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CERN and Czechia

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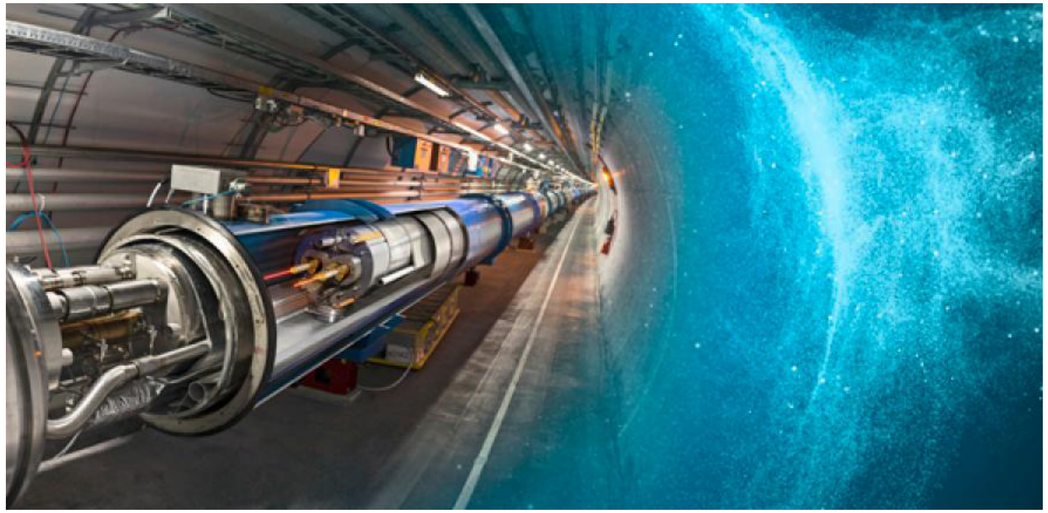


Day with particle and astroparticle research infrastructures, Praha, Oct 17, 2022

Czech Engagement at CERN

LRI CERN-CZ organises and covers the participation of CZ research institutions at CERN

- Charles University
- Czech Technical University in Prague
- Palacký University Olomouc
- Technical University of Liberec
- University of West Bohemia
- Institute of Physics of the CAS
- Nuclear Physics Institute of the CAS

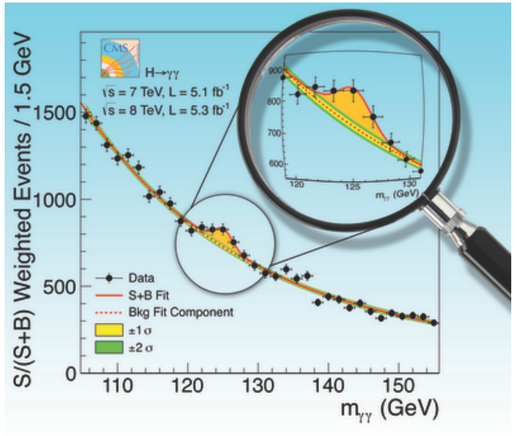
mostly ATLAS, ALICE, Forward Physics and Computing


LHCb
ATLAS
CERN Meyrin
PS 0.78 km
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km
CERN

Physics Goals of the LHC at the start in 2009

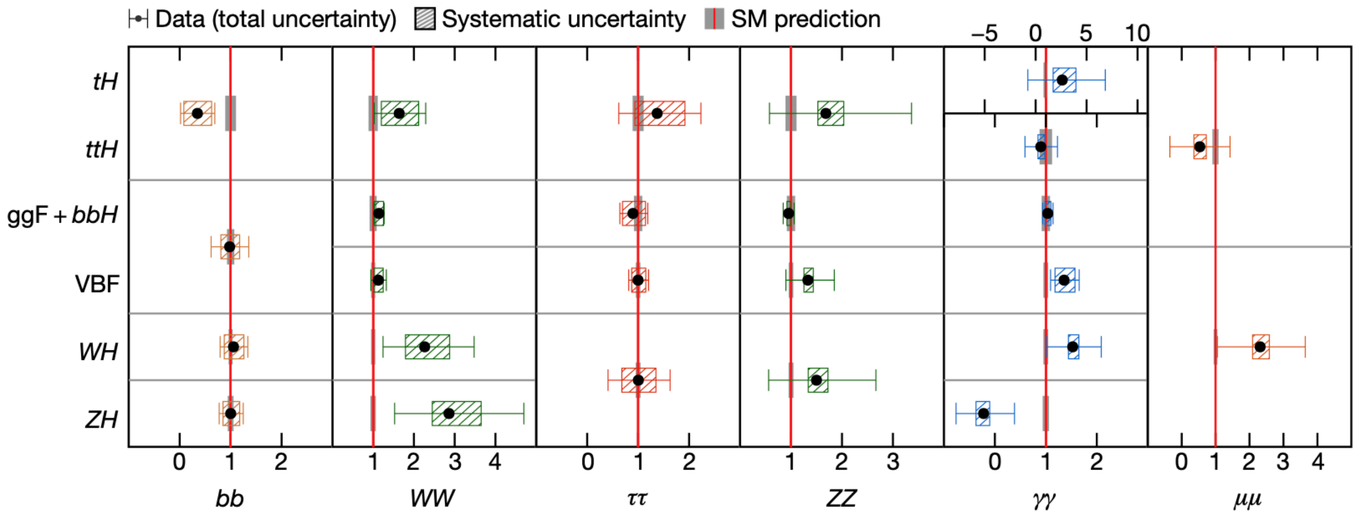
- Explore the electroweak scale to discover new physics
  - SUSY ?
  - Provide an explanation for Dark Matter
- Discover the Higgs particle
  - *done*
  - much more fertile ground than anticipated

?



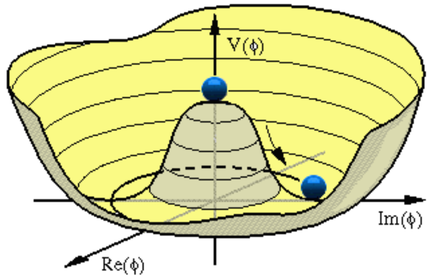
Higgs Particle – the only fundamental scalar in the SM

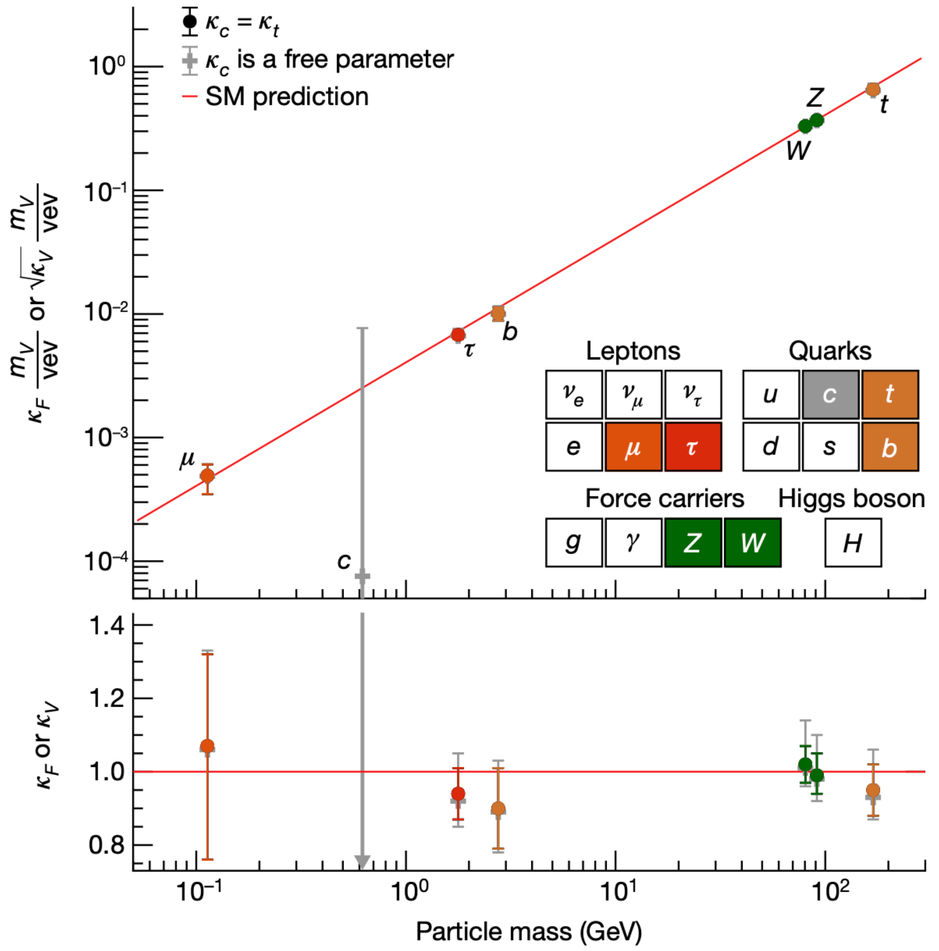
ATLAS Run II



$\sigma B_r/\mathrm{SM}$

Need to examine Higgs potential





Lessons learnt have been cast into a new Strategy for Particle Physics in 2020

European Strategy for Particle Physics Update 2020…

- The successful completion of the high-luminosity upgrade of the (LHC) machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques.
  - *New experimental ideas are welcome and key to progress*
- The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.
  - *ATLAS, CMS, LHCb and ALICE will continue to be upgraded and run till the end of the 2030s or early 2040s and beyond*

and High-Priority future initiatives…

An electron-positron **Higgs factory is the highest-priority** next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors

- Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron **Higgs and electroweak factory** as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

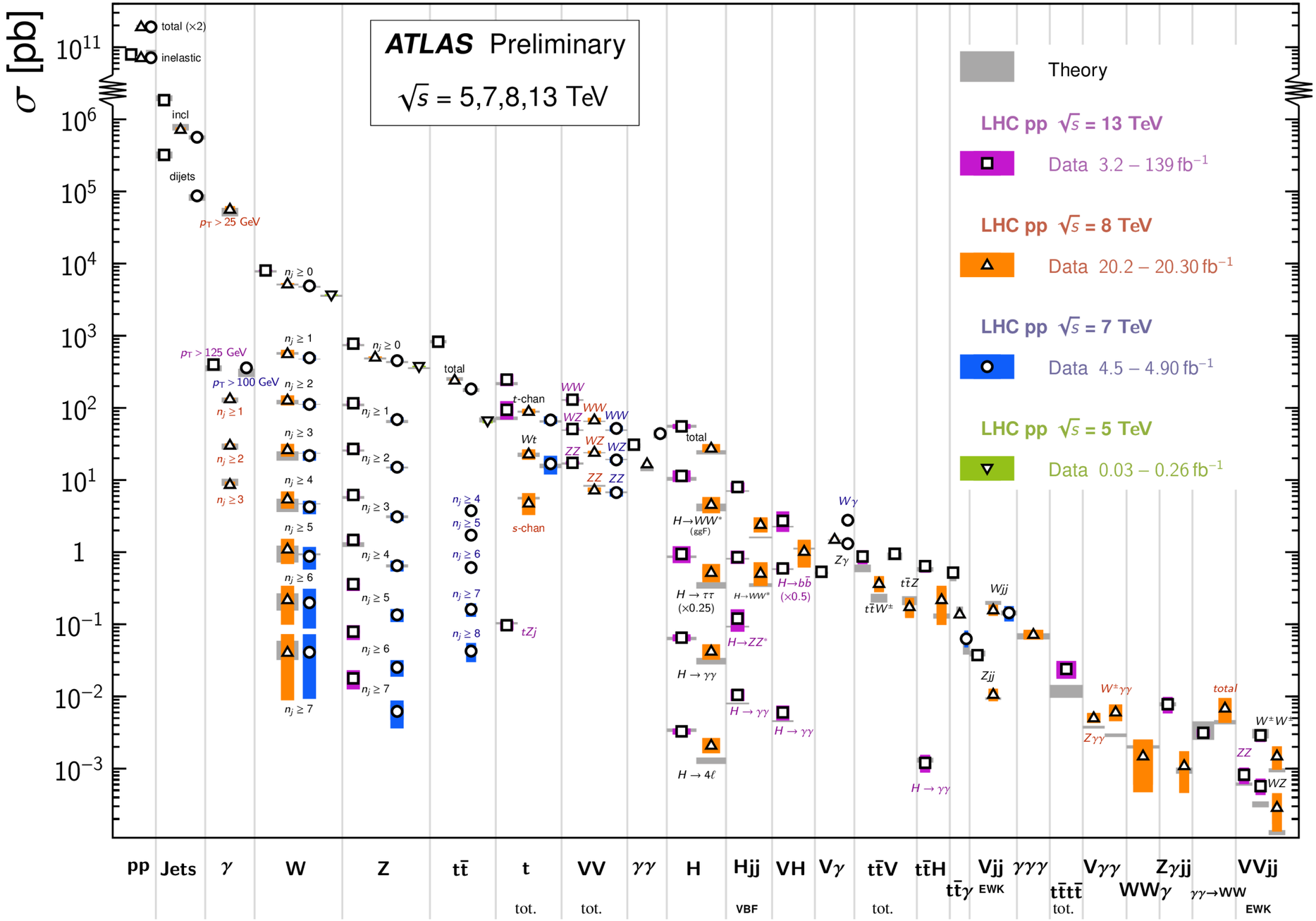
The LHC / HL-LHC will be our primary tool for research at the energy frontier for the next years to come

The advantage and dilemma of the LHC

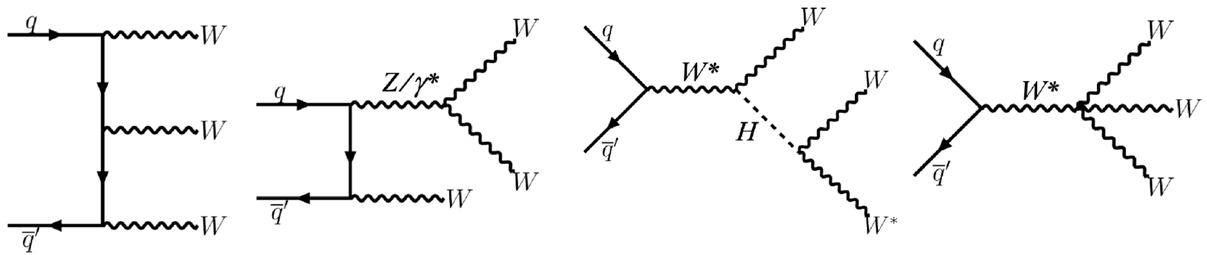
- pp-collisions offer tremendous interaction rates
  - We have learnt from Run 1 and 2 that New Physics is not strongly coupled to quarks and gluons in the energy regime we can explore up to a few TeV
  - Hence we have to resort to electroweak processes to search for New Physics or allow for very weakly interacting particles
    - LHC will serve predominantly as a factory of weakly interacting particles - very much like an e^+e^-- or $\mu^+\mu^-$-collider
    - the strong interaction is seemingly only a large background

Standard Model Production Cross Section Measurements

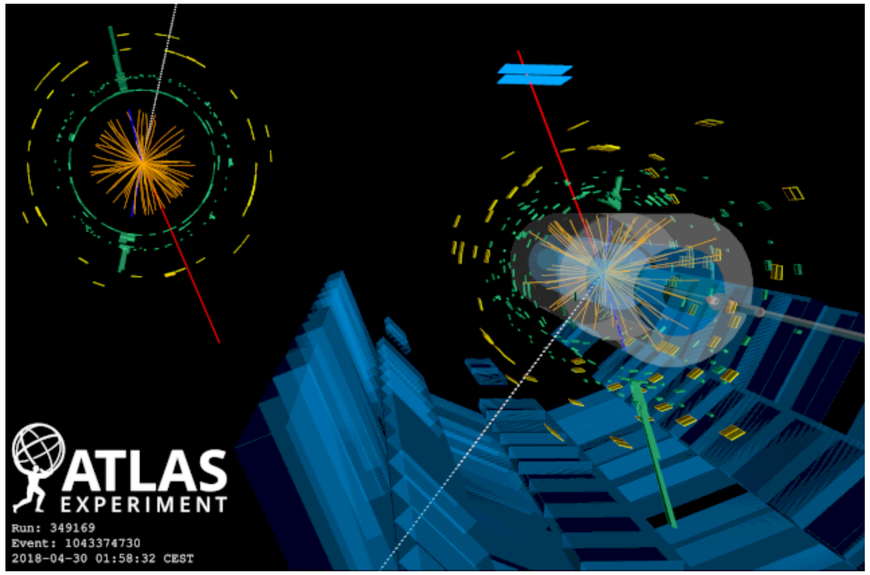
Status: March 2021



Production of WWW



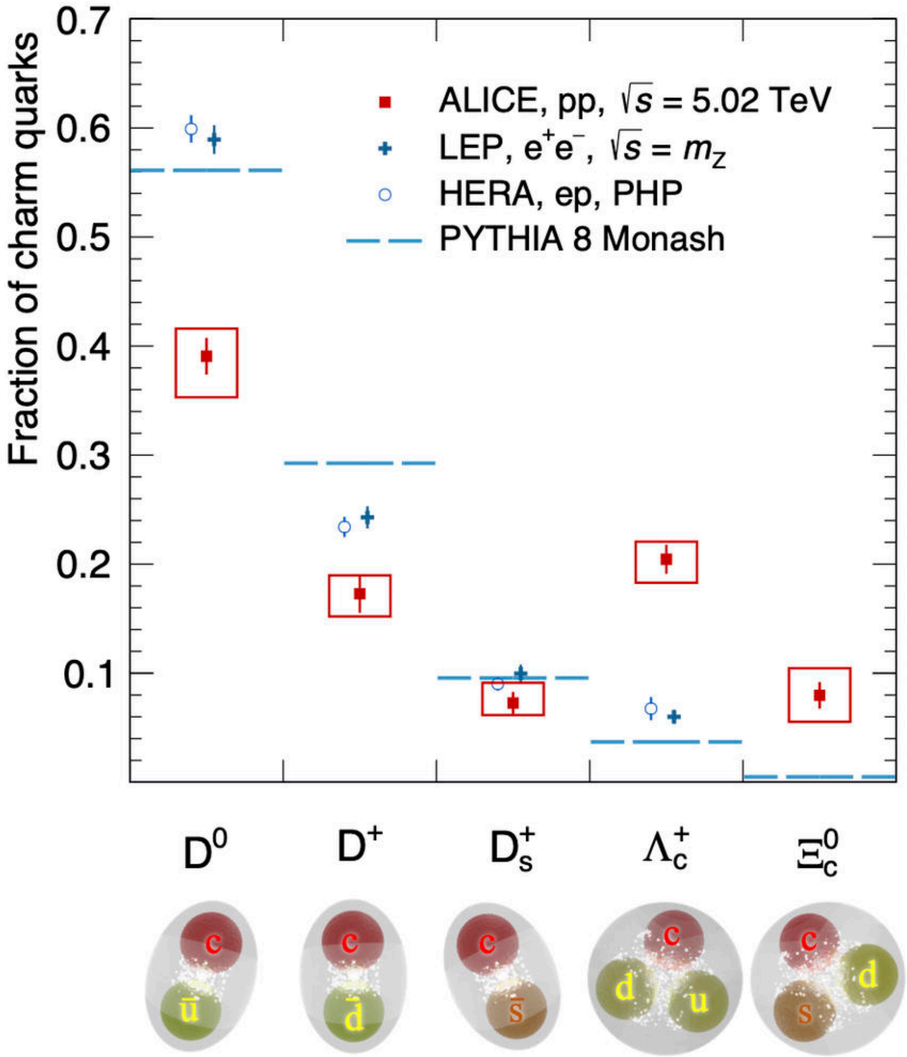
a purely electroweak process



WWW-production has also been observed in the CMS experiment

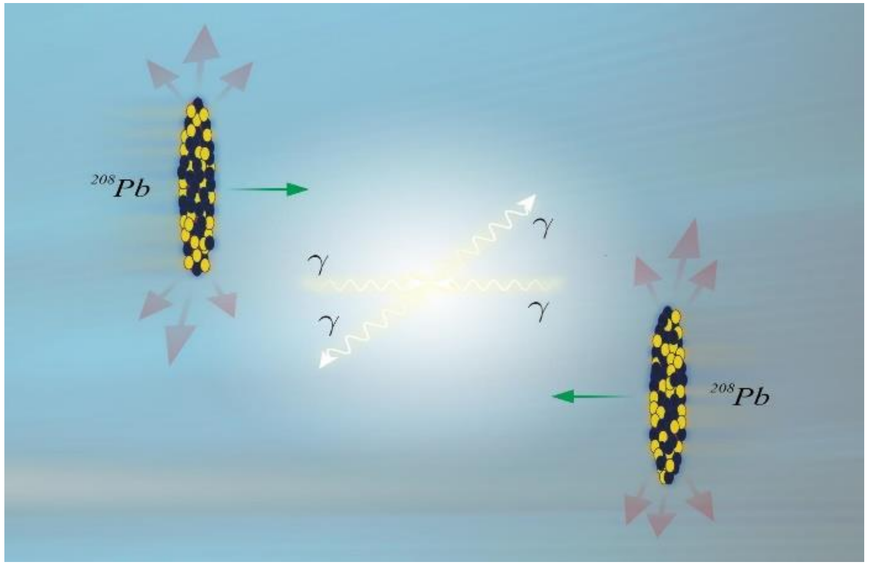
Charm production in pp-collisions

- Production of charm-quarks has been measured by the ALICE experiment
  - Λ_c^+ are much more copiously. produced than in e^+e^- or in ep-collisions

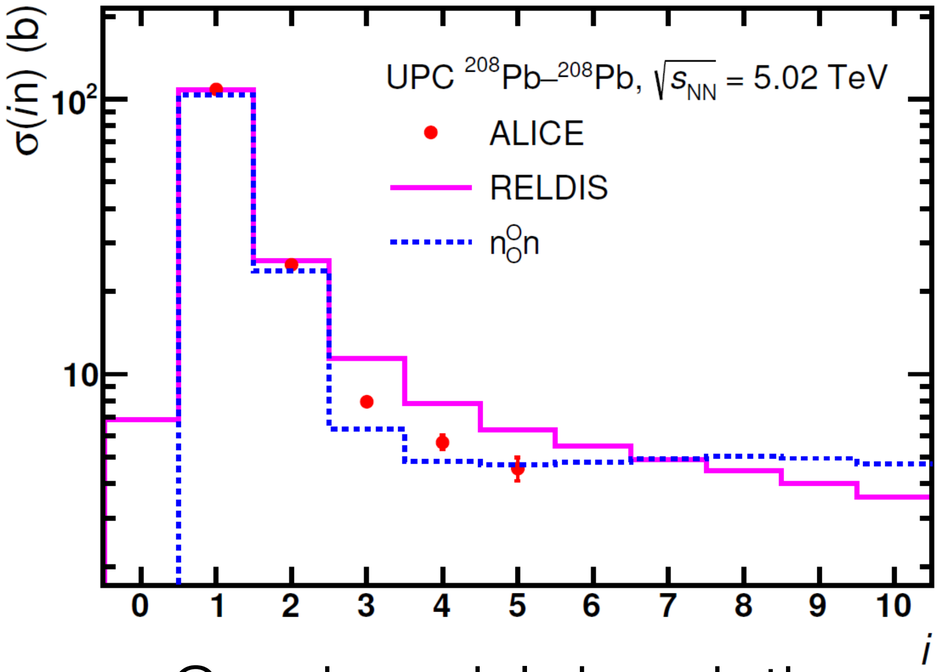


Neutron Production in Ultra-peripheral Heavy Ion Collisions

LHC as a $\gamma\gamma$-colider

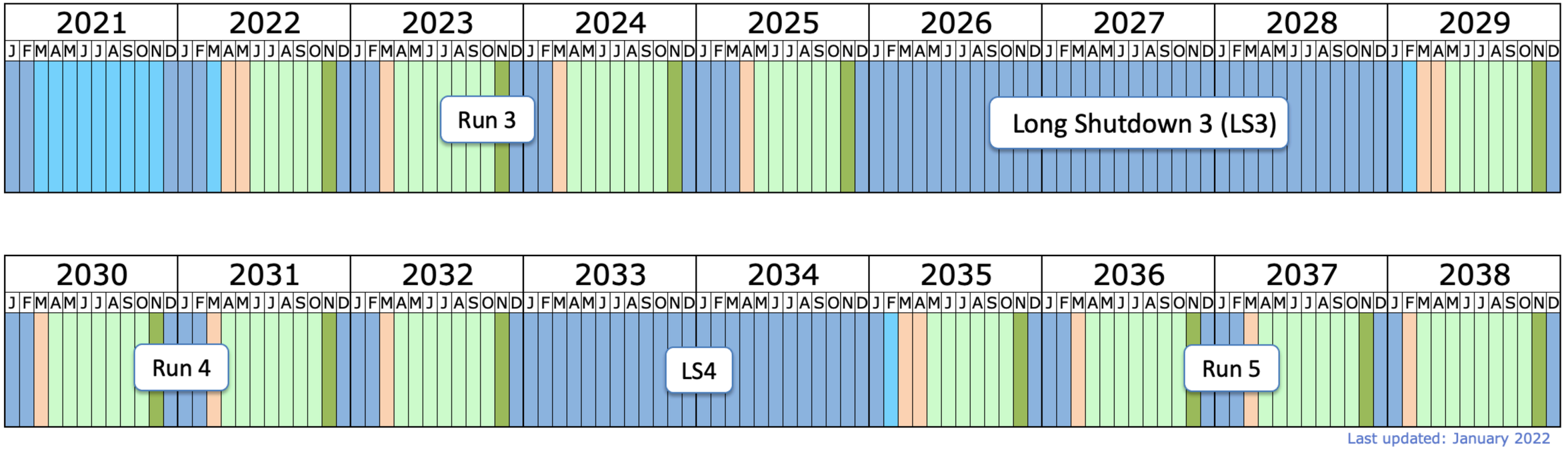


Electromagnetic dissociation leads to *neutron* production at beam rapidities



Good model description currently only for small multiplicities

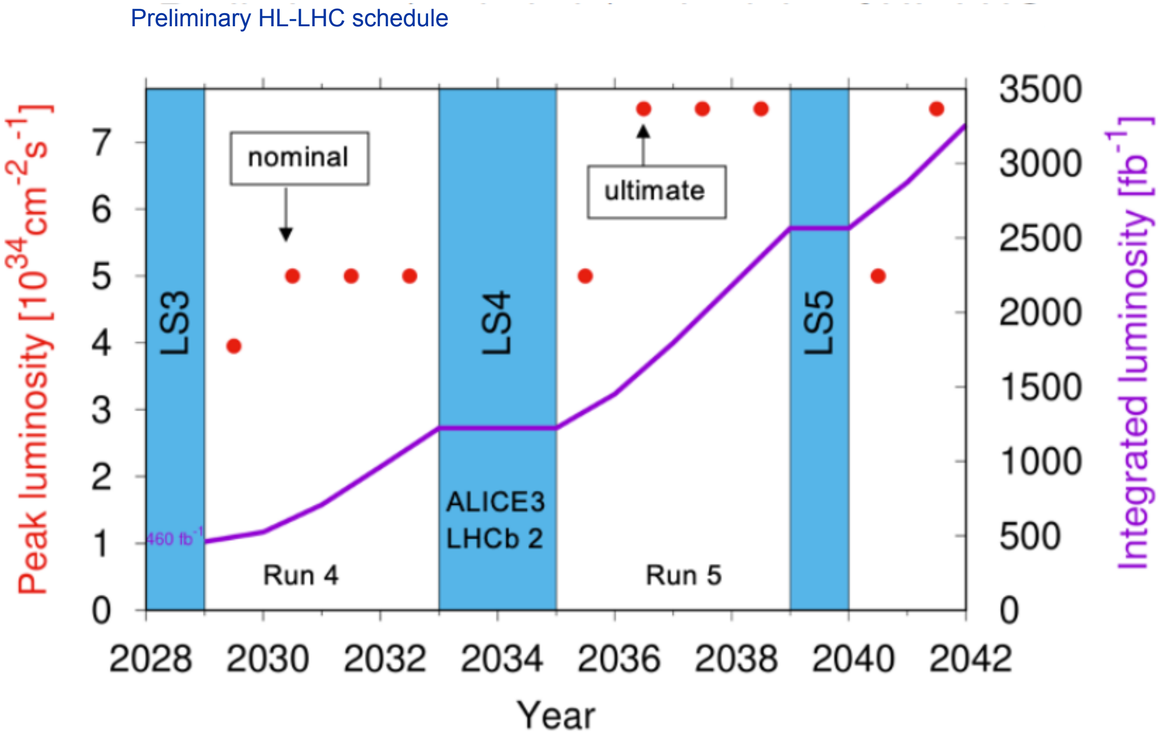
LHC Schedule as of January 2022



The schedule does not include the shortening of runtimes to save energy.

Longterm Operation of HL-LHC for sensitivities beyond 1 fb^{-1}

- Long shutdown 2026 - 2028 to upgrade accelerator and detectors (ATLAS & CMS)
  - Will increase luminosity by factor 5 to 7
- Final goal is ≥ 3000 fb^{-1}
  - ~20-fold increase over today
- Long shutdown 4 (LS4) to upgrade ALICE and LHCb for even higher rates and precision



Beware: This is a technically driven schedule. Fold in economic development, energy cost, political changes…

Detector resolution

- We have learnt from LEP and SLD, from BaBar and Belle/Belle II that full reconstruction of the complex final states is only possible with ultimate resolution
  - momentum and energy reconstruction
  - flavour tagging
  - particle identification

Experiments at the LHC / HL-LHC in perspective

- Experiments at the LHC must - at least - provide the resolution of the best proposed detectors at e^+e^- factories and still reject the pile-up of other events
  - e.g. **Timing** has be added as an important tool to reject (slightly) out-of-time interactions (pile-up). This is a tremendous challenge and added complexity but a necessary tool to provide sensitivity to new physics.
    - ps-timing will also be key to making LHCb during Run 5 feasible

Flavour physics

- LHCb profits from the large cross section for b-quark production in pp-collisions but has to throttle the rate due to detector limitations (LHC is separating the beams laterally at the IP).
  - LHCb has published a wealth of results on b-physics and observed CP-violation in the charm system
  - For rare decays the detector rate capability needs to be improved; hence the LS2 upgrade, a rebuild of the detector, and plans for a further upgrade in LS4
  - so far the physics is limited by the performance (granularity) of the detector

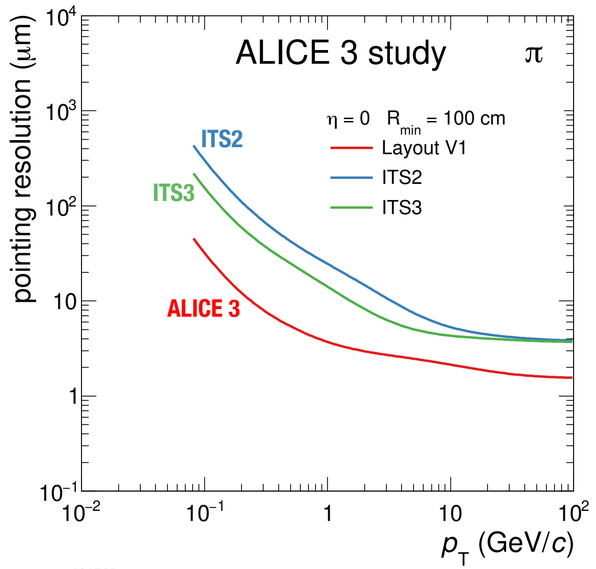
Heavy Ion Physics

- The purpose of ALICE is primarily to study the strong interaction
  - comparison of PbPb to pp and pPb collisions and other ions
  - large cross sections and hence use only a small fraction of possible pp-luminosity
- Lessons, in particular from Run 1 and 2:
  - strangeness, charm and beauty production originate from different phases of the quark gluon plasma and hence prove particularly interesting
  - Need for higher rate capability

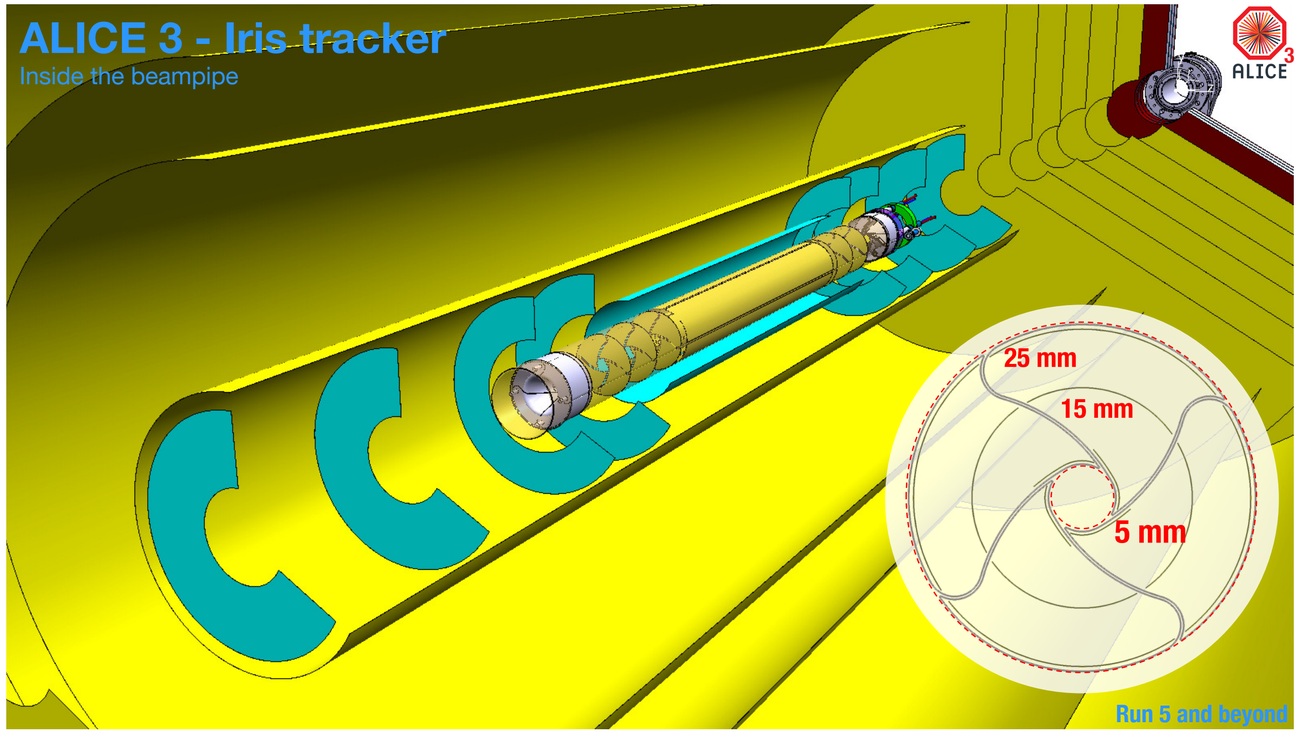
Experimental tools

Low mass detectors near beam - Example: Plans of ALICE 3

- 3 Inner layers closer to IP, (e.g. Iris tracker)
  - retractable innermost layer ~ 5 mm
  - X/X_0 ~0.1 % / layer



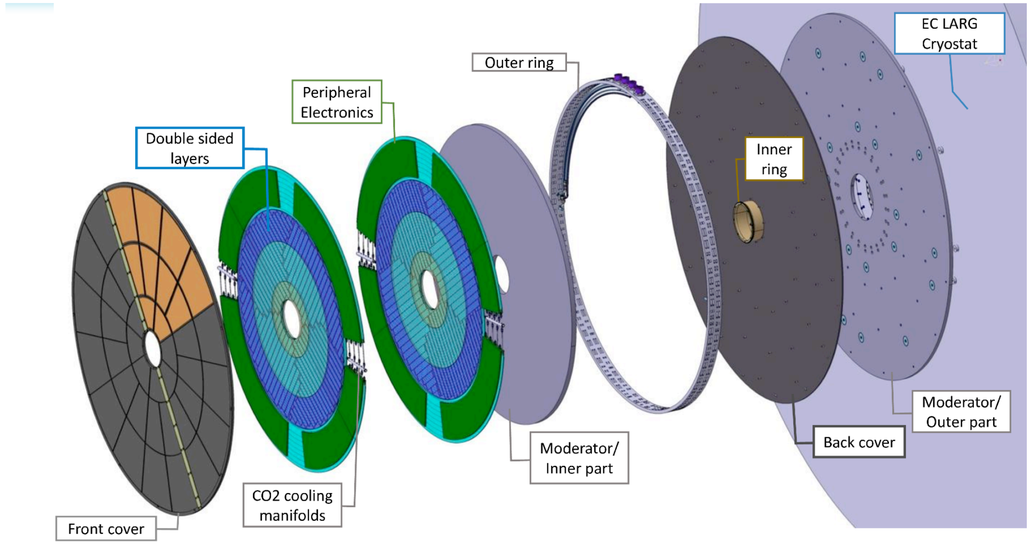
ALI-SIMUL-491785

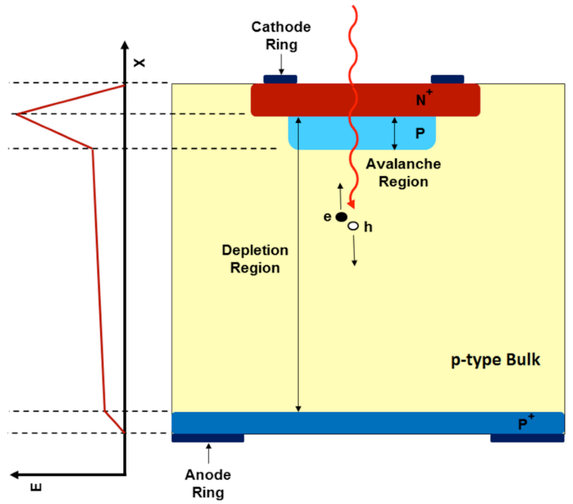


Will be used for flavour tagging

Timing - Example ATLAS HGTD

- 2 disks either side in gap between ATLAS barrel and end cap.
- Each instrumented double-sided layer supported by cryostat/support structure, moderator pieces for protection against back splash.
  - Acceptance at $2.4 < |\eta| < 4$
  - Low-Gain Avalanche Silicon Detectors (LGAD) sensors
  - Enable precision timing, retain signal efficiency after heavy irradiation



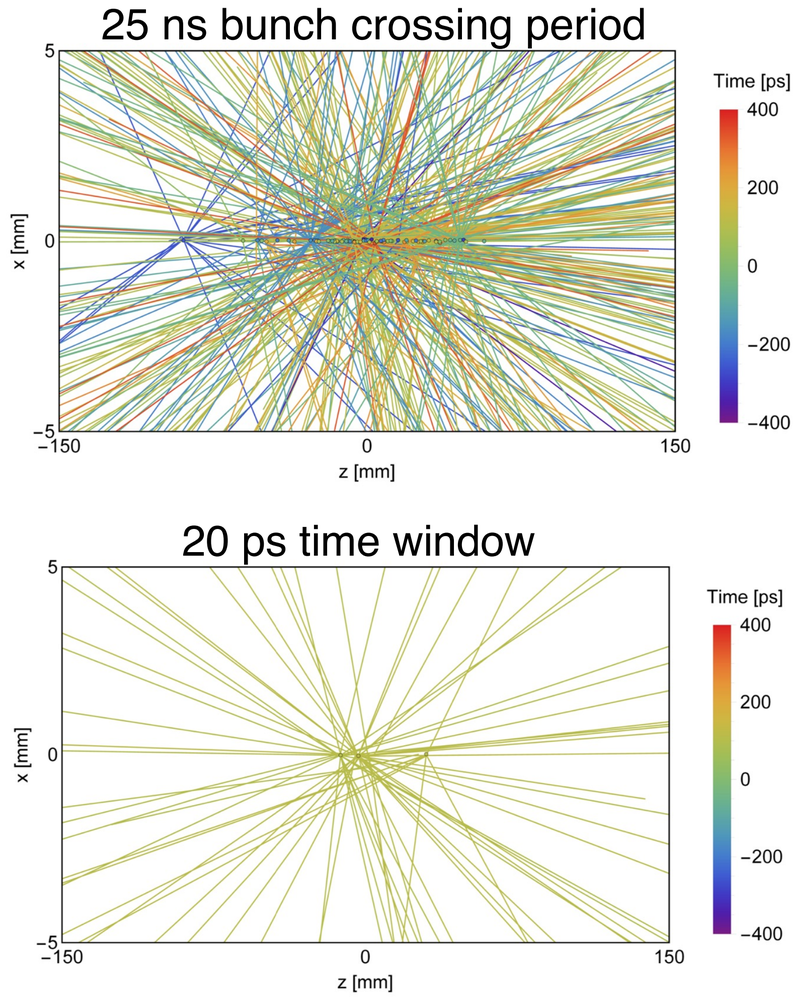


LGAD sensor: Silicon detector with internal low gain

pile-up protection

Integrated Fast Timing - Example LHCb for Run 5

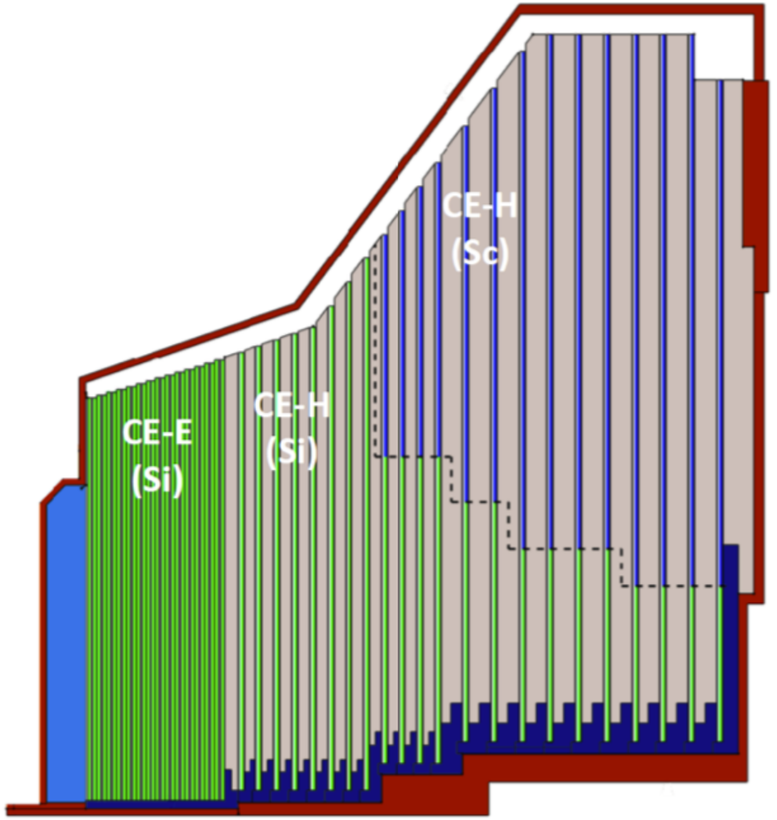
- Fast Timing for
  - VELO
  - RICH
  - ECAL
  - TORCH



disentangling events

Precision Calorimetry - Example CMS

- Full replacement of existing CMS endcap ECAL and HCAL
- Integrated sampling calorimeter
- Absorber
  - EM section: Pb, CuW, Cu
  - Hadronic section: steel, Cu
- Active material
  - High radiation area: 8” hexagonal silicon sensors
  - Low radiation area: scintillator tiles with on-tile SiPM
- 5D imaging calorimeter
  - Extends tracking in forward regions
  - Highly granular spatial information
    - Si cell size: 0.5 cm^2 and 1.2 cm^2
    - Scintillator tile size: $(23\ mm)^2$ – $(55\ mm)^2$
  - Large dynamic range for energy measurements
  - Timing information to tens of picoseconds



Cut-away side view

Particle Flow Calorimetry

e.g. W-production in forward direction

Reconstruction and Simulation

- Some of the results from the LHC have been obtained earlier than expected from the integrated luminosity
  - This is largely owed to the advances in reconstruction and simulation
    - detailed simulation and parametrisation - understanding of pile-up
    - machine learning and much more
    - dedicated event streaming
      - optimising data formats

Upgrading / re-inventing the Software

- In addition to providing better resolution detectors also need the software to improve
  - Better algorithms yield:
    - better resolutions
    - lower backgrounds
    - and hence better signals

What does this mean for Particle Physics around 2040?

- We could be lucky and New Physics turns up directly
- LHC / HL-LHC will define the yardstick for physics reach of any other facility (e^+e^- and $\mu^+\mu^-$)
  - Today's predictions for HL-LHC physics reach are probably **too pessimistic** in view of new experimental ideas and reconstruction capability
  - Flavour physics becomes more important and better accessible; competition/ complementarity from Belle II and its possible upgrade is interesting
- LHC / HL-LHC will continue as the copious source of physics

Example of new ideas

- FASER and SND
  - Neutrinos and non-interacting particles in the very forward direction
- SMOG at LHCb
  - pA collisions in front of the VELO detector
- Crystal channeling for rare charm decays
- MATHUSLA
  - a cosmic telescope and detector for long lived particles from the LHC

Summary

- LHC / HL-LHC will be the workhorse for Particle Physics for the next two decades
  - Direct observation of New Physics?
  - Its scope for precision is considerably better than originally expected and rivals the precision of lepton colliders
- But New Physics could hide elsewhere
  - Low mass Dark Matter searches
  - Neutrino Physics

Fully exploit LHC

Don't forget other experimental tools