Beam-beam effects in the LHC

(and some perspectives for 7 TeV operation)

W. Herr

for LHC beam-beam working group

Beam-beam observations in the LHC (2011 - 2012)

- **Relevant questions we have addressed:**
  - **Head-on beam-beam: are we limited ?**
  - **Do we see long range effects ?**
  - **Do we see ”PACMAN” effects (i.e. bunch-to-bunch differences) ?**
  - **Are coherent beam-beam effects a problem ?**
  - **Can we level the luminosity ?**
  - **Can we extrapolate to other configurations ?**

Observations: head-on beam-beam effects I

- **First dedicated experiment with few bunches**
- **Test <u>maximum beam-beam parameter</u> (at injection energy) - head-on only**
  - **Intensity 1.9 $\cdot$ 10^{11} p/bunch (nominal: 1.15 $\cdot$ 10^{11})**
  - **Emittances 1.1 - 1.2 μm (nominal: 3.75 μm)**

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- **First dedicated experiment with few bunches**
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  - **Intensity 1.9 $\cdot$ 10^{11} p/bunch (nominal: 1.15 $\cdot$ 10^{11})**
  - **Emittances 1.1 - 1.2 μm (nominal: 3.75 μm)**
  - **Achieved:**
    ξ = **0.017 for single collision ($\approx$ 5 times nominal !)**
    ξ = **0.034 for two collision points (IP1 and IP5)**
  - **No obvious emittance increase or lifetime problems during collisions (maximum ξ not yet found)**

⚠ **No long range encounters present !**

Can we understand the large beam-beam parameter ?

- "Nominal" value was conservative choice (50% of SPS value !)
- Twice "nominal" value is standard in operation
- Large value (likely) due to:
  - Low noise, vibrations etc.
  - Small tune modulation (small PC ripple, low Q')

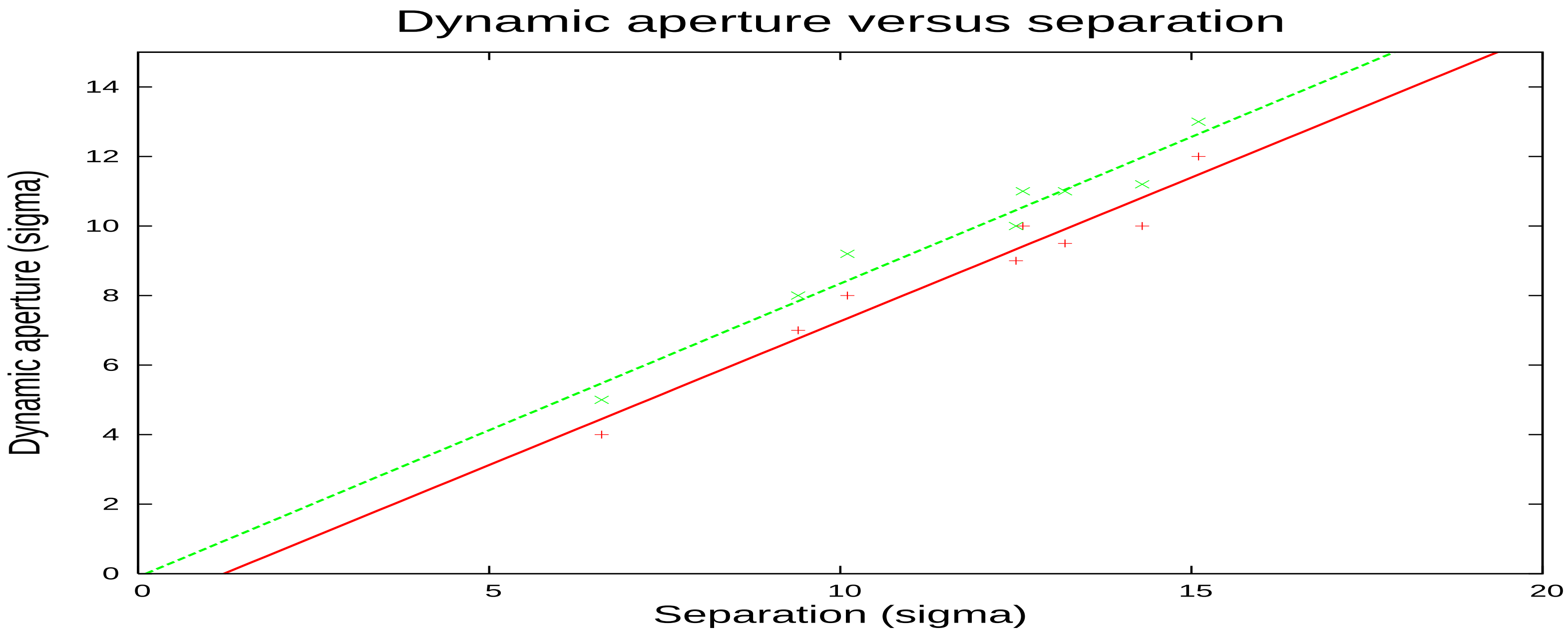
→ Not really our biggest problem (as expected)

→ But important to provide Landau damping !

Experimental study of long range beam-beam interactions

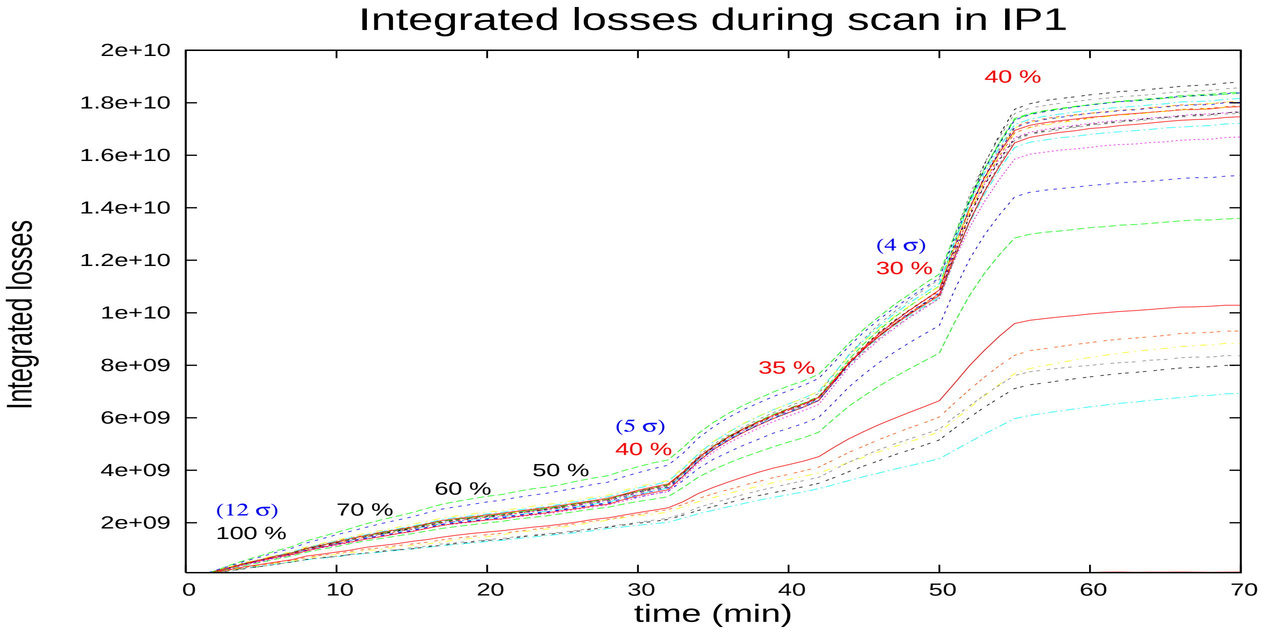
- **Test long range interactions with present machine in dedicated experiments**
- **Trains of 36 bunches per beam**
- **Spacing 50 ns, maximum 48 parasitic encounters**
- **Study collisions in IP1 and IP5 (small β^* → strong long range), procedure:**
  - **Reduce crossing angle (separation in small steps)**
  - **Observe losses bunch by bunch**

What do we expect ?



- **Dynamic aperture as function of normalized separation (W.Herr, D.Kaltchev, LPN 416, 2008)**
- **Simulations for 50 ns (x) and 25 ns (+)**
- **"Visible" losses expected for dynamic aperture below 3** σ

Experiment 1: scan of crossing angle - losses

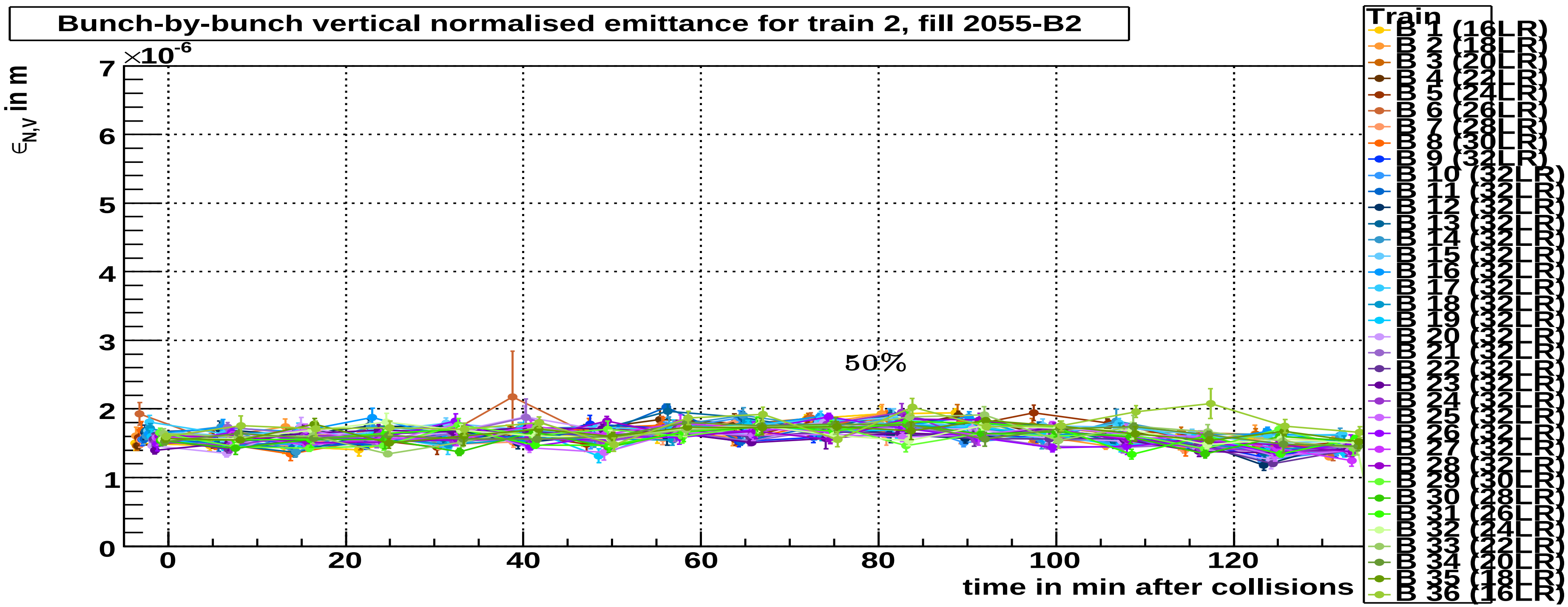


- **First test (2011) with $\beta^* = 1.50$ m, intensity: 1.2 10^{11} p/b, emittance: 2.0 - 2.5 μm**

→ **Bunch by bunch loss as function of crossing angle in IP1**

→ **Different behaviour of the bunches in the train**

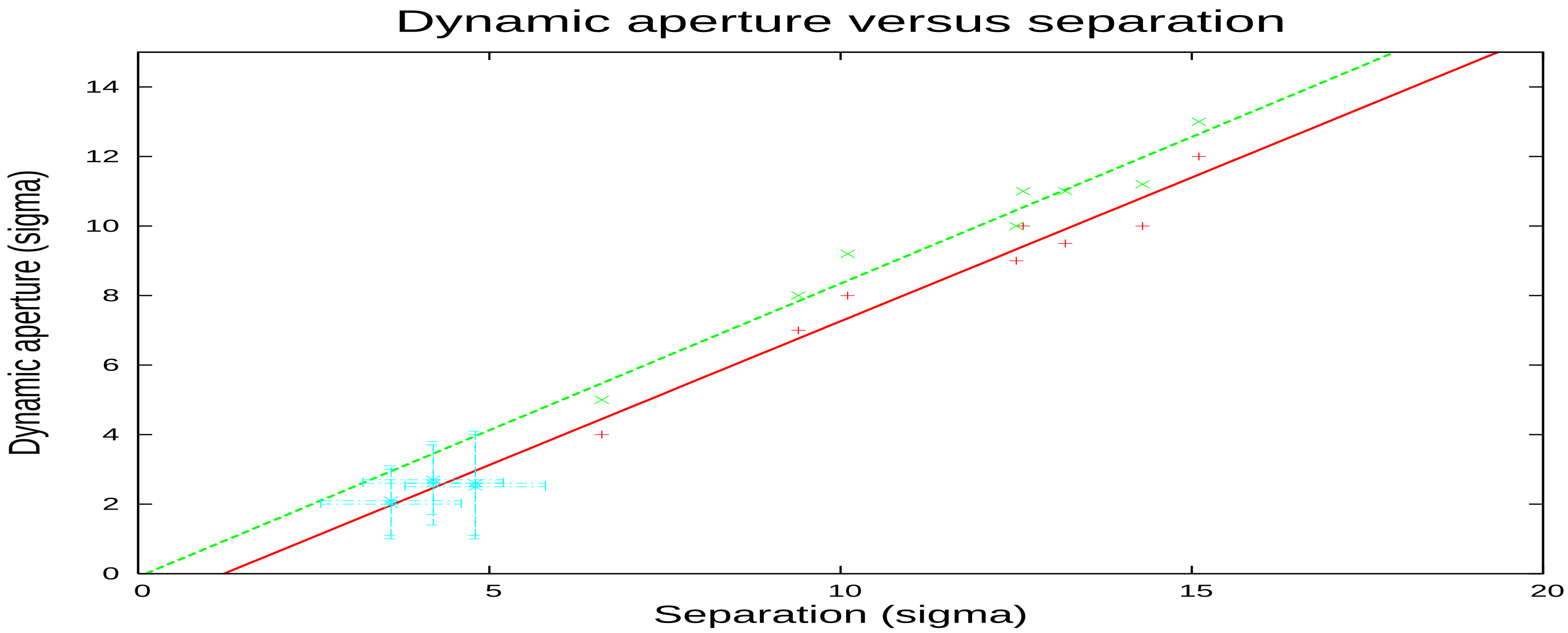
Experiment 2: scan of crossing angle - emittances



Courtesy M. Schaumann

- **Emittances during scan, vertical, beam 2, train 2**
- **No emittance increase → reduced dynamic aperture**

Comparison with our expectations



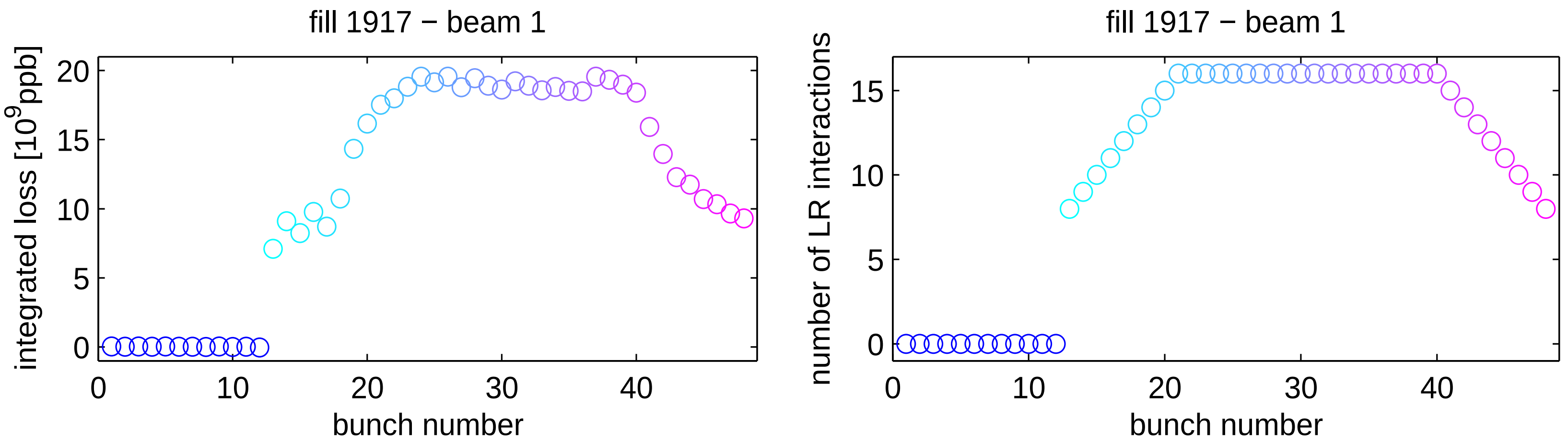
- **Data estimated from separation scan (50 ns, 3.5 TeV, 1.25 10^{11}p)**
- **Dynamic aperture as function of normalized separation (W.Herr, D.Kaltchev, LPN 416)**

Summary: scan of crossing angle

- **Observations:**
  - **Losses start after some threshold (4 - 5 σ separation)**

    remember: 48 parasitic encounters (nominal 120 !)
  - **Smaller separation leads to increased losses (dynamic aperture !) as predicted**
  - **No effect on emittances**
  - **Different bunches have different threshold !**
  - **Strong evidence for PACMAN effects**

PACMAN effects along train



(Courtesy G. Papotti)

- **Integrated losses and number of long range interactions**
- **Losses directly related to number of long range interactions**

→ **So-called 'PACMAN' bunches have better life time !**

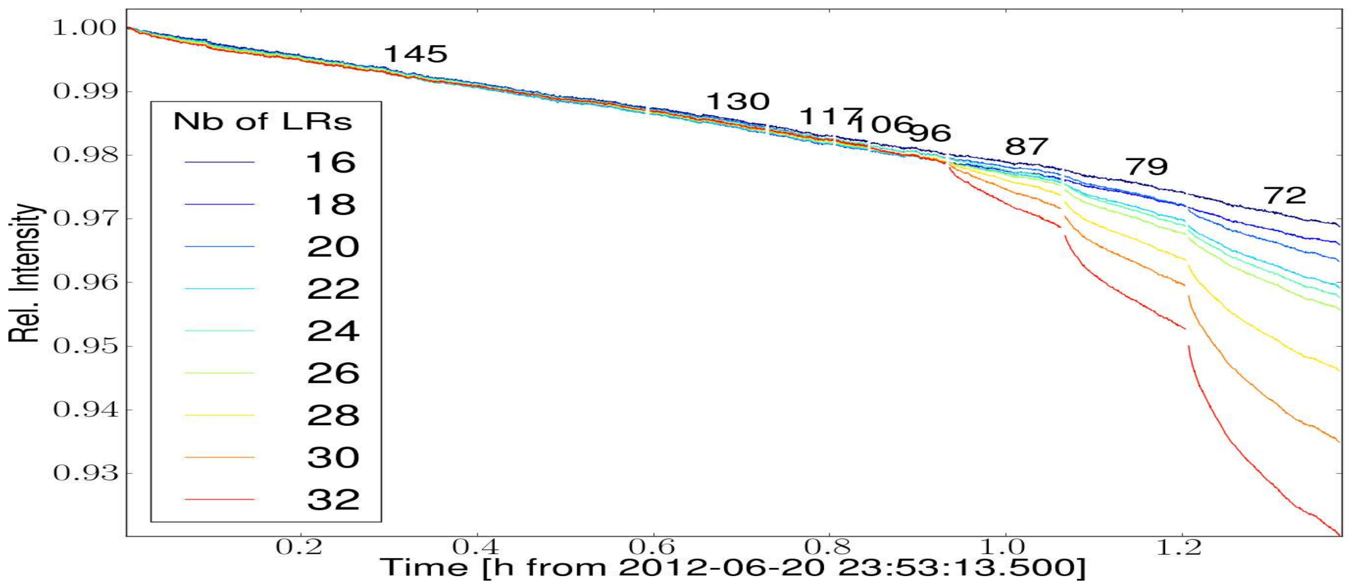
→ **'PACMAN' effects clearly visible, and exactly reproducible !!**

Can we understand the observations ?

- **Try an analytical model (allows to study parametric dependences)**
- **Based on computation of beam-beam invariants and smear (W.Herr, D.Kaltchev; IPAC09) → backup slides**
- **Can compute invariants for individual long range encounters**
  - **Derive scaling laws for dynamic aperture (losses) etc.**
  - **Estimate PACMAN effects (loss pattern)**
  - **Find the "critical" long range encounters**

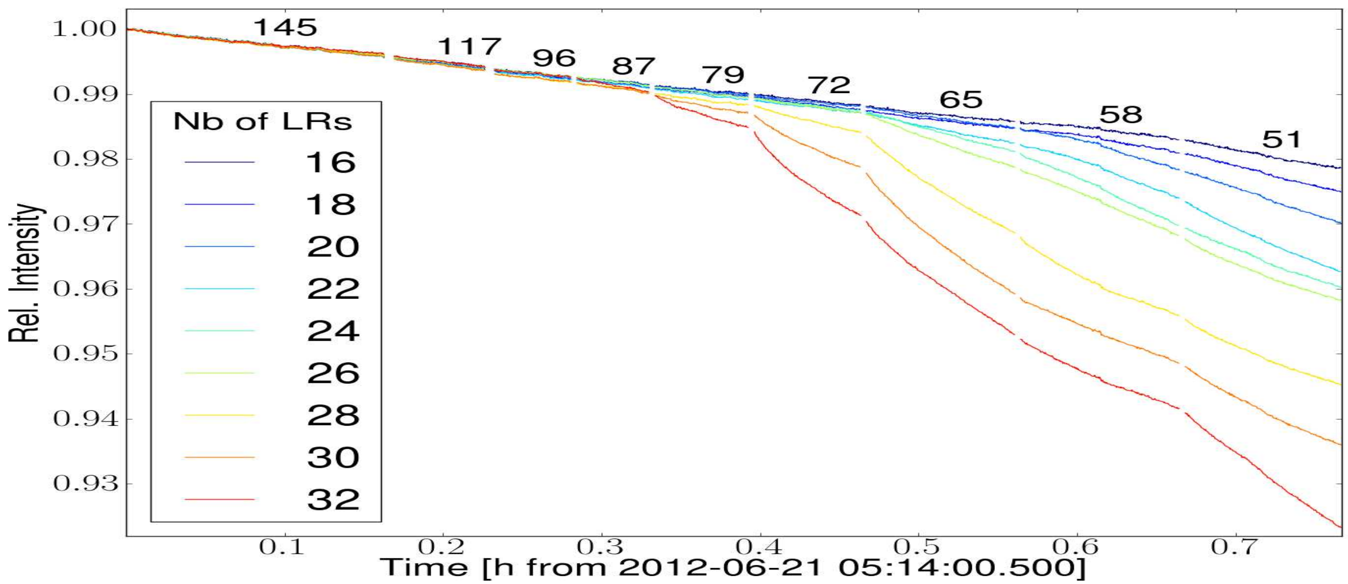
→ **Results are in good agreement with expectations**

Test of parametric dependence (separation, intensity)



- **Recent test (2012) with $\beta^* = 0.60$m, intensity: 1.6 10^{11} p/b**
- **Initial separation $\approx$ 9 - 9.5 σ**
- **Losses start $\approx$ 6 σ separation**

Test of parametric dependence (separation, intensity)



- **Recent test (2012) with $\beta^* = 0.60$m, intensity: 1.2 10^{11} p/b**
- **Initial separation ≈ 9 - 9.5 σ**
- **Losses start ≈ 5 σ separation**

PACMAN effects

- **Due to different number of long range <u>and head-on</u> collisions expected:**
  - **Systematic tune differences between nominal and PACMAN bunches**
  - **Systematic orbit differences between nominal and PACMAN bunches**
  - **Significant difference in tune spread (missing head-on)**
- **In LHC: alternating crossing scheme (horizontal and vertical crossing planes) removes tune difference by compensation for collisions in IP1 and IP5**

PACMAN effects in operation

- **Different tunes and orbits**

  (do we see a problem in 2012 ?)

- **Very different tune spread**

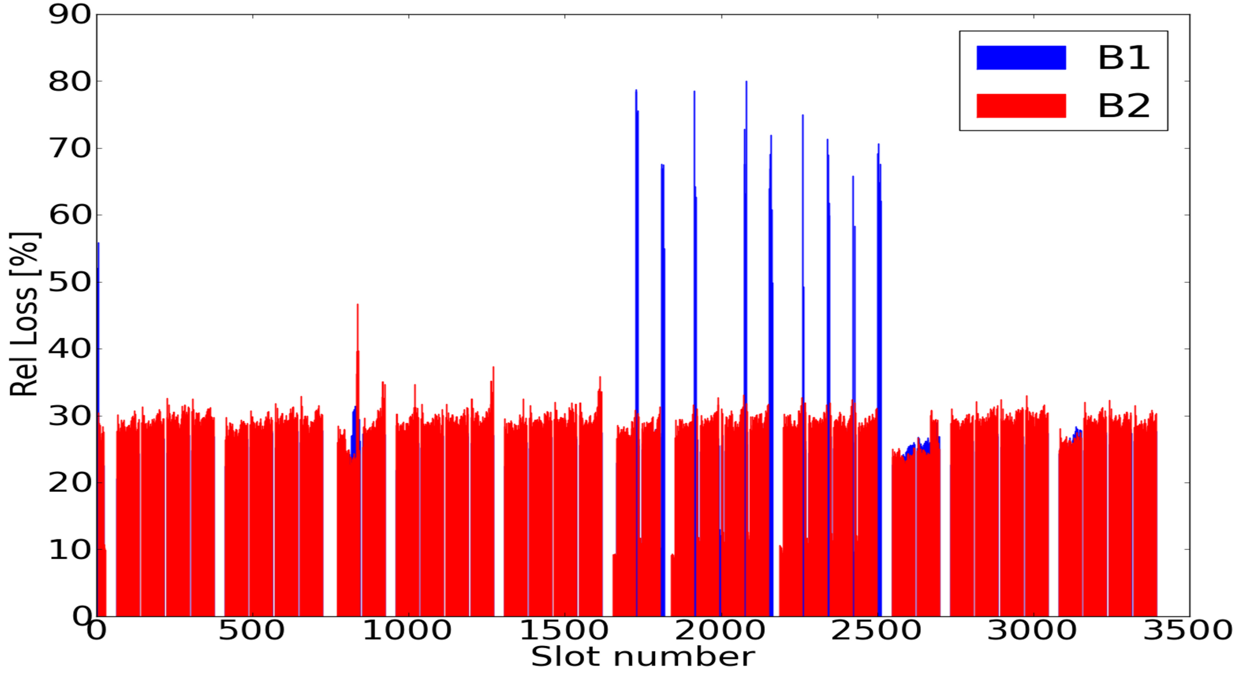
  (different number of head-on collisions: 0 - 4)

- **Frequently observe "selective" losses**

  Loss of Landau damping ???

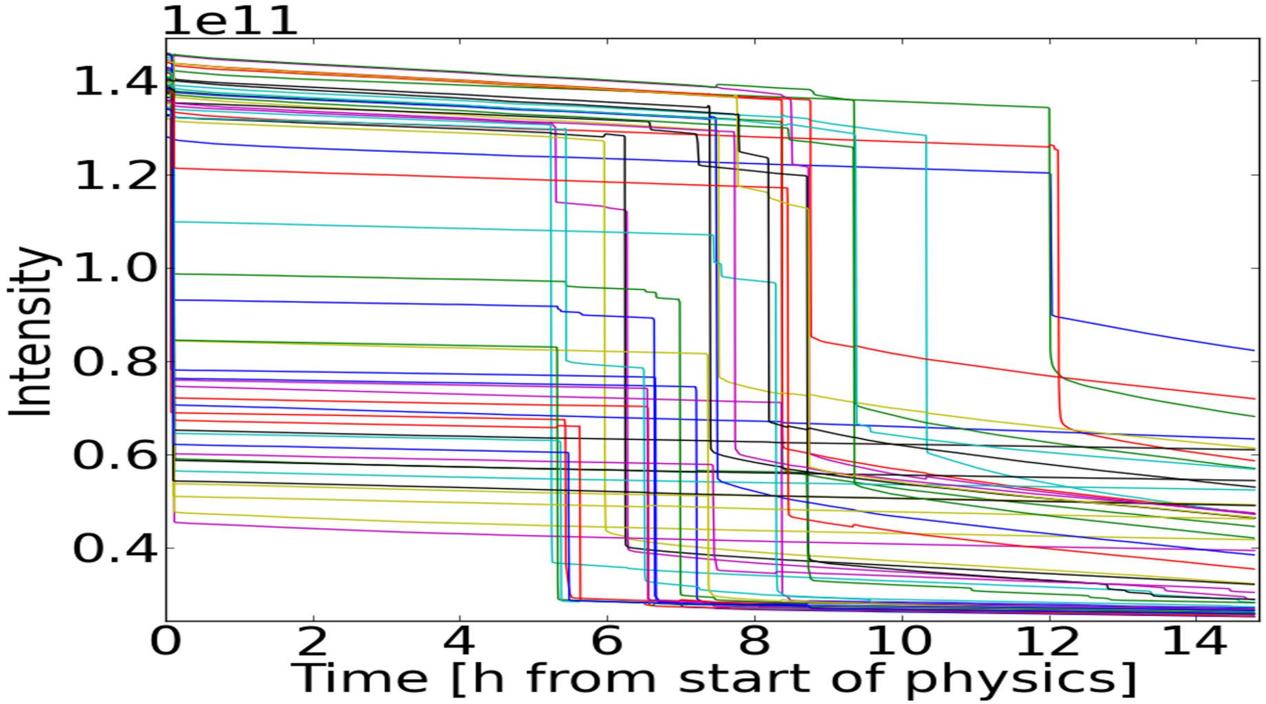
  (see: W. Herr, L. Vos; LHC Project Note 316, 2003)

PACMAN effects in operation



- Strong losses of selected bunches
- Out of 1380 bunches, 48 bunches without a head-on collision

PACMAN effects in operation



- Out of 1380 bunches, 48 bunches without a head-on collision
- Losses appear without manipulation after long time in store

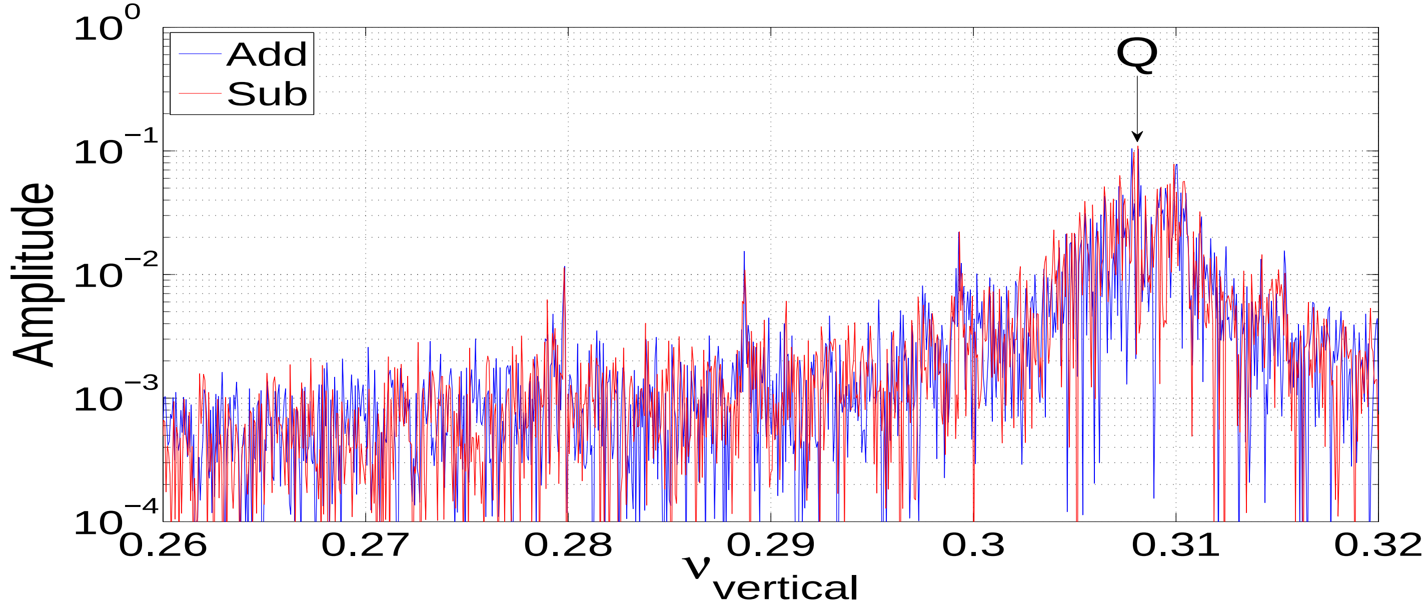
PACMAN effects in operation

- No head-on collisions because of special filling scheme and luminosity levelling in IP8
- Change of filling scheme (avoiding no head-on) immediately cured the problem.
- Head-on beam-beam by far the best tool for Landau damping:
  - → Large tune spread in the core of the beam (unlike octupoles or long range tune spread)
  - → Small tune spread in the tails of the beam (unlike octupoles or long range tune spread)

Strong-strong: coherent modes

- **Coherent beam-beam modes have been observed colliding few bunches**
- **Provide high degree of symmetry**
  - **Demonstrated by analysis of sum and difference signals between bunches (X. Buffat, IPAC11)**
  - **Symmetry breaking suppresses modes as expected (see: T. Pieloni, PhD thesis, 2008)**
- **But not (yet) a problem for operation**

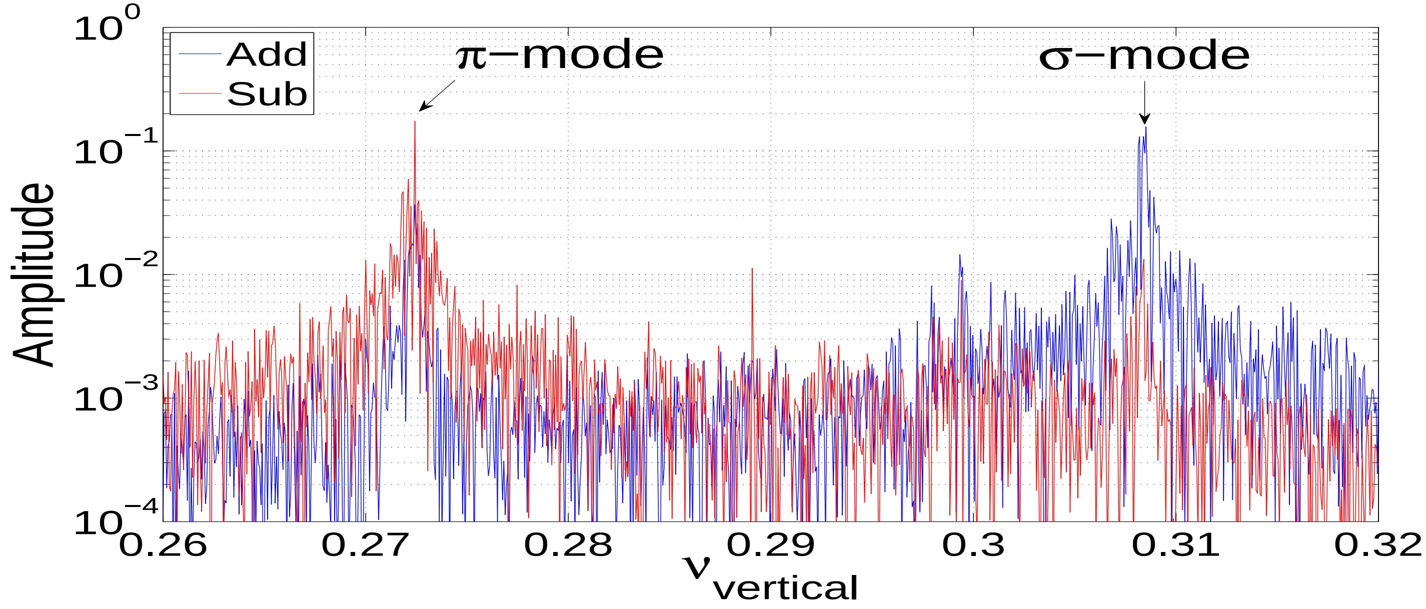
Coherent beam-beam modes



Courtesy X. Buffat

- **Signal without beam-beam collisions**

Coherent beam-beam modes



Courtesy X. Buffat

- **Sum and difference signals**
- **Clearly observed and identified coherent beam-beam modes**

Luminosity levelling

- **Luminosity levelling required already in 2011 (reduce luminosity and keep constant)**
  - **Achieved by transversely offset collisions (simple to do, very large range)**
  - **Separation ≈ 4 σ (IP2) and ≈ 0.5 - 1.5 σ (IP8)**
  - **Routinely done without detrimental beam-beam effects**

→ **But:**
potential loss of Landau damping ! (if no other collision)

→ **Better: levelling with β^* (constant head-on tune spread)**

(see presentation G. Papotti)

Summary of observations

- **Obtained large head-on tune shifts above nominal**

  In daily operation: twice "nominal" value is standard

- **Effect of long range interactions clearly visible (losses, dynamic aperture), no data yet on 25 ns spacing ..**

- **Number of head-on and/or long range interactions important for losses, strong PACMAN effects !**

- **All observations in excellent agreement with expectations and well understood (so far)**

Perspectives after Long Shutdown 1:

(from beam-beam POV)

- **Can we reach the nominal luminosity after LS1 ?**
  - **Which parameters needed, which bunch spacing ?**
- **Can we exceed the nominal luminosity after LS1 ?**

  (until LS2, not in 2015)
  - **Which are the limits and constraints ?**
  - **Which parameters are important ?**

Implications from head-on beam-beam:

- **Can collide high intensities (good for luminosity)**
- **Unknowns (hopefully with input from 2012):**
  - **Effect of noise**
  - **Effect of bunch by bunch fluctuation**
  - **Modulation effects**
- **For estimates: assume no limit on ξ**
- **In dedicated tests: reach pile up $\approx$ 70 per IP**

  (Intensity $\approx$ 3 10^{11}, emittances $\approx$ 3 μm)

Additional considerations

- **Peak luminosity is not the full story**
- **Integrated luminosity is not the full story either**
  - **Total beam intensity - machine protection**
  - **Event pile up in detectors**

Pile up

- **Events per crossing for given Luminosity:**

$$PU = \frac{1}{f_{rev}} \frac{\mathcal{L}}{n_b} \cdot 72 \text{ mbarn}$$

Assume pile up is limited to 42 events/crossing (twice nominal):

- N_b **= 1380 (50 ns spacing):** $\mathcal{L}_{max} = \mathbf{0.9\ 10^{34}cm^{-2}s^{-1}}$
- N_b **= 2520 (25 ns spacing):** $\mathcal{L}_{max} = \mathbf{1.75\ 10^{34}cm^{-2}s^{-1}}$

→ **Close to or above nominal luminosity: 25 ns is required !**

→ **Doubles number of long range, will be the main issue !**

Implications from long-range beam-beam:

- **Long-range beam-beam reduces dynamic aperture, i.e. losses and lower lifetime**
- **Scaling of the losses:**
  - **Separation** ($\alpha, \beta^*, \epsilon$)
  - **Number of long-range encounters (but no experience with 25 ns)**
  - **Dependence on intensity: tests show good agreement with model → backup slides**
- **For estimates: extrapolate from 2011/2012 experience and model**

Which crossing angle do we need ?

For comparison ➡ always use normalized separation in the drift space (for small enough β^*):

$$d_{sep} \approx \frac{\sqrt{\beta^*} \cdot \alpha \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}}$$

- ➡ **Proposed (minimum) separation $\approx$ 12 σ**
- ➡ **Crossing angle α depends on β^* (in crossing plane) !**
- ➡ **Smaller emittance ϵ_n allows smaller crossing angle α**

Importance of emittance:

Scaling properties of emittance:

$$d \propto \frac{1}{\sqrt{\epsilon_n}} \qquad \mathcal{L} \propto \frac{1}{\epsilon_n} \qquad \Delta Q_{LR} \propto \epsilon_n$$

$$\alpha = \frac{d \cdot \sqrt{\epsilon_n}}{\sqrt{\beta^*} \cdot \sqrt{\gamma}}$$

➡ **Difficult to lose with smaller emittance ...**

➡ **Emittance preservation should have high priority (in particular for 25 ns), e-cloud ??**

(see related talks: V. Kain, G. Rumolo, B. Mikulec)

Low transverse emittances with 25 ns

- **With reduced intensity and small emittance (see H. Dameraú)**

- **Aim at:**
  - → $\approx$ **0.7 - 1.0** $\cdot$ **10^{11} p/b**
  - → $\approx$ **1.2 - 1.3 μm**

→ **Fewer bunches: 2808 → 2520/2688 (depending on filling scheme, 36, 48, 64, 72 b/train)**

→ **Small emittances <u>very</u> profitable for LHC (beam-beam and luminosity)**

→ **Nominal luminosity even with low total intensity ...**

Other potential improvements:

- **Small emittances allow further squeeze of β^***
- **$\beta^* = 0.4$ m not out of reach**
  (but geometric loss $\approx$ 30 - 40 %)
- **Pseudo-flat beams (a la $Sp\bar{p}S$, 1982 - 1991):**
  - → $\beta_x^* \neq \beta_y^*$ → **e.g. (0.5,0.3) higher $\mathcal{L}$ than (0.4,0.4)**
  - → **Crossing angle in plane with larger β^***
  - → **squeeze further, (can avoid large crossing angle)**
  - → **May simplify levelling with β^***
    i.e. luminosity increase, no change of crossing angle

→ **Hope for tests this year ...**

Summary (through the beam-beam eyes):

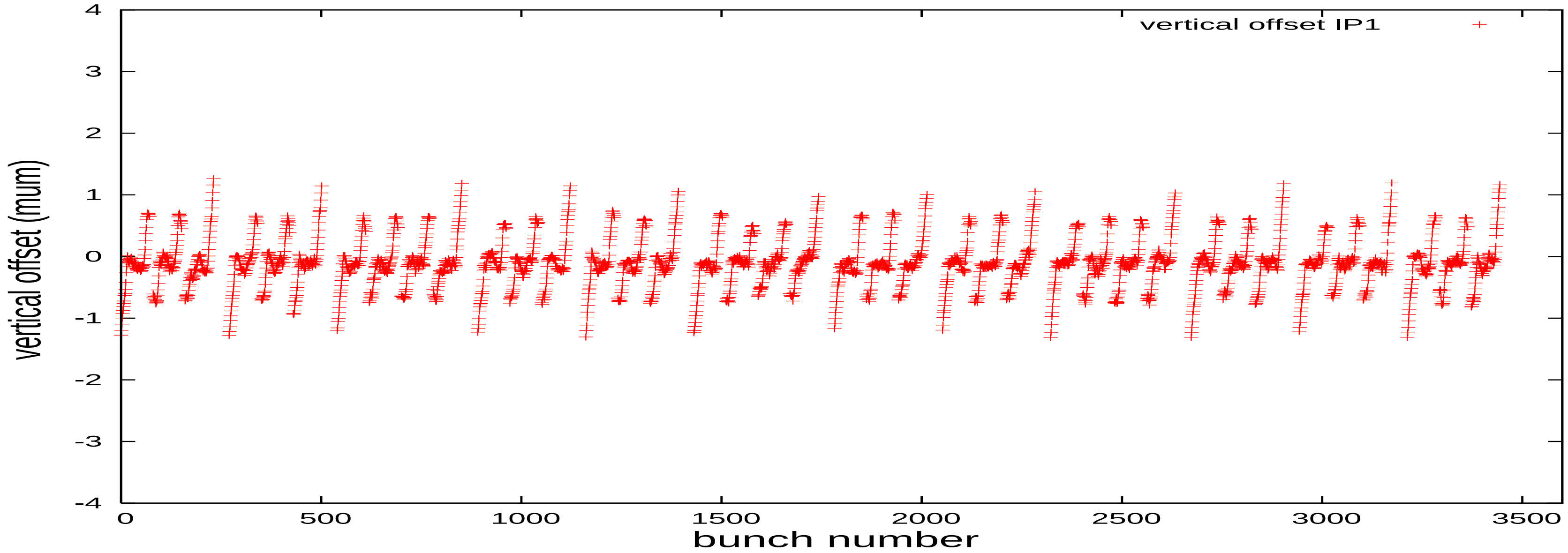
- **Nominal luminosity clearly in reach (early !)**
  - **Possible with conservative parameter sets (25 and 50 ns). For 50 ns at expense of high pile up.**
  - **For 25 ns reduced emittances, larger perspectives for improvement, emittance preservation important**
  - **Levelling probably required (better with β^* ??)**
- **Twice nominal luminosity should be a reasonable target**

- BACKUP SLIDES -

Beam-beam Orbit effects

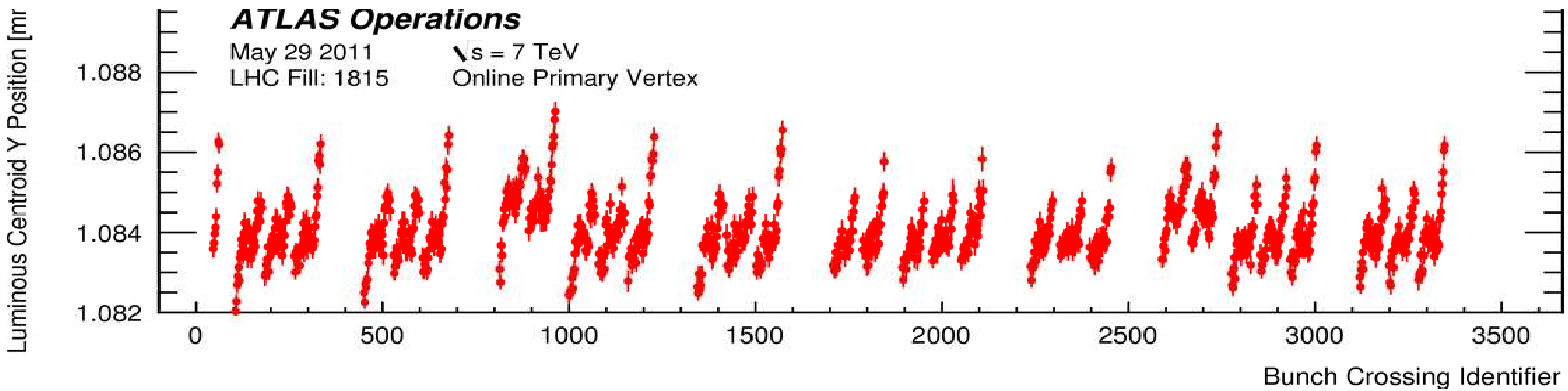
- **Strong beam-beam interaction with static offset produces dipole kick**
  - **Orbit changes due to beam-beam kick**
  - **Used for LEP: deflection scan**
  - **Expect strong effect for reduced separation**
- **What about orbits for PACMAN bunches ?**
  - **Different kicks - different orbits**
  - **Cannot be fully compensated by alternating crossing schemes (but minimized and made symmetric) !**

PACMAN Orbit effects: calculation



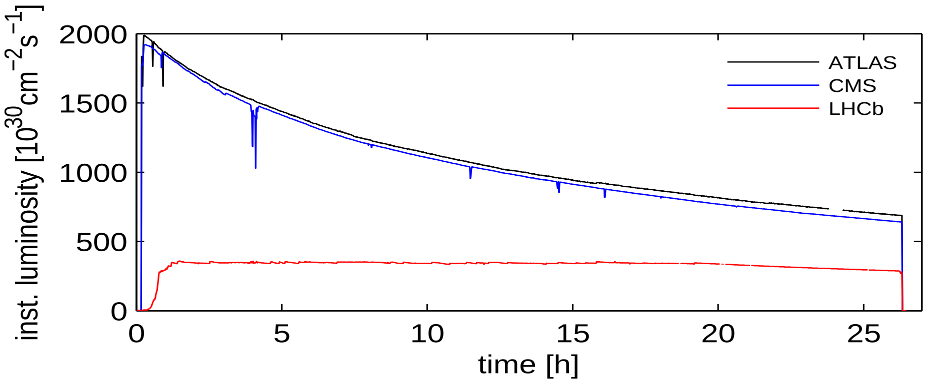
- In regular operation: offsets expected at collision point
- Predicted orbits from self-consistent computation, here vertical IP1 (H. Grote, W. Herr, 2001)
- Cannot be resolved with beam position measurement, but ..

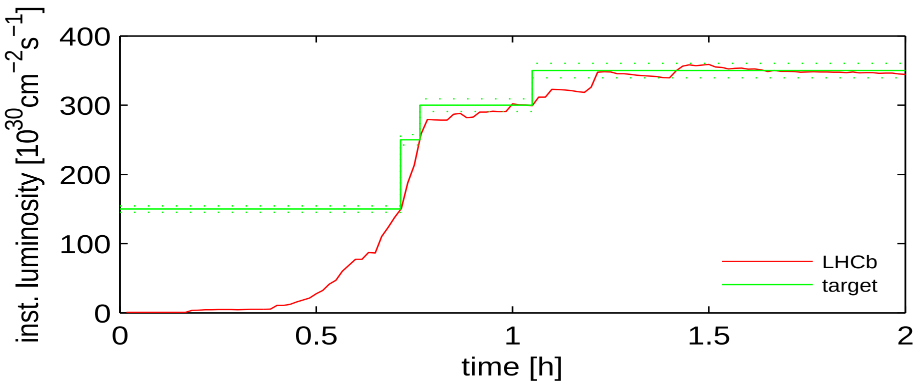
PACMAN Orbit effects: observation



- Measurement of vertex centroid by ATLAS (IP1)
- Qualitatively: follows exactly predicted behaviour
- Must be kept under control (sufficient separation) !

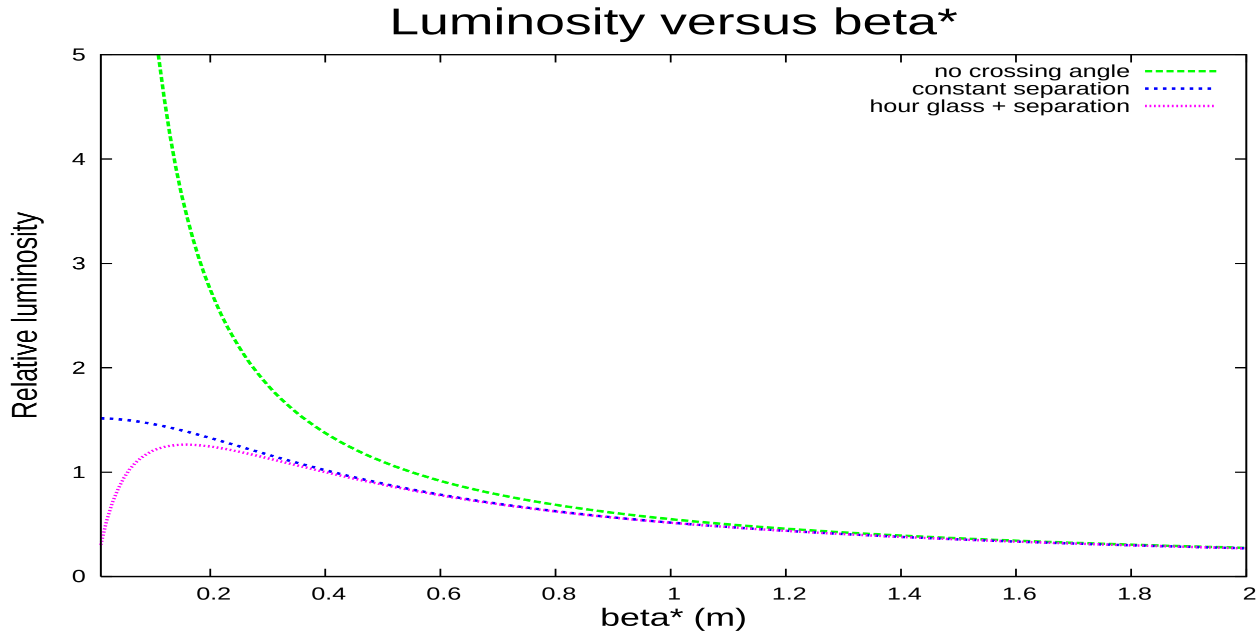
Luminosity levelling





- **Luminosity in LHC experiments during levelling**
- **Luminosity very constant in IP8, no effect on other IPs**

Smaller β^* - sure, but:



- **Luminosity for different β^* (round beams, constant intensity)**
- **Without and with crossing angle (for 10 σ), hour glass effect**
- **Small β^* require crab cavities (not for 2015)**

→ **No point to go below $\beta^* = 0.4$ m**

What about pile up ?

- **Levelling, do we need it ? If yes, how ?**
- **For 50 ns, almost certainly yes, for 25 ns maybe.**
  - **Crossing angle: too small, requires change of collimators etc.**
  - β^***: with constant crossing angle, successfully tested in 2012, would also ensure sufficient Landaua damping at all times ...**
  - **Transverse offset: IP1 and IP5 need much smaller offset ! Not obvious ..**

Strength of beam-beam interactions in the LHC

or: why do bunches behave differently ?

W. Herr

With material from:

[1] W. Herr, D. Kaltchev; LHC Project Report 1082 (2008)

[2] W. Herr, D. Kaltchev; Contribution IPAC 2009 (2009)

[3] A. Dragt; SLAC-PUB-2624 (1980)

[4] W. Herr; CAS, Chios (2011)

Beam-beam strength

- **In LHC a bunch can have many beam-beam interactions: head-on (4) and long-range (120).**
- **Which are important and which are not ?**
- **Which ones need special "care" ?**
- **Look at individual contributions**
- **Technique [1] extended to long range encounters [2]**
- **Compute contribution of smear for each encounter**

Beam-beam kicks (weak-strong)

Study effect of beam-beam encounters in weak-strong model, using (non-linear) transfer maps [3, 4]

$$M = \prod_{k=1}^{N_{IP}} e^{:F^{(k)}:} e^{:F_2^{(k)}:} \quad = \quad e^{:h:}$$

- N_{IP} **number of collision points (head-on and long-range)**
- $e^{:F^{(k)}:} e^{:F_2^{(k)}:}$ **operators associated with (**k**-th) beam-beam kick and linear matrix (between** k **and** $k+1$**)**
- $e^{:h:}$ **is the non-linear one turn map, (eff. Hamiltonian, invariant)**

Beam-beam kicks

Beam-beam potential $F^{(k)}(x)$ re-written from force $f(x)$ [4]:

$$f(x) = \lambda \cdot \frac{2(x+d_x)}{(x+d_x)^2 + d_y^2} \cdot \exp\left[-\frac{(x+d_x)^2 + d_y^2}{2\sigma^2}\right]$$

- **With $\lambda = \frac{N_b r_0}{\gamma}$ we write $F^{(k)}(x)$ as [4]:**

$$F^{(k)}(x) = \int_0^x f^{(k)}(x')dx'$$

- $f^{(k)}(x)$ **denote k-th encounter,** $\rightarrow$ $\lambda^{(k)}, d_{x,y}^{(k)}$ **and** $\sigma_{x,y}^{(k)}$

from now: using $d_{x,y}^{(k)}$ normalized to beam size $\sigma_{x,y}^{(k)}$

$$d_{x,y}^{(k)} \rightarrow d_{x,y}^{(k)}/\sigma_{x,y}^{(k)}$$

Beam-beam kicks

Going to action angle variables, the integral $F^{(k)}(A,\Phi)$ becomes:

$$F^{(k)}(A,\Phi) = \int_0^1 \frac{dt}{t}\left(1 - e^{-t\left[\left(\sqrt{A}sin(\Phi)+\frac{d_x^{(k)}}{\sqrt{2}}\right)^2 - \frac{{d_y^{(k)}}^2}{2}\right]}\right)$$

we can expand as Fourier series (for later use):

$$F^{(k)}(A,\Phi) = \sum_{n=-\infty}^{\infty} c_n^{(k)}(A) e^{in\Phi}$$

- **Can be solved numerically:**
  1. **Head-on ($d_{x,y}^{(k)} = 0$): with Bessel functions (see: e.g. Chao, and [1])**
  2. **Long-range ($d_{x,y}^{(k)} \neq 0$): through incomplete Γ function (see: Herr, Kaltchev, PAC09 [2])**

Interlude (I):

What about the constant part of the kick (dipole, orbit kick) ?
In tracking, subtract constant part (x = 0):

$$f^{(k)}(x) \quad \Longrightarrow \quad f^{(k)}(x) - f^{(k)}(0)$$

we need now to compute the coefficients $c_n^{(k)}$ **from modified potentials:**

$$F^{(k)} \quad \Longrightarrow \quad F^{(k)} - F_1^{(k)}$$

where $F_1^{(k)}$ **is the linear part of** $F^{(k)}$**.**
We have:

$$F_1 = \frac{2\sqrt{2A} sin\Phi}{d^2} \cdot d_x \cdot (1 - exp\frac{-d^2}{2})$$

with $d^2 = d_x^2 + d_y^2$

Interlude (II):

If you get bored:

What happens when we subtract the quadratic parts of the potential as well ?

$$F^{(k)} \quad \Longrightarrow \quad F^{(k)} - F_1^{(k)} - F_2^{(k)}$$

with:

$$F_2 = \frac{2A \cdot \sin^2\Phi}{d^4} \cdot \left[-d_x^2 + d_y^2 + (d_x^2 + d_x^4 - d_y^2 + d_x^2 d_y^2) \cdot \exp\frac{-d^2}{2} \right]$$

Would that be useful ?

Good luck ..

Beam-beam invariant

The invariant h we get with the CBH formula:

$$h(A,\Phi) = -\mu A + \mu \sum_{k=1}^{N_{IP}} \frac{\lambda^{(k)}}{\epsilon} \tilde{h}^{(k)}(A)$$

for the individual contributions $\tilde{h}^{(k)}$ of encounters:

$$\tilde{h}^{(k)}(A) = c_0^{(k)}(A) + \sum_{n=1}^{m} \frac{(-1)^n n}{2sin(\frac{n\mu}{2})} \left[c_n^{(k)}(A) e^{in(\frac{1}{2}\mu - \mu^{(k)} - \Phi)} + c.c. \right]$$

and the coefficients $c_n^{(k)}(A)$ (remember the Fourier expansion):

$$c_n^{(k)}(A) = \frac{1}{2\pi} \int_0^{2\pi} e^{-in\Phi} F^{(k)}(A,\Phi) d\Phi$$

Remarks:

- **Invariant away from resonances**

  (because $\frac{(-1)^n n}{2sin(\frac{n\mu}{2})}$**)** → **"exit invariant"**

- **Use individual** $\lambda^{(k)}$

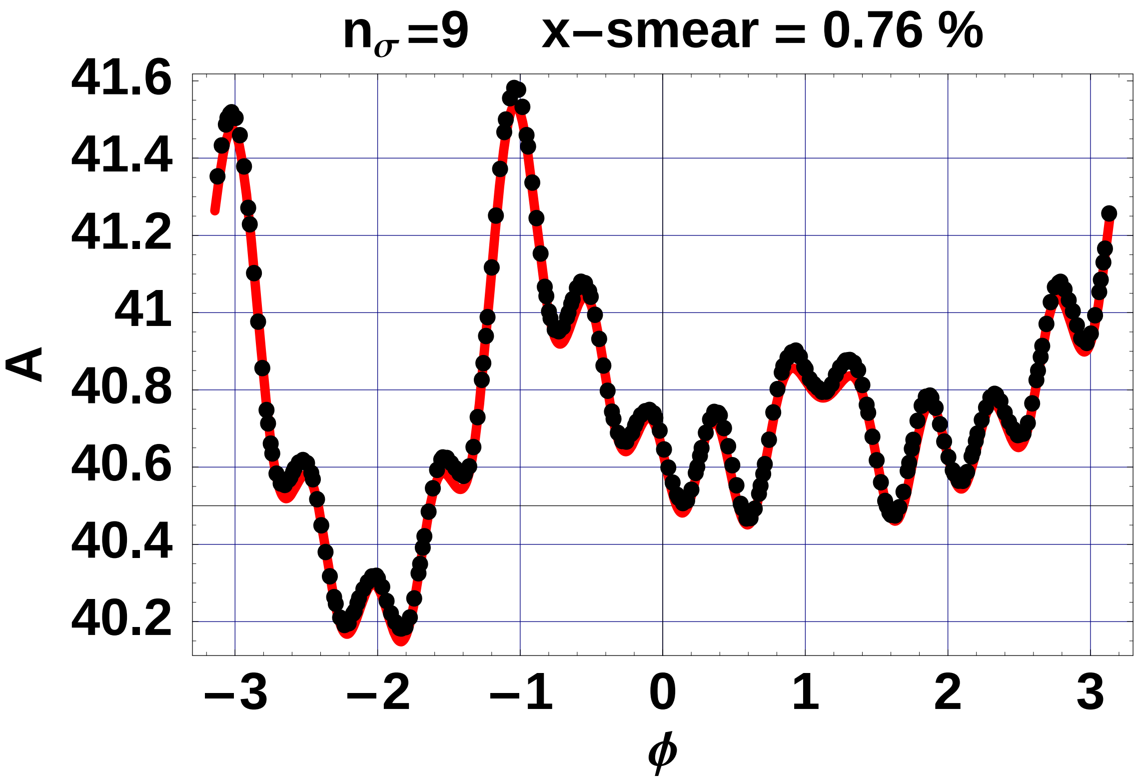
  Could model "poor men's simulation" with lumped interactions (not done here)

From the invariant to the smear

- **The $\tilde{h}^{(k)}$ are the contributions of the k-th collision (head-on or long range)**
- **Use $h(A, \Phi)$ to express A as a function of Φ**

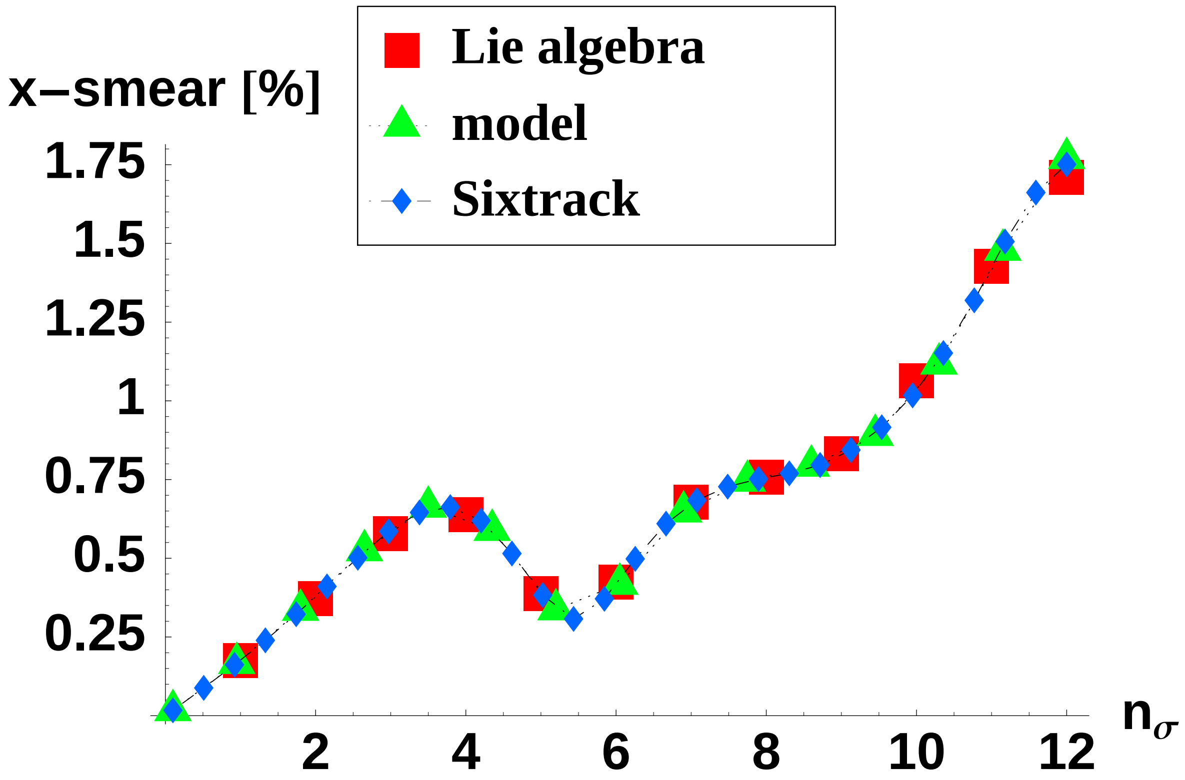
  With $(A_0, \Phi_0) = (\frac{n_\sigma^2}{2}, \frac{\pi}{2})$ and $h(A, \Phi) = h(A_0, \Phi_0)$ since invariant: → $A(A_0, \Phi, \Phi_0)$
- **The smear is the r.m.s. deviation of A from the mean**
- **Can compare the individual contribution of $\tilde{h}^{(k)}$ to the overall smear**

Comparison: model and tracking



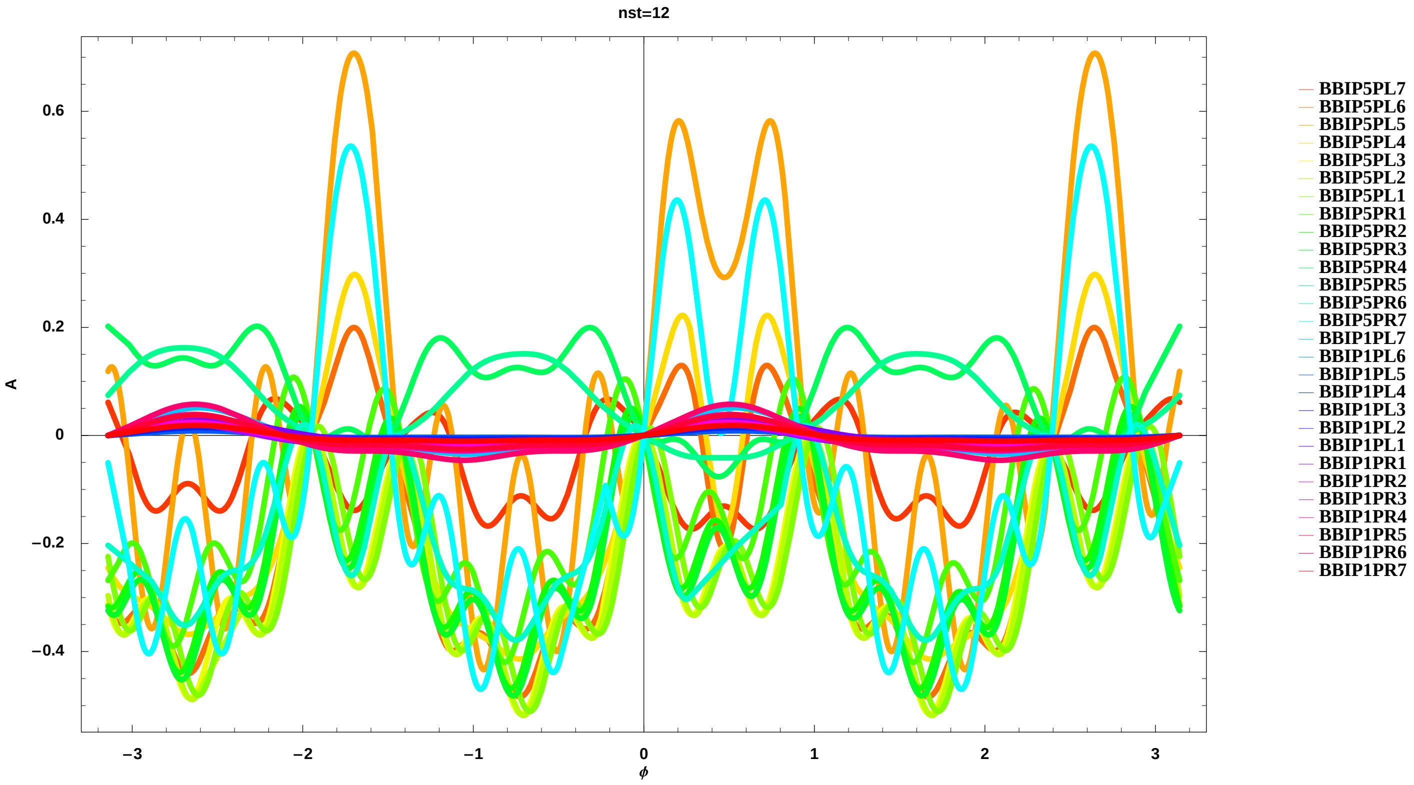
➡ **Invariant, model and tracking**

Comparison: model and tracking



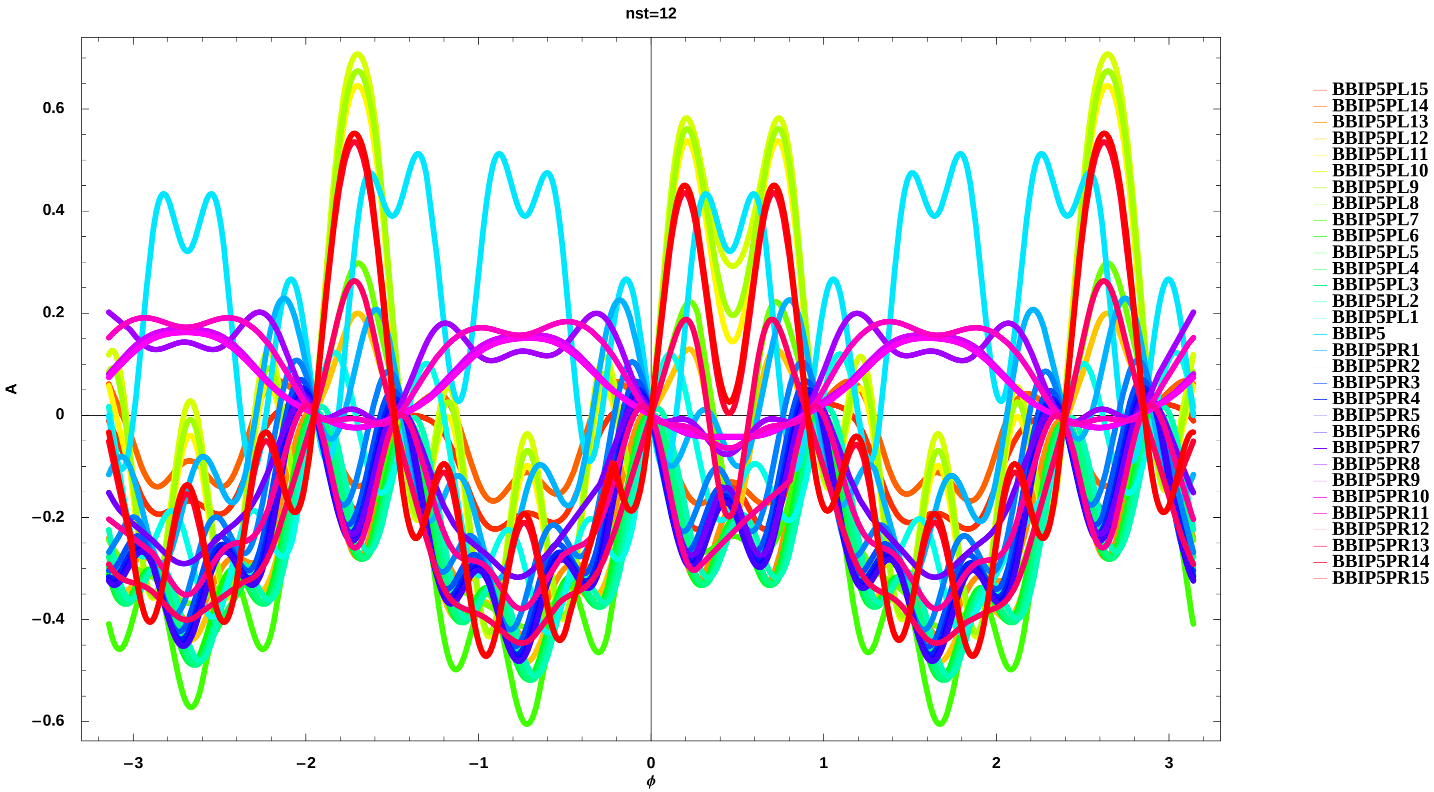
➡ Smear: model and tracking (SIXTRACK)

Contribution of long range encounters



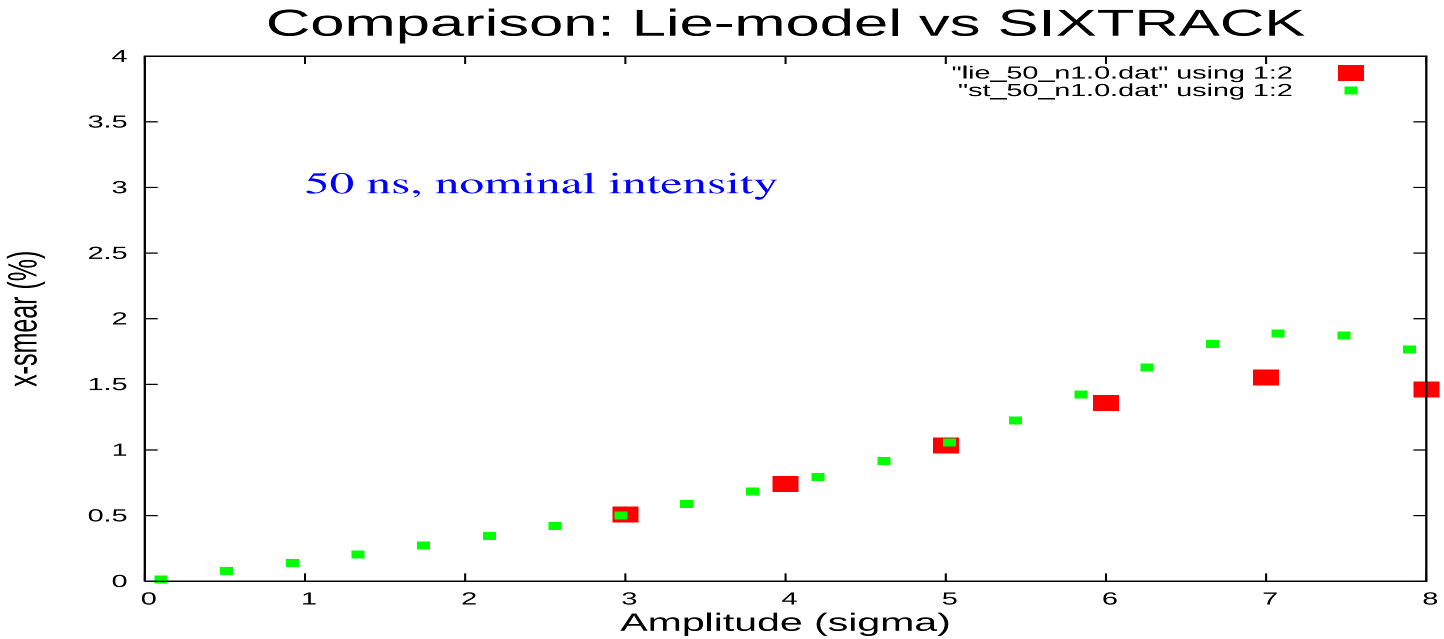
➡ **Individual contributions, 50 ns spacing**

Contribution of long range encounters



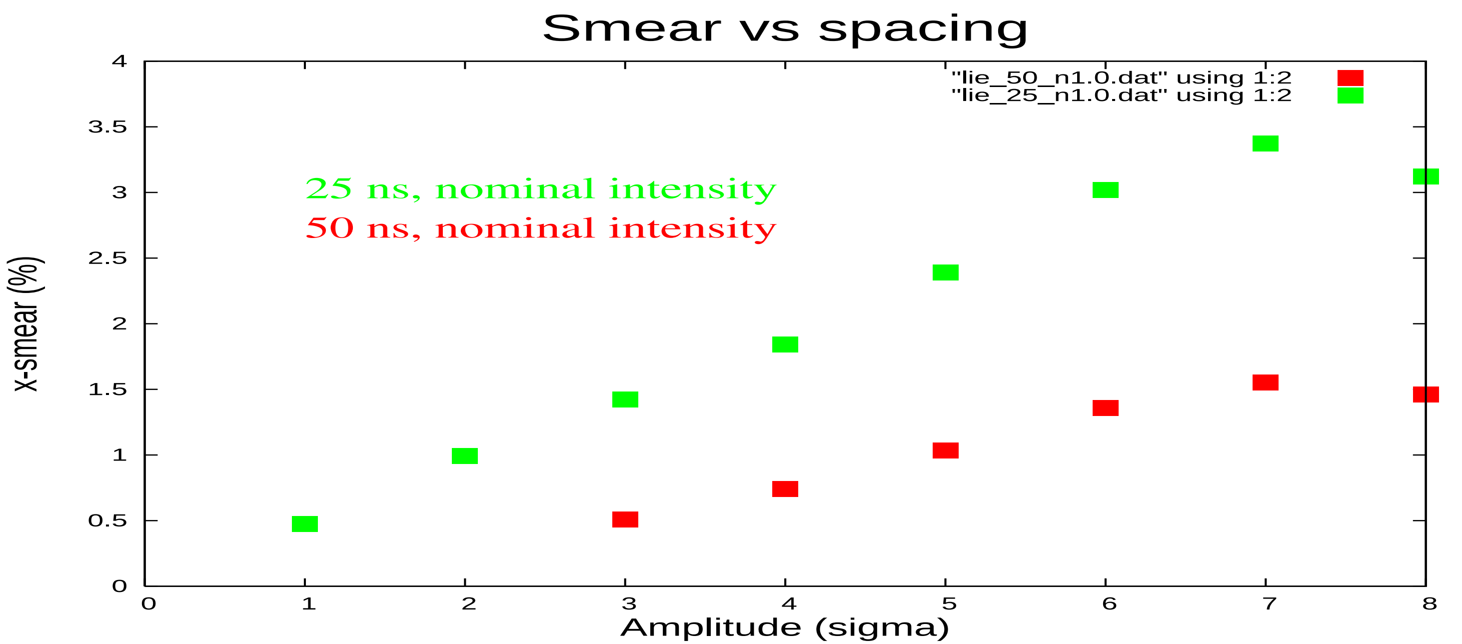
→ **Individual contributions, 25 ns spacing**

Comparison with tracking



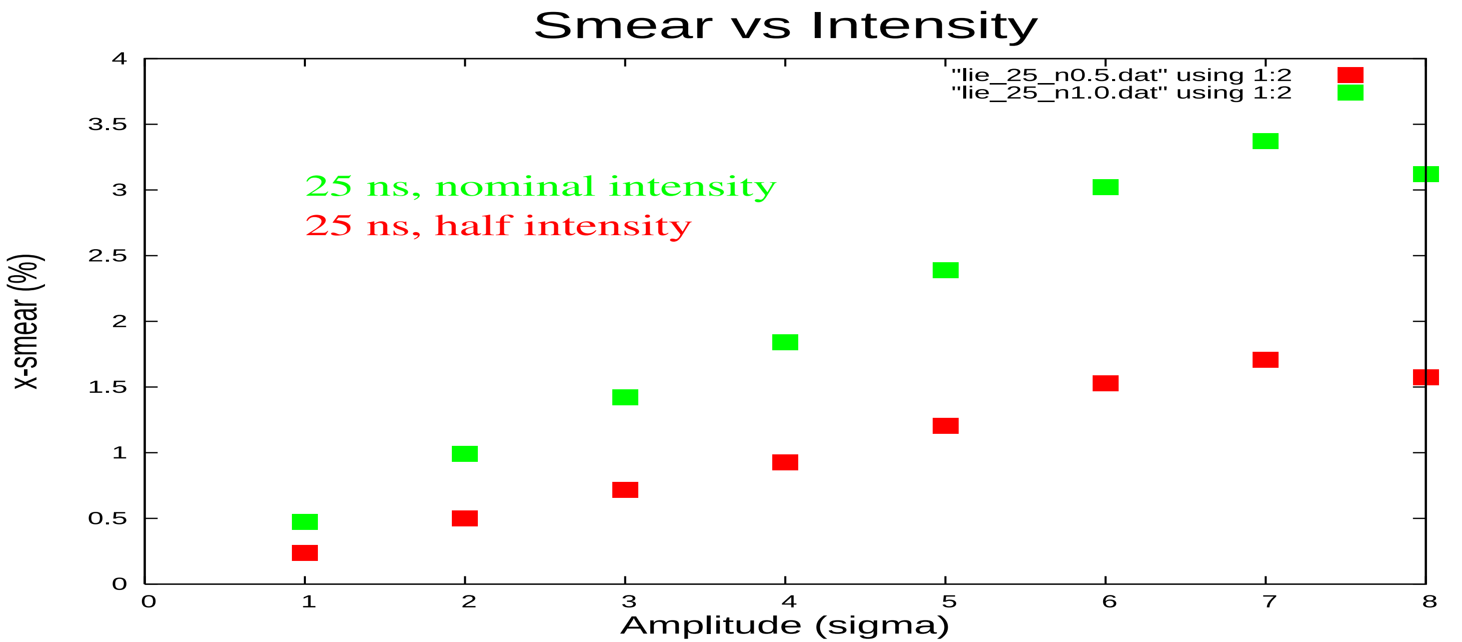
- **Comparison: model versus tracking (SIXRACK)**

Dependence on spacing



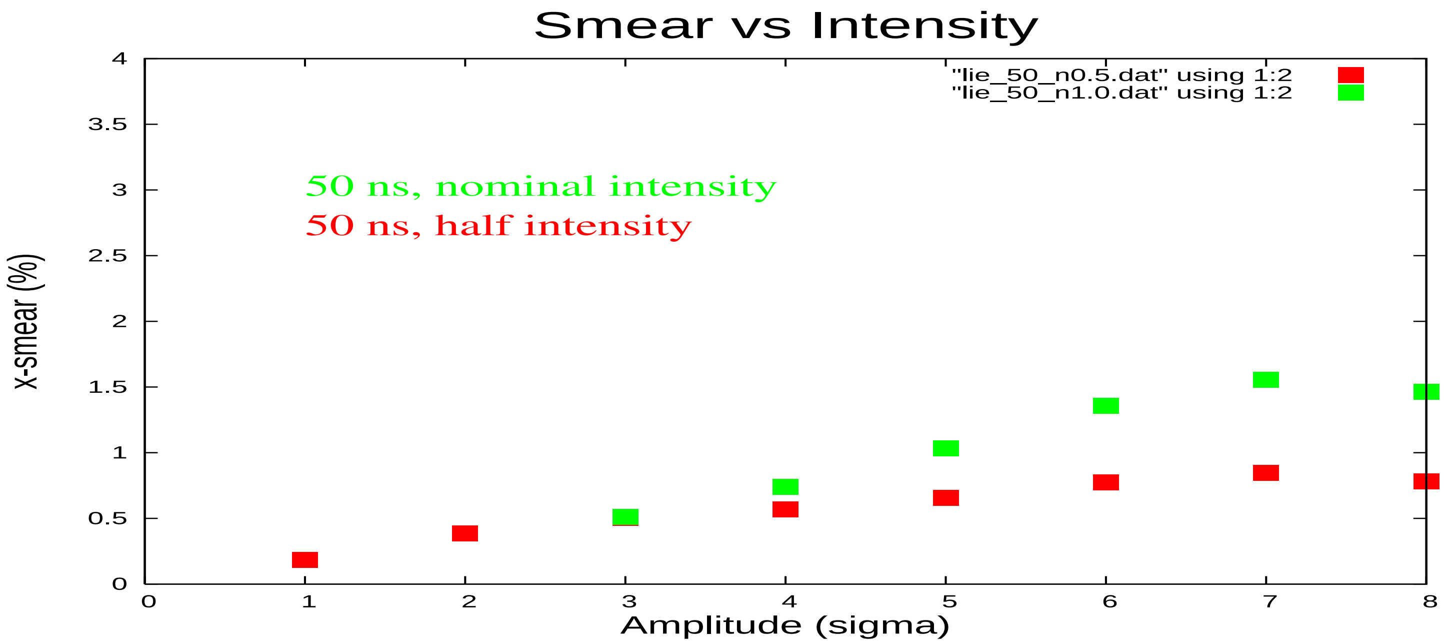
- **Strength of non-linearity for 25 ns and 50 ns spacing**

Dependence on intensity (25 ns)



- **Strength of non-linearity for different intensity (nominal and half nominal)**

Dependence on intensity (50 ns)



- **Strength of non-linearity for different intensity (nominal and half nominal)**
- **Less sensitive for 50 ns than for 25 ns (see backup slides)**

Expected scaling laws: tune shift

- **Scaling laws for long range tune shift $\Delta\mathbf{Q}_{lr}$**

$$\Delta\ Q_{lr} \propto N \quad \text{(Intensity)}$$

$$\Delta\ Q_{lr} \propto n_b \quad \text{(number of bunches)}$$

$$\Delta\ Q_{lr} \propto \epsilon$$

$$\Delta\ Q_{lr} \propto \frac{1}{d_{sep}^2} \propto \frac{1}{\alpha^2}$$

$$\Delta\ Q_{lr} \propto \frac{1}{d_{sep}^2} \propto \frac{1}{\beta^*}$$

Expected scaling laws: dynamic aperture

- **Scaling laws for long-range dynamic aperture DA**

$$DA \;\propto\; \frac{1}{n_b} \quad \text{(number of bunches)}$$

$$DA \;\propto\; \frac{1}{\sqrt{\epsilon}}$$

$$DA \;\propto\; d_{sep} \;\propto\; \alpha$$

$$DA \;\propto\; d_{sep} \;\propto\; \sqrt{\beta^*}$$

$$DA \;\propto\; \frac{1}{N} \quad \text{(Intensity, still to be checked)}$$

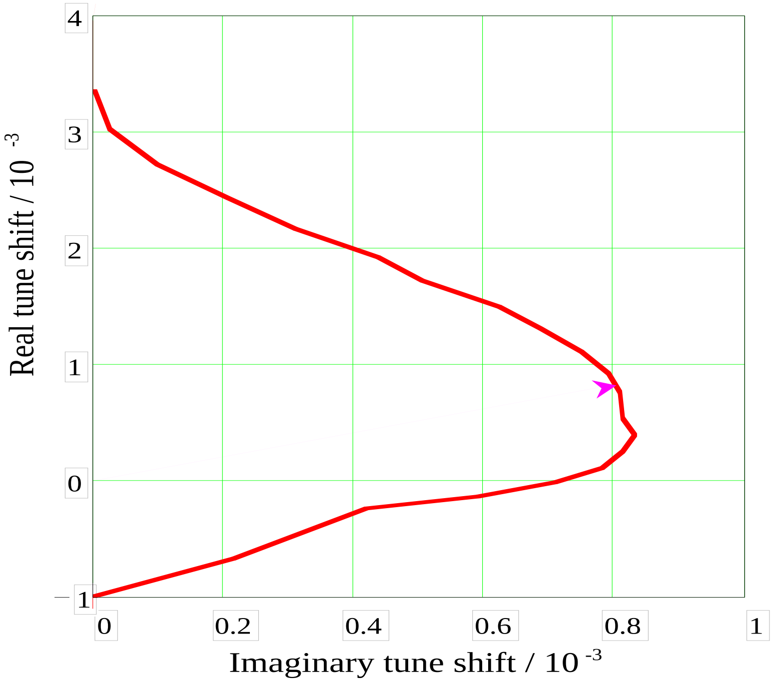
Summary

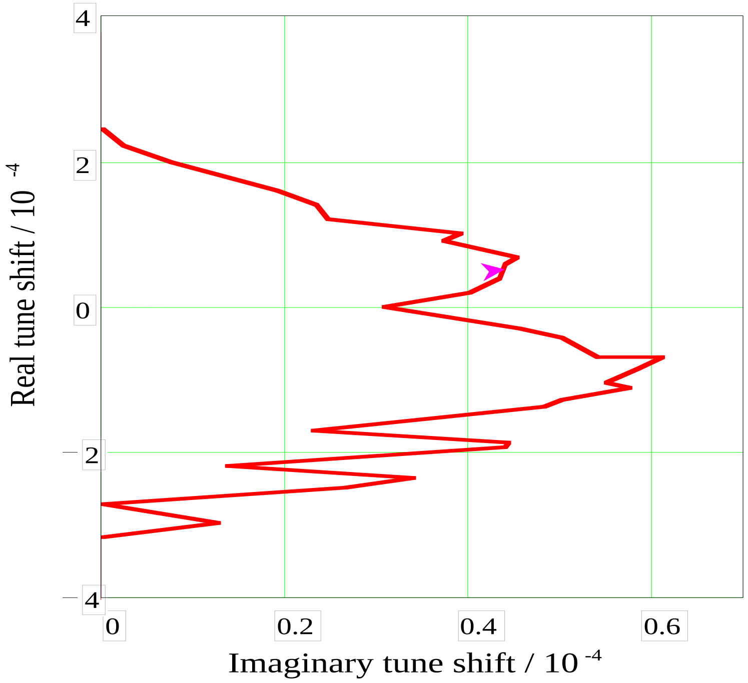
- **Energy: 7 TeV**
- **25 ns spacing**
- **Intensity:** $\approx$ **1.7** $\cdot$ $\mathbf{10^{11}}$ **p/bunch**
- **Emittance: 2.0** μ**m,** $\beta^* =$ **(0.50, 0.35)**
- **Separation 10** σ

→ $\xi_{bb} \leq$ **0.008**

→ $\mathcal{L} \geq$ **4**$\cdot$ $\mathbf{10^{34} cm^{-2} s^{-1}}$ **(depending on filling scheme)**

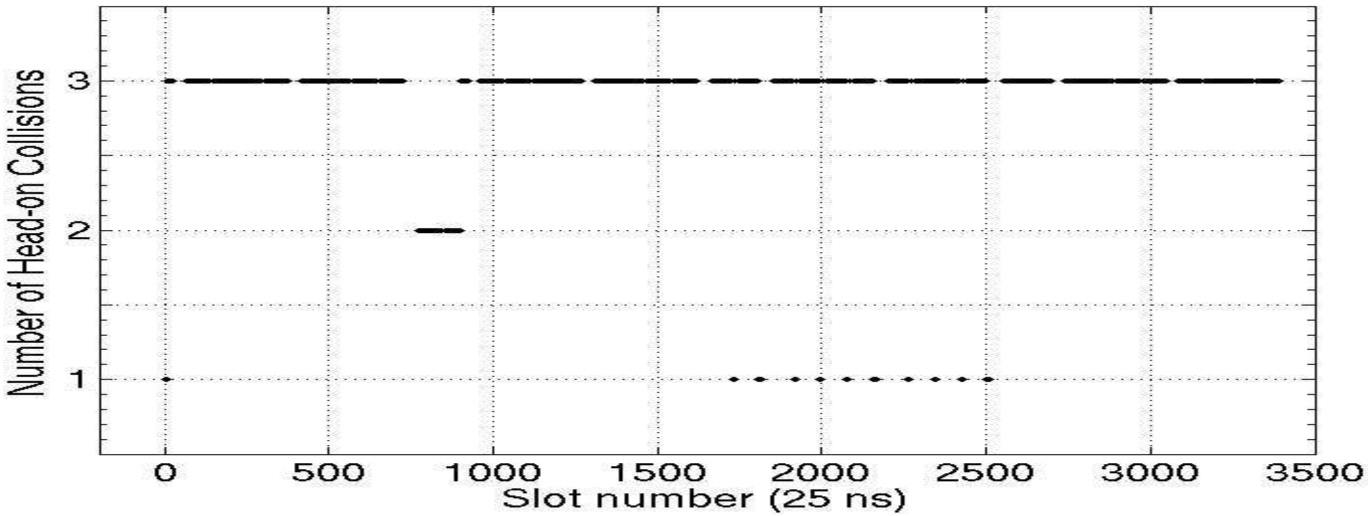
Stability from beam-beam





- **LHC parameters (2003), 25 ns, emittance 3.75 μm**
- **Left: HO + LR, Right: LR only**

Losses in collision



- **Collision pattern .....**
- **Lost bunches with (not even) single head-on collision only**