HSE
Occupational Health & Safety
and Environmental Protection unit

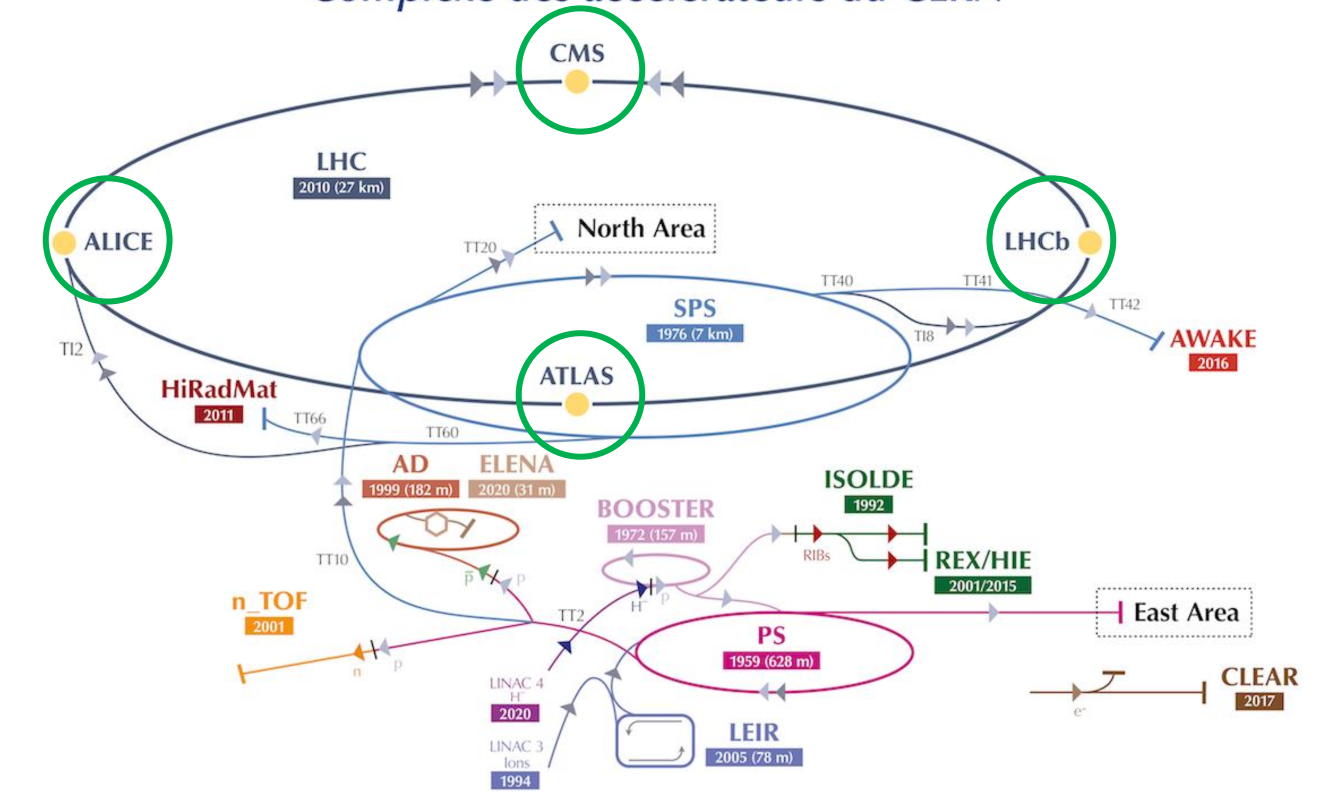
# Challenges and strategies in planning **Long Shutdown 3** for the **HL-LHC Upgrades** of the **LHC experiments** at CERN

R. Froeschl, D. Bozzato, T. Lorenzon

30/05/2024 SATIF-16 workshop

EDMS 3092765

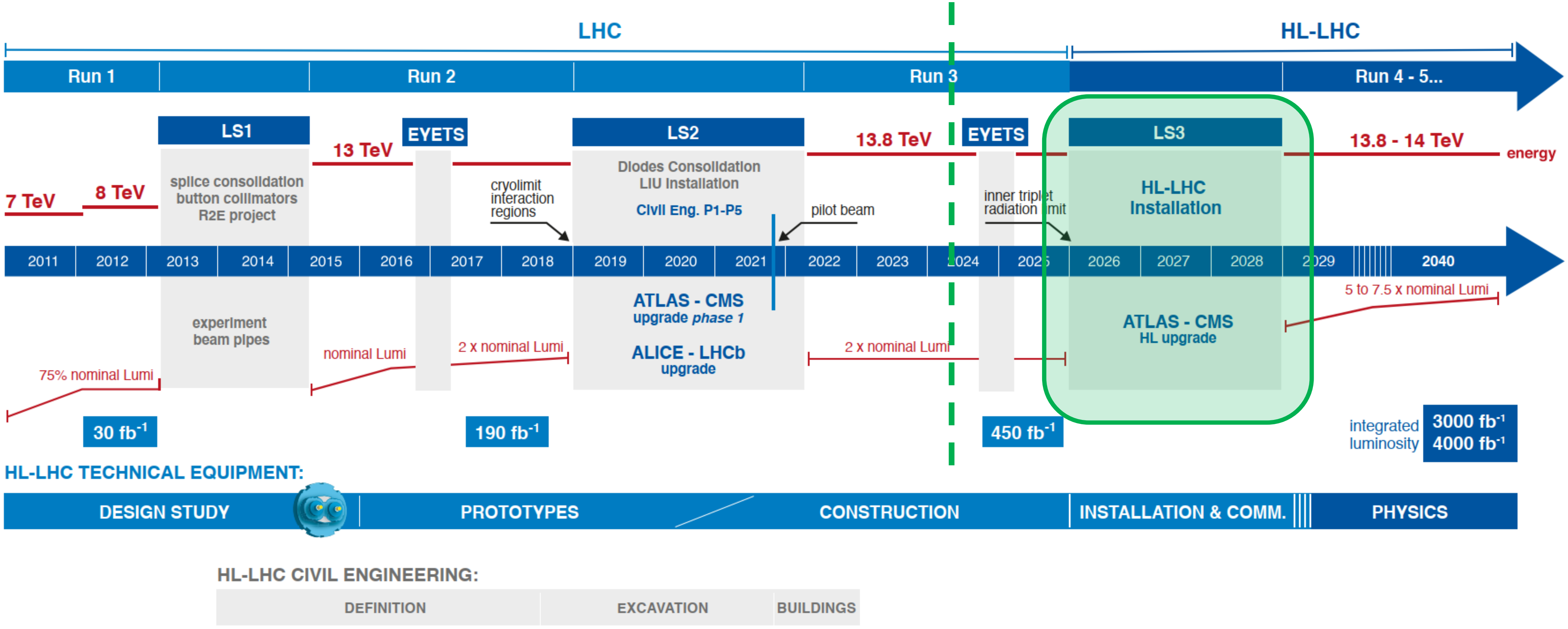
# The CERN accelerator complex
*Complexe des accélérateurs du CERN*




H⁻ (hydrogen anions) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons)

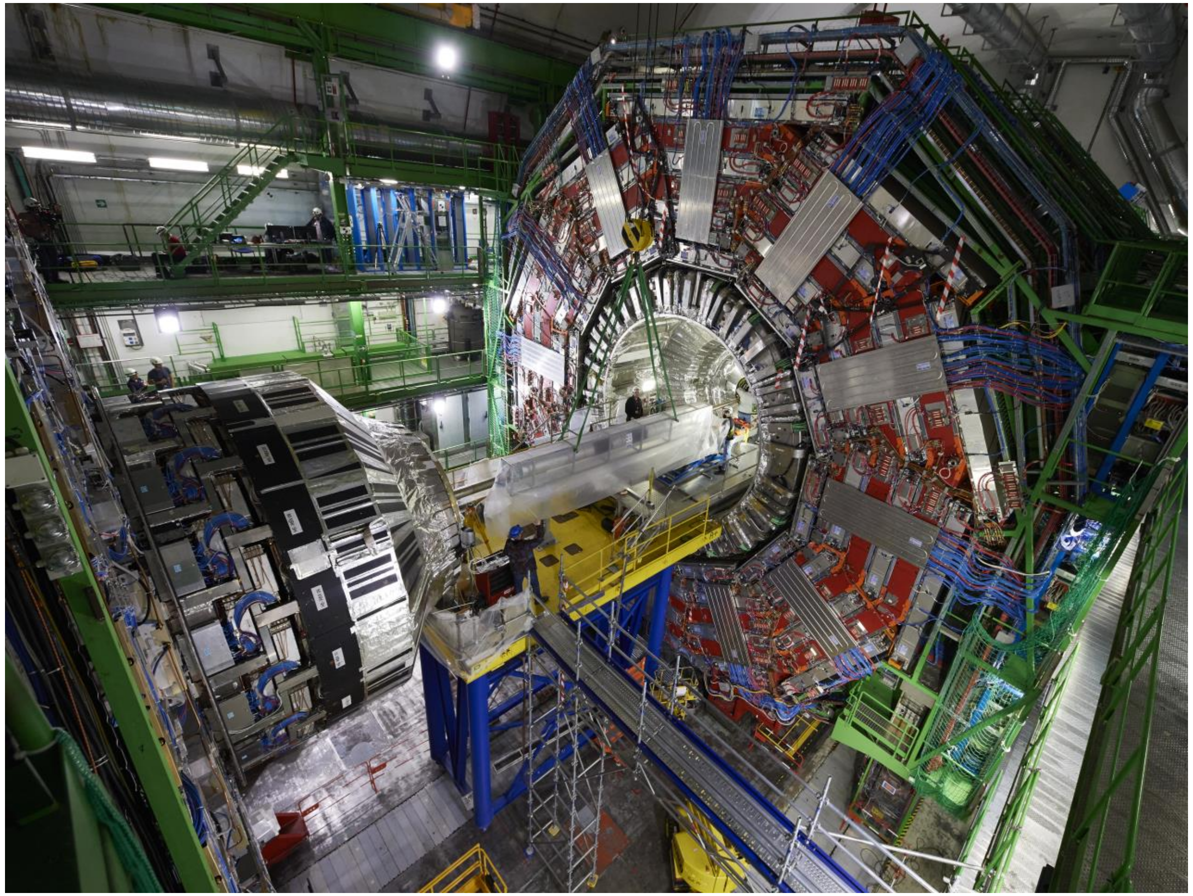
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

# LHC / HL-LHC Plan



# Radiation Protection Aspects of LHC Experiments in LS3

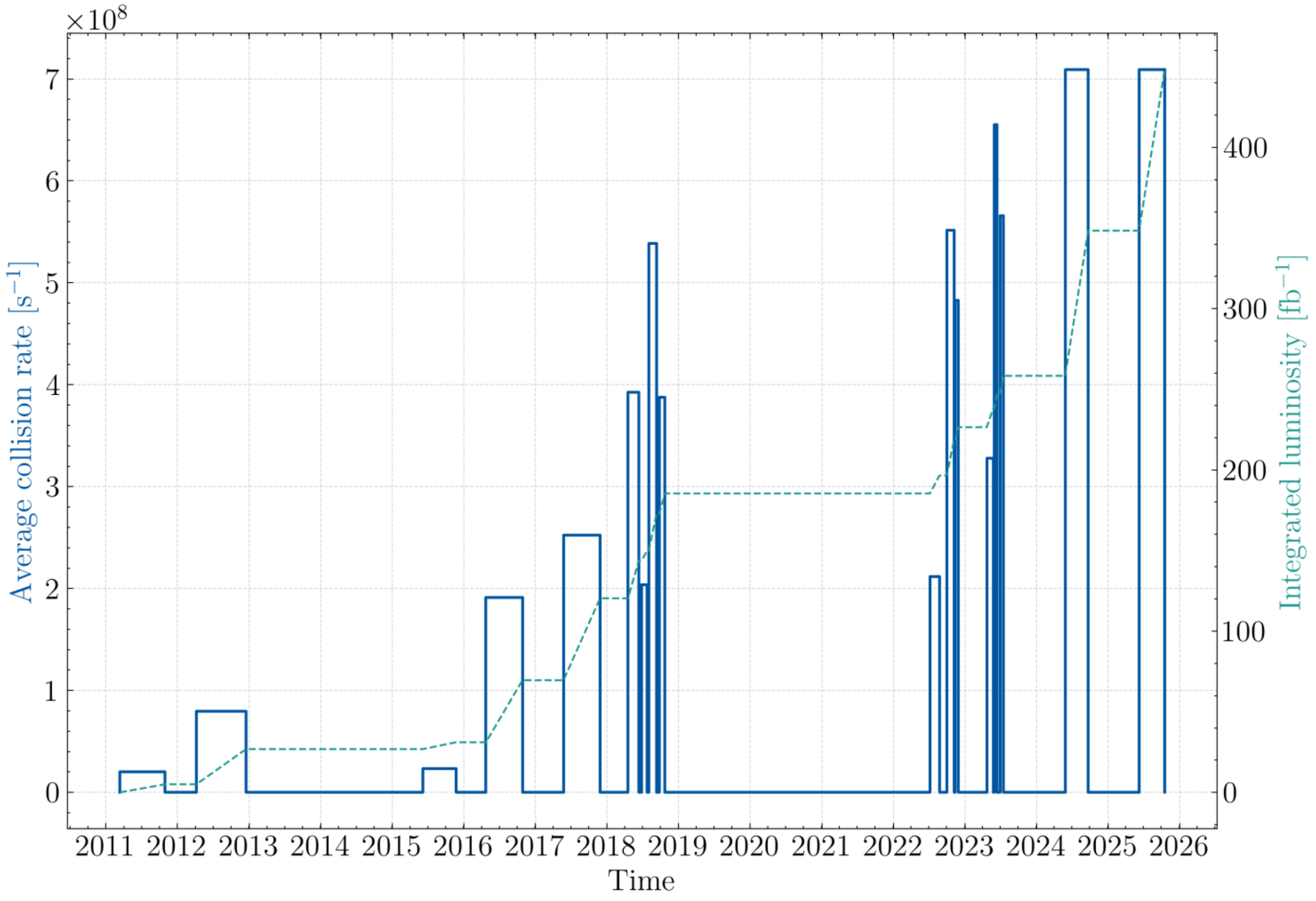
- Radiation sources
- Multiple and prolonged interventions in radiation areas
- Radiological characterization of detector components and infrastructure
- Planning for re-start



# Radiation Sources

- Main radiation source: **Collisions** at the **interaction point**
- Collision rate (luminosity) **predictions** for **future operation**
- **Process** to **update collision profiles annually** with measured data from the last operational year

https://op-webtools.web.cern.ch/vistar/?usr=LHC1

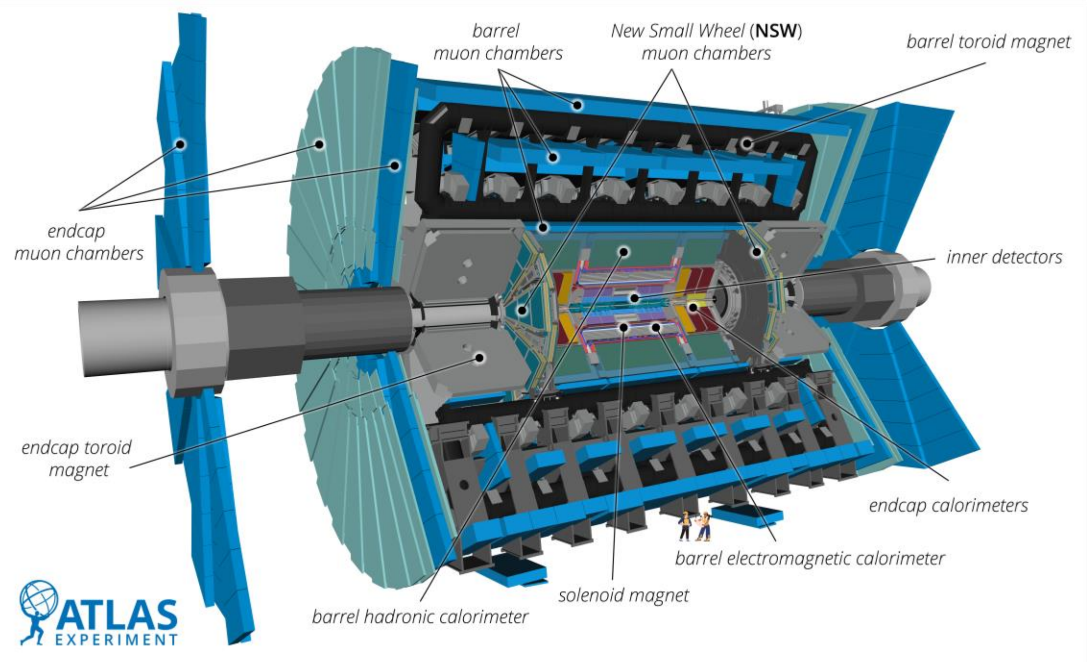


# Interventions in the LHC Experiments

- LS3 will last **3 years**
  - **Many** and **long interventions** in the experimental caverns (radiation areas)
- CERN **ALARA** rules require establishment of **Work-Dose-plannings**
  - guide **optimization process**
  - define appropriate **approval process**
  - **Ensure dose limits** and **constraints** are respected
- Estimates of **residual dose rates** at workplaces for several **detector configurations** for a multitude of cool-down times needed as **input for Work-Dose-plannings**

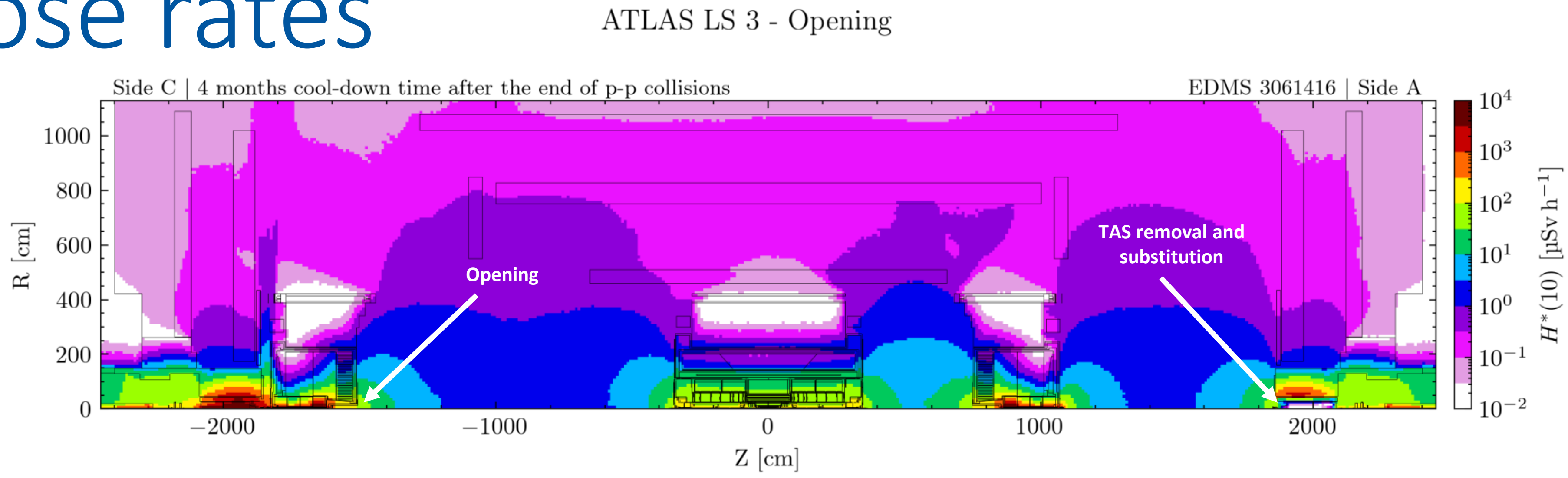
# Residual dose rates assessments – ATLAS

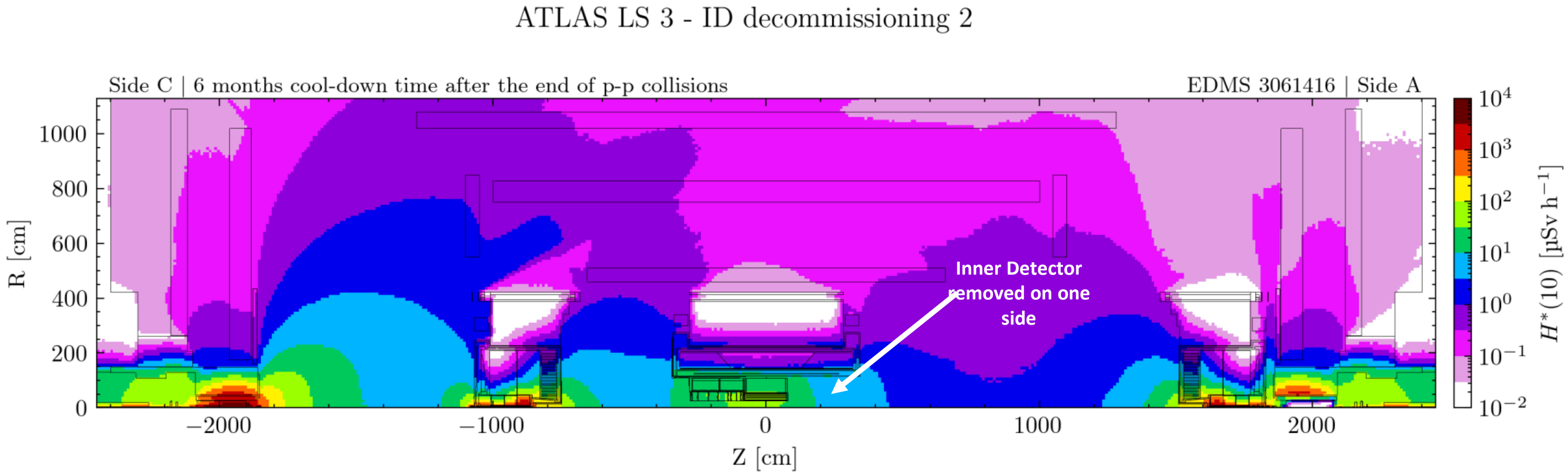
- ATLAS:
  - **General-purpose detector** at the LHC
  - 46 m long, 25 m high and 25 m wide, **~7000 tons weight**
  - **Opening procedure** is in steps
- Long shutdown 3:
  - **Upgrades** and **new installations** in view of HL-LHC
  - Multiple and **prolonged interventions** in residual radiation environments
  - **Monte Carlo simulations** to provide input for the **Work Dose Planning**



# Residual dose rates

- ATLAS Detector **configurations**: **16 scenarios** defined **with ATLAS Technical Coordination** to reach sufficient level of detail
- **FLUKA-SESAME**[1] two-step simulations
- Full irradiation history up to the end of Run 3
- Cool-down times: **Grid of 25 cool-down times** (from days to 30 years)
- A **few hundreds of CPU-days** of simulation time

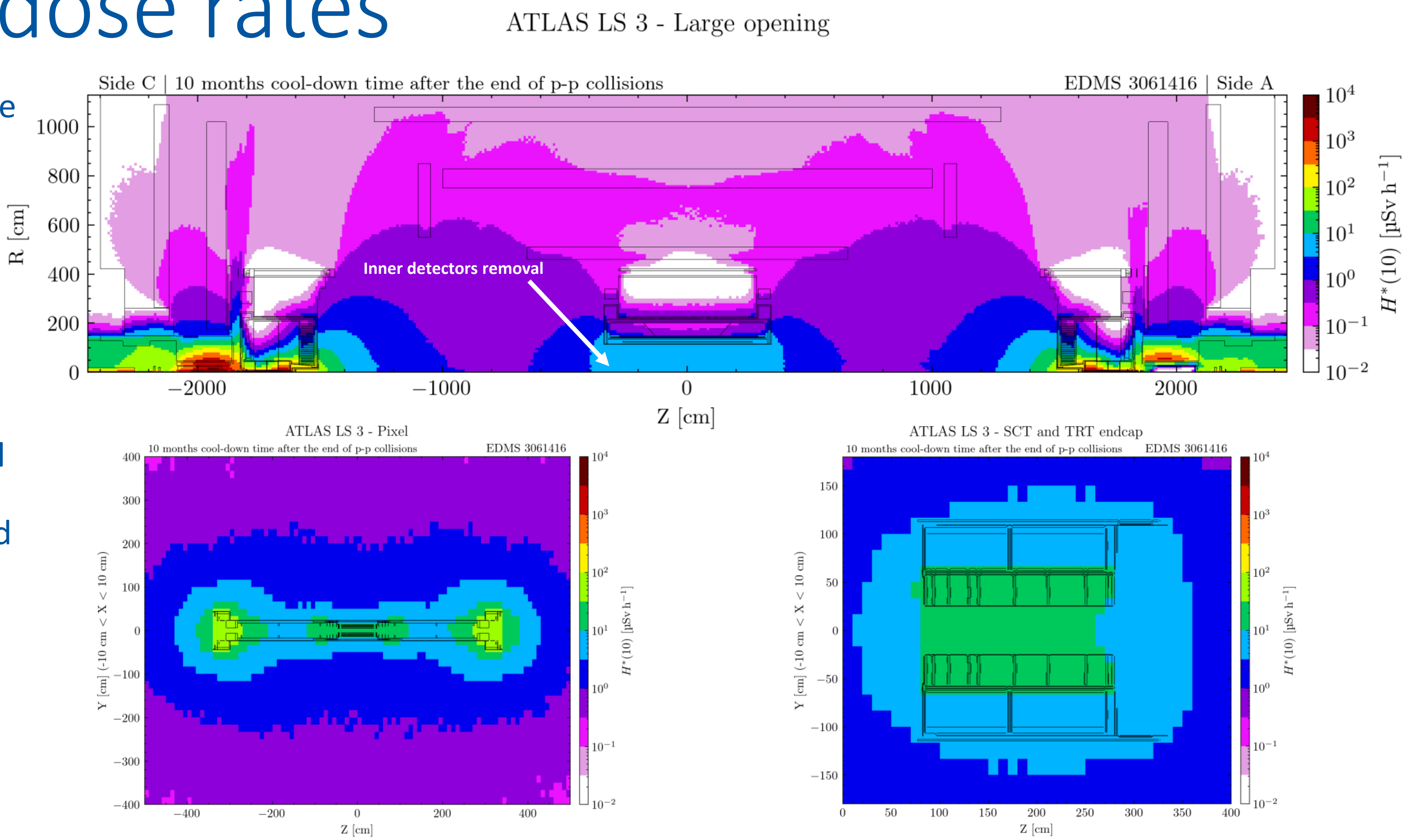



[1] See T. Lorenzon at SATIF-15

# Residual dose rates

- **Considerable** auxiliary code **production**
  - **FLUKA geometry modifications** for all **scenarios**
  - Scripting
  - Plotting
  - **Visualization tool** for ATLAS technical coordination
- Assessments for **individual components** (dismantling, transport and storage purposes)

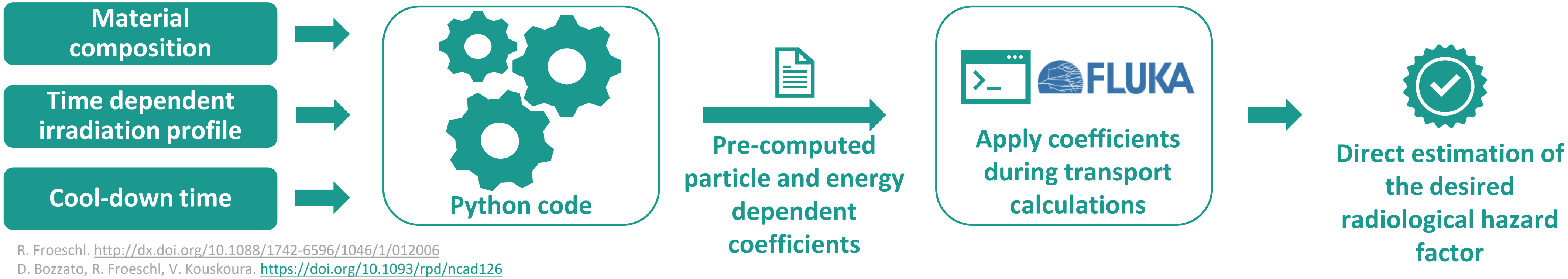


# Radiological characterization of detector components and infrastructure

- Zoning
- Characterization for transport classification
- Characterization for storage requirements definition
- Refurbishment of detector components
- Pre-characterization for clearance and waste

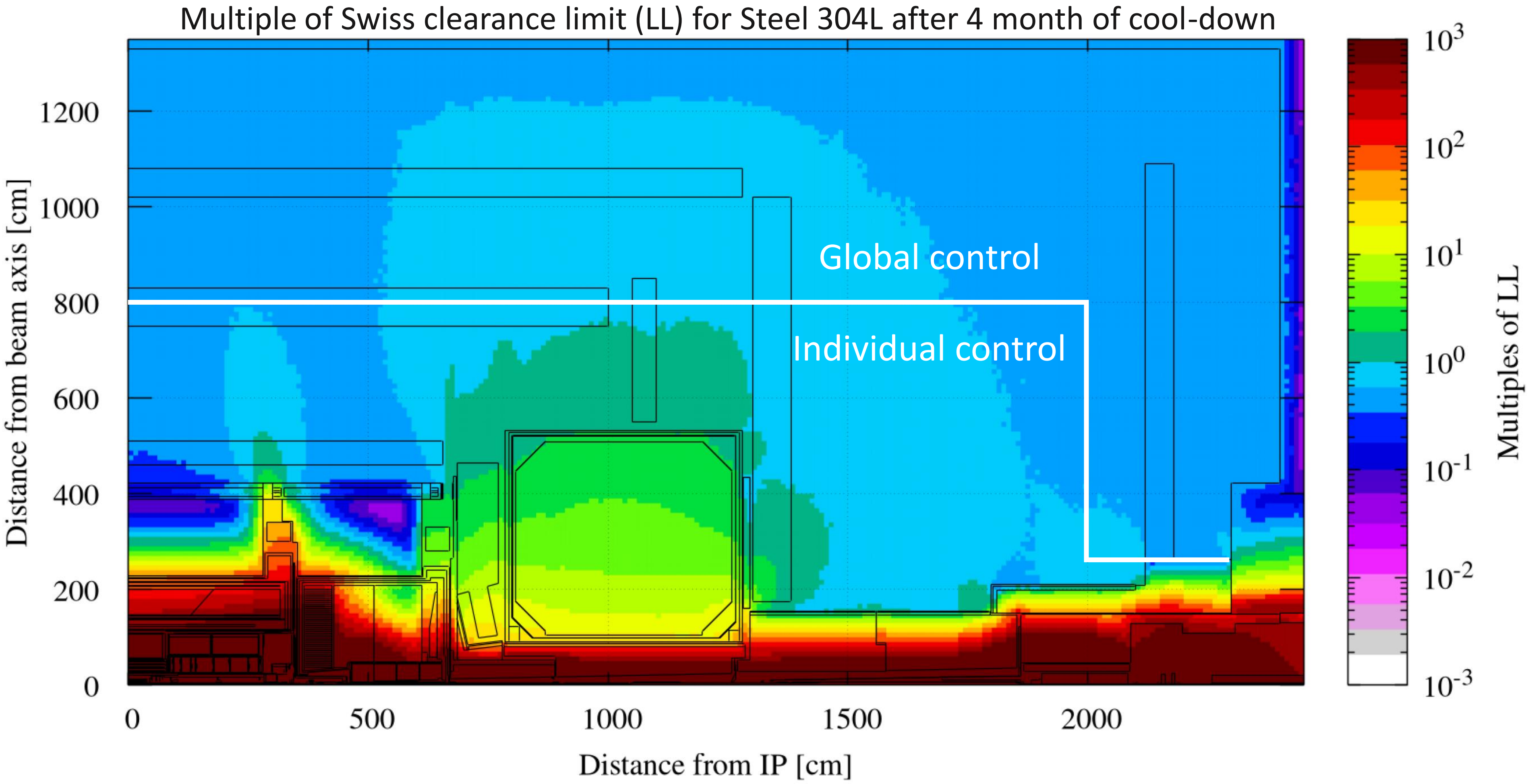
# Zoning concept for clearance

- **Partitioning** of experimental cavern in **2 zones**
  - **Global control** zone: Activation levels **a priori expected** to be **below clearance limit**
  - **Individual control** zone: Activation levels **not excluded** to **exceed clearance limit**
- **Different measurement procedures** for these zone (verification / clearance measurements)
- **Definition** of zones **based** on **simulations** + verification with **samples**
- **Simulations assessment** performed in most cases with **dedicated methodology**
  -> **Fluence Conversion coefficients method**




R. Froeschl. http://dx.doi.org/10.1088/1742-6596/1046/1/012006
D. Bozzato, R. Froeschl, V. Kouskoura. https://doi.org/10.1093/rpd/ncad126

# Zoning – ATLAS in LS3

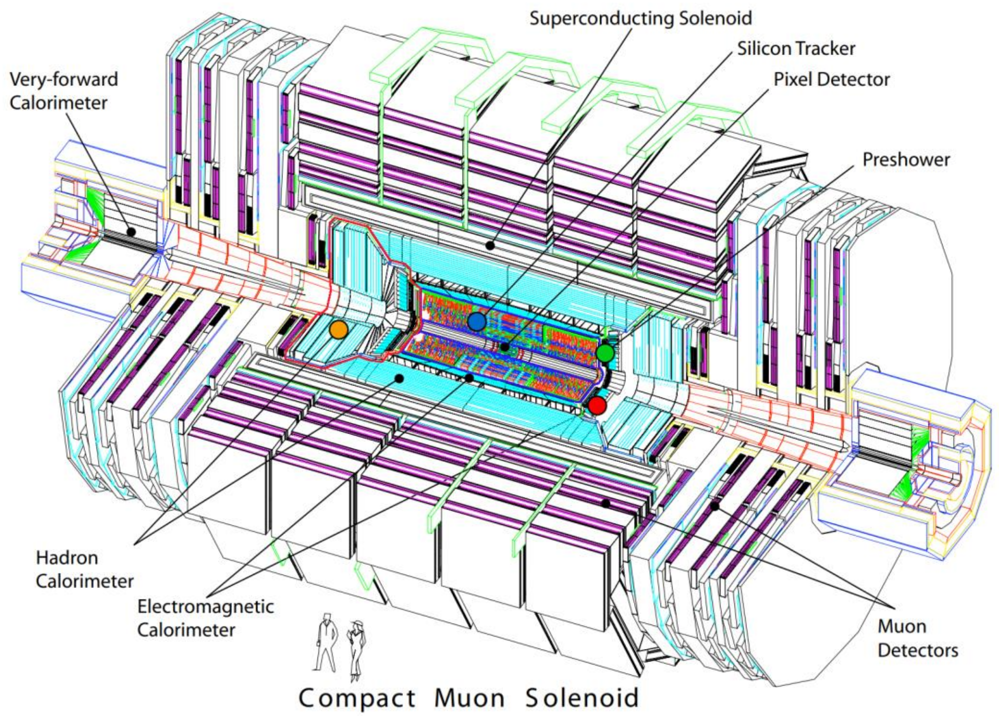


# Characterization for transport classification

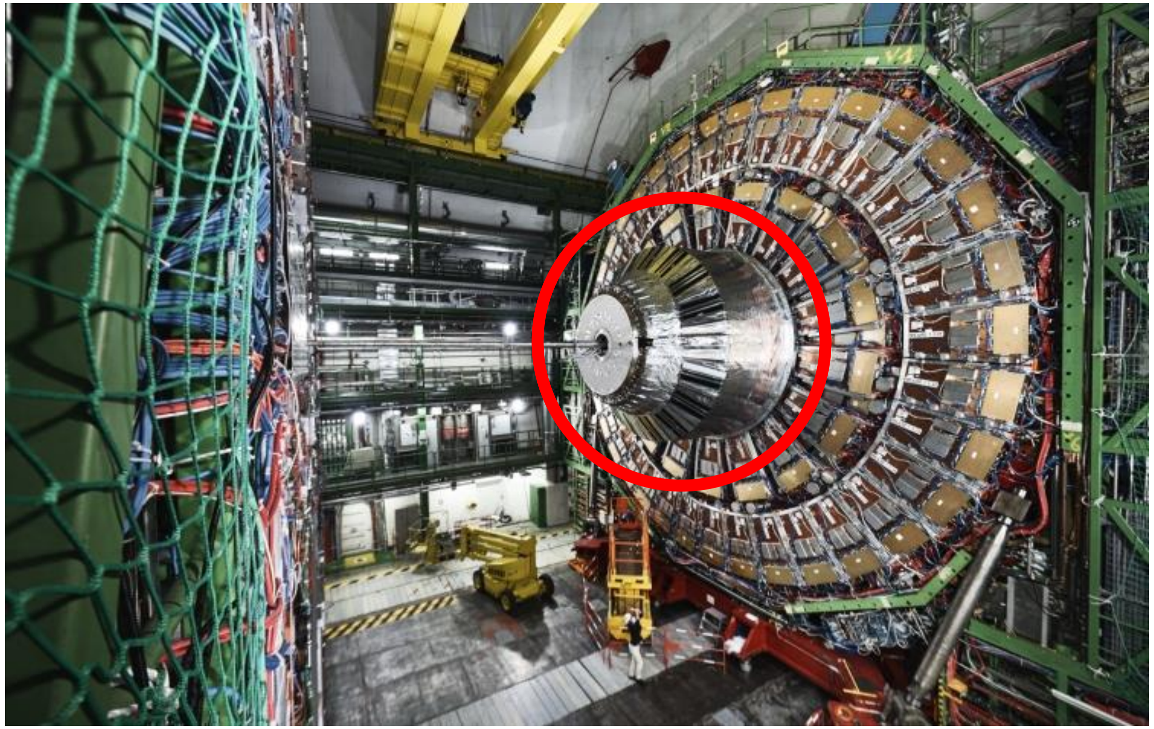
- Radionuclide inventories needed to **ensure ADR compliant** classification of **transports**
  - **Very large objects** for which **certified containers** are **difficult to obtain**
- **FLUKA** Monte Carlo simulations to compute **radionuclide inventories**
  - Standard FLUKA simulations with RESNUCLE scoring
  - Post-processing of SESAME data
  - Spectra-based
- These results are passed to **radioactive transport service** for **proper transport classification**

Example: CMS Endcap (YE1) noses

6 meters diameter, ~150 tons



# Characterization for transport classification

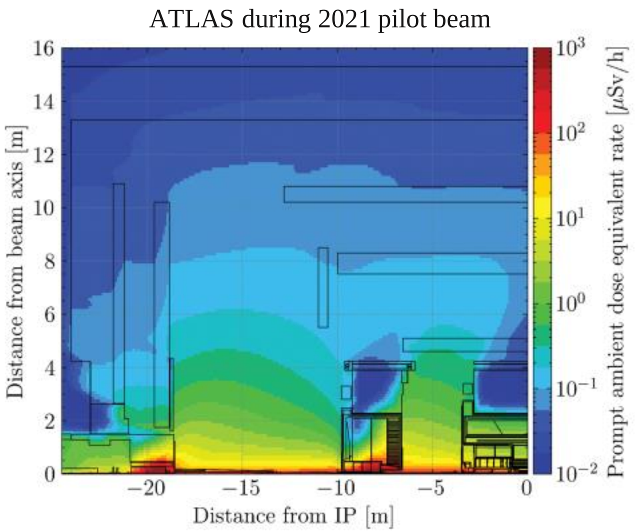


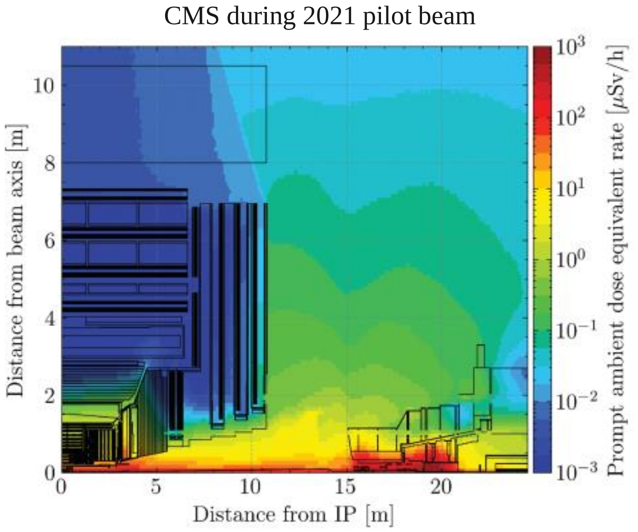
Mass-specific radionuclide inventory in one CMS YE1 nose after 90 days of cool-down (top contributors only)

| Isotope | Activity [Bq/g] |
|---|---|
| $^{65}$Zn | 2.07E+01 $\pm$ 0.19 % |
| $^{185}$W | 1.69E+01 $\pm$ 0.30 % |
| $^{3}$H | 4.00E+00 $\pm$ 0.15 % |
| $^{181}$W | 3.80E+00 $\pm$ 0.32 % |
| $^{58}$Co | 3.60E+00 $\pm$ 0.23 % |
| $^{57}$Co | 3.49E+00 $\pm$ 0.24 % |
| $^{55}$Fe | 2.05E+00 $\pm$ 0.20 % |
| $^{179}$Ta | 1.64E+00 $\pm$ 0.33 % |
| $^{54}$Mn | 1.43E+00 $\pm$ 0.26 % |
| $^{56}$Co | 9.38E-01 $\pm$ 0.29 % |
| $^{7}$Be | 8.87E-01 $\pm$ 0.22 % |
| $^{175}$Hf | 8.72E-01 $\pm$ 0.36 % |
| $^{60}$Co | 8.70E-01 $\pm$ 0.24 % |
| $^{49}$V | 6.55E-01 $\pm$ 0.32 % |

# Planning for re-start

- **Restart period** might require assessments of detector configurations and beam conditions **different** from **nominal operation**
  - Pilot beam in 2021
    - Prompt radiation for **modified shielding** configuration
    - **Dedicated clearance zoning** in the experiments (scaffoldings, structural supports, …)
    - **RP input** needed to **define beam parameters**
- The **actual start-up configurations** will **depend** on the **progress of LS3**
- Importance of **knowledge conservation**




D. Bozzato, R. Froeschl. https://doi.org/10.1080/00295639.2023.2211191 (ICRS14/RPSD-2022)

# Conclusions

- **Long Shutdown 3** will be **very complex** in terms of radiation protection for the **LHC Experiments**
- **Residual dose rate estimates** for Work-Dose-plannings
- **Radiological characterization** of big and complex environments and detector components
- **Dedicated tools** coupled to FLUKA code **developed** to perform required assessments
- Need to plan for the **re-start after LS3**

www.cern.ch

# Backup

# ALARA levels at CERN for the classification of interventions

**Group 1 Criteria: 'hard'** limits used to determine the minimum ALARA Level

| | | | | | |
|---|---|---|---|---|---|
| Individual dose equi. | Level I | 100 µSv | Level II | 1 mSv | Level III |
| Collective dose equi. | | 500 µSv | | 5 mSv | |

**Group 2 Criteria:** base of a radiological risk assessment

| | | | | | |
|---|---|---|---|---|---|
| Ambient dose equivalent rate | Level I | 50 µSv/hr | Level II | 2 mSv/hr | Level III |
| Airborne activity in CA | | 5 CA | | 200 CA | |
| Surface contamination in CS | | 10 CS | | 100 CS | |

# Fluence conversion coefficients method

Let's consider a compound material constituted by a certain number of elements $e$ having mass fractions $m_e$. The material is irradiated, and residual activity is left. The specific activity of a radionuclide $b$ in the material can be expressed as

$$A_b = \sum_r \sum_e T_{br} \frac{N_{AV}}{M_e} m_e \sum_{i=p,\pi^\pm,n,\gamma} \int \sigma_{i,e,r}(E)\, \phi_i(E)\, dE \approx \sum_r \sum_e T_{br} \frac{N_{AV}}{M_e} m_e \sum_{i=p,\pi^\pm,n,\gamma} \sum_{\bar{E}} \sigma_{i,e,r}(\bar{E}) \Phi_i(\bar{E})$$

**Specific activity $A_b$** of radionuclide b

**Time evolution matrix $T_{br}$** : build up of **radionuclide r** and full decay chain to **isotope b** depending on time dependent **irradiation time/profile** and **cooling time** (Bateman coefficients).

Production term $P_{r,e}$ : production of **radionuclide r** from **element e** due to **particles $i = p, \pi^\pm, n, \gamma, \dots$**

Production cross section of radionuclide $r$ from element e due to particle $i$ evaluated at the average energy $\bar{E}$ for the considered bin

Fluence energy spectrum integrated over the energy bin of width $dE$ centered around energy $\bar{E}$

$$H = \sum_b \frac{1}{w_b} A_b \approx \sum_{i=p,\pi^\pm,n,\gamma} \sum_{\bar{E}} \Phi_i(\bar{E}) \left( \sum_{b,r,e} \frac{1}{w_b} T_{br} \frac{N_{AV}}{M_e} \sigma_{i,e,r}(\bar{E}) m_e \right)$$

**Weighting coefficient that can be applied for particle $i$ and for the energy bin that is centered around $\bar{E}$**