Prospects for light-ion operation at the HL-LHC

machine developments and physics opportunities

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On behalf of the **Future Ions Working Group, Oxygen for LHC Project & Physics Beyond Colliders Accelerator Opportunities Working Group**

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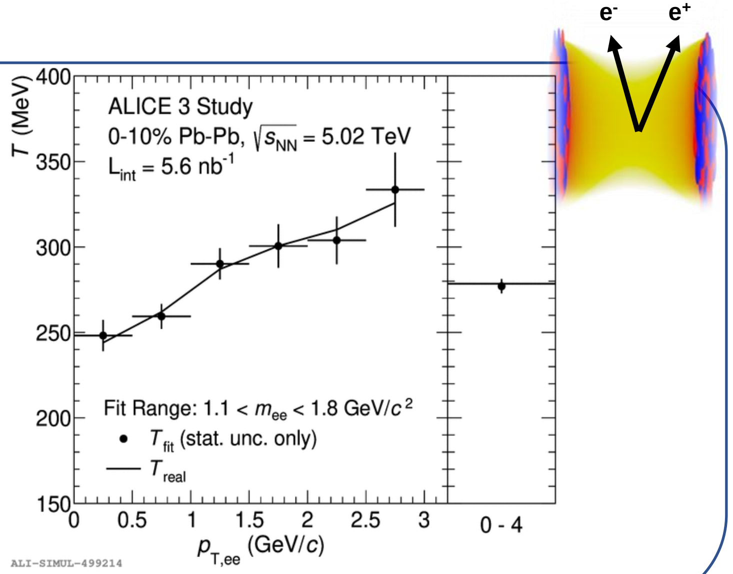
12th Edition of the Large Hadron Collider Physics Conference

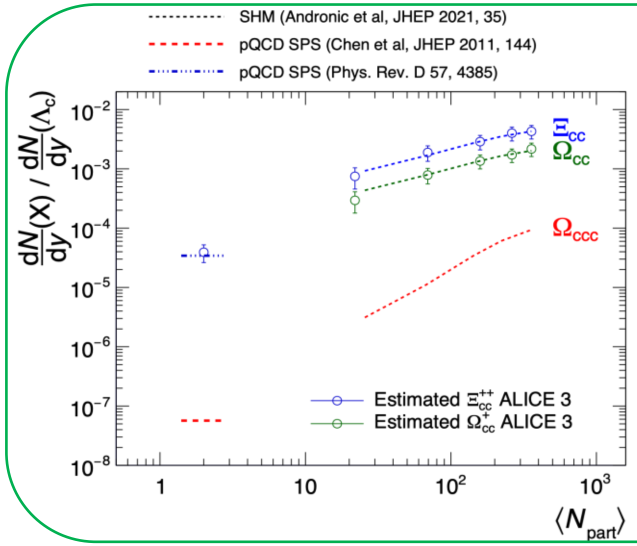
Physics opportunities requiring large L_{nn}

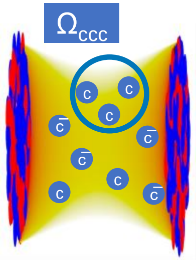
Ions lighter than Pb could potentially give higher L_{nn}

- Accurate measurements of charm and beauty hadrons + correlation over a wide η range
  - study transport of heavy quarks in the QGP down to the thermal scale
- Systematic measurements of multiply heavy-flavoured hadrons
  - study how quarks combine into hadrons depending on their degree of thermalisation
- Time-evolution of QGP temperature with thermal dileptons
- Precise measurement of double-charm hadrons:
  - Multi-charm baryons vs system size → new insights in thermalisation and hadronisation

Differential study of thermal radiation (temperature), including elliptic flow, requires very large samples





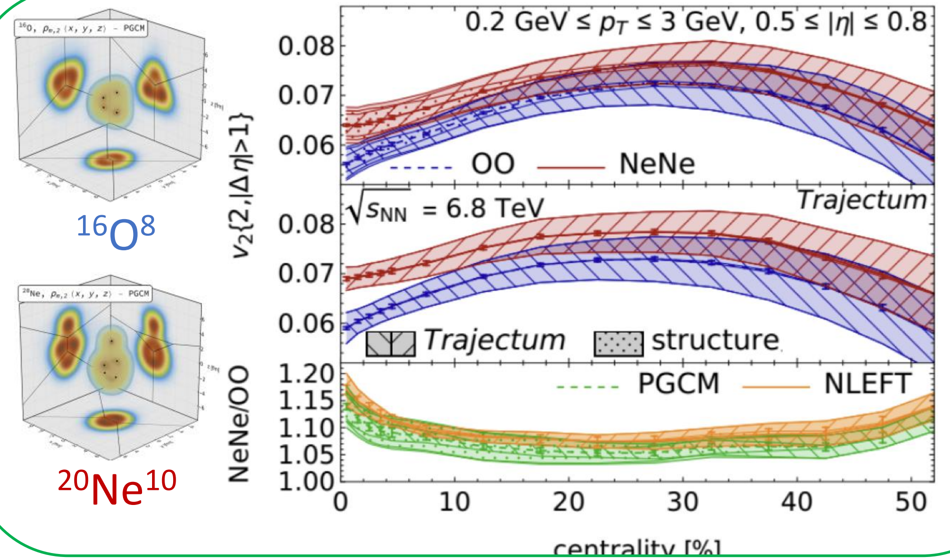


Double-charm hadrons accessible with Pb-Pb, but larger L_{NN} would provide precise measurements

Physics opportunities with lighter ions

- QGP transport coefficients: quantitative tests of hydrodynamics in a small system ➔ observation of unambiguous imprints of the initial-state geometry on the collective flow [3]
  - Collisions of pairs to cancel theoretical uncertainties
  - Not very demanding in luminosity ➔ pilot runs could be sufficient

- Clustering plays a crucial role in studying nuclear structure. Protons and neutrons in many-body nuclear systems tend to form clusters in order to reduce overall energy or boost system stability [5]



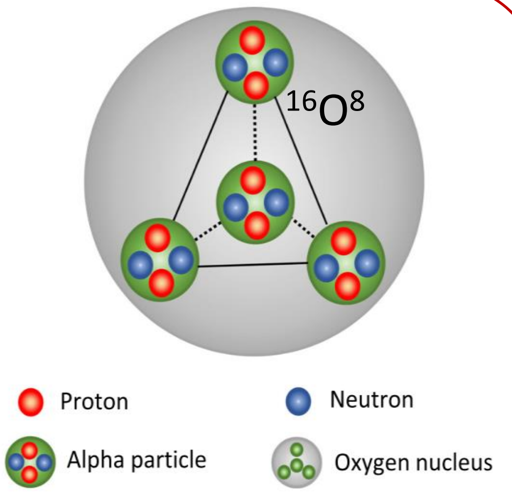


Fig. 2 Depiction of α-clustered structure in oxygen nucleus

Physics opportunities with lighter ions

- Fixed-Target collisions at LHC: LHCb SMOG2 ➔ perform beam-target collisions at relativistic energy of $\sqrt{s_{NN}}$ ~ 100 GeV to image nuclear ground states [6,7]
  - No difference in the observed J/ψ suppression trend when comparing p-Ne and Pb-Ne peripheral collisions with Pb-Ne central collisions

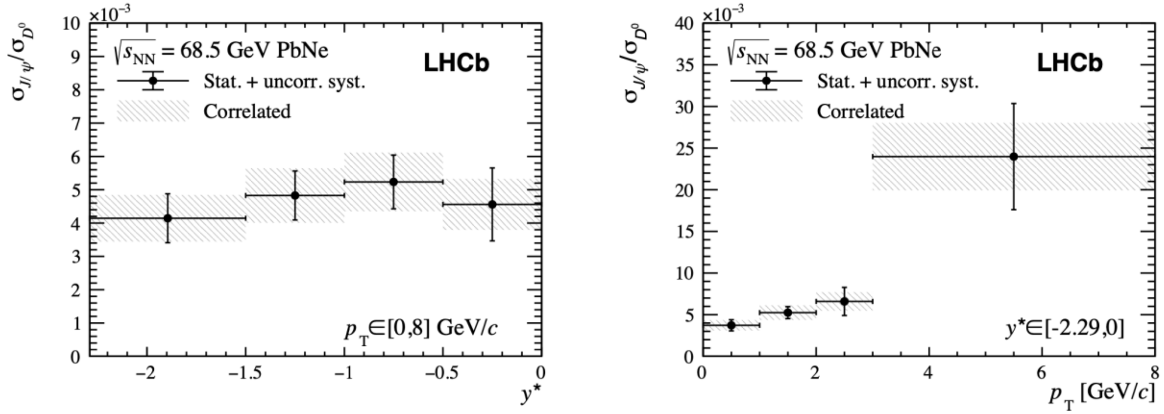
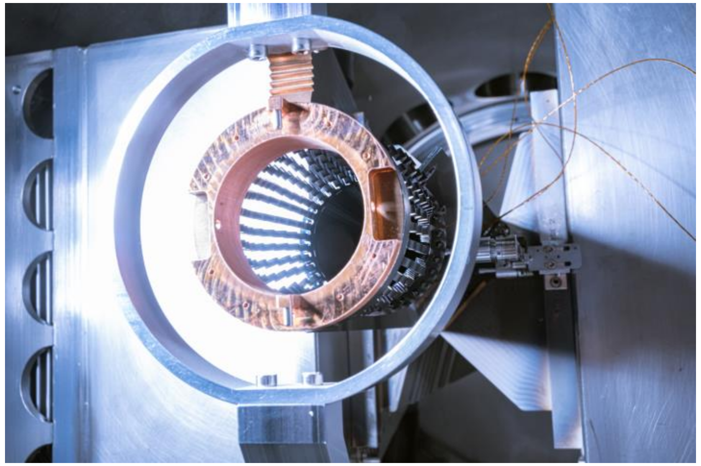


Figure 2: Ratios of J/ψ to D^0 cross-sections as a function of (left) $y^\star$ and (right) transverse momentum. The error bars represent uncertainties that are uncorrelated bin-to-bin while the boxes represent the correlated uncertainties.

Projectile	Gas target
Pb	Ne O …
p	
Ne	
O	
…	



LHCb SMOG2

Motivation for using different ions

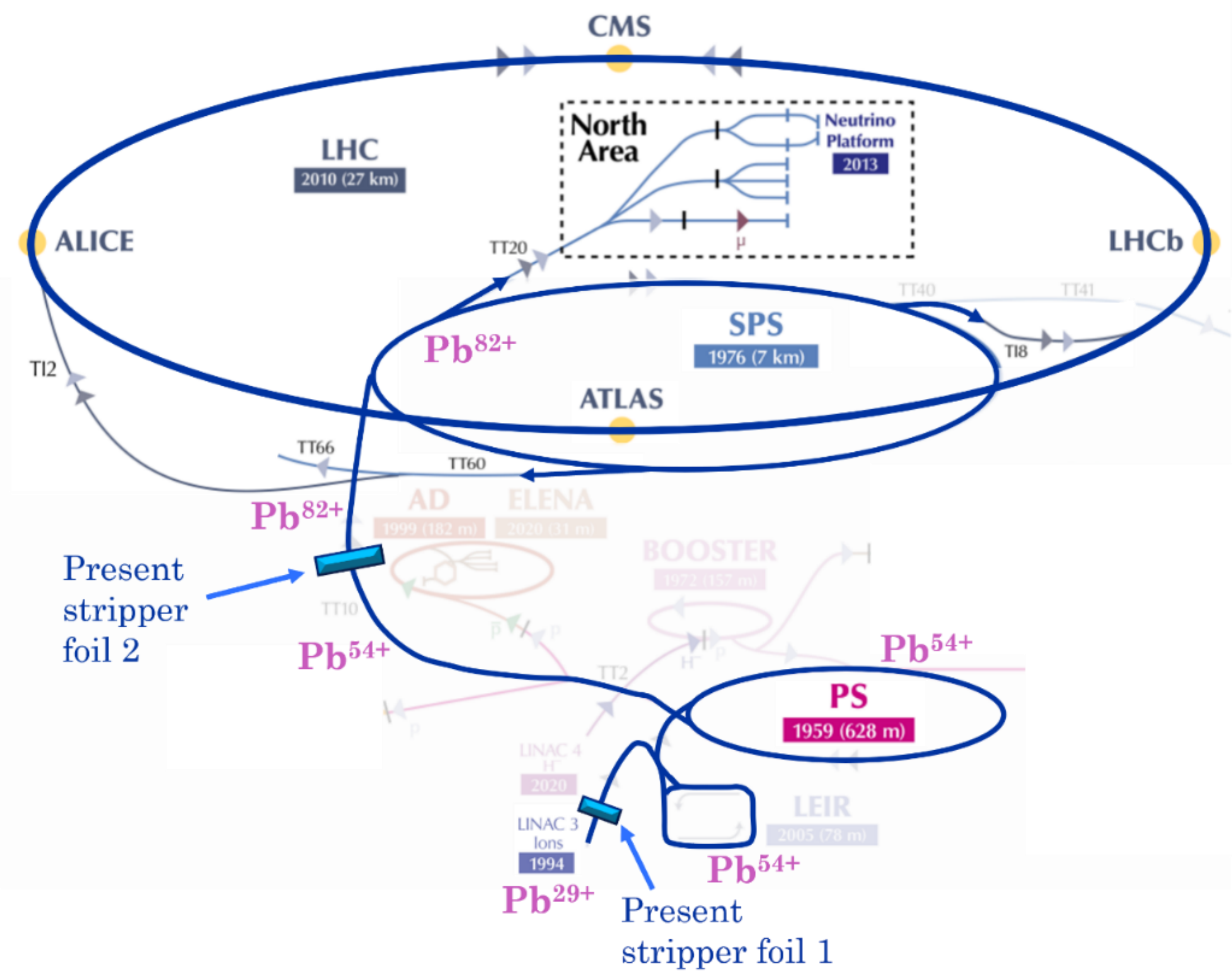
Experimental landscape at CERN

Multiple and strong syner

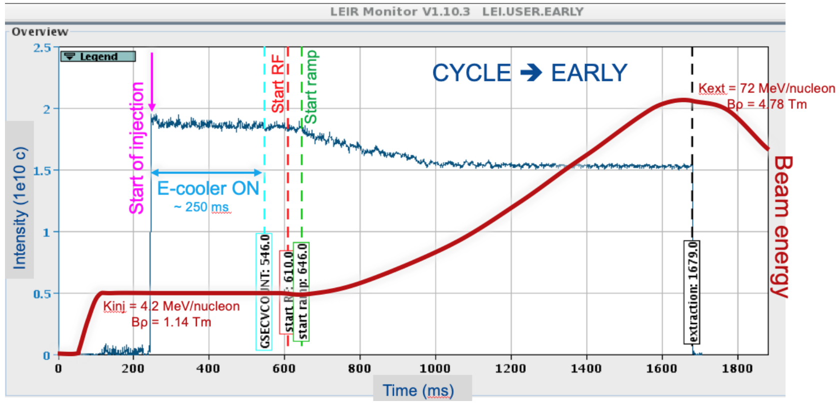
		5 B Boron 10.811 (LS3)	8 O Oxygen 15.9994 (2023/25)	10 Ne Neon 20.1797	12 Mg Magnesium 24.305 (2024)	18 Ar Argon 39.948 (2015)	20 Ca Calcium 40.078	36 Kr Krypton 83.80 (2023)	49 In Indium 114.818 (2003)	54 Xe Xenon 131.29 (2017)	82 Pb Lead 207.2
SPS Fixed target exp.	SHINE NA61++	☆ (grey)	★ (green)		★ (orange)						★ (green)
SPS Fixed target exp.	NA60+										★ (green)
Maximise L_{nn}, while keeping large QGP effects	HL-LHC exp. ALICE3					★ (green) or	☆ (grey) or	★ (green) or	★ (green) or	★ (green) or	★ (green)
	NUCLEAR PHYSICS AT LHC		★ (green)	☆ (grey)		★ (green)	☆ (grey)	★ (green)	★ (green)	★ (green)	
Facilities: Most demanding	R2E HEARTS		★ (green)			★ (green)		★ (green)		★ (green)	★ (green)
Facilities: PoP in preparation	GAMMA FACTORY						☆ (grey)				★ (green)

HEARTS[8]: High-Energy Accelerators for Radiation Testing and Shielding for space applications

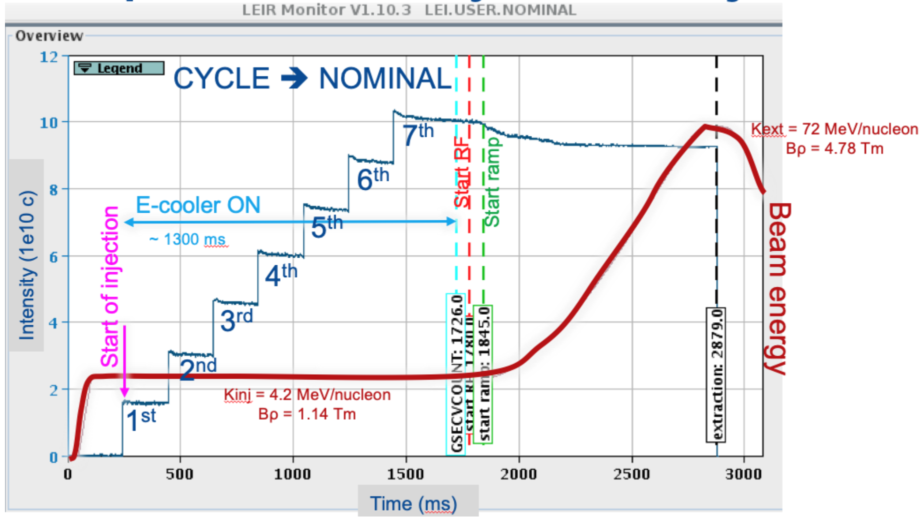
CERN Ion Accelerator Complex

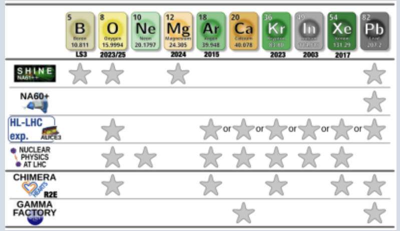


LEIR EARLY cycle for LHC Pilot Runs



LEIR NOMINAL cycle for HL-LHC

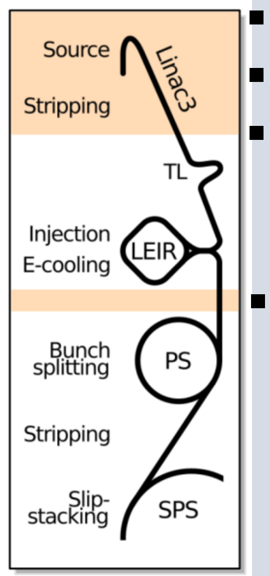




Projects' status and challenges

Feasibility studies driven by Future Ions WG, OXY4LHC project and PBC

- Despite limitation of only one Linac3 source & priority set to Pb production, important tests conducted in Run3
  - O, Mg, Kr
  - Assess source performance with new ions & get data across complex to benchmark simulations
- LHC experiments have two types of requests:
  - Maximize L_{nn} ➔ need to deliver the highest brightness beams ➔ very demanding
  - Pilot runs ➔ e.g. physics from isobar collisions ➔ relatively straight forward: Xe-Xe & O-O pilot runs
- HEARTS remains the most demanding facility:
  - Ideally provide: O, Ar, Kr & Pb
  - Every operational day, with switching times between species of 15'
  - Users can switch ions at will
  - Impossible with present injectors: switching between ions takes weeks
  - *(Alternatively, 2 ions with 2-3 hours switch time)*
- If NA61++ approved in Run4, no possibility to continue new ions R&D: ion complex will focus on production of B, Mg, O & Pb



CERN Ion Accelerator Complex

- Second source
- Low energy elements to pulsed versions
- New low energy diagnostics lines
- New stripper foil between LEIR and PS

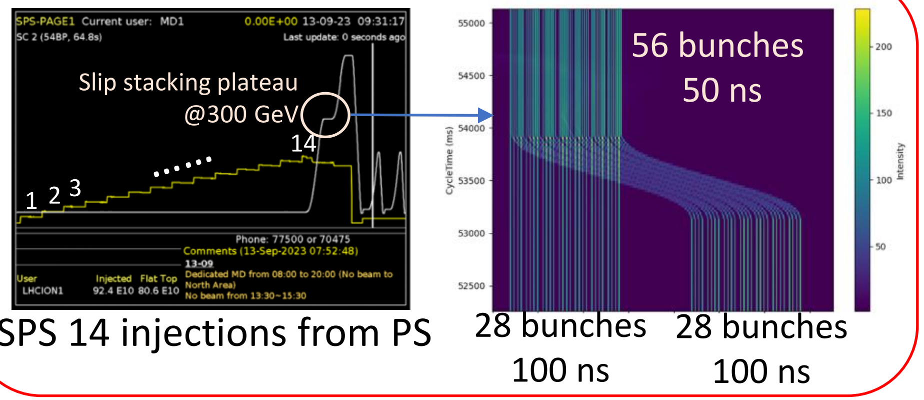
Maximize L_{nn}

Ion Complex upgrade needed

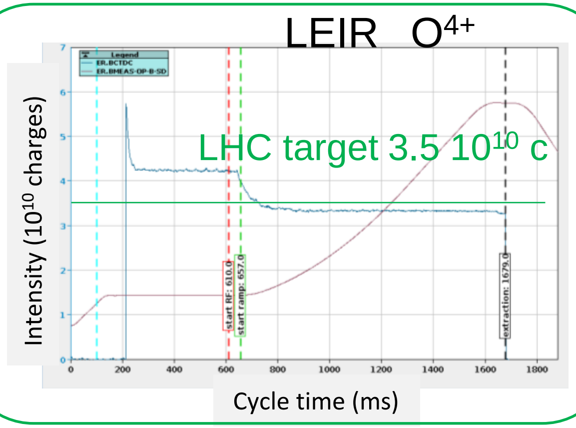
Performance assessment for LHC beams

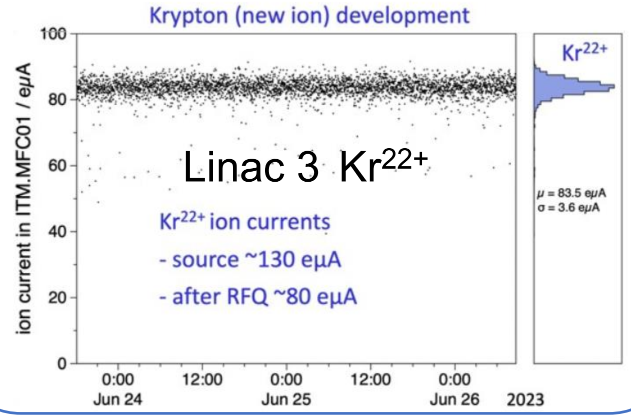
Experimental tests

- Lead physics run
  - Excellent, stable Pb^{54+} beam from Linac3 with ≥ 30 eμA
  - SPS slip-stacking with LIU parameters demonstrated
  - 2024 ➔ ensure reliable and stable delivery of LIU beams
- Oxygen tests up to PS in Nov 2023
  - Ready for 2025 O-O & p-O collisions at LHC
  - Beam intensity from Linac3: 88 eμA (target: 70 eμA)
- Krypton tests in 2023
  - New Kr^{22+} beam, good stability
  - Intensity after source 130 eμA and 80 eμA after RFQ



After 2 days of commissioning!!

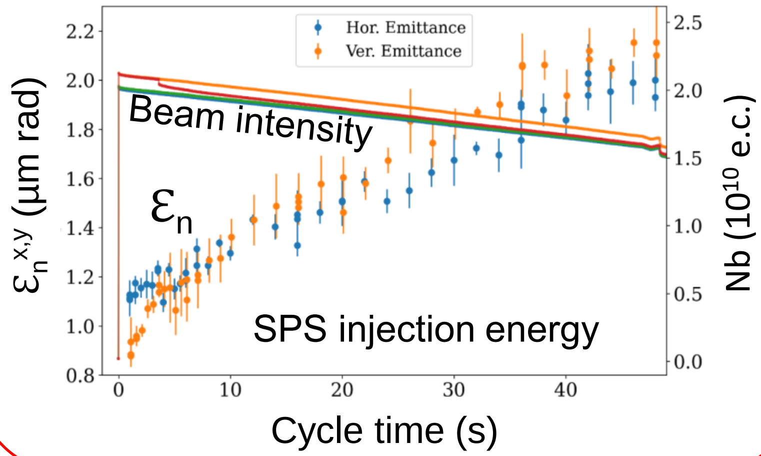


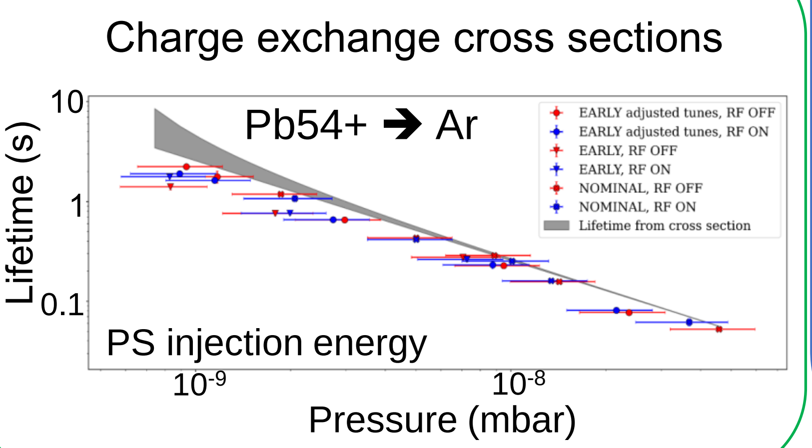


Performance assessment for LHC beams

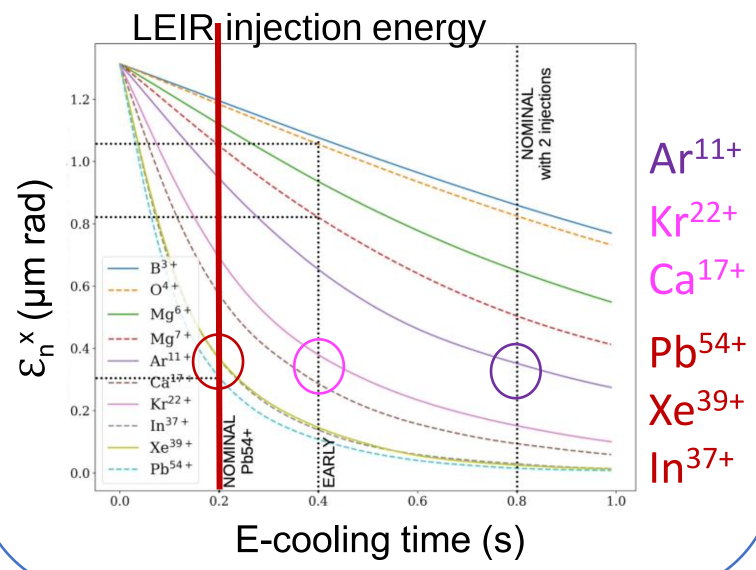
Benchmark simulations

- Detailed measurements with Pb in 2023 [9]
  - Beam intensity and emittance
  - IBS growth rates
  - Tune shifts from Space Charge
  - Beam gas interactions studies with Pb & Mg [10]
  - LEIR Electron cooler [11]





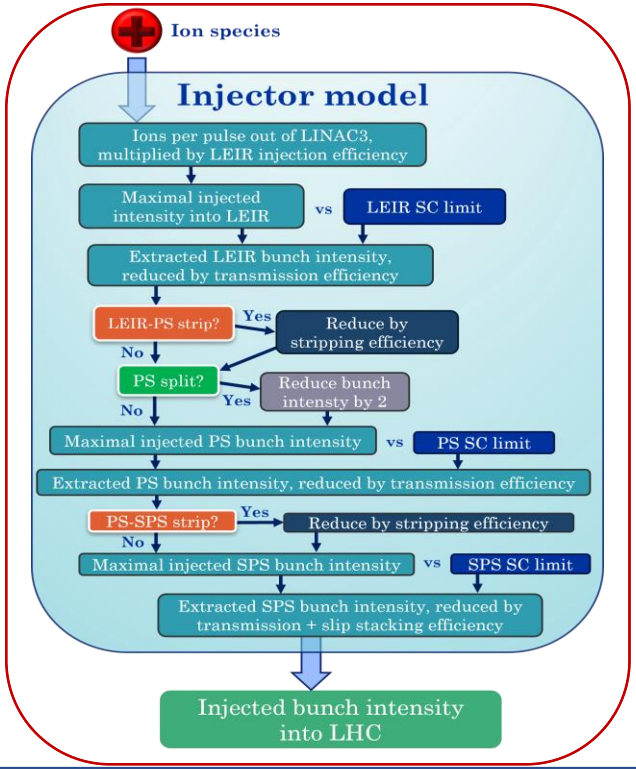
NOMINAL beam for LHC high performance = 200 ms/injection



Performance assessment for LHC beams

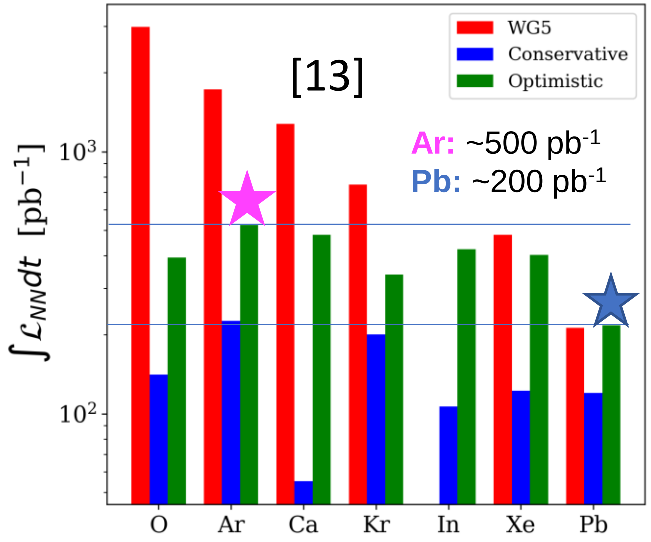
Benchmark simulations

- First time an **LHC Injector Model** being developed for ions including:
  - Space charge
  - Intra Beam Scattering growth rates
  - Tune shifts from Space Charge
  - Beam gas interactions studies with Pb & Mg
  - LEIR Electron cooler



Very Preliminary Results

Nucleon-Nucleon integrated luminosity for 1 month run



WG5 [12]: too optimistic no Beam Dynamics Limits (BDL) in the injectors

Conservative:
today's Ion Complex

Optimistic:
LEIR-PS stripping
PS no-splitting
Isotope optimization

Both Conservative and Optimistic includes BDL

Performance assessment for LHC beams

- Request from the LHC experiments [14]

L_{int} (nb^{-1})	Accessible physics
0.01	Luminosity equivalent to Xe–Xe run. This would already provide interesting physics
0.5	Sufficient for comprehensive soft physics program
2	Equivalent to 2010 Pb–Pb run for hard-probes
30	Equivalent to 2011 Pb–Pb run for hard-probes

Table 2: Integrated luminosity requests for O–O collisions.

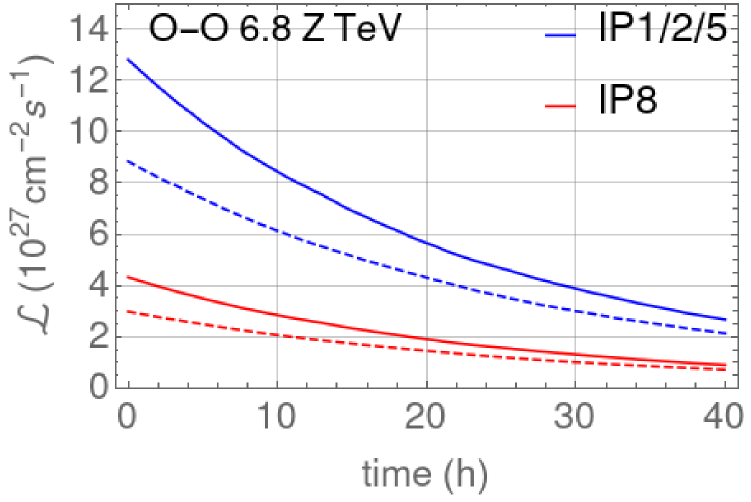
Reachable in ~ 1 week run

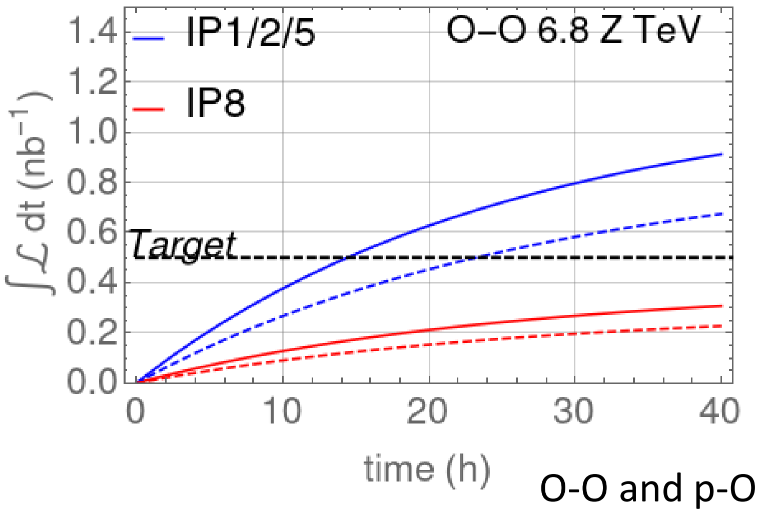
L_{int} (nb^{-1})	Accessible physics
> 2	$\approx$ 10^4 J/Ψ in LHCb
≈ 1.5	$\approx$ $4 \cdot 10^5$ $\pi\Theta$ in LHCf

Table 3: Integrated luminosity requests for p–O collisions.

- Simulations indicate we can reach [15]
  - **O-O** targets in about a day for ALICE, ATLAS, CMS, with 1-2 long fills, need *more time to reach LHCb target*
  - **p-O** targets in about 2.5 days (Large uncertainty applies!)
- Including commissioning and contingency, total of 6-8 days
- Oxygen run a priori feasible and compatible with targets, but challenging
- Some work still remains:
  - Optimize machine configuration and filling schemes
  - Study transmutation effect

Simulated performance O-O collisions [16]



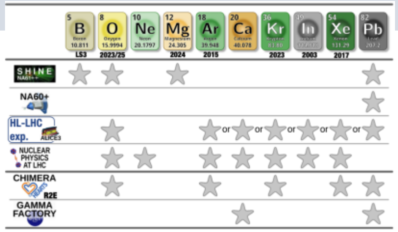


Dashed lines: 21 bunches with 1.5×10^9 O/bunch

Solid lines: 18 bunches with 2×10^9 O/bunch

O-O and p-O physics opportunities at LHC [17,18]

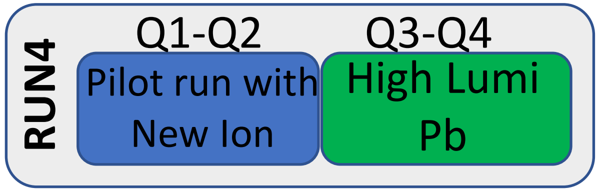
Conclusions



- Increased interest of physics with lighter ions from different physics communities and facilities
- All show important synergies ➔ explore different physics landscapes with the same effort
- The current CERN Ion Accelerator Complex offers opportunities to test new ions at the same time it fulfils its physics production commitments
- But we are hitting the limits
- To go beyond this limits an upgrade of part of the Ion Complex is needed

Next important milestone ➔ prepare a **project request** for the ion injector **upgrade**

- ATS sector **framework exists** now, Future Ions WG, OXY4LHC project & PBC, where light ions operation feasibility is addressed taking into account beam dynamics limitations, alternative beam production schemas, beam intensities and LHC luminosity predictions …
- We can rather easily provide ion-gasses for pilot runs, e.g. O-O, p-O, Xe-Xe, Ne-Ne …
- High Luminosity is more involved and more time is needed for preparation



- **1-week TH Institute Workshop @CERN** in Autumn 2024 to bring together theorists, experimentalists and accelerator physicists to assess our current understanding of **small system collectivity** and to discuss perspectives for how this understanding could be developed further in an interplay between advanced theoretical modelling and future experiments with light-ion beams

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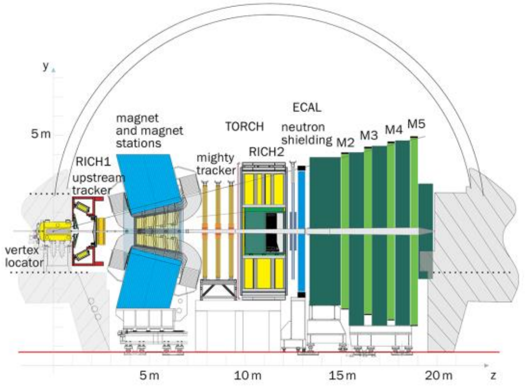
Abbreviations

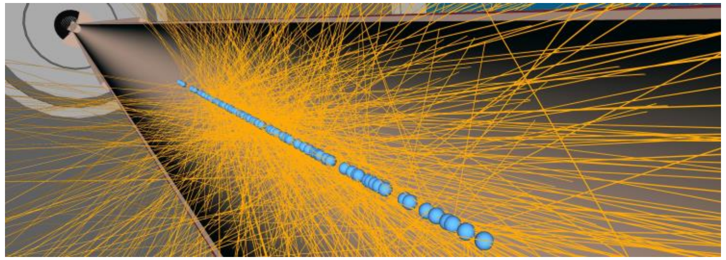
ATS: Accelerator and Technical Sector
Beam brightness = bunch intensity/bunch emittance
DAQ: Data Acquisition System
ε_n : normalized emittance
EIC: Electron-Ion Collider, BNL
EoS: Equation of State
HL-LHC: High Luminosity LHC
IBS: Intra-Beam Scattering
L_{nn} : nucleon-nucleon integrated luminosity
LIU: LHC Injectors Upgrade project
LS3: Long Shutdown 3
OXY4LHC: Oxygen for LHC project
PBC: Physics Beyond Colliders
PID: Particle Identification
PoP: Proof of Principle
QGP: Quark Gluon Plasma
v_n: azimuthal anisotropies
VTX: Vertex

Physics opportunities with lighter ions

- Ions lighter than Pb could potentially give higher L_{nn}
- All LHC detectors foresee important upgrades in the coming years:
    - DAQ & trigger, unprecedented VTX precision, extensive PID, large acceptance …
    - Exploit maximally this investment
- Study different ion species with the same detector offers the advantage:
    - If different size and shape, take ratios and study influence of geometry
    - Systematics cancellation (compared to cross-experiment comparison)
- Ions operation beyond Run 4 ➔ overlap with EIC, LHC competes and complements
    - LHC access lower-x
    - Constrain same parameters in LHC and EIC with different photon flux

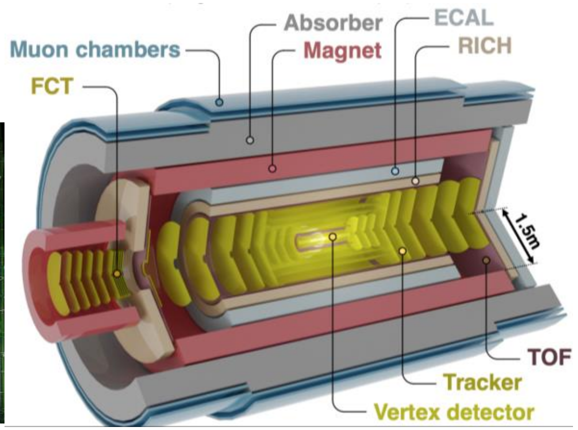


LHCb PHASE 2



ATLAS PHASE 2

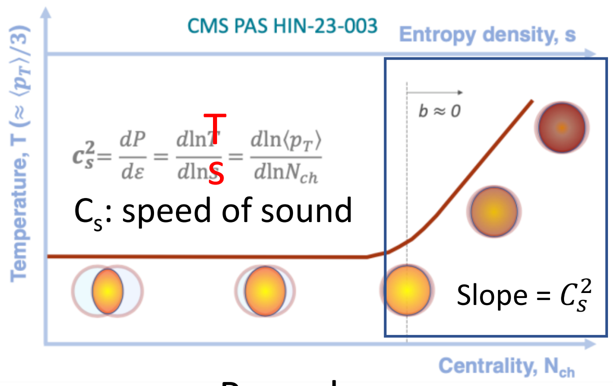
CMS PHASE 2



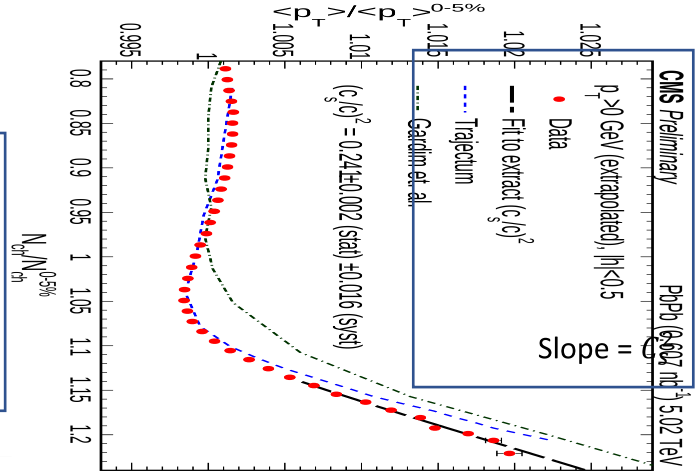
ALICE3

Physics opportunities with lighter ions

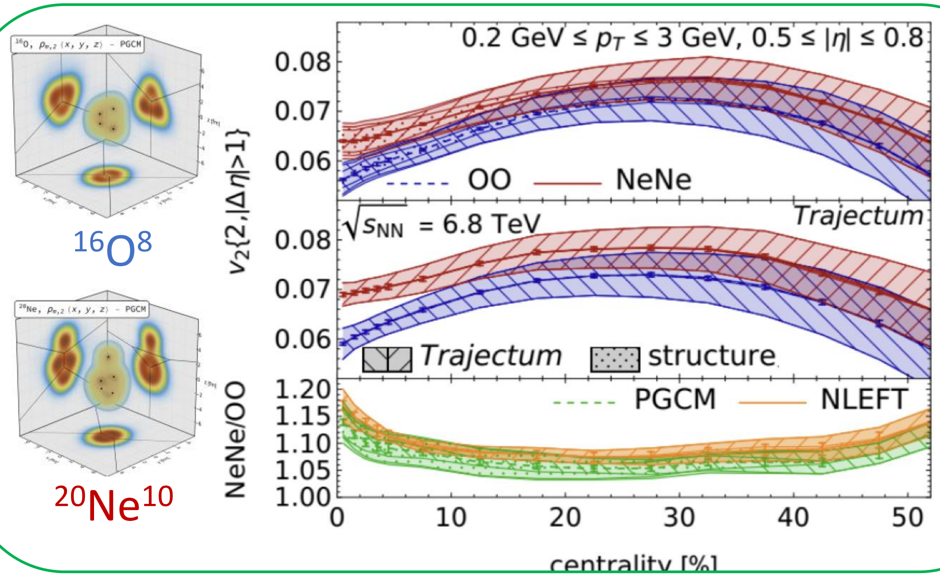
- Ultra-central HI collisions due to their exceptionally large multiplicity probe an interesting regime of QGP where the size is (mostly) fixed and fluctuations of initial entropy ($\approx N_c$) and temperature ($\approx p_T$) in the initial condition dominate ➔ direct information on the EoS ➔ Measurements from CMS [1] & ATLAS [2]
  - Seeing such a slope in small system collisions at the LHC (e.g. O-O) would be a unique signature of hydrodynamics
- QGP transport coefficients: quantitative tests of hydrodynamics in a small system ➔ observation of unambiguous imprints of the initial-state geometry on the collective flow [3]
  - Collisions of pairs to cancel theoretical uncertainties
  - Not very demanding in luminosity ➔ pilot runs could be sufficient



Procedure:
fix volume, vary N_c and p_T

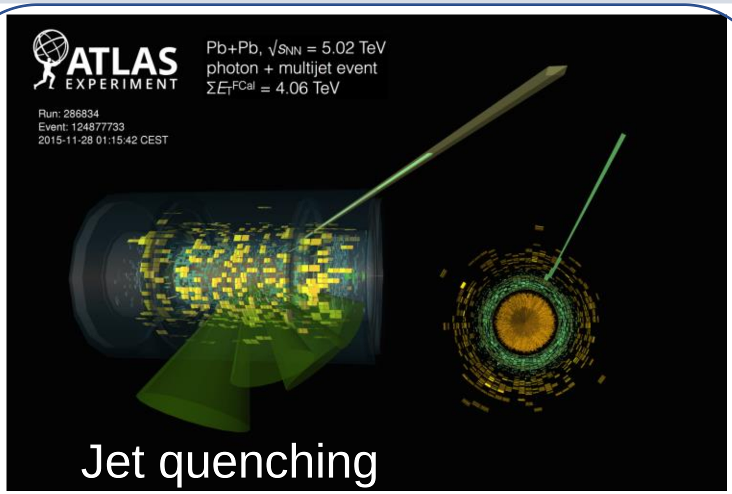


$$$ Slop and quantitative agreement with hydrodynamic model

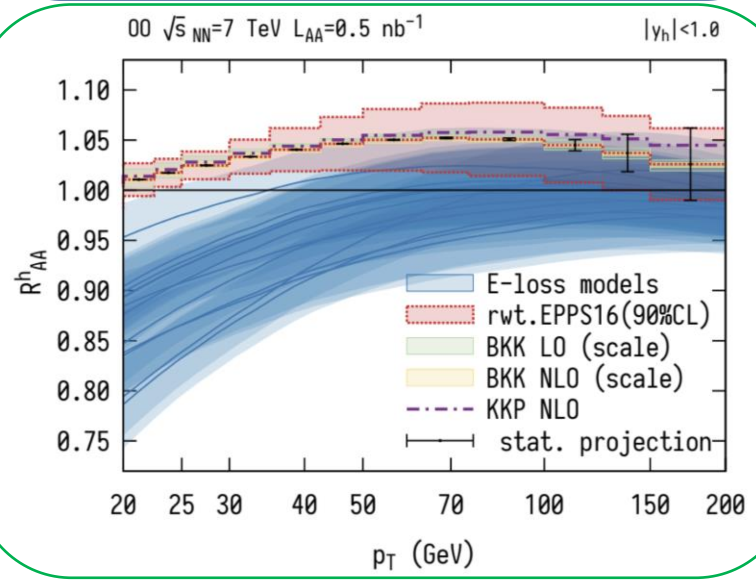


Physics opportunities with lighter ions

- Jet quenching (quenching" of high-p_T quarks/gluons in QGP): done with Pb-Pb and Xe-Xe. Advantages of small systems:
  - Many theoretical treatments w/ different assumptions
  - Experimental constraints needed, especially on the path length dependence which is simpler to do with small systems
  - Jet quenching in O-O collisions should be possible with the 2025 pilot run



- Partonic rescattering (suppression of high-momentum hadronic yields): prerequisite for QGP formation & direct logical consequence of the standard interpretations of v_n in terms of final state interactions [4]:
  - Discovery of parton energy loss in small collision systems
    ➔ one of the most important challenges
  - O-O collisions at the LHC provide unprecedented sensitivity to parton energy loss in a system whose size is comparable to those created in very peripheral HI collisions

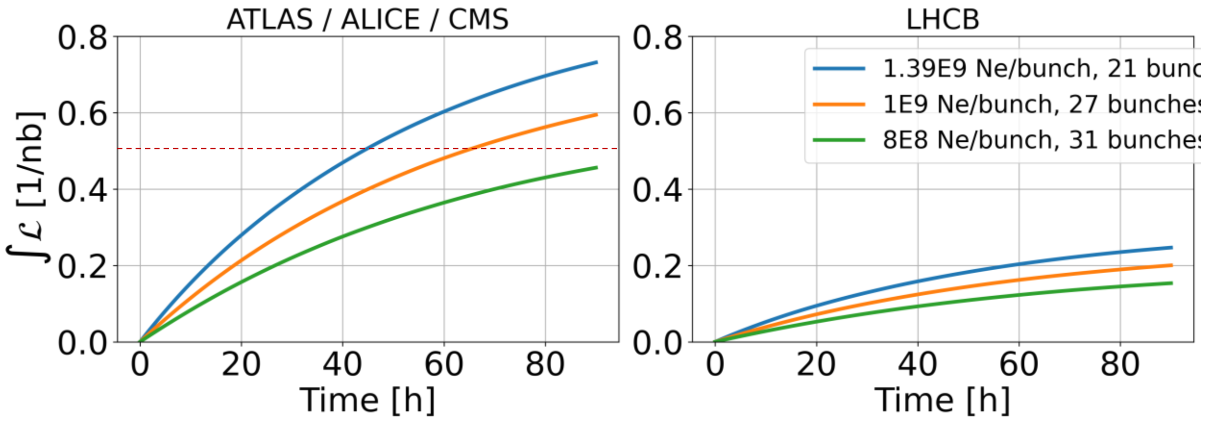


Performance assessment for LHC beams

- Preliminary studies of beam intensity across injectors and luminosity evolution of Ne-Ne collisions at LHC [19]
- Simulated three cases:
  - **1.33 10^9 Ne/bunch**, 21 bunches, 7 collisions/experiment
  - **1 10^9 Ne/bunch**, 27 bunches, 9 collisions/experiment
  - **8 10^8 Ne/bunch**, 32-31 bunches, 10 collisions/experiment

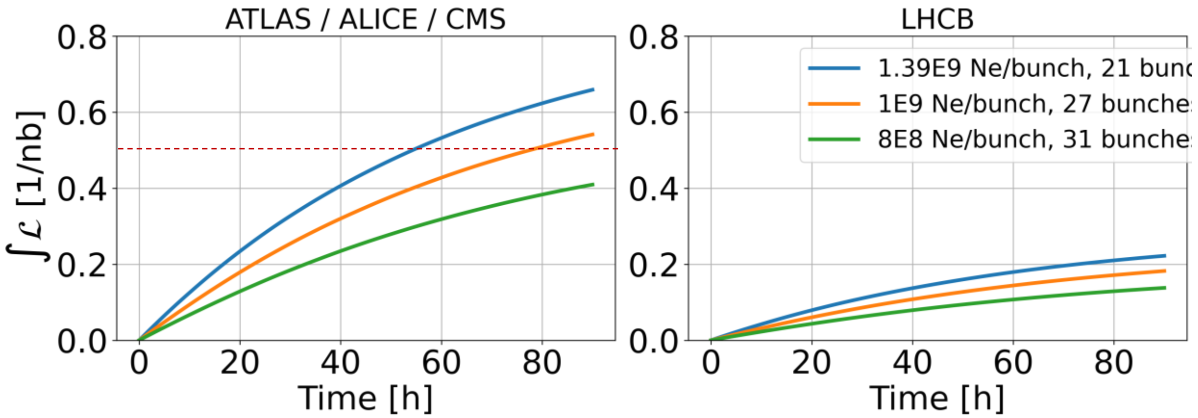
Very preliminary
Not published

$\varepsilon_n^{x,y}$ = 1.65 µm rad @start of collisions



0.5 nb^{-1} can be reached in one fill of ~ 50 hours

$\varepsilon_n^{x,y}$ = 2.1 µm rad @start of collisions



0.5 nb^{-1} can be reached in one fill of ~70 hours