Luminosity Measurements

Status summary and **requests** from experiments

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Lumi Days 13–14 January 2011

- Disclaimer
- What we have learnt in 2010
- Thoughts on the van der Meer scans for 2011
- Thanks to Alice, Atlas, CMS and LHCb speakers, theorists, machine experts and Massi for valuable input

Disclaimer

This is not ...

- a workshop summary
- a summary of results of the existing measurements
- a formal request for running conditions

This is

- A collection of thoughts how to do the measurements in 2011
- An attempt to reconcile the requirements for the different experiments

Which precision do we want?

Answer from our theorist friends:

Example III (W and Z production, and determination of PDFs)

$$\int dx_1\, dx_2 \sum_{i,j} f_i(x_1)\, f_j(x_2)\, \hat{\sigma}_{(ij\to Z)}(M_Z, g_{EW}, \ldots) = \frac{N_{events}(Z)}{\text{Luminosity}}$$

- $\hat{\sigma}_{(ij\to Z)}$: **known to 2%, most accurately known elementary cross section at the LHC**
- M_Z, g_{EW}: **known to sub-‰ level**
- $N_{events}(Z)$: **will be measured to sub-% level**

$$\sigma(f_i\, f_j) \sim 2\% \oplus \sigma(\text{lum})$$

The real precision cannot be estimated naively like this, because of the convolution integral, external constraints on the range of PDFs, etc. See later for concrete examples

This is the process that defines, as of today, the ultimate target of the absolute luminosity measurements:

± 2%

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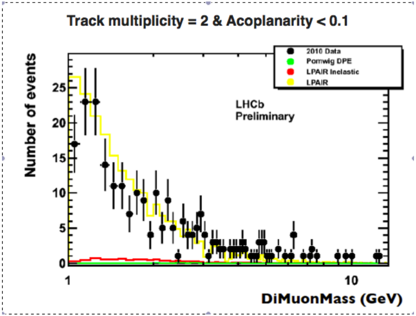
Which precision do we want?

Benchmark with EW processes



Luminosity measurements with exclusive dimuons from photon fusion

- Cross-sections predicted with < 1% uncertainty
- 250 candidate events selected in 17.5 pb^{-1}
- Purities seem high (more work needed)
- Work on understanding efficiencies has only just begun
- Exclusive JPsi, Psi' and ChiC events have also been isolated and compared to MC

LHC Lumi Days (13/01/11)

Jonathan Anderson

Direct measurements

Average instantaneous luminosity for one pair of colliding bunches

$$L = n_1 n_2 f \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \frac{(\vec{v}_1 \times \vec{v}_2)^2}{c^2}} \int \rho_1(x,y,z,t)\rho_2(x,y,z,t)\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z\, \mathrm{d}t \ , \tag{1}$$

revolution frequency f (11245 Hz)
numbers of protons in the bunches n_1 and n_2
velocities $\vec{v}_1$ and $\vec{v}_2$
half crossing-angle θ
normalized bunch densities $\rho_j(x,y,z,t)$

for highly relativistic beams colliding with a very small half crossing-angle θ the Møller factor reduces to $2c\cos^2\theta \simeq 2c$

Beam–gas imaging method

The beam–gas imaging method (proposed by Massi in 2002) uses this equation directly

$$L \approx \frac{n_1 n_2 f}{4\pi \sqrt{\left(\sigma_1^{x\,2} + \sigma_2^{x\,2}\right)\left(\sigma_1^{y\,2} + \sigma_2^{y\,2}\right)}} \tag{2}$$

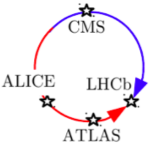
neglecting the crossing angle and beam positioning offsets

LHCb has used this method
in addition to the van der Meer scan method $\rightarrow$
Emphasis in this talk on the van der Meer method

Beam-gas imaging

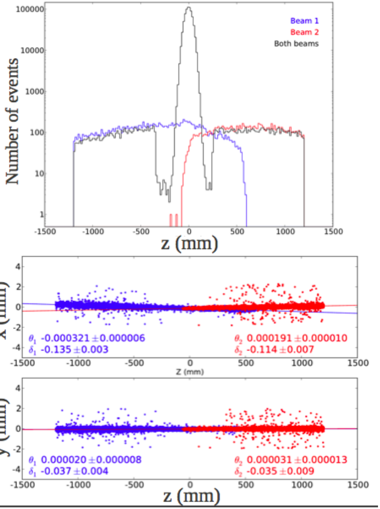
Beam Images

- Visualize the beams with beam-gas interaction vertices
- Fill 1101: 4 bunches/beam, 2 colliding pairs in LHCb



- Crossing angle [µrad]:

	measured	expected
horizontal plane:	512 ±16	540
vertical plane :	11 ± 21	0



P. Hopchev LHC Lumi Days 2011 5

Van der Meer method

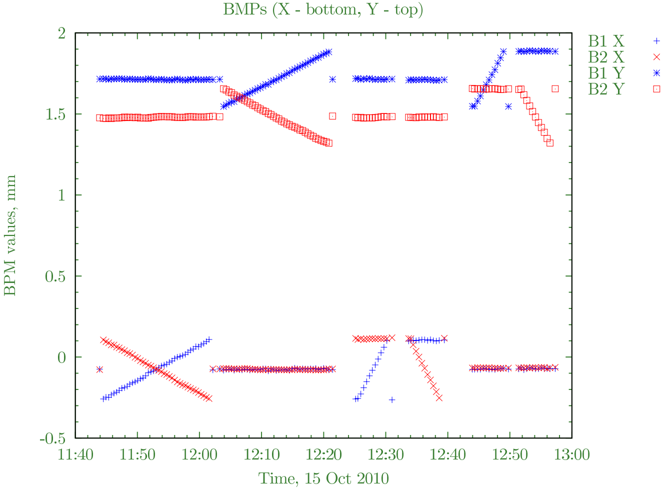
Van der Meer proposed the scanning method for the ISR

$$\sigma = \frac{\int R(\Delta(x),\Delta(y_0))d\Delta(x) \times \int R(\Delta(x_0),\Delta(y))d\Delta(y)}{n_1 n_2\, f\, R(\Delta(x_0),\Delta(y_0))} \tag{3}$$

using scans by creating offsets $\Delta(x)$ and $\Delta(y)$
measure the rates $R(\Delta(x_0),\Delta(y))$
Under the assumption that he functions factorize in x and y:
One “crossed” measurements moving x and then y is sufficient

Typical scanning procedure

BPM positions as a function of time.



Measurements in VDM fills

Experiments have shown that the VDM scans of 2010 can already give ≈5% precision.
One needs to perform the following measurements:

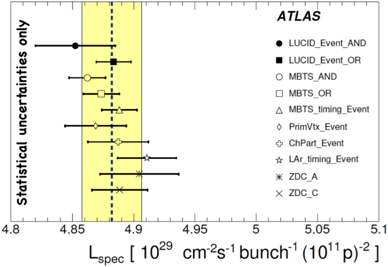
- VDM scan
  - x-scan, then y-scan
  - two x–y scans for cross-checks
  - simultaneous/single beam movements
- Length scale calibration
- x–y coupling checks
- Satellite and Ghost current measurements
- **Beam Current Normalization!**

Precision of Atlas measurement in May

New analysis of beam currents halves the biggest systematics and more improvements are possible.

Specific luminosities – May

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



Systematic uncertainties (will discuss in next slides)

Source	Uncertainty on σ_{vis} (%)
Beam intensities	10
Length-Scale	2
Beam centering	2
Emittance growth*	3
μ 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%

Optimizing next year's runs

Take parameters one-by-one and profit from 2010 experience.

Warning: every change may need new machine development and qualification.

Choice of filling scheme

Limited number of bunches:

- NO trains! Isolated bunches. (satellite current, afterglow in detectors)
- per-bunch analysis
- enable wire-scanners
- *private* bunches, i.e. colliding in 1+5, 2 and 8 separately

Atlas about 6 bunches

CMS 'few", up to 12, bunches

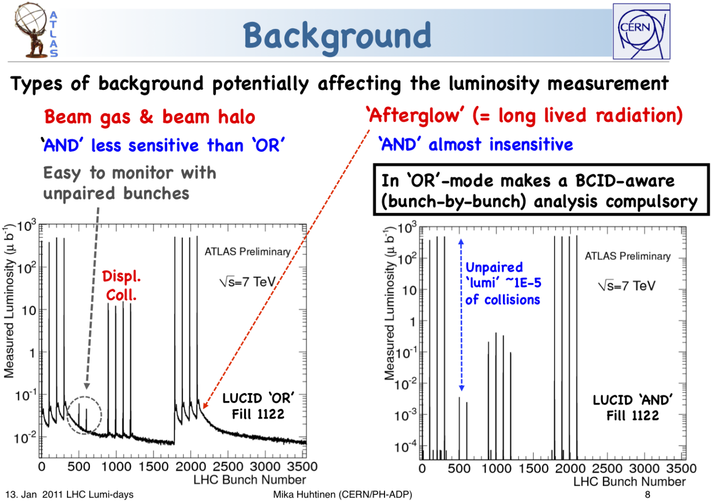
Alice 1 bunch

LHCb 12 bunches

For DAQ: surplus bunches can be masked
Wirescan sets limit at 20–30 for the total
Thus a sum of 6–12 + 1 + 12 looks reasonable

"Afterglow" seen in Atlas

Large bunch spacing helps:



Choice of μ

μ: number of visible interactions per bunch crossing

Atlas, CMS, LHCb favour $\mu \approx 1$ or a bit higher (up to $\mu \approx 2$)
This value gives reasonable pile-up
optimizes rate, important at large separation

Alice favours $\mu \approx 0.1$ or a bit higher (up to $\mu \approx 0.5$)

rate optimization sets constraints on combination of ϵ, β^*, and intensity

Statistics of fits (example: CMS)

Rate is fine for the measurements

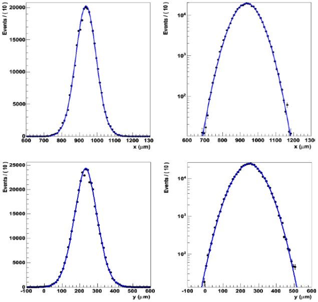
Fit examples

B1H Bx=101

B2H Bx=101

B1V Bx=1

B2V Bx=1



- ✓ Error is estimated from the distribution of the A_{eff} obtained by varying the fit parameters (+/-1 σ) around the minimum accordingly to the covariance matrix
- ✓ In all cases, statistical uncertainty of the order of few per mille

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Choice of β^*

- use preferentially existing optics to reduce MD time
- may need qualification in collision
- large values make it easier for vertex detector to measure shape
- ... but rate needs to stay high enough

Atlas not too small, i.e. 3.5–10 m (10m may give too low rate)

CMS 3.5 m is OK

Alice no specific request, just rate (maybe needed to go to 10 m to reconcile all requests)

LHCb 3.5 (or to combine with beam-gas method 10 m is better)

Choice of ϵ

- in 2010 emittance was increased in SPS for physics
- too low values enhance beam-beam effects
- using either the physics value, or slightly enlarged values seems reasonable
- It is good to make the colliding bunch-pairs symmetric (beam1 vs beam2)

- For Atlas "physics" values are acceptable
- LHCb prefers "2010" values, important to equalize beams (BG method)

No specific request, but ϵ can be used to tune the rate and beam sizes
Is it feasable to apply emittance blow-up in SPS on individual bunches?
Interesting to study systematics!

Choice of bunch intensities

- lower bound given by beam instrumentation
- ... and required counting rate
- high values may increase beam-beam effects
- ... and pile-up corrections (experiment dependent)
- if wire scans required, total current is limited

The following values are approximate and depend on the β^* and ϵ values

Atlas E11

CMS E11

Alice 5E10 orbit measurements $\rightarrow$6E10

LHCb E11

Together with the requested number of bunches, these intensities make offset corrections in the BCTs negligible.

Putting it together

ballpark numbers!

Vary I, β^* and ϵ values to reconcile requests
Try to stay within reasonable limits

Atlas 6-12 bunches, E11, and $\beta^* = 3.5$m

CMS 6-12 bunches, E11, and $\beta^* = 3.5$m

Alice 1 bunch, 6E10, and $\beta^* = 10$m

LHCb 12 bunches, 1.2E11, and $\beta^* = 10$m or 1E11, and $\beta^* = 3.5$m if no beam-gas

question:

Is it optimal to run the machine with this intensity pattern?

Choice of crossing angle

- Alice and LHCb have an internal crossing angle
- Atlas and CMS can run without, if they wish
- zero angle allows measurement of satellites
- If the LDM (longitudinal density monitor) is operational it can provide the satellite measurement.

The crossing angle does not introduce corrections to the VDM method (except for effects of satellites)
No compelling reason to have a zero angle, especially when LDM can be used to measure satellites.
LHCb prefers a finite angle (≈ 0.4 mrad to eliminiate parasitic collisions which kill the beam-gas method.)

$\rightarrow$Could run at physics crossing angles

Scanning procedures

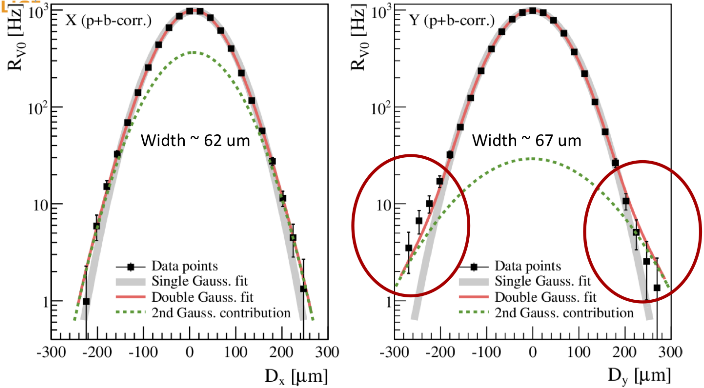
- separations of up to 6 sigma seem optimal
- e.g. first x, then y
  - can choose working point different from maximum
  - Atlas prefers to recenter after the first coordinate
- benefit from two full scans in one fill
- beam movements
  - symmetrically opposite with two beams (control beamspot position)
  - or fix one beam and move the other (may limit separation, helps for imaging method)
  - different procedures can reveal some systematics

Important to have fully automated procedures: reduce time spent, and allows experiments to follow on-line For flexibility in the operations it may be needed to make the "file-based"

Tails observed in Alice scans

Sufficient number of σ in important

Fitting Methods (Scan-I)



- **Normal gaussian and double gaussian (g1+g2 with same center) were tested**
- **For Y-scan, tail needs double gaussian or even asymmetric gaussian**

Jan. 13, 2011 **K. Oyama, LHC Lumi-day workshop** **18**

Supporting measurement procedures

Study x–y coupling

- at least one "u"-scan

Study length scale

- original Atlas method may be a bit too time-consuming (find maximum at each point)
- CMS/LHCb method by co-moving beams at 1 sigma separation reveal some interresting effects
- combine the two methods by a single simplified procedure, "leap-frog" movement where each point in x is measured against 3 in y (at 1 sigma) – need automated procedure!

Hysteresis

There is some fear that hysteresis effects limit us.

- Good ideas needed to get more knowledge
- What constraint is given by scans in inverted directions?
- May want to design specific tests – e.g. separate at 1σ moving one beam and back and measure rate?

Beam instrumentation

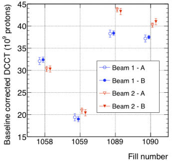
Experiments rely on the excellent performance of the beam instrumentation

- DCCT systems for absolute scale
- FBCT for bunch-to-bunch
- LDM for satellites
- wire scanners
- BPMs
- emittance measurement
- etc.

In addition, LHCb beam-gas trigger can provide constraints on debunched beam.

Beam current measurement is essential!

Baseline offset results for April/May scans



- use average (System A + B)/2
- fix baseline offset uncertainty to largest uncertainty: 0.8 x 10^9 p

Fill nr.	LHC ring j	Detailed analysis (System A + System B) LHC intensity $N_{\mathrm{tot},j} \cdot 10^{-9}$ baseline-corrected	Preliminary analysis (System A) LHC intensity $N_{\mathrm{tot},j} \cdot 10^{-9}$ baseline-corrected
1058	1	32.3 ± 0.8	31.8 ± 2.0
	2	30.3 ± 0.7	28.4 ± 2.0
1059	1	19.2 ± 0.8	18.9 ± 2.0
	2	20.7 ± 0.7	20.6 ± 2.0
1089	1	38.4 ± 0.8	38.1 ± 2.0
	2	43.5 ± 0.7	43.7 ± 2.0
1090	1	37.4 ± 0.8	37.4 ± 2.0
	2	40.6 ± 0.7	40.0 ± 2.0

baseline offset uncertainty only

unify to 0.8

- baseline offset uncertainty reduced from 2×10^9 to 0.8×10^9
- some central values changed

Thilo Pauly -- Bunch Current Normalisation Analysis Results -- LHC Lumi Days 13 January 2011 10

Combination with beam-gas imaging method

Important systematics check by performing VDM and BG in the same fill
LHCb would like to make combined fill

- Can be in the shadow of the other experiments' scans
- Pressure bump (Degraded vacuum) – tested, gives factor 4 rate
- Need a few hours of stable conditions
- Beam current normalization effects drop out (in the comparison)
- Offsets can be precisely cancelled first
- Ratio of beam sizes can also be measured using scans (looking at the beam spot position)

Many cross-checks possible!
Common optimization of requirements push towards largish β^* (vertex resolution)

Other ideas

Can we do the scans simultaneously?
Obvious gain in time
Do we control the induced beam movements?

More frequent VDM scans at end of fills under physics conditions?

- Useful for width measurements
- Can we get competing luminosity measurements?

LHCb could run beam-gas measurements at 10 m during TOTEM/ALPHA runs (to be discussed)

Conclusions

- A precise measurement of the luminosity is wanted down to the % level
- For first year operation the precision reached is surprisingly good
- This was only possible thanks to close collaboration of machine experts and experiments
- Requirements of the experiments are quite diverse
- Still they may be accommodated by the machine
- This talk is just an attempt to start the discussion

Disclaimer:

The above is no formal request yet!