Validation of Geant4 Proton Scattering
- A CERN Summer Student Project -

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Supervised by
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Outline

Objectives

Task: Implement new test on scattering of hadrons allowing to validate combined electromagnetic and hadronic models for elastic scattering.

Multiple Coulomb Scattering of 160 MeV protons

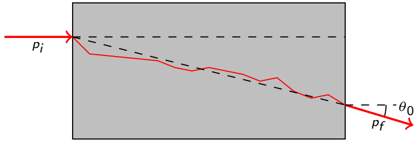
by

B. Gottschalk, A.M. Koehler, R.J. Schneider, J.M. Sisterson and M.S. Wagner
Nucl. Instrum. Method B 74 467
(1993)

- Development of a Geant4 test application
- Deployment of the software as a part of the Geant4 testing infrastructure

Multiple Scattering in Geant4

Due to repeated scattering on atoms, charged particles get deflected when traversing matter.



Different EM Algorithms

- **Urban Model** (opt3)
  - Based on Lewis Theory of MSC and phenomenological approximations
- **Wenzel-VI Model** (opt0)
  - Multiple scattering for small θ
  - Single scattering for large θ
  - Wentzel cross section

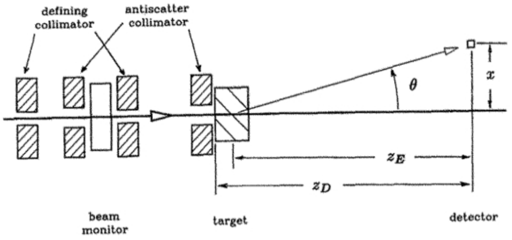
Different HAD Algorithms

- **Chips Elastic Model** (elastic)
- **Hadron Elastic Diffuse Model** (DElastic)
- **Glauber Hadron Elastic Model** (HElastic)

Experimental Setup

- Target as stack of foils
- Scan plane is positioned 100 cm downstream of the target front
- Protons were detected by small silicon diode positioned across the beam by means of a lead screw
- Measure transverse position $x_i \Rightarrow \theta_i = \arctan\left(\frac{x_i}{z_E}\right)$, where $z_E = z_D - z_0$ effective detector distance

Typical Setup



[Gottschalk et al., 1993]

Multiple Coulomb Scattering of 160 MeV protons

What is provided by the paper from Gottschalk et al.?

- In order to measure MSC of low energy protons in matter, characteristic angles, θ_M and θ_0, are presented for 14 different materials
- Targets ranged from thin (negligible energy loss) to very thick (greater than the mean proton range)
- Data fitting with Moliere scattering distribution

$$f(\theta) = \frac{1}{2\pi\theta_M^2}\frac{1}{2}\left[f^{(0)}(\theta') + \frac{f^{(1)}(\theta')}{B} + \frac{f^{(2)}(\theta')}{B^2}\right], \quad (1)$$

  where $\theta' = \frac{\theta}{\sqrt{2}\theta_M}$ and $\theta_M^2 = \frac{\chi_c^2 B}{2}$
- Data fitting with Gaussian Distribution

$$f(\theta) = \frac{1}{2\pi\theta_0^2}\exp\left[-\frac{\theta^2}{2\theta_0^2}\right] \quad (2)$$

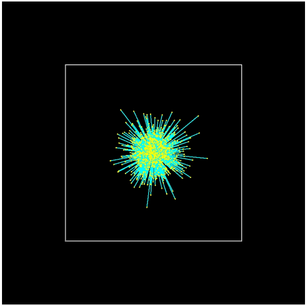
- Data fitting compared with Highland formula

$$\theta_H = \frac{14.1\text{MeV}}{pv} z\sqrt{\frac{L}{L_R}}\left[1 + \frac{1}{9}\log_{10}\left(\frac{L}{L_R}\right)\right] \quad (3)$$

Simulation Setup

- Particle gun produces one proton per event
- On a target scattered protons are measured by a scoring plane (SD)
- 10^5 events per run, one run per thickness value
- Angle distributions are fitted with Gaussian in $\pm 2.5\sigma$ range

Front



Side

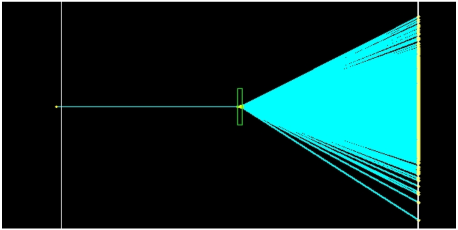
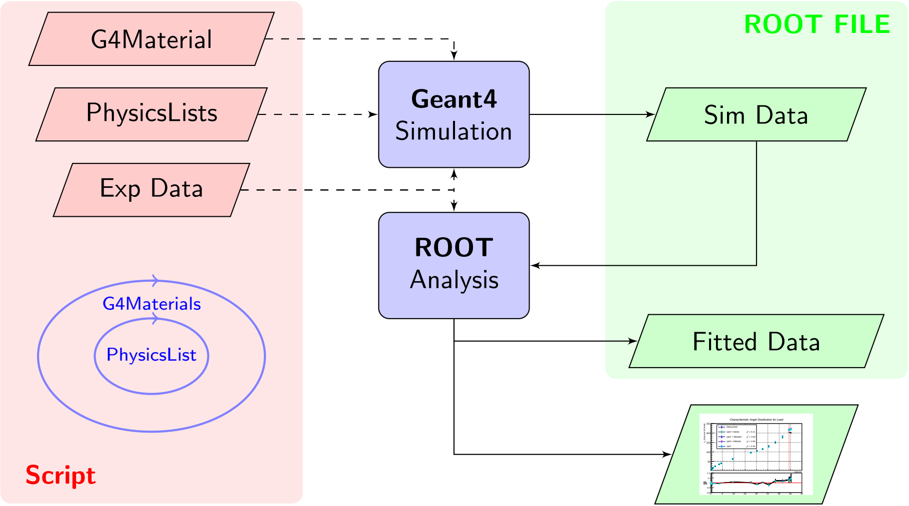


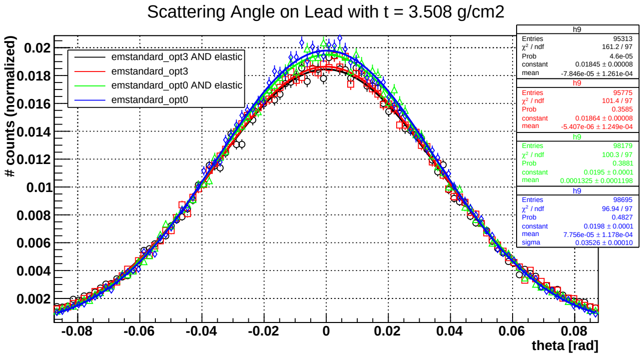
Chart Flow


G4Material
PhysicsLists
Exp Data
G4Materials
PhysicsList
Script
Geant4
Simulation
ROOT
Analysis
ROOT FILE
Sim Data
Fitted Data

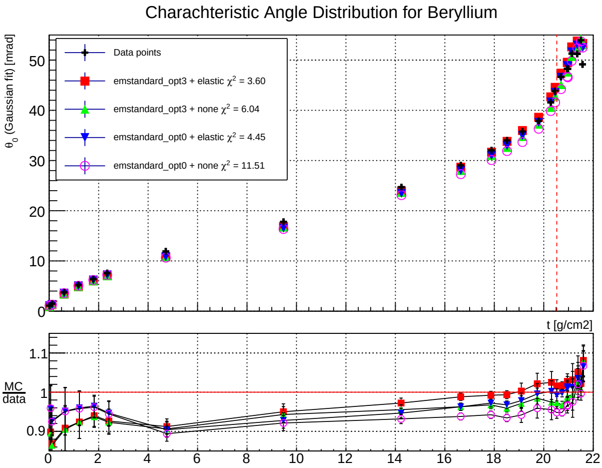
Scattering Angle Fitting

Since the fitting was performed with a Gaussian, the range limitation like $\pm 2.5\sigma$ becomes important cause of non-Gaussian behaviour at the angle distribution tails

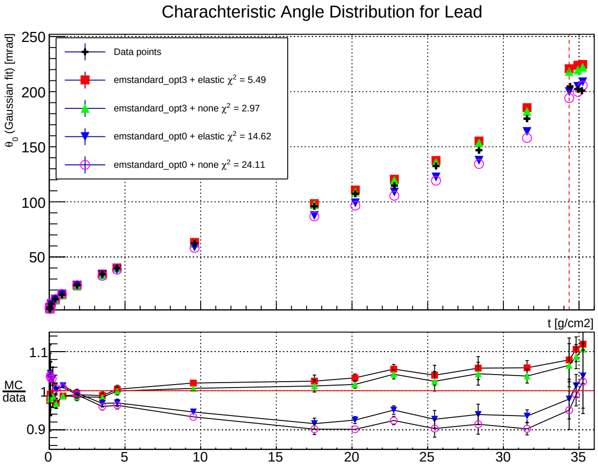
Gaussian Fit



Electromagnetic PhysicsList Comparison

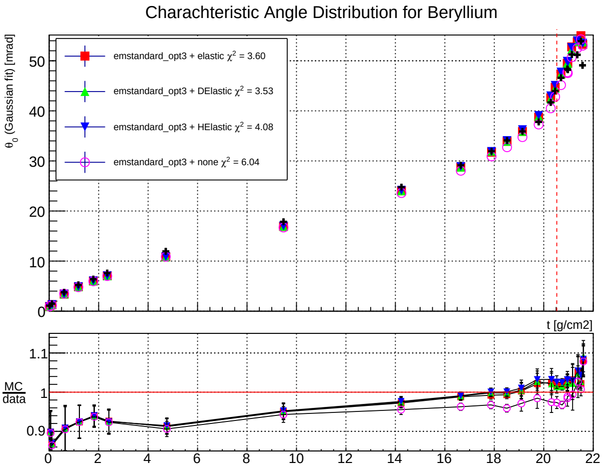


Adding hadron elastic PhysicsList yields improvements

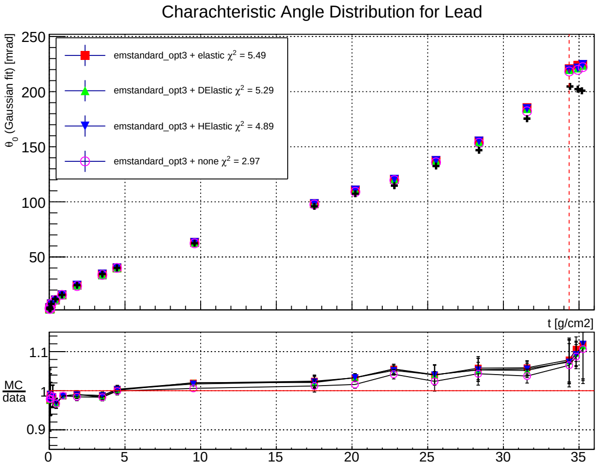


But shows an overestimating for more dense materials in the case of opt3

Hadron Elastic PhysicsList Comparison



No difference between elastic, DElastic and HElastic for thin targets



But slightly differ between each other for thicker targets

Summary I

χ^2 values	opt3				opt0			
Material	**no**	**el**	**DE**	**HE**	**no**	**el**	**DE**	**HE**
Beryllium	6.04	3.60	3.53	4.08	11.51	4.45	4.03	3.87
Polystyrene	28.63	24.20	24.29	23.64	23.98	19.60	18.60	18.52
Carbon	6.36	5.92	5.61	5.89	1.91	1.67	1.73	1.79
Lexan	16.57	15.82	16.12	16.10	3.85	4.01	3.94	3.95
Nylon	1.70	1.60	1.64	1.57	3.85	4.01	3.94	3.95
Lucite	19.64	19.04	19.83	19.32	4.41	4.25	4.02	3.98
Teflon	10.49	4.71	3.81	3.40	13.61	5.80	4.54	4.38
Aluminium	10.29	6.68	6.04	6.23	11.56	6.73	5.58	5.82
Copper	13.41	7.74	7.66	7.71	26.05	13.35	11.99	11.26
Zinc	2.75	2.88	2.87	2.85	0.14	0.13	0.13	0.12
Brass	43.16	78.21	74.34	91.35	69.89	22.30	24.96	26.08
Tin	2.10	1.92	1.93	1.92	0.29	0.34	0.34	0.33
Lead	2.97	5.49	5.29	4.89	24.11	14.62	15.78	15.56
Uranium	5.60	9.61	9.95	9.08	76.45	52.52	54.98	53.61

Summary II (RangeFactor = 0.04)

χ^2 values	opt3				opt0			
Material	**no**	**el**	**DE**	**HE**	**no**	**el**	**DE**	**HE**
Beryllium	6.03	3.60	3.51	4.09	11.51	4.45	4.03	3.87
Polystyrene	28.63	24.21	24.30	23.65	23.98	19.60	18.60	18.52
Carbon	6.36	5.92	5.61	5.92	1.91	1.67	1.73	1.79
Lexan	16.58	15.84	16.03	16.09	3.95	4.01	3.94	3.85
Nylon	1.70	1.60	1.67	1.54	0.12	0.12	0.13	0.13
Lucite	19.46	19.04	19.82	19.32	4.41	4.25	4.02	3.98
Teflon	10.49	4.70	3.82	3.40	13.61	5.80	4.54	4.38
Aluminium	10.26	6.70	6.03	6.22	11.56	6.73	5.58	5.82
Copper	13.45	7.68	7.63	7.72	26.05	13.35	12.00	11.26
Zinc	2.74	2.89	2.88	2.86	0.14	0.13	0.13	0.12
Brass	43.09	78.34	74.73	89.93	69.89	22.22	24.90	26.10
Tin	2.10	1.92	1.93	1.92	0.29	0.34	0.34	0.33
Lead	2.97	5.49	5.21	4.91	15.60	9.49	9.63	9.65
Uranium	5.61	9.42	9.72	9.22	39.41	23.49	24.23	23.50

Summary III (StepLimit = 1mm)

χ^2 values	opt3				opt0			
Material	**no**	**el**	**DE**	**HE**	**no**	**el**	**DE**	**HE**
Beryllium	7.52	3.09	2.76	2.98	3.39	2.08	1.91	2.80
Polystyrene	26.95	21.66	21.31	20.73	11.13	8.50	8.24	7.87
Carbon	3.86	3.66	3.79	3.71	1.54	1.48	1.47	1.55
Lexan	11.79	11.09	11.30	11.14	3.24	3.10	3.23	3.23
Nylon	0.98	0.92	0.94	0.96	0.09	0.10	0.09	0.09
Lucite	11.76	12.65	12.38	12.35	3.58	3.33	2.93	3.05
Teflon	11.46	4.31	3.20	2.86	6.27	1.50	1.02	0.89
Aluminium	8.86	4.88	4.11	3.96	5.20	2.55	2.40	2.18
Copper	12.15	6.75	5.99	5.57	15.48	6.64	6.18	5.44
Zinc	2.75	2.88	2.87	2.85	0.14	0.13	0.13	0.12
Brass	39.70	65.41	76.72	85.82	42.45	23.65	22.52	28.14
Tin	2.10	1.92	1.93	1.92	0.29	0.34	0.34	0.33
Lead	2.85	5.62	4.84	5.55	11.19	4.72	5.36	5.28
Uranium	7.01	13.44	11.63	12.64	32.35	18.15	20.04	19.43

Conclusion

1. **Physics**:
   - Better agreements for *opt3* than for *opt0*
   - Hadron elastic effects contributes essentially to the peak for thick targets
   - Changing hadron elastic PhysicsLists yields only slightly differences (largest χ^2 value for default PhysicsList *elastic*)
   - Step limitation dependence
   - There is a room to improve Geant4 models
2. **Software**:
   - New test is created and committed to repository
   - Validation tool offers possibility to change PhysicsLists, list of materials, step limitations and cuts
   - Approximated run times: $t_{\text{default}} \approx 3h$, $t_{\text{RangeFactor}} \approx t_{\text{StepSizeLimit}} \approx 5h$

Thank you for your attention! Questions?

BACKUP SLIDES

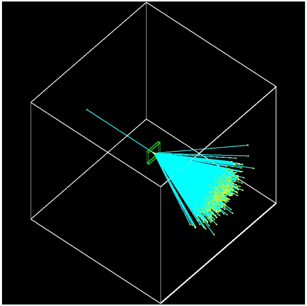
Air Runs

- For each new setup at least one 'air' scan was taken to determine the target out beam profile at the diode
- Each θ_0^{exp} then was subtracted in quadrature by θ_0^{air} coming from the corresponding air scan
- air scans are usually used to correct several thin target runs
- additional effects due to multiple scattering of protons in air, beam widths and beam divergence

$\Rightarrow$ No air scans

$\Rightarrow$ Use vacuum as world volume material

MSCP Test App



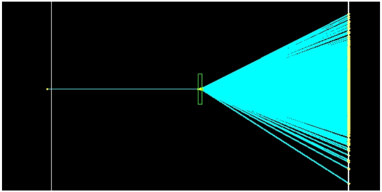
Effective Detector Distance

As a small correction to the source to detector distance, we need to know the effective origin of protons coming from a target in which they have multiple scattered

- The same analysis is done as presented by Gottschalk et al.
- Characteristic transverse kick projected to the scoring plane from layer of target:

$$y_0(Z) = 14.1\text{MeV}\left(1 + \frac{1}{9}\log_{10}\frac{t}{L_R}\right)\left[\int_0^{z_{\max}}\left(\frac{Z-z}{pv}\right)^2\frac{\rho}{L_R}dz\right]^{\frac{1}{2}}$$

MSCP Test App

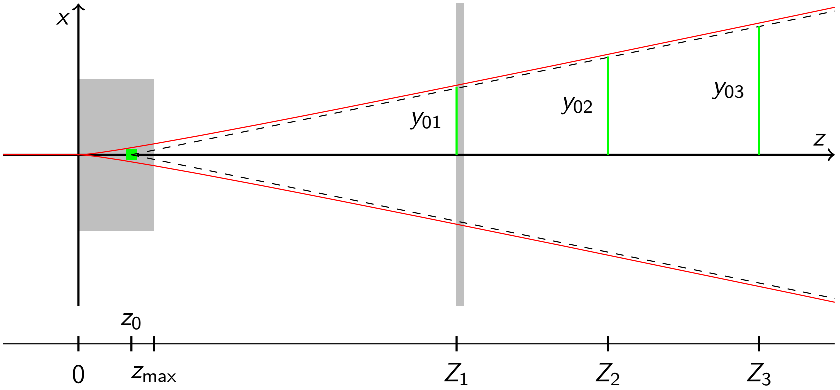


$$Z_1 = L$$

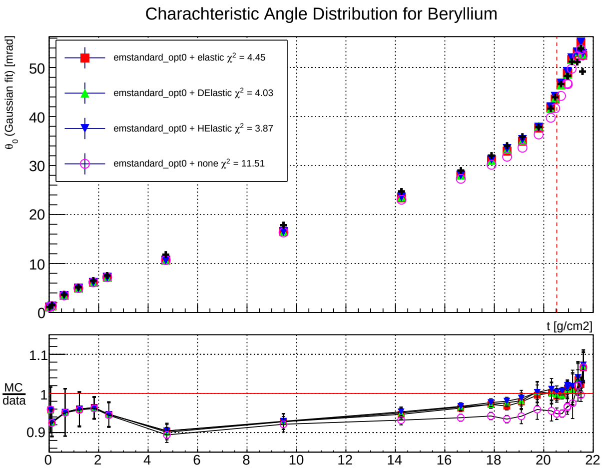
$$Z_{2,3} = Z_1 + c_{2,3}\frac{y_{01}}{\theta_0}, \quad c_i = \begin{cases} 10 & i = 2 \\ 20 & i = 3 \end{cases}$$

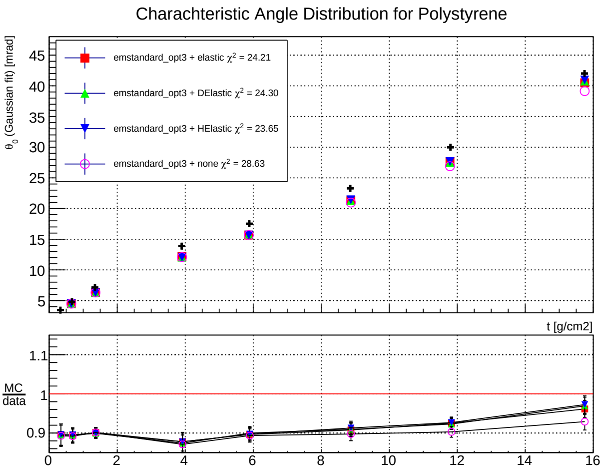
$$z_0 = \frac{y_{03}Z_2 - y_{02}Z_3}{y_{03} - y_{02}}, \quad \theta_0 = \frac{y_{03} - y_{02}}{Z_3 - Z_2}$$

Effective Detector Distance Derivation

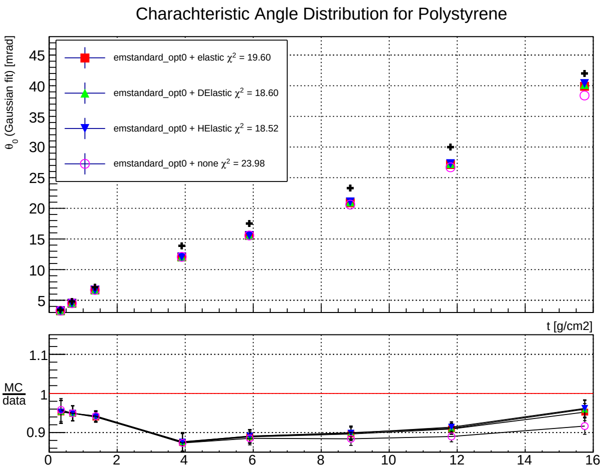


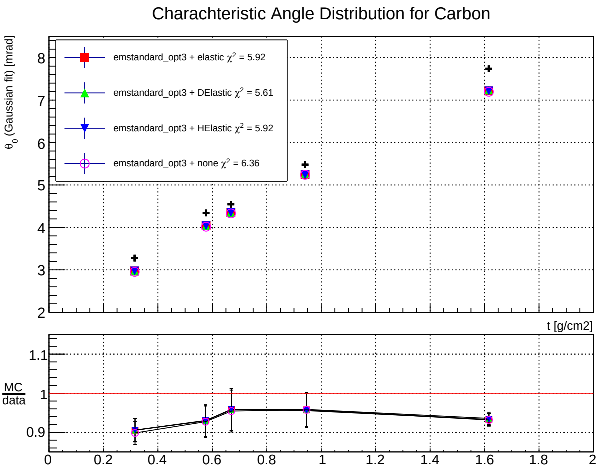
$$\frac{y_{02}}{Z_2 - z_0} = \frac{y_{03}}{Z_3 - z_0} \quad \Rightarrow \quad z_0 = \frac{y_{03}Z_2 - y_{02}Z_3}{y_{03} - y_{02}}$$

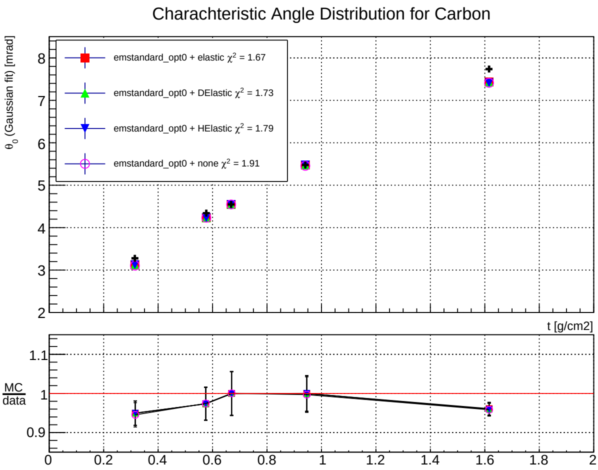

Charachteristic Angle Distribution for Beryllium
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 4.45
emstandard_opt0 + DElastic χ2 = 4.03
emstandard_opt0 + HElastic χ2 = 3.87
emstandard_opt0 + none χ2 = 11.51
t [g/cm2]
MC/data
0
2
4
6
8
10
12
14
16
18
20
22
10
20
30
40
50
0.9
1
1.1

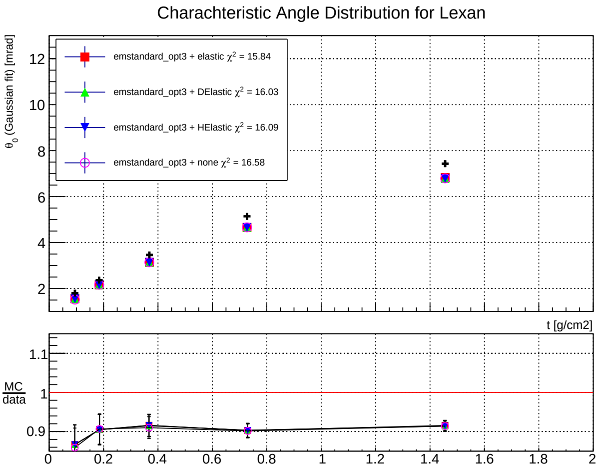


Charachteristic Angle Distribution for Polystyrene
θ0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ2 = 24.21
emstandard_opt3 + DElastic χ2 = 24.30
emstandard_opt3 + HElastic χ2 = 23.65
emstandard_opt3 + none χ2 = 28.63
45
40
35
30
25
20
15
10
5
t [g/cm2]
MC
data
1.1
1
0.9
0
2
4
6
8
10
12
14
16

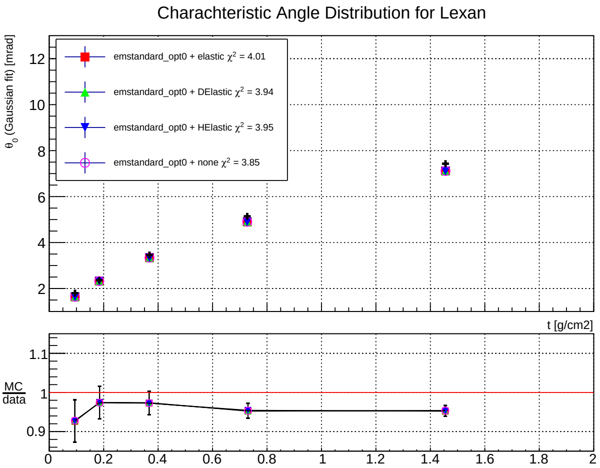

Charachteristic Angle Distribution for Polystyrene
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 19.60
emstandard_opt0 + DElastic χ2 = 18.60
emstandard_opt0 + HElastic χ2 = 18.52
emstandard_opt0 + none χ2 = 23.98
t [g/cm2]
MC/data
45
40
35
30
25
20
15
10
5
1.1
1
0.9
0
2
4
6
8
10
12
14
16


Charachteristic Angle Distribution for Carbon
emstandard_opt3 + elastic χ2 = 5.92
emstandard_opt3 + DElastic χ2 = 5.61
emstandard_opt3 + HElastic χ2 = 5.92
emstandard_opt3 + none χ2 = 6.36
θ0 (Gaussian fit) [mrad]
t [g/cm2]
MC/data
2
3
4
5
6
7
8
0.9
1
1.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

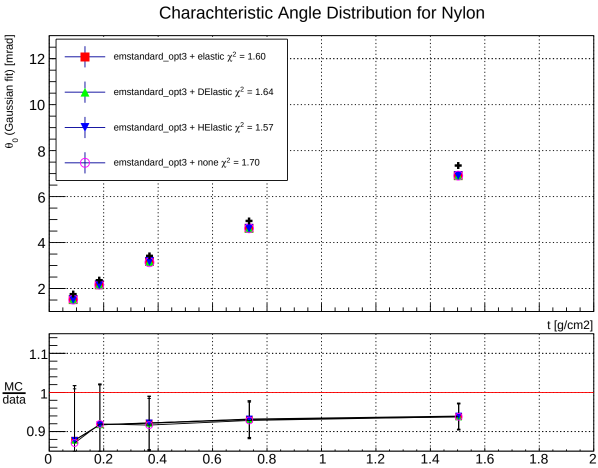

Charachteristic Angle Distribution for Carbon
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 1.67
emstandard_opt0 + DElastic χ2 = 1.73
emstandard_opt0 + HElastic χ2 = 1.79
emstandard_opt0 + none χ2 = 1.91
t [g/cm2]
MC
data
2
3
4
5
6
7
8
0.9
1
1.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

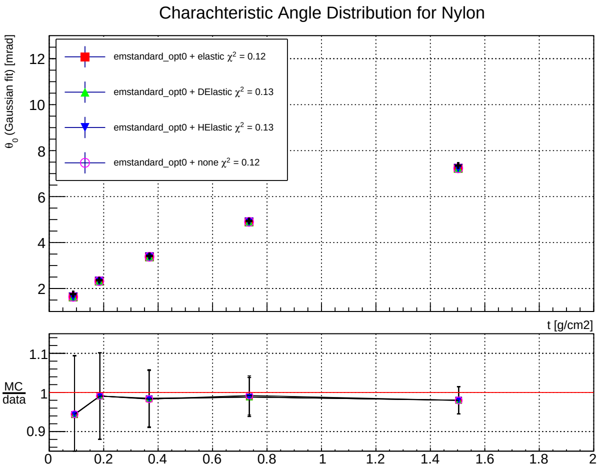


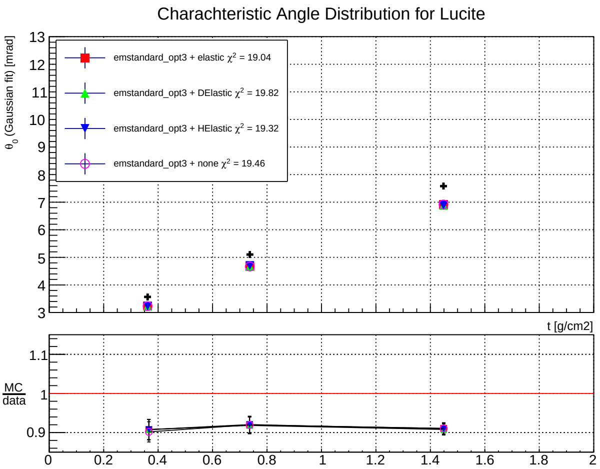
Charachteristic Angle Distribution for Lexan
θ_0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ^2 = 15.84
emstandard_opt3 + DElastic χ^2 = 16.03
emstandard_opt3 + HElastic χ^2 = 16.09
emstandard_opt3 + none χ^2 = 16.58
12
10
8
6
4
2
t [g/cm2]
1.1
MC / data
1
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

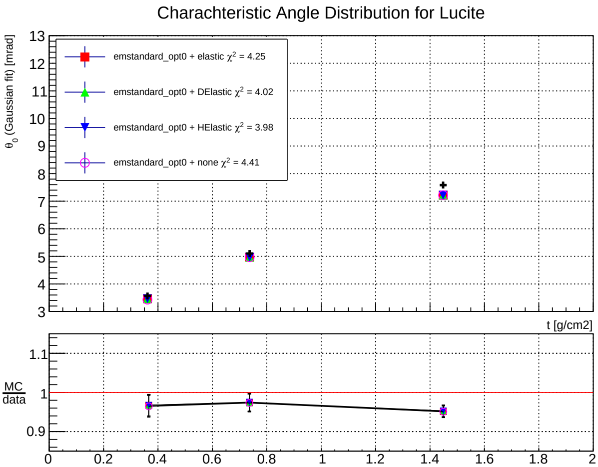


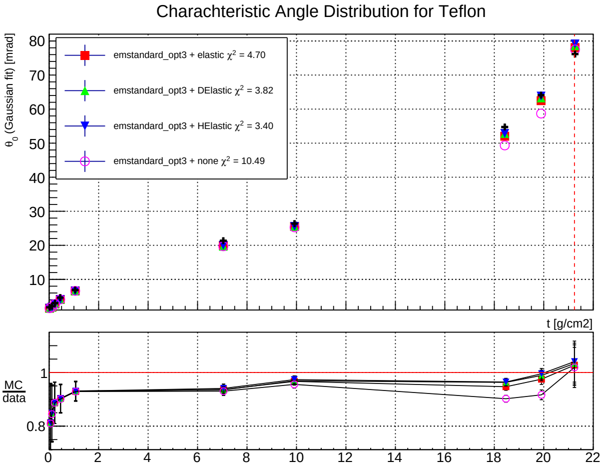
Charachteristic Angle Distribution for Lexan
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 4.01
emstandard_opt0 + DElastic χ2 = 3.94
emstandard_opt0 + HElastic χ2 = 3.95
emstandard_opt0 + none χ2 = 3.85
t [g/cm2]
MC/data

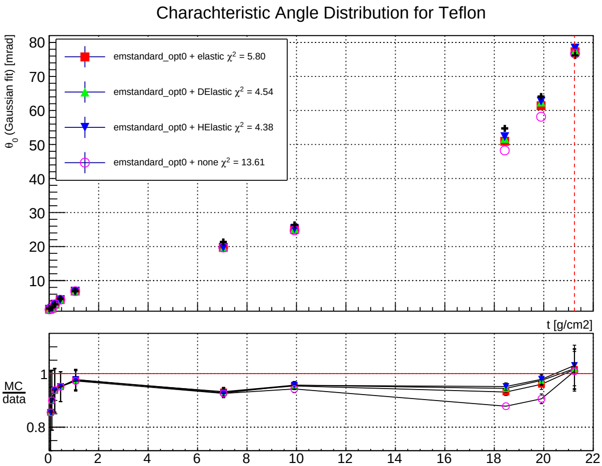

Charachteristic Angle Distribution for Nylon
θ0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ2 = 1.60
emstandard_opt3 + DElastic χ2 = 1.64
emstandard_opt3 + HElastic χ2 = 1.57
emstandard_opt3 + none χ2 = 1.70
t [g/cm2]
MC/data
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


Charachteristic Angle Distribution for Nylon
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 0.12
emstandard_opt0 + DElastic χ2 = 0.13
emstandard_opt0 + HElastic χ2 = 0.13
emstandard_opt0 + none χ2 = 0.12
t [g/cm2]
MC/data
12
10
8
6
4
2
1.1
1
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

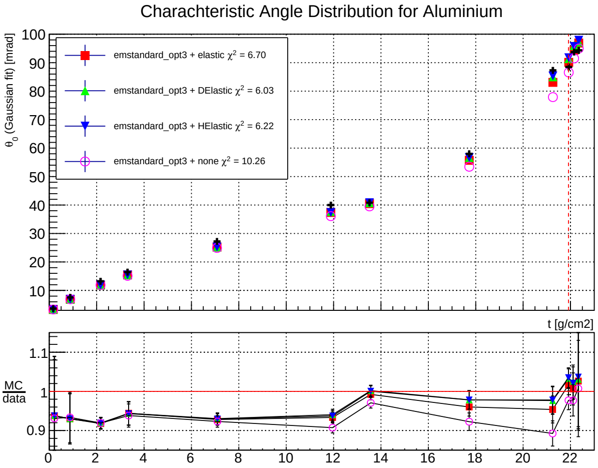

Charachteristic Angle Distribution for Lucite
θ0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ2 = 19.04
emstandard_opt3 + DElastic χ2 = 19.82
emstandard_opt3 + HElastic χ2 = 19.32
emstandard_opt3 + none χ2 = 19.46
t [g/cm2]
MC
data
13
12
11
10
9
8
7
6
5
4
3
1.1
1
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

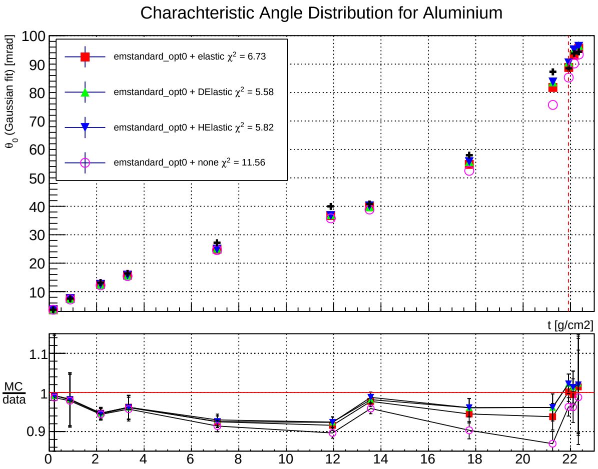

Charachteristic Angle Distribution for Lucite
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 4.25
emstandard_opt0 + DElastic χ2 = 4.02
emstandard_opt0 + HElastic χ2 = 3.98
emstandard_opt0 + none χ2 = 4.41
t [g/cm2]
MC/data
13
12
11
10
9
8
7
6
5
4
3
1.1
1
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


Charachteristic Angle Distribution for Teflon
θ0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ2 = 4.70
emstandard_opt3 + DElastic χ2 = 3.82
emstandard_opt3 + HElastic χ2 = 3.40
emstandard_opt3 + none χ2 = 10.49
t [g/cm2]
MC
data

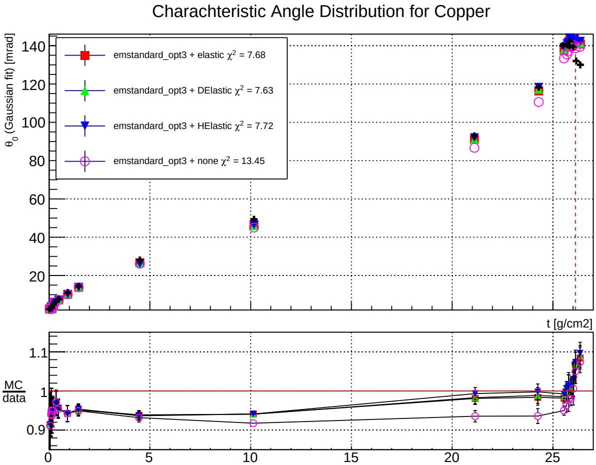


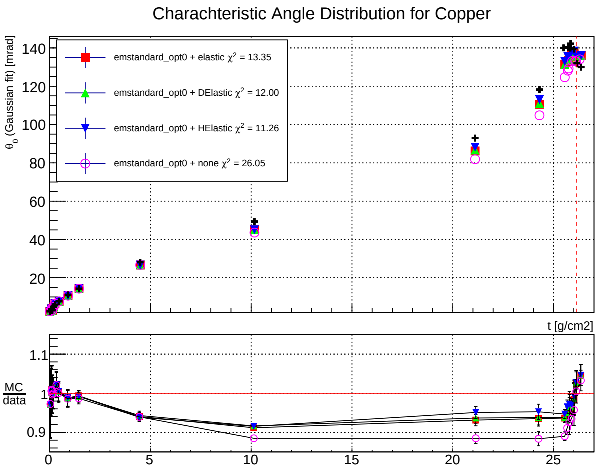
Charachteristic Angle Distribution for Teflon
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 5.80
emstandard_opt0 + DElastic χ2 = 4.54
emstandard_opt0 + HElastic χ2 = 4.38
emstandard_opt0 + none χ2 = 13.61
t [g/cm2]
MC/data
0
2
4
6
8
10
12
14
16
18
20
22

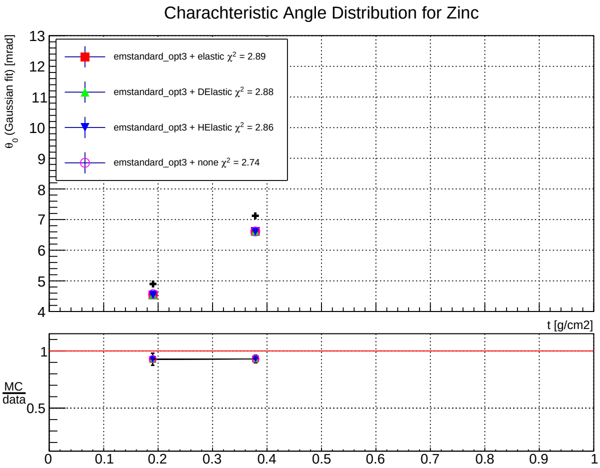

Charachteristic Angle Distribution for Aluminium
θ_0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ^2 = 6.70
emstandard_opt3 + DElastic χ^2 = 6.03
emstandard_opt3 + HElastic χ^2 = 6.22
emstandard_opt3 + none χ^2 = 10.26
t [g/cm2]
MC / data
0
2
4
6
8
10
12
14
16
18
20
22
10
20
30
40
50
60
70
80
90
100
0.9
1
1.1

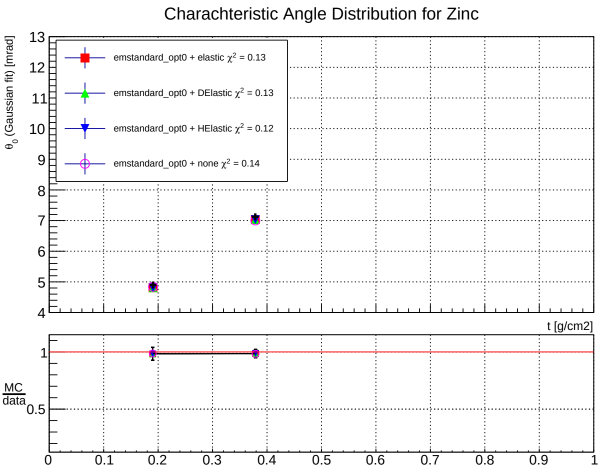


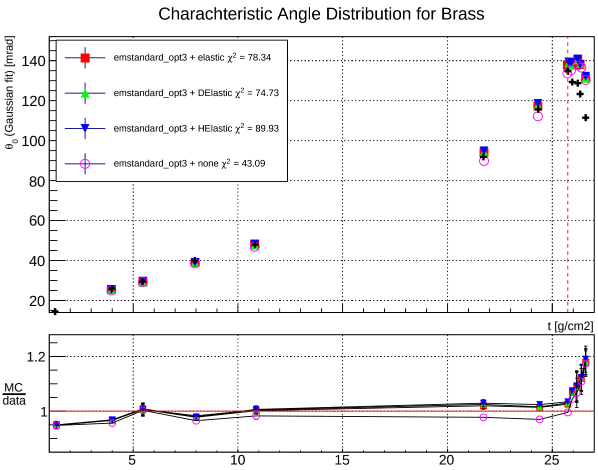
Charachteristic Angle Distribution for Aluminium
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 6.73
emstandard_opt0 + DElastic χ2 = 5.58
emstandard_opt0 + HElastic χ2 = 5.82
emstandard_opt0 + none χ2 = 11.56
t [g/cm2]
MC
data

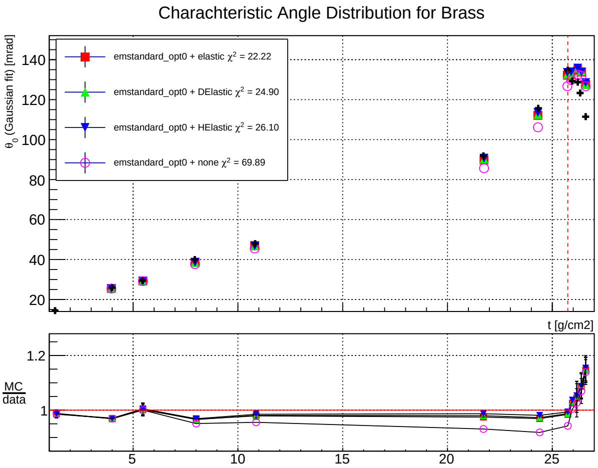

Charachteristic Angle Distribution for Copper
θ_0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ^2 = 7.68
emstandard_opt3 + DElastic χ^2 = 7.63
emstandard_opt3 + HElastic χ^2 = 7.72
emstandard_opt3 + none χ^2 = 13.45
140
120
100
80
60
40
20
t [g/cm2]
MC/data
1.1
1
0.9
0
5
10
15
20
25


Charachteristic Angle Distribution for Copper
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 13.35
emstandard_opt0 + DElastic χ2 = 12.00
emstandard_opt0 + HElastic χ2 = 11.26
emstandard_opt0 + none χ2 = 26.05
t [g/cm2]
MC / data
0
5
10
15
20
25
20
40
60
80
100
120
140
0.9
1
1.1

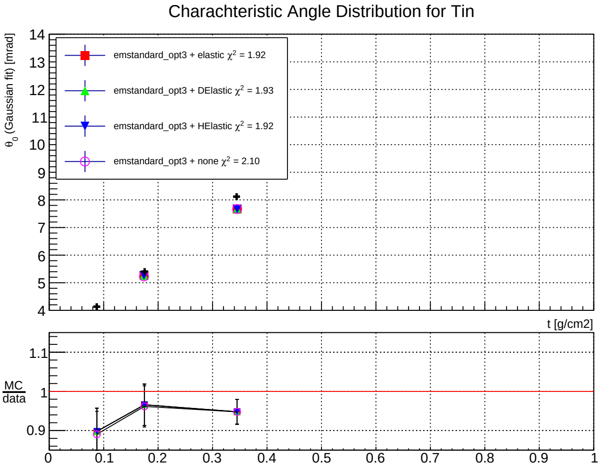

Charachteristic Angle Distribution for Zinc
θ_0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ² = 2.89
emstandard_opt3 + DElastic χ² = 2.88
emstandard_opt3 + HElastic χ² = 2.86
emstandard_opt3 + none χ² = 2.74
t [g/cm2]
MC
data
13
12
11
10
9
8
7
6
5
4
1
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

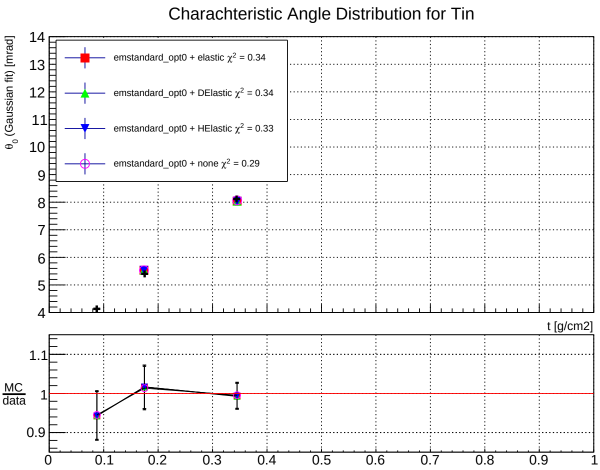

Charachteristic Angle Distribution for Zinc
θ_0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ^2 = 0.13
emstandard_opt0 + DElastic χ^2 = 0.13
emstandard_opt0 + HElastic χ^2 = 0.12
emstandard_opt0 + none χ^2 = 0.14
t [g/cm2]
MC/data
13
12
11
10
9
8
7
6
5
4
1
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

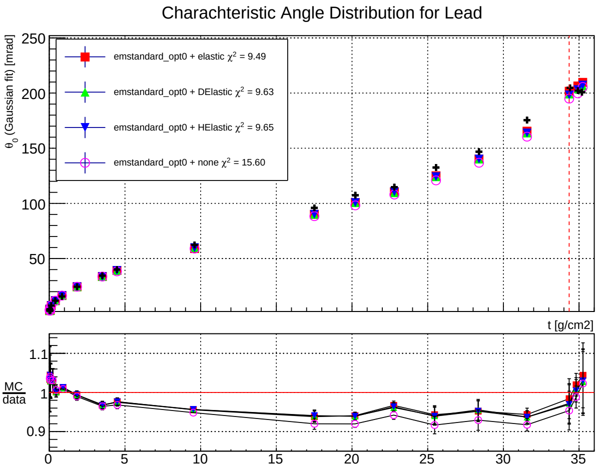

Charachteristic Angle Distribution for Brass
emstandard_opt3 + elastic χ2 = 78.34
emstandard_opt3 + DElastic χ2 = 74.73
emstandard_opt3 + HElastic χ2 = 89.93
emstandard_opt3 + none χ2 = 43.09
θ0 (Gaussian fit) [mrad]
140
120
100
80
60
40
20
t [g/cm2]
MC
data
1.2
1
5
10
15
20
25



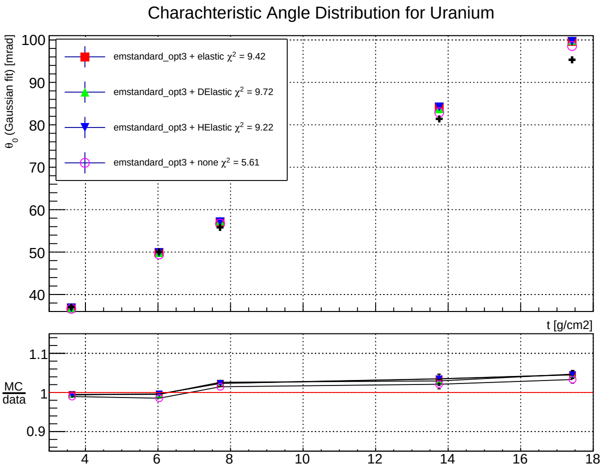
Charachteristic Angle Distribution for Brass
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 22.22
emstandard_opt0 + DElastic χ2 = 24.90
emstandard_opt0 + HElastic χ2 = 26.10
emstandard_opt0 + none χ2 = 69.89
t [g/cm2]
MC/data
20
40
60
80
100
120
140
1
1.2
5
10
15
20
25

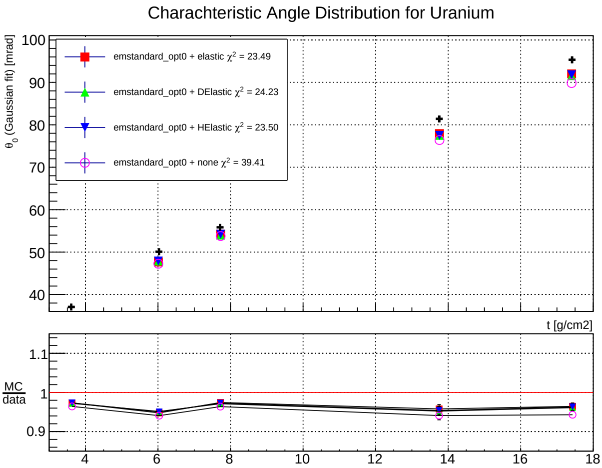

Charachteristic Angle Distribution for Tin
θ0 (Gaussian fit) [mrad]
emstandard_opt3 + elastic χ2 = 1.92
emstandard_opt3 + DElastic χ2 = 1.93
emstandard_opt3 + HElastic χ2 = 1.92
emstandard_opt3 + none χ2 = 2.10
t [g/cm2]
MC/data


Charachteristic Angle Distribution for Tin
θ0 (Gaussian fit) [mrad]
emstandard_opt0 + elastic χ2 = 0.34
emstandard_opt0 + DElastic χ2 = 0.34
emstandard_opt0 + HElastic χ2 = 0.33
emstandard_opt0 + none χ2 = 0.29
t [g/cm2]
MC / data
4 5 6 7 8 9 10 11 12 13 14
0.9 1 1.1
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1



Charachteristic Angle Distribution for Lead
emstandard_opt0 + elastic χ2 = 9.49
emstandard_opt0 + DElastic χ2 = 9.63
emstandard_opt0 + HElastic χ2 = 9.65
emstandard_opt0 + none χ2 = 15.60
θ0 (Gaussian fit) [mrad]
250
200
150
100
50
t [g/cm2]
1.1
MC
data
1
0.9
0
5
10
15
20
25
30
35


Charachteristic Angle Distribution for Uranium
θ0 (Gaussian fit) [mrad]
100
90
80
70
60
50
40
emstandard_opt3 + elastic χ2 = 9.42
emstandard_opt3 + DElastic χ2 = 9.72
emstandard_opt3 + HElastic χ2 = 9.22
emstandard_opt3 + none χ2 = 5.61
t [g/cm2]
MC / data
1.1
1
0.9
4
6
8
10
12
14
16
18


Charachteristic Angle Distribution for Uranium
θ0 (Gaussian fit) [mrad]
100
90
80
70
60
50
40
emstandard_opt0 + elastic χ2 = 23.49
emstandard_opt0 + DElastic χ2 = 24.23
emstandard_opt0 + HElastic χ2 = 23.50
emstandard_opt0 + none χ2 = 39.41
t [g/cm2]
MC
data
1.1
1
0.9
4
6
8
10
12
14
16
18