Non factorization at LHCb : Two-dimensional vdM scans

LHC Lumi Days, 4-5 June 2019

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Outline:

(1) Introduction: why two-dimensional vdM scans?

(2) First 2D scans in Nov’17 (5 TeV) and Jun’18 (13 TeV)

Conclusions

X-Y factorization : brief reminder

Pile-up μ at beam separation Δ*x*, Δ*y* :

$$\mu(\Delta x,\ \Delta y) = \sigma L = \sigma N_1 N_2 \int \rho_1(x-\Delta x,\ y-\Delta y)\rho_2(x,y)\,dx\,dy$$

After integration over Δ*x*, Δ*y*, overlap integral collapses to 1 → van der Meer formula for 2D case :

$$\int \mu(\Delta x,\ \Delta y)\,d\Delta x\,d\Delta y = \sigma N_1 N_2$$

For LHC stability, transverse « betatron » oscillations are well decoupled in X and Y, so one expects :

$$\rho_{1,2}(x,y) = \rho^x_{1,2}(x)\cdot\rho^y_{1,2}(y)$$

$$\mu(\Delta x,\Delta y) = \ \mu^x(\Delta x)\cdot\mu^y(\Delta y)$$

= 1

$$\sigma = \frac{\int \mu(\Delta x,\Delta y)\,d\Delta x\,d\Delta y}{N_1 N_2} = \frac{\int \mu^x(\Delta x)\,d\Delta x \int \mu^y(\Delta y)\,d\Delta y}{N_1 N_2}\cdot\boxed{\frac{\mu^y(\Delta y_0)\mu^x(\Delta x_0)}{\mu^y(\Delta y_0)\mu^x(\Delta x_0)}} =$$

$$\boxed{\frac{\int \frac{\mu(\Delta x,\Delta y_0)}{N_1 N_2}\,d\Delta x\cdot\int\frac{\mu(\Delta x_0,\Delta y)}{N_1 N_2}\,d\Delta y}{\frac{\mu(\Delta x_0,\Delta y_0)}{N_1 N_2}}.}$$

Main formula for cross-section measurement

X+Y scans (at constant arbitrary Δx_0, Δy_0) are sufficient if $\mu(\Delta x,\Delta y) = \ \mu^x(\Delta x)\cdot\mu^y(\Delta y)$
Faster than 2D : save beam time, reduce orbit drift.

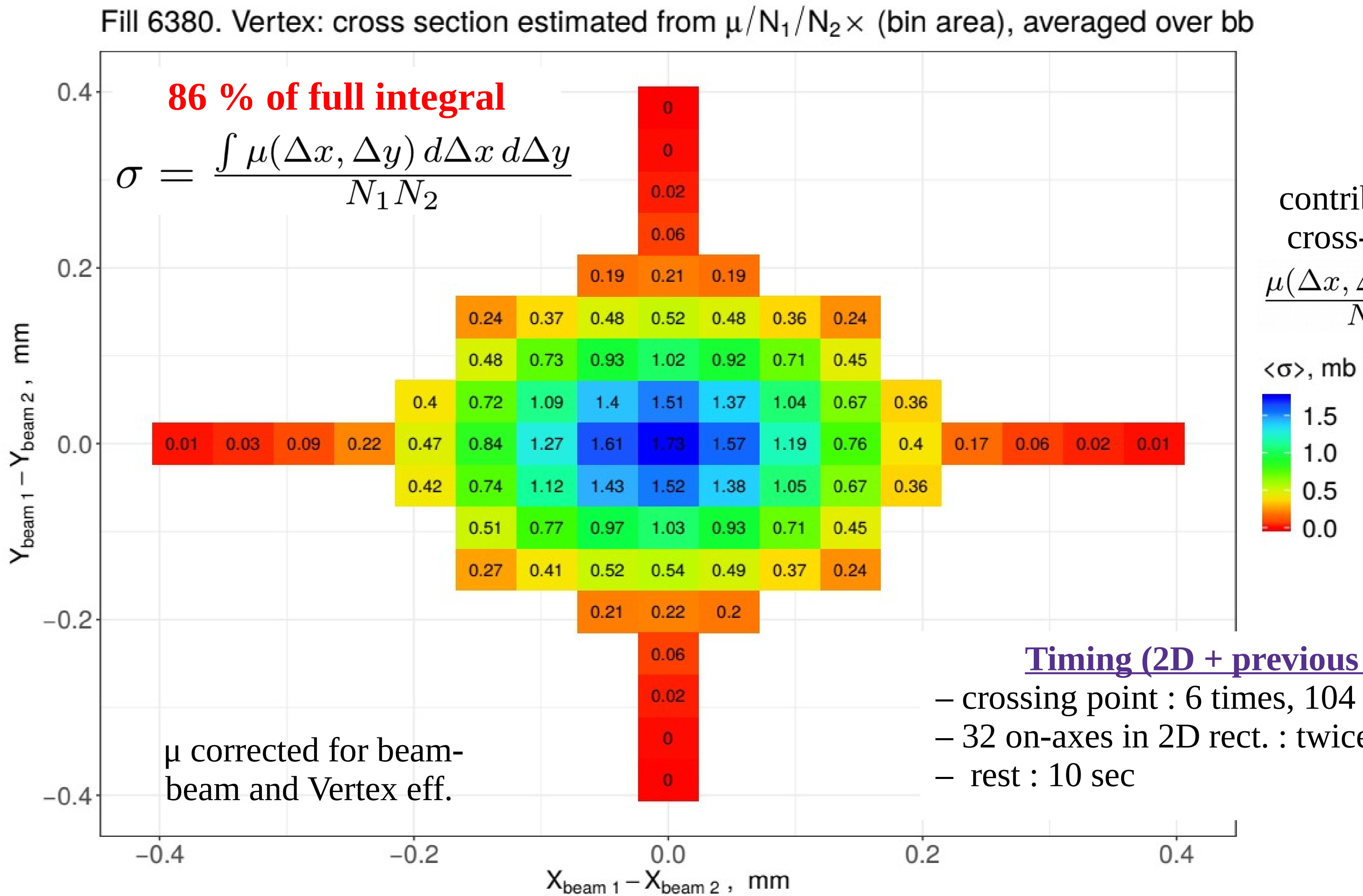
But : how to estimate non-factorizability ? **The simplest solution : make 2D scan !**

First 2D at LHC in Nov'17, fill 6380

***pp*, 5 TeV**

Sufficient to cover central 2D region - not expensive !
(9 min X-Y + 18 min 2D scan – 11 min to move beams = 17 min, 10 sec / point)

Automatic beam steering granted to experiments – **many thanks to Michi Hostettler (LHC), great job!**



86 % of full integral

$$\sigma = \frac{\int \mu(\Delta x, \Delta y)\, d\Delta x\, d\Delta y}{N_1 N_2}$$

contribution to cross-section

$$\frac{\mu(\Delta x, \Delta y)\, \Delta x\, \Delta y}{N_1 N_2}$$

μ corrected for beam-beam and Vertex eff.

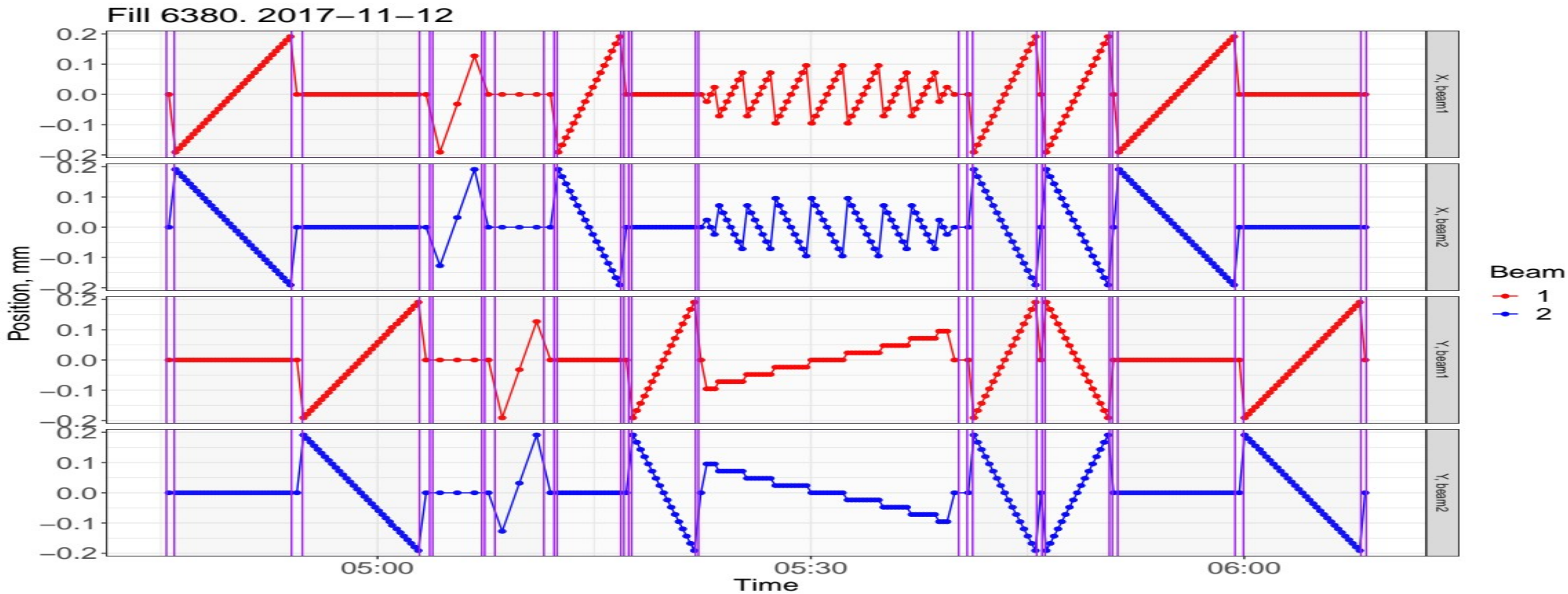
Timing (2D + previous 1D X-Y)

– crossing point : 6 times, 104 sec in total
– 32 on-axes in 2D rect. : twice, 20 sec/ point
– rest : 10 sec

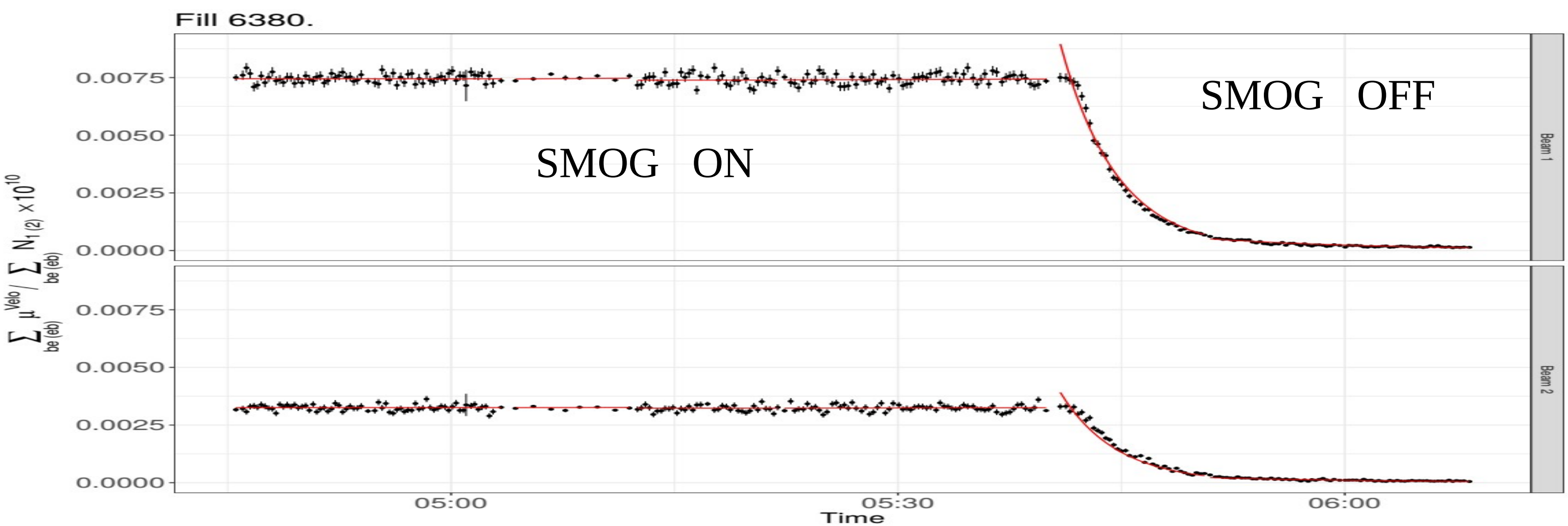
LHCb in fill 6380

pp, 5 TeV

No beam adjustments, everything in one go, all program in 1h 23 min !



X+Y LSC X+Y 2D Diagonal X+Y

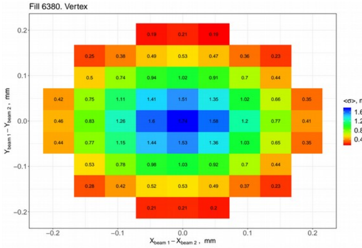


Relative mismatch b.t.w. sum(2D) and sum(factorization)

Approximate $\int \mu(\Delta x,\, \Delta y)\, d\Delta x\, d\Delta y \approx \sum_{i,j} \mu_{i,j} \Delta x\, \Delta y$. Approximation error should largely cancel in

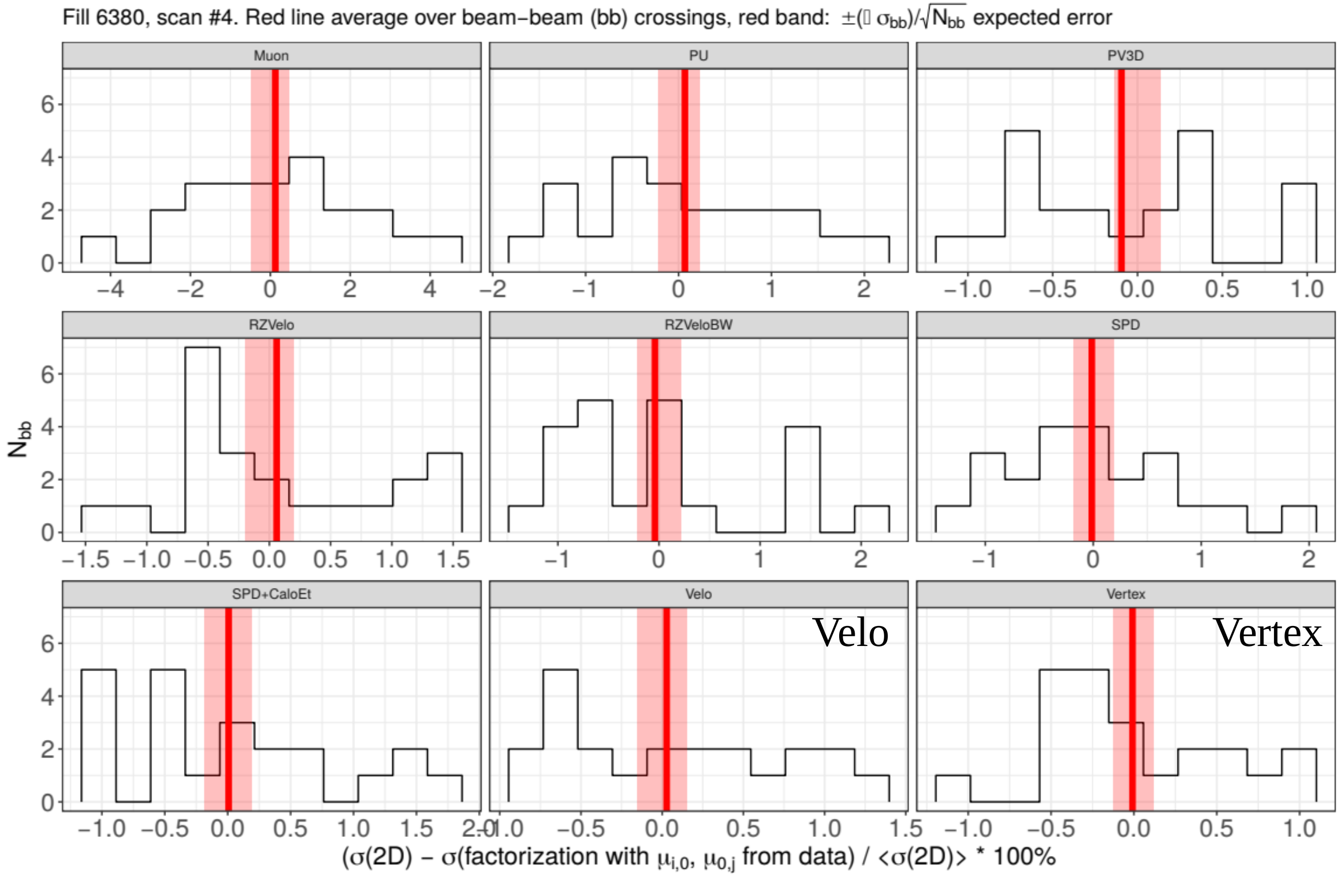
$$\boxed{\frac{\sum_{i,j}(\mu_{i,j} - \mu_{i,0}\cdot\mu_{0,j}/\mu_{0,0})}{\sum_{i,j}\mu_{i,j}}}$$

Sums over 2D scanned area



Mismatch of x-section from 2D and X-Y factorization, for all LHCb luminometers in %

2D scan data alone



22 histogram entries = 22 beam-beam crossings. Red line - average, band - its expected error, ± st.deviation / √22. Bunch crossing measurements are uncorrelated up to negligible common fluctuation of background.

Vertex : -0.01±0.12 % mismatch – excellent sensitivity and confirmation of 86% of x-section

Relative mismatch b.t.w. sum(2D) and sum(factorization)

Approximate $\int \mu(\Delta x,\, \Delta y)\, d\Delta x\, d\Delta y \approx \sum_{i,j} \mu_{i,j} \Delta x\, \Delta y$. Approximation error should largely cancel in

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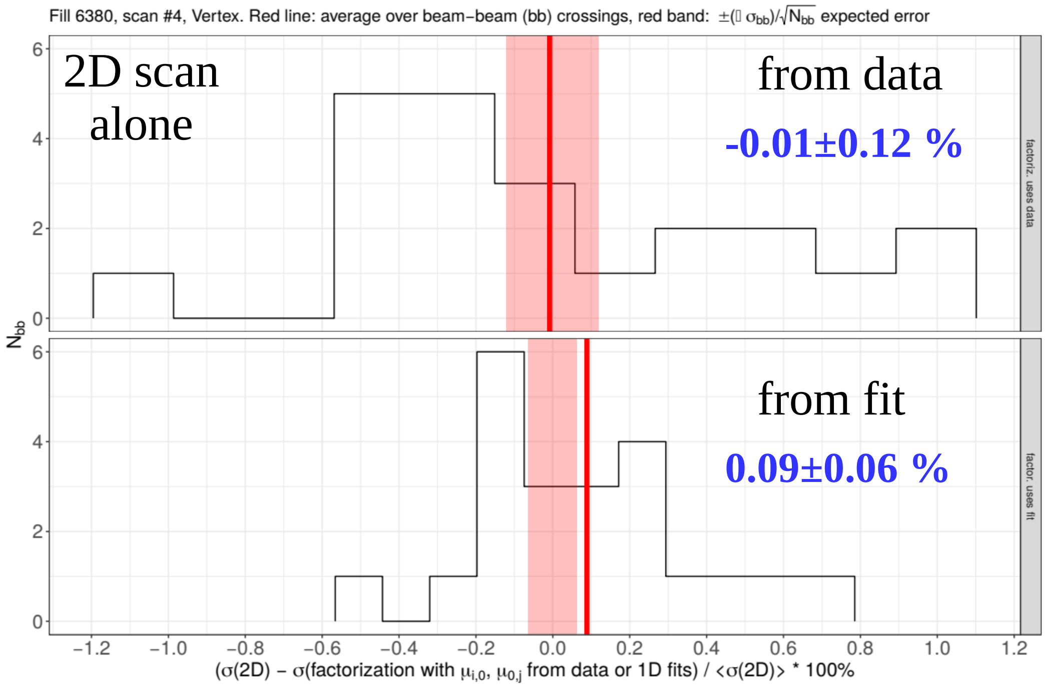
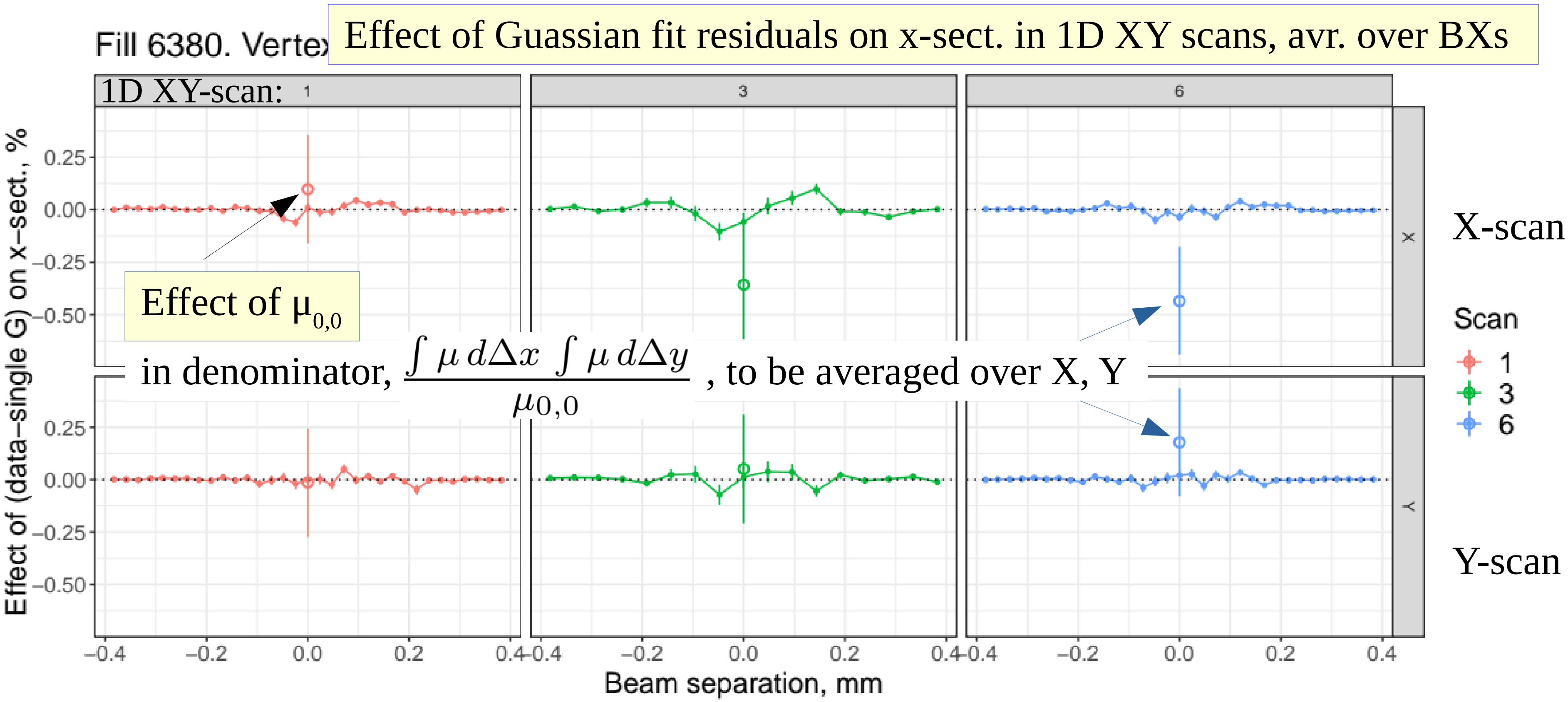
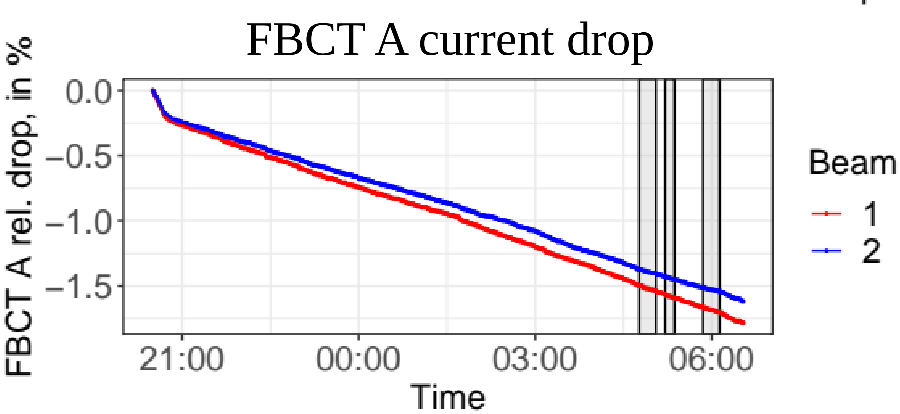
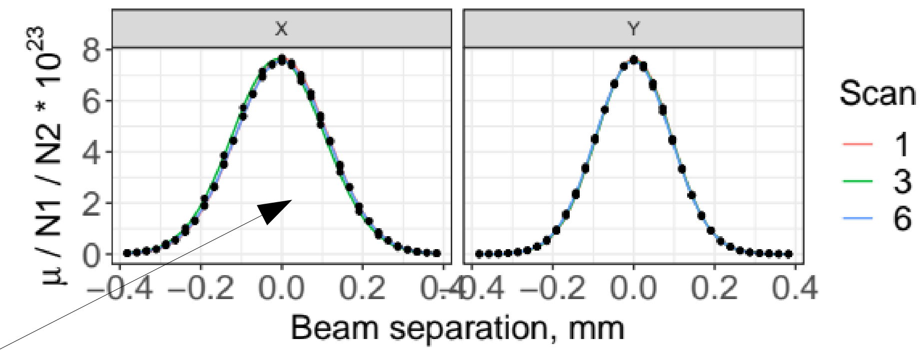
On-axes $\mu_{i,0},\ \mu_{0,j},\ \mu_{0,0}$ can be taken from data (top) or from single Gaussian fit (bottom)



1D Gaussian fit residuals, orbit X-drift btw. scans #1 - #3







Approximately Gaussian shapes and 9 um orbit drift btw. scans 1 and 3 in all bunch crossings.

Relative mismatch b.t.w. sum(2D) and sum(factorization)

Approximate $\int \mu(\Delta x,\, \Delta y)\, d\Delta x\, d\Delta y \approx \sum_{i,j} \mu_{i,j} \Delta x\, \Delta y$. Approximation error should largely cancel in

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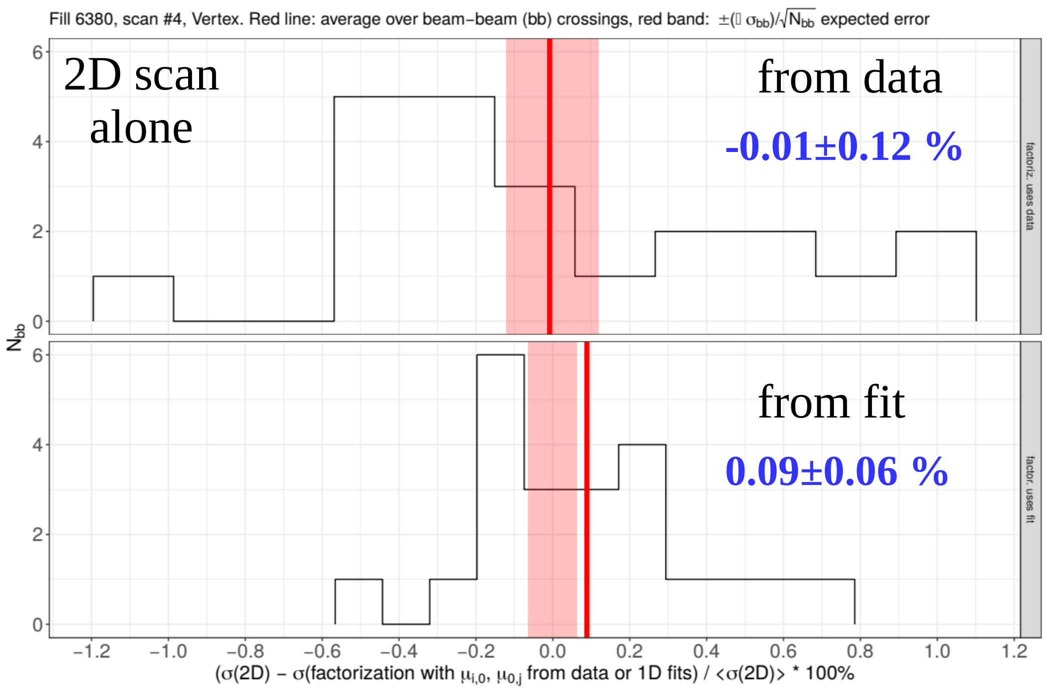

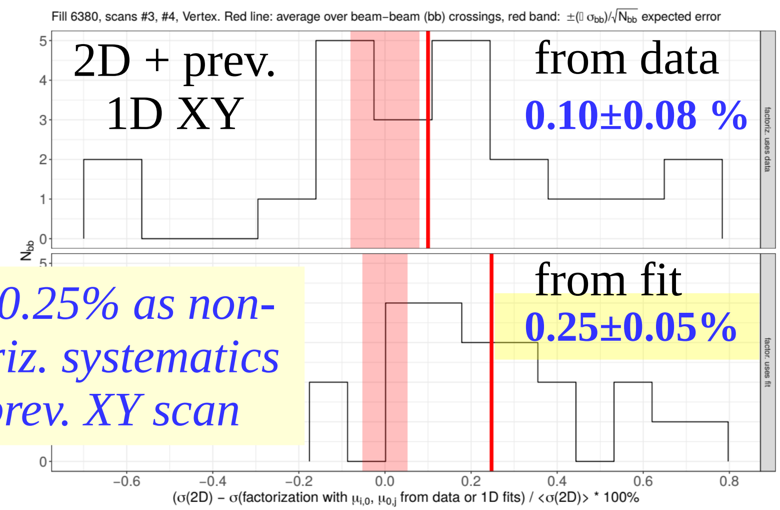

Take 0.25% as non-factoriz. systematics of prev. XY scan

Mixing of 2D and 1D X-Y scan

Relative mismatch b.t.w. sum(2D) and sum(factorization)

Approximate $\int \mu(\Delta x,\, \Delta y)\, d\Delta x\, d\Delta y \approx \sum_{i,j} \mu_{i,j} \Delta x\, \Delta y$. Approximation error should largely cancel in

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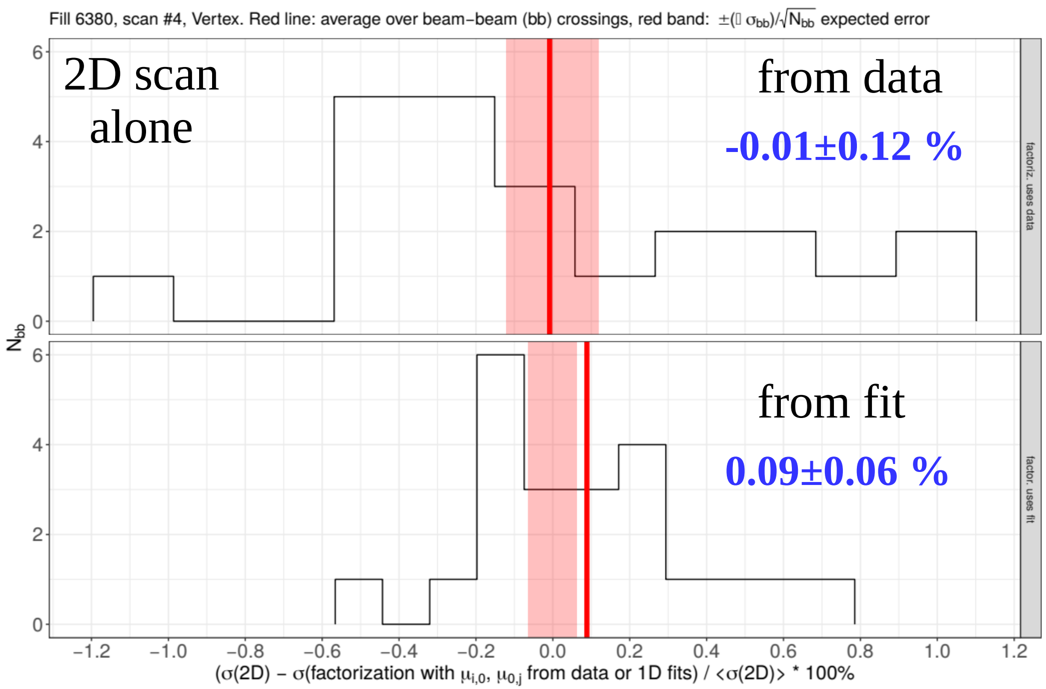
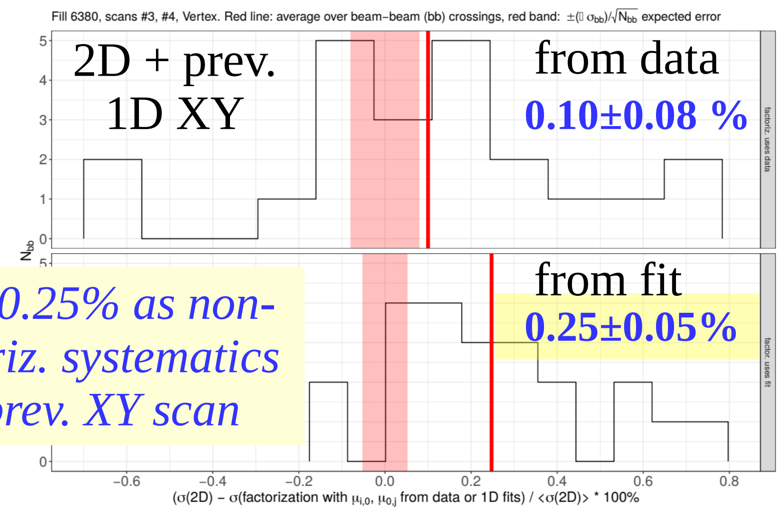
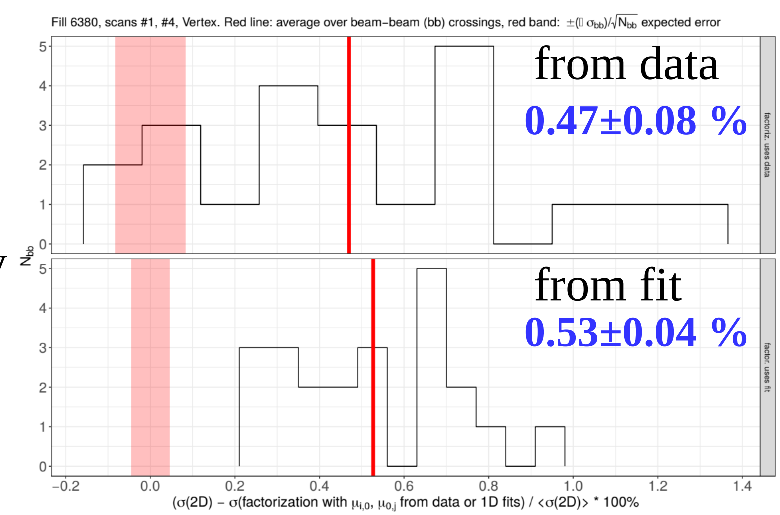




Take 0.25% as non-factoriz. systematics of prev. XY scan

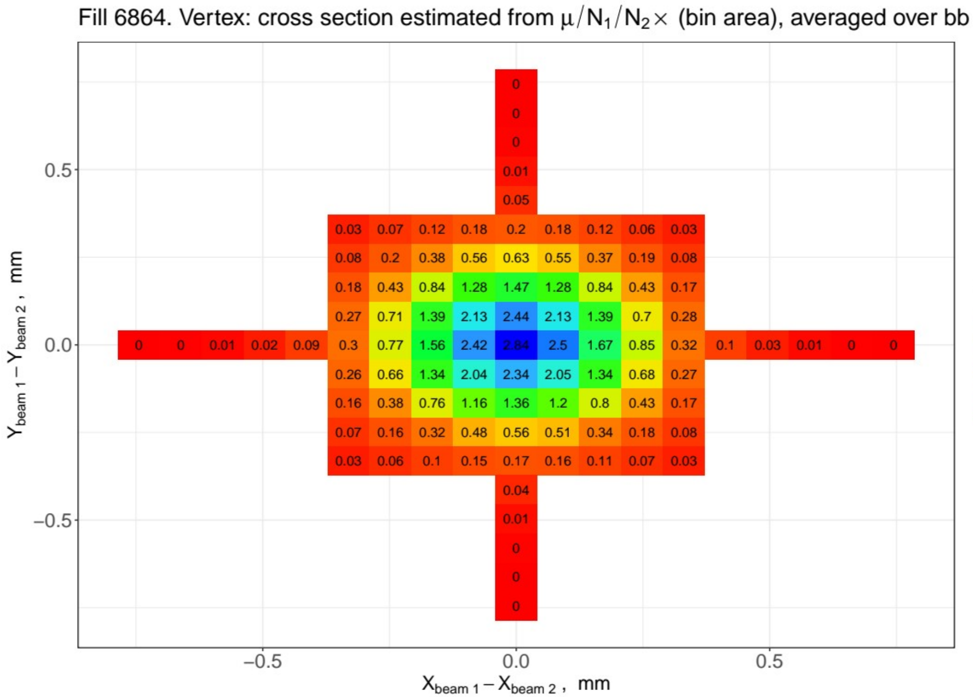
Mixing of 2D and 1D X-Y scan

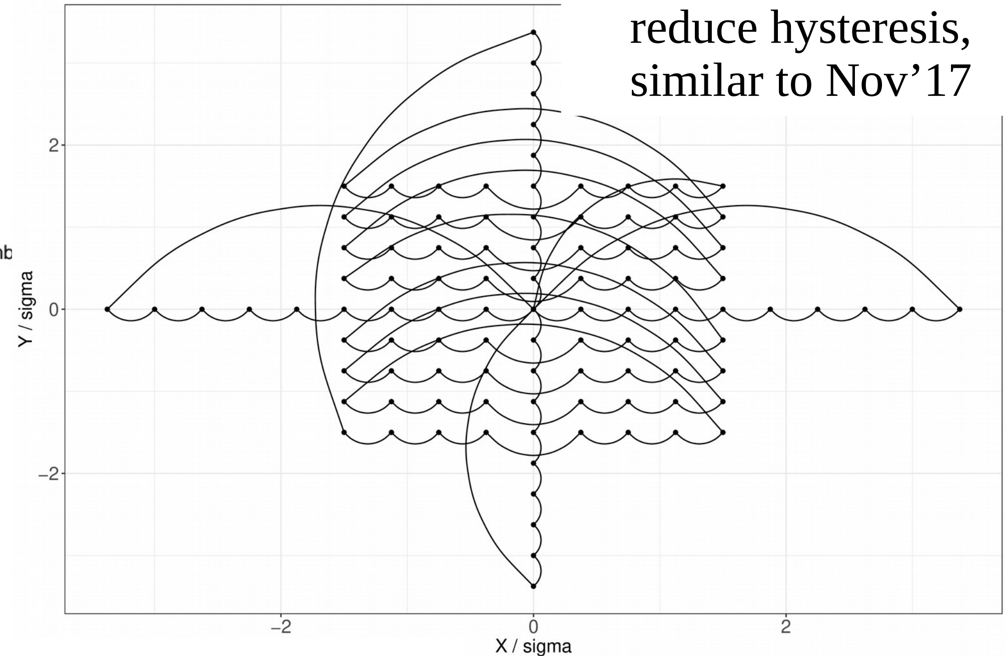
2D + 1st XY scan shifted by 9 um in X



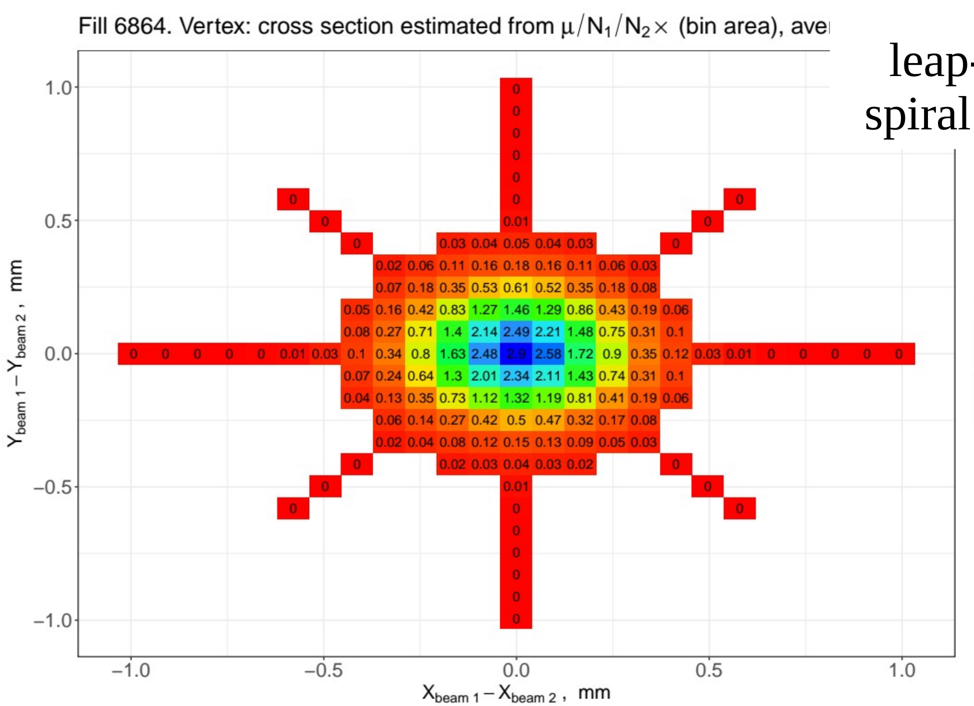
Two more 2D scans in Jun 2018, fill 6864

pp, 13 TeV

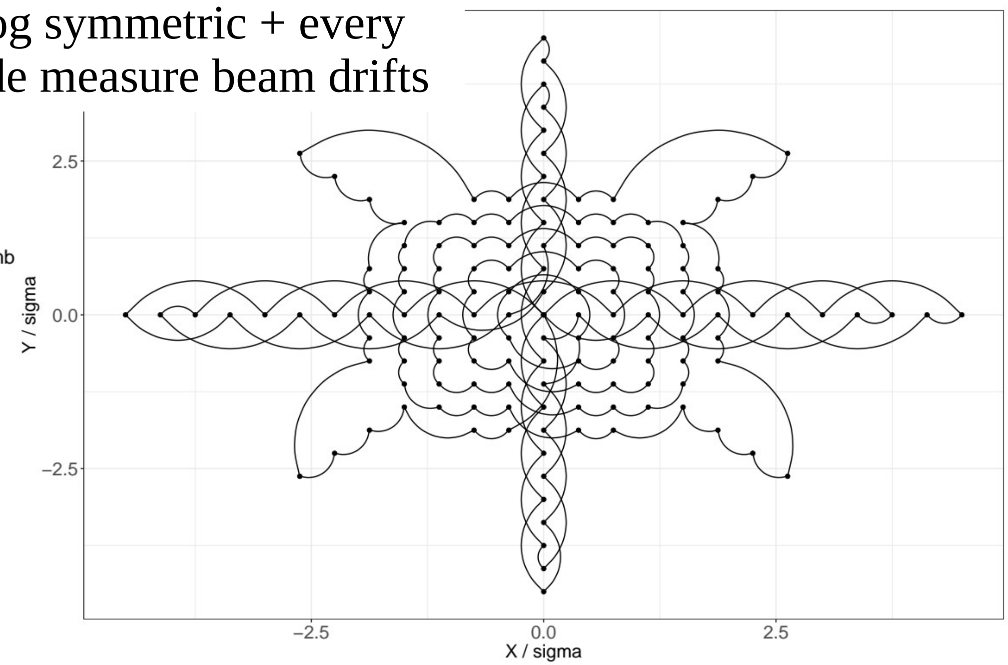




one-directional in X to reduce hysteresis, similar to Nov’17



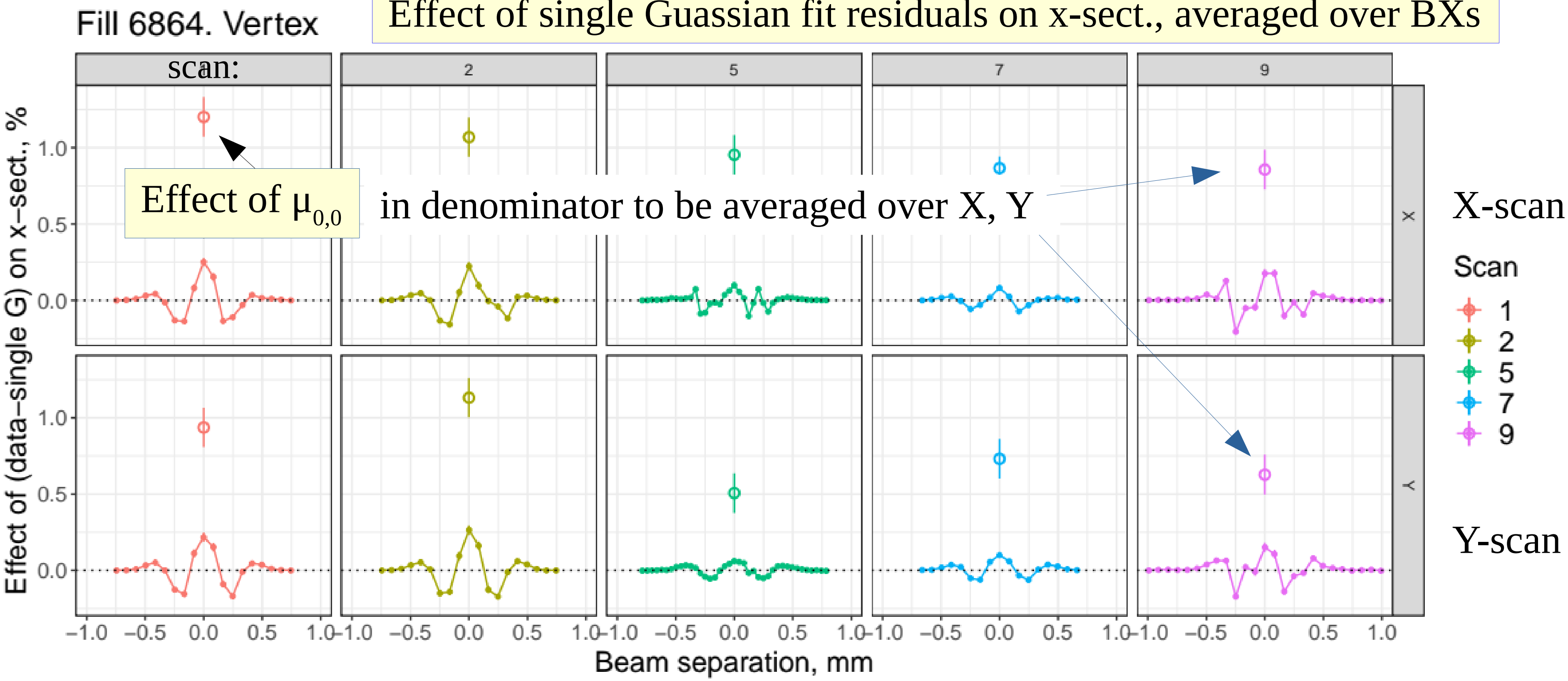
with new ideas :
leap-frog symmetric + every spiral side measure beam drifts



Gaussian fit residuals

pp, 13 TeV

Effect of single Guassian fit residuals on x-sect., averaged over BXs

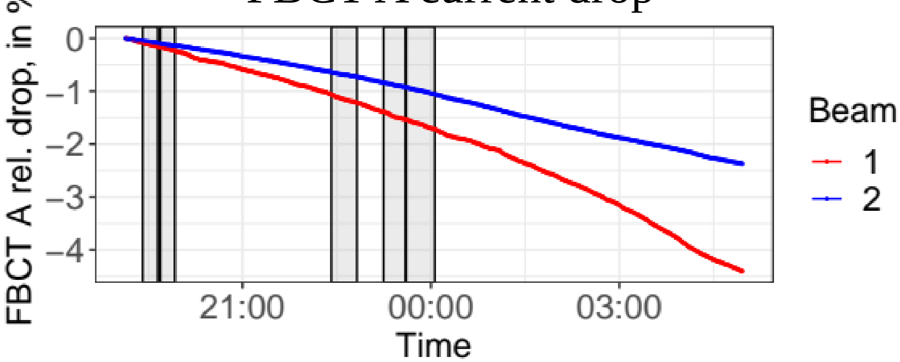


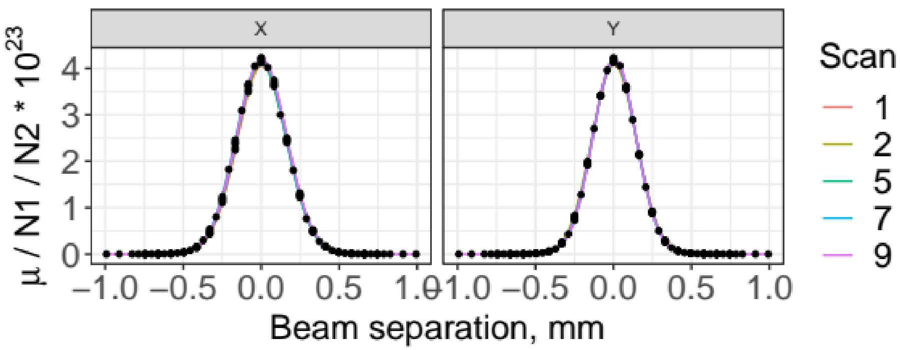
Effect of $\mu_{0,0}$ in denominator to be averaged over X, Y

X-scan

Y-scan

FBCT A current drop





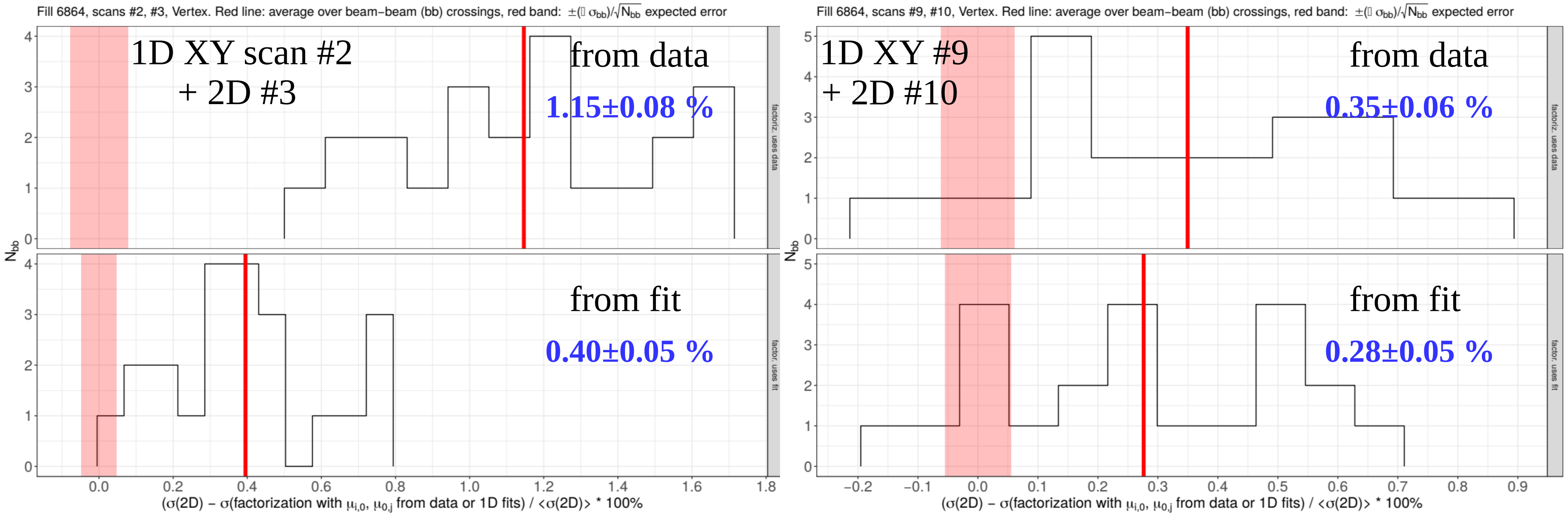
Deviations from G. are compensated in integrals, but strongly affect $\mu_{0,0}$ in $\dfrac{\int \mu \, d\Delta x \int \mu \, d\Delta y}{\mu_{0,0}}$

Relative mismatch b.t.w. sum(2D) and sum(factorization)

Approximate $\int \mu(\Delta x,\, \Delta y)\, d\Delta x\, d\Delta y \approx \sum_{i,j} \mu_{i,j} \Delta x\, \Delta y$. Approximation error should largely cancel in

$$\boxed{\frac{\sum_{i,j}(\mu_{i,j} - \mu_{i,0}\cdot\mu_{0,j}/\mu_{0,0})}{\sum_{i,j}\mu_{i,j}}}$$

On-axes $\mu_{\mathrm{i},0},\ \mu_{0,\mathrm{j}},\ \mu_{0,0}$ can be taken from data (top) or from single Gaussian fit (bottom)

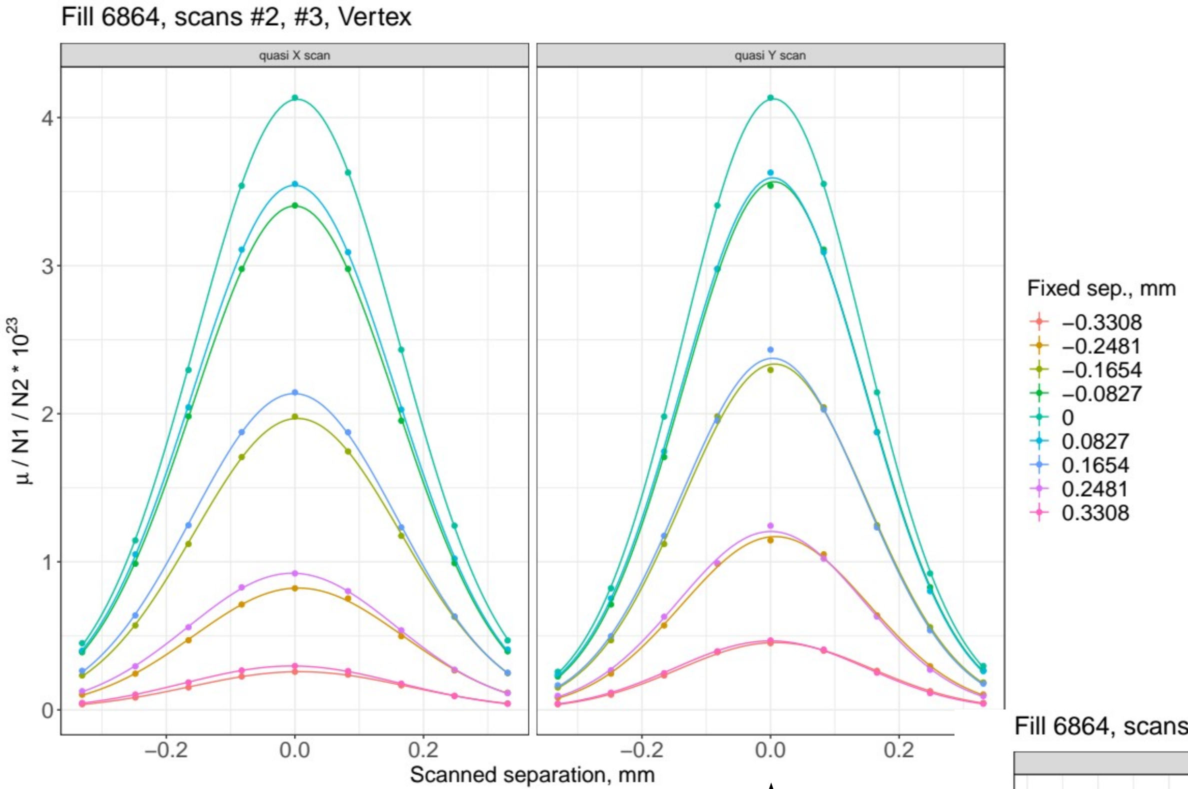


Default x-section in 1D XY-scans is obtained from more precise fitted (not data) μ-values. 2D shows that fit also reduces non-factorization systematics, mainly since $\mu_{0,0}$ strongly affecting x-section, jumped above Gaussian in scan #2 by 1.1 % (maximally across all analyzed vdM fills). Taking $\mu_{0,0}$ from fit gives much better agreement. $\mu_{0,0}$ deviation from Gaussian was reducing in time, and non-factorization systematics in second 2D (right) also reduced to 0.28 %.

Take maximal deviation 0.4% as non-factoriz. systematics of all XY scans, and maximal 1.1 % deviation of $\mu_{0,0}$ as systematics of fit model.

2D viewed as X,Y-offset scans

pp, 13 TeV

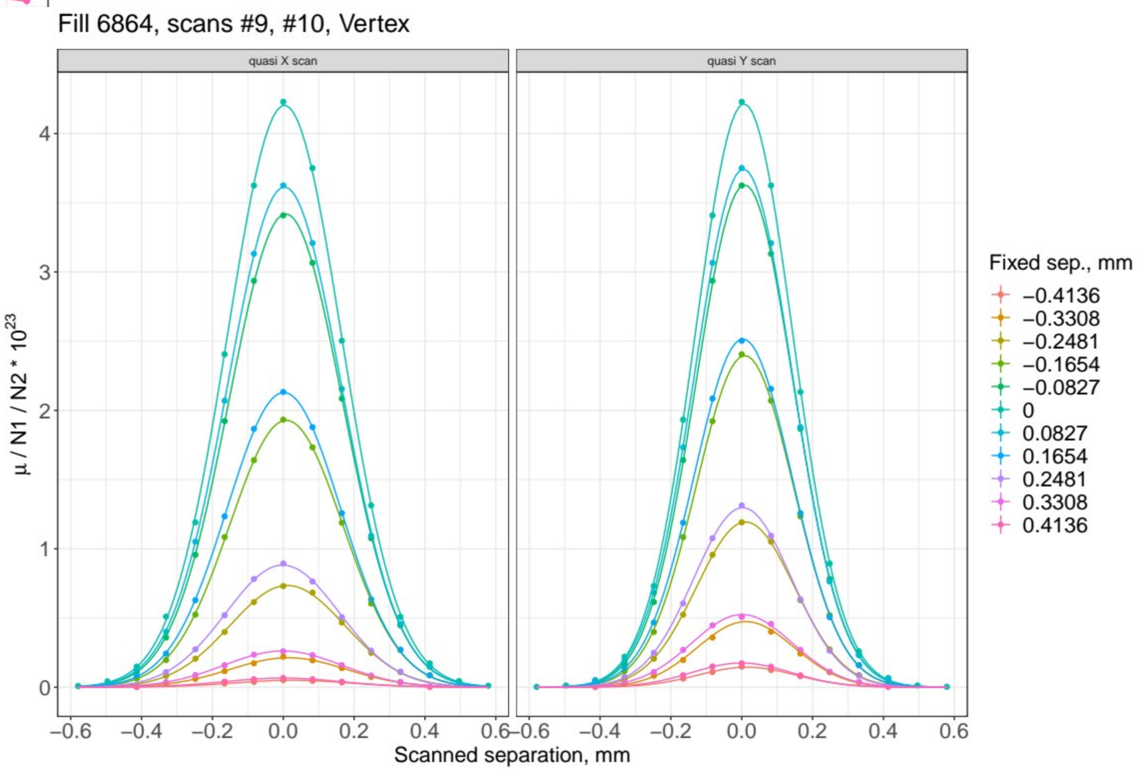


Every point is duplicated
(once in X and once in Y).

Data are fit per BX and then averaged.

Deviations around zero

Second 2D scan is better

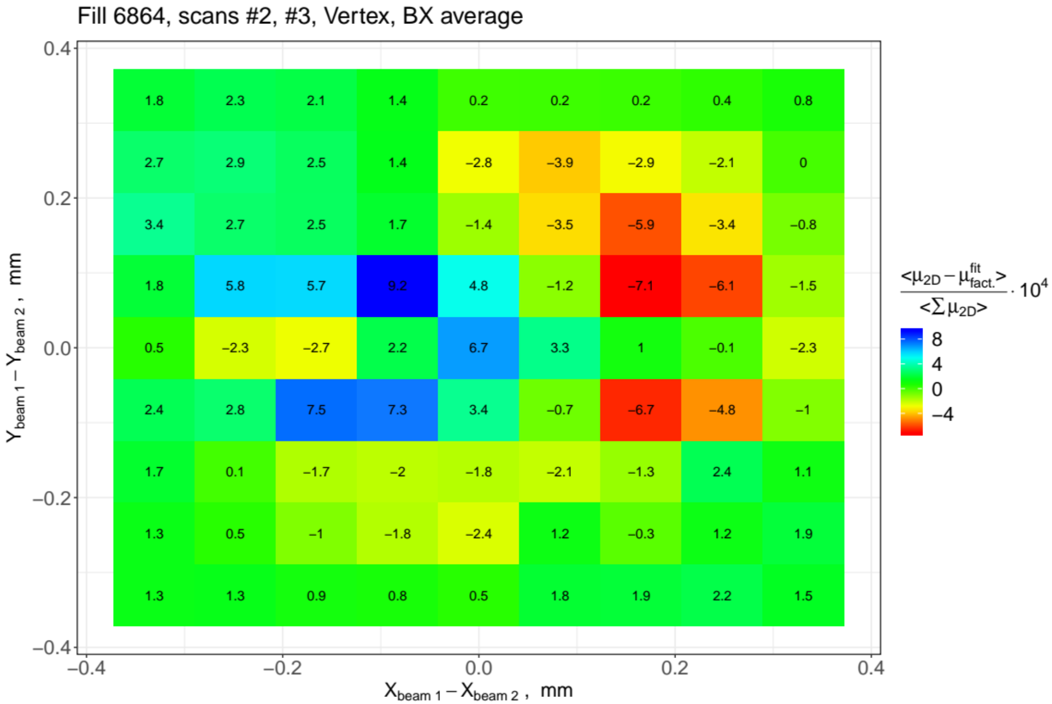


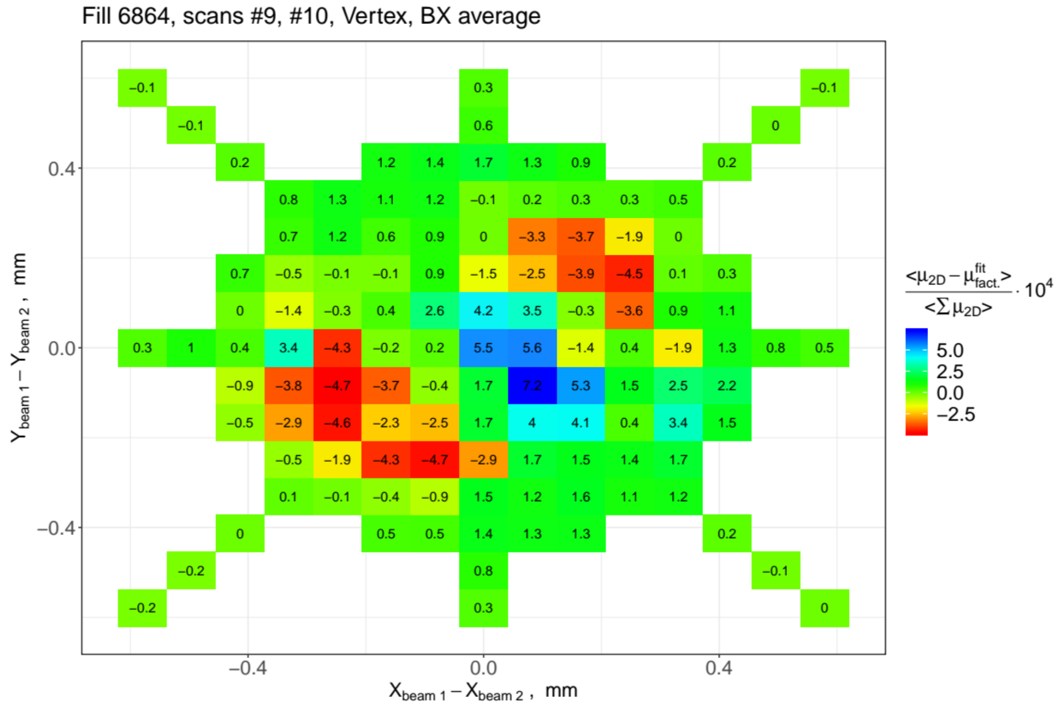
2D map of residuals

pp, 13 TeV

$$\boxed{\frac{\mu_{i,j} - \mu_{i,0} \cdot \mu_{0,j} / \mu_{0,0}}{\sum_{i,j} \mu_{i,j}}}$$

On-axes $\mu_{i,0}$, $\mu_{0,j}$, $\mu_{0,0}$ are from single Gaussian fits





Data are fit per bunch crossing and then averaged. Mismatches are scaled by 10^{-4}

Conclusions

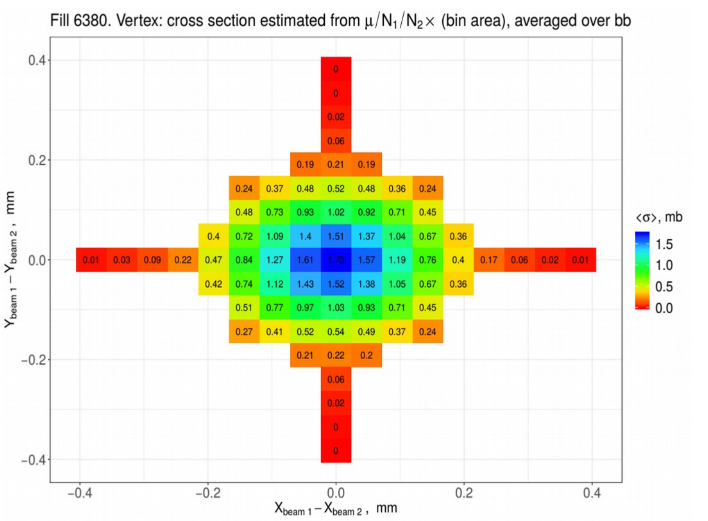
1. Integration of 2D scan pile-up μ yields correct cross-section for arbitrarily complex (non-Gaussian) bunch shapes :

$$\sigma = \int \frac{\mu(\Delta x, \Delta y)}{N_1 N_2} \, d\Delta x \, d\Delta y$$

Simple and powerful.

2D scan is a way to go to avoid X-Y non-factorization systematics.

2. 3 scans performed up to now : Nov’17, Jun’18 (5 and 13 TeV). Despite the common belief, scanning only central region with maximal contribution to integral is fast
(eg. 18 min in Nov’17, 10 sec / point).



Conclusions

3. Contrary to 5 TeV Gaussian beams in fill 6380, 13 TeV bunches in fill 6864 were not Gaussian and not fully X-Y factorizable, especially in central part.

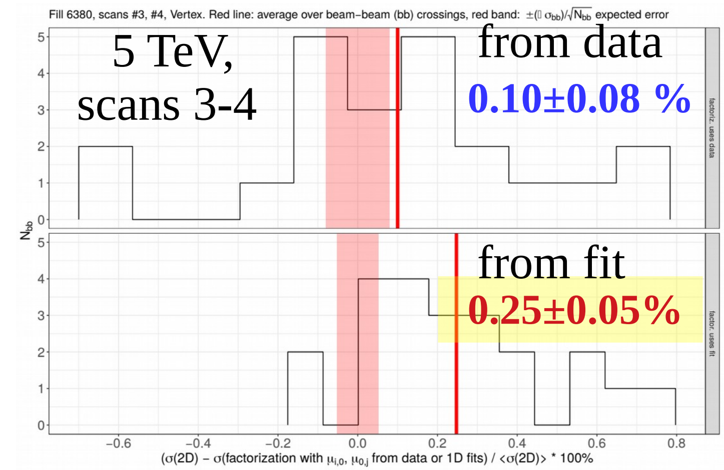
In factorization x-sect., this mainly affected $\mu_{0,0}$ in $\frac{\int \mu\, d\Delta x \int \mu\, d\Delta y}{\mu_{0,0}}$, but largely canceled in 1D integrals.

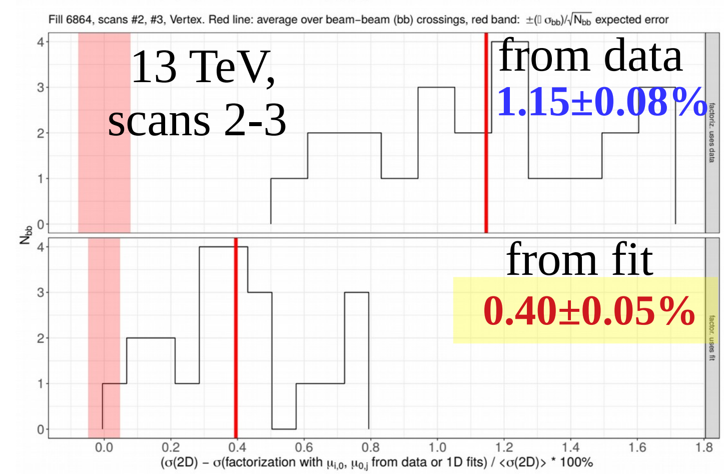
Mismatch with 2D was less when $\mu_{0,0}$ was taken from fit (default, as fitted $\mu_{0,0}$ had better precision). Maximal (data–fit) mismatch in $\mu_{0,0}$ **(1.1%)** was already taken into account as « fit model » systematics.

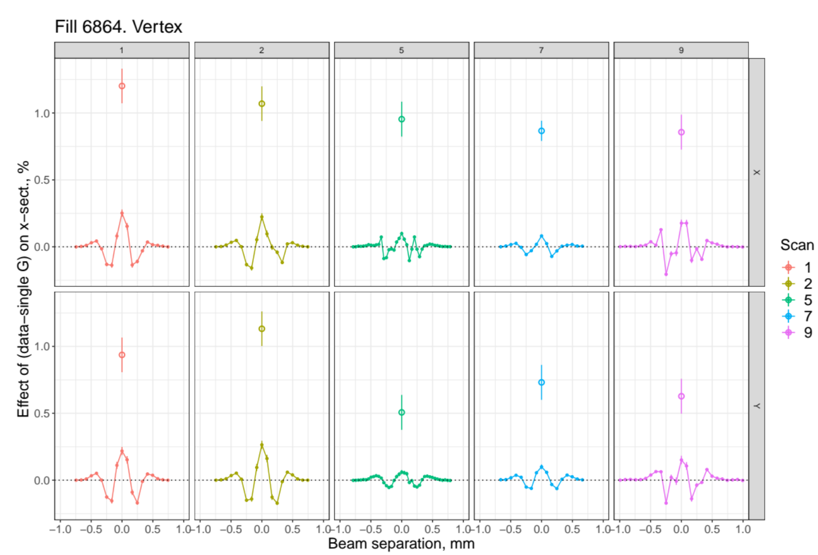
Remaining maximal discrepancy with 2D, **0.4 %**, is assigned as non-factorization systematics to all 13 TeV scans. This should be conservative since in other fills (data – fit) $\mu_{0,0}$ mismatch was ≤0.6 % and, generally, Gaussian fit residuals were smaller.

Envelope (ie. again, maximal) variation of scan-to-scan measurements is taken as another systematics **(0.9%).** In this way, 2D scan is « propagated » to other fills where it was not performed.

Corresponding systematics at 5 TeV : **0.2 %, 0.3 % and 1.0 %,** respectively.





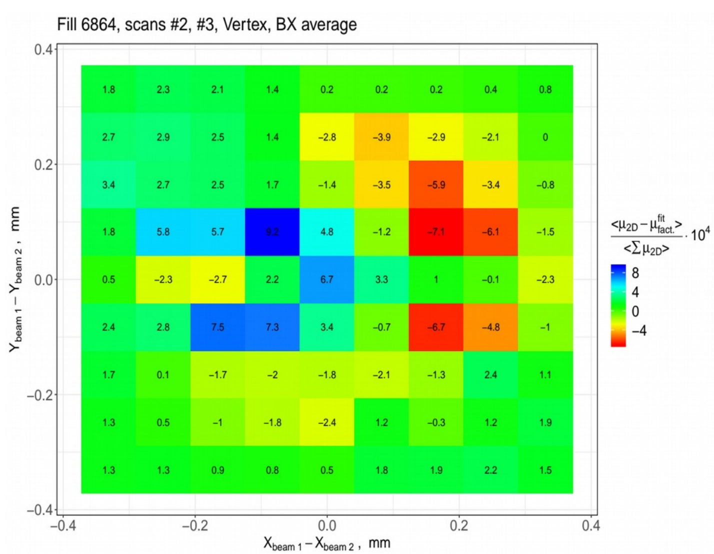


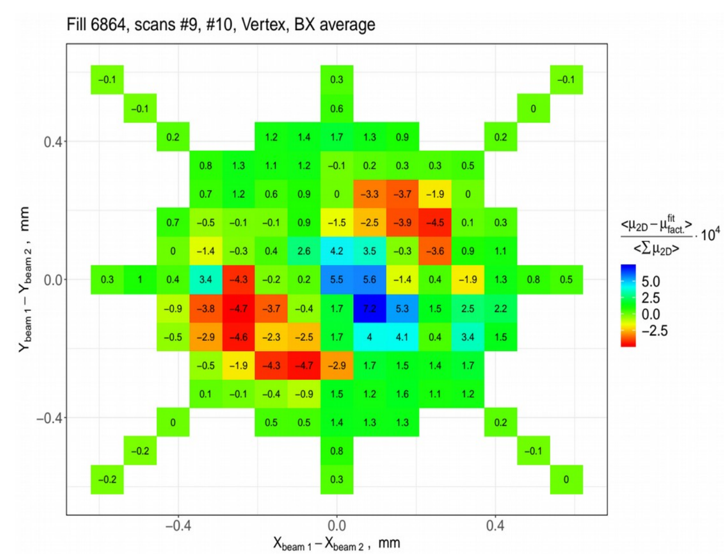
Conclusions

4. In addition to real non-factorization, many effects can mimic it :

beam-beam effects	background subtraction	hysteresis in LHC magnets
orbit drifts	beam timing difference (in X, due to X-Z crossing angle)	

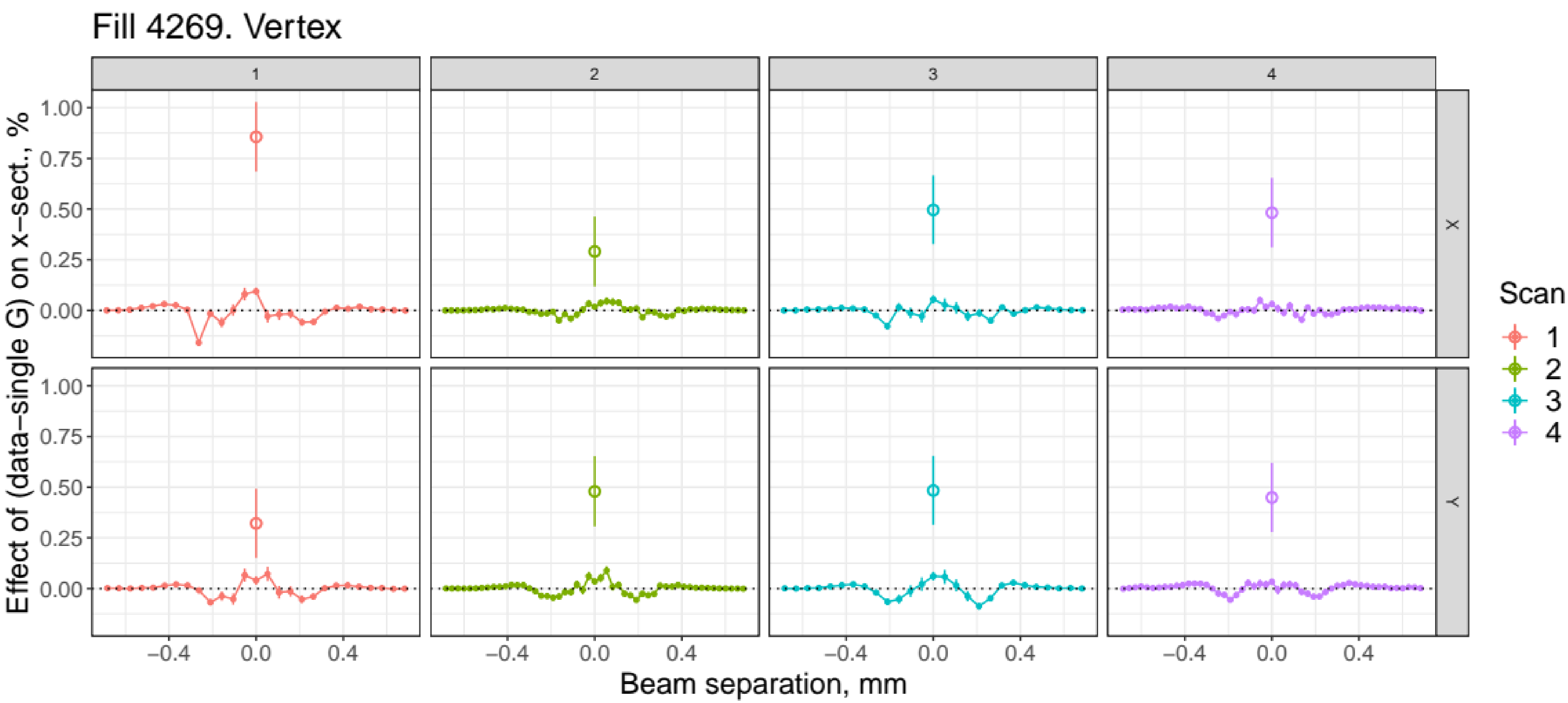
They all have been tested with current sensitivity.



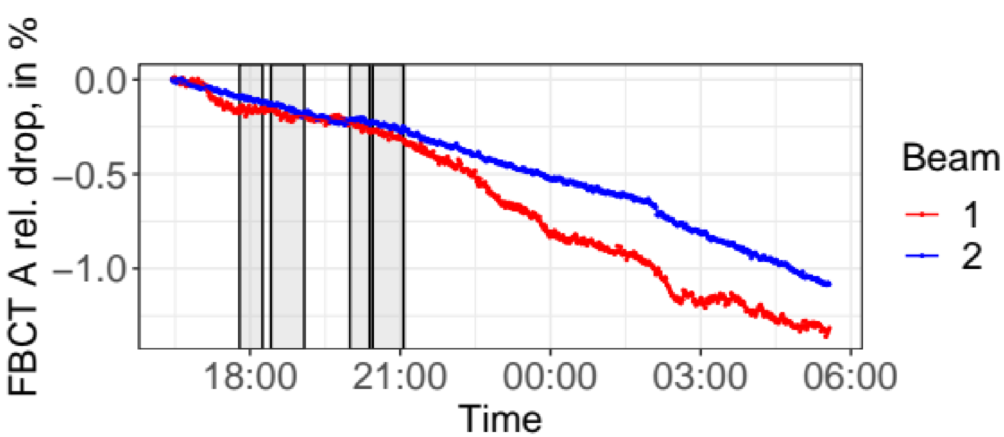


Backup slides

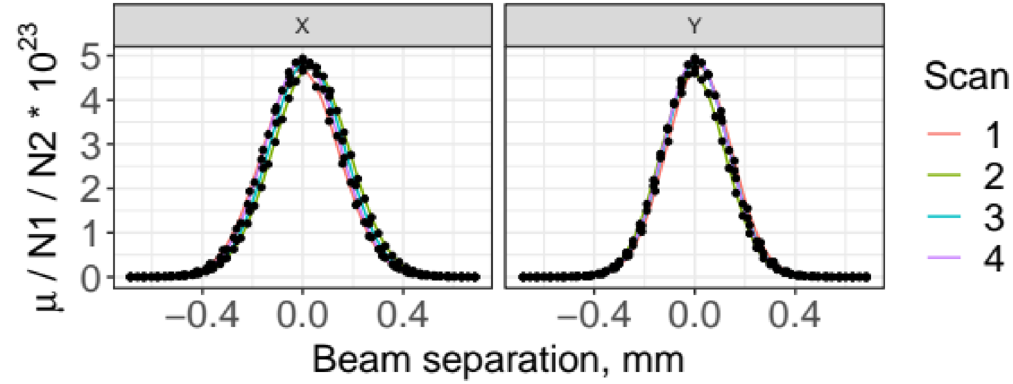
pp, 13 TeV



Fill 4269. Vertex
1
2
3
4
X
Y
Effect of (data−single G) on x−sect., %
1.00
0.75
0.50
0.25
0.00
−0.4
0.0
0.4
Beam separation, mm
Scan
1
2
3
4

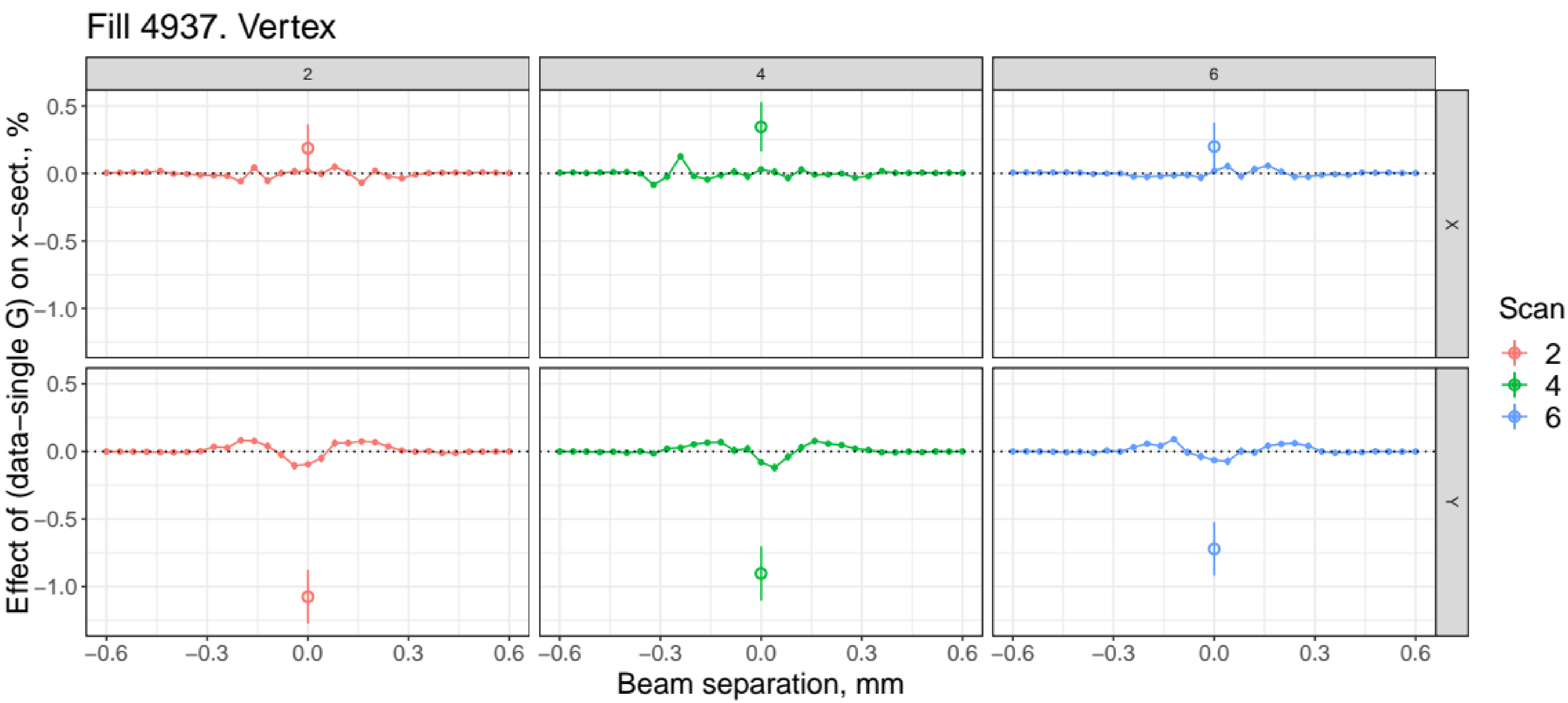


FBCT A rel. drop, in %
0.0
−0.5
−1.0
18:00
21:00
00:00
03:00
06:00
Time
Beam
1
2

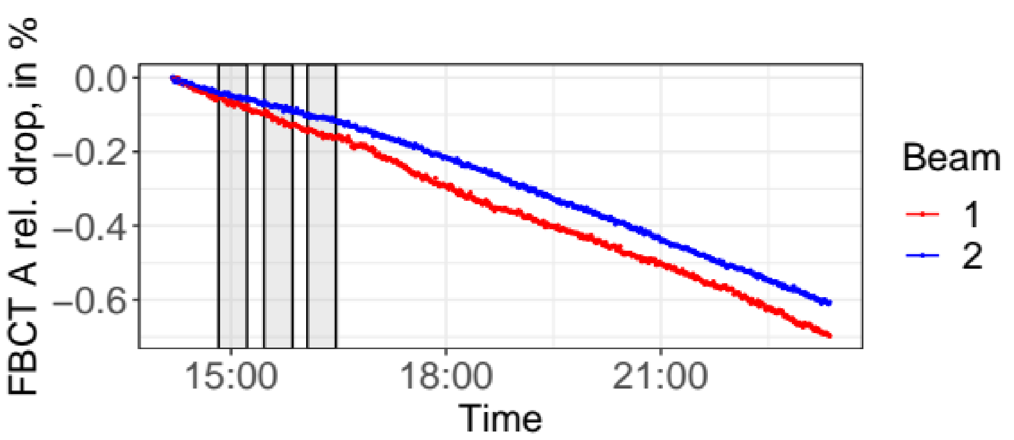


X
Y
μ / N1 / N2 * 10^23
5
4
3
2
1
0
−0.4
0.0
0.4
Beam separation, mm
Scan
1
2
3
4

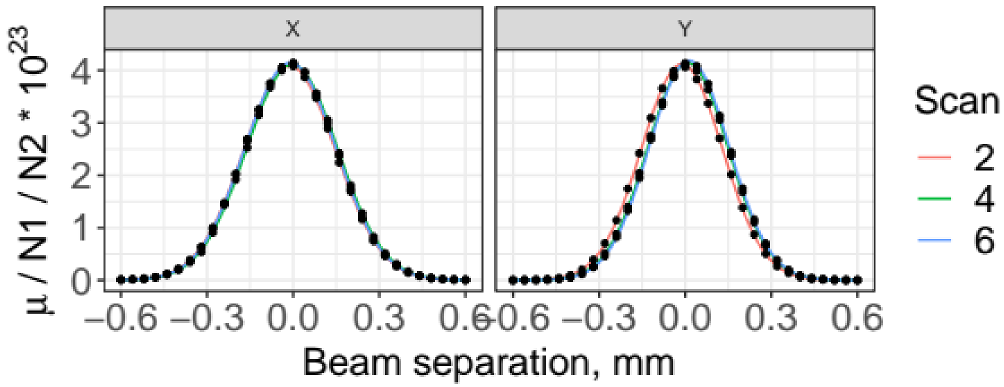
pp, 13 TeV



Fill 4937. Vertex
2
4
6
X
Y
Effect of (data−single G) on x−sect., %
Beam separation, mm
Scan
2
4
6

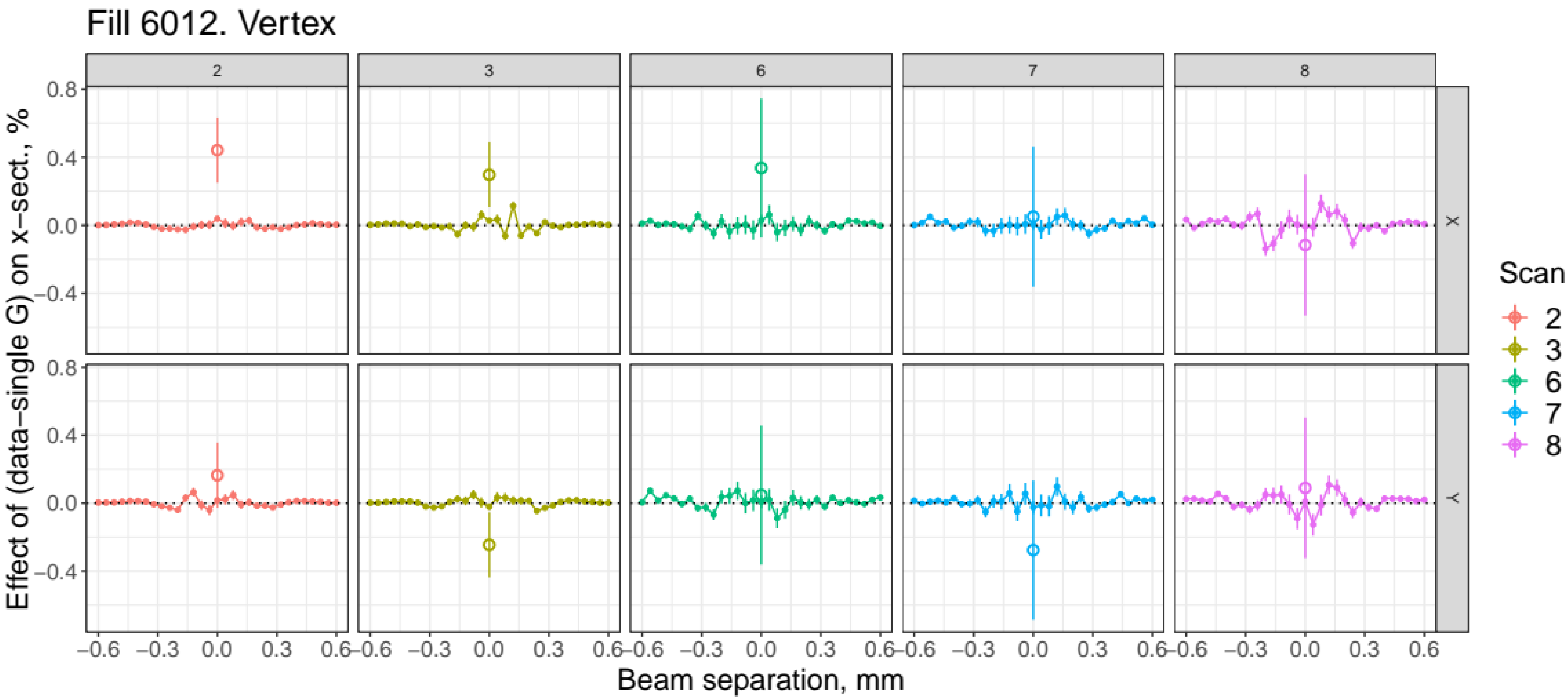


FBCT A rel. drop, in %
Time
15:00
18:00
21:00
Beam
1
2

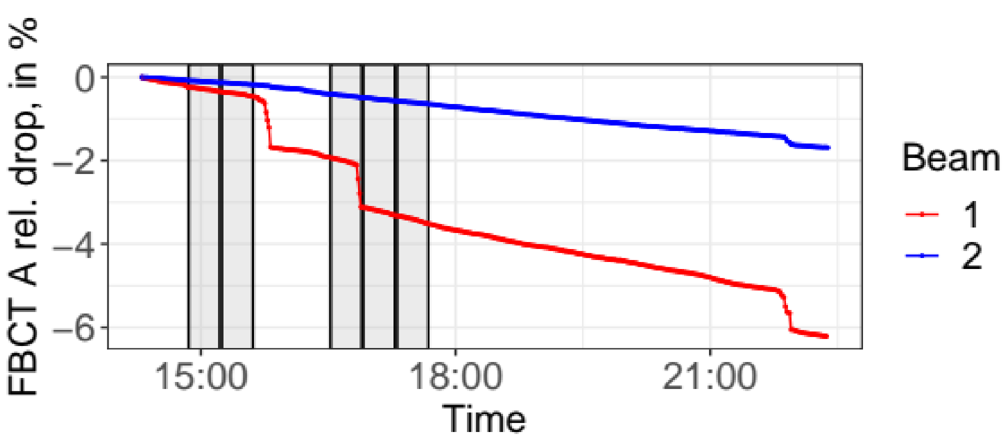


X
Y
μ / N1 / N2 * 10^23
Beam separation, mm
Scan
2
4
6

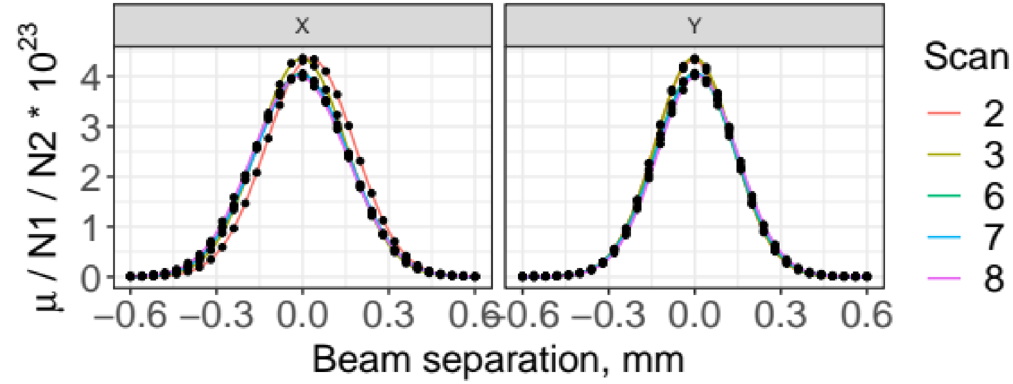
pp, 13 TeV



Fill 6012. Vertex
2
3
6
7
8
X
Y
0.8
0.4
0.0
−0.4
Effect of (data−single G) on x−sect., %
−0.6
−0.3
0.0
0.3
0.6
Beam separation, mm
Scan
2
3
6
7
8

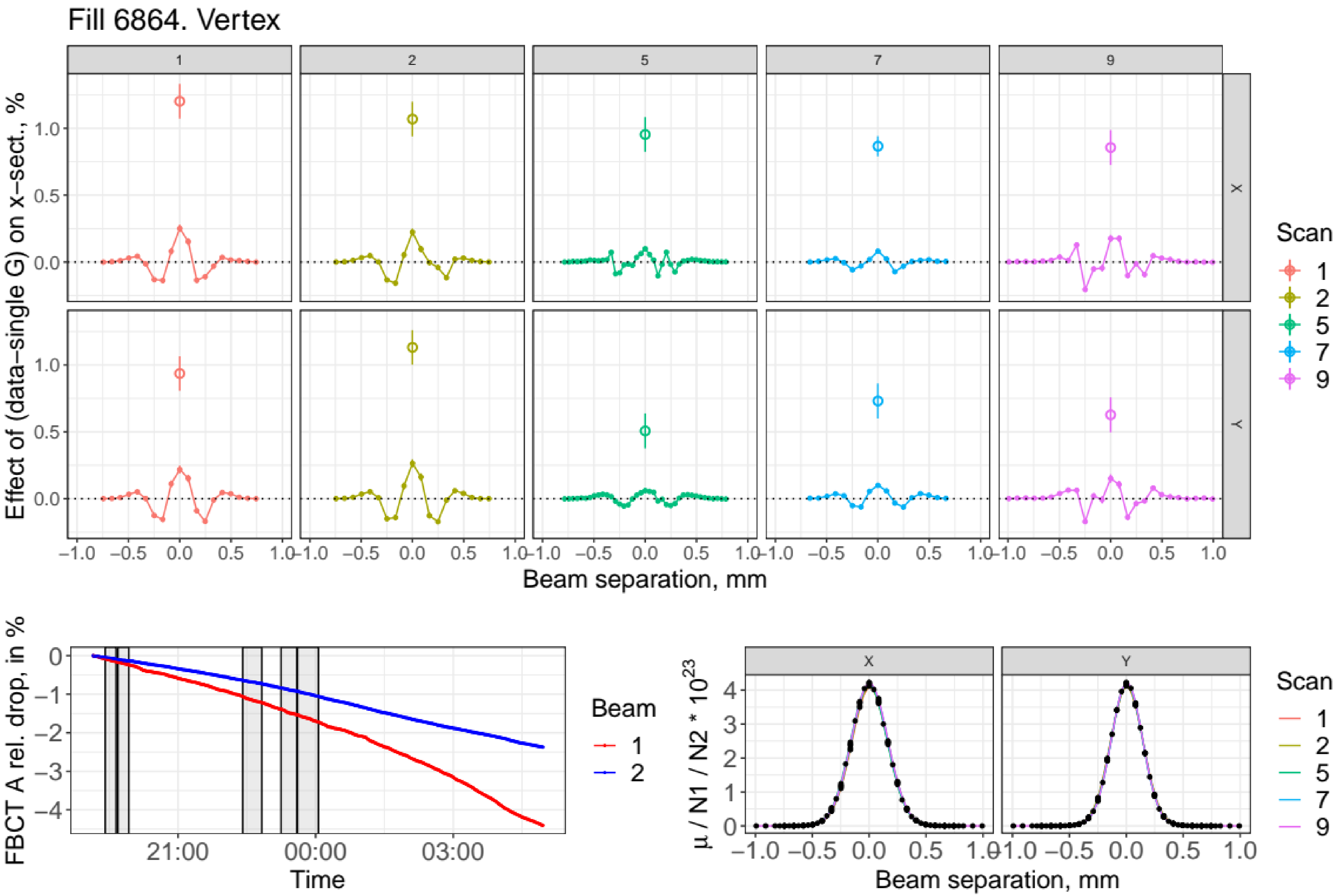


FBCT A rel. drop, in %
0
−2
−4
−6
15:00
18:00
21:00
Time
Beam
1
2



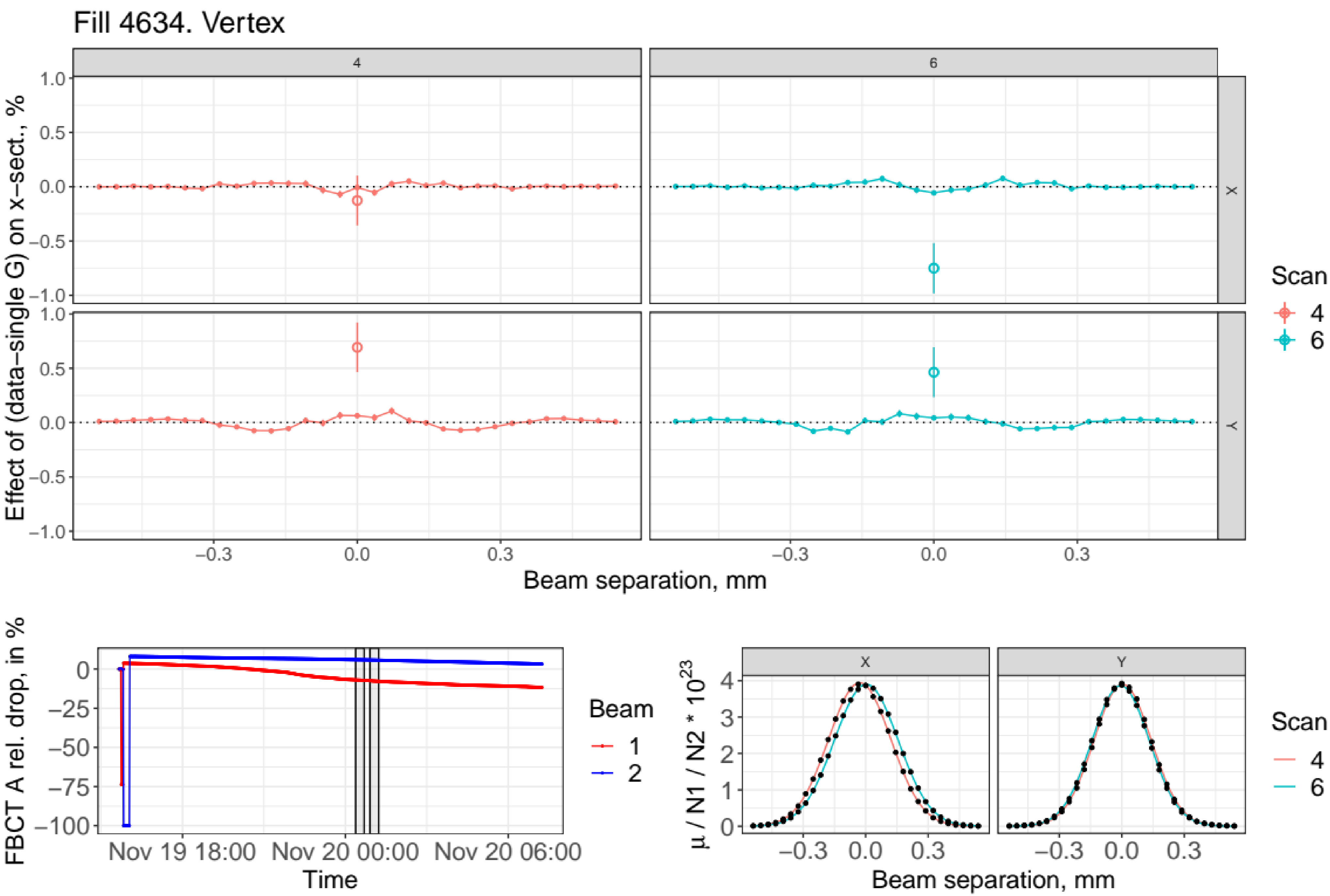
X
Y
μ / N1 / N2 * 10^23
0
1
2
3
4
−0.6
−0.3
0.0
0.3
0.6
Beam separation, mm
Scan
2
3
6
7
8

pp, 13 TeV



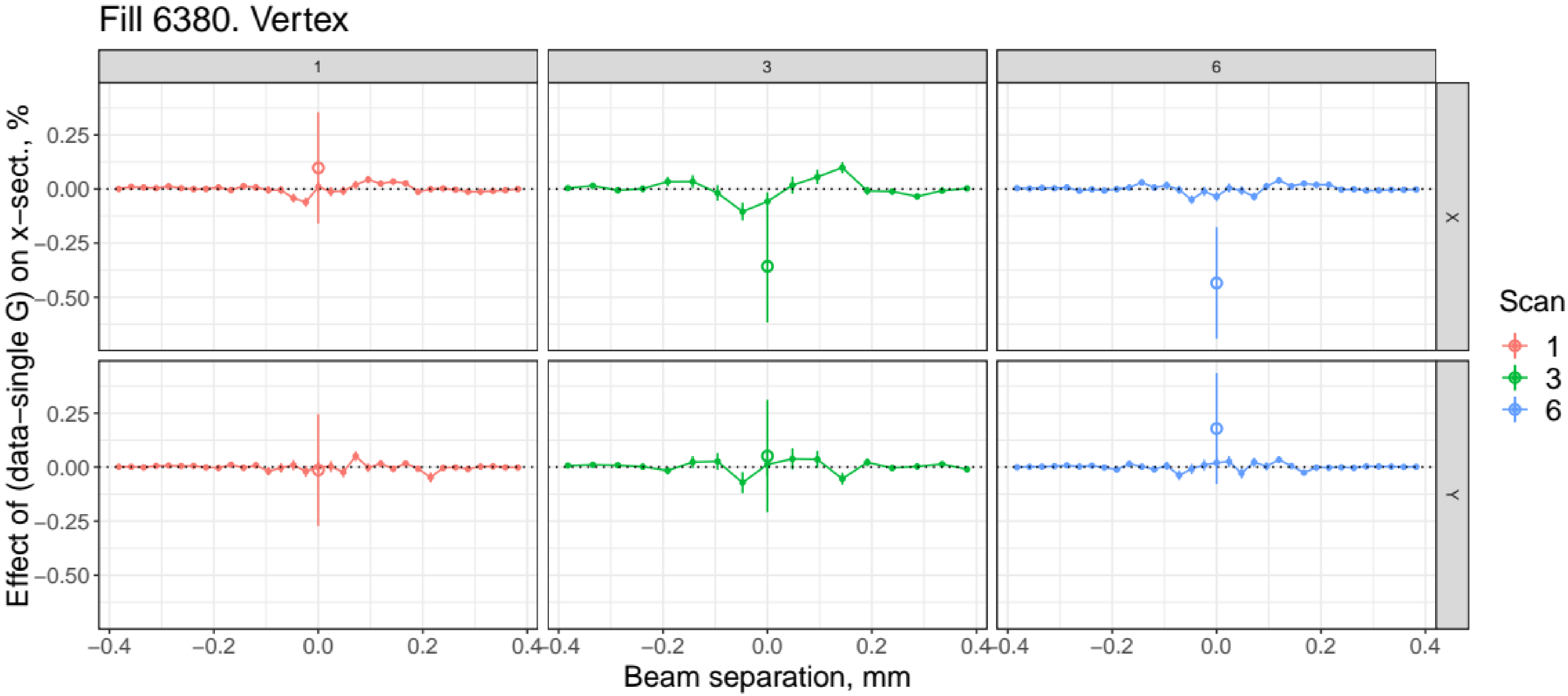
Fill 6864. Vertex
1
2
5
7
9
X
Y
Effect of (data−single G) on x−sect., %
Beam separation, mm
Scan
FBCT A rel. drop, in %
21:00
00:00
03:00
Time
Beam
μ / N1 / N2 * 10^23

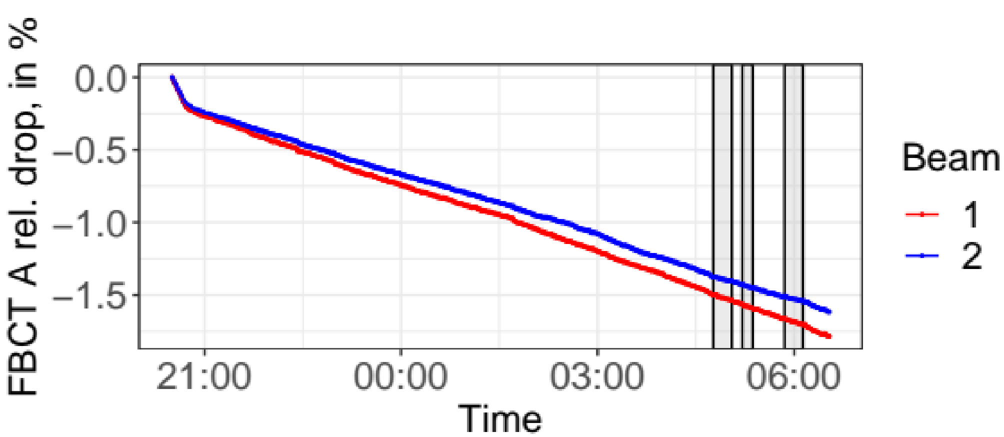
pp, 5 TeV

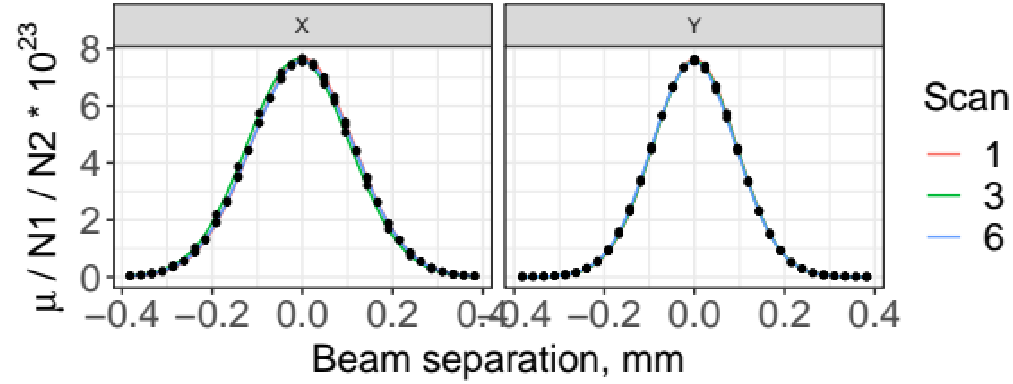


Fill 4634. Vertex
4
6
X
Y
Effect of (data−single G) on x−sect., %
1.0
0.5
0.0
−0.5
−1.0
−0.3
0.0
0.3
Beam separation, mm
Scan
4
6
FBCT A rel. drop, in %
0
−25
−50
−75
−100
Nov 19 18:00
Nov 20 00:00
Nov 20 06:00
Time
Beam
1
2
μ / N1 / N2 * 10^23
4
3
2
1
0
X
Y
−0.3
0.0
0.3
Beam separation, mm
Scan
4
6

pp, 5 TeV


Fill 6380. Vertex
1
3
6
X
Y
Effect of (data−single G) on x−sect., %
0.25
0.00
−0.25
−0.50
−0.4
−0.2
0.0
0.2
0.4
Beam separation, mm
Scan
1
3
6


FBCT A rel. drop, in %
0.0
−0.5
−1.0
−1.5
21:00
00:00
03:00
06:00
Time
Beam
1
2

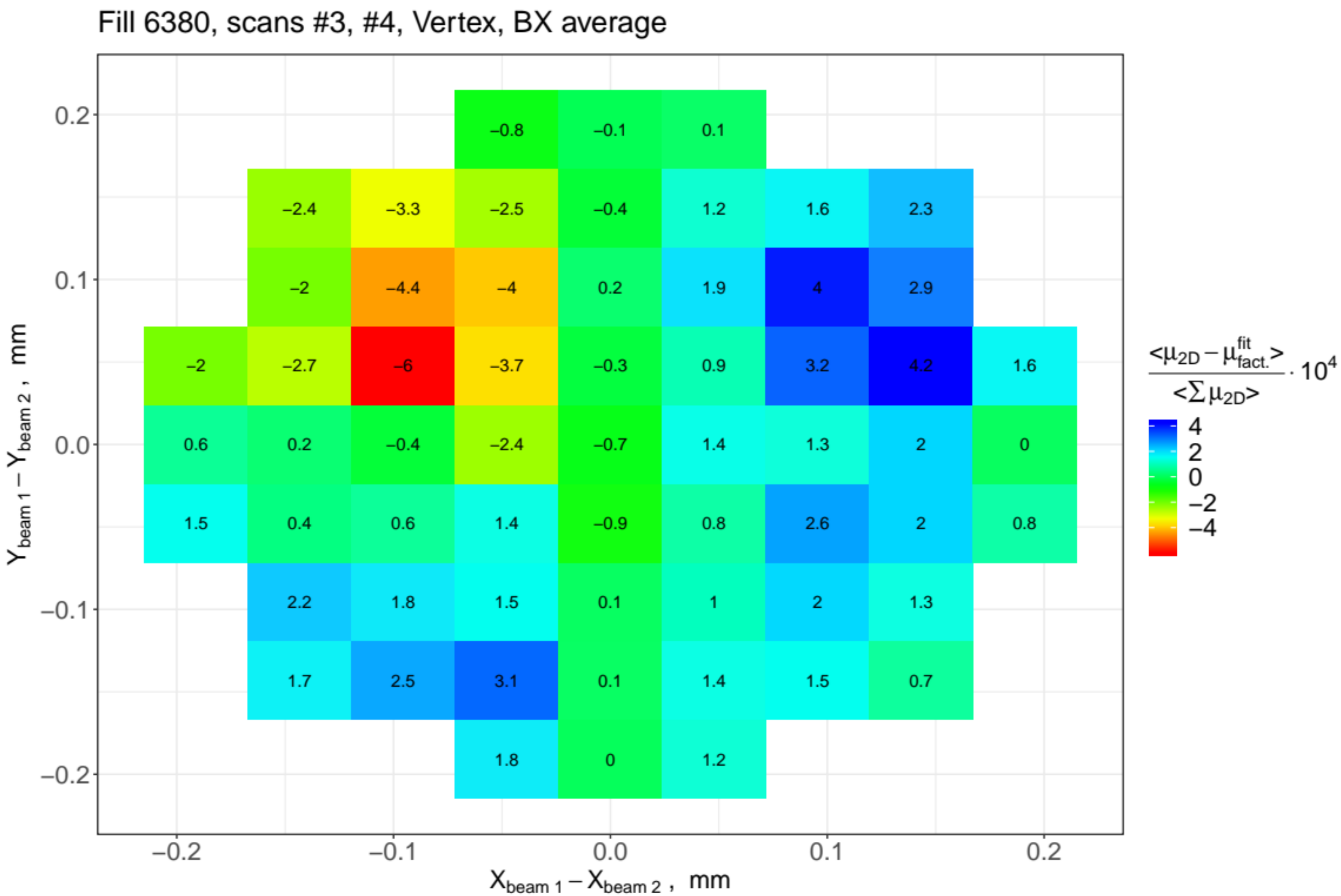

X
Y
μ / N1 / N2 * 10^23
8
6
4
2
0
−0.4
−0.2
0.0
0.2
0.4
Beam separation, mm
Scan
1
3
6

2D map of residuals

pp, 5 TeV

$$\frac{\mu_{i,j} - \mu_{i,0} \cdot \mu_{0,j} / \mu_{0,0}}{\sum_{i,j} \mu_{i,j}}$$

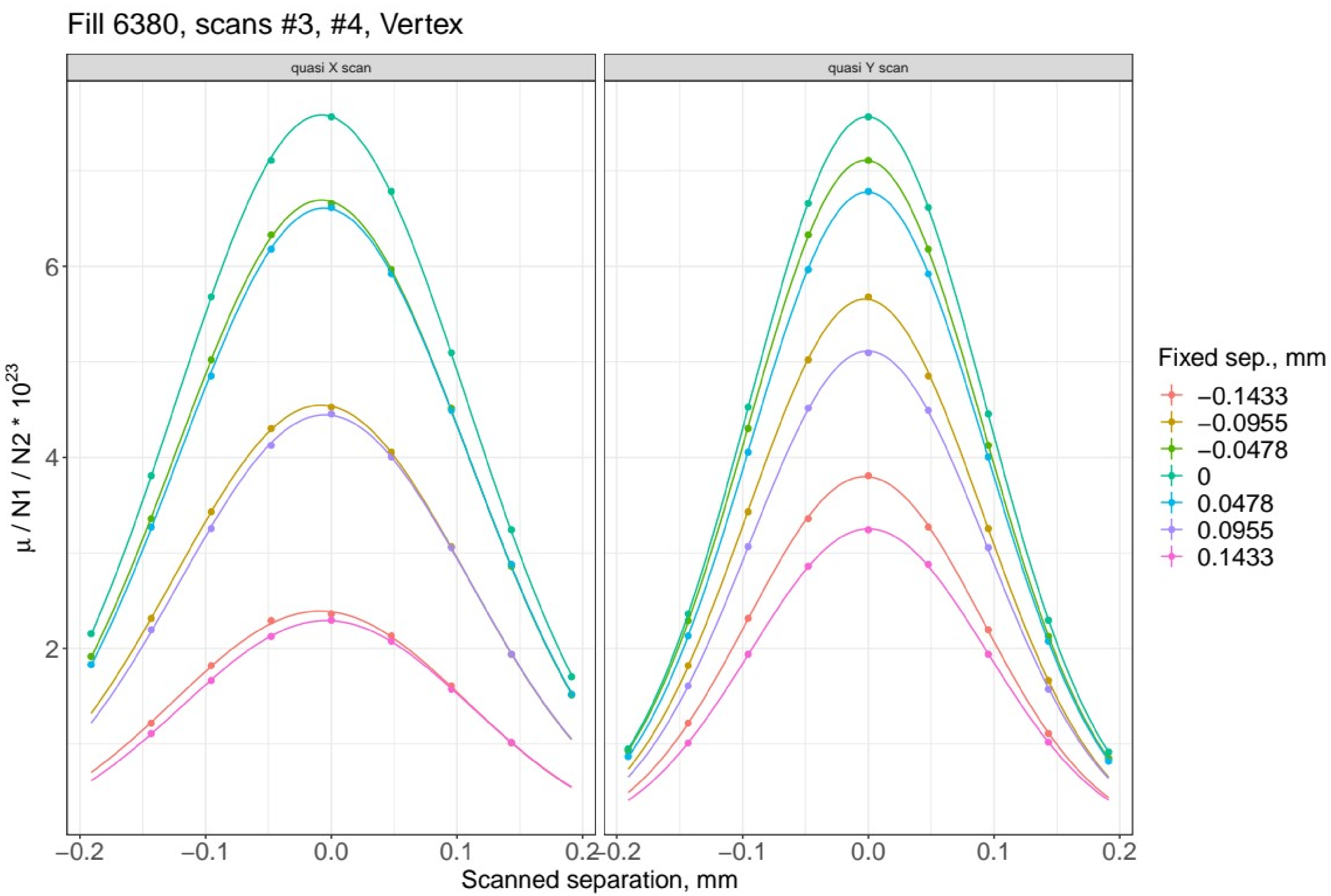
On-axes $\mu_{\mathrm{i},0}$, $\mu_{0,\mathrm{j}}$, $\mu_{0,0}$ are from single Gaussian fits



Data are fit per bunch crossing and then averaged. Mismatches are scaled by 10^{-4}

2D viewed as X,Y-offset scans

pp, 5 TeV



Every point is duplicated (once in X and once in Y).
Data are fit per BX and then averaged.