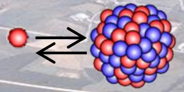
Proton-nucleus collisions at the LHC: The machine point-of-view



R. Bruce, with material and essential inputs from J. Jowett, M. Jebramcik

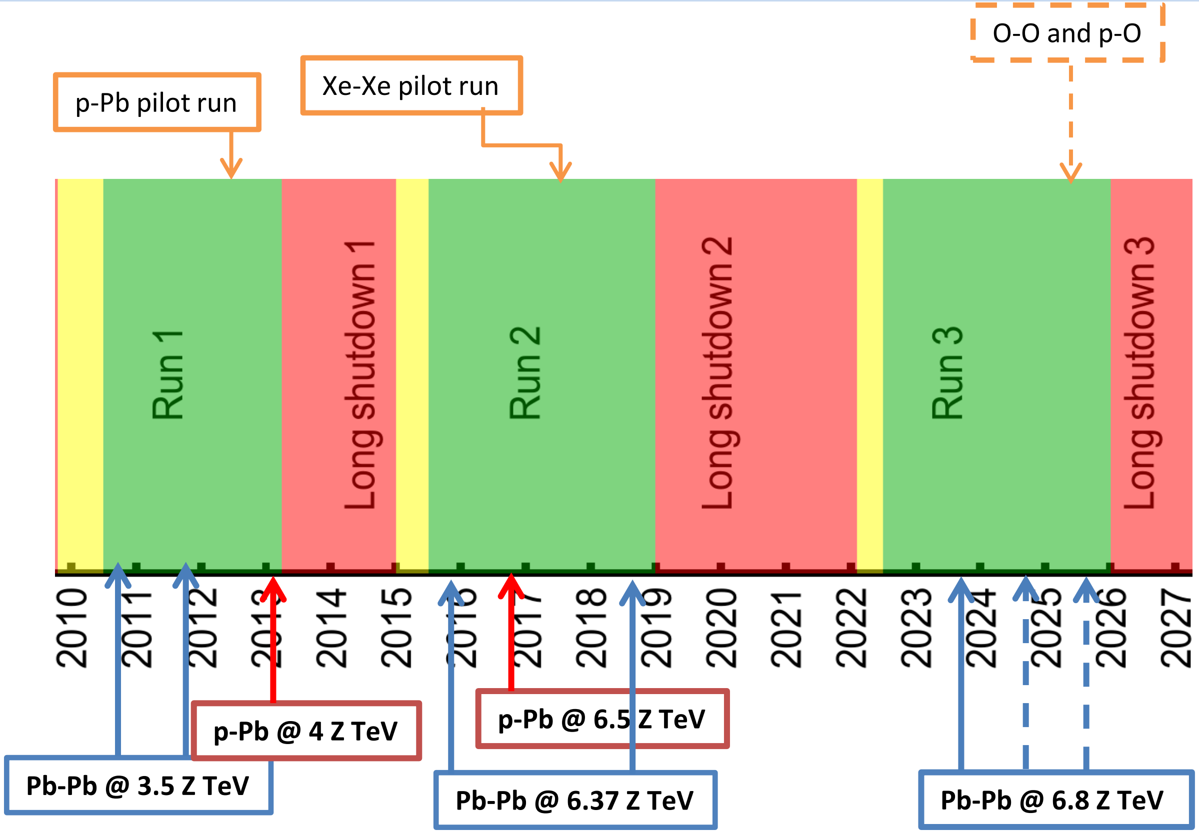
Outline

- **Introduction: LHC ion program and p-nucleus collisions**
- **Machine challenges with p-Pb operation**
- **Past results of p-Pb at LHC**
- **Future plans for p-nucleus and expected performance**
  - p-O
  - p-Pb
- **Conclusions**

LHC heavy-ion program

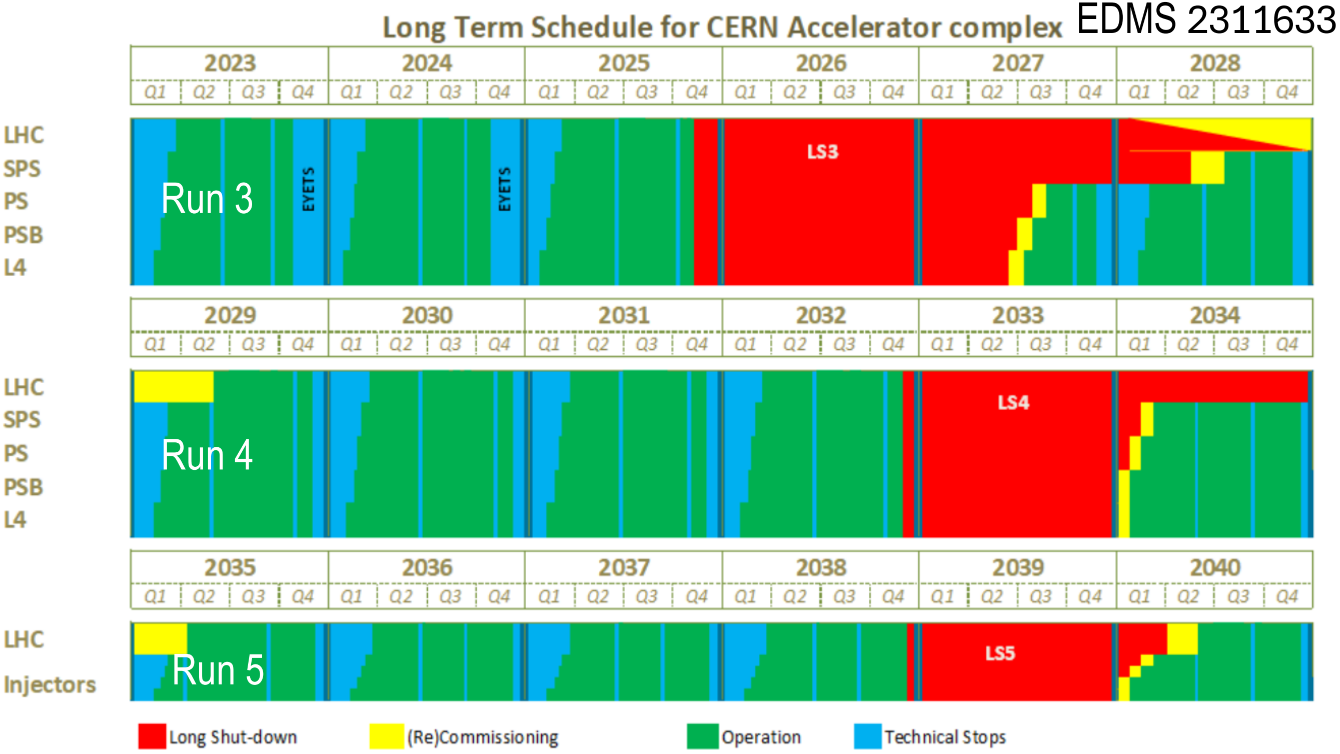
- **LHC typically operates 1 month per year with heavy ions**
  - So far Pb-Pb (5 runs), p-Pb (2 runs)
  - Short pilot runs in other configurations

- **Run 3**
  - Pb-Pb run in 2023 – first operation with all HL-LHC ion upgrades implemented
  - p-Pb presently not scheduled in Run 3
  - O-O and p-O pilot run in 2025



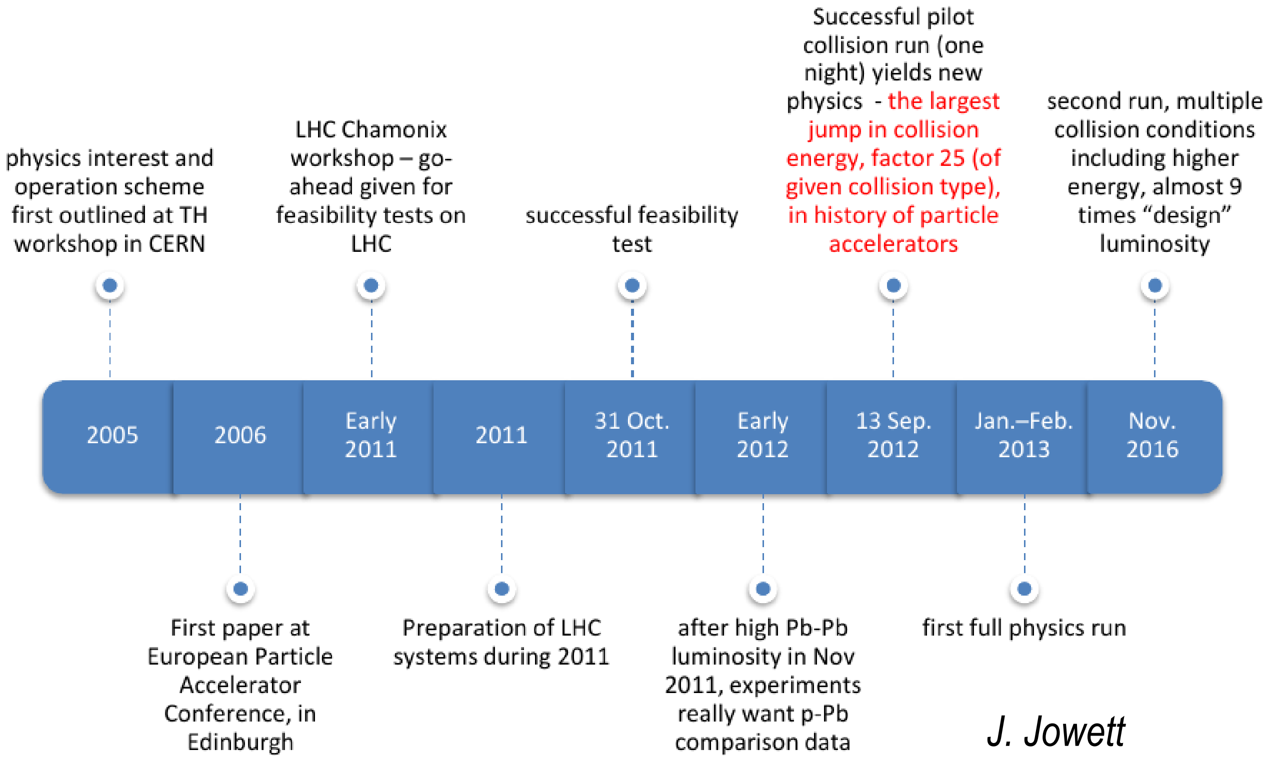
Future of LHC heavy-ion program

- **Run 4**
  - Yearly Pb-Pb and/or p-Pb operation
  - Sharing between Pb-Pb and p-Pb not yet decided, assume now one p-Pb run
- **Beyond Run 4**
  - No further ion runs formally approved
  - Advanced studies of continued heavy-ion program, potentially using other species (ALICE3 etc)



History of p-nucleus collisions at LHC

- Only Pb-Pb foreseen in LHC design
- Interest in p-Pb grew in mid-2000's



J. Jowett

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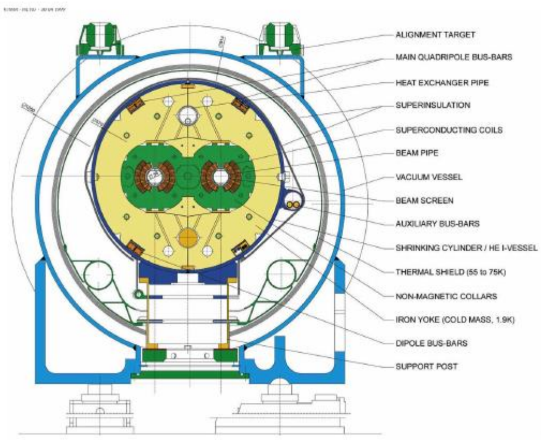
Machine challenges for p-Pb

- **Many of the same challenges with Pb beam as for the Pb-Pb program**
  - Collimation and beam losses
  - Achieving design beam parameters – injectors, long LHC injection plateau

- **Challenges specific to unequal species**
  - Filling schemes
    - p and Pb beams not produced in the same way in injectors. Need to take care to maximize overlap and the number of collisions at all experiments
  - Beam instrumentation
    - Potentially need different settings in the two beams
  - Collisional losses
    - Asymmetric pattern of losses, need to keep absolute losses below BLM thresholds and quench limit
  - Unequal revolution frequencies and resulting effects
    - See next slide
  - Beam-beam effects
    - Moving long-range encounters – studied extensively in thesis by Marc Jebramcik

Revolution frequencies

- **Revolution frequencies**
  - Same fixed magnetic field in the two apertures (unlike RHIC), but RF frequencies can be different
  - Unequal charge-to-mass ratio in the two beams
  - => the two beams have different γ, speed, and revolution frequency
  - If nothing is done, collision points and long-range beam-beam encounters that move over time
    - unacceptable for experiments; could drive instabilities
    - Studied extensively in thesis by Marc Jebramcik – presently not limiting LHC



- **Solution: change path length to compensate for difference in speed**
  - Done by putting both beams slightly off-momentum
  - Can equalize revolution frequencies

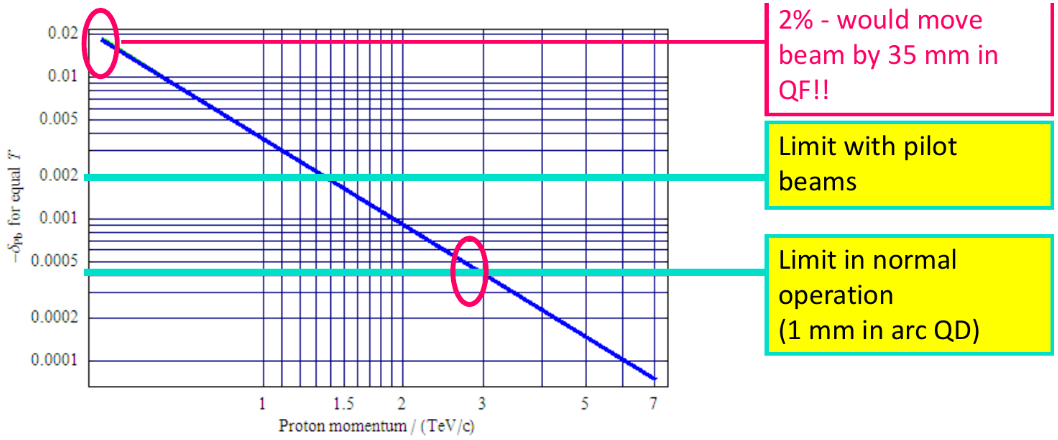
$$B\rho = \frac{p}{Z\,e} = \frac{m}{Z\,e}\gamma\beta c$$

$$\frac{\Delta\tau}{\tau} = -\left(\frac{1}{\gamma^2} - \alpha_c\right)\frac{\mathrm{d}p}{p}$$

LHC p-Pb configuration

- **Off-momentum orbits feasible only above ~2.7 TeV**
  - At lower energy, orbits too close to the aperture

- **LHC p-Pb cycle**
  - Injection and energy ramp done with same magnetic rigidity but different revolution frequencies
  - At top energy, lock equal frequencies, bringing beams off-momentum, shift bunch encounters to the collision points (“cogging”)
  - Collide with beams slightly off-momentum
    - At 6.5 TeV in 2016, needed $\delta=\pm9\times10^{-5}$ - easier than 4 TeV in Run 1



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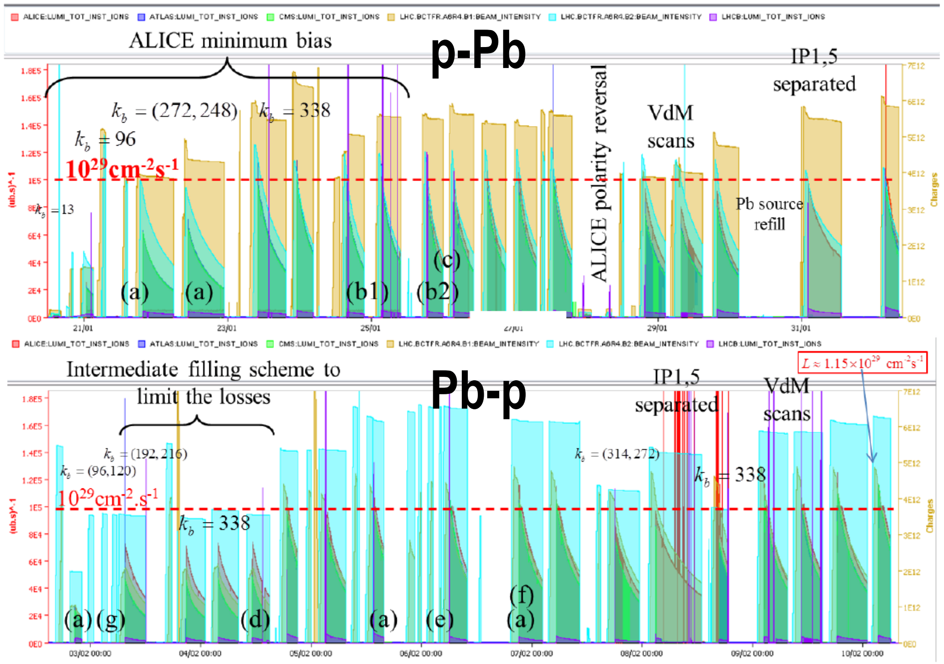
p-Pb operation in Run 1

- **2012: Pilot run in $\sqrt{s} = 5.02$ TeV**
  - 4 Z TeV beam energy
  - One ~9h fill, low intensity (8 collisions per experiment), keeping injection optics (β^*=10-11m), L≈10^{26} cm^{-1} s^{-1}
- **2013: Physics run at $\sqrt{s} = 5.02$ TeV**
  - 4 Z TeV beam energy
  - 25 days dedicated to physics, ~300 collisions per experiment, β^*=0.8 m, L≈10^{29} cm^{-1} s^{-1}
  - Did both p-Pb and Pb-p



Intensity and luminosity in 2013 p-Pb run

2016 p-Pb run

- **2016: physics run at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 8.16$ TeV**
  - Conflicting requirements from experiments → run split in two parts at different energies – heavy commissioning
  - 23 days dedicated to physics, up to ~400 collisions per experiment, β*≥0.6 m, L≤8.9×10^{29} cm^{-1} s^{-1}

- **$\sqrt{s} = 5.02$ TeV**
  - Requested by ALICE
  - 1 week with very long fills with levelled luminosity

- **$\sqrt{s} = 8.16$ TeV**
  - requested by ATLAS/CMS/LHCb
  - p-Pb and Pb-p
  - Record-high luminosity
  - Had to limit luminosity with levelling due to collisional beam losses

$\sqrt{s}$ =5.02 TeV (4 Z TeV)

β^* in IP1/5, 2, 8	(11, 2, 10) m
No. of p, Pb bunches	702, 548
Protons/bunch	2.2×10^{10}
Pb/bunch	1.8×10^{8}
Collisions in IP1/5, 2, 8	81, 389, 54
$\varepsilon_{n(x,y)}$ (p/Pb)	$(1.4 \pm 0.2, 1.6 \pm 0.2)$ μm
Luminosity at IP2	1×10^{28} $cm^{-2}s^{-1}$
Stable beams duration	14.9 h

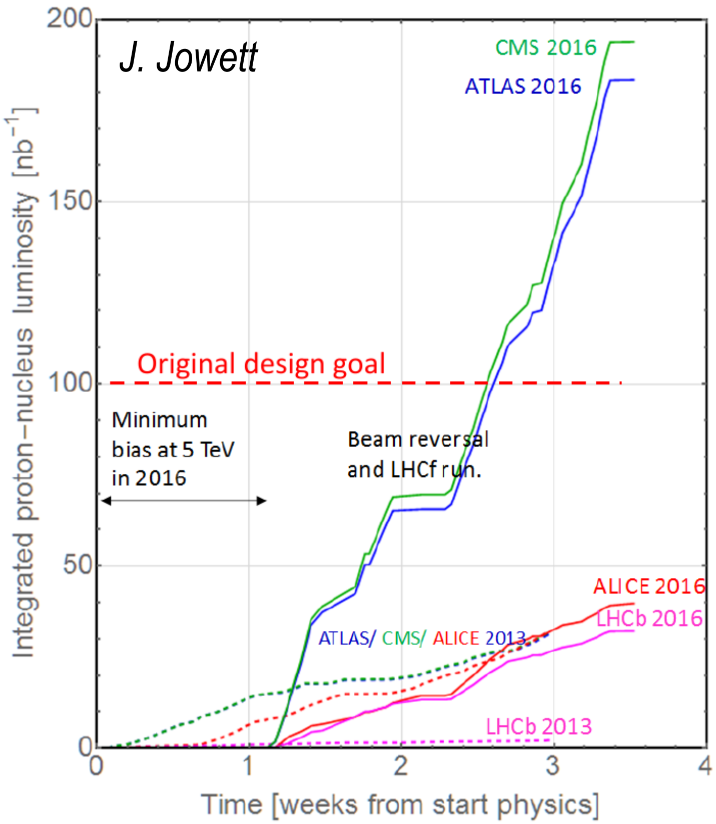
$\sqrt{s}$ = 8.16 TeV (6.5 Z TeV)

β^* in IP1/5, 2, 8	(0.6, 2, 1.5) m
No. of p, Pb bunches	684, 540
Protons/bunch	2.8×10^{10}
Pb/bunch	2.1×10^{8}
Collisions in IP1/5, 2, 8	405, 351, 251
$\varepsilon_{n(x,y)}$ (p/Pb)	$(1.3 \pm 0.2, 1.6 \pm 0.4)$ μm
Luminosity at IP1/5	8.9×10^{29} $cm^{-2}s^{-1}$
Stable beams duration	2.5 h

Summary of achieved performance

- **Integrated luminosity so far**
  - 75 nb^{-1} in ALICE
  - ~220 nb^{-1} in ATLAS/CMS
  - 36 nb^{-1} in LHCb

Year		Run 1 '13 [4]	Run 2 '16 [5]
Beam energy E_b	Z TeV	4	4, 6.5
Collision energy $\sqrt{s_{\mathrm{NN}}}$	TeV	5.02	5.02, 8.16
Run duration	weeks	3	1, 2
Bunch spacing	ns	200/225	100
Number of bunches n_b	1	358	540
Pb bunch intensity N_b	10^8	1.2	2.1
Normalised emittance ϵ_n	μm	2	1.5
Minimum β^* at the IP	m	0.8	10, 0.6
Peak luminosity $\mathcal{L}$	$10^{29}\ \frac{\mathrm{Hz}}{\mathrm{cm}^2}$	1.16	8.9
IP1/5 int. luminosity $\int \mathcal{L}$	nb^{-1}	32	190



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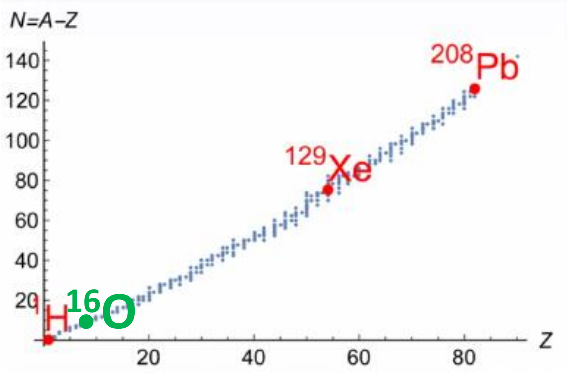
Plans for future p-nucleus operation

- **Run 3**
  - No p-Pb scheduled
  - Low-intensity pilot run with oxygen in 2025 (O-O and p-O)

- **Run 4**
  - Expect ~1 month of heavy-ion operation per year
  - Detailed sharing between Pb-Pb and p-Pb not decided, presently assuming one p-Pb run

2025 oxygen pilot run

- **Target: about one week, low luminosity**
  - Including both O-O and p-O
  - Use pilot beams with single injections (staying below 3×10^{11} charges per beam) – reduced commissioning
  - Most efficient: re-use Pb-Pb machine cycle
    - β*=0.5m at IP1/2/5, but flatten crossing angles



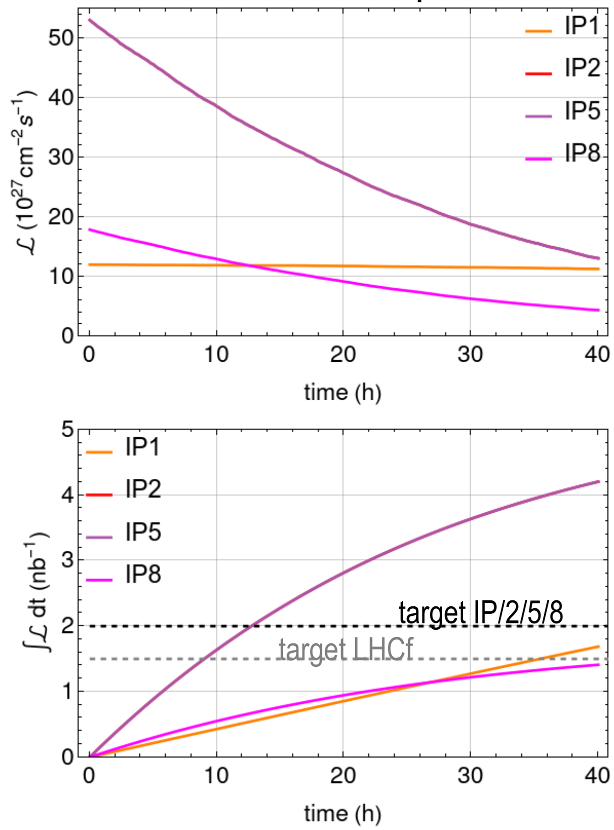
- **Wish list from experiments:**
  - O-O: 0.5/nb for all experiments
  - **p-O: 2/nb for all experiments, LHCf would like ~1.5/nb**
  - LHCf requests low pileup of 0.02 in p-O
  - ALICE wants low pileup of 0.1-0.2

- **Beam parameters**
  - Not easy to estimate – never sent O beams to LHC before
  - Note: successful test of O beam in LEIR in 2023 gives good hope
  - For p-O: pileup constraint from LHCf →
    - Split beam in many bunches at lower intensity
    - Assuming 36 bunches of 9×10^{8} O ions or 7×10^{9} protons

Estimated performance with oxygen

- **Simulation of p-O fill show**
  - ALICE, CMS: Could reach targets in in one long fill of about 14 h
  - LHCf/ATLAS: can level for >40h, need total stable-beam time of ~36h
  - LHCb: would need several fills, e.g. 3 fills of 12-15h in stable beams + turnaround
  - Could p-O targets in about 2.5 days (with optimistic ~100% LHC availability)
  - **Large uncertainty applies!**
- **Including commissioning time, could need 6-8 days**
  - Oxygen run seems a priori feasible and mainly compatible with targets, but will certainly also be challenging
  - **Needed time strongly depends on machine availability**
- **Some work still remains**
  - optimize machine configuration and filling schemes
  - If available, use MD optics?
  - study transmutation effect

Simulated fill p-O



More details: See IPAC paper

Considerations for p-Pb in Run 4

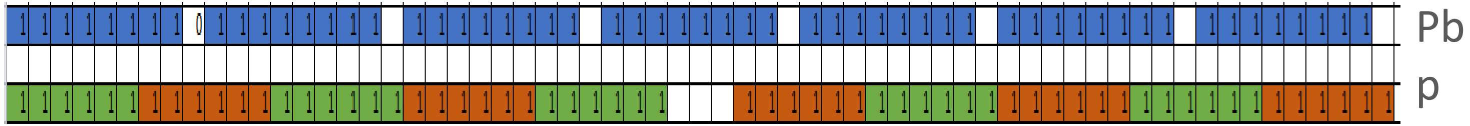
- **Machine configuration**
  - As for Pb-Pb: β*=0.5 m at IP1/2/5, β*=1.5 m at IP8
    - Improvements under study
  - Conservatively using $\sqrt{s} = 8.54$ TeV (6.8 Z TeV)
    - Should lower energy be considered?
    - In Run 2, lower-than-max energy chosen for Pb-Pb to have same $\sqrt{s}$ as in 2013 p-Pb
  - Level ALICE at 5×10^{29} cm^{-1} s^{-1}
  - Assume collisional beam losses do not limit luminosity

- **Considerations for commissioning**
  - Beam and spectrometer reversal needs commissioning time → less time for physics
    - Are both p-Pb and Pb-p needed?
    - ALICE spectrometer reversal(s) needed?
  - Commissioning risks being less efficient if something hasn't been done for a long time
    - Changes to software
    - Are the experts still around?
    - Important to "exercise" – good opportunity in 2025 p-O run
  - Can crystal collimation be used on the proton beam? Otherwise, extra commissioning overhead

Assumed beam structure

- **Pb beam**
  - Use slip-stacked Pb beam as in 2023 Pb-Pb with 50 ns bunch spacing
  - Hope to improve performance w.r.t. 2023 and reach HL-LHC target (1.8×10^{8} Pb/bunch, ε=1.65 μm)
  - Conservatively, compare performance with 2023 achieved parameters (1.5×10^{8} Pb/bunch, ε=2 μm)

- **Proton beam**
  - Baseline: 50 ns and low intensity (3×10^{10} p/bunch, ε=2.5 μm)
  - Production scheme in injectors is different for p and Pb → non-trivial to construct a 50 ns proton beam that overlaps 50 ns Pb beam
  - Proton schemes based on 6*n bunches/batch, 200 ns gap between batches
  - Two proton batches of 30 bunches almost fit a slip-stacked Pb train
  - Direct overlap shows collisions at IP1/5 – but we need to have many collisions at all IPs



LHC filling schemes for p-Pb

- **Range of LHC filling schemes produced, using 50 ns or 25 ns proton beams**

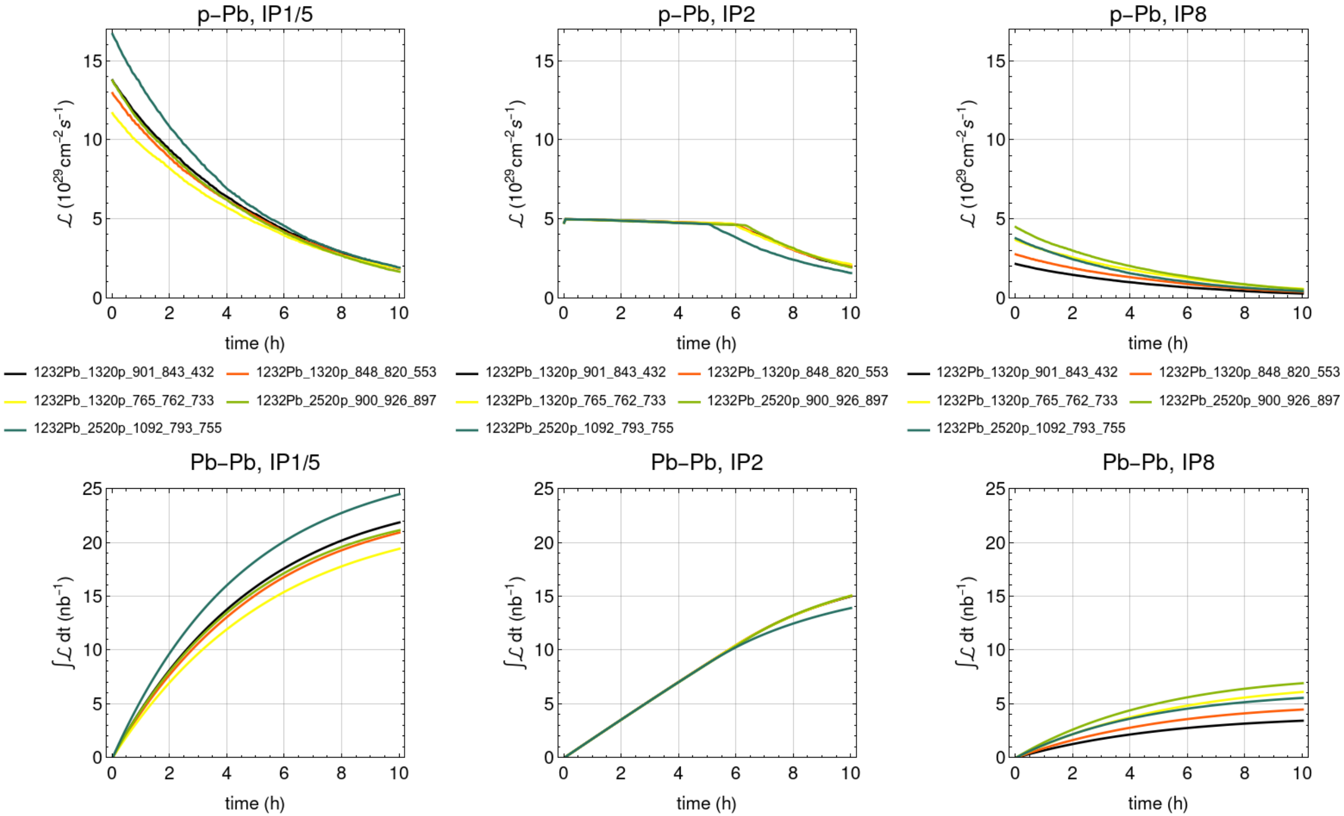
- **50 ns proton scheme**
  - Assume 5 injections in PS, triple-split at injection (→15b), double-split at PS flat top (→ 30b)
  - Taking 2×30 bunches from PS to SPS
  - Brute-force optimization to maximize number of collisions

- **25 ns proton scheme – feasibility for p-Pb remains to be proven**
  - Assume 5 injections in PS, triple-split at injection (→15b), double-split at PS flat top (→ 30b), another double-splitting to get 25 ns (→60b)
  - Taking 2×60 bunches from PS to SPS
  - Could possibly be further optimized

	no. Pb bunches	no. p bunches	p bunch spacing (ns)	no. collisions at IP1/5	IP2	IP8
1232_Pb_1320_p_765_762_733	1232	1320	50	765	762	733
1232_Pb_1320_p_848_820_553	1232	1320	50	848	820	553
1232_Pb_1320_p_901_843_432	1232	1320	50	901	843	432
1232_Pb_2520_p_1092_793_755	1232	2520	25	1092	793	755
1232_Pb_2520_p_900_926_897	1232	2520	25	900	926	897

Simulation of typical fills

- Beam and luminosity evolution simulated with CTE for typical fill
- Assuming nominal HL-LHC Pb beam – parameters not yet achieved regularly
- $\sqrt{s} = 8.54$ TeV (6.8 Z TeV beam energy)
- Level ALICE at 5×10^{29} cm^{-1} s^{-1}



Integrated luminosity in one month

- Possibly optimistic assumptions:
  24 days of physics excluding commissioning, 50 % operational efficiency, Pb beam parameters reaching HL-LHC target

Total integrated luminosity (nb^{-1})	IP1/5	IP2	IP8
1232_Pb_1320_p_765_762_733	474.	329.	149.
1232_Pb_1320_p_848_820_553	517.	329.	111.
1232_Pb_1320_p_901_843_432	542.	327.	85.4
1232_Pb_2520_p_1092_793_755	628.	314.	143.
1232_Pb_2520_p_900_926_897	529.	325.	173.

25 ns protons – feasibility to be proven

- With 2023 Pb parameters: ~20% lower integrated luminosity; ALICE less affected
- One p-Pb run is not enough to reach initial targets for Run3+Run4 (1.2 pb^{-1} in ATLAS/CMS, 0.6 pb^{-1} in ALICE/LHCb)

Potential performance improvements

- **Higher intensity on Pb beam**
  - Depends on what injectors can deliver on tight schedules
- **25 ns proton beam on 50 ns Pb beam**
  - many p bunches would be useless, but the aim is to have as many collisions as possible
  - Can get many more collisions at LHCb without penalizing the other experiments
  - Needed feasibility studies: beam-beam effects, instrumentation
  - Gain up to 30% at ATLAS/CMS, 15% LHCb
- **High-intensity proton beam**
  - Many potential showstoppers to be studied: beam-beam effects, instrumentation, collisional losses, collimation, machine protection
  - Could give significant gain to ATLAS, CMS, LHCb
- **Smaller β* and/or crossing angles**
  - Enough aperture to squeeze β* further or open collimators
  - For 2024 propose to open collimators → less sensitive to beam losses
  - Unclear if we ever can go down in β* - operational experience needed
  - Otherwise, chance of reaching maybe β*=40 cm at IP1/2/5, β*=1 m at IP8
  - Gain up to maybe 20% at ATLAS/CMS, more at LHCb
- **Large uncertainties apply and potential showstoppers must be studied**

Higher peak luminosity → Pb beam burns off much faster → shorter fills → bad for ALICE (levelled) → Workaround: level all experiments, can keep fills longer

Gain mainly for ATLAS, CMS, LHCb, not ALICE (levelled)

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Conclusions

- **Proton-nucleus collisions require a special mode of operation of the LHC**
  - in addition to the challenges of the HL-LHC Pb beams
  - simultaneous operation of the two injector chains.
  - Nevertheless past runs were very efficient

- **A full one-month run of p-Pb at $\sqrt{s} = 8.54$ TeV could yield**
  - ~0.3 pb^{-1} at ALICE, ~0.45 pb^{-1} at ATLAS/CMS, ~0.15 pb^{-1} at LHCb
  - Performance strongly dependent on beam parameters and machine availability
    - Example: 2023 Pb-Pb run
    - nominal Pb beam parameters not yet achieved regularly
    - Long faults and low availability would yield lower integrated luminosity
  - Potential performance improvements under study (less important for ALICE)
    - Higher Pb intensity
    - 25 ns proton beam
    - High-intensity proton beam
    - Smaller β* and crossing angles

    Feasibility not proven – potential showstoppers to be studied

- **Short p-O run in 2025**

- **Continued program for nuclear collisions beyond Run 4 under study**

Thanks for the attention!

Backup

25 ns proton schemes?

- **50 ns vs 25 ns**
  - With 50 ns, no “natural” collisions at LHCb if quadrant symmetry is respected
  - With 25 ns, collisions do occur naturally at LHCb
- **If we collide 50 ns Pb beam with 25 ns p beam**
  - Obviously many p bunches would be useless, but the aim is to have as many collisions as possible
  - Can get many more collisions at LHCb without penalizing the other experiments
  - Possibly need to think about beam-beam – will get many more parasitic encounters.
    - Some studies done in thesis by Marc Jebramcik
  - First try: take similar length as 2*30 b 50-ns scheme: take 2*60b at 25 ns to maximize overlap
    - To be checked: e-cloud aspects based on latest LHC experience
- **25 ns protons could give a potential performance gain, but feasibility and potential showstoppers needs studies**
  - Beam-beam, instrumentation, ...

Recap: 2023 LHC configuration for Pb-Pb

- **2023 run relied on several new concepts – first ion run with all HL-LHC ion upgrades implemented**
  - **Slip-stacked 50 ns beams** from the injectors to provide higher intensity
    - **Slip-stacking successfully set up, demonstrated LIU target intensity**
  - **Crystal collimation** to handle the higher intensity without beam dumps or quenches
    - **First high-intensity physics run relying on crystal collimation; excellent cleaning performance demonstrated**
  - **TCLD collimators + BFPP bump** in IR2 to avoid quenches from BFPP secondary beam
    - **Successful demonstration of factor 6 higher ALICE luminosity**
  - **New BFPP bump in IR8** to increase quench margin and allow higher LHCb luminosity
  - **Full squeeze in ramp**

	IP1/5	IP2	IP8
β* (m)	0.5	0.5	1.5
Spectrometer half crossing (μrad)	0	±72	-139
External half crossing (μrad)	170	±170	-135
Net half crossing (μrad)	170	±98	-274

	Run 3 design
Beam energy	6.8 Z TeV
Bunch spacing	50 ns
Bunch intensity (start of collision)	1.8×10^{8} Pb
Normalized transverse emittance	1.65 μm

Main operational schemes

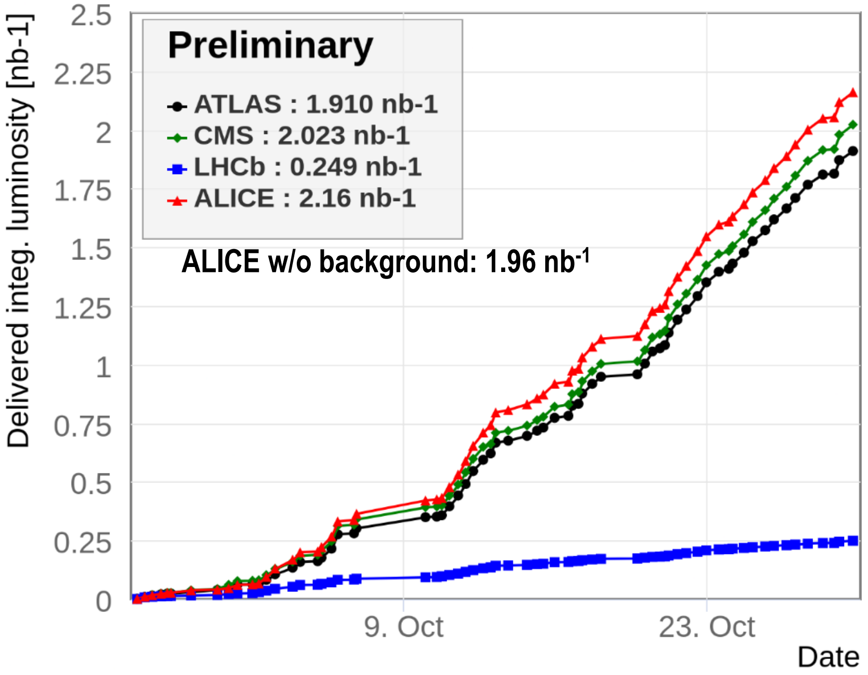
		Collisions		
N.o. bunches	**Bunches/train**	**IP1/5**	**IP2**	**IP8**
1240	56 / 40	1088	1088	398
1080	40	960	960	288
960	40	875	875	218

Reminder: 2023 performance

- **Integrated luminosity in full run around 2 nb^{-1} to ALICE, ATLAS, CMS**
  - About 2/3 of initial target, but still more than in 2018

- **Performance negatively affected by several problems**
  - ALICE background
  - Beam losses in the ramp
  - Radiation effects on quench detection system
  - 10 Hz losses
  - Crystal channeling stability
  - Intensity and emittance not reaching targets in most fills
    - Did not take all injections from LEIR during a part of the run due to limit on injected intensity from TDIS in the LHC

Delivered Luminosity 2023



Comparison 2018:

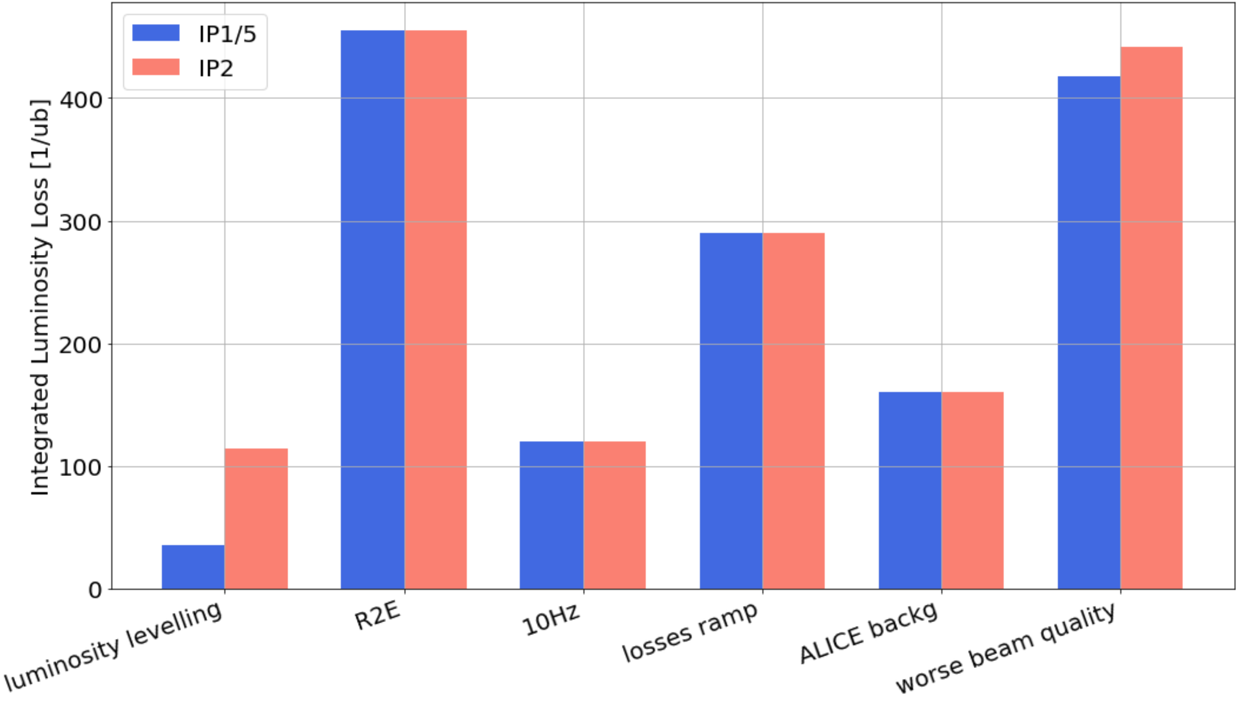
ATLAS: 1.797 nb^{-1}
CMS: 1.802 nb^{-1}
LHCb: 0.235 nb^{-1}
ALICE: 0.905 nb^{-1}

More details: LMC talk, LHCC talk

2023: Impact of problems on luminosity

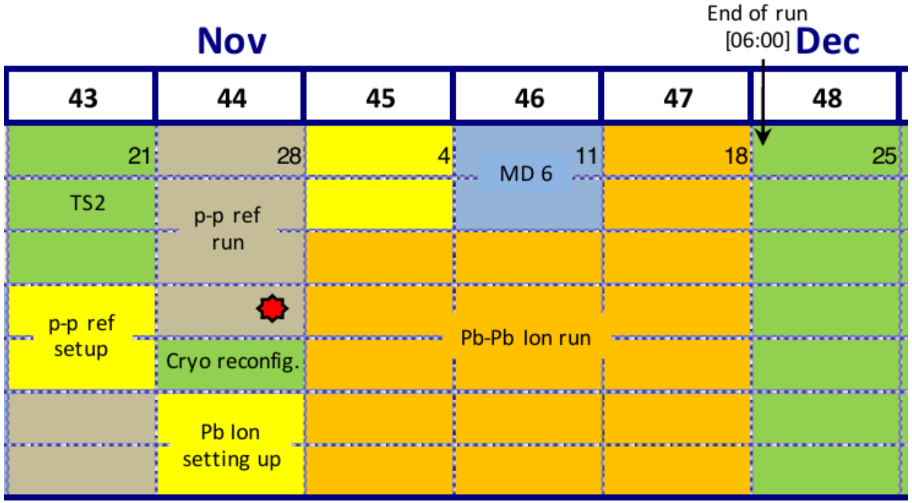
- **Could have had maybe up to 1.5-1.6 nb^{-1} more without encountered problems**
  - Only about 1/3 of the time spent in stable beams

N. Triantafyllou, see [LBOC talk]()



2024 ion operation

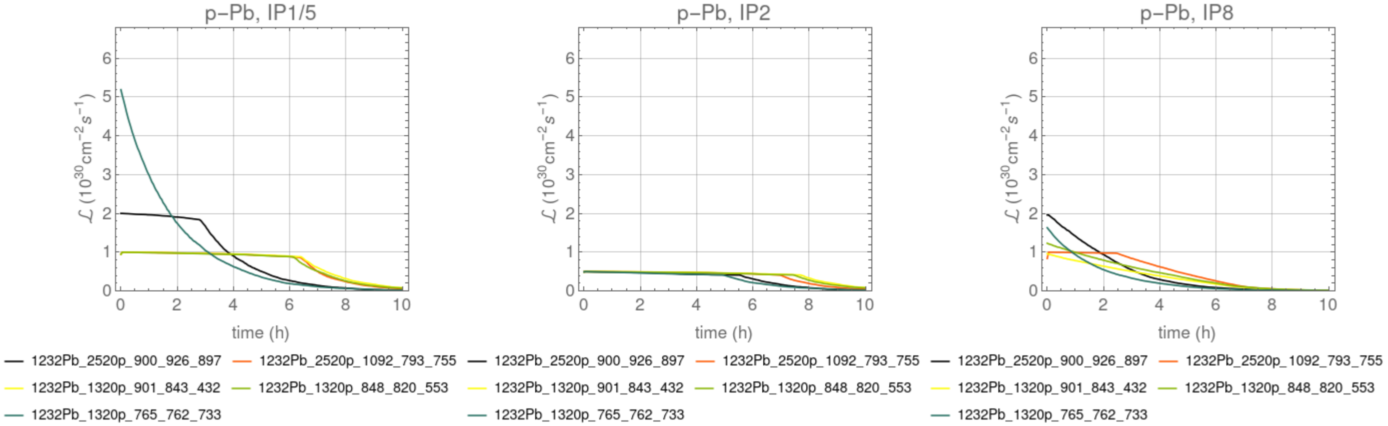
- **2024 pp reference run after TS2**
  - 2 days of setup, 6 days of physics
  - Detailed splitting of days between 2024 and 2025 being discussed by the experiments
  - See talk by Reyes
- **2024 Pb-Pb run**
  - 4 days of setting up – challenging!
  - 17 days of physics, including
    - 4 days of assumed intensity rampup
    - 1 day of VdM
    - ALICE polarity reversal → ~0.5 day commissioning
    - 2 days of MD
    - Might have maybe 11-11.5 days dedicated to physics with full machine
- **The ion run is short – must be very efficient**

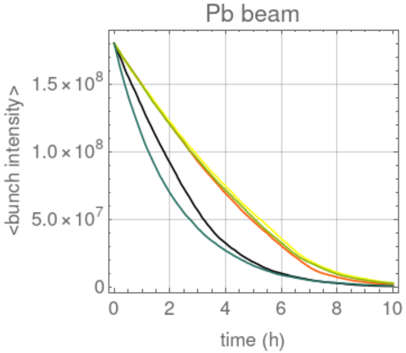


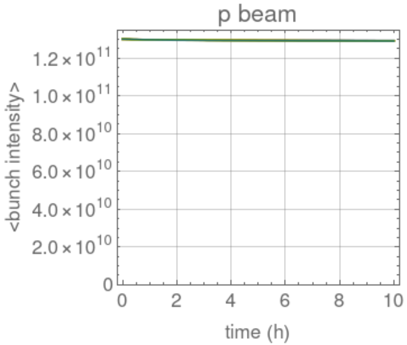
LHC planning 2024, v2.0

Levelling scenarios

- **Different levelling scenarios studied with high-intensity proton beam (1.3e11 p/bunch)**







High-intensity proton beams?

- **If we use “nominal” proton intensity**
  - Significantly higher peak luminosity
  - Pb beam burns off much faster → shorter fills → bad for ALICE (levelled)
  - Workaround: level all experiments, can keep fills longer → potential gain for all

- **Possible intensity**
  - 1.3×10^{11} p/bunch was reached so far with 50 ns protons
    - Studied on next slide
  - With 25 ns, aim at 2.2×10^{11} p/bunch in Run 4 (HL-LHC)

- **Simulated performance gain - add**

Feasibility of high-intensity protons

- **To verify feasibility, several points need study**
  - Beam-beam effects with weak and strong beam – some studies done in thesis by Marc
  - Higher instantaneous luminosity → Collisional losses to be studied carefully
  - Instrumentation, especially BPMs: can they work reliably with a large intensity difference between beams?
  - Collimation: Would need crystal system on Pb beam and standard system on p beam → Significant commissioning overhead
  - BLM thresholds: can one set of thresholds protect the machine with both beam types?
  - Machine protection: cogging of full p beam OK? Potential overhead in qualification and intensity rampup

Physics goals from yellow report

- 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 $\sqrt{s_{NN}}$ = 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. $L_{int}^{Ar-Ar} = 3\text{–}9\ pb^{-1}$ (about 3 months) gives NN luminosity equivalent to Pb–Pb with $L_{int} = 75\text{–}250\ nb^{-1}$

In Run 3 + Run 4