Beam profile measurements based on modern vertex detectors and beam-gas interactions

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Beam profile

Experiments
- Measure (calibrate) instantaneous luminosity

Accelerator
- Monitor emittance
- Optimize luminosity

$$L = f \cdot N_1 N_2 \cdot \underbrace{Overlap}$$

- Transverse beam profile
- Crossing angle
- Beam offset

$$\approx \frac{1}{4\pi \, \sigma_x \sigma_y}$$

In LHCb experiment:
- Van der Meer method
- **Beam-gas imaging**

$$L \approx \frac{f \cdot N_1 N_2}{4\pi\sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}}$$

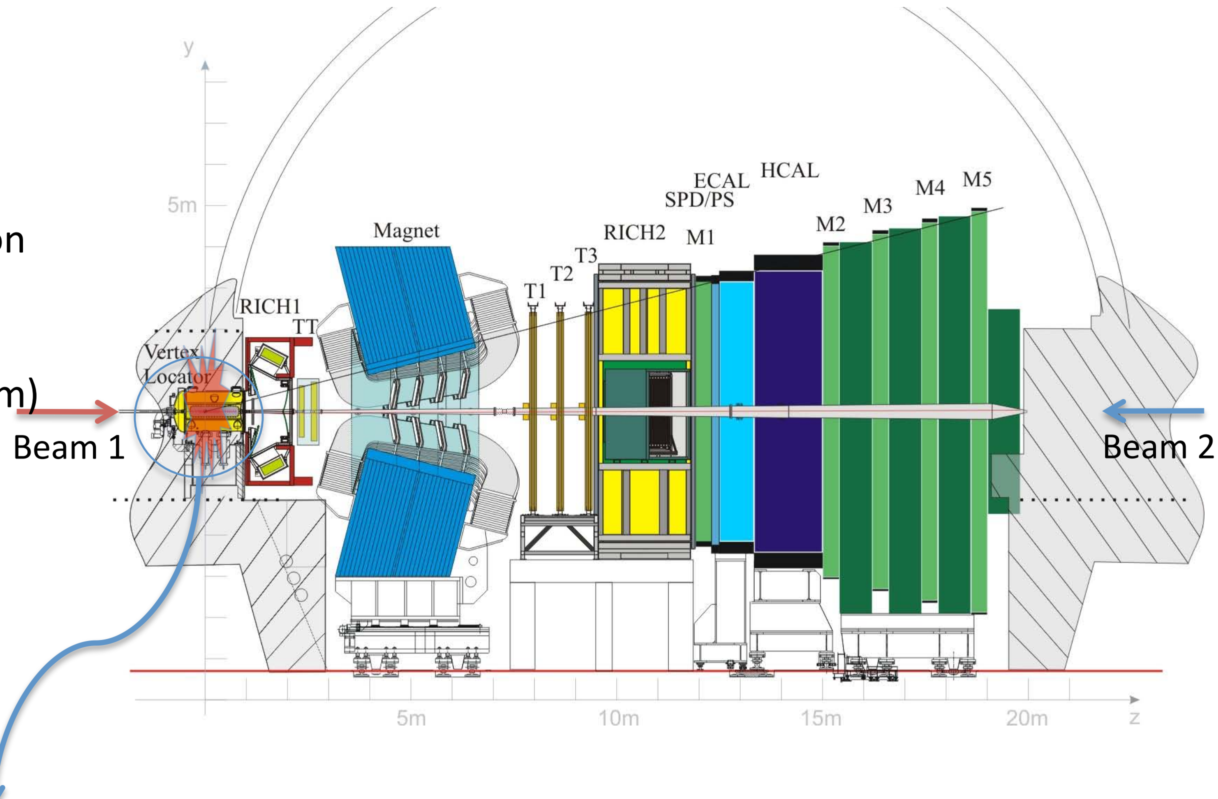
Beam profiles (and emittance) are difficult to measure (in particular with low emittance of 2 µm vs. 3.75 µm nominal)
Multiple instruments are used in the LHC:
- Wire Scanners
- Synchrotron Light monitor
- Beam-Gas Ionization monitor

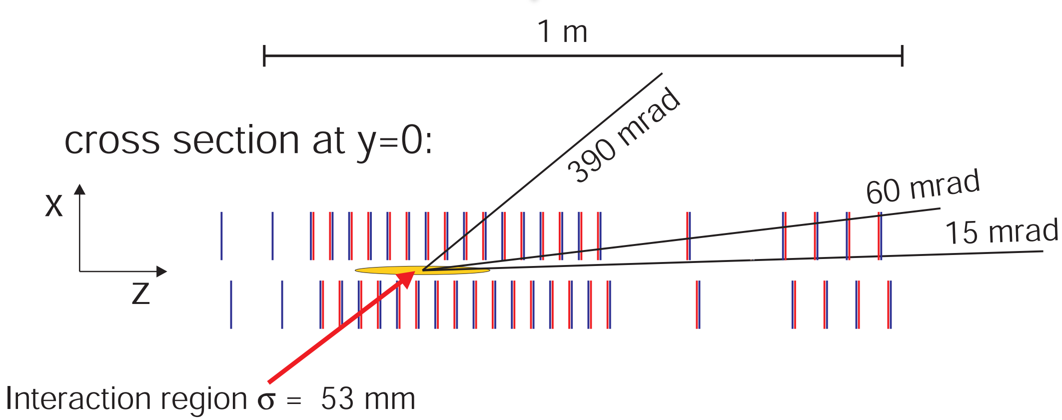
(beta functions are measured by other instruments)

LHCb detector

LHCb VELO (Vertex LOcator) is ideally suited to measure beam-gas vertices:

- Large acceptance in forward region
- Good spatial vertex accuracy
  (15-50 µm)
  Sensors close to the beam (8 mm)
  Excellent hit resolution
  ($\sigma_{hit} \approx 5$ µm)
- Dedicated beam-gas trigger





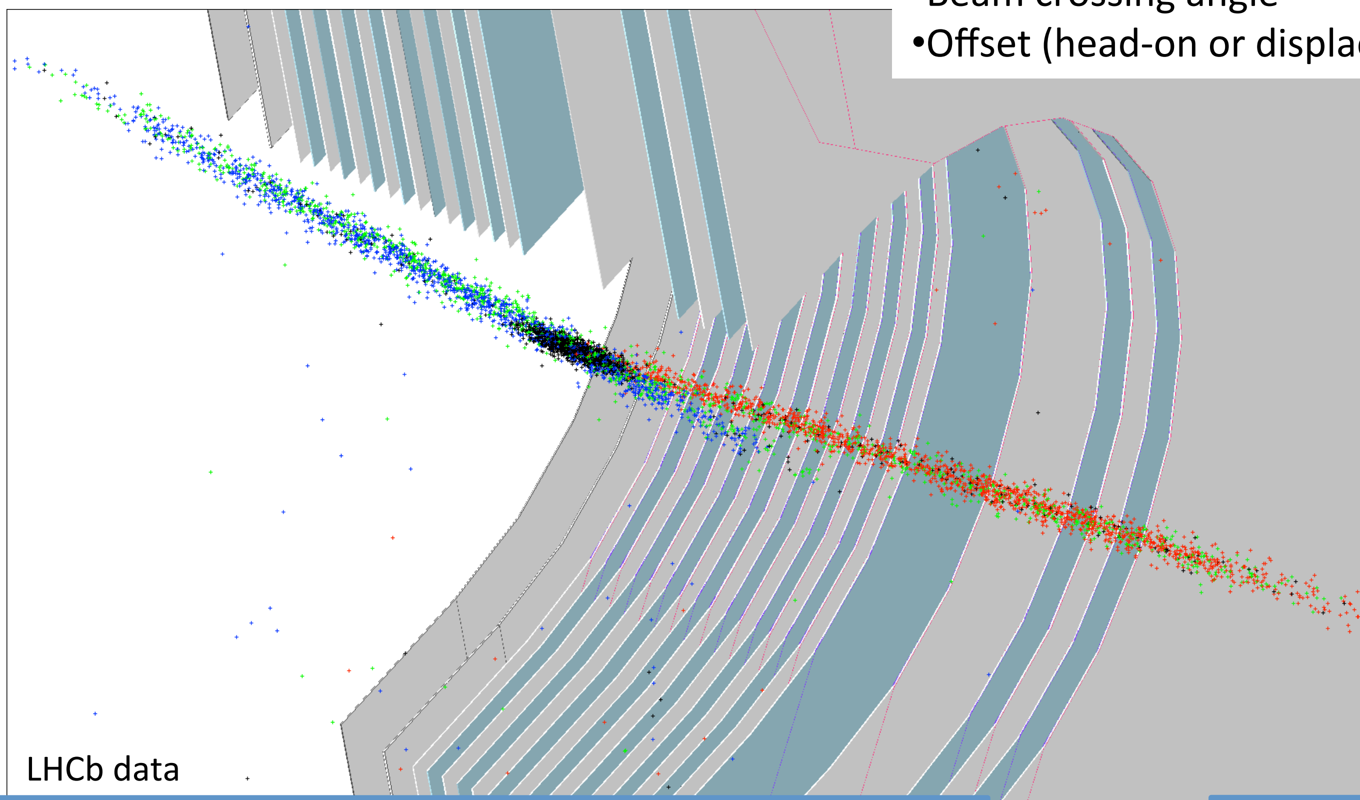
Beam-gas vertices are used to measure the beams overlap

Beam-Gas Imaging (BGI)

$$Overlap = 2c\int \rho_1(x,y,z,t)\rho_2(x,y,z,t)\,dxdydzdt$$

Single bunch density function of colliding bunch pair

Overlap integral depends on:
- Single bunch spatial dimensions (X,Y shape)
- Beam crossing angle
- Offset (head-on or displaced)



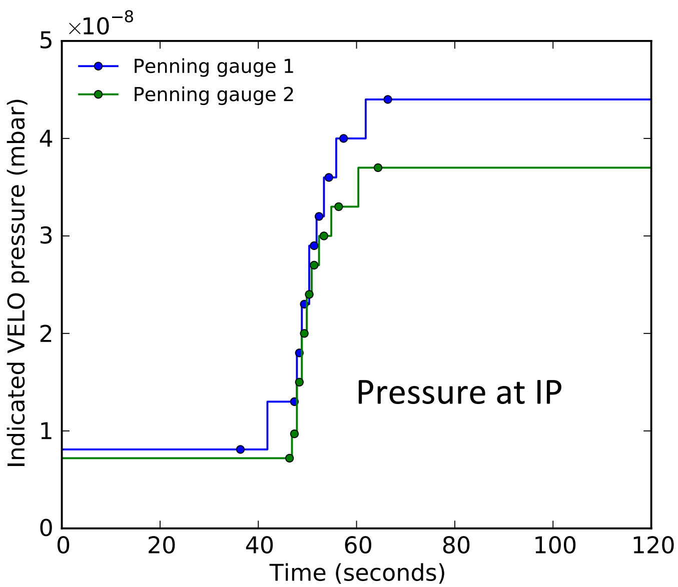
Goal of BGI method: measure overlap integral using **beam-gas interactions** to measure single beam shapes and position

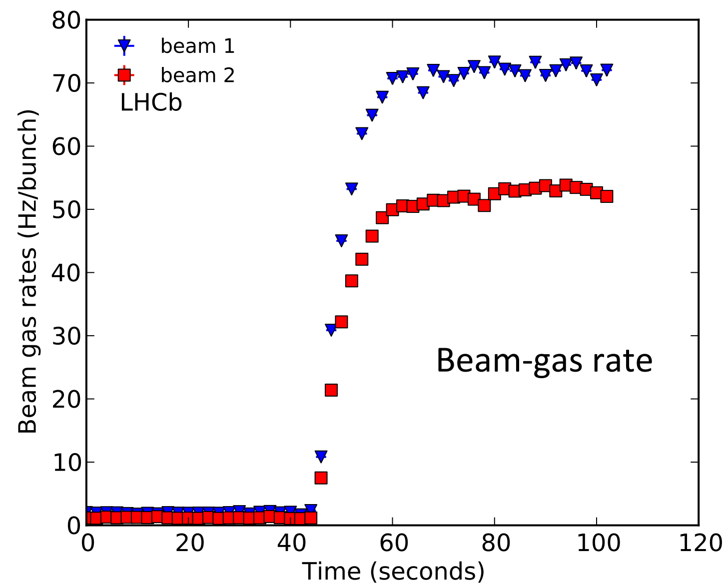
We need: Enough data (rate) + good resolution

Improve beam gas imaging: increase rate

One major limitation of BGI: low beam-gas rate (low statistics, long integration time)

Solution: **degrade vacuum at interaction point**
- shorter time integration (beam is stable)
- better fit accuracy
- improve debunched charges measurements (ghost charge)



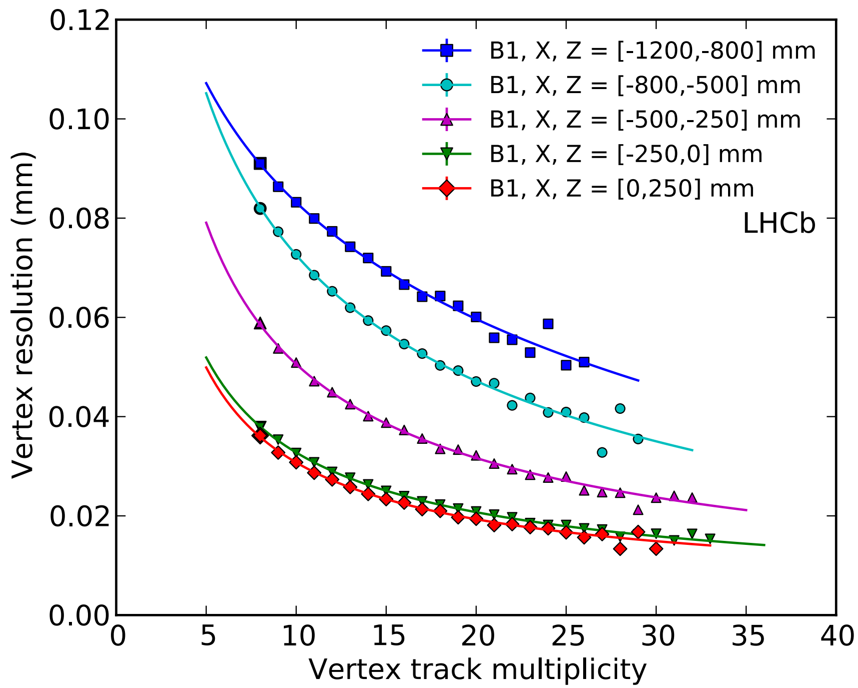


How to measure the (true) beam width

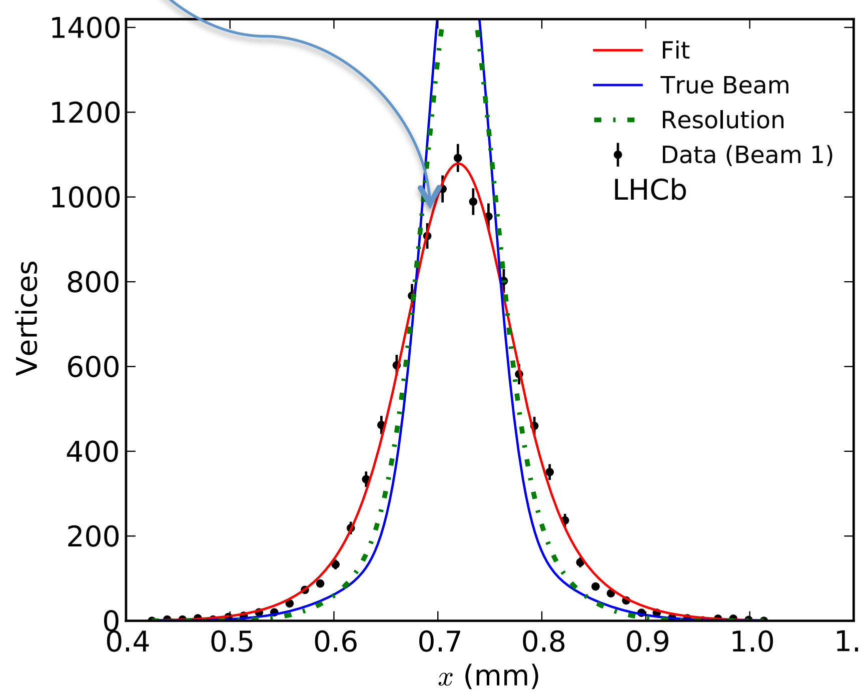
Observed beam width is a convolution of the beam with the detector resolution

$$M(x) = \int_{-\infty}^{+\infty} \sum_{k=1}^{K} c_k g(x; \sigma_{\mathrm{res},k})\, \rho(x-\tau)\, d\tau.$$

Vertex resolution for different z-ranges

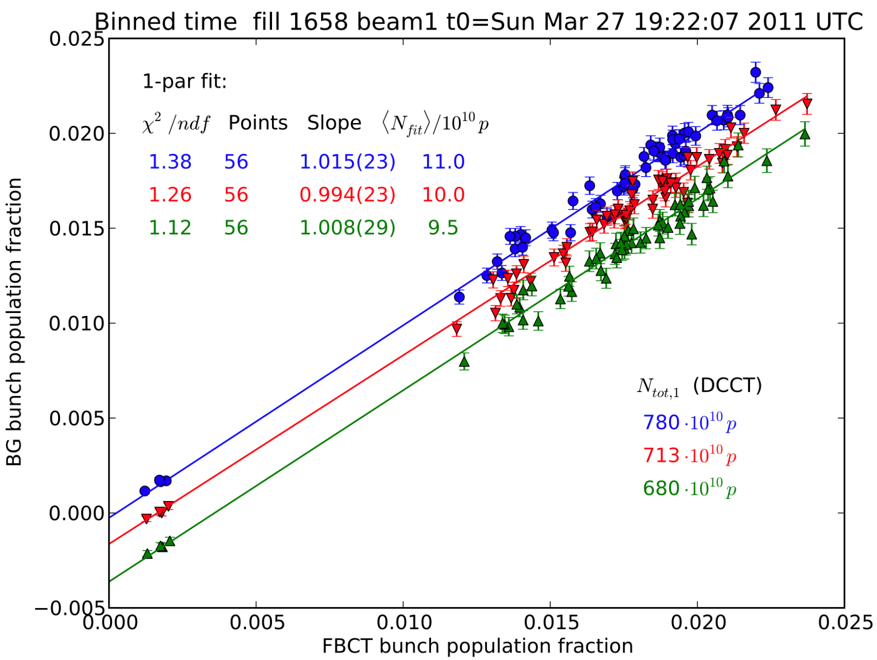


Observed distribution with deconvolution

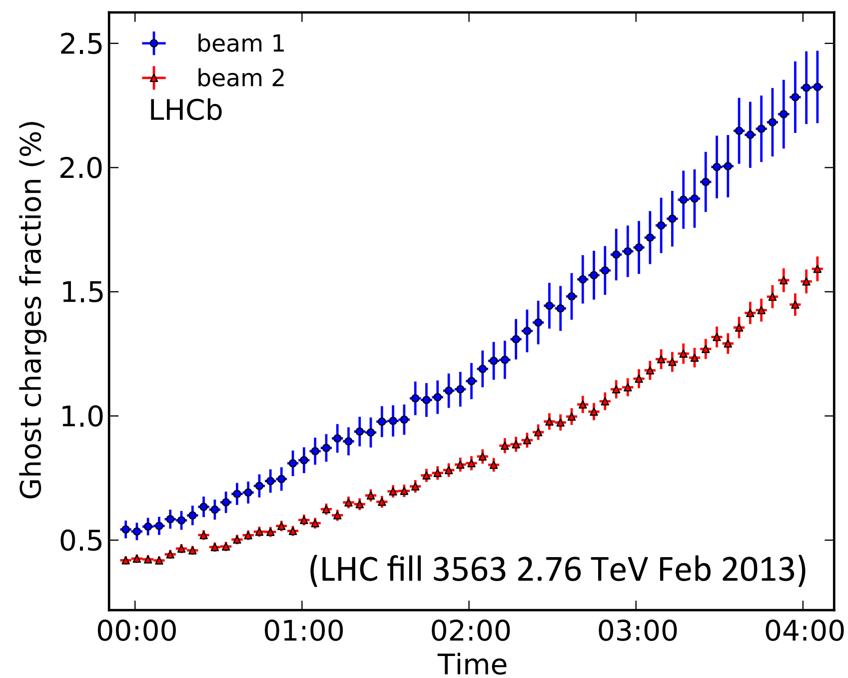


Beam-gas can do more

Relative measurement of bunch charges
Compared with LHC FBCT instrument



Measurement of unbunched charges
(ghost charge faction)

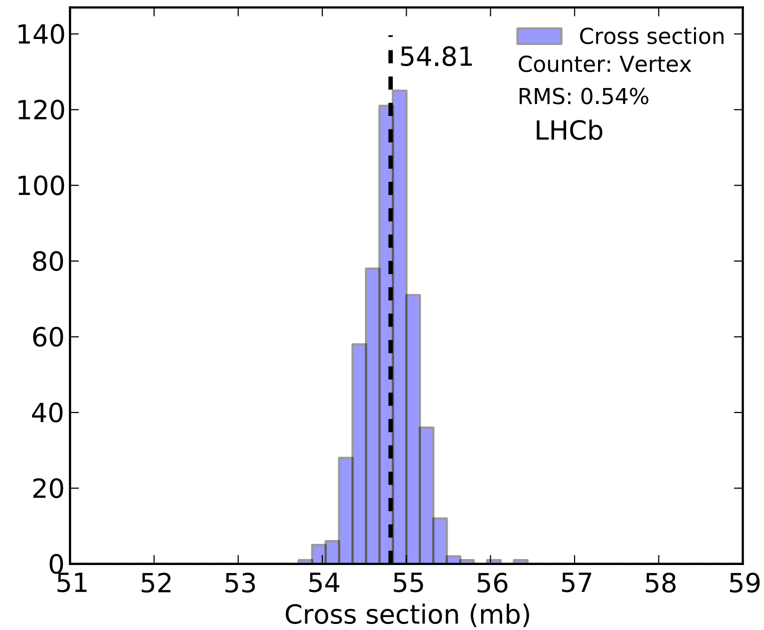


Knowledge of ghost charge is important for the experiments during a luminosity calibration

With the BGI method LHCb reached an unprecedented precise luminosity calibration of 1.4% (better than any other bunched-beam proton collider)

Gas injection was required to get enough events
VELO resolution is small compared to beam size

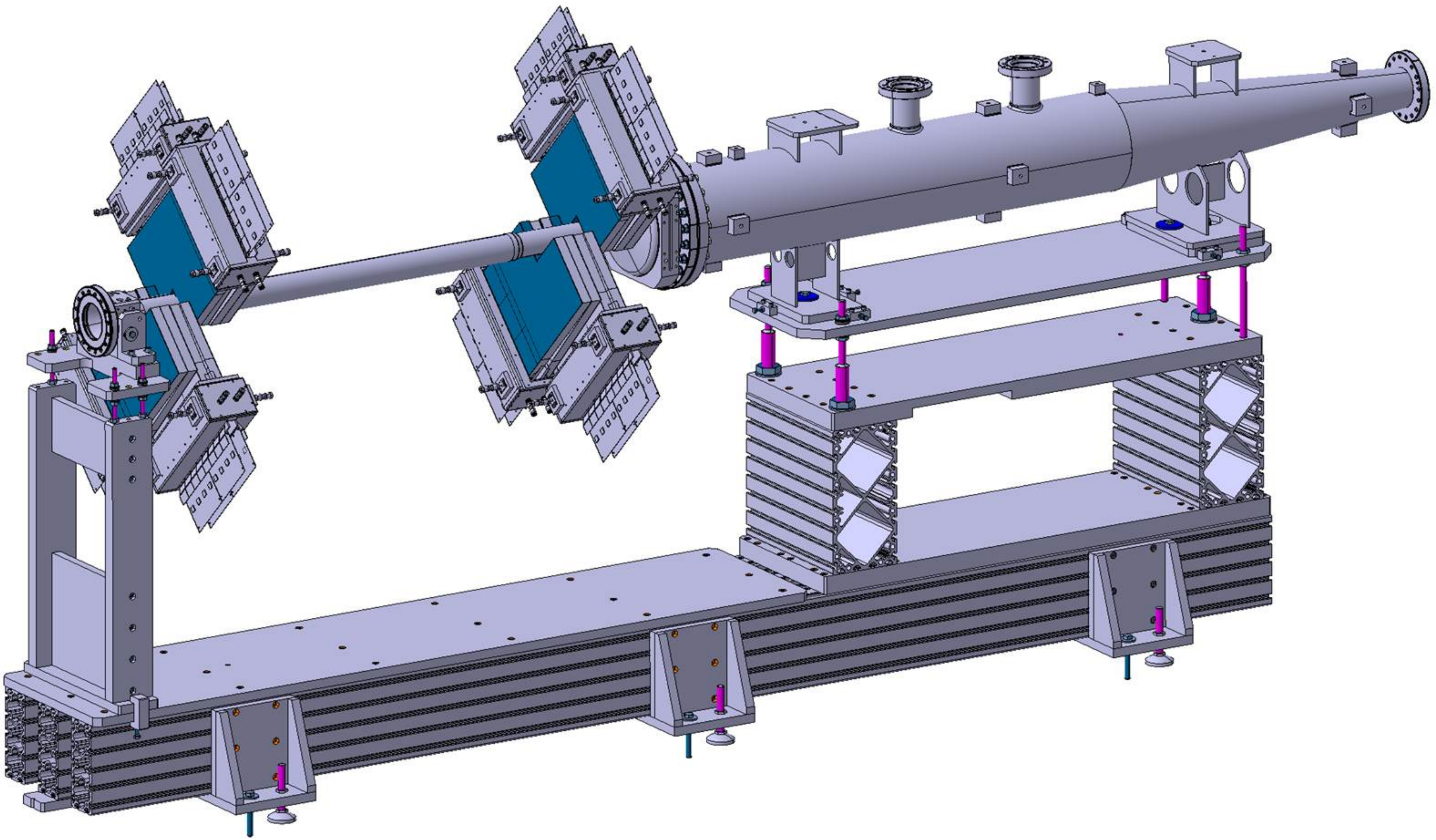
Additionally:
- Two dimensional beam shape determination provides a measure of beam factorizability
- Beam-gas counting also provides a measure of unbunched charges (ghost charge)
- Measure beam width evolution over time



550 colliding bunch pair measurements taken over 6 fills in different conditions are with 0.5% RMS

25 ns filling scheme is crucial for LHCb upgrade
(most so than for other experiments)
Electron cloud formation leading to emittance blowup is difficult to understand and control
LHC instrumentation is not sufficient to measure the emittance in all beam conditions (injection, ramp)
LHC needs a mini LHCb… now called BGV (Beam-Gas Vertex monitor)

From LHCb to ~~mini LHCb~~ BGV



BGV Goal and constraints

- Provide non-disruptive measurement of transverse beam shapes
(stat. and sys. uncertainty <5% in 3 minutes for 10^{11} protons)
- Provide meaningful measurements during the energy ramp period of the LHC cycle
- Overcome the limitations and complement the existing beam profile monitors

Develop, build and install a new tracker for beam profile monitoring.
Using the beam-gas vertexing technique (BGV = Beam Gas Vertex monitor).
A demonstrator system is prepared for installation on one beam at the LHC.

2 main requirements:

Precise vertex resolution →

- Sensor technology
- Detector geometry and acceptance
- Material budget

Sufficient beam-gas rate →

- Gas type and pressure
- Detector acceptance

Optimize resolution and rate while keeping costs and complexity low

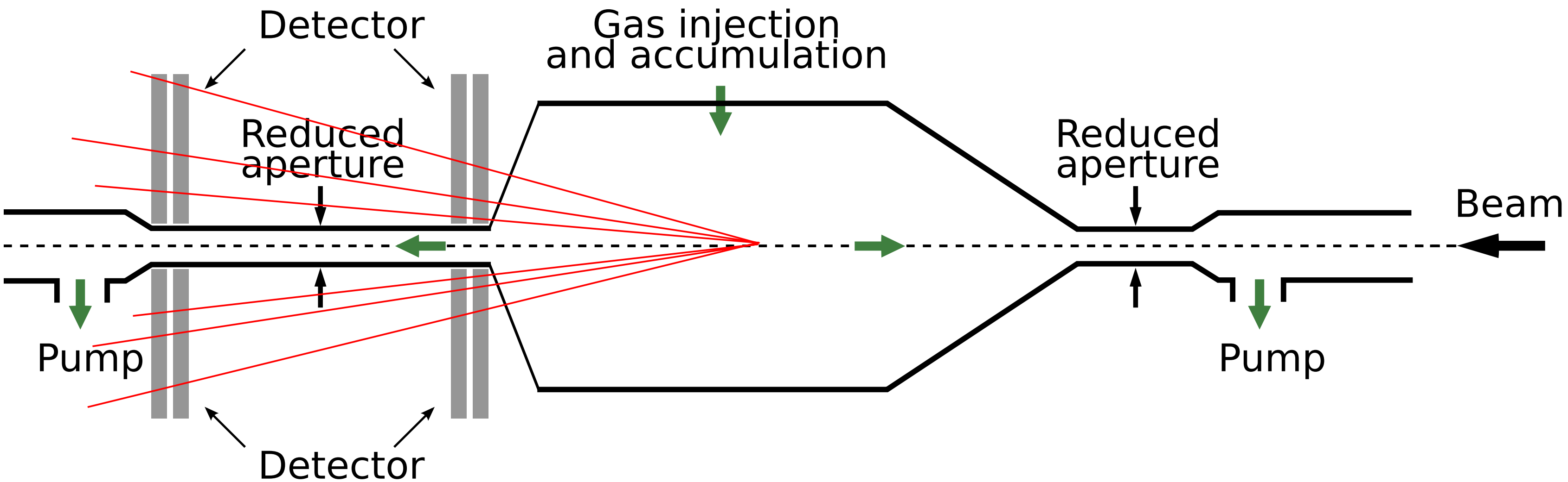
BGV collaboration

V. Baglin, C. Barschel, E. Bravin, G. Bregliozzi, N. Chritin, B. Dehning, M. Ferro-Luzzi, C. Gaspar, M. Giovannozzi, E. van Herwijnen, P. Hopchev, R. Jacobsson, L. Jensen, O. Rhodri Jones, N. Jurado, V. Kain, M. Kuhn, B. Luthi, P. Magagnin, R. Matev, N. Neufeld, J. Panman, M. Rihl, V. Salustino Guimaraes, B. Salvant, R. Veness, **CERN, Geneva, Switzerland**

A. Bay, F. Blanc, S. Gianì, G. Haefeli, T. Nakada, B. Rakotomiaramanana, O. Schneider, M. Tobin, Q. Veyrat, Z. Xu, **EPFL, Lausanne, Switzerland**

R. Greim, W. Karpinski, T. Kirn, S. Schael, A. Schultz von Dratzig, G. Schwering, M. Wlochal, **RWTH, Aachen, Germany**

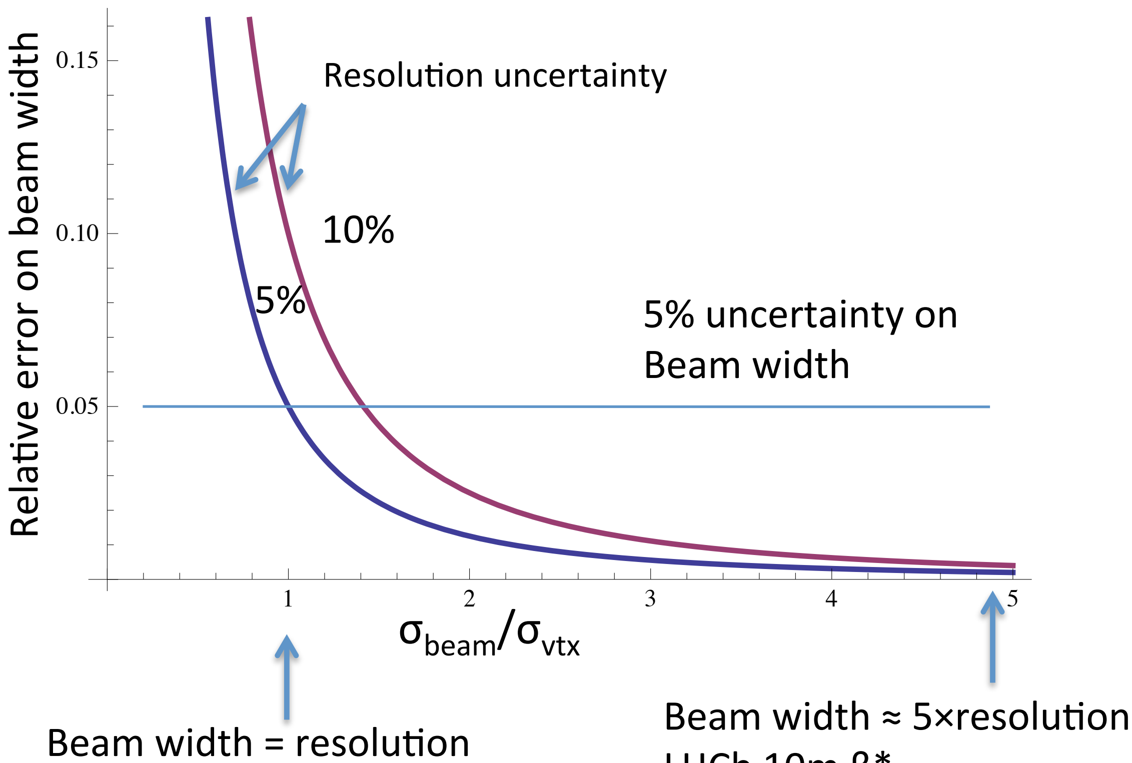
BGV principle



- Scintillating-fiber (SciFi) mattress build by **RWTH Aachen**
(light measured by Silicon Photomultipliers (SiPM))
- Detector modules are being developed by **EPFL**
- Vacuum chamber developed and made by **CERN**
- Acquisition electronics provided by **LHCb**

Vertex resolution

$$\sigma_{raw}^2 = \sigma_{beam}^2 + \sigma_{vtx}^2 \rightarrow \frac{\delta\sigma_{beam}}{\sigma_{beam}} = \frac{\sigma_{vtx}^2}{\sigma_{beam}^2}\frac{\delta\sigma_{vtx}}{\sigma_{vtx}}$$



From LHCb experience we know that a 5% resolution accuracy is a challenge, 10% is ok

Beam width should be a least 2-3× resolution width -> measure where the beam is large (large β^*)

Vertex resolution

Reducing vertex resolution is crucial for a precise beam width measurement
Depends on:
-> Impact Parameter σ_{IP} (quality of the track)
-> Number of tracks forming a vertex (N_{Tr})

$$\sigma_{IP}^2 = \sigma_{MS}^2 + \sigma_{extrap}^2$$

Radiation length traversed by tracks
-> minimize exit window thickness & sensor material
Transverse distance of hit position (and p_T)
-> Set sensors as close to the beam as possible

Distance between tracking stations
(large distance requires large sensors)
Hit resolution σ_{hit}

$$\sigma_{vtx}^2 \approx \sigma_{IP}^2 \sqrt{N_{Tr}}$$

Depends on:
-> Detector acceptance
-> Gas target (heavy gas = more tracks)
-> Cut requiring larger multiplicity
(at the cost of statistics)

With $\sigma_{vtx} \approx 200$ µm and $\sigma_{beam} \approx 200$ µm
It is a challenge to reach systematic uncertainty 3-5%

Beam-gas rate

Number of "good" events (enough track multiplicity)

Retention fraction of "good" events

Proton-gas inelastic rate

Integration time

$$N_{good} = f_{good}\, R_{inel}\, \Delta t$$

$$\rho\, \Delta z\, N\, f\, \sigma_{pA} \approx 70 \text{ Hz}$$

10^{-7} mbar over 1 m

10^{11} protons/bunch

LHC frq. 11245 Hz

Neon cross-section (243 mb)

Retention fraction f_{good} evaluated with MC studies

$f_{good} \approx 0.14$ for xenon

$f_{good} \approx 0.02$ for neon

-> Can reach ≈3% statistical uncertainty in 1 minute (pushing $P \approx 10^{-6}$ mbar with neon)

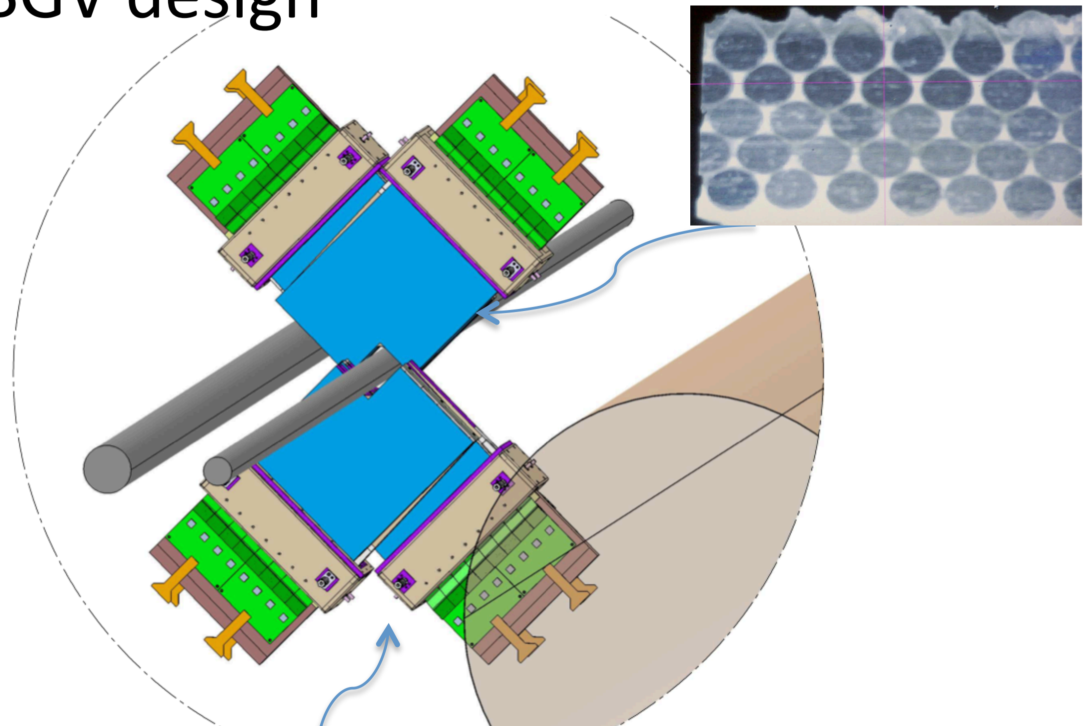
BGV design

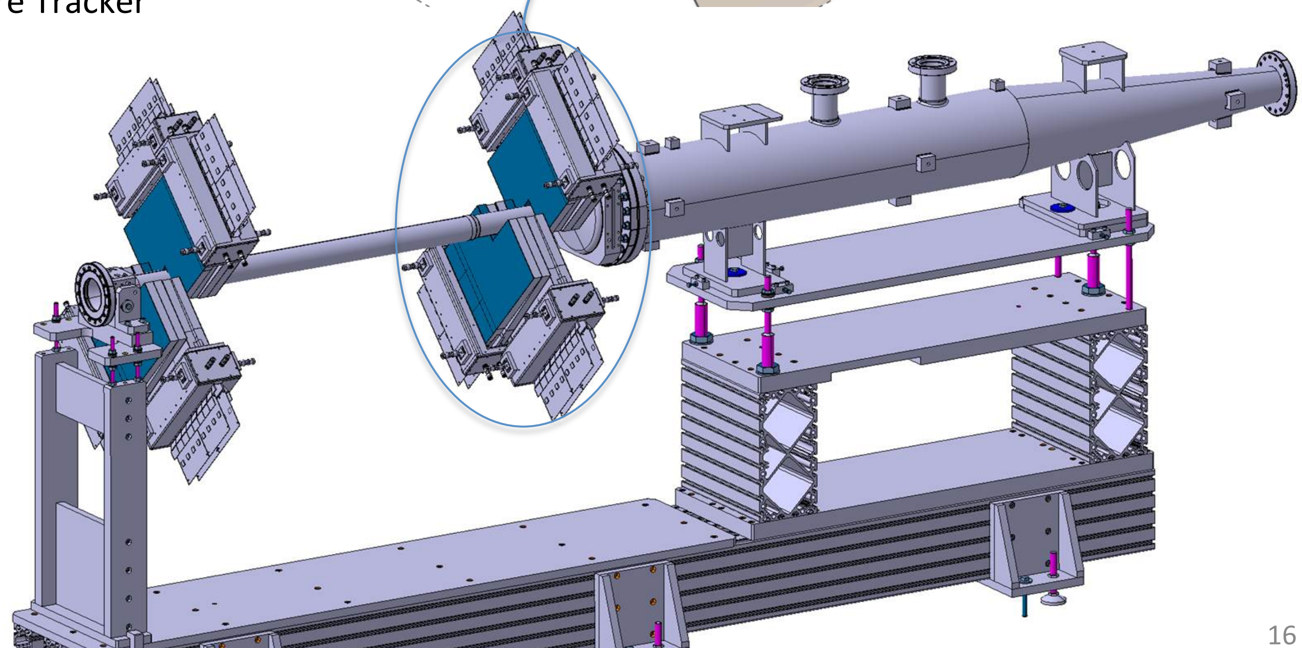
8 SciFi modules in 2 tracking stations
Each module has 2 mattress of SciFi
(250 µm fibers) with $\sigma_{hit} \approx 60$ µm

Synergy with LHCb Upgrade fiber tracker
See related talks:

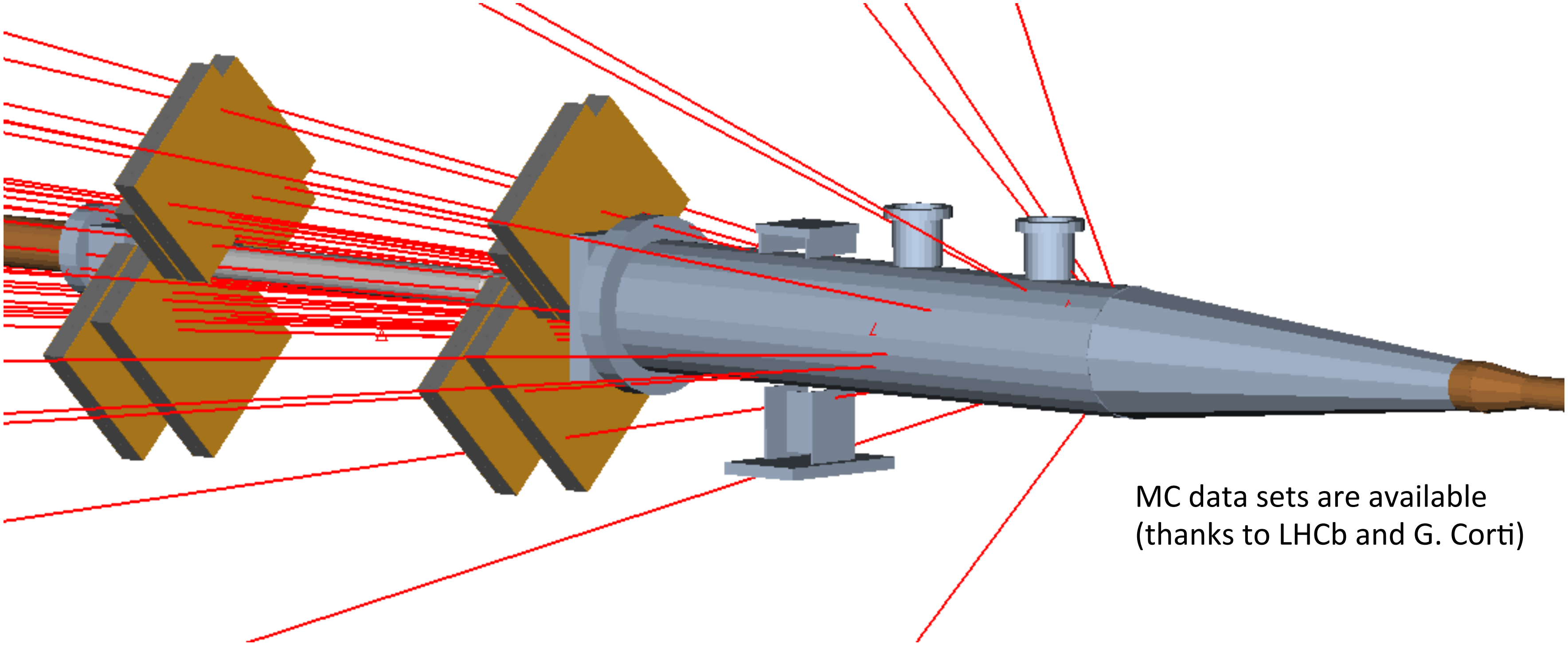
Thomas Kirn today 17:30 in Experiments & Upgrades: Session 5
"Production of Scintillating Fiber Modules for high resolution tracking devices"

Blake Leverington Friday 14h40 Experiments & Upgrades: Session 6
"The LHCb Upgrade Scintillating Fibre Tracker"





Ongoing



MC data sets are available
(thanks to LHCb and G. Corti)

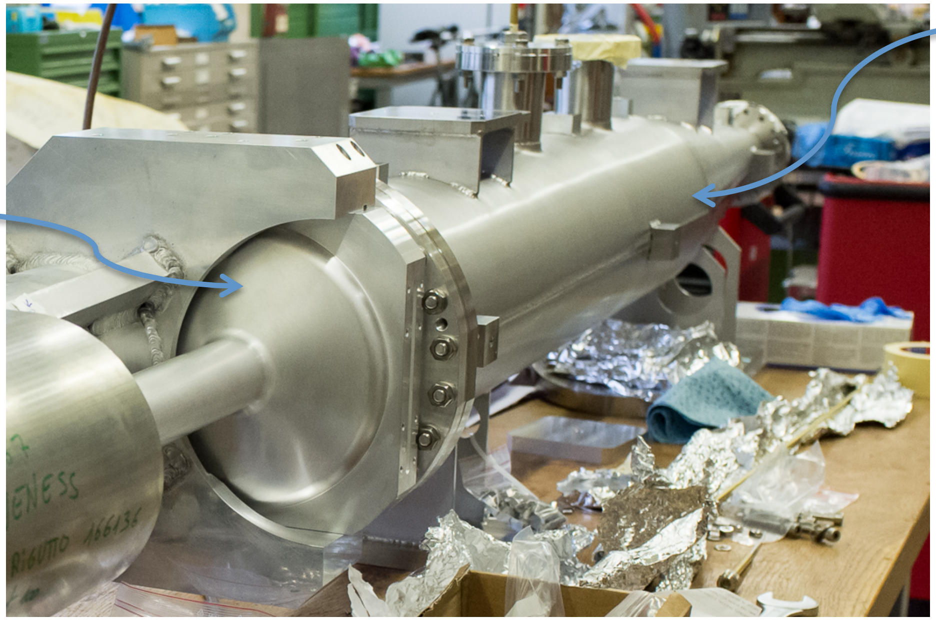
Ongoing work:
Modules are now being build by Aachen and EPFL
Vacuum chamber is in final stage
Detector support and cooling solution
DAQ setup, trigger, computing farm
Full MC, software, analysis, LHC interface, …

extremely aggressive schedule for the BGV demonstrator
First design ideas started in Oct 2012 and aiming for a commissioning in 2015.

Summary

Beam-gas imaging technique was a success for LHCb
- Precise luminosity calibration
- Multiple additional measurements were provided to the other experiments and the LHC (i.e. ghost charge, beam factorizability)

BGV instrument based on LHCb technology and knowhow
- Synergy with LHCb Upgrade fiber tracker
- Overcome the limitations and complement the existing emittance monitors at the LHC
- Identify possible constraints for long and large SciFi module for LHCb
- Gain experience in SciFi+SiPM operation and aging (expect 16 Gy/year)



We are working on installing everything by the end of the year and operate the BGV in 2015

Questions, comments?