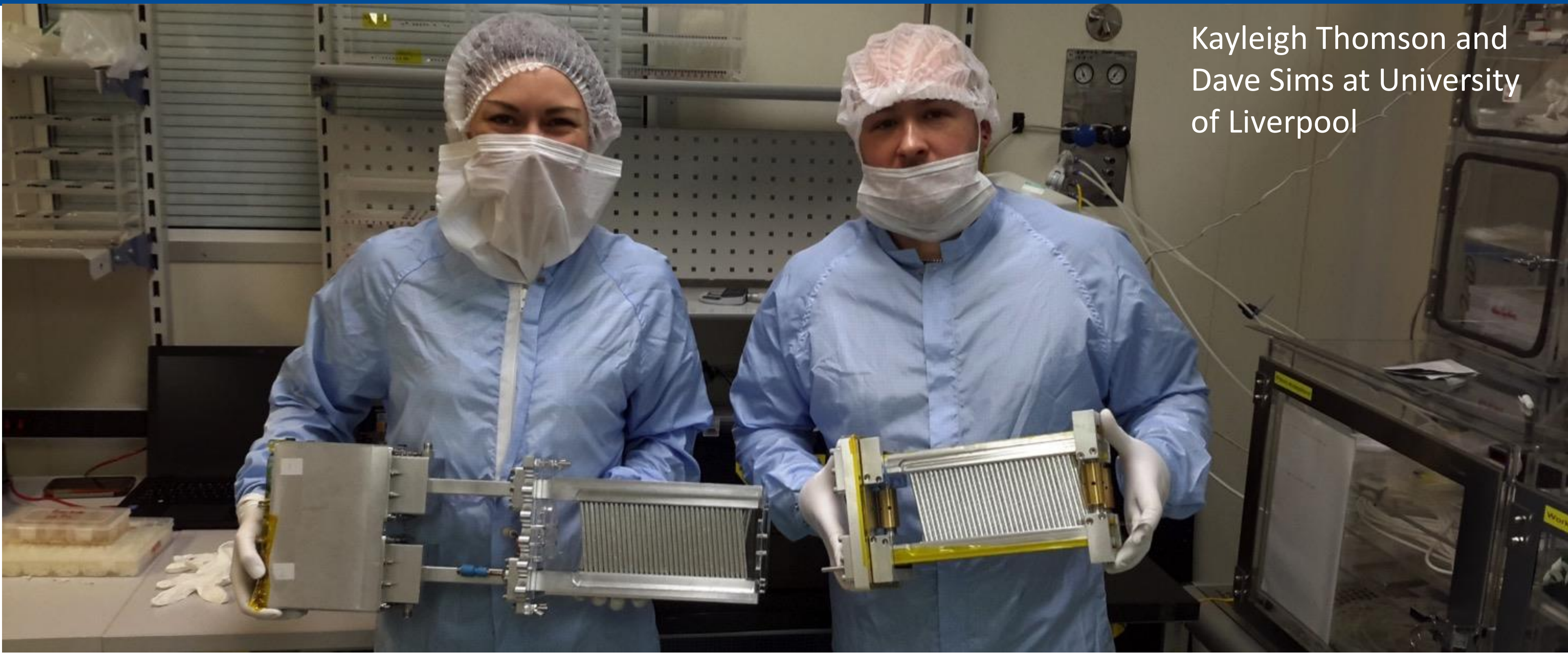


Tracking and muon g-2

Brendan Casey

13 August 2019

Outline

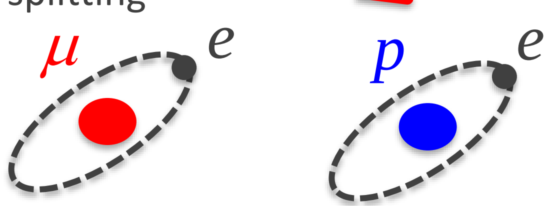
- Why we need tracking
  - Two simple examples
  - Two more complex examples
  - What we learn from up-down asymmetries
- Design
  - Driving factors
  - Alternatives
  - What we finally chose
  - Results from prototypes
- Construction
  - What is happening where
  - Progress to date
- Tracking algorithms
  - Progress to date
- Conclusions

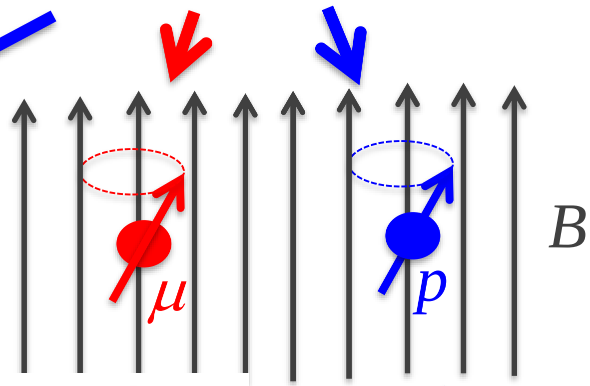
What we just learned from Chris:

Experimental goal is a measurement of muon g-2 to 140 ppb precision

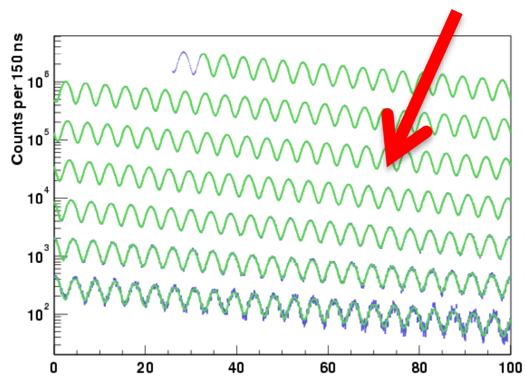
$$\frac{(g-2)_m}{2} = a_m = -\frac{m}{q}\frac{w_a}{B} = \frac{w_a / w_p}{m_m / m_p - w_a / w_p}$$

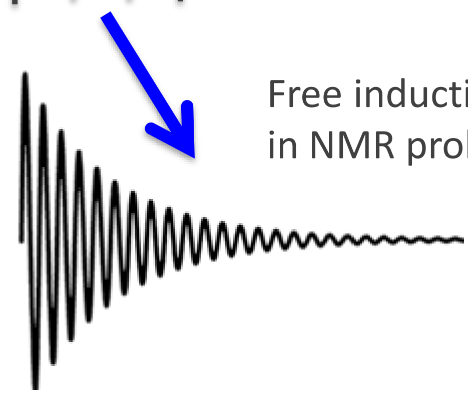
Muonium and hydrogen hyperfile splitting





high energy positrons versus time from the stored muon beam



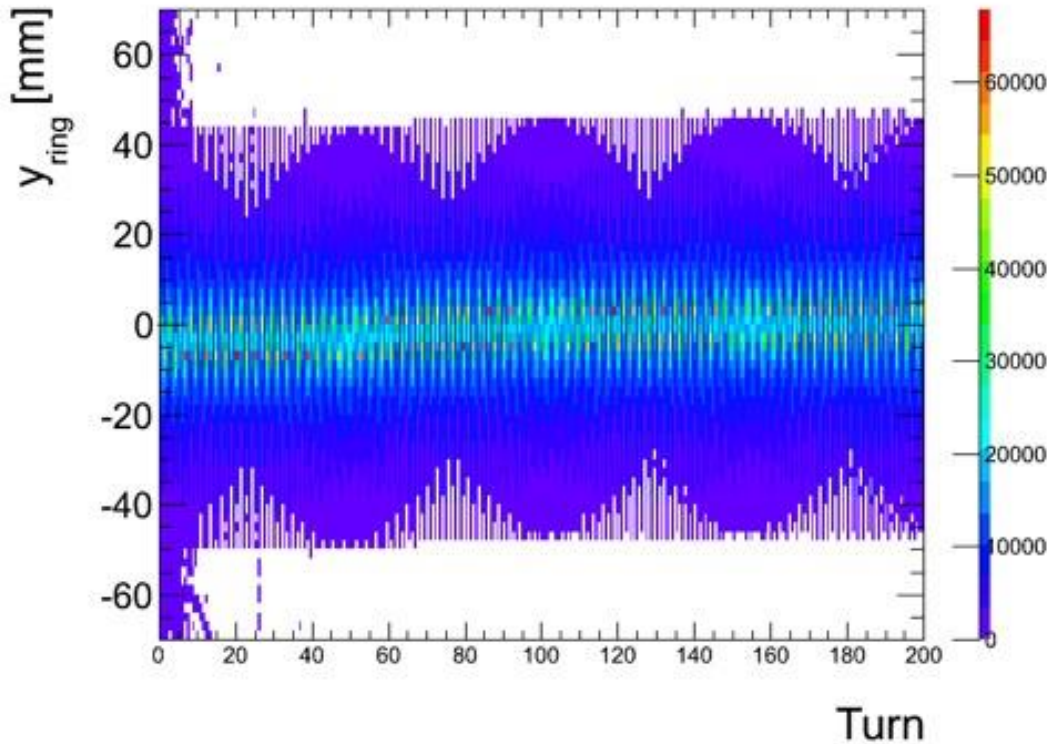


Free induction decay in NMR probes

One more thing….

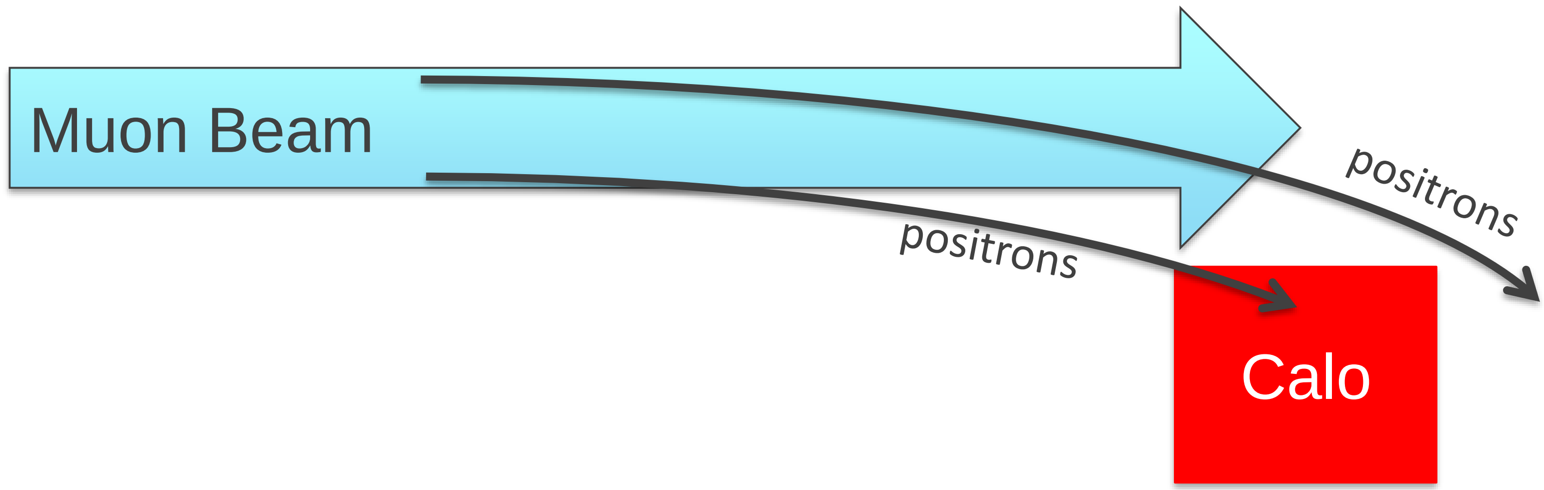
- We do not measure one muon at a time
  - Roughly 10,000 muons injected into the ring
  - They do not all have exactly the magic momentum
  - They are not all on the magic radius
- They pretty much go everywhere, we use terms like
  - The beam breaths
  - The beam swims

Thomas Gadfort



- This beam motion couples into both the measurements of the muon and proton spin precession frequencies in non-trivial ways.
  - We have to have a complete understanding of the beam dynamics in the ring to properly extract g-2.

Example 1: Fake wiggles



Muons on the inside and outside for the storage ring have slightly different acceptance in the calorimeter

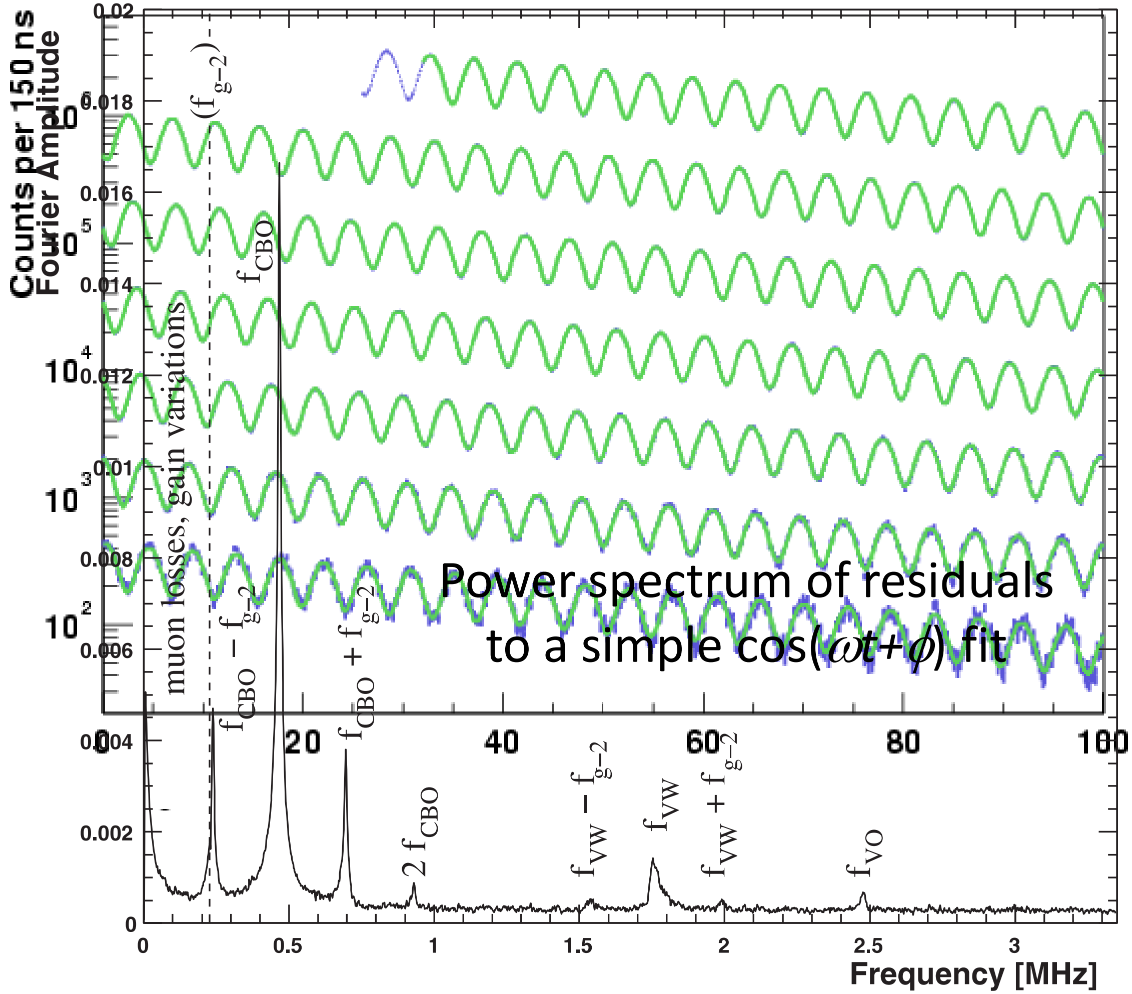
How big of an effect is this?

Can we see this?

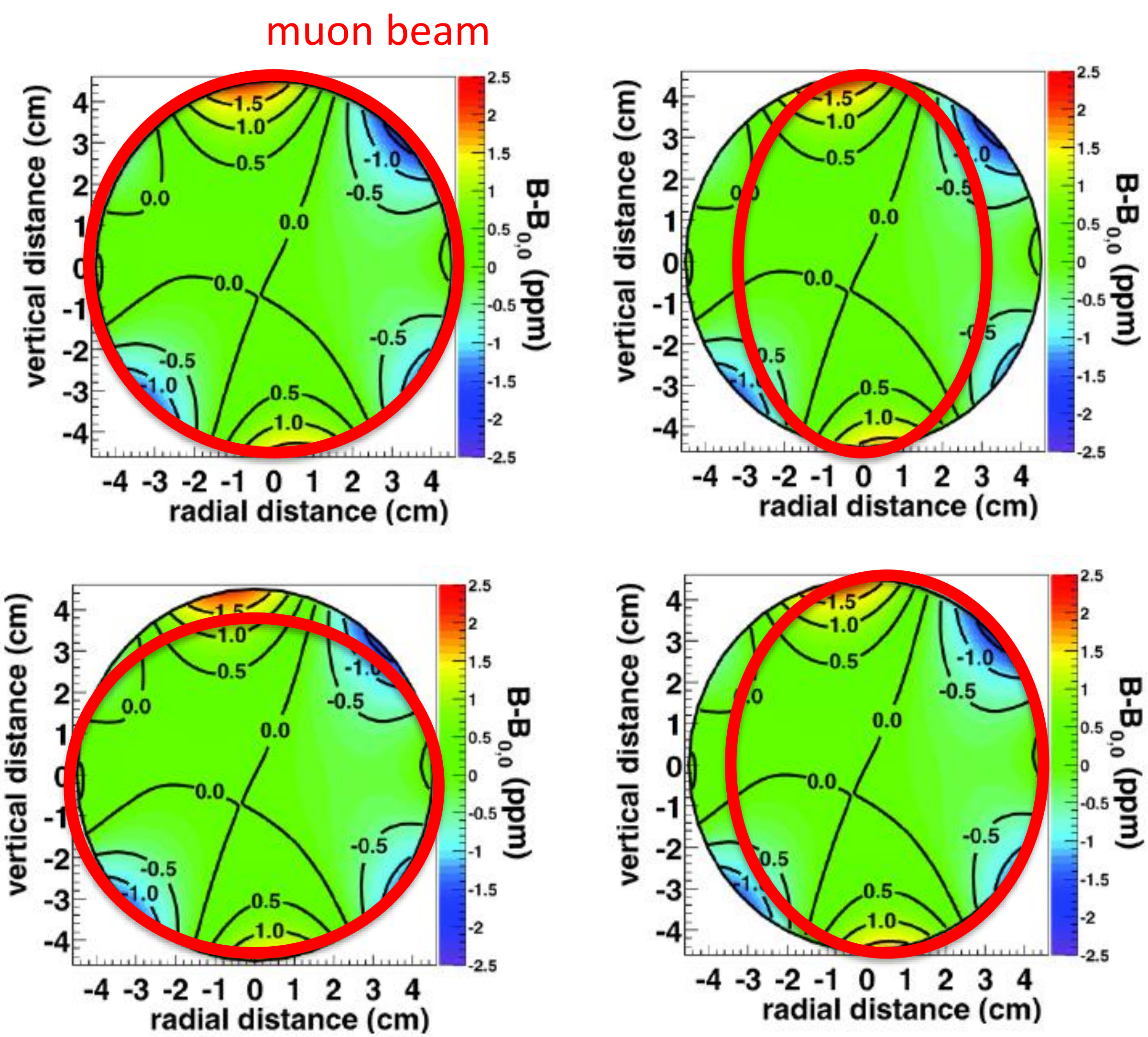
This is the wiggle plot

This is what we see after subtracting the main wiggle

This turns a ~5 parameter fit into a ~25 parameter fit



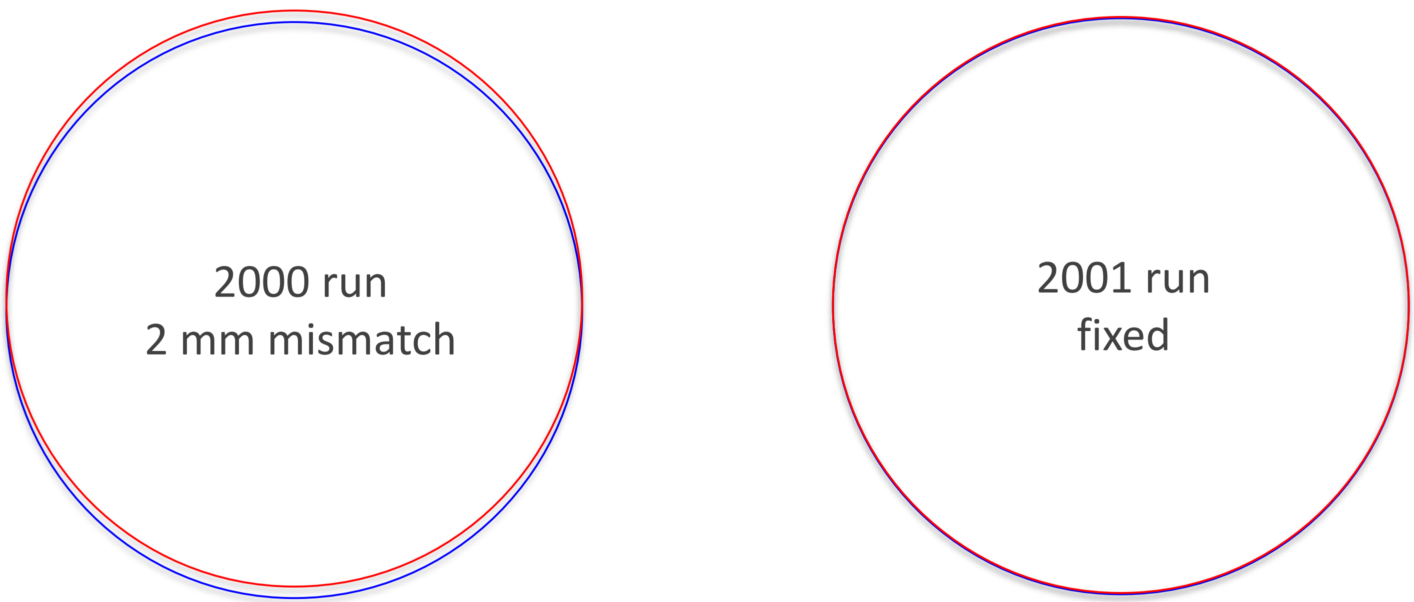
Example II: Which magnetic field?



How big of an effect is this?

Can we see this?

Blue = field   Red = beam



~20 ppb extra error in 2000 from this shift
Remember 70 ppb is total error budget of Fermilab experiment

More complex examples

This is the term we want

These are the terms we are stuck with

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

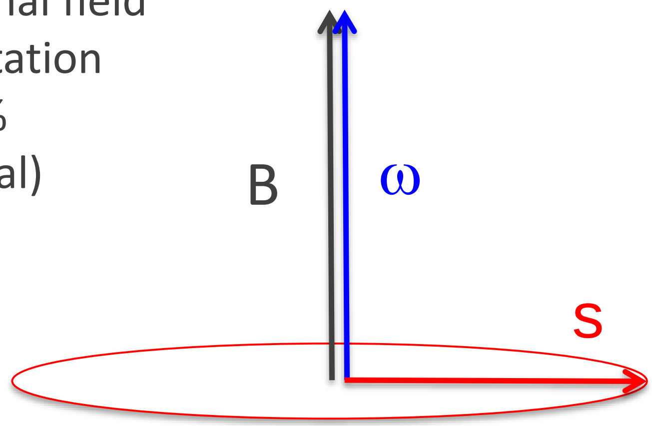
This is the term is non zero due to vertical momentum in the beam
Vertical momentum leads to a vertical distribution in the beam
Correction proportional to $<y^2>$

This is the term is non zero due to momentum spread around the magic momentum
Momentum spread leads to a radial distribution in the beam
Correction proportional to $<x^2>$

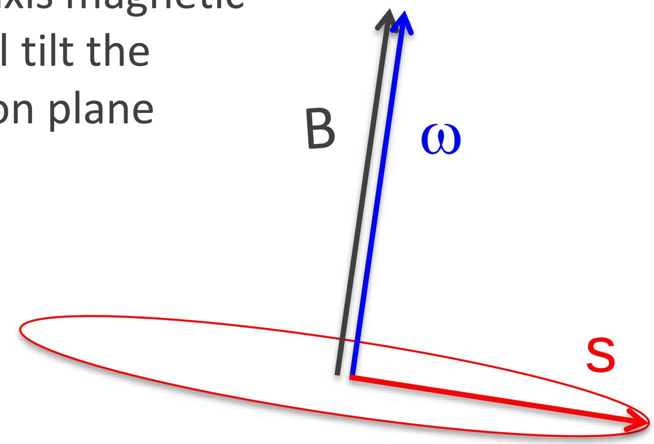
Can we see these?
These corrections add up to close to a ppm. Almost 10 times the systematic errors.

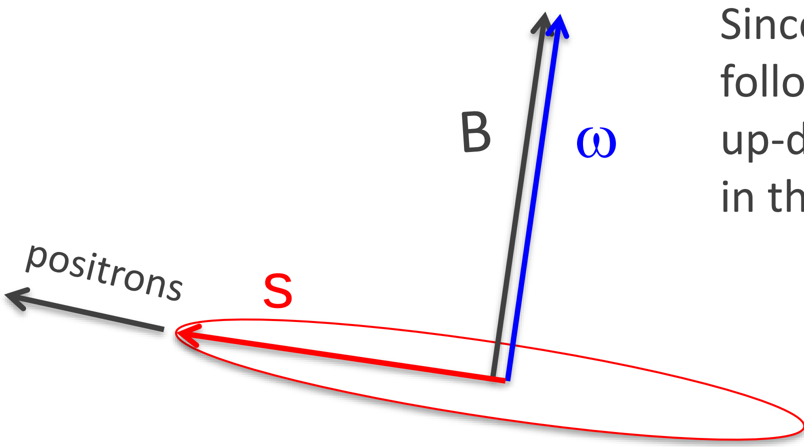
Up-down asymmetries

Nominal field orientation (100% vertical)

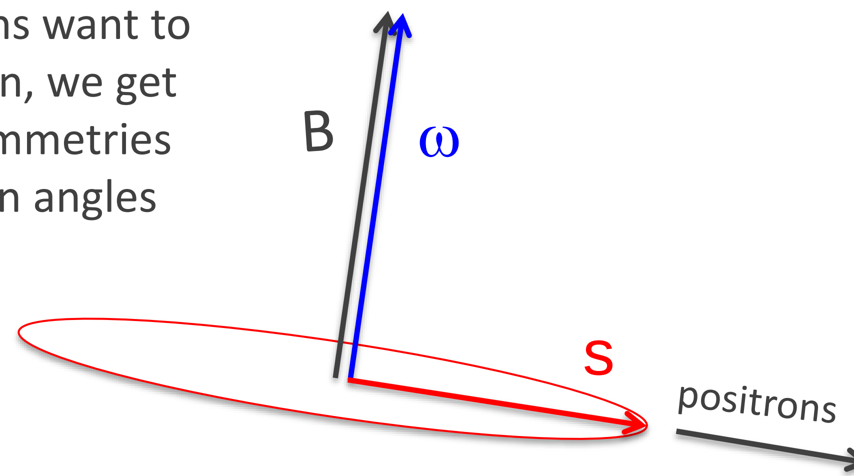


Any off-axis magnetic fields will tilt the precession plane





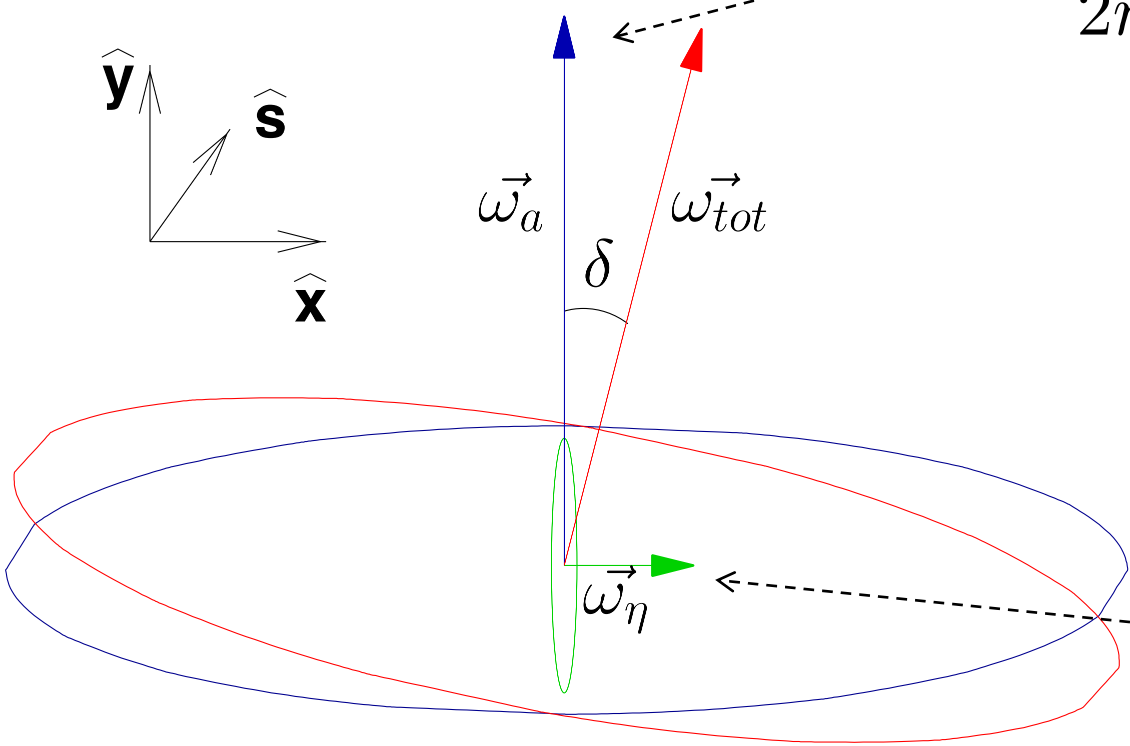
Since positrons want to follow the spin, we get up-down asymmetries in the positron angles



Special case: EDM

No E field in lab frame but muon sees an E field in its rest frame.
EDM will slowly precess around this (will never see this)
But the entire precession plane tilts (can see this)

$$\vec{\omega}_S = g\frac{e\vec{B}}{2m}$$



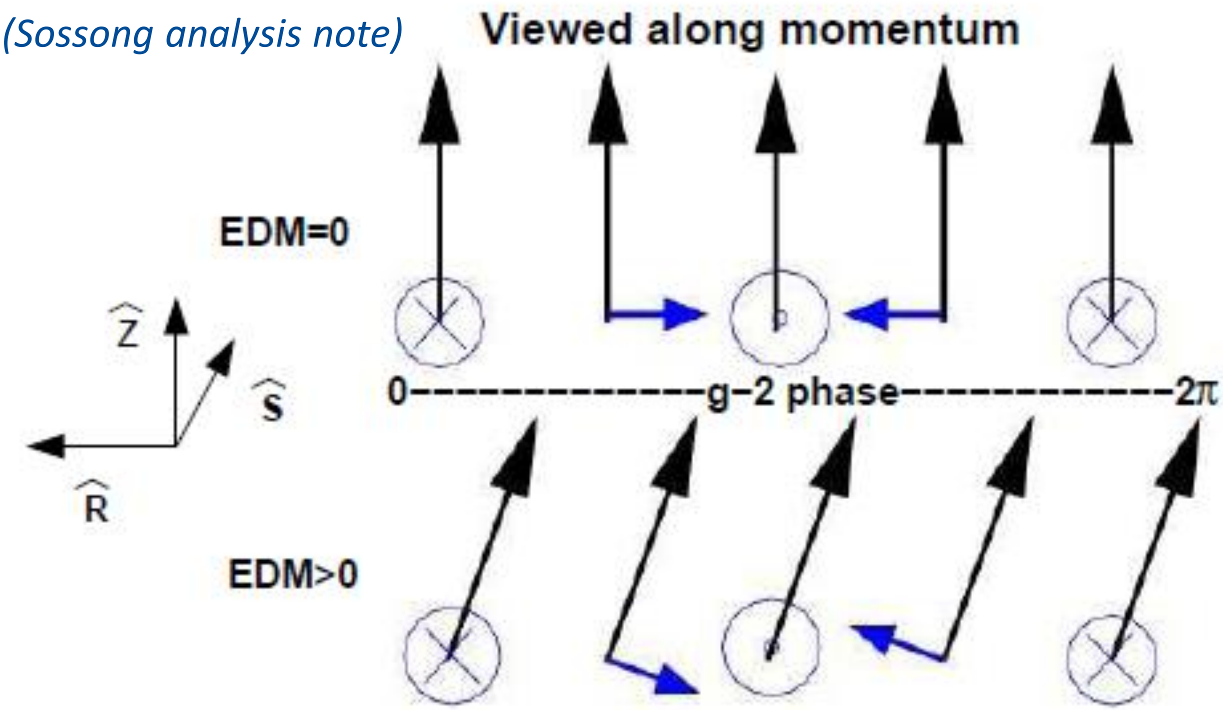
$$\delta = \tan^{-1}(\frac{\eta\beta}{2a})$$

~mrad in rest frame
~μrad in lab frame

$$\vec{\omega}_S = \eta\frac{e\vec{E}}{2mc}$$

EDM Signature

(Sossong analysis note)



When polarization points into the ring, positrons point down

When polarization points out of the ring, positrons point up

Effect:
'North-south' asymmetry in calorimeter position

Positive-negative asymmetry in tracker angle

Both asymmetries are time dependent, have same period as g-2, and are 90 degrees out of phase

This allows us to make a completely independent physics measurement with the experiment

And many more…

- Some of the things I didn't mention
  - Verifying calorimeter pileup algorithms
  - Verifying calorimeter absolute energy scale early-to-late
  - Differential decay systematics
  - Closed orbit effects
  - ……..
- Many things that were small enough to ignore in the Brookhaven experiment are no longer small enough. Goal is to pin these down with tracking.

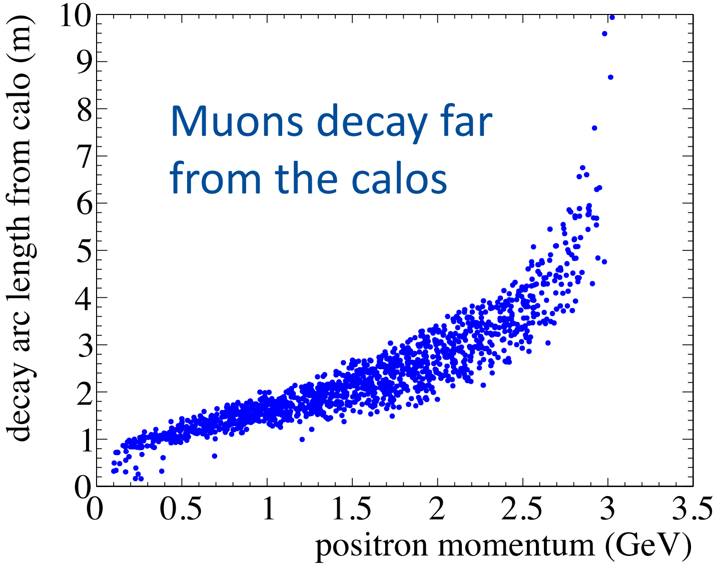
Lets design a tracker

Physics goals

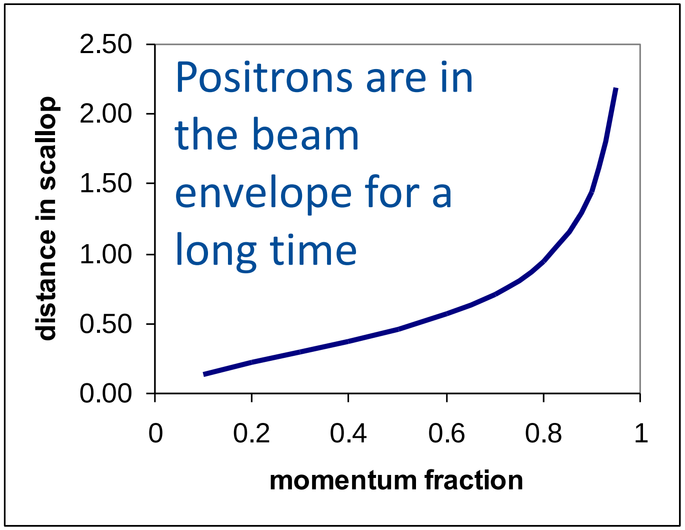
- Measure the beam profile in multiple locations around the ring.
  - Validates our model of beam dynamics needed to
    - Understand calorimeter acceptance changes due to beam breathing
    - Determine ppm level corrections to ω_a due momentum spread and betatron oscillations
    - Determine effective magnetic field map seen by the muons
    - Limit the size or radial and longitudinal magnetic fields

- Make an independent measurement of positron momentum
  - Can be used to validate calorimeter-only methods of determining pileup and gain systematic uncertainties in regions where tracker and calorimeter acceptance overlap

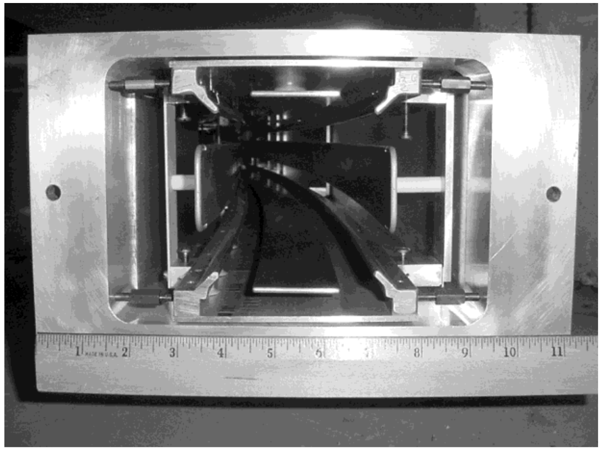
Design drivers



Effects of multiple scattering explode due to long extrapolation



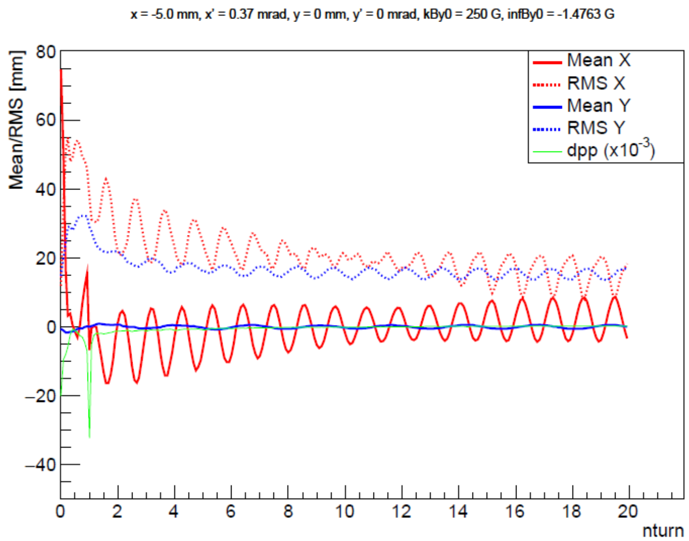
There are only a few places in the ring with a clear line of sight to the beam

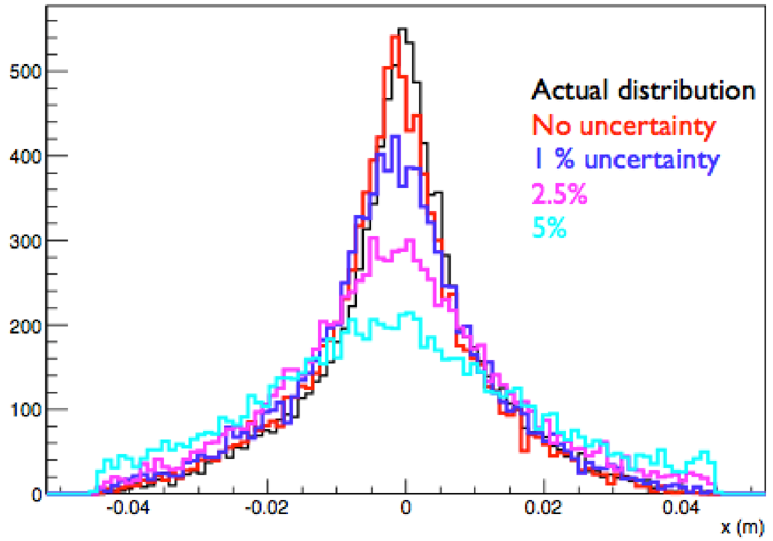


Symmetry of calorimeters very useful for canceling and understanding systematics.
Must be invisible to the calorimeters.

Requirements

- Need to measure beam profile with mm level accuracy
- Large extrapolation back to decay position requires percent level uncertainty on curvature and minimal material
- Requires better than 300 micron uncertainty on individual position measurements





Requirements

Parameter	value	comments
Impact parameter resolution	$\ll 1$ cm	Set by RMS of the beam
Vertical angular resolution	$\ll 10$ mrad	Set by angular spread in the beam
Momentum resolution	$\ll 3.5\%$ at 1 GeV	Set by calorimeter resolution
Vacuum load	5×10^{-5} Torr l/s	assumes 10^{-6} Torr vacuum and E821 pumping speed
Instantaneous rate	10 kHz/cm^2	Extrapolated from E821
Ideal coverage	16×20 cm	Front face of calorimeter
Number of stations	≥ 2	Required to constrain beam parameters
Time independent field perturbation	< 10 ppm	Extrapolation from E821
Transient (< 1 ms) field perturbation	< 0.01 ppm	Invisible to NMR

Technology choice: Si versus gas

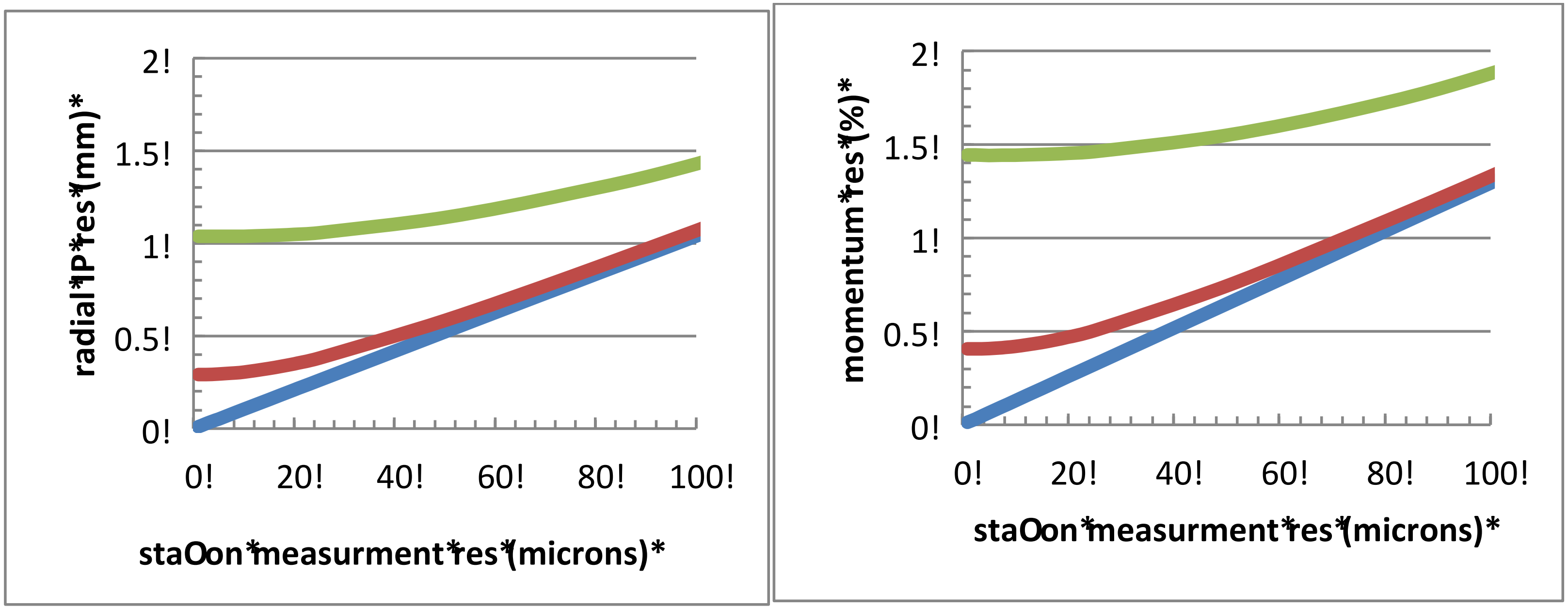


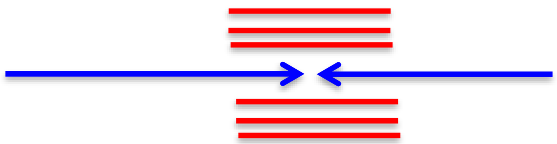
Figure 8: Simulated impact parameter resolution (left) and momentum resolution (right) for a 1.5 GeV positron versus the radial spatial resolution on a hit at a given station assuming a 50 cm lever arm in the tracking volume and a decay point 50 cm before the first tracking station. The blue curve is for a massless detector. The red curve includes multiple scattering from a detector with 0.05% X_0 per station. The green curve includes multiple scattering from a detector with 0.5% X_0 per station.

Answer: both look good for 4 planes

Technology choice: Si versus gas

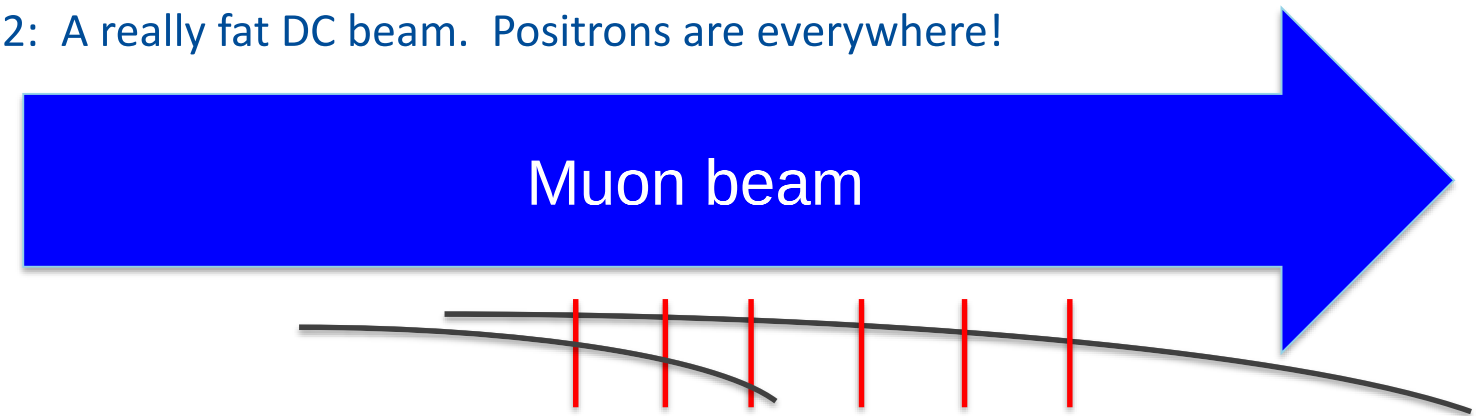
Both are OK for performance. Next question is geometry

Collider:



You know where all the particle come from and you know exactly where to put the detector. Si always wins.

g-2: A really fat DC beam. Positrons are everywhere!



You need several planes and Si material adds up very quickly. So for high acceptance only choice is gas. In a vacuum, only choice is straws.

Tracker team

- Now we know what to build, first step is to build the team

BOSTON UNIVERSITY

UNIVERSITY OF LIVERPOOL

UCL

Fermilab

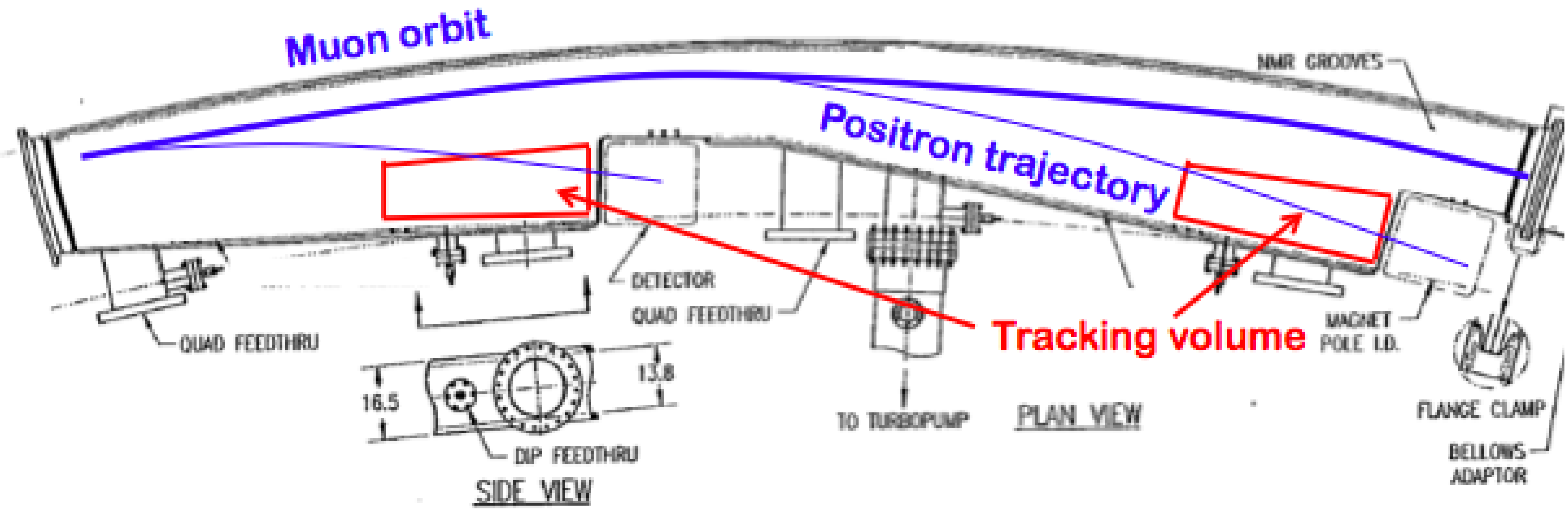
NIU
Northern Illinois University

MANCHESTER 1824
The University of Manchester

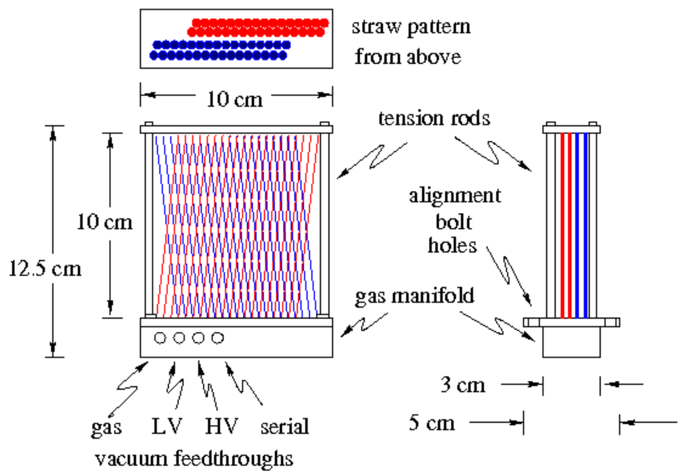
Plus several years of Italian summer students

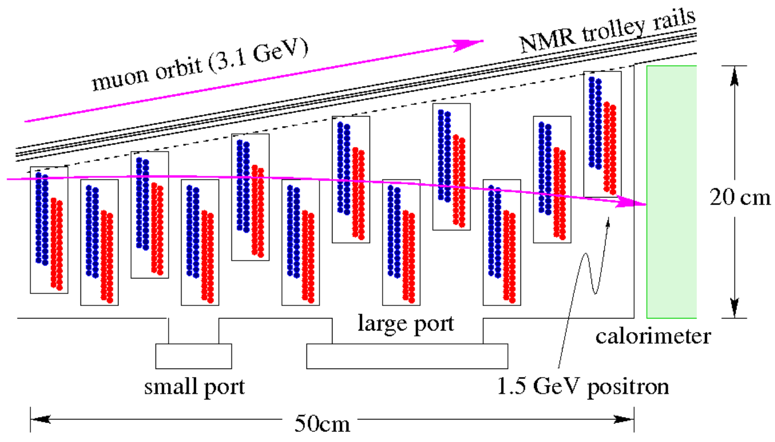
Canvas

- Baseline is straw systems in the vacuum optimized for EDM measurement in front of all calorimeter stations



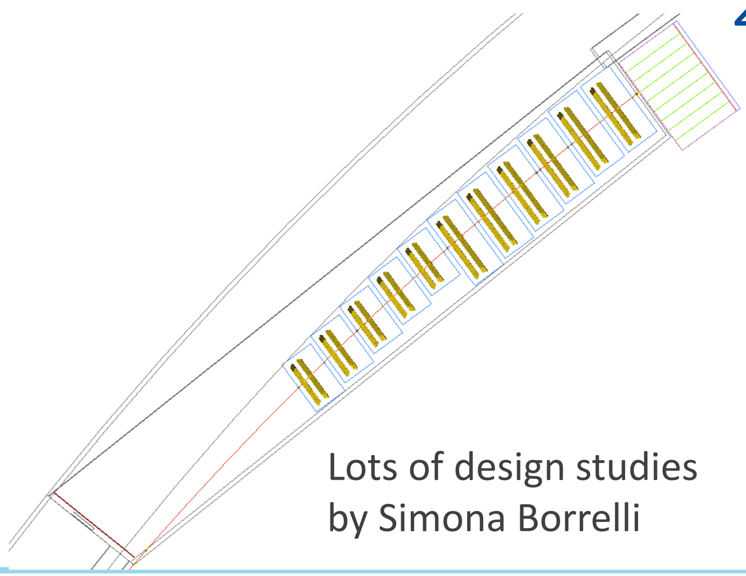
Iterations





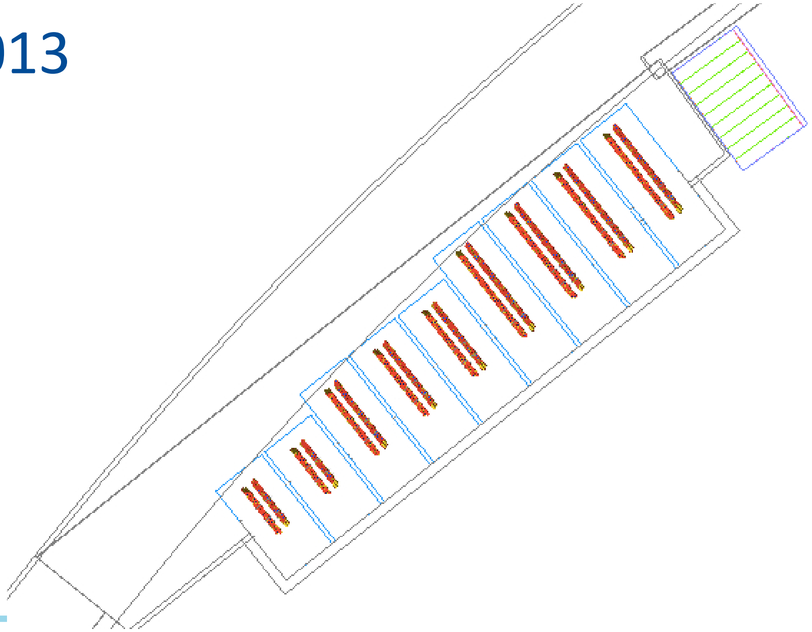
2012

2013

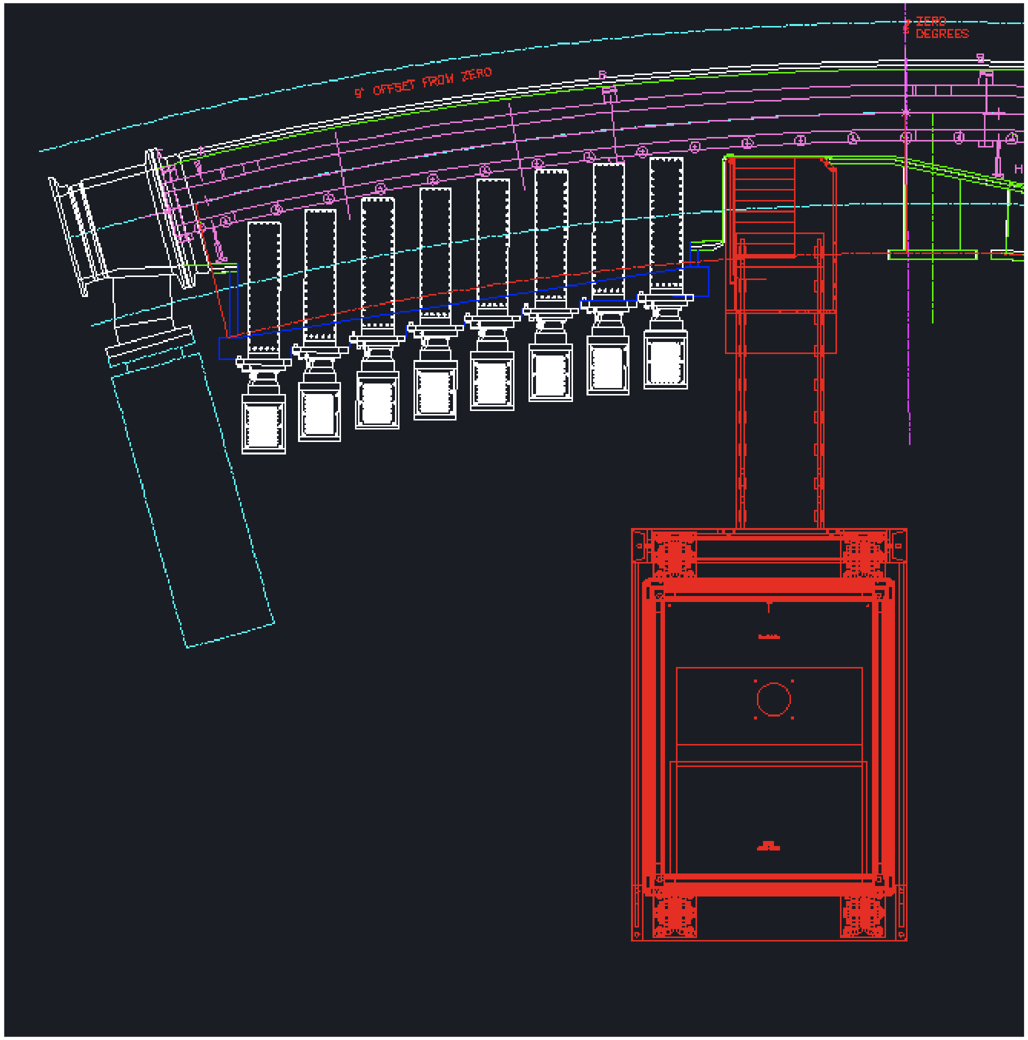


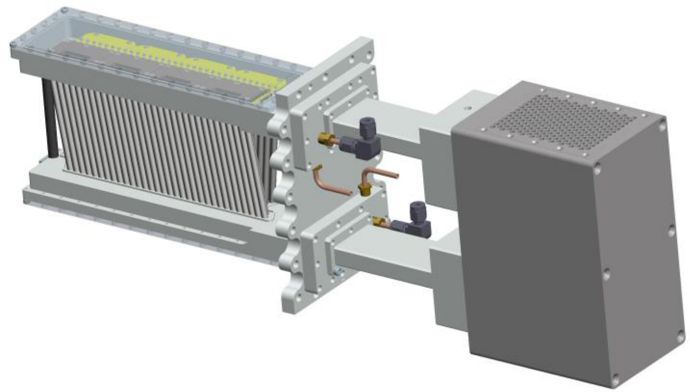
Lots of design studies
by Simona Borrelli

2014



Final iteration 2015





Lots of help on drafting from Dario Lusso

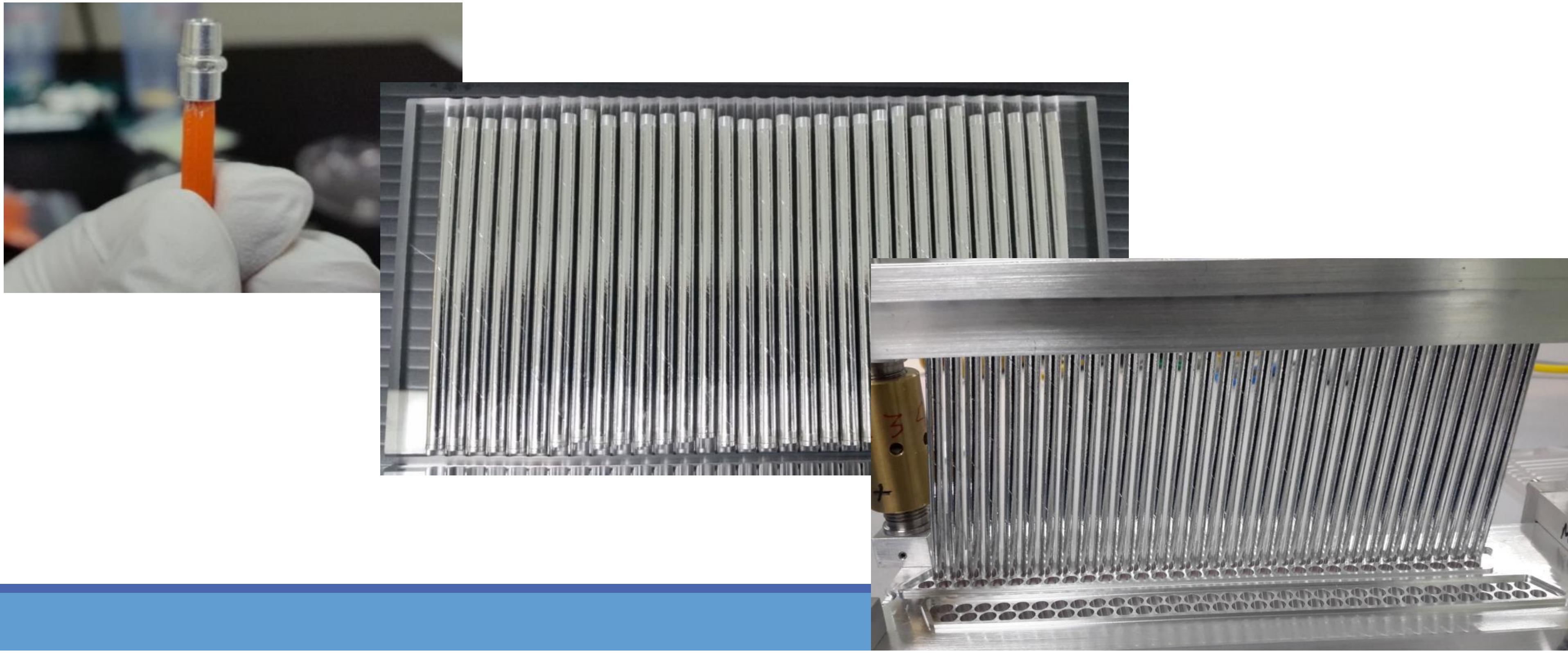
Lets start building

Straw production

Slides from Kayleigh Thomson

UNIVERSITY OF LIVERPOOL

Straws cut to 90.6mm lengths and aluminium ends bonded to straws using silver epoxy, every straw resistance tested

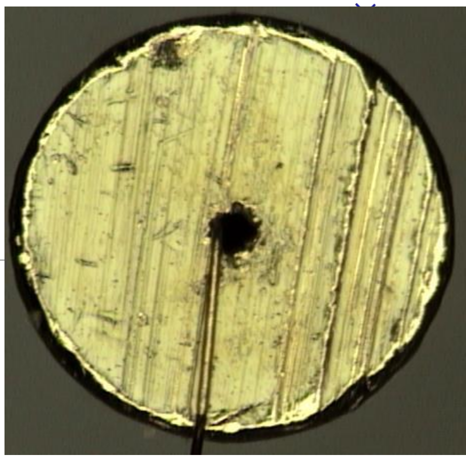


Stringing

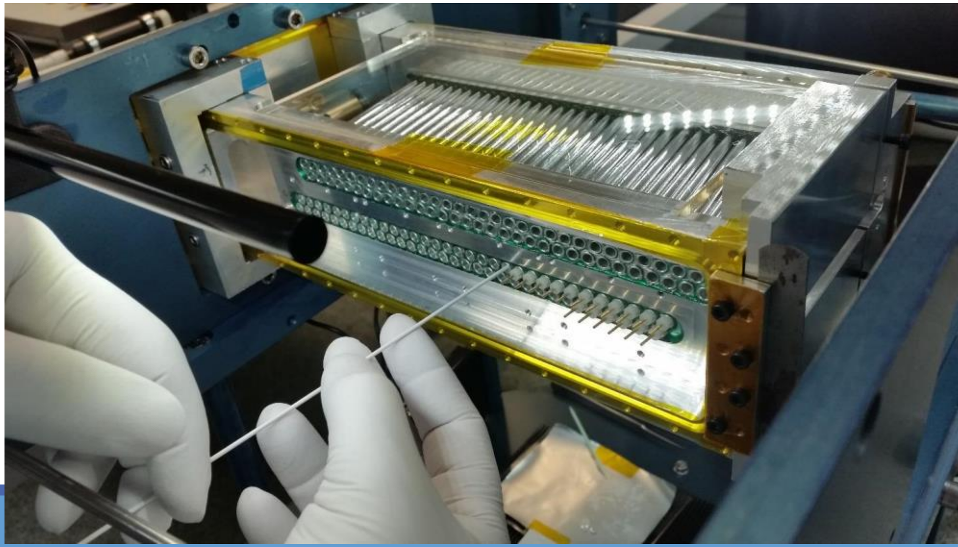
Slides from Kayleigh Thomson

UNIVERSITY OF LIVERPOOL

Module stringing

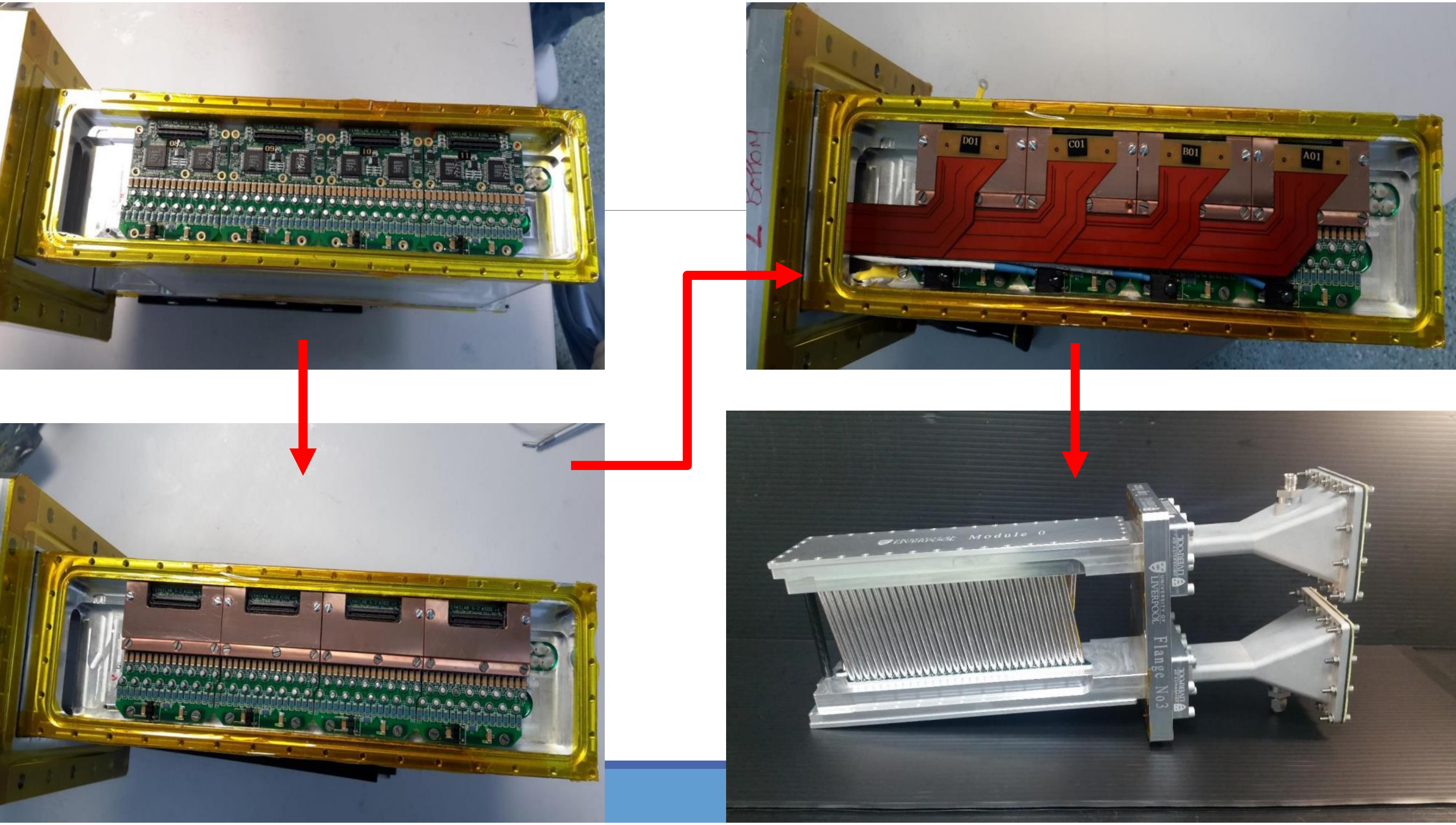


- Long readout pins threaded with 25µm wire and crimped on materials tester
- Wire threaded through module straw and short annealed pin on opposite side
- Wire pre-tensioned to 30 grams
- Short pin hand-crimped
- Module jacked apart by 70µm to create 50 gram tension in wires



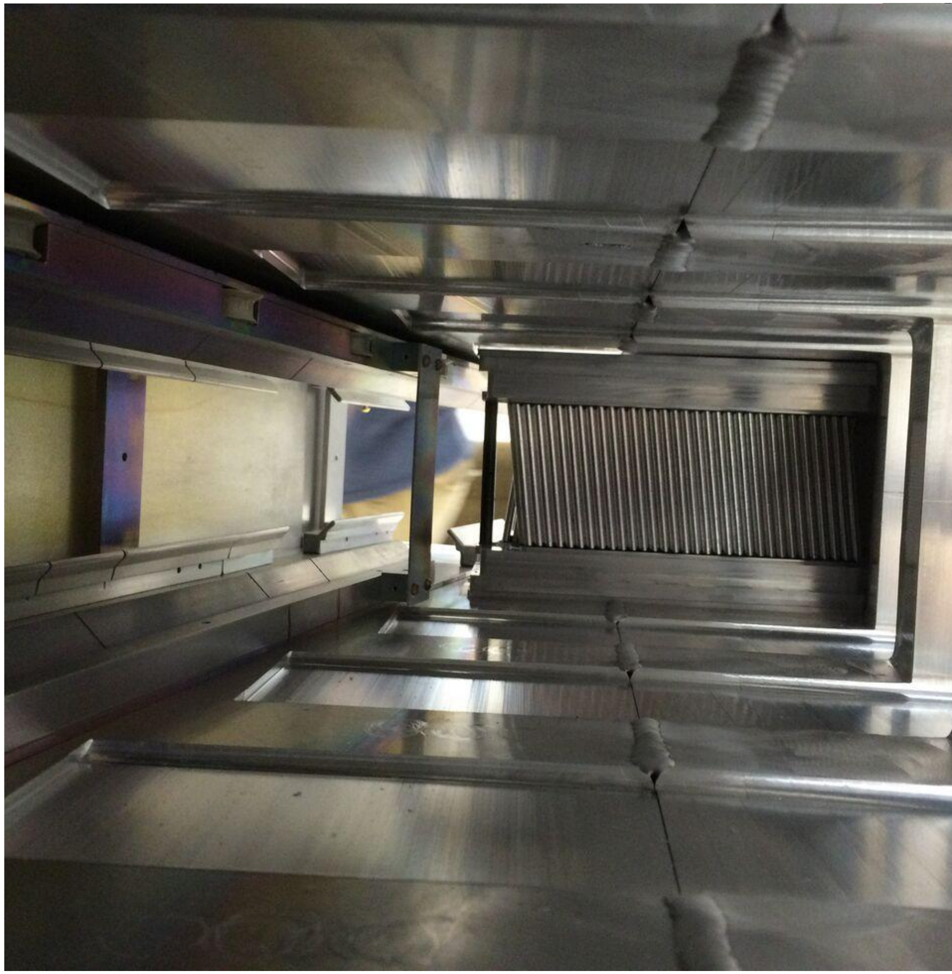
Inserting the electronics

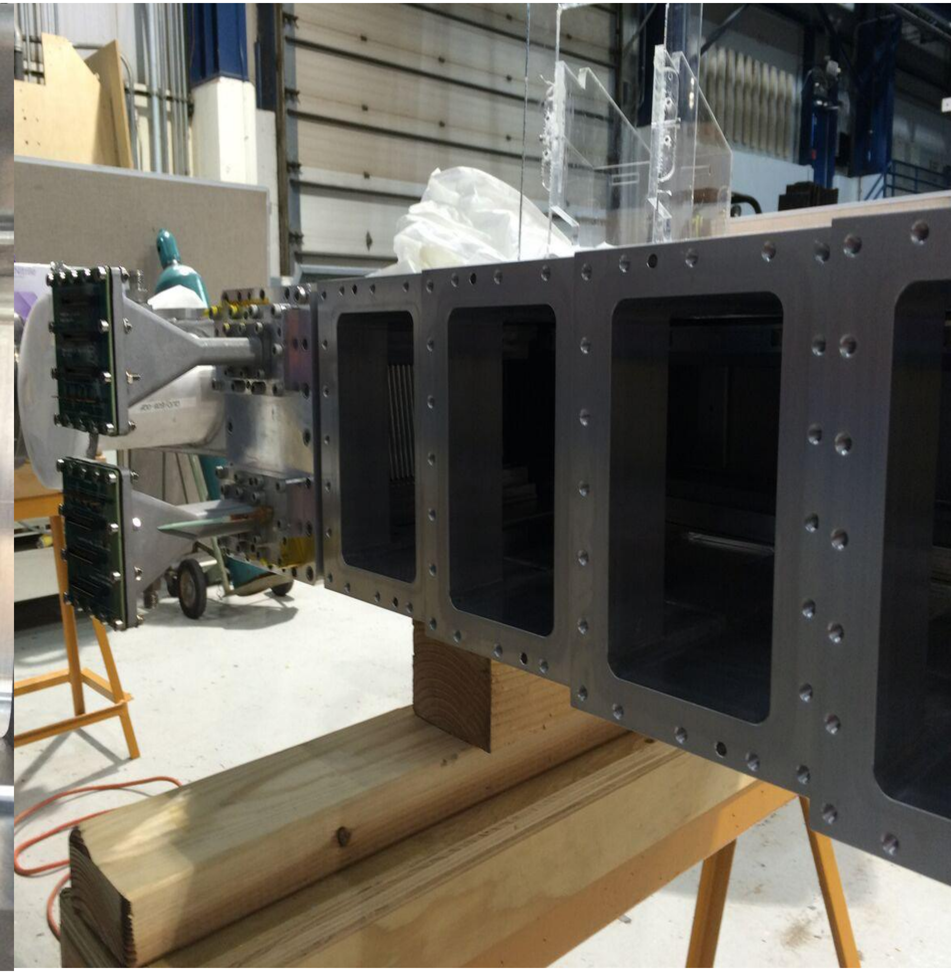
Slides from Kayleigh Thomson



Inserting the modules

Slide from Mark Lancaster

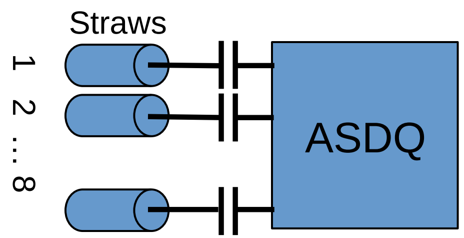


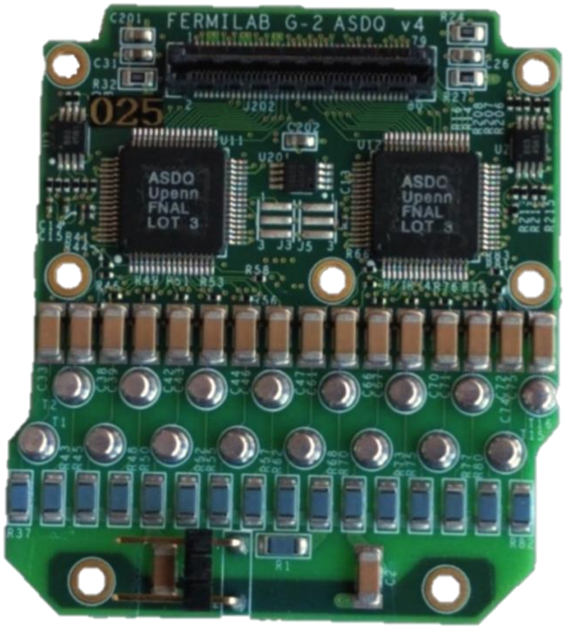


Slides from James Mott

Frontend Electronics: Single Layer (64 straws)

8 ASDQs (in 4 boards):
- Shaping/discrimination
- Digital output





ASDQ

Electronics

Slides from James Mott

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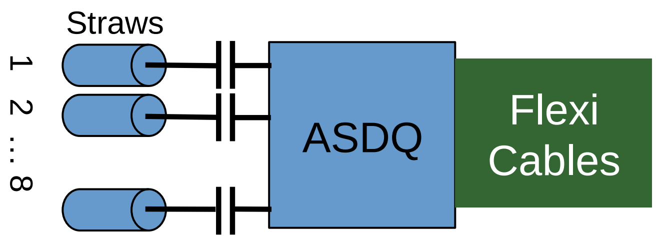

4 Flexicables:
- Power & signals to/from ASDQs

Flexicables

Electronics

Slides from James Mott

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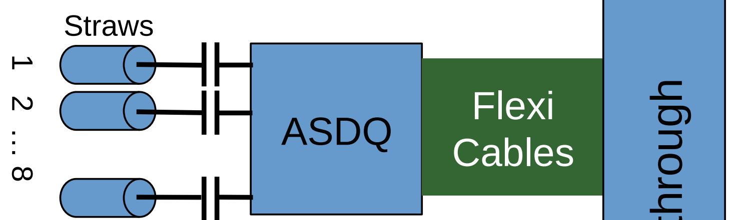
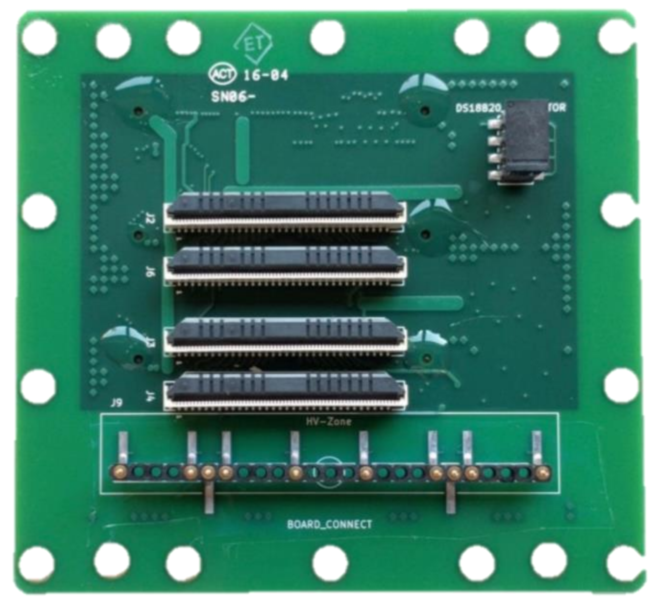
- Shaping/discrimination
- Digital output



4 Flexicables:
- Power & signals to/from ASDQs

1 Feedthrough board:
- Backplane for all boards
- Gas seal

Feedthru



Electronics

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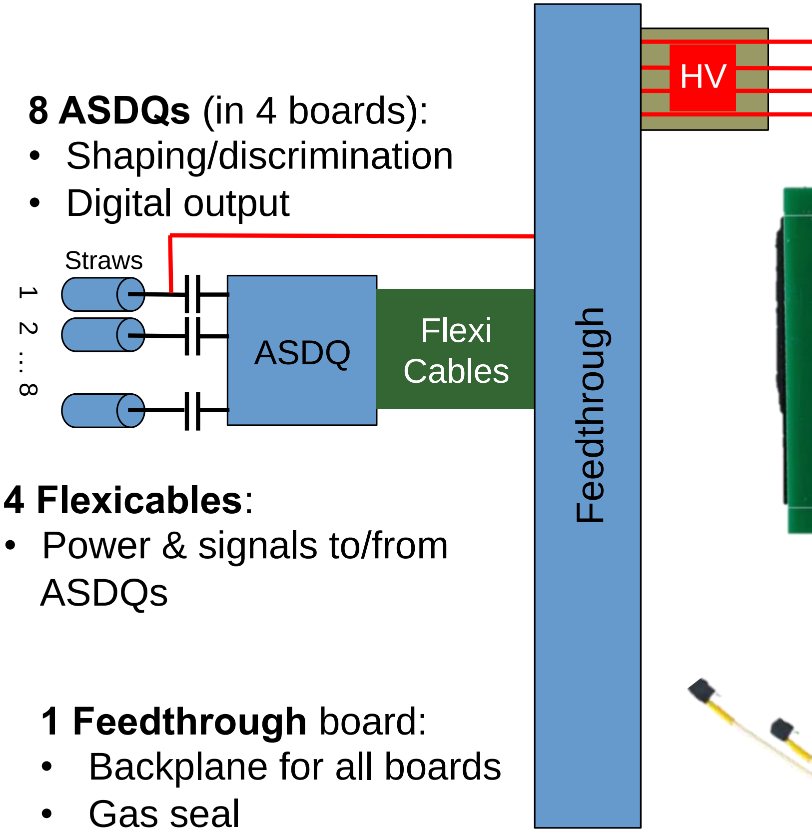
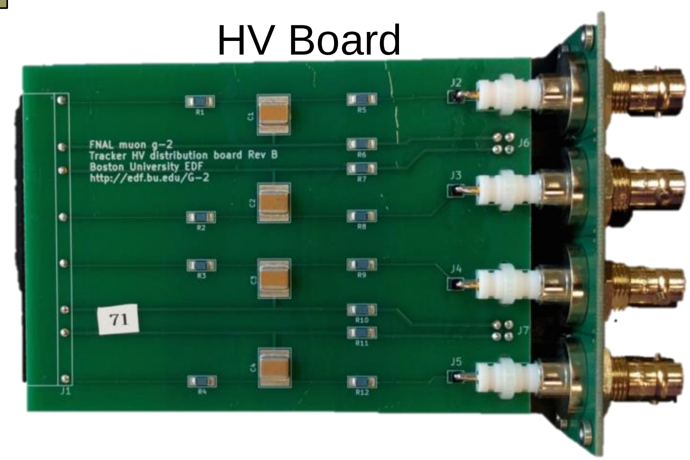


1 HV Board (1 ch. per ASDQ board)

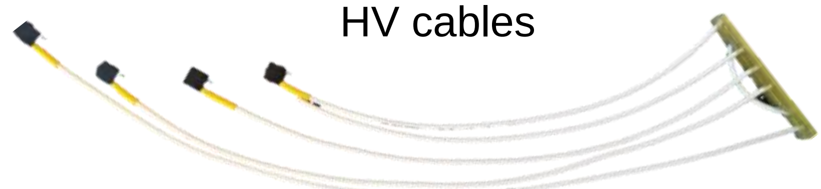
HV Board



4 Flexicables:
- Power & signals to/from ASDQs

1 Feedthrough board:
- Backplane for all boards
- Gas seal

HV cables



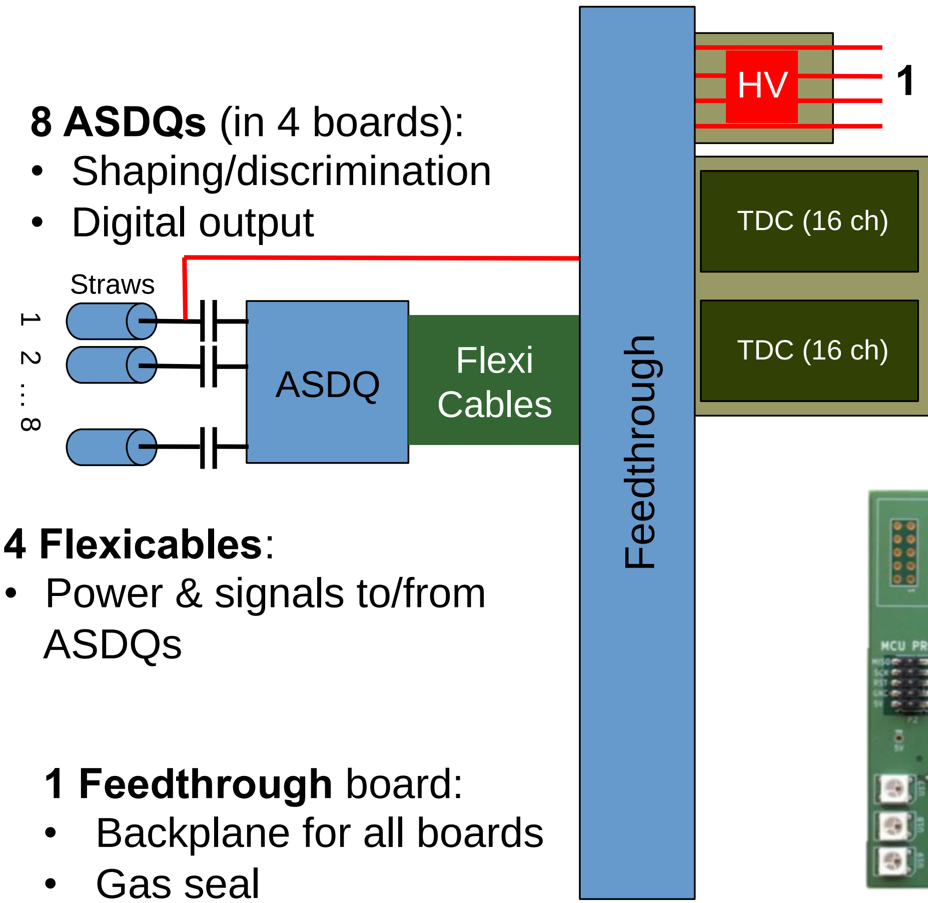
5

Electronics

Slides from James Mott

Frontend Electronics: Single Layer (64 straws)

8 ASDQs (in 4 boards):
- Shaping/discrimination
- Digital output



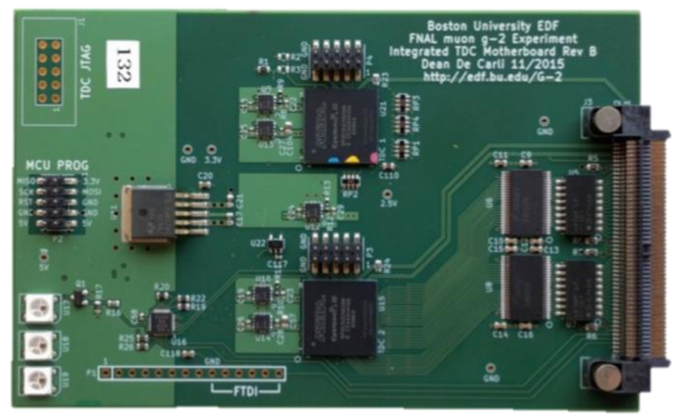
1 HV Board (1 ch. per ASDQ board)

2 TDC Boards:
- Signals from ASDQs timed

4 Flexicables:
- Power & signals to/from ASDQs

1 Feedthrough board:
- Backplane for all boards
- Gas seal

TDC Board

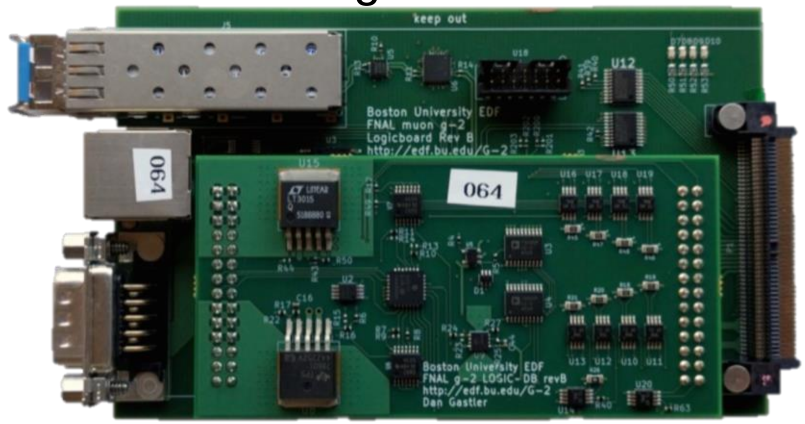


Electronics

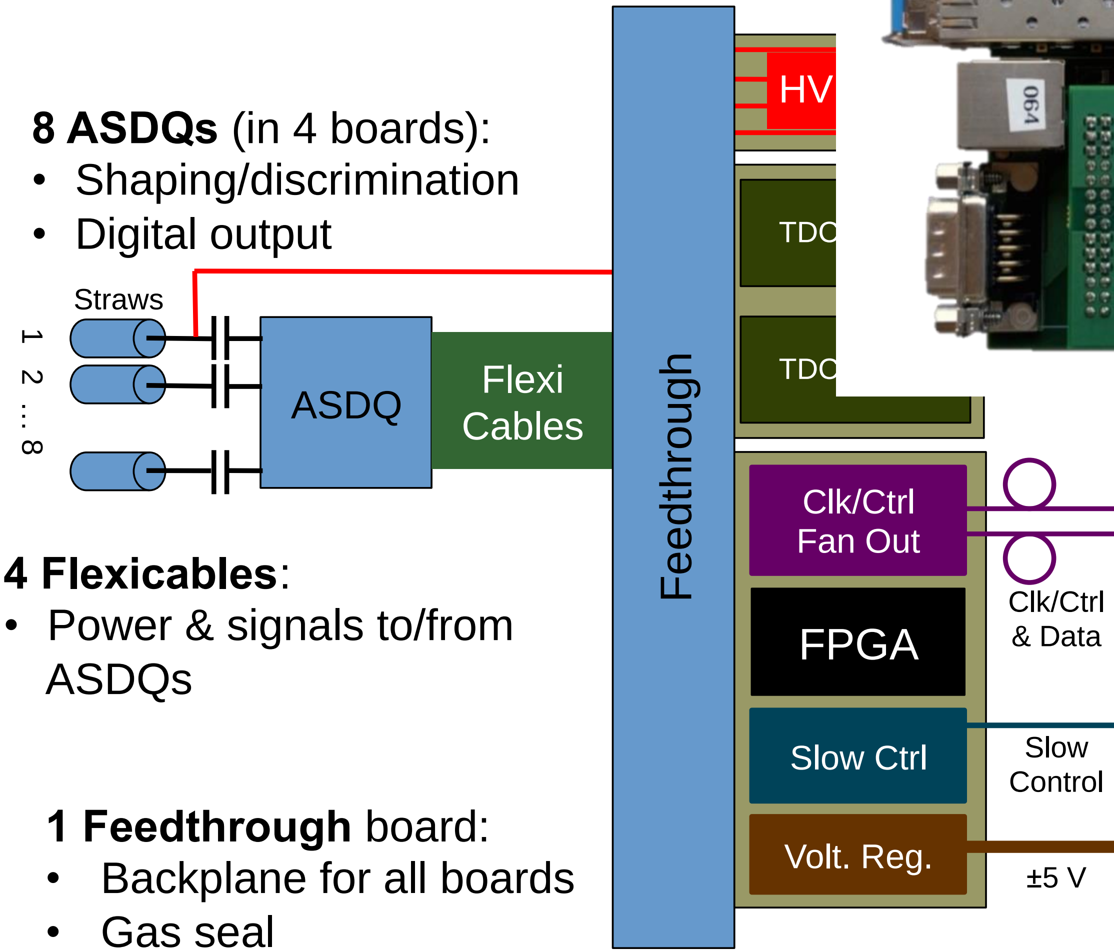
Slides from James Mott

Frontend Electronics:

Logic Board



8 ASDQs (in 4 boards):
- Shaping/discrimination
- Digital output



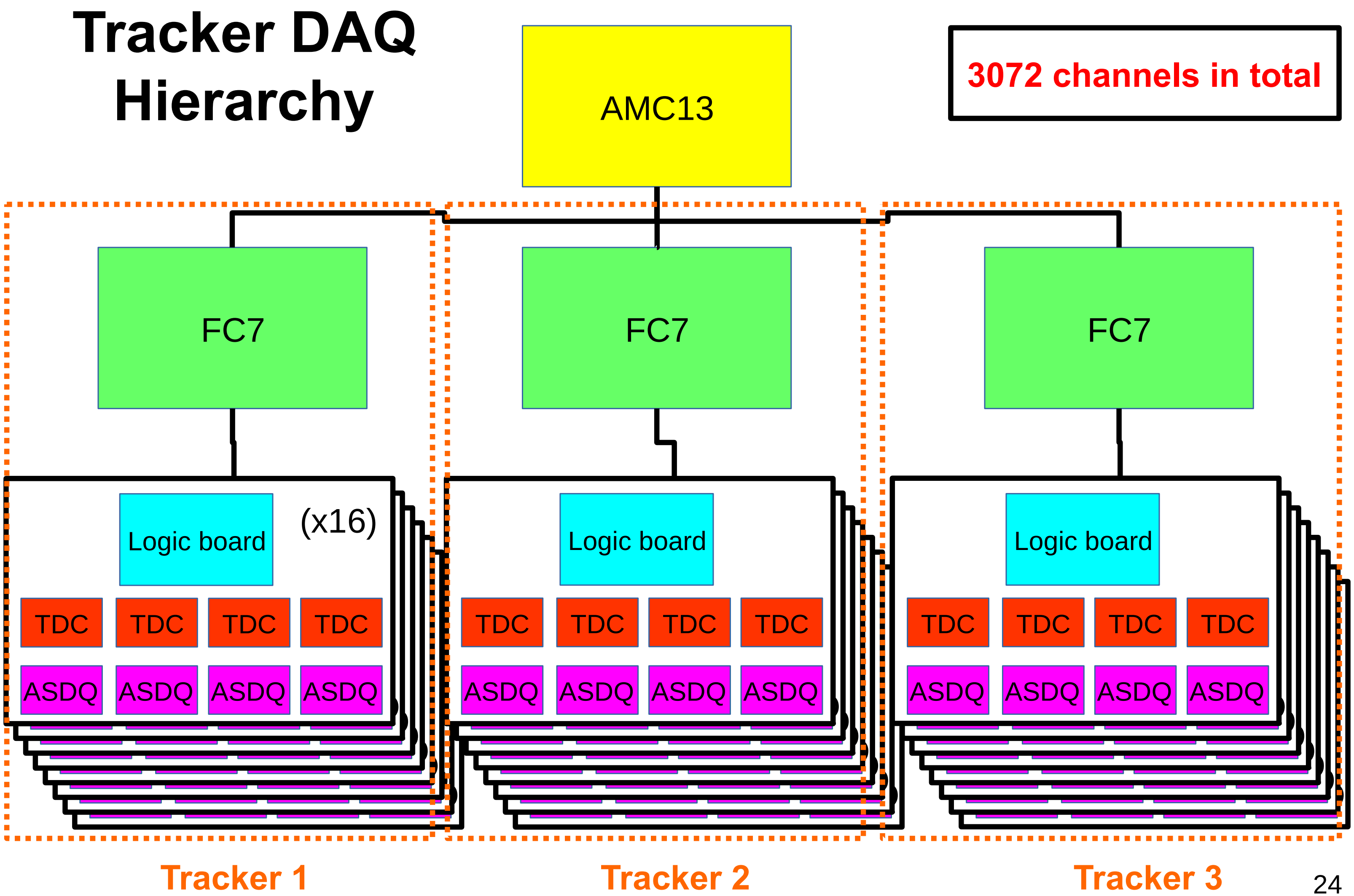
4 Flexicables:
- Power & signals to/from ASDQs

1 Feedthrough board:
- Backplane for all boards
- Gas seal

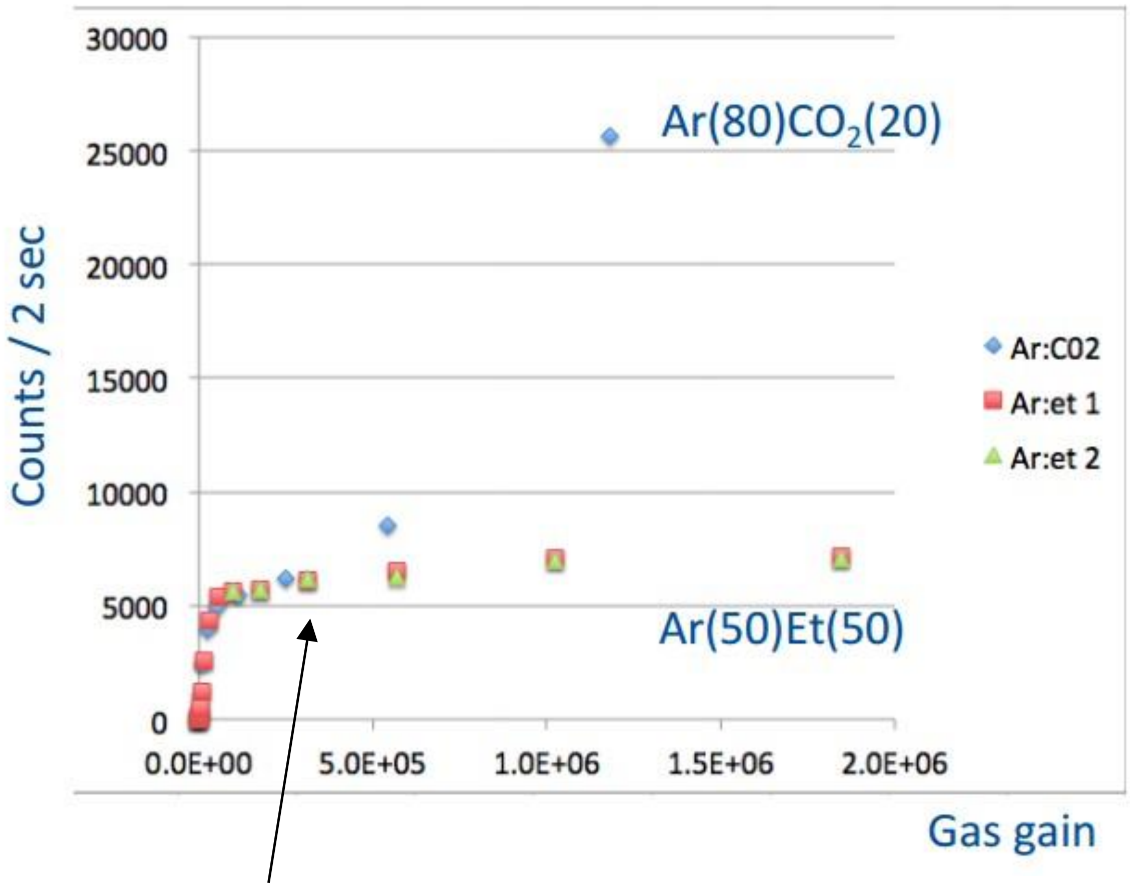
1 Logic board:
- Interface to outside world
- Takes clock, control & power
- Buffers & sends data from TDCs

DAQ

Slides from Tom Stuttard



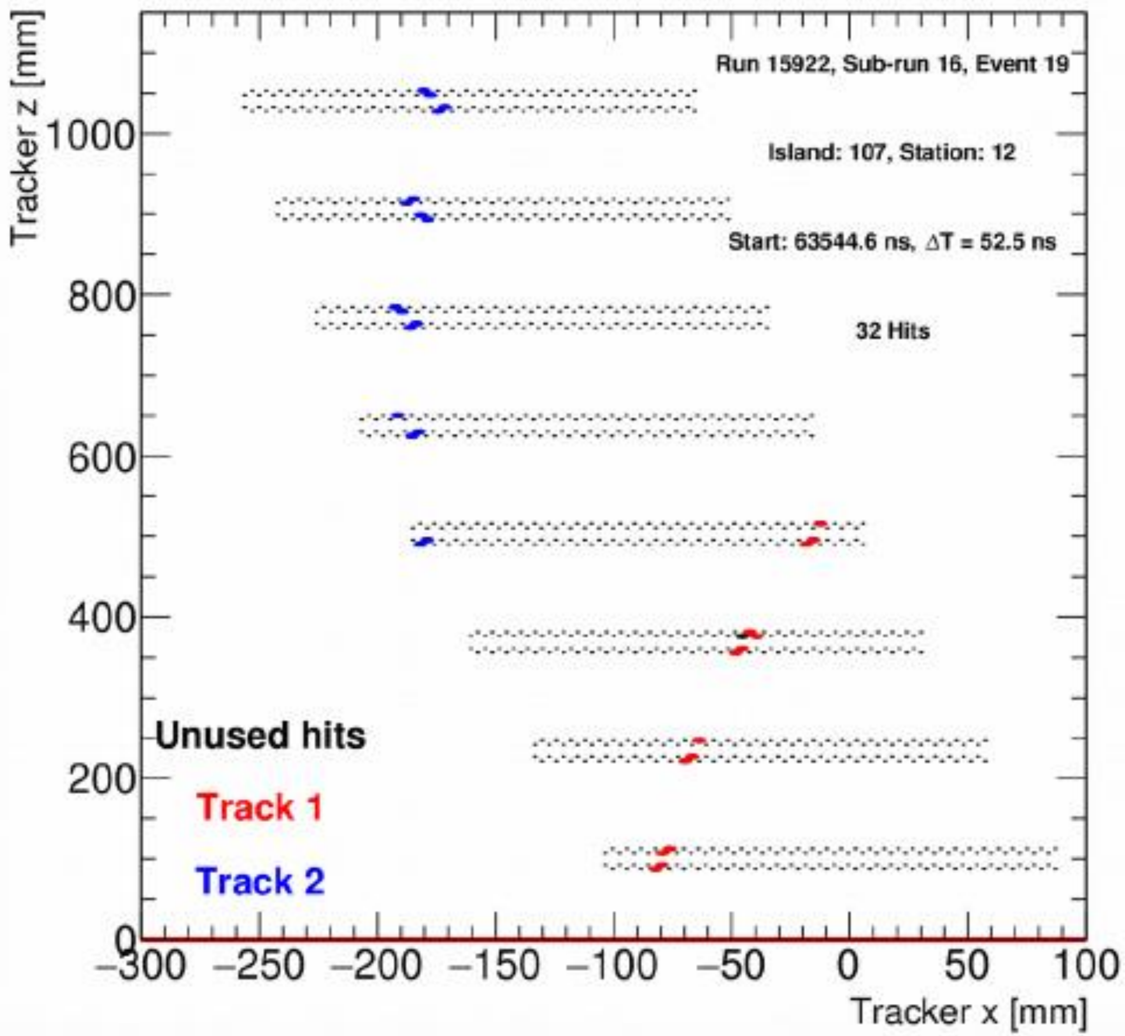
Performance with prototypes: It works!



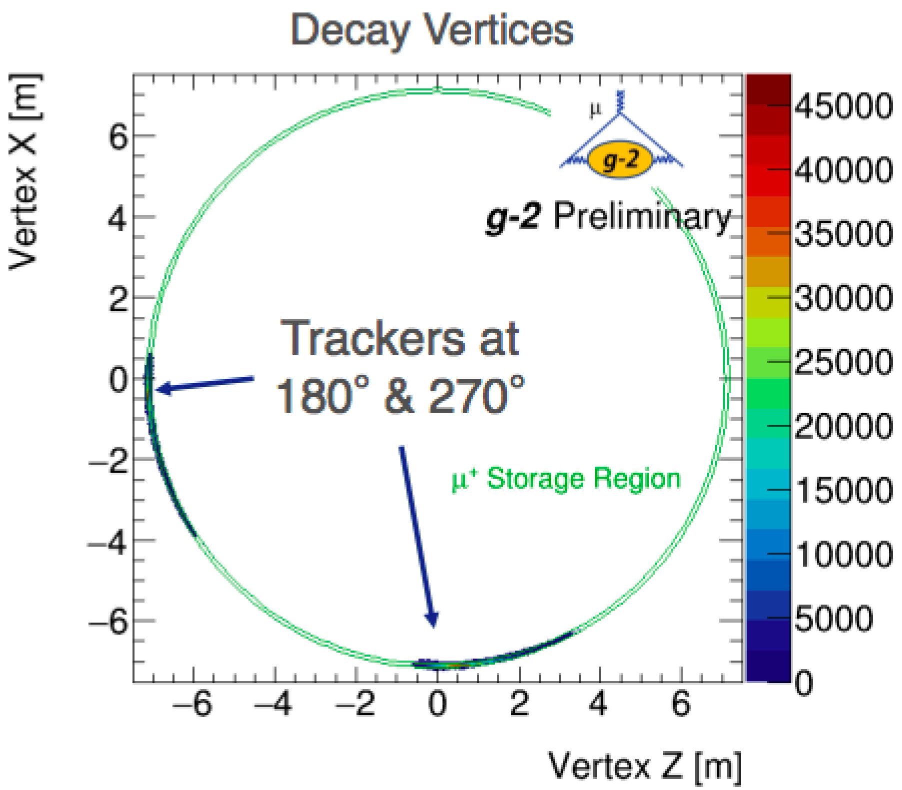
Data taken by Eleonora Rossi from 2015 summer student program

These are based on prototypes. Verified the performance of the production modules this summer by Alessia Renardi and Marco Di Bella from the 2016 program

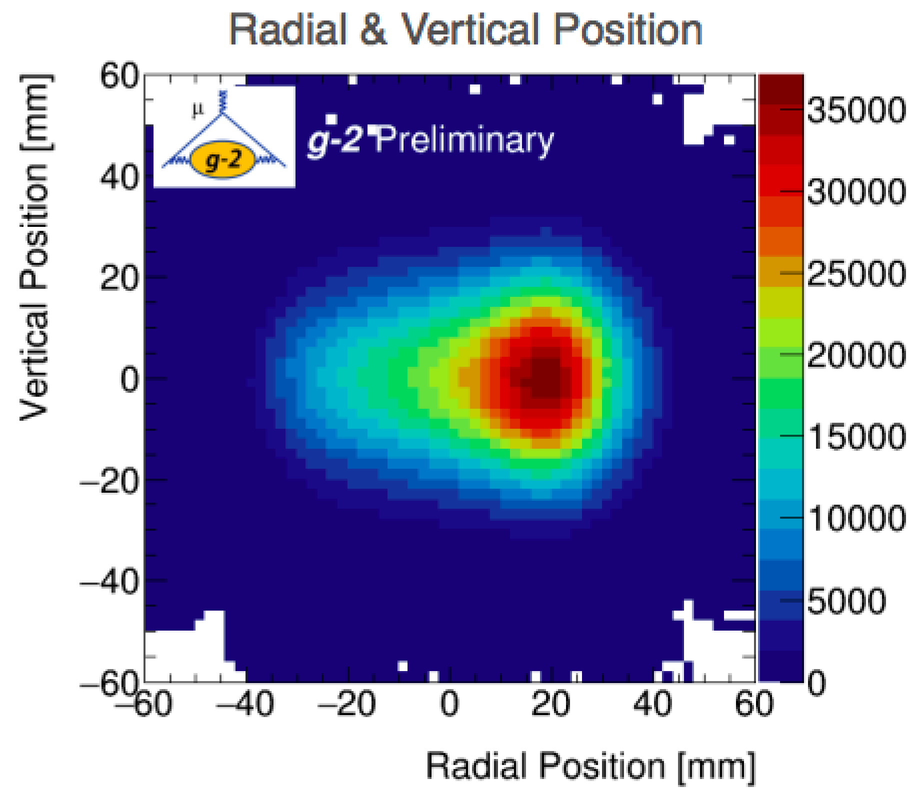
Performance in data: It works!



Measuring the beam position

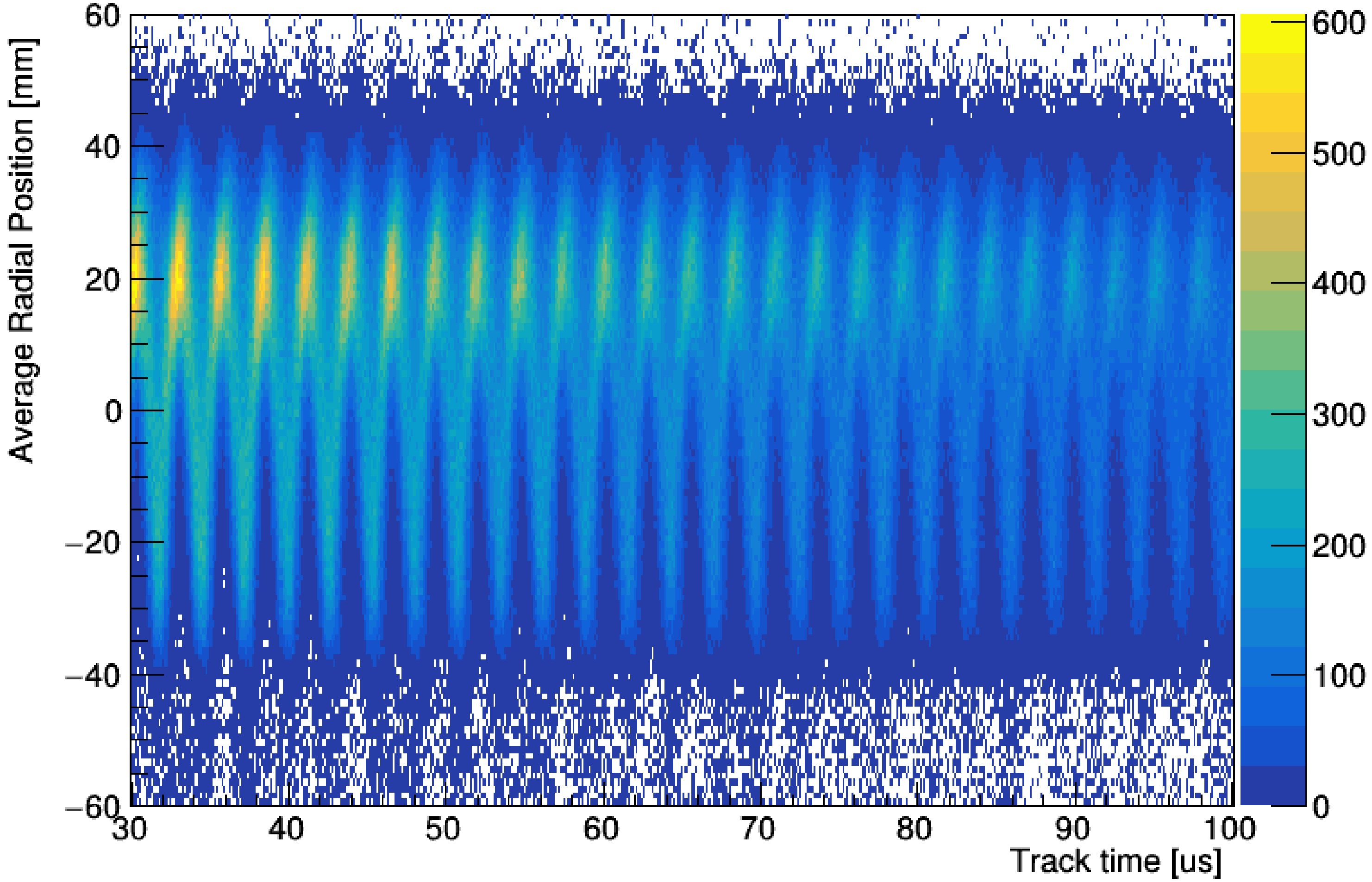


Top-down view of decay vertices

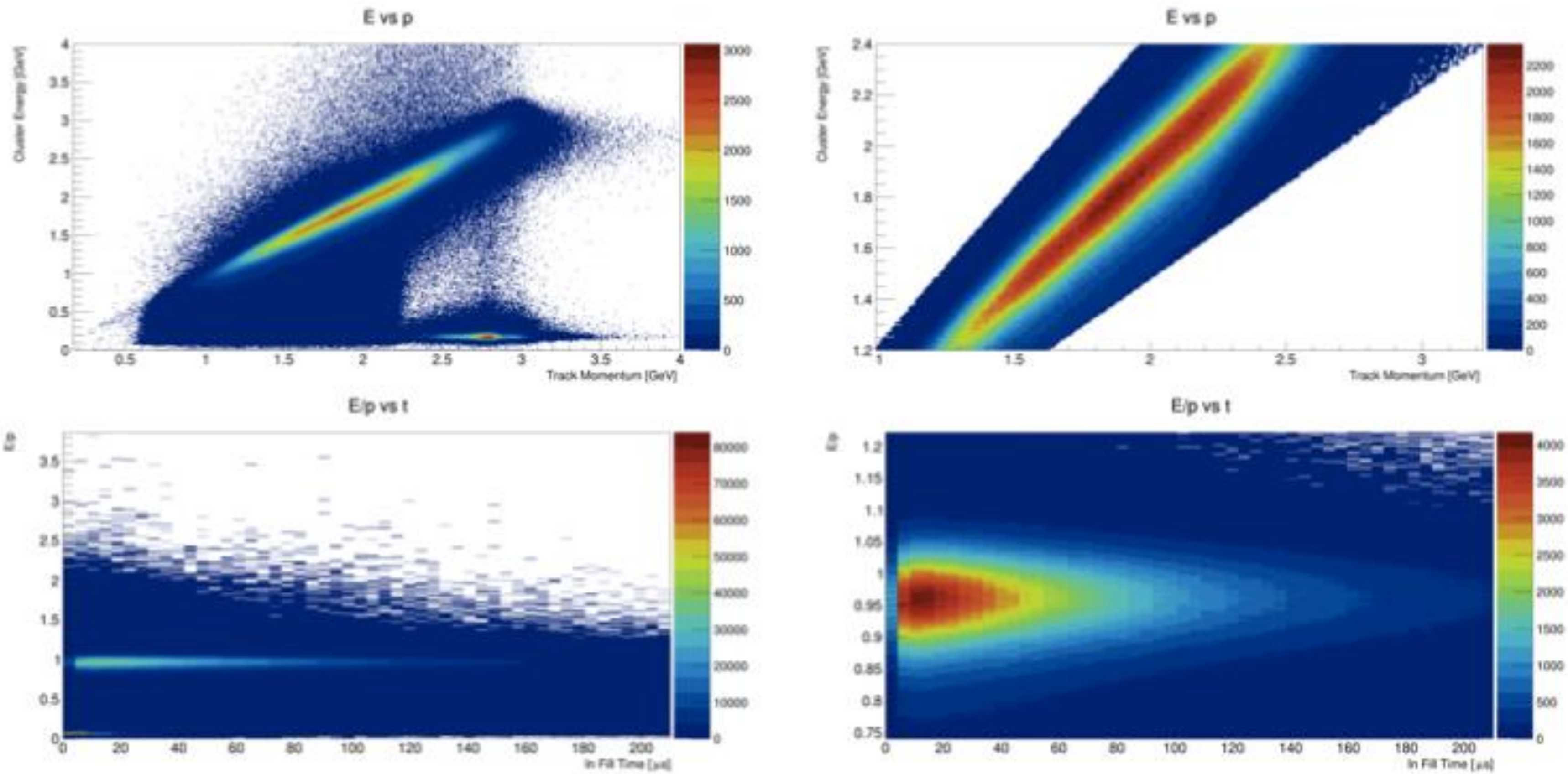


Projection of beam onto radial slice

Measuring the beam motion



Matching to the calorimeters



Conclusions

- The trackers work!
- We got a lot of help along the way from Italian summer students
- We still have a lot of software work to maximize the information we can extract from the beam but the info we are already getting is making a huge difference in understanding the experiment