Luminosity at LHCb

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Outline:

- Luminosity measurement (in the past fully done at CERN)
 a) Relative luminosity monitoring during physics data taking – analysis is recently taken by Tsinghua Uni
 Methods of absolute luminosity measurement:
 b) Beam-gas imaging (BGI) - ?? (C.Barshel is leaving this fall)
 c) van der Meer scans (VDM) - LLR

- Conclusions

Why LHCb luminosity?

Task of “common interest”, high visibility.
my rough estimation: luminosity measurement was used in 50 LHCb papers (out of 428)

from the sample of LHCb papers with the words “production” and “cross-sections” in the title:

W,Z	Y	J/psi, psi(2S)	c	B, Lambda_b	Bc	J/psi+ J/psi
16	6.5	8.5	2	3	2	2

One publication per production of top, Higgs (upper limit), c+c, eta_c, phi, hadrons, K0S, “V0”
2 publications devoted exclusively to the luminosity measurement.

8 TeV: luminosity accuracy=1.16%, record at bunch-beam hadron colliders (eg. among 4 LHC experiments), published in

”Precision luminosity measurements at LHCb”, J. Instrum. 9 (2014) P12005, arXiv:1410.0149.

For future measurements: the more precise the better, but even 3% might be good enough. Time needed to achieve better precision exponentially explodes.

Proposed work on LHCb luminosity

Frédéric Fleuret:

1) VDM Pb-Pb analysis together with Yiming Li (postdoc at LAL)
2) maintenance of condition DB, luminosity part
3) luminosity liason for IFT

Emilie Maurice:

participation in the improvement of pressure measurement at CERN, needed for (fixed target) cross section

V.B. (was CERN project associate in LHCb luminosity group in 2009 – 2012):

50%: Continue VDM analyses other than Pb-Pb, at 50% of time

(Aug'15 pp 13 TeV, Nov'15 pp 5TeV, May'16 pp 6.5+6.5Z TeV, planned p-Pb in Nov'16, plus at least one per year for stability checks requested by ATLAS and CMS)

No experience in heavy ions. Potentially: LHCb analysis on B or charm physics

50%: in SiW ECAL for CALICE/ILD.

How luminosity is measured

- Continuous monitoring of pile-up rates (relative measurement)

- Absolute calibration in a few dedicated LHC fills per year:
  a) beam-gas imaging (exclusive for LHCb)
  b) van der Meer scans (used in 4 LHC experiments)

Pile-up event rate monitoring at LHCb

… measured in random events collected at about 0.8-1 kHz. HLT strips them to “nano”-events containing only “luminometers”:

- Number of VELO (LHCb Vertex LOcator) reconstructed tracks
- N vertexes
- N tracks or vertexes close to nominal collision point
- Number of hits in the upstream part of VELO or N backward tracks
- N hits in the preshower (SPD)
- Calorimetric transverse energy
- Number of muons

- To reduce systematics due to potential nonlinearity or instabilities of “luminometers”, pile up (μ) is calculated from the fraction of “empty” events (eg. N vertexes == 0 or N tracks < 2) assuming Poisson statistics (P(n) = exp(-μ) * μ^n/n!) as $\mu = -\log(P(0))$. Typical $\mu \sim 2$.
- Backgrounds are small. Beam-gas background is estimated from “beam-empty” and “empty-beam” crossings and is subtracted from beam-beam as bb – be – eb. The empty-empty backgrounds are negligible.
- After processing, the luminosity information from the best luminometer (N VELO tracks from IP) is added to the end of every LHCb file (~10 sec running), to “F(ile) S(ummary) R(ecord)”. Overall, lumi-stream gives <1% load to DAQ (CPU, data traffic, storage) and “just works”.

- Ratio with other luminometers gives systematics: 0.3% (8TeV) – 1% (pPb, 5TeV).
In the past this was done by CERN. **Recently, the group from Tsinghua University has taken this responsibility.** Currently, they are checking the systematics in Run II due to a switch from 50 to 25 nsec.

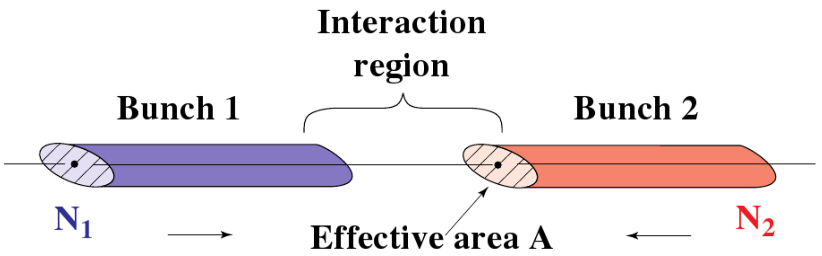
Absolute calibration of L

The number of interactions N (time integrated pile-up μ) is not sufficient for the luminosity measurement. One needs to know the associated "visible" cross section (eg. the cross-section of the reaction pp → event with at least 2 VELO tracks).
Then, $N = L^*\sigma_{vis}$ gives L.

σ_{vis} is determined in dedicated LHC fills a few times per year, where L is measured "directly" using its definition:

$$L = \frac{N_1 N_2 f}{A_{eff}},$$

$$A_{eff} = \iint \rho_1(x,y)\rho_2(x,y)\,dxdy$$



Here, $N_{1,2}$ are number of protons in colliding bunches, f – frequency of collisions, A_{eff} – overlap integral.

f is precisely known. $N_{1,2}$ are measured by LHC equipment in three steps:
- the total beam1,2 charges are determined from beam currents (slowly) measured with high accuracy by DCCT (direct-current current-transformers),
- background current in the nominally empty LHC slots is subtracted (1-2%). It is measured either with LHC equipment (LDM) and/or with beam-gas interactions in LHCb.
- charge fraction in a given bunch is determined with LHC fast transformers FBCT

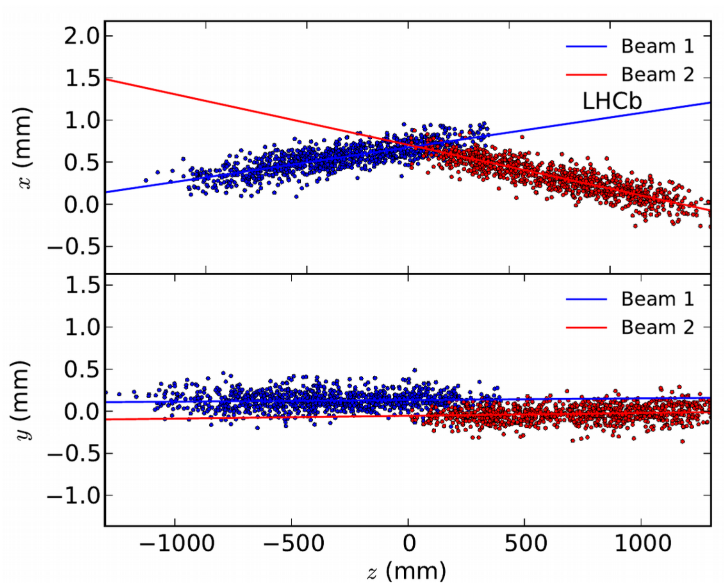
Average N_1N_2 uncertainty for 8 TeV: 0.22%.

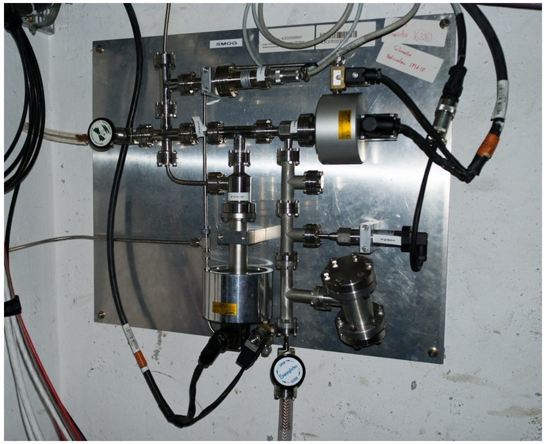
Beam-gas imaging (unique to LHCb)

The main problem is to measure the overlap $A_{eff} = \iint \rho_1(x,y)\,\rho_2(x,y)\,dxdy$

One approach: determine ρ_1, ρ_2 from the beam images ("photos") revealed in beam-gas interactions (proposed by M.Ferro-Luzzi, current luminosity group leader) NIM A 553, 3 (2005) 388

- It allowed the first measurement of L in LHC pilot run already in Dec 2009 @0.9 TeV
  Phys.Lett. B 693 (2010) 69.
- Then, to increase the amount of gas, in 2011 VELO pumps were switched off
- Finally, from Nov 2011 on, a very little amount of gas was injected on purpose using the dedicated injection system called SMOG. The statistics is increased by ~50.





The method is more complicated than VDM scan (requires a vertex deconvolution).

SMOG as fixed target

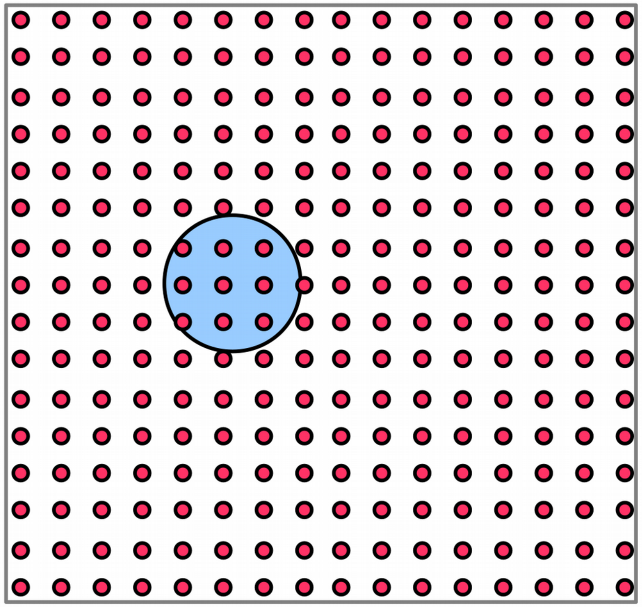
SMOG as a fixed target can be used to measure p-A or Pb-A cross-sections (for heavy ion physics). The knowledge of the gas density is required.

Currently, there are gauges which measure the pressure in the beam pipe within a factor of 2.

CERN is installing new much more precise gauges, though 7 m upstream from IP.
Emilie is involved in this activity.

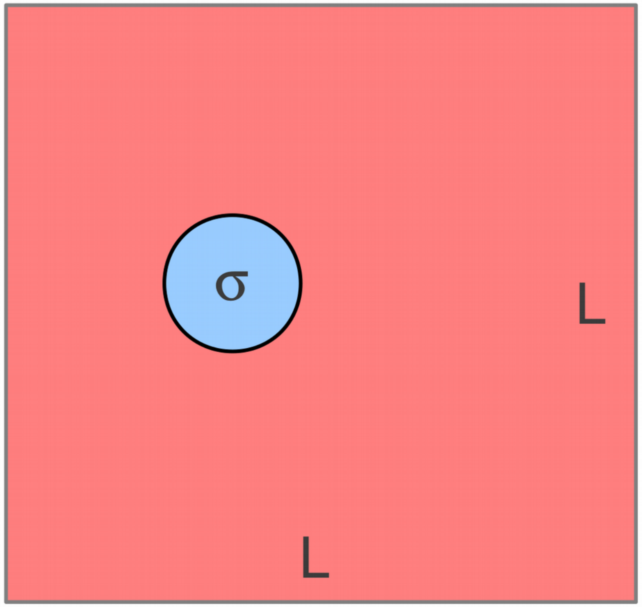
Van der Meer scan

Idea: sweep one beam across the plane



Van der Meer scan

When averaged over all scan points, a first beam profile effectively becomes broad and uniform in red square, so that ρ_1 = const.



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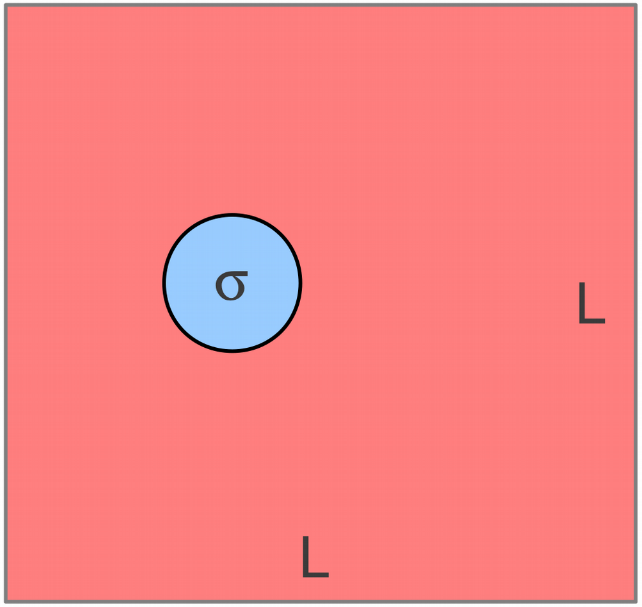


After smearing and integrating over Delta x,y, the overlap integral simplifies to:

$$\iint \rho_1(x+\Delta x, y+\Delta y)\rho_2(x,y)\, d\Delta x\, d\Delta y\, dx\, dy = 1$$

so that $$\iint \mu(\Delta x, \Delta y)\, d\Delta x\, d\Delta y = N_1 N_2 \sigma$$

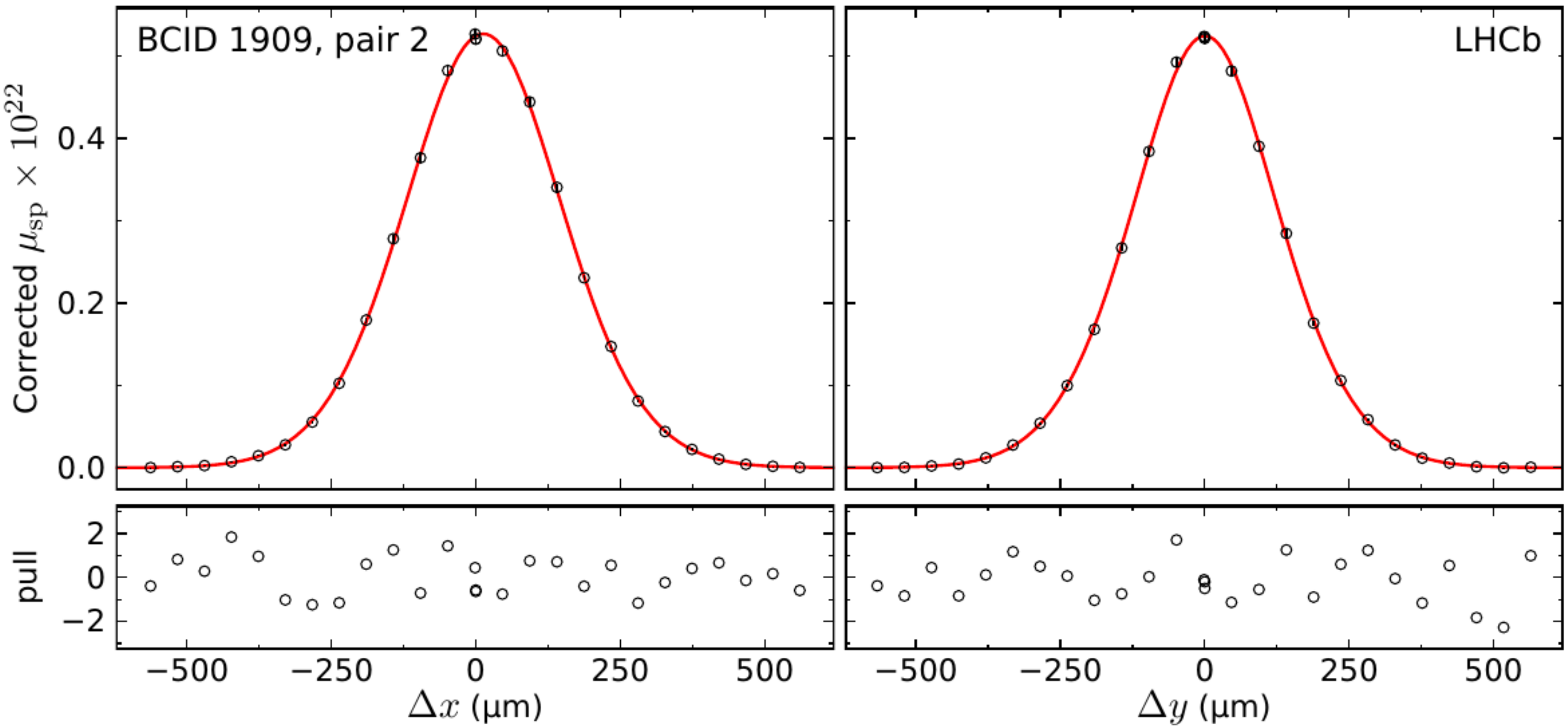
This allows to measure σ (suggested by van der Meer in 1968, CERN note ISR-PO-68-31). The method works for any $\rho_{1,2}$. If they factorize in x,y, the "raster" scan across the full plane may be substituted by the scans along x- and y-axes only (done at LHC).

Another possibility: use "beam-beam imaging" using uniform beam as gas in BGI, V.Balagura, NIM, A 654 (2011) 634, arXiv:1103.1129, successfully used for Oct'10 VDM scan in LHCb, J. Instrum. 7 (2012) P01010.

Van der Meer scan

The rate of “lumi” events during VDM scans is 45 kHz (starting from 2015).

Example of visible pile-up measured in x (left) and y (right) scans for one bunch crossing (they are always analyzed individually):



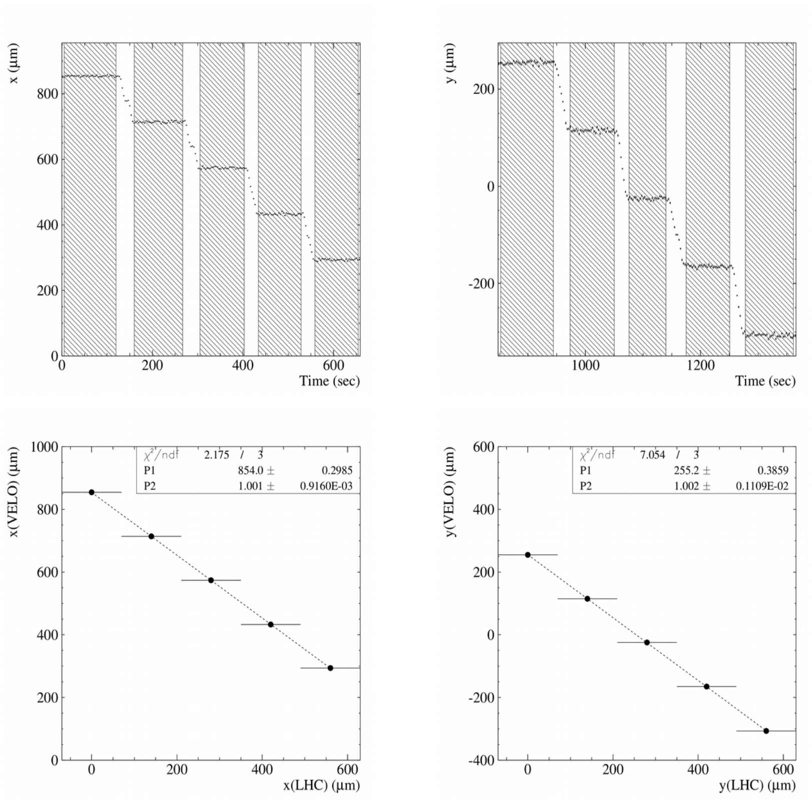
The curves are fit to one or a sum of Gaussians. For the best precision, a small x-y non-factorizability is taken from BGI.
From Aug’15 on, one novelty: diagonal scan to check X-Y non-factorizability. It is still waiting to be analyzed.

VDM length scale calibration

In $$\iint \mu(\Delta x, \Delta y)\, d\Delta x\, d\Delta y = N_1 N_2 \sigma$$

the scale of Delta X,Y directly enters σ. Initially, it is approximately given by LHC (calculated from steering magnet currents). Then, it is precisely measured by VELO detector in a dedicated **“Length Scale Calibration”** in the same LHC fill as VDM.

The beams are moved synchronously together by Delta X,Y in several steps. This also moves the “luminous” region (IP) by the same amount (regardless of the beam shapes). IP reconstruction by VELO gives precise Delta X,Y calibration.



Conclusions

- 10% of LHCb publications use luminosity (50 up to now), high visibility.

- Luminosity measurement in the past was performed only by CERN. For 8 TeV data, LHCb has reached a record precision for bunched hadron colliders (eg. among 4 LHC experiments). Two key persons in lumi group who made 1.16% possible have left (the former group leader retired, another went to HLT) and one is leaving in the end of the year. Lack of manpower, external contributions are very welcome.

- Tasks:
  - “relative” continuous monitoring. Analysis of luminometers stability is recently taken by Tsinghua Uni (normally, the easiest task among the three).
  “Absolute” calibration, two methods with different systematics and comparable precision:
    1) BGI, Colin Barshel finishes CERN fellowship this fall
    2) VDM scan, LLR and LAL
  - Pb-Pb scan: Frédéric and Yiming Li (from LAL)
  - other scans (3 in 2015-16 plus 1 p-Pb this week): V.B. (50% of time, was in CERN lumi group in 2009-12).

  - Emilie is helping to upgrade the SMOG system with the new pressure gauges to measure the fixed target cross sections.

Backup slides

LHCb or Belle II ?

Proposal exists in IN2P3 to join Belle II in the future if there will be enough physicists (I participated in Belle in 2004-2008, in the author list until 2011).
What to choose in LLR: Belle II or LHCb? My opinion: both are attractive.

Advantage of Belle: **clean environment,** of LHCb: **huge statistics**

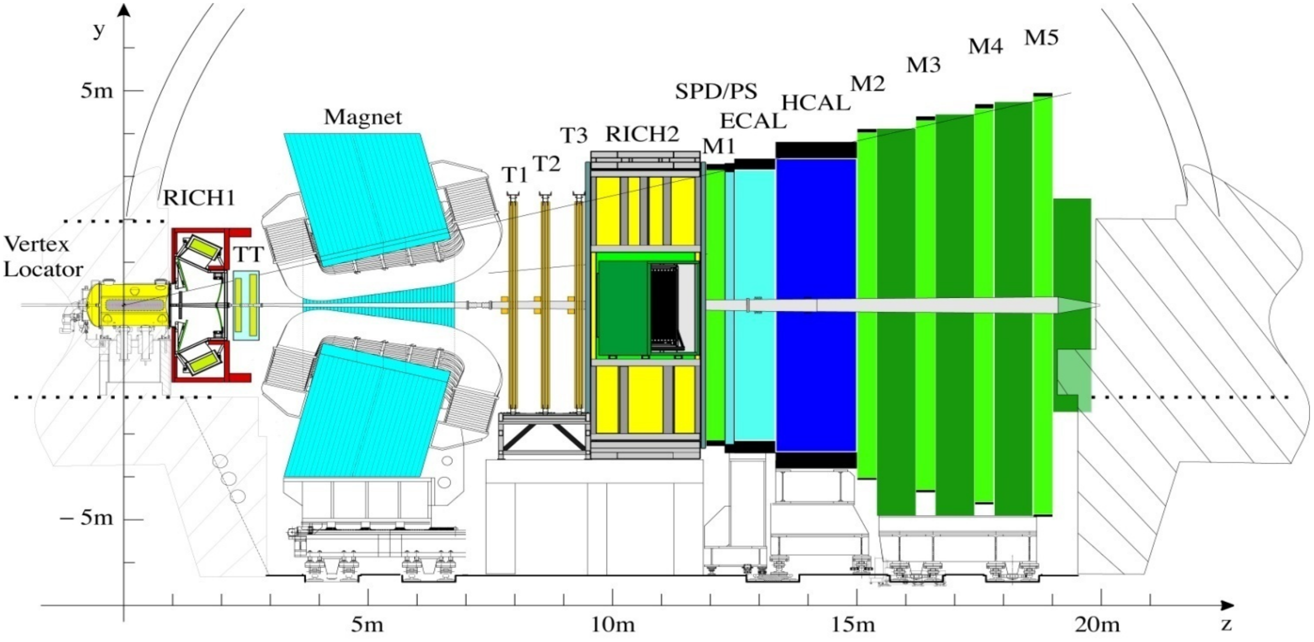
Belle, after about 10 years of operation: $8*10^8$ BB-pairs, without reconstruction efficiencies.
Belle II should increase the luminosity by 40, then the statistics in 2028 will be $(3\text{-}4)*10^{10}$

LHCb, in "optimal" for reconstruction di-muon channel, in 2011 + 2012 (1+2 /fb) expected for $Br(B0 \rightarrow \mu+\mu-)=1.1*10^{-10}$: 4.5 $B0 \rightarrow \mu+\mu-$ events after reconstruction.
This corresponds approximately to
N(BB pairs) * di-muon reconstruction efficiency = $5*10^{10}$.
In Run II with 25 nsec instead of 50 nsec and 13 TeV instead of 7-8 TeV, the statistics should be larger.

<u>My conclusion:</u>

- Belle II will start in 2018. There will be no competition during 2 years.
- After that LHCb statistics will continue to dominate at least in channels with only charged particles in the final states.

LHCb experiment



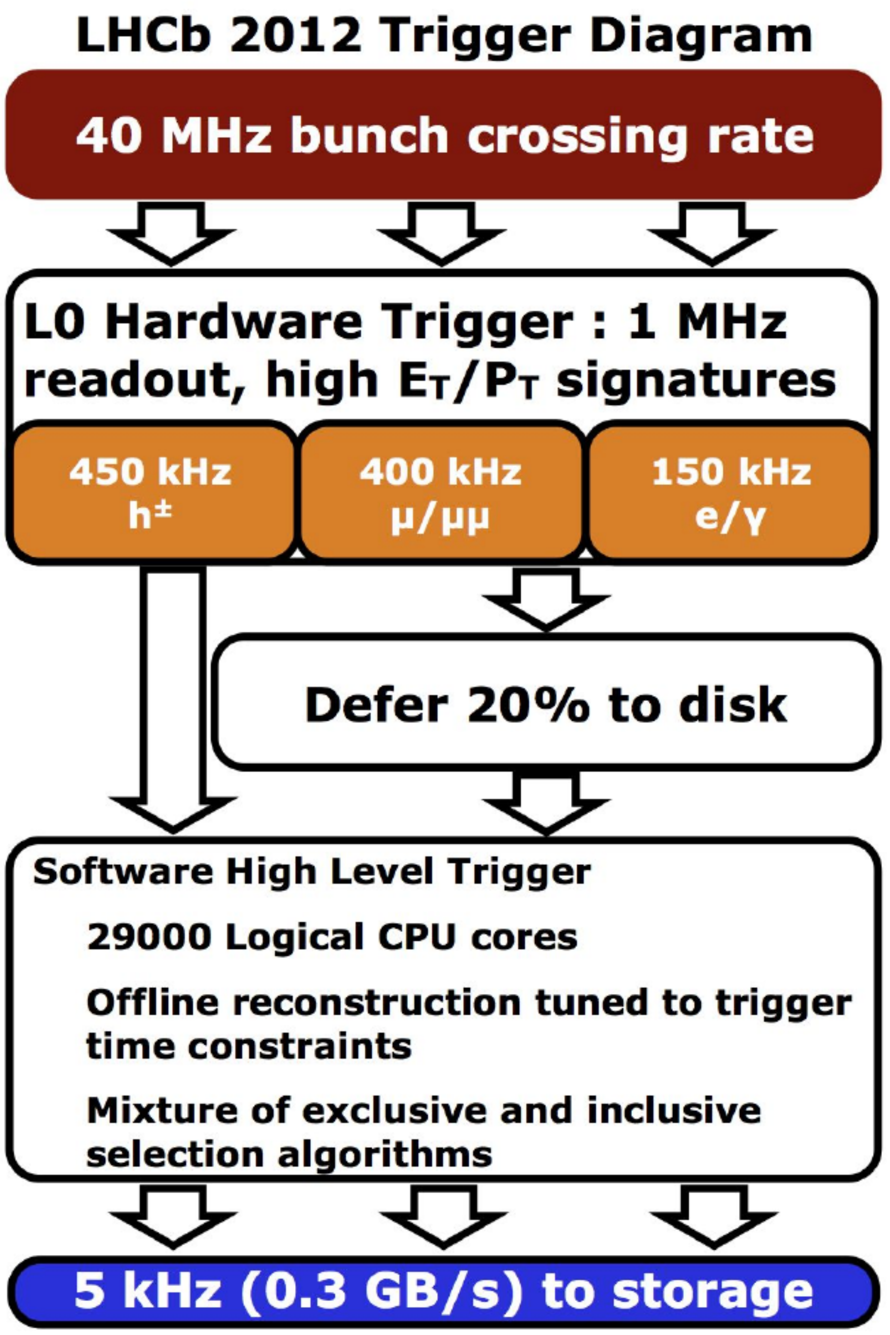
Single-arm forward spectrometer covering rapidity range 2...5 (only 4% solid angle but catches 40% of b-hadrons).

~45 kHz bb pairs and ~1 MHz cc pairs at 13 TeV and L = 4×10^{32} /cm^2/sec

Excellent tracking with efficiency >90% above a few GeV, B mass resolution ~ 20 MeV, primary vertex resolution in X,Y / Z = ~ 15 / 75 um.
Excellent particle identification, $\pi^{\pm}$ / $K^{\pm}$ separation in momentum range 2...100 GeV, muon misidentification probability ~2%.

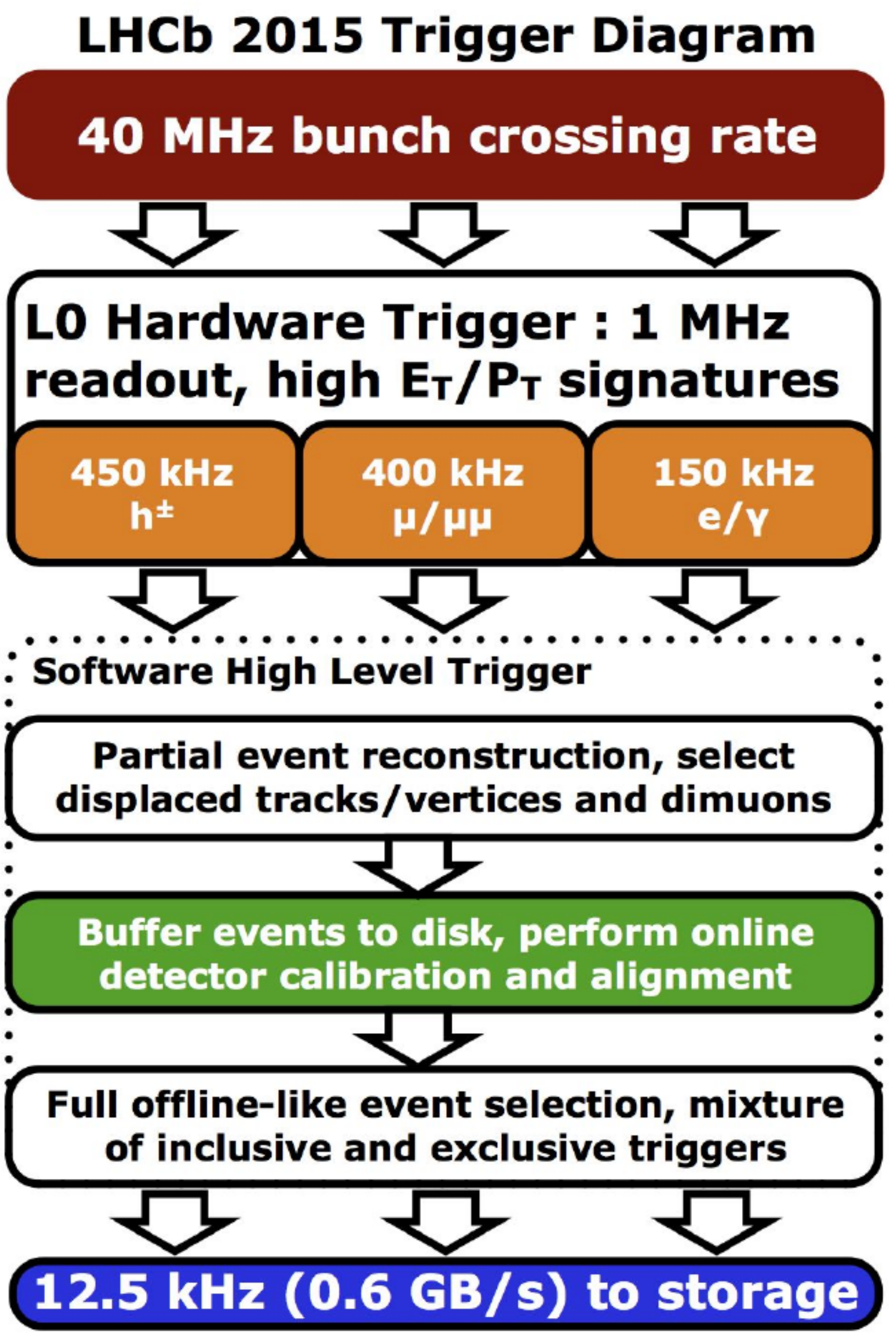
LHCb trigger in Run I

- Hardware trigger, L(evel)0
  - Based on calo and muon detectors
  - Fixed latency of 4 usec
- Software trigger, H(ight) L(evel) T(rigger)
  - Runs on farm of computers (26k CPU cores)
  - 35 msec / event
  - In 2012: 20% of L0 events are stored to disk and processed between LHC fills (“stable beams” ~35% of time).



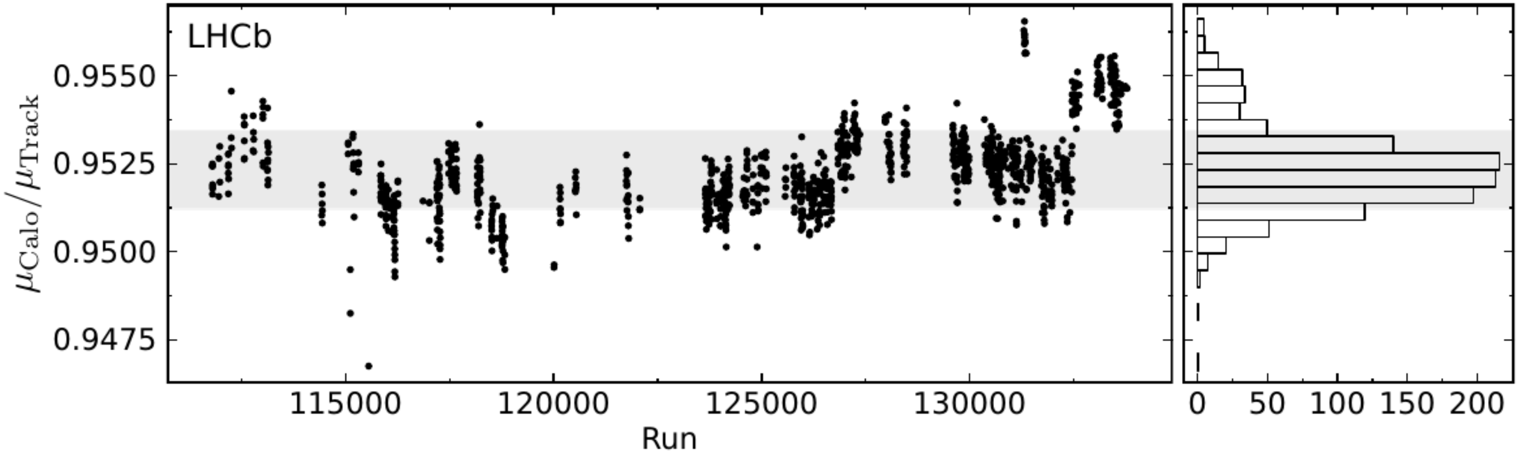
Trigger in Run II, compared to Run I

- Hardware trigger, L(evel)0
  - Same, reoptimized (typically higher) thresholds
- Software trigger, H(ight) L(evel) T(rigger)
  - HLT farm of computers is nearly doubled (51k cores, >5 MCHF)
  - HLT software 40% faster
  - HLT is split in two applications: HLT1 and HLT2, 100% of events are stored to disk after HLT1 at 150 kHz for later processing in HLT2.
    Compared to Run I: 20% of events are stored at 1 MHz.
  - Offline (final) quality alignment and calibration are calculated using stored data and applied already in HLT2. Ie. same reconstruction online and offline.
  - HLT2 output rate is increased to 12.5 = 10 + 2.5kHz.
  - The latter is a "TURBO" stream, with only information on HLT reconstructed objects, most of raw detector data is removed (>90% of space).
    Standard: 10kHz x 70 kB/ev.= 700 MB/sec
    TURBO: 2.5 kHz x 5 kB/ev. = 12.5 MB/sec
    arXiv:1604.05596



Precision of relative L monitoring

Ratio between mu from different luminometers should be constant (not exactly 1 as luminometers have different acceptance and are sensitive to different events). It is a powerful cross check, as various luminometers have different systematics.
From ”Precision luminosity measurements at LHCb”, J. Instrum. 9 (2014) P12005, arXiv:1410.0149, the overall stability of the ratio between eg. “Tracks from IP” and “Calo” luminometers in 2012 is 0.12%:



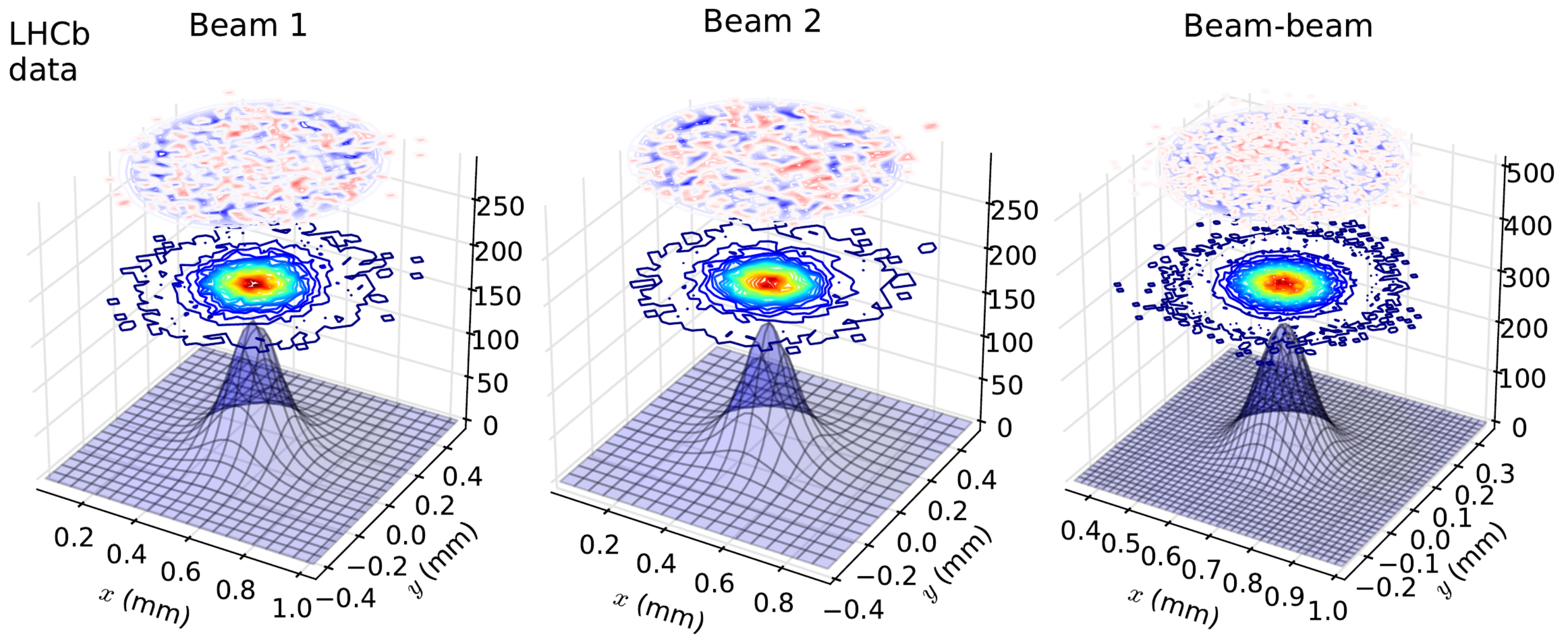
Full systematic uncertainty of relative L monitoring at 8 TeV: 0.31%
(0.53% at 7 TeV, 1.03% in p-Pb at 5 TeV)

Recently, the group from Tsinghua University has taken this responsibility (CERN in the past).
Currently, they are checking the systematics due to a switch in Run II from 50 to 25 nsec.

Beam-gas imaging

Beam profiles are deconvolved with VELO spatial resolution. The latter is determined from data by "split vertex method": split each vertex in two halves, fit them independently and measure a mismatch.
The obtained VELO resolution is parameterized by number of tracks and in z bins.

Two beam-gas images are finally fit to a sum of Gaussians. In addition, the profile of beam-beam interactions proportional to $\rho_1 * \rho_2$ product and measured with high statistics, is used as a stringent constraint. Ie. the fits of ρ_1, ρ_2 from beam-gas and $\rho_1 * \rho_2$ from beam-beam are performed simultaneously.



The best BGI luminosity calibration precision (8 TeV data): 1.43%