Strip Silicon Charge Detector Performance

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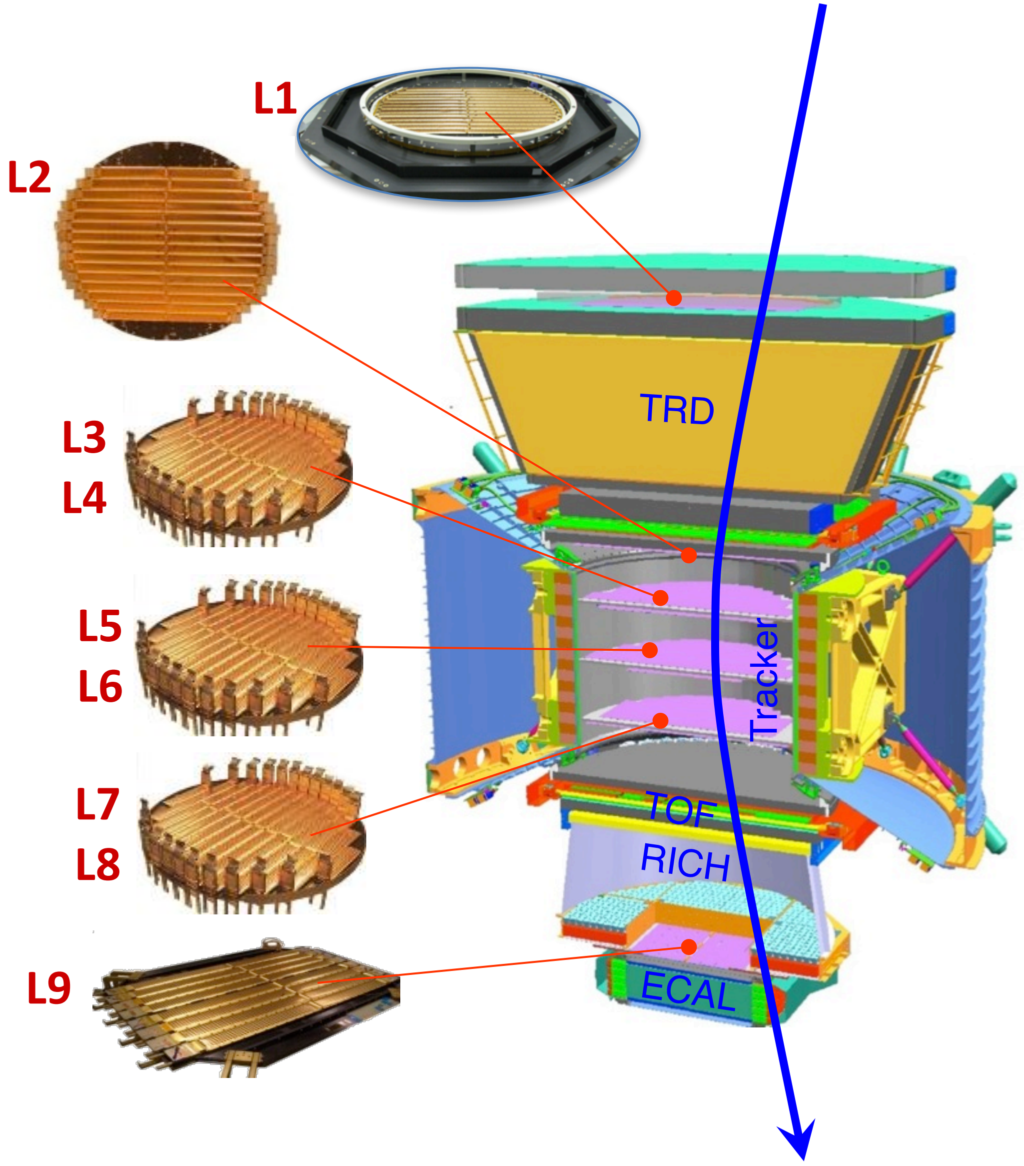
AMS-02 Silicon Tracker



9 layers of **300 μm** thickness **double-sided** silicon sensors arranged in 192 ladders.

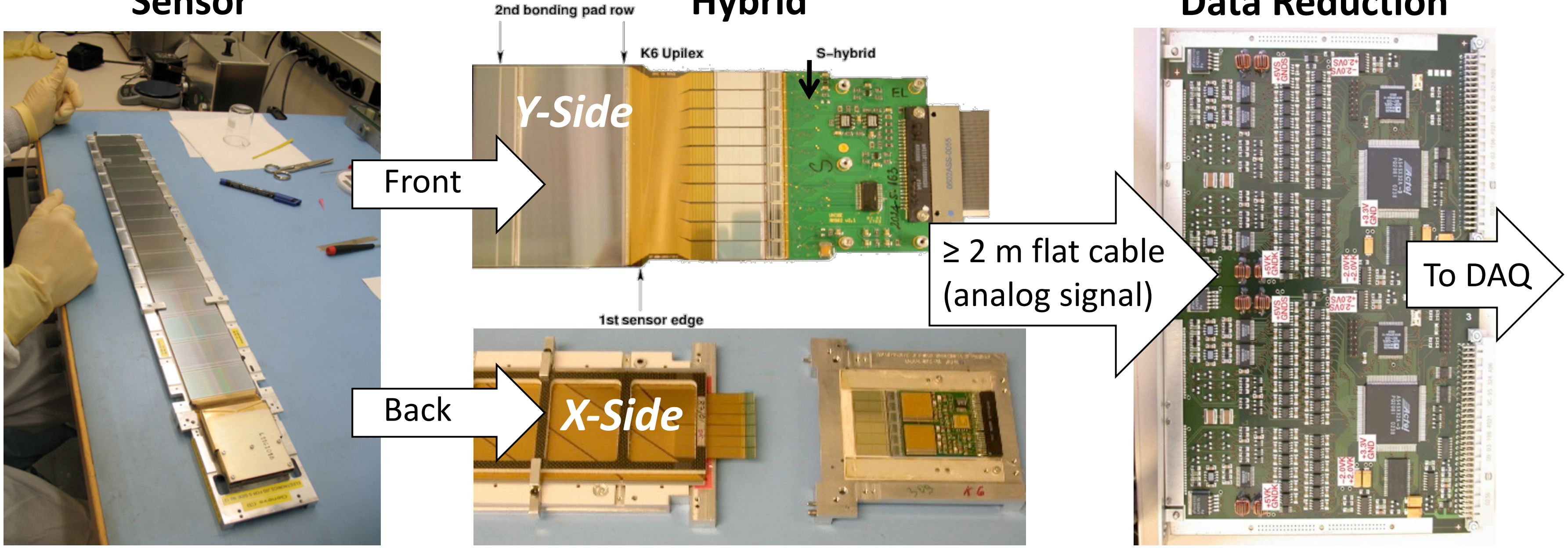
6 honeycomb carbon fiber planes. Overall detector material of about 0.04 X_0.

A total of **196k channels**.

About **10 μm for Z=1 and 5 μm for Z>1** bending coordinate spatial resolution.

High dynamic range front end for charge measurement (Z measurement up to Iron).

AMS-02 Silicon Tracker Readout



Sensor

Front

Back

Hybrid

≥ 2 m flat cable
(analog signal)

Data Reduction

To DAQ

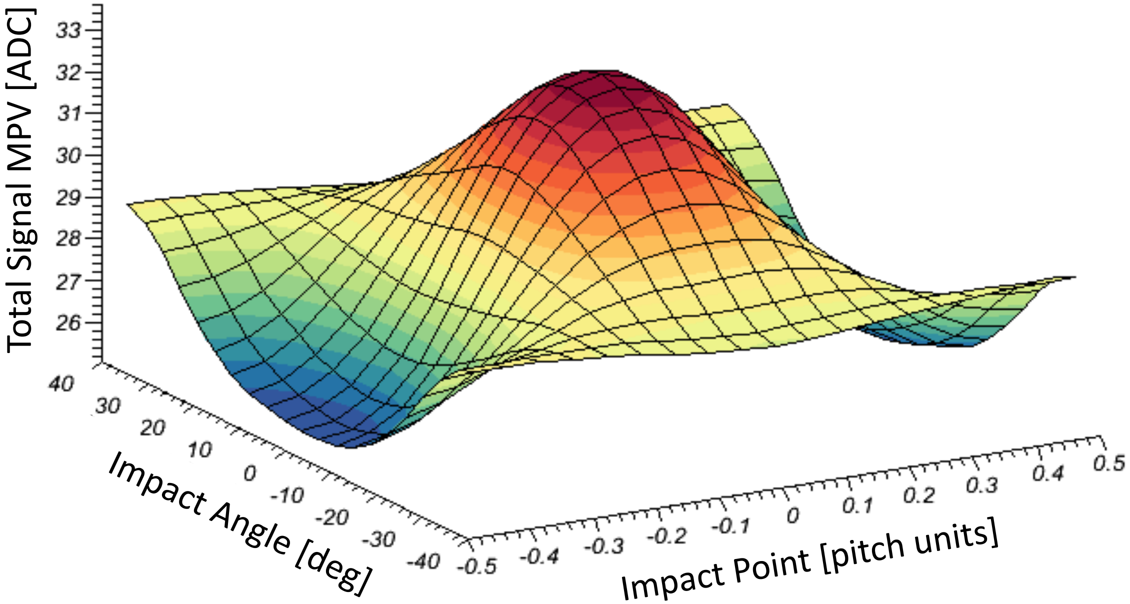
300 μm, 7 × 4 cm^2
27.5(104) μm strip impl. pitch
110(208) μm readout pitch
Charge sharing
Capacitive coupling (1 pF/cm)

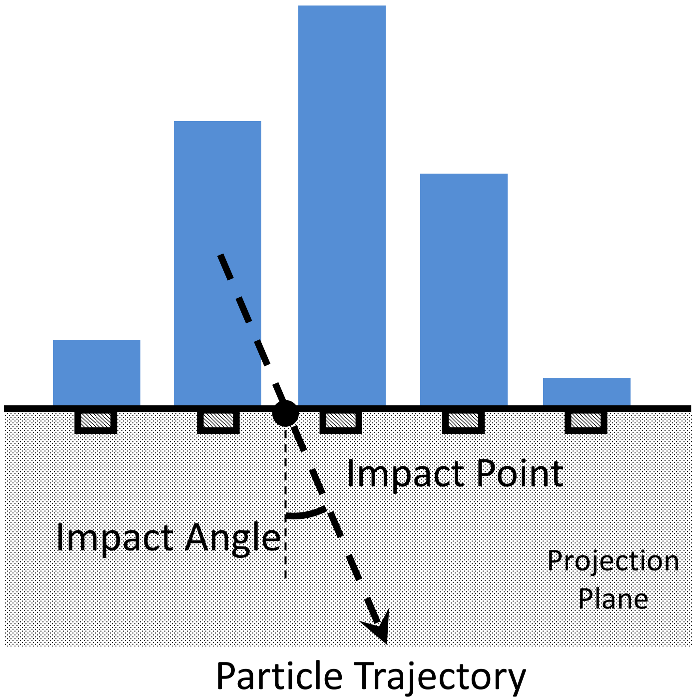
640(384) readout channels
Amplification (100 MIP range)
Shaping (4 μs)
Sample-and-Hold
Each channel 0.7 mW power
10(6) VA_hdr64a

3 ADC
Pedestal/Noise eval.
Common noise sub.
Cluster search
Comp. factor of ~ 1000

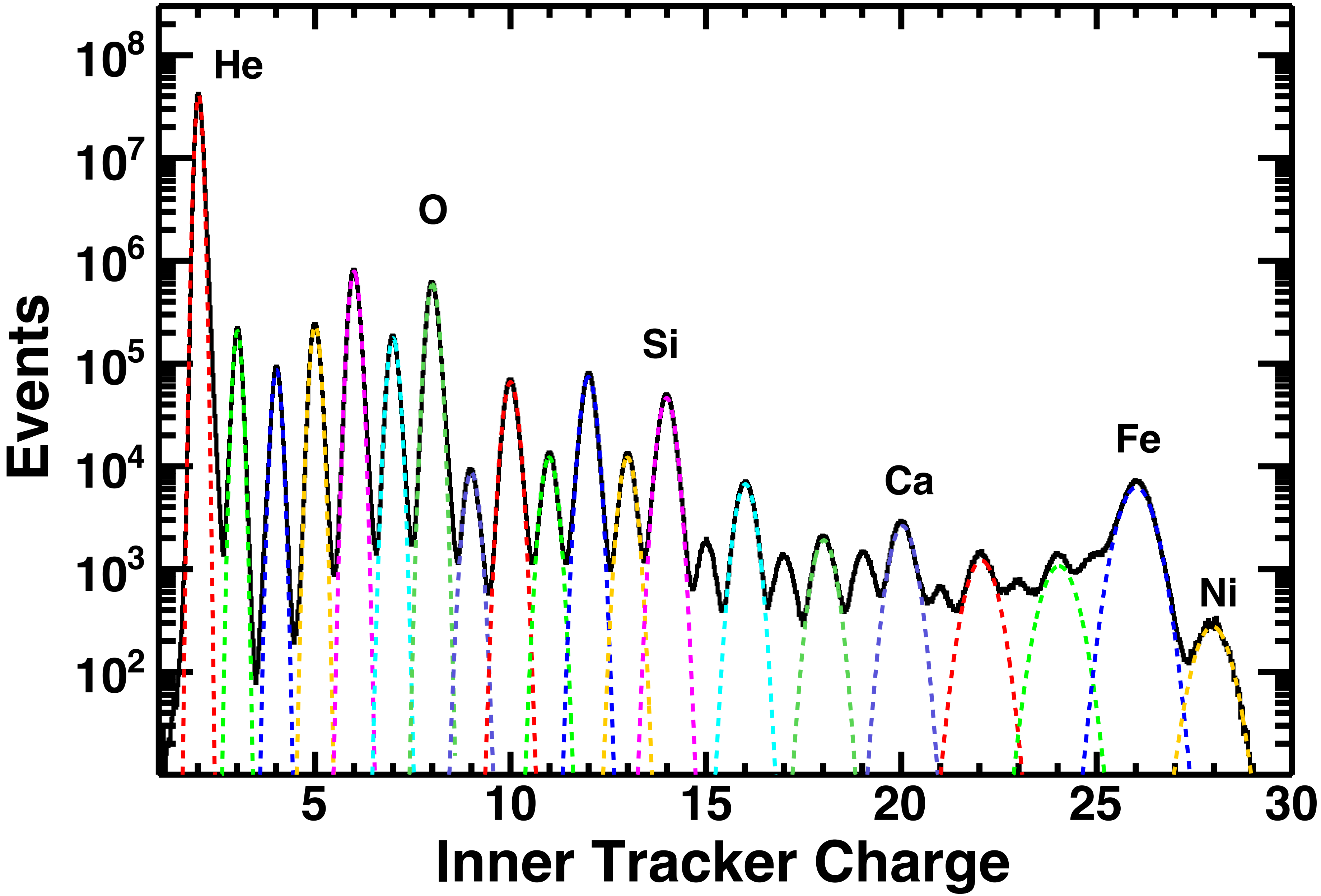
AMS-02 Tracker Charge Calibration

Use of the first highest 5 strips of the cluster separately.
Equalization of 3072 VAs as function of charge (non-linearities).
Path-length correction.
Correction of charge collection effects (coordinate and angular dependences).
Description of the dependence with energy (~ $1/\beta^2$).
Time variation correction.

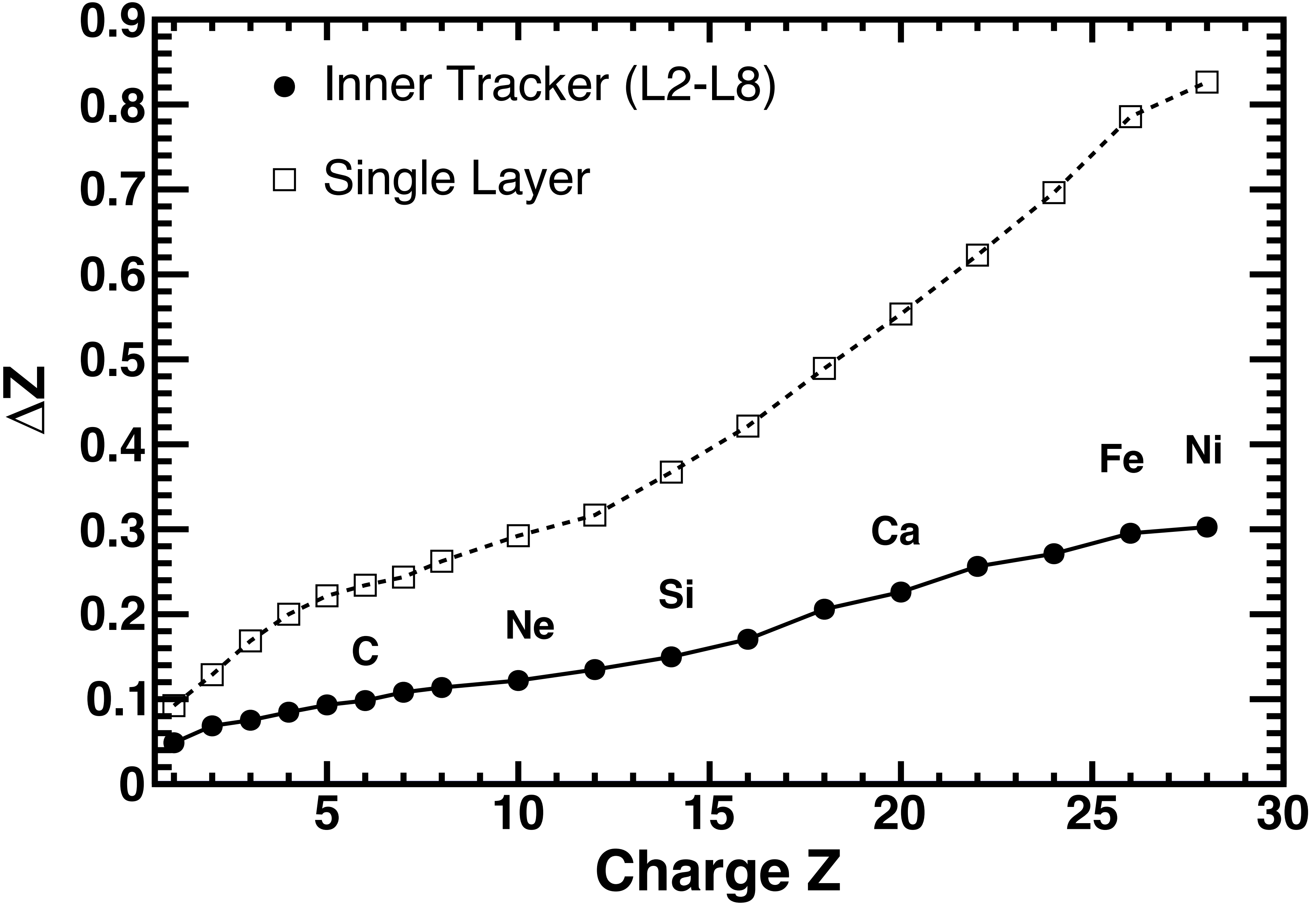




AMS-02 Inner Tracker Charge (L2-L8)

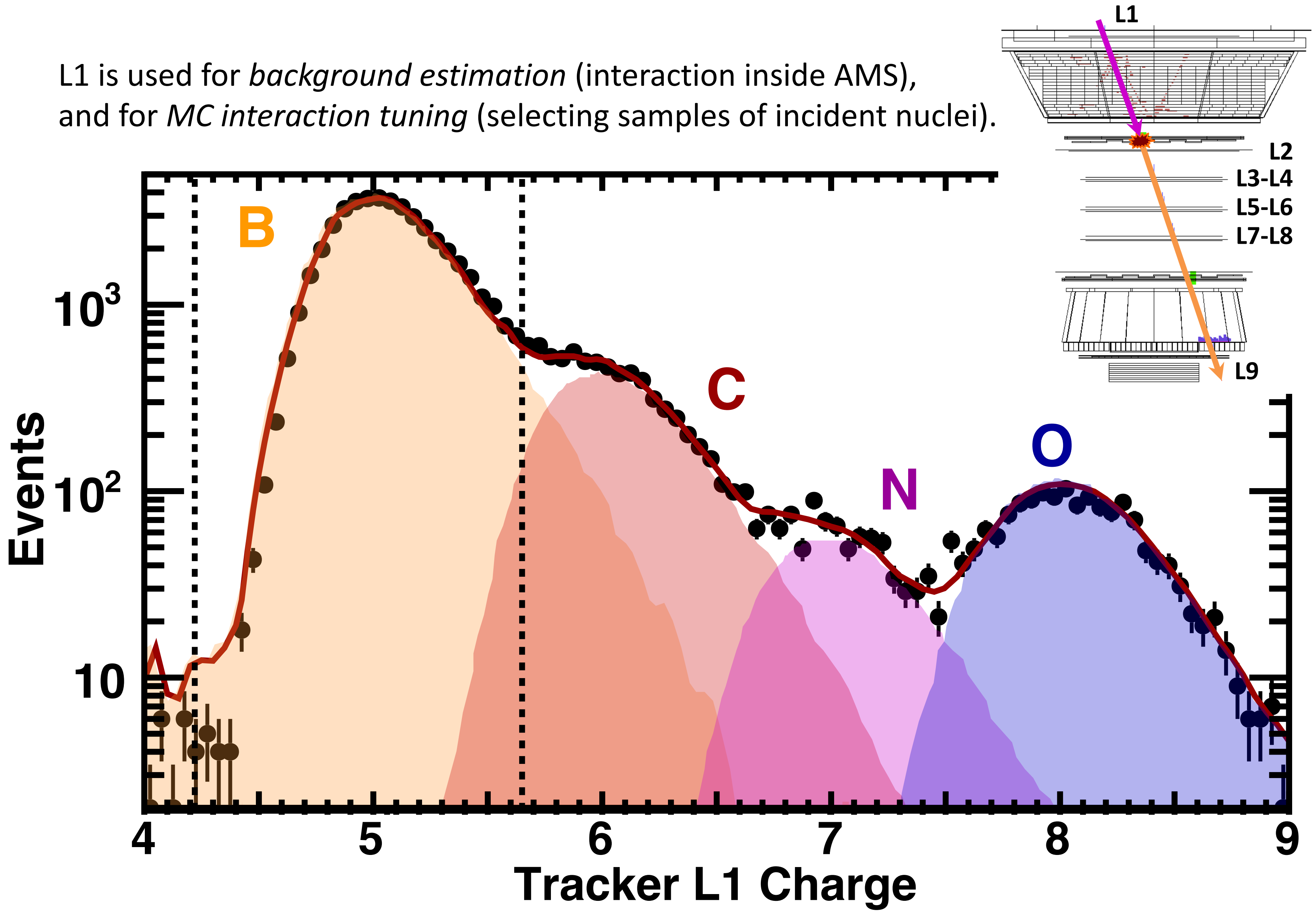


AMS-02 Tracker Charge Resolution



The Importance of Measuring Charge at the Top-of-the-Instrument

L1 is used for *background estimation* (interaction inside AMS),
and for *MC interaction tuning* (selecting samples of incident nuclei).



Energy Loss (from Particle Data Book)

$$k = \frac{\xi}{W_{\max}}$$

Vavilov parameter

$$\xi = \frac{K}{2}\frac{Z}{A}\frac{z^2}{\beta^2}\rho x \qquad \xi[\mathrm{MeV}] = 0.1535\frac{K}{2}\frac{Z}{A}\frac{z^2}{\beta^2}X[\mathrm{g/cm^2}]$$

Landau width

$$W_{\max} = \frac{2m_e c^2\beta^2\gamma^2}{1+2\gamma\frac{m_e}{M}+\left(\frac{m_e}{M}\right)^2} \overset{m_e\gamma\ll M}{=} 2m_e c^2\beta^2\gamma^2$$

Maximum energy transfer to e^-

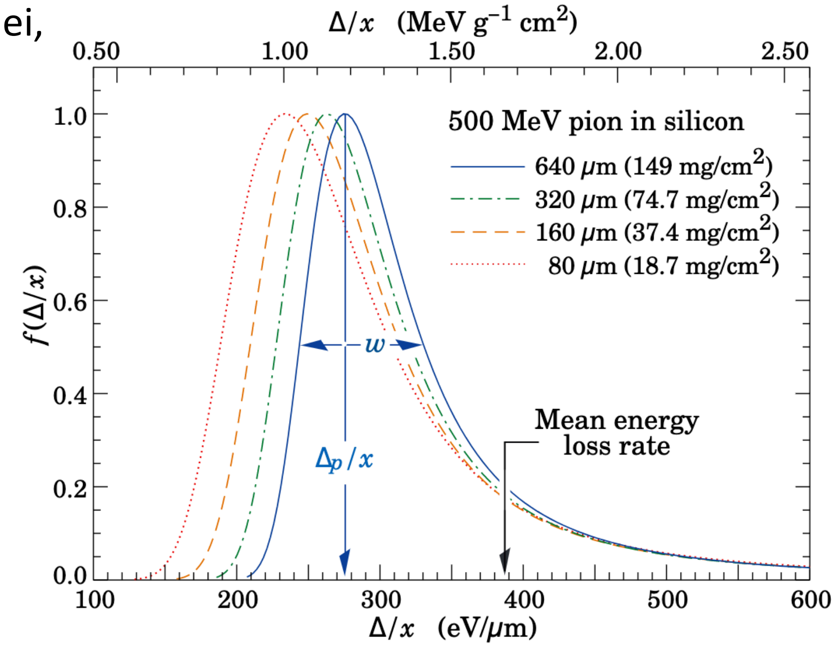
For Silicon below 1 mm Silicon, β≈1, and impinging nuclei, **k is below 0.1**, corresponding to **Landau regime**.

Landau most probable energy loss:

$$\Delta_p = \xi\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + 0.2 - \beta^2 - \delta(\beta\gamma)\right]$$

Landau full-width at half maximum (FWHM):

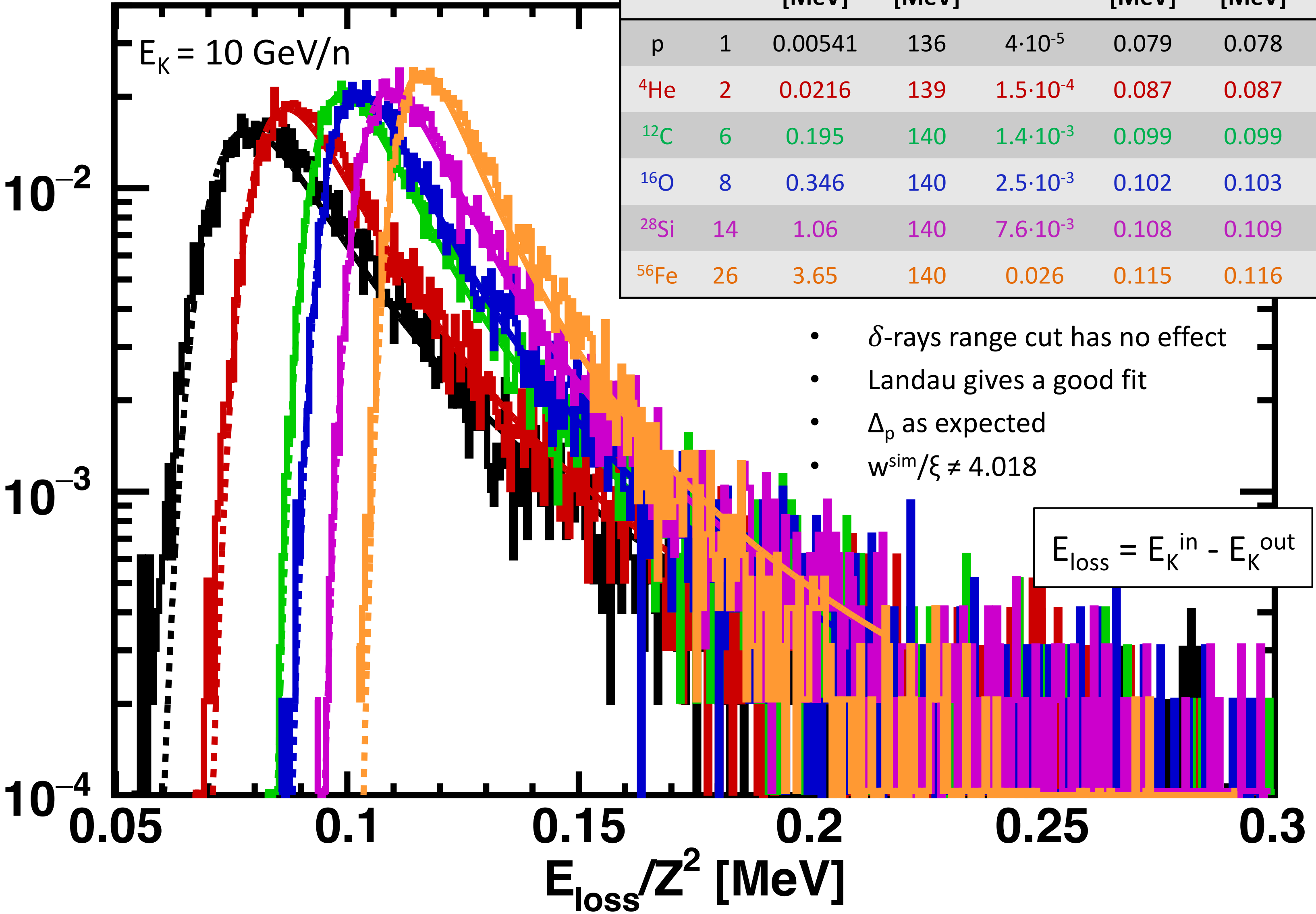
$$w_L \sim 4.018\xi$$



→ **Verification with MC**

Energy Loss in 300 μm Silicon

From a simple GEANT4 simulation.

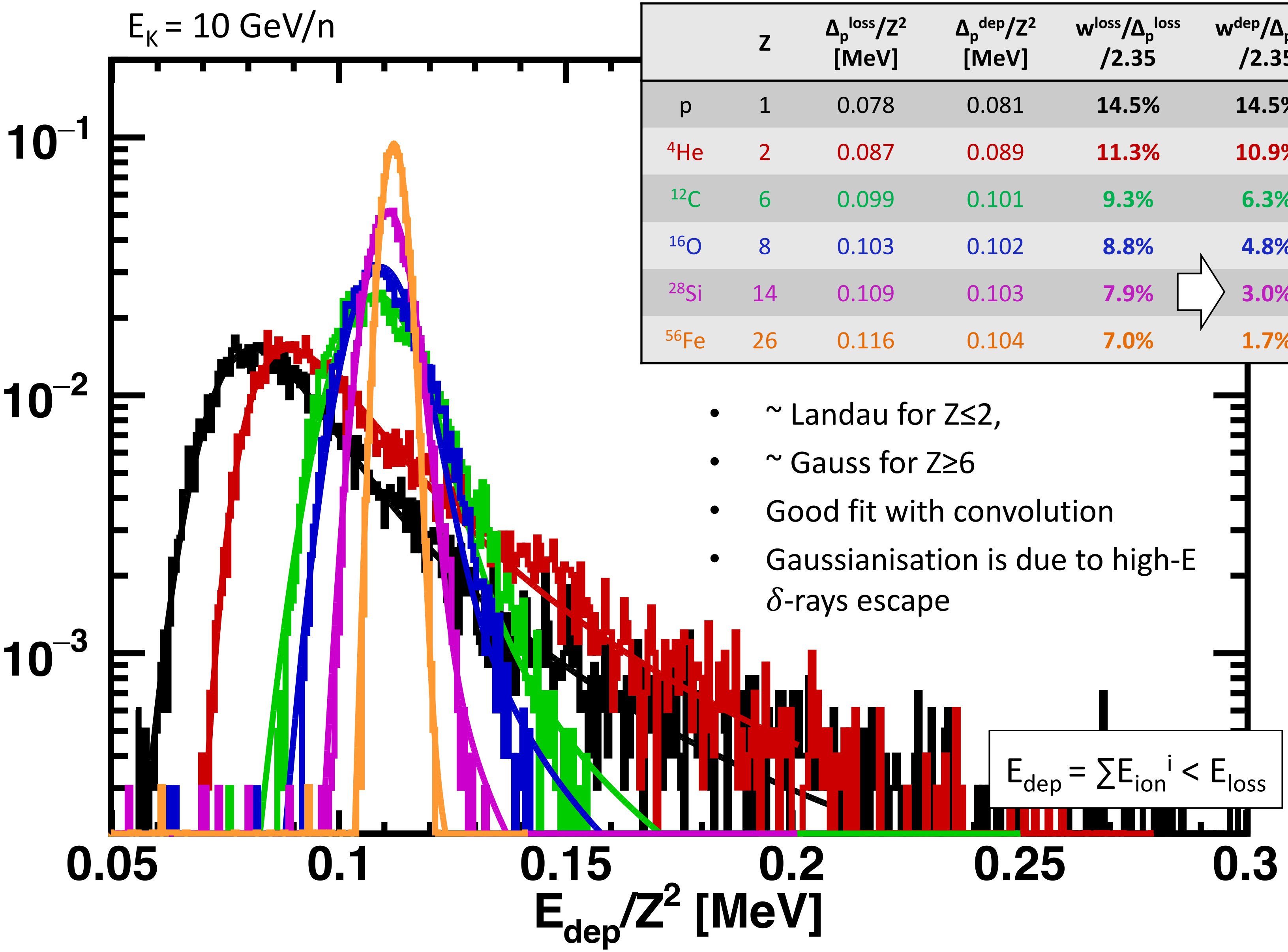


	Z	ξ [MeV]	W_{max} [MeV]	k	Δ_p^{th}/Z^2 [MeV]	Δ_p^{loss}/Z^2 [MeV]	w^{loss}/ξ
p	1	0.00541	136	$4\cdot10^{-5}$	0.079	0.078	4.92
^{4}He	2	0.0216	139	$1.5\cdot10^{-4}$	0.087	0.087	4.26
^{12}C	6	0.195	140	$1.4\cdot10^{-3}$	0.099	0.099	4.00
^{16}O	8	0.346	140	$2.5\cdot10^{-3}$	0.102	0.103	3.91
^{28}Si	14	1.06	140	$7.6\cdot10^{-3}$	0.108	0.109	3.74
^{56}Fe	26	3.65	140	0.026	0.115	0.116	3.55

- δ-rays range cut has no effect
- Landau gives a good fit
- Δ_p as expected
- $w^{sim}/\xi \neq 4.018$

$$E_{loss} = E_K^{in} - E_K^{out}$$

Energy Deposition in 300 µm Silicon



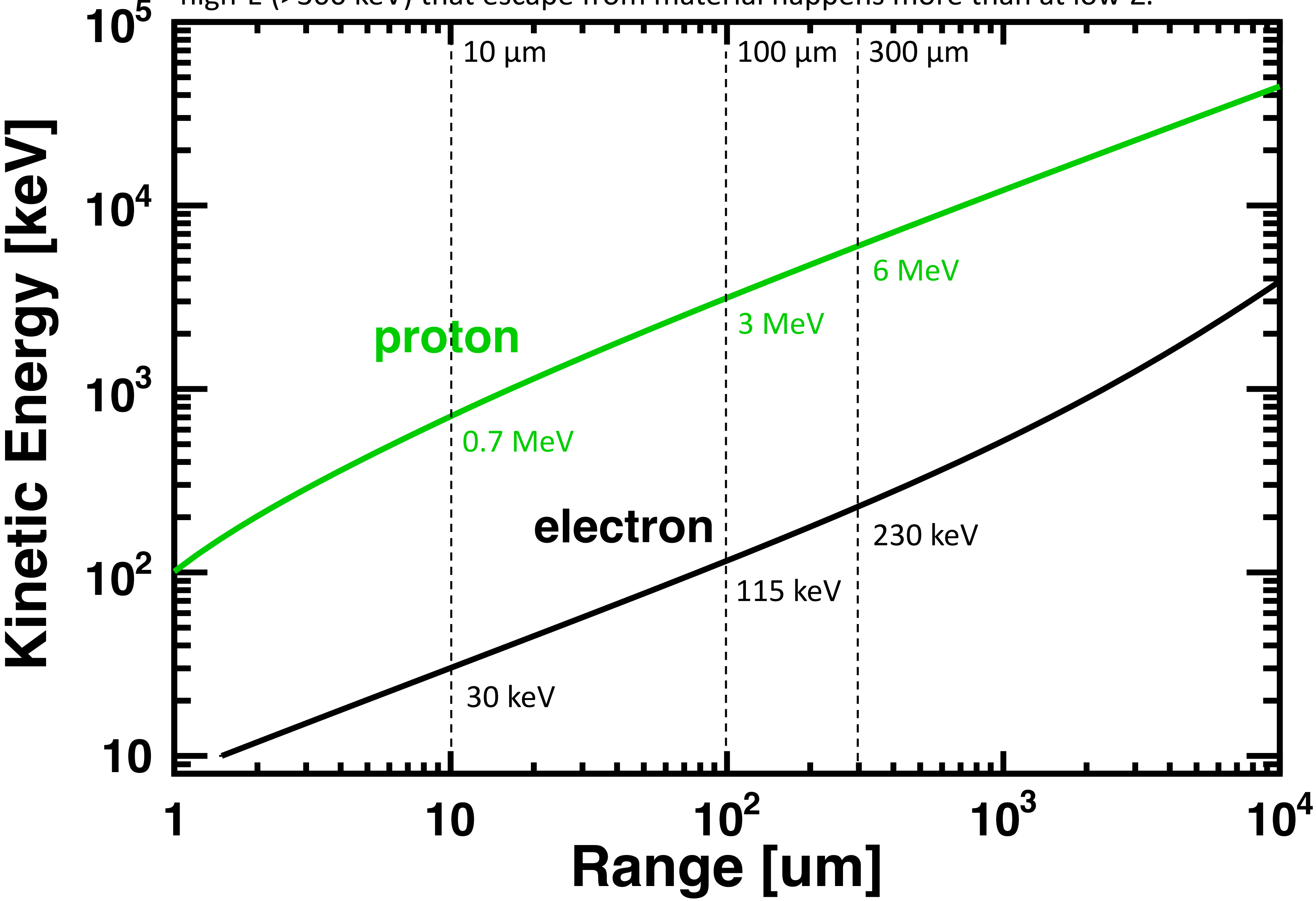
	Z	Δ_p^{loss}/Z^2 [MeV]	Δ_p^{dep}/Z^2 [MeV]	w^{loss}/Δ_p^{loss} /2.35	w^{dep}/Δ_p^{dep} /2.35
p	1	0.078	0.081	**14.5%**	**14.5%**
^{4}He	2	0.087	0.089	**11.3%**	**10.9%**
^{12}C	6	0.099	0.101	**9.3%**	**6.3%**
^{16}O	8	0.103	0.102	**8.8%**	**4.8%**
^{28}Si	14	0.109	0.103	**7.9%**	**3.0%**
^{56}Fe	26	0.116	0.104	**7.0%**	**1.7%**

- ~ Landau for Z≤2,
- ~ Gauss for Z≥6
- Good fit with convolution
- Gaussianisation is due to high-E δ-rays escape

$E_{dep} = \sum E_{ion}^{i} < E_{loss}$

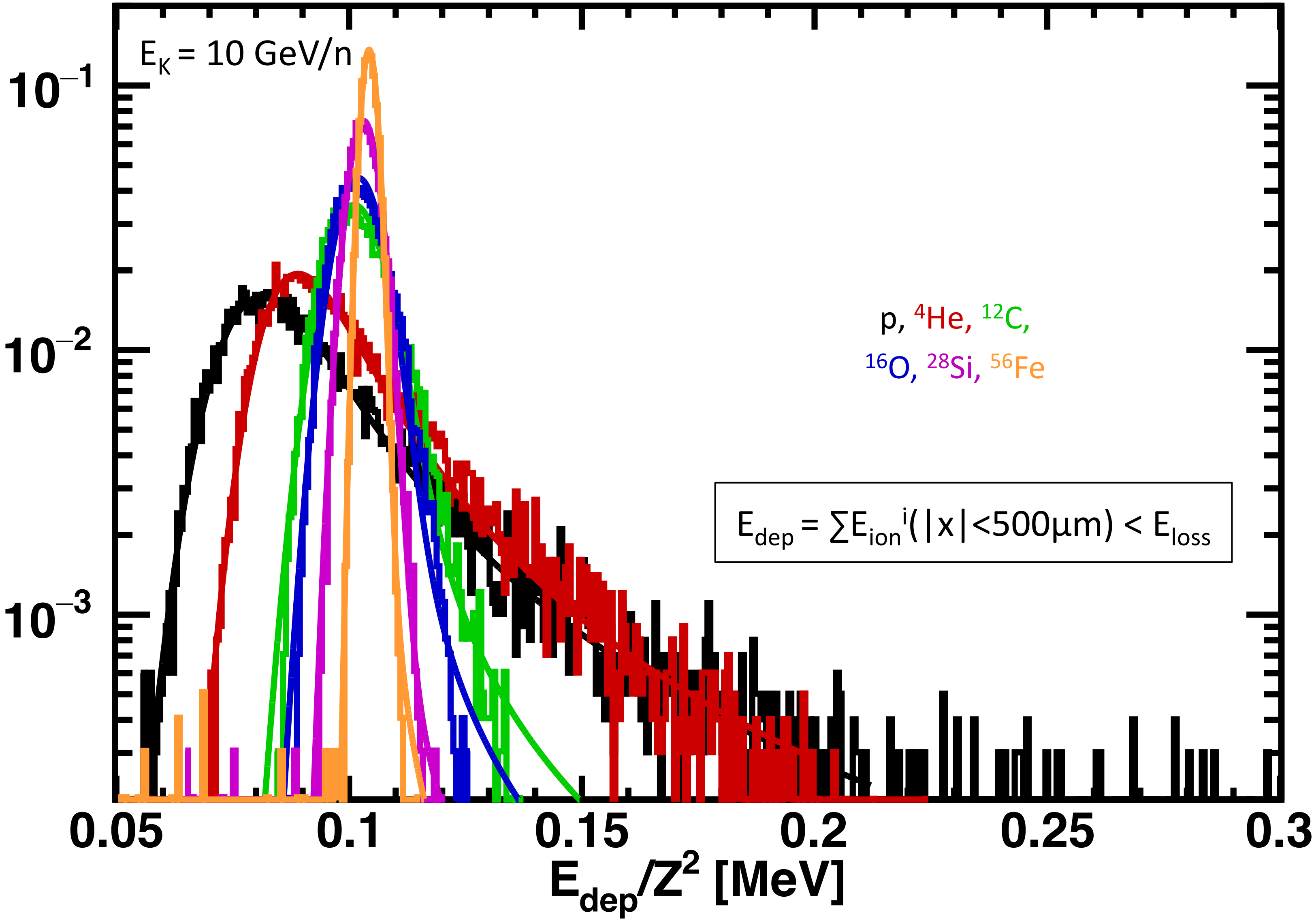
δ-Rays Escape

δ-rays production cross section $d\sigma/dE \approx kZ^2/E^2$. At high-Z emission of δ-rays of high-E (>300 keV) that escape from material happens more than at low-Z.



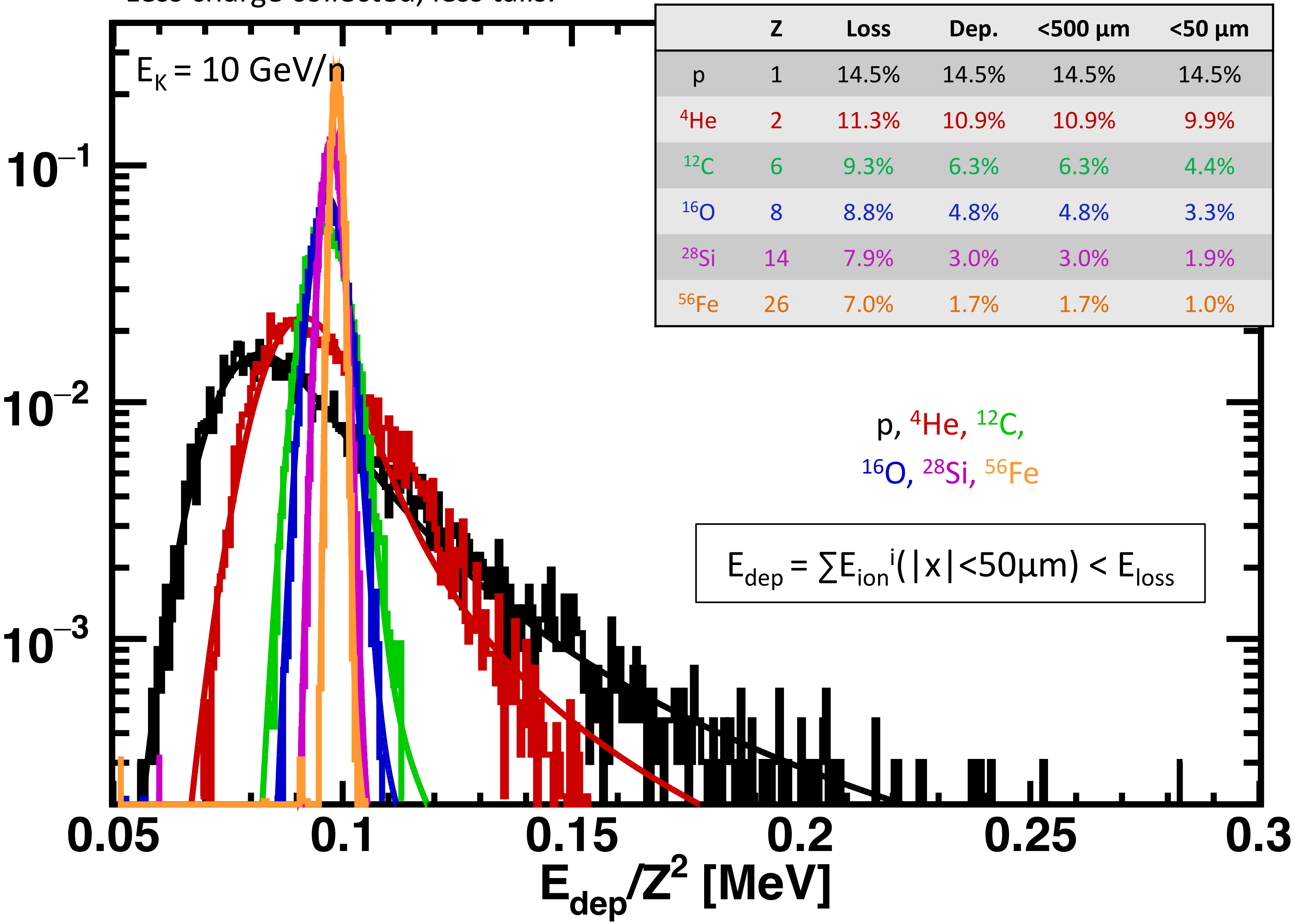
Energy Loss in 300 μm Silicon (“cluster”)

Pretty similar to previous.



Energy Loss in 300 μm Silicon (“strip”)

Less charge collected, less tails.



	Z	Loss	Dep.	<500 μm	<50 μm
p	1	14.5%	14.5%	14.5%	14.5%
^{4}He	2	11.3%	10.9%	10.9%	9.9%
^{12}C	6	9.3%	6.3%	6.3%	4.4%
^{16}O	8	8.8%	4.8%	4.8%	3.3%
^{28}Si	14	7.9%	3.0%	3.0%	1.9%
^{56}Fe	26	7.0%	1.7%	1.7%	1.0%

$E_{dep} = \sum E_{ion}^{i}(|x|<50\mu m) < E_{loss}$

Charge Measurement and Resolution

$$\boxed{E = k\frac{z^2}{\beta^2} f(\beta\gamma) = Kz^2}$$

$$\sigma_E = \frac{dE}{dz}\sigma_z = 2Kz\sigma_z$$

$$\boxed{\frac{\sigma_z}{z} = \frac{1}{2}\frac{\sigma_E}{E}}$$

$$\left(\frac{\sigma_E}{E}\right)_{\mathrm{stra}} = \frac{1}{2.35}\frac{w_L}{\Delta_p} \propto \frac{1}{\sqrt{z}}$$

Straggling
(from simulation)

$$\left(\frac{\sigma_E}{E}\right)_{\mathrm{stat}} = \sqrt{\frac{WF}{E}} \propto \frac{1}{z}$$

E/W = number of carriers (W = 3.6 eV for Si)
F = Fano's factor (0.12 for Si)

Statistical
(below % even with 50 µm)

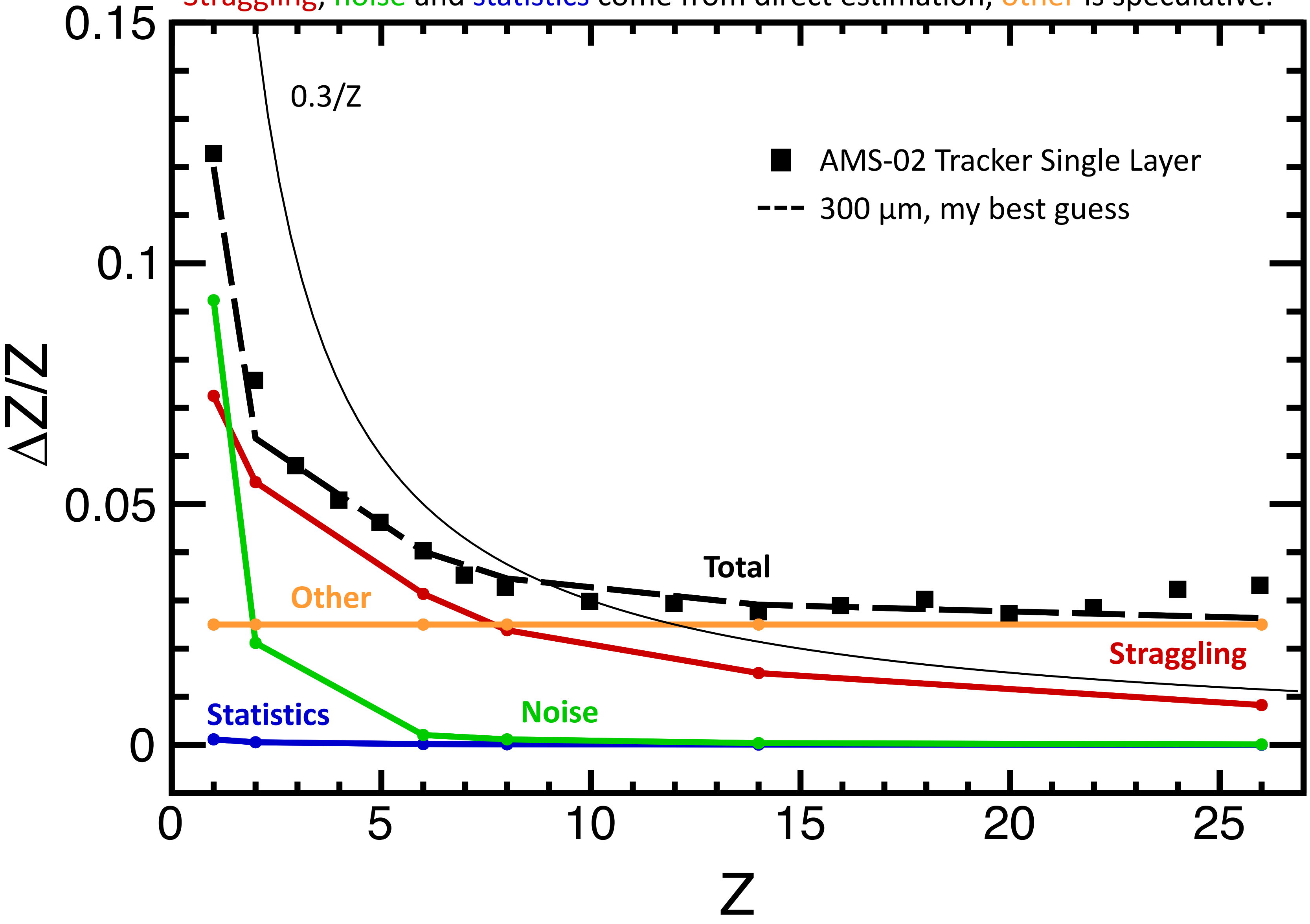
$$\left(\frac{\sigma_E}{E}\right)_{\mathrm{noise}} = \frac{c_{\mathrm{noise}}}{E} \propto \frac{1}{z^2}$$

Noise
(depends on S/N)

Other: systematics due *detector effects*, that can be *irreducible* (saturation, space charge, sample-and-hold) or that can be *improved* with better understanding of the detector (amplification non-linearities, angular and spatial dependencies, ...). For the latter, large statistics at high-Z may help.

AMS-02 Single Layer Charge Resolution

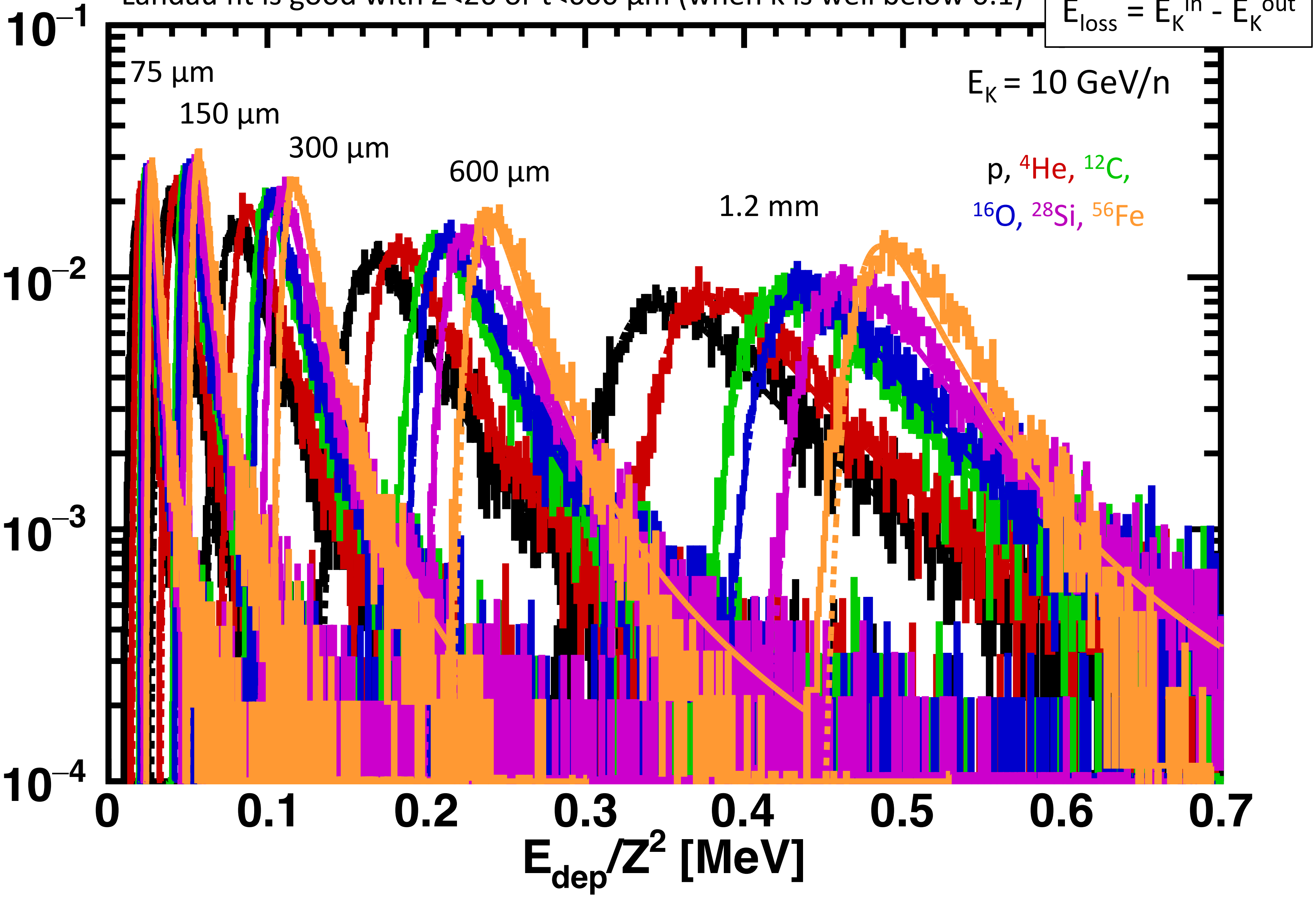
Straggling, noise and statistics come from direct estimation, other is speculative.



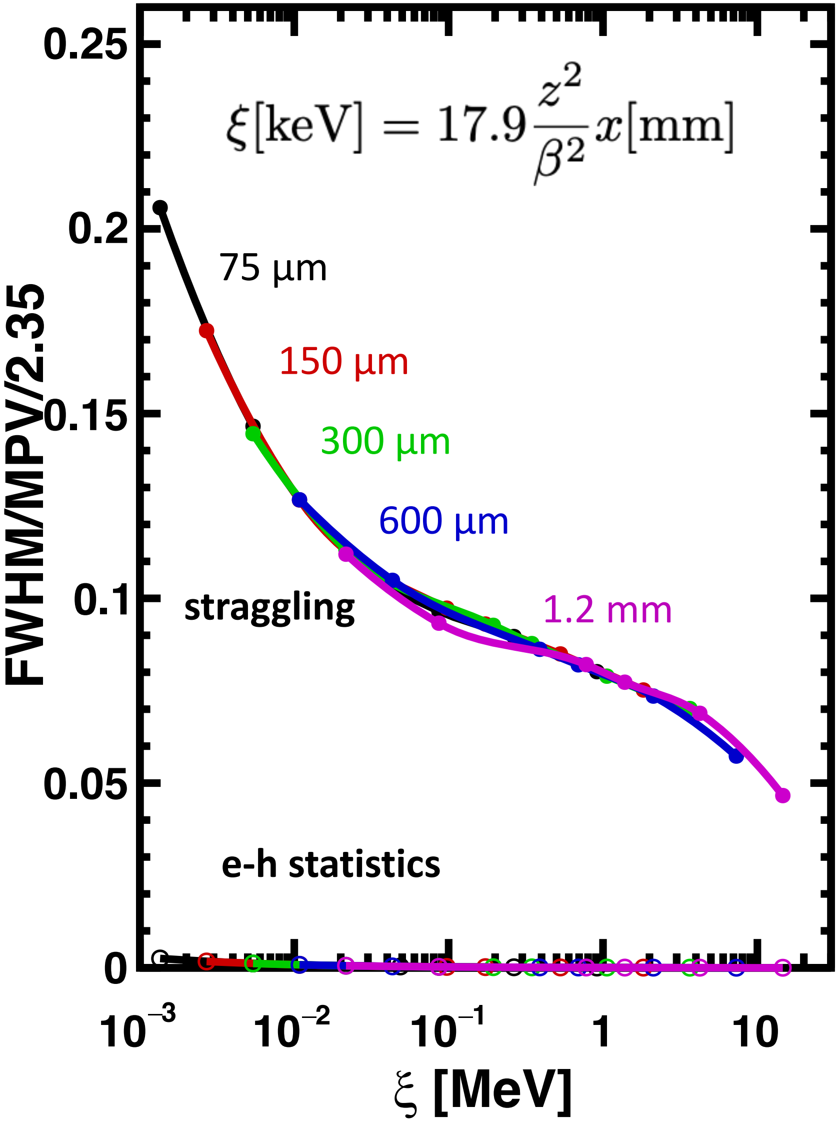
Single Layer Energy Loss for Different Thicknesses

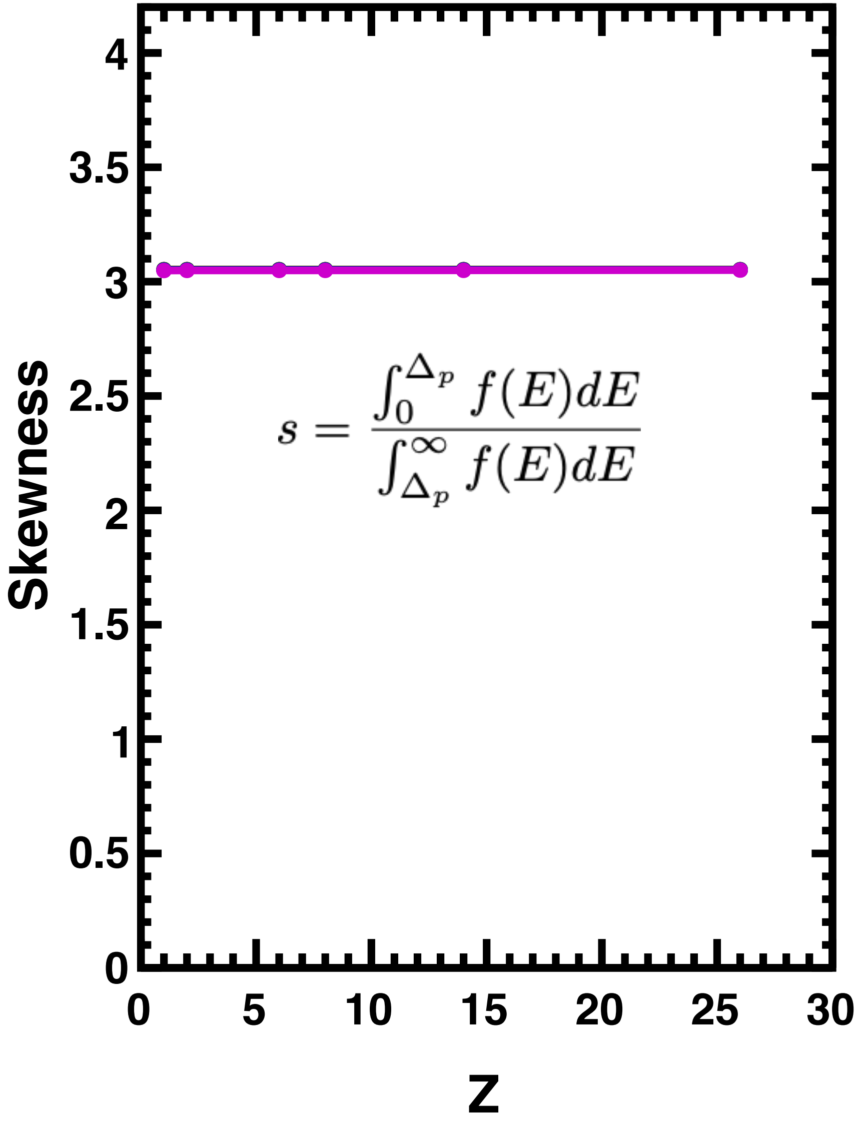
Landau fit is good with Z<26 or t<600 μm (when k is well below 0.1)

$E_{loss} = E_K^{in} - E_K^{out}$



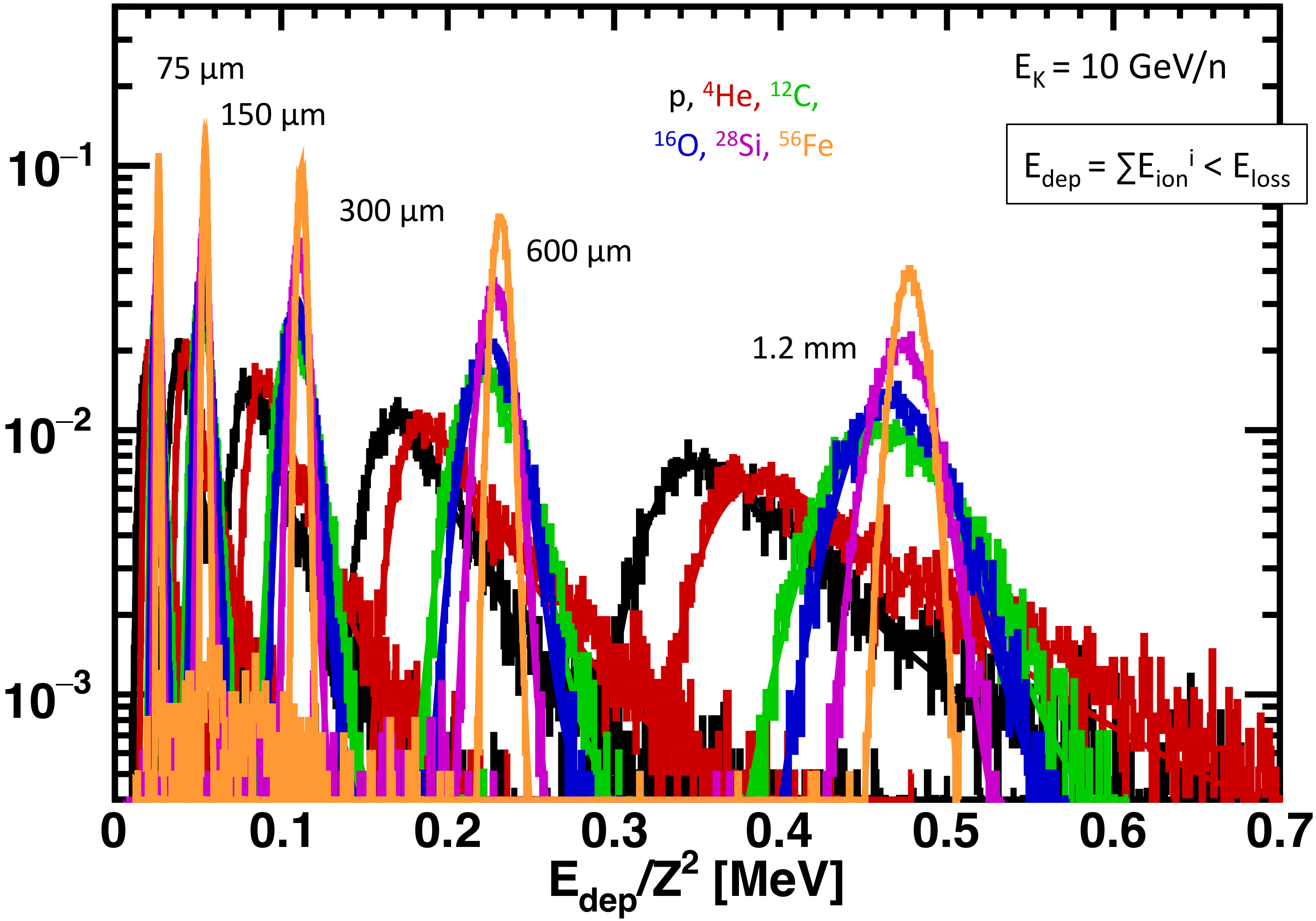
Single Layer Energy Loss for Different Thicknesses





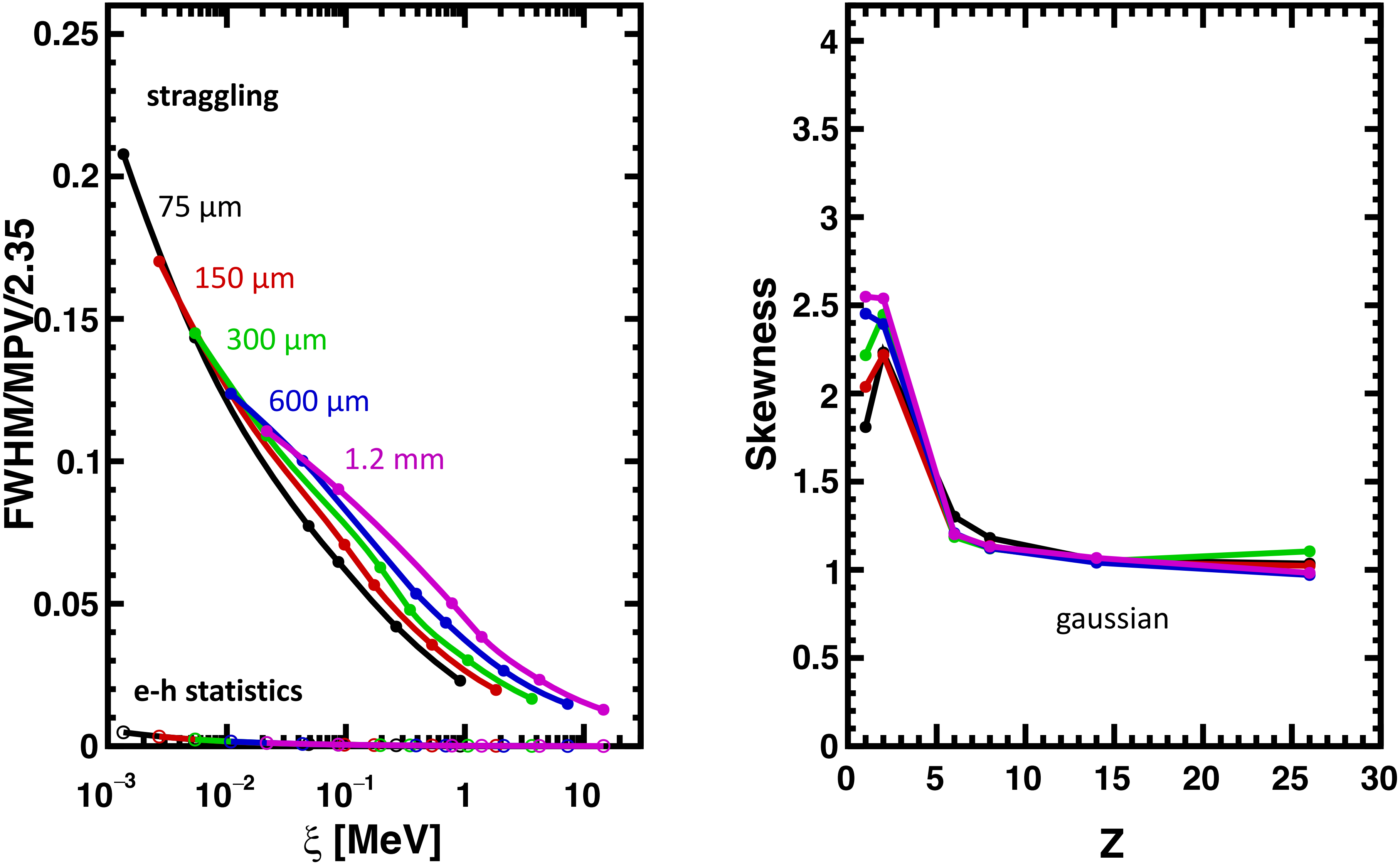
Single Layer Energy Deposit inside 500 µm for Different Thicknesses

Gaussian above Z=6, independently from thickness (high-E δ-rays escaping).



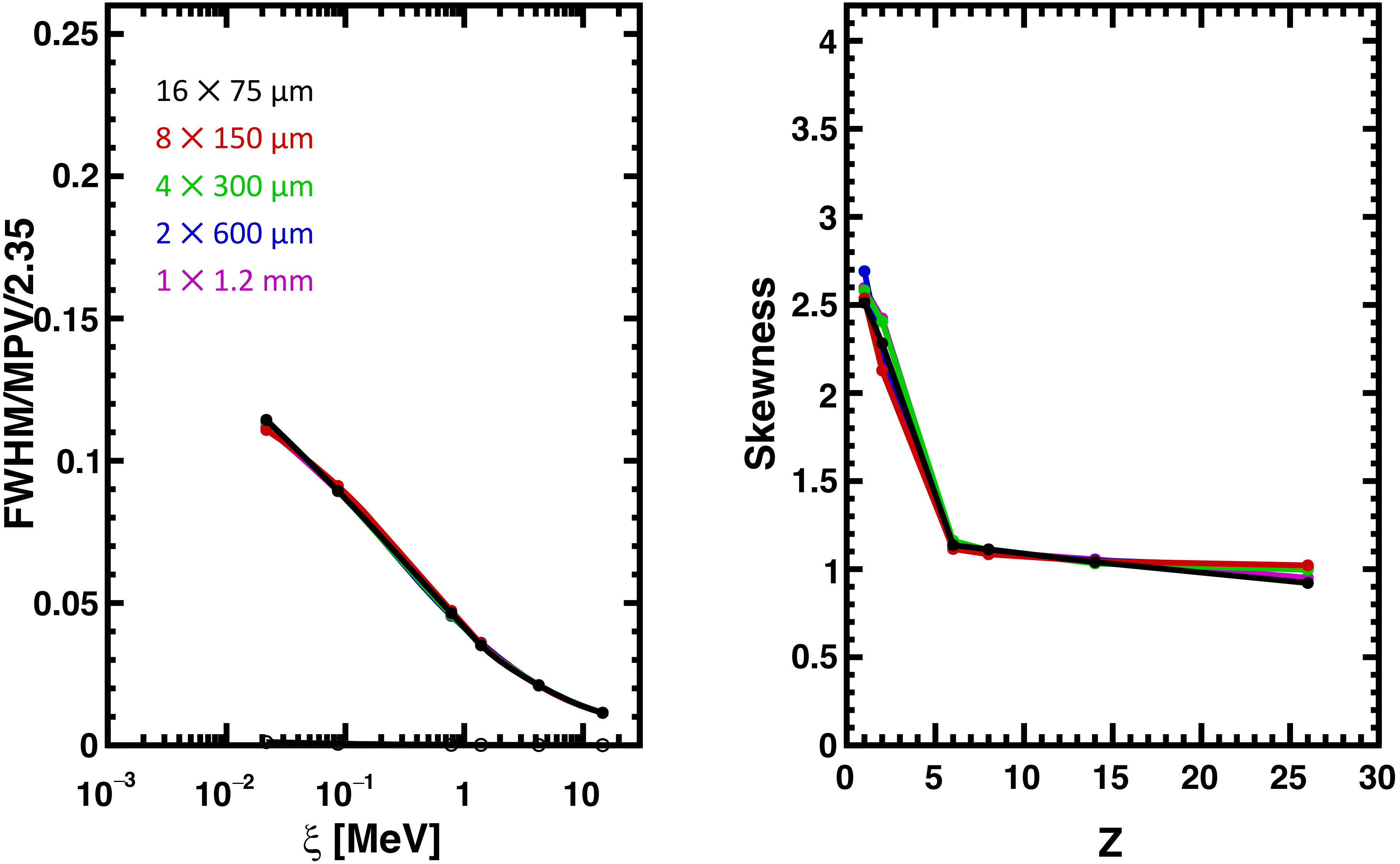
Single Layer Energy Deposit inside 500 μm for Different Thicknesses

Similar things can be seen for integral and <50 um energy deposit.



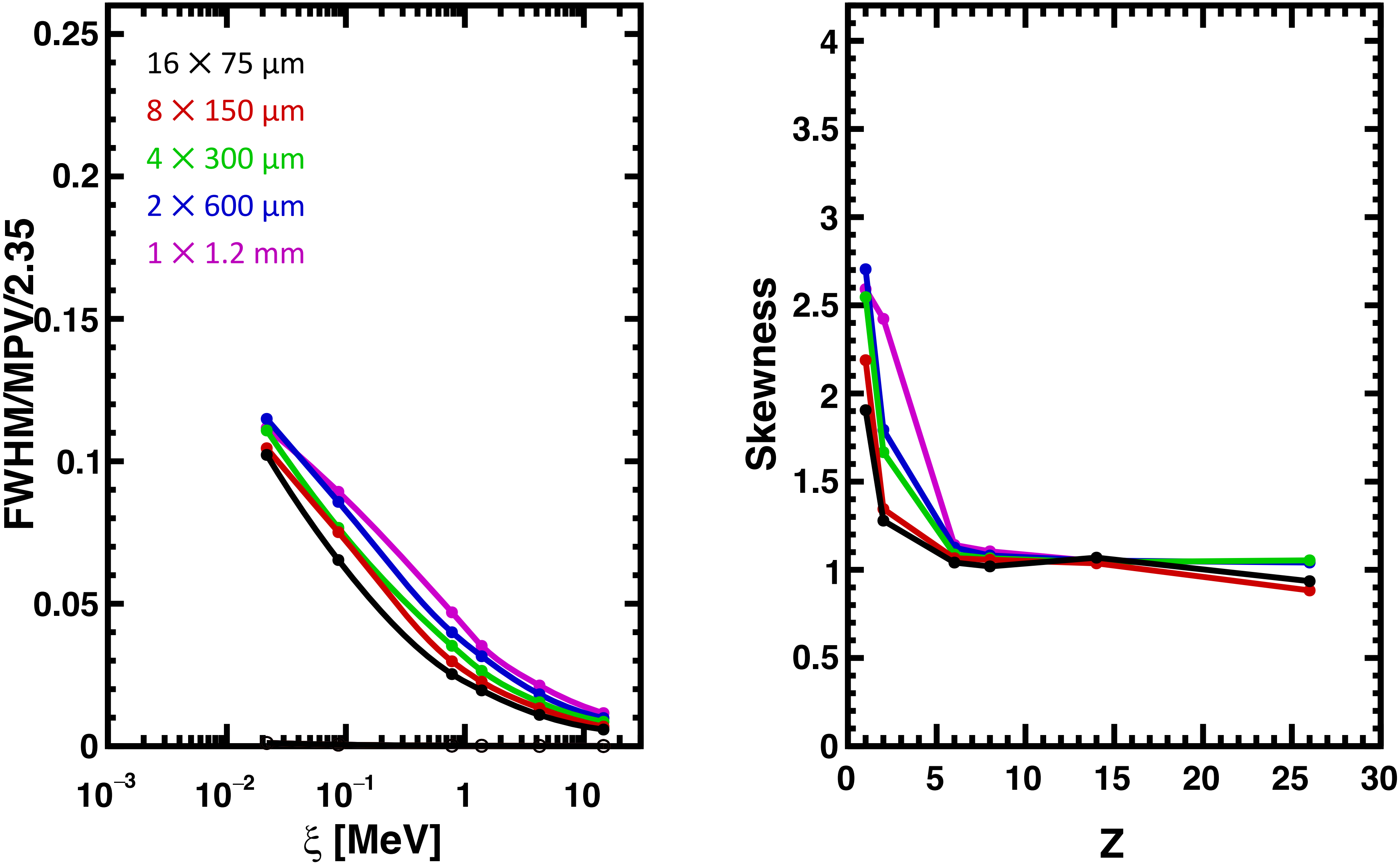
Energy Deposit inside 500 μm for the Same Overall Thickness of 1.2 mm

As expected, just by simple segmentation, there is no difference for any energy deposition/loss.



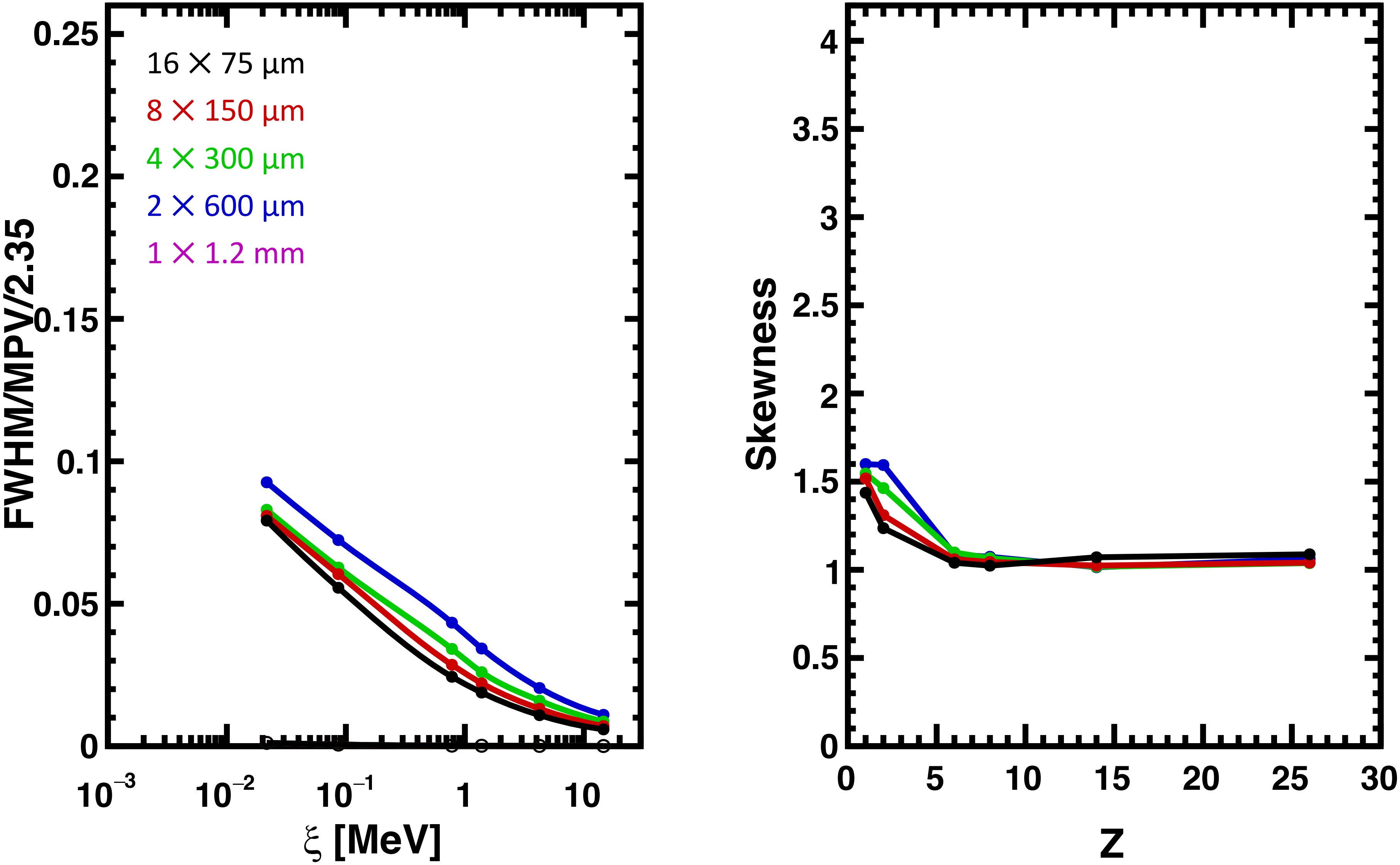
Energy Deposit inside 500 μm for the Same Overall Thickness of 1.2 mm

Some improvement arise if there is a gap, here of 1 cm (reduce δ-rays correlations).



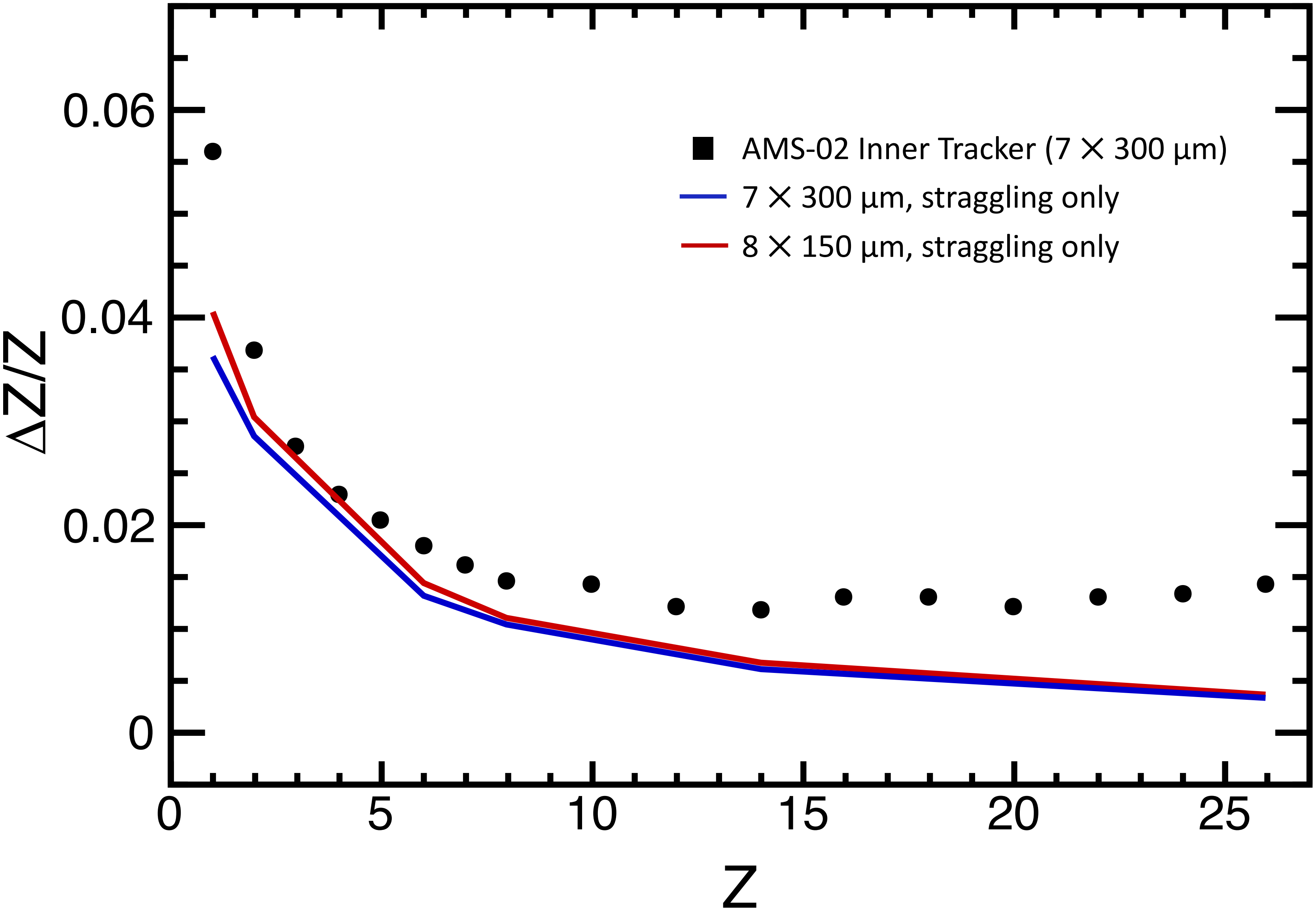
Energy Deposit inside 500 μm for the Same Overall Thickness of 1.2 mm

Additional improvement comes from the use of truncated mean (use of likelihood …).



AMS-02 Inner Tracker Charge Resolution

Even if the use of 8 × 150 μm has an intrinsic lower performance, it seems adequate.



Conclusions

A simple simulation able to give a baseline charge performance has been developed and verified with AMS-02 data.

At low-Z important contribution from straggling and noise.

At high-Z systematics could be dominant. It is important to plan ion beam test campaigns to check the linearity of the system and understand charge dependence from impact angle and coordinate. Also a uniformity of the response of the front-end electronics can be important for an accurate calibration.

A thin SCD with 8 layers of 150 µm has been studies and has an intrinsic resolution that is adequate (to be confirmed in test beam).

A more detailed performance evaluation of different scenarios will be carried out with HERD simulation.