Summary of beam profile measurement uses in LHC

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LHC Beam Size Measurement Review
01/10/2019

Motivation

Beam Profile measurements

WS and BSRT

→ **beam size**

(assumed to be Gaussian)

→ **emittance**

& losses

→ **luminosity**

Along the cycle, the evolution of measured emittances does not agree with the model (IBS, SR, Coupling, Noise, Burn-off, Elastic scattering) ones

→ emittance blow-up mechanisms beyond the model predictions

Following the bbb profiles (in many cases non-Gaussian) along the cycle

→ explain impact on emittance and luminosity evolution

→ understand discrepancy between different emittance measurements

Outline

- Observations
  - Emittance growth
  - Agreement between emittance estimates
- Luminosity evolution
  - Measured and Model
- Unknown emittance growth
- Non-Gaussian bunch profiles
  - Impact on beam size and luminosity
  - Simulations
- Studies heavily based on bunch profiles
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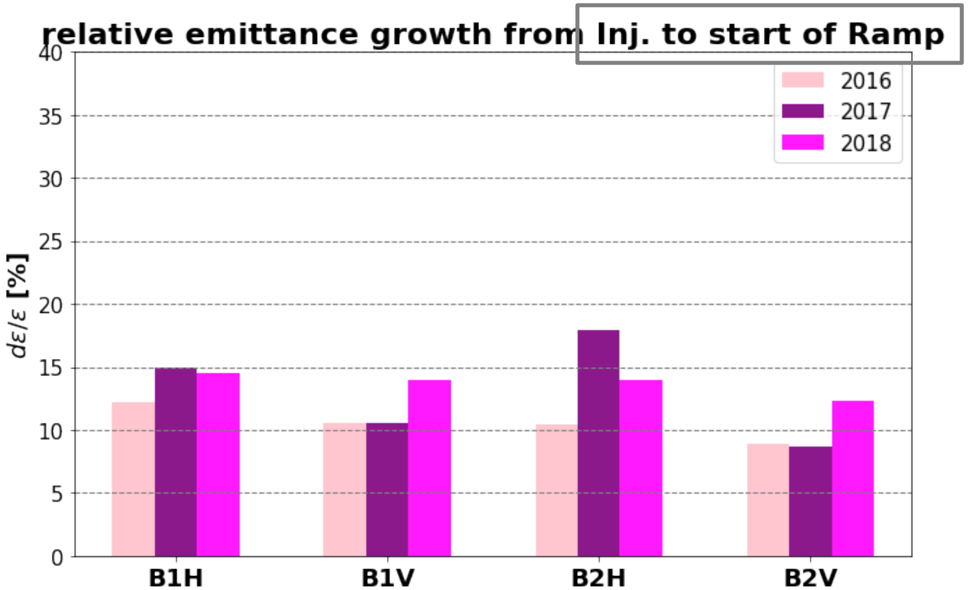
Observations: emittance growth

Considering only BCMS Fills, for which the BSRT emittances can be trusted

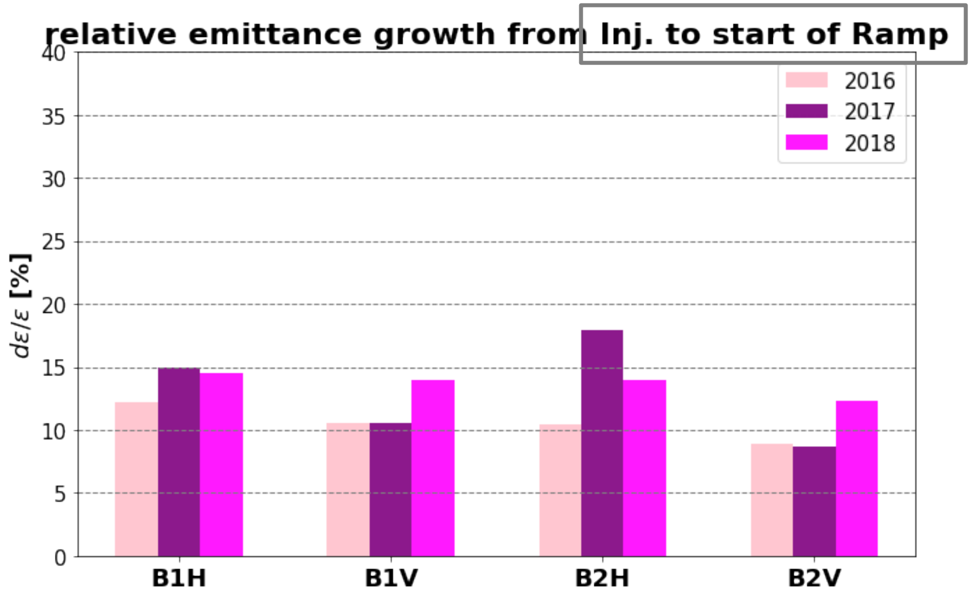


Growth at Flat Bottom

- Apart from IBS and e-cloud contribution, part of the growth not understood (studies to correlate it with noise)
- bbb profiles necessary

Observations: emittance growth

Considering only BCMS Fills, for which the BSRT emittances can be trusted



Growth at Flat Bottom

- Apart from IBS and e-cloud contribution, part of the growth not understood (studies to correlate it with noise)
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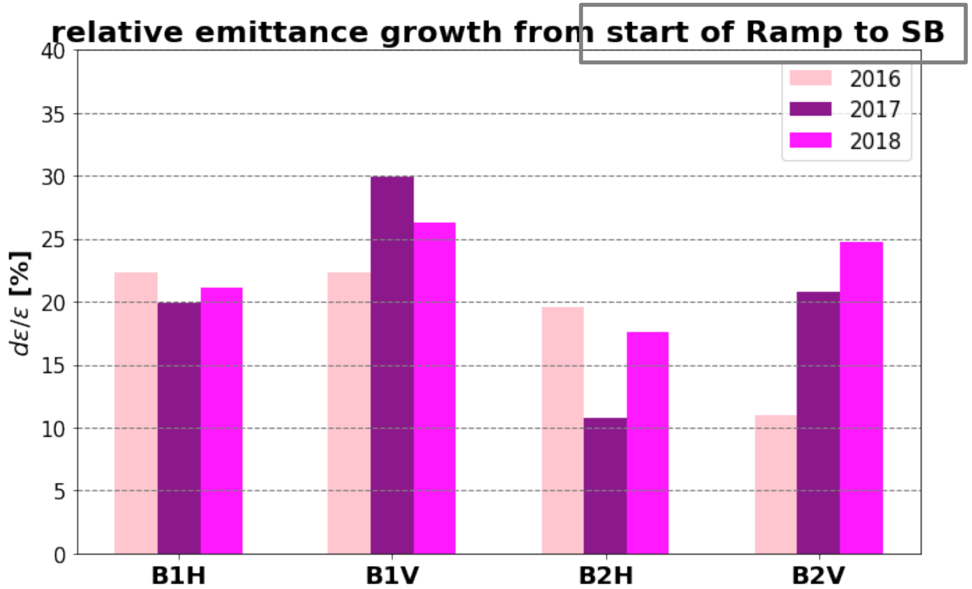
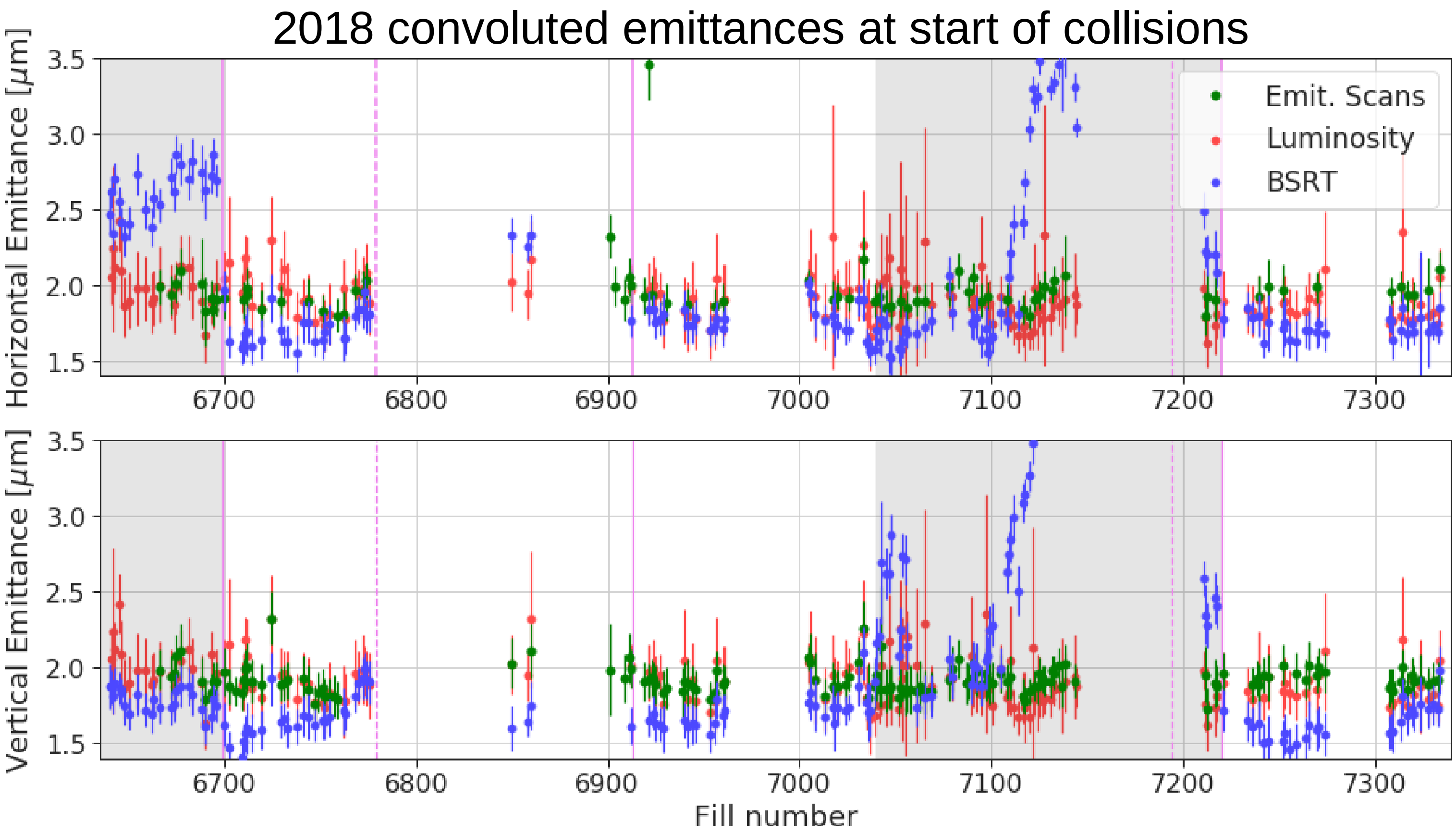


Growth at Ramp

- More in vertical compared to horizontal
- Blow-up not understood
- Lack of diagnostics

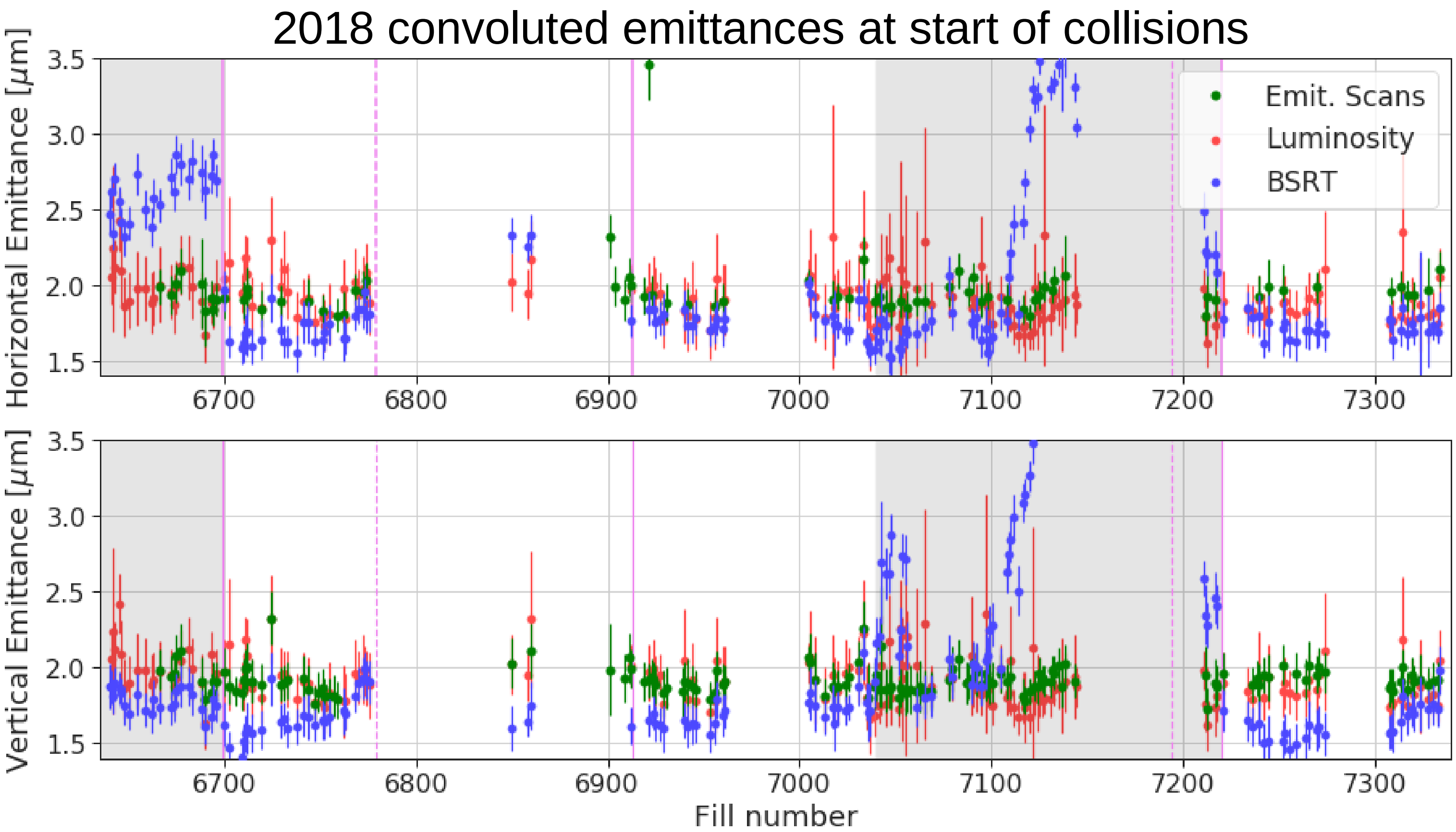
Observations: agreement between emit. estimates



- Agreement of convoluted emittances from Emittance Scans with respect to the ones from Luminosity is 5-15% (depending on the plane)
- Emittances from WS up to 5-15% lower than the Luminosity predicted ones

G. Trad, E. Bravin
link→BSRTcalibr_LMC

Observations: agreement between emit. estimates



- Agreement of convoluted emittances from Emittance Scans with respect to the ones from Luminosity is 5-15% (depending on the plane)
- Emittances from WS up to 5-15% lower than the Luminosity predicted ones

→ For 2018, only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 15% are considered

G. Trad, E. Bravin
link→BSRTcalibr_LMC

- Understanding discrepancy between BSRT (calibrated against WS) and emittance from Luminosity is important

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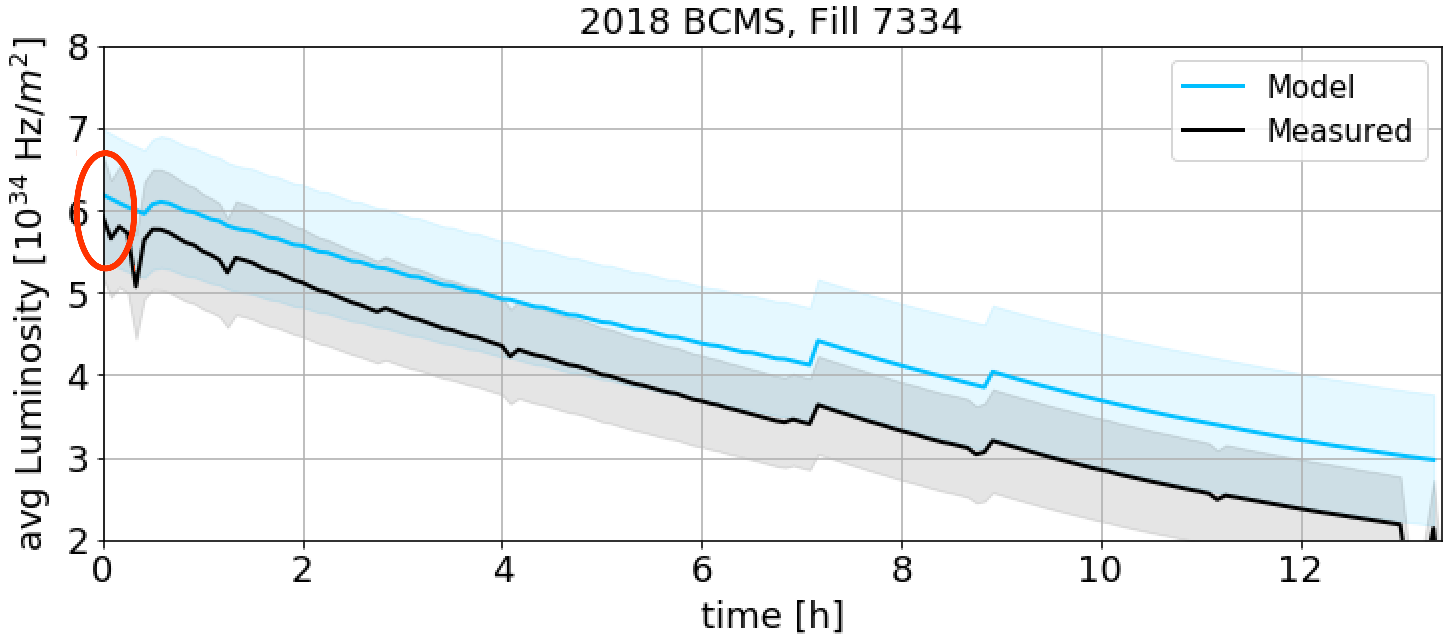
Luminosity evolution

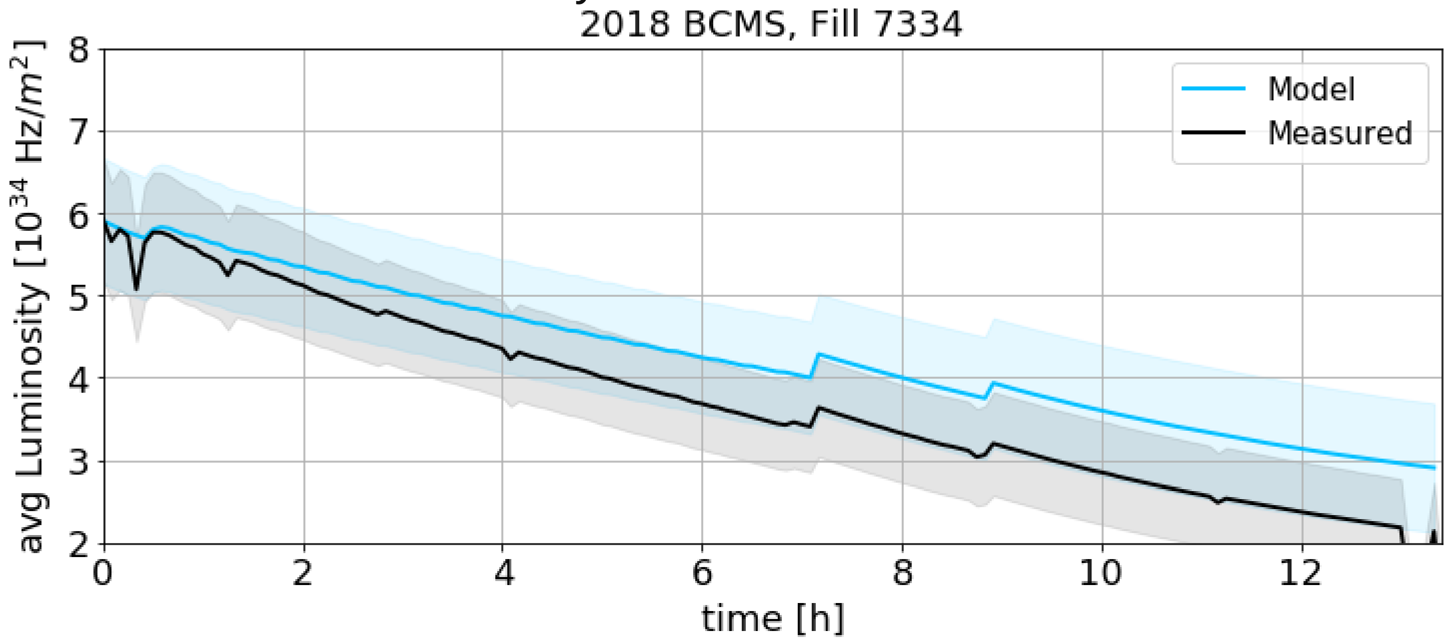
model input → initial BSRT emittances



The model is **sensitive to the initial conditions** (emittances, intensities, etc), the agreement of the calculated luminosity from the model with the measured one can be used as a **validation of the data quality**

Luminosity evolution

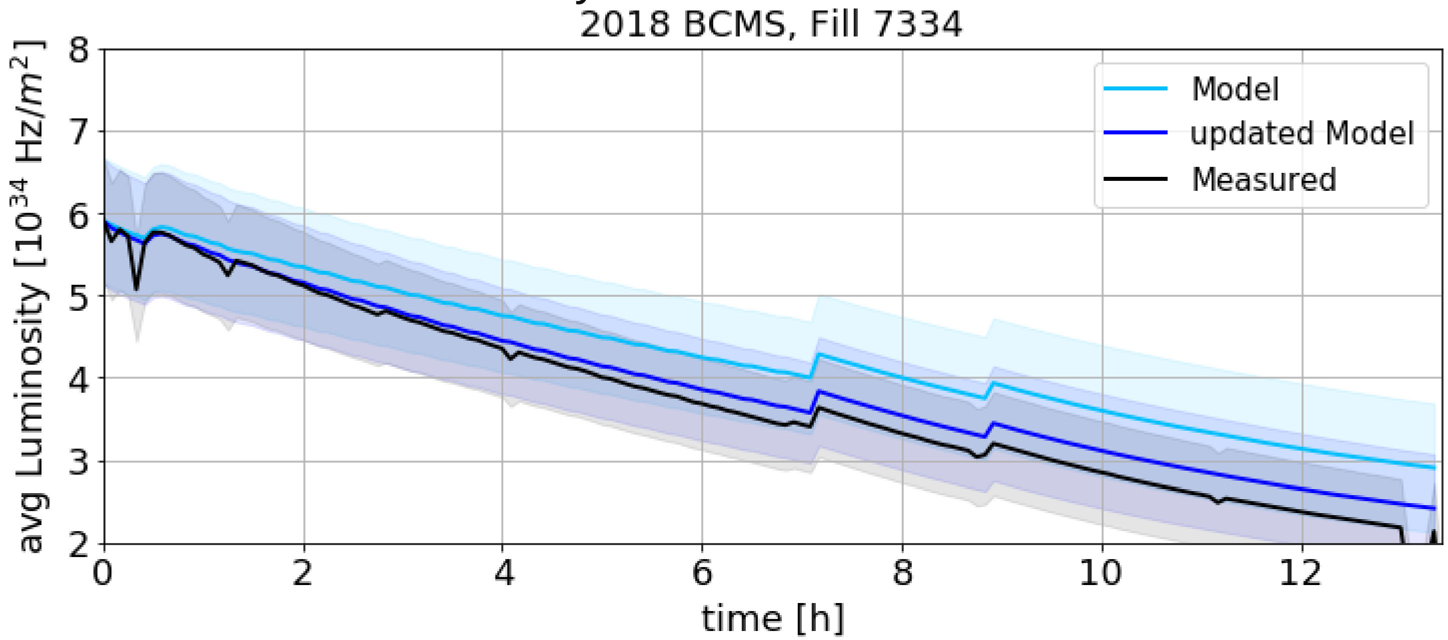
model input→ initial BSRT emittances **corrected** with respect to the ones expected from the measured Luminosity



Comparison of **Model-Measured**,
to understand the **luminosity degradation due to mechanisms that are beyond the model**

Luminosity evolution

model input → initial BSRT emittances
corrected with respect to the ones
expected from the measured Luminosity



link → upLuminosityModel_WP2_stef

Including the mechanisms of noise & coupling & burn-off for the emittance growth,
the **updated Model** gives significantly better luminosity predictions
→ **to be used for HiLumi estimations**

Can be improved if we understand sources of the remaining emittance growth

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Unknown emittance growth

Comparing model to measured emittances
→extra (on top of the model) emittance growth

Flat Bottom		
Emittance growth on top of the model (& e-cloud) [μm/h]	**H**	**V**
	0.1	0.3

Stable Beams		
Emittance growth on top of the model (& e-cloud) [μm/h]	**H**	**V**
	0.01-0.02	0.01

- At collisions, very good emittance and luminosity predictions
- At Flat Bottom, e-cloud explains 30-50% of the growth that is beyond the model, but there is still a remaining part coming from unknown mechanisms (more in vertical compared to horizontal)
- Rest of emittance growth needs to be understood→bbb profiles would be helpful to reveal/qualify emittance growth mechanisms

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Non-Gaussian bunch profiles→beam size

The **q-Gaussian function** is used to describe more accurately the non-Gaussian tails of the LHC bunch profiles, having a probability density function that is:

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

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

q<1→ light tailed
q=1→ Gaussian
q>1→ heavy tailed

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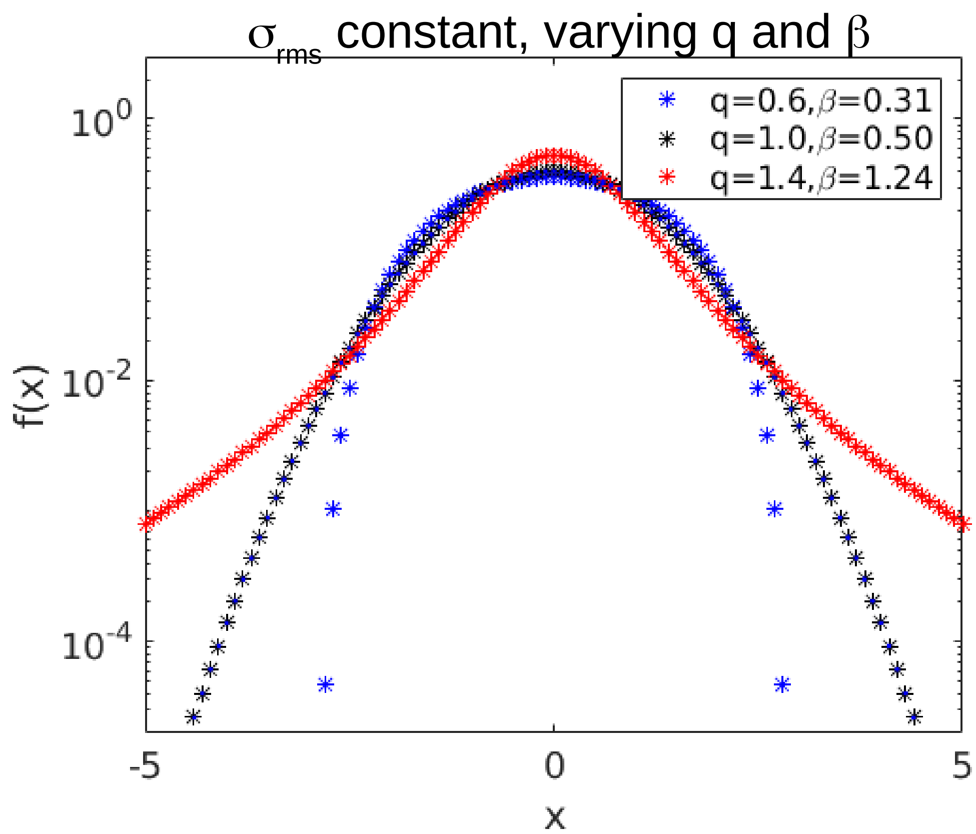

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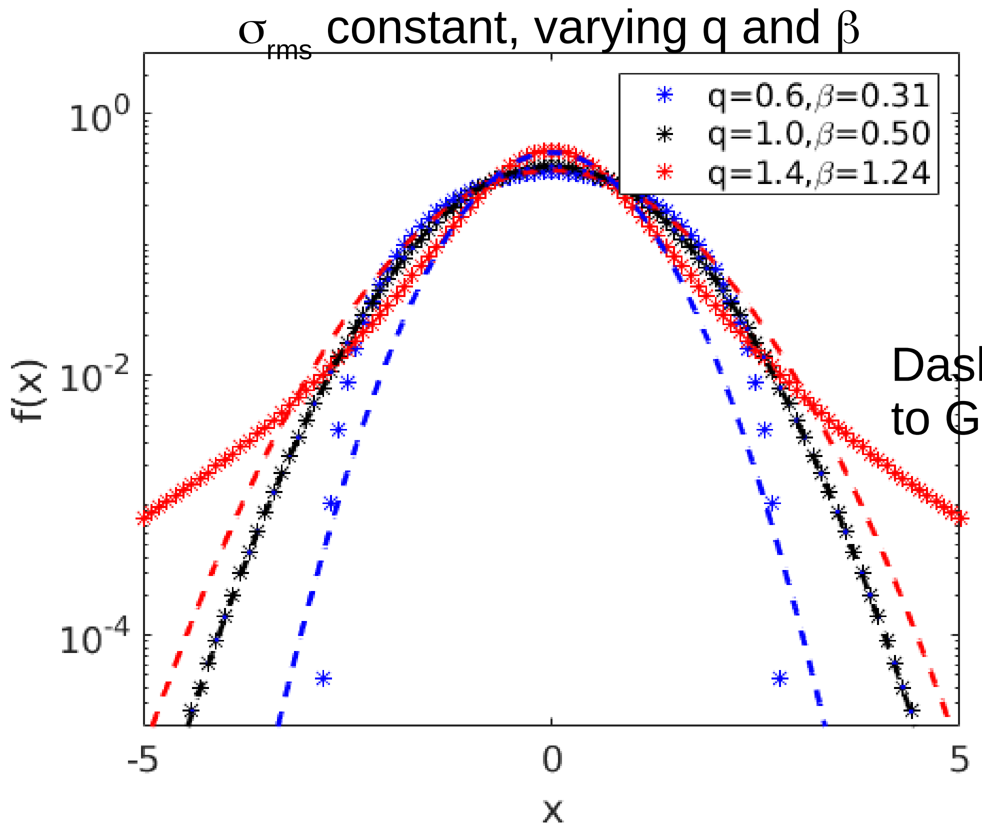

q<1→ light tailed
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q>1→ heavy tailed

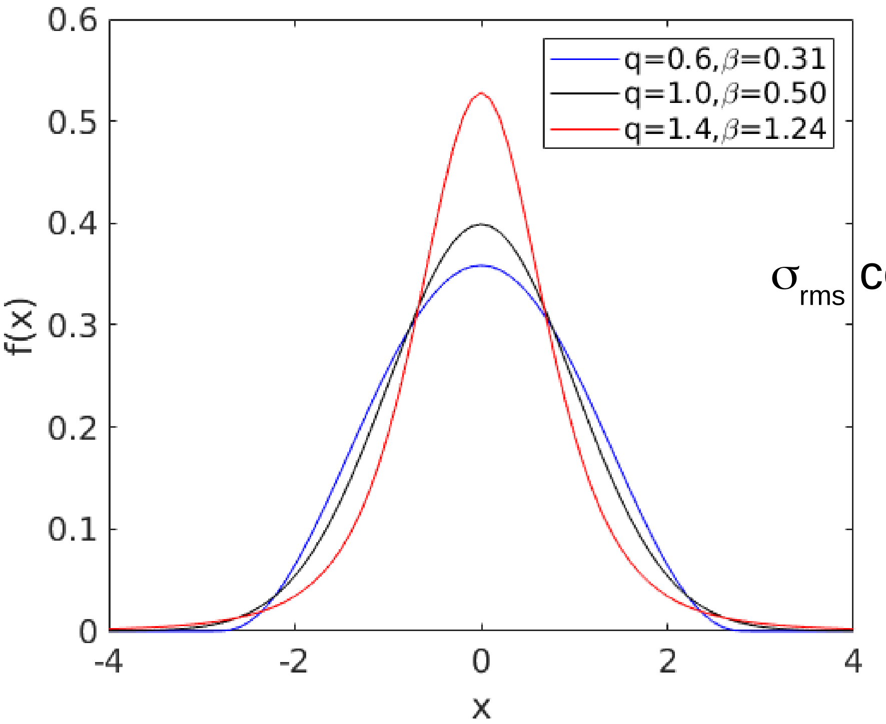
Dashed lines correspond to Gaussian fitting

	q-Gaussian rms	Gaussian rms
Light tailed (q=0.8)	1.00	1.10
Gaussian (q=1.0)	1.00	1.00
Heavy tailed (q=1.2)	1.00	0.74

rms is overestimated

rms is underestimated

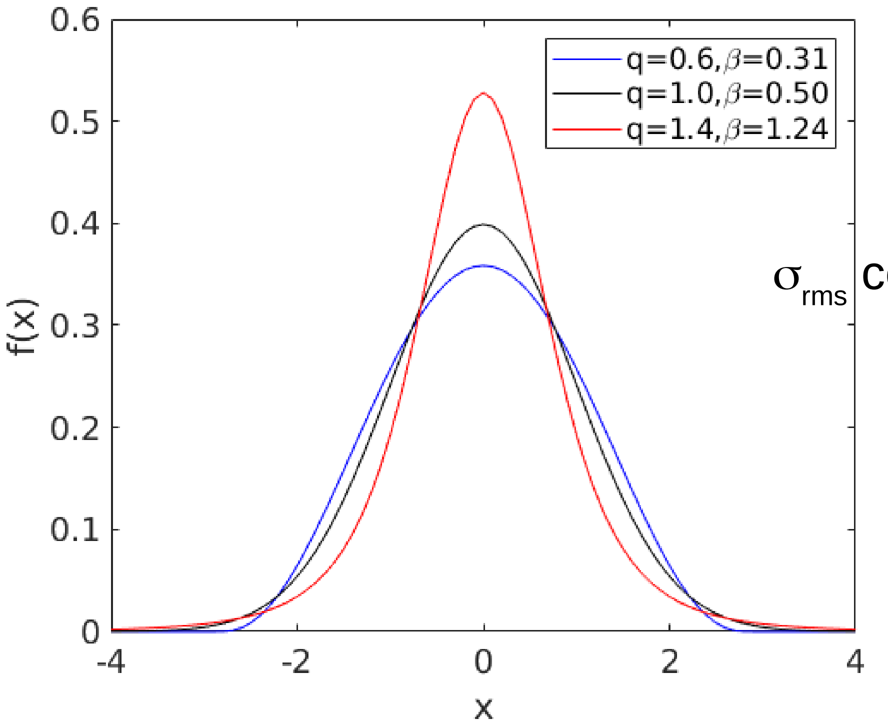
Non-Gaussian bunch profiles→luminosity



σ_{rms} constant, varying q and β

Varying the tails of the transverse distributions in the same way for both beams

Non-Gaussian bunch profiles→luminosity



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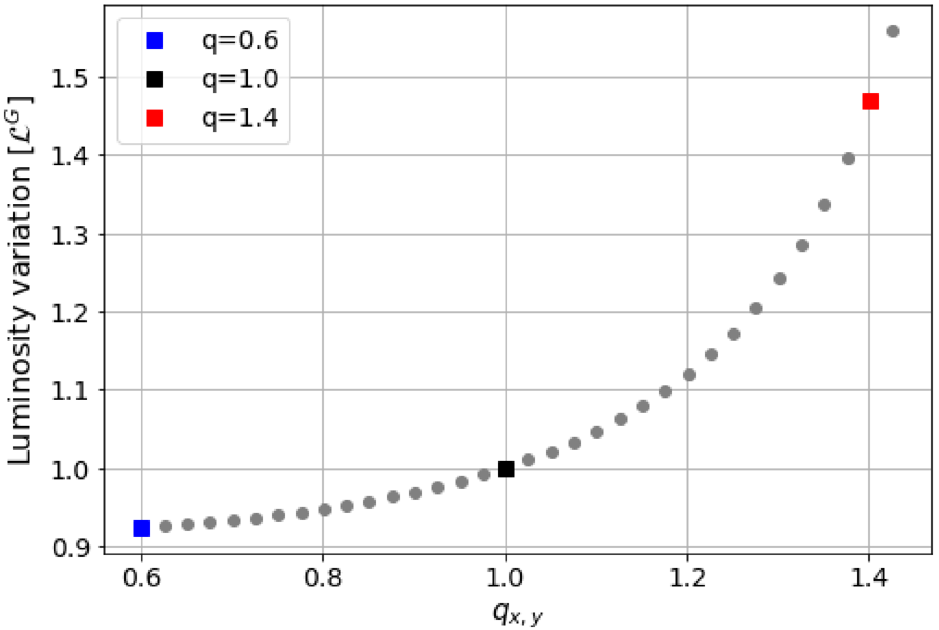
Varying the tails of the transverse distributions in the same way for both beams

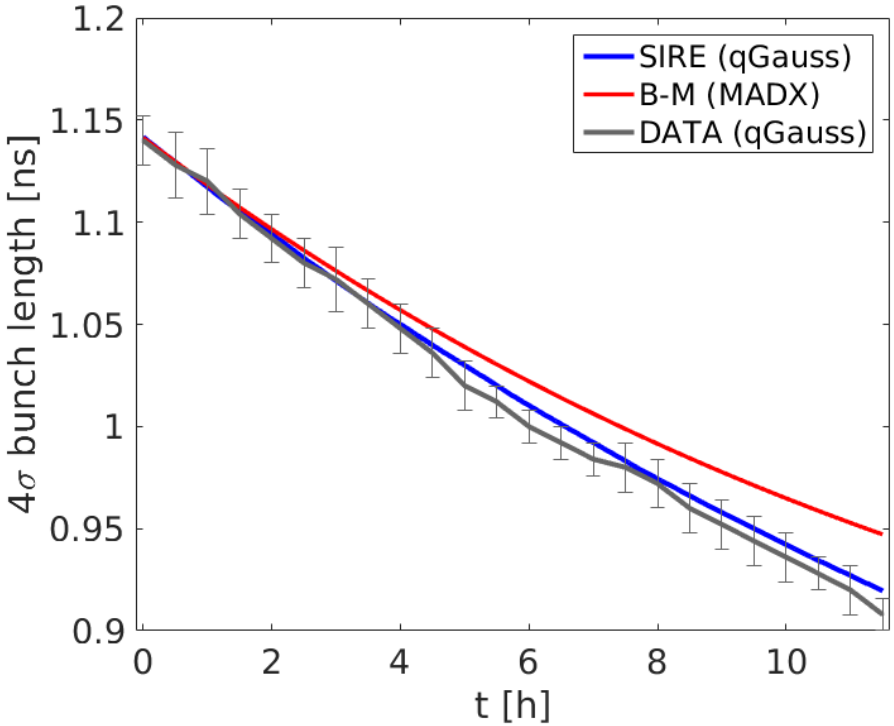


For a constant σ_{rms}, by increasing the tails of a distribution (q and, also β) the Luminosity gets higher (with respect to the Luminosity for Gaussian distributions $\mathcal{L}^G$)

Non-Gaussian bunch profiles→simulations

using the **S**oftware for **I**BS and **R**adiation **E**ffects (**SIRE**),
a Monte Carlo multi-particle simulation code developed by A. Vivoli and M. Martini
(see backup slides)

-**SIRE** calculates IBS for any distribution
-**MAD-X** IBS module assumes Gaussian distributions



Bunch length evolution at collisions, based on a longitudinal profile which arrives at FT with a non-Gaussian shape and is fitted with the q-Gaussian function. Assuming that the transverse bunch profiles are Gaussian.

The results encourage the idea of using the code for tracking any distribution, in order to study the impact of the distribution's shape on the evolution of the bunch characteristics

Non-Gaussian bunch profiles→simulations

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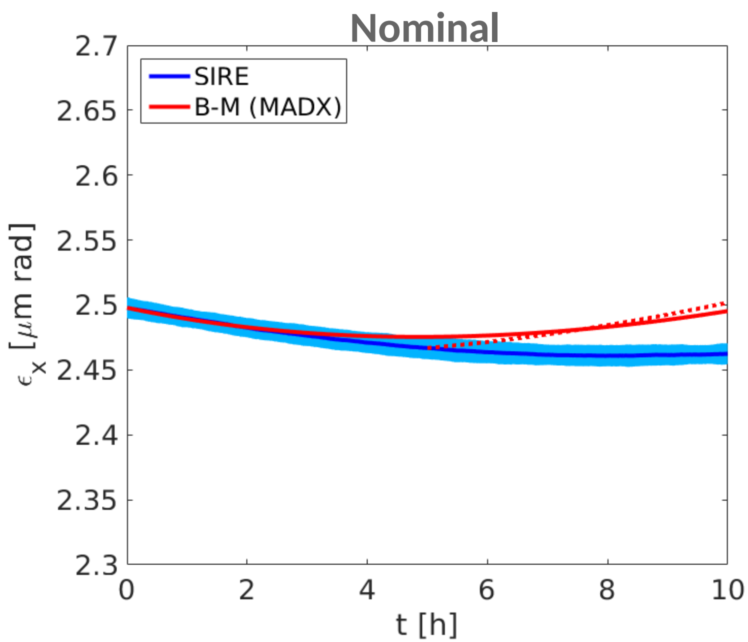
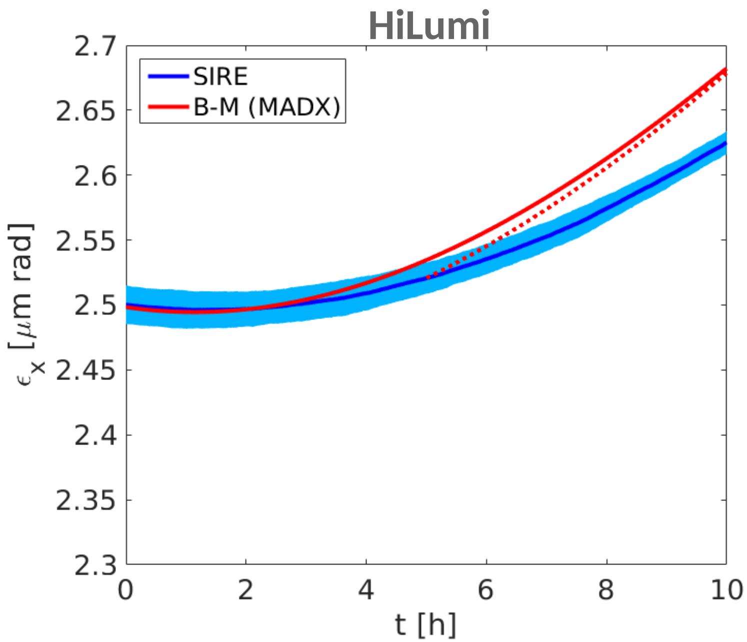
Parameters @ FT	Nominal	HiLumi
$\varepsilon_{x,y}$ [mm]	2.5	2.5
4σ bunch length [ns]	1.0	1.2
Bunch population $[10^{11}]$	1.1	2.2





The divergence between SIRE and MAD-X is expected since the distribution shape in SIRE is updated, while in MAD-X it remains Gaussian

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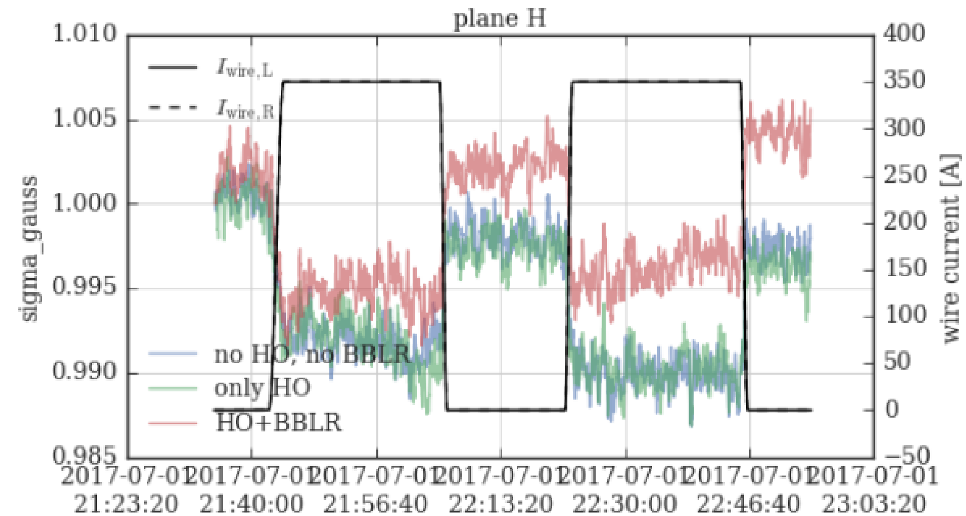
Studies heavily based on bunch profiles

- Beam-beam studies
- E-cloud studies
- Octupoles & chromaticity impact
- Optics measurements
- Instabilities/Noise studies
- BSRT calibration Fills
- etc...

-Performed mostly at constant (top) energy
-Different rms estimation/variation if the profiles are not Gaussian?

LR BB compensation with wire
link → BBLR_wire_MD2202



-Define the bbb profile tails evolution
-Correlate bbb losses with transverse (and longitudinal) profiles

G. Sterbini et al.

Studies heavily based on bunch profiles

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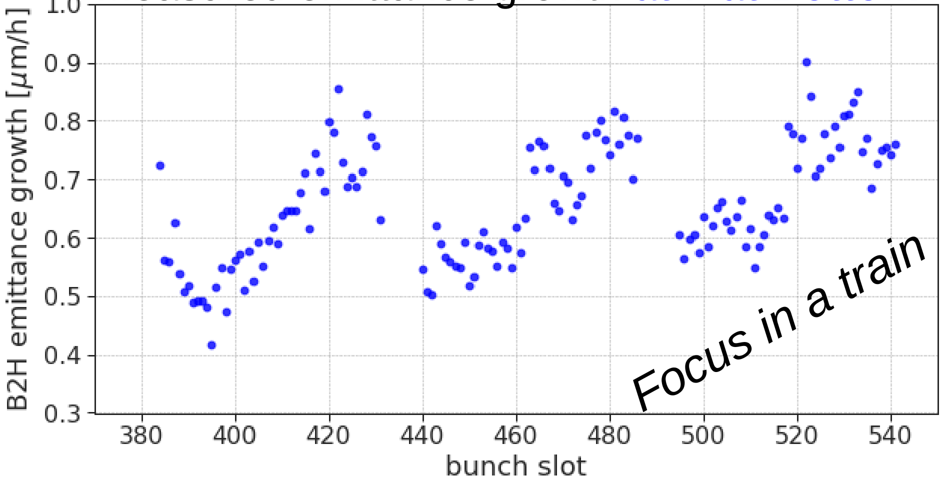
-Emittance growth (instability) in tail of bunch trains
-Beam size increased, leading to losses

Measured emittance growth **at Flat Bottom**



-Different growths along batches and trains
-bbb intensity and profile measurement necessary

Studies heavily based on bunch profiles

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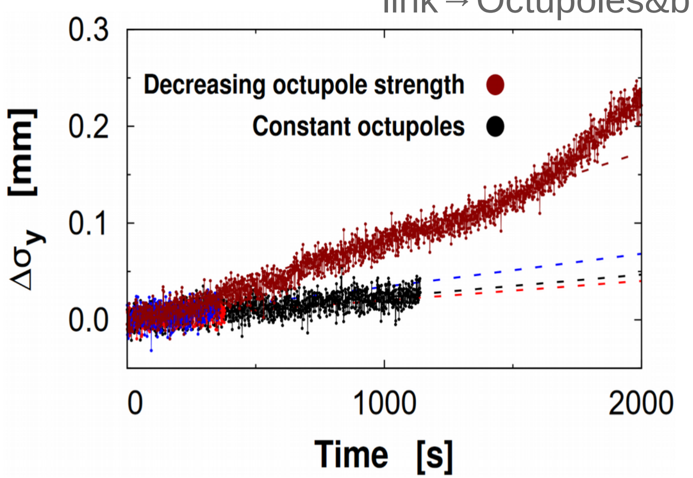
<u>Mechanisms for emittance growth during LHC Ramp</u>:
-impact of nonlinear islands and dynamic octupole powering
-bunch profiles during Ramp

link→Octupoles&blowUp



E.H. Maclean et al.

Studies heavily based on bunch profiles

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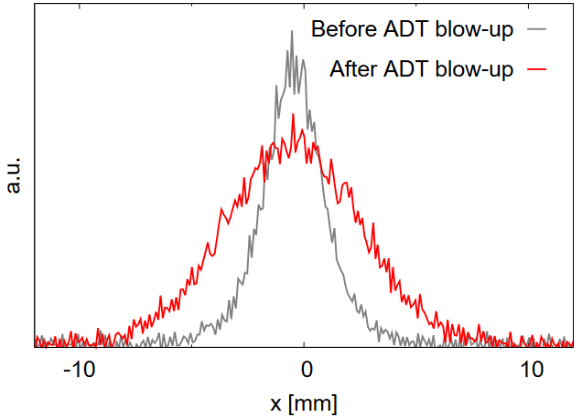
Direct study of DA requires pilot intensity and profile:
-Typically measure profile with BWS before/after kick, and monitor losses with BCT
-Alternatively, measure DA via emit. blow-up with ADT
-Optics/DA studies utilize pilots with a large range of emittances
-Use BSRT to continuously monitor bunch profile during studies of DA as function of time



E.H. Maclean et al.

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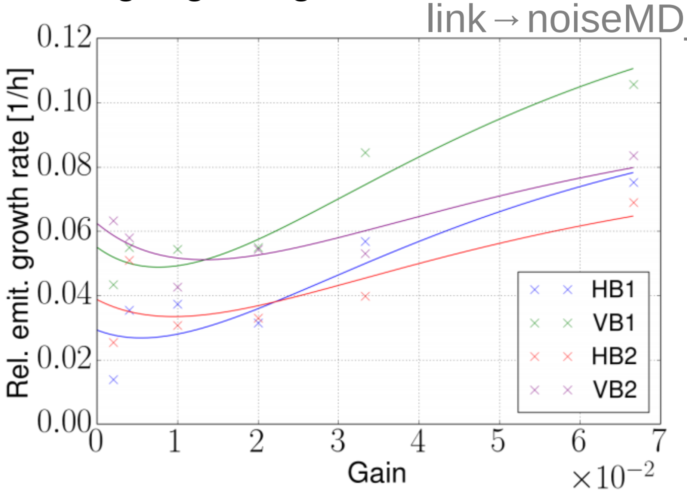
Determine indirectly the noise level in the LHC, isolating the contribution of the transverse damper, through their impact on the emittance of colliding high brightness bunches

link→noiseMD_Xavier



Measured relative emittance growth rate of the different bunches experiencing different gains

X.Buffat et al.

Studies heavily based on bunch profiles

- Beam-beam studies
- E-cloud studies
- Octupoles & chromaticity impact
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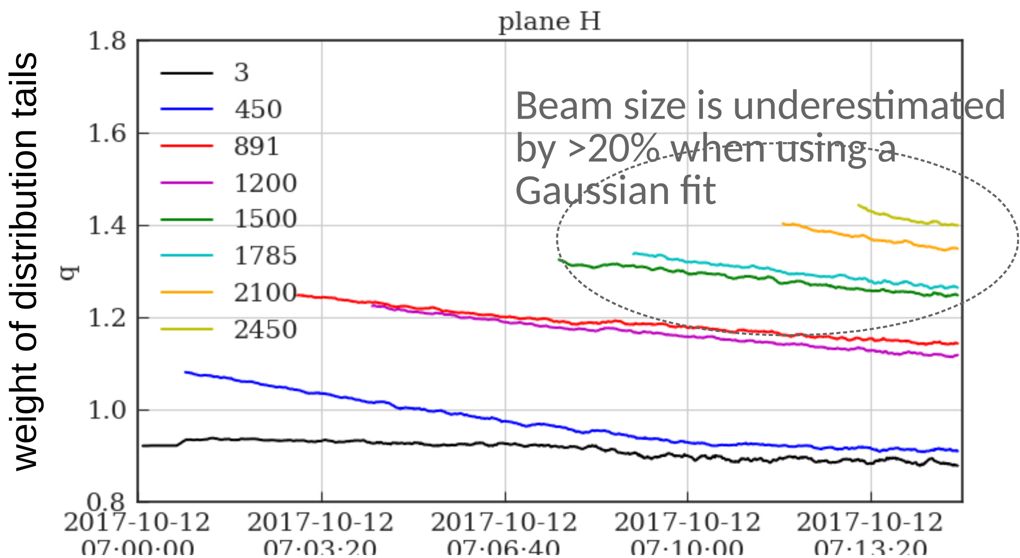
- etc...

-Few bunches per beam of various emittances (blown up in the injectors). How close to Gaussian are the profiles of the different emittances?



-Fitting appropriately the bunch profile determines the beam sizes used for calibration

Summary

Evolution of the bunch profile shape along the LHC cycle

- Accurate beam size/emittance measurements
- Understand the bbb emittance growth along the cycle

  -at FB, there is still a blow-up coming from unknown mechanisms

  -at Ramp, obtain profiles to explain observed blow-up

  -at collisions, a small remaining emittance growth (can be improved)
- Agreement between different emittance estimations
- Better predictions using the Luminosity model

  and Simulations based on realistic profile shapes
- Understand tail population, important for effects at the far tail regime (e-cloud, beam-beam)
- On-line and off-line measurements

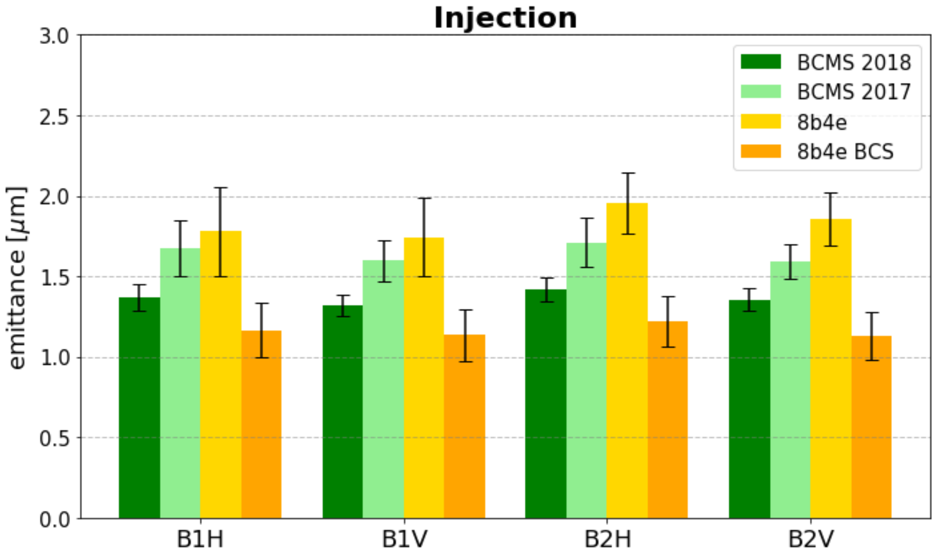
  -monitoring during collisions to improve performance

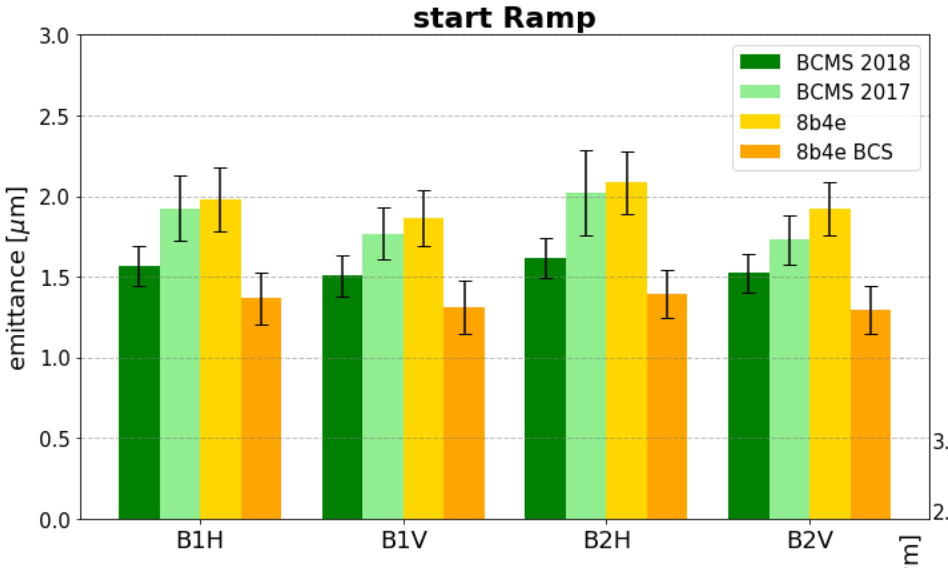
  -useful also for MDs
- Agreement with the SPS emittance estimates and transverse beam quality monitoring

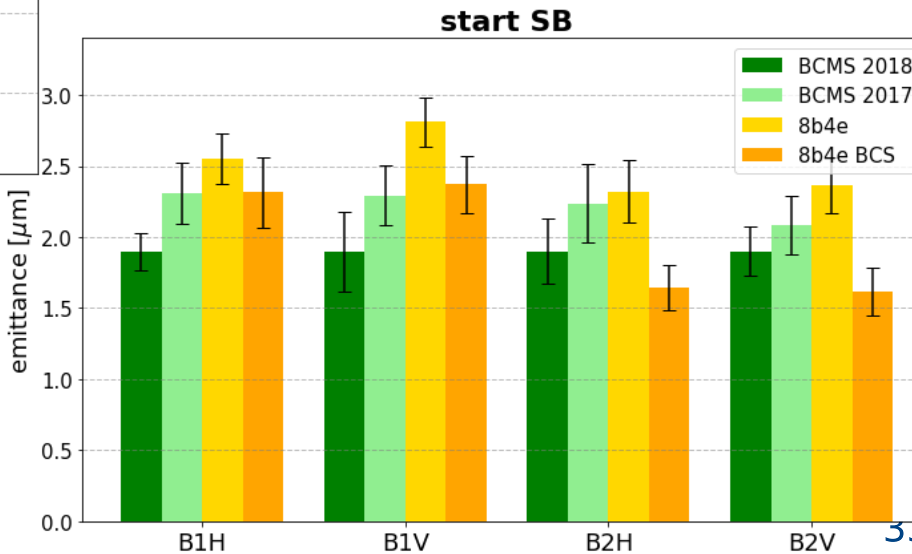
Thank you!

extra slides

Run2 emittances along the cycle





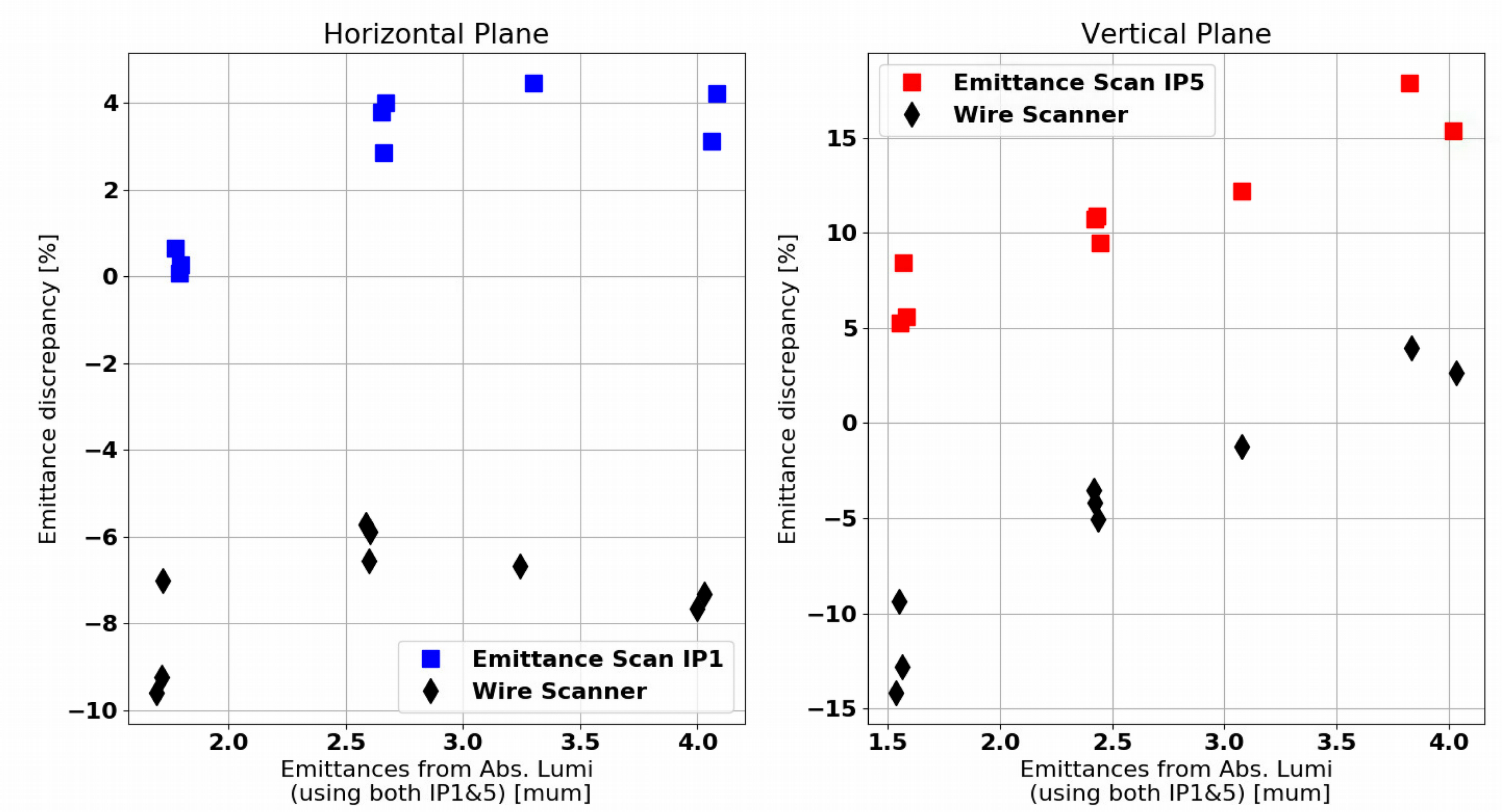


BSRT calibration Fill results

E. Bravin, G. Trad
link:BSRTcalibr_LMC

BSRT calibration Fill 7220

Comparison of convoluted emittances from Emittance Scans and WS with Luminosity



- Agreement of convoluted emittances from Emittance Scans with respect to the ones from Luminosity is 5-15% (depending on the plane)
- Emittances from WS up to 5-15% lower than the Luminosity predicted ones

Luminosity model description

At each time step, the model is applied bunch-by-bunch,
for colliding and non-colliding bunches, considering:

- Intrabeam Scattering (IBS) based on (based on MAD-X IBS module)
- Synchrotron Radiation (SR)
- Coupling
  -linear coupling
- Noise
  -noise floor of the machine and of the transverse damper
- Intensity variation
- Burn-off & emittance variation
  -caused by transverse bunch core depletion in collisions
- Elastic scattering

Including β*, luminosity leveling, x-ing angle anti-leveling options

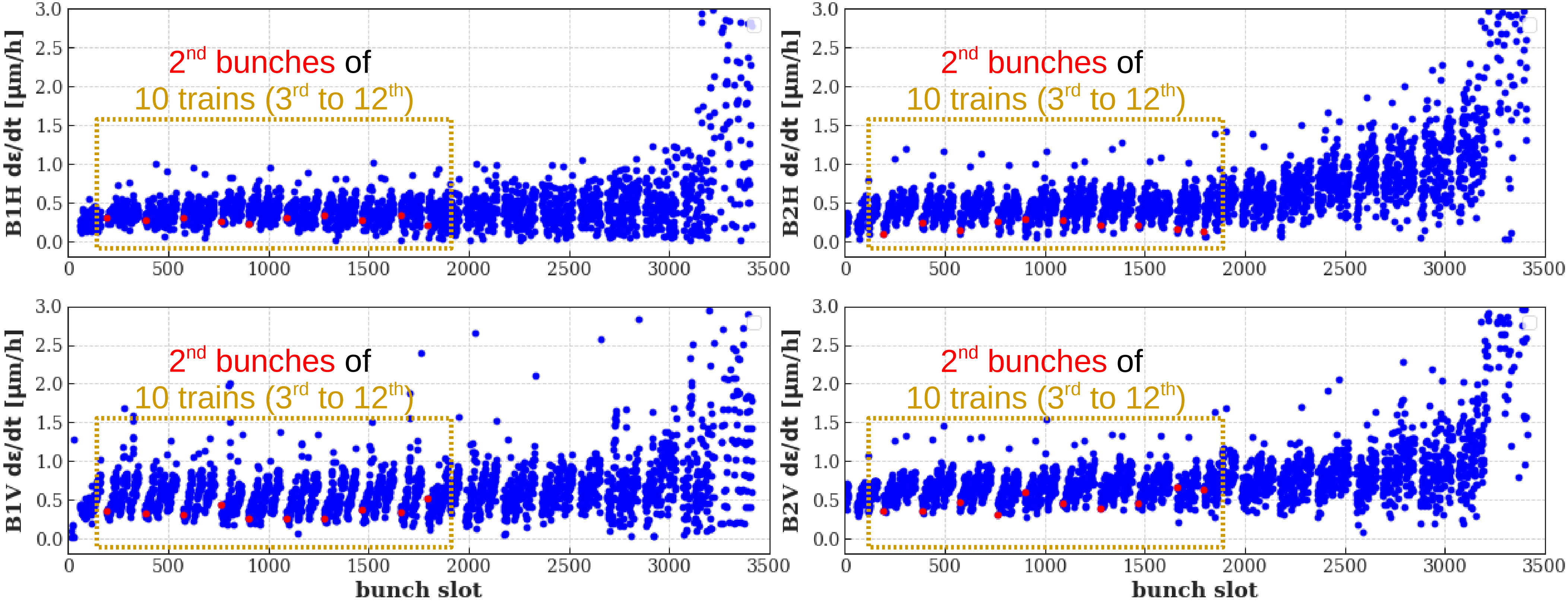
→ Combination of transverse emittances, bunch length and bunch intensity to compute the luminosity at each time step

F. Antoniou, Y. Papaphilippou et al.,
link→TUPTY020, proc. of IPAC' 15
link→evian16, proc. of Evian 2016

Extra emittance growth at FB

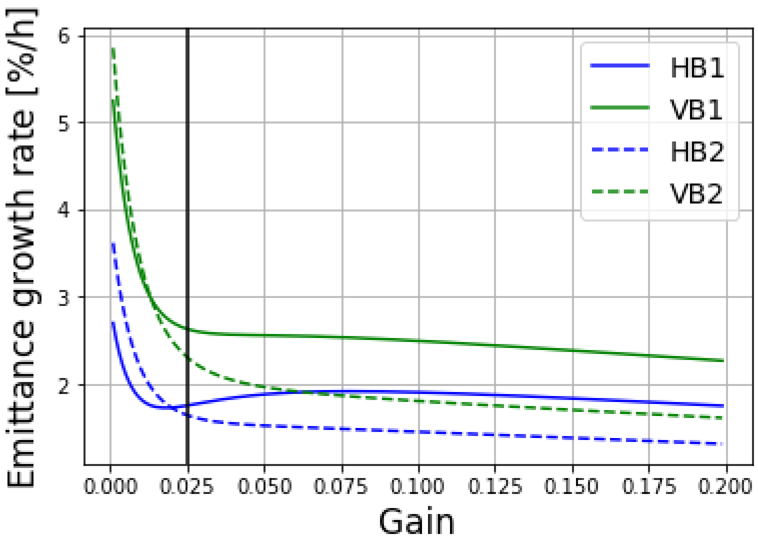
Measured-Model emittance difference over time at FB vs bunch slot, for a Fill
dε/dt → extra emittance growth **<u>on top of IBS</u>**

Fill 7035



Assuming that the first bunches of a train experience no e-cloud, the **dε/dt** of the 2nd bunch of 10 trains (3rd to 12th) gives the extra emittance growth <u>on top of IBS and e-cloud</u>

Emittance growth due to noise at SB



Input beam parameters:
-an emit. at start of SB of 1.9um or 2.3um for both planes and beams and a bunch length of 1.1ns=0.0824m
-a betastar that is 30 cm
-a xing of 2*160urad
-a GainSB=0.025

+

noise MD results

δ_0 the noise floor of the machine normalised to the beam size
δ_{BPM} the noise floor of the transverse feedback pickup normalised to the beam size

$\delta_0$hb1 = 3.8e-5	δ_{BPM}hb1 = 220e-5
$\delta_0$vb1 = 5.3e-5	δ_{BPM}vb1 = 250e-5
$\delta_0$hb2 = 4.4e-5	δ_{BPM}hb2 = 190e-5
$\delta_0$vb2 = 5.6e-5	δ_{BPM}vb2 = 210e-5

link→ noiseMD_Xavier

noise growth dε/dt [μm/h]

for 1.9um at SB

	H	V
B1	0.038	0.057
B2	0.036	0.050

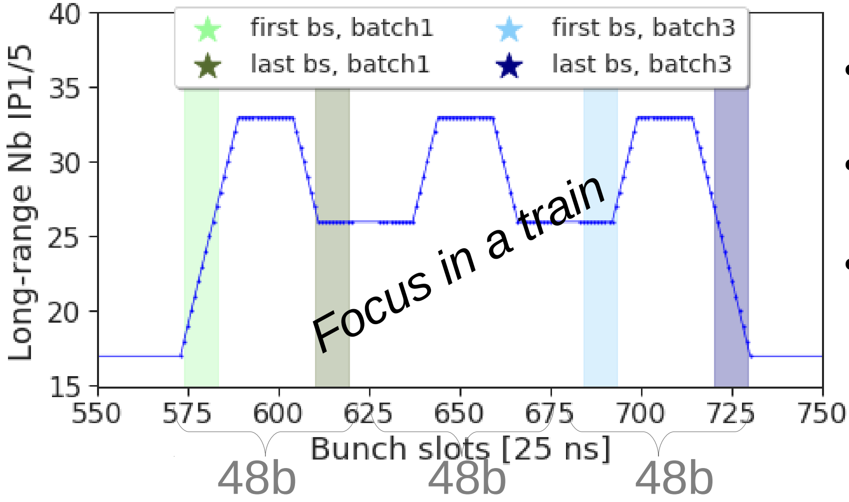
for 2.3um at SB

	H	V
B1	0. 040	0.061
B2	0.038	0.053

X. Buffat, et al.

Extra emittance growth at SB, 2018

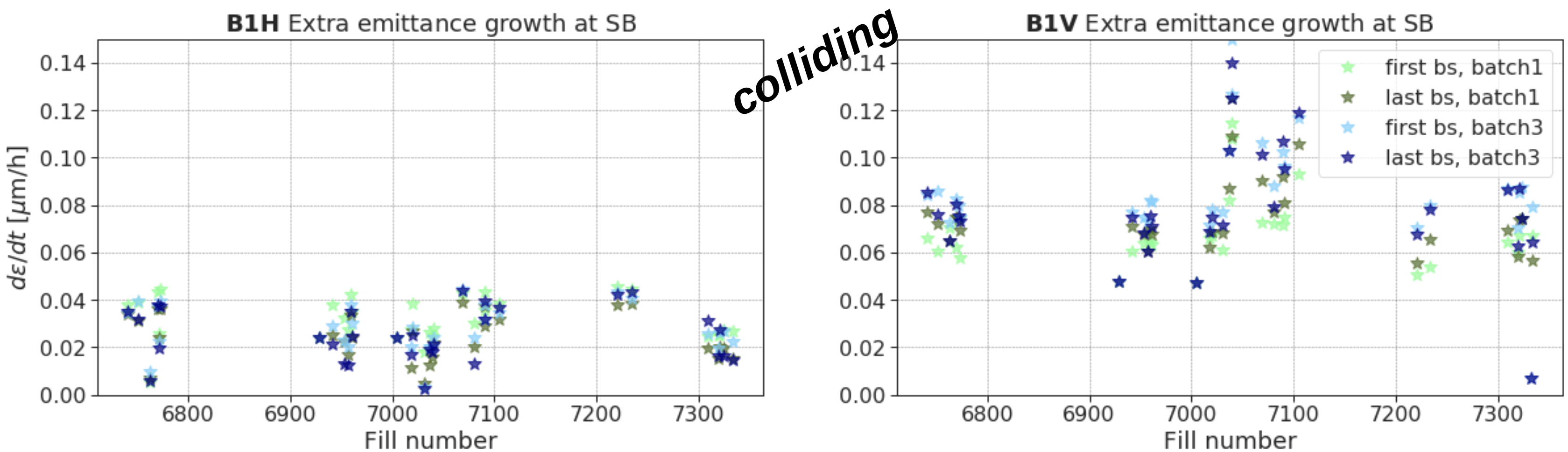
Definition of bunch classes based on the position of bunches in the batches and train



- Averaging over 10 bunches per class
- Time considered at SB before β* change (at ~8h)
- Model: emittance from model and losses from data

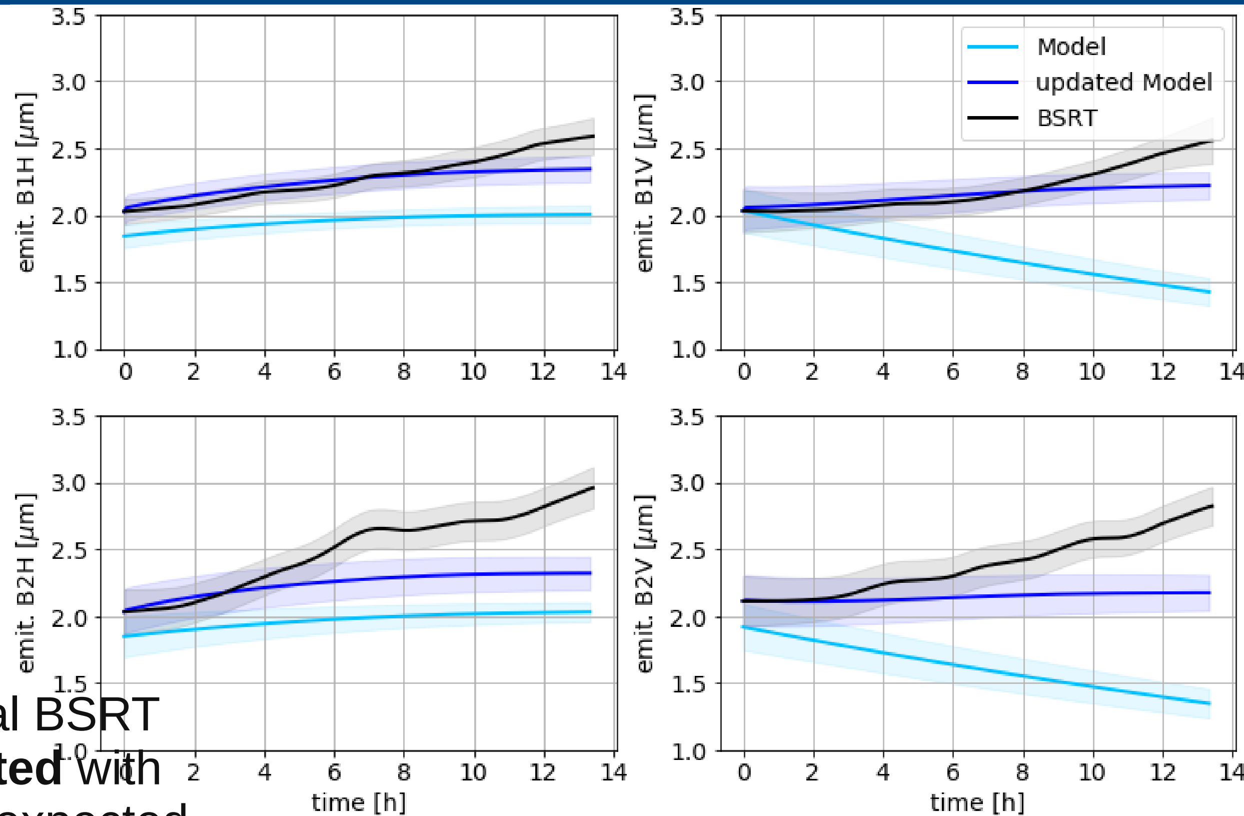
Extra emittance growth

Measured (BSRT)-Model emit. difference

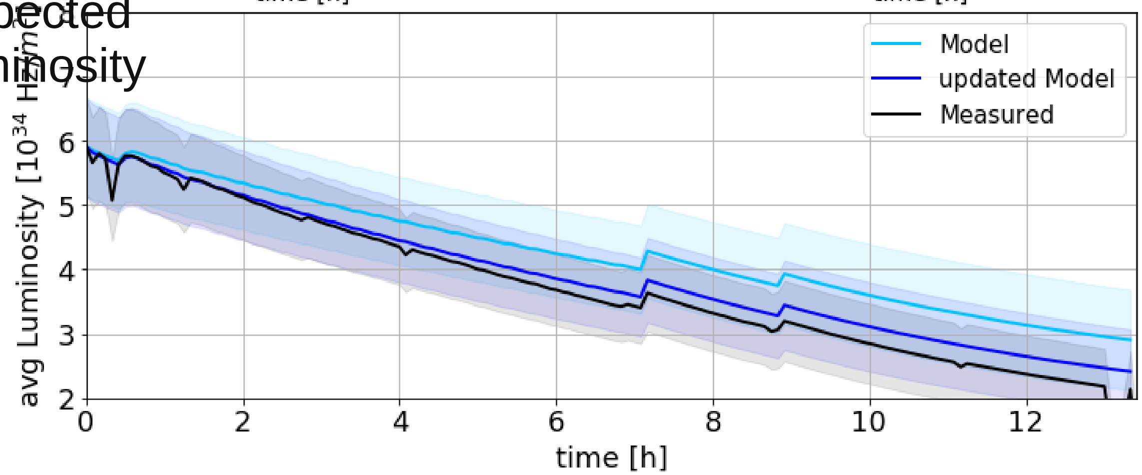


- Practically no differences between the bunches along a batch or a train → no correlation of extra growth with e-cloud

Luminosity and emittance evolution



model input→ initial BSRT emittances **corrected** with respect to the ones expected from the measured Luminosity



Including the mechanisms of noise & coupling & burn-off for the emittance growth, the **updated Model** gives significantly better luminosity predictions

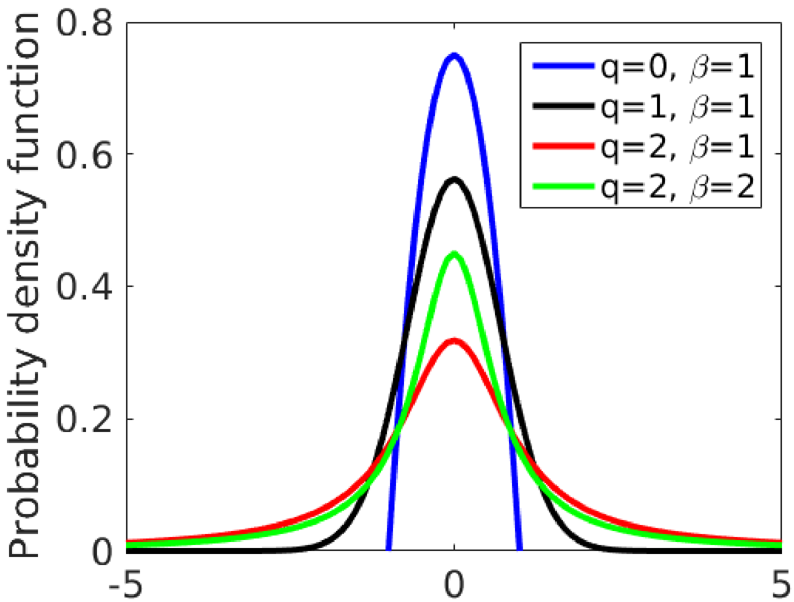
→ **to be used for HiLumi estimations**

A generalized Gaussian function

In many cases, the bunch profiles in the LHC, appear to have **tails that differ from the ones of a normal distribution**.
In order to describe them more accurately, the **q-Gaussian function** is used, having a probability density function that is:

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

q<1→"light" tailed
q=1→Gaussian
q>1→ "heavy" tailed



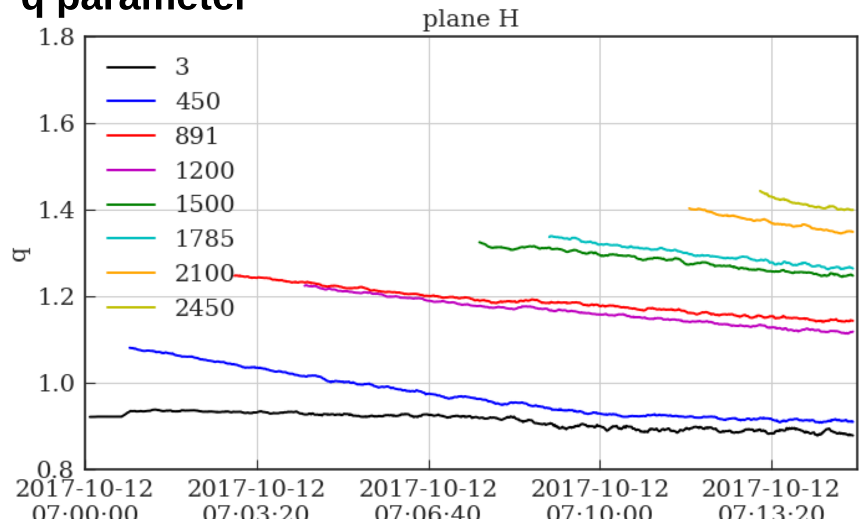
$$\sigma = \sqrt{\frac{1}{\beta(5-3q)}}$$

for q<5/3

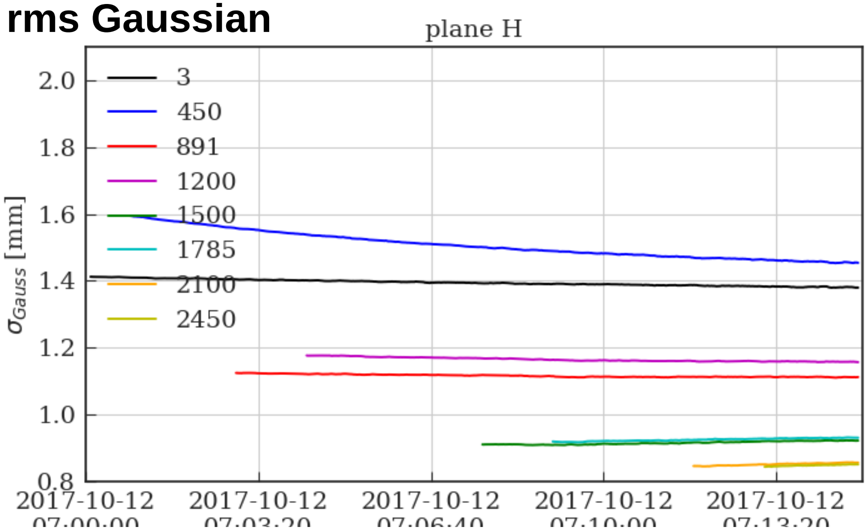
Extra emittance growth at SB, 2018

BSRT sigma (Gaussian and qGaussian) vs time

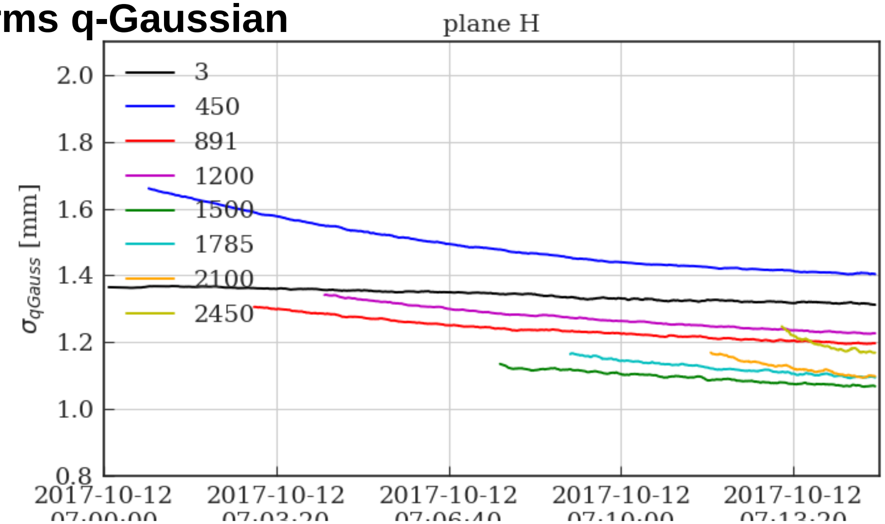
q parameter



rms Gaussian



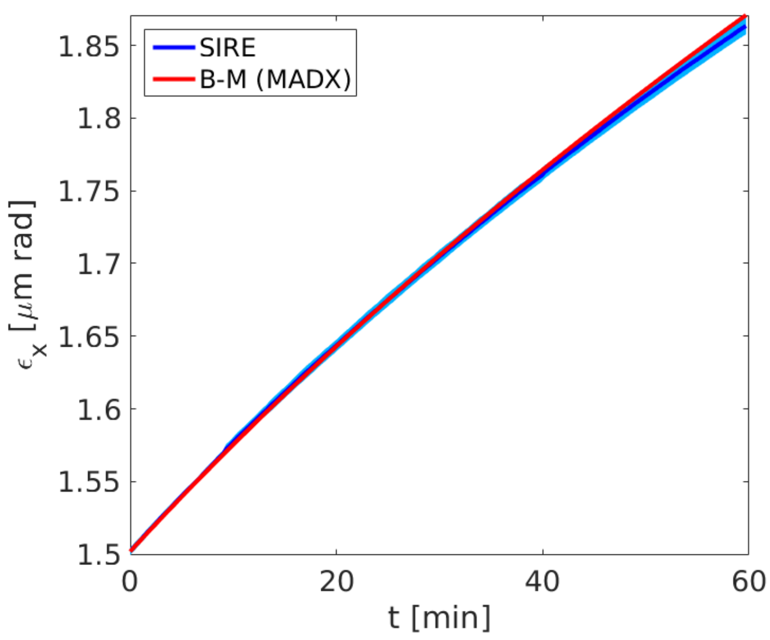
rms q-Gaussian

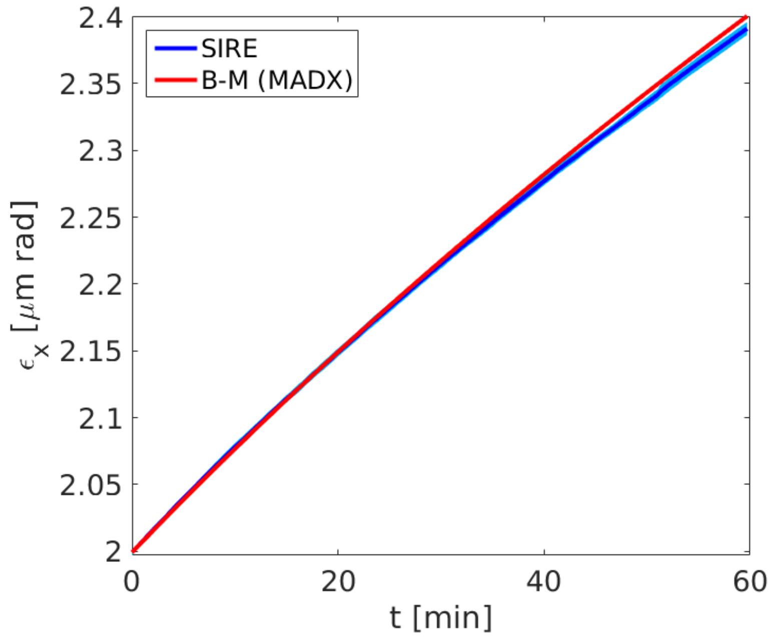


Non-Gaussian bunch profiles→simulations

-**SIRE** calculates IBS for any distribution
-**MAD-X** IBS module assumes Gaussian distributions

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



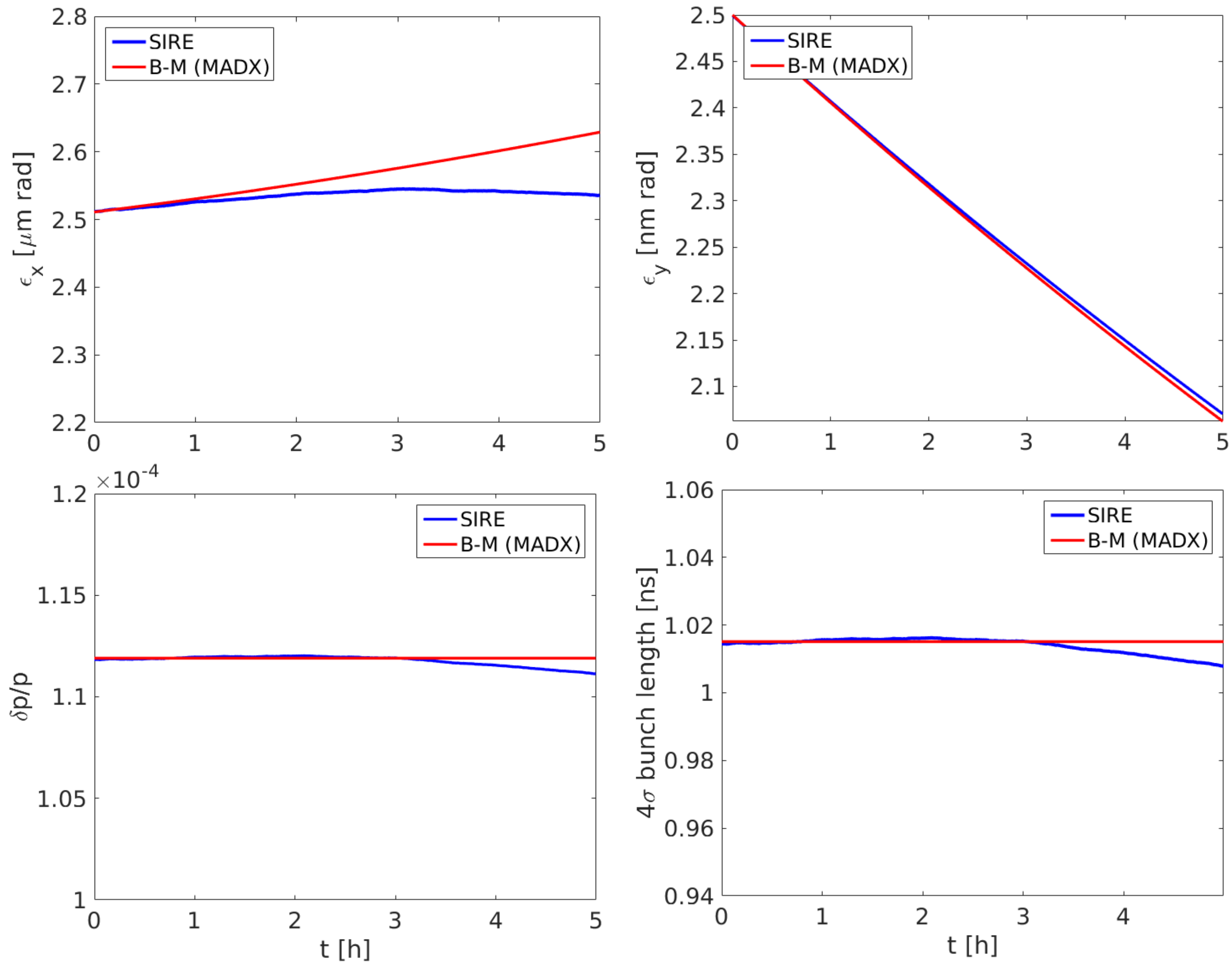


Non-Gaussian bunch profiles→simulations

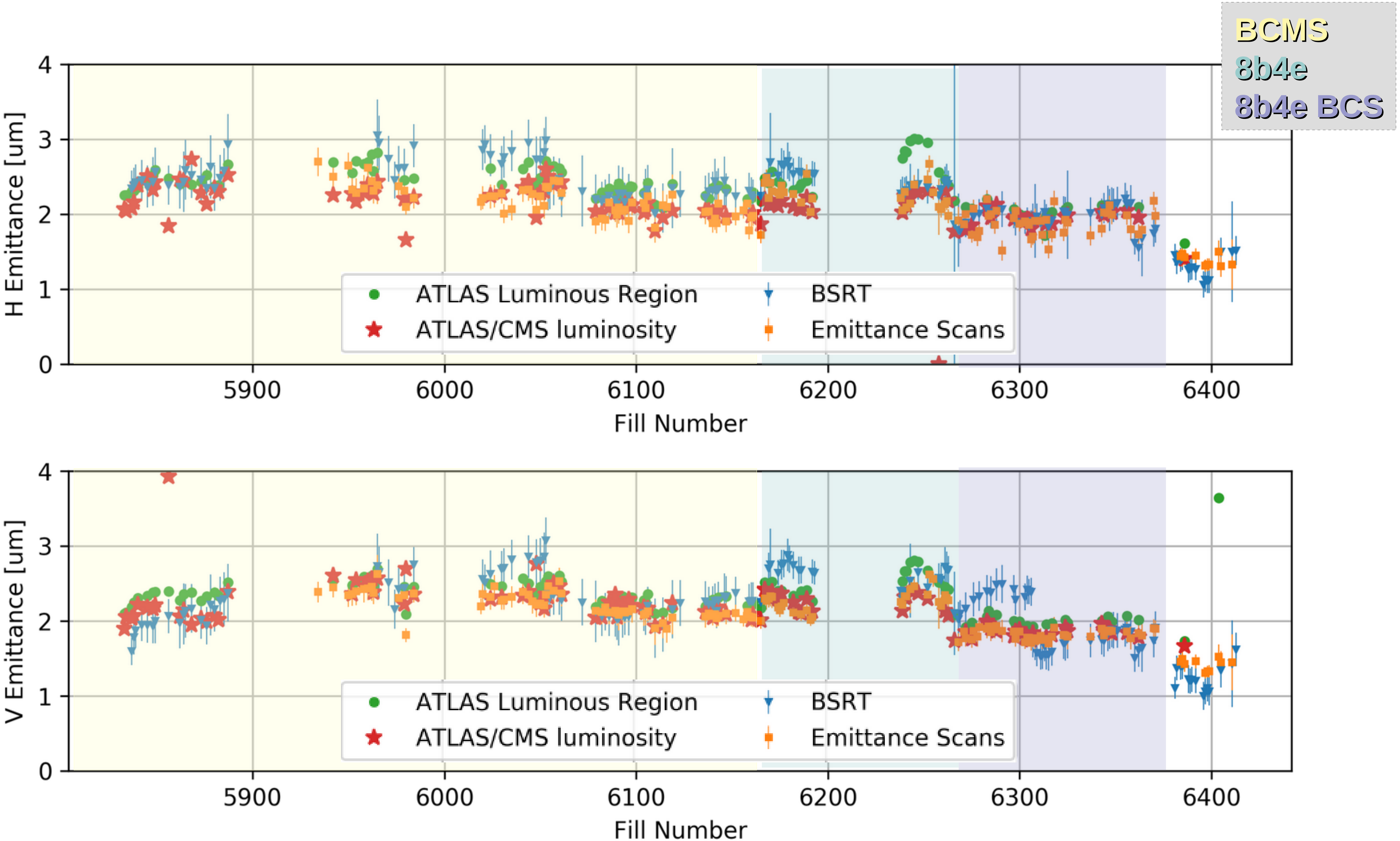
Keep bunch length constant, for the qGaussian case with q=0.6 and rms 7.6cm

Evolution of the transverse emittances, energy spread and bunch length during 5h

-**SIRE** calculates IBS for any distribution
-**MAD-X** IBS module assumes Gaussian distributions



Convoluted emittances at start of SB



-Convoluted emittance measurements with different methods

-Another data quality validation step

-Only fills that pass the data quality validation are considered for statistics