Field off Multiple Scattering Studies

Current Status

Ryan Bayes

Department of Physics and Astronomy
Laurentian University

February 14, 2017

Previously in Field Off MCS Studies...

- A TOF selection and calibration method was proposed.
- Studies of systematic errors were presented.
- A momentum dependent multiple scattering measurement was shown.

Since CM46...

- The MAUS v2.6.1 reconstruction has been assumed.
- The momentum calibration from the TOFs was refined.
- A scattering acceptance has been determined from the MC.
- A new set of scattering angles have been defined.
- The fiducial selection criteria has been reviewed.

Previously in Field Off MCS Studies...

- A TOF selection and calibration method was proposed.
- Studies of systematic errors were presented.
- A momentum dependent multiple scattering measurement was shown.

Since CM46...

- The MAUS v2.6.1 reconstruction has been assumed.
- The momentum calibration from the TOFs was refined.
- A scattering acceptance has been determined from the MC.
- A new set of scattering angles have been defined.
- The fiducial selection criteria has been reviewed.
- ... And I've changed continents, jobs and driver's licence.

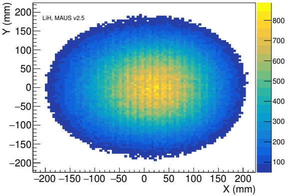
Summary of MCS Studies

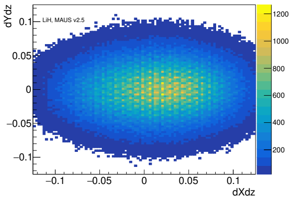
- Field off data sets were collected in ISIS run periods 2015/03 and 2015/04
- Data was reconstructed using MAUS (now up to 2.6.1)
- "Official" simulation completed with MAUS v2.5
- Events with TOF1 spacepoints collected from data and MC runs.
- Events with upstream tracks suspected of passing through DS tracker withing a 200ps TOF01 window are binned by associated momentum calculated from TOF12 time.
- Empty absorber distribution convolved with model of scattering in absorber.
- Convolution used to provide response for deconvolution.
- Figures of merit for raw and deconvolved spectra:
  - χ^2 comparison between data and prediction
  - Width of scattering distribution: Θ

Data Collected

Collected Data

State	TOF1	TOF2
Xe 240 MeV/c, Pion	883118	75879
He 240 MeV/c, Pion	185983	16155
Empty 172 MeV/c, Muon	624577	94722
Empty 200 MeV/c, Muon	384909	56314
Empty 240 MeV/c, Muon	314739	62546
LiH 172 MeV/c, Muon	1282488	174405
LiH 200 MeV/c, Muon	1223560	177460
LiH 240 MeV/c, Muon	1239827	232982



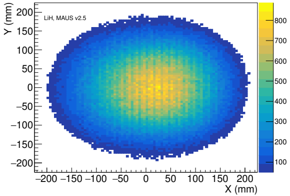


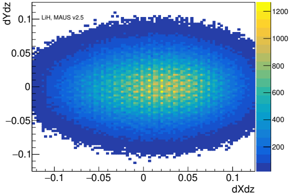
- Data recently re-analyzed with MAUS v2.5.0
- Collection of 100000 good muons targeted

Data Collected

Collected Data

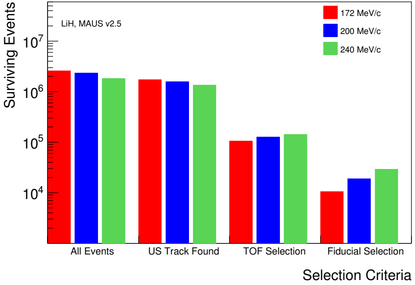
State	TOF1	TOF2
Xe 240 MeV/c, Pion	883118	75879
He 240 MeV/c, Pion	185983	16155
Empty 172 MeV/c, Muon	624577	94722
Empty 200 MeV/c, Muon	384909	56314
Empty 240 MeV/c, Muon	314739	62546
LiH 172 MeV/c, Muon	1282488	174405
LiH 200 MeV/c, Muon	1223560	177460
LiH 240 MeV/c, Muon	1239827	232982

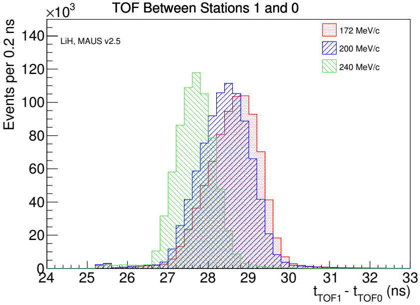




- Data recently re-analyzed with MAUS v2.5.0
- Collection of 100000 good muons targeted

Event Selection





- Require a US track. If a DS track not extant, statistics are set to overflow values.
- Assumed a 200 ps selection
- Require projection of US tracks to appear within central 140 mm radius of DS plane 1 projected with 12 mrad radial angle added.

TOF/Momentum Calibration

Calibration by Set[a]

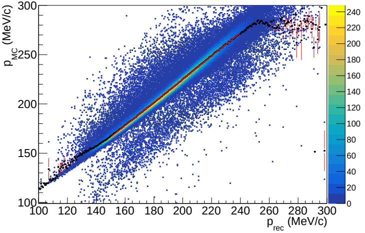
Set	a	b (MeV/c)
172 MeV/c	1.107 ± 0.002	1.1 ± 0.3
200 MeV/c	1.104 ± 0.004	1.1 ± 0.7
240 MeV/c	1.175 ± 0.001	-9.4 ± 0.3
Sum	1.176 ± 0.0007	-10.0 ± 0.1

[a] Using fit $\langle p_{MC} \rangle = a p_{rec} + b$

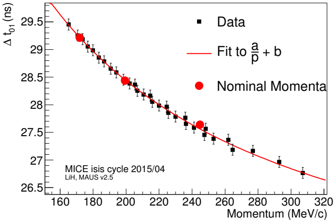
Nominal TOF bins

p (MeV/c)	Δt_{10}^{min} (in ns)	Δt_{10}^{max} (in ns)	p^{min} (MeV/c)	p^{max} (MeV/c)
172	29.104	29.304	167.2	173.8
200	28.342	28.542	192.1	202.0
240	27.560	27.760	237.4	252.6

Sum of MC Sets



With Calibration



Raw Scattering Distributions

- Define projection angles

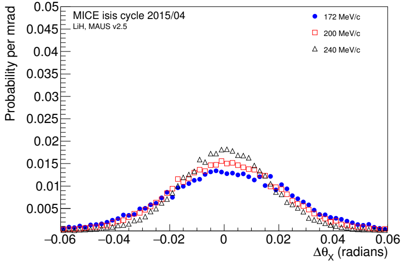
$$\theta_y = \text{atan}\left(\frac{\mathbf{p}_{DS}\cdot(\hat{\mathbf{y}}\times\mathbf{p}_{US})}{|\hat{\mathbf{y}}\times\mathbf{p}_{US}||\mathbf{p}_{DS}|}\right)$$

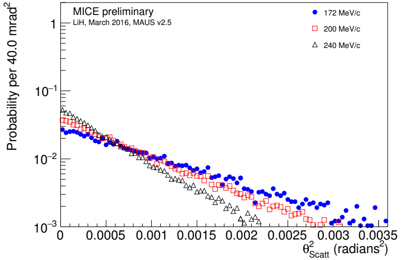
and

$$\theta_x = \text{atan}\left(\frac{\mathbf{p}_{DS}\cdot(\mathbf{p}_{US}\times(\hat{\mathbf{y}}\times\mathbf{p}_{US}))}{|\mathbf{p}_{US}\times(\hat{\mathbf{y}}\times\mathbf{p}_{US})||\mathbf{p}_{DS}|}\right)$$

- Alternatively $\theta_X^2 + \theta_Y^2 \approx \theta_{Scatt}^2$ where

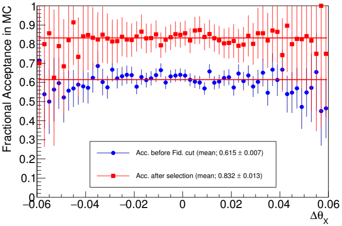
$$\theta_{Scatt} = \frac{\mathbf{p}_{US}\cdot\mathbf{p}_{DS}}{|\mathbf{p}_{US}||\mathbf{p}_{DS}|}$$



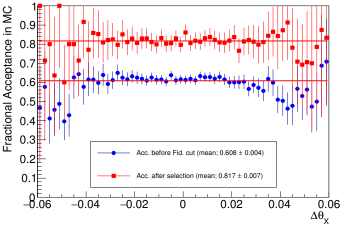


Scattering Angle Acceptances

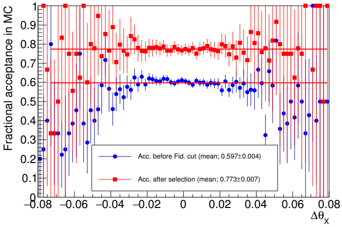
172 MeV/c



200 MeV/c

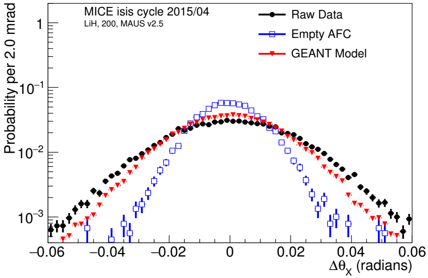


240 MeV/c

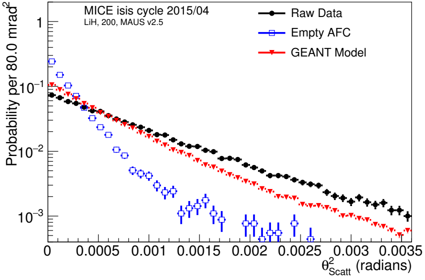


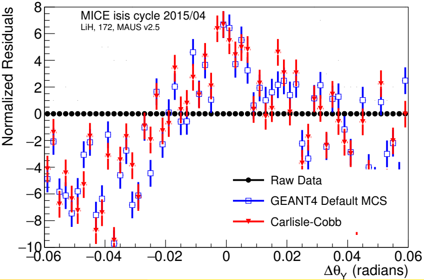
- Fraction of events reconstructed at a scattering angle over the events generated.
- Can only be done in MC.
- Appears flat for $\theta_{X(Y)} < 40$ mrad or $\theta_{Scatt} < 56$ mrad

Convolution of Empty Data and Scattering Models



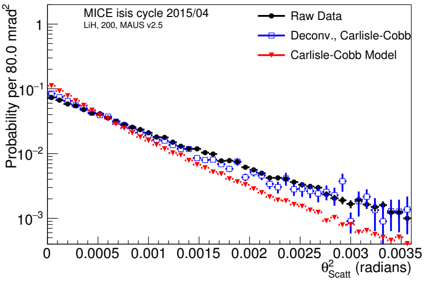
- Add model of scattering in LiH to the Empty AFC data.
- Model is sampled 10 times for each Empty AFC event to increase statistics.
- Ideal for model testing;
  - Calculate "T-test" χ^2 from data and model convolution.

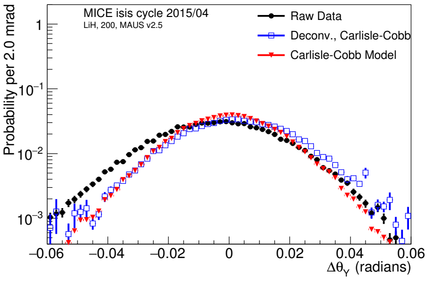




Deconvolution of Absorber Data Using Scattering Models

- Use a iterative algorithm that uses the conditional probability to characterize the response of the reconstructed scattering angle to the true scattering angle.
- Requires a model of the true scattering in the absorber material.
- Convolution between Empty AFC data and scattering models used to provide response.





Summary of Systematics

- Have considered
  - Material thickness uncertainties
  - Alignment uncertainties
- Both found to be negligible
- TOF systematic affects the momentum scale (dominant systematic).
- Fiducial selection could contribute, but more thought in execution required.

Effect	172 MeV/c	200 MeV/c	240 MeV/c
TOF (mrad)	0.6	0.4	0.5
Fiducial Radius (mrad)	0.007	0.006	0.0001
Fiducial Angle (mrad)	0.01	0.01	0.004

Scattering at Three Reference Momenta in LiH

Raw versus convolved distribution

p (MeV/c)		Meas. (mrad)	G4 Pred.	χ^2/DoF	CC Pred.	χ^2/DoF
171.96(5)	Θ_X	22.56±0.28±0.64	20.4(1)	$\frac{630.6}{45}$	20.4(1)	$\frac{597.5}{45}$
171.96(5)	Θ_Y	23.03±0.3±0.52	20.5(1)	$\frac{705.2}{45}$	20.4(1)	$\frac{687.1}{45}$
199.18(4)	Θ_X	19.7±0.13±0.43	18.31(6)	$\frac{688.4}{45}$	17.98(6)	$\frac{874.8}{45}$
199.18(4)	Θ_Y	19.71±0.13±0.41	18.54(6)	$\frac{1131.3}{45}$	18.25(6)	$\frac{1311.4}{45}$
242.54(6)	Θ_X	16.47±0.08±0.49	15.46(4)	$\frac{858.3}{45}$	15.23(4)	$\frac{1597.5}{45}$
242.54(6)	Θ_Y	16.71±0.08±0.48	15.54(4)	$\frac{2455.8}{45}$	15.39(4)	$\frac{2014.1}{45}$
171.96(5)	$\langle\theta^2_{Scatt}\rangle$	32.75±0.77±0.58	28.7(3)	$\frac{959.4}{46}$	28.6(3)	$\frac{1110.8}{46}$
199.18(4)	$\langle\theta^2_{Scatt}\rangle$	27.75±0.3±0.56	25.8(1)	$\frac{872.3}{46}$	25.4(1)	$\frac{1302.1}{46}$
242.54(6)	$\langle\theta^2_{Scatt}\rangle$	23.29±0.18±0.63	21.7(9)	$\frac{1122.7}{46}$	21.53(9)	$\frac{1674.5}{46}$

Scattering at Three Reference Momenta in LiH

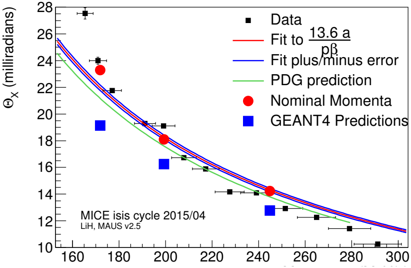
Deconvolved versus Prediction in Absorber

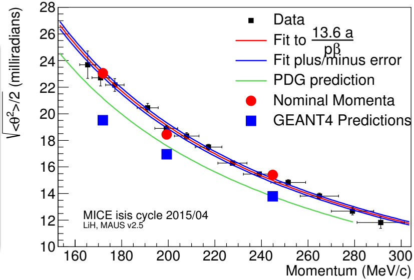
p (MeV/c)		Meas. (mrad)	G4 Pred.	χ^2/DoF	CC Pred.	χ^2/DoF
171.96(5)	Θ_X	22.51±0.24±0.8	19.19(7)	$\frac{2621.1}{45}$	19.38(8)	$\frac{2682.0}{45}$
171.96(5)	Θ_Y	22.5±0.24±0.56	19.15(7)	$\frac{2550.2}{45}$	19.15(7)	$\frac{3038.6}{45}$
199.18(4)	Θ_X	18.52±0.09±0.39	16.54(4)	$\frac{3637.6}{45}$	16.19(3)	$\frac{5513.0}{45}$
199.18(4)	Θ_Y	18.02±0.09±0.36	16.41(4)	$\frac{5174.1}{45}$	16.08(3)	$\frac{5721.0}{45}$
242.54(6)	Θ_X	14.28±0.06±0.42	13.2(3)	$\frac{5159.0}{45}$	13.02(3)	$\frac{8502.1}{45}$
242.54(6)	Θ_Y	14.35±0.06±0.5	13.08(3)	$\frac{10079.2}{45}$	12.91(2)	$\frac{9981.9}{45}$
171.96(5)	$\langle\theta^2_{Scatt}\rangle$	33.84±0.92±0.39	26.9(2)	$\frac{6009.2}{46}$	27.0(2)	$\frac{5908.0}{46}$
199.18(4)	$\langle\theta^2_{Scatt}\rangle$	25.63±0.22±0.58	23.21(8)	$\frac{6955.5}{46}$	22.67(8)	$\frac{10703.0}{46}$
242.54(6)	$\langle\theta^2_{Scatt}\rangle$	20.02±0.12±0.57	18.59(5)	$\frac{7697.3}{46}$	18.31(5)	$\frac{11874.2}{46}$

Momentum Dependence of Scattering

- Most efficient use of data is to add all data together and sample momentum from the sum.
- Extract $a = \sqrt{\frac{z}{X_0}}(1 + 0.038\ln\frac{z}{X_0})$ from fit to 13.6 a/$p\beta$

Width	a
Θ_X	236±2
Θ_Y	232±2
$\sqrt{\langle\theta^2_{scatt}\rangle/2}$	247±3
PDG	228

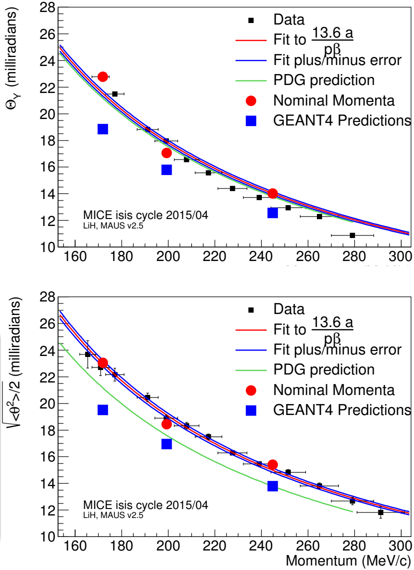




Momentum Dependence of Scattering

- Most efficient use of data is to add all data together and sample momentum from the sum.
- Extract $a = \sqrt{\frac{z}{X_0}}(1 + 0.038\ln\frac{z}{X_0})$ from fit to 13.6 $a/p\beta$

Width	a
Θ_X	236 ± 2
Θ_Y	232 ± 2
$\sqrt{\langle\theta^2_{scatt}\rangle/2}$	247 ± 3
PDG	228



Conclusions

- Work on MCS studies continues.
- Dealt with some worrisome anomalies over Christmas that prevented the release of a new version of the analysis note.
- Remaining house keeping:
  - Clarify systematic effects of the fiducial selection.
  - Implement changes represented here in the note.
- To be continued...?