LHC Lumi Days 2019

June 4-5, 2019 @ CERN

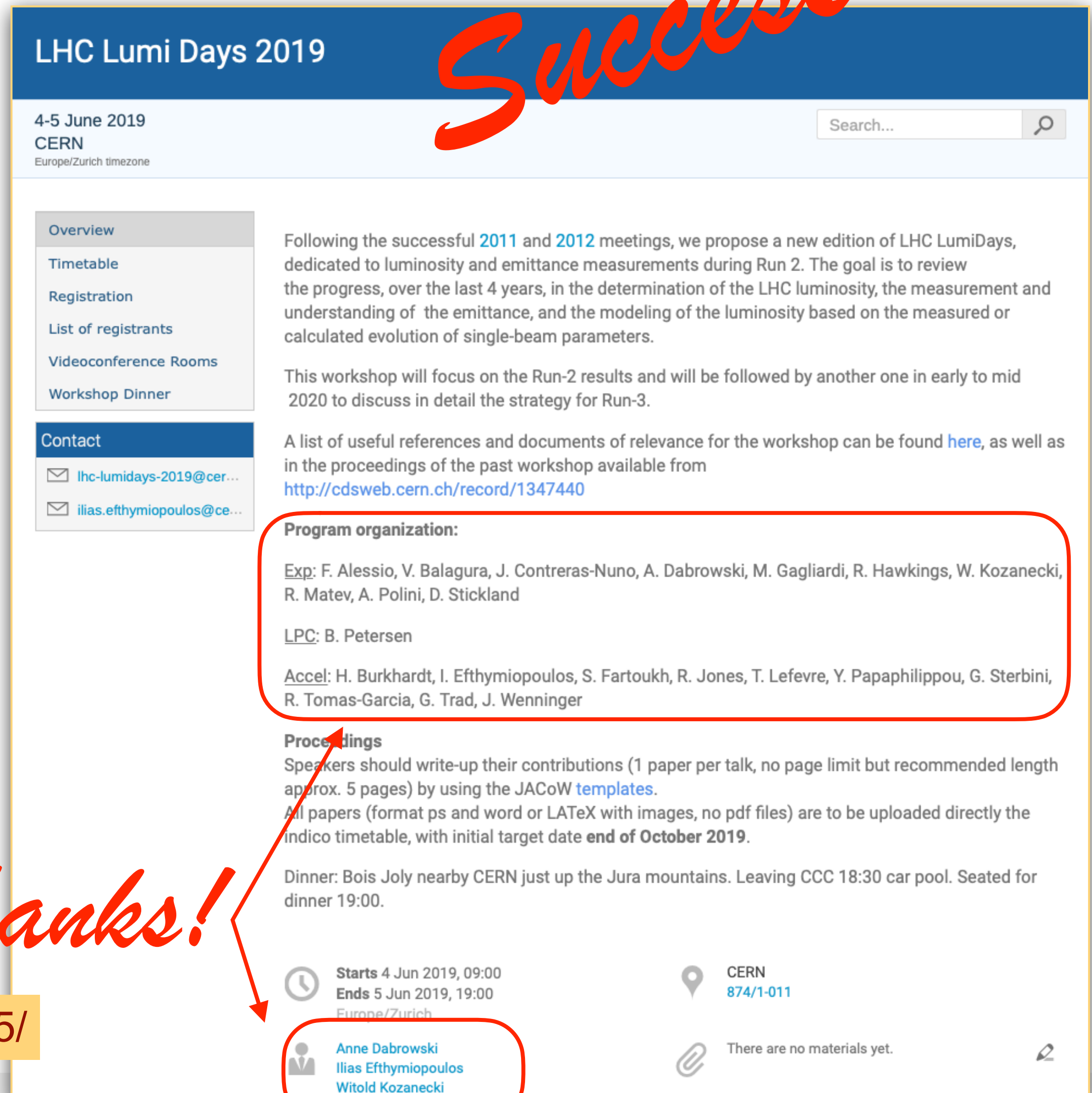
Workshop Highlights

I. Efthymiopoulos

LumiDays 2019

- **93 participants**, full auditorium
- excellent presentations, lively discussions and debates
- excellent work being done and presented for experiments & machine

Success!


LHC Lumi Days 2019

4-5 June 2019
CERN
Europe/Zurich timezone

Search...

Overview
Timetable
Registration
List of registrants
Videoconference Rooms
Workshop Dinner

Contact
lhc-lumidays-2019@cer...
ilias.efthymiopoulos@ce...

Following the successful 2011 and 2012 meetings, we propose a new edition of LHC LumiDays, dedicated to luminosity and emittance measurements during Run 2. The goal is to review the progress, over the last 4 years, in the determination of the LHC luminosity, the measurement and understanding of the emittance, and the modeling of the luminosity based on the measured or calculated evolution of single-beam parameters.

This workshop will focus on the Run-2 results and will be followed by another one in early to mid 2020 to discuss in detail the strategy for Run-3.

A list of useful references and documents of relevance for the workshop can be found here, as well as in the proceedings of the past workshop available from http://cdsweb.cern.ch/record/1347440

Program organization:

Exp: F. Alessio, V. Balagura, J. Contreras-Nuno, A. Dabrowski, M. Gagliardi, R. Hawkings, W. Kozanecki, R. Matev, A. Polini, D. Stickland

LPC: B. Petersen

Accel: H. Burkhardt, I. Efthymiopoulos, S. Fartoukh, R. Jones, T. Lefevre, Y. Papaphilippou, G. Sterbini, R. Tomas-Garcia, G. Trad, J. Wenninger

Proceedings
Speakers should write-up their contributions (1 paper per talk, no page limit but recommended length approx. 5 pages) by using the JACoW templates.
All papers (format ps and word or LATeX with images, no pdf files) are to be uploaded directly the indico timetable, with initial target date **end of October 2019**.

Dinner: Bois Joly nearby CERN just up the Jura mountains. Leaving CCC 18:30 car pool. Seated for dinner 19:00.

Starts 4 Jun 2019, 09:00
Ends 5 Jun 2019, 19:00
Europe/Zurich

CERN
874/1-011

Anne Dabrowski
Ilias Efthymiopoulos
Witold Kozanecki

There are no materials yet.

Thanks!

https://indico.cern.ch/event/813285/

LumiDays 2019

2020(?)

*Planning for **Run 3 & HL-LHC***

2019

New edition of LHC LumiDays, dedicated to luminosity and emittance measurements during Run 2.

Share work in progress & ideas across various working groups

2012

Review the progress made in 2011 both in the determination of the LHC luminosity, and in successfully exploiting this increased accuracy in physics analysis

Links to reference material !!

2011

Review the results of the first luminosity calibration measurements at the LHC and to stimulate a discussion on future measurements

Links to reference material !!

Workshop Sessions

Luminosity-determination Methodology in Run 2

- Overview presentations from machine & experiments

Impact of Accelerator Instrumentation to vdM Calibrations

- Beam current & ghost charge measurement
- Orbit measurement & control
- Orbit & hysteresis effects in vdM calibration

Impact of Beam Dynamics on vdM Calibrations: Sources and Mitigation

- Beam preparation in the injectors & beam optics for vdM fills
- Non factorisation impact on luminosity calibration from experiments
- Beam-beam effects

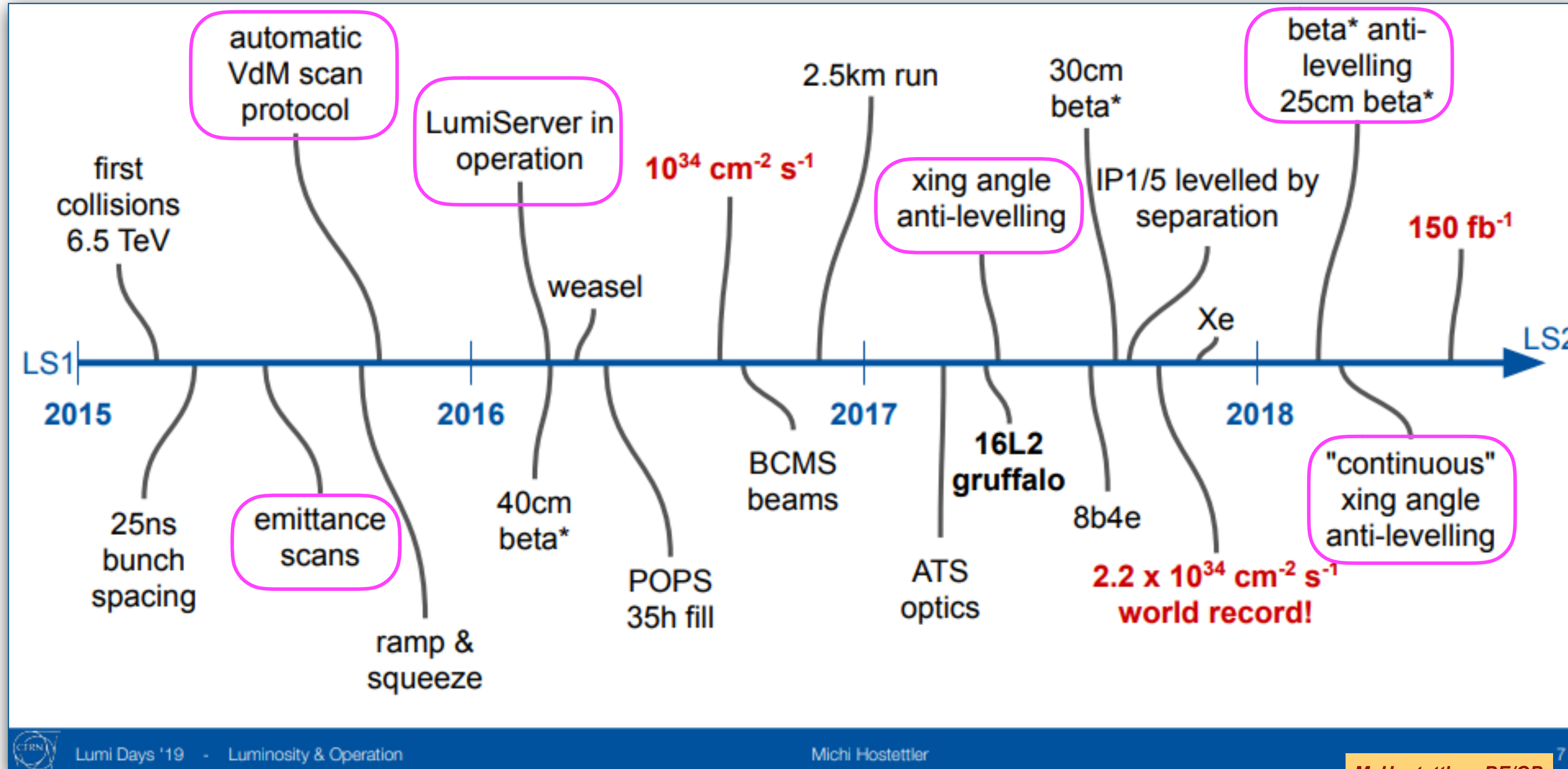
Luminosity & Emittance in Physics

- Long-term monitoring of delivered luminosity & calibration stability in the experiments
- Transverse & long beam emittance measurement and evolution in the cycle and at SB
- The luminosity model
- Combining the luminosity uncertainties from several data-sets

Summary

- conclusions for experiments & machine, follow-up, LumiDays 2020!

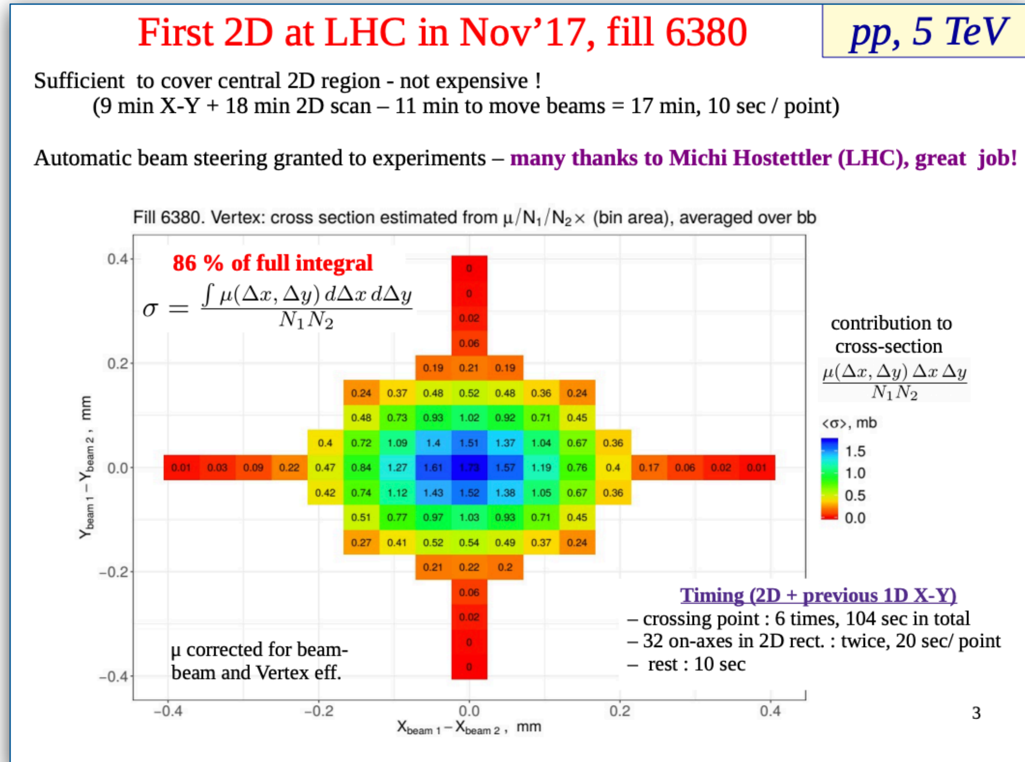
Overview Run 2 operations & lumi



M. Hostettler - BE/OP

- Full OP panoply available for Run 3

Luminosity scans (vdM, SB,…)



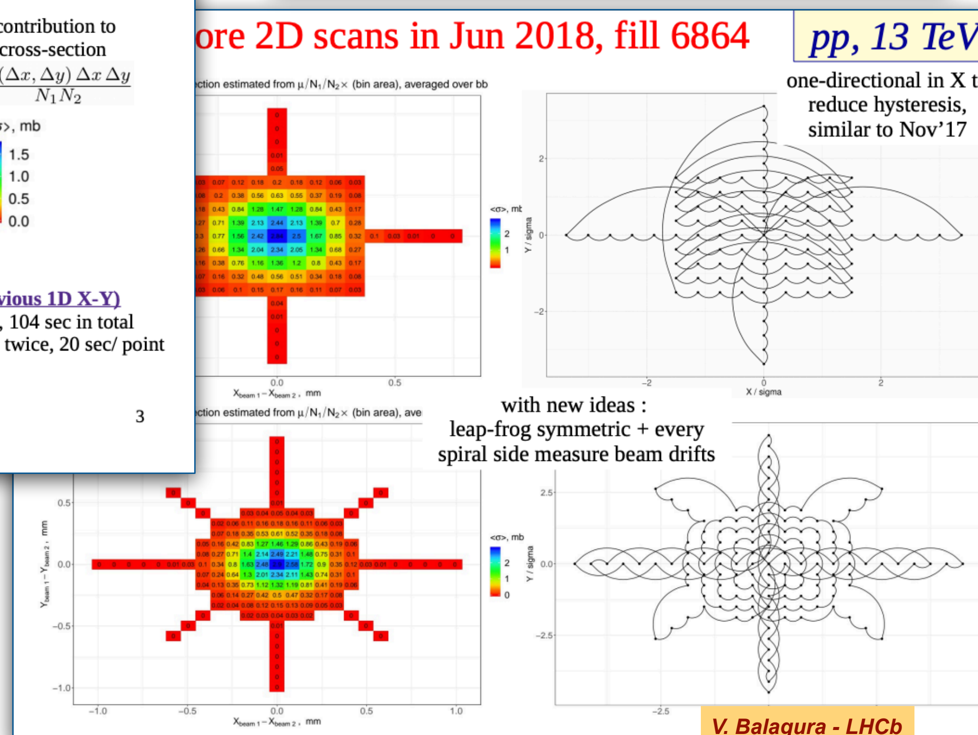
$$\rho_{1,2}(x,y) = \rho^x_{1,2}(x)\cdot\rho^y_{1,2}(y)$$

$$\mu(\Delta x,\Delta y) = \mu^x(\Delta x)\cdot\mu^y(\Delta y)$$

$$\sigma = \frac{\int\mu(\Delta x,\Delta y)\,d\Delta x\,d\Delta y}{N_1N_2} = \frac{\int\mu^x(\Delta x)\,d\Delta x\int\mu^y(\Delta y)\,d\Delta y}{N_1N_2}\,\frac{\mu^y(\Delta y_0)\mu^x(\Delta x_0)}{\mu^y(\Delta y_0)\mu^x(\Delta x_0)} = \frac{\int\frac{\mu(\Delta x,\Delta y_0)}{N_1N_2}\,d\Delta x\cdot\int\frac{\mu(\Delta x_0,\Delta y)}{N_1N_2}\,d\Delta y}{\frac{\mu(\Delta x_0,\Delta y_0)}{N_1N_2}}.$$

= 1

Main formula for cross-section measurement

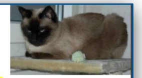


- Excellent performance of the automatic scan in vdM fills
- Allows scanning in 2D, even with complicated algorithm
- 2D scans can bring major improvement in the non-factorization systematics of the lumi calibration

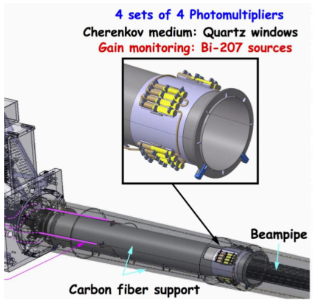
Luminosity Measurement in LHC

R. Hawkings - ATLAS

ATLAS luminosity detectors: LUCID & BCM



- Primary Run 2 bunch-by-bunch (b-b-b) measurement from LUCID

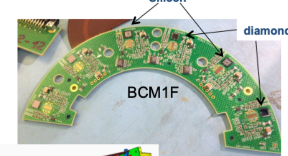


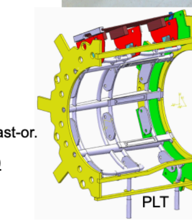
- Cherenkov light from quartz windows of 2x16 PMTs at z=±17m from IP
  - b-b-b measurements for every bunch crossing, integrated over 'luminosity blocks' of typically 60 seconds
  - PMT windows coated with Bismuth calibration source
    - Gain adjusted run-by-run
  - Several 'algorithms' to combine PMTs
    - 'HitOR' combination of 2x4 PMTs
    - Many channels had problems in 2018
    - … used single best PMT (C12) offline instead of OR of surviving 7
- Secondary b-b-b measurements from Beam Conditions Monitor (BCM)

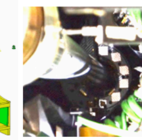
CMS luminosity instruments

CMS BRIL

- Only bunch-by-bunch measurement
  - ~1.45 s (2^{14} LHC turns) granularity
  - ~1% precision / BX / s
- Hadron Forward calorimeter
  - Quartz fibers in Steel absorber.
  - Dedicated lumi back-end.
  - Two algorithms: Zero counting (**HFOC**), transverse energy sum (**HFET**)
- Pixel Luminosity Telescope (**PLT**)
  - Three phase-0 CMS Pixel planes in telescope arrangement.
  - Tipple coincidences of detector module fast-or.
- Fast Beam Condition Monitor (**BCM1F**)
  - Pad detector with fast analog front end.
  - Hit counting with 6.25 ns time resolution.
- One of these systems provides Luminosity to LHC.







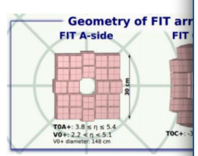
DESY. CMS Luminosity in Run-2 | M. Guthoff | 3rd June 2019 4

M. Guthoff - CMS

Run 3 prospects

Fast Interaction Trigger replaces 3 detectors in ALICE: T0, V0, and FMD

https://cds.cern.ch/record/781854/files/lhcc-2004-025.pdf https://cds.cern.ch/record/1603472/files/ALICE-TDR-015.pdf



FIT will consist of two arrays of Cherenkov radiators with MCP-PMT sensors (T0+) and of a single, large-size scintillator ring (V0+)

(+ ZDC and AD, which will stay)

(FIT = T0+ and V0+ for ALICE after LS2)

M. Gagliardi – Overview of ALICE luminosity-determination methodology in Run 2 – LHC Lumi days 2019

M. Gagliardi - ALICE

Luminosity of fixed target p-SMOG samples

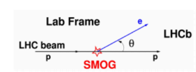
PAMELA + AMS-02: excess in anti-p / p fraction :

- 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.

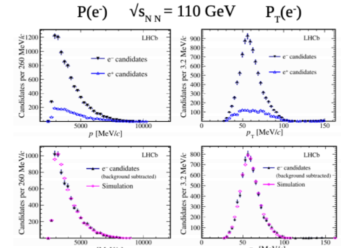
Difficult to measure precisely low SMOG pressure

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



Phys. Rev. Lett. **121** (2018) 222001

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



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

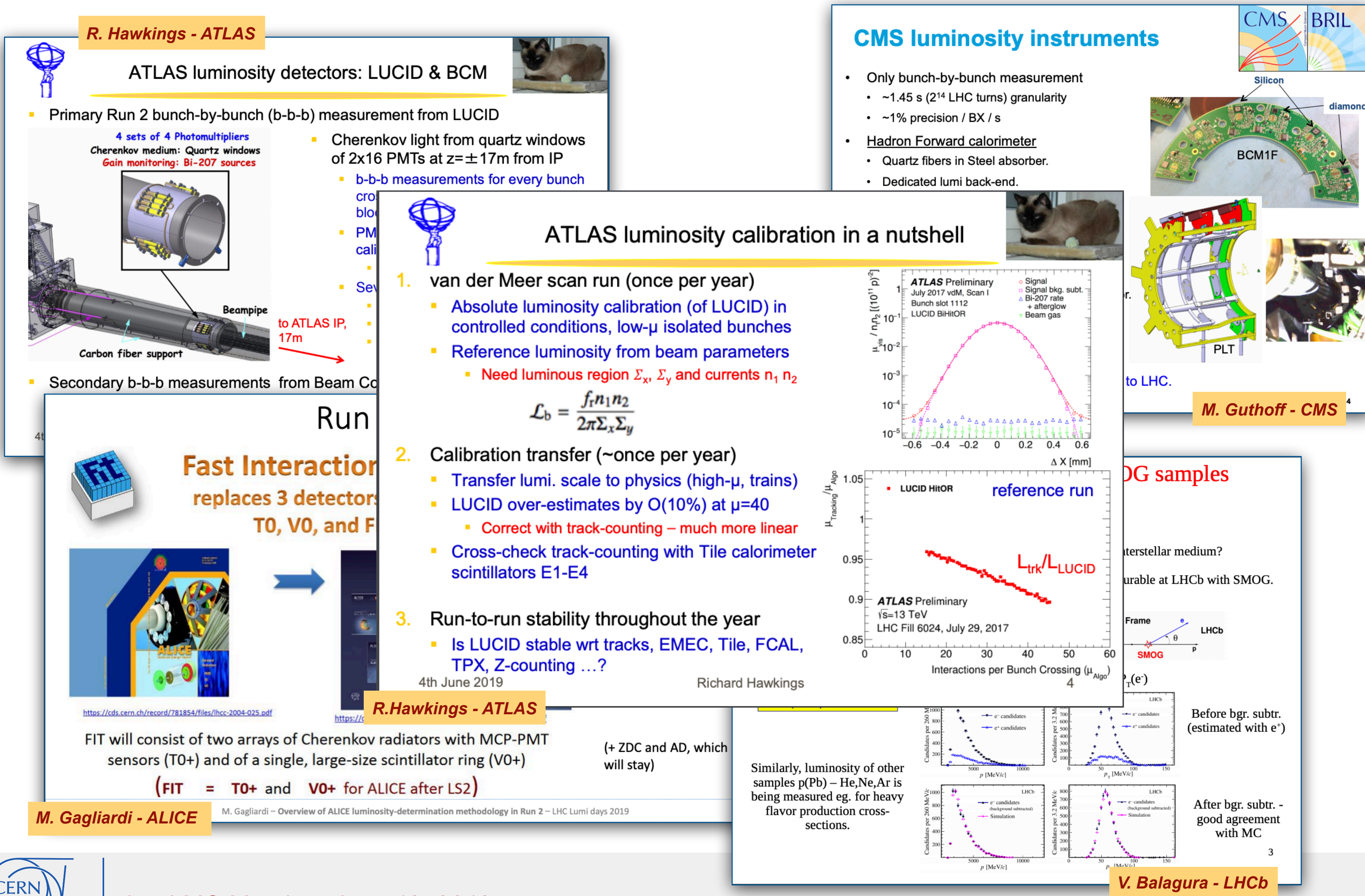
After bgr. subtr. - good agreement with MC

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

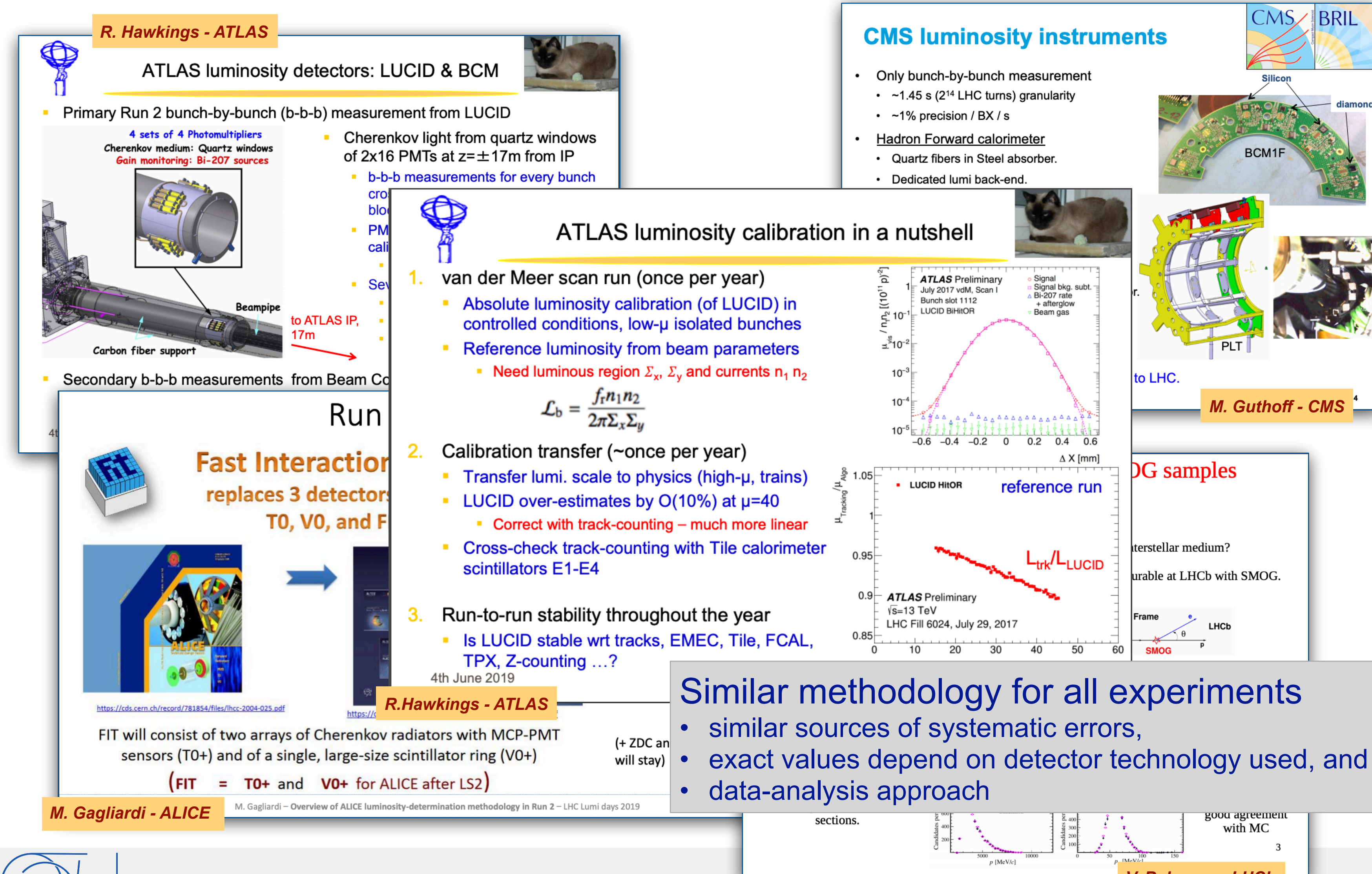
3

V. Balagura - LHCb

Luminosity Measurement in LHC



Luminosity Measurement in LHC



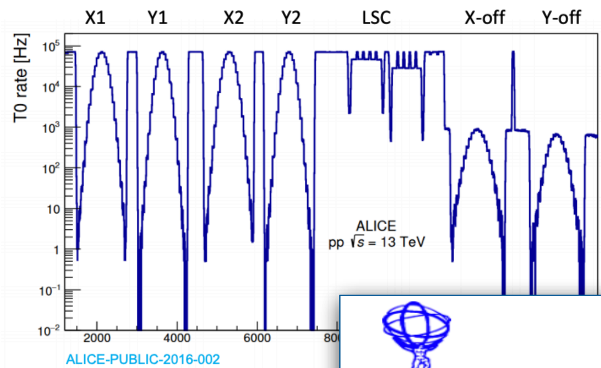
Similar methodology for all experiments

- similar sources of systematic errors,
- exact values depend on detector technology used, and
- data-analysis approach

Luminosity Calibration - vdM scans

ALICE standard scan sequence

- **Two standard, symmetric scans** (X1-Y1, X2-Y2)
  - -6 σ_{beam} -> +6 σ_{beam} in steps of 0.5 σ_{beam}
  - 30 s/step
- **Length-scale** calibration
  - 5 steps of ~ σ_{beam} each
  - beams kept at a distance of ~ Σ
- **Offset** scan
  - typical offset ~ 4σ_{beam}
  - input to non-factorisation fits
- **Bunch intensity** measurements:
  - LHC instrumentation
  - ATLAS BPTX
  - LHCb ghost charge
  - **(thanks to all!)**

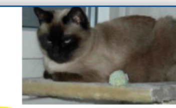


M. Gagliardi – **Overview of ALICE luminosity-determination methodology in Run 2** – LHC Lumi

M. Gagliardi - ALICE

- *I focus in the slides on **pp collisions**. For the work done for **PbPb** and **pPb** please refer to the **workshop indigo***

vdM analysis details



- Various corrections must be taken into account (additional systematics)
  - ★ Orbit drifts during scans, measured using LHC arc and triplet (DOROS) BPMs
    - See dedicated discussion in talk of W. Kozanecki
  - Beam position jitter (beam movement within one scan step)
    - BPMs constrain possible movement within a scan step, input to simulated vdM scans
  - ★ Beam-beam effects (scan curve distortion, dynamic β)
    - Depends on beam energy, transverse beam size, bunch currents, actual β^* and tune
    - Calculated using MADX simulation, as in Run 1
    - Significant (positive) corrections of 1.3-1.7% on σ_{vis}
    - Systematics from variation of ±20% on assumed β^*, ±0.01 on tune (0.2-0.3% on σ_{vis})
  - Emittance growth (uncertainty carried over from run 1 analysis)
    - Only if horizontal and vertical emittances grow at different rates (which they do)
  - ★ Non-factorisation effects: $\Sigma_x\Sigma_y$ does not fully represent the 2D overlap integral
    - Dedicated studies and off-axis scans – see talk of M. Dyndal

R. Hawkings - ATLAS

Non-Factorisation effects in vdM Calibration

- Calibration of the luminosity in a vdM scan
  - Assuming factorisation of particle densities in each bunch into independent **vertical** and **horizontal** components
  - This assumption is not accurate
- To estimate the non-factorisation correction to σ_{vis} we calculate (analytically) a quantity **R**

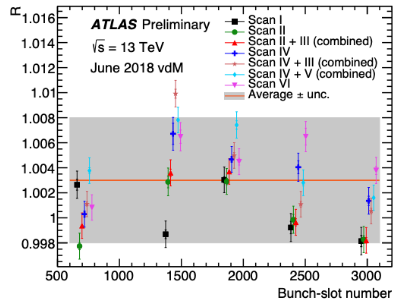
$$R = \frac{\text{True luminosity}}{\text{Factorised luminosity}} \equiv \frac{\int \rho_1(x,y)\rho_2(x,y)dxdy}{\int \rho_1(x)\rho_2(x)dx \int \rho_1(y)\rho_2(y)dy}$$

- $\sigma_{vis}^{corr} = \frac{\sigma_{vis}}{R}$

ρ1, ρ2 are the proton density distributions

ATLAS 2018 13 TeV pp results

- Spread of the results larger than in 2017
- Possible effects:
  - Small R-dependence on bunch properties (incl. n1*n2)
  - …



<R> = 1.003
shaded band (±0.005) represents the uncertainty
-> conservative estimate

5 BCIDs are shown (points are shifted for better visibility)

ATLAS-CONF-2019-021

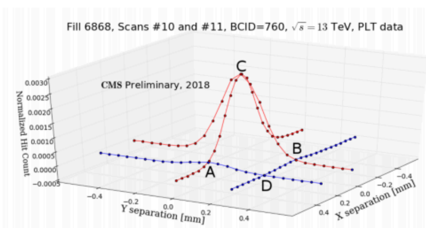
M. Dyndal Non-factorization in ATLAS & AL

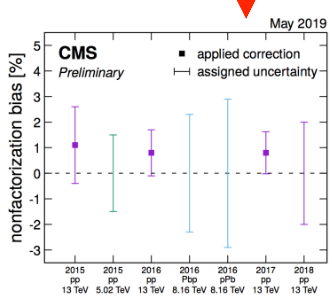
M. Dyndal - ATLAS

X/Y-correlations

Dedicated talk by J. Knolle, today 16:50

- Observation: Width of the beam overlap transversal to scanning direction not constant.
- Measurement methods to estimate:
  - **Beam Imaging scans**: One beam is used to probe the shape of the other beam. Beam shape reconstructed from vertex data.
  - **Offset scans**: 2D correlated Gaussian fit to luminometer data.





DESY. CMS Luminosity in Run-2 | M. Guthoff | 3rd June

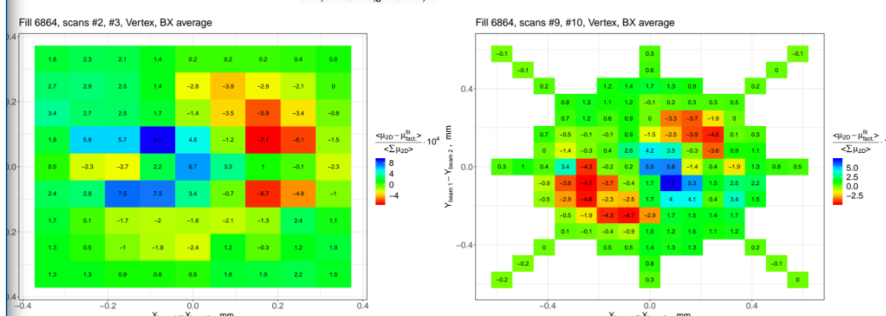
M. Guthoff - CMS

2D map of residuals

pp, 13 TeV

$$\frac{\mu_{i,j}-\mu_{i,0}\cdot\mu_{0,j}/\mu_{0,0}}{\sum_{i,j}\mu_{i,j}}$$

On-axes $\mu_{i,0}$, $\mu_{0,j}$, $\mu_{0,0}$ are from single Gaussian fits



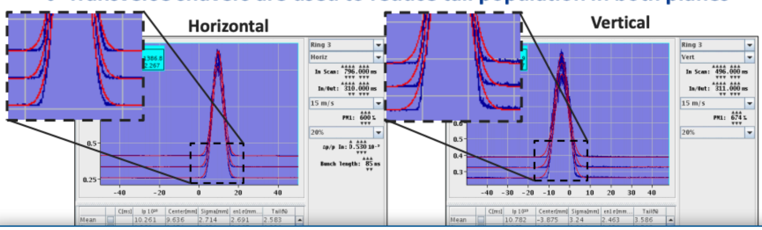
Data are fit per bunch crossing and then averaged. Mismatches are scaled by 10^{-4}

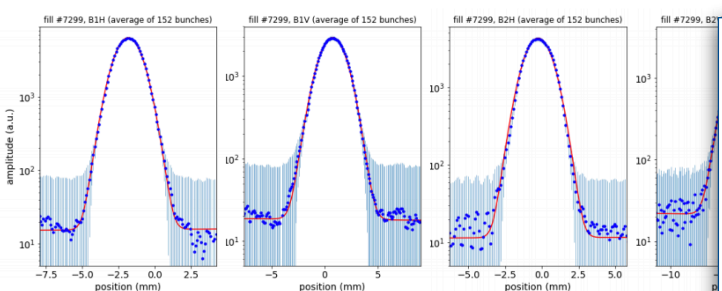
V. Balagura - LHCb

Beam Parameters for vdM Fills

Beam preparation in PSB – in Run 2

- **Intensity adjusted through controlled longitudinal blow-up before reaching longitudinal acceptance bottle-neck**
  - Better reproducibility of beam intensity
- **Transverse emittance adjusted through working point control**
  - Controlled blow-up close to integer tunes
- **Transverse shavers are used to reduce tail population in both planes**





WS @ LHC

LHC lumi days 2019

H. Bartosick - BE/ABP

Outlook for Run 3

- **PSB**
  - New injection scheme with H⁻
  - Linac4 provides much smaller emittance
  - Higher injection energy
  - Transverse painting through injection offset
  - Bunched beam injection

  production schemes for single bunch LHC beams (with large emittance) remain to be established

  - Transverse blow-up through excitation with damper might become available (could be used to adjust transverse emittances)
- **PSB-to-PS transfer at 2 GeV**
  - New transfer line optics with matched dispersion (possibly less halo formation)
- **New beam instrumentation**
  - Upgraded wire scanners in all injectors (should allow for better measurements at SPS extraction with higher sampling due to variable rotation speed and higher accuracy of position readout)

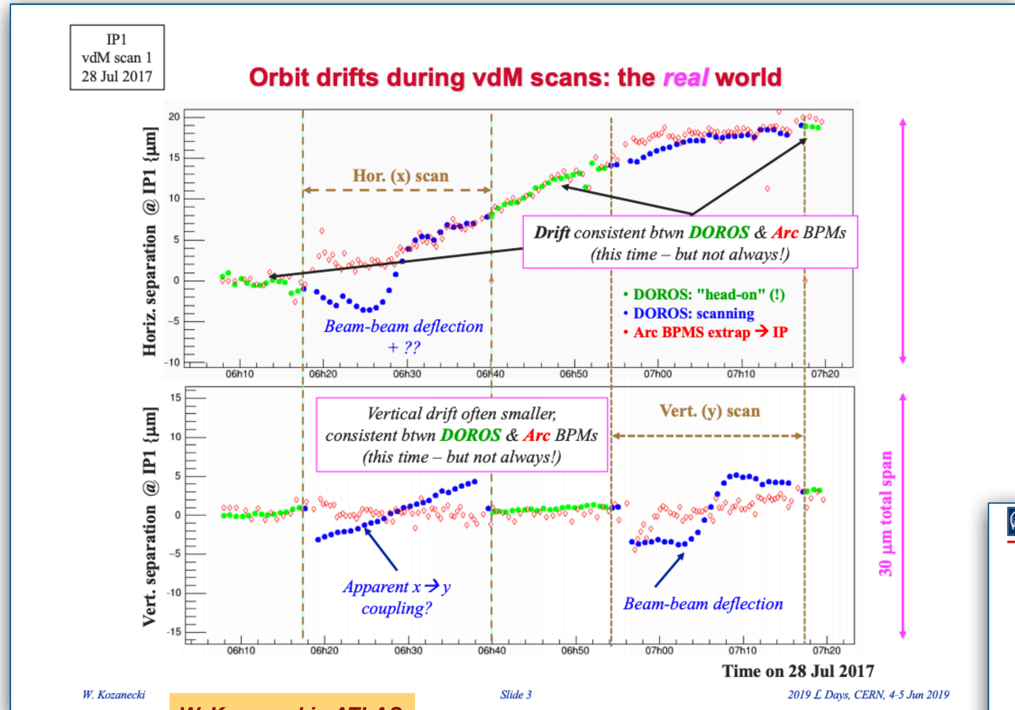
Conclusions — Beam Optics

- Experimentally, $\beta^* = 19$ m seems not to be a good choice.
- The smaller β^* the better (from the machine perspective).
- Safety margin accounting for β-beating.
  - Exlude region: $\beta^* = L^* \pm 20\%$.
- $\beta^* \leq 17$ m seems to be a reasonable choice.
  - Uncertainty below 0.5% for near to ideal case.
- Larger β^* is also possible (40 m?) but not for HL.
- Further analysis required to better estimate β^* uncertainty.
  - MC-like simulations including β-beating and waist beating.
- The uncertainty on β^* might be further reduced if some time is devoted to vdM optics correction (i.e. reduce waist, β-beating...).

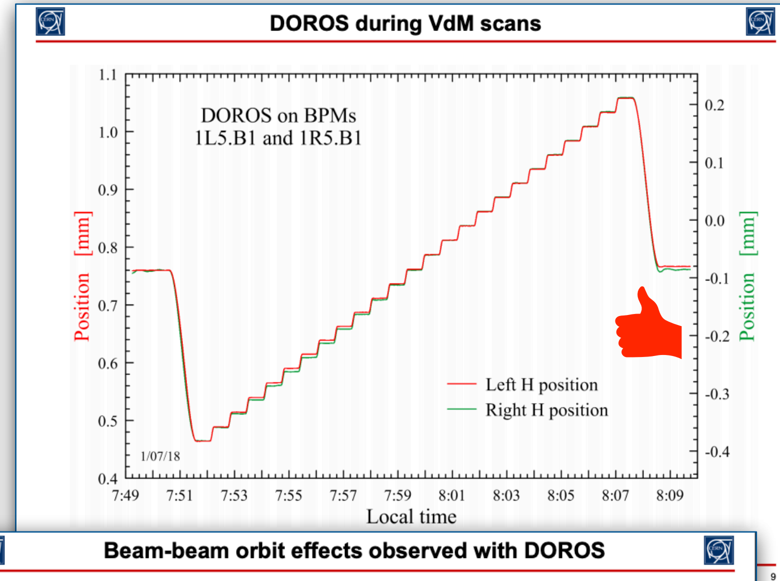
H. Morales, R. Tomas - BE/ABP

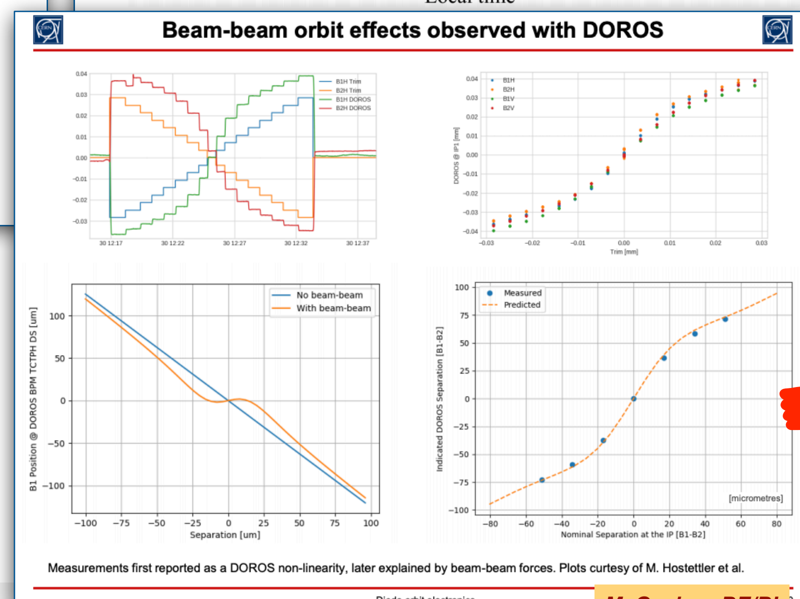
- Beam parameters to review for Run 3 and HL-LHC also considering the experimental conditions (e.g. rates) and overall beam variations as well.

Orbit Drifts in vdM scans



W. Kozanecki - ATLAS

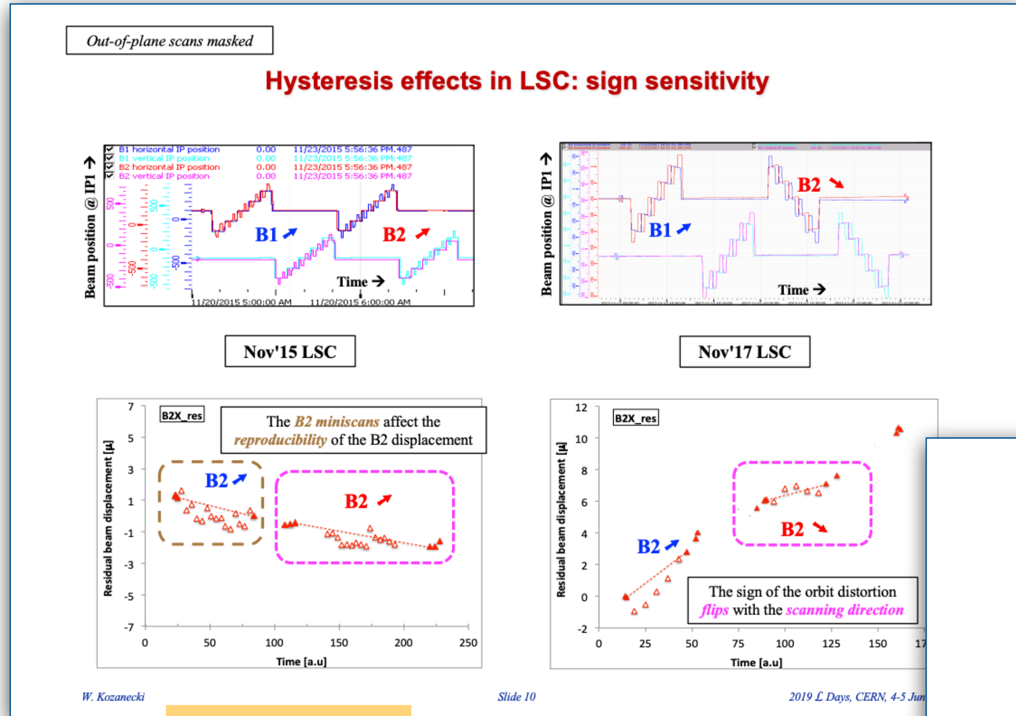




M. Gasior - BE/BI

- Excellent performance of the DOROS system in Run 2
- Good performance for vdM fills too. However need to understand in detail the system performance in view of completing the analysis of Run 2 and
- Understand the precision requirements projecting to Run 3 (feedback to BE/BI)
    - *New PBMs could be included in the system!*

Orbit Drifts & Hysteresis in vdM scans



W. Kozanecki - ATLAS

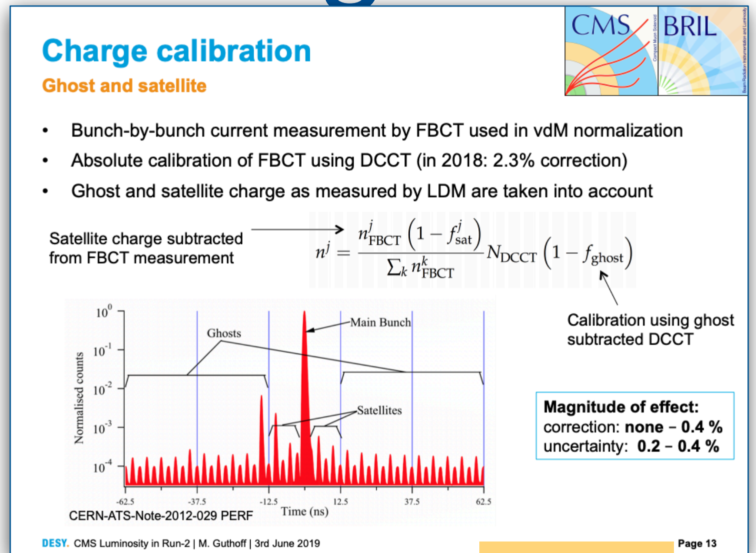
Summary

- **Orbit drifts (OD)** — Help needed from our LHC colleagues to identify the sources!
  - drifts as large as 20 μm/beam were observed during both vdM & LSC scans
    - consistency between Arc & DOROS BPMs varies scan-to-scan: → multiple sources?
  - main impact is scan-to-scan reproducibility of vdM calibrations [~ O (1-1.5%)]
  - vdM (LSC) uncertainty on OD *correction* ~ 0.2 % (0.3%) (partial cancellations!)
- **Hysteresis effects** — Systematic characterization during Run 3 needed (easy!)
  - Unambiguous evidence for small magnetic non-linearity of IP knobs
    - independently from DOROS BPMs (LSC & vdM) & luminous-region data (LSC)
  - The sign of the non-linearity is correlated, and flips, with the scan direction (ascending or descending), for both beams/both planes
    - the characterization of the shape of the non-linearity (best attempted in LSC scans (b-b deflections!) is limited by the quality of the data (limited # points, orbit drifts)
  - Implications
    - essential to apply consistent + reproducible scan protocols in vdM & LSC scans
    - reproducibility of magnetic non-linearity in consecutive vdM scans to be analyzed
    - associated systematics on LSC & vdM calibrations to be quantified for final Run-2 ℒ
- Orphan topics: beam-position jitter & apparent x-y coupling

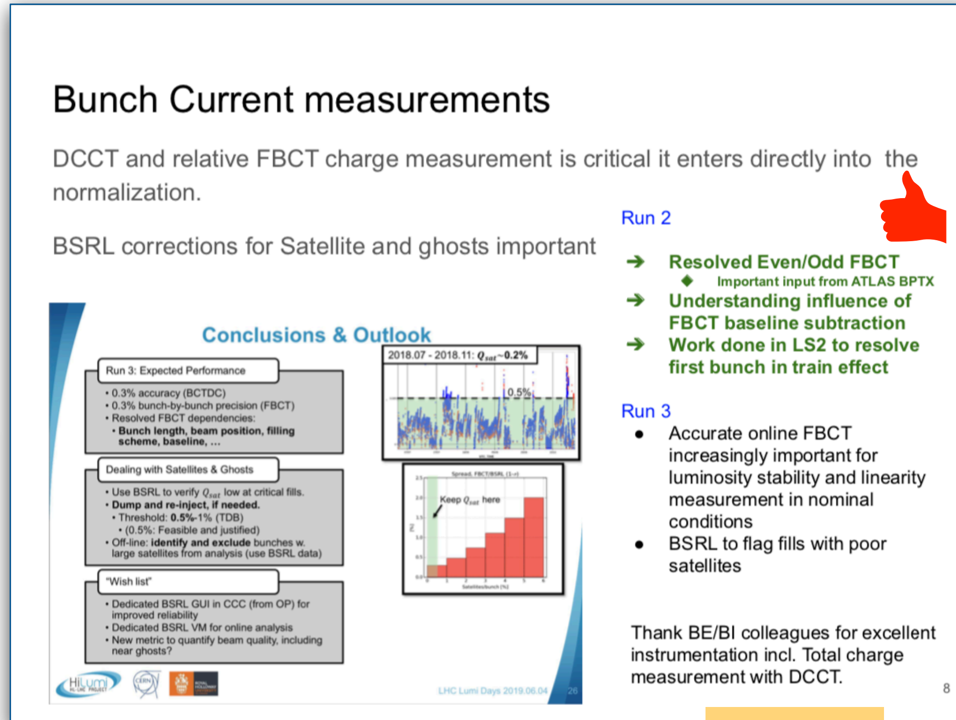
W. Kozanecki   Slide 12   2019 ℒ Days, CERN, 4-5 Jun 2019

W. Kozanecki - ATLAS

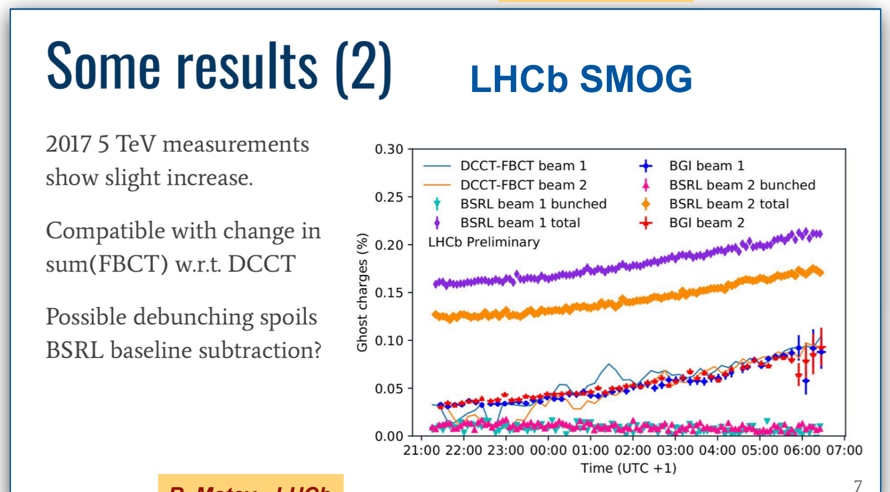
Charge calibration



M. Guthoff - CMS



M. Palm - BE/BI

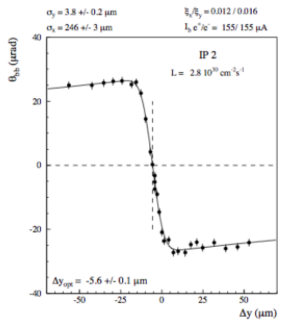


R. Matev - LHCb

Beam-beam effects in vdM calibration

Angular deflection and Orbit effect

- Well understood effect
- Several models (formula, MADX, TRAIN, COMBI)
- Several observations



[LEP measurement](#)
[J. Wenninger, SL Note 96-01 (OP)](#)

Beam-beam angular kick: $$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

Closed Orbit effect: $$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

...her IPs

Summary

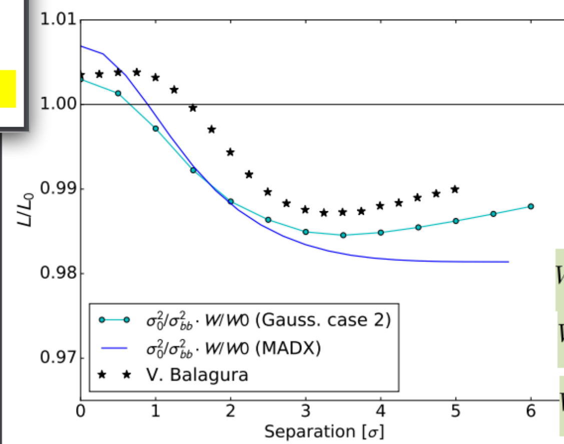
- Beam-beam effects modify the overlap integral of the two colliding beams during VdM scans with not negligible impact to the luminosity precision measurements
  - "dynamic beta" (beam size effect)
  - Orbit effect
- Past corrections were based on small amplitude particle approximation and frozen Gaussian distributions
- Different particles depending on their amplitude of oscillations sample different parts of the BB force which also couples x-y planes
- Higher order effects can be quantified with multi-particle simulations
- Distributions are modified and become non Gaussian → Luminosity formulas not valid to compute the correct overlap integral
- Results are qualitatively consistent with findings by Balagura but significant differences still need to be understood
- **If this is confirmed it implies that all Luminosity calibrations since 2012 are biased by an over correction of the order of 1%**

T. Pieloni - EPFL

25

- Simulation studies using variants of multi-paricle tracking codes (V. Balagura) and (COMBI) ongoing
- Results generally agree, ×2, but details and uncertainties must be fully understood
- *Understanding the beam-beam corrections is a key ingredient for the vdM scan calibration and the emittance scans in SB corrections*

COMBI vs V. Balagura results



Vladik uses an integrator for Lumi calculations
We used so far Luminosity equations for Gaussian distribution but with beam-beam effects distributions deviates from Gaussian.

$$W = exp(-\frac{1}{4\sigma_{x,bb}^2} \cdot (Orb_{bb} + sep)^2)$$

$$W_0 = exp(-\frac{1}{4\sigma_0^2} \cdot sep^2)$$

$$W_1 = exp(-\frac{1}{4\sigma_0^2} \cdot (Orb_{bb} + sep)^2)$$

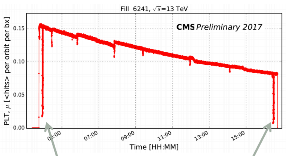
Integrator to compute overlap integral shows different effect respect to luminosity formulas for Gaussian beams

22

Emittance scans during SB fills

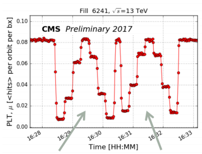
4

Emittance scan difference from VdM scan



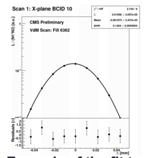
Beginning of fill "early scan", β*=30cm, α/2=160μrad

End of fill "late scan", β*=25cm, α/2=130μrad



Scan in X plane

Scan in Y plane



Example of the fit to measure beam overlap $\Sigma_{X(Y)}$ and peak

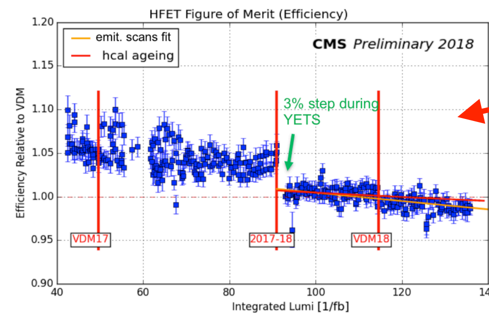
$$\sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y}{N_1 \cdot N_2 \cdot f} \cdot R_{peak}$$

VdM scan | Emittance scan

6

Emittance scans for stability monitoring (2/2)

- Less scatter in 2018 emittance scans
  - more optimized beam conditions and more consistent filling schemes (in 2017 filling scheme was changed several times).
- Detector performance change was spotted from the first emittance scans in the year in 2018 after YETS HF!



Radiation damage measured from emittance scans is slightly more pronounced than predicted by HCAL ageing model.

10

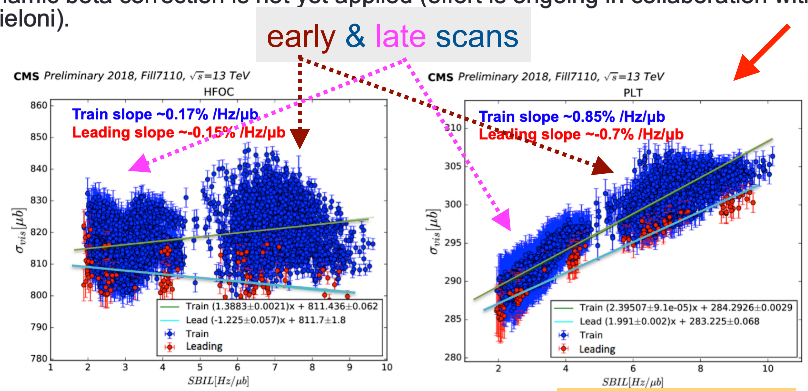
Emittance scans for non-linearity measurement (2/2)

- The linear fit to σ_{vis} vs. SBIL is used for non-linearity correction (quadratic term):

$$L = k\,\mu + s\,k^2\,\mu^2,$$

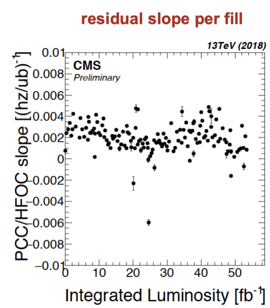
μ average number of hits per orbit per bunch crossing (equivalent to rate),
k = f_{LHC}/σ_{vis0}, σ_{vis0} – VdM calibration (at SBIL 0), **s** slope per unit of SBIL in (Hz/μm)$^{-1}$.

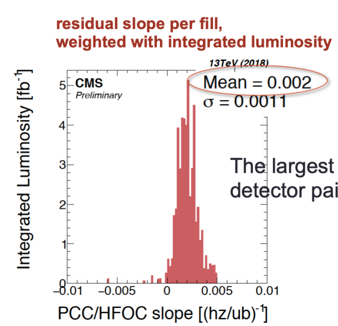
- Dynamic beta correction is not yet applied (effort is ongoing in collaboration with T.Pieloni).



Final luminosity uncertainty due to non-linearity

- "End of year comparison" ➔ residual slope per fill:
  - to measure residual non-linearity (after non-linearity correction)
  - the linear fit to the ratio of measured luminosity vs. SBIL (for each detectors pair)
- The largest residual non-linearity among all detector pairs is propagated to the whole year luminosity to estimate effect on the integrated luminosity (e.g. 0.2% (Hz/μm)$^{-1}$ slope in the ratio leads to 1% non-linearity uncertainty).





The largest across all detector pairs in 2018.

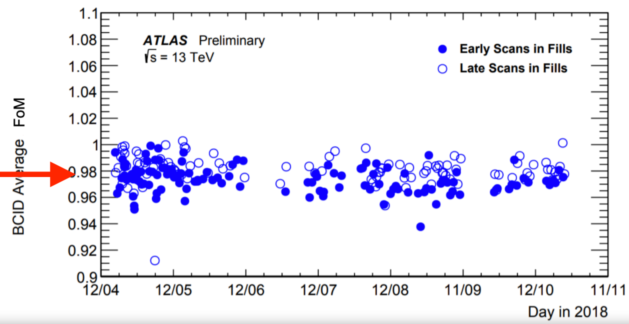
O. Karacheban - CMS

Lumi calibration stability

Stability throughout 2018

First take-aways of emittance scan procedure in ATLAS

- Average FoM over all bunches in fill
  - Early scans = <1st hr of the fill, late scans = after that



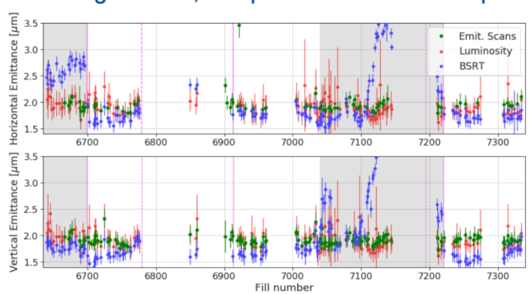
- Good agreement of early and late scans
- LUCID calibration checked from emittance scans stable within ±2%
- Global offset in FoM for LUCID of ~-2%
- Possible explanations for FoM ≠ 1
  - Non-factorization, long range beam-beam effects, ghost charge, poor fit model, 3σ integration?

→ Further investigations ongoing

- The emittance scans provide additional cross-check for the luminosity follow up and stability for the experiments, in particular for CMS
- Having emittance scans in both IP1&IP5 are also important for the machine to understand and follow the beam emittance evolution without complicated assumptions
- Should continue during Run 3, exact conditions still to define

Emittance evolution – Run 2

- Compare emittances at start of SB measured by BSRT and extracted from the experiment Luminosity and emittance scans
  - 10-15% agreement, compatible with the BSRT precision



- Validate the emittance at start of SB → overall growth

June 5, 2019 13

I. Efthymiopoulos, S. Papadopoulou - BE/ABP

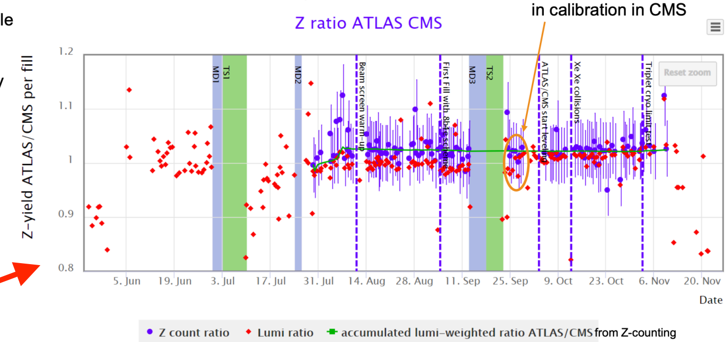
Comparing across experiments

ATLAS vs. CMS

- Comparison of central luminosity and Z-counting estimates between ATLAS and CMS
  - ATLAS values: Full offline calibration, CMS: Online calibration
  - Fully automated comparison from 2017 onwards, first offline comparisons since 2015
  - Allows to monitor possible issues in the online (quick after data-taking) and the offline luminosity estimates

→ Good agreement of ATLAS vs. CMS within ~5% uncertainties on online CMS values and Z-counting

Potential cause: Change in calibration in CMS



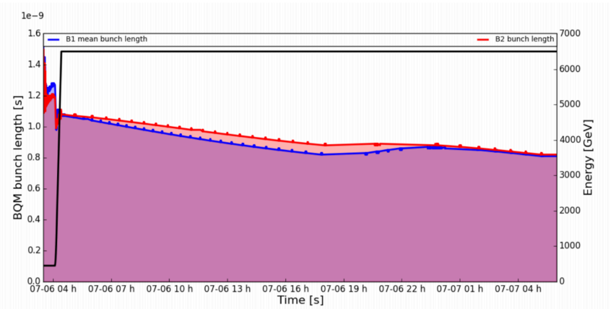
DESY. Page 15

V. Lang - ATLAS

Emittance in SB

Bunch Length Evolution in Physics

- Slow bunch length oscillations occur when the single-bunch threshold of loss of Landau damping is reached
  - Bunch flattening is applied at 0.95 ns when LHCb is in positive polarity



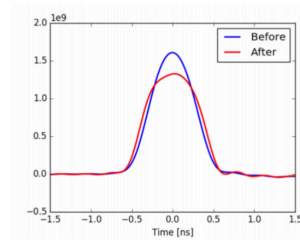
Average bunch length evolution in a typical long physics fill, without bunch flattening

T. Argyropoulos, D. Dlugosz, H. Timko, LHC Lumi Days 21

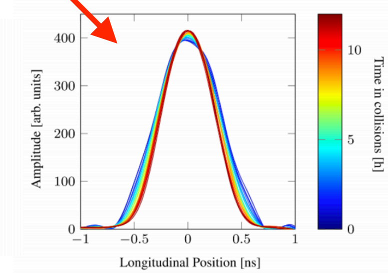
T. Argyropoulos, D. Dlugosz, H. Timko - BE/RF

Evolution of Bunch Distribution

- At 6.5 TeV, it takes about 10 h in total for the beam to become Gaussian again
  - Bunch flattening creates a flat core, done through RF phase modulation



Bunch flattening in physics, 2016 (B2)



Typical bunch profile evolution in physics, *M. Hostettler et al., PRAB 21,102801 (2018)*

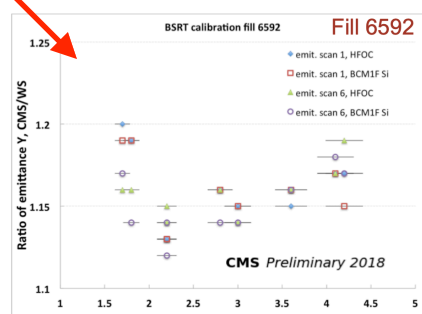
T. Argyropoulos, D. Dlugosz, H. Timko, LHC Lum...

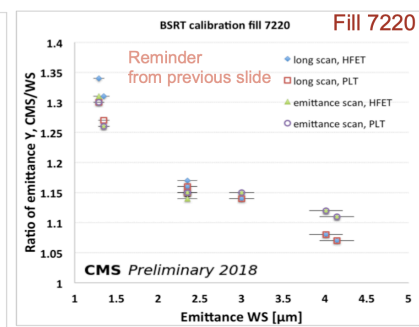
T. Argyropoulos, D. Dlugosz, H. Timko - BE/RF

7

CMS emittance Y vs. WS emittance in BSRT calibration fill 6592

- 9 bunches of different emittance, starting conditions similar to fill 7220
- **CMS systematically measures ~15-20% higher emittance than WS for all bunches.**
  - ~3-5% spread is detector related (HFOC-forward calorimeter occupancy method or BCM1F Si – Fast Beam Condition Monitor, silicon sensor) or scan related (first scan or last scan of the fill).
  - Note: we do not have bunches narrower than 1.7μm in fill 6592!



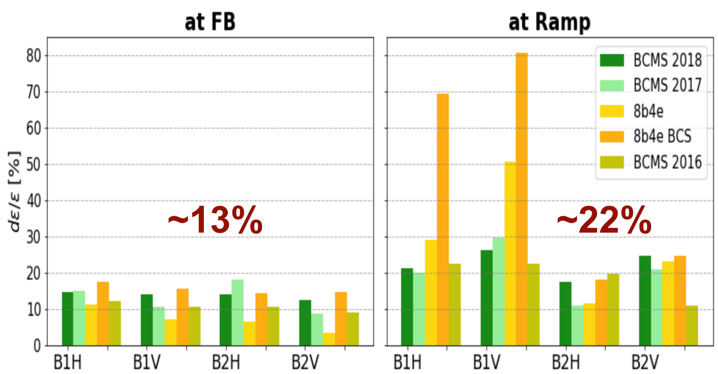


O. Karacheban - CMS

- The longitudinal profile is important ingredient in many luminosity studies and calculations
- Unfortunately not sufficient data available to monitor its evolution in Run 2.
  - Corrections from few measurements applied through the years, with not always positive contribution!
  - Need to improve for Run 3

Emittance in SB

- Average relative emittance growth [%]



ie - LumiDays 2019 June 5, 2019 12

- Average relative emittance growth [%]

	2016-BCMS				2018-BCMS			
	B1H	B1V	B2H	B2V	B1H	B1V	B2H	B2V
Inj/Ramp	12.2±8.3	10.5±7.8	10.4±4.9	8.9±7.6	14.5±4.2	14.0±4.2	14.0±4.7	12.3±4.7
Ramp/SB	22.3±42.0	22.4±38.2	19.6±12.6	11.0±11.0	21.2±11.1	26.2±13.5	17.6±16.0	24.8±11.8

Total growth from injection to SB : **~35%**

2017-BCMS	B1H	B1V	B2H	B2V
Inj/Ramp	15.0±4.7	10.7±5.3	17.9±6.8	8.7±2.7
Ramp/SB	19.9±5.7	29.7±9.2	10.8±7.0	20.8±3.8

2017 – 8b4e

B1H	B1V	B2H	B2V
11.3±41.2	7.1±38.8	6.6±3.5	3.3±3.0
29.0±63.7	50.7±73.6	11.4±17.1	23.2±13.8

2017 - BCS

B1H	B1V	B2H	B2V
11.3±41.2	7.1±38.8	6.6±3.5	3.3±3.0
29.0±63.7	50.7±73.6	11.4±17.1	23.2±13.8

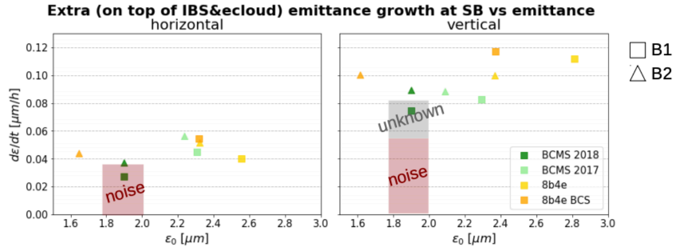
Details on the understating and modeling of the e-growth and luminosity in following presentation by Stefania

ie - LumiDays 2019 June 5, 2019 14

I. Efthymiopoulos, S. Papadopoulou - BE/ABP

Extra emittance growth at SB, run 2

Measured (BSRT)-Model emit. difference over time vs the initial emittance averaged over all Fills for each beam flavor, for both beams and planes



- No correlation of the extra growth with initial emittances at SB
- No correlation of extra growth with intensity *(see backup slides)*

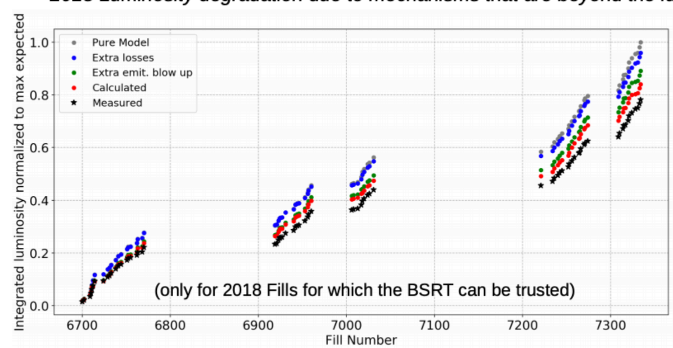
2018	Emit. growth [μm/h]	
	H	V
extra	0.04	0.08
noise	0.04	0.05
unknown	-	0.03

- **Noise** can explain all of the extra growth in horizontal and 60% of the extra growth in vertical
- **Non-colliding** see an extra growth of 0.04 μm/h in vertical and almost nothing in horizontal
- Due to the inelastic collisions, the depletion of the bunch transverse core is faster than the one of the tail, resulting in emittance blow-up that is <0.01 μm/h link→BoffGrowth_Guido

19

Cumulated integrated Luminosity

2018 Luminosity degradation due to mechanisms that are beyond the luminosity model



2018	2017
-5%	-1%
-11%	-10%
-16%	-12%
~~-22%~~	-11%

(see backup slides)

In 2018 the impact of the extra losses is larger compared to 2017

evolution	*model cases*			
	Pure model	Extra losses	Extra emit. growth	Calculated
Emittance	model	model	data	data
Intensity	model	data	model	data

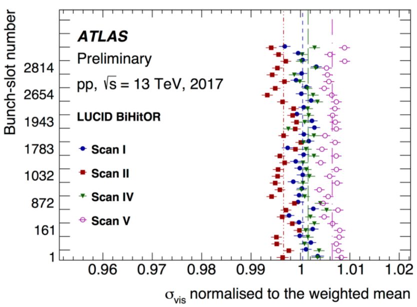
- Extra emittance blow up plays an important role in the degradation of the **cumulated integrated luminosity.** Extra losses have a smaller impact

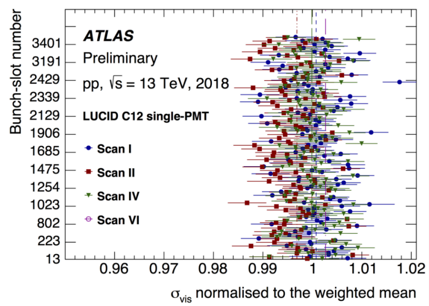
25

Combining errors on Luminosity

vdM scan consistency - I

- Should get same σ_{vis} for different bunch pairs and scan sets





- Spread of values for different bunches within same scan gives bunch-by-bunch consistency uncertainty, after subtracting expected spread from statistical errors
- Maximum difference between extreme scans (for any algorithm) gives scan-to-scan consistency error which is then symmetrised
  - Gives 1.2% in 2017, only half that in other years

4th June 2019 Richard Hawkings 11

R. Hawkings - ATLAS

Uncertainties and combination – from yesterday

- Per-year uncertainty summary
  - Treating 2015+16 as one dataset
  - Absolute vdM calibration subtotal
  - +Contributions to physics lumi.
  - Total uncertainties for individual years are 2.0-2.4%
    - Largest single uncertainty from calibration transfer
- Combination of years
  - Taking correlations into account
  - */+=fully/partially correlated
- Total run 2 lumi: 139.0±2.4 fb^{-1}
  - Uncertainty **1.7%**, dominated by calibration transfer and then long-term stability
  - Significant reduction in error as some sources only partially correlated

Data sample	2015+16	2017	2018	Comb.
Integrated luminosity (fb^{-1})	36.2	44.3	58.5	139.0
Total uncertainty (fb^{-1})	0.8	1.0	1.2	2.4
Uncertainty contributions (%):				
DCCT calibration†	0.2	0.2	0.2	0.1
FBCT bunch-by-bunch fractions	0.1	0.1	0.1	0.1
Ghost-charge correction*	0.0	0.0	0.0	0.0
Satellite correction†	0.0	0.0	0.0	0.0
Scan curve fit model†	0.5	0.4	0.5	0.4
Background subtraction	0.2	0.2	0.2	0.1
Orbit-drift correction	0.1	0.2	0.1	0.1
Beam position jitter†	0.3	0.3	0.2	0.2
Beam-beam effects*	0.3	0.3	0.2	0.3
Emittance growth correction*	0.2	0.2	0.2	0.2
Non-factorization effects*	0.4	0.2	0.5	0.4
Length-scale calibration	0.3	0.3	0.4	0.2
ID length scale*	0.1	0.1	0.1	0.1
Bunch-by-bunch σ_{vis} consistency	0.2	0.2	0.4	0.2
Scan-to-scan reproducibility	0.5	1.2	0.6	0.5
Reference specific luminosity	0.2	0.2	0.4	0.2
Subtotal for absolute vdM calibration	1.1	1.5	1.2	-
Calibration transfer†	1.6	1.3	1.3	1.3
Afterglow and beam-halo subtraction*	0.1	0.1	0.1	0.1
Long-term stability	0.7	1.3	0.8	0.6
Tracking efficiency time-dependence	0.6	0.0	0.0	0.2
Total uncertainty (%)	2.1	2.4	2.0	1.7

5th June 2019 2

R. Hawkings - ATLAS

Summarizing in this talk: CMS-PAS-LUM-15-001 (2015), CMS-PAS-LUM-17-001 (2016), CMS-PAS-LUM-17-004 (2017), CMS-PAS-LUM-18-002 (2018)

2018	Systematic	Correction (%)	Uncertainty (%)
Normalization (vdM →)	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	—	0.5
	Background subtraction	0 to 0.8	0.1
Integration (data taking →)	Afterglow (HFOC)	0 to 4	$0.1\oplus0.4$
	Cross-detector stability	—	0.6
	Linearity	—	1.1
	CMS deadtime	—	<0.1
	Total		2.5

DESY. CMS Luminosity in Page 2

M. Guthoff - CMS

- To combine the errors across years, the achieved accuracy / resolution and systematics of all instruments and measurements need to be documented
  - follow variations/modifications/improvements in years to apply in legacy luminosity analysis
  - per bunch dependence or fill type or global measurements

Conclusions - Roadmap

- Many systematic studies performed in all experiments, in collaboration with machine experts
- Elaborated data-analysis in an effort to approach the **1% target** on the lumi measurement
- Key remaining topics for **vdM calibration**:
    - Impact of beam-beam corrections in the calibration
    - Scan-to-scan reproducibility
        - orbit drifts (extra BPMs in operation for Run 3), bunch charge per BX
    - Non-Factorisation
        - Evaluate the different fit methods proposed, compare, pros/cons of each within and among experiments for all vdM fills of Run 2
        - Finalise the beam-beam correction in the beam spot shape (CMS)
- **Future vdM program** - Run 3 - first reflections
    - Important to devote sufficient time to perform vdM fills to probe and understand the underlying effects to achieve the 1% error goal!
    - Resolve choice of optics parameters: e.g. 19 or 17 m in beta*?
    - Prepare and evaluate the beam quality from the new injectors after LIU upgrade
    - Spend extra time in vdM fills to perform tests: e.g, optics measurements, different scan directions to probe hysteresis effects, scan beam parameters for verification of beam-beam parameters (say stronger regime compared to normal) or non-factorisation
    - Effort to improve the Massi file quality and possibly include beam spot (6D) info per bunch (if would be helpful for analyses)

Summary

- We had an excellent workshop, a good opportunity to present the work done in all experiments and the machine
- The goal of 1% error on luminosity is challenging, not reached yet but with concentrated efforts may be not far!
- With the excellent performance of LHC many physics measurements are no longer dominated by statistical but rather systematic uncertainties
- Therefore the pressure to improve on the luminosity systematics would only increase, for Run 3 and even more for HL-LHC
- Renewed the appointment for **LumiDays 2020** to review the “final” Run 2 off-line luminosity performance and plan for Run 3 and project for HL-LHC