Review of halo measurements at LHC with collimator scans

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Motivation

- Gaussian profiles are assumed for the beam distribution, but **beam tails** are usually **overpopulated**

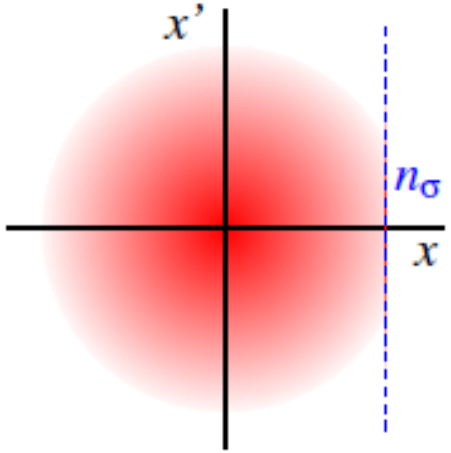
- Particles at the tails may create **uncontrolled losses**, cause magnets to **quench** and **increase** the experimental **background**

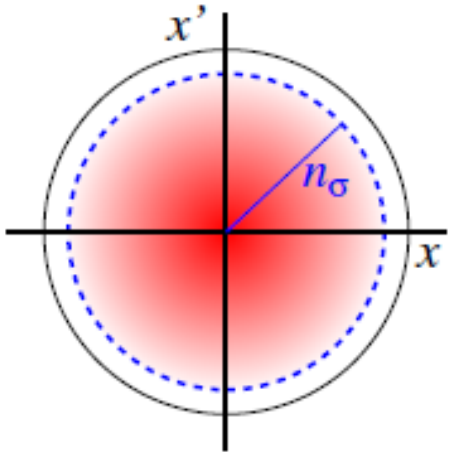
- A **good modeling** of the beam distribution is essential in order to find the **best strategy for** understanding the **impact on the operation** and **how to clean** these **particles**

- Useful not only for the current LHC, but it's also important to identify limitations of future machine upgrades (**HL-LHC**) with respect to machine protection requirements

Scraping for profile reconstruction (1/2)

The beam halo measurements in the LHC were conducting through collimators scraping



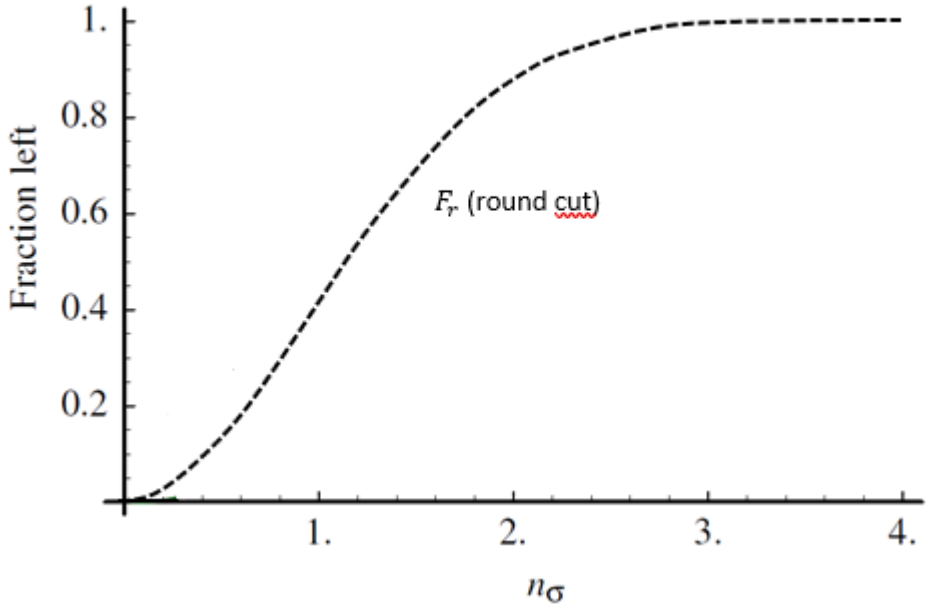


Round cut after many passages at the scraper [Ref. here]

Fraction of the particles left after many passages at a scraper (Gaussian distribution) [Ref here]

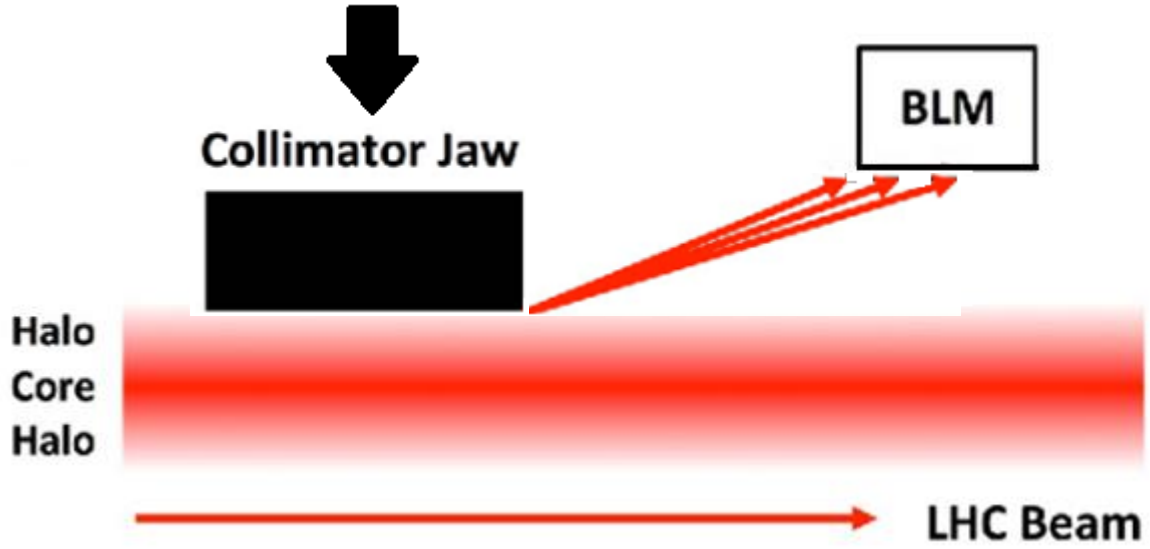
$$F_r = \frac{1}{2\pi}\int_0^{n_\sigma}\int_0^{2\pi} r\, e^{-r^2/2} d\varphi dr = \int_0^{n_\sigma} r\, e^{-r^2/2} dr = \left[-e^{-\frac{r^2}{2}}\right]_0^{n_\sigma} = 1 - e^{-n_\sigma^2/2}$$

$$0 \le r \le n_\sigma$$



Scraping for profile reconstruction (2/2)

- The reconstruction of the beam profile is performed taking into account the beam losses recorded in the **BLMs** close to the collimator used for the scraping and the **bunch intensity reduction**

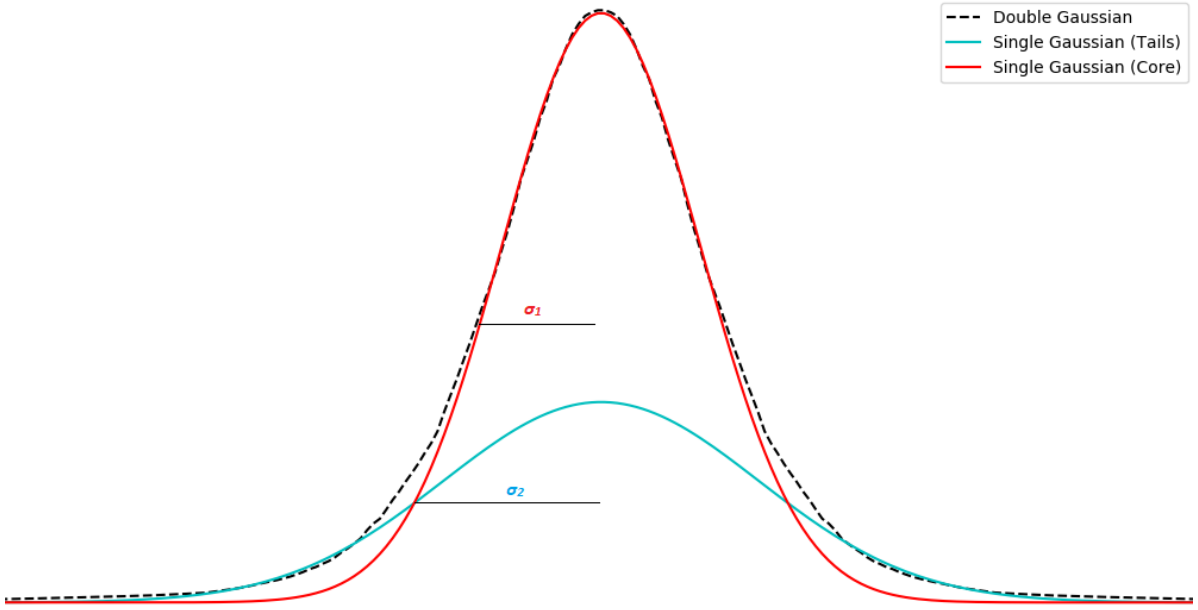


- The BLM signal, as a function of the collimator position, can be translated into protons with the proper conversion factor, normalizing subsequently to the intensity we obtain the **fraction of scraped particles**

- The use of the BLM for the profile reconstruction is dictated by the greater **accuracy** of the instrument compared to the ones of the **BWS**, however a comparison between the data of both instruments was made

Models for Profile Reconstruction

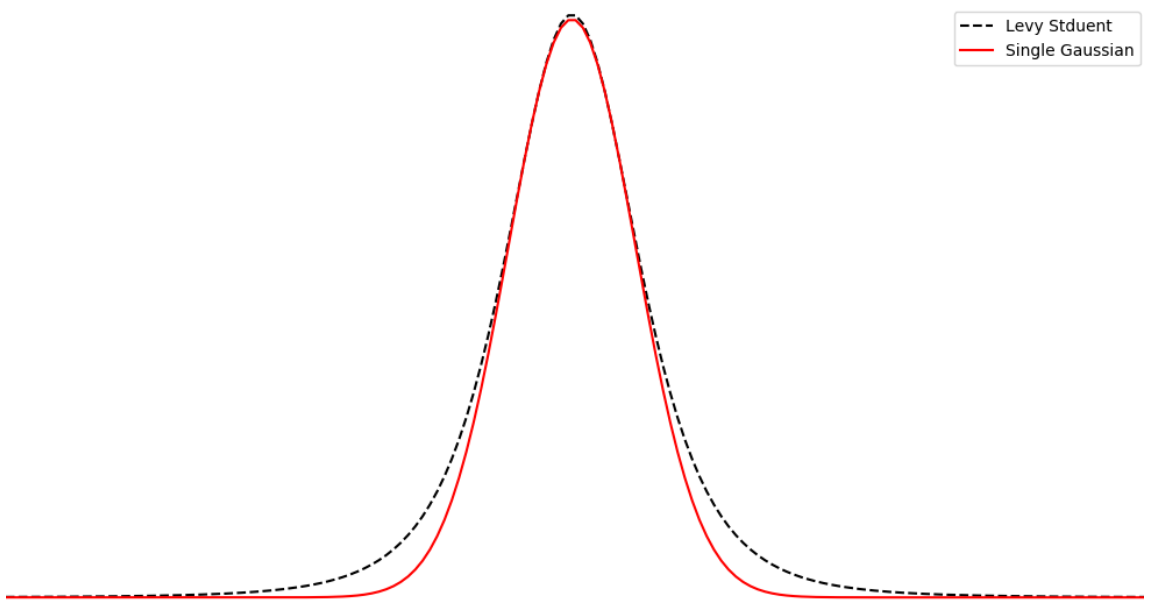
DOUBLE GAUSSIAN [Ref. here]



$$f(x) = \frac{I_1}{\sigma_1\sqrt{2\pi}} e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + \frac{I_2}{\sigma_2\sqrt{2\pi}} e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}}$$

- One single Gaussian to fit the **core** and one to fit **tails**
- **4 parameters** model
- I_1, I_2 Gaussian intensity, σ_1, σ_2 Gaussian variance
- **3 parameters** model (constrain $I_1 + I_2$ = integral of the distribution)

LEVY STUDENT [Ref. here]



$$f(x) = \frac{\Gamma\left(\frac{n+1}{2}\right)}{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{n}{2}\right)} \frac{a^n}{(x^2+a^2)^{\frac{n+1}{2}}}$$

- **Heavier tails** than the Gaussian distribution
- **2 parameters** model
- *n* rules the power decay of the tails
- *a* plays the role of a scale parameter

Curve fitting and Optimization Routine (1/2)

- **NUMERICAL INTEGRATION**

ρ = distribution
x_i = collimator position
t_i = time stamp
I_i = loss rate
C = calibration factor

$$\int_{x_i}^{x_j} \rho(x)dx = \int_{x(t_i)}^{x(t_j)} \rho(x)dx = C\int_{t_i}^{t_j} l(t)dt$$

$$\int_{x_i}^{x_j} \rho(x)dx = \sum_{k=i}^{j} \alpha_k \rho(x_k) \qquad \int_{t_i}^{t_j} l(t)dt = \sum_{k=i}^{j} \beta_k l(t_k)$$

$$\sum_{k=i}^{j} \alpha_k \rho(x_k) = \sum_{k=i}^{j} \beta_k l(t_k)$$

- Numerical integration method: **Simpson's rule integration**

- The **least square method** has been implemented to evaluate the difference between the two integral by cycling and increasing the values of the parameters of the Double Gaussian distribution at each step

PROBLEMS:
- Choose the intial values of the model parameters correctly
- Define the number of cycles necessary to find the optimal parameters to obtain a good fit

Curve fitting and Optimization Routine (2/2)

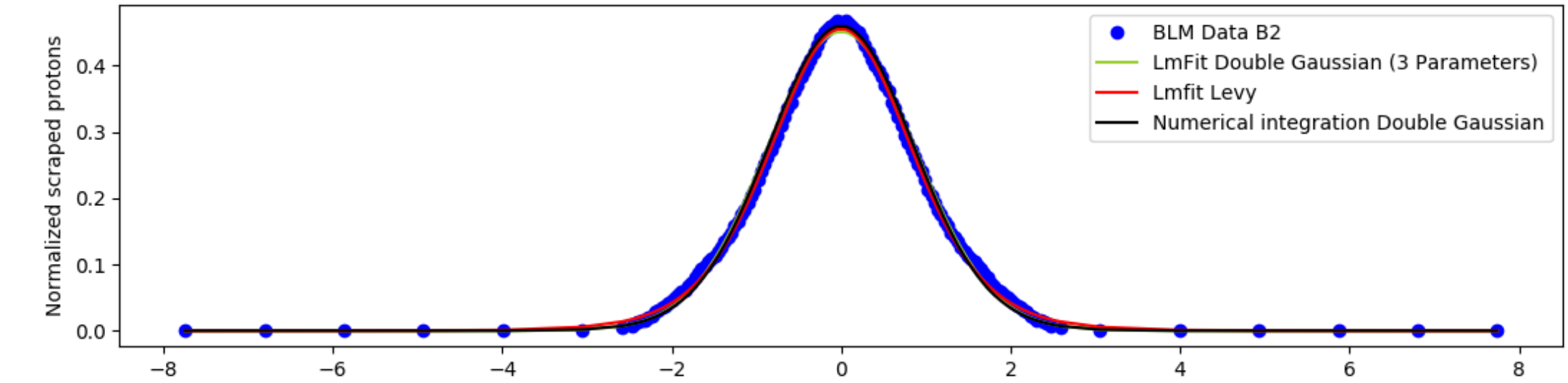
- **LMFIT LIBRARY**
  - It provides a high-level interface to non-linear **optimization** and curve **fitting problems**
  - Starting from a function of the **parametrized model**, it adjusts the numerical values of the model so that it correspondes more closely to the set of data
  - The optimization method that exploits is the **least square method**, but it allows to modify the adaptation algorithm
  - It offers the advantage of being able to define **constrains** for the **parameters** of the model distribution

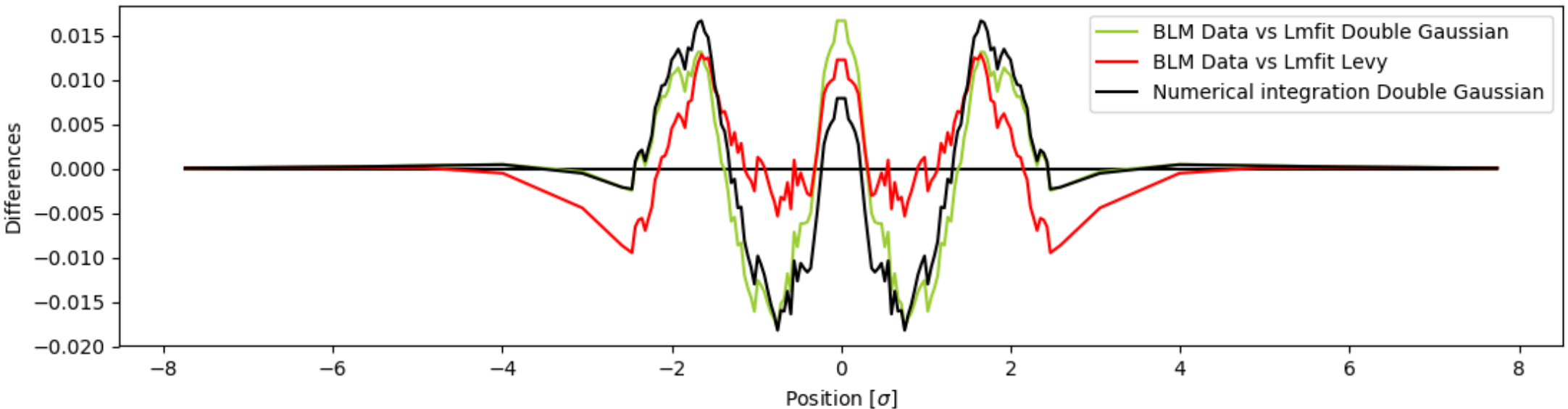
Available Set of Data

LHC CYCLE	SCRAPING	BEAM	HORIZONTAL PLANE	VERTICAL PLANE	SKEW PLANE
INJECTION	FULL	B1	5	2	1
		B2	4	2	1
	TAILS	B1	1	-	-
		B2	1	-	-
FLAT TOP	FULL	B1	-	1	-
		B2	-	1	-

Horizontal Full Scraping (1/2)

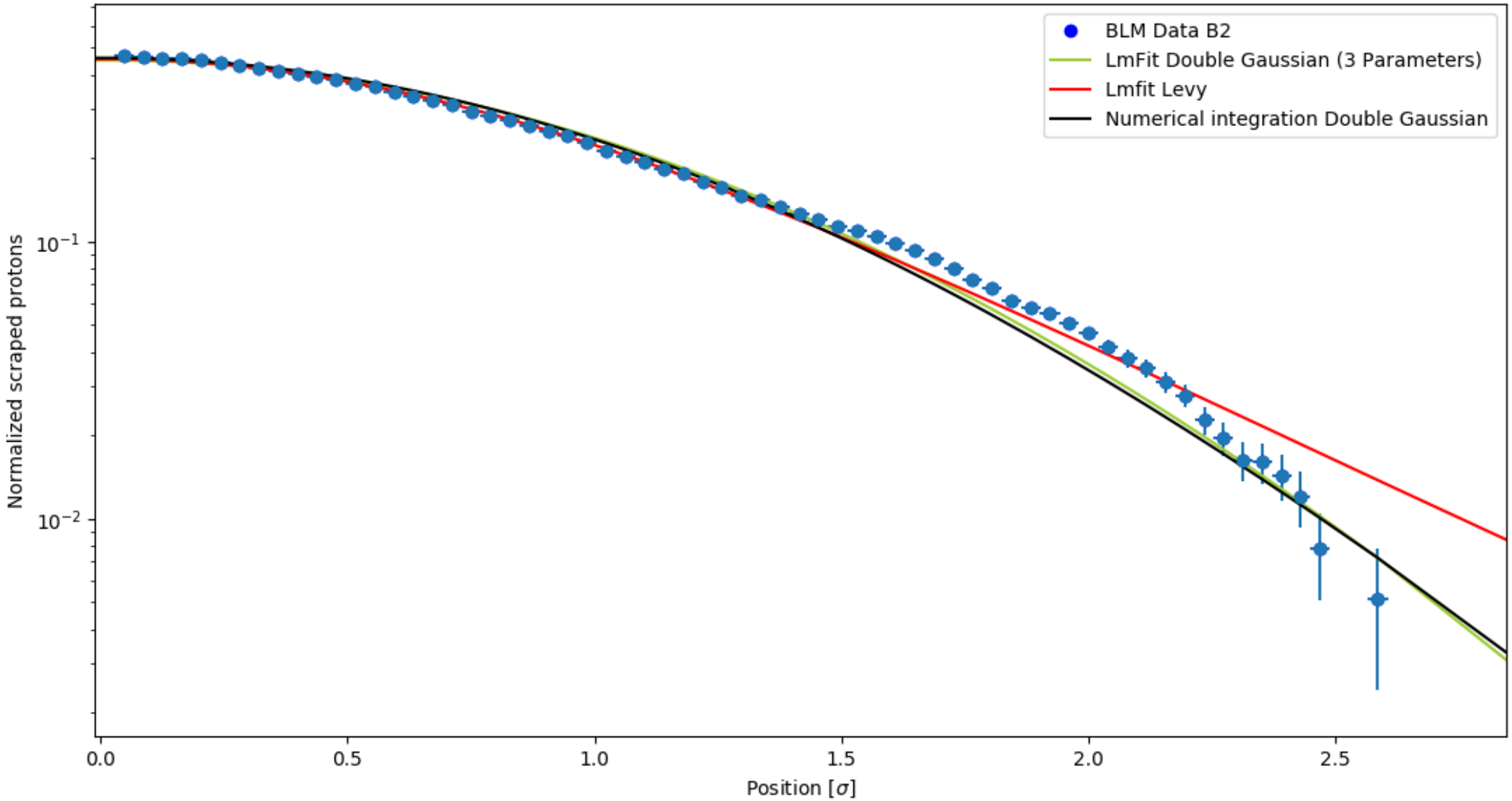
Scraping at **injection** performed with a step size of 50 µm every 2 seconds(1 Hz data)





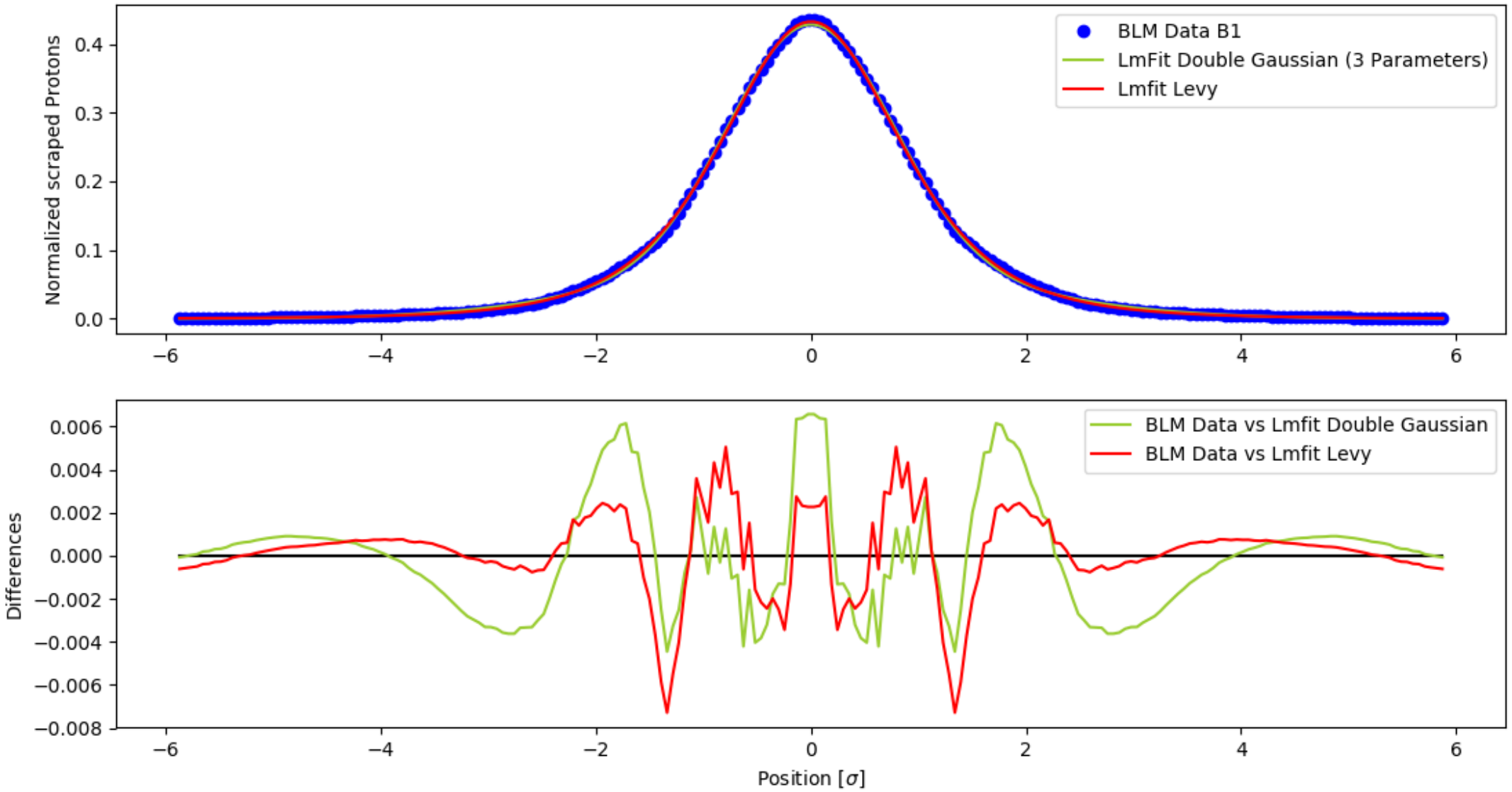
Horizontal Full Scraping (2/2)

Scraping at **injection** performed with a step size of 50µm every 2 seconds(1 Hz data)



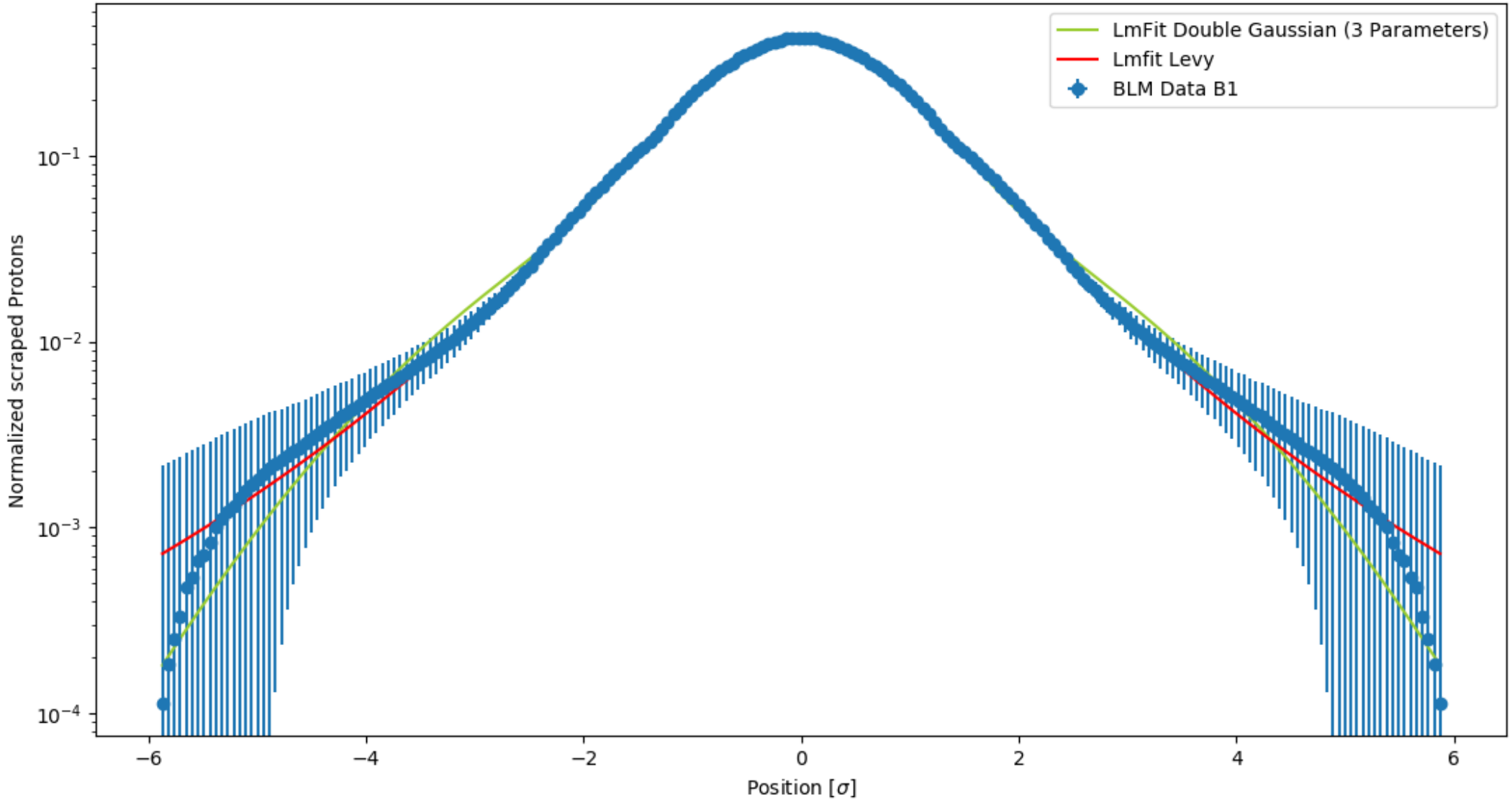
Horizontal Full Scraping (1/4)

Scraping at **injection** performed with a step size of 50 µm every 5 seconds (1 Hz data)



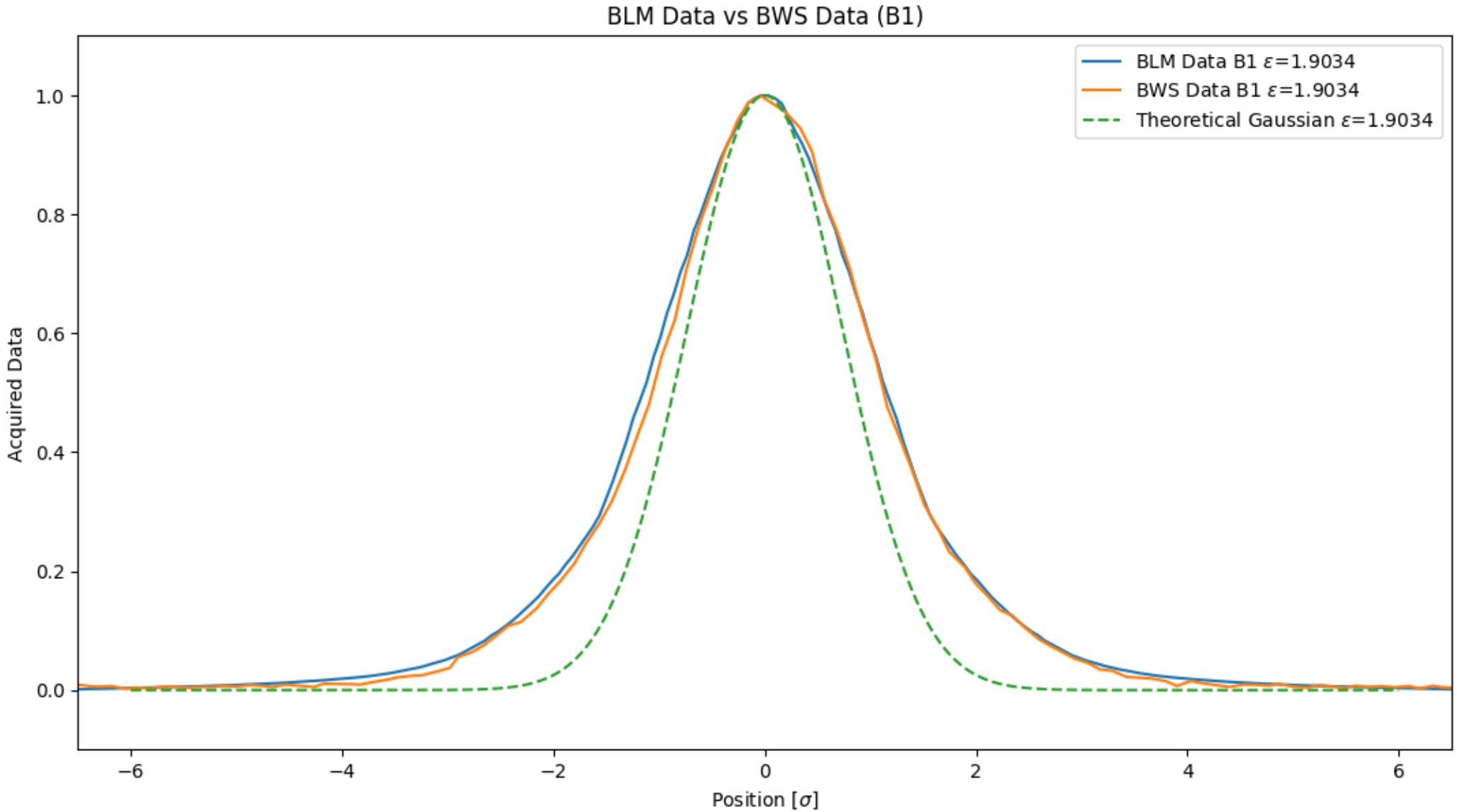
Horizontal Full Scraping (2/3)

Scraping at **injection** performed with a step size of 50 µm every 5 seconds (1 Hz data)



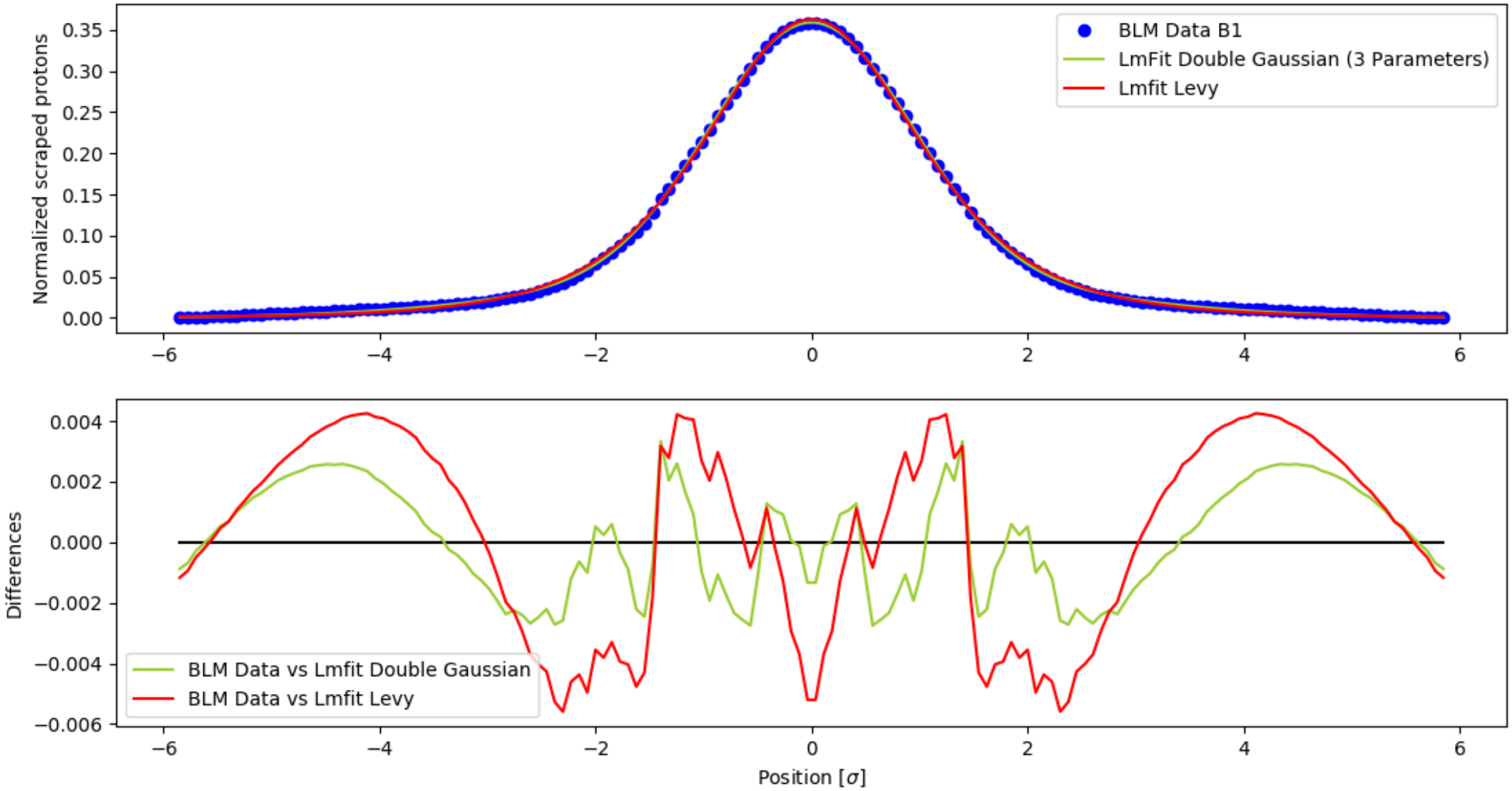
Horizontal Full Scraping (3/3)

NORMALIZATION TO INTENSITY



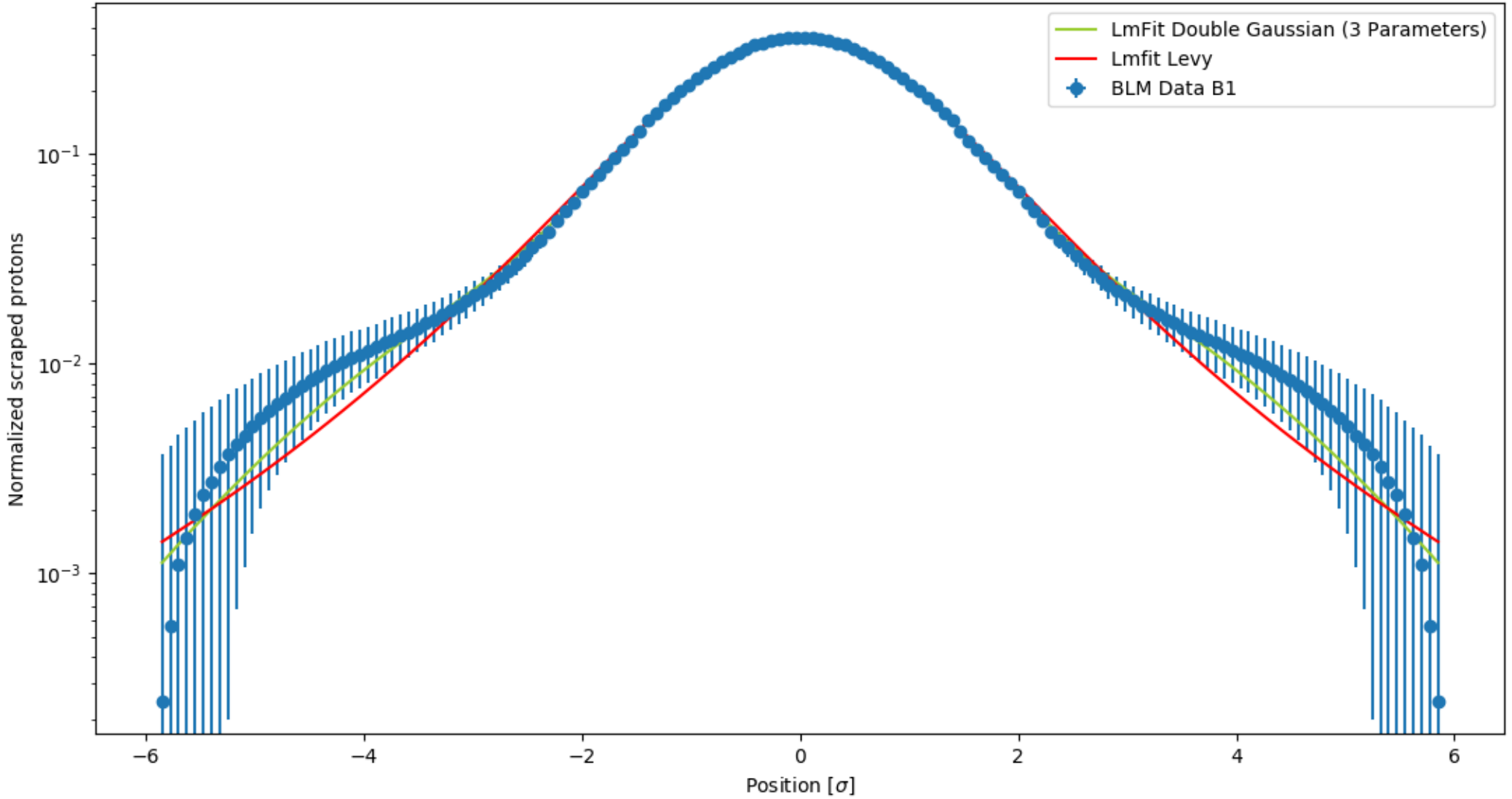
Vertical Full Scraping (1/3)

Scraping at **injection** performed with a step size of 50 µm every 5 seconds (1 Hz data)



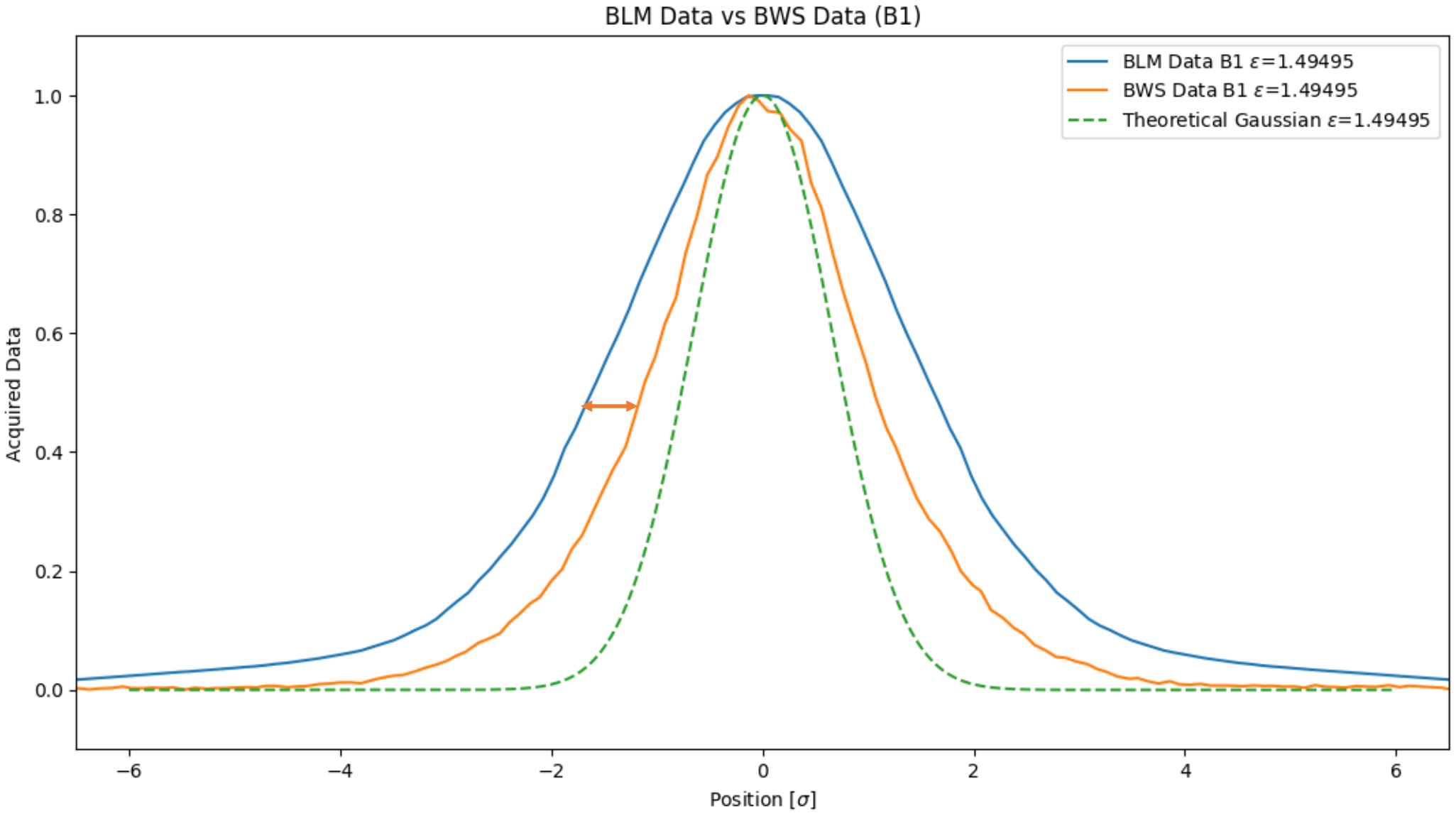
Vertical Full Scraping (2/3)

Scraping at **injection** performed with a step size of 50 µm every 5 seconds (1 Hz data)



Vertical Full Scraping (3/3)

NORMALIZATION TO INTENSITY



Fraction of particles in tails at injection

The sigma to which we refer is the one of the distribution, evaluated using the emittance value extracted from the BWS

HORIZONTAL PLANE

	DATA ACQUISITION	SCRAPING	Beyond 2σ	Beyond 3σ	Beyond 4σ
B1	30/07/2018	FULL	18%	5.3%	2%
		FULL	22%	7.7%	3%
		FULL	24%	8%	3%
	19/09/2018	FULL	25%	8%	1.9%
B2	30/07/2018	FULL	21%	6%	2%
		FULL	25%	10%	3%
		FULL	19%	6%	2%

VERTICAL PLANE

	DATA ACQUISITION	SCRAPING	Beyond 2σ	Beyond 3σ	Beyond 4σ
B1	30/07/2018	FULL	34%	13%	6%
		FULL	27%	9%	4%
B2	30/07/2018	FULL	30%	9%	3%
		FULL	29%	10%	3%

SKEW PLANE

	DATA ACQUISITION	SCRAPING	Beyond 2σ	Beyond 3σ	Beyond 4σ
B1	30/07/2018	FULL	15%	7%	3.6%
B2	30/07/2018	FULL	19%	10%	3.7%

In the past it was found that the fraction of particles above 4σ was 2,7% for the horizontal plane, 1.9% for the vertical plane and 3,6% for the skew plane [Ref. here]

Chi-square values of the models

HORIZONTAL

DATA ACQUISITION	SCRAPING	BEAM	MODEL	
			DOUBLE GAUSSIAN	LEVY STUDENT
15/09/2017	FULL	B2	0,0132241	3,5722e-05
25/05/2018	TAILS	B1	0,00108838	2,3858e-04
		B2	8,3143e-05	8,3989e-05
30/07/2018	FULL	B1	0,00140776	7,3229e-04
		B2	0,001866	4,4269e-04
	FULL	B1	8,6894e-04	9,0674e-04
		B2	0,00268119	1,4804e-05
	FULL	B1	8,2711e-04	8,2907e-04
		B2	0,00340409	0,00100129
19/09/2018	FULL	B1	0,00289972	4,4149e-04
		B1	0,0086841	0,00513951

VERTICAL

DATA ACQUISITION	SCRAPING	BEAM	MODEL	
			DOUBLE GAUSSIAN	LEVY STUDENT
30/07/2018	FULL	B1	4,6725e-04	0,00150505
		B2	2,2359e-04	8,2438e-04
	FULL	B1	3,5398e-04	0,00129819
		B2	7,8406e-04	3,1245e-05
	FULL	B1	0,04156923	0,05360191
		B2	0,03949707	0,0187776

SKEW

DATA ACQUISITION	SCRAPING	BEAM	MODEL	
			DOUBLE GAUSSIAN	LEVY STUDENT
30/07/2018	FULL	B1	0,00669643	0,03350926
		B2	0,00288375	0,00142876

Parameter values of the Final Model

CONSTRAINS →
- Double Gaussian : $I_1 > I_2$ and $\sigma_1 < \sigma_2$
- Lèvy Student : $n > 2$

SCRAPING	BEAM	AVERAGE ± STANDARD DEVIATION					
		DOUBLE GAUSSIAN				LEVY STUDENT	
		I_1	I_2	σ_1	σ_2	n	a
HORIZONTAL	B1	0,66 ± 0,028	0,33 ± 0,025	1,01 ± 0,411	1,85 ± 0,178	4,56 ± 1,273	2,43 ± 1,211
	B2	0,64 ± 0,049	0,35 ± 0,049	0,76 ± 0,053	1,47 ± 0,297	5,27 ± 2,014	1,92 ± 0,389
VERTICAL	B1	0,71 ± 0,015	0,29 ± 0,085	0,9 ± 0,025	2,11 ± 0,034	4,11± 0,005	2,03 ± 0,064
	B2	0,71 ± 0,085	0,29 ± 0,085	0,97 ± 0,08	2,01 ± 0,195	5,95 ± 1,415	2,63 ± 0,43

DOUBLE GAUSSIAN MODEL	
I_1/I_2	σ_2/σ_1
2	1,83
1,82	1,93
2,44	2,34
2,44	2,07

- In most cases the standard deviation is small enough to say that for each parameter the values are quite the same
- The values of the parameters between B1 and B2 are quite close to each other
- The ratio σ_2/σ_1, that in the past was extimated to be 1.8 [Ref. here], is ~2

Summary

- To evaluate **particles distributions** in the **transvers plane** of the beam, different scans, with only one bunch, were performed with TCP in IR7 in the **horizontal, vertical and skew plane** at different stages of the LHC cycle
- A **more detailed set of tools** has been created and it's **model indipendent**
- It **works in different stages of the cycle** of the LHC
- In the **horizontal plane** the **Lèvy Student** model fits better most of the cases analyzed
- In the **vertical plane** the **Double Gaussian** model turns out to be the best
- The results show that in most cases the ratio $\boldsymbol{\sigma_2/\sigma_1}$, for the Double Gaussian model, is **about 2**
- The **fraction of particles in the tails** beyond 4σ for the horizontal plane is in a range between 2% and 3%, while in the vartical plane it's in the range between 3% and 6%
- From the data available we have done a **statistical analysis** from which we have seen that the model that we have implemented works with **small error**

What's next?

- Repeat the analysis with **new models** to check if they fit better the beam profile
- Find a valid method for assigning weights to the set of data so that we can implement a **weighted analysis**
- Compare the profile obtained from the BLM and the BWS with the one from the **BSRT** in order to understand, where there is a relevant difference between the curves, which one is less accurate

Parameters Horizontal plane

CONSTRAINS →
- Double Gaussian : $I_1 > I_2$ and $\sigma_1 < \sigma_2$
- Lèvy Student : $n > 2$

	DATA ACQUISITION	SCRAPING	MODEL: DOUBLE GAUSSIAN I_1	I_2	σ_1	σ_2	LEVY STUDENT n	a	DOUBLE GAUSSIAN MODEL I_1/I_2	σ_2/σ_1
B1	25/05/2018	TAILS	0,69	0,3	1,99	1,96	7,82	5,18	2,1	1,01
	30/07/2018	FULL	0,66	0,33	0,76	1,68	4,14	1,76	2	2,33
		FULL	0,62	0,37	0,76	1,73	3,56	1,68	1,67	2,27
		FULL	0,67	0,32	0,79	1,83	3,81	1,76	2,09	2,31
	19/09/2018	FULL	0,7	0,3	1,72	2,14	6,74	4,53	2,33	1,24
			0,7	0,3	1,65	1,72	9,41	4,92	2,33	1,04
		BLOW-UP								
B2	15/09/2017	FULL	0,59	0,4	0,83	0,97	8,52	2,48	1,47	1,16
	25/05/2018	TAILS	0,85	0,14	1,88	2,21	99,99	19,11	6,07	1,17
	30/07/2018	FULL	0,72	0,27	0,77	1,7	4,67	1,83	2,66	2,2
		FULL	0,61	0,38	0,77	1,52	4,88	1,99	1,6	1,97
		FULL	0,63	0,36	0,68	1,69	3	1,39	1,75	2,48

The ratio σ_2/σ_1, that in the past was extimated to be 1.8 [Ref. here], is ~2

Parameters Vertical and Skew plane

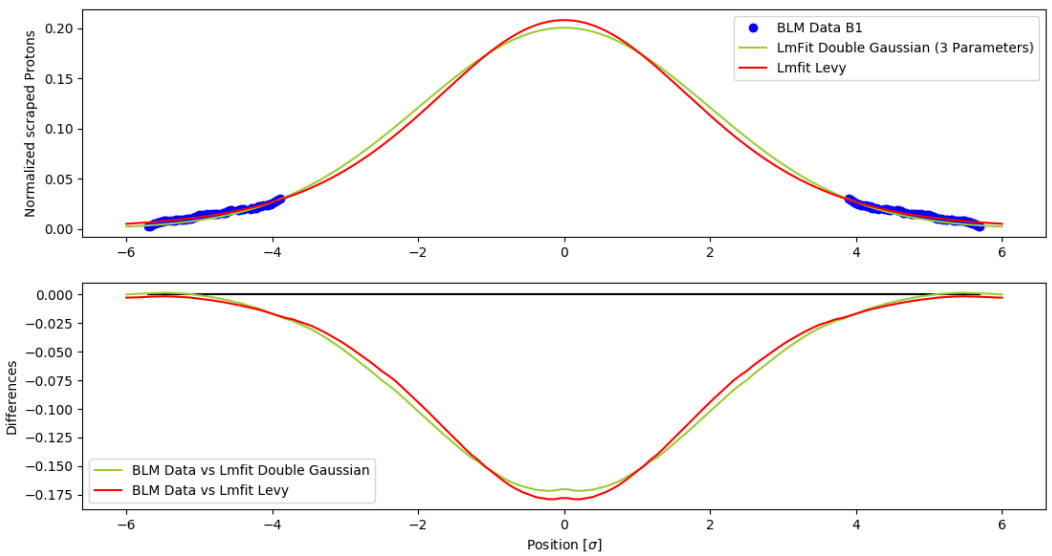
CONSTRAINS →
- Double Gaussian : $I_1 > I_2$ and $\sigma_1 < \sigma_2$
- Lèvy Student : $n > 2$

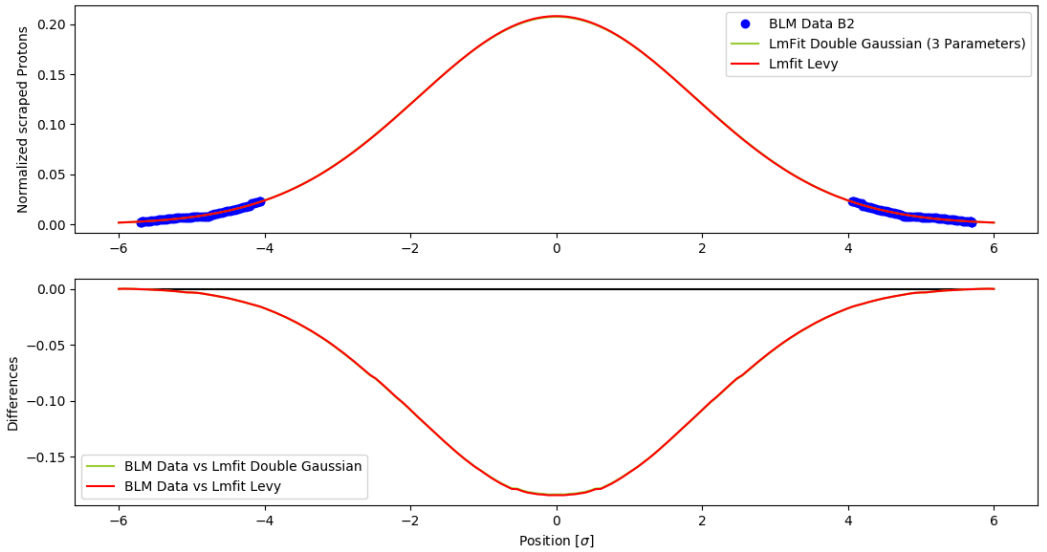
	DATA ACQUISITION	SCRAPING	MODEL: DOUBLE GAUSSIAN I_1	I_2	σ_1	σ_2	LEVY STUDENT n	a	DOUBLE GAUSSIAN MODEL I_1/I_2	σ_2/σ_1	
B1	30/07/2018	FULL	0,69	0,3	0,92	2,07	4,1	2,09	2,3	2,25	VERTICAL
		FULL	0,72	0,27	0,87	2,14	4,11	1,96	2,66	2,45	
		FULL	0,54	0,45	0,17	0,52	2	0,31	1,2	3,05	
		FLAT TOP									
B2	30/07/2018	FULL	0,79	0,2	1,05	2,2	7,36	3,06	3,95	2,09	
		FULL	0,62	0,37	0,89	1,81	4,53	2,2	1,67	2,03	
		FULL	0,77	0,22	0,24	0,59	4,96	0,58	3,5	2,45	
		FLAT TOP									
B1	30/07/2018	FULL	0,82	0,17	0,71	2,07	2	0,97	4,82	2,91	SKEW
B2	30/07/2018	FULL	0,76	0,23	0,72	1,73	4,62	1,67	3,3	2,4	

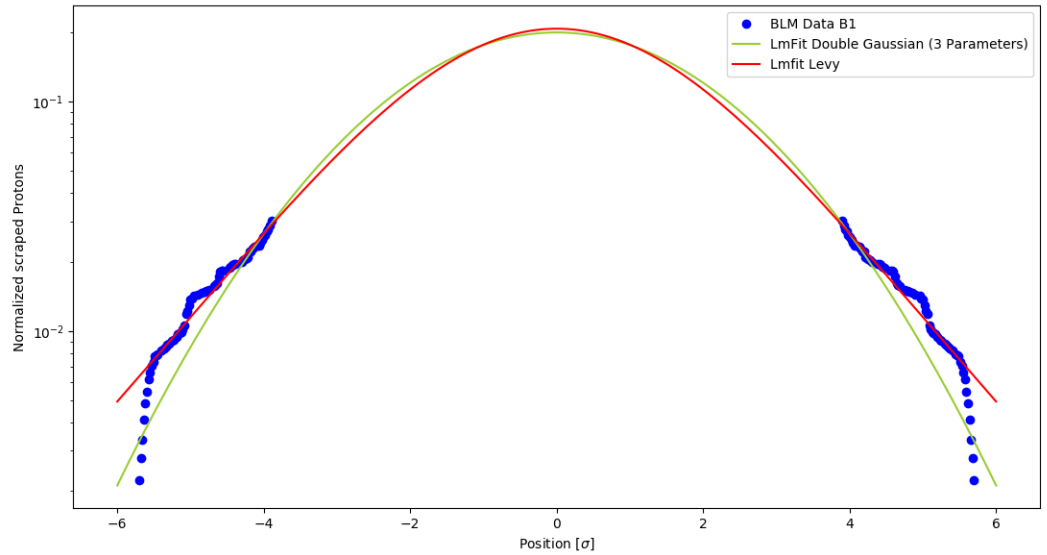
The ratio σ_2/σ_1, that in the past was extimated to be 1.8 [Ref. here], is ~2

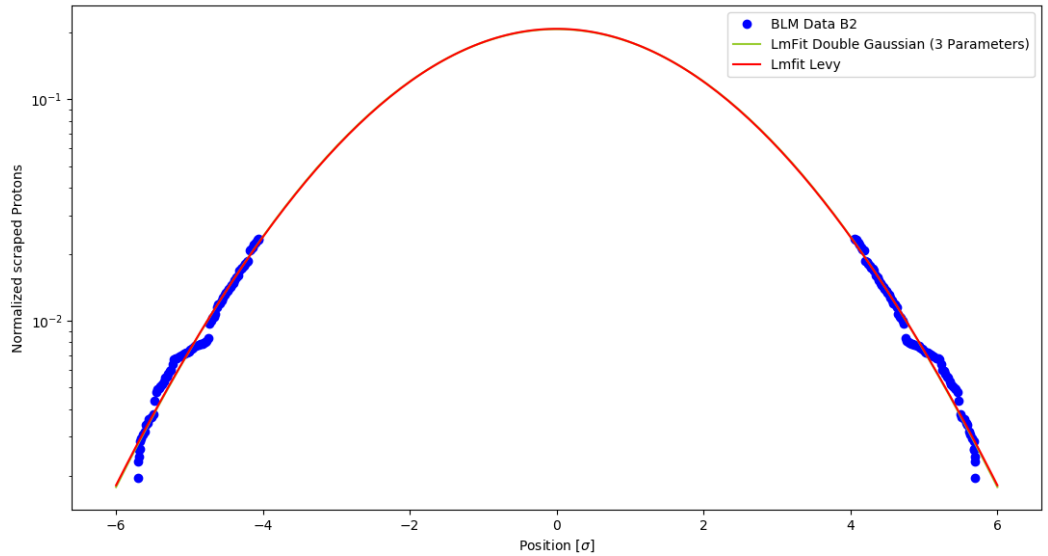
Appendix

Horizontal Tail scraping



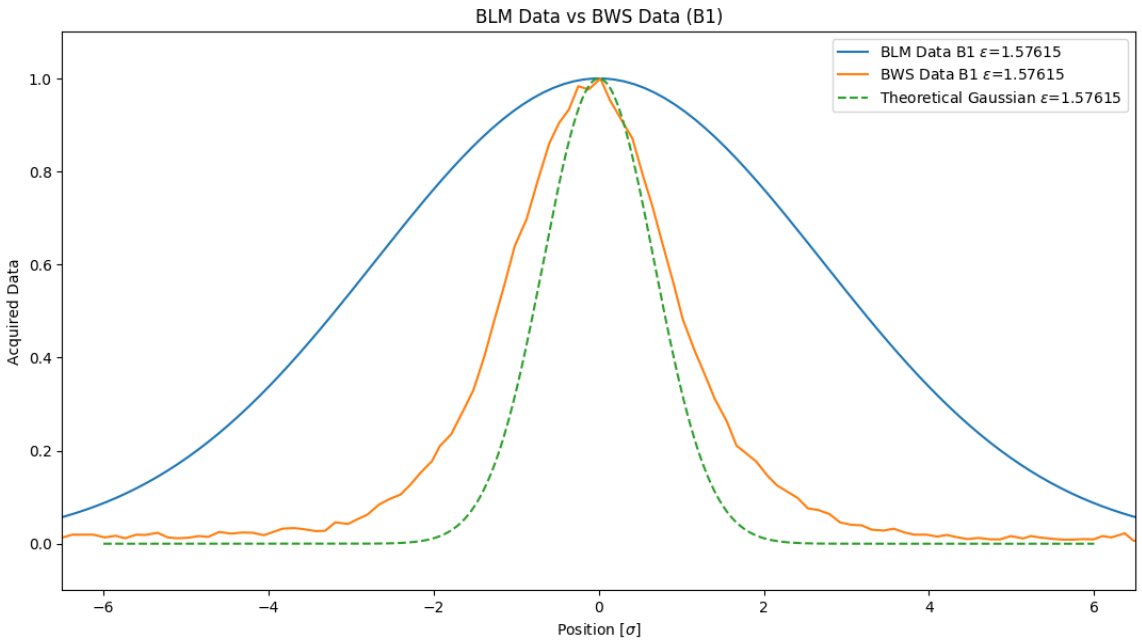


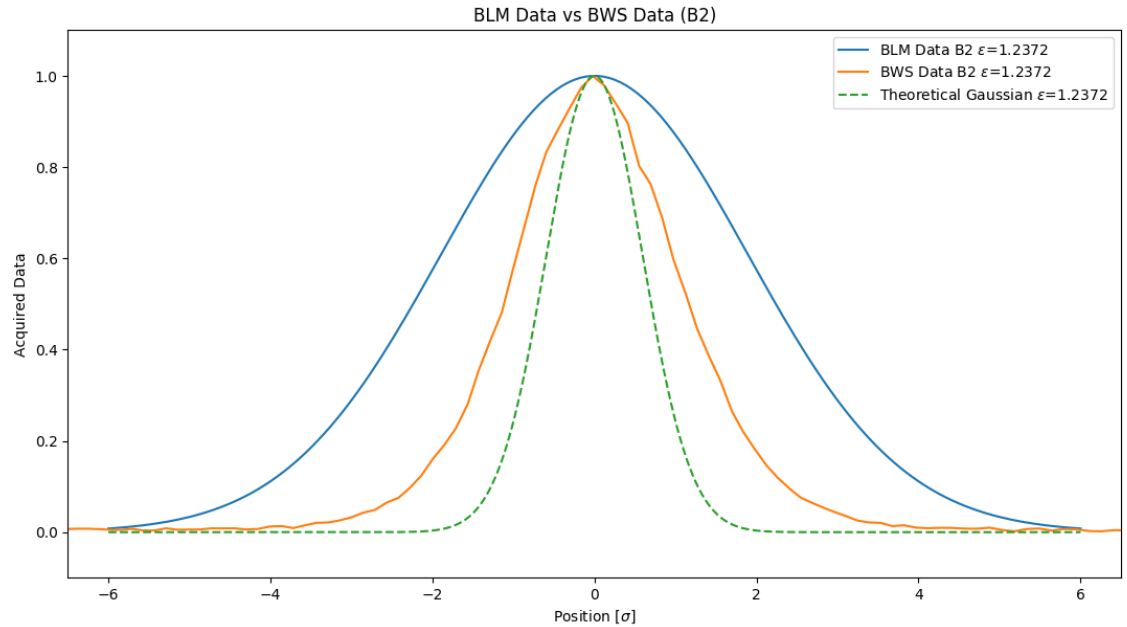




Appendix

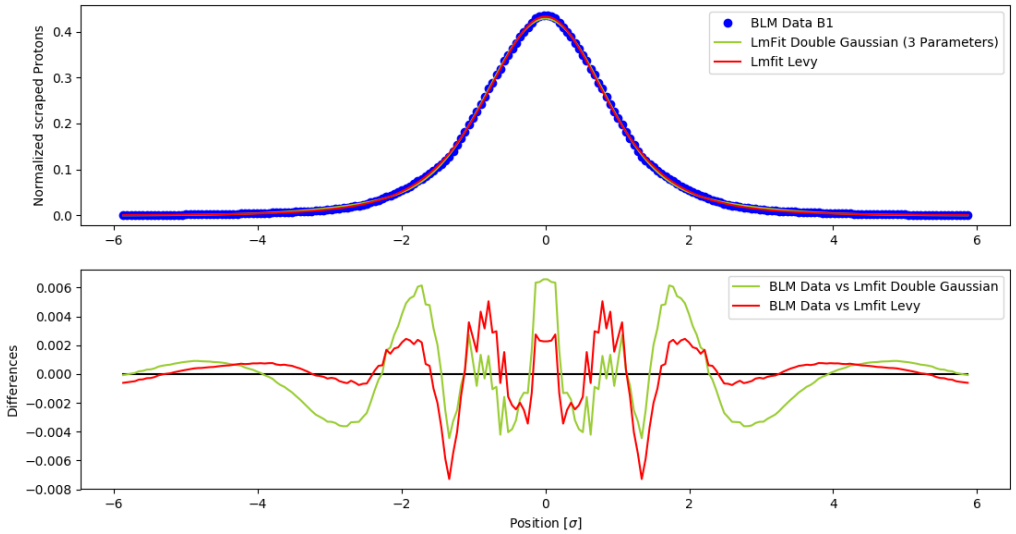
Horizontal Tail scraping

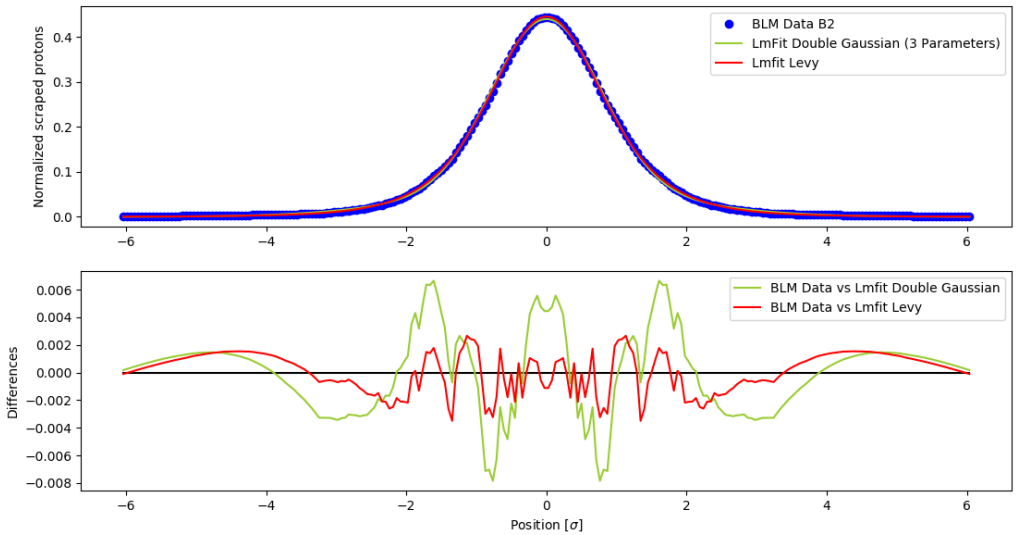


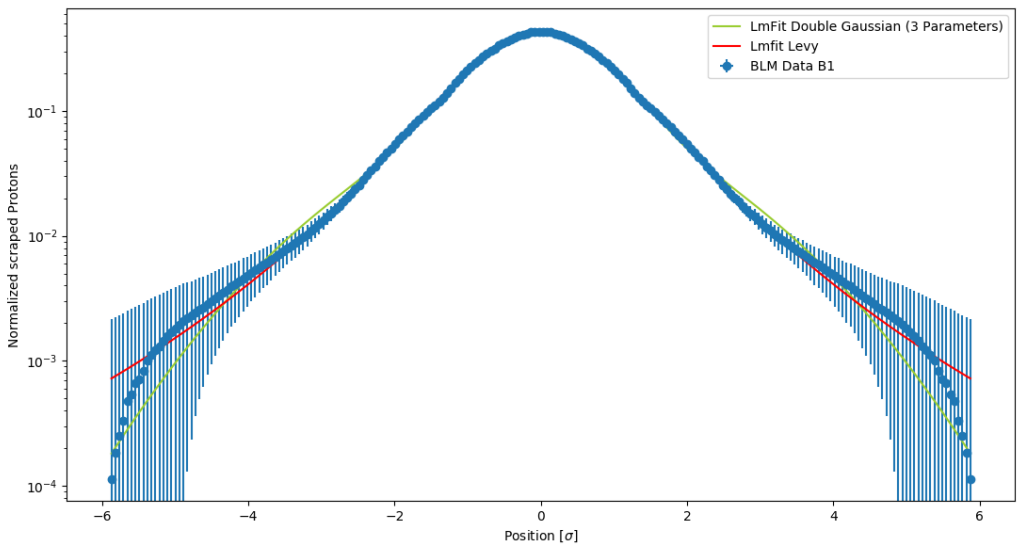


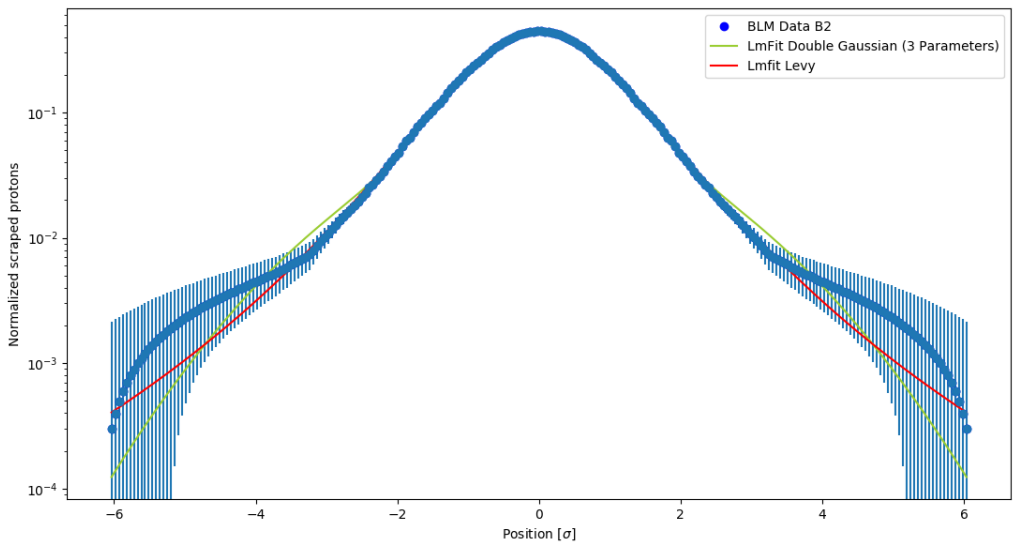
Appendix

Horizontal scraping 1

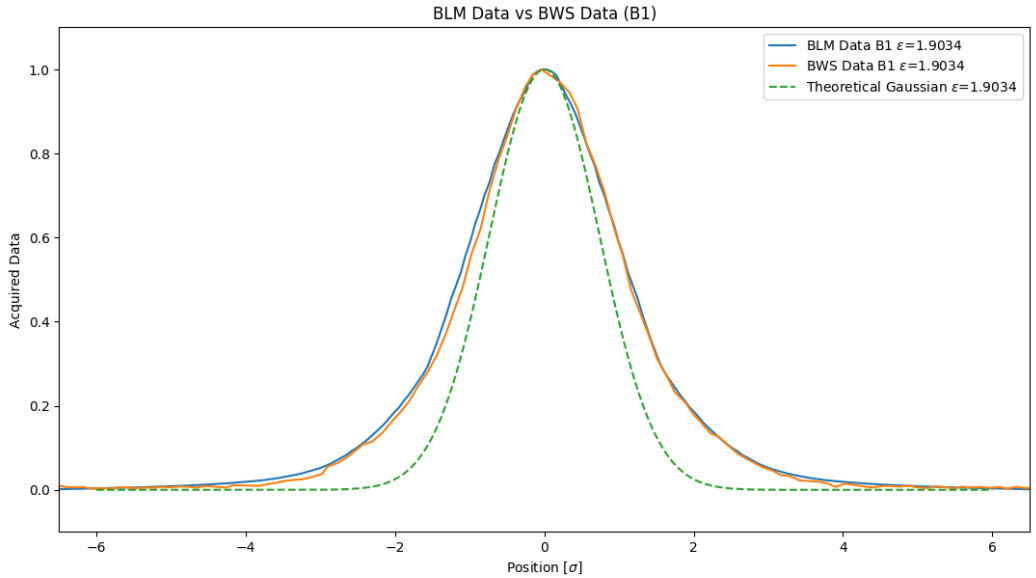


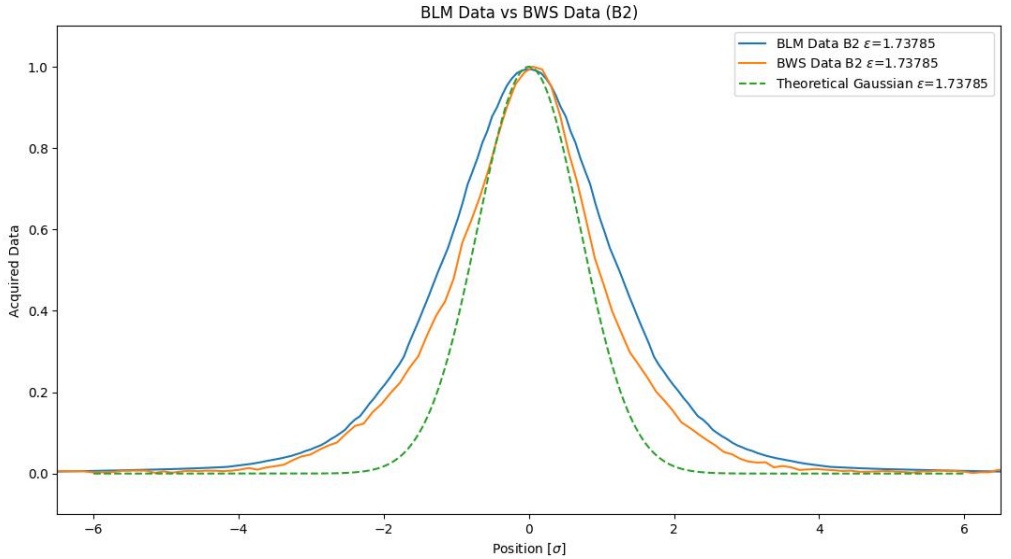


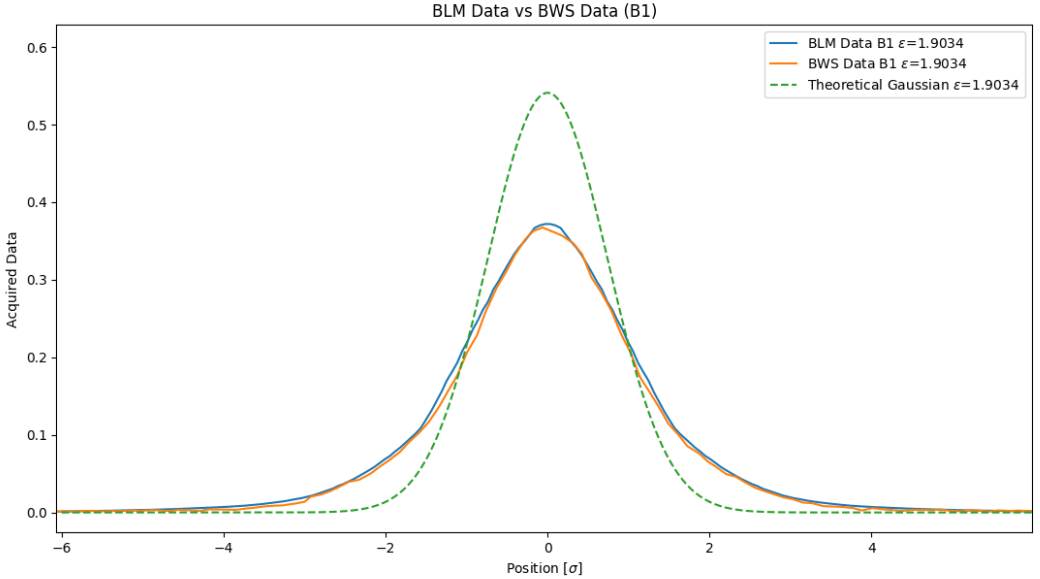


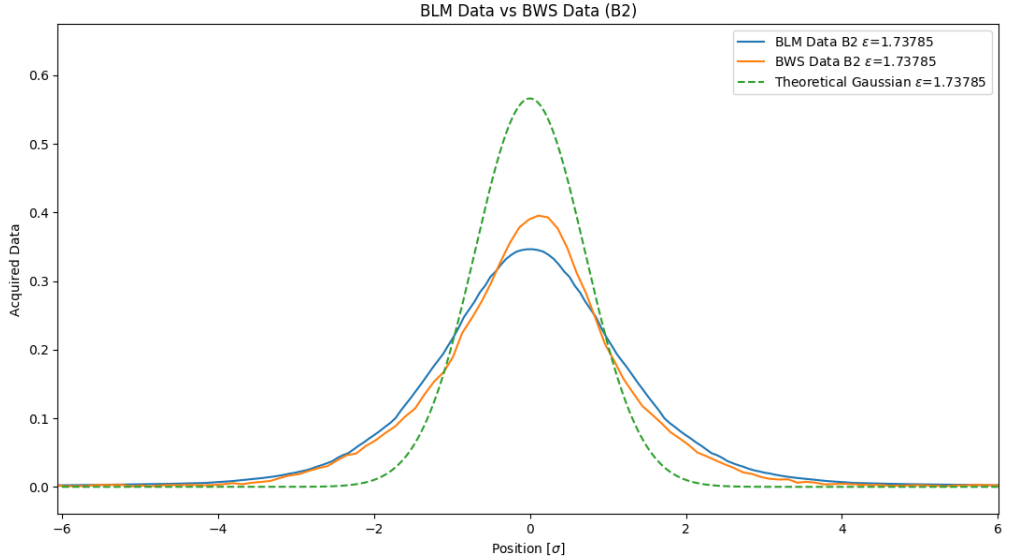


Appendix


BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.9034
BWS Data B1 ε=1.9034
Theoretical Gaussian ε=1.9034
Acquired Data
Position [σ]

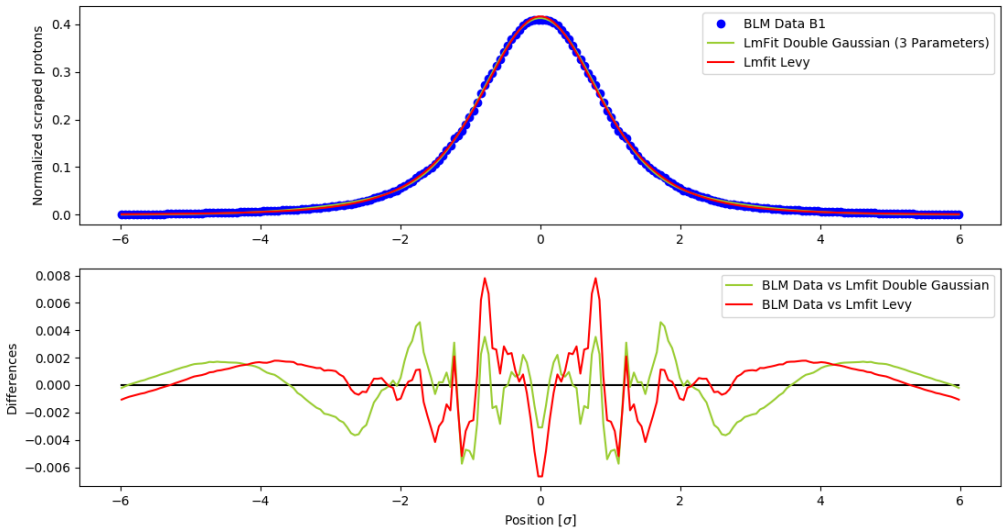

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.73785
BWS Data B2 ε=1.73785
Theoretical Gaussian ε=1.73785
Acquired Data
Position [σ]

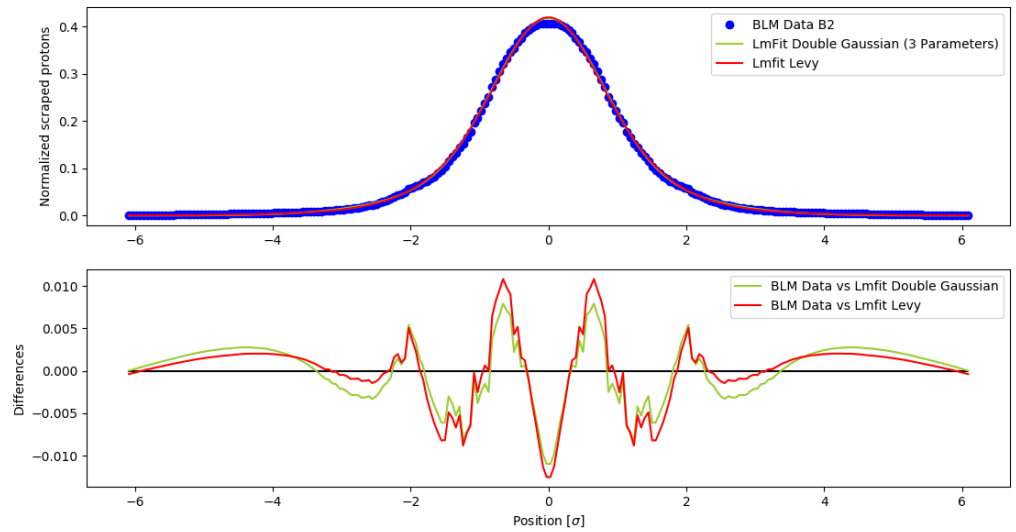

BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.9034
BWS Data B1 ε=1.9034
Theoretical Gaussian ε=1.9034
Acquired Data
Position [σ]

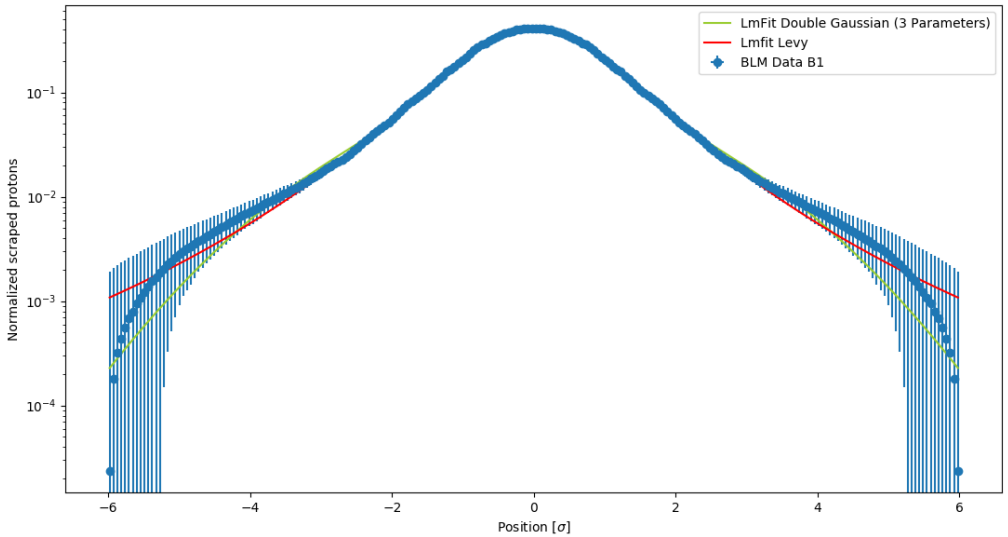

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.73785
BWS Data B2 ε=1.73785
Theoretical Gaussian ε=1.73785
Acquired Data
Position [σ]

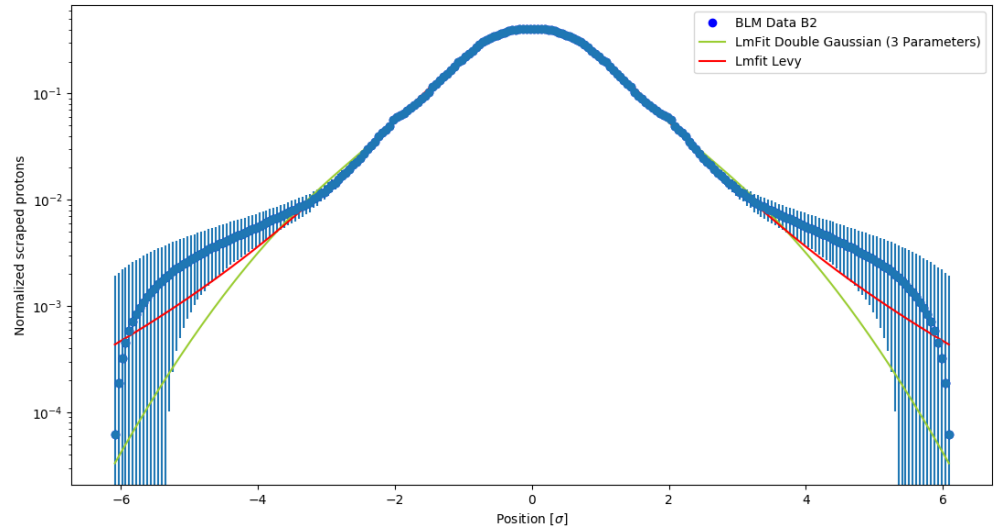
Appendix

Horizontal scraping 2

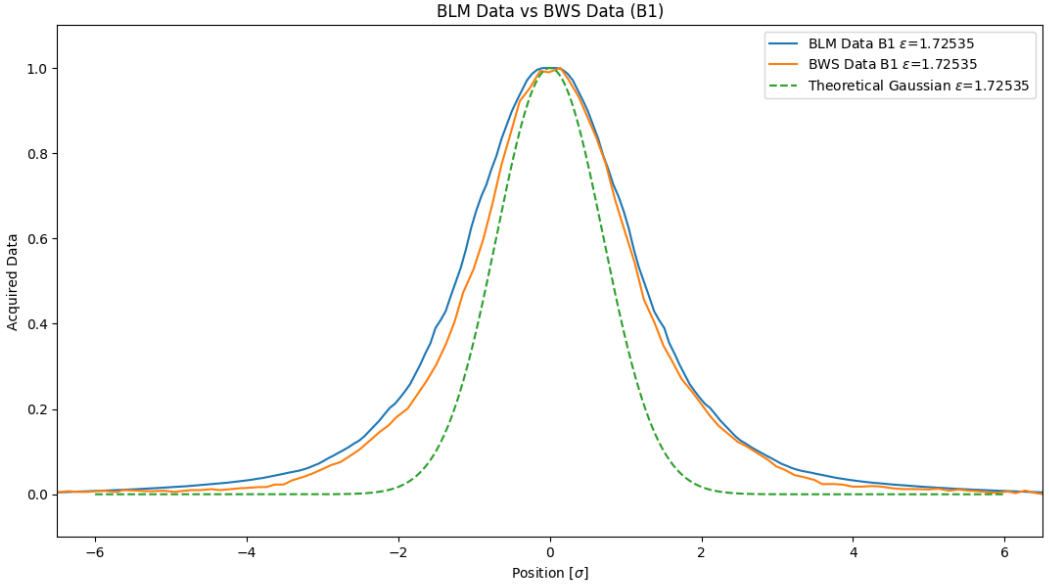


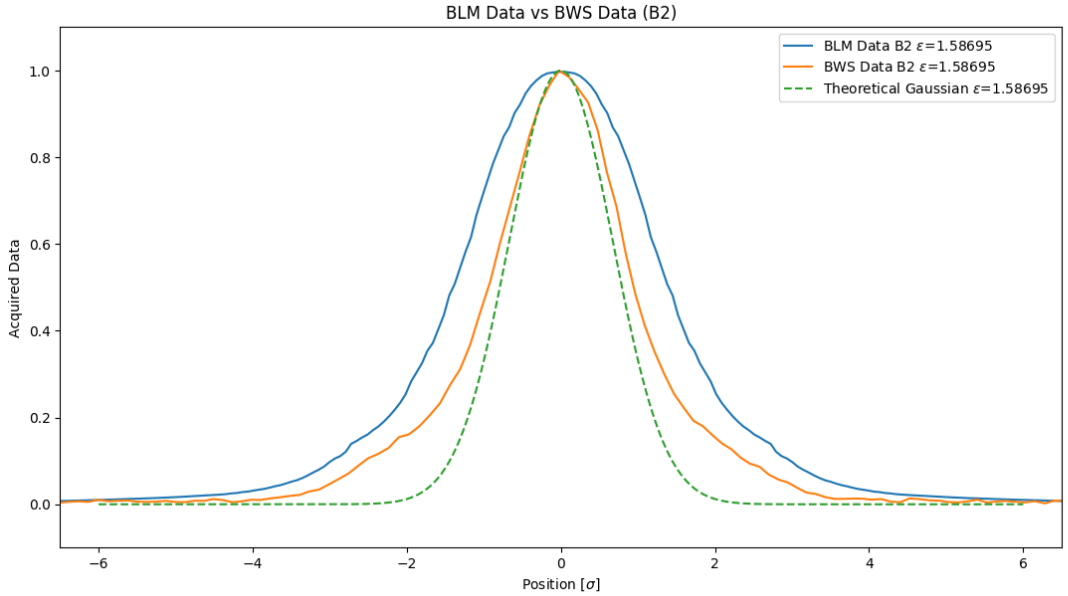


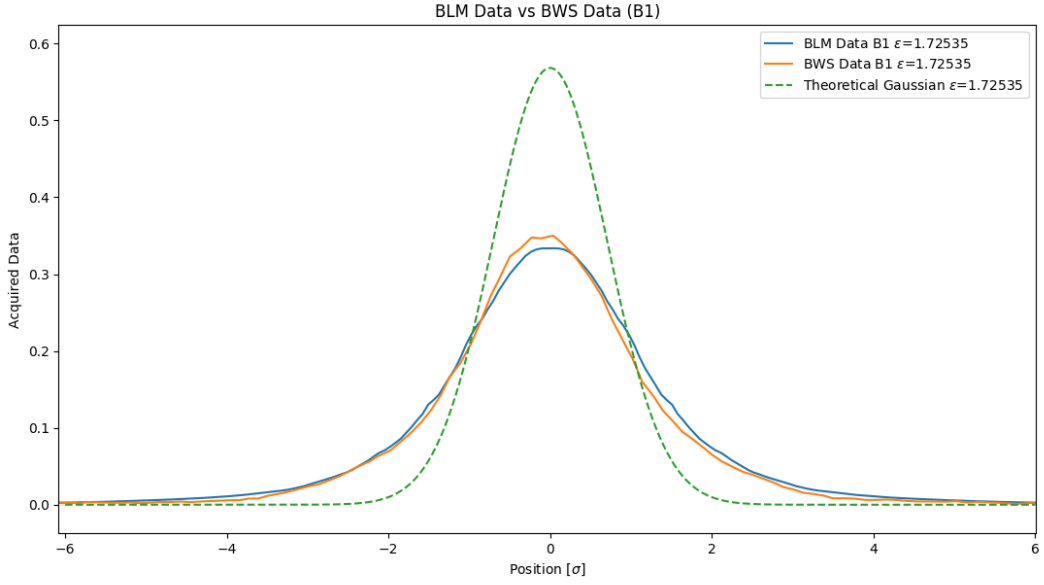


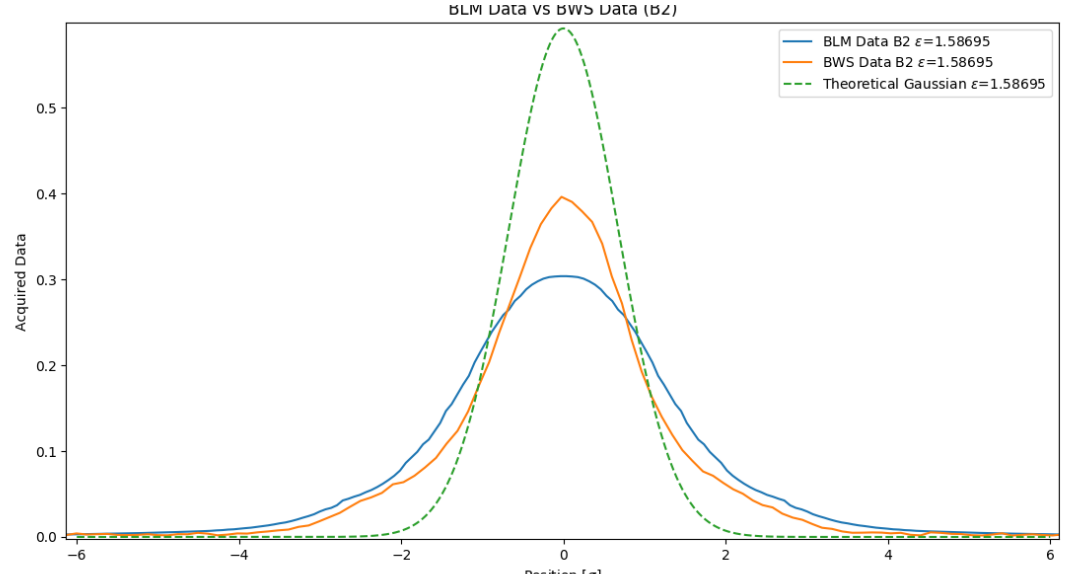


Appendix


BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.72535
BWS Data B1 ε=1.72535
Theoretical Gaussian ε=1.72535
Acquired Data
Position [σ]

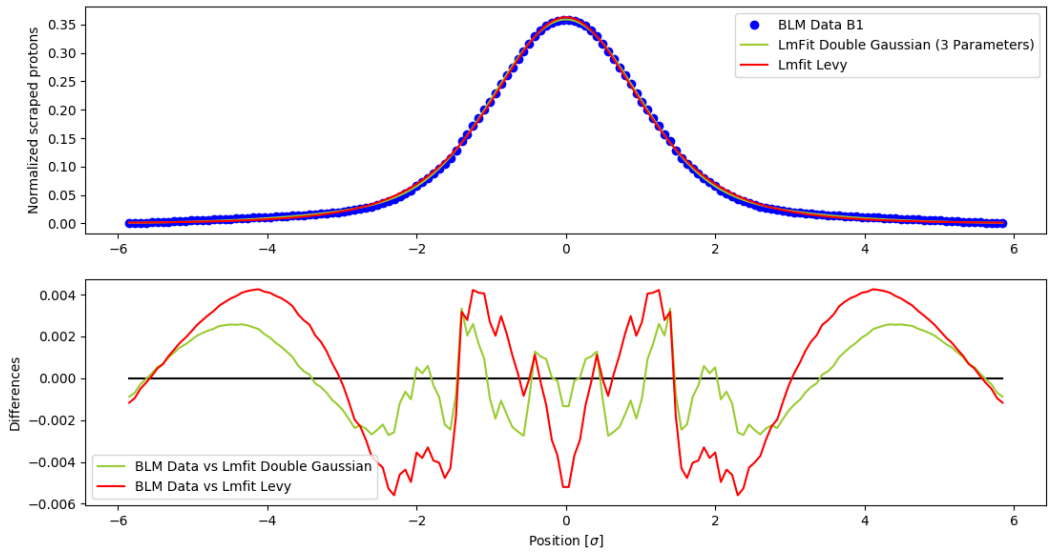

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.58695
BWS Data B2 ε=1.58695
Theoretical Gaussian ε=1.58695
Acquired Data
Position [σ]

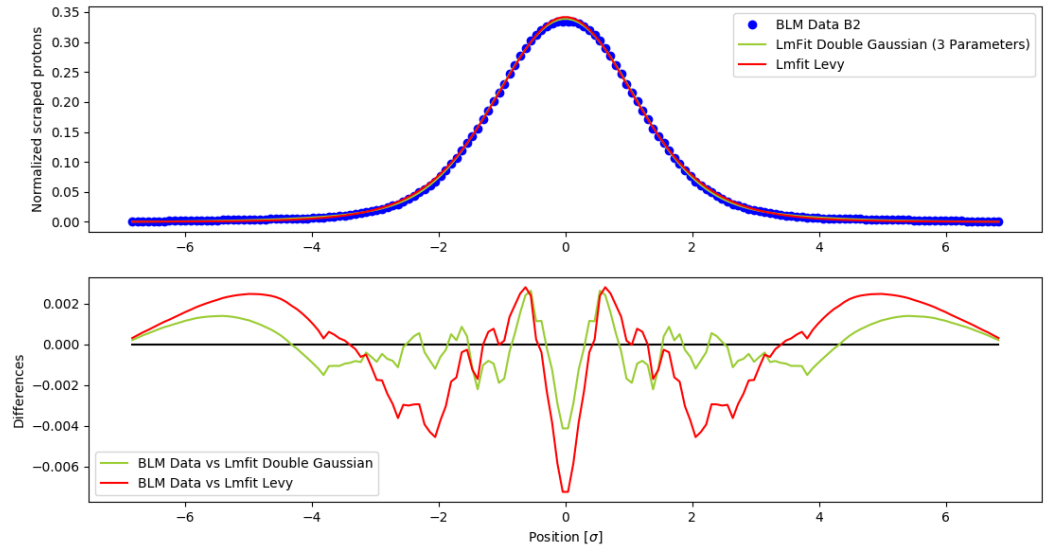

BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.72535
BWS Data B1 ε=1.72535
Theoretical Gaussian ε=1.72535
Acquired Data
Position [σ]

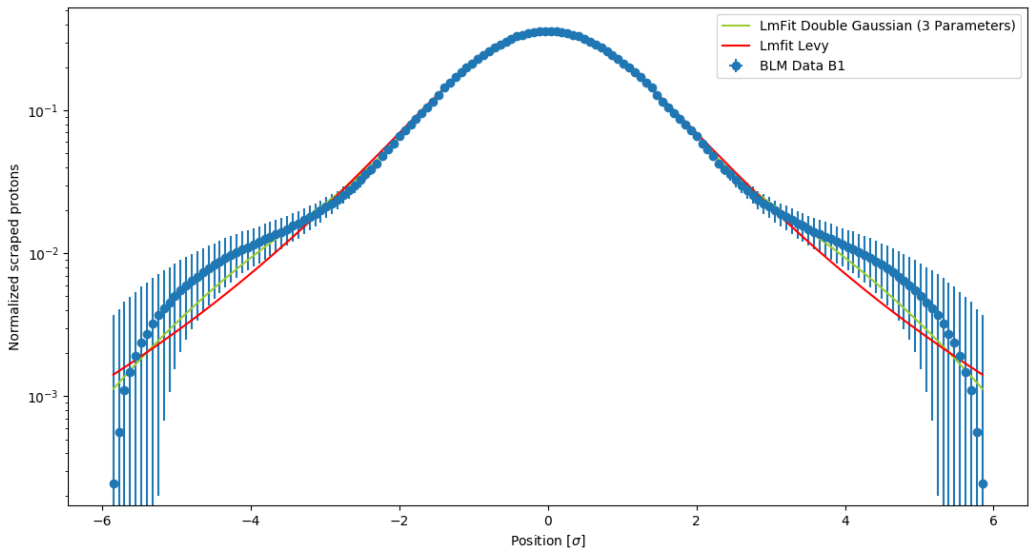

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.58695
BWS Data B2 ε=1.58695
Theoretical Gaussian ε=1.58695
Acquired Data

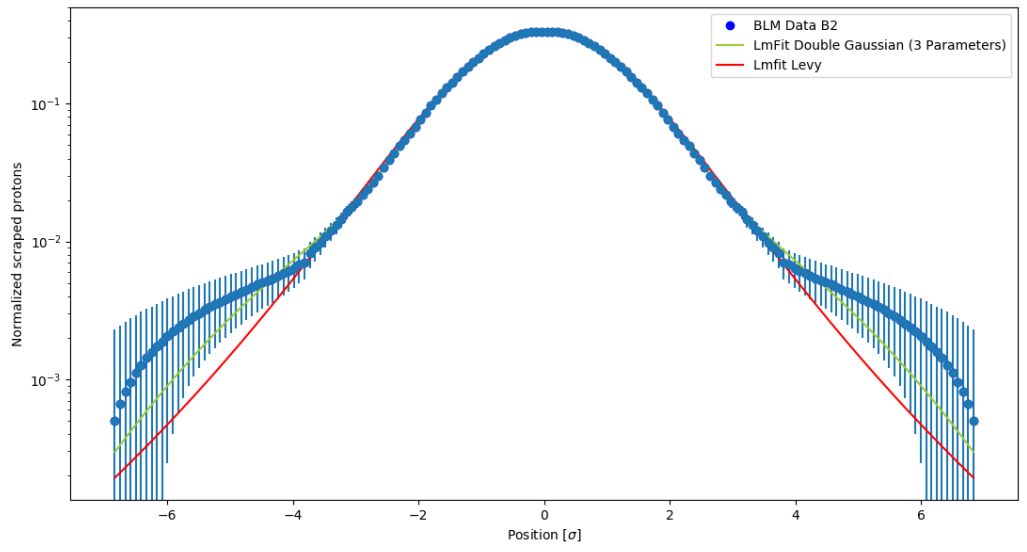
Appendix

Vertical scraping 3

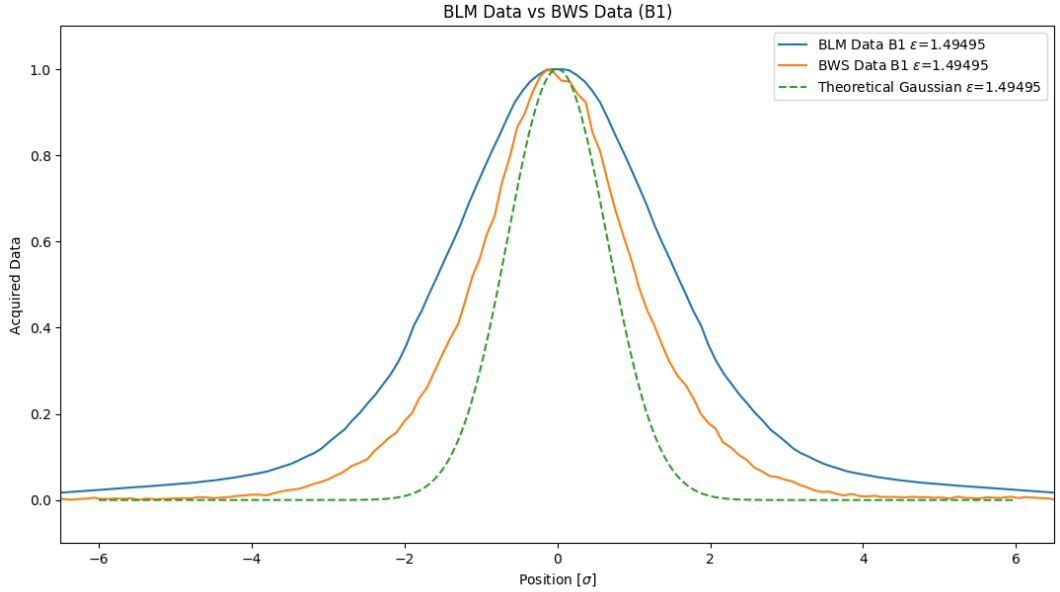


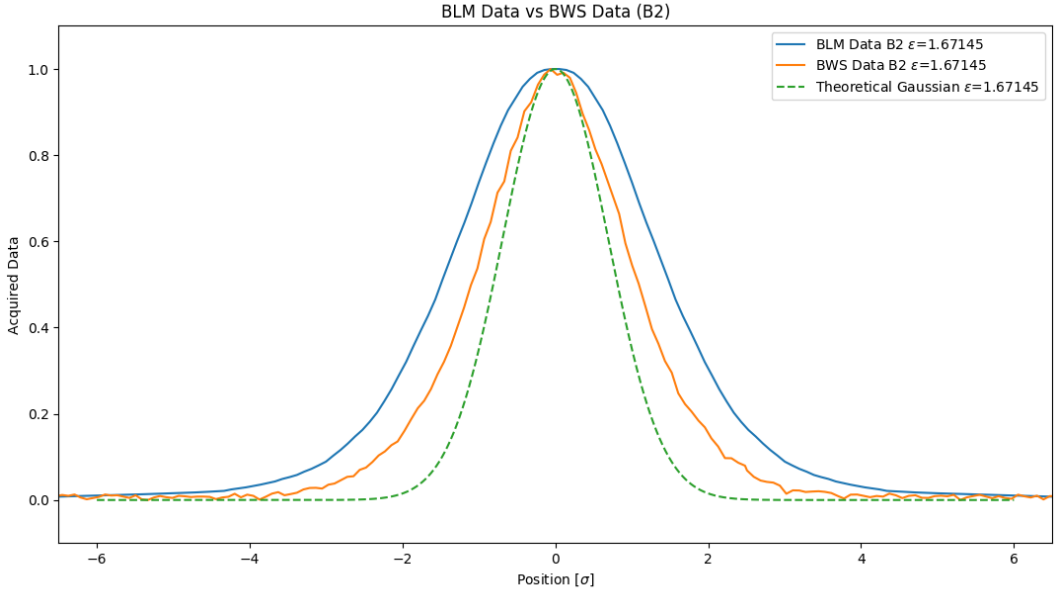


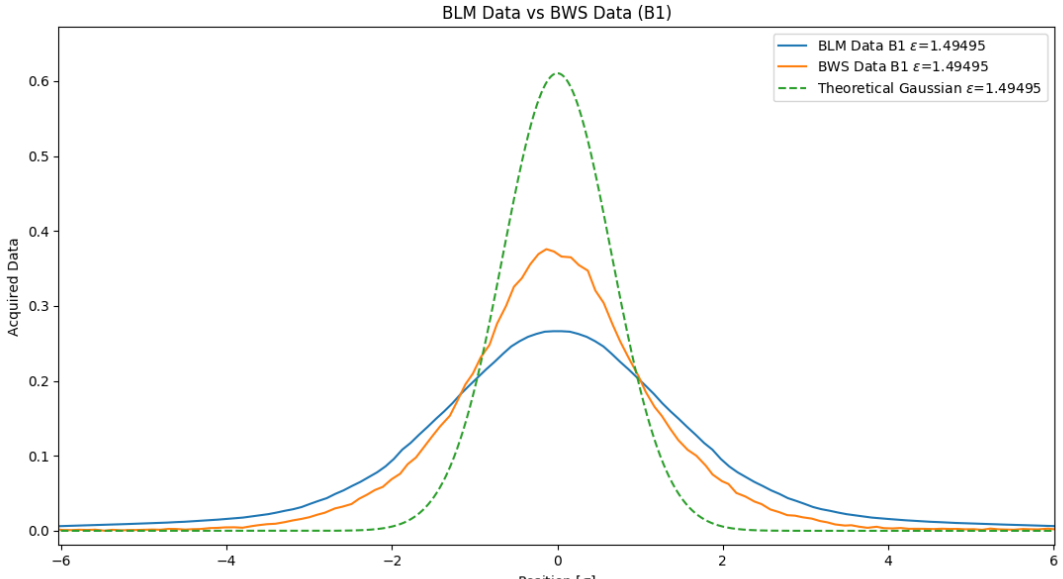


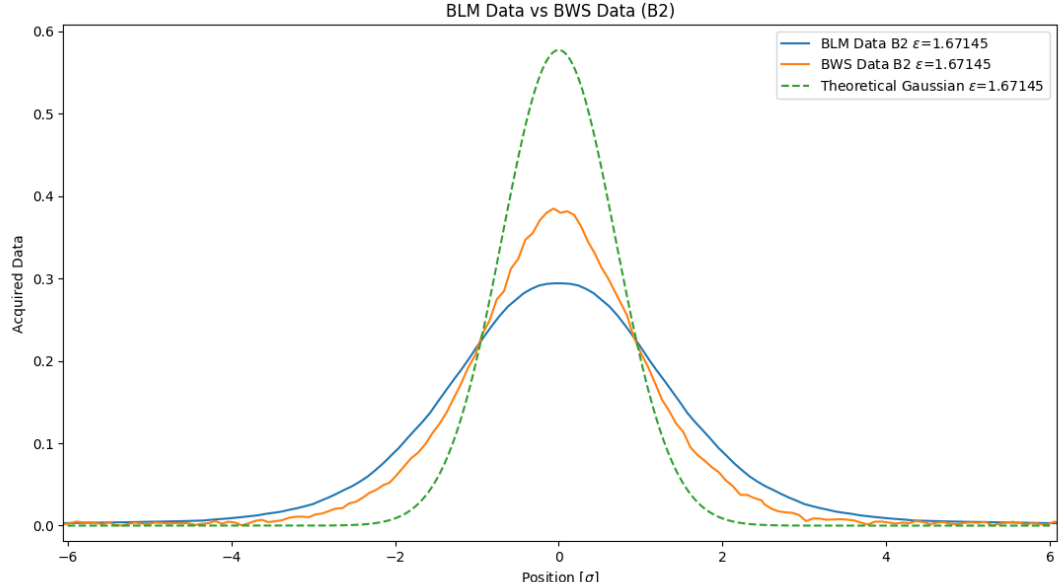


Appendix


BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.49495
BWS Data B1 ε=1.49495
Theoretical Gaussian ε=1.49495
Acquired Data
Position [σ]

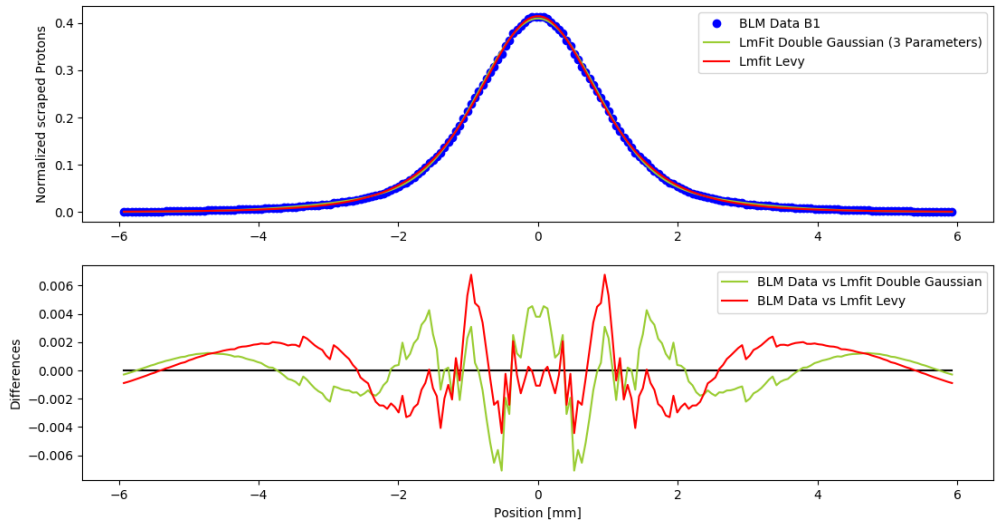

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.67145
BWS Data B2 ε=1.67145
Theoretical Gaussian ε=1.67145
Acquired Data
Position [σ]

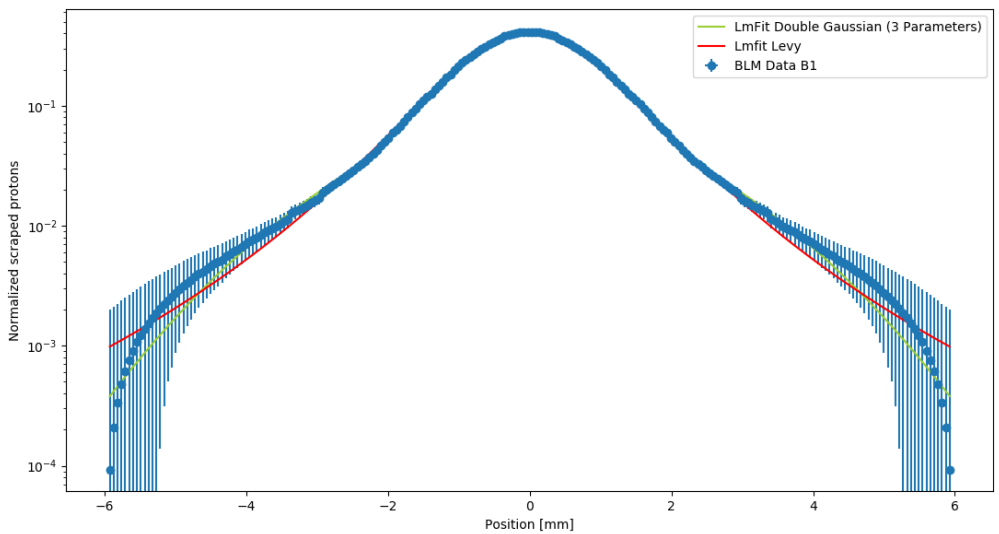

BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.49495
BWS Data B1 ε=1.49495
Theoretical Gaussian ε=1.49495
Acquired Data
Position [σ]

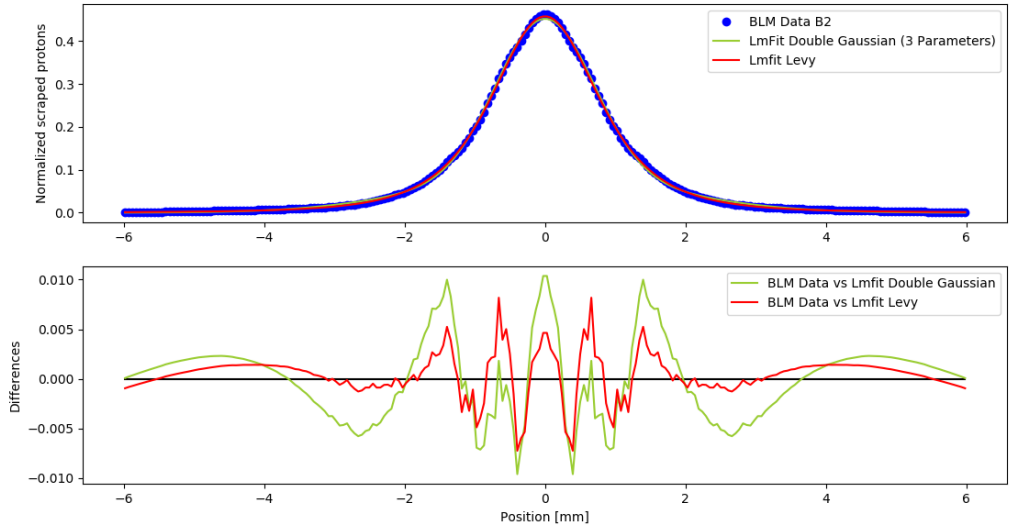

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.67145
BWS Data B2 ε=1.67145
Theoretical Gaussian ε=1.67145
Acquired Data
Position [σ]

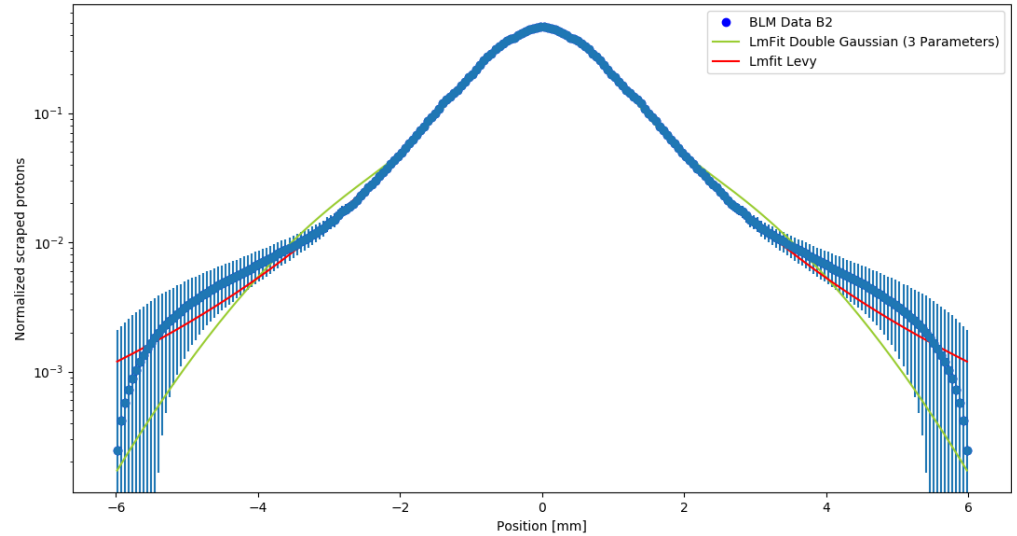
Appendix

Horizontal scraping 4









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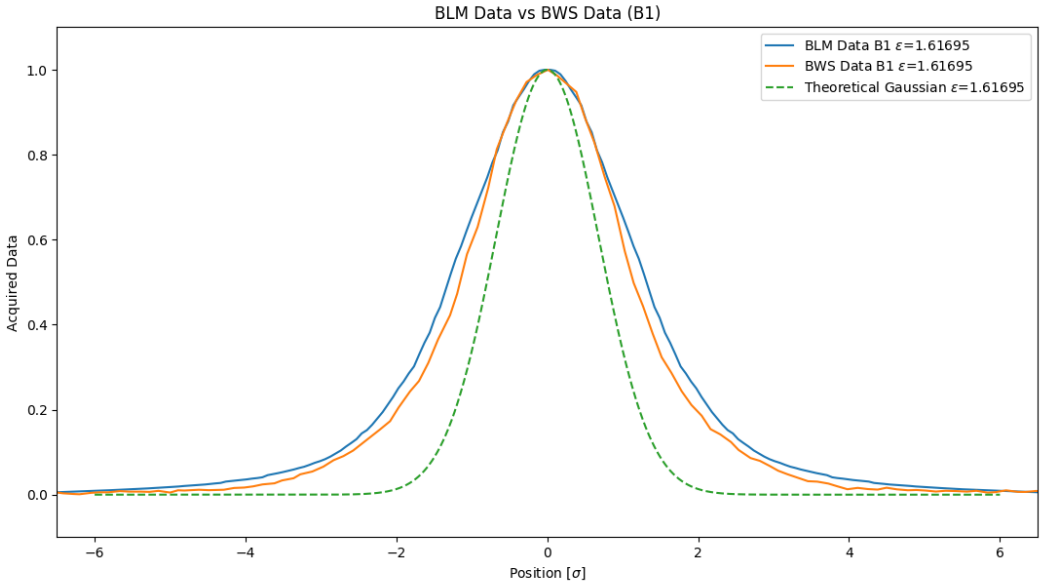
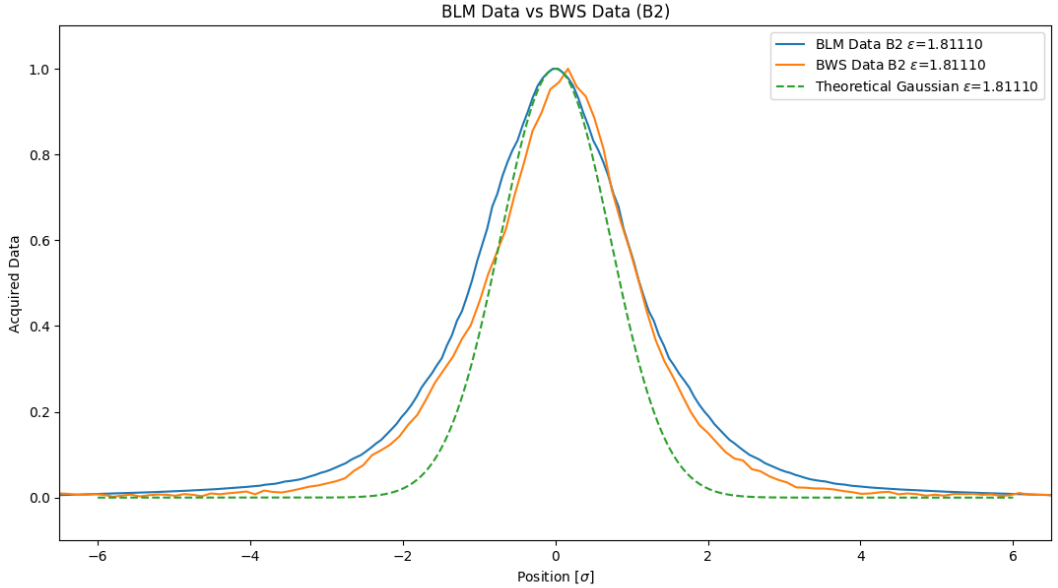
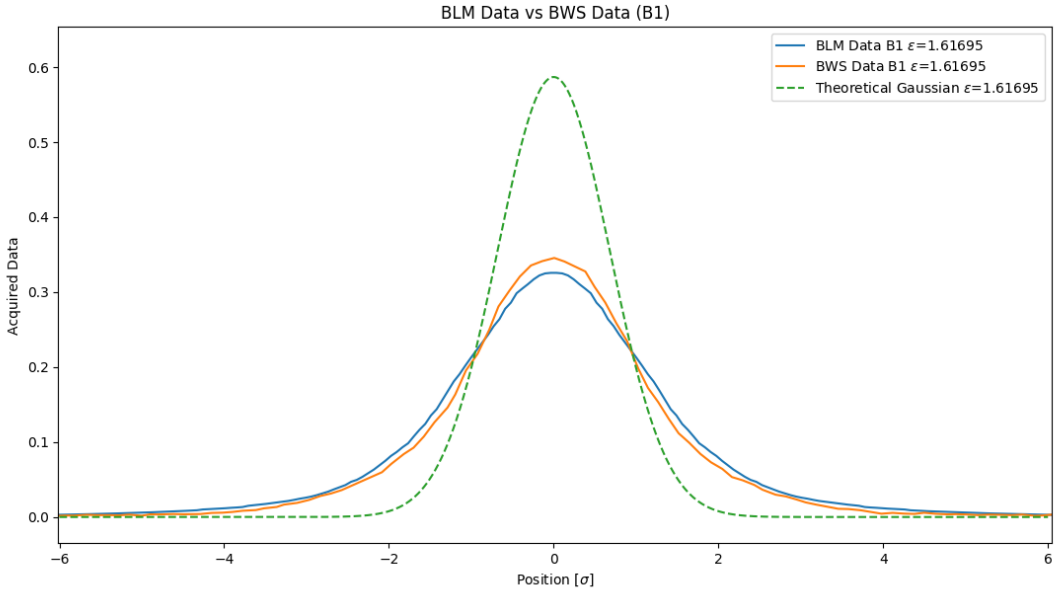
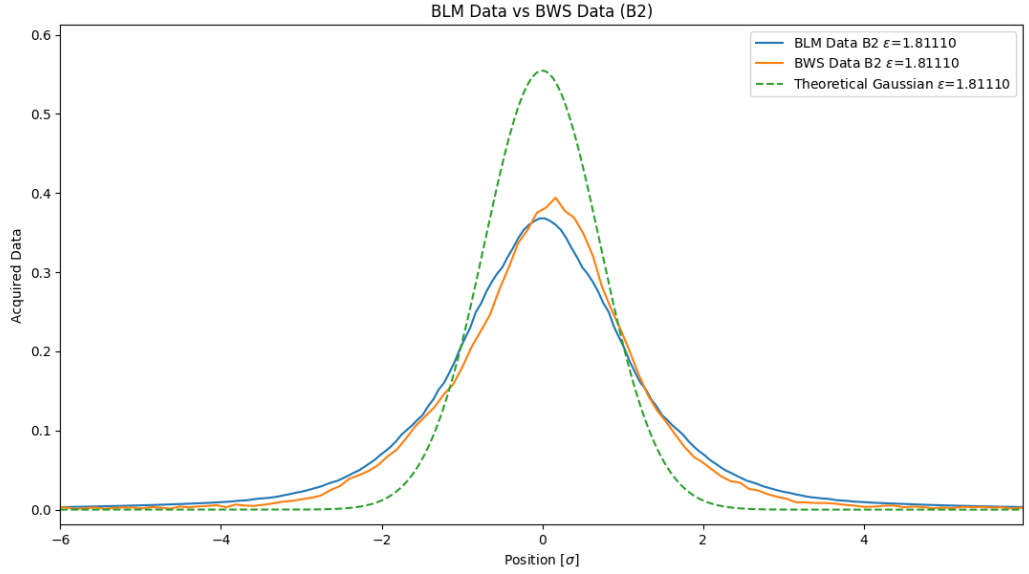

BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.61695
BWS Data B1 ε=1.61695
Theoretical Gaussian ε=1.61695
Acquired Data
Position [σ]

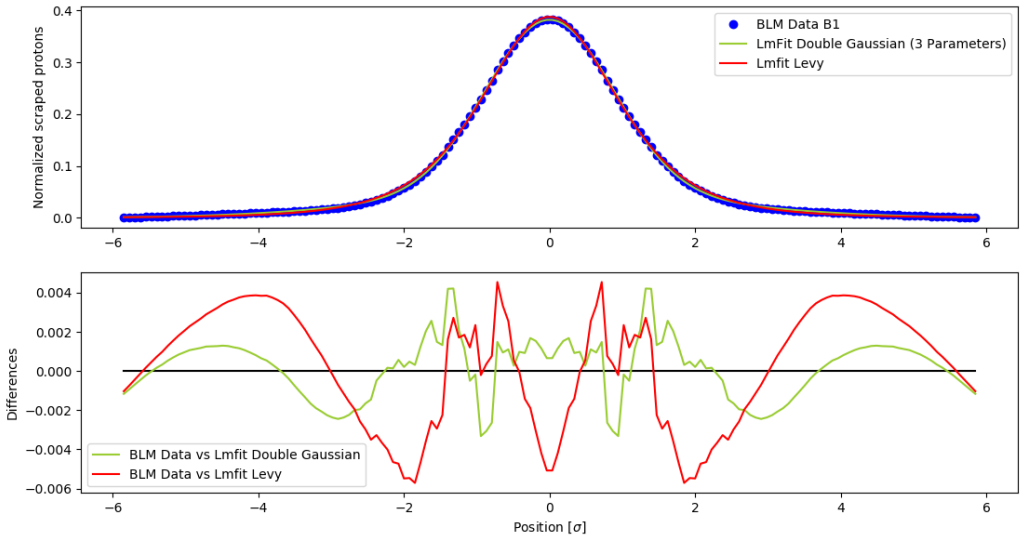

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.81110
BWS Data B2 ε=1.81110
Theoretical Gaussian ε=1.81110
Acquired Data
Position [σ]

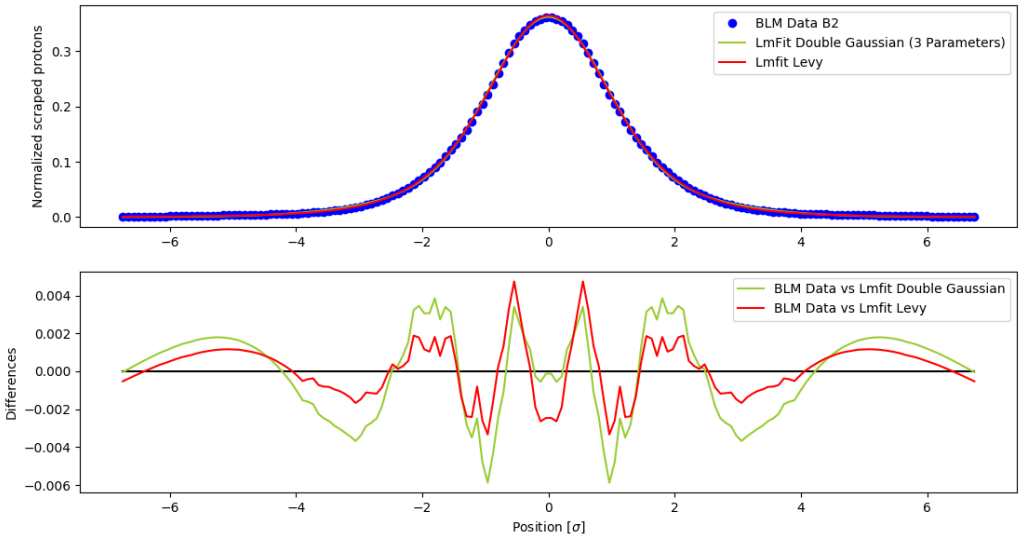

BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.61695
BWS Data B1 ε=1.61695
Theoretical Gaussian ε=1.61695
Acquired Data
Position [σ]

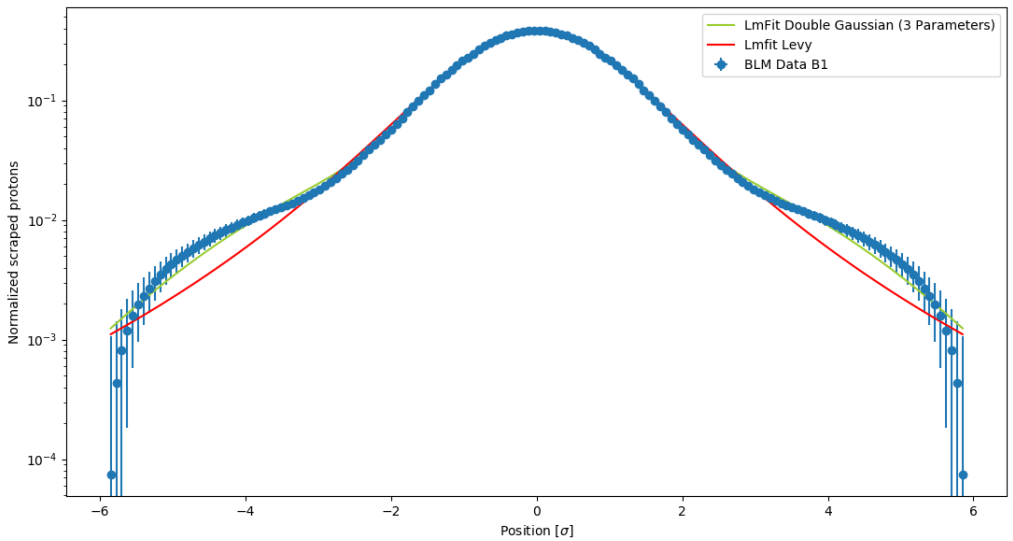

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.81110
BWS Data B2 ε=1.81110
Theoretical Gaussian ε=1.81110
Acquired Data
Position [σ]

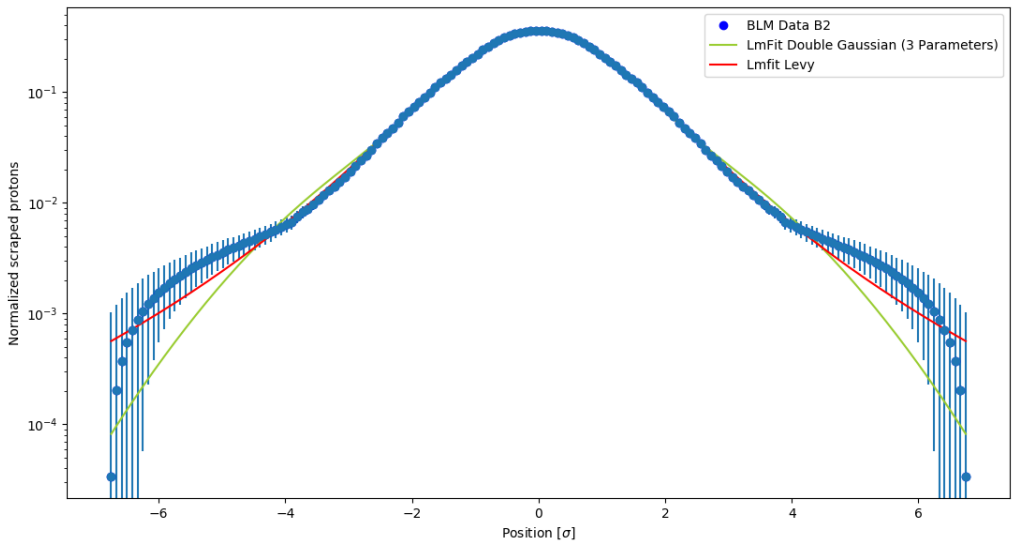
Appendix

Vertical scraping 5

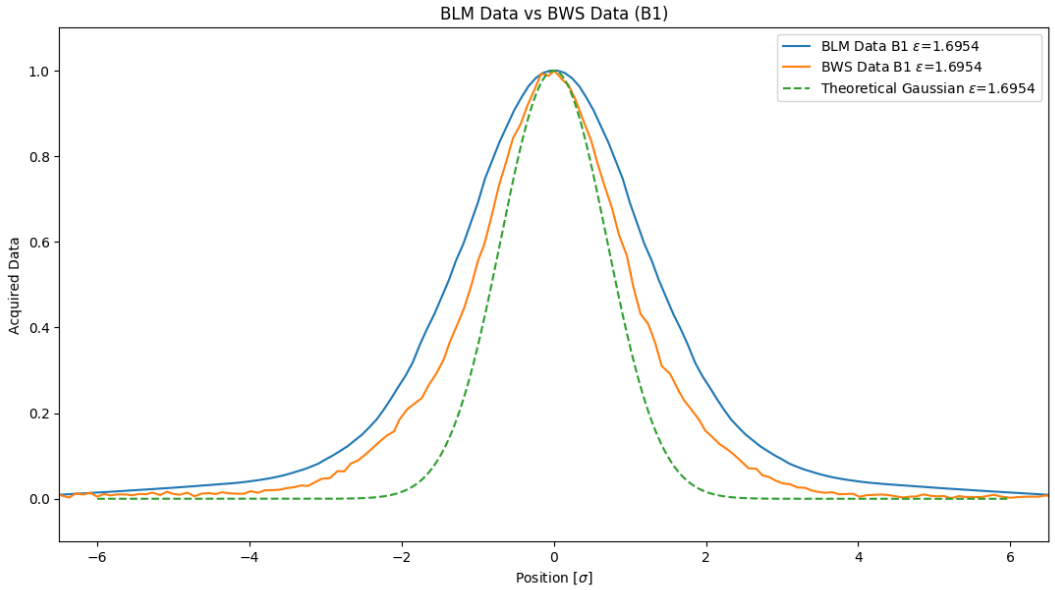


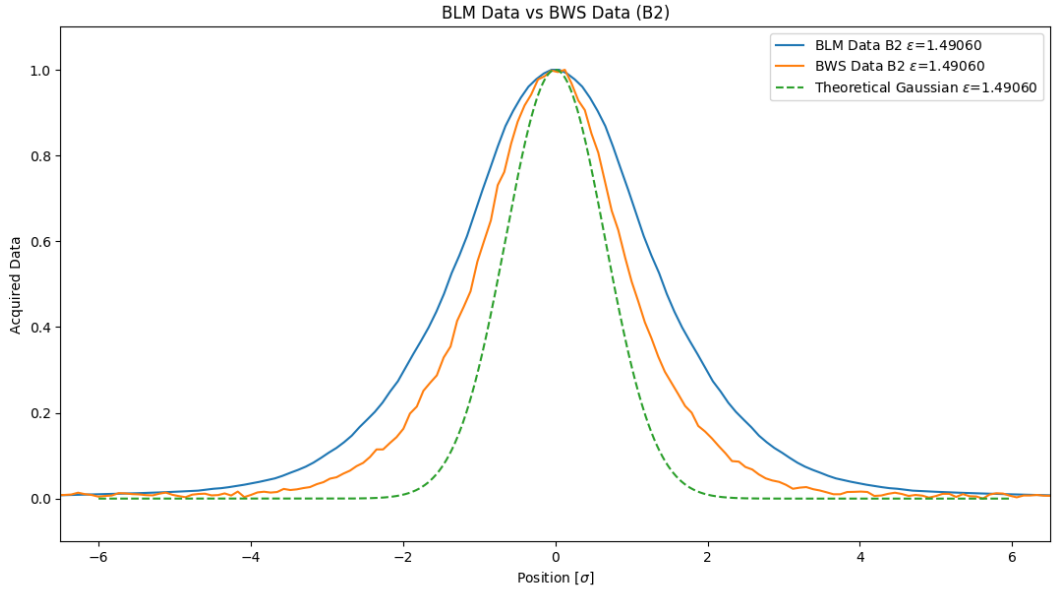


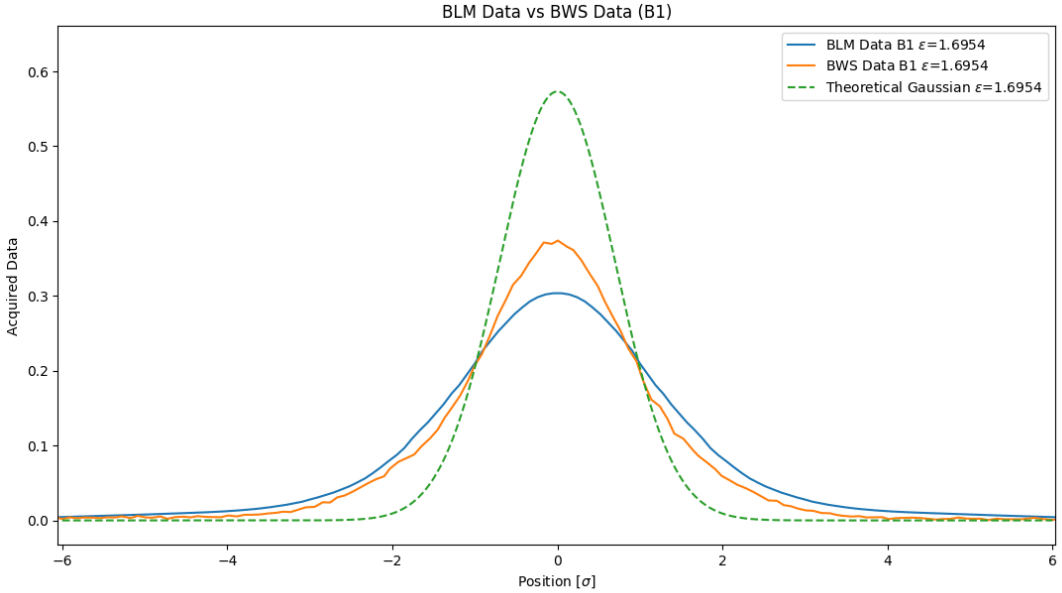


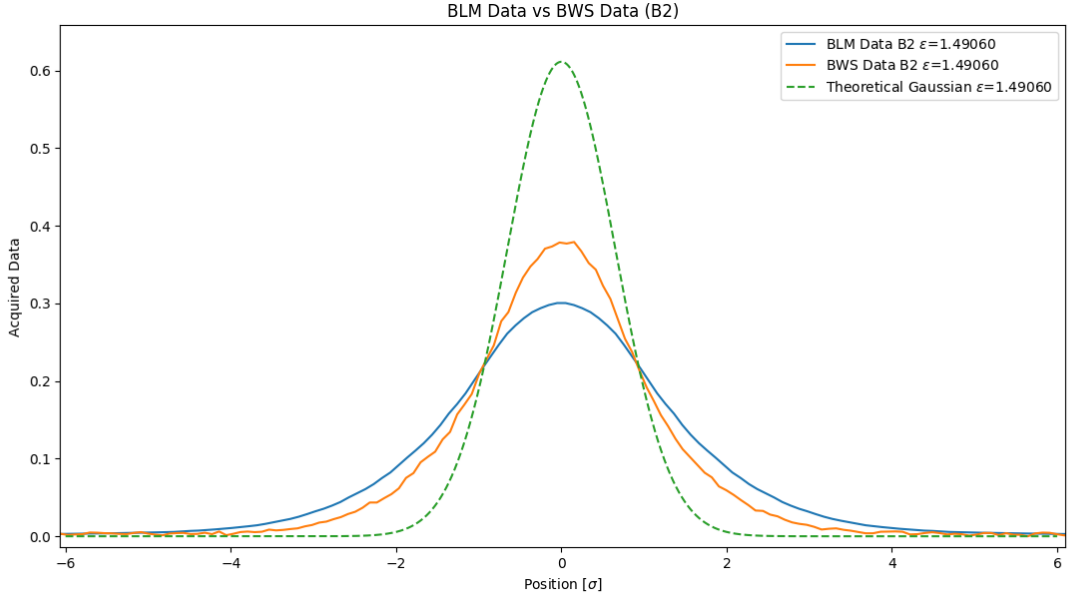


Appendix


BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.6954
BWS Data B1 ε=1.6954
Theoretical Gaussian ε=1.6954
Acquired Data
Position [σ]

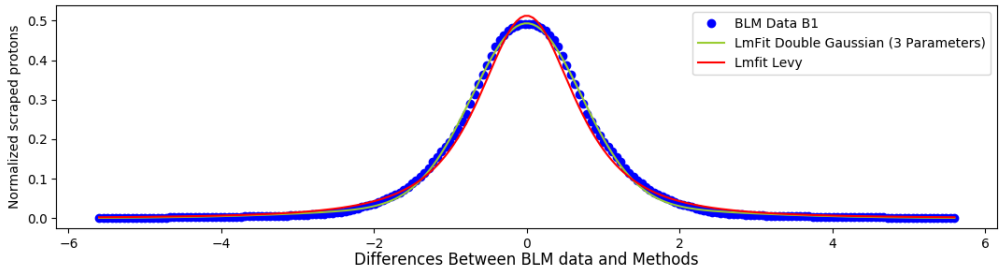

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.49060
BWS Data B2 ε=1.49060
Theoretical Gaussian ε=1.49060
Acquired Data
Position [σ]

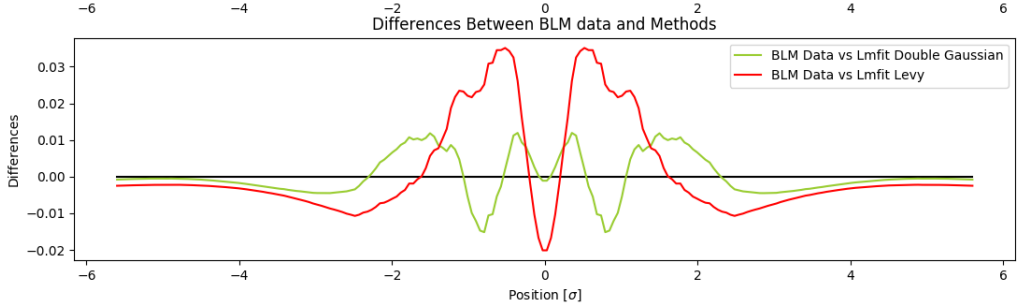

BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.6954
BWS Data B1 ε=1.6954
Theoretical Gaussian ε=1.6954
Acquired Data
Position [σ]

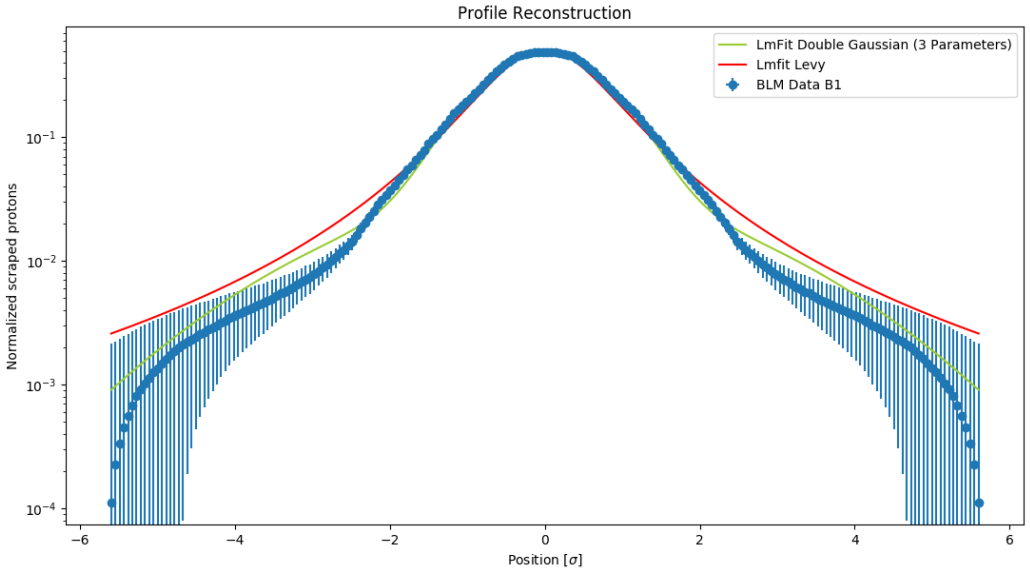

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.49060
BWS Data B2 ε=1.49060
Theoretical Gaussian ε=1.49060
Acquired Data
Position [σ]

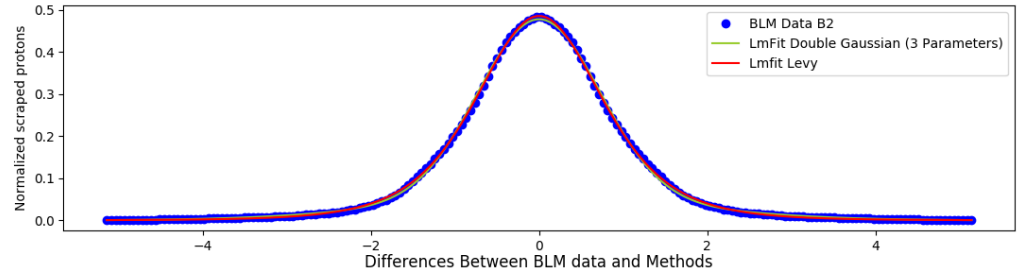
Appendix

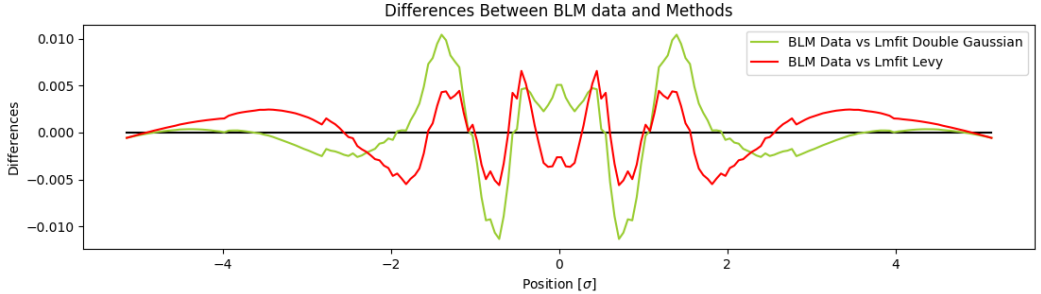
Skew scraping 6

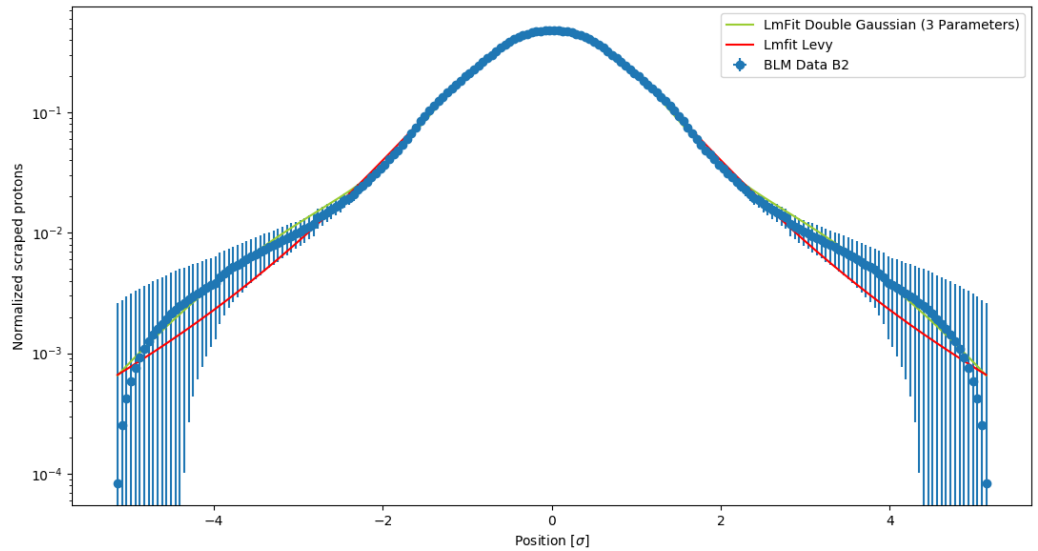






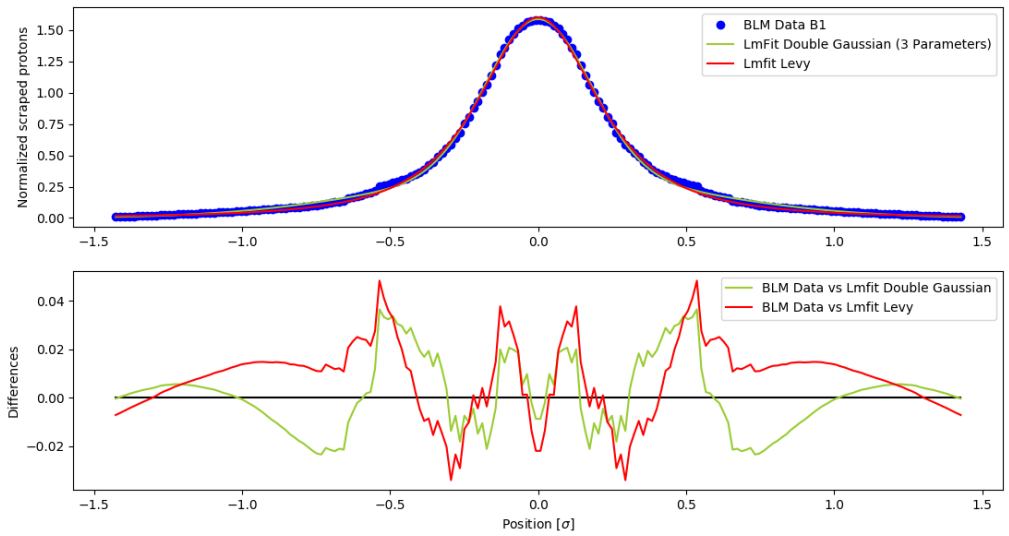


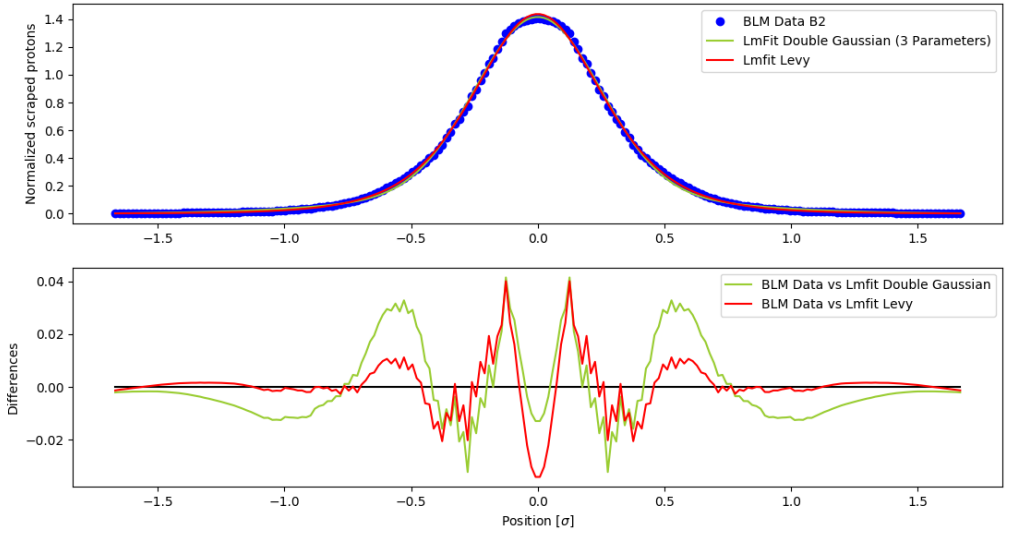


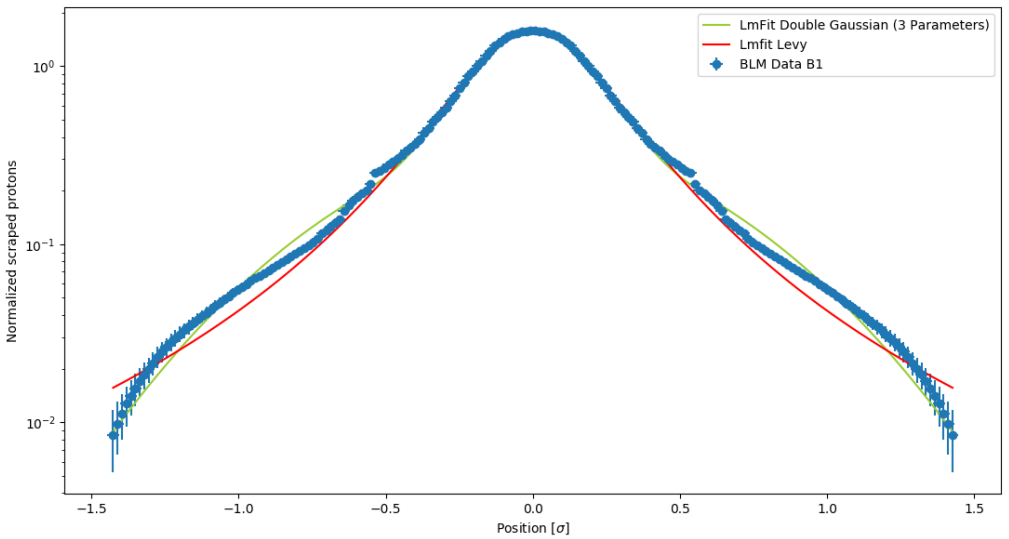


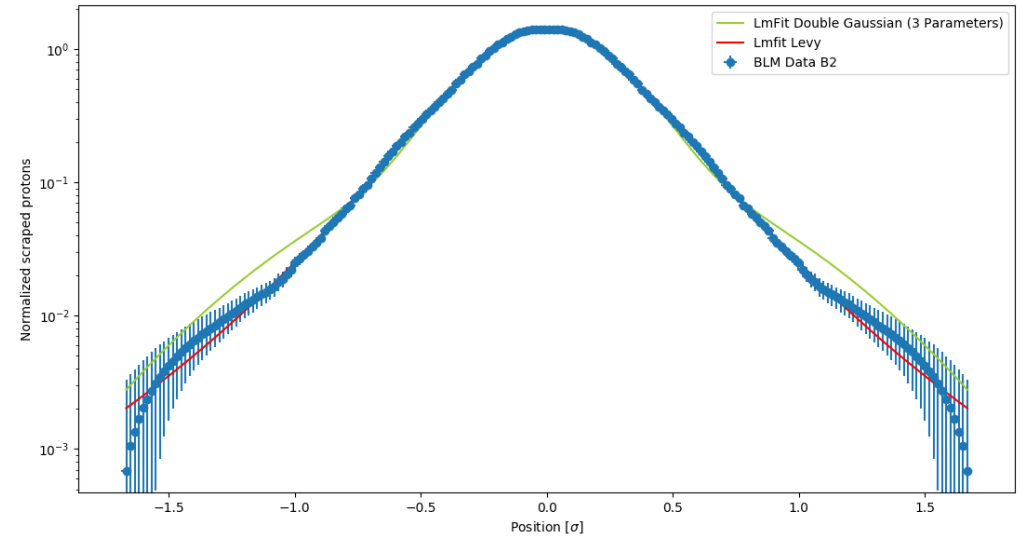
Appendix

Vertical scraping 7

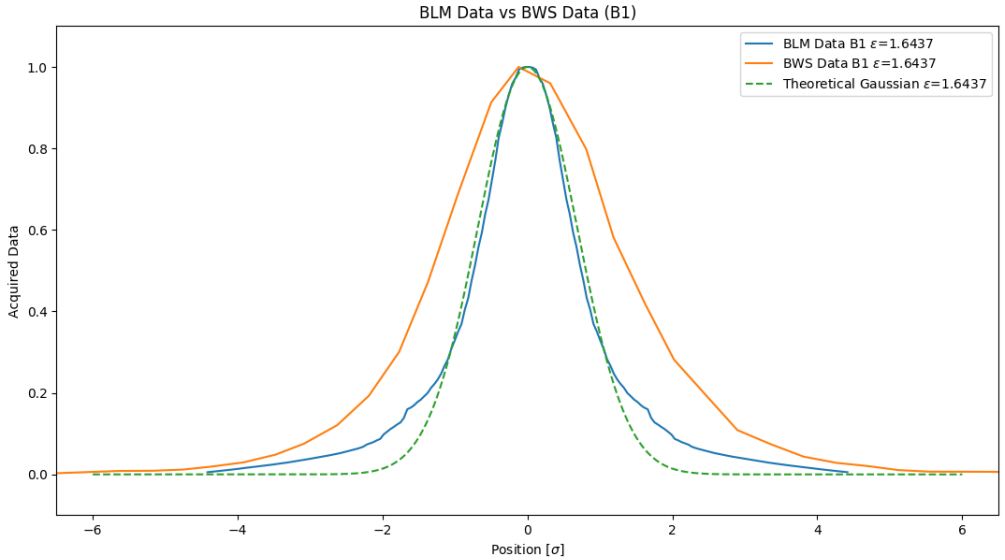


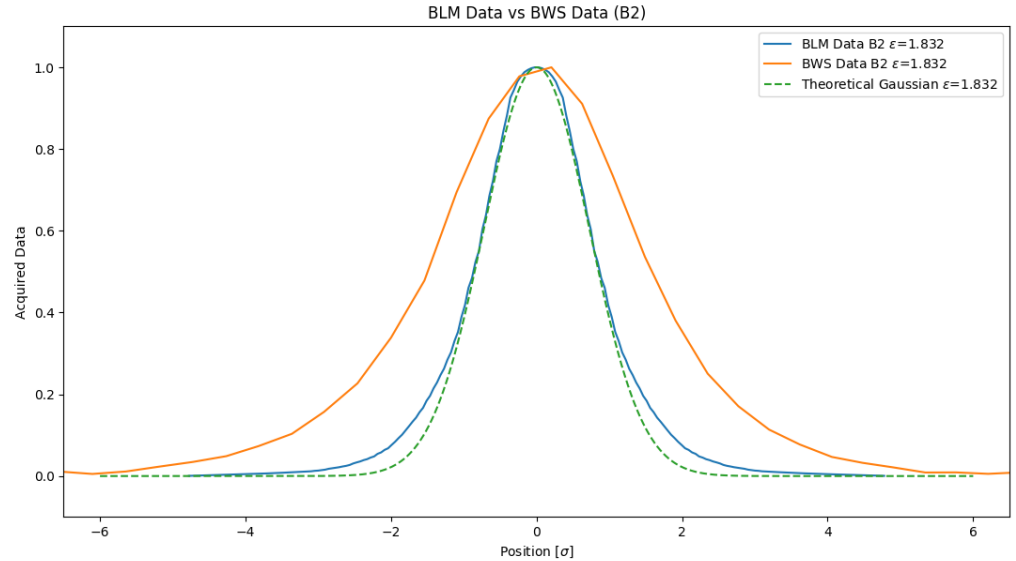


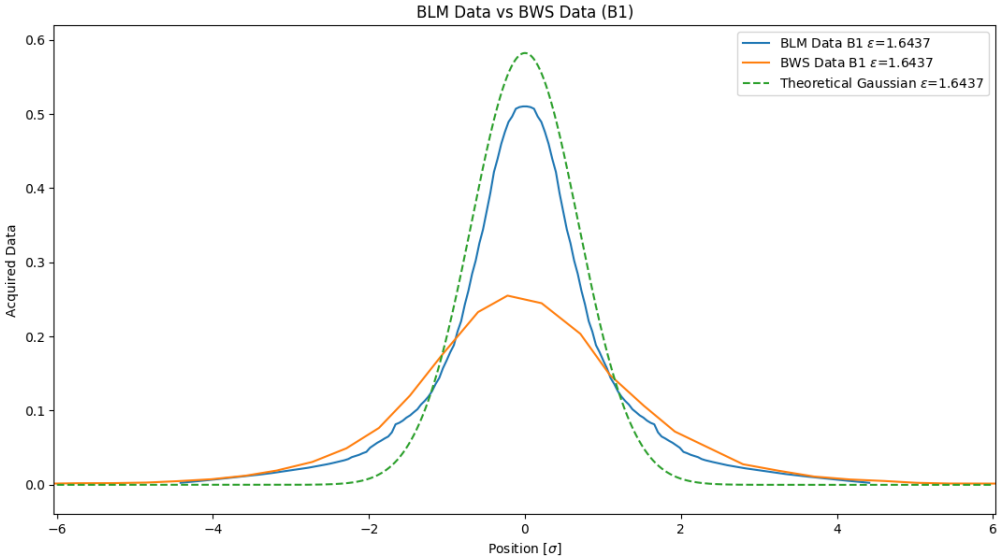


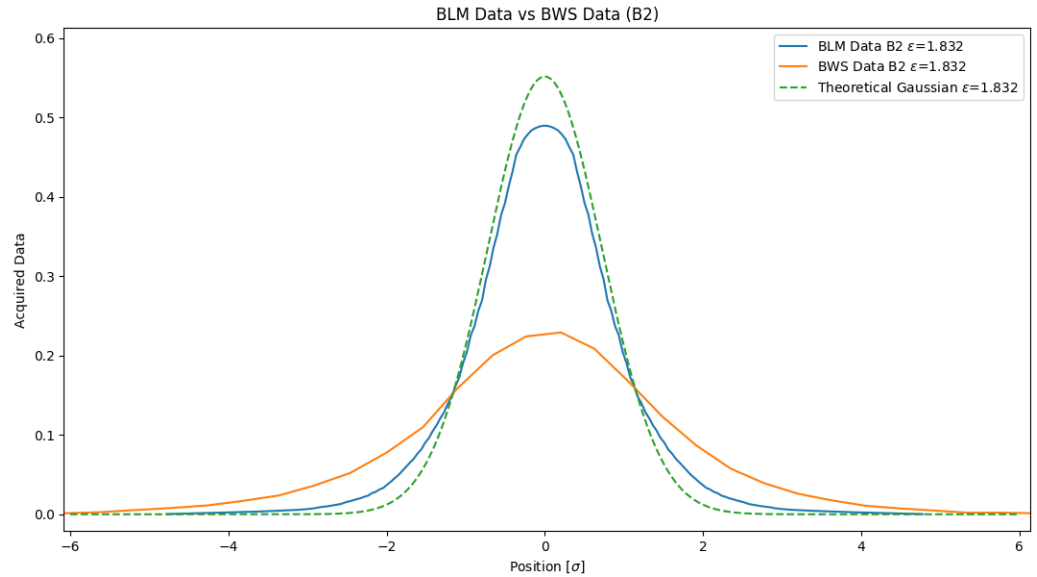


Appendix


BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.6437
BWS Data B1 ε=1.6437
Theoretical Gaussian ε=1.6437
Acquired Data
Position [σ]

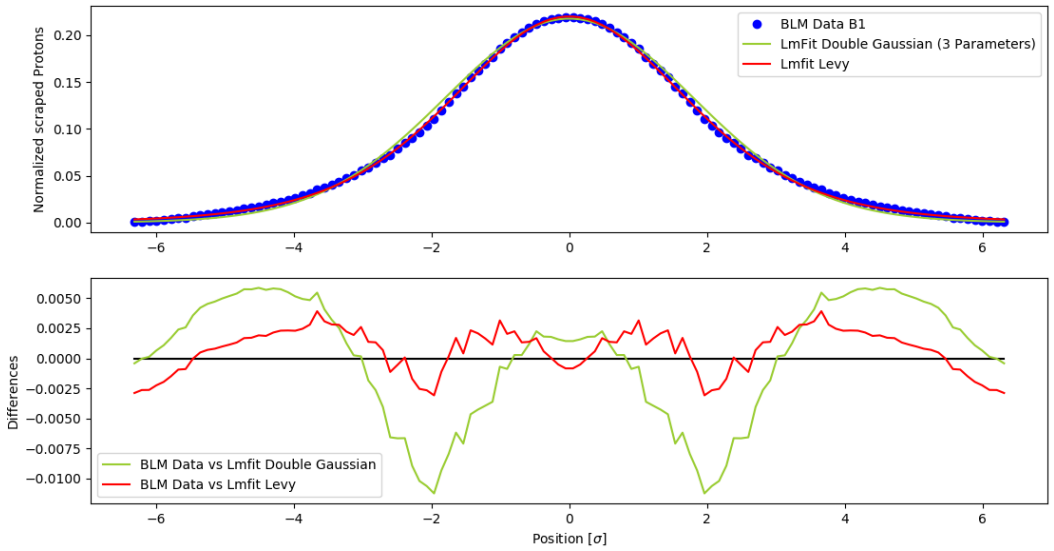

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.832
BWS Data B2 ε=1.832
Theoretical Gaussian ε=1.832
Acquired Data
Position [σ]

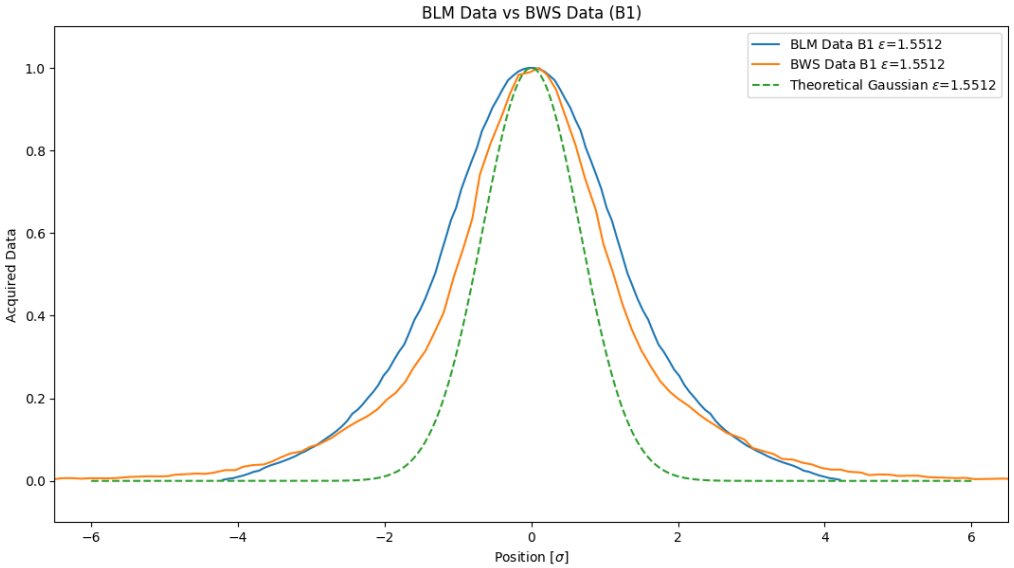

BLM Data vs BWS Data (B1)
BLM Data B1 ε=1.6437
BWS Data B1 ε=1.6437
Theoretical Gaussian ε=1.6437
Acquired Data
Position [σ]

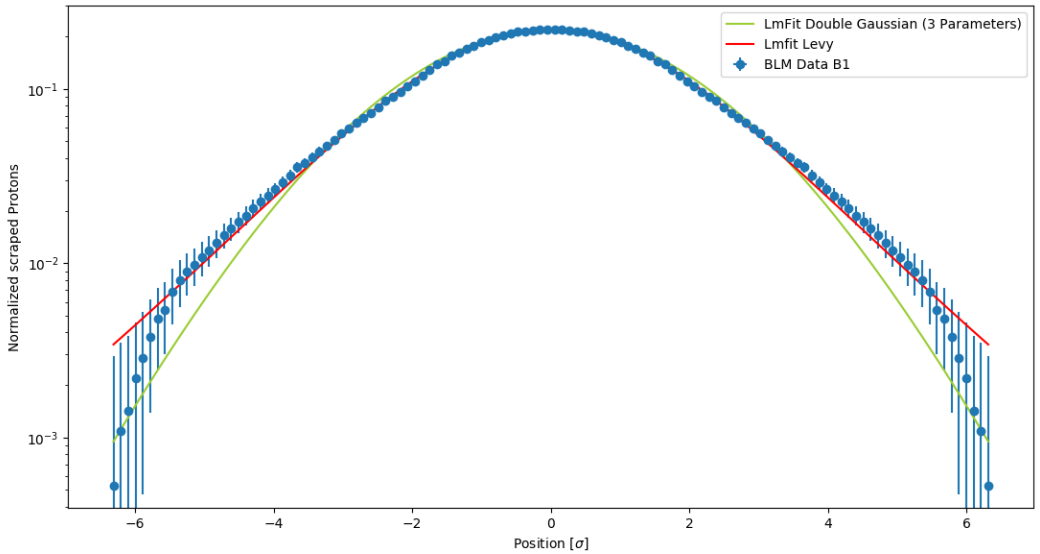

BLM Data vs BWS Data (B2)
BLM Data B2 ε=1.832
BWS Data B2 ε=1.832
Theoretical Gaussian ε=1.832
Acquired Data
Position [σ]

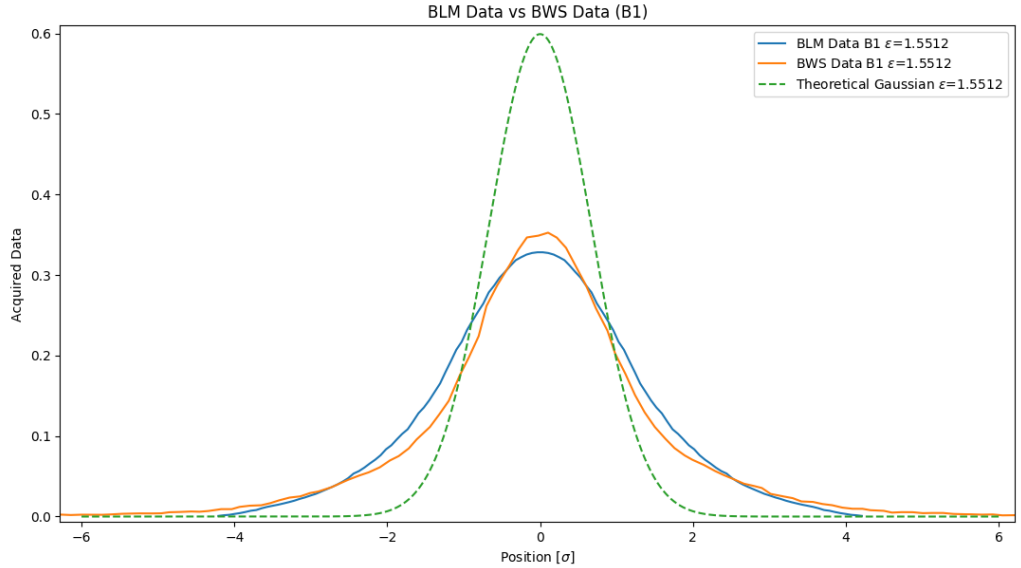
Appendix

Horizontal scraping 1 MD



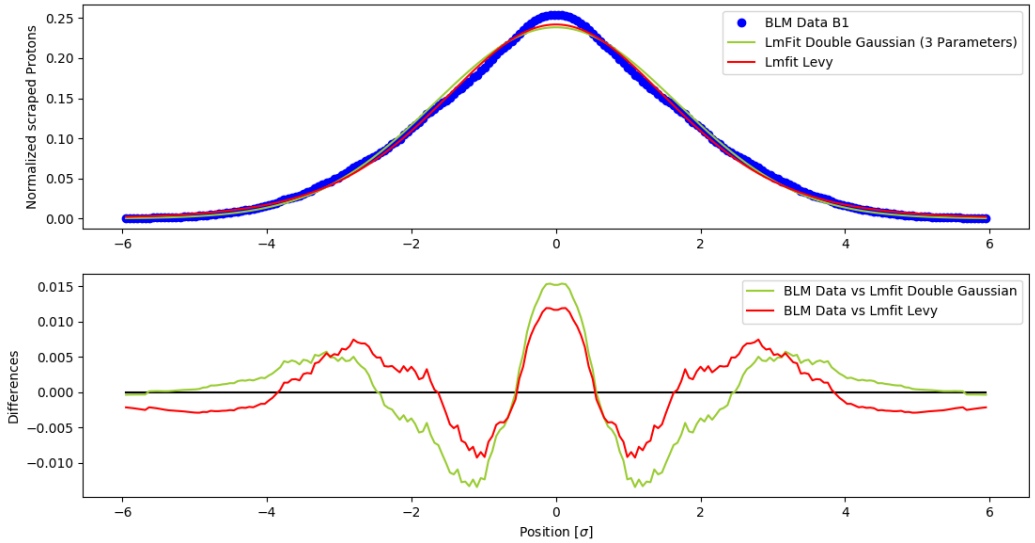


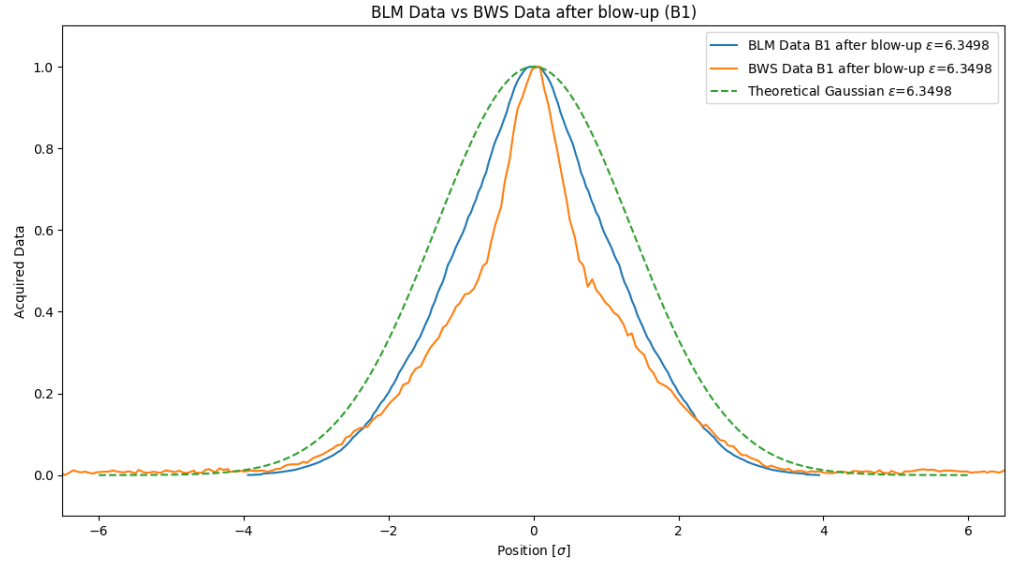


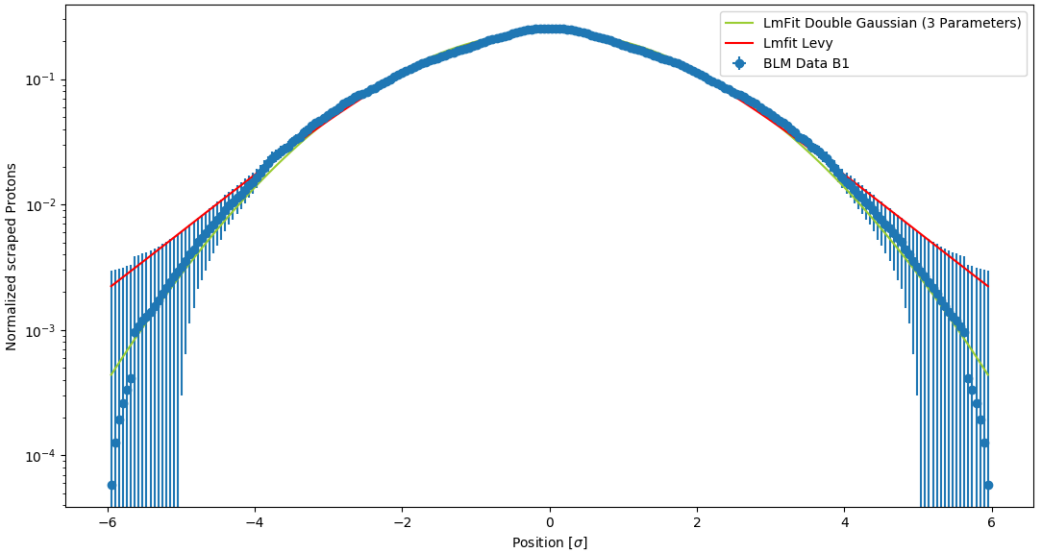


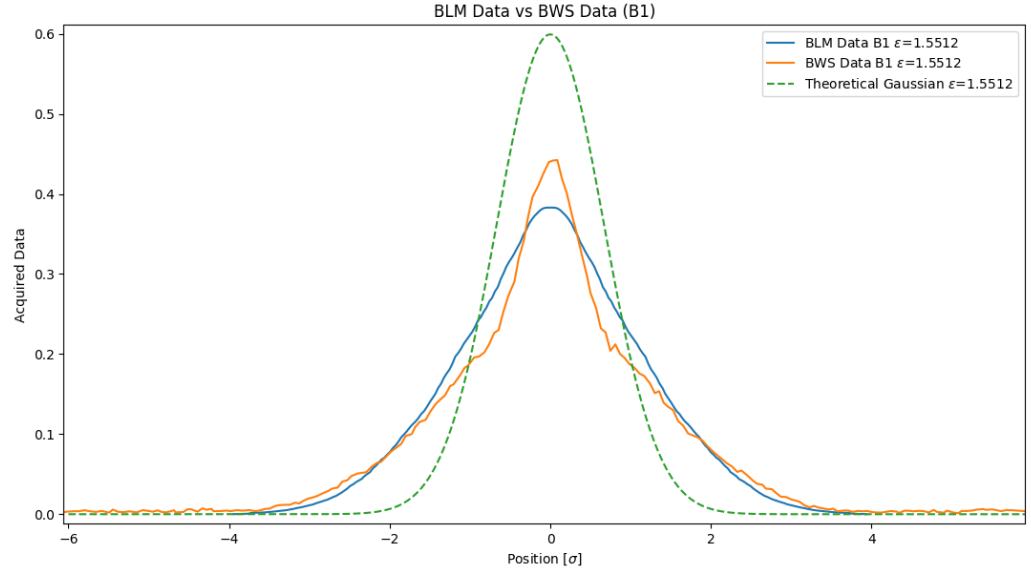
Appendix

Horizontal scraping 2 MD



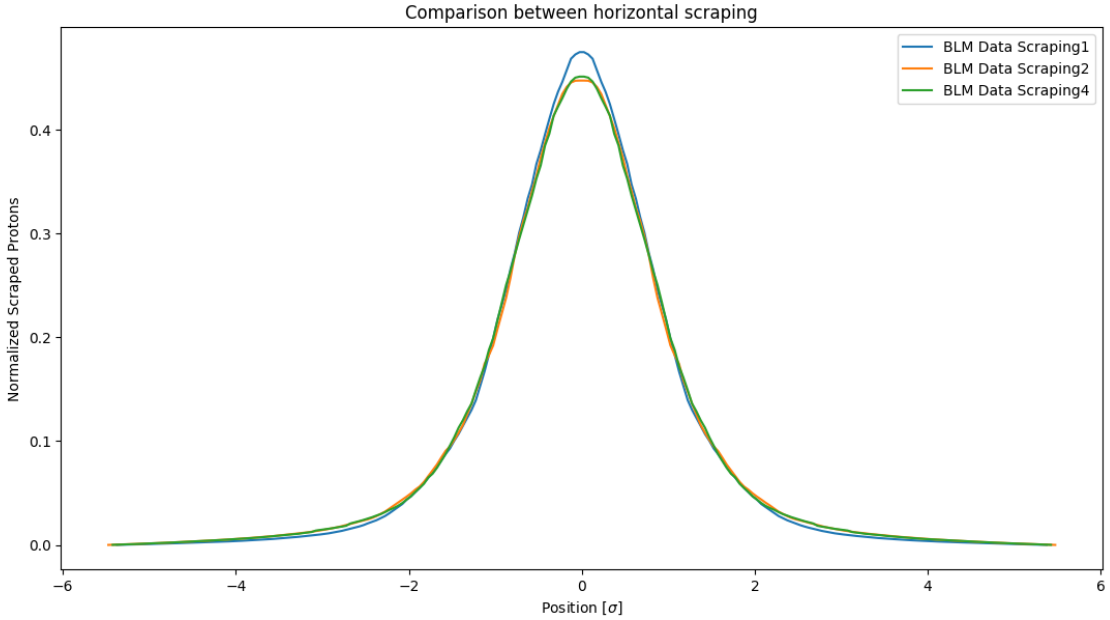




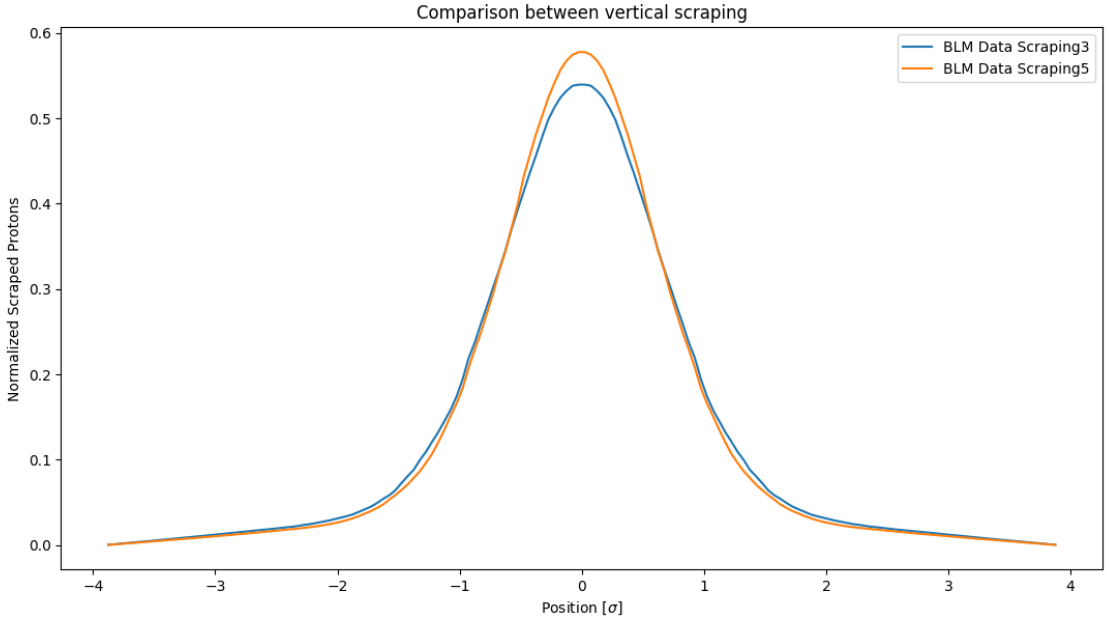


Appendix

Overlap scraping 30/07/2018



Horizontal plane



Vertical plane

Emittance and Sigma (1/2)

- The BSRT has several degrees of freedom for optimization, but the measure of beam size and emittance are still biased by intrinsic lmitiation
- The accurancy of the BWS is of the order of 1%

HORIZONTAL

DATA ACQUISITION	SCRAPING	BEAM	BWS		BSRT	
			σ	ε	σ	ε
15/09/2017	FULL	B2	-	-	-	-
25/05/2018	TAILS	B1	0,79	1,57	0,93	1,62
		B2	0,69	1,23	1,01	1,84
30/07/2018	FULL	B1	0,87	1,9	0,97	1,8
		B2	0,81	1,73	0,99	1,58
	FULL	B1	0,83	1,72	0,93	1,62
		B2	0,78	1,58	0,99	1,15
	FULL	B1	0,8	1,61	0,91	1,52
		B2	0,83	1,81	1,02	1,04
19/09/2018	FULL	B1	0,78	1,55	0,91	1,58
		B1	1,59	6,34	1,55	5,3

BLOW-UP

Emittance and Sigma (2/2)

- The BSRT has several degrees of freedom for optimization, but the measure of beam size and emittance are still biased by intrinsic limitiation
- The accurancy of the BWS is of the order of 1%

VERTICAL

DATA ACQUISITION	SCRAPING	BEAM	BWS		BSRT	
			σ	ε	σ	ε
30/07/2018	FULL	B1	1,02	1,49	1,06	1,61
		B2	1,2	1,67	1,24	1,45
	FULL	B1	1,09	1,69	1,04	1,55
		B2	1,13	1,49	1,28	1,58
	FULL	B1	0,28	1,64	-	-
		B2	0,33	1,83	0,46	1,72

SKEW

DATA ACQUISITION	SCRAPING	BEAM	BWS		BSRT	
			σ	ε	σ	ε
30/07/2018	FULL	B1	0,97	-	0,9	-
		B2	0,99	-	1,05	-