SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

# HEAVY-ION PHYSICS AT THE LHC WITH DETECTOR UPGRADES FOR RUNS 3 AND 4


SARAH PORTEBOEUF HOUSSAIS

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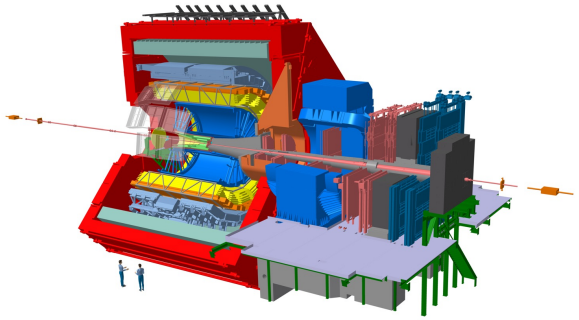
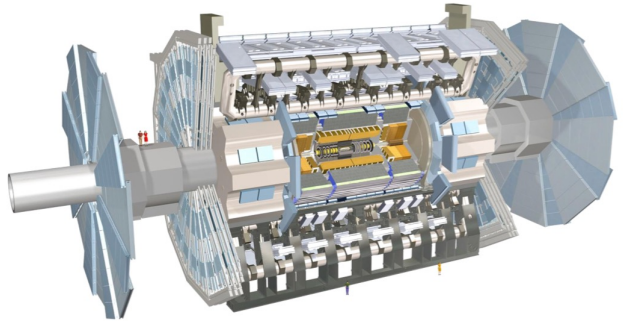
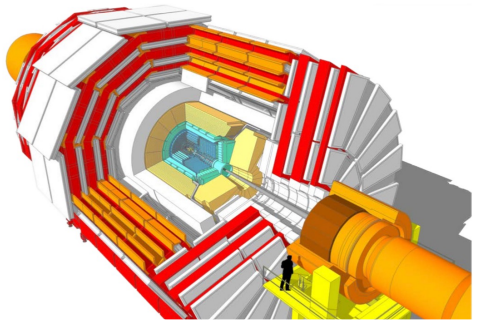
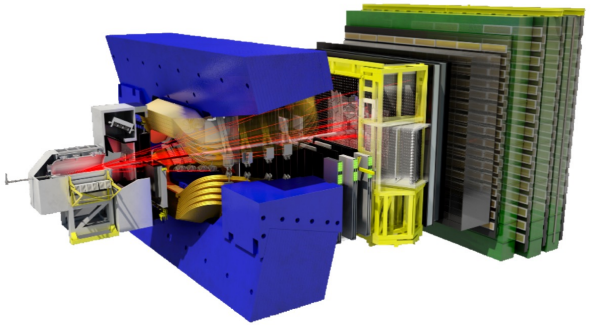

And pp, small systems

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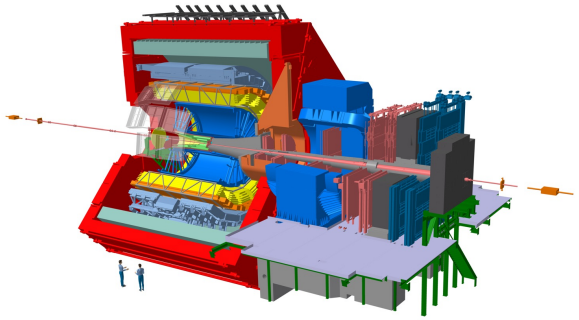
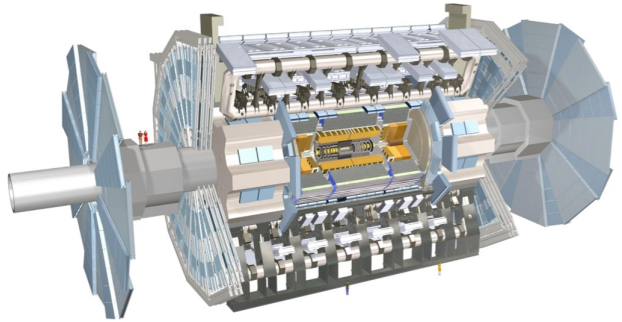
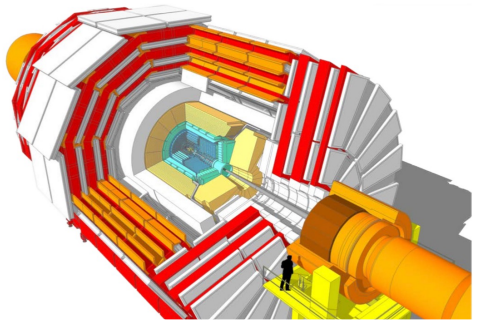
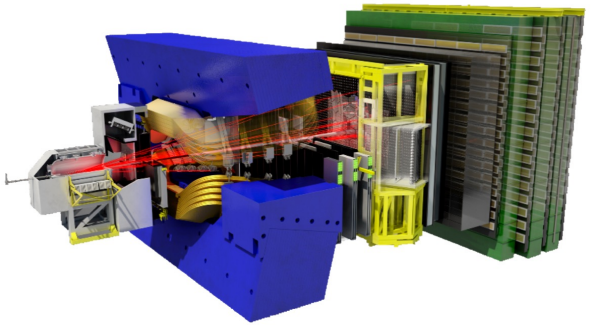
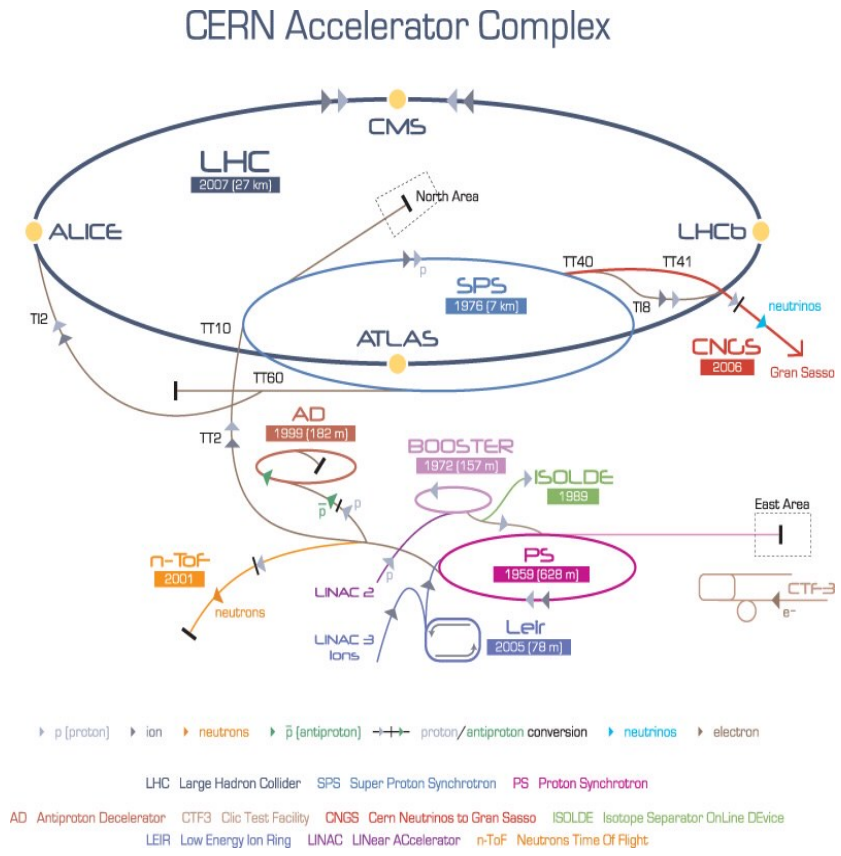
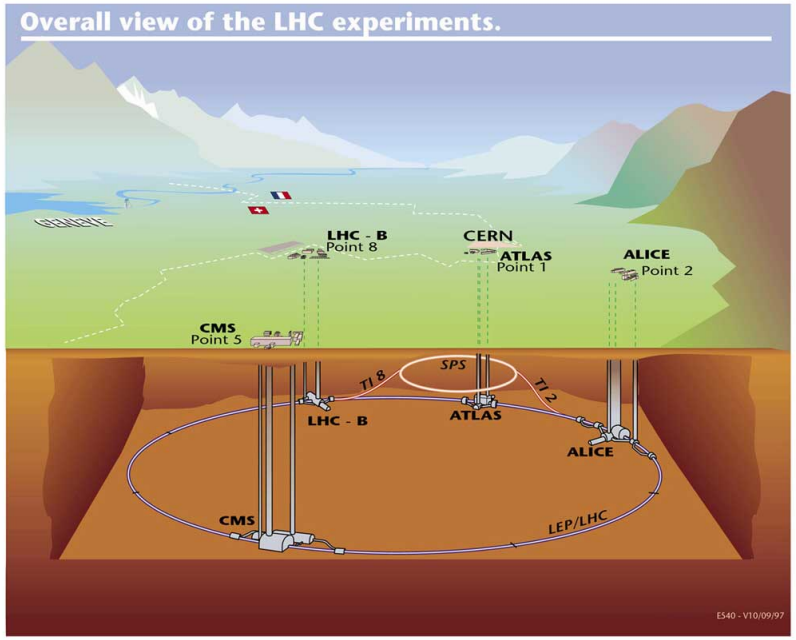





# The Large Hadron Collider (LHC)



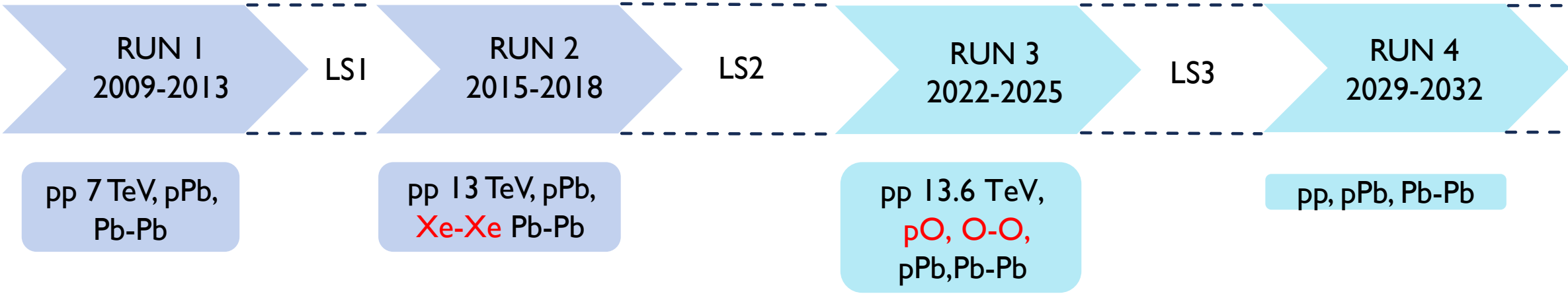

LHC 27 km circumference
50 to 175 m underground
At the French-Swiss border (Geneva area)




Collision systems and energies at RUN 1 and 2

- pp $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8, 13 TeV
- p-Pb $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV
- Pb-Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
- Xe-Xe $\sqrt{s_{NN}}$ = 5.44 TeV

# LHC program




Roderik Bruce, Considerations for 2022 heavy-ion run and LHC status, https://indico.cern.ch/event/1150497/

# LHC program

| RUN 1 2009-2013 | LS1 | RUN 2 2015-2018 | LS2 | RUN 3 2022-2025 | LS3 | RUN 4 2029-2032 |
|---|---|---|---|---|---|---|
| pp, pPb, Pb-Pb | | pp, pPb, Xe-Xe Pb-Pb | | pp, pO, O-O, pPb,Pb-Pb | | pp, pPb, Pb-Pb |

- **Pb-Pb luminosity limited** by LHC ~1-2·$10^{27}$ $cm^{-2}$ $s^{-1}$ (beam losses )
- Several fills lost on beam dumps due to 10 Hz beam oscillation events; collimation efficiency

**RUN 3**
- **High Luminosity for ions** (~7·$10^{27}$ $cm^{-2}$ $s^{-1}$)
- **Oxygen** (small to large system bridge, cosmic ray)
- Improved collimation systems
  ⇢ lifted limitation in the LHC from bound-free pair production
  ⇢ ion luminosities now limited by bunch intensities from injectors

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# LHC program

RUN 1 2009-2013 | LS1 | RUN 2 2015-2018 | LS2 | RUN 3 2022-2025 | LS3 | RUN 4 2029-2032

pp, pPb, Pb-Pb

pp, pPb, Xe-Xe Pb-Pb

pp, pO, O-O, pPb,Pb-Pb

pp, pPb, Pb-Pb

- **Pb-Pb luminosity limited** by LHC ~1-2·$10^{27}$ $cm^{-2}$ $s^{-1}$ (beam losses )
- Several fills lost on beam dumps due to 10 Hz beam oscillation events; collimation efficiency

**RUN 3**
- **High Luminosity for ions** (~7·$10^{27}$ $cm^{-2}$ $s^{-1}$)
- pp energy increased
- Pb-Pb 6.8 TeV, 6.37 as a fallback

**RUN 4**
- **High-Lumi LHC** pp luminosity to 5·$10^{34}$ $cm^{-2}$ $s^{-1}$

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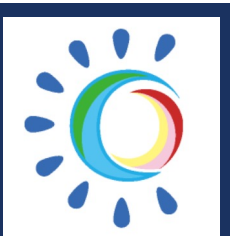
# LHC program



RUN 1 2009-2013 | LS1 | RUN 2 2015-2018 | LS2 | RUN 3 2022-2025 | LS3 | RUN 4 2029-2032

pp, pPb, Pb-Pb

pp, pPb, Xe-Xe Pb-Pb

pp, pO, O-O, pPb,Pb-Pb

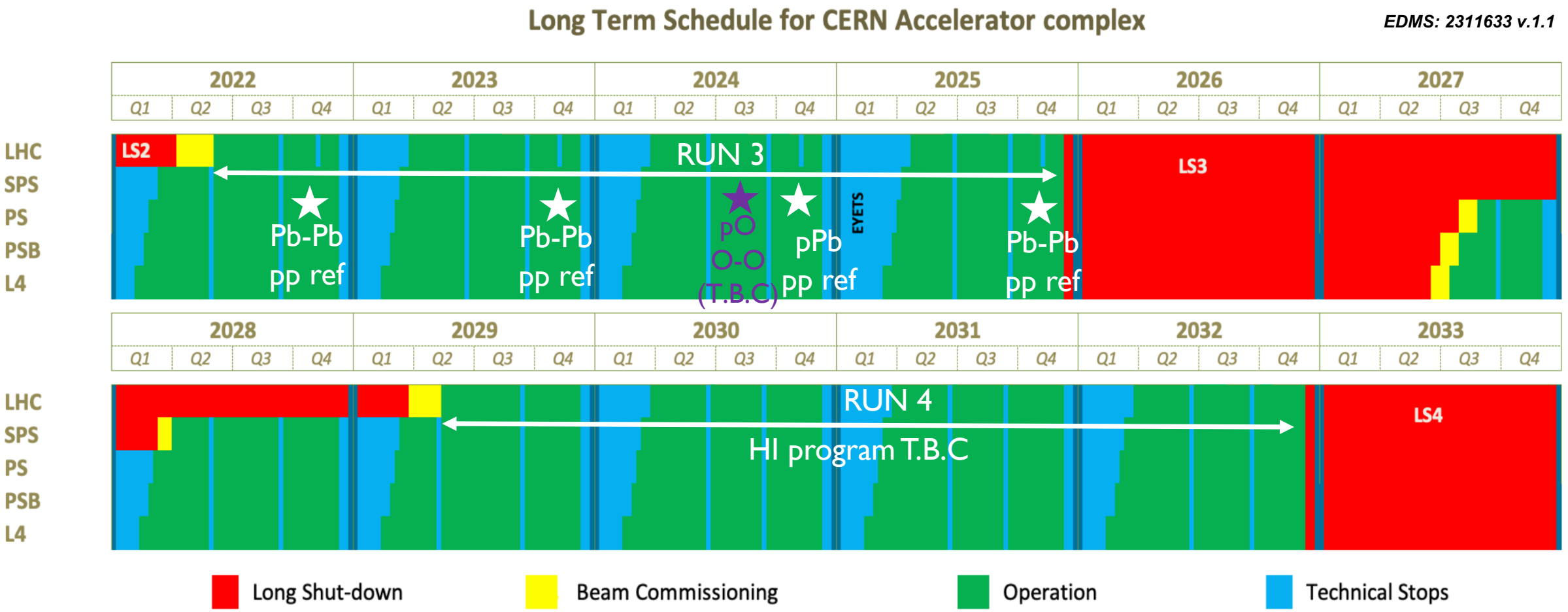
pp, pPb, Pb-Pb

**Total integrated Luminosity RUN 1+2**
**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

**Target Luminosity RUN 3+4**
**Pb-Pb: 13 $nb^{-1}$** in ALICE/ATLAS/CMS, 2 $nb^{-1}$ in LHCb
**p-Pb:** 0,5 $pb^{-1}$ in ALICE, 1$pb^{-1}$ in ATLAS/CMS, 0.2 $pb^{-1}$ in LHCb
To be continued in RUN 5, see talk by R. Bailhache

Roderik Bruce, Considerations for 2022 heavy-ion run and LHC status, https://indico.cern.ch/event/1150497/

# LHC program RUN 3

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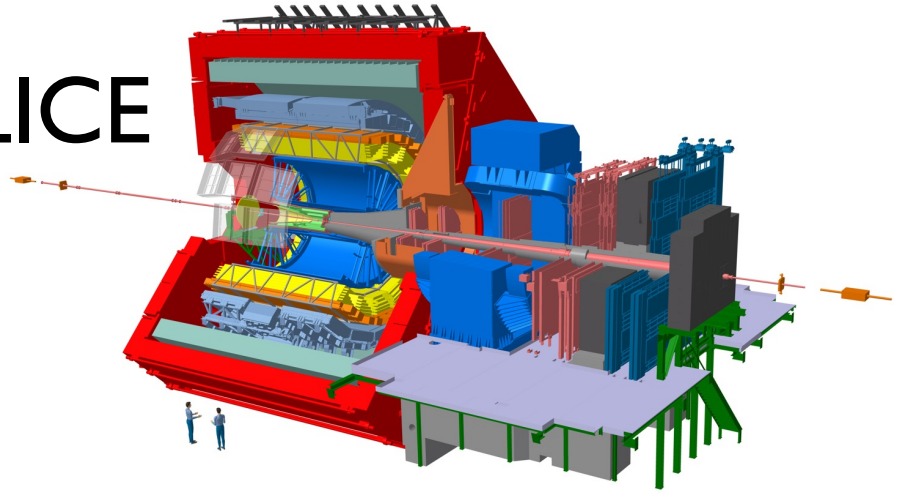
# QGP experience at the LHC

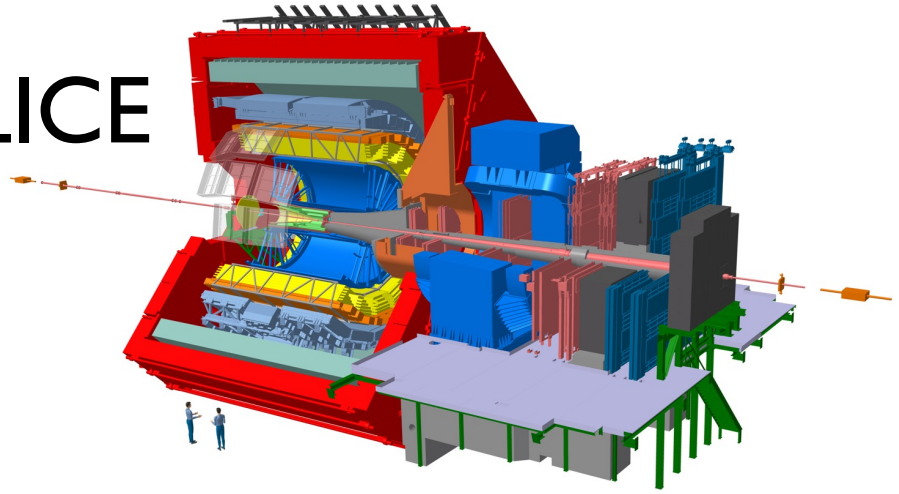
ALICE



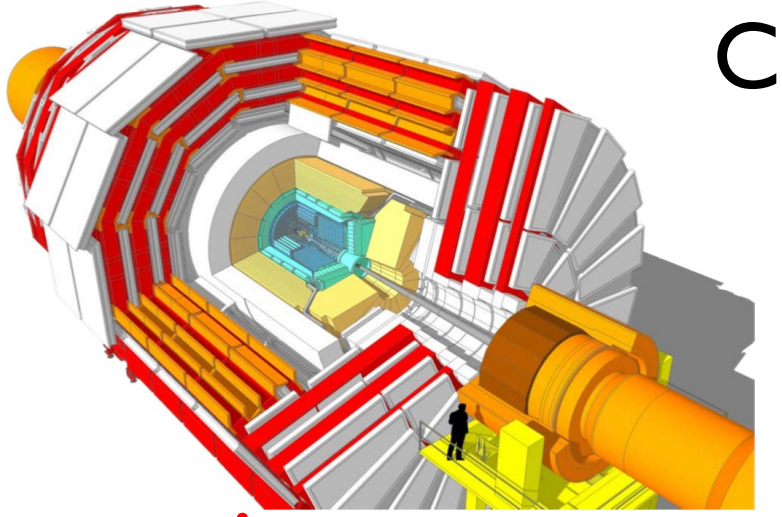
Dedicated to heavy-ion physics

# QGP experience at the LHC

ALICE

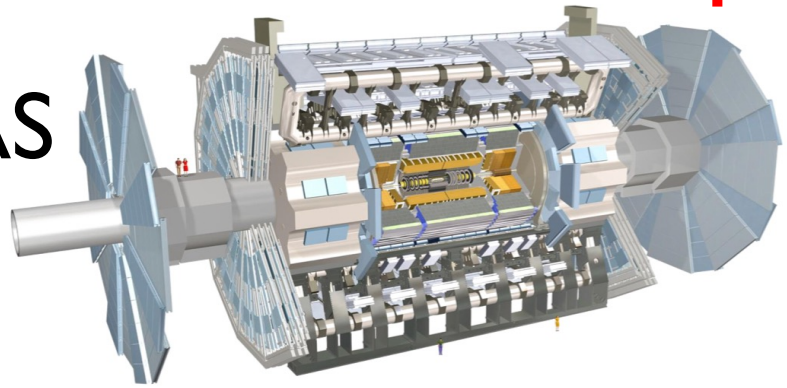


CMS

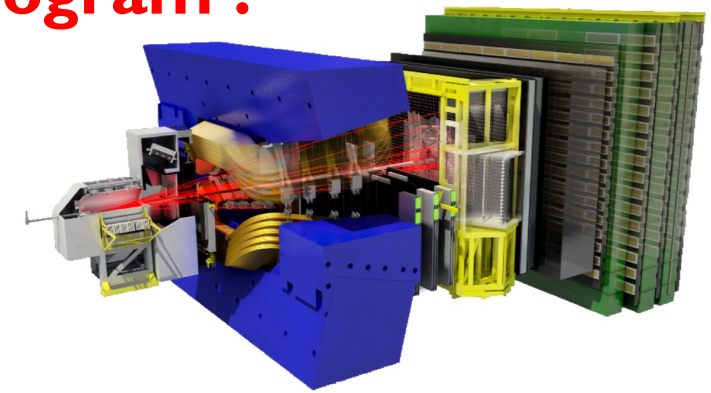


**Developed an HI program !**

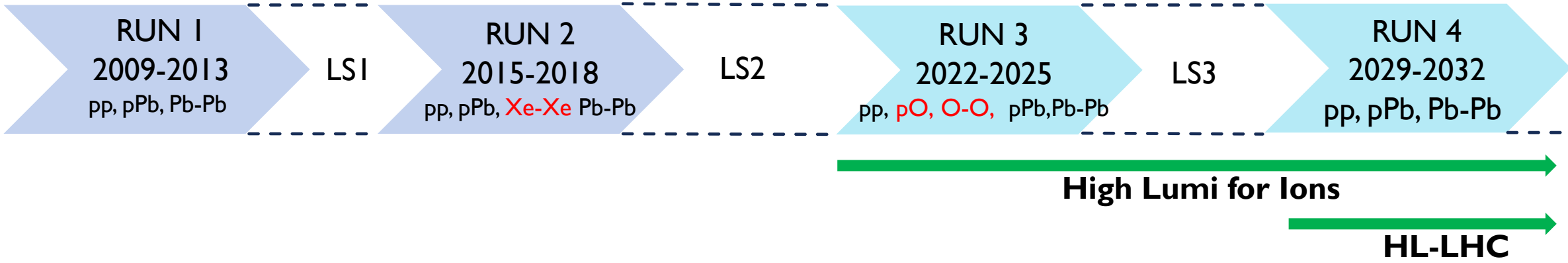
ATLAS



LHCb



# Upgrade planning



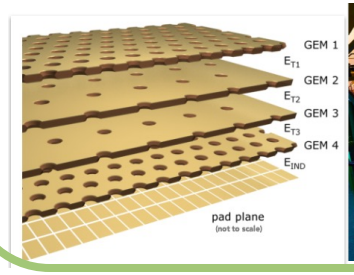

- Major upgrade for **ALICE** and **LHCb** during **LS2** (in red)
- Major upgrade for **ATLAS** and **CMS** during **LS3** (in red)

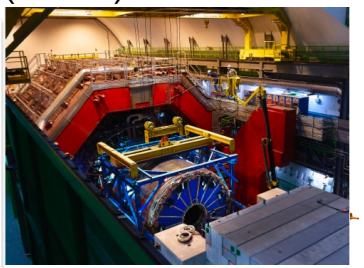
| | |
|---|---|
| ALICE 2 | ALICE 2.1 |
| ATLAS PHASE I | ATLAS PHASE II |
| CMS PHASE I | CMS PHASE II |
| LHCb Upgrade I(a) | LHCb Upgrade I(b) |

# ALICE 2 – RUN 3

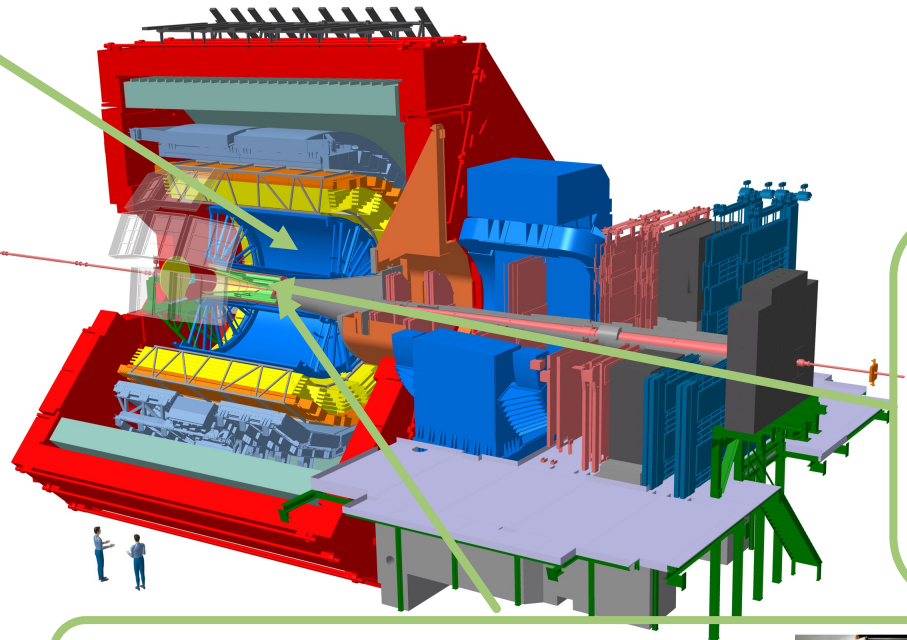
## Time Projection Chamber (TPC)

New readout chambers: from Multi Wire Proportinal Chamber (MWPC) to Gas Electron Multiplier (**GEM**)

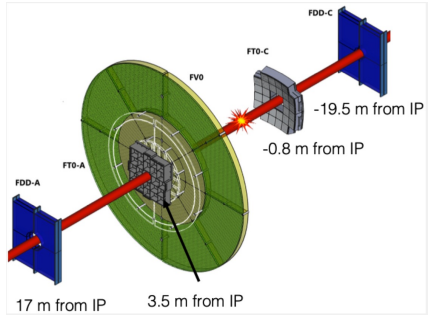


## Consolidation and readout upgrade of all subsystems

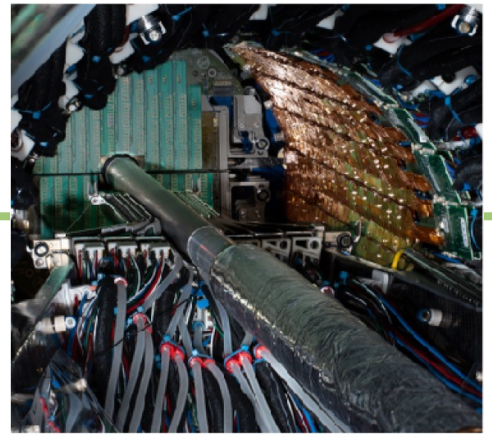


## Fast Integration Trigger




## Inner Tracking System (ITS 2)

3+2+2 cylindrical layer of MAPS (~ 10m$^2$)
Improved vertexing at high rate



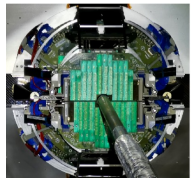
## Integrated on-/off-line System

**Continous Readout** with First Level Processors (FLPs)
Event Processing Nodes (EPNs) for GPU-based Synchronous reconstruction

**Online Data Compression**

## Muon Forward Tracker (MFT)

5 planes of MAPS
Forward vertexing for Muons



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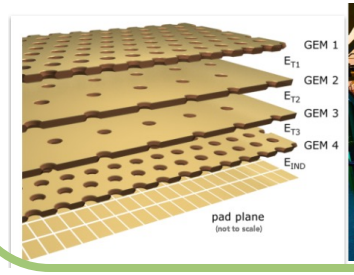
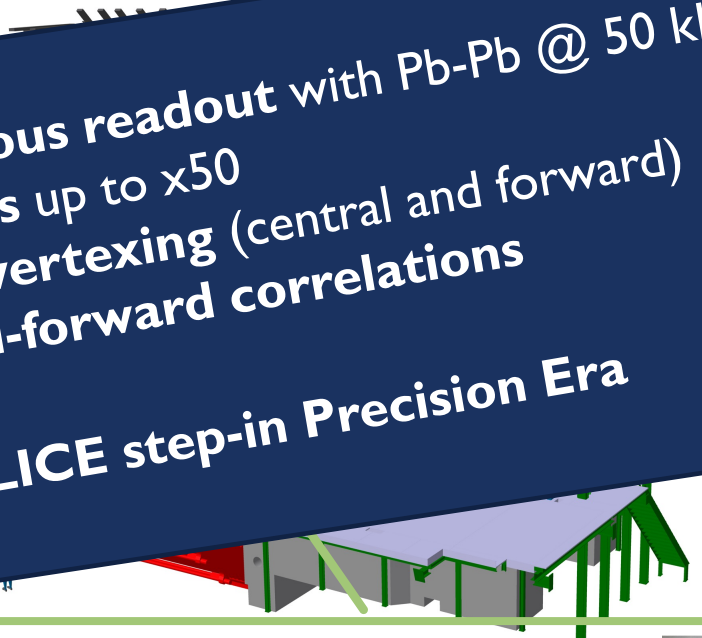
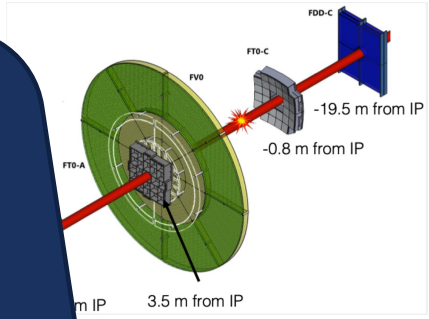



## Consolidation and readout upgrade of all subsystems



## Fast Integration Trigger

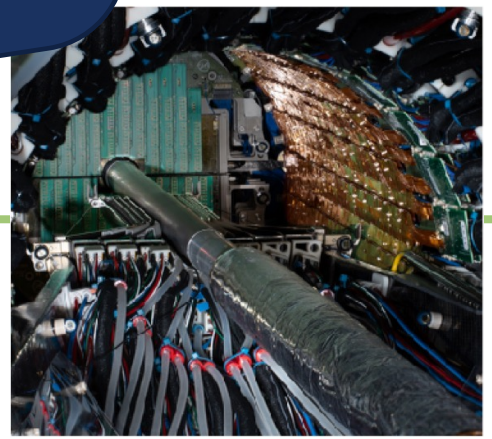



- **Continuous readout** with Pb-Pb @ 50 kHz
- **Statistics** up to x50
- **Better vertexing** (central and forward)
- **Central-forward correlations**

**ALICE step-in Precision Era**

## ing System (ITS 2)

cal layer of MAPS (~ 10m$^2$)
xing at high rate



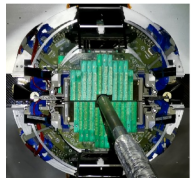
## Integrated on-/off

**Continous Readout**
Processors (FLPs)
Event Processing Nodes
based Synchronous reco

**Online Data Compression**

## Muon Forward Tracker (MFT)

5 planes of MAPS
Forward vertexing for Muons



# ATLAS and CMS PHASE I – RUN 3

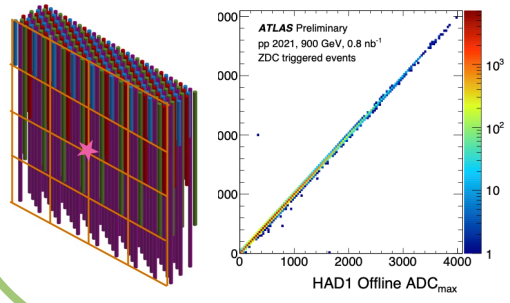
## ATLAS

- **Muon System**: New Small Wheel
- **Trigger and DAQ**

Many upgrades for Run 3 on the way to HL-LHC

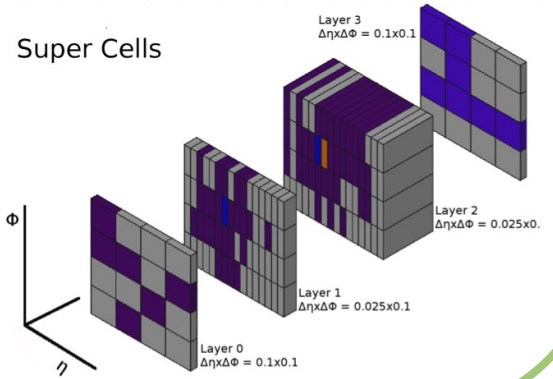
- **LAr calorimeter**

Segmented super-cells: shower-shape discrimination at trigger level




- **ZDC**

Fused silica rods for radiation tolerance. On-detector processing



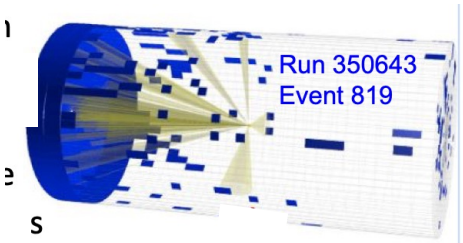

## CMS

- **Trigger**

FPGAs for L1 trigger Inclusion of CSC and GEM for track algorithm for L1 GPU modules for HLT

- **Forward muon system**

144 GEM chambers installed • new frontend electronics for CSC endcaps

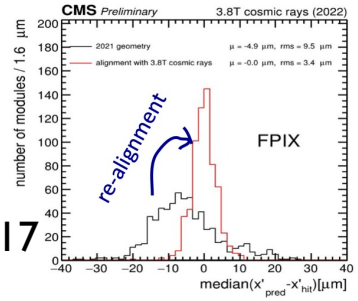


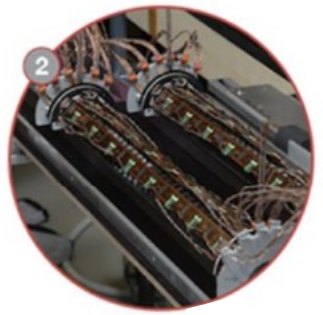

- **HCal**

HPD → SiPMs
Upgraded readout

- **Tracker**

Phase-I pixel detector:
3 → 4 barrel layers
2 → 3 forward disks
30 → 22.5 mm beampipe
Installed in EYETS 2016/2017
**In data taking in 2018**



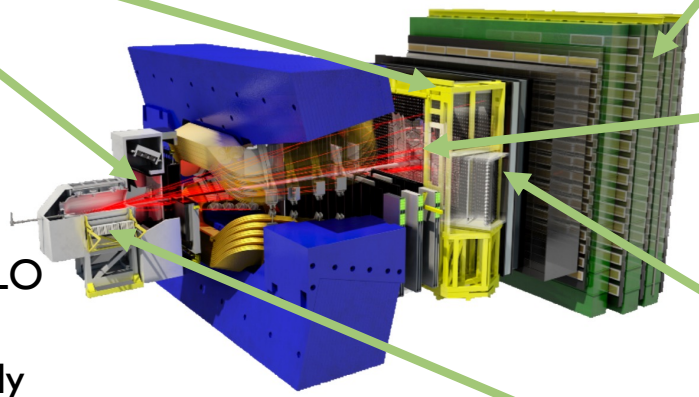



# LHCb Ia – RUN 3

**RICH**
RICH 1 renewed
RICH 2 upgraded
New readout ASIC (CLARO)

**Readout and data processing**
Full SW trigger on GPU: readout at 40 MHz

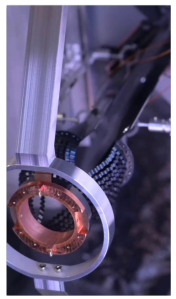
**Muon stations**
M1 (GEM) removed
new electronics (triggerless)



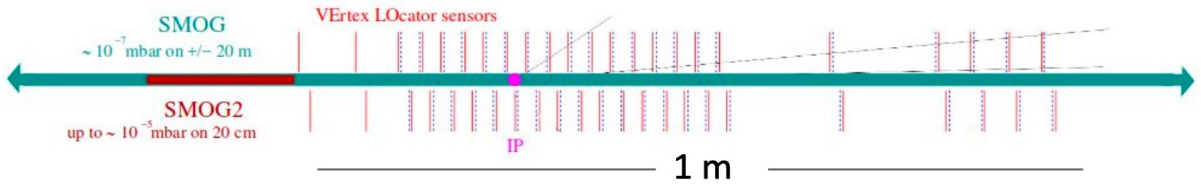
**Tracking**
Upstream tracker
Silicon micro-strips SciFi tracker (new)
SiPM readout

**Calorimeter**
New electronic (triggerless, non-zs data)
Reduced PMT gain

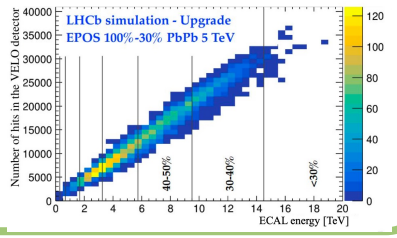
**SMOG 2**



Confinement cell installed
Two movable halves to follow the VELO
New gas feed system
Parallel operation with pp under study
Higher pressure (x100)
Also non-noble gases (H2, D2, O2, N2)




**Vertex Locator**
new VeloPix sensor
closer to beam (8.1 mm → 5.1 mm)
thin RF foil



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[illegible] (triggerless)

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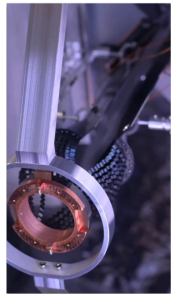
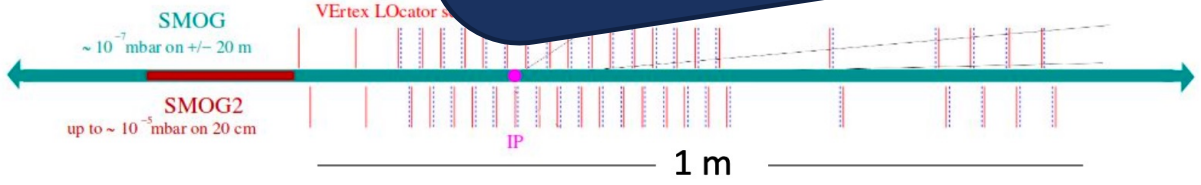


Confinemer
Two movable
New gas feed
Parallel opera
Higher pressu
Also non-nobl




- **50 kHz Pb-Pb** (> 30 % centrality), full centrality for Upgrade II
- **Improved vertexing**
- Higher luminosities for **fixed target**

**LHCb major step toward an HI forward-exp in collider mode**
**Unique HI experiment in fixed-target mode**

[illegible]r
[illegible]ps SciFi tracker (new)

[illegible]electronic (triggerless, non-zs data)
Reduced PMT gain

**Vertex Locator**
new VeloPix sensor
closer to beam (8.1 mm → 5.1 mm)
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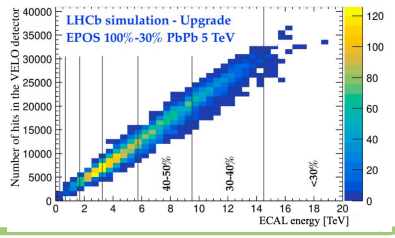
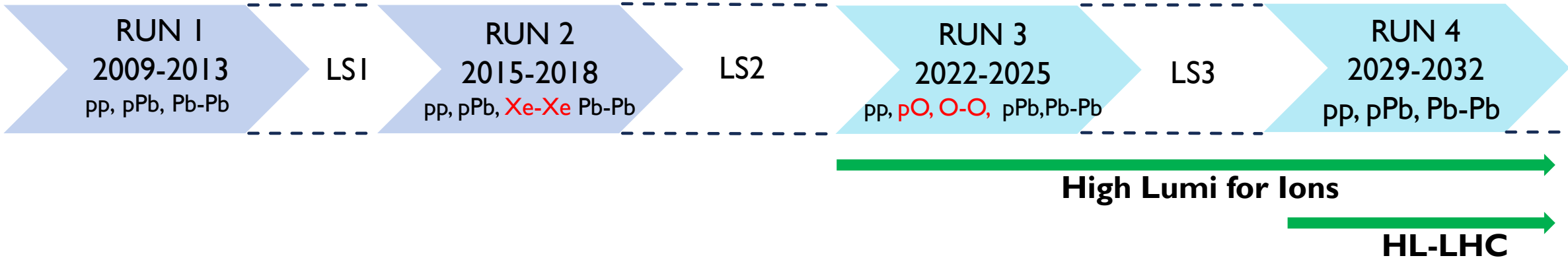


# Upgrade planning




- Major upgrade for **ATLAS** and **CMS** during **LS3** (in red)

ALICE 2.1

ATLAS
PHASE II

CMS
PHASE II

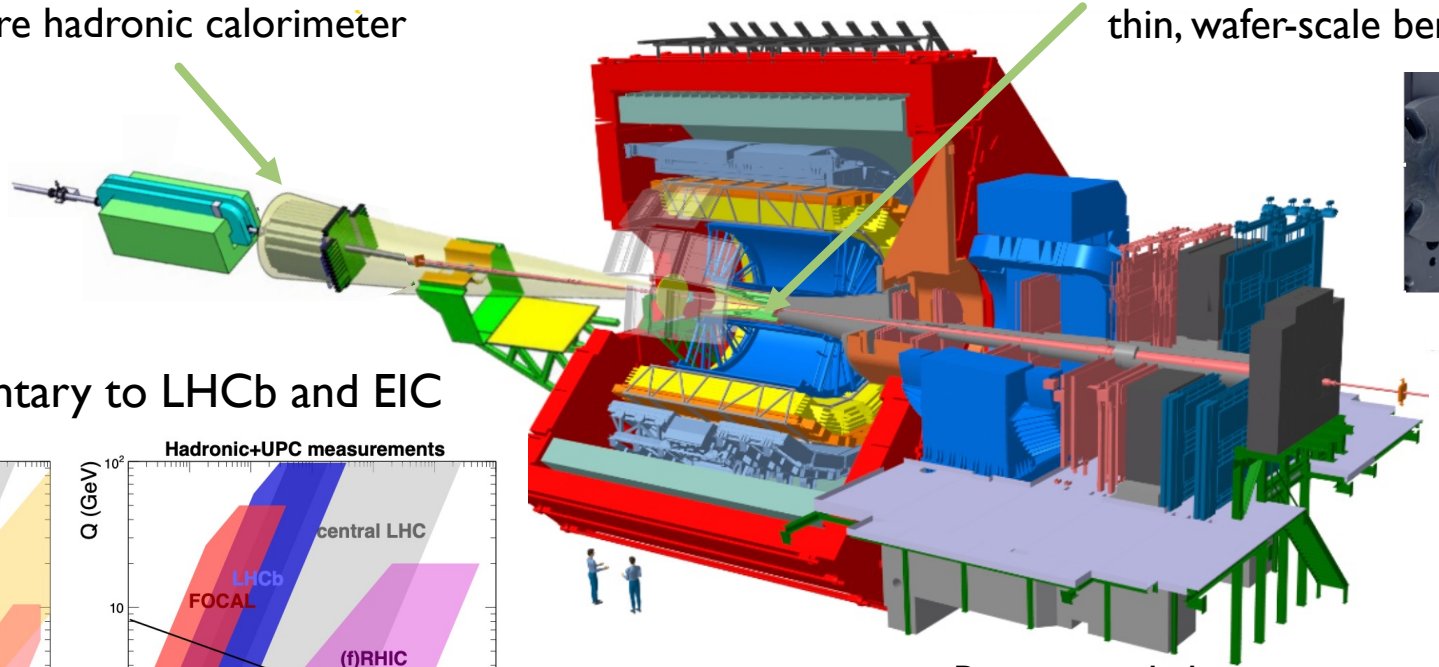
LHCb
Upgrade I(b)

# ALICE 2.1 – RUN 4

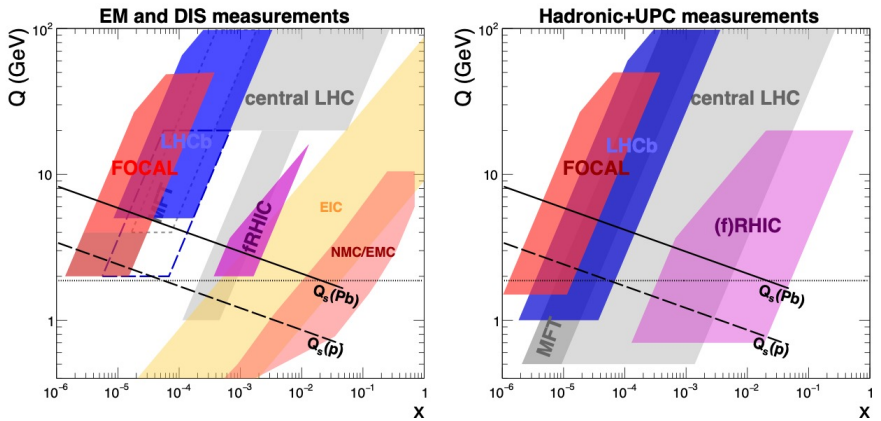
## FoCal

- FoCal-E, Si-W high granular elem. calorimeter
- FoCal-H, Cu-fibre hadronic calorimeter

**Poster Session Tuesday**
**62. Dong Geon Kim**



Small-x complementary to LHCb and EIC

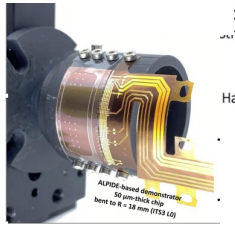


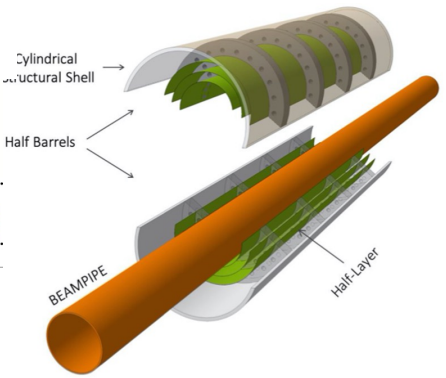

CERN-LHCC-2020-009

## ITS 3

**PA. Det. And Upgrade**
**Alperen Yuncu, Wednesday**

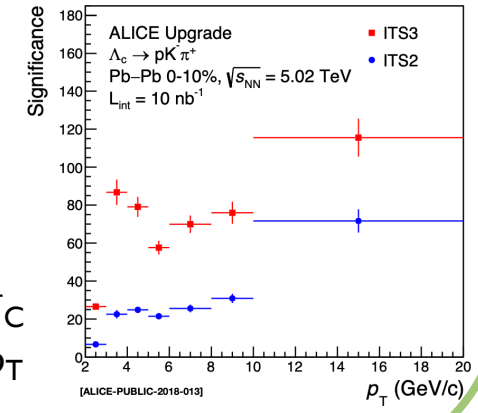
- Inner-most tracking layers to be replaced by ultra-thin, wafer-scale bent MAPS






Beauty- and charm-strange mesons+baryons: $B^0_s$, $\Lambda_b^0$, $\Lambda_C^0$, $\Xi^0_C$, $\Xi^+_C$

**Heavy-flavour vertexing** at low $p_T$ with prompt $\Lambda_C^+$, $Ds^+$, $\Xi_C$

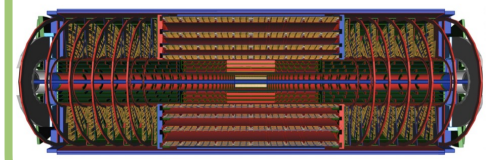


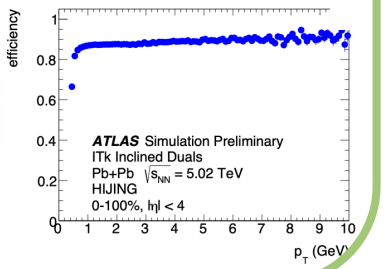
# ATLAS PHASE II – RUN 4

**Muon System: new muon chamber**

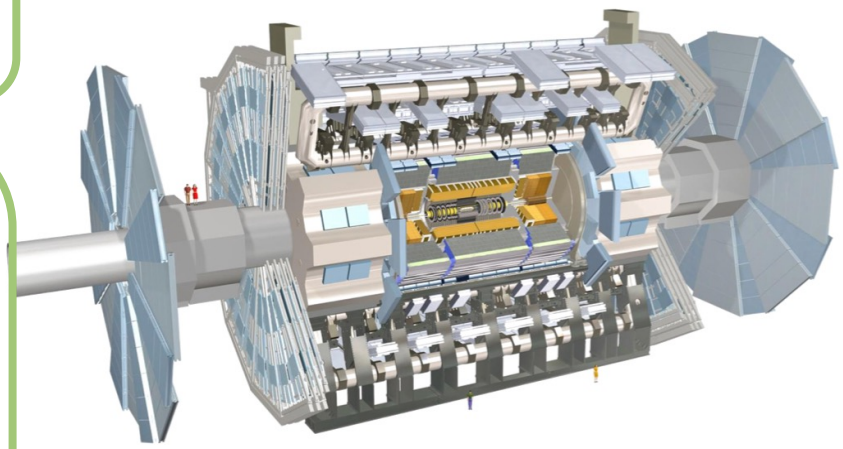
**High-granularity timing detector**
Based on LGADs
PID with σTOF ≈ 35 ps
Baseline trigger for HI

**New tracker** hybrid silicon pixeland strip sensors coverage up to $|\eta| < 4$
higher granularity
Improve flow measurement






**Upgrade of Trigger, DAQ, electronic and luminosity detectors**

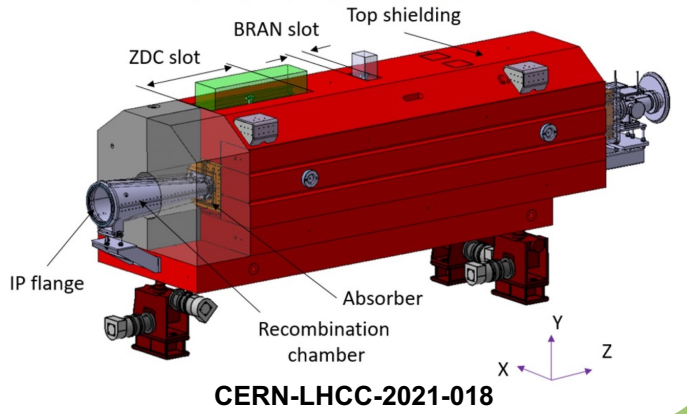


**Endcap calorimeter:** high granularity

**HL-ZDC**

PA. Det. And Upgrade
Riccardo Longo, Tuesday

JZCaP (jointly with CMS) adapt to new optics increase radiation hardness Reaction plane detector




CERN-LHCC-2021-018

# ATLAS PHASE II – RUN 4

**Muon System: new muon chamber**

**High-granularity timing detector**
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Baseline trigger for HI

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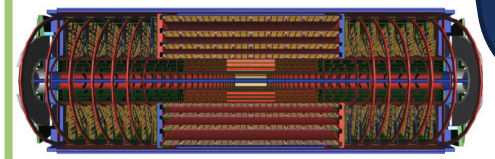
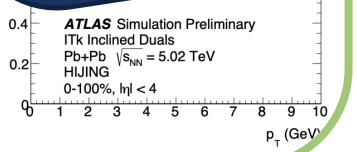
strip sensors coverag
higher granularity
Improve flow measur





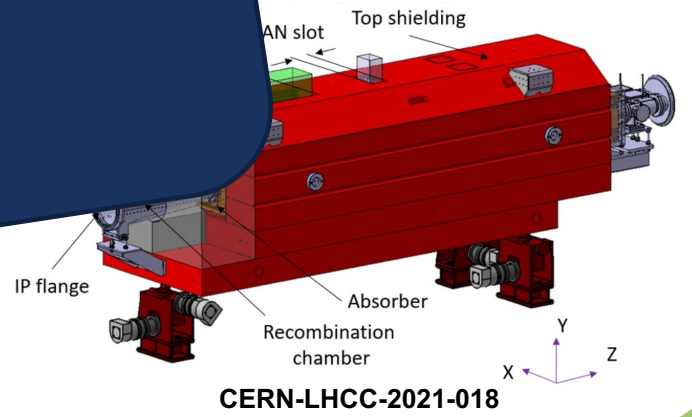

**Upgrade of Trigger, DAQ, electronic and luminosity detector**

- New ZDC
- Extend tracker acceptance to $|\eta| < 4$
- Time-of-flight PID $2.5 < |\eta| < 4$
- Endcap calorimeters with high granularity

**Centrality determination, Hermiticity and PID**
**Characteristic of HI exp**

**PA. Det. And Upgrade**
**Riccardo Longo, Tuesday**

ith CMS) adapt to new
adiation hardness Reaction



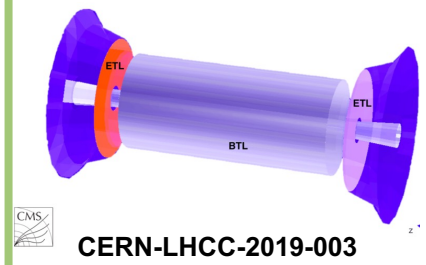

CERN-LHCC-2021-018

**Endcap calorimeter:** high granularity

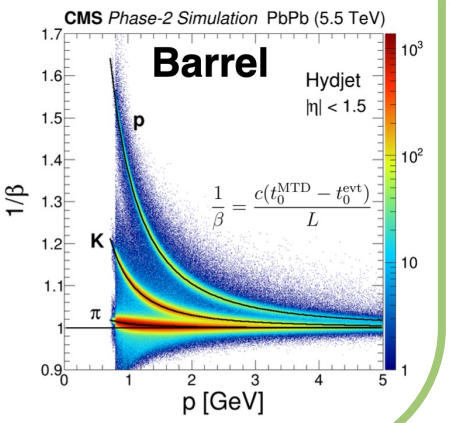
# CMS PHASE II – RUN 4

## MIP Timing Detector (MTD)

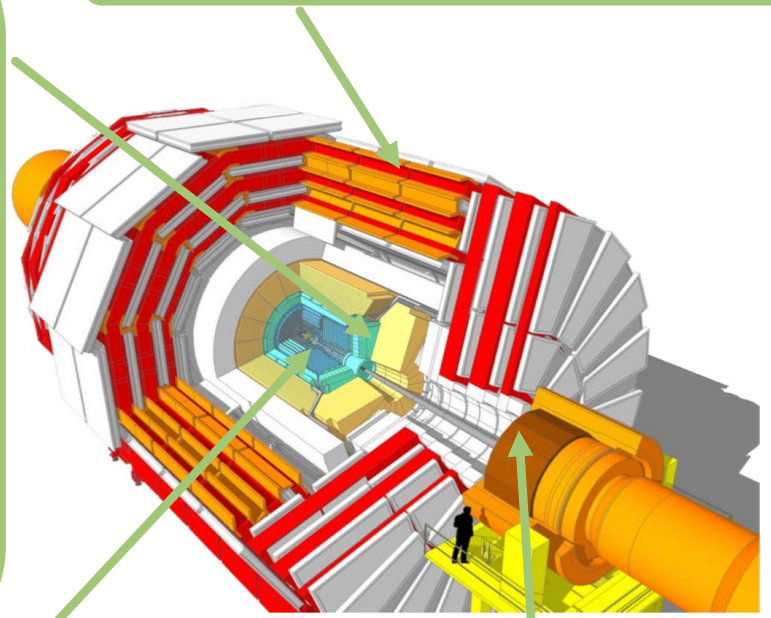
barrel: LYSO + SiPMs
endcaps: LGADs
σTOF ≈ 30 ps
**hermetic coverage** up to |η| = 3




CERN-LHCC-2019-003




## New Readout for muon systems



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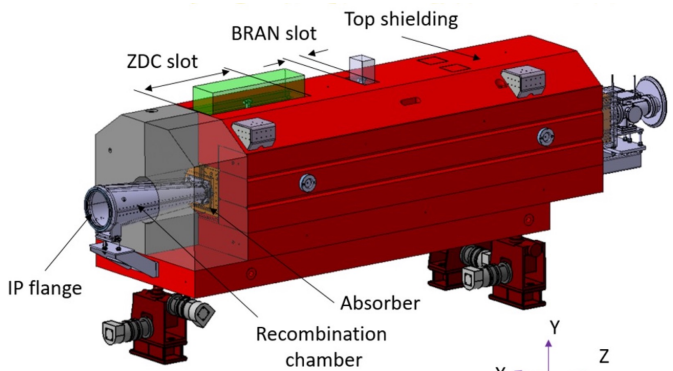
PA. Det. And Upgrade
Riccardo Longo, Tuesday

JZCaP (jointly with ATLAS) adapt to new optics increase radiation hardness Reaction plane detector



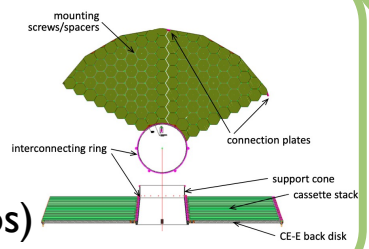

CERN-LHCC-2021-018

## Tracker

hybrid silicon pixels + strips for outer
Radiation tolerance, High granularity
Reduced material, $|\eta|<2.4 \rightarrow |\eta|<4$

## Endcap calorimeter

High-granular ECal + HCal
4d showers (σt ≈ 20 ps)



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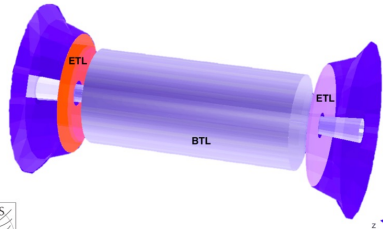



CERN-LHCC-2019-003

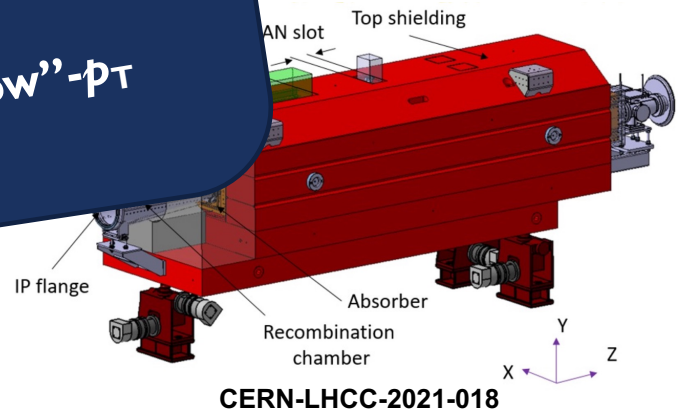
- Charged particle tracking up to |η| < 4
- Muons up to |η| < 3
- Time-of-flight PID up to |η| < 3
- High-precision vertexing
- Wide coverage calorimetry
- ZDC

Centrality determination, Hermiticity and PID at "low"-$p_T$
Characteristic of HI exp

## New Readout for muon systems

PA. Det. And Upgrade
Riccardo Longo, Tuesday

…ith ATLAS) adapt to new
…adiation hardness Reaction




CERN-LHCC-2021-018

## Tracker

hybrid silicon pixels + strips for outer
Radiation tolerance, High granularity
Reduced material, $|\eta|<2.4 \rightarrow |\eta|<4$

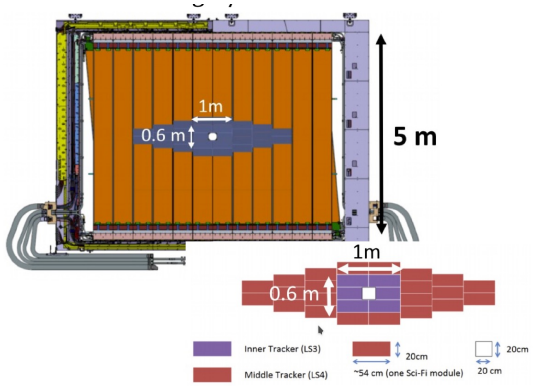
## Endcap calorimeter

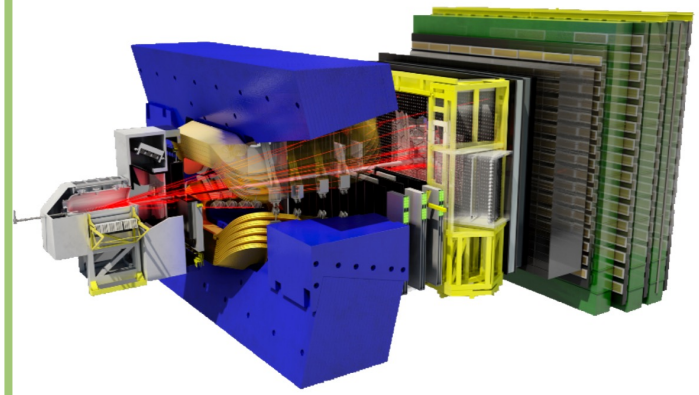
High-granular ECal + HCal
4d showers (σt ≈ 20 ps)

# LHCb Ib – RUN 4

## Tracking

Upstream tracker
SciFi tracker: first Mighty Tracker (MAPS) elements inserted in SciFi
Magnet stations: $p_T$ below 5 GeV/$c$



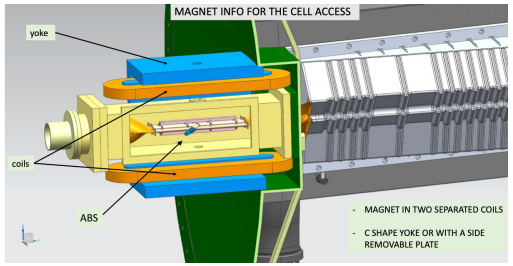



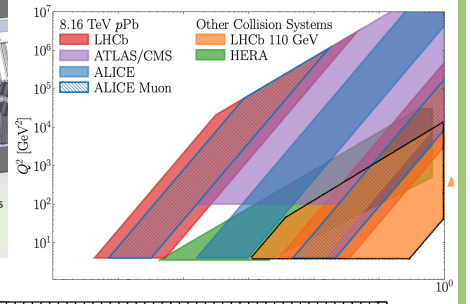
Not yet full centrality reconstruction
T.B.D RUN 5 (Mighty Tracker and Upstream Tracker)

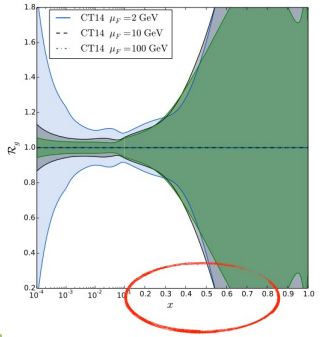
## Proposal for LHCSpin

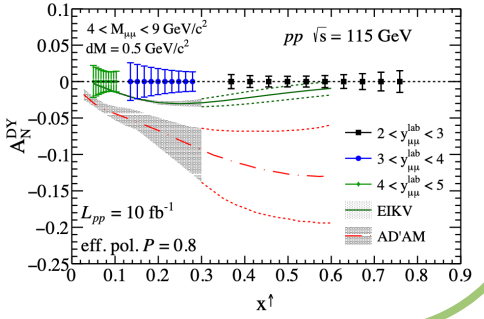
PA. Det. And Upgrade
Marco Santimaria, Wednesday

Upgrade of SMOG, RUN4, not yet approved
Bring a **polarized gas target** at LHCb
Nucleon Structure (TMD, Gluon Sivers function, PDF) and HI



# PHYSICS Outlook* – RUN 3+4

* Not an exhaustive overview

- **Upgraded machine:**
  - increase in energy and luminosity
  - Intermediate systems with Oxygen
- **Upgraded experiments**
  - To cope with the machine upgrade and collect more statistics
  - All experiments developed upgrade for HI physics

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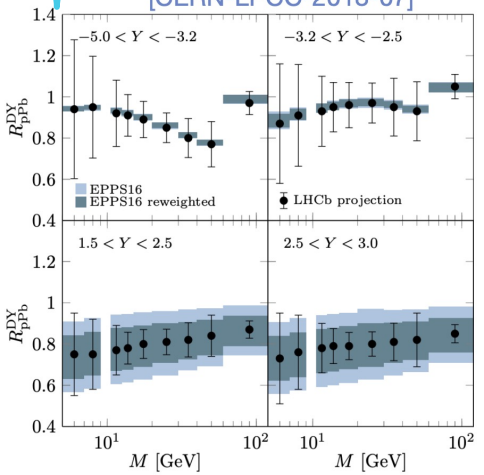
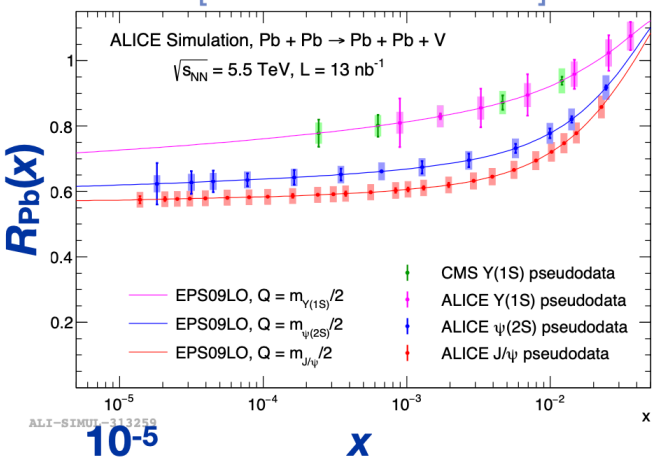
  - Total c cross section

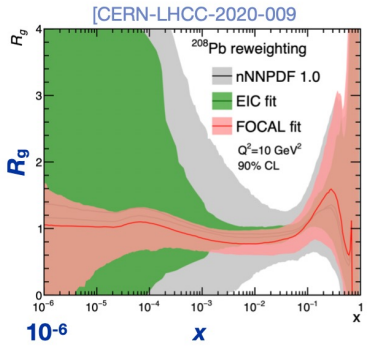
[CERN-LPCC-2018-07]



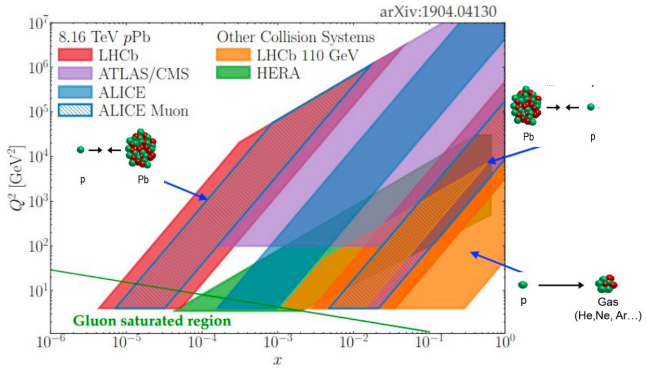

[CERN-LPCC-2018-07]




[CERN-LHCC-2020-009




arXiv:1904.04130



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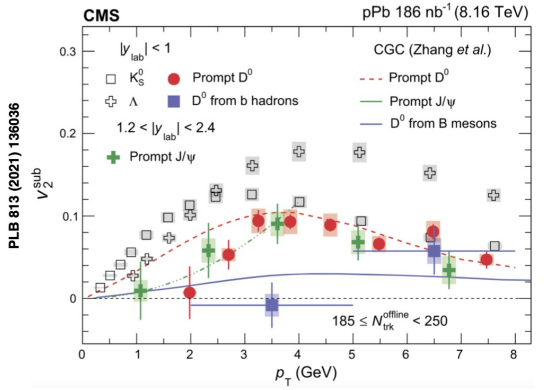
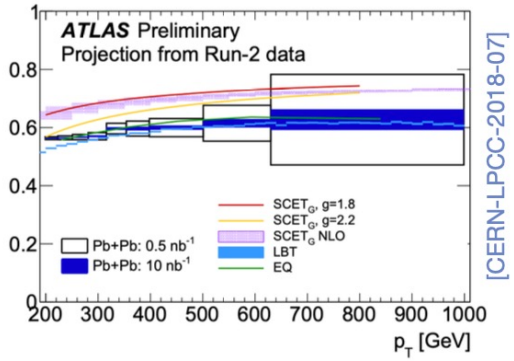
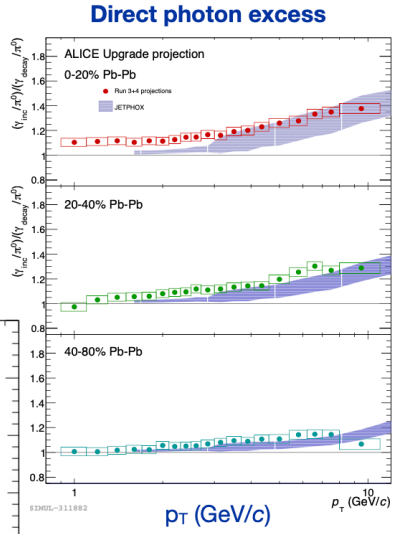
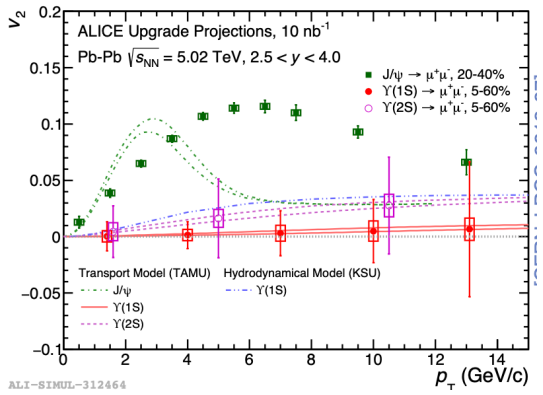
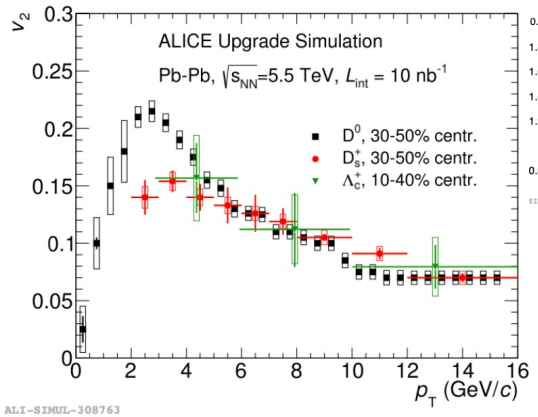
  - Thermal radiation with photon and dielectron
  - Susceptibilities and net baryon fluctuations
  - Jet Quenching: mass and time dependance
  - Heavy flavor transport, precision measurement for $R_{AA}$ and $v_2$, bottomonia



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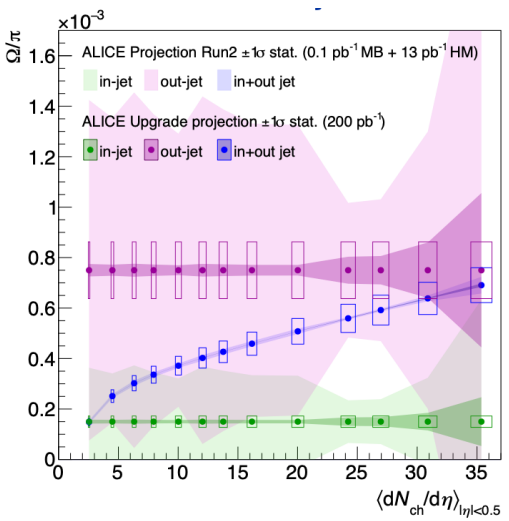
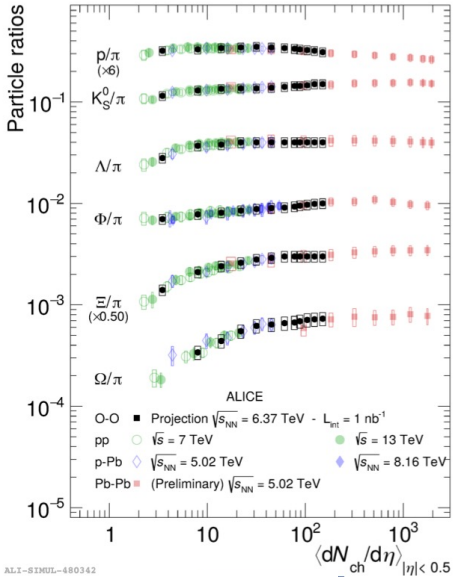
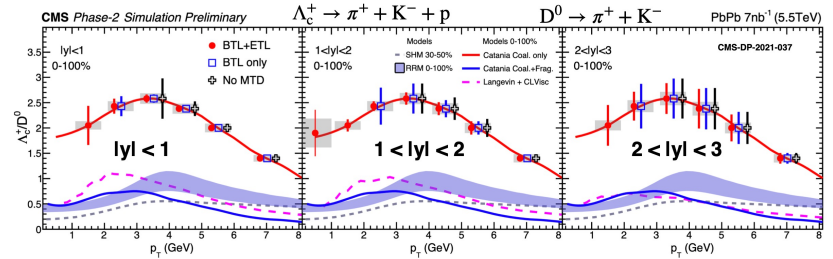
- **Onset of collective behavior from small to large systems**
  - Systematic measurements of QGP legacy probes vs. mult, vs. systems, vs. energy
  - Onset of energy loss and thermal radiation
  - High mult pp sample and new collision systems



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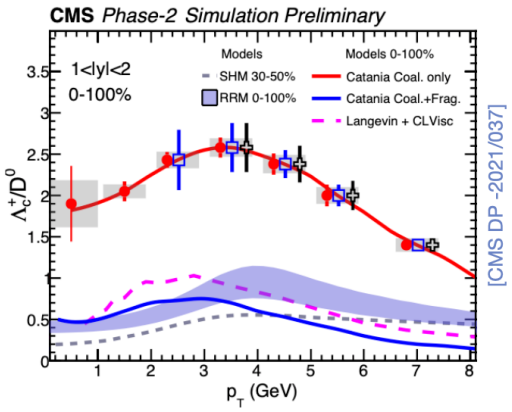
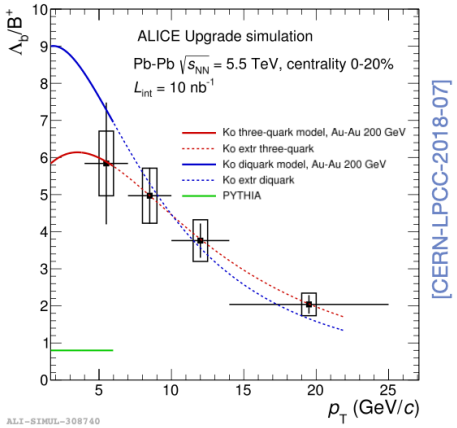
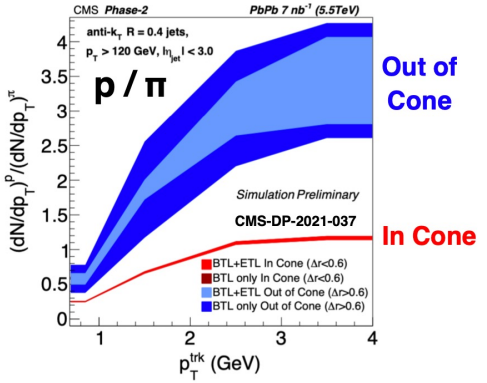
  - Onset of energy loss and thermal radiation
  - High mult pp sample and new collision systems
- **Hadronisation**
  - Baryon/meson ratios, flow
  - Multi-charm baryons
  - Jets

$\Lambda_c/D^0$

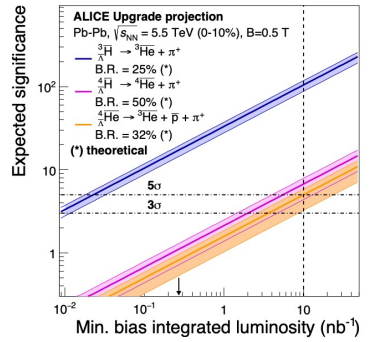



$\Lambda_b/B^+$



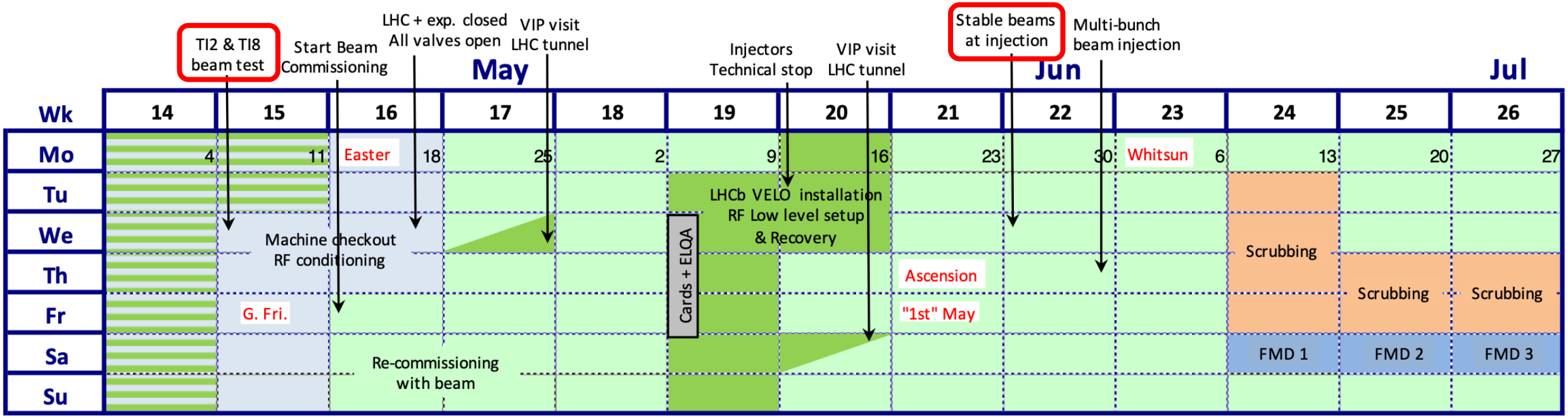




anti-hyper-nuclei



# LHC 2022 Planning

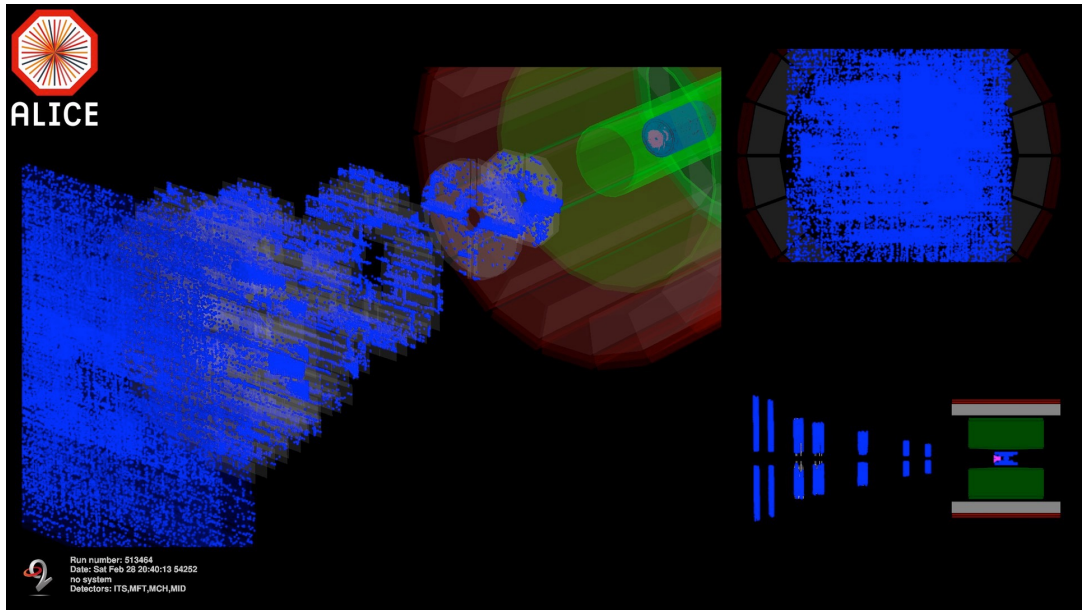
- **April to July 2022 : Machine and Experiment commissioning**

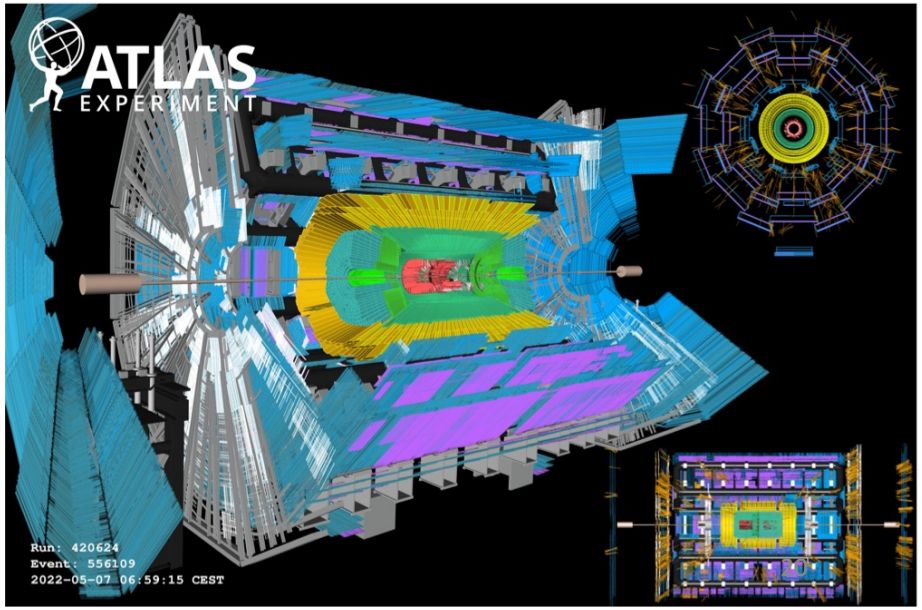



LHC Schedule, last update 25th April 2022 https://edms.cern.ch/ui/file/2664630/LATEST/2022-LHC-schedule_v1.1.pdf

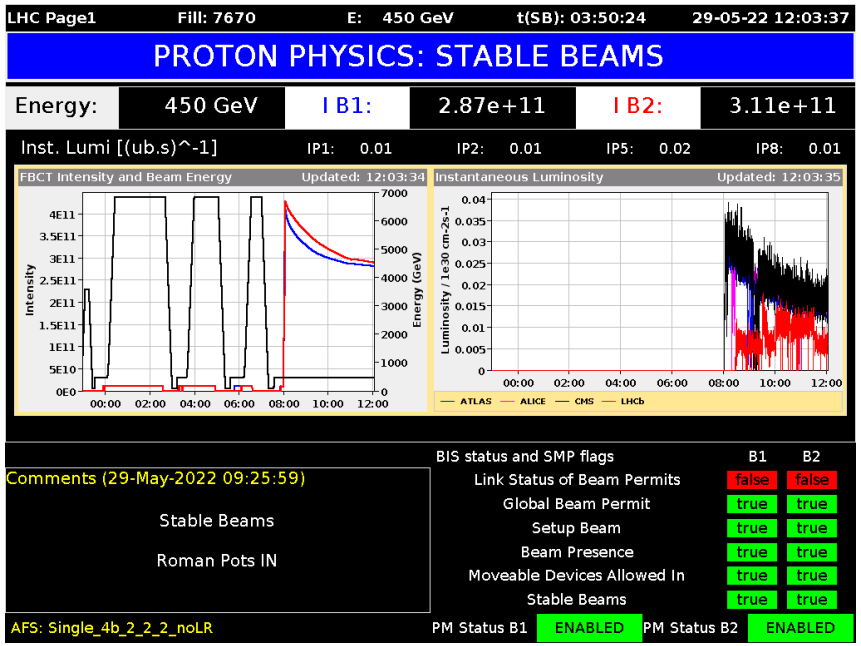
# LHC 2022 Splashes

- **Beam splashes** on TED/TDI
- Muon showers
- Commissioning exercise for experiments: readiness and timing



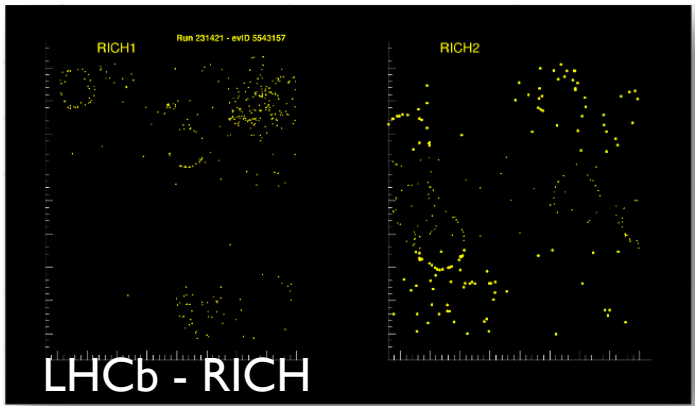



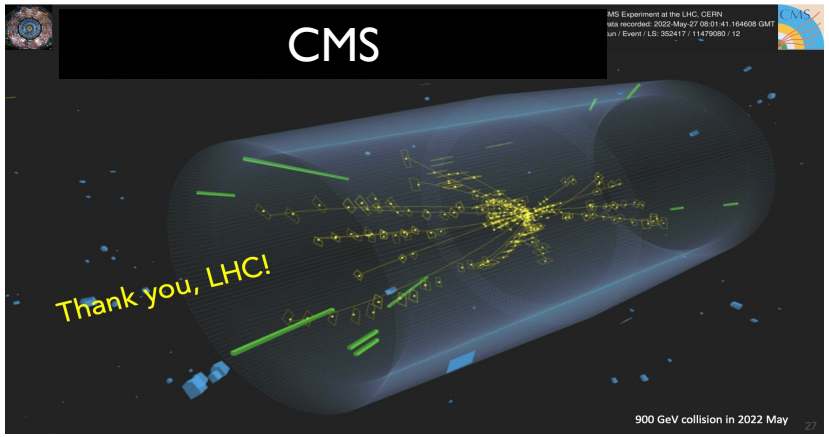
# LHC 2022 Collisions 900 GeV

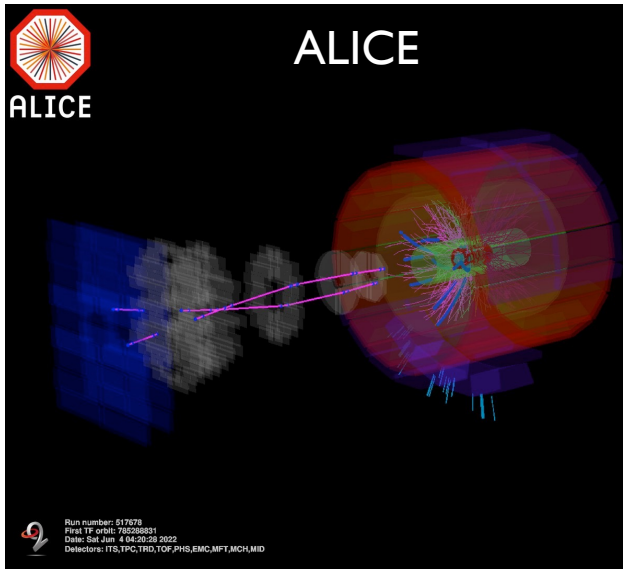


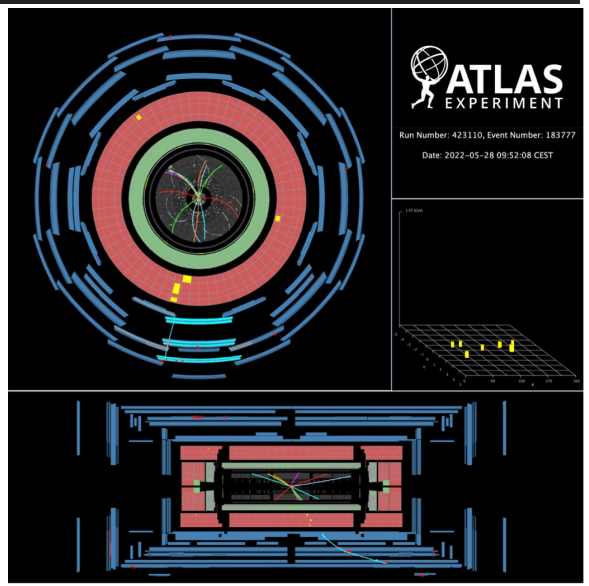

~ 42h of Stable Beam at 900 GeV in 2021

**~ 45h hours so far in 2002**



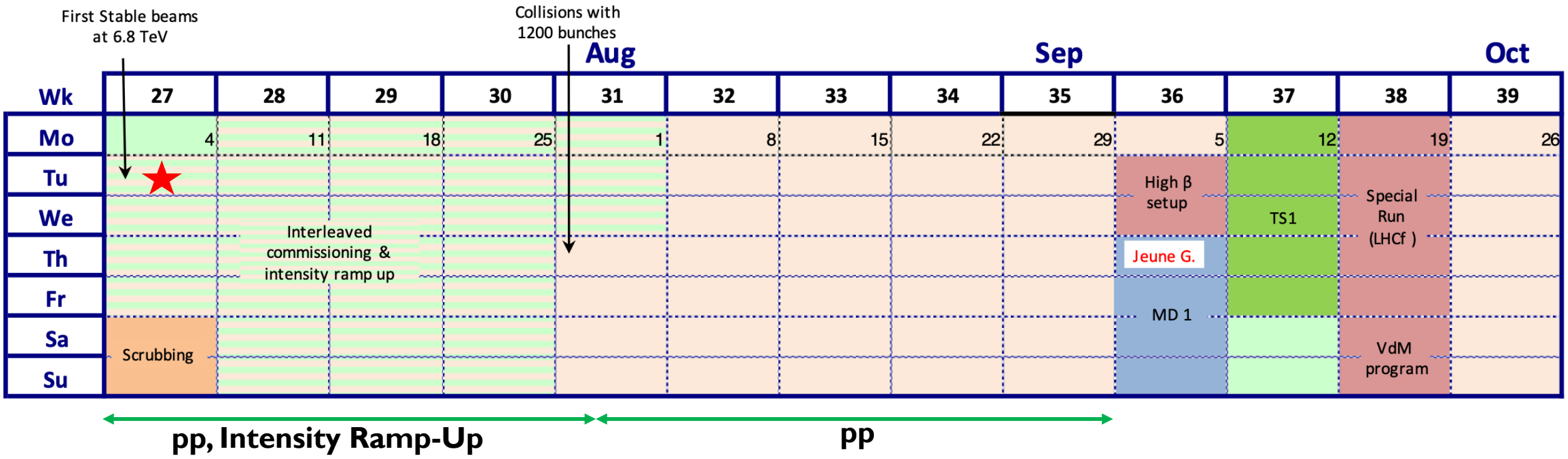



# LHC 2022 Planning

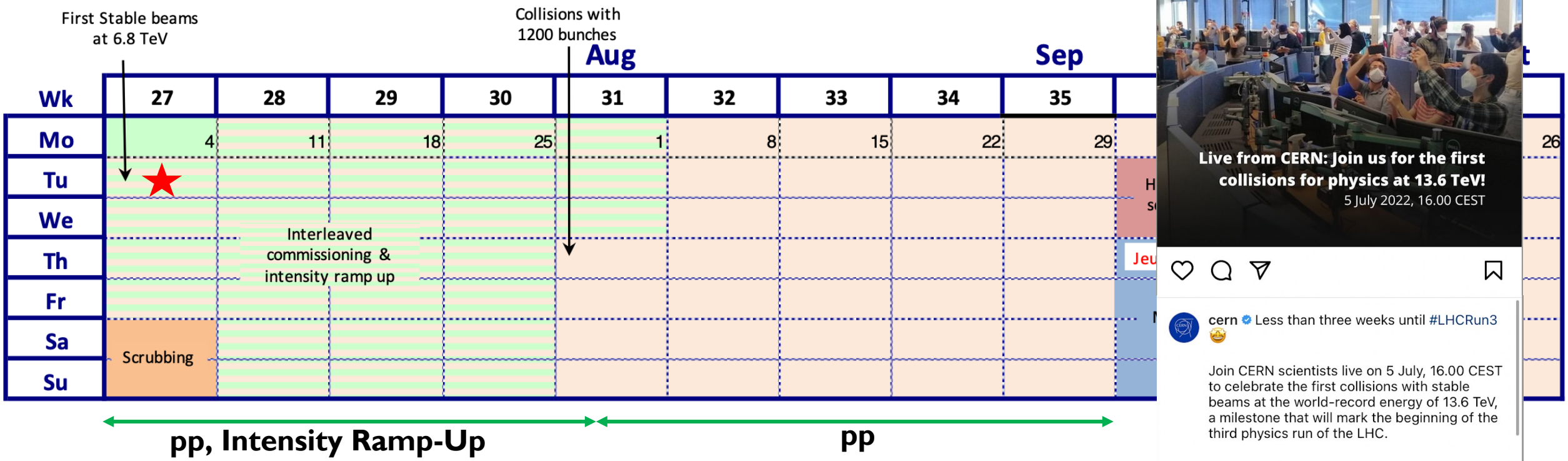
➢ **5th July 2022: First Stable Beam at 13.6 TeV**




LHC Schedule, last update 25th April 2022 https://edms.cern.ch/ui/file/2664630/LATEST/2022-LHC-schedule_v1.1.pdf

# LHC 2022 Planning

➢ **5th July 2022: First Stable Beam at 13.6 TeV**



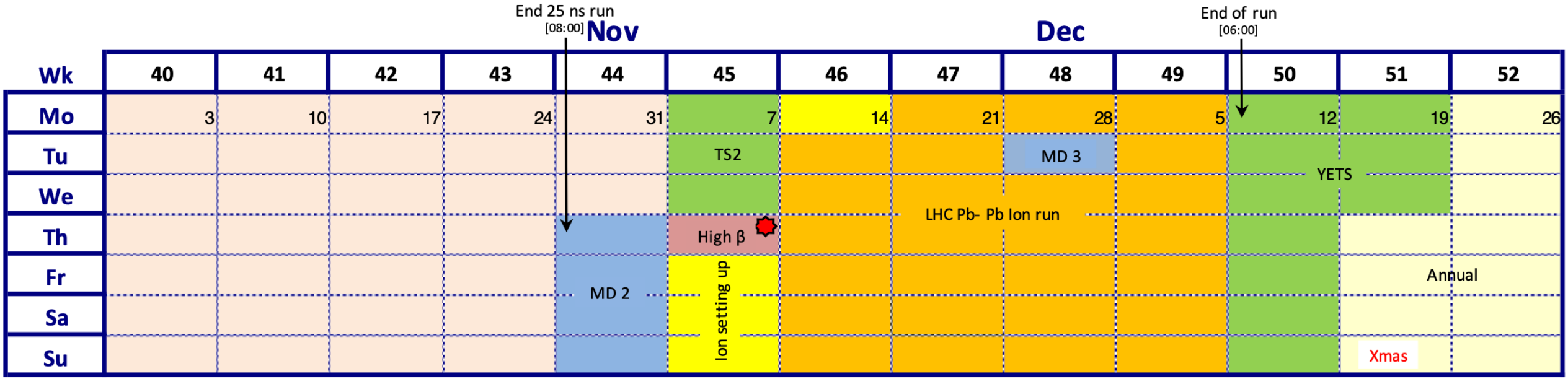




LHC Schedule, last update 25th April 2022 https://edms.cern.ch/ui/file/2664630/LATEST/2022-LHC-schedule_v1.1.pdf

# LHC 2022 Planning

- **Dec 2022: Pb-Pb**




LHC Schedule, last update 25th April 2022 https://edms.cern.ch/ui/file/2664630/LATEST/2022-LHC-schedule_v1.1.pdf

# Conclusions

RUN 1
2009-2013
pp, pPb, Pb-Pb

LS1

RUN 2
2015-2018
pp, pPb, Xe-Xe Pb-Pb

LS2

RUN 3
2022-2025
pp, pO, O-O, pPb,Pb-Pb

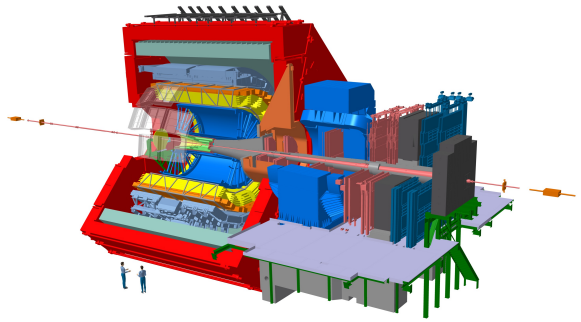
LS3

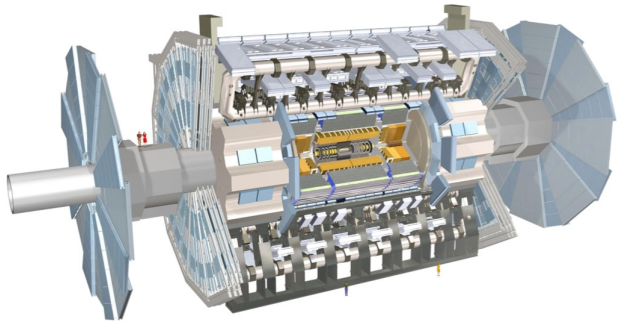
RUN 4
2029-2032
pp, pPb, Pb-Pb

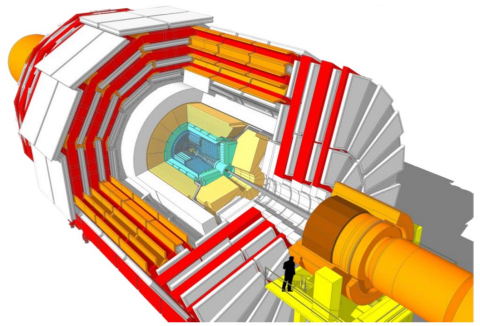
**High Lumi for Ions**

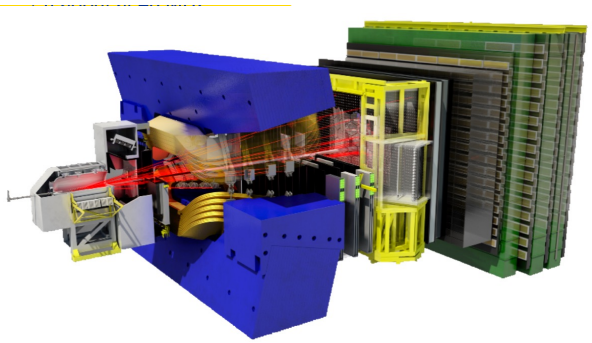
**HL-LHC**

**RUN 3 + 4 A New Era for HI@LHC**
**LHC RUN 3 Top Energy Collisions Imminent !**
**LHC Experiments Upgraded and Ready !**









# Conclusions

RUN 1 2009-2013 pp, pPb, Pb-Pb — LS1 — RUN 2 2015-2018 pp, pPb, Xe-Xe Pb-Pb — LS2 — RUN 3 2022-2025 pp, pO, O-O, pPb,Pb-Pb — LS3 — RUN 4 2029-2032 pp, pPb, Pb-Pb

**High Lumi for Ions**

**HL-LHC**

Many Thanks to the ALICE ATLAS CMS and LHCb collaboration and Run Coordination

**RUN 3 + 4 A New Era for HI@LHC**
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**LHC Experiments Upgraded and Ready !**

To be continued in RUN 5, see talk from Raphaelle Bailhache