Impact of Beam-Beam Effects on Precision Luminosity Determination at the LHC

W. Kozanecki (CEA Saclay), with W. Herr & T. Pieloni (CERN)

- **Introduction**: luminosity-determination strategy & precision goals
- **Beam-beam effects**
- **Do’s & don’t ‘s: lessons learnt**
- **Do’s & don’t ‘s: wish list for 2015 (& somewhat beyond)**
  - all known issues – not just those beam-beam related
- **In conclusion...**
Introduction: luminosity-determination strategy and precision goals

Physics running

- Max. pile-up parameter (2012): $\mu_{pk} \leq 35$ inel. pp collisions/BX

L determination

- absolute calibration
  - van der Meer scans, $\mu_{pk} \sim 0.5 - 5$
- high rate effects & $\mu$-dependence: physics conditions
  - non-invasive monitoring
  - $\mu$-scan: msre relative $\mu$-dep. at one point in time
- long-term stability: physics conditions
  - non-invasive monitoring

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>$\delta L / L$</th>
<th>2010</th>
<th>2011</th>
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<tbody>
<tr>
<td>Bunch Population Product</td>
<td></td>
<td>3.1%</td>
<td>0.5%</td>
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<td>Other vdM</td>
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<td>0.5%</td>
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<tr>
<td>Calibration Uncertainties</td>
<td></td>
<td>1.3%</td>
<td>1.4%</td>
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<tr>
<td>Long-Term Consistency</td>
<td></td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\mu$ Dependence</td>
<td></td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3.4%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

ATLAS

Note: This document is for internal circulation only.
Luminosity Basics

- $\mu$: mean number of inelastic interactions per BX
- $\mu_{\text{vis}} = \epsilon \mu$: Mean number of interactions per BX seen by detector
- Total inelastic rate: $\mathcal{L} = \frac{\mu n_b f_r}{\sigma_{inel}}$
- Inelastic cross section (unknown)
- Cross section seen by detector: $\frac{\mu_{\text{vis}} n_b f_r}{\sigma_{\text{vis}}}$

$\sigma_{\text{vis}}$ is determined in dedicated fills based on beam parameters.
Calibrating $\sigma_{\text{vis}}$ in van der Meer (aka “vernier”) Scans

- Luminosity in terms of beam densities $\rho_1$ and $\rho_2$:
  \[
  \mathcal{L} = n_b f_r n_1 n_2 \int \rho_1(x, y) \rho_2(x, y) \, dx \, dy
  \]

- Under the condition that the integral factorises into uncorrelated $x$ & $y$ components:
  \[
  \mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \sum x \sum y}
  \]

- Detector independent
- Detector dependent

Measured by beam instrumentation

Measured in vdM scan

Detector independent

LHC fill: 2520
\[\sqrt{s} = 8\text{TeV}\]
Colliding beams exert strong force on each other

- optics changes due to (de)focusing force
  - for head-on collisions
    - small amplitude: linear force (~ quad)
    - loss or gain in $L_{\text{peak}}$
    - but no $L$-calibration bias
  - during $vdM$ scan
    - large amplitude: non-linear force
    - distorts scan curve $\Rightarrow$ $L$-calibration error?

Focusing by b-b interaction $\Delta k(s)$ leads to phase change $\Delta \mu$ and "optical error" $\Delta \beta(s_0)$

- In perturbation theory:
  $$\Delta \beta(s_0) = -\frac{\beta(s_0)}{2 \sin(2\pi Q)} \int_{s_1+C}^{s_1+C} \beta(s) \Delta k(s) \cos [2(\mu(s) - \mu(s_0)) - 2\pi Q] \, ds$$
  - $s$ and $s_0$ are interaction points (IP)
  - must take into account all potential IPs
  - special case: $s = s_0$ (1 IP), head-on
    $$\frac{\beta^*}{\beta_0^*} = \frac{\sin(2\pi Q)}{\sin(2\pi (Q + \Delta Q))} = \frac{1}{\sqrt{1 + 4\pi \xi \cot(2\pi Q) - 4\pi^2 \xi^2}}$$

Optics code required

- If optics change $\Rightarrow$ beam-beam force changes $\Rightarrow$ optics change: self-consistent calculation needed
- Take into account all IP’s
- Build beam-beam element $\Rightarrow$ MADX
W. Herr

Dynamic $\beta$: head-on ("static") case

- Simulation parameters:
  May’11 vdM scans  [typ. physics]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$E_b$ (TeV)</td>
<td>3.5</td>
</tr>
<tr>
<td>$N_p$ ($10^{11}$)</td>
<td>0.85 [1.5]</td>
</tr>
<tr>
<td>$\varepsilon_N$ (µm-rad)</td>
<td>4 [2.0-2.5]</td>
</tr>
<tr>
<td>$\beta^*_0$ (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>$Q_x/Q_y$</td>
<td>0.31 / 0.32</td>
</tr>
</tbody>
</table>

- Observations
  - Dynamic $\beta$ for (multiple) head-on collisions visible
  - Depends on
    - Beam-beam parameter $\xi (N_p, \varepsilon_N)$
      - note $\xi_{vdM} < \xi_{physics}$
    - Collision pattern
    - Phase advance between IP’s

- Collisions at IP1 only

  ![Dynamic beta* graph]

- Collisions in IP1 &/or IP5 only

<table>
<thead>
<tr>
<th>Collisions</th>
<th>$\beta^<em>_x/\beta^</em>_0x$</th>
<th>$\beta^<em>_y/\beta^</em>_0y$</th>
<th>$\beta^<em>_z/\beta^</em>_0z$</th>
<th>$\beta^<em>_y/\beta^</em>_0y$</th>
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</thead>
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<tr>
<td>no</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>IP1</td>
<td>0.994</td>
<td>0.993</td>
<td>0.989</td>
<td>1.018</td>
</tr>
<tr>
<td>IP5</td>
<td>0.989</td>
<td>1.018</td>
<td>0.994</td>
<td>0.993</td>
</tr>
<tr>
<td>IP1 + IP5</td>
<td>0.983</td>
<td>1.011</td>
<td>0.983</td>
<td>1.011</td>
</tr>
</tbody>
</table>

- Other collision patterns
Dynamic $\beta$: variation during luminosity scan

- **During luminosity scan**
  - Strength of the force is changing (both planes)
  - Sign of the force is changing (in scanning plane, defocusing $\rightarrow$ focusing)
  - Must expect more complicated pattern
    - Illustrate with simulated scans in IP1
    - Effects for scans at other IPs similar
    - Add’l collisions change starting values

- For a given plane ($\beta^* x$ or $y$) and scan direction ($x$ or $y$)
  - Dependence on separation always the same
  - Starting value different, depends on $\xi$ and on collision pattern
**Dynamic-β: impact on luminosity-scan curves**

- Compute effect of dynamic $\beta$ on x & y scans: $\mathcal{L} \sim 1 / \sqrt{\beta_{\text{dyn}, x}} \sqrt{\beta_{\text{dyn}, y}}$

- Refit gaussians and compute impact on $\sigma_{\text{vis}} \sim \Sigma_x \Sigma_y \mu_{\text{vis, pk}}$

  $\Delta \sigma_{\text{vis}} / \sigma_{\text{vis}} = 0.5\%$ significant in view of total uncertainty $\Delta \mathcal{L} / \mathcal{L} = \pm 1.8\%$

  included in $\Delta \mathcal{L} / \mathcal{L}$
The bad: beam-beam-induced orbit shift during scan

**Impact on $\Sigma$?**
- sign/magnitude
- Q-dependent
- worse than dyn. $\beta$?
- to be investigated!

**Impact Parameters:**
- $E_b$ (TeV): 4
- $N_p$ ($10^{11}$): 0.8
- $\epsilon_N$ ($\mu$m-r): 3.75
- $\beta^*$ (m): 11
- $Q_x$: 64.28
- $Q_y$: 59.31

**List of Parameters:**
- $\Delta y = 0$
- $0.26 \mu$rad
- $\Delta y = 4\sigma_b$
- $\Delta y = 1\sigma_b$
- $3.7 \mu$ ($\Sigma_x = 140 \mu$)

**Equations and Expressions:**

\[ \Delta y = 0 \]
\[ 0.26 \mu \text{rad} \]
\[ \Delta y = 4\sigma_b \]
\[ \Delta y = 1\sigma_b \]
\[ 3.7 \mu \]
The ugly: beam-separation scans under physics conditions

- Example of opportunistic study during intensity ramp-up (fill 3109)
  - Beam conditions representative of physics running
    - $\beta' = 0.6$ m, $\theta_c = \pm 145$ $\mu$rad
    - 50 ns trains, 1.2 E11 p/bunch, 726 bunches
  - Goals
    - Provide check on absolute $\mathcal{L}$ calibration?
    - Characterize transverse phase space (tails, non-linear x-y correlations)
    - Check stability of scan results wrt scanning protocol (e.g. hysteresis,...)
    - $\mu$-dependence check: quantify relative linearity of different luminometers & algorithms at one point in time (< 1% ?)

![Graph showing luminosity data with $0.001 < \mu < 24$]
The ugly: impact of long-range encounters on $\mathcal{L}$ scans

May 2011
vdM scan

Orbit drift

Total # Long-Range Encounters

$\mu$-Scan I
$\mu$-Scan II

W. Kozanecki
The ugly: impact of bunch trains on $\mathcal{L}$-calibration systematics

- $\varepsilon$ growth $\leftrightarrow$ long-range b-b?
- scan distortions $\leftrightarrow$ b-b kicks?
- non-linear correlations from injector chain or within LHC?
- any other ideas?

May 2011 $vdM$ scan
Do ‘s and don’t ‘s: lessons learnt (1)

- Don’t use...
  - bunch trains
    - beam-beam kicks (+ distortions?) from long-range encounters
    - injected phase-space quality
    - satellites & ghost charge
      - more abundant
      - harder to analyze
    - \( \mathcal{L} \) afterglow
  - high bunch intensities (> 1 E11 p)
    - orbit distortions during scan
    - dynamic \( \beta \) during scan
    - injected phase-space quality
    - satellites & ghost charge (?)
    - instabilities (impedance? \( Q \) spread from LR beam-beam ?)
    - \( \mu \) too high (if low \( \beta^* \)) \( \rightarrow \) potential detector non-linearities

- Do favor...
  - sparse patterns of indiv. bunches
    - no parasitic encounters
    - weaker satellites & ghost charge
    - sparse pattern \( \rightarrow \) low afterglow
    - no Xing-angle constraints
    - keep ‘your’ bunches private
    - allows tailoring of injected phase space
  - moderate bunch intensities (~ 8-9 E10 p/b)
    - if higher: scan curve distortions
      - beam-beam kicks \( \rightarrow \) orbit
      - dynamic \( \beta \)
    - if much lower
      - \( \mathcal{L} \)-calibration statistics- & systematics-limited
      - machine-protection constraints
A detour: beam-gas & luminous-region imaging

Resolution systematics critical: 10% on resolution $\rightarrow$ 1% on each of $\sigma_1, \sigma_2$

- Beam-gas imaging (LHCb only)
  $\Rightarrow$ measure $\sigma_{1,x,y}, \sigma_{2,x,y}$ separately $\Rightarrow$ independent absolute $L$ calibration

- Luminous-region imaging
  $\Rightarrow$ msre $\sigma_{L,x,y}$ + their dependence on $\Delta_{x,y}$ during $vdM$ scan

Measured ($\sigma_{1,2} \sim 90 \mu$m for $\varepsilon = 3.5 \mu$m, $\beta^* = 11m$)

Vertex resolution $\sim 30 \mu$m

Colliding bunch (beam 1)

Interaction between beam and residual gas molecule

Shape and position of luminous region
Absolute-\(\mathcal{L}\) calibration challenge: non-factorization effects

- Two very challenging issues in first two 2012 \(vdM\) scans (Apr + Jul ‘12)
  - Scan-to-scan irreproducibility and/or systematic trend: 2-3 \% (\(\Rightarrow \sigma_{\text{syst, ATL}} \sim 3.6 \%, \sigma_{\text{syst, CMS}} \sim 4.4 \%\))
  - Breakdown of x-y factorization in the 3-d \(\mathcal{L}\) distribution
    - aka ‘non-linear x-y correlations’
    - observed during \(vdM\) scans by all of ATLAS, CMS, LHCb (evidence compelling, but available data sets make quantitative comparisons difficult)

- These 2 issues
  - are clearly beam-dynamics effects, time-dependent & different fill-to-fill (instrumental drifts ruled out)
  - appear mutually related

- Factorization assumes that shape of \(vdM\) scan curve during an x (y) scan is independent of the separation \(\Delta y\) (\(\Delta x\)) in the orthogonal plane
  - if this assumption is satisfied, the combination of 1 x-scan and 1 y-scan is sufficient to characterize the entire distribution \(\mathcal{L}\) (\(\Delta x, \Delta y\))
  - if this is violated at a “significant” level, the \(vdM\) formalism could be generalized to 2-d by performing a full 2-D grid scan (but: impractical!)
Testing factorization of $L (\Delta x, \Delta y)$ during $vdM$ scans

**Convolved beam size $\Sigma$ (width of $vdM$ scan curve)**

**Vertical luminous size $\sigma_L$ (beamspot width)**

---

**Convolved beam size $\Sigma$ (width of $vdM$ scan curve)**

- **Fill 2855**
  - Data (Centred $x$-scan VI July 2012)
  - Simulated profile of each beam: 3-D triple Gaussian

- **Fill 2856**
  - Data (Centred $x$-scan VI July 2012)
  - Simulated profile of each beam: 3-D triple Gaussian

---

**Vertical luminous size $\sigma_L$ (beamspot width)**

- **Fill 3311**
  - Data (Centred $x$-scan XIV November 2012)
  - Simulated profile of each beam: 3-D double supergaussian

- **Fill 3311**
  - Data (Centred $x$-scan XIV November 2012)
  - Simulated profile of each beam: 3-D double supergaussian

---
Testing factorization of $L (\Delta x, \Delta y)$ during $vdM$ scans

Convolved beam size $\Sigma$ (width of $vdM$ scan curve)

Vertical luminous size $\sigma_L$ (beamspot width)

The large reduction in non-linear $x$-$y$ correlations, between the July & Nov 2012 scans, was achieved mainly by careful preparation of highly gaussian beams in the injectors.

The elimination of $\varepsilon$ blowup by multiple scattering in a transfer line, and the reduction of the LHC octupole strength, may also have played a role.

The beam-beam contribution to non-factorization effects was deemed negligible by comparison.
Do’s and don’t ‘s: lessons learnt (2)

Don’t...

- use small $\beta^*$
  - reconstructed luminous width $\sigma_L$ (= beamspot width) becomes resolution-dominated and very difficult to analyze
  - $\mu \sim 5$ too high for comfort: potential detector non-linearities

- push for small emittances
  - the smaller $\epsilon$, the more $\sigma_L$ is resolution-dominated

- set nominal crossing angle
  - complicates measurement/characterization of satellites
    - notable exception: LHCb needs large Xing-angle for beam-gas enhanced ghost-charge measurement

- scan > 1 IP at a time
  - beam-beam defl + leaking bumps

Do favor...

- large $\beta^*$ (present injection optics: $\beta^* = 11$ m)
  - make $\sigma_L$ ALAP ($\leftrightarrow$ resolution)

- nominal emittances
  - make $\sigma_L$ ALAP ($\leftrightarrow$ resolution)
  - BUT avoid anything that creates non-gaussian tails (e.g. $\epsilon$ blowup by screen in transfer line)

Large enough $\sigma_L$ critical for

  (a) non-factorization systematics
  (b) $L$ calibration by beam-gas imaging

- beams as gaussian as possible in SPS + LHC
  - tailor injected phase space (still an art more than a science...)
  - avoid strong octupoles

- zero crossing angle
  - optimize satellite reconstruction
Do ‘s and don’t ‘s: wish list for vdM scans in 2015 (& beyond...)

- Reproducibly “tailor” injected $p$ phase space to minimize non-linear correlations
  
  Critical for limiting non-factorization systematics

- “Generous” luminous width $\sigma_L$
  
  - injection optics or larger ($\beta^* > 10$)
  
  - “nominal” emittance ($\epsilon_N \sim 3 \mu$)

  Large enough $\sigma_L$ critical for BGI and non-factorization systematics

  Note that the $E_{beam}$ increase ($4 \rightarrow 6.5$ TeV) shrinks the beams by $\sqrt{2}$ – while the vertex resolution remains the same

- Round beams ($\beta_x^* = \beta_y^*$)
  
  - The vdM method can handle tilted elliptical beams (residual x-y coupling!) – but at the cost of additional scans ($x/y \rightarrow x/y/u/v$)

- No crossing angle (except LHCb)
  
  - reconstruct satellites by vtxg

- Crab off (when it appears...)
  
  - avoid banana shapes, phase/ Xing angle jitter,....

- Sparse patterns (no trains!)

- Low bunch intensities

- Flexible, file-driven scan-control software
  
  - allow for complex scan patterns
    
    - diagonal scans, off-axis scans,...
    
    - leapfrog length-scale calibration
  
  - minimize scanning time, costly cockpit errors

  - must provide for rigorous MPP validation pre-checks
In conclusion...

- **Need to refine understanding of head-on beam-beam effects during scans:** impact on $L$ calib. systematics larger than thought so far?
  - more careful evaluation (+ correction?) of dynamic-$\beta$ scan distortions
  - quantify (+ correct?) impact of in-plane orbit distortions during scans
  - quantify impact of (i) orbit distortions & (ii) b-b induced skew quad on off-axis scans ($\rightarrow$ crisper evaluation of non-factorization symptoms)

- **Limitations in long-term luminosity & beam-background monitoring**
  - EOF scans impractical because of beam-beam (+ non-linear correlations)
    - makes long-term monitoring of $L$ stability much more difficult
  - Landau damping vs. instabilities & single-beam background monitoring
    - removing non-colliding bunches unfortunate – any way to rescue these?

- **The need to limit, during $L$-calibration scans, the impact of**
  - head-on beam-beam kicks + dynamic $\beta$, on scan-shape distortions
  - long-range encounters, on scan-shape distortions
  - vertexing resolution, on B-G imaging & quantification of non-factorization effects

significantly constrains the operational conditions during $vdM$ scans
$\rightarrow$ iterate with LHC operations group on pragmatic solutions
Additional material
Systematic uncertainties on 2011 $\mathcal{L}$ determination (ATLAS)

<table>
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<tr>
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<td>Total</td>
<td>3.4%</td>
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</tr>
</tbody>
</table>

Table 7: Relative systematic uncertainties on the determination of the visible cross-section $\sigma_{\text{vis}}$ from vdM scans in 2011.

<table>
<thead>
<tr>
<th>Scan Number</th>
<th>VI–VII</th>
<th>Fill Number</th>
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<td>Beam centring</td>
<td>0.10%</td>
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<tr>
<td>Beam-position jitter</td>
<td>0.30%</td>
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<tr>
<td>Emittance growth</td>
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<tr>
<td>and other non-reproducibility</td>
<td>0.67%</td>
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<tr>
<td>Bunch-to-bunch $\sigma_{\text{vis}}$ consistency</td>
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<td>Fit model</td>
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<td>Background subtraction</td>
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<td>Specific Luminosity</td>
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<tr>
<td>Beam–beam effects</td>
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<td>Transverse correlations</td>
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<tr>
<td>$\mu$ dependence</td>
<td>0.50%</td>
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<td>Scan subtotal</td>
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<td>Bunch population product</td>
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<tr>
<td>Total</td>
<td>1.53%</td>
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</tr>
</tbody>
</table>

$\sigma_{\text{vis}}$ uncertainty (vdM scans)

Total $\mathcal{L}$ uncertainty (physics runs)
Direct measurement of $\mu$-dependence: pile-up (‘$\mu$’) scan

‘$\mu$ sweep’ performed by beam-separation in F 2086 ($873 b, \mathcal{L} \sim 1.9 \times 10^{33}$)

$\rightarrow$ characterize the relative $\mu$-dep. of BCM H/V, FCal, LUCID, TILE, vtx algos

3 scans, covering $10 - 15 > \mu > 0.02$

i.e. all the way from normal physics conditions to (slightly below) the $\mu$ regime for the $\beta^* = 90 \text{ m} \ ALFA \ run$
μ-dependence during 2012 physics running: individual runs

April vdM scan: Run 201351

ATLAS Internal
Data 2012, √s = 8 TeV
Run 209629, September 2 2012

ATLAS Internal
Data 2012, √s = 8 TeV
Run 213539, Oct 28 2012

ATLAS Internal
Data 2012, √s = 8 TeV
Run 203636, May 19 2012
Long Term Stability 2012

BCM and Lucid internally consistent

Calorimeters + Mpx suggest drift of 2%

± 2% envelope
The mild: emittance growth during scans

Emittance growth for different static offsets with beams colliding in one IP only and no long-range interactions

\[ \langle \Delta \varepsilon / \varepsilon \rangle \sim 3 \times 10^{-5} / \text{sec} \Rightarrow \sim 0.1 \% \text{ over duration of a scan} \]
The mild: beam-beam kicks during scan from shared bunches

Colliding bunches experience ≠ b-b kicks at IP 2 & 8 – but “moderate” wrt ∑

Σ ~ 57 μm
Luminosity afterglow

$\mathcal{L}$ @ ATLAS: vdM scans

Beam-gas + halo

$\mathcal{L}$ @ ATLAS: physics

Afterglow

$\mathcal{L}$ @ CMS: physics

Afterglow
A fundamental assumption: x-y factorization of $L(\Delta x, \Delta y)$

- A key assumption of the $vdM$ scan method as currently applied is that the luminosity

$$L = n_b f_1 n_1 n_2 \int \hat{\rho}_1(x, y) \hat{\rho}_2(x, y) dx dy$$

factorizes in $x$ & $y$:

$$L = n_b f_1 n_1 n_2 \Omega_x(\rho_{x1}, \rho_{x2}) \Omega_y(\rho_{y1}, \rho_{y2}) \quad \Omega_x(\rho_{x1}, \rho_{x2}) = \int \rho_{x1}(x) \rho_{x2}(x) dx$$

- This is equivalent to assuming that the shape of the scan curve during an $x$ ($y$) scan is independent of the separation $\Delta y$ ($\Delta x$) in the orthogonal plane
  - if this is the case, the combination of 1 $x$-scan and 1 $y$-scan is sufficient to characterize the entire distribution $L(\Delta x, \Delta y)$
  - if this is violated at a “significant” level, the $vdM$ formalism can be generalized to 2 dimensions by performing a grid scan (impractical!)

- Although linear $x$-$y$ coupling does violate this assumption, the induced bias is typically very small ($\Delta L/L \sim 0.1\%$) with present LHC optics (small $x$-$y$ coupling coeff., $\varepsilon_x \sim \varepsilon_y$, $\beta^*_x \sim \beta^*_y$)
To estimate (roughly) the magnitude of a potential NLC-induced bias, ATLAS routinely compared the visible cross-sections (i.e. the $L$ calibration scales) obtained by fitting the x- & y- $vdM$-scan curves using either

- an uncorrelated model (= baseline): $g+g$ (can simplify to $g$, or to $g+p0$)

$$L(x,y) = A \left( f_x e^{-\Delta x^2/2\sigma x_1^2} + (1 - f_x) e^{-\Delta x^2/2\sigma x_2^2} \right) \times \left( f_y e^{-\Delta y^2/2\sigma y_1^2} + (1 - f_y) e^{-\Delta y^2/2\sigma y_2^2} \right)$$

- a correlated double-gaussian model (naïve & by no means unique)

$$L(x,y) = A \left( f e^{-\Delta x^2/2\sigma x_1^2} e^{-\Delta y^2/2\sigma y_1^2} + (1 - f) e^{-\Delta x^2/2\sigma x_2^2} e^{-\Delta y^2/2\sigma y_2^2} \right)$$

that reduces to the uncorrelated model at $\Delta x = \Delta y = 0$ (but with $f_x = f_y$)

Observed impact on visible cross-sections at $\sqrt{s} = 7$ TeV (ATLAS)

- $\Delta \sigma_{vis} / \sigma_{vis} \sim 3\%$, 2\%, 0.9\%, 0.5 \% for Apr ’10, May ’10, Oct ’10, May ’11

- The more single-gaussian the scan curves, the smaller the potential bias (a property of this model – but probably not a general property?)

- As the effect looked small for the two main 7 TeV scan sessions, and for lack of manpower, didn’t look much further until large 2012 signal
Comparison of uncorrelated & correlated fits to vdM scan curves

April 2012, 8 TeV p-p VDM Scans

Uncorrelated (= factorizable)
\[ \mathcal{L} \sim G_1(x) G_2(y) \]

Correlated (non-factorizable)
\[ \mathcal{L} \sim \alpha g_N(x, y) + (1 - \alpha) g_W(x, y) \]

July 2012, 8 TeV p-p VDM Scans

Uncorrelated

Correlated

0.4 %

1.8 %

1.6 %

3.0 %

2.8 %
**Comparison of uncorrelated & correlated fits to vDM scan curves**

**Notes**
- The true bias may be larger than the difference between uncorrelated & correlated fits (coupling-model dependence?)
- There may be other coupling models which also yield a stable central value, but significantly different from the present one.

**Uncorrelated**

\( L \sim G_1(x) G_2(y) \) (= factorizable)

**Correlated**

\( L \sim \alpha g_N(x, y) + (1 - \alpha) g_W(x, y) \) (non-factorizable)

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**July 2012, 8 TeV p-p VDM Scans**

- **Scan 1**: Uncorrelated
  - Count: \( \sigma \) ~ 36 + 1.6 %
  - Correlated
  - Count: \( \sigma \) ~ 36 + 1.6 %
- **Scan 2**: Uncorrelated
  - Count: \( \sigma \) ~ 35 + 3.0 %
  - Correlated
  - Count: \( \sigma \) ~ 35 + 3.0 %
- **Scan 3**: Uncorrelated
  - Count: \( \sigma \) ~ 35 + 2.8 %
  - Correlated
  - Count: \( \sigma \) ~ 35 + 2.8 %
Production of (more) gaussian beams in the injector chain:
PSB/PS/SPS MD of 2 Nov 12 for vdM improvement

SPS WS profile (H)
18 Jul 12, LHCb vdM fill

Injector MD of 2 Nov 12
(G. Rumolo, H. Bartosik)

In PSB:
• inject high intensity, large $\varepsilon$
• longitudinal shaving (RF $V \downarrow \downarrow$)
• transverse shaving
$\Rightarrow N \sim 8E10/p$, $\varepsilon \sim 2-3$ $\mu$m into CPS

In SPS:
• slight scraping at flat top

Other methods also tried (injection missteering in PSB, $Q \Rightarrow$ integer on SPS flat bottom) but were less successful
Production of (more) gaussian beams in the injector chain (2)

SPS WS profiles
18 Jul 12
LHCb $vdM$ fill

SPS WS profiles
02 Nov 12
Injector MD

Data
$g + p0$ fit