Bunch-by-Bunch Analysis of the LHC Heavy-Ion Luminosity

The CERN Accelerator School

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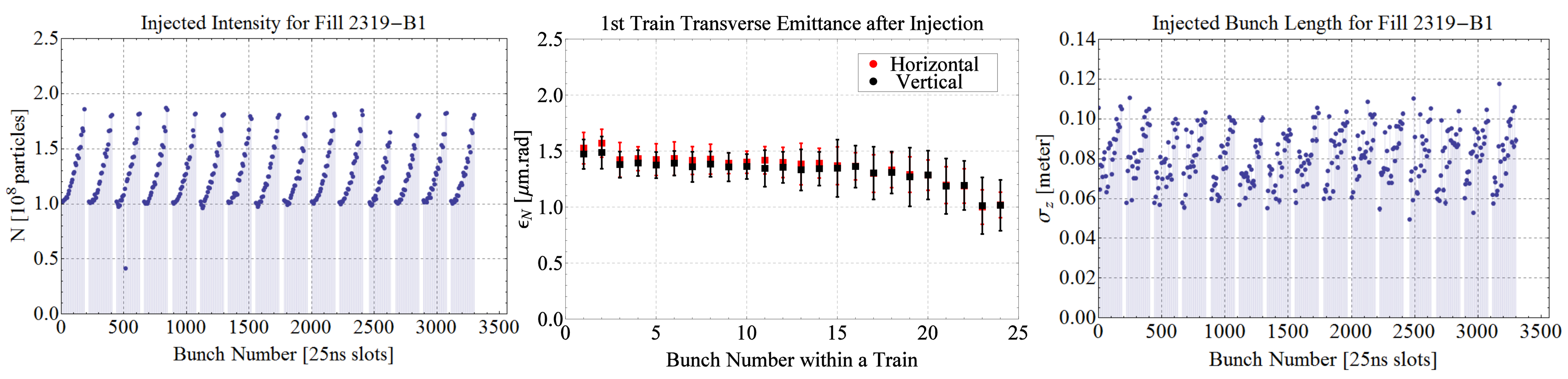
Bunch-by-Bunch Differences

- Heavy-ion operation in the LHC: [1] 2010: Pb-Pb, [2] 2011: Pb-Pb, [3] 2013: p-Pb.
- Beam dynamics of high intensity Pb (lead) beams are strongly influenced by IBS.
- Pb ions injection chain: **source → LINAC3 → LEIR → PS → SPS → LHC**.
- Each train injected from SPS spends a different time at the **LHC injection plateau**, introducing significant changes from *train to train*.
- Within a LHC train an even larger spread is imprinted from *bunch to bunch* by the **SPS injection plateau**:
  - Inject 2 bunches from PS → SPS: 12 injections to construct LHC train.
  - While waiting for remaining injections form PS, bunches are strongly affected by **IBS ($\propto \gamma^{-3}$) at low energy**.

  ⇒ Emittance growth and particle losses.
- This results in a spread of the luminosity L, produced in each bunch crossing.

LHC: Large Hadron Collider
IBS: intra-beam scattering
L: luminosity
N_b: bunch intensity
ϵ_N: normalised emittance
σ_z: bunch length

In LHC right after injection



N_b **increase** from 1st to the last bunch in a train.

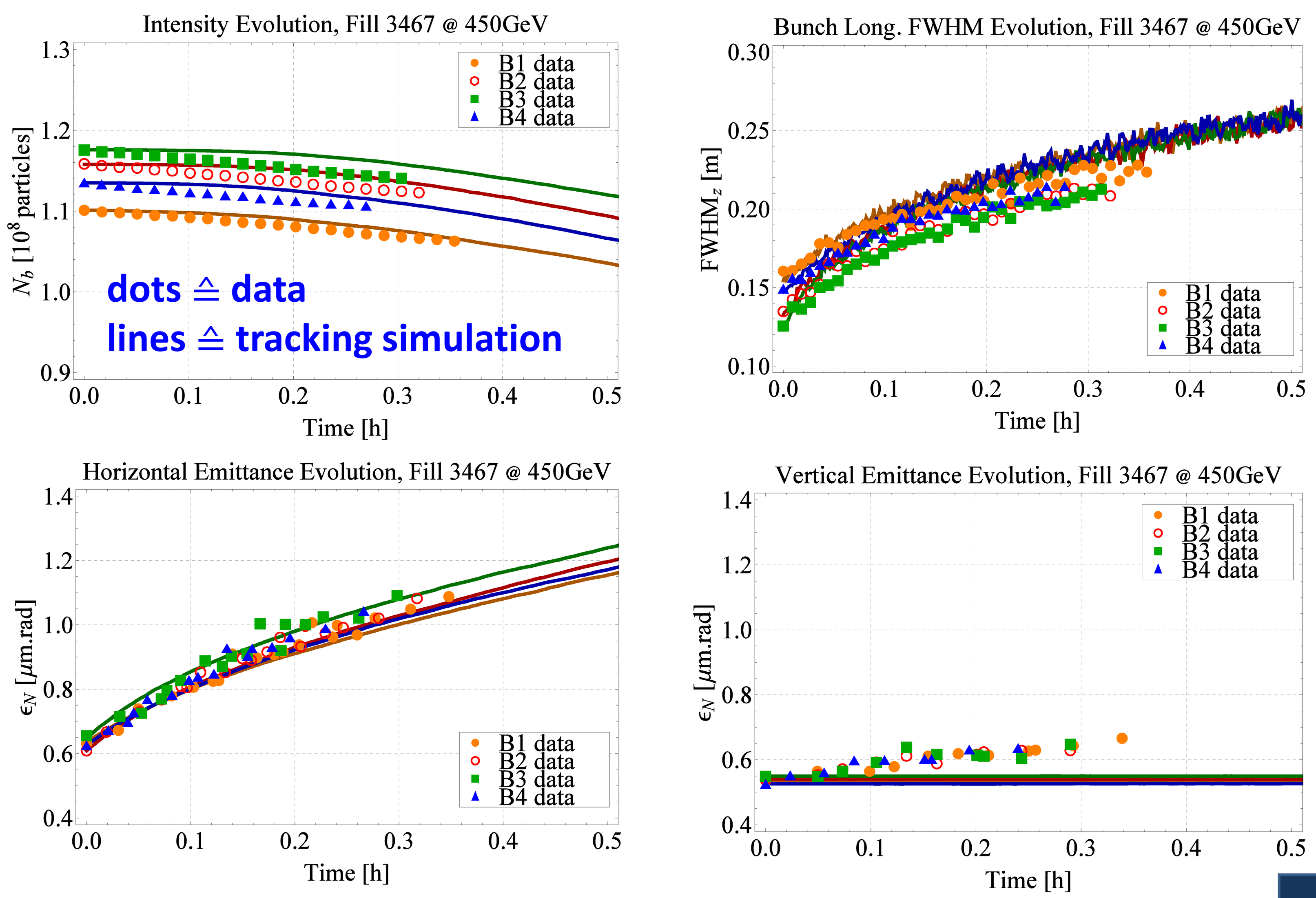
ϵ_N **decreases** from 1st to last bunch in a train.

σ_z shows similar behaviour as N_b.

Single Bunch Evolution at Injection

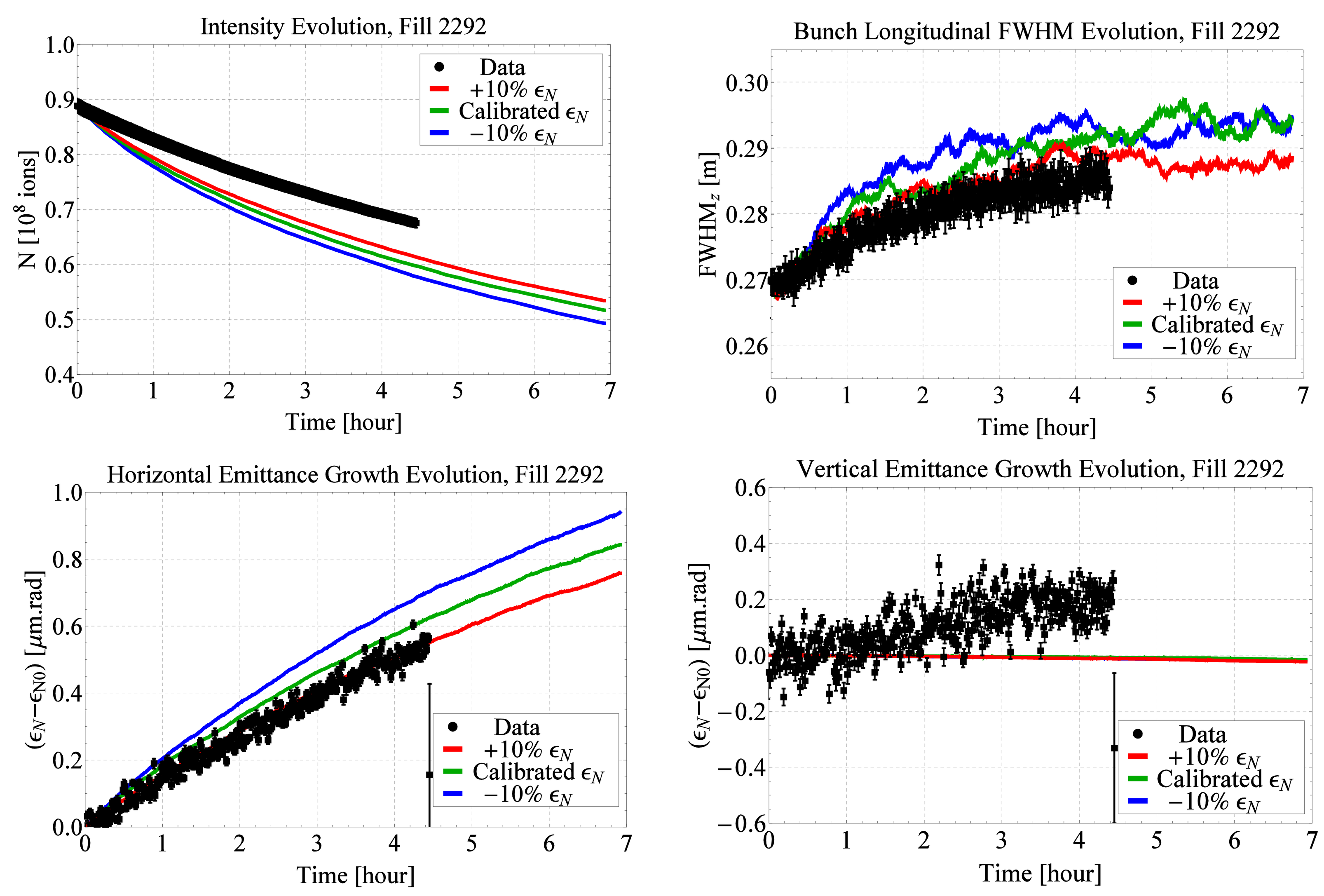
- *Simulation Code: **Collider Time Evolution (CTE)** [4].*
- *Tracking of 2 bunches of macro-particles in time in a collider.*
- *Simulation of IBS, radiation damping, but, eg, no beam-beam.*

- Evolution of **4 single Pb bunches at injection** (E = 450GeV).
- Horizontal IBS growth stronger than vertical due to horizontal dispersion, → no vertical dispersion in model (for speed).
- Additional growth in vertical ϵ_N due to coupling.

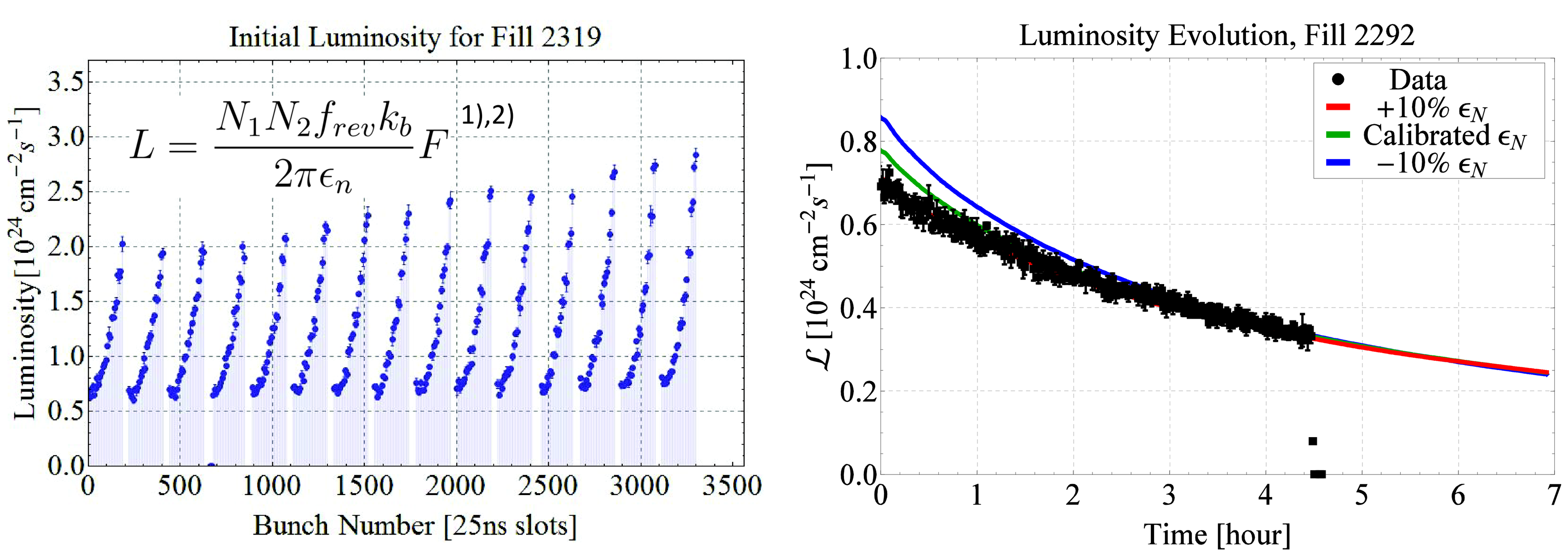


Evolution of Colliding Bunches

- *3 simulation runs with varying initial ϵ_N to account for calibration uncertainties.*
- Losses in N_b are overestimated by the simulation, due to assumption of Gaussian longitudinal profile.
- The calibrated ϵ_N seems to be underestimated by about 10%.
- **L, ϵ_N and σ_z fit very well to the simulation for +10% initial ϵ_N.**

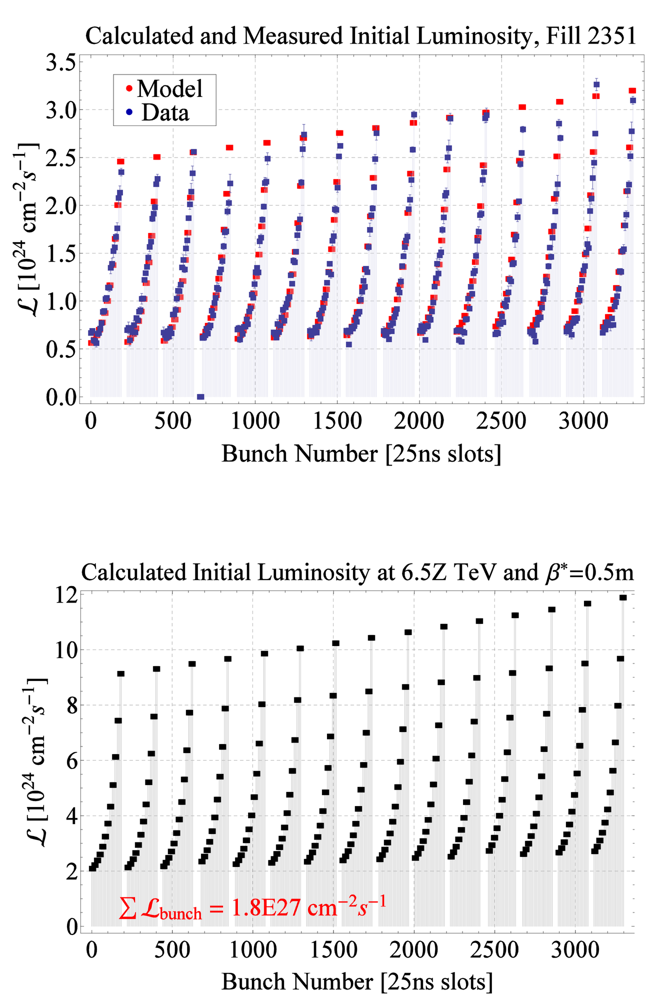


Luminosity



- Collisions of equivalent bunches (with similar N_b and ϵ_N).
- L_{Bunch} varies by a factor 6 along a train - introducing different lifetimes.
- Slope between last bunches of trains introduced by IBS at LHC injection plateau.
- Particle losses during collisions are dominated by nuclear EM processes, → leading to non-exponential N_b decay and short lifetimes at E = 3.5Z TeV.

Projections for after LS1



- Running conditions after LS1:

  → higher **E = 6.5Z TeV** and lower **β^* = 0.5m**.
- Estimate peak luminosity at start of collisions:

  → Model based on 2011 bunch-by-bunch luminosity, predicts peak L_{Bunch} as a function of position inside the beam.

  → Assumption: 2011 beam conditions.

⇒ 2011 filling scheme & scaling to E = 6.5Z TeV yields $L_{\mathrm{Peak}} = \mathbf{1.8\times10^{27}\,cm^{-2}s^{-1}} = \mathbf{1.8}\,L_{\mathrm{Design}}$.

- Alternating 100/225ns bunch spacing to increase total number of bunches.

⇒ Possible to reach $L > 2\times10^{27}\,\mathrm{cm^{-2}s^{-1}}$.

- In 2013 p-Pb run **N_b could be increased by 30%.**

[1] T. Mertens *et al.*, TUPZ017, IPAC 2011.
[2] M. Schaumann *et al.*, TUPFI025, IPAC 2013.
[3] J. Jowett *et al.*, MOODB201, IPAC 2013.
[4] R. Bruce *et al.*, Phys. Rev. ST Accel. Beams **13**, 091001 (2010).

Footnotes: 1) $F = 1/\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$

2) $\epsilon_n = \frac{\gamma}{\beta^*}\sqrt{\sigma_{x1}^2+\sigma_{x2}^2}\sqrt{\sigma_{y1}^2+\sigma_{y2}^2}$

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