Beam lifetime under various Luminosity conditions

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Simulations and measurements of Long Range Beam-Beam effects in the LHC
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Outline

- Introduction: Luminosity
- The Luminosity model components
- Run I Vs Run II Luminosity decay
- Observations from RunI data
- Observations from RunII data
- Summary and Conclusions

Introduction: Luminosity

$$L = \frac{n_b f_{rev}}{2\,\pi} \frac{N_{B1}(t) N_{B2}(t)}{\sigma_x(t)\sigma_y(t)} H\left(\frac{\sigma_s(t)}{\beta^*}\right) F_{geom}(\sigma_s(t), \beta^*)$$

$$\frac{1}{\tau_L} = \frac{1}{L}\frac{dL}{dt} = \frac{1}{\tau_{N1}} + \frac{1}{\tau_{N2}} - \frac{1}{\tau_{\sigma_x}} - \frac{1}{\tau_{\sigma_y}} + \frac{1}{\tau_F}$$

- Model components :
  - Beam current decay with time
  - Beam size (or emittance) evolution with time

- Geometric Factor

$$F_{geom} = \left(\sqrt{1 + \left(\frac{\sigma_s(\varphi/2)}{\sqrt{\epsilon_t \beta^*}}\right)^2}\right)^{-1}$$

- Hourglass effect
  - Very small for LHC params
  - Should be considered for HL-LHC params

Model components (1)

- **Emittance and bunch length evolution at Flat Top energy**:
  - **Intrabeam scattering (IBS)**:
    - Multiple Coulomb scattering effect leading to the redistribution of phase space and finally to emittance blow up in all three planes
    - $\frac{d\epsilon_i}{dt} = f\left(En, N_{b0}, \varepsilon_{x0}, \epsilon_{y0}, \sigma_{l0}, optics\right)$ → Complicated integrals
    - Iteration in time as the beam characteristics are evolving
  - **Synchrotron Radiation (SR):**
    - At high energies becomes important for proton beams as well, leading to emittance damping in all three planes
    - $\varepsilon_i = \varepsilon_{i0} exp\left(-\frac{t}{\tau_i}\right)$, τ_i: emittance damping time
  - The emittance evolution due to IBS and SR has been fully parameterized
    - The parameterization is based on MADX computations using the IBS module
    - Their effect in any plane can be calculated through a simple function:

[$\varepsilon_x(t_1)$, $\varepsilon_y(t_1)$,$\sigma_l(t_1)$,]=LHCEmitEvolFB($N_b(t_0)$,$\varepsilon_x(t_0)$, $\varepsilon_y(t_0)$,$\sigma_l(t_0)$, t_1-t_0)

Model components (2)

- Bunch intensity degradation
  - **Luminosity burn-off**: Luminosity decay due to the collisions themselves
    - $\boldsymbol{\tau_{nuclear} = \frac{N_{tot,0}}{L_0 \sigma_{tot} k}}$
    - $\boldsymbol{N_{tot}(t) = \frac{N_{tot,0}}{1+t/\tau_{nuclear}},}$

    $N_{tot,0}$: the initial beam intensity, L_0: the initial Luminosity, σ_{tot} the total cross section and *k* the number of interaction points
    - This can be easily folded into the emittance evolution function

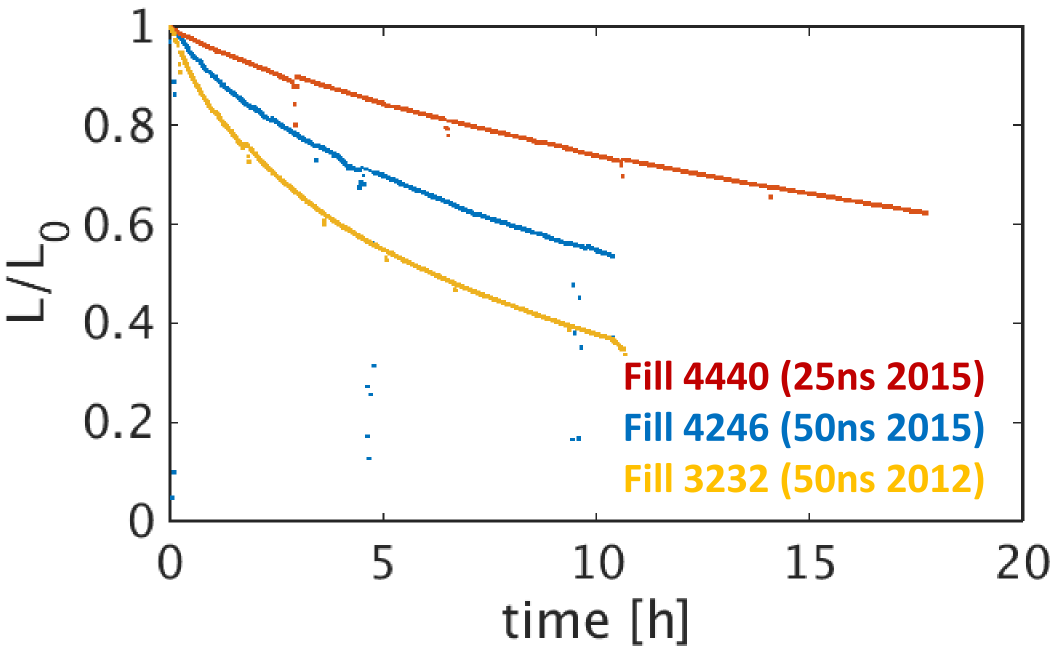
- The model can be used for bunch by bunch studies of the emittance, bunch length, bunch intensity and luminosity evolution due to IBS, SR and Burn-off

Other components

- Other sources need to be considered
  - Non-linearities of the machine
  - Noise effects
  - Scattering on residual gas
  - …

- Understanding the behavior of the machine analyzing the data from RunI and RunII
  - On going effort to find correlations from the data from average and bunch by bunch behavior

Run I Vs Run II Lumi decay



- Mean bunch characteristics at the beginning of Stable Beams:
  - Fill 4440
    - N_{b0} =1.08e11ppb
    - ε_0 = 3.08 μm-rad
  - Fill 4246
    - N_{b0} =1.2e11 ppb
    - ε_0 = 2.1 μm-rad
  - Fill 3232
    - N_{b0} =1.6e11ppb
    - ε_0 = 2.8 μm-rad

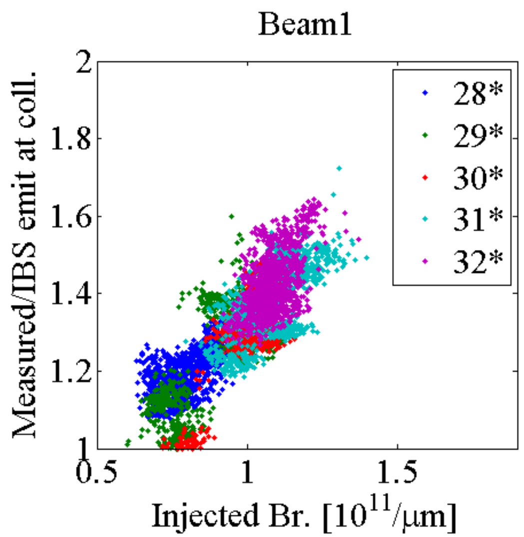
- Luminosity decay from ATLAS data
- The luminosity decay is much slower for the current runs
  - Lower bunch brightness
  - Weaker beam-beam effect

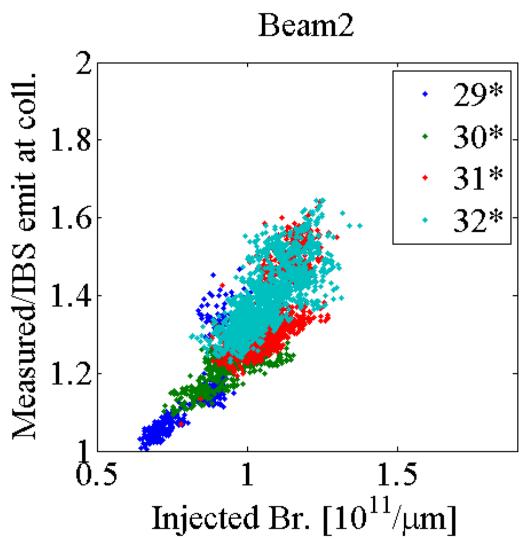
OBSERVATIONS FROM RUN I

Observations from Run 1 data

- Fills with WS data at Flat Bottom
  - Not always data for both beams and both plane
  - The convoluted emittance is used
- The IBS model from injection to the beginning of collisions is applied
  - The expected conv. emittance of the selected 144 bunches (with WS data) at the beginning of collisions is calculated
  - Comparison with the measured one
- The data from many Fills are put together

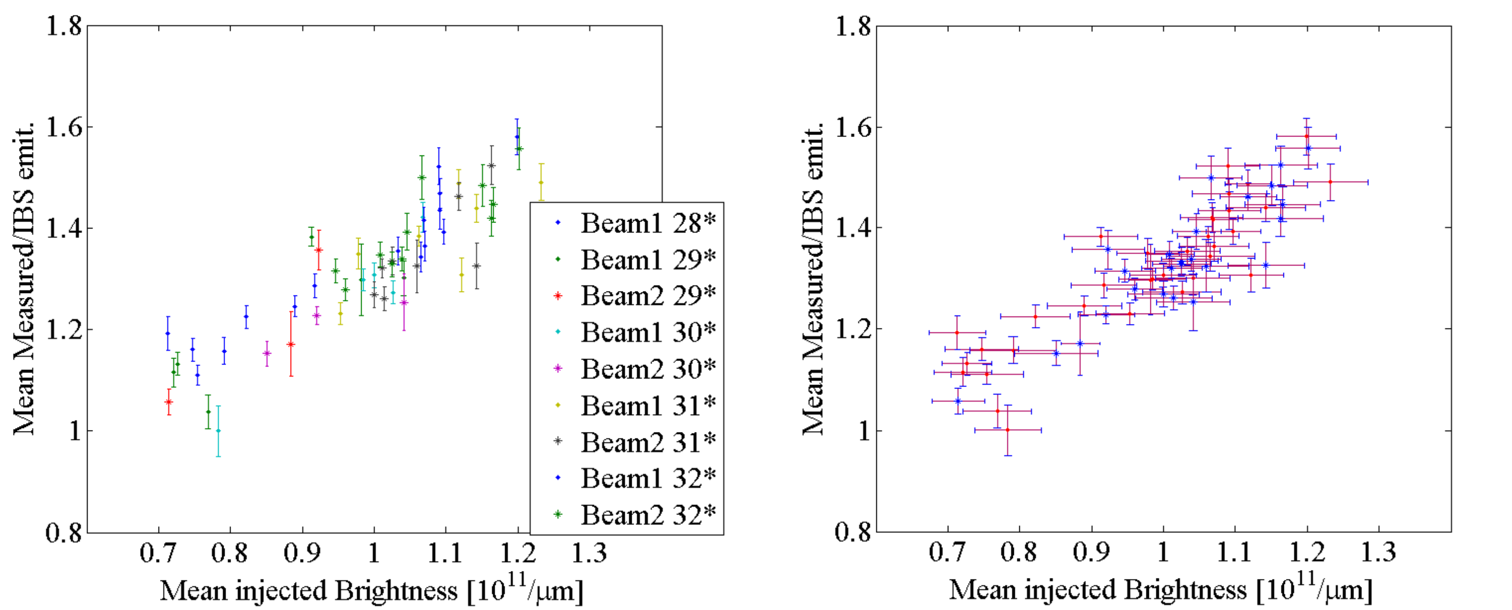
Data to model comparison





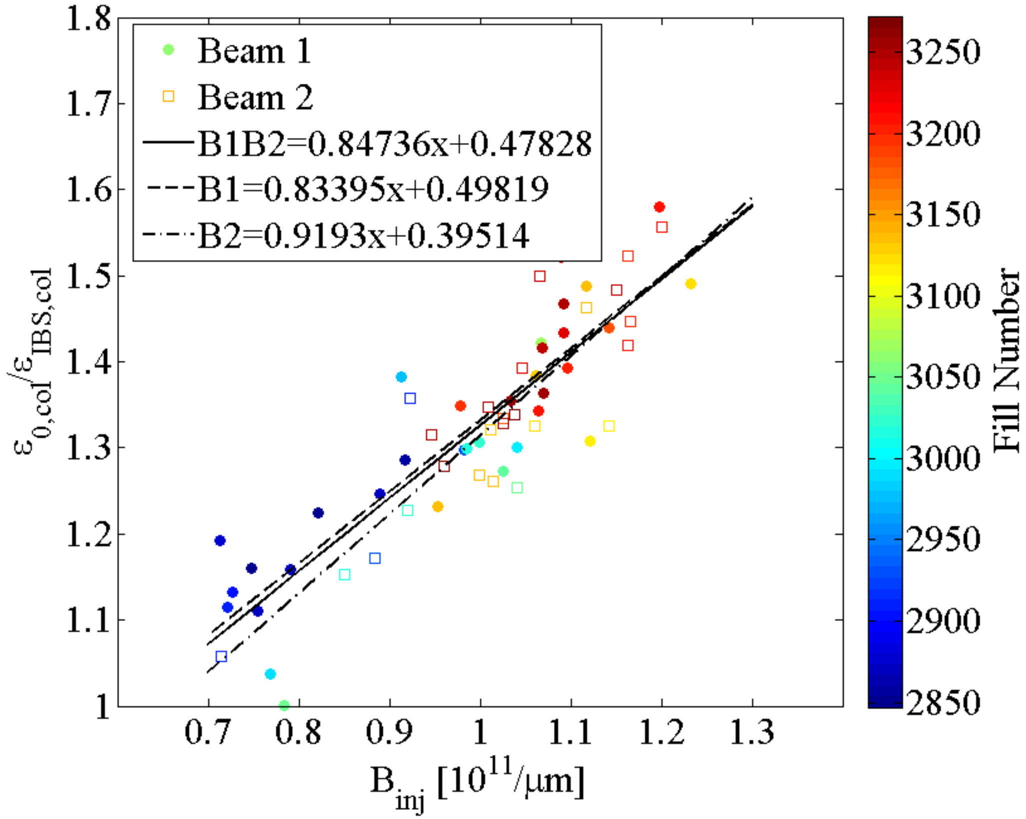
- 28* → Fills 2800-2900, etc.
- Only stable bunches are used
- Linear dependence of the emittance ratio (or blow up factor) with the injected brightness

Data to model comparison



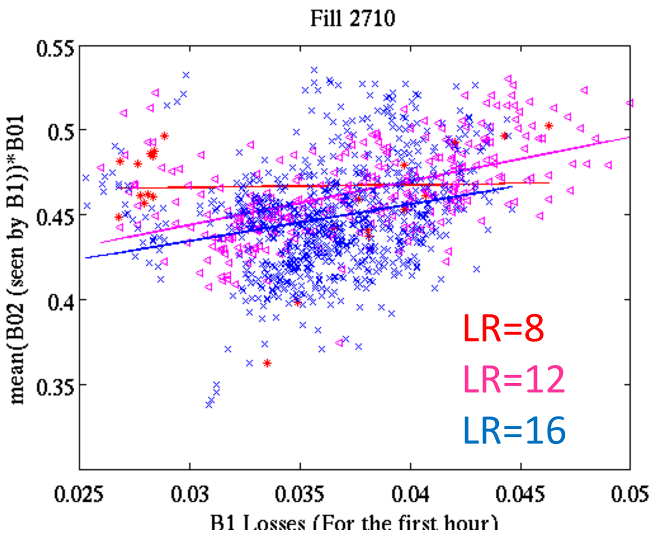
- The same exercise is repeated using the mean values for each Fill
- The errorbars show the std from the mean for each Fill

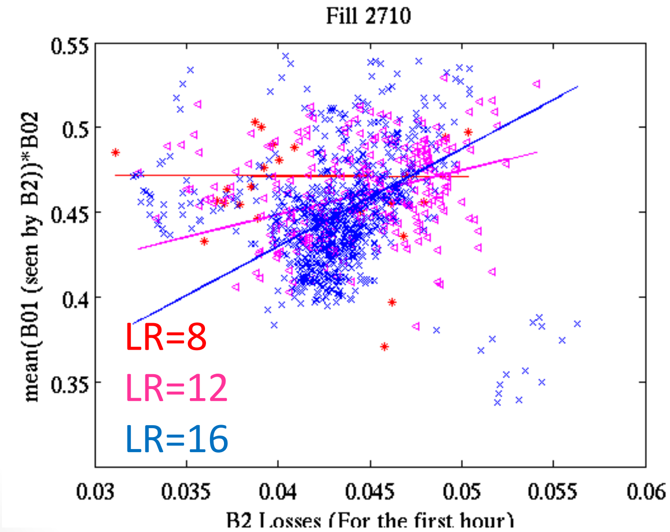
Data to model comparison



- Similar slope for both beams
- Can we use a global fit?

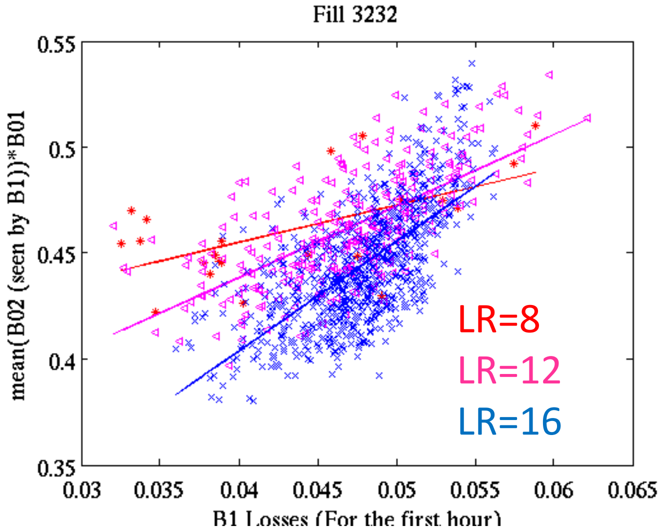
Correlations with long range

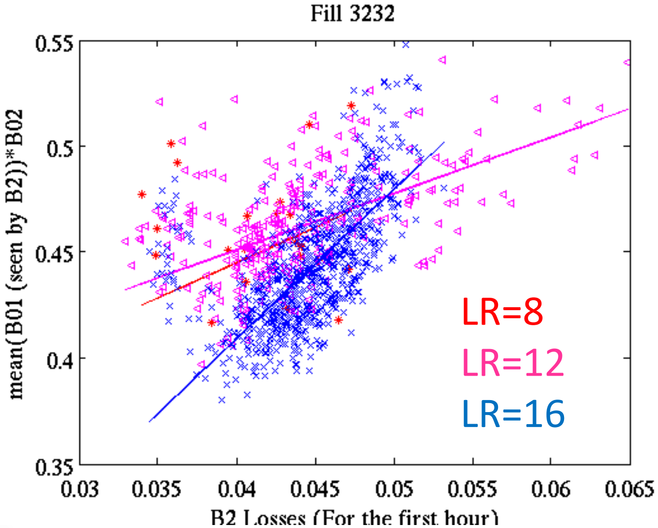




- The plots show the product of the mean brightness of the longrange encounters seen by B1 (top) or B2 (bottom) and the brightness of B1 (top) or B2 (bottom) versus the Beam losses after 1h of run
- The bunches with **8**, **12** and **16** longrange encounters are plotted with different colors
- Linear correlation is observed with different slope for different number of longrange encounters
  - The slope is steeper for larger longrange encounters
  - Same trend for both B1 and B2

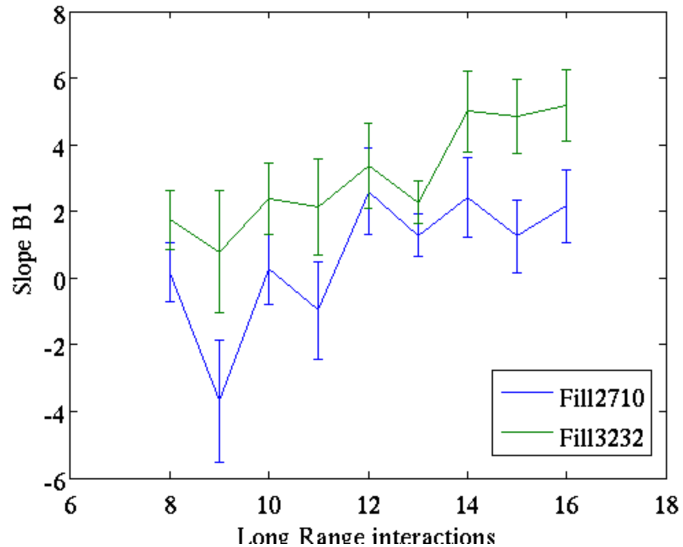
Correlations with long range

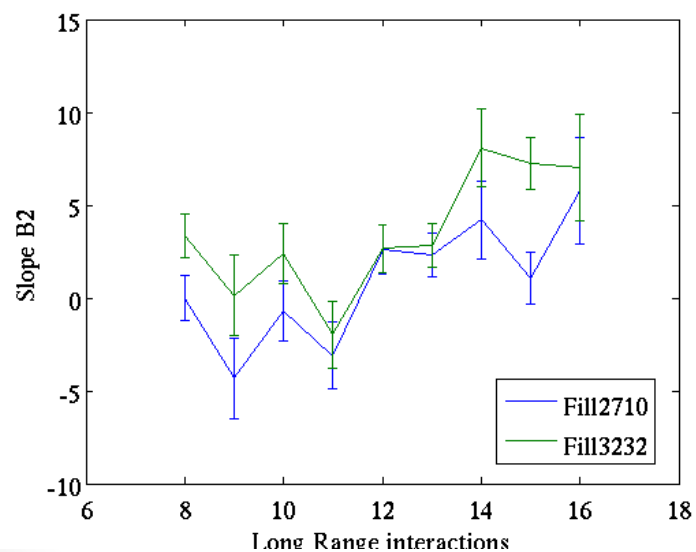




- The same analysis is applied to Fill3232
- Exactly the same trend is observed for both beams
  - Steeper slopes in this case

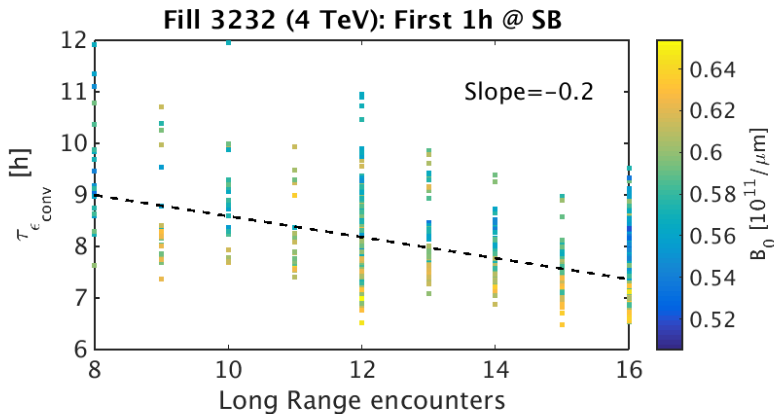
Correlations with long range

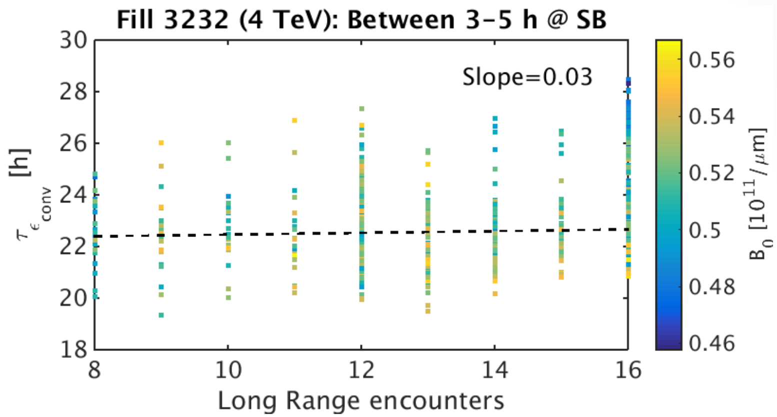




- Calculating the slope for each of those curves for all different cases of long-range encounters (8-16)
  - Clear trend of slope increase with the number of long-range encounters
  - The effect is enhanced for Fill3232 where the brightness is higher
  - Need to generalize the observation for other fills
    - Data need carefull cleaning (unstable bunches,…)
  - The brightness estimation is not accurate because the convoluted emittance (from luminosity) is used
    - Necessity for bunch-by-bunch transverse emittance diagnostics
    - Some first analysis can be done using luminous region data

Effect of number of LRs on emittance lifetime





- A bunch-by-bunch exponential fit was applied for different time intervals at SB:
  - Left: The bbb emittance growth time vs the number of LRs and colorcoded with the injected bunch brightness

    → Dependence on both the number of LRs and the bunch brightness
  - Right: The bbb emittance growth time for the time interval between 3 and 5 h at SB

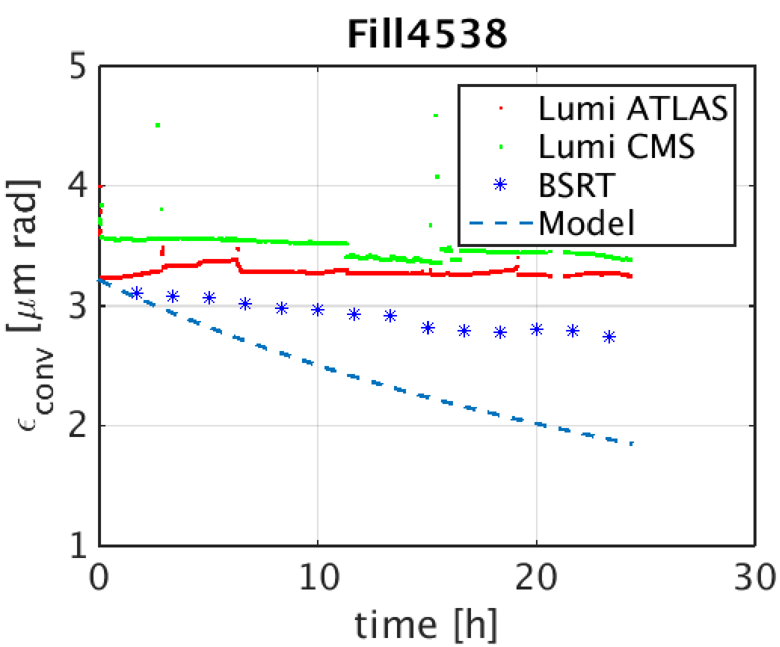
    → Dependence on LRs is lost

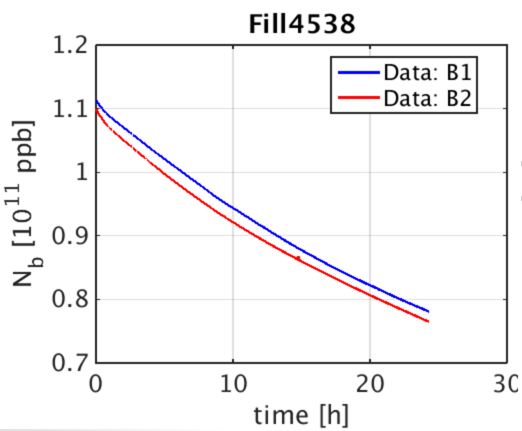
OBSERVATIONS FROM RUN II

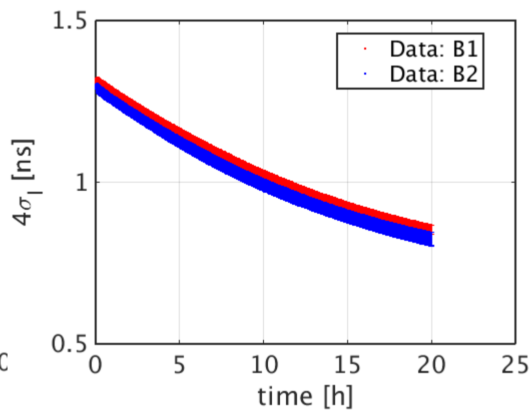
Analyzing RunII data (1)

- Most of the Fills that arrived at Stable Beams have been analyzed
- In this Run we have emittance measurements both at Flat Bottom and Flat Top
  - BSRT data for both beams and both planes
  - Convoluted emittance from luminosity
  - Convoluted horizontal and vertical emittance from OP scans
- Comparisons between the different methods not always in good agreement
  - Work in progress to understand the data
- Bunch by bunch analysis can guide our model and add missing pieces

Lumi model predictions Vs RunII data: Emittance @ SB

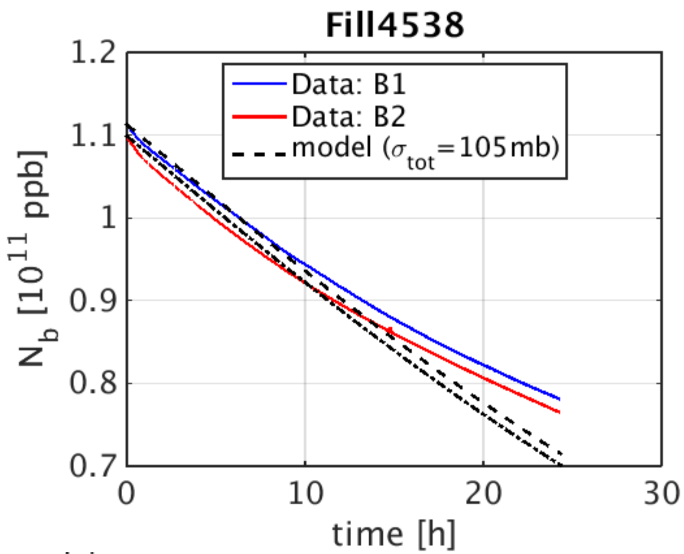


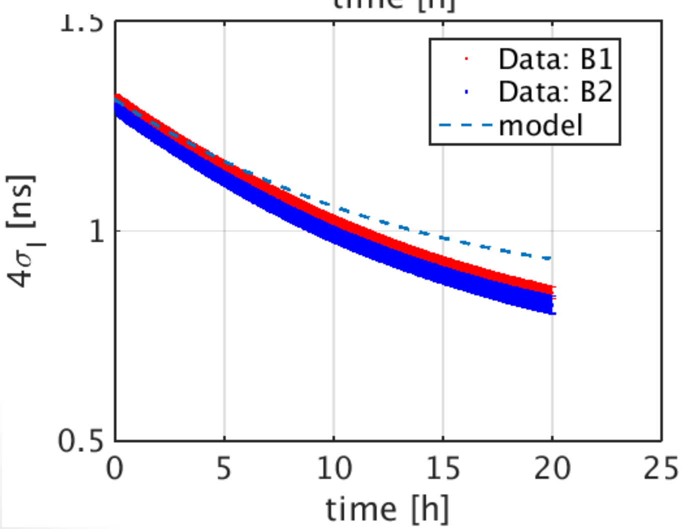




- Fill 4538 is used as an example here
- Emittance evolution during SB from BSRT, Lumi ATLAS and Lumi CMS show different evolution
- IBS+SR+Burn-off prediction is shown with thw blue dashed line
- The Bunch length and mean bunch current evolution is shown on the bottom plots
- Blow up is observed in both planes, with respect to the model
- We need to understand the data and include other sources of emittance blow-up

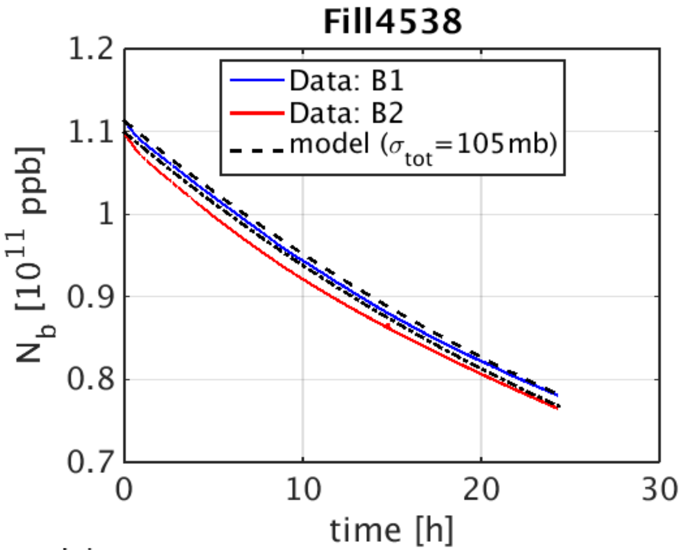
Lumi model predictions Vs RunII data: Bunch current & bunch length @ SB

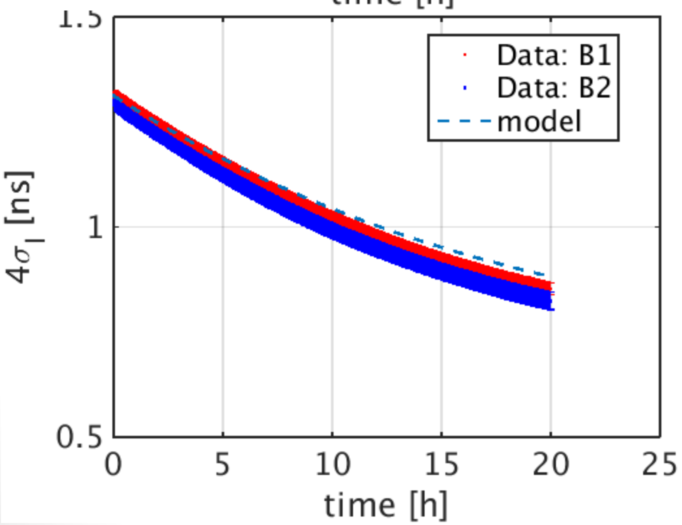




- Looking at the other two observables (Top: Bunch current, Bottom: bunch length)
- Smoother current decay and more bunch length damping is observed with respect to the model prediction
- Same analysis is done for all the Fills that arrived at SB
  - Similar behavior with the same or more pronounced divergence from the model is observed in all the Fills

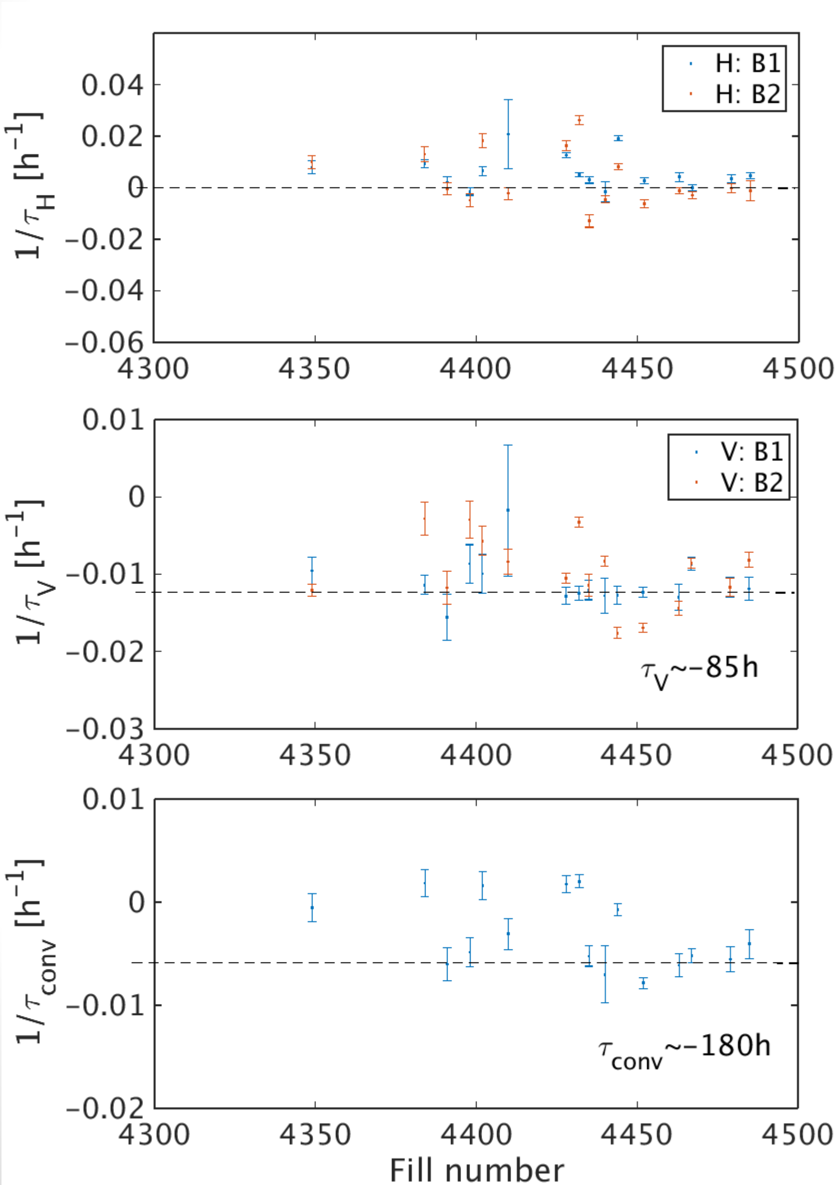
Lumi model comparison with RunII data: Bunch current & bunch length





- Using the emittance evolution from the data and recalculating the current decay and bunch length evolution from model → the agreement is much better
- Modeling the emittance evolution at Stable beams correctly is crucial for the luminosity model
  - Need to understand the data!
  - Need to understand and add other sources of emittance blow up to our model

Emittance evolution during SB



- For each Fill an exponential fit is applied to the SB emittance evolution from the BSRT data → estimation of damping/growth times
- Trends observed
  - H plane: both slight damping and slight growth have been observed
  - V plane: always damping with $\tau_V \sim -85h$ mainly for the last Fills
  - Convoluted: $\tau_{conv} > -180h$ basically constant
- From OP scans: $\tau_V \sim -50h, \tau_H \sim 25h$ (for Fill4440)

➢ **More statistics needed to extract conclusions.**

Summary and Outlook

- A model including IBS, SR and Burn-off at Flat Top (4TeV, 6.5TeV and 7TeV) and Flat Bottom energy & is ready
  - A full parameterization has been performed and we can describe the evolution with a function (per energy)
  - Bunch-by-bunch

- Observations from RunI data
  - Emittance blow up and bunch current decay at the beginning of stable beams correlated with the number of LRs and bunch brightness
  - The effect is more pronounced for higher brightness
  - Simulations needed in order to verify and quantify the effect in order to be added as a component to our Lumi model

- Observations from RunII data
  - Differences have been observed on the emittance evolution from the different methods of measurement → Needs to be understood
    - Modeling the emittance evolution is a very important component of the model
    - Using the emittance from the data, good prediction for the bunch length and bunch current evolution
  - No emittance blow up or bunch current decay correlated with the long range encounters have been observed for the moment
    - More relaxed conditions for 2015 with relatively low bunch brightness