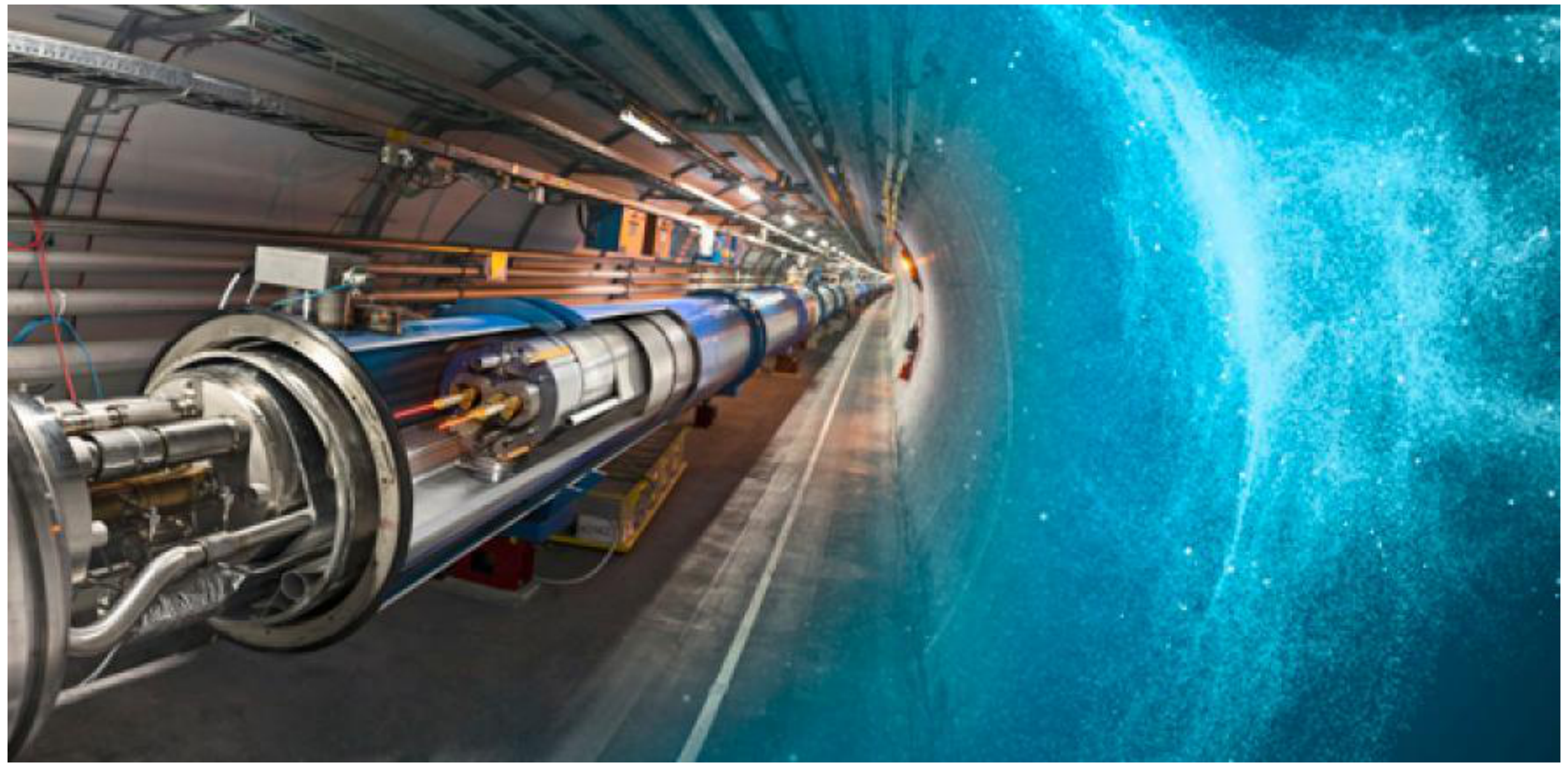
The experimental challenge at the LHC / HL-LHC

Eckhard Elsen

Director Research and Computing (2016-2020)

CERN

now DESY



Disclaimer – Detailed presentations from existing LHC Experiments (*)

Experiment	Title	Speaker	Time (Europe)
ATLAS	Upgrade and physics plans for ATLAS in LHC Run4	Claire Antel	6.7.2021 16:35
CMS	Physics by CMS during HL-LHC	Ulrich Heintz	8.7.2021 16:20
LHCb	LHCb as a 4D precision detector in Upgrade II	Floris Keizer	7.7.2021 14:30
ALICE	Upgrade of the ALICE experiment for LHC Run 4 and	Francesca Carnesecchi	7.7.2021 16:15

* and presentations on specific physic topics

no need to repeat the details of the ambitious upgrade plans

Thanks to Introductory Keynotes

- Laura Reina
- Nathaniel Craig

- for explaining on theoretical grounds the need for precision and disentangling complexity and the progress made
  - Higher order calculations
  - pdfs and scale dependence
  - $b\bar{b}H$ calculations

The progress in theoretical calculations and modelling is mandatory for the future LHC programme

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.

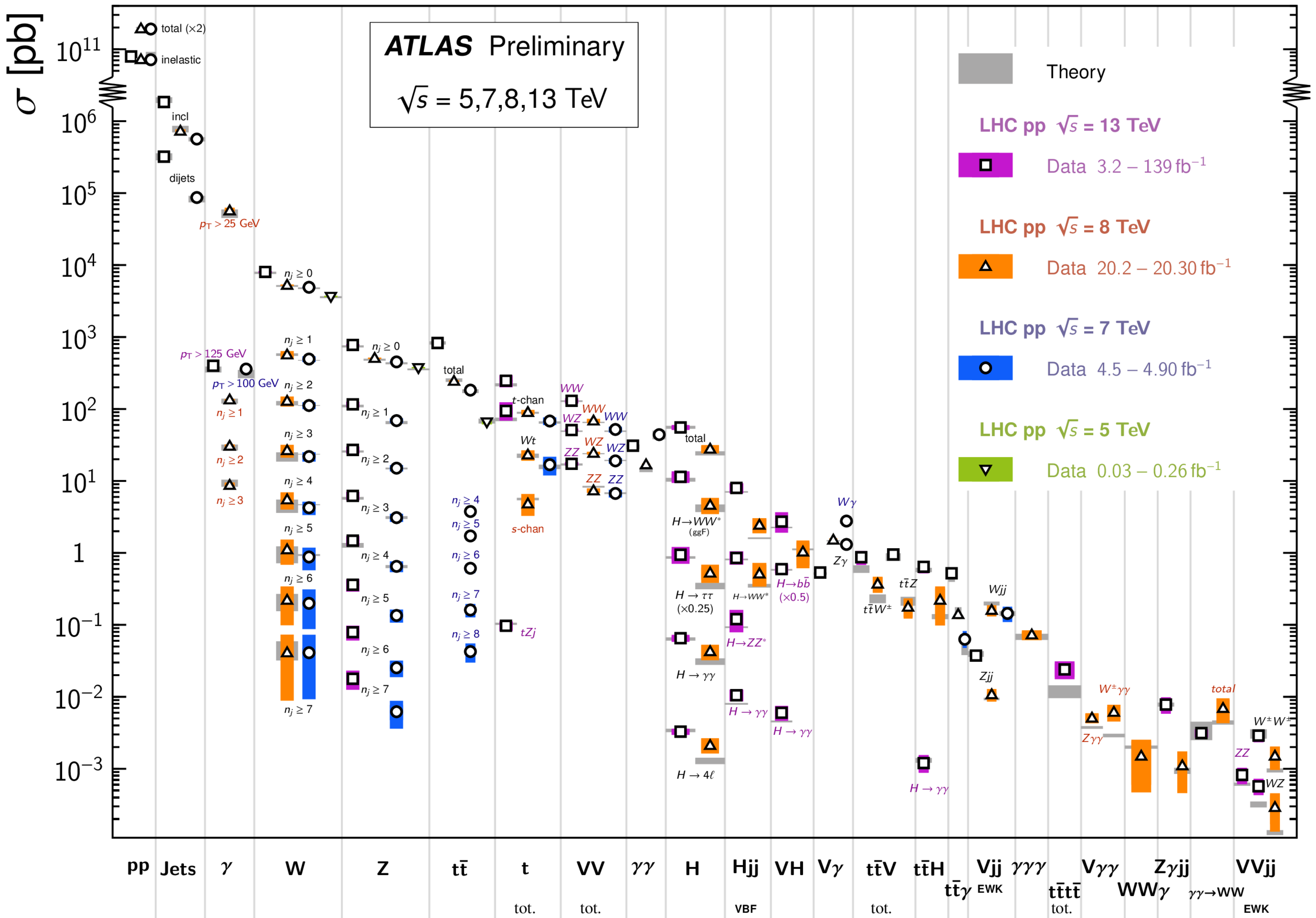
Why is this more than reasonable?

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.
    - the strong interaction is largely a background
    - LHC will serve predominantly as a factory of weakly interacting particles - very much like an e^+e^-- or $\mu^+\mu^-$-collider

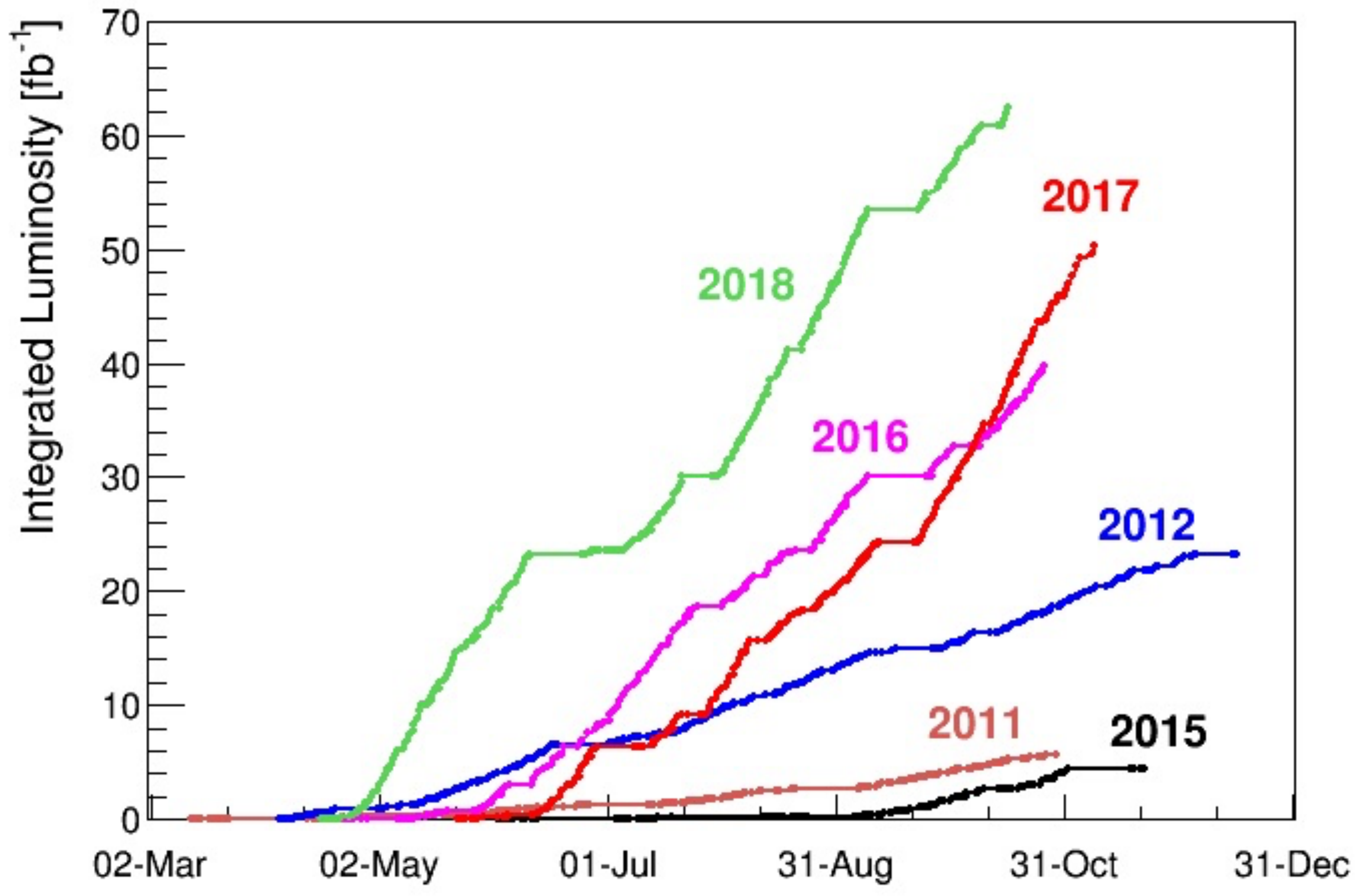
Standard Model Production Cross Section Measurements

Status: March 2021



Luminosities

- Effective cross sections range from ~nb to ~fb and smaller
- Searches thus require the highest sustainable luminosities at the LHC and the experiments to deal with the huge backgrounds
- The rates of "interesting events" are dominated by the smallest cross section. The current sensitivity is at the level of ~fb.
- HL-LHC will attain 3-4 ab^{-1} at ≥13.6 TeV; a factor ~20 of what is available today



LHC past and present and HL-LHC Plan

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 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 make LHCb during Run 4 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

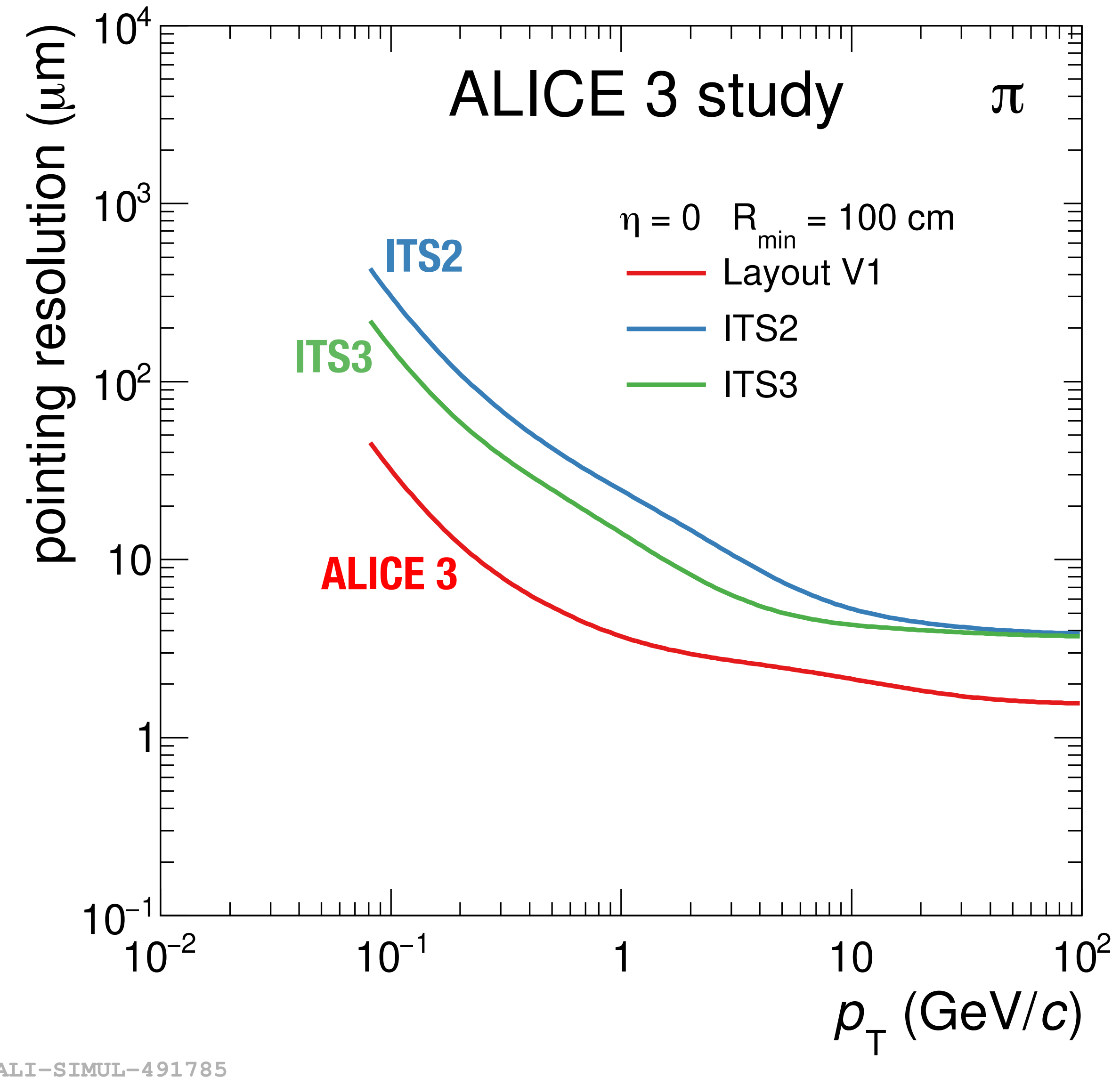
Heavy Ion Physics

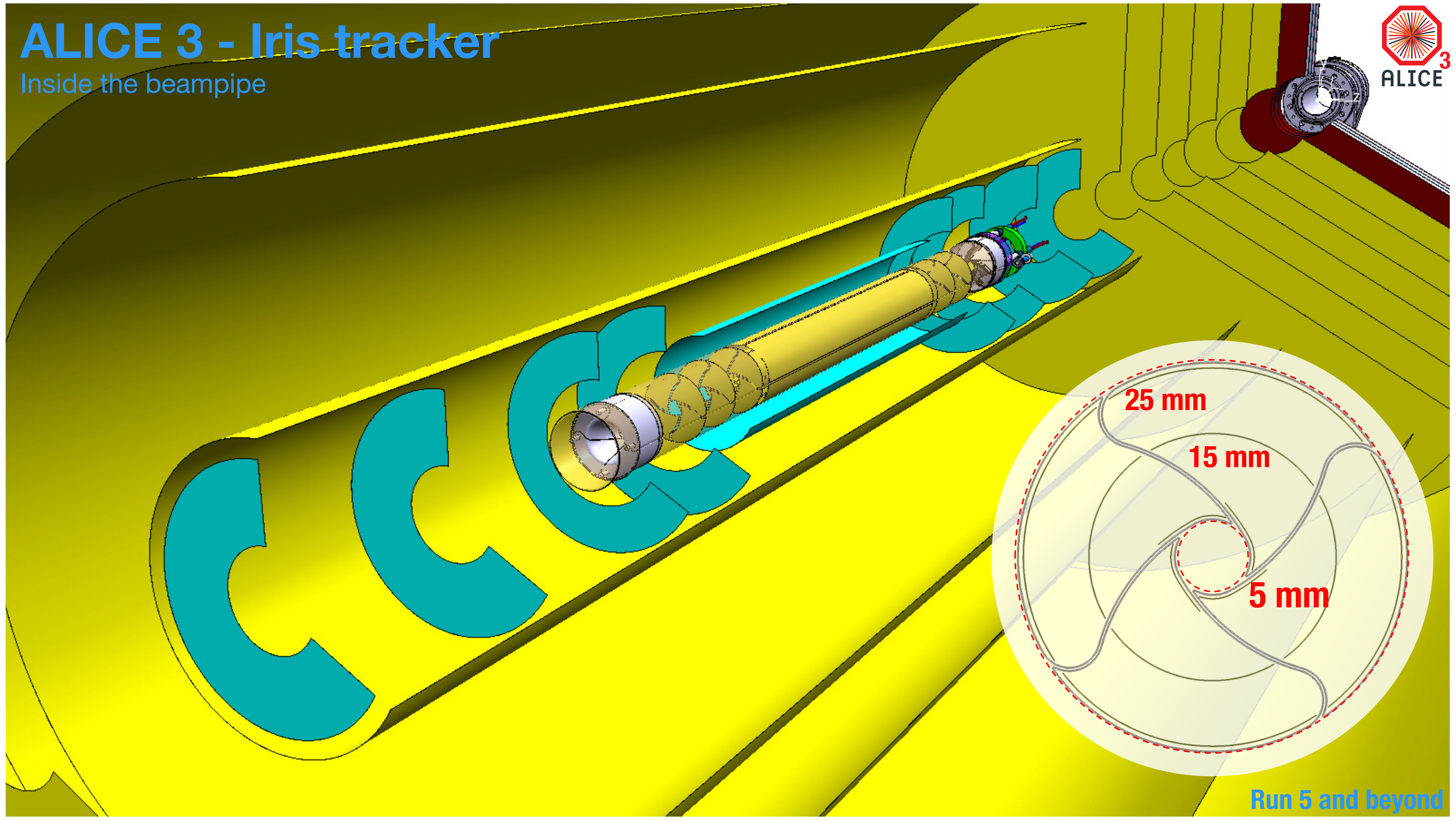
- The purpose of ALICE is primarily to study the strong interaction
  - comparison of PbPb to pp and pPb collisions and other ions
  - large cross sections and hence use only a small fraction of possible pp-luminosity
- Lessons, in particular from Run 1 and 2:
  - strangeness, charm and beauty production 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

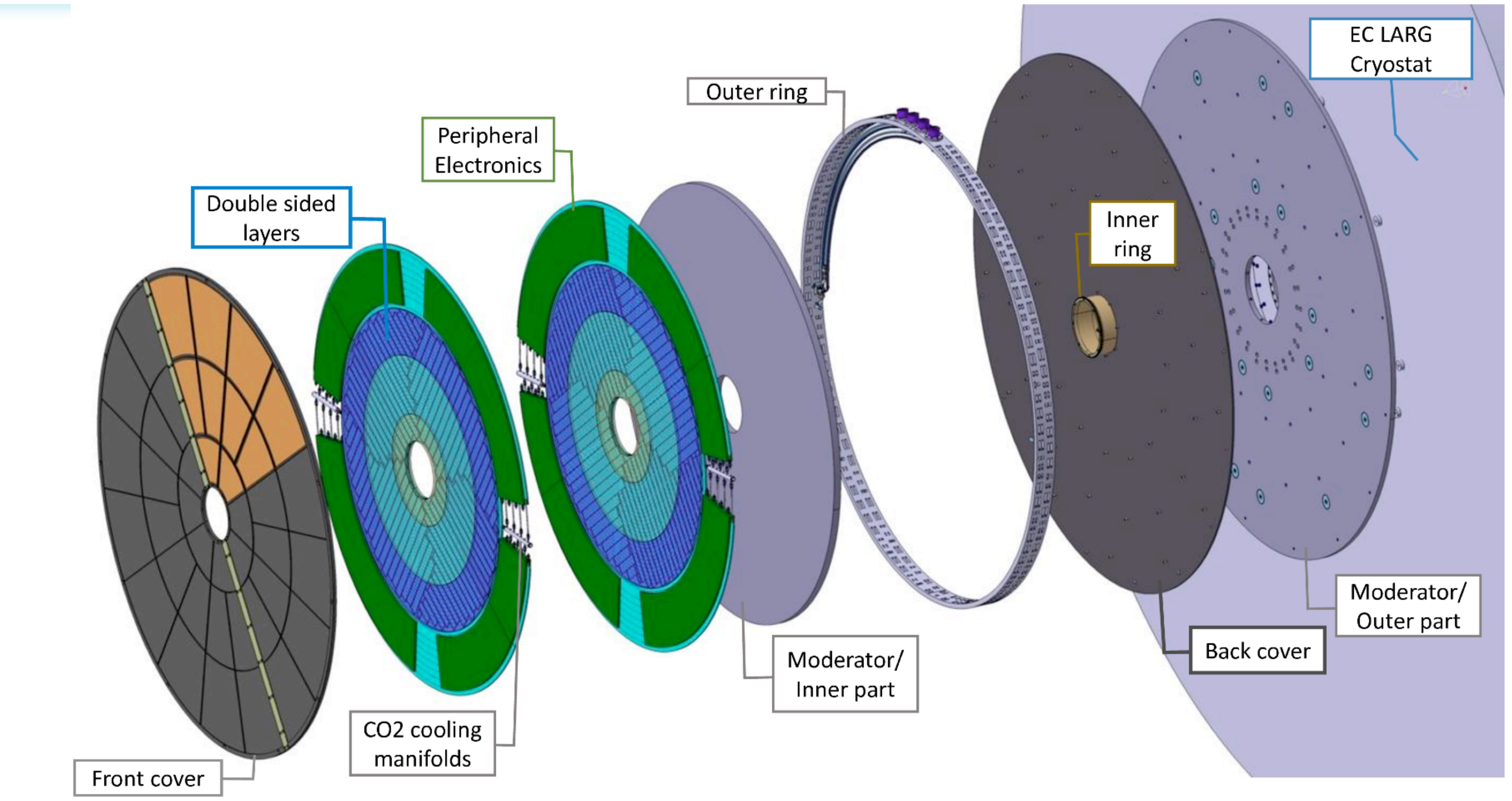


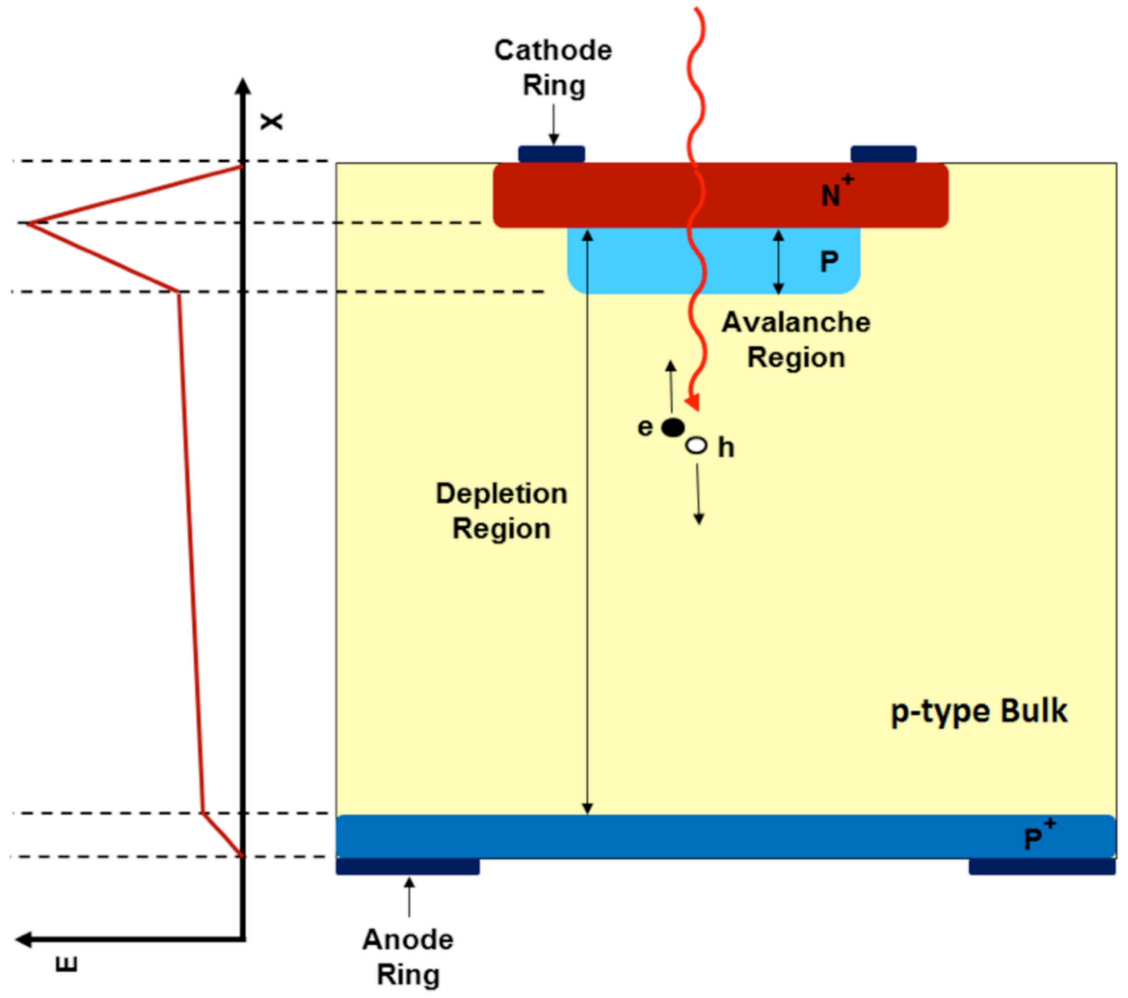


Will be used for flavour tagging

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 < |η| < 4
    - Low-Gain Avalanche Silicon Detectors (LGAD) sensors
    - Enable precision timing, retain signal efficiency after heavy irradiation



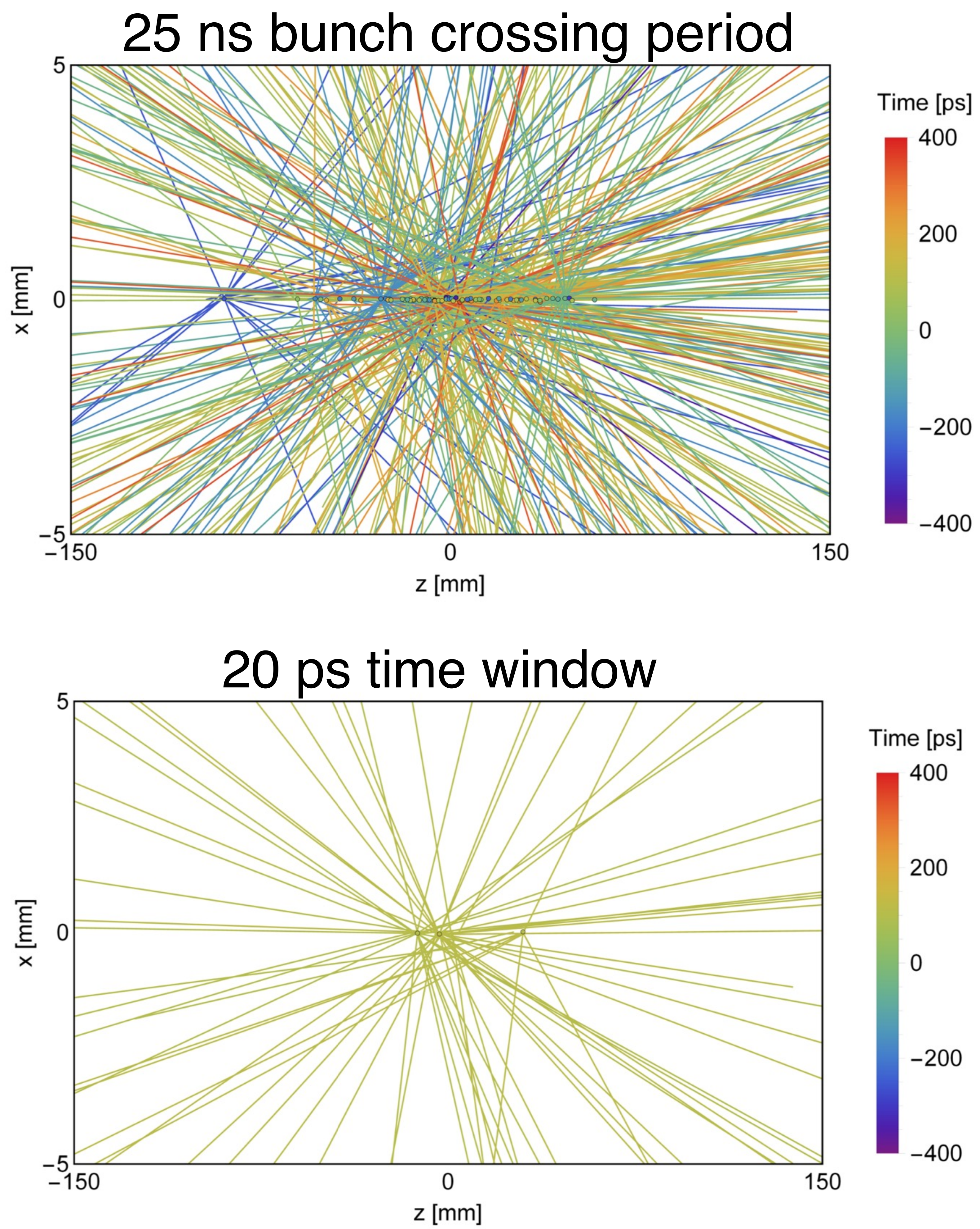


LGAD sensor: Silicon detector with internal low gain

pile-up protection

Integrated Fast Timing - Example LHCb for Run 5

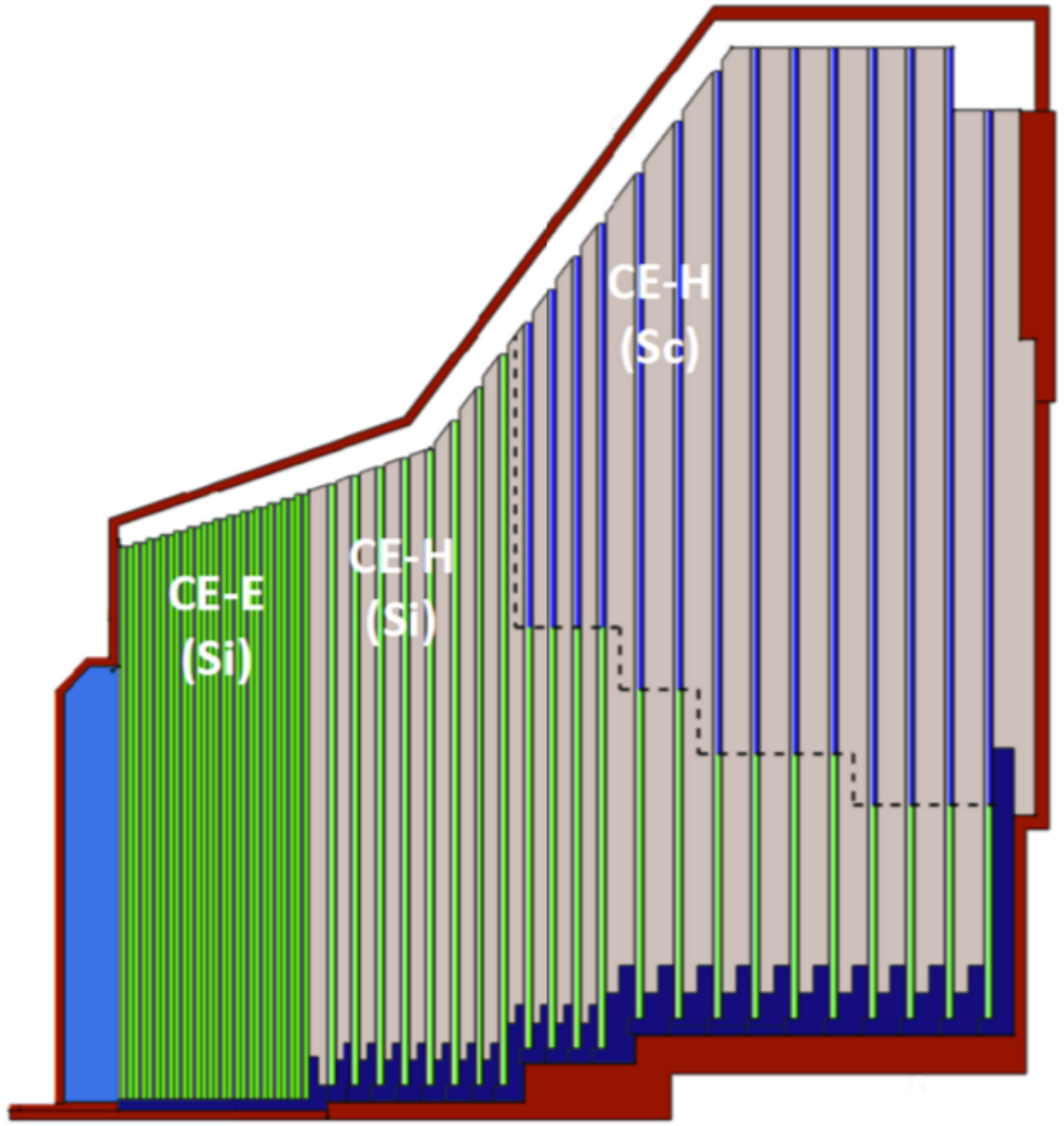
- Fast Timing for
  - VELO
  - RICH
  - ECAL
  - TORCH



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

See following two talks on ML and MC simulation

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

Fully exploit LHC

- But New Physics could hide elsewhere
  - Low mass Dark Matter searches
  - Neutrino Physics

Don't forget other experimental tools