MEASURING MATERIAL PROPERIES

- **WHY?**
  - **Only worth doing if there's a plan to use results, e.g.**
    - **Extrapolate to different cooling channel designs**
      - **Thicker / Thinner absorbers**
      - **Different materials**
    - ***Requires a model***
      - ***Tweak parameters***

- ***"MICE can make precision measurements of Energy Loss and Multiple Scattering"***
  - **Often advertised by the management**
    - **Are they right?**
      - ***My arguments (& opinion)***

THE PHYSICS

- **Muons traversing matter interact electromagnetically with *atoms***
- $M_N > 2000\ m_e$

- **Collisions with bound *electrons* + Atomic *excitation***
  - ➔ **Energy loss (*aka* dE/dX, ionisation)**
    - σ **~ proportional to Z**

- **Collisions with screened *nuclei***
  - ➔ **(Multiple) scattering**
    - σ **~ proportional to Z^2**

- **Good approximation for all but lowest Z elements**

THE PROBLEM

- **Per cm of LH2 a 200 MeV/*c* muon makes (very) approximately**
  - **1200 collisions with nuclei**
  - **1200 collisions with electrons**
  - **mfp ~ 5 microns**

- **Per cm of Al (very) approximately**
  - **62000 collisions with nuclei**
  - **5000 collisions with electrons**
  - **mfp ~ 0.16 microns**

- **Can’t afford to simulate at atomic level in G.P. Monte Carlo**
- **Such MCs didn’t exist in ’40s and ’50s when theories developed**
  - **MCs use ‘condensed’ parameterised distributions for finite thicknesses of material**

‘CONDENSED’ DISTRIBUTIONS

- Famously:
  - Landau – energy loss distribution
  - Molière – multiple scattering distribution
  - *Other distributions are available*
    - *Vavilov, Blunck & Leisegang, Simon, Bethe…*
- Assume form of atomic cross-section for process (dE/dX, MCS)

  \+ Semi-analytic / numerical convolution of many collisions

  ➔ Numerical (or analytic) distributions of

  - ΔE and scattering angle
    - ~ scaleable to different thicknesses of material
- Beware:
  - *Strict limits of validity* (esp. thickness / momentum)
  - Incorporation of *electrons* into MCS usually fudged
- A few ‘atomistic’ distributions exist:
  - ELMS, XYZ, Allison & Cobb

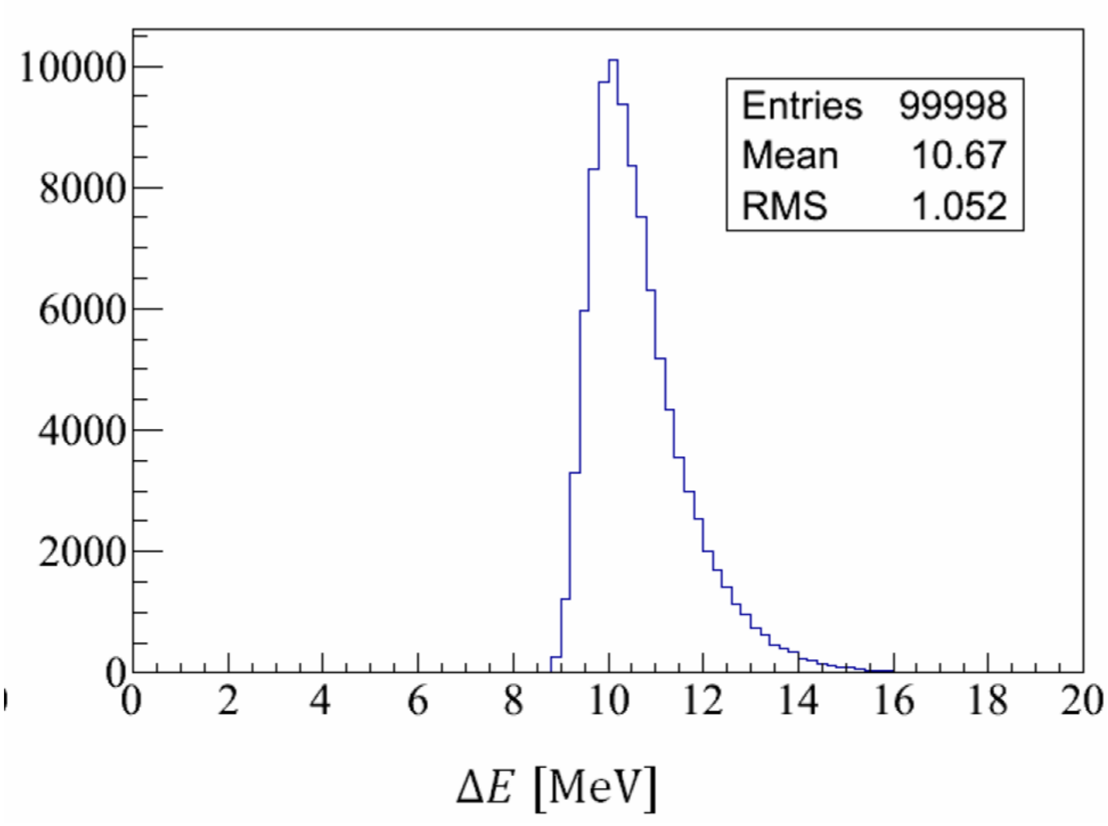
Do you know what model your MC is using?

Do you know if it’s valid?

Do you know what the parameters mean?

G4 seems impenetrable

ENERGY LOSS DISTRIBUTION



FWHH ~ 2.5 MeV

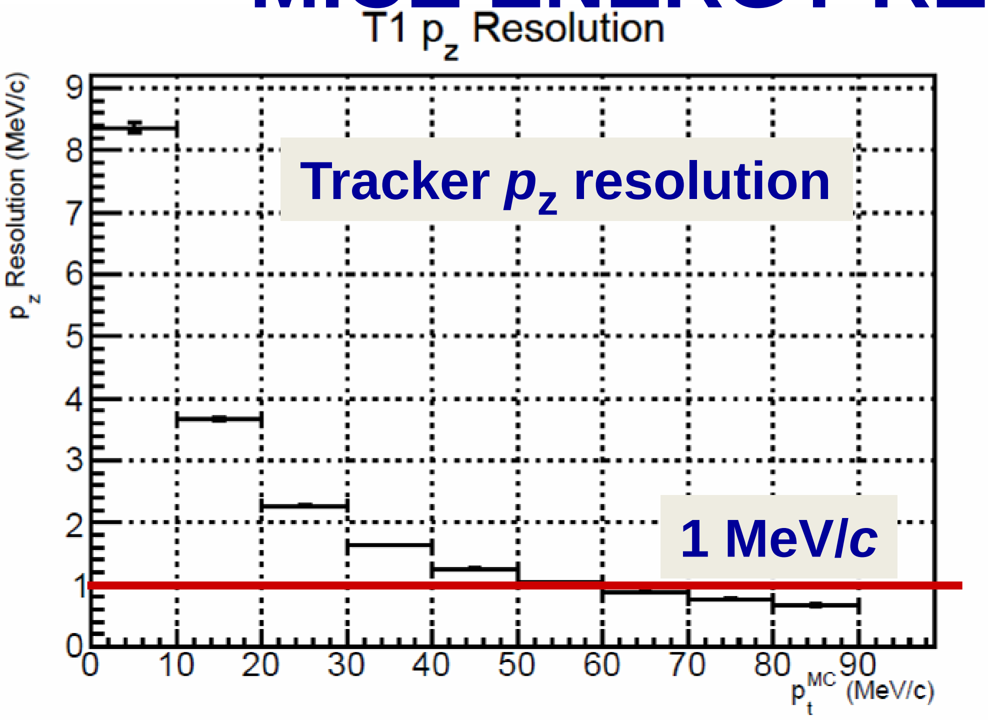
➔ σ ~ 1 MeV

To be compared with energy resolution of of MICE…

Energy loss distribution for 200 MeV/*c* muons in 35 cm LH2

(G4MICE, T. Carlisle thesis)

MICE ENERGY RESOLUTION(S)



TOF 0 + 1 and EMR have σ_E ~ 2 MeV

Might help a bit but *beware* straggling in
(a) Diffuser
(b) KL
(c) TOFs

Need two measurements of E to get $\Delta E = E_u - E_d$

Energy resolution > or >> 1 MeV for most muons

➔ *Too poor to usefully measure dE/dX distribution (imho)*

SCATTERING DISTRIBUTION

6.3 The Bethe and Fano modifications to Molière theory 77

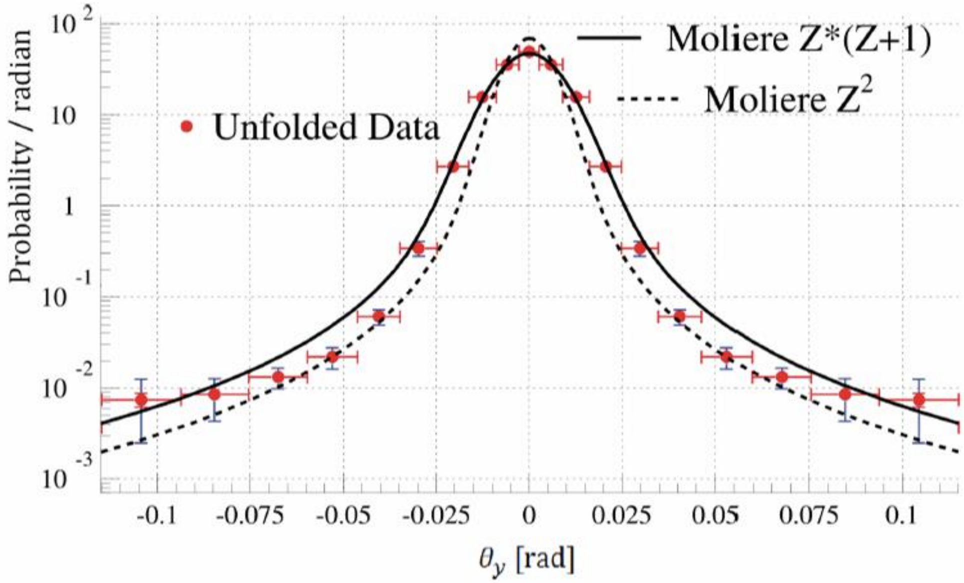


Figure 6.2: Projected scattering angle distribution for $p = 172\,\mathrm{MeV}/c$ muons in 15.9 cm LH_2 as measured by MuScat and predicted by Molière theory, taken from [27].

σ ~ a few mr.

To be compared with angular resolution of of MICE…

Note: *Z(Z+1)* fudge for electrons doesn't work

Projected scattering angle of 172 MeV/*c* muons in 15.9 cm LH2 (From Muscat…)

MUSCAT

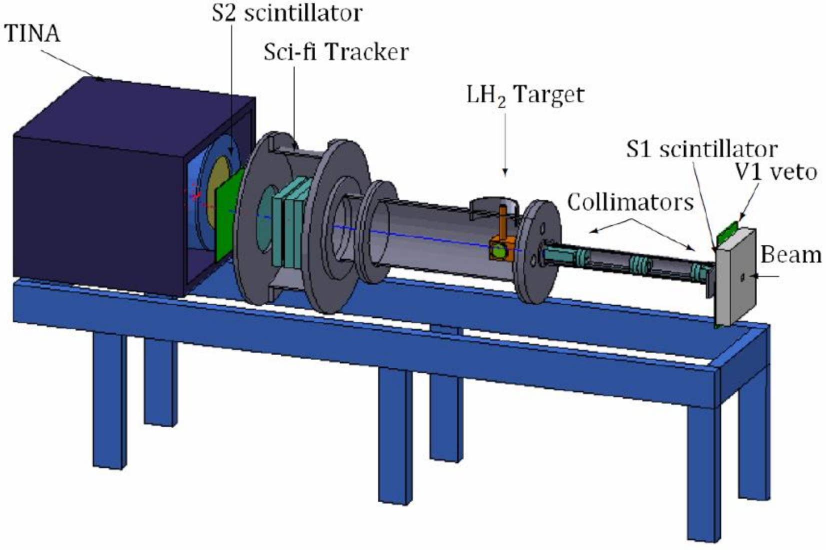


Figure 7.4: The MuScat detector, from the Geant4 model. Figure and caption taken from [27].

Definitive measurement of MCS of 172 MeV/*c* muons in low *Z* materials

Incoming muon angle defined by collimators

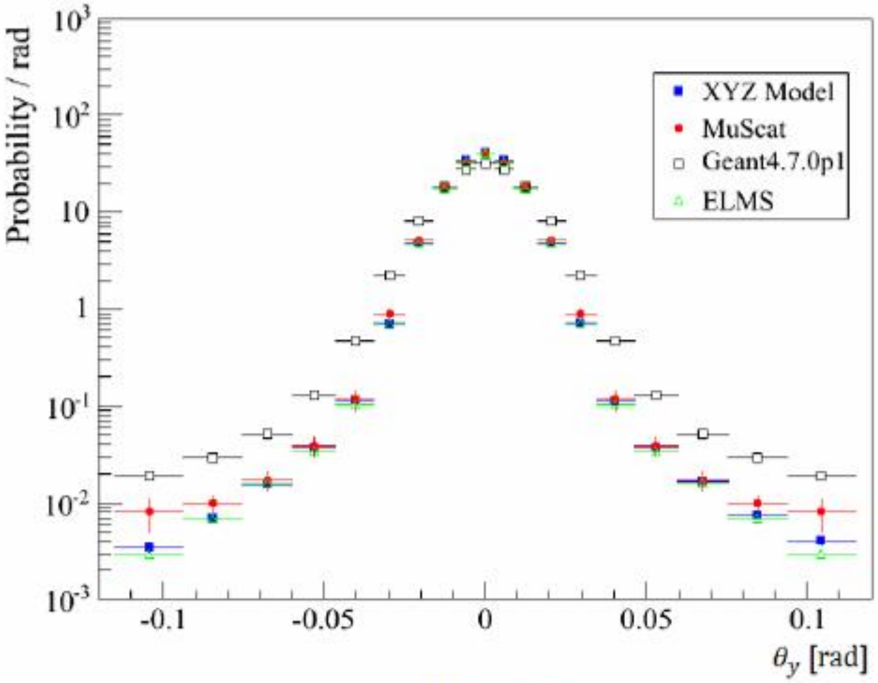
Scattering angle measured by SciFi tracker plane

σ_θ ~ a 1 – 2 mr (ish)

SCATTERING MEASUREMENTS IN MICE

- Two ways:
  - With magnetic fields
    - Can be done at the same time as emittance measurements
  - Without fields
    - Dedicated runs
- Both looked at by Tim Carlisle
  - Also developed ‘XYZ’ atomistic model of scattering
    - Oxford Thesis 2013

XYZ MODEL

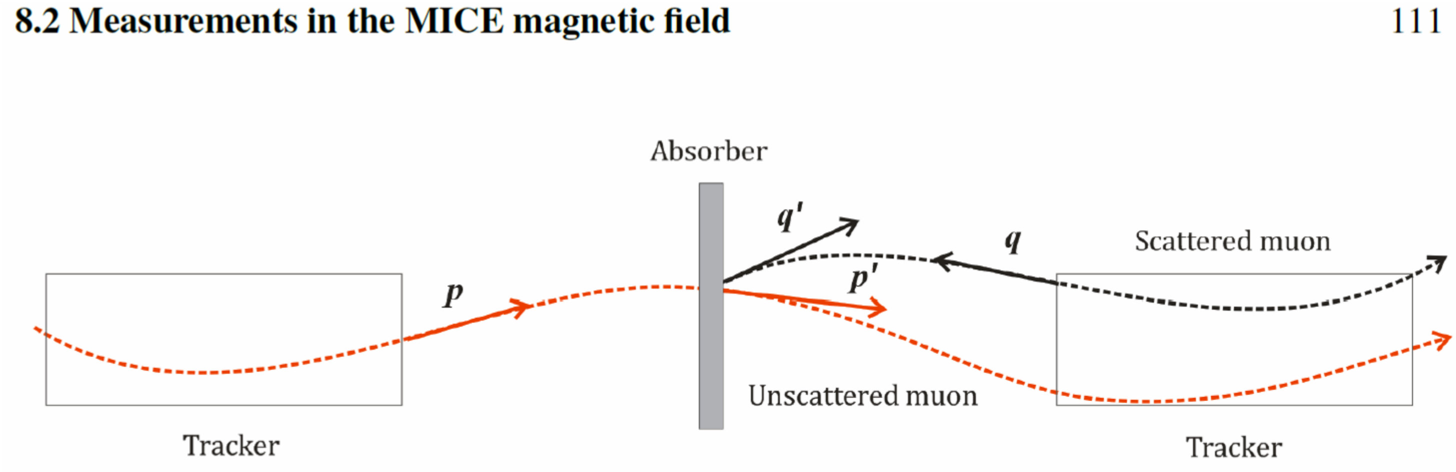


(b) 15.9 cm LH_2

Figure 7.5: Scattering probability distributions for liquid hydrogen (LH_2) obtained using the XYZ model compared with the MuScat data and other Monte Carlo, for p = 172 MeV/c muons. The θ_1 parameter is defined according to the Born approximation.

Excellent agreement with Muscat
ELMS also agrees (LH2 only)
Geant4.7.0p1 not satisfactory

MEASUREMENTS WITH FIELDS



- Extrapolate upstream measured muon vector to downstream face of absorber ➔ *p’* [without absorber, of course]

- Track downstream muon vector back to same place ➔ *q’*

- Space angle θ

$$\cos\ \theta = \frac{\vec{p'}.\vec{q'}}{|p'||q'|}.$$

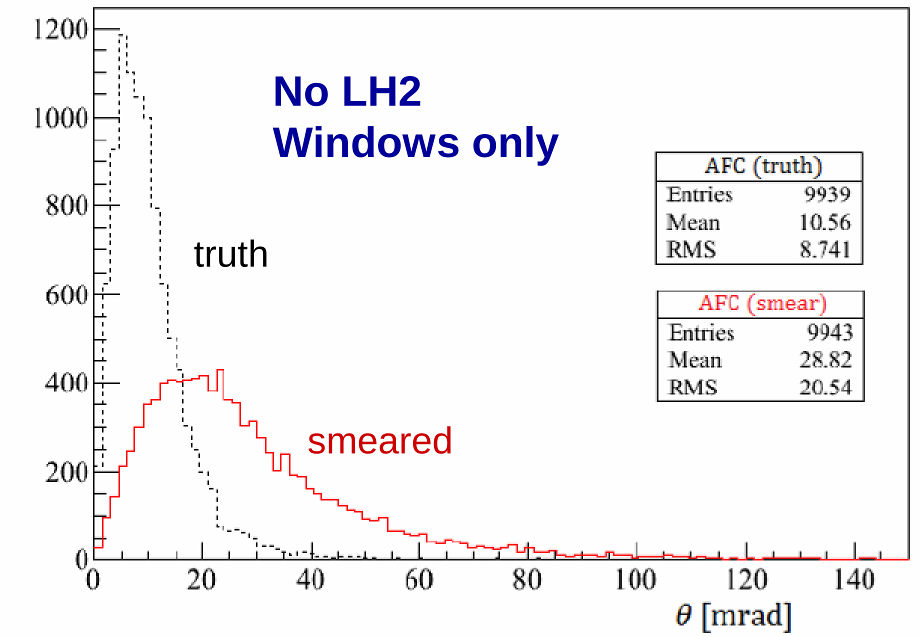
- Tracker momentum resolutions determine angular resolution

MC STUDY WITH FIELDS (1)

(MICE Note 90)

u_i	$\sigma(u_i)$
x [mm]	0.54
y [mm]	0.44
p_x [MeV/c]	2.05
p_y [MeV/c]	1.52
p_z [MeV/c]	4.58
E [MeV/c^2]	3.46

Tracker resolution in phase-space coordinates u_i.



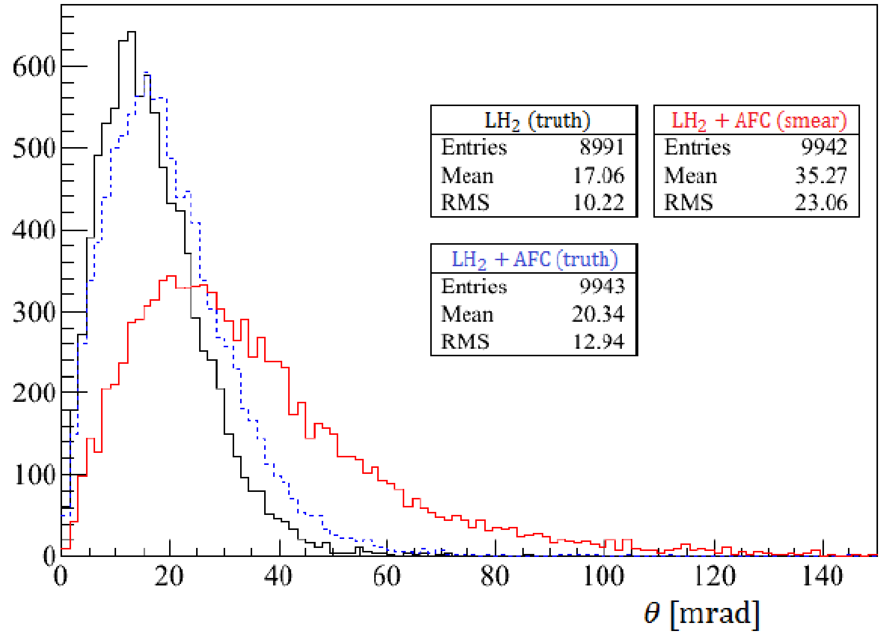
(a) Space angle (3D).

No Tracker reconstruction was available

➔ Smear truth muon coordinates in trackers with nominal resolutions before tracking forward and backward

Black = true (MC!) scattering distribution in absorber & safety windows
Red = After simulated reconstruction / resolutions
σ_θ ~ 30 mradians (space angle) ➔ 20 mr projected angle

MC STUDY WITH FIELDS (2)



(a) Space angle (3D).

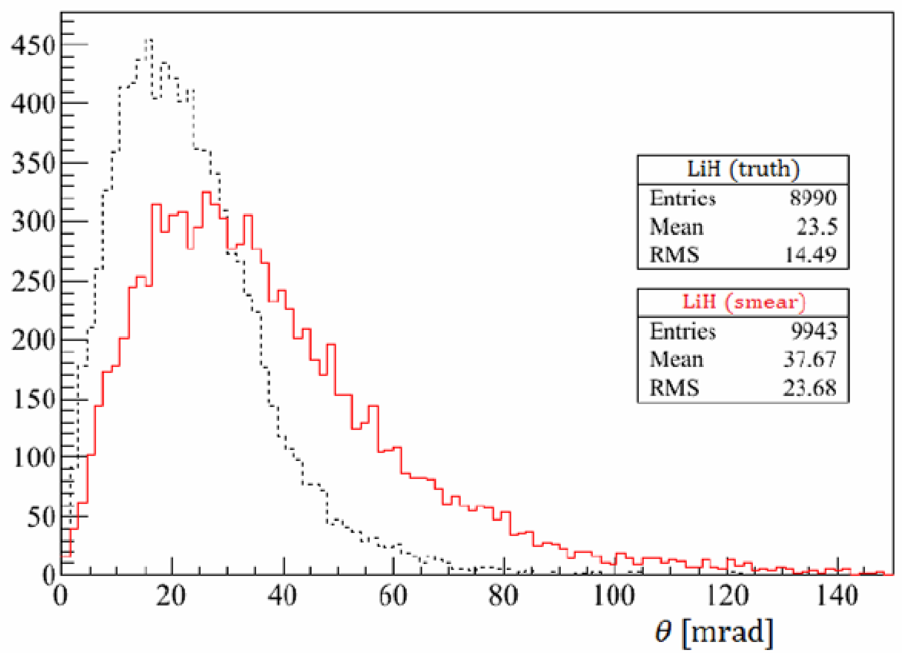
Black = True 35 cm of LH2

Blue = True LH2 + windows

Red = LH2 + windows after simulated reconstruction

Substantial unfolding would be required

May be do-able if resolutions very well understood



(a) Space angle (3D).

LiH looks easier – more scattering

But still a lot of unfolding

MEASUREMENTS WITHOUT FIELDS

Not **Monte Carlo'd**

Back of envelope estimates

~ 4.7 mr scatter / station (projected angle)

➔ $\sigma_{x,y}$ ~ 1.87 mm

Allow for scattering in last station

➔ σ_θ ~ 5 mr / tracker

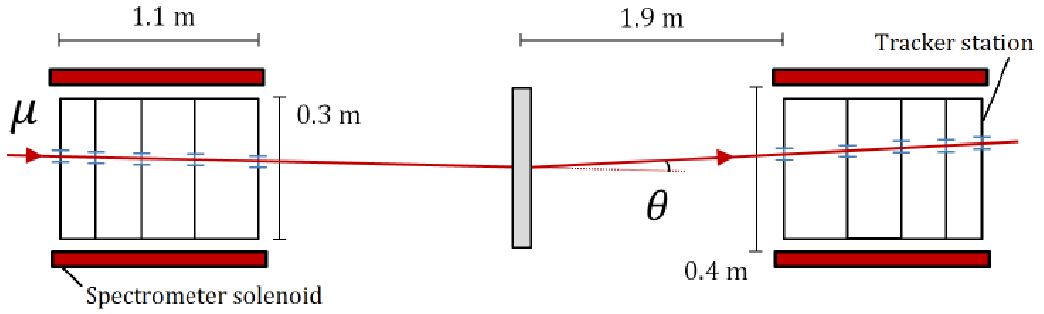


Figure 8.8: Scattering angle measurements using straight muons tracks (no magnetic field) in Step IV.

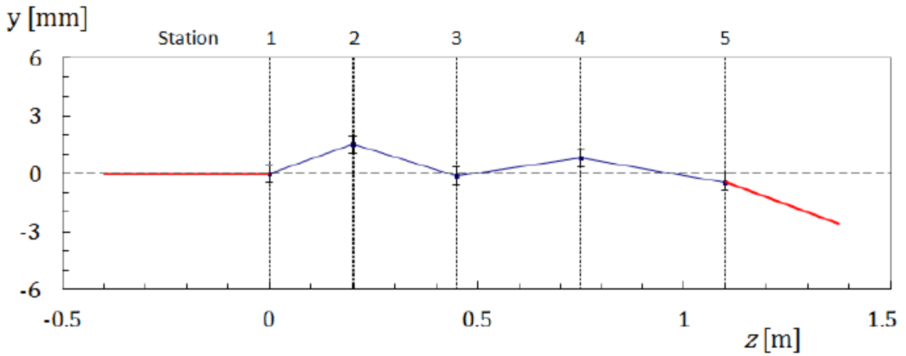


Figure 8.9: An incoming muon will scatter in each scintillating-fibre station in the tracker, which can significantly change its trajectory. This diagram comes from a simple spreadsheet Monte Carlo using realistic scattering angles.

➔ σ_θ ~ 7 mr for measurement – much better than with field (~20 mr)

NO FIELD SUMMARY

	Al windows	Rms projected angle, θ_0 [mrad] Truth	Smeared
Empty		0.0	7.1
AFC	$4 \times 175\,\mu$m	9.5	11.9
35 cm LH_2		13.8	15.5
AFC + 35 cm LH_2	$4 \times 175\,\mu$m	16.6	18.2
63 mm LiH		19.3	20.6

Table 8.4: Rms projected angles for the simulated distributions, in no magnetic field. The smeared values are obtained by adding the truth value and angular resolution (7.1 mrad) in quadrature.

This needs re-visiting but must be much easier than with-field measurement.

Would still not be very easy to unfold the true LH2 scattering distribution.

SUMMARY

1. **Must have model if measurements are to be useful**

2. **Forget about measuring dE/dX distributions**
   - **Energy resolution just not good enough**

3. **May be possible to measure scattering**
   - **Doesn’t beat MUSCAT**
   - **Straight track angular resolution better than with fields**
   - **Substantial unfolding required in either case**
   - **Conclusions should be checked with full tracker recons.**