Burn-off with asymmetric interaction points

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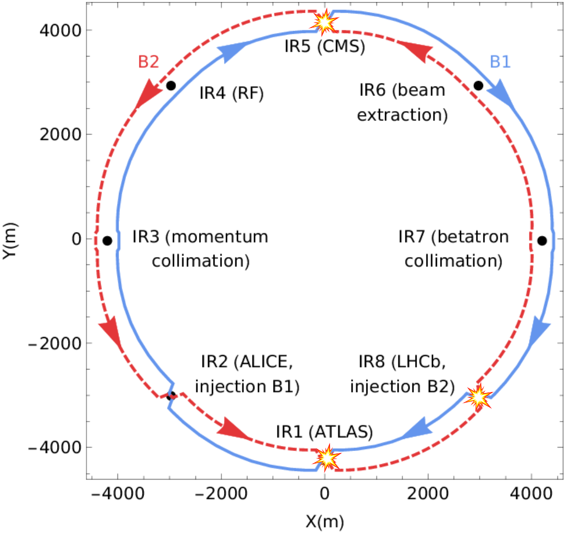
Asymmetric Interaction Points in (HL-)LHC

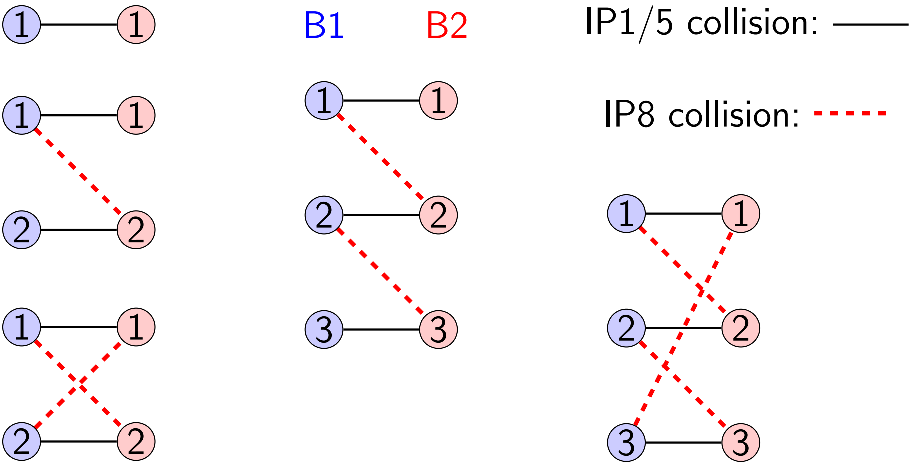


IP1 & IP5 produce high luminosity collisions placed symmetrically.

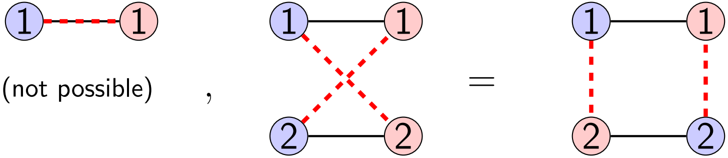
IP8 produces low luminosity collisions for different bunch pairs than IP1 & 5

Bunches colliding in IP1/IP5/IP8 suffer more intensity burnoff than the rest, **generating bunch-by-bunch variations which affect detector performance**.

Collision patterns up to 3 bunches

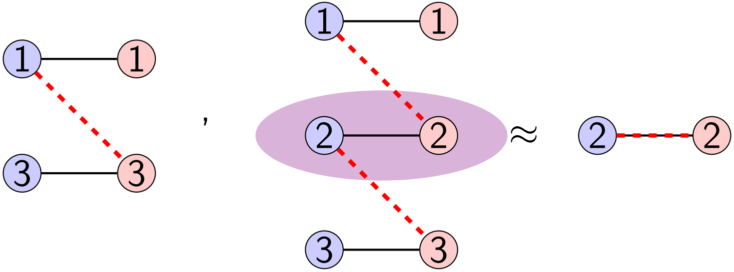


Type 1: **cycle** graph



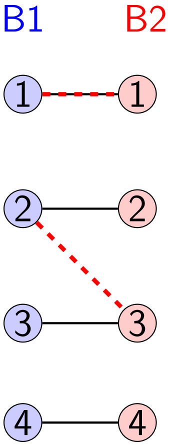
All bunches in any cycle graph (any number of bunches) will follow the same burn-off (ignoring initial variations).

Type 2: **string** graph



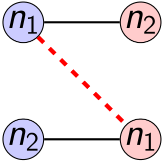
All bunches in string graphs have different burn-off but it is a good approximation to consider internal bunches as loops.

Relevant configurations



Standard	BCMS
2376	2017
186	345
186	345
0	29

Analytical equations for the simulation code



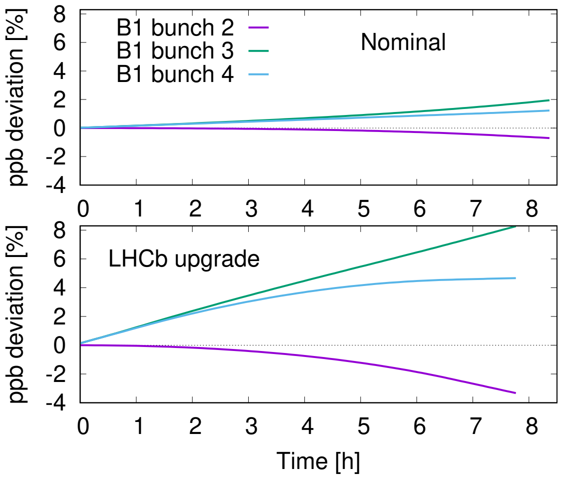
$$\frac{\mathrm{d}n_1}{\mathrm{d}t} = -\sigma n_1 n_2 - \sigma_8 n_1^2 \,, \qquad \frac{\mathrm{d}n_2}{\mathrm{d}t} = -\sigma n_1 n_2 \,.$$

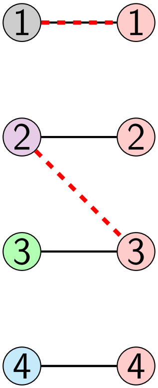
$$\Rightarrow n_1 = C n_2^{\frac{\sigma_8}{\sigma}} + \frac{n_2}{1-\frac{\sigma_8}{\sigma}} \,.$$

Defining $n_r = \frac{n_{1,0}}{n_{2,0}}$, $\sigma_r = \frac{\sigma_8}{\sigma} \ll 1$ and $\chi = n_r(1-\sigma_r) - 1$, gives:

$$\begin{aligned} n_1(t) &= n_2(t) n_r \mathrm{e}^{\sigma n_{2,0} \chi t} \\ n_2(t) &= n_{2,0} \frac{\chi}{n_r \mathrm{e}^{\sigma n_{2,0}\chi t} - \sigma_r n_r - 1} \,. \end{aligned}$$

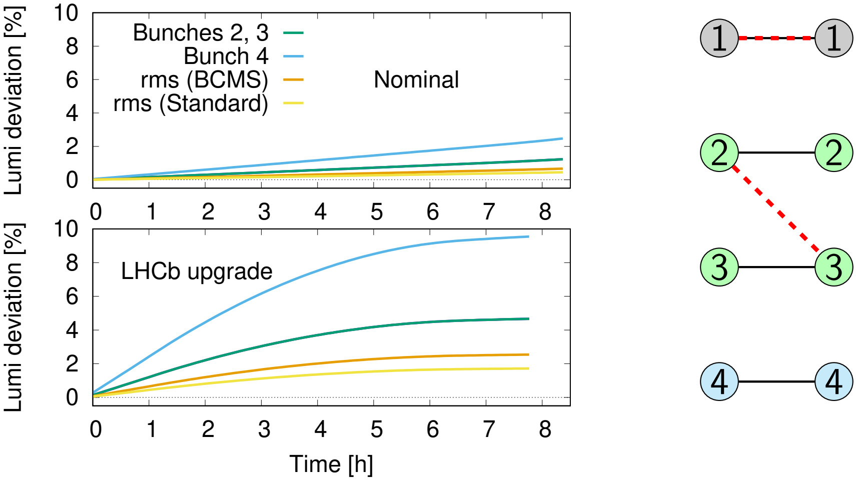
PPB: HL-LHC Nominal & LHCb upgrade





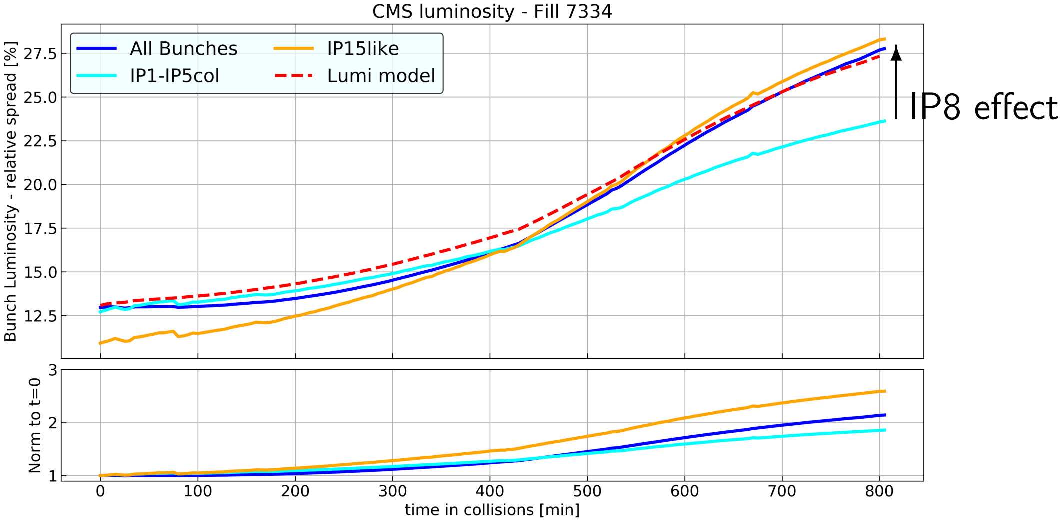
Worst bunch here is 3 in the string of 2 bunches.

Lumi: HL-LHC Nominal & LHCb upgrade

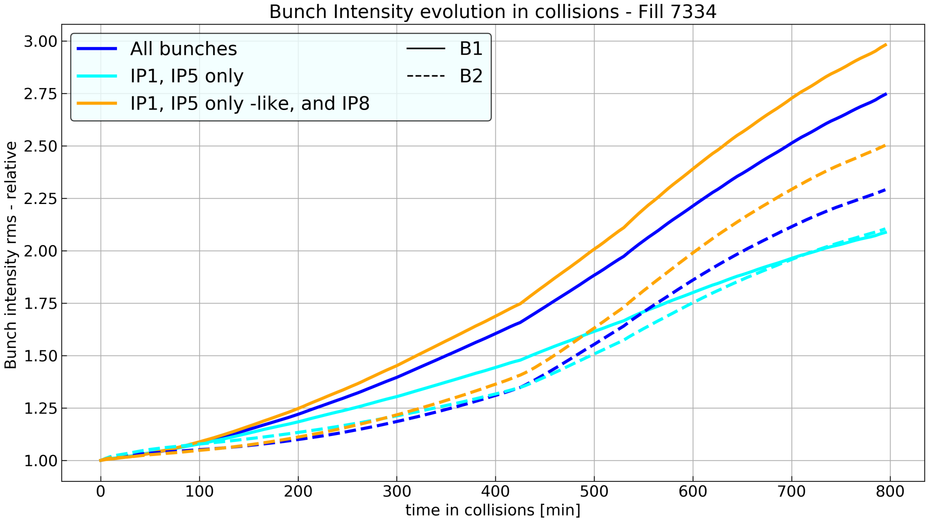


Maximum lumi difference of 10%, rms of about 2%. Is this an issue?

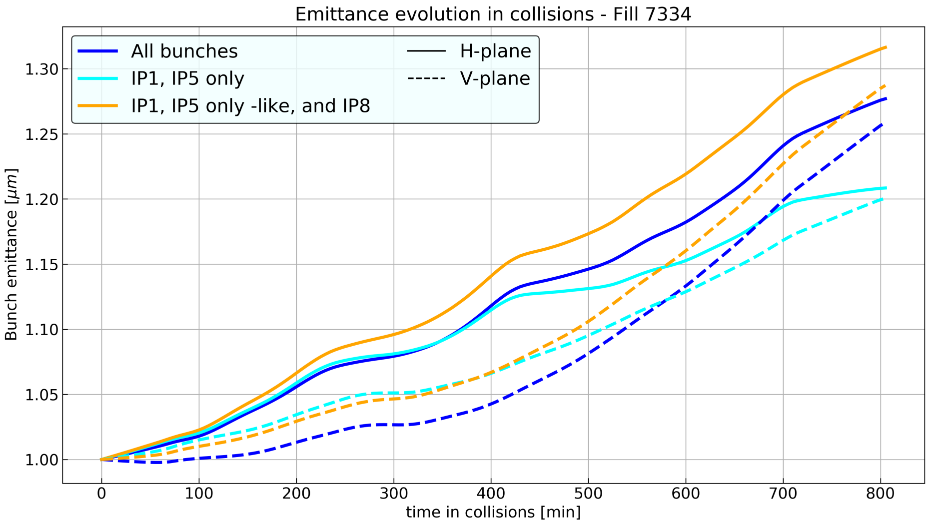
Experimental evidence in LHC: luminosity



Experimental evidence in LHC: intensity



Experimental evidence in LHC: emittance

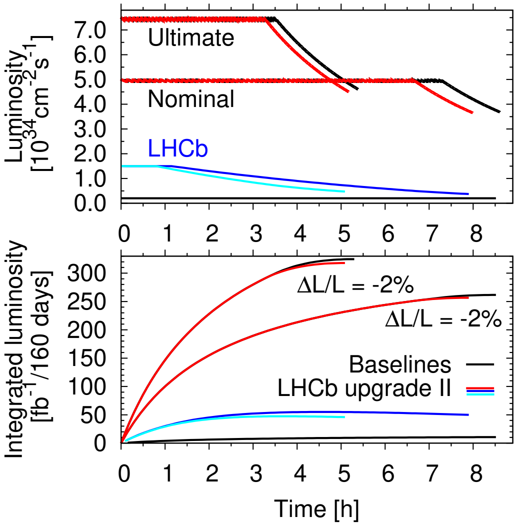


Summary & outlook

- ★ Bunch-by-bunch luminosity variations from burn-off are expected
- ★ with rms of about 2% in HL-LHC with LHCb upgrade II.
- ★ Tolerance is 10% rms and injectors could take most of it with 3% rms on bunch intensity and 9% on emittance.
- ★ Need to simulate fills with initial fluctuations from injectors.
- ★ Experimental evidence observed in LHC. However further beam dynamics effects enter into play via emittance blow-up.
- ★ Further observations in Run 3: LHCb @ 2×10^{33}, IP1/5 @ 1-2×10^{34}.

Extra slides

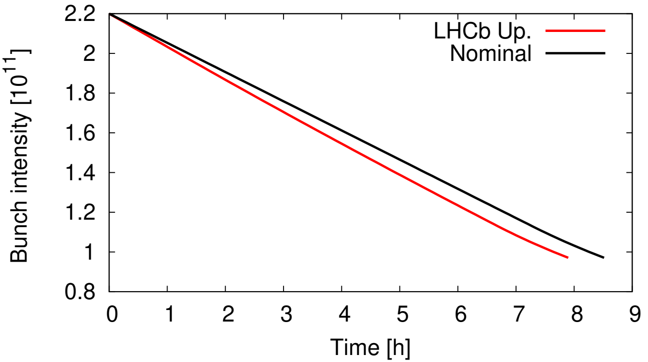
Impact of LHCb upgrade II on ATLAS/CMS



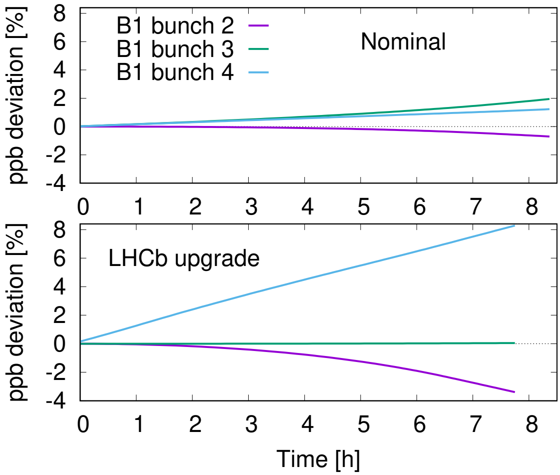
LHCb upgrade II would reduce ATLAS/CMS integrated luminosity by 2% for both Nominal and Ultimate.

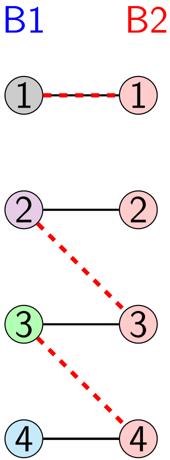
Impact on bunch population

Increasing LHCb luminosity to 1.5×10^{34} cm^{-2}s^{-1} comes with *a priori* a small impact on IP1&5 performance but introduces bunch-by-bunch variations



String: HL-LHC Nominal & LHCb upgrade





Analytical solution for asymmetric collisions

It is possible to solve the differential equations for burn-off with unequal bunch charges and constant emittance (single IP):

$$\frac{\mathrm{d}n_1}{\mathrm{d}t} = -\sigma_r n_1 n_2 \quad , \qquad \frac{\mathrm{d}n_2}{\mathrm{d}t} = -\sigma_r n_1 n_2 \quad .$$

giving, for $n_{1,0} > n_{2,0}$:

$$n_1(t) = \frac{n_{1,0}\mathrm{e}^{\sigma_r(n_{1,0}-n_{2,0})t}}{\frac{n_{1,0}}{n_{1,0}-n_{2,0}}\left(\mathrm{e}^{\sigma_r(n_{1,0}-n_{2,0})t} - 1\right) + 1} \quad ,$$

$$n_2(t) = \frac{n_{2,0}}{\frac{n_{1,0}}{n_{1,0}-n_{2,0}}\left(\mathrm{e}^{\sigma_r(n_{1,0}-n_{2,0})t} - 1\right) + 1} \quad .$$

Burn-off amplification of bunch charge ratio

The ratio n_1/n_2 computed from previous eqs. gives:

$$\frac{n_1(t)}{n_2(t)} = \frac{n_{1,0}}{n_{2,0}} \mathrm{e}^{\sigma_r(n_{1,0}-n_{2,0})t} \quad ,$$

featuring an exponential divergence!

Therefore the interplay between bunch-by-bunch variations generated by the injectors, IP8 and the exponential amplificaion is of concern.

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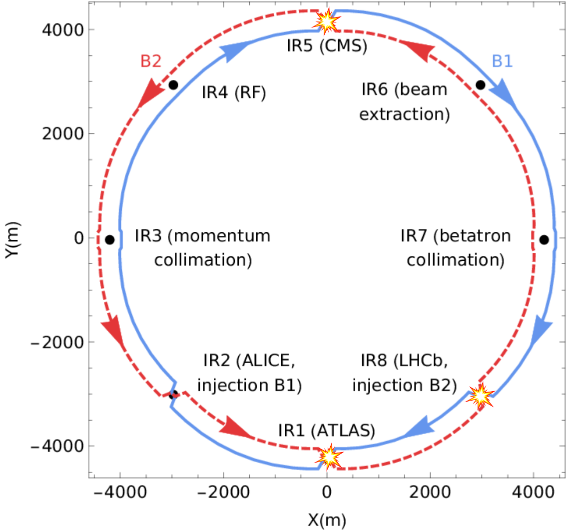

Bunch collision patterns: