Options for ion operational scenarios with increased performance

R. Bruce

Acknowledgement: H. Bartosik, G. Iadarola, J.M. Jowett

WP2 meeting, 28/09/2021

Introduction

- Recently updated operational scenario for Pb-Pb and p-Pb in Runs 3-4
  - Improved filling schemes and modelling
  - See CERN report and EPJ Plus paper; WP2 talk, TCC talk

- Range of filling schemes with varying number of collisions at LHCb
  - Motivated by recent request from LHCb for significant luminosity - comes at the expense of the other experiments
  - Updated performance estimates for typical one-month run
    - Only studied one-month performance due to large uncertainties in detailed planning

Pb-Pb

Table 6 Integrated luminosity (given in nb^{-1}) during a one-month Pb–Pb run at each experiment for the considered filling schemes from Ref. [13], assuming an operational efficiency of $\eta = 0.5$ h and 24 days available for physics operation in Eqs. (5)–(6)

Filling scheme	$\mathcal{L}_{tot}$ IP1/5	$\mathcal{L}_{tot}$ IP2	$\mathcal{L}_{tot}$ IP8
1240b_1240_1200_0	2.5 [2.5]	2.7 [2.8]	0 [0]
1240b_1144_1144_239	2.4 [2.4]	2.7 [2.7]	0.18 [0.21]
1240b_1088_1088_398	2.4 [2.3]	2.6 [2.7]	0.30 [0.34]
1240b_1032_1032_557	2.3 [2.2]	2.5 [2.6]	0.39 [0.44]
1240b_976_976_716	2.2 [2.1]	2.5 [2.5]	0.46 [0.50]
733b_733_702_468	1.7 [1.7]	1.9 [1.9]	0.35 [0.36]

The first number is calculated using CTE and the number in square brackets is calculated using MBS

From EPJ Plus paper

p-Pb

Table 7 Integrated luminosity (in nb^{-1}) during a one-month p–Pb run at each experiment for the considered filling schemes from Ref. [13], using Eqs. (5)–(6)

Filling scheme	$\mathcal{L}_{tot}$ IP1/5	$\mathcal{L}_{tot}$ IP2	$\mathcal{L}_{tot}$ IP8
1240b_1240_1200_0	677 [705]	306 [313]	0 [0]
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Requests from experiments

- WG5 in the 2018 HL-LHC / HE-LHC physics workshop dealt with heavy-ion physics
- Yellow report with proposal for extended heavy-ion running: CERN-LPCC-2018-07
- Request up to the end of Run 4:

  - **Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV**, $L_{\mathrm{int}} = 13\ \mathrm{nb}^{-1}$ (ALICE, ATLAS, CMS), $2\ \mathrm{nb}^{-1}$ (LHCb)
  - **pp at $\sqrt{s} = 5.5$ TeV**, $L_{\mathrm{int}} = 600\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $6\ \mathrm{pb}^{-1}$ (ALICE), $50\ \mathrm{pb}^{-1}$ (LHCb)
  - **pp at $\sqrt{s} = 14$ TeV**, $L_{\mathrm{int}} = 200\ \mathrm{pb}^{-1}$ with low pileup (ALICE, ATLAS, CMS)
  - **p–Pb at $\sqrt{s_{\mathrm{NN}}} = 8.8$ TeV**, $L_{\mathrm{int}} = 1.2\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.6\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
  - **pp at $\sqrt{s} = 8.8$ TeV**, $L_{\mathrm{int}} = 200\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb), $3\ \mathrm{pb}^{-1}$ (ALICE)
  - **O–O at $\sqrt{s_{\mathrm{NN}}} = 7$ TeV**, $L_{\mathrm{int}} = 500\ \mu\mathrm{b}^{-1}$ (ALICE, ATLAS, CMS, LHCb)
  - **p–O at $\sqrt{s_{\mathrm{NN}}} = 9.9$ TeV**, $L_{\mathrm{int}} = 200\ \mu\mathrm{b}^{-1}$ (ALICE, ATLAS, CMS, LHCb)
  - **Intermediate AA**, e.g. $L_{\mathrm{int}}^{\mathrm{Ar-Ar}} = 3$–$9\ \mathrm{pb}^{-1}$ (about 3 months) gives NN luminosity equivalent to Pb–Pb with $L_{\mathrm{int}} = 75$–$250\ \mathrm{nb}^{-1}$

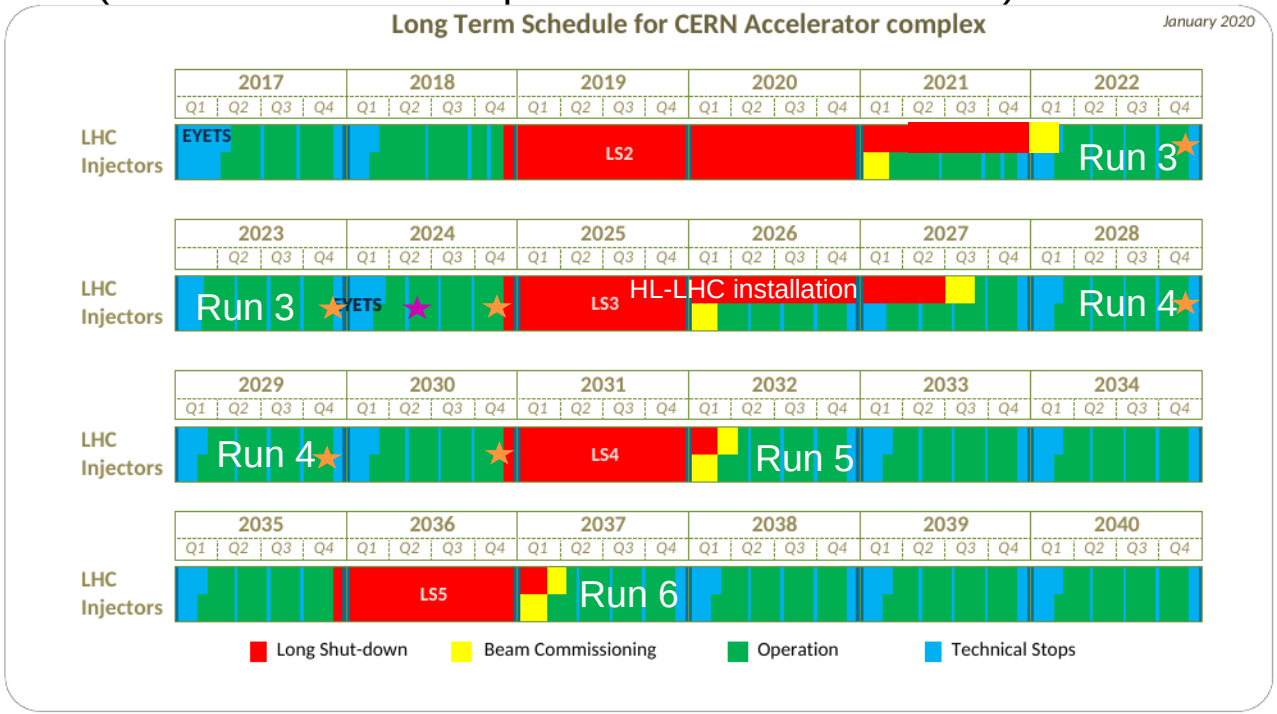
In Run 3 + Run 4

after Run 4: topic of next presentation

Future heavy-ion runs

- Present planning: Would have four Pb-Pb runs (one two-month run in 2024) and two p-Pb runs until the end of Run 4
  - In addition, have to fit pp reference runs
- Allows to calculate approximate luminosity requirement for one-month run

Tentative schedule, ***could well change***
(Jan 2020 schedule updated with LS2 extension)



★ *Guess on future heavy-ion runs – detailed schedule still to be defined*
★ *Oxygen pilot run?*

Estimated vs required performance

- Approximate requirements from experiments for one month:
  - Pb-Pb
    - 2.6 nb^{-1} at IP1/2/5
    - 0.4 nb^{-1} at IP8
  - p-Pb
    - 600 nb^{-1} at IP1/5
    - 300 nb^{-1} at IP2/8
- Estimated performance
  - For Pb-Pb: expect in the range of **2.2-2.7 nb^{-1} for IP1/2/5, 0.2-0.5 nb^{-1} at IP8** in a one-month run
  - For p-Pb: expect in the range of **550-700 nb-1 for IP1/5, ~300 nb^{-1} at IP2, 50-150 nb^{-1} at IP8** in a one-month run
- We're in the right ballpark, but with present schedule assumptions, no filling scheme simultaneously fulfills requirements at all IPs
  - For p-Pb, miss at least a factor 2 at IP8
  - Note: approximate figures for p-Pb without detailed filling schemes

Pb-Pb

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p-Pb

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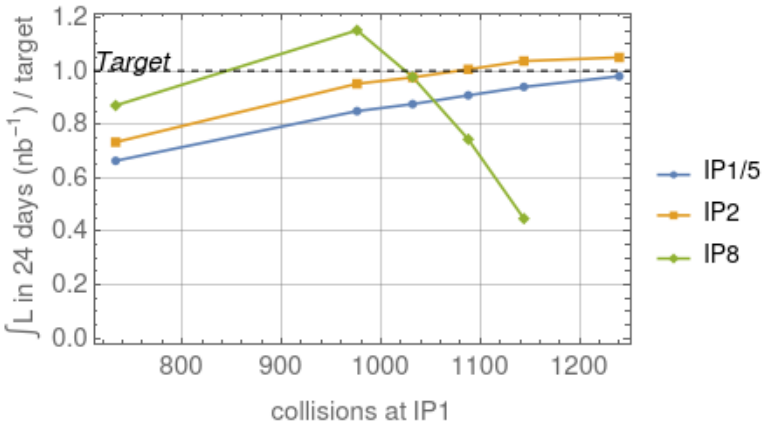
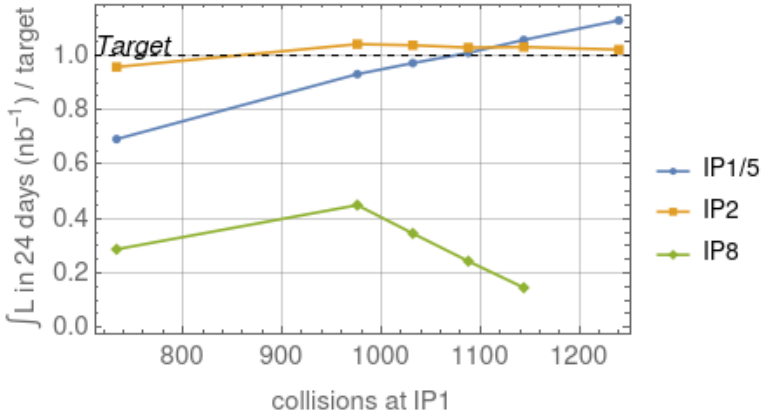
One-month performance vs target

- In Pb-Pb, lower luminosity at IP1/5 than IP2 due to crossing angle
  - Spectrometer bump at IP2 makes net angle smaller; external angle is the same
  - Up to about 10% missing at worst IP for the best filling scheme
- In p-Pb, LHCb is the main problem
- Targets not reached simultaneously for any filling scheme
- Possibly no reason for panic – applying the same assumptions for 2018, get significantly lower luminosity than achieved in the machine
  - Operational efficiency >50% achieved





Improvements?

- Need to study improvements to find a scenario that reaches targets with present assumptions
  - For now, exploring different paths of improvement, i.e. trying to answer “what would have to be done to reach target on paper”
  - For now, not exploring the feasibility of each path – possibly need beam tests

- Assuming for now that Pb bunch intensities from injectors and LHC operational efficiency are fixed
  - Might be conservative, but cannot know now

- Ways to improve LHC performance (Pb-Pb)
  - Improving further the filling schemes
    - Work out detailed filling schemes in p-Pb with realistic 50 ns proton beam
  - Skip levelling at IP1/5
  - Smaller crossing angle : present baseline is 170 μrad half external angle at each IP
    - Gives net half angles of 170 μrad / 100 μrad / -305 μrad
  - Smaller β* : present baseline assumes 0.5m / 0.5 m / 1.5 m
    - Possibly more aperture and strength margin in IR8
  - Change levelling assumptions at IP2/8
    - Presently assumed levelling is 6.4E27 $cm^{-2}s^{-1}$at IP1/2/5 (ALICE detector saturation and “fair sharing”) , 1E27 $cm^{-2}s^{-1}$ at IP8 (avoid quenches from BFPP)

- Performance improvements for p-Pb
  - Similar methods as for Pb-Pb (filling schemes, β*, crossing angle)
  - In addition, increase proton bunch intensities (weak bunches of 3E10 p assumed so far)

- Following slides: Checking each option, re-running luminosity studies with CTE using the same assumptions as in baseline scenario, unless stated otherwise

Pb-Pb filling schemes

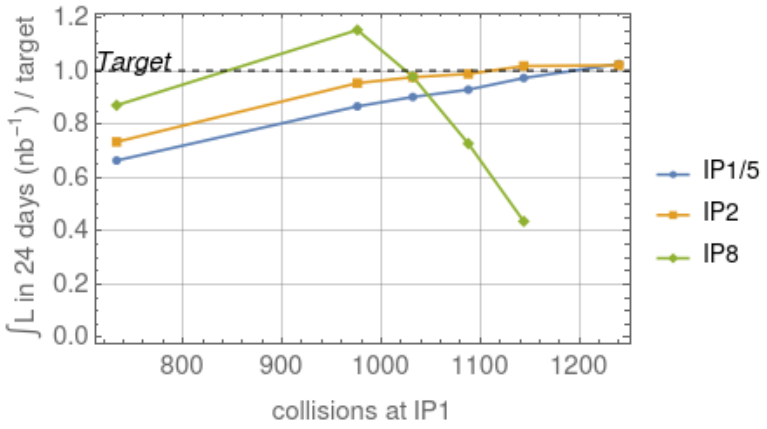
- Best scheme (i.e. best compromise) so far seems to be 1240b_1088_1088_398

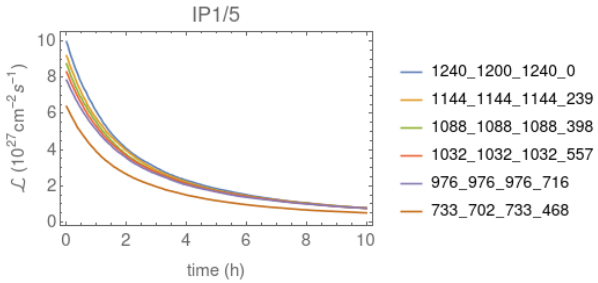
- Does a “better” scheme exist, with more collisions at each experiment?
  - “Brute-force” scan of collisions – checked more than 5×10^{10} permutations of longer gap between trains and the position of shorter trains
  - Found many equivalent permutations, but no better schemes
  - Cannot exclude that a better scheme exists – almost infinite parameter space. But maybe not so likely, and not evident to find

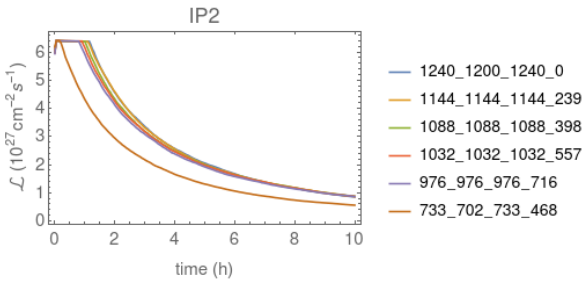
- Possible route forward: take longer trains from SPS with 8*8 bunches or more, instead of presently assumed 7*8 bunches
  - Would result in more beam degradation in the SPS => not obvious that we actually gain
  - See Hannes’ talk at Chamonix 2017

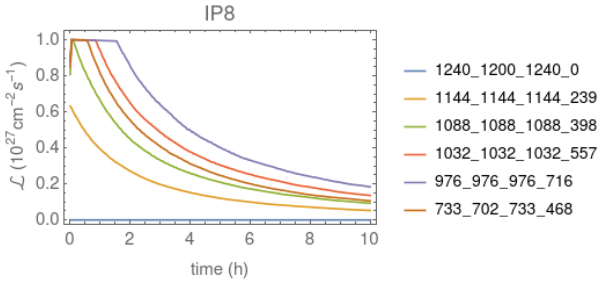
Skip levelling at IP1/5

- Levelling at IP1/5 probably not needed to avoid BFPP quenches – FLUKA studies indicate significant margin
- Redoing beam evolution study with CTE, for the range of filling schemes, followed by calculation of 1-month luminosity using standard method (re-calculating optimal fill time, 50% OP efficiency)
- Only very minor improvement at IP1/5 (gives slightly more equal sharing of luminosity between IP1/2/5)



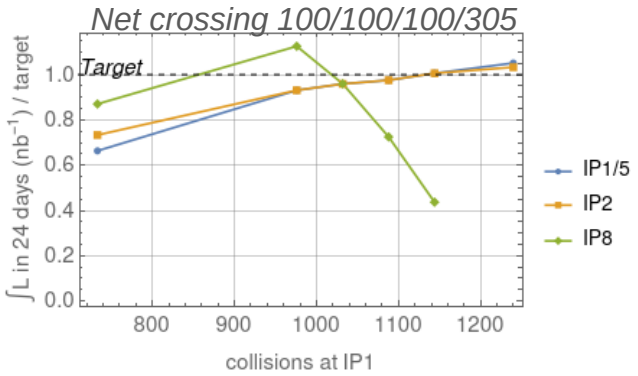


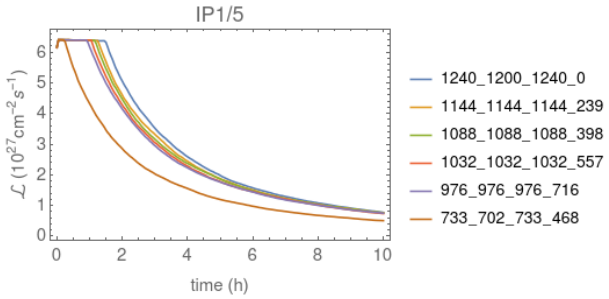


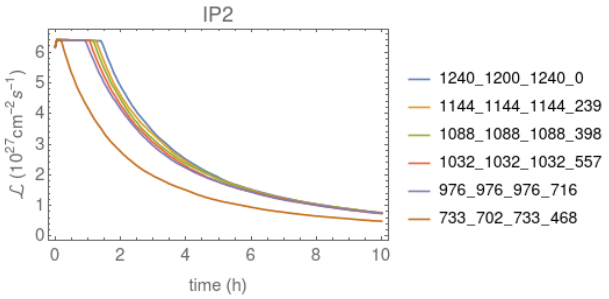


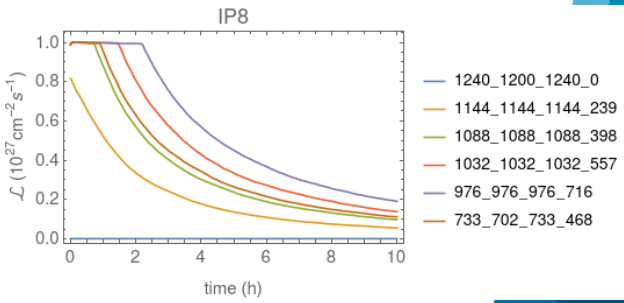
Decreased crossing angles

- Smaller crossing angle limited by beam-beam and parasitic collisions
  - Good hope that decrease is possible (see talk by Sofia)
  - At IP2, have UPPER 100 urad limit from ZDC acceptance
- At IP8: no preference from LHCb on spectrometer polarity.
  - Could use opposite polarity of spectrometer to crossing bump, e.g. half external angle = -235 μrad, spectrometer = +135 μrad
- First try: using 100 μrad net half angle at IP1/5, as already in baseline for IP2 – better, but not enough
- Second try: using 70 urad net half angle at all IPs, as studied by Sofia – almost there, still miss 2% in best case





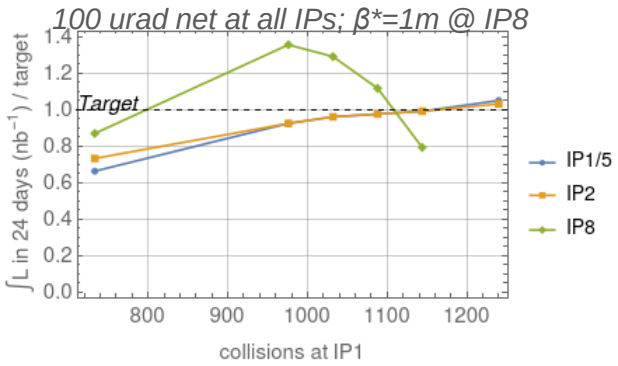


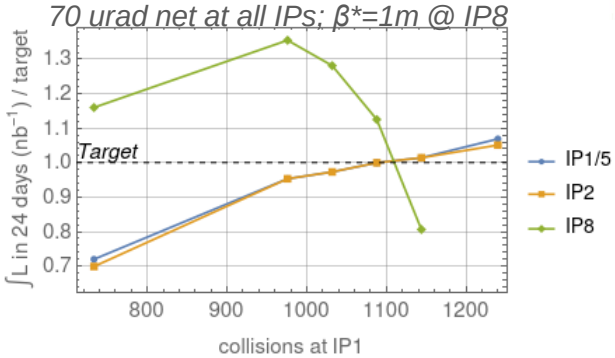


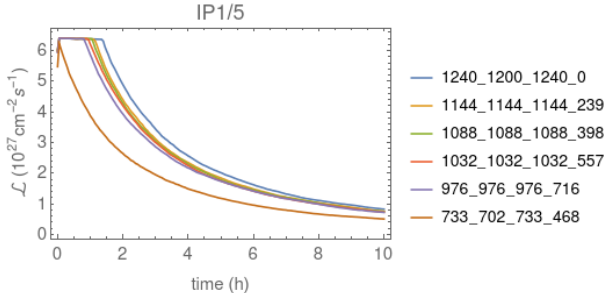
Smaller crossing, smaller IP8 β*

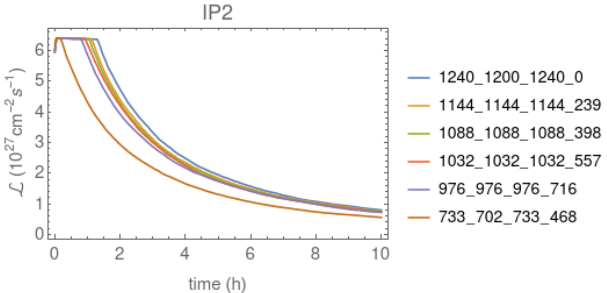
- Assuming 100 μrad net half angle at all IPs, β*=1m at IP8: very close to targets: miss by 2% in best scheme

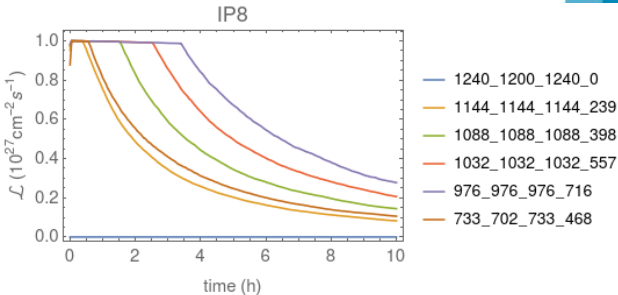
- Assuming 70 μrad net angle at all IPs, β*=1m at IP8: reach target exactly at IP1/2/5, get more at IP8
  - Could consider switching between filling schemes during the run to distribute more to IP1/2/5





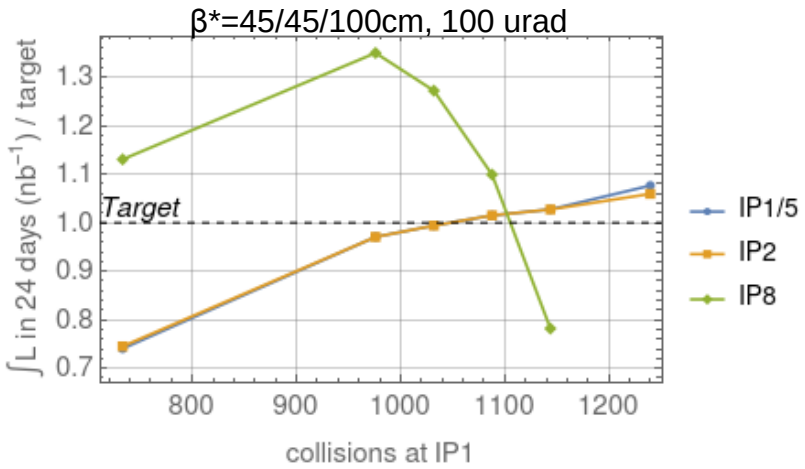


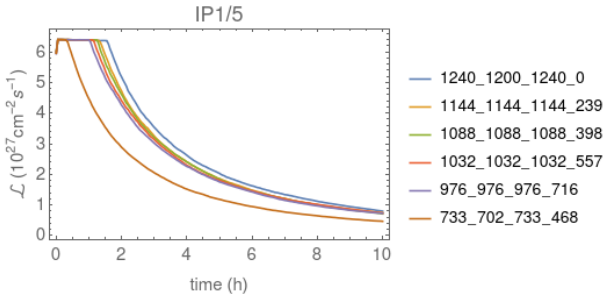


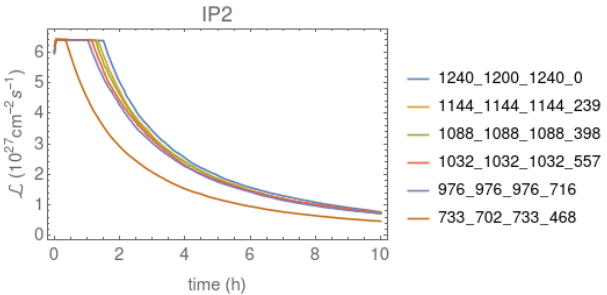


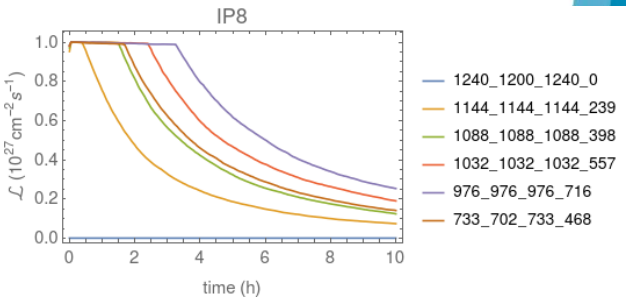
Decreased β* at all IPs

- Decreasing β* only, even to 40 cm at IP1/2/5 and 50 cm at IP8, keeping nominal crossing: still no scheme satisfying all – IP1/5 limiting
- 100 urad crossing at all IPs, β*=0.45 m at IP1/2/5, β*=1m at IP8 => Reach targets at all IPs with one scheme, with quite some margin at IP8
  - Could consider switching filling schemes throughout the run to get more margin also at IP1/2/5 – to be discussed and agreed with the experiments





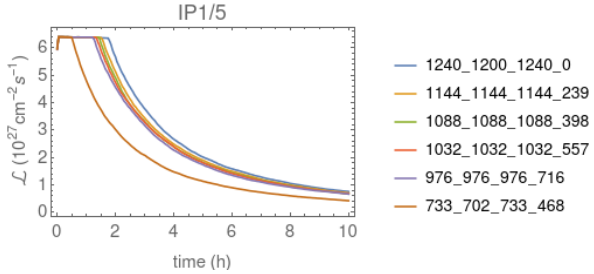


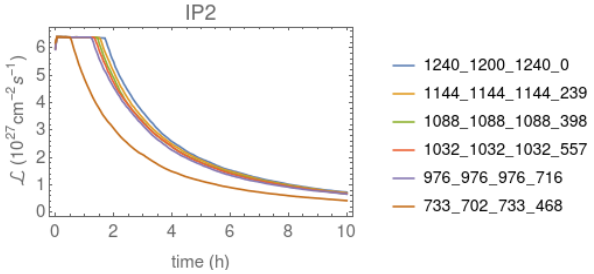


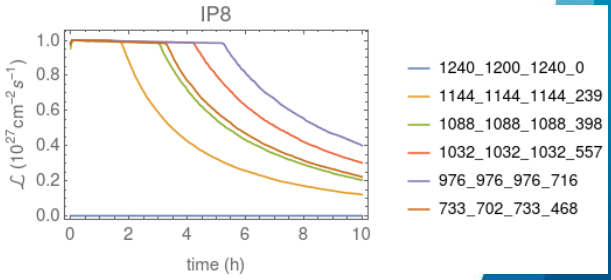
Pushed configuration

- Assuming aggressively β*=40 cm at IP1/2/5, β*=50 cm at IP8, 100 urad net angle at all Ips => comfortably reach targets with some margins for several filling schemes

- This configuration might not be feasible – further studies required



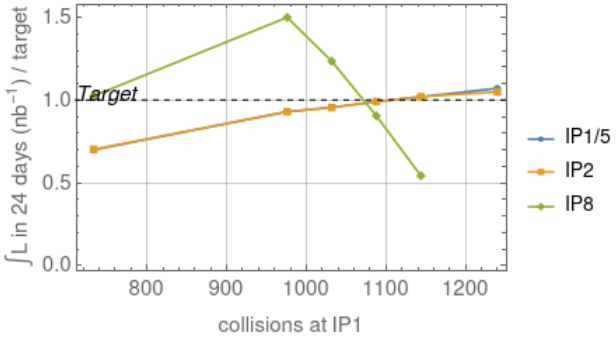




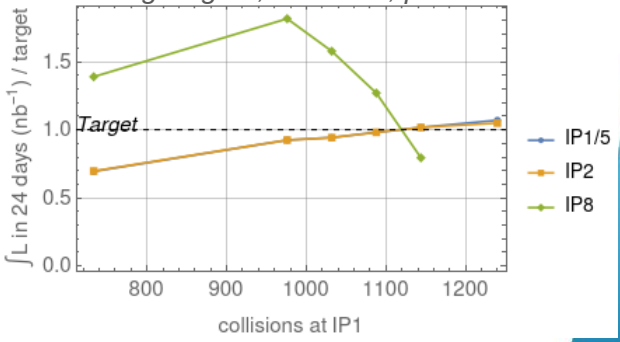
Increased leveling targets

- Increasing IP8 levelling target L=to 1.5E27
  - Note: in 2015 quench test, quenched at L=2.3E27
  - Don't know if we can do this in IP8 – limiting luminosity might be different. Needs further study
- Increasing IP1/2/5 levelling to L=7E27
  - Will be slightly above limiting 50 kHz rate at ALICE in the beginning of the fill – possibly OK, to be seen
  - Used as tentative levelling value in previous iteration at Chamonix 2017
- Result: Increasing levelling targets to these values alone is not enough
- In combination with 100 urad net half crossing at all IPs and β*=1m at IP8:
  - 2% short for any single scheme
  - Can reach targets if we combine two filling schemes, running half of the time with each

Higher levelling targets, otherwise basline

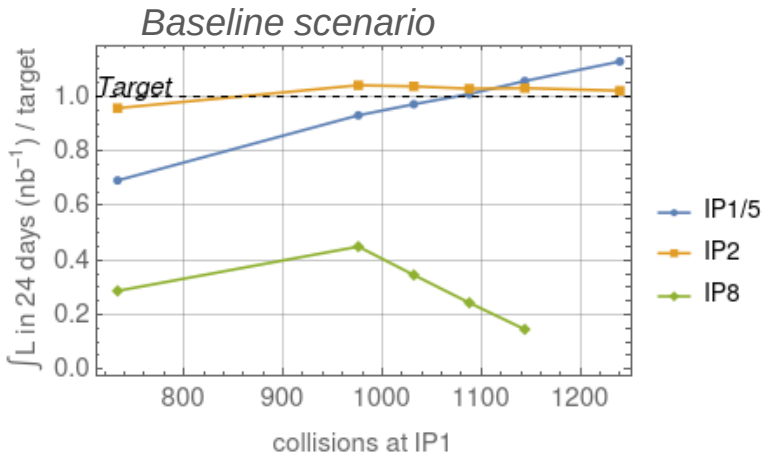


Higher levelling targets, 100 urad, β=1m at IP8*



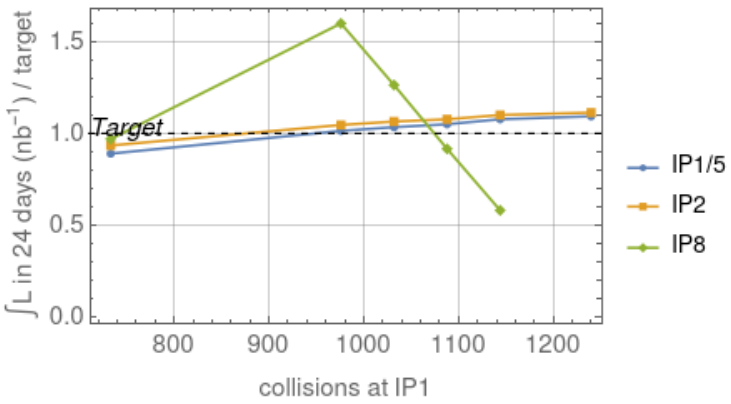
p-Pb

- Missing a factor 2 at LHCb – not easy…. Need significant improvement
- Even with very pushed machine configuration (β*=40 cm at IP1/2/5, β*=50 cm at IP8, 100 urad net angle at all IPs), almost at target
- Other option: work on proton beams
  - Increase proton bunch intensity
  - Work out detailed filling schemes – should be done anyway



Increasing proton intensity

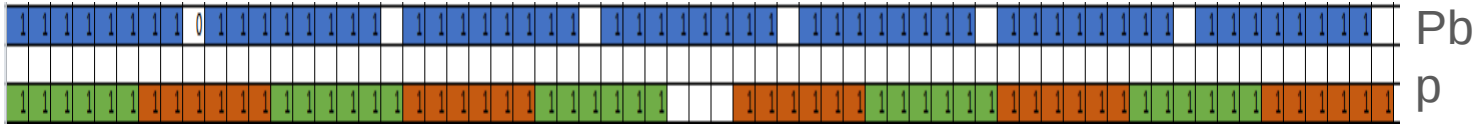
- Present baseline assumed so far: 3E10 p/bunch
  - With higher p intensities, beam burns off quickly, which is bad for ALICE (levelled at 5E29)
- Alternative approach:
  - increase to 1.3E11 p/bunch (already had this with 50 ns beams – higher is only better)
  - level IP1/5 at 1E30
  - don't level IP8
  - => can reach targets, without any change of optics or crossing angle!
- Caveats: Using approximate approach with Pb filling schemes and overall 5% penalty on integrated luminosity
  - Clearly need to check realistic schemes before concluding
  - Possibly check beam-beam : any consequences of running in this weak-strong scenario?
  - Some studies done in thesis by Marc



Proton filling schemes

- Goal: match a 50 ns proton beam that matches as well as possible the 50 ns Pb beam. not evident:
  - SPS Pb batches have 8 bunches, 100 ns batch spacing, typically 7 trains = 56 Pb bunches
  - Proton schemes based on 6*n bunches, 200 ns gap between batches

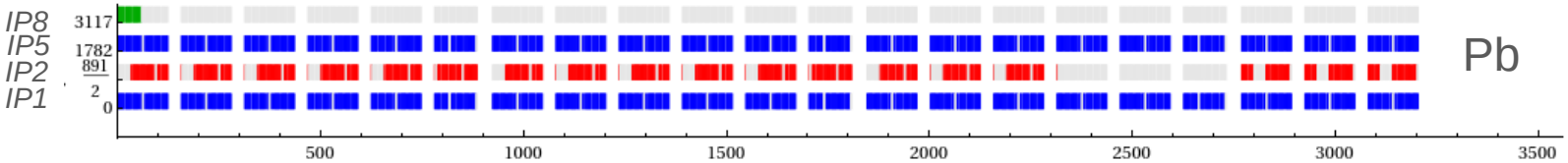
- With Gianni: one potential solution seems to be proton 30 bunches per train
  - Two proton trains almost fit the 7 Pb trains
  - Direct overlap shows collisions at IP1/5 – but we need to have many collisions at all IPs

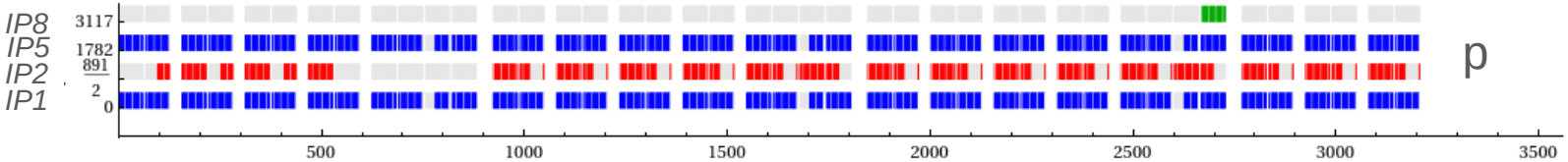


Developing candidate filling schemes

- First try: basic scheme with quadrant symmetry
  - Adjusting abort gap keeper to longest train
  - Can fit 5 Pb/p trains per quadrant
  - To fill up the rest of the quadrant: make last train longer, or inject shorter train
  - Seems most efficient to make p train longer (4*30 instead of 2*30) and add a shorter Pb train

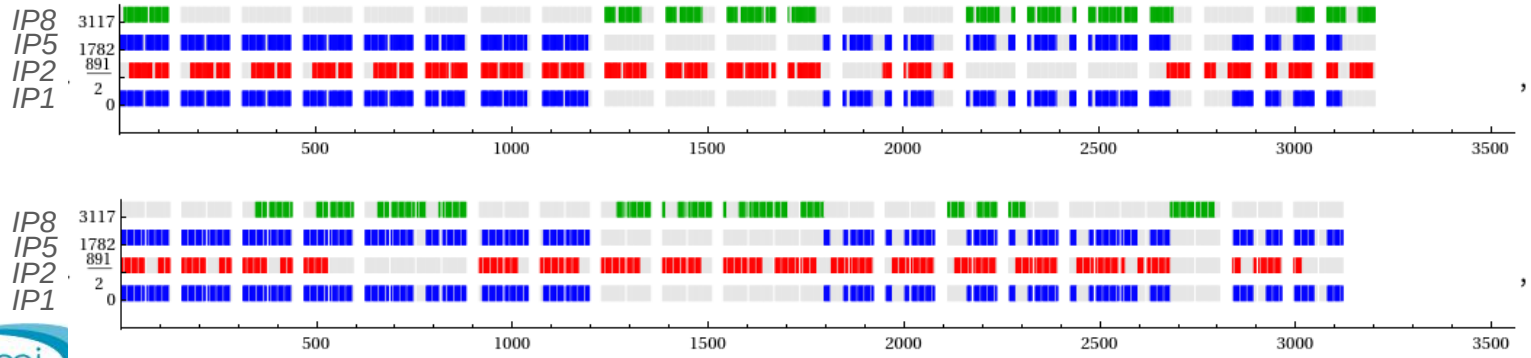
- Scheme gives decent amount of collisions at IP1/5, but less at IP2/8
  - 1152 Pb, 1260 protons
  - 1083 / 714 / 26 collisions at IP1/2/8





Optimizing p-Pb filling schemes (1)

- Trying to move around trains to displace collisions to LHCb – gives large penalty at IP1/2/5, larger than for Pb-Pb
  - Brute-force scan of all permutations within each quadrant (displacing single trains to get collisions at LHCb) =>
    if >800 collisions at IP1/2/5, max 137 collisions at IP8 => not good
  - Example with more IP8 collisions: 724 / 724 / 427 collisions =>
    not enough at IP1/2/5, not really efficient use of bunches
  - Similar to what was done in 2016 with fewer bunches

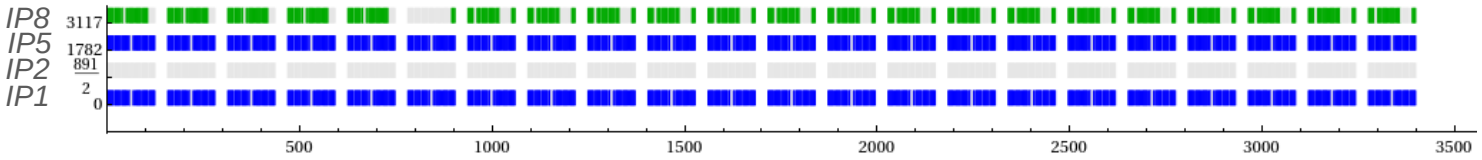


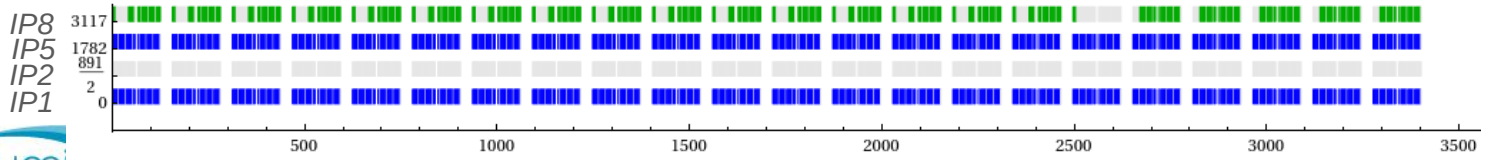
Optimizing p-Pb filling schemes (2)

- Second approach: neglecting quadrant symmetry, fill up both rings as much as possible
  - 22 trains each for p (2*30) and Pb (7*8)
    - Longer kicker gaps between Pb trains to match p structure
  - “Default scheme”: many collisions at IP1/5/8, no collisions at IP2
  - Brute-force scan with 0-3 longer gaps between trains in each beam, all permutations checked
  - Found range of candidate filling schemes - still a bit worse than assumed when scaling the Pb schemes

50 ns

Pb bunches	p bunches	IP1/5 coll.	IP2 coll.	IP8 coll.
1232	1320	1166	0	870
1232	**1320**	**901**	**843**	**432**
1232	**1320**	**848**	**820**	**553**
1232	1320	795	843	602
1232	1320	795	724	735
1232	1320	765	762	733



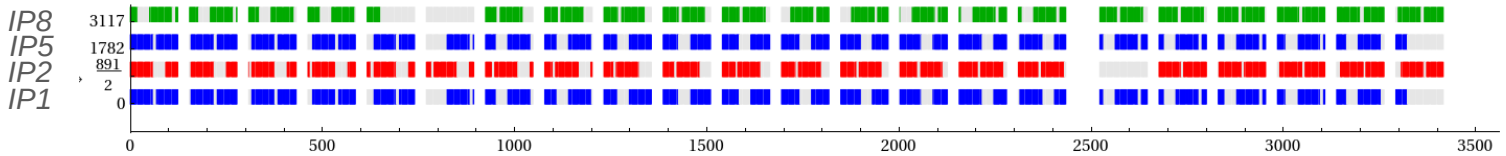


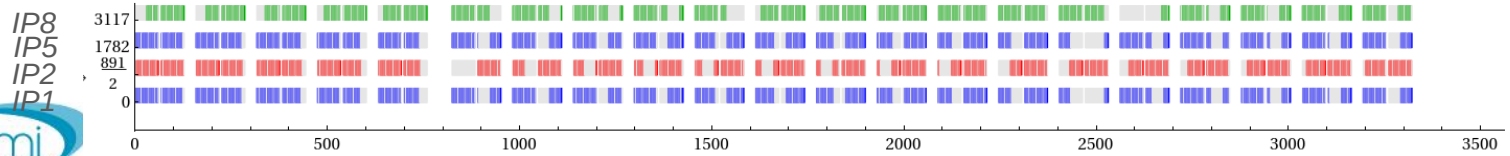
Using 25 ns proton scheme

- So far tried to match the Pb beam as closely as possible, using 50 ns protons
  - With 50 ns, no “natural” collisions at LHCb if quadrant symmetry is respected
  - With 25 ns, collisions do occur naturally at LHCb
  - Try to collide 50 ns Pb beam with 25 ns p beam – obviously many p bunches would be “wasted”, but the aim is to have as many collisions as possible
  - Possibly need to think about beam-beam – will get many parasitic encounters. Some studies done in thesis by Marc
  - First try: similar length as 2*30 b 50-ns scheme: take 2*60b at 25 ns
- With a little fiddling, could get about 900 collisions in all IPs
- Could possibly find even better scheme with brute-force scan, and checking other train lengths for protons

25ns

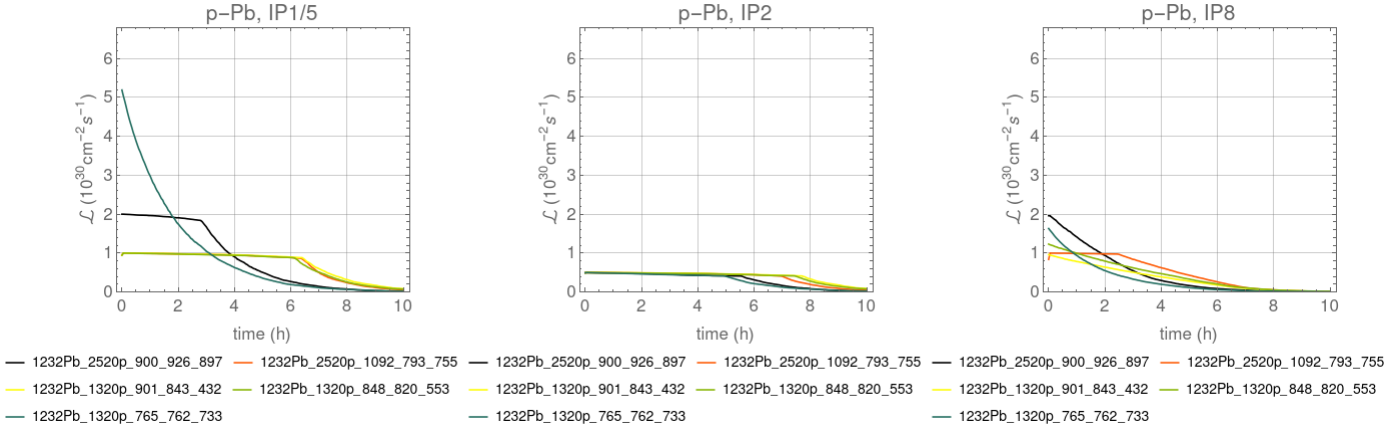
Pb bunches	p bunches	IP1/5 coll.	IP2 coll.	IP8 coll.
1232	**2520**	**1092**	**793**	**755**
1232	2520	918	838	904
1232	2520	906	912	896
1232	2520	902	878	935
1232	**2520**	**900**	**926**	**897**

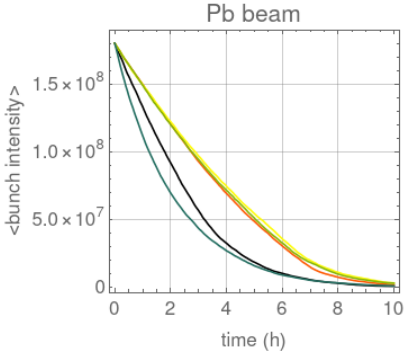


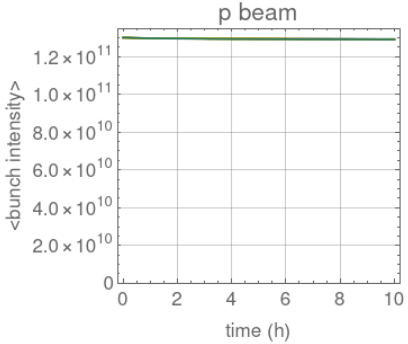


Simulated beam evolution with new p-Pb schemes

- Assuming 1.3E11 p/bunch – proton beam intensity is almost unchanged
- Assuming baseline machine configuration without changes in crossing or β*
- Exploring different levelling scenarios at all IPs – here are some examples. Could still be optimized to find the best compromise

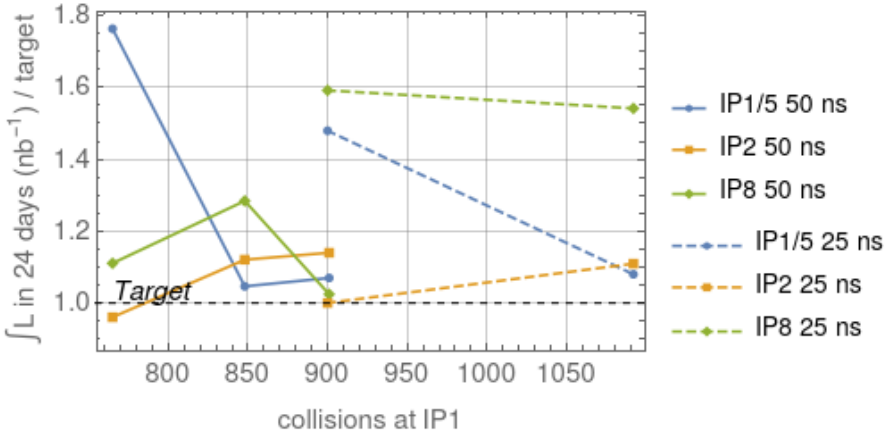






Integrated luminosity in 1-month run

- Several of the new filling schemes, both 50 ns and 25 ns, satisfy all experiments simultaneously (relies on 1.3E11 p/bunch)
- The levelling scenarios can still be optimized to have a more equal share, or one could switch between filling schemes during a run



Estimated 1-month luminosity

Pb bunches	p bunches	IP1/5 coll.	IP2 coll.	IP8 coll	IP1/5 lum. (nb^{-1})	IP2 lum. (nb^{-1})	IP8 lum. (nb^{-1})
1232 Pb	2520 p	900	926	897	887.417	300.126	477.351
1232 Pb	2520 p	1092	793	755	648.028	332.866	462.335
1232 Pb	1320 p	901	843	432	641.956	341.989	307.366
1232 Pb	1320 p	848	820	553	627.963	336.202	385.22
1232 Pb	1320 p	765	762	733	1057.47	288.246	333.227

Summary

- Assuming baseline parameters, and 50% OP efficiency
  - We're 10% short of the luminosity target in Pb-Pb,
  - We miss factor 2 at LHCb for p-Pb

- For both Pb-Pb and p-Pb, there are ways to reach the targets, acting on machine configuration and beams. Still need some checks to verify feasibility

- For Pb-Pb, could reach the target in several ways. Examples:
  - 70 μrad net angle at all IPs, β*=1m at IP8
  - 100 urad crossing at all IPs, β*=0.45 m at IP1/2/5, β*=1m at IP8
  - Higher levelling (7E27 / 1.5E27), β*=1m at IP8, 100 urad net half angle at all IPs
  - Of course, any combination or more pushed configuration would only improve
  - Feasibility of decreased β*, crossings, and levelling targets has not been verified – need further studies, ideally with beam
  - Could also increase luminosity through higher operational efficiency and/or higher than nominal intensity, but cannot count on this

- For p-Pb, improvements of machine configuration are possibly not enough to gain factor >2 at LHCb
  - A very pushed machine configuration with β*=0.4 m at IP1/2/5 and β*=0.5 m at IP8, combined with smaller crossing angles, gives luminosity very close to targets – might not be feasible in operation
  - Increasing proton bunch intensities to 1.3E11 gives needed improvement – but think about possible constraints
  - New realistic filling schemes developed for p-Pb with 50 ns and 25 ns proton beams – for both beam types, schemes found where all experiments reach their respective targets from WG5 with p intensity of 1.3E11
    - Constraints for using 25 ns proton beams? Beam-beam to be checked? Beam instrumentation with very asymmetric beams?
  - Leveling targets and filling schemes still to be further optimized

Thanks for the attention