Luminosity determination at the LHCb experiment

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Universität Zürich

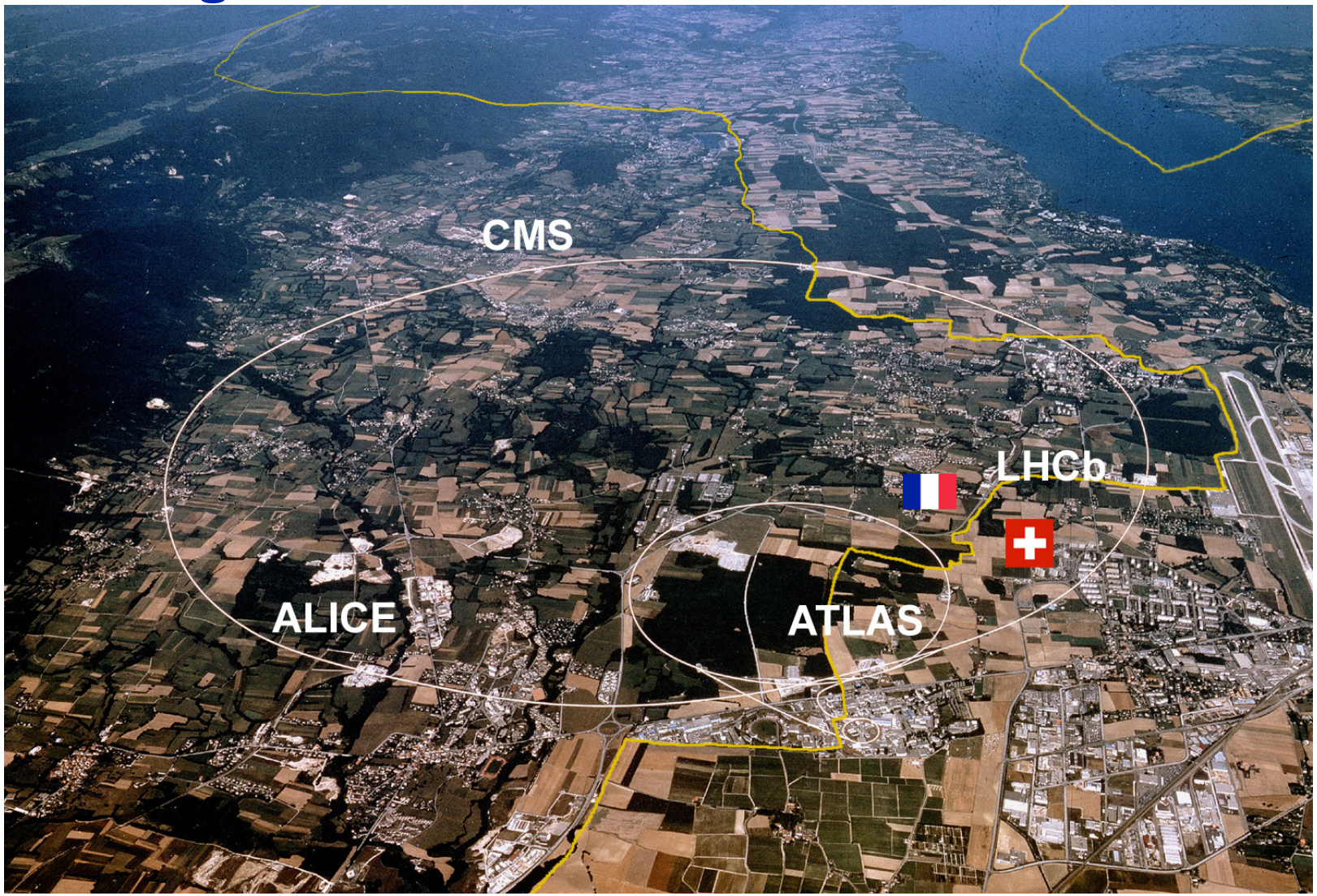
The LHCb experiment

What is luminosity?

Van-der-Meer method

Beamgas Imaging method

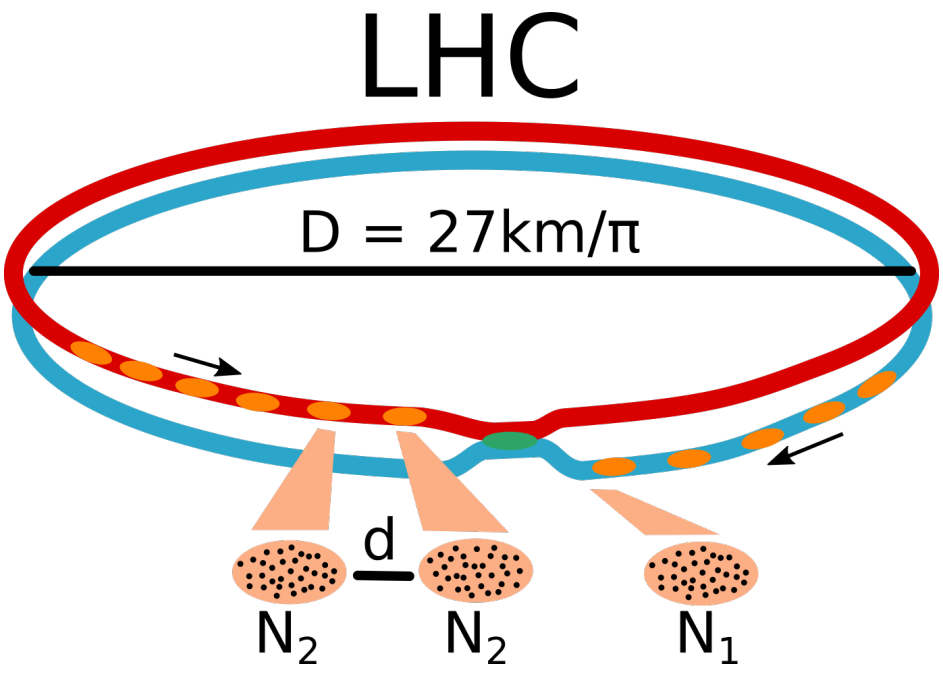
The Large Hadron Collider



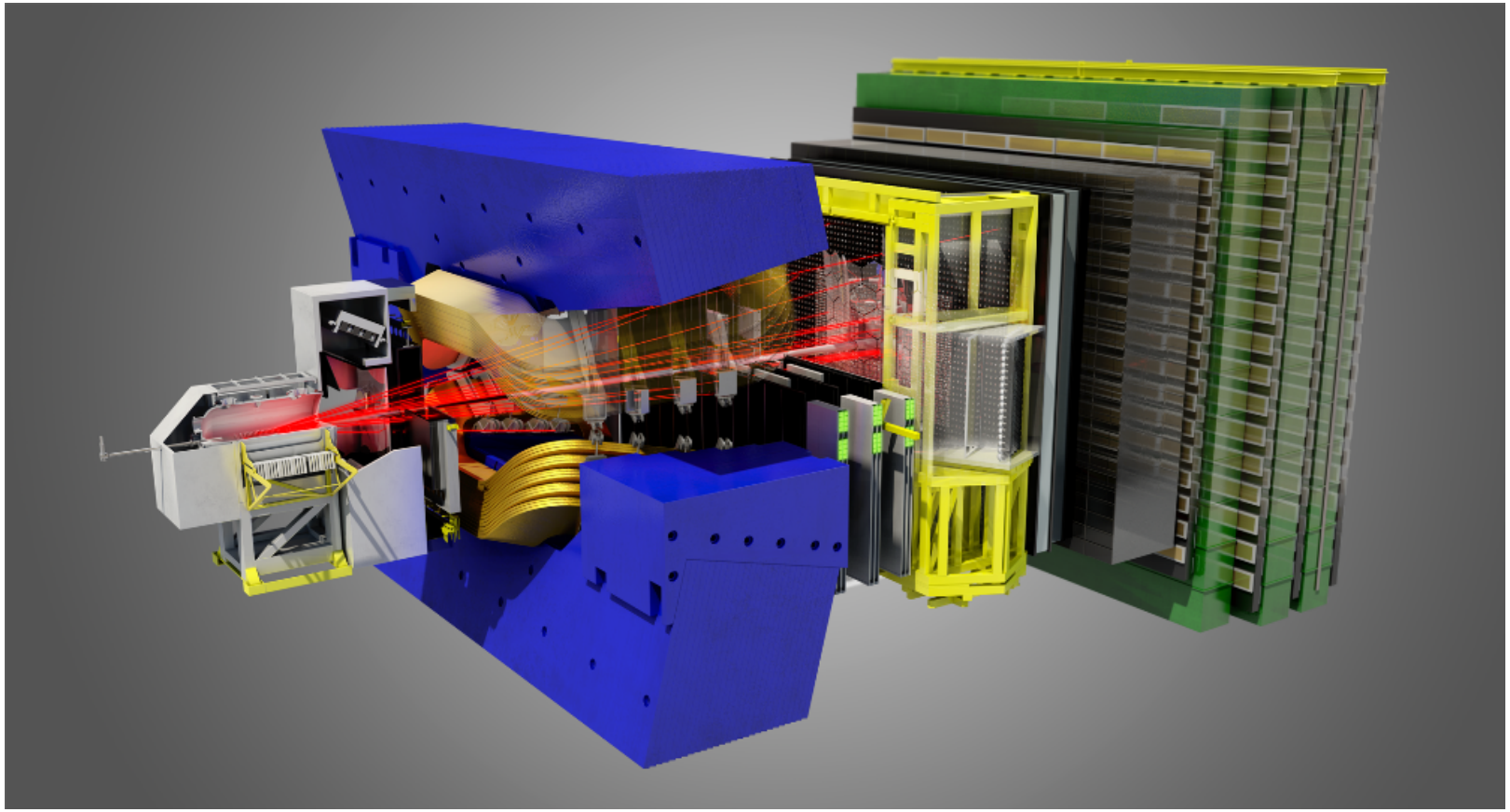
The Large Hadron Collider

A bunched collider

- No continuous beam
- up to 3000 bunches
- Separation:
  d = 7.5m (25ns)
- $N_1,\ N_2 \approx 10^{11} p$
- $f_{rev} = \frac{c}{\pi D} = 11.3\text{kHz}$

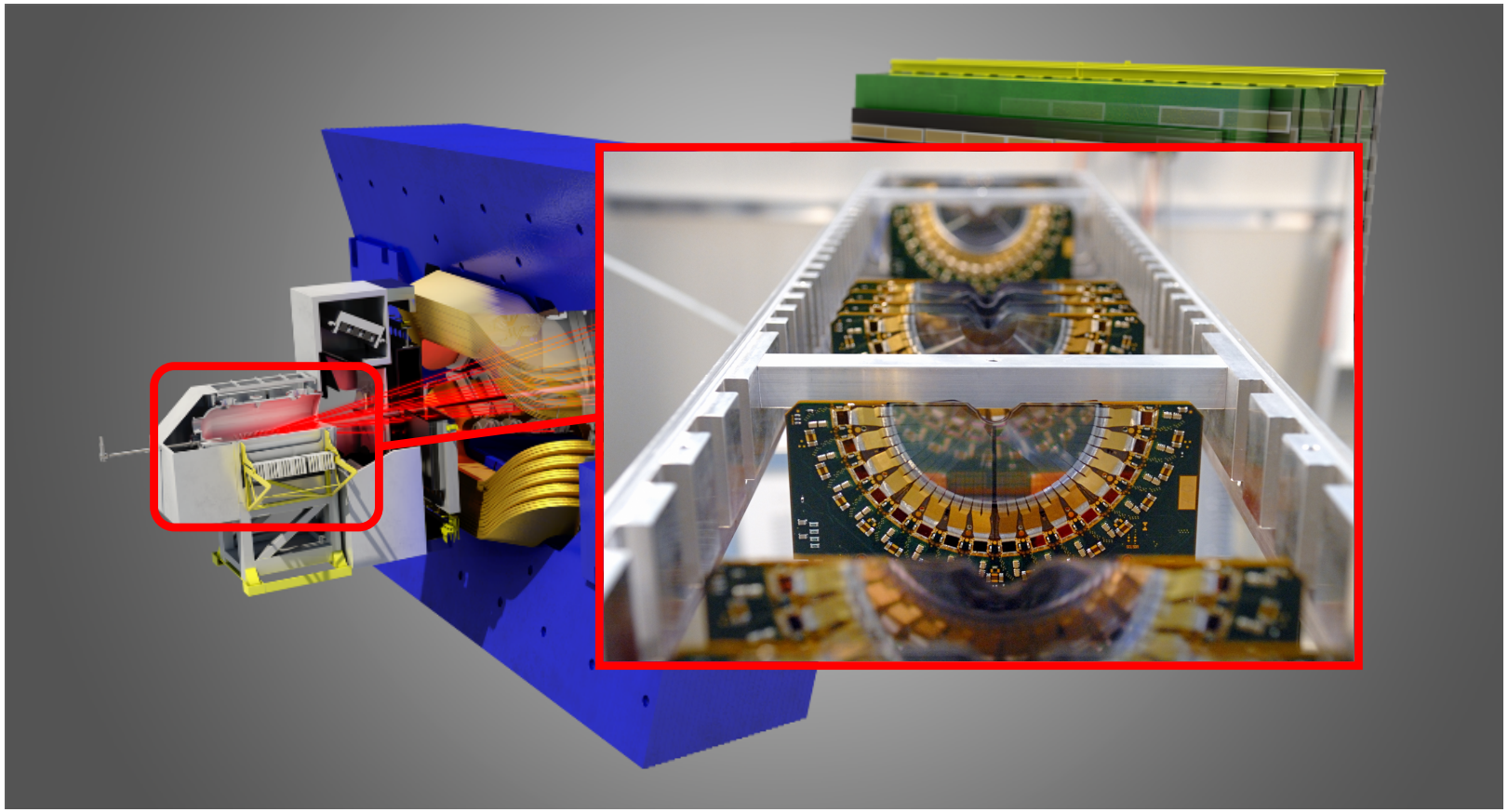


The LHCb detector



21 metres long, 10 metres high and 13 metres wide.
Situated at collision point 8 of the LHC at CERN, near Geneva.

VErtex LOcator



VELO: Vertex detector, moveable to within 7mm of the beams. Achieves a vertex resolution of $11\mu\mathrm{m}$ (in x/y) and $60\mu\mathrm{m}$ (in z).

Luminosity

Motivation:

Given an observed number of events in my detector, what is the cross-section of that process?

$$\dot{N} = \mu f_{rev} = \varepsilon \sigma \mathcal{L},$$

with the rate $\dot{N}$ of a given process, the average number of those processes per crossing μ, the revolution frequency f_{rev}, the cross-section of that process σ, the luminosity $\mathcal{L}$ and the detector efficiency ε (neglected from now on).
Integrated over time:

$$L_{int} = \int \mathcal{L} dt = \frac{1}{\sigma} N$$

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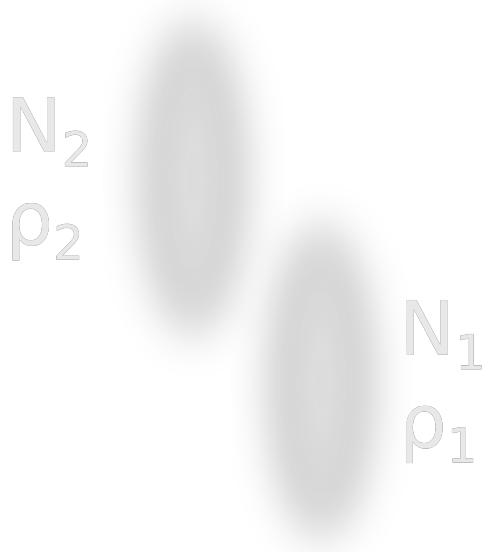
Luminosity

How many beam particles collide in a given time and space?

The unit of luminosity is $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

For two bunches of particles with N_1 and N_2 particles and density distributions ρ_1 and ρ_2, respectively:

$$\mathcal{L} = f_{rev} N_1 N_2 \int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y$$



For gaussian beams (same widths, no offset):

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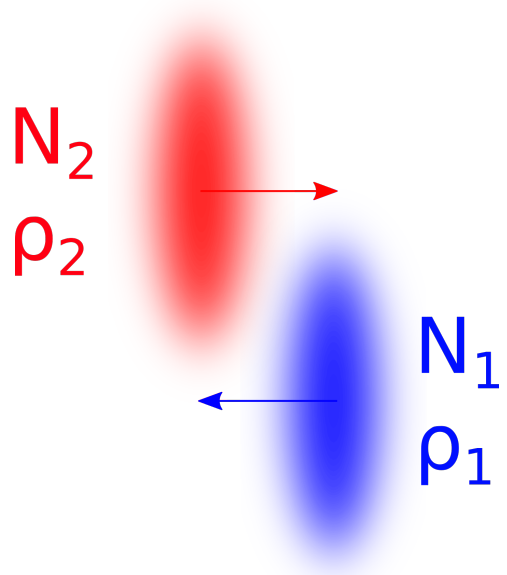

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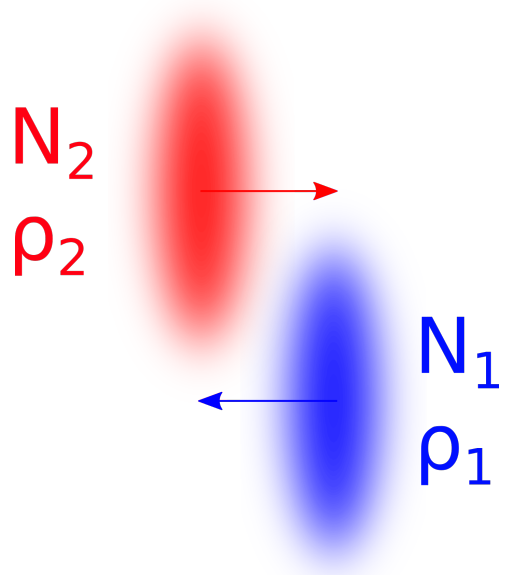

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Relative luminosity calibration

$\mathcal{L}$ is not easy to measure continuously. Therefore pick a reference process and observe the reference variable n_i in each event i:

$$L_{int} = \frac{1}{\sigma} N = \frac{1}{\sigma_{ref}} \sum_i n_i,$$

with the reference cross-section σ_{ref} to be determined.

Possible n_i include:

- Number of tracks reconstructed
- Number of vertices reconstructed
- Number of muon tracks reconstructed
- Energy deposition in the calorimeters

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Relative luminosity calibration

The aim then is to provide a a calibration for the reference process. For this we need to measure σ_{ref}.

LHCb is the only LHC experiment which can measure this in two complementary ways:

- Van-der-Meer scan
- Beamgas Imaging

Average interactions per bunch crossing

Poissonian probability to have no interaction, with an average number of interactions of μ:

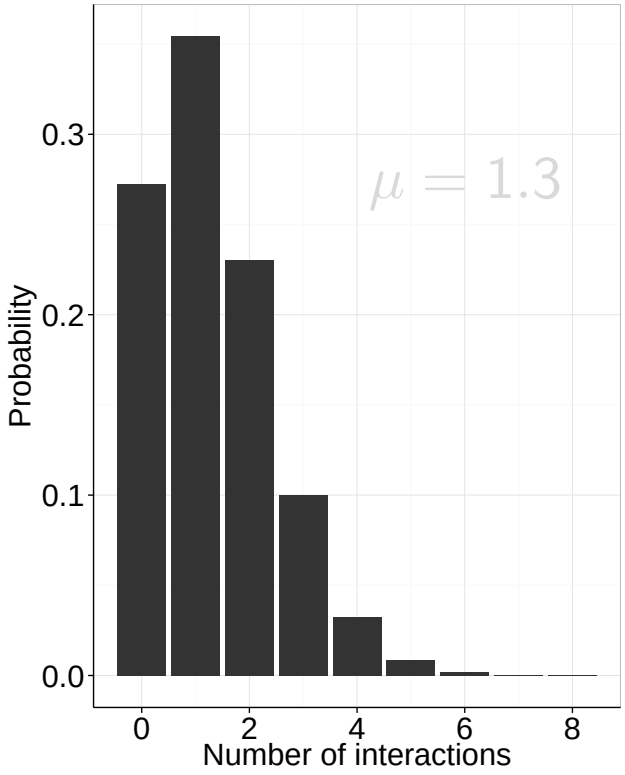
$$P_\mu(0) = \frac{\mu^0}{0!}\,\mathrm{e}^{-\mu} = \mathrm{e}^{-\mu}$$

Number of zeros out of n_{tot} events:

$$n_0 = n_{tot} \cdot P_\mu(0) = n_{tot} \cdot \mathrm{e}^{-\mu}$$

Average number of (visible) interactions:

$$\mu = -\log\left(\frac{n_0}{n_{tot}}\right)$$



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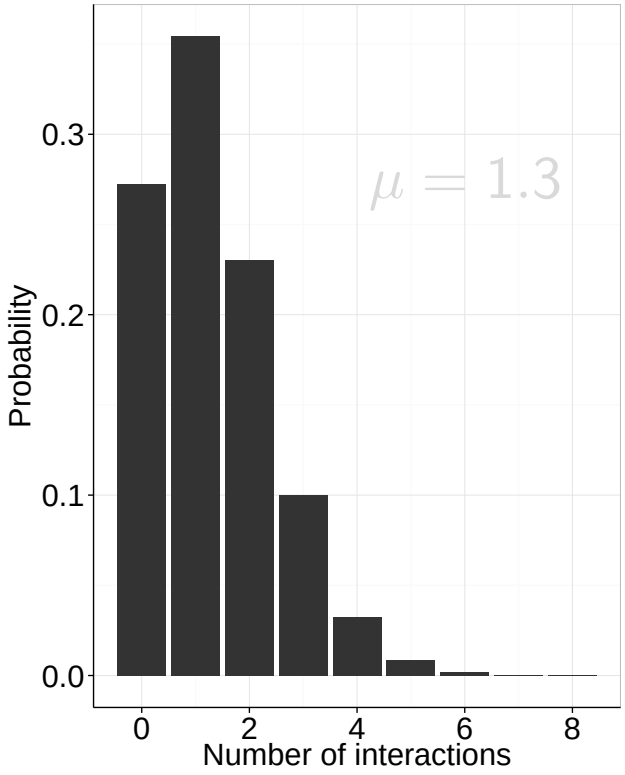

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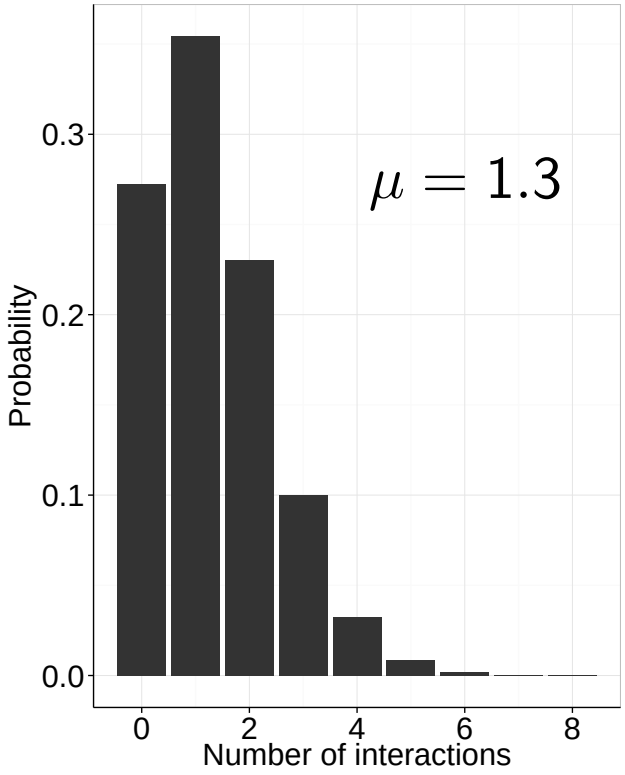

Van-der-Meer method

Average number of interactions per bunch crossing:

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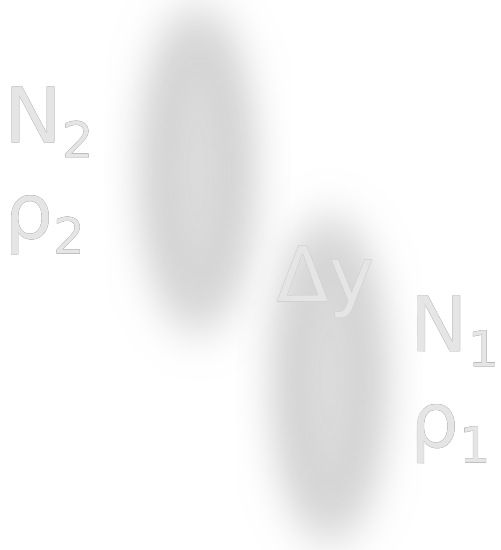
Separate the beams by Δx, Δy:

$$\mu(\Delta x, \Delta y) = \sigma_{ref} N_1 N_2 \int \rho_1(x,y)\rho_2(x+\Delta x, y+\Delta y)\,\mathrm{d}x\,\mathrm{d}y$$



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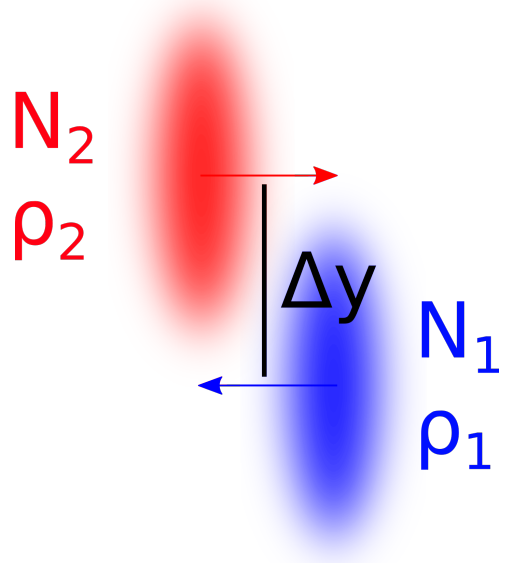

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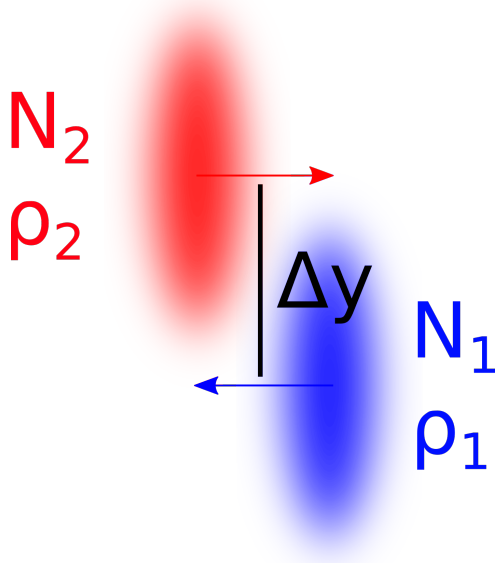
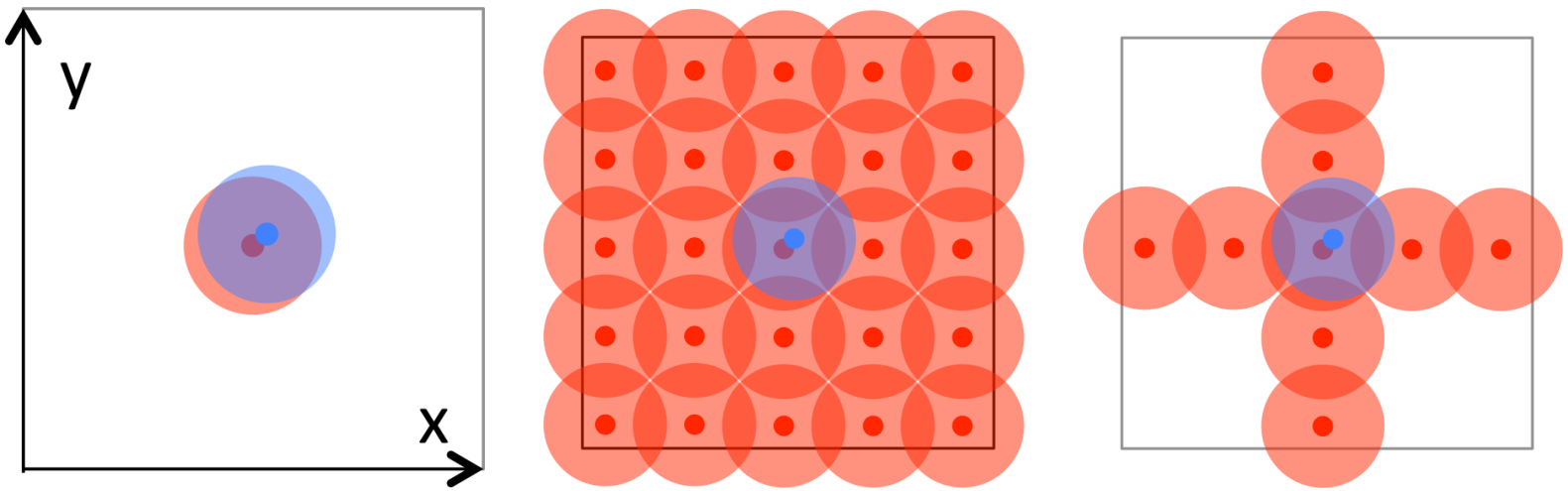


Van-der-Meer method

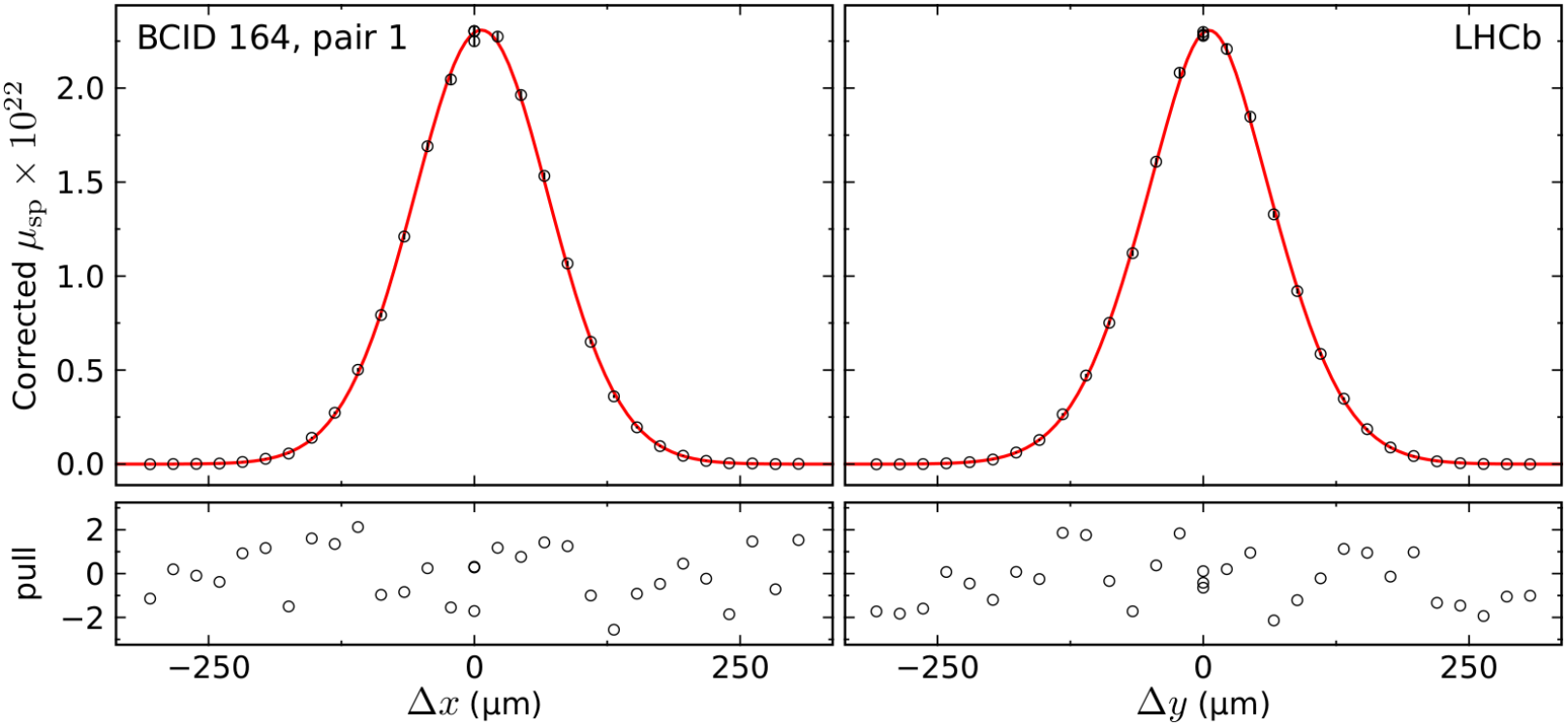
Scanning the beam profile of beam 1 with beam 2:



In reality: finer steps and move both beams.

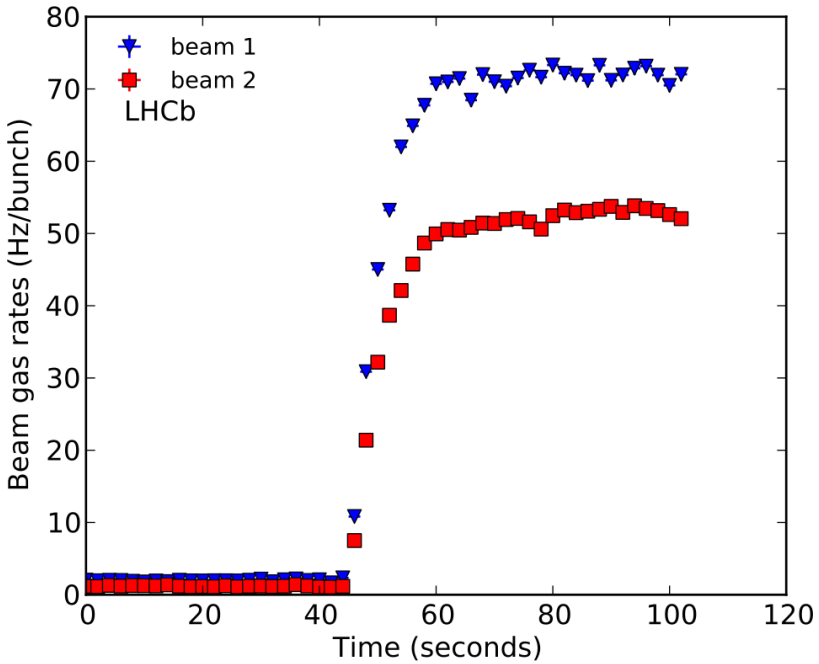
Example Van-der-Meer scan

μ_{vis} as function of displacement in x (left) and y (right) for one specific bunch pair, fitted with a gaussian distribution:



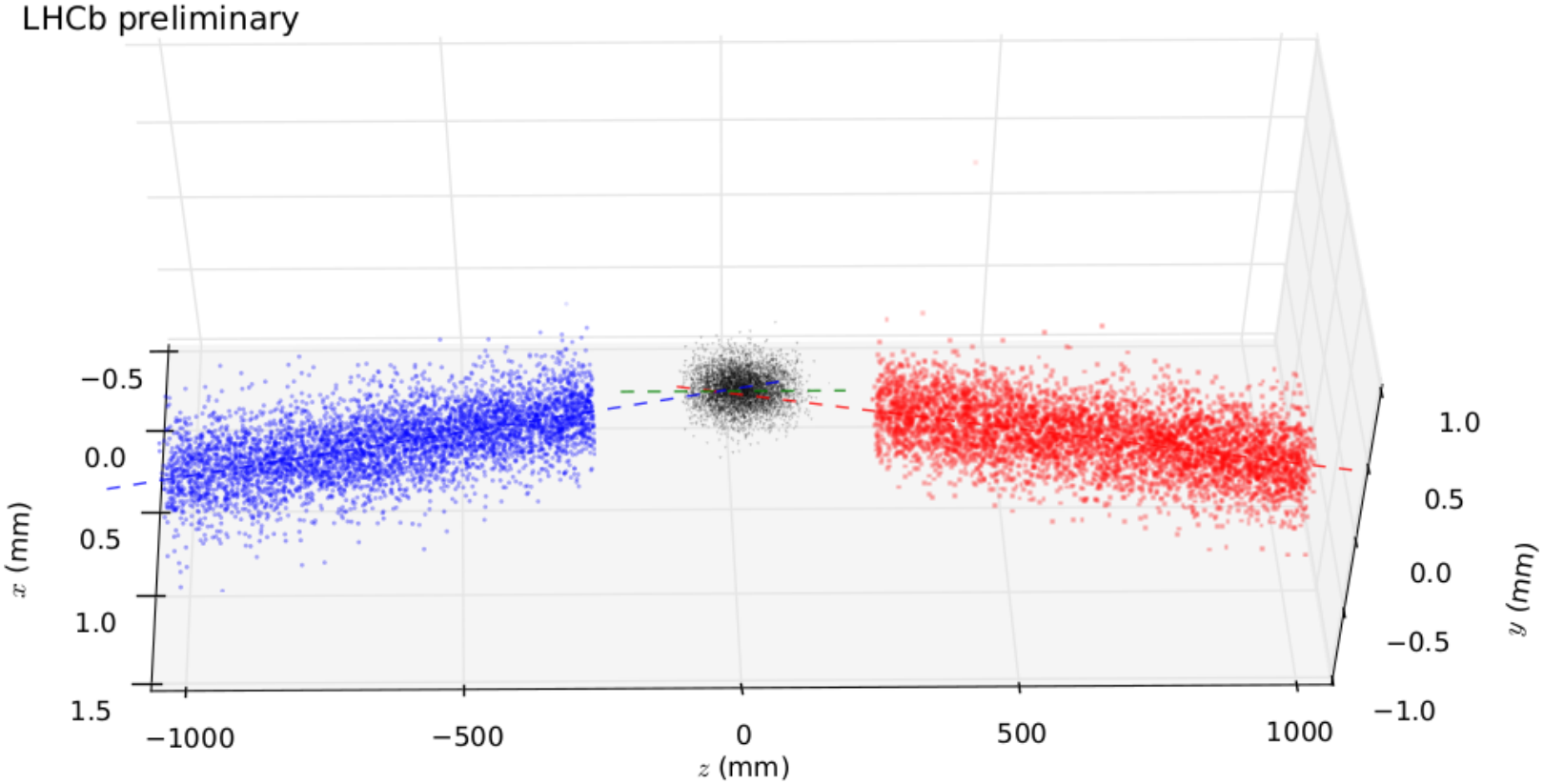
Beamgas Imaging method
SMOG

- Unique feature of LHCb: Ability to inject neon gas into the VELO volume.
- Raises the pressure from 10^{-9}mbar to 10^{-7}mbar.
- Increases interaction rate of beams with gas by almost a factor 100.



Beamgas Imaging method

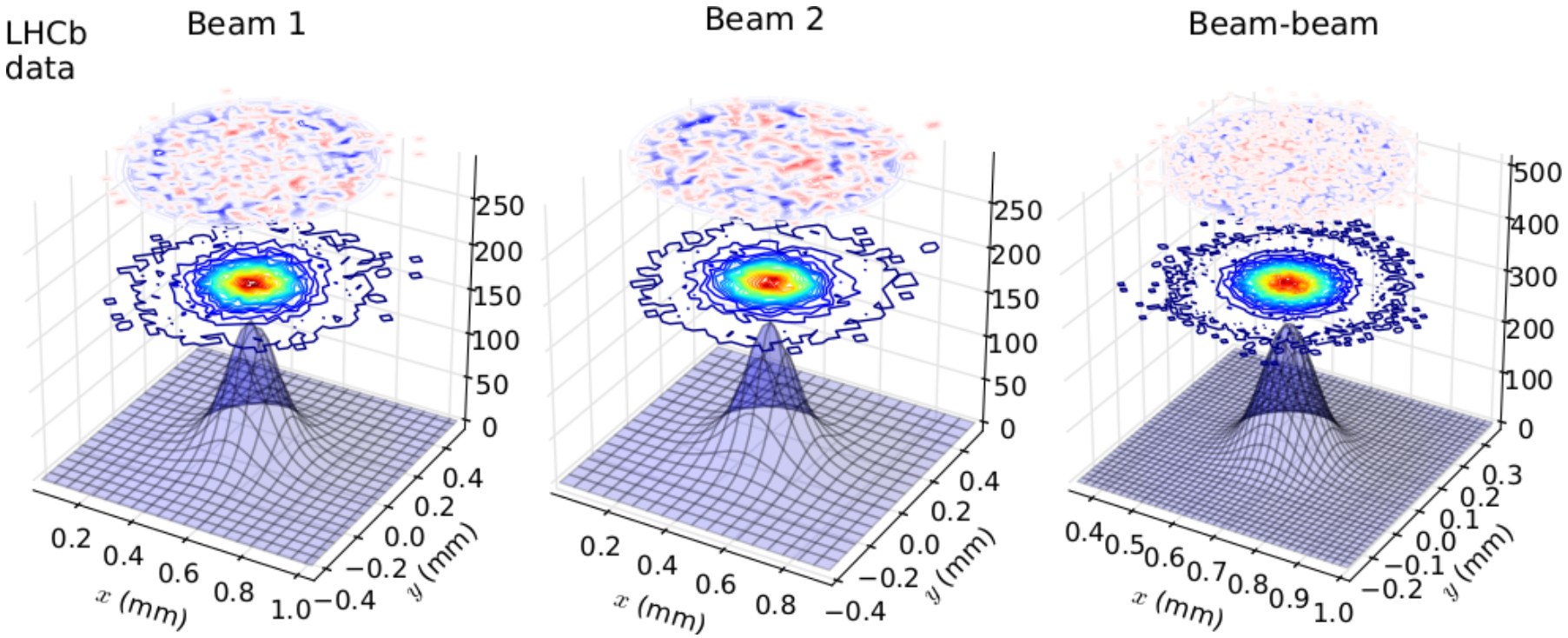
Vertices reconstructed in the VELO



beam 1 – gas, beam 2 – gas and beam 1 – beam 2.

Beamgas Imaging method

Fit to beamgas vertices



Summary

At LHCb, the luminosity can be calibrated using two methods:

- Van-der-Meer scan
- Beamgas imaging

Using both methods, LHCb was able to calibrate its luminosity for 2011 and 2012 with a combined relative precision of 1.12% arXiv:1410.0149.

This is the most precise luminosity calibration at a bunched hadron collider to date.

A preliminary calibration for 2015 data is already available (with a relative precision of 3.9%). Data for a more precise calibration was taken this week.

Appendix

Main uncertainties

Van-der-Meer scan

- Bunch populations (N_1, N_2)
  - Ghost charge (measured with BGI)
  - Satellites (external input)
  - Total beam population (from DCCTs)
  - Relative bunch populations (from FBCTs)
- Beam separation
  - Absolute scale of Δx and Δy
  - separation drift (orbits drift)
- Shape model
  - Factorizibility (controlled by BGI)

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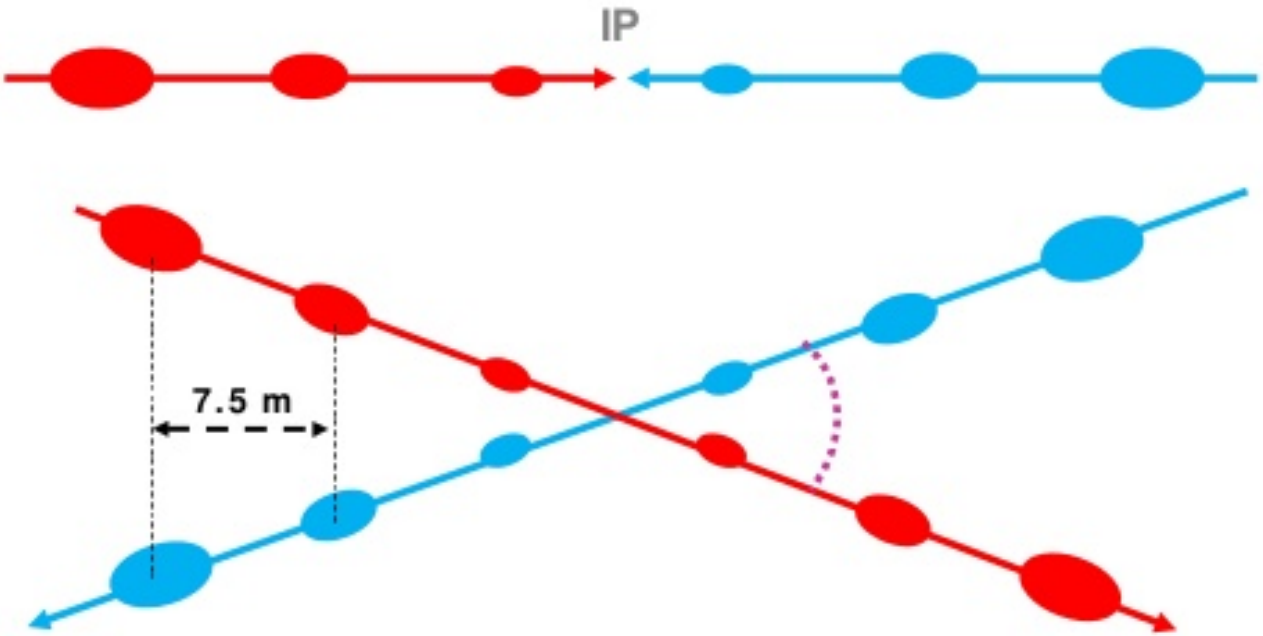
Corrections

Crossing-angle

Effective beamsize:

$$\sigma_{eff} = \sigma \cdot \sqrt{1 + \left(\frac{\sigma_z}{\sigma_x}\frac{\phi}{2}\right)}$$



Corrections

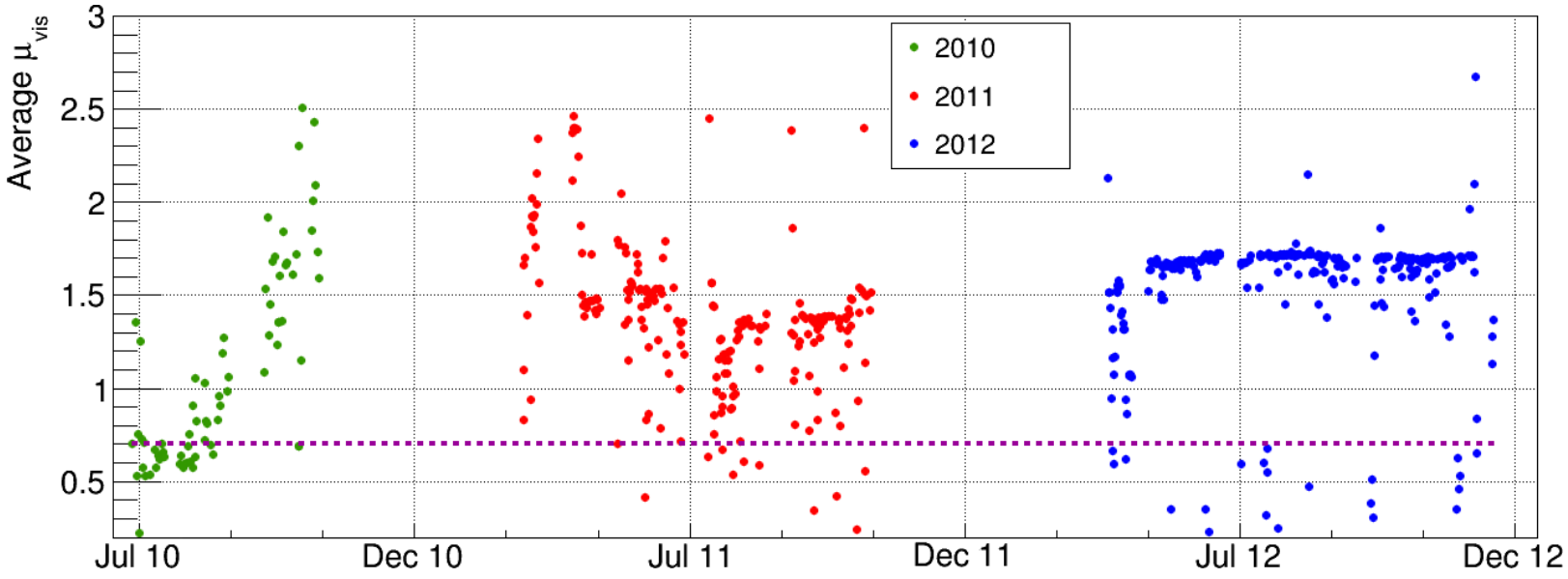
Hourglass effect

Assumption so far: transverse beam sizes are constant over the whole collision region. But:

$$\beta(z) = \beta^* \left(1 + \left(\frac{z}{\beta^*}\right)^2\right)$$

Average interactions per bunch crossing

LHCb



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ATLAS