Luminosity at LHCb

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on behalf of LHCb collaboration

Outline:

(1) LHCb experiment

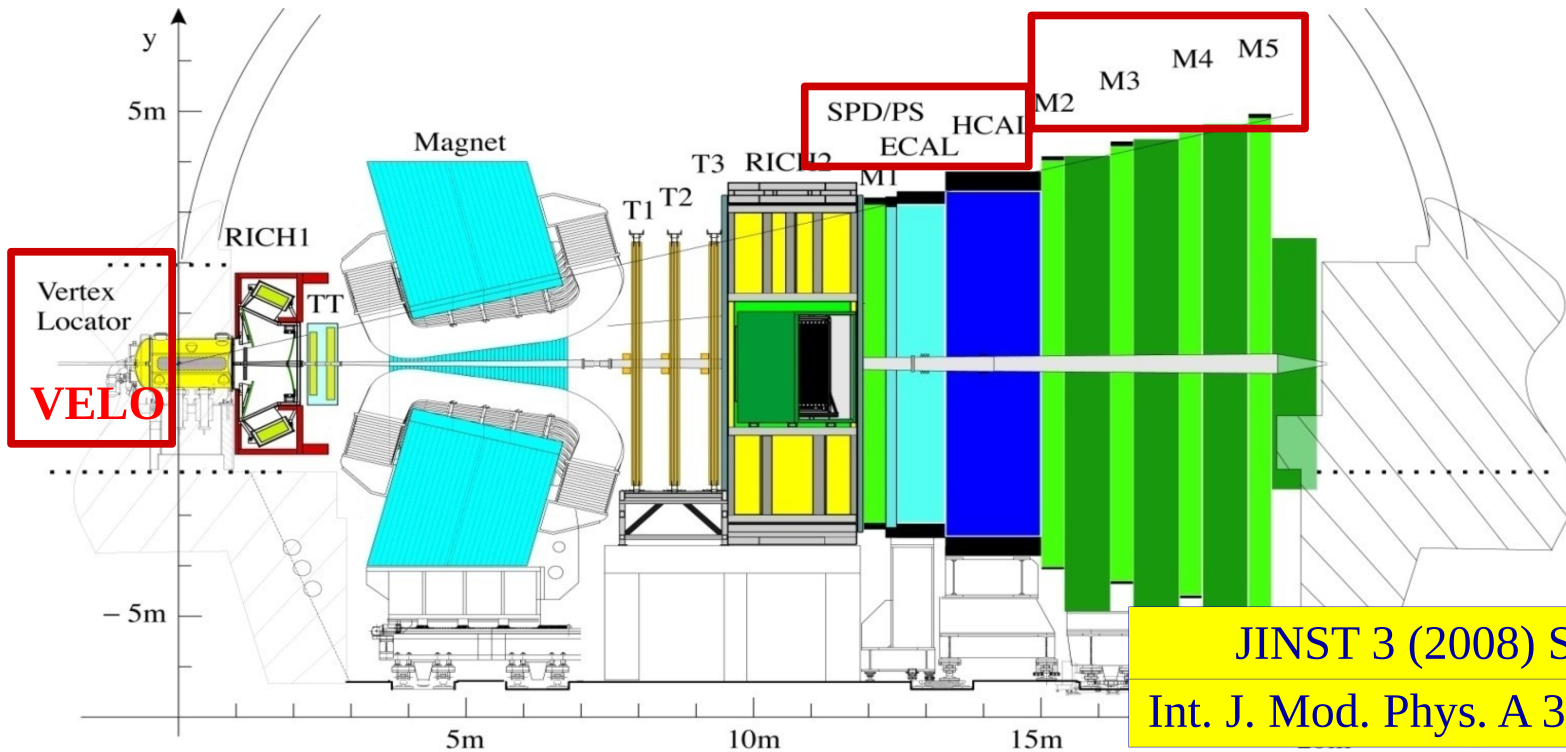
(2) Relative luminosity monitoring during physics data taking

(3) Methods of absolute luminosity calibration:

- beam-gas imaging (BGI) up to now exclusive to LHCb,
- van-der-Meer scan (VDM) used in all 4 LHC experiments

Conclusions

LHCb experiment



JINST 3 (2008) S08005

Int. J. Mod. Phys. A 30 1530022

Single-arm forward spectrometer, $2<\eta<5$ (40% of b-hadrons in 4% solid angle).

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

Track efficiency ≥94% above a few GeV, σ(B mass) ~ 20 MeV, σ(primary VX) ~ 15/75 um in X,Y/Z.

Excellent particle identification, $\pi^\pm$ / $K^\pm$ separation for $2 < p < 100$ GeV, $\mu^\pm$ misID ~ 2%.

Sophisticated hardware (Level 0) and software (High Level) triggers. Online reconstruction = offline.

LHCb luminosity measurement

Task of “common interest”, rough estimation: luminosity measurement was used in 54 LHCb papers (out of 363 published or submitted, ie. about 15%):

W, Z	Y	J/Ψ, Ψ(2S)	c	b	top	Beyond SM
14	6.5	11.5	4	5	2	2

plus

- 1 publication per production of Higgs (upper limit), X(3872), φ, K0S, “V0”,
- 2 publications devoted exclusively to the luminosity measurement and 1 for inelastic σ(pp)

Continuous pile-up monitoring at LHCb

(1) Pile-up = μ = N interactions per bunch crossing ~ 1-2.

(2) Measured in ~1 kHz random events containing only "luminometers":
- VELO: N tracks, vertices (all or close to collision point IP), upstream hits, backward tracks
- SPD preshower: N hits
- Calorimeters: transverse energy
- N muons

(3) Poisson law: $\mu = -\log(P(0))$, P(0)=fraction of "empty" events, eg. N vertexes = 0 or N tracks < 2

(4) Small beam-gas backgrounds ($\leq$1-3%): estimated from non-colliding bunches and subtracted

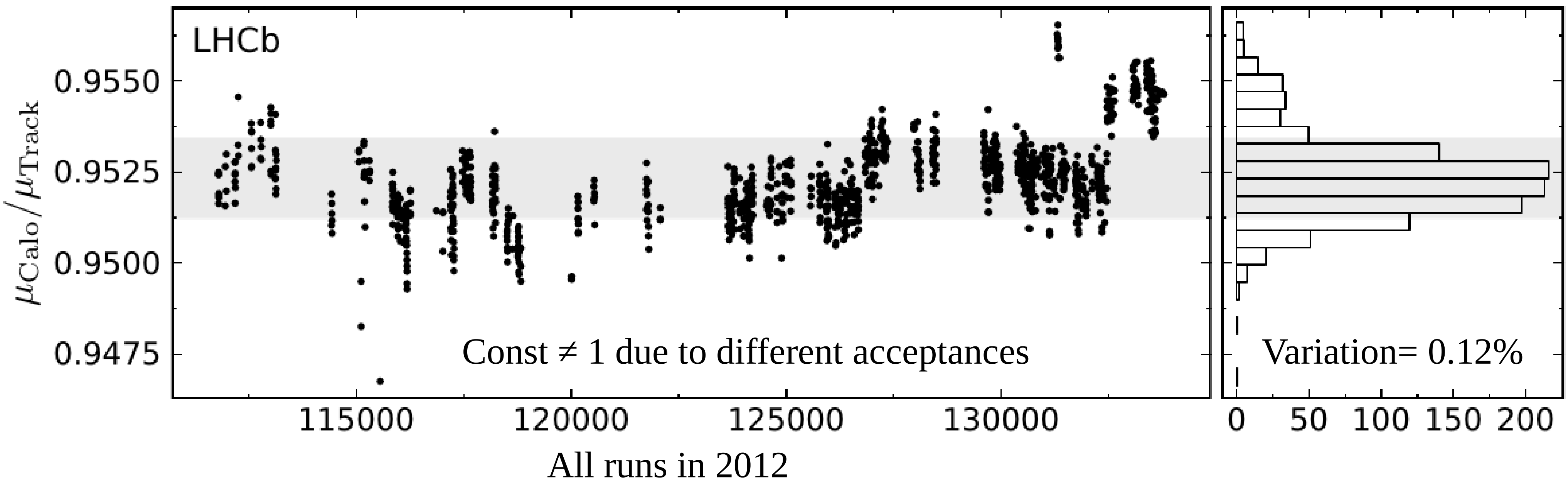
(5) μ is stored per smallest data unit (~10 sec running): low level "mixing" of physics and lumi-data

(6) Lumi-data load to DAQ (CPU, data traffic, storage) << 1%

Precision of relative *L* monitoring

Pile-up ratio between different luminometers (with different systematics) should be constant.
This allows

- to make powerful cross checks and
- to estimate systematic errors



Full systematic uncertainty of relative *L* monitoring: 0.3% (8TeV) – 1% (pPb, 5TeV) in Run I

J. Instrum. 9 (2014) P12005

Absolute calibration of L

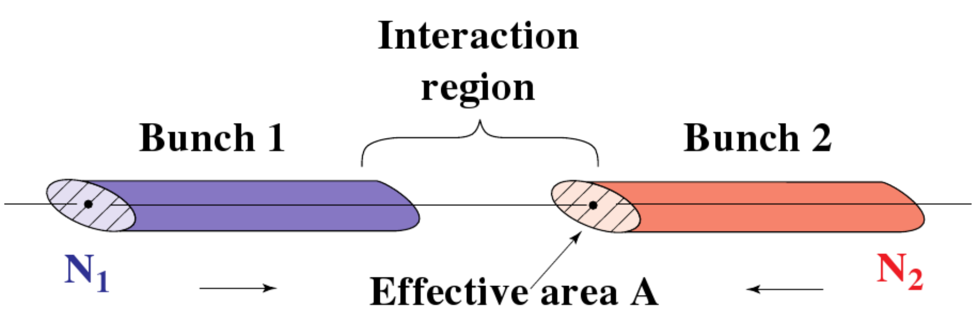
To infer L from N interactions (time integrated μ), one needs “visible” cross section $L = N / \sigma_{vis}$
eg. σ_{vis} of $pp \rightarrow$ event with at least 2 VELO tracks.

(1) The “indirect” absolute calibration using $pp \rightarrow \mu^+\mu^- pp$ or $p \rightarrow Z^0(\mu^+\mu^-)X$ with “known” σ has not reached competitive precision.

(2) Instead, σ_{vis} is determined in dedicated LHC fills from N and L in calibrated samples, where L is measured “directly”, per bunch crossing as

$$L = \frac{N_1 N_2 f}{A_{eff}} = N_1 N_2 f \iint \rho_1(x,y)\,\rho_2(x,y)\,dxdy$$

f – frequency of collisions (precisely known), $N_{1,2}$ – bunch populations, $\rho_{1,2}$ – beam profiles.



Absolute calibration of *L*

$$L = \frac{N_1 N_2 f}{A_{eff}} = N_1 N_2 f \iint \rho_1(x,y)\rho_2(x,y)\,dxdy$$

$N_{1,2}$ are measured in three steps:

- total beam intensities are determined from total beam currents (slowly) measured with high accuracy by LHC direct-current current-transformers (DCCT),
- background (1-2%) in nominally empty LHC bunches or buckets is determined either with LHC equipment (BSRL) and/or with beam-gas interactions in LHCb and subtracted ,
- charge fraction per bunch is measured with LHC fast transformers (FBCT)

Average N_1N_2 uncertainty for 8 TeV pp: 0.22%.

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Beam-gas imaging (BGI)

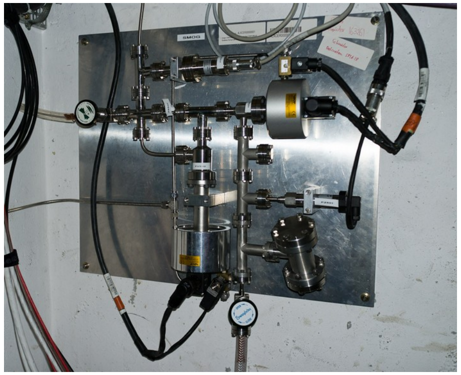
Main difficulty: $\iint \rho_1(x,y)\rho_2(x,y)\,dxdy$

Only at LHCb: find $\rho_{1,2}$ from beam images recorded with beam-gas interactions.

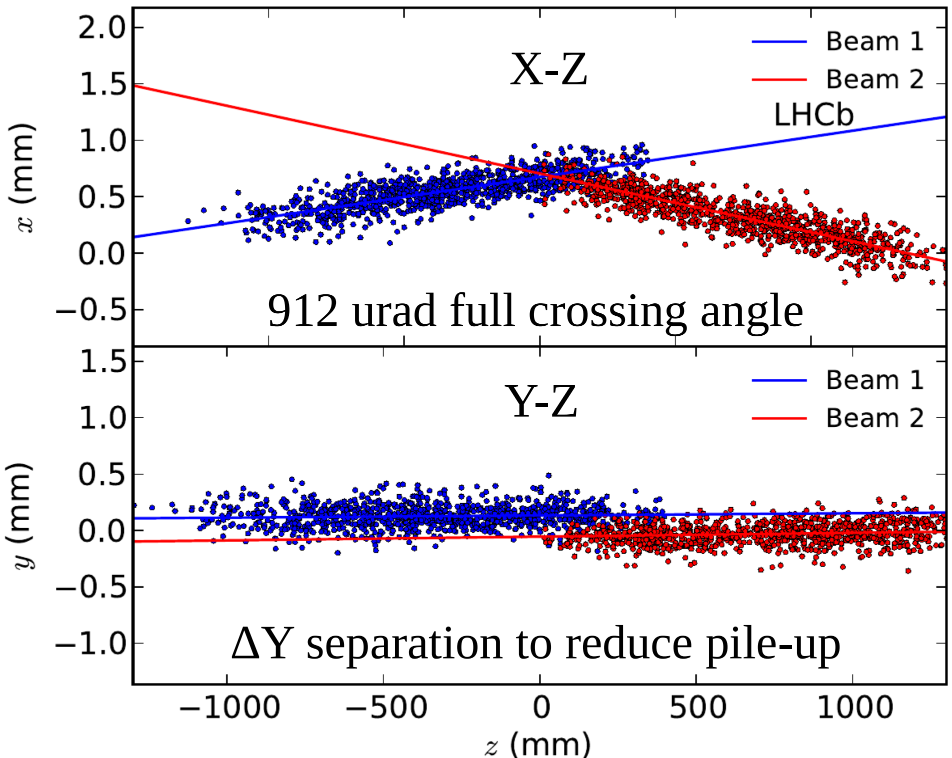
NIM A 553 (2005) 388

PLB 693 (2010) 69

- The very first *L* measurement at LHC in 0.9 TeV pilot run in Dec 2009
- To increase statistics: switch off VELO pumps;
  from Nov 2011 on: inject a tiny amount of gas using a dedicated injection System for Measuring the Overlap with Gas (SMOG) (~50 more interactions)
- SMOG can be used as a fixed target eg. for heavy ion physics



pAr: LHCb-ANA-2017-010
presented at Quark Matter'17
https://indico.cern.ch/event/433345/contributions/2358535/



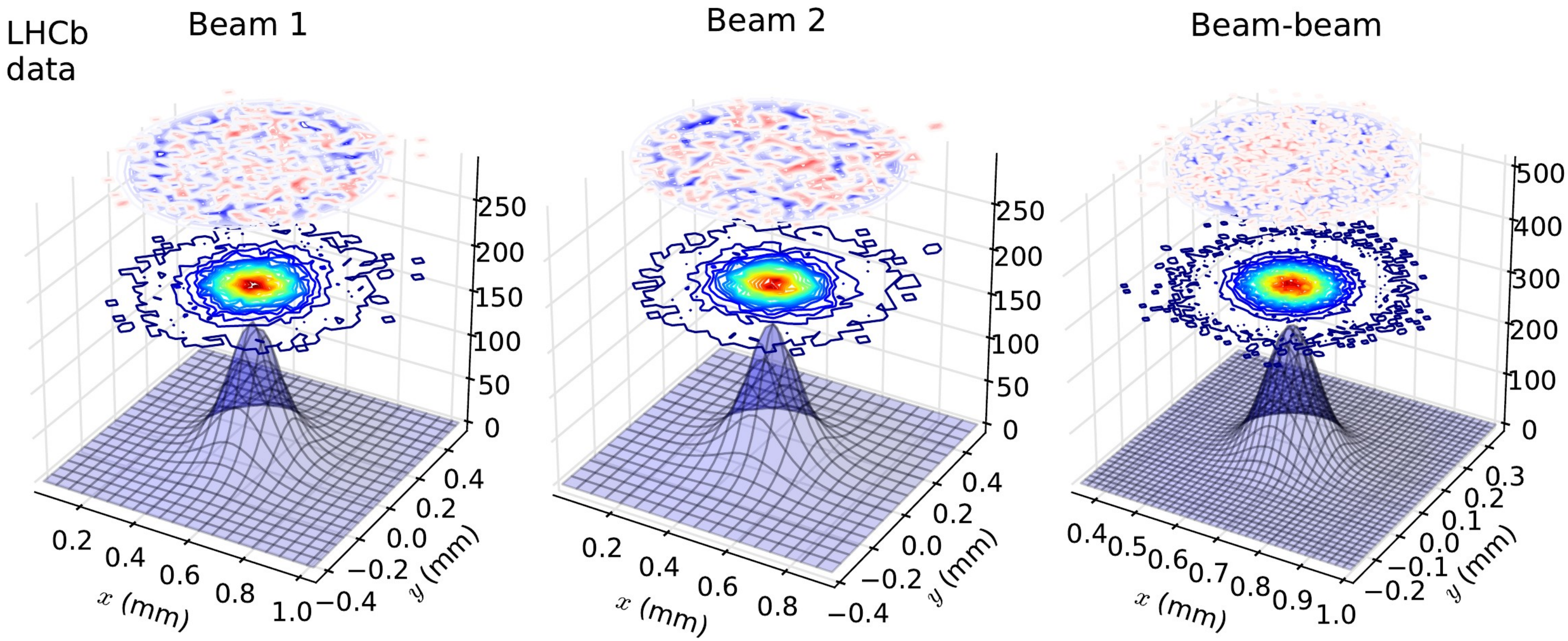
First 1000 vertexes in fill 2852 (Run I).

Typical x,y (z) beam widths: 0.1 (40) mm

Beam-gas imaging

Beam profiles are unfolded with VELO spatial resolution, determined from data as a function of N tracks, z position and interaction type (beam-beam or beam-gas).

To improve precision: $\rho_{1,2}$ are fit to a sum of Gaussians simultaneously with the precisely measured beam-beam profile $IP(x,y) \sim \rho_1\rho_2$.

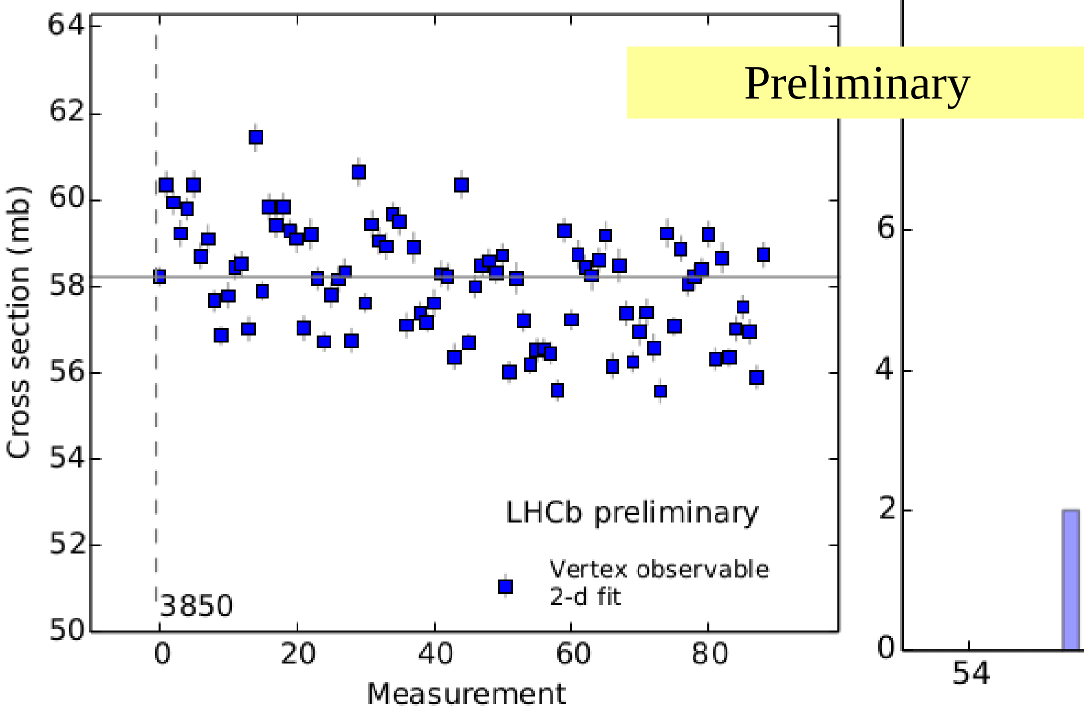


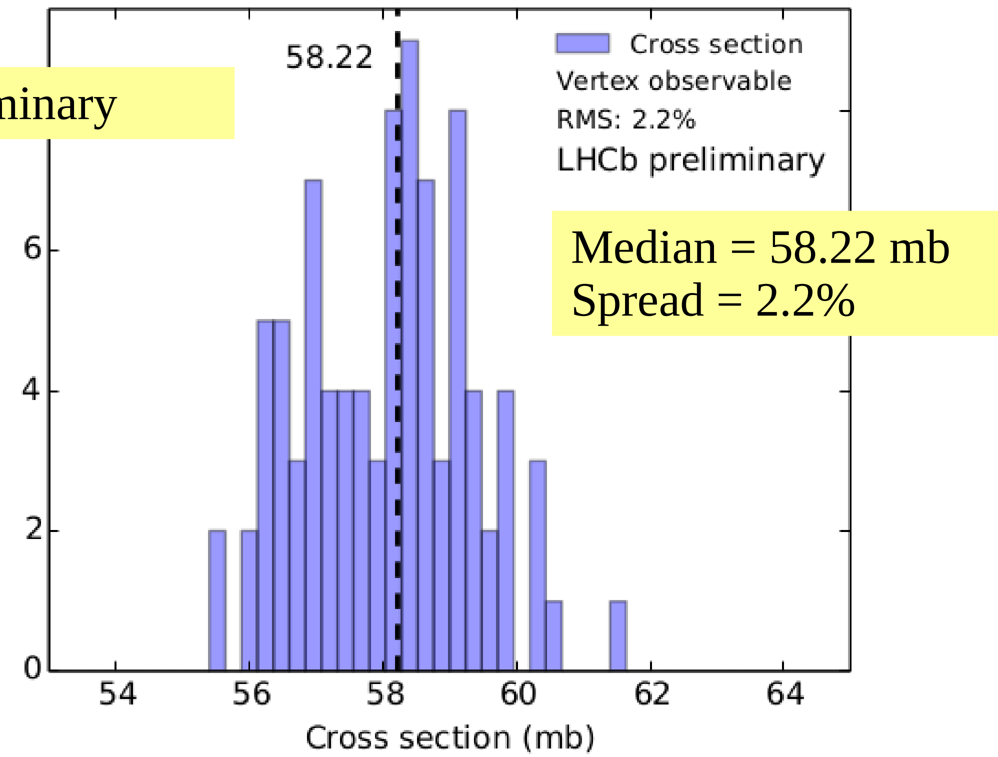
2D fit for one bunch pair as an example. Pulls are shown by color in ±3 range in the top.

The best BGI luminosity calibration precision (8 TeV data): 1.43% J. Instrum. 9 (2014) P12005

Beam-gas imaging for 13 TeV pp in Run II

σ_{vis} for “Vertex” observable per bunch crossing and 20 minute interval



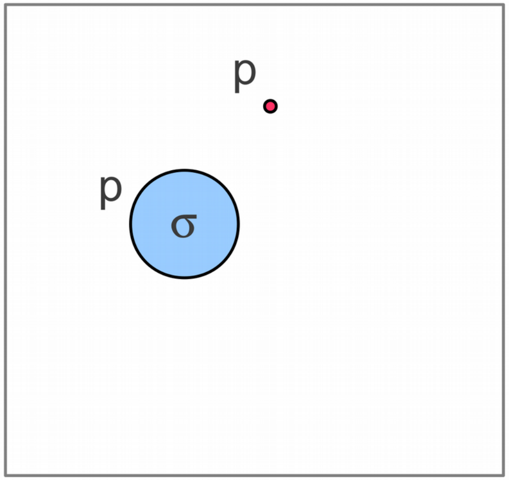


Preliminary luminosity precision in Run II for pp at 13 TeV: 3.9% (“fast estimation”).

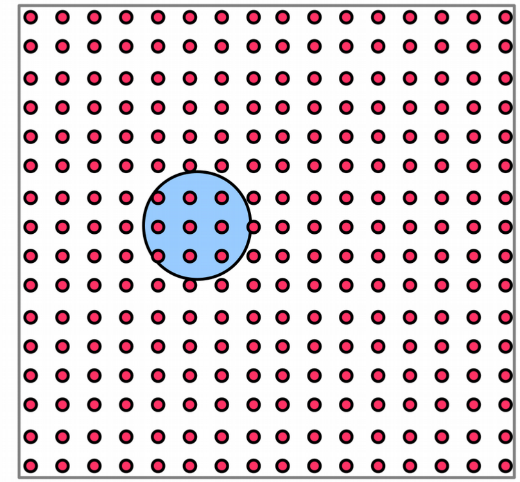
Ultimate <2% accuracy will require significantly more work and cross checks.

Van der Meer scan

Idea: sweep one beam across the plane.



Van der Meer scan



Idea: sweep one beam across the plane. This integrates its ρ out:

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

and

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

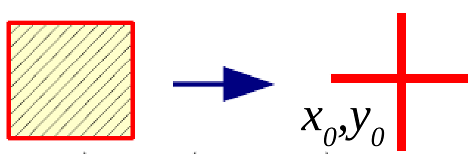
Suggested by van der Meer in 1968.

CERN ISR-PO-68-31

Works for any $\rho_{1,2}$ and any LHC crossing angle

(relativistic correction due to transverse velocity is negligible).

If $\rho_{1,2}$ factorize in x,y:



Raster scan

Scan along X,Y axes (done at LHC)

$$\sigma = \frac{\int \mu(\Delta x, y_0)\, d\Delta x \cdot \int \mu(x_0, \Delta y)\, d\Delta y}{\mu(x_0, y_0)\, N_1 N_2}$$

“Crossing point” x_0,y_0 may be chosen arbitrarily.

Another possibility: swept beam effectively becomes broad and uniform.

Similarly to “beam gas” it provides beam-beam imaging after unfolding with VELO resolution V:

$$IP = (\rho_1 \rho_2) \circ V$$

$$[\rho_2 \circ V](x) \ \propto \ \int IP(x, \Delta x)\, d\Delta x$$

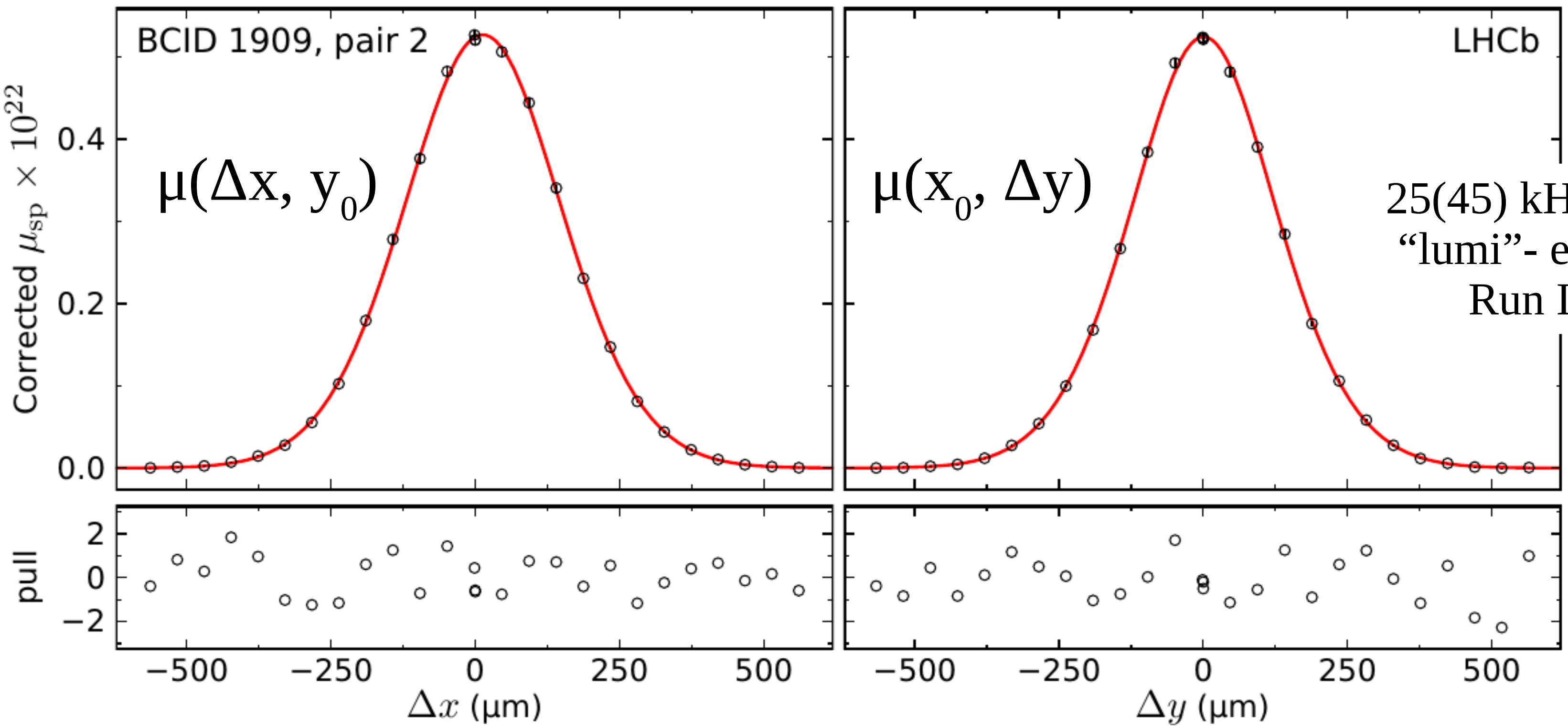
(for Δx in frame of fixed beam 2)

NIM, A 654 (2011) 634

J. Instr. 7 (2012) P01010

Van der Meer scan

μ in one bunch crossing in X, Y scans, fit to sum of Gaussians.
Small x-y non-factorizability is taken from BGI



$\mu(\Delta x, y_0)$ $\mu(x_0, \Delta y)$

25(45) kHz rate of "lumi"- events in Run I (II)

$$\sigma = \frac{\int \mu(\Delta x, y_0) d\Delta x \cdot \int \mu(x_0, \Delta y) d\Delta y}{\mu(x_0, y_0) N_1 N_2}$$

Future analysis:

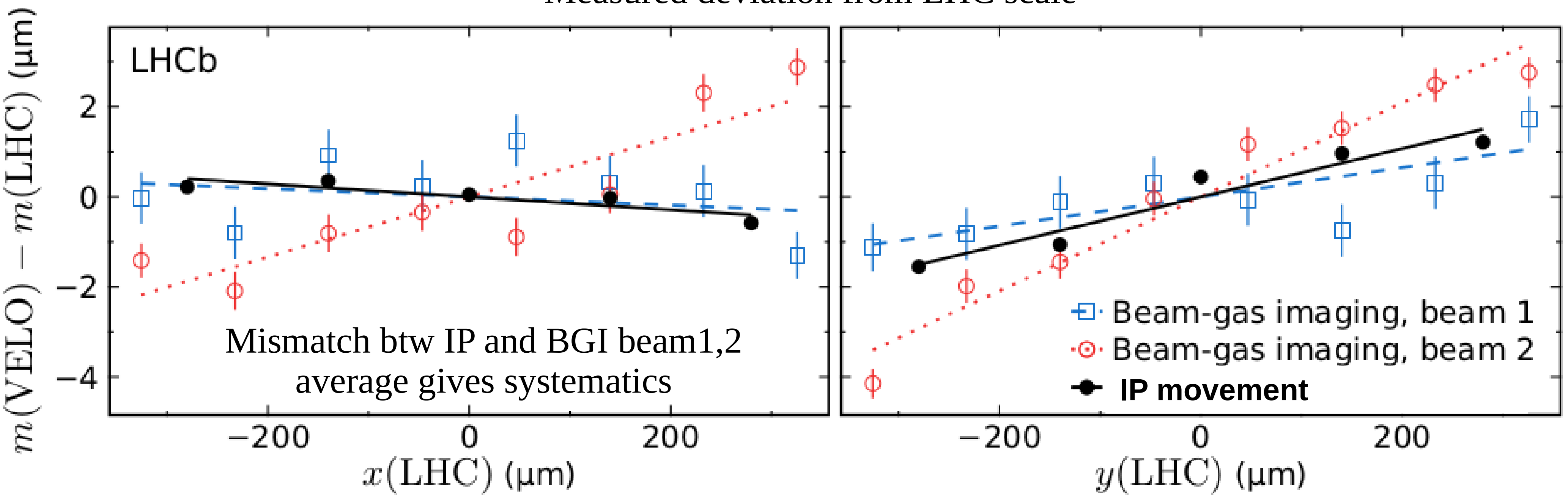
- "diagonal" scans in 2015-16 to assess x-y factorizability,
- comparison of VDM beam-beam and BGI images.

VDM length scale calibration

$\sigma \propto \int ...d\,\Delta x \int ...d\,\Delta y$ directly depends on Δx,Δy scale.

Calibration: beams move ***synchronously*** in X or Y.
IP movement (by the same amount) is precisely measured by VELO and cross-checked by BGI.

Measured deviation from LHC scale



The best VDM luminosity calibration precision (8 TeV data): 1.47%

J. Instrum. 9 (2014) P12005

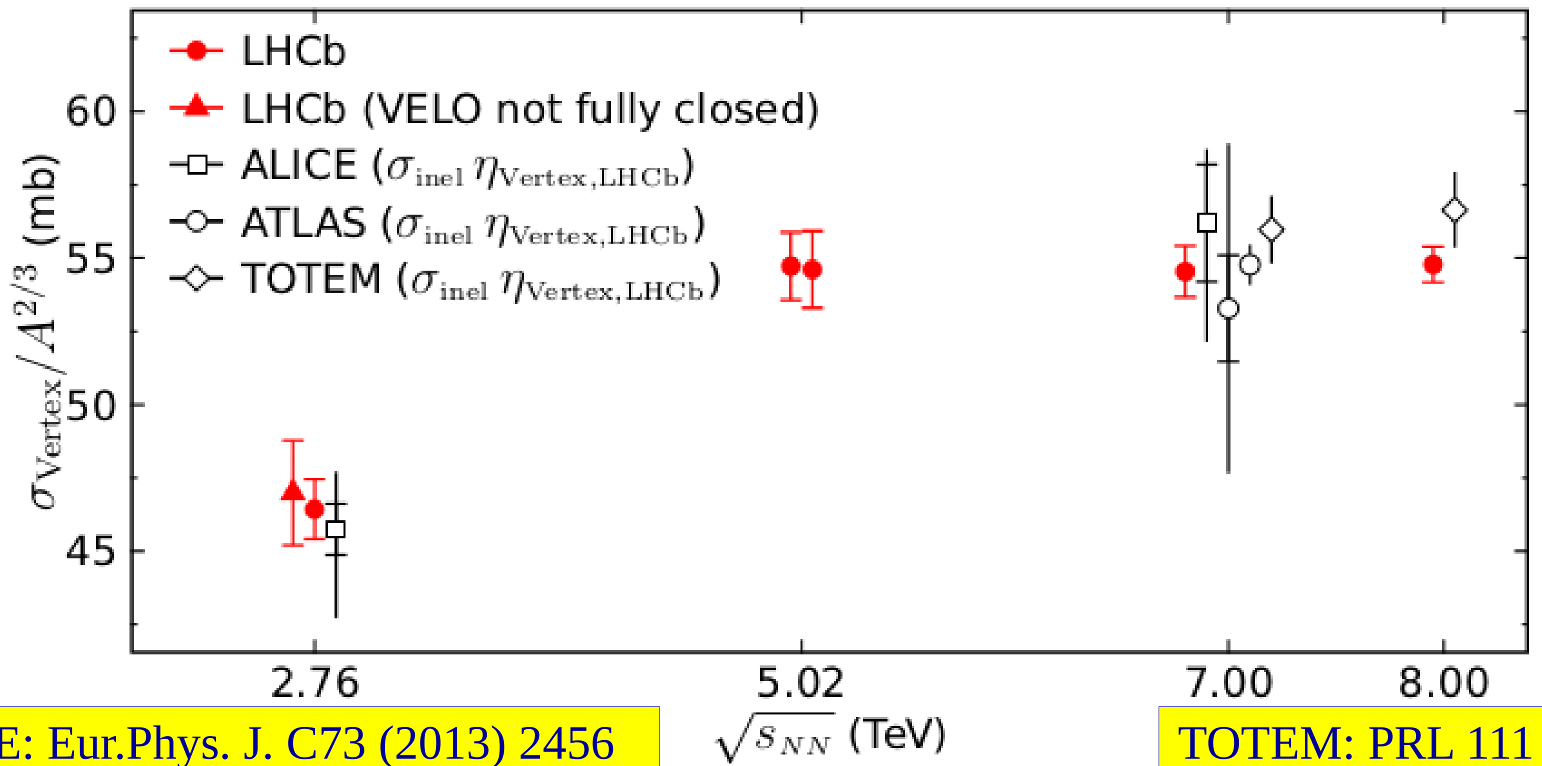
Results

Method	σ_{vis} (mb)	Absolute calibration Weight	Absolute calibration Uncertainty (correlated)	Relative calibration uncertainty	Total uncertainty
pp at $\sqrt{s} = 8$ TeV					
BGI	60.62 ± 0.87	0.50	1.43% (0.59%)		
VDM	60.63 ± 0.89	0.50	1.47% (0.65%)		
Average	60.62 ± 0.68		1.12%	0.31%	1.16%
pp at $\sqrt{s} = 7$ TeV					
BGI	63.00 ± 2.22	0.13	3.52% (1.00%)		
VDM	60.01 ± 1.03	0.87	1.71% (1.00%)		
Average	60.40 ± 0.99		1.63%	0.53%	1.71%
pp at $\sqrt{s} = 2.76$ TeV					
BGI	52.7 ± 1.2		2.20%	0.25%	2.21%
pPb at $\sqrt{s_{NN}} = 5$ TeV					
VDM	2126 ± 49		2.05%	1.03%	2.29%
Pbp at $\sqrt{s_{NN}} = 5$ TeV					
VDM	2120 ± 53		2.36%	0.82%	2.50%

Preliminary result from Run II, BGI pp:
σ_{vis} = 63.4 mb (3.9% precision) at 13 TeV and 56.4 mb (3.8% precision) at 5 TeV.

Comparison with other experiments

Inelastic σ scaled to LHCb “Vertex” lumi-counter acceptance using MC efficiency η_{Vertex}.
p-Pb cross-section at 5.02 TeV is scaled by $A^{-2/3}$. From J. Instrum. 9 (2014) P12005



ALICE: Eur.Phys. J. C73 (2013) 2456

ATLAS: Nature Com. 2 (2011) 463;
Nucl.Phys. B889 (2014) 486-548

TOTEM: PRL 111 (2013) 012001;
Europhys. Lett. 101 (2013) 21004)

Most recent results
(not plotted, 1.9% precision for 2012 data)

ATLAS: Eur. Phys. J. C 76 (2016) 653

Conclusions

(1) LHCb pile-up μ

- continuously measured in ~1 kHz random events using "luminometers" (default: N VELO tracks from IP).
- Fraction of empty events P(0) (eg. with N(tracks)<2) gives μ = - log(P(0)).
- Small beam-gas backgrounds are subtracted.
- Comparison between "luminomiters" gives estimation of systematics.
- Lumi-data load to DAQ (CPU, data traffic, storage) << 1%.

(2) Absolute calibration, ie. conversion from pile-up rates to luminosity, is performed mostly in the dedicated LHC fills a few times per year using

- Beam-Gas Imaging (exclusive to LHCb) and
- van der Meer scans (all LHC experiments).

They are largely independent and give a comparable precision. The procedures are rather complex and determine the resulting systematics.

(3) Precision for Run I is very good, eg. for 8 TeV pp data (2012) it is 1.16%, the record for bunched-beam hadron colliders (in particular, the best among 4 LHC experiments), J. Instrum. 9 (2014) P12005, arXiv:1410.0149. Preliminary result for Run II 13 TeV (5 TeV) pp exists and has 3.9% (3.8%) precision, analysis is ongoing.

Backup slides

Trigger in Run II

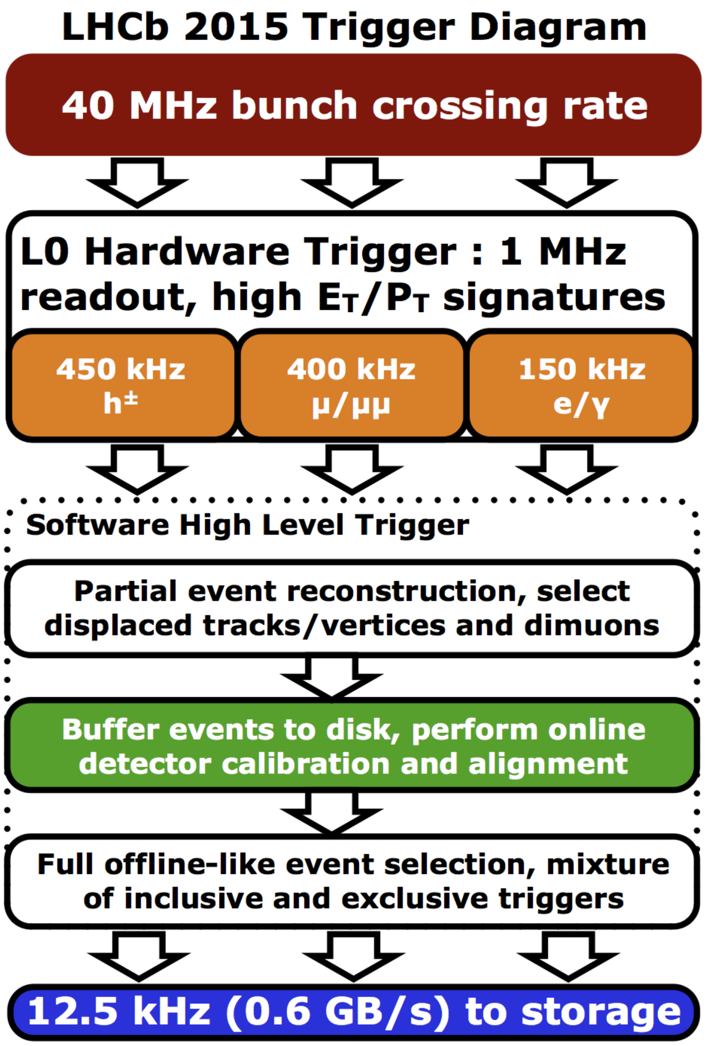
(1) Hardware "level 0" trigger, 4 usec fixed latency.

(2) Software, H(ight) L(evel) T(rigger) = HLT1 + HLT2

Many changes w.r.t. to Run I:

- 51k CPU cores, nearly doubled
- 40% faster HLT code
- After HLT1 all events are stored to disk at 150 kHz, then asynchronously processed in HLT2 independently of LHC fills (stable beams ~ 1/3 time)

  In Run I: 20% of events stored at 1 MHz before HLT.
- Final, offline quality alignment and calibration are calculated during first minutes and applied in HLT2, no offline reconstruction (online = offline).
- In aqddition to "standard" evetns, HLT2 outputs also "TURBO" stream of events containing only HLT reconstructed objects without raw detector data (>90% of space), arXiv:1604.05596.



Systematics pp, 8 TeV

Every measurement includes lots of cross-checks and evaluation of associated systematics.

Here, the list of errors is presented for 8 TeV pp measurement with the best overall precision 1.16%.

Source	BGI	VDM	Correlated
Bunch population uncertainties			
FBCT offset	0.04	0.05	yes
BPTX cross-check	n.a.	0.09	yes
DCCT population product	0.22	0.23	yes
Ghost charge	0.02	0.04	yes
Satellite charge	0.06	0.02	yes
Missing satellite measurements	n.a.	0.23	no
Rate measurement			
Background subtraction	0.20	0.14	yes
Ratio of observables *Track* to *Vertex*	0.20	n.a.	no
Efficiency of rate observables	negl.	0.09	no
Fit model	0.50	0.50	yes
VELO transverse scale	0.05	0.05	yes
BGI specific			
Beam-beam resolution	0.93		no
Beam-gas resolution	0.55		no
Detector alignment	0.45		no
Measurement spread	0.54		no
Bunch length	0.05		no
Reconstruction efficiency	0.04		no
Pressure gradient	0.03		no
VDM specific			
Length scale		0.50	no
Beam-beam effects		0.28	no
Fit bias		0.20	no
Linear correlation		0.08	no
Parameter assumptions		0.74	no
Constraints from BGI		0.30	yes
Scan variation and drift		0.32	no
Non-reproducibility		0.80	no
Statistical		0.04	no
Uncorrelated	1.31	1.32	
Correlated	0.59	0.65	

J. Instrum. 9 (2014) P12005