Luminosity measurement at LHCb and other LHC experiments

French-Ukrainian workshop, LAL, 26 Sep 2018
Vladislav Balagura (LLR – Ecole polytechnique)

Outline:

(1) Luminosity mesurement in general

(2) LHC luminometers, comparison

(3) Absolute calibration

- from beam-gas “photos” of colliding bunces
- van der Meer (vdM) scans
- from reaction with known cross-section (fixed-target)

(4) Novelties in two last vdM LHCb scans

Conclusions

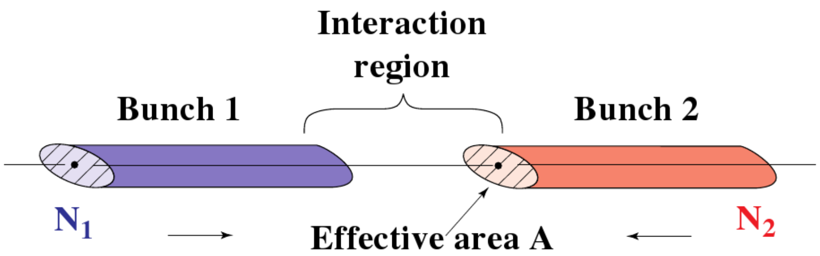
How to measure luminosity?

1) Relative luminosity measurement can use any linear detector:

$$R = \sigma_{vis} L$$

where R is event rate, σ_{vis} - « visible » cross section and L – instantaneous luminosity. Having several luminometers crucial for systematics estimation.

2) Absolute luminosity calibration, ie. σ_{vis}, from :



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

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

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

TOTEM and ALFA measurements based on optical theorem will not be covered.

Where do we need luminosity?

Online – to optimize performance of detectors, monitor beams and for adjusting luminosity (leveling)

Offline – ultimate precision for physics analyses

- Integrated Luminosity uncertainty already is the dominant in (some) SM measurements

	$\sigma^{\mathrm{fid},\mu}_{W\to\mu\nu}$ [pb]
$W^+ \to \mu^+\nu$	2839 ± 1 (stat) ± 17 (syst) $\boxed{\pm\ 51\ \text{(lumi)}}$
$W^- \to \mu^-\bar{\nu}$	1901 ± 1 (stat) ± 11 (syst) $\boxed{\pm\ 34\ \text{(lumi)}}$
	$\sigma^{\mathrm{fid},\mu}_{Z/\gamma^*\to\mu\mu}$ [pb]
$Z/\gamma^* \to \mu^+\mu^-$	477.8 ± 0.4 (stat) ± 2.0 (syst) $\boxed{\pm\ 8.6\ \text{(lumi)}}$

"Precision measurement and interpretation of inclusive W^+, W^- and Z/γ^* production cross sections with the ATLAS detector", ATLAS Collaboration, Eur. Phys. J. C (2017) 77:367"
(2011 data, $\sqrt{s}$ = 7 TeV, 4.6 fb^{-1})

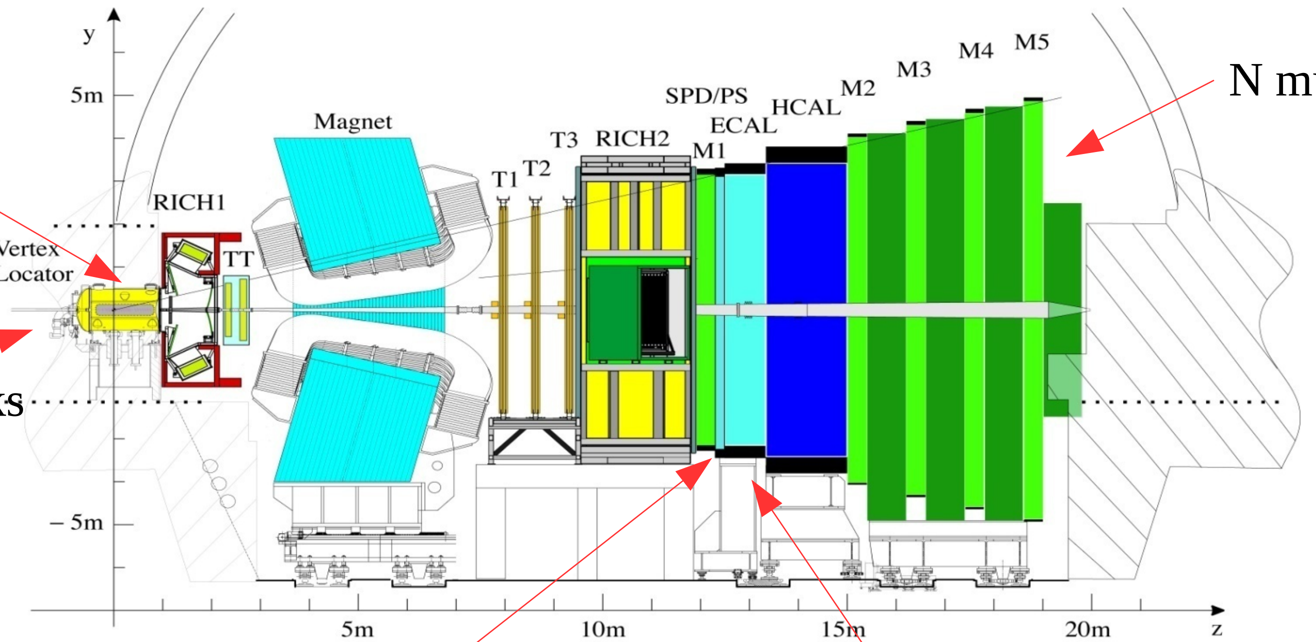
- Theorists are pushing for a ~1% Luminosity measurement at HL-LHC
  - see e.g. G. Salam @ ECFA 2016 (https://indico.cern.ch/event/524795/contributions/2235443/attachments/1347759/2034269/HL-LHC-SMHiggs-theory.pdf)
- Total Higgs production cross-section uncertainty estimated to be ~3% given a luminosity uncertainty of 1.5%

LHCb luminometers

N vertices
N Velo tracks (best)

N backward tracks
N upstream hits

N muons



N hits in preshower (SPD)

Calorimetric transverse energy

Measured in ≈1 kHz random stream of « nano-events » containing only “luminometers”.

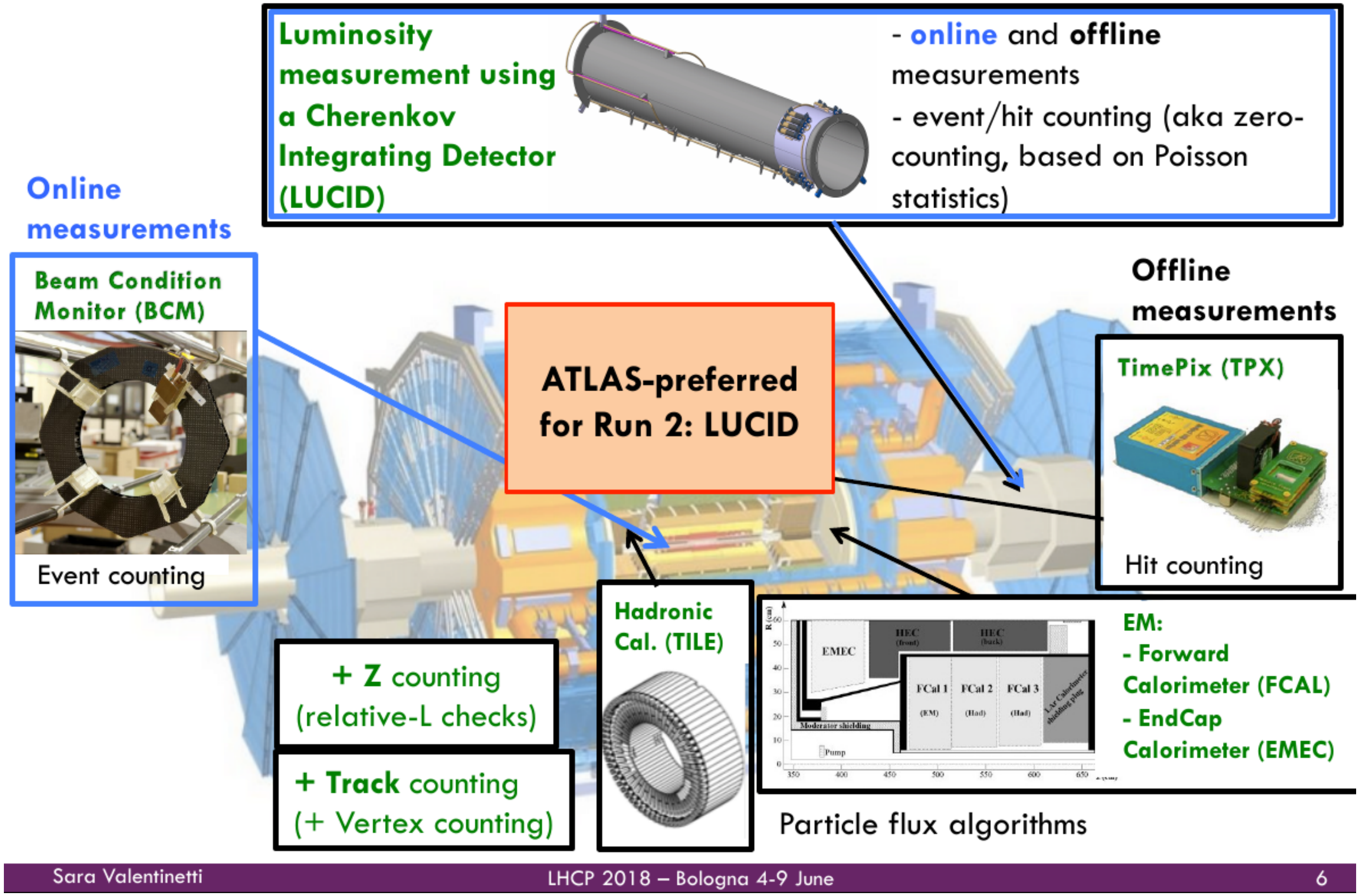
N interactions per bunch crossing: μ ~ 1-2, calculated from Poisson law, $\mu = -\log(P(0))$, P(0)=fraction of “empty” events (eg. N vertexes = 0 or N tracks < 2). Less systematics as no strict linearity required.

Small beam-gas backgrounds (≤1-3%): estimated from non-colliding bunches and subtracted

Level 0 CALO trigger (or BCM when L0CALO is OFF) for online luminosity monitoring

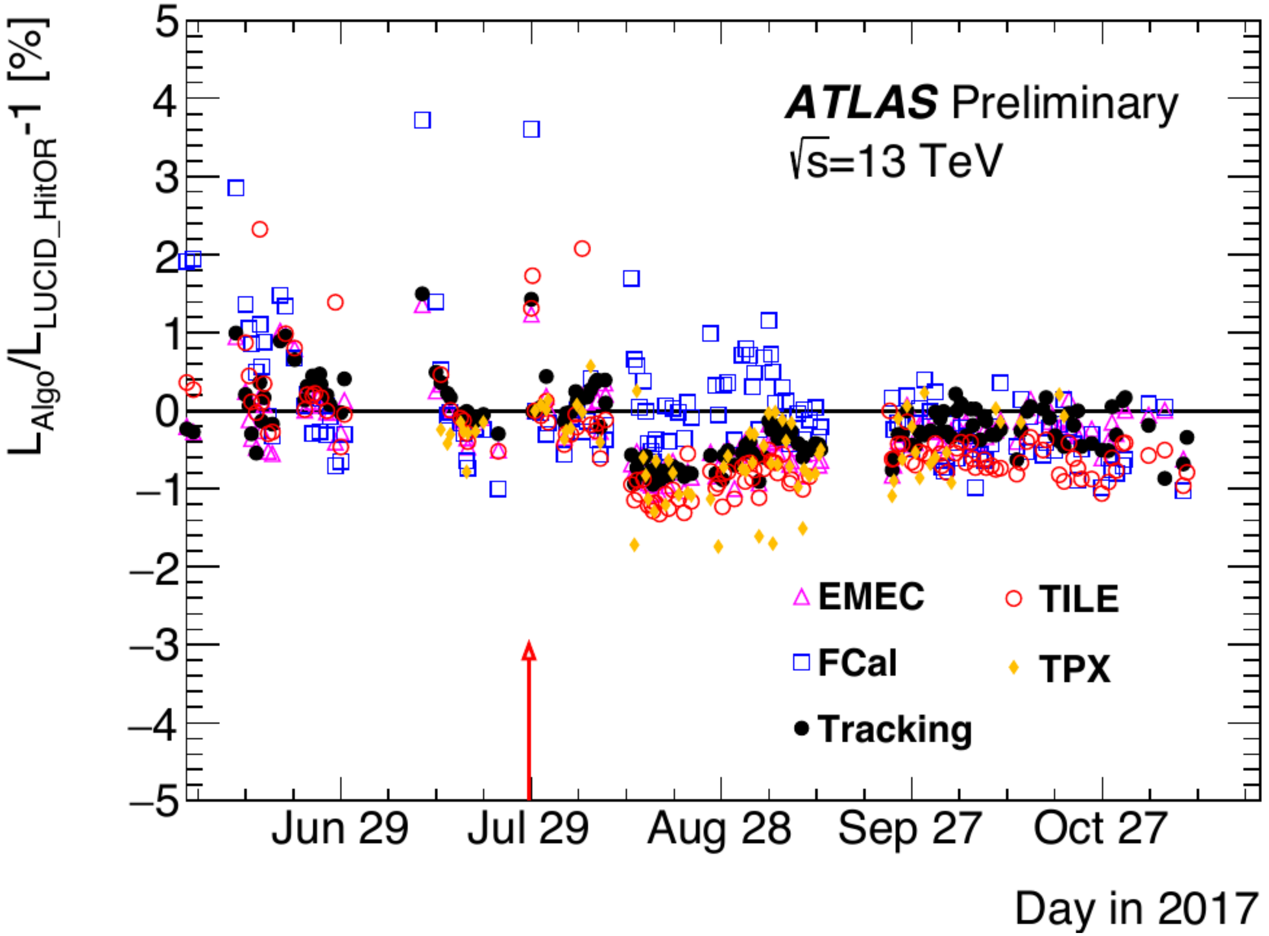
μ is stored per smallest data unit (~10 sec running): low level “mixing” of physics and lumi-data
<<1 % load to DAQ in CPU, data trafic and disk space.

ATLAS luminometers



1. BCM (diamond sensors) from LHC – best in Run I, train dependency in Run II
2. LUCID – newly installed and best in Run II: provides offline + online luminosity
3. Inner Detector (tracks) – bunch-by-bunch, but rate limited
4. Calorimeters: bunch integrating, currents in TileCal PMT, in EMEC and FCAL LAr gaps

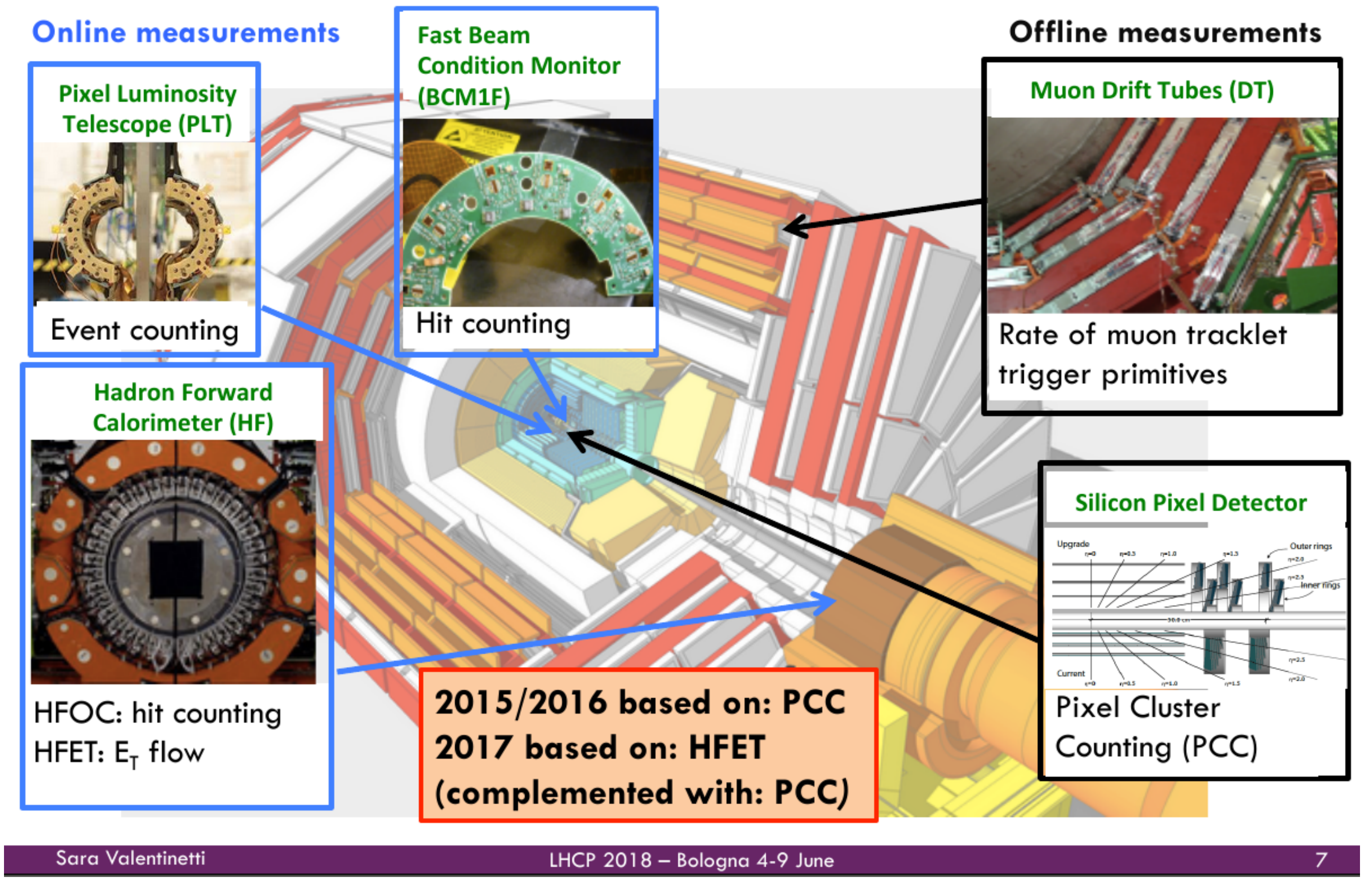
ATLAS luminometers



Fractional stability between LUCID and other ATLAS luminometers versus time,
LUCID run-to-run stability = 1.3%

CMS luminometers

Run II



- 3 luminometers independent of central DAQ ("always" operational):
  a) Pixel Luminosity Telescope (PLT),
  b) Fast Beam Conditions Monitor (BCM1F), with a) uses zero-counting method,
  c) dedicated readout on hadronic forward calorimeter (HF), afterglow correction, best online+offline

- 2 luminometers in main CMS DAQ:
  a) muon drift tube "track" counter (DT), integrates bunches,
  b) pixel cluster counting (PCC) with "zero-bias" trigger, after exclusion of some modules and time dependent afterglow corrections – similar precision to offline HF

ATLAS and CMS

- high pile-up $\mu \sim 40$: fraction of “empty” bunch crossings is essentially zero, $\mu = -\log(P(0))$ method directly not applicable (but can be recovered by redefining “visible” event as occupying 1/40 phase space eg. in acceptance, having muon etc.)

- without $\mu = -\log(P(0))$: luminometer linearity = dominating source of systematics: dependence on pile-up, LHC filling scheme (eg. bunch spacing) etc.

- in vdM calibration fills: $\mu \sim 1$, large linear dynamic range required to extrapolate to physics $\mu \sim 40$

- special emphasis (not really justified?) to have ***precise*** luminometer independent of common detector DAQ

- ageing of luminometers and other instrumental instabilities require
a) corrections and
b) vdM re-calibrations every year.
In LHCb measured visible cross-section is stable.

- CMS: beam-gas background can not be estimated from be, eb crossings and subtracted (by luminometers design), parameterized in vdM scan fits.

- CMS: a few minutes, short vdM scans (called “emittance”) in beginning / end of every fill.
Take physics time, but necessary to (approximately) re-calibrate luminometers, measure ageing effects and pile-up dependences

CMS luminosity in 2017

Table 4: Summary of the systematic uncertainties entering the CMS luminosity measurement for $\sqrt{s} = 13$ TeV pp collisions. When applicable, the percentage correction is shown.

	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	-0.9	0.3
	Orbit drift	—	0.2
	x-y correlations	+0.8	0.8
	Beam-beam deflection	+1.6	0.4
	Dynamic-β^*	—	0.5
	Beam current calibration	—	0.3
	Ghosts and satellites	—	0.1
	Scan to scan variation	—	0.9
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	0.4–0.6	0.6
Integration	Afterglow (HF)	—	$0.2 \oplus 0.3$
	Cross-detector stability	—	0.5
	Linearity	—	1.5
	CMS deadtime	—	0.5
	Total		2.3

ATLAS and CMS overall precision

High luminosity i.e. Standard data taking

	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
Running period	2012 pp	2012 pp	2015 pp	2015 pp	2016 pp	2016 pp	2017 pp	2017 pp
$\sqrt{s}$ [TeV]	8	8	13	13	13	13	13	13
σ_L/L [%]	1.9	2.6	2.1	2.3	2.2	2.5	2.4 *preliminary*	2.3

ATLAS Ref: https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics

CMS Ref: CMS-PAS-LUM-17-004/17-004/15-001/13-001

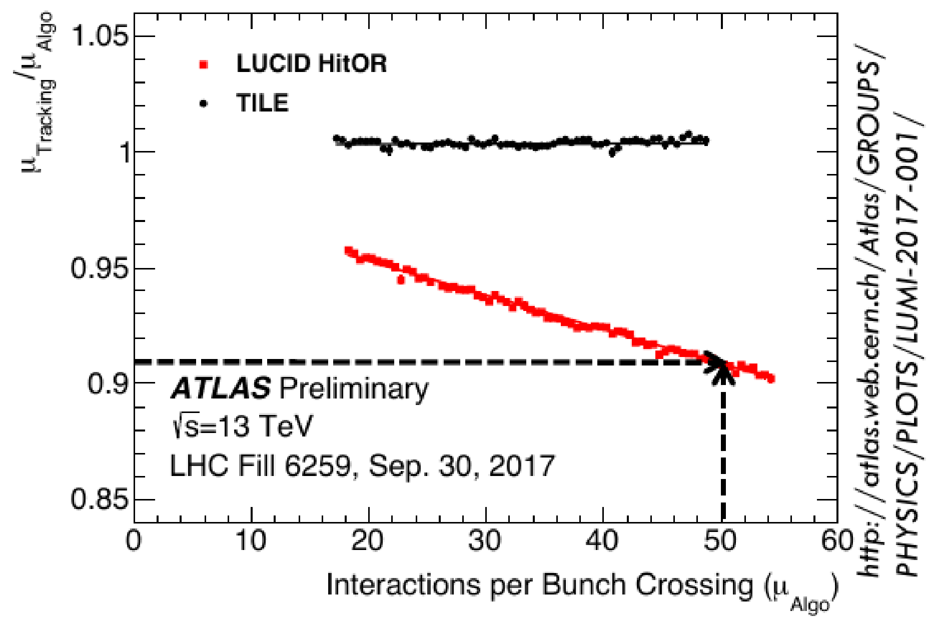
Excellent precision!

Extrapolating from vdM to physics

Shift in luminometer response between vdM (low $\mathcal{L}$, low μ, few bunches far apart) and physics (high $\mathcal{L}$, high μ, more than 2000 bunches in trains of 25 ns)

➢ ATLAS:

- Non-linearity correction from Track-based $\mathcal{L}$
  - typical correction @ μ = 50 for LUCID hit counting in 2017: - 9%
- Systematic uncertainty evaluated by comparing with calorimeter-based correction in 2017: ±1.3%



➢ CMS:

- Non-linearity correction from emittance-scan analysis (i.e. "absolute")
  - typical correction @ μ = 50 for HFET in 2017: 1.5 %
- Systematic uncertainty evaluated by comparing residual relative non-linearity of luminometers on 2017: ±1.5%

ATLAS Ref.: https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics
CMS Ref.: *CMS-PAS-LUM-17-004*

ALICE luminometers

- **V0**

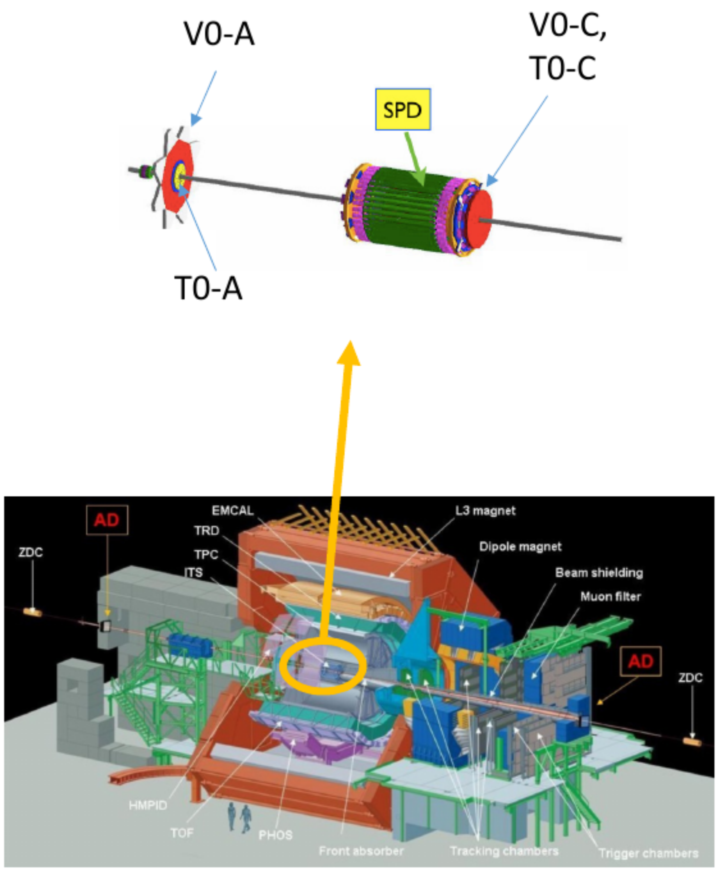
  - two **scintillator** arrays on opposite side (A and C) of the IP
  (**2.8 < η < 5.1** ; **-3.7 < η < -1.7**)

  - coincidence of A and C side

- **T0**

  - two **Cherenkov** detector arrays on opposite sides of the IP
  (**4.61 < η < 4.92** ; **-3.28 < η < -2.97**)

  - coincidence of A and C side
  with hardware cut on the signal arrival time difference



- Very low μ = 0.001 - 1
- Only two detectors (no redundancy)
- In 2015 overall luminosity measurement precision = 2.3% for isolated bunches,
3.4% for bunch trains (because of non-trivial systematics in V0)

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)

Typical $N_1 N_2$ uncertainty: ~0.2-0.3%.

Beam-gas imaging (BGI)

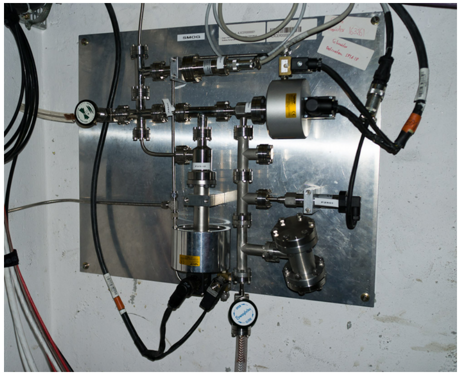
Main difficulty: $\iint \rho_1(x,y)\rho_2(x,y)\,dxdy$

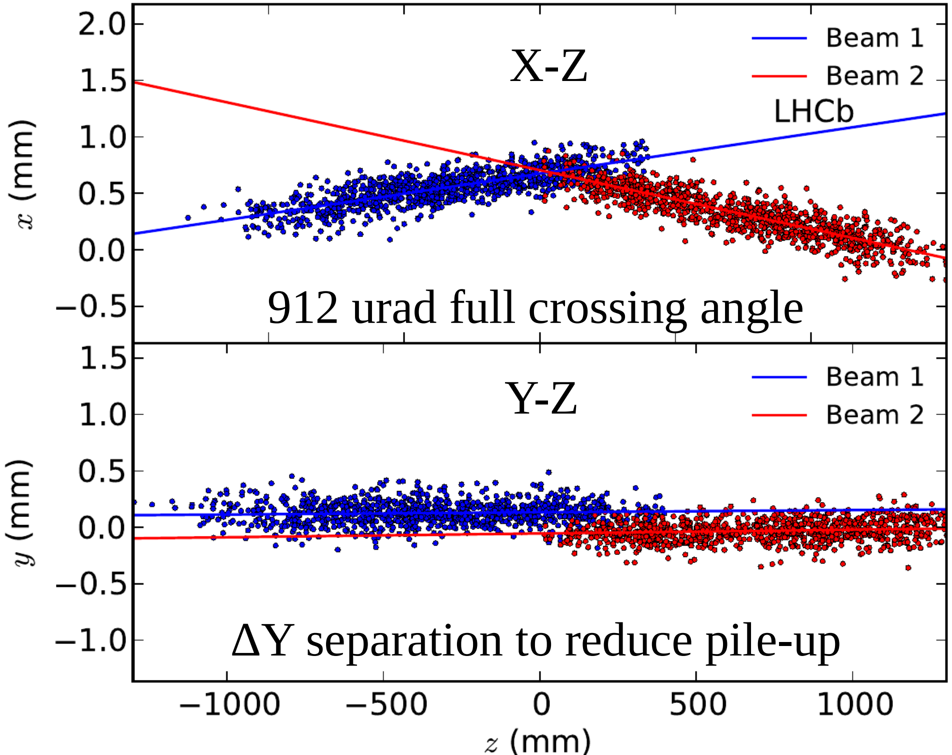
Only at LHCb: find $\rho_{1,2}$ from beam images recorded with beam-gas interactions.

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 is also used as a fixed target eg. for heavy ion physics
- Beam-gas allows to measure "ghost" charge in nominally empty bunches





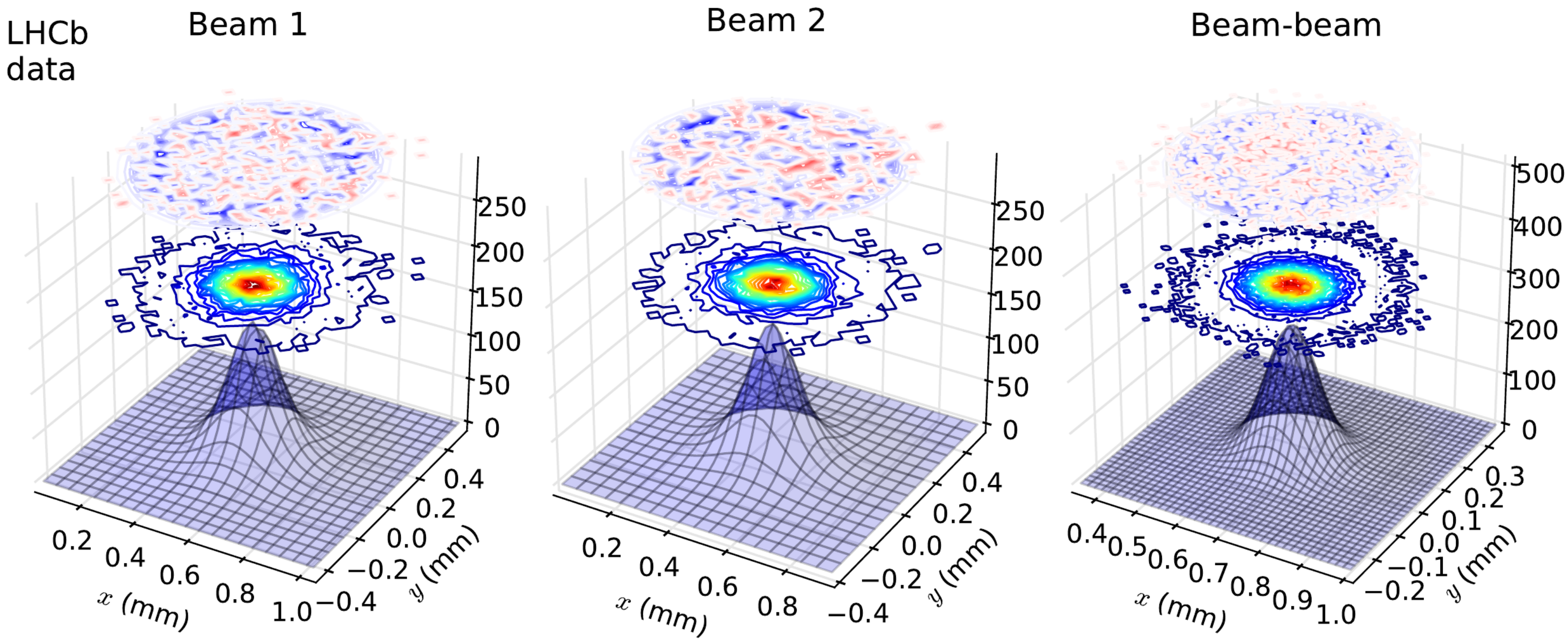
First 1000 vertexes in fill 2852 (Run I).

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 $IP(x,y) \sim \rho_1\rho_2$.



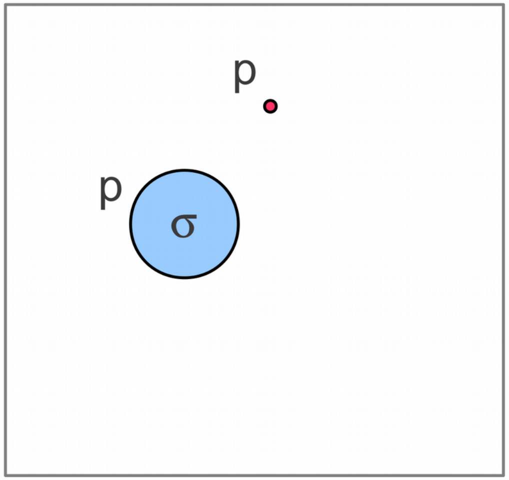
2D fit for one bunch pair as an example. Pulls are shown by color in ±3 range in the top.

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

J. Instrum. 9 (2014) P12005

Van der Meer scan

Idea: sweep one beam across the plane.



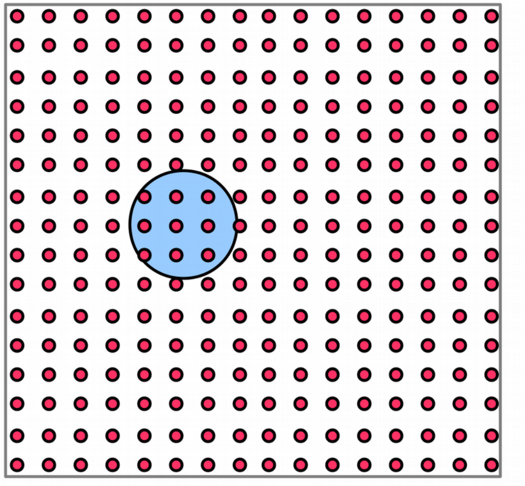
Van der Meer scan

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

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



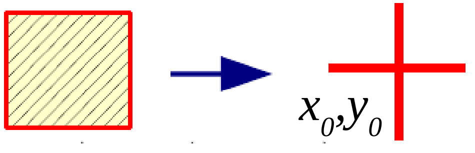
Suggested by van der Meer in 1968.

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:

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

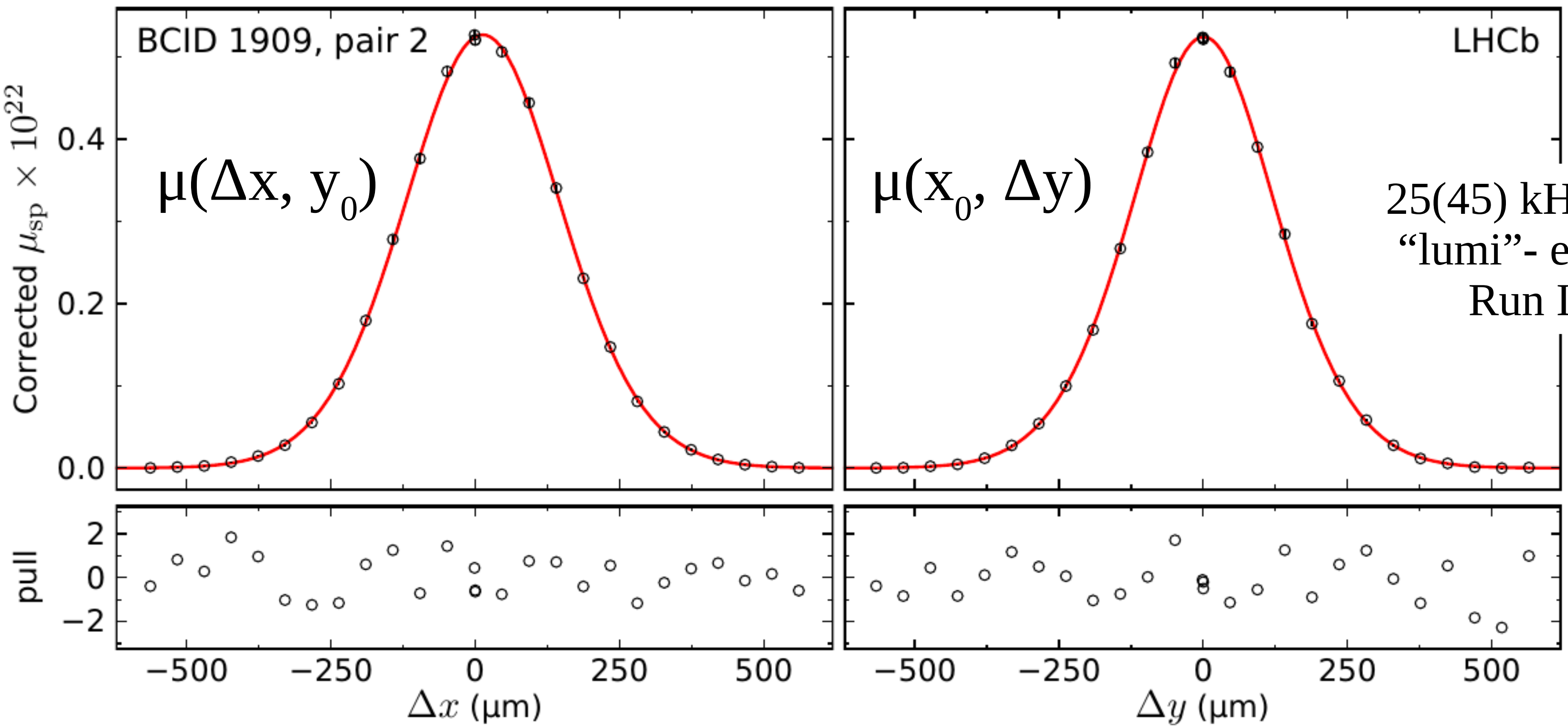
NIM, A 654 (2011) 634

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

(for Δx in frame of fixed beam 2)

Van der Meer scan

μ in one bunch crossing in X, Y scan



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

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

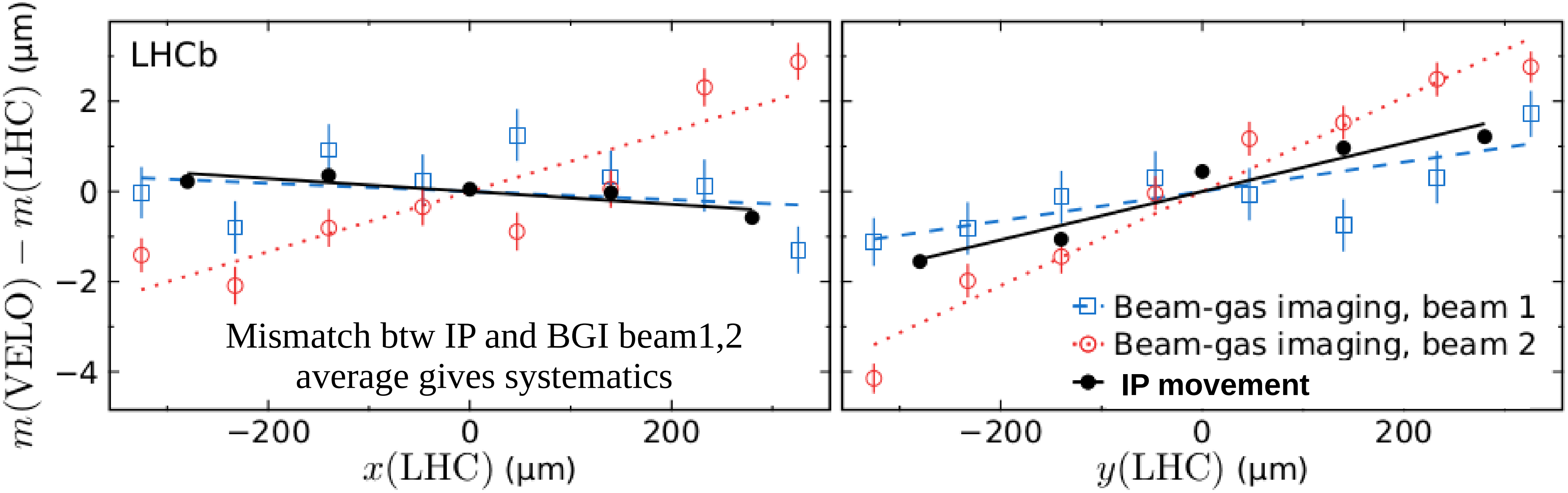
X-Y non-factorizability can give ~1% bias, not easily visible (except with BGI):
- from luminous region fits
- "offset" and "diagonal" scans

vdM length scale calibration

$\sigma \propto \int \ldots d\,\Delta x \int \ldots d\,\Delta y$ 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 can be cross-checked by BGI).

Measured deviation from LHC scale

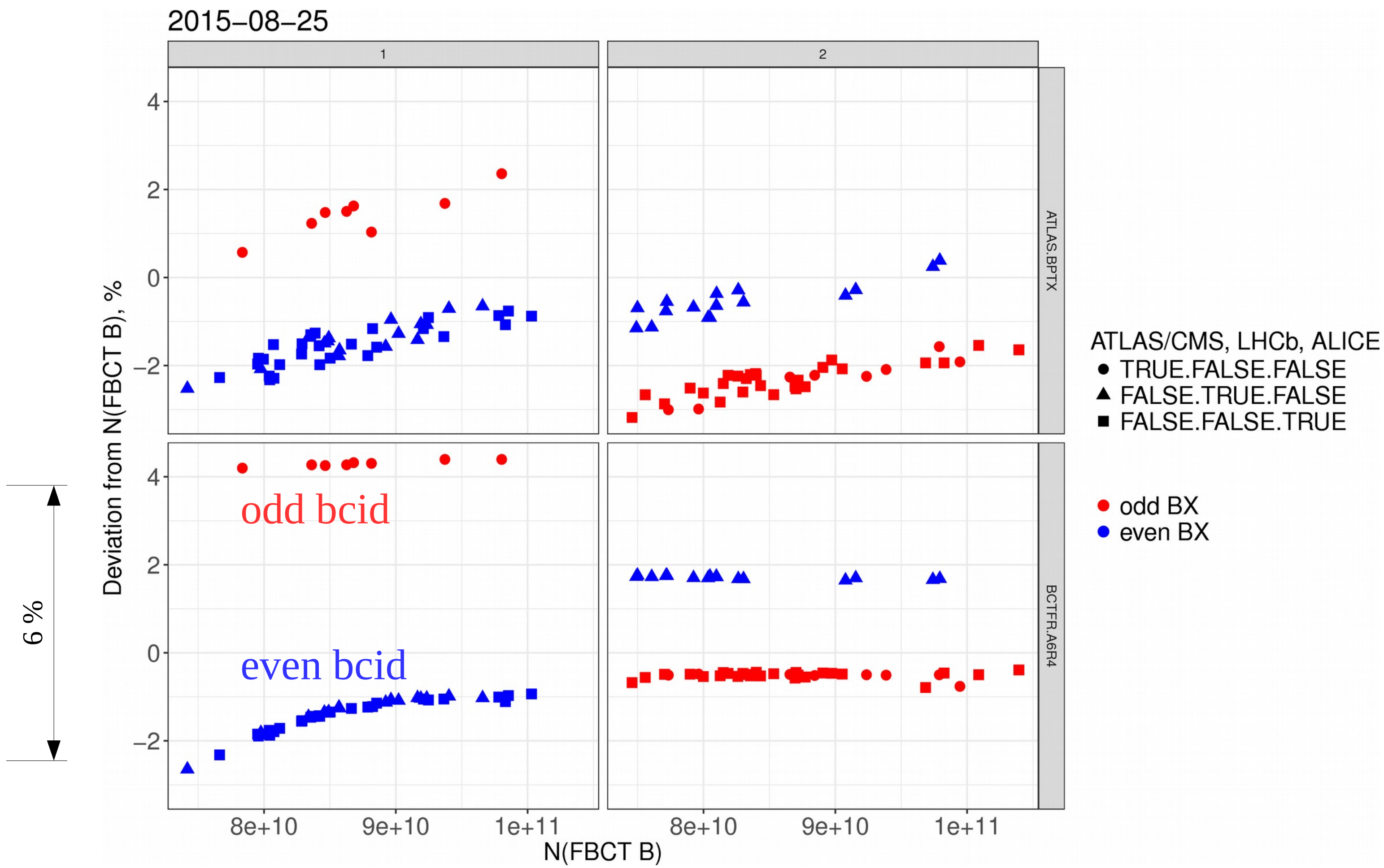


Observations in recent pp vdM scans at LHCb

Recent pp vdM scans at LHCb: observations

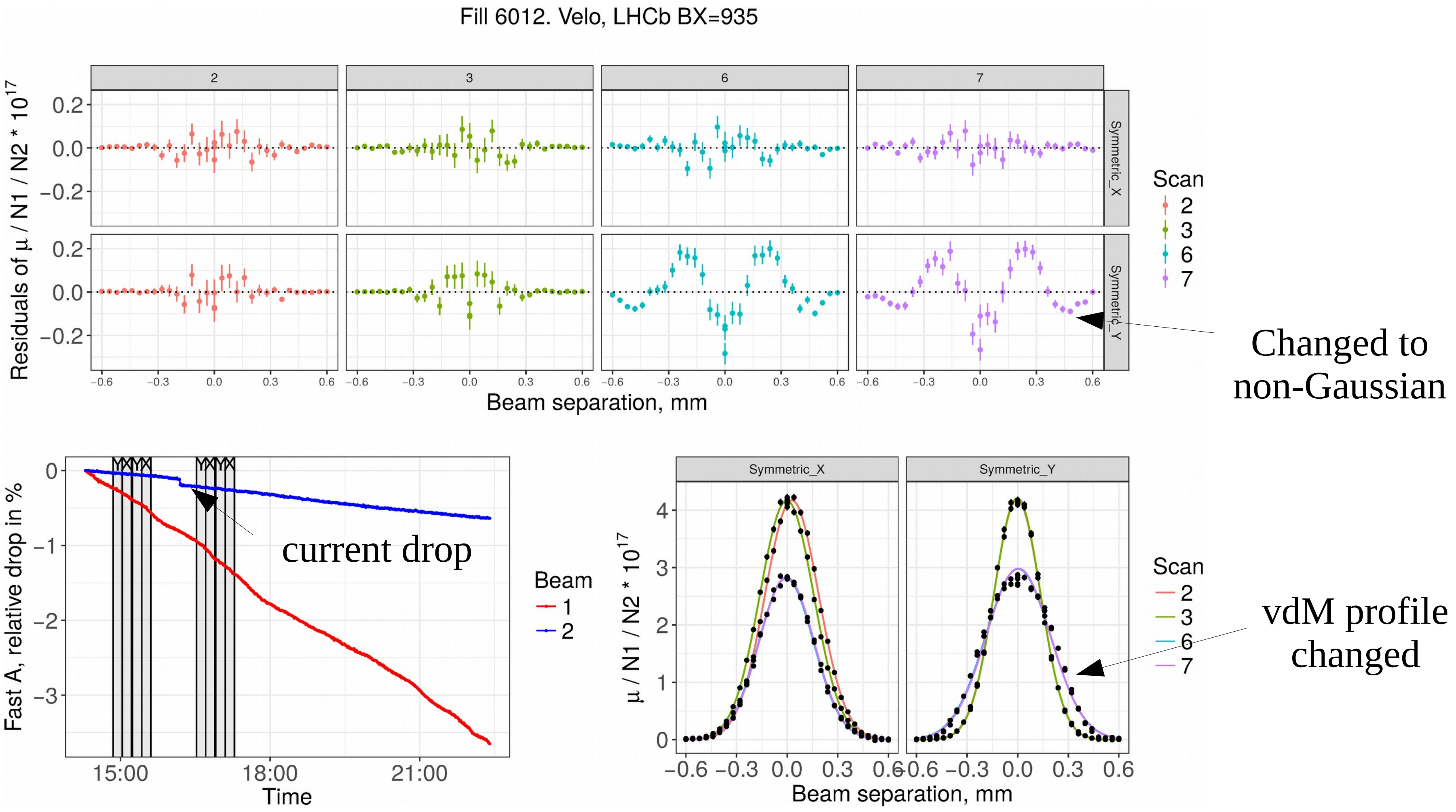
Length Scale Calibration (LSC) in fill 4269, 25 Aug'15 : LHC X- and Y-displacements were incorrectly written manually as equal. 3.5% mistake found by checking the bump magnet recordings in LHC data base. In later vdM scans the displacements were logged automatically.

FBCT measurement of N particles per bunch before 2017 :
2-in-1 device for odd / even bcid, with a few % different slopes and offsets.
To equalize : ATLAS BPTX (noisier but immune to odd-even difference). Bcid can be wrong by 1-4.
Now : much better new FBCT



Recent pp vdM scans at LHCb: observations

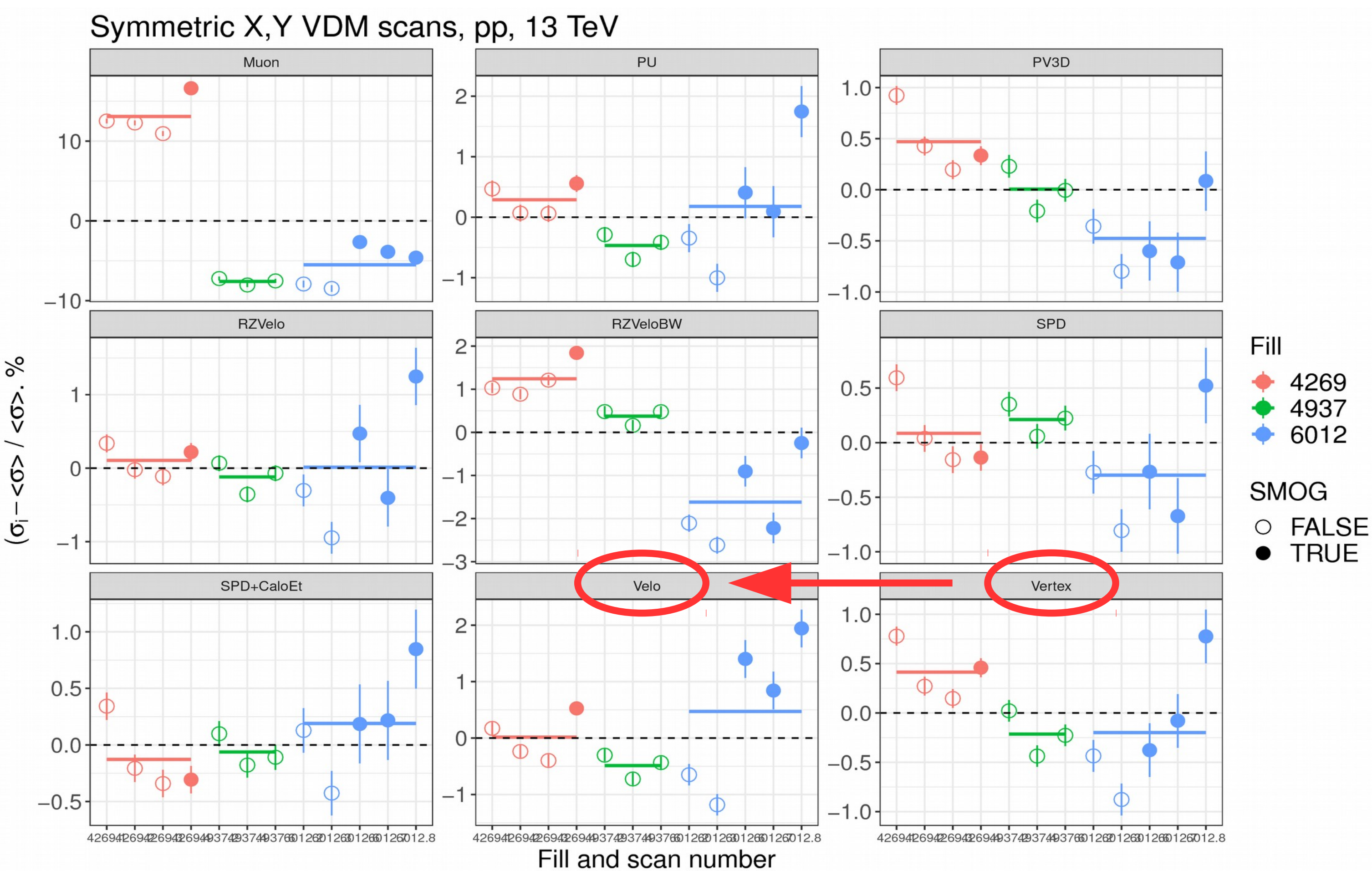
Fill 6012 (Jul'17) : unexpected instabilities in 3 and, after 2 scans, in 19 out of 24 bunch crossings (current drops, width increase)
Only 5 good pairs used in all scans



vdM scan with beam gas imaging

SMOG during vdM scan is very attractive cross-check:
+ measures individual bunch profiles, their movements and length scale, but
- introduces huge backgrounds.
Solid points: background is **not fully subtracted** from *Velo-based track and hit counters.*
In fill 6012, Jul'17 : μ(head-on beam-beam) ~ 0.25, μ(SMOG) ~ 0.13,
after background subtraction Δμ(SMOG) ~ 0.001 – 0.002 remains.

Therefore, final cross-section is obtained from Vertex>0 by rescaling with coefficient determined without SMOG.



Preliminary 13 TeV pp cross section

Preliminary: still, a few things to finalize.
Spread between 15 scans in 2015,16,17,18:
0.5 % – excellent time stability without any corrections (!) contrary to ATLAS/CMS.
Probably, final systematics will be ~2% or less.

σ(Velo>1), mb	**63.7**
Early 2015 BGI measurement	63.4 ± 3.9 % (-0.6%)
preliminary BGI, fill 4937	65.8 (+3.1 %)
	Error, %
DCCT	0.16
Ghost charge, BGI+LDM	<0.1
FBCT A/B/BPTX	<0.1
LSC	<0.5
Fit model	0...0.5
statistics	<0.1
Scan-to-scan variations within one fill	0.2...0.6
Fill-to-fill variations	0.4
RZ Velo – Velo diff.	0...0.2 when SMOG off

Typical uncertainty of extrapolation from vdM to physics: ~ 0.5% (stability of luminometer ratios)

Other methods of luminosity calibration

LHCb: Luminosity of p-He sample $\sqrt{s}$ =110 and 86 GeV

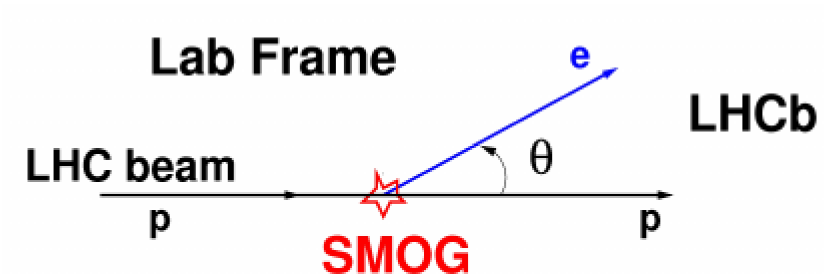
PAMELA + AMS-02: excess in anti-p / p fraction
– sign of dark matter or wrong model of anti-p production in interstellar medium of galactic disk?
Largest uncertainty from $\sigma(p+He \rightarrow \text{anti-}p\ X)$

Measurable at LHCb as fixed target process: p – He (SMOG)

Critical to know SMOG pressure, but difficult to measure precisely because it is very low

Take SMOG density from p - (atomic) e elastic scattering, using its known Rosenbluth cross-section.

Precision: 6% !



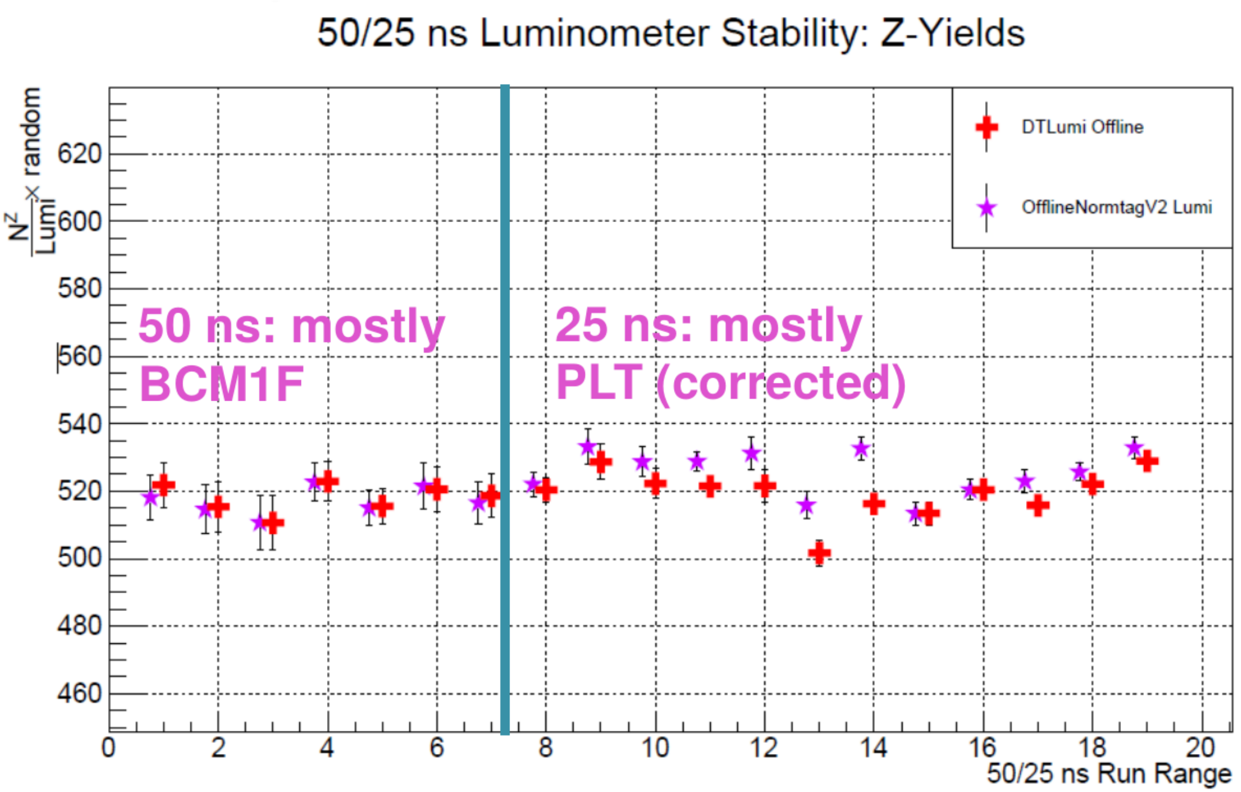
"Measurement of antiproton production in p-He collisions at $\sqrt{s_{NN}}$=110 GeV", https://arxiv.org/abs/1808.06127, submitted to PRL.

Same approach will be used for heavy flavor production measurements in p-He.

Physics reaction as a luminometer

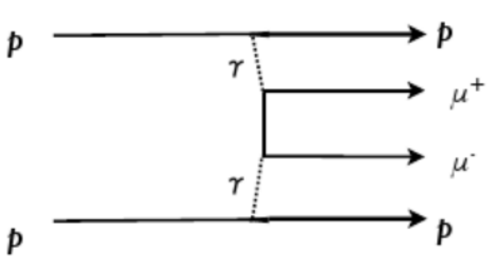
$Z^0 \rightarrow ll$ counting (used in ATLAS and CMS) can be useful in relative luminosity debugging (validate corrections, long-term stability)

Example: $N(Z^0)$ / L, should be constant, from 2015 CMS report



Z efficiency from tag and probe

Earlier proposal (eg. in LHCb): two-photon $pp \rightarrow pp\, \mu^+\mu^-$,
proton compositeness can be neglected, QED precise cross-section allows to calibrate luminosity;
but very low statistics and requires very forward coverage to veto backgrounds – not competitive.



Novelties in 2 most recent vdM scans at LHCb

Experiments typically do symmetric X,Y vdM scans with minimal variations.
From end 2015 LHC allows to define scan points arbitrarily, however.

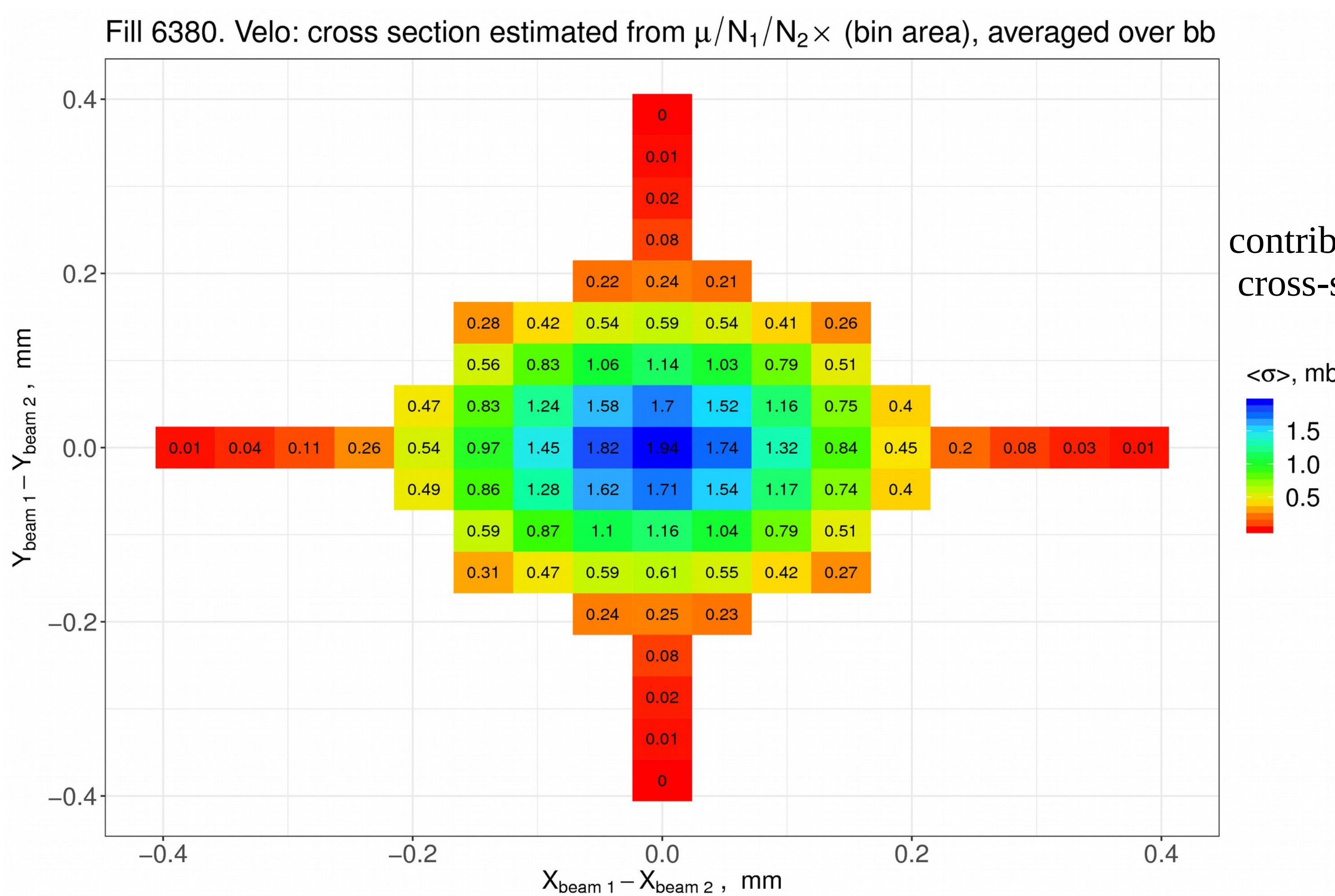
1) Nov’17, 5 TeV pp, 1 hour: LHCb has tried for the first time two-dimensional vdM scan

2) Jun’18, 13 TeV pp, 3.5 hours: many novelties (on the next slides)

First ever quasi two-dimensional scan, Nov'17

Cross-section ~ integral over X-Y beam separation plane.
Standard vdM: along X, Y axes, assuming factorization : $\mu(\Delta x, \Delta y) = \mu(\Delta x, 0)\,\mu(0, \Delta y) / \mu(0, 0)$.
Factorization cross-checks up to now: diagonal scans and scans along x=const or y=const lines.

Full two-dimensional scans are expensive (too many points). In Nov'17 LHCb scanned central region giving maximal contribution to the integral.

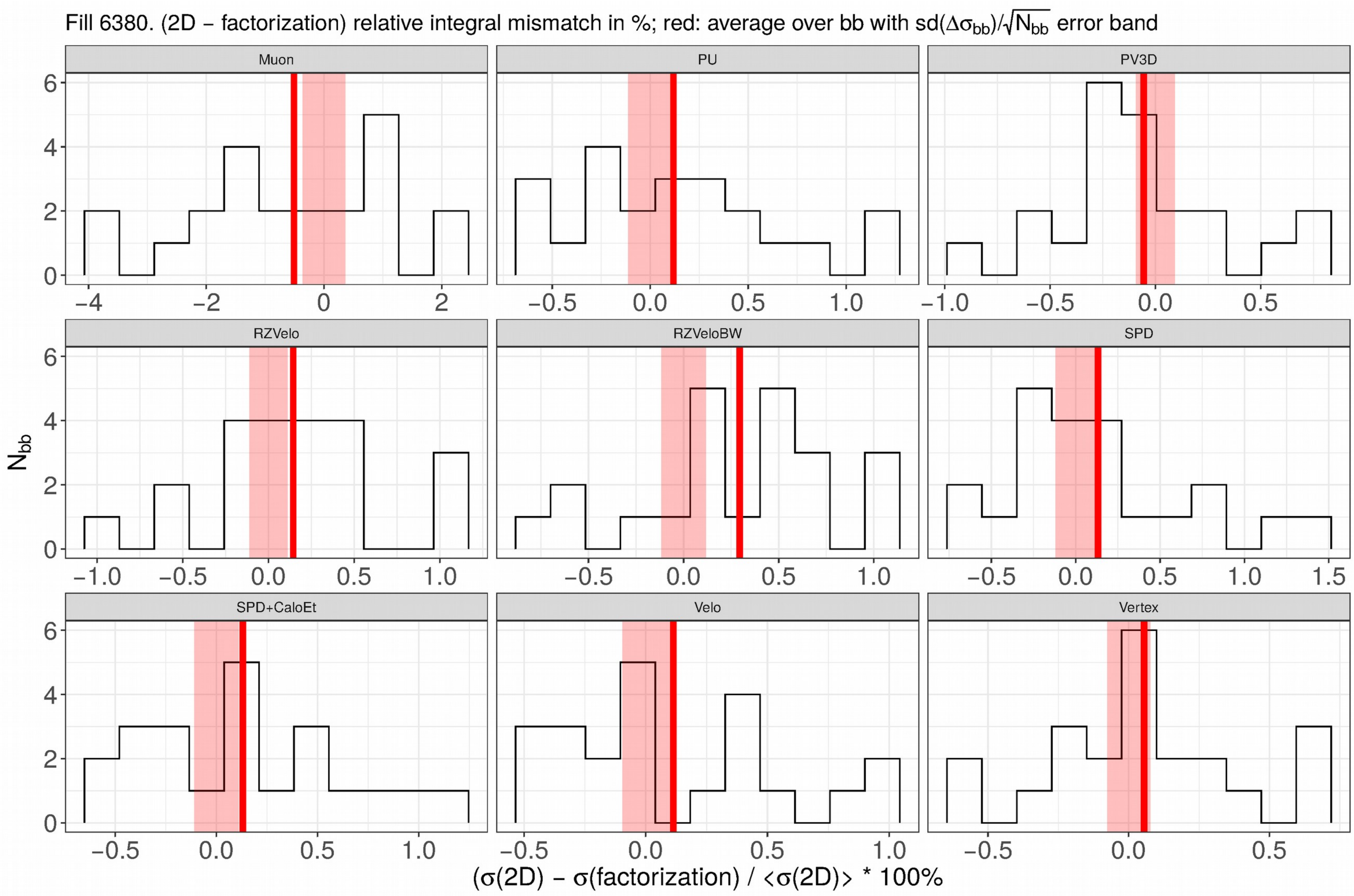


contribution to cross-section

Mismatch btw. factorization and 2D cross-section integrals

… for 22 bunch crossings. Red : average line with expected from spread error band.
Mismatch for Velo : 0.11±0.10 % – excellent accuracy and agreement.

Full χ^2 analysis of 44 scan points, ie. of 22 x 44 = 968 underdetermined factorizability equations also gives reasonable agreement (deviation at only 6σ probability in spite of excellent stat. precision).

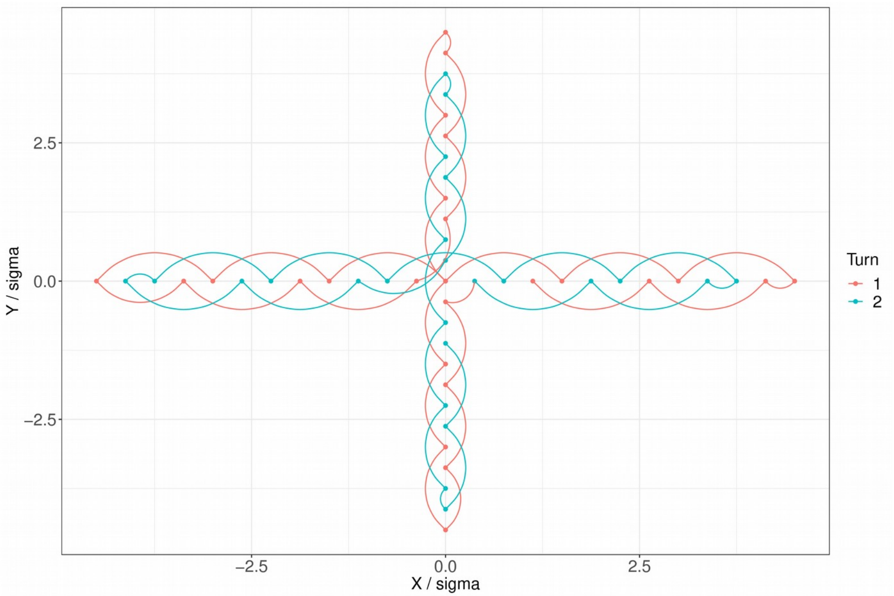


Jun’18, 13 TeV pp vdM scan

- Same 2D scan as in Nov’17

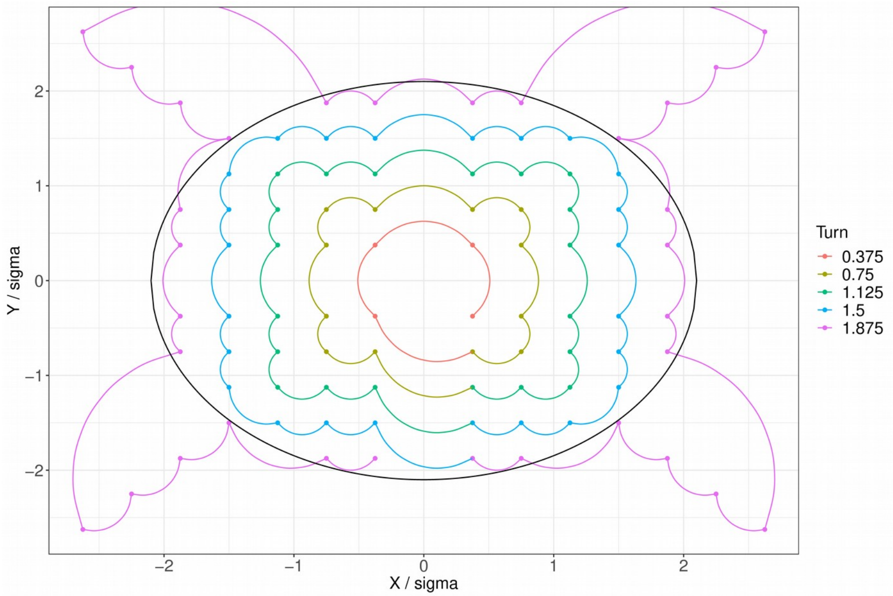
- Special program to study beam orbit drifts (difficult to control during “standard” scans)

a) multi-pass X,Y scans



4 passes (2 forward + 2 backward) instead of one, each allows to find when beams are head-on and measure drifts during the scan

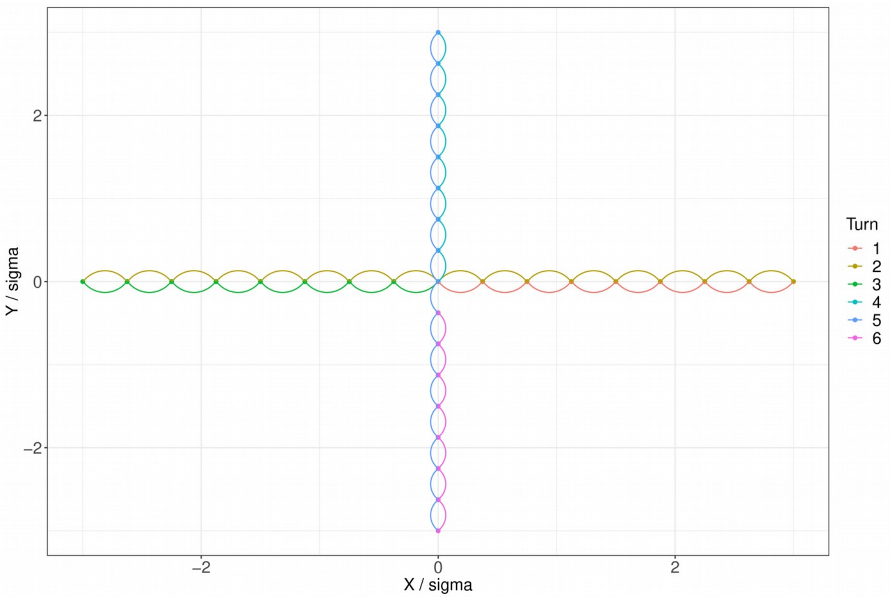
b) spiral 2D



every side of the spiral allows to find head-on position and measure drifts

Jun'18, 13 TeV pp vdM scan

- since beams are moving not in one direction during scan, important to check the absence of hysteresis effects in LHC magnets: forward – backward through the same points



in addition,

- more sophisticated length scale calibration

- beam-beam imaging when one beam is at rest

Lot's of interesting and new data to analyze!

Conclusions

(1) Luminosity measurement is a technical service, but very much needed.
Eg. in LHCb used in ~15% of all publications.

(2) Current LHCb pp luminosity precision 3.9-3.8% from early BGI measurements in 2015.
When finalized, vdM scans should give ~ twice better precision.
Run I, 8 TeV pp: 1.16% from combination of vdM and BGI, record for bunched colliders,
J. Instrum. 9 (2014) P12005, arXiv:1410.0149.

(3) My opinion: LHCb luminosity measurement is very well designed, excellent time stability,
reference calibrations stable in 2015-2018 without need of any correction at hardware level

(4) Lack of manpower in LHCb lumi group, only 2-3 experts and having also other duties.
Rosen Matev (convener) is now on CERN long duration contract fully on HLT.
BGI not covered, George Coombs finishes his PhD.

(5) Many novelties in last 2 vdM scans at LHCb, data to be analyzed.
First 2D scan results are very positive.

(6) Ideas for upgrade are welcome