

# Luminosity Determination in pp Collisions using the ATLAS Detector at the LHC



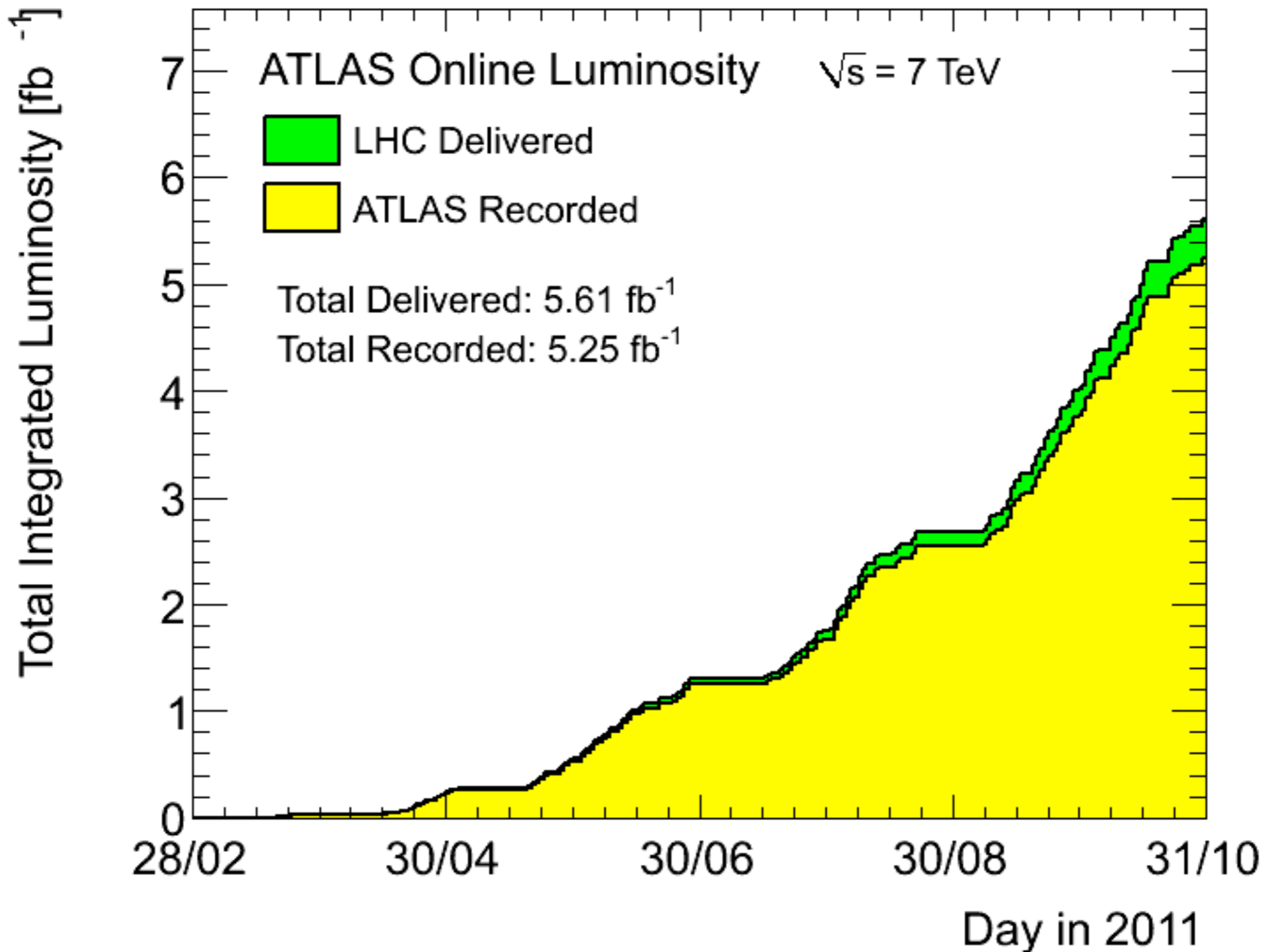
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for the ATLAS Collaboration



ATLAS

36th ICHEP  
6 July, 2012





<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults>

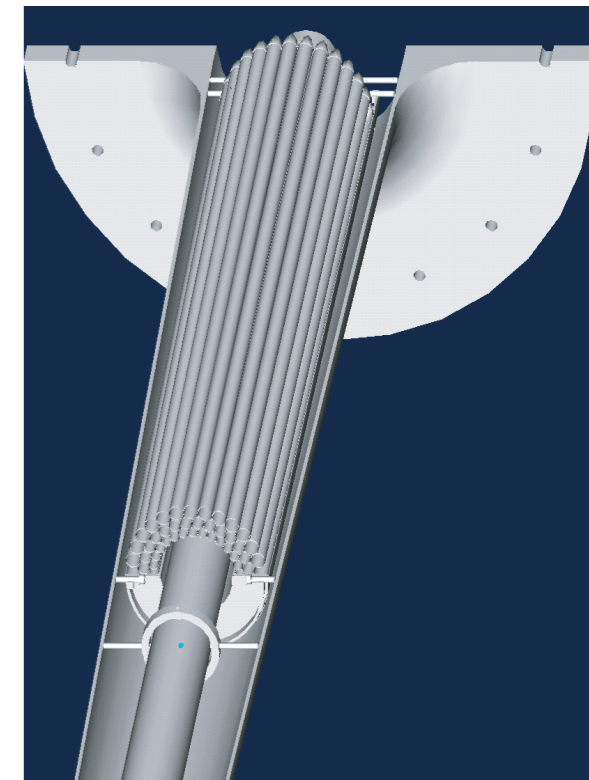
2011 Delivered Luminosity:  $\int L dt = 5.61 \pm 0.10$  fb<sup>-1</sup>

Reference Reaction: **inelastic pp scattering**

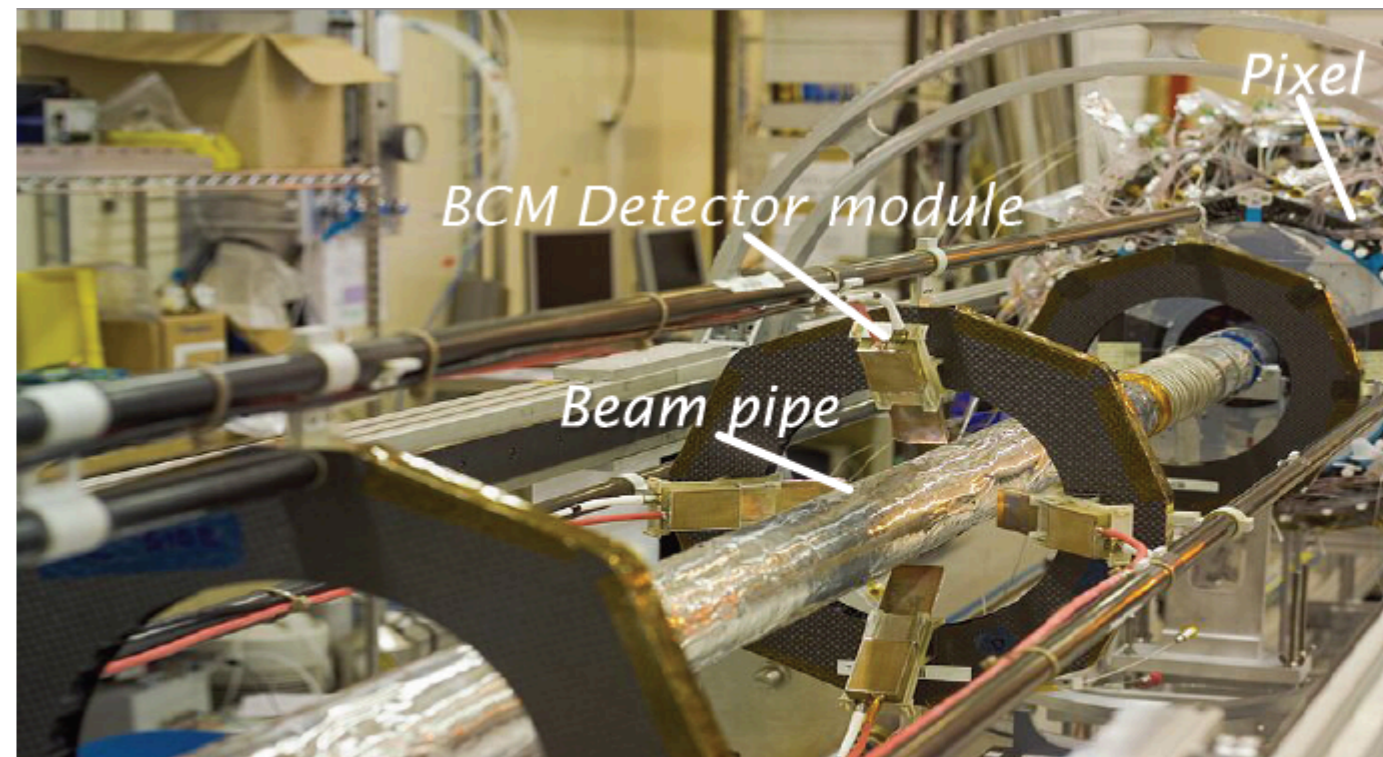
- LUCID
  - Dedicated Luminosity Monitor
  - Gas Cherenkov Tubes,  $5.6 < |\eta| < 6.0$
- Beam Conditions Monitor (BCM)
  - Designed for beam abort system
  - Diamond Sensors,  $|\eta| \sim 4.2$
- Primary Vertex Counting
  - Limited trigger bandwidth
  - Special conditions only
- Calorimeter currents
  - TileCal PMT currents
  - FCal LAr HV currents
  - Total luminosity only

every  
25 ns

LUCID



BCM



**Redundancy key for evaluating systematic uncertainties**

Algorithm Specific

$$L = \mu n_b f_r / \sigma_{inel} = \mu_{vis} n_b f_r / \sigma_{vis}$$

Inelastic Interactions  
per Beam Crossing

Measured quantity

$\epsilon \times \sigma_{inel}$   
To be calibrated

$n_b$  - Bunch pairs colliding  
 $f_r$  - Revolution Frequency

Event counting:  $f = N_{evt}/N_{BC}$

$\mu_{vis}$  from observable rates

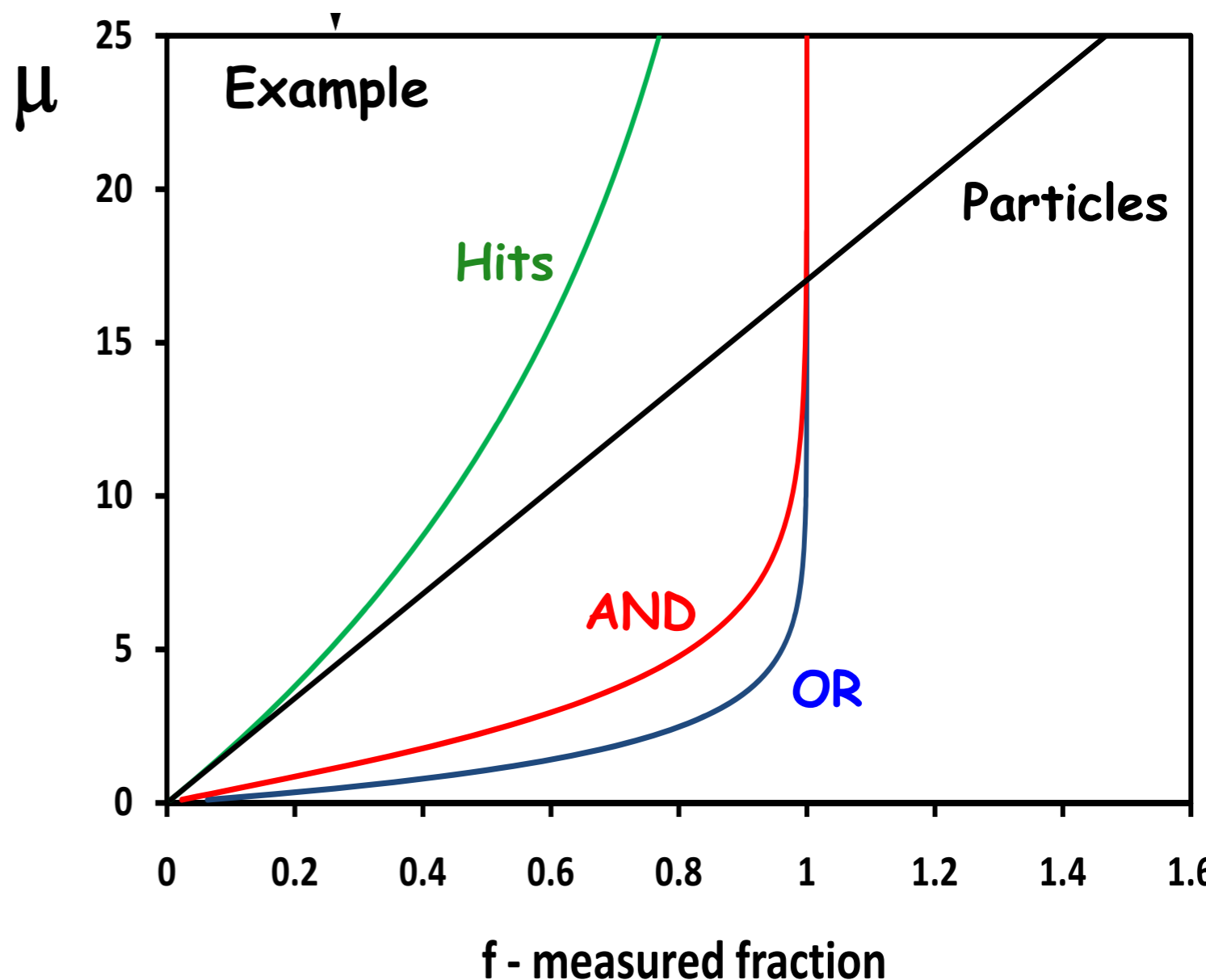
$$f_{OR} = \frac{N_{OR}}{N_{BC}} = 1 - e^{-\mu_{vis}}$$

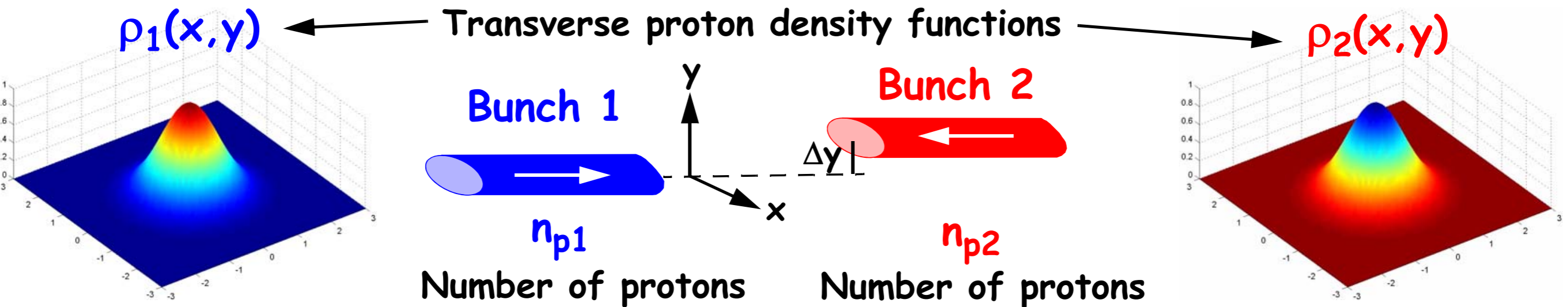
$$f_{AND} = \frac{N_{AND}}{N_{BC}} = 1 - 2e^{-(1+R)\mu_{vis}/2} + e^{-R\mu_{vis}}$$

$$R = \sigma_{vis}^{OR} / \sigma_{vis}^{AND}$$

$$f_{hits} = \frac{N_{hits}}{N_{BC} N_{Ch}} = 1 - e^{-\mu_{vis}}$$

$$f_{part} = \frac{N_{part}}{N_{BC} N_{Ch}} = \mu_{vis}$$





Beam separation scans provide **absolute** luminosity calibration

$$\mathcal{L}_{peak} = f_r n_1 n_2 \iint \rho_1(x,y) \rho_2(x,y) dx dy$$

$$= f_r n_1 n_2 \frac{1}{2\pi \Sigma_x \Sigma_y}$$

$\Sigma_x, \Sigma_y$  - convolved beam widths

$n_1 n_2$  - bunch population product



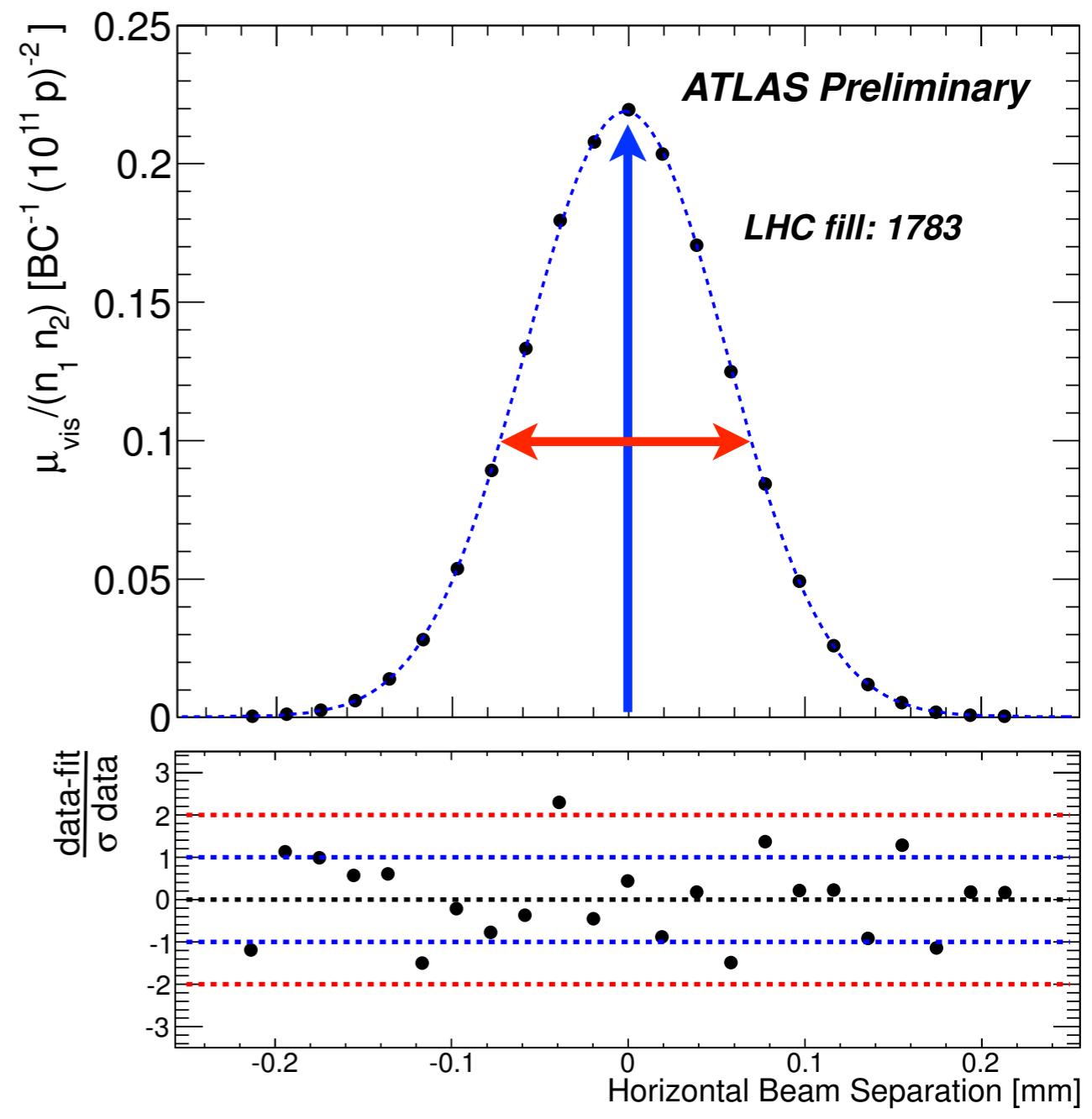
S. van der Meer, CERN-ISR-PO-68-31 (1968)

- Separate beams and measure specific interaction rate
- Directly calibrate  $\sigma_{vis}$  for each algorithm

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

Peak Rate  $\mu_{vis}^{MAX}$  Scan Widths  $2\pi \Sigma_x \Sigma_y$  Bunch Population  $n_1 n_2$

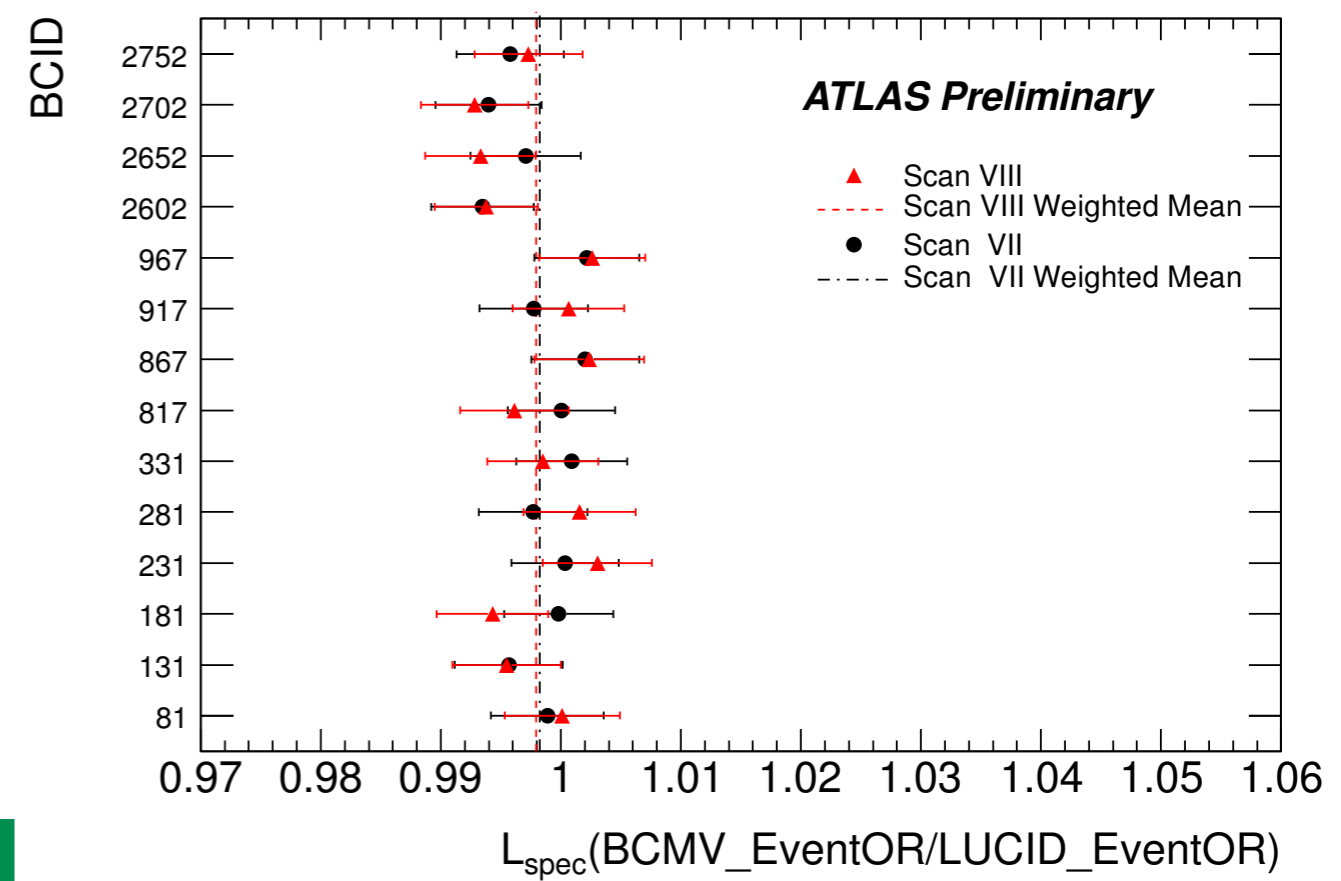
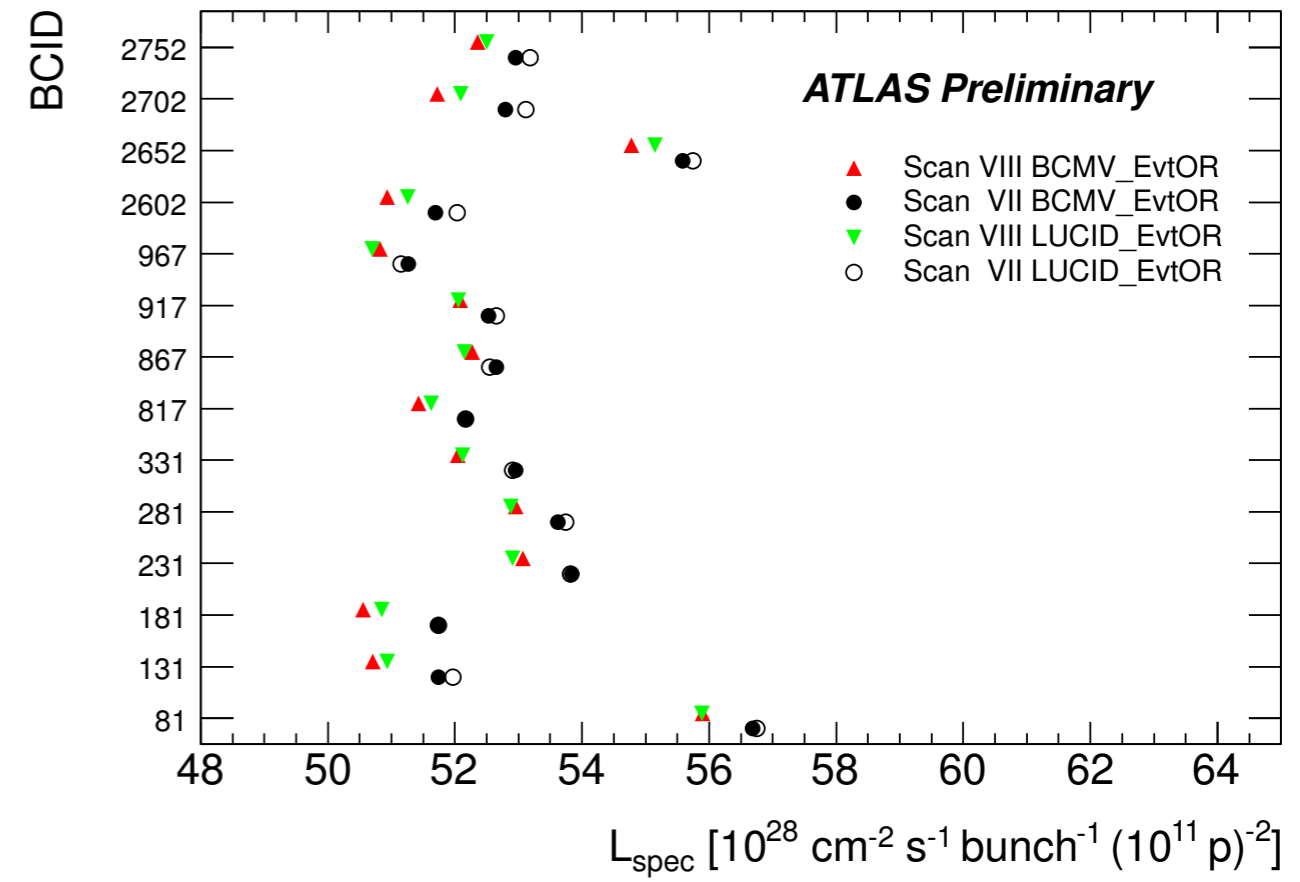
- Specific rate  $\mu_{vis} / (n_1 n_2)$  removes current dependence
- Requires careful control of machine parameters (beam time)
  - Low numbers of bunches (14 in 2011)
  - Modest peak  $\mu$  ( $\sim 2.5$  in 2011)
  - Multiple scan consistency used to assess systematics (2 in 2011)



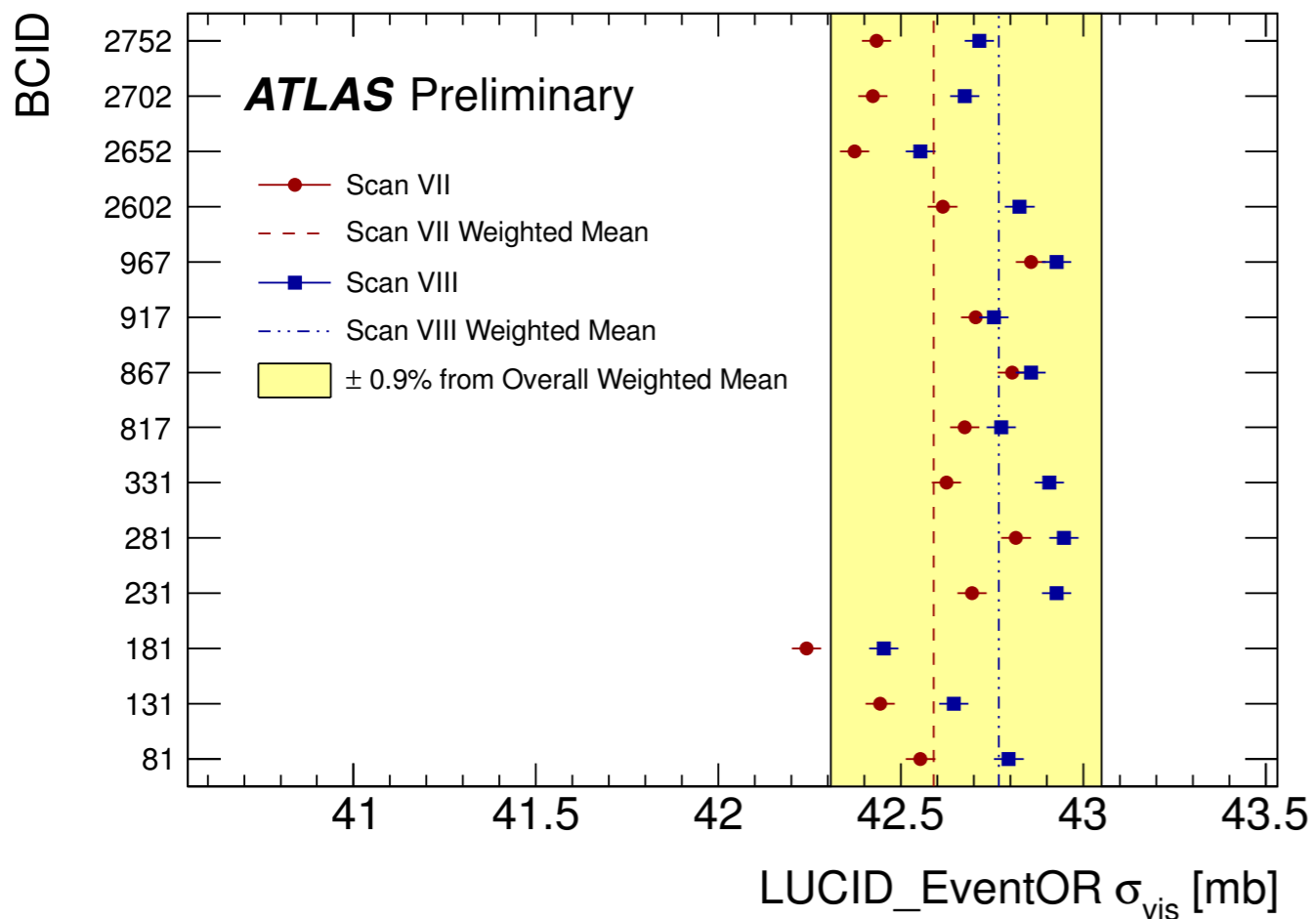
$$\mathcal{L}_{\text{spec}} = \mathcal{L}/(n_b n_1 n_2) = \frac{f_r}{2\pi \Sigma_x \Sigma_y}$$

- All algorithms/detectors should measure the same  $\mathcal{L}_{\text{spec}}$
- Spec. Luminosity varies per colliding bunch pair (BCID) by up to  $\sim 10\%$
- Varies between scans by  $\sim 2\%$  (due to emittance growth)
- Good consistency between algorithms/detectors
- Residual variation taken as systematic uncertainty

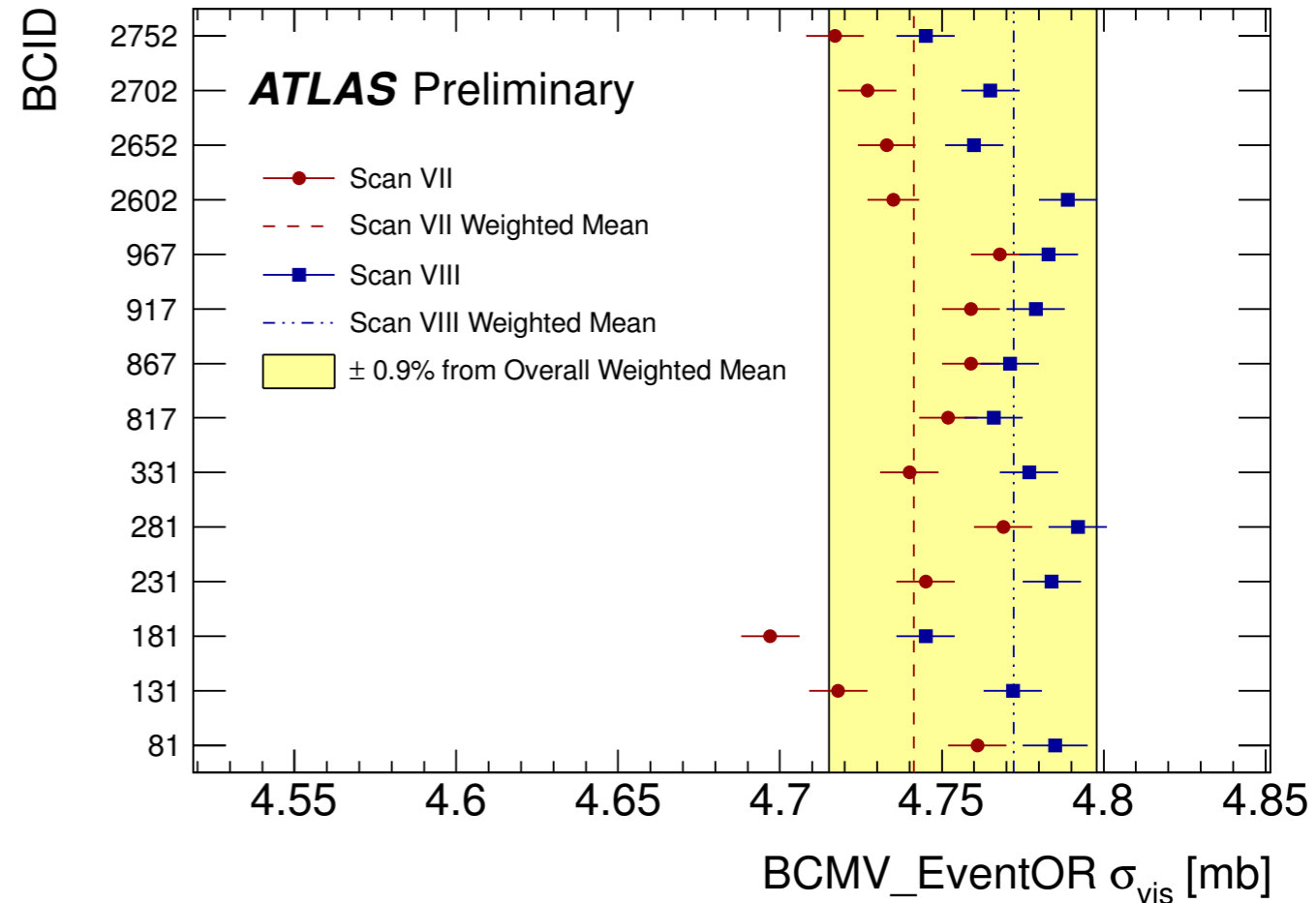
$\pm 0.3\%$  uncertainty on  $\sigma_{\text{vis}}$



## LUCID\_EventOR



## BCMV\_EventOR

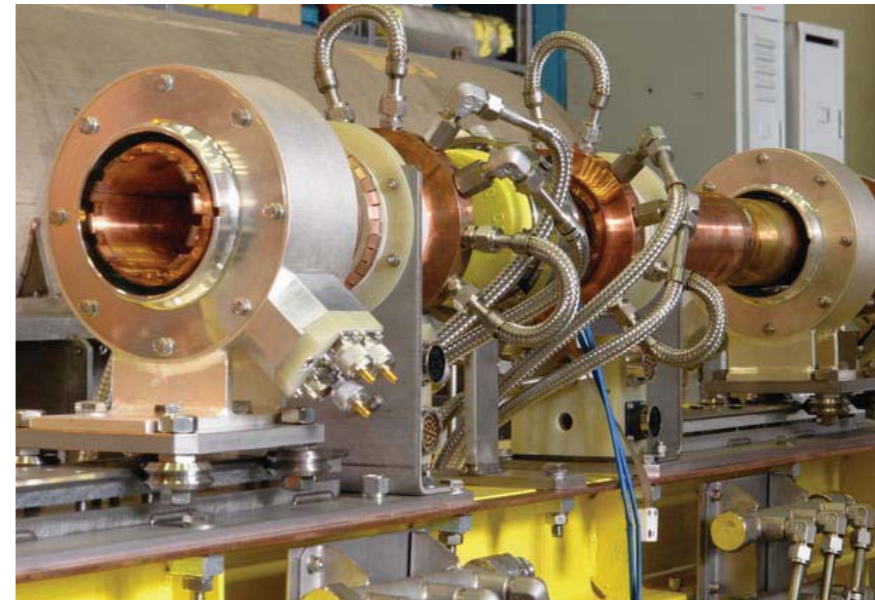


- Variations seen by BCID and by scan (similar across detectors)
- Band is (RMS variation over BCIDs)  $\oplus$  (variation between scans)
- Uncertainty taken from data-driven consistency check

**$\pm 0.9\%$  uncertainty on  $\sigma_{vis}$**



**DCCT - DC Current Transformer**  
accurate, but measures everything



**FBCT - Fast Beam Current Transformer**  
bunch-by-bunch measurements

$$n_i = (\alpha S^{\text{DCCT}} - S_{\text{Baseline}} - S_{\text{ghost}}) S_i^{\text{FBCT}} / \sum S_i^{\text{FBCT}}$$

Uncertainty needed on  $n_1 n_2$   
(from BCN WG)

DCCT: [CERN-ATS-Note-2012-026](#)

FBCT: [CERN-ATS-Note-2012-028](#)

G/S: [CERN-ATS-Note-2012-029](#)

**±0.54% uncertainty on  $\sigma_{\text{vis}}$**

	2010	2011
DCCT Baseline	0.1%	0.10%
DCCT Scale $\alpha$	2.7%	0.21%
$S_i^{\text{FBCT}} / \sum S_i^{\text{FBCT}}$	1.6%	0.20%
Ghost Charge/Satellites		0.44%
<b>Total Uncertainty</b>	<b>3.1%</b>	<b>0.54%</b>

## Uncertainty on $\sigma_{\text{vis}}$ from vdM calibration

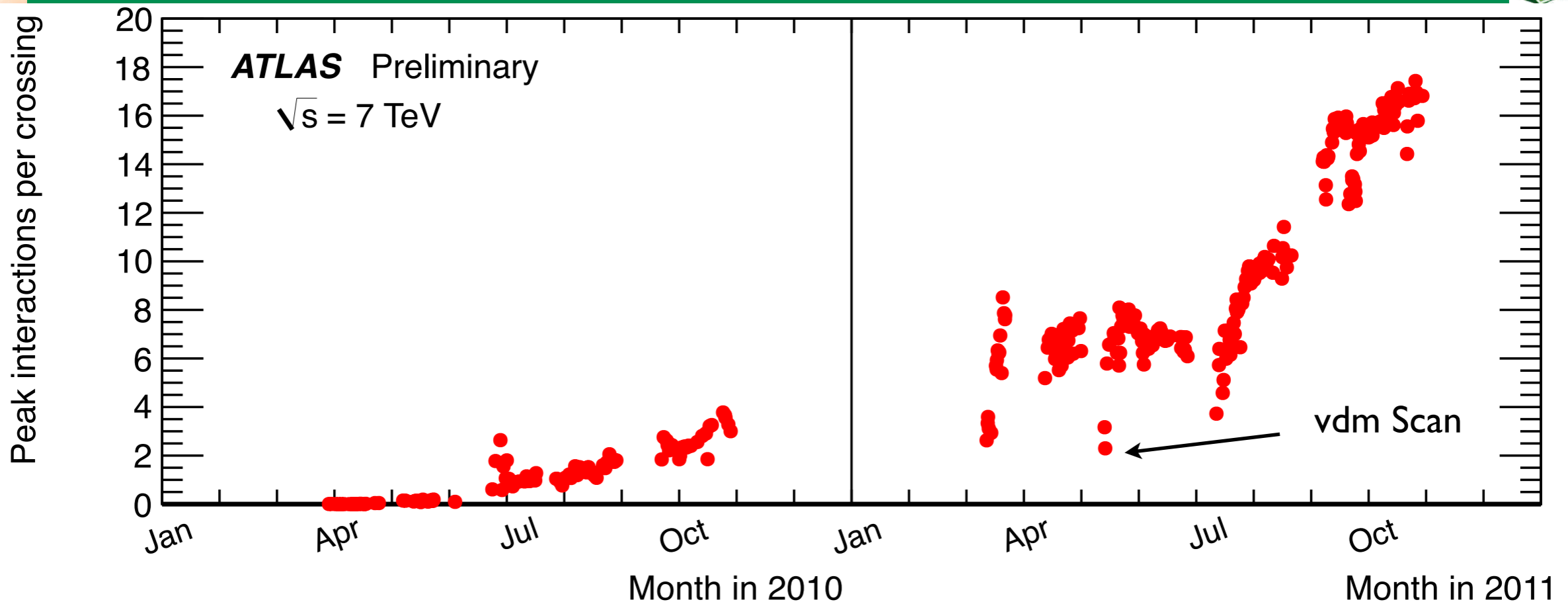
**2011: 1.5%**  
**(2010: 3.4%)**

Main improvement  
from  $(n_1, n_2)$

More complete  
determination of  
other uncertainties

Largest observed deviation  
typically sets uncertainty

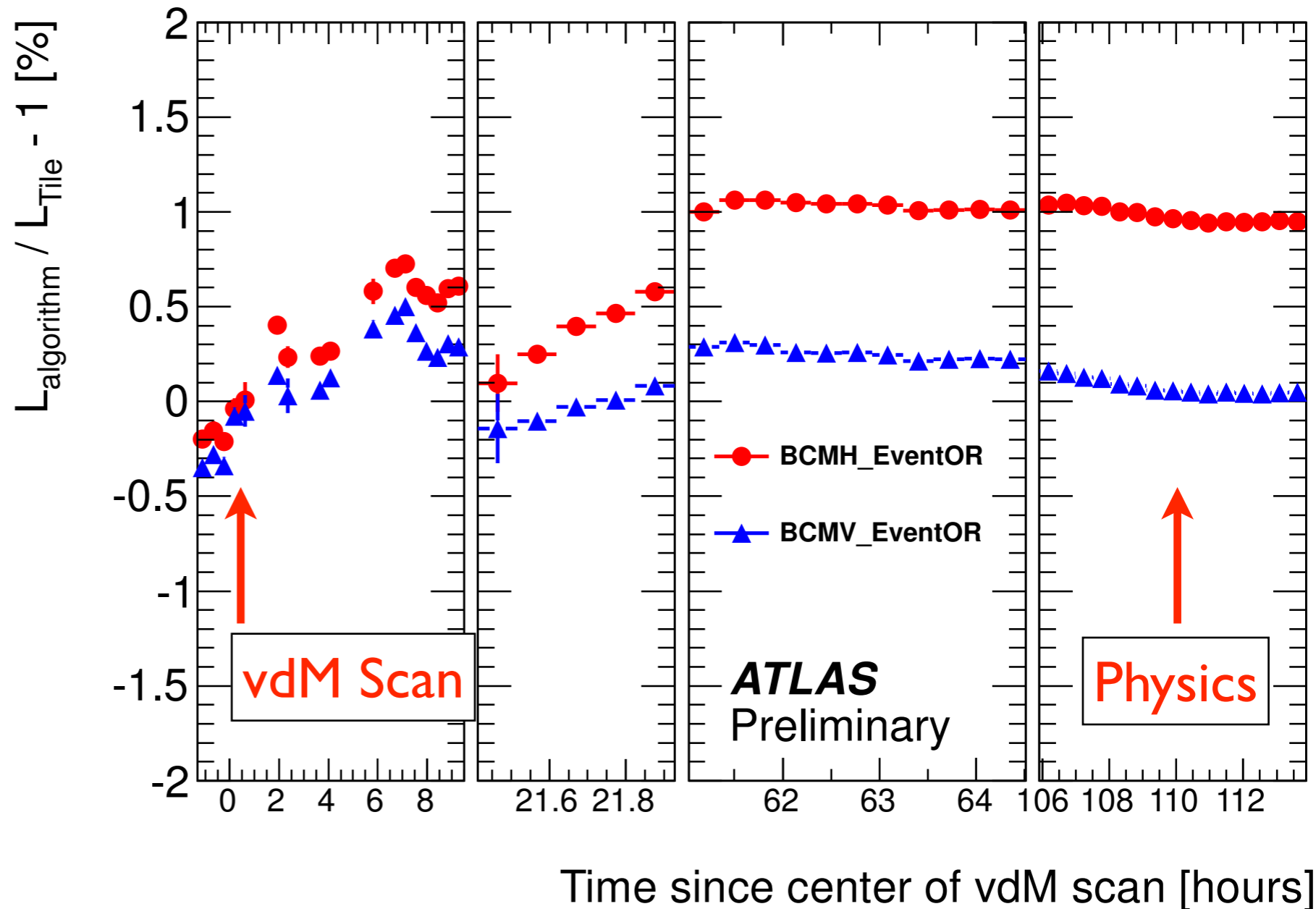
Scan Number	VI–VII
Fill Number	1783
Beam centering	0.10%
Beam-position jitter	0.30%
Emittance growth and other non-reproducibility	0.67%
Bunch-to-bunch $\sigma_{\text{vis}}$ consistency	0.55%
Fit model	0.28%
Background subtraction	0.31%
Specific Luminosity	0.29%
Length scale calibration	0.30%
Absolute ID length scale	0.30%
Beam-beam effects	0.50%
Transverse correlations	0.50%
$\mu$ dependence	0.50%
Scan subtotal	1.43%
Bunch population product	0.54%
Total	1.53%



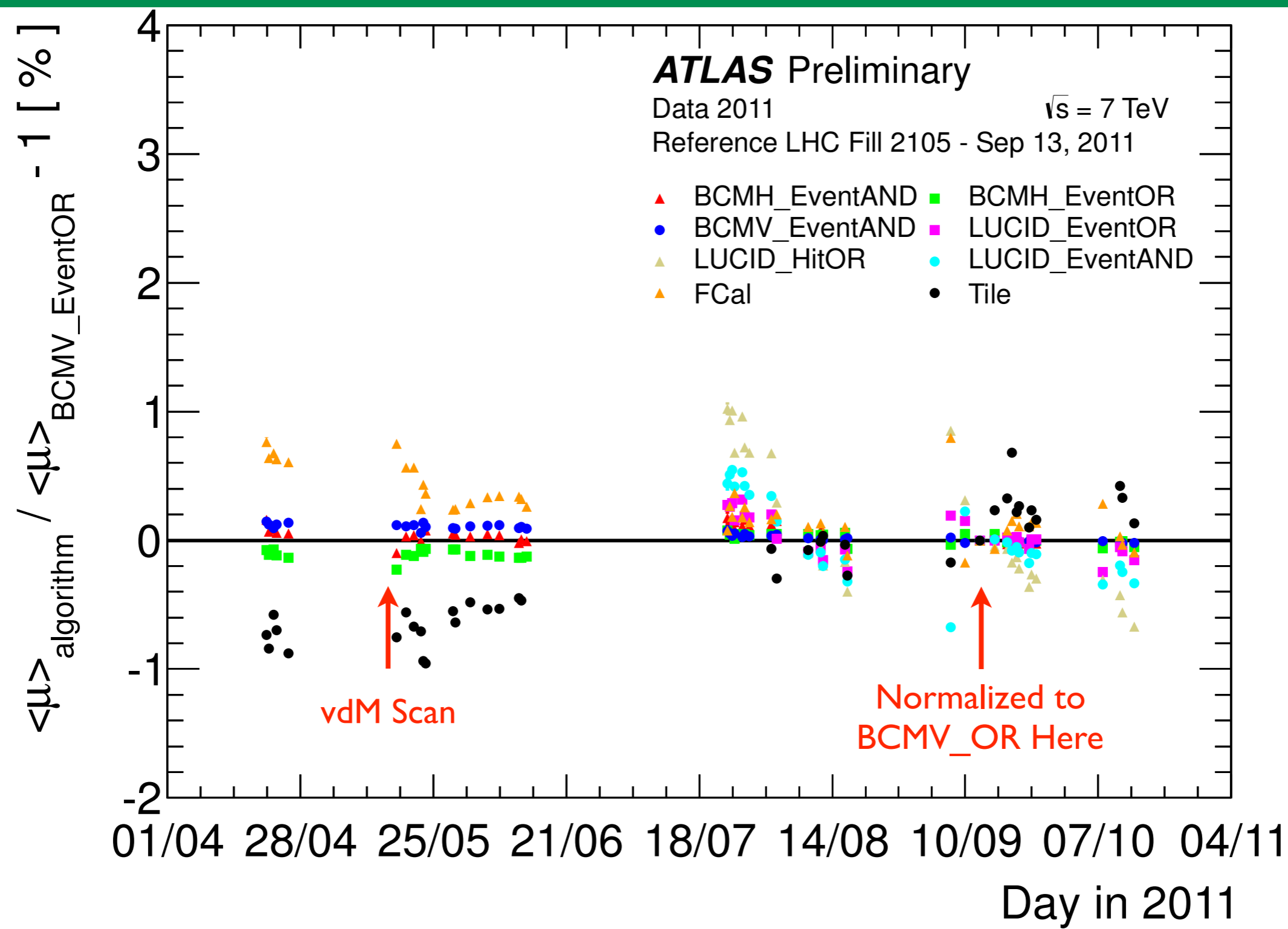
- Must apply vdM calibration over entire 2011 data period
  - time stability
  - different bunch structure (50 ns bunch trains)
  - linearity to highest interaction rates ( $\mu$ )
- One algorithm provides central value (BCM<sub>V</sub>\_EventOR in 2011)
- Consistency between all methods determines uncertainty

**Data-driven uncertainties determined from redundant measurements**

- BCM is CVD diamond sensor with separate H/V readout pairs
- BCM response 'drifts' after each technical stop (no beam)
- Seen separately in all 4 BCM sensors

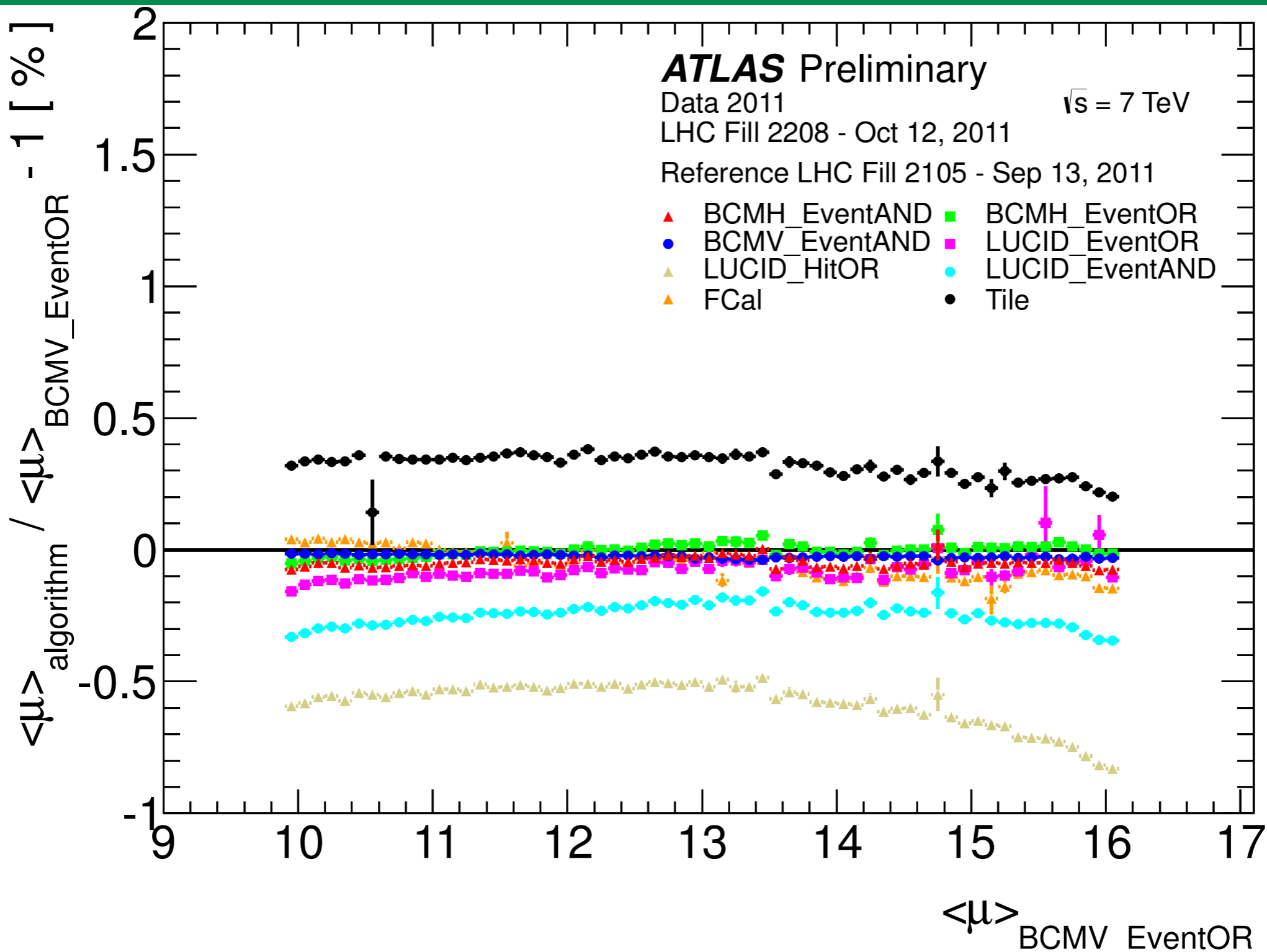


- Asymptotically stable value after exposure of about  $\int L dt \sim 5 \times 10^{36} \text{ cm}^{-2}$
  - **Unfortunately**, May 2011 vdM scan taken just after technical stop...
  - BCMH  $\sigma_{\text{vis}}$  calibration corrected by observed drift
  - No net drift observed in BCMV
- $\pm 0.25\%$  unc. on Lumi**



Tile variation likely explained by residual PMT gain drifts  
 Uncertainty:  $\pm 0.7\%$  on Lumi

# Single Run $\mu$ dependence



Offsets due to long-term stability variation

Algorithms linear to better than  $\pm 0.5\%$  over this high- $\mu$  range

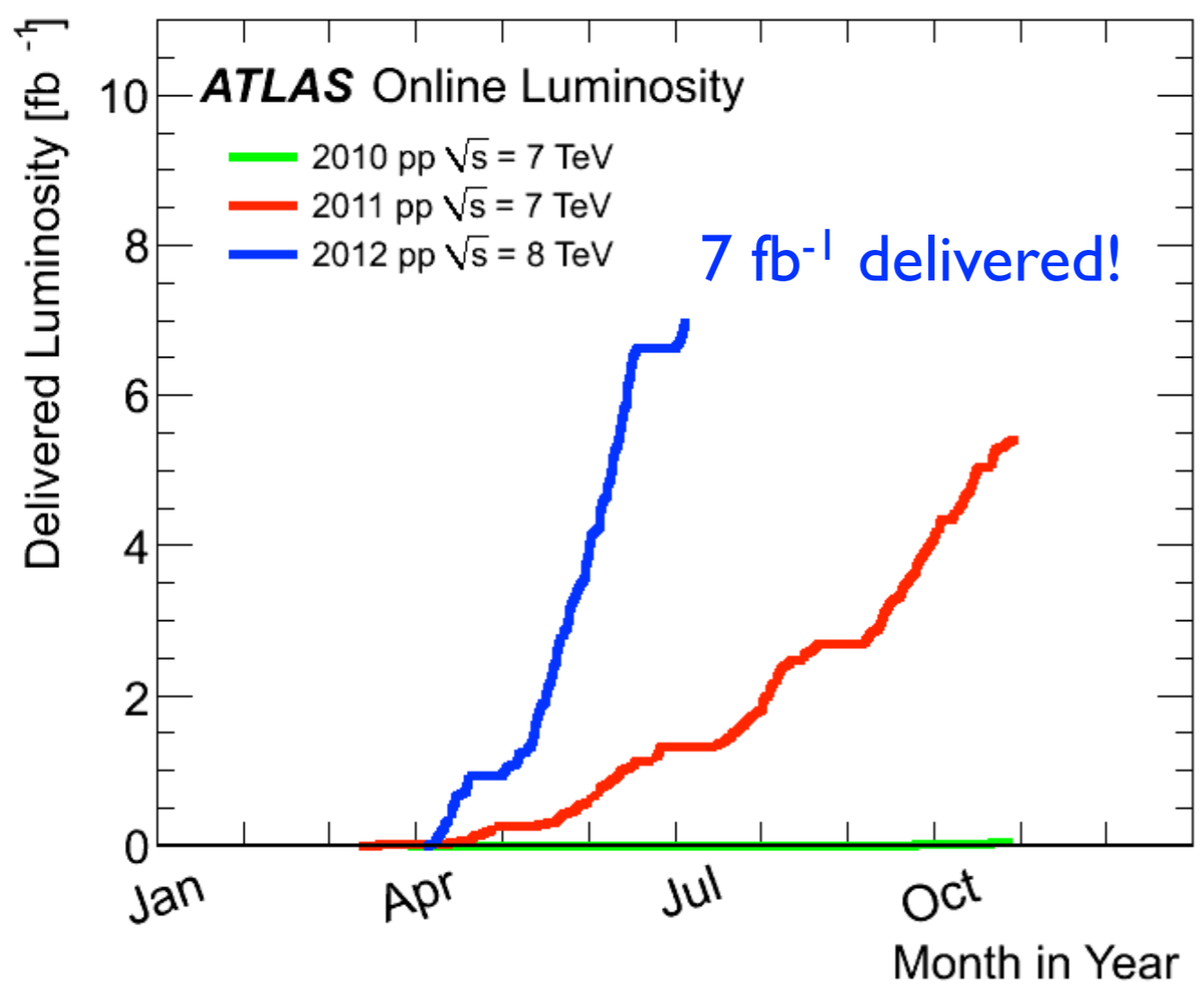
Extrapolation to  $\mu \sim 2$  dominates uncertainty:  **$\pm 0.5\%$  on Lumi**



Uncertainty Source	$\delta\mathcal{L}/\mathcal{L}$		
	2010	2011	
Bunch Population Product	3.1%	0.5%	} vdM Calibration
Other <i>vdM</i>			
Calibration Uncertainties	1.3%	1.4%	
Afterglow Correction		0.2%	} Extrapolation
BCM Stability		0.2%	
Long-Term Consistency	0.5%	0.7%	
$\mu$ Dependence	0.5%	0.5%	
Total	3.4%	1.8%	

Bunch population product significantly reduced  
 Other uncertainties remain largely similar to 2010  
**even with significantly larger pileup, bunch trains**

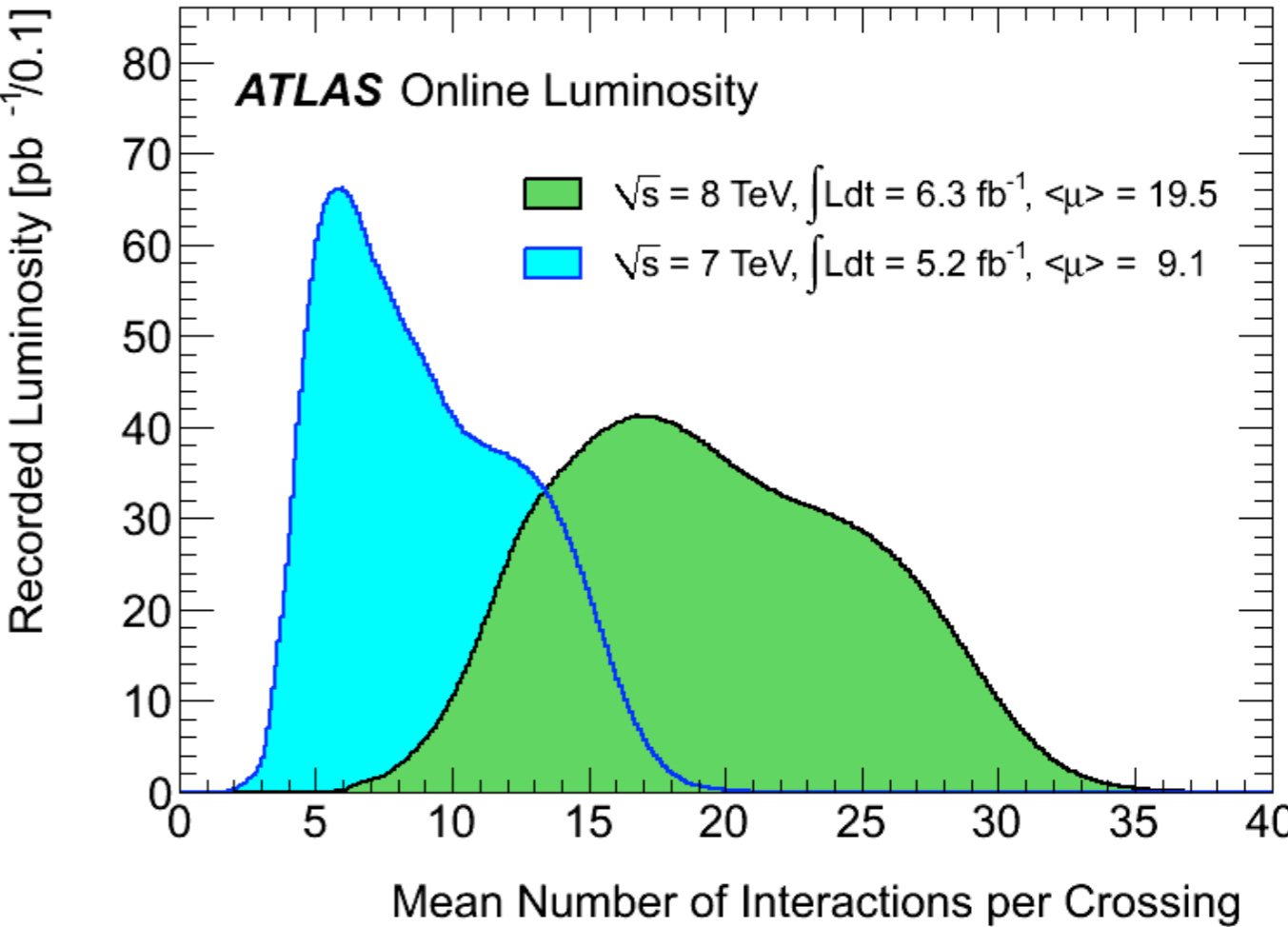
Preliminary, but nearly final: [ATLAS-CONF-2012-080](#)



New year, new challenges...

2012 luminosity has exceeded 2011  
Average interaction rate doubled

Will continue to rely on redundancy  
to demonstrate reliability of  
ATLAS luminosity scale

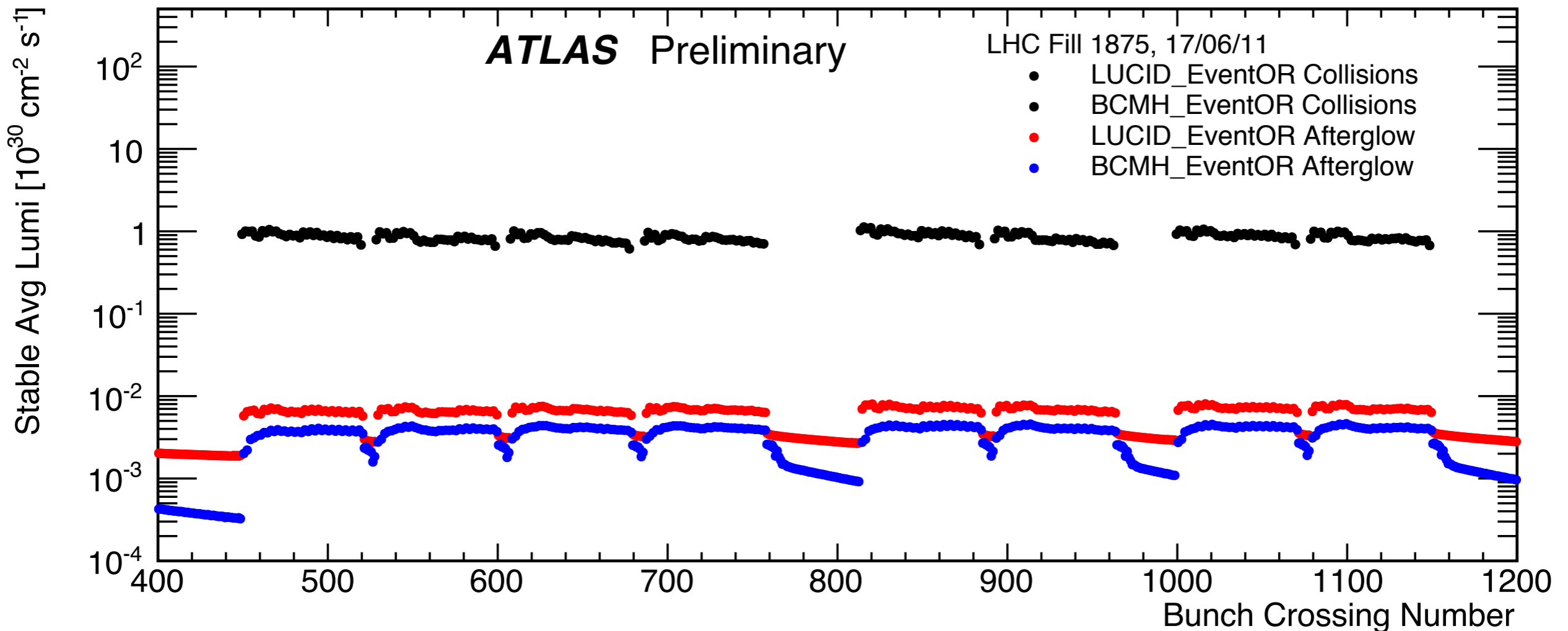


Lumi analysis for 2012 ongoing

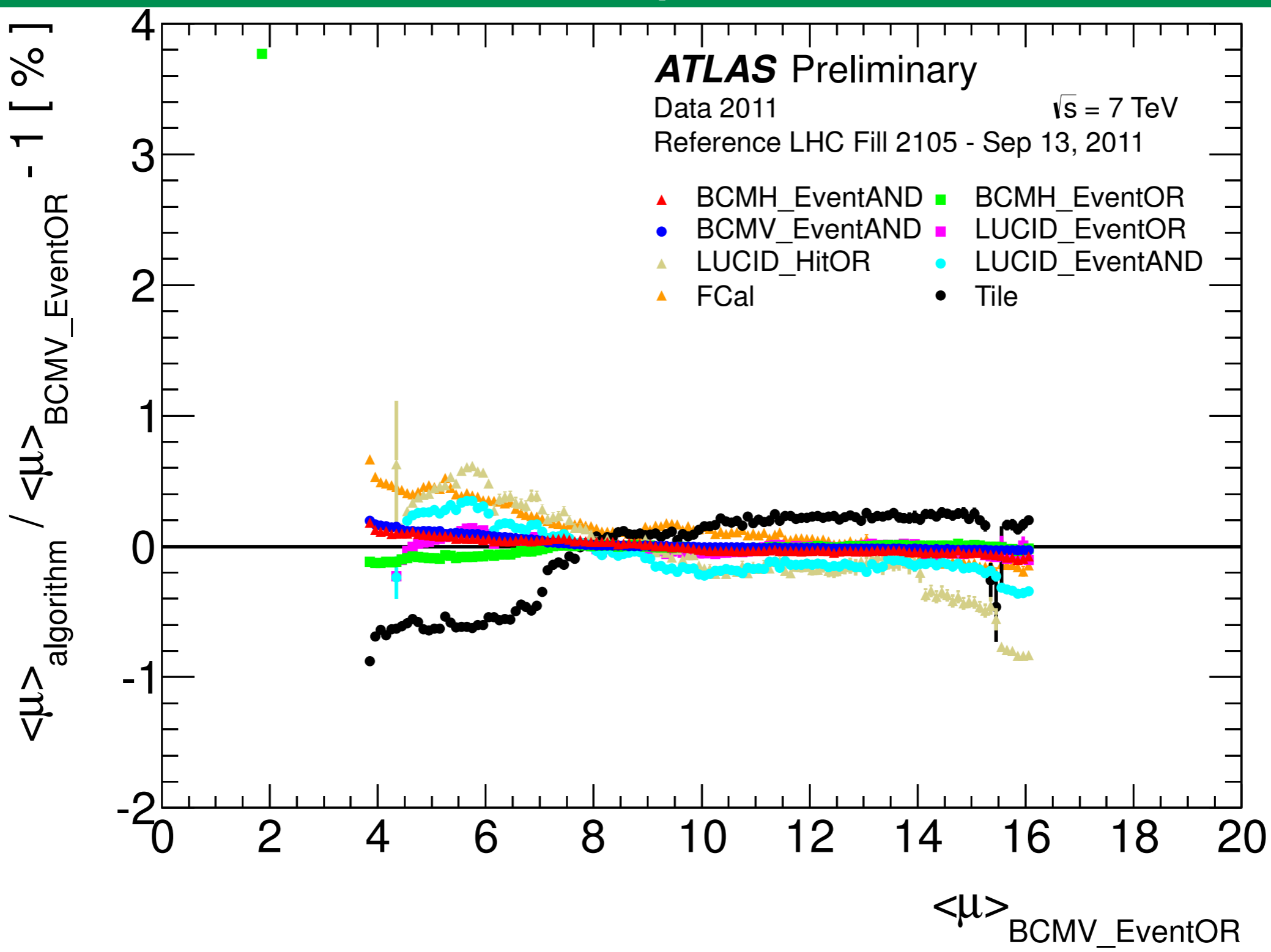
First vdM scan taken in April  
Second scan planned for mid-July

Initial (**preliminary**) analysis  
for ICHEP '12:  $\delta L/L = \pm 3.6\%$

# Additional Material

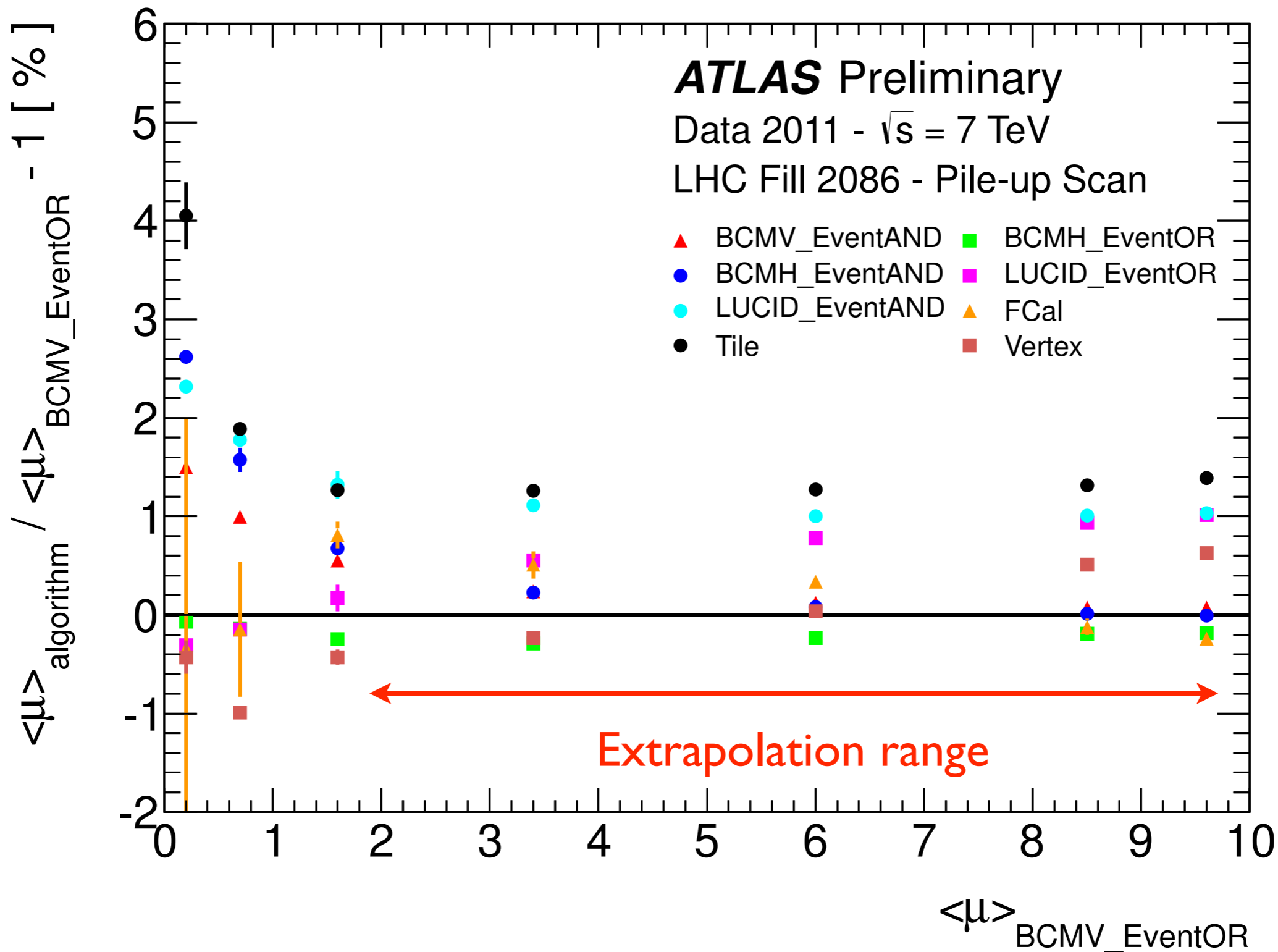


- Afterglow creates a luminosity background in bunch trains
- Relatively small effect ( $\sim 0.8\%$  for LUCID\_OR,  $\sim 0.4\%$  for BCM\_OR)
- Simple correction by subtracting effective lumi in BCID-I
- More correct (but slow) 'template' analysis gives same results



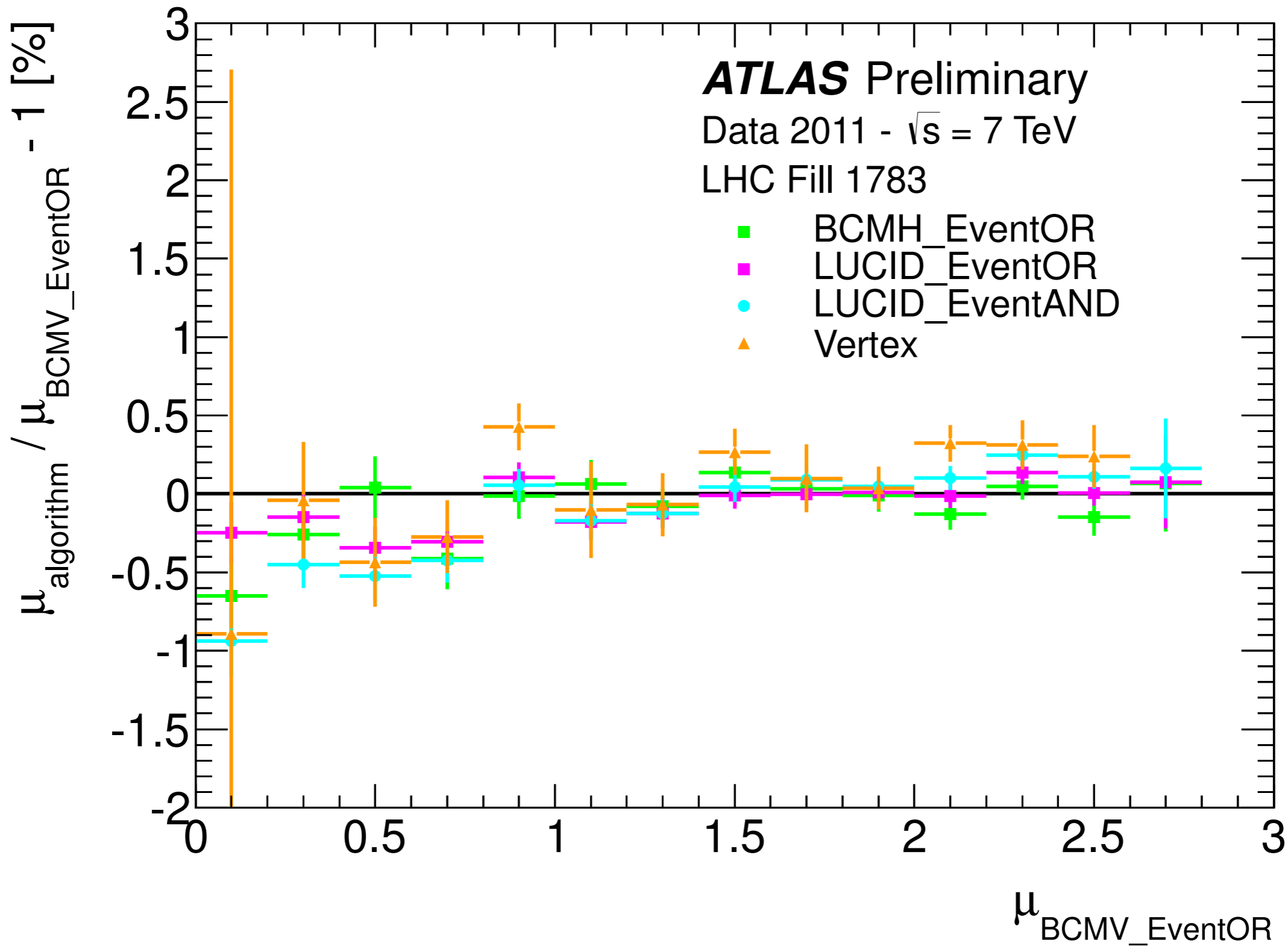
$\pm 0.5\%$   
on Lumi

Same data as time history  
 Tile variation from time dependence



End-of-fill data taken by separating beams

Very-low  $\mu$  behavior dominated by background issues (bunch trains)



Good linearity at low  $\mu$  seen in vdM scan (no bunch trains)