(Towards a) Luminosity model for LHC and HL-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
- Projections to HL-LHC
- 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
    - $\frac{d\epsilon_i}{dt} = f(En, N_{b0}, \varepsilon_{x0}, \epsilon_{y0}, \sigma_{l0}, optics)$ → 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
    - $\tau_{nuclear} = \frac{N_{tot,0}}{L_0 \sigma_{tot} k}$
    - $N_{tot}(t) = \frac{N_{tot,0}}{1+t/\tau_{nuclear}}$,

    $N_{tot,0}$: 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

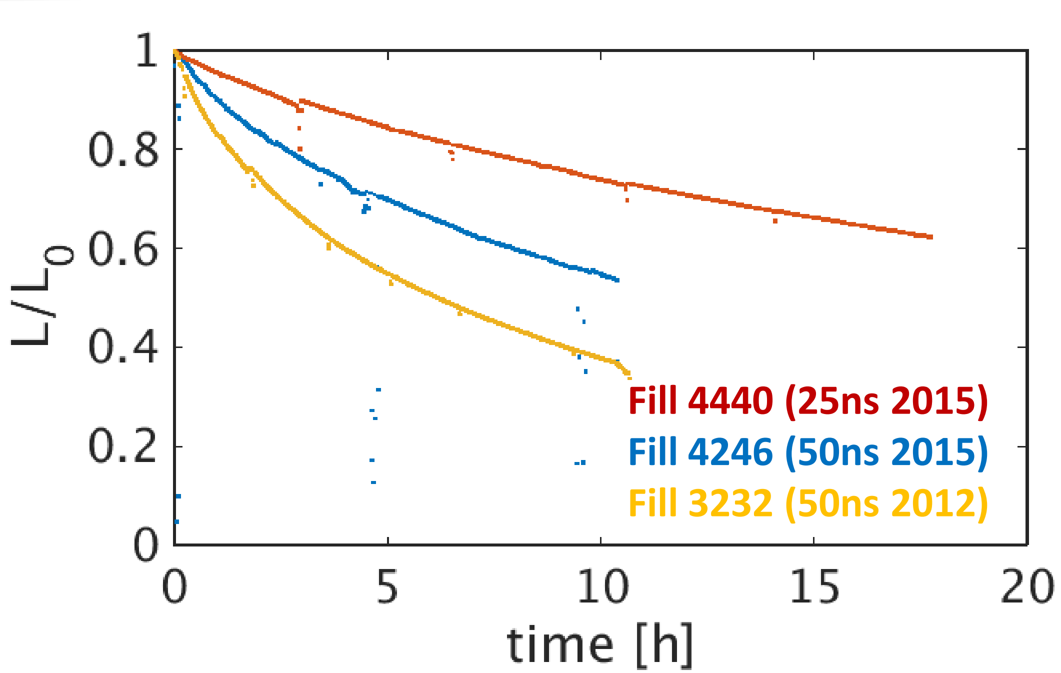
- The model can be used for bunch by bunch studies of the emittance, bunch length, bunch intensity and luminosity evolution due to IBS, SR and Burn-off

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

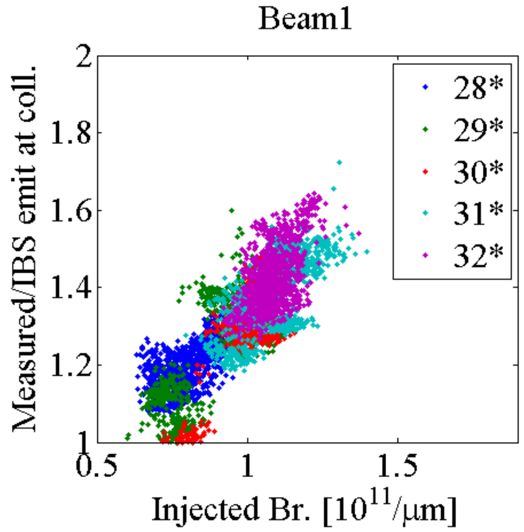
- Luminosity decay from ATLAS data
- The luminosity decay is much slower for the current runs
  - Lower bunch brightness
  - Weaker beam-beam effect

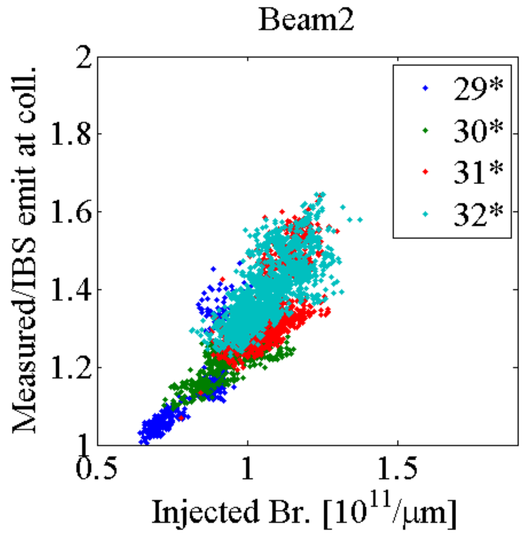
OBSERVATIONS FROM RUN I

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

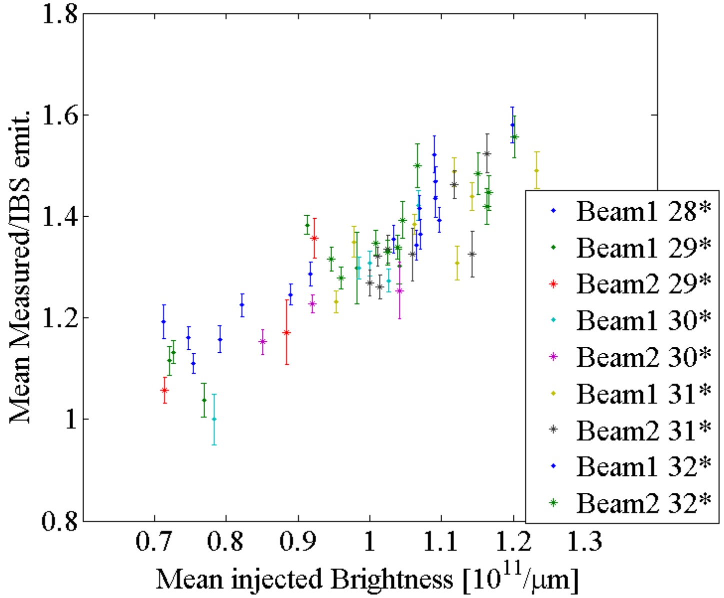
Data to model comparison

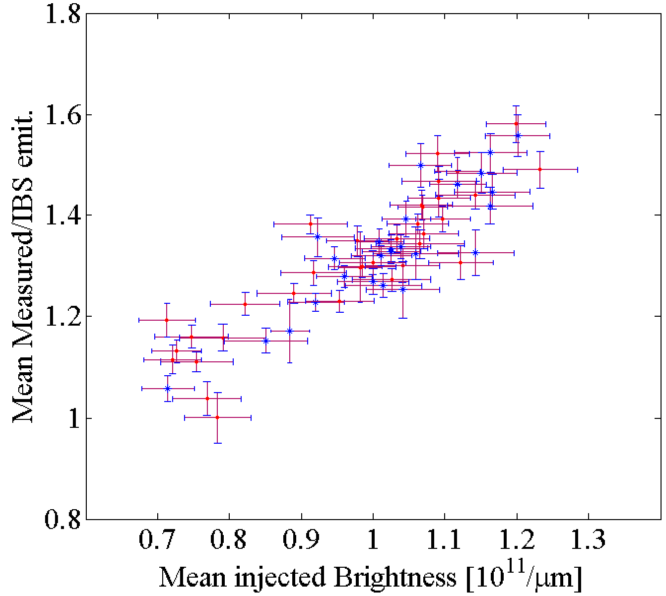




- 28* → Fills 2800-2900, etc.
- Only stable bunches are used
- Linear dependence of the emittance ratio (or blow up factor) with the injected brightness

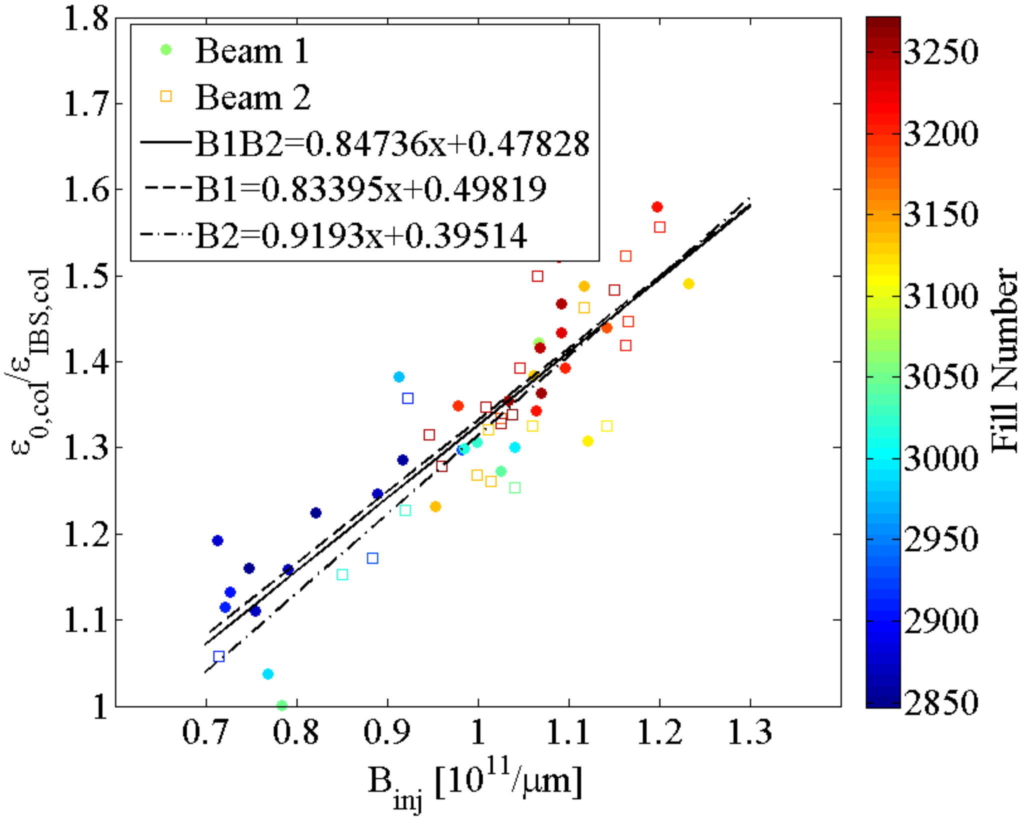
Data to model comparison





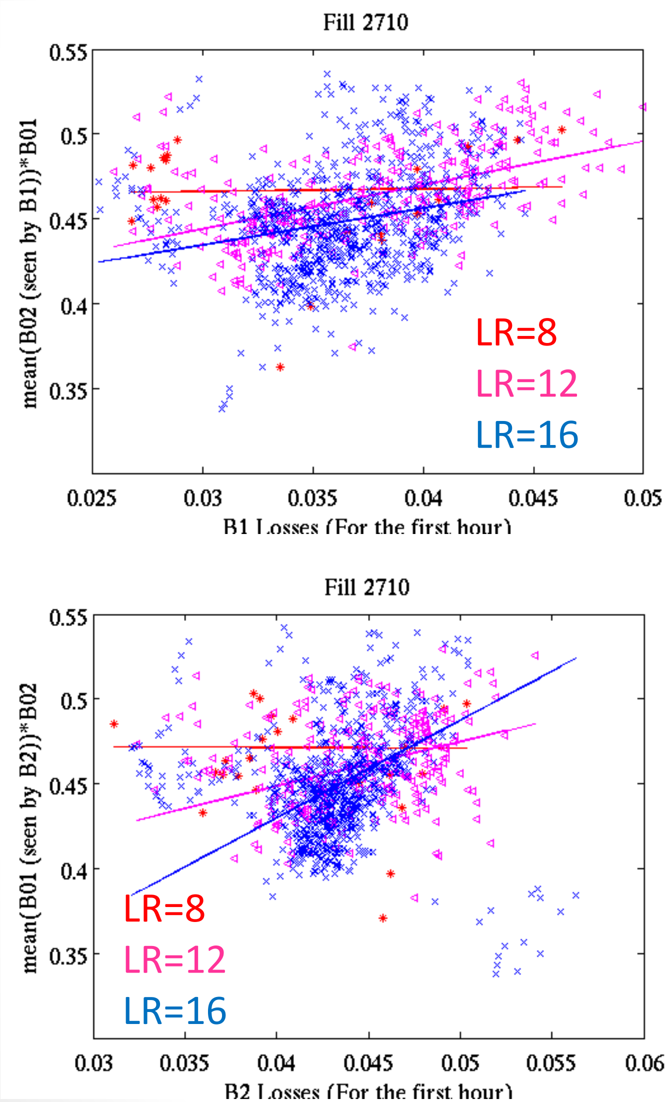
- The same exercise is repeated using the mean values for each Fill
- The errorbars show the std from the mean for each Fill

Data to model comparison



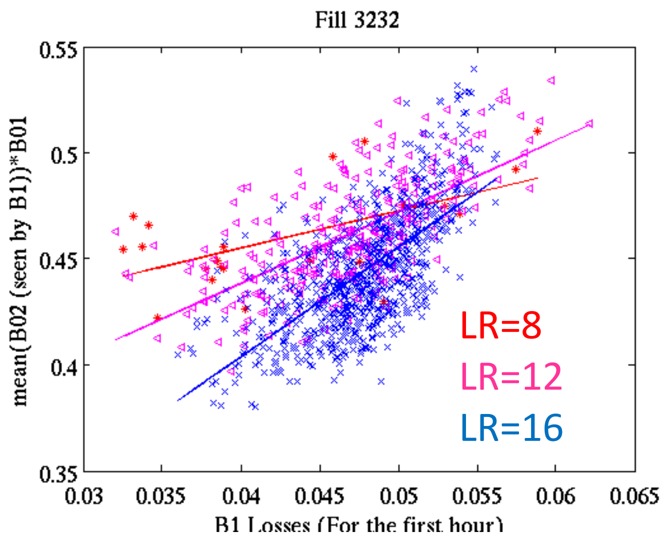
- Similar slope for both beams
- Can we use a global fit?

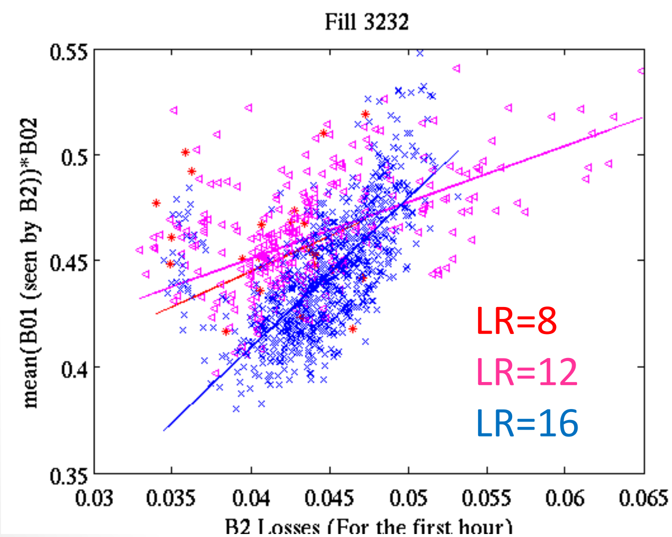
Correlations with long range



- 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

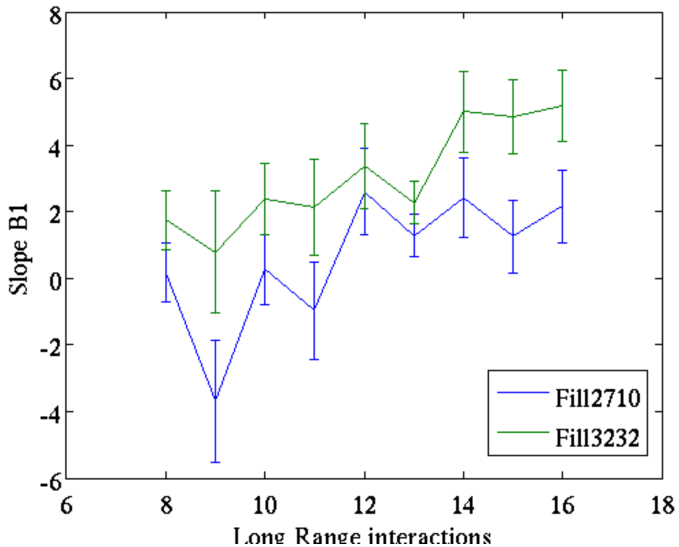
Correlations with long range

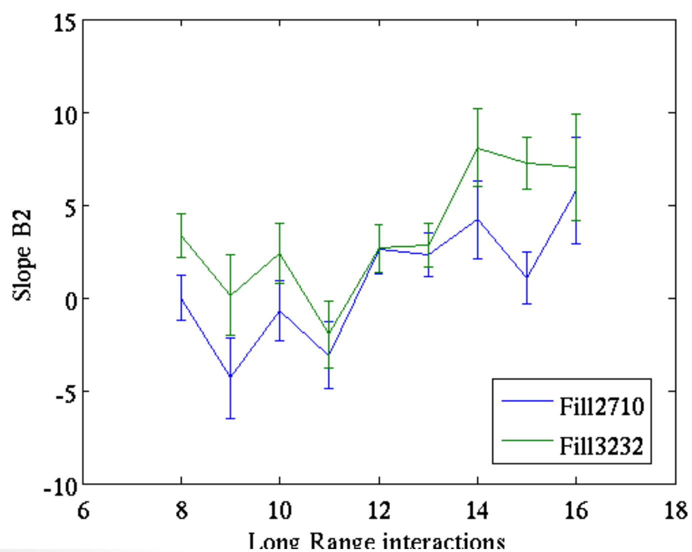




- The same analysis is applied to Fill3232
- Exactly the same trend is observed for both beams
  - Steeper slopes in this case

Correlations with long range





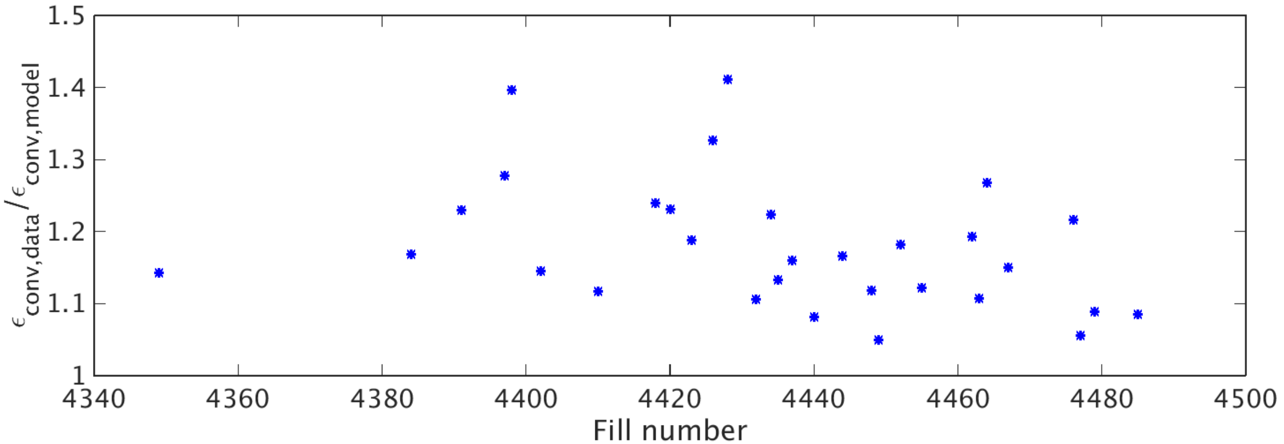
- Calculating the slope for each of those curves for all different cases of long-range encounters (8-16)
  - Clear trend of slope increase with the number of long-range encounters
  - The effect is enhanced for Fill3232 where the brightness is higher
  - Need to generalize the observation for other fills
    - 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

OBSERVATIONS FROM RUN II

Analyzing RunII data

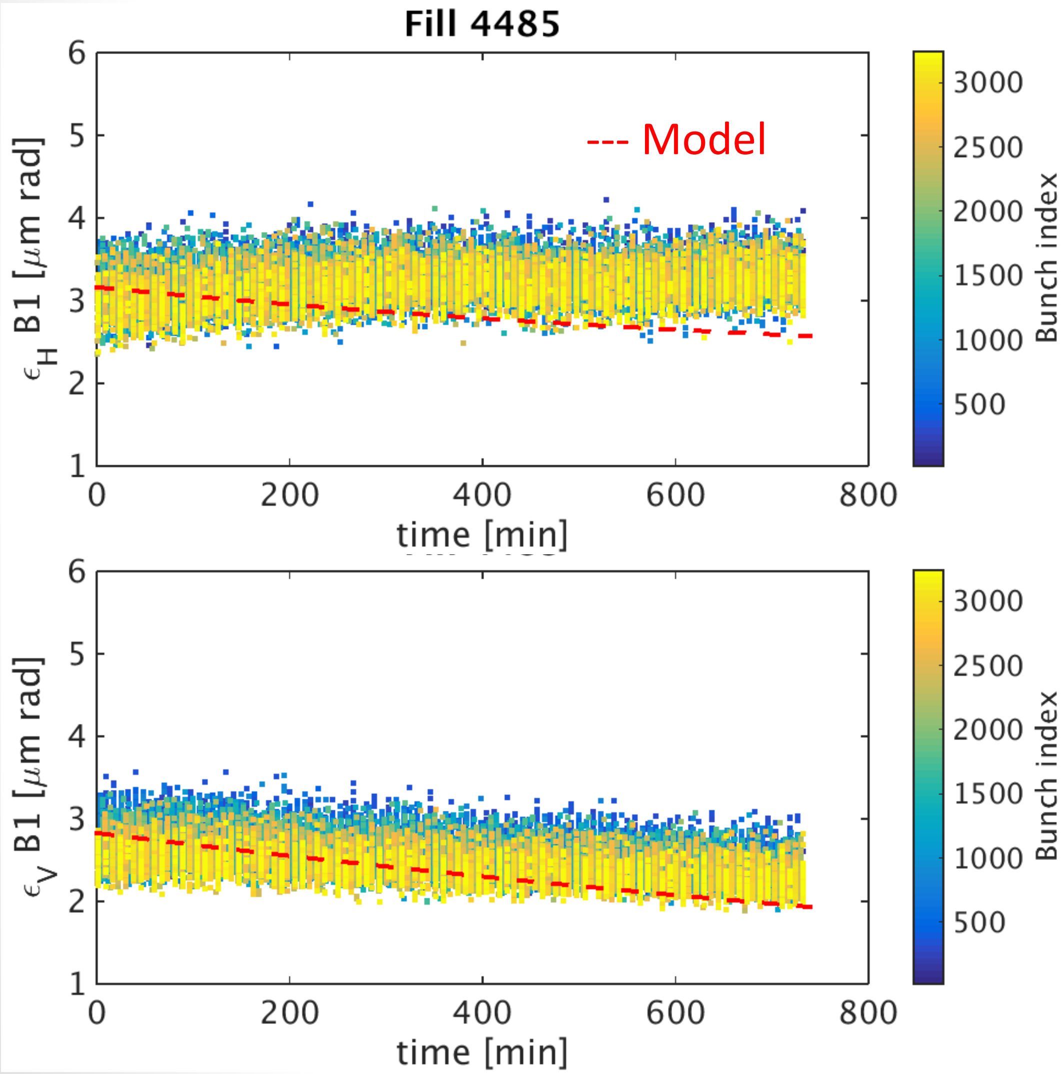
- Most of the Fills that arrived at Stable Beams have been analyzed
- In this Run we have emittance measurements both at Flat Bottom and Flat Top
  - BSRT data for both beams and both planes
  - Convoluted emittance from luminosity
  - Convoluted horizontal and vertical emittance from OP scans
- Comparisons 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

Emittance evolution from Injection to Stable Beams



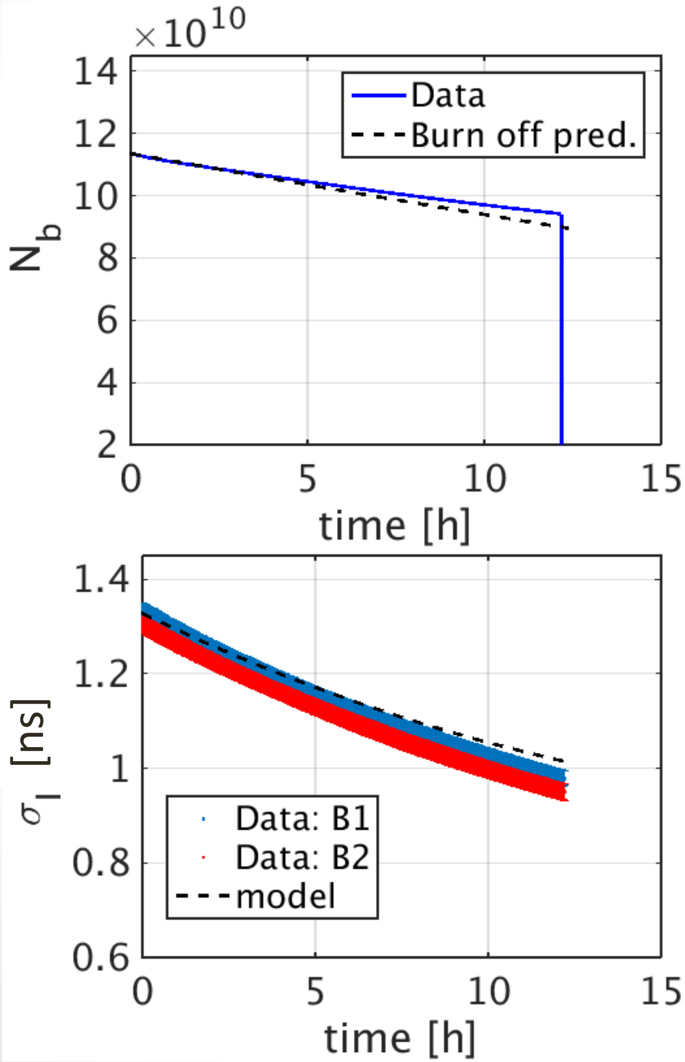
- The injected bunch characteristics and the time each bunch stayed at Flat Bottom were used from the data
- Using those initial parameters the expected emittance evolution from Injection to the beginning of Stable beams due to IBS and SR was computed for all fills
- The convoluted emittance from lumi was compared to the one predicted by the model
- An extra emittance blow-up is observed (10-20% for the last Fills) which cannot be explained only by IBS and SR
    - ~10% can be explained from an extra emittance blow up at Flat Bottom (e-cloud, non-linearities…)
    - Work in progress

Lumi model predictions Vs RunII data: Emittance @ SB



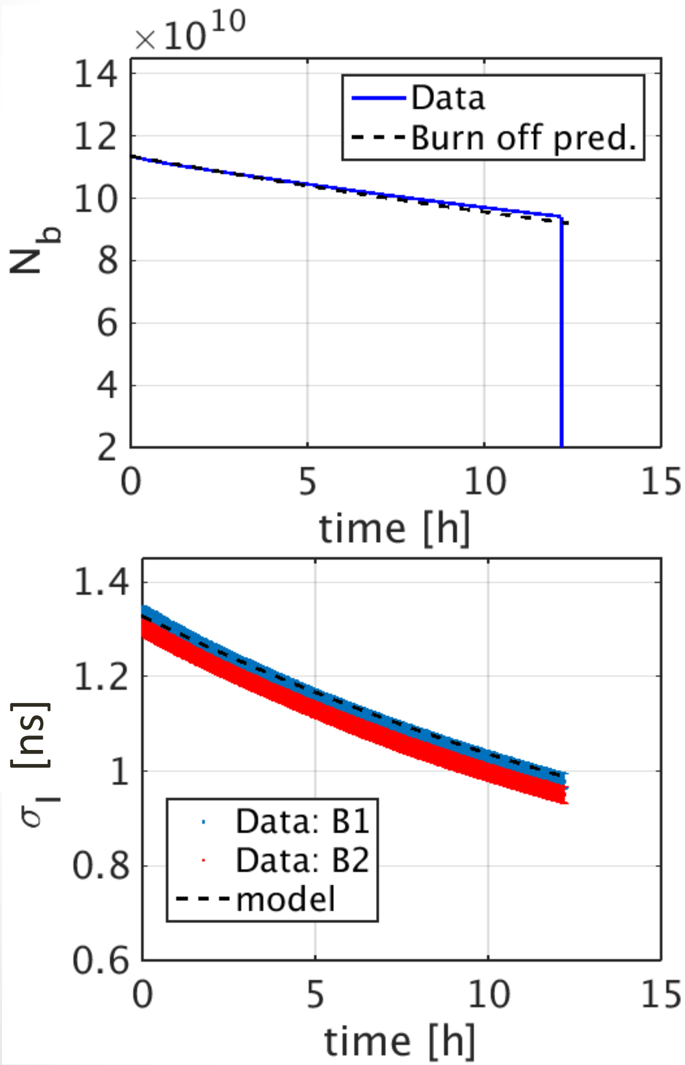
- Fill 4485 is used as an example here
  - Average bunch intensity: 1.01e11
- Emittance evolution during SB from BSRT
- The initial bunch parameters from the data are used and then the model (IBS + SR + Burn-off) is iterated in time
- Damping of the emittances in both horizontal and vertical planes is predicted (red dashed line)
- Blow up is observed in both planes, with respect to the model
- We need to understand and include other sources of emittance blow-up

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



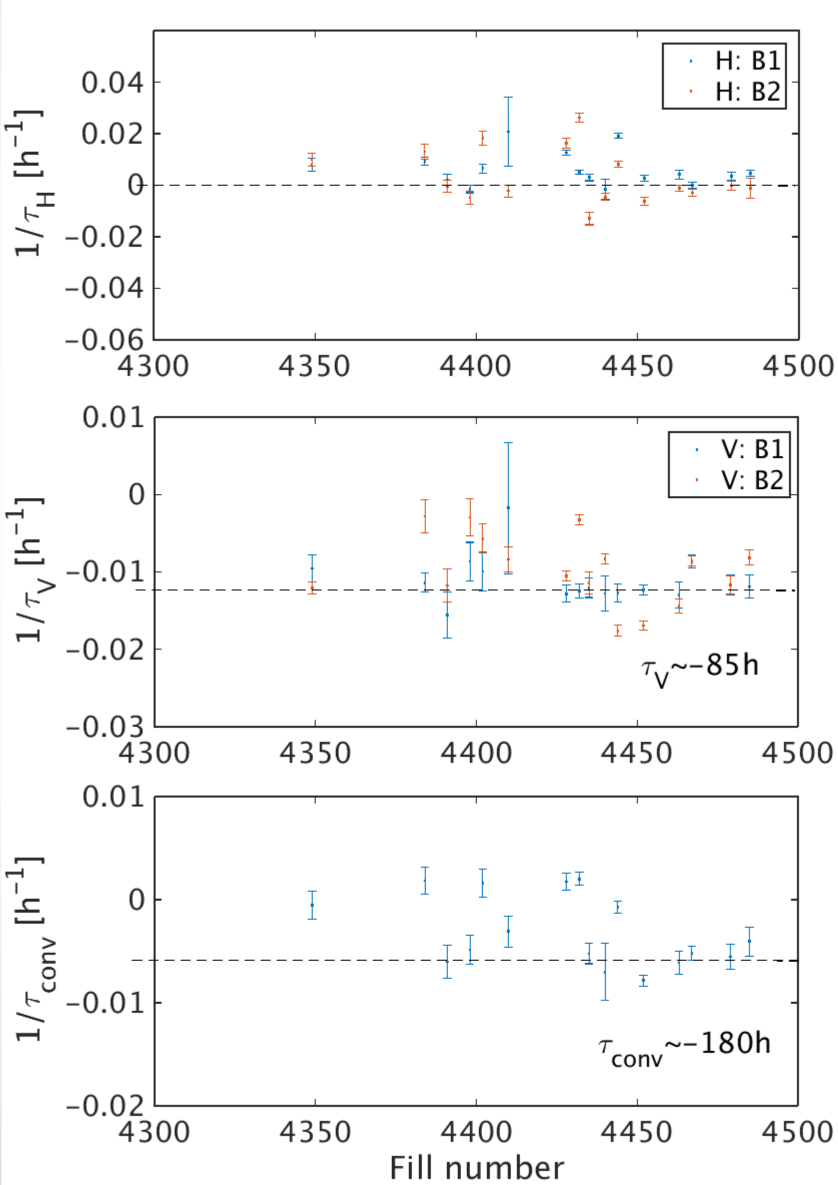
- Looking at the other two observables (Top: Bunch current, Bottom: bunch length)
- Smoother current decay and more bunch length damping is observed with respect to the model prediction
- Same analysis is done for all the Fills that arrived at SB
  - Similar behavior with the same or more pronounced 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 → very good agreement
- Modeling the emittance evolution at Stable beams correctly is crucial for the luminosity model
  - Need to understand and add other sources of emittance blow up to our model

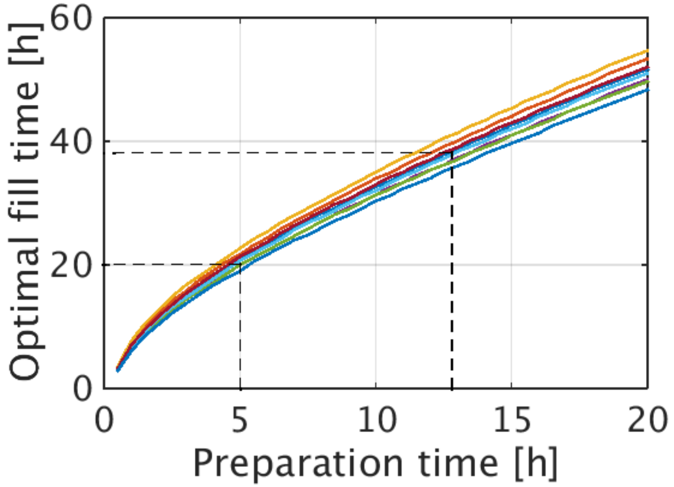
Emittance evolution during SB

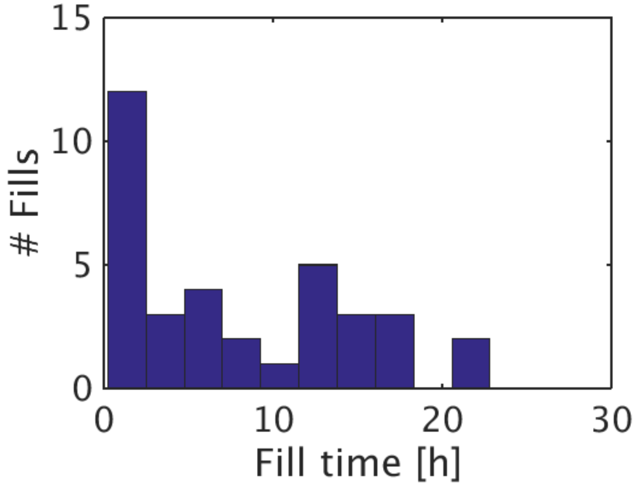


- For each Fill an exponential fit is applied to the SB emittance evolution from the BSRT data → estimation of damping/growth times
- Trends observed
  - H plane: both slight damping and slight growth have been observed
  - V plane: always damping with $\tau_V \sim -85h$ mainly for the last Fills
  - 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.**

Optimum Fill time from model



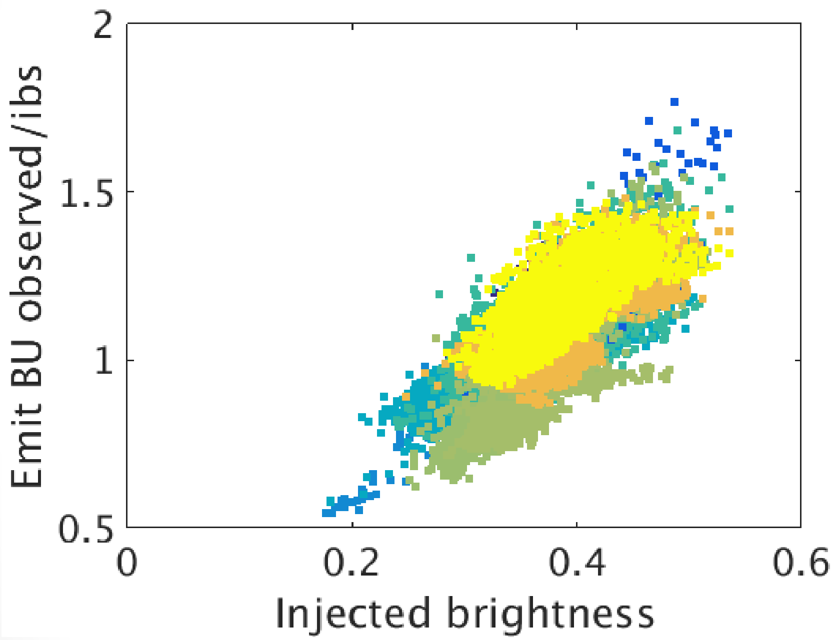


- The evolution of beam parameters and thus the luminosity was calculated based on the Lumi model and different assumptions for the emittance damping/growth rates (based on the statistics presented earlier)

- The optimal fill time was calculated for different example cases (here for two different convoluted emittance values at the beginning of SB and different damping or growth times

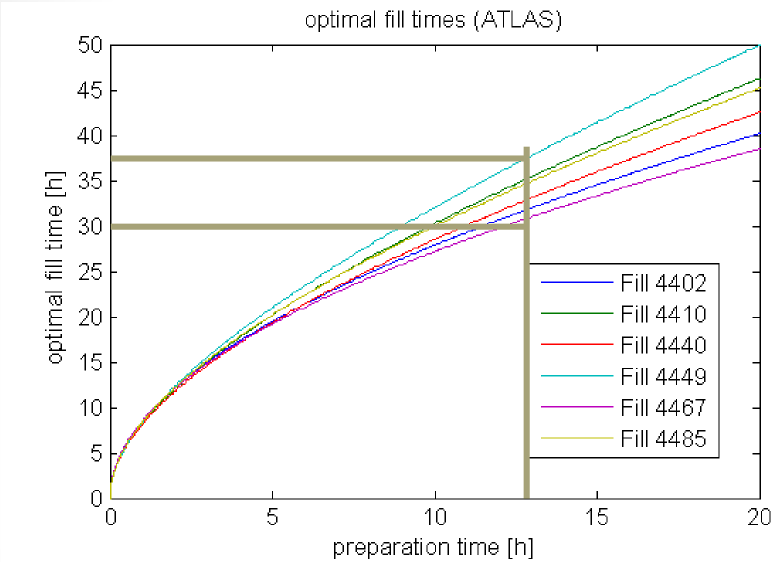
➢ **Long Fills are favorable!**

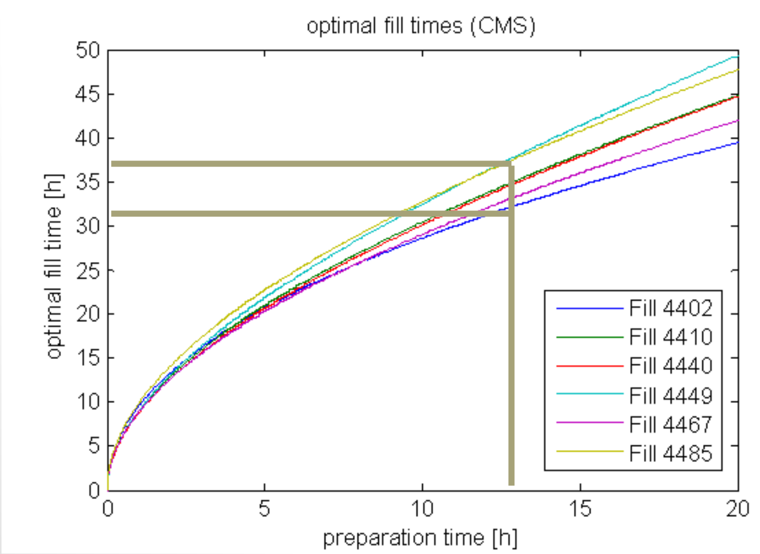
Bunch by bunch studies



- For each Fill and each bunch the emittance blow up after 2 hours at Stable beams is compared to the one expected from the model.
- The ratio of the two is plotted versus the injected bunch brightness at SB
- It is a very preliminary result but it seems to have a brightness depended effect

Optimum Fill time from data





- Optimal fill time calculated from fit to luminosity curves
  - Top: Atlas, Bottom: CMS
- For a preparation time of ~13h → Optimal Fill time of **~35h**

➢ 'Do not do any OP dumps'

➢ Even for small preparation times (~3-5h) the optimal Fill times are long (>15h)

PROJECTIONS TO HL-LHC

Parameters table

Parameter	Nominal	25ns HL-LHC	8b+4e
Bunch population N_b [10^{11}]	1.15	2.2	2.3
Number of bunches	2808	2748/2604	1968
Beam current [A]	0.58	1.09/1.03	0.82
Crossing angle [μrad]	285	590	554
Beam separation [σ]	9.9	12.5	12.5
Minimum β^* [m]	0.55	0.15	0.15
Normalized emittance ε_n [μm]	3.75	2.5	2.2
ε_L [eVs]	2.5	2.5	2.5
r.m.s. bunch length [m]	0.075	0.081	0.081
Virtual Luminosity (w/o CC) [10^{34} cm^{-2}s^{-1}]	1.2 (1.2)	18.9 (6.73)	16.8 (6.0)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.30	3.6
Levelled Pile-up/Pile-up density [evt. / evt./mm]	27/0.2	140/1.2	140/1.2
Integrated luminosity [fb^{-1}/year]	45	260	190

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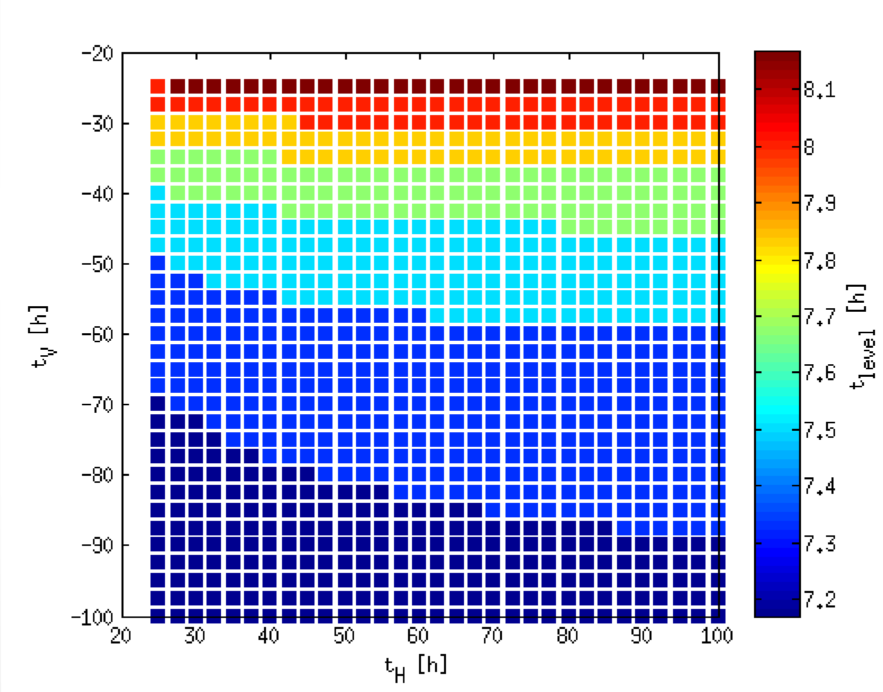
Emittance blow up effect on leveling



- Parameterization of the leveling time with the horizontal (H) and vertical (V) emittance growth/damping time
  - More sensitive to the vertical emittance blow up
  - Big impact on the leveling time

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
- The model is compared with RunI and RunII data
- Based on the observations first projections to H-LHC are done

THANKS FOR YOUR ATTENTION!