Update on the Modeling and Measurements of Bunch Profiles at the LHC

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Acknowledgements: T. Argyropoulos, M. Fitterer, N. Karastathis,
K. Skoufaris, G. Trad, P. Zisopoulos

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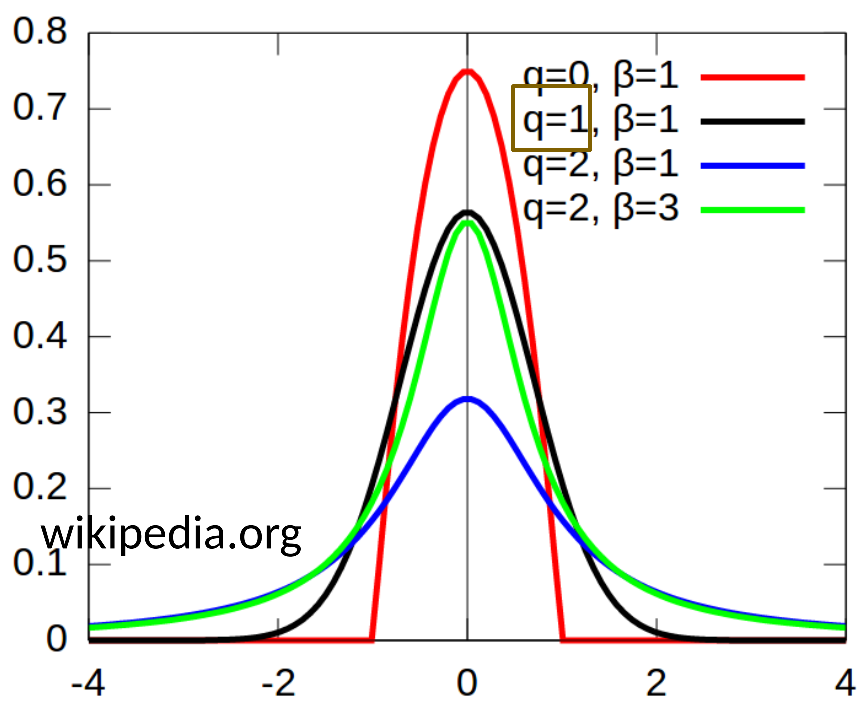
The q Gaussian distribution

In many cases, the bunch profiles in the LHC, appear to have **heavier tails than a normal distribution**. In order to describe them more accurately, the **q-Gaussian function**, is used. This distribution has a probability density function given by:

$$f(x) = \frac{\sqrt{\beta}}{C_q} e_q(-\beta x^2), \; e_q(x) = [1 + (1-q)x]^{\frac{1}{1-q}}$$

In the heavy tail domain (1 < q < 3)

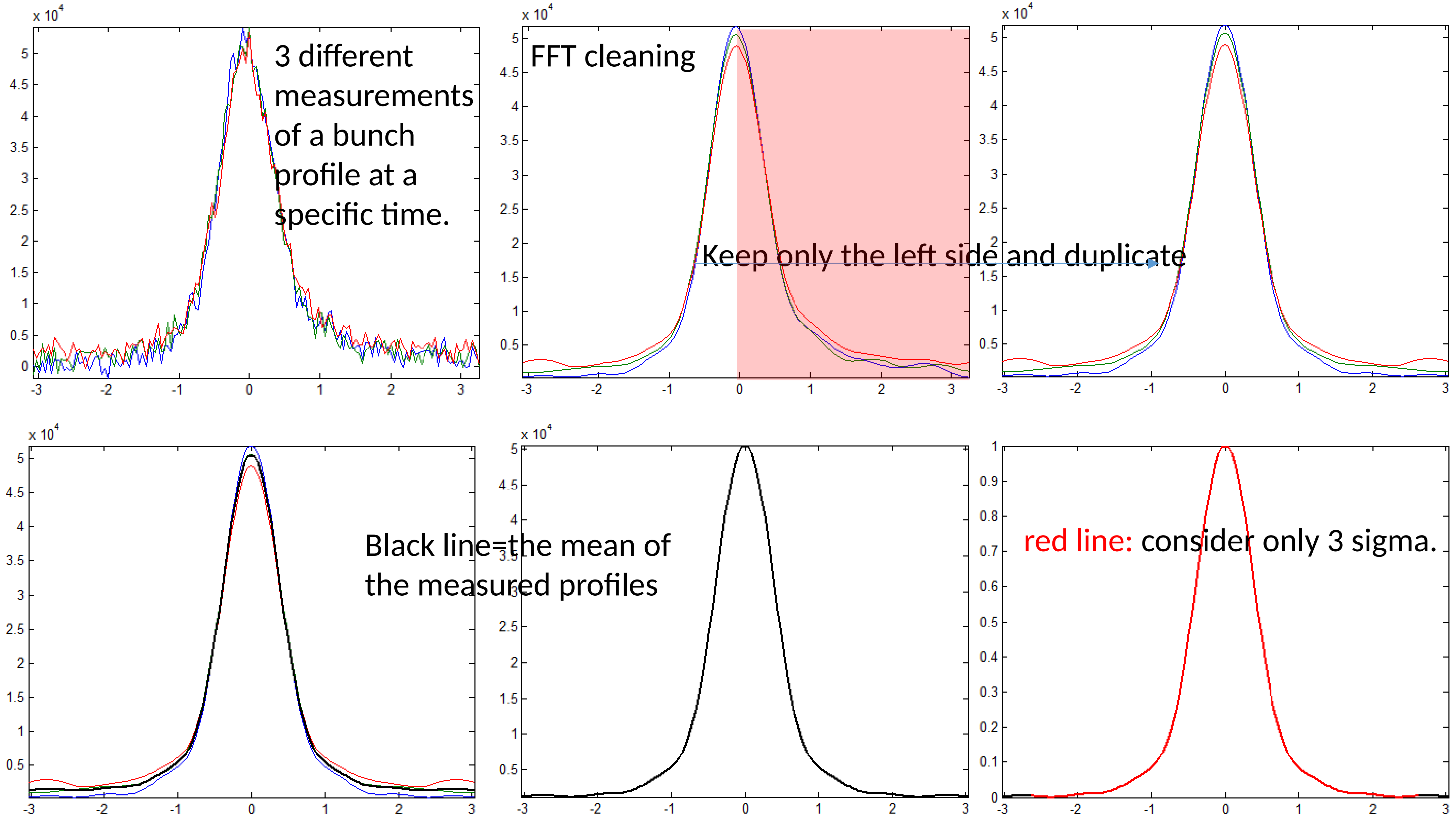
$$C_q = \sqrt{\pi}\Gamma\left(\frac{3-q}{2(q-1)}\right) / \left[\sqrt{q-1}\Gamma\left(\frac{1}{q-1}\right)\right]$$



$$\sigma = \sqrt{\frac{1}{\beta(5-3q)}}$$

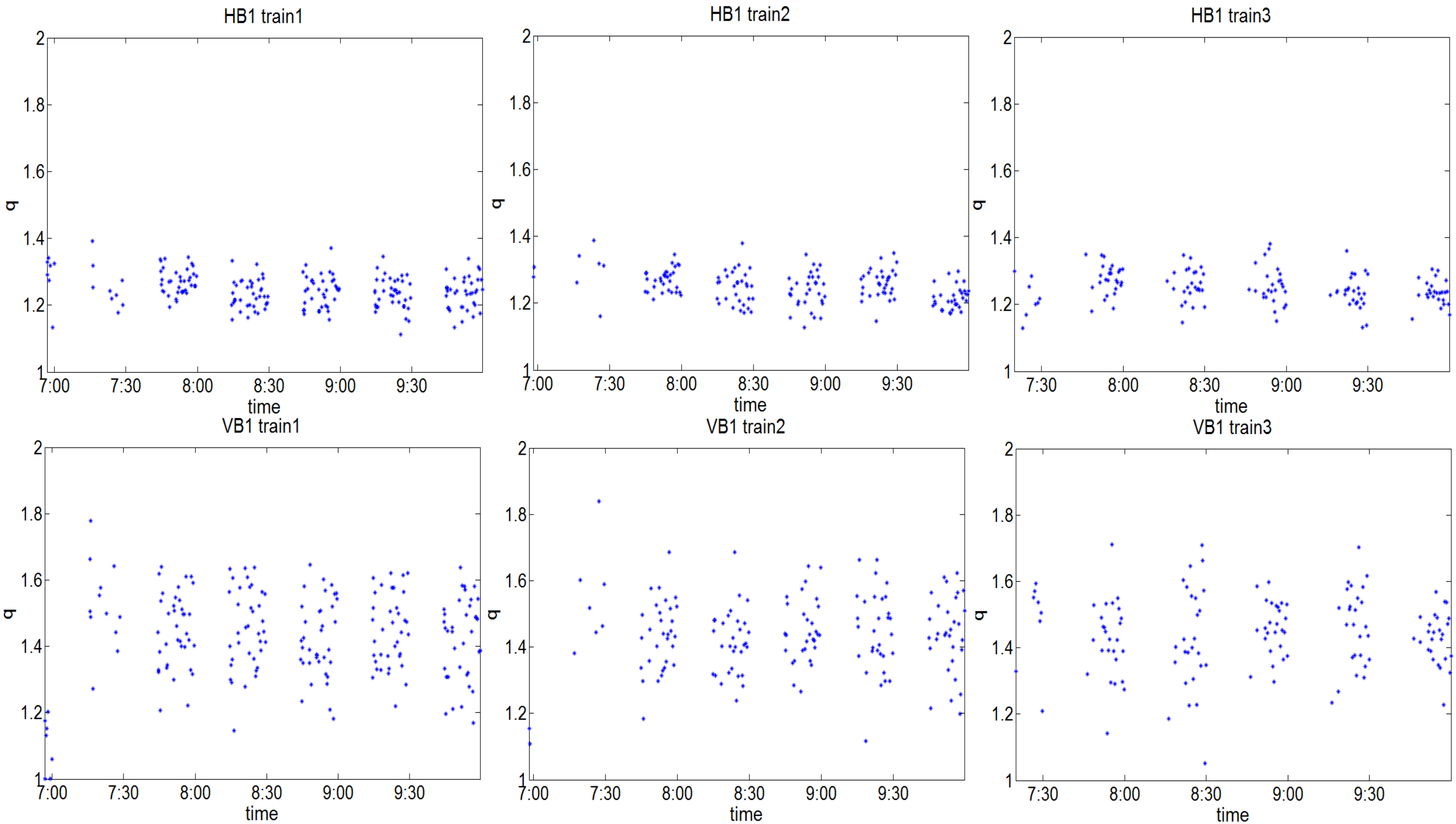
for q<5/3

Transverse bunch profiles at FT (Fill 5137)



sigma'=sqrt(sigma^2- LSF^2)

Transverse bunch profiles at FT (Fill 5137)



SIRE

Software for **I**BS and **R**adiation **E**ffects (a Monte Carlo multiparticle simulation code) developed by A. Vivoli and M. Martini and revised by Fanouria

Inputs

-The optics along a lattice (MADX twiss file).
-The parameters file.
-The particles distribution (default: Gaussian distribution).

The analytical models that describe the IBS effect assume Gaussian beam distributions. In the case of non-Gaussian beam distributions no theoretical models exist. **SIRE calculates IBS for any distribution.**

Computing IBS and Radiation Effects

-Particles are tracked from point to point in the lattice by their invariants.
-At each point of the lattice the scattering routine is called.
-6-dim coordinates of particles are calculated.
-Particles of the beam are grouped in cells.
-The intrabeam collisions between pairs of macro-particles are iteratively computed, the momentum of particles is changed because of scattering.
-Invariants of particles are recalculated.
-Radiation damping and excitation effects are evaluated at the end of every loop.

Outputs

-The beam distribution is updated and the rms beam emittances are recomputed, giving finally **the evolution of the emittance and particle distribution in time.**

SIRE

Parameters file

Fastrun → **The Fastrun is applied in order to speed up the simulation.**
-the IBS is applied in oneturn and the growth rate per particle is calculated
-the emittance per particle is recalculated based on the exponential IBS growth in a specific timestep.
-continue tracking with the interpolated distribution

NIBSruns → Number of timesteps that the time is divided to calculate IBS

nturnstostudy → Number of turns (total time)

ncellx
ncellz
ncells
} Number of cells in each plane

numpart → Number of macroparticles

SIRE

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ncellx
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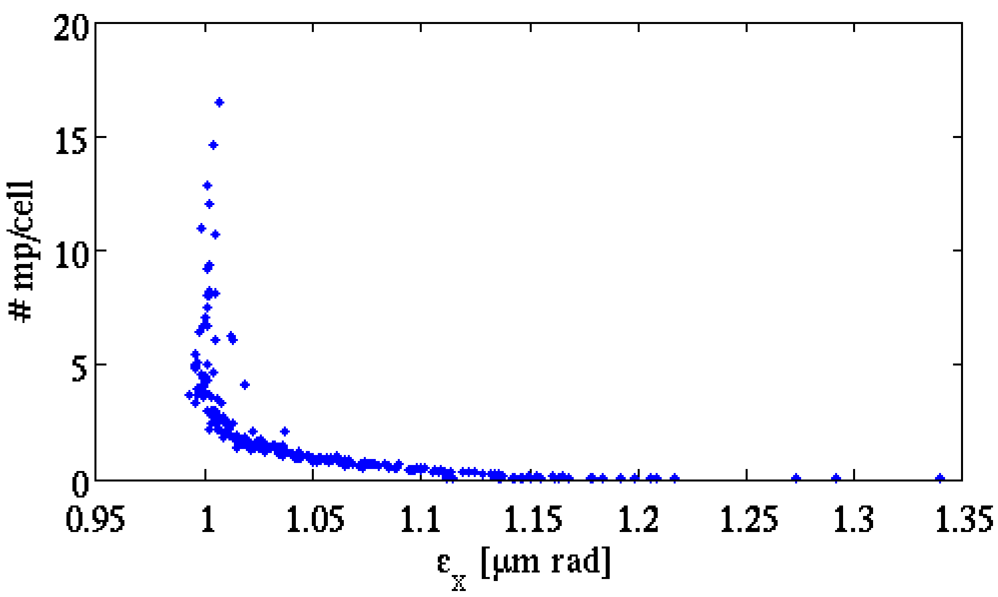
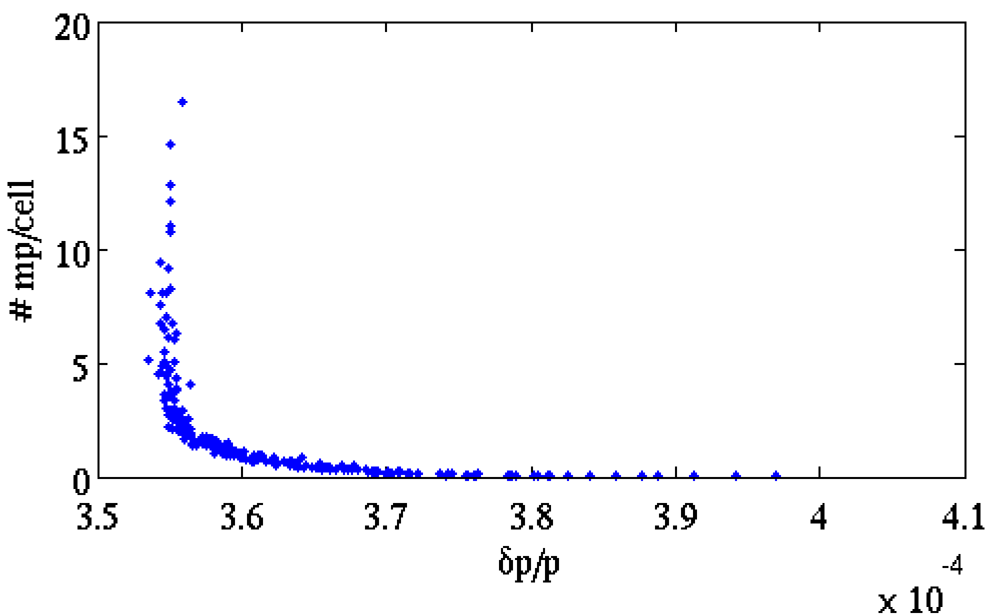
Number of cells in each plane

numpart → Number of macroparticles

In order to avoid combinations which give very small #macroparticles/cell, it was observed (by Fanouria) that 5macroparticles/cell is the optimal minimum number.





SIRE

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Fastrun → **The Fastrun is applied in order to speed up the simulation.**

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numpart → Number of macroparticles

scanning

In order to avoid combinations which give very small #macroparticles/cell, it was observed (by Fanouria) that 5macroparticles/cell is the optimal minimum number.

tested

Parameters @ FB	Nominal (BCMS)	HiLumi
E [GeV]	450	450
$\varepsilon_{x,y}$ [μm]	1.5	2.0
4σ bunch length [ns]	1.0	1.2
Bunch population [10^{11}]	1.2	2.3

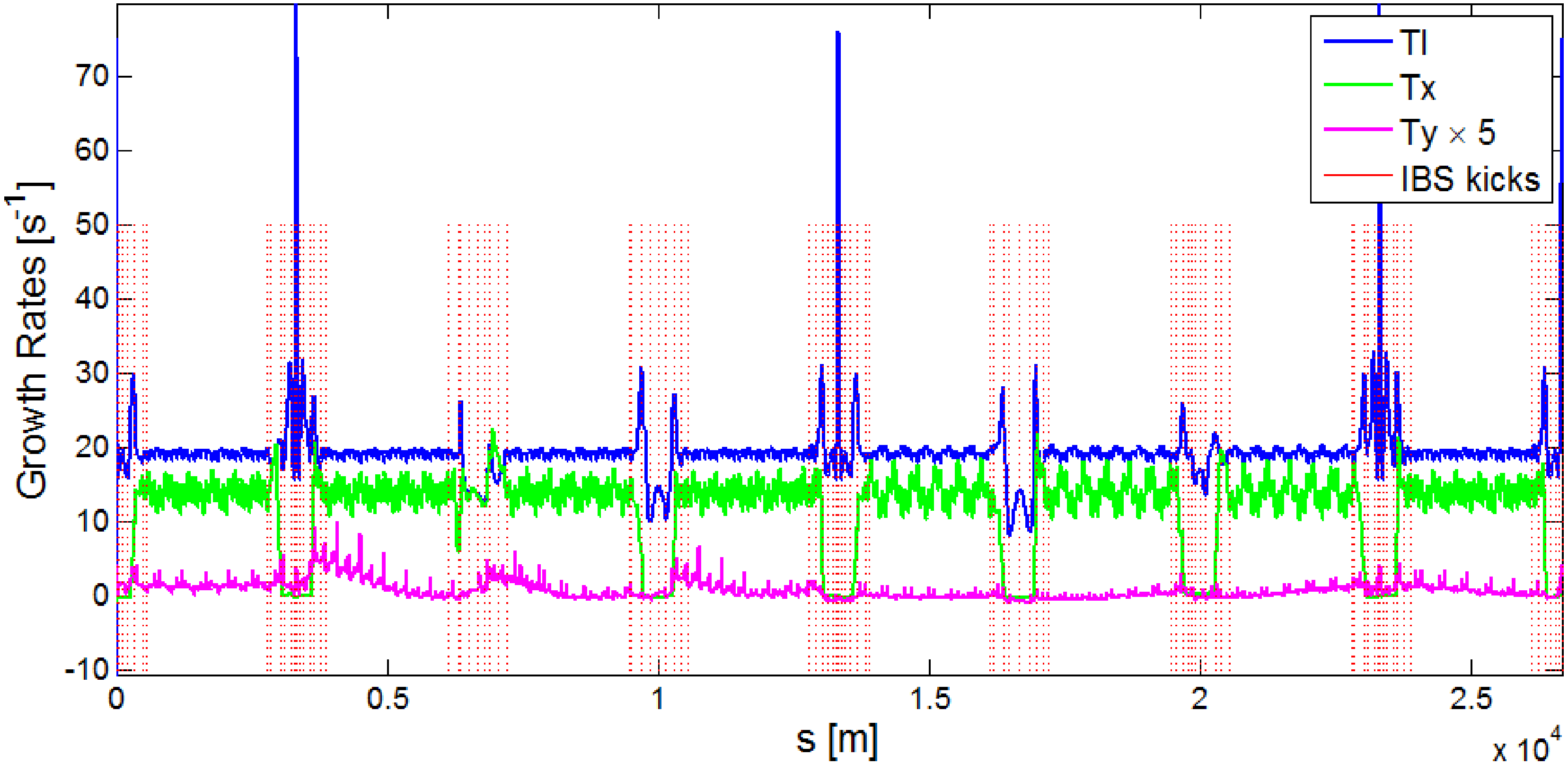
Parameters @ FT	Nominal (BCMS)	HiLumi
E [GeV]	6.5	7.0
$\varepsilon_{x,y}$ [μm]	2.5	2.5
4σ bunch length [ns]	1.0	1.2
Bunch population [10^{11}]	1.1	2.2

Reduced lattice

As the LHC has a large number of elements (more than 11000), the computational time that SIRE needs to track the distribution for all of them along the ring is very long.

- The IBS growth rates were calculated for the LHC's full optics, using the IBS module of the MADX, based on the B-M formalism.
- The optimal minimum number of IBS kick points around the lattice, without affecting the overall effect, are identified.

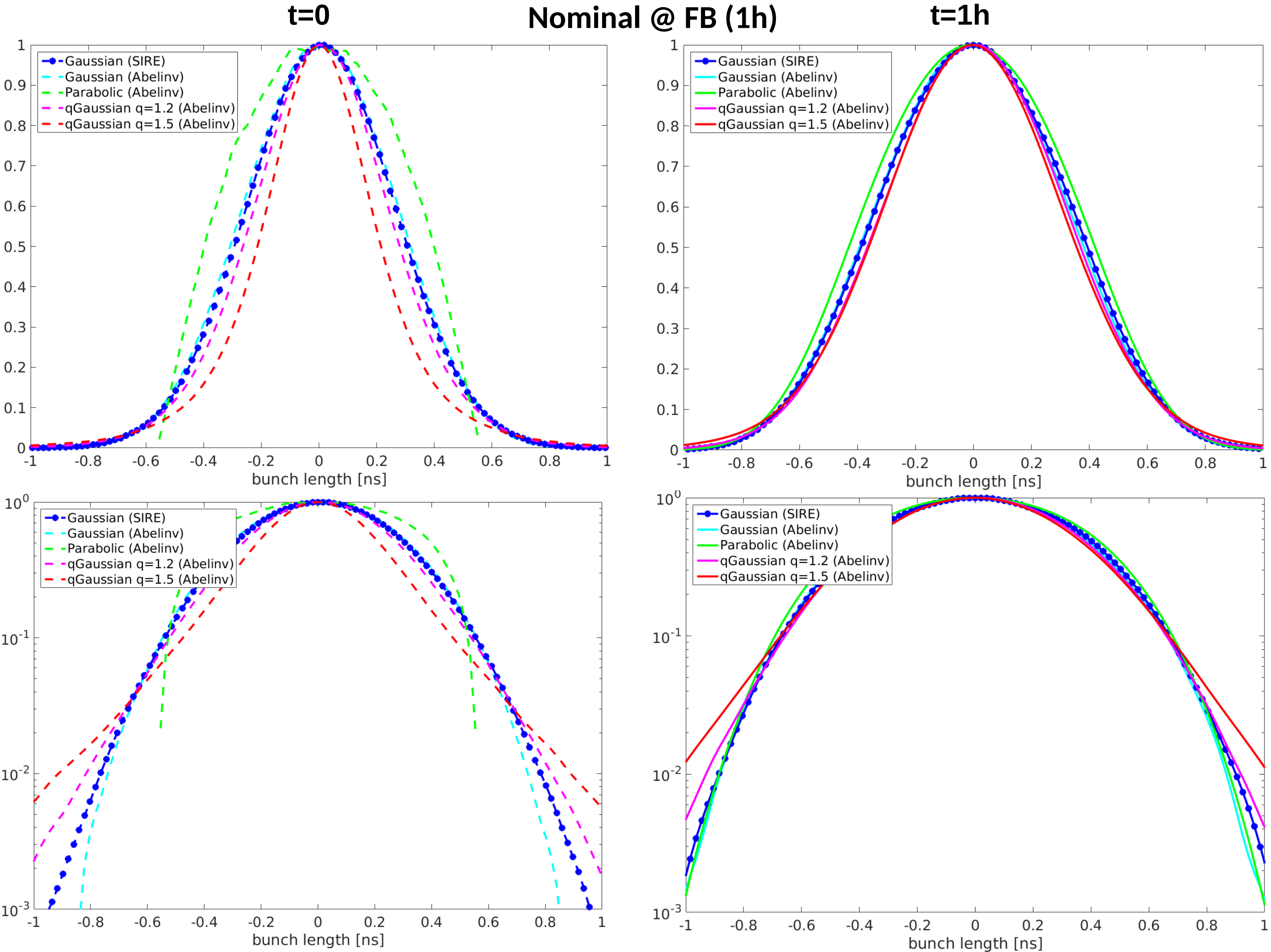
Finally, the reduced lattice used in SIRE has only 92 points (much lower computational time).



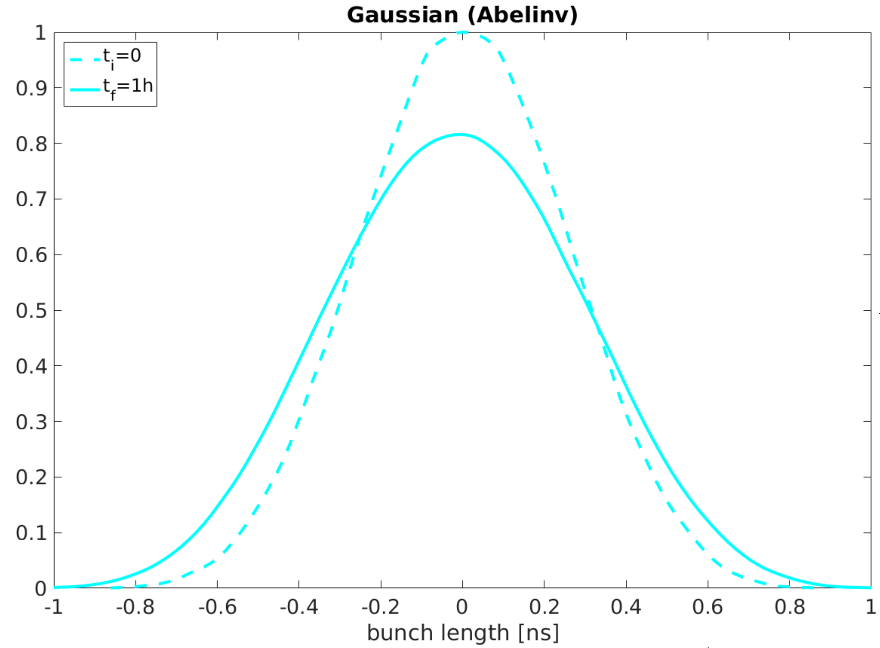
lattice recurrences → Elements of the lattice with twiss functions differing of less than prec.% are considered equal

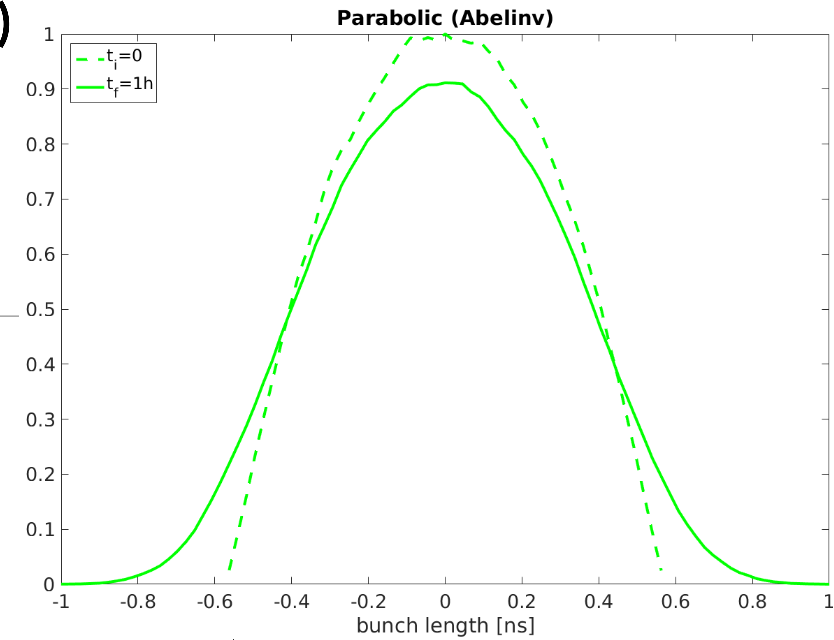
Flat Bottom (IBS)

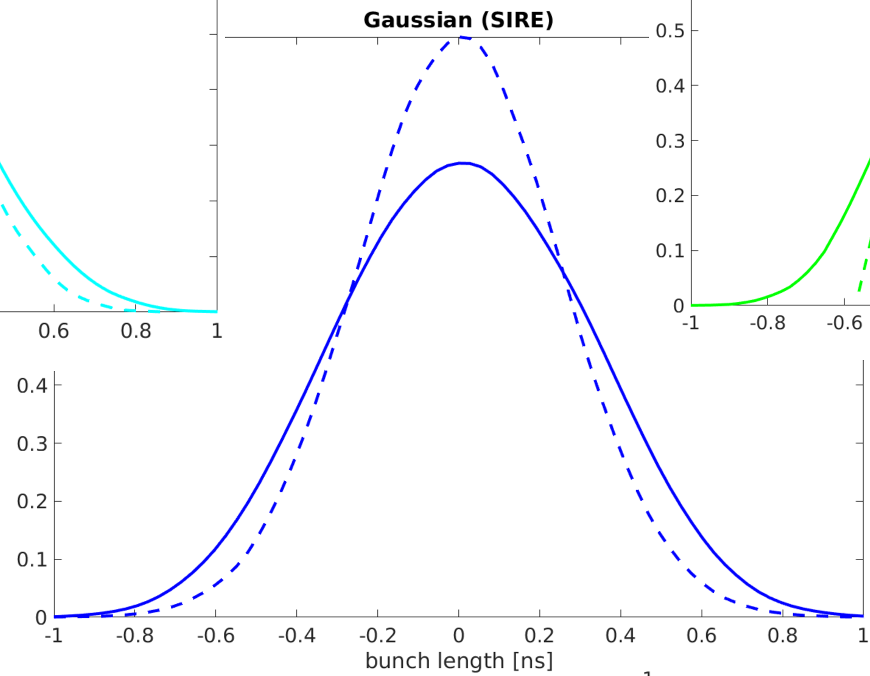
Nominal @ FB (1h)

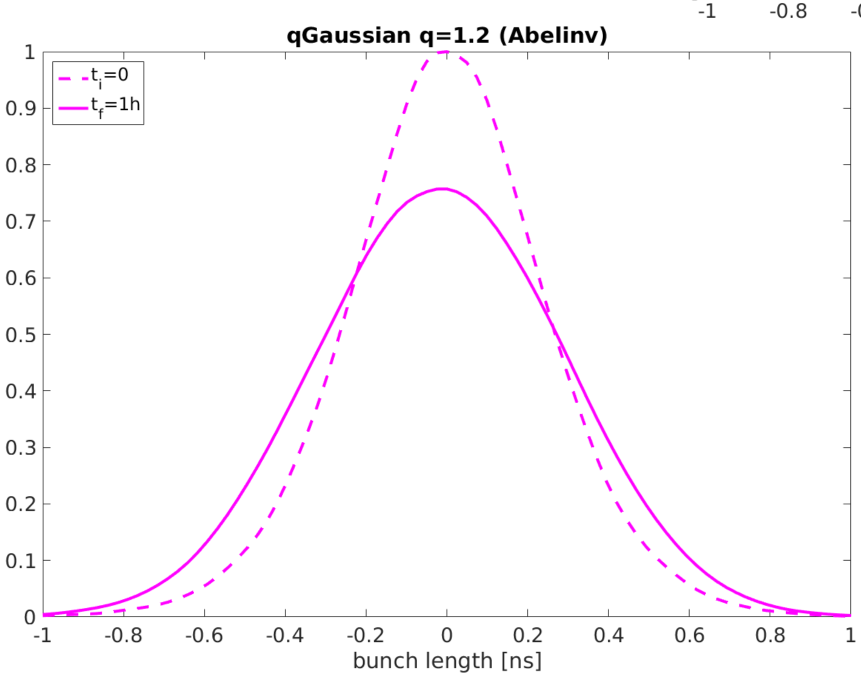


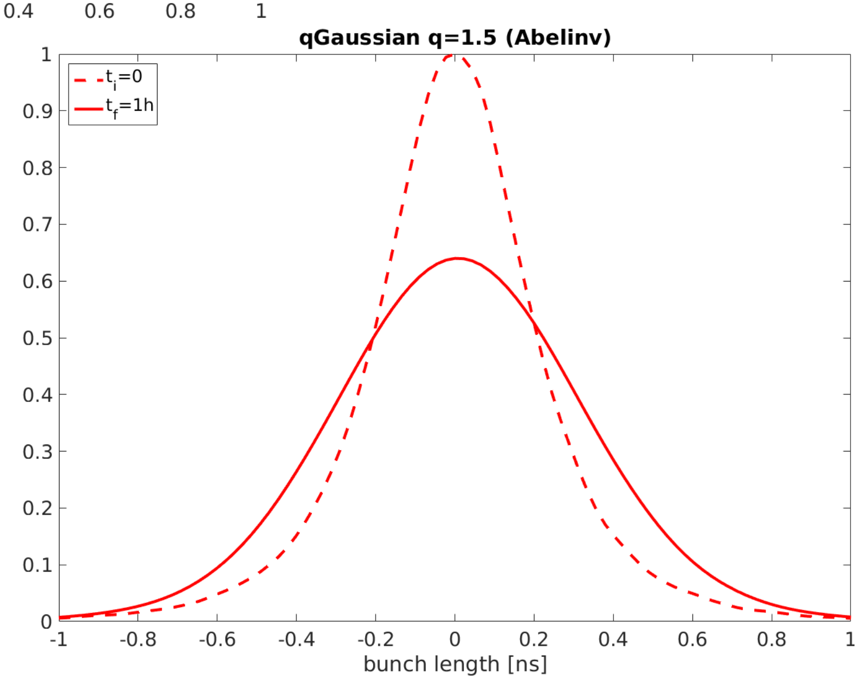
Nominal @ FB (1h) (qGaussian fits)



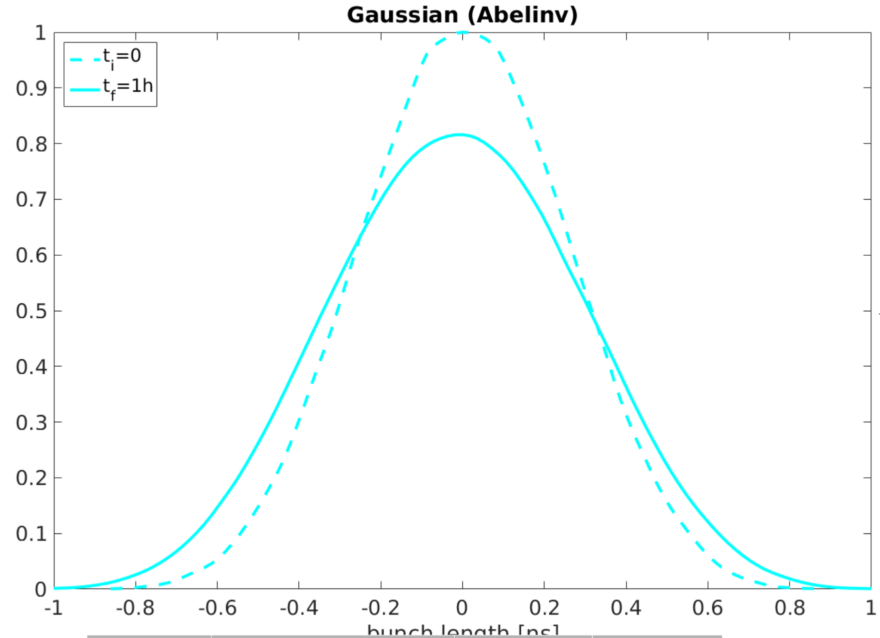


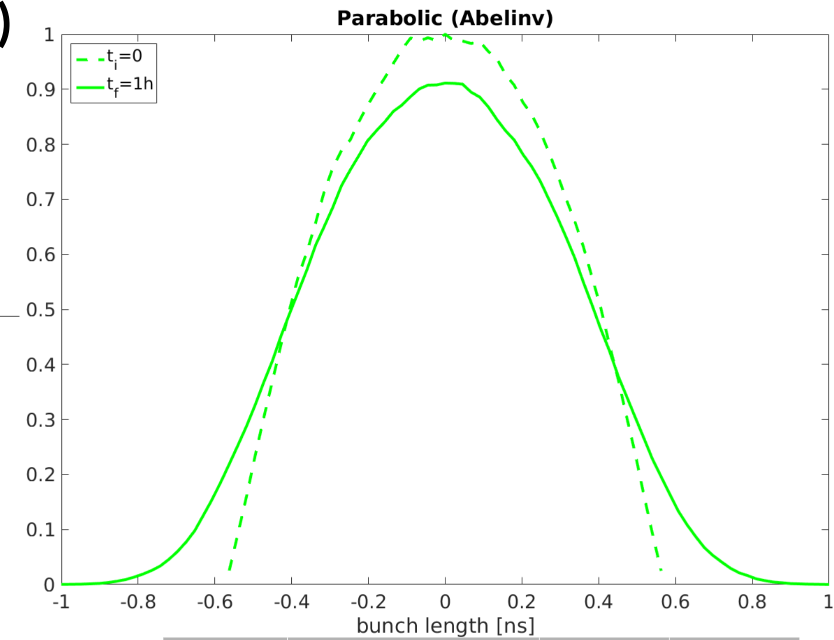


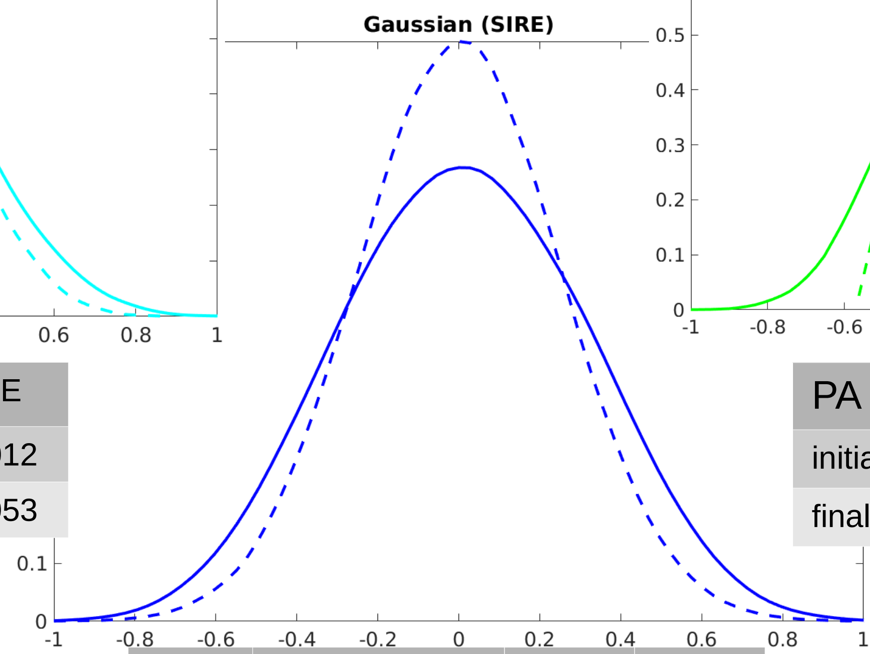




Nominal @ FB (1h) (qGaussian fits)



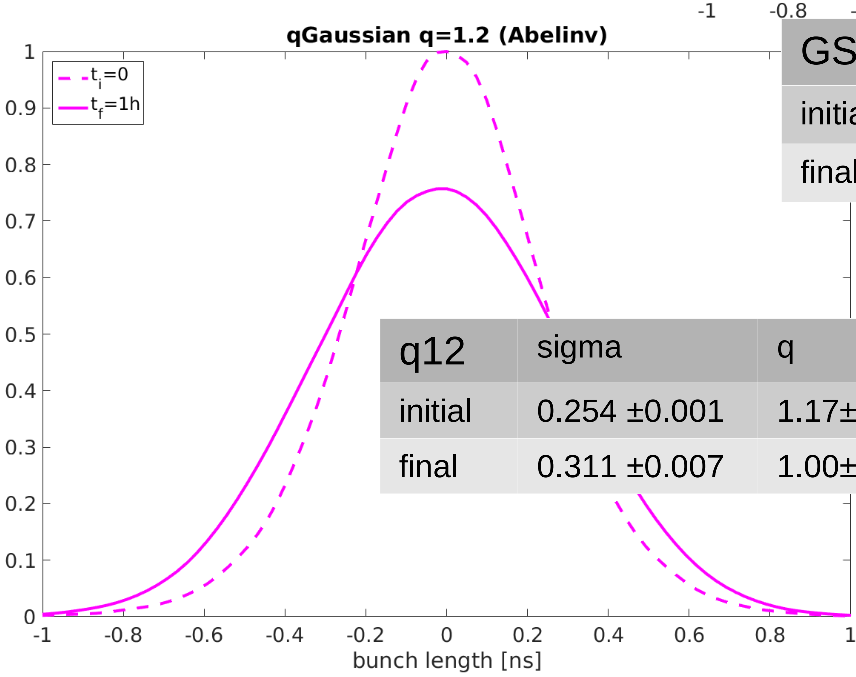


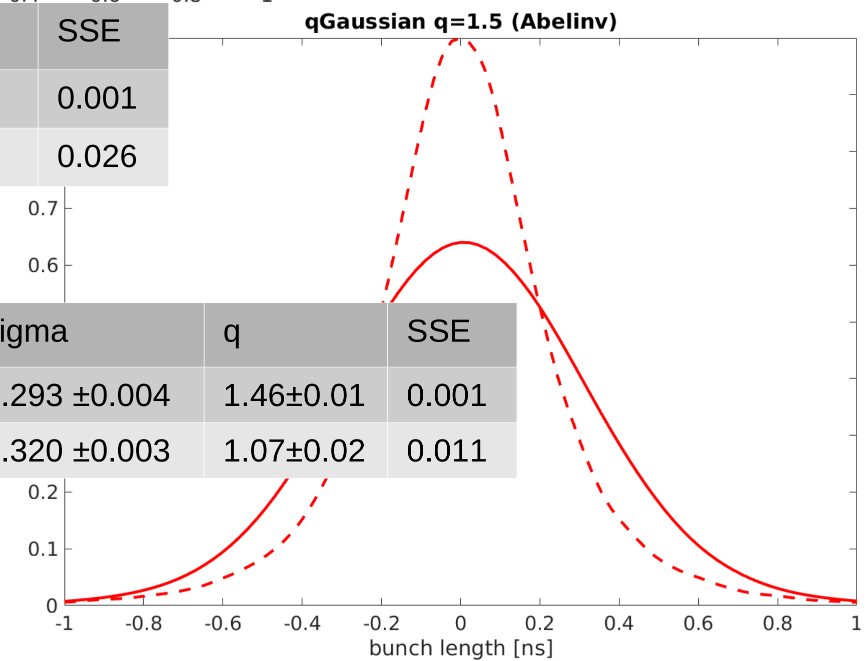


GA	sigma	q	SSE
initial	0.261 ±0.003	1.±0.	0.012
final	0.321 ±0.007	1.±0.	0.053

PA	sigma	q	SSE
initial	0.324 ±0.031	1.±0.2	0.280
final	0.337 ±0.010	1.±0.1	0.128

GS	sigma	q	SSE
initial	0.252 ±0.001	1.±0.	0.001
final	0.323 ±0.004	1.±0.	0.026

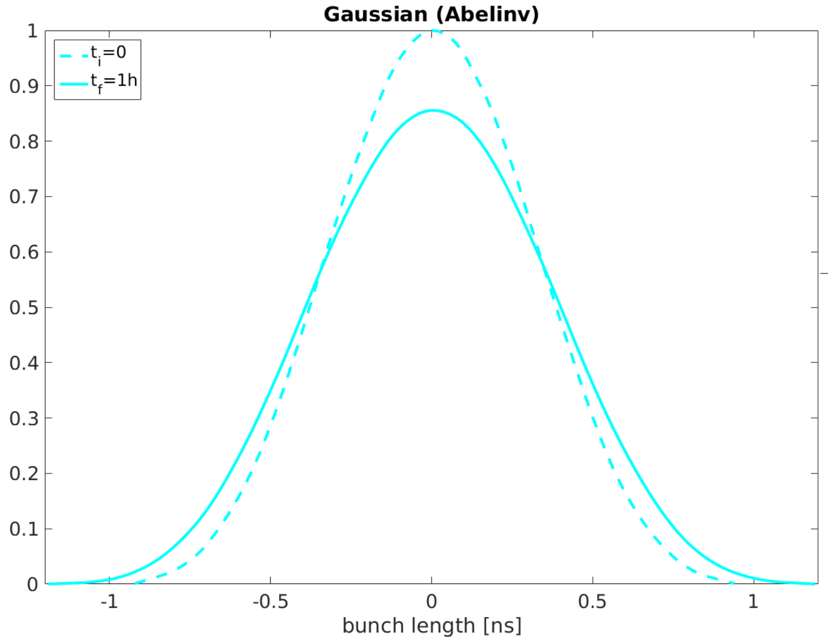


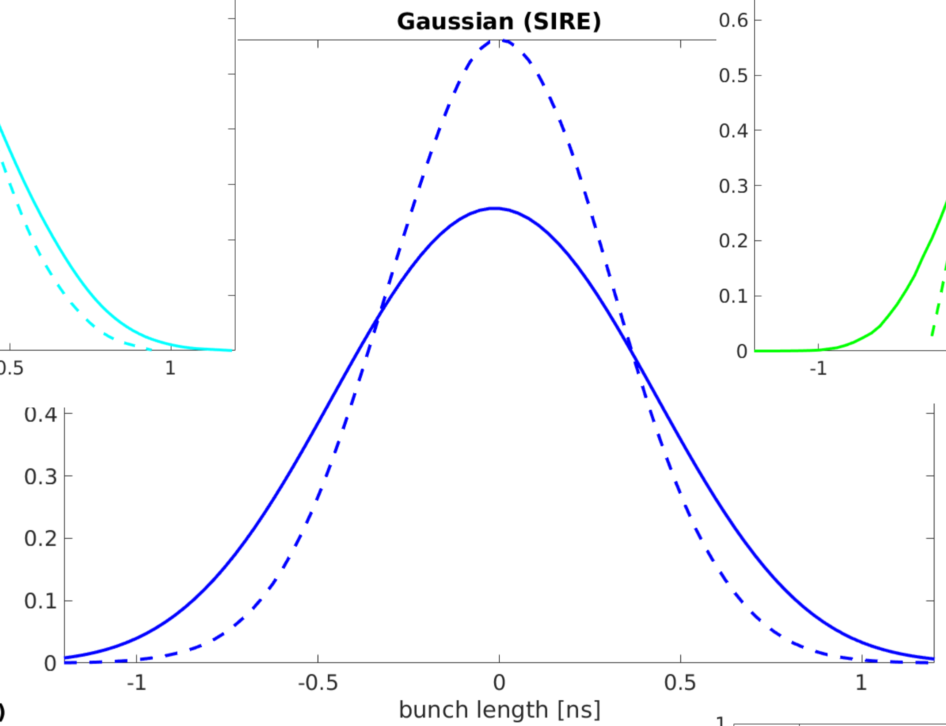


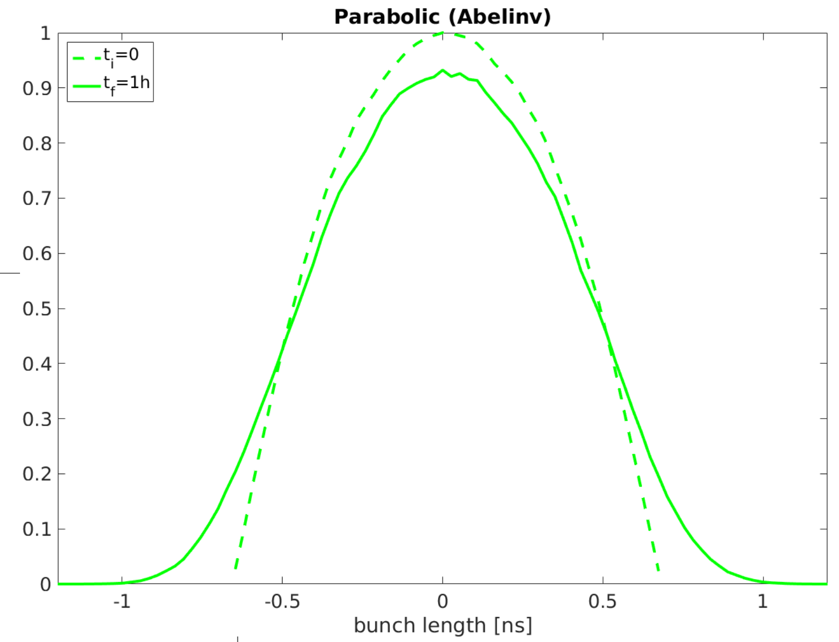
q12	sigma	q	SSE
initial	0.254 ±0.001	1.17±0.01	0.001
final	0.311 ±0.007	1.00±0.04	0.030

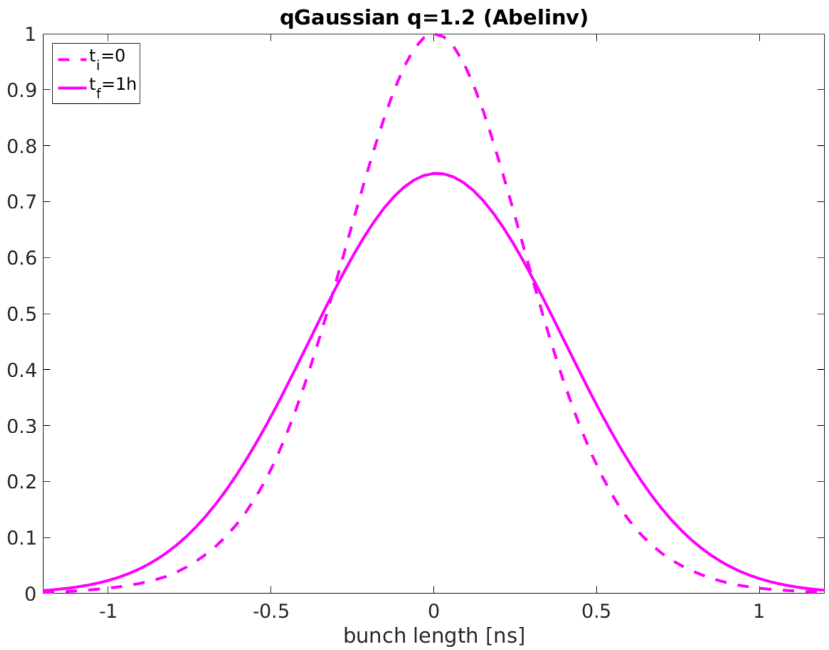
q15	sigma	q	SSE
initial	0.293 ±0.004	1.46±0.01	0.001
final	0.320 ±0.003	1.07±0.02	0.011

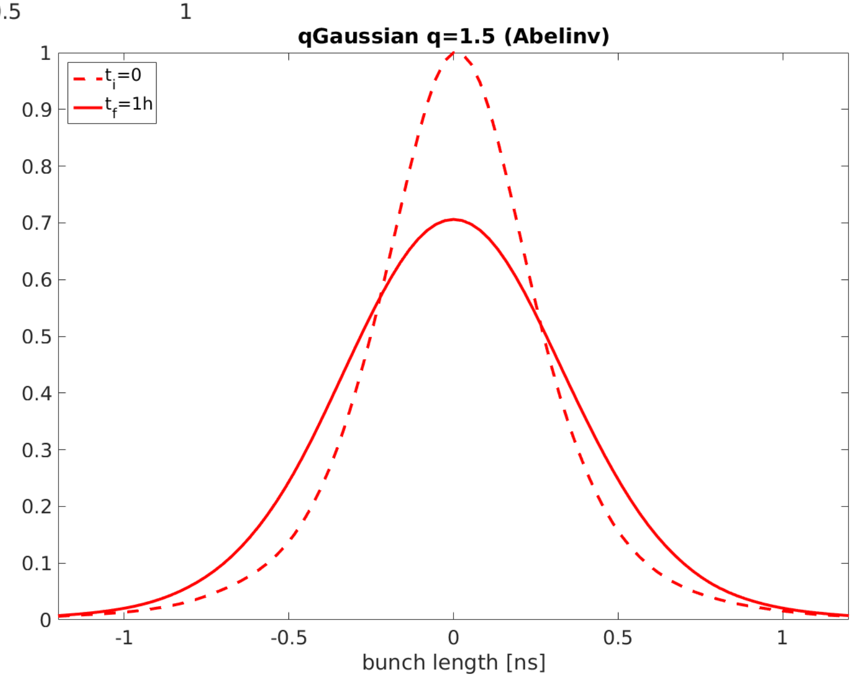
HiLumi @ FB (1h)
(qGaussian fits)



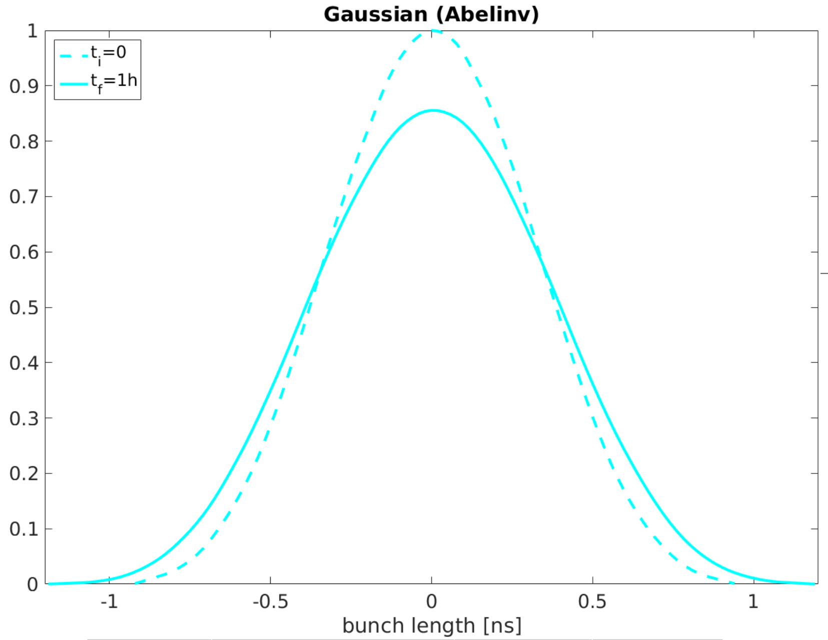




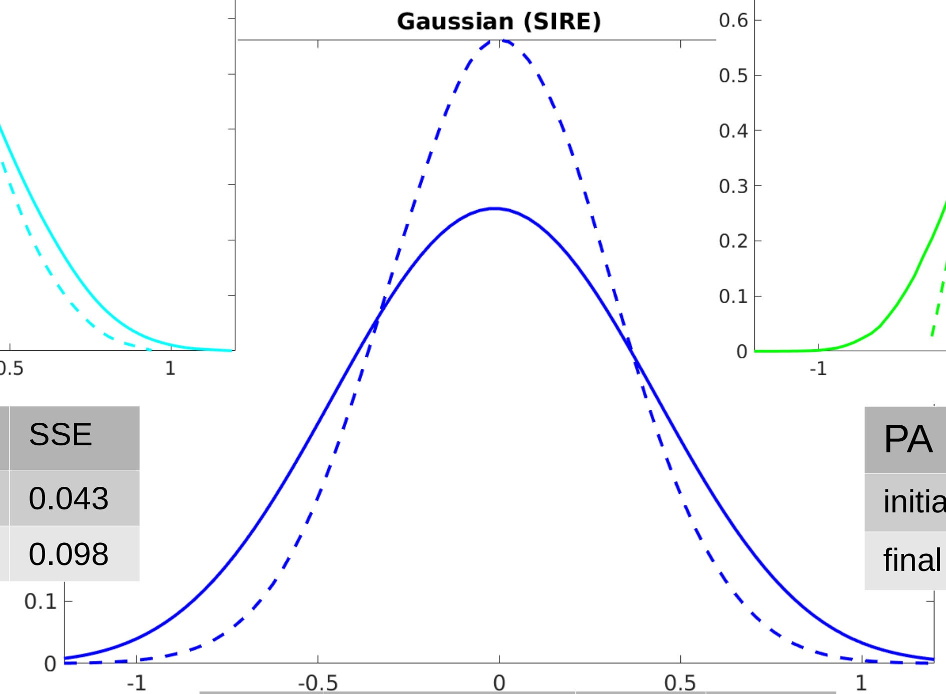




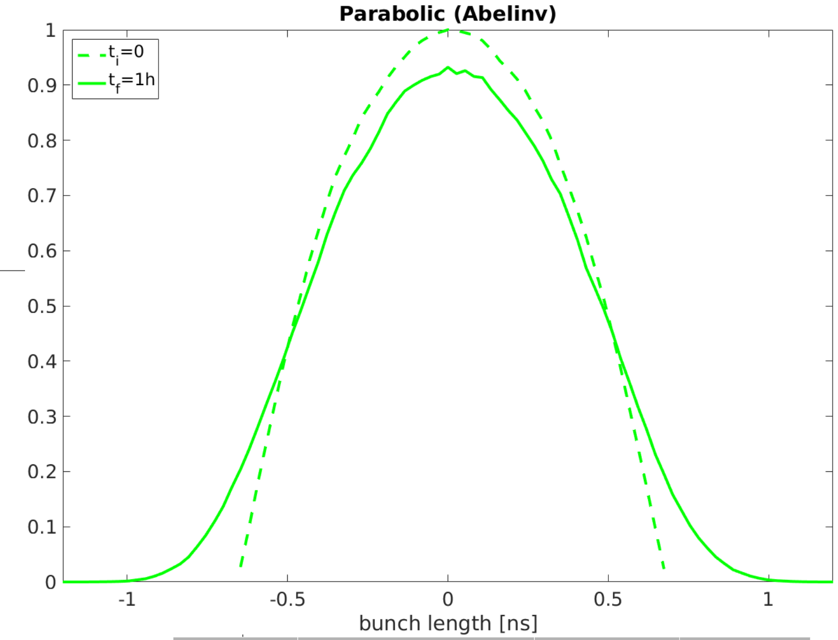
HiLumi @ FB (1h) (qGaussian fits)



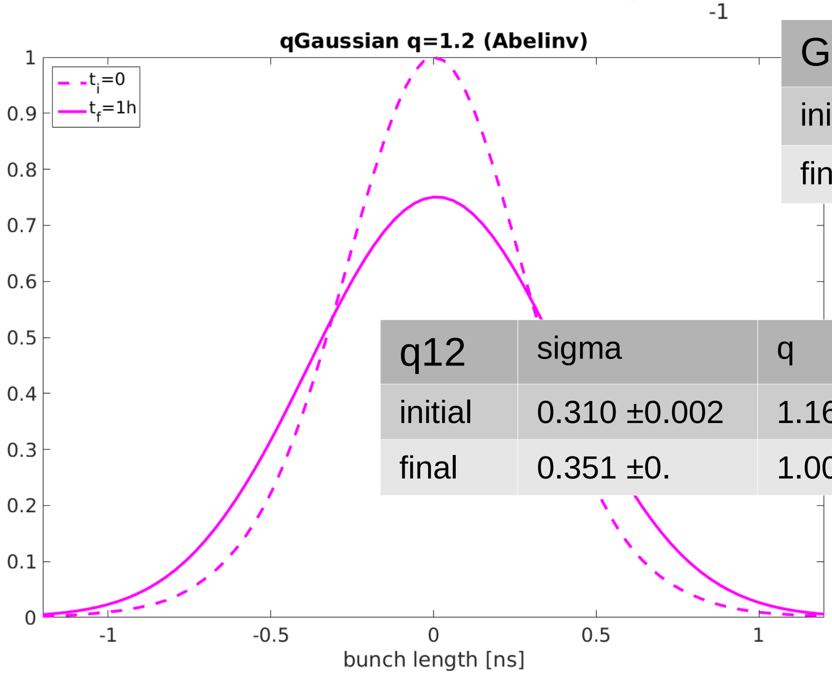
GA	sigma	q	SSE
initial	0.318 ±0.	1.±0.	0.043
final	0.369 ±0.	1.±0.	0.098



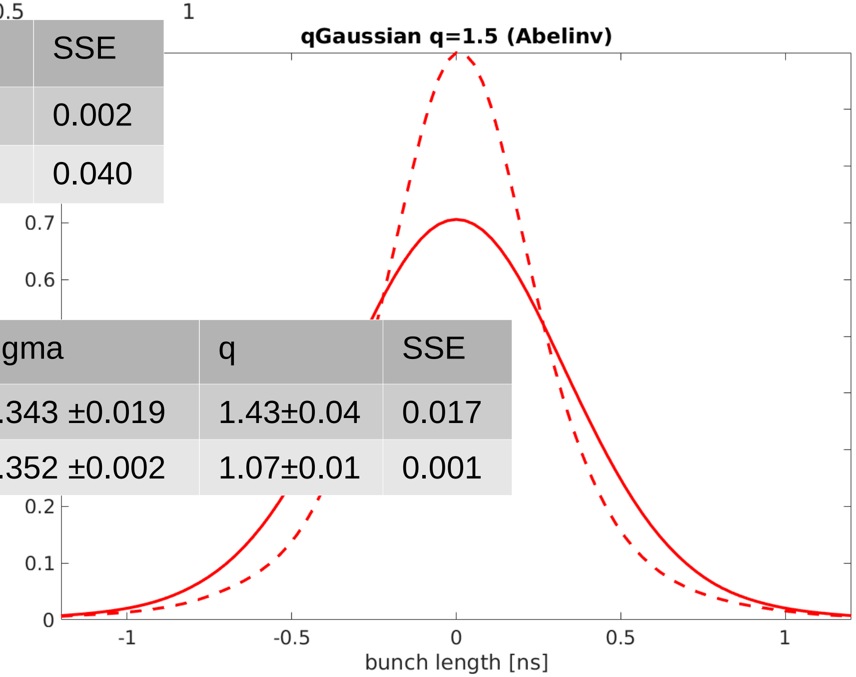
GS	sigma	q	SSE
initial	0.307 ±0.002	1.±0.	0.002
final	0.372 ±0.007	1.±0.	0.040



PA	sigma	q	SSE
initial	0.385 ±0.054	1.±0.20	0.293
final	0.395 ±0.010	1.±0.04	0.155

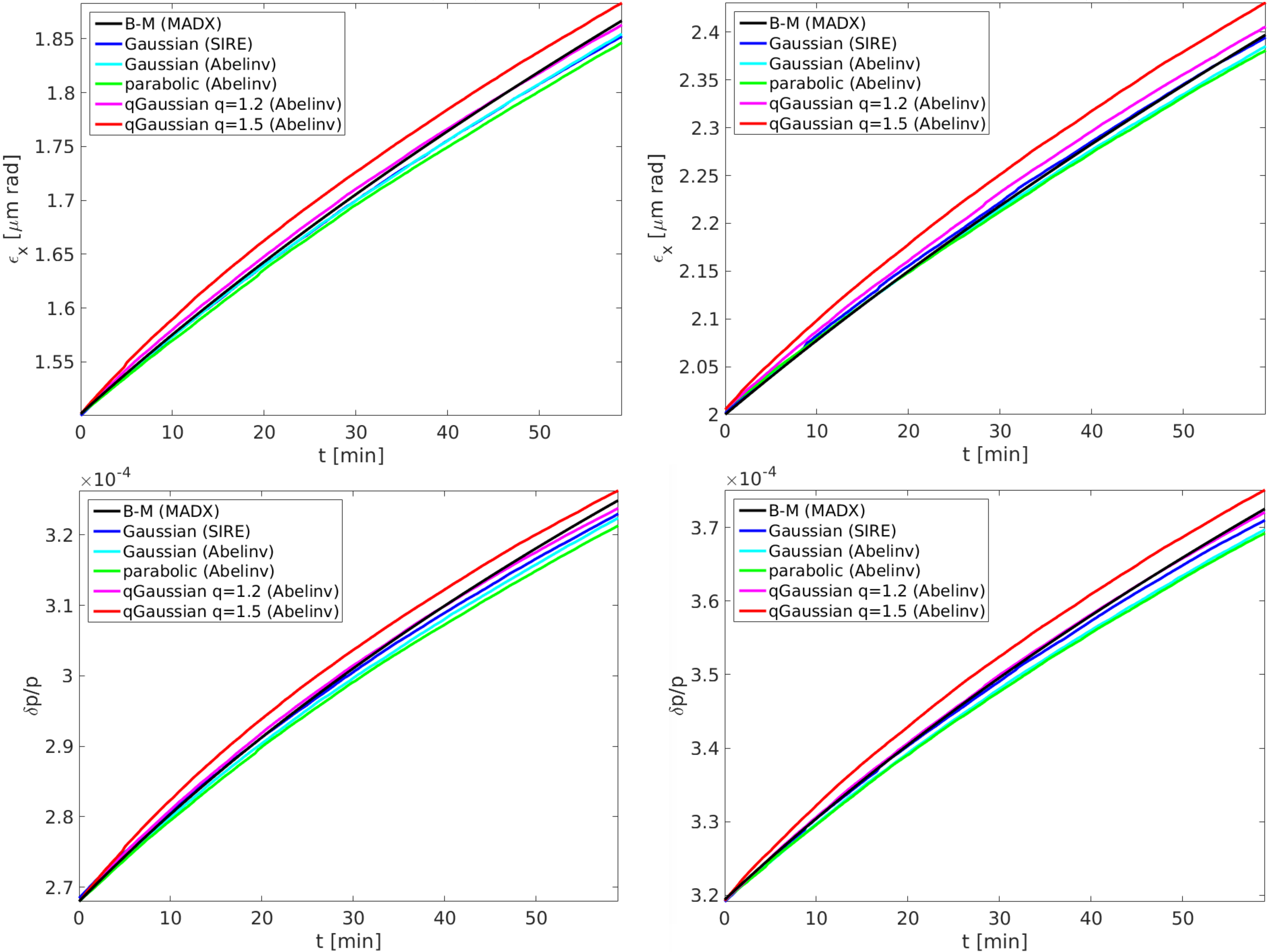


q12	sigma	q	SSE
initial	0.310 ±0.002	1.16±0.01	0.001
final	0.351 ±0.	1.00±0.	0.008



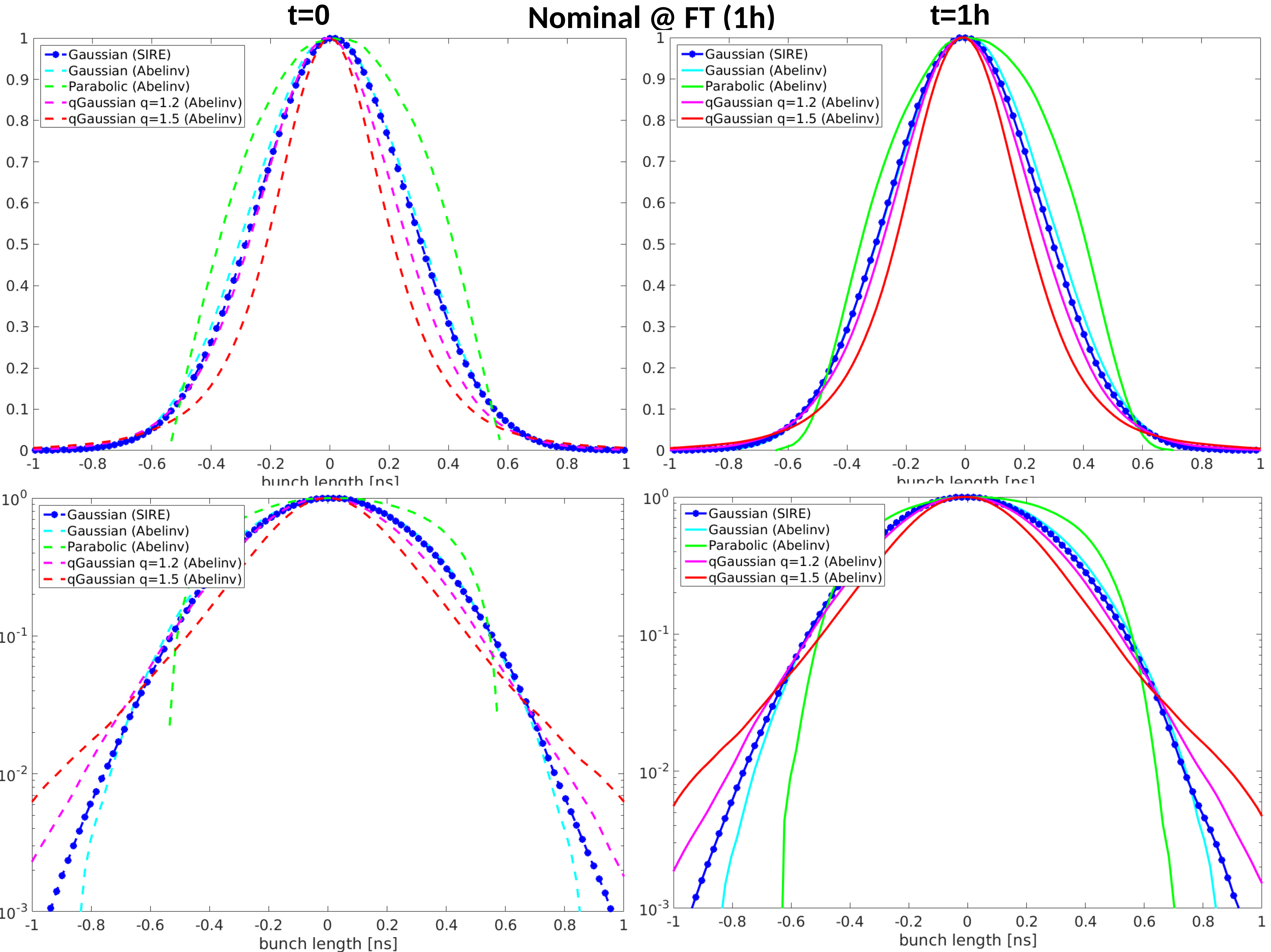
q15	sigma	q	SSE
initial	0.343 ±0.019	1.43±0.04	0.017
final	0.352 ±0.002	1.07±0.01	0.001

Nominal @ FB (1h) **HiLumi @ FB (1h)**

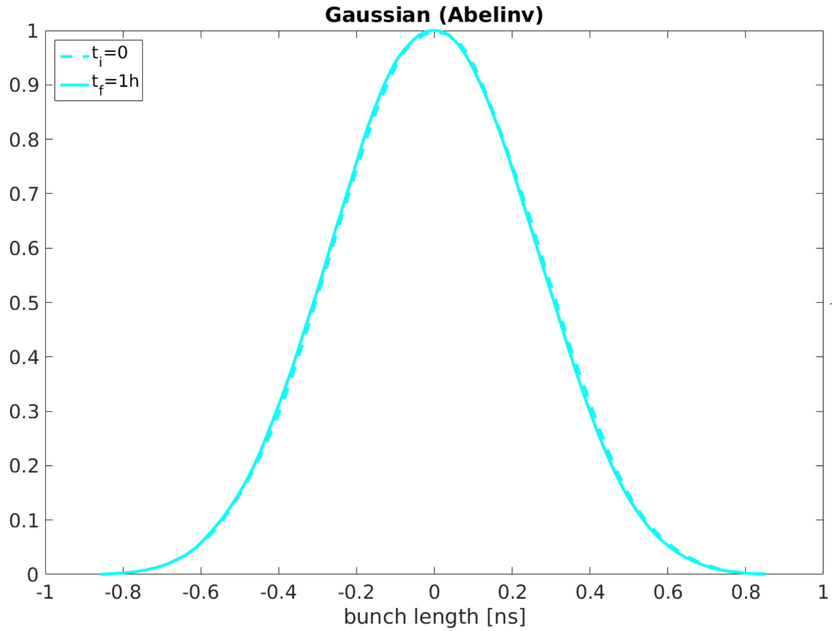


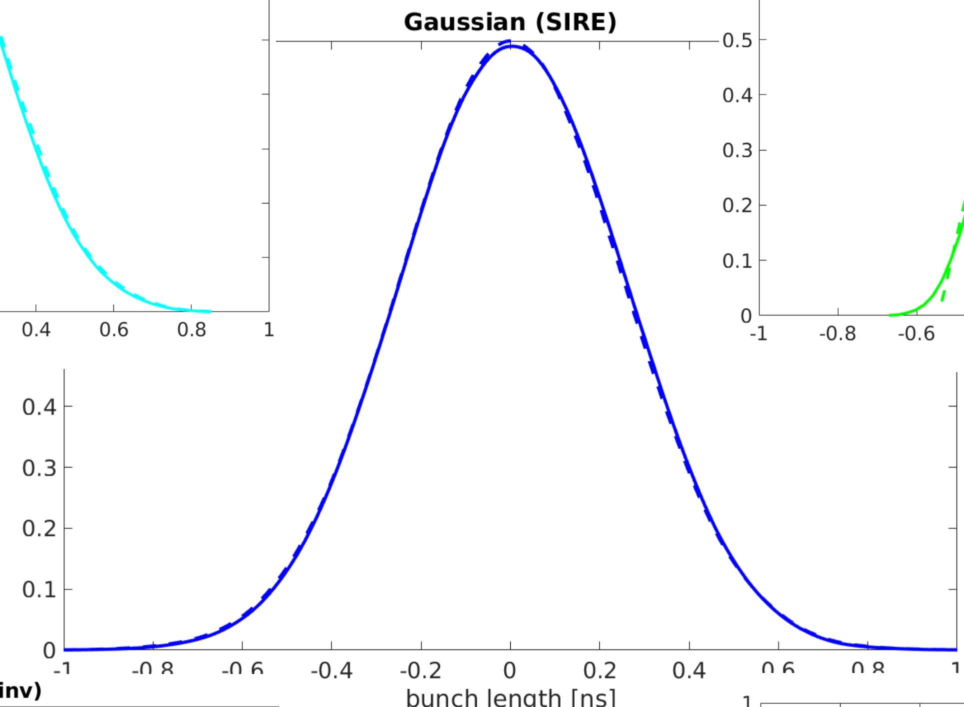
Flat Top (IBS&SR)

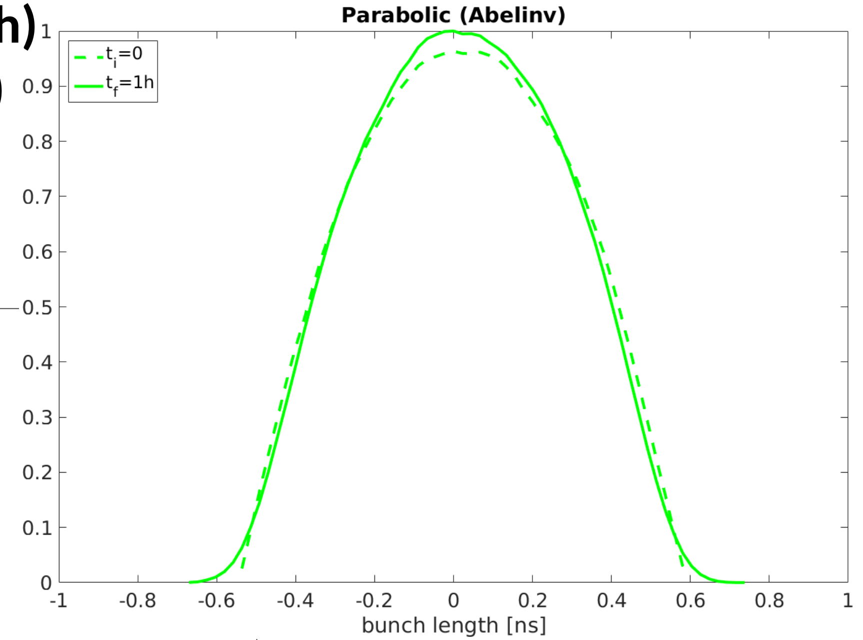
Nominal @ FT (1h)

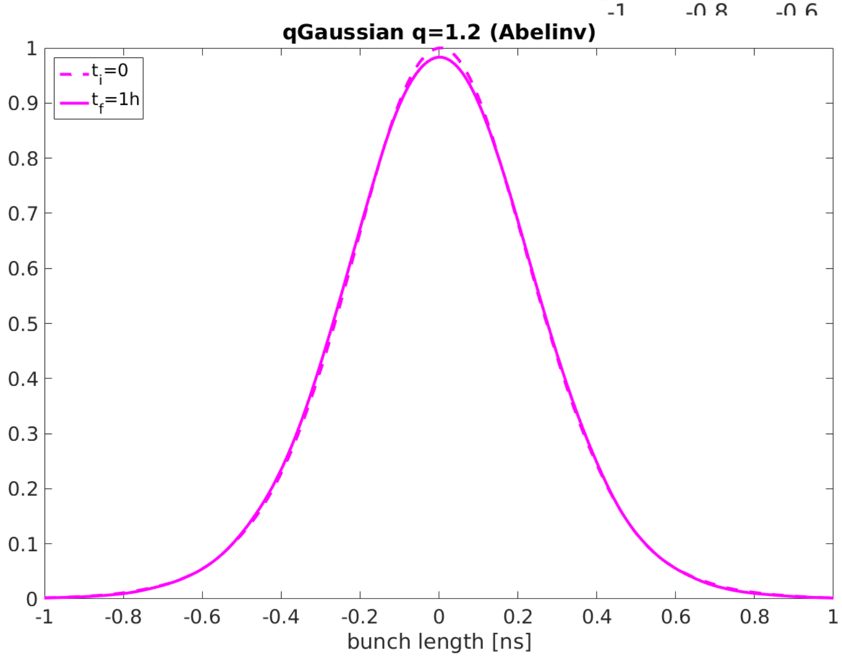


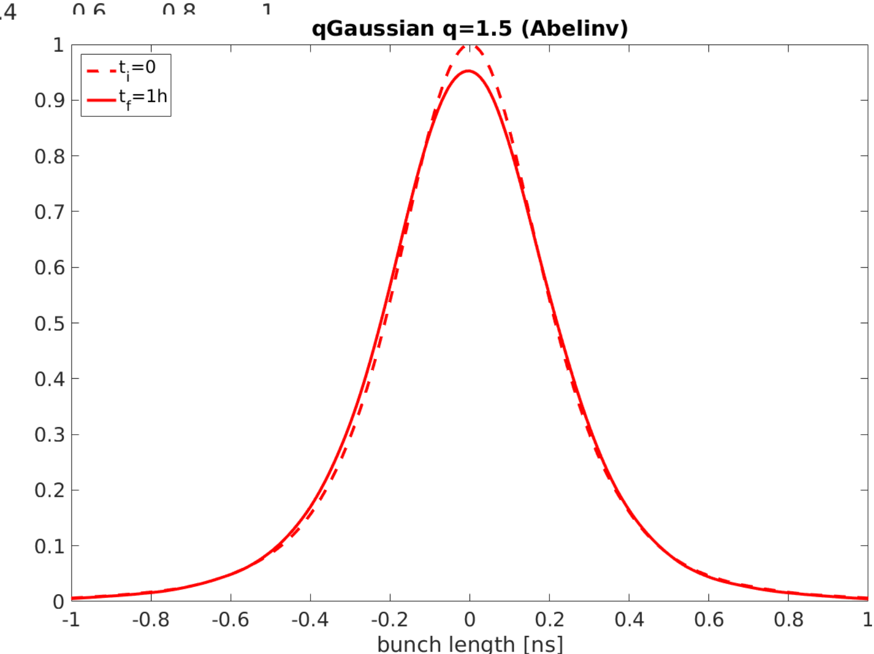
Nominal @ FT (1h) (qGaussian fits)



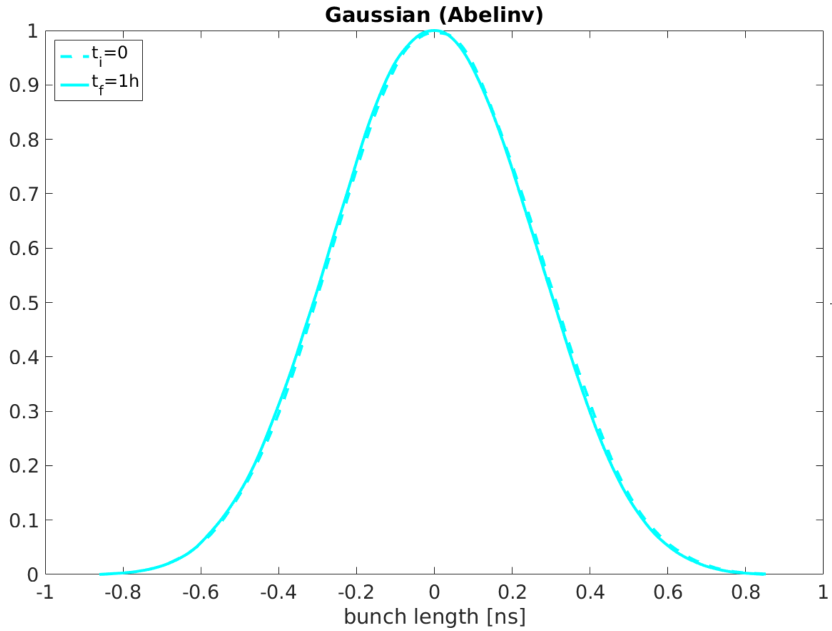




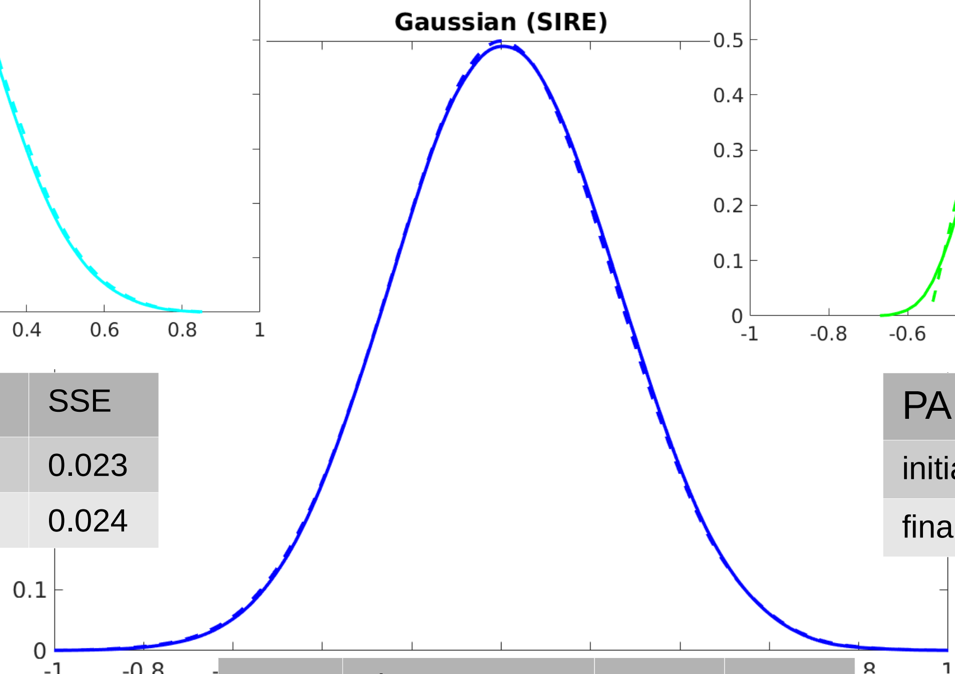




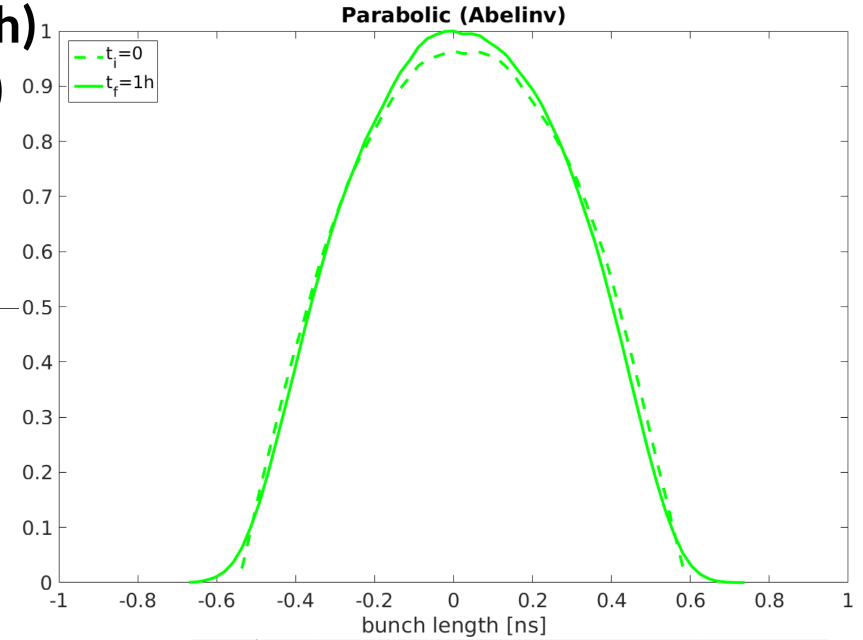
Nominal @ FT (1h) (qGaussian fits)



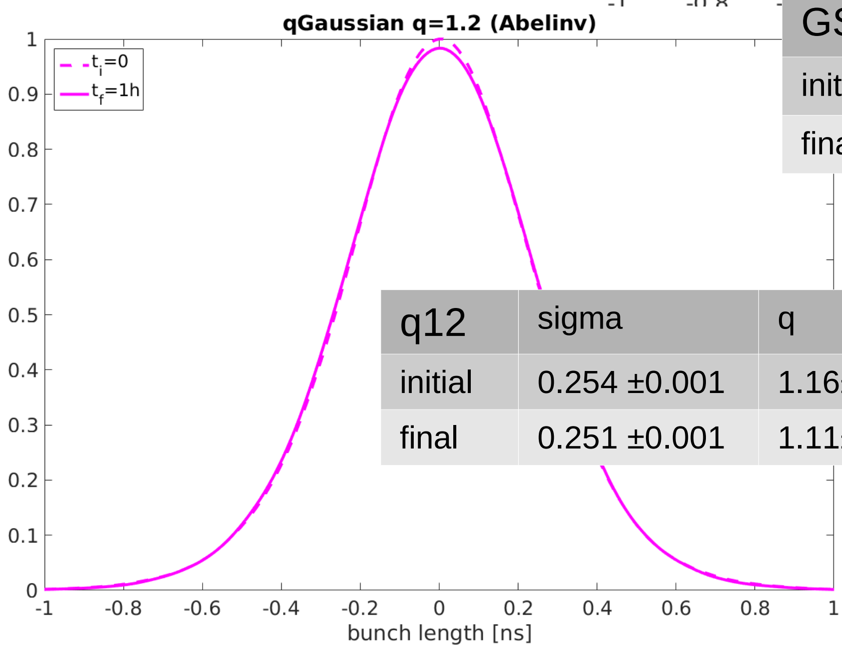
GA	sigma	q	SSE
initial	0.259 ±0.	1.±0.	0.023
final	0.259 ±0.	1.±0.	0.024



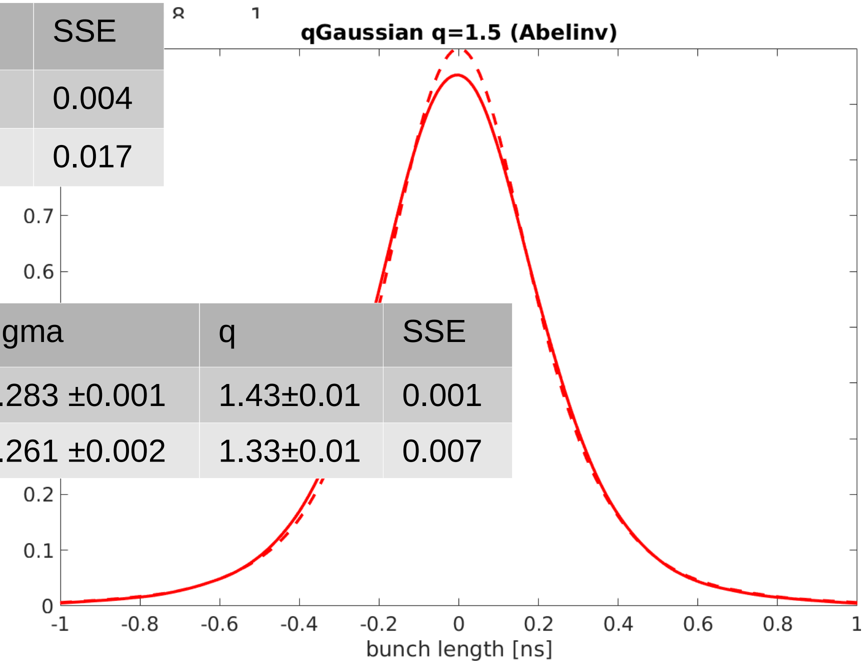
GS	sigma	q	SSE
initial	0.253 ±0.001	1.±0.	0.004
final	0.254 ±0.001	1.±0.	0.017



PA	sigma	q	SSE
initial	0.324 ±0.054	1.±0.15	0.347
final	0.297 ±0.	1.±0.	0.396

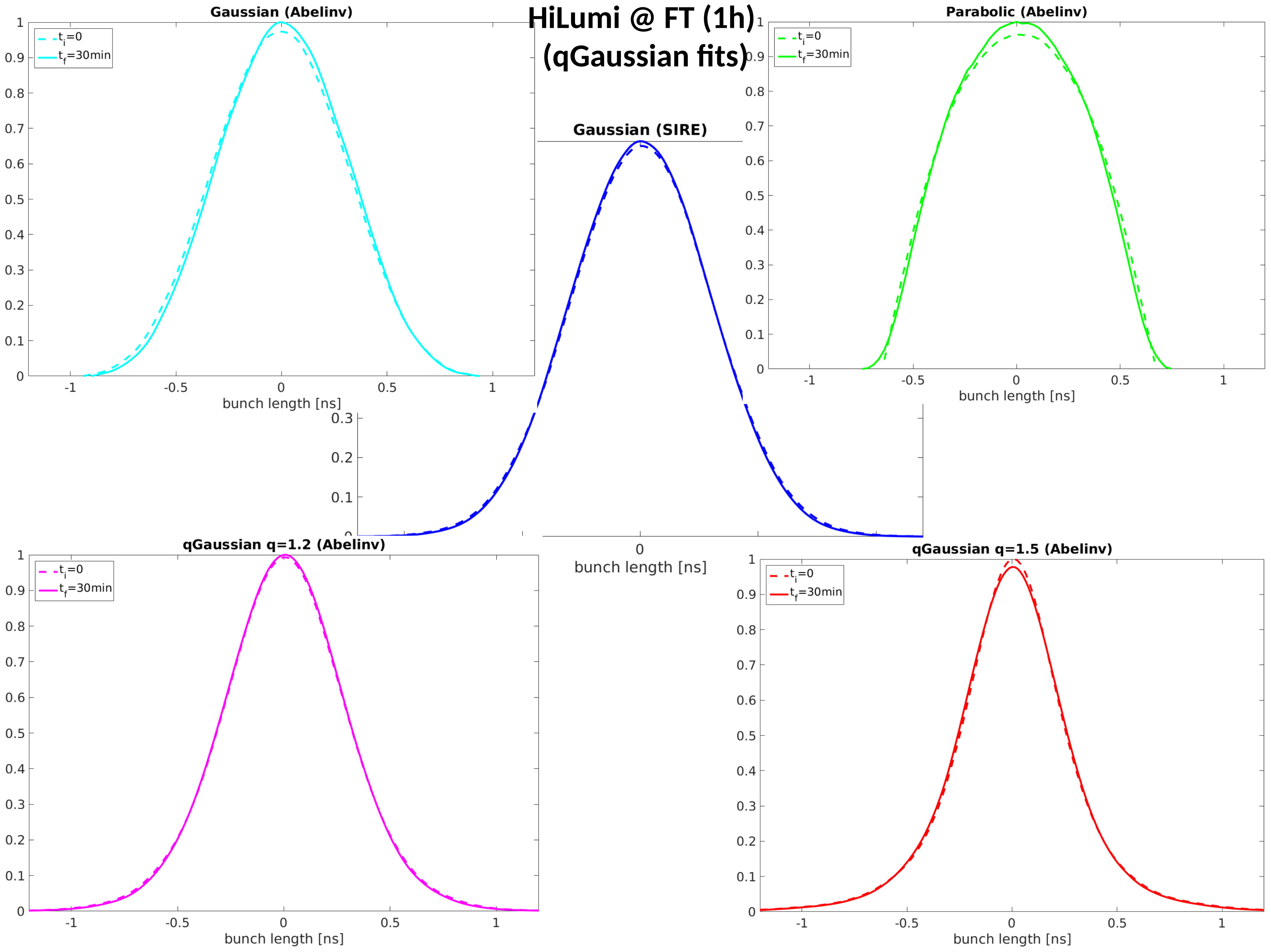


q12	sigma	q	SSE
initial	0.254 ±0.001	1.16±0.01	0.006
final	0.251 ±0.001	1.11±0.01	0.004

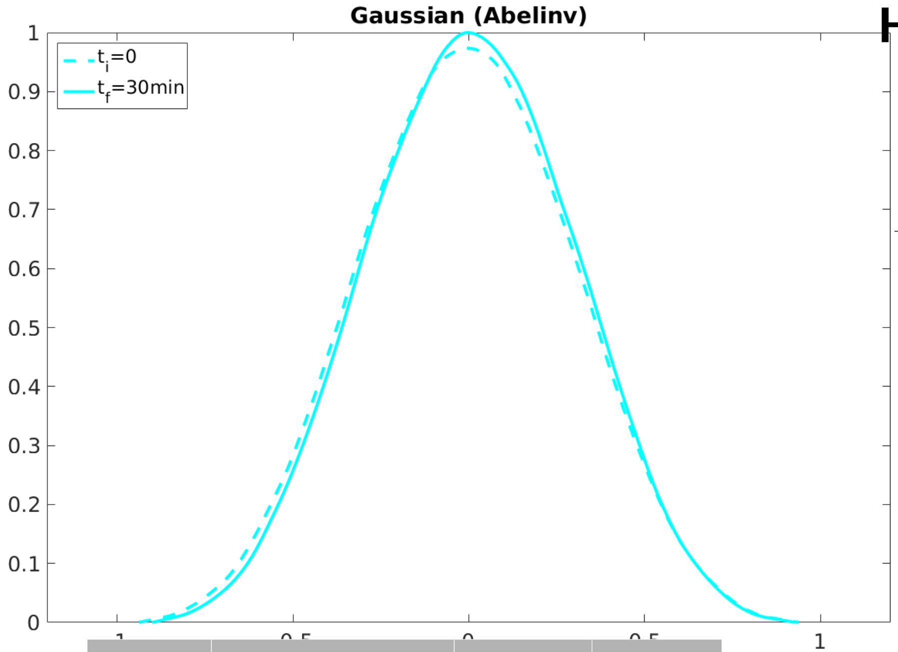


q15	sigma	q	SSE
initial	0.283 ±0.001	1.43±0.01	0.001
final	0.261 ±0.002	1.33±0.01	0.007

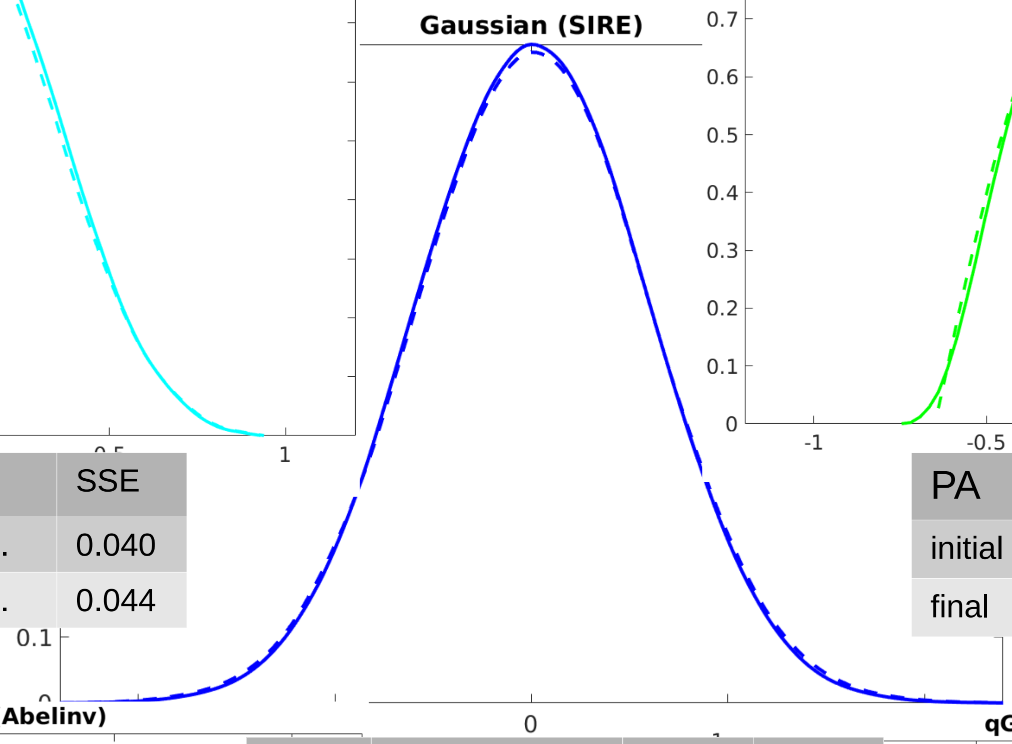
HiLumi @ FT (1h) (qGaussian fits)



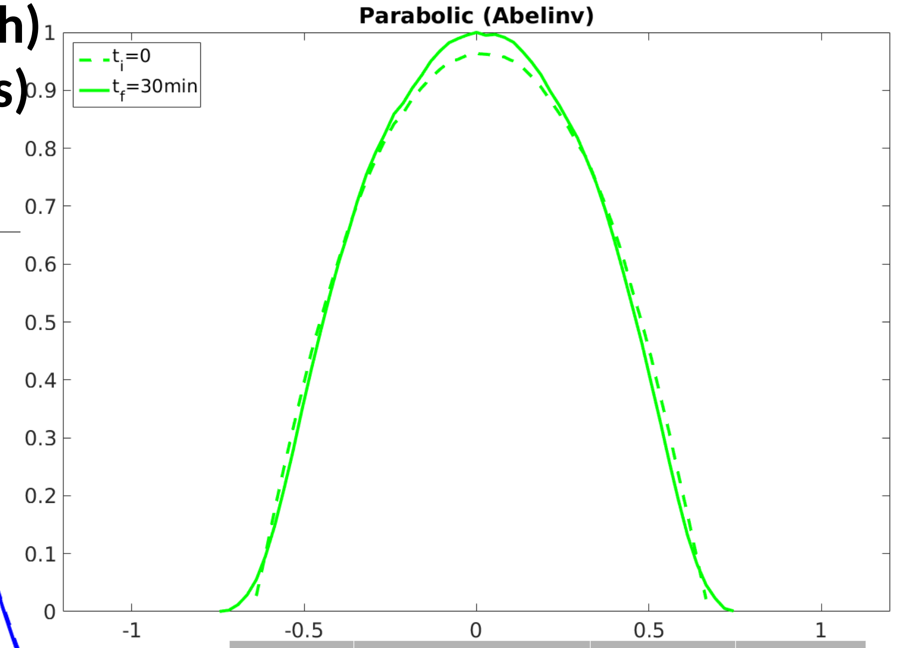
HiLumi @ FT (1h) (qGaussian fits)



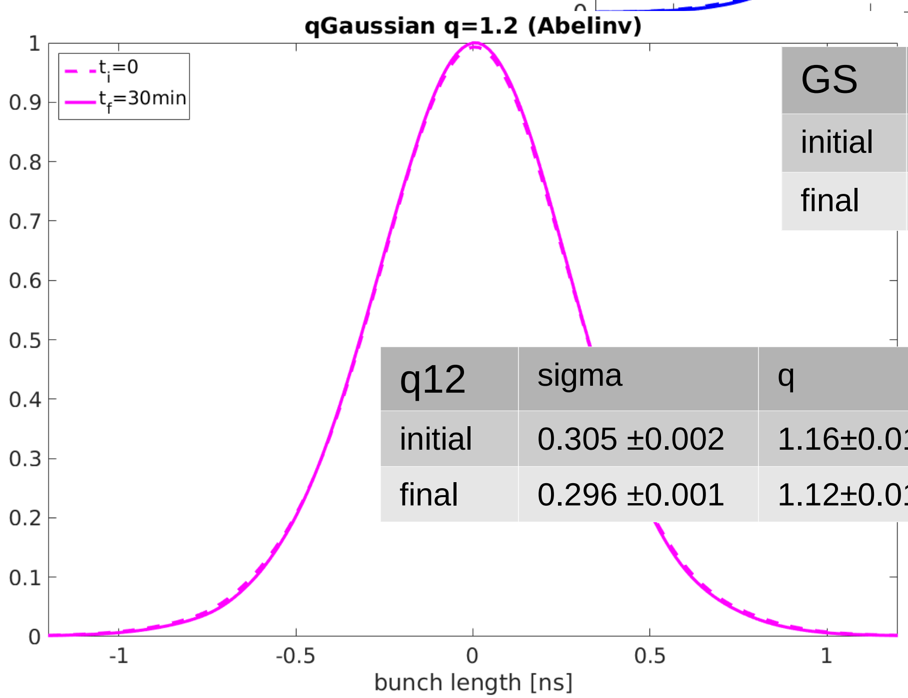
GA	sigma	q	SSE
initial	0.315 ±0.002	1.±0.	0.040
final	0.307 ±0.002	1.±0.	0.044



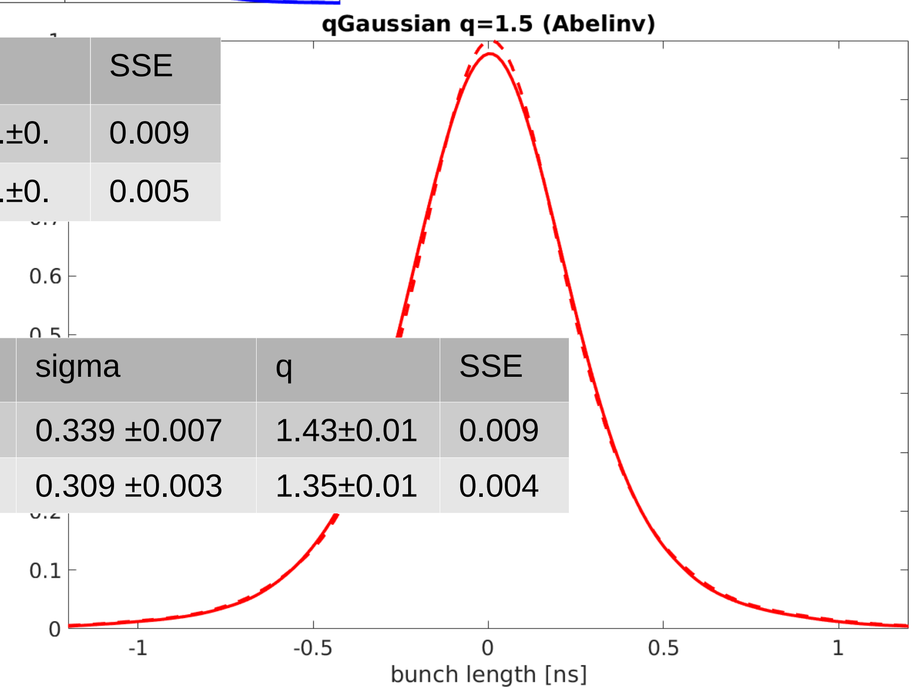
GS	sigma	q	SSE
initial	0.300 ±0.002	1.±0.	0.009
final	0.297 ±0.001	1.±0.	0.005



PA	sigma	q	SSE
initial	0.382 ±0.022	1.±0.09	0.312
final	0.354 ±0.	1.±0.	0.375

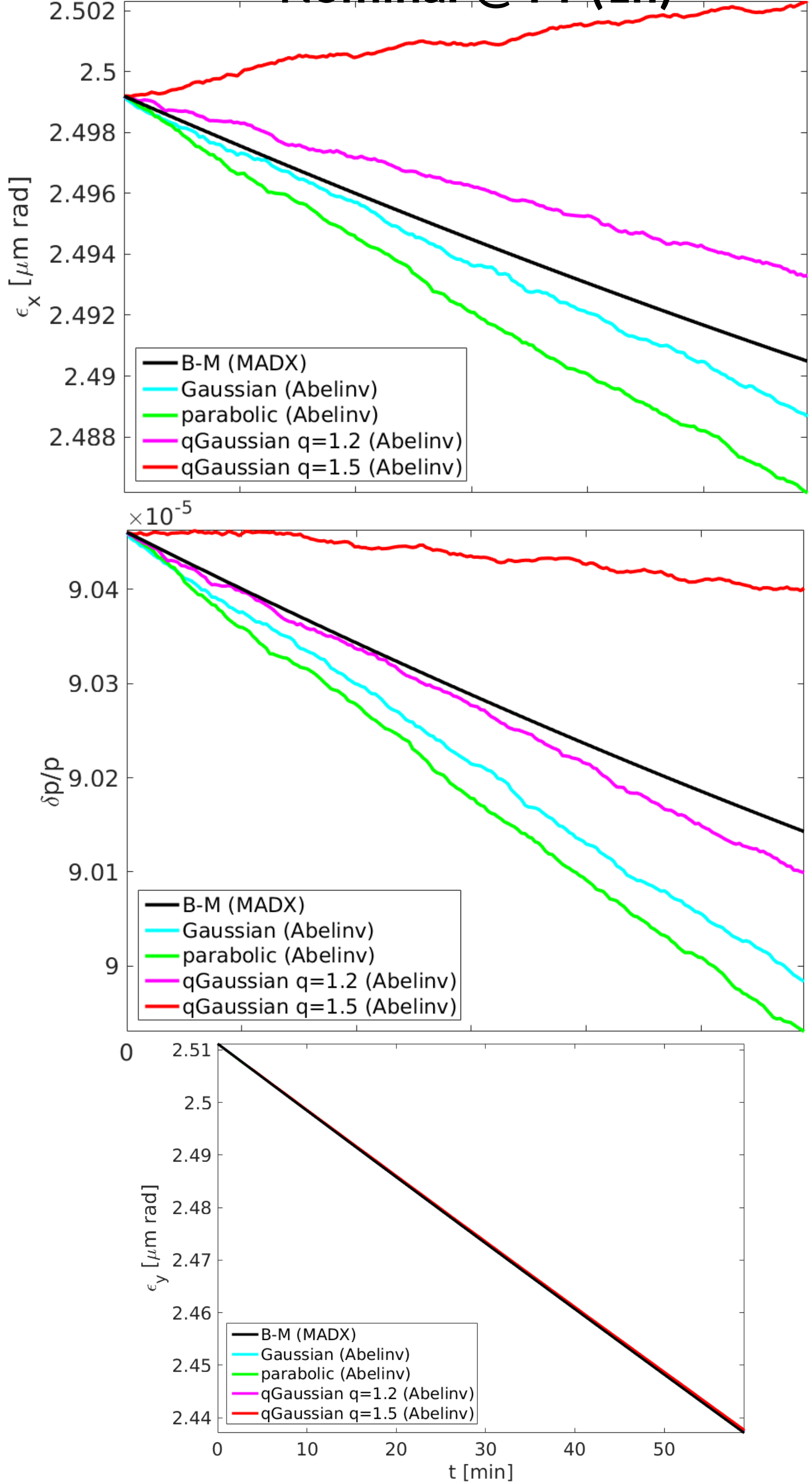


q12	sigma	q	SSE
initial	0.305 ±0.002	1.16±0.01	0.003
final	0.296 ±0.001	1.12±0.01	0.003

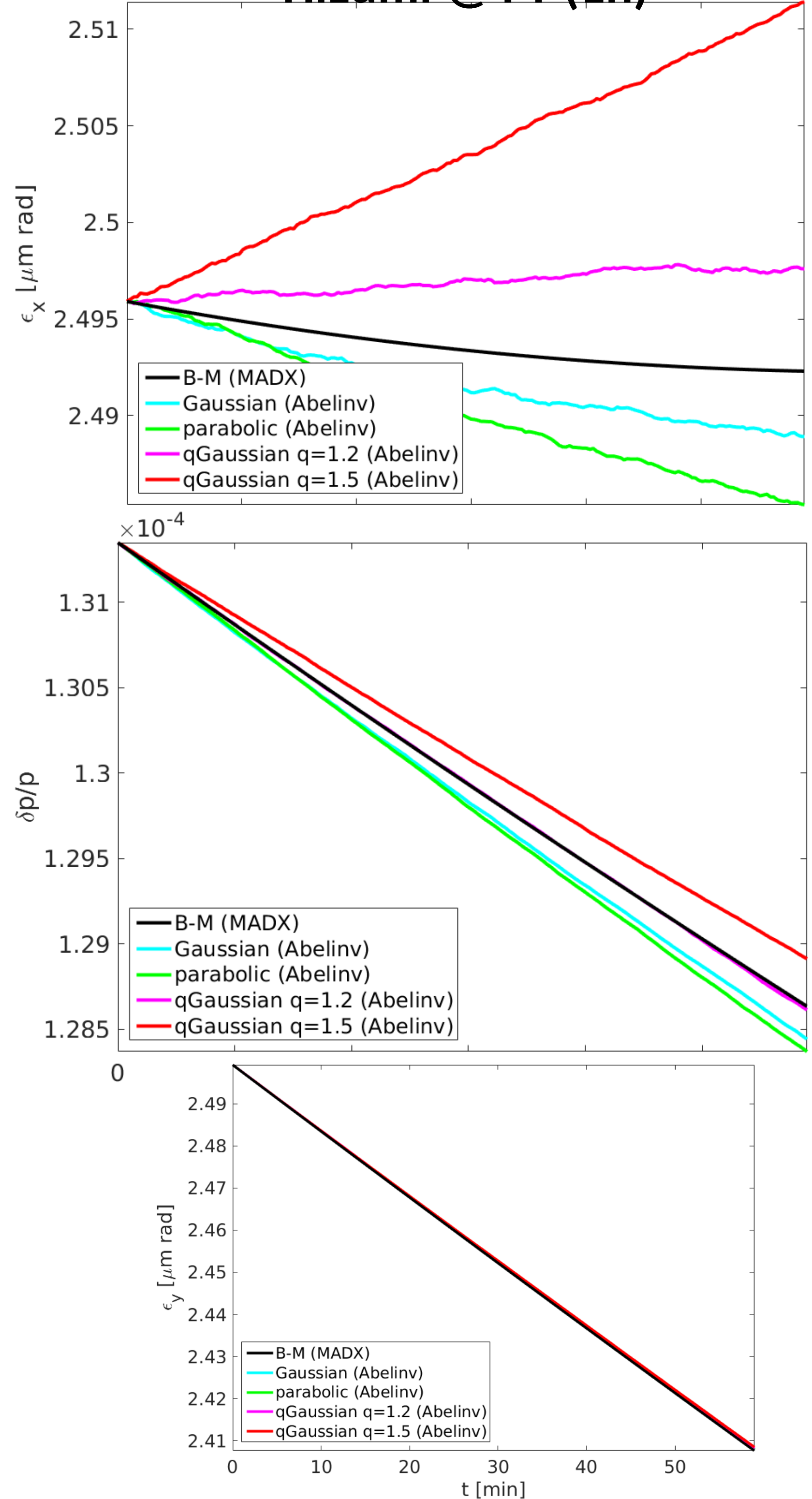


q15	sigma	q	SSE
initial	0.339 ±0.007	1.43±0.01	0.009
final	0.309 ±0.003	1.35±0.01	0.004

Nominal @ FT (1h)



HiLumi @ FT (1h)



Summary and next steps

- **Measurements of bunch profiles at the LHC FT**
  -The FFT data cleaning improves significantly the initially noisy BSRT profiles, yet not perfect cleaning.
  -The qGaussian function describes more accurately the fat tailed distributions.

- **SIRE**
  -Use of the reduced lattice, results in a much lower computational time.
  -Non Gaussian distributions (in longitudinal plane) are studied for both Nominal and HiLumi parameters, at FB and FT. At FB (IBS only) for 1h, the initially heavy tailed distributions become Gaussian. At FT (IBS&SR) for 1h, for the initially heavy tailed distributions the q parameter is reduced about 5%, meaning that the distributions become more Gaussian.
  -Benchmarking with B-M (MADX) for the 2 parameter cases, for 1h at FB and FT energies.

- Run SIRE:
  -at FT energy for many hours. After the longitudinal beam manipulations during the energy ramp, the longitudinal bunch profiles arrive at FT with a clearly non-Gaussian shape.
  -for non-Gaussian distributions also in transverse plane.
  -for other parameter cases.
- How much time does it take for a distribution to become Gaussian?
- Depending on the brightness how do the distributions evolve?

- J.D Bjorken, S.K. Mtingwa, Intrabeam Scattering, Part. Accel. Vol. 13, p. 115-143 (1983).
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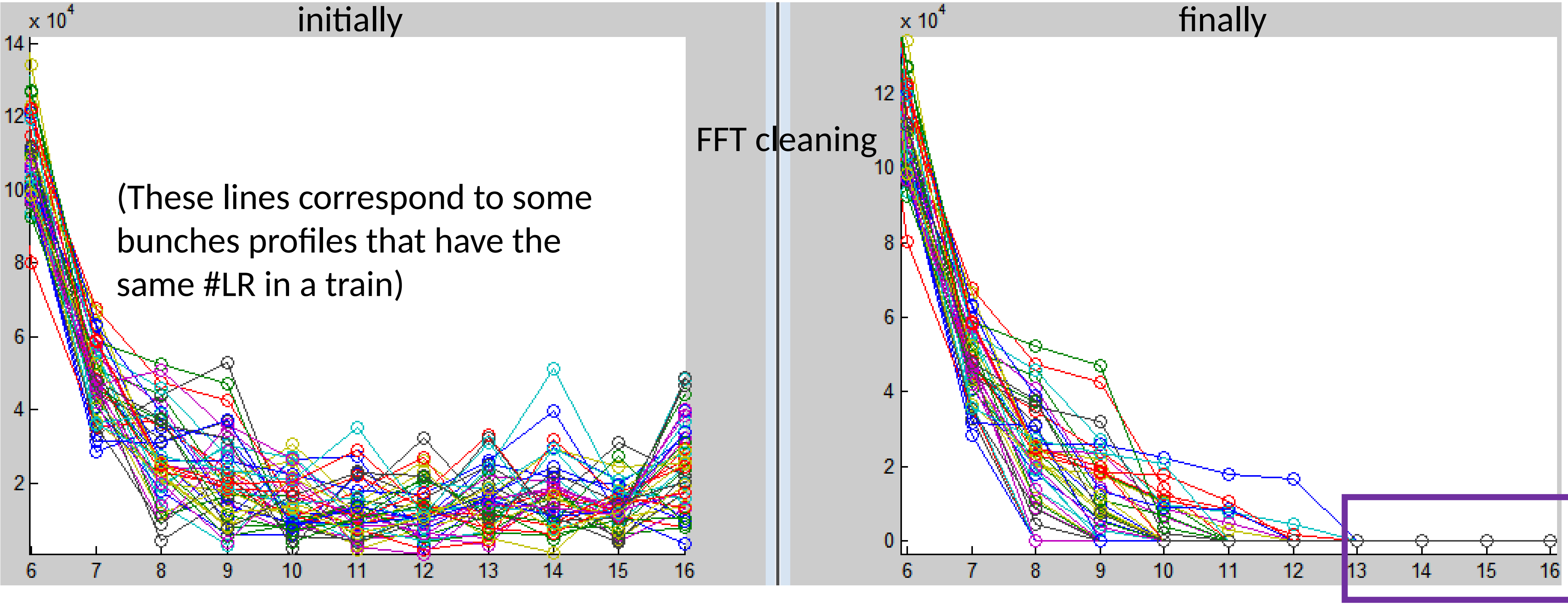
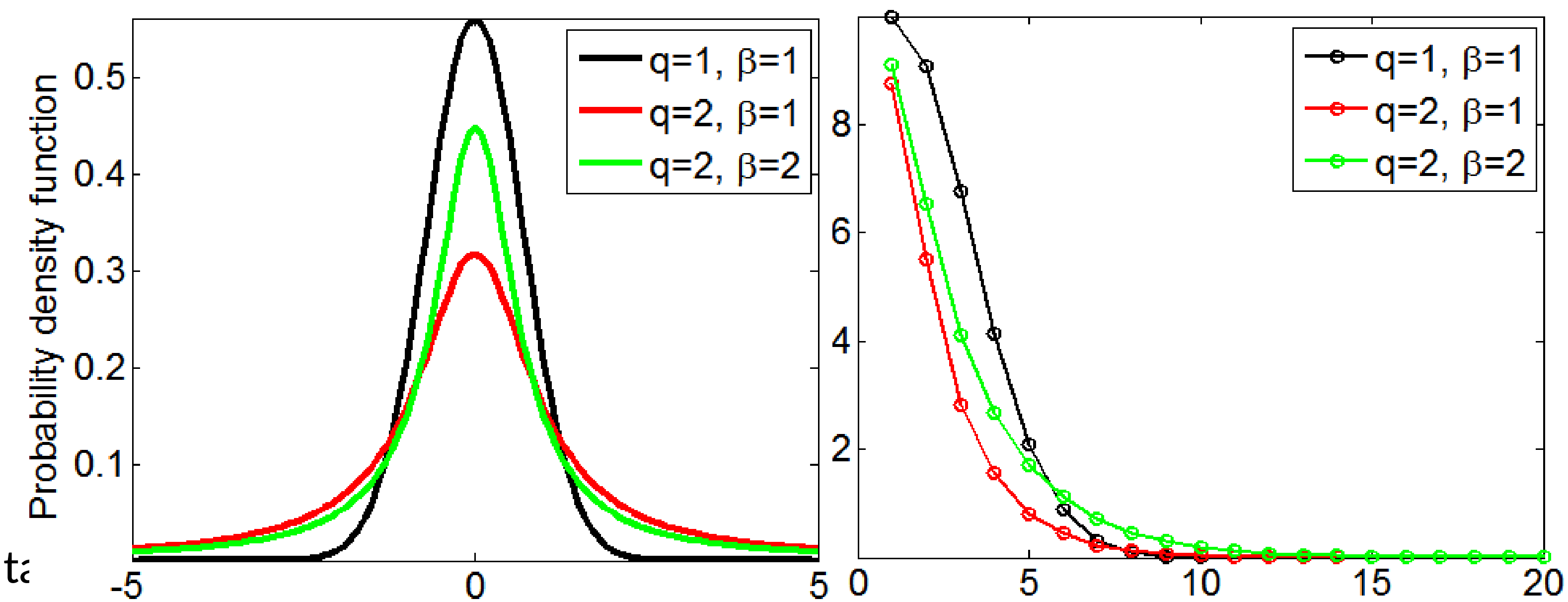
Thank you!

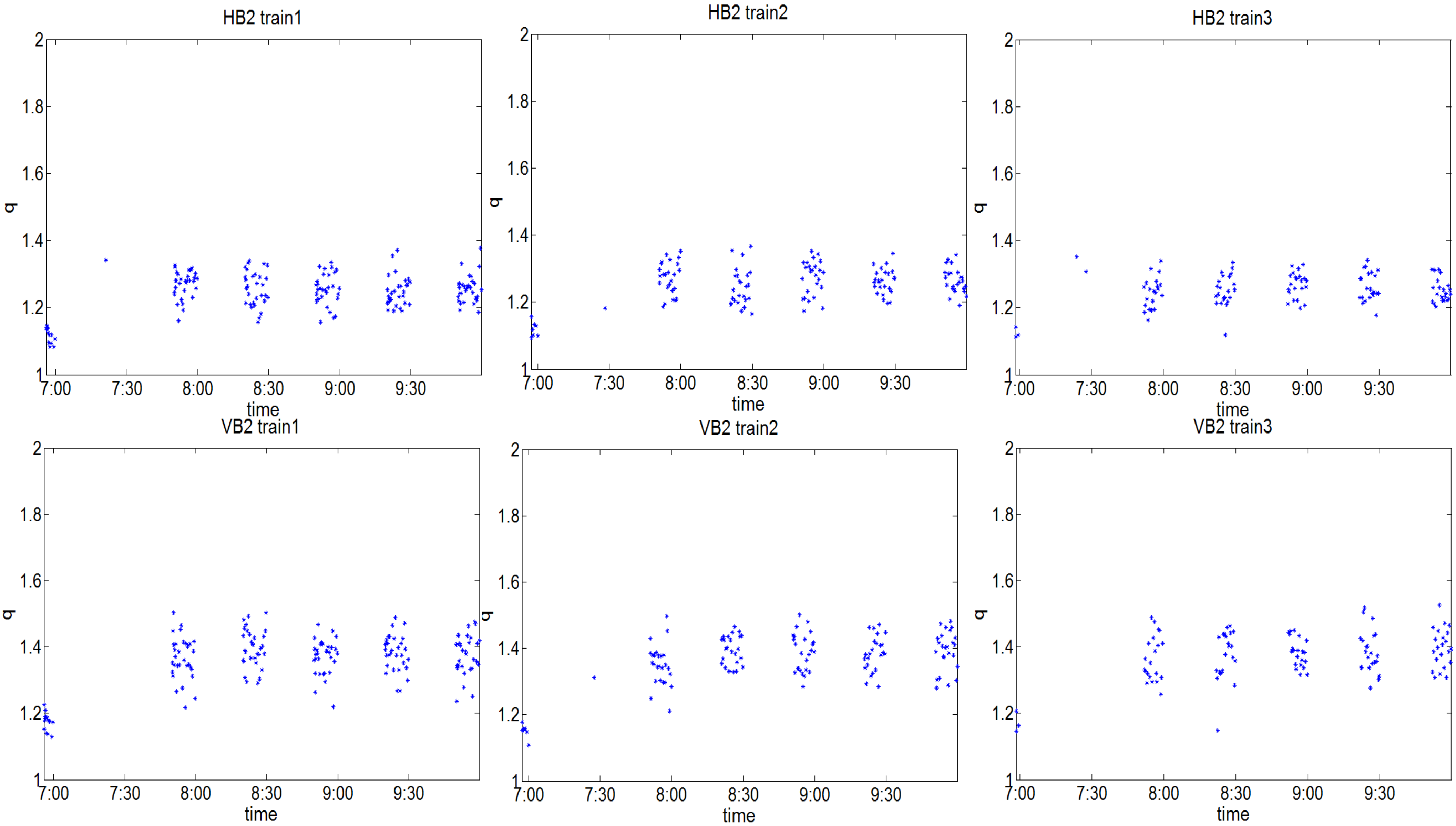
```
%remove the peaks, using some iterations (around 15 loops is ok). So during the first iteration it removes the peaks it first sees, then the ones created after the first iteration, then the next ones, etc….
```

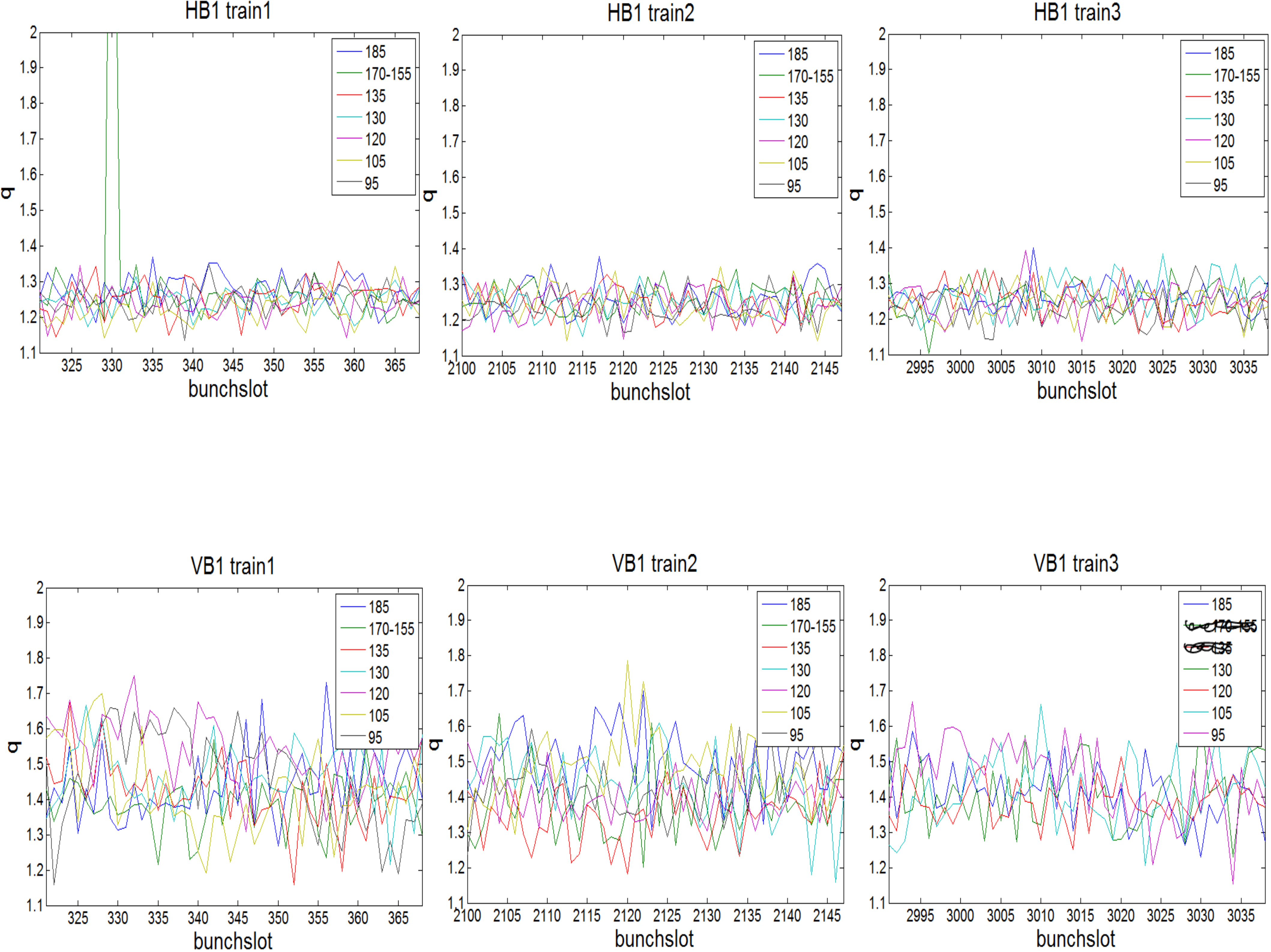


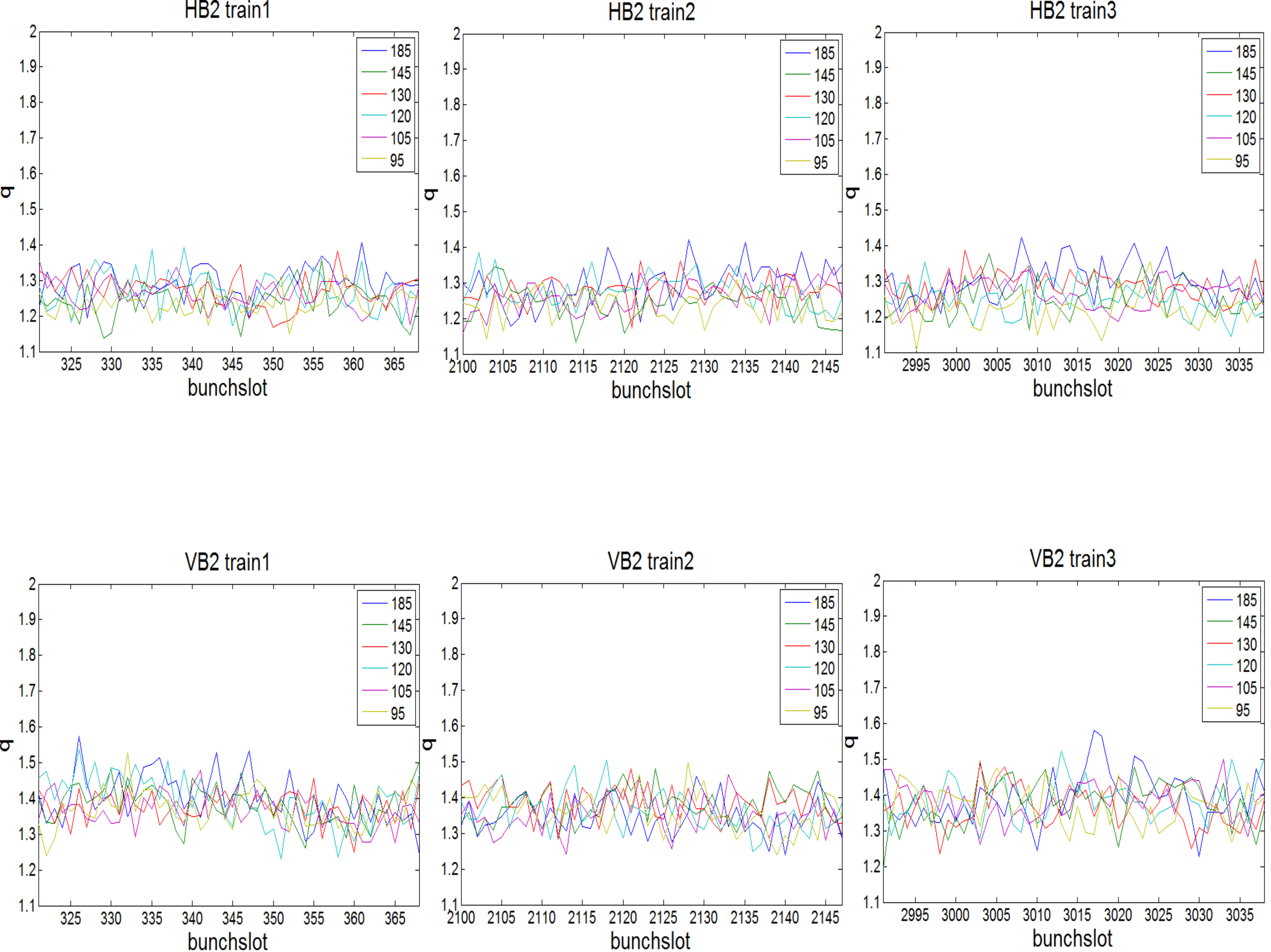
Example of FFT for a qGaussian with different ta



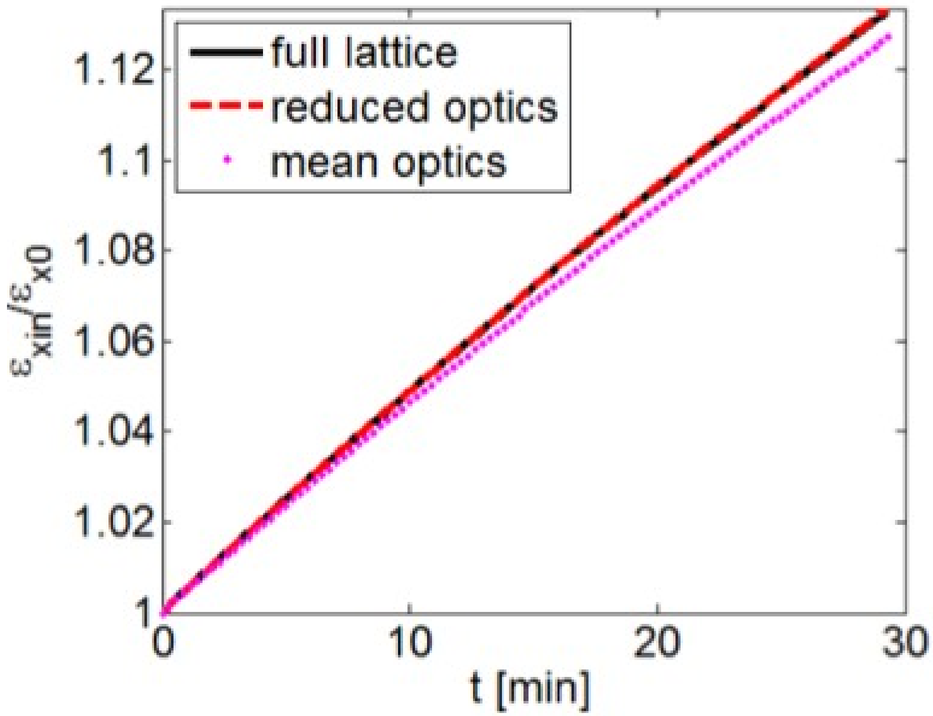
Transverse bunch profiles at FT (Fill 5137)




HB1 train1
HB1 train2
HB1 train3
VB1 train1
VB1 train2
VB1 train3
q
bunchslot
185
170-155
135
130
120
105
95



HB2 train1
HB2 train2
HB2 train3
VB2 train1
VB2 train2
VB2 train3
185
145
130
120
105
95
q
bunchslot
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
325 330 335 340 345 350 355 360 365
2100 2105 2110 2115 2120 2125 2130 2135 2140 2145
2995 3000 3005 3010 3015 3020 3025 3030 3035



The growth of the horizontal emittance due to IBS, in a time period of 30 min at FB, when considering the full lattice (black solid line), the reduced lattice (red dashed line) and the mean optics (magenta dots), as computed by MADX.