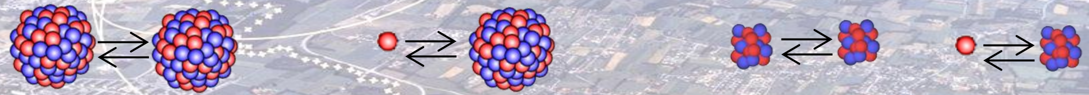
The LHC Ion program in Run 3 and Run 4



R. Bruce, R. Alemany Fernandez, H. Bartosik, R. Cai, M. D’Andrea, J.M. Jowett, D. Mirarchi, F. Moortgat, B. Petersen, S. Redaelli, M. Solfaroli, J. Wenninger

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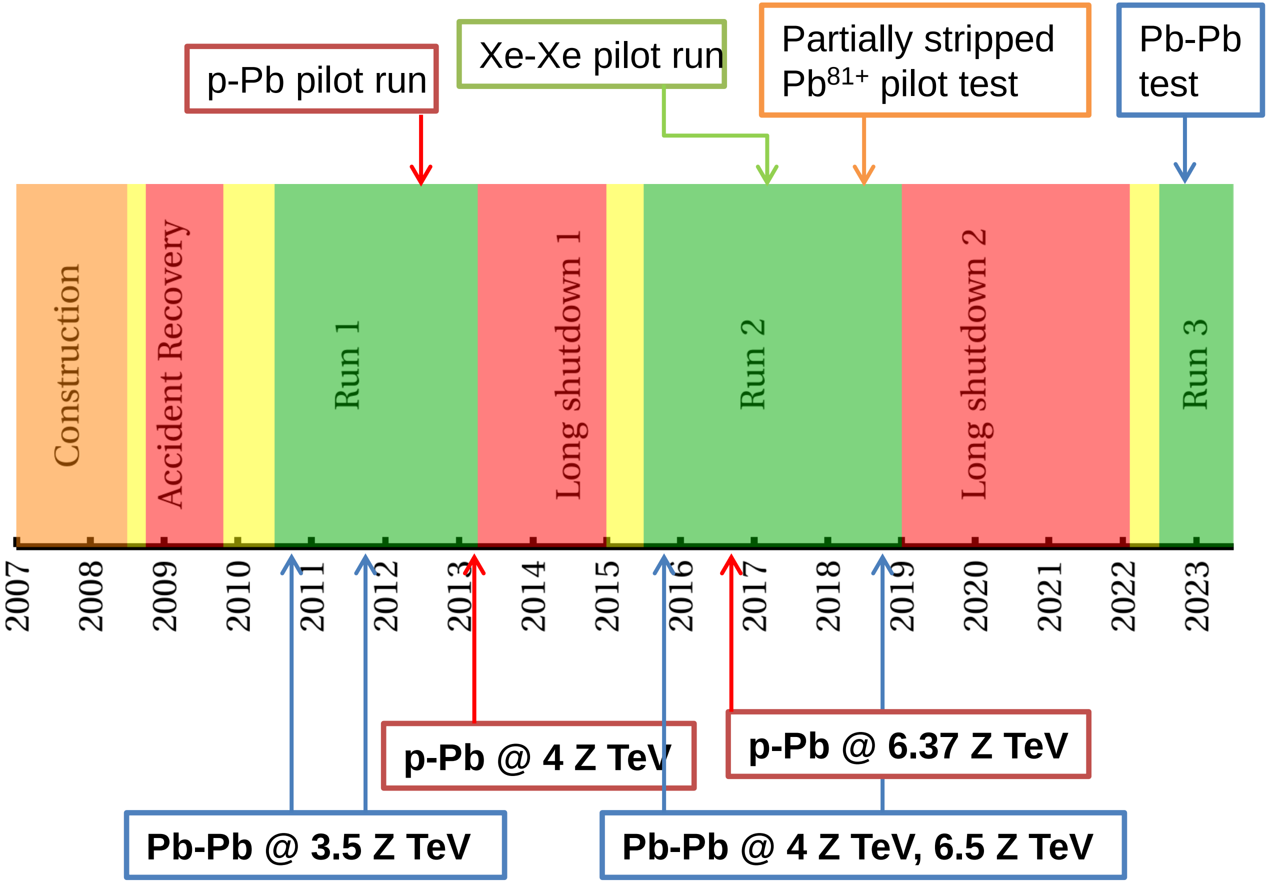
Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in Run 3-4
- Performance estimates for Pb-Pb and p-Pb
- Oxygen pilot run
- Conclusions

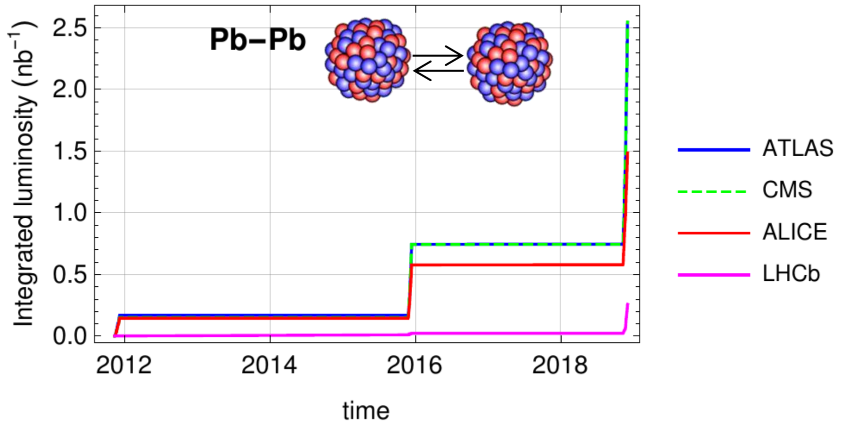
History of heavy-ion runs in the LHC

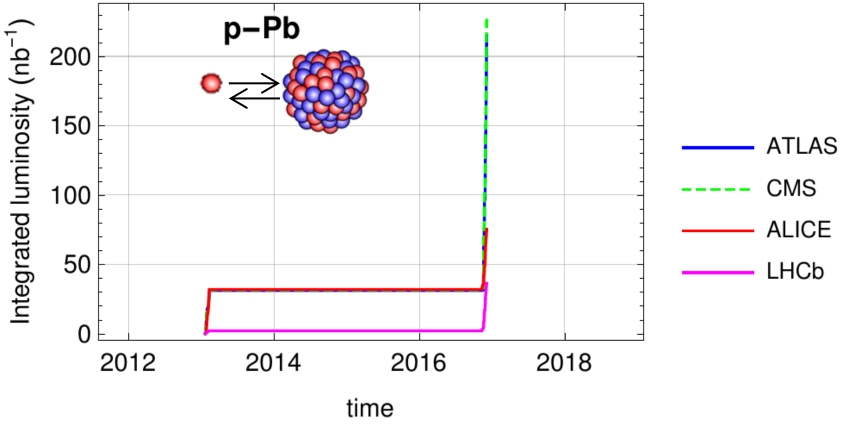
- **Typically one month per year with heavy-ion operation**
  - So far Pb-Pb or p-Pb
  - Six runs so far
- **In addition, had short "pilot runs"**
  - First p-Pb
  - Xe-Xe
  - partially stripped Pb81+ (no collisions)
  - Pb-Pb in 2022
    - 2022 Pb-Pb physics run cancelled



Previous luminosity production

- **Total integrated luminosity so far**
  - Pb-Pb: 1.5 nb^{-1} in ALICE, 2.54 nb^{-1} in ATLAS/CMS, 0.26 nb^{-1} in LHCb
  - p-Pb: 75 nb^{-1} in ALICE, ~220 nb^{-1} in ATLAS/CMS, 36 nb^{-1} in LHCb
  - Luminosity added over all energies

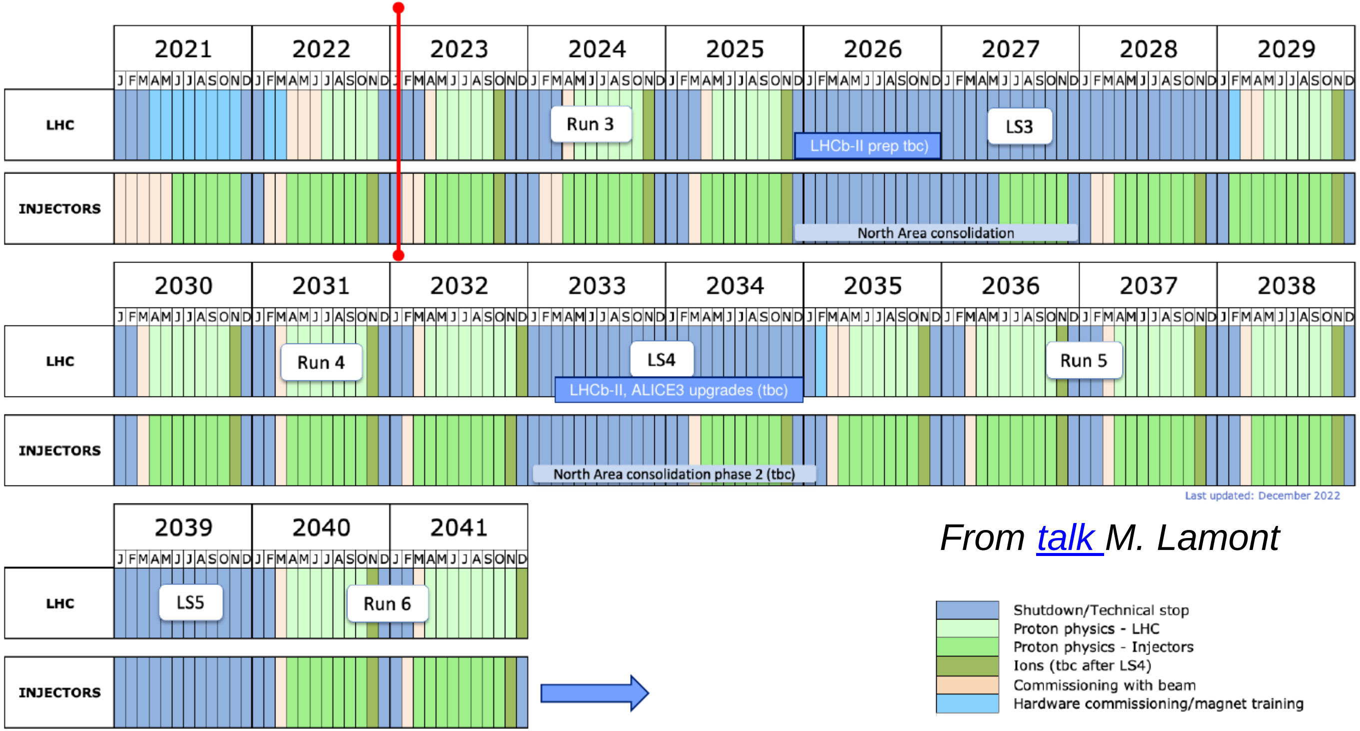




Future LHC heavy-ion operation

- In the future, continue with one-month ion runs at the end of the year
- 3 ion runs planned in Run 3, after cut of 2022 run
- Planning not yet fully fixed for Run 4
  - Having 4 ion runs would facilitate achieving the targets

Indicative timeline



From talk M. Lamont

Requests from experiments

- WG5 in the 2018 HL-LHC / HE-LHC physics workshop dealt with heavy-ion physics
- Yellow report released with luminosity requests and proposal for extended heavy-ion running: CERN-LPCC-2018-07

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

In Run 3 + Run 4

LHCb has since then halved the request

Proposal for after Run 4

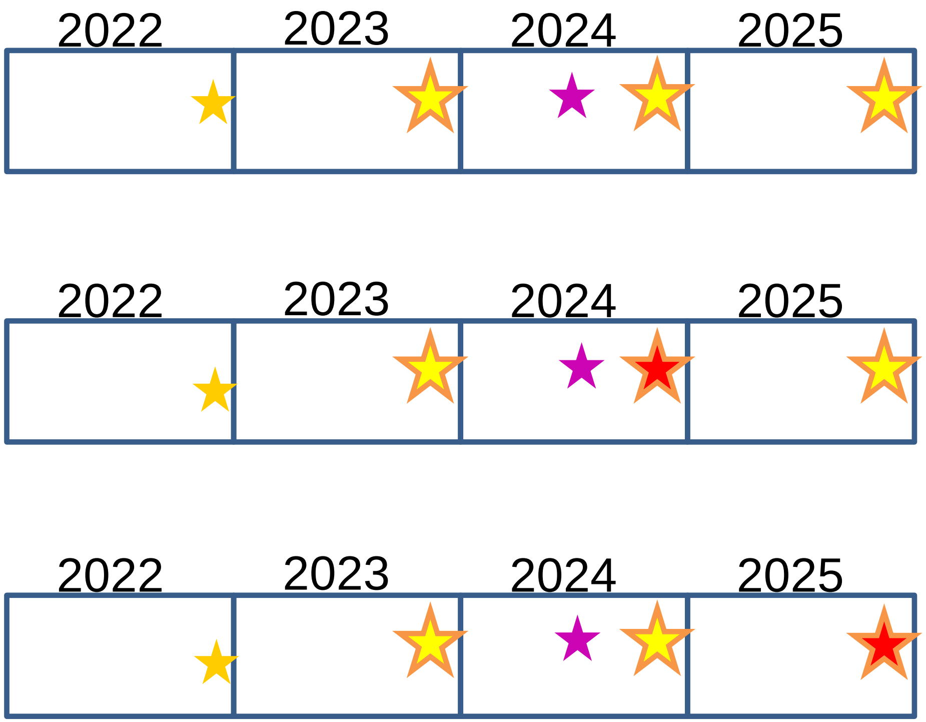
- Heavy-ion operational scenario for Run 3-4: see CERN-ACC-report and EPJ Plus paper
  - Updates since then: target beam energy for Run 3 changed to 6.8 Z TeV; deferral of installation of 11T dipoles and IR7 DS collimators

Ion operation in Run 3

- **Ion runs foreseen in 2023, 2024, 2025**
  - 2023: **Pb-Pb in October**
  - 2024-2025 : Pb-Pb only, or one year of p-Pb if it is found that Run 3 target can be reached with only two Pb-Pb run
    - If so, will likely have 5 weeks Pb-Pb runs and and 3 weeks p-Pb

- **1-week O-O and p-O pilot run likely in 2024**

Options for ion operation in Run 3



★ 2-day Pb ion test

★ Pb-Pb

★ p-Pb

★ O-O, p-O: ~ 1 week

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Machine scenario for Run 3 and 4

- **Same LHC machine scenario foreseen for Run 3 and Run 4**

- **High-Luminosity LHC (HL-LHC) Upgrades for ions have been recently implemented in LS2**
  - Crystal collimators
    - Needed for handling beam losses with the higher intensity
    - Two devices replaced in LS2, the remaining two replaced in 22-23 YETS – completely new system compared to Run 2
  - IR2 dispersion suppressor collimators
    - Intercept collision products to enable higher instantaneous ALICE luminosity
  - Slip-stacked beams with 50 ns spacing thanks to SPS RF upgrade
    - Gives ~70% more bunches in the LHC

- **In addition, upgraded ALICE detector to handle higher event rate**

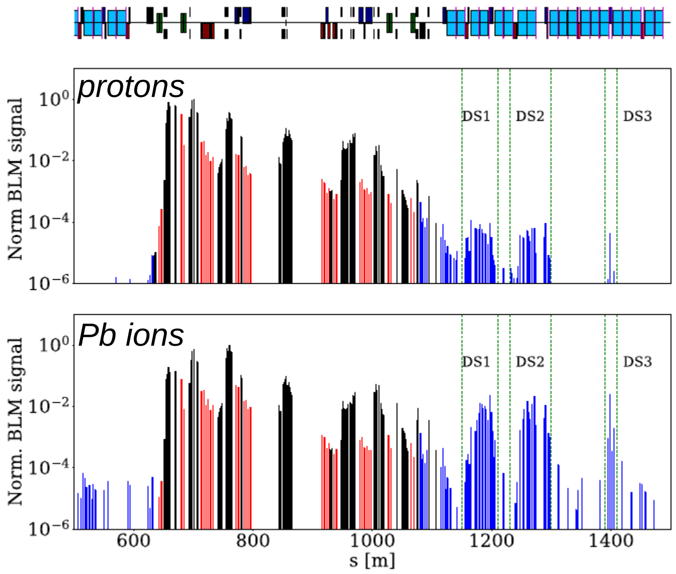
- **Thanks to these upgrades, targeting HL-LHC performance already in Run 3**

Collimation and beam losses

- **Regular or irregular beam losses risk to hit the aperture of cold magnets**
  - Could cause a magnet quench or even damage
  - Foreseen total stored energy of ion beam: 20 MJ

- **LHC collimation is ~2 orders of magnitude less efficient with Pb than with protons**
  - Losses with ions risk to become limiting in Run 3 due to higher beam intensity
  - Risk of magnet quenches or frequent beam aborts limiting the availability

- **Mitigation plan: Crystal collimation**
  - If losses are really limiting, could consider staying at Run 2 energy of 6.37 Z TeV – discussions ongoing some discussions on beam energy with experiments
  - Default option is 6.8 Z TeV unless serious issues with crystal system

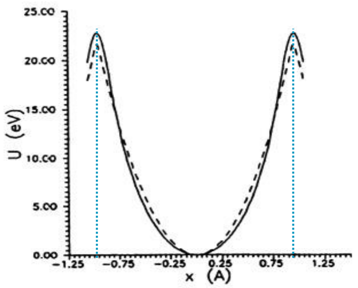


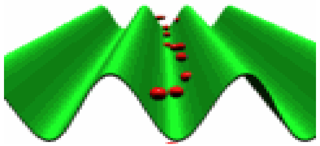
Principles of crystal collimation

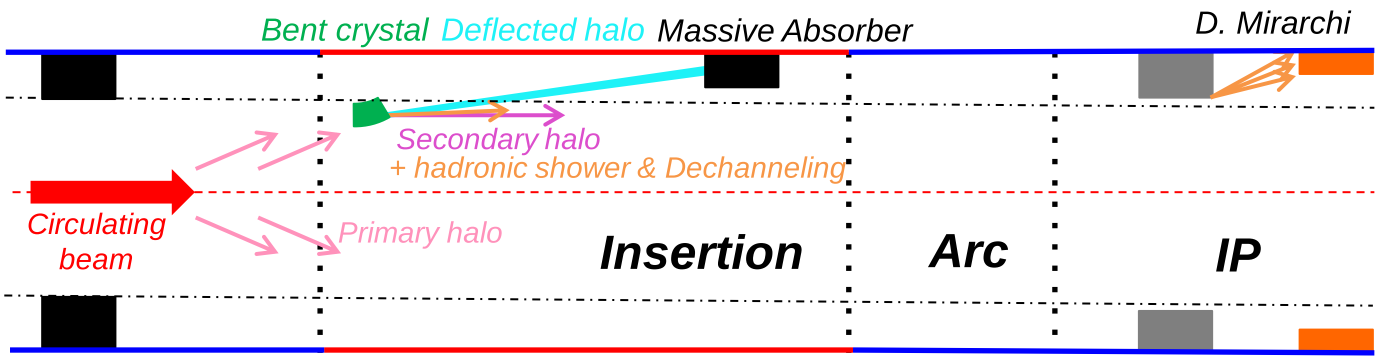
- **Collimation of halo with bent crystals**
  - Charged particles trapped in potential well from crystalline planes
  - Reduced interaction rate → reduced leakage to cold magnets of fragmented ions
  - Bent crystals steer halo particles onto massive absorber

- **Four crystal upgraded collimators recently installed in the LHC**
  - One per beam per transverse plane
  - Future ion operation will rely on crystal collimation (first time!)

- **Targeting significantly better cleaning of the beam halo**
  - Expect fewer beam aborts due to high irregular losses







Collisional losses

- **In heavy-ion collisions, ultra-peripheral electromagnetic interactions create secondary beams with changed charge-to-mass ratio**
  - Cause of localized beam losses in the machine, downstream of the IP
  - Continuous power of 165 W for BFPP expected at 6.4×10^{27} cm^{-2}s^{-1}

$$\text{BFPP:}\ {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$
$$\sigma = 281\ \text{b},\quad \delta = 0.01235$$

$$\text{EMD1:}\ {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n\ ,$$
$$\sigma = 96\ \text{b},\quad \delta = -0.00485$$

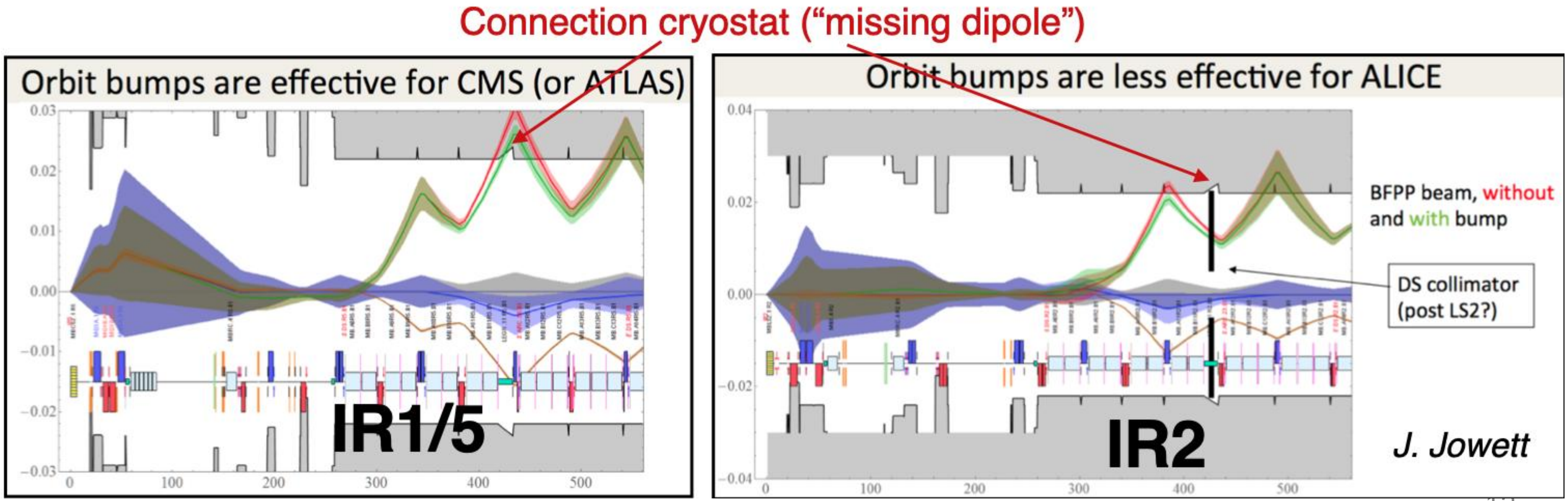
$$\text{EMD2:}\ {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{206}\text{Pb}^{82+} + 2n\ ,$$
$$\sigma = 29\ \text{b},\quad \delta = -0.00970$$

- **6 times higher luminosity foreseen at ALICE in Run 3 (6.4×10^{27} cm^{-2}s^{-1})**
  - Need to safely intercept collision products exiting the detector without risk of quenching magnets

Alleviation of collisional losses

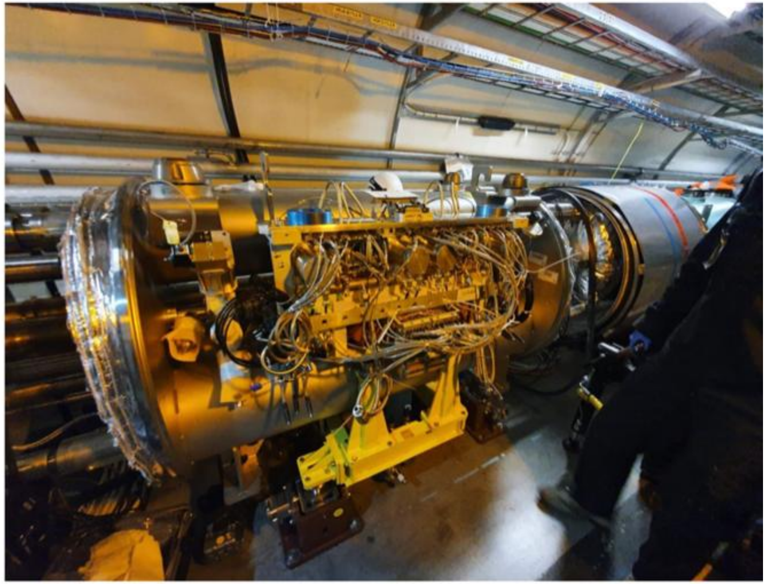
- **Orbit bumps successfully deployed in IR1/5 already in run 2 to steer losses into empty connection cryostat**
  - By now, a well-established operational procedure

- **In IR2 (ALICE experiment), bumps alone do not work**
  - Need new TCLD collimator in combination with orbit bump



TCLD collimators installed in IR2

- In LS2, one TCLD successfully installed per side of IR2



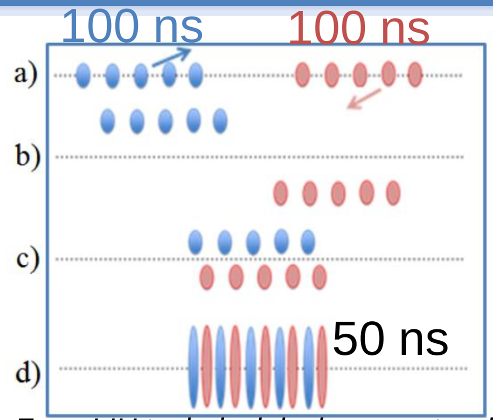
- Foreseen alleviation measures have been deployed – **green light for high-luminosity operation at ALICE!**

Slip-stacked beams

- SPS slip-stacking: **interleave two 100 ns bunch trains; create a train with 50 ns bunch spacing**
  - Allows to fit 70% more bunches in the LHC than in Run 2
  - In 2018, used 75 ns spacing

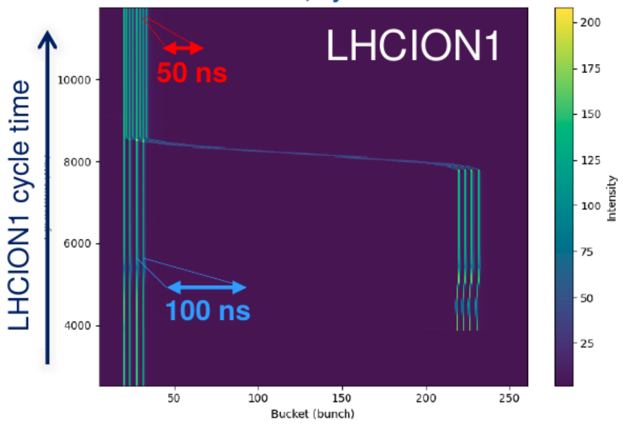
- **8-bunch trains successfully used in 2022 Pb ion test**
  - Variations, but could reach intensity and emittance beyond upgrade specification at LHC injection
  - Had first LHC collisions with slip-stacked beams

- **Filling schemes for 2023 rely on 56-bunch trains**
  - to be commissioned during 2023
  - Expect some brightness degradation compared to 8-bunch trains
  - 75 ns remains available as backup



From LIU technical design report, vol. 2

2-batches, symmetric



Beam parameters and filling schemes

- **Range of 50 ns Pb-Pb filling schemes worked out**
  - Trade-off between collisions at ALICE/ATLAS/CMS and LHCb
  - Final scheme to be selected by LHCC/LPC, variations during a run possible

- **Projected Pb beam parameters in collision**
  - Based on LIU target for injection, with some degradation before reaching collision

		n.o. collisions at			
Filling scheme	n.o. bunches	IP1/5	IP2	IP8	spacing
1240b_1240_1200_0	1240	1240	1200	0	50 ns
1240b_1144_1144_239	1240	1144	1144	239	50 ns
1240b_1088_1088_398	1240	1088	1088	398	50 ns
1240b_1032_1032_557	1240	1032	1032	557	50 ns
1240b_976_976_716	1240	976	976	716	50 ns
733b_733_702_468	733	733	702	468	75 ns

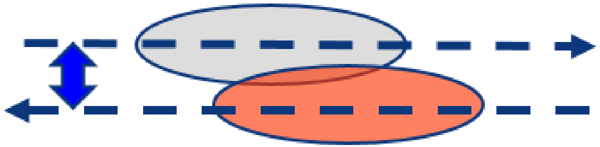
	LHC design	2018	Run 3
Beam energy (Z TeV)	7	6.37	6.8 or 6.37
Bunch spacing (ns)	100	75	50
Total n.o. bunches	592	733	1240
Bunch intensity (10^7 Pb ions)	7	21	18
Normalized transverse emittance (μm)	1.5	2.3	1.65

LHC optics configuration

- **Foresee similar optics as in 2018 Pb-Pb run** (S. Fartoukh)
  - different cycle from protons, squeezing also IR2
  - Configuration could stay similar for all years in Run 3-4
  - Implications of reversed-polarity optics for protons to be evaluated
  - Study possibility of smaller β* and/or crossing angle in 2024-2025
  - ALICE spectrometer reversals expected

	IP1	IP2	IP5	IP8
β^* (m)	0.5	0.5	0.5	1.5
crossing plane	V	V	H	H
spectrometer half crossing (μrad)	0	$\mp$72	0	-139
external half crossing (μrad)	170	$\pm$172	170	-170
net half crossing (μrad)	170	$\pm$100	170	-309
spectrometer polarity	-	pos/neg	-	pos

- **Luminosity levelling targets:**
  - L=6.4×10^{27} cm^{-2} s^{-1} for IP1/2/5
    - Could potentially be higher for IP1/5
  - L=1.0×10^{27} cm^{-2} s^{-1} at IP8
    - Could potentially be a bit higher – under study
  - Assuming separation levelling



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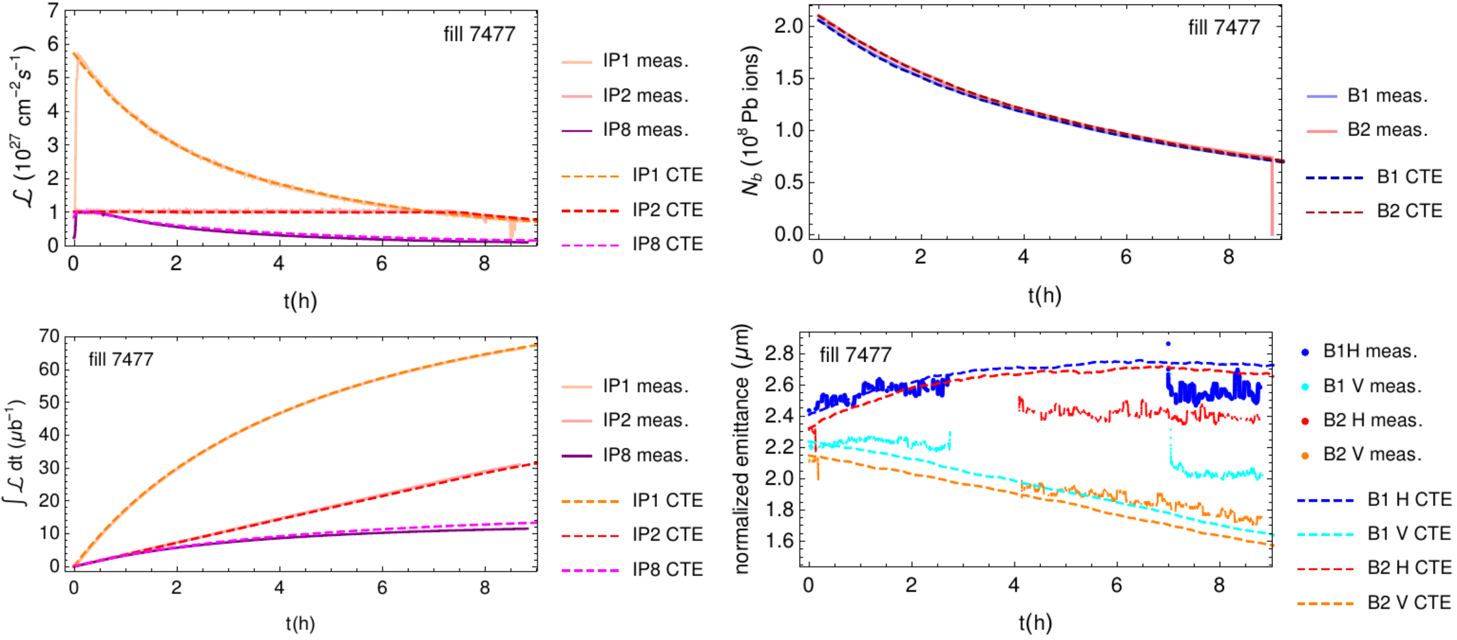
Simulation models of luminosity performance

- **Recently updated simulation tools for beam evolution - here using Collider Time Evolution (CTE):**
  - Particle tracking with 1-turn map accounting for of burnoff, intrabeam scattering, synchrotron radiation,filling scheme, non-collisional losses, emittance blowup….)
  - Ref: 2010 PRSTAB paper, T. Mertens MSc thesis, M. Schaumann PhD thesis, 2021 EPJ Plus paper

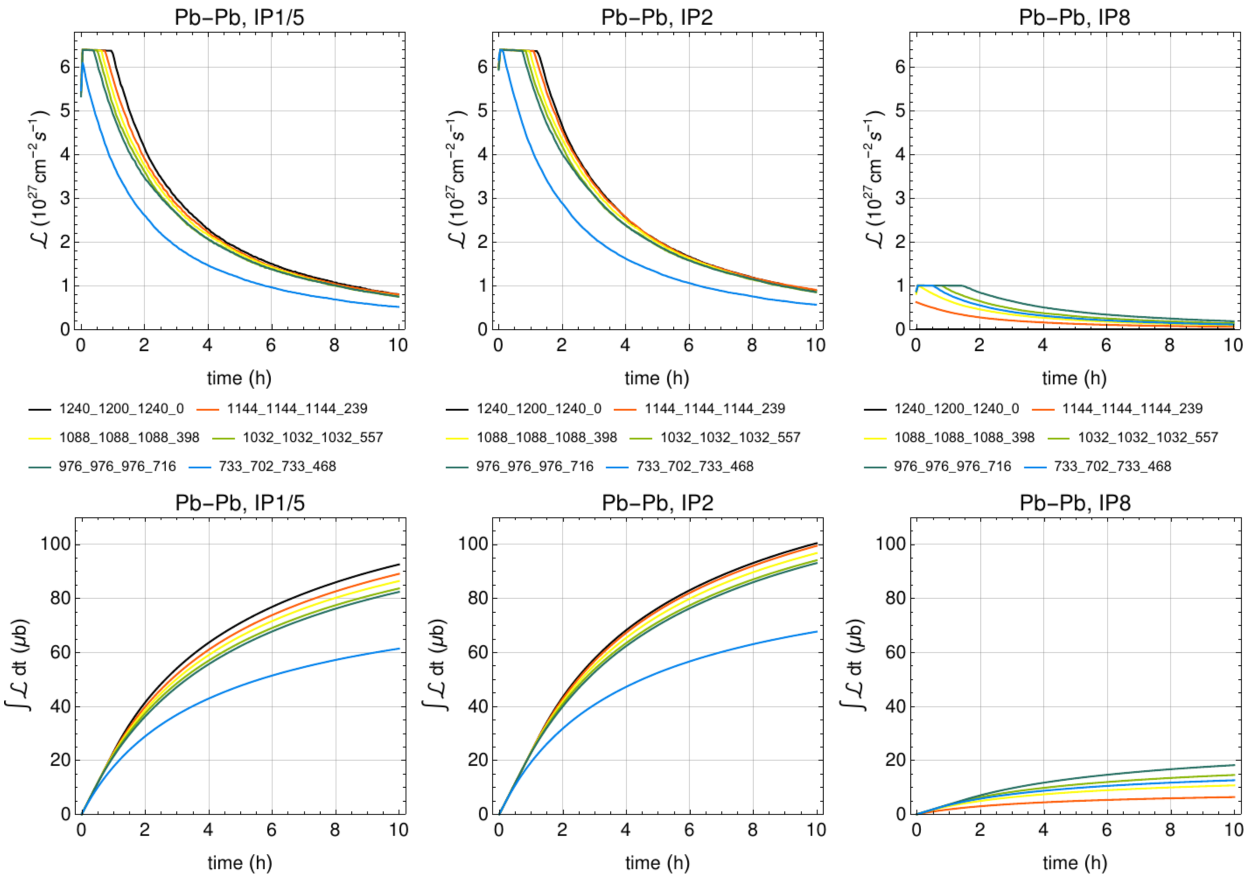
- **Performed extensive benchmark on 2018 data** – found excellent agreement in the simulation of single fills with given starting conditions taken from beam data



CTE simulation vs measurements of fill 7477, Pb-Pb @6.37 Z TeV, 2018

Simulations of typical 2023 fill, Pb-Pb 6.8 Z TeV

- **Simulated future fill**
  - using projected upgraded beam parameters - might not be achieved immediately at the start
  - For different filling schemes



Reference: EPJ Plus paper

Integrated luminosity in a 1-month run

- **From the single fill, calculate optimum fill time, and average luminosity**
  - Optimal fill length of ~4.5h with ideal turnaround, goes up to 5.5h with achieved turnaround distribution from 2018
  - For two energies: 6.8 Z TeV and 6.37 Z TeV, and for all filling patterns

- **Estimate luminosity in a typical 1-month ion run as**

$$\mathcal{L}_{\mathrm{tot}} = \mathcal{L}_{\mathrm{avg}}(T_{\mathrm{f,opt}}) \times T_{\mathrm{run}} \times \eta$$

- **Assumptions**
  - 200 min turnaround time (detailed estimate from J. Jowett, Chamonix 2017)
  - Operational efficiency η assumed to be either (see LIU specification document)
    - 62% as in LIU specification
      - Could be challenging – feasibility needs to be demonstrated for future higher beam intensities
    - 50% as for Run 3 and HL-LHC protons
  - T_{run}=27 days of physics available after initial commissioning in 2023

Projected 2023 performance, Pb-Pb

Integrated luminosity over **27 days in nb^{-1}**

6.8 Z TeV, 50%	IP1/5	IP2	IP8
1240_1200_1240_0	2.8	3.	0.
1144_1144_1144_239	2.7	3.	0.2
1088_1088_1088_398	2.6	2.9	0.33
1032_1032_1032_557	2.5	2.8	0.43
976_976_976_716	2.5	2.8	0.52
733_702_733_468	1.9	2.1	0.39

6.8 Z TeV, 62%	IP1/5	IP2	IP8
1240_1200_1240_0	3.5	3.7	0.
1144_1144_1144_239	3.3	3.7	0.24
1088_1088_1088_398	3.2	3.6	0.4
1032_1032_1032_557	3.1	3.5	0.54
976_976_976_716	3.	3.4	0.64
733_702_733_468	2.4	2.6	0.48

6.37 Z TeV, 50%	IP1/5	IP2	IP8
1240_1200_1240_0	2.7	2.9	0.
1144_1144_1144_239	2.6	2.8	0.18
1088_1088_1088_398	2.5	2.8	0.31
1032_1032_1032_557	2.4	2.7	0.42
976_976_976_716	2.3	2.6	0.5
733_702_733_468	1.8	2.	0.37

6.37 Z TeV, 62%	IP1/5	IP2	IP8
1240_1200_1240_0	3.4	3.6	0.
1144_1144_1144_239	3.2	3.5	0.23
1088_1088_1088_398	3.1	3.4	0.38
1032_1032_1032_557	3.	3.4	0.52
976_976_976_716	2.9	3.3	0.62
733_702_733_468	2.3	2.5	0.46

Considerations on Pb-Pb performance

- **Estimated performance has large uncertainties**
  - Especially from machine availability and beam parameters in collision

- **Depending on scenario, estimate about**
  - 2.7-3.6 nb^{-1} at ALICE
  - 2.4-3.2 nb^{-1} at ATLAS/CMS
  - 0.3-0.5 nb^{-1} at LHCb

- **Similar estimated performance in future 1-month runs**
  - to be scaled by the actual number of days in physics

- **3-5% loss in integrated luminosity at 6.37 Z TeV**

Assumptions for p-Pb

- For p-Pb, **new filling schemes developed recently with realistic proton train structure**
  - Note: previously using approximations without detailed filling schemes worked out
  - Considered both 50 ns and 25 ns proton beams
    - Possibly need further studies (instrumentation, beam-beam…) to verify impact of 50 ns ion beam and 25 ns p beam

- **Baseline assumptions, used for simulations**
  - ALICE levelled at $L=5\times10^{29}$ cm^{-2} s^{-1}, following upgrade, the other experiments not levelled
  - Assuming a proton beam with 3E10 p/bunch, and 2.5 µm emittance

- **Could revise some of these assumptions to gain in performance**

Projected 1-month performance, p-Pb

Green: above target
Red: Below target

Integrated 1-month luminosity **in nb^{-1}**

		IP1/5	IP2	IP8
50 ns p	1232_Pb_1320_p_765_762_733	474., 588.	329., 408.	149., 185.
	1232_Pb_1320_p_848_820_553	517., 641.	329., 407.	111., 137.
	1232_Pb_1320_p_901_843_432	542., 672.	327., 406.	85.4, 106.
25 ns p	1232_Pb_2520_p_1092_793_755	628., 778.	314., 389.	143., 177.
	1232_Pb_2520_p_900_926_897	529., 656.	325., 403.	173., 215.

50% OP eff. *62% OP eff.*

- **Assuming two p-Pb runs until the end of Run 4, we can satisfy the experiments' requests**
  - In one month, would need 500 nb^{-1} at IP1/5, 250 nb^{-1} at IP2, 100 nb^{-1} at IP8
  - Note: about factor 2 below initial LHCb request from yellow report
- **Potential performance improvement under study: Increase proton bunch intensities**
  - Need to verify feasibility of strong p beam vs weak Pb beam: Beam instrumentation, beam-beam …
    - First beam-beam studies done in PhD thesis M. Jebramcik

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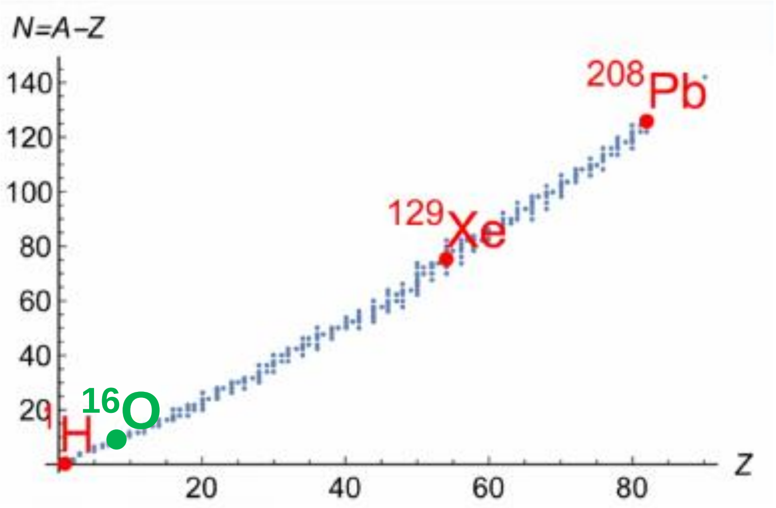
Oxygen pilot run

- **O-O and p-O run scheduled in 2024**

- **Motivations:**
  – Physics interest from experiments
    - See talk F. Moortgat
  – Study limitations and performance, in view of proposed Run 5 high-intensity operation with lighter ions

- **Wish list from experiments:**
  – O-O: ~0.5/nb for ALICE, ATLAS, CMS
  – p-O: LHCb would like 2/nb, LHCf would like ~1.5/nb
  – LHCf requests low pileup of 0.02 in p-O (update: previously 0.01)
  – ALICE wants low pileup of 0.1-0.2



Oxygen run parameters

- **Target: about one week, low luminosity**
  - Most efficient: re-use machine cycle of the previous Pb-Pb
    - O-O run would be done at the same energy per charge as Pb-Pb
  - Use pilot beams with single injections (staying below 3×10^{11} charges per beam)
    - Minimizes validation time

- **Beam parameters at LHC (gu)estimated**
  - Only previous CERN-experience with O-beam: LEIR commissioning in 2005
  - Very hard to estimate what we will get in 2024 in the LHC
  - Some options for intensity in collision and filling schemes,
    - 2E9 O/bunch, 18 bunches (12 collisions per experiment), 2.3 um emittance
    - 1.5E9 O/bunch, 21 bunches (14 collisions per experiment), 2.3 um emittance

- **Simulated luminosity performance for 6.8 Z TeV or 6.37 Z TeV beam energy**

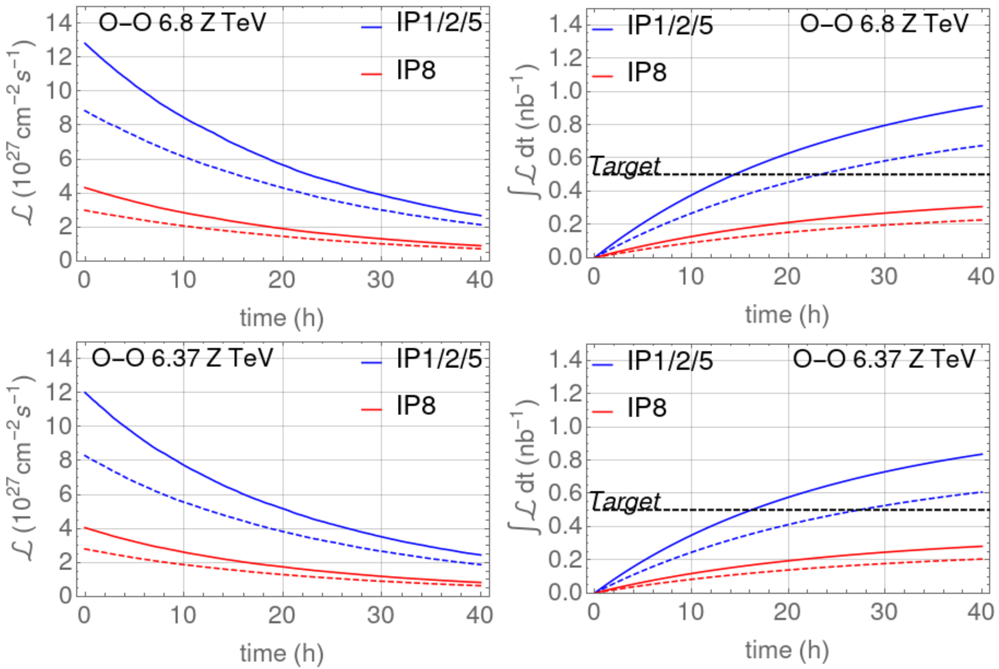
Performance with oxygen

- Simulations indicate we can reach
  - O-O targets in about a day, with 1-2 long fills
  - p-O targets in about 2.5 days
  - Large uncertainty applies!

- **Including commissioning time and contingency, could need 6-8 days**
  - Oxygen run seems a priori feasible and compatible with targets, but will certainly also be challenging

- Some work still remains: optimize machine configuration and filling schemes, study transmutation effect

Simulated performance O-O



Dashed lines: 21 bunches with 1.5x10^9 O/bunch ,
Solid lines: 18 bunches with 2x10^9 O/bunch
More details: See [IPAC'21 paper]

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Conclusions

- **Heavy-ion operation will continue in Run 3-4 with Pb-Pb and p-Pb**
  - In Run 3, operational periods at the end of 2023, 2024, 2025
  - Pb-Pb operation, p-Pb to be slotted in depending on Pb-Pb results

- **Pb-Pb run foreseen for 2023**
  - 27 days of physics, 4 days of commissioning scheduled
    - Commissioning seems tight – could consider commissioning optics already with protons as in 2018

- **New machine scenario for Run 3-4 relies on several recent upgrades**
  - Slip-stacked 50 ns beams, new crystal collimators, dispersion suppressor collimators in IR2
  - Significant performance increase – targeting full HL-LHC performance already in Run 3

- **Estimated performance for typical run (with 27 days of physics as in 2023)**
  - Pb-Pb: 2.4-3.6 nb^{-1} in ATLAS/ALICE/CMS, 0.3-0.5 nb^{-1} in LHCb
    - Could envisage to increase luminosity further through β*, crossing angle, levelling targets - need further feasibility studies

- **1-week oxygen pilot run foreseen for 2024**
  - Re-use existing Pb cycle, setup beam intensity
  - potential to reach experiments' targets in 6-8 days, but large uncertainties apply

Thanks for the attention!