ATLAS EXPERIMENT

Institute of Physics Belgrade

# Absolute luminosity calibration in pp collisions at 900 GeV center-of-mass energy in the ATLAS experiment


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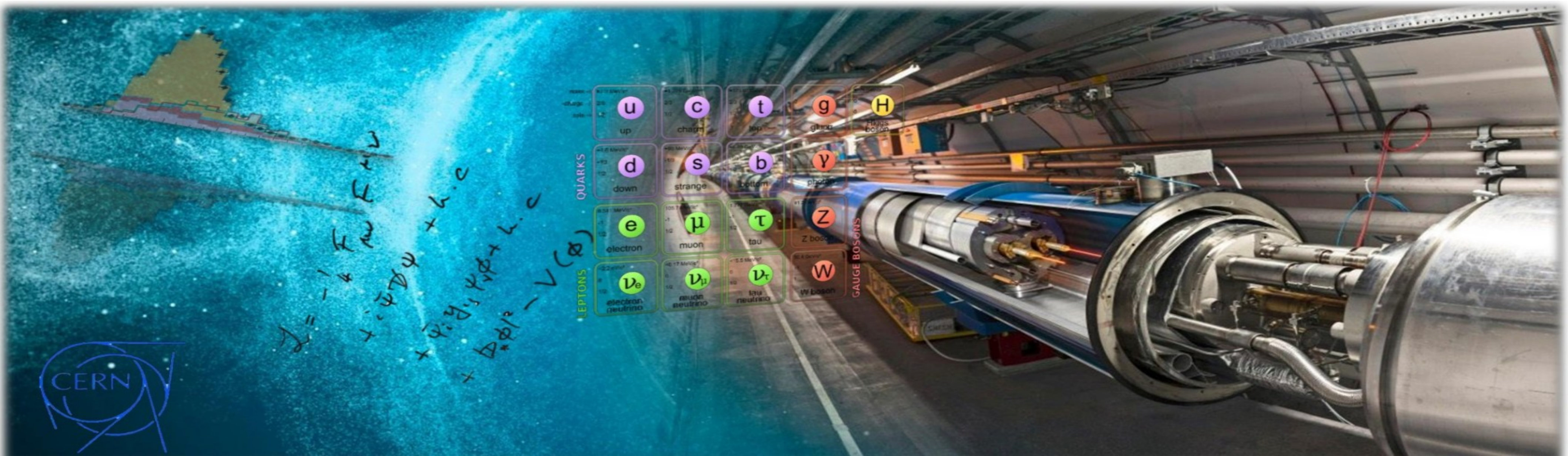

# Luminosity definition and measurement

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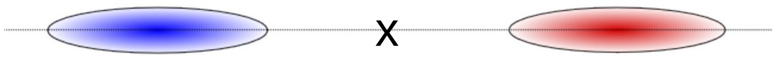
bunch with $n_1$ protons — bunch with $n_2$ protons

IP




$\rho_1(x,y,z,t)$ — $\rho_2(x,y,z,t)$

normalized particle densities

Luminosity describes the capability of an accelerator to produce particle interactions.

**LUMINOSITY** ←

$$\mathcal{L} = \frac{dN}{dt}\frac{1}{\sigma} \quad [cm^{-2}s^{-1}]$$

number of interactions per unit time (rate, $R$)

cross-section of a given process

| | |
|---|---|
| [1] | arXiv: 1603.09222 [hep-ex] |
| [2] | arXiv: 1910.08819 [hep-ex] |

Number of pp collisions per one bunch-crossing

Number of colliding bunches

Revolution frequency (11246 Hz at the LHC)

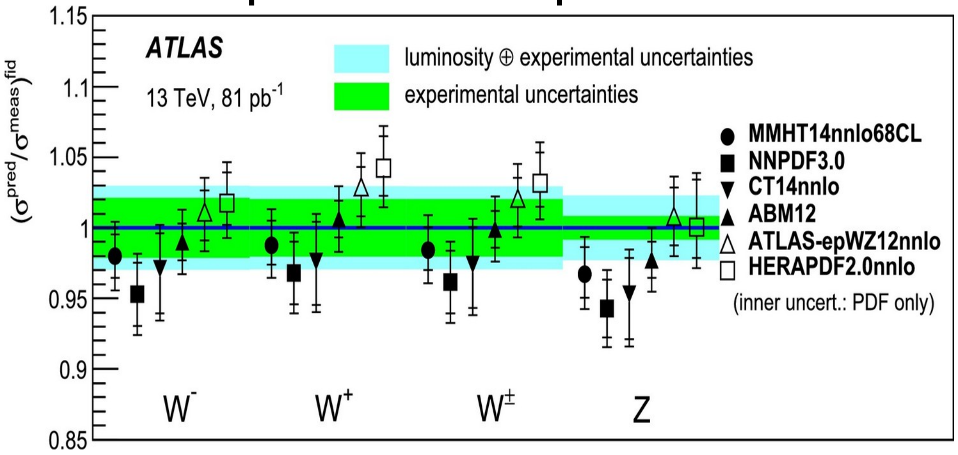
$$\mathcal{L} = \frac{R}{\sigma} = \frac{\mu\, n_b\, f_r}{\sigma_{inel}} = \frac{\epsilon\mu\, n_b\, f_r}{\epsilon\sigma_{inel}} = \frac{\mu_{eff}\, n_b\, f_r}{\sigma_{eff}}$$

Detector efficiency

Inelastic cross-section

Effective or visible quantities measured in experiment

**Impact of $\sigma_L$ on SM precision test**




[1] $\sigma^{tot}_{W^+} = 11.83 \pm 0.02\ (\text{stat}) \pm 0.32\ (\text{syst}) \pm 0.25\ (\text{lumi})$

[2] $\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\text{stat}) \pm 11.5\,(\text{syst}) \pm 15.7\,(\text{lumi}) \pm 1.9\,(\text{beam})\ \text{pb}$

# ATLAS EXPERIMENT — Total $\sigma_{pp}$ measurement and $\mathcal{L}$ determination at $\sqrt{s}=900\,\mathrm{GeV}$

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- Measuring $\sigma_{tot}(pp \to X) \to$ fundamental quantity
- CAN NOT be calculated from the first principles
- CAN be measured using Optical theorem:

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{d\sigma_{el}}{dt}|_{t=0},$$

$\rho$ is small correction related to elastic scattering amplitude: $\rho = \frac{Re[f_{el}(t)]}{Im[f_{el}(t)]}|_{t\to 0}.$

$t$ is variable related to the scattering angle used to describe elastic-scattering events.

- $t \to 0$ requires SPECIAL RUNS:

1) Special beam optics> giving the proton beams a very small angular spread

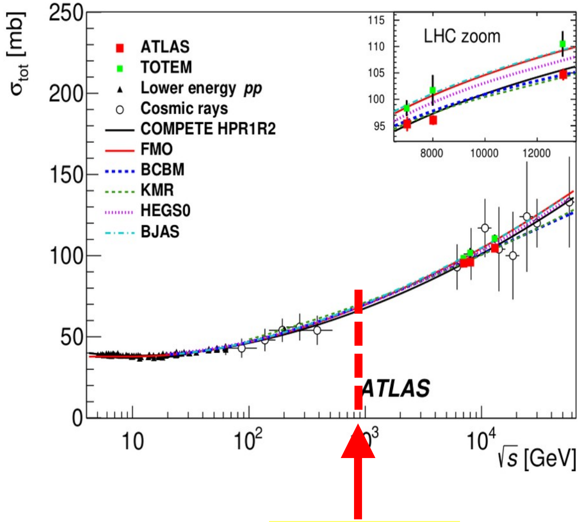
2) Special detectors> Far away from the IP but very close to the proton beams

- ATLAS uses the method for a precise luminosity measurement to obtain the absolute normalization
- Differential elastic cross section:

$$\frac{d\sigma}{dt_i} = \frac{1}{\Delta t_i} \times \frac{\mathcal{M}^{-1}[N_i - B_i]}{A_i \times \epsilon^{\mathrm{reco}} \times \epsilon^{\mathrm{trig}} \times \epsilon^{\mathrm{DAQ}} \times L_{\mathrm{int}}}$$

**One of main uncertainties**

Energy evolution of the total cross section



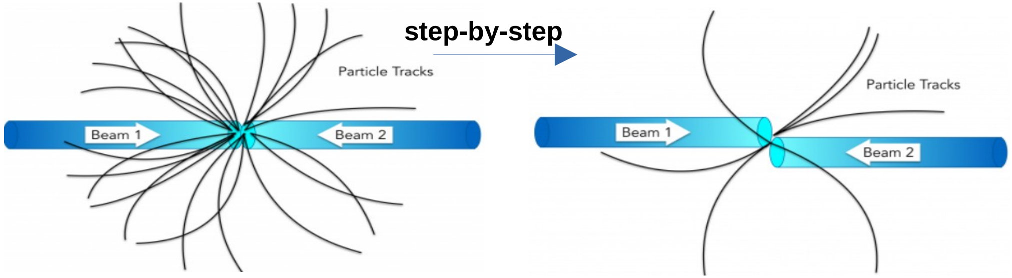

$\sqrt{s}=900\,GeV$

**$\sqrt{s}=900$ GeV 2018 data-set:**

- Luminosity calibration data taken in two different sessions: in October and in November
- Higher bunch intensities then usually
- Larger transverse beam sizes then usually
- 150 colliding bunch-pairs
- 2 unpaired bunches per beam

# Van der Meer (vdM) scan formalism

- The absolute luminosity scale can be determined from dedicated beam-separation scans (Van Der Meer scans)




- Luminosity can be expressed using beam parameters:

$$\mathscr{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

bunch current product

convolved beam-sizes (computed from overlap integrals)

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R(\Delta x) d(\Delta x)}{R(\Delta x^{max})}$$

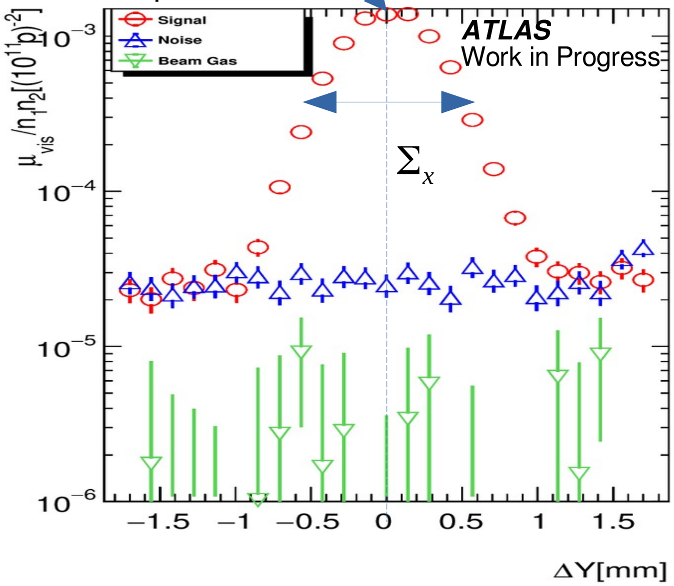
It is assumed that particle density functions (in each bunch) **can be factorized** into independent x and y components
$\longrightarrow$ non-factorization correction

- Measuring interaction rate as a function of beam separation → $\Sigma_x, \Sigma_y$

- Visible cross-section is a **calibration constant**:

$$\sigma_{vis} = \mu_{vis}^{max} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

Interaction rate at zero nominal separation

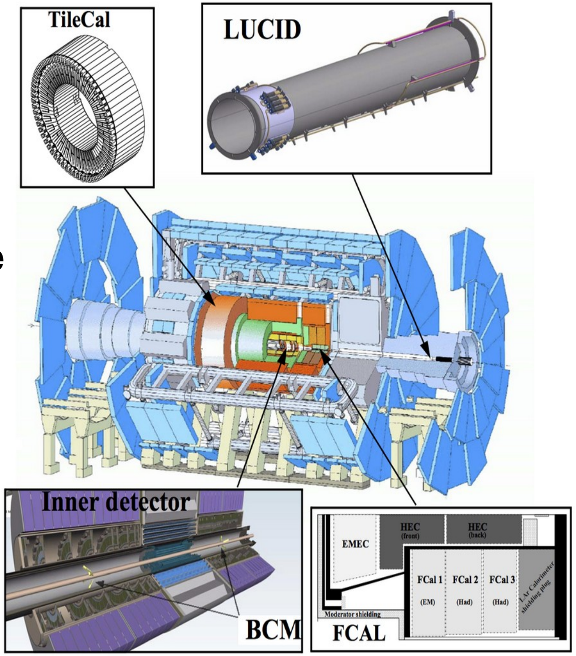


# Luminosity detectors and algorithms



## Luminosity detectors:

- RUN-2 primary detectors:
  - **LUCID* Čerenkov detector**
    - >Far forward region
    - >Provides bunch-by-bunch measurements
    - >Contains 16 photomultiplier tubes (PMTs)
    - >PMTs coated with radioactive $^{207}\mathrm{Bi} \rightarrow$ calibration signal
  - **BCM** diamond detector**
    - >Provides bunch-by-bunch measurements
    - >1.84 m from the beam pipe
- Calorimeters:
  - **EMEC, FCal, TileCal**
    - >Measure bunch–integrated luminosity
- Track counting detectors
  - **Pixel and SCT detectors**




## Algorithms:

- Fundamental assumptions:
  1) The distribution of pp interactions is a Poisson distribution
  2) The efficiency to detect a single pp interaction is independent of a total number of interactions
- **EventOR-** Signal on A OR C side of the IP
- **HitOR-** Sum of recorded signals in all available detector modules Nmodules:

$$\mu_{vis}^{HIT} = -\ln\left(1 - \frac{N_{HIT}}{N_{BC} N_{Modules}}\right)$$

- Advantage: Large number of modules

- **EventAND-** Recorded signal on both sides of the IP

*LUCID: LUminosity Čerenkov Integrating Detector
**BCM: Beam Condition Monitor

# Ghost charge and satellites bunches

$$\sigma_{vis} = \mu_{vis}^{max} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

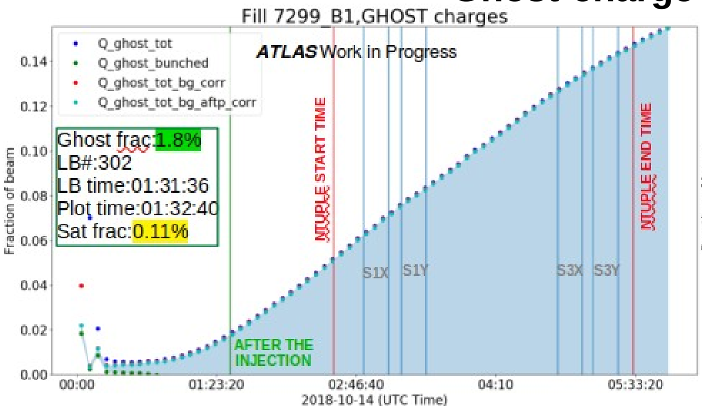
- Devices for measuring bunch currents:
  - FBCT*, BPTX*
    - >sensitive to bunch structure
    - >have non-linear behavior
      - → Offset correction
  - DCCT*
    - >more accurate
    - >measures only bunch integrated current

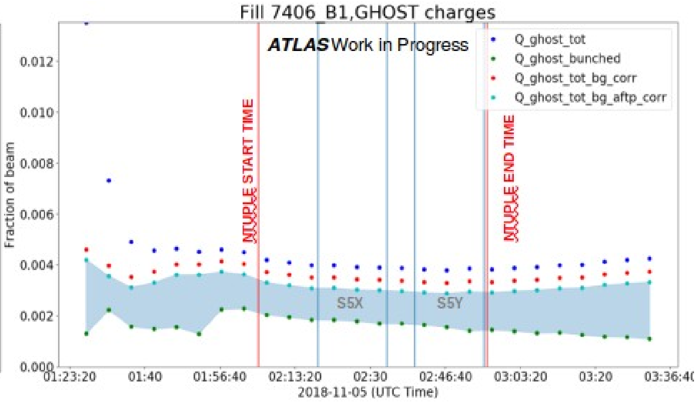
**Ghost charge and satellites bunches:**

- Ghost charge → protons present in nominally empty bunch slots picked up by the more sensitive DCCT
- Satellites → protons present in the collision bunch slots measured by the FBCT in nominally empty RF buckets (10 RF buckets per 25 ns bunch slot)
- Bunch currents must be corrected for ghost charge and satellites as part of bunch integrated normalization

* DCCT – DC Current Transformers
FBCT – Fast Beam-Current Transformers
BPTX – Beam-Pickup Timing system

## Ghost-charge time evolution




## Ghost-charge and satellites fraction of beam

| | Ghost[%] | | Satellites[%] | | Effect on $\sigma_{vis}$ |
|---|---|---|---|---|---|
| Scan | B1 | B2 | B1 | B2 | |
| 1 | 7.5 | 7.0 | 0.35 | 0.36 | 16% |
| 3 | 13.5 | 13.0 | 0.6 | 0.6 | 34% |
| 4 | 7.5 | 8.0 | 0.3 | 0.4 | 19% |
| 5 | 0.3 | 0.25 | 0.05 | 0.05 | 0.6% |
| 6 | 0.3 | 0.26 | 0.05 | 0.05 | 0.6% |

October session: Extremely large level of ghost charge bias the determination of the visible cross-section

November session: Typically level of ghost charge: Uncertainty estimated using only scans 5 and 6

November session vdM scans were performed with better LHC RF system settings
→ Therefore much worse ghost charge for scans 1, 3, 4

# Background estimation



**Noise** background
- Dominant source
- For LUCID algorithms is signal from Bismuth calibration source
- Estimated from the bunch-slot preeceding colliding bunch-pair

$$\mu^{i}_{\mathrm{vis,\ spec}} = \frac{\mu^{i}_{\mathrm{vis}}}{n_1 n_2} - \frac{\mu^{i-1}_{\mathrm{vis}}}{n_1 n_2} - \frac{n_1 \cdot \mu^{\mathrm{beam-gas}}_{\mathrm{vis},B1} + n_2 \cdot \mu^{\mathrm{beam-gas}}_{\mathrm{vis},B2}}{n_1 n_2}$$

Fills 7299-7300

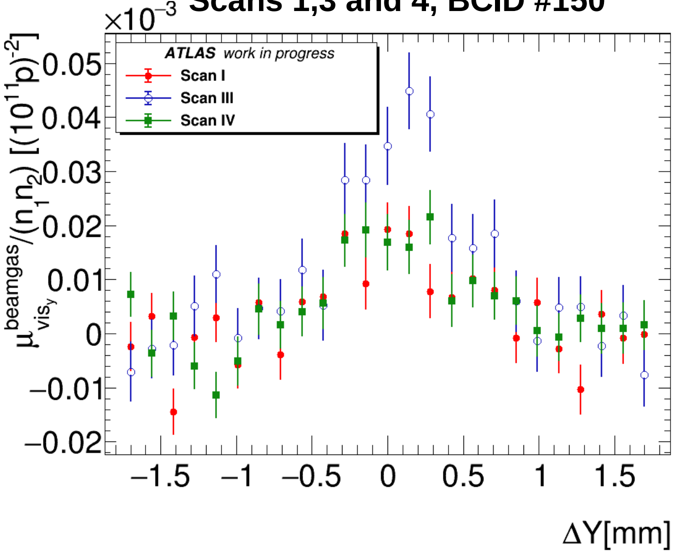
**Beam-gas** background
- Subdominant effect
- Calculated using unpaired bunches:

$$\mu^{\mathrm{beam-gas}}_{\mathrm{vis},Bk} = \frac{1}{N_{\mathrm{unpaired}}} \sum_{i \in \mathrm{unpaired}} \left( \frac{\mu^{i}_{\mathrm{vis}} - \mu^{i-1}_{\mathrm{vis}}}{n_{i,k}} \right)$$

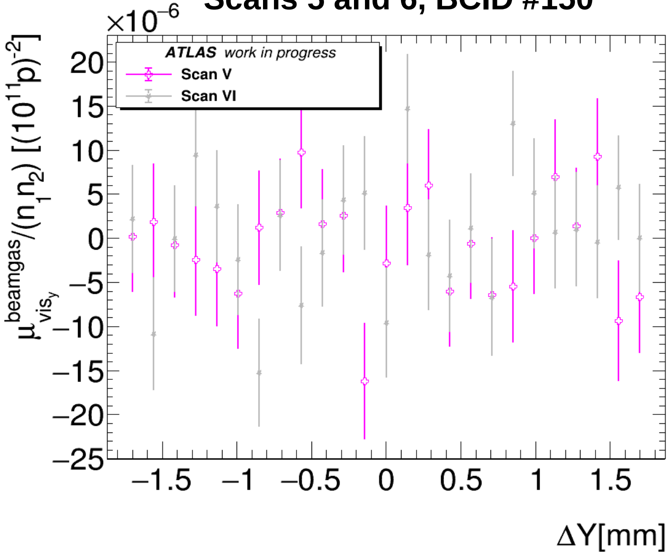
- Scaled with bunch currents in colliding bunch-pairs

Estimated beam-gas background for a given colliding bunch

**Scans 1,3 and 4, BCID #150**




**Scans 5 and 6, BCID #150**




- The largest peak is consistent with the largest ghost-charge contamination for scan 3 (plot left)
- Scans 5 and 6 are only used for estimating background uncertainty (plot right)

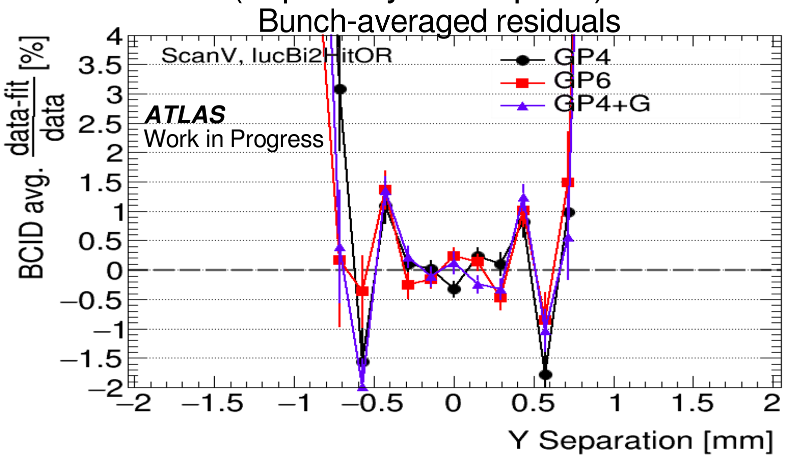
# Scan curve fitting

- Parameters are determined empirically from the fit of Gaussian-like functions after subtracting background
- Single Gaussian example:

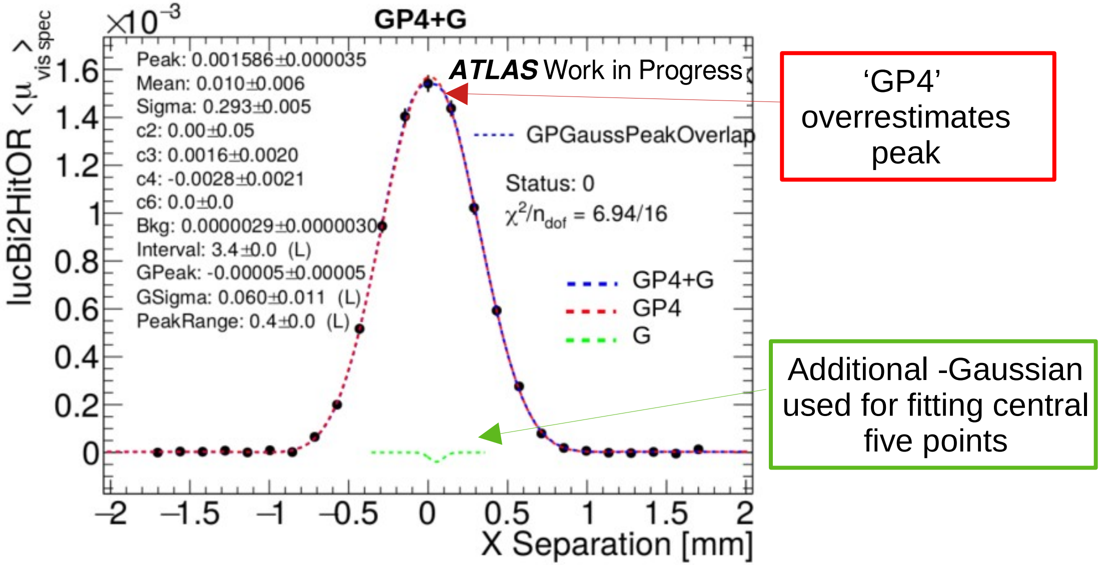
$$\mathcal{R}(\Delta x) = \frac{A}{\sqrt{2\pi}\sigma}\exp\left(-\frac{\Delta x^2}{2\sigma^2}\right) \longrightarrow \Sigma_x = \frac{1}{\sqrt{2\pi}} \cdot \frac{\int_{-\infty}^{\infty}\mathcal{R}(\Delta x)d(\Delta x)}{\mathcal{R}(0)} = \sigma$$

Convolved beam size equals Gaussian width

- Choice fit models:
  - Best chi2/ndof
  - Best residuals (especially at the peak)




- Default fit function for 900 GeV was 'GP4+G':
  - Linear combination of Gaussian multiplied by a 4th order polynomial and a single Gaussian
  - Single Gaussian for fitting the bulk of the distribution in order to ensure unbiased estimates of $\mu_{\text{vis}}^{\text{max}}$
- 'GP4+G' fitting example

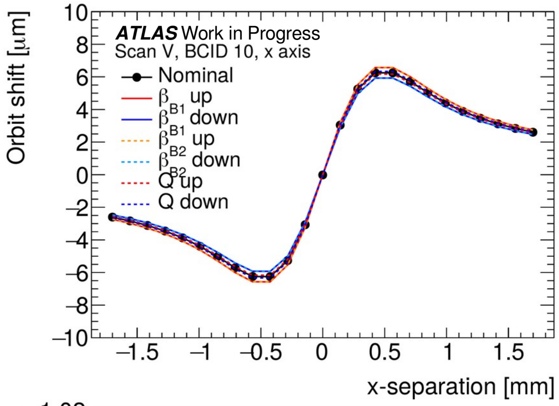


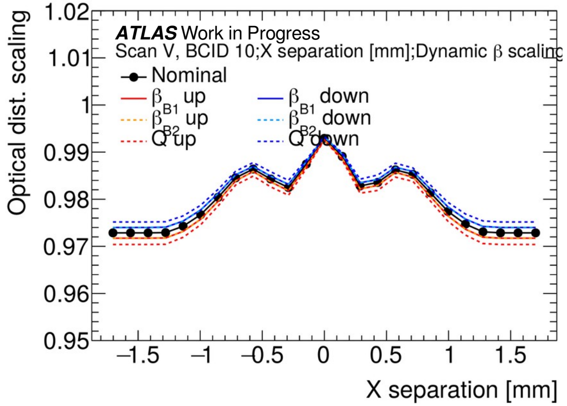
# Beam-beam effects and Orbit-drift

- **Beam-beam effects**:
  LHC beams interact electromagnetically:
  **1)** Mutual deflection of the two beams (computed using analytical equation)
  **2)** Defocussing leading to optical distortion(computed from simulations)

- Beam-beam effects parameters:
  - Beam-beam separation
  - Beam energy and transverse sizes of the beams
  - Bunch currents
  - Beta* values
  - Fractional tune

- Beam-beam deflection :
  -Orbit shift is computed using the Bassetti-Erskine formula
- Optical distortion:
  - Based on simulations
  - Parametrization: xi, Q_x, Q_y
- Systematic effects are calculated by varying initial parameters within their errors

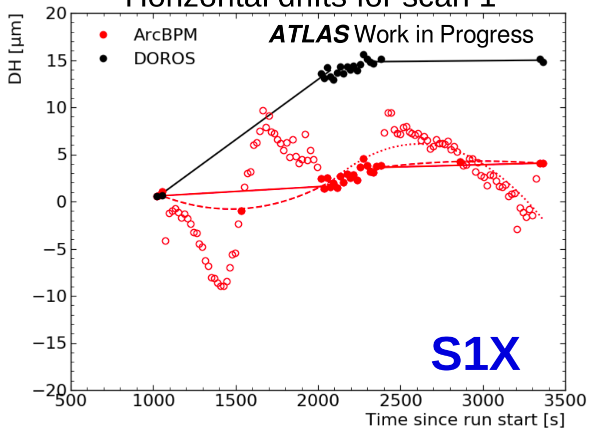



- **Size of beam-beam effects:**
  Beam-beam deflection (2.42- 3.11%) compensated by the Optical distortion (–1.84 - –2.31%)
- Total beam-beam correction ~ 0.6%

- **Orbit-drift:**
  Drifts of the beam orbit affect the vdM calibration
  1) In-plane drift distort the scan curve and affect Σ
  2) Drifts between scan peaks reduce peak luminosity and lower visible cross-section
  3) Out-of-plane drifts lead to lower Σ

Horizontal drifts for scan 1




- Devices for measuring beam positions:
  -DOROS (Diode Orbit and Oscillation System)
  -arcBPM (BPMs located in the LHC arcs)
- Size of corrections: 0.03 - 0.12%
- Uncertainty estimation: Visible cross-section fractional difference between DOROS and arcBPM readings

# VdM calibration systematics

| Source of uncertainty | Uncertainty [%] |
|---|---|
| FBCT offset correction | 0.02% |
| Orbit-drift correction | 0.32% |
| Beam position jitter | 0.14% |
| Emittance growth | 0.34% |
| Bunch-by-bunch consistency | 0.00% |
| Fit model | 0.36% |
| Background subtraction | 0.49% |
| Beam-beam effects | 0.43% |
| Reference specific luminosity | 0.56% |
| Ghost-charge and satellites subtraction | 0.14% |
| Magnetic non-reproducibility and LSC | 0.05% |
| Scan-to-Scan reproducibility | 0.84% |
| Total uncertainty | 1.35% |

**Beam-conditions dependent uncertainties** (FBCT offset correction through Beam-beam effects)

**Instrumental uncertainties** (Reference specific luminosity through Scan-to-Scan reproducibility)

- Uncertainties in table left uncorrelated between each other
- Dominant sources of uncertainty:
  > Scan-to-scan reproducibility
  > Reference specific luminosity
  > Background subtraction
  > Beam-beam effects
- Non-factorization uncertainty not included in the table left (uncertainty yet to be assessed)
- Total precision achieved ~ **1.35%**

# Conclusions

- Luminosity is an important parameter of accelerator
- L systematics dominate several key SM measurements, like W, Z top cross sections as well as total pp cross section
- Calibration of the measured luminosity is done by analysing data from beam separation scans (van der Meer scans)
- The absolute precision lies in 1-2% range for pp
- In this talk we present vdM analysis of a special dataset at $\sqrt{s} = 900$ GeV
- Main contribution to the systematic uncertainties arise from Scan-to-Scan reproducibility, reference specific luminosity and background subtraction
- Overall uncertainty is 1.35% with non-factorization uncertainty yet to be assessed

# BACKUP

# Length scale calibration and Magnetic non-linearity

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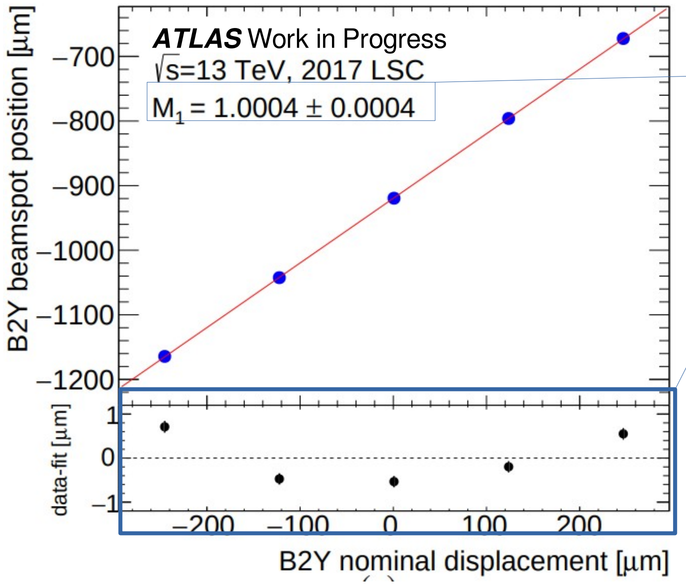
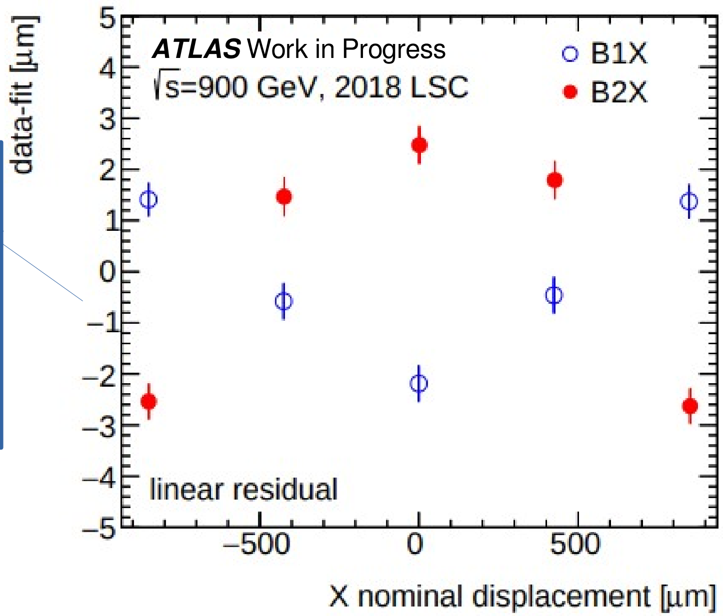
- Nominal beam displacement so far = Intended beam separation using LHC steering magnets
- $\Sigma_x, \Sigma_y$ measurements requires knowledge of the ACTUAL beam displacement
- Length scale calibration scans are used for this purposes:
  - Target beam was moved to five equally-spaced positions
  - Target beam position measured using BEAMSPOT position
  - BEAMSPOT position: Position fitted from primary vertices reconstructed in the ID for head-on collision
  - HEAD-ON collision satisfied using miniscans of the non-target beam




Estimating linear length scale

Small deviation from linearity and Inverted shape of residuals for different beams → comes from hysteresis effect in the steering magnets



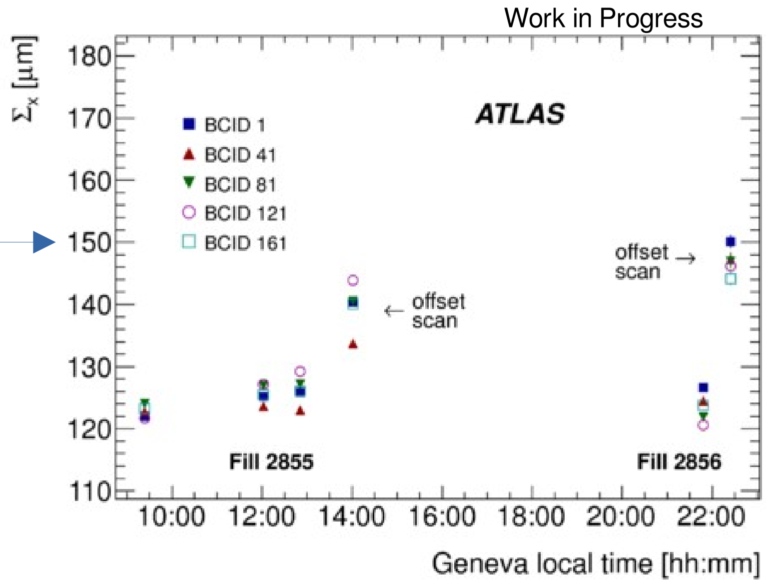

- Estimated combined uncertainty for 900 GeV centre-of-mass energy ~0.05%

# Non-factorization correction

- Formalism based on the following assumption:

$$\mathscr{L}\left(\delta_x, \delta_y\right) = f_x\left(\delta_x\right) f_y\left(\delta_y\right)$$

- Evidance for non-factorization effect:
  - $\Sigma_x, \Sigma_y$ are larger in offset scans




- Single beam parametrization for Non-Factorization effect:
  - Fitting Luminosity vs. Beam separation → True luminosity unbiased by non-factorization effects
  - Fitting Beamspot displacement vs. Beam separation
  - Fitting Beamspot width vs. Beam separation

- Impact of non-factorization correction → Scan-to-scan reproducibility improvement

- 900 GeV 2018 data-set → Non-factorization effect uncertainty yet to be assessed (with maximal value of Run-2 pp 13 TeV vdM ~0.6%)

# Bunch currents normalization

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$$\sigma_{vis} = \mu_{vis}^{max} \frac{2\pi\Sigma_x\Sigma_y}{n_1 n_2}$$

- Devices for measuring bunch currents:
  - FBCT*, BPTX*
    >sensitive to bunch structure
    >have non-linear behavior
  - DCCT*
    >more accurate
    >measures only bunch integrated current

- Bunch-current normalization:

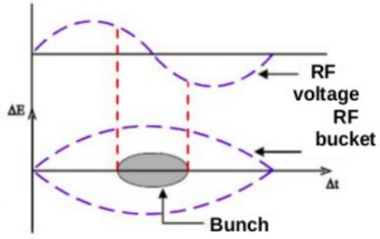
3) 1)

$$FBCT_{ikc} = GS \times \frac{DCCT_i}{FBCT_{iR}} \times FBCT_{ikR}$$

1) Bunch integrated measurement normalization to more accurate DCCT measurements
2) Determination of bunch-by-bunch fraction: FBCT & BPTX offset fits
3) Ghost-charge and satellites correction

**Ghost charge and satellites**

- Ghost charge →
  protons that are present in nominally empty bunch slots that will still be picked up by the more sensitive DCCT
- Satellites →
  protons present in the collision bunch slots that are measured by the FBCT in nominally empty RF buckets (10 RF buckets per 25 ns bunch slot)

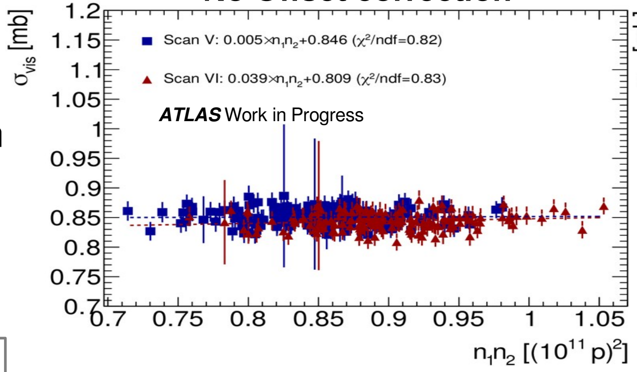



**Offset correction**

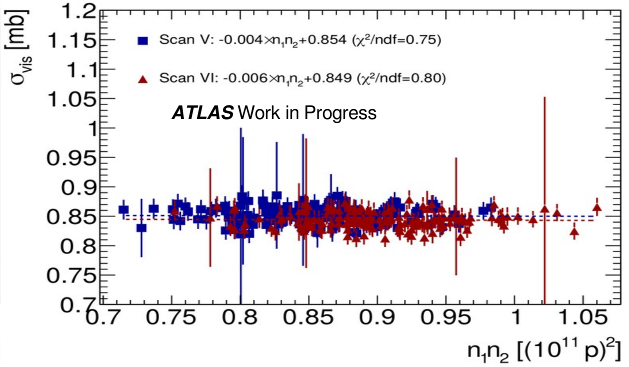
- Non-linear behaviour of bunch-currents is corrected by minimazing:

$$\chi^2(\bar{\sigma}_{\text{vis}}, b_1, b_2) = \sum_{i \in \text{BCIDs}} \left( \frac{S(\bar{\sigma}_{\text{vis}}, b_1, b_2, n_1^i, n_2^i) - \sigma_{\text{vis}}^{\text{no offs.},i}}{\Delta\sigma_{\text{vis}}^{\text{no offs.},i}} \right)^2$$

**No Offset correction**




**Offset corrected**




* DCCT – DC Current Transformers
FBCT – Fast Beam-Current Transformers
BPTX – Beam-Pickup Timing system

# fBCT offset correction

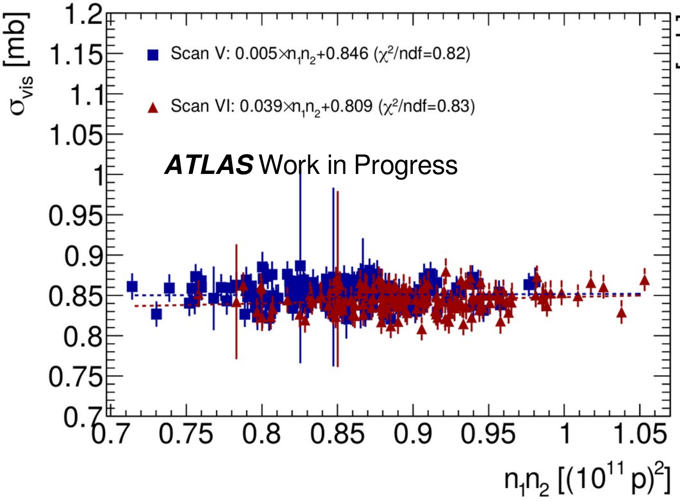


- Non-linear behaviour of bunch-currents is corrected by minimazing:

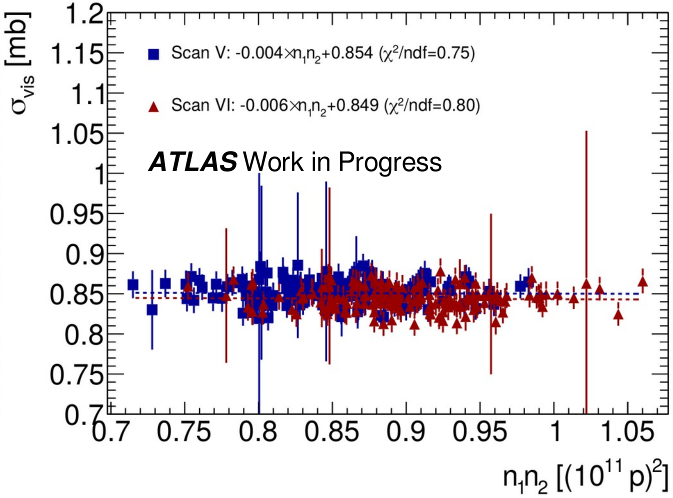
$$\chi^2(\bar{\sigma}_{\text{vis}}, b_1, b_2) = \sum_{i \in \text{BCIDs}} \left( \frac{S(\bar{\sigma}_{\text{vis}}, b_1, b_2, n_1^i, n_2^i) - \sigma_{\text{vis}}^{\text{no offs.},i}}{\Delta\sigma_{\text{vis}}^{\text{no offs.},i}} \right)^2 \text{, with}$$

$$S(\bar{\sigma}_{\text{vis}}, b_1, b_2, n_1^i, n_2^i) = \bar{\sigma}_{\text{vis}} \frac{n_1^i + b_1 \cdot (n_1^i - \bar{n}_1)}{n_1^i} \frac{n_2^i + b_2 \cdot (n_2^i - \bar{n}_2)}{n_2^i} .$$

**No Offset correction**




**Offset corrected**




**Calculated per-beam offsets**

| Scan | B1 | B2 |
|---|---|---|
| I | $-0.06 \pm 0.04$ | $-0.019 \pm 0.034$ |
| III | $-0.019 \pm 0.034$ | $-0.01 \pm 0.05$ |
| IV | $0.04 \pm 0.04$ | $-0.06 \pm 0.04$ |
| V | $-0.03 \pm 0.05$ | $0.04 \pm 0.05$ |
| VI | $0.03 \pm 0.05$ | $0.05 \pm 0.05$ |

- For the final systematic uncertainty November session is used
- Syst. unc. is estimated as the largest difference between fBCT and BPTX SigVis (Nov session only used)

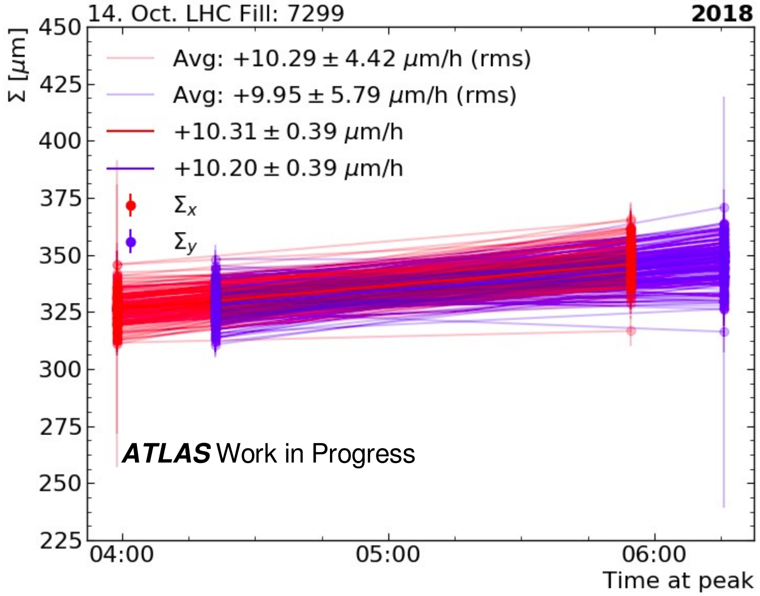
| | Visible cross-section [mb] | | SigVis Fractional difference [%] | |
|---|---|---|---|---|
| Scan # | No OFF corr. | fBCT OFF corr. | No/fBCT OFF corr. | FBCT/ BPTX {OFF corr.} |
| I | 0.887597 | 0.88302 | 0.52% | / |
| III | 0.913962 | 0.910215 | 0.41% | / |
| IV | 0.886374 | 0.885146 | 0.14% | / |
| V | 0.85081 | 0.850686 | 0.01% | 0.023% |
| VI | 0.84413 | 0.843731 | 0.05% | 0.013% |

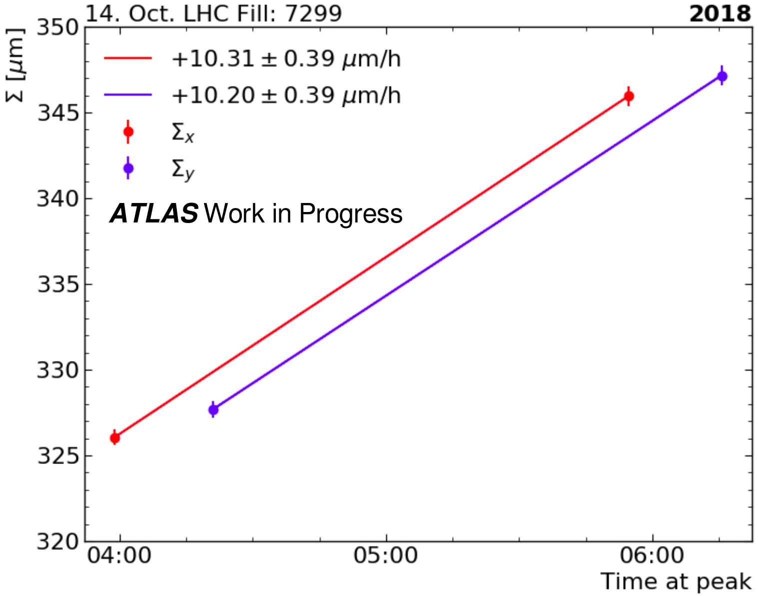
# Emittance growth



- Convolved beam sizes measured during a small period of time
- Emittance grow or shrink affecting calibration:
  1) Scan curves can be distorted by change of beam width
  2) Horizontal and vertical widths are measured at different periods of time → bias on $\sigma_{vis}$

- Change of $\Sigma$ is shown for Fill 7299
- Fill 7299 → $\Sigma$ increasing both for x-scan and y-scan
- Fills 7300, 7406 ,7407 → **less then two** on-axis scan available for estimating emitance growth
- Less transparent lines show the BbyB $\Sigma$ change
- Slope of average ~ Average of slopes




| Fill # | On-axis scans |
|---|---|
| 7299 | S1, S3 |
| 7300 | S4 |
| 7406 | S5 |
| 7407 | S6 |

# Emittance growth correction



- Using following equation of SigVis for estimating corections:

$$\sigma_{\text{vis}}(t_x, t_y) = 2\pi \times \frac{1}{2}\left(\mu^{\text{max}}_{\text{vis.}}(t_x) + \mu^{\text{max}}_{\text{vis.}}(t_y)\right) \times \Sigma_x(t_x)\Sigma_y(t_y)$$

- Expected Peak rates are estimated with assumption that SigVis is constant with time $\mathrm{d}\sigma_{\text{vis}}/\mathrm{d}t = 0$ which yields:

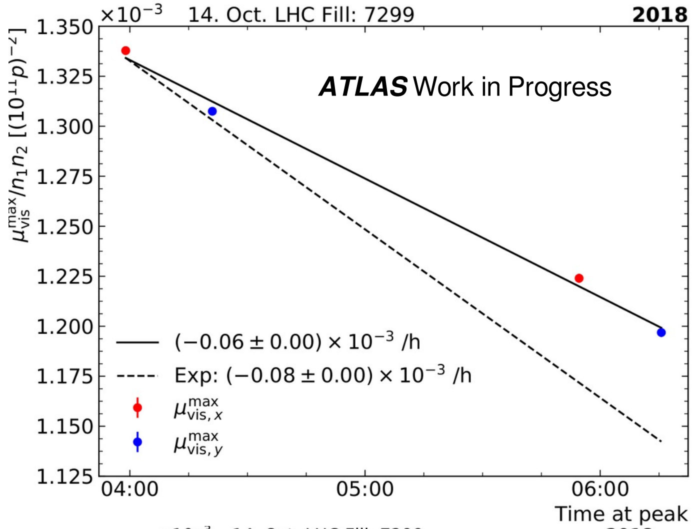
$$\frac{\mathrm{d}\mu^{\text{max}}_{\text{vis.}}}{\mu^{\text{max}}_{\text{vis.}}\,\mathrm{d}t} = -\left(\frac{\mathrm{d}\Sigma_x}{\Sigma_x\,\mathrm{d}t} + \frac{\mathrm{d}\Sigma_y}{\Sigma_y\,\mathrm{d}t}\right)$$

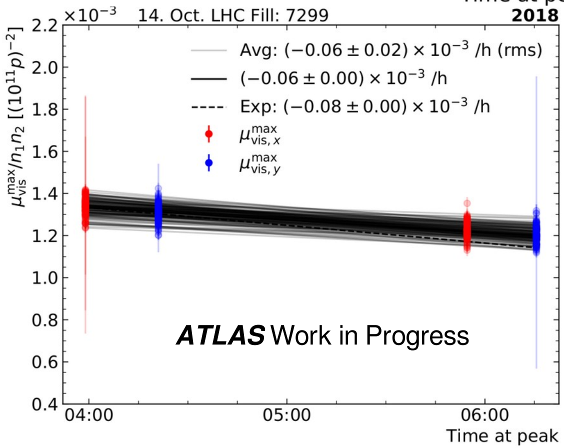
- Correction is : $c_\varepsilon = \sigma_{\text{vis}}(t_{\text{mid}}, t_{\text{mid}})/\sigma_{\text{vis}}(\hat{t}_x, \hat{t}_y)$

time between peaks — at the peak times

$$\frac{1}{2}\left|\frac{\sigma_{\text{vis}}(\hat{t}_x) - \sigma_{\text{vis}}(\hat{t}_y)}{\sigma_{\text{vis,ref}}}\right|$$

| S# | Uncor. SigVis | Corr. SigVis | c [%] | delta c (x/y) | delta c (fit) |
|---|---|---|---|---|---|
| I | 0.8897 | 0.8898 | 0.006 | 0.338 | 0.032 |
| III | 0.9148 | 0.9149 | 0.005 | 0.185 | 0.027 |



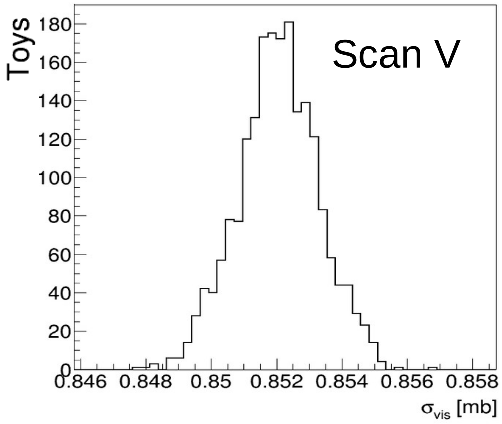
# Beam position jitter ; B-by-B consistency



- Performing pseudo-experiment randomly changing samples:

$$x_{new} = x + rnd.Gauss(0, \sigma_{jitter})$$

- Using 2000 iterations (toys)
- Using RelRMS = RMS/SigVIs to estimate uncertainty ~ 0.14%




| Scan | SigVis | RMS | RelRMS |
|---|---|---|---|
| I | 0.879024 | 0.000894 | 0.10% |
| III | 0.908484 | 0.000863 | 0.09% |
| IV | 0.880739 | 0.000957 | 0.11% |
| V | 0.852059 | 0.001227 | **0.14%** |
| VI | 0.849463 | 0.001034 | 0.12% |

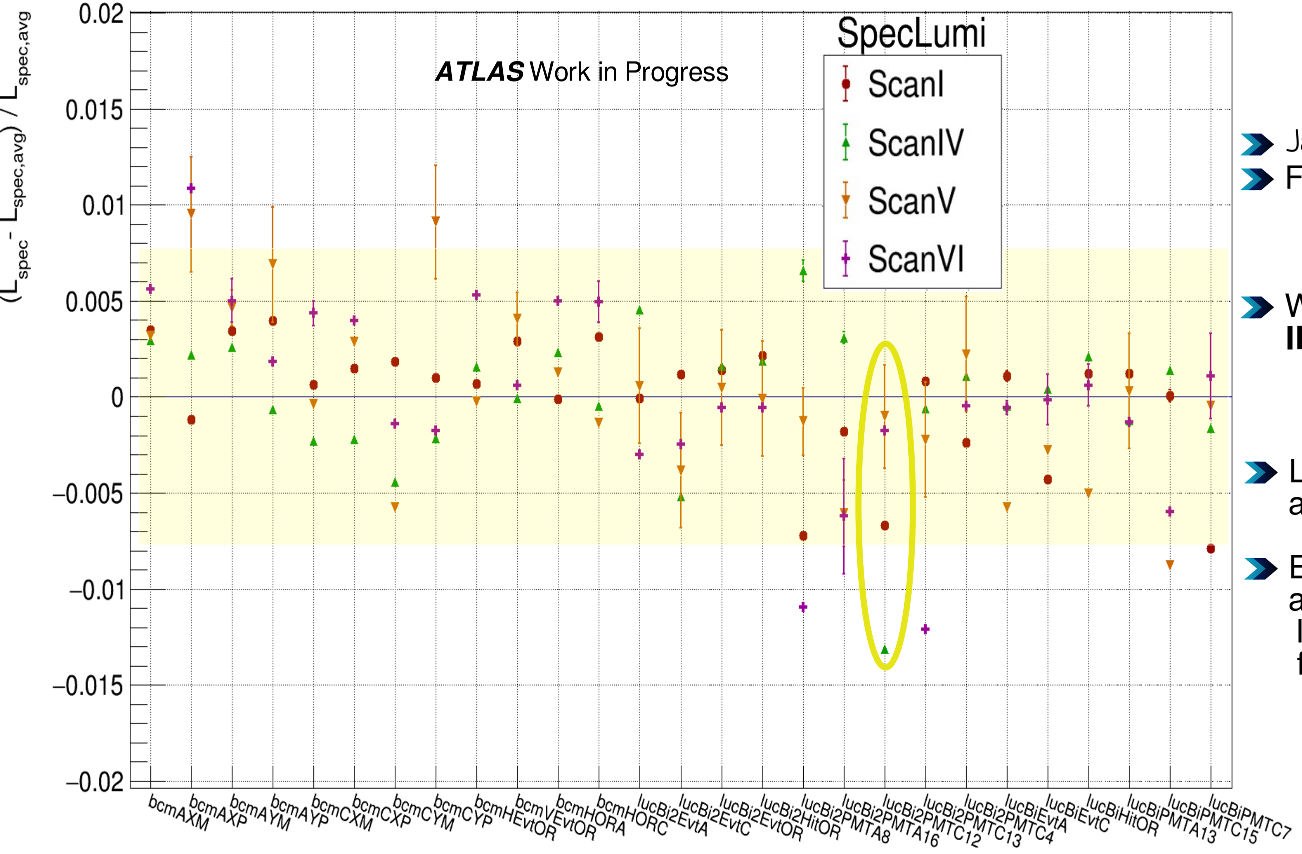
| Scan | B-by-B |
|---|---|
| I | 0 |
| III | 0.49% |
| IV | 0 |
| V | 0 |
| VI | 0 |

- Bunch-by-bunch uncertainty is calculated RMS corrected for average $\sigma_{vis}$ stat. unc:

$$RMScorr = \frac{1}{\sigma_{vis}}\sqrt{RMS^2 - (\delta\sigma_{vis})^2}$$

- Bunch-by-bunch consistency is zero if RMS is smaller than $\delta\sigma_{vis}$

# Reference specific luminosity




- Jan`s method has been used (explained here in detail):
- For each algorithm ***a***, we use relative difference $\Delta^a(s,b)$

$$\Delta^a(s,b) = \frac{L^a_{spec.}(s,b) - < L_{spec.}(s,b) >}{< L_{spec.}(s,b) >}$$

- Where ***s*** and ***b*** are **scan numbers** and **colliding bunch IDs** respectively

- Largest uncertianty due to mbts* algorithms and scan III.

- Excluding mbts* algorithms and scan III from averaging we get ~0.56% of uncertainty with largest scan averaged deviation coming from lucBi2PMTC12 algorithm.