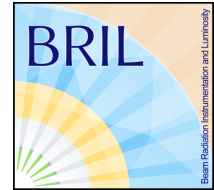
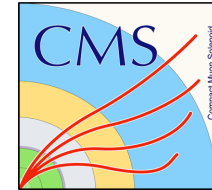


- Close look at the emittance scans during SB – issues
- Emittance evolution in SB from LHC instruments, and experimental data (conv emit, luminous region)



# UNDERSTANDING OF THE BEAM EMITTANCE EVOLUTION DURING SB

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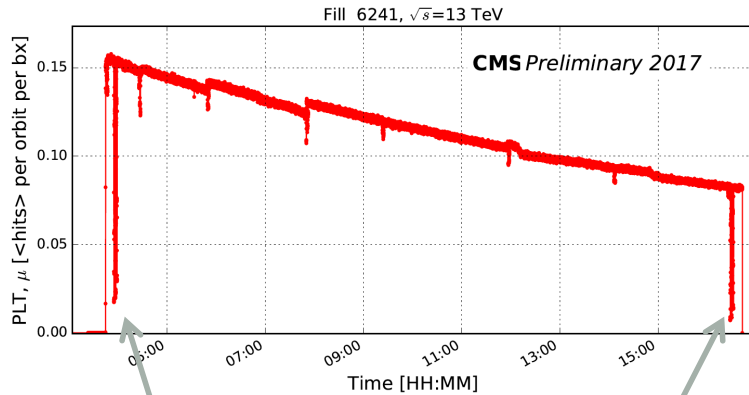
Olena Karacheban on behalf of CMS Collaboration

Acknowledgements to other colleagues: M.Hostettler, G.Trad,  
I.Efthymiopoulos, S.Papadopoulou, T. Pieloni

# Devices for emittance measurement

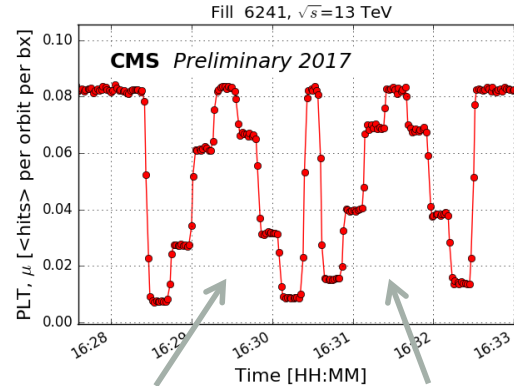
- Wire scanner (WS)
  - The most precise LHC device, but can not be used for emittance measurement of all bunches in the machine (limitations are ~240 nominal bunches @450 GeV or ~12 bunches @6.5TeV).
- Beam Synchrotron Radiation Telescope (BSRT)
  - Cross calibrated to WS in the “BSRT calibration fills” carried out several times during the year. Far in time from the “BSRT calibration fills”, the absolute calibration of BSRT drifts due to radiation damage.
  - Used during the LHC operation for the relative change of the emittance during the fill.
- Emittance scans (as focus of this talk)
  - From 2017, emittance scans are done in every fill at CMS at the beginning and at the end of the fill.
  - From 2018 at CMS (IP5) and ATLAS (IP1).
  - In addition to powerful handle on luminometers performance, emittance scans are used for emittance evolution studies in long LHC fills.

# CMS emittance scans for beam emittance measurement

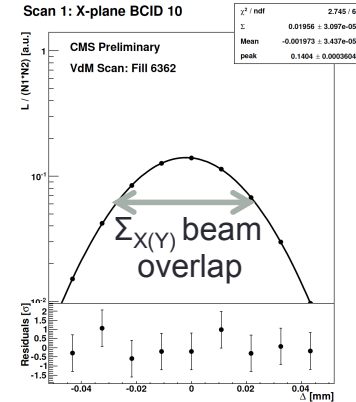


Beginning of fill  
“early scan”

End of fill  
“late scan”



Scan in X plane      Scan in Y plane



Example of the fit  
for one bunch  
crossing

- Beams are scanned at CMS (IP5) in 7-9 separation steps in X and Y plane.
- The effective beam overlap  $\Sigma_{X(Y)}$  is measured from the width of the Gaussian fit to the emittance scan data in X(Y) and used to calculate emittance X(Y).

$$\epsilon_X = \left[ \Sigma_X^2 \gamma - 2\gamma \sigma_Z^2 \sin^2(\alpha/2) \right] / \left[ 2\beta^* \cos^2(\alpha/2) \right]$$

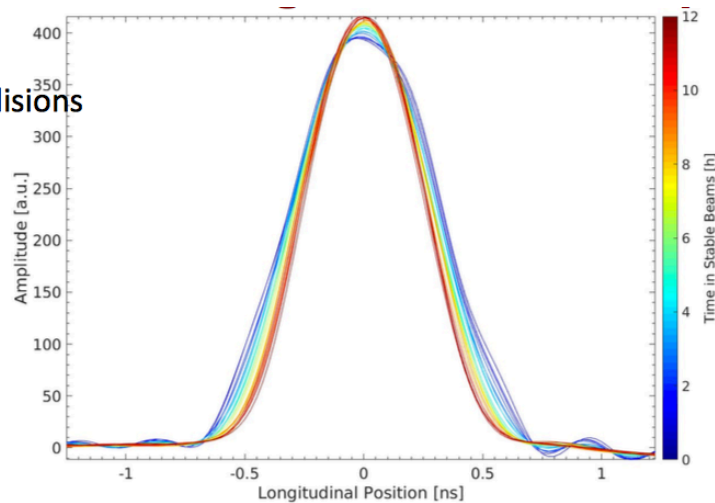
$$\epsilon_Y = \Sigma_Y^2 \gamma / 2\beta^*$$

( $\alpha/2$ ) crossing angle,  $\gamma$  relativistic factor,  $\beta^*$  beam optics,  $\sigma_Z$  bunch length.

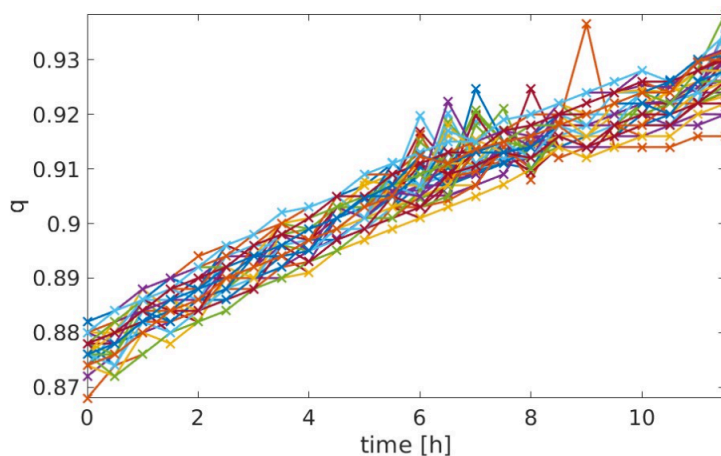
$\epsilon_X$  calculation requires precisely measured bunch length

# Longitudinal bunch profiles (LHC)

~11.5h at collisions



[Link](#) to the talk S.Papadopoulou

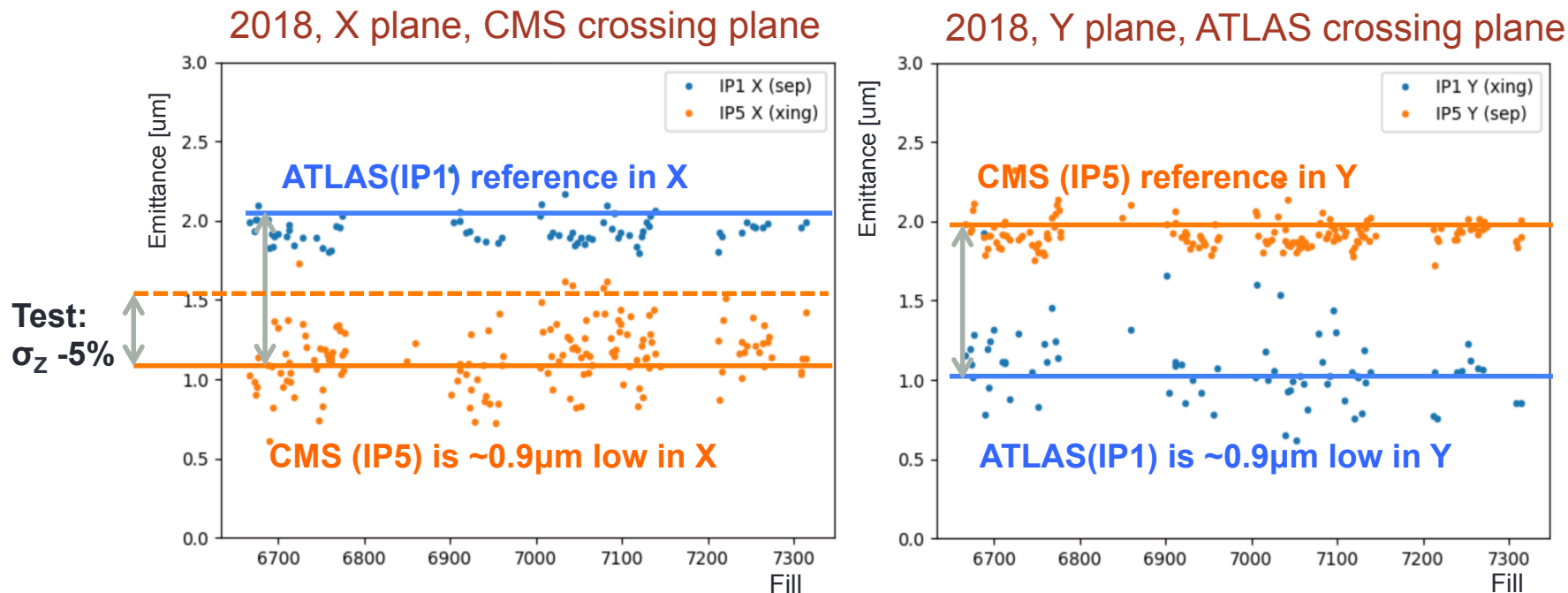


- **q-parameter of q-Gaussian approaches 1, beams become more Gaussian with time.**

- **Non-Gaussian longitudinal profile of the beam leads to overestimated  $\sigma_z$  by ~5%** (difference of estimate from q-Gaussian fits and values reported by BQM).

# Why do we need IP5 and IP1 scans

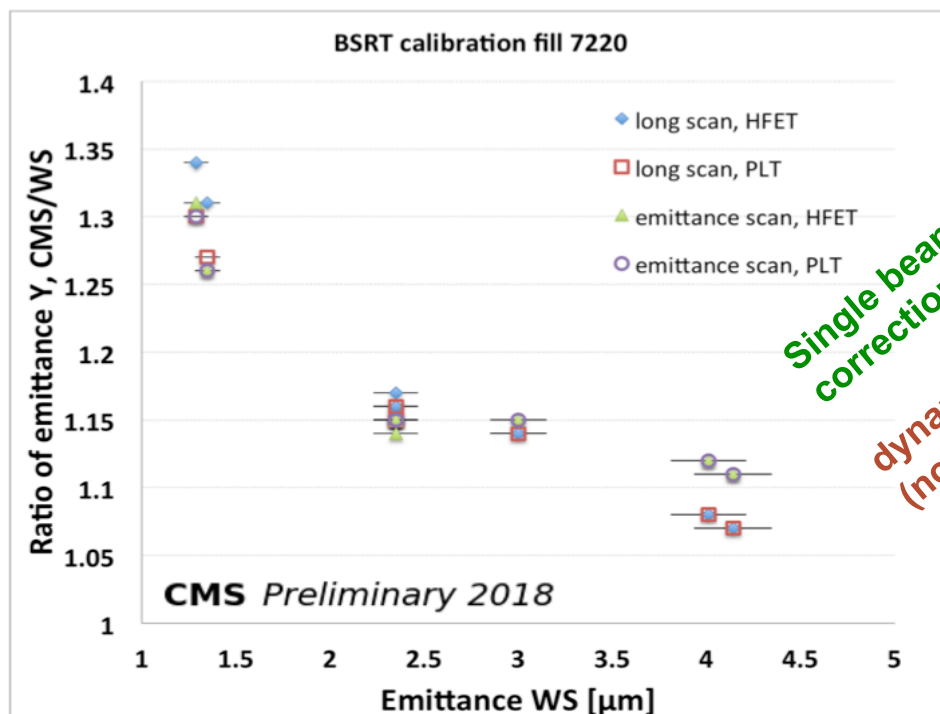
M.Hostettler



- Assuming round optics, ATLAS and CMS emittance measured agree for the non-crossing plane.
- The crossing plane emittance measurement is biased:
  - Cross-experiment correction shows big fill-to-fill variation.
  - Correction can be only quantified when CMS and ATLAS emittance scans are carried out one after another!

# CMS emittance Y vs. WS emittance in BSRT calibration fill 7220

- 9 bunches of different emittance, but similar intensity were used in the BSRT calibration fill 7220 ( $\beta^* = 30$  cm,  $\alpha/2 = 160$   $\mu$ rad,  $I = 0.9-1.1 \times 10^{11}$  protons per bunch)
- One regular emittance scan and one extended emittance scan were done for CMS.
- **CMS systematically measures higher emittance than wire scanner.**
  - ~5% spread for this emittance family is detector related (HFET-forward calorimeter transverse energy  $E_T$  counting or PLT – pixel luminosity telescope) or scan type related (9 separation steps or 15 steps).



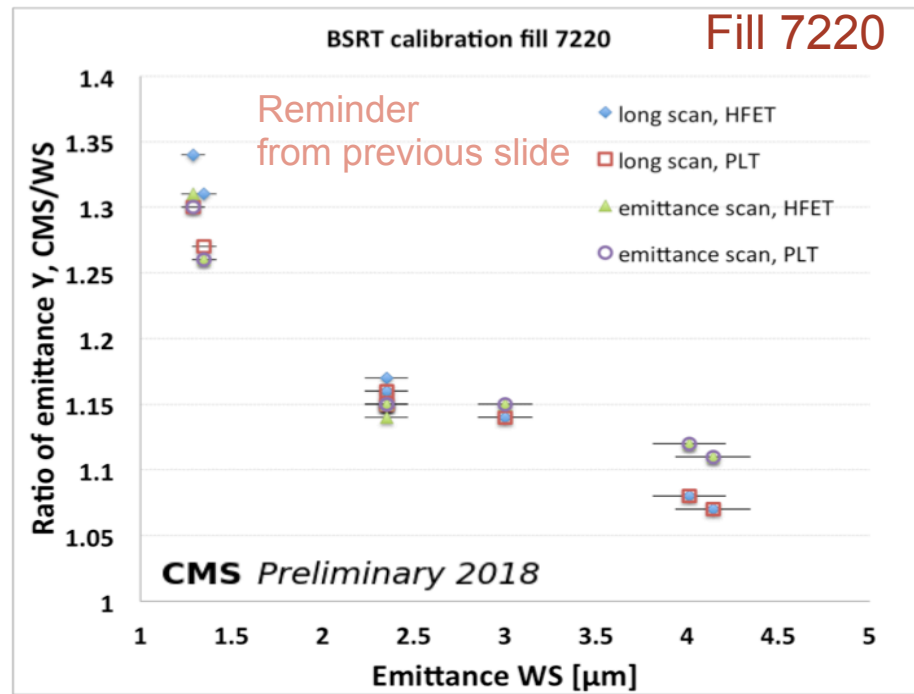
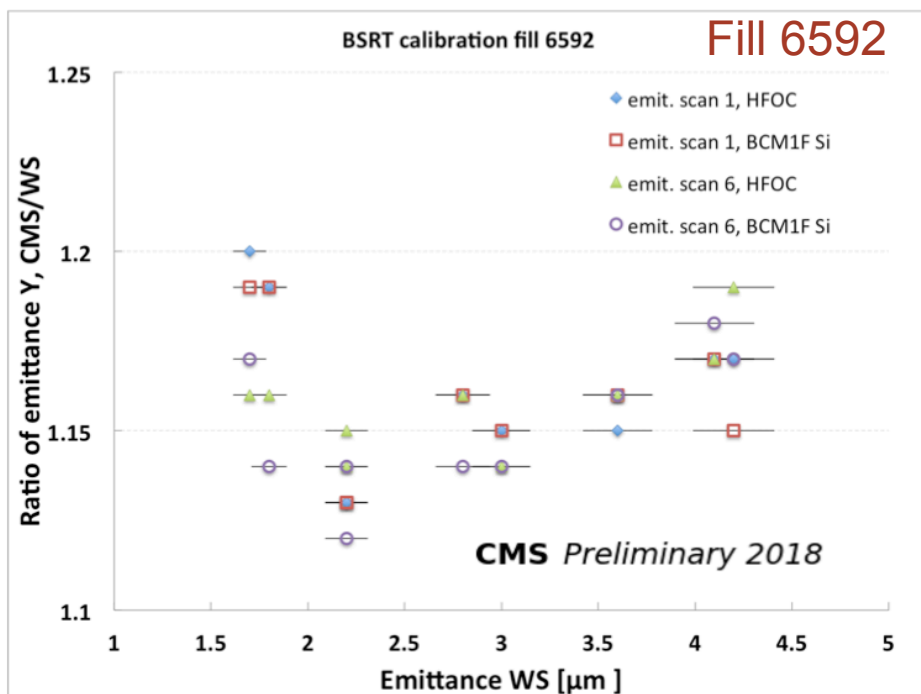
Single beam-beam deflection  
correction applied

dynamic  $\beta^*$  corr.  
(not yet)

Typical error on  $\Sigma_{x(Y)}$  is <1%  
(only statistical), resulting into ~2%  
effect on emittance from this source.

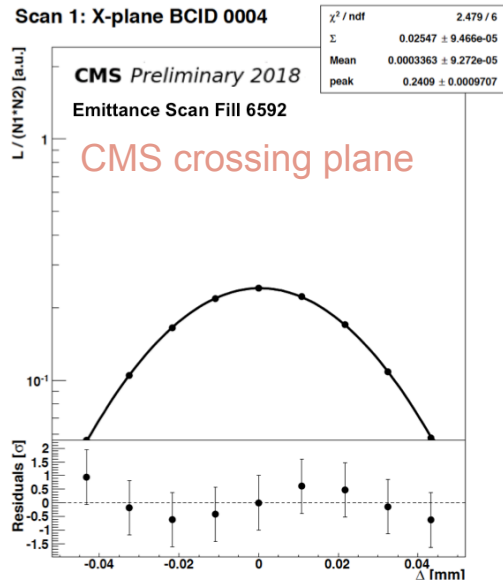
## CMS emittance $Y$ vs. $WS$ emittance in BSRT calibration fill 6592

- 9 bunches of different emittance, starting conditions similar to fill 7220
- **CMS systematically measures ~15-20% higher emittance than WS for all bunches.**
  - ~3-5% spread is detector related (HFOC-forward calorimeter occupancy method or BCM1F Si – Fast Beam Condition Monitor, silicon sensor) or scan related (first scan or last scan of the fill).
  - **Note: we do not have bunches narrower than  $1.7\mu\text{m}$  in fill 6592!**



# Observed bunch shapes, BSRT calibration fill 6592

Wide bunch  $\sim 4.5\mu\text{m}$

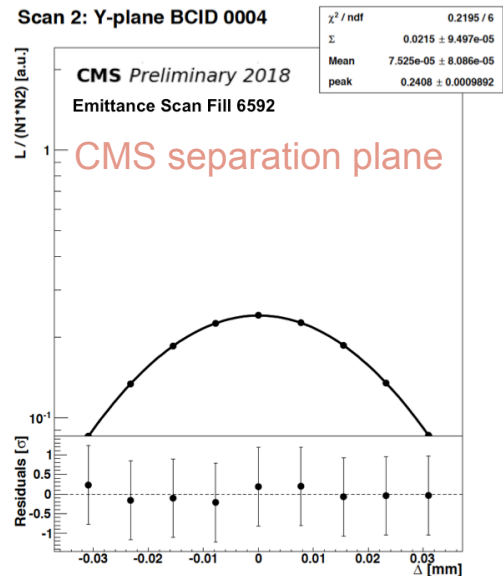


- Non-Gaussian profile of the beams:
  - “S-like shape” in the residuals in X scan
  - “W-like” shape in the residuals Y scan

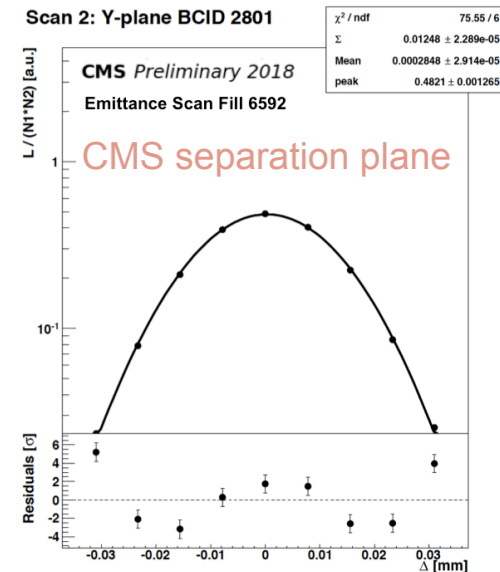
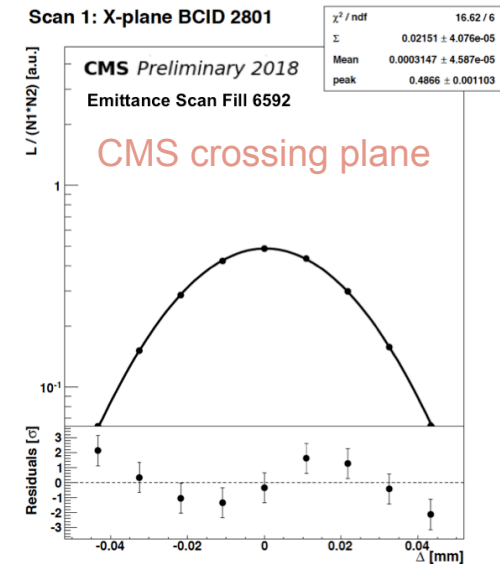
- Shapes in the residuals are more pronounced for the narrow bunches.

- Similar shapes are seen in the residuals to Gaussian fit of ATLAS emittance scans.

- Scanning the beams in opposite to usual scan direction (e.g. not left  $\rightarrow$  right, but right  $\rightarrow$  left) did not change the observation  $\rightarrow$  real beam effect.



Narrow bunch  $\sim 1.8\mu\text{m}$



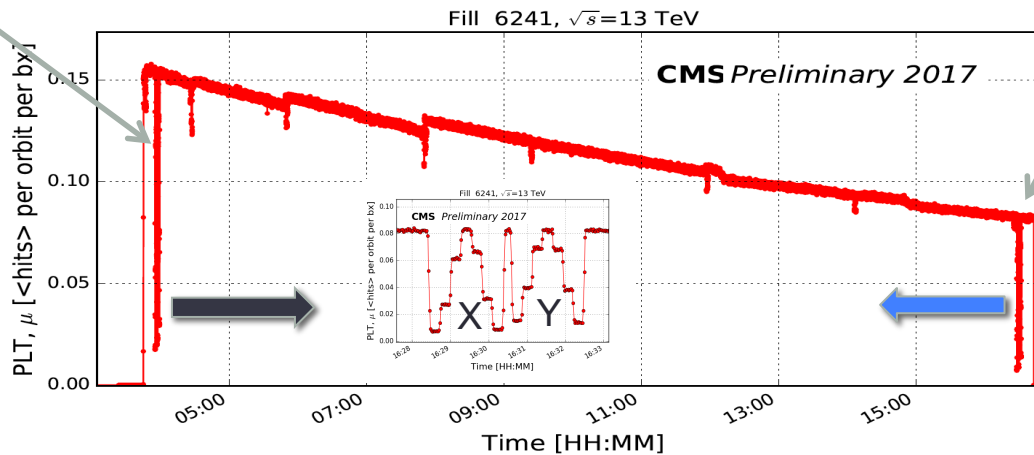
[Link](#) to the talk from M.Hostettler



# Emittance scans for emittance evolution study

Beginning of fill  
“early scan”

End of fill  
“late scan”



Using single Gaussian fit to all colliding bunches we can measure:

In the early scan

- Effective beam overlap ( $\Sigma_{X(Y)}$ )
- Beam width ( $\sigma_{X(Y)}$ )
- Emittance ( $\epsilon_{X(Y)}$ )

In the late scan

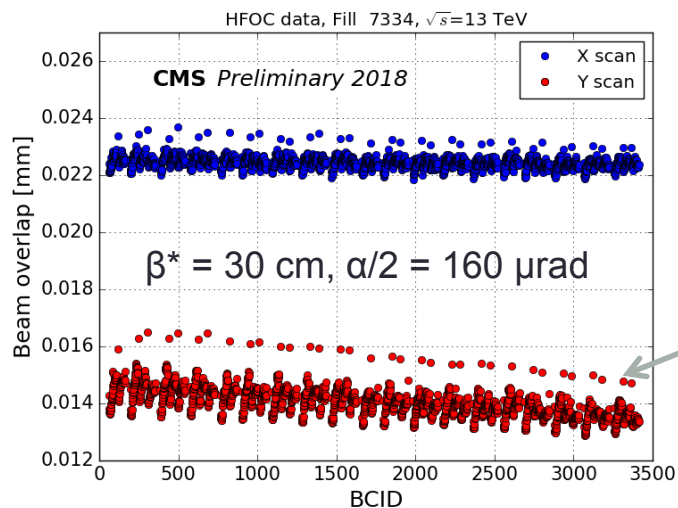
- Effective beam overlap ( $\Sigma_{X(Y)}$ )
- Beam width ( $\sigma_{X(Y)}$ )
- Emittance ( $\epsilon_{X(Y)}$ )

Difference we call evolution

In the long LHC fills early and late scans are 12-15 hours separated.

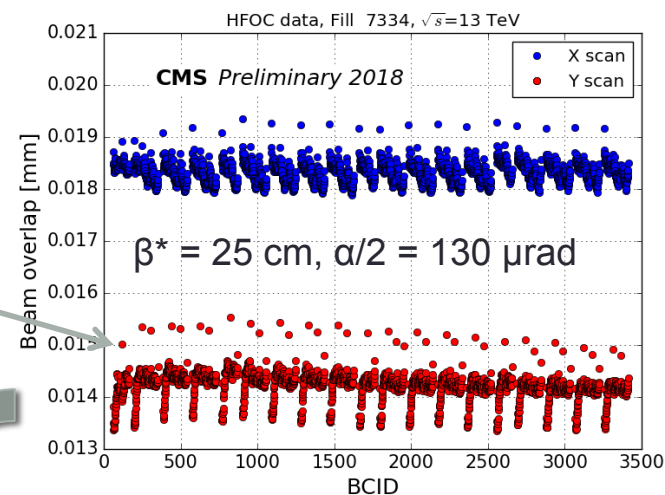
# Fill 7334, effective beam overlap $\Sigma_{X(Y)}$

In the “early scan”

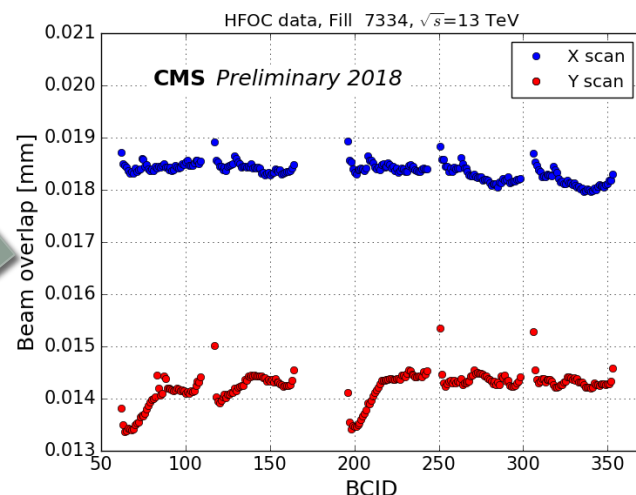
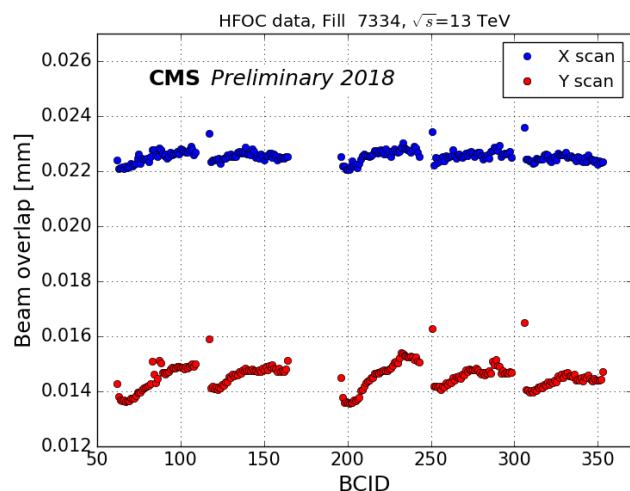


First bunch in the train

In the “late scan”



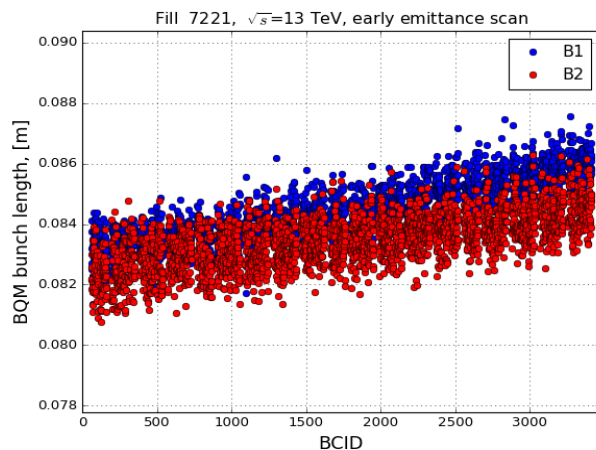
Zoom in



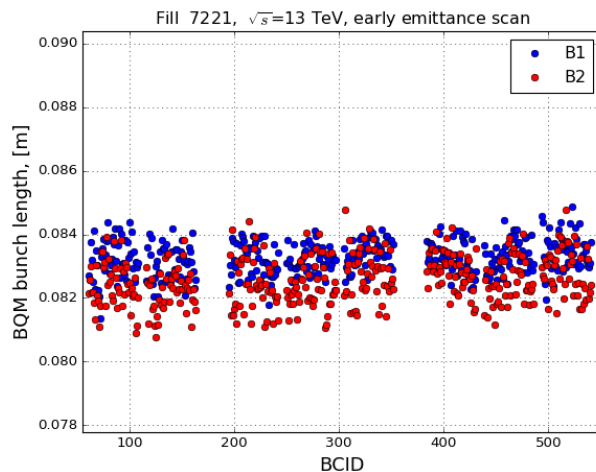
4  $\mu$ m decrease in the  $\Sigma_X$ , almost no change in  $\Sigma_Y$ . Not the same trend as in VdM, as  $\Sigma_X$  should be corrected for Crossing angle (see  $\sigma_{X(Y)}$  evolution and VdM slide in backup).

# Fill 7334, BQM bunch length measurement, $\sigma_z$

at the time of “early scan”

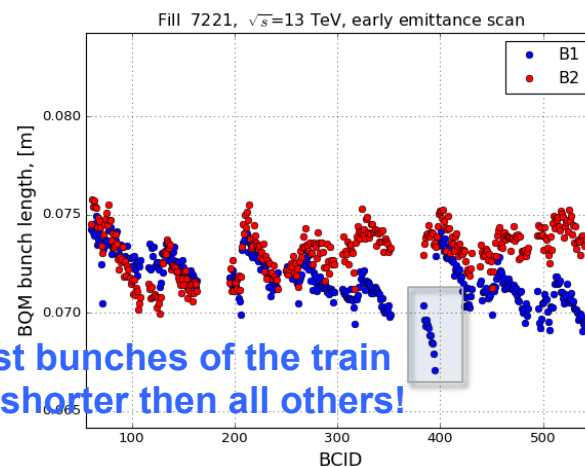
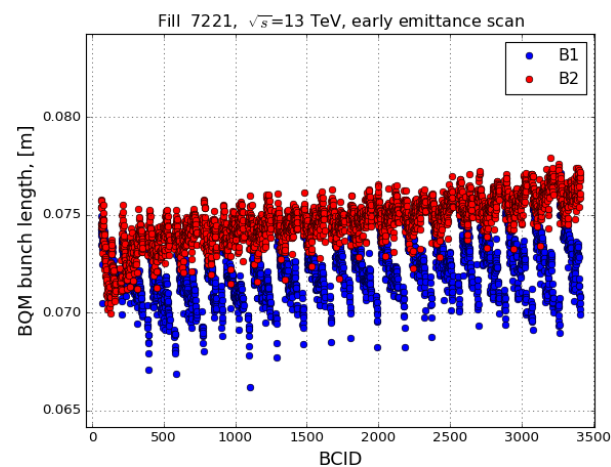


Note: the slope along the orbit!



Zoom in

at the time of “late scan”

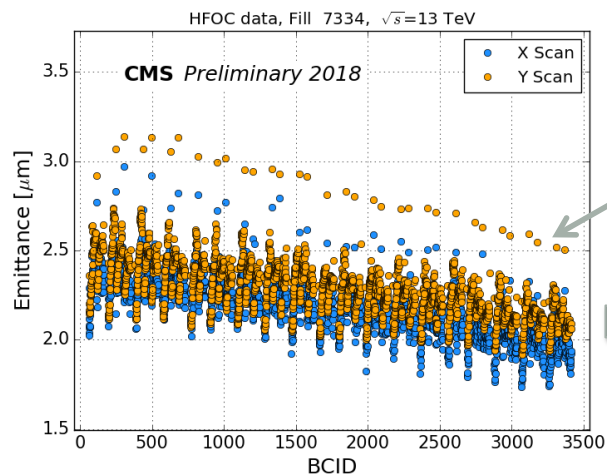


Note: first bunches of the train become shorter than all others!

These per bunch crossing BQM measurements are showing evolution of the bunches in the longitudinal plane and are used in emittance X calculation.

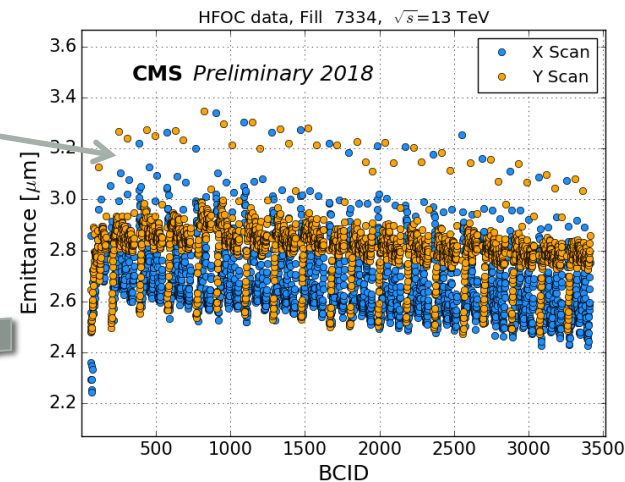
# Fill 7334, CMS emittance evolution $\epsilon_{X(Y)}$

In the “early scan”

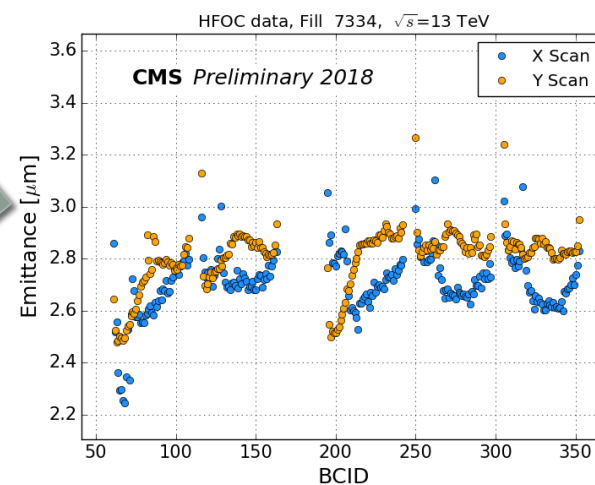
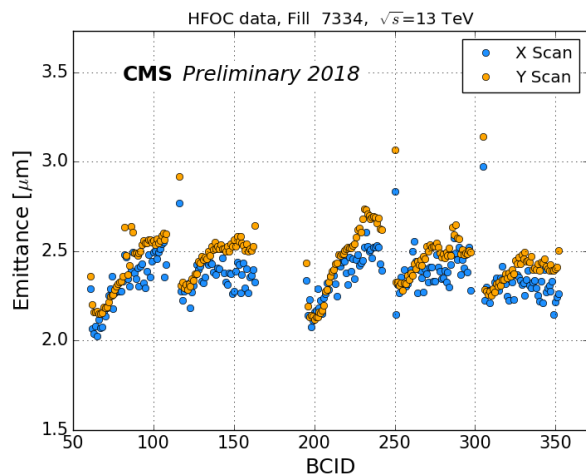


First bunch in the train

In the “late scan”



Zoom in



+0.5 $\mu\text{m}$  correction to  $\epsilon_x$  is applied to take into account  $\sigma_z$  non-Gaussian shape.

No additional corrections to  $\epsilon_x$ !  
 $\sigma_z$  considered to be Gaussian in late scan.

# Comparison of CMS emittance Y with BSRT

- As bunches evolve differently, 4 groups were proposed for evolution study (see the [talk](#))
- CMS emittance always higher than BSRT.
  - Just after the BSRT calibration, Fill 7221, ~25% difference** seen for both scans in Y. CMS measures higher emittance in Y and similar emittance growth in 13 hours relative to the emittance at the beginning of the fill. Up to 3% difference is seen in the measured emittance when using HFOC or HFET data.



Fill 7221	Emittance Y from CMS			Emittance Y(V) from Machine (BSRT)			Vertical plane (Y)	
	Early scan	Late scan	Delta $\epsilon$ (13h)	Time of Early scan	Time of Late scan	Delta $\epsilon$ (13h)	EarlyCMS/EarlyBSRT	LateCMS/LateBSRT
first_bs_batch1	1.91	2.61	37%	1.53	2.07	35%	1.25	1.26
last_bs_batch1	2.3	3.01	31%	1.87	2.40	28%	1.23	1.25
first_bs_batch3	1.99	2.94	48%	1.59	2.33	47%	1.25	1.26
last_bs_batch3	2.17	3.04	40%	1.77	2.42	37%	1.23	1.26

- In a different fill, Fill 7334 ~10% difference seen for late scan in Y and ~20% in the early scan. CMS measures less emittance growth in 13 hours in this fill (delta  $\epsilon$  - difference of emittance in early and late scan relative to early emittance).

Fill 7334	Emittance Y from CMS			Emittance Y(V) from Machine (BSRT)			Vertical plane (Y)	
	Early scan	Late scan	Delta $\epsilon$ (13h)	Time of Early scan	Time of Late scan	Delta $\epsilon$ (13h)	EarlyCMS/EarlyBSRT	LateCMS/LateBSRT
first_bs_batch1	2.14	2.59	21%	1.79	2.33	30%	1.20	1.11
last_bs_batch1	2.64	2.92	11%	2.14	2.60	21%	1.23	1.12
first_bs_batch3	2.27	2.86	26%	1.86	2.59	39%	1.22	1.10
last_bs_batch3	2.41	2.84	18%	1.98	2.61	32%	1.22	1.09

# Work planned and open questions

Summer 2019

- There is still a lot of work to do... We looked at several fills from 85 long fills available in CMS data and ~25 fills with good BSRT data in 2018.
  - Dynamic  $\beta^*$  correction to be finalized and applied to all emittance scans.
  - Emittance evolution comparison in all long fills in 2017-2018 to study trends and compare with emittance evolution from BSRT data.
  - Test: for how much we have to reduce  $\sigma_z$  to bring CMS/ATLAS emittance measurements into agreement in the crossing plane.
  - Compare  $\sigma_z$  from BQM and from CMS beamspot measurement

Depends from experts availability

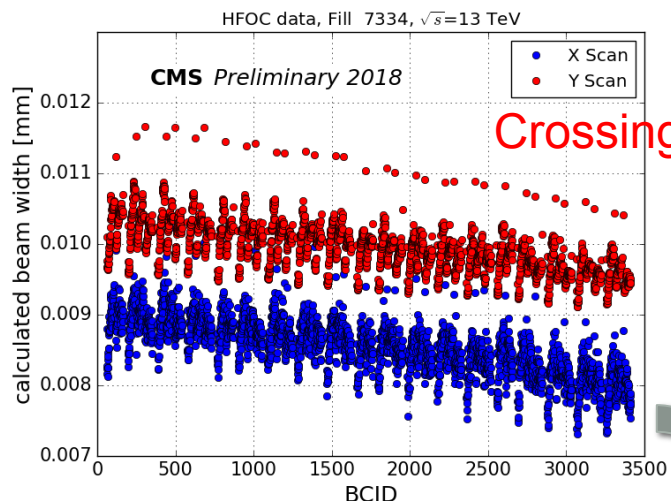
- Longitudinal profiles study in any fill where data is available in 2017-2018 (in contact with Helga Timko).
  - Goal: to understand why correction to emittance scan is  $\sim 0.5\mu\text{m}$  in 2016,  $\sim 0.7\mu\text{m}$  in 2017 and  $\sim 0.9\mu\text{m}$  in 2018 with big variations from fill to fill.
- Using ATLAS emittance scans for the cross check emittance in the crossing plane and the best longitudinal profiles from BQM can we gain understanding and get consistency in CMS emittance X?
- BSRT calibration fills analyses:
  - if we have data from more scans, analyze all for consistency check (including 2017 BSRT calibration fills and all BRIL detectors with final corrections).
- Do we have a handle on non-factorization (XY correlation)? If it is changing during the fill, it has an impact on emittance evolution we extract.

# References and additional material



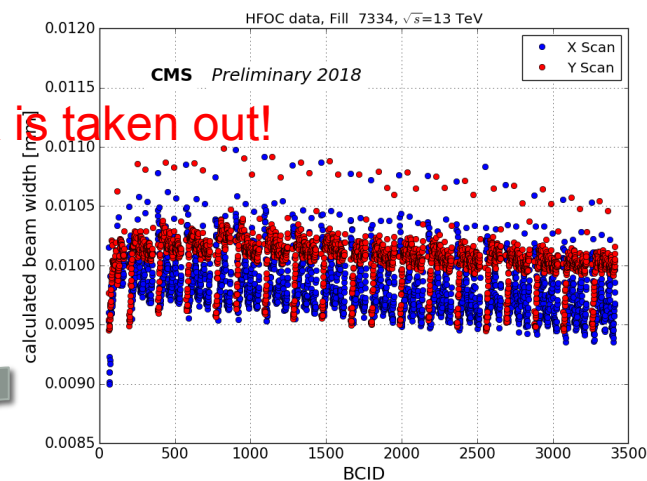
# Fill 7334, beam width evolution $\sigma_{X(Y)}$

In the “early scan”

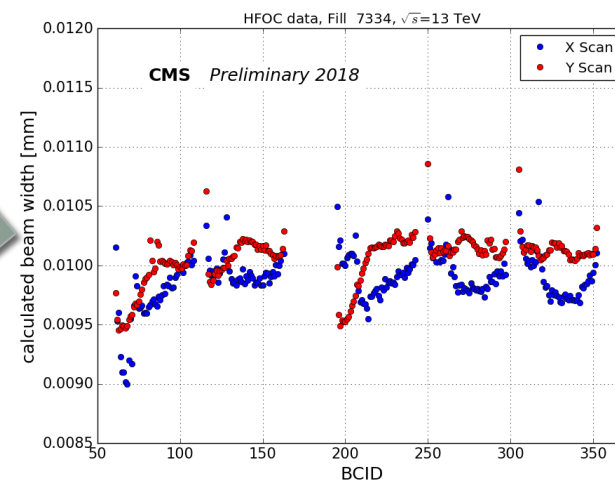
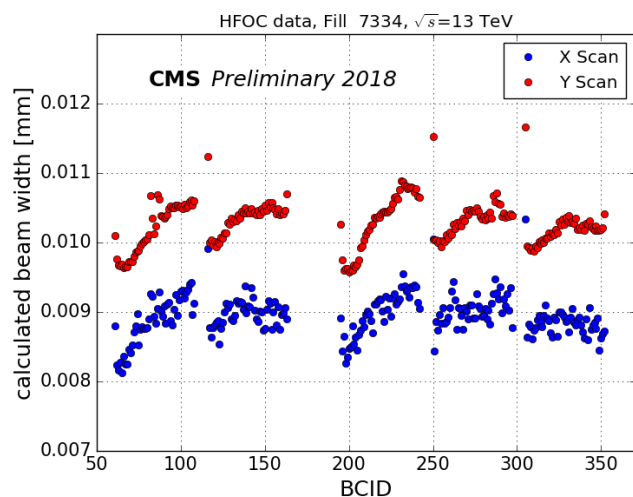


Crossing angle change in X is taken out!

In the “late scan”



Zoom in

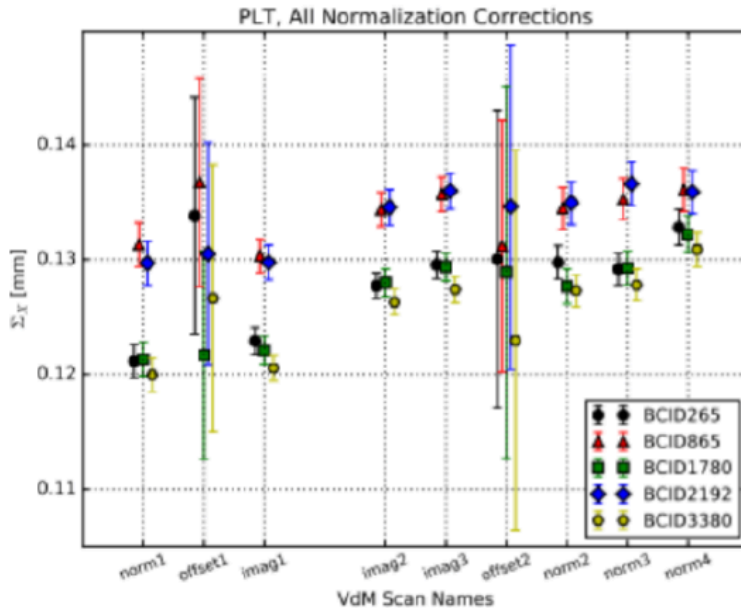


1  $\mu\text{m}$  increase in the calculated SigmaX, almost no change in SigmaY.  
 Trend similar to VdM fill (see on the next slide).

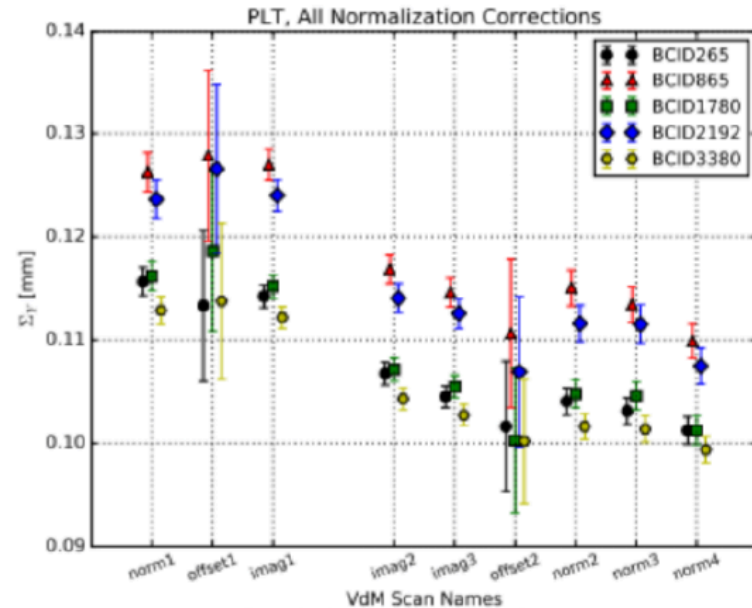


# Beam width evolution in VdM Scans 2018

CMS Preliminary 2018, Fill6868,  $\sqrt{s}=13$  TeV



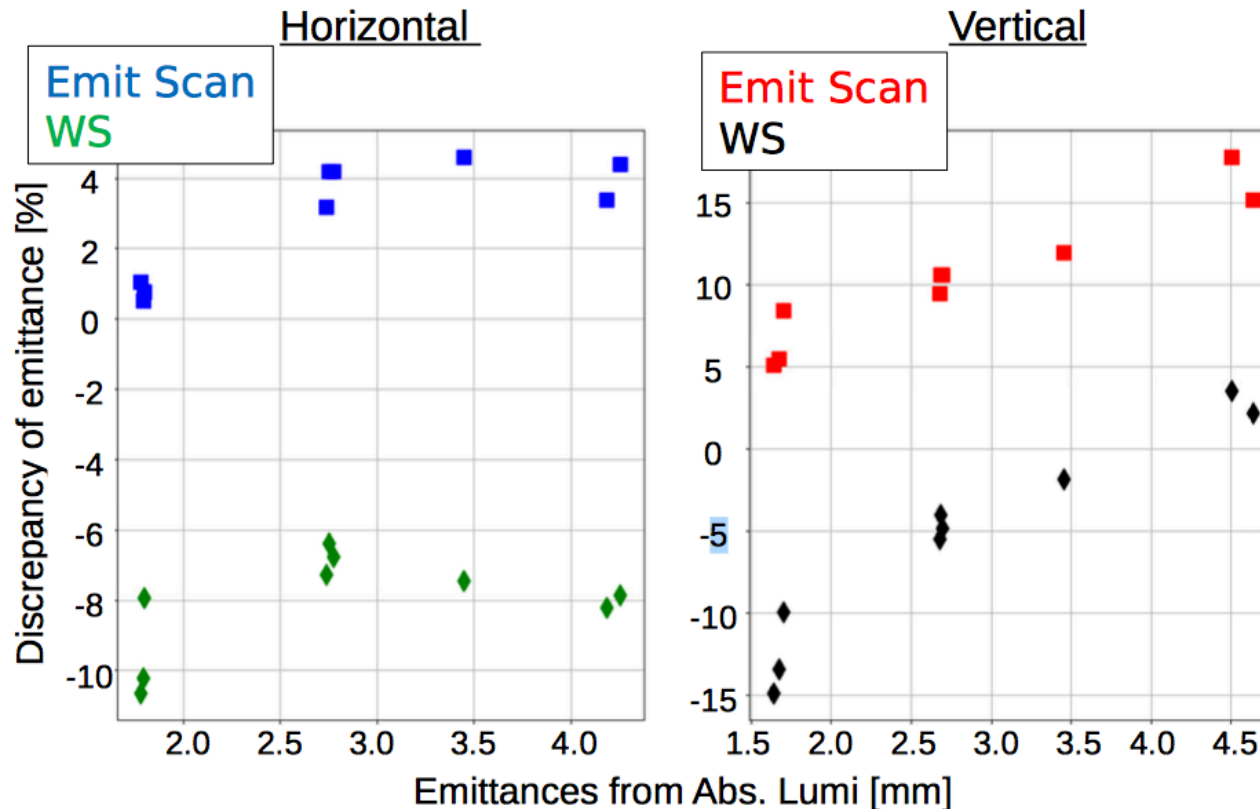
CMS Preliminary 2018, Fill6868,  $\sqrt{s}=13$  TeV



- Beam grows in X and shrinks in Y. First scan in VdM program (norm1) and the last scan (norm4) are  $\sim 18$ h separated. This change of beam width is slow:
  - E.g. from  $\sim 120\mu\text{m}$  for BCID 3380 at the beginning to  $130\mu\text{m}$  at the end of the fill in X plane
  - From  $\sim 115\mu\text{m}$  at the beginning to  $\sim 100\mu\text{m}$  at the end of the fill
- Those points with big error bars are offset scans, they have small statistics.
- The same evolution in VdM 2017 was observed.

## BSRT calibration Fill 7220

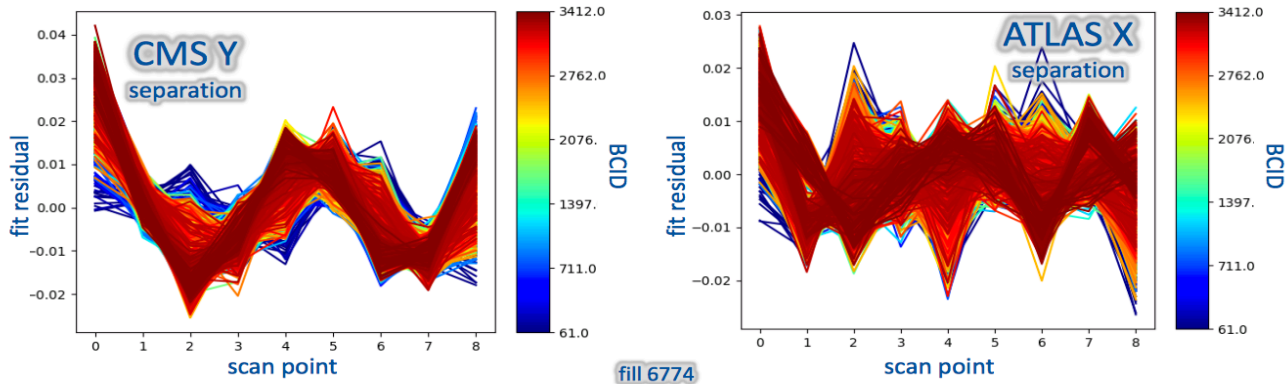
Comparison of convoluted emittances from Emittance Scans and WS with Luminosity



- Agreement of Emittance Scans with the ones from Luminosity is 5-20%
  - Emittances from WS up to 10-15% lower than the Luminosity ones
- Revealing discrepancy between BSRT (calibrated against WS) and emittance from Luminosity → understanding this difference is important

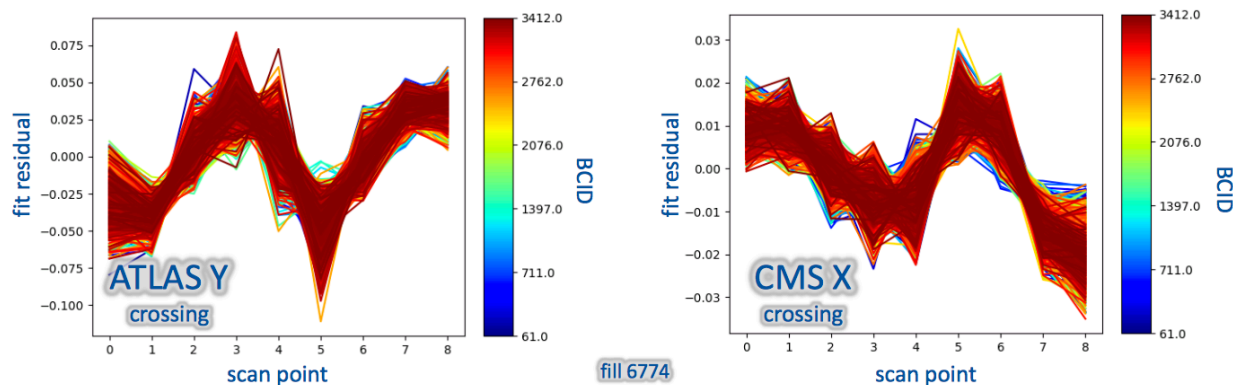
## residuals: bunch structure, separation, EOF

- residuals factor of  $\sim 4$  smaller, structure getting lost ...
  - more Gaussian bunches?



## residuals: bunch structure, crossing

- overall structure reproducible for all BCIDs
  - but NOT between ATLAS and CMS (unlike separation!)

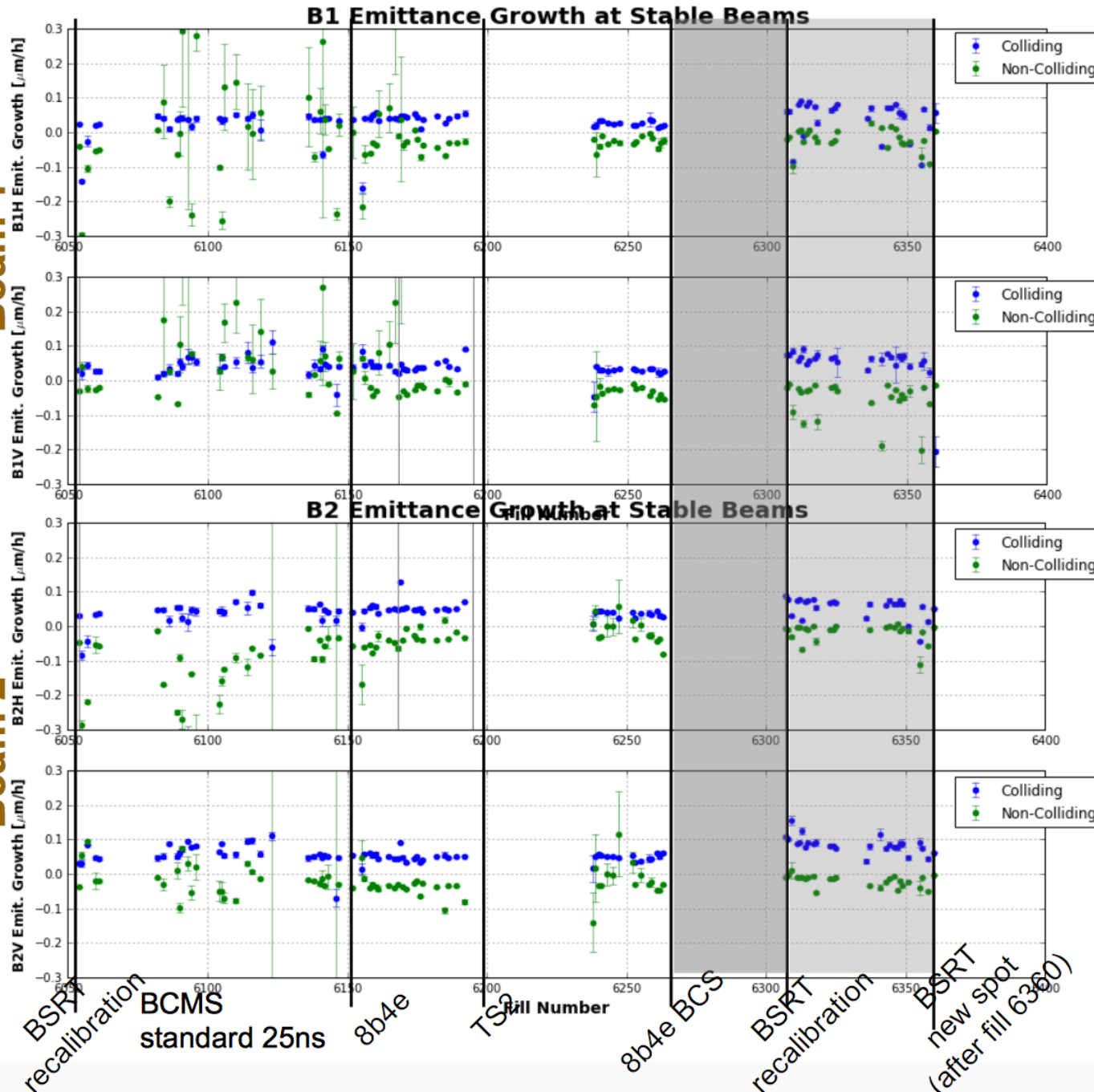


[Link](#) to the talk

# Emittance evolution during stable beams 2017

Beam 1

Beam 2



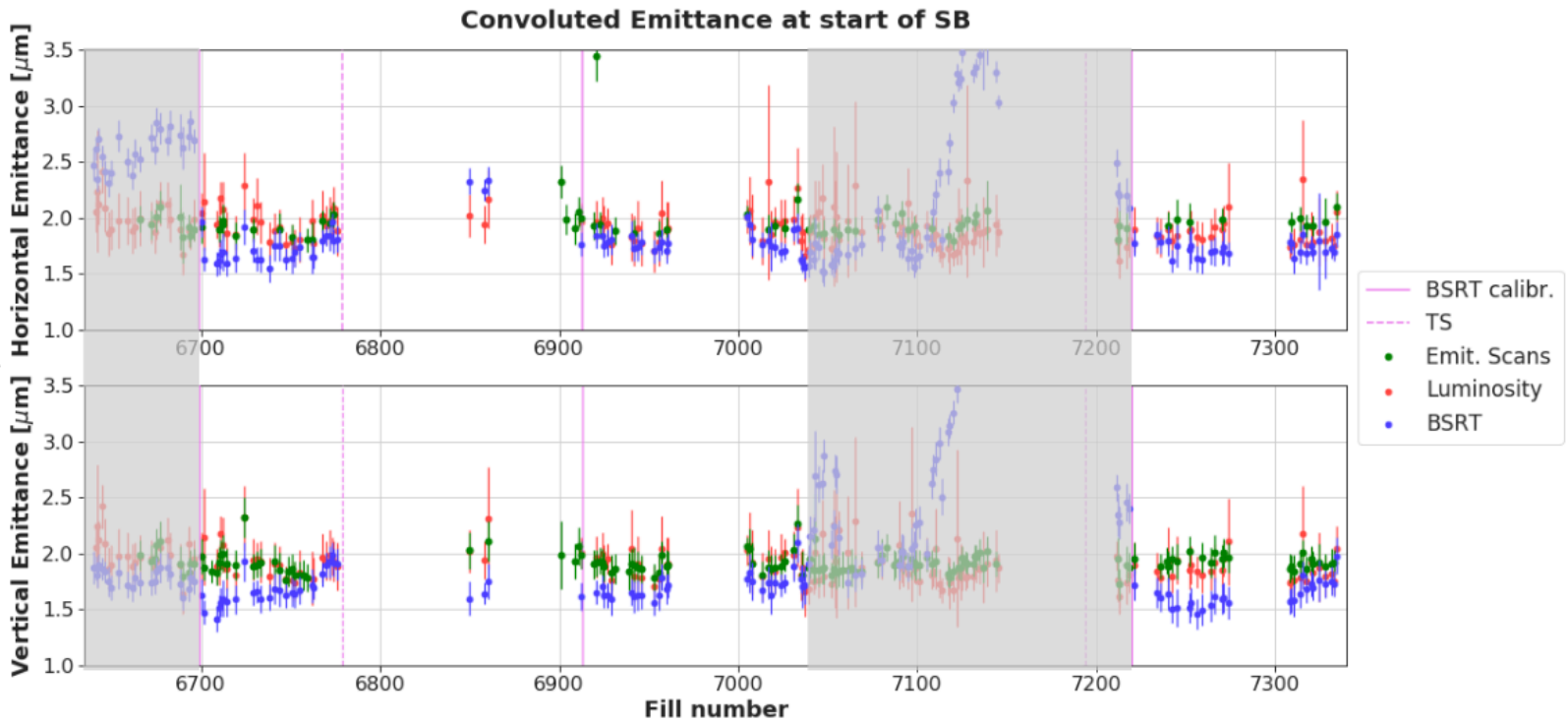
Colliding bunches have similar growth for any beam and plane along the 2017 run.

Non-colliding bunches usually damp, unless they get unstable.

Non-colliding closer to model and colliding over model.

[Link to the talk](#)

# Convolved emittances at start of SB



Emittances from Luminosity agree within 10-15% with the ones from Emittance Scans and BSRT (see appendix)

[Link to the talk](#)

Considering only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%

	Average emittance values [ $\mu\text{m}$ ]		Relative emittance blow-up [%]		
	B1H, B2H	B1V, B2V		B1H, B2H	B1V, B2V
Stable Beams	1.9	1.9	Ramp	~20	~25

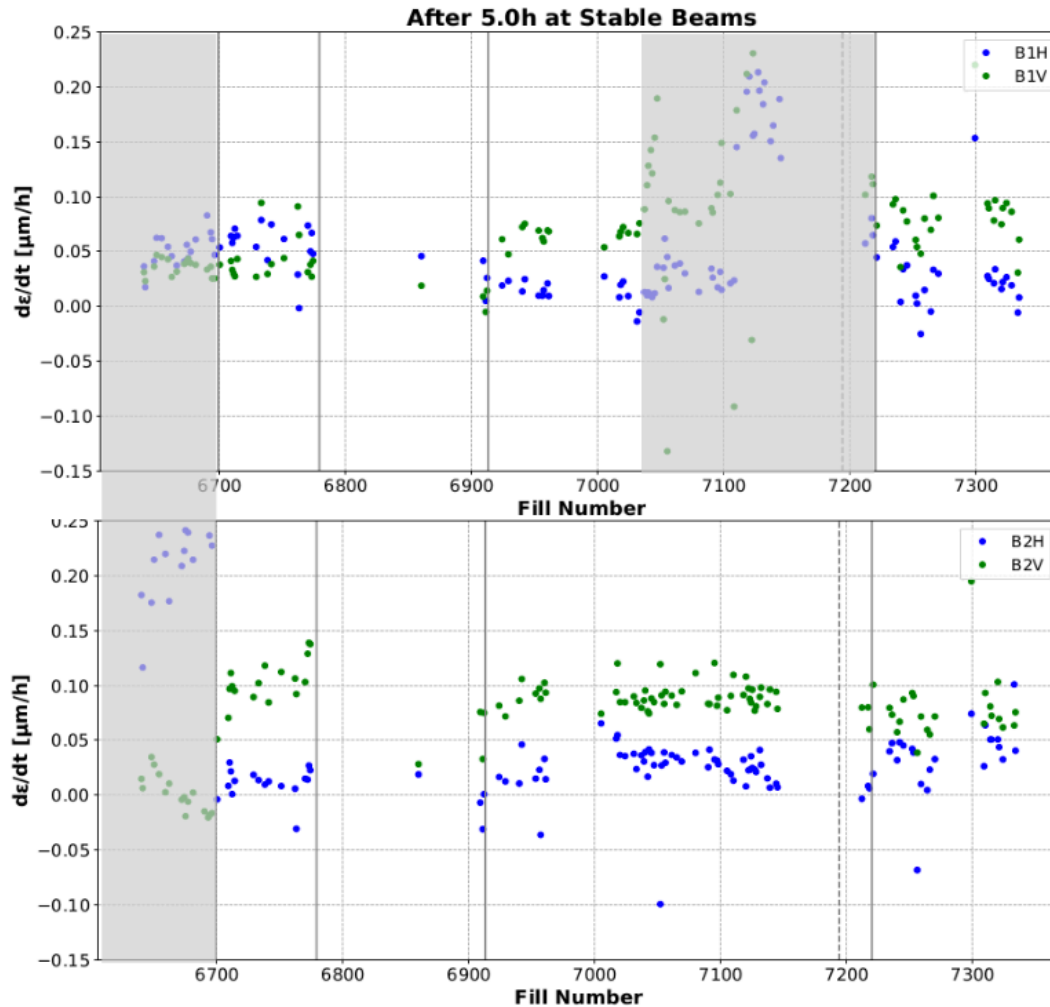
# Extra emittance growth at SB

Measured (BSRT)-Model emit. difference after 5h at SB vs Fill number  
 $d\epsilon/dt \rightarrow$  **extra emittance growth on top of IBS**

9th LHC Operations Evian Workshop  
 31/01/2019



[Link to the talk](#)



(Taking into account only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

Emit. growth after 5h @ SB [ $\mu\text{m}/\text{h}$ ]				
	B1H	B1V	B2H	B2V
extra	0.02	0.07	0.02	0.09

Not constant extra growth along a fill in horizontal

In 2017, the extra emittance growth at SB was around  $0.05\mu\text{m}/\text{h}$  and  $0.1\mu\text{m}/\text{h}$  in the horizontal and the vertical plane, respectively

These values are close to what is observed as emittance growth from noise at SB (X. Buffat)