Luminosity Calibration at ATLAS in 2011

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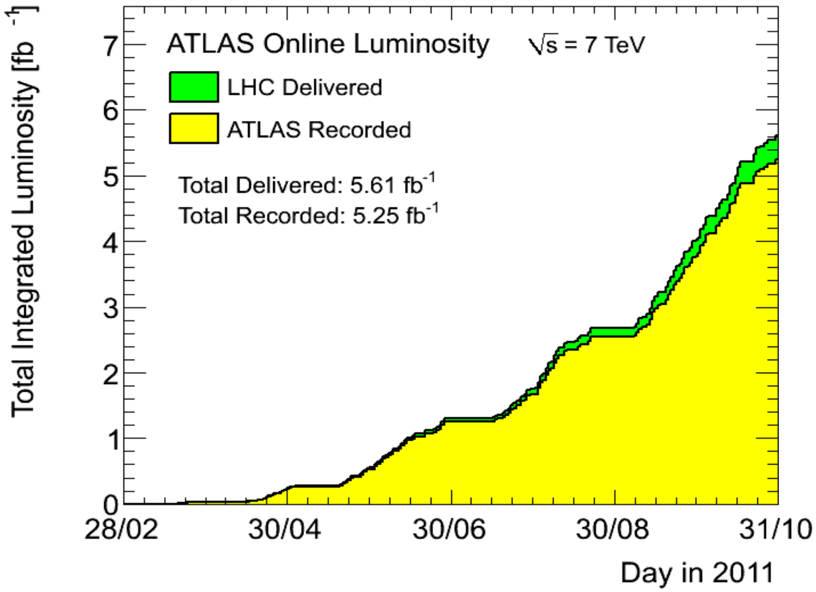
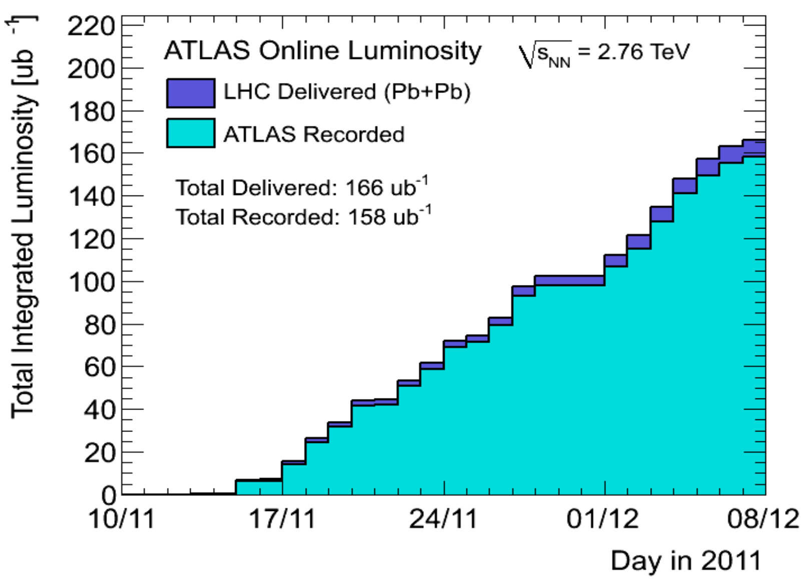
Lumi Days Workshop 1st March 2012

Outline

- Introduction
- 2011 7TeV Proton-Proton Calibration
- Luminosity for Other Running Conditions in 2011
- Plans and Requests for 2012
- Summary

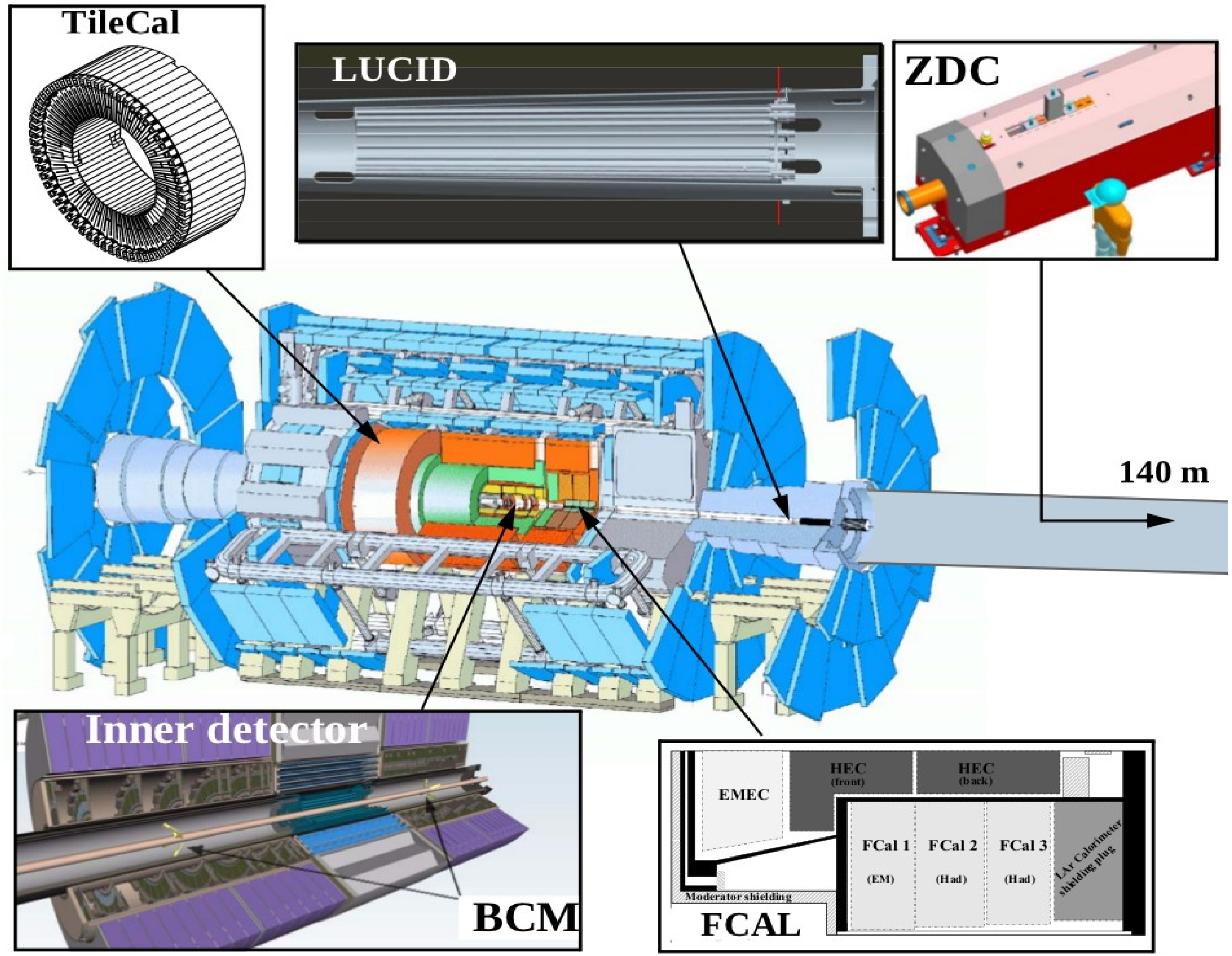




Introduction

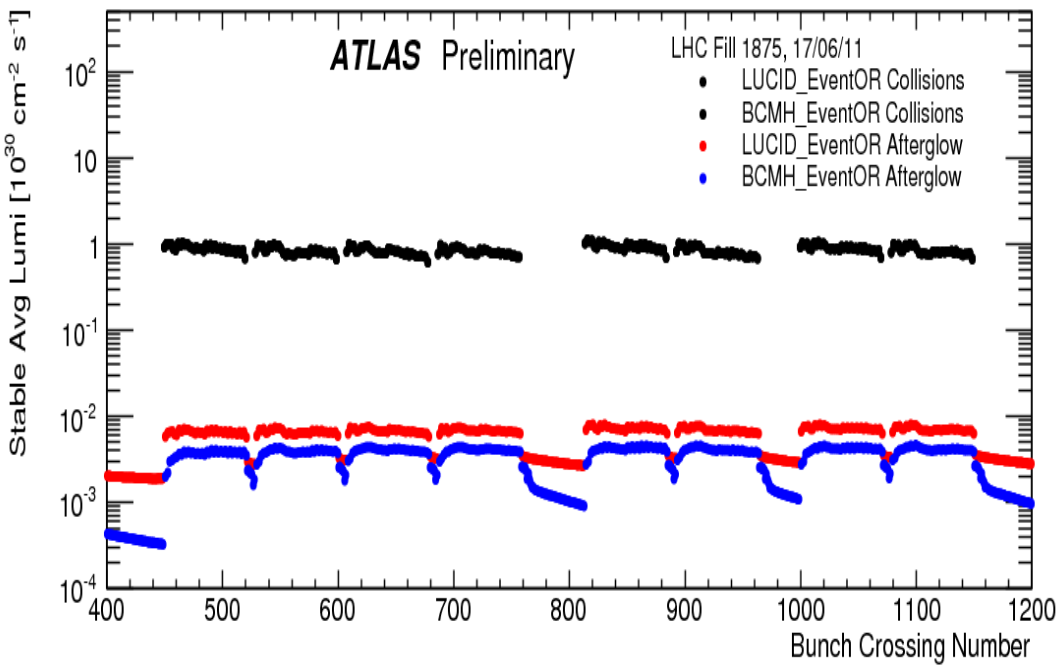
Detectors and Algorithms in 2011

- Bunch by bunch
  - BCM
    - Evt OR,AND
    - Separate measurement from H/V modules
  - LUCID
    - Evt OR,AND,A,C
    - Hit OR
  - ZDC (HI only)
    - Evt Incl OR A & C
  - Vertex methods
    - Evt & vtx counting
- BCID-blind
  - FCal (forward LAr)
    - Gap currents
  - TILE cal
    - PMT currents



Redundancy essential for assessing long term stability & μ dependence

Physics Running in 2011



- LHC page 1 & ATLAS control room preferred algorithm
  - Insensitive to bkgd & afterglow
  - Linear for physics pileup conditions
  - Sufficient statistical sensitivity
  - 2011 7TeV pp was BCMH_EvtAND
- Offline (physics analysis) preferred algorithm
  - Best absolute luminosity determination
  - 2011 7TeV pp was BCMH_EvtOR

- 'Afterglow' in physics running
  - Collision induced radiation >> instrumentation
  - Proportional to inst. lumi
  - ~1% for LUCID_EvtOR
  - ~0.5% for BCMH_EvtOR
- Level inferred from activity in adjacent empty BCIDs
  - Stable level across train
  - Subtracted with precision of 0.2%

Algorithm	$\varepsilon = \sigma_{vis}/\sigma_{inel}$
LUCID_EvtOR	59.5 %
LUCID_EvtAND	18.8 %
BCMH_EvtOR	6.6 %
BCMH_EvtAND	0.2 %

Hit counting commissioned for LUCID in preparation for 2012 <μ>

van der Meer Scan Overview

- Scan Sequence
  - Initial horizontal followed by vertical scan
    - Recentering after scan (usually unnecessary)
  - Second horizontal followed by vertical scan in same fill
    - Check reproducibility of key luminosity variables
    - Essential for evaluation of beam dependent systematic uncertainties

$$L = \frac{f_r}{\sigma_{vis}} \sum_{i}^{n_b} \mu_{vis}^{i}$$

Derive algorithm calibration constant σ_{vis}

$$\Sigma_\delta = \frac{1}{\sqrt{2\pi}} \frac{\int \mu_{vis}^{sp}(\delta)\, d\delta}{\mu_{vis}^{sp}(0)}$$

Calculated analytically or numerically depending on scan curve fit method

Algorithm dependent →

$$\sigma_{vis} = 2\pi \Sigma_x \Sigma_y \left(\frac{\mu_{vis}}{n_1 n_2} \right)_{\delta=0}$$

← $\mu_{vis}^{sp}(0)$

Algorithm independent →

$$L_{sp} = 10^{22} (\mathrm{p/bunch})^2 \frac{f_r}{2\pi \Sigma_x \Sigma_y}$$

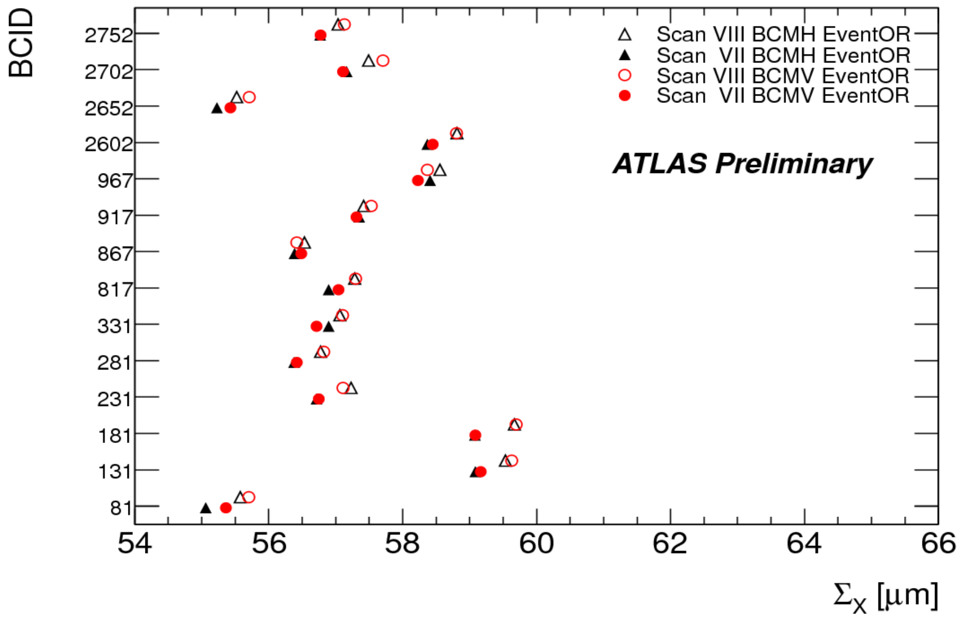
vdM Calibrations Analysed in 2011

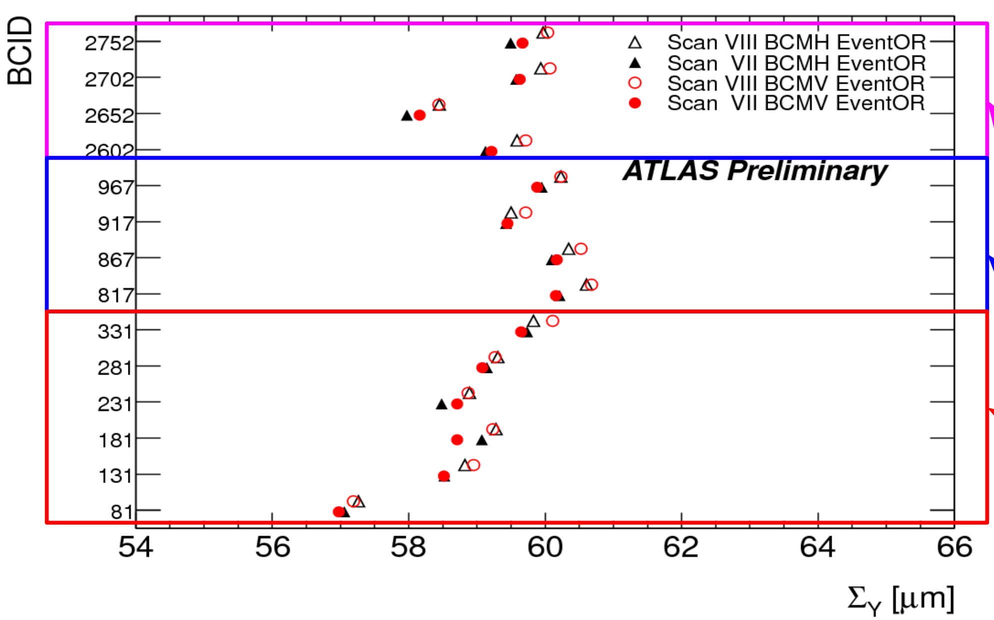
	2010 PbPb	2.76TeV pp	7TeV May	Fill lost (7TeV Oct)	2011 PbPb
LHC Fill(s)	1533	1653 & 1658	1783	N/A	2337
Paired Bunches	113	64 (sans pilots)	14	N/A	344
Peak μ	$1.4\text{x}10^{-4}$	0.36	2.3	N/A	$6\text{x}10^{-4}$
β*	3.5m	11m	1.5m	N/A	1m
Length scale calibration	done	yes	yes	N/A	yes
Calibrated	LUCID, BCM, ZDC	LUCID, BCM, Vtx	LUCID, BCM, Vtx	N/A	LUCID,BCM, ZDC, Vtx
Status	Ongoing	Ongoing	Being finalised for publication	N/A	Ongoing

- Focus in ATLAS has been on the May 7TeV pp scan and long term stability of this calibration
- With reduction in bunch current uncertainties, systematics at sub-percent level become important and must be exhaustively evaluated

7 TeV Proton-Proton Calibration

May 2011 7TeV pp Scan



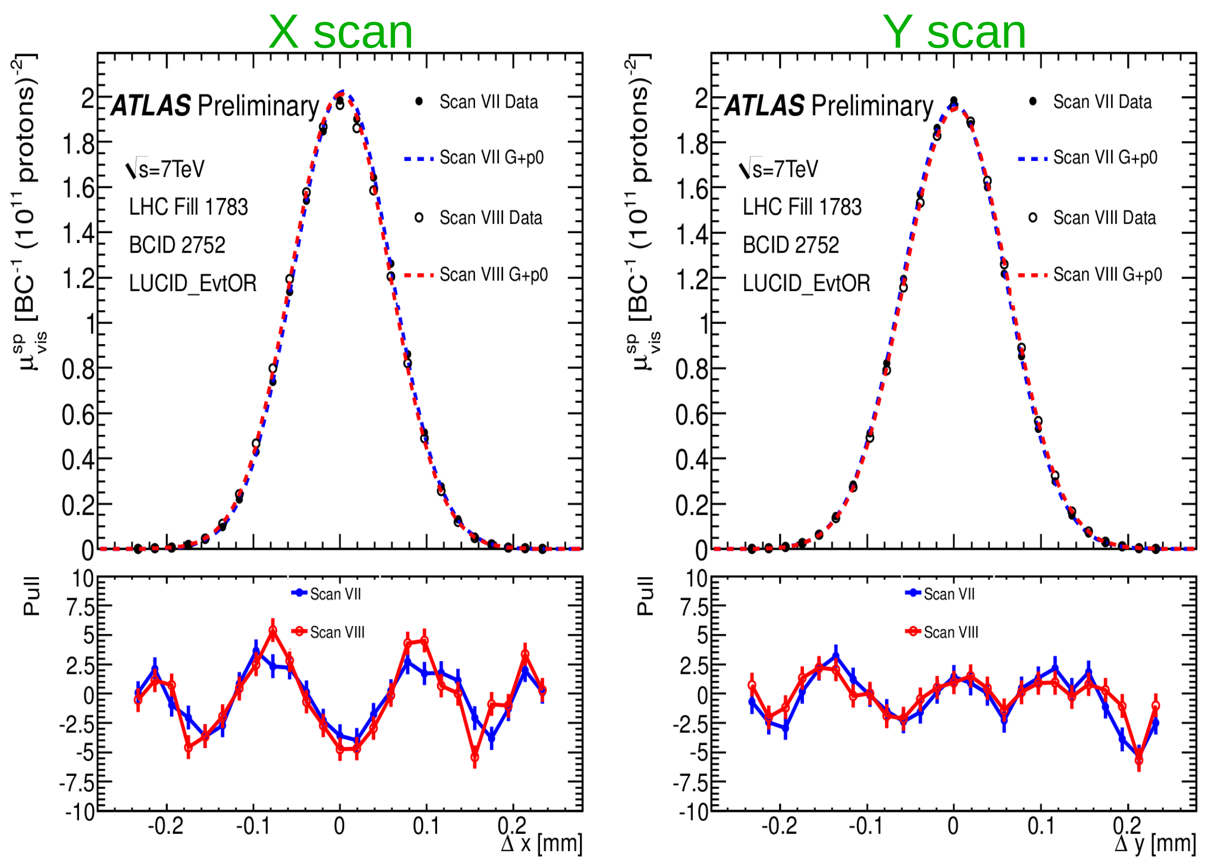


- Only precision 7TeV calibration in 2011 for ATLAS
- 14 colliding bunches
  - Beam size and bunch current product vary 10-20% bunch to bunch
  - Determine σ_{vis} for each colliding bunch
- Moderate emittance growth between scans
- Fill had additional pair of x-y scans with offset of 3Σ in non-scanning plane
  - Constrain x-y coupling
  - Analysis on-going, not presented here

BCIDs	Collide At
2602, 2652,2702, 2752	IP1, IP5 & IP8
817, 867, 917, 967	IP1, IP5 & IP2
81, 131, 181, 231, 281, 331	IP1 & IP5

Scan Curve Interpretation

- 2010 vdM data well described by sum of 2 Gaussians & constant term
    - Constant then interpreted as background from beam gas
- 2011 data favours single Gaussian component only
- Rates can be corrected for background
    - Beam gas from unpaired bunches
    - Noise & afterglow from adjacent empty bunches
- Fit to background corrected data can still have statistically significant constant component
    - 2nd Gauss with $\sigma \rightarrow \infty$?
    - Must be included in evaluation of luminosity observables

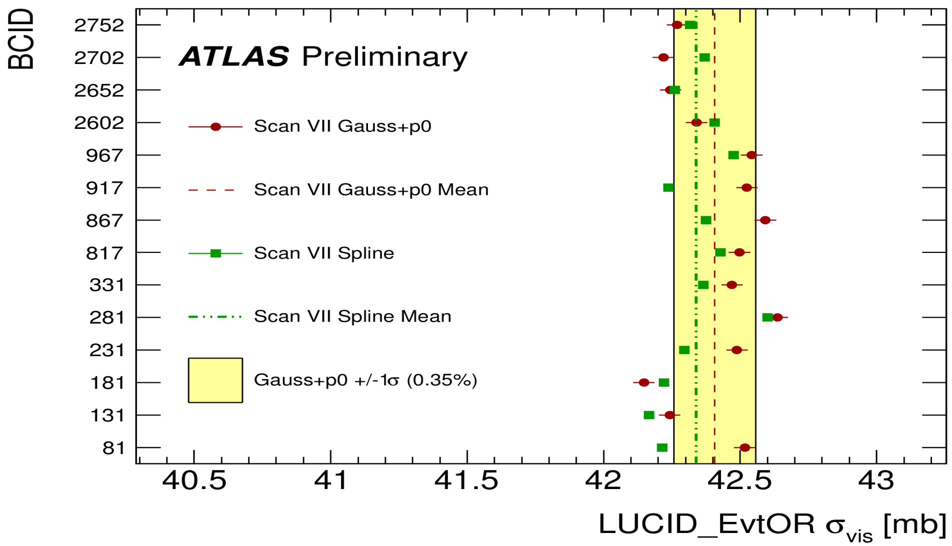


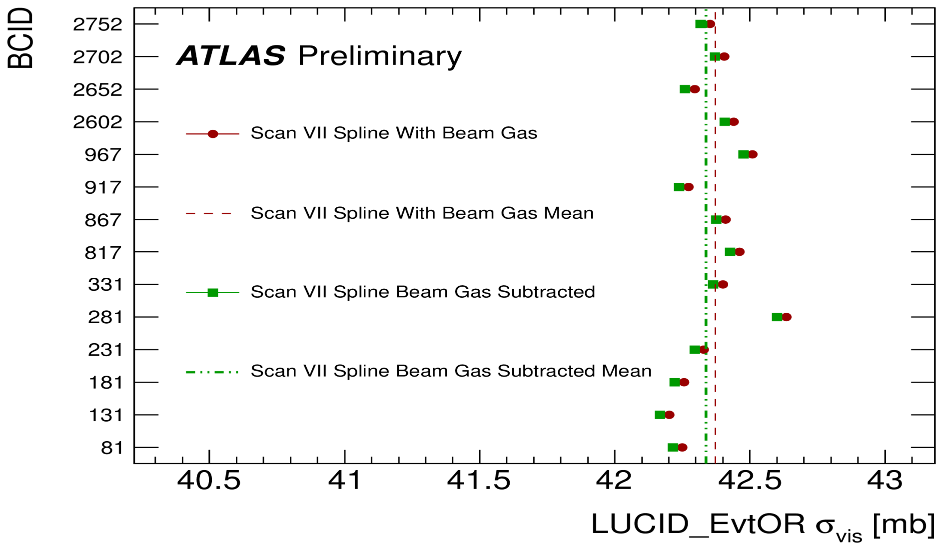
Gauss+p0 fit quality suffers in some BCIDs due to non-Gaussian beam profile component particularly in horizontal plane

Scan Curve Fit Model

REMINDER: σ_{vis} should be identical for all BCIDs

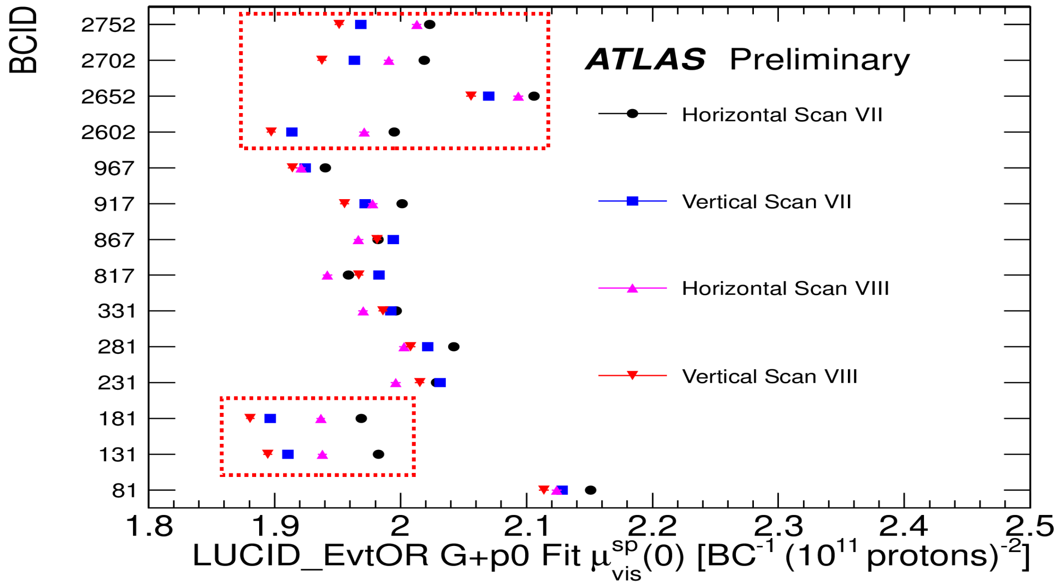
- Refit data with alternative models
  - Cubic spline
  - Gauss+p0 fit to background subtracted data
    - p0 included in Σ & $\mu_{vis}(0)$
  - Gauss+p0 fit to uncorrected data
    - p0 as background
- Largest deviation in means for any one algorithm/scan assigned as fit model systematic (0.3%)

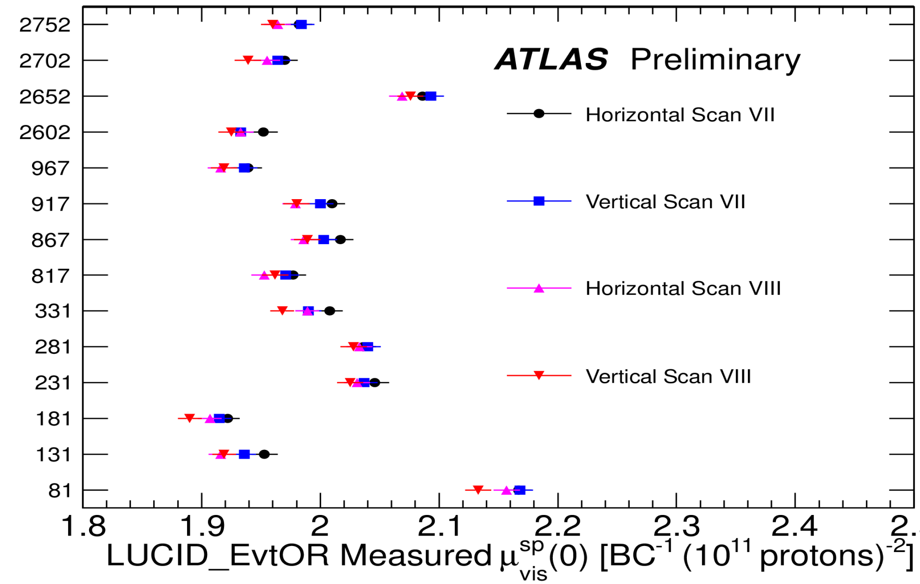




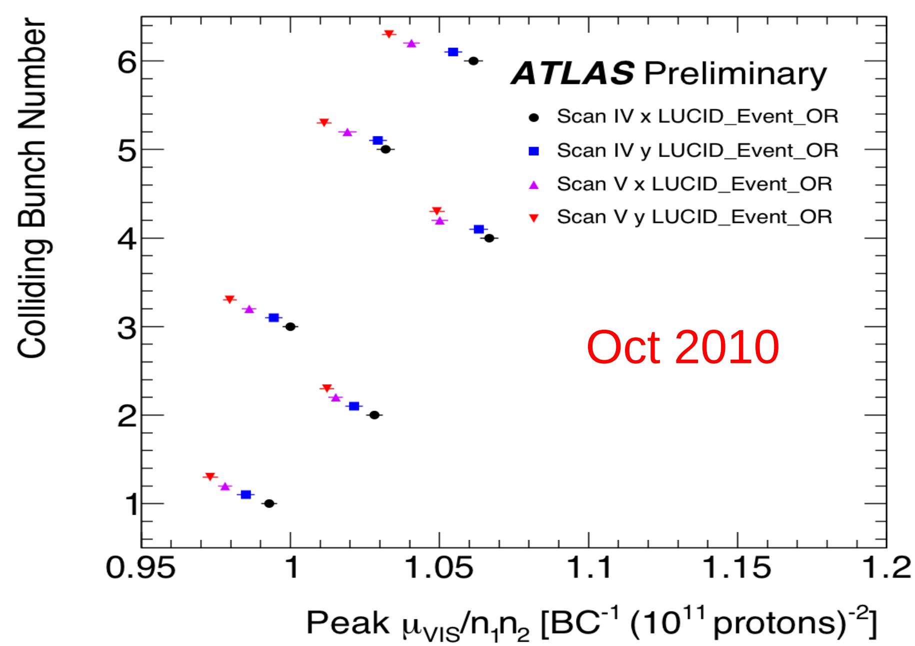
Statistical uncertainties for spline method (0.3-0.4%) not shown here

Scan Curve Model (Aside)

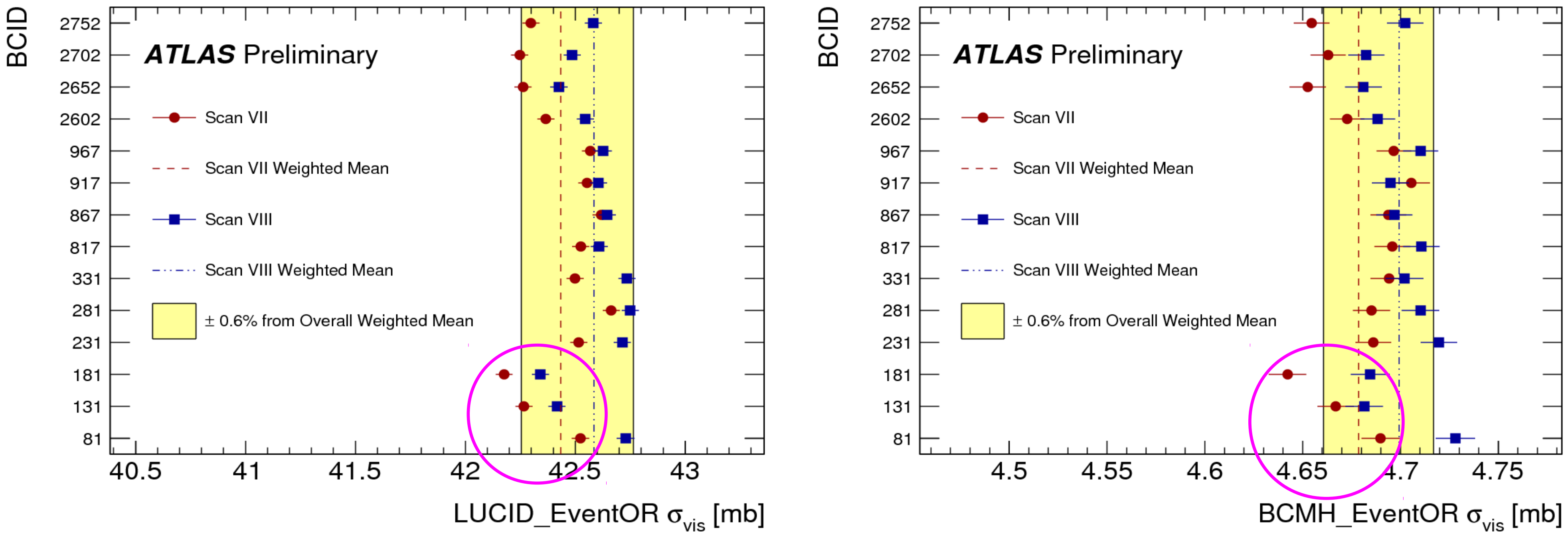




- Fitted peak μ_{vis} values violate expected chronology for some BCIDs
  - Correlated to fits with poor χ^2 (significant non-Gaussian pulls)
  - Measured peak ok within statistics
    - Hence spline fit too
- Effect not observed in 2010 scan data

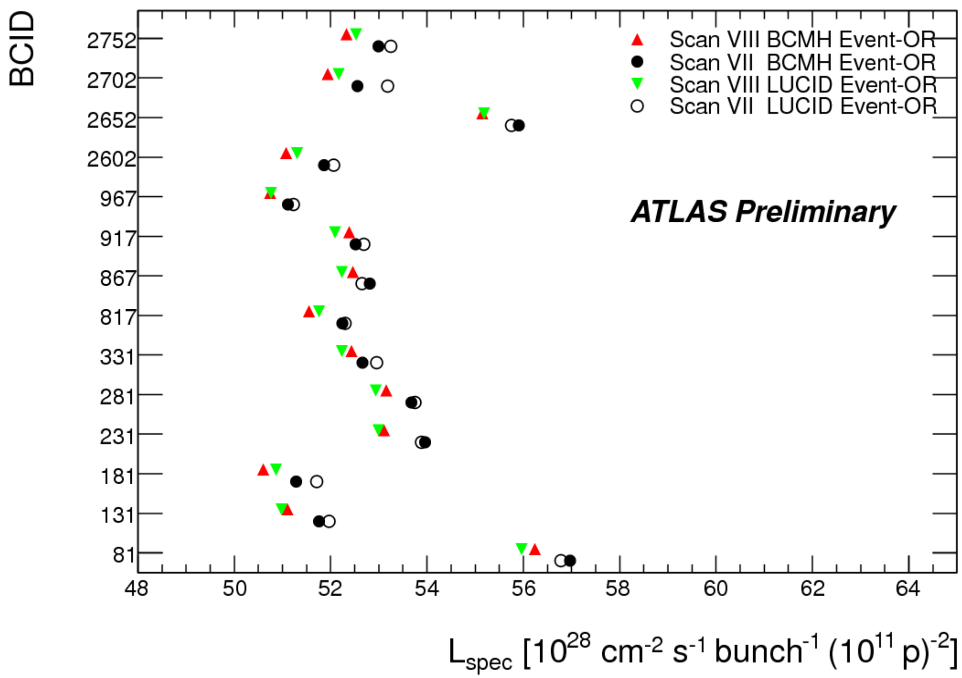


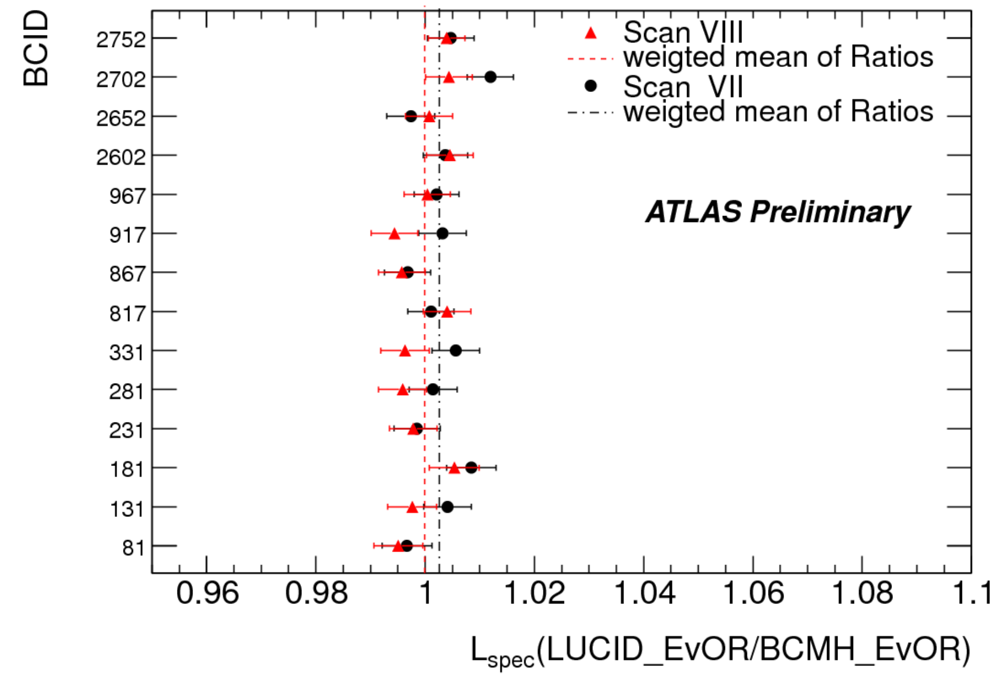
Bunch by Bunch Calibration Consistency



- Independent algorithms (same fit) show correlated systematic spreads within a scan
  - Bunch by bunch spread of σ_{vis} values taken as consistency systematic (0.55%)
- Difference between scan VII & scan VIII mean interpreted as emittance growth and other non-reproducibility
  - Largest difference for any one algorithm assigns overall systematic (0.8%)

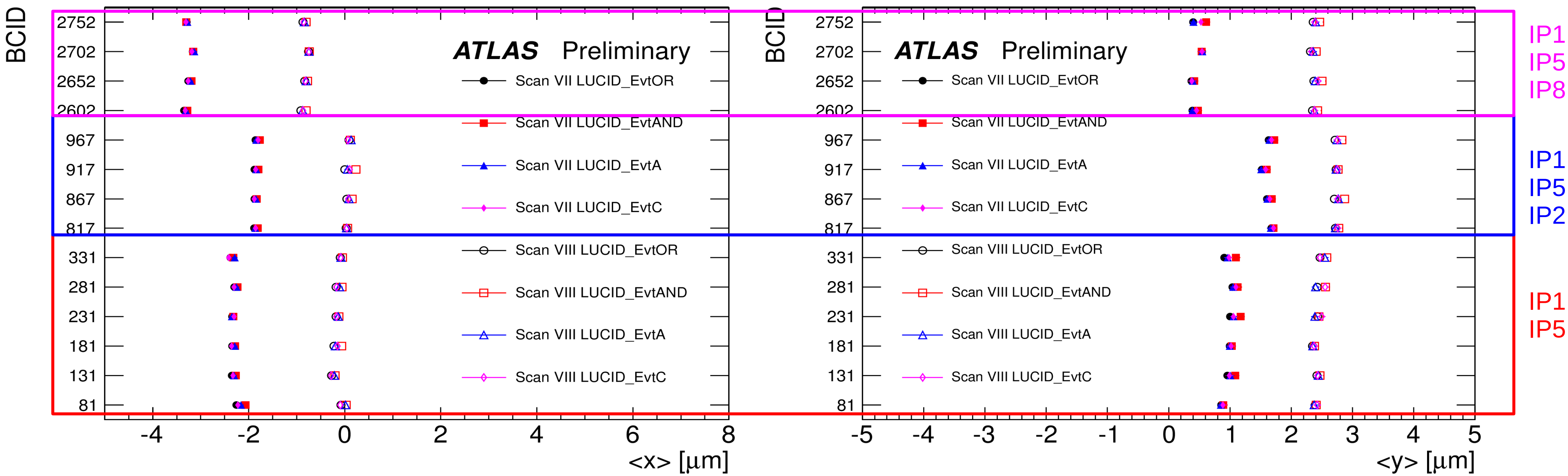
L_{sp} Consistency





- Comparison of L_{sp} between LUCID and BCM algorithms shows good consistency
  - Difference in L_{sp} bunch by bunch reflects different beam overlap profiles
  - Largest difference in ratio to 1 taken as systematic uncertainty of 0.3% on $\Sigma_x \Sigma_y$ product & hence σ_{vis}

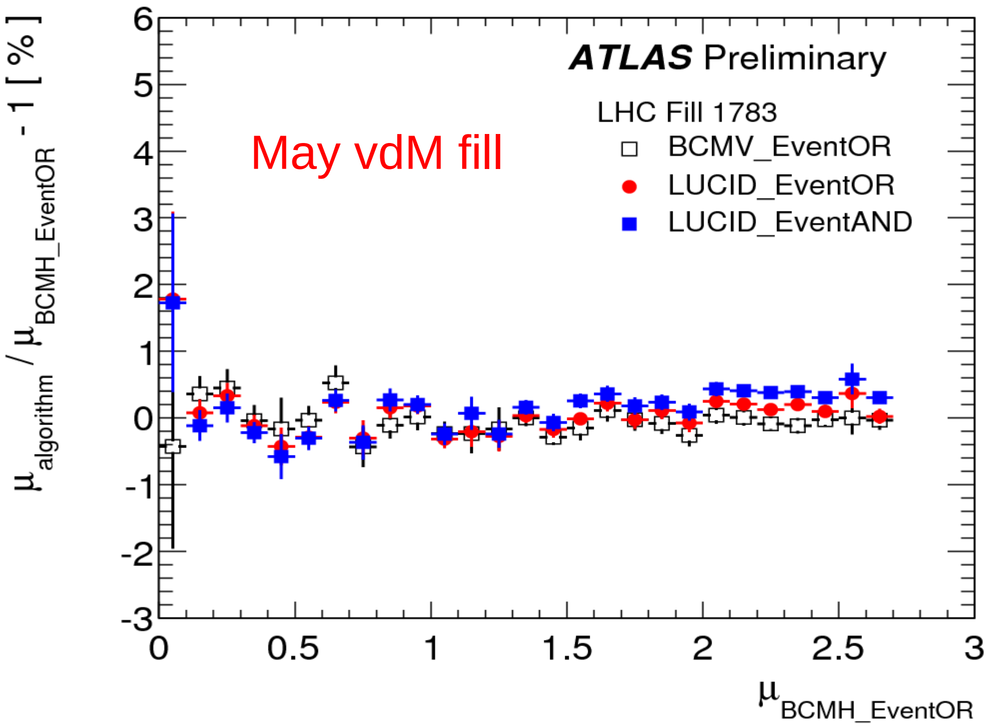
Beam Recentering

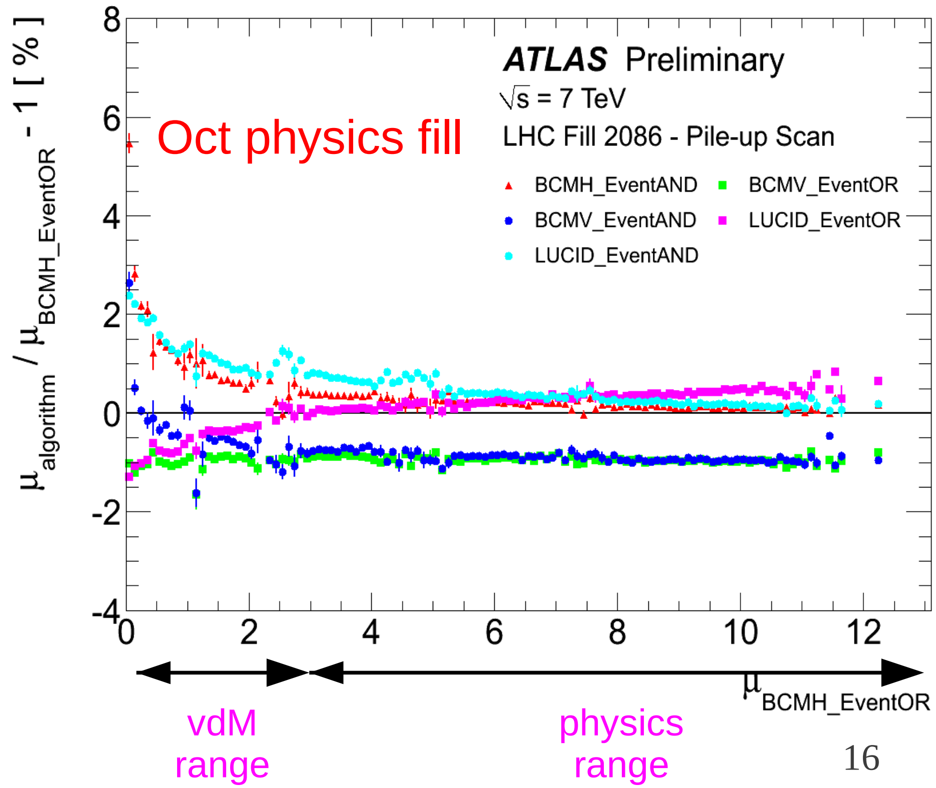


- Observe up to 2 micron non-reproducibility in fitted peak position
  - NB. Beams not recentered between scans
  - Observed effect larger at larger β*; should scale as sqrt(β*)
  - Affects estimate of μ_{vis} at peak, impact on σ_{vis} is 0.1%
- Visible systematic difference depending on cross-talk with other IPs

μ Dependence & BCMH vs BCMV

- In vdM fill algorithms consistent across μ range to 0.5%
- Under physics conditions BCMH & BCMV show ~0.7% discrepancy
  - Instrumentation effect not currently understood
    - Diamond charge pumping?



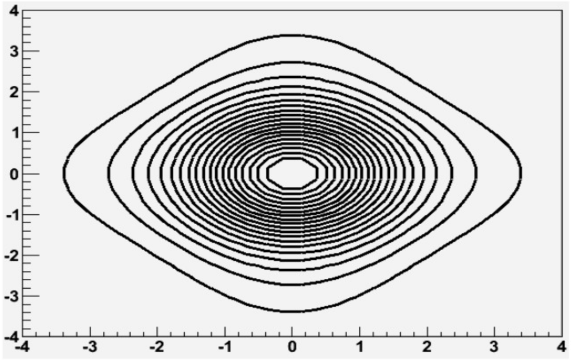


Non-Linear Correlations

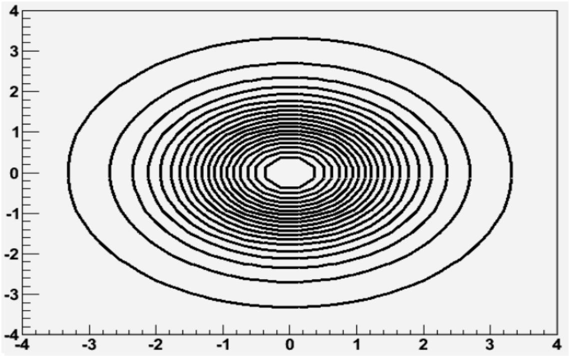
- Do beam overlap profiles transversely factorise?
  - NB. Not linear x-y coupling
- ATLAS use 'pessimistic' correlated sum of 2 Gaussian as alternative fit
  - Model arbitrary; effect if any fill dependent
- Potential for vertex imaging of luminous region to address this in future
  - Requires larger β* (11m) to allow sufficient resolution of beam overlap region

vdM Scan	Uncertainty
April 2010	3%
May 2010	2%
Oct 2010	0.9%
May 2011	0.5%

Reminder: 2010 data exhibited 2^{nd} Gaussian component not seen in 2011

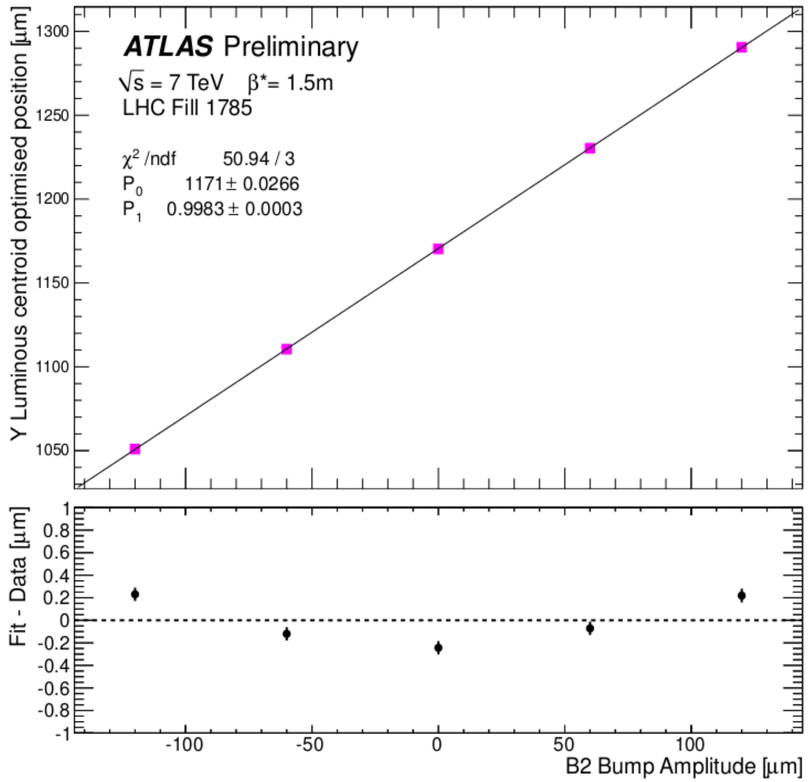


VS.



Length Scale Calibration (β^*=1.5m)

- σ_{vis} relies on LHC nominal separation determined by 4 closed orbit bumps
- Scale checked with dedicated scan:
  - Move one beam by nominal amount
  - Follow with other beam & scan around 1st beam to find maximum
  - Beamspot position at peak calibrates nominal movement of 1st beam
  - Repeat to extract four calibration constants
- In vdM scan beams moved simultaneously in opposite directions
  - Overall separation scale is average of two beams in given plane
- Calibration uncertainty of 0.3%
  - Non-linear residuals observed at ~0.2 micron level



Scale	Horizontal	Vertical
Beam 1	-1.0010±0.0004	+0.9955±0.0003
Beam 2	-0.9981±0.0003	+0.9983±0.0003
Separation	-0.9996±0.0003	+0.9969±0.0002

7TeV vdM ATLAS Uncertainties

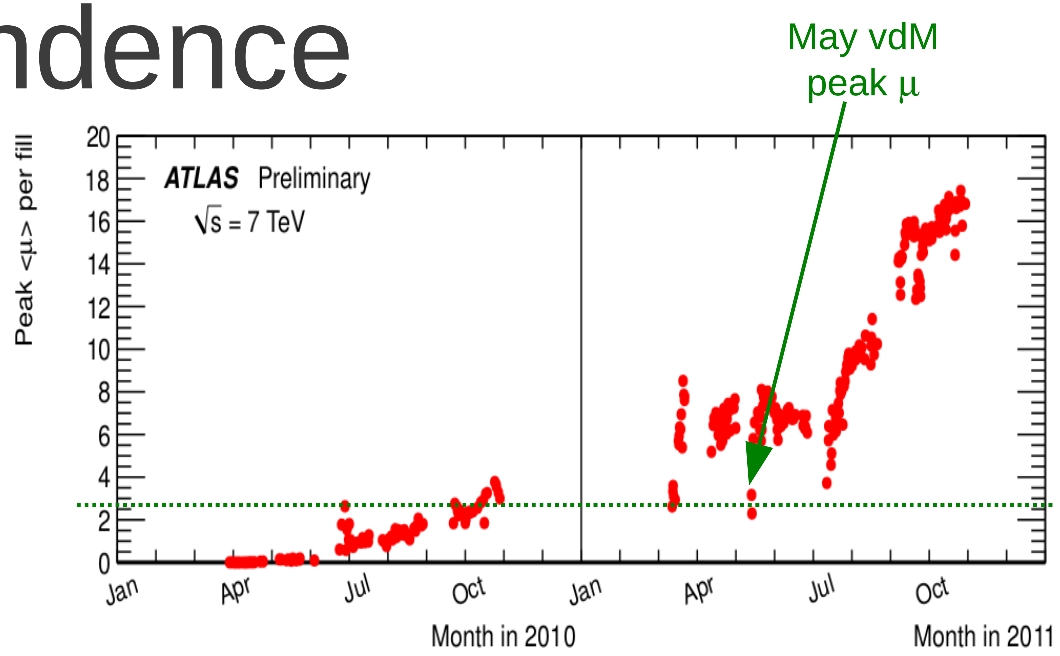
	ATLAS-CONF-2011-117 (Aug 2011 2/fb)	2011 5/fb projected	2012 projected	Comment
Beam centering	0.1	0.1	Measured in scan	Fill dependent
Beam jitter	0.3	0.3		
Non-reproducibility	0.4	0.8	Measured in scan	Fill dependent
Bunch consistency	0.4	0.5	Measured in scan	Fill dependent
Fit model	0.8	0.3	Measured in scan	Fill dependent
Bkgd subtraction		0.3	Measured in scan	Fill dependent
Reference L_{sp}		0.3	Measured in scan	Fill dependent
Dynamic beta		0.8		Collisions at IP1 only
Non-linear correlations	0.5	0.5	Measured in scan	Fill dependent
μ-dependence in scan	0.5	0.5	Measured in scan ~2011?	
Length scale calibration	0.3	0.3		Depends on β^*
Inner det. Length scale	0.3	0.3		
BCM H/V consistency	0.7	0.7	?	
Total vdM uncertaity	1.5	1.75	~2011?	Without beam current

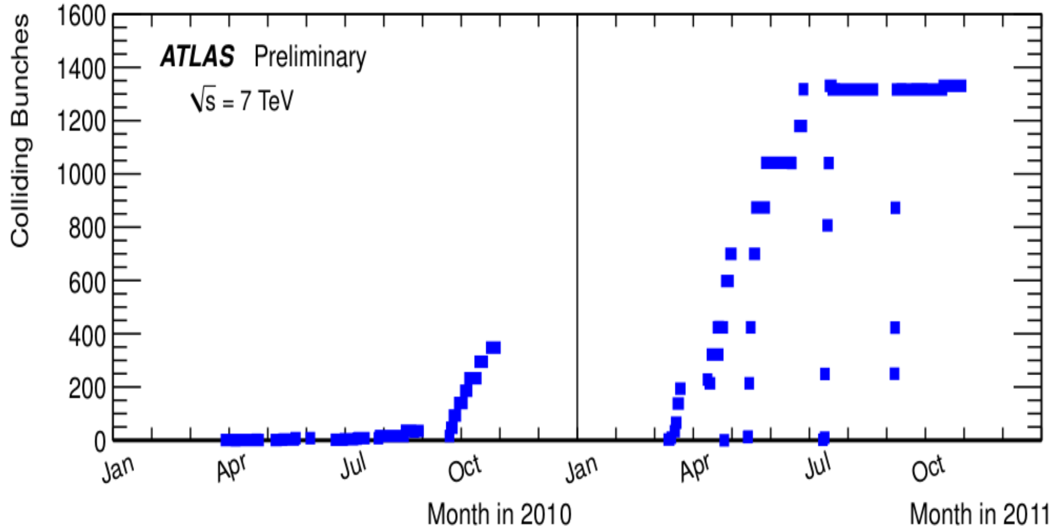
Fill dependent uncertainties will be uncorrelated between 7TeV (2011) and 8TeV (2012)

5/fb UNCERTAINTY ANALYSIS BEING FINALISED
THESE NUMBERS PRELIMINARY & SUBJECT TO CHANGE

Long Term Stability & μ Dependence

- vdM determines σ_{vis} at single point in time with peak μ~2.5
- Must confirm algorithm (μ_{vis}/μ) stable over time and for μ range of physics running
- ATLAS strategy is to partially separate the 2 effects
  - Scan significant range of μ in single LHC fill
    - Algorithm stability in μ at single point in time
  - Investigate μ dependence for all 2011 physics running 7TeV pp data
    - Algorithm stability in μ for conditions across the year

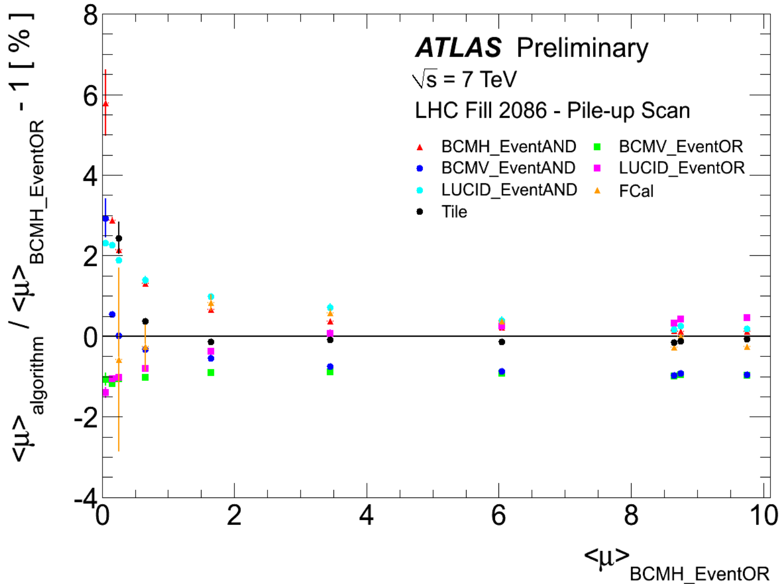


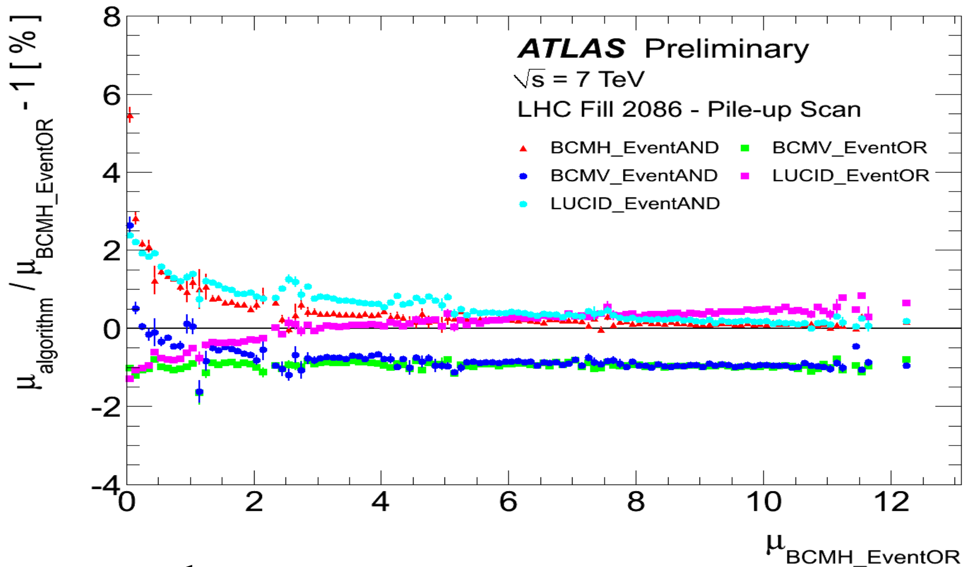


Luminosity From Calorimeters

- FCal (gap current) and Tile (PMT current) calorimeters have response proportional to luminosity
  - Calibrating relative response to known luminosity algorithm at specific time & μ allows extrapolation to other times & μ
- Tile is calibrated to LUCID_EvtOR at peak μ of May vdM fill
- FCal is calibrated to BCMH_EvtOR in dedicated physics fill scanning across μ
- For 2011 cross-calibration of LUCID & BCM to calorimeter methods proved essential in addressing initial discrepancies observed after winter shutdown

Scan in Single Physics Fill





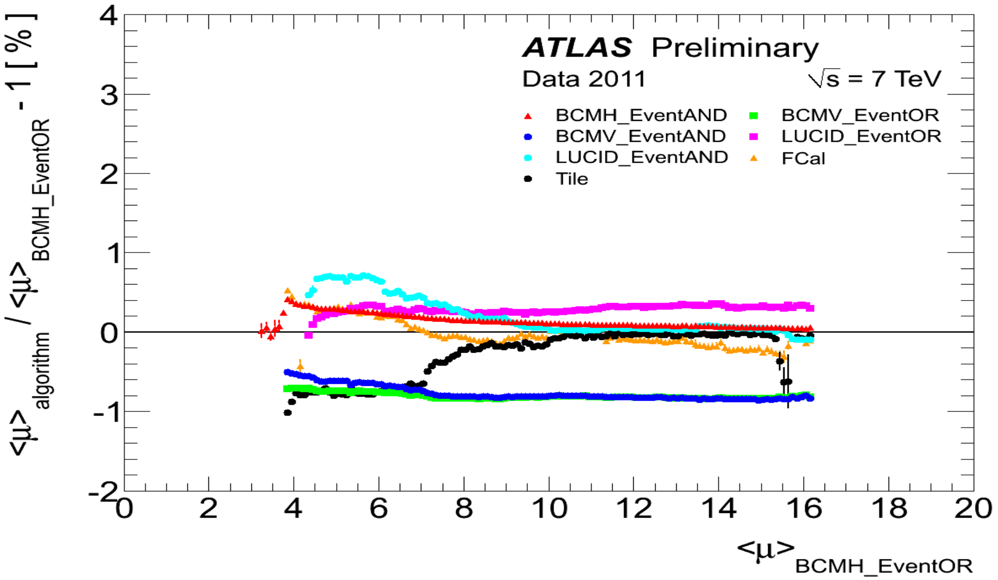
Beams Separated ⟷ Beams Centered

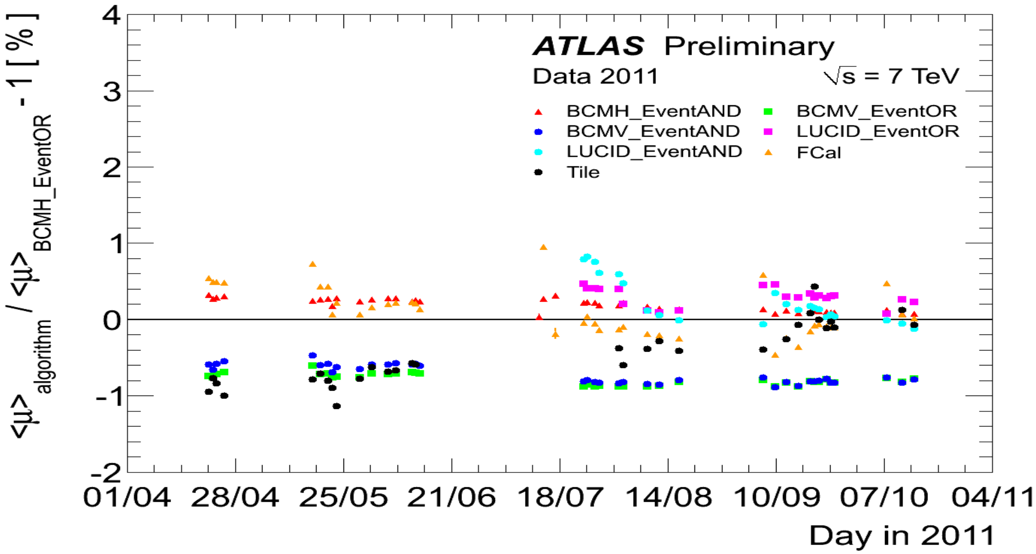
Notation: <μ> is average μ for an algorithm over all bunches

- LHC Fill 2086 beams separated at IP1 then recentered
  - Effectively samples wide range of μ
    - Peak μ~12
  - FCal calibrated to BCM in this fill
    - Observe residual non-linearity
- Comparison between BCM, LUCID & Tile suggests consistency across physics μ range (2-12) of 1%
- AND algorithms diverge at $\mu < 2$
  - Imperfect background subtraction in the region it becomes important
  - Subject of investigation, plot likely to change in this region

Long Term Stability

- Can check relative variation of <μ> between algorithms for all 2011 7TeV pp data
- See no deviation beyond 1%
  - Assign this as uncertainty in addition to previous μ dependence
- Work ongoing to add vertexing algorithms to these μ dependence studies
  - Pileup scan in particular





Full 2011 7TeV Uncertainty Table

	ATLAS-CONF-2011-117 (2/fb Aug 2011)	5/fb projected	2012 projection	Comment
DCCT	2.73	0.23		
FBCT	1.30	0.20		
Ghost charge	0.18	0.18		
Total BCP	3.0	0.35	~2011?	Thanks to BCNWG!
Total vdM	1.5	1.75	~2011?	
Total σ_{vis} uncertainty	3.4	1.8	~2011?	
Long term stability	1.0	1.0	~2011	Detector aging in 2012?
μ-dependence in physics running	1.0	1.0	~2011	Larger μ range for 2012
Afterglow subtraction	0.2	0.2		
Total monitoring	1.4	1.4	~2011	Unchanged from summer despite more data & higher μ values
Total 2011 7TeV pp	3.7	2.3	~2011?	

No reason why 2012 would be worse than 2011 but much depends on what the data looks like!

For the most part (vdM & monitoring) 2011 and 2012 uncertainties will be uncorrelated

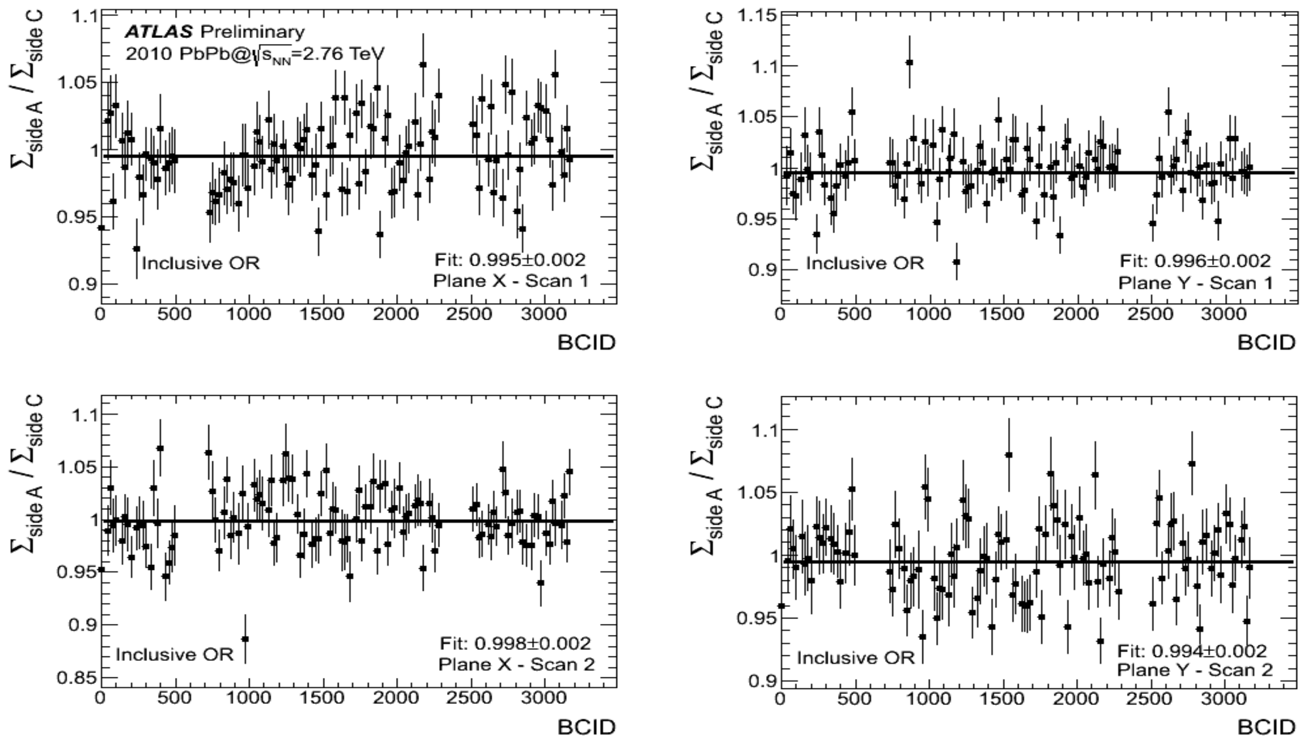
5/fb UNCERTAINTY ANALYSIS BEING FINALISED

THESE NUMBERS PRELIMINARY & SUBJECT TO CHANGE

Luminosity for Other Running Conditions in 2011

Pb-Pb Scans

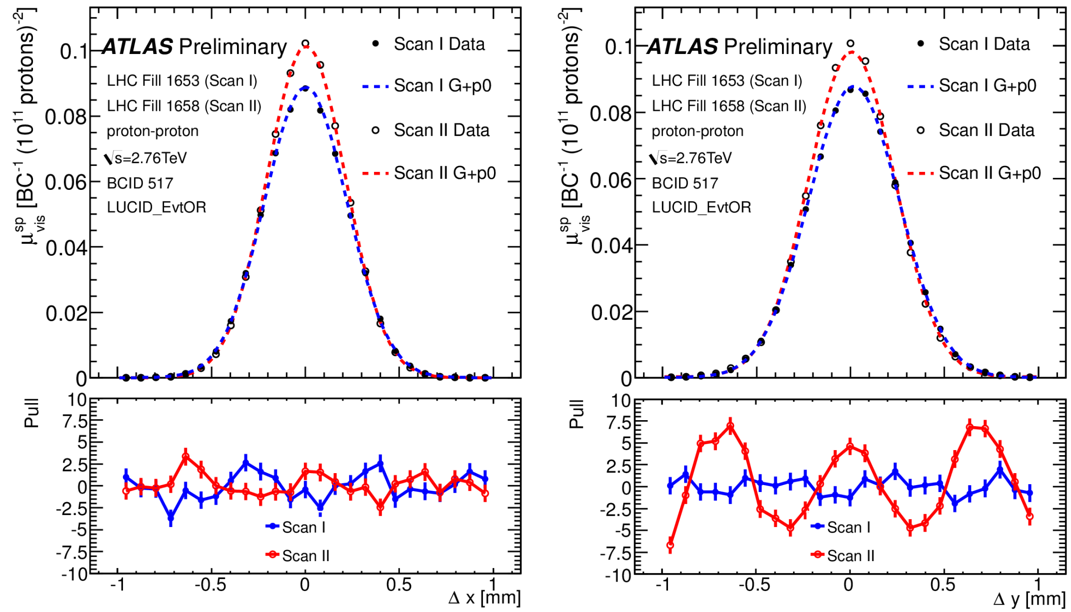
- Both 2010 and 2011 vdM scan analyses maturing
  - Uncertainties to be evaluated
    - DCCT, FBCT
    - Satellites, ghost charge
    - Background
    - 2-4% inconsistencies between algorithms under investigation

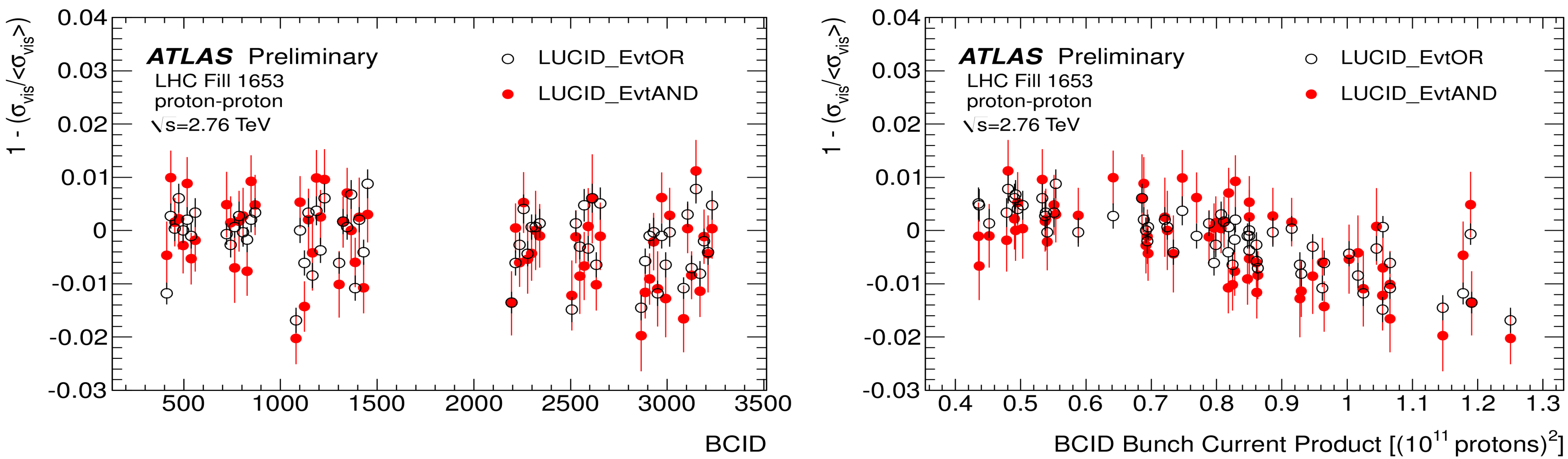


Nov 2010 PbPb preliminary analysis shows reasonable agreement between ZDC A & C side algorithms for beam profile determination

March 2.76TeV pp Scan

- Beam dump between scans leads to complications in reproducibility
  - Different Σ
  - Vertical beam profile changes significantly between fills
- Preliminary investigation of scan I with LUCID Evt algorithms only





Bunch by bunch consistency in scan I is ~1-2%; Partially explained by BCP offset

Limits in Understanding at Low μ

- Relevant to ALFA run luminosity determination
  - μ~0.03-0.04, β*=90m
- Preliminary investigation suggests large difference in algorithms relative to BCMH_EvtOR over the range of μ
  - Apparent residual spread of BCMV_EvtOR, LUCID_EvtOR, LUCID_EvtAND relative to BCMH_EvtOR under investigation
  - Significant average deviation for some algorithms
    - LUCID_EvtOR: -8%
    - LUCID_EvtAND: -15%
    - BCMV_EvtOR: -2%
- Currently investigating vertex based algorithms
  - Initial results suggest consistency with BCM at ~2% level

Plans and Requests for 2012

Luminosity Calibration in 2012

- Initial calibrations extrapolating from 2011 likely to be crude
  - Change in σ_{inel} & algorithm efficiencies with sqrt(s) increase of 7TeV → 8TeV difficult to predict
    - Preliminary study suggests dL/L~ 5-17%?
  - Experience from 2011 suggests uncertainties in detector consistency can become significant after extended winter shutdown
    - For 2011 startup effect was as large as ~8%
- To address these points & for L uncertainty comparable to 2011 calibration scans are essential

ATLAS Preferred Calibration Strategy

Option 1 (Chamonix)

- Early precision vdM scan with β^*=11m
- Distance scale calibration

Option 2

- Early scan at normal optics with sparse pattern
- Precision scan after closure of ICHEP dataset
  - β^*=11m & Distance scale calib.

- Both options under discussion within ATLAS
  - Early scan from option 2 expected to achieve <5% precision
  - Precision scan aims at matching 2011 uncertainty or better
- Additional needs
  - Pileup scan (cf. Fill 2086 in 2011)
    - Essential for controlling systematics given potential detector aging & higher μ in 2012
    - Requires L>2x10^{33} for calorimeters & μ as high as stable running permits
  - Afterglow scan
    - Calibrate afterglow subtraction for BCM & LUCID at highest possible μ
    - <5 colliding bunches >700 BCIDs apart, no unpaired bunches in between

Further Prospects for 2012

- Calibration of still more luminosity detectors & algorithms for consistency checks
  - RPC, Medipix, LUCID tube hit counting
  - Dedicated Inner Detector DAQ stream with prompt track & vertex reco for online lumi monitoring from these objects
    - Well advanced, cut definitions only limited by CPU constraints
  - Z counting luminosity comparisons

Summary

- Close to a precision calibration for 7TeV pp data in 2011 approaching 2% uncertainty
  - Order of magnitude improvement in bunch current uncertainties requires exhaustive evaluation of sub-percent uncertainties
    - Detailed analysis of vdM scan calibration uncertainties
    - Examination of μ dependence and algorithm consistency for
      - Single high luminosity fill
      - Across the entire 2011 data taking period
- In 2012 we hope to achieve comparable results
  - Prepared for challenges of higher pileup
  - 2012 uncertainty for the most part uncorrelated with 2011
- Thanks to the LHC for superb performance in 2011!

Backup

Event Counting Pileup Corrections

Inclusive counting (EventOR):

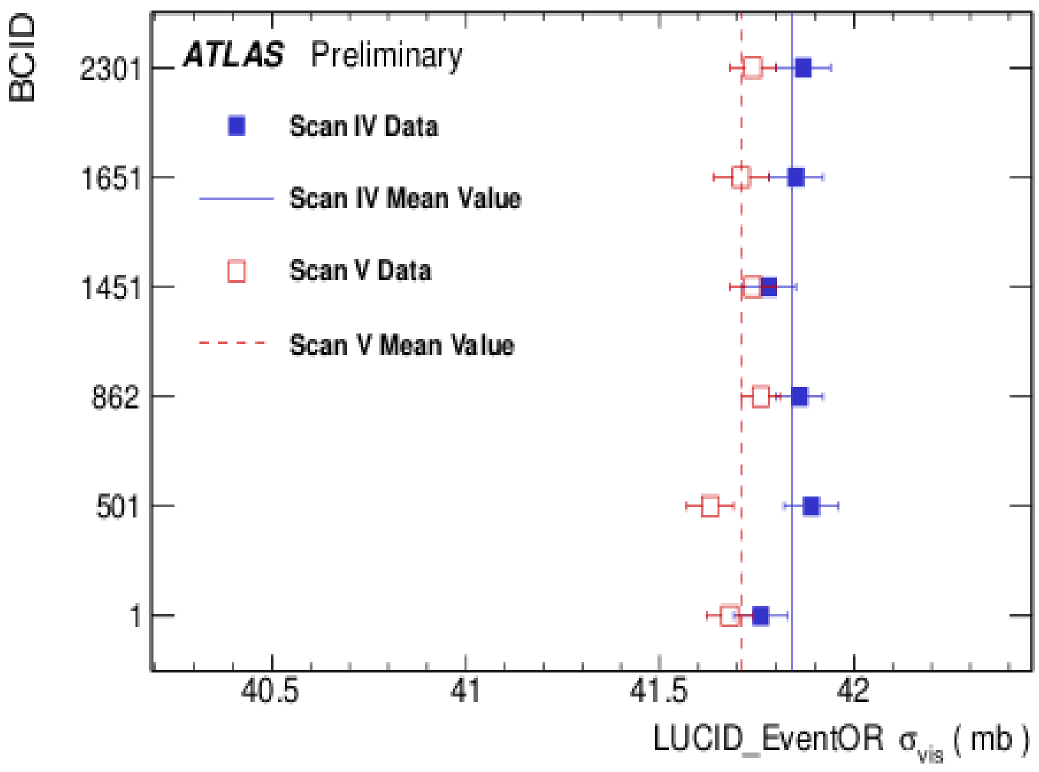
$$P_{\mathrm{EventOR}}(\mu_{vis}^{OR}) = 1 - e^{-\mu_{vis}^{OR}} = \frac{N_{OR}}{N_{BC}} \quad \Rightarrow \quad \mu_{vis}^{OR} = -\ln\left(1 - \frac{N_{OR}}{N_{BC}}\right)$$

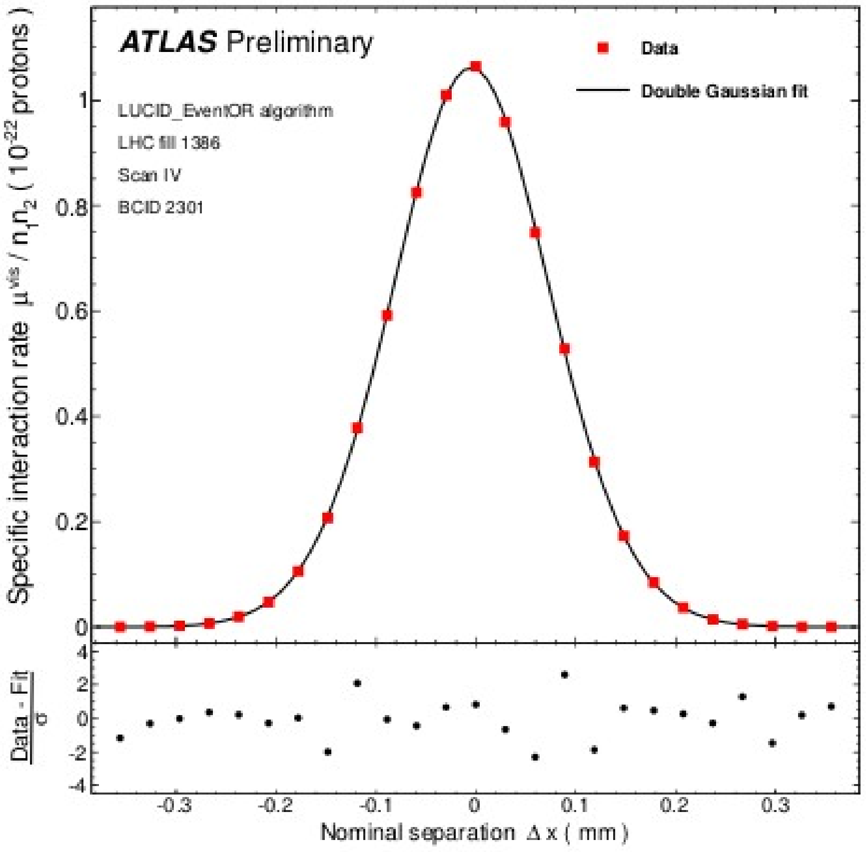
Coincidence counting (EventAND):

$$P_{\mathrm{EventAND}}(\mu_{vis}^{AND}) = 1 - 2e^{-(1+\sigma_{vis}^{OR}/\sigma_{vis}^{AND})\mu_{vis}^{AND}/2} + e^{-(\sigma_{vis}^{OR}/\sigma_{vis}^{AND})\mu_{vis}^{AND}} = \frac{N_{AND}}{N_{BC}}$$

- Cannot analytically invert (use e.g. lookup table)
- Dependence on $\sigma_{vis}^{OR}/\sigma_{vis}^{AND}$ requires analysis iterated

Oct 2010 vdM





Less systematic variation in each scan, all fits with good quality for double Gaussian+p0

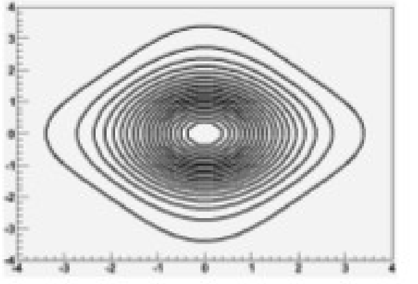
Beam Jitter Uncertainty

- Random deviations from nominal position at given scan point
- Length scale calibration gives 0.8 μm RMS on relative beam centering
- Randomly vary toy MC scan points by RMS to estimate σ_{vis} uncertainty

Inner Detector Length Scale Uncertainty

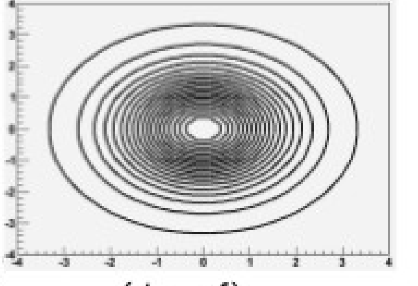
- Length scale calibration relies on absolute ID length scale
- Uncertainty from study of 9 ID misalignment MC samples
  - True vs. reconstructed vertex position
- Correlated across all scans

More on Double Gaussian Non-Linear Modelling



- Fit strategy assumes Gaussian sums factor transversely

$$[f_{1x}G_{1x}(h)+(1-f_{1x})G_{2x}(h)][f_{1y}G_{1y}(k)+(1-f_{1y})G_{2y}(k)] \Rightarrow \frac{1}{\Sigma_{x(y)}} = \frac{f_{1x(y)}}{\sigma_{1x(y)}} + \frac{(1-f_{1x(y)})}{\sigma_{2x(y)}}$$



- In case where overlap region has distinct sub-populations in tail/core sum will be of two 2D Gaussians

$$[f_1 G_{1x}(h)G_{1y}(k) + (1-f_1)G_{2x}(h)G_{2y}(k)] \Rightarrow \frac{1}{\Sigma_x\Sigma_y} = \frac{f}{\sigma_{1x}\sigma_{1y}} + \frac{(1-f)}{\sigma_{2x}\sigma_{2y}}$$