Evaluation of absolute scale calibration method for MUonE

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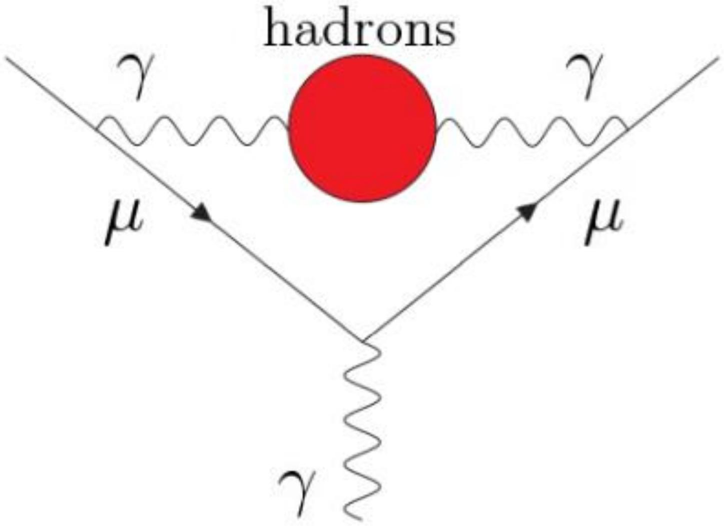
Overview

- Introduction to muon *g-2*
- Summary of MUonE Experiment
- Absolute Scale Calibration Method
- Procedure
- Analysis
- Conclusion

Muon *g-2*

- Famous problem with the Standard Model
- Experimental value of gyromagnetic factor (*g*) of muon significantly deviated from theoretical value computed using QED
- Deviation was significant enough (4.2σ) to suggest BSM physics!
- However, at such high levels of precision, QED becomes an incomplete description
- Need to account not just for virtual leptons, but virtual hadrons as well, necessitating QCD calculations
- Very difficult to perform theoretical calculation with the addition of hadron loops…



The MUonE Experiment

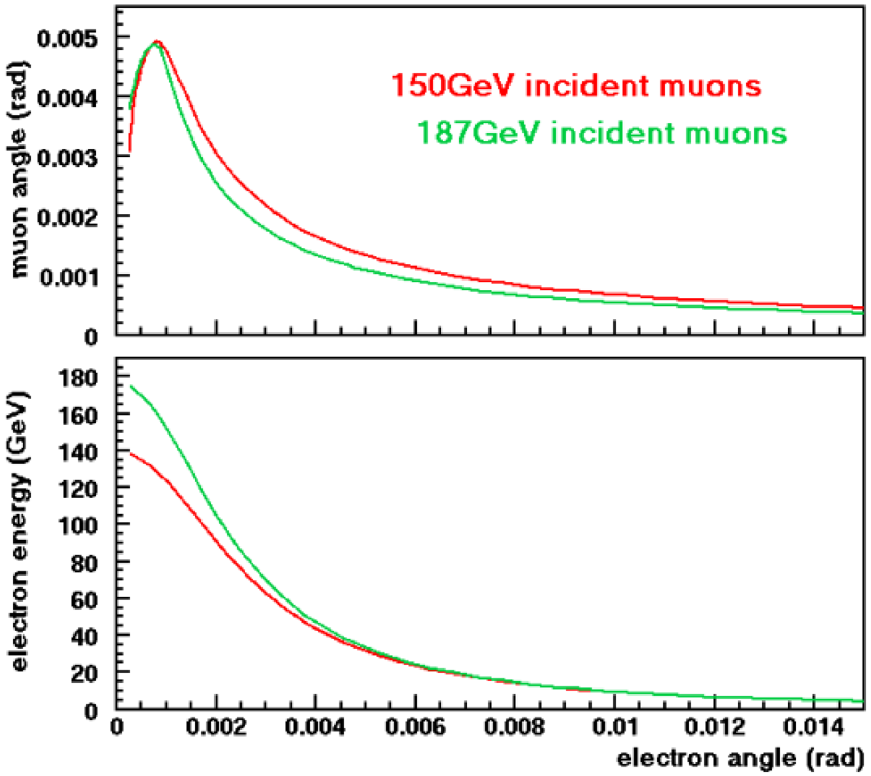
- New experiment to determine *g-2* to unprecedented precision by computing the leading order hadronic contribution which is very difficult to compute from theory alone
- Aims to do so by measuring running coupling constant α(t) to high precision
- Allows one to compute the hadronic contribution using a dispersion integral

$$\alpha(t) = \frac{\alpha_0}{1 - (\Delta\alpha_{\mathrm{lep}}(t) + \Delta\alpha_{\mathrm{had}}(t))}$$

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{\mathrm{had}}[t(x)]$$

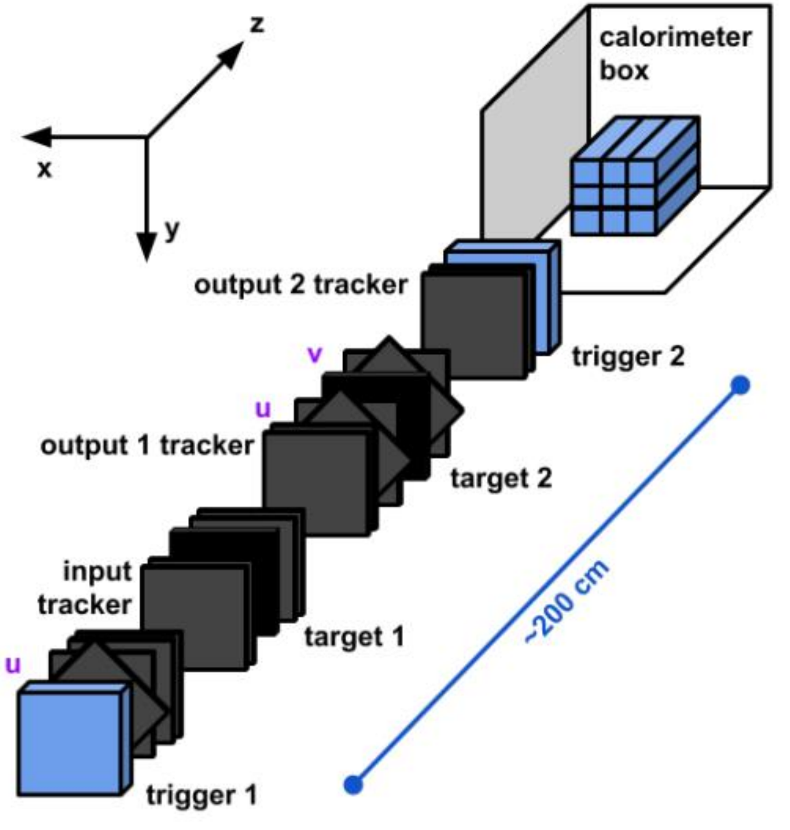
The MUonE Experiment

- Proposed method uses $\mu e^- \rightarrow \mu e^-$ scattering to compute the running coupling constant
- From a precise measurement of the scattering cross-section, the running coupling constant can be computed
- Cross-section determined through the reconstruction of μe^- elastic scattering kinematic curve
- Primary objective of experiment is the determination of this cross-section through the scattering angle data

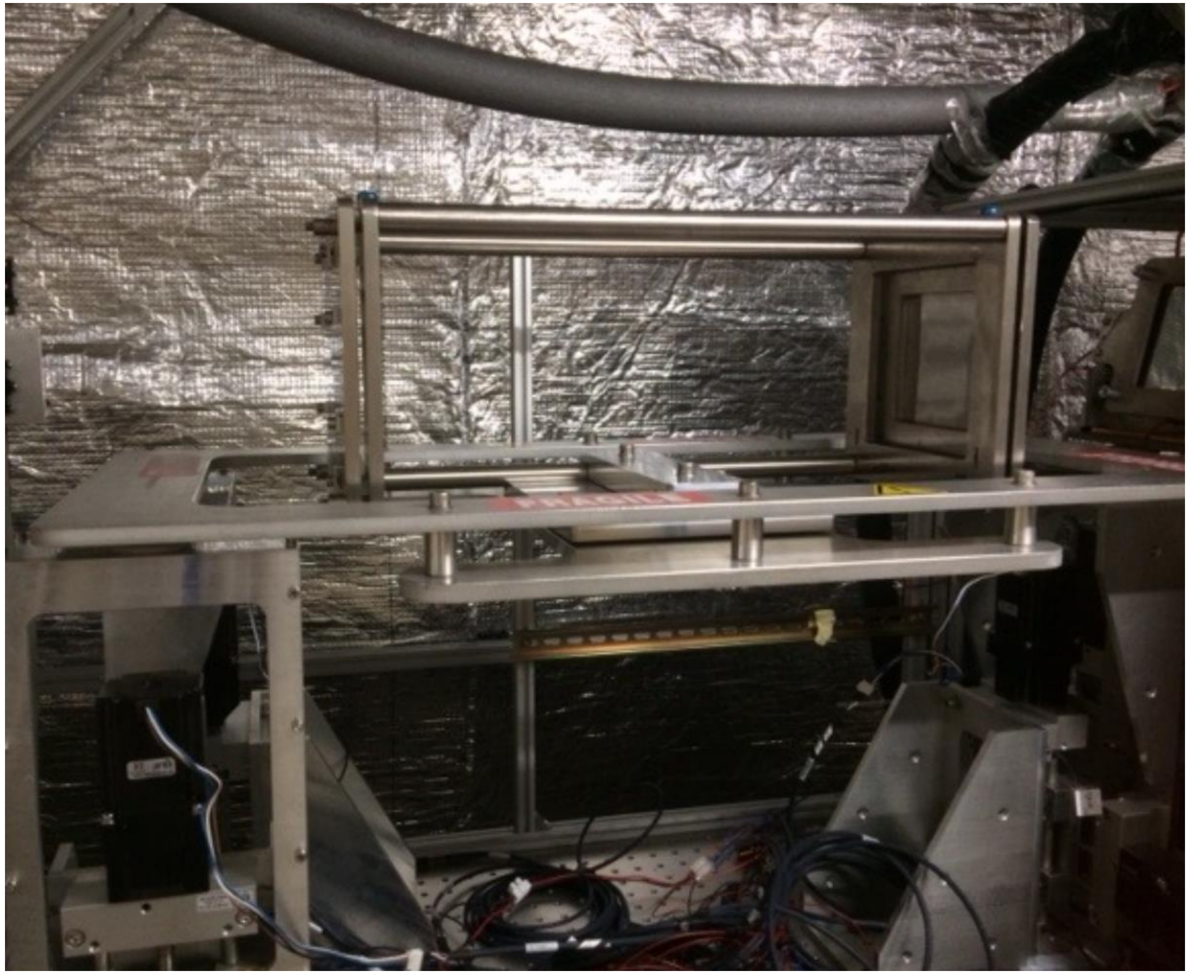


The MUonE Experiment

- Proposed experimental apparatus consists of a high energy muon beam fired at a light scattering target (beryllium) with a series of silicon detectors behind the scattering material
- Silicon detector hit data can be used to reconstruct the tracks of the scattered muons and electrons to compute the scattering curve at the specified beam energy (160 GeV)



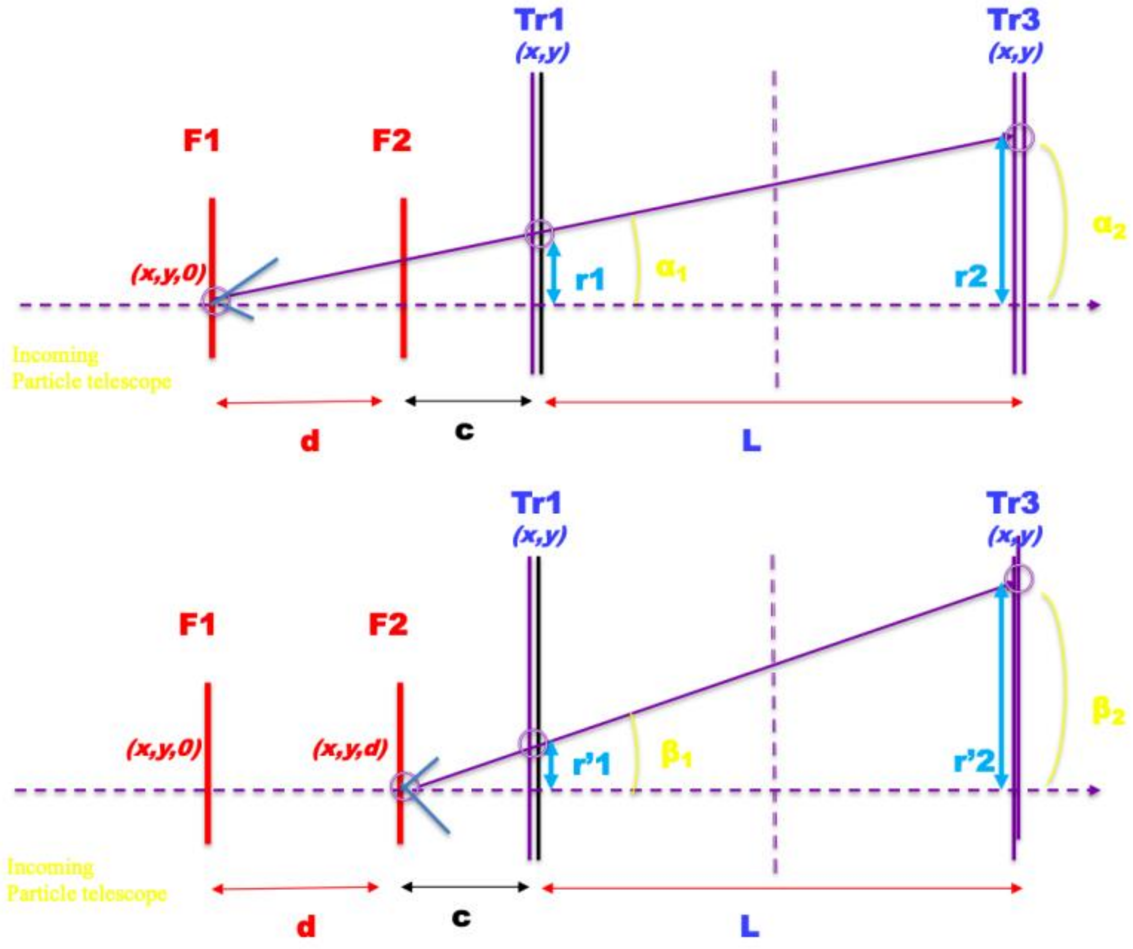
Absolute Scale Calibration



- The required precision of the experimental measurements necessitates extremely controlled experimental error
- Beam energy of 160 GeV must be controlled to within 3 MeV
- Implies an upper bound of order O(10 μm) on the measurement error in the z-position of each detector
- Positioning the detectors with such precision is not feasible mechanically
- Proposed solution: a “standard meter” etalon consisting of two foils with predetermined distance known to order O(1 μm)

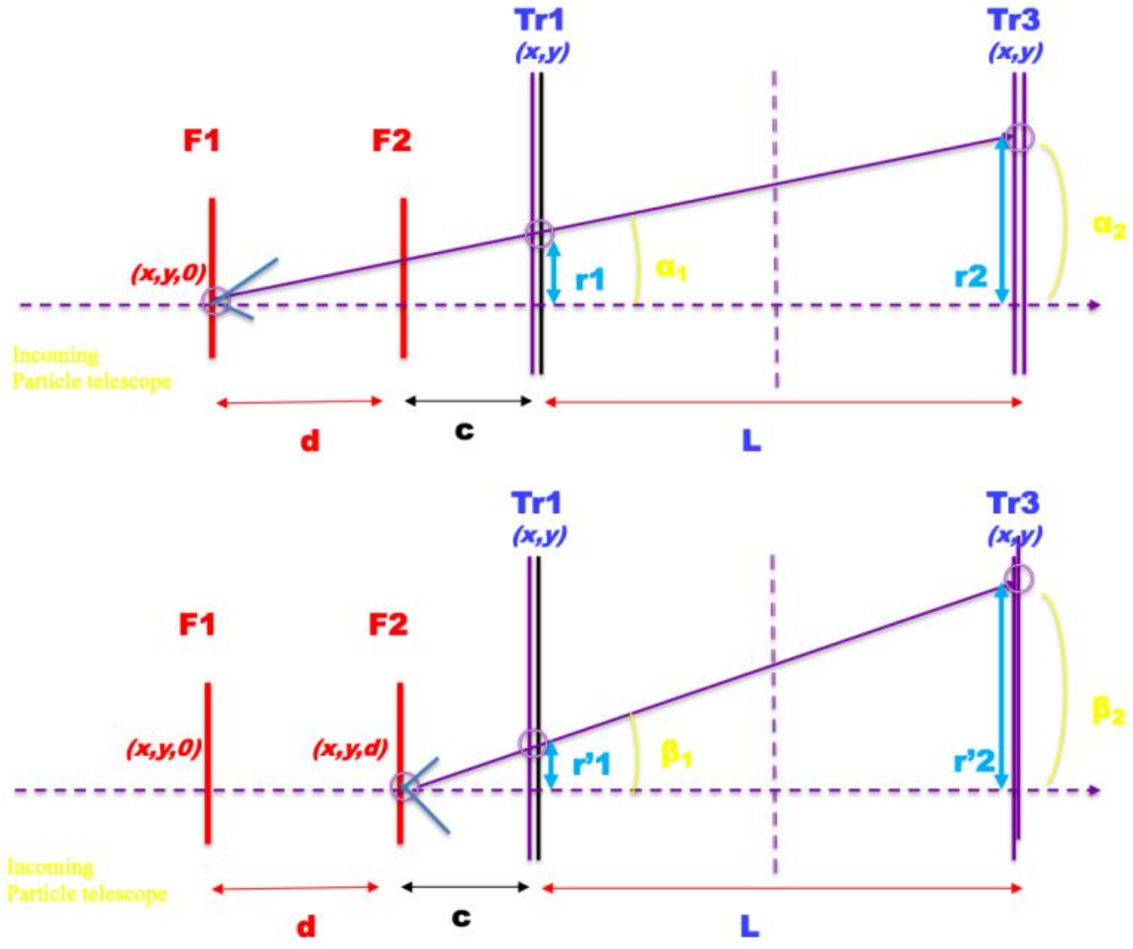
Absolute Scale Calibration

- The 2023 test beam was used to test the etalon calibration method with a 100 GeV hadron beam
- Etalon provided by engineering team with precise length of *d* = 50.40811 cm!
- Core idea of the method is essentially to “propagate” the precision of the etalon
- Beam is shot through the two tungsten foils of the etalon (F1 and F2)
- Scattering data collected in the downstream triggers (Tr1 and Tr3)



Calibration Procedure

- Goal is to compute distances *L* and *c* to 10 micron precision
- Set location of first etalon plane z=0
- Once the scattering data is collected, we reconstruct the tracks corresponding to each scattering event
- Allows us to compute the transverse displacements (labeled r and r') of the scattered particles
- We can use geometry to compute *L* and *c* from the transverse distances



Calibration Procedure

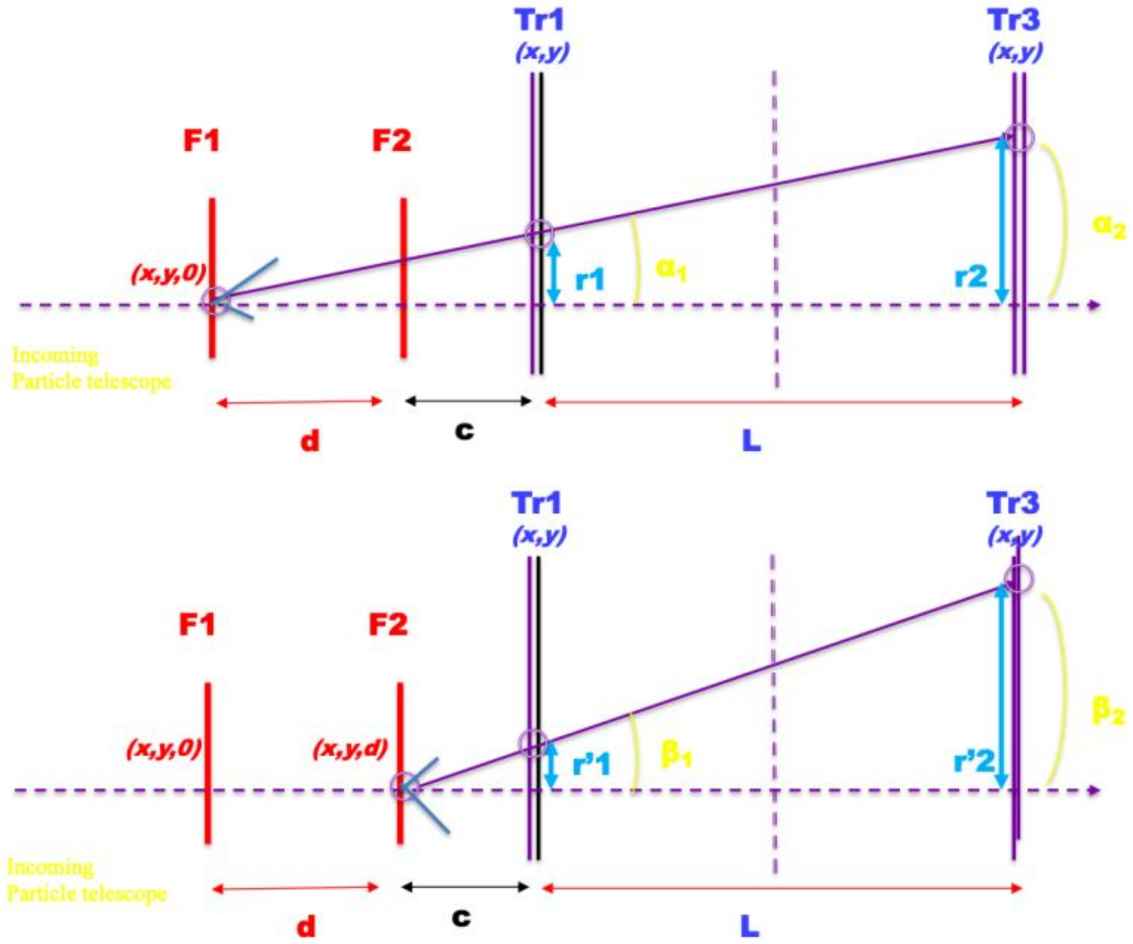
$$\rho_1 \equiv \frac{r_1}{r_2} \qquad \rho_2 \equiv \frac{r'_1}{r'_2}$$

$$\rho_1 = \frac{d+c}{d+c+L}$$

$$\rho_2 = \frac{c}{c+L}$$

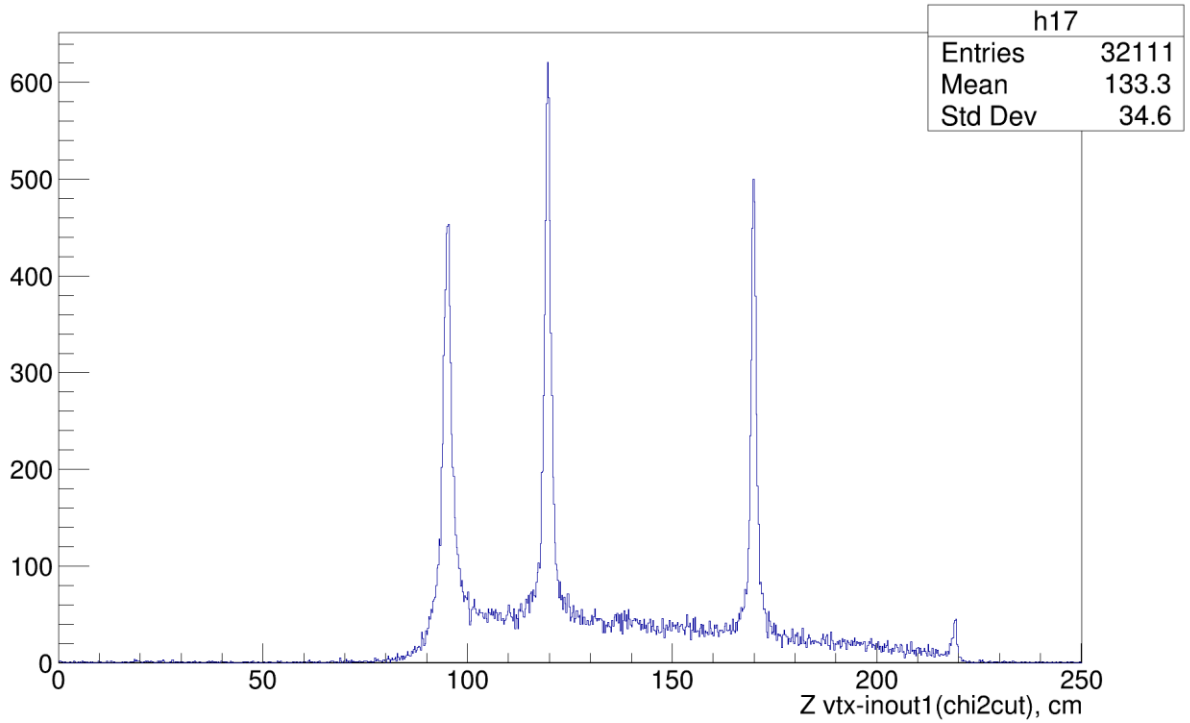
$$c = \rho_2 d \left(\frac{1-\rho_1}{\rho_1-\rho_2}\right)$$

$$L = (1-\rho_2) d \left(\frac{1-\rho_1}{\rho_1-\rho_2}\right)$$



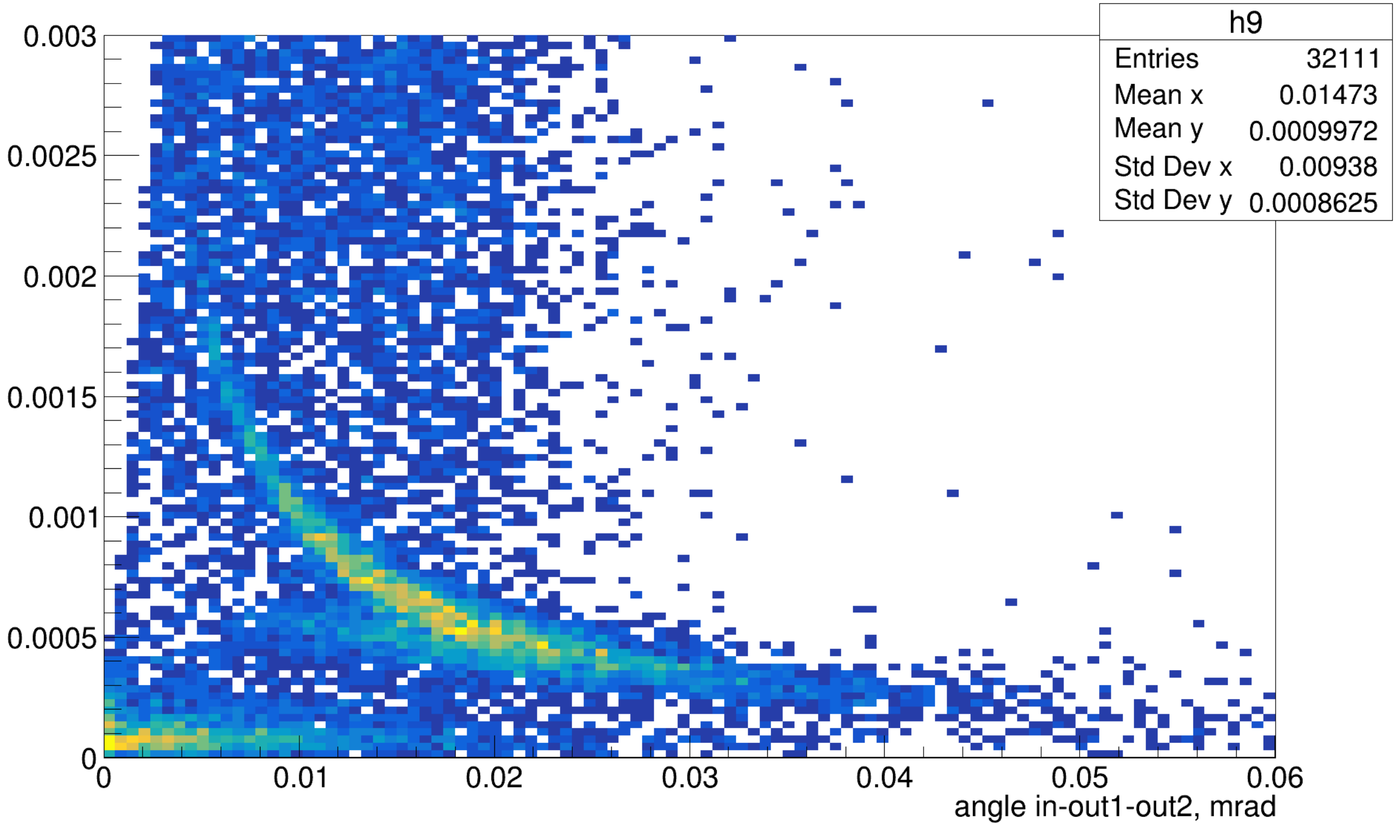
Analysis

- Run reconstruction with measured values of L = 71.90 cm and c = 50.0 cm, yielding roughly 100,000 events
- Perform a χ^2 cut of $\chi^2 < 5$ to isolate the well-constructed tracks that are more likely to come from the target scattering events, reduces count to about 30,000



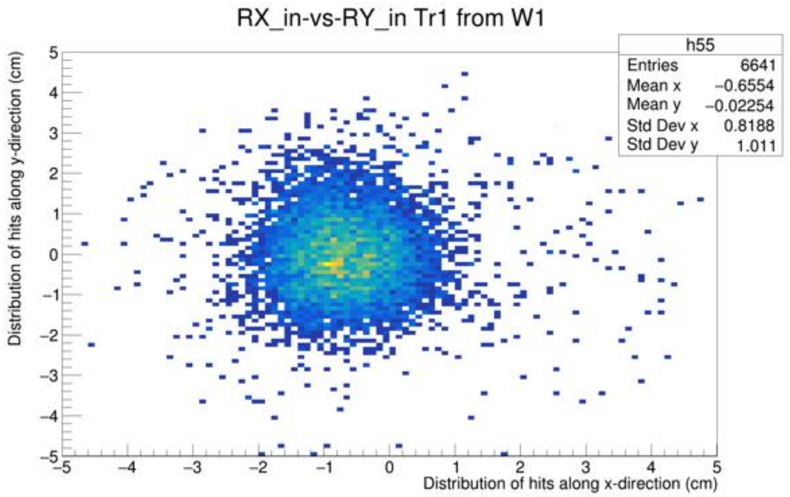
Analysis

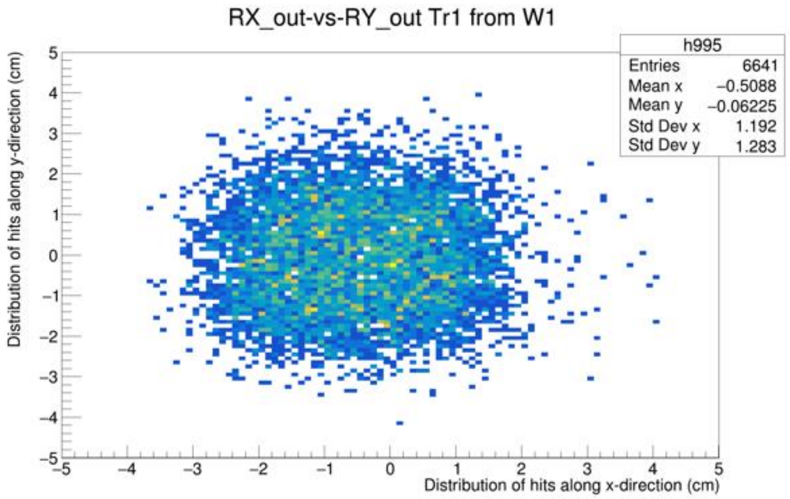
- Able to reconstruct the kinematic curve similar to the theoretical one previously shown

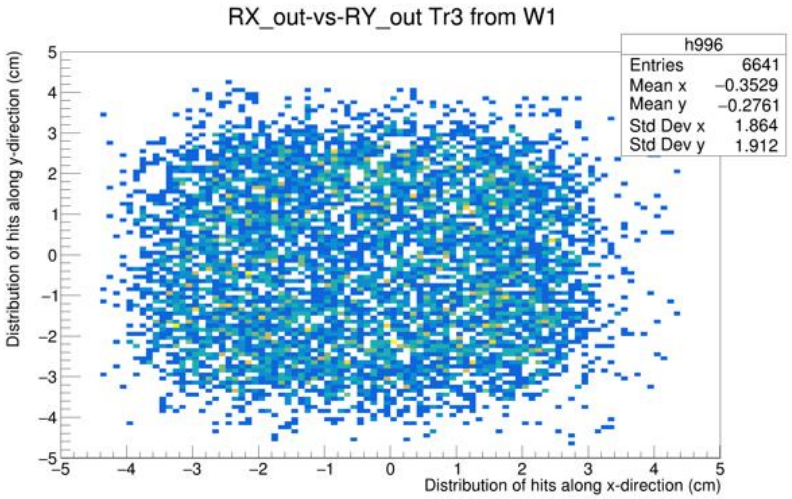


Analysis

Resulting hit pattern used to compute r1

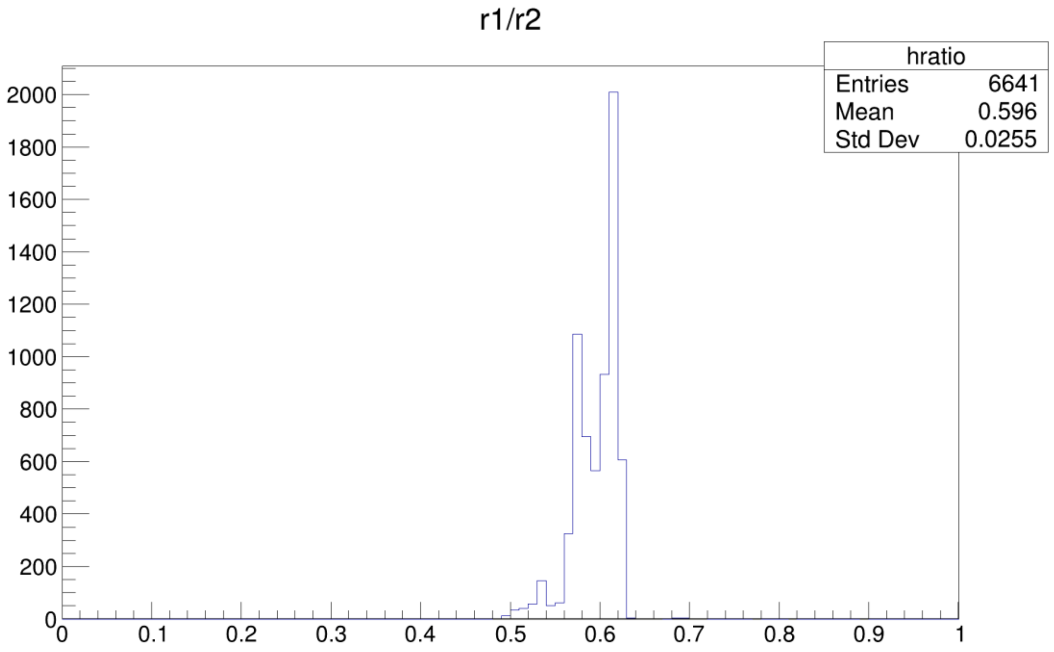


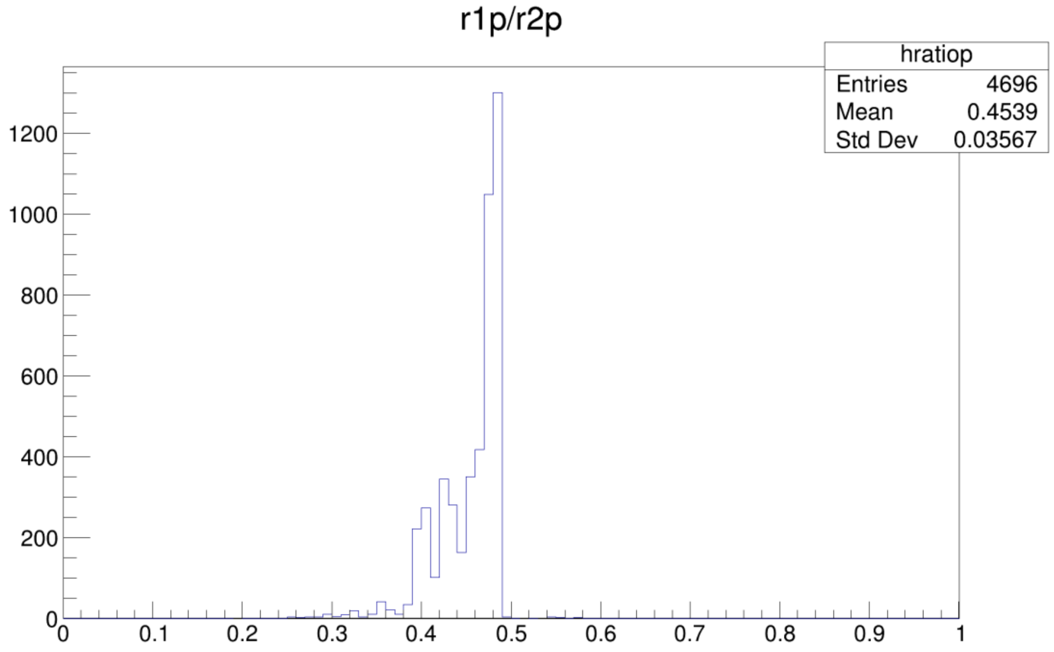




Previous result…

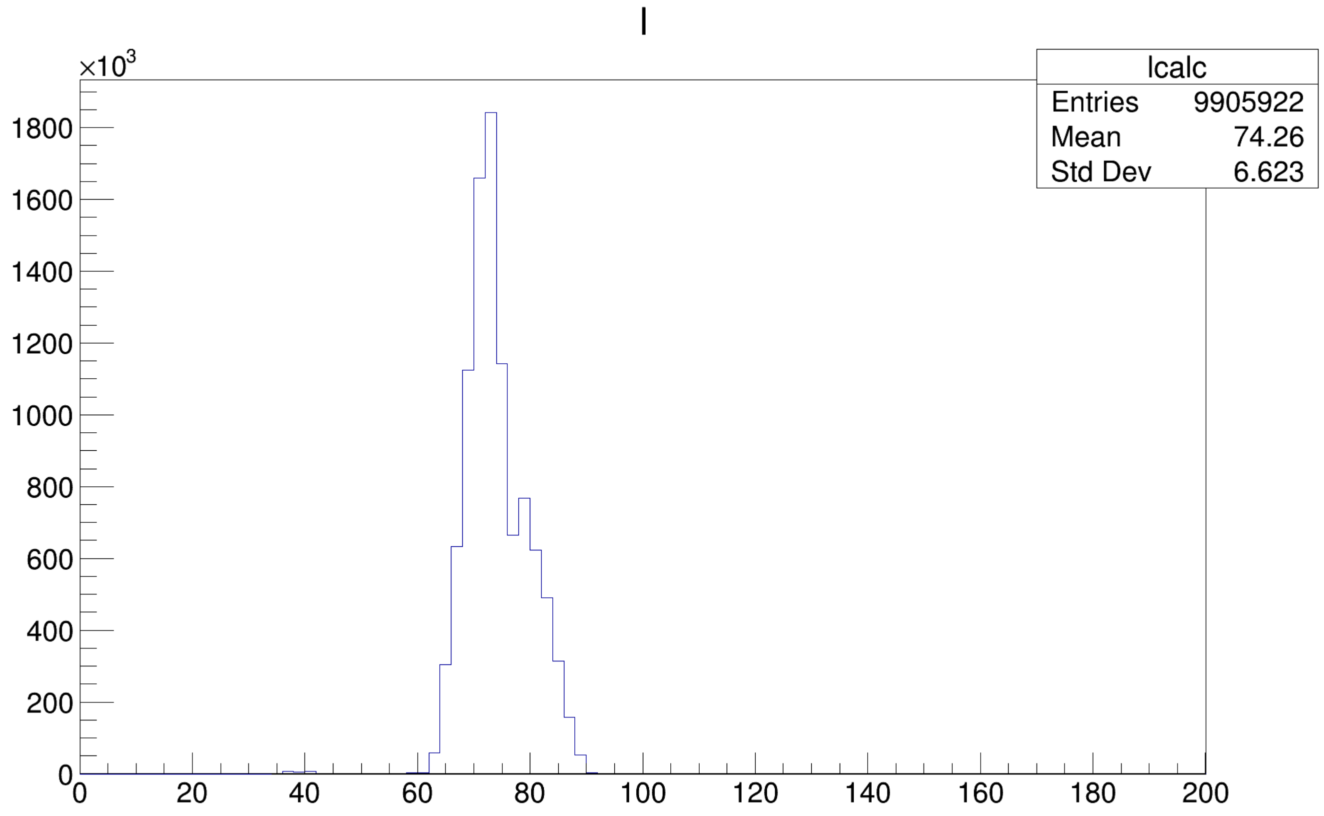
- Until recently, the distributions of each ratio looked like this





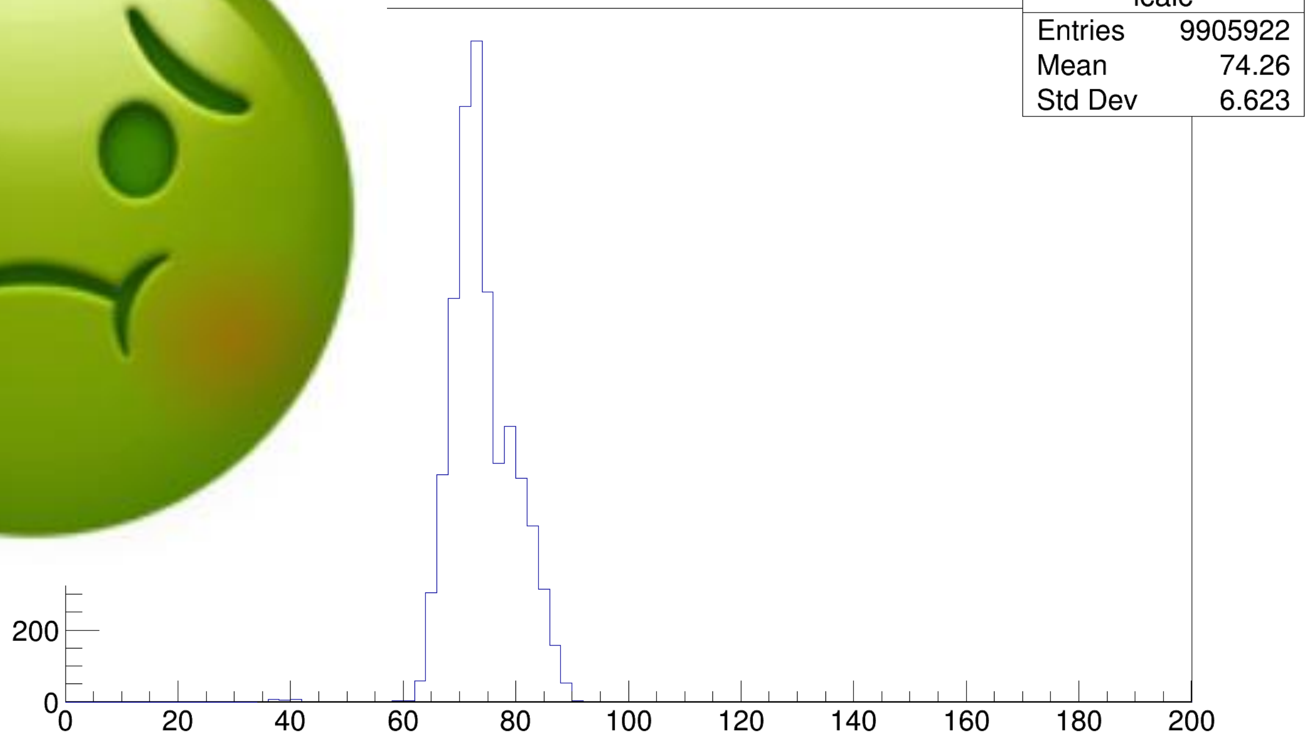
Previous result…

- Which computed the following distribution of *L*



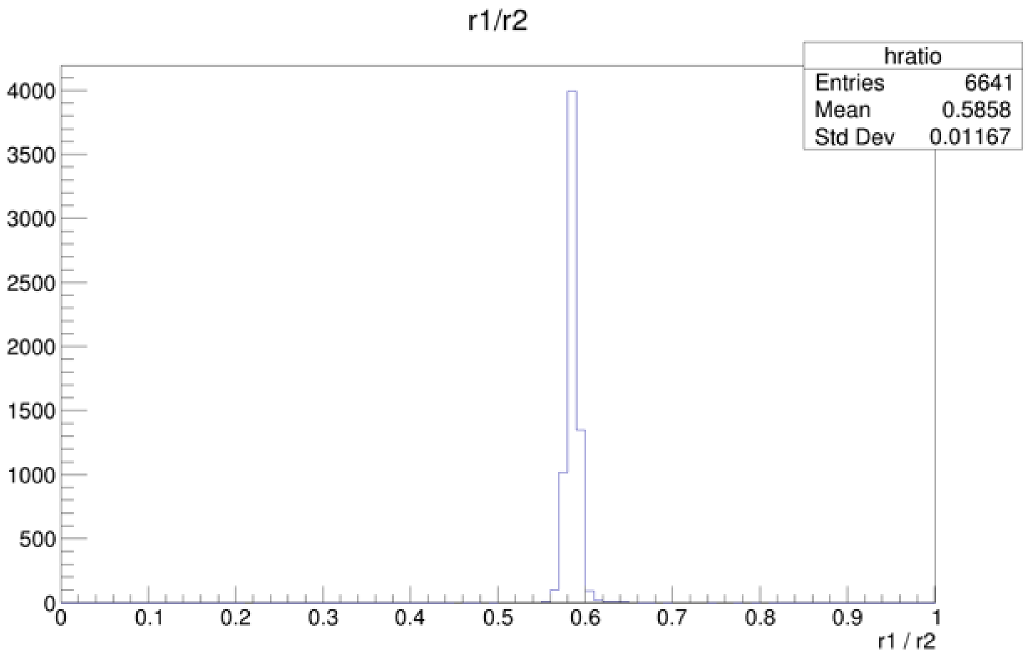
Previous result…

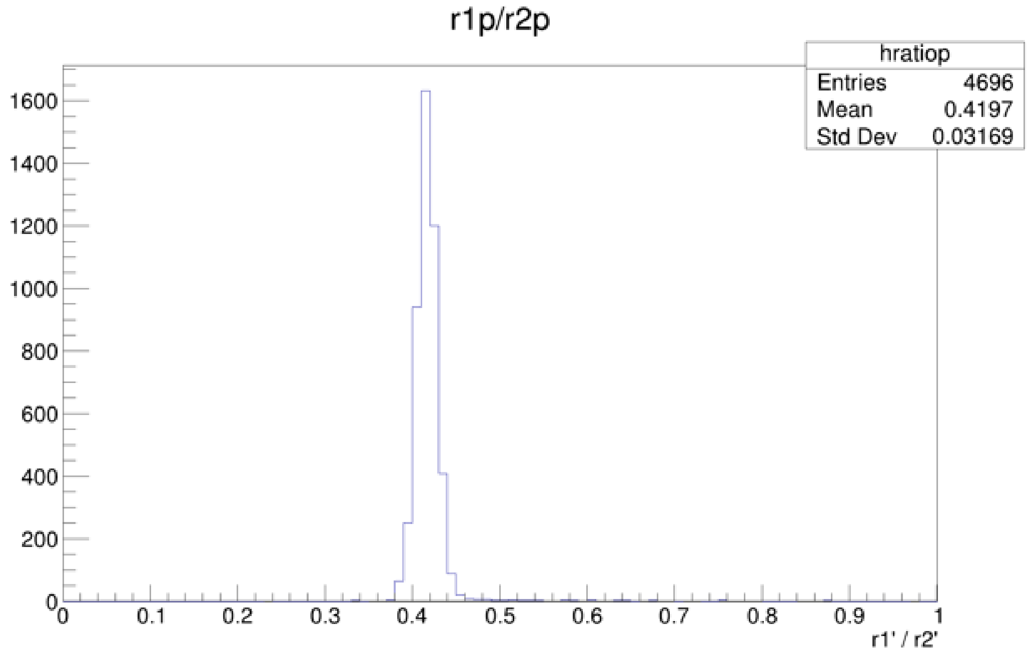
- Which computed the following distribution of *L*



Fixed Distributions!

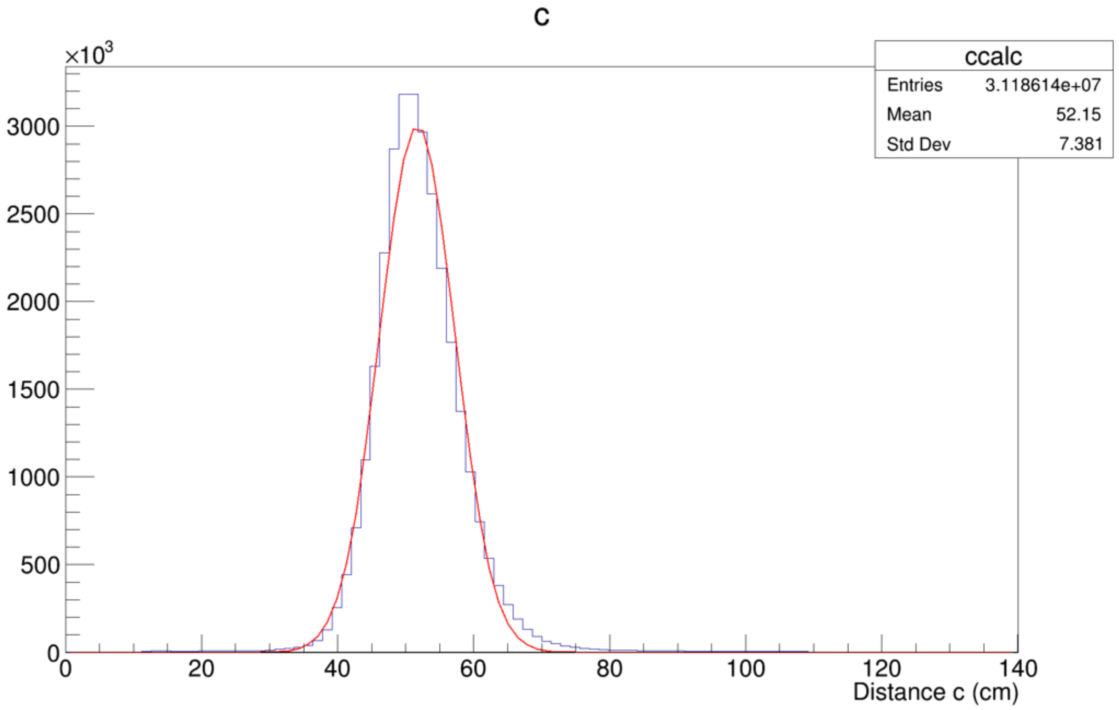
- As hypothesized previously, there was an issue in the extrapolation of the target hits back to the source plane – now our data makes sense

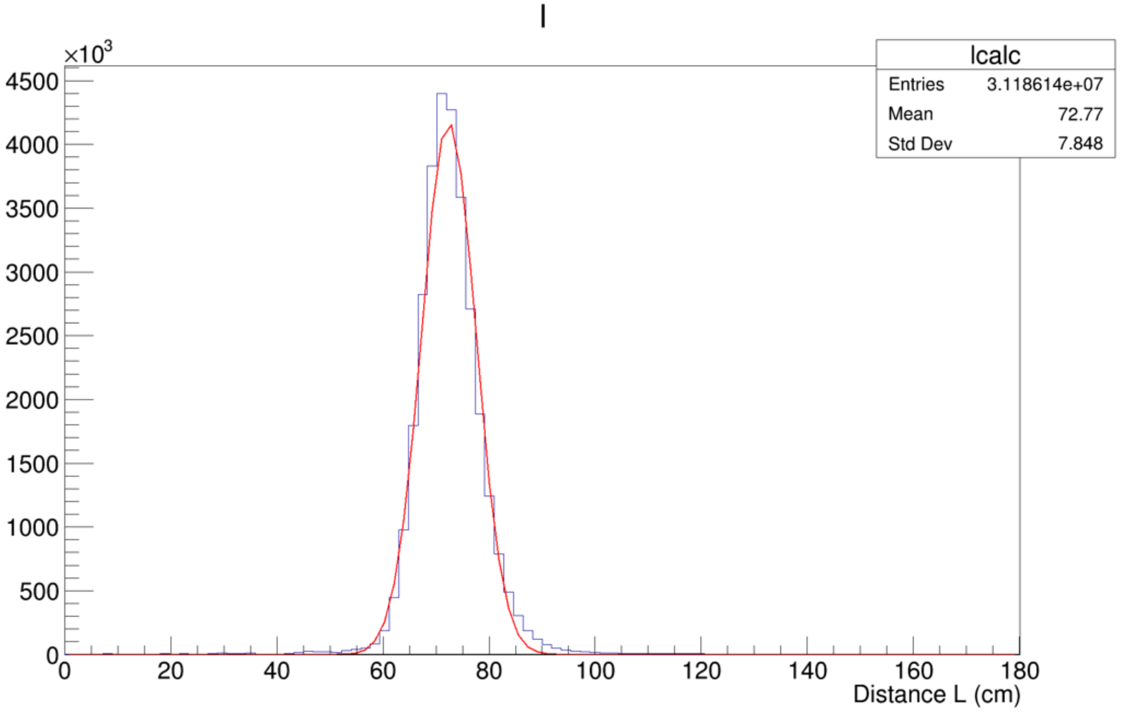




Analysis

- We obtain the following, more reasonable, distributions for *c* and *L*
- We perform a Gaussian fit on each to determine the mean precision





Analysis

```
****************************************
Minimizer is Minuit2 / Migrad
Chi2                      =   1.15107e+06
NDf                       =            94
Edm                       =   3.60103e-11
NCalls                    =            87
Constant                  =   4.63033e+06   +/-   1118.2
Mean                      =        72.389   +/-   0.00098818
Sigma                     =          5.12   +/-   0.000805052     (limited)
****************************************
Minimizer is Minuit2 / Migrad
Chi2                      =   1.11503e+06
NDf                       =            95
Edm                       =   1.17449e-07
NCalls                    =            84
Constant                  =   4.27702e+06   +/-   1033.25
Mean                      =       51.7197   +/-   0.00107801
Sigma                     =       5.54681   +/-   0.000873305     (limited)
Processing finished!
```

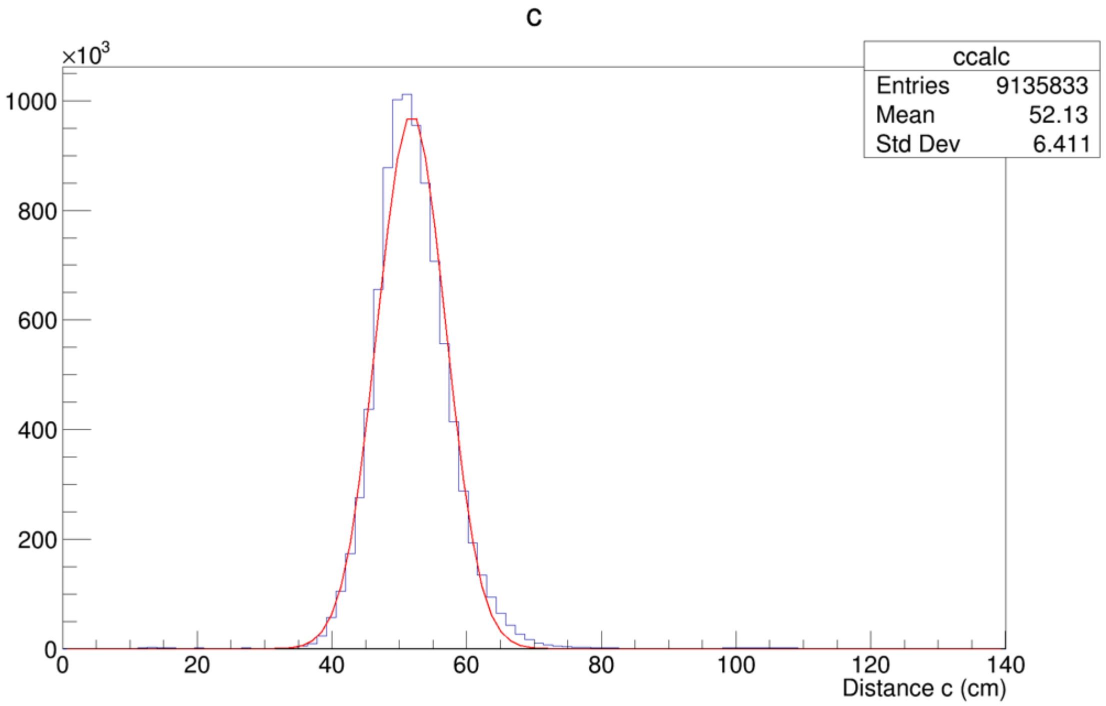
We obtain an estimate of 72.389 cm for L and 51.7197 cm for c with errors of about 10 microns for each

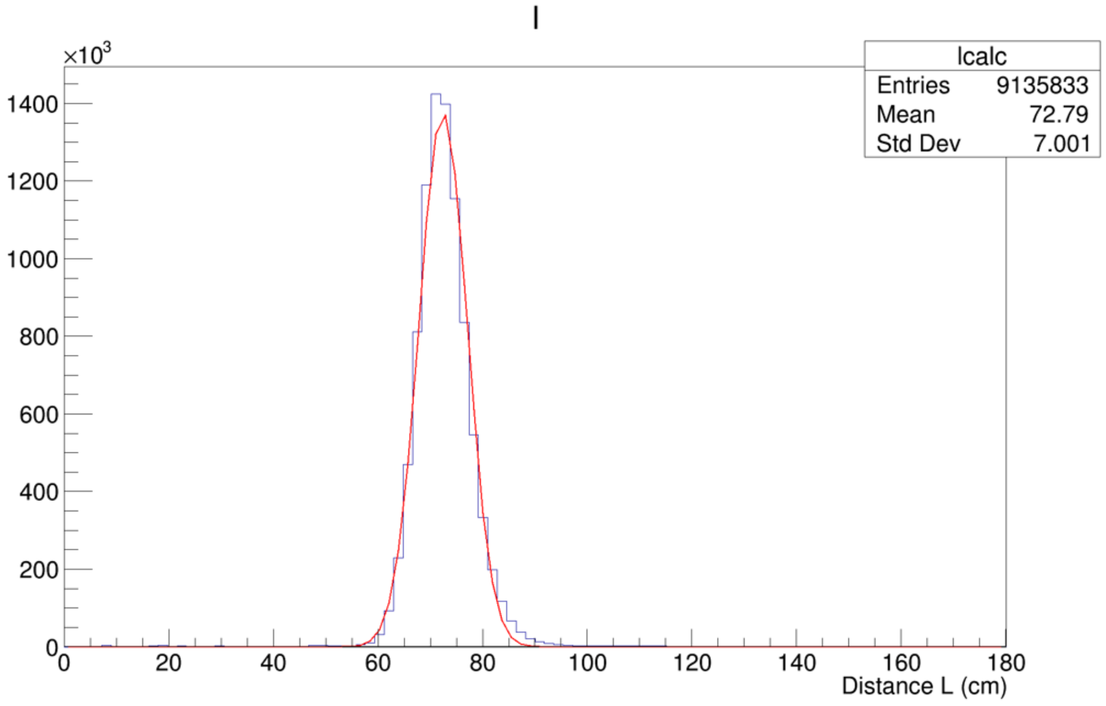
Analysis

- The mean distances are quoted at the required precision of roughly 10 microns!
- This acts as a first validation of the calibration method
- However, the mean values of L and c are well beyond the measured values we used as input
- This indicates that a recalibration is necessary
- The spreads of the distributions themselves are also quite large
- Indicates that we may want to set limit on minimum scattering angle to prioritize ideal scattering events and possibly approach the true distance more closely

Analysis

- We perform another “wide-angle” cut, restricting our analysis to events with scattering angles > 0.015 mrad, yielding the following tighter distributions for *c* and *L*





Analysis

```
***************************************
Minimizer is Minuit2 / Migrad
Chi2                      =       253198
NDf                       =           91
Edm                       =  3.19053e-09
NCalls                    =          103
Constant                  =  1.52764e+06   +/-   664.115
Mean                      =      72.4229   +/-   0.00164001
Sigma                     =      4.61446   +/-   0.00127036      (limited)
***************************************
Minimizer is Minuit2 / Migrad
Chi2                      =       230559
NDf                       =           93
Edm                       =  6.89614e-08
NCalls                    =          102
Constant                  =  1.38929e+06   +/-   603
Mean                      =       51.812   +/-   0.00179214
Sigma                     =      5.08247   +/-   0.00139514      (limited)
Processing finished!
```

Errors are still on the order of 10 microns, but they have significantly increased

Analysis

- Means have shifted slightly, spreads have decreased by a fair amount, mean error has increased significantly
- Precision on each mean is reduced due to the decreased number of degrees of freedom
- If we want to decrease spread this way, more data needs to be collected to avoid comprising the primary function of the algorithm

Conclusion

- The algorithm functions by computing improved values of L and c over different iterations
- Output of one run becomes the input for the next until we obtain convergence when the measured and derived values of L and c are within the computed error bounds
- An obvious next step is to perform this process and obtain the optimized values of L and c for which the next beam test should be performed
- Also need to consider full array of 40 stations for final experiment
- Can calibrate each station individually using this method (slow)
- Can attempt to utilize precisely calculated energy loss of muons propagating through each trigger to "carry-over" the precision from just a single station
- Ultimately, a promising method, especially after this summer's analysis

References

- G. Abbiendi et al., Letter of Intent: The MUonE project, Tech. Rep. CERN-SPSC-2019-026. SPSC-I-252, CERN, https://cds.cern.ch/record/2672249, 2019.
- Marconi U. Cundy, D. and C. Matteuzzi. An absolute longitudinal scale calibration for the MUonE project. MUonE Internal Note, 2022.