Absolute luminosity measurements at LHCb

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Outline

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Introduction

What is luminosity?

- **Interaction rate = Luminosity** $\times$ **Cross-section** $(R = L \times \sigma)$
- Luminosity for two identical Gaussian bunches, colliding head-on and without offset:

$$L = \frac{N_1 N_2 f}{4\pi\sigma_x\sigma_y}$$

  - $N_{1,2}$: bunch populations
  - f: revolution frequency
  - $\sigma_{x,y}$: transverse widths

Why do we need to know it?

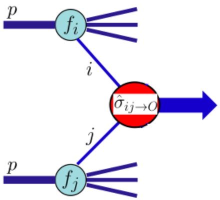
- Measure particle production cross-sections
- Quantify the collider performance

RELEVANCE OF ABSOLUTE LUMINOSITY MEASUREMENTS (1)

Theoretical description

- Hadron collisions $\rightarrow$ QCD
  - Factorization
  - Calculation of hard-scattering cross-sections

$$\boxed{\sigma_{pp\rightarrow O} = \int_0^1 dx_1 dx_2 \times \sum_{i,j} f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, \hat{\sigma}_{ij\rightarrow O}}$$



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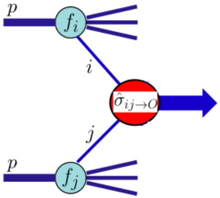


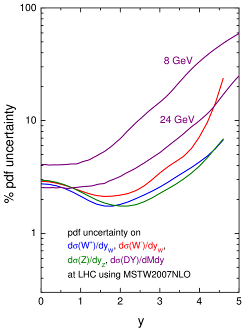
Measure cross-sections

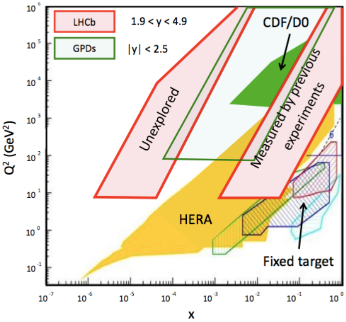
- Test models of heavy flavor production (use knowledge of PDFs)
- Improve PDFs (use well-known partonic processes)

RELEVANCE OF ABSOLUTE LUMINOSITY MEASUREMENTS (2)

Improve knowledge of PDFs

- W/Z and low-mass Drell-Yan production
  - At large rapidity, the production cross-section uncertainty is dominated by PDFs
  - Cross-section measurements at LHCb can constrain PDFs





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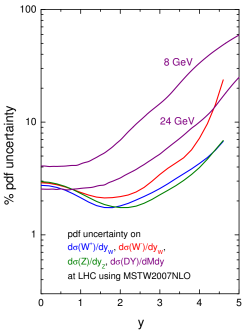
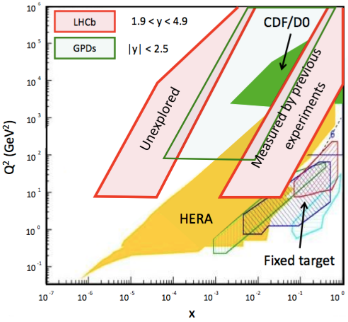




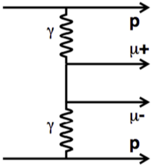
Partonic cross-section for Z production known to $\sim 2\%$
Defines a target for the knowledge of the absolute luminosity: 2%

METHODS FOR MEASURING THE LUMINOSITY: *Indirect*

Do not rely on the knowledge of the beam parameters

Using a "reference" reaction (σ_{ref})

- $L = R_{\text{ref}}/\sigma_{\text{ref}}$
- Previously measured cross-section
- Precisely calculable process, *e.g.* $pp \to pp\,\mu^+\mu^-$
  - At LHCb with 1 fb^{-1} the expected precision is $\sim 2\%$ [J. Anderson, CERN-THESIS-2009-020]



Optical theorem and Coulomb interference region

- Measure elastic *pp* scattering at low momentum transfer
  - Determine total *pp* cross-section and luminosity
- Used in TOTEM/CMS and ALFA/ATLAS
  - Expected ultimate precision $\sim 1 - 3\%$ [TOTEM TDR, CERN-LHCC-2004-002], [ATLAS-ALFA, CERN-LHCC-2008-004]

$\boxed{\textbf{Indirect methods not discussed in the rest of this talk}}$

Methods for measuring the luminosity: *Direct*

Determine L from beam parameters

- General formula for one pair of colliding bunches:

$$\boxed{L = N_1 N_2 \; f \; 2c\cos^2\alpha \int \rho_1(\mathbf{x}, t)\, \rho_2(\mathbf{x}, t)\, \mathrm{d}^3x\, \mathrm{d}t}$$

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  - Bunch revolution frequency: 11.245 kHz

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  - Beam Overlap Integral ($\rho_{1,2}$ are normalized bunch densities)

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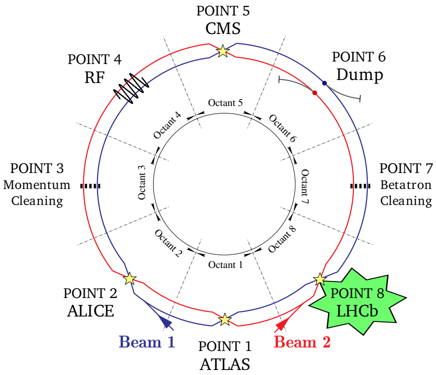
- Measurement of bunch populations is essential for all methods
- Different approaches for the measurement of the Beam Overlap Integral
  - Wire scan method (not discussed) [J. Bosser et al., NIM A **235** (1985)]
  - **van der Meer scan method** [S. van der Meer, CERN-ISR-PO-68-31]
  - **Beam-gas imaging method** [M. Ferro-Luzzi NIM A **553** 3 (2005)]

Outline

Large Hadron Collider

LHC

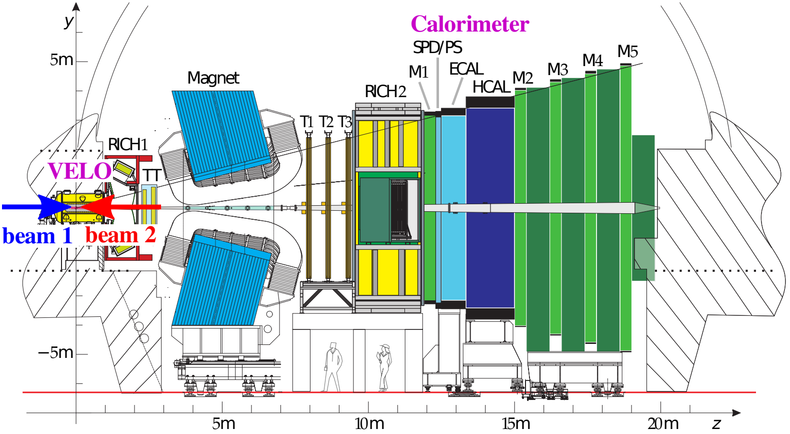
- 27-km accelerator and collider
- Separate vacuum pipes for the two beams
- 4 collision points
- Beam instrumentation at Point 4



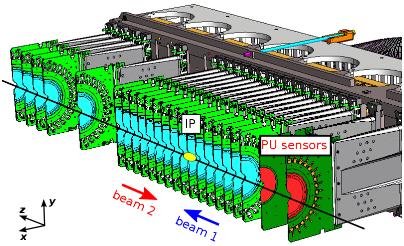
Parameter	2010	Nominal
Beam energy [TeV]	3.5	7
$\beta^\star$ [m]	**2**/3.5 (all IP)	0.55/10
Norm. emittance [μm rad]	2 − 3.5	3.75
Maximum n_{coll}/IP	348	2808
Bunch intensity [protons]	$2 \times 10^{10} - 1.2 \times 10^{11}$	1.15×10^{11}
Max. peak luminosity [$\text{cm}^{-2}\,\text{s}^{-1}$]	2×10^{32}	10^{34}

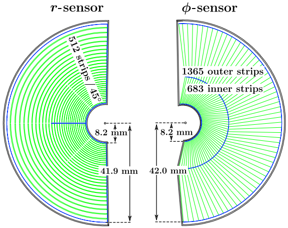
LHCb DETECTOR

- Dedicated to b-physics
- Single arm spectrometer, covers $\eta \in [2, 5]$
- Design luminosity: $2 \times 10^{32} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ ($2\ fb^{-1}$ per year)
  - Low probability for multiple interactions per bunch-crossing
- VErtex LOcator (VELO) and Calorimeter are essential for the luminosity measurement



VErtex LOcator and Calorimeter system



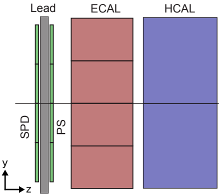


VELO

- 21 stations with r- and ϕ-measuring sensors and 2 “Pile-Up” (PU) stations
- Good acceptance for displaced vertices

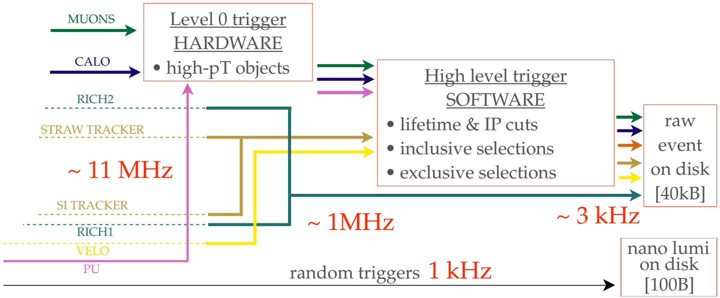
Calorimeter

- Four detectors located at $z = 12 - 15$ m
- SPD (Scintillating Pad Detector)
- PS (PreShower)
- ECAL and HCAL



LHCb trigger

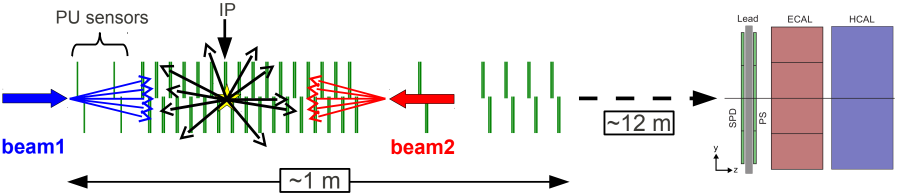
- L0: custom electronics (40 MHz)
  - Reduce visible interaction rate 11 MHz $\to$ 1 MHz
- HLT: farm of 2000 multi-processor boxes
  - Select 3 kHz of events to be written to disk



Triggers for lumi measurement

- Acquire 1 kHz of random triggers for the measurement of the relative luminosity
- **Dedicated beam-gas selections in L0 and HLT**

Beam-gas trigger



Types of BX (bunch crossings)

- bb : bunches of beam1 and beam2 are filled
- be : bunch of beam1 is filled, bunch of beam2 is empty
- eb : bunch of beam1 is empty, bunch of beam2 is filled
- ee : bunches of beam1 and beam2 are empty

L0 beam-gas

- Only in non-bb BX
- Exploit the directionality of the interaction products
- Use hit multiplicity in PU and transverse energy in HCAL

HLT beam-gas

- All types of BX
  - In bb BX search for beam-gas overlapped with *pp*; veto lumi region
- Look for VELO tracks coming from the same point in z (pseudo-vertex)
  - z within 1.5–2 m from IP

Outline

1. Introduction: Luminosity
2. LHC & LHCb
3. **Relative luminosity measurement**
4. Absolute luminosity measurement
   - Beam intensity measurement
   - van der Meer scan method
   - Beam-gas imaging method

Measurement of the relative luminosity (1)

For two colliding bunches: $L = \dfrac{f\mu_{\text{vis}}}{\sigma_{\text{vis}}}$

- Valid for an arbitrary process
- The *absolute* luminosity calibration determines σ_{vis}
  - It is the result of a comprehensive analysis over short periods of data taking
- Measuring the *relative* luminosity means measuring μ_{vis}
  - Needs to be done in all data-taking periods

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Measuring μ_{vis}

- Different methods exist to determine μ_{vis} from "luminosity counters" (multiplicity of fired channels in a given detector, reconstructed tracks, etc.)
- LHCb uses the "zero-count" method
  - Assuming that the number of visible pp interactions follows a Poisson distribution: $\boldsymbol{\mu_{\text{vis}} = -\ln P(0)}$
  - $P(0)$ is determined from a sample of randomly triggered events

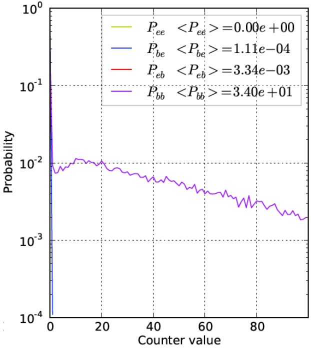
Measurement of the relative luminosity (2)

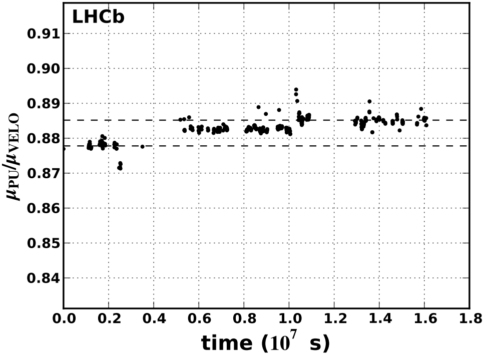
Choosing lumi counters

- Stability over time
- Possibility to be measured easily online

In 2010 LHCb used

- zero-count method and number of VELO tracks
  - "Empty" events defined as having 0 or 1 VELO track
  - Counter stability determined by comparing μ_{VELO} with μ_{vis} obtained from other counters





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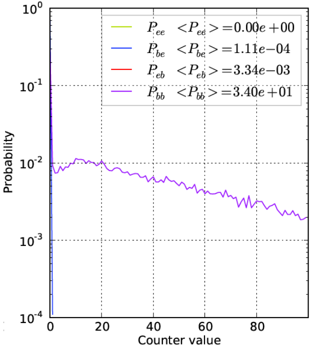

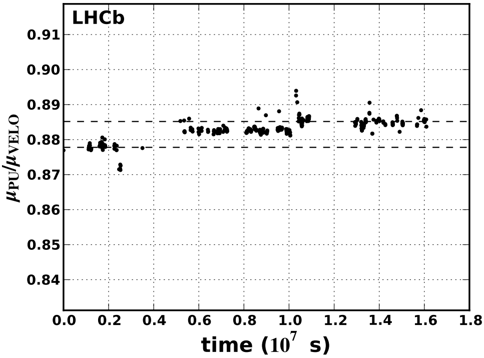

Systematic error of the relative luminosity measurement in 2010: 0.7%

Rate of visible interactions

Luminosity

Visible pp cross-section

$$\boxed{\mathrm{Rate}_{\mathrm{vis}}} = \boxed{n_{\mathrm{bunches}} \cdot N_1 N_2 \cdot f \cdot 2c \cdot \text{Beam Overlap Integral}} \times \boxed{\sigma_{\mathrm{vis}}}$$

Measurement of bunch intensities

Bunch current analysis – Introduction

DCCT (DC Current Transformer):

- Measures the total current in each of the two LHC beams N_{tot}
- Calibrated with a precise current source
- Noise $\mathcal{O}(10^9)$ charges (nominal bunch: 1.15×10^{11} charges)

FBCT (Fast Beam Current Transformer):

- Relative measurement of the current in all 25-ns bunch slots S_i ($i = 1, \ldots, 3564$)
- Noise $\mathcal{O}(10^8)$ charges

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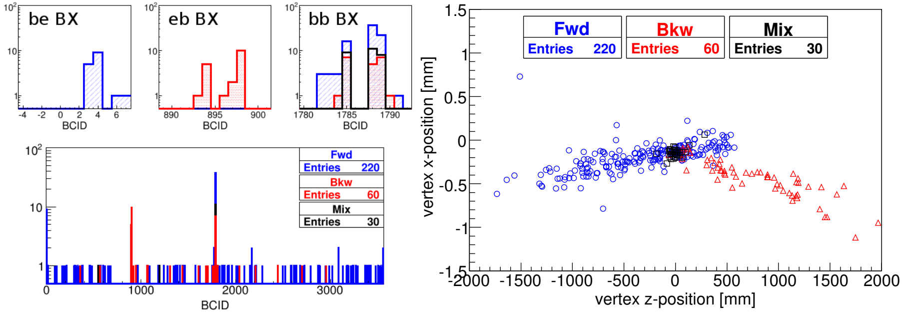
Estimation of the bunch populations

- For each beam define a common scale factor: $$a = \frac{N_{\text{tot}} - N_{\text{ghost}}}{\sum_{i \in \text{filled slots}} S_i}$$
- Ghost charge N_{ghost}: occupies nominally-empty slots
  - Visible to DCCT, but not to FBCT
  - **In 2010 measured by LHCb**
- Individual bunch populations: $N_i = a\,S_i$

Ghost charge measurement (1)

- Rate of beam-gas interactions $\propto$ beam current
- Determined ghost charge from ratio of events in ee and be/eb crossings
  - Forward, Backward and Mixed vertices
  - BCID (Bunch Crossing ID)



- The typical number of beam-gas interactions used in the measurement (per beam):
  - be/eb BX: $\mathcal{O}(10^4)$
  - ee BX: $\mathcal{O}(10^2)$ (large fraction is concentrated near the filled bunches)

Ghost charge measurement (2)

- Calculation of the ghost charge fraction in beam1 (similarly for beam2)

$$f_{\mathrm{ghost},1} = \frac{N_{\mathrm{ghost},1}}{N_{\mathrm{tot},1}} = \frac{F_{\mathrm{ee}}}{F_{\mathrm{be}}} \times \frac{\sum_{i \in \mathrm{be}} S_i}{\sum_{i=1}^{n} S_i}$$

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  - Ratio of the number of forward vertices in ee and be crossings

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  - Beam1 current in be crossings compared to the total current in beam1

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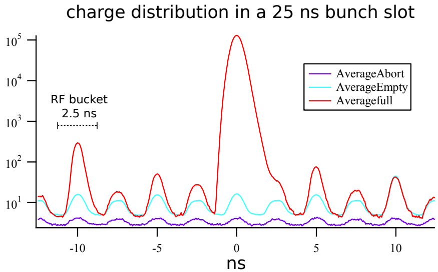
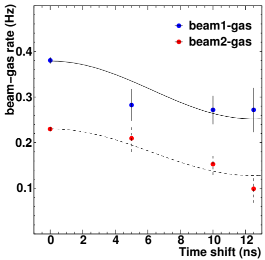
- This method has intrinsic time granularity of 25 ns
- A systematic error arises due to
  - Unknown distribution of the ghost charge inside the 25 ns bunch slots
  - Non-uniform efficiency of the LHCb trigger with respect to timing shifts



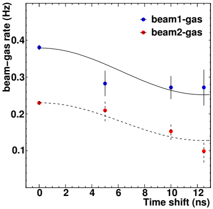


Ghost charge measurement (3)

Systematic error due to unknown distribution in the 25 ns slots

- Method 1: Average of two "extreme" cases
  - Case 1: All charge is in the central RF bucket → trig.eff. = 100%
  - Case 2: Charge is equally distributed in the 5, 10 and 12.5 ns RF buckets
- Method 2: Assume uniform distribution in all RF buckets
  - Fit the measured trigger efficiency to the sum of a cosine and a constant

	Beam1	**Beam2**
5, 10, 12.5 ns average	0.73	0.67
$\epsilon_{\text{average}}$	0.86 ± 0.14	0.84 ± 0.16
ϵ_{fit}	0.83 ± 0.04	0.78 ± 0.04



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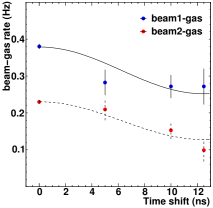

- To apply the correction for the ghost charge calculate:

$$f_g = \left(1 - \frac{f_{g1} \pm \Delta f_{g1}}{\epsilon_{\text{average1}}}\right) \times \left(1 - \frac{f_{g2} \pm \Delta f_{g2}}{\epsilon_{\text{average2}}}\right)$$

The typical values of the corrections is 1%
Assume systematic equal to half of the correction, *i.e.* $\sim 0.5\%$

Bunch current analysis – Results

Analysis performed by the Bunch Current Normalization WG

- Results for the May and October 2010 data taking periods are documented in [CERN-ATS-Note-2011-004], [CERN-ATS-Note-2011-016]
- Used by all experiments

Uncertainties

Source	**Uncertainty on $N_1 N_2$**	**Estimation method**
DCCT baseline offset	Up to a few % for "low-intensity" fills	DCCT measurements over long periods (hours) before and after fills. Min-to-max of noise defines the error.
DCCT absolute scale	2.7%	Scale reproducibility in three absolute calibrations in 2010. Peak to peak variations transformed to 68% CL.
FBCT offset	$2 - 3\%$	Comparison to ATLAS BPTX.
Ghost charge	$\sim 0.5\%$	LHCb measurement of beam-gas interactions in ee crossings.

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These four uncertainties are uncorrelated
The total error on the bunch current product depends on the fill

Rate of visible interactions

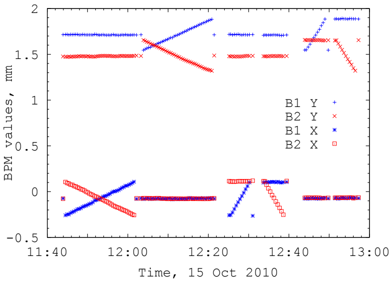
Luminosity

Visible pp cross-section

$$\boxed{\text{Rate}_{\text{vis}}} = \boxed{n_{\text{bunches}} \cdot N_1 N_2 \cdot f \cdot 2c \cdot \text{Beam Overlap Integral}} \times \boxed{\sigma_{\text{vis}}}$$

Absolute luminosity determination with the van der Meer method

van der Meer method – Introduction



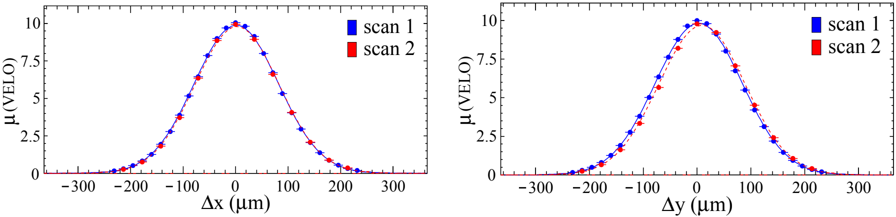
- Measure interaction rate while separating the two beams
- One "scan" = consecutive separations in each transverse direction

- For a single bunch pair: $$\boxed{\sigma_{\text{vis}} = \frac{\int \mu_{\text{vis}}(\Delta_x, \Delta_{y_0}) \mathrm{d}\Delta_x \int \mu_{\text{vis}}(\Delta_{x_0}, \Delta_y) \mathrm{d}\Delta_y}{N_1 N_2 \cos\alpha \, \mu_{\text{vis}}(\Delta_{x_0}, \Delta_{y_0})}}$$
  - $\mu_{\text{vis}}(\Delta_x, \Delta_y)$: average number of interactions per crossing as function of the separation in x and y
  - $\Delta_{x_0}, \Delta_{y_0}$: beam separation at the nominal ("working") point
  - $N_{1,2}$: bunch intensities
  - α: half crossing angle

- LHCb scans in 2010: April and **October**

VDM scans – Cross-section determination

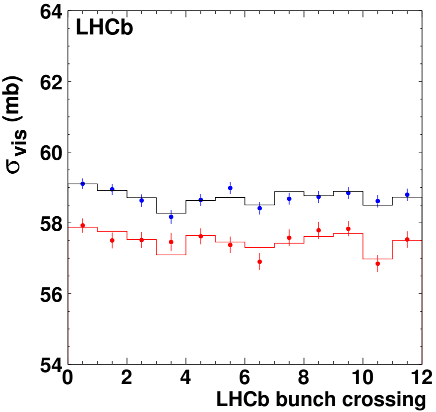
- "VDM profiles" summed over all bunches



- Fit the VDM profiles with a double Gaussian
- Fit simultaneously the x and y profiles, constrain $\mu_{\text{vis}}(\Delta_{x_0},\Delta_{y_0})$ to be the same
- Length scale calibration: use VELO vertex measurements to cross-check absolute beam displacement provided by LHC

VDM scans – Results (1)

- Results from the two scans in October:
  - indicated with circles
  - ∼ 2% discrepancy between the two scans, included as a systematic
- Fit the results of all 12 colliding bunches
  - Use FBCT offsets as free parameters
  - Fit functions are indicated with lines



VDM scans – Results (2)

Largest systematic errors

Source	**April (%)**	**Oct (%)**
DCCT scale	**2.7**	**2.7**
DCCT offset and FBCT	**4.9**	0.2
Ghost charge	0.08	0.15
Working point stability	–	0.4
Length scale	2	1
x-*y* coupling	–	0.3
Difference between scans	**4.4**	**2.1**

	σ_{VELO} (mb)	**relative uncertainty (%)**		
		total	**systematic**	**statistical**
April	59.7	7.5	7.4	0.9
October	**58.35**	3.64	3.64	0.09

VDM scans – Results (2)

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DCCT scale	**2.7**	**2.7**
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Better precision in October: result retained as a final 2010 VDM luminosity calibration

Rate of visible interactions

Luminosity

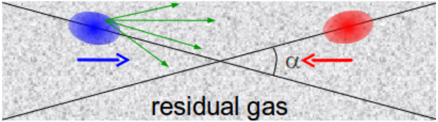
Visible *pp* cross-section

$$\boxed{\mathrm{Rate}_{\mathrm{vis}}} = \boxed{n_{\mathrm{bunches}} \cdot N_1 N_2 \cdot f \cdot 2c \cdot \text{Beam Overlap Integral}} \times \boxed{\sigma_{\mathrm{vis}}}$$

Absolute luminosity determination with the beam-gas imaging method

Beam-gas imaging method (BGI) [M. Ferro-Luzzi NIM A 553 3 (2005)]

$$L = N_1 N_2 f\, 2c \int \rho_1(\mathbf{x}, t)\, \rho_2(\mathbf{x}, t)\, \mathrm{d}^3 x\, \mathrm{d}t$$



- Residual gas near interaction point used as a beam visualizing medium
- Reconstruct beam-gas interaction vertices to measure
  - beam crossing angles
  - positions and shapes of the colliding bunches
- Determine the Beam Overlap Integral of the colliding bunches

- **Use the copious and better measured *pp* vertices to improve the precision on the beam overlap**

Strength with respect to the VDM method

- Avoid effects related to beam displacement
- Can be applied during physics fills

BGI method requires

- Vertex resolution better or comparable to the beam size ($\mathcal{O}(30)$ μm in x/y)
- Sufficient residual pressure and good acceptance for beam-gas interactions

Measurement of the Beam Overlap Integral with the BGI method

- Assuming two Gaussian bunches (transverse widths σ_{ij}, $i = 1, 2$, $j = x, y$):

$$L = \frac{f\ N_1\ N_2}{2\pi\sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1y}^2 + \sigma_{2y}^2)}} \times C_{\text{offset}} \times C_{\text{angle}}$$

MEASUREMENT OF THE Beam Overlap Integral WITH THE BGI METHOD

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- Measure bunch widths
  - Measure the beam angles
  - Determine primary vertex resolution

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- Measure bunch widths
  - Measure the beam angles
  - Determine primary vertex resolution
- Calculate offsets and crossing angle corrections

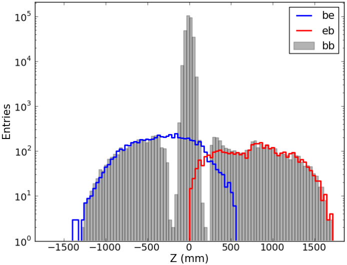
The analysis is applied for each individual colliding bunch pair

Data selection

- **Select fills on the basis of stability and availability of all data**

Fill	n_{tot}	n_{coll}	N	T (h)	#ev 1	#ev 2
1089	2	1	$2\ 10^{10}$	15	1270	720
1090	2	1	$2\ 10^{10}$	4	400	300
1101	4	2	$2\ 10^{10}$	6	730	400
1104A	6	3	$2\ 10^{10}$	5	510	350
1104B	6	3	$2\ 10^{10}$	5	520	350
1117	6	3	$2\ 10^{10}$	6	700	500
1118	6	3	$2\ 10^{10}$	5	500	400
1122	13	8	$2\ 10^{10}$	3	300	250

- **Online: dedicated beam-gas trigger**



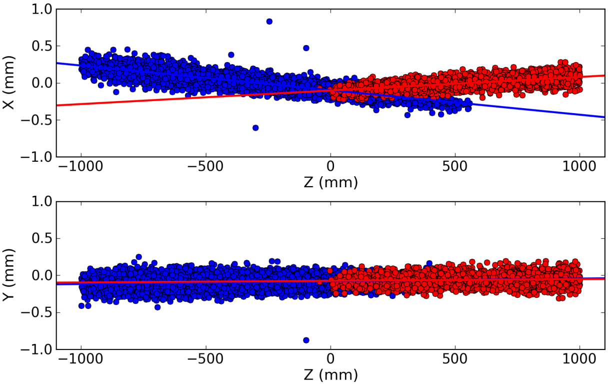
- **Offline vertex reconstruction and selection:**

	Type of Interaction		
	beam1-gas	beam2-gas	*pp*
Type of BX	be/bb	be/bb	bb
Only Fwd/Bkwd	Fwd	Bkwd	–
Min. tracks/vtx	11		21
z position [mm]	$[-1000, 500]$	$[0, 1000]$	$[-150, 150]$
Δr to beam [mm]	2		

- In bb crossings veto luminous region ($\pm$250 mm)
- Reduced z range for measuring beam widths

Measurement of the beam angles

- Beam angles are determined from straight-line fits to the beam-gas vertices in be and eb crossings



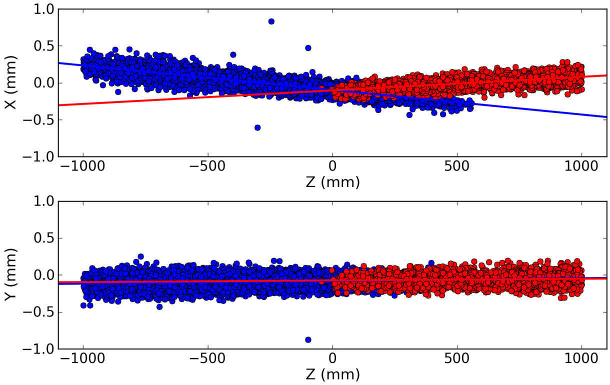
- Fill 1117:

Plane	Variable	|b1 - b2|	|b1 - b2| expected
X–Z	offset [μm]	5 ± 3	0
	angle [μrad]	515 ± 5	540
Y–Z	offset [μm]	7 ± 3	0
	angle [μrad]	15 ± 5	0

Measurement of the beam angles

- Beam angles are determined from straight-line fits to the beam-gas vertices in be and eb crossings

- Project beams onto a plane perpendicular to trajectory to determine width



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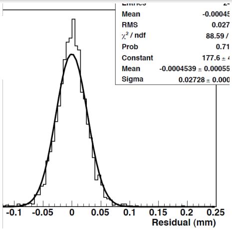
Plane	Variable	|b1 - b2|	|b1 - b2| expected
X–Z	offset [μm]	5 ± 3	0
	angle [μrad]	515 ± 5	540
Y–Z	offset [μm]	7 ± 3	0
	angle [μrad]	15 ± 5	0

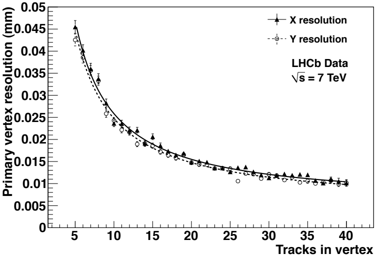
Primary vertex resolution: dependence on the number of tracks

- The measured vertex distribution is a convolution of the true width and the resolution
- Parametrize resolution as function of N_{Tr} (number of tracks in the vertex) and z

Track-splitting method

- Split tracks into two collections (at random)
- Reconstruct two vertices (require $N_{\mathrm{Tr}\,1} = N_{\mathrm{Tr}\,2}$)
- For each N_{Tr} fill histograms with x and y residuals
- Fit to a Gaussian to determine the resolution for each N_{Tr}



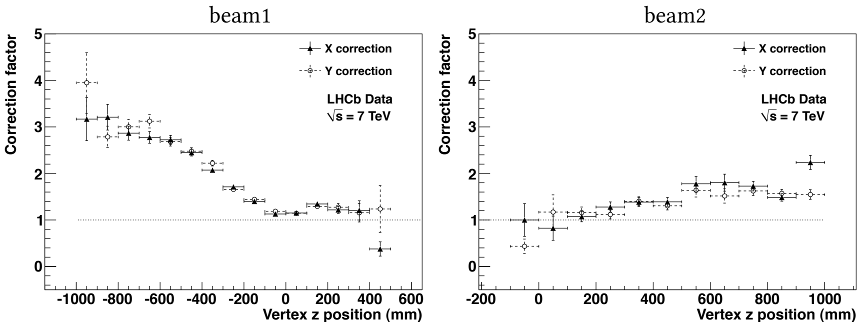


- The N_{Tr} dependence of the vertex resolution is parametrized as $\sigma_{\mathrm{res}} = \dfrac{A}{N_{\mathrm{Tr}}^{B}} + C$

	x	y
A (mm)	0.215 ± 0.020	0.202 ± 0.018
B	1.023 ± 0.054	1.008 ± 0.053
C (10^{-3} mm)	5.463 ± 0.675	4.875 ± 0.645

Primary vertex resolution: dependence on the z position

- A similar procedure is used with beam-gas vertices in be and eb crossings
- $N_{\text{Tr}\,1}$ can be different from $N_{\text{Tr}\,2}$
- Determine the pull $P_z = \dfrac{\xi_1 - \xi_2}{\sqrt{\sigma^2_{N_{\text{Tr}_1}} + \sigma^2_{N_{\text{Tr}_2}}}}$ $(\xi = x, y)$
- Depending on z fill P_z into different histograms
  - The width of the fitted Gaussian determines the z correction factor



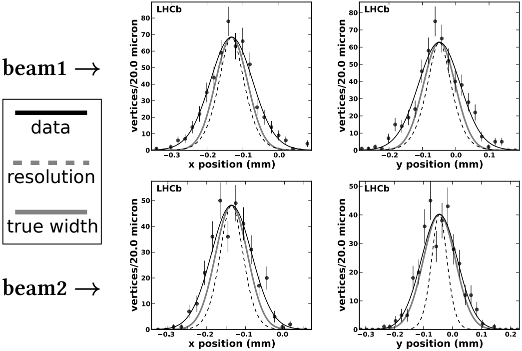
Resolution unfolding

- The effect of the vertex resolution is parametrized as a sum of 6 Gaussians:

$$R(x) = \sum_{n=1}^{6} c_n g_n(x; \sigma_n)$$

  - The amplitudes c_n and the widths σ_n are determined separately for each vertex distribution

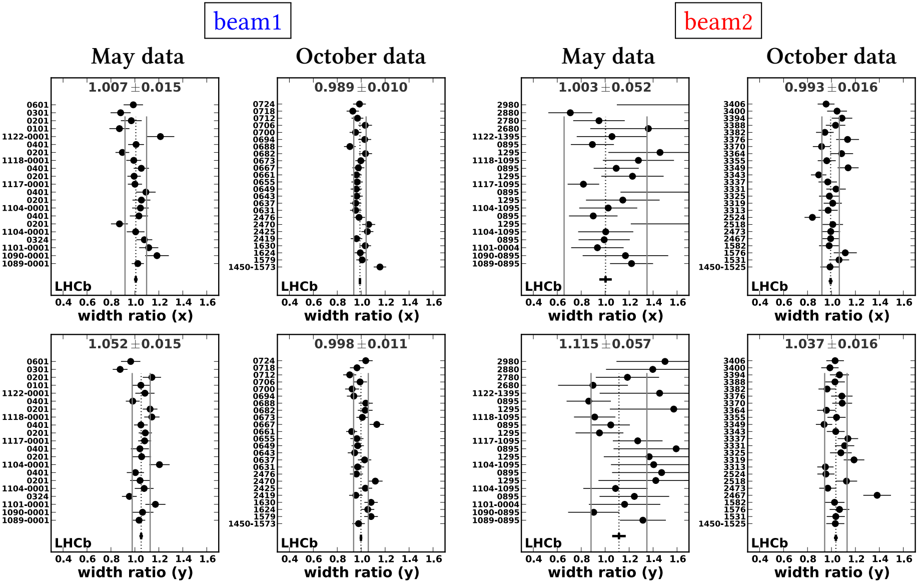
- The true bunch profiles are obtained by deconvolving the vertex resolution from the measured vertex distribution
- The effect of the vertex resolution for *pp* events is much smaller than for beam-gas interactions



The knowledge of resolution is essential

Consistency check: resolution unfolding

Ratio of beam widths measured close and away from $z = 0$ (be and eb crossings)



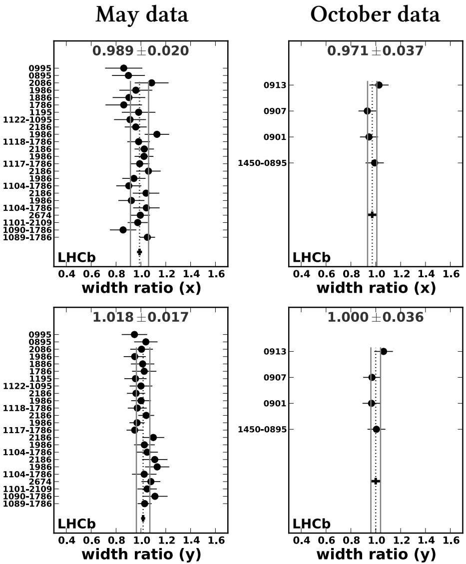
Consistency check: resolution unfolding

Ratio of lumi region widths measured with *pp* and beam-gas interactions (bb crossings)

- The product of two Gaussians with widths σ_1 and σ_2 is a Gaussian with width

$$\sigma_{\otimes}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} \qquad (1)$$

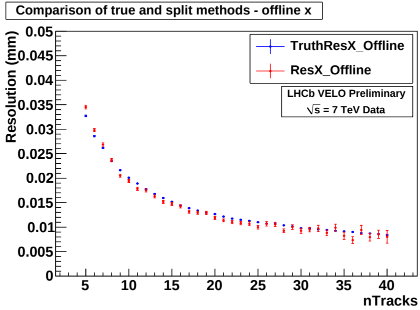
- For each transverse coordinate measure the bunch widths with beam-gas interactions away from $z = 0$
- Compare the luminous region width obtained with Eq. (1) and the one measured with *pp* interactions



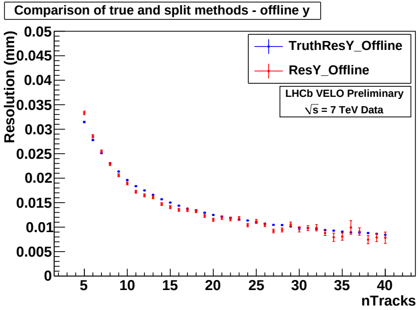
Cross-check of track-splitting method with MC

- Using MC simulated events, the N_{Tr} parametrization obtained with the track-splitting method is compared to the resolution obtained from MC-truth
- Consistency within 5%

pp events – X resolution

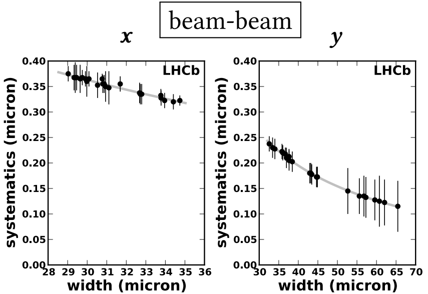


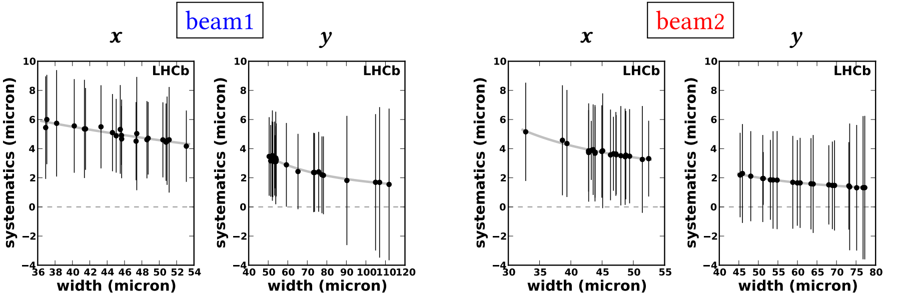
pp events – Y resolution



Systematic error from resolution uncertainty

- Parametrize error on widths of lumi region and beams
  - Determine the width twice using the upper and the lower limits of the resolution error (vary N_{Tr} and z resolution coherently)
  - Error = difference between the two widths





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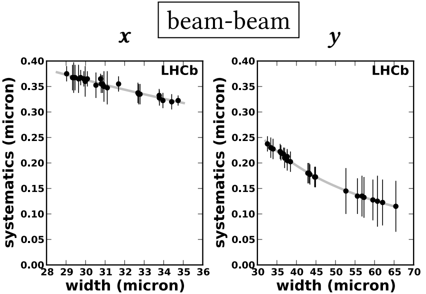
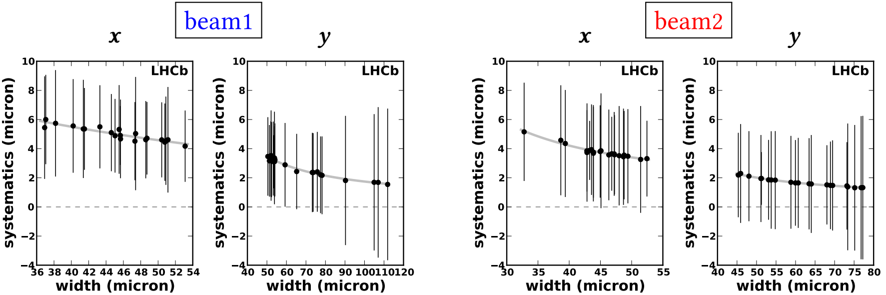
Error on cross-section depends on the beam widths. On average it is 2.5%



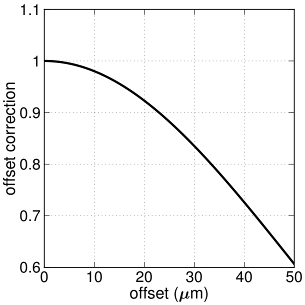


Additional factors

$$L = \frac{f N_1 N_2}{2\pi\sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1y}^2 + \sigma_{2y}^2)}} \times C_{\text{offset}} \times C_{\text{angle}}$$

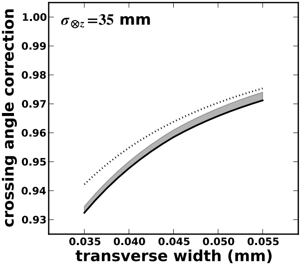
Transverse offset of the beams

- Per transverse coordinate: $C_{\text{offset}} = \exp\left(-\frac{1}{2}\frac{\Delta_\mu^2}{\sigma_1^2 + \sigma_2^2}\right)$



Crossing angle

- In the presence of a crossing angle, the Beam Overlap Integral depends on the bunch lengths σ_{1z} and σ_{2z}
- $C_{\text{angle}} = \left[1 + \tan^2\alpha(\sigma_{1z}^2 + \sigma_{2z}^2)/(\sigma_{1x}^2 + \sigma_{2x}^2)\right]^{-\frac{1}{2}}$
- However, σ_{1z} and σ_{2z} are not directly measured
- Workaround: use an equation relating the luminous length $\sigma_{\otimes z}$ with $\sigma_{1z}^2 + \sigma_{2z}^2$



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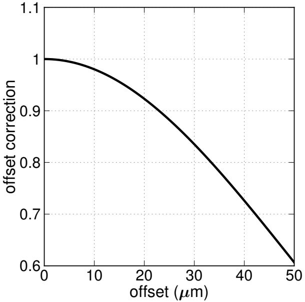
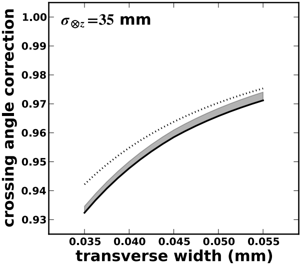
In the fills used in this analysis $C_{\text{angle}} \sim 0.95$
Systematic error: 1%





Systematic errors

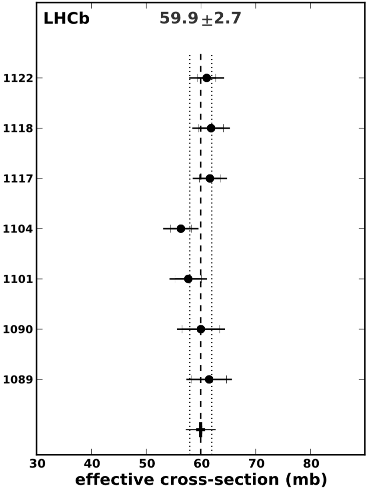
- Seven independent measurements of an *effective reference cross-section*
  - one measurement per fill
- Correlations for the averaging:
  - ***u*** : uncorrelated between bunches and between fills
  - ***f*** : correlated between bunches, uncorrelated between fills
  - ***c*** : correlated between bunches and between fills

relative cross-section errors [%]

	correl.	average
Statistics	***u***	**0.96**
Overlap syst		**3.35**
Crossing angle	*c*	1.00
Width syst		3.20
Resolution syst	*c*	2.56
Trend syst	*c*	1.00
Bias syst	*c*	1.61
Beam normalisation		**2.88**
DCCT scale	*c*	2.70
DCCT baseline	*f*	0.10
Ghost charge	*f*	0.19
FBCT offset	*f*	0.91
Relative lumi	***c***	**0.50**
Weight		1.38
Total Systematics		4.45
Uncorrelated syst	*f*	0.93
Correlated syst	*c*	4.33
Total		**4.55**
Excluding norm		3.63

Results

Results of BGI method
σ_{VELO} [mb]

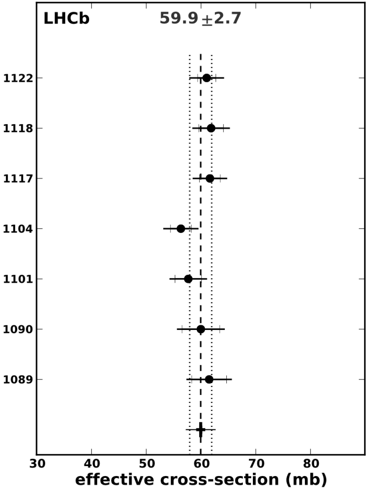


Combination of VDM and BGI results

	Average	VDM	BGI
Cross-section σ_{VELO} [mb]	58.8	58.4	59.9
DCCT scale uncertainty [%]	2.7	2.7	2.7
Uncorrelated uncertainty [%]	2.0	2.4	3.7
Cross-section uncertainty [%]	3.4	3.6	4.6

Results

Results of BGI method
σ_{VELO} [mb]



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Cross-section uncertainty [%]	3.4	3.6	4.6

Overall precision of the absolute luminosity normalization: 3.4%

Conclusion

Two methods were applied for the absolute luminosity normalization of the data collected by LHCb in 2010

- van der Meer scans in dedicated fills in April and October (precision 3.6%)
- Beam-gas imaging during physics fills in May and using the residual gas in the beam vacuum pipe (precision 4.6%)
  - **Demonstrating the potential of the BGI method**
- Error on the integrated luminosity: 3.5%
  - 3.4% from the determination of the absolute scale
  - 0.7% from the measurement of the relative luminosity
- The luminosity is *not* the dominating uncertainty in most of the physics cross-section measurements

Conclusion

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Ways to improve the precision (goal: 2%)

- Beam intensity: improve uncertainty on DCCT scale
- VDM: systematic studies of non-reproducibility
- BGI: apply in a fill with optimal conditions (broader beams and higher gas pressure)

Backup Slides

Resolution unfolding

- It is assumed that the effect of the vertex resolution can be parametrized as a superposition of Gaussian functions $g_n(x;\sigma_n)$ centered at zero:

$$R(x) = \sum_{n=1}^{N} c_n g_n(x;\sigma_n)$$

- Estimate the total effective resolution for a given vertex distribution
  - Fill a 1-d histogram with the expected resolution of each vertex (using the N_{Tr} and z parametrization)
  - Divide the histogram in N bins
  - The number of entries in each bin determine the weight coefficient c_n
  - The average resolution in each bin gives the corresponding value of σ_n
  - Six bins are sufficient to give a good description of the resolution

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$$R(x) = \sum_{n=1}^{N} c_n g_n(x;\sigma_n)$$

- The physical beam shape is assumed to be described by a Gaussian with amplitude a, position μ and width σ: $f(x;a,\mu,\sigma)$
- The measured vertex distribution $M(x)$ is a convolution of the physical beam shape and the resolution function $R(x)$:

$$M(x) = \int_{-\infty}^{+\infty} \sum_{n=1}^{N} c_n g_n(x-t;\sigma_n)\, f(t;a,\mu,\sigma)\, dt \qquad (2)$$

- Using the basic algebraic properties of the convolution and defining $\sigma_n^* = \sqrt{\sigma_n^2 + \sigma^2}$ this equation can be rewritten as:

$$M(x) = \sum_{n=1}^{N} c_n f_n(x;a,\mu,\sigma_n^*)\,, \qquad (3)$$

- The physical beam position, μ, and width, σ, are obtained by fitting $M(x)$ to the data

BIAS DUE TO UNEQUAL BEAM SIZES AND BEAM OFFSETS

- Using the second lumi-region constraint (Eq. (4)) and introducing $\boxed{\rho = \sigma_2/\sigma_1}$ it can be shown that: $\sigma_{\otimes} = \dfrac{\rho\sigma_1}{\sqrt{1+\rho^2}}$
- Then, *per transverse coordinate*, the Beam Overlap Integral is proportional to $\dfrac{\rho}{(1+\rho^2)\sigma_{\otimes}}$
  - This form is used for the calculation of the Beam Overlap Integral
  - The value of $\sigma_{\otimes}$ is the best measured quantity entering the Beam Overlap Integral
  - The measurement of ρ is associated with a larger statistical uncertainty

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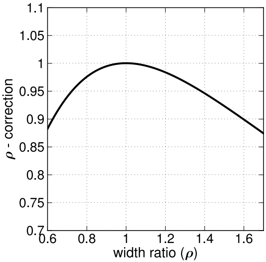
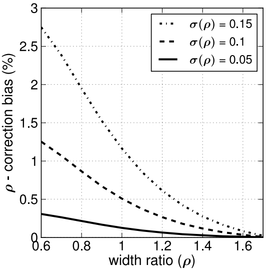
  - This form is used for the calculation of the Beam Overlap Integral
  - The value of $\sigma_\otimes$ is the best measured quantity entering the Beam Overlap Integral
  - The measurement of ρ is associated with a larger statistical uncertainty
- This expression has an extremum at $\rho = 1$ and can only take values smaller than unity
- The precision of measuring ρ (about $10 - 15\%$) is similar to its difference from unity
- The experimental estimate of the ρ-correction factor $2\rho/(1+\rho^2)$ is *biased* towards smaller values

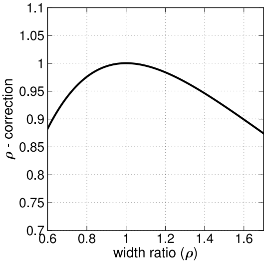


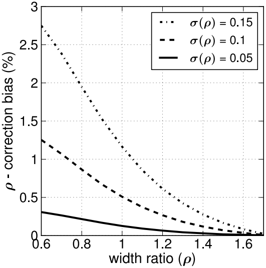


Bias due to unequal beam sizes and beam offsets

- Using the second lumi-region constraint (Eq. (4)) and introducing $\boxed{\rho = \sigma_2/\sigma_1}$ it can be shown that: $\sigma_\otimes = \dfrac{\rho\sigma_1}{\sqrt{1+\rho^2}}$
- Then, *per transverse coordinate*, the Beam Overlap Integral is proportional to $\dfrac{\rho}{(1+\rho^2)\sigma_\otimes}$
  - This form is used for the calculation of the Beam Overlap Integral
  - The value of $\sigma_\otimes$ is the best measured quantity entering the Beam Overlap Integral
  - The measurement of ρ is associated with a larger statistical uncertainty
- This expression has an extremum at $\rho = 1$ and can only take values smaller than unity
- The precision of measuring ρ (about $10 - 15\%$) is similar to its difference from unity
- The experimental estimate of the ρ-correction factor $2\rho/(1+\rho^2)$ is *biased* towards smaller values

- A correction for this bias is applied on a bunch-by-bunch basis
  - Systematic uncertainty: half of the correction





BIAS DUE TO UNEQUAL BEAM SIZES AND BEAM OFFSETS

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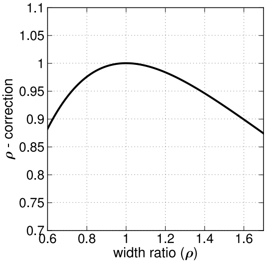
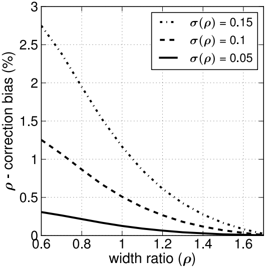
  - Systematic uncertainty: half of the correction
- **A similar situation occurs for the transverse-offset correction**





Lumi region constraints

- For each transverse coordinate we have relations between the widths and the positions of the two bunches (index 1, 2), and their luminous region (index $\otimes$)
  - *lumi region constraints*

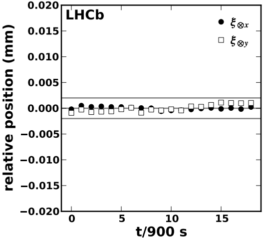
$$\mu_\otimes = \frac{\mu_1\sigma_2^2 + \mu_2\sigma_1^2}{\sigma_1^2 + \sigma_2^2} \quad \text{and} \quad \sigma_\otimes^2 = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2 + \sigma_2^2} \tag{4}$$

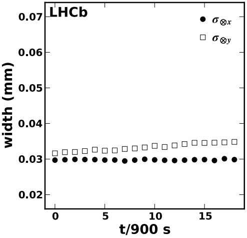
- The precision of the measured properties of the luminous region is higher than for the separate beams
- Employ the lumi region constraints to fit 4 parameters using 6 measurements (fit parameters are $\sigma_{1,2}$ and $\mu_{1,2}$): Significant improvement of the precision
- An alternative choice of the fit parameters makes the corresponding luminosity error propagation easier without changing the result (the motivation for this choice will become clear later):
  - $\sqrt{\sigma_1^2 + \sigma_2^2}$, σ_2/σ_1, $\Delta_\mu = \mu_1 - \mu_2$ and $\mu_\otimes$

TIME DEPENDENCE AND STABILITY

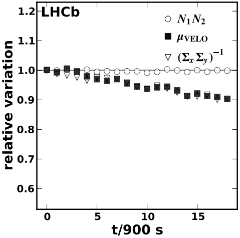
- The beam stability is essential, given the long integration times for collecting sufficient beam-gas statistics
  - Use only fills where the variation of the beam intensity and emittance are smooth

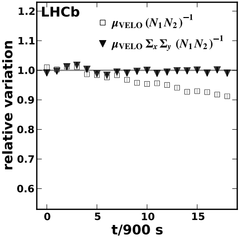
- Time variation of the transverse position and width of the luminous region of one colliding bunch pair





- The time variation of quantities determining the interaction rate of the same bunch pair
- The average position and size of the luminous region is used together with the beam profiles measured in the same period with beam-gas interactions
  - Systematic error of 1% is assigned to account for the variations

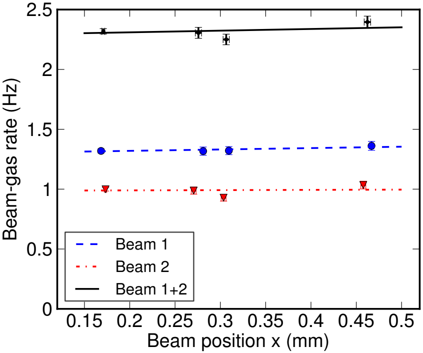




GAS PRESSURE GRADIENT

- In the BGI method, the gas in the beam-vacuum pipe is used to obtain an image of the transverse profile of the beams
- In case of gas inhomogeneity in the transverse plane the beam image will be distorted

- A measurement of the gas homogeneity is performed by displacing the beams and recording the rate of beam-gas interactions at these different beam positions
- An upper limit on the gradient of the interaction rate: 0.62 Hz/mm at 95% CL, compared to a rate of 2.14 ± 0.05 Hz observed with the beam at its nominal position
- With the measured limit on the gradient, the maximum relative effect on the Beam Overlap Integral is estimated to be 4.2×10^{-4}
- In practice, the effect would be smaller, as the beam widths enter the Beam Overlap Integral measurement through $\rho = \sigma_2/\sigma_1$



BGI results

		average	1089	1090	1101	1104	1117	1118	1122
Cross-section (mb)		59.94	61.49	59.97	57.67	56.33	61.63	61.84	61.04
Statistics	*u*	0.96	4.06	4.73	3.09	2.56	1.89	2.66	1.82
Overlap syst		3.35	3.33	3.58	3.21	3.70	3.00	3.15	3.49
Crossing angle	*c*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Width syst		3.20	3.18	3.43	3.05	3.56	2.83	2.99	3.34
Resolution syst	*c*	2.56	2.79	2.74	2.54	2.86	2.37	2.47	2.44
Trend syst	*c*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bias syst	*c*	1.61	1.14	1.81	1.35	1.89	1.19	1.35	2.05
Beam normalisation		2.88	4.21	4.21	3.91	3.48	3.65	3.67	3.37
DCCT scale	*c*	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
DCCT baseline	*f*	0.10	0.97	1.01	0.43	0.29	0.29	0.29	0.14
Ghost charge	*f*	0.19	0.70	0.65	1.00	0.60	0.38	0.55	0.35
FBCT offset	*f*	0.91	3.00	3.00	2.61	2.10	2.41	2.41	1.98
Relative lumi	*c*	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Weight		1.38	5.19	5.73	4.19	3.38	3.10	3.64	2.72
Total Systematics		4.45	5.39	5.55	5.08	5.11	4.75	4.87	4.88
Uncorrelated syst	*f*	0.93	3.23	3.23	2.83	2.20	2.46	2.49	2.02
Correlated syst	*c*	4.33	4.32	4.51	4.22	4.61	4.07	4.18	4.44
Total		4.55	6.75	7.29	5.95	5.71	5.11	5.55	5.20
Excluding norm		3.63	6.17	6.75	5.28	5.01	4.31	4.82	4.42