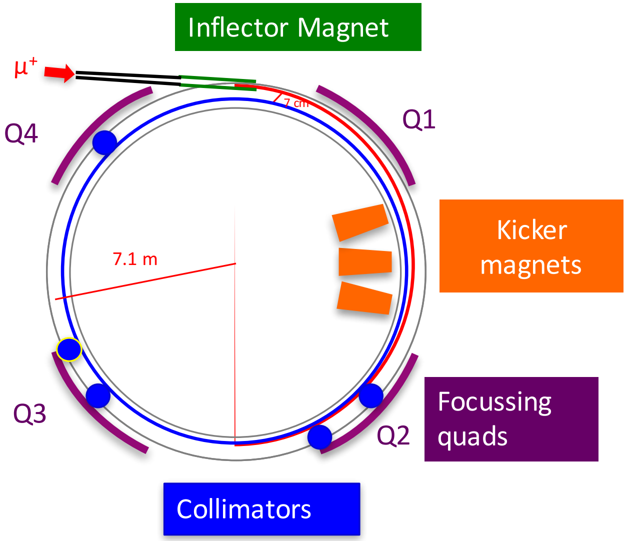
$\longrightarrow$ $d_\mu = (-0.04 \pm 1.6) \times 10^{-19}$ e•cm

$\longrightarrow$ $|d_\mu| < 3.2 \times 10^{-19}$ e•cm (95% C.L)

Dominated by the statistical error

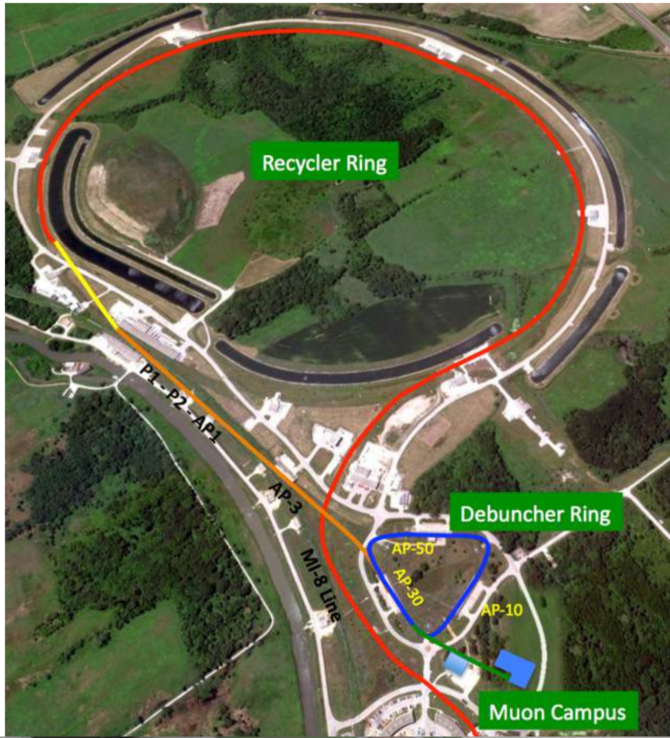
Vertical decay angle at Fermilab

The new tracking detectors at Fermilab should increase the statistics and allow for a 2 orders of magnitude reduction in the limit on an EDM



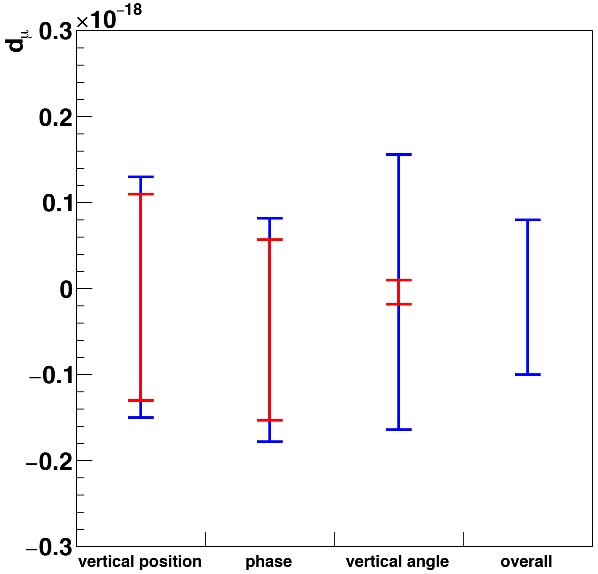
Expect O(1000) times the E821 statistics :

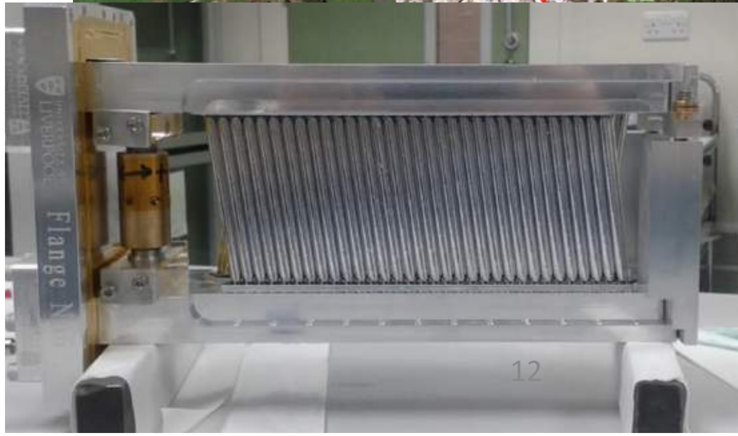
- 20 times more muons
  - → Fermilab accelerator complex
  - → Improvements in the ring design
- Increased tracker acceptance
  - → 3 tracker stations
  - → Better coverage for each station



Better control of the systematic errors:

- Amplitude of CBO reduced by factor 4
- Geometrical acceptance increased
- Tracker in vacuum chamber
- Better beam simulation
- Precision alignment tools





Reduce error by 1 order of magnitude quickly (with no improvements in systematics), approaching 2 orders of magnitude by the end

Summary

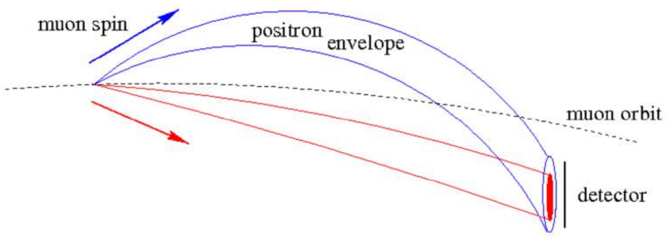
The new g-2 experiment at Fermilab has just finished the commissioning run and will start data taking in November

- The g-2 experiment has new straw tracking stations
- Much work has been done to understand the behaviour of the straws in advance on analysing the data
- The straw tracking detectors will help to
    - Characterise the beam profile
    - Calibrate the calorimeters
    - Look for an EDM signal
- The experiment should improve on the EDM limit by 2 orders of magnitude
    - Increased statistics (improved detector acceptance)
    - Better control of systematics

Back up

Measuring the EDM – vertical position

Look for an oscillation in the average vertical position out of phase with the number oscillation



1. Plot the vertical RMS width as a function of time

Average width

fixed

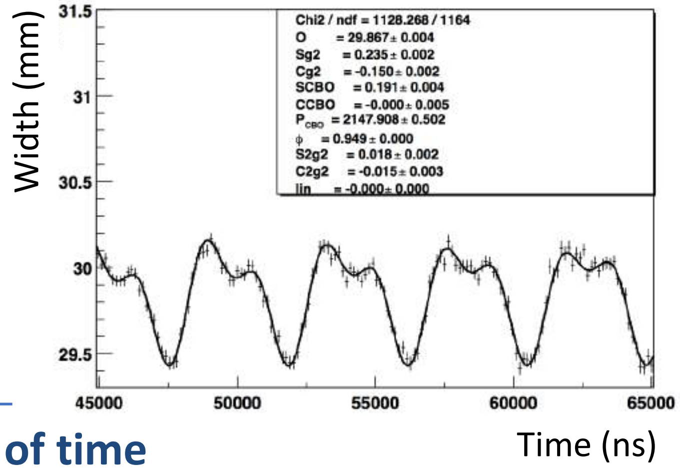
g-2 terms: changes in average energy and time of flight

$$f(t) = W + \overbrace{S_{g2}\sin(\omega t) + C_{g2}\cos(\omega t) + S_{2g2}\sin(2\omega t) + C_{2g2}(2\omega t)}$$

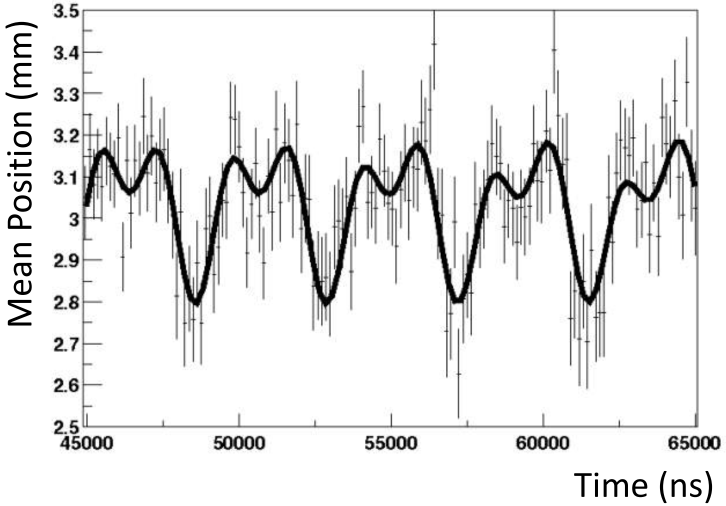
$$\underbrace{+e^{-t/\tau_{CBO}}\left[S_{CBO}\sin\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right) + C_{CBO}\cos\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right)\right]} + Lt$$

CBO (coherent betatron oscillation) terms : different radii lead to different times of flight

deadtime



2. Plot the mean vertical position of hits of hits as a function of time



Detector misalignment

EDM

$$f(t) = K + \boxed{S_{g2}\sin(\omega t)} + C_{g2}\cos(\omega t)$$

$$+e^{-t/\tau_{CBO}}\left[S_{CBO}\sin\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right) + C_{CBO}\cos\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right)\right]$$

$$+Me^{-t/\tau_M}$$

fixed

Slow changes in detector response/pileup

Vertical position uncertainties

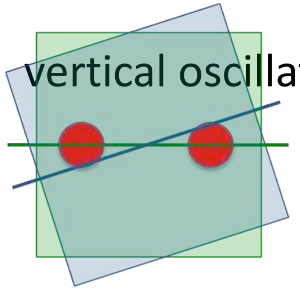
Statistical error
5.88 μm

Systematics dominated measurement

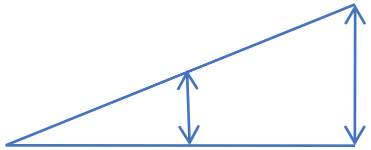
Horizontal oscillation + tilted detector

=

vertical oscillation



Vertical spin
+ longer path length
for outward positrons
= vertical oscillation



Effect	Error (μm)
Detector Tilt	6.1
Vertical Spin	5.1
Quadrupole Tilt	3.9
Timing Offset	3.2
Energy Calibration	2.8
Radial Magnetic Field	2.5
Albedo and Doubles	2.0
Fitting Method	1.0
Total Systematic	10.4
Statistical	5.9
Total Uncertainty	11.9

Differences between the top and bottom halves of the calorimeter

Would cause a tilt in the precession plane

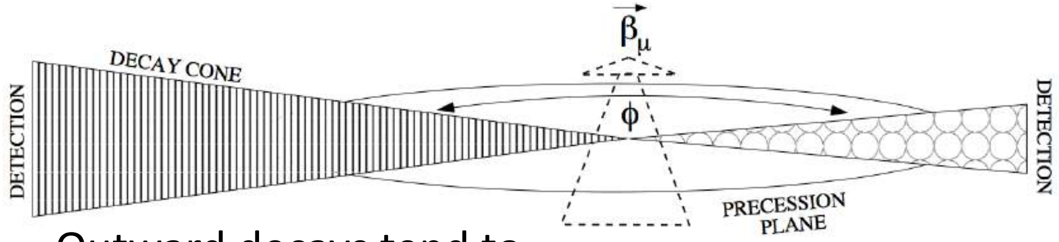
Back scattering from the calorimeter

E821 : S_{g2} = (1.27 ± 11.9) μm → d_μ = (-0.1 ± 1.4) x 10^{-19} e•cm

→ $|d_\mu|$ < 2.9 x 10^{-19} e•cm (95% C.L.)

Measuring the EDM – phase

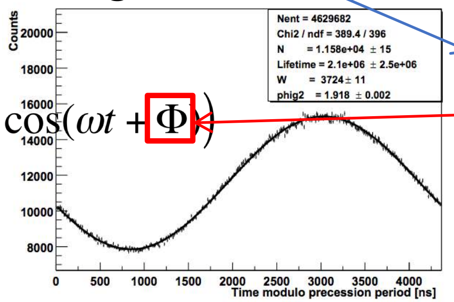
Consider the phase variation as a function of vertical position



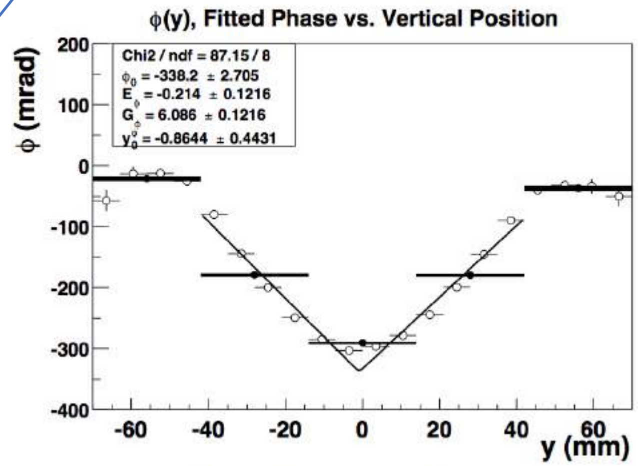
Outward decays tend to travel further up or down due to longer path length

Decays that strike higher in the detector have to travel further

$$N(t) = e^{-t/\tau_e}\left(N_0 + W\cos(\omega t + \boxed{\Phi})\right)$$



The fitted phase depends on the vertical position



A non zero EDM tips the precession plane

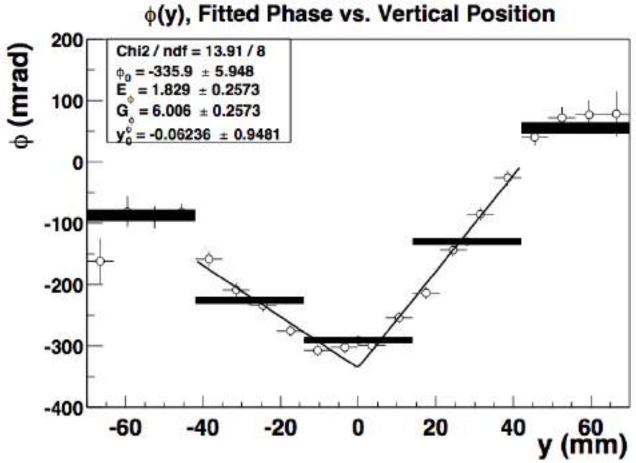
- More outward decays at the top
- More inward decays at the bottom

→ **suppresses the phase difference at the bottom of the calorimeter**

$$\Phi(y) = p_0 + \boxed{p_1}(y - p_2) + \underbrace{\left|p_3(y - p_2)\right|}$$

Up-down asymmetry
EDM

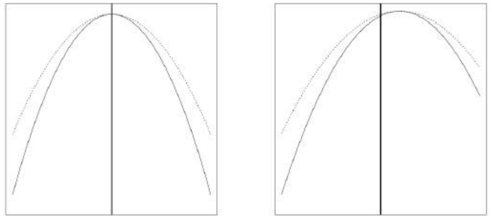
Phase changes not related to EDM



Phase uncertainties

The systematic uncertainities are similar to the vertical position measurement

Detector misalignment is more important

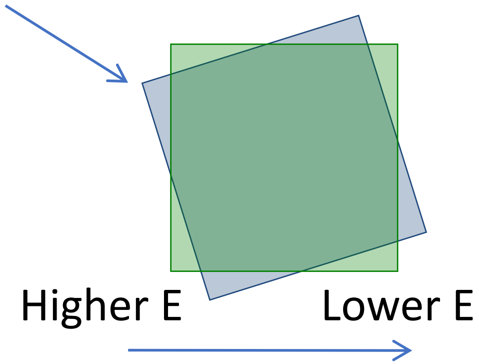


induces an up down asymmetry

→ fake EDM signal

Detector Tilt

causes asymmetric vertical loses



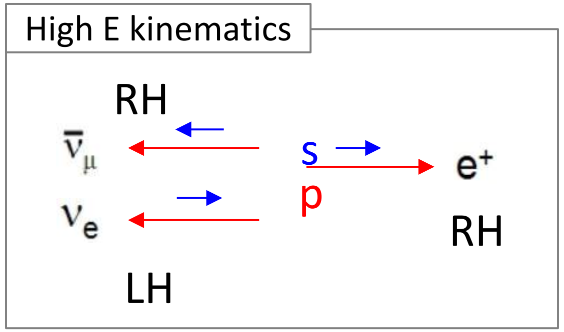
Source	Sensitivity	Result
Detector Tilt	26 μrad/mm/mrad$\times$ 0.75 mrad	20 μ rad/mm
Detector Misalignment	138 μrad/mm/ mm $\times$ 0.2 mm	28 μ rad/mm
Energy Calibration	43 μrad/mm/ % $\times$ 0.1%	4.3 μ rad/mm
Muon Vertical Spin	1.0 μrad/mm $\times$ 8%	8.0 μ rad/mm
Radial B field	0.72 μrad/mm/ppm $\times$ 20.0 ppm	14.4 μ rad/mm
Timing	17.0 μrad/mm/ns $\times$ 0.2 ns	3.4 μ rad/mm
Total systematic		38 μrad/mm (0.93 $\times 10^{-19}$ e·cm)
Total statistical		28 μrad/mm (0.73 $\times 10^{-19}$ e·cm)
Total		47 μrad/mm (1.2 $\times 10^{-19}$ e·cm)

E821: $d_\mu = (-0.48 \pm 1.3) \times 10^{-19}$ e•cm

Again systematics dominated, although statistics play a larger role

Measuring the EDM - Indirect

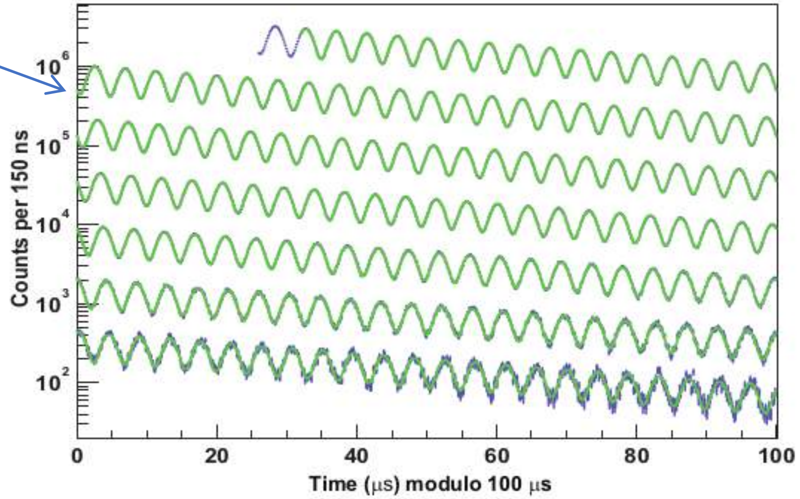
Look for an increase in the precession frequency (compared to SM prediction)



Measure the spin precession via the anti-muon decays:

→ Positrons are preferentially emitted parallel to the muon spin

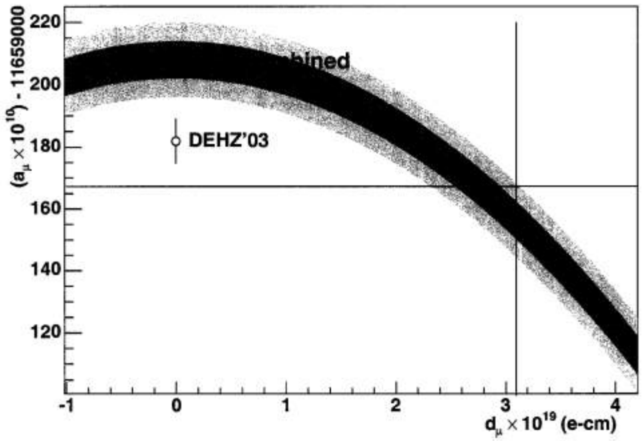
Count the number of positrons with E > 1.2 GeV hitting the calorimeters



Fit to extract the spin precession:

$$N(t,E_{th}) = N_0(E_{th})e^{-t/\gamma\tau}\left[1 + A(E_{th})\cos\left(\omega_a t + \phi(E_{th})\right)\right]$$

Agrees with SM : use error to set limit
Larger than SM : use difference to set limit



E821:

Δa_μ (E821 – SM) = (26.1 ± 9.4) x 10^{-10}

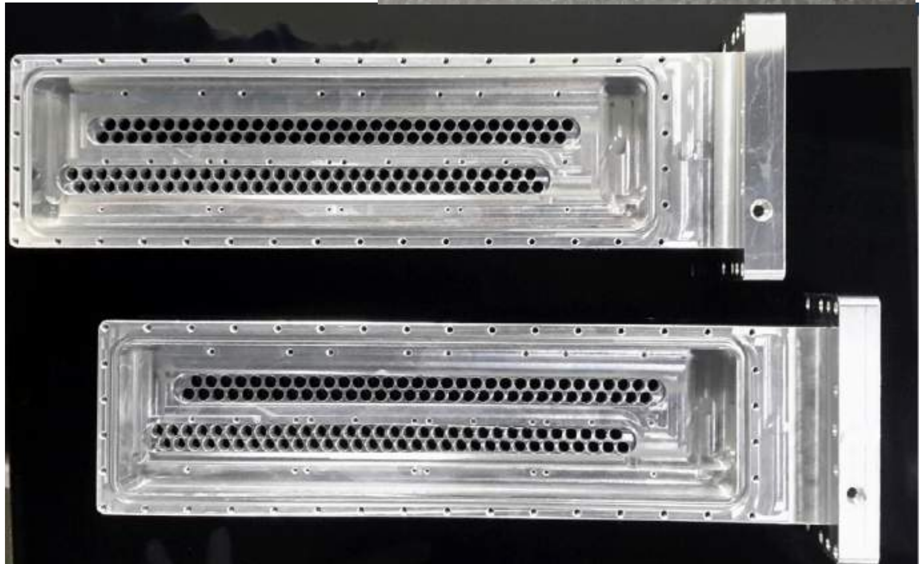
→ $|d_\mu| < 3.1 \times 10^{-19}$ e•cm (95% C.L.)

Tracker Construction

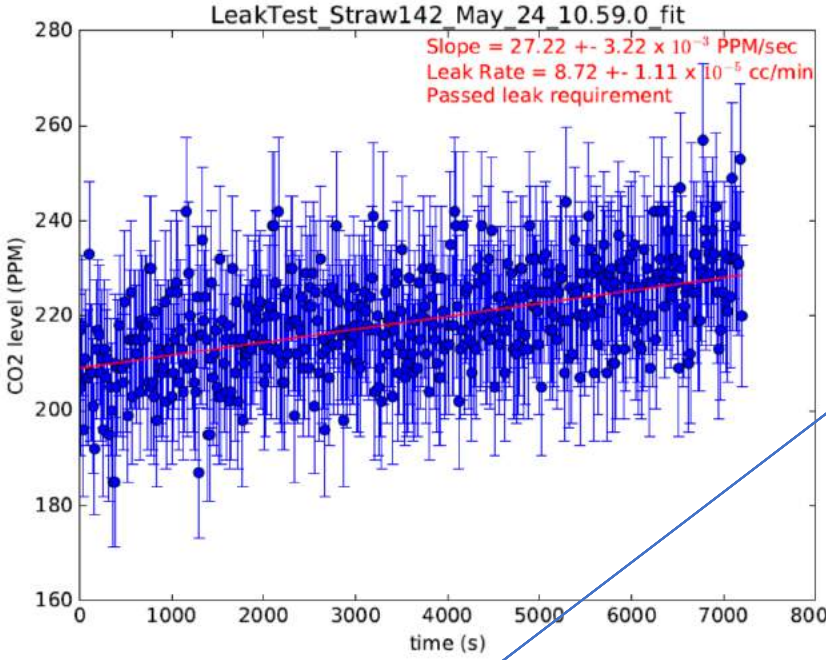
A brief overview of the construction of a single tracker module

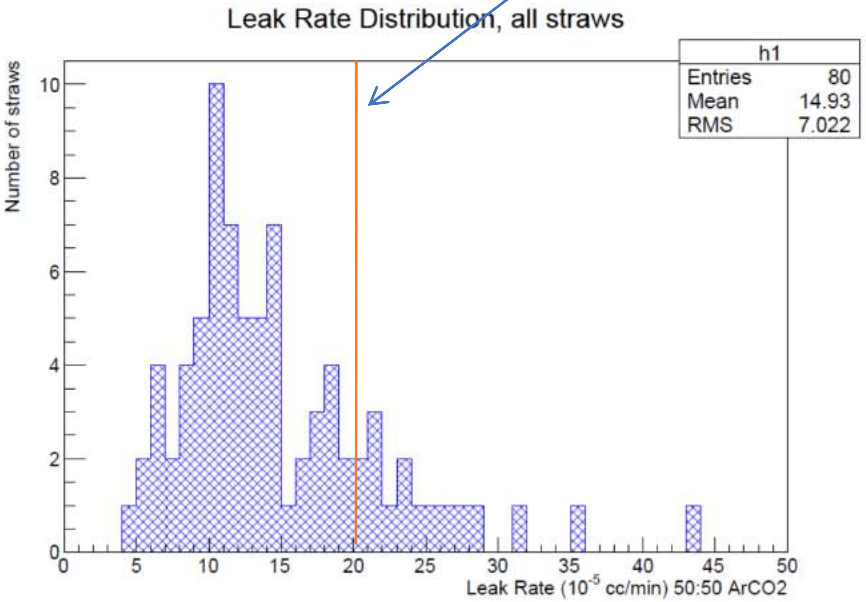
See the Straw Tracker Assembly Procedure document (docdb 3190)

1. **Machine the manifold, vacuum flange and snouts**
   - Manifolds and vacuum flange machined out of a single piece of aluminium
   - Snouts are being cast
   - Currently have enough for 4 modules, the rest are in process



Tracker Construction

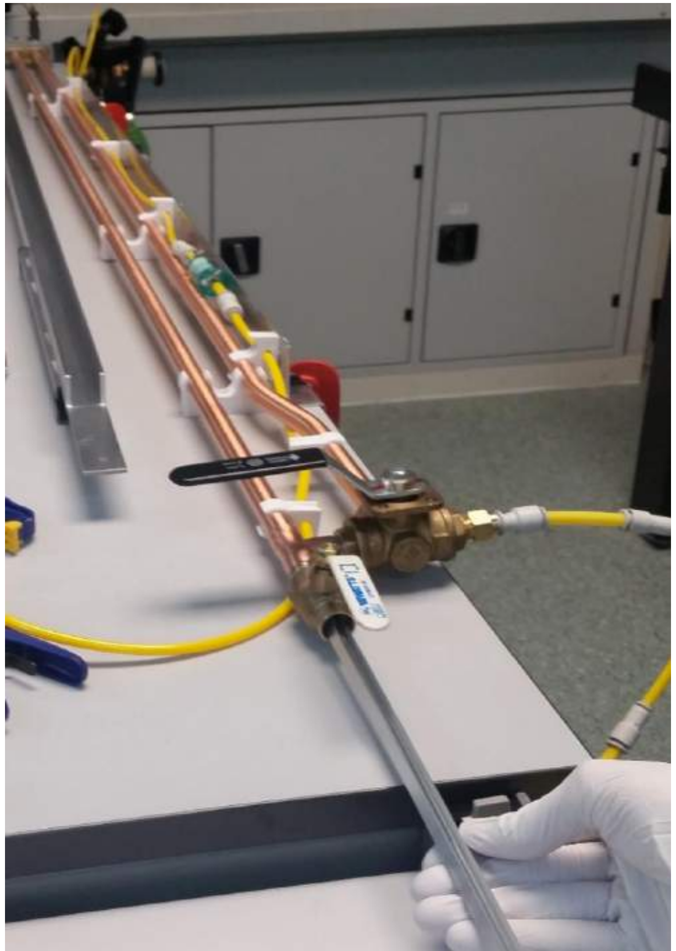




2. Leak test the long straws

- Fill straws with Ar-CO_2
- Detect CO_2 as a function of time (over 2 hours)
- Require a leak rate of less than 2×10^{-4} cc/min

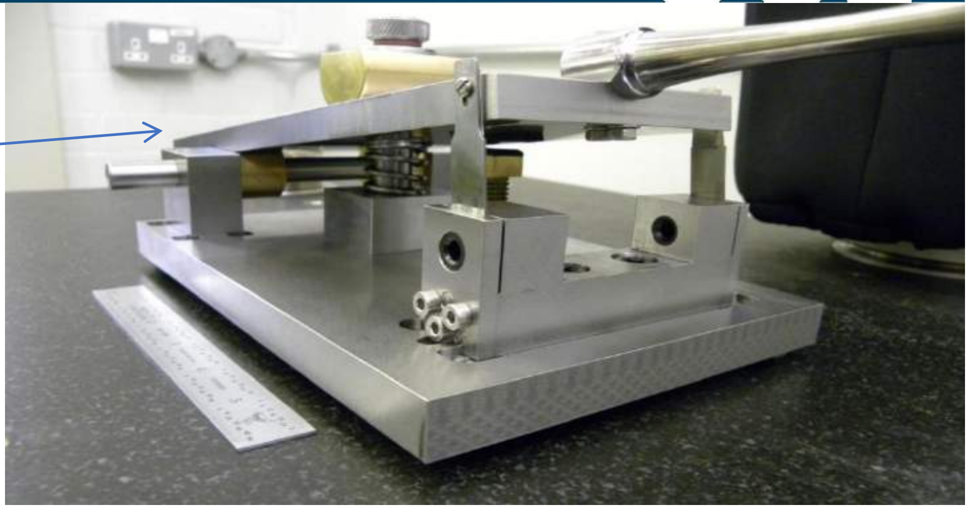
NB. The leak rate with Ar-Ethane will be lower

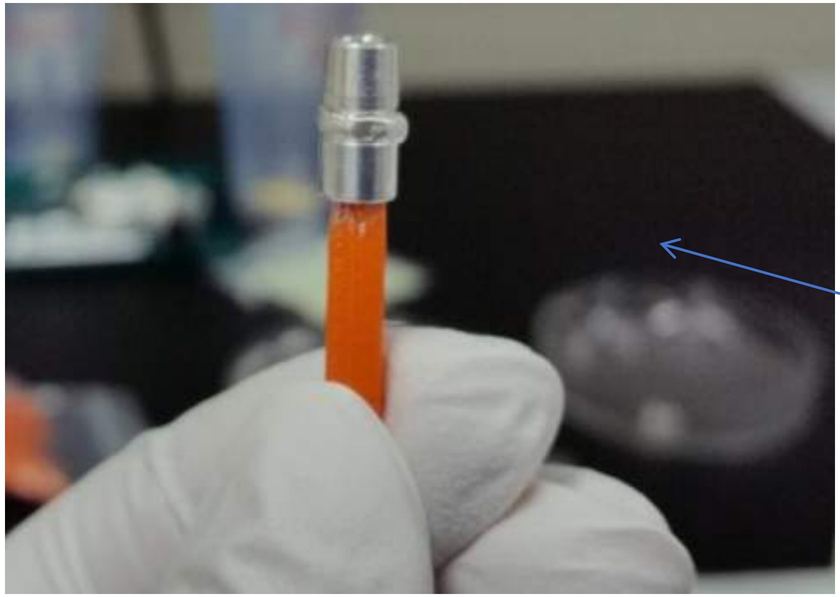


Tracker Construction

3. Cut the straws to 90.6mm length

Use a cutting jig to ensure accuracy and consistancy



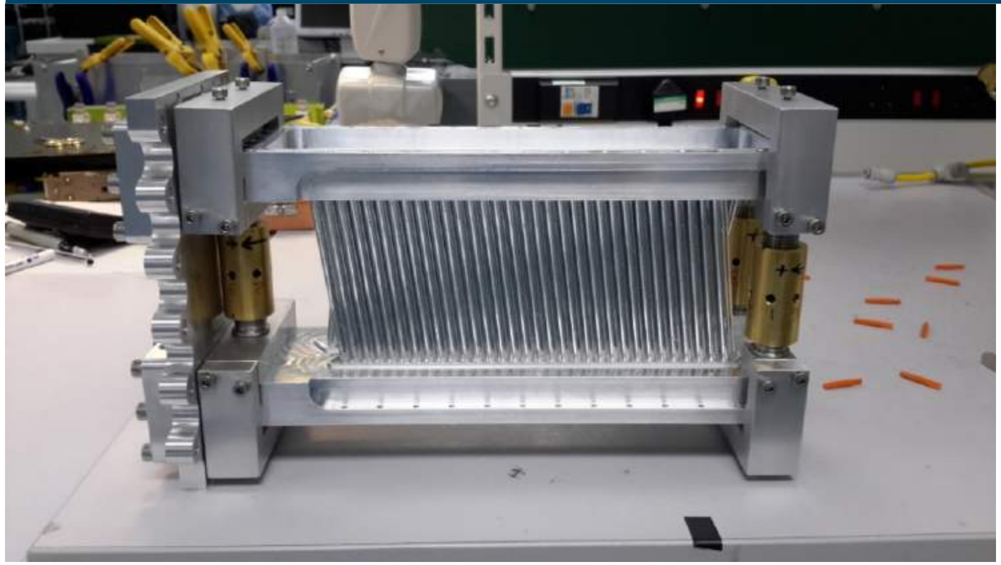


4. Bond aluminium ends to the straws using silver epoxy

5. Check the resistance of the straw

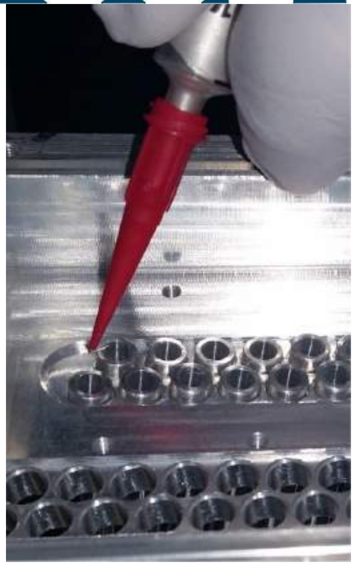
- Require < 30 ohms

Tracker Construction



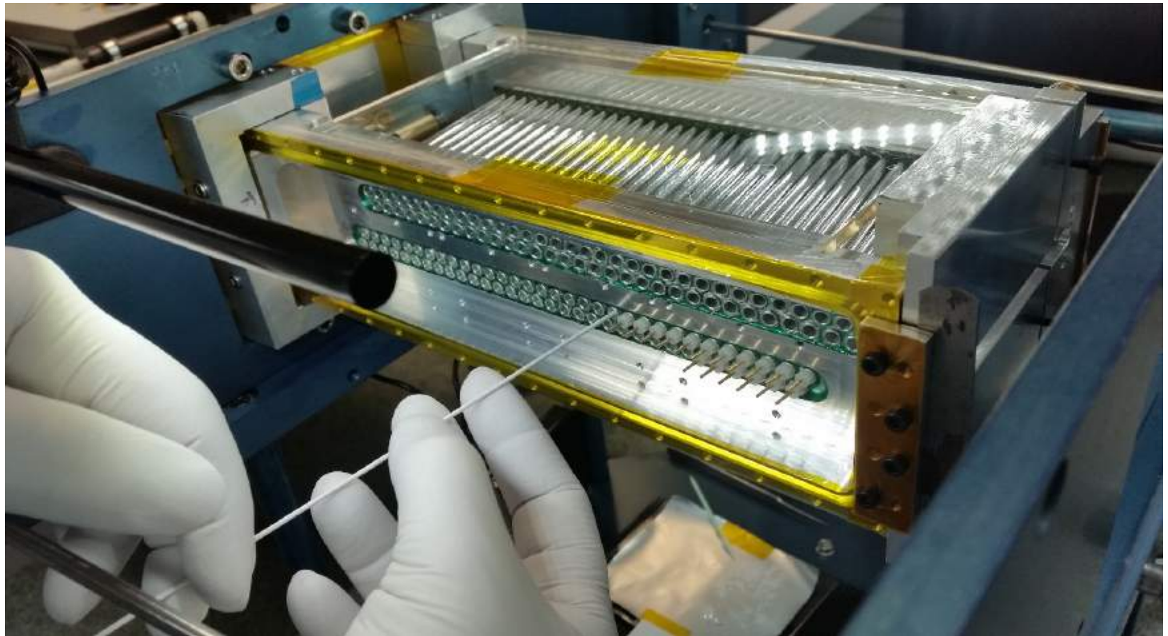
6. Populate the manifolds

- Insert the straws into jacked apart manifolds
- Glue straws in place assisted by wells in manifold (~5 days)



7. Module stringing

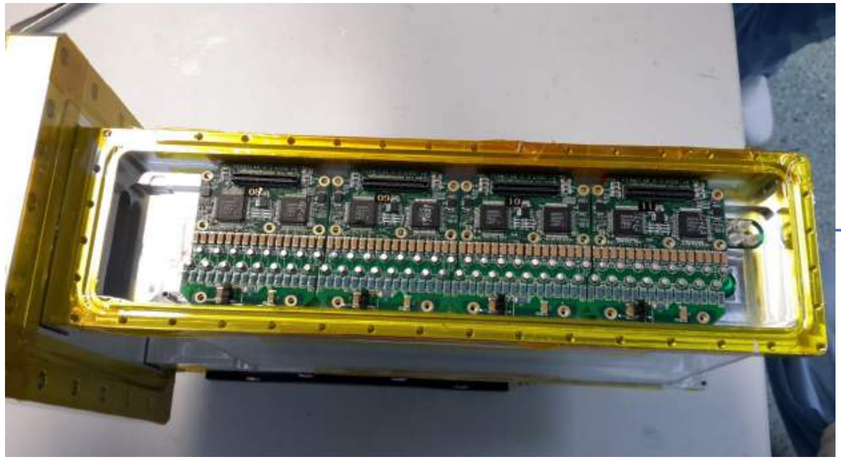
- Long readout pins threaded onto wire and crimped
- Wire threaded through straw and short pin
- Wire pre tensioned
- Short pin hand crimped
- Jack module apart to the final wire tension



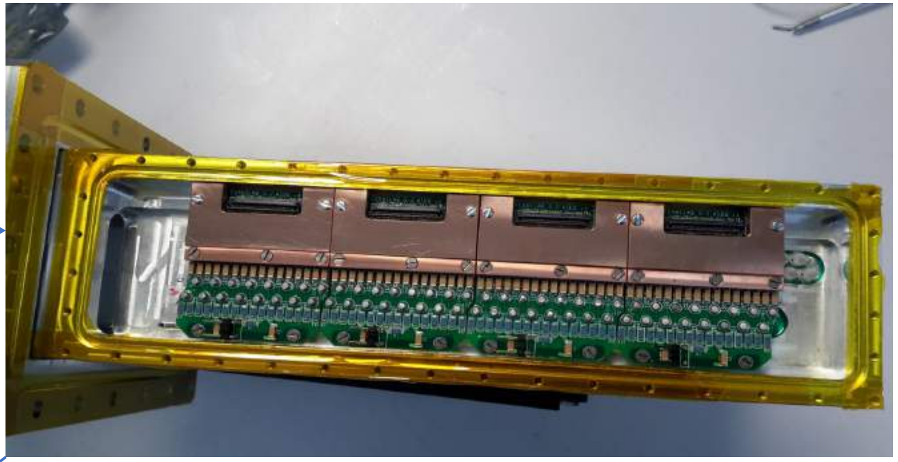
Tracker Construction

8. Final assembly – electronics and cabling

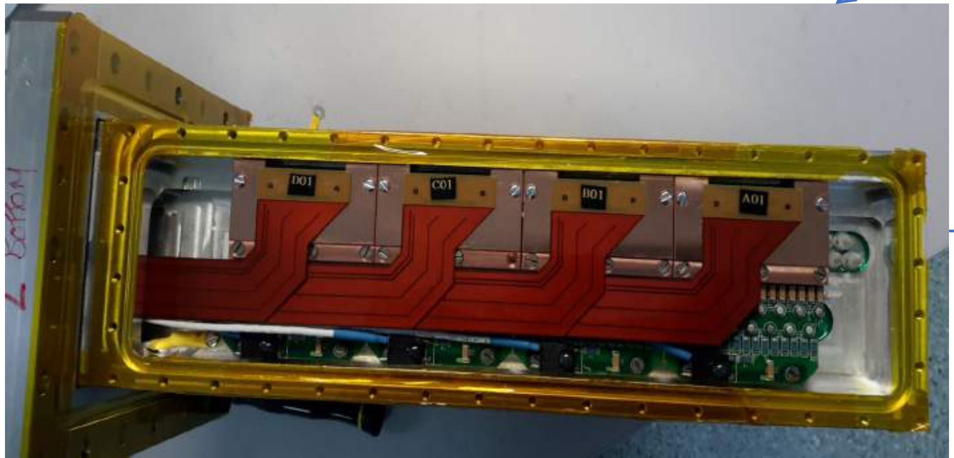
Insert the ASDQs (connect to the end of the straws)



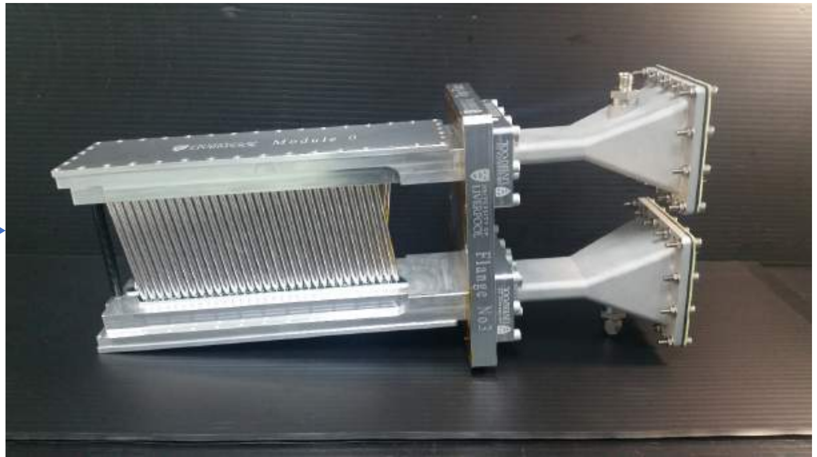
Add the cooling bar (water cooled)



Connect the HV and flexi cables



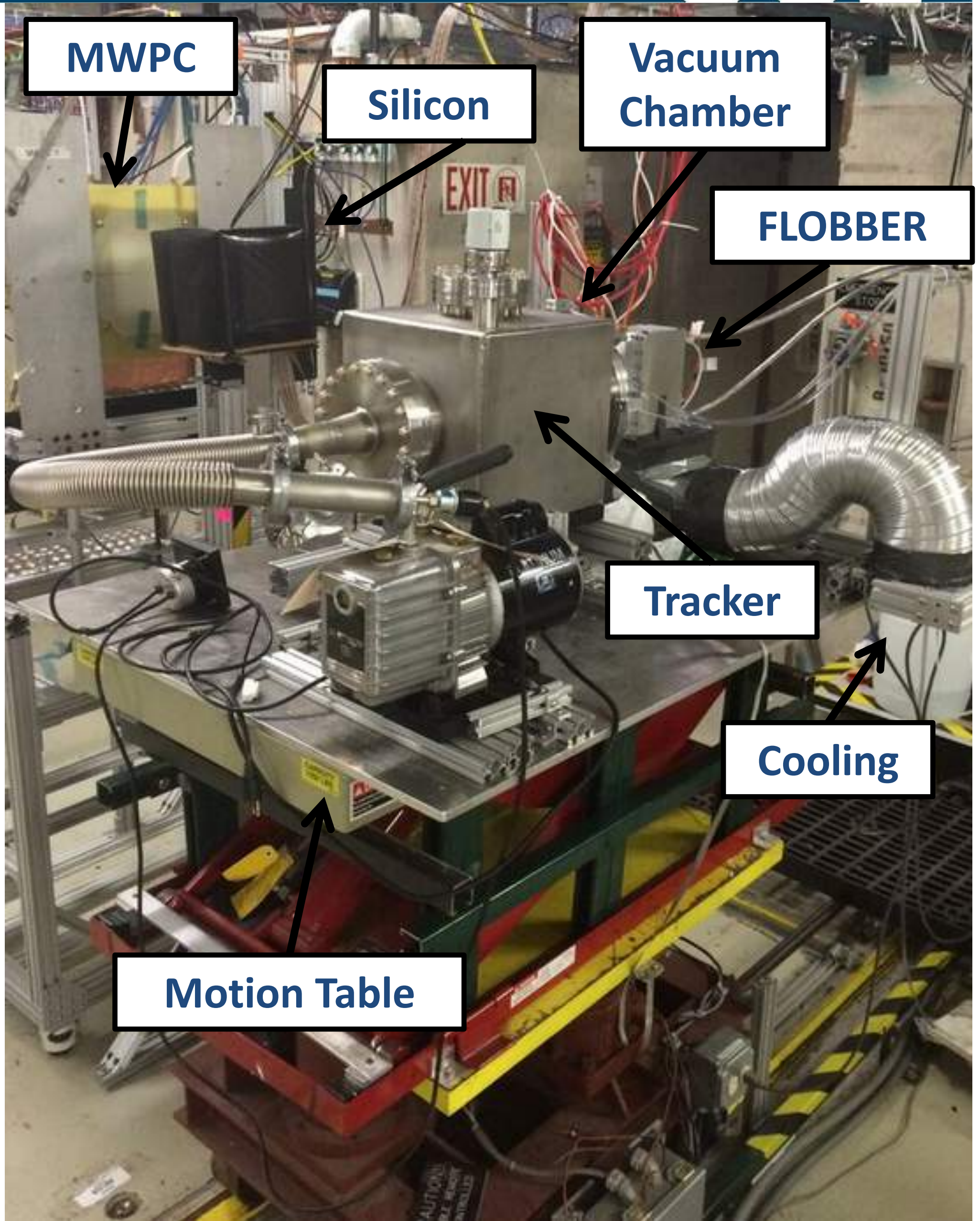
Module ready to go!



2015 Tracker Test Beam

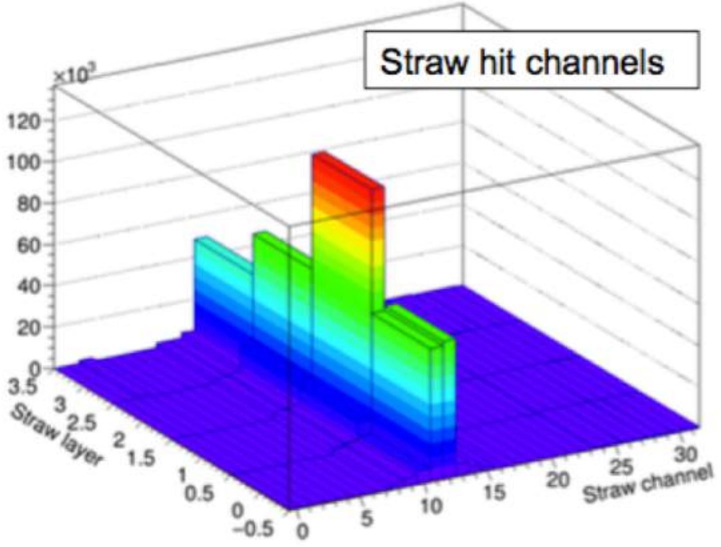
Two week test beam at the Fermilab MTest facility

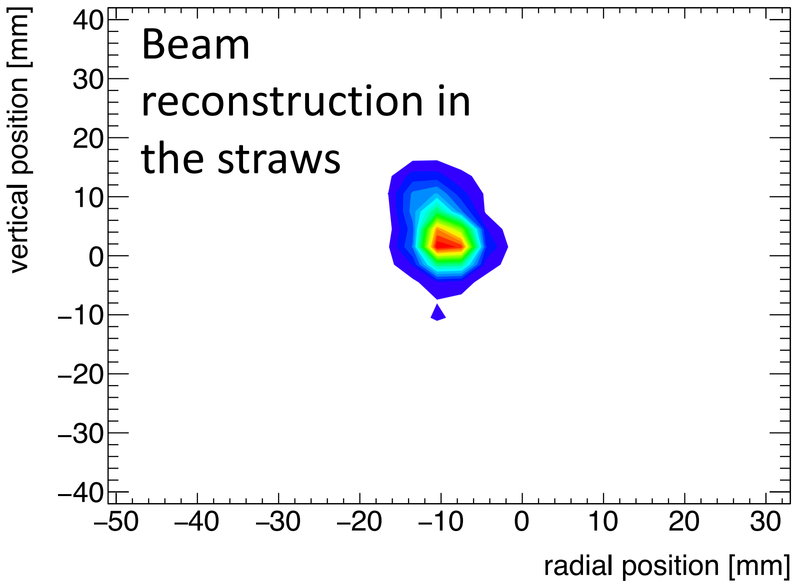
- ✓ **Exercise the full data chain:**
  - ✓ Test the reliability of near production electronics
  - ✓ Check the robustness of the DAQ
  - ✓ Test the DQM software (ROME)
  - ✓ Use art for simulation and data analysis
- ✓ **Test the tracker performance with different gases, HV, thresholds**
- ✓ **Determine the resolution of the module**
- ✓ **Measure the straw efficiency**
- ✓ **Investigate straw cross talk**
- ✓ **Measure the straw dead time**

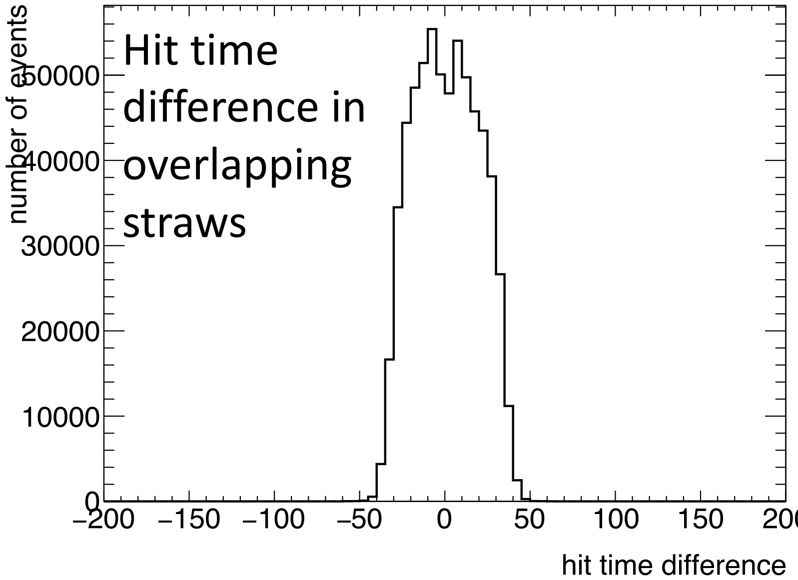


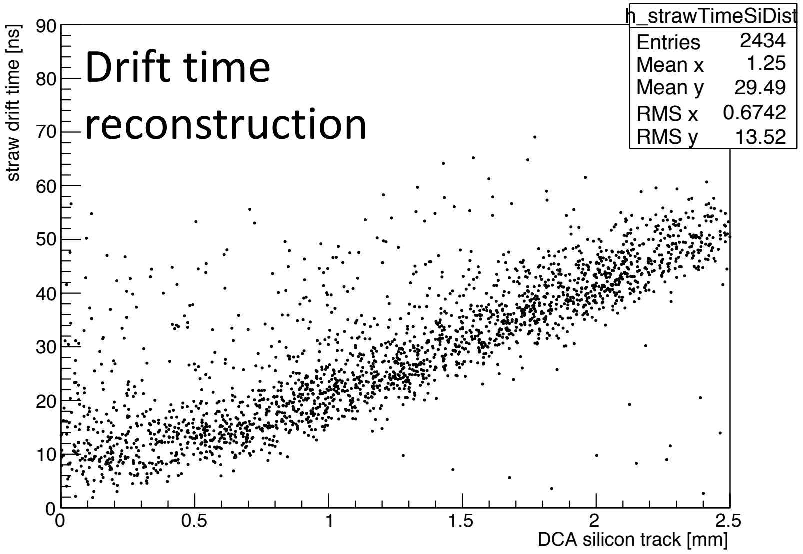
2015 Test Beam Results

A snapshot of some of the results obtained at the test beam









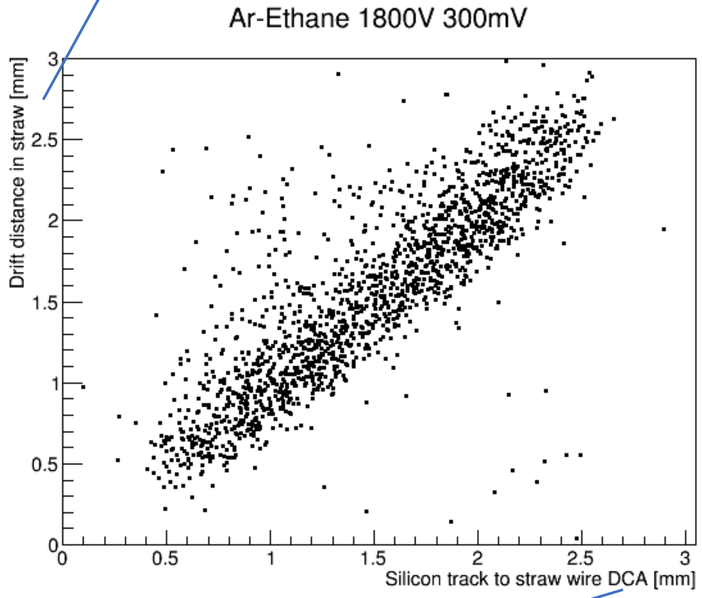
2015 Test Beam Results

UCL

Require < 300µm resolution

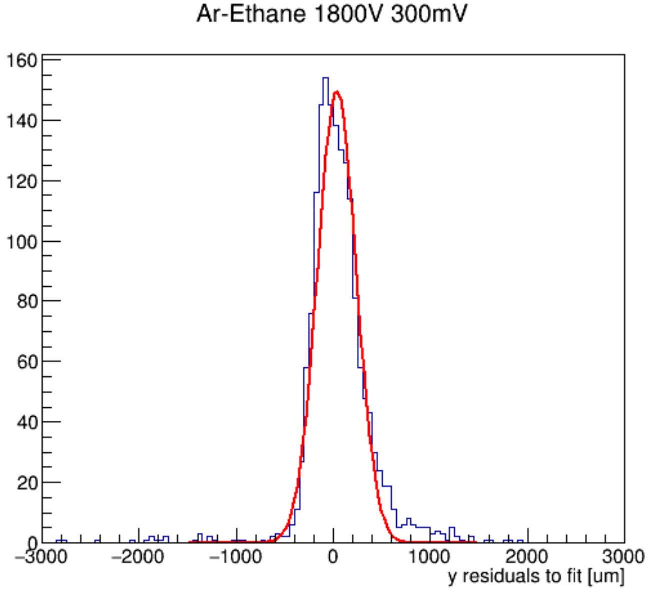
Straw resolution results from the test beam

Convert straw drift time into a drift distance using the drift velocity

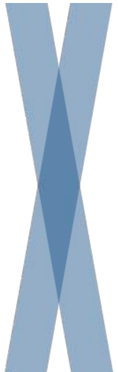


Distance of closest approach of the silicon track to the wire

Plot the residuals to the fit:



→ **Measured resolution : 180µm**



The radial and vertical resolutions are different due to the stereo angle of the straws:

200µm single straw resolution →

→ **100µm radial resolution**

Liverpool Test Stand

Before the modules are shipped to Fermilab the modules are tested at Liverpool

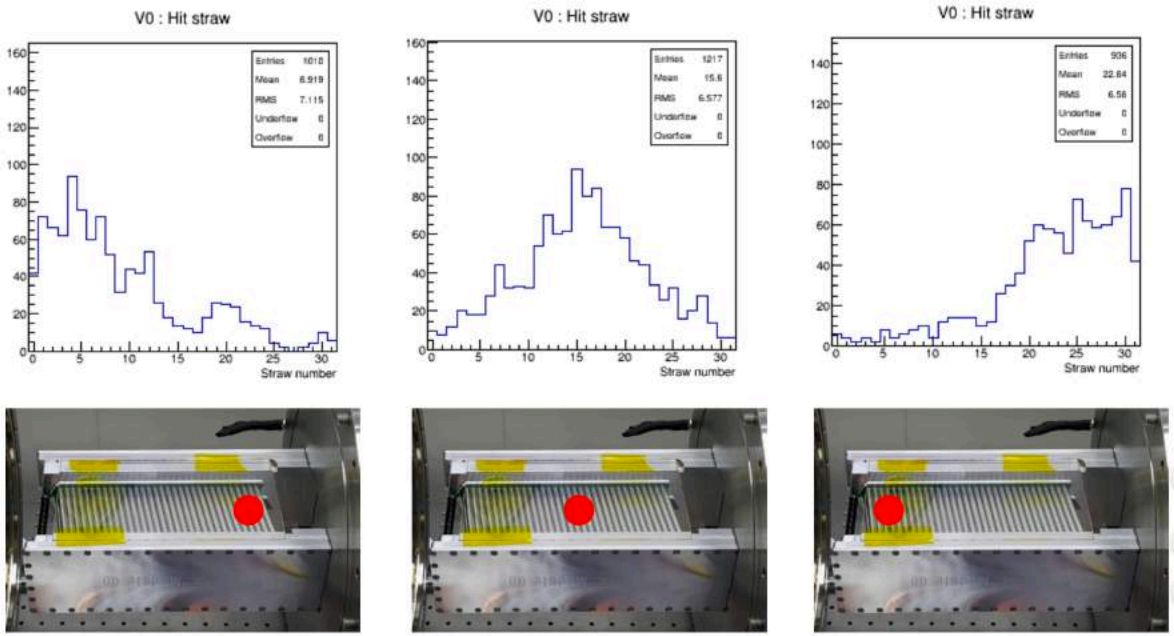
Check that the module can be taken down **to vacuum** – no leaks

Ensure that the straws **hold HV** up to 1500V with Ar-CO_2 (overnight)

Take data with a source to make sure that hits are seen in all the straws

Perform **noise scans**

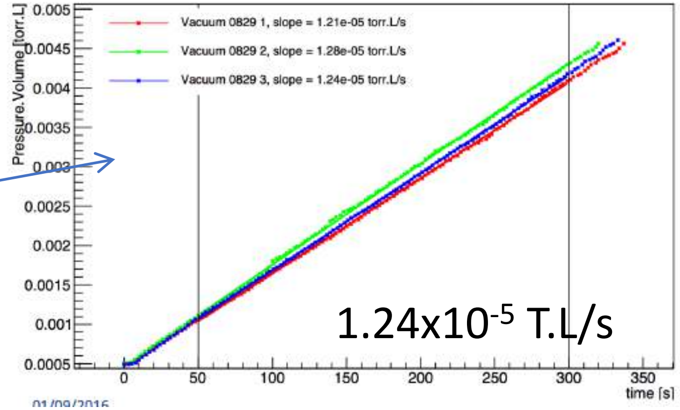
Example data taken with the first module with the source in different locations:



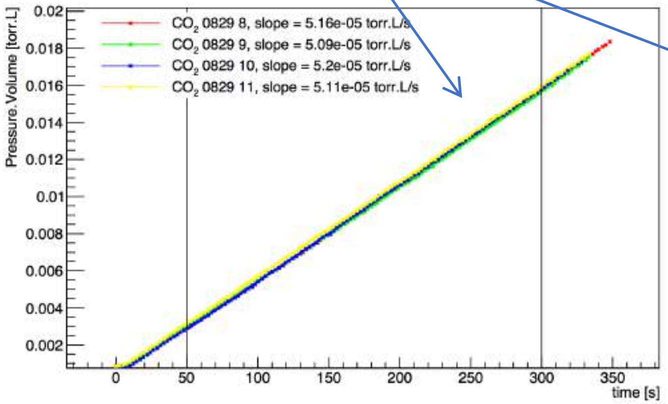
Module leak testing

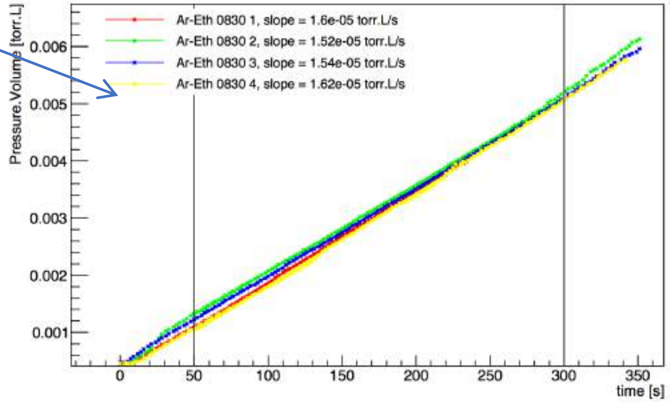
Check the leak rate of the module as a whole once it arrives at Fermilab

- Pump the module down to vacuum
- Measure the change in pressure as a function of time
  - First test with vacuum to extract the outgassing rate
  - Fill straws with different gases (N_2, CO_2, Ar-Ethane) and repeat
  - Subtract outgassing rate off to get final module leak rate
  - Require per tracker station leak rate < 4.5×10^{-5} T.L/s



1.24×10^{-5} T.L/s





Gas	Raw rate (T.L/s)	Gas Correction Factor	Background rate (T.L/s)	Final number Mod 0 (T.L/s)	Final number Mod 00 (T.L/s)
CO_2	5.14×10^{-5}	1.42	1.24×10^{-5}	2.4×10^{-5}	3.4×10^{-5}
N_2	1.79×10^{-5}	1.0	1.20×10^{-5}	5.5×10^{-6}	4.0×10^{-6}
$Ar:C_2H_6$	1.56×10^{-5}	1.3	1.10×10^{-5}	1.0×10^{-6}	1.8×10^{-6}

1.5×10^{-4} T.L/s leak rate (3 x under requirement)

Lab 3 Test Stand

Set up a cosmic test stand (up to 3 modules) in the clean room at Fermilab to test the modules as they arrive