Impact of Beam-Beam Effects on Precision Luminosity Determination at the LHC

W. Kozanecki (CEA Saclay), with W. Herr & T. Pieloni (CERN)

- ❍ **Introduction: luminosity-determination strategy & precision goals**
- ❍ **Beam-beam effects**

- ❍ **Do 's & don't 's: lessons learnt**
- ❍ **Do' s & don't 's: wish list for 2015 (& somewhat beyond)**
  - **all known issues – not just those beam-beam related**
- ❍ **In conclusion...**

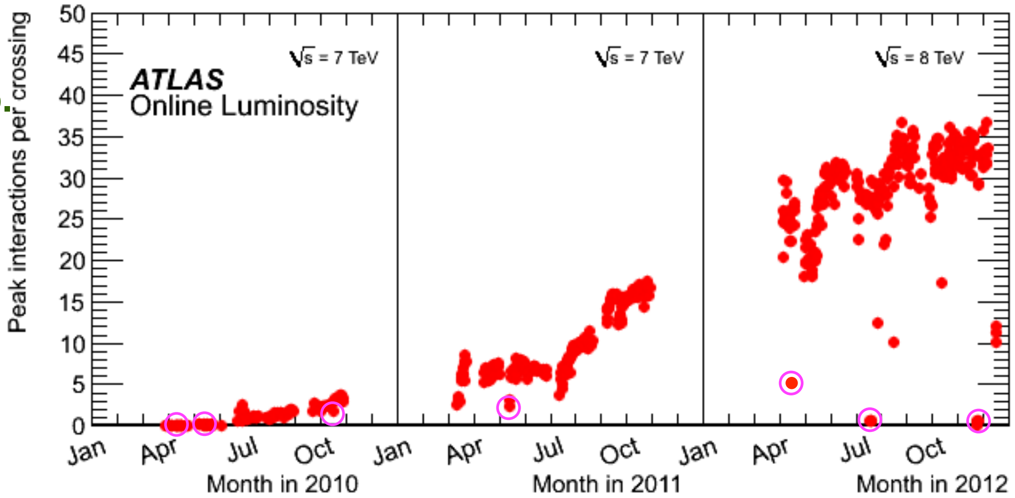
Introduction: luminosity-determination strategy and precision goals

- **Physics running**
  - **Max. pile-up parameter (2012): $\mu_{pk} \leq 35$ inel. pp collisions/BX**

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

ATLAS

- **$\mathcal{L}$ determination**
  - **absolute calibration**
    - van der Meer scans, $\mu_{pk} \sim 0.5 - 5$
  - **high rate effects & μ-dependence: physics conditions**
    - non-invasive monitoring
    - μ-scan: msre relative μ-dep. at one point in time
  - **long-term stability: physics conditions**
    - non-invasive monitoring



Luminosity Basics

$\mu_{vis} = \varepsilon{*}\mu$ = Mean number of interactions per BX seen by detector

μ: mean number of inelastic interactions per BX

Total inelastic rate

$$\mathcal{L} = \frac{\mu\, n_b\, f_r}{\sigma_{inel}} = \frac{\mu_{vis}\, n_b\, f_r}{\sigma_{vis}}$$

Inelastic cross section (unknown)

Cross section seen by detector

- σ_{vis} is determined in dedicated fills based on beam parameters

Calibrating σ_{vis} in van der Meer (aka "vernier") Scans

- **Luminosity in terms of beam densities ρ_1 and ρ_2:**

$$\mathcal{L} = n_b\, f_r\, n_1 n_2 \int \rho_1(x,y)\rho_2(x,y)dxdy$$

- **<u>Under the condition</u> that the integral <u>factorises</u> into uncorrelated x & y components:**

$$\mathcal{L} = \frac{n_b\, f_r\, n_1 n_2}{2\pi\, \Sigma_x \Sigma_y}$$

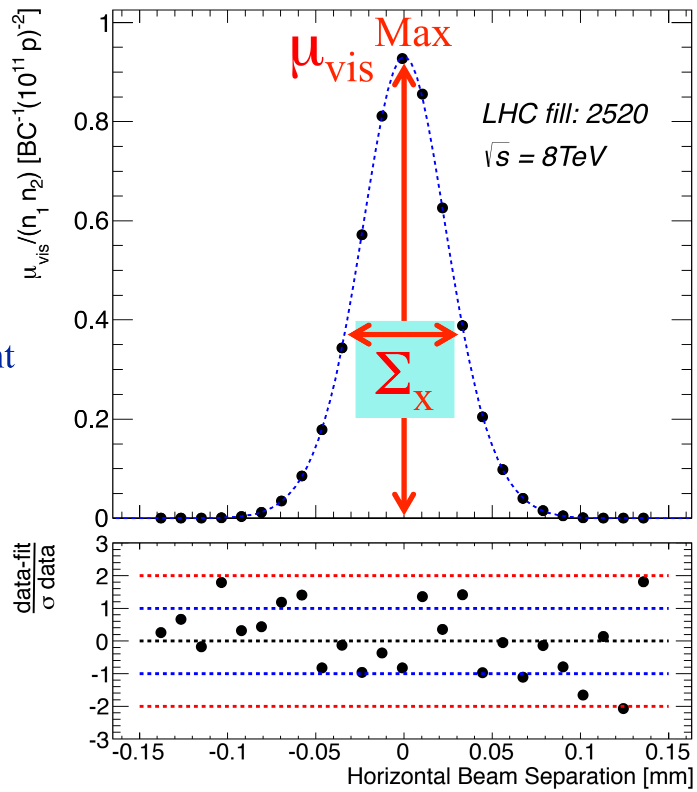
Measured in vdM scan

Detector independent

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

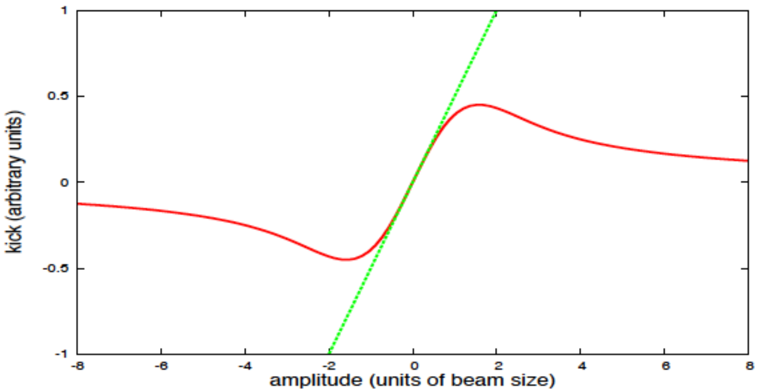
Detector dependent

Measured by beam instrumentation



The not-so-good: dynamic β

- **Colliding beams exert strong force on each other**
  - optics changes due to (de)focusing force
    - for head-on collisions
      - small amplitude: linear force (~ quad)
      - loss or gain in $\mathcal{L}_{peak}$
      - but no $\mathcal{L}$-calibration bias



    - during *vdM* scan
      - large amplitude: non-linear force
      - distorts scan curve → $\mathcal{L}$-calibration error ?

- **Focusing by b-b interaction Δk(s) leads to phase change Δμ and "optical error" $\Delta\beta(s_0)$**
  - In perturbation theory:

$$\Delta\beta(s_0) = -\frac{\beta(s_0)}{2sin(2\pi Q)} \quad X$$

$$\int_{s_1}^{s_1+C} \beta(s)\Delta k(s) cos\left[2(\mu(s)-\mu(s_0))-2\pi Q\right] ds$$

    - s and s_0 are interaction points (IP)
    - must take into account all potential IPs
  - special case: $s = s_0$ (1 IP), head-on

$$\frac{\beta^*}{\beta_0^*} = \frac{sin(2\pi Q)}{sin(2\pi(Q+\Delta Q))} = \frac{1}{\sqrt{1+4\pi\xi cot(2\pi Q) - 4\pi^2\xi^2}}$$

- **Optics code required**
  - If optics change → beam-beam force changes → optics change: self-consistent calculation needed
  - Take into account all IP's
  - Build beam-beam element → MADX

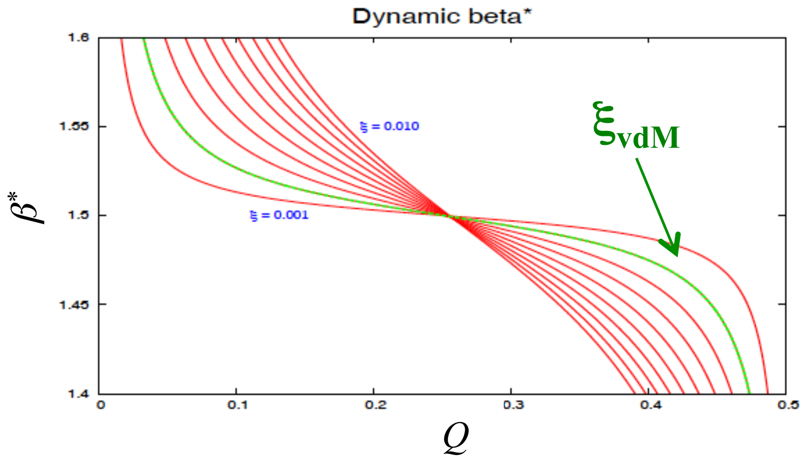
Dynamic β: head-on (“static”) case

- **Simulation parameters: May’11 vdM scans [typ. physics]**

E_b (TeV)	3.5
N_p (10^{11})	0.85 [1.5]
ε_N (μm-rad)	4 [2.0-2.5]
β^*_0 (m)	1.5
Q_x/Q_y	0.31 / 0.32

- **Observations**
  - Dynamic β for (multiple) head-on collisions visible
  - Depends on
    - Beam-beam parameter ξ (N_p, ε_N)
      - note $\xi_{vdM} < \xi_{physics}$
    - Collision pattern
    - Phase advance between IP’s

- **Collisions at IP1 only**



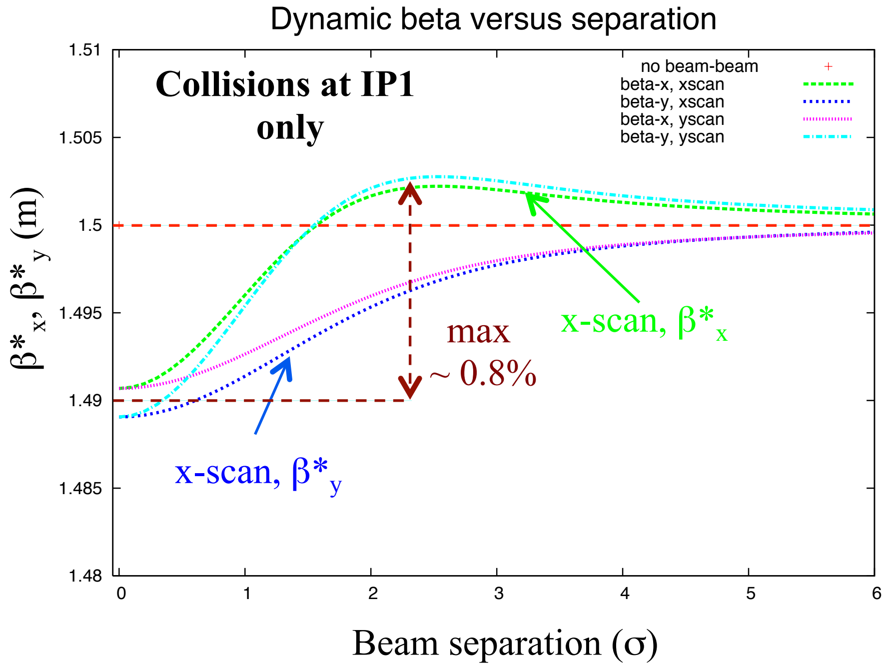
- **Collisions in IP1 &/or IP5 only**

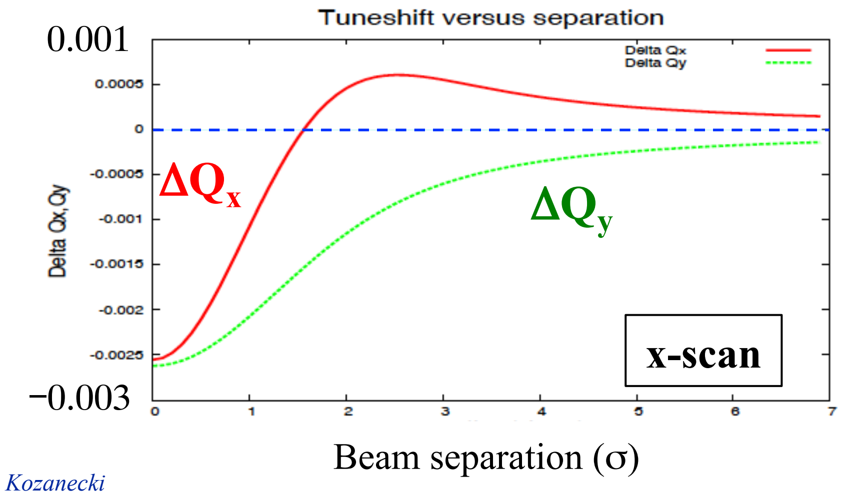
	IP1		IP5	
Collisions	β^*_x/β^*_{0x}	β^*_y/β^*_{0y}	β^*_x/β^*_{0x}	β^*_y/β^*_{0y}
no	1.000	1.000	1.000	1.000
IP1	0.994	0.993	0.989	1.018
IP5	0.989	1.018	0.994	0.993
IP1 + IP5	0.983	1.011	0.983	1.011

- **Other collision patterns**
  - see W.H., Proc. Lumi Days 2012

Dynamic β: variation during luminosity scan

- **During luminosity scan**
  - **Strength of the force is changing (both planes)**
  - **Sign of the force is changing (in scanning plane, defocusing → focusing)**
  - **Must expect more complicated pattern**
    - **Illustrate with simulated scans in IP1**
    - **Effects for scans at other IPs similar**
    - **Add'l collisions change starting values**

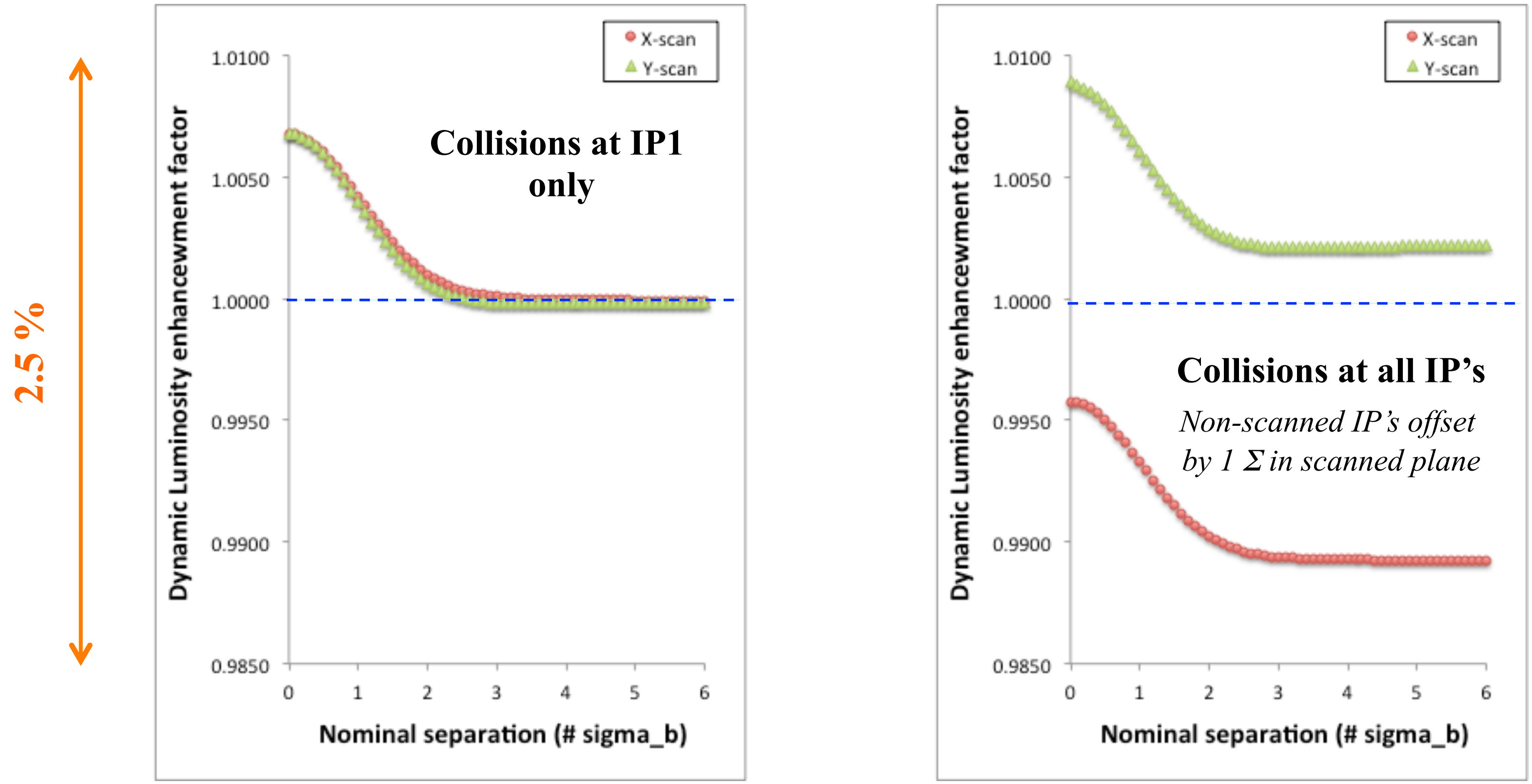




- **For a given plane (β^* x or y) and scan direction (x or y)**
  - **Dependence on separation always the same**
  - **Starting value different, depends on ξ and on collision pattern**

Dynamic-β: impact on luminosity-scan curves

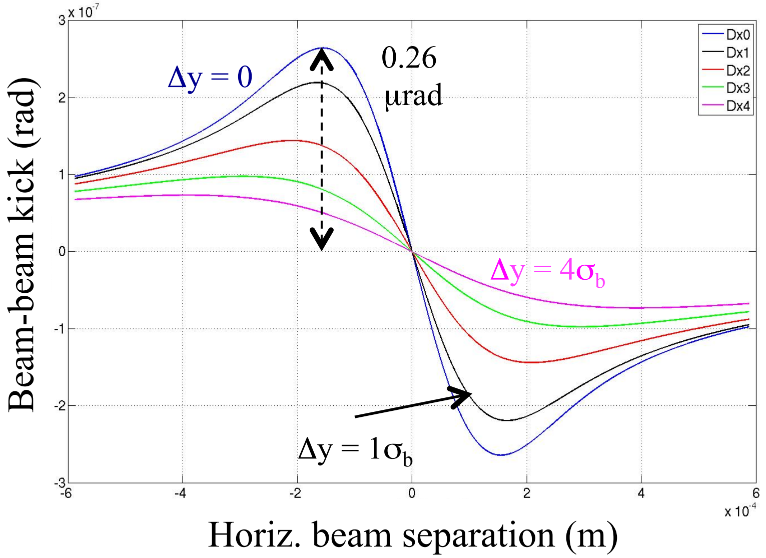
- Compute effect of dynamic β on x & y scans: $\mathcal{L} \sim 1 / \sqrt{\beta^*_{dyn,\,x}}\ \sqrt{\beta^*_{dyn,\,y}}$

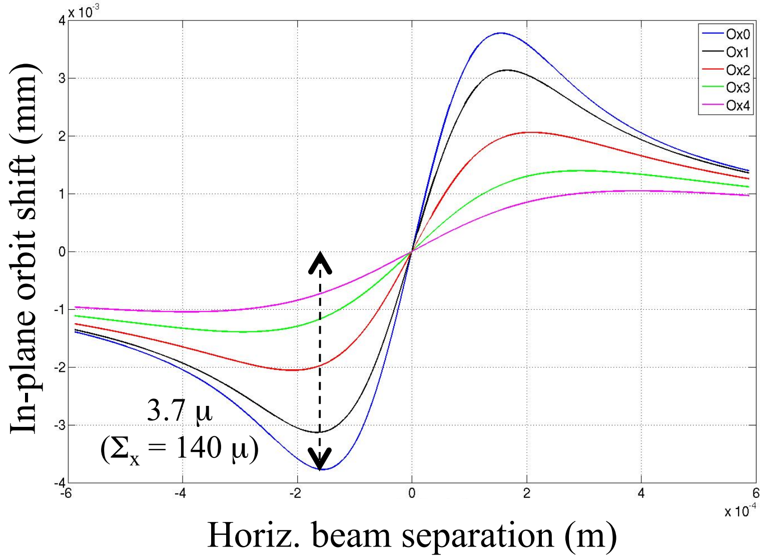


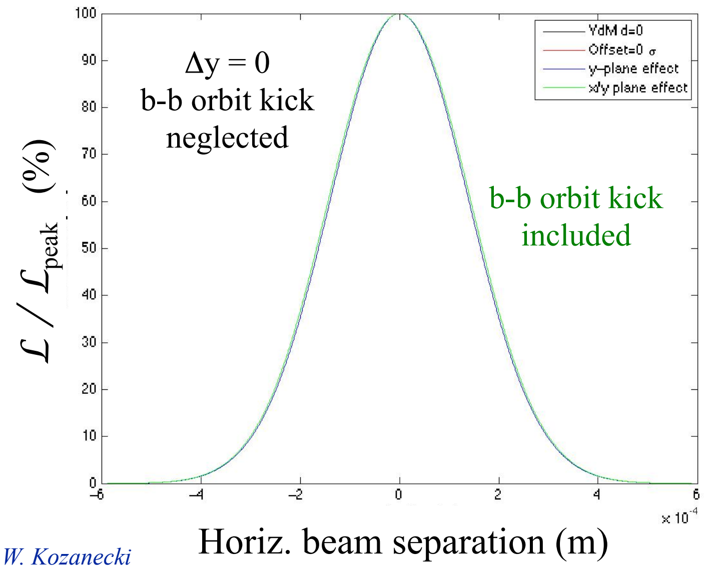
- Refit gaussians and compute impact on $\sigma_{vis} \sim \Sigma_x\ \Sigma_y\ \mu_{vis,pk}$
  → $\Delta\sigma_{vis} / \sigma_{vis} = 0.5\ \%$ *significant in view of total uncertainty* $\Delta\mathcal{L}/\mathcal{L} = \pm\ 1.8\ \%$
  included in $\Delta\mathcal{L}/\mathcal{L}$

T. Pieloni

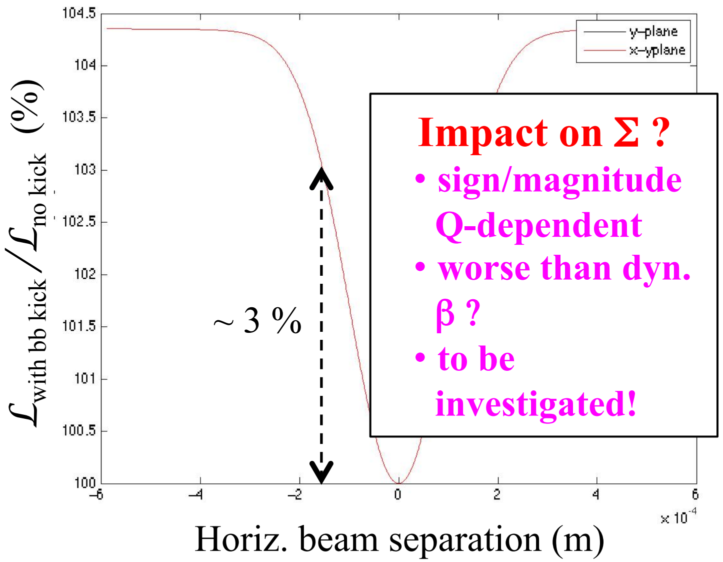
The bad: beam-beam-induced orbit shift during scan





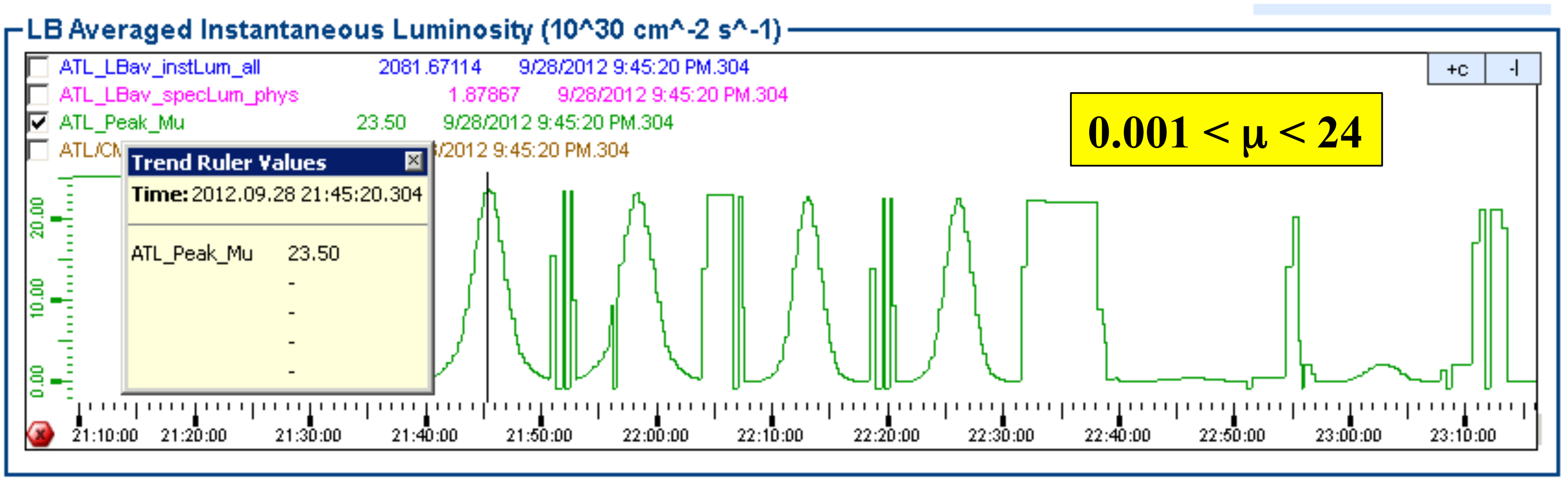


E_b (TeV)	4
N_p (10^{11})	0.8
ε_N (μm-r)	3.75
β^*(m)	11
Q_x	64.28
Q_y	59.31

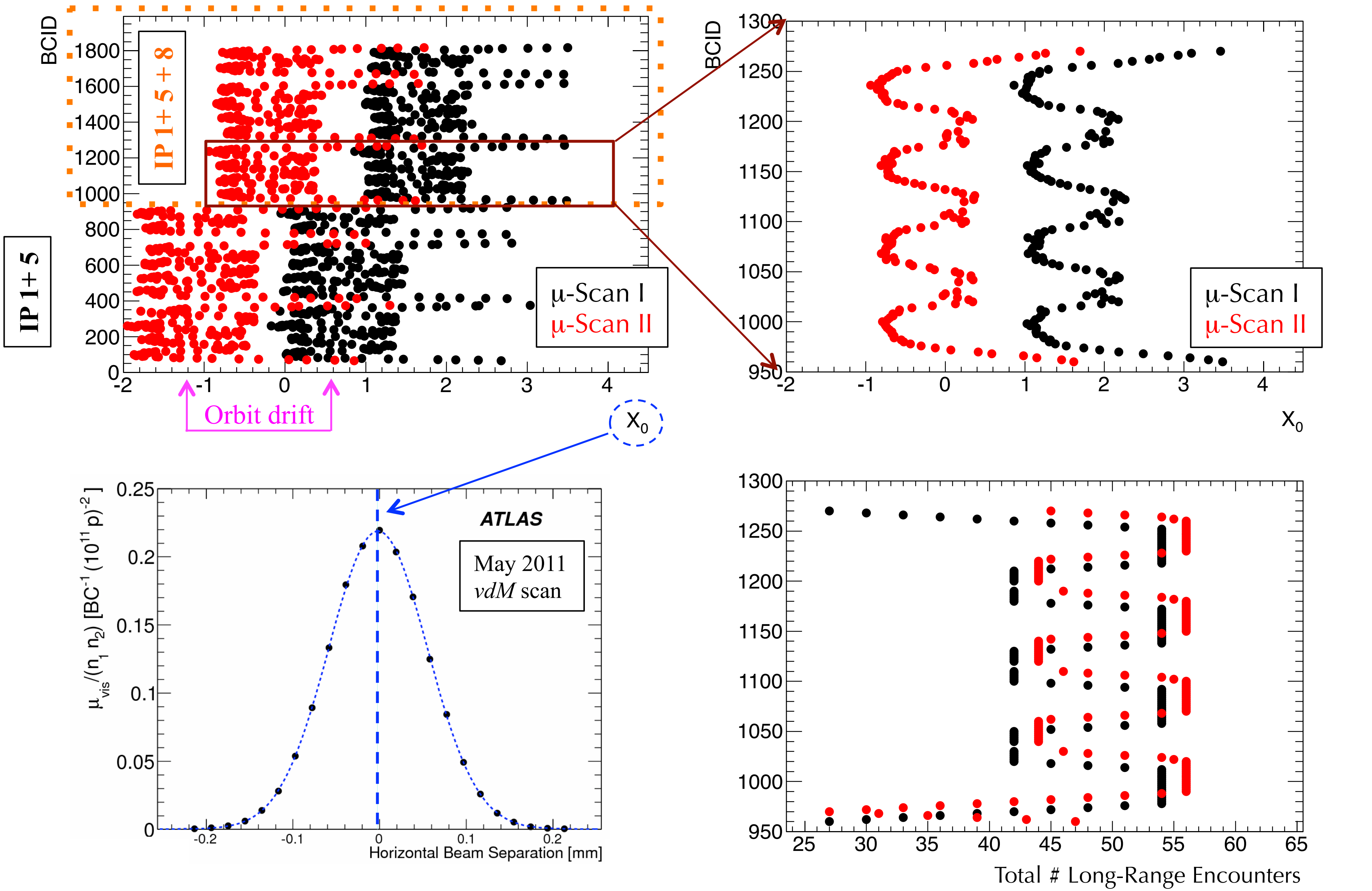


The ugly: beam-separation scans under physics conditions

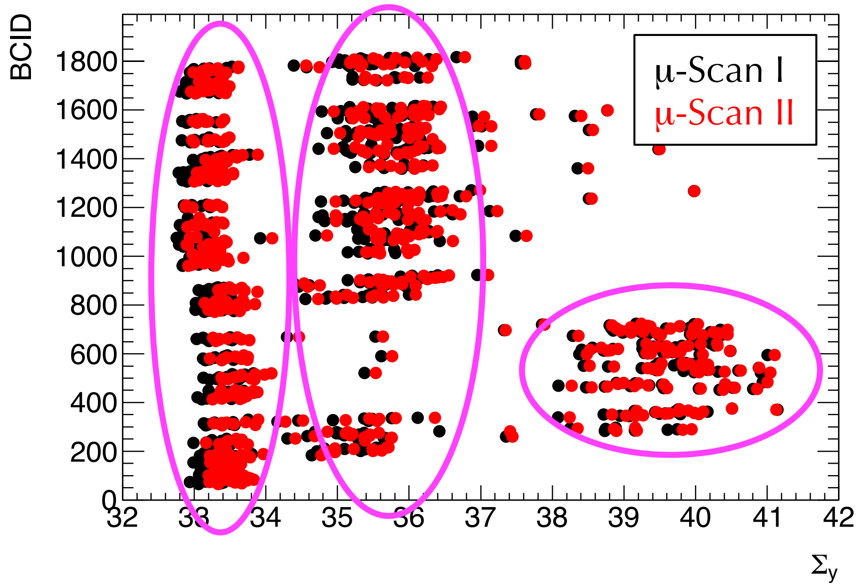
- Example of opportunistic study during intensity ramp-up (fill 3109)
  - Beam conditions representative of physics running
    - $\beta^* = 0.6$ m, θ_c = +- 145 μrad
    - 50 ns trains, 1.2 E11 p/bunch, 726 bunches
  - Goals
    - ~~provide check on absolute $\mathcal{L}$ calibration ?~~ *Impractical !*
    - characterize transverse phase space (tails, non-linear x-y correlations)
    - check stability of scan results wrt scanning protocol (*e.g.* hysteresis,...)
    - μ-dependence check: quantify relative linearity of different luminometers & algorithms at one point in time (< 1% ?)

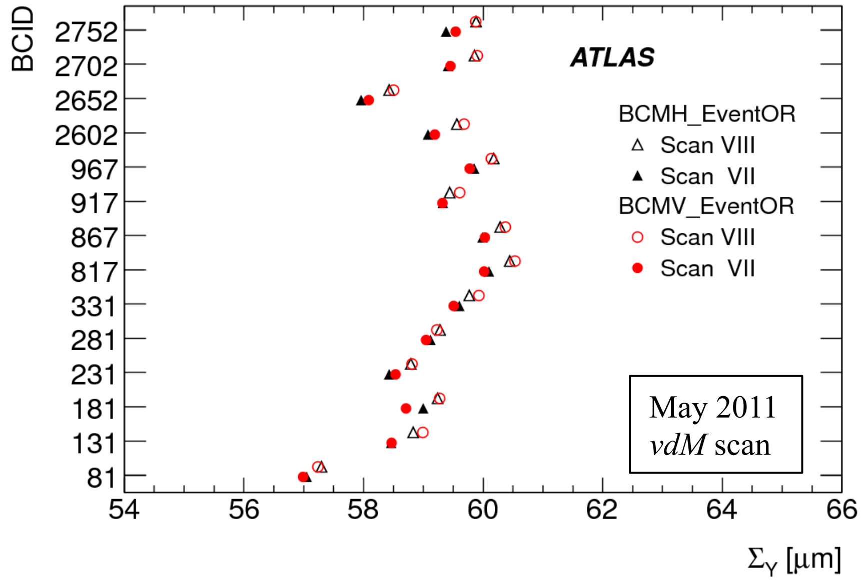


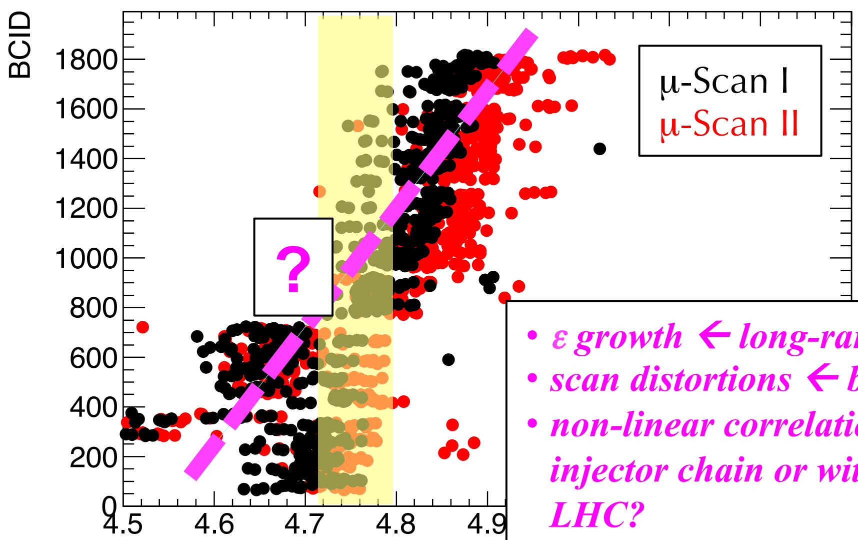
The ugly: impact of long-range encounters on $\mathcal{L}$ scans



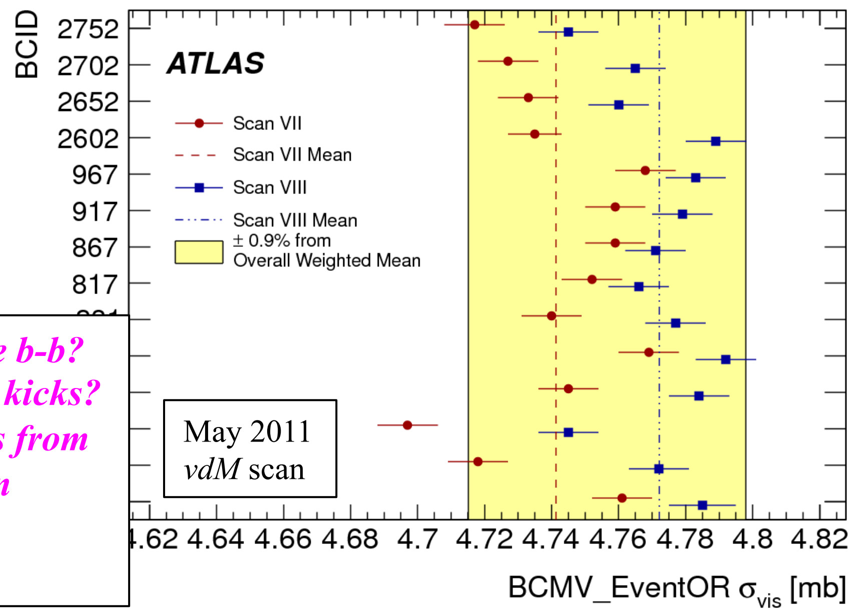
The ugly: impact of bunch trains on $\mathcal{L}$-calibration systematics







- *ε growth ← long-range b-b?*
- *scan distortions ← b-b kicks?*
- *non-linear correlations from injector chain or within LHC?*
- *any other ideas?*



Beam-beam related

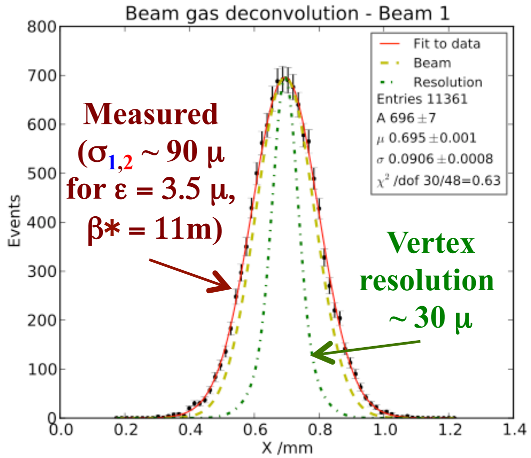
Do 's and don't 's: lessons learnt (1)

- **Don't use...**
  - bunch trains
    - beam-beam kicks (+ distortions?) from long-range encounters
    - injected phase-space quality
    - satellites & ghost charge
      - more abundant
      - harder to analyze
    - $\mathcal{L}$ afterglow
  - high bunch intensities (> 1 E11 p)
    - orbit distortions during scan
    - dynamic β during scan
    - injected phase-space quality
    - satellites & ghost charge (?)
    - instabilities (impedance? Q spread from LR beam-beam ?)
    - μ too high (if low β*) → potential detector non-linearities

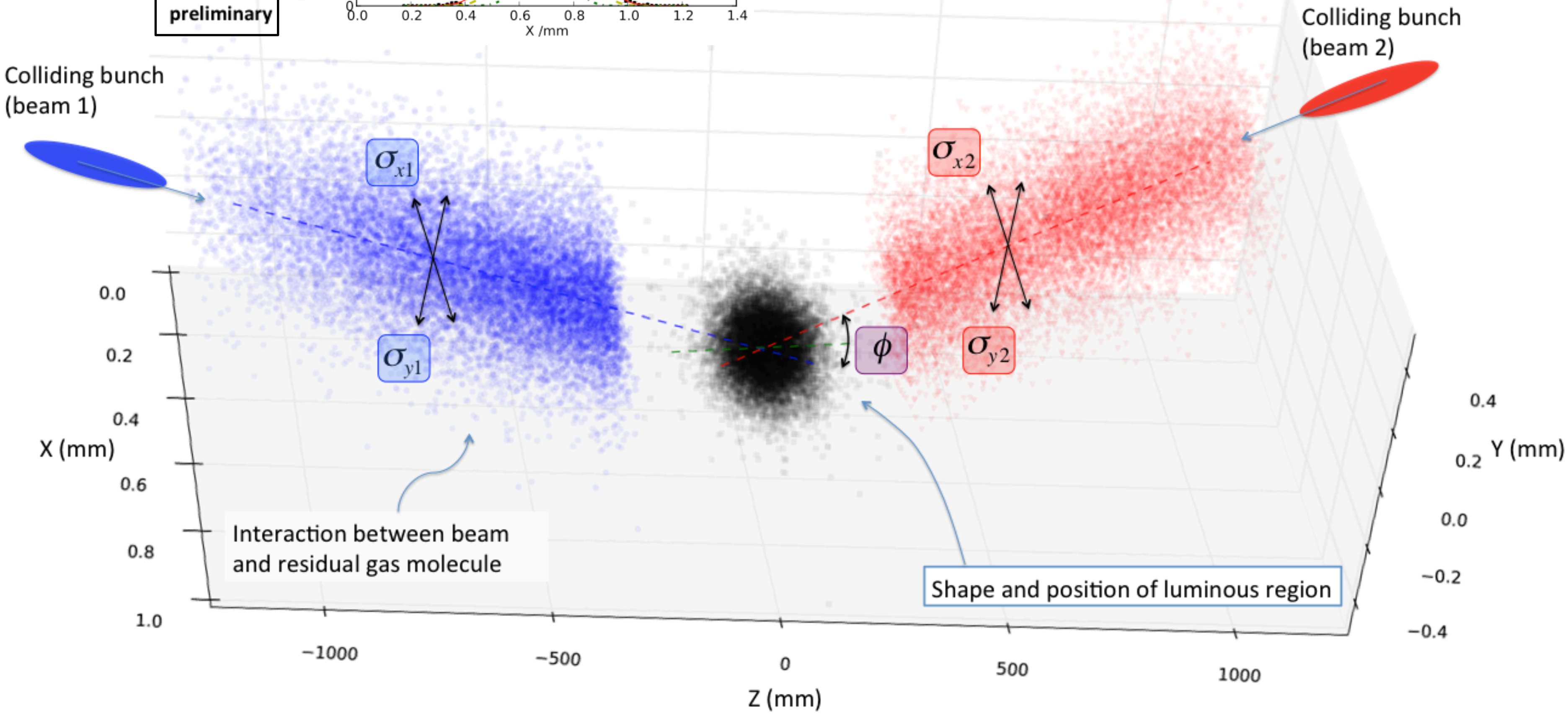
- **Do favor...**
  - sparse patterns of indiv. bunches
    - no parasitic encounters
    - weaker satellites & ghost charge
    - sparse pattern → low afterglow
    - no Xing-angle constraints
    - keep 'your' bunches private
    - allows tailoring of injected phase space
  - moderate bunch intensities (~ 8-9 E10 p/b)
    - if higher: scan curve distortions
      - beam-beam kicks → orbit
      - dynamic β
    - if much lower
      - $\mathcal{L}$-calibration statistics- & systematics-limited
      - machine-protection constraints

A detour: beam-gas & luminous-region imaging

Resolution systematics critical: 10% on resolution → 1 % on each of σ_1, σ_2

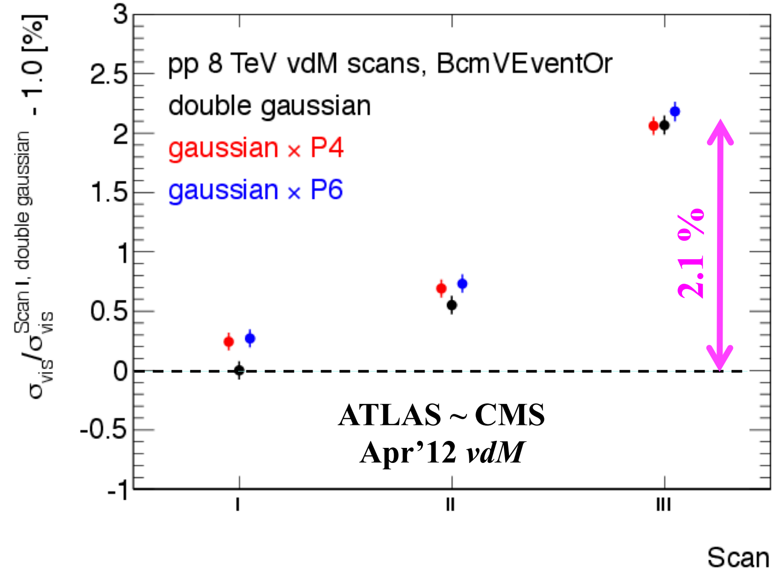


- **Beam-gas imaging (LHCb only)**
  - ➢ **measure $\sigma_{1\ x,y}$, $\sigma_{2\ x,y}$ separately → independent absolute $\mathcal{L}$ calibration**
- **Luminous-region imaging**
  - ➢ **msre $\sigma_{\mathcal{L}\ x,y}$ + their dependence on $\Delta_{x,y}$ during *vdM* scan**



Absolute-$\mathcal{L}$ calibration challenge: non-factorization effects

- **Two very challenging issues in first two 2012 *vdM* scans (Apr + Jul '12)**
  - **Scan-to-scan irreproducibility and/or systematic trend: 2-3 %**
    (➔ $\sigma_{syst, ATL}$ ~ 3.6 %, $\sigma_{syst, CMS}$ ~ 4.4 %)
  - **Breakdown of x-y factorization in the 3-d $\mathcal{L}$ distribution**
    - **aka 'non-linear x-y correlations'**
    - **observed during vdM scans by all of ATLAS, CMS, LHCb (evidence compelling, but available data sets make quantitative comparisons difficult)**
  - **These 2 issues**
    - **are clearly beam-dynamics effects, time-dependent & different fill-to-fill (instrumental drifts ruled out)**
    - **appear mutually related**

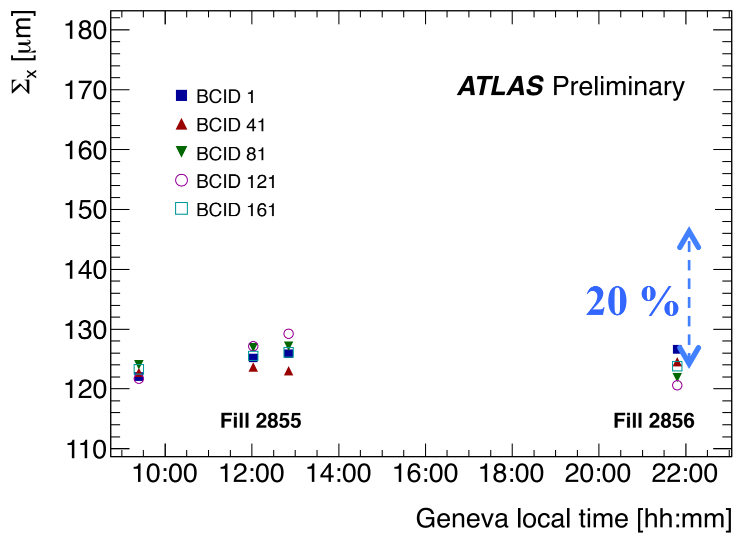


- **Factorization assumes that shape of *vdM* scan curve during an x (y) scan is independent of the separation Δy (Δx) in the orthogonal plane**
  - **if this assumption is satisfied, the combination of 1 x-scan and 1 y-scan is sufficient to characterize the entire distribution $\mathcal{L}$ (Δx, Δy)**
  - **if this is violated at a "significant" level, the *vdM* formalism could be generalized to 2-d by performing a full 2-D grid scan (but: impractical!)**

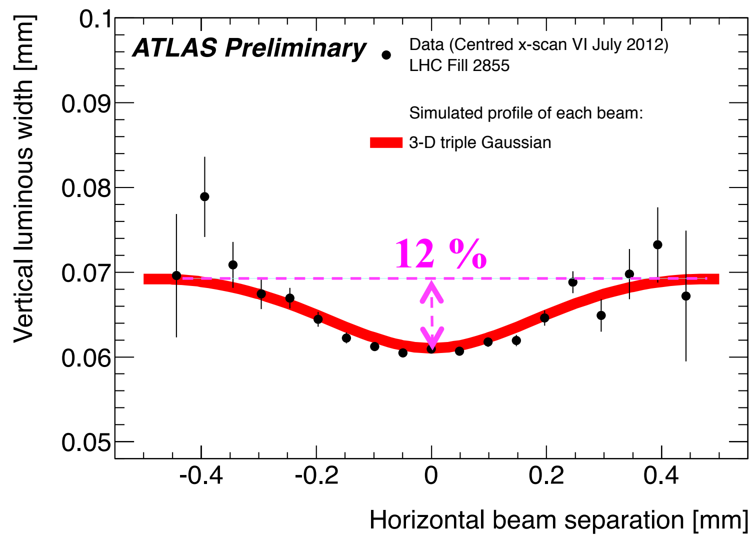
Testing factorization of $\mathcal{L}$ (Δx, Δy) during *vdM* scans

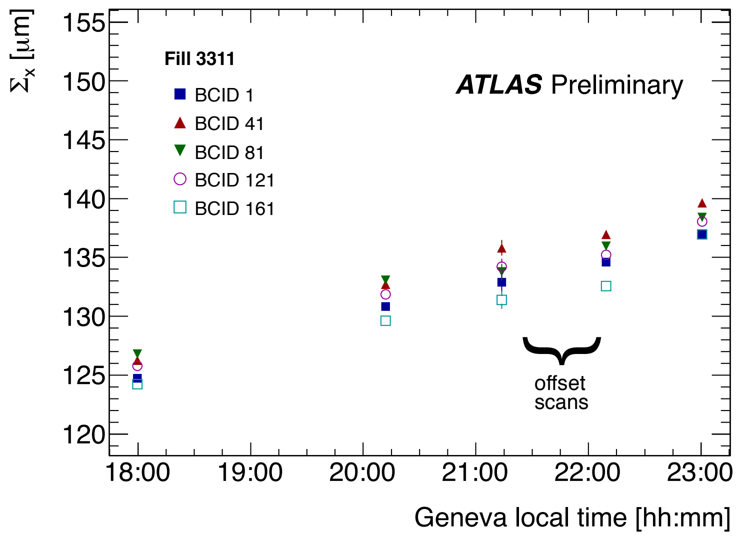
Convolved beam size Σ (width of vdM scan curve)

Vertical luminous size $\sigma_{\mathcal{L}}$ (beamspot width)

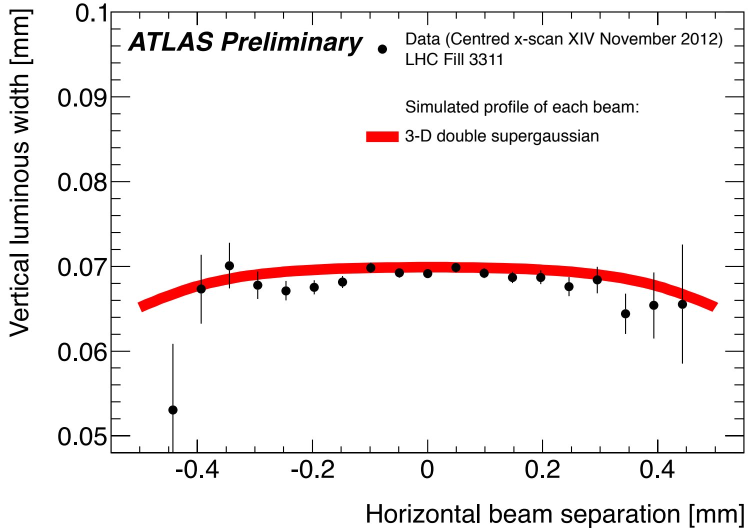


July 2012
vdM scan



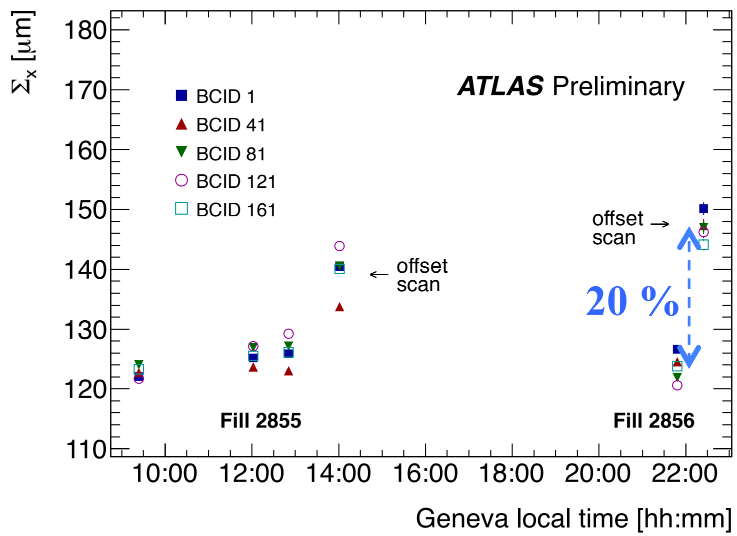


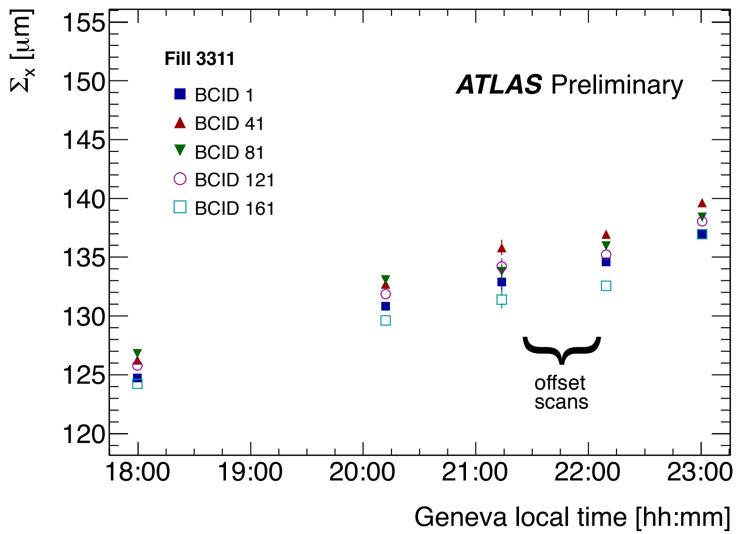
Nov 2012
vdM scan



Testing factorization of $\mathcal{L}$ (Δx, Δy) during *vdM* scans

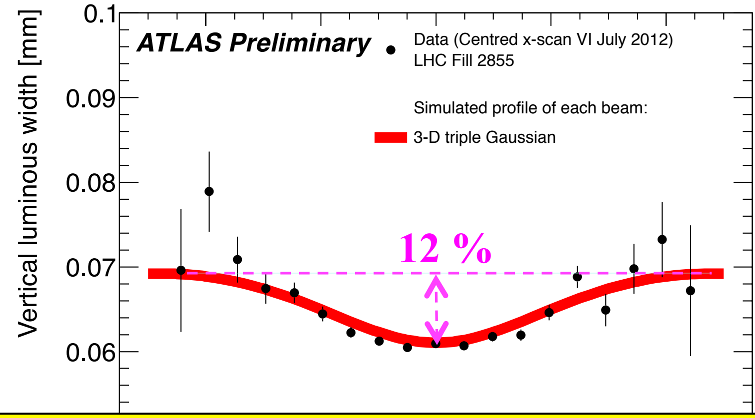
Convolved beam size Σ (width of vdM scan curve)





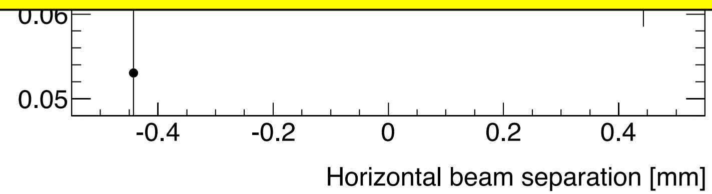
Vertical luminous size $\sigma_{\mathcal{L}}$ (beamspot width)

July 2012
vdM



The large reduction in non-linear x-y correlations, between the July & Nov 2012 scans, was achieved mainly by careful preparation of highly gaussian beams in the injectors.
The elimination of ε blowup by multiple scattering in a transfer line, and the reduction of the LHC octupole strength, may also have played a role.
The beam-beam contribution to non-factorization effects was deemed negligible by comparison.

Nov 2012
vdM scan



Do's and don't 's: lessons learnt (2)

Beam-beam related

Don't...

- use small β^*
  - reconstructed luminous width $\sigma_{\mathcal{L}}$ (= beamspot width) becomes resolution-dominated and very difficult to analyze
  - $\mu \sim 5$ too high for comfort: potential detector non-linearities
- push for small emittances
  - the smaller ε, the more $\sigma_{\mathcal{L}}$ is resolution-dominated
- set nominal crossing angle
  - complicates measurement/ characterization of satellites
    - notable exception: LHCb needs large Xing-angle for beam-gas enhanced ghost-charge measurement
- scan > 1 IP at a time
  - beam-beam defl + leaking bumps

Do favor...

- large β^* (present injection optics: $\beta^* = 11$ m)
  - make $\sigma_{\mathcal{L}}$ ALAP (←→ resolution)
- nominal emittances
  - make $\sigma_{\mathcal{L}}$ ALAP (←→ resolution)
  - BUT <u>avoid</u> anything that creates <u>non-gaussian tails</u> (e.g. ε blowup by screen in transfer line)

Large enough $\sigma_{\mathcal{L}}$ critical for

(a) non-factorization systematics

(b) $\mathcal{L}$ calibration by beam-gas imaging

- beams as gaussian as possible in SPS + LHC
  - tailor injected phase space (still an art more than a science...)
  - avoid strong octupoles
- zero crossing angle
  - optimize satellite reconstruction

Do ’s and don’t ‘s: wish list for *vdM* scans in 2015 (& beyond...)

- <u>Reproducibly</u> “tailor” injected *p* phase space to minimize non-linear correlations

  Critical for limiting non-factorization systematics

- “Generous” luminous width $\sigma_{\mathcal{L}}$
  - injection optics or larger ($\beta^* > 10$)
  - “nominal” emittance ($\varepsilon_N \sim 3\ \mu$)

  Large enough $\sigma_{\mathcal{L}}$ critical for BGI and non-factorization systematics

  Note that the E_{beam} increase (4→ 6.5 TeV) shrinks the beams by √2 – while the vertex resolution remains the same

- Round beams ($\beta^*_x = \beta^*_y$)
  - The vdM method <u>can</u> handle tilted elliptical beams (residual x-y coupling!) – but at the cost of additional scans (x/y → x/y/u/v)

- No crossing angle (except LHCb)
  - reconstruct satellites by vtxg
- Crab off (when it appears...)
  - avoid banana shapes, phase/ Xing angle jitter,....
- Sparse patterns (no trains!)
- Low bunch intensities
- Flexible, file-driven scan-control software
  - allow for complex scan patterns
    - diagonal scans, off-axis scans,...
    - leapfrog length-scale calibration
  - minimize scanning time, costly cockpit errors
  - must provide for rigorous MPP validation pre-checks

In conclusion...

- **Need to refine understanding of head-on beam-beam effects during scans: impact on $\mathcal{L}$ calib. systematics larger than thought so far?**
  - more careful evaluation (+ correction?) of dynamic-β scan distortions
  - quantify (+ correct?) impact of in-plane orbit distortions during scans
  - quantify impact of (i) orbit distortions & (ii) b-b induced skew quad on off-axis scans (→ crisper evaluation of non-factorization symptoms)
- **Limitations in long-term luminosity & beam-background monitoring**
  - **EOF scans impractical because of beam-beam (+ non-linear correlations)**
    - makes long-term monitoring of $\mathcal{L}$ stability much more difficult
  - **Landau damping vs. instabilities & single-beam bakground monitoring**
    - removing non-colliding bunches unfortunate – any way to rescue these?
- **The need to limit, during $\mathcal{L}$-calibration scans, the impact of**
  - head-on beam-beam kicks + dynamic β, on scan-shape distortions
  - long-range encounters, on scan-shape distortions
  - vertexing resolution, on B-G imaging & quantification of non-factorization effects

significantly constrains the operational conditions during *vdM* scans
→ iterate with LHC operations group on pragmatic solutions

Additional material

Systematic uncertainties on 2011 $\mathcal{L}$ determination (ATLAS)

σ_{vis} uncertainty (vdM scans)

Table 7 Relative systematic uncertainties on the determination of the visible cross-section σ_{vis} from *vdM* scans in 2011.

Scan Number	VI–VII
Fill Number	1783
Beam centring	0.10%
Beam-position jitter	0.30%
Emittance growth and other non-reproducibility	0.67%
Bunch-to-bunch σ_{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%
μ dependence	0.50%
Scan subtotal	1.43%
Bunch population product	0.54%
Total	1.53%

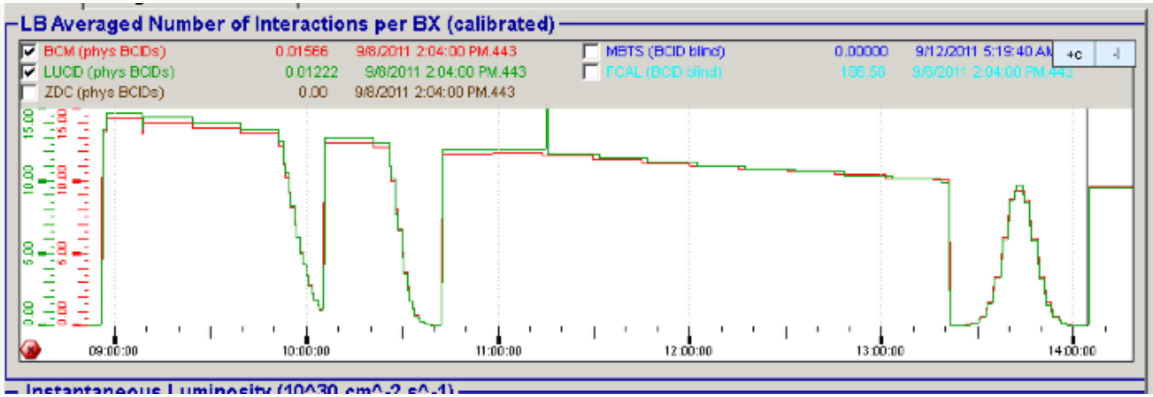
Total $\mathcal{L}$ uncertainty (physics runs)

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

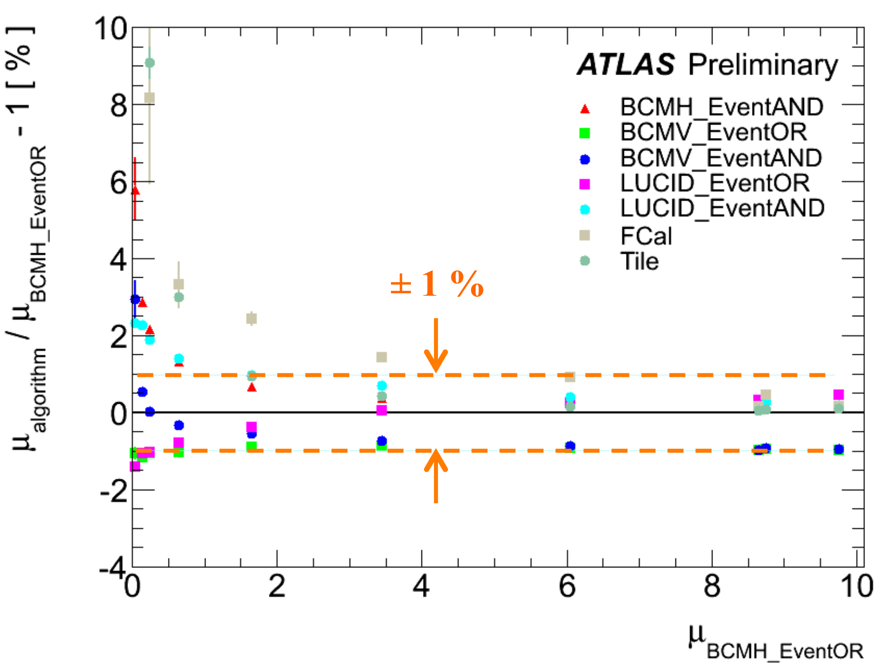
Direct measurement of μ-dependence: pile-up ('μ') scan

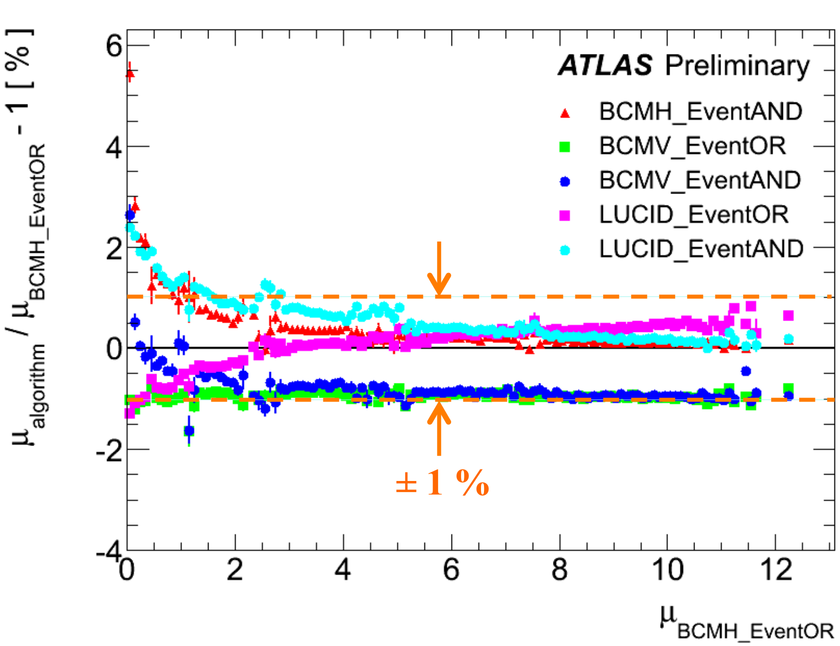
'μ sweep' performed by beam-separation in F 2086 (873 b, $\mathcal{L}$ ~ 1.9 10^{33})

→ characterize the relative μ-dep. of BCM H/V, FCal, LUCID, TILE, vtx algos

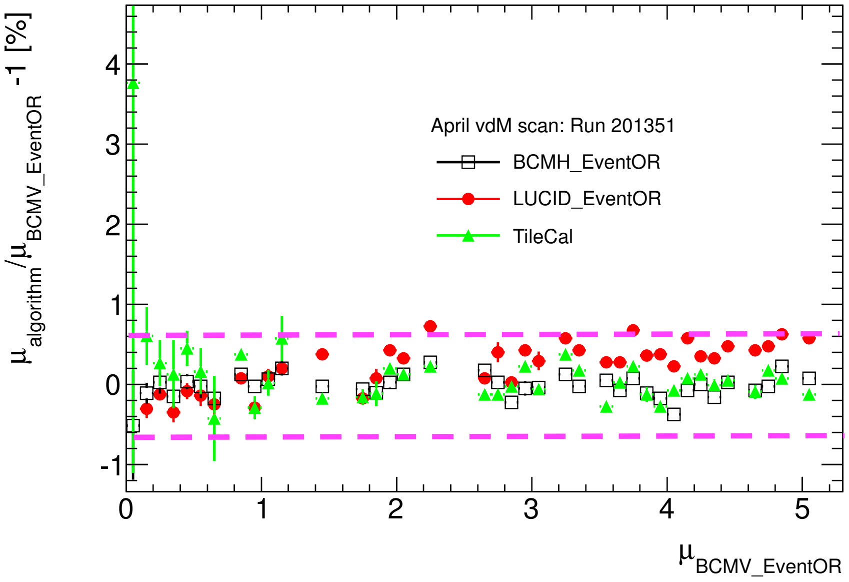


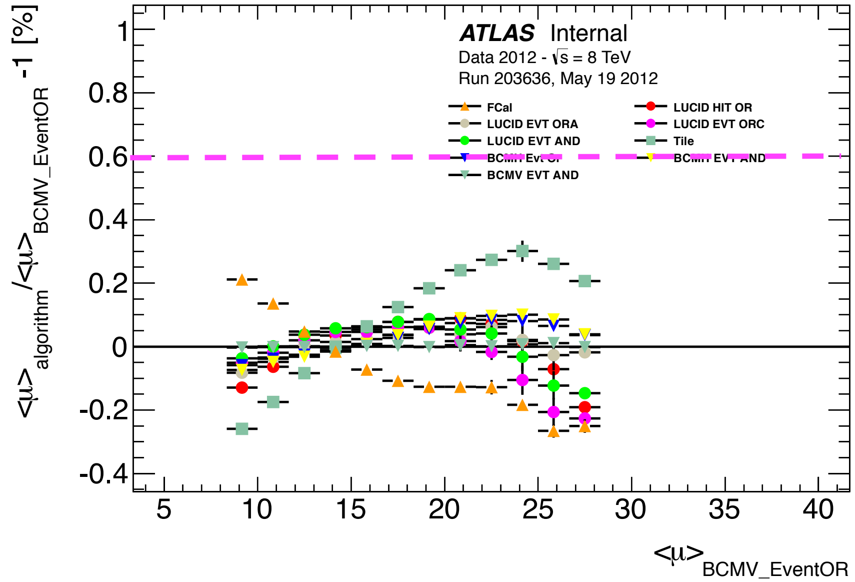
3 scans, covering
10 - 15 > μ > 0.02
i.e. all the way from
normal physics conditions
to (slightly below) the μ regime
for the β = 90 m ALFA run*

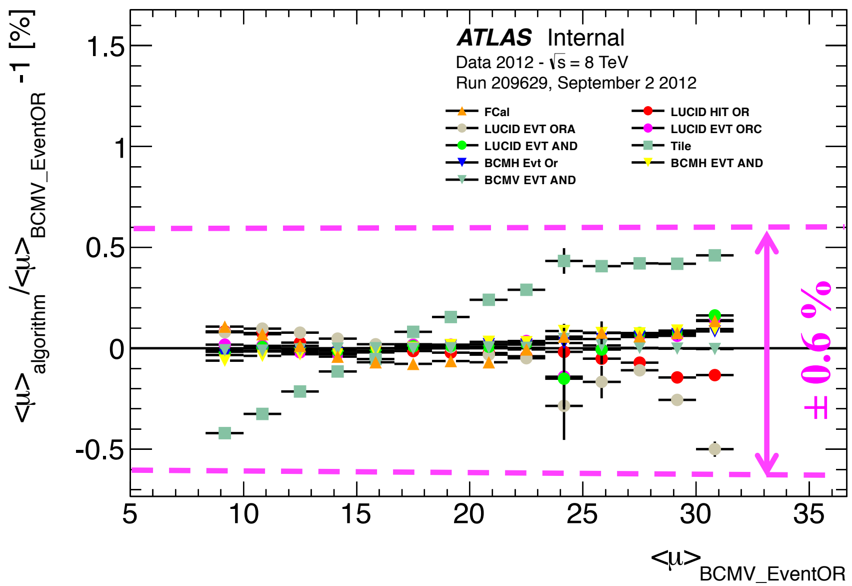


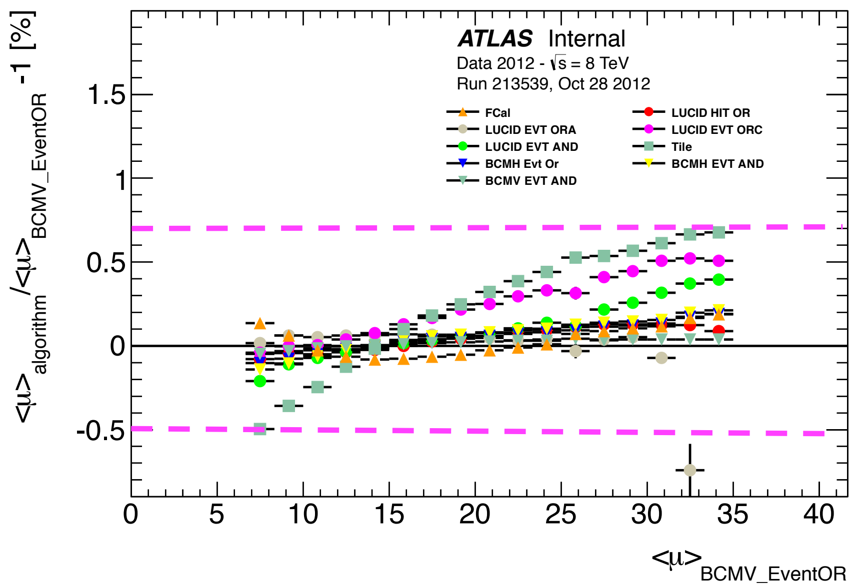


μ-dependence during 2012 physics running: individual runs

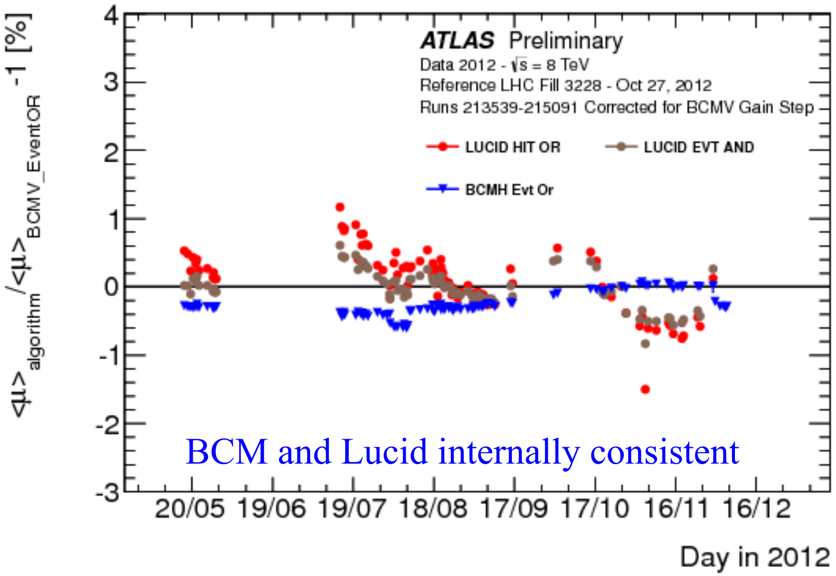


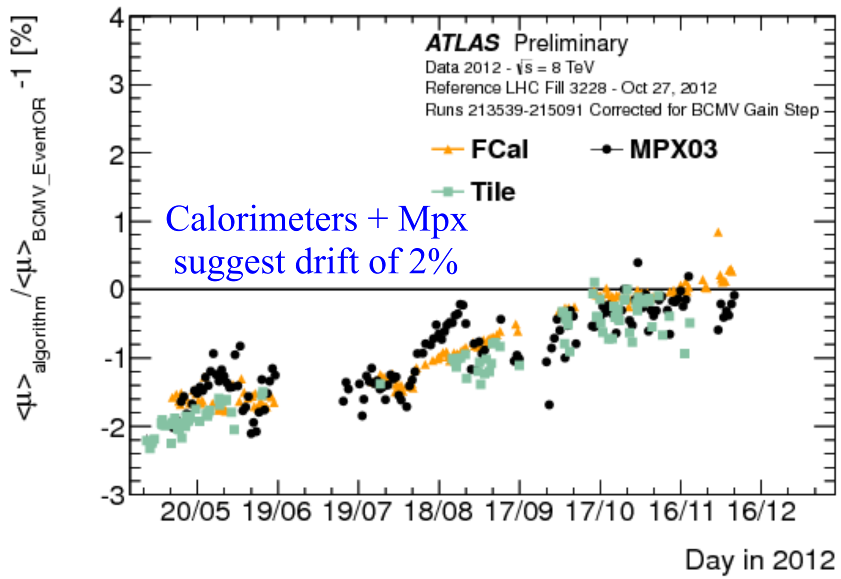


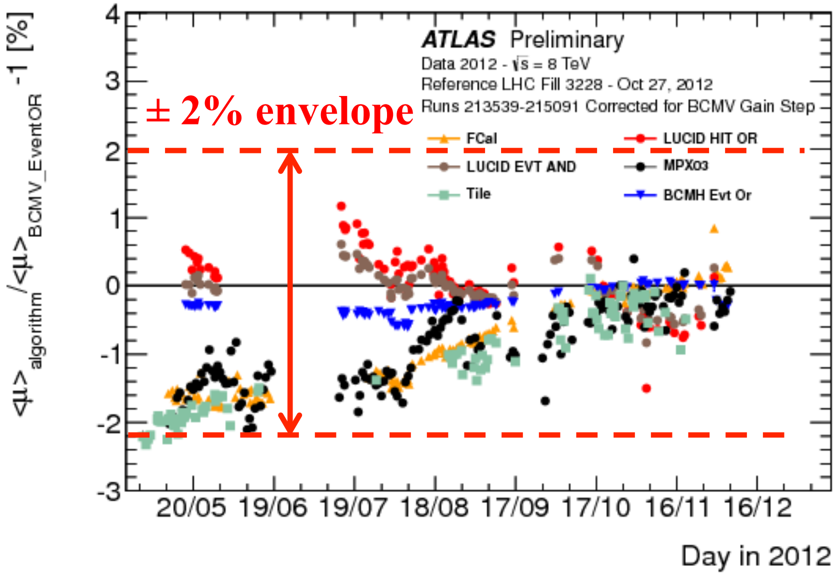




Long Term Stability 2012

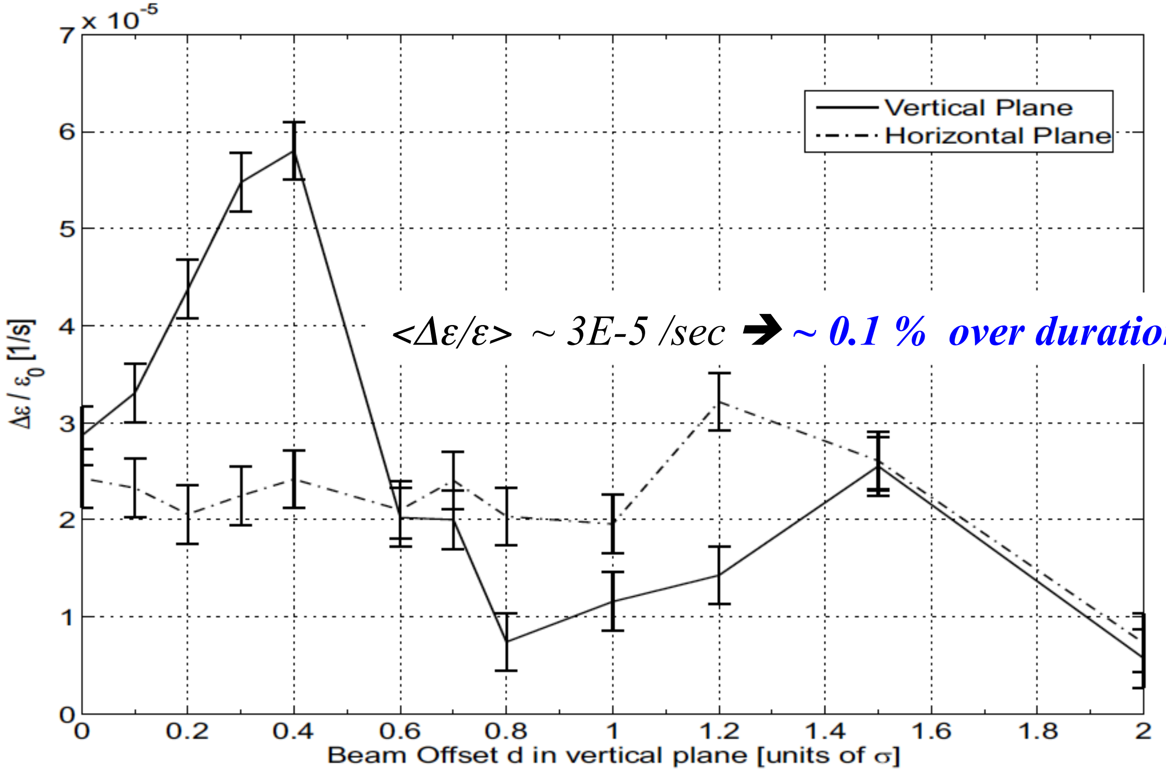






T. Pieloni, W. Herr
& Ji Qiang
Pac'09

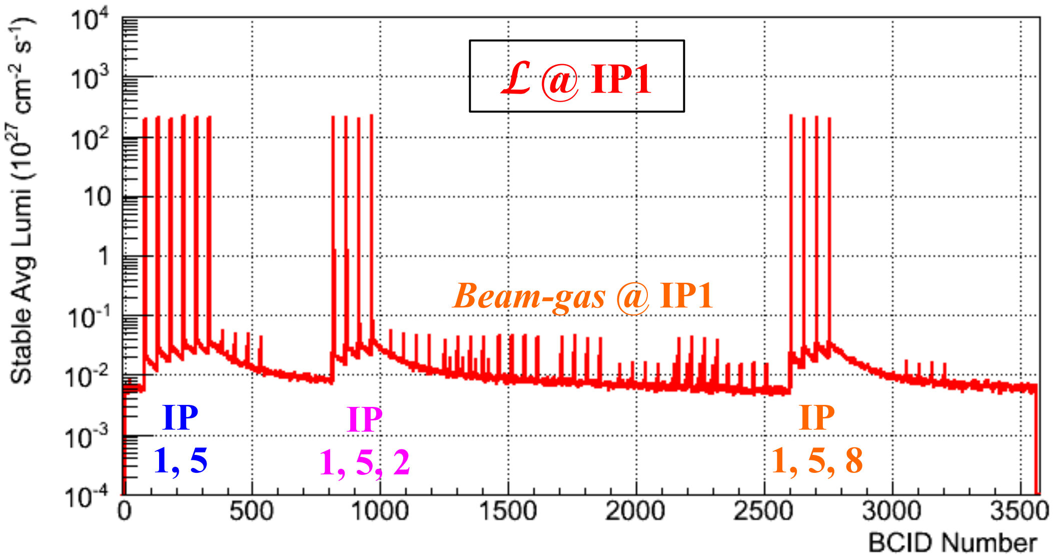
The mild: emittance growth during scans

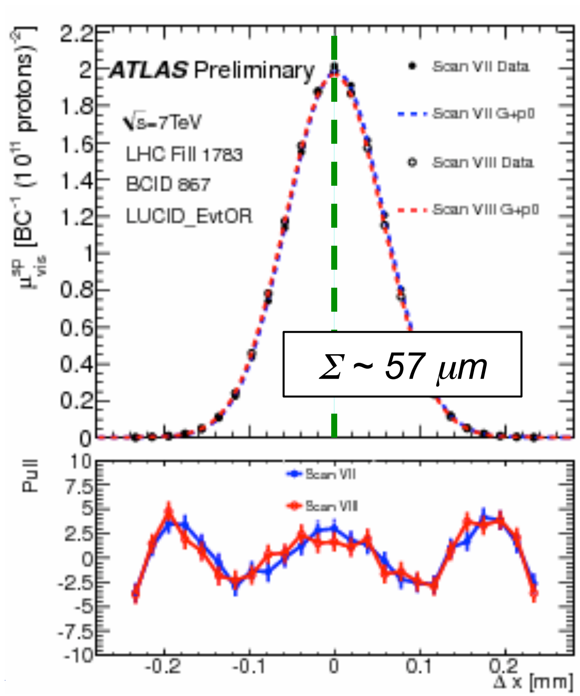


<Δε/ε> ~ 3E-5 /sec ➔ ~ 0.1 % over duration of a scan

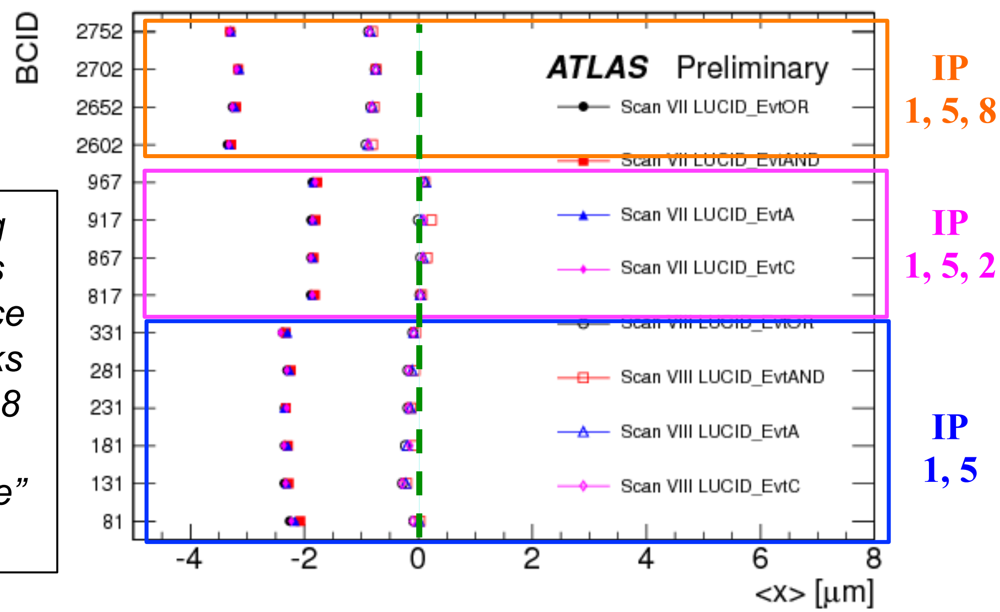
Emittance growth for different static offsets with beams colliding in one IP only and no long-range interactions

The mild: beam-beam kicks during scan from shared bunches

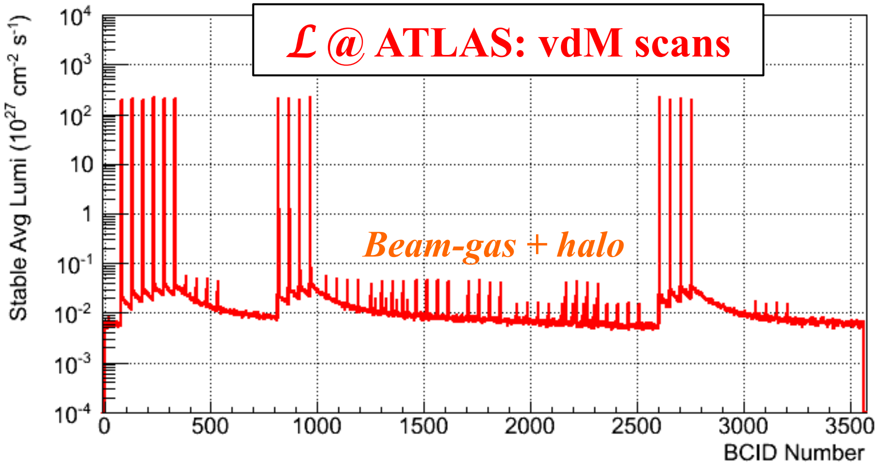


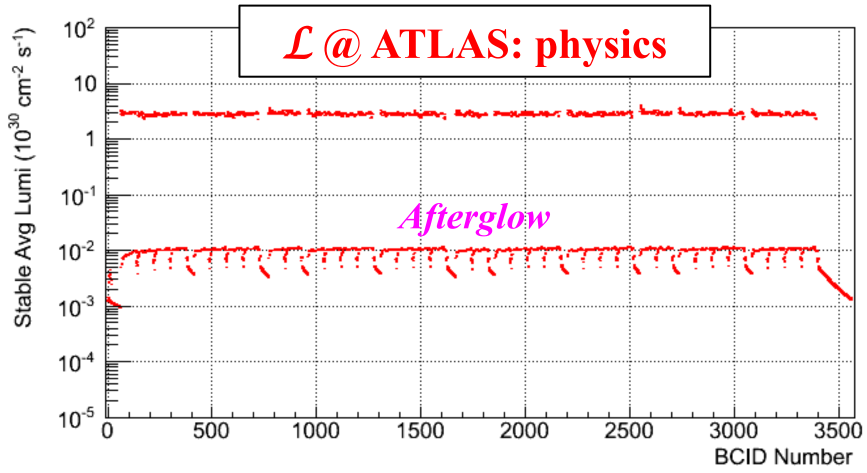


Colliding bunches experience ≠ b-b kicks at IP 2 & 8 – but "moderate" wrt Σ

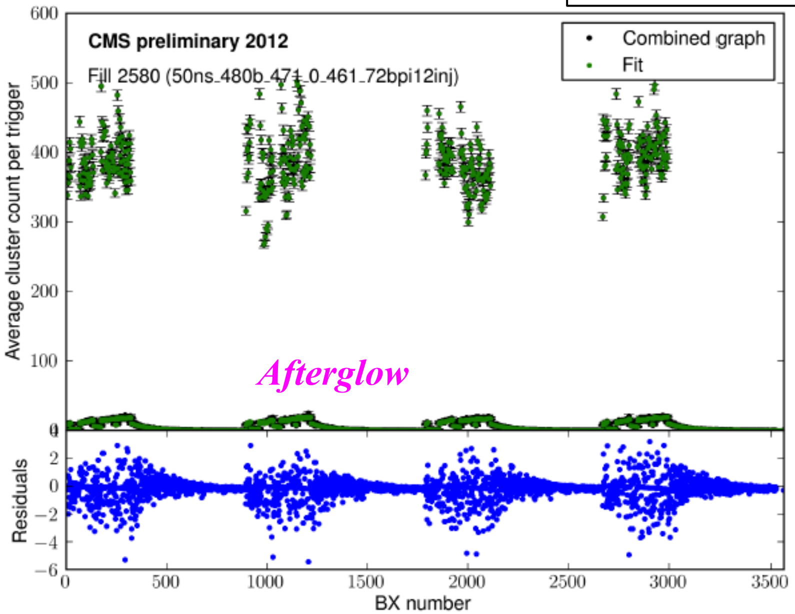


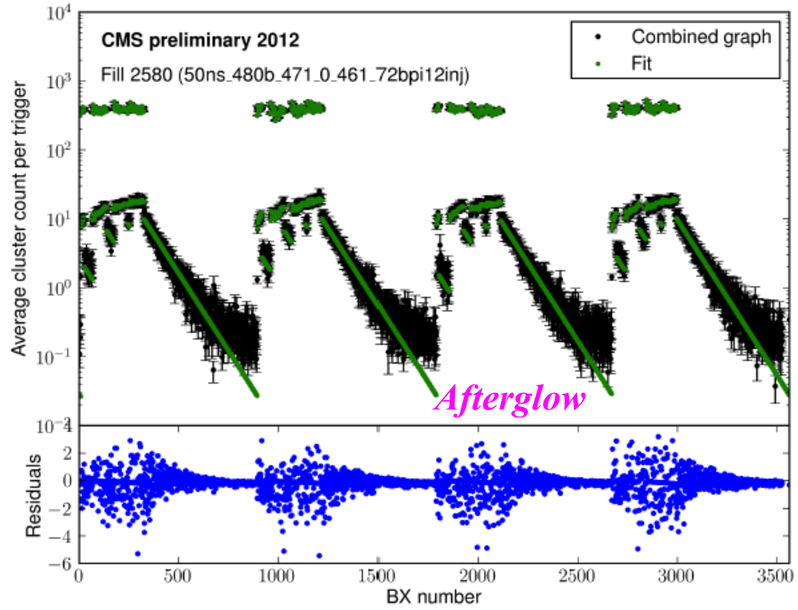
Luminosity afterglow





ℒ @ CMS: physics





A fundamental assumption: x-y factorization of $\mathcal{L}$ (Δx, Δy)

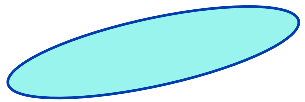
- **A key assumption of the *vdM* scan method as currently applied is that the luminosity**

$$\mathcal{L} = n_{\mathrm{b}} f_{\mathrm{r}} n_1 n_2 \int \hat{\rho}_1(x,y) \hat{\rho}_2(x,y) dx dy$$

factorizes in x & y:

$$\mathcal{L} = n_{\mathrm{b}} f_{\mathrm{r}} n_1 n_2 \; \Omega_x(\rho_{x1}, \rho_{x2}) \; \Omega_y(\rho_{y1}, \rho_{y2}) \qquad \Omega_x(\rho_{x1}, \rho_{x2}) = \int \rho_{x1}(x) \rho_{x2}(x) dx$$

- **This is equivalent to assuming that the shape of the scan curve during an x (y) scan is independent of the separation Δy (Δx) in the orthogonal plane**
  - **if this is the case, the combination of 1 x-scan and 1 y-scan is sufficient to characterize the entire distribution $\mathcal{L}$ (Δx, Δy)**
  - **if this is violated at a "significant" level, the *vdM* formalism can be generalized to 2 dimensions by performing a grid scan (impractical!)**

- **Although linear x-y coupling**  **does violate this assumption, the induced bias is typically very small ($\Delta\mathcal{L}/\mathcal{L}$ ~ 0.1%) with present LHC optics (small x-y coupling coeff., $\varepsilon_x \sim \varepsilon_y$, $\beta^*_x \sim \beta^*_y$)**

A complementary approach: correlated fits to *vdM* scan curves

- To estimate (roughly) the magnitude of a potential NLC-induced bias, ATLAS routinely compared the visible cross-sections (i.e. the $\mathcal{L}$ calibration scales) obtained by fitting the x- & y- *vdM*-scan curves using either
  - an uncorrelated model (= baseline): g+g (can simplify to g, or to g+p0)

$$\mathcal{L}(x,y) = A\left(f_x e^{-\Delta x^2/2\sigma_{x1}^2} + (1-f_x)e^{-\Delta x^2/2\sigma_{x2}^2}\right) \times \left(f_y e^{-\Delta y^2/2\sigma_{y1}^2} + (1-f_y)e^{-\Delta y^2/2\sigma_{y2}^2}\right)$$

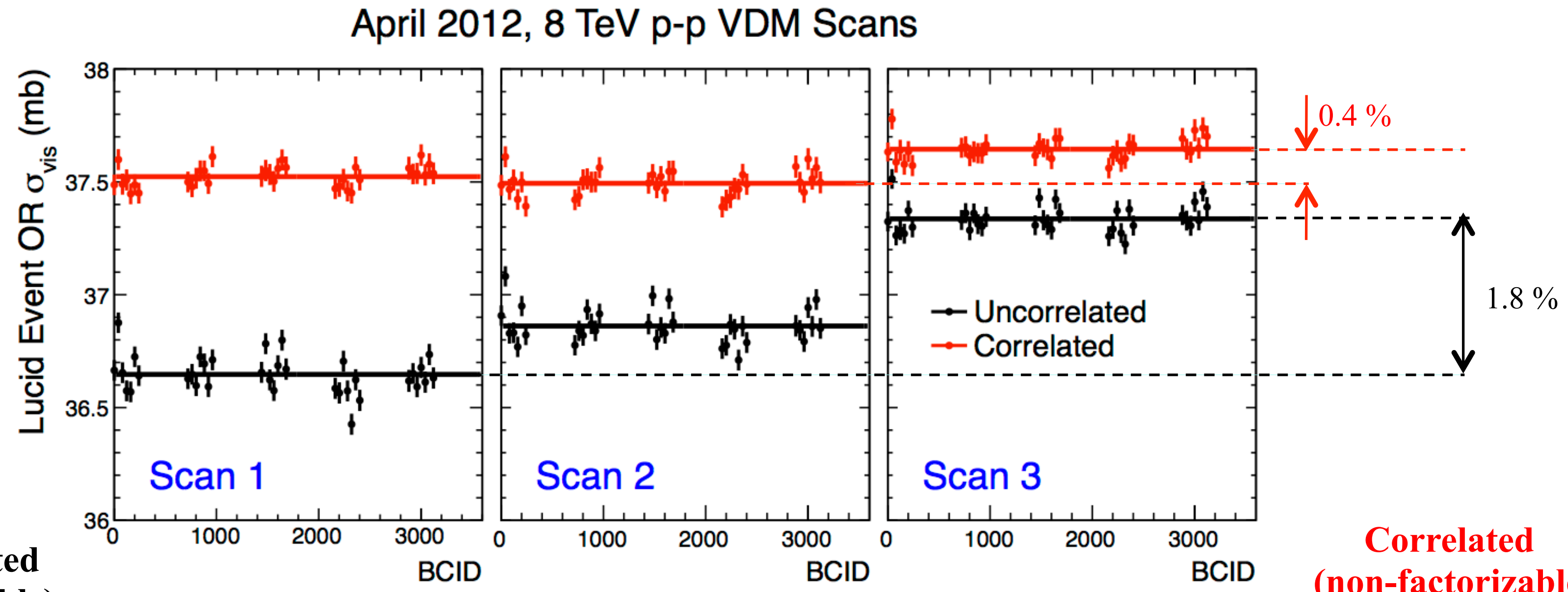
  - a correlated double-gaussian model (naïve & by no means unique)

$$\mathcal{L}(x,y) = A\left(f e^{-\Delta x^2/2\sigma_{x1}^2} e^{-\Delta y^2/2\sigma_{y1}^2} + (1-f)e^{-\Delta x^2/2\sigma_{x2}^2} e^{-\Delta y^2/2\sigma_{y2}^2}\right)$$

  that reduces to the uncorrelated model at $\Delta x = \Delta y = 0$ (but with $f_x = f_y$)

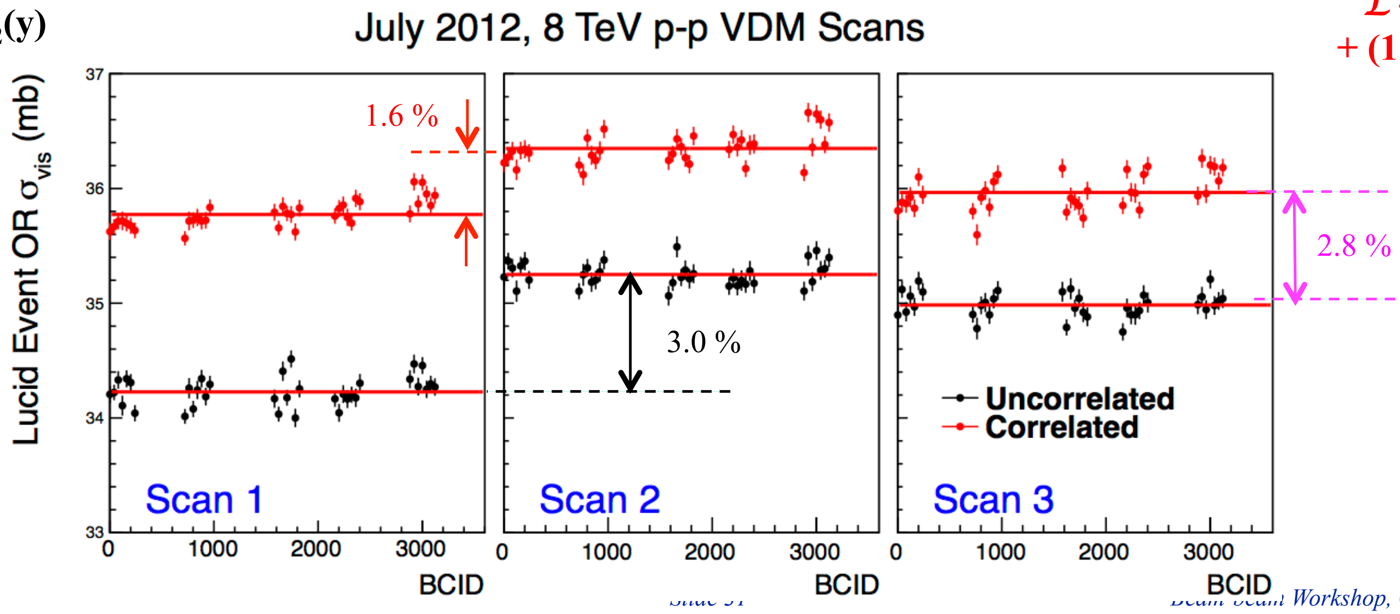
- Observed impact on visible cross-sections at $\sqrt{s}$ = 7 TeV (ATLAS)
  - $\Delta\sigma_{vis} / \sigma_{vis}$ ~ 3%, 2%, 0.9%, 0.5 % for Apr '10, May '10, Oct '10, May '11
  - The more single-gaussian the scan curves, the smaller the potential bias (a property of this model – but probably not a general property?)
  - As the effect looked small for the two main 7 TeV scan sessions, and for lack of manpower, didn't look much further until large 2012 signal

Comparison of uncorrelated & correlated fits to *vdM* scan curves



Uncorrelated
(= factorizable)
$\mathcal{L} \sim G_1(x)\, G_2(y)$

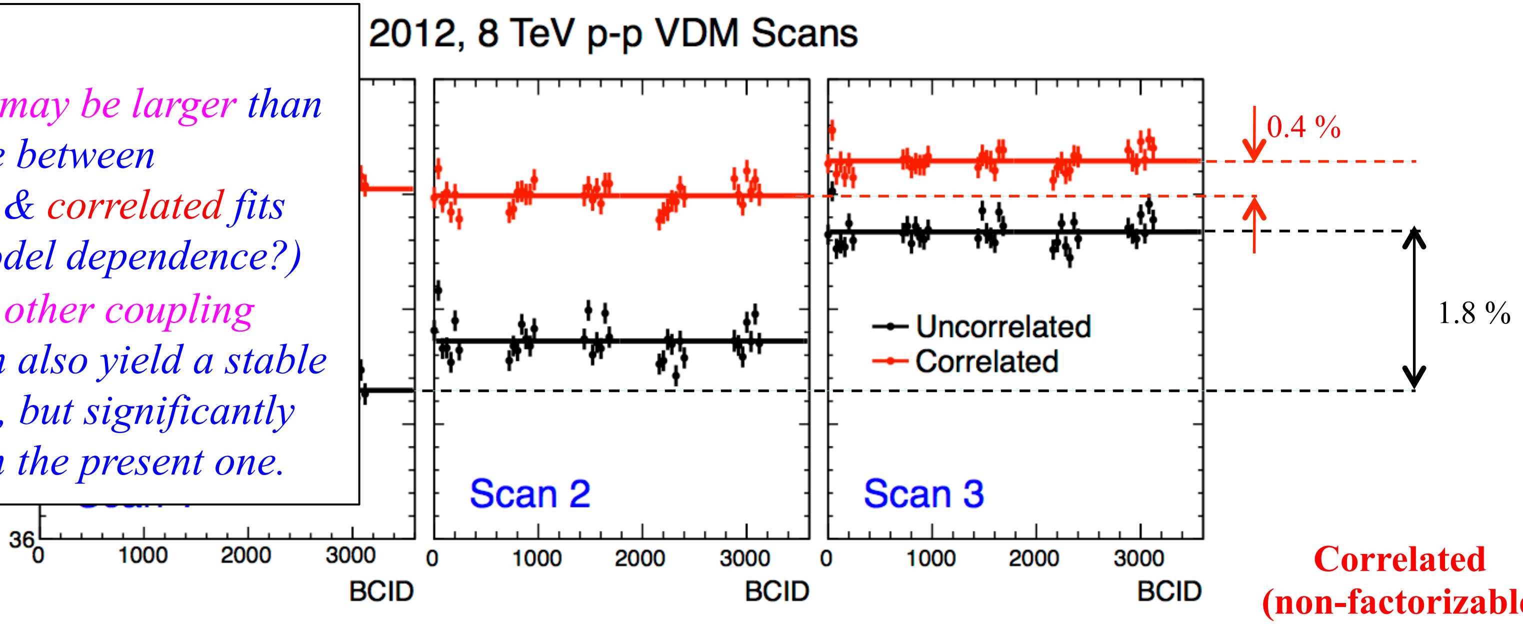
Correlated
(non-factorizable)
$\mathcal{L} \sim \alpha\, g_N(x, y) + (1 - \alpha)\, g_W(x,y)$



Comparison of uncorrelated & correlated fits to *vdM* scan curves

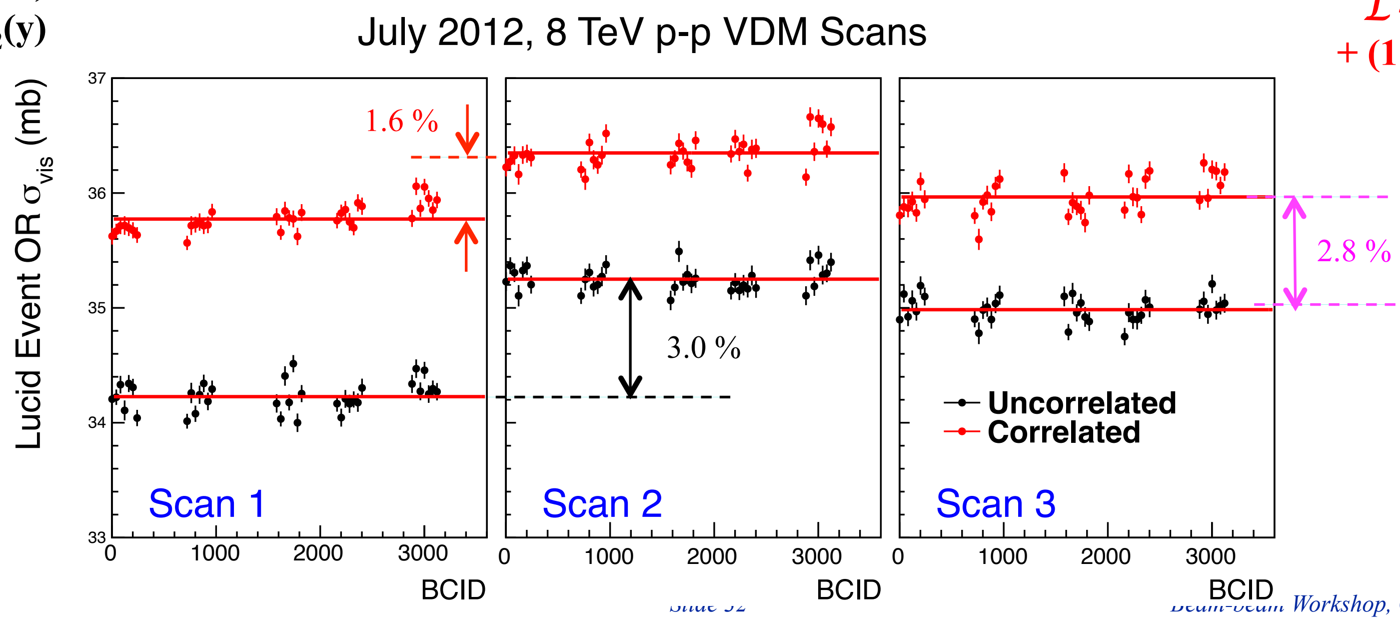
Notes

- *the true bias may be larger than the difference between uncorrelated & correlated fits (coupling-model dependence?)*
- *there may be other coupling models which also yield a stable central value, but significantly different from the present one.*



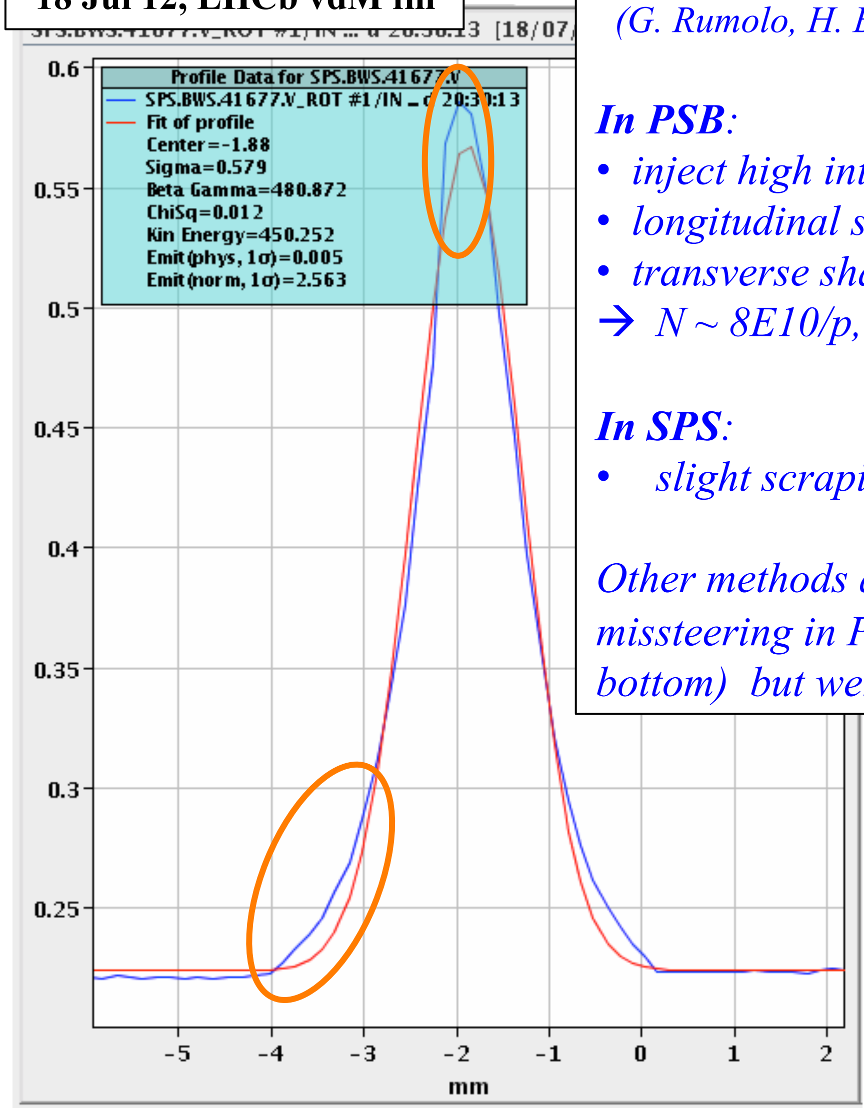
Uncorrelated
(= factorizable)
$\mathcal{L} \sim G_1(x)\, G_2(y)$

Correlated
(non-factorizable)
$\mathcal{L} \sim \alpha\, g_N(x, y) + (1 - \alpha)\, g_W(x,y)$



Production of (more) gaussian beams in the injector chain: PSB/PS/SPS MD of 2 Nov 12 for *vdM* improvement

SPS WS profile (H)
18 Jul 12, LHCb vdM fill



Injector MD of 2 Nov 12
(G. Rumolo, H. Bartosik)

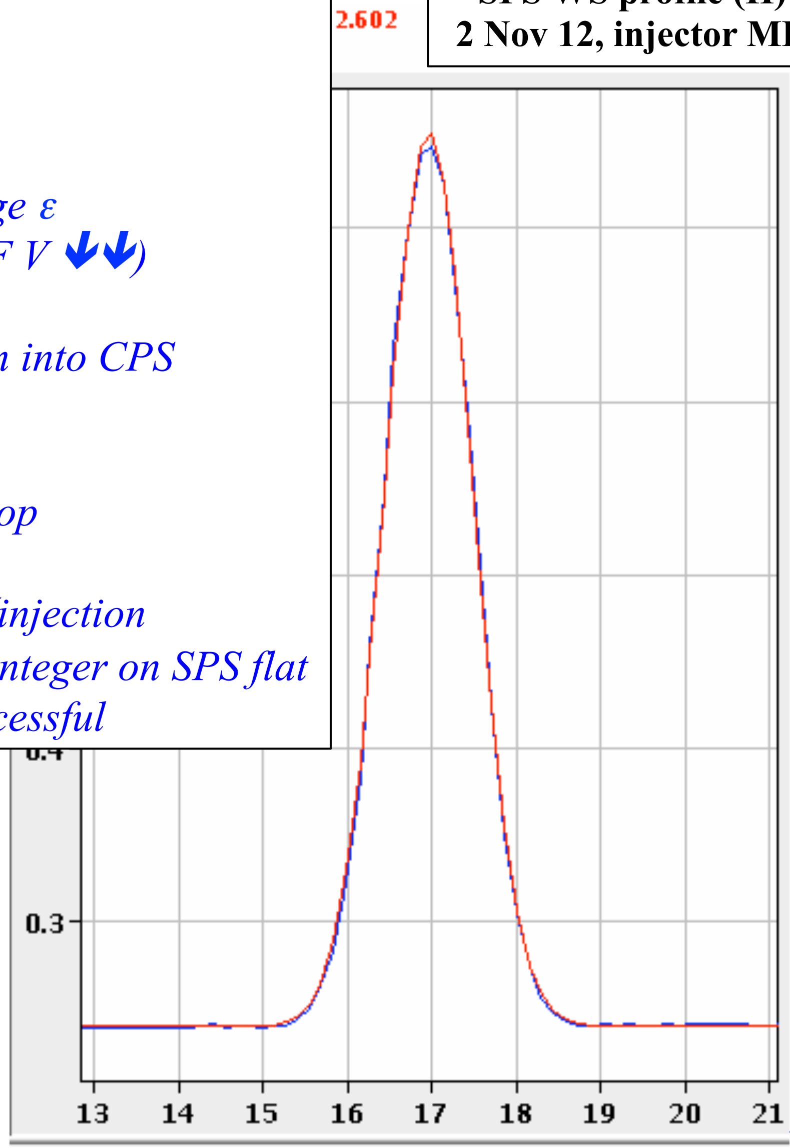
In PSB:
- *inject high intensity, large ε*
- *longitudinal shaving (RF V ↓↓)*
- *transverse shaving*

→ N ~ 8E10/p, ε ~ 2-3 μm into CPS

In SPS:
- *slight scraping at flat top*

Other methods also tried (injection missteering in PSB, Q → integer on SPS flat bottom) but were less successful

SPS WS profile (H)
2 Nov 12, injector MD



Production of (more) gaussian beams in the injector chain (2)