XV CPAN DAYS

A Monte Carlo Study of Different LET Definitions using PENH

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Protontherapy

- Growth of proton therapy.

- Biological effect may not only be given by physical dose.

- (Unrestricted) **linear energy transfer (LET)** = Electronic Stopping Power = $\frac{dE}{dz}$

- Only defined for a determined particle with specific energy.

LET Averages

- Average of LET needed for many particles.

- In our previous studies, we used the intuitive formulas:

$$\bar{L}_t(z) = \frac{\int \phi_E(z)\, S(E)\, dE}{\int \phi_E(z)\, dE} \qquad \bar{L}_d(z) = \frac{\int \phi_E(z)\, S^2(E)\, dE}{\int \phi_E(z)\, S(E)\, dE}$$

- Analytical formulas available (Wilkens et al., 2003).

Monte Carlo Simulations

- Monte Carlo simulations are the gold standard in radiation transport.
- Different options to implement LET averages. -> No consensus (Kalholm, 2021)
- Source of uncertainty for treatment's biological effect.

Implementations Considered

$$\bar{L}_t(z) = \frac{\sum_{E_i} \phi_{E_i}(z)\ S(E_i)\ \Delta E}{\sum_{E_i} \phi_{E_i}(z)\ \Delta E}$$

$$\bar{L}_d(z) = \frac{\sum_{E_i} \phi_{E_i}(z)\ S^2(E_i)\ \Delta E}{\sum_{E_i} \phi_{E_i}(z)\ S(E_i)\ \Delta E}$$

- ϕ_{E_i} : proton energy spectrum.
- $S(E_i)$: electronic stopping power.
- Implicit assumption:

$$D(E_i) = \phi_{E_i} \cdot S(E_i)$$

Implementations Considered

- Previous formulas have issues.

- Here (Granville et al., 2015):

$$\bar{L}_t = \frac{\sum_i^N dx_i \, S_i(E)}{\sum_i^N dx_i} \qquad \bar{L}_d = \frac{\sum_i^N e_i \, S_i(E)}{\sum_i^N e_i}$$

- We will test them and compare with TOPAS and FLUKA.

Benchmarking

- Self consistency tests.

    1. Nuclear reactions suppressed.

    2. Full calculations.

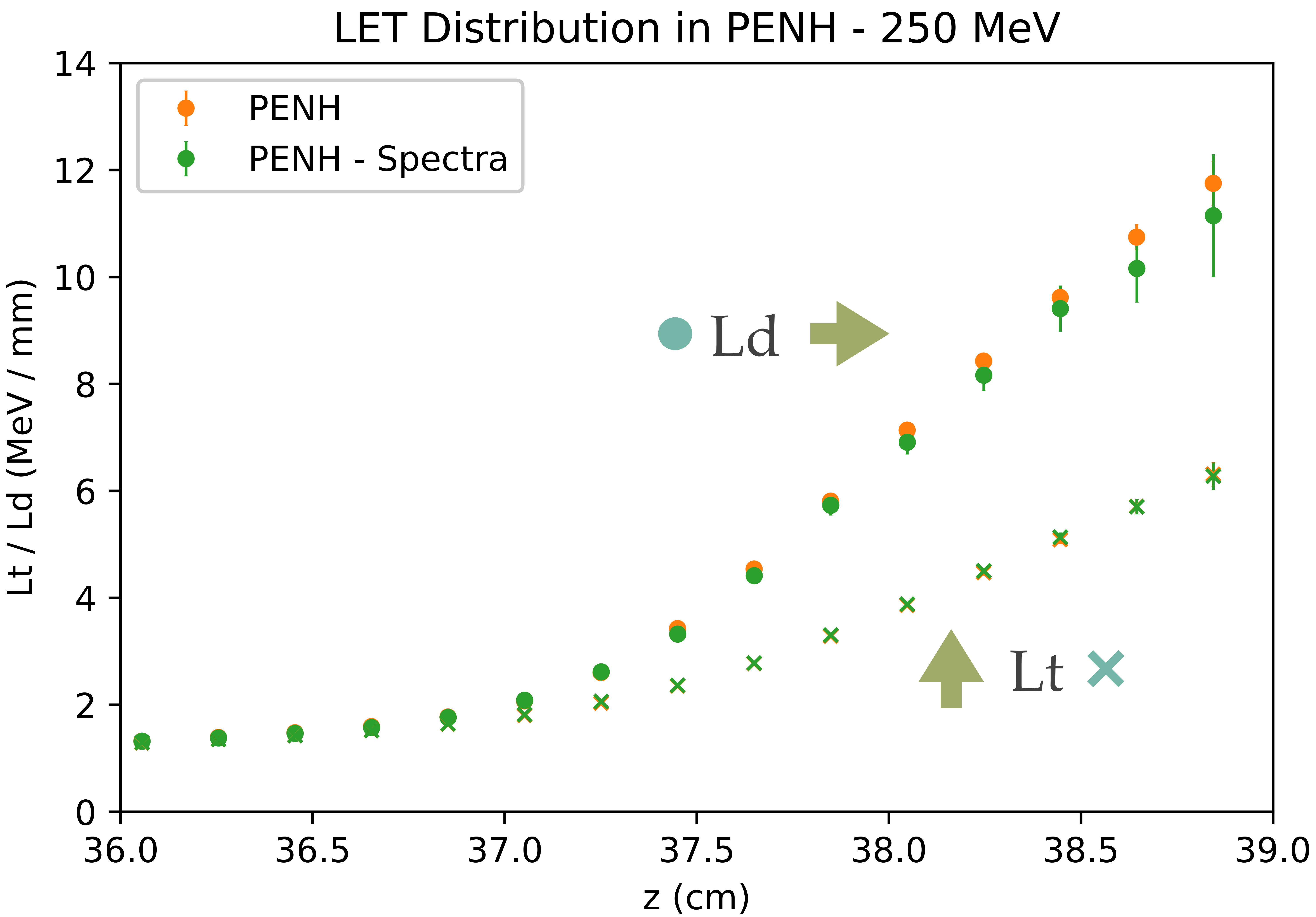
- Comparison with previous Monte Carlo studies.

Simulation Details

MC Codes Comparison	TOPAS, FLUKA
Type of beam	Pencil beam
Energies	75, 160, 250 MeV
Geometry	1 cm x 1cm x (7, 30.1, 50) cm
Voxelization	1 cm x 1 cm x (0.07, 0.2, 0.2) cm
Cutoffs protons	0.025 MeV
Quantity	Unrestricted LET in water. Only protons contribute.

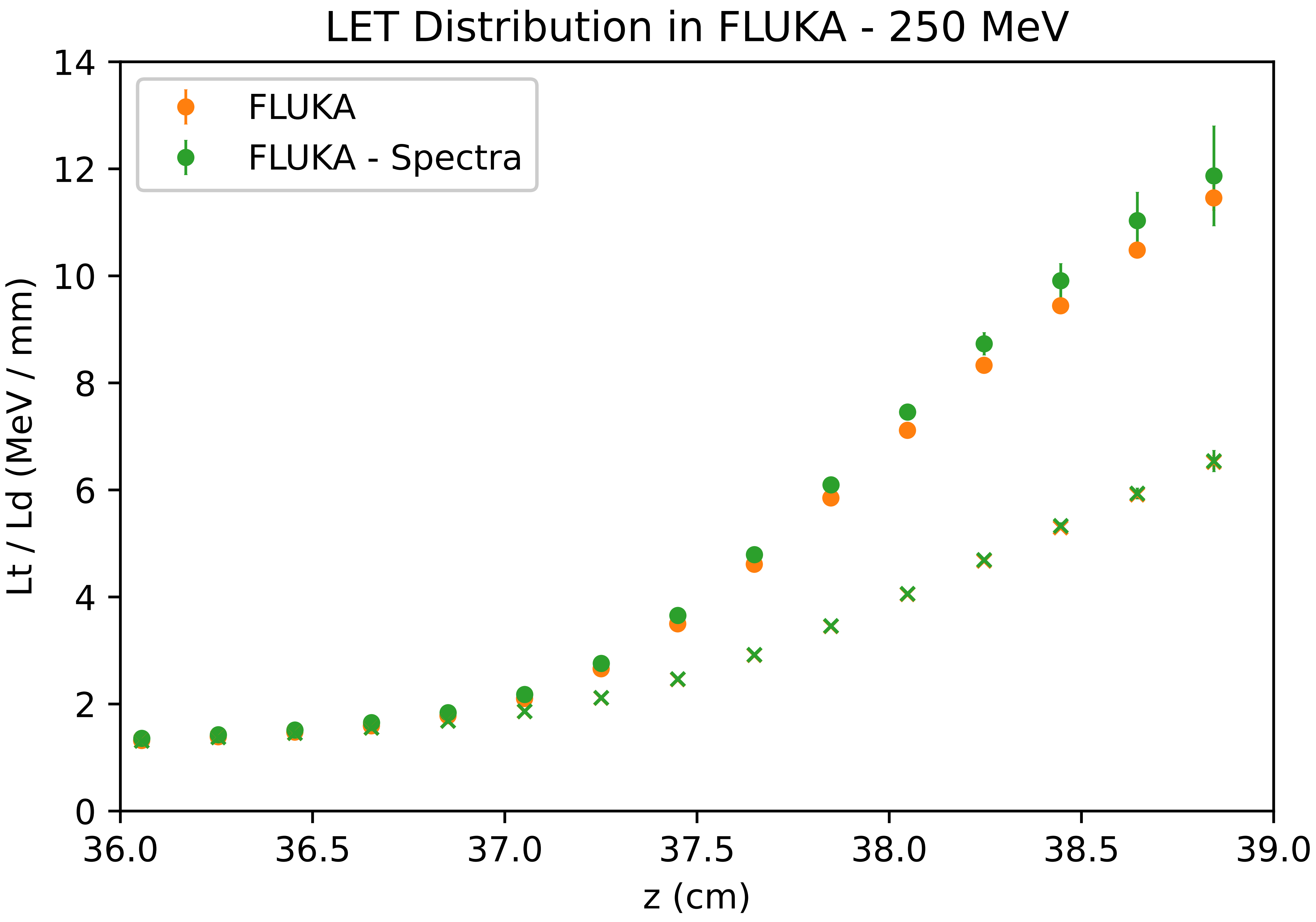
Nuclear Reactions Suppressed

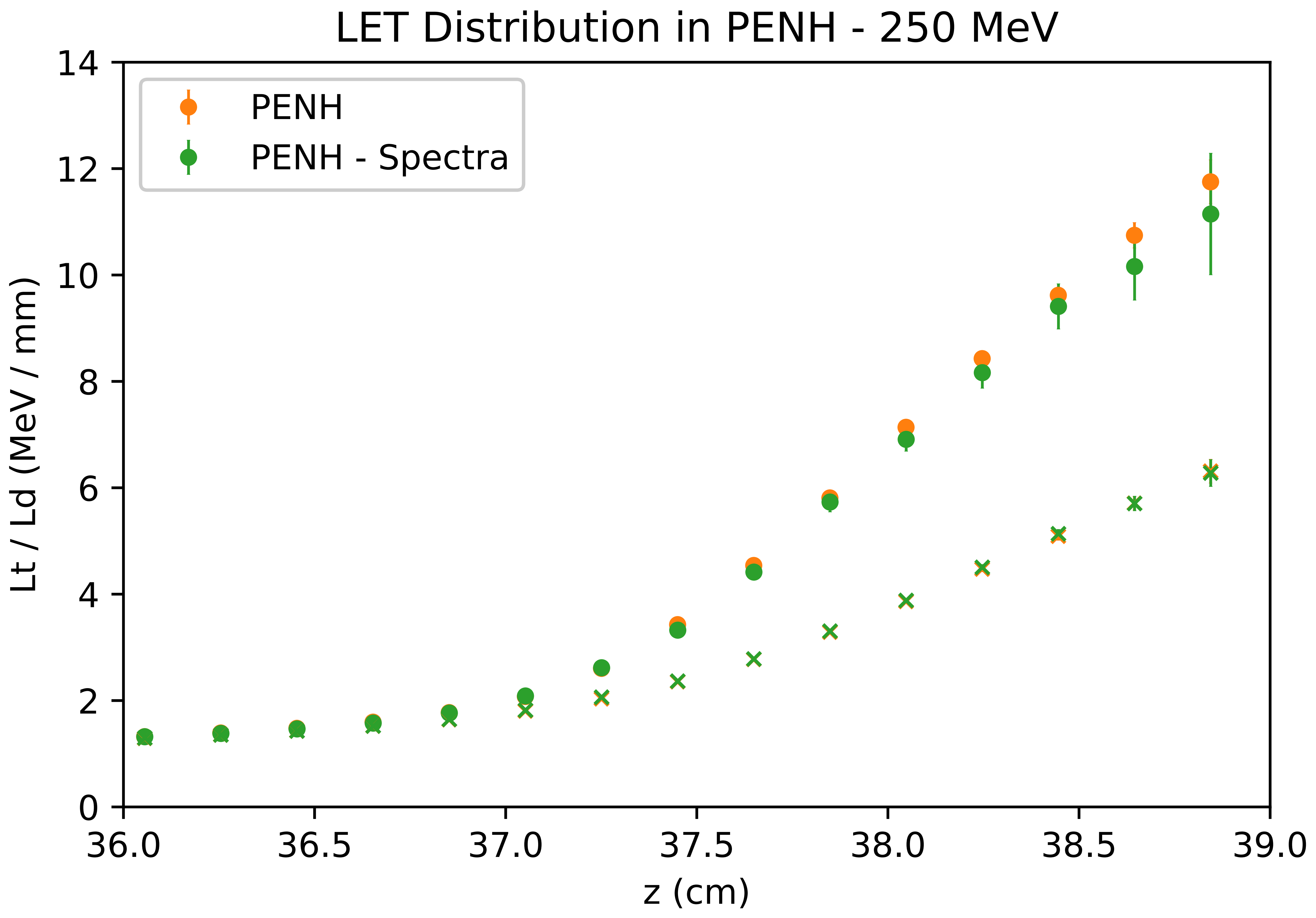
Example



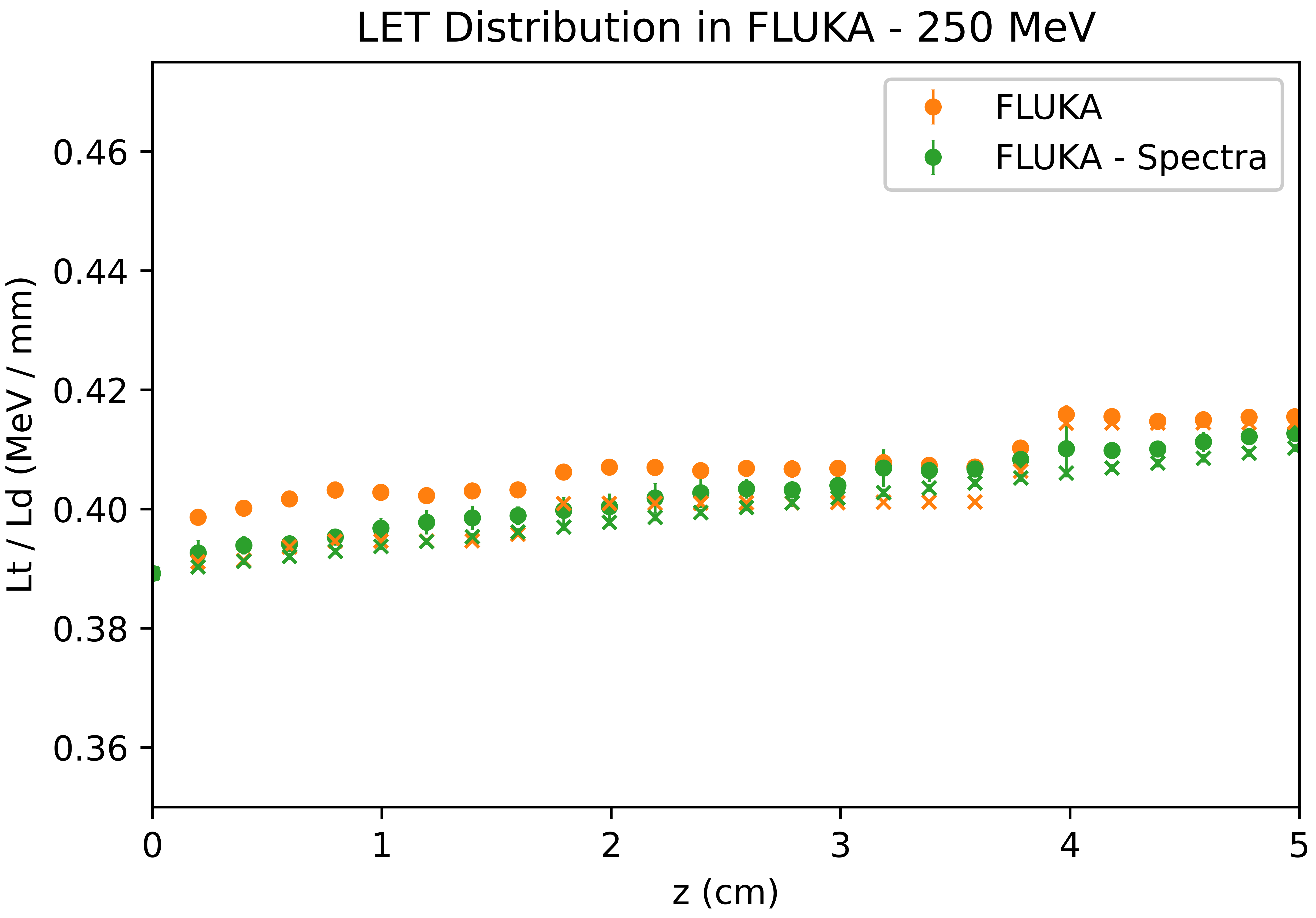
LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Ld
Lt
Lt / Ld (MeV / mm)
z (cm)
0
2
4
6
8
10
12
14
36.0
36.5
37.0
37.5
38.0
38.5
39.0

250 MeV

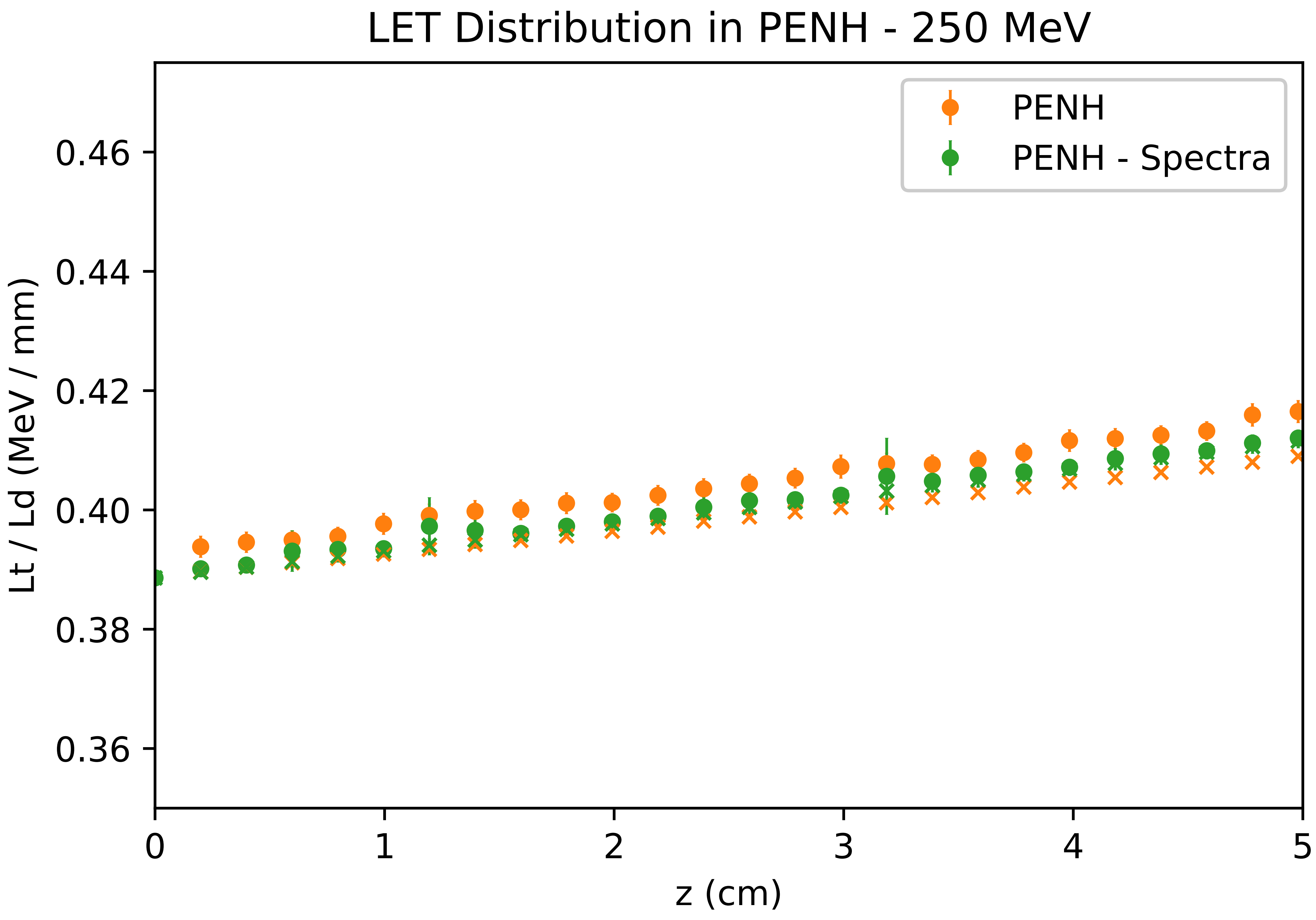

LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
0
2
4
6
8
10
12
14
36.0
36.5
37.0
37.5
38.0
38.5
39.0


LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
0
2
4
6
8
10
12
14
36.0
36.5
37.0
37.5
38.0
38.5
39.0

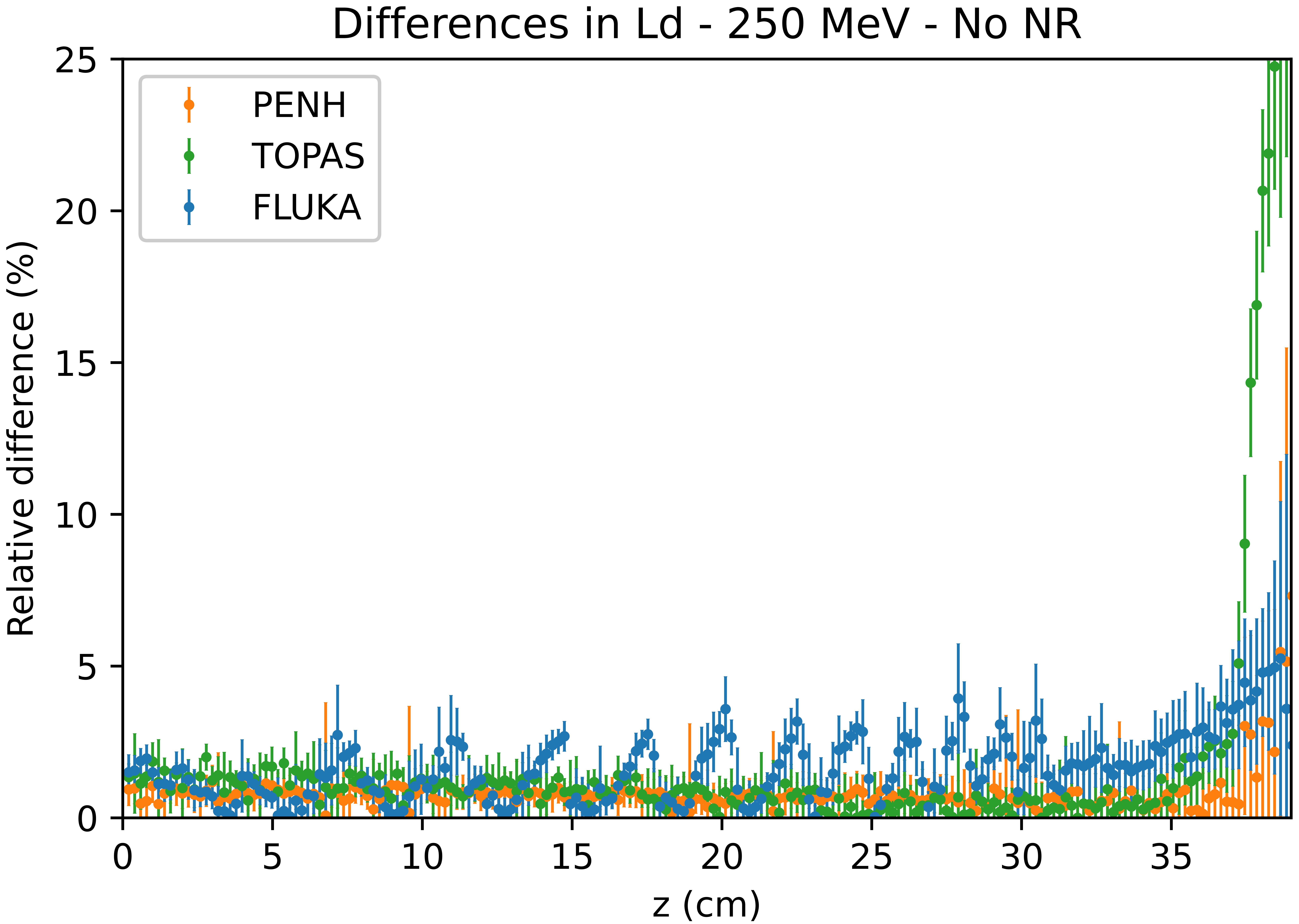
250 MeV



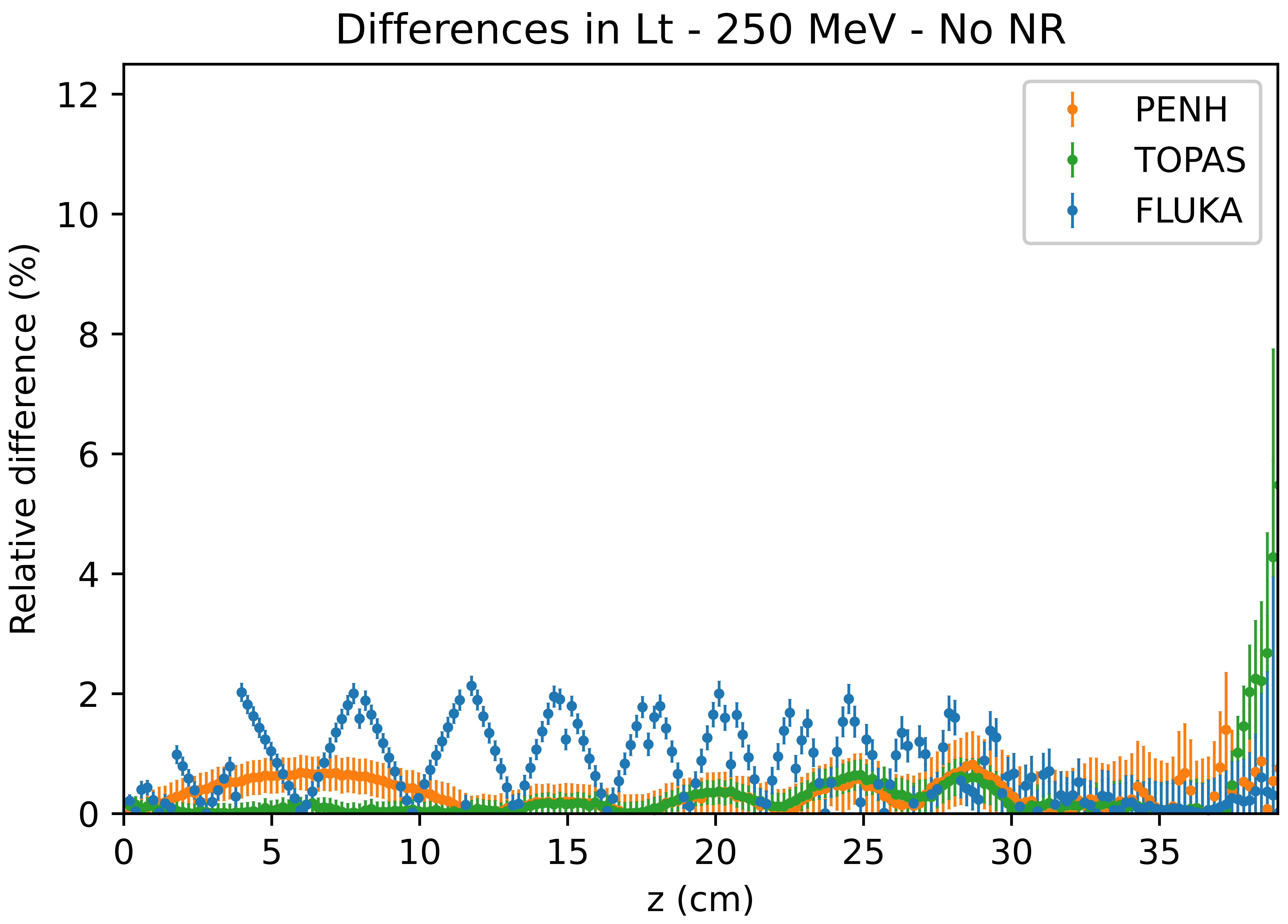
LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.46
0.44
0.42
0.40
0.38
0.36
0
1
2
3
4
5



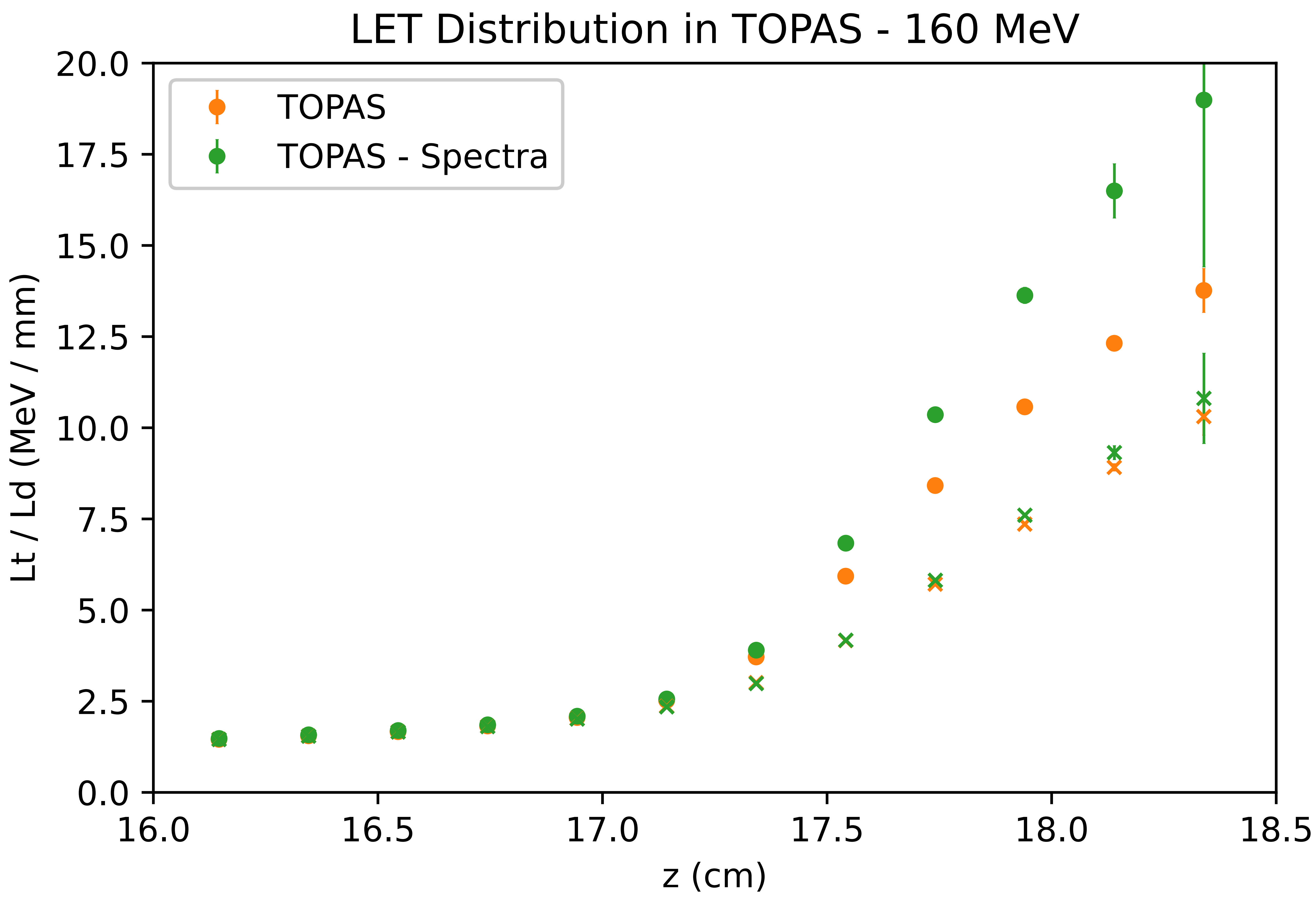
LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.46
0.44
0.42
0.40
0.38
0.36
0
1
2
3
4
5



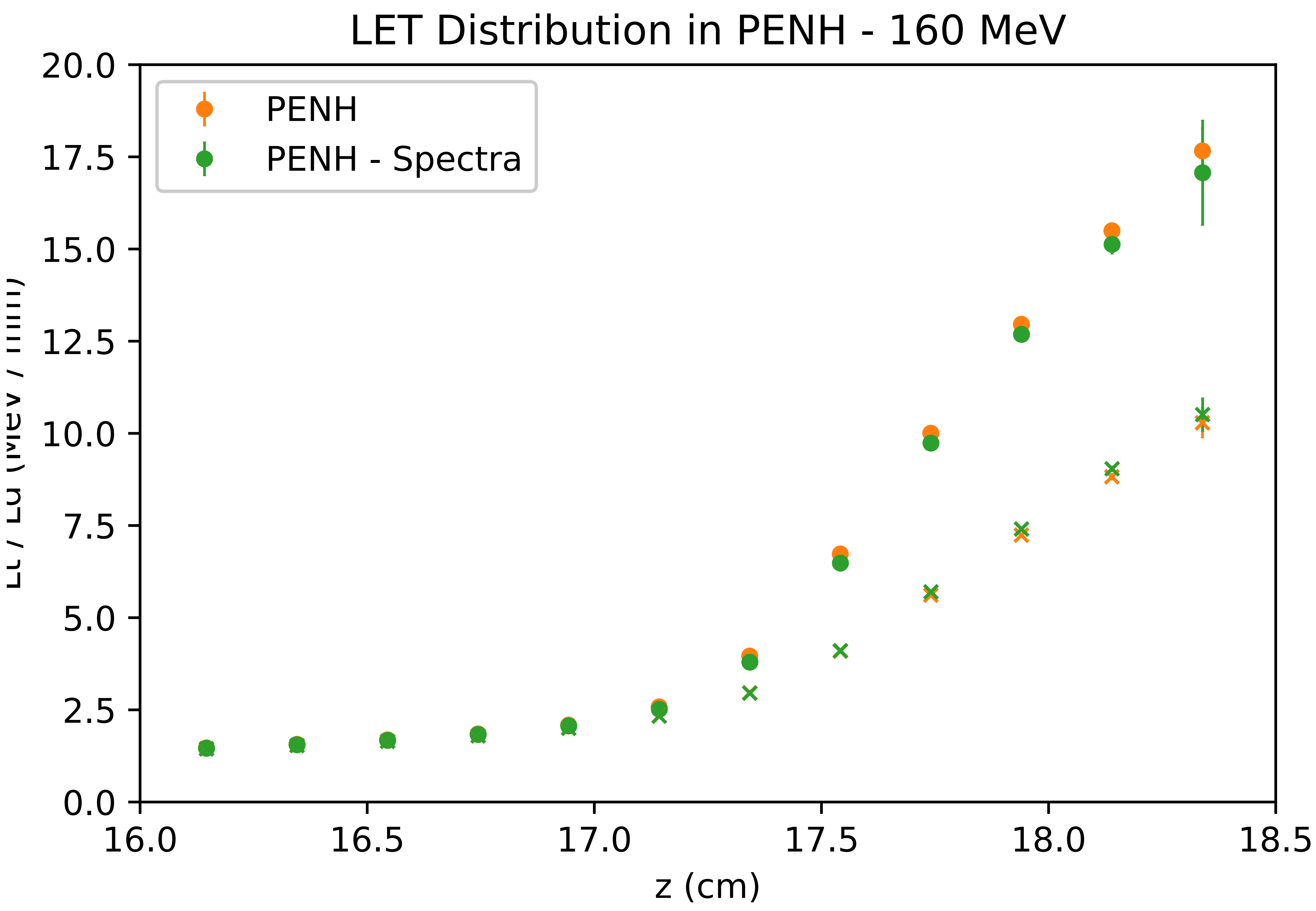
Differences in Ld - 250 MeV - No NR
PENH
TOPAS
FLUKA
Relative difference (%)
z (cm)
0
5
10
15
20
25
30
35


Differences in Lt - 250 MeV - No NR
Relative difference (%)
z (cm)
PENH
TOPAS
FLUKA
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35

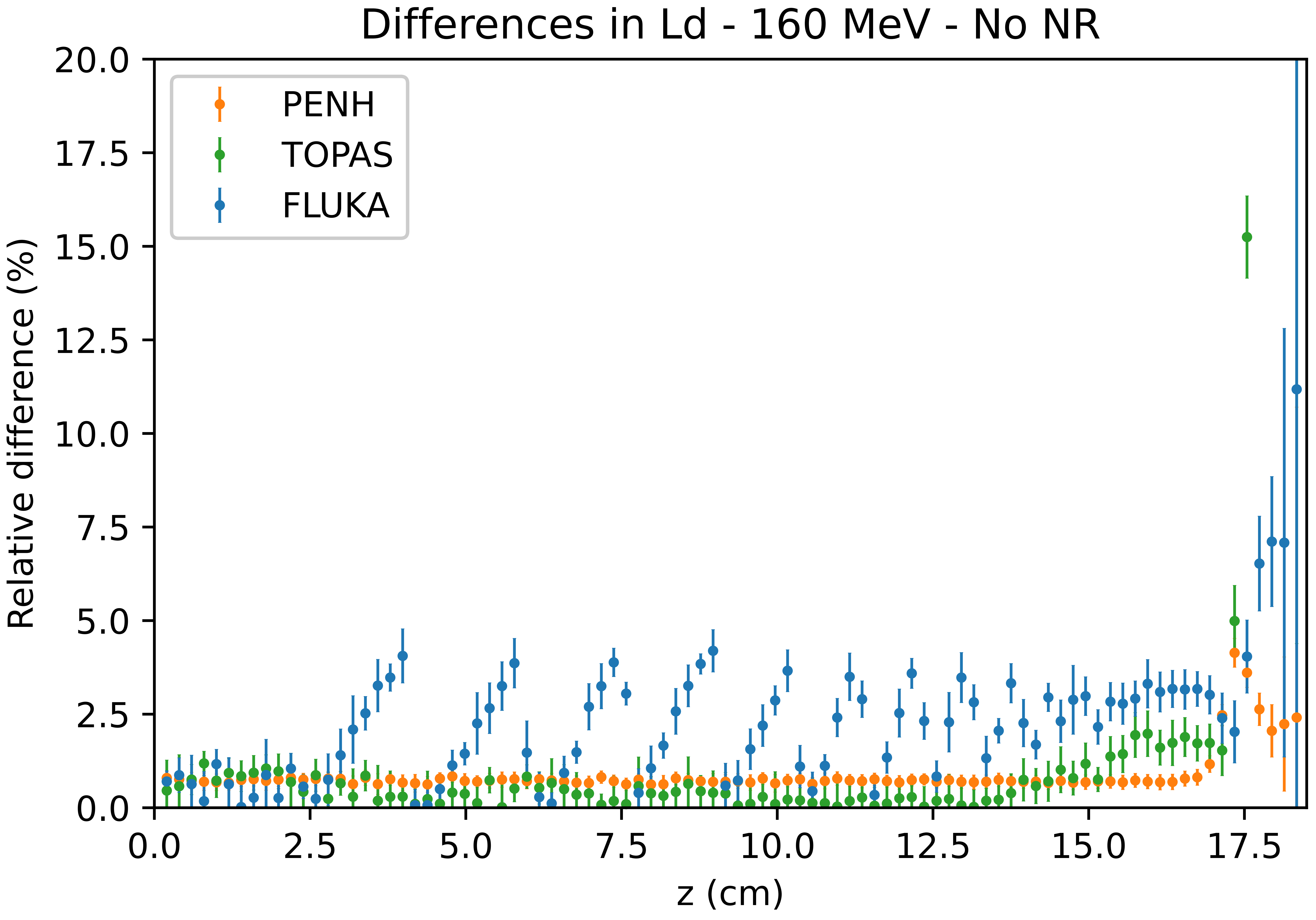
160 MeV



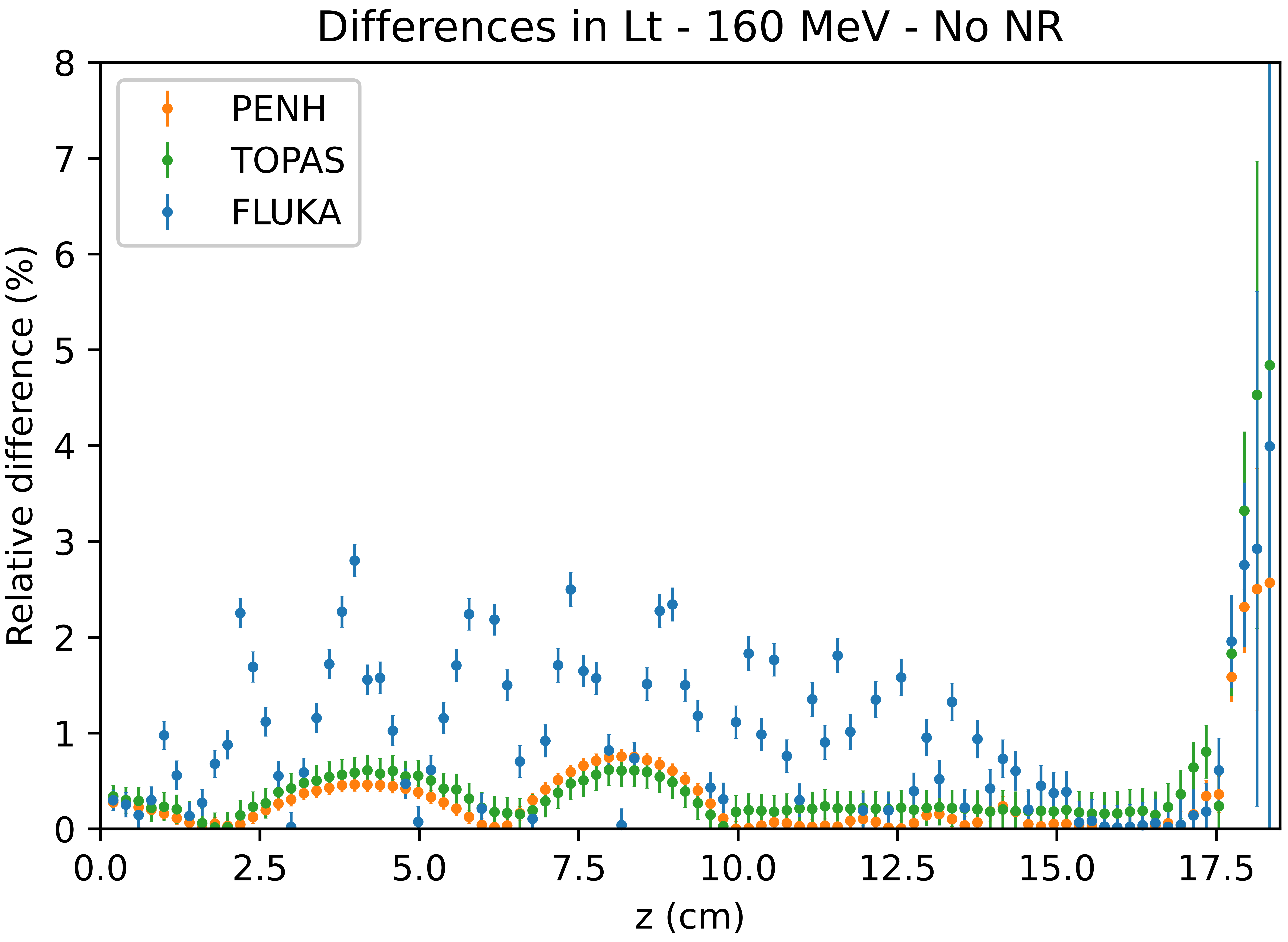
LET Distribution in TOPAS - 160 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.0
16.5
17.0
17.5
18.0
18.5



LET Distribution in PENH - 160 MeV
PENH
PENH - Spectra
z (cm)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.0
16.5
17.0
17.5
18.0
18.5

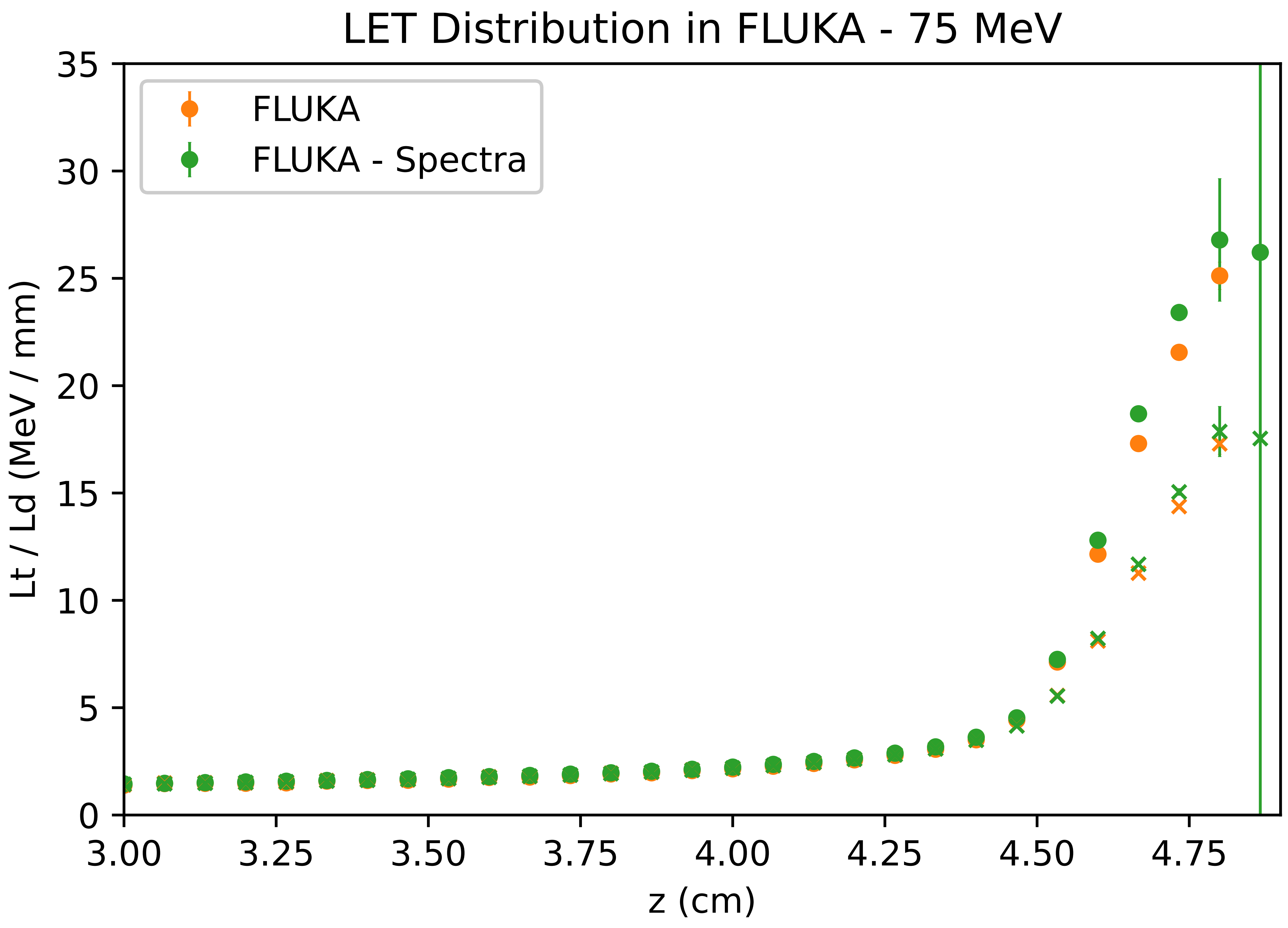


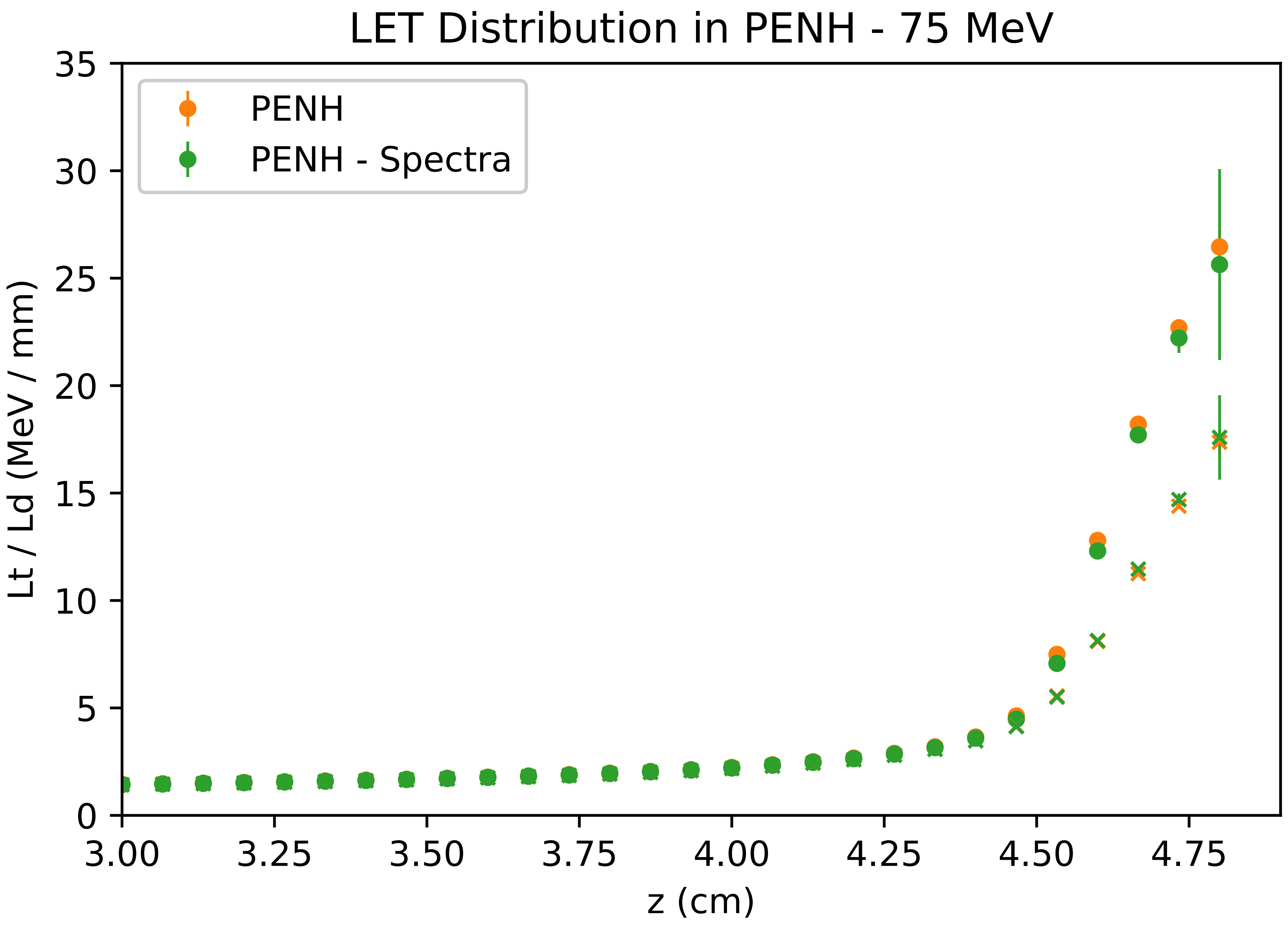
Differences in Ld - 160 MeV - No NR
PENH
TOPAS
FLUKA
Relative difference (%)
z (cm)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

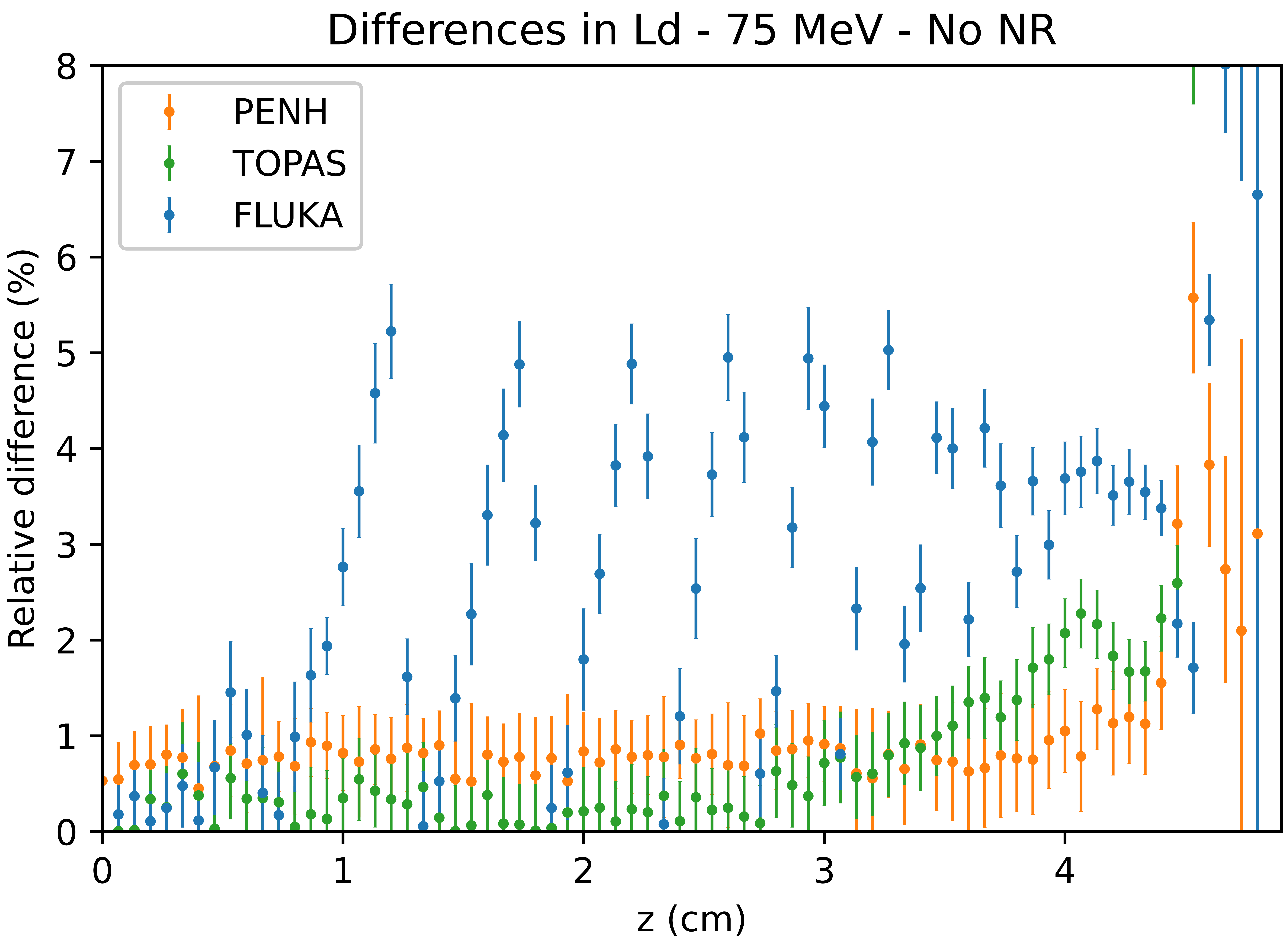


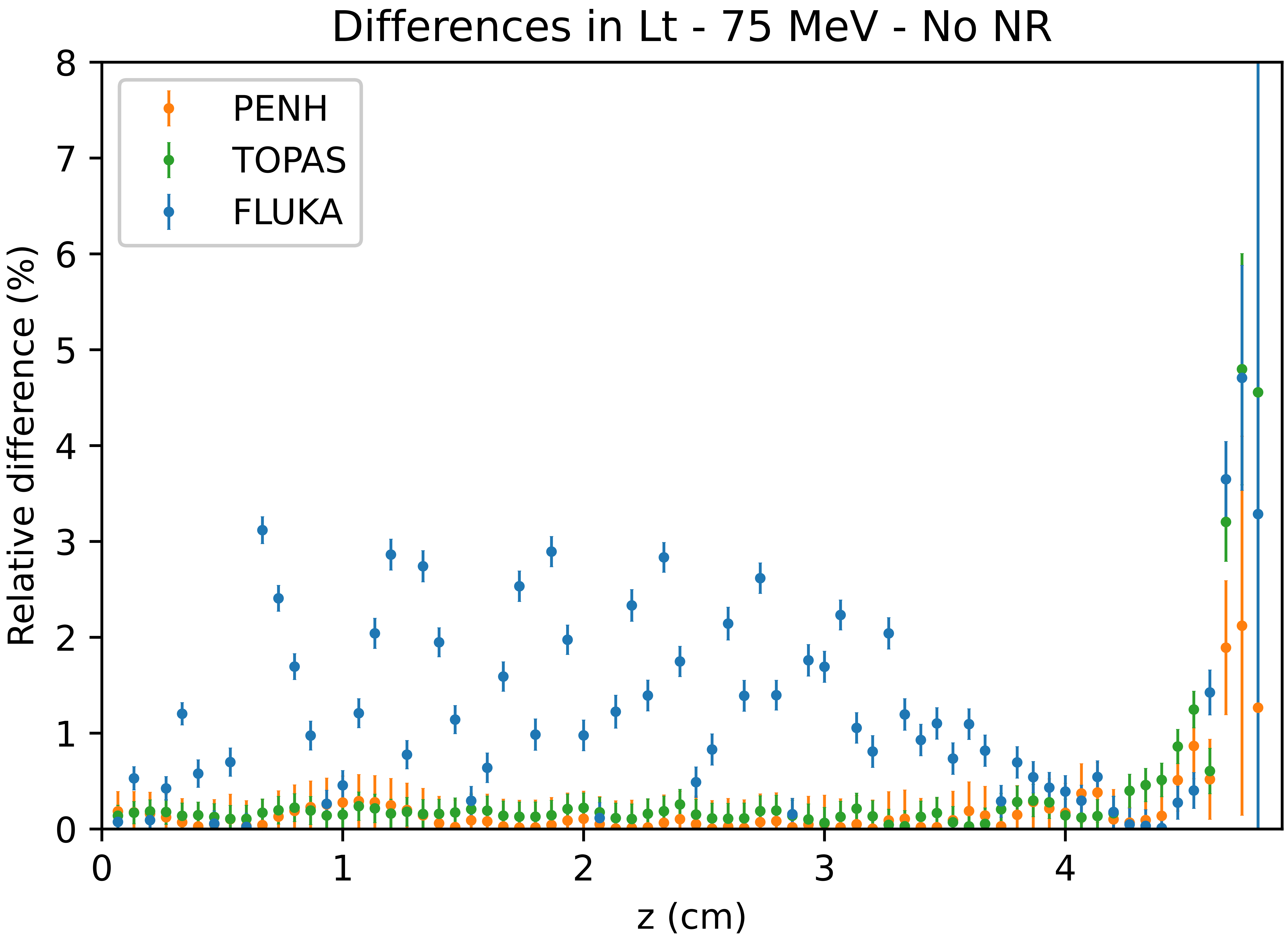
Differences in Lt - 160 MeV - No NR
PENH
TOPAS
FLUKA
Relative difference (%)
z (cm)
0
1
2
3
4
5
6
7
8
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5

75 MeV


LET Distribution in FLUKA - 75 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
0
5
10
15
20
25
30
35
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75


LET Distribution in PENH - 75 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
0
5
10
15
20
25
30
35
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75

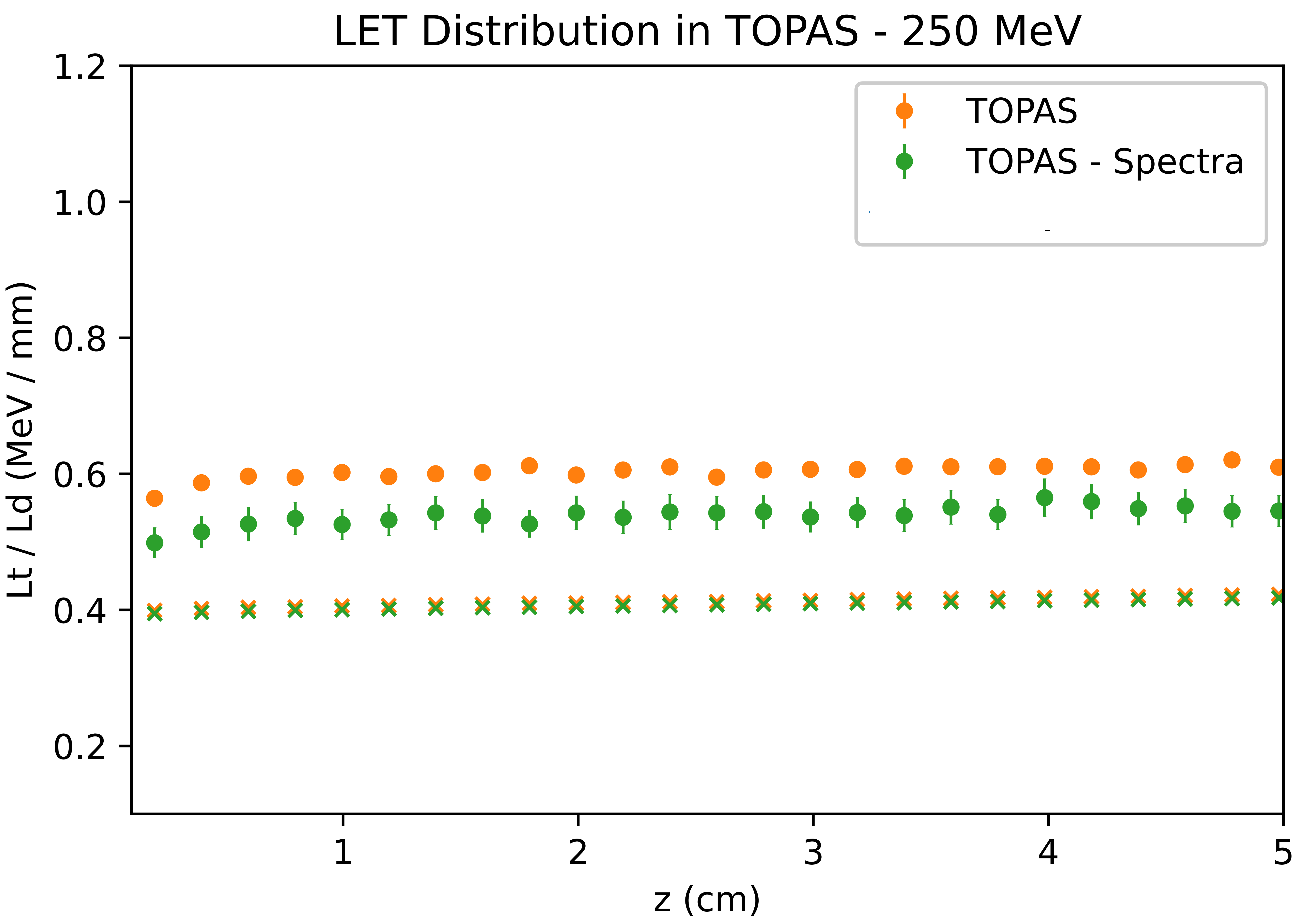

Differences in Ld - 75 MeV - No NR
PENH
TOPAS
FLUKA
Relative difference (%)
z (cm)
0
1
2
3
4
5
6
7
8

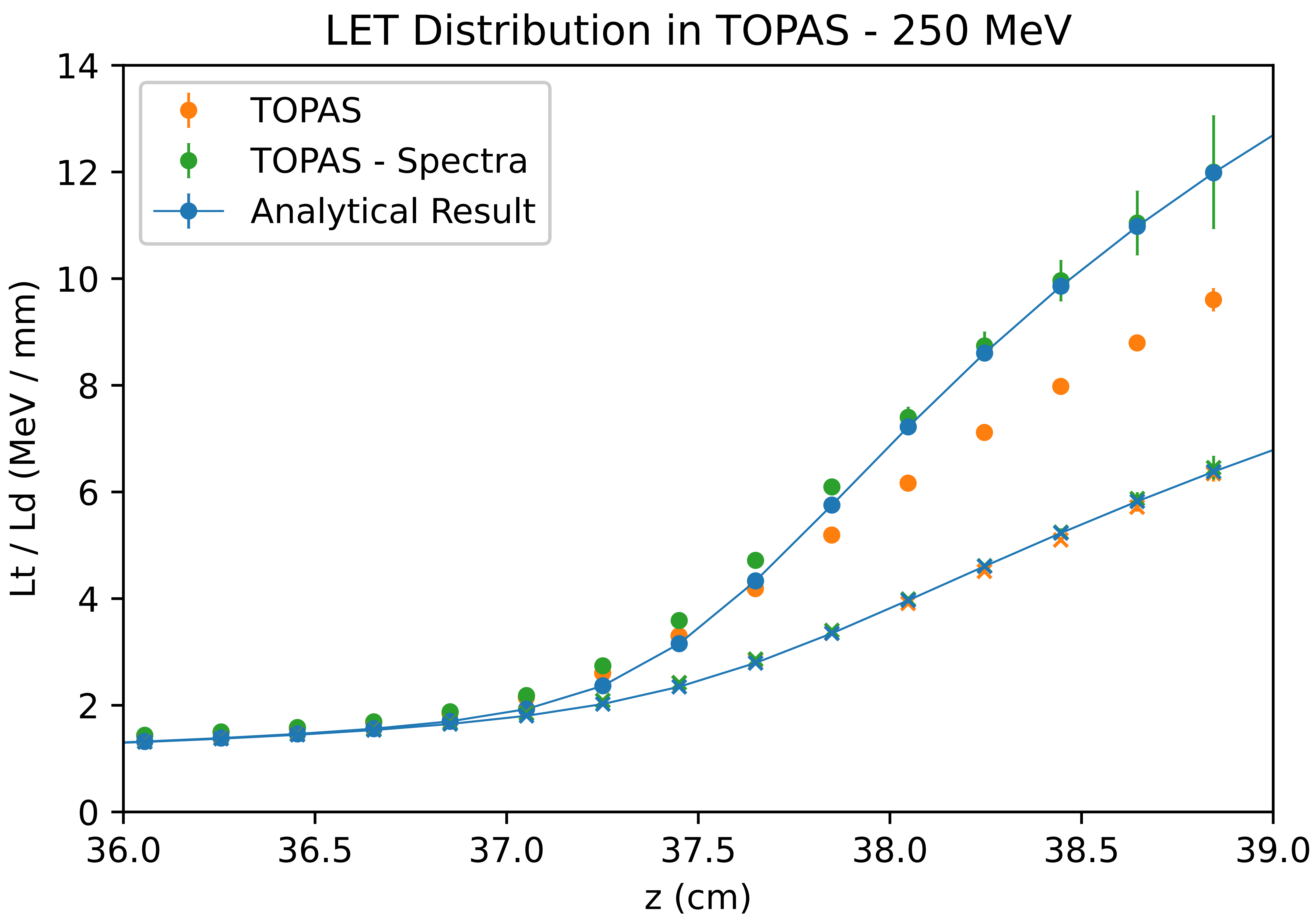


Differences in Lt - 75 MeV - No NR
PENH
TOPAS
FLUKA
Relative difference (%)
z (cm)
0
1
2
3
4
5
6
7
8

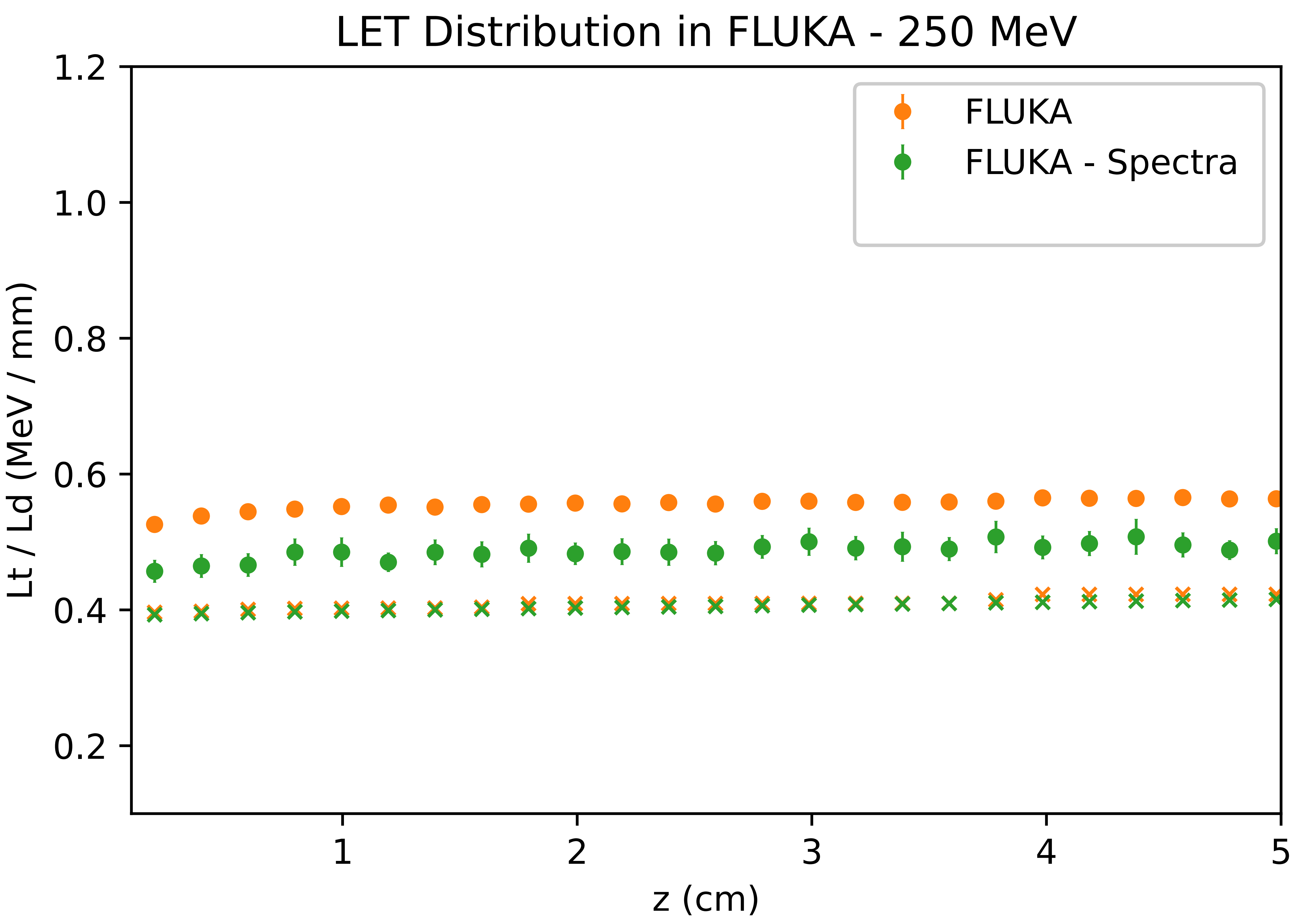
Full Calculations

250 MeV

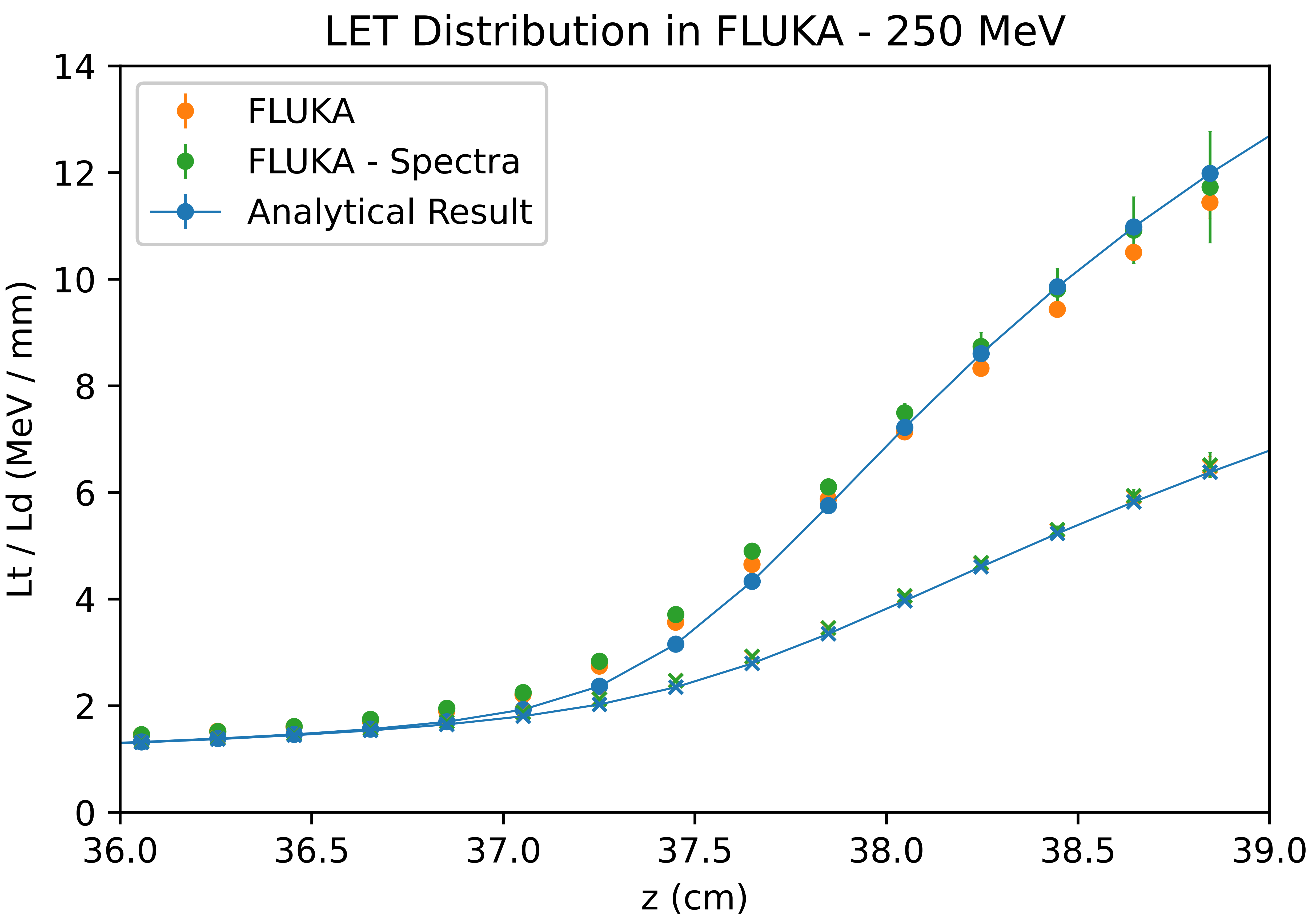

LET Distribution in TOPAS - 250 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)
1.2
1.0
0.8
0.6
0.4
0.2
1
2
3
4
5


LET Distribution in TOPAS - 250 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
14
12
10
8
6
4
2
0
36.0
36.5
37.0
37.5
38.0
38.5
39.0

250 MeV

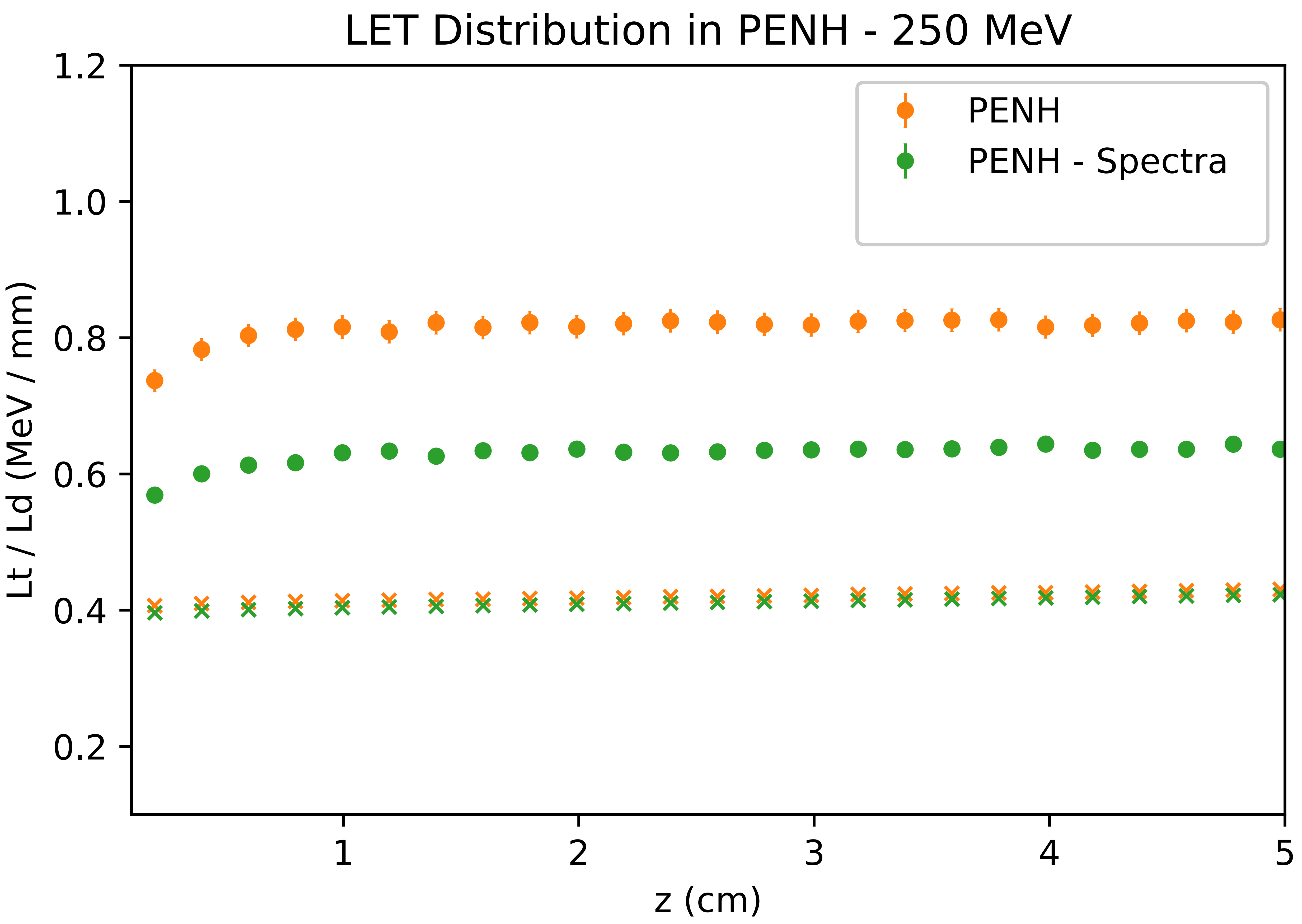


LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.2
0.4
0.6
0.8
1.0
1.2
1
2
3
4
5

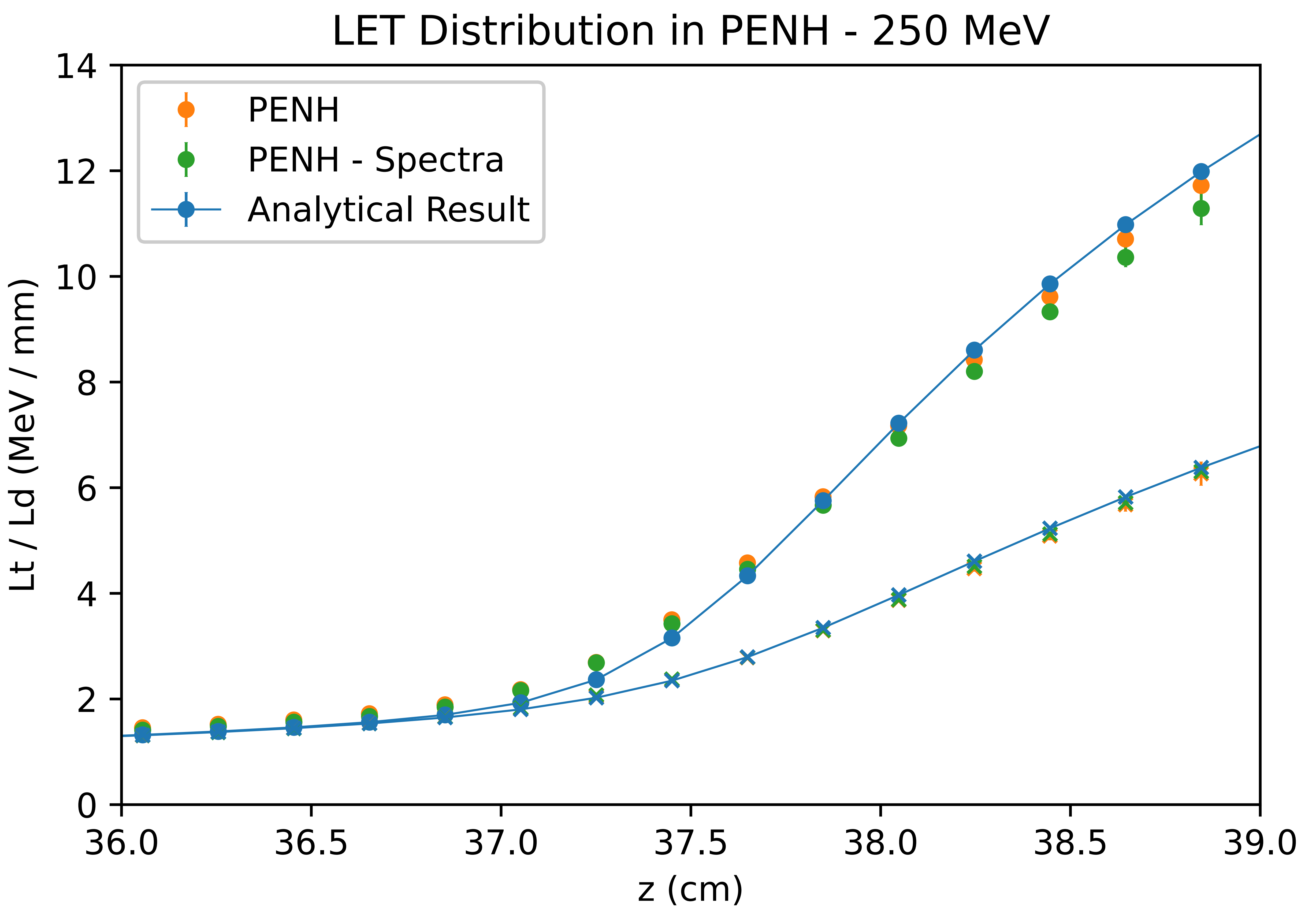


LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
0
2
4
6
8
10
12
14
36.0
36.5
37.0
37.5
38.0
38.5
39.0

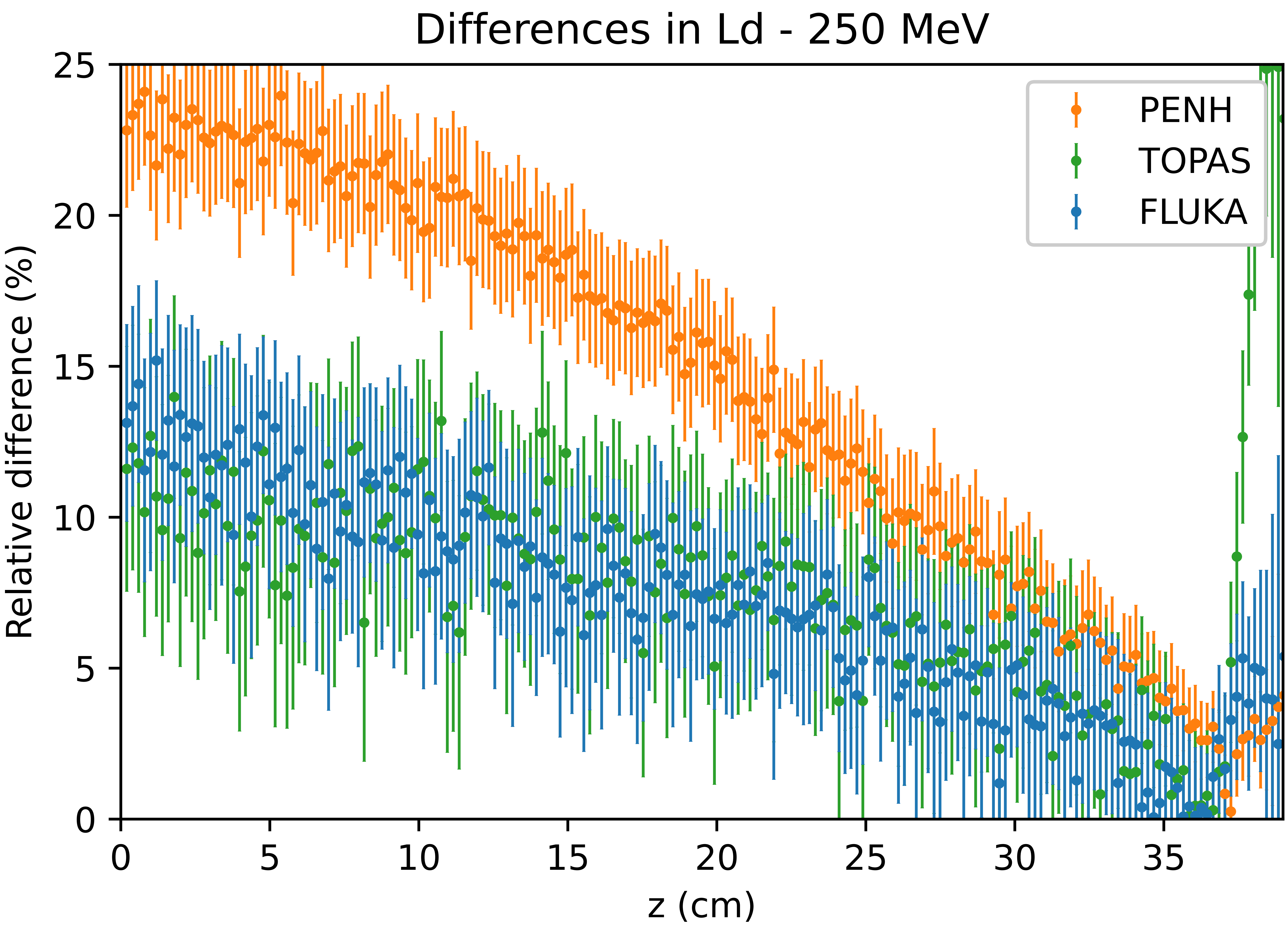
250 MeV



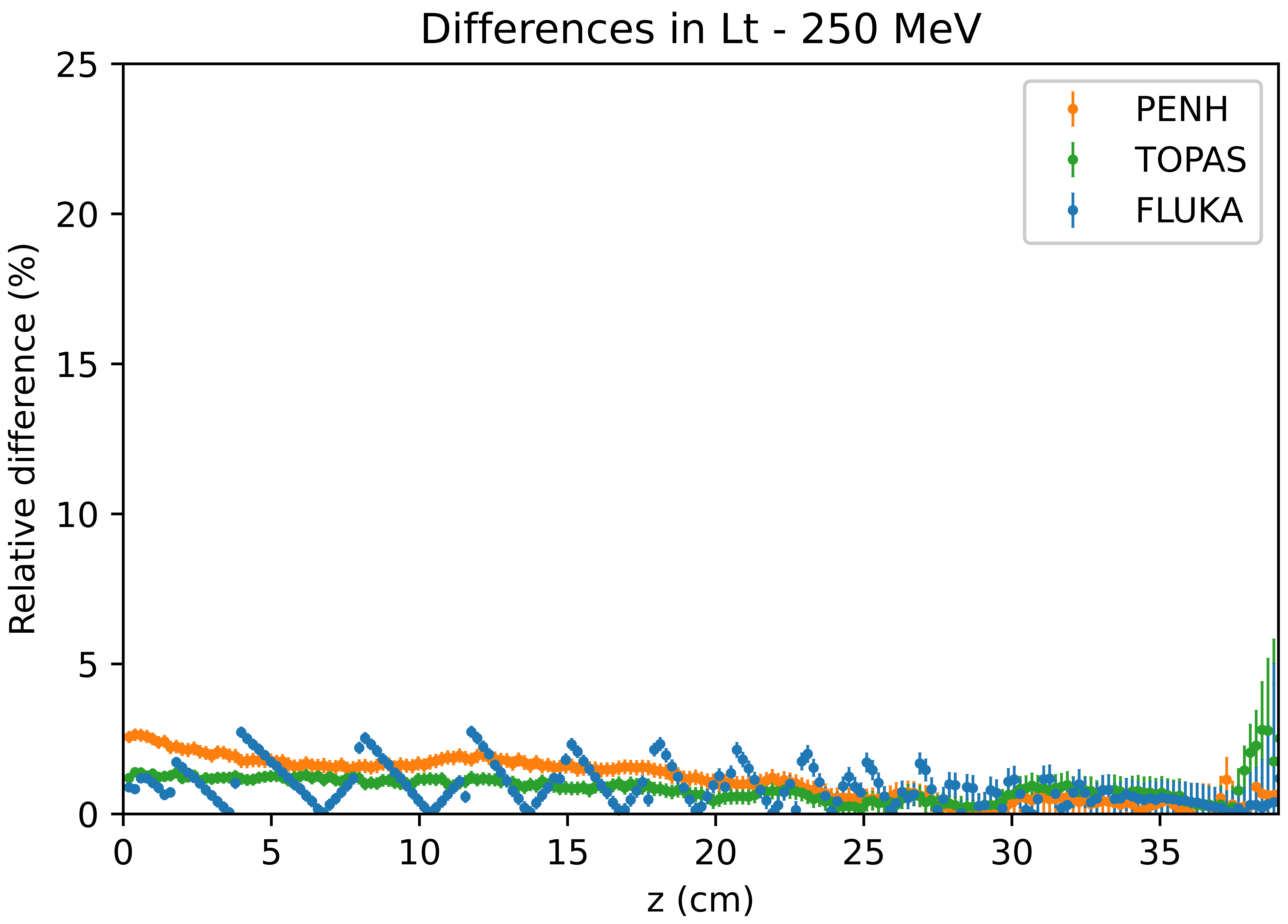
LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)



LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)



Differences in Ld - 250 MeV
Relative difference (%)
z (cm)
PENH
TOPAS
FLUKA
0
5
10
15
20
25
30
35


Differences in Lt - 250 MeV
Relative difference (%)
z (cm)
PENH
TOPAS
FLUKA
0
5
10
15
20
25
30
35

Upshot

Difference between implementations is lower for **Lt**.

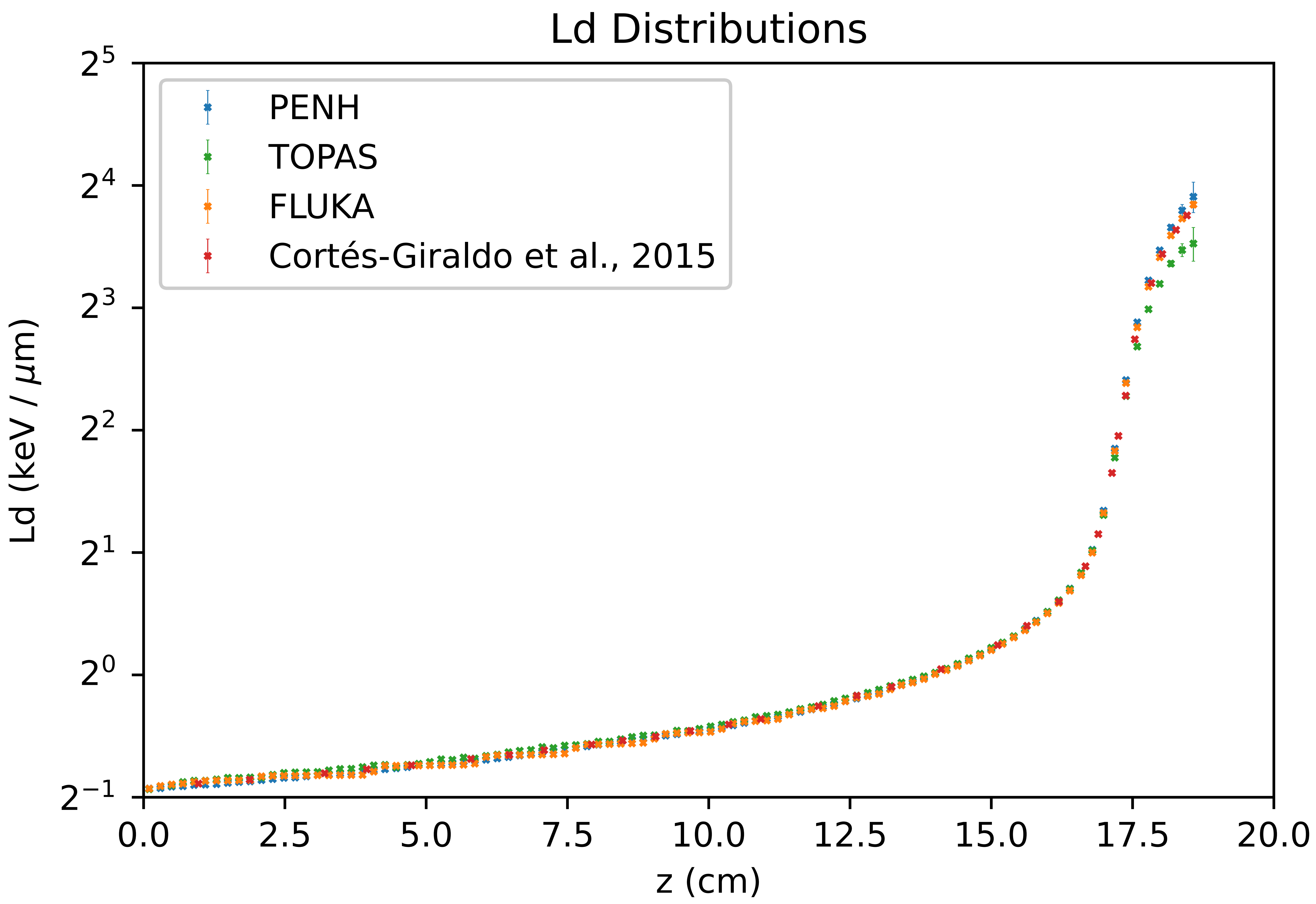
Replication of Previous Studies

- Granville et al., 2015.
- **Cortés-Giraldo et al., 2015.**
- Grassberger et al., 2011.
- Wilkens et al., 2003.

Cortés-Giraldo et al., 2015 - Figure 5 (bottom)

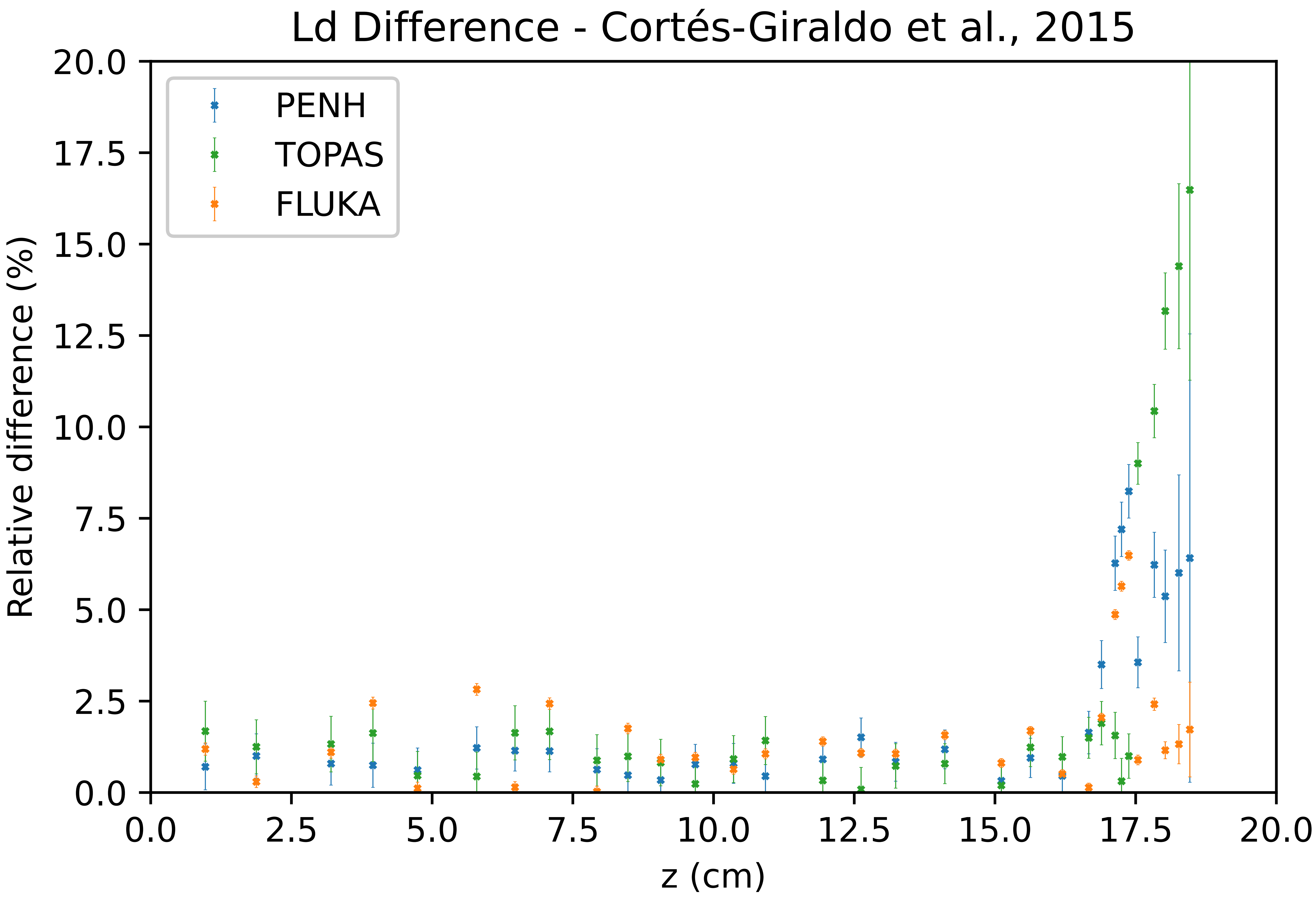
- Gaussian beam in energy and spatial distribution. ($\bar{E} = 160$ MeV; $\sigma_E = 1.04$ MeV)

- Only electronic contribution to dose considered.



Cortés-Giraldo et al., 2015 - Figure 5 (bottom)

- Gaussian beam in energy and spatial distribution.
- Only electronic contribution to dose considered.



Summary

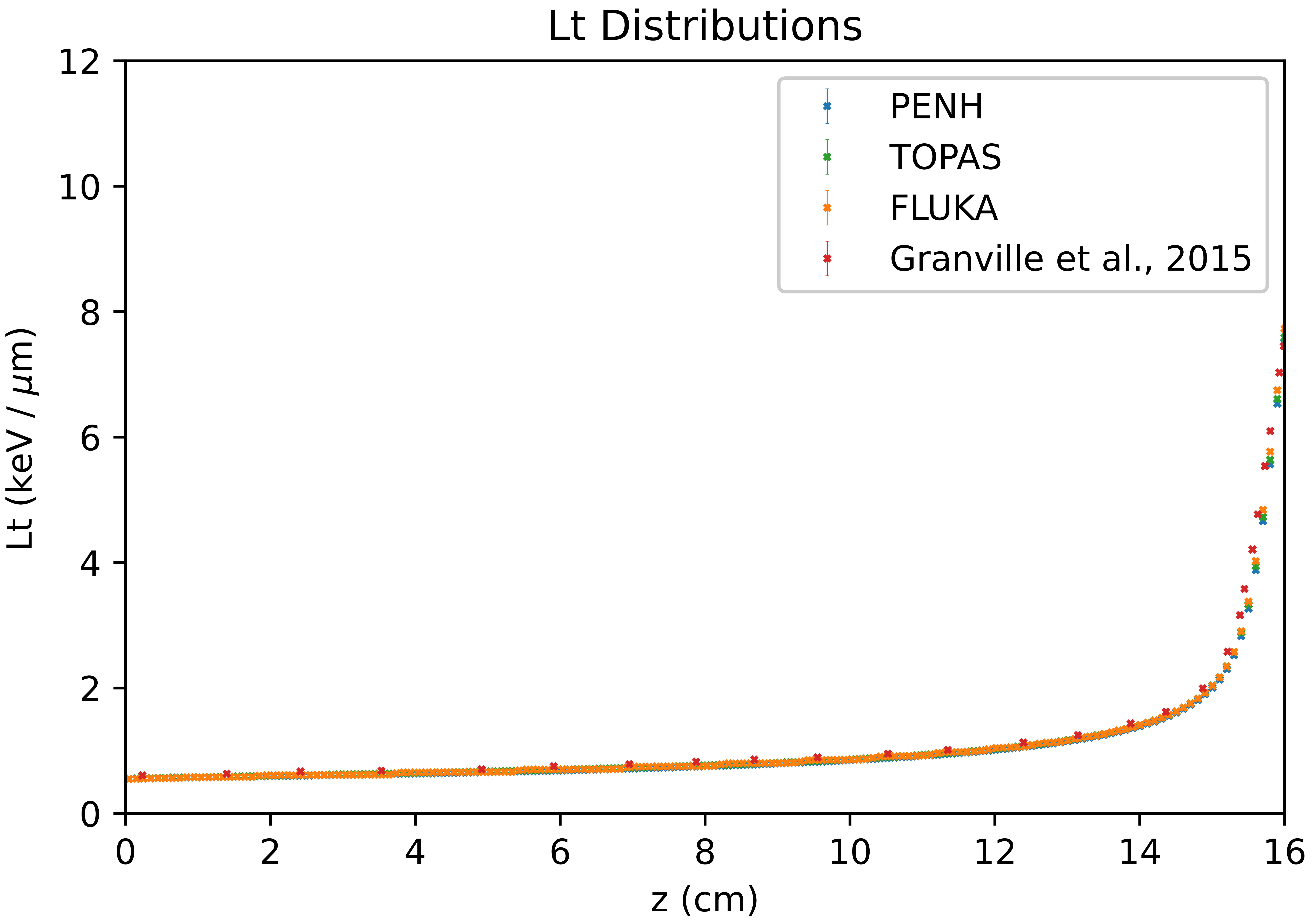
- Implemented a new format of LET calculation in PENH.
- Lt results are more stable.
- All codes' implementations reproduce previous studies' behaviour.

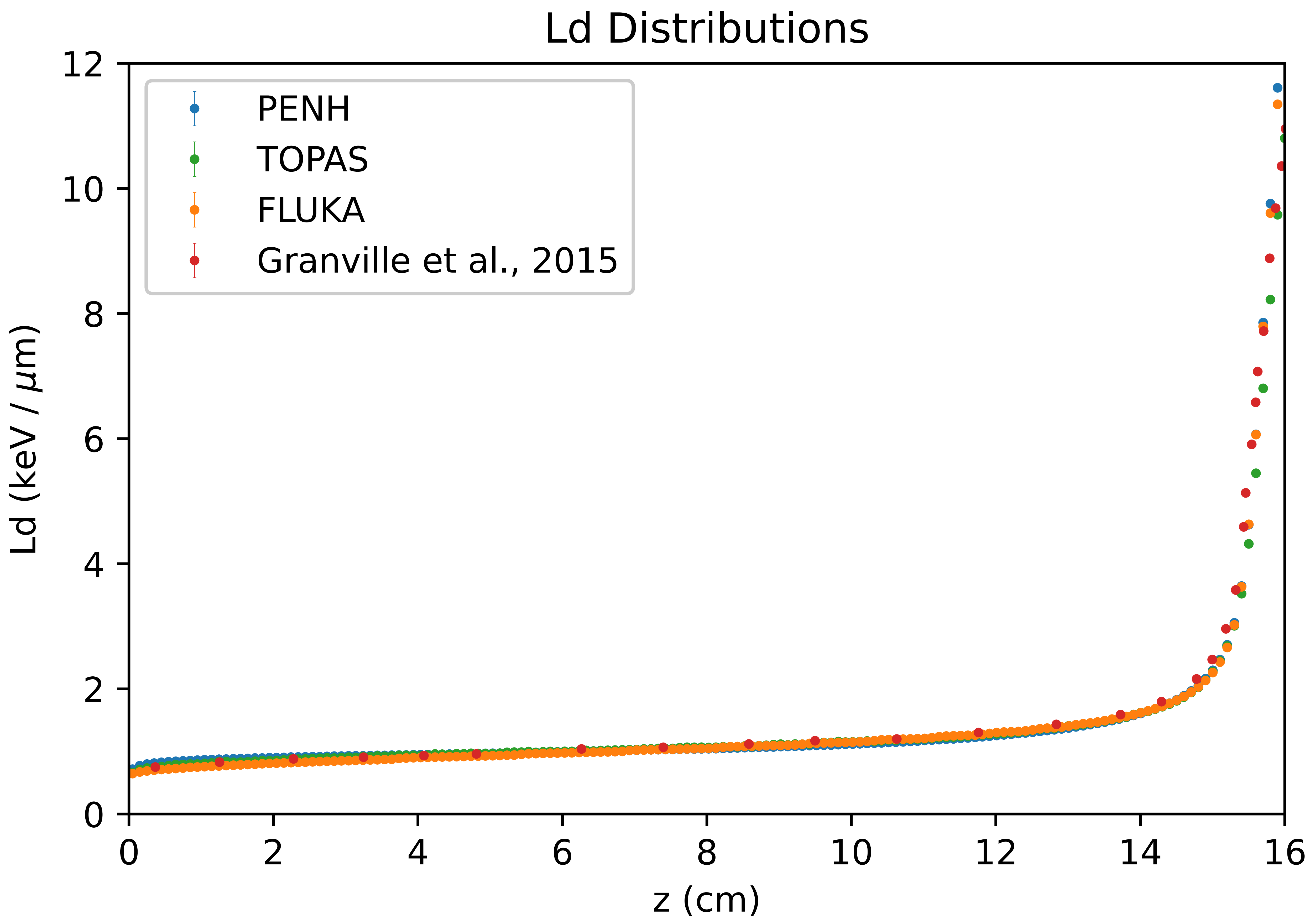
Extra Slides

References

- [1] Paganetti, "Relative biological effectiveness (RBE) values for proton beam therapy. Variations as a function of biological endpoint, dose, and linear energy transfer". Phys Med Biol. 2014 Nov 21;59(22):R419-72.
- [2] Kalholm, F., Grzanka, L., Traneus, E., & Bassler, N. "A systematic review on the usage of averaged LET in radiation biology for particle therapy". In Radiotherapy and Oncology (Vol. 161, pp. 211–221). Elsevier BV, (2021).
- [3] Wilkens and Oelfke, "Analytical linear energy transfer calculations for proton therapy". Med Phys. 2003 May;30(5):806-15.
- [4] D. A. Granville and G. O. Sawakuchi, "Comparison of linear energy transfer scoring techniques in Monte Carlo simulations of proton beams" 2015 Phys. Med. Biol. 60 N283.
- [5] M. A. Cortés-Giraldo and A. Carabe, "A critical study of different Monte Carlo scoring methods of dose average linear-energy-transfer maps calculated in voxelized geometries irradiated with clinical proton beams" 2015 Phys. Med. Biol. 60 2645
- [6] F. Salvat, J.M. Fernández-Varea and J. Sempau, "Penelope 2018: a code system for Monte Carlo simulation of electron and photon transport", Nuclear Energy Agency, Barcelona 2018; F. Salvat and J. M. Quesada, Nucl. Ins. Meth. Phys. Res. B 475 (2020) 49.
- [7] G. Batistone, "The FLUKA code", Annals of Nuclear Energy 82 (2015) 10.
- [8] J. Perl et al, "TOPAS: an innovative proton Monte Carlo platform for research and clinical applications", Med. Phys. 39 (2012) 6818.
- [9[Guan, F., et al.. (2015). “Analysis of the track- and dose-averaged LET and LET spectra in proton therapy using the geant4 Monte Carlo code”. In Medical Physics (Vol. 42, Issue 11, pp. 6234–6247).

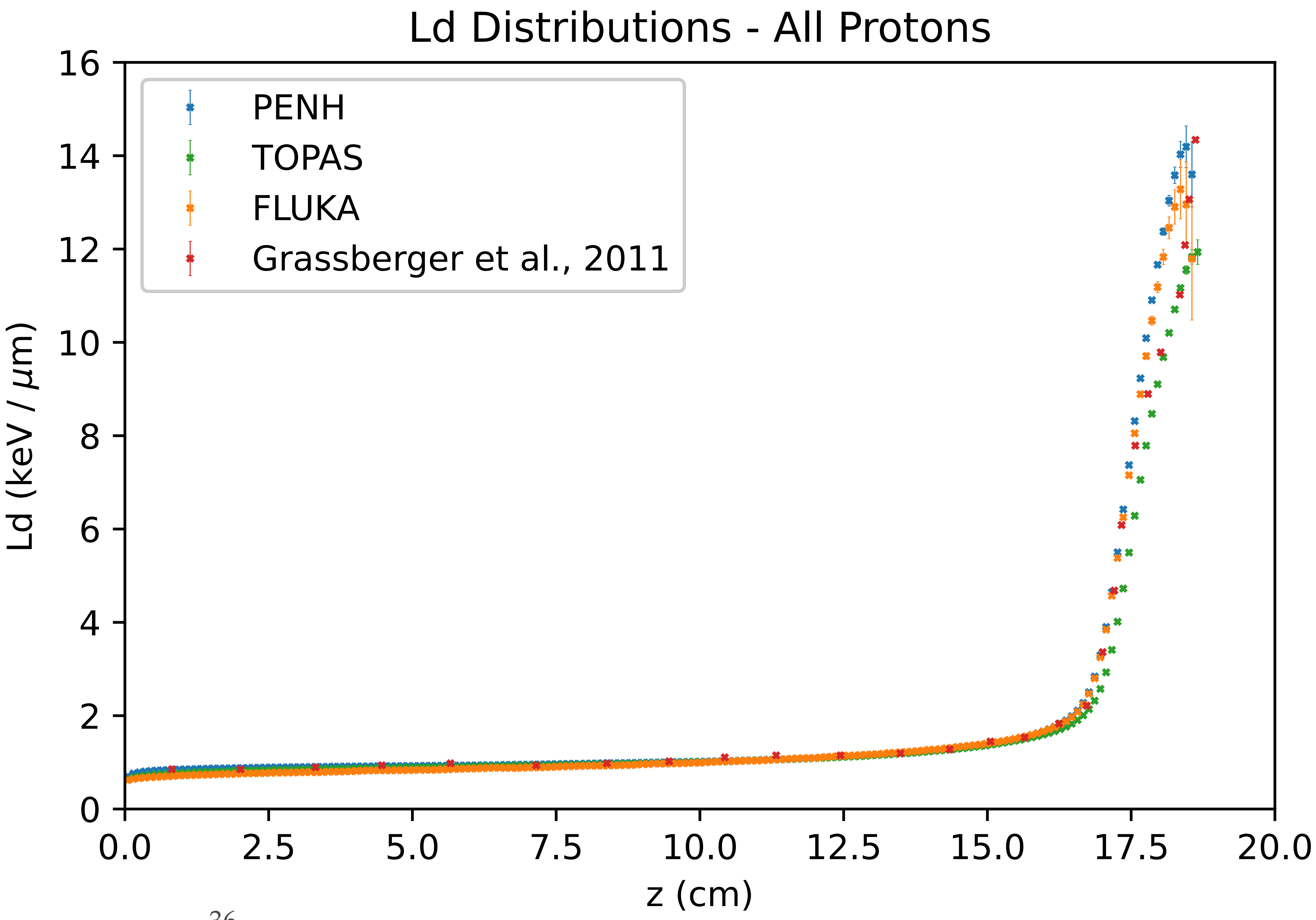
Granville et al., 2015 - Figure 2 a)





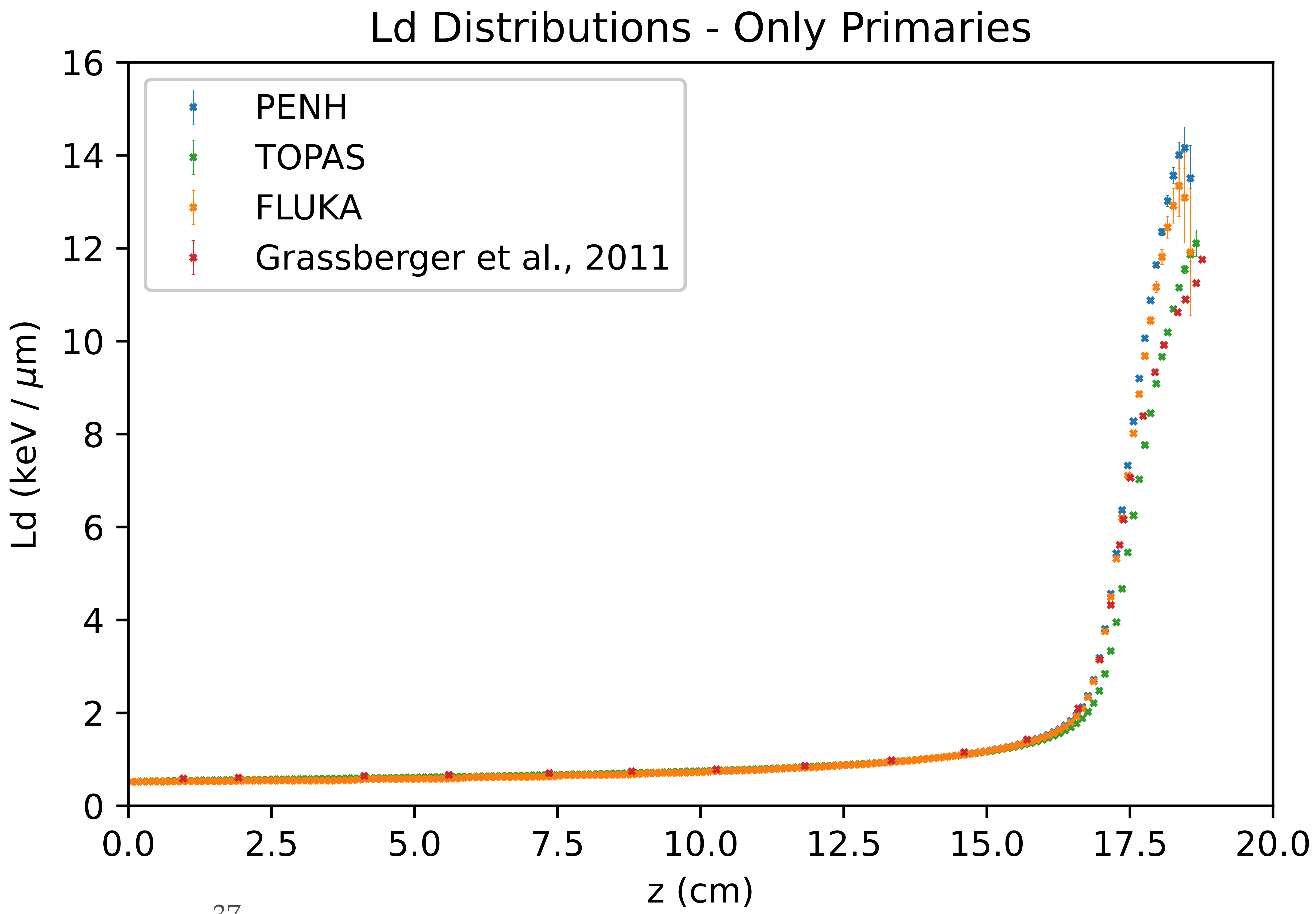
Grassberger et al., 2011 - Figure 2 (All Protons)

- Gaussian beam in energy, spatial distribution and direction.
- Differences observed at the peak.



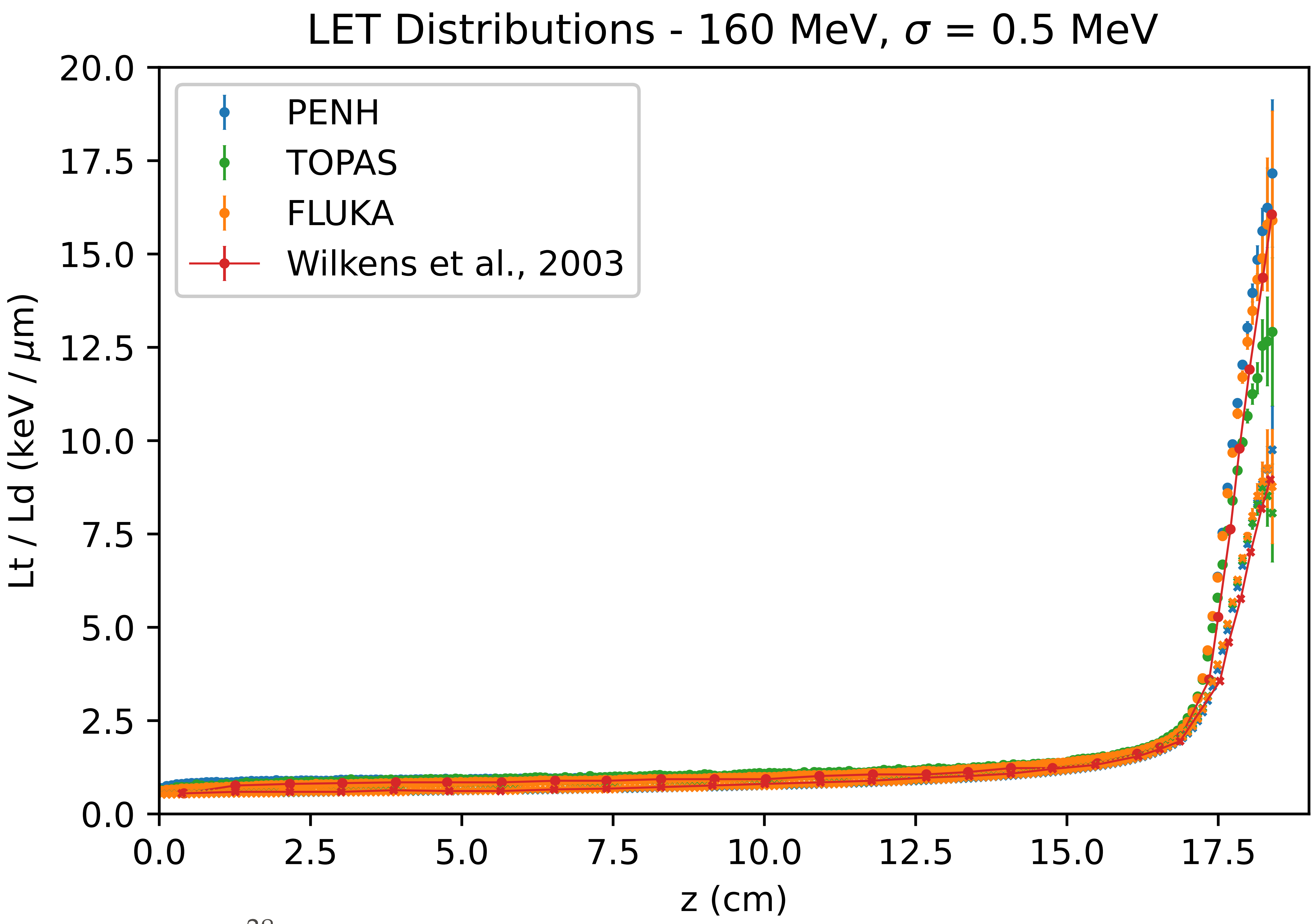
Grassberger et al., 2011 - Figure 2 (Primaries Only)

- Differences observed at the peak.



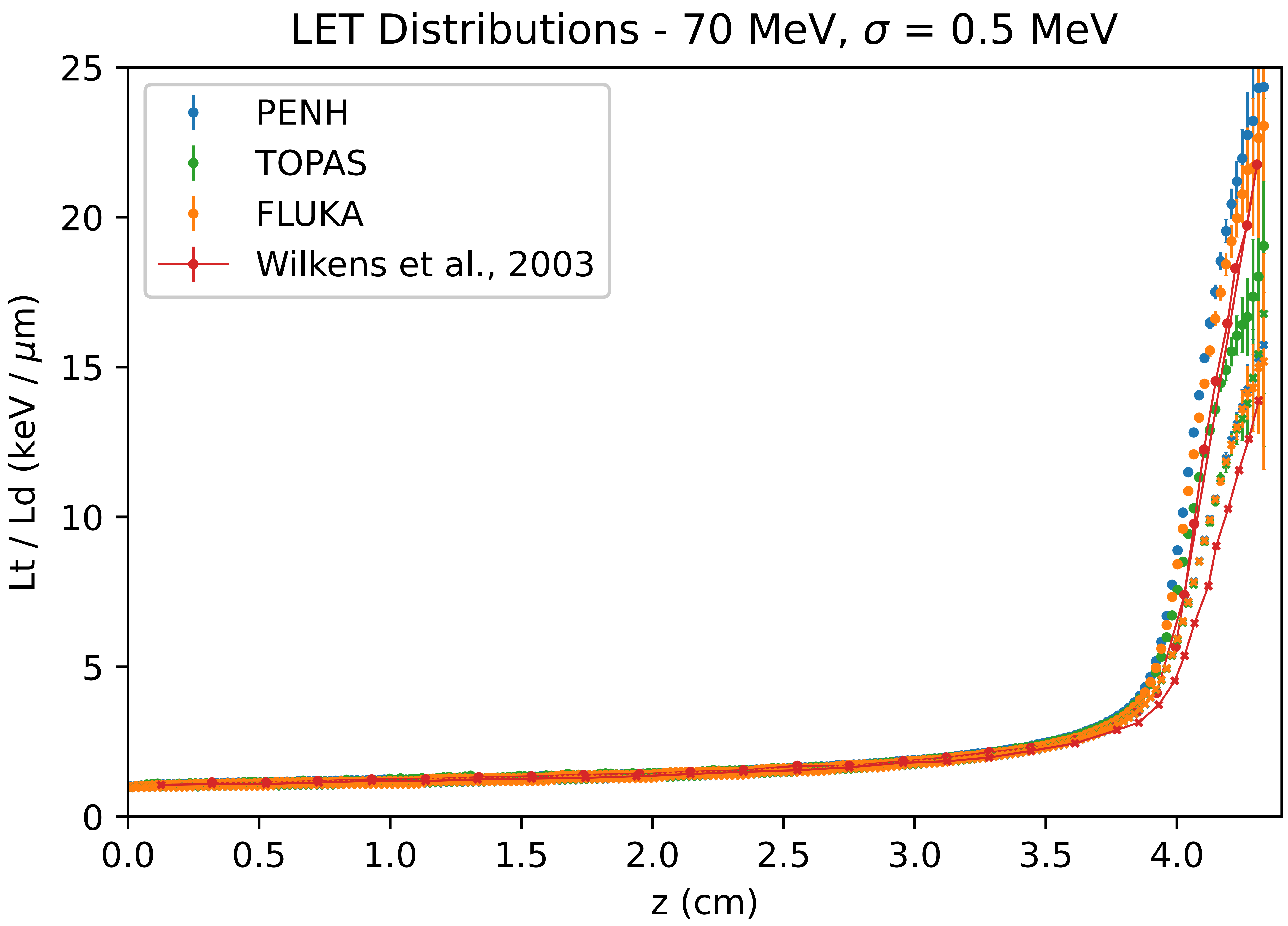
Wilkens et al., 2003 - Figure 2

- Wide beam, gaussian energy.
- Shift of data needed.



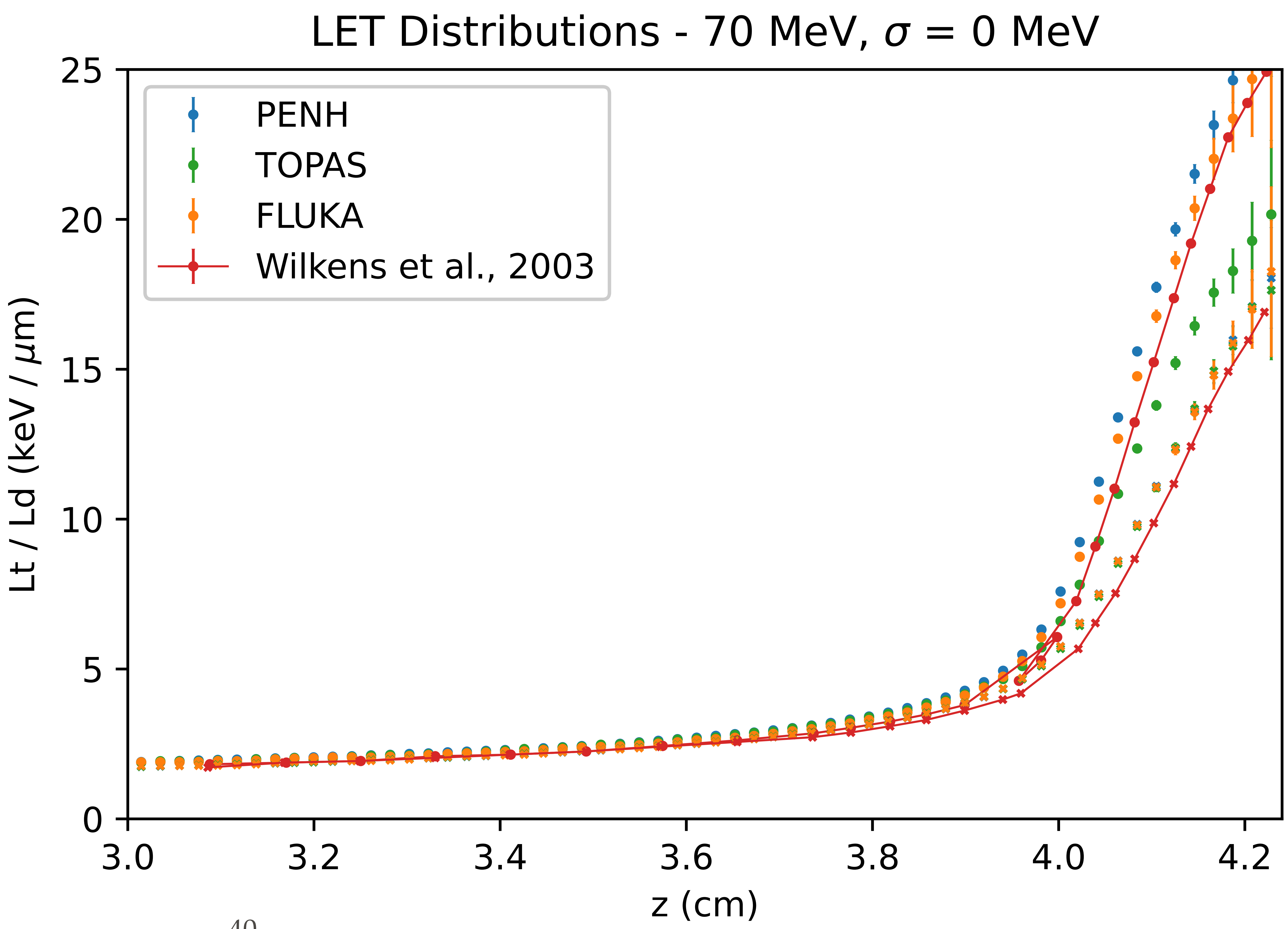
Wilkens et al., 2003 - Figure 4

- Wide beam, gaussian energy.
- Shift of data needed.



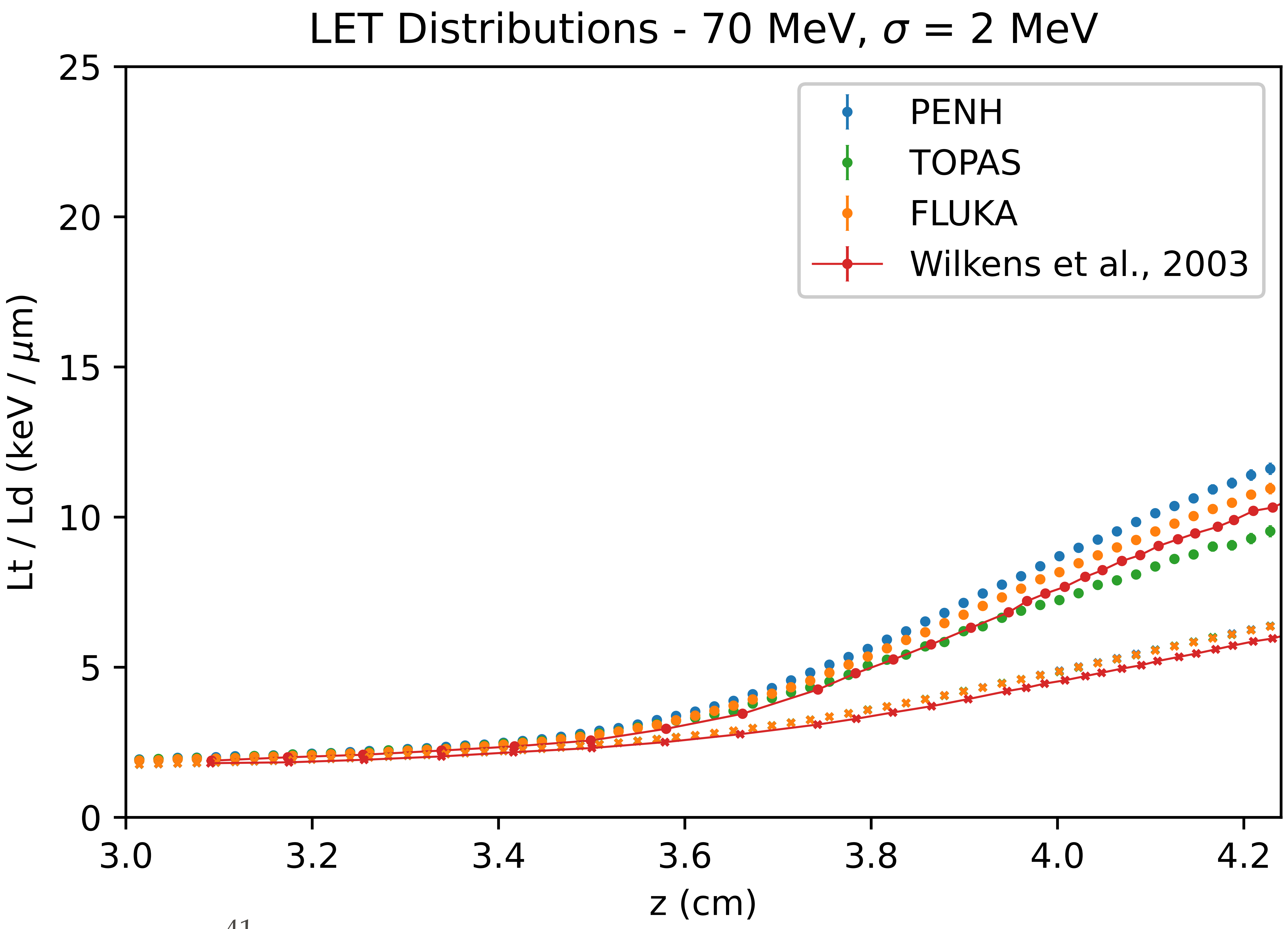
Wilkens et al., 2003 - Figure 5

- Wide beam, gaussian energy.
- Shift of data needed.



Wilkens et al., 2003 - Figure 5

- Wide beam, gaussian energy.
- Shift of data needed.



Simulation PENH Parameters

Absorption energy for electrons and positrons	1e9 eV (Previous studies; Guan et al., 2015)
Absorption energy for photons	1e4 eV
WCC, WCR	1e5 eV
C1, C2, C1H, C2H	0.05
Absorption energy for neutrons	1e4 eV
C1N, C2N	0
FNABS	0.8

Analytical Formula

- $$LET_d = \frac{\int_0^\infty \phi_r(z) S^2(r) dr}{\int_0^\infty \phi_r(z) S(r) dr}$$

- $$\phi_r(z) = \frac{\Phi_0}{\sqrt{2\pi}\sigma} e^{-(r-(R_0-z))^2/2\sigma^2}$$

- $$S_R(r) = \frac{1}{R\alpha^{1/p}} \left[(r+R)^{1/p} - r^{1/p} \right]$$

Analytical Formula

- $LET_d(z) = \frac{\langle S^2(z)\rangle}{\langle S(z)\rangle}$

- $\langle S(z)\rangle = \frac{\Phi_0}{\sqrt{2\pi}\sigma R\alpha}\left[\sigma^{1+1/p}\Gamma\left(1+\frac{1}{p}\right)\tilde{D}_{1+1/p}(\epsilon,\zeta) - R\left(\frac{1}{2}R\right)^{1/p} e^{-(\epsilon+\zeta)^2/8}\right]$

- $\langle S^2(z)\rangle = \frac{\Phi_0}{\sqrt{2\pi}\sigma R\alpha^{2/p}p(2-p)}\left[\sigma^{2/p}\Gamma\left(\frac{2}{p}\right)\tilde{D}_{2/p}(\epsilon,\zeta) - 2\left(\frac{1}{2}R\right)^{2/p} e^{-(\epsilon+\zeta)^2/8}\right]$

- $\tilde{D}_v(\epsilon,\zeta) = e^{-\epsilon^2/4}D_{-v}(\epsilon) - e^{-\zeta^2/4}D_{-v}(\zeta)$

- $\zeta = (z-R_0)/\sigma$ $\epsilon = (z-R_0-R)/\sigma$ -> Problem for “small” z because D_v gives huge values.

LET Averages

- Two most common averages definitions (ICRU, 1970):

$$\bar{L}_t = \int L\, t(L)\, dL \qquad \bar{L}_d = \int L\, d(L)\, dL$$

Ingredients

$$\bar{L}_t(z) = \frac{\sum_{E_i} \phi_{E_i}(z)\, S(E_i)\, \Delta E}{\sum_{E_i} \phi_{E_i}(z)\, \Delta E}$$

$$\bar{L}_d(z) = \frac{\sum_{E_i} \phi_{E_i}(z)\, S^2(E_i)\, \Delta E}{\sum_{E_i} \phi_{E_i}(z)\, S(E_i)\, \Delta E}$$

- ϕ_{E_i} : proton energy spectrum.
- $S(E_i)$: electronic stopping power.
- Implicit assumption:

$$D = \phi_{E_i} \cdot S(E_i)$$

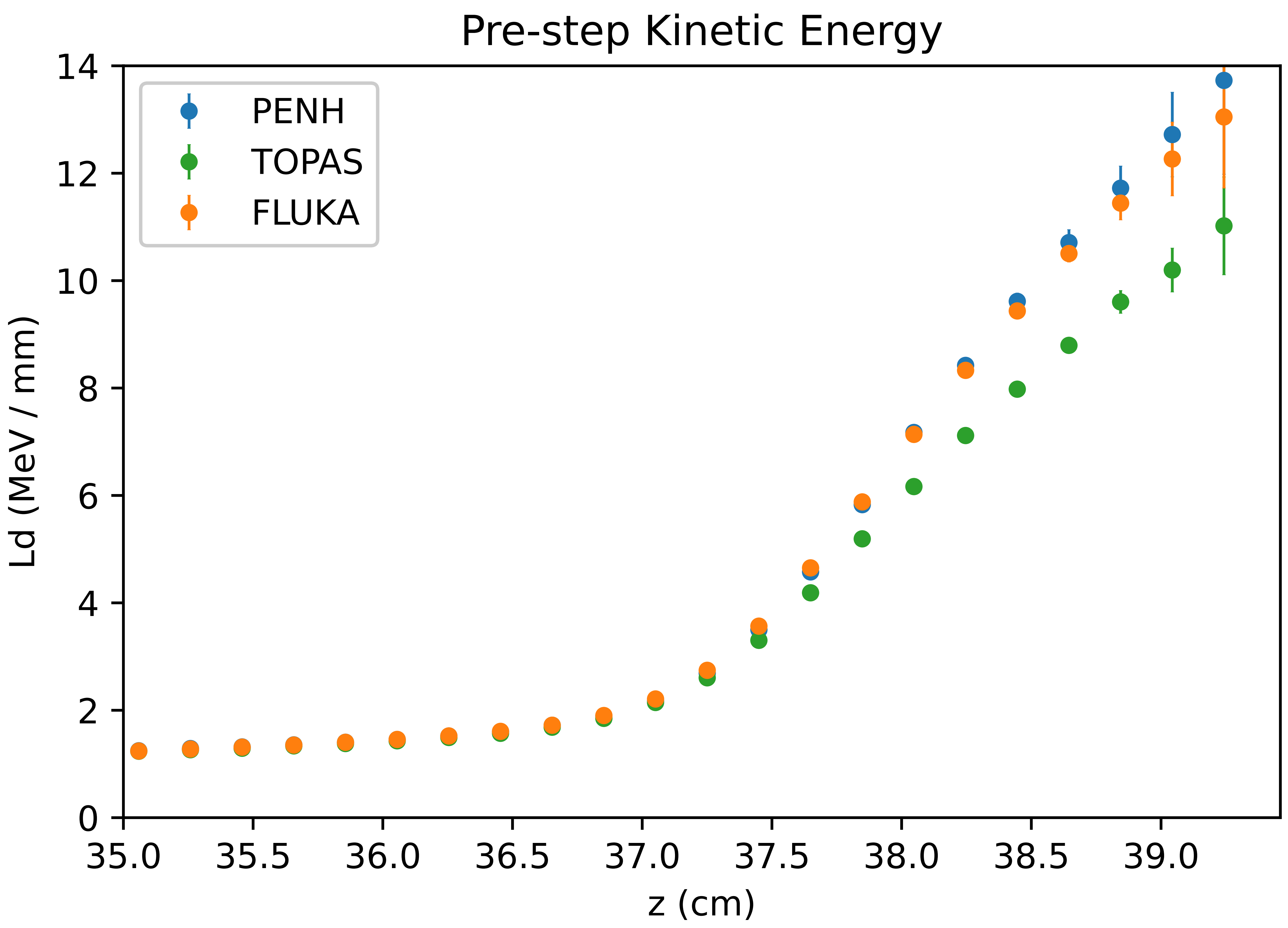
Ingredients

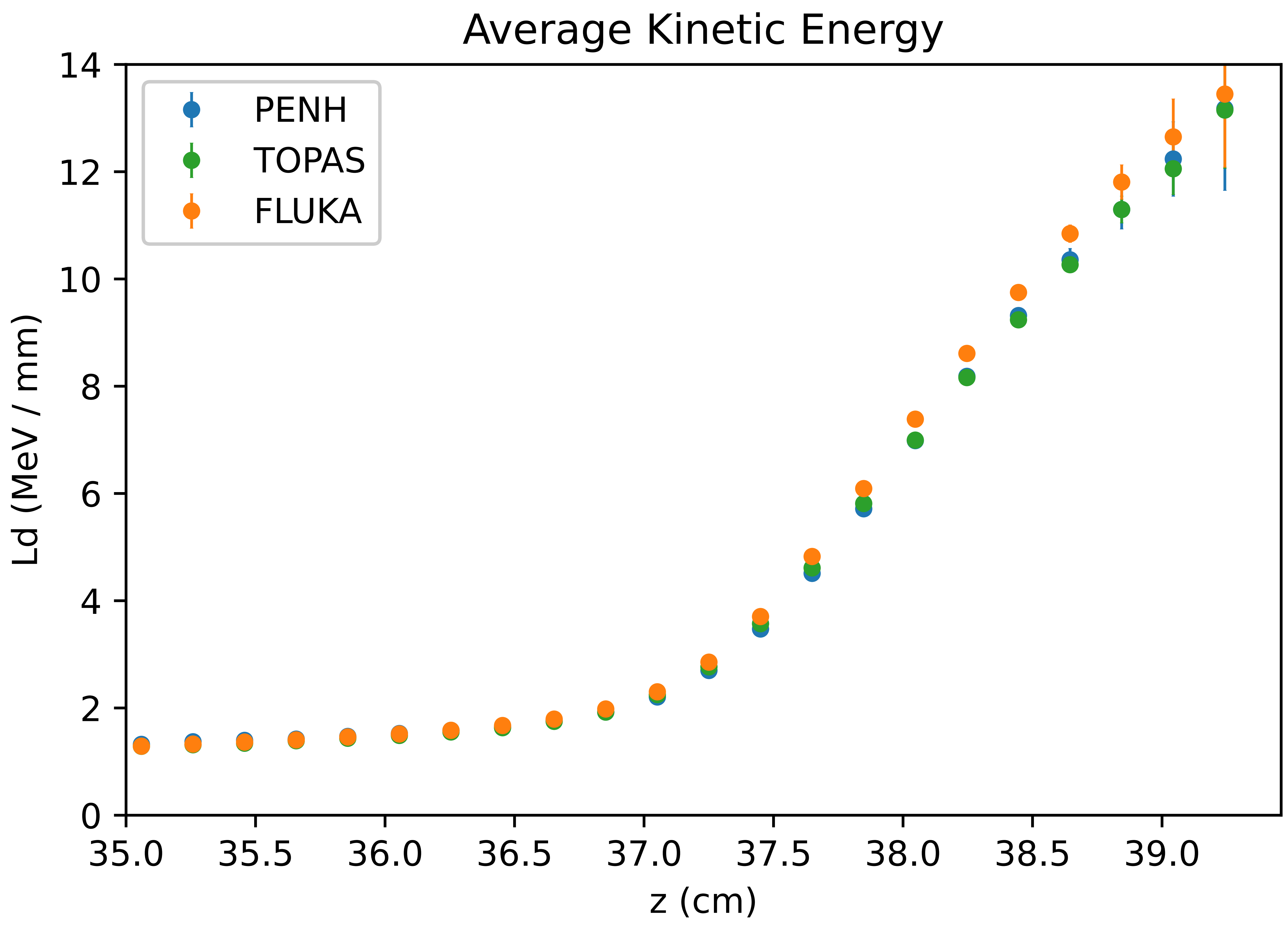
$$\bar{L}_t = \frac{\sum_i^N dx_i \, S_i(E)}{\sum_i^N dx_i}$$

$$\bar{L}_d = \frac{\sum_i^N e_i \, S_i(E)}{\sum_i^N e_i}$$

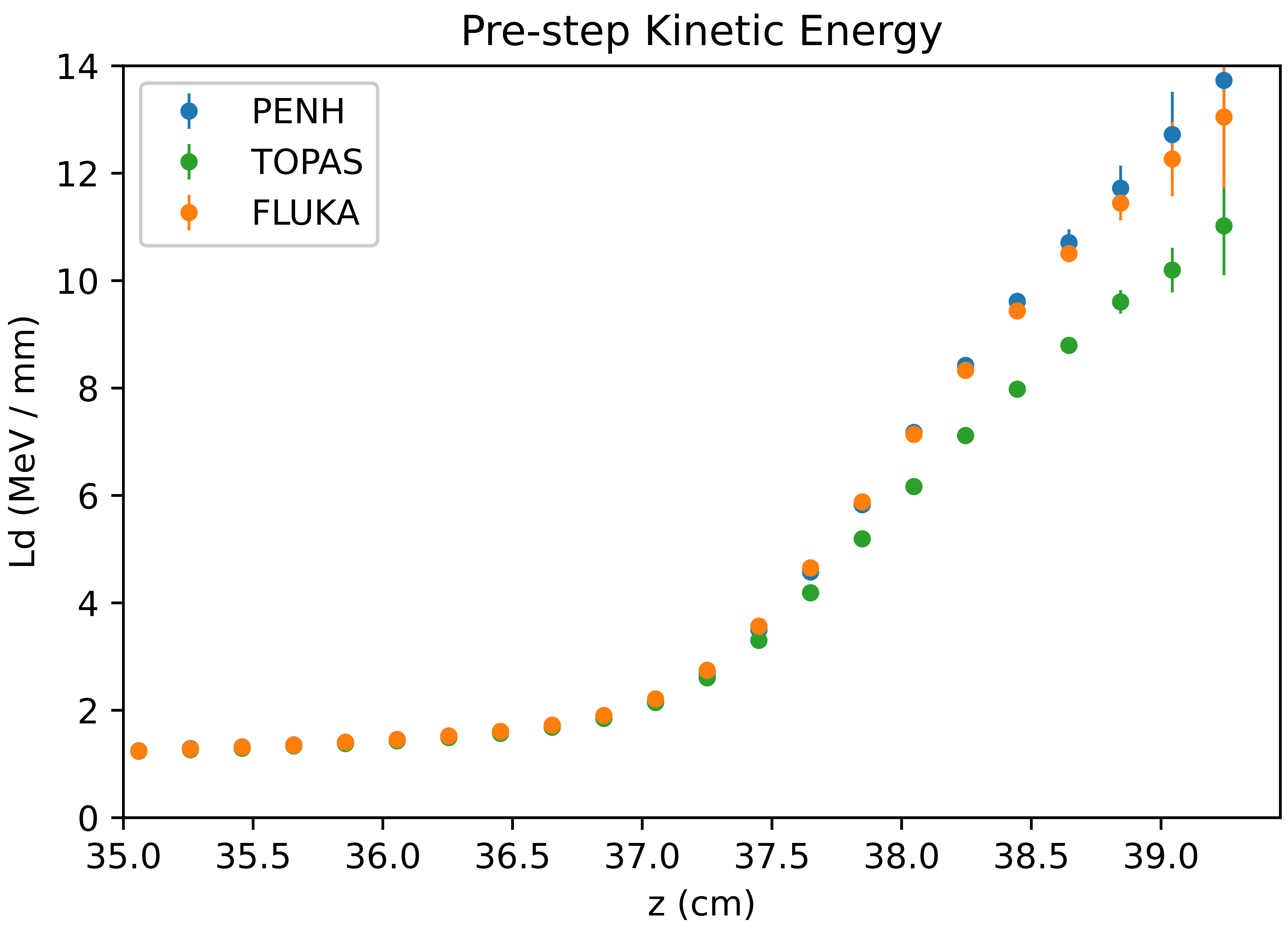
- dx_i : length of simulation step.
- e_i : energy deposited in step.
- $S_i(E)$: stopping power of particle depositing energy.

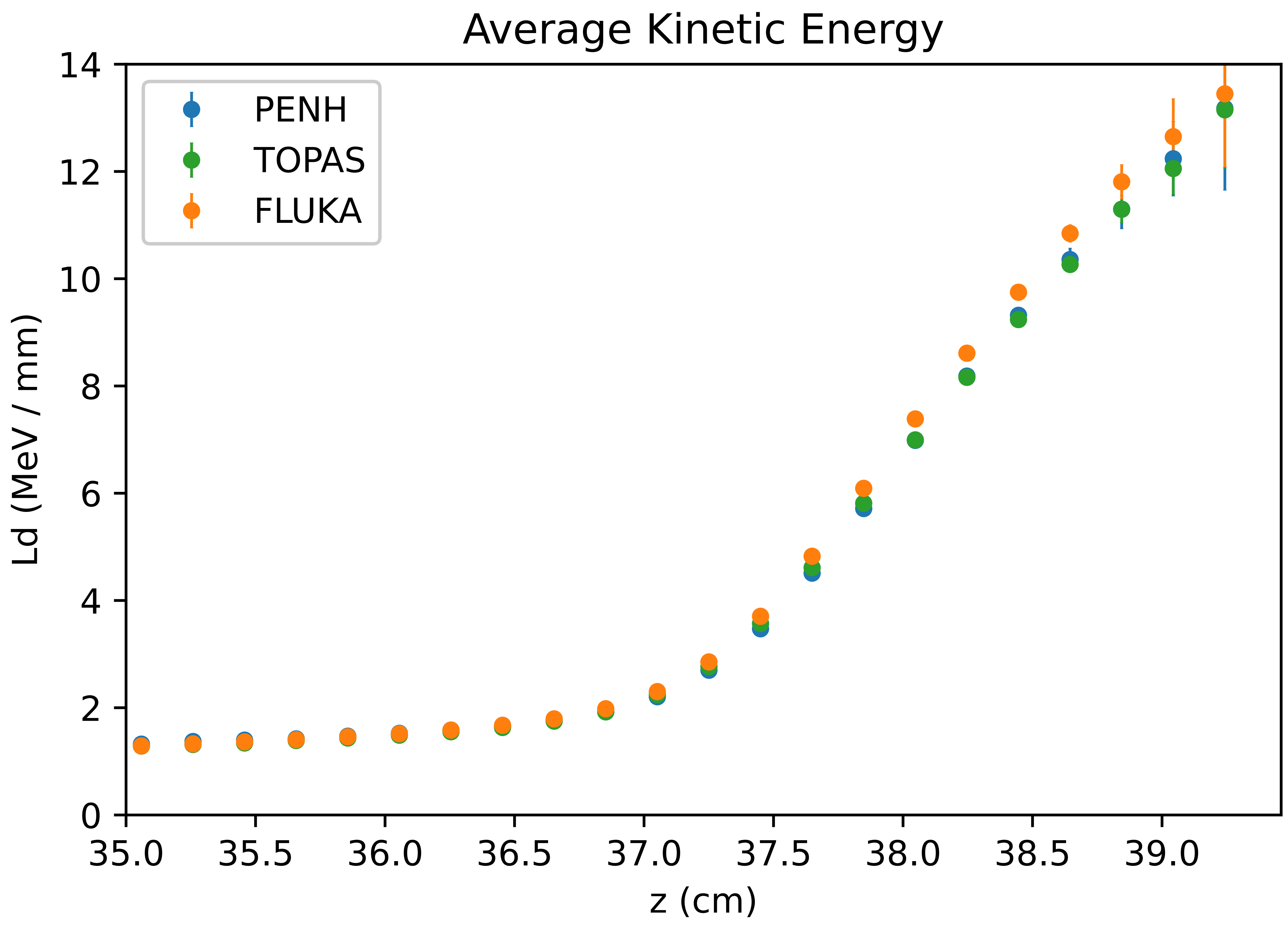
Correcting TOPAS? (Cortés-Giraldo et al., 2015)





Correcting TOPAS? (Cortés-Giraldo et al., 2015)





- Using a different stopping power $S_i(E)$ seems to give more stable results.

Definition of Dose (ICRU 85)

- Absorbed dose: $D = \frac{d\bar{\epsilon}}{dm}$

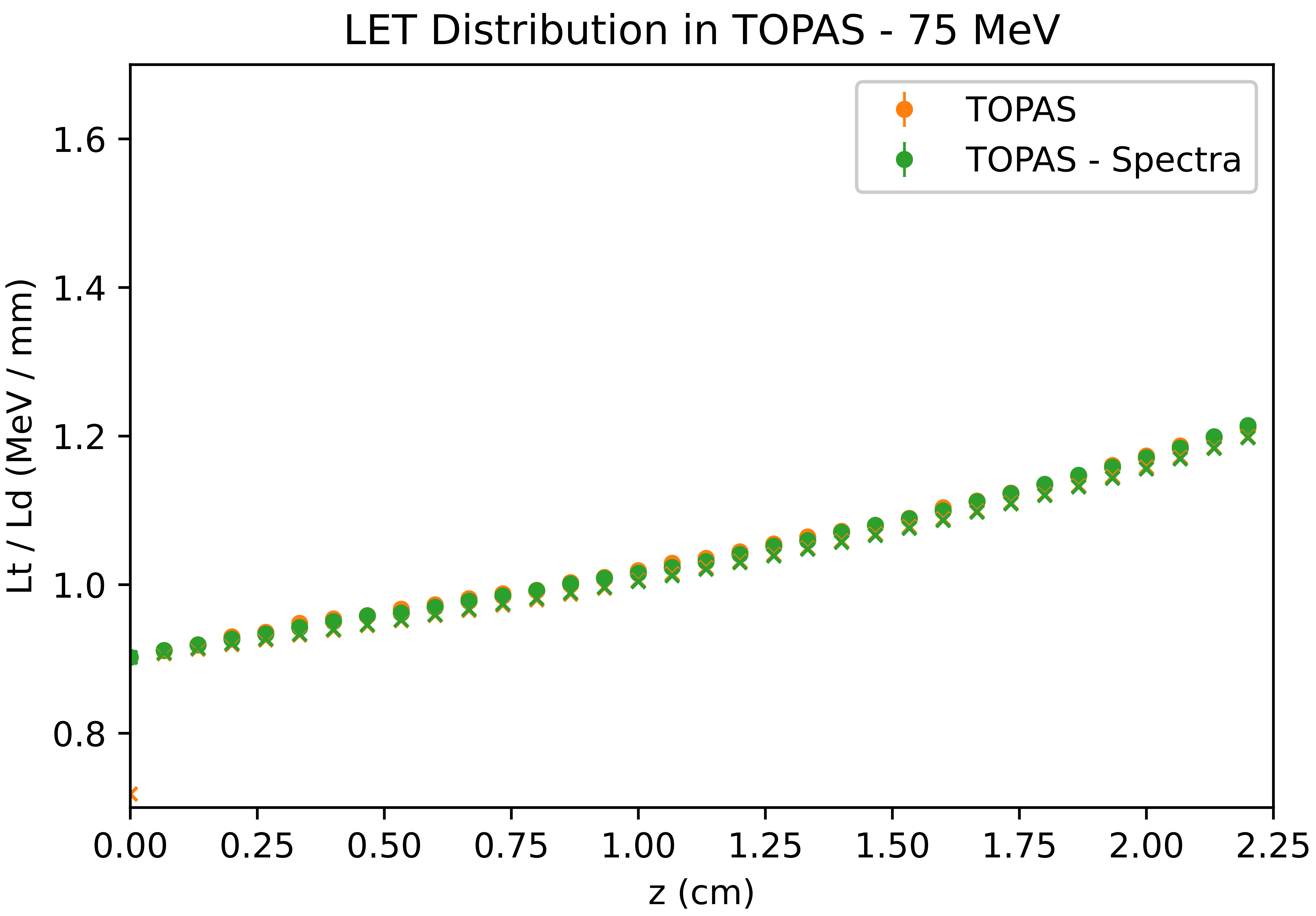
- $\epsilon = \epsilon_{in} - \epsilon_{out} + Q$

- Grussell, 2014: “A desirable property of the absorbed dose is that it should depend only on the set of initial ionizing particles released during the irradiation, and the geometry.”

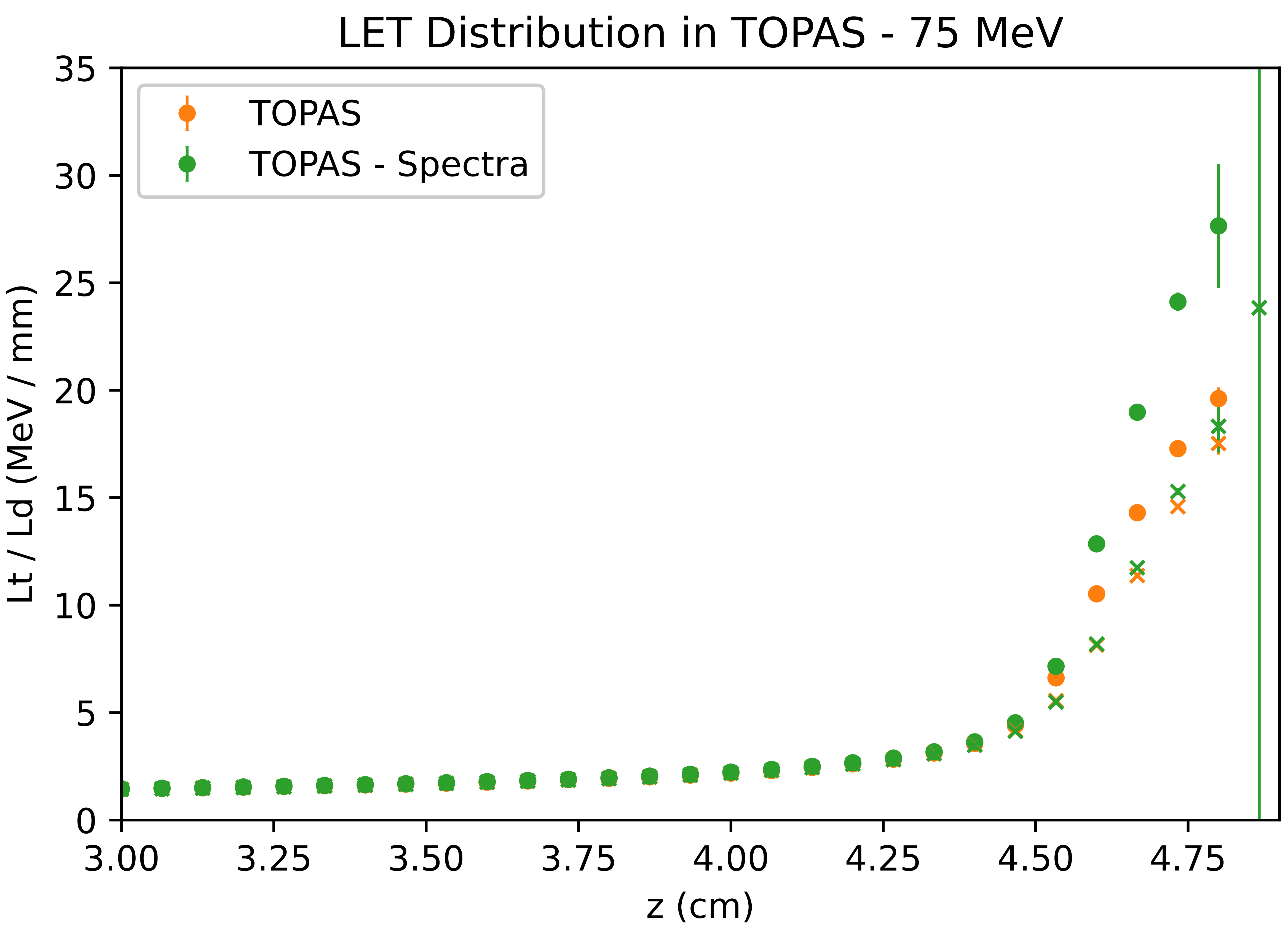
Consistency Results

No Nuclear Reactions

75 MeV

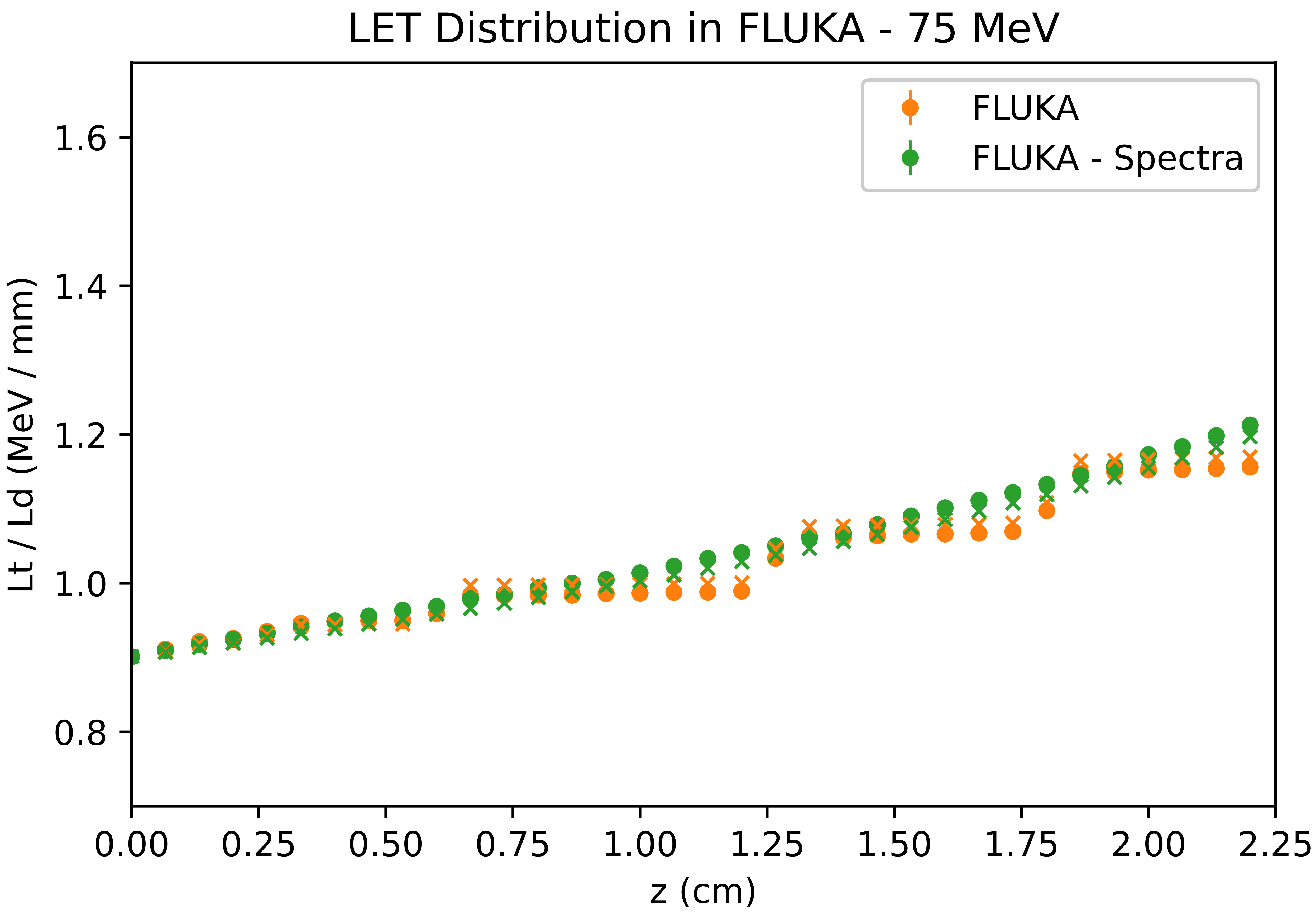


LET Distribution in TOPAS - 75 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)

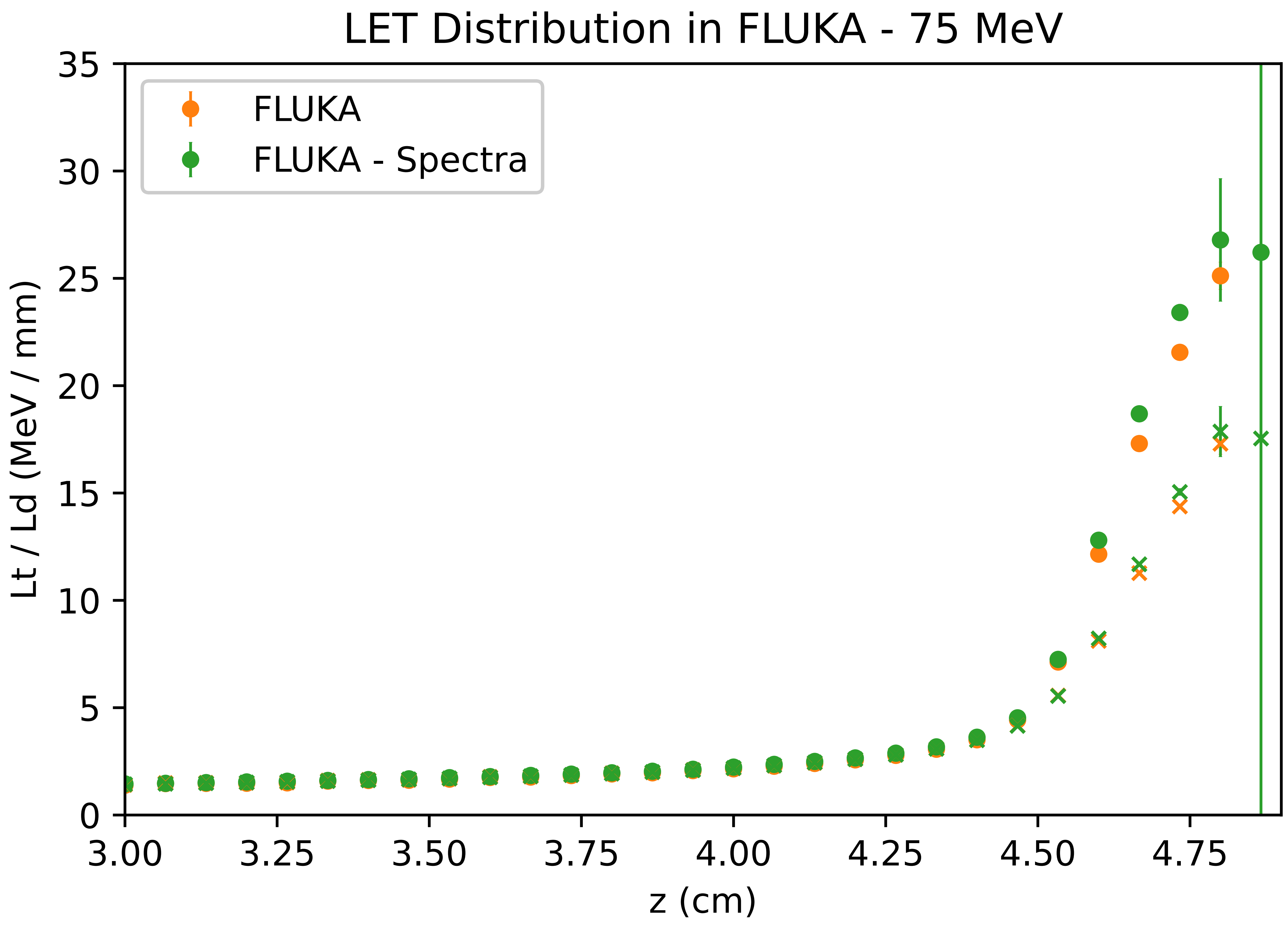


LET Distribution in TOPAS - 75 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)

75 MeV

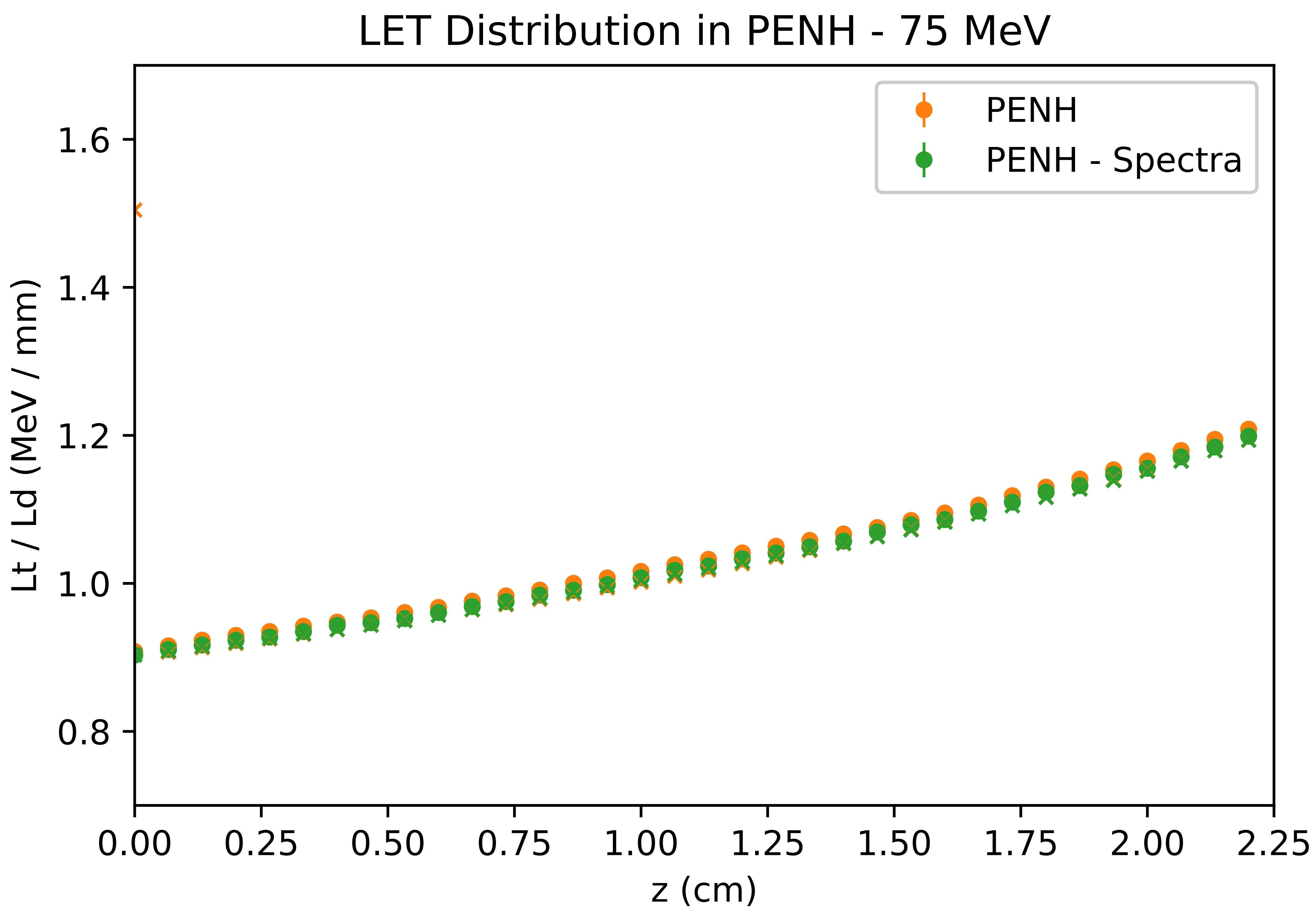


LET Distribution in FLUKA - 75 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)

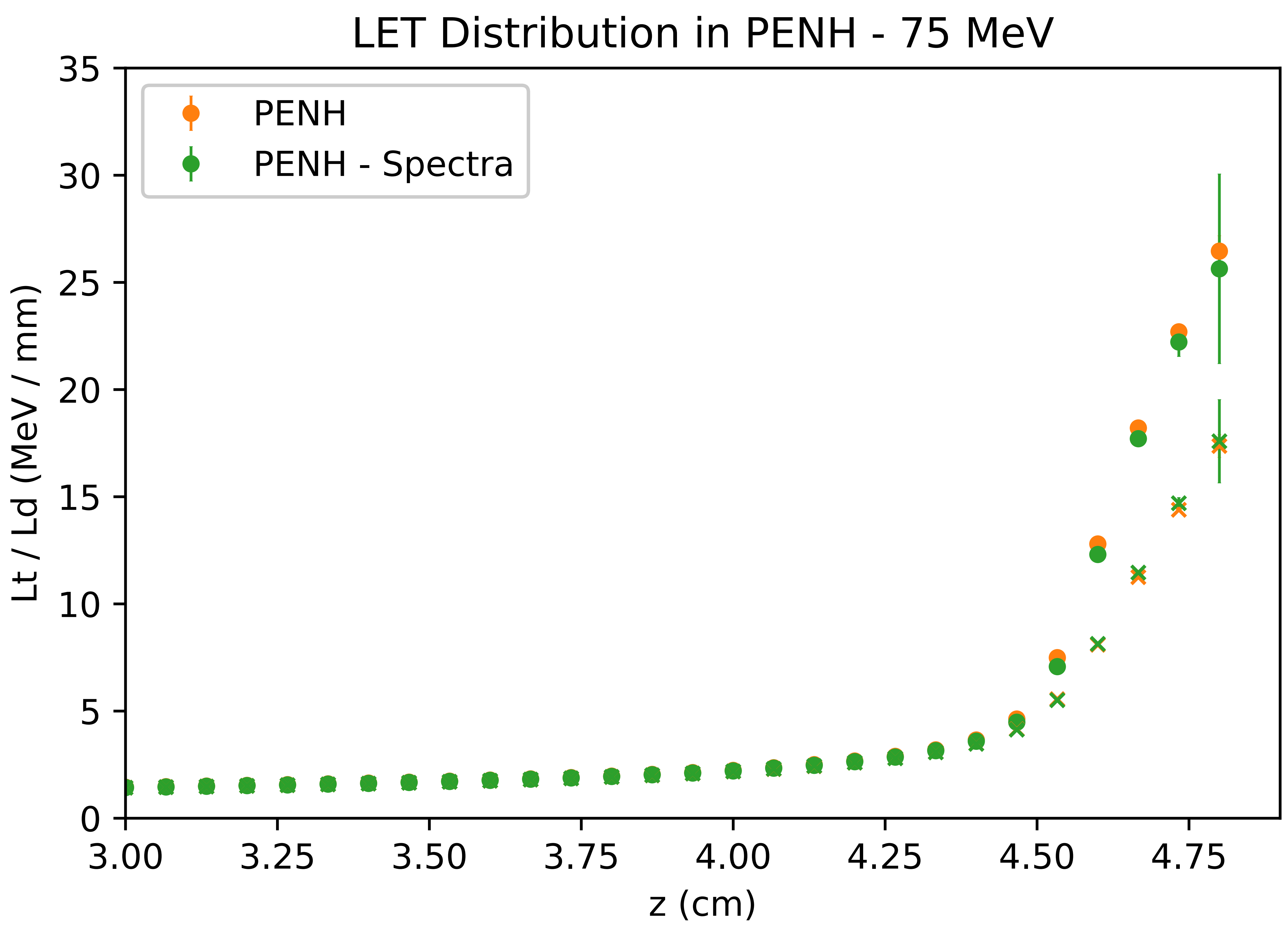


LET Distribution in FLUKA - 75 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)

75 MeV

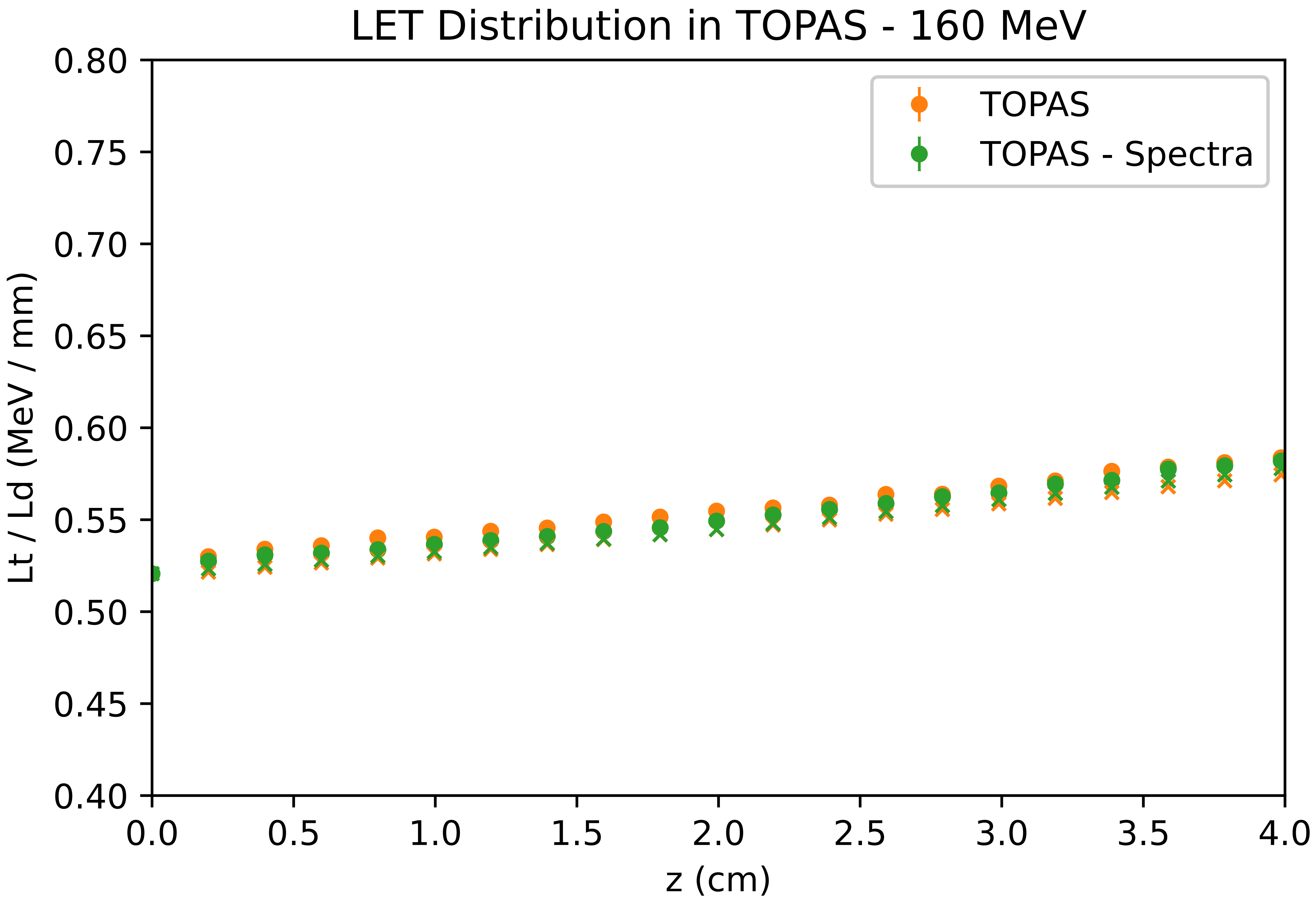


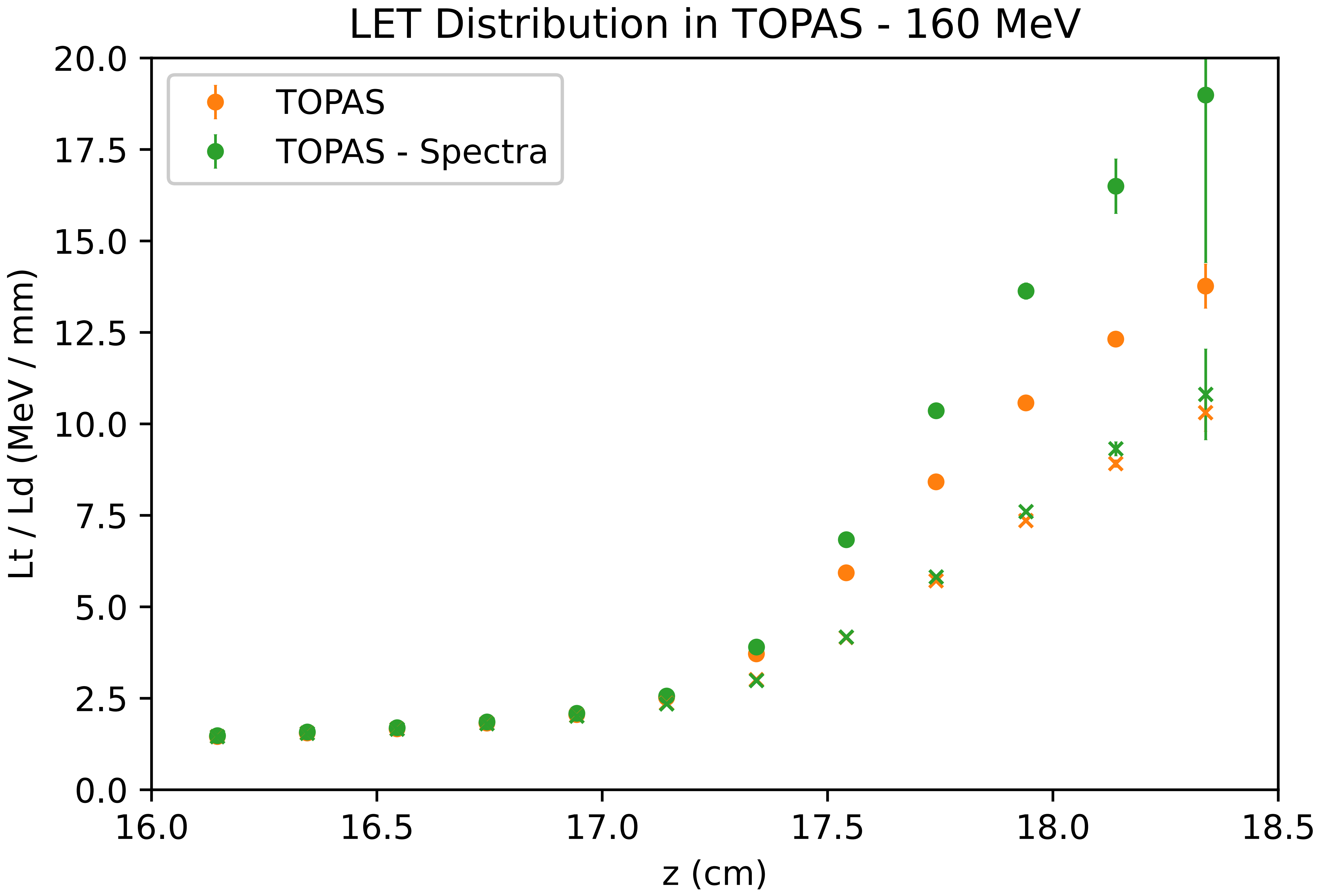
LET Distribution in PENH - 75 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
1.6
1.4
1.2
1.0
0.8
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25



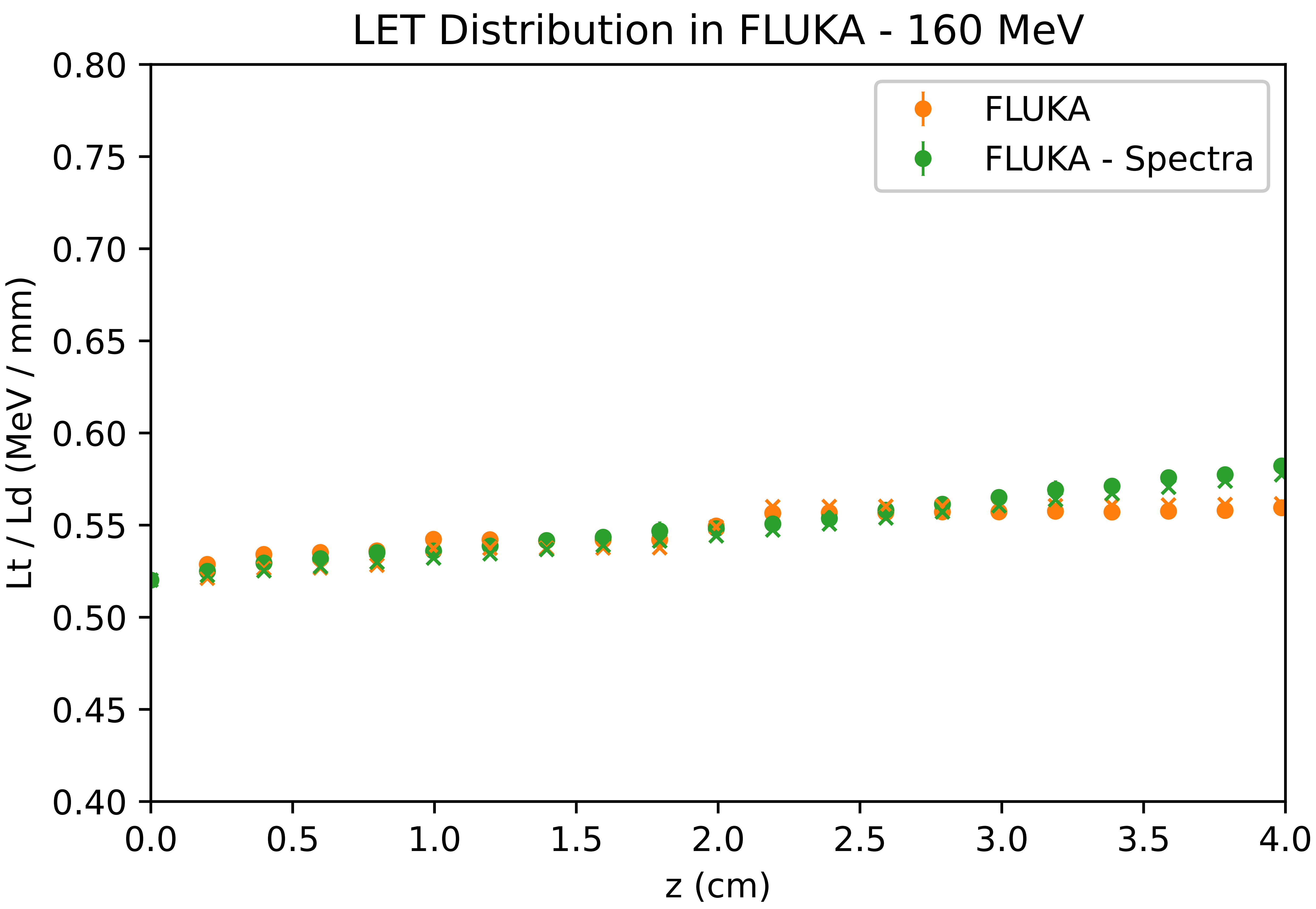
LET Distribution in PENH - 75 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
35
30
25
20
15
10
5
0
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75

160 MeV

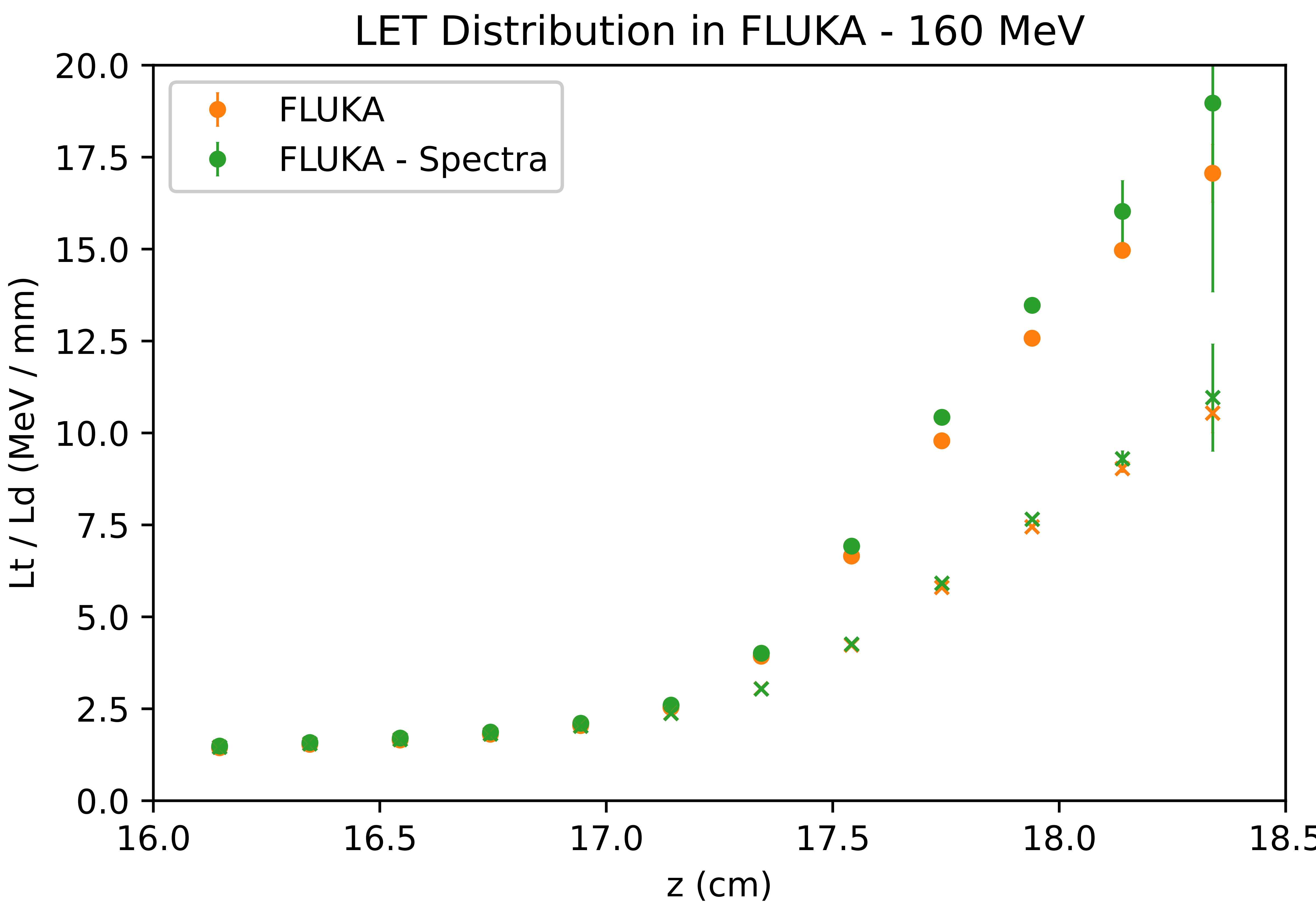

LET Distribution in TOPAS - 160 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


LET Distribution in TOPAS - 160 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.0
16.5
17.0
17.5
18.0
18.5

160 MeV

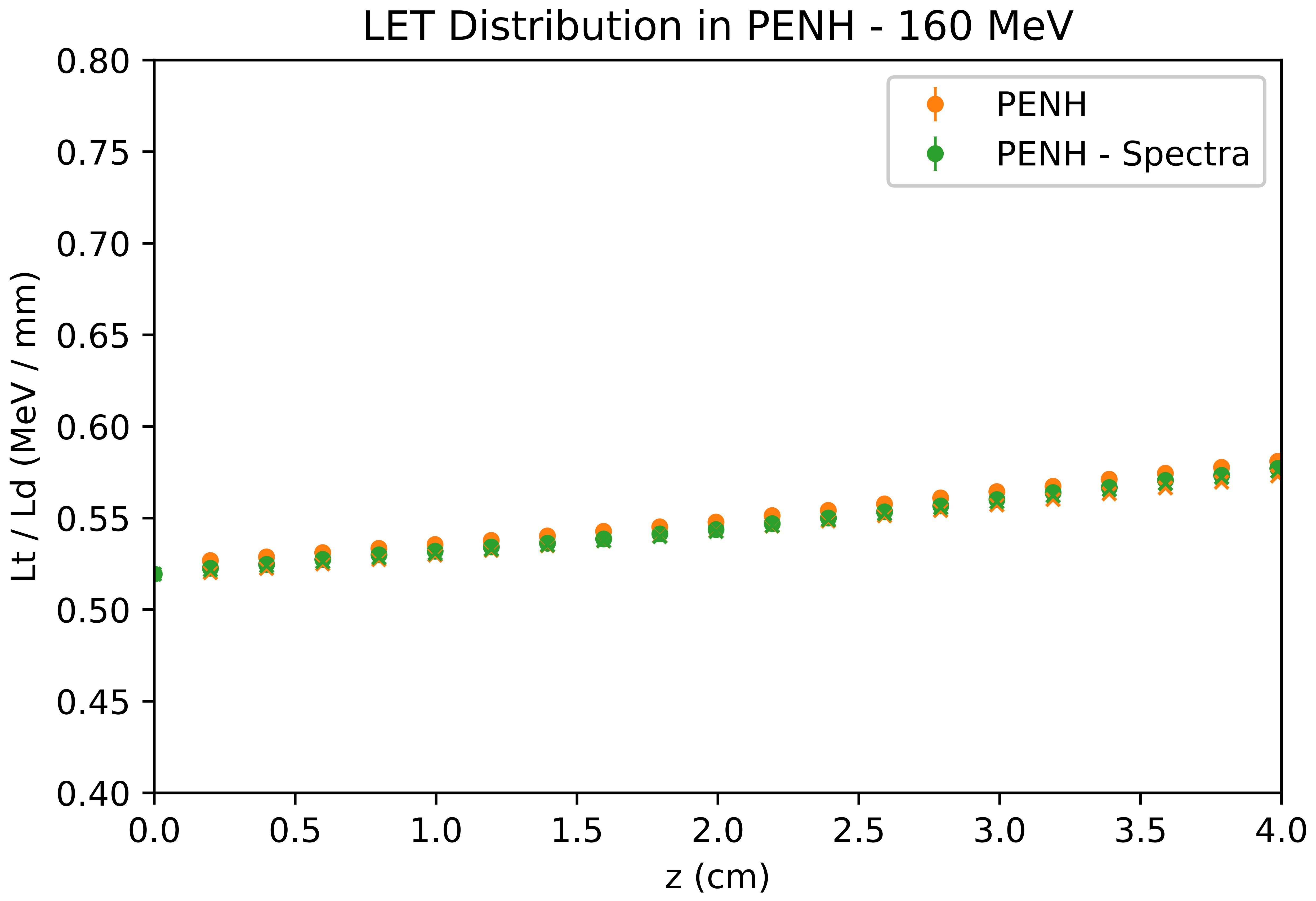


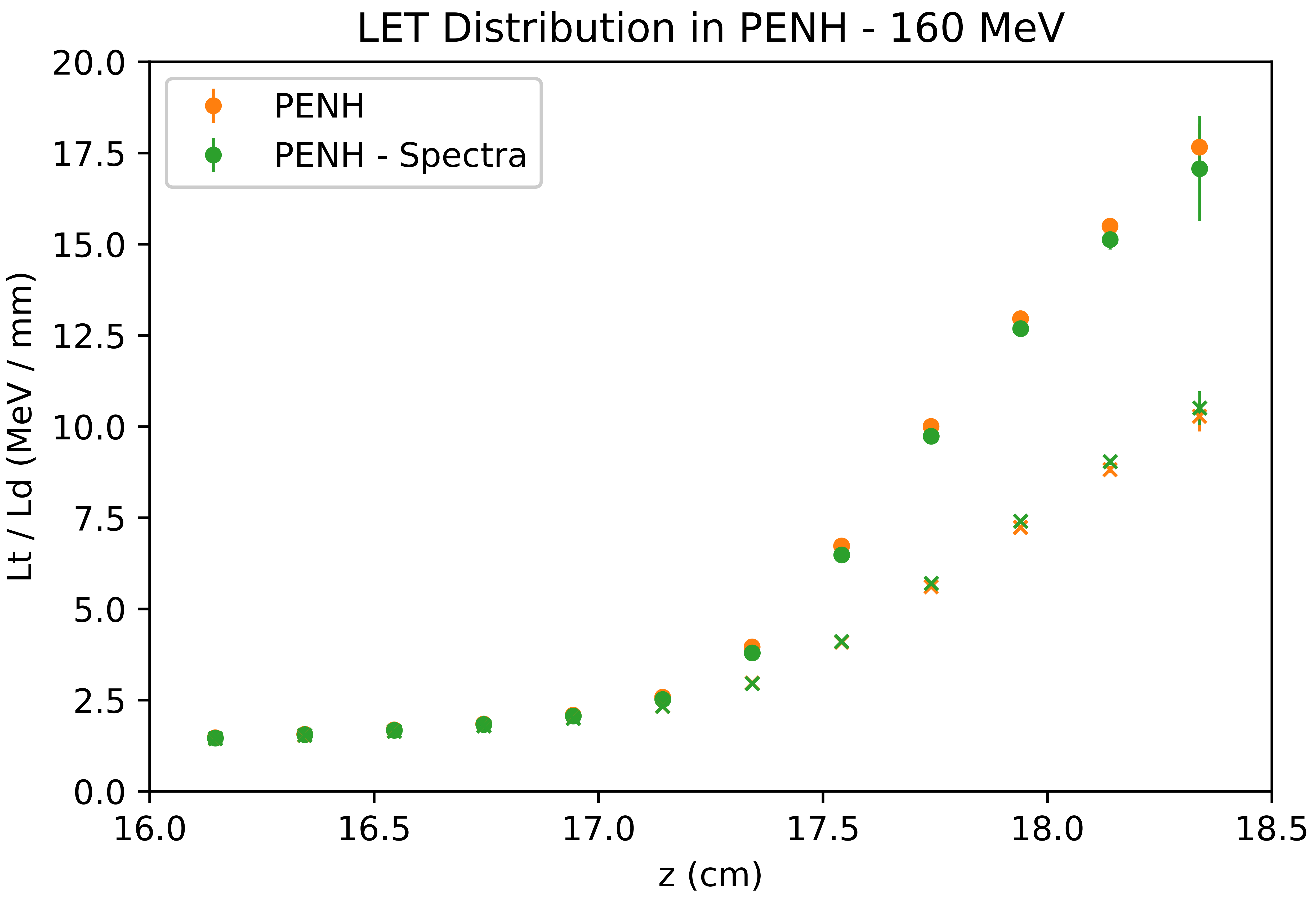
LET Distribution in FLUKA - 160 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0



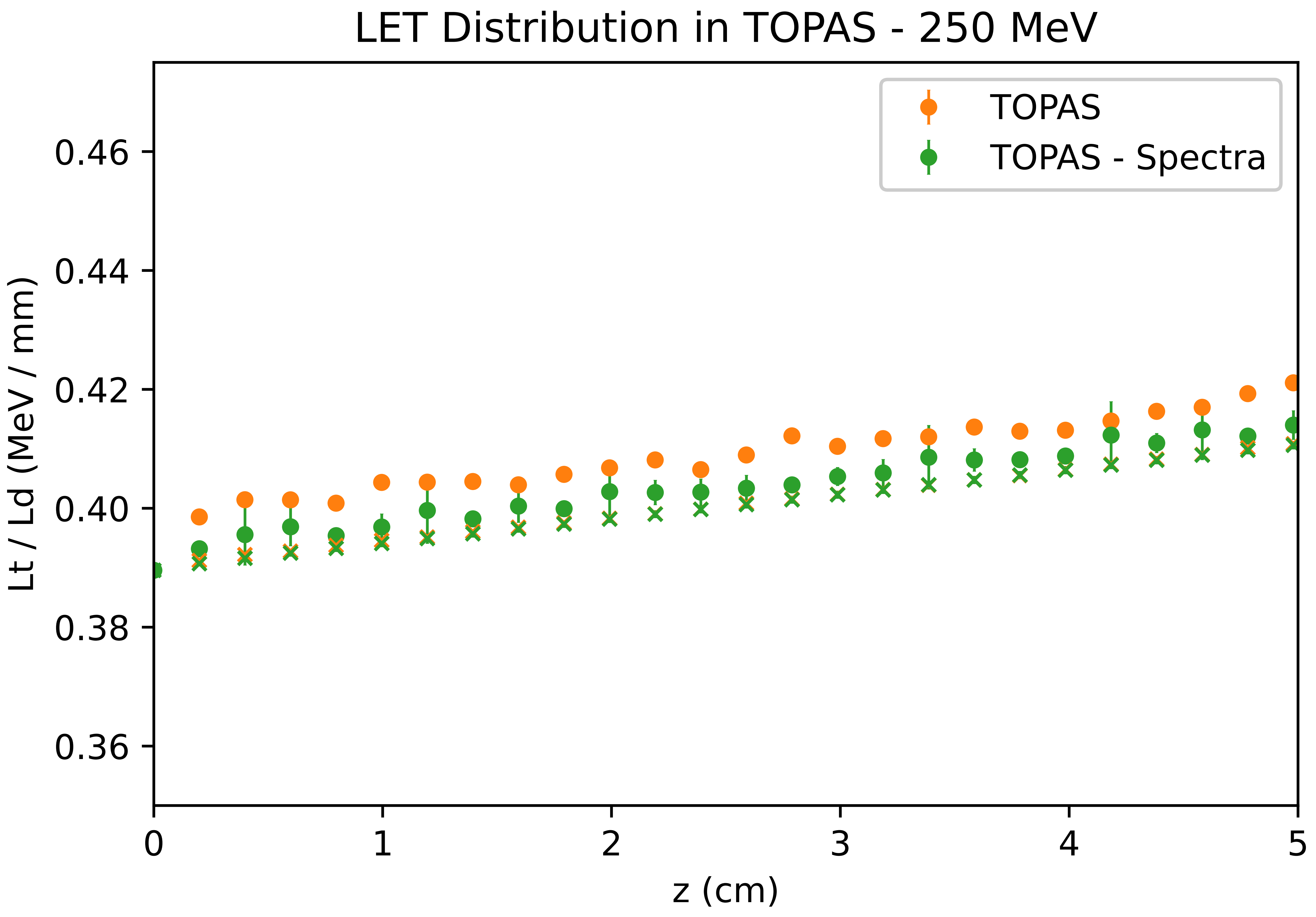
LET Distribution in FLUKA - 160 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.0
16.5
17.0
17.5
18.0
18.5

160 MeV

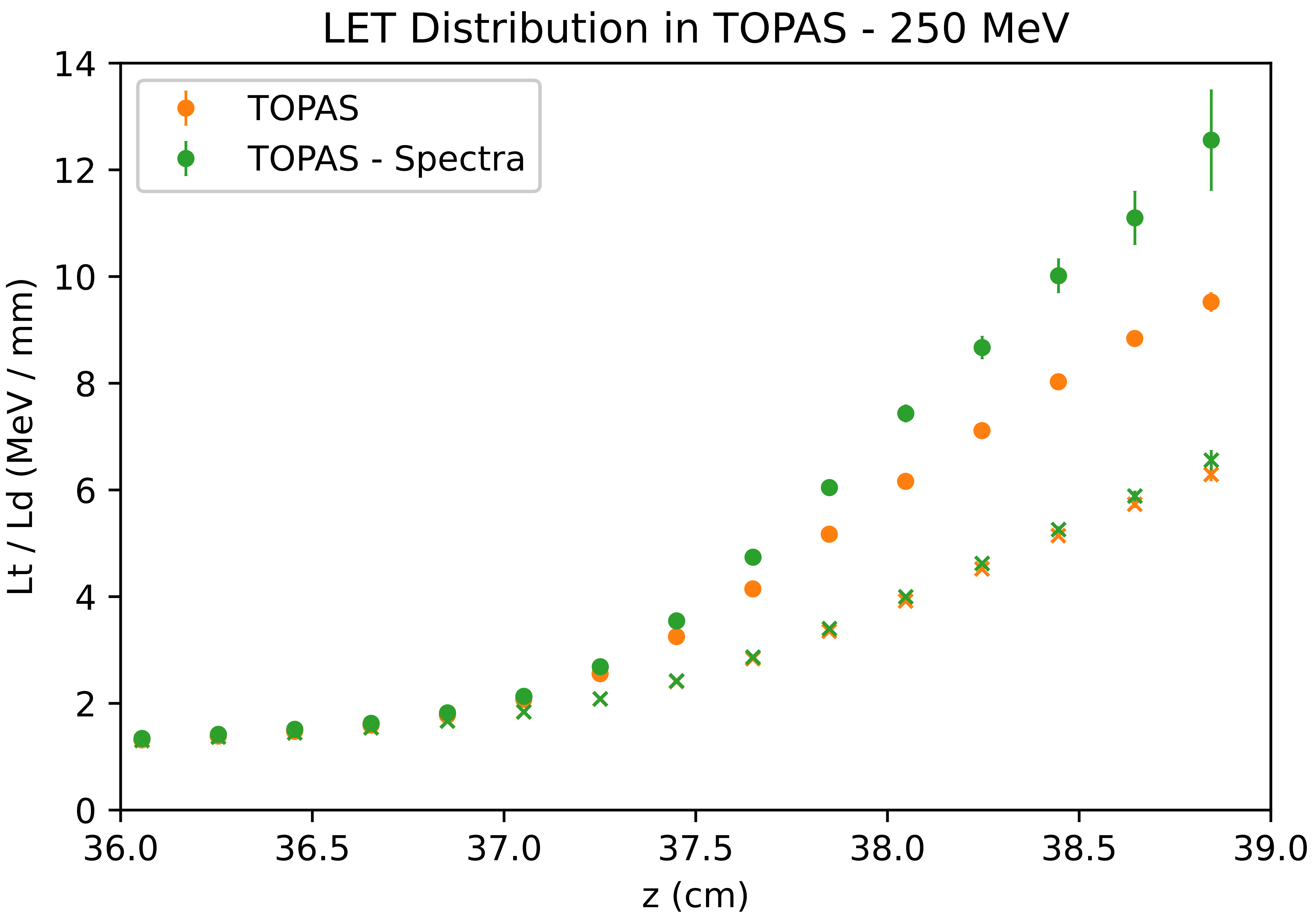

LET Distribution in PENH - 160 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


LET Distribution in PENH - 160 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
16.0
16.5
17.0
17.5
18.0
18.5

250 MeV

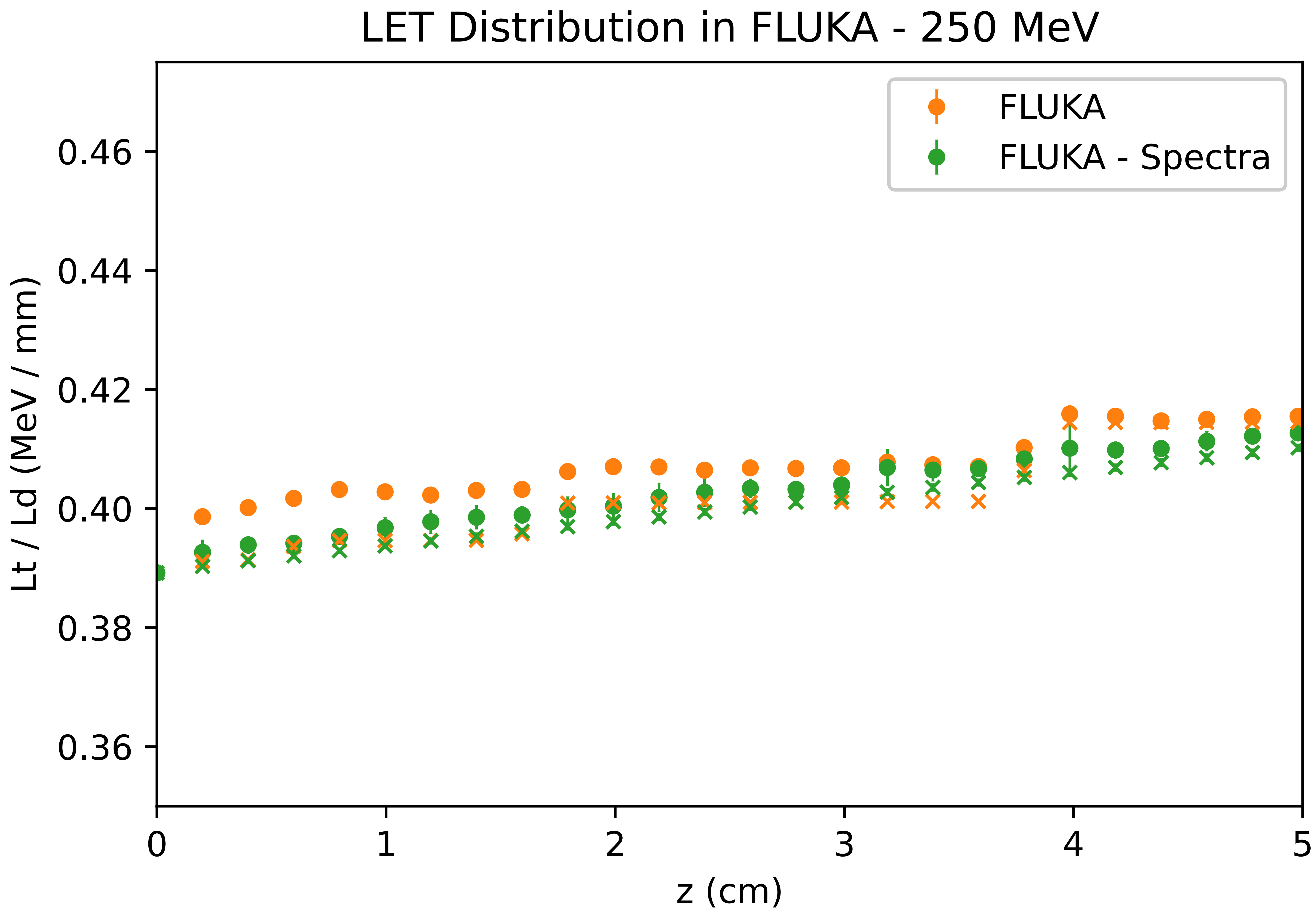


LET Distribution in TOPAS - 250 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.36
0.38
0.40
0.42
0.44
0.46
0
1
2
3
4
5

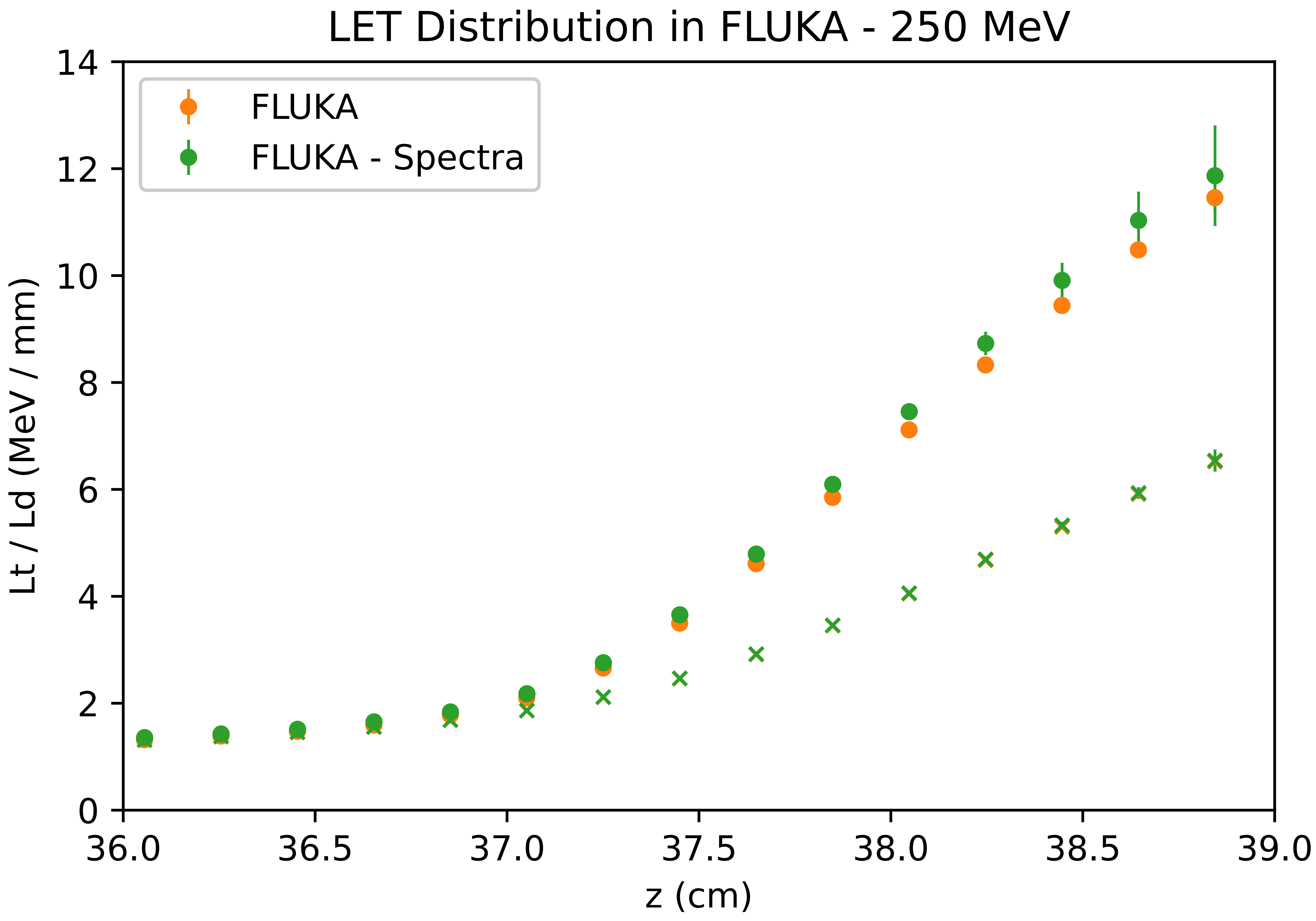


LET Distribution in TOPAS - 250 MeV
TOPAS
TOPAS - Spectra
Lt / Ld (MeV / mm)
z (cm)
0
2
4
6
8
10
12
14
36.0
36.5
37.0
37.5
38.0
38.5
39.0

250 MeV

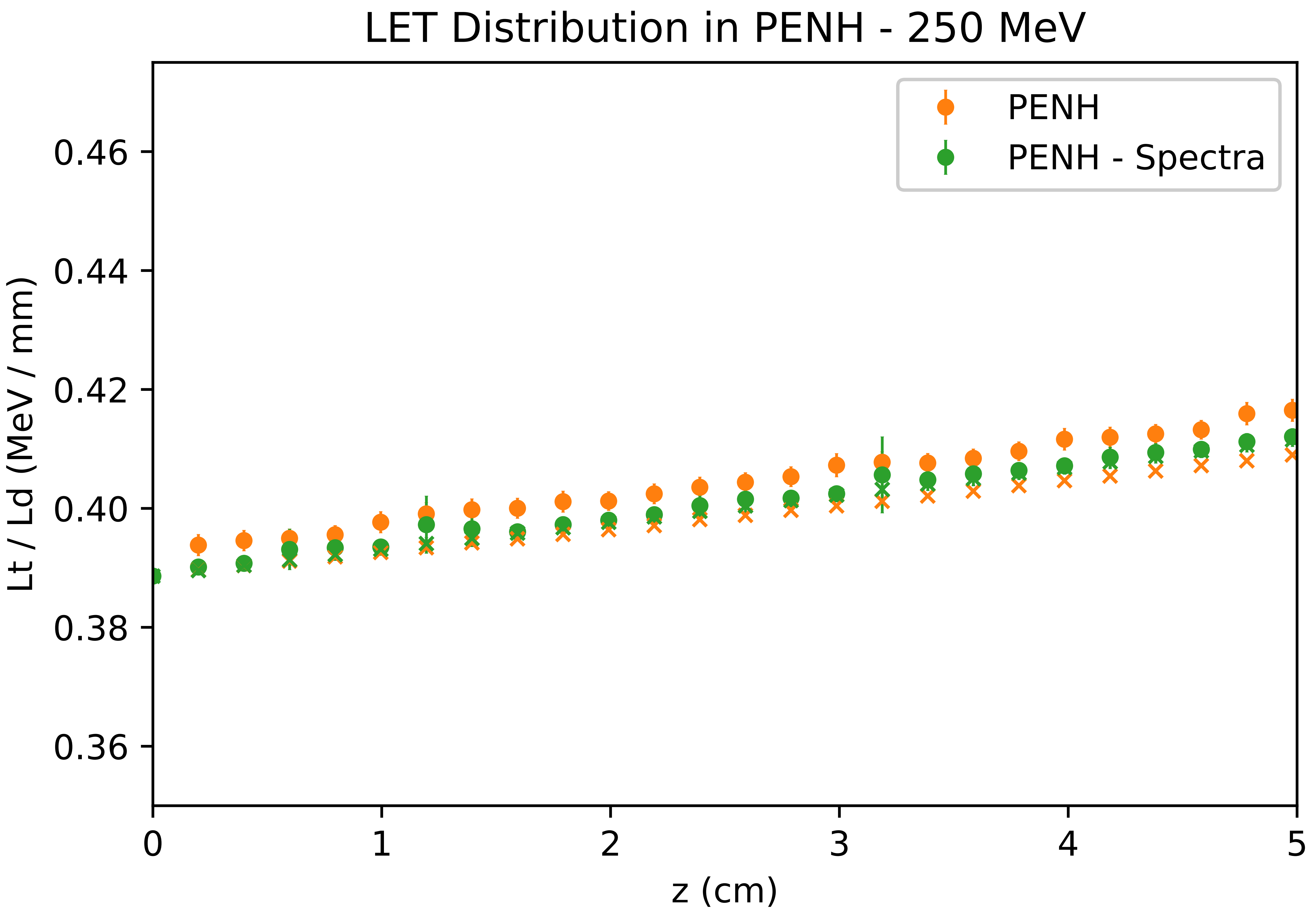


LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.46
0.44
0.42
0.40
0.38
0.36
0
1
2
3
4
5

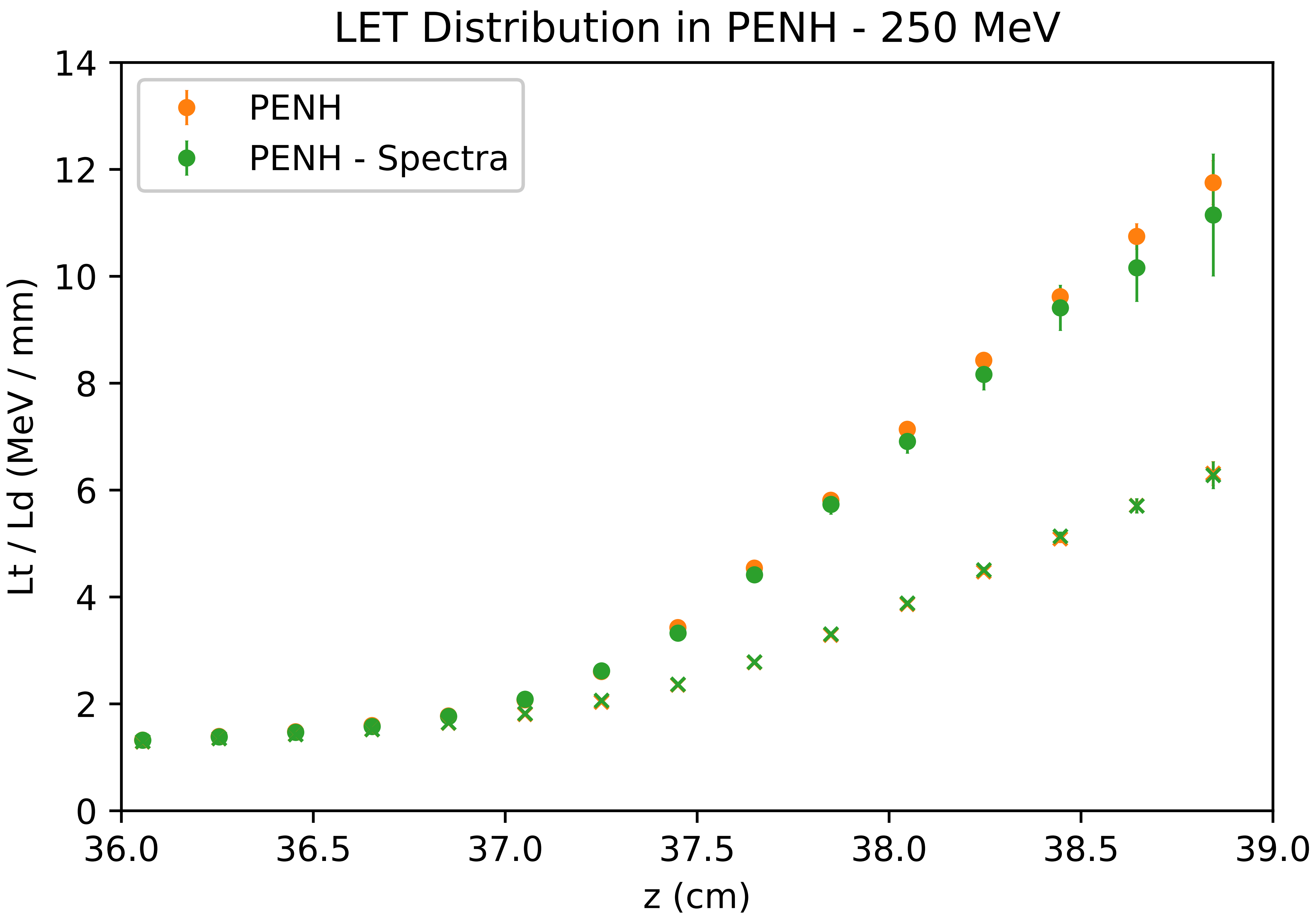


LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Lt / Ld (MeV / mm)
z (cm)
14
12
10
8
6
4
2
0
36.0
36.5
37.0
37.5
38.0
38.5
39.0

250 MeV



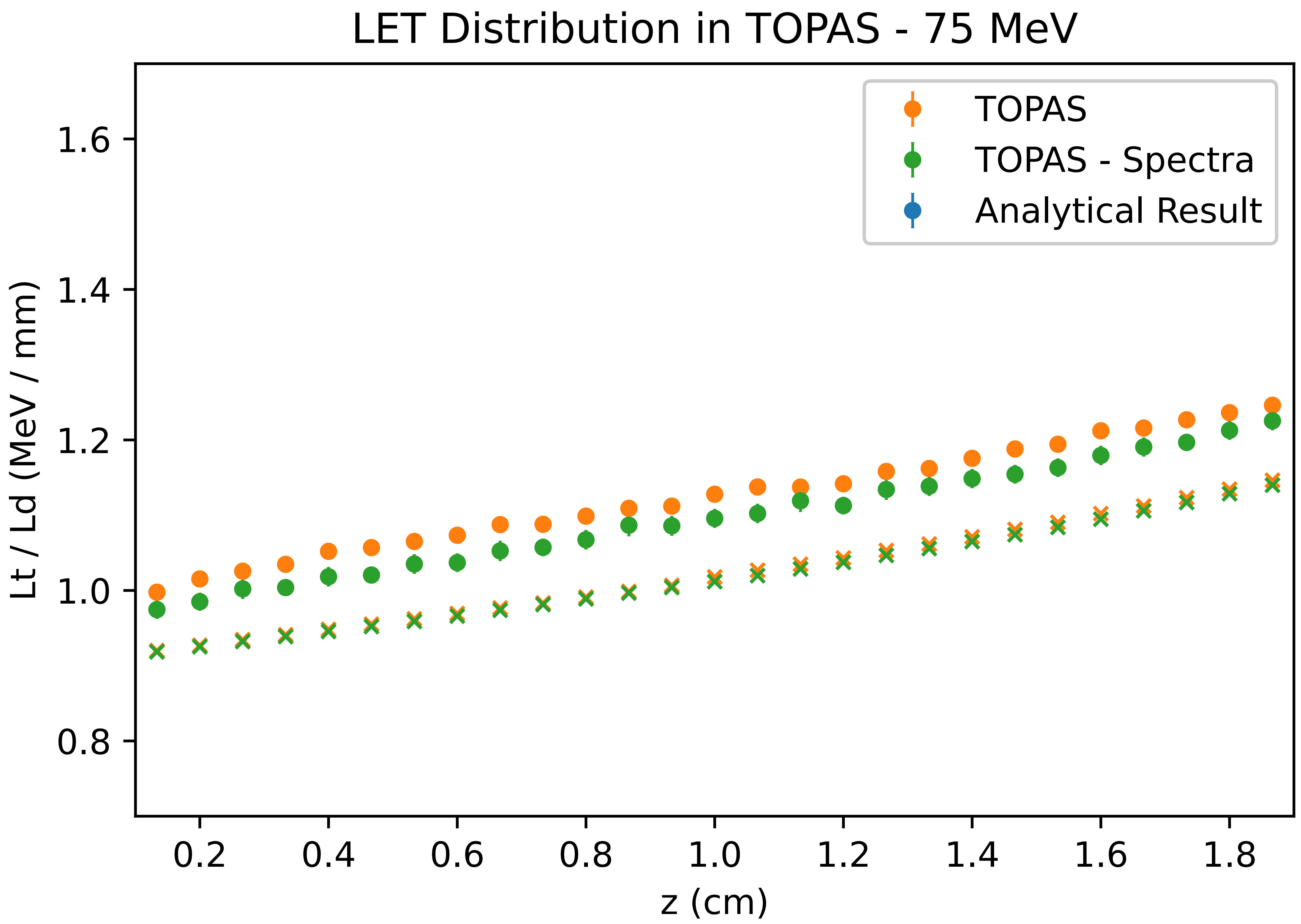
LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
0.36
0.38
0.40
0.42
0.44
0.46
0
1
2
3
4
5



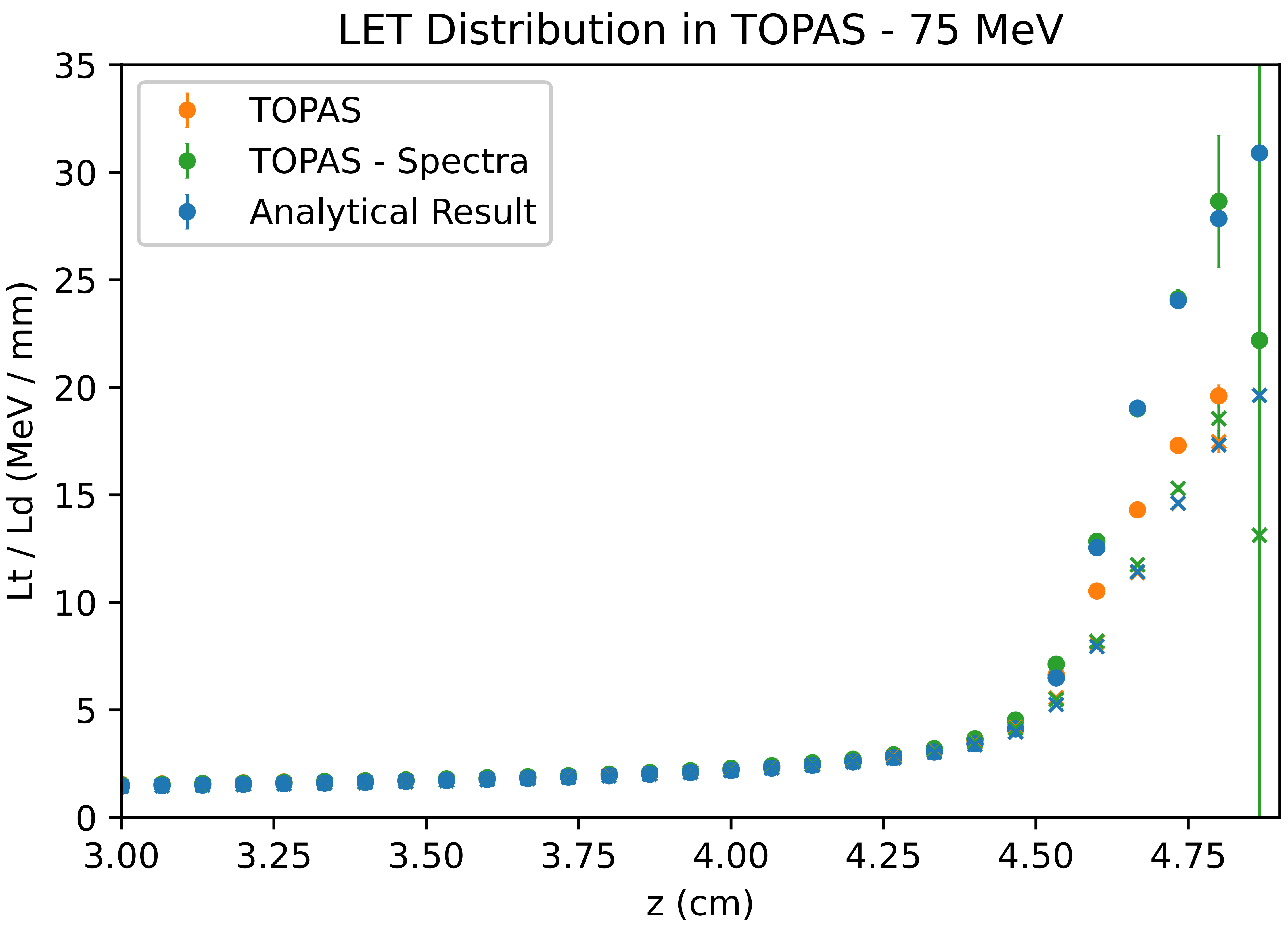
LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Lt / Ld (MeV / mm)
z (cm)
0
2
4
6
8
10
12
14
36.0
36.5
37.0
37.5
38.0
38.5
39.0

Full Calculations

75 MeV

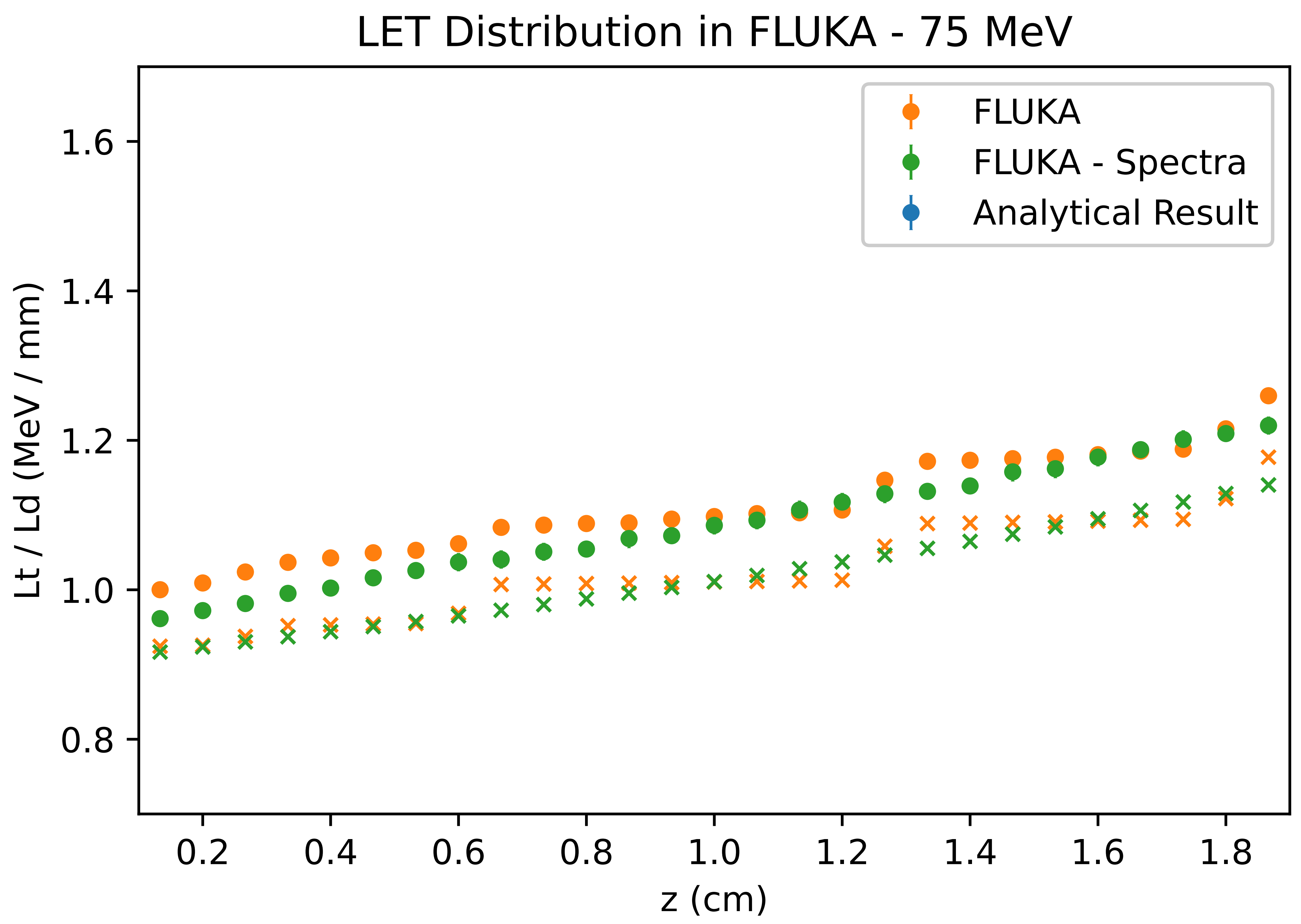


LET Distribution in TOPAS - 75 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
1.6
1.4
1.2
1.0
0.8
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

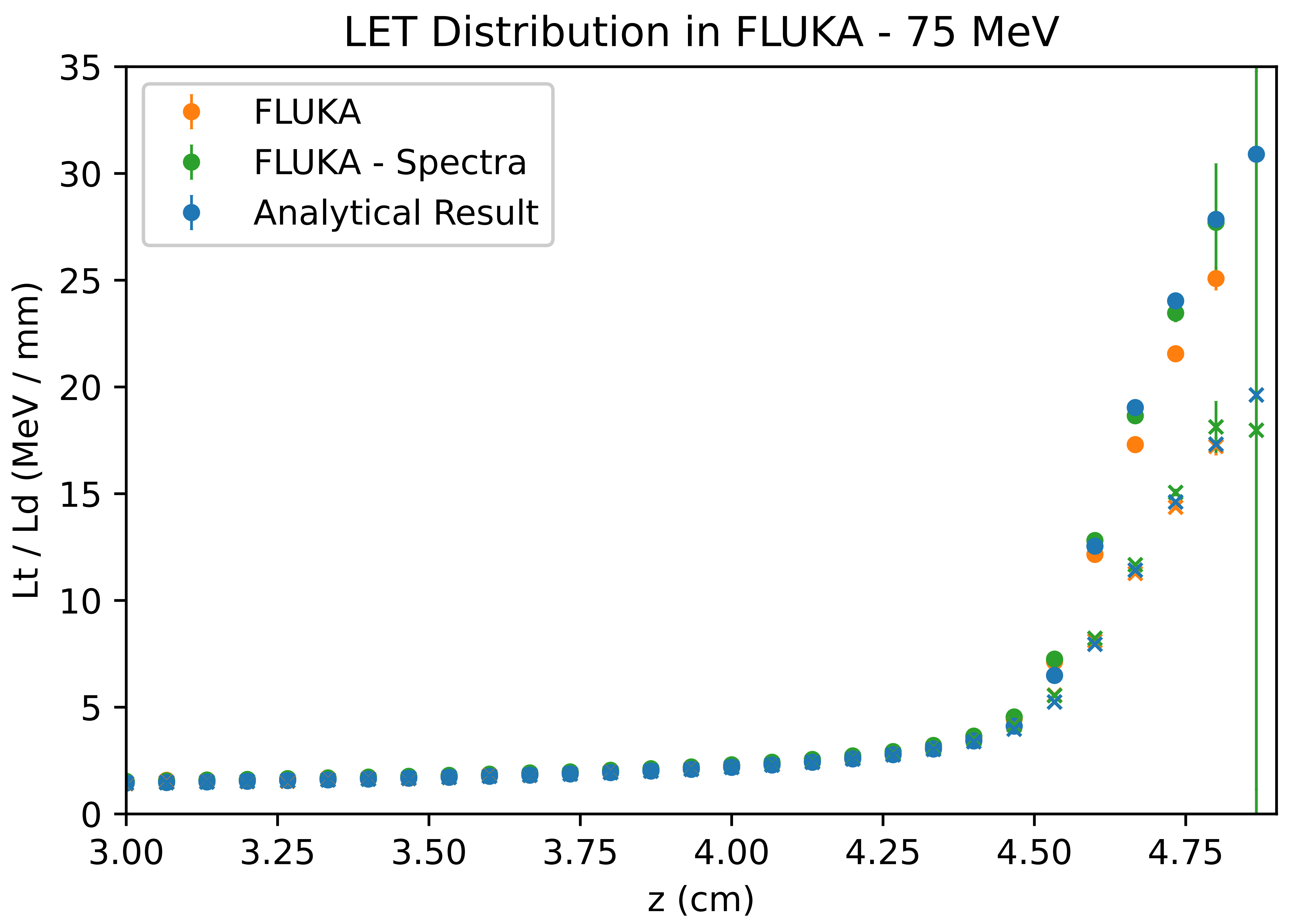


LET Distribution in TOPAS - 75 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
35
30
25
20
15
10
5
0
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75

75 MeV

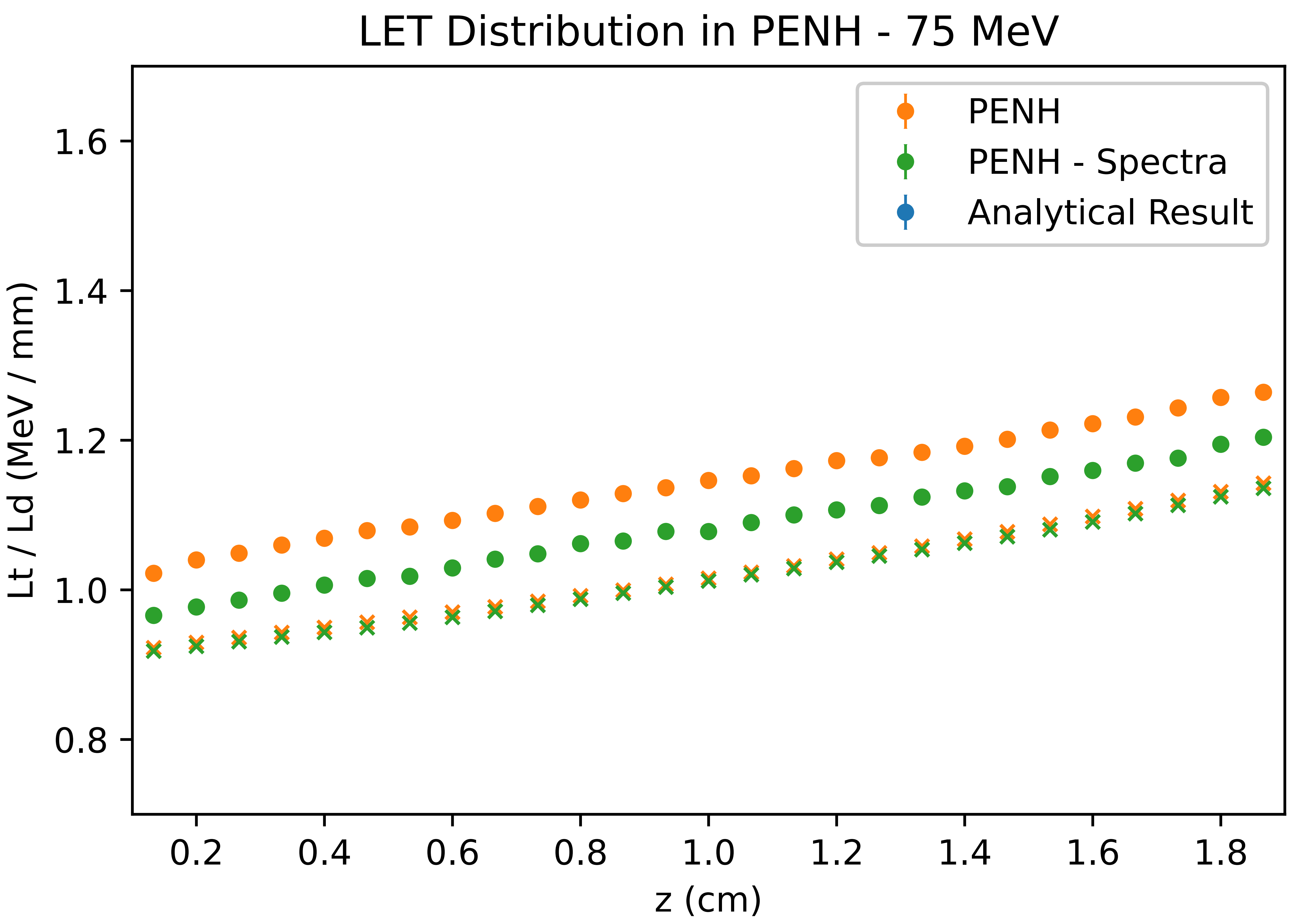


LET Distribution in FLUKA - 75 MeV
FLUKA
FLUKA - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
0.8
1.0
1.2
1.4
1.6
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

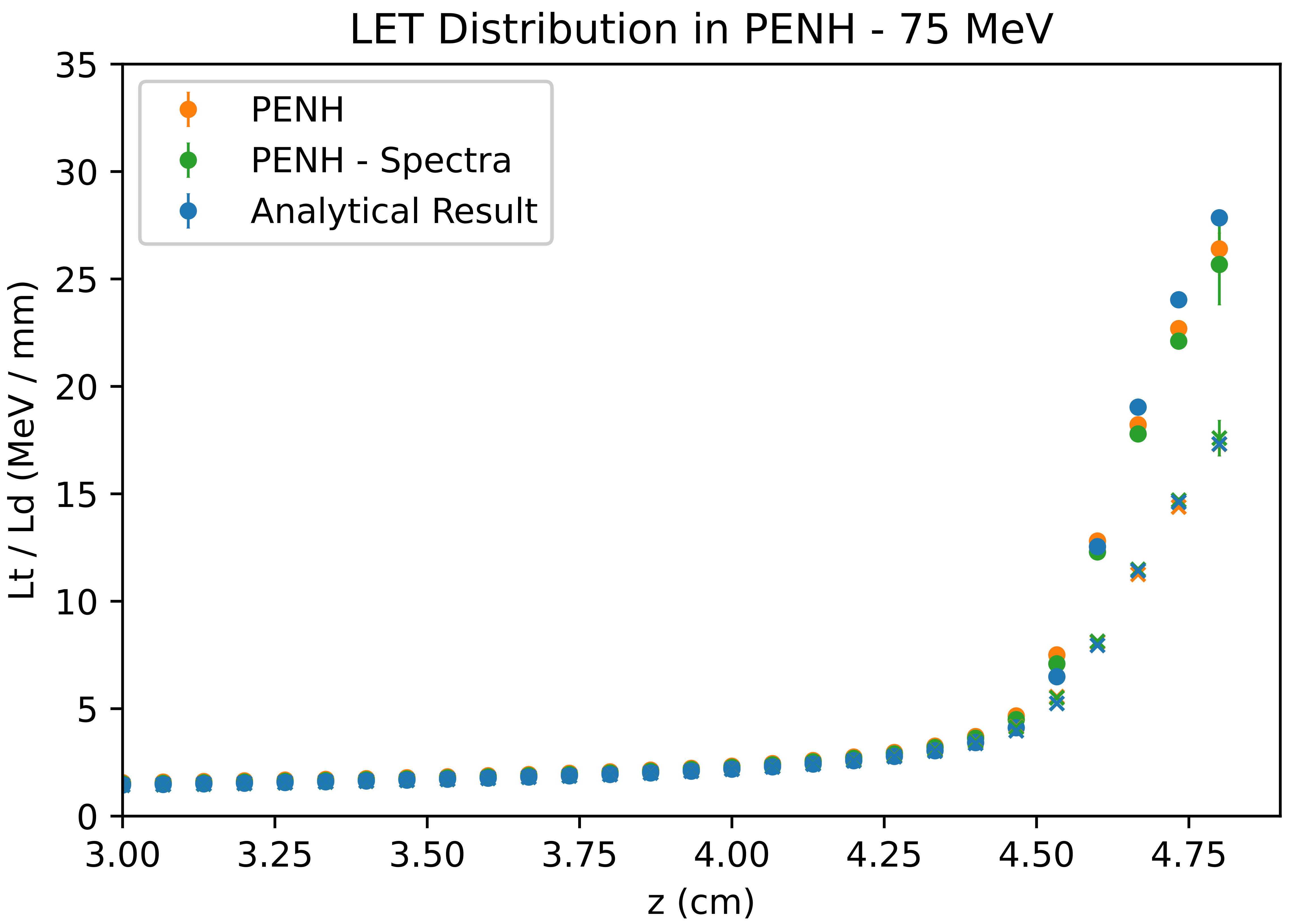


LET Distribution in FLUKA - 75 MeV
FLUKA
FLUKA - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
0
5
10
15
20
25
30
35
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75

75 MeV

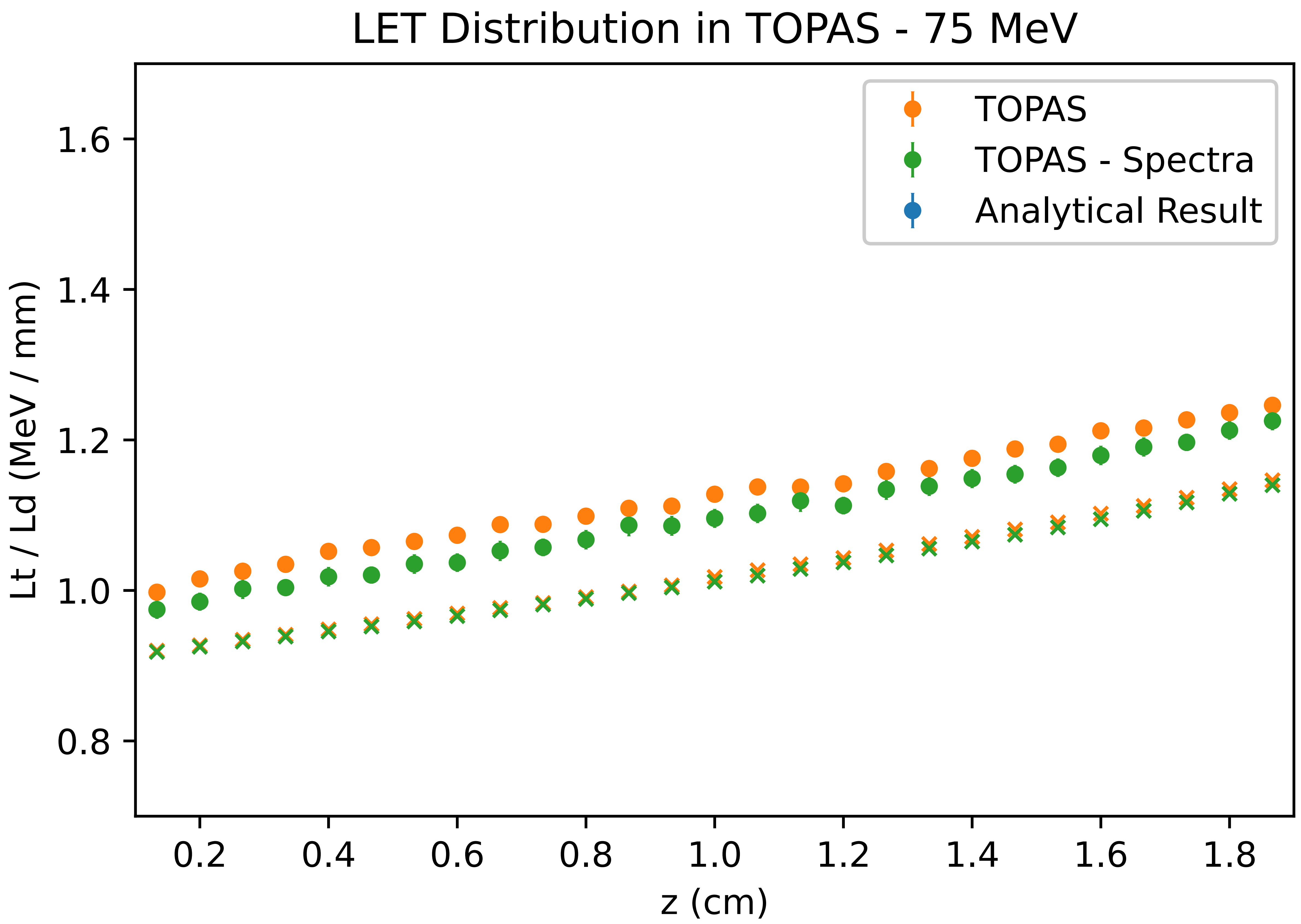


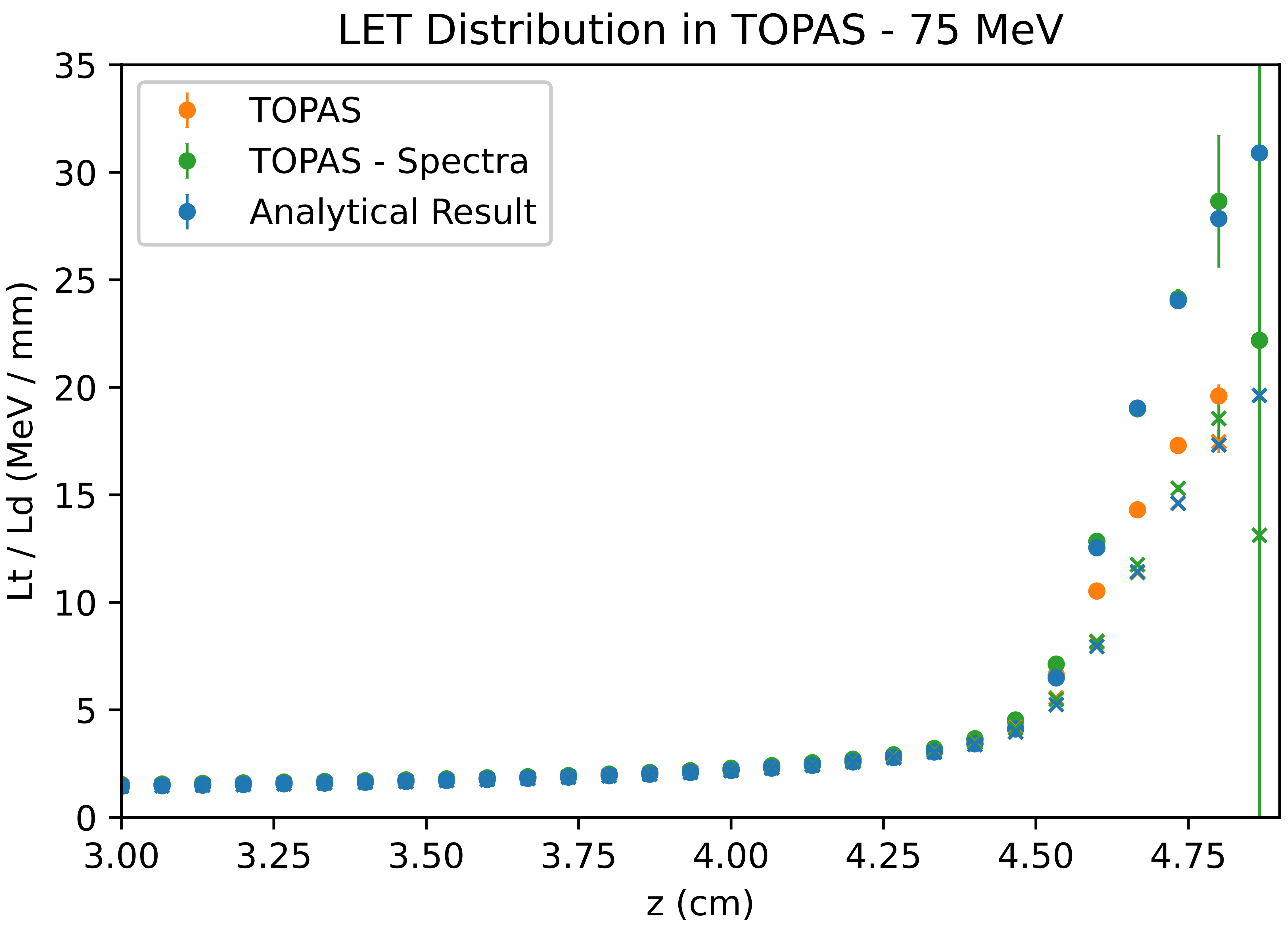
LET Distribution in PENH - 75 MeV
PENH
PENH - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)



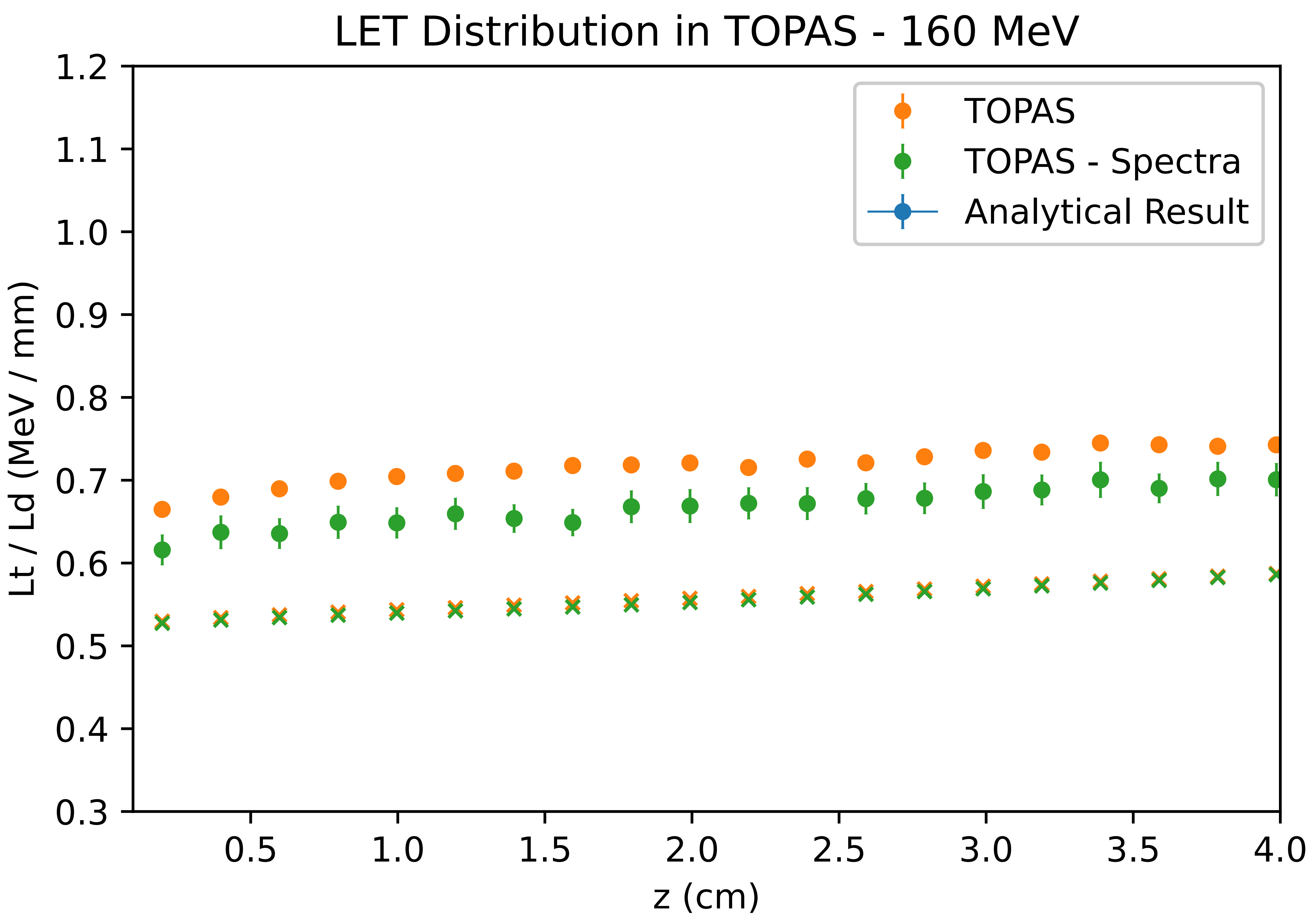
LET Distribution in PENH - 75 MeV
PENH
PENH - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)

75 MeV

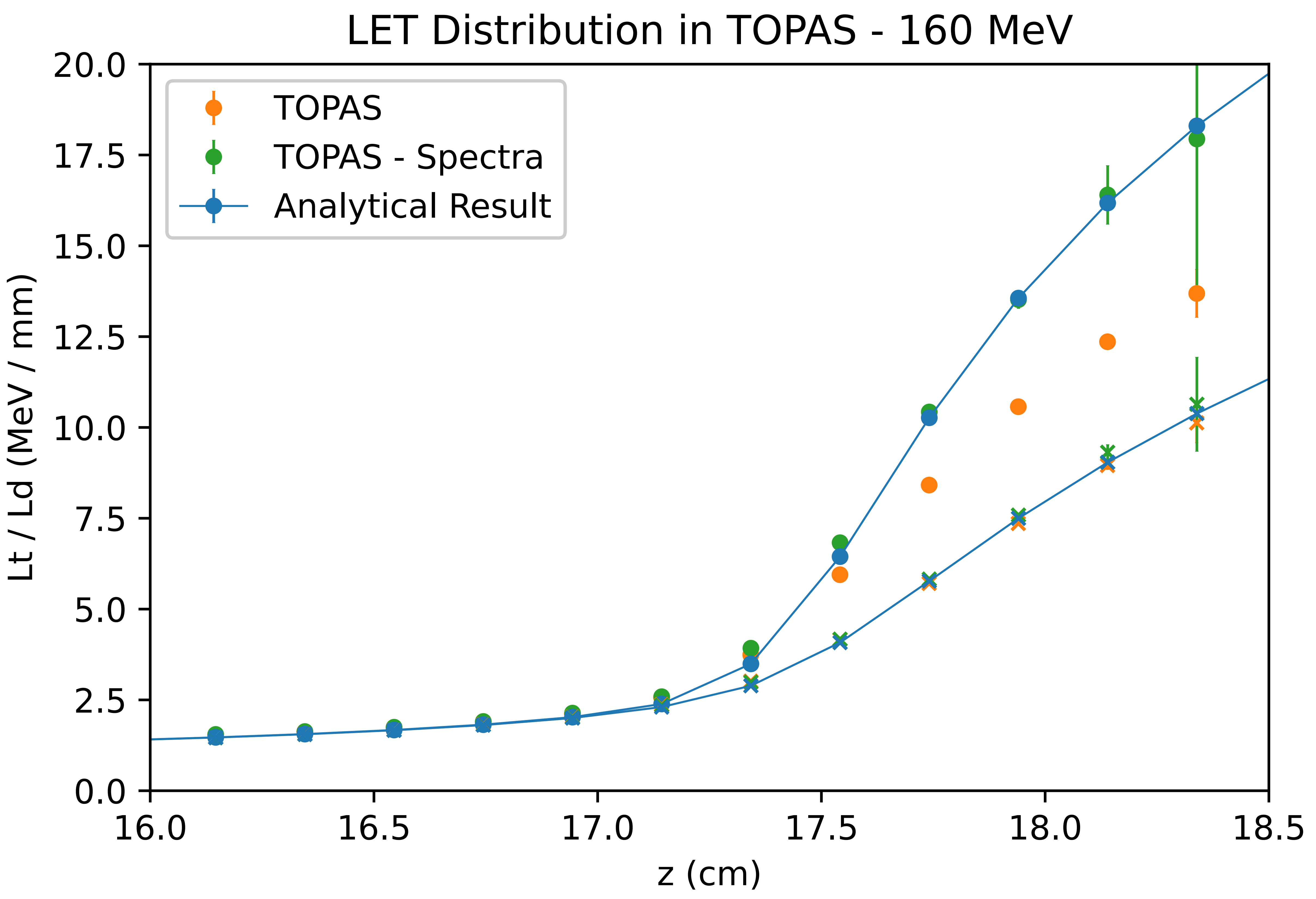

LET Distribution in TOPAS - 75 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
1.6
1.4
1.2
1.0
0.8
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8


LET Distribution in TOPAS - 75 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
35
30
25
20
15
10
5
0
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75

160 MeV

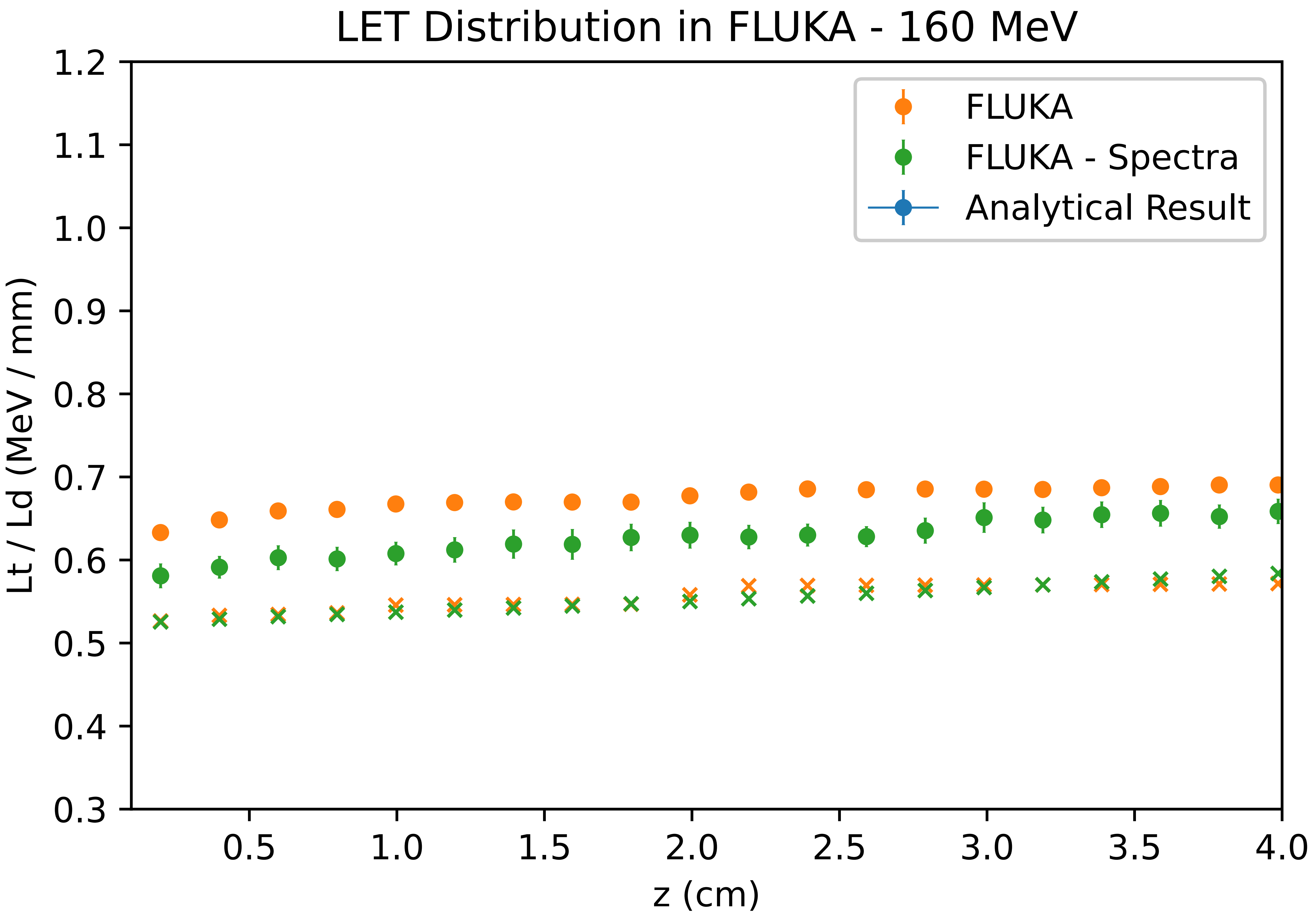


LET Distribution in TOPAS - 160 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

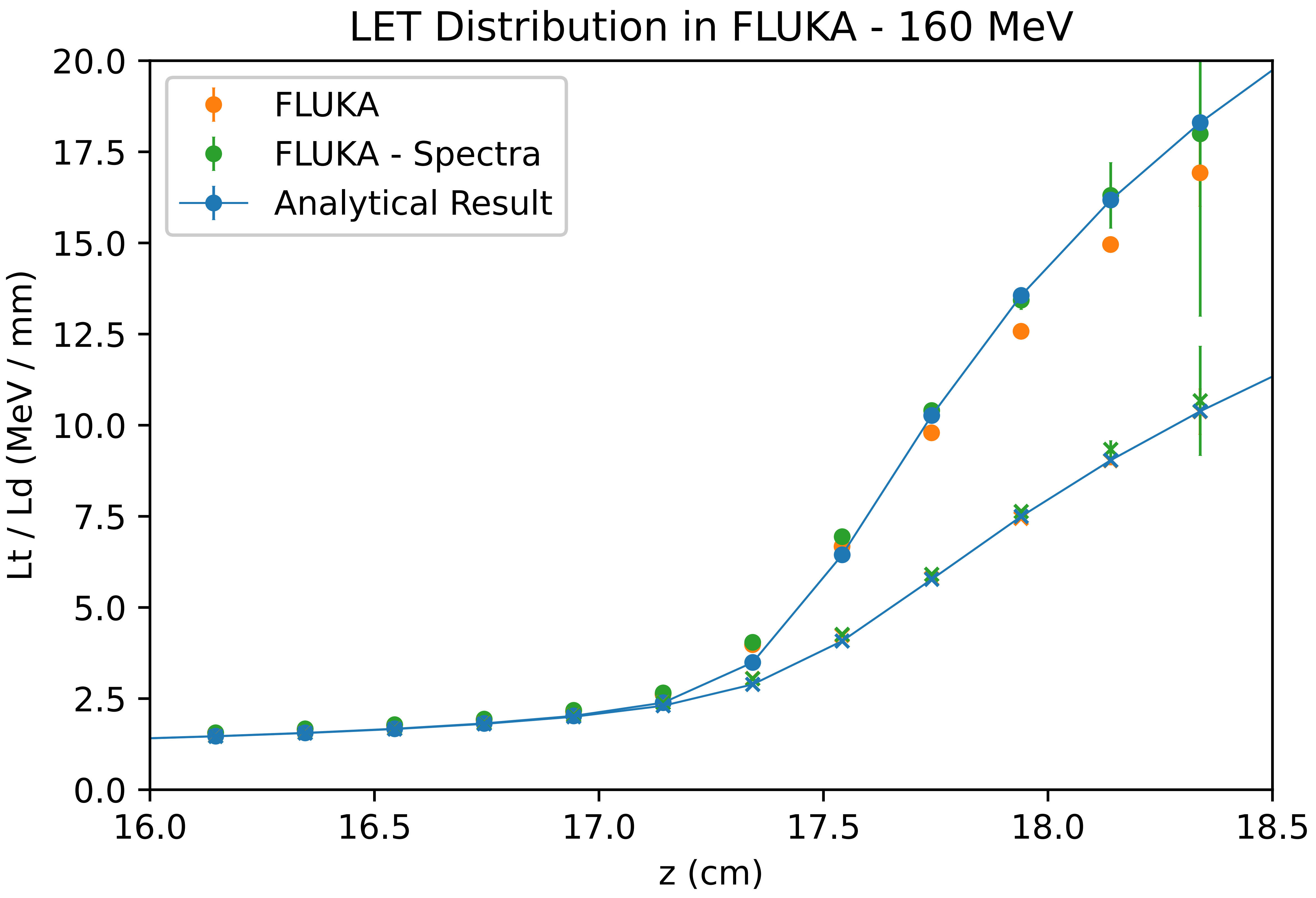


LET Distribution in TOPAS - 160 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.0
16.5
17.0
17.5
18.0
18.5

160 MeV

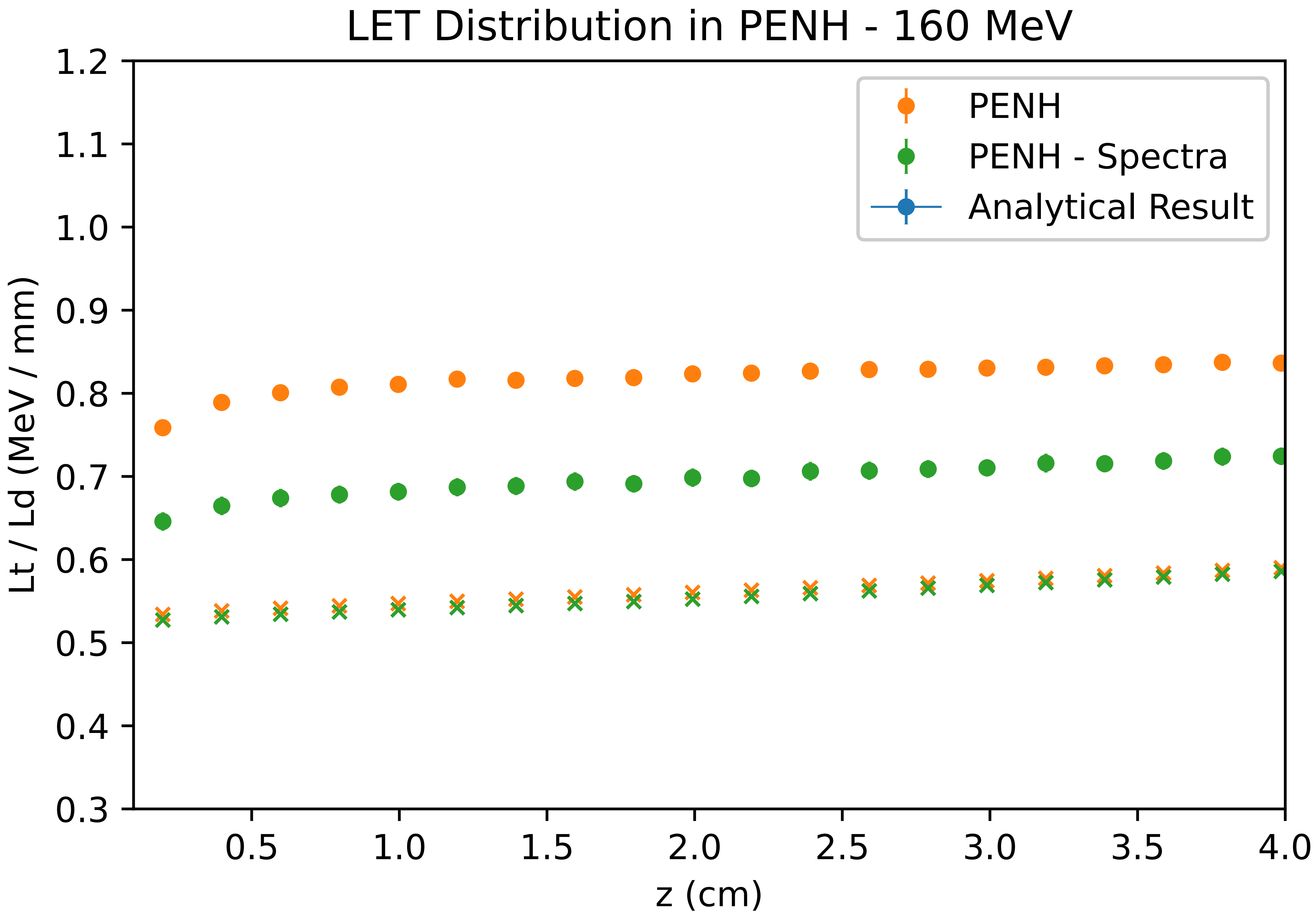


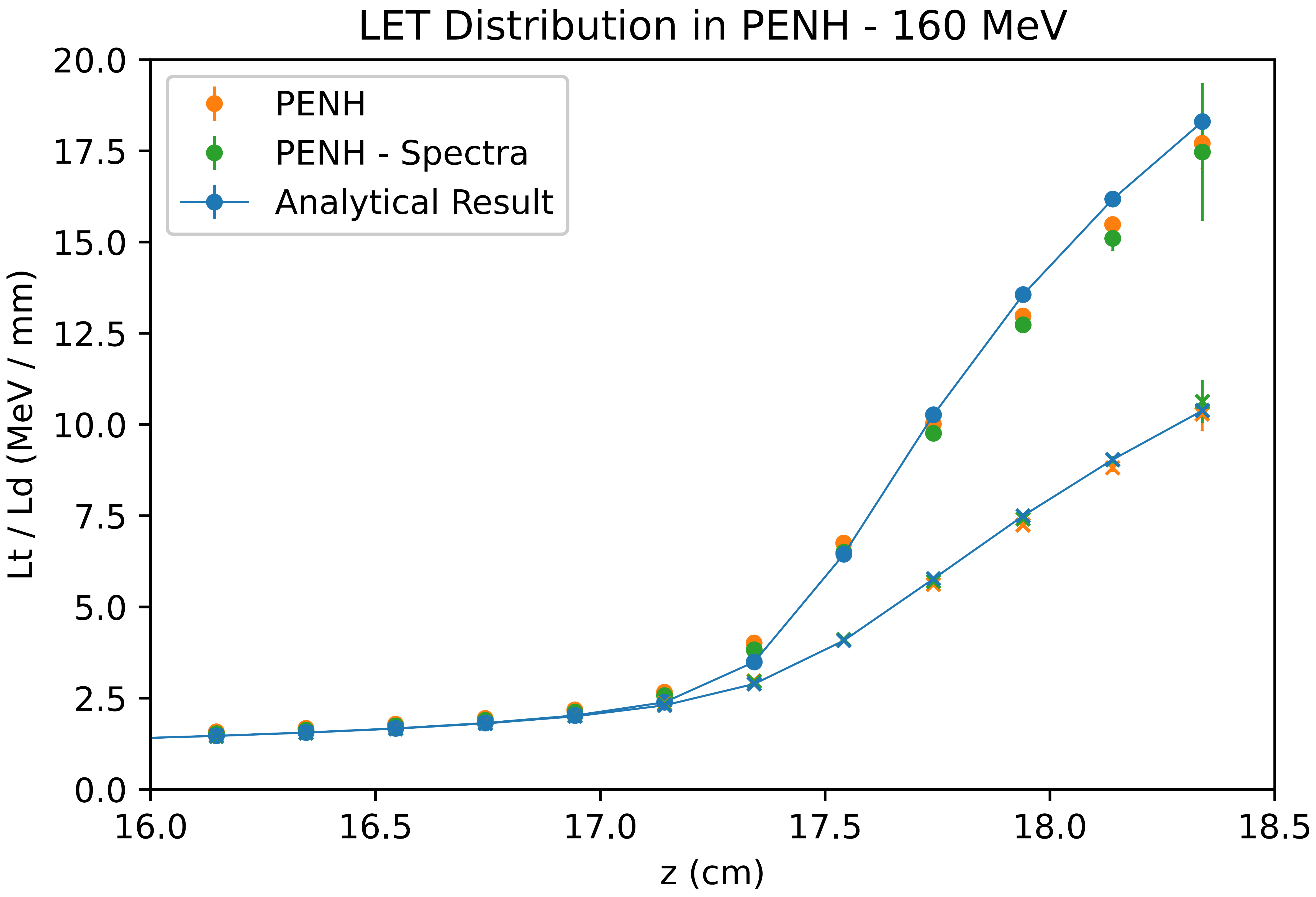
LET Distribution in FLUKA - 160 MeV
FLUKA
FLUKA - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0



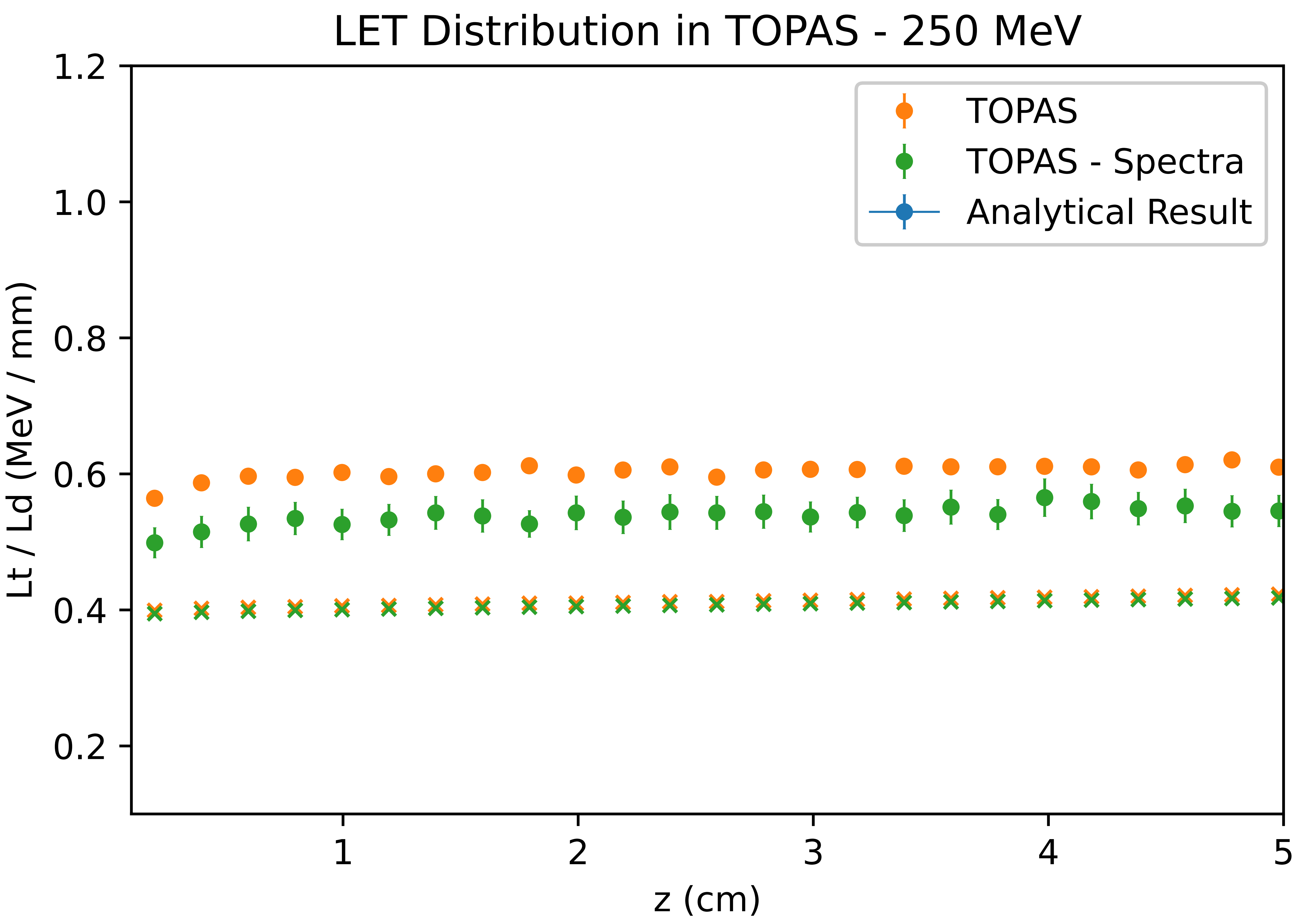
LET Distribution in FLUKA - 160 MeV
FLUKA
FLUKA - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.0
16.5
17.0
17.5
18.0
18.5

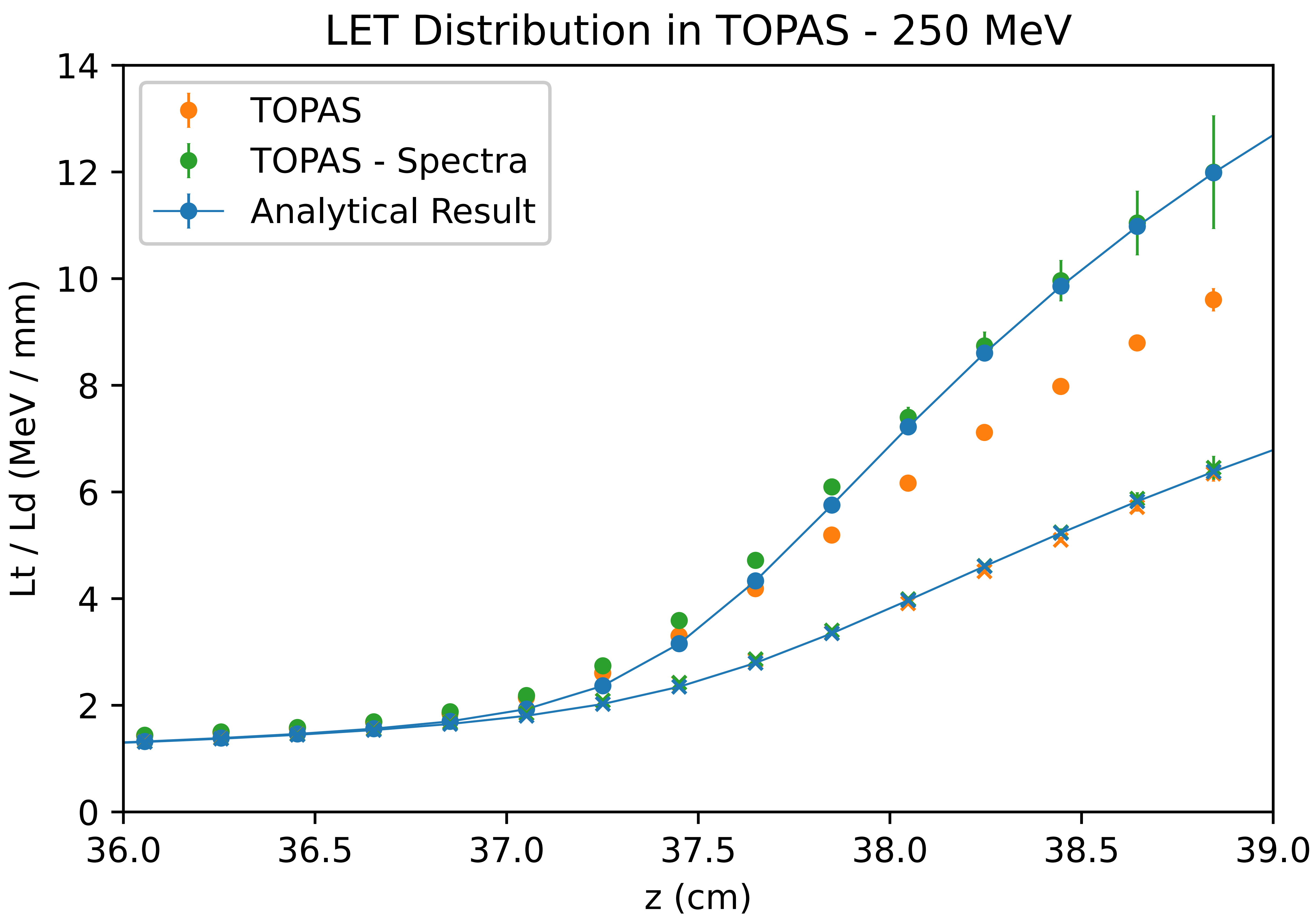
160 MeV


LET Distribution in PENH - 160 MeV
PENH
PENH - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

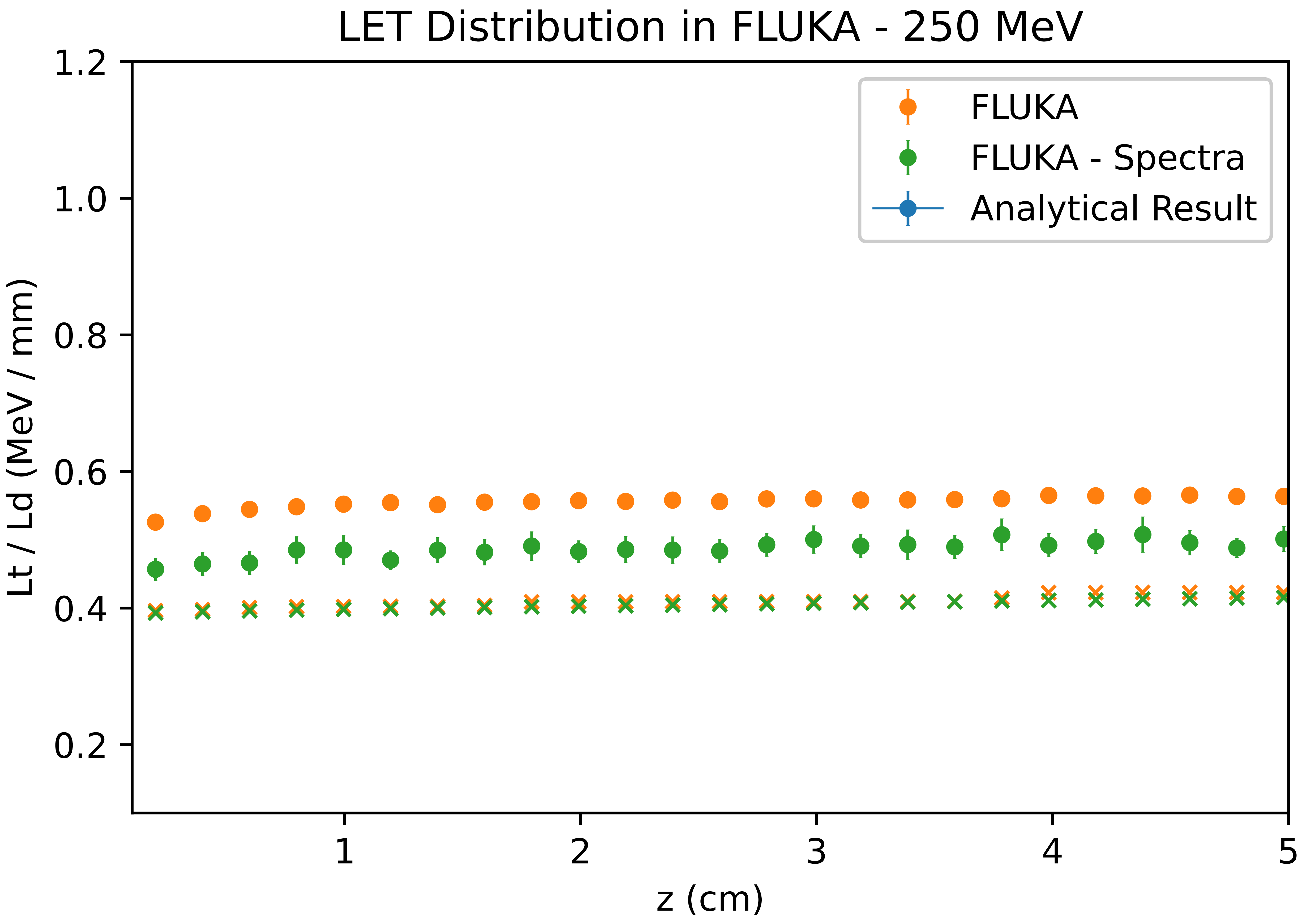

LET Distribution in PENH - 160 MeV
PENH
PENH - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.0
16.5
17.0
17.5
18.0
18.5

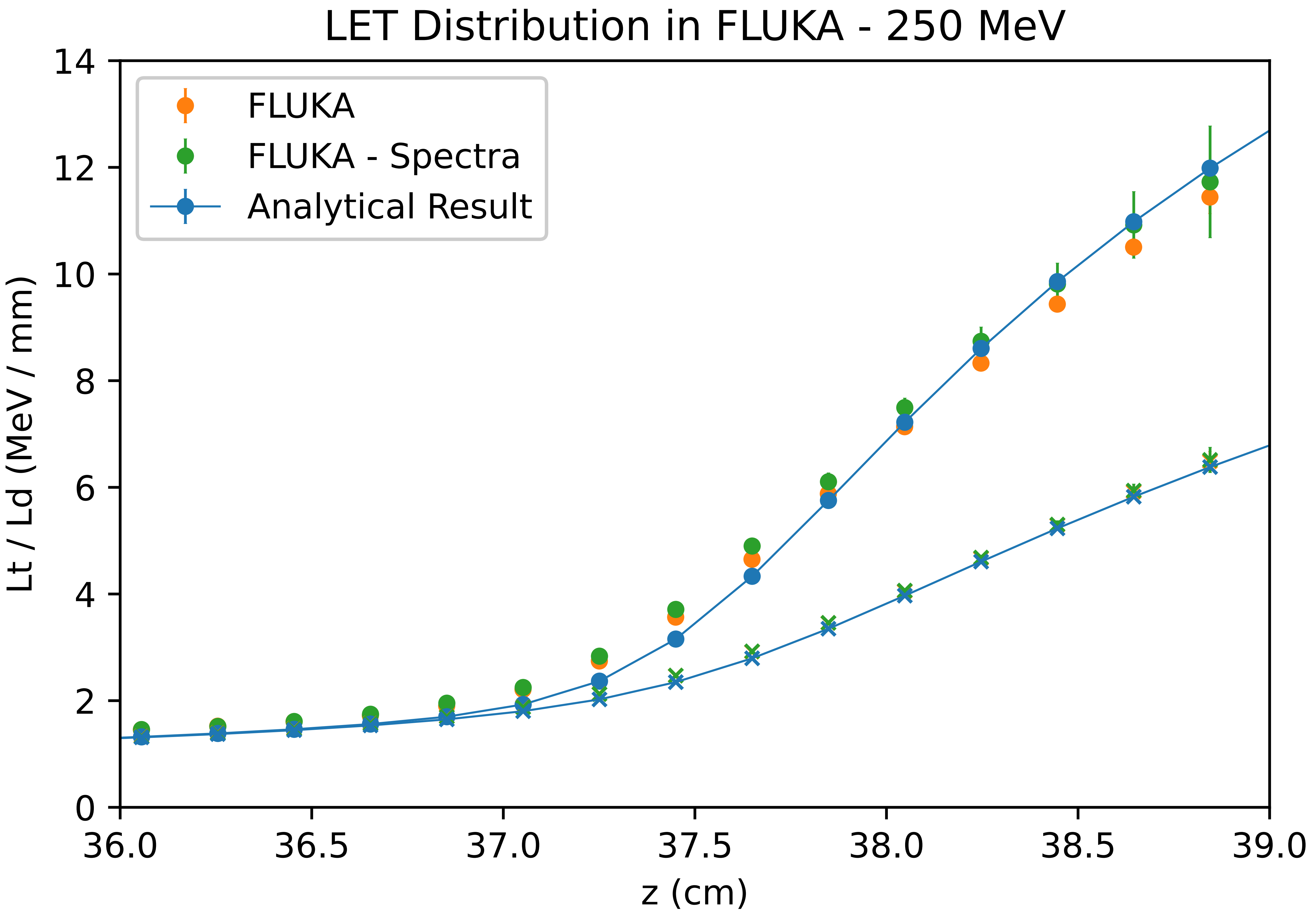
250 MeV


LET Distribution in TOPAS - 250 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
1.2
1.0
0.8
0.6
0.4
0.2
1
2
3
4
5


LET Distribution in TOPAS - 250 MeV
TOPAS
TOPAS - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
14
12
10
8
6
4
2
0
36.0
36.5
37.0
37.5
38.0
38.5
39.0

250 MeV


LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
1.2
1.0
0.8
0.6
0.4
0.2
1
2
3
4
5


LET Distribution in FLUKA - 250 MeV
FLUKA
FLUKA - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
14
12
10
8
6
4
2
0
36.0
36.5
37.0
37.5
38.0
38.5
39.0

250 MeV

LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
0.2
0.4
0.6
0.8
1.0
1.2
1
2
3
4
5
LET Distribution in PENH - 250 MeV
PENH
PENH - Spectra
Analytical Result
Lt / Ld (MeV / mm)
z (cm)
0
2
4
6
8
10
12
14
36.0
36.5
37.0
37.5
38.0
38.5
39.0