Non factorization at LHCb: Two-dimensional vdM scans

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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 $\mu$ at beam separation $\Delta x$, $\Delta y$:

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

After integration over $\Delta x$, $\Delta y$, overlap integral collapses to $1 \rightarrow$ 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:

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

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

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

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

Main formula for cross-section measurement

X+Y scans (at constant arbitrary $\Delta x_0$, $\Delta y_0$) 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

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!

Fill 6380. Vertex: cross section estimated from $\mu/N_1/N_2 \times$ (bin area), averaged over bb

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

\begin{align*}
\text{86% of full integral} & \\
\text{Timing (2D + previous 1D X-Y)} & \\
- \text{crossing point: 6 times, 104 sec in total} & \\
- \text{32 on-axes in 2D rect.: twice, 20 sec/point} & \\
- \text{rest: 10 sec} & \\
\end{align*}

$\sigma$, mb

\begin{array}{c}
1.5 \\
1.0 \\
0.5 \\
0.0 \\
\end{array}

\begin{array}{c}
\text{1.5} \\
\text{1.0} \\
\text{0.5} \\
\text{0.0} \\
\end{array}

$\mu$ corrected for beam-beam and Vertex eff.
LHCb in fill 6380

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

$$\sum_{i,j} \left( \frac{\mu_{i,j} - \mu_{0,i} \cdot \mu_{0,j}}{\mu_{0,0}} \right) \frac{1}{\sqrt{22}}.$$ 

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 / $\sqrt{22}$. 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

\[
\left( \sum_{i,j} \left( \mu_{i,j} - \mu_{i,0} \cdot \mu_{0,j} / \mu_{0,0} \right) \right) / \sum_{i,j} \mu_{i,j}
\]

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

2D scan alone

- from data: \(-0.01\pm0.12\%\)

- from fit: \(0.09\pm0.06\%\)
Approximately Gaussian shapes and 9 um orbit drift btw. scans #1 - #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

$$\sum_{i,j} \left( \frac{\mu_{i,j} - \mu_{i,0} \cdot \mu_{0,j}}{\mu_{0,0}} \right) \sum_{i,j} \mu_{i,j}$$

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

2D scan alone

from data

-0.01±0.12 %

from fit

0.09±0.06 %

2D + prev. 1D XY

from data

0.10±0.08 %

from fit

0.25±0.05%

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

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

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

- **2D scan alone**
  - from data: $-0.01 \pm 0.12 \%$
  - from fit: $0.09 \pm 0.06 \%$

- **2D + prev. 1D XY**
  - from data: $0.10 \pm 0.08 \%$
  - from fit: $0.25 \pm 0.05 \%$ 

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

- **Mixing of 2D and 1D X-Y scan**
  - from data: $0.47 \pm 0.08 \%$
  - from fit: $0.53 \pm 0.04 \%$

- **2D + 1st XY scan shifted by 9 um in X**
  - from data: $\ldots$
  - from fit: $\ldots$
Two more 2D scans in Jun 2018, fill 6864

fill 6864

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

with new ideas:

leap-frog symmetric + every spiral side measure beam drifts

pp, 13 TeV
Deviations from \( G \) are compensated in integrals, but strongly affect \( \mu_{0,0} \) in Gaussian fit residuals. The effect of single Gaussian fit residuals on x-sect., averaged over BXs, is shown in the plots. The effect of \( \mu_{0,0} \) in denominator to be averaged over X, Y. FBCT A current drop is also shown over time. The integral of the deviation is given by \( \int \mu \, d\Delta x \int \mu \, d\Delta y / \mu_{0,0} \).
Default x-section in 1D XY-scans is obtained from more precise fitted (not data) $\mu$-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

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

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

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 $\mu$ 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).
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 $\int \mu \, d\Delta x \int \mu \, d\Delta y / \mu_{0,0}$, 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 $\leq$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.
4. In addition to real non-factorization, many effects can mimic it:

<table>
<thead>
<tr>
<th>beam-beam effects</th>
<th>background subtraction</th>
<th>hysteresis in LHC magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>orbit drifts</td>
<td>beam timing difference (in X, due to X-Z crossing angle)</td>
<td></td>
</tr>
</tbody>
</table>

They all have been tested with current sensitivity.
Backup slides
Fill 6012. Vertex

Effect of (data−single G) on x-sect., %

Beam separation, mm

FBCT A rel. drop, in %

Time

Beam

μ / N1 / N2 * 10^23

Beam separation, mm

Scan

pp, 13 TeV
Fill 6380. Vertex

Effect of (data-single G) on x-sect., %

Beam separation, mm

FBCT A. rel. drop, in %

Time

Beam
- 1
- 2

Scan
- 1
- 3
- 6

\[ \mu / N_1 / N_2 \times 10^{23} \]

Beam separation, mm

Scan
- 1
- 3
- 6

pp, 5 TeV
2D map of residuals

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

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 \(10^{-4}\)
Every point is duplicated (once in X and once in Y). Data are fit per BX and then averaged.