# Prospects for ions at HL-LHC and outlook for FCC-hh

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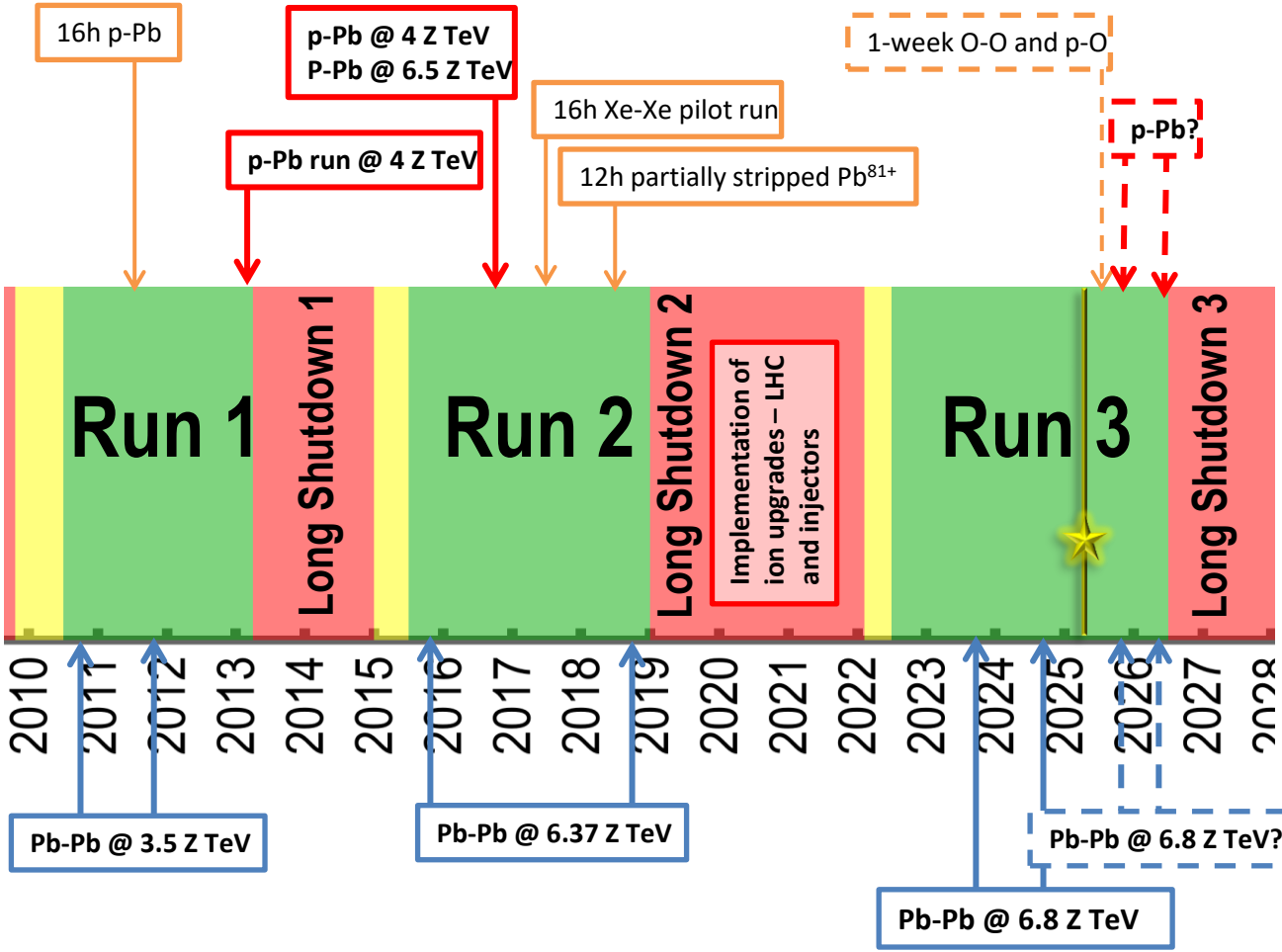
# Outline

- Introduction: LHC ion programme
- Ion operation in Run 3 and Run 4
- Ion operation beyond Run 4
- FCC-hh ion operation
- Summary

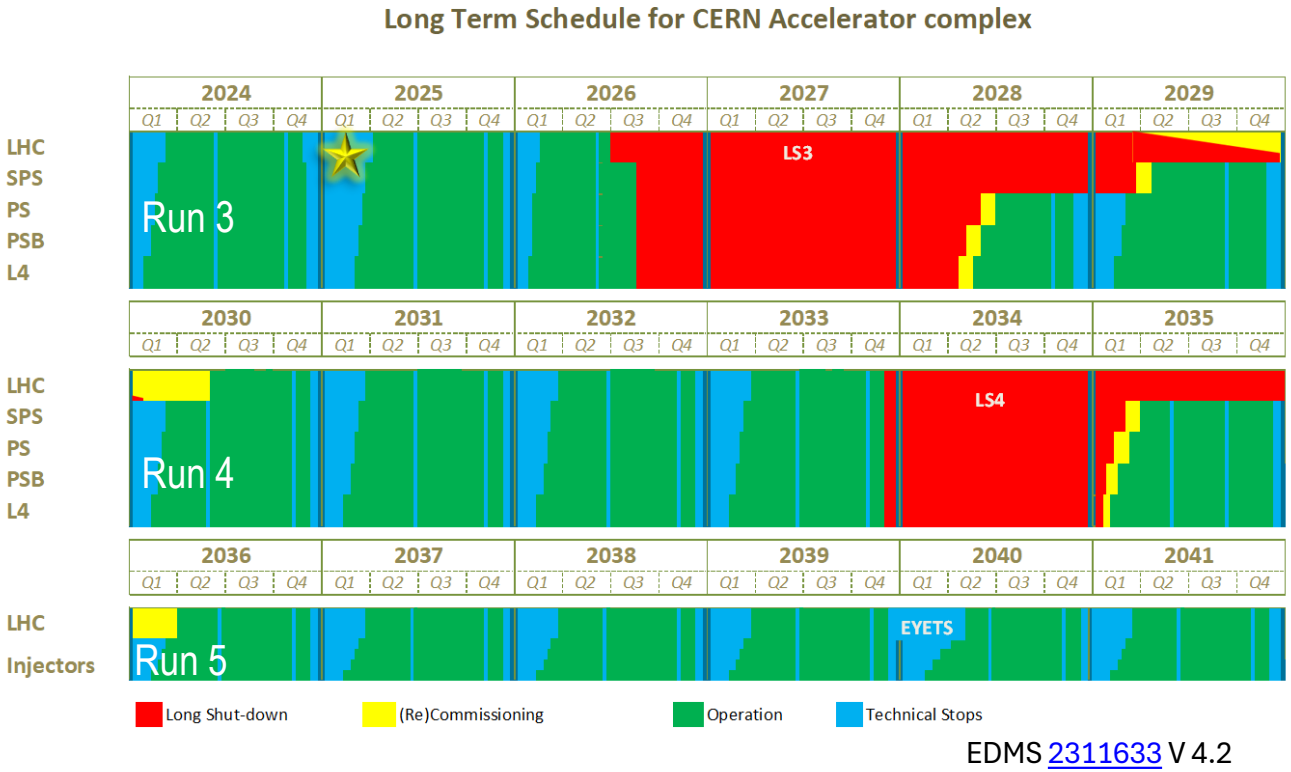
# Past LHC ion runs and main achievements

- **LHC typically runs 1 month per year with heavy ions**
  - So far Pb-Pb (6 runs), p-Pb (2 runs)
  - Short pilot runs in other configurations
- **LHC Run 3**
  - First Pb-Pb runs with all HL-LHC ion upgrades implemented
    - Shorter 50 ns bunch spacing from SPS, alleviation of collisional losses, …
    - ALICE 2 upgrade allowed higher luminosity



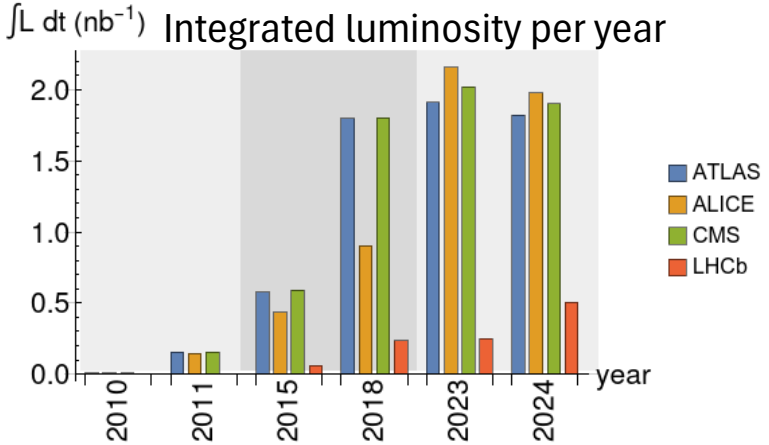
# Future of LHC heavy-ion programme

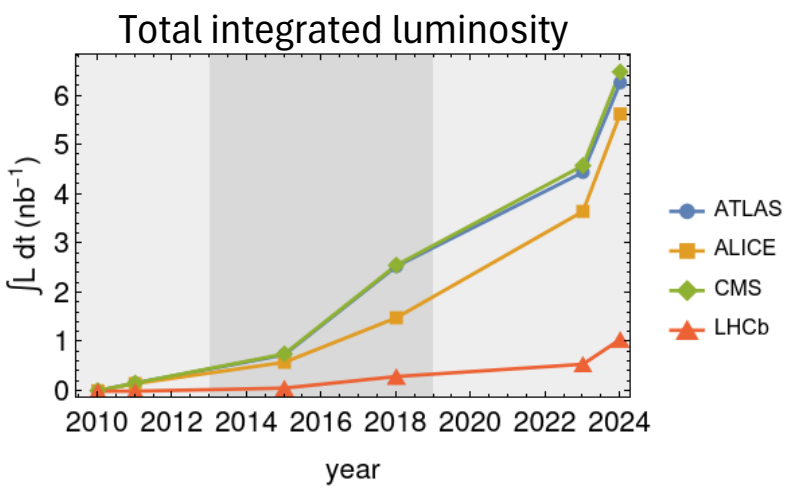
- **Run 4: HL-LHC**
  - Yearly Pb-Pb and/or p-Pb operation except 2030
  - Sharing between Pb-Pb and p-Pb not yet decided
  - Shorter pilot runs with other ions?
- **Beyond Run 4**
  - ALICE3: new detector for significantly higher nucleon-nucleon luminosity
    - Under study, not yet approved
  - LHC ion runs formally approved if ALICE3 goes ahead




EDMS 2311633 V 4.2

# Integrated luminosity so far




ALICE2 and HL-LHC upgrades in LS2 allowed higher luminosity from 2023

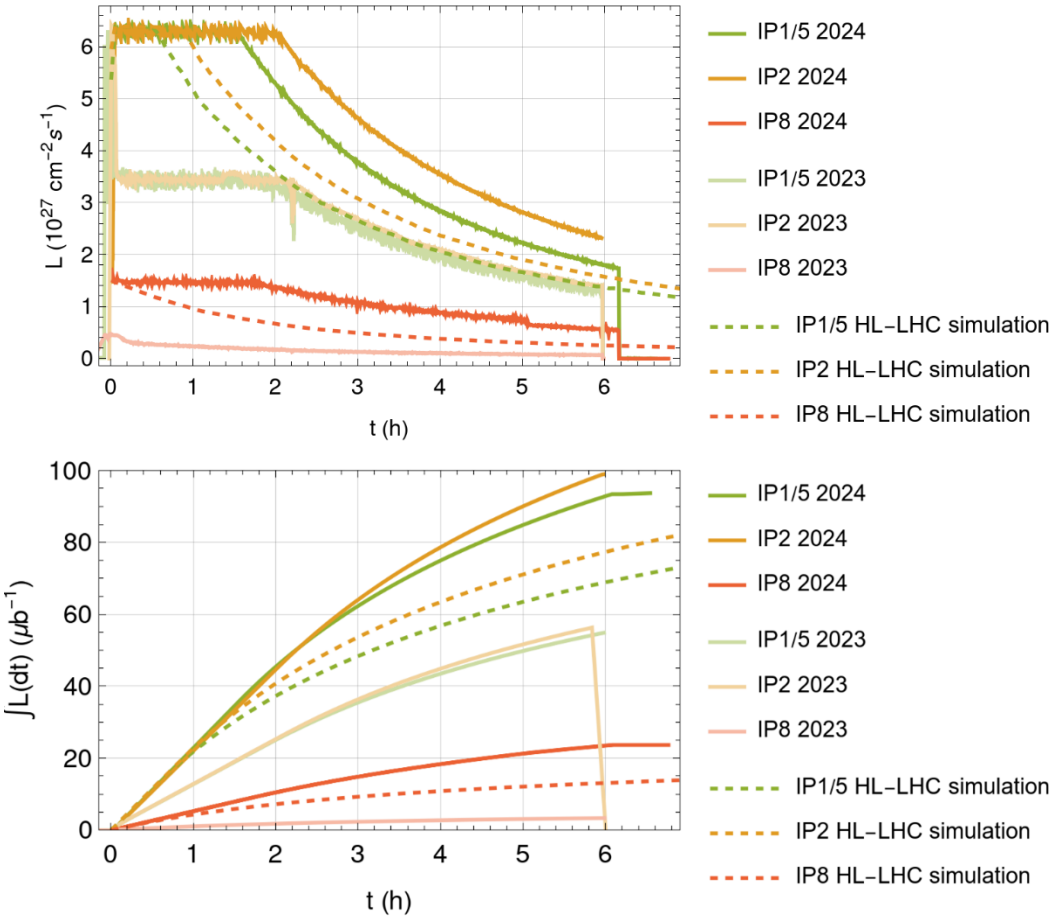
- **2024 was the by far best run so far**
  - Half of the time allocated compared to 2023

- **Total integrated Pb-Pb luminosity**
  - ATLAS: 6.3 $nb^{-1}$
  - ALICE: 5.6 $nb^{-1}$
  - CMS: 6.5 $nb^{-1}$
  - LHCb: 1.05 $nb^{-1}$

# 2024: surpassing nominal HL-LHC performance

- Achieved **levelling time up to about 2h** in ALICE
- 2024 luminosity production in single fills **surpasses by far 2023, and even HL-LHC projections**
  - After 6h, ALICE has about 80% more data than in 2023 and 30% more than HL-LHC prediction
  - After 6h, LHCb has 80% more data than in HL-LHC prediction
  - Reason: significantly higher bunch intensity from injectors; mitigation of LHC limitations
- **Plan for rest of Run 3 and Run 4: continue production as in 2024**
  - incremental improvements may be within reach, but probably not big factors

2024: fill 10400; 2023: fill 9285 (among the best fills each year)



# Physics goals from yellow report

- WG5 in the 2018 HL-LHC / HE-LHC physics workshop dealt with heavy-ion physics
- Yellow report details requests for Run 3 and Run 4, as well as proposal for extended heavy-ion running: CERN-LPCC-2018-07

– **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

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# LHC ion operation beyond Run 4

- **Aim at significantly higher nucleon-nucleon luminosity** than HL-LHC Pb-Pb
  - New ALICE3 detector under study, letter of intent prepared - to be installed in LS4 if approved

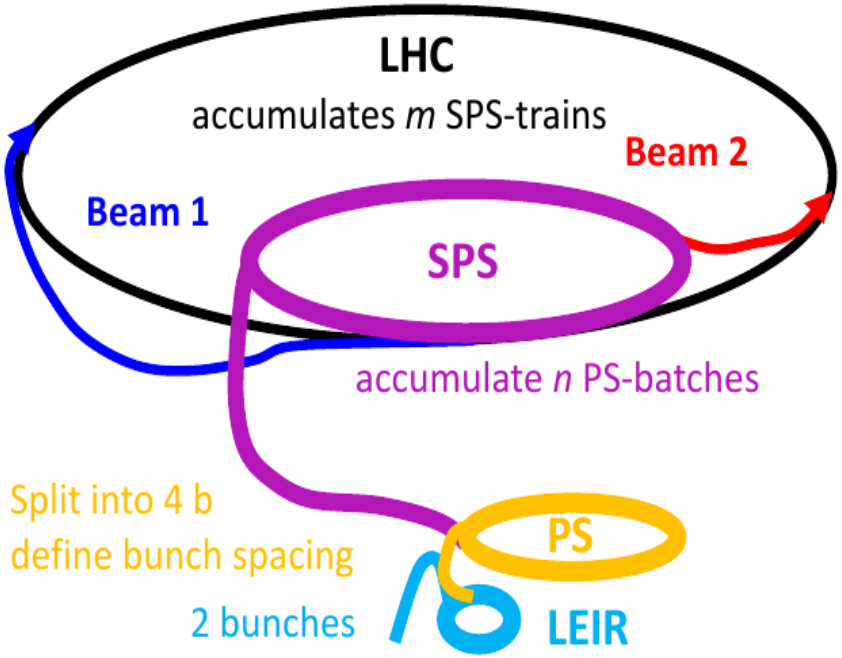
- Many optimizations and upgrades in the injectors already gave **factor >3 higher bunch intensities and factor >2 more bunches in 2024 than in LHC design report** (2004)
  - Not straight-forward to gain additional significant factors in Pb-Pb luminosity

- **Different ways to further increase luminosity under study**
  - Further optimizations and upgrades to the Pb beam production scheme in the injectors
  - Use another ion species than Pb
    - Potential to achieve higher bunch intensities from the injectors, and higher NN luminosity
    - Electromagnetic cross sections in the LHC collisions scale with powers of the charge – will be less limiting
  - Could combine both ways…

# Injector model

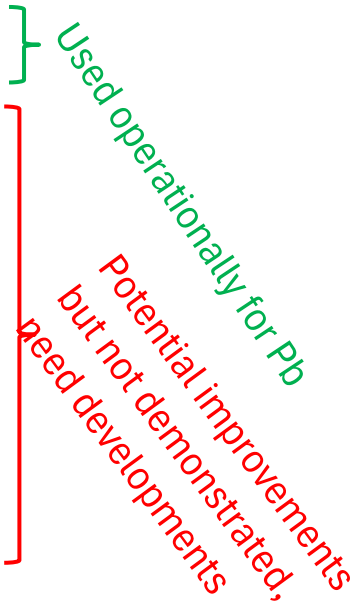
- **Need to estimate potential luminosity with other beams and ion species than Pb →**
  - Need to estimate beam properties given by the injectors
  - First rough estimate in WG5 yellow report based on fitted power law scaling
  - Detailed limitations in injectors not accounted for

- **"Injector model" developed over the last years**
  - For any ion, propagate beam through the injector chain, accounting for realistic limitations depending on ion charge, mass and energy
    - Space charge, electron cooling, …
  - Still under development - hope to add further features in the future



# Studied ions and scenarios

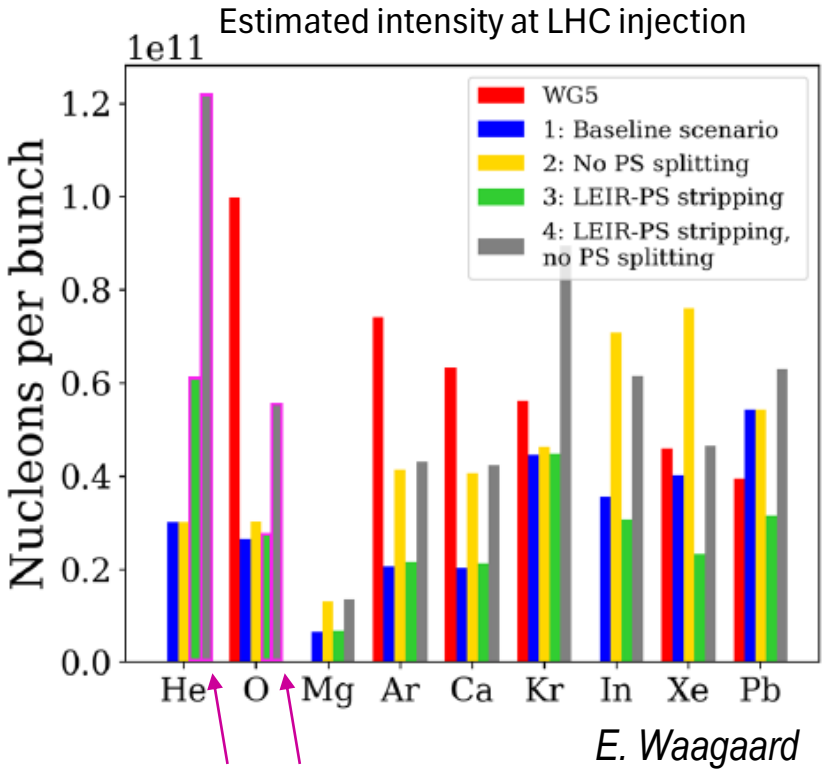
- **Range of ion species studied**
  - based on previous experience and ion source constraints
- **Range of beam production scenarios in injectors**
  - 50 ns baseline
    - Same as presently used for Pb in LHC
  - 50 ns, no splitting in the PS
    - Higher bunch intensity but fewer bunches and longer injection time
  - Any of the above scenarios with optimized charge state or isotope
  - Any of the above scenarios with additional electron stripping between LEIR and PS
  - 25 ns spacing
    - Requires upgrade of RF system in PS
    - 40% more bunches in LHC but longer injection time
    - Consider also scheme with 6 bunches from PS instead of 4 → more bunches in LHC and faster injection time, but lower bunch intensity




| Ion | Z | A |
|---|---|---|
| He | 2 | 4 |
| O | 8 | 16 |
| Mg | 12 | 24 |
| Ar | 18 | 40 |
| Ca | 20 | 40 |
| Kr | 36 | 86 |
| In | 49 | 115 |
| Xe | 54 | 129 |
| Pb | 82 | 208 |

# Projected intensities at LHC injection

- **Several iterations**
  - Latest version: scaling from demonstrated performance with 2024 Pb beams
- **Baseline scenario gives significantly lower bunch intensity than WG5**
  - Difference is larger for lighter ions
  - Much lower LHC luminosity to be expected than WG5

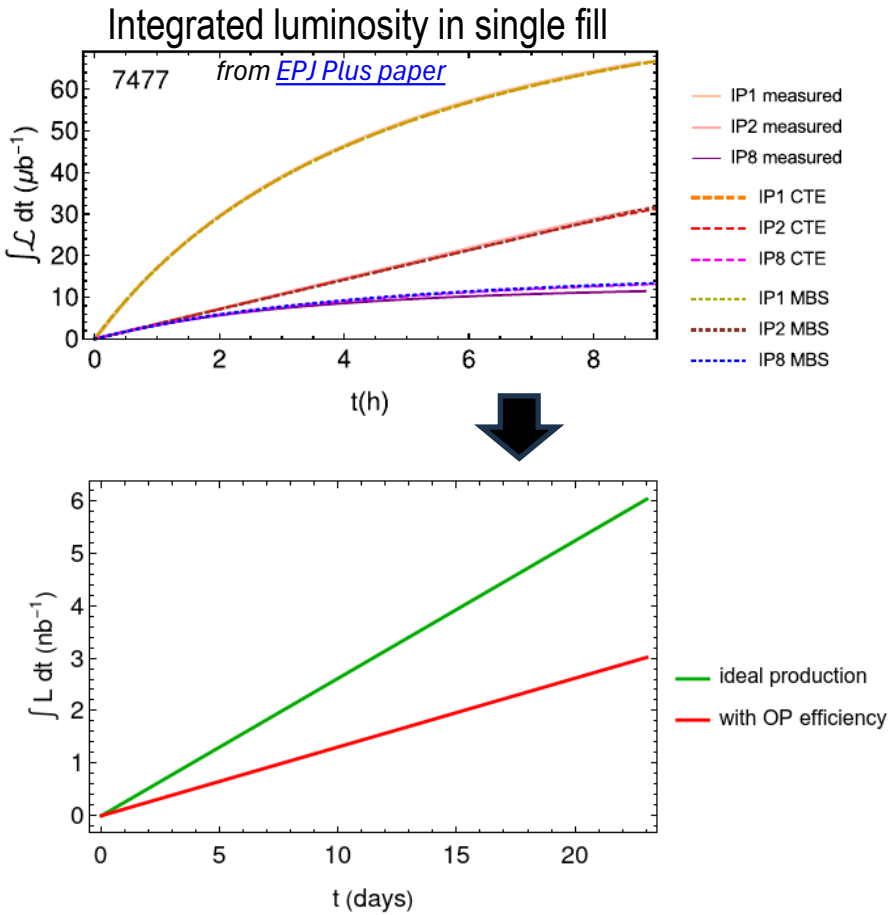


# 3 scenarios for LHC studies

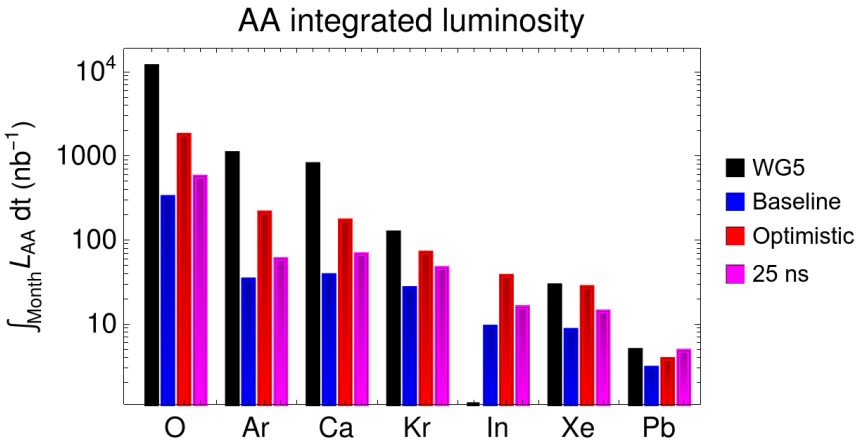
- **Baseline**
  - Using the well-proven scheme for Pb, extrapolate to other ions using our best knowledge and conservative assumptions
  - Assume proven LHC performance (β*, energy, transmission, operational efficiency)
- **Optimistic**
  - Assume scenario with no splitting in PS and best charge state; reduced β*,crossing in LHC
  - Account for fewer bunches, longer injection in LHC, giving also additional emittance blowup and lower transmission, extra LEIR injection from improved electron cooling
  - Has some optimism, clearly relies on assumptions that have not been proven yet
- **25 ns**
  - Assume bunch parameters and LHC configuration as in baseline scenario, but with small additional emittance blowup and intensity loss due to longer injection time
  - Not given that the experiments can handle 25 ns
  - Relies on assumptions that have not been proven yet and also additional hardware upgrades of the PS RF system
- **In all scenarios, assume that luminosity levelling is no longer needed. Assume also that collimation and collisional losses are not limiting → to be studied**

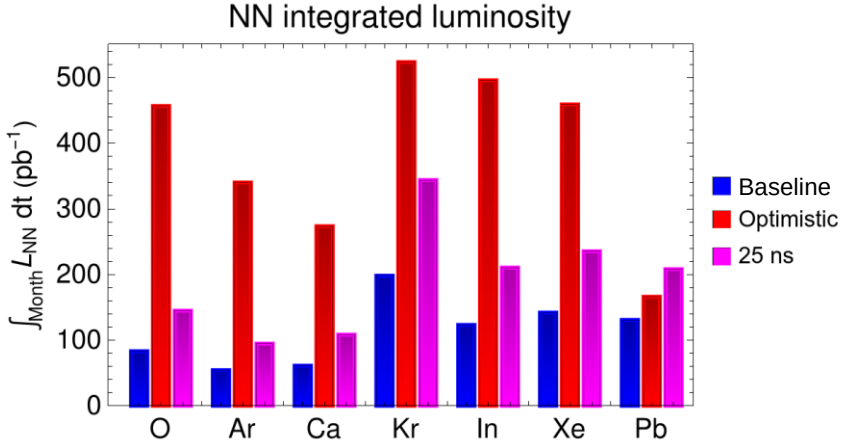
# LHC simulation setup

- **LHC luminosity in single fills simulated with Collider Time Evolution programme (CTE)**
  - Benchmarked with LHC Pb data – gives excellent agreement for known starting conditions
- **Single fill luminosity extrapolated to total data in typical 1-month run (23 days for physics)**
  - Calculate optimal fill time, calculate total production in ideal conditions, reduce results by assumed operational efficiency factor



# Projected one-month luminosity




- Even in optimistic scenario, we get significantly lower luminosity than in WG5 for most considered ions
- For optimistic scenario, we get up to a factor 4 gain in NN-luminosity compared to Pb-Pb
  - About 500 $pb^{-1}$ for Kr in optimistic scenario; 131 $pb^{-1}$ for Pb in baseline
  - WG5 had gain ratio of 25 compared to Pb-Pb (for O)
- In baseline scenario, up to 50% gain by using Kr instead of Pb
- 25 ns: with present assumptions pays off the best for the heavier ions
  - About 60% gain over Pb in baseline scenario
- Both optimistic and 25 ns scenarios rely on assumptions that have not been proven yet

# Projected one-month luminosity

Projected integrated AA luminosity over 23 days ($nb^{-1}$)

| | WG5 | 2025 cons. | 2025 opt. | 2025 25 ns |
|---|---|---|---|---|
| O | 11 700 | 325. | 1780. | 566. |
| Ar | 1080 | 34. | 213. | 59.2 |
| Ca | 799 | 38.2 | 171. | 67.7 |
| Kr | 123 | 26.8 | 70.8 | 46.5 |
| In | -- | 9.32 | 37.5 | 15.9 |
| Xe | 28.9 | 8.53 | 27.6 | 14.1 |
| Pb | 4.92 | 3.03 | 3.84 | 4.81 |

Projected integrated NN luminosity over 23 days ($pb^{-1}$)

| | WG5 | 2025 cons. | 2025 opt. | 2025 25 ns |
|---|---|---|---|---|
| O | 3000. | 83.2 | 457. | 145. |
| Ar | 1730. | 54.4 | 340. | 94.8 |
| Ca | 1280. | 61.1 | 274. | 108. |
| Kr | 748. | 198. | 524. | 344. |
| In | 0. | 123. | 496. | 211. |
| Xe | 481. | 142. | 459. | 235. |
| Pb | 213. | 131. | 166. | 208. |

# Evolution of predictions

- Over the years, the **predicted luminosity has evolved**, following improvements of the modelling and accounting for the progress in operation

- **Work is ongoing - results likely to evolve further in the future**
  - Expect further updates based on achieved performance in 2025 oxygen run
  - Several parts of modelling still missing: interplay between intrabeam scattering and space-charge, space-charge tune shift dependent transmissions instead of hard cut-off

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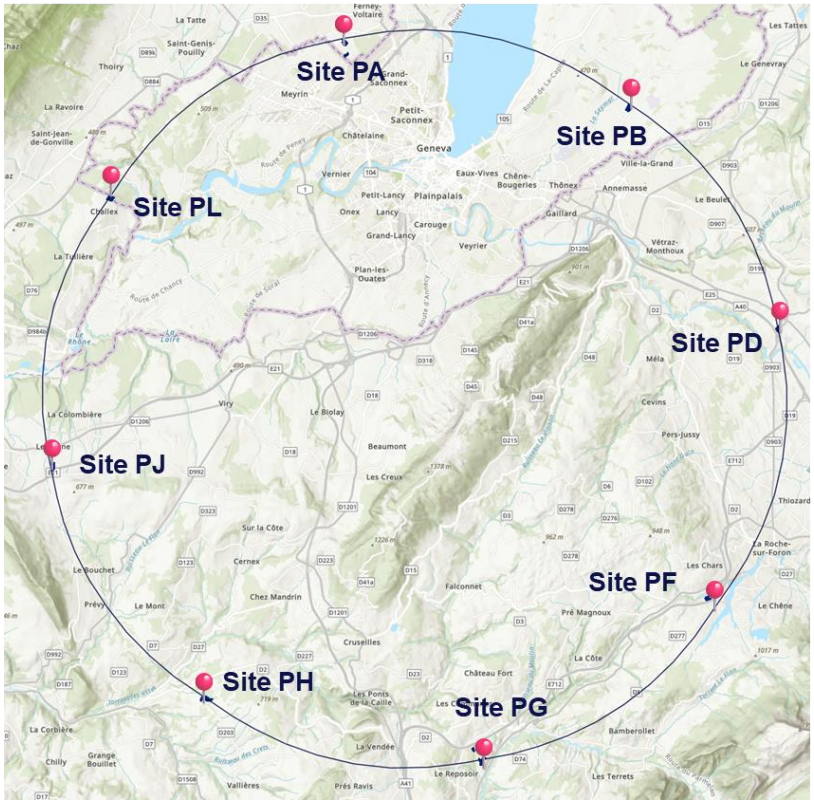
# FCC-hh

- **FCC: design study of future ~91 km ring**
  - Would operate after HL-LHC
  - **FCC-ee**: First stage with e+e- collisions
  - **FCC-hh**: Second stage with p-p and A-A collisions
    - Present assumption: 14 T magnets, 85 TeV c.m. energy
    - CDR (2018): 16 T magnets, 100 TeV c.m. energy

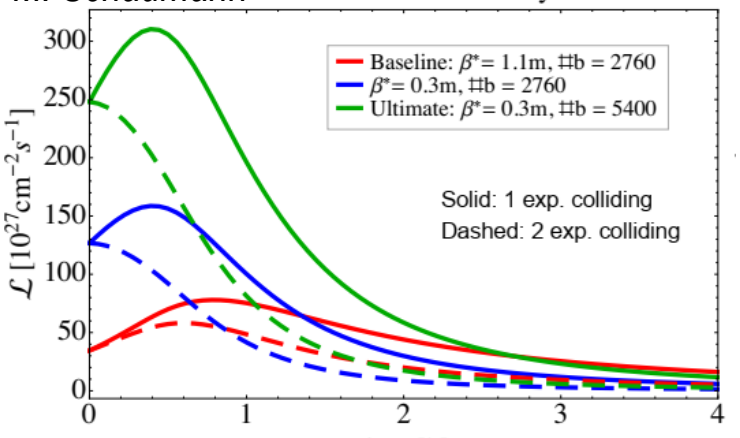
- **Nuclear collisions part of FCC-hh programme**
  - In 2019 CDR, assumed Pb-Pb and p-Pb collisions



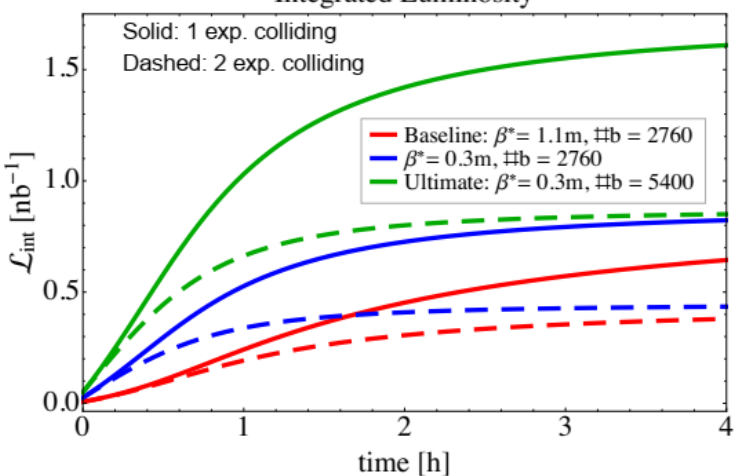
# Heavy-ion studies for FCC-hh (CDR)

- **Assumptions:**
  - up to 5400 bunches per ring with $2\times10^8$ Pb/bunch, 50 ns spacing
  - LHC as injector – rather slow filling
  - 100 Z TeV c.m. energy
  - 1 or 2 experiments taking ion collisions
- **FCC-hh has potential to give very high ion luminosity**
  - With 2 experiments, estimated 30-day integrated Pb-Pb luminosity of 23-62 $nb^{-1}$
- **All studies need to be updated for the latest baseline**
  - Pb bunch intensity, fewer bunches, lower energy
  - IP optics remained the same
- **Challenges to be studied and solved**
  - collisional losses, collimation, long injection cycle, maintaining ion injector capabilities
  - Potentially consider other ions than Pb – relaxes limits from collisional losses

*M. Schaumann* Instantaneous Luminosity




Integrated Luminosity



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# Summary

- **In Run 3 and Run 4**
  - LHC will continue operation with Pb-Pb and/or p-Pb for about 1 month per year
  - HL-LHC performance established and significantly surpassed in 2024
  - Envisage shorter “pilot runs” with other ions as for Xe in 2017 and oxygen in 2025?

- **Beyond Run 4**
  - LHC ion runs approved
  - Aiming at significantly higher NN luminosity
  - Investigating alternative ion species and beam production schemes

- **Performance studies for beyond Run 4**
  - Injector model developed to estimate achievable intensity for a range of ions
  - LHC simulations to study luminosity
  - Potential to reach up to factor ~4 higher NN luminosity with alternative ions and production schemes
    - Relies on optimistic assumptions, still to be proven

- **Studies will continue**
  - Important to gather further information and improve the models – simulations and experimentally
  - Expect valuable information from 2025 oxygen run and updated results

- **FCC-hh**
  - Potential for large leap in ion luminosity
  - Scenarios to be updated and several challenges to be studied

# Thanks for the attention!

# Backup

# Past LHC ion runs and main achievements