Luminosity Calibration & Beam Gas Imaging at LHCb

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Luminosity

- Luminosity is the ratio between the number of interactions observed and the cross-section of the interaction:

$$\mathcal{L} = \frac{N}{\sigma} \tag{1}$$

- Can be calculated "indirectly" from a precisely known cross-section: e.g. $e^{+}e^{-}$ scattering (∼0.1%)
- Difficult to find such a cross-section at the LHC: need to measure beam parameters directly

Calibration Procedure

- Calibration sessions take place each year with a special configuration of the LHC
- Larger bunch spacing to reduce backgrounds and beam-sizes are increased at the LHCb IP
- A precise cross-section measurement is made in these fills and used to assign the Luminosity for physics fills

Luminosity determination

- The luminosity for a single bunch crossing depends on the intensities of the two colliding bunches and their overlap:

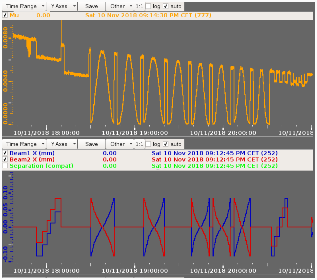
$$\mathcal{L} \propto \mathcal{O} I_1 I_2 \tag{2}$$

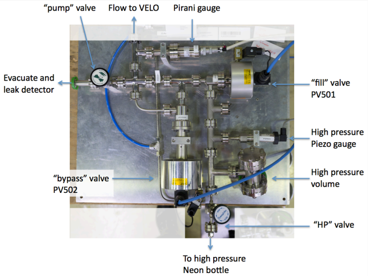
- The overlap is a geometric quantity dependent on the size/shape of the bunches as well as the angle/offset between the beams.
- General form is a 4D integral over the bunch density functions:

$$\mathcal{O} = \int\int\int\int \rho_1(x, y, z, t)\rho_2(x, y, z, t)\,dxdydzdt \tag{3}$$

Measuring the Overlap

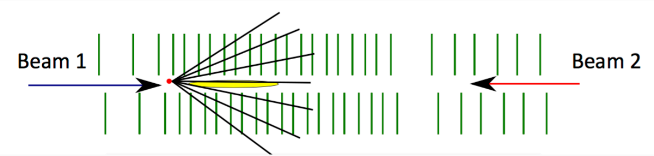
- Two different methods in use at LHCb: van der Meer (vdM) scans and Beam Gas Imaging (BGI)
- vdM scans measure the overlap from the rates observed as the two beams scan across each other in x and y
- BGI measures the bunch densities directly and the two method's uncertainties are uncorrelated





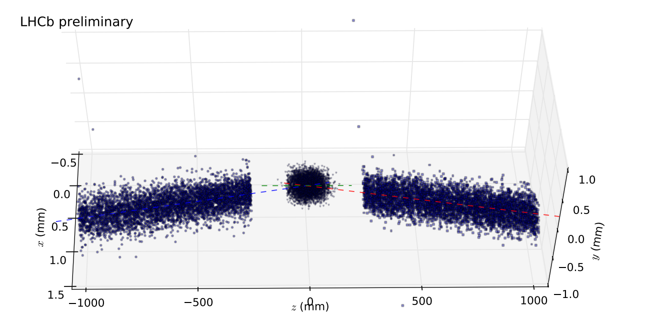
Beam-gas at LHCb

- Due to its role as a forward physics detector LHCb is ideally suited for measuring the small angle tracks resulting from beam-gas interactions.
- The VELO has an angular acceptance that allows it to measure beam-gas vertices along large longitudinal range.
- The directionality of tracks allows discrimination between beam-gas and beam-beam vertices



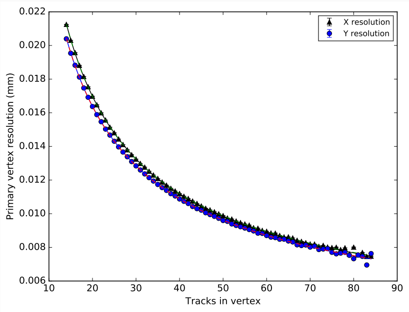
Longitudinal Selection

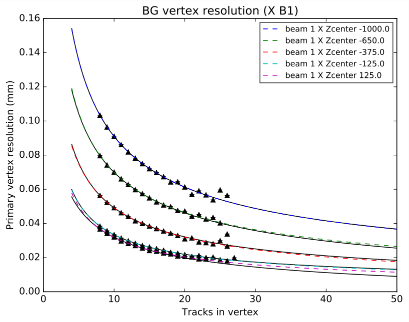
- Beam-beam vertices selected within a small region around the beam spot with track directionality cuts to exclude background
- Beam-gas vertices selected outside the luminous region within the acceptance for each beam



Vertex Resolution

- Understanding the VELO resolution is very important:
- The observed beam shape is a convolution of the resolution with the true beam shape
- The resolution is different for beam-gas and beam-beam vertices
- The resolution also varies as a function of vertex multiplicity and z position

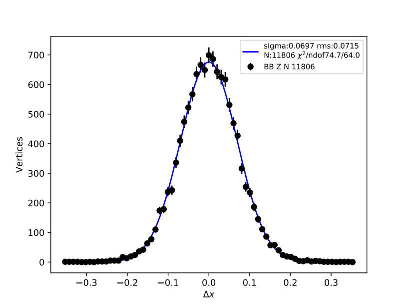




How do we measure the resolution?

The resolution is measured using split vertices:

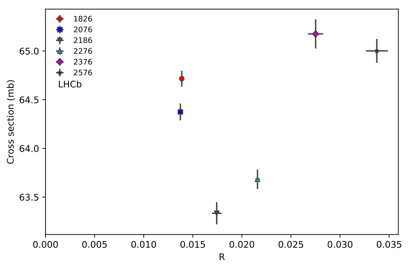
- The tracks making up each primary vertex are divided randomly into two samples
- New vertices are reconstructed from the tracks in each sample
- The resolution is then defined as the Gaussian width of the differences in position between these two split vertices



How well do we measure the resolution?

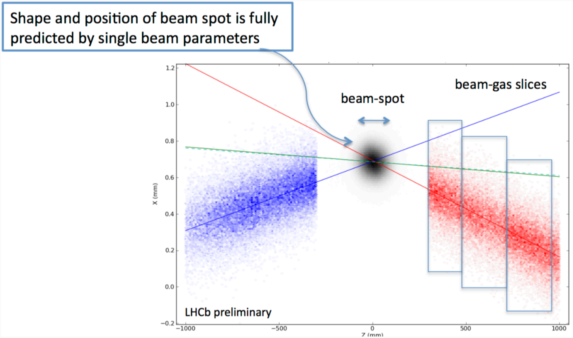
- Our (imperfect) understanding of the vertex resolution is one of the limiting systematic uncertainties on the cross-section measurement
- If the resolution correction were perfect then a cross-section wouldn't vary with the importance of the resolution
- However, in data from bunches of varying size we see a variation of the cross-section at the percent level

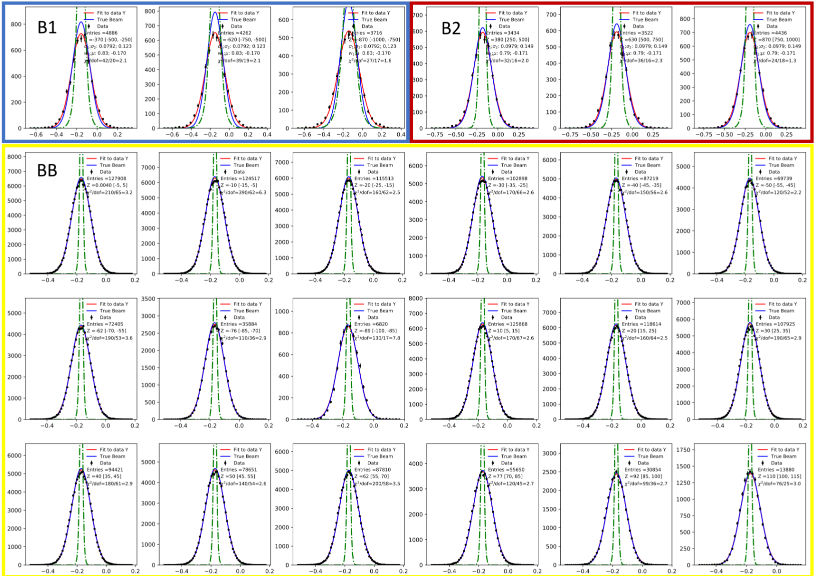
$$R = \frac{2\sigma^2_{res,x}}{4\sigma^2_x + \sigma^2_z \sin^2(\phi)} + \frac{\sigma^2_{res,y}}{2\sigma^2_y} \quad (4)$$

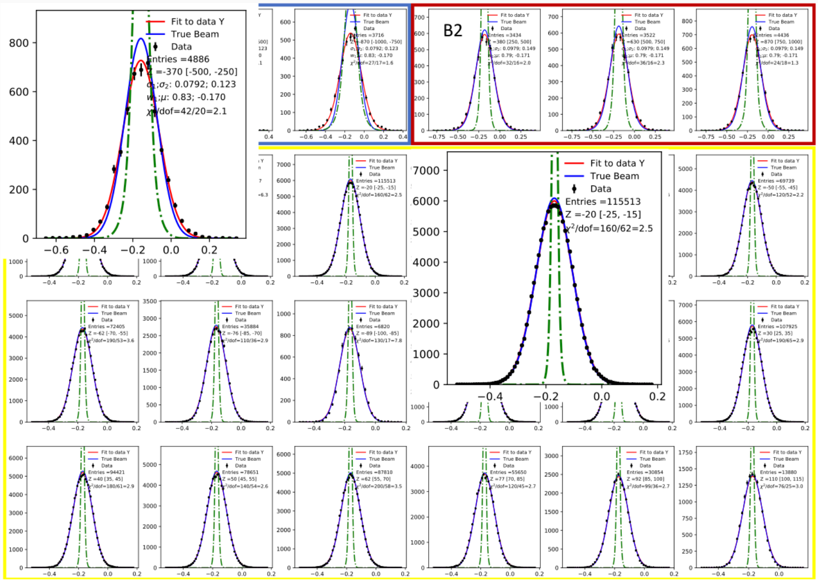


Global Fit

- A global fit is performed using both the collision and beam-gas vertices
- A double Gaussian fit shape is employed and a factorisability parameter allows for correlations in x and y
- The fit to beam-gas vertices is performed in 3 z bins due to the strong longitudinal resolution dependence




B1
B2
BB
Fit to data Y
True Beam
Data


Fit to data Y
True Beam
Data
Entries =4886
Z =-370 [-500, -250]
B2
Entries =115513
Z =-20 [-25, -15]
χ^2/dof=160/62=2.5

One final ingredient...

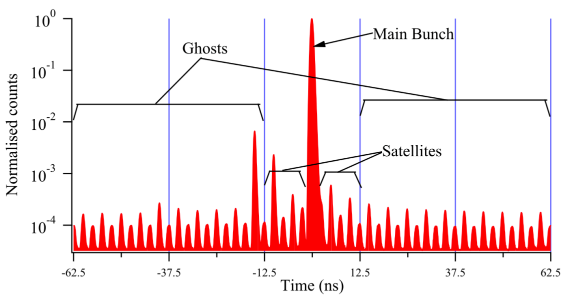
- Once we have the overlap we still need the bunch intensity product:

$$\mathcal{L} \propto \mathcal{O} I_1 I_2 \tag{5}$$

- For this we need some information from the LHC...

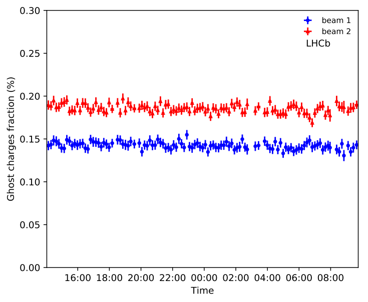
Intensity Measurements

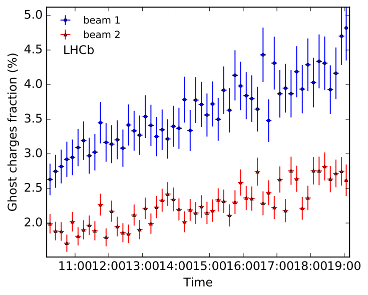
- Two LHC instruments to measure the bunch intensities:
- The FBCT measures the relative populations of each bunch
- The DCCT measures the total charge circulating in the ring: used for normalisation of FBCT
- DCCT measurement needs to be corrected for charges outside the nominal filling scheme: Ghost Charges



Ghost charges

- These ghost charges can be measured directly by LHCb
- Count beam-gas vertices in empty-empty and use beam-empty to convert to absolute charge
- Generally a very small correction in *p*-*p* calibration fills but can be significant in special runs: Pb-Pb, low-E etc.





Conclusions

- The BGI technique is a powerful tool for luminosity and beam measurements
- Calibration at $\sqrt{s} = 8$ TeV achieved a precision of 1.43%

  LHCb-PAPER-2014-047
- Vertex resolution is a limiting systematic in Run 2 as in Run 1, $\sim$1%
- Aiming to finalise the 13 TeV calibration in the coming months with a target precision of $<$2%

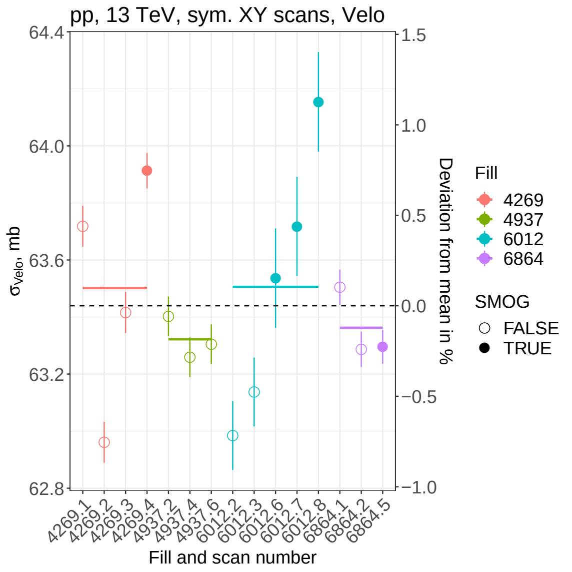
Backup Slides

BGI Uncertainties

- Central value: σ_{Track}=65.8mb
- Values based on 2016 Calibration Session and MD data
- Analysis of data from 2015/7 very advanced and 2018 in progress
- Model does not fit data perfectly: vdM cross-check needed

Uncertainty	Error (%)
Beam-Beam Resolution	$\sim$2
Beam-Gas Resolution	0.06
DCCT	0.16
FBCT	0.1
Ghost Charge	0.1
Satellite Charge	0.01
Bunch length	0.11
Alignment	0.5
Fit model	??
Factorisability	$\sim$0.1
Fill-to-fill variation	??
Statistical	0.1
μ value	0.2

Latest vdM Results



vdM Uncertainties

- Central value: 63.4mb
- New value based on data from 2015-18
- Beam-beam corrections are not included: will increase by ~2%

Uncertainty	Error (%)
DCCT	0.16
Ghost Charge	0.1
FBCT	0.1
Length Scale	0.5
Fit model	0.5
Statistical	0.1
Scan-to-scan variation	0.6
Fill-to-fill variation	0.4
Factorisability	~0.1
μ value	0.2

Plan for Final Run II Calibration

- Need to finalise 13 TeV p-p: aim for Q1 2019
- Target precision: $< 2\%$
- 2017 5 TeV vdM analysis is very advanced

See Vladik's talk at June LHCb week

- Expected precision: $< 2\%$ to be finished by Q1 2019
- Pb-Pb: no clear time estimate
- Problems with μ calculation due to soft interactions
- Can be better understood with 2018 no-bias data (can also be applied to 2015 data)
- Fixed target: calibration for p-He done
- p/Pb-Ar/Ne to be done in 2019

Definition: Ghost Charge

$$I(gc_1) = \frac{N(ee) + N(eb)}{\epsilon_{tt}} \frac{I(be)}{N(be)} \tag{6}$$

$$f_{gc_1} = \frac{I(gc_1)}{I(beam1)} \tag{7}$$

- ϵ_{tt} - Timing dependence of the trigger
- $N(xx)$ - The number of beam1-gas events observed in xx crossings
- I(xx) - The intensity in xx crossings from the FBCT
- Equivalent expression for beam 2 with $be \leftrightarrow eb$ and N(xx) the number of beam2-gas vertices