Observations of Beam-Beam Effects at High Intensities in the LHC

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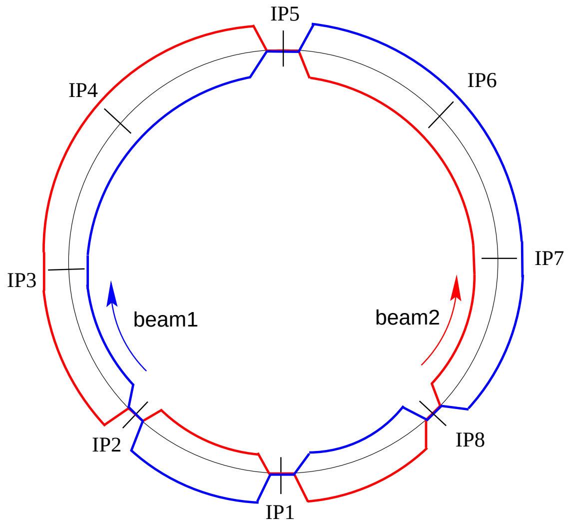
(for LHC Beam-Beam Studies Team)

Beam-beam effects in the LHC

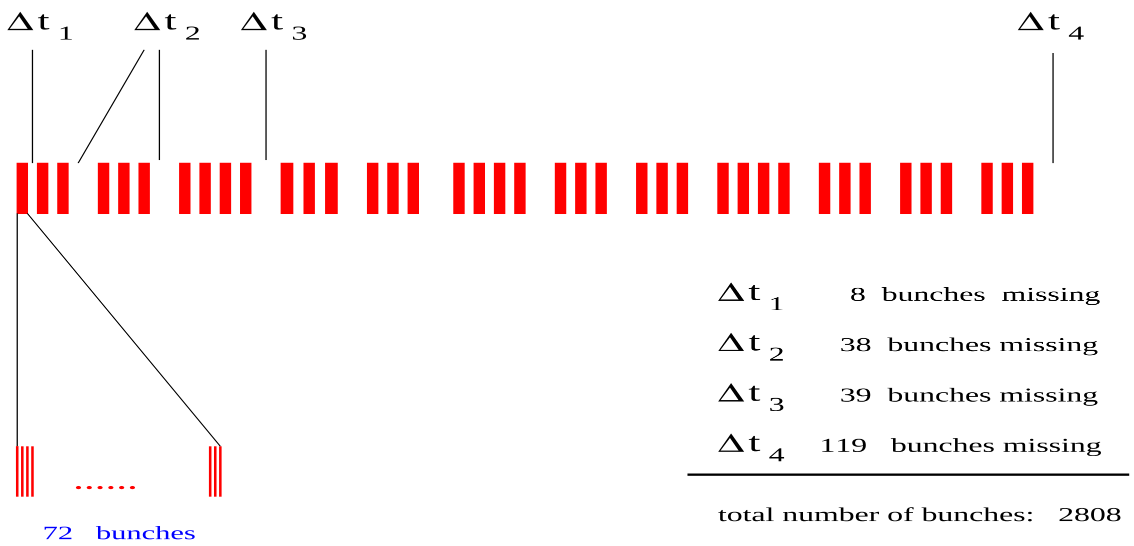
- Some important features of the LHC:
  - Equally charged beams and separate rings
  - Large number of bunches
  - Strong-strong beam-beam interaction
  - Users (experiments) with very different requirements
- All have significant implications for beam-beam effects
- Studied in dedicated tests and during operation
- An overview, details presented in posters

Where it happens: LHC collision layout



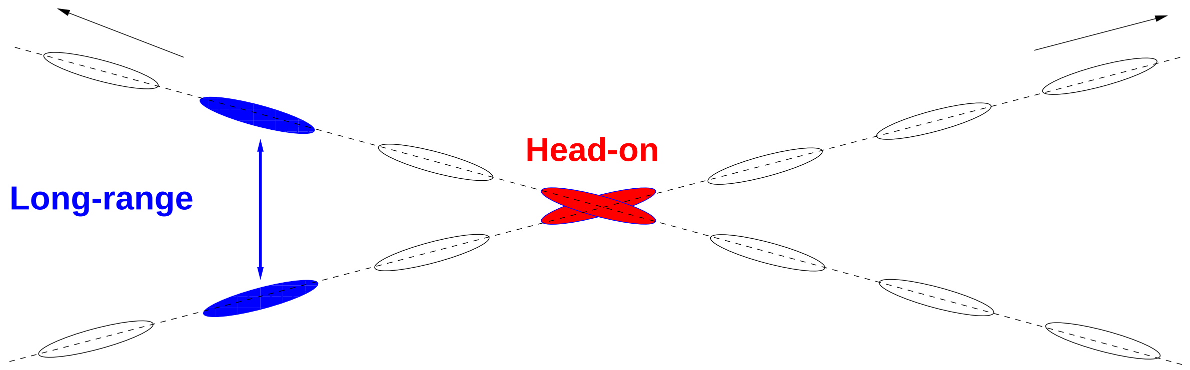
- **Two rings with 4 interaction regions (4 experiments)**
- **High luminosity (strong long range) in IP1 and IP5 (opposite in azimuth)**
- **"Low" luminosity in IP2 and IP8**

LHC bunch filling pattern



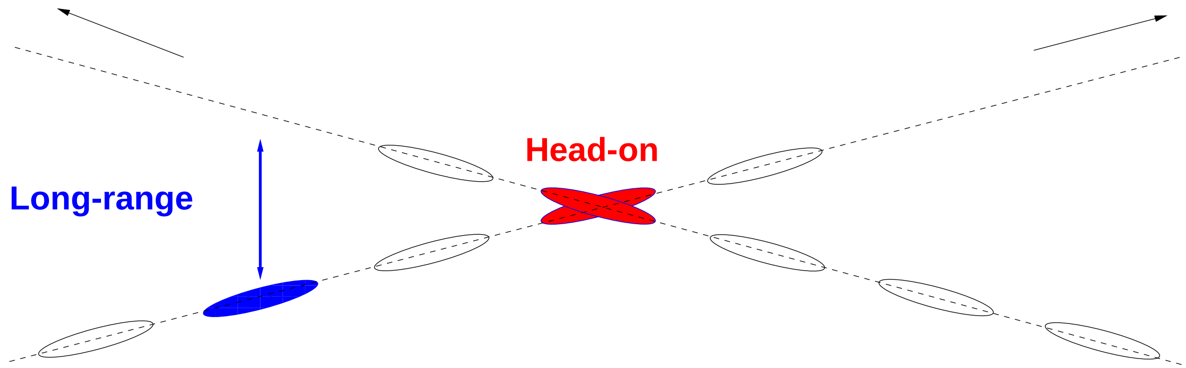
- **Large number of bunches for high luminosity, (nominal: max. 2808 bunches)**
- **Arranged in 39 trains of 72 bunches, spaced by 25 ns, with gaps between trains**

Large number of bunches



- **Implications :**
  - **Crossing angles (horizontal or vertical, $\approx$ 200 - 300 μrad)**
  - **Long range interactions**
  - **Separation typically 8 - 12 σ**
- **What about gaps in the train ?**

Large number of bunches



- **Due to gaps:**
  - **No head-on or long range interactions when bunches "meet" gaps (once named "PACMAN" bunches)**
  - **Max: 4 head on, 120 long range interactions**
    Min: 1 head on, 40 long range interactions
  - **Strong bunch to bunch differences expected**

The "nominal" LHC

- **Parameters relevant for beam-beam:**
  - **Bunch intensity (1.15 · 10^{11} p/bunch)**
  - **Bunch emittance (3.75 μm)**
  - β^* **(0.55 m)**
  - **Crossing angle α ($\approx$ 300 μrad)**
  - **Number of bunches (2808, spaced by 25 ns)**

→ **Nominal beam-beam parameter: $\xi = 0.0035$**

- **Can be considered conservative**
- **Defined to reach design luminosity:** 10^{34} **cm**$^{-2}$ **s**$^{-1}$

The LHC in 2010/2011

- **Energy is 3.5 TeV instead of 7.0 TeV**
- **Limitations from machine protection, aperture and electron cloud:**
  - **Bunch spacing 50 ns (max. 1380 bunches)**
  - **Larger $\beta^* = 1.5$ m**
  - **Emittances smaller than nominal ($\approx$ 1.5 - 2.5 μm)**
- **In very first collisions at injection energy: nominal beam-beam parameter/tune shift exceeded !**
- **Can we collide higher intensities ?**

Observations: head-on beam-beam effects

- **Dedicated experiment with fewer bunches**
- **Test maximum beam-beam parameter achievable (at injection energy), single bunches - head-on only**
  - **Intensity 1.9 $\cdot$ 10^{11} p/bunch**
  - **Emittances 1.1 - 1.2 μm**

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  - **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**

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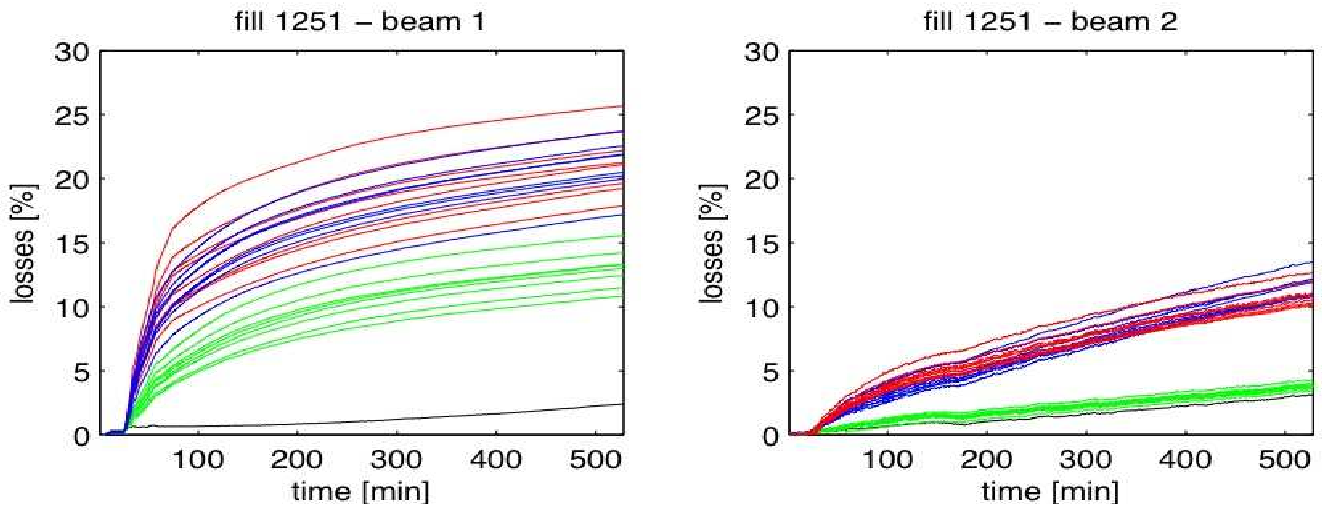
⚠ No long range encounters present !

Head-on beam-beam effects

- **Other observations (during normal operation):**
  - **LHC allows very flexible bunch filling schemes**
    Many different used ($\approx$ 60 !)
  - **Different filling pattern implied different collision pattern**
  - **Different number of head-on collisions (1 - 4)**
  - **Overall beam-beam effect very different**
  - **Differences in lifetime and emittance observed**

(details: poster TUPZ023)

Collision pattern effects



- Different losses of bunches with different collision scheme
- blue (3 coll), red (2 coll), green (1 coll), black (no coll)
- Largest effect at start of the collisions !

Luminosity leveling

- **LHC has 4 experiments:**
  2 require highest luminosity,
  2 require lower luminosity (up to factor 10^{-4})

- **Luminosity leveling required (reduce luminosity and keep constant)**
  - **Achieved by transversely offset collisions**
  - **Separation $\approx 4\ \sigma$ (IP2) and $\approx 1\ \sigma$ (IP8)**
  - **Routinely done without detrimental effects**

(details: poster TUPZ025)

Strong-strong beam-beam interactions

- (Main) implications expected:
  - Coherent beam-beam effects
  - Strong orbit effects
- Requires self-consistent treatment in many (most) calculations, simple non-linear mapping insufficient

→ Self-consistent: many bunches, many particles, "real" collision pattern

→ Required new tools and techniques

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**
  - **Symmetry breaking suppresses modes as expected**
  - **More detailed studies foreseen**
- **But not a problem for operation**

(details: poster TUPZ029)

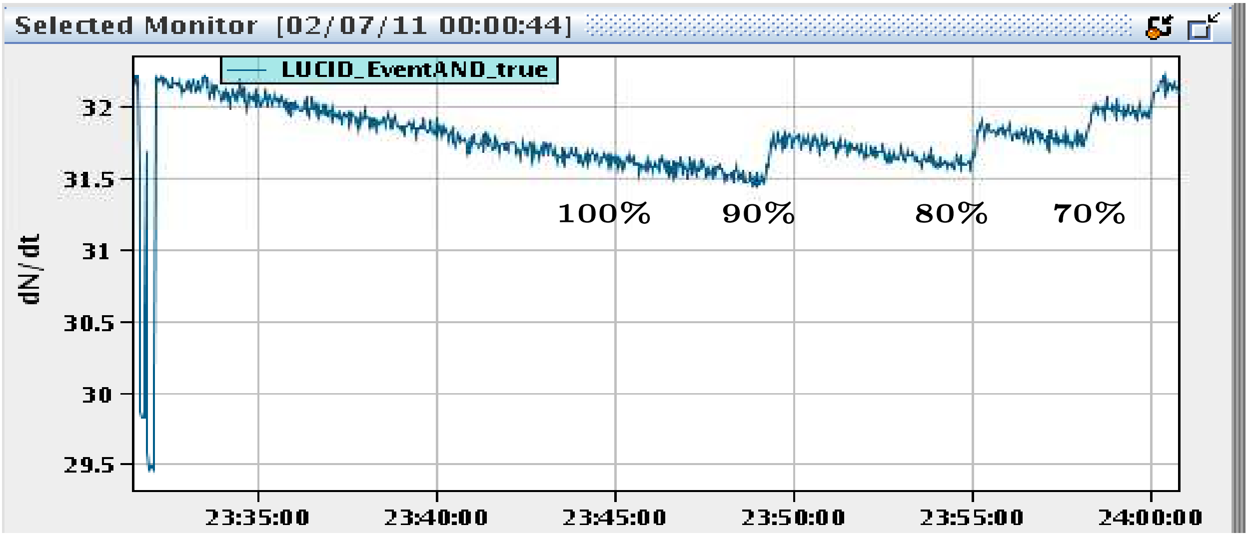
Experimental study of long range beam-beam interactions

- **Test long range interactions with present machine in dedicated experiment, collisions only in 2 experiments**
- **Colliding in IP1 (vertical crossing) and IP5 (horizontal crossing), alternating planes for partial, passive compensation**
- **One train of 36 bunches per beam, full complement of long range interactions (50 ns)**
  - **Provides ≈ 32 parasitic encounters**
  - **In standard operation (2011): separation is kept at ≈ 12 σ (normalized)**

Experimental study of long range beam-beam interactions

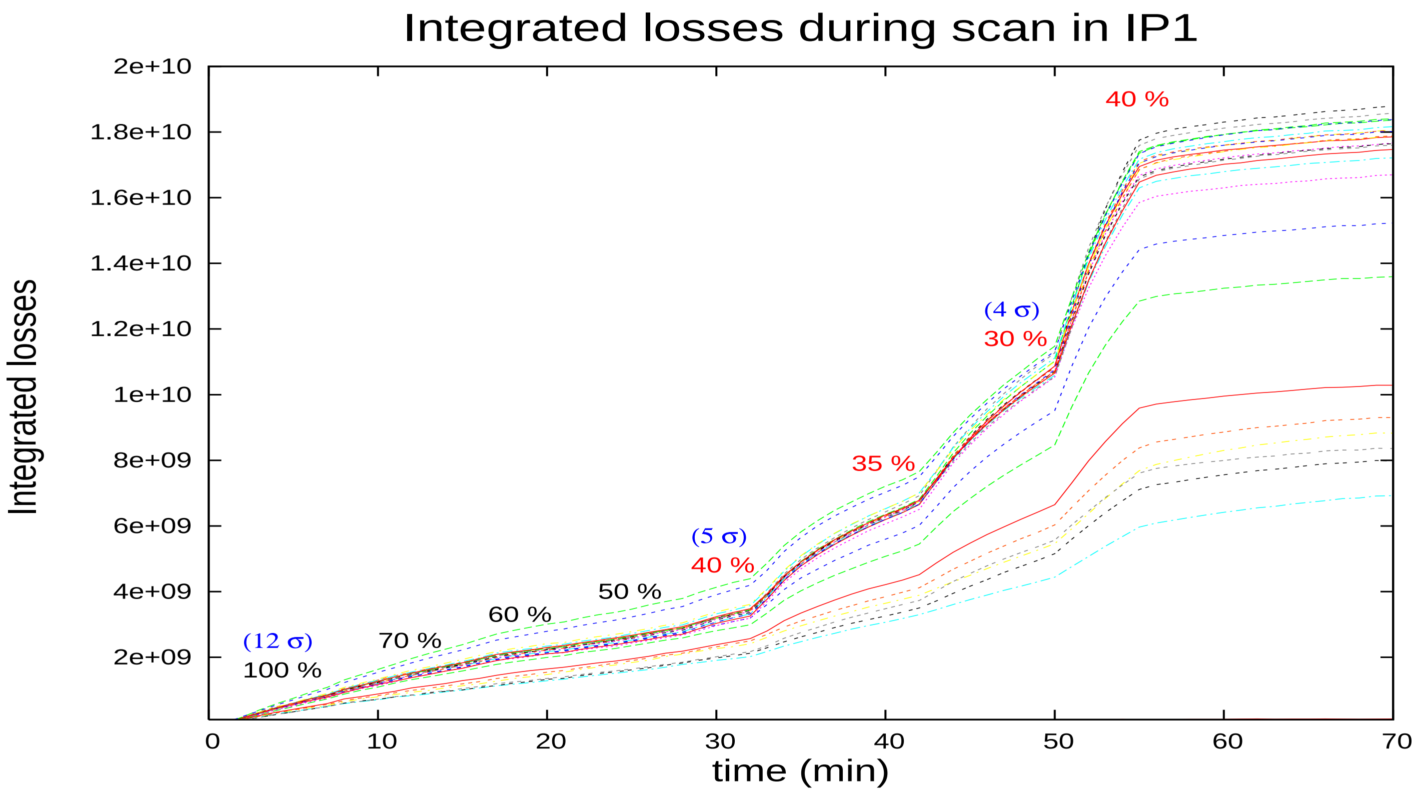
- **Procedure:**
  - **Reduce crossing angle (separation) in one IP (IP1) in steps until effect on losses, life times or emittances**
  - **At reduced separation in IP1: reduce crossing angle in second IP5 (crossing in other plane)**
- **From simulations: expect effect on dynamic aperture, i.e. increased losses, but little effect on emittances**

Scan of crossing angle: luminosity



- **Luminosity in IP1 as function of crossing angle in IP1**
- **Reduction factor exactly as calculated !**
- **"Leveling" with crossing angle, no effect on 2nd IP**

Scan of crossing angle: losses

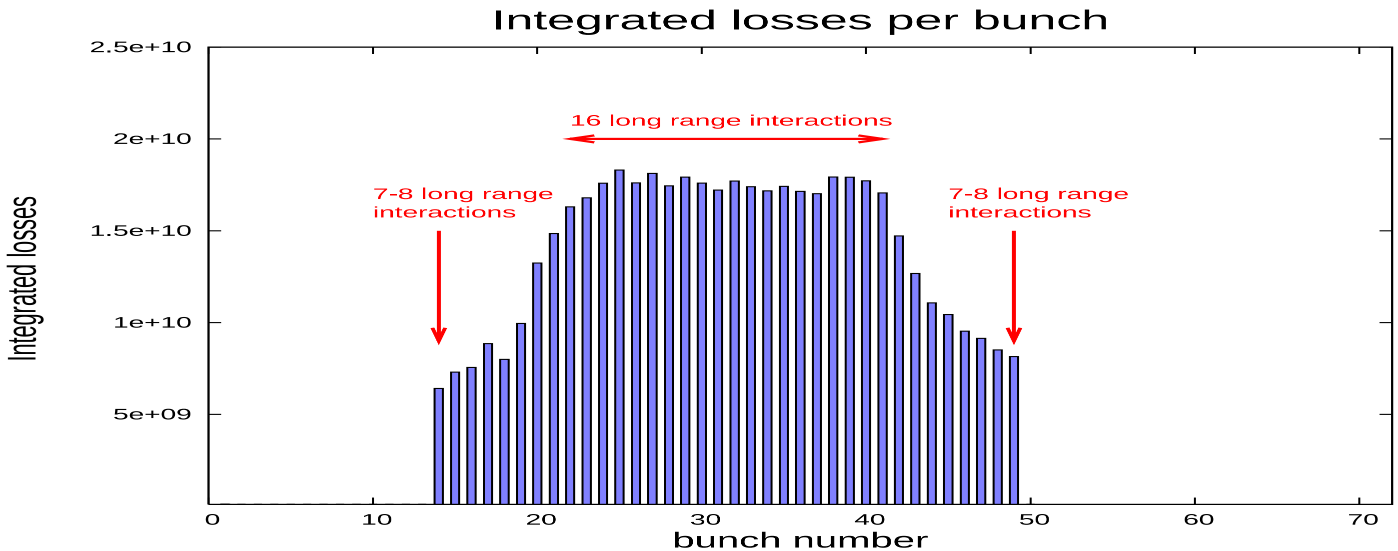


➡ **Bunch by bunch loss as function of crossing angle in IP1**

Scan of crossing angle

- **Observations:**
  - **Losses start after some threshold (4 - 5 σ separation)**
    remember: 32 parasitic encounters !
  - **Smaller separation leads to increased losses (dynamic aperture !)**
  - **Little (if any) effect on emittances**
  - **Different bunches have different threshold !**
  - **Strong evidence for PACMAN effects**

PACMAN effects



- **Integrated losses of the bunches in the train (36 bunches)**
- **Losses directly related to number of long range interactions**
- **So-called 'PACMAN' bunches have better life time !**

(more in: poster TUPZ023)

PACMAN effects

- **Due to different number of long range collisions expected:**
  - **Systematic tune differences between nominal and PACMAN bunches**
  - **Could have reduced lifetimes when machine is optimized for nominal bunches**
  - **Bunches at head and tail of train would be lost first (origin of the name)**

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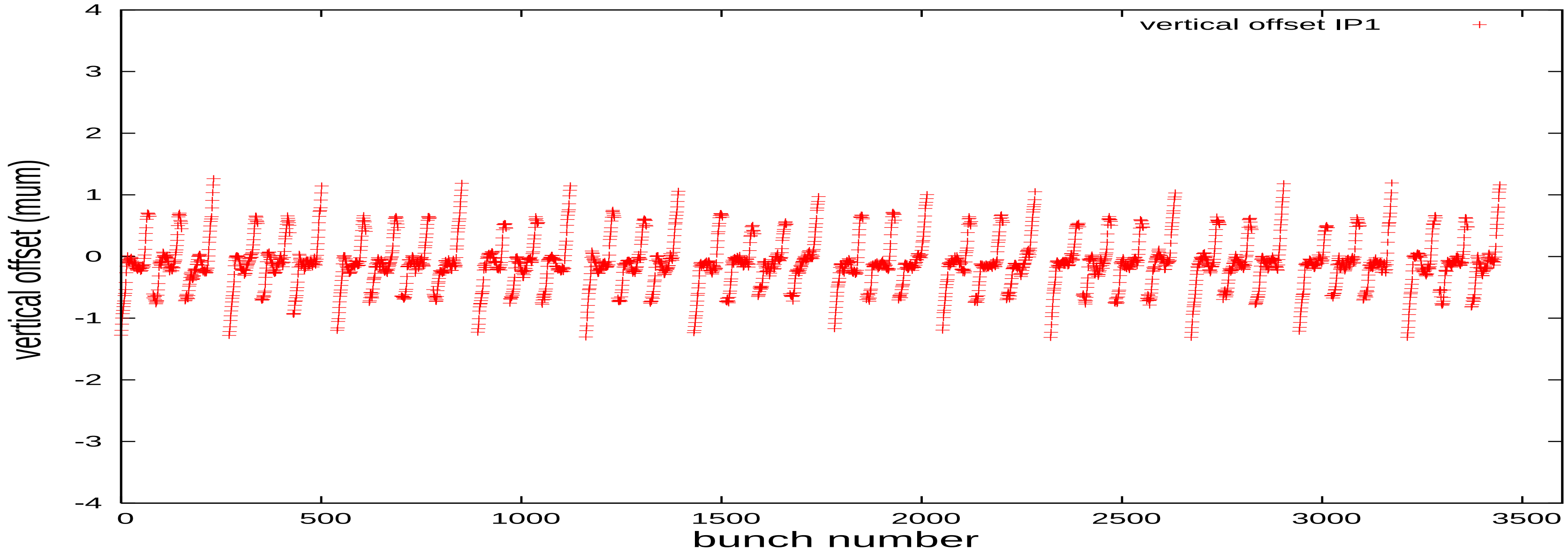
- **In LHC: alternating crossing scheme (horizontal and vertical crossing planes) removes tune difference by compensation**

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**
- **What about orbits for PACMAN bunches ?**
  - **Different kicks - different orbits**
  - **Cannot be fully compensated by alternating crossing schemes !**

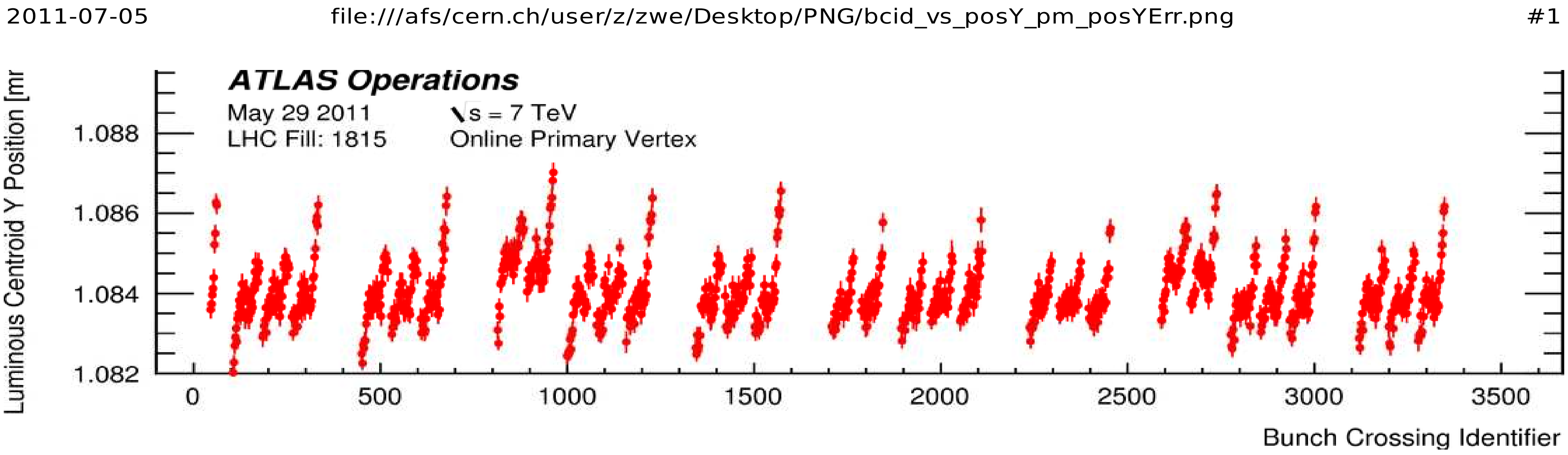
(details: poster WEPC081)

PACMAN Orbit effects: calculation



- **Vertical offset expected at collision point in IP1**
- **Predicted orbits from self-consistent computation (2003)**
- **Cannot be resolved with beam position measurement, but ..**

PACMAN Orbit effects: observation



- **Measurement of vertex centroid by LHC experiments (ATLAS)**
- **Qualitatively: follows exactly predicted behaviour**

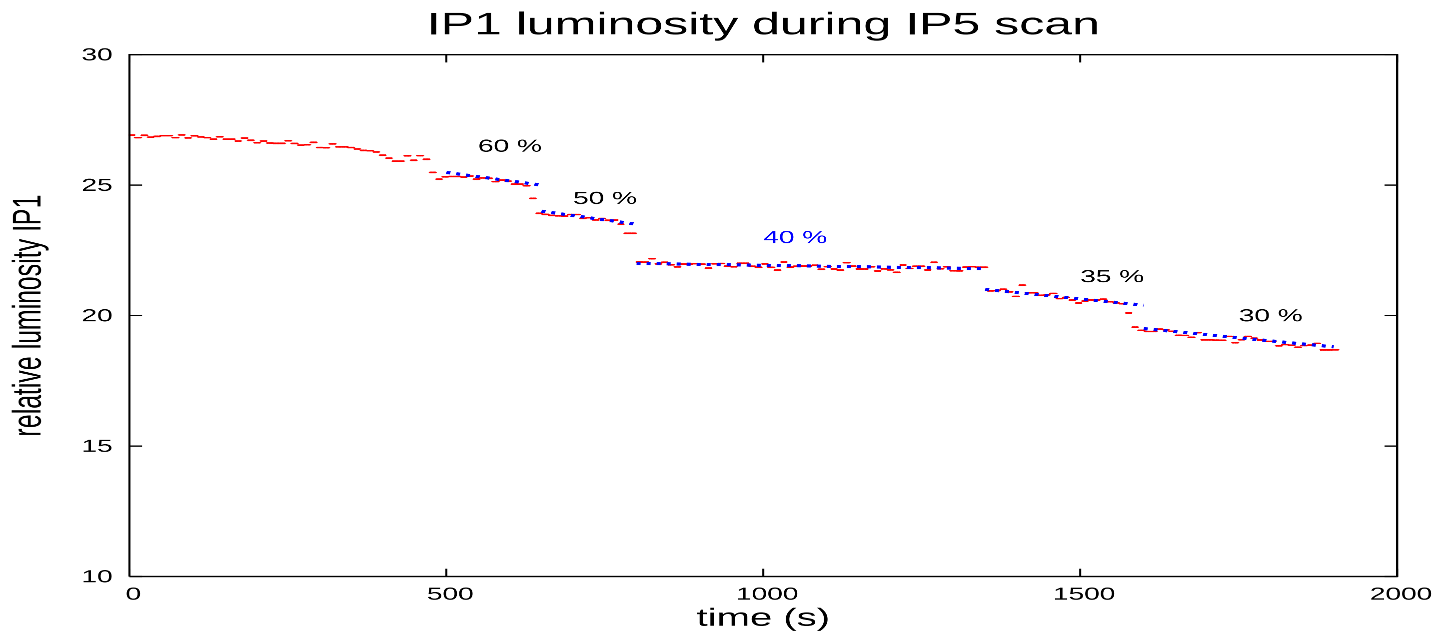
SUMMARY

- **First clear beam-beam observations in the LHC are presented**
- **Obtained large head-on tune shifts above nominal**
- **Effect of long range interactions clearly visible**
- **Number of head-on and/or long range interactions important for losses**
- **All observations in excellent agreement with expectations and well understood**
- **Beam-beam effects should allow nominal luminosity (at 7 TeV)**

Back up

- backup slides -

Other signs of compensation ?



- **Luminosity in IP1 during crossing angle scan in IP5**
- **Separation in IP1 kept constant at 40%**
- **Life time best for equal crossing angles in both IPs**

More studies needed