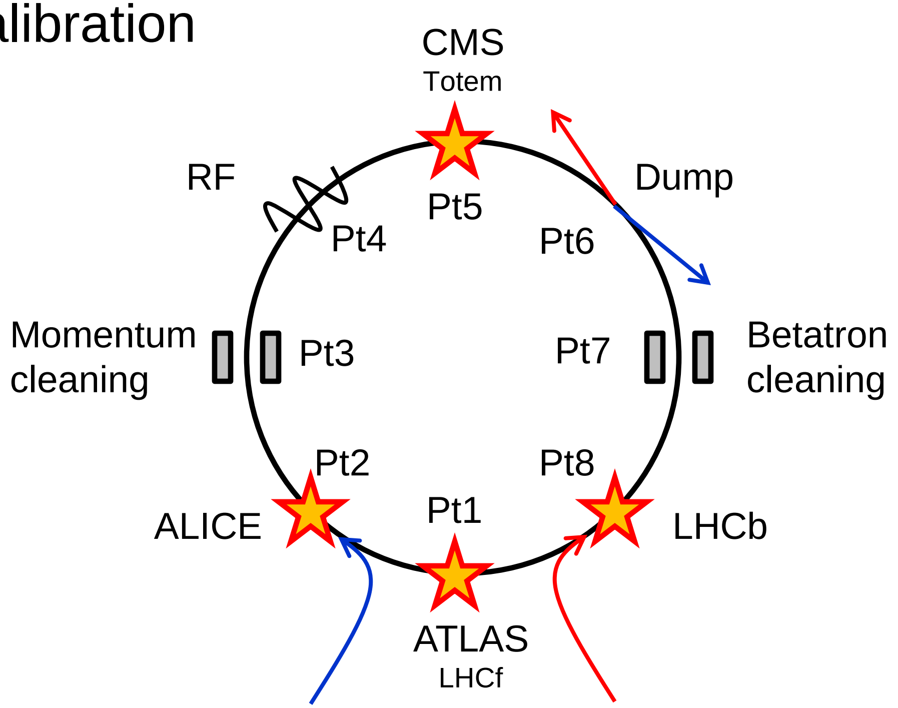
Overview of LHC luminosity calibration measurements

- Introduction:
  - Why luminosity calibration
  - Luminosity formulae and calibration methods
- Experimental conditions of LHC calibration measurements
  - 2009: 450 GeV
  - 2010: 3.5 TeV ⟵ clear focus
- Results
  - 4 interaction points
- Conclusions and outlook



Acknowledgements

Many thanks to

- ALICE Collaboration
- ATLAS Collaboration
- CMS Collaboration
- LHCb Collaboration
- LHC machine groups

Direct luminosity determination

Will focus here on the two methods used at LHC:

- Van der Meer method
  - based on beam separation scans

- Beam-gas imaging method
  - based on beam-gas vertex reconstruction

Why luminosity determination is important

Rate = Luminosity x Cross section

- Allows to determine cross section of interaction processes on an absolute scale
  - At the LHC: Heavy flavour production, couplings of new particles, total (inelastic, elastic) cross section, …

- Allows to quantify the performance of the collider
  - Important to verify experimental conditions, to understand quantitatively beam-beam effects, …

Chronology

2009

- All experiments started off with a normalisation based on a generator model including detector simulation

  => uncertainties at the level of 20% for 450 GeV

- LHCb performed first direct luminosity normalisation at 450 GeV using the beam-gas imaging method (see later)

2010

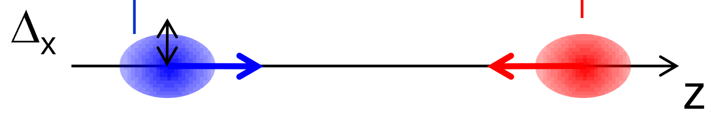
- At 3.5 TeV, started off again with a normalisation based on a generator model including detector simulation

- Then, April-May, performed first direct luminosity measurement at each IP with van der Meer scans (+continuous beam-gas imaging normalisation, LHCb)

Van der Meer's trick — See Ref. [1]

Consider single circulating & colliding bunch pair with zero crossing angle

$$R = \sigma \cdot L = \sigma \cdot f\, N_1\, N_2 \int \rho_1(x,y)\, \rho_2(x,y)\, dx\, dy$$



With transverse displacements Δ_x , Δ_y of one beam w.r.t. the other:

$$R(\Delta_x, \Delta_y) = \sigma \cdot L(\Delta_x, \Delta_y) = \sigma \cdot f\, N_1\, N_2 \int \rho_1(x-\Delta_x, y-\Delta_y)\, \rho_2(x,y)\, dx\, dy$$

$$\int R(\Delta_x, \Delta_y)\, d\Delta_x\, d\Delta_y = \sigma\, f\, N_1\, N_2 \int \rho_1(x-\Delta_x, y-\Delta_y)\, \rho_2(x,y)\, dx\, dy\, d\Delta_x\, d\Delta_y$$

$$= \sigma\, f\, N_1\, N_2 \int \rho_2(x,y) \underbrace{\left[\int \rho_1(x-\Delta_x, y-\Delta_y)\, d\Delta_x\, d\Delta_y \right]}_{=1} dx\, dy$$

$$= \sigma\, f\, N_1\, N_2 \overbrace{\int \rho_2(x,y)\, dx\, dy}^{=1} = \sigma\, f\, N_1\, N_2$$

Factorization

Assume x-y factorizable $\rho_i(x,y) = \rho_{ix}(x)\ \rho_{iy}(y)$

$$L(\Delta_x , \Delta_y) = f\, N_1\, N_2 \cdot \underbrace{\int \rho_{1x}(x-\Delta_x)\ \rho_{2x}(x)\ dx}_{1/h_x(\Delta_x) = O_x(\Delta_x)} \cdot \underbrace{\int \rho_{1y}(y-\Delta_y)\ \rho_{2y}(y)\ dy}_{1/h_y(\Delta_y) = O_y(\Delta_y)}$$

$$L(\Delta_x , \Delta_y) = f\, N_1\, N_2\, O_x(\Delta_x)\, O_y(\Delta_y)$$

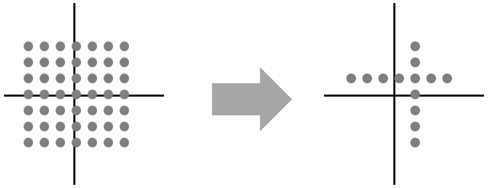
Re-use van der Meer's trick that for a=x or a=y :

$$\int O_a(\Delta_a)\, d\Delta_a = \int \rho_{2a}(a) \underbrace{\left[\int \rho_{1a}(a-\Delta_a)\, d\Delta_a \right]}_{\text{normalised to unity}} da = \int \rho_{2a}(a)\ da = 1$$

Result with factorization

Measure R while scan Δ_x (at $\Delta_y = \Delta_{y0}$), then while scan Δ_y (at $\Delta_x = \Delta_{x0}$)

$$R(\Delta_x, \Delta_{y0}) = \sigma \; f N_1 N_2 \; O_x(\Delta_x) \; O_y(\Delta_{y0})$$
$$R(\Delta_{x0}, \Delta_y) = \sigma \; f N_1 N_2 \; O_x(\Delta_{x0}) \; O_y(\Delta_y)$$



$$R(\Delta_x, \Delta_y) = \frac{R(\Delta_x, \Delta_{y0}) \cdot R(\Delta_{x0}, \Delta_y)}{R(\Delta_{x0}, \Delta_{y0})} \qquad R_0 = R(\Delta_{x0}, \Delta_{y0})$$

$$\int R(\Delta_x, \Delta_y) \; d\Delta_x \; d\Delta_y = R_0^{-1} \int R(\Delta_x, \Delta_{y0}) \, d\Delta_x \cdot \int R(\Delta_{x0}, \Delta_y) \, d\Delta_y$$

$$\int R(\Delta_x, \Delta_y) \; d\Delta_x \; d\Delta_y = \sigma f N_1 N_2 \cdot \int O_x(\Delta_x) \; O_y(\Delta_y) \; d\Delta_x \; d\Delta_y$$

$$= \sigma f N_1 N_2 \cdot \int O_x(\Delta_x) \, d\Delta_x \cdot \int O_y(\Delta_y) \, d\Delta_y$$

$$= \sigma f N_1 N_2$$

Van der Meer scan with crossing angle see Ref. [2]

- It has been pointed out that the van der Meer method with bunched beams (like at the LHC) can equally be applied to the case with non-zero crossing angle (V. Balagura).

- General formula with full crossing angle ϕ :

$$\sigma = \frac{f\, N_1\, N_2 \int R(\Delta_x , \Delta_{y0})\, d\Delta_x \cdot \int R(\Delta_{x0} , \Delta_y)\, d\Delta_y}{\cos(\phi/2) \cdot R_0(\Delta_{x0} , \Delta_{y0})}$$

(here shown for the case with x-y factorized)

Assumptions…

- Beams do not change when they are moved across each other
  - correct for (or neglect) beam-beam effects
  - correct for (or neglect) slow emittance growth
  - correct for (or neglect) slow bunch current decay

- Scan range sufficiently large to cover the distributions
  - negligible tails

- Relation between transverse displacement parameters (magnet currents) and the actual displacement is known on absolute scale
  - calibrate the absolute displacement scale with vertex detectors

LHC VdM scan measurements at 3.5 TeV/beam (1)

- Six vdM scan experiments performed so far (in 2010)
- Typical procedure:
  - Optimized IP luminosity (mini scans) in both planes
  - Scanned first plane (X or Y)
  - Set optimum on first plane (not always)
  - Scanned second plane
- For these scans the beam separation was limited to approx +/-6 beam sigmas.
- In addition, length scale calibration
  - Moved both beams in same direction
  - Optimised locally the luminosity
  - Compared reconstructed displacement of luminous region (tracking) with the displacement inferred from magnets settings.
  - Alternatively: move only one beam relative to other
- Remark: IP1+5 had zero crossing angle, while IP2 had 280 urad (vertical plane) and IP8 had 540 urad (horizontal plane).

LHC Measurements at 3.5 TeV/beam (2)

- 6 vdM scan experiments performed so far (in 2010)
- k_b = number of stored bunches / beam
- n_b = number of colliding pairs per IP

LHC fill nr	date	IP scanned	k_b	n_b	N (p/bch)	
1058	Apr 24	IP5 (CMS)	3	2	~1e10	ΔX, ΔY
1059	Apr 26 Apr 26	IP1 (ATLAS) IP8 (LHCb)	2	1	~1e10	ΔX, ΔY ΔX, ΔY, X_1,Y_1
1089	May 8 May 9	IP5 (CMS) IP1 (ATLAS)	2	1	~2e10	ΔX, $-\Delta X$, ΔY, $-\Delta Y$ ΔX, $-\Delta X$, ΔY, $-\Delta Y$
1090	May 10	IP2 (ALICE)	2	1	~2e10	ΔX, ΔY

- ΔX, ΔY : moving both beams by same amount (in opposite direction), minus sign indicating a reversed scan direction.
- X_1,Y_1 : moving only beam 1

Nota Bene

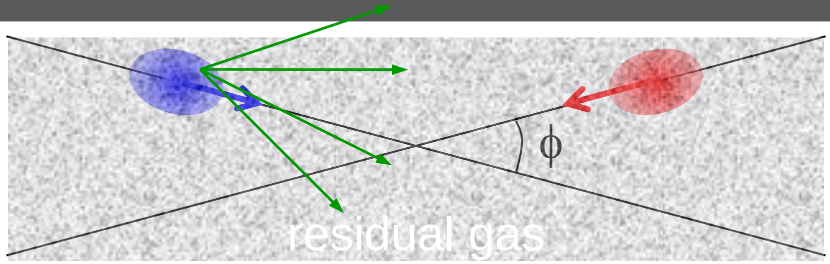
- The cross sections that are going to be presented here are **NOT** total or inelastic cross sections.

- These cross sections **are detector-dependent cross sections** that, once calibrated, are used for monitoring the luminosity on an absolute scale.

- These are typically "visible cross sections" (include geometrical and trigger acceptance, and possibly a reconstruction efficiency)

Beam-gas imaging method see Ref. [3]

Again, luminosity



$$L = f N_1 N_2 \; 2c \; \cos^2(\phi/2) \int \rho_1(\mathbf{r},t) \; \rho_2(\mathbf{r},t) \; d^3r \, dt$$

- Beam interacts with residual gas around the interaction region
- Reconstruct beam-gas interaction vertices

  => sample transverse beam profile

  measure <u>individually</u> the ρ_1 and ρ_2 and rebuild the overlap

  (measure also ϕ and hourglass effect and and and…)

> Requires:
> (1) vtx detector resolution smaller (or at least comparable) to the beam sizes
> (2) residual pressure & acceptance must be adapted to this method

- Strength with respect to van der Meer method:

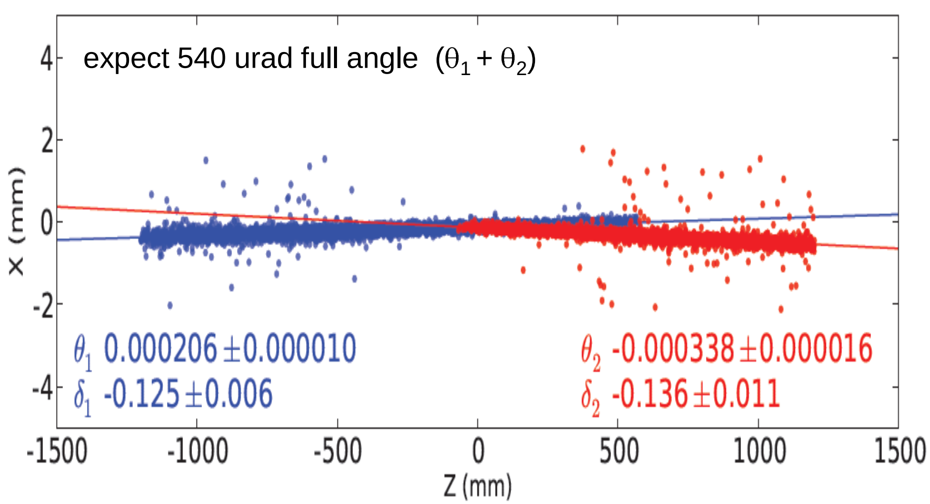
  (a) non disruptive, **<u>do not affect the beams</u>** !

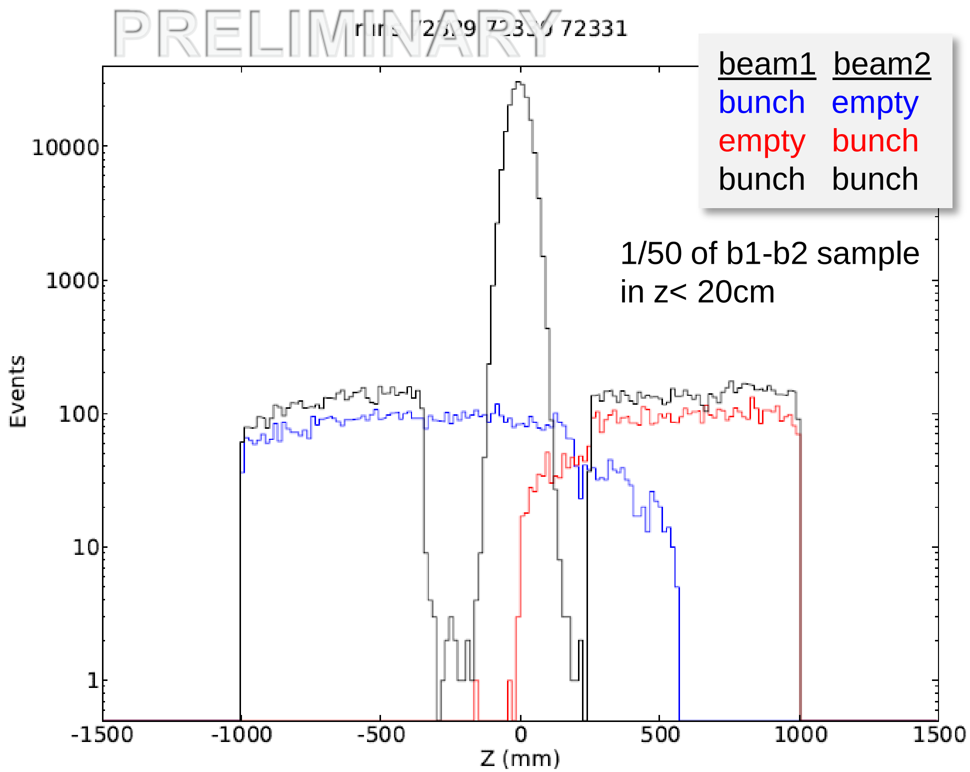
  (b) can run fully parasitically during physics running time

  => potentially smaller systematics uncertainties

LHCb beam-gas imaging at 3.5 TeV

- 3.5 TeV, 2m optics at IP8, bunch intensity ~2e10 p/bch
- 13 bunches: 8 colliding, 5 not colliding per beam
- L ~ 2.5e28 Hz/cm^2 per colliding pair
- 3 hours of data
- z resolution ~ 0.1 mm

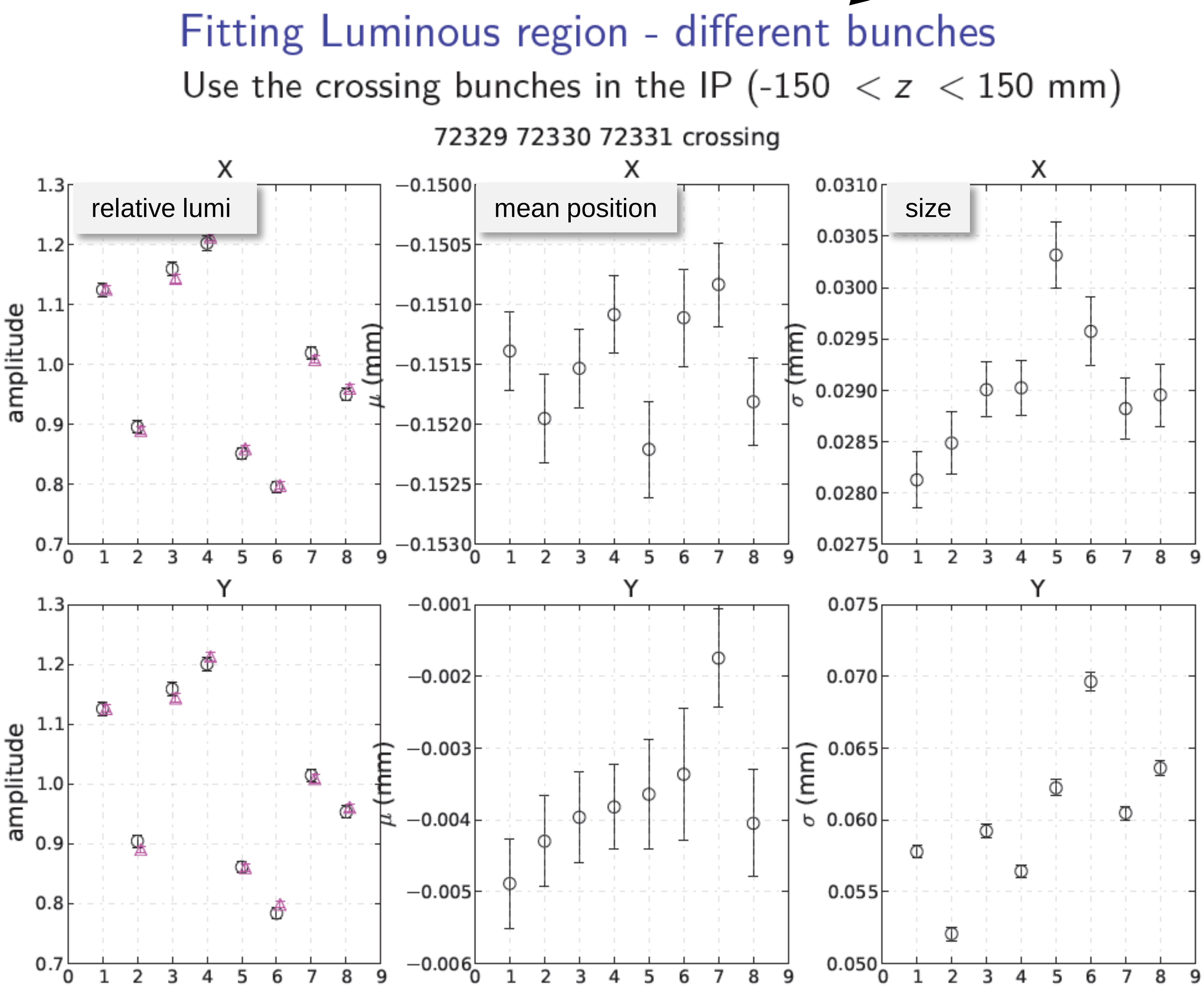




LHCb beam-gas combined with lumi region imaging

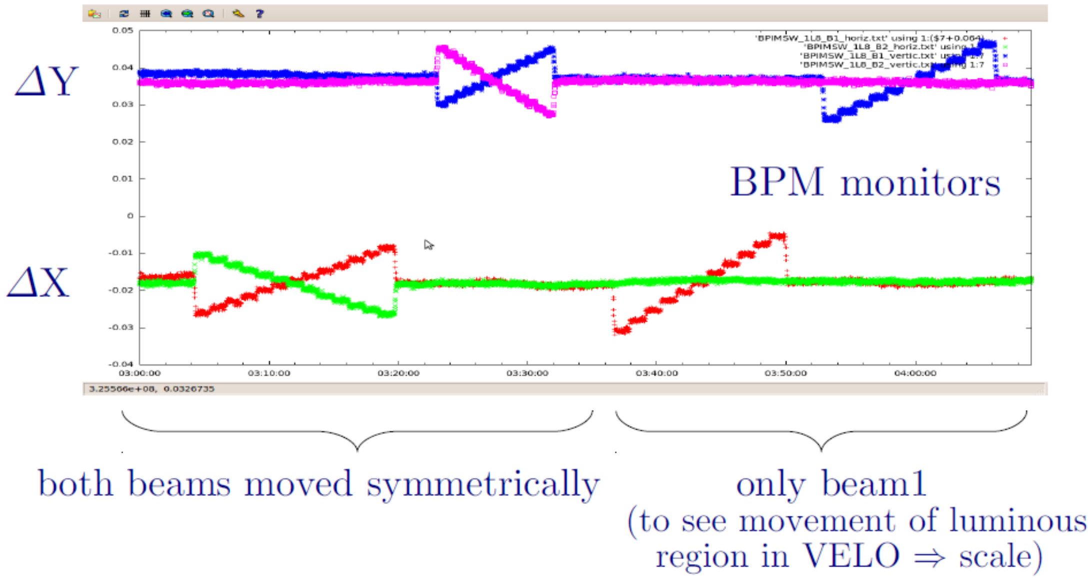
- Single bunch analysis is important
- bunch-bunch luminous region can be used to constrain the single beam distributions:
  - combine data with the beam-gas data
  - much more stats in the bunch-bunch data

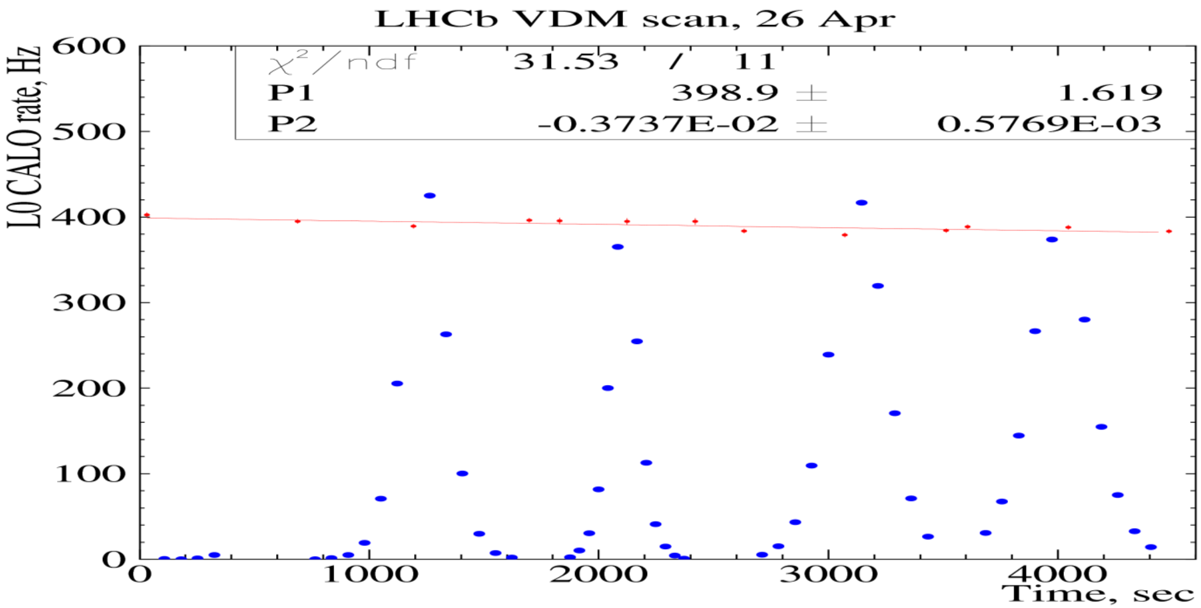
8 distinct colliding pairs



colliding bunch pair number

LHCb scans (fill 1059)

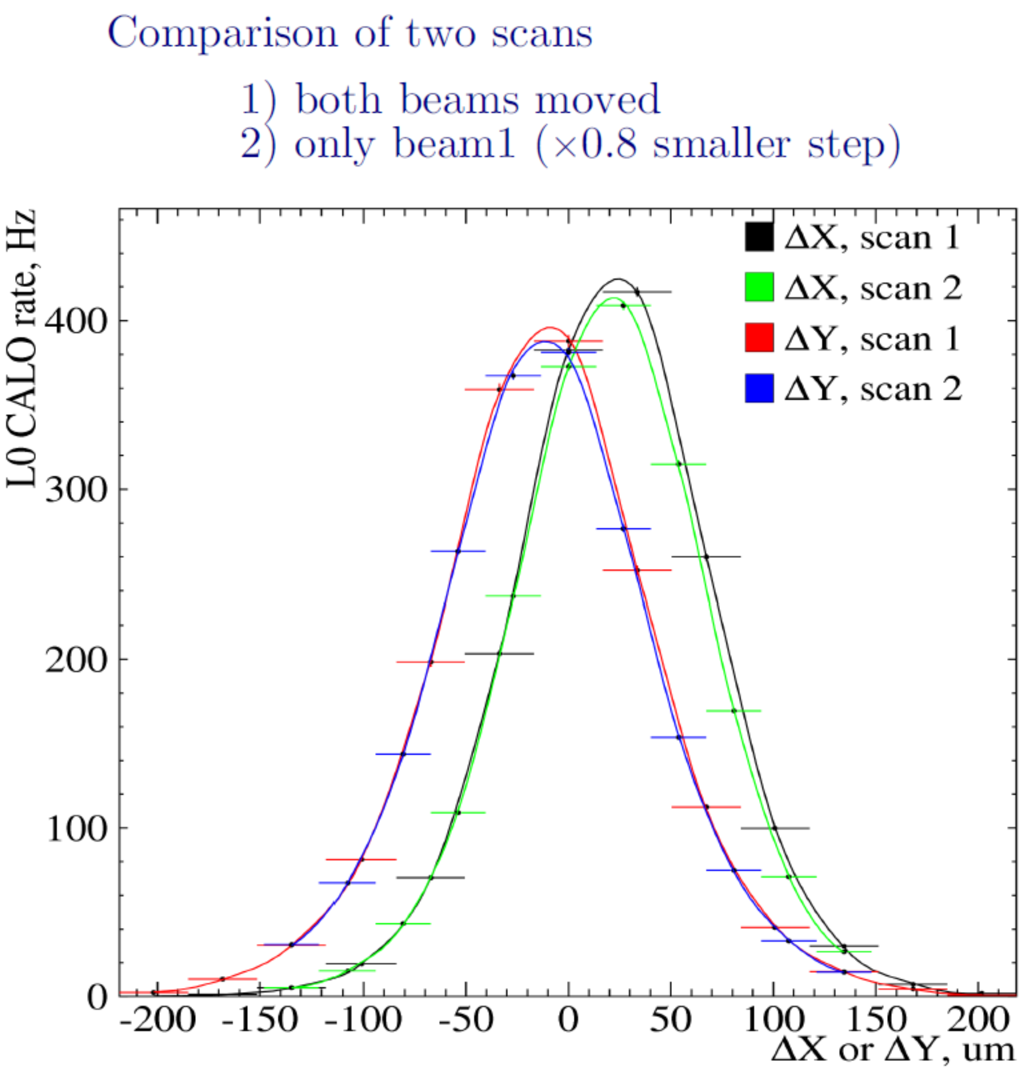




- 4 scans
- L0CaloRate corrected for small pile-up effect

- Checked rate at "working point" $R(\Delta_{x0}, \Delta_{y0})$, red points, throughout the scans (~1h)
  - correct for small decay (~30 h life time)

LHCb comparing two scans

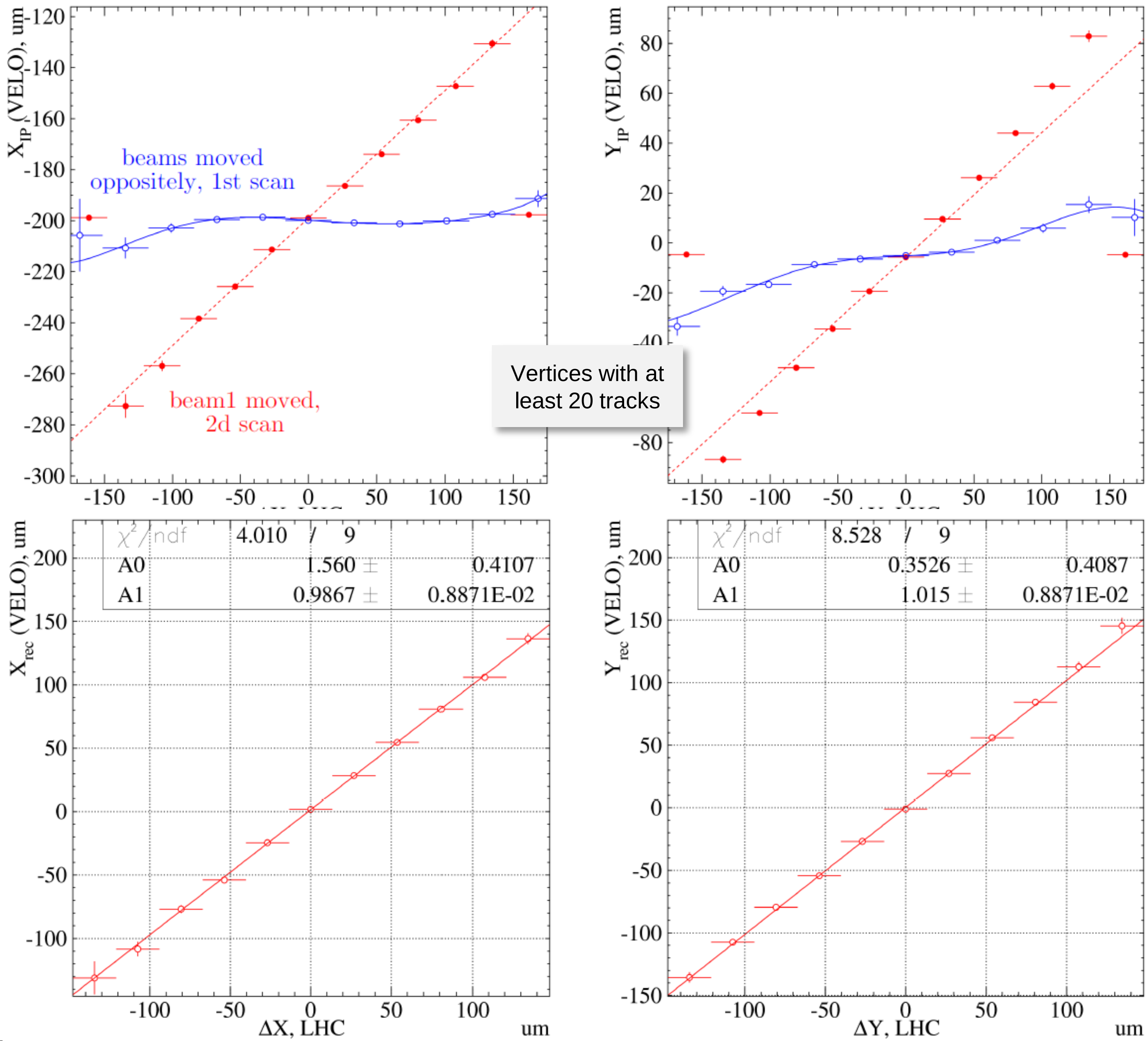


LHCb length scale calibration

- Comparing position of luminous region from the two scans (both beams moved vs single beam moved)

  => allows determining the length scale

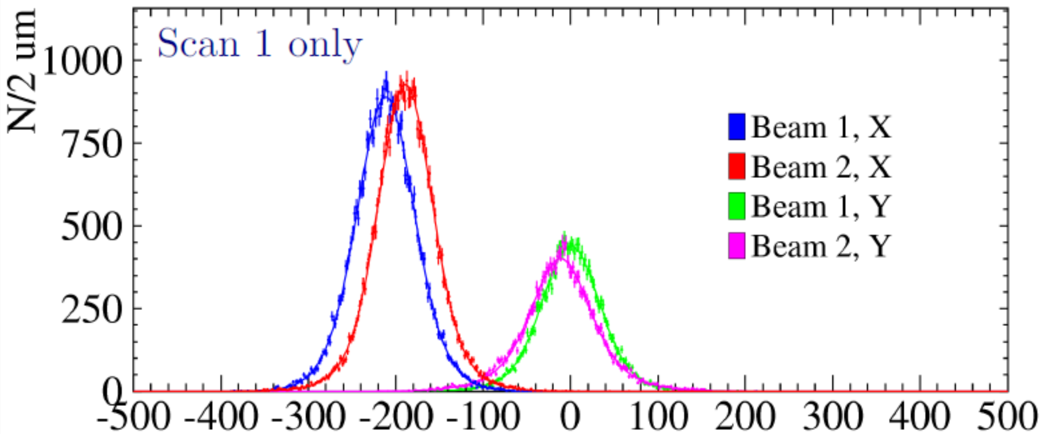
  (removes the beam1/beam2 size differences)



LHCb: deconvoluting two beams

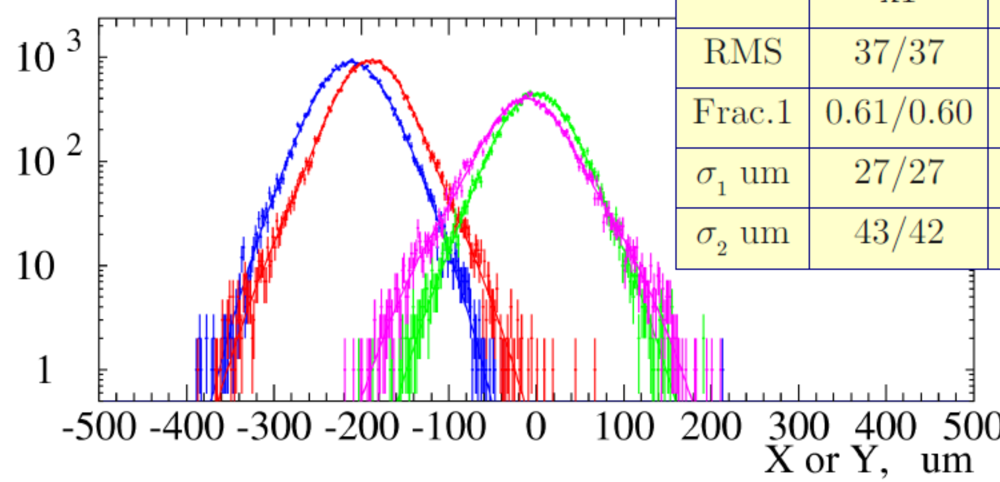
- Using the full vtx reconstruction, the scans can also be used to deconvolute the individual bunch shapes (beam1 and beam2)

V. Balagura



Profiles visible from moving frame

(relevant for luminosity)



Scan 1 / Scan 2

	x1	x2	y1	y2
RMS	37/37	37/36	38/37	45/43
Frac.1	0.61/0.60	0.73/0.70	0.68/0.69	0.57/0.42
σ_1 um	27/27	26/25	26/26	25/22
σ_2 um	43/42	50/46	46/45	55/48

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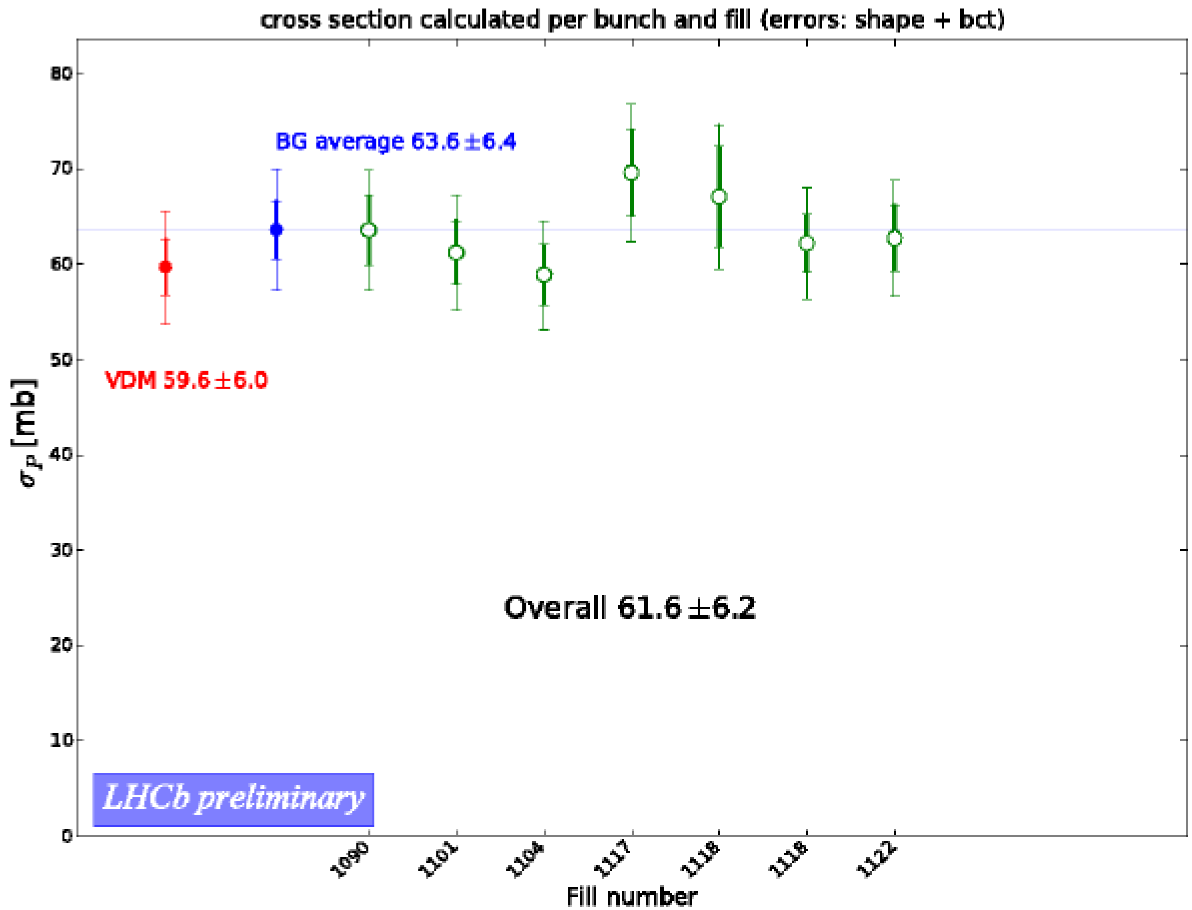
LHCb beam-gas imaging results at 3.5 TeV PRELIMINARY

- Agreement between two methods (vdm and beam-gas)
- Thin error bars include beam current normalisation uncertainty
- Thick error bars: without beam current normalisation uncertainty

Putting it together in a plot

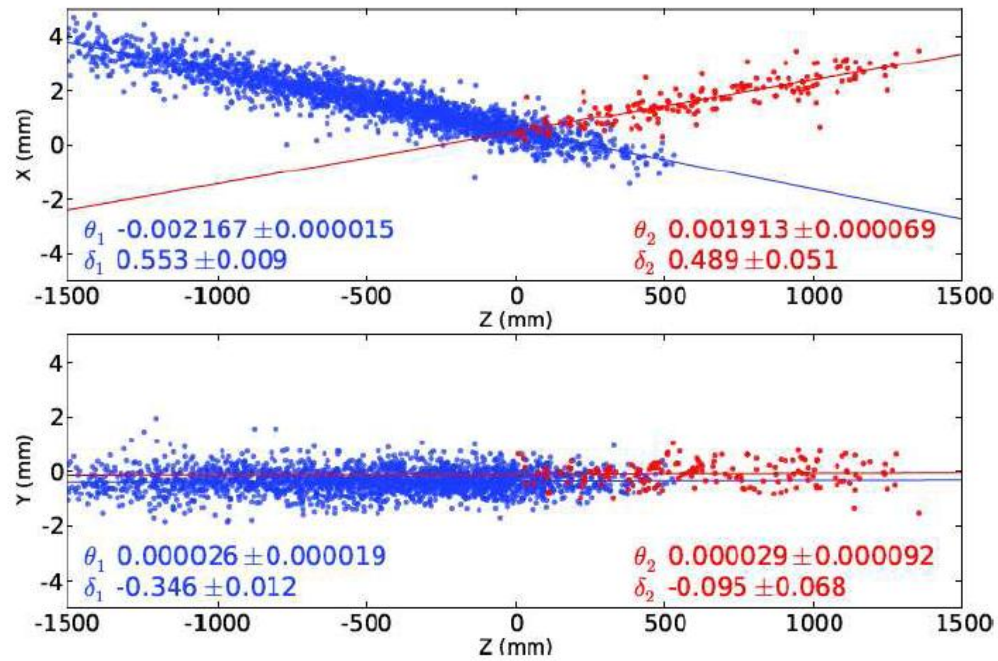
Effective cross-section results (assuming ±8% for the I^2 error)

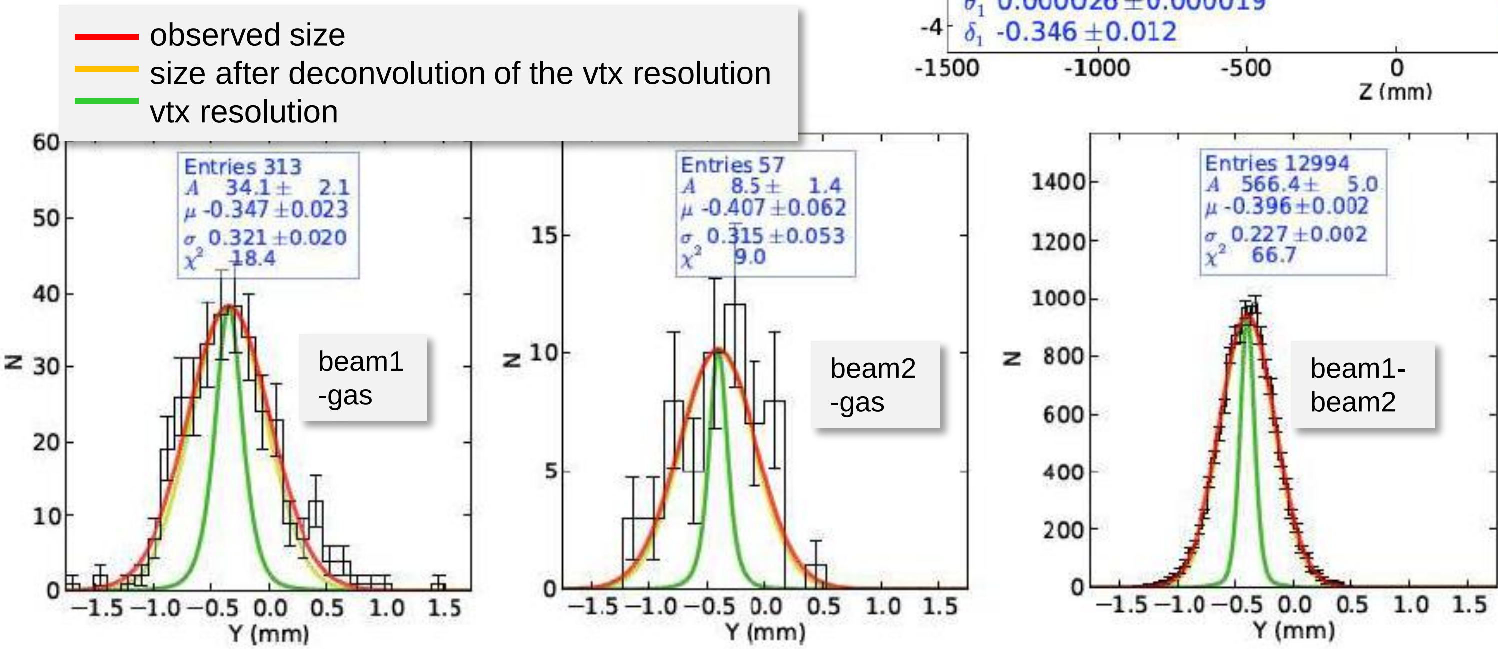
σ_P = cross section of event with 2 or more RZVelo tracks



LHCb beam-gas imaging at 450 GeV

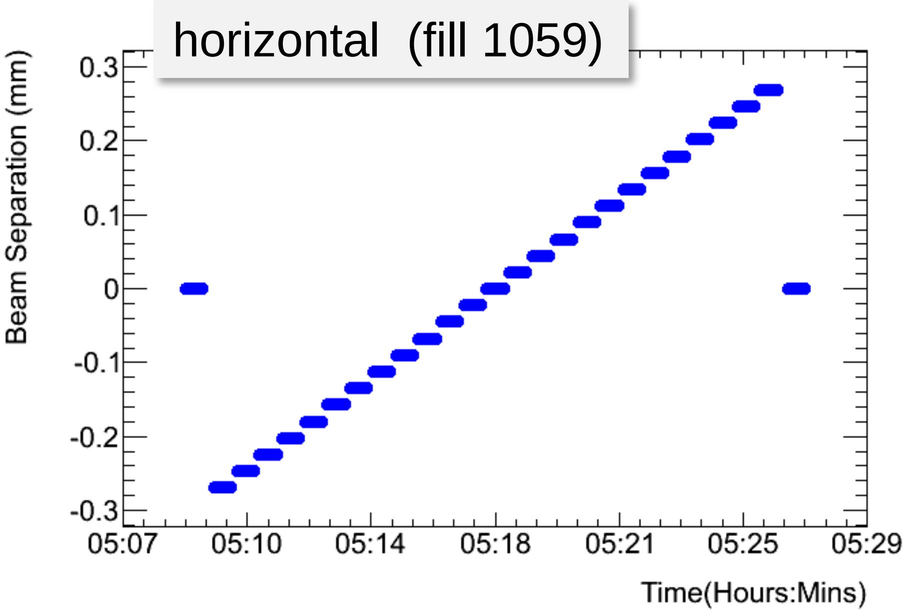
- VELO only half closed around the beams!
- 450 GeV, 10m optics at IP8, bunch intensity ~ 1…2e10 p/bch
- L ~ 1…5 e26 Hz/cm^2 per pair
- up to 8 colliding pairs + 4 not colliding per beam

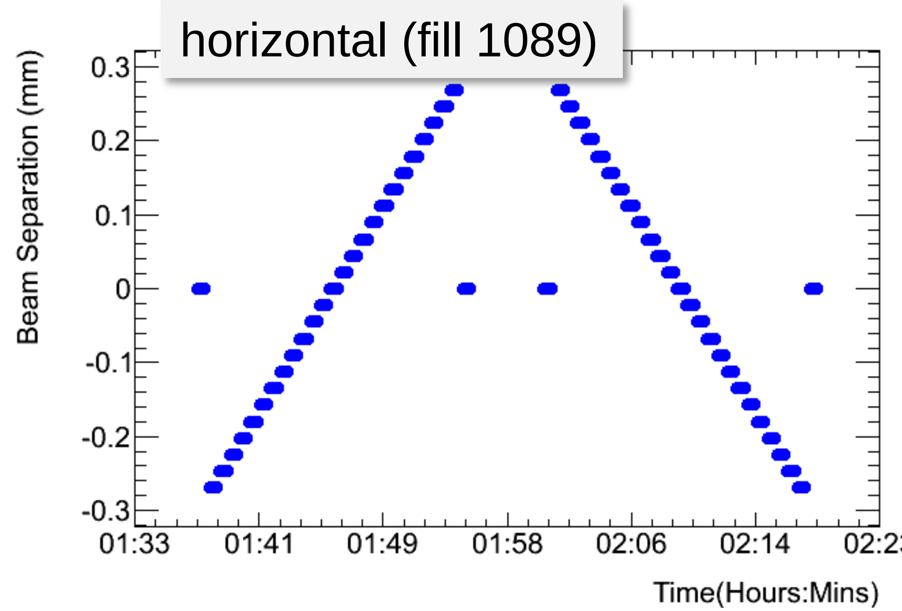


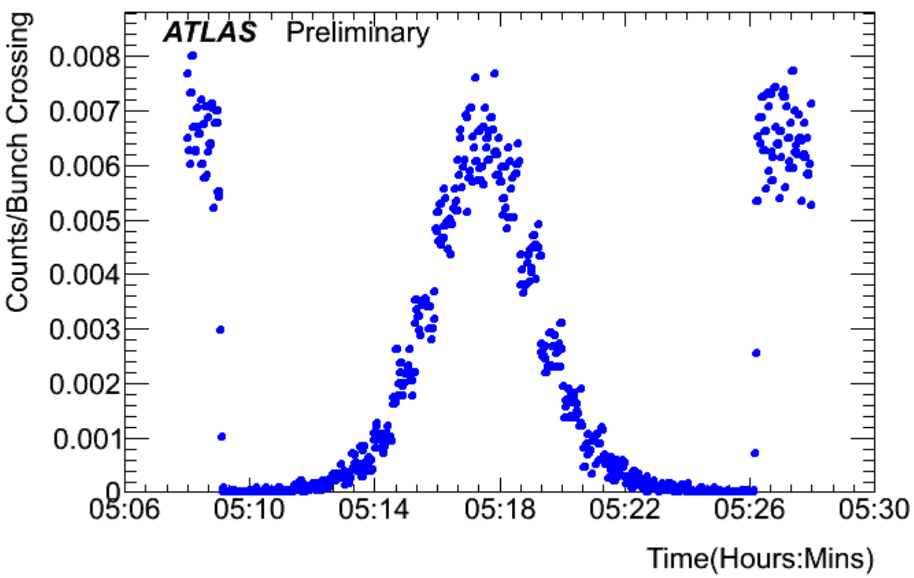


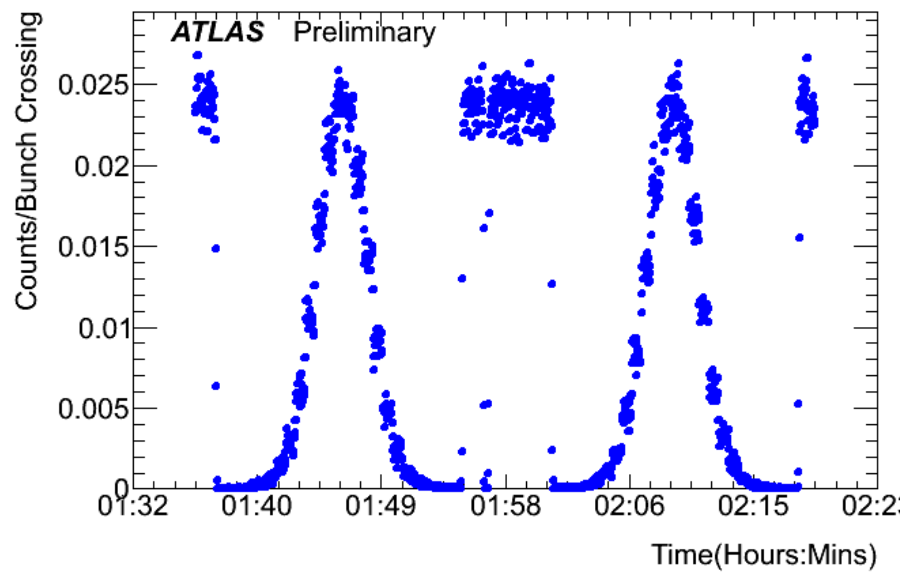
Absolute normalisation at 15% obtained (uncertainty dominated by bunch current normalisation)

ATLAS scans (fills 1059 and 1089) see Ref. [7]

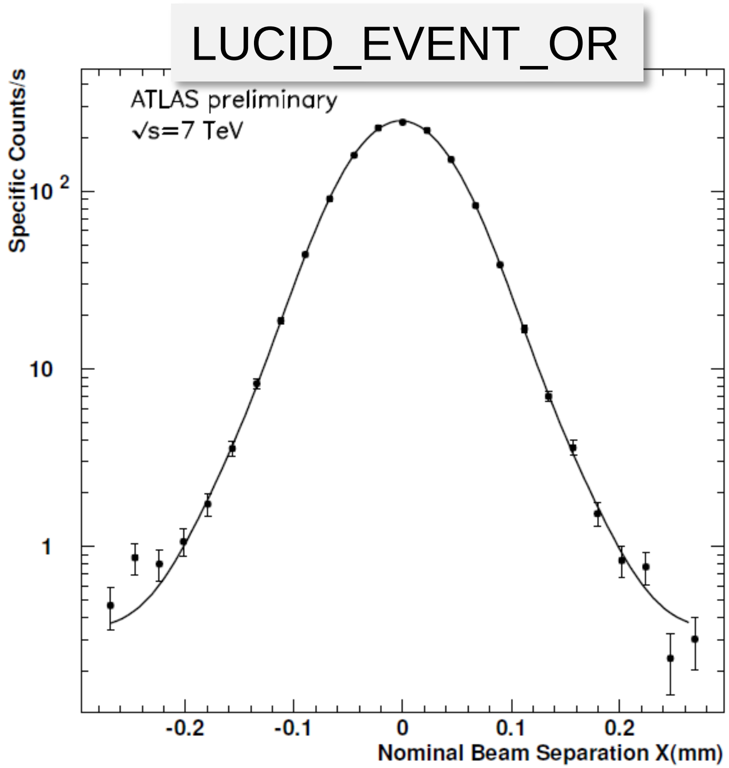


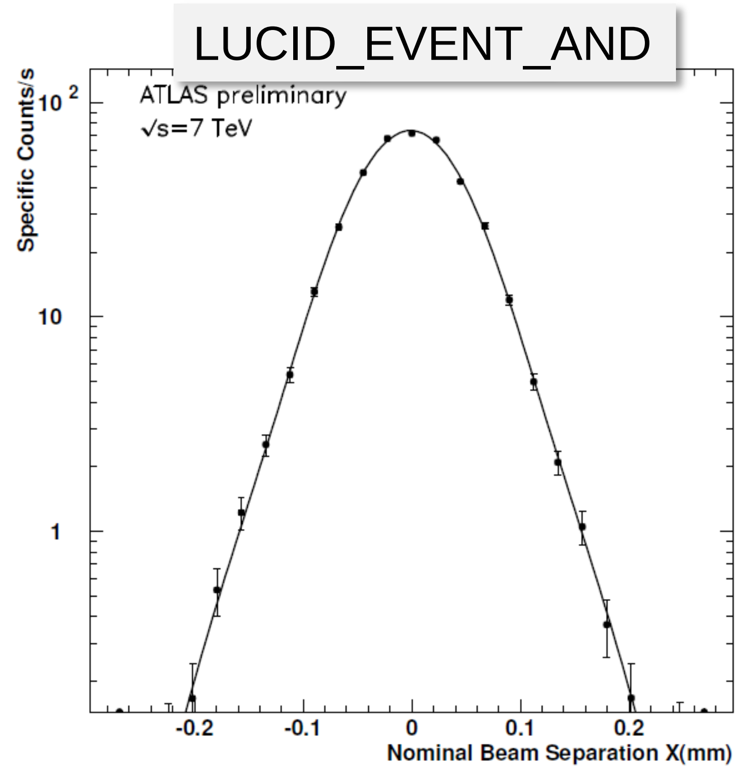






ATLAS scan fits





- Fit with double Gaussian (common mean) and constant bkg
- Similar for Y

$$R_x(x) = \frac{R_x(0)}{\sqrt{2\pi}} \left[\frac{f_a e^{-(x-x_0)^2/2\sigma_a^2}}{\sigma_a} + \frac{(1-f_a) e^{-(x-x_0)^2/2\sigma_b^2}}{\sigma_b} \right]$$

$$\frac{1}{\Sigma_x} = \left[\frac{f_a}{\sigma_a} + \frac{1-f_a}{\sigma_b} \right] \quad \rightarrow \quad \mathscr{L} = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y}$$

ATLAS results PRELIMINARY

Algorithm	σ_{vis}^{meas} (mb)	σ_{vis}^{PYTHIA} (mb)	$\frac{\sigma_{vis}^{PYTHIA}}{\sigma_{vis}^{meas}}$	σ_{vis}^{PHOJET} (mb)	$\frac{\sigma_{vis}^{PHOJET}}{\sigma_{vis}^{meas}}$
LUCID_Event_AND	$12.40 \pm 0.06 \pm 1.36$	15.7	1.27	16.8	1.35
LUCID_Event_OR	$40.18 \pm 0.12 \pm 4.42$	46.7	1.16	53.4	1.32
L1_MBTS_1_1_paired	$51.87 \pm 0.21 \pm 5.70$	58.4	1.13	68.7	1.32
L1_MBTS_1_paired	$58.65 \pm 0.23 \pm 6.45$	66.6	1.14	73.7	1.26
MBTS_1_timing	$50.4 \pm 0.2 \pm 5.7$	57.6	1.14	67.8	1.35
Primary Vertex Counting	$53.6 \pm 0.2 \pm 5.9$	57.9	1.08	70.0	1.31

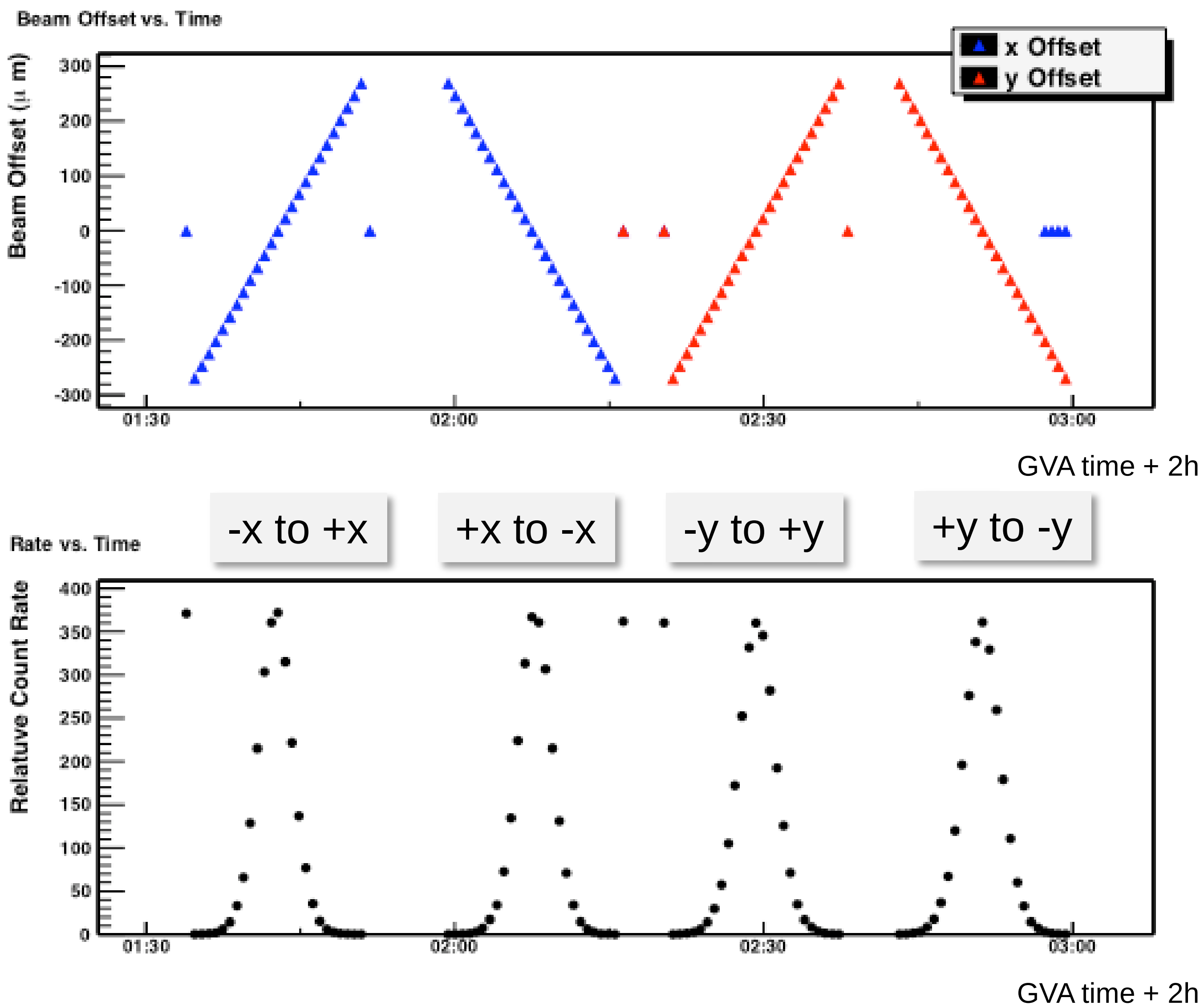
Scan Number	σ_{vis} mb	$\mathscr{L}_{spec}$ (10^{29} cm^{-2}s^{-1})
1	12.15 ± 0.14	6.80 ± 0.08
2	12.55 ± 0.10	4.85 ± 0.03
3	12.73 ± 0.10	4.88 ± 0.09
1	39.63 ± 0.32	6.85 ± 0.06
2	40.70 ± 0.13	4.88 ± 0.01
3	40.77 ± 0.14	4.92 ± 0.02
1	51.14 ± 0.39	6.78 ± 0.05
2	52.59 ± 0.16	4.87 ± 0.01
3	52.64 ± 0.16	4.90 ± 0.02
1	57.83 ± 0.43	6.79 ± 0.05
2	59.47 ± 0.18	4.89 ± 0.01
3	59.43 ± 0.25	4.90 ± 0.02
1	49.28 ± 0.31	6.76 ± 0.05
2	51.64 ± 0.23	4.87 ± 0.03
3	51.29 ± 0.24	4.93 ± 0.03
1	53.48 ± 0.29	6.73 ± 0.05
2	53.64 ± 0.22	4.89 ± 0.03
3	53.78 ± 0.23	4.89 ± 0.02

- Using six different count rate methods

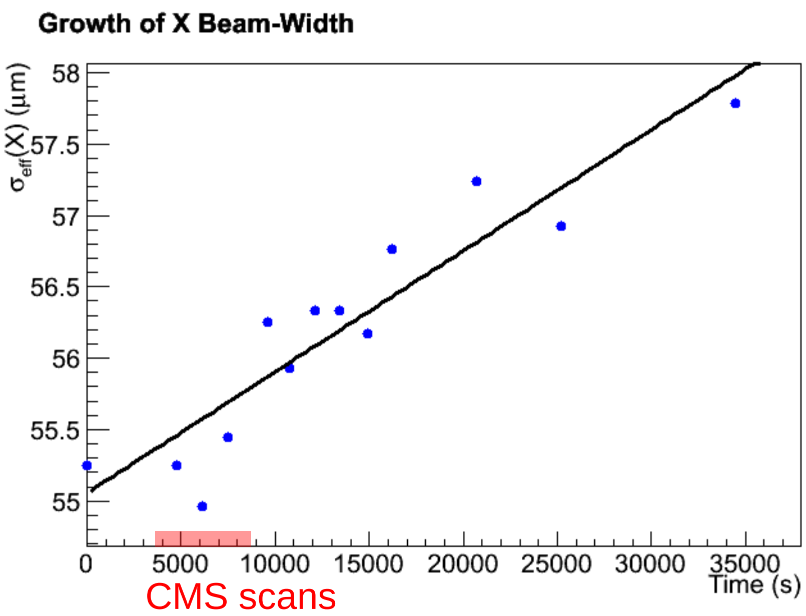
Source	Uncertainty on σ_{vis} (%)
Beam Intensities	10
Length Scale Calibration	2
Imperfect Beam Centering	2
Transverse Emittance Growth & Other Sources of Non-Reproducibility	3
μ Dependence	2
Total	11

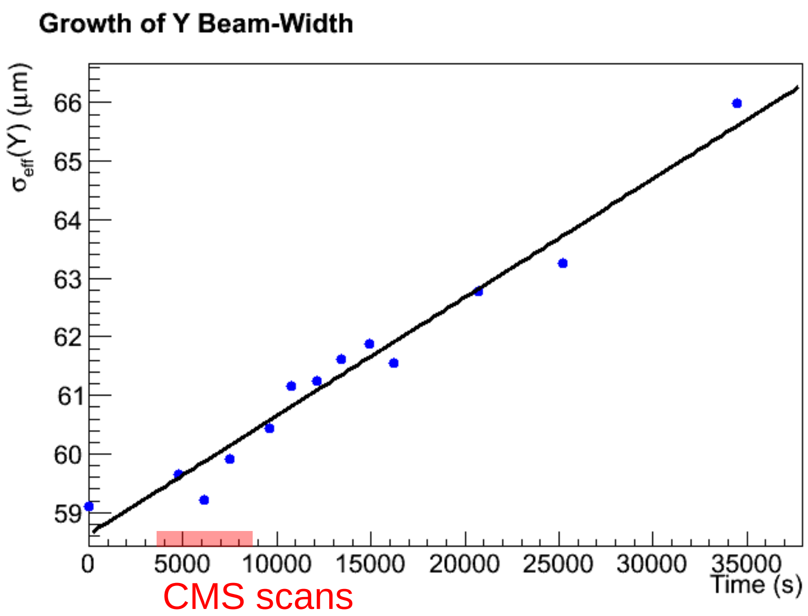
NB: 4.5% uncertainty if knew beam current perfectly

CMS scans (fill 1089) see Ref. [8]



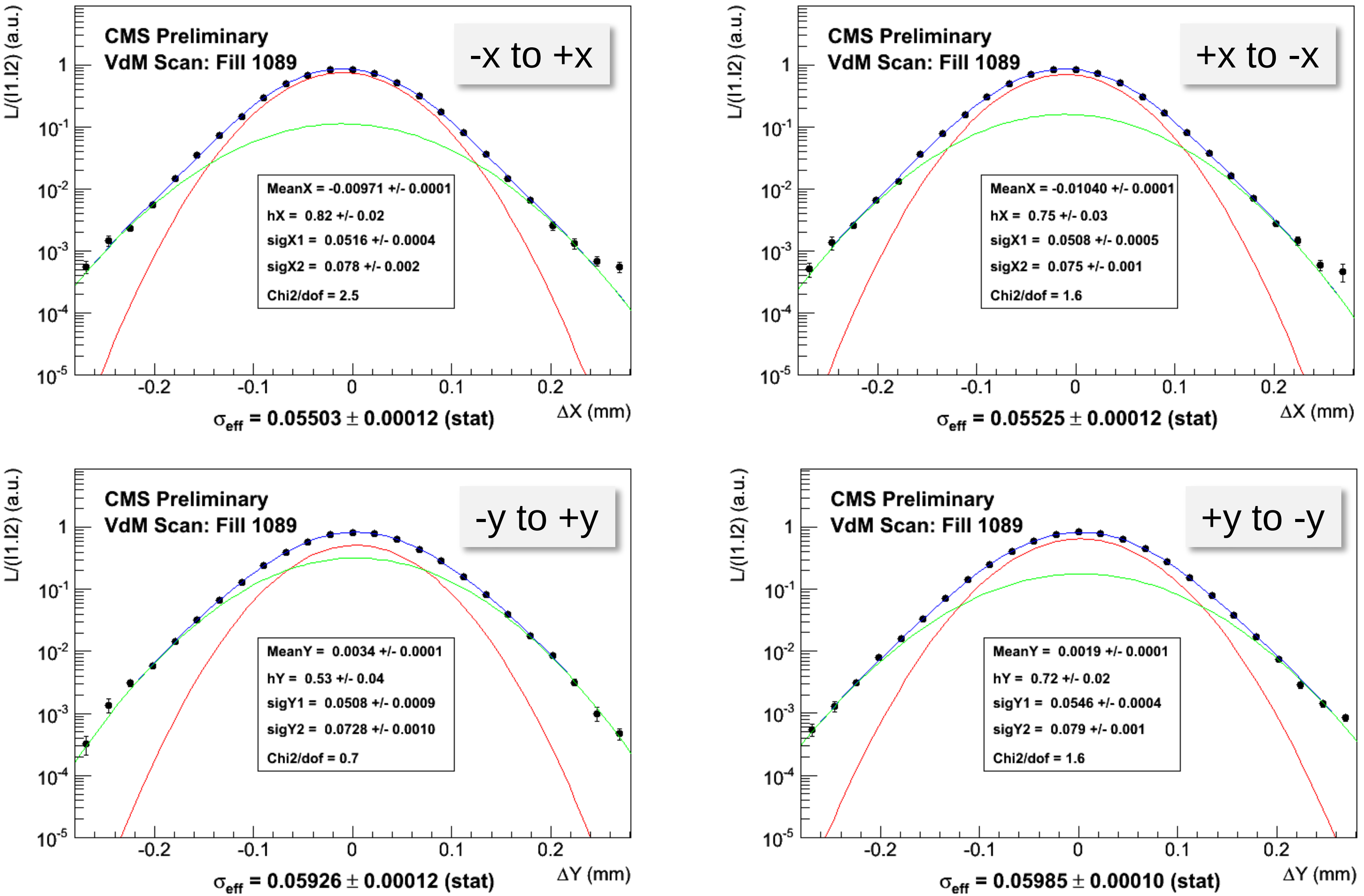
Observed beam blow up during scans





- Beam width growth as calculated from the measured emittances during fill 1089 with LHC wire scanners. The slopes from the lines can be used to correctly extrapolate the measured widths to their corresponding values at the zero points of the scan.
- Note the zero-suppressed vertical scale

CMS scan fits



CMS results PRELIMINARY

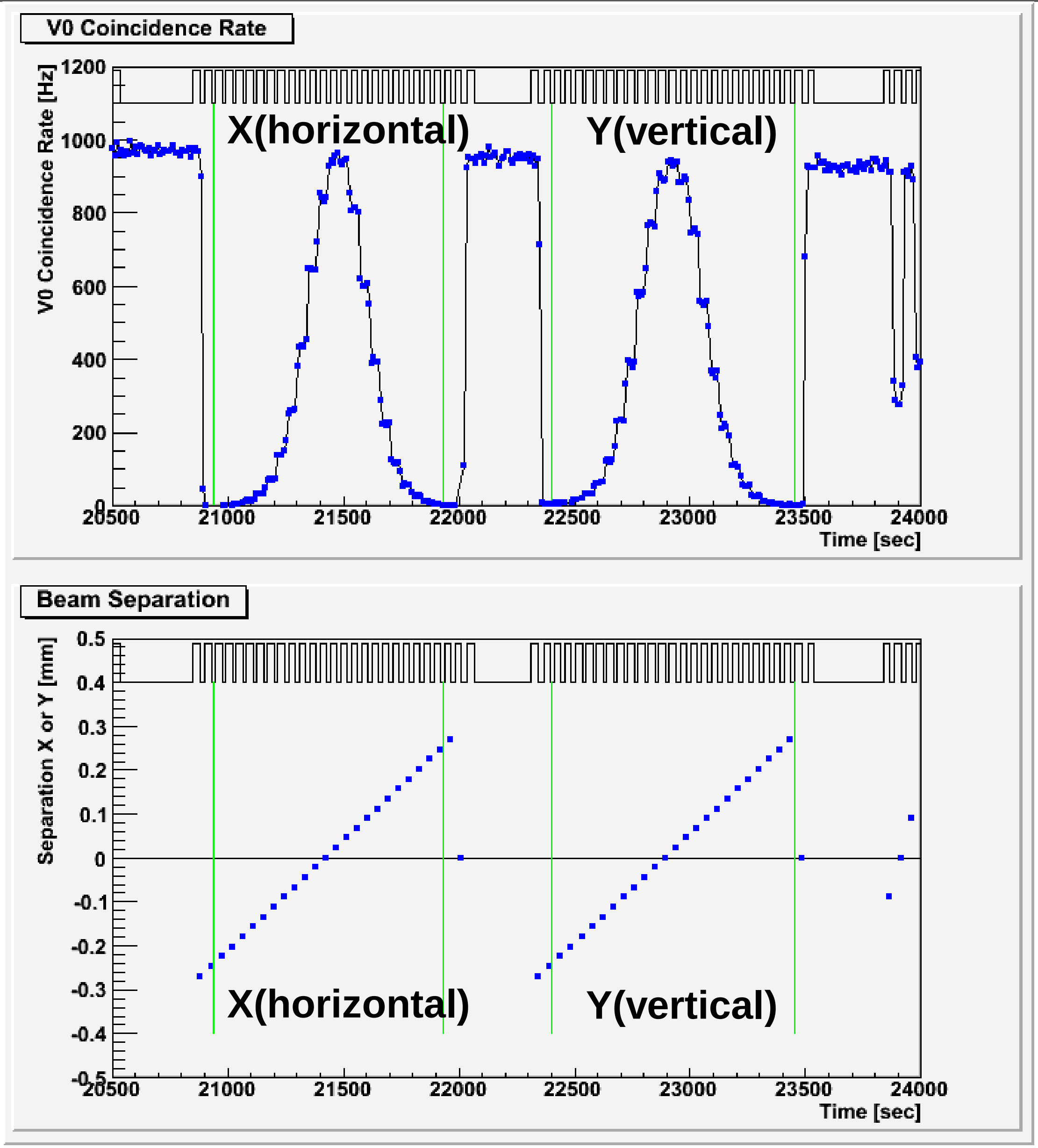
$$R_{\mathrm{Scan/MC}} = 1.007 \pm 0.003(\mathrm{stat}) \pm 0.110(\mathrm{syst}).$$

Method	Efficiency	Visible Cross-section
Total Cross-section	=100%	71.3 mb
HF Coincidence	63.4%	45.2 mb
Vertex Counting	73.6%	52.4 mb

Error	Value (%)
Beam Background	0.1
Fit Systematics	1.0
Beam Shape	3.0
Scale Calibration	2.0
Zero Point Uncertainty	2.0
Beam Current Measurement	10.0
Total	11.0

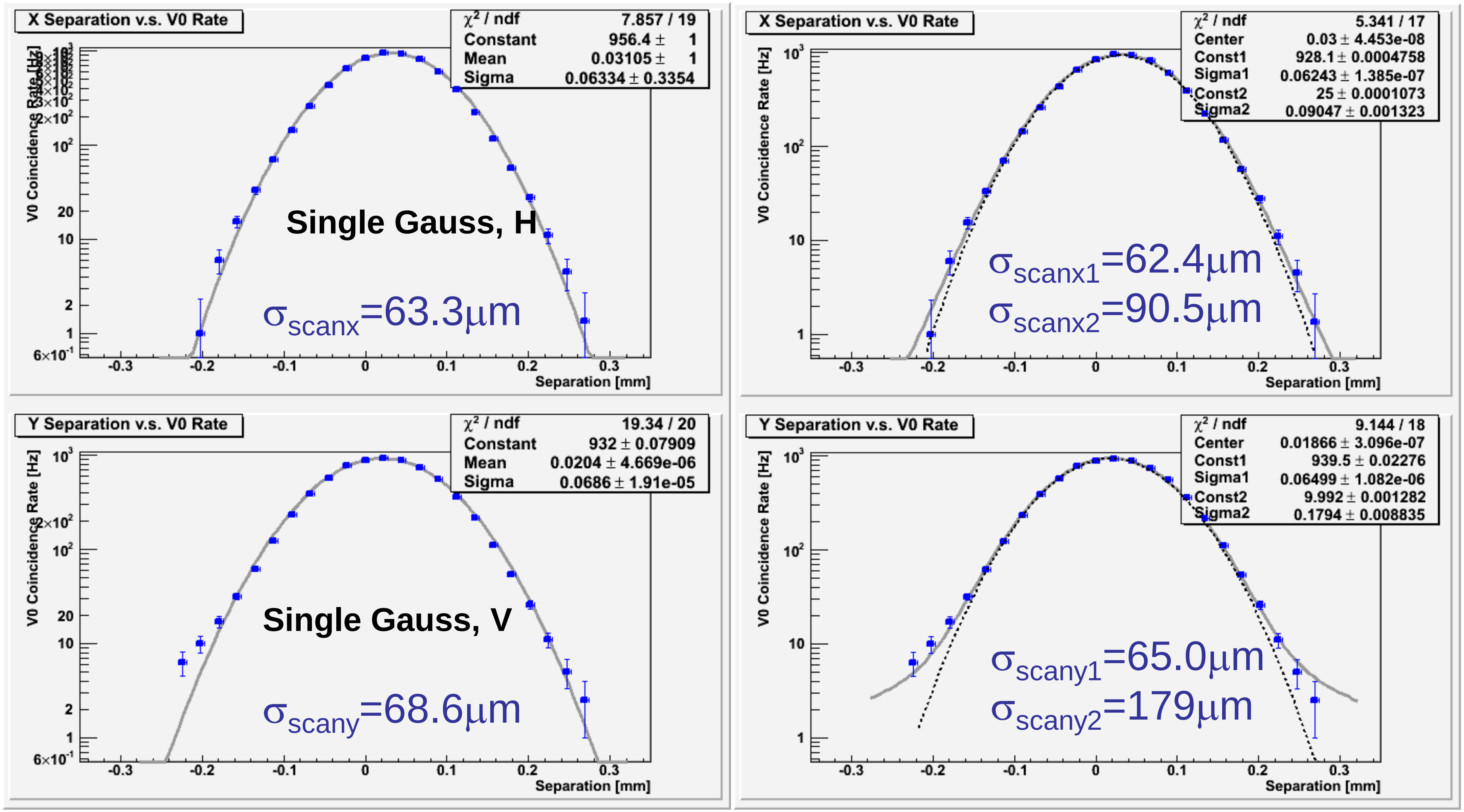
- NB: if perfect current measurement, uncertainty: ~4% !

ALICE scans (fill 1090)



- one horizontal scan
- one vertical scan

ALICE scan fits



- Dashed line in double Gauss shows only primary Gaussian
- Single Gauss does not fit tail, however double Gauss as well (asymmetric tail for Y scan)

ALICE results PRELIMINARY

- Integrals
  - $S_x = 152.17 \pm 0.67$(stat.) Hz mm $S_y = 162.20 \pm 0.69$(stat.) Hz mm
- Zero-separation rate with pile-up corrections applied (<4% correction)
  - $R_{x\text{-scan}}(0,0) = 986.72 \pm 10.93$(stat.) Hz $R_{y\text{-scan}}(0,0) = 975.08 \pm 10.87$(stat.) Hz
- Luminosity and cross section
  - **$L = (1.576 \pm 0.027^{stat}) \times 10^{32}\ s^{-1}m^{-2}$**
  - **$\sigma_{v0} = 62.2 \pm 0.1$(stat) mb**   used average R(0,0) = 980.90 Hz

    (cross section visible to V0, where V0 = fwd & bwd scintillator counters, both sides of IP, in coinc)
- Uncertainties
  1. Bunch intensity error dominated by DCCT baseline shifts and scale, 5% per beam
  2. V0 top rate discrepancy for X and Y scan … 2%
  3. Separation has 2 μm error (known from bump calibration) … 4%
- Overall systematic uncertainties yet to be finalized
- Single and double Gaussian fit results show that the result will stay within systematic uncertainties
- Numerical sum method does not have influence of fitting, and also independent from Gaussian approximations:
  → Use this value as central value

ALICE σ_{v0} = 62.2 mb ± 0.2 % (stat.) ± 8%(syst.) (preliminary)

Bunch current measurement see Ref. [4,5,6]

- Both *Van der Meer* and *beam-gas imaging* methods require an absolute measurement of the bunch charge in order to produce an absolute luminosity measurement
- LHC: each beam current is measured by two types of devices:

  DCCT (see Ref. [4,5])

  Measures the total current in the machine (also satellite bunches and uncaptured beam).

  Fast BCT (see Ref. [4,6])

  Measures total charge stored in a nominal 25ns bunch slot.

If no satellites and no uncaptured beam, then
sum of Fast BCT bunch currents = total DCCT beam current
(true to <2% level for the measurements presented here)

Bunch current uncertainty

- DCCT and Fast BCT still under commissioning
- Systematics due to:
  - DCCT scale normalisation
  - DCCT random noise (small…)
  - DCCT offset variations (drifts)
  - Fast BCT sensitivity to clock phase
  - Fast BCT numerical algorithms, "spillover", …
- Currently, conservative estimate => ~10% error into the luminosity
- Largely dominating the luminosity uncertainty
- A more precise quantitative characterization of these errors and of their degree of correlation is still in progress
- May improve in the near future (both more analysis and more measurements)

Conclusions / summary

- First absolute normalisation of luminosity and cross section were performed at the LHC (450 GeV / beam and 3.5 TeV / beam)

- Two methods were used:
  - van der Meer method
  - beam-gas imaging method

- Results accuracy dominated by beam current normalisation uncertainty (~10%, being worked on)

- Potentially, could hope to aim for total uncertainty ~5% (future measurements)
  - will first have to work hard on the beam current normalisation
  - then on other smaller systematic uncertainties

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