Luminosity modeling for the LHC

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Acknowledgements:
Beam-Beam and Luminosity studies working group, J.E.Muller, M. Lamont, R . Tomas, B. Salvachua, M.Solfaroli

EVIAN meeting, 15-17 Dec 2015

Outline

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- Luminosity model Vs RunII data
- Optimal Fill times for 2016
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Introduction: Luminosity

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

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

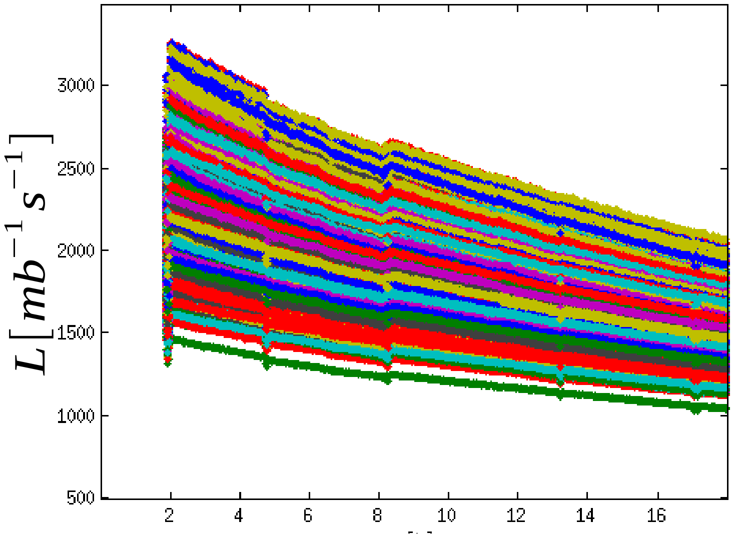
- Model components :
  - Beam current decay with time
  - Beam size (or emittance) evolution with time

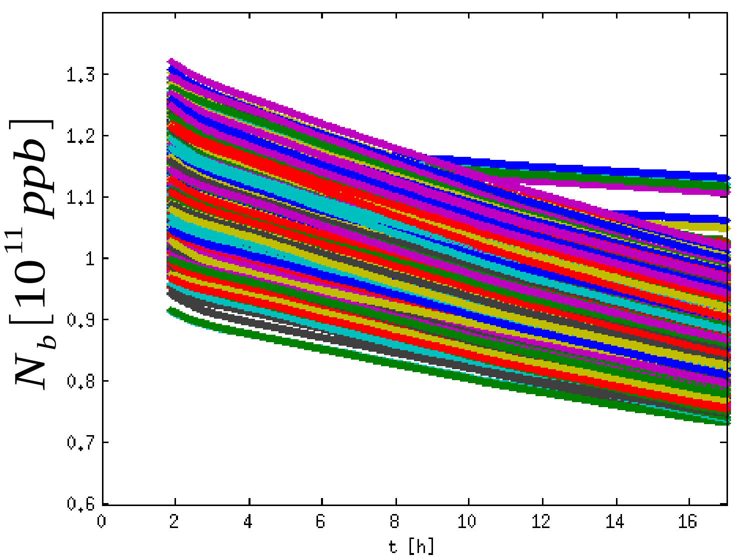
- Geometric Factor

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

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

Luminosity decay





- During stable beams the interplay between different effects affects the bunch characteristics evolution:
  - Intra-beam scattering, Burn-off, Synchrotron Radiation, Beam-beam, noise, other unknown mechanisms, ...
- Many of the effects depend on the initial bunch brightness
- Big spread in the bunch by bunch behavior is observed

➔ **We need a model that takes the bunch-by-bunch variations into account**

Model components (1)

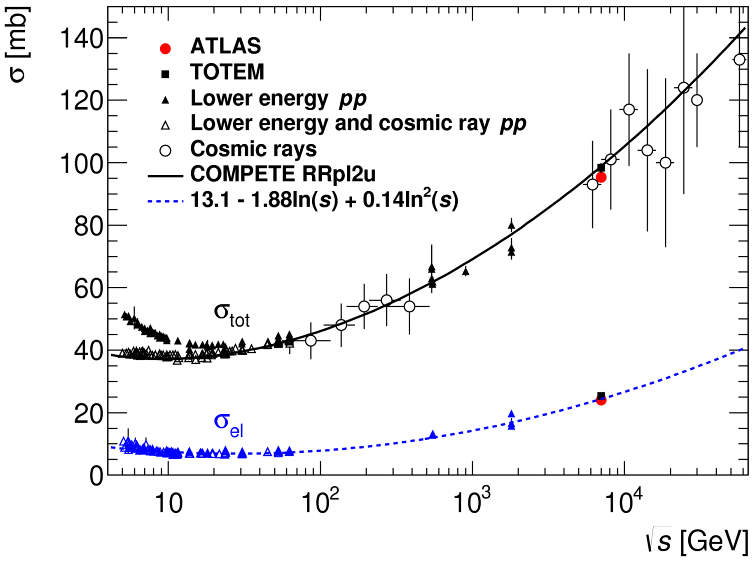
- **Emittance and bunch length evolution at Flat Top energy**:
  - **Intrabeam scattering (IBS)**:
    - Multiple Coulomb scattering effect leading to the redistribution of phase space and finally to emittance blow up in all three planes
    - $\frac{d\varepsilon_\iota}{dt}=f\left(En, N_{b0}, \varepsilon_{x0}, e_{y0}, \sigma_{l0}\right)$ → Analytical 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
    - $\varepsilon_\iota=\varepsilon_{i0}\exp\left(-t/\tau_i\right), \tau_i$: 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 function:

$$\left[\varepsilon_x\left(t_i\right), \varepsilon_y\left(t_i\right), \sigma_l\left(t_i\right)\right]=ComputeIBSEmitEvol\left(En, N_{b0}, \varepsilon_x\left(t_0\right), \varepsilon_y\left(t_0\right), \sigma_l\left(t_0\right), timestep\right)$$

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
      - *k* the number of interaction points



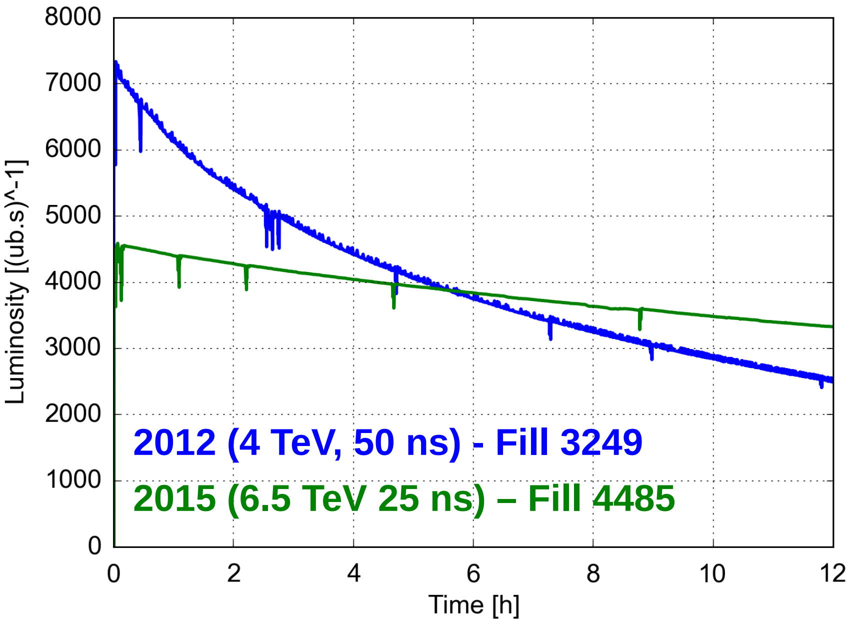
✔ It can be easily folded into the emittance evolution function in order to have a **self consistent evolution**

Luminosity model summary

- The **basic model** includes the three main mechanisms of the transverse emittance, bunch length, bunch intensity and luminosity evolution due to **IBS**, **SR** and **Burn-off**
- It can be easily applied and compared with the data for **bunch by bunch** and averaged quantities studies
  - On going effort to find correlations from the data from average and bunch by bunch behavior (brightness, long ranges, losses, blow-up,…)
- Other sources need to be considered
  - Non-linearities of the machine
  - Noise effects
  - Scattering on residual gas
  - …

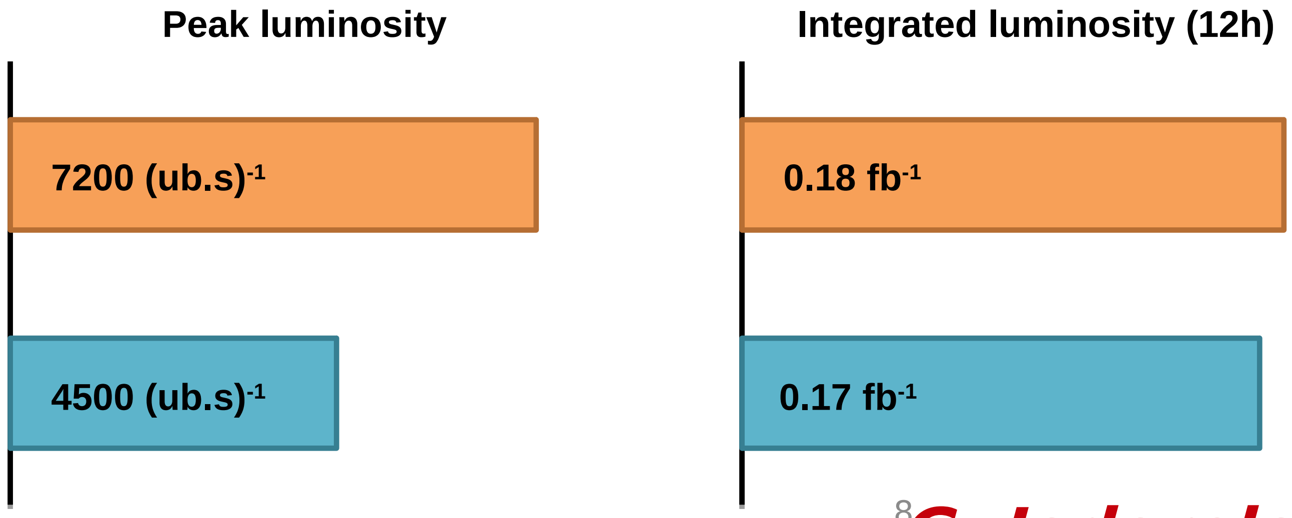
Luminosity performance: RunI Vs RunII

- 2015 configuration with **low bunch intensity**, low brightness and relaxed β* results in:
  - **Low peak luminosity**
  - **Long luminosity lifetime**
- **Integrated luminosity** over a "typical" fill is **very similar to what we used to get in 2012**



2012 (4 TeV)
50 ns, 1380 b.
1.7e11 ppb, 1.6 um (inj.)
β* = 60 cm

2015 (6.5 TeV)
25 ns, 1825 b.
1.1e11 ppb, 2.5 um (inj.)
β* = 80 cm

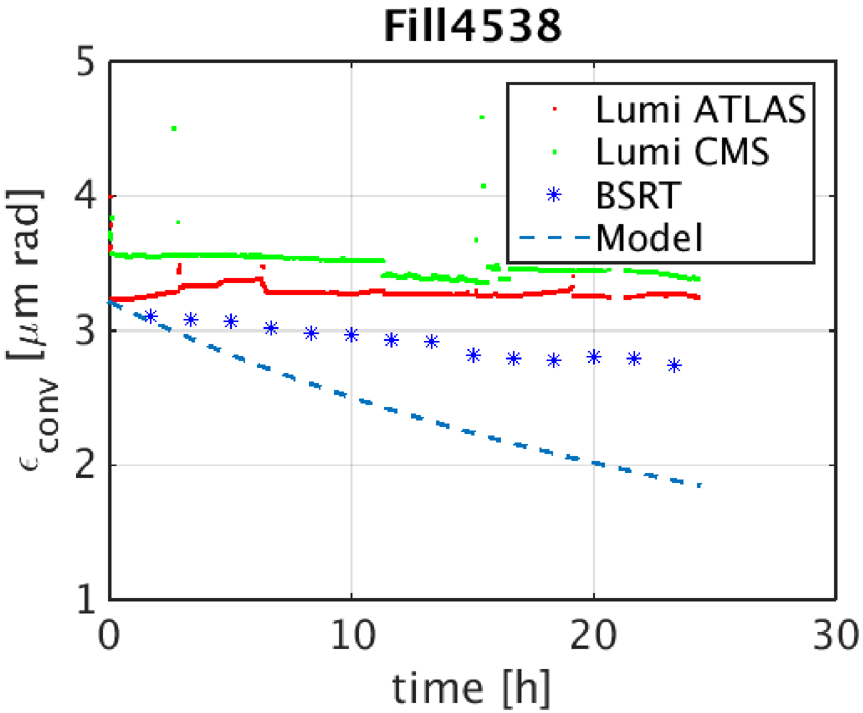


G. Iadarola

Analyzing RunII data

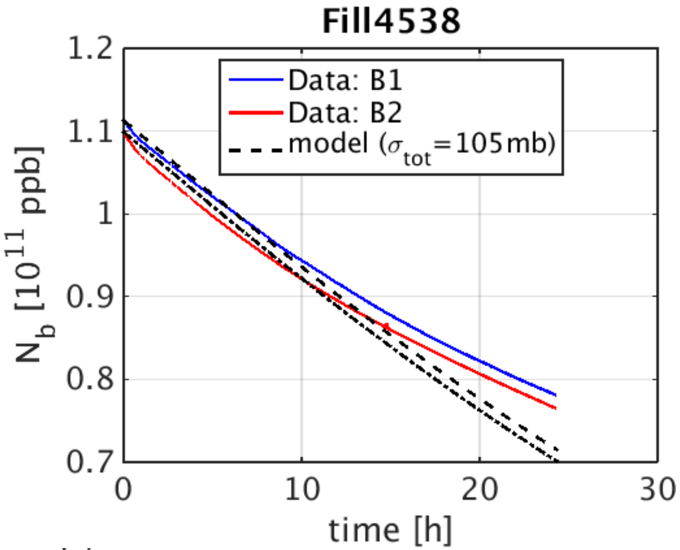
- In Run II we have **emittance measurements both at Flat Bottom and Flat Top**
  - **BSRT** data for both beams and both planes
  - Convoluted emittance from luminosity from the **experiments**
  - Convoluted horizontal and vertical emittance from **OP scans**
- Comparison between the **different methods not always in good agreement**
  - Work in progress to understand the data
- The data were compared with the model predictions for all Fills that arrived at Stable Beams

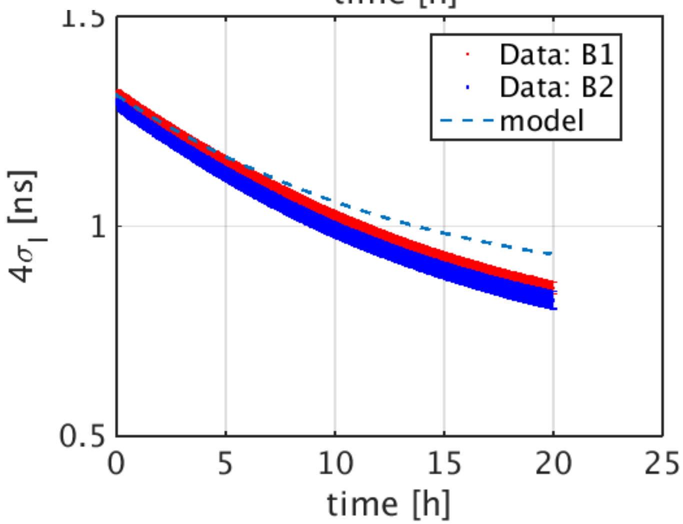
Luminosity model Vs RunII data: Emittance @ SB



- Fill 4538 is used as an example here
- Emittance evolution (averaged) during SB from BSRT, Lumi ATLAS and Lumi CMS
  - Different evolution
- **Blow up** observed, with respect to the model
- We need to understand the data and include **other sources of emittance blow-up**

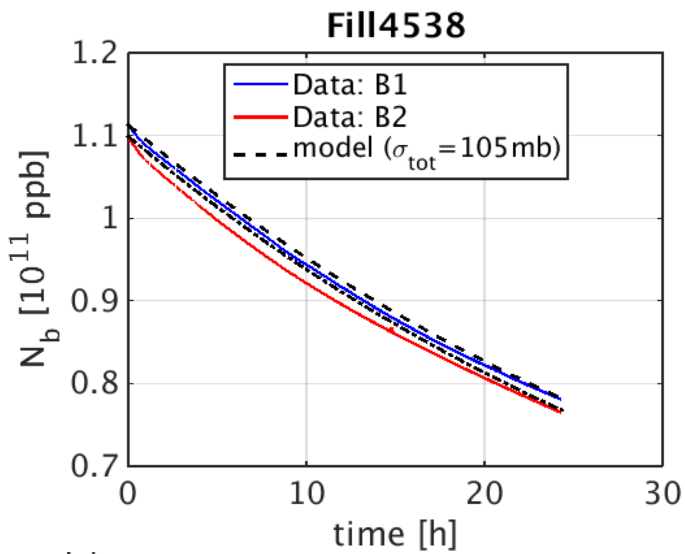
Luminosity model Vs RunII data: Bunch current & bunch length @ SB

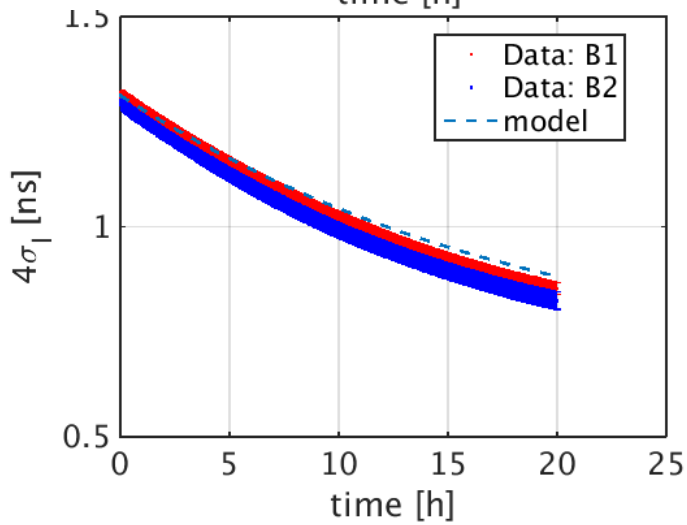




- Smoother current decay and more bunch length damping is observed with respect to the model prediction

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

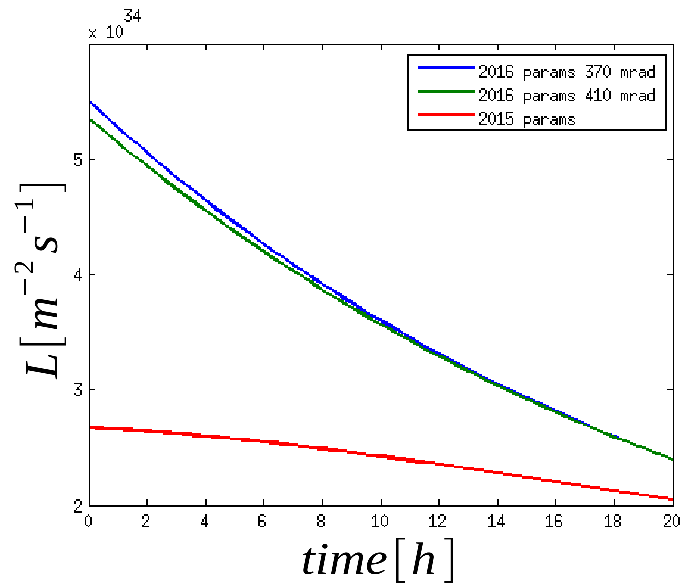


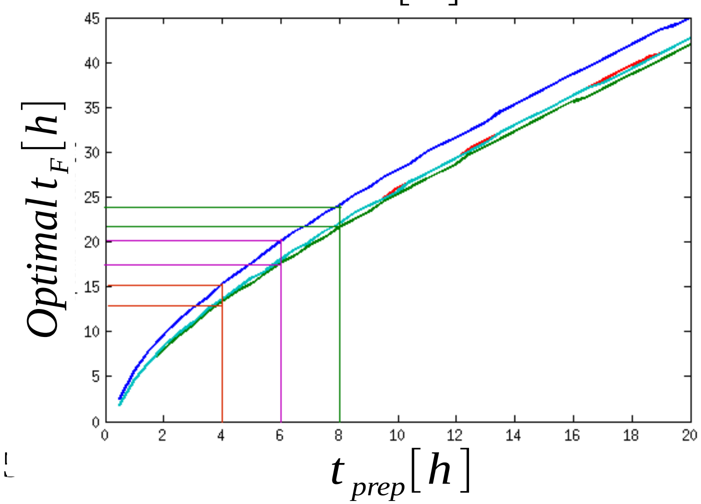


- Smoother current decay and more bunch length damping is observed with respect to the model prediction
- Using the **emittance evolution from the data (mean)** → Very good prediction for the current and bunch length evolution
- Identify and add other sources of emittance evolution to the model is very important!
- The emittance blow up results in an **integrated luminosity reduction of the order of 20%**

Optimal Fill times for 2016

- 2016 proposed parameters:
  - β*=40 cm in IP1/5
  - 410 μrad (11 σ) or 370 μrad (10 σ) in IR1 and 5
  - Similar bunch brightness and bunch length as in 2015 (1.2e11, 3μm, 1.3ns)
- Most probable turnaround time (based on 2015) of 6-8h (see M. Solfaroli)
- Using different emittance evolution scenarios (based on 2015 observations)
  - Long Fills are favorable
  - For 6h prep. Time: 18-20h
  - For 8h prep. Time: 22-24h
  - For 4h prep. Time: 13-15h





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
  - Can be easily applied bunch-by-bunch

- The model is based on analytical formulas which assume Gaussian distributions
  - This is not always the case for the LHC (especially in the longitudinal plane)
  - Work in progress to understand the effect of the beam distribution on the IBS evolution of the bunch characteristics (S. Papadopoulou)

Summary and Outlook

- Observations from RunII data:
  - Differences have been observed on the emittance evolution from the different methods of measurement → Need to be understood
  - Using the emittance from the data, good prediction for the bunch length and bunch current evolution
  - Modeling the emittance evolution is a very important component of the model
- Based on the model and the observations, in 2016 long Fills should still be favorable
- Bunch-by-bunch analysis is in progress
  - Aims to identify correlations between the observed emittance blow-up and the bunch “lifestyle” (brightness, long-ranges, etc..)

THANK YOU FOR YOUR ATTENTION!