# ATLAS 2010 Luminosity Determination

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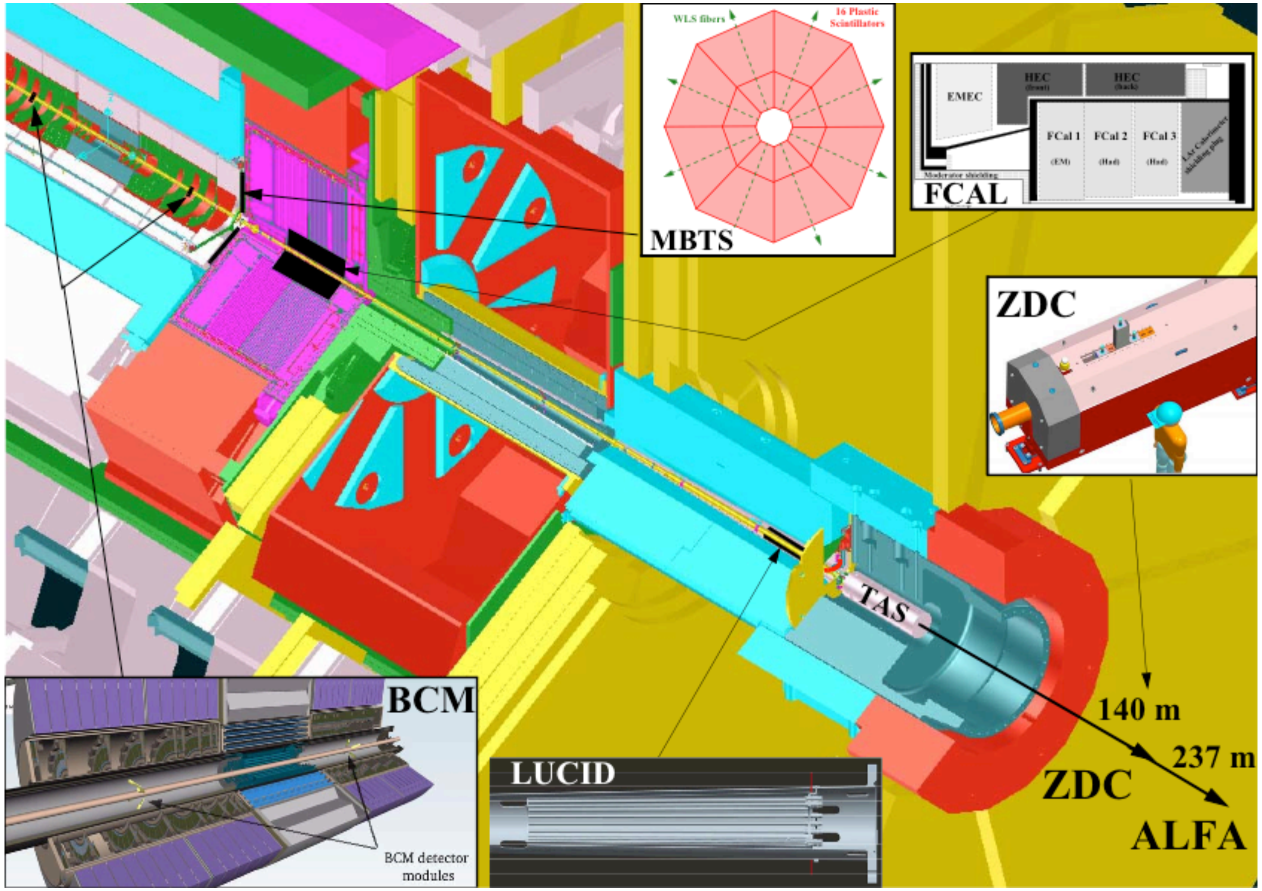
On behalf of the ATLAS Luminosity WG

# Lumi detectors used in 2010




**Online & offline**

MBTS $(2.1<|\eta|<3.8)$

Event AND (& OR)

BCM $(|\eta|=4.2)$

Event OR & AND

LUCID $(5.6<|\eta|<6.0)$

Event OR & AND

ZDC $(|\eta|>8.3)$

Event OR & AND (HI-runs only)

**Offline only:**

MBTS with time cuts
LAr timing ($\mu$<<1)
Primary Vertex Event counting
Charged Track Event counting

Event-OR:
$\geq$ 1 hit on either side
Event-AND:
$\geq$ 1 hit on both sides

# ATLAS philosophy on lumi

**Redundancy:**

We tried to commission as early as possible several Luminosity detectors/algorithms

- Handle on systematics
- Complementarity (best algo depends on beam conditions)
- Stability checks (calibration drifts with time/beam conditions)

At all times we had at least 2 independent operational luminosity monitors

**Keep it simple:**

For 2010 we did not try to use a most sophisticated method valid for throughout all $\mu$-values

We rather adapted to the conditions and used whatever was the simplest and best understood adequate method

We have improvements in our pocket for 2011 challenges & beyond

# Online Luminosity monitoring

**LUCID**

Dedicated ATLAS luminosity detector
15+15 ('+' & '-' side of IP) Cherenkov tubes used 2010
Bunch-by-bunch capability
In 2010 event counting: event = hit(s) in ≥1 of the tubes

**BCM**

2+2 small diamond sensors around beam-pipe
Bunch-by-bunch event counting
Low acceptance -> low statistics. Used only at high lumi end of 2010

**MBTS**

16+16 scintillator petals, event counting
High efficiency – very good at early luminosities
Long pulses – not usable online with ≤150ns bunch spacing

**ZDC**

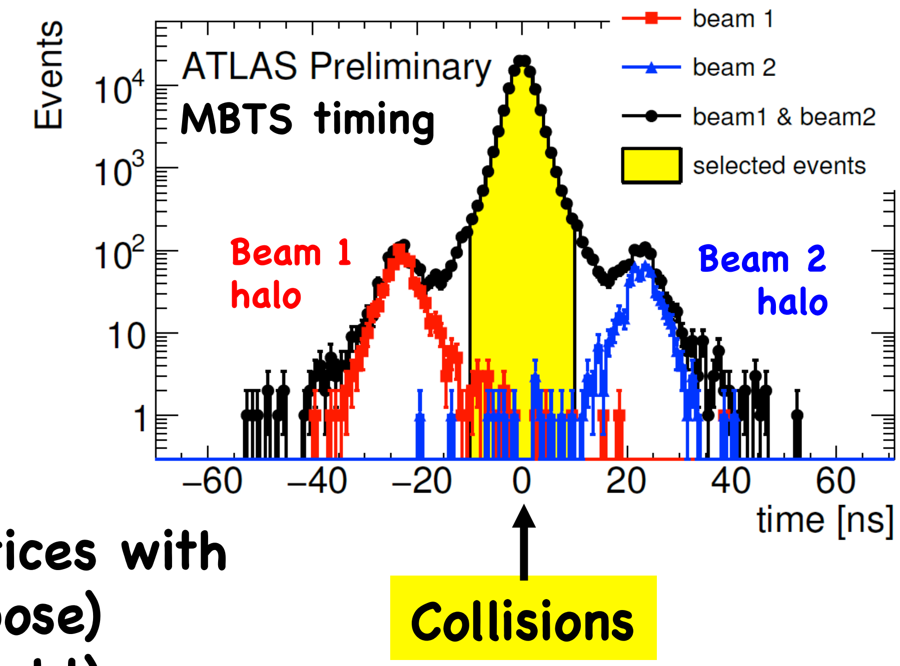
Fully commissioned for luminosity only during HI run

# Offline luminosity methods

**All offline methods have bunch-by-bunch capability**

## MBTS (& LAr timing)

Request a conincidence within 10 ns to cut beam-gas & halo




## Primary Vertex Event counting

Count BX with ≥1 primary vertices with
≥2 tracks > 100MeV/c (loose)
≥5 tracks > 150MeV/c (tight)

## Charged track event counting

For rate comparisons, see talk by B. Heinemann

# Basic concepts and methods

# μ (=pileup) corrections

**Here:** Event ≡ LHC BX event SEEN by given detector/algo

**In Event-counting mode a detector sees either 0 or 1 events per BX**

If μ (number of pp/BX) not <<1, event counting

- shows saturation effects (e.g. > 1 pp never can give > 1 event)
- can have pileup coincidences (in AND-mode)

Event and 'Zero' counting are equivalent

$$P_{EventAND} = 1 - P_{ZeroOR}$$

$$P_{EventOR} = 1 - P_{ZeroAND}$$

μ-dependence in Event-OR:

$$\mu = \frac{\mu_{\mathrm{vis,OR}}}{\epsilon_{\mathrm{OR}}} = -\frac{\ln(1 - \frac{N_{\mathrm{OR}}}{BX})}{\epsilon_{\mathrm{OR}}}$$

μ-dependence in Event-AND (if efficiency ε on both sides identical):

$$\frac{N_{\mathrm{AND}}}{BX} \approx 1 - 2e^{-\frac{1}{2}(\epsilon_{\mathrm{AND}}+\epsilon_{\mathrm{OR}})\mu} + e^{-\epsilon_{\mathrm{OR}}\mu}$$

No analytical solution for μ

# Background

## Types of background potentially affecting the luminosity measurement

**Beam gas & beam halo**

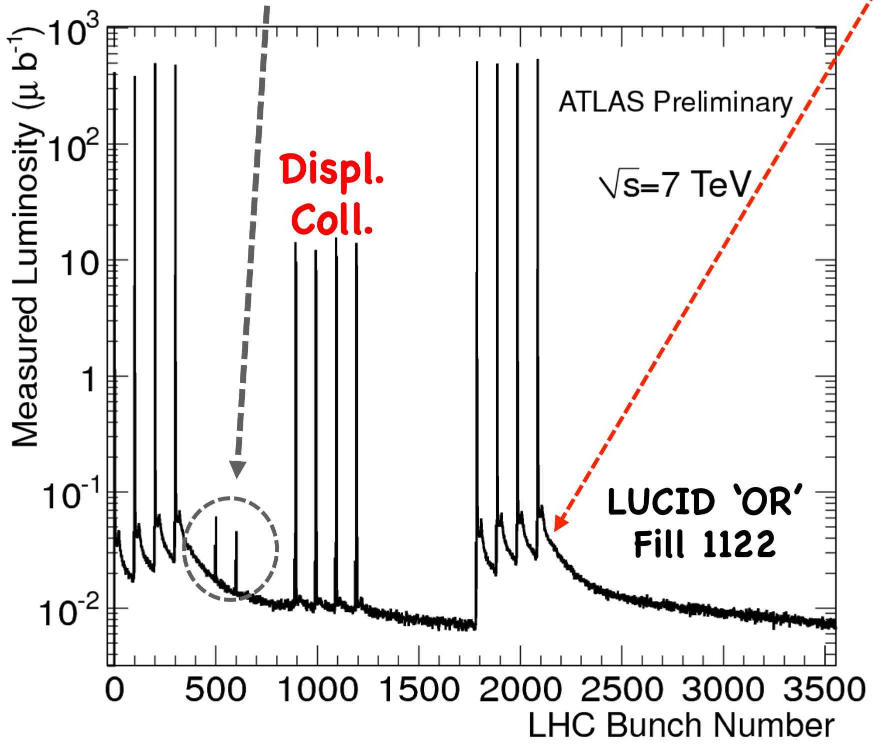
**'AND' less sensitive than 'OR'**

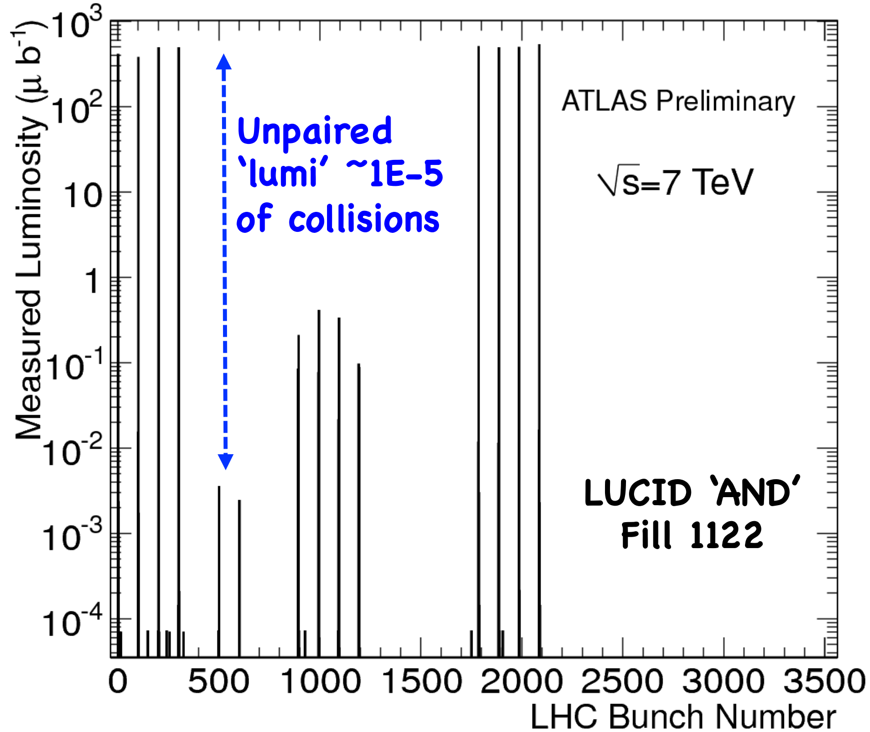
Easy to monitor with unpaired bunches

**'Afterglow' (= long lived radiation)**

**'AND' almost insensitive**

**In 'OR'-mode makes a BCID-aware (bunch-by-bunch) analysis compulsory**



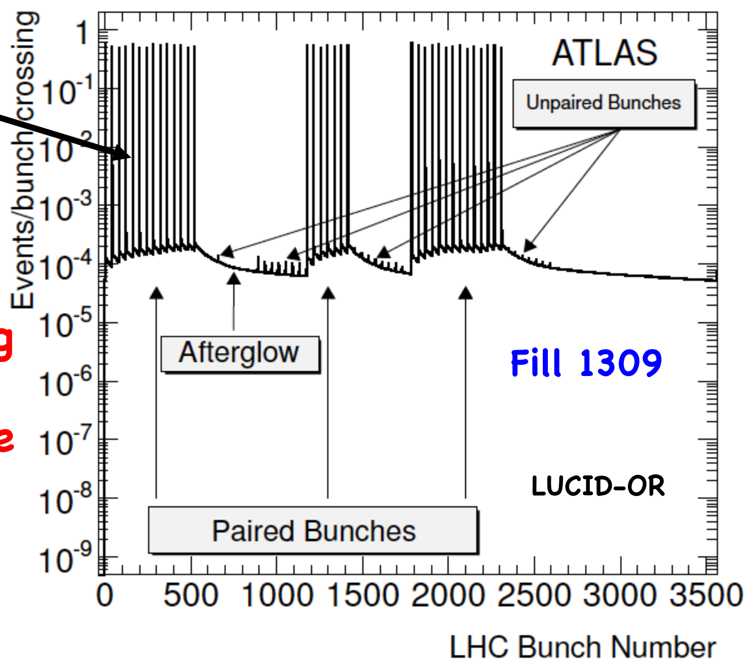



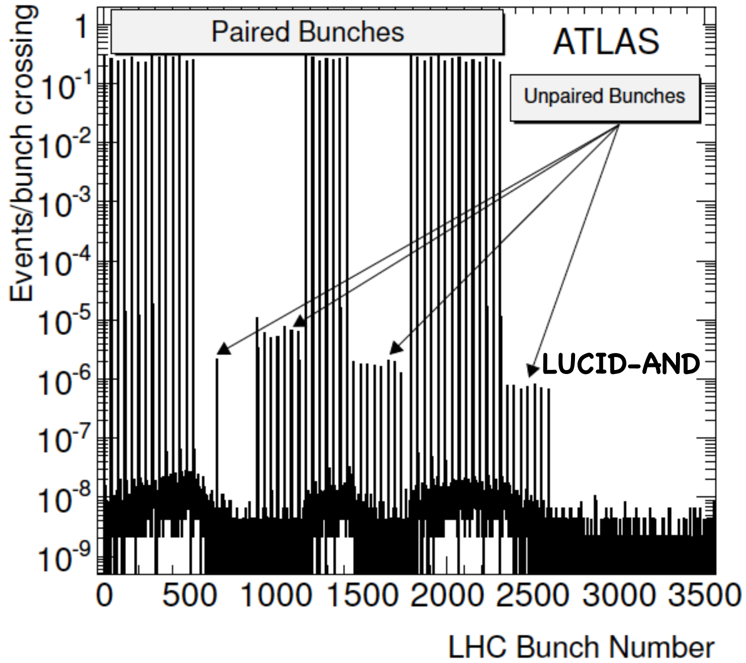
# Preferred Luminosity algorithm

- We use coincidence ('AND') algorithms for online monitoring (& LHC Page 1)
  - + Intrinsically (almost) background free
  - + BCID blind and BCID aware give almost equal result
  - + The μ-correction is more complicated and has no analytical expression. Only analysis of high-μ data convinced us that we handle it as accurately as 'OR'
- In 2010 we prefered BCID-aware 'OR' of LUCID as our base 'offline' luminosity
  - + The μ-correction is simple and well understood for wide μ-range
  - - Need to estimate background from unpaired bunches
  - - The 'OR' is prone to background, esp. 'afterglow' (up to 0.1% at 150ns)

Bunch spacing 1 μs

At 50 (75) ns spacing the afterglow might make 'AND' preferable



# Satellite & displaced collisions

In the early 2010 run displaced collisions gave non-negligible background in BCID-blind 'OR' algorithms (plot on slide 8)

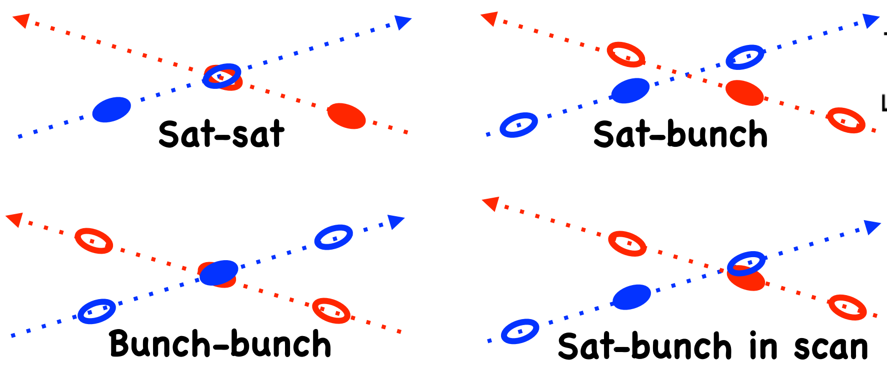
Satellite-satellite was negligible (and hopefully stays so)

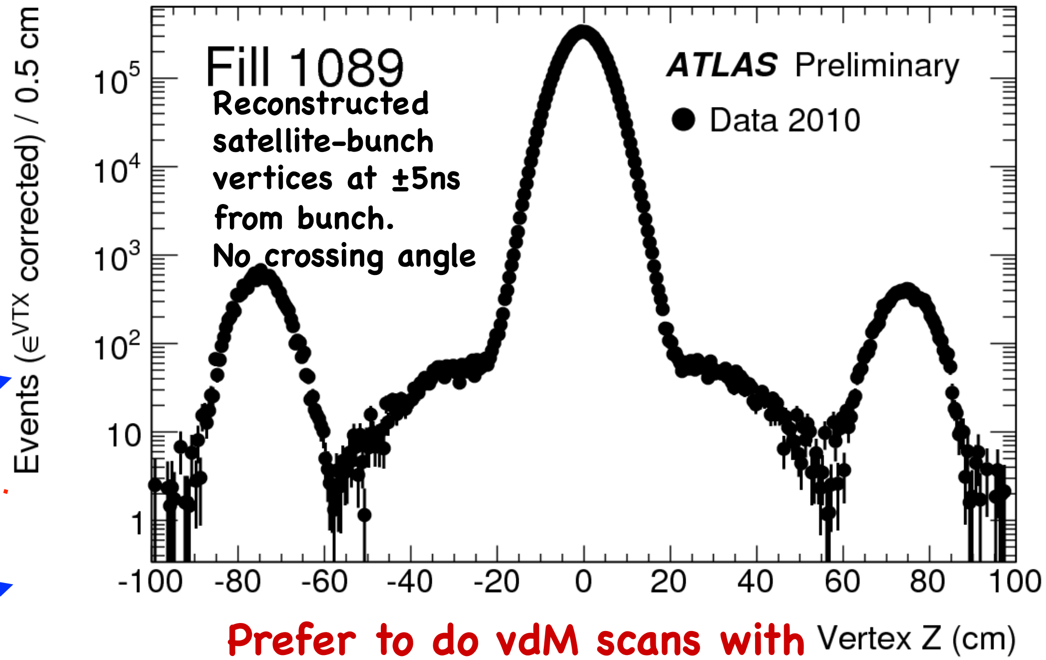
**Bunch-satellite not an issue with crossing angle**

Only in tails of vdM scan (with Xing angle) bunch-satellite might become visible

Developing tools to monitor displaced (satellite-bunch) collisions by MBTS timing.

For 2.5 or 5ns satellites also vertices can be reconstructed




Prefer to do vdM scans with Xing angle to mitigate satellites for centered beams

# The van der Meer (vdM) method to determine absolute luminosity

# Absolute Luminosity from vdM scans

$$\mathscr{L} = \frac{\mu n_b f_r}{\sigma_{inel}} = \frac{\mu_{vis} \; n_b f_r}{\varepsilon \sigma_{inel}} = \frac{\mu_{vis} \; n_b f_r}{\sigma_{vis}}$$

$\mu_{vis}$ = Number of interactions per BX seen by detector N (measurement)

$\sigma_{vis}$ = Cross section seen by detector N (calibration constant)

$$\sigma_{\rm vis} = 2\pi \mu_{\rm sp,max} \Sigma_x \Sigma_y$$

$$\mu_{\rm sp} = \frac{\mu_{\rm vis}}{n_1 n_2}$$

Determined in vdM scan by each lumi-det.

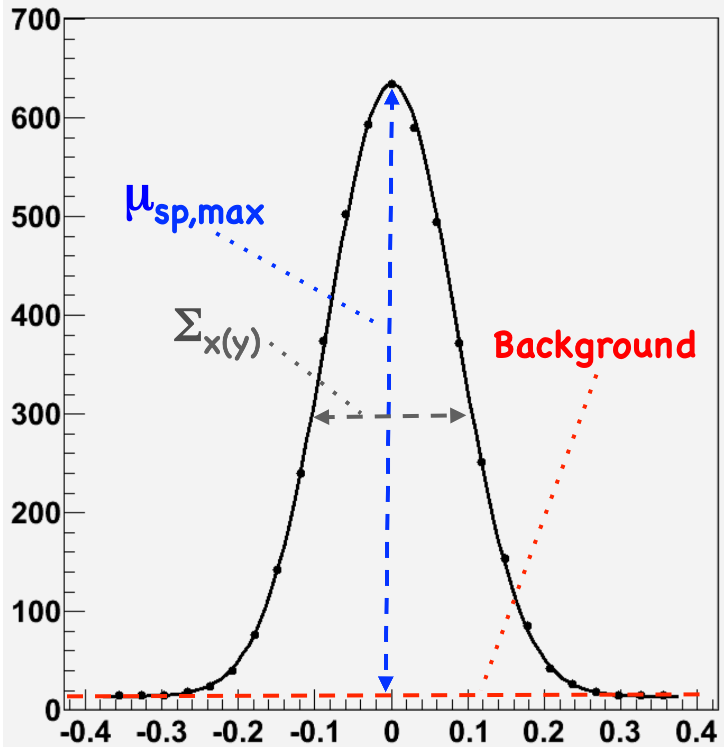
Measured by beam-instr. during scan

Where $n_{1(2)}$ are # of particles per colliding bunch in beam 1 (2)

# Fitting the VdM scan

We observed that the LHC VdM data is best fitted by a double-gaussian + constant:

$$P(x) = \frac{P(x_0)}{\sqrt{2\pi}} \left[ \frac{f_a e^{-(x-x_0)^2/2\sigma_a^2}}{\sigma_a} + \frac{(1-f_a) e^{-(x-x_0)^2/2\sigma_b^2}}{\sigma_b} \right] + c$$




From which $\Sigma_{x(y)}$ is obtained by

$$\frac{1}{\Sigma_x} = \left[ \frac{f_a}{\sigma_a} + \frac{1-f_a}{\sigma_b} \right]$$

$\Sigma$ is a property of the colliding beams only

And $\mu_{\mathrm{sp,max,x}} = \frac{P(X_0)}{\sqrt{2\pi}\Sigma_x}$

if the fit is done on μ-corrected $\mu_{sp}$ values

We approximate $\mu_{\mathrm{sp,max}} = 0.5(\mu_{\mathrm{sp,max,x}} + \mu_{\mathrm{sp,max,y}})$

Not exact if any emittance growth between scans

$\mu_{vis}$ different for each detector

# The 2010 vdM scans in ATLAS

| Date | Fill | # coll. b. | β* (m) | Crossing (μrad) | $N_b$ (1e11) | μ at peak | comment |
|---|---|---|---|---|---|---|---|
| Apr 26 | 1059 | 1 | 2 | 0 | 0.1 | 0.03 | Scan 1 |
| May 9 | 1089 | 1 | 2 | 0 | 0.2 | 0.11 | Scans 2 & 3 |
| Oct 1 | 1386 | 6 | 3.5 | 200 | 0.9 | 1.4 | Scans 4, 5 & 6 |
| Oct 4 | 1393 | 186 | 3.5 | 200 | 1.0 | 2.4 | Length scale |
| Nov 30 | 1533 | 113 | 3.5 | 0 | 0.1 | 0.00016 | Heavy Ion |

**Analysis for the April & May scans completed (CERN-PH-EP-2010-069)**

- **Will summarize these - official - ATLAS values**

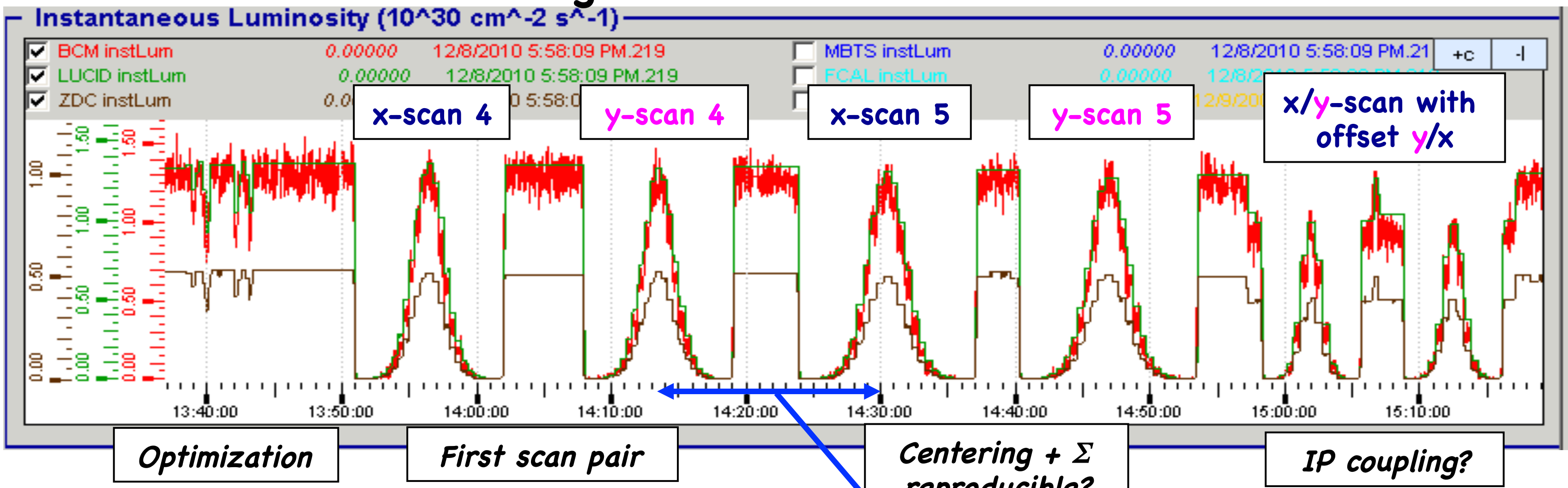
**Analysis of the October scans in progress**

- **Will show some results of these analyses**
- **Expect clear improvements (esp. on systematics)**

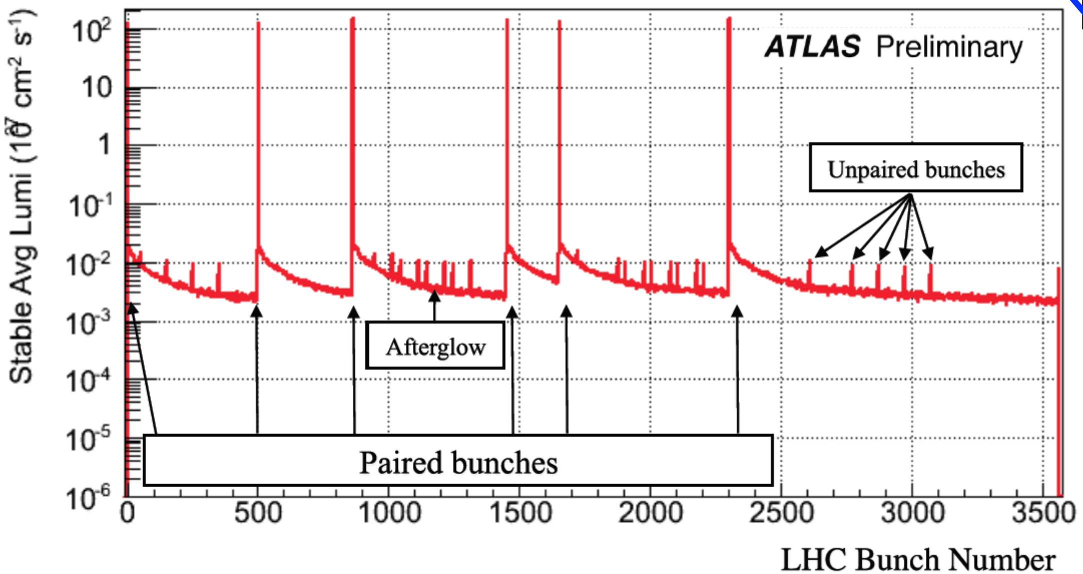
**Will not discuss the Heavy-ion scan in this talk**

# The October VdM fill (1386)

As seen in online monitoring




About 20min between scans (peak-to-peak)



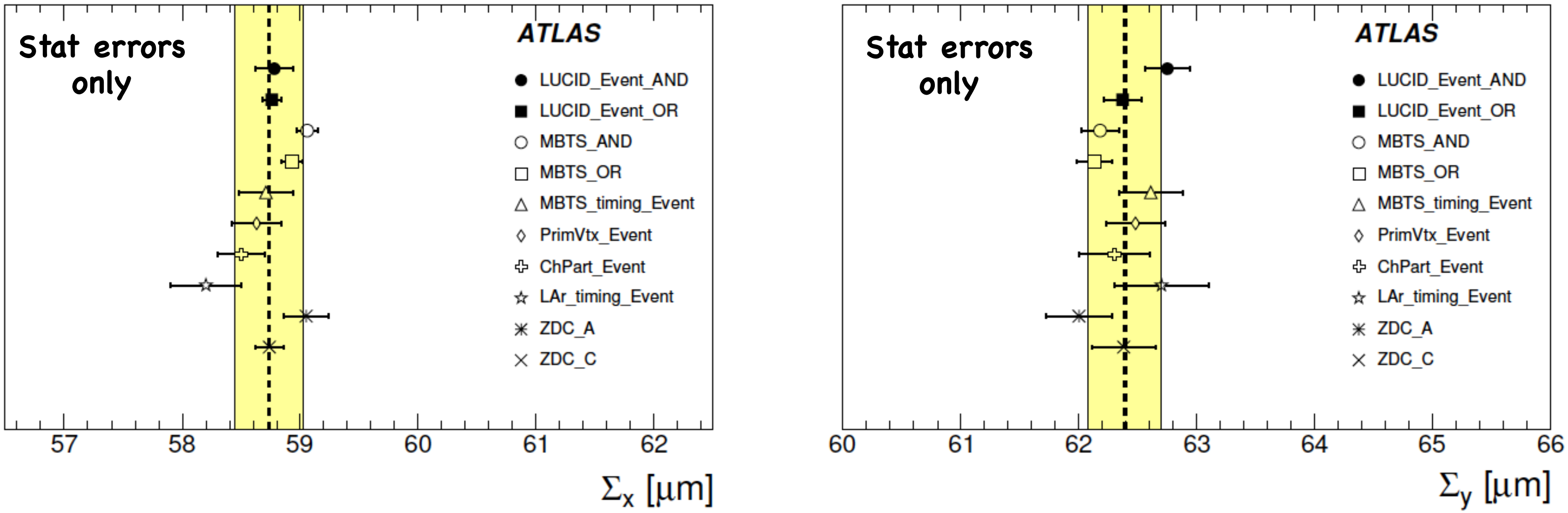

Each scan total $\pm 6\sigma$, moving both beams $\pm 3\sigma$, 25 points, 20 s/point

Per-bunch 'luminosity' by LUCID-Event-OR (Afterglow & unpaired even more suppressed in 'AND')

# The April/May vdM results

# Comparison of $\Sigma$ for all detectors – May

**Values of $\Sigma$ for various luminosity detectors/methods used during the first vdM scans in May (Fill 1089)**

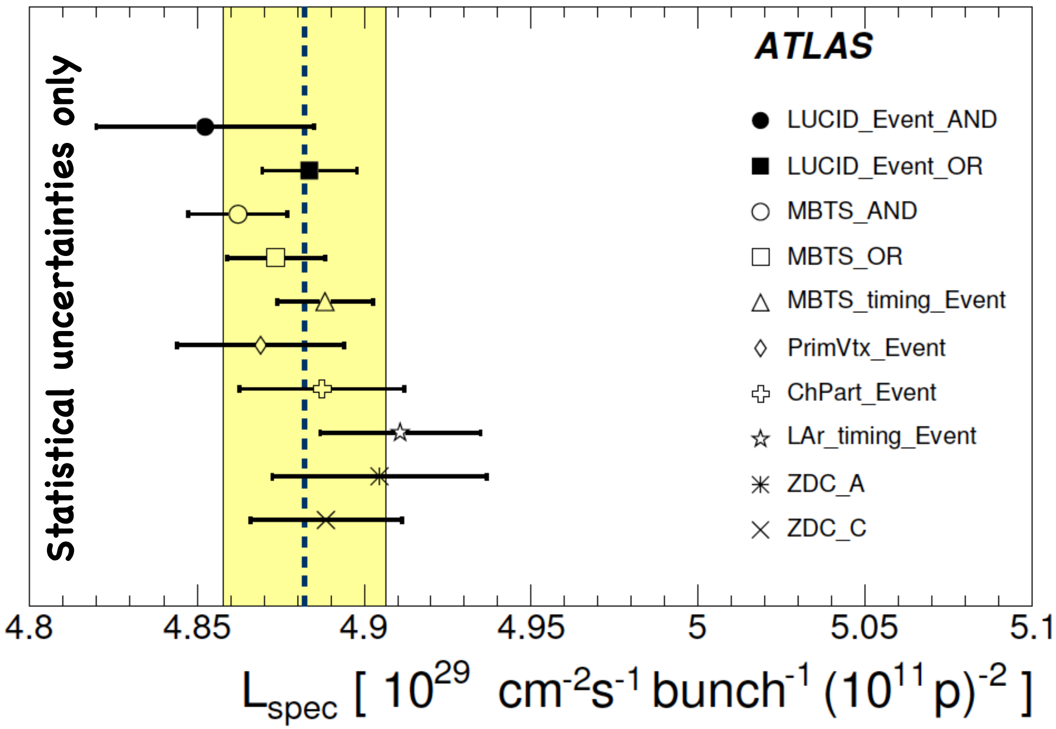



**Shaded area shows a ±0.5% deviation around the common mean (dashed)**

**All luminosity detectors give consistent widths**

# Specific luminosities – May

$L_{spec} = Rate/(\sigma_{vis} * n_1 * n_2)$




**Systematic uncertainties (will discuss in next slides)**

| Source | Uncertainty on $\sigma_{vis}$ (%) |
|---|---|
| Beam intensities | 10 |
| Length-Scale | 2 |
| Beam centering | 2 |
| Emittance growth* | 3 |
| $\mu$ dependence | 2 |
| Fit model | 1 |

*Including other sources of non-reproducibility

**The systematic uncertainties assigned to the April/May vdM results were in most cases conservative estimates**

**Total luminosity uncertainty: 11%**

# vdM systematic uncertainties

**October scans**

# Beam currents

The measurement of $n_b$ has been the (by far) dominating systematic uncertainty for the determination of absolute luminosity. In summer (ICHEP) it was assigned a (conservative) 10%.

Some scans were done in different fills for ATLAS, CMS,… so the beam-current uncertainty might not fully cancel in a comparison of two experiments.

A new analysis has significantly reduced these uncertainties. See dedicated talk by T.Pauly:

| LHC Fill (date) | 1059 (Apr 26) | 1089 (May 9) | 1386 (Oct 1) |
|---|---|---|---|
| $n_1 n_2$ uncertainty | 5.5 % | 4.4 % | 2.9 % |

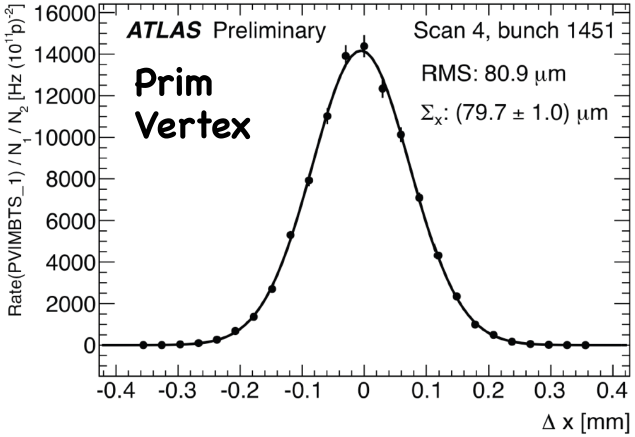
Major improvement wrt the old analysis

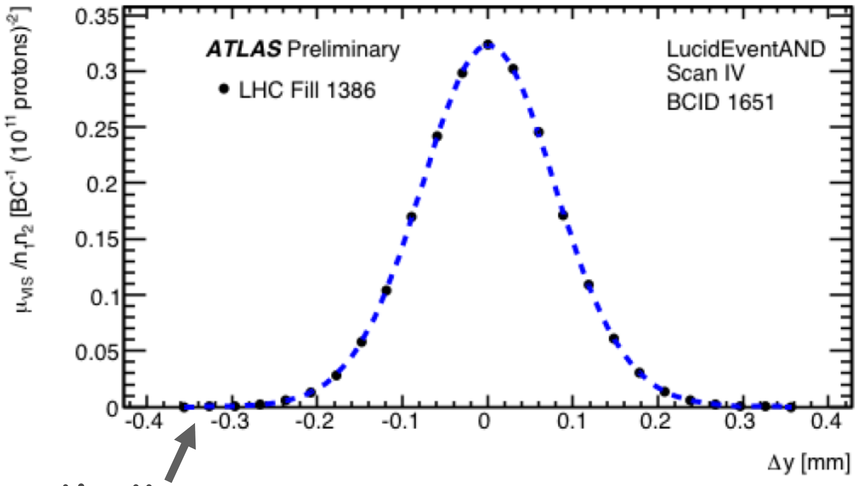
This alone drops the total systematic uncertainty from 11% to 5.3%,
But we are confident that the detector systematics will improve also

# Fit model

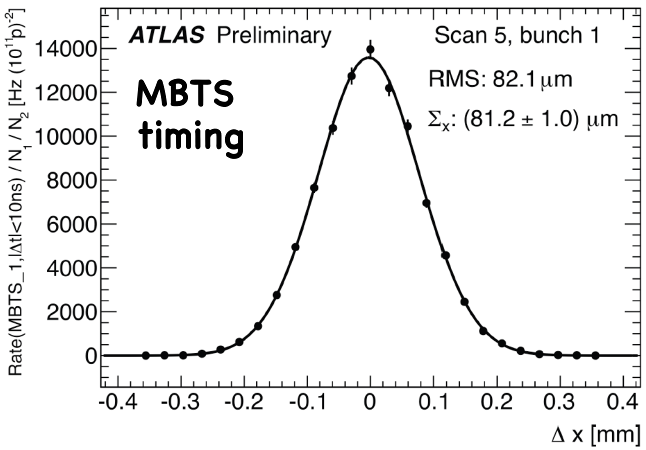
**All lumi detectors find that a double-Gaussian + background gives best fit**

Just some example fits

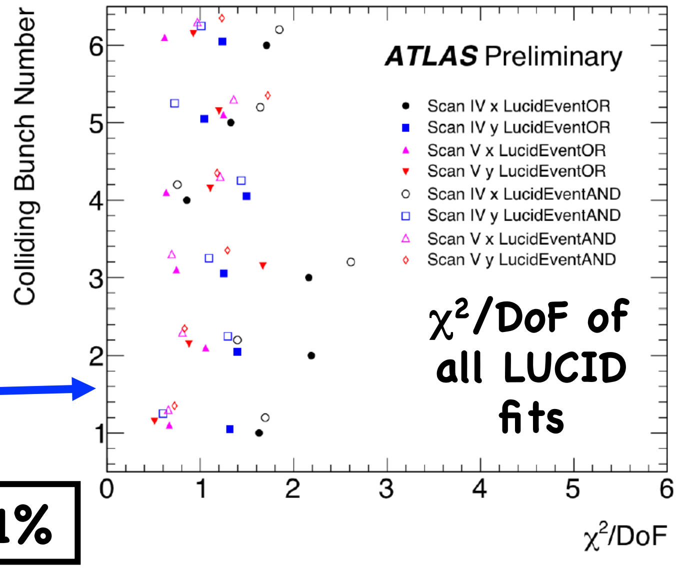



Practically zero constant term (LUCID) confirms low background (As seen from unpaired bunches)



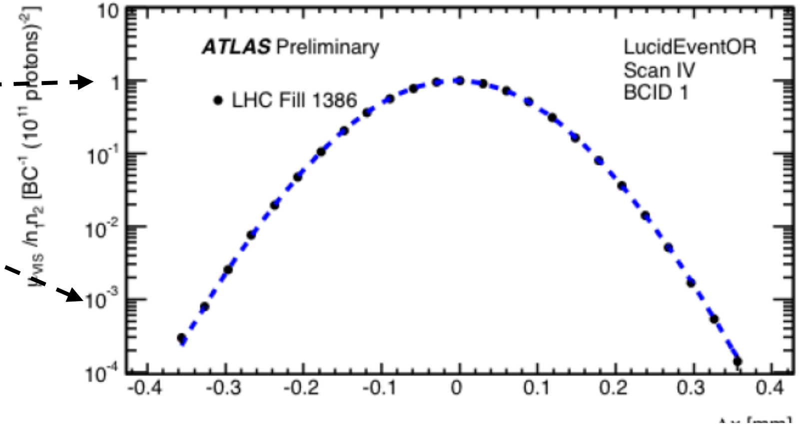

**Very good Fit quality**




**Checked with spline fits -> agrees within < 1%**

# $\mu$-dependence

Over a VdM-scan $\mu$ varies by ~3 orders of magnitude




At $\mu$<<1:

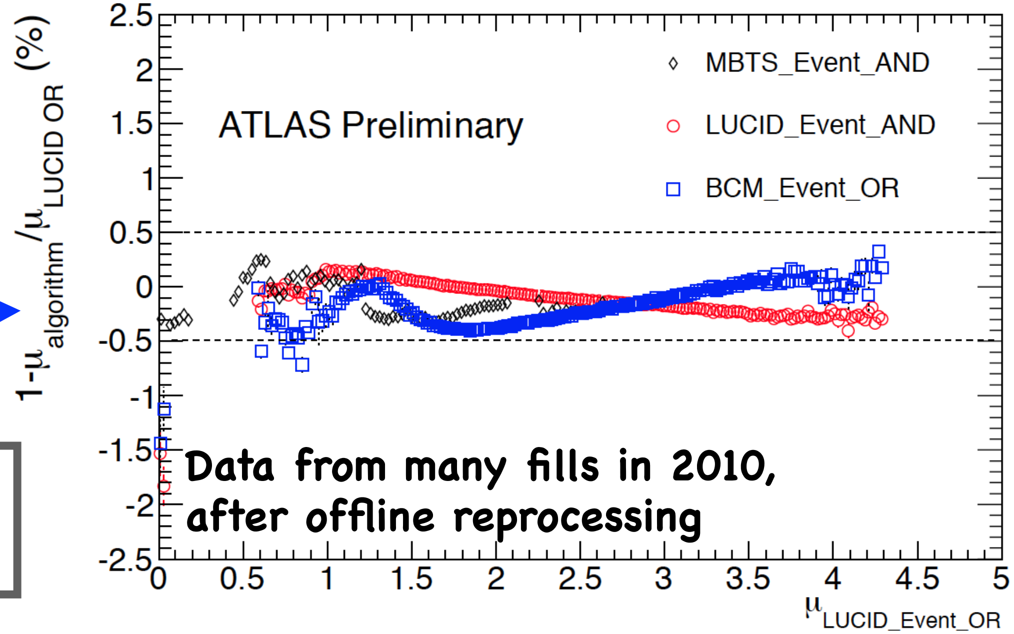
Rate = $\mu_{vis}$ = $\varepsilon\mu$

In Oct 1 scans $\mu_{max}$~1.4

Rate = $1-\exp(-\mu_{vis}) = 1-\exp(-\varepsilon\mu)$

-> pileup correction ~35% for LUCID OR ($\varepsilon$ ~ 0.6)

**Very different detectors ($\varepsilon,\eta$) and algorithms (AND) consistent (0.5%) with LUCID-OR up to $\mu$=4.5**

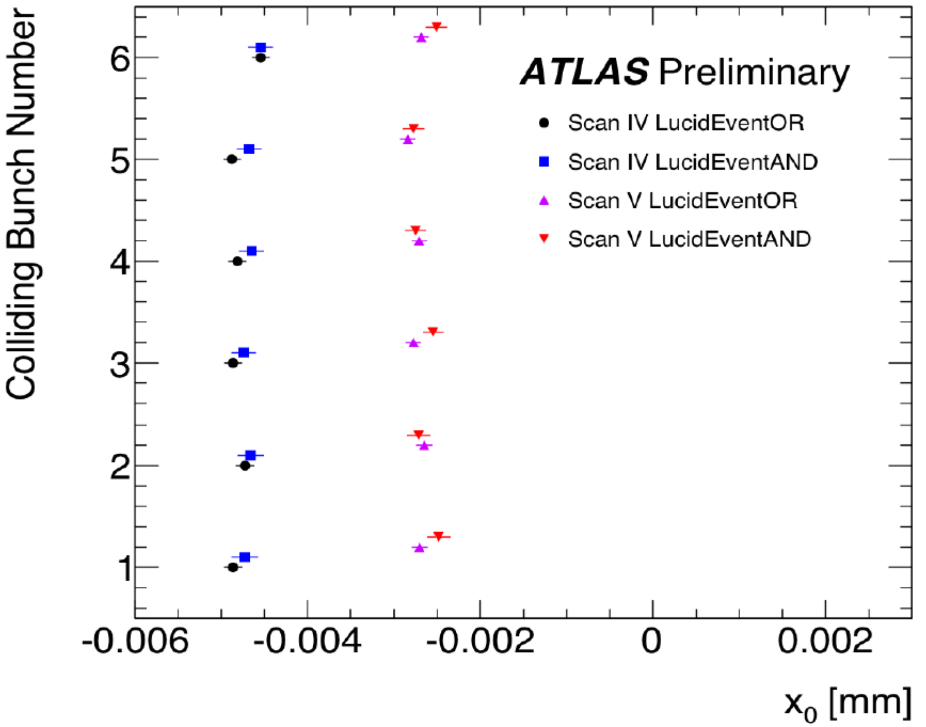


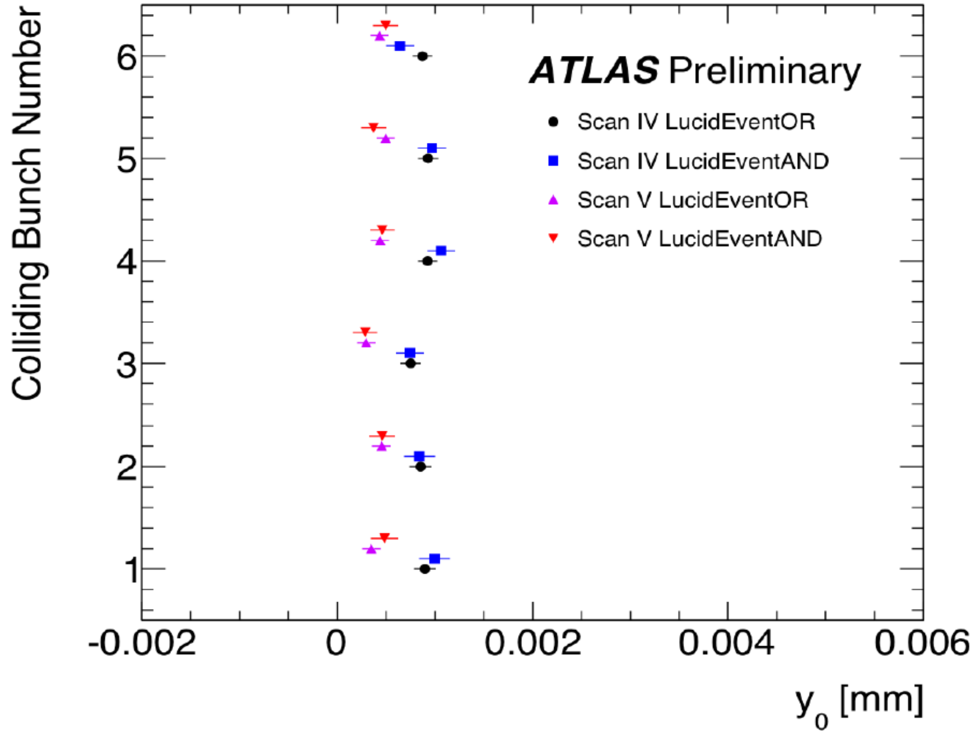

The $\mu$-dependence syst. uncertainty reduces from 2% to 0.5%

We prefer scans at $\mu\approx2$ (to have enough per-bunch statistics for BCM)

# Beam (re)centering

Peak position as obtained from the double-gaussian fits on LUCID data




Observe a ~2μm shift in x even after recentering between the scans

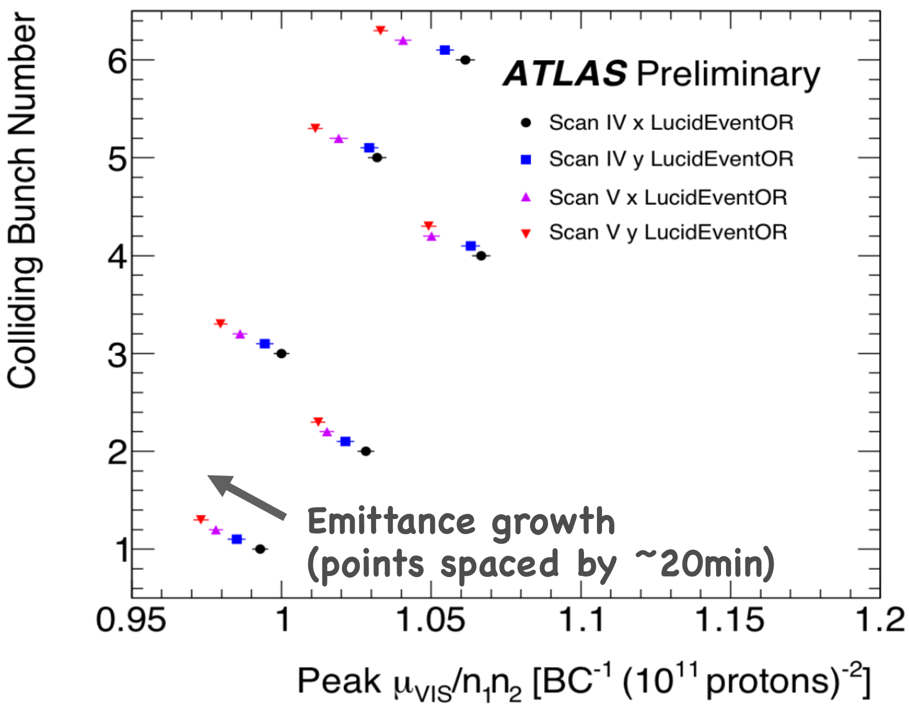
Possible xy-coupling to be studied.

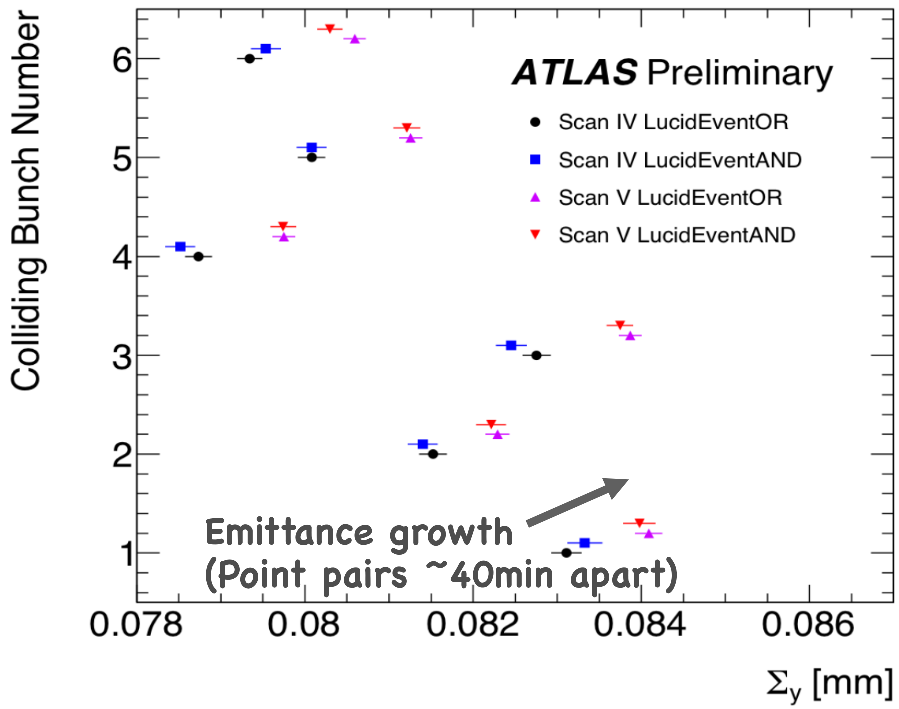
Centering uncertainty likely to improve wrt the May estimate

2 pairs of scans mandatory to have a handle on this systematic

# Emittance growth

**Leads to increase of Σ and decrease of μ – these almost cancel**




**$\mu$ and $\Sigma_y$ per bunch fitted on LUCID data for Oct 1 scans (fill 1386)**

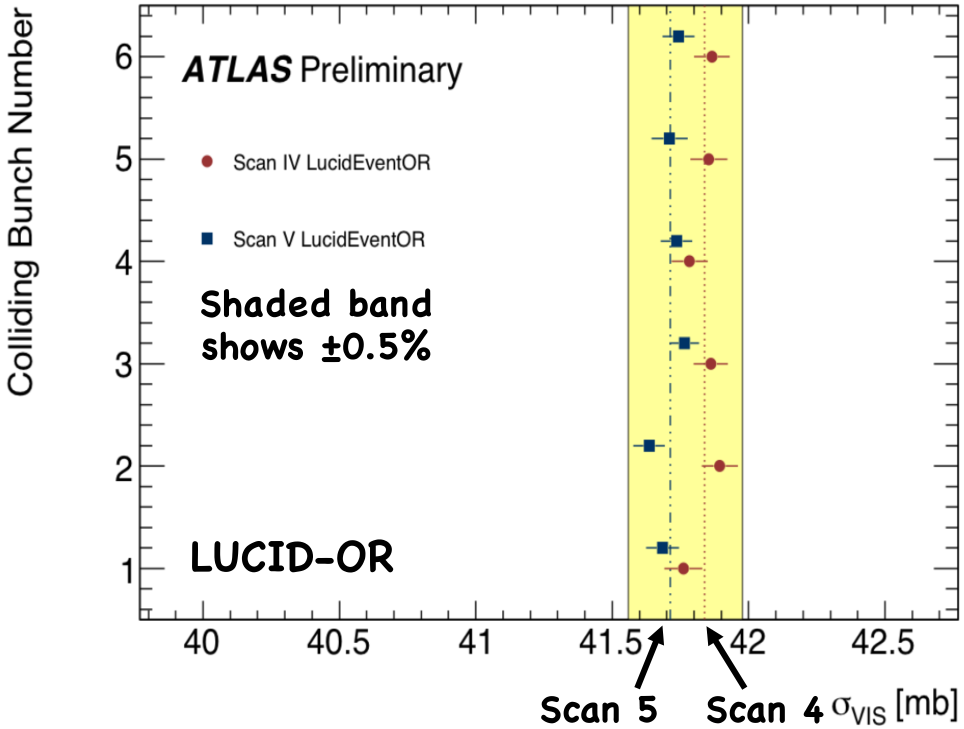
**Emittance growth ~2% between scans 4 & 5 (should ~cancel from $\sigma_{vis}$)**

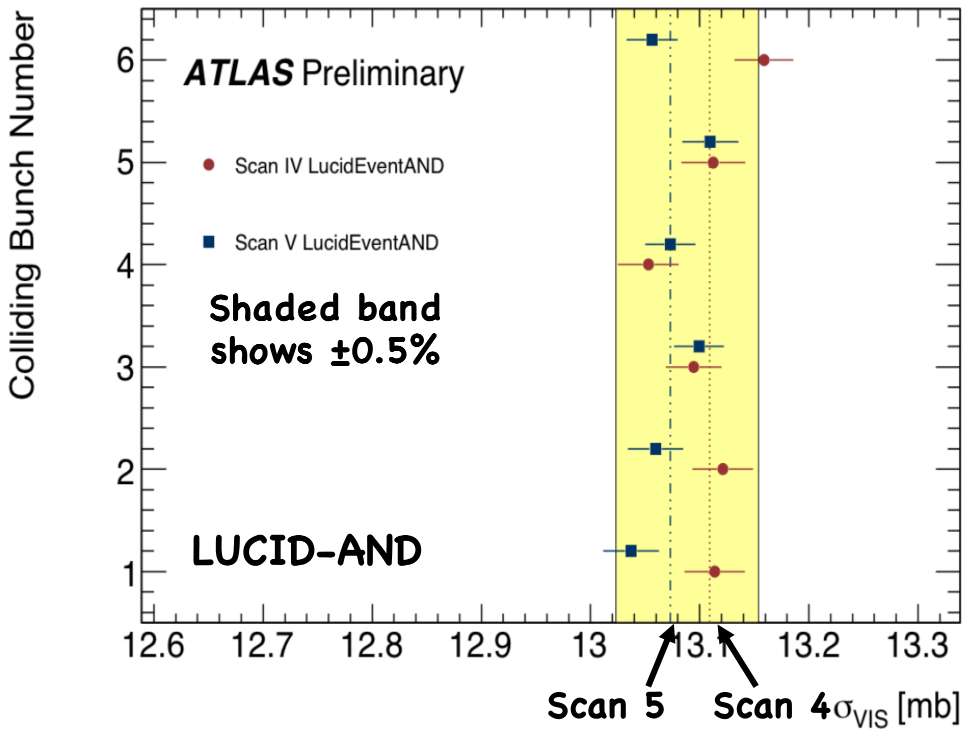
**Emittance growth in the x-plane was negligible**

**Consistent with wire scanners/synch-light monitors**

**Need 2 pairs of scans to have this handle on emittance growth**

# LUCID $\sigma_{vis}$ for scans 4 & 5




$\sigma_{vis}$ values for 'OR' and 'AND' reflect large difference in efficiency

Good agreement between scans 4 & 5 suggest that emittance growth & other non-reproducibility affect results by < 1%

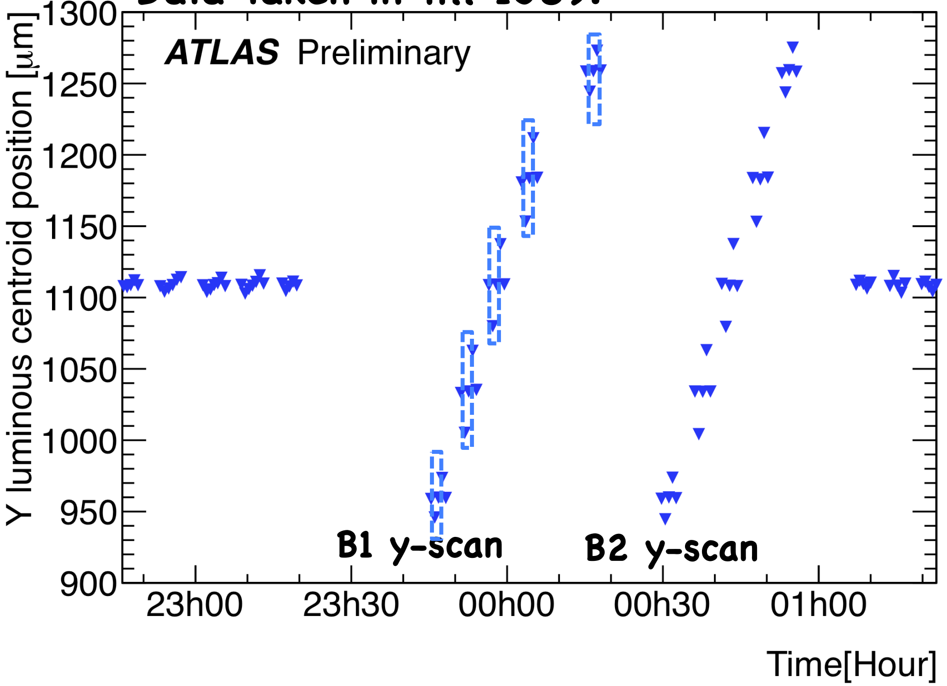
Confirms that no explicit correction for emittance is needed

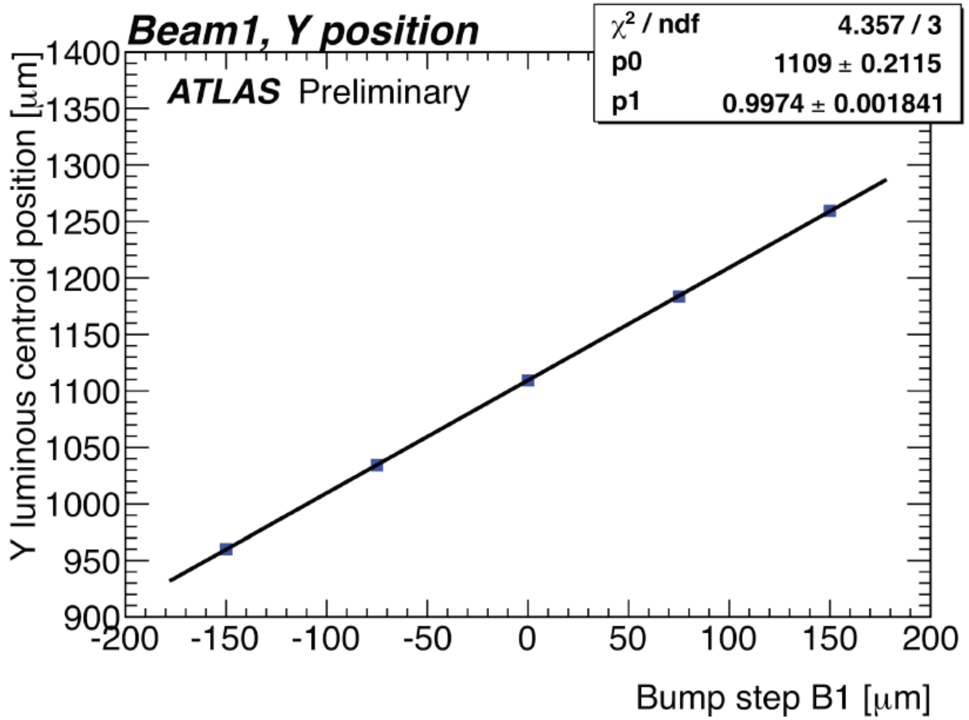
# Length scale calibration

**Aim:** calibrate the nominal displacement wrt seen vertex movement

**Method:** Move one beam off-center and scan with the other to find its new position (minimize hysteresis effects). Take vertex data at each scan point (linearity)

Data taken in fill 1389.




All 4 scans fit very well. Seen movement agrees with nominal displacement within <0.5%

However, at this level of µm precision inner Det. Alignment needs further checks

# Other systematic effects

There are some additional possible systematic effects

xy-coupling, possible drift in the plane opposite to the scanned

Crossing angle (zero in Apr/May sans).

Satellite bunches, - mitigated by crossing angle, but may affect current measurement
- satellite-bunch collision possible at large displacement (in scan tails)

Backgrounds, i.e. beam-gas and beam-halo

Beam shapes, overlap integrals, tilts & correlations

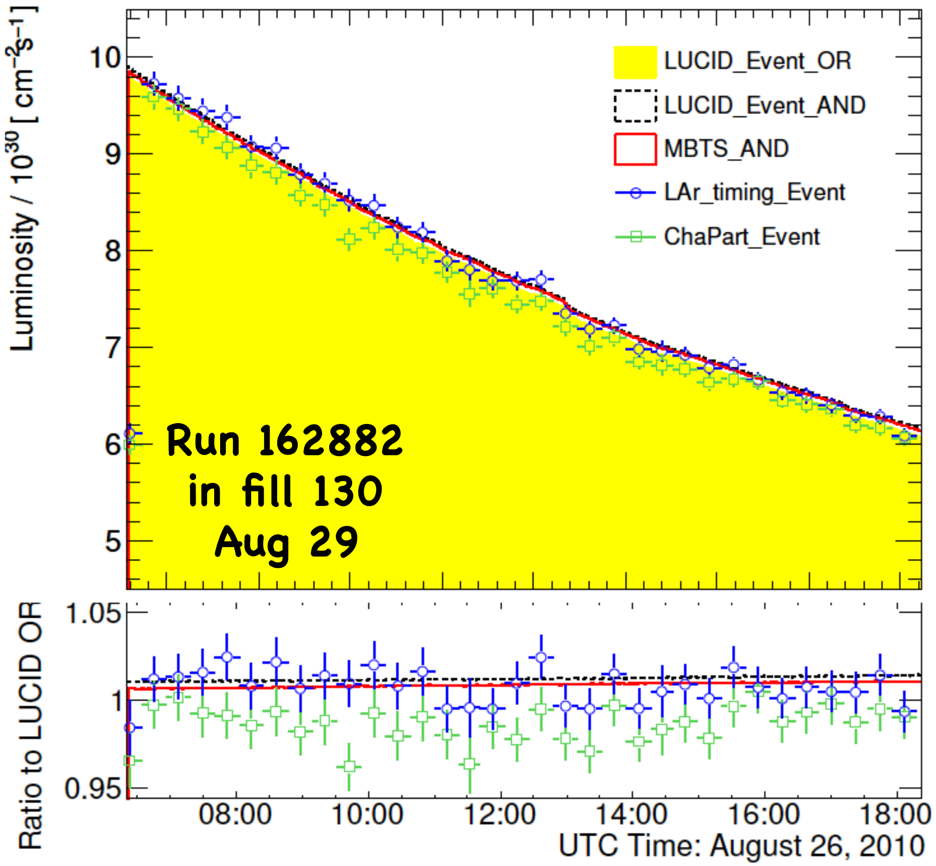
- The first 3 are under study. Indication so far is that all might be ≤ 1%
- Backgrounds are seen from unpaired bunches to be below 0.01% in the vdM fills
- Study on beam shapes just started

# Consistency checks

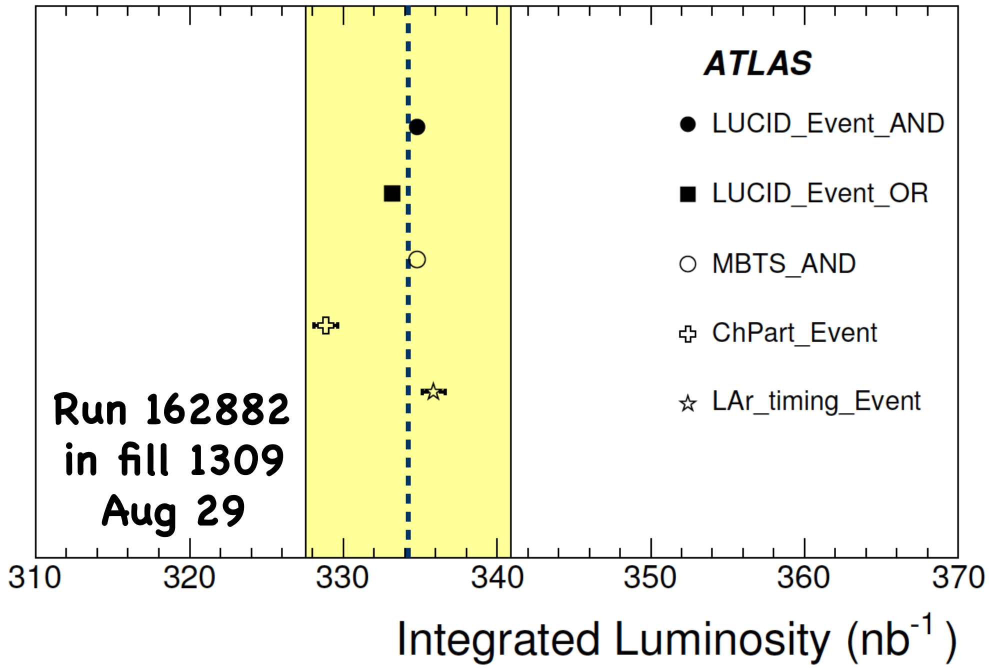
...exploiting our redundancy

## Luminosity analyzed with Apr/May vdM calibrations

**Different detectors track each other within ±2%**



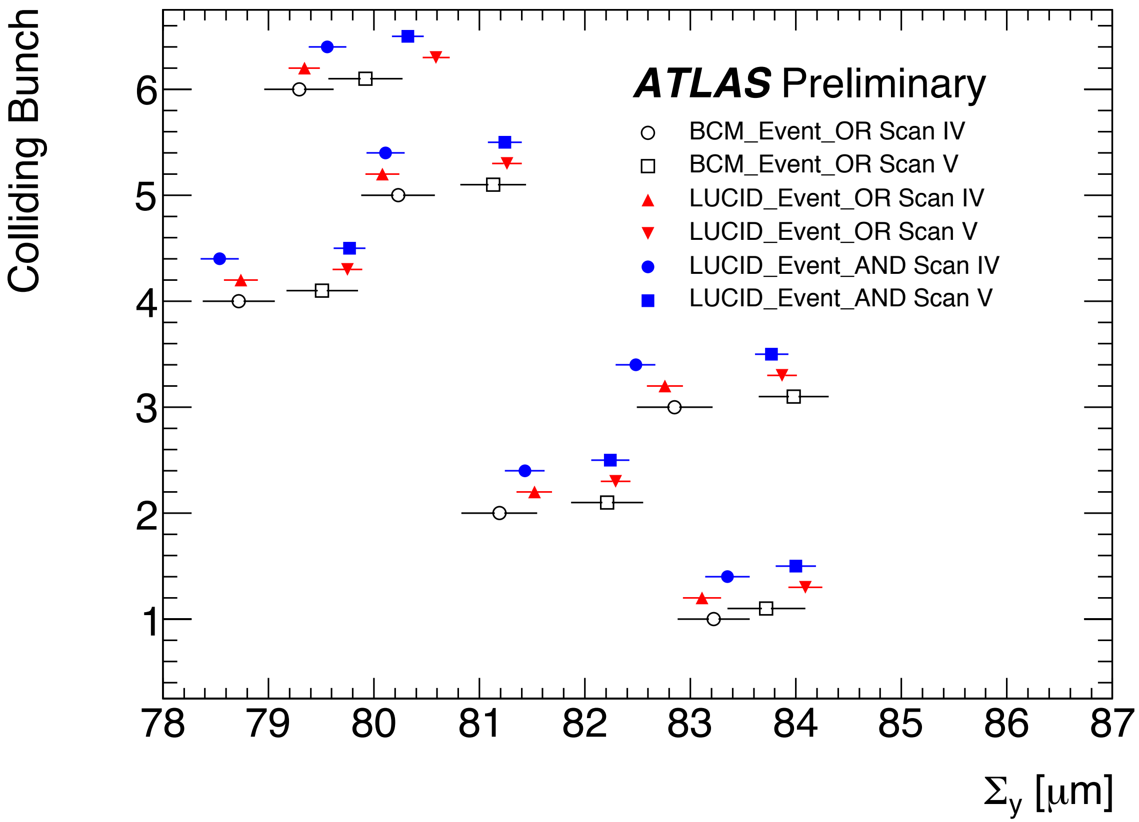

**Integrated luminosities agree within ±2% (shaded band)**



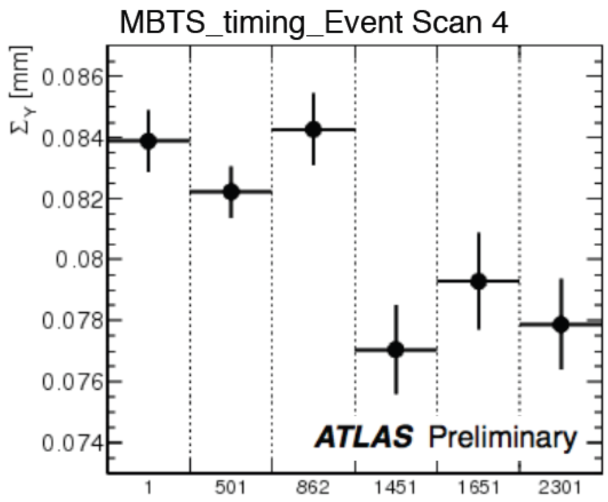
# Comparison of $\Sigma_y$ for various detectors

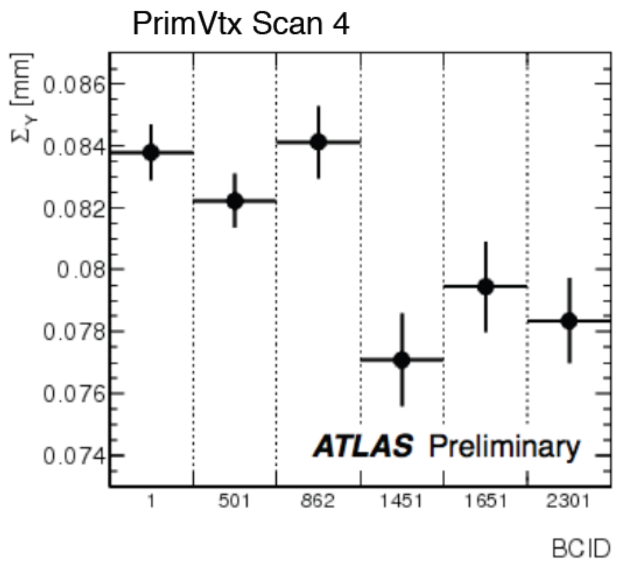
**All analyses done bunch-by-bunch**

## 'Online' methods: LUCID & BCM




## Offline methods

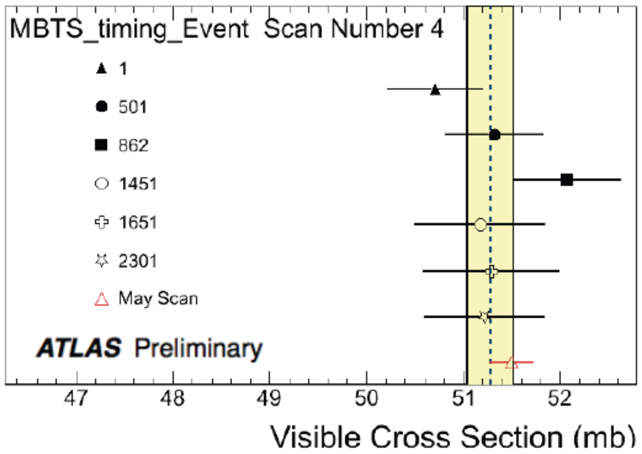


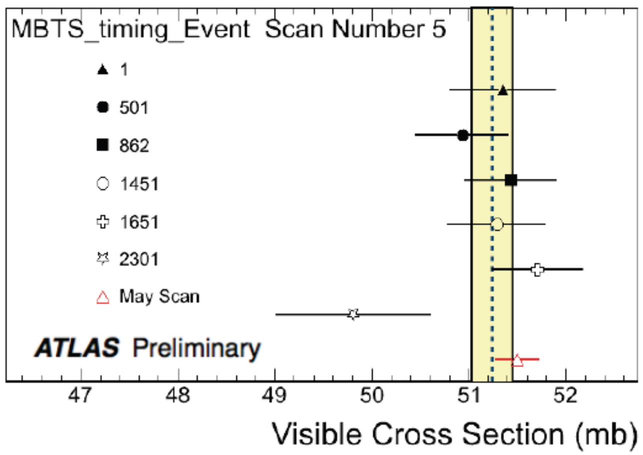




**Very consistent results from all detectors ($\Sigma_x$ not shown, but similar agreement)**

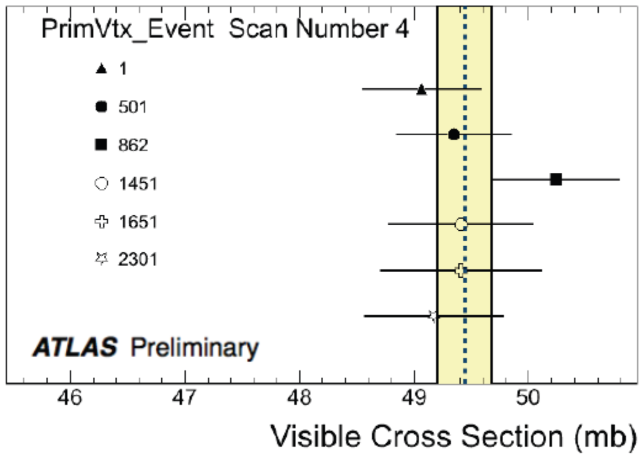
# $\sigma_{vis}$ values per bunch

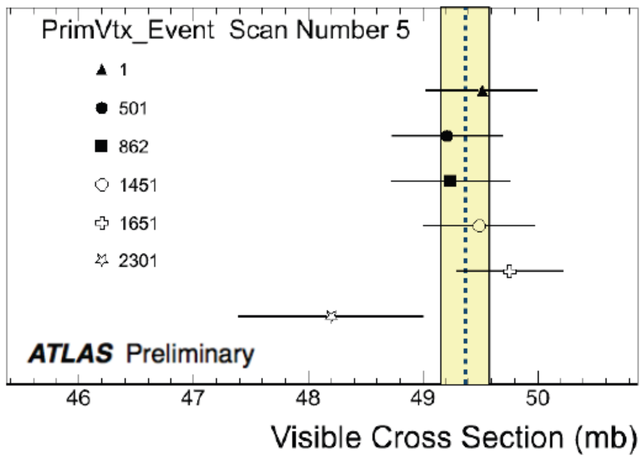
**MBTS_timing: 1 MBTS hit at L1 & MBTS coincidence within 10 ns**




**Primary Vertex: 1 MBTS hit at L1 & PV with ≥ 5 tracks above 150 MeV/c**




**Scans 4&5 agree – another proof that emittance growth cancels from $\sigma_{vis}$**

# Comparison of scans

Using corrected currents for all scans (talk of T. Pauly)

Assuming 5% detector related systematics for all scans
(known to be pessimistic for October scans)

| | Scan 1 (Apr) | Scans 2&3 (May) | Scans 4&5 (Oct) |
|---|---|---|---|
| LUCID-AND | 12.0 ± 0.9 | 12.8 ± 0.9 | 13.1 ± 0.8 |
| LUCID-OR | 39.0 ± 2.9 | 41.3 ± 2.8 | 41.6 ± 2.4 |
| MBTS-AND | 50.4 ± 3.7 | 53.3 ± 3.5 | 54.0 ± 3.1 |
| MBTS-Timing | 48.5 ± 3.6 | 52.2 ± 3.5 | 51.3 ± 3.0 |

Published $\sigma_{vis}$ corrected with values Thilo presented earlier today

Scans 2&3 and 4&5 consistent within << 1 $\sigma$ - another indication that our (5%) detector* systematic is too conservative (or correlated)
(*all except the bunch current)

Scan 1 is lower than the others by ≈1 $\sigma$ systematic

# Prospects & issues for 2011

# Dealing with higher pileup

- Rumor has it that μ might get as high as 10-15 in 2011

  The Event counting verified up to μ~4.5 in 2010 is known to suffer at μ>10 (saturation, migration,…)

  Counting hits in individual detector elements (e.g. LUCID tubes) helps to mitigate these problems. No need for it in 2010.

  We need to fully commission hit-counting with 2010 or early 2011 data (preliminary analysis of Oct vdM data already done for LUCID hit counting)

- Afterglow is expected to become relatively more important at 50 or 75 ns and might motivate to move from 'OR' to 'AND'

- MBTS online luminosity will not work with ≤150 ns bunch spacing

- BCM was fully commissioned as a lumi detector by the October vdM scans. With low efficiency and excellent time resolution it is expected to be a powerful lumi-monitor in 2011 and beyond.

# Scan requests

Just our main points (see talk of J. Panman tomorrow)

**Need a scan similar to the October one early 2011 (esp. if at 8 TeV)**

We do request some dedicated vdM fills in 2011

- Optimum number of colliding bunches ~6 (± few) with large spacing
- Fill can (should) contain well isolated unpaired bunches
- 2 pairs of scans like in October (to check drifts & emittance)
- No strong feeling on $\beta^*$, but need $\mu \approx 2$ for statistics in BCM
- Slight preference to scan with Xing-angle (to mitigate satellites)

Monitoring needs during scans:

- Beam sizes (wire-scans, synch-light, LHCb beam gas)
- Per-bunch intensities (obviously)
- Satellite & ghost intensities (if possible)

# Summing up

# 2010 vdM scans

- 3 scans performed (2 of them double)
- Bunch currents dominated uncertainty (10% of total 11%) until recently
- New current analysis has reduced this significantly – now good hope to get below 5% when analysis completed.
- So far it seems that in the October scans all systematics are well controlled (at percent-level or better)
- Calibrations of all ATLAS luminosity detectors very consistent.
- Very consistent results from bunch-by-bunch analysis
- The first scan is a slight outlier, the May & Oct scans agree very well

The vdM scans gave us good calibrations, but we also need to ensure stability of detector efficiency.
Having more than one luminosity detector is invaluable to diagnose and quantify possible shifts & glitches promptly

# ATLAS luminosity 2010

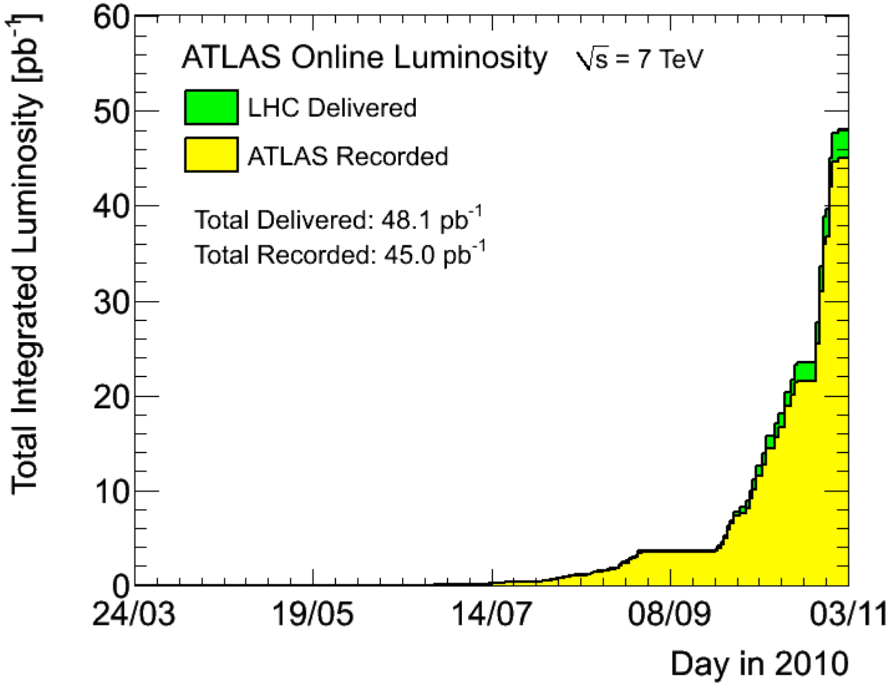
Over the year we used several luminosity monitoring methods

- This redundancy gave use complementarity & confidence
- Ultimately all of them got individually calibrated by vdM
- The measured luminosities are in good agreement, verifying stability of calibrations over time

**So we are confident that our 45 $pb^{-1}$ for 2010 pp is a good measurement**

Final uncertainty to be confirmed.

**Many thanks to the LHC for a MAGNIFICENT job**



# Backup

# Comparison with MC

Our early luminosity was scaled to $\sigma_{inel}$=71.5 mb (PYTHIA 6)

The vdM allowed us to determine $\sigma_{vis}$ (= $\varepsilon * \sigma_{inel}$)

These $\sigma_{vis}$ we can compare with the MC generators