Overview of LHCb luminosity determination methodology in Run 2

LHC Lumi Days, 4-5 June 2019
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Outline:

(1) Fixed-target luminosity: p-SMOG

(2) vdM pp calibration @ $\sqrt{s}$ = 13 and 5 TeV

(3) p-Pb and Pb-p vdM @6.5Z TeV / beam

Conclusions

Cross-calibrations between experiments

pp inelastic cross-section @13 TeV : JHEP 06 (2018) 100

(elegant **probability generating functions** to correct for track inefficiencies and ghosts, proposed by M. Schmelling)

7 % accuracy dominated by extrapolation to full phase-space

→ Measurement of Z production cross-section in phase-space ***common*** to ATLAS/CMS and LHCb, without extrapolation errors, could cross-calibrate and validate luminosity measurements btw. experiments with better precision

Luminosity of fixed target p-SMOG samples

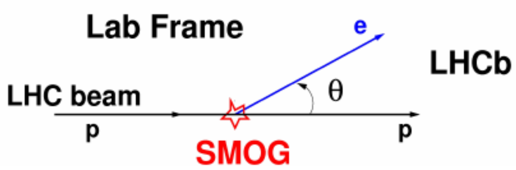
PAMELA + AMS-02: excess in anti-p / p fraction :

- sign of dark matter or
- wrong model of anti-p production in spallation of cosmic rays in the interstellar medium?

10-100 GeV anti-p: largest uncertainty from σ(p+He → anti-p X), measurable at LHCb with SMOG.

Difficult to measure precisely low SMOG pressure

SMOG density from p - (atomic) e elastic scattering:
6% lumi determination!



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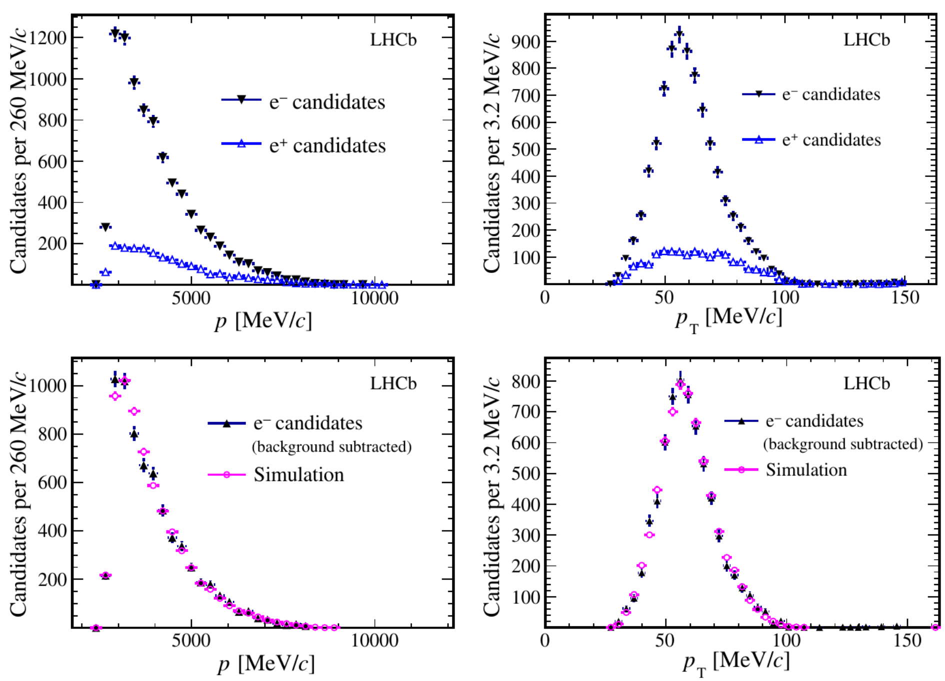
P(e^-) $\sqrt{s_{NN}}$ = 110 GeV P_T(e^-)



Before bgr. subtr. (estimated with e^+)

Similarly, luminosity of other samples p(Pb) – He,Ne,Ar is being measured eg. for heavy flavor production cross-sections.

After bgr. subtr. - good agreement with MC

Next: vdM calibrations

1. pp @ 13 and 5 TeV

2. p-Pb and Pb-p at 6.5Z TeV

Will be covered in separate talks at this workshop:

- Extrapolation to physics data (stability of counters),
- X-Y factorization (measured with 2D scans)
- Beam-beam effects

Will not be discussed at this workshop:

- Non-linearity of LHCb lumi counters observed in Pb-Pb vdM in 2015, 18
- BGI calibration (analysis is discontinued at the moment, 3-year PhD term is finished in March)

vdM fills, pp (13 and 5 TeV), p-Pb & Pb-p (6.5+6.5Z TeV)

pp, 13 TeV : 4 fills once a year in May-Aug in 2015-2018

pp, 5 TeV : Nov 2015, 2017

p-Pb, Pb-p, 6.5+6.5Z TeV : Nov-Dec 2016

	pp 13 TeV	pp 5 TeV	p-Pb, Pb-p
Fill	4269, 4937, 6012, 6864	4634, 6380	5533, 5565
N colliding BX	16, 16, 24, 22	22, 22	162-163
β^*, m	24.1	3.1, 7.0	1.5
pile-up at zero	0.1-0.5	0.2-0.7	

(1) 9 luminometers in LHCb:
- VELO: N tracks, vertices (all or close to collision point IP), upstream hits, backward tracks
- SPD preshower: N hits
- Calorimeters: transverse energy
- N muons

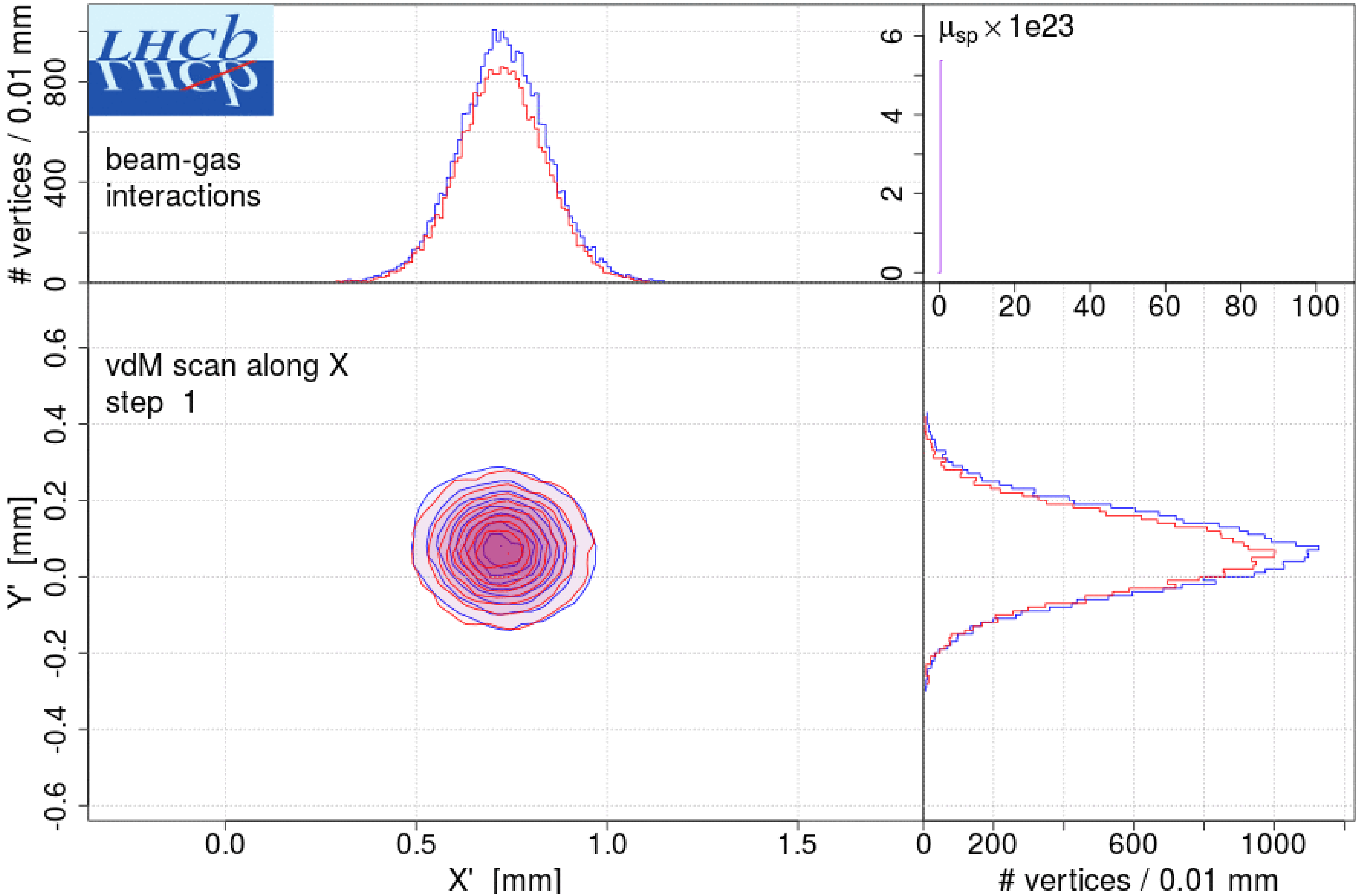
(2) During vdM lumi events are taken at **45 kHz** with random trigger, **10-11 sec** per step.
In some fills selected bunches were triggered at 11 kHz with ≥ **100 kHz** total rate!

(3) Poisson law: $\mu = -\log(P(0))$, P(0)=fraction of “empty” events
eg. N tracks < 2 (reference), N vertexes = 0 (2nd best)

(4) Beam-gas backgrounds (<1% without SMOG but 10-60% with SMOG wrt. peak signal in pp): estimated from non-colliding bunches and subtracted

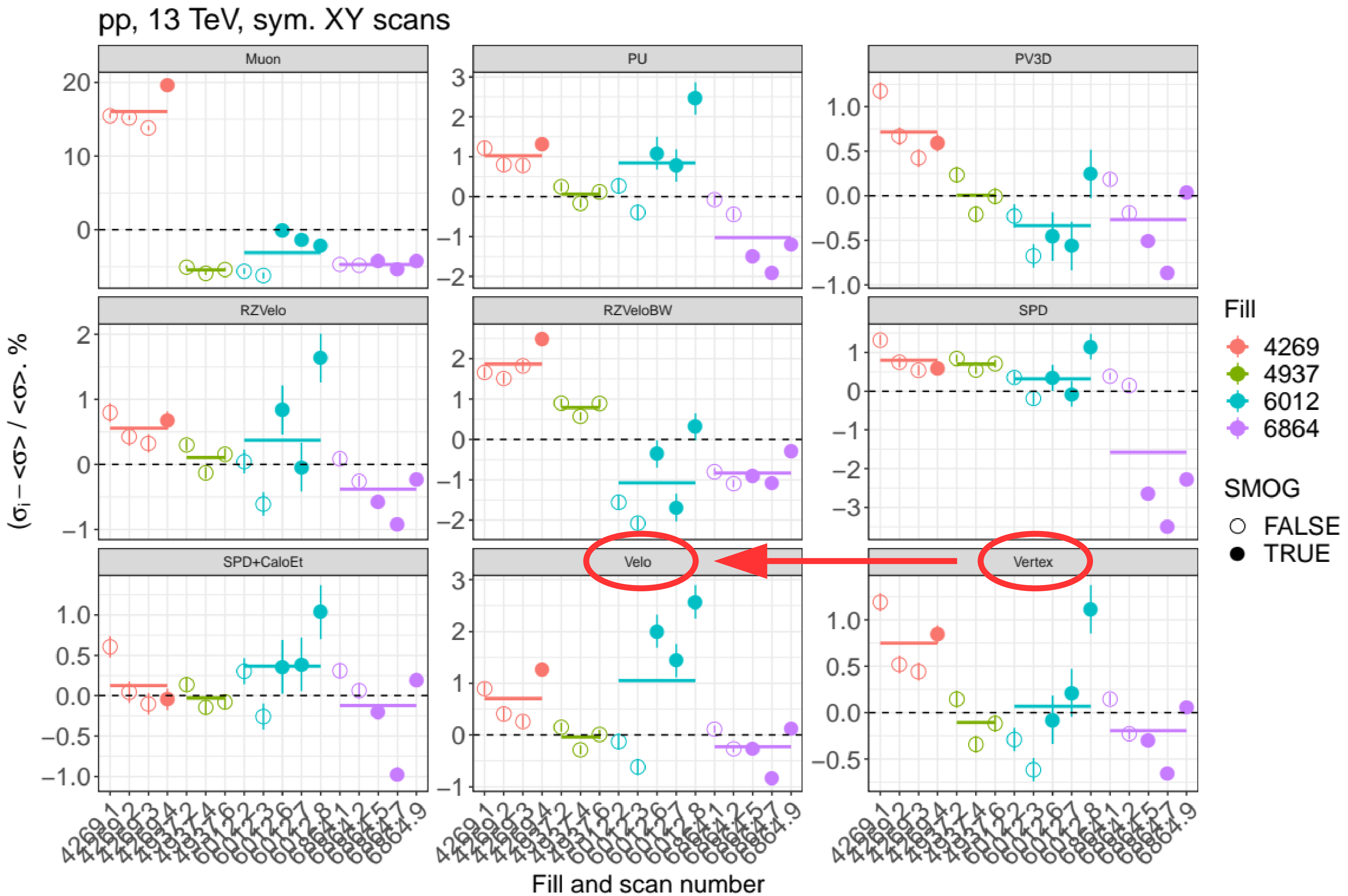
BGI video: first vdM with SMOG, 25 Aug'15

pp, 13 TeV



Cross-section variations in % for all counters

pp, 13 TeV

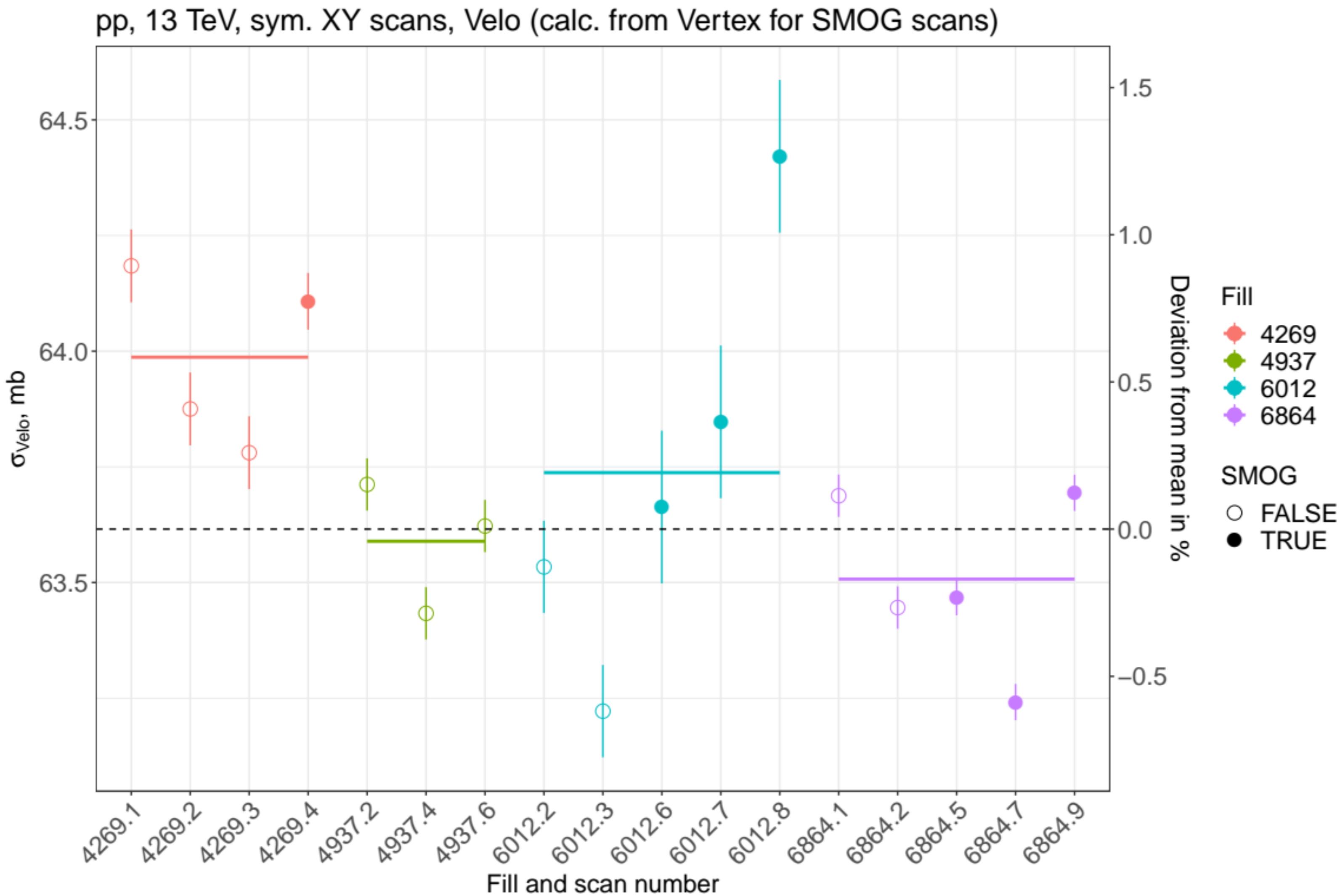


SMOG background (in solid points) **not fully subtracted** from *Velo-based track and hit counters.*
Eg. in fill 6012 : μ(head-on) ~ 0.25, μ(SMOG) ~ 0.13, after bgr. subtr. Δμ(SMOG) ~ 0.001–2 remains (visible from Velo/Vertex ratio). Vertex SMOG bgr. smaller by ~ 8 is properly subtracted.

Reference x-section (N Velo tracks > 1)

pp, 13 TeV

Reference **σ_{vis}(Velo>1) = 63.6 mb** @13 TeV (56.2 @ 5 TeV) is obtained from Vertex>0 by rescaling with coefficient determined without SMOG.

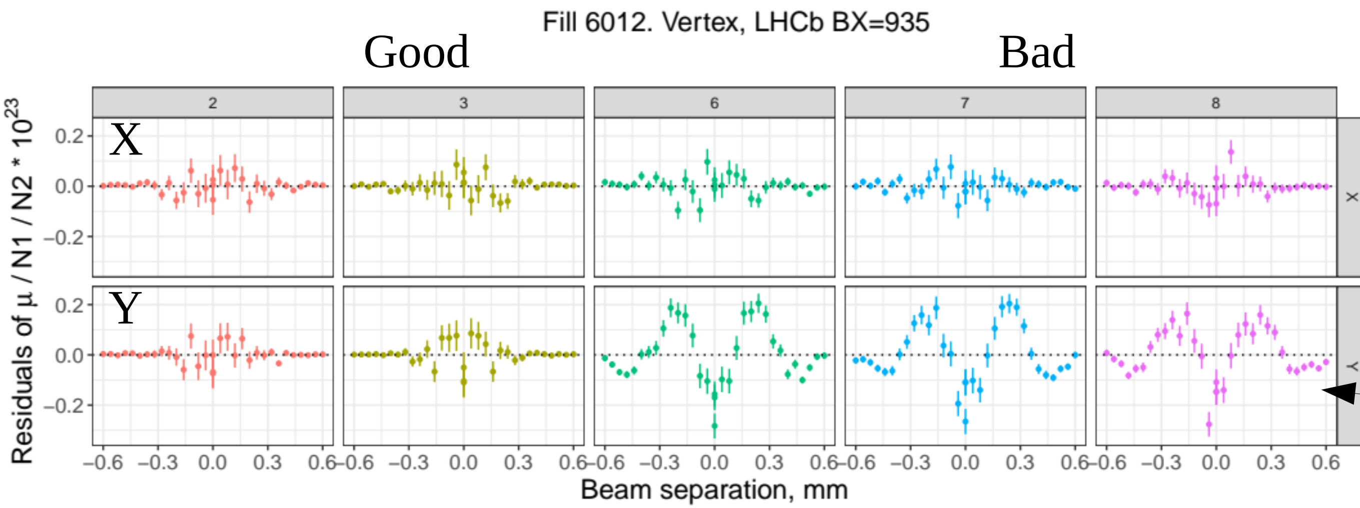


Instabilities in fill 6012 (Jul’17)

pp, 13 TeV

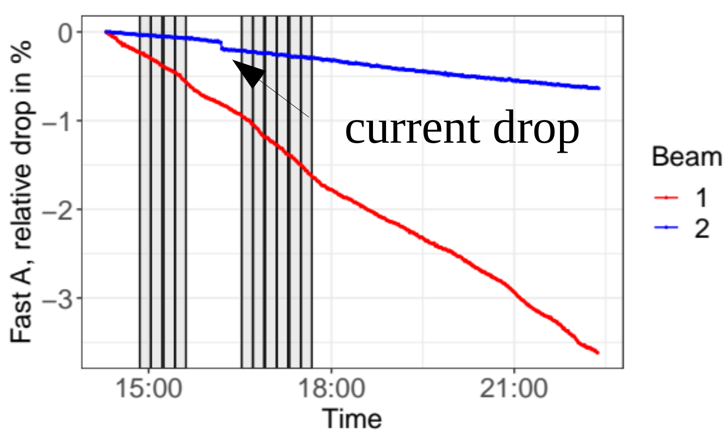
3 bad bunch crossings from beginning; after 2 scans: 19 bad out of 24 (current drops, width increase).
In 5 good pairs both bunches shared with ATLAS/CMS, could remain stable due to Landau dumping.

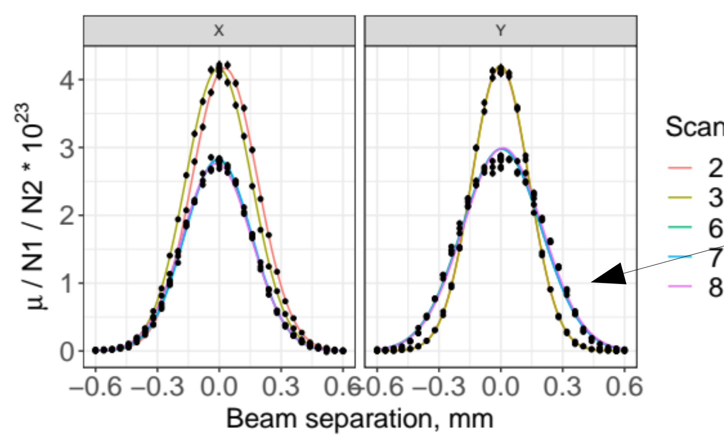
Gaussian fit residuals



Example of bad bunch pair

Not Gaussian





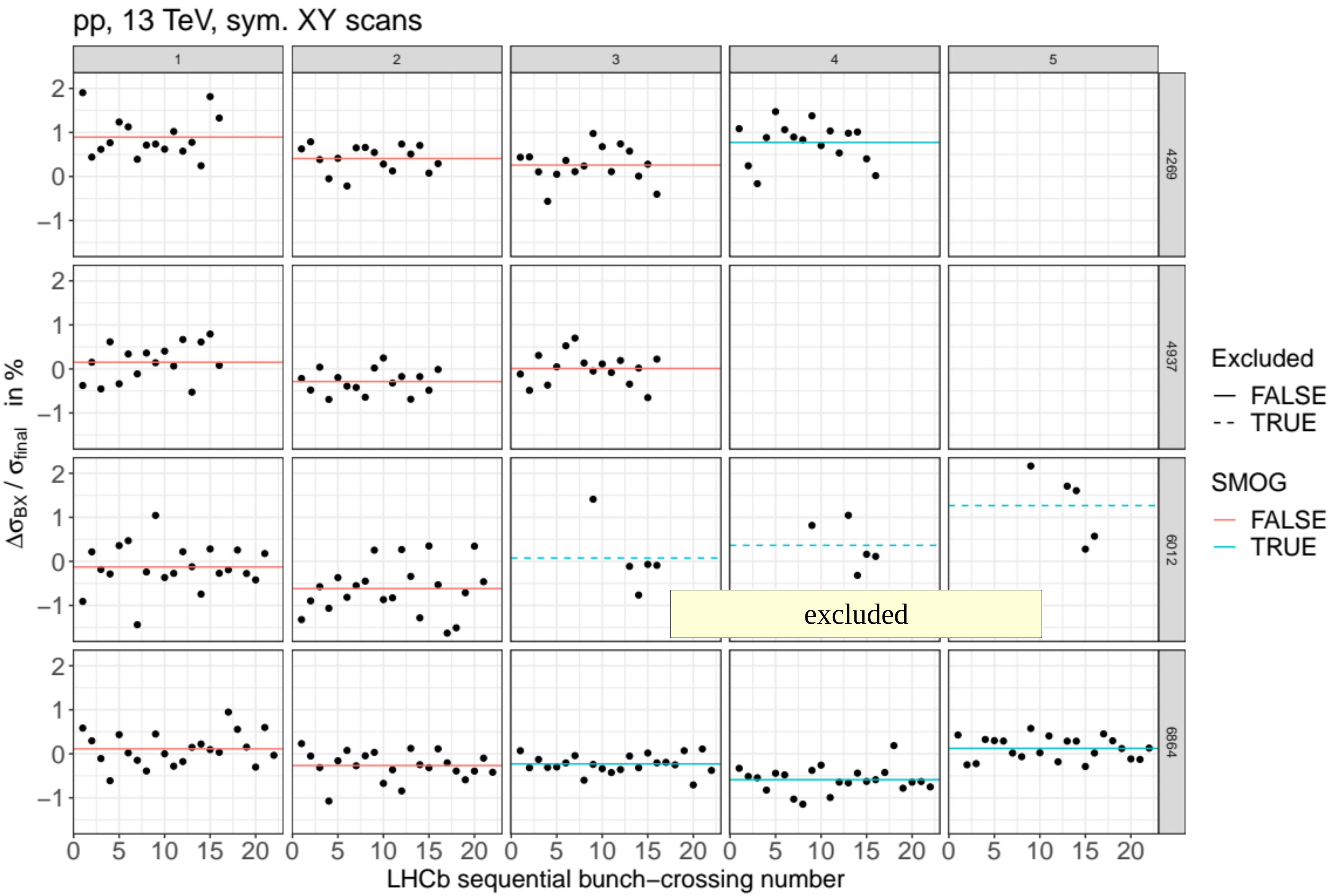
vdM profile changed

Except bad bunch pairs, other vdM luminosity curves are not far from Gaussian (more details in talk on 2D scans). Double Gaussian can indicate significant X-Y non-factorizability.

Reference x-section per BX

pp, 13 TeV

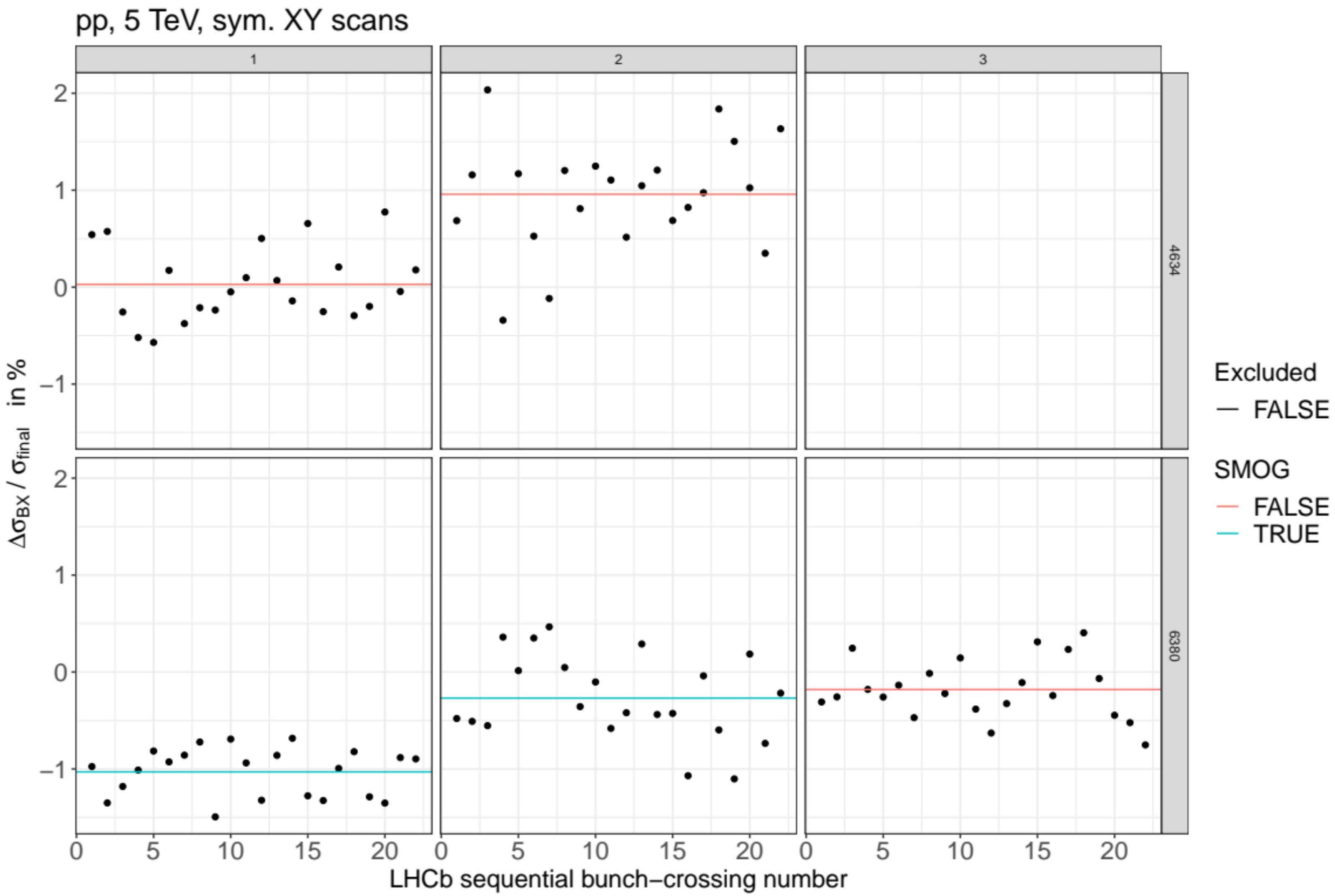
Fluctuations of bunch pairs within scan are largely statistical. Scan averages over ~ 20 BX differ systematically, however (stat. error ~ negligible)
Scans (solid lines) are averaged per fill and final reference **σ_{vis}(Velo>1) = 63.6 mb** @13 TeV is calculated as average over fills. Scans with 19 bad BX out of 24 (5 points remaining, dashed lines) are *excluded*. In SMOG scans Velo is rescaled from Vertex (lower bgr.). **Envelope** of all 14 included scan averages : **±0.9 % -** conservative systematic error reflecting changes in running conditions.



Reference x-section per BX

pp, 5 TeV

Final reference **σ_{vis}(Velo>1) = 56.2 mb**, **envelop** across 5 scans, **±1.0 %**.
Note, how stable the results are across years (no time dependent corrections eg. for aging).

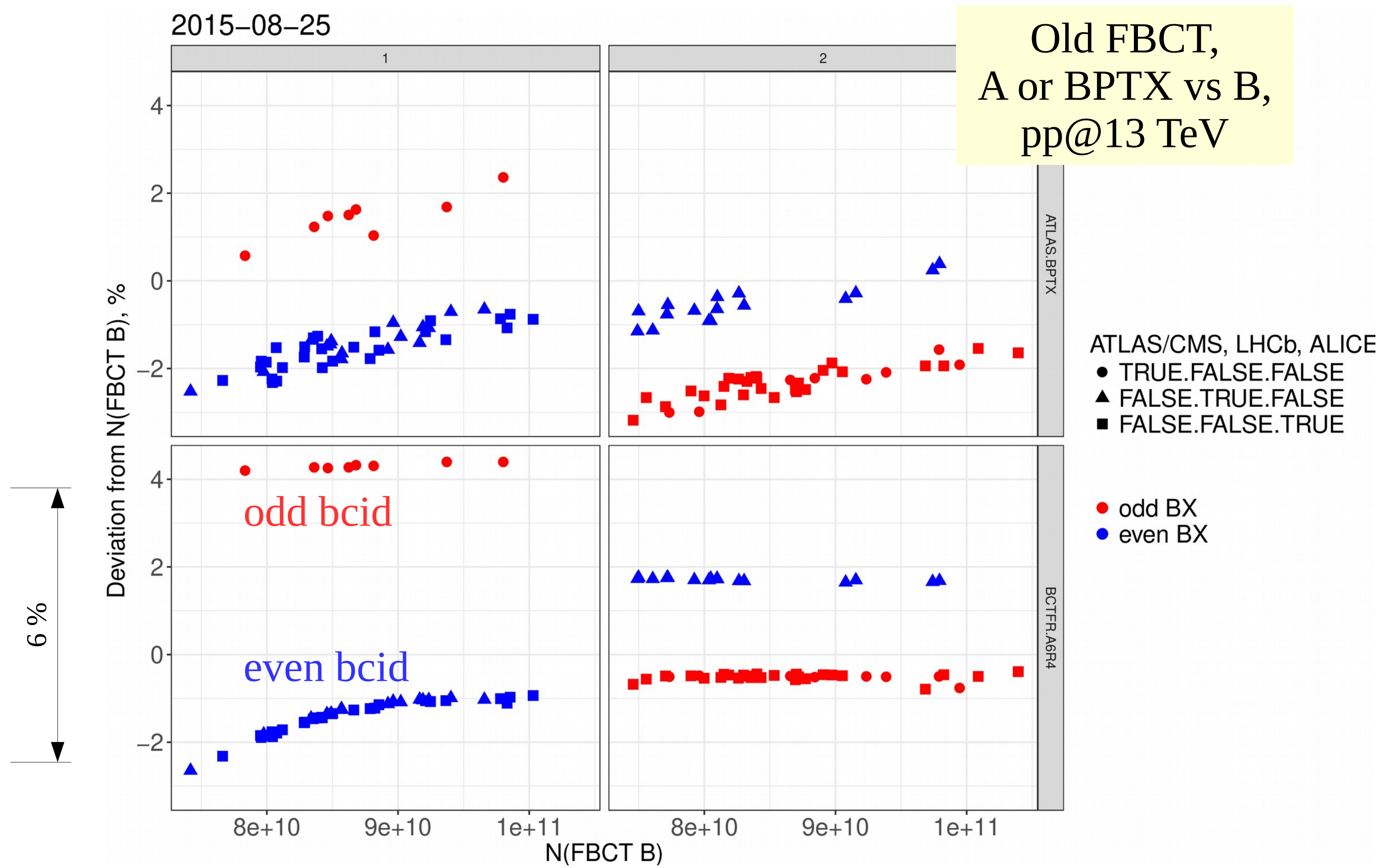


Some details: old FBCT (before 2017)

pp

Two independent devices for even and odd bunch ID (to gain x2 in speed).
Systematic difference btw. even-odd (a few % in slopes and offsets) cross-calibrated and corrected with ATLAS BPTX (noisy but becomes precise ater averaging over long periods and many bunches).
More details in Rosen's talk « LHCb ghost-charge measurement & FBCT corrections ».

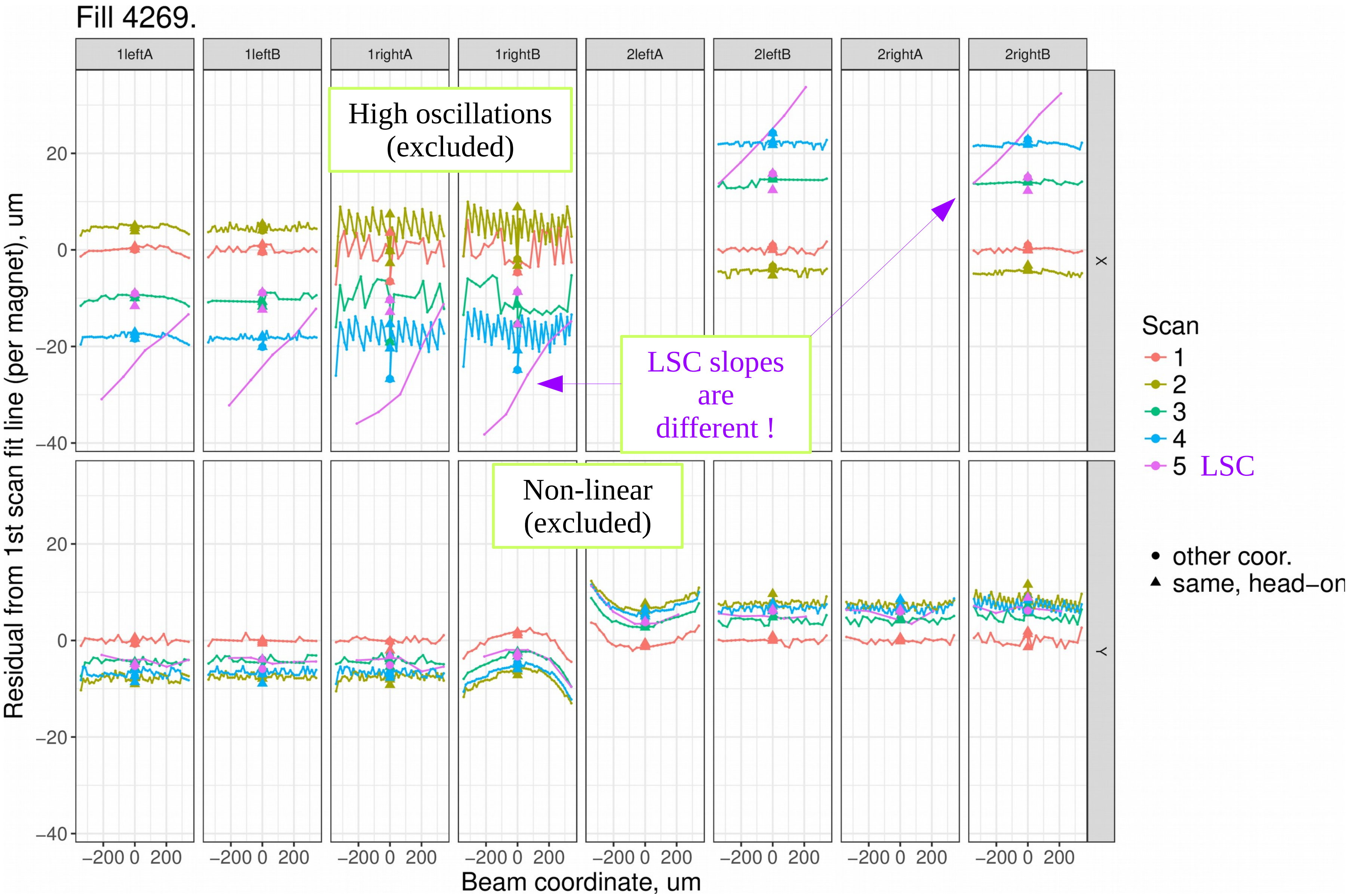
New FBCT from 2017 on, are excellent, no corrections needed.
No FBCT offset parameters are required in cross-section fits for both new and even/odd corrected old measurements (<0.1 % x-section change)



Some details: LSC in fill 4269

pp, 13 TeV

LHC X- and Y-displacements were incorrectly written manually as equal.
Mistake found by checking bump magnet recordings (3.5 % change).



Position residuals in um w.r.t. to linear fit in 1st scan, per magnet.
Offsets vary across scans but slopes should be constant (not for LSC).

More on LSC, cross checks with BGI

pp

LSC correction stable across fills in 2015-18 (fit error negligible, <0.1%) and agrees well with beam movements measured with SMOG in 2017-18. Conservatively assign maximal found error : 0.3 % @13 TeV and 0.27 % @ 5 TeV

13 TeV

fill	LSC-X	LSC-Y	X*Y	SMOG	BGI-X	BGI-Y	**max $\lvert BGI – LSC \rvert_{X,Y}$**
4269	0.9973	0.9991	0.9964	no			
4937	0.9973	0.9961	0.9934	no			
6012	0.9974	0.9973	0.9947	yes	(0.9974 + 1.0005) / 2	(1.0004+ 0.9921) / 2	**0.15 %**
6864	0.9974	0.9985	0.9960	yes	(0.9966+ 1.0010) / 2	(1.0018+ 0.9961) / 2	**0.14 %**
max|Δ|	**0.01 %**	**0.30 %**	**0.30 %**				

5 TeV

fill	LSC-X	LSC-Y	X*Y	SMOG	BGI-X	BGI-Y	**max $\lvert BGI – LSC \rvert_{X,Y}$**
4634	0.9948	0.9949	0.9897	no			
6380	0.9920	0.9909	0.9830	yes	(0.9917+ 0.9945)/2	(0.9929+ 0.9943)/2	**0.27 %**
max|Δ|	*0.28 %*	*0.40 %*	*0.67 %*	*ignore,*	*optics (β*)*	*were*	*different*

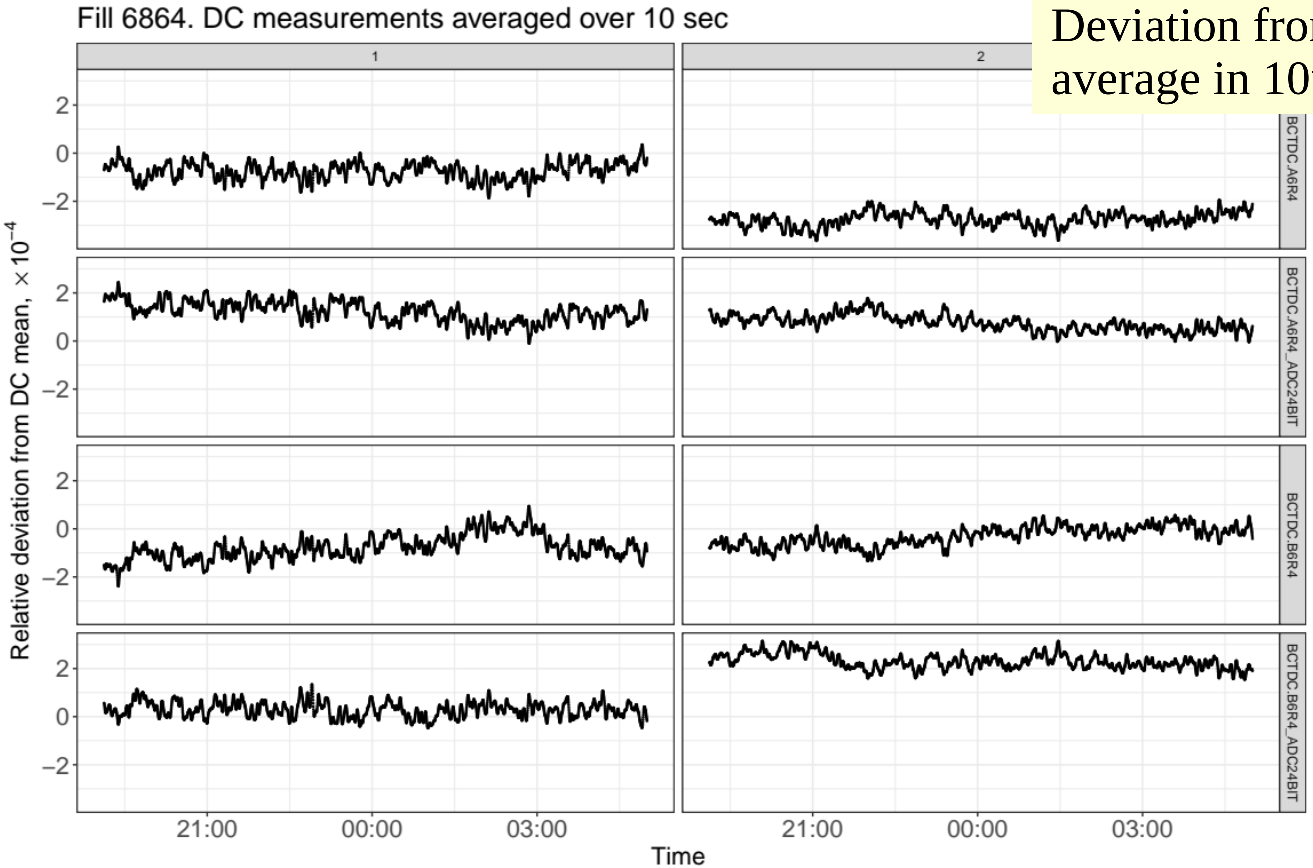
Current measurements

pp

Example for fill 6864	correlated btw. beams	beam 1, %	beam 2, %
Current source precision	yes	0.034	0.034
Bunch pattern dependence (laboratory test)	yes	0.068	0.068
Non-linearity of 12-bit ADC	yes	0.028	0.028
Baseline correction	no	0.011	0.011
Long term stability of baseline on range 3	no	0.027	0.027
Long term stability of calibration on range 3	no	0.028	0.028
Difference between systems	no	0.010	0.021
Total:			0.17%

From CERN-ATS-Note-2012-026 PERF

for 12 bits DCCT. Might be conservative for 24 bit DCCT as several uncertainties were at 1 LSB



Deviation from average in 10^{-4}

FBCT systematics from FBCT A-B comparison is found negligible

DC : excellent agreement btw. 4 devices per beam in all fills

Fit model and μ_0

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

pp

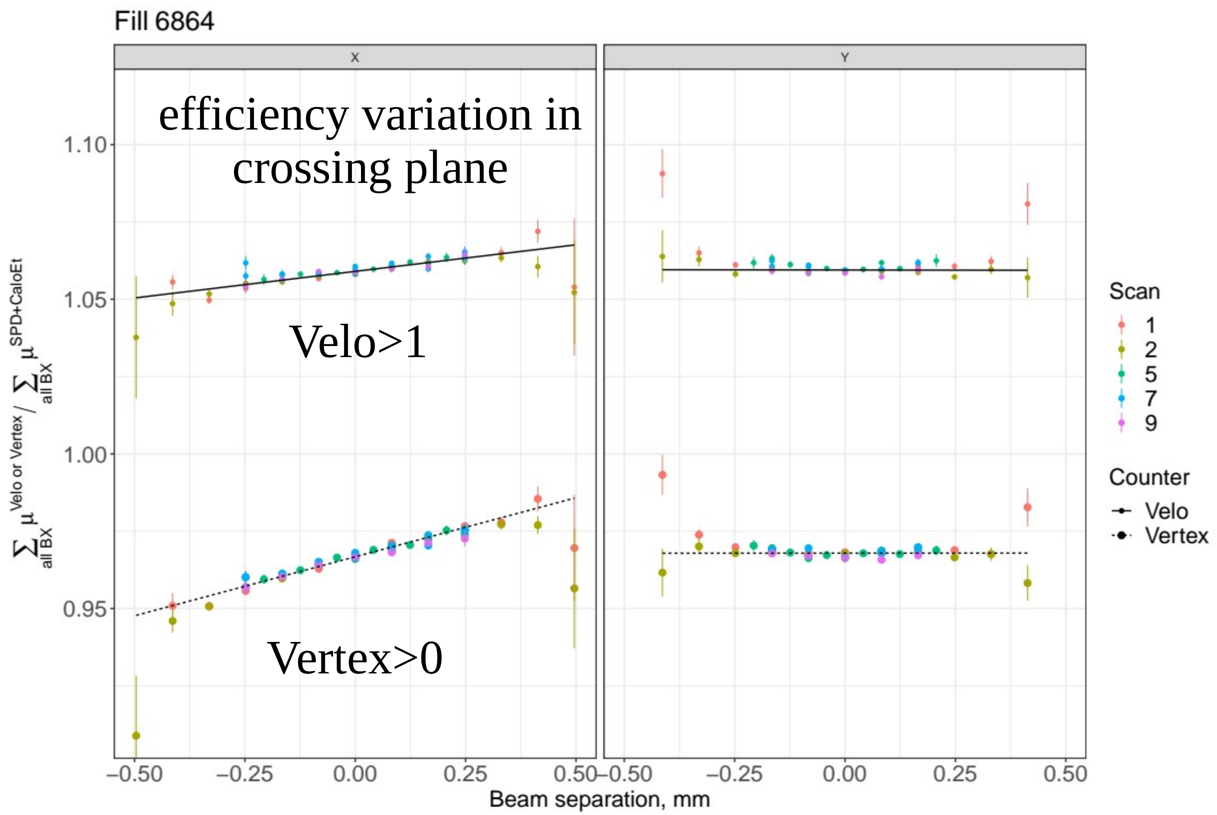
	13 TeV	5 TeV
Btw. Simpson integration and integral under Gaussian fits (default)	0.23 %	0.15 %
Max $\mu(\Delta x_0, \Delta y_0)$ mismatch btw. fit and data	1.1 %	0.3 %

Velo efficiency dependence on z (on x via crossing angle)

Corrected from data using z-independent Calo+SPD luminometer.

Systematics is negligible (mismatch btw. polynomial fits with varying degree).

Compensation in integral to 1st order.



Cross-sections and known systematics (preliminary)

pp

	pp, 13 TeV	pp, 5 TeV
σ(Velo>1), mb	**63.6 ± 1.6 %**	**56.2 ± 1.3 %**
Early 2015 BGI measurement	63.4 ± 3.9 % (- 0.3% off)	56.4 ± 3.8 % (+ 0.4% off)
preliminary BGI, fill 4937	65.8 ± 2.1 % (+3.5 % off)	
	Error, %	**Error, %**
DCCT	0.2	0.2
Ghost charge, BGI+LDM	0.0	0.3 (in fill 4634)
FBCT A/B/BPTX	0.0	0.0
LSC	0.3	0.3
Fit model	**1.1**	0.3
statistics	0.0	0.0
Scan-to-scan variations	**0.9**	**1.0**
RZ Velo – Velo diff.	0.1	0.1
Velo z-efficiency	0.0	0.0
X-Y non-factorizability (2D scans)	0.3	0.1
beam-beam	**0.5**	**0.5**

Beam-beam uncertainty is set to 0.5 % (correction +0.18 % / +0.15 % @ 13 and 5 TeV).
Orbit drifts have not yet been estimated, but expected to be small.

Lead vdM cross-sections

p-Pb, Pb-p, 6.5Z+6.5 TeV

group	source	correlation	c_pA	d_pA	c_Ap	d_Ap	comment
Intensity	DCCT	no		0.55%		0.52%	
Intensity	Offset	no		0.11%		0.10%	
Intensity	BPTX/FBCT	no		0.94%		0.45%	
Intensity	Ghost charge	no	+0.82%	0.86%	+1.04%	0.80%	
Intensity	Satellites	no	+0.65%	0.19%	+0.67%	0.20%	
Rate (mu)	Beam-beam background	yes		0.63%		0.65%	
Rate (mu)	Counter efficiency	yes	+0.32%	0.32%	+0.51%	0.51%	100% of correction
Separation	Length scale	no	-2.07%	0.20%	-2.08%	0.35%	
Shape	Fit model	yes		1.10%		1.10%	Max diff
Reproduc.	Diff + drift	no		0.95%		1.00%	

calibration	sigma	total unc.	abs. calib	rel. calib	correlated	uncorrelated
pA	(2.220 +- 0.058) b	2.61%	2.23%	1.35%	1.31%	1.81%
Ap	(2.125 +- 0.053) b	2.48%	2.13%	1.26%	1.38%	1.63%

2017 analysis, beam-beam was calculated with old method, needs to be redone

Conclusions

- Fixed target luminosity (in **p - SMOG gas** data sample) is calculated by counting p-(atomic) e elastic scatterings, ~ 6% precision

- Standard vdM calibration for collider data **p-Pb, Pb-p and pp @6.5Z and 2.5 TeV / beam** reaches 1.3 – 2.2 % precision.

- 1) Beam-beam,

  2) two-dimensional vdM scans,

  3) SMOG ghost charge measurements and

  4) propagation of the calibration to physics data sample

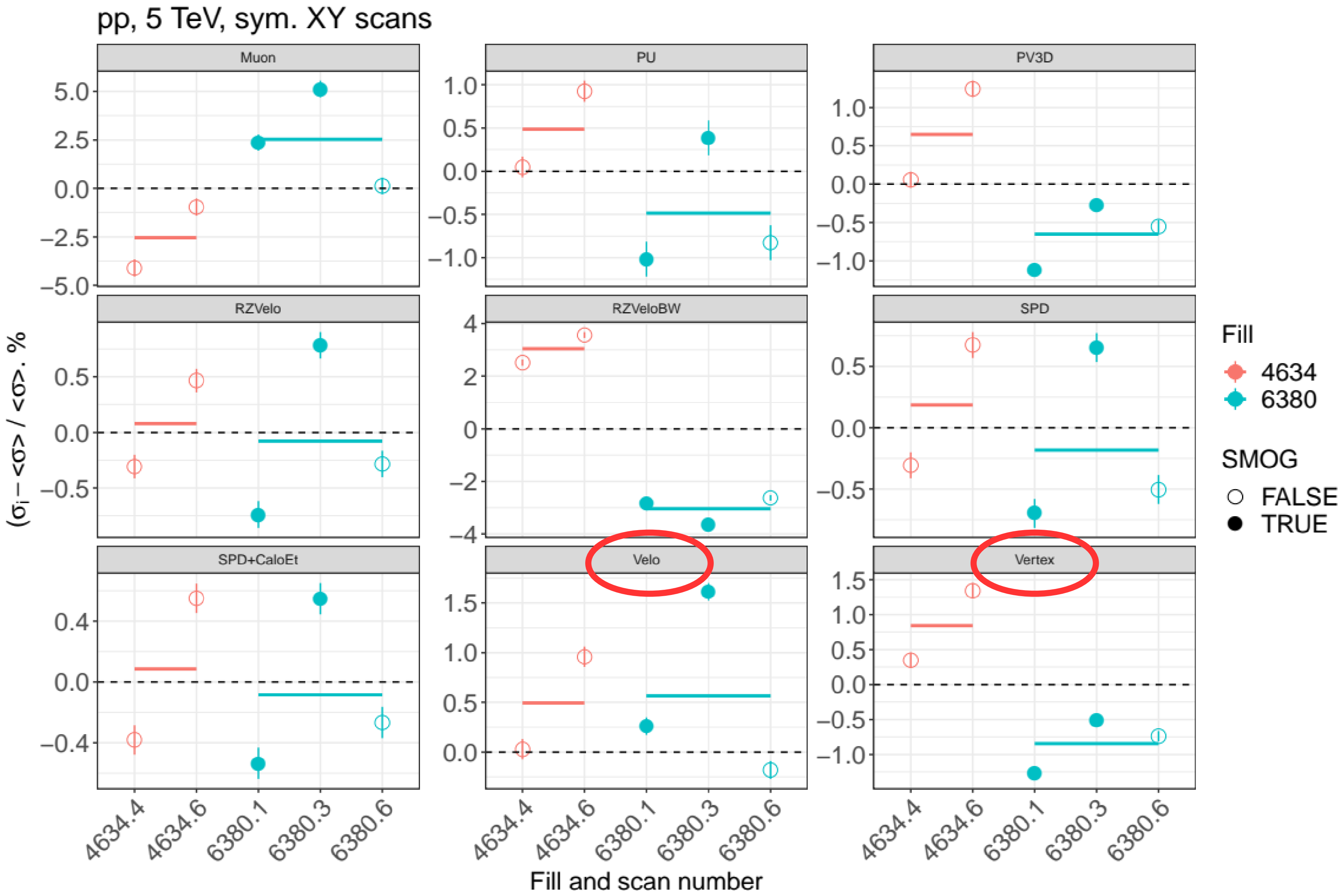
  will be discussed in the following 4 separate talks.

Backup slides

vdM pp, 5 TeV luminosity calibration

2 fills, every scan point is average over ~20 bunch crossing measurements

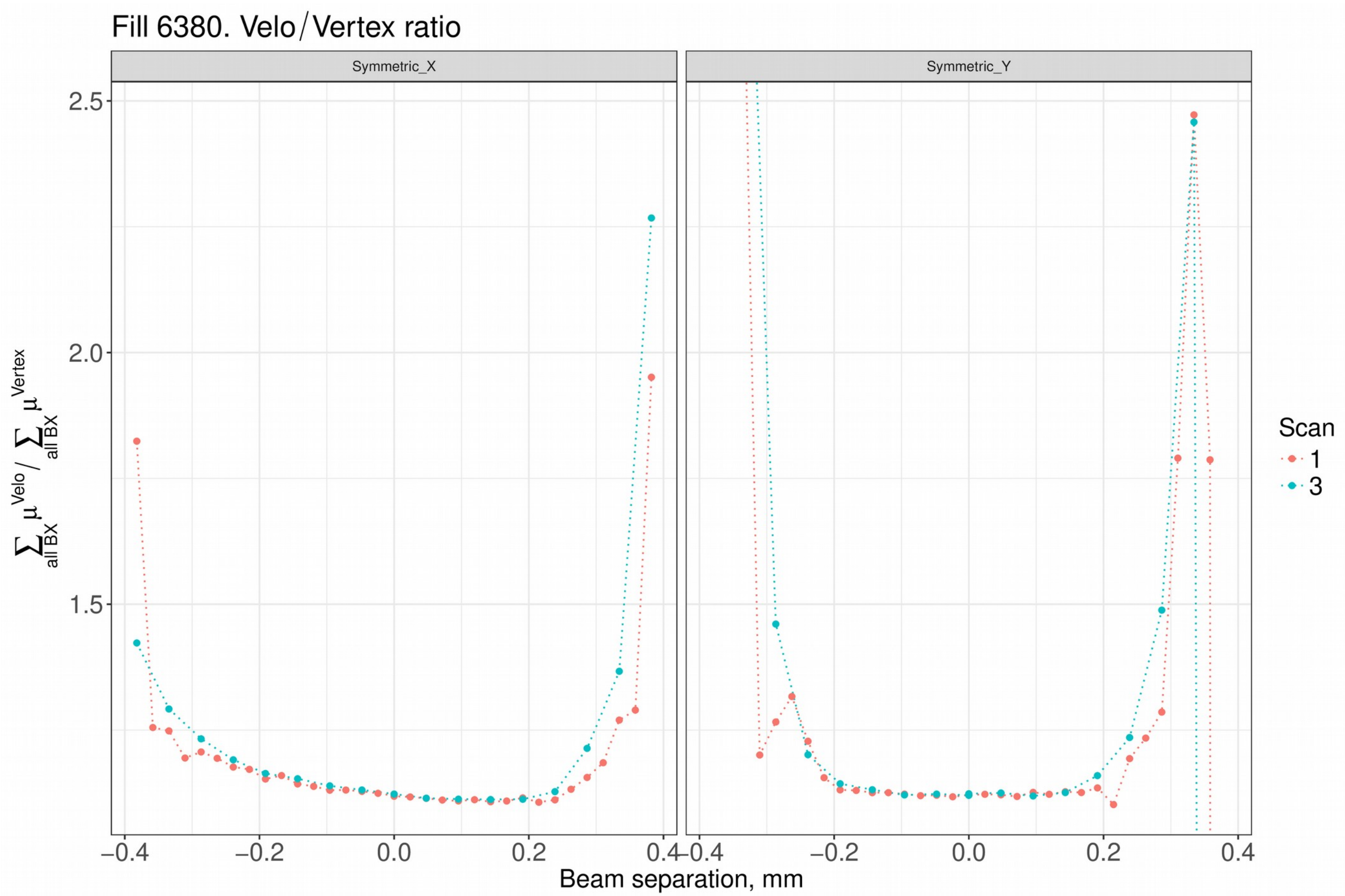
9 visible cross-sections for LHCb lumi counters, reference - Velo (N tracks > 1). Should be rescaled from Vertex>0 for SMOG scans.



μ(Velo) / μ(Vertex) vs beam separation after background subtraction

Residual SMOG bgr. visible in Velo>1 for widely separated beams :
μ(Velo) → μ_{VELO}(SMOG), μ(Vertex) → 0, and μ(Velo) / μ(Vertex) explodes.

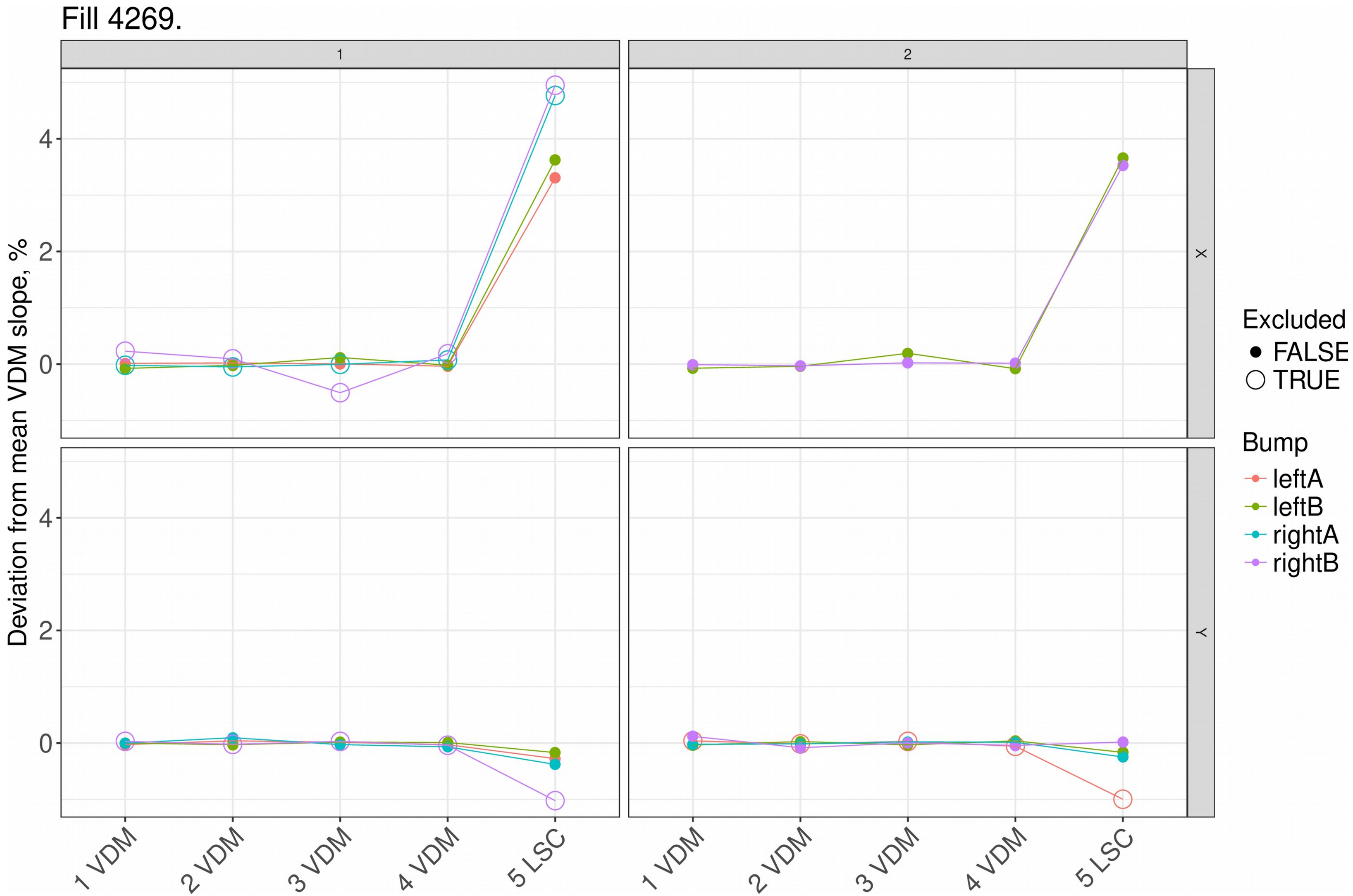
Slope in the middle part of X-scan is due to stronger Vertex efficiency dependence on Z and X-Z beam crossing angle.



Correcting wrong LSC slope with VDM in fill 4269

2 + 2 problematic magnets with oscillations and non-linearities are excuded (empty circles).

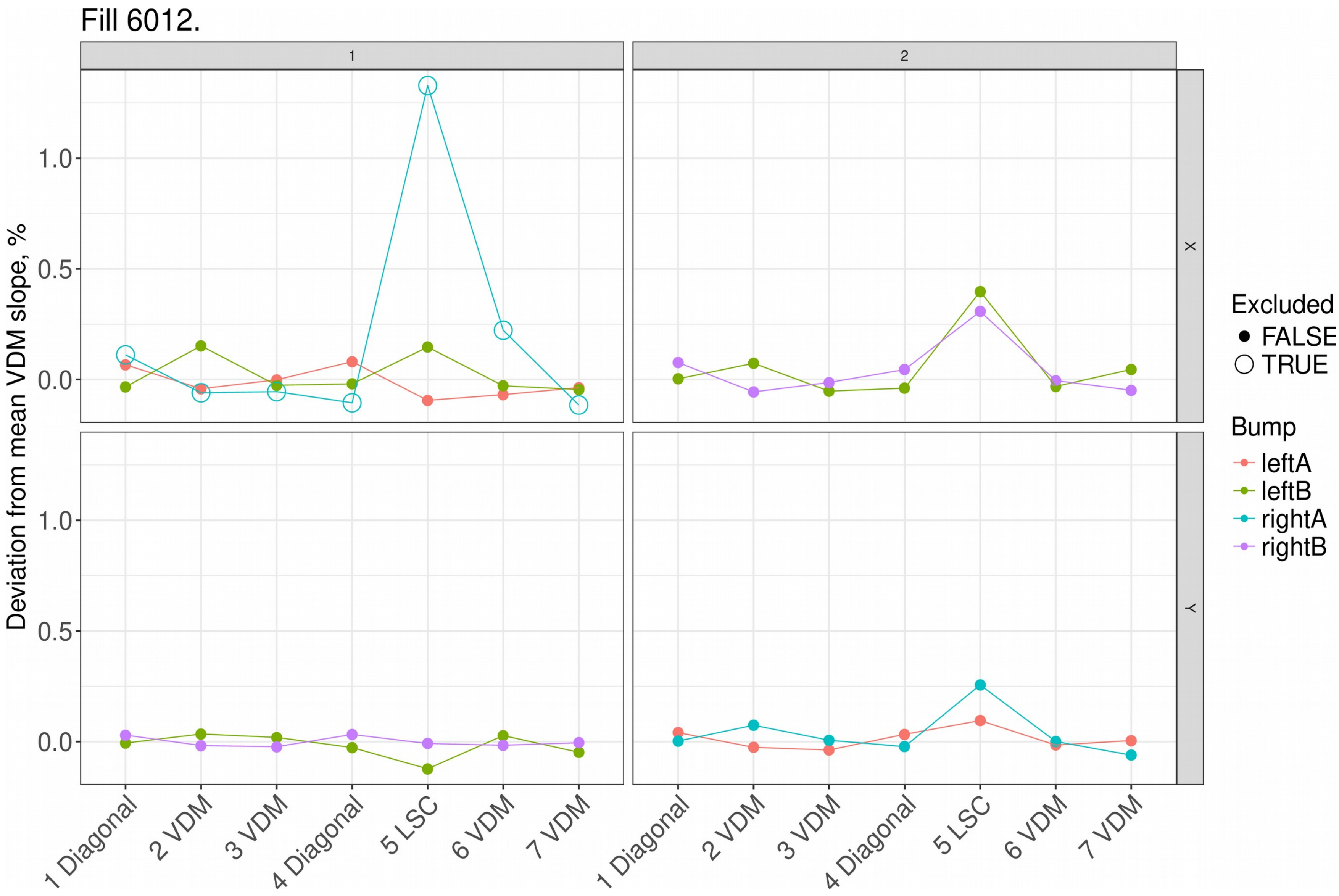
Result : LSC_X slope deviates from mean VDM scale by 3.53+/-0.16 %, where 0.16 % is RMS between the magnets.
Y correction is compatible with zero, 0.19+/-0.22.



Same cross-check in fill 6012 with correct LSC

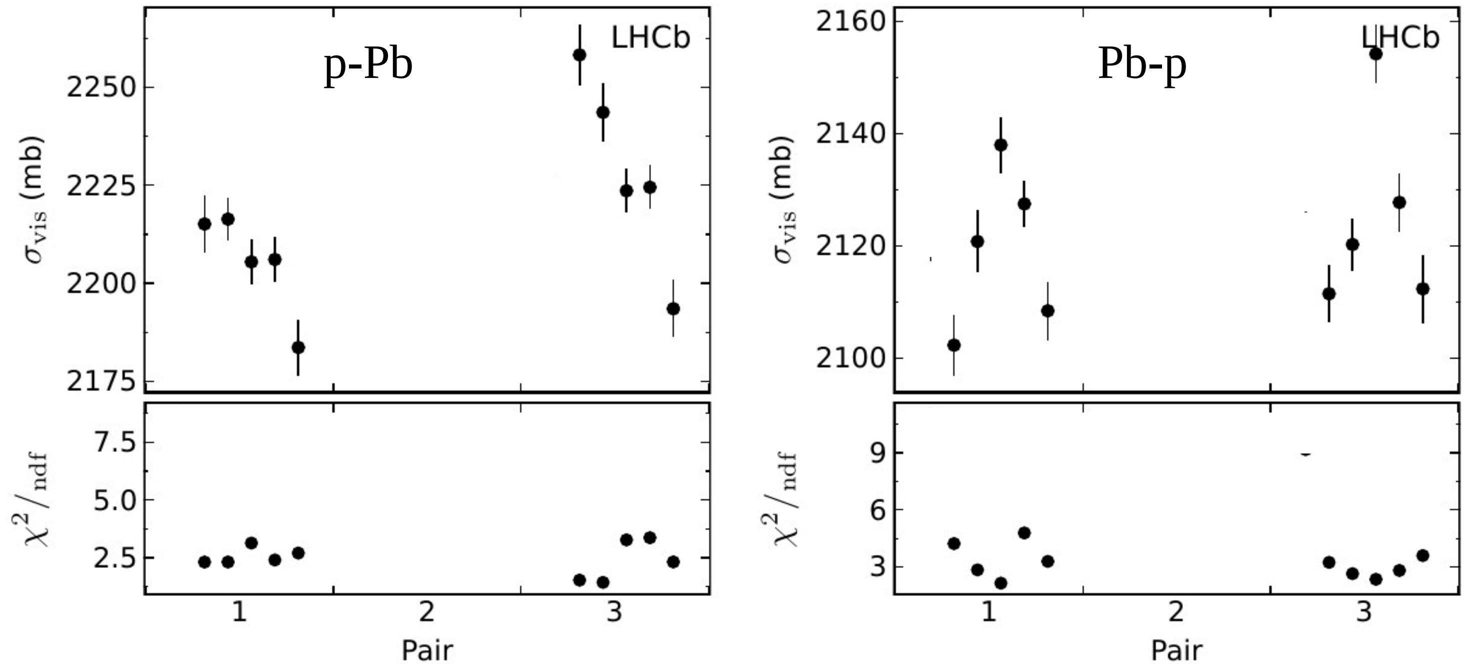
1 problematic magnet with oscillations is excuded (empty circles).

Result : LSC_X,Y slopes are consistent with mean VDM scale, deviations : 0.19+/-0.22 % (X) and 0.05+/-0.16 % (Y) where errors are RMS between the magnets. .

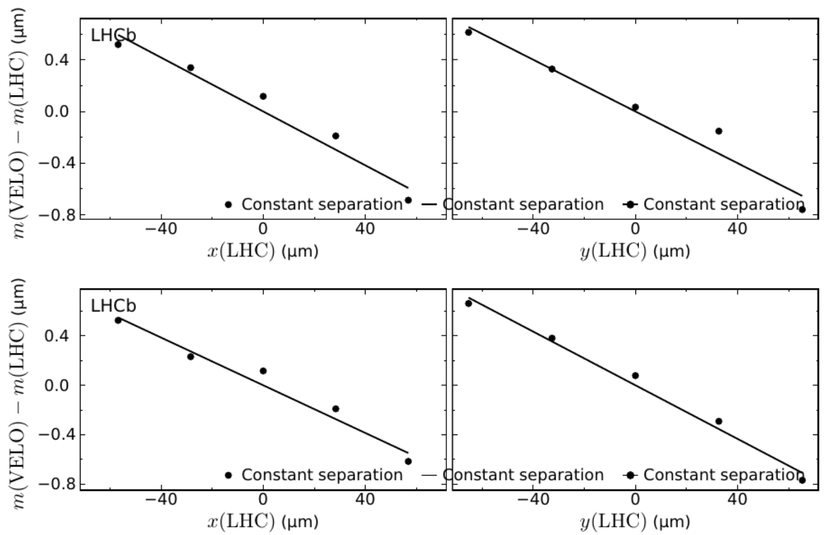


p-Pb, Pb-p VDM at 6.5Z TeV

>100 bunches, high trigger rate only for 5 to collect enough statistics, others are ignored.
Pair 1,3 == two VDM scans

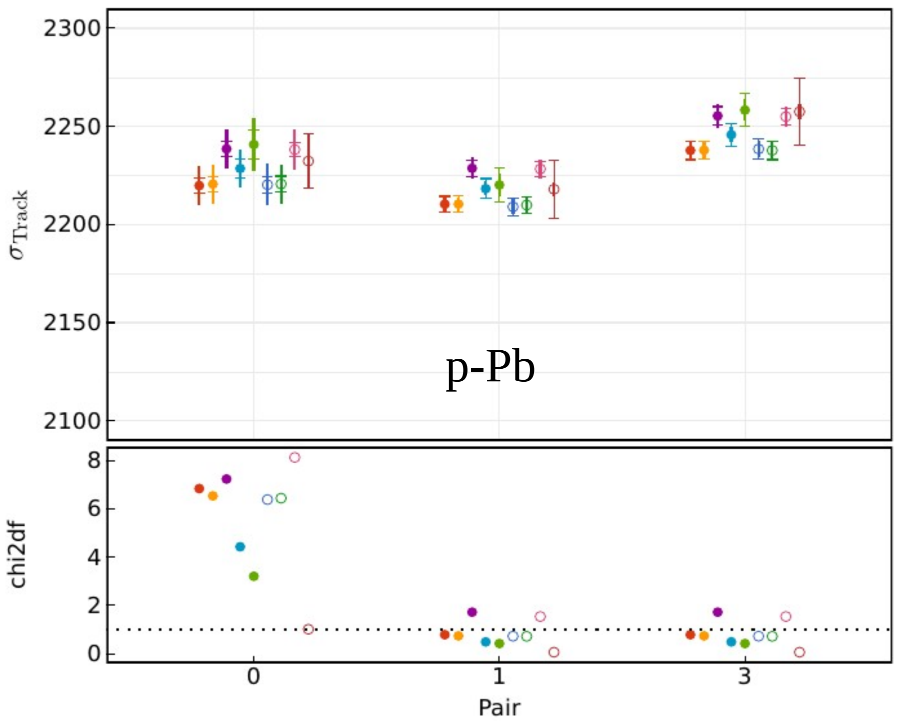


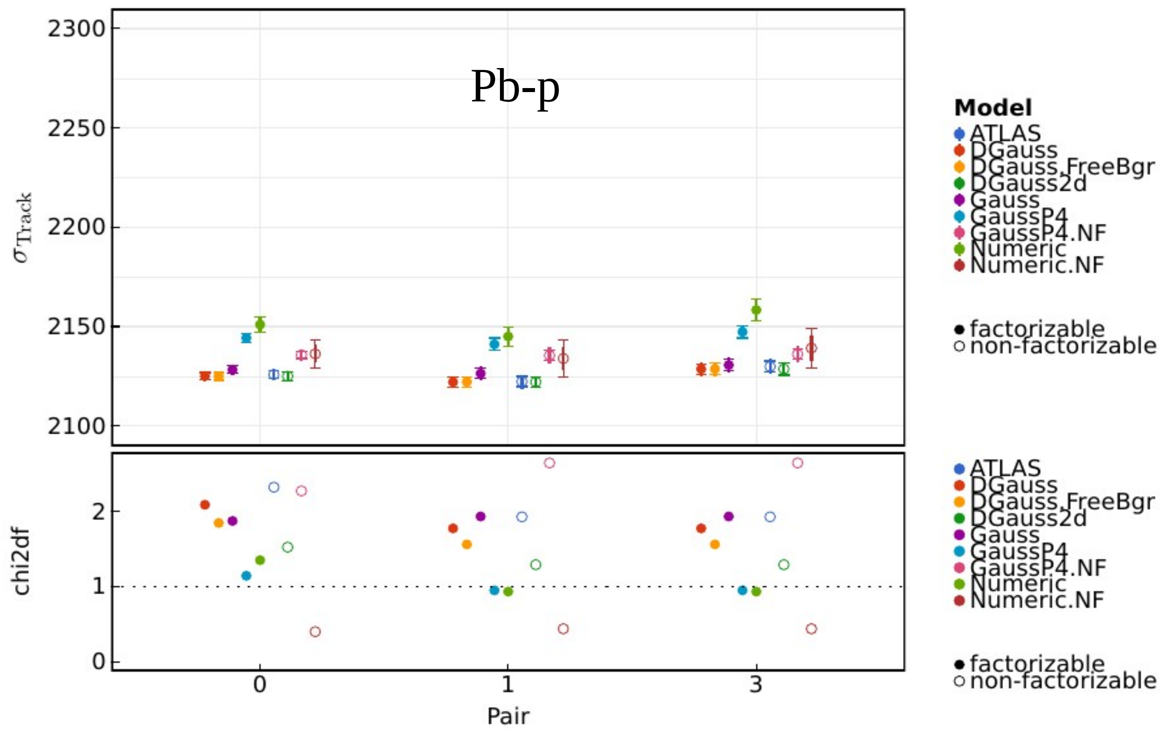
Length scale calibration (LSC)



Fit models for p-Pb, Pb-p vdM @6.5Z TeV

Various fit models, approximately Gaussian beams. Average over bunch crossings.
Pair 0 == scan average.





BGI RF-bucket timing with Outer Tracker (OT)

LHCb Outer Tracker – 5x6 m^2 area, 12 double-layers of 2.4 m long gaseous straw tubes, ø 4.9 mm.
Run 2 with improved and real-time alignment: ~ 170 um spatial, ~ 2.4 nsec time resolution (dominated by ionization and drift properties of $Ar/CO_2/O_2$ gas)

JINST 12 (2017) no.11, P11016

Track time-stamp resolution (weighted average of ~ 22 hits) for $B \rightarrow l X$ sample: 0.57 nsec. Can be used for Time-Of-Flight PID.

Track fitting assumes nominal bunch crossing timing - difficulty for ghost interactions.
Current solution: reconstruct same event 10 times with shifts in OT hit times in steps of 2.5 nsec across 25 nsec slot.

sum over all nominally empty crossings

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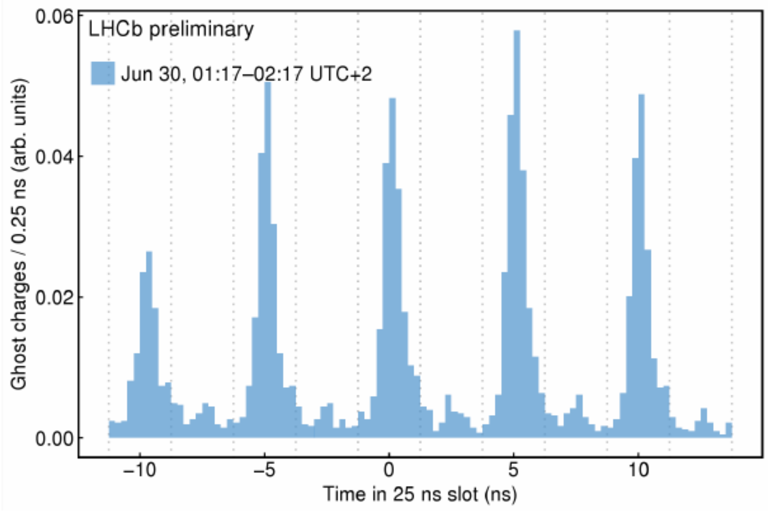
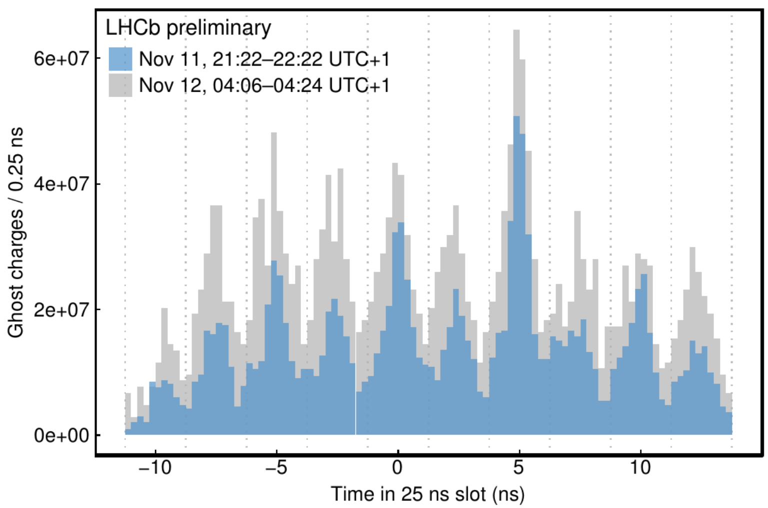


No debunching,
RF buckets clearly separated



Debunching visible