The 2018 Heavy-Ion Run of the LHC

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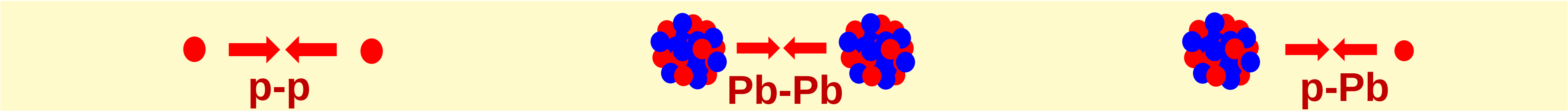
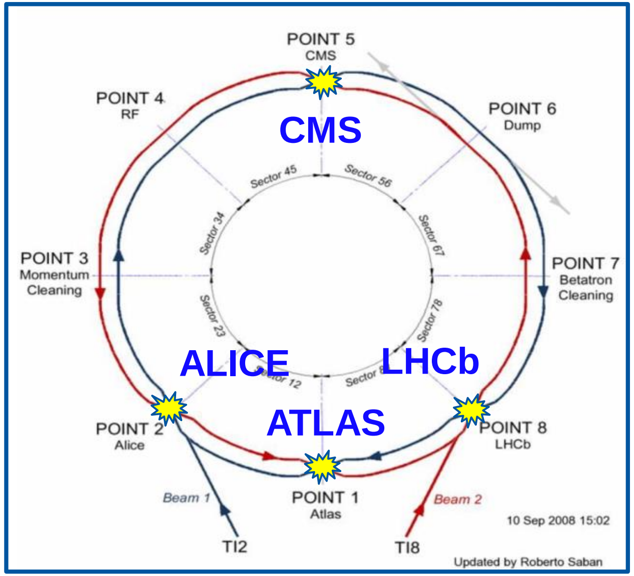
LHC Control Room: One of the last Pb-Pb physics fills before the start of LS2

Content

- Heavy-Ion Operation of the LHC
- 2018 Run
  - Configuration
  - Highlights and Hurdles
  - Limitations and Luminosity Performance
- Approaching ”HL-LHC” performance

Heavy-Ions in the LHC





The LHC spends most of its time colliding proton-proton (p-p) in its 4 main experiments.

All are also highly capable heavy-ion experiments:
ALICE (IP2) and ATLAS (IP1) / CMS (IP5)
LHCb (IP8) since 2012

1 month/year colliding fully stripped lead ($^{208}\mathrm{Pb}^{82+}$) or Pb ions with protons.

History and Future …

12 one-month heavy-ion runs between 2010 and 2030. **6/12 done**.

Upgrade: new collision mode
16h p-Pb
pilot run

1st p-Pb
high luminosity run
@ 4 Z TeV

p-Pb
@ 4 Z TeV
@ 6.5 Z TeV

LS2 Hardware Upgrades:
- ALICE detector upgrade to 7 x design luminosity
- Dispersion Suppressor collimators for BFPP losses.
- SPS RF (smaller bunch spacing)

Run 1 | Run 2 | LS2 | Run 3 | Run 4

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 TODAY 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

HL-LHC

1st Pb-Pb collisions
@ 3.5 Z TeV

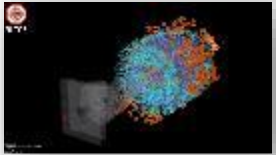
Pb-Pb @ 3.5 Z TeV
0.5 x design luminosity

Pb-Pb @ 6.37 Z TeV
3.5 x design luminosity

"Upgrade": new species
16h Xe-Xe operation

Pb-Pb @ 6.37 Z TeV
6.1 x design luminosity

"Upgrade": new species
12h Pb81+ operation



Run 5 | Run 6

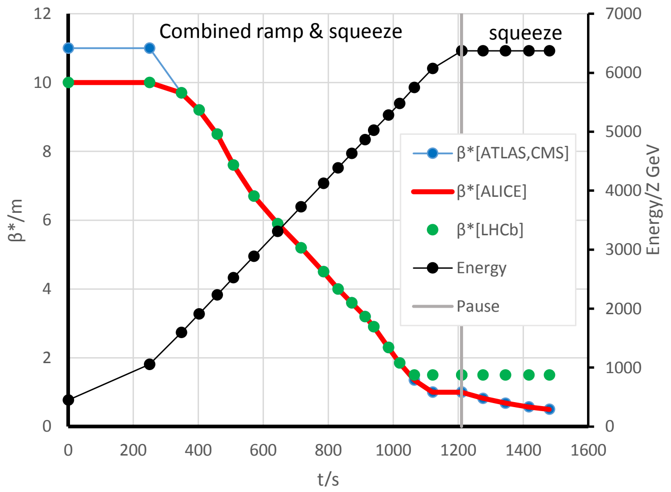
2031 2032 2033 2034 2035 2036 2037

HL-LHC

Currently no heavy-ion runs foreseen in Run 5 & 6, but a revised schedule is under discussion.

New Optics and Magnetic Cycle

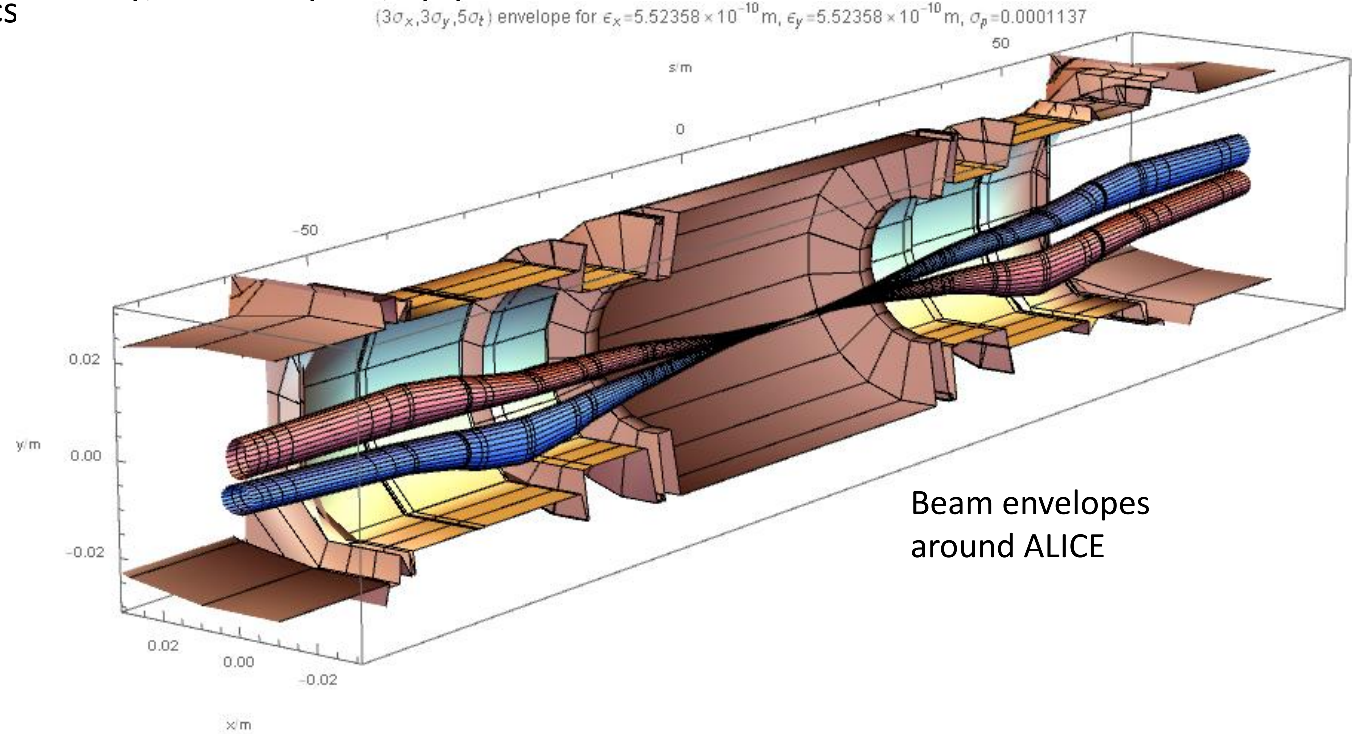
- Same optics as p-p only in 2010.
- Since then heavy-ion cycles had their own specifications, incl. lower β^* and crossing angle in ALICE (IP2).
- With implementation of Achromatic Telescopic Squeeze (ATS) optics for p-p the decision was taken to fully decouple proton and ion cycles, leading to a redesign of the whole heavy-ion cycle in 2018:
  - ➢ Redesign of Ramp & Squeeze
  - ➢ Smallest $\boldsymbol{\beta}^*$ ever in ALICE & LHCb



β^* in m	IP1	IP2	IP5	IP8
Combined Ramp & Squeeze (proton cycle)	1 (1)	1 (10)	1 (1)	1.5 (3)
Squeeze at top energy (proton cycle)	0.5 (0.3)	0.5 (10)	0.5 (0.3)	1.5 (3)

Pb-Pb in 2018: new optics with smallest ever β* in ALICE, LHCb

- Optics design by S. Fartoukh, new combined ramp & squeeze
- Gradual divergence from identical to pp optics in 2010 to a completely new cycle in 2018
- Initial problem with beam size in ALICE now ~completely understood
- Fixed for reversed-polarity part of run
- Some lessons for optics

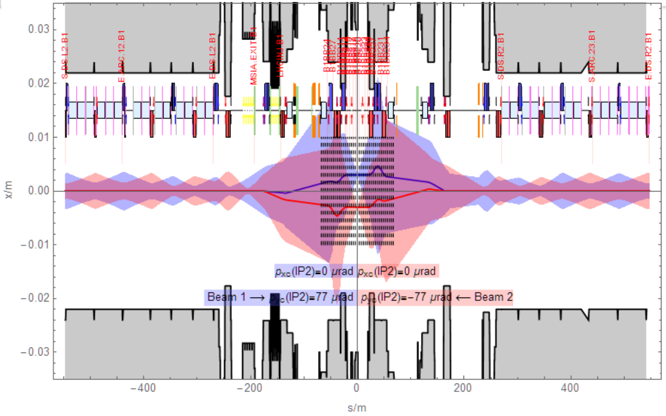


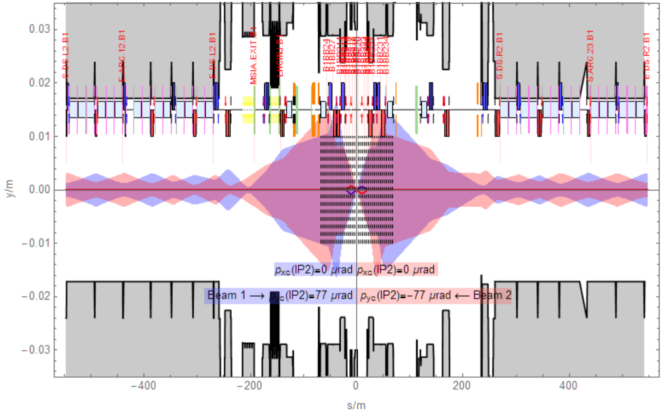
Beam envelopes around ALICE

IR2 ALICE +ve: external angle passed through zero in every fill

ON_ALICE

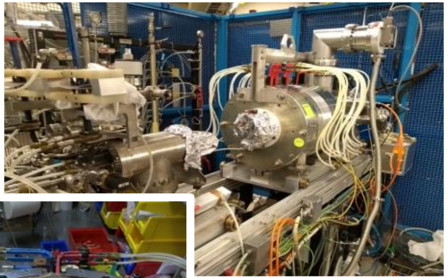
	x_c/m	y_c/m	p_{xc}/μrad	p_{yc}/μrad	β_x/m	β_y/m
IP1	-0.00055	0	-0.000445022	160.	0.500001	0.5
IP2	0.003	0	0.320649	76.9224	0.5	0.5
IP5	1.58497×10^{-18}	-0.00125	160.	-0.000108878	0.500001	0.5
IP8	-2.96858×10^{-18}	-0.001	-318.339	-1.98865	1.5	1.5

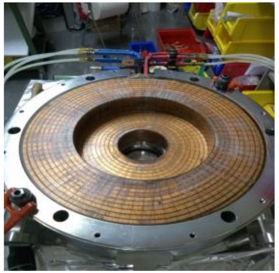




Horizontal parallel separation increased to ±3 mm
IP shift bump still off
Transition through zero external bump to unfavourable polarity with respect to IP (neutrons moving down)
No sign of beam-beam effects.

Major Hurdles of the 2018 run …



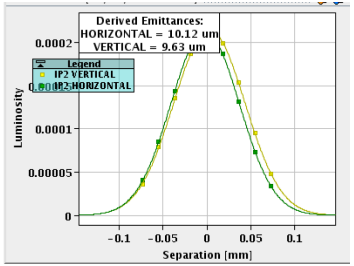


Ion source fault: No ions available for the first few days of the run.

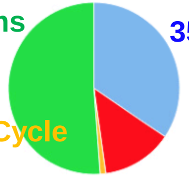
- Many commissioning tasks were advanced with protons.
- Degraded beam quality during the first week of the run.
  - ➢ Resulting in lower beam intensity and longer turn around time.
  - ➢ Shorter levelling periods and less time in physics.

ALICE luminosity initially lower than expected:

- Cause: beam deformation and reduced overlap at IP introduced by strong local betatron coupling at IP2
- Solution: correction with skew-quadrpoles implemented during ALICE polarity reversal to reverse error made in setting
- Luminosity sharing strategies used until solution was found:
  - Filling schemes (number and distribution of bunches).
  - Luminosity levelling target of ATLAS/CMS.

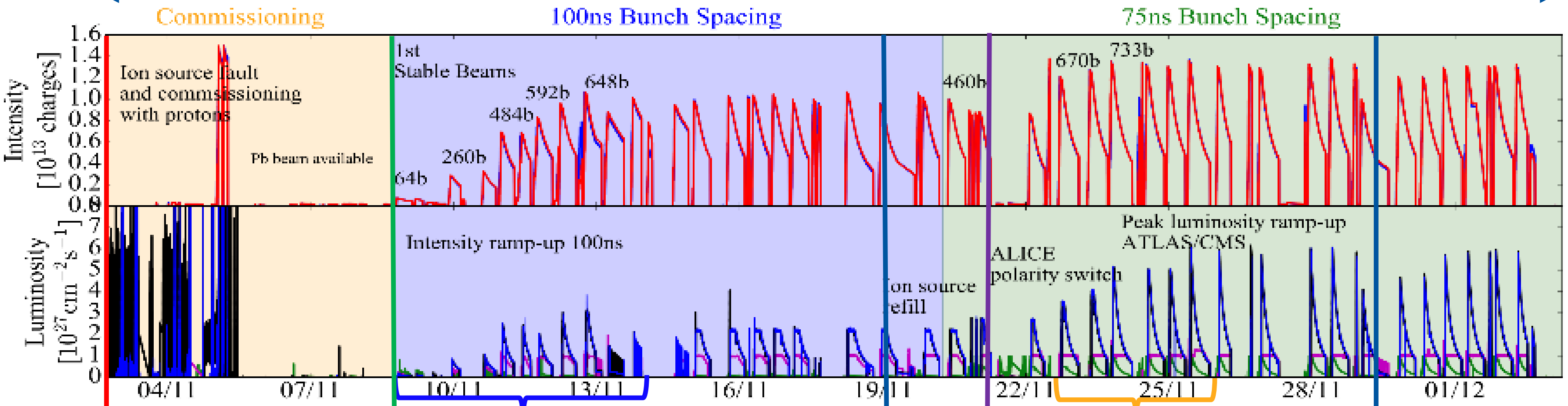


2018 Run Overview



Availability 87%

30 days



Ion source fault
no ions available

Intensity ramp-up 100ns beams

1^{st} Pb-Pb
Stable Beams

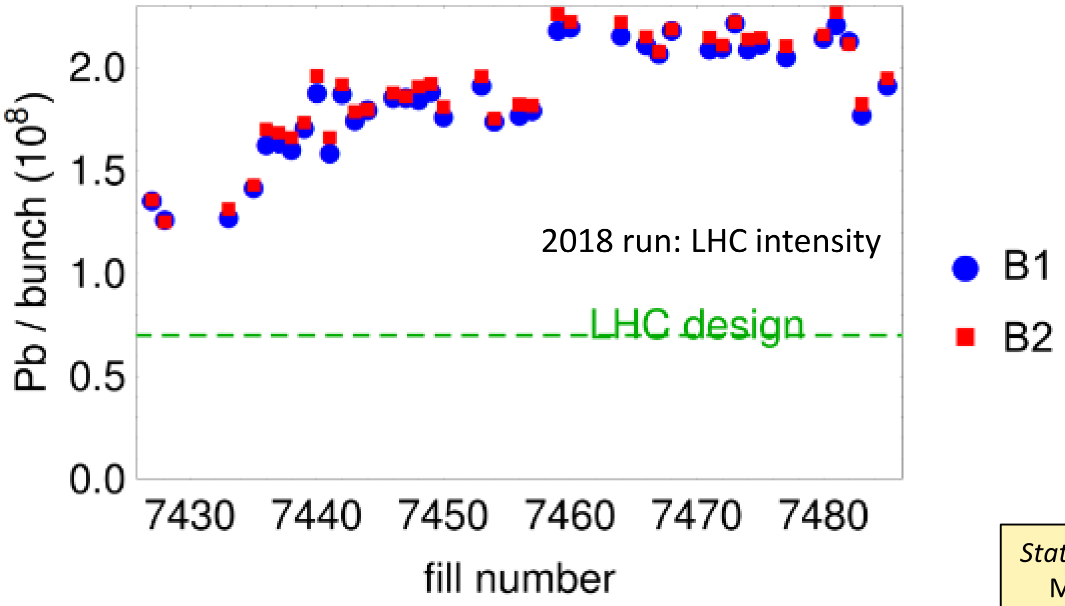
1^{st} source refill

New Record Peak luminosity in every fill up to $6.1 \times 10^{27} cm^{-2}s^{-1}$

ALICE polarity switch

2^{nd} source refill

Pb bunch intensities in 2018



As usual, LHC luminosity depends on injected intensity.

Major increase with switch from 100 ns to 75 ns scheme during 2018 run.

Status and studies of Pb beam in LHC injectors:

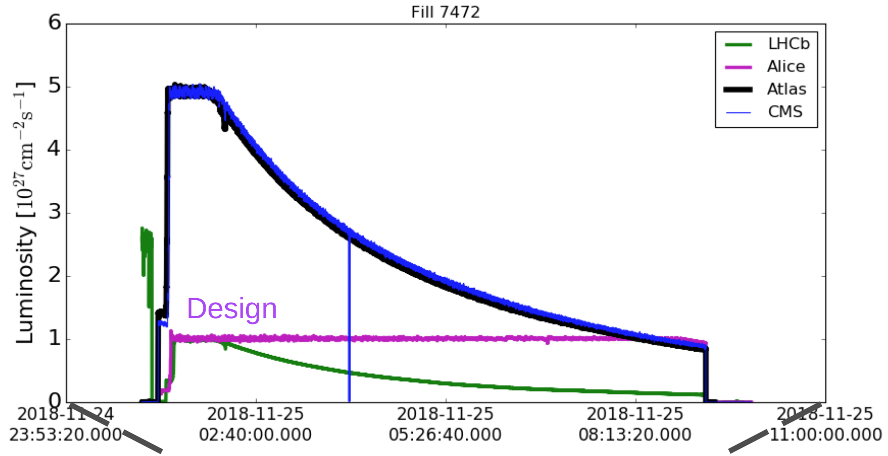
- M. Meddahi et al, **THXPLM1**
- S. Hirlaender et al, **WEPTS040**
- A. Saa Hernandez et al, **WEPTS042**
- H. Bartosik et al, **MOPGW069**
- T. Argyropoulos et al, **WEPTS039** and **MOPGW070b**

Typical Luminosity Evolution in 2018

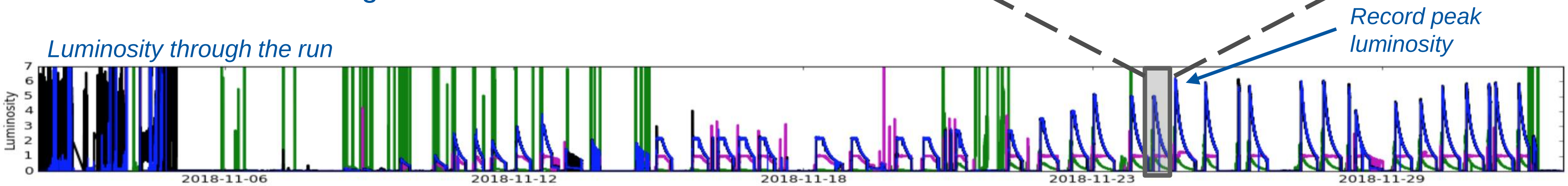
ATLAS & CMS:
Short levelling period
Record: $6.1\times10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ peak luminosity

ALICE:
Levelled to design saturation level most of the time in physics.
Upgrade to ~$7\times10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in LS2.

LHCb:
Also levelled to design value



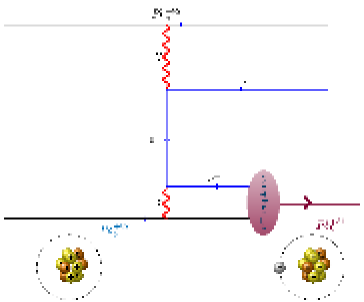
Luminosity through the run



Secondary beams created in nuclear collisions

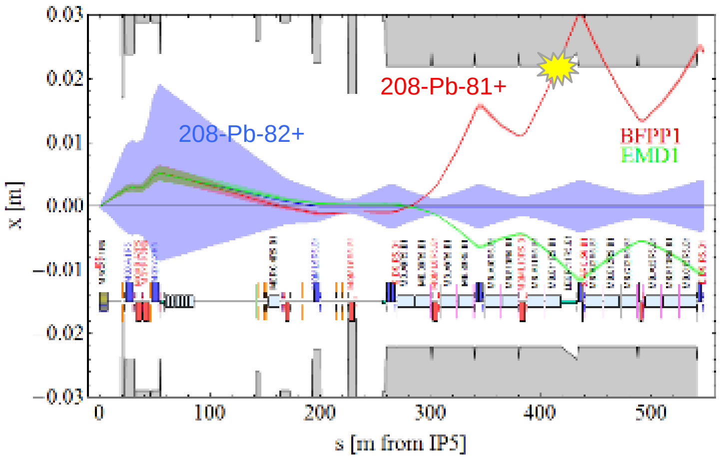
Bound-free pair production (BFPP)

$$^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+}$$



Has large interaction cross-section (~280b) in Pb-Pb collisions and is the main contribution to (~500 b) fast luminosity burn-off.

Secondary beams impact in superconducting magnets downstream the interaction points.

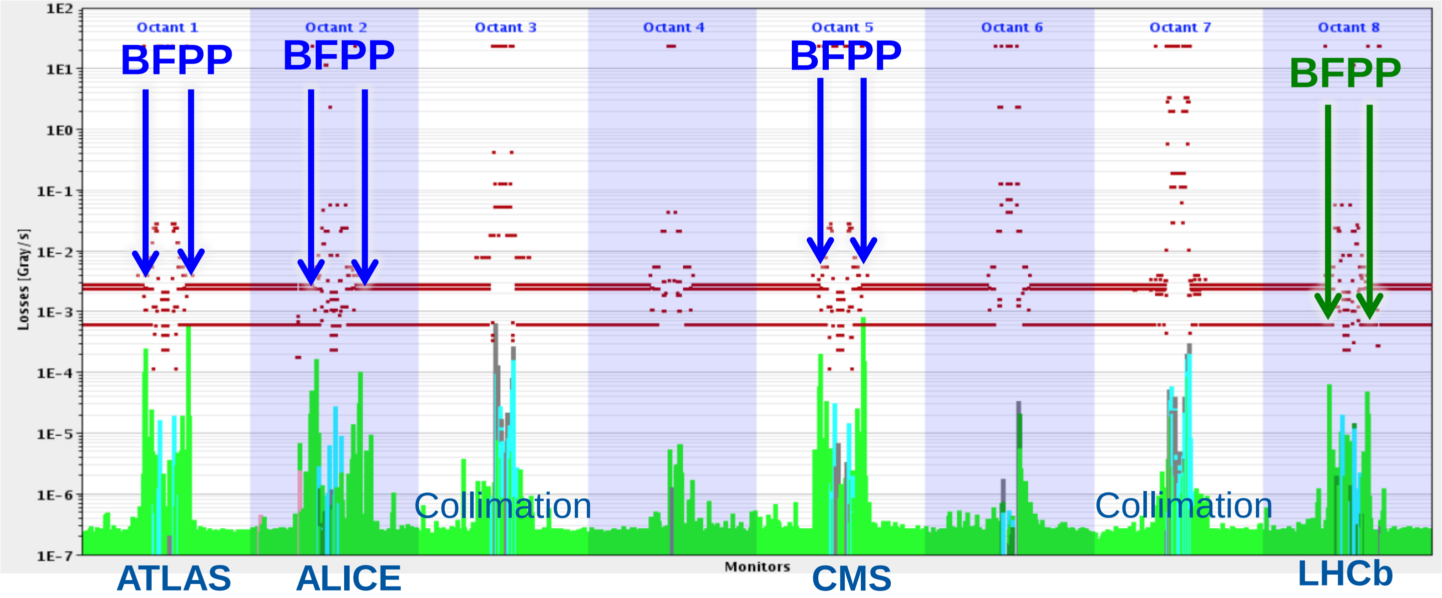


Loss Pattern around the Ring

Loss spikes around all IPs where ions collide …

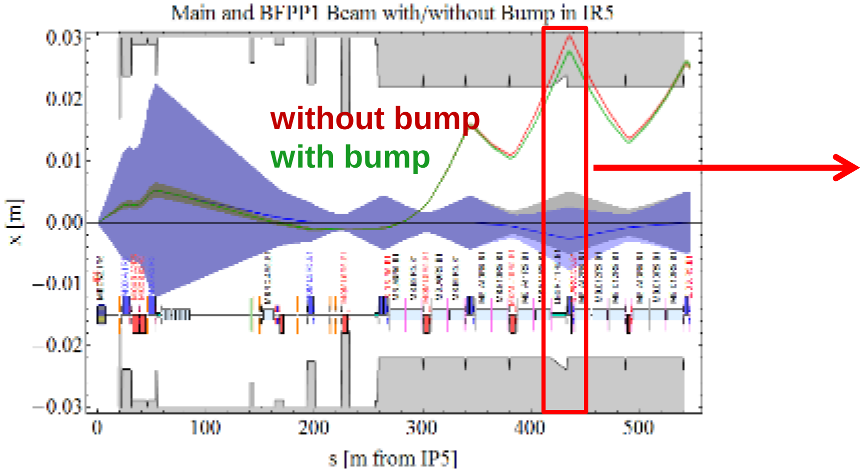
Deposited power >140W exceeds quench limit of the superconducting magnets.

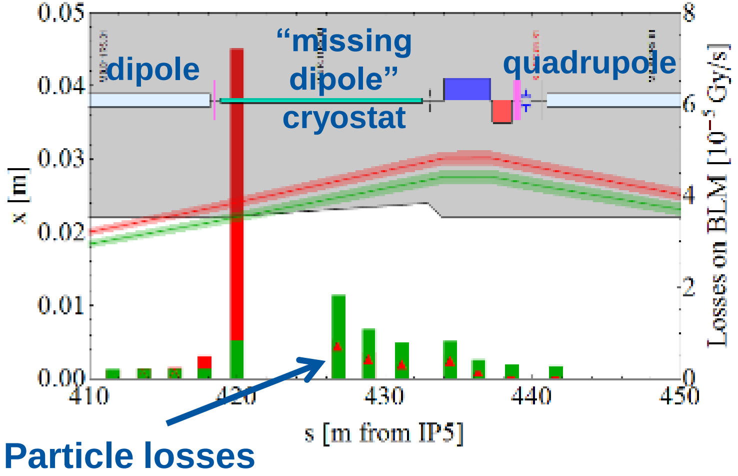
Luminosity limit found at $L \approx 2.3\times10^{27} cm^{-2}s^{-1}$ in 2015 (≅50W into magnet)



Quench Risk Mitigation with Orbit Bumps

Orbit bumps are used to move the secondary beam losses to a less vulnerable location in order to reduce risk of quench.





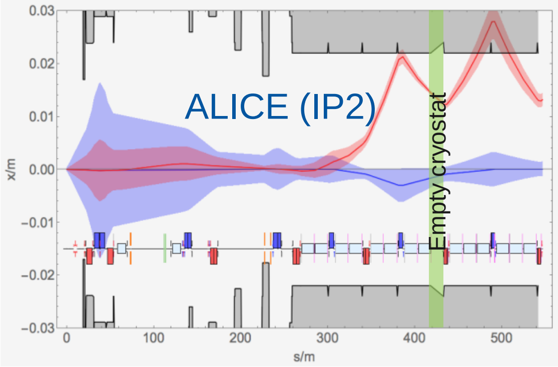
Technique operationally used in ATLAS/CMS since 2015.
2018 run showed that it guarantees "HL-LHC" nominal luminosity (and beyond).

BFPP Mitigation around ALICE & LHCb

Because of different optics around ALICE and LHCb, bump technique does not work.

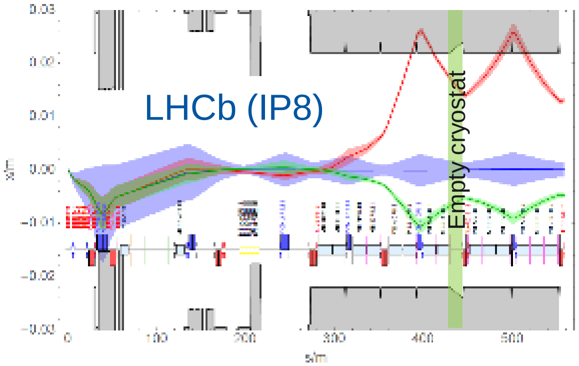
ALICE

- Peak luminosity limited by detector saturation to **$1 \times 10^{27} cm^{-2} s^{-1}$**.
- Bump to distribute losses over two cells.



LHCb

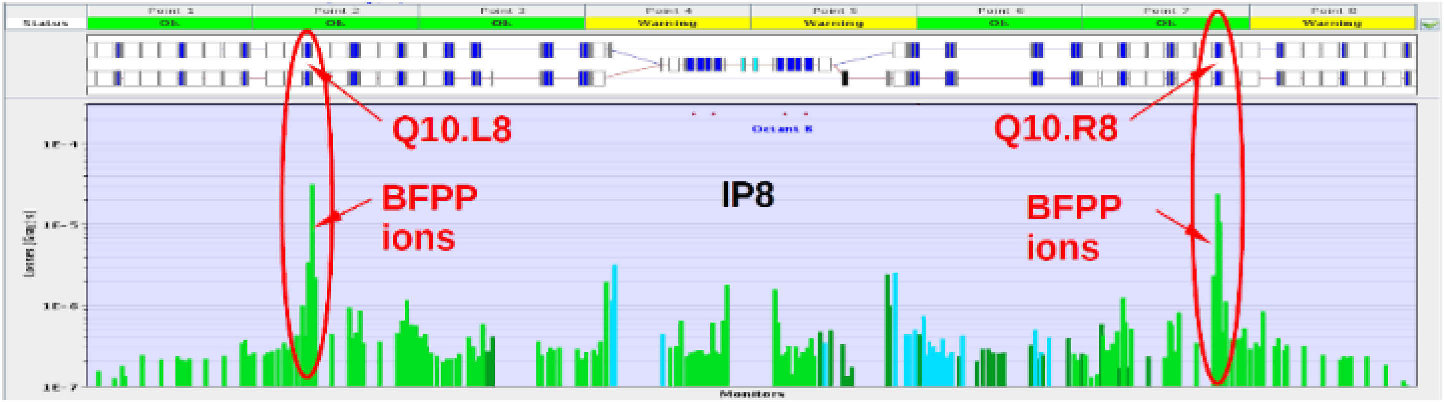
- **No mitigation implemented.**
- 75ns bunch scheme provides many more collisions in LHCb.
- Peak luminosity levelled **$1 \times 10^{27} cm^{-2} s^{-1}$**



BLM Threshold changes

BFPP-related threshold changes essential for luminosity reach:

1) **Prevent premature dumps due to BFPP ions in IR1/5**
   - Several threshold and orbit bump optimizations around BFPP loss location (connection cryostats) -> could reach the target luminosity (6-7x10^{27}cm^{-2}s^{-1}) while still protecting against quenches
2) **Prevent premature dumps due to BFPP ions in IR8**
   - Luminosity reach in LHCb higher than in previous years (10^{27}cm^{-2}s^{-1}) thanks to 75 nsec bunch spacing
   - BFPP loss location around Q10: Q10s had low thresholds to reduce the risk of symmetric quenches -> would have prevented reaching the target lumi
   - Decided to temporarily decrease QPS thresholds, which allowed an increase of the Q10 BLM thresholds



A. Lechner et al

Collimation of Heavy Ions

Heavy-ion runs are challenging for collimation:

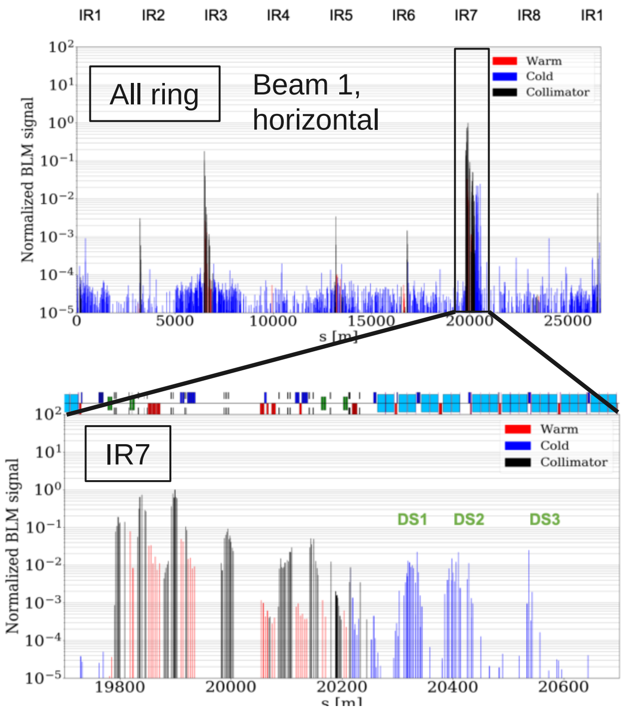
- Fragmentation and electromagnetic dissociation of nuclei within the collimator jaws.
- Cleaning efficiency ~100× worse than for protons.
- More cold losses (blue), especially in the dispersion suppressor (DS) behind collimation insertion (IR7).
- Risk of limiting the intensity

2018:

- Mitigation of loss spikes by optimizing collimator settings motivated by simulations.
- 7 out of 48 fills dumped by high losses.

For future runs: replacement of a dipole magnet by two 11T dipoles with a collimator in between.

From: N. Fuster-Martinez et al, **MOPRB050**



Plots courtesy of N. Fuster-Martinez

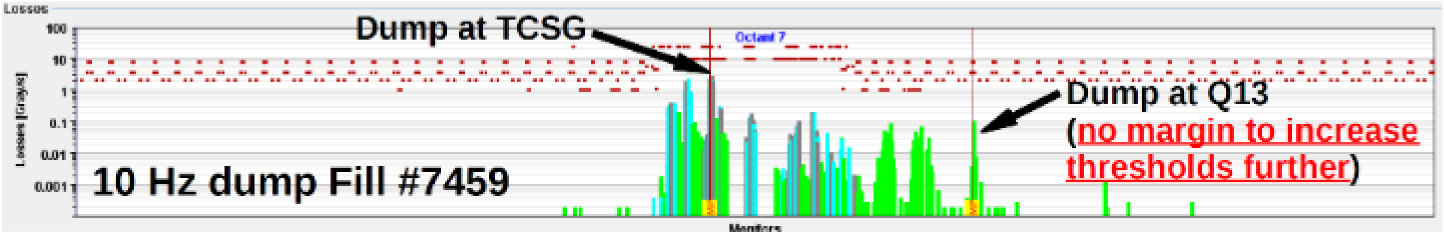
Measurement of collimation efficiency by introducing transverse losses on a safe low-intensity beam.

BLM Threshold changes

Collimation-related threshold changes essential for Pb halo losses:

1) **Adjusted the dumping hierarchy for Pb losses in IR7**
   - With proton thresholds, would dump first at cold magnets in DS (cleaning inefficiency about a factor of 100 worse for Pb than for protons)
   - Decreased master thresholds at two skew secondary collimators to dump first at these collimators
2) **Aligned corrections for collimation losses to the energy of the Pb run**
   - In proton operation FT corrections only active above 6.39 TeV (Pb run: 6.37 TeV)
   - Extended all collimation-related FT corrections to 6.37 TeV
3) **Removed bottlenecks due to leakage of ion fragments from IR7**
   - Increased the master thresholds at DS magnets according to 2015 Pb quench test to avoid premature dumps

Despite all optimizations in DS, **10 Hz dumps in IR7 were unavoidable**:



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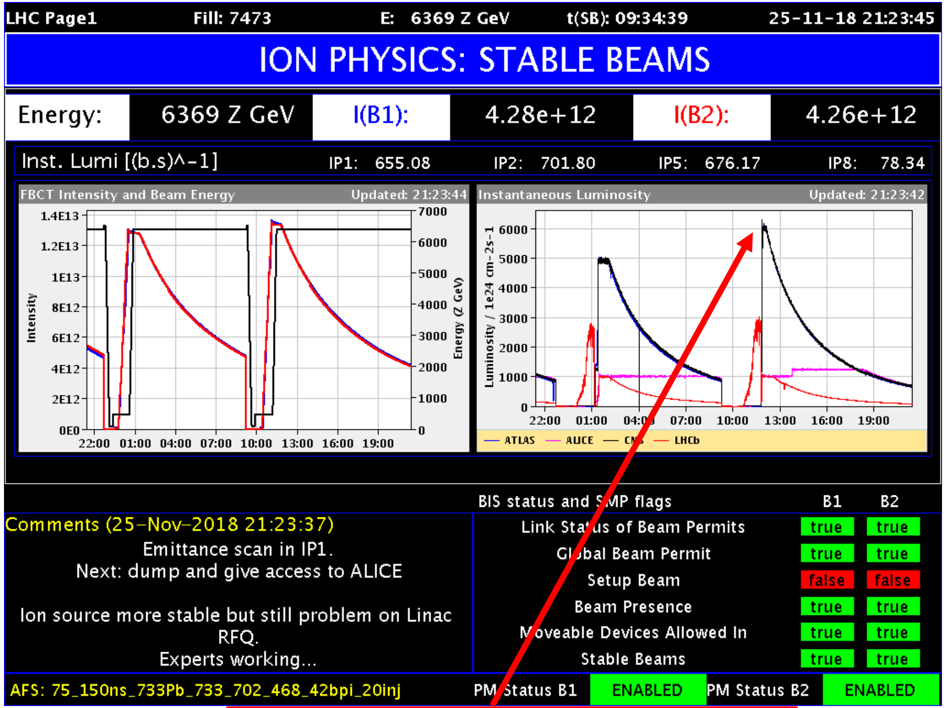
Peak Pb-Pb luminosity record, 25 November 2018



$$L = 6 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

$$= 6 \times \text{design}$$

= (47 kHz hadronic event rate)

Nominal HL-LHC levelling value is

$$L = 7 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

Comparison of BFPP losses with dump thresholds (specially set in BFPP loss zones) shows that we can go considerably further.

Status vs. nominal "HL-LHC"

Most of HL-LHC performance demonstrated!

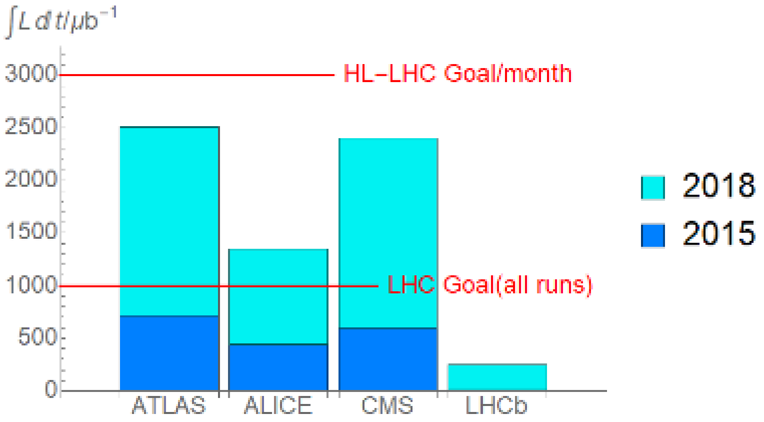
	Pb-Pb (Design)	Pb-Pb (2018 achieved)	"HL-LHC" Pb-Pb (after LS2)	Upgrade Status	
Energy [TeV]	7 Z	**6.37 Z**	7 Z	red	Magnet training
β* at IP (1/2/5,8) [m]	(0.5, -)	**(0.5, 1.5)**	(0.5, 1.5)	green	
Emittance [μm]	1.5	**~2**	1.65	green	
Bunch **Intensity** [10^8 ions]	0.7	**2.2**	1.8	green	
No. Bunches	592	**733**	1232	red	SPS RF Upgrade (slip-stacking)
Bunch Spacing	100ns	**100ns → 75ns**	50ns	red	SPS RF Upgrade (slip-stacking)
Peak **Luminosity** at IP1/2/5/8 [10^{27}cm^{-2}s^{-1}]	- / 1 / 1 / -	**6.1 / 1 / 6.1 / 1**	7 / 7 / 7 / ?	yellow	Lumi levelling

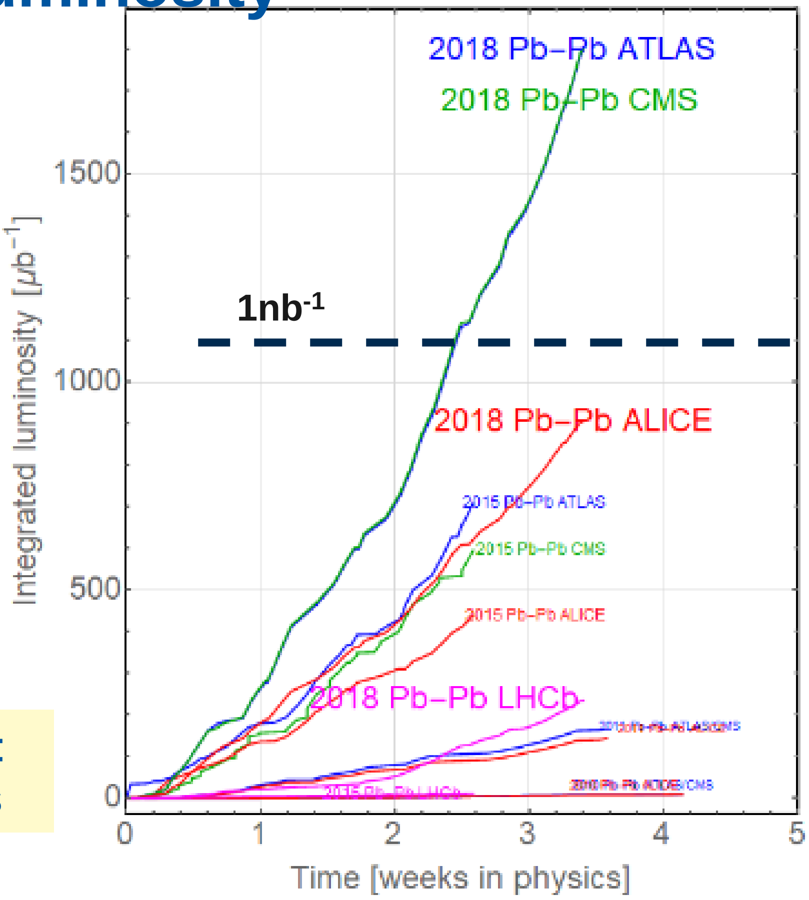
Green values reached & exceeded LHC design

Some collisions in LHCb (not considered in detail yet)

Delivered Luminosity

LHC design first phase goal of 1 nb^{-1} Pb-Pb luminosity (in 2 experiments) already far exceeded.

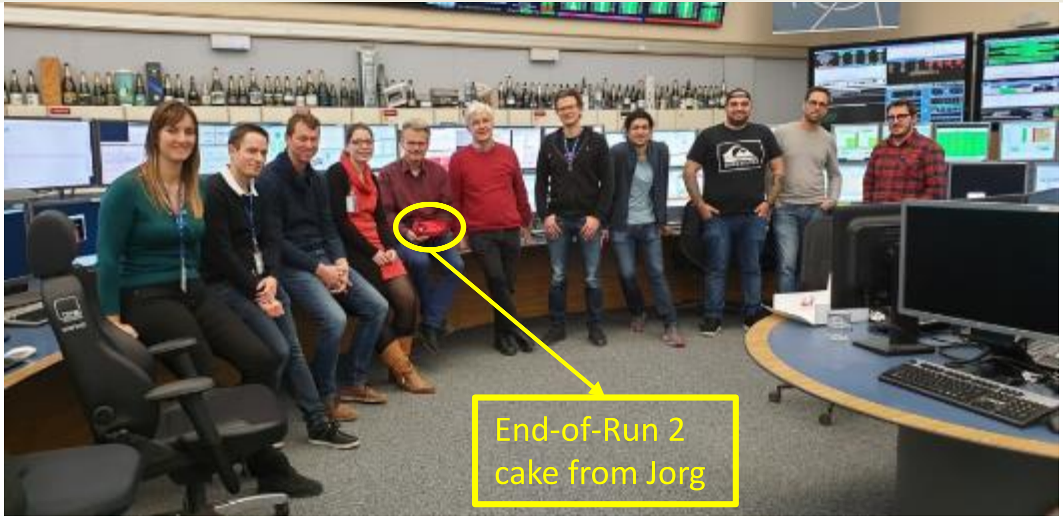




Future Pb-Pb performance from 2021 onwards:
3 nb^{-1}/run → 12 nb^{-1} in 4 more Pb-Pb runs

Unfinished business … the BFPP Quench MD

Thanks to everyone concerned for 3 years of analysis and elaborate preparation following the first successful beam-induced quench with BFPP from Pb-Pb in 2015.



Scheduled from 00:00 to 06:00, 3 Dec, the last few hours of Run 2.
Intended to resolve ambiguities from misaligned chamber in 2015 BFPP quench experiment.

Thanks to PS, LEIR and Linac3 teams who all scrambled in the middle of the night to repair a series of faults and intervene.

- PS main magnet fault
- LEIR performance degraded, cannot fix?
- HI source instability and unexpected deterioration of stripper foil after Linac3

We hope to (re-)measure the steady-state quench level of the LHC dipole in **Nov 2021** …

Lessons from the 2018 Pb-Pb run

- BFPP bump mitigation allows HL-LHC peak luminosity in ATLAS/CMS without quenches (> 6 × design).
- 75 ns filling scheme works very well, bunches at limit of stability in SPS
  - Provides many more collisions for LHCb, who can take them!
  - Peak luminosity up to 10^{27} $cm^{-2}s^{-1}$ does not quench LHCb
- "Invisible" local coupling at IR2 reduced ALICE luminosity in first half of run
  - Solved by skew-quad knob that reversed error in settings
  - Avoid same problem in future with specific checks
  - More generally, one should plan set-up phases with *just-in-time validation*
    - We had planned to validate reversed polarity earlier, before finding the solution. This would have been lost time. *So leave validation until just before luminosity operation.*

Conclusion

extraordinary injector performance

Rapid commissioning a & upgrade steps during runs

The LHC Heavy-Ion performance is much higher than originally foreseen.

Control of heavy-ion beam losses, like collimation & BFPP, is critical, complicated and may surprise.

"first 10-year" Pb-Pb luminosity goal of $1 nb^{-1}$ has been exceeded

demonstrated "HL-LHC" peak luminosity performance

Heavy ions will continue at LHC at the end of 2021 after the injector and LHC hardware upgrades with the full "HL-LHC" configuration.

Backup slides

New Energy Frontier

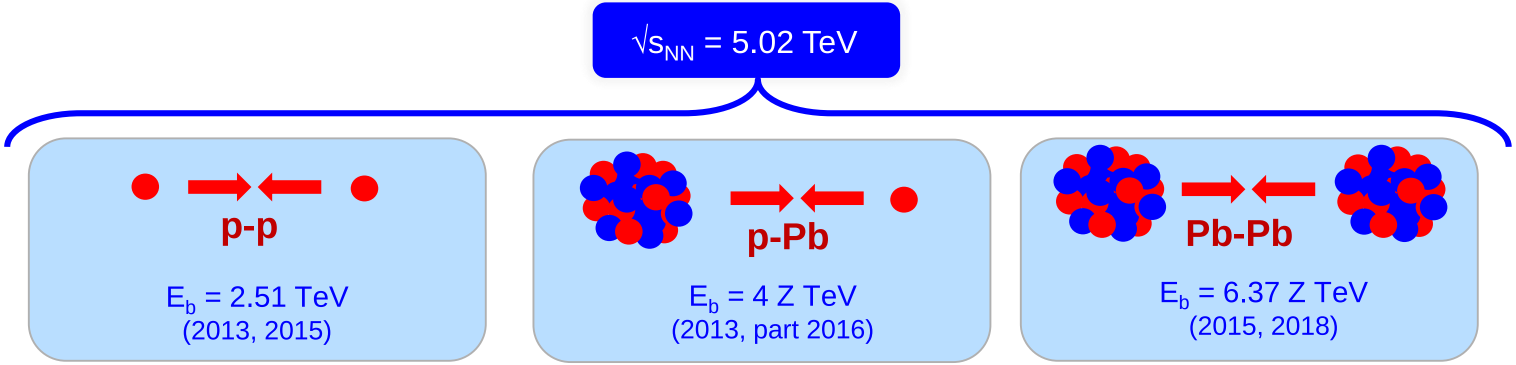
New energy frontier in nucleus-nucleus collisions.
Continues beyond RHIC ($\sqrt{s_{NN}} = \mathbf{0.2\ TeV}$) and previous fixed target experiments.

centre-of-mass energy per colliding nucleon pair:

$$\sqrt{s_{\mathrm{NN}}} \approx 2c\, p_{\mathrm{proton}} \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}$$

particle charge

Max. beam energy achieved in p-p collisions: E_b = 6.5 Z TeV.
For Pb-Pb, **beam energy** reduction to **E_b = 6.37 Z TeV.** → Compare 3 collision modes at the **same** $\sqrt{s_{NN}}$



Heavy-Ion vs. Proton Operation

- **Higher charge and mass: Beam dynamics and performance limits of heavy ions are quite different from those of protons.**

- Many beam dynamic effects are proportional to **high powers of Z**.
  → Strong Intra-beam scattering (IBS) α Z^4/A^2.
  → Radiation damping α Z^5/A^4.
  → Large event cross-sections for electromagnetic processes.

⇒ Fast intensity decay and **short luminosity lifetimes**.
⇒ **Secondary beams emerging from the interaction point** (IP).

BFPP Mitigation around ALICE

Due to different optics around **ALICE** (and LHCb), **bump technique does not work.**

→2018: Peak luminosity limited by detector saturation to 1 x $10^{27}cm^{-2}s^{-1}$

→LS2 Upgrades:

- ALICE detector upgrade to handle ~7 x $10^{27}cm^{-2}s^{-1}$
- Installation of **collimator in the empty cryostat** location.