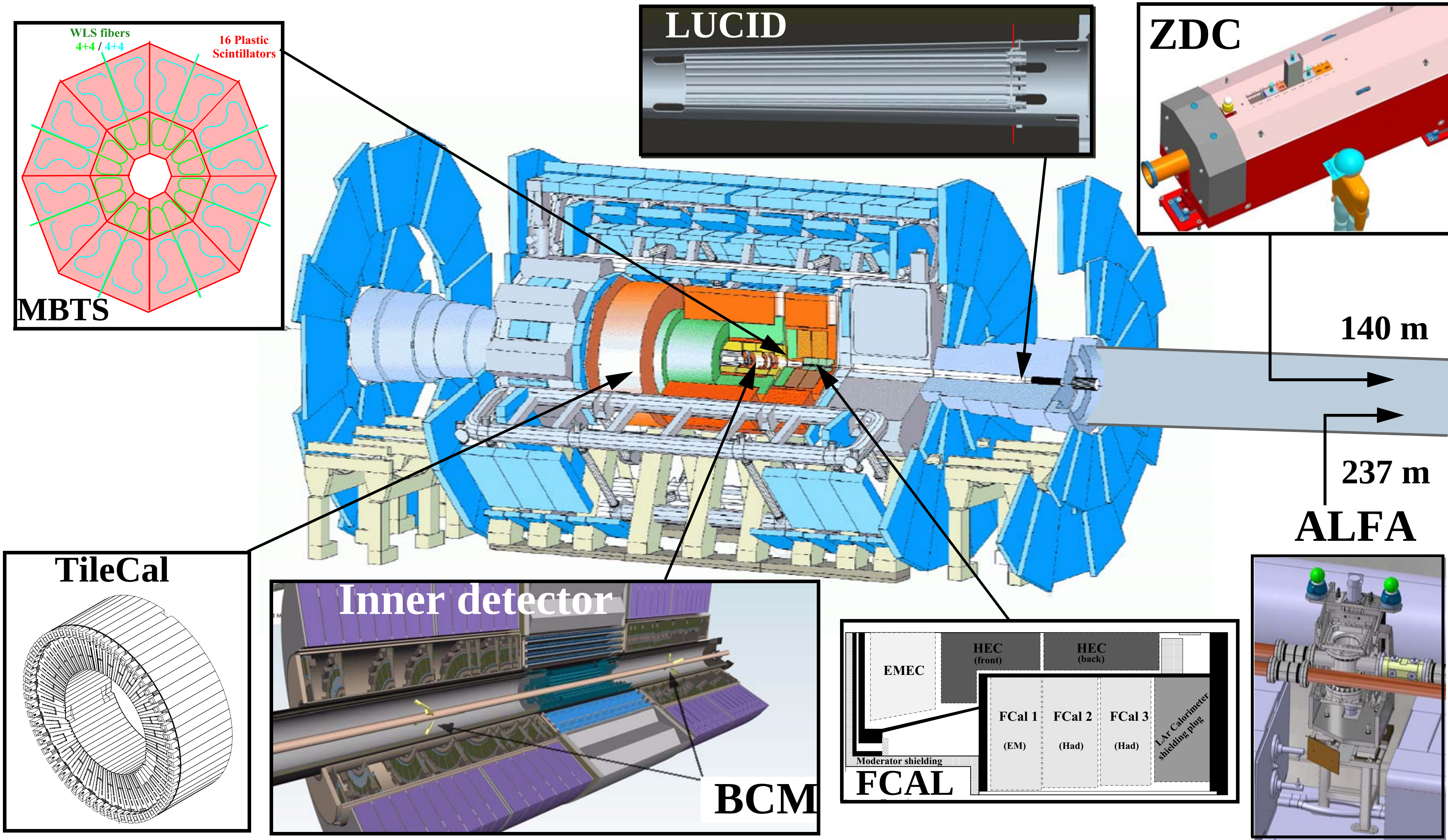
Precision measurement of the luminosity in ATLAS



Measuring the luminosity

ATLAS measures the luminosity for each individual pair of colliding LHC bunches:

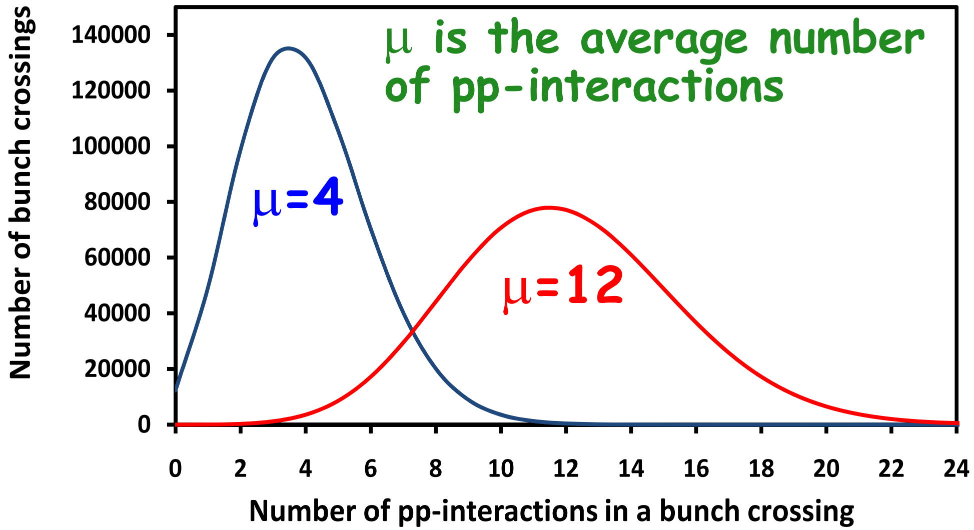
11245.5 Hz (LHC revolution frequency)

$$\mathcal{L}_{BC} = f_{LHC} \frac{\mu}{\sigma_{inel}} = f_{LHC} \frac{\mu_{vis}}{\sigma_{vis}}$$

$\mu_{vis} = \varepsilon\mu$ Measured from detector rates

$\sigma_{vis} = \varepsilon\sigma_{inel}$ Measured in beam separation scans

ε: efficiency & acceptance



How can one measure σ_{vis} ?

Measuring the luminosity

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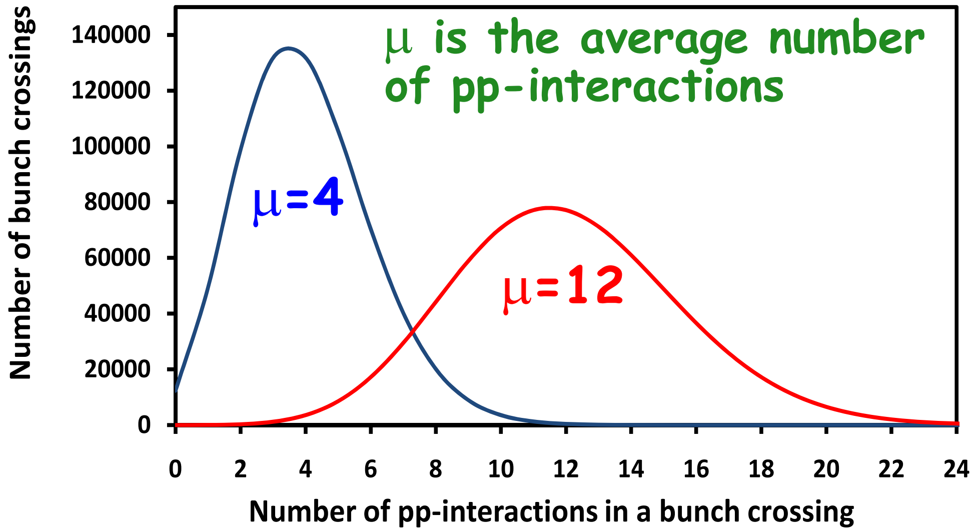
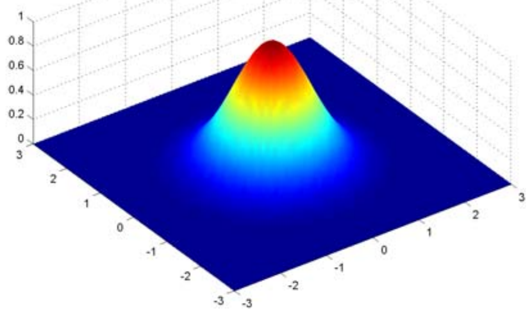


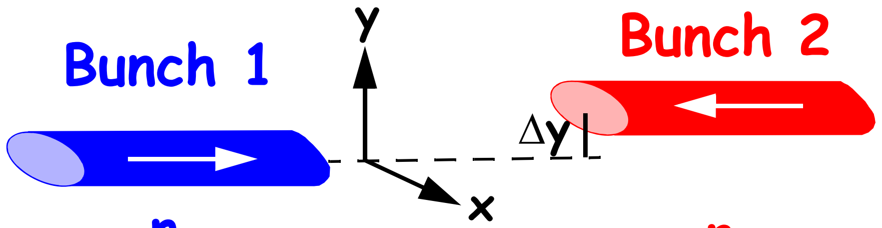
Transverse proton density functions

$\rho_1(x,y)$

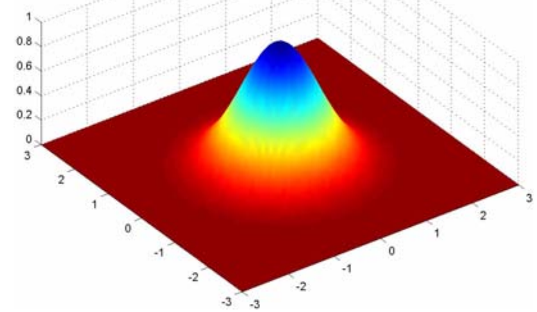


Bunch 1

Bunch 2



$\rho_2(x,y)$



n_{p1} Number of protons

n_{p2} Number of protons

$$\mathcal{L}_{BC}^{peak} = f_{LHC}\, n_{p1} n_{p2} \int \rho_1(x,y)\rho_2(x,y)\,dxdy = f_{LHC} n_{p1} n_{p2} \frac{1}{2\pi\Sigma_x\Sigma_y}$$

The sigma of scan curves

Beam separation scans

Lumi. from scan:

$$\mathcal{L}_{BC}^{peak} = f_{LHC} \frac{n_{p1} n_{p2}}{2\pi \Sigma_x \Sigma_y}$$

+

Lumi. from counting events:

$$\mathcal{L}_{BC}^{peak} = f_{LHC} \frac{\mu_{vis}^{peak}}{\sigma_{vis}}$$

→

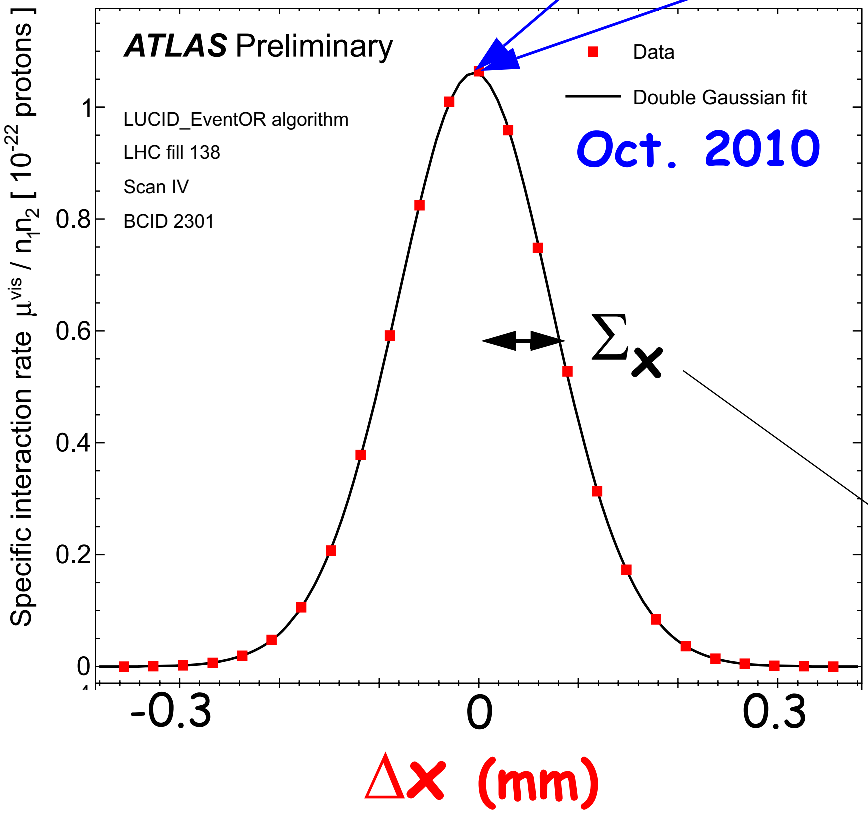
Calibration constant:

$$\sigma_{vis} = 2\pi \frac{\mu_{vis}^{peak} \Sigma_x \Sigma_y}{n_{p1} n_{p2}}$$

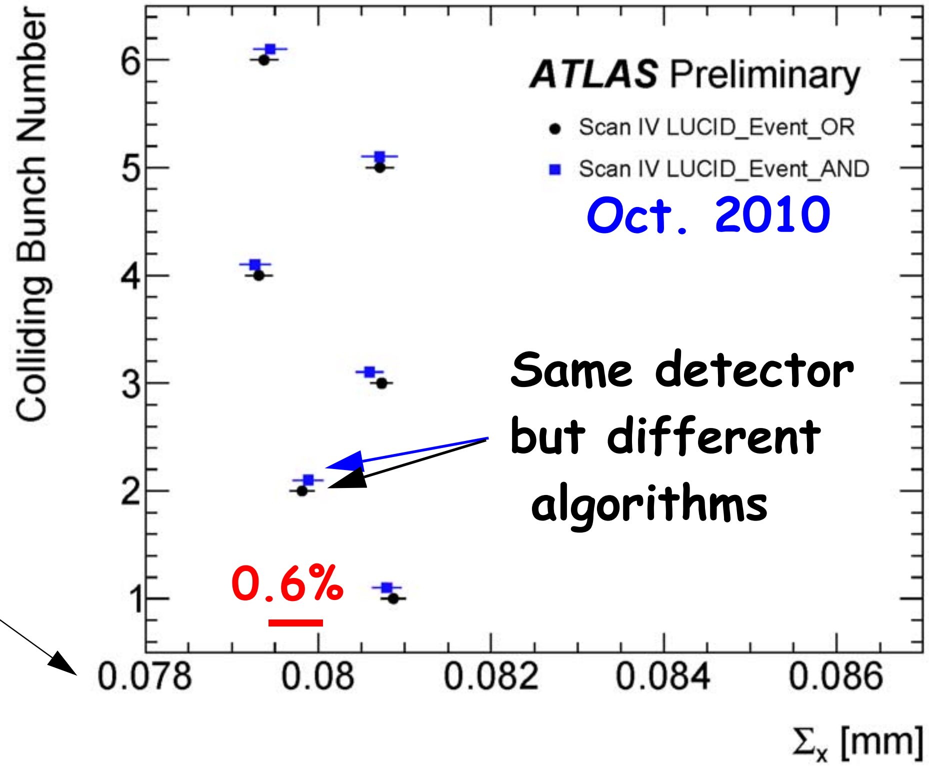
Scan curves ($\mu_{vis}^{peak} \Sigma_x \Sigma_y$)

Current measurements ($n_{p1} n_{p2}$)

μ_{vis} **Scan profile**



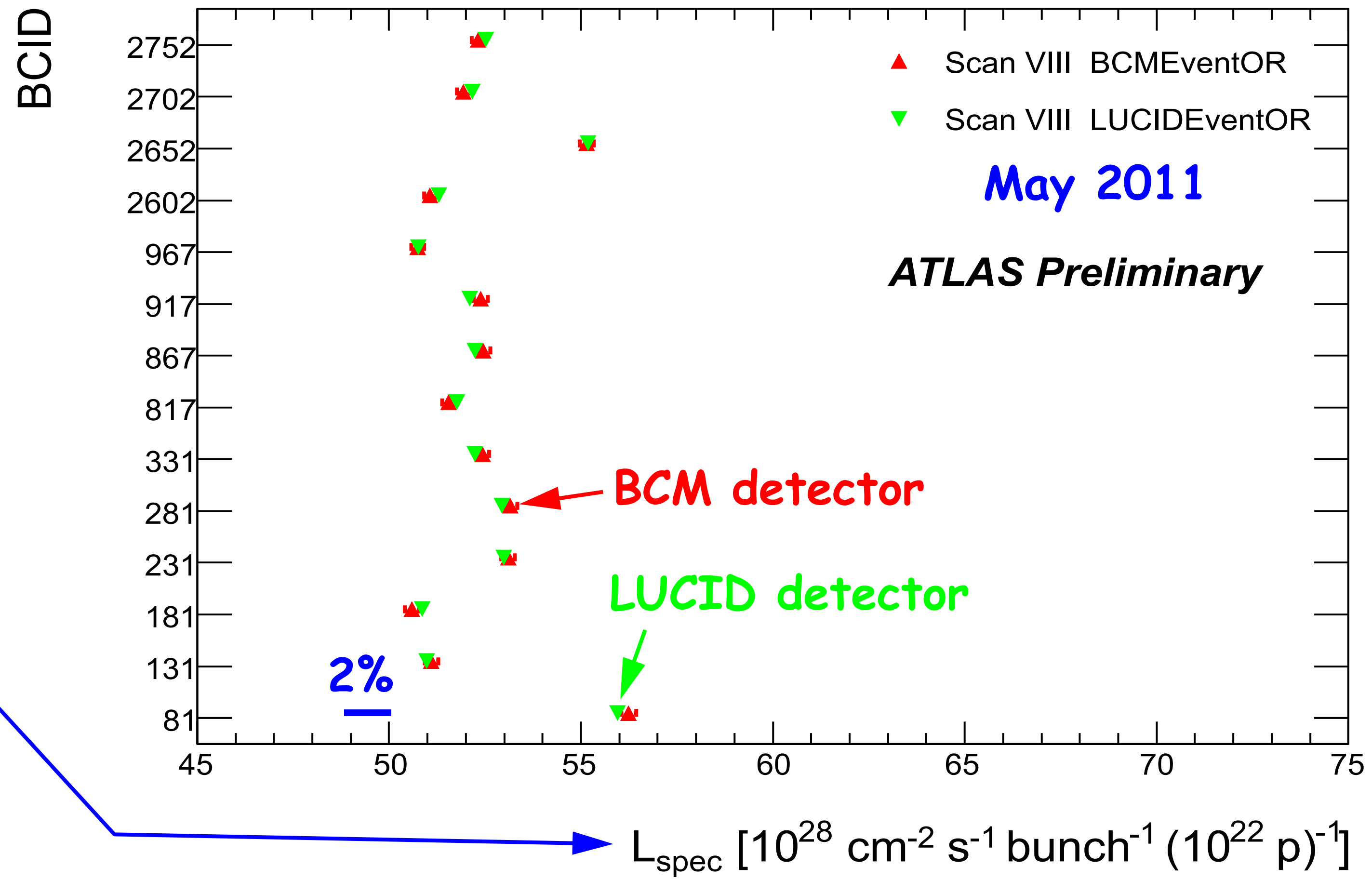
Scan width from fit



Beam separation scans

Specific luminosity:

$$\mathcal{L}^{peak}_{spec} = \frac{f_{LHC}}{2\pi}\frac{1}{\Sigma_x\Sigma_y}$$

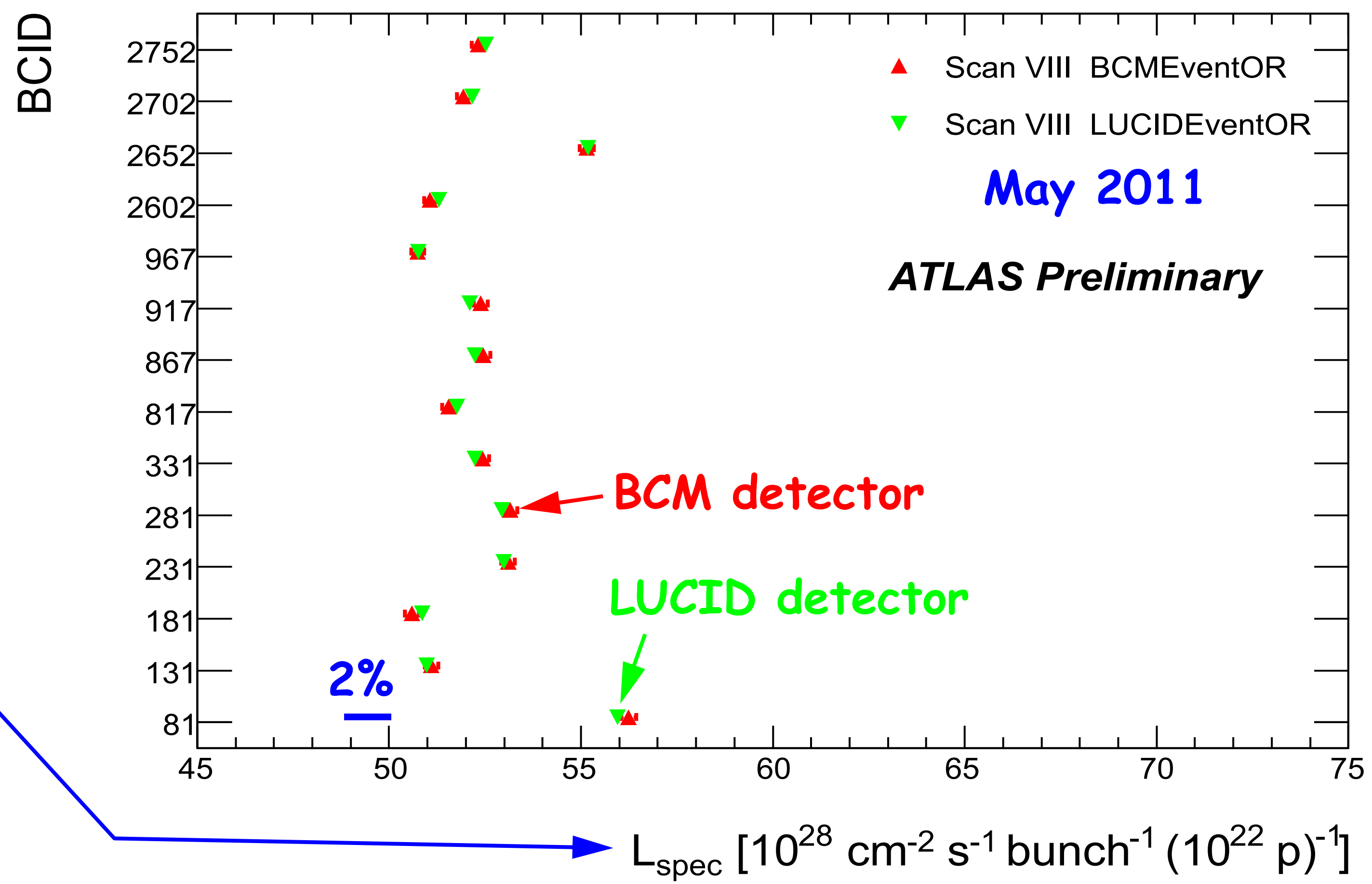


What is the systematic error on $\mu^{peak}_{vis}\Sigma_x\Sigma_y$?

Beam separation scans

Specific luminosity:

$$\mathcal{L}_{spec}^{peak} = \frac{f_{LHC}}{2\pi}\frac{1}{\Sigma_x \Sigma_y}$$



Syst. error on $\mu_{vis}^{peak}\Sigma_x\Sigma_y$ (in 2010)

$\rho(x,y) \neq \rho(x)\rho(y)$ - 0.9%

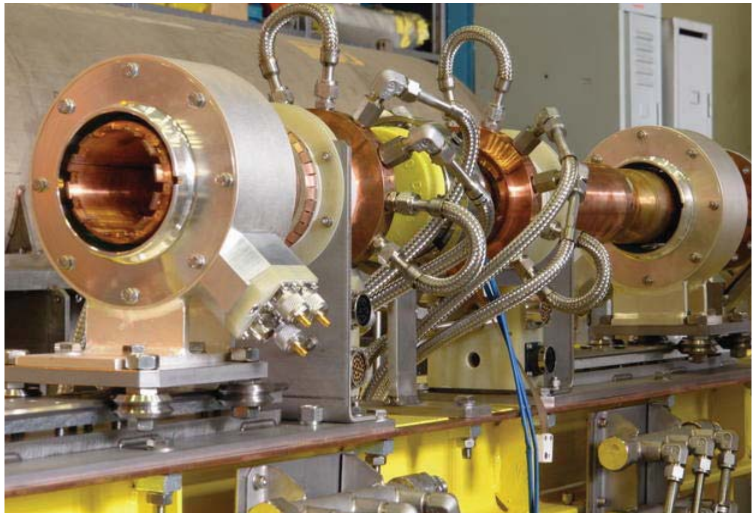
Emmittance growth - 0.5%

Measurement of μ_{vis} - 0.5%

The rest (beam centering, beam position jitter, length scale & fit model) have all $\lesssim$ 0.3% each.

Total error: 1.3%

Current measurements



DCCT: DC Current Transformer
Measures the total current

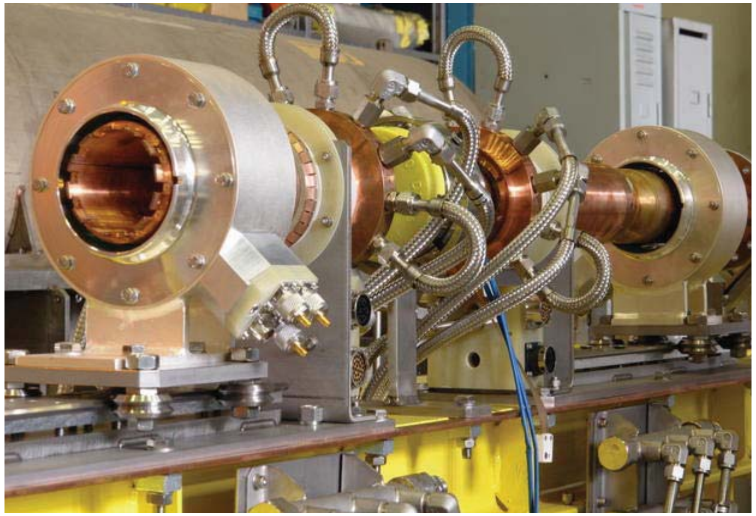
FBCT: Fast Beam Current Transformer
Measures the fraction of the current in each bunch.

Number of protons in bunch j →
Calibrated scale factor → α

$$n_{pj} = \left(\alpha N^{DCCT} - N_{baseline} - N_{ghostcharge} \right) \frac{N_j^{FBCT}}{\sum_j N_j^{FBCT}}$$

What is the systematic error ?

Current measurements



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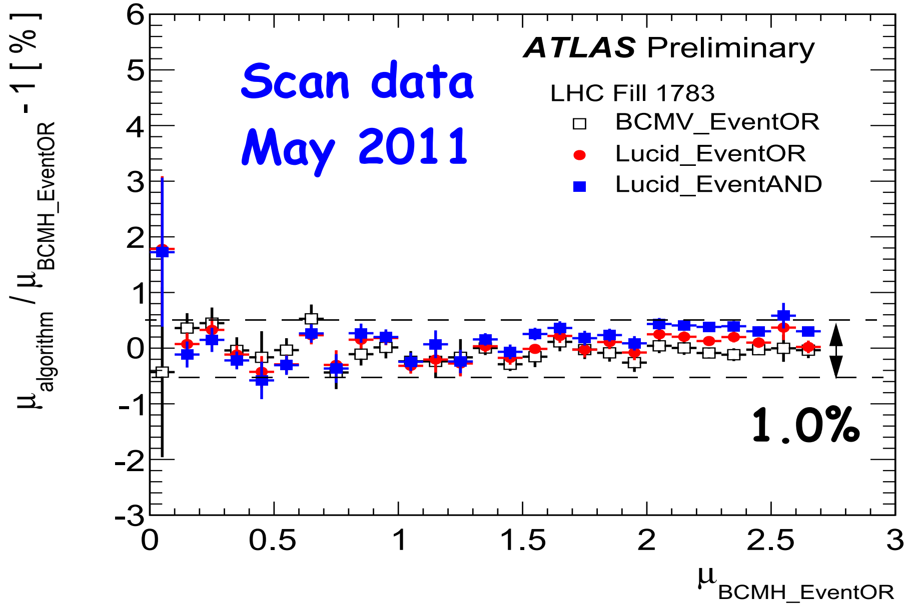
$$n_{pj} = \left(\alpha N^{DCCT} - N_{baseline} - N_{ghostcharge} \right) \frac{N_j^{FBCT}}{\sum_j N^{FBCT}}$$

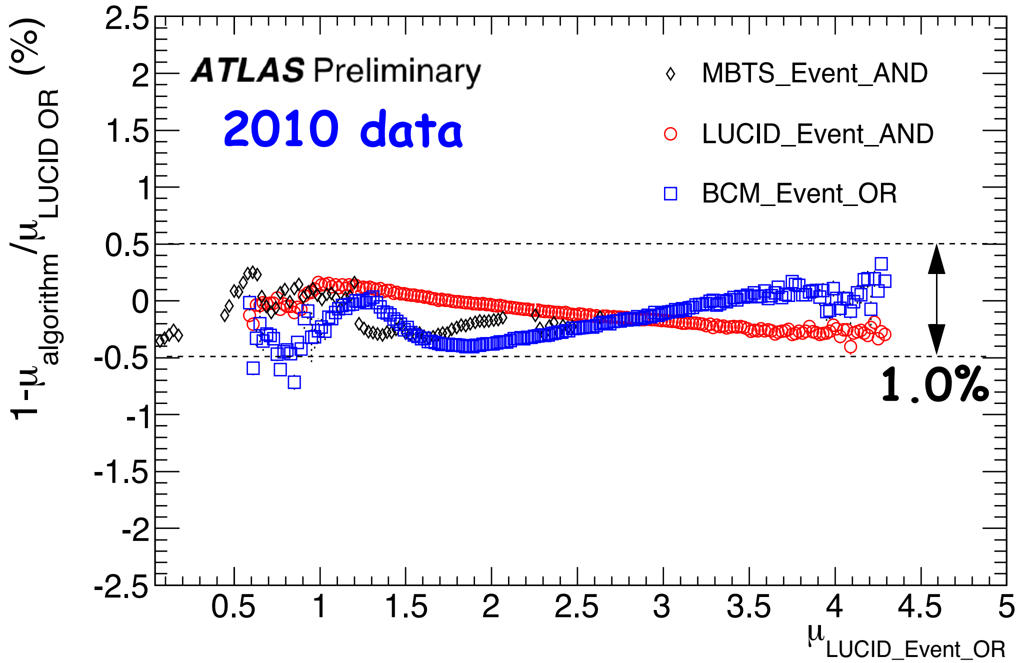
Syst. error on $n_{p1} n_{p2}$: 2.7% $\oplus$ <0.1% $\oplus$ negligible $\oplus$ 1.6% = 3.1%

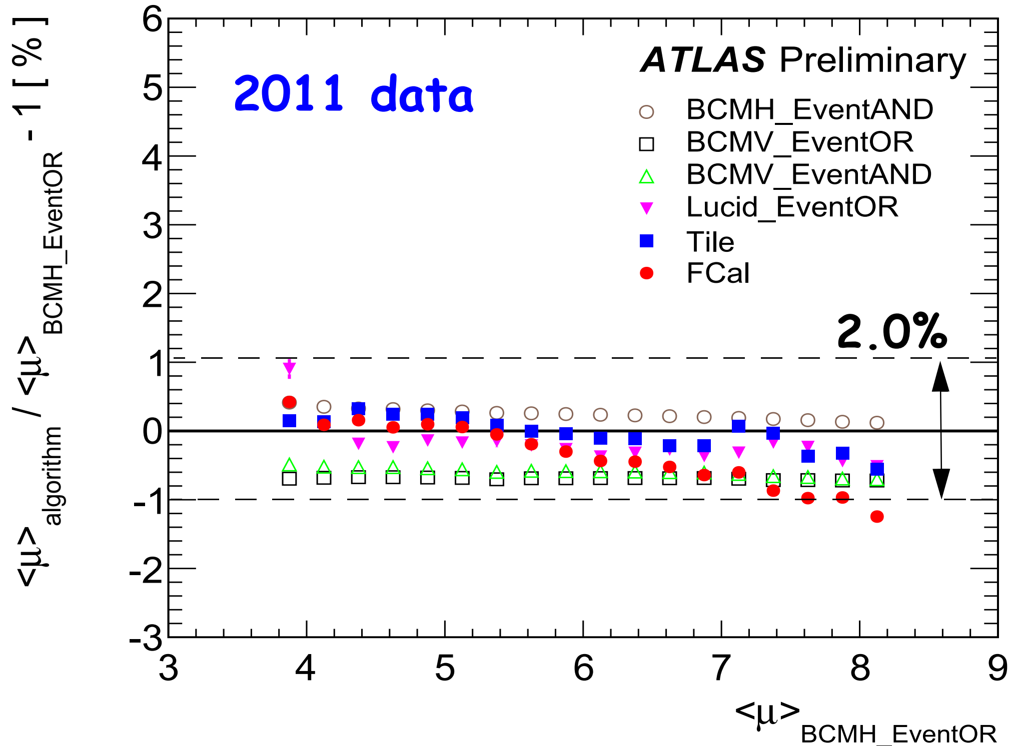
Total calibration error = Error scan $\oplus$ Error current = 1.3% $\oplus$ 3.1% = 3.4%

The determination of μ

Comparison of the μ- (or μ_{vis}) value obtained from different methods and detectors provide the systematic errors in the determination of μ.

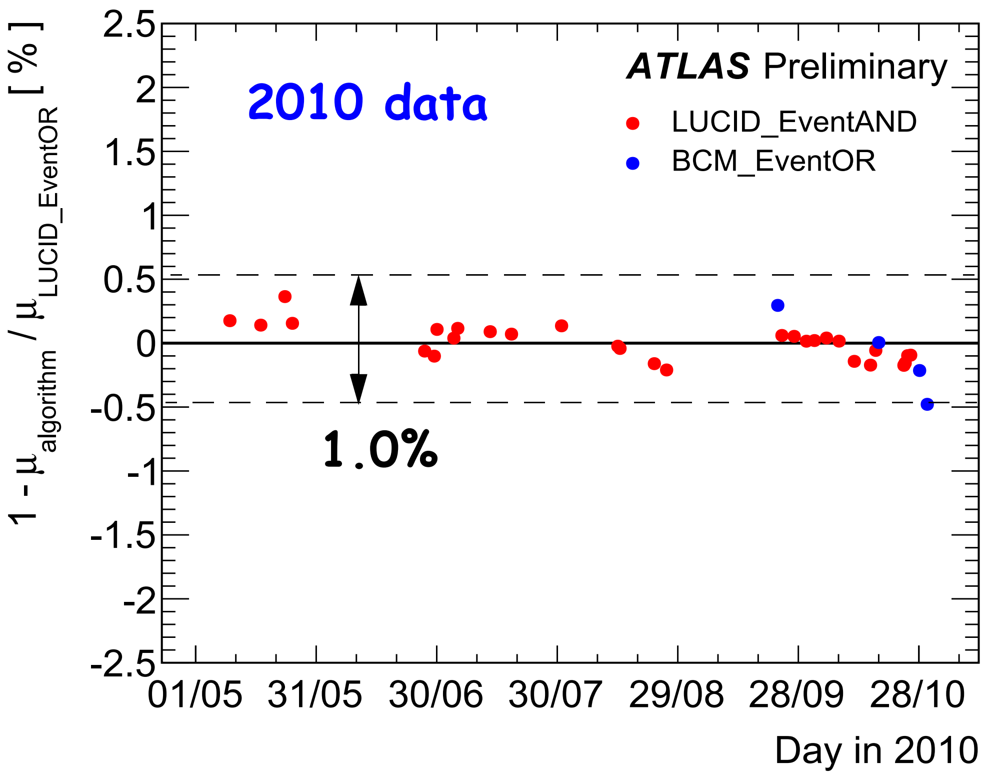


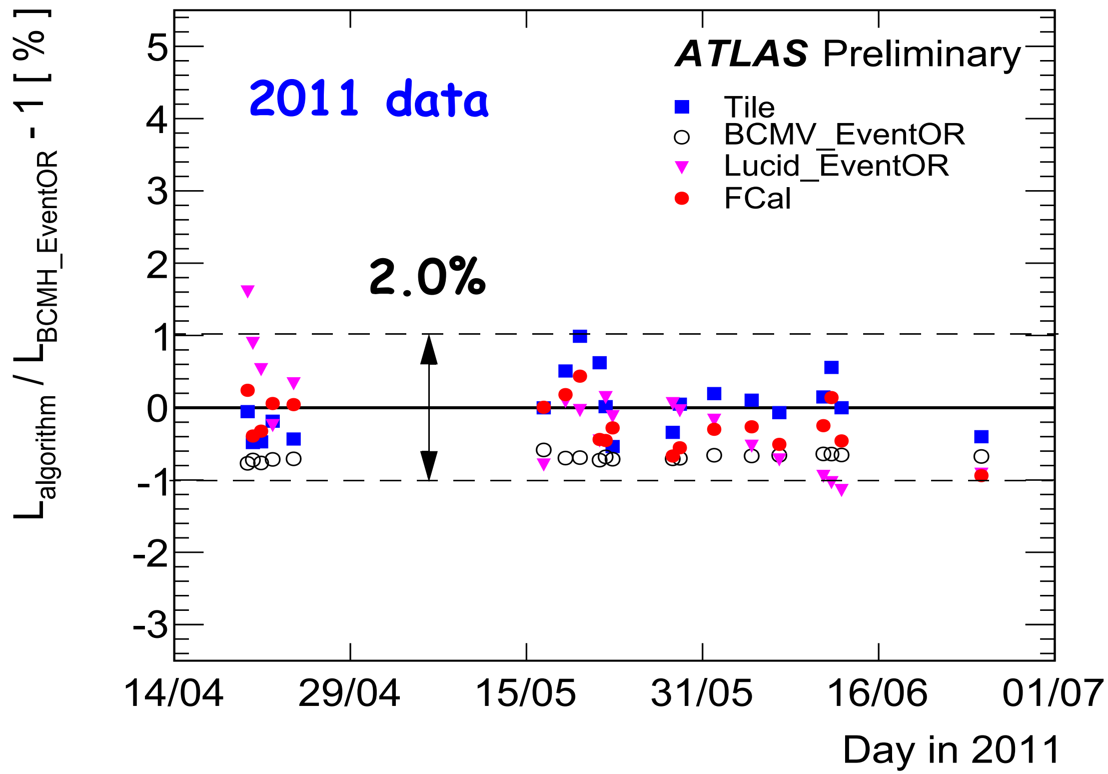




Long-term detector stability

Comparisons of average μ-values from different methods and detectors as a function of time give information about the long-term stability.





Summary

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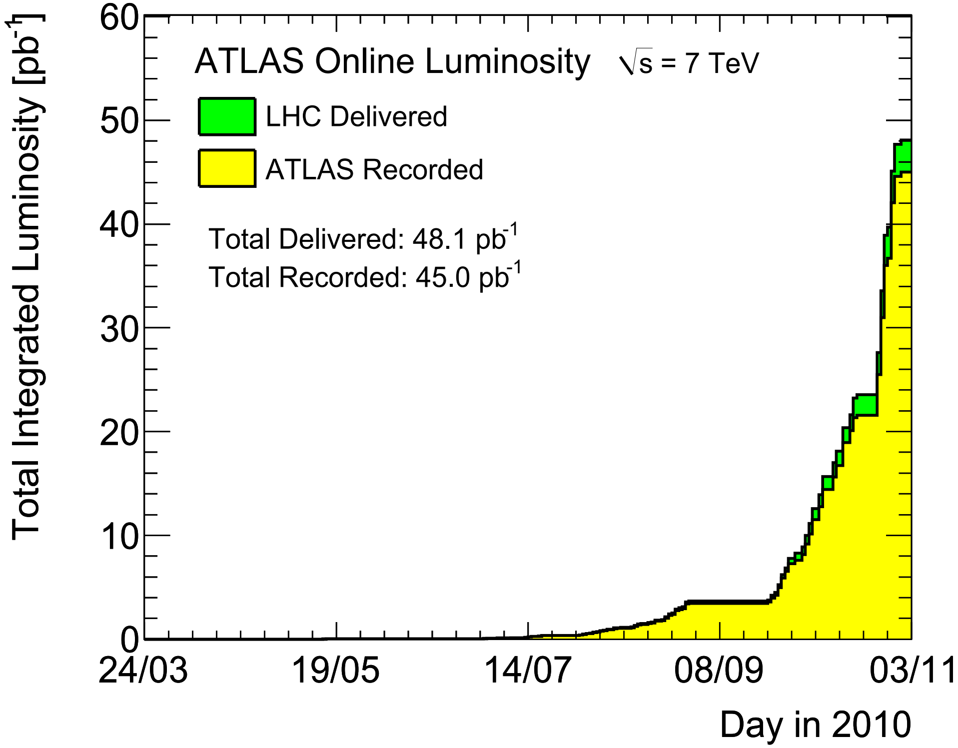
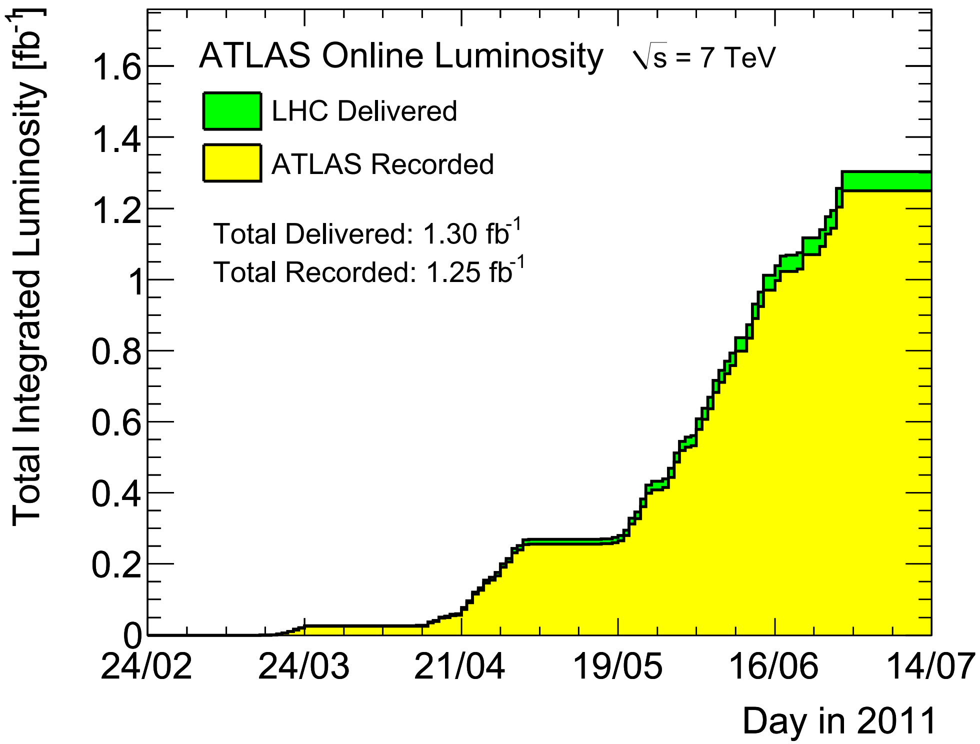
2010



2011 (preliminary)

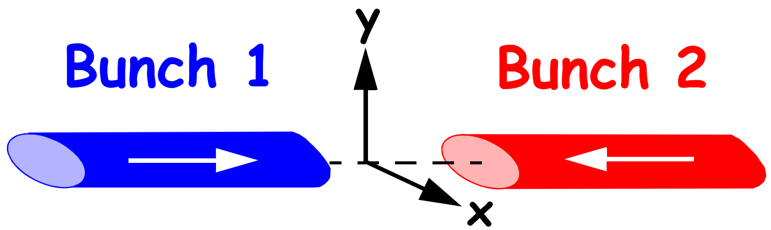


2010		2011	
Calibration error:	±3.4%	Calibration error:	±3.4%
μ determination:	±0.5%	μ determination:	±1.0%
Detector stability:	±0.5%	Detector stability:	±1.0%
Background subtraction:	±0%	Background subtraction:	±0.2%
Total error:	**±3.4%**	**Total error:**	**±3.7%**

Back-up slides

Ways of measuring luminosity

Machine parameters:



n_{p1} n_{p2}

$\rho_1(x,y)$ $\rho_2(x,y)$

$$\mathcal{L}_{BC} = f_{LHC}\, n_{p1} n_{p2} \int \rho_1(x,y)\rho_2(x,y)\,dx\,dy$$

- Number of protons in bunch 1 and 2 → n_{p1}, n_{p2}
- Transverse proton density functions → $\rho_1(x,y)$, $\rho_2(x,y)$
- f_{LHC}: 11245.5 Hz (LHC revolution frequency)

Counting events:

$$\int \mathcal{L} = \frac{N_{events}}{\varepsilon\ \sigma}$$

- N_{events}: Measured number of W,Z or inelastic events
- σ: Cross section from theory
- ε: Efficiency and acceptance from simulation

Elastic scattering:

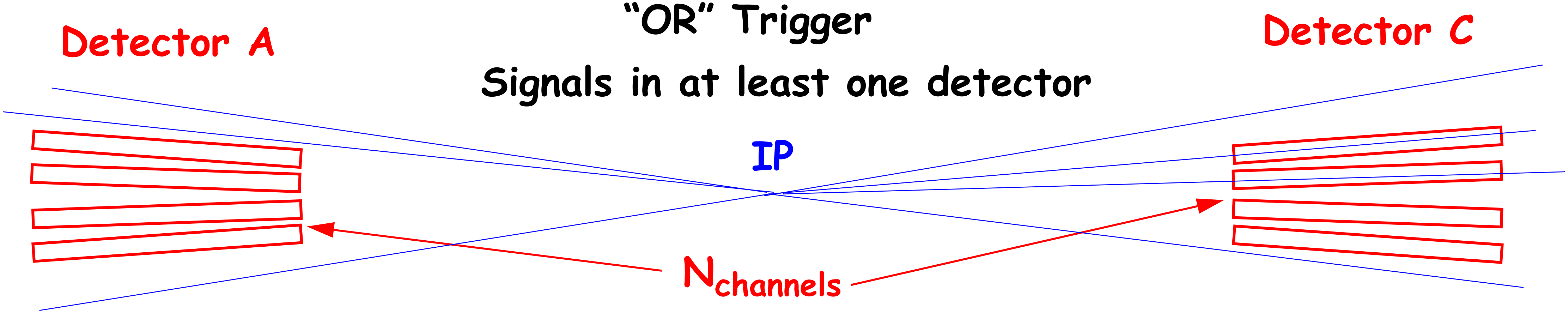
$$\frac{dN}{dt} = \pi \mathcal{L} \left| -\frac{2\alpha}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)\, e^{-b|t|/2} \right|^2$$

- ρ: Ratio of real to imaginary part of the elastic scattering amplitude
- b: Slope parameter

Luminosity triggers

"OR" Trigger

Signals in at least one detector

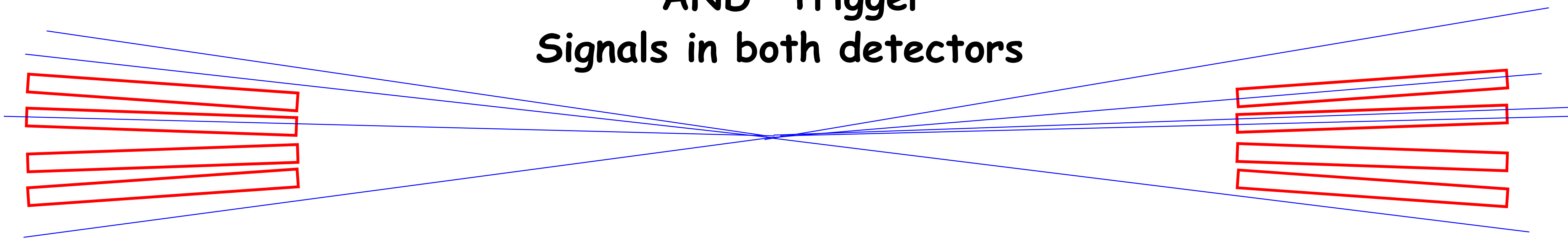


"OR" Trigger

Signals in at least one detector

"AND" Trigger

Signals in both detectors



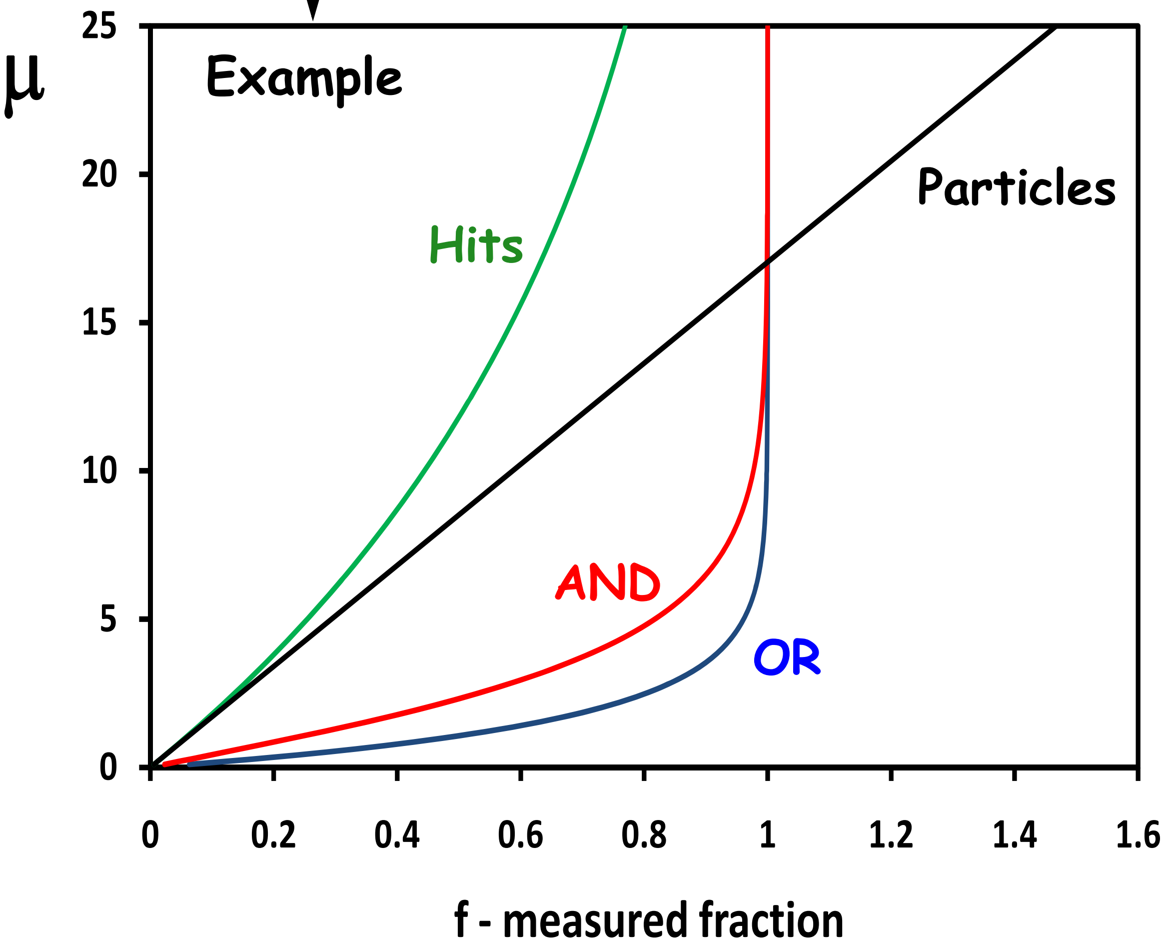
In this example there is 3 "hits" and 4 "particles"

Ways of measuring luminosity

$$\mathcal{L}_{BC} = f_{LHC}\frac{\mu(f)}{\sigma_{inel}} = f_{LHC}\frac{\mu_{vis}(f)}{\sigma_{vis}}$$

"visible μ" is the μ-value obtained from a measurement of a fraction (f) of events, hits or particles .

The "visible cross section" is a calibration constant.



OR-event-counting:

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

AND-event-counting:

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

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

Hit-counting:

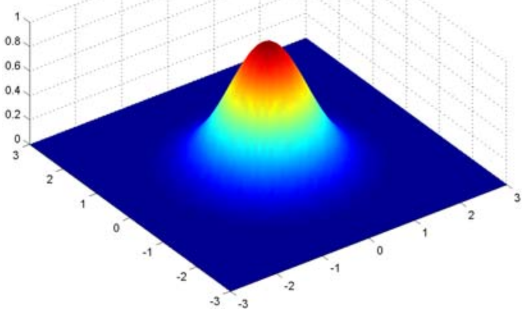
$$f_{hits} = \frac{N_{hits}}{N_{BC}\,N_{ch}} = 1 - e^{-\mu_{vis}}$$

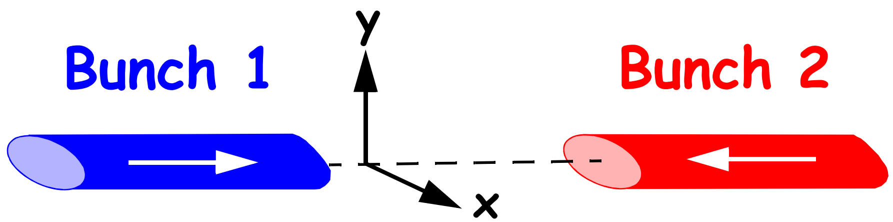
Particle-counting:

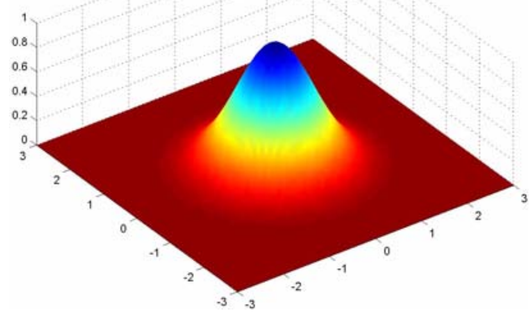
$$f_{part} = \frac{N_{part.}}{N_{BC}\,N_{ch}} = \mu_{vis}$$

Beam separation scans

$\rho_1(x,y)$ ← Transverse proton density functions → $\rho_2(x,y)$





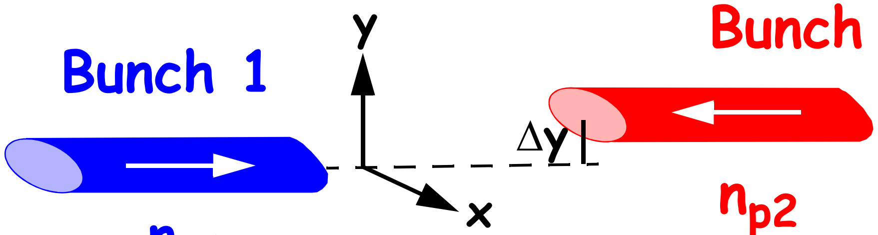


n_{p1} Number of protons

n_{p2} Number of protons

$$\mathcal{L}_{BC}^{peak} = f_{LHC} n_{p1} n_{p2} \int \rho_1(x,y)\rho_2(x,y)\,dx\,dy = f_{LHC}\frac{n_{p1}n_{p2}}{4\pi\sigma^2}$$

If both beams are Gaussian and circular with width = σ.

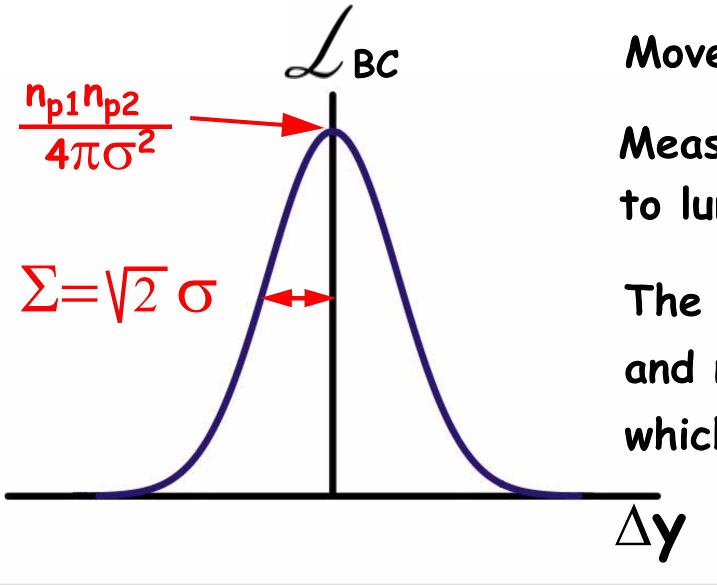


n_{p1}

n_{p2}

$$\mathcal{L}_{BC}^{offset} = f_{LHC}\frac{n_{p1}n_{p2}}{4\pi\sigma^2}e^{-\frac{\Delta y^2}{4\sigma^2}}$$

$$\mathcal{L}_{BC}^{peak} = f_{LHC}\frac{n_{p1}n_{p2}}{2\pi\Sigma^2} = f_{LHC}\frac{n_{p1}n_{p2}}{2\pi\Sigma_x\Sigma_y}$$



Basic idea:

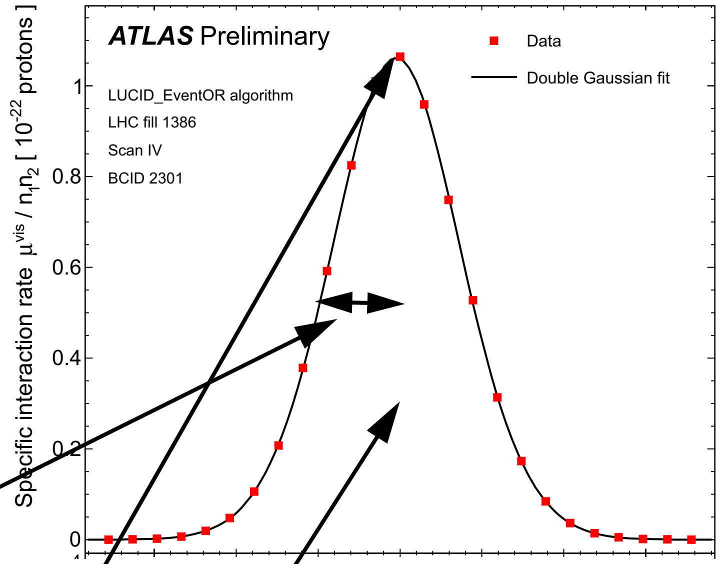
Move the beam(s).

Measure a rate proportional to luminosity.

The Σ from the scan curves and n_p gives peak luminosity which calibrates peak rate.

Beam separation scans

μ_{vis}



Δx

Circular Gaussian beam; $$\mathcal{L}_{BC}^{peak} = f_{LHC} \frac{n_{p1} n_{p2}}{2\pi \Sigma^2}$$

Elliptical Gaussian beam; $$\mathcal{L}_{BC}^{peak} = f_{LHC} \frac{n_{p1} n_{p2}}{2\pi \Sigma_x \Sigma_y}$$

Beam of any shape: $$\mathcal{L}_{BC}^{peak} = f_{LHC} \frac{n_{p1} n_{p2}}{2\pi} \frac{\mu_{vis}(x_0)}{\int \mu_{vis}(\Delta x) d\Delta x} \frac{\mu_{vis}(y_0)}{\int \mu_{vis}(\Delta y) d\Delta y}$$

Background

$\mathcal{L}_{BC}$: **Luminosity for each pair of bunches in the LHC**