Imperial College London

Future upgrades to the LHC

Alex Tapper

IOP Institute of Physics

Joint annual HEPP and APP conference

21–23 March 2016, University of Sussex, Brighton, UK

Imperial College London

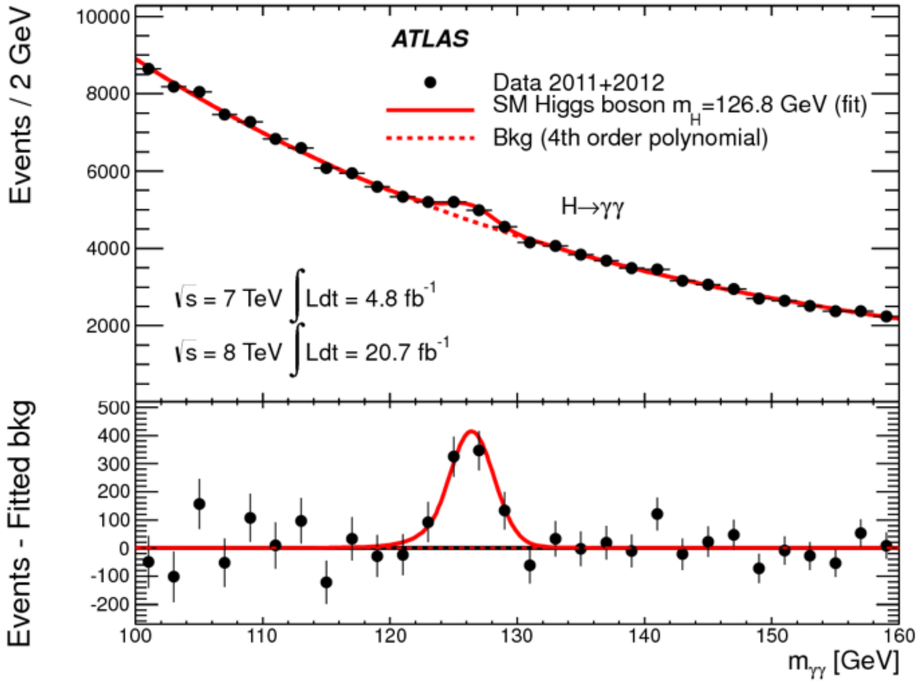
Outline

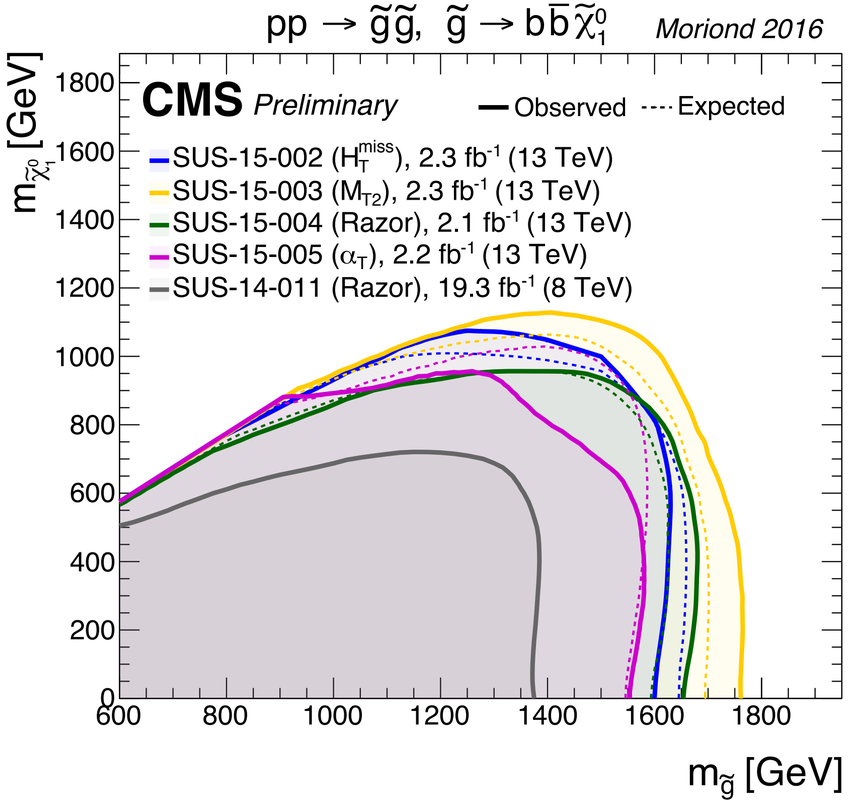
- Physics motivation
- Accelerator overview
- Detector upgrades
- Summary

Imperial College London

LHC Run 1 and Run 2 (so far…)

Great success in Run 1…





… and a strong start to Run 2

Imperial College London

Future physics: Higgs

- Measurements of Higgs will play a big role in future

- Upgraded LHC is a *Higgs factory*

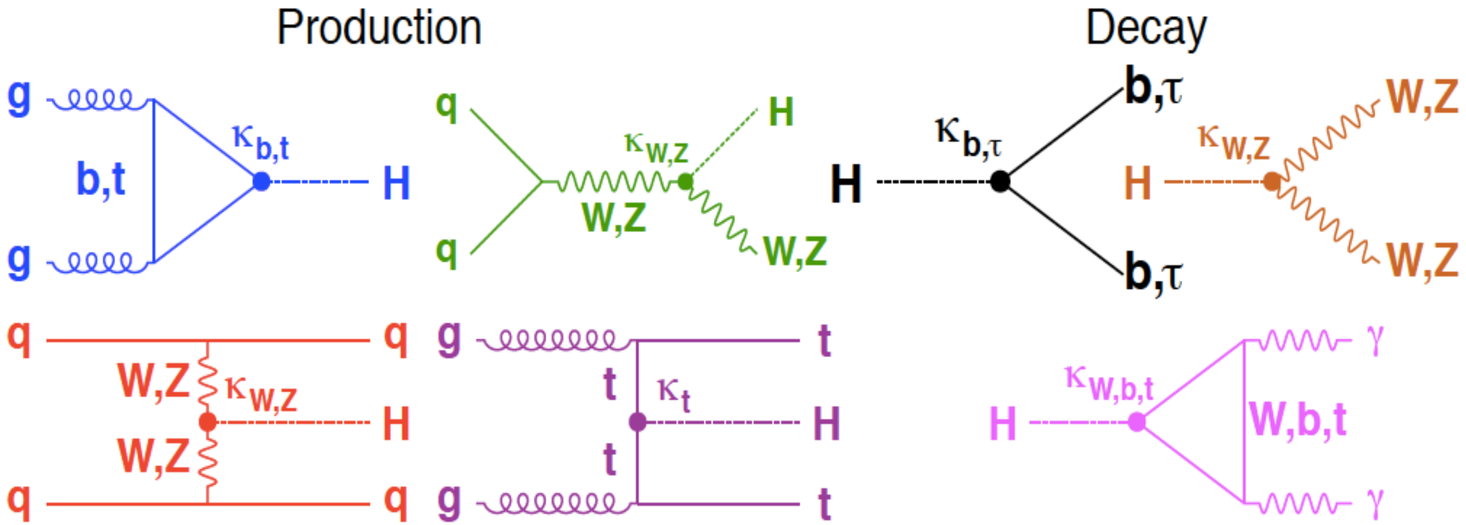
  - Run 1 $\mathcal{O}(1000)$ Higgs bosons at LHC
  - Upgrade factor 4-10 better measurements than today
  - Millions of events in all production modes
  - Access to rare decays of Higgs

	Total Higgs Bosons
LHC Run 1	**660k**
HL-LHC, 3000 fb^{-1}	**170M**
VBF (all decays)	13M
ttH (all decays)	1.8M
H → γγ	390k
H → Zγ	230k
H → μμ	37k
H→J/ψγ	400
HH (all)	121K
HH → WWWW	9200
HH → bbγγ	320
HH → γγγγ	1

Imperial College London

Future physics: Higgs

- Measurements of Higgs couplings
  - Answering the question, *is this the SM Higgs?*
  - Express the production and decay of the Higgs in terms of deviation from SM coupling

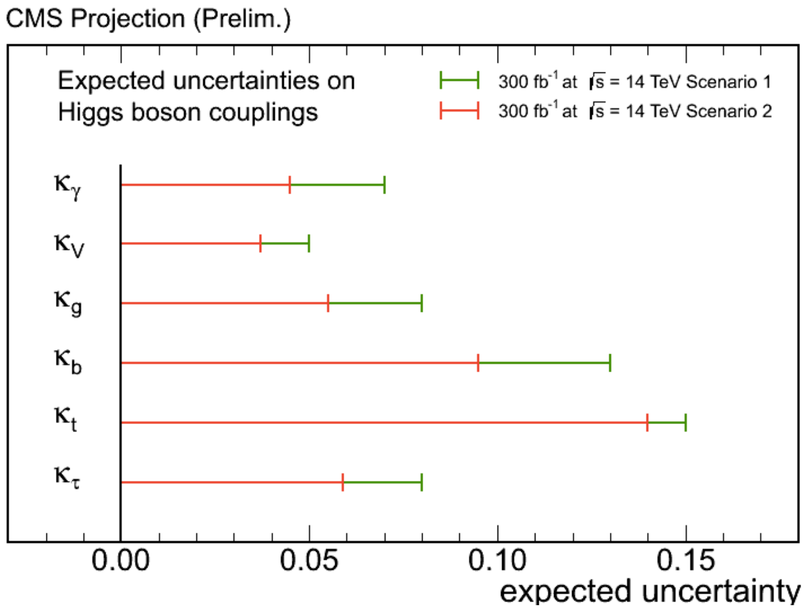


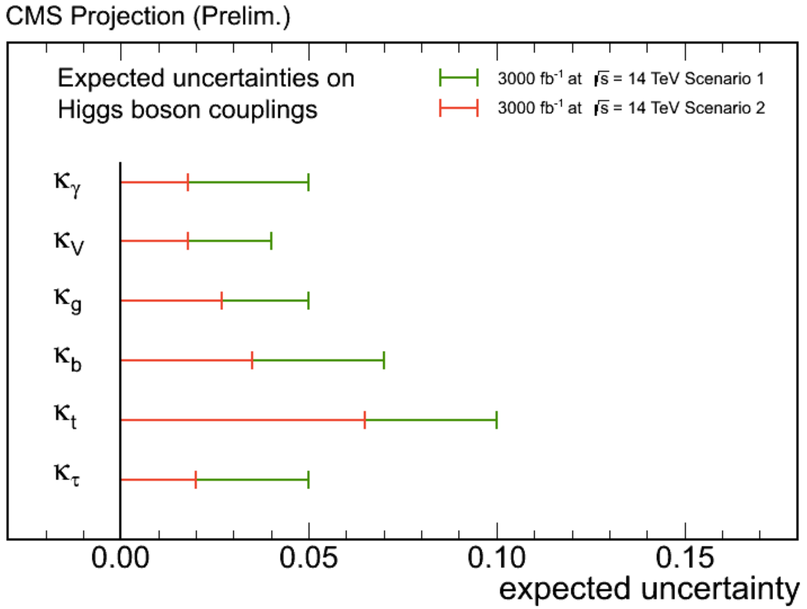
  - Requires great performance across the board
    - Electrons, muons, taus, forward jets, b-tagging, trigger, MET….

Imperial College London

Future physics: Higgs

- Scaling of signal and background yields as:
  - **Scenario1** - systematic uncertainties remain the same: conservative
  - **Scenario 2** - theoretical uncertainties scaled by ½: expt. systematic uncertainties scaled by $1/\sqrt{L}$



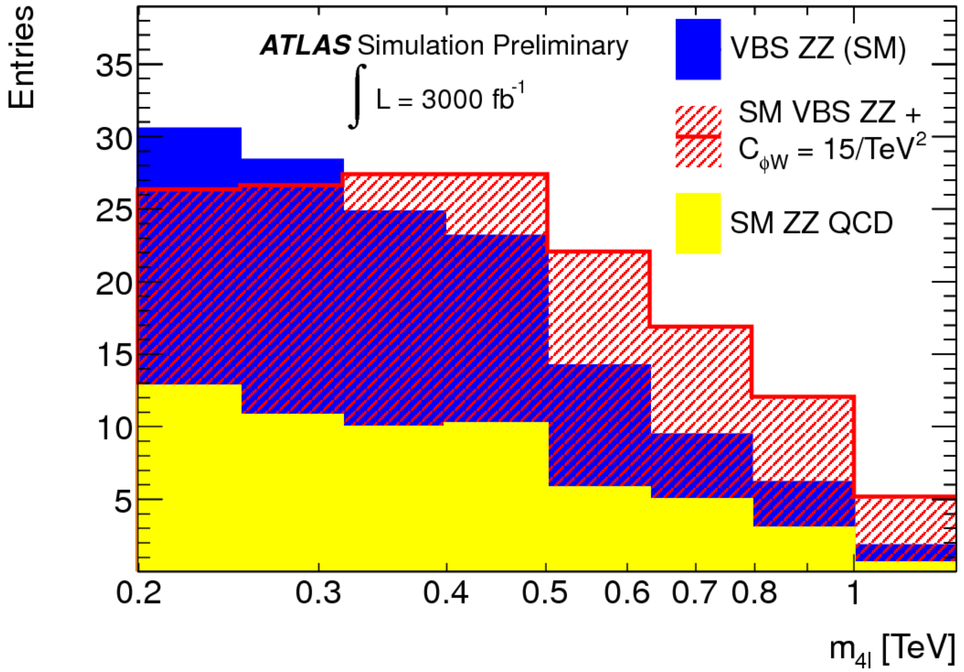


- Example beyond the Standard Model theories predict up to ~5% deviation

Imperial College London

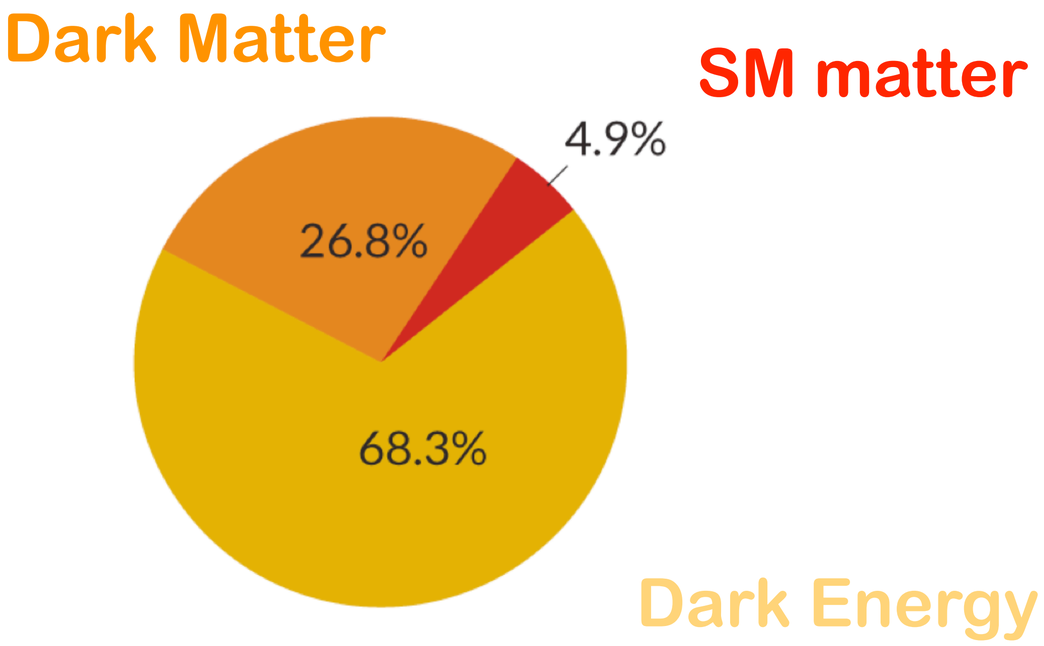
Future physics: VV scattering

- Without the Higgs VV scattering would violate unitarity
  - Complementary probe of EWSB to direct Higgs measurements
  - Example ZZ scattering to 4 leptons
    - Low cross section but cleanest channel
    - 30% with 300 fb^{-1}
    - 10% with 3000 fb^{-1}
  - Requires excellent detector performance
    - VBF signature (forward jets), pile up control
    - Boosted decay of V to leptons or jets (substructure)
    - …



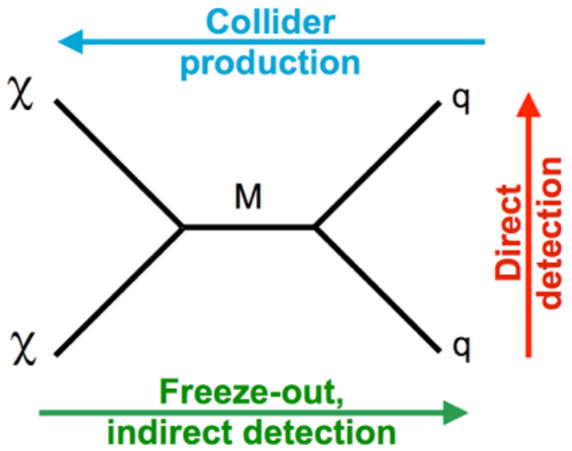
Imperial College London

Future physics: Dark Matter



More than 95% of the matter-energy in the Universe is of unknown origin!

- What can the LHC contribute?
  - Complementary to direct detection experiments and observations

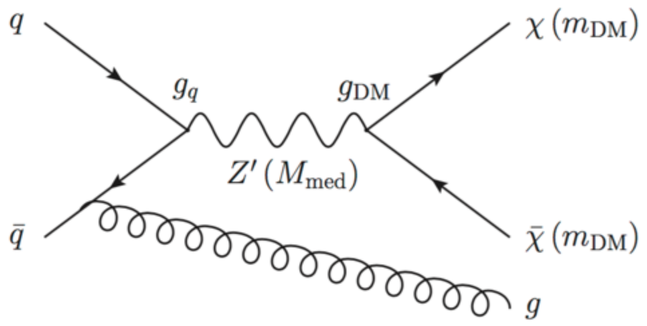


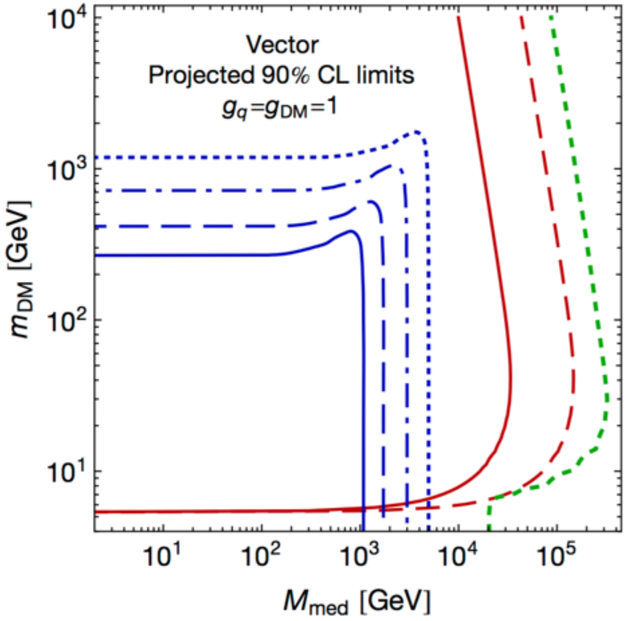
Imperial College London

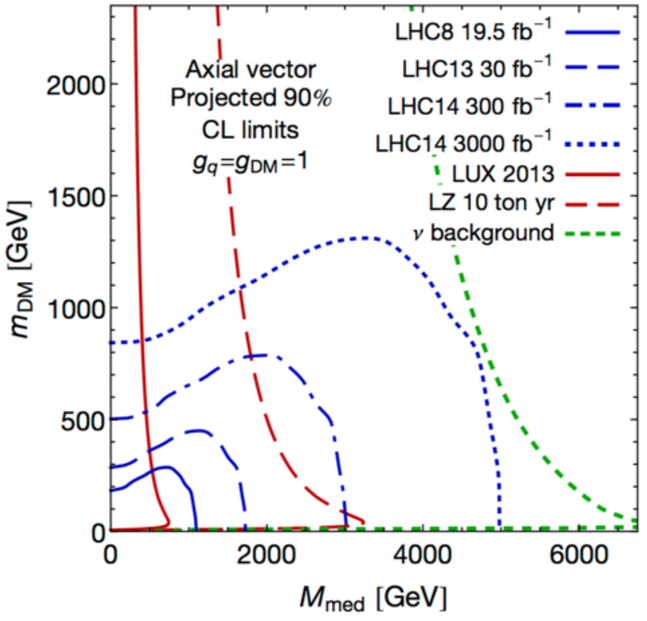
Future physics: Dark Matter

- How do you observe something invisible?

  - Monojet (and other) events







  - Large gains with 300 fb^{-1} to 3000 fb^{-1}

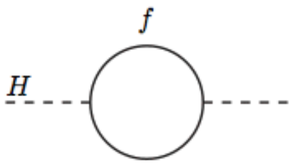
Buchmüller et al.
arXiv:1407.8257

  - Requires excellent performance for jets and missing energy

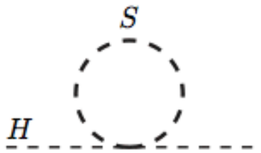
Imperial College London

Future physics: SUSY

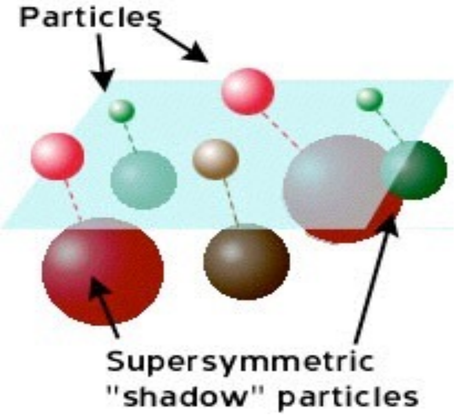
- Why we love supersymmetry…
  - Hierarchy problem



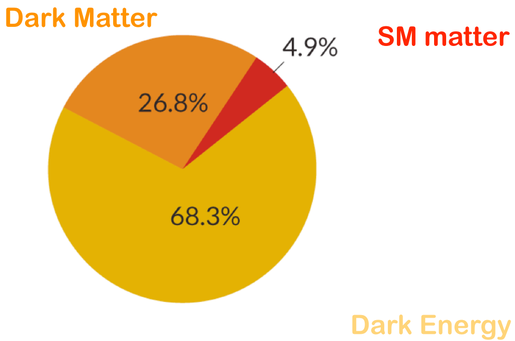
$$\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 ln\,\frac{\Lambda}{m_f}]$$



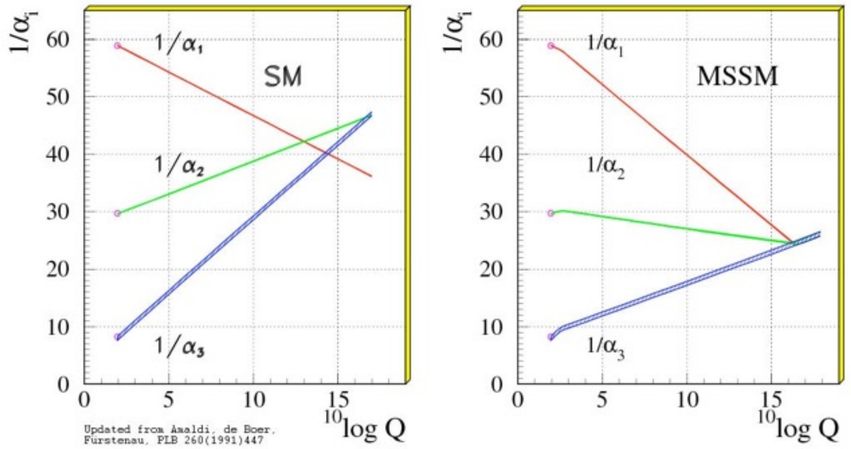
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 ln\,\frac{\Lambda}{m_S}]$$



  - Dark Matter candidate



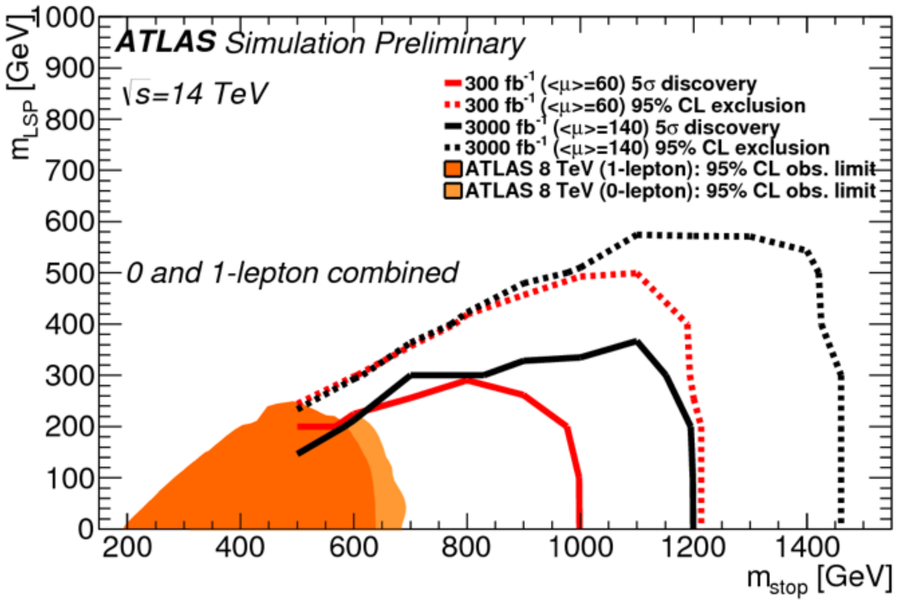
  - Unification



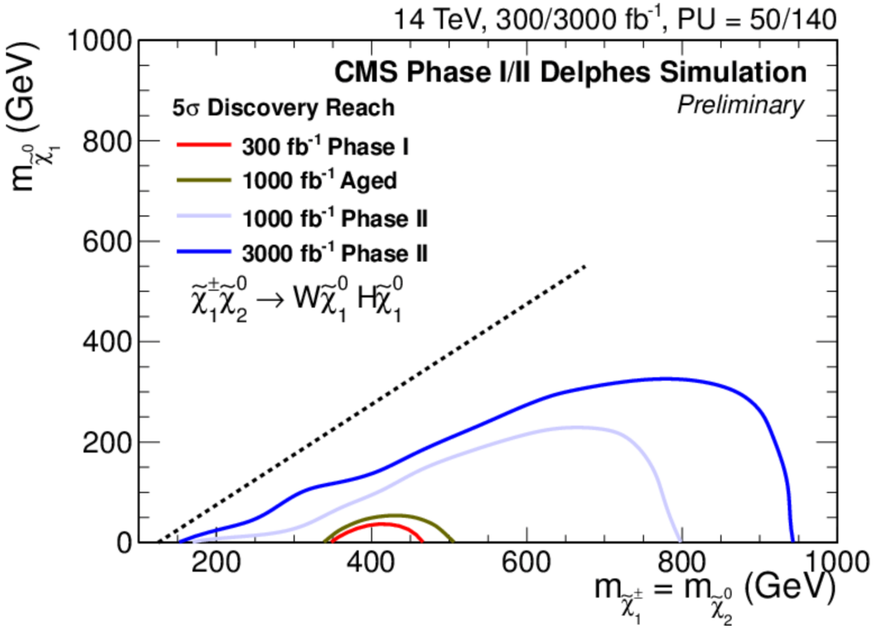
Imperial College London

Future physics: SUSY

- Natural SUSY
  - M_{stop} < ~1 TeV
  - Constraints on sbottom and gluino
  - Maybe still alive with 300 fb^{-1}?



- Electroweak production of SUSY
  - Lower cross sections than strong production → needs higher luminosity
  - Also shows effect of detector degradation
  - WH channel: lepton, MET and 2 b-tags



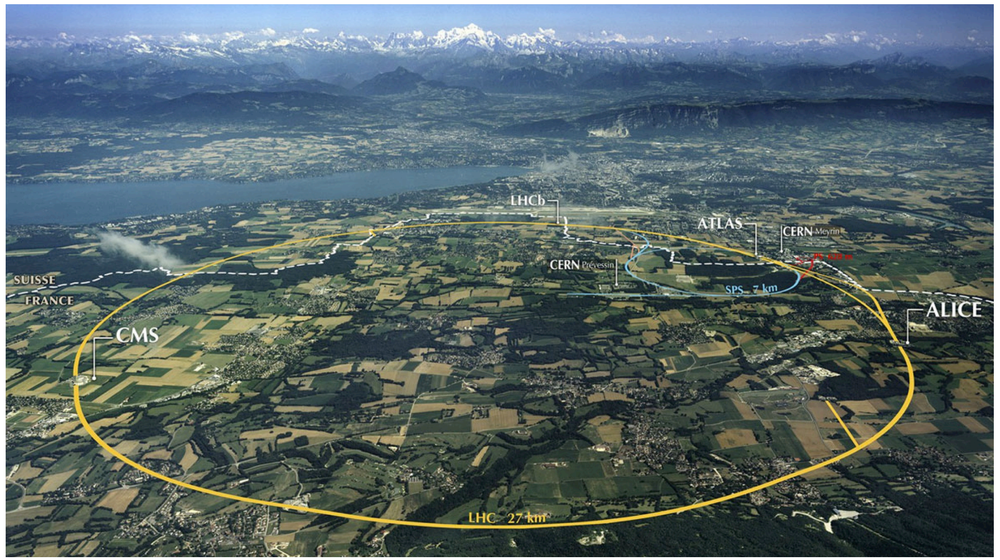
Imperial College London

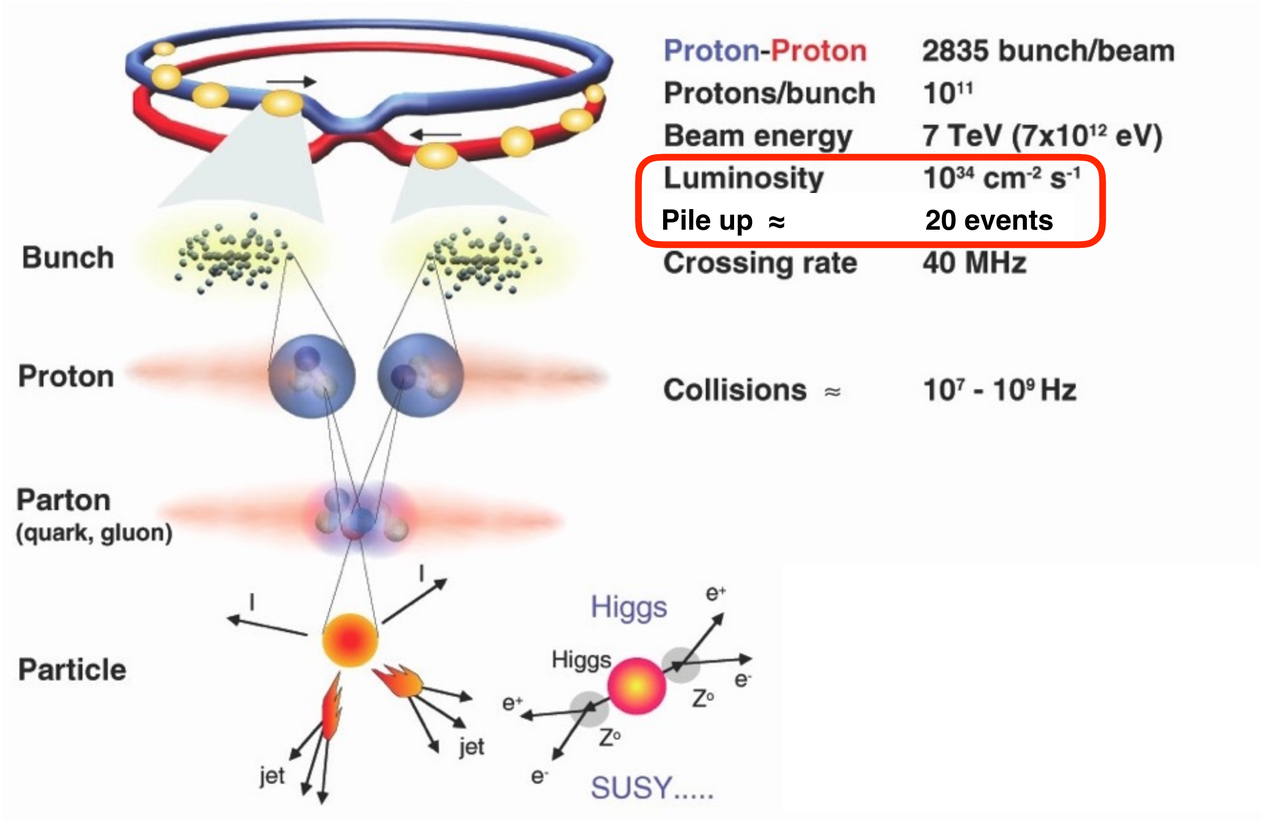
Physics summary

- Broad physics programme
  - Precision SM (including Higgs) measurements
  - Searches for new physics
- Complementary to other (potential) colliders
- Highlighted key areas for detector performance
- **Bottom line**: will need to maintain current high level of detector performance

Imperial College London

LHC: Introduction

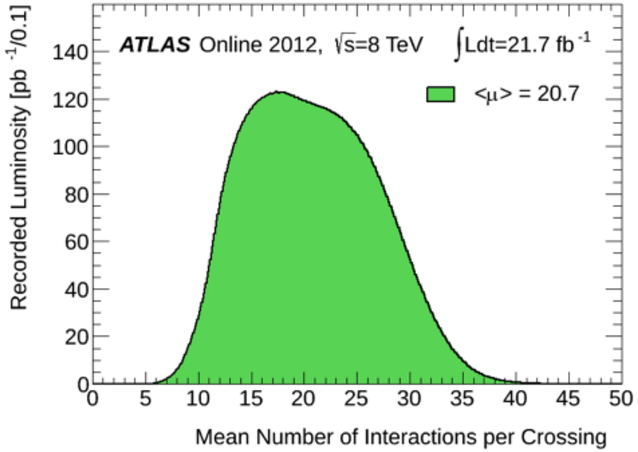




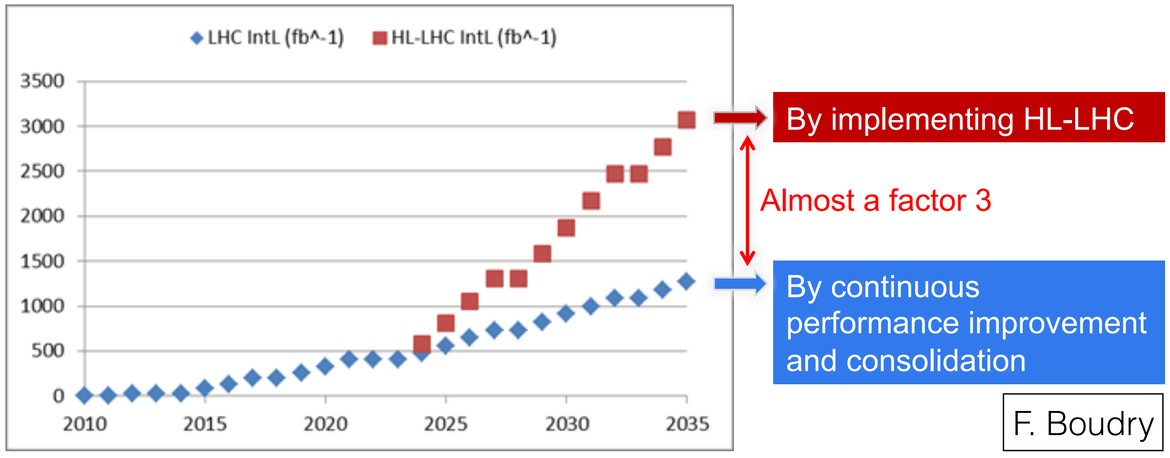
Imperial College London

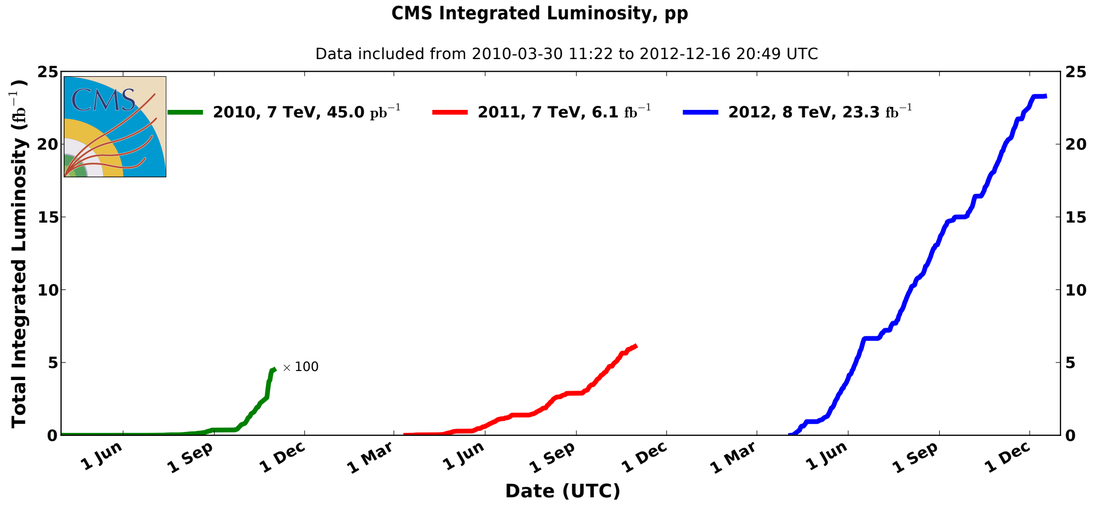
LHC: Running conditions

- Close to design luminosity reached already
  - $7x10^{33}$ cm^{-2} s^{-1} *vs* $1x10^{34}$ cm^{-2} s^{-1}
  - With 50 ns bunch spacing *vs* nominal 25 ns
  - Higher than design pile up already
  - Integrated luminosities up to 0.3 fb^{-1} / day



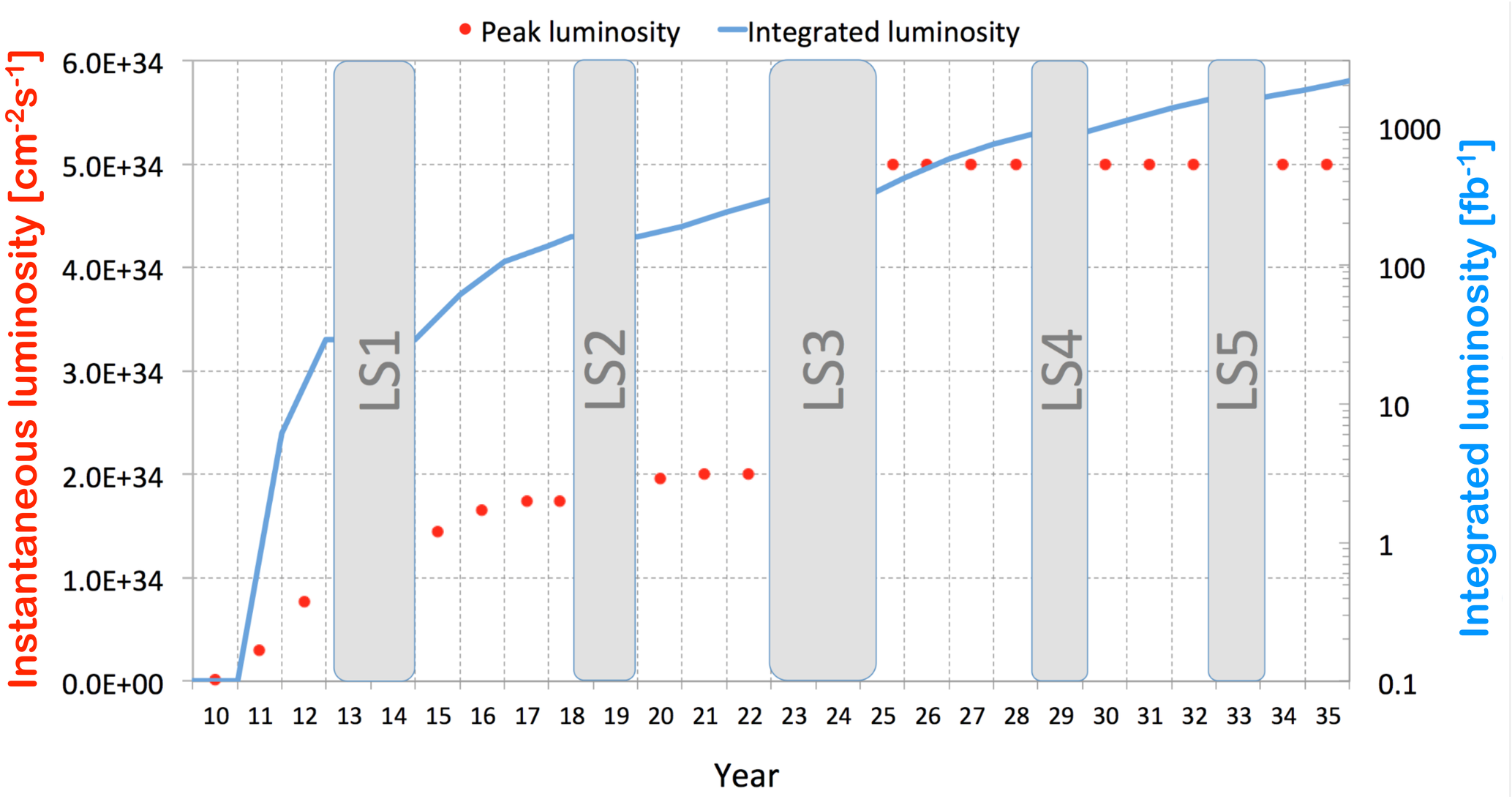
- So why upgrade?





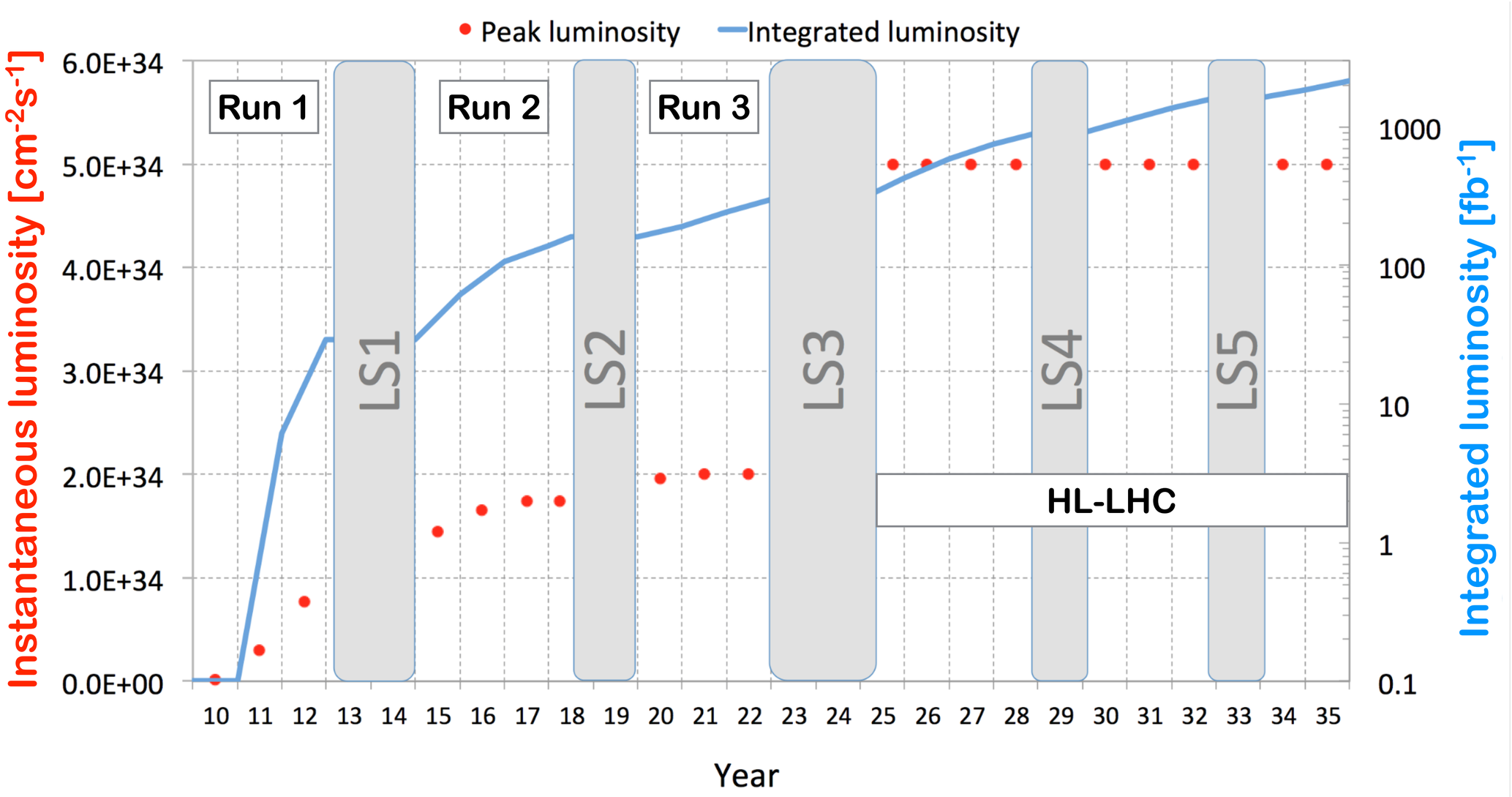
Imperial College London

LHC: Future plans



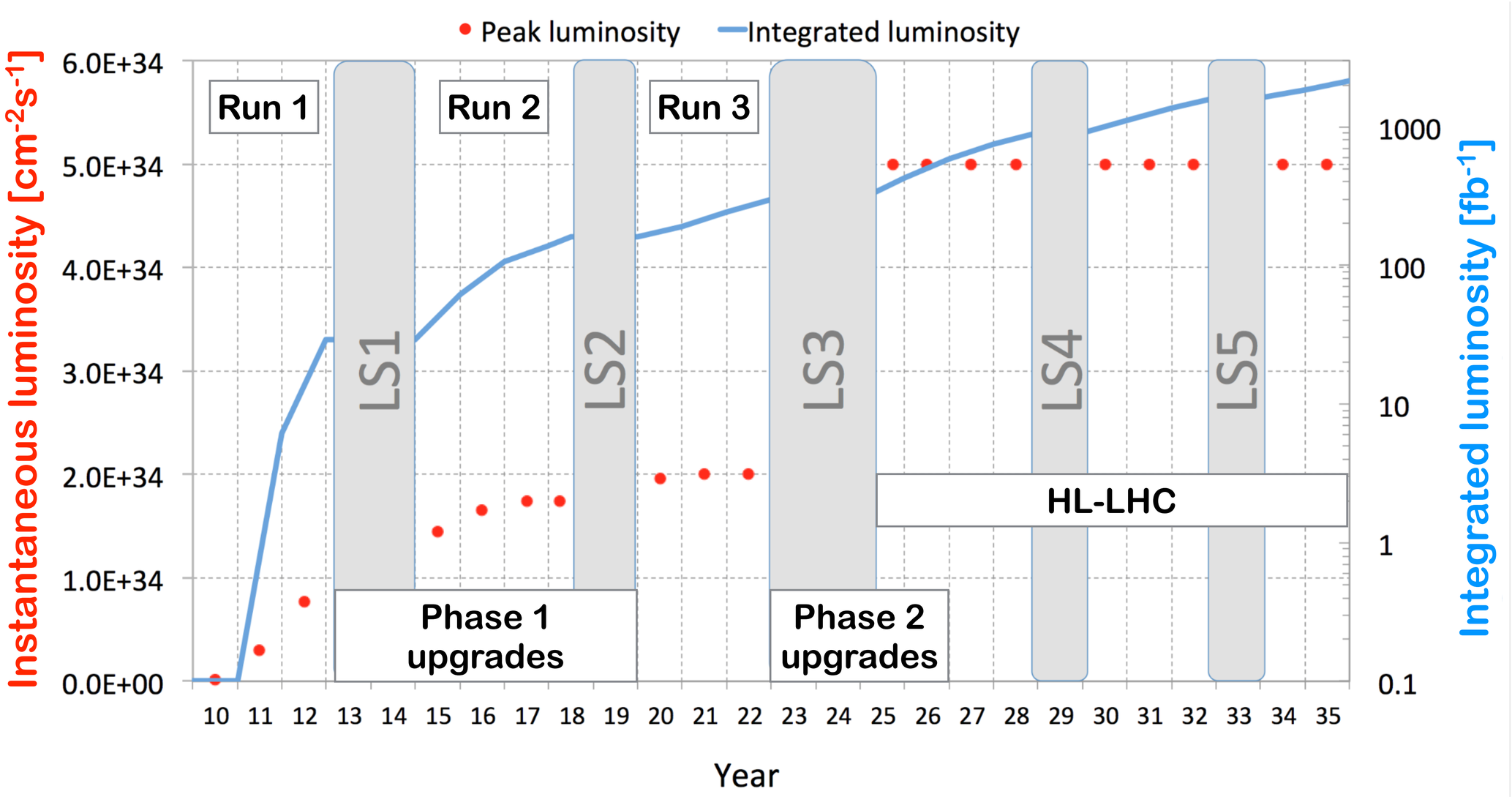
Imperial College London

LHC: Future plans



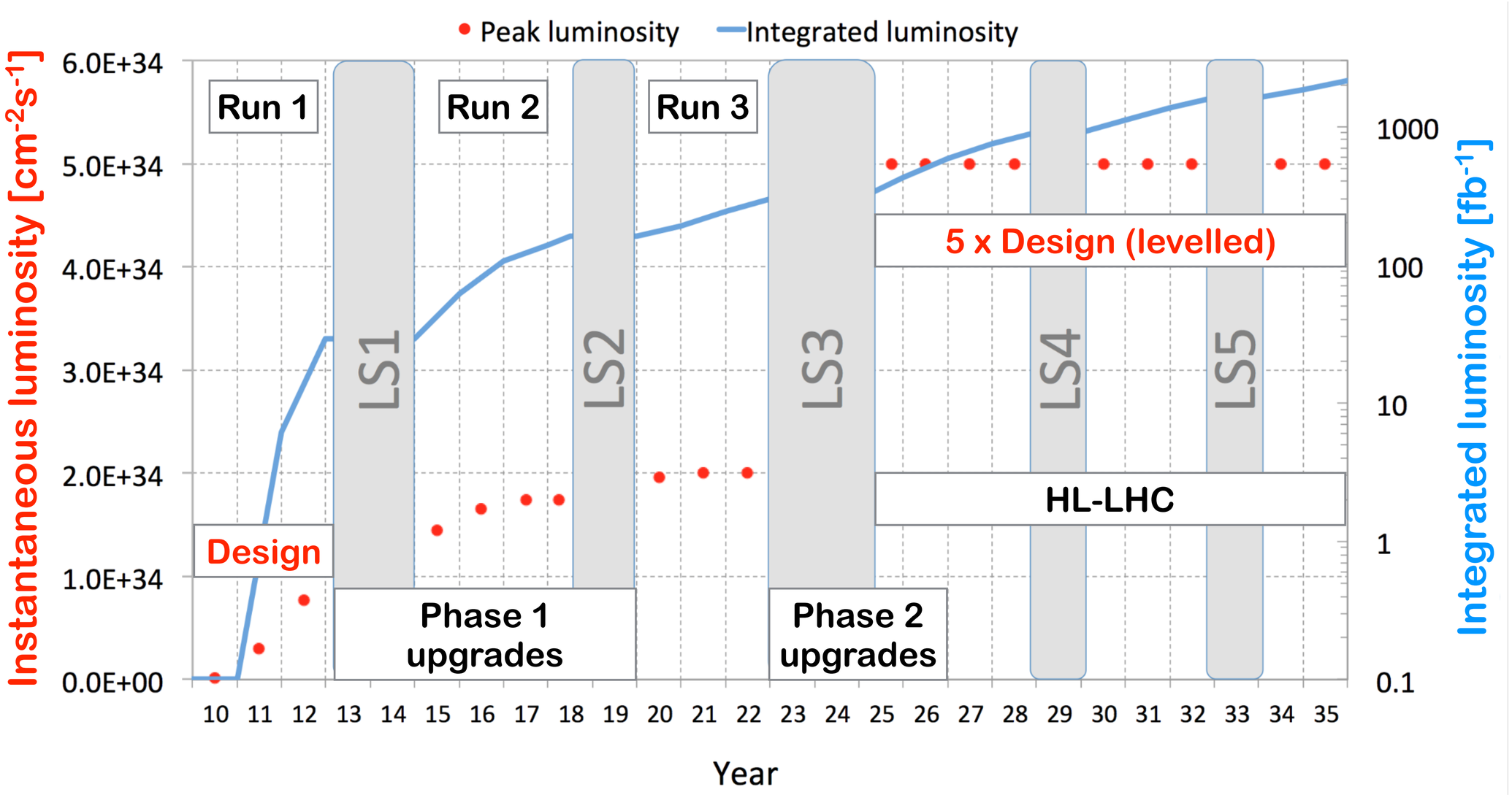
Imperial College London

LHC: Future plans



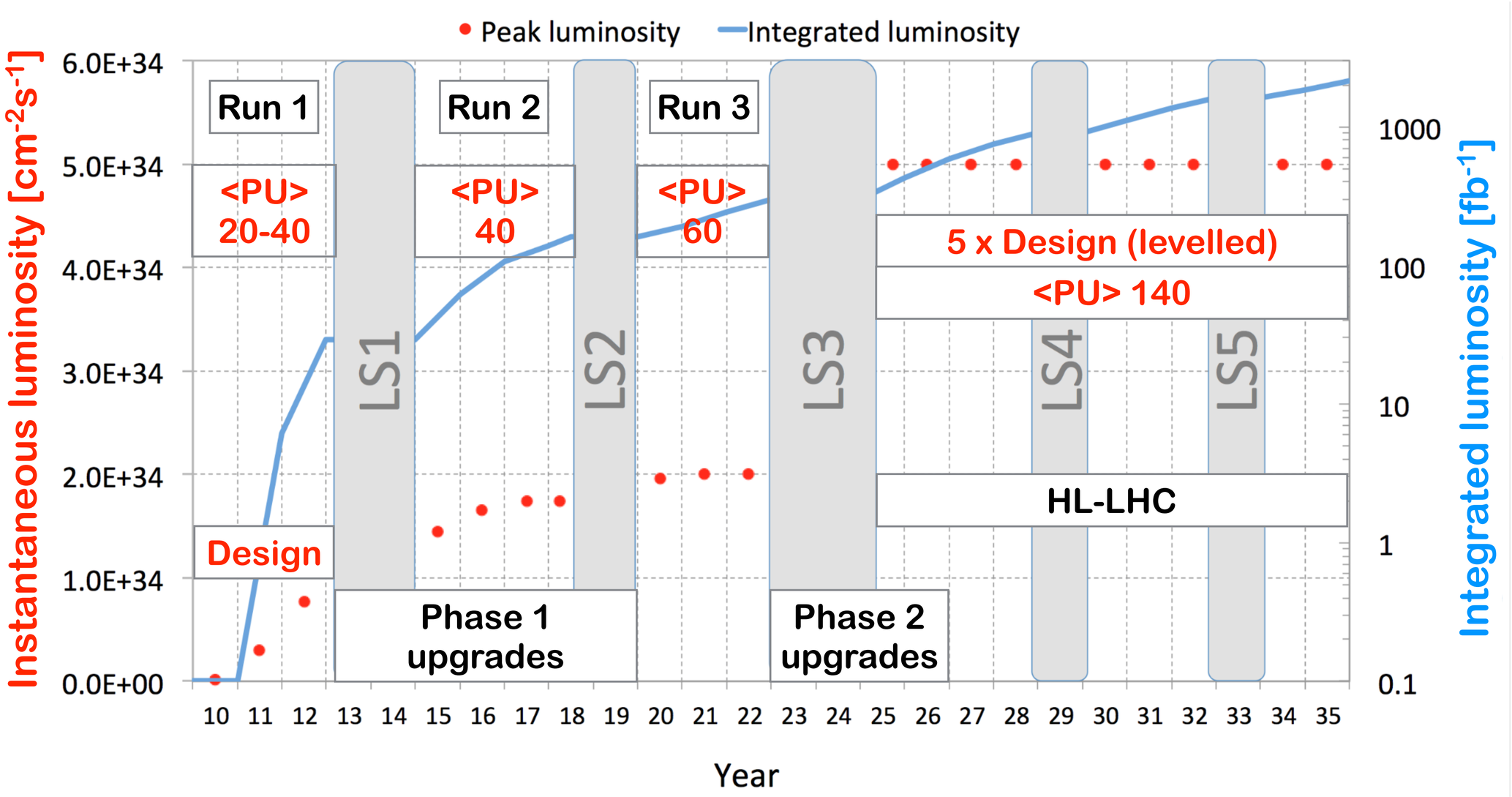
Imperial College London

LHC: Future plans



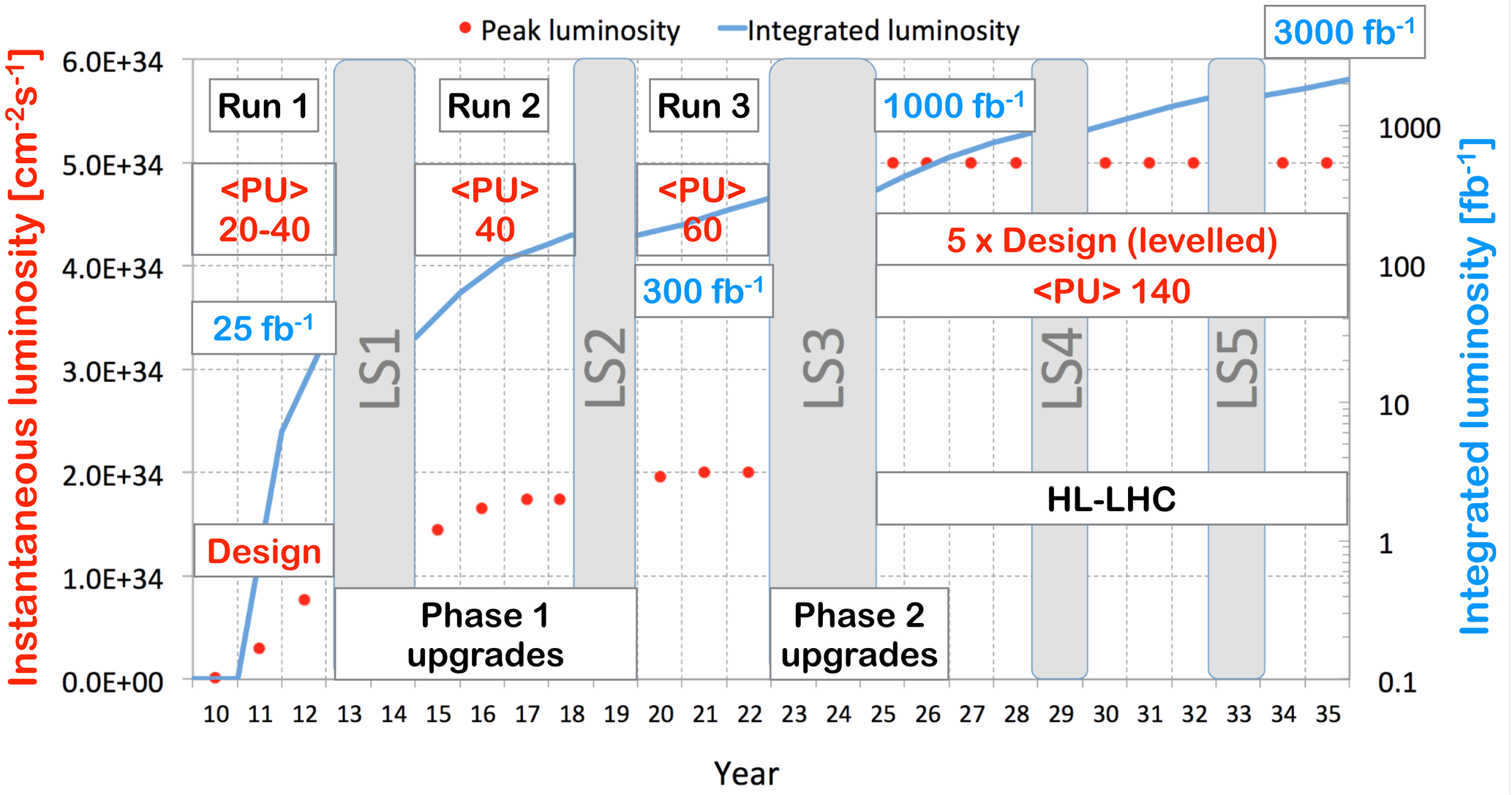
Imperial College London

LHC: Future plans



Imperial College London

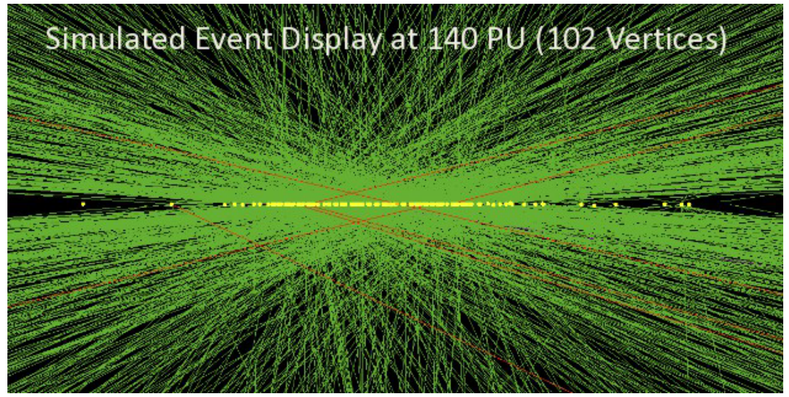
LHC: Future plans



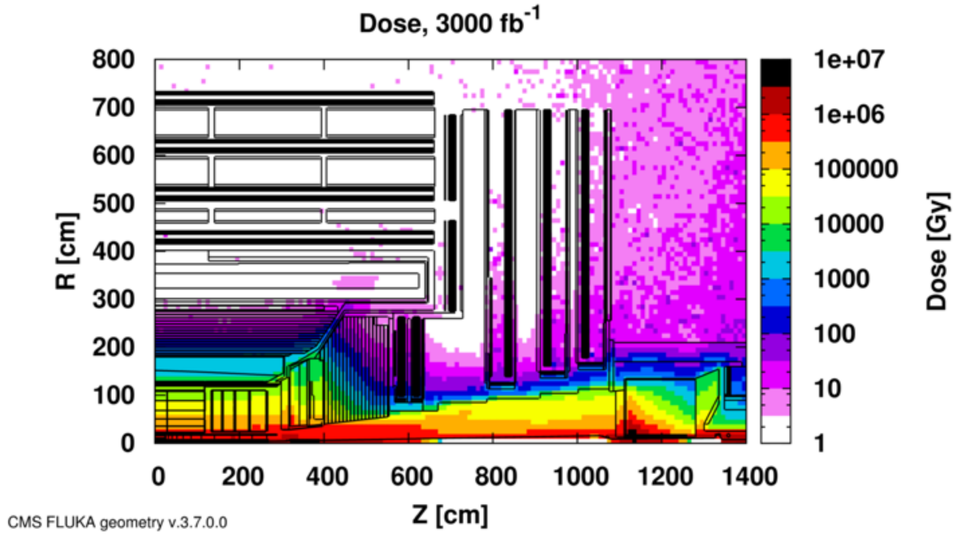
Imperial College London

Detector upgrades: challenges

- Pile up
  - Detector performance degraded (e.g. pattern recognition)
  - Offline reconstruction complexity



- Radiation
  - High fluencies and high doses for trackers and endcap calorimeters
  - Degraded performance



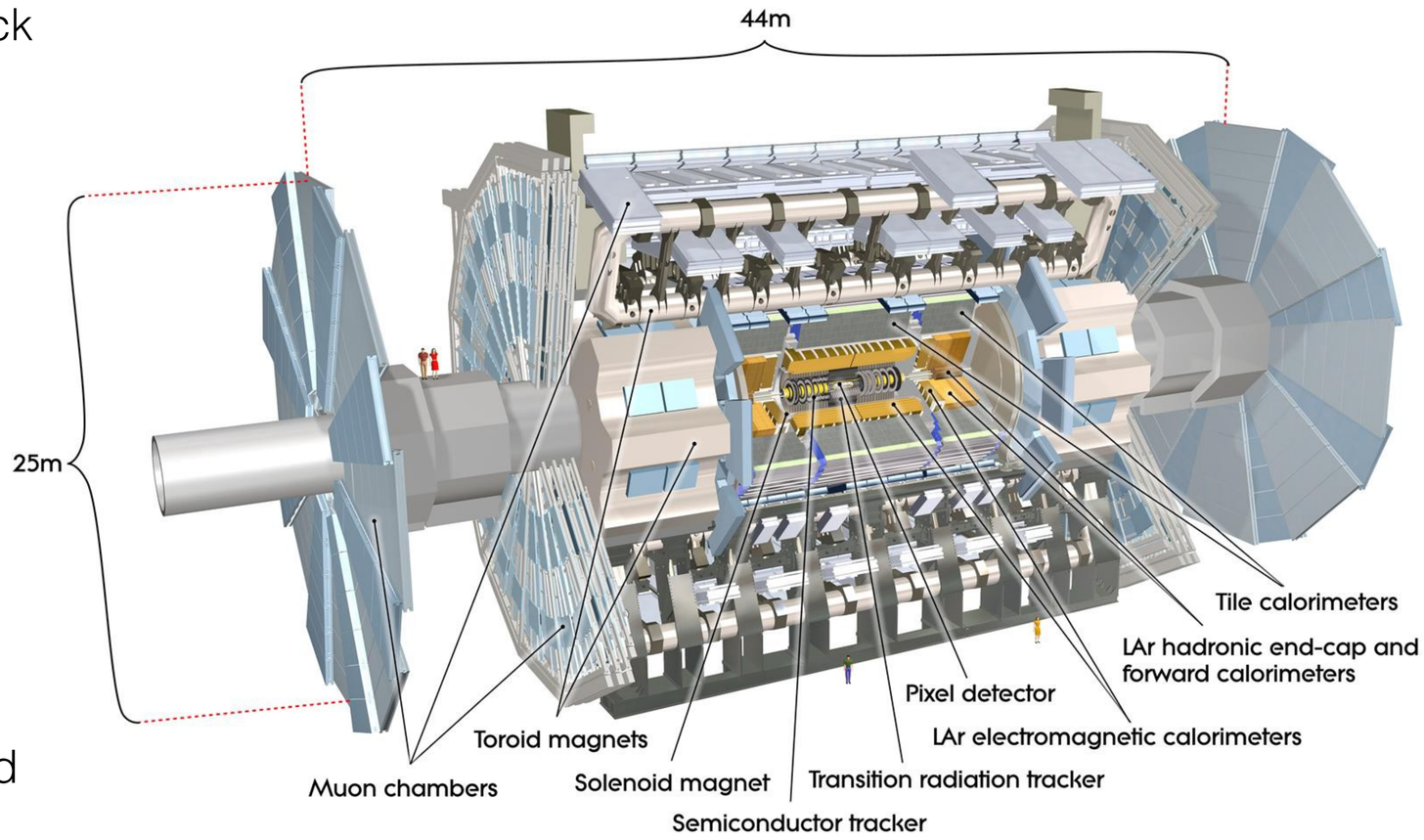
- Rates
  - Trigger rates increase with instantaneous luminosity and performance degrades with pile up (e.g. isolation)

Run	W→lν rate
Run1	80 Hz
Run 2	200 Hz
Run 3	400-600
HL-LHC	1KHz

Imperial College London

ATLAS: Phase 1 upgrade

- Fast Track Trigger
  - Hardware (Associative Memory) based track finder (pattern matching)
  - FPGA-based track fitting
- Trigger and DAQ
  - Level-1 Calorimeter Trigger (UK)
    - New electronics
    - Finer granularity
- Forward muon detectors
  - Muon “small wheels” improve tracking and trigger in forward regions



Imperial College London

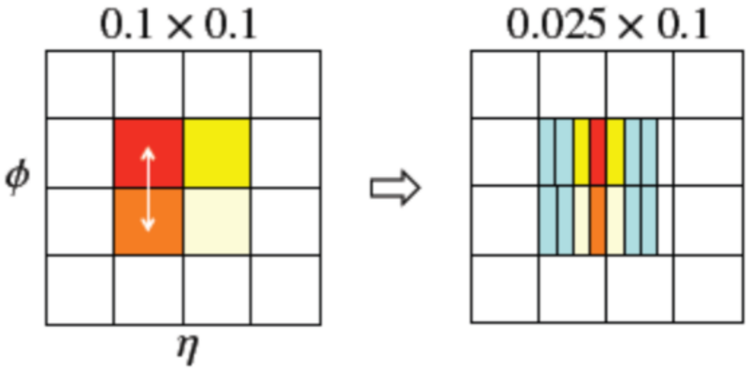
ATLAS: Phase 1 upgrade

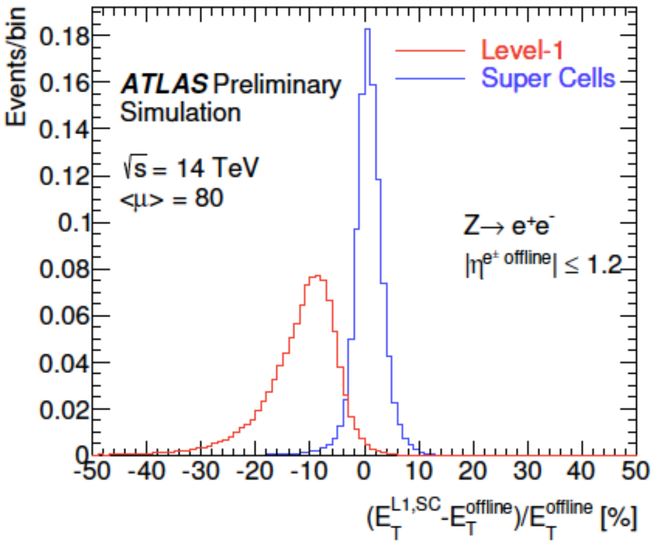
- Level-1 Calorimeter Trigger

  - Upgrade calorimeter electronics will provide finer granularity data to Level-1 trigger in η and depth information

  - Preserve thresholds for single electron trigger at p_T ~ 25 GeV for LHC luminosity increasing to ~2-3x nominal

  - UK developing electron feature extractor and associated readout (ATCA and high speed optical links)

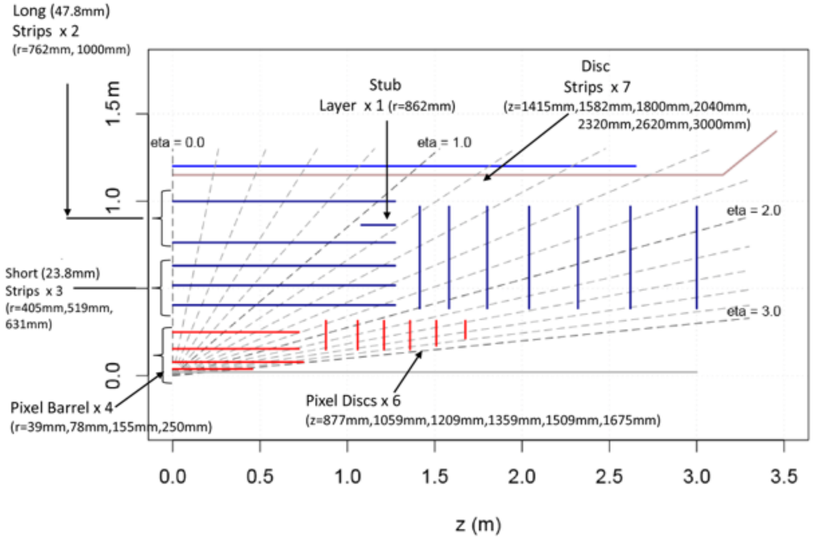


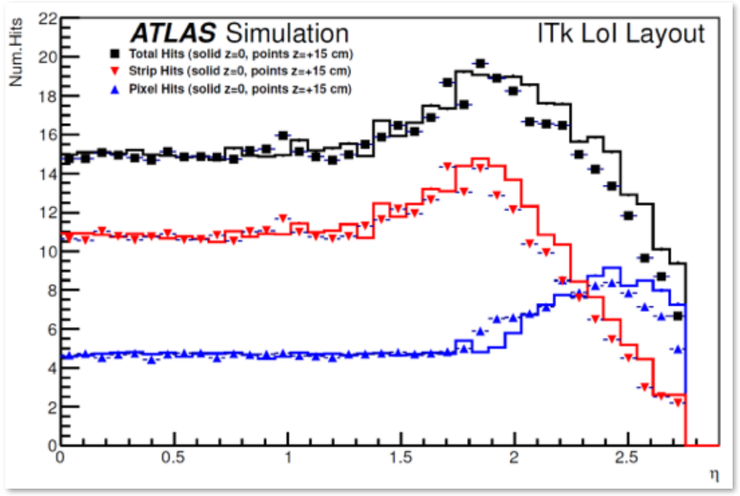


Imperial College London

ATLAS: Phase 2 upgrade

- Full replacement of Inner Tracker (UK)
  - Existing Inner Detector performance degraded by radiation damage and high occupancy in Phase 2
  - Replace with all silicon tracker
    - pixels and microstrips
  - Significantly increase granularity
    - Pixel system (LOI layout) 4 barrel layers and 6 disks (~8 m^2)
    - Strip system 5 barrel layers plus 7 disks (~190 m^2)
    - Robust tracking with 14 layers →
  - Minimise material budget within tracking acceptance



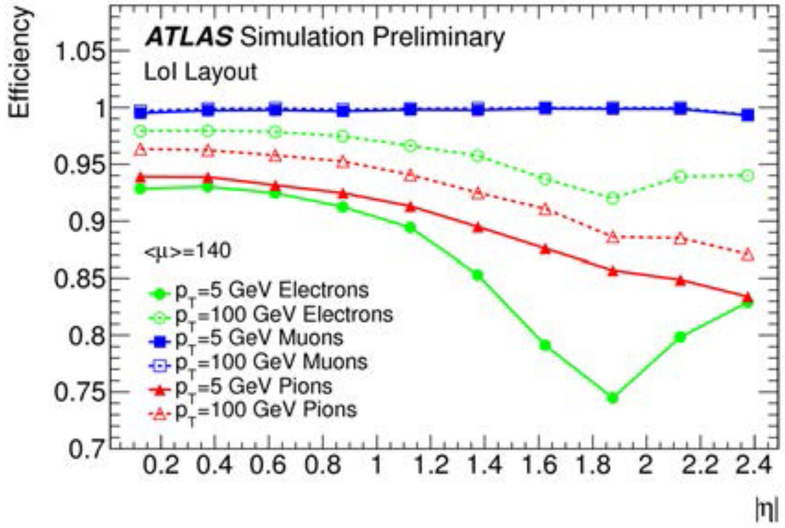


Other layouts with extended η under study

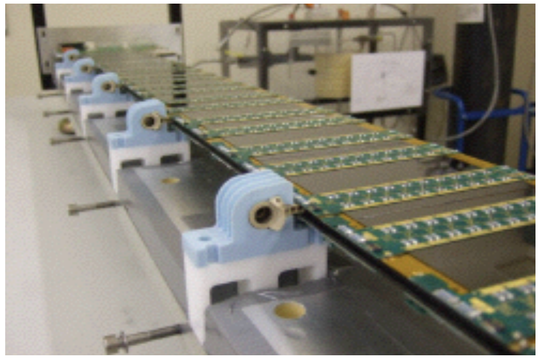
Imperial College London

ATLAS: Phase 2 upgrade

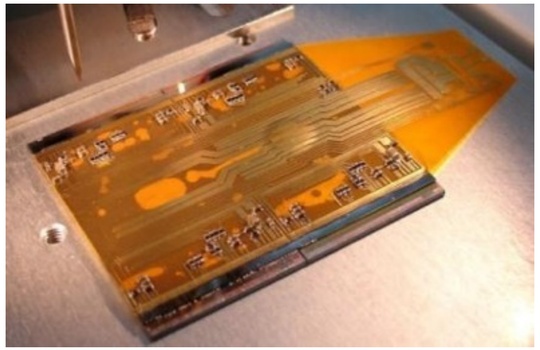
- Sufficient hits on track to maintain high efficiency and combat combinatorics at high pile up
  - Excellent tracking efficiency →
- UK interest in large contribution to new tracker
- Extensive R&D underway for several years



Microstrip Stave Prototype



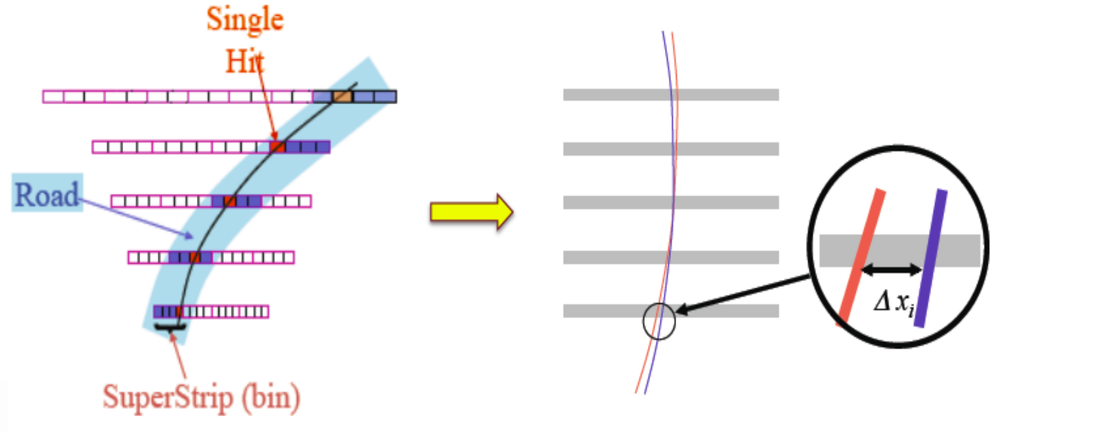
Quad Pixel Module Prototype



Imperial College London

ATLAS: Phase 2 upgrade

- Trigger upgrade
  - New Trigger Architecture
  - Two Level Hardware trigger
    - L0: 1 MHz, 6μs latency (calorimeter and muons)
    - L1: 300-400 kHz 24μs latency



Pattern recognition in coarse resolution (superstrip➔road)

Track fit in full resolution (hits in a road)

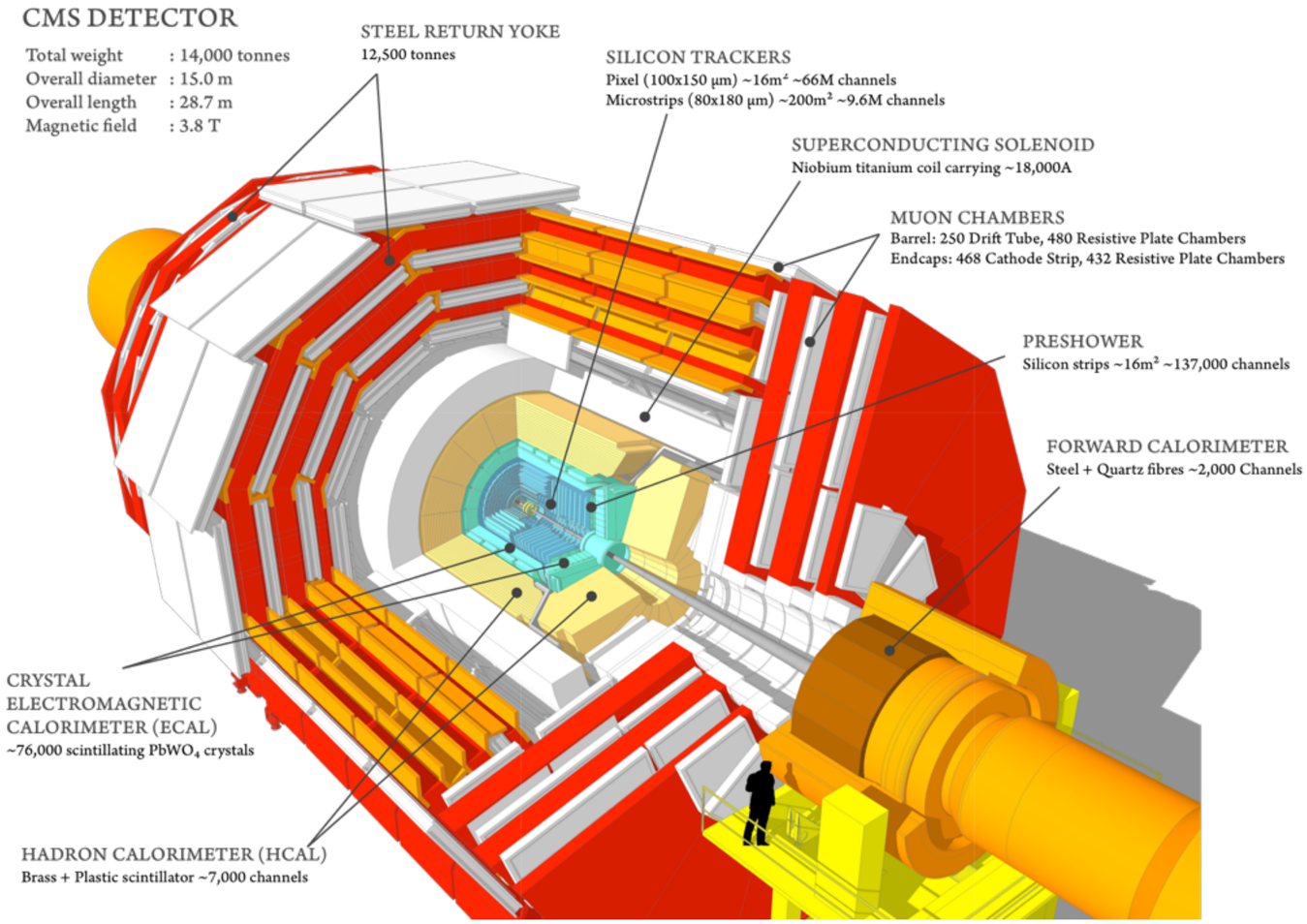
$F(x_1, x_2, x_3, \ldots) \sim a_0 + a_1\Delta x_1 + a_2\Delta x_2 + a_3\Delta x_3 + \ldots = 0$

  - L1Track: Use tracking information earlier in trigger processing
    - Regional information from ITk
    - Associative Memory ASICs for track finding and FPGAs for track fitting (similar to FTK)
  - Phase 1 L1 calorimeter trigger becomes Phase 2 L0

Imperial College London

CMS: Phase 1 upgrade

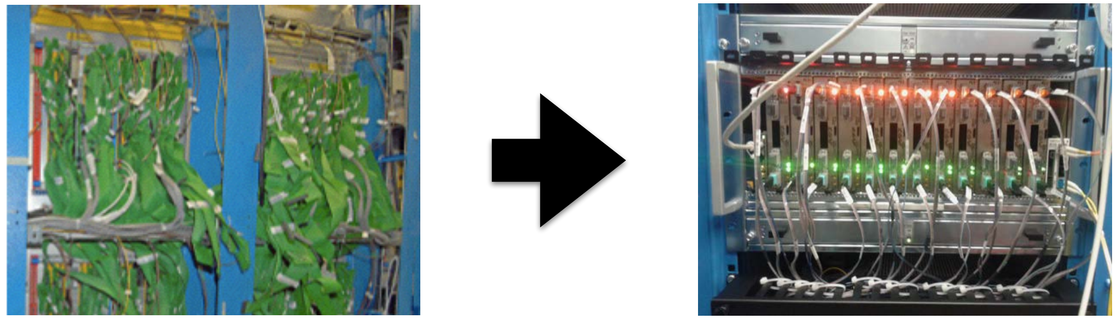
- Hadron calorimeter
  - Replace photodetectors and electronics between LS1 and LS2 → add depth information and improved noise performance
- Level-1 Trigger (UK)
  - New system with latest electronics runs from 2016 → **now running in cosmic-ray runs!**
- Pixel detector
  - New detector to be installed 2016/17
- Forward muon detectors
  - New GEM detectors to be installed in LS2



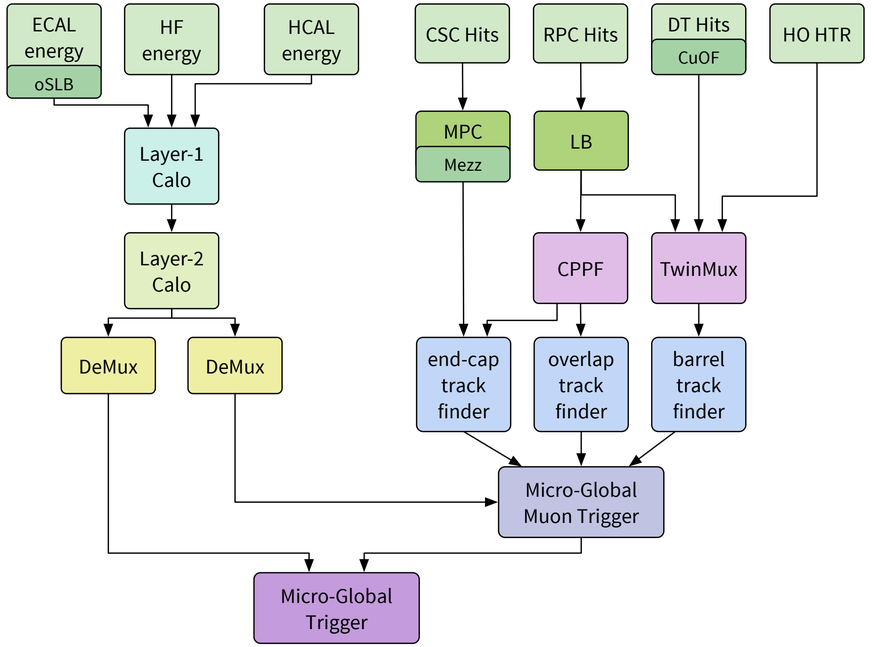
Imperial College London

CMS: Phase 1 Level-1 Trigger upgrade

- Replace older VME electronics with latest μTCA (telecoms standard) electronics → latest, powerful processing (FPGAs) and high speed serial links

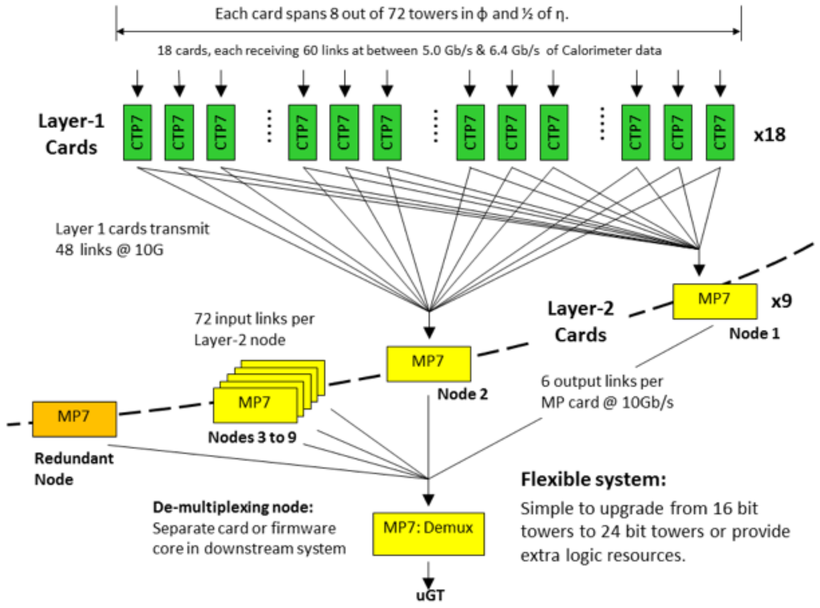


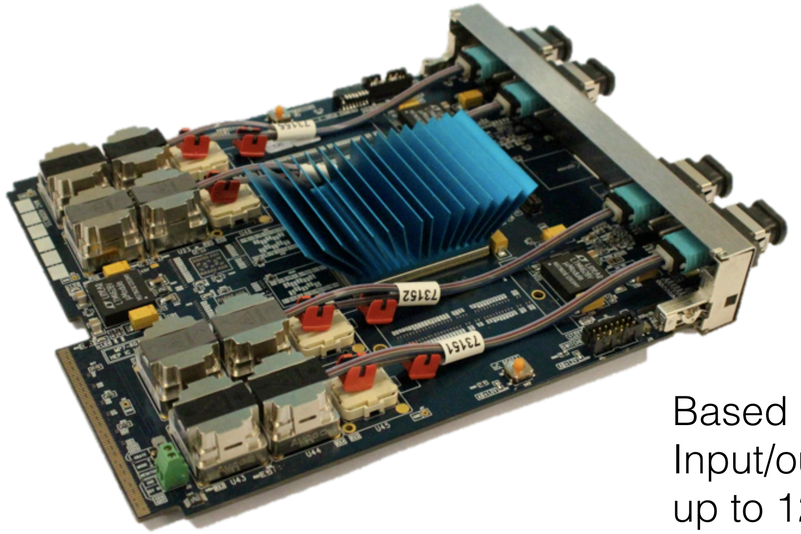
- Replace copper links with optical fibres almost everywhere
- Earlier merging of detector data in muon system → better reconstruction
- Pile up subtraction in calorimeter system for object energies and isolation energies



Imperial College London

CMS: Phase 1 Level-1 Trigger upgrade

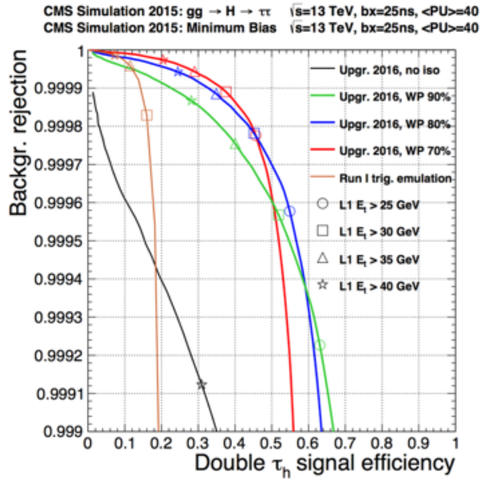


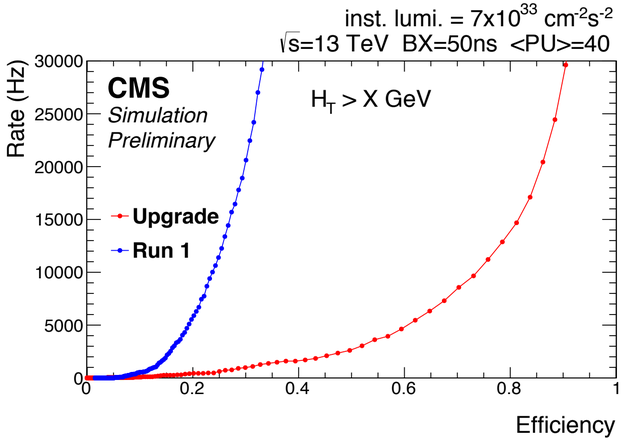


IMPERIAL MP7

Based on µTCA telecoms standard
Input/output 72 optical links running up to 12.5 Gb/s → 0.9 Tb/s

- Higher granularity (tower level)
- One processing FPGA sees the entire detector for one event
  - Seamless coverage of detector
  - Sophisticated algorithms (closer to offline)

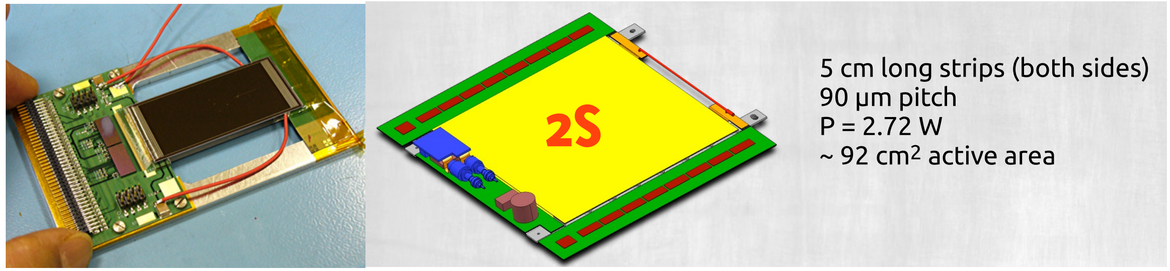




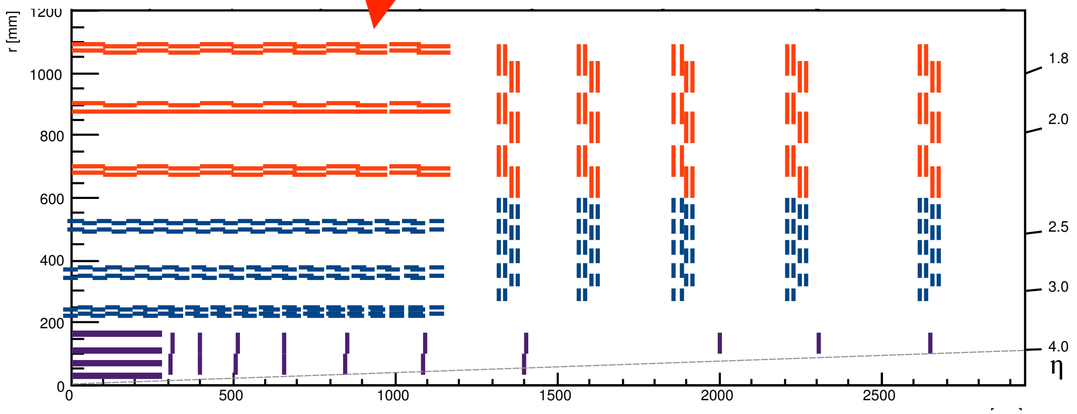
Imperial College London

CMS: Phase 2 Tracker upgrade

- Pixel detector
  - Similar configuration as Phase 1
    - 4 layers and 10 disks to cover up to $|\eta| = 4$
  - Thin sensors 100 μm
  - Smaller pixels 30 x 100 μm



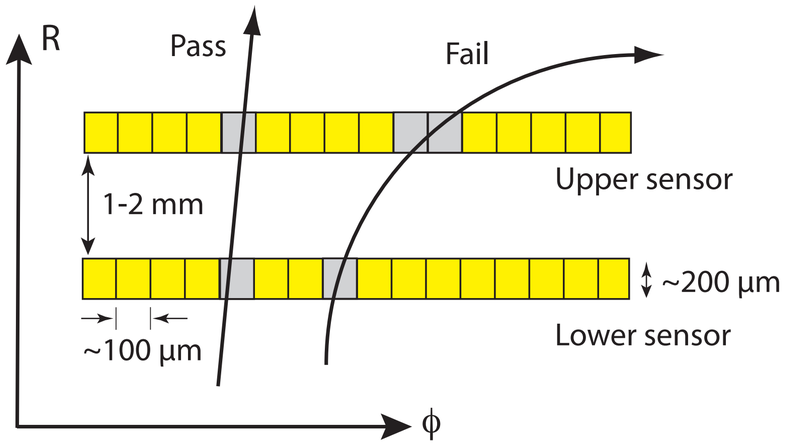
- Outer tracker (UK)
  - High granularity for efficient track reconstruction beyond 140 PU
  - Improved material budget
  - *P_T-modules* to provide trigger for tracks with $P_T \geq 2$ GeV

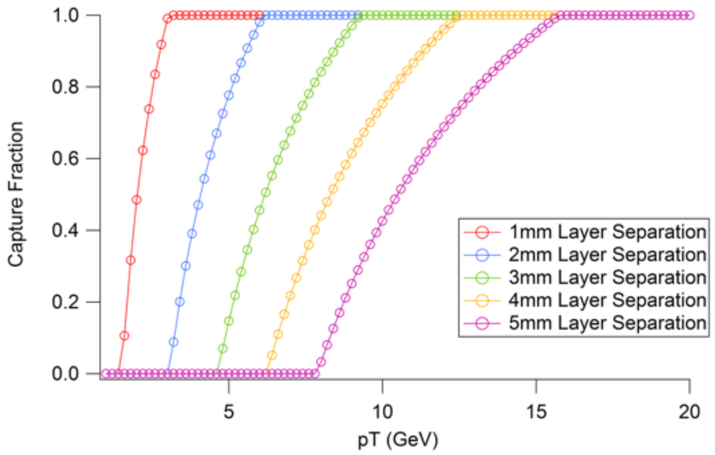


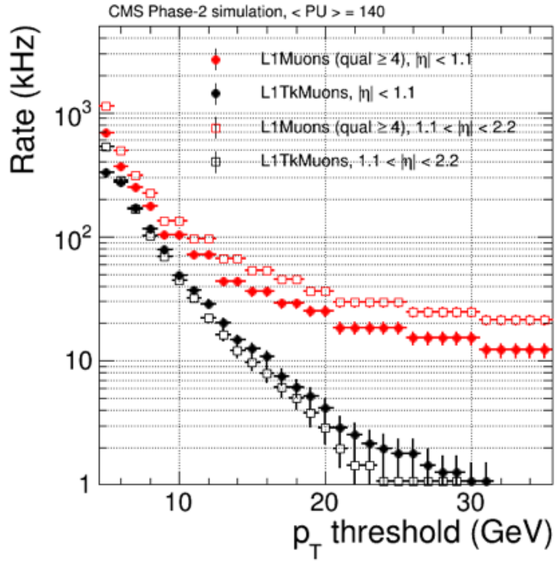
Imperial College London

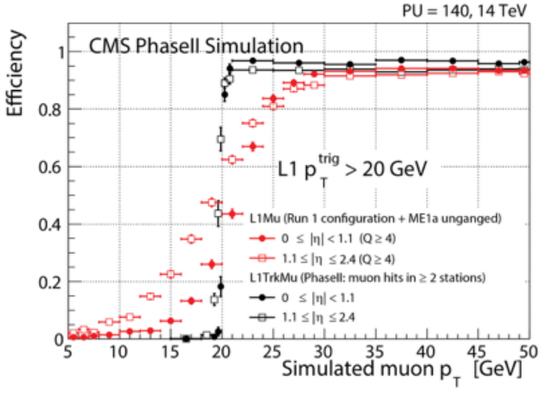
CMS: Phase 2 Tracker upgrade

- Outer tracker
  - P_T-modules → doublet sensors with common electronics to correlate hits and form stubs for trigger
  - Distance between sensors give track p_T lower cut







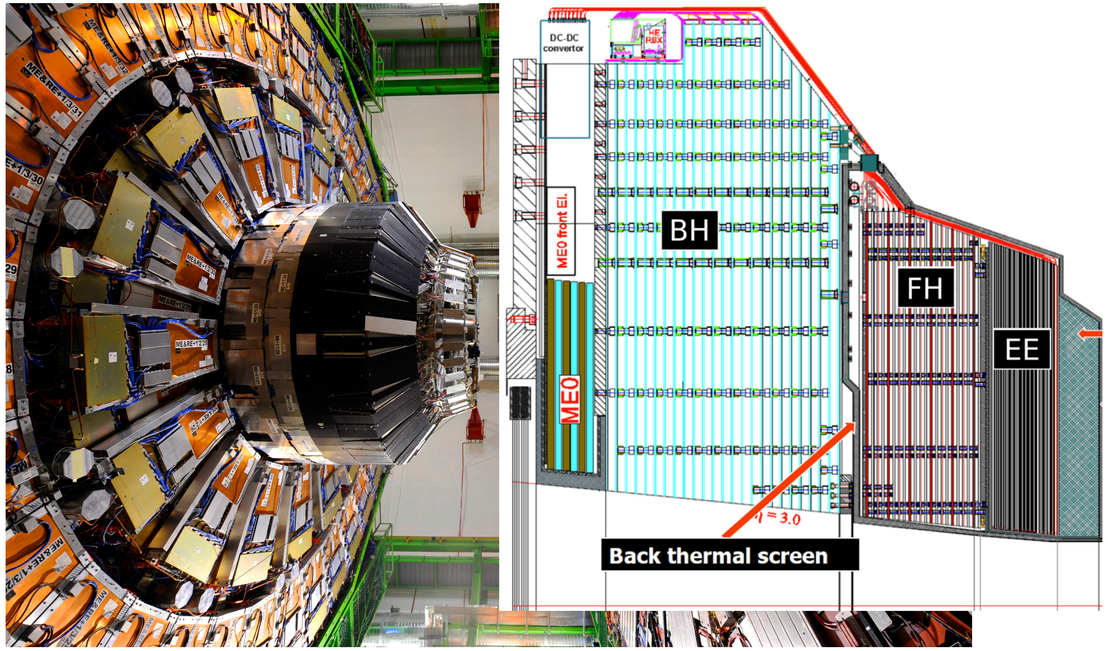


- Allows control of trigger rates and hugely improved p_T resolution
- FPGA and AM based track finding under study

Imperial College London

CMS: Phase 2 Calorimeter upgrade

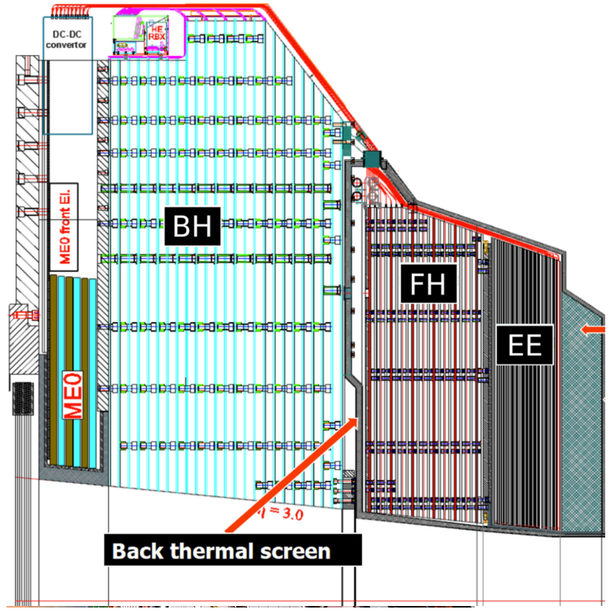
- Current endcap calorimetry will not remain performant after LS3
  - Combination of radiation damage and high pile up conditions
- Plan to replace by integrated high-granularity calorimeter
  - Sampling calorimeter with silicon sensors, optimised for high pile up
  - High granularity readout (~1cm^2) and precision timing capability (<50ps)



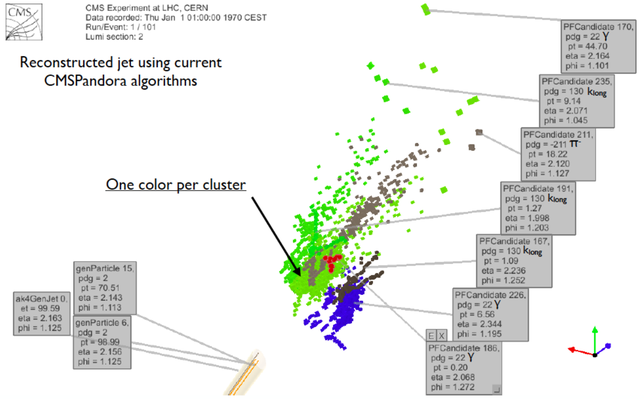
Imperial College London

CMS: Phase 2 Calorimeter upgrade

- High Granularity Calorimeter with 4D (space-time) shower measurement
  - Electromagnetic section (26 X0, 1.5λ): 28 layers of Silicon-W/Cu absorber
  - Front Hadronic section (3.5 λ): 12 layers of Silicon/Brass or Stainless Steel
  - Back Hadronic Calo. (BH) - radiation tol. - granularity
  - BH (5 λ): 12 layers of Scintillator/Brass or Stainless Steel (2 depth readout)



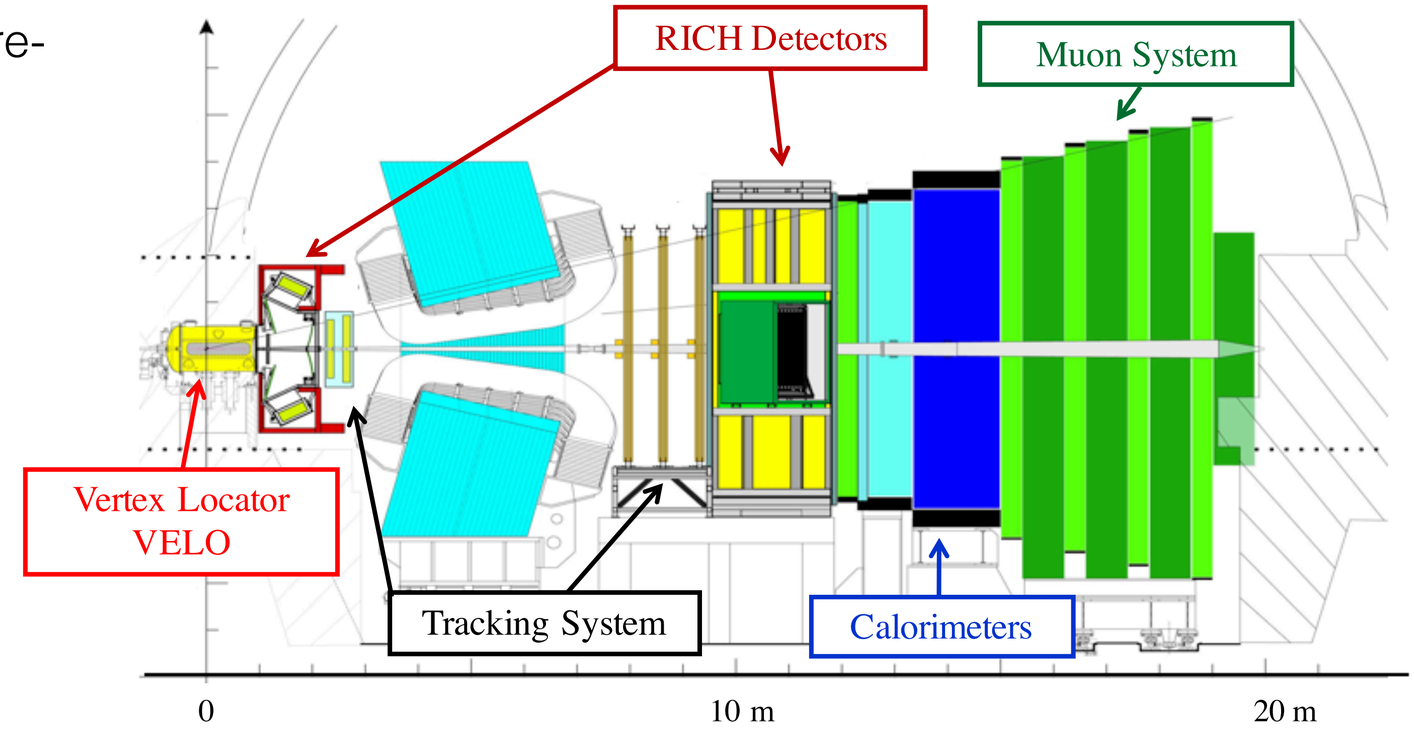
- Major new areas of R&D (UK)
  - Level-1 Trigger, reconstructions algorithms, analogue and digital electronics…



Imperial College London

LHCb upgrade (Run 3)

- Trigger
  - Upgrade readout to 40 MHz → fully software-based trigger
  - New electronics and DAQ
- VELO (UK)
  - New detector and electronics
- RICH (UK)
  - New detector and electronics
- More tomorrow morning…



Imperial College London

Summary and conclusions

- LHC Run 1 a great success!
  - Discovery of Higgs boson
  - Key measurements and searches for beyond the Standard Model physics
- LHC Run 2 underway
  - Hoping for even more excitement than Run 1
- Beyond Run 2
  - HL-LHC has a well motivated physics programme
  - Very significant upgrades to detector → almost new experiments
  - Great opportunities to shape the future of our field

Imperial College London

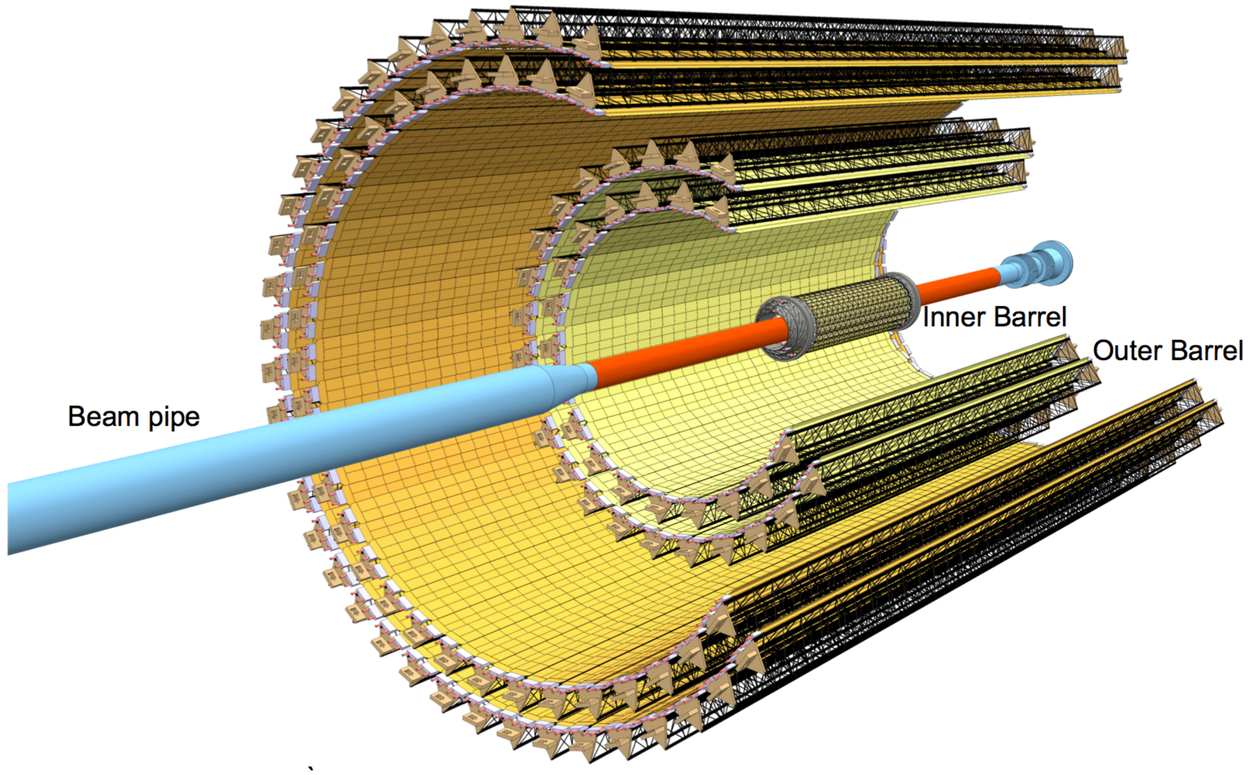
Bibliography

- ATLAS Upgrade Physics projections
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
- CMS Upgrade Physics projections
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
- ATLAS LOI and LHCC Scoping Document
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2012-022/index.html
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2015-020/index.html
- CMS Technical Proposal and LHCC Scoping Document
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TDR-15-002/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/phase2sd/index.html

Imperial College London

ALICE upgrade

- Readout systems
  - Readout Pb - Pb collisions up to 50 KHz (currently 0.5-1 KHz)
- New, high-resolution, low-material Inner Tracking System (ITS)
  - Improve tracking at low p_T
  - 7 layers of pixels
  - 25G pixels based on MAPS



Imperial College London

Higgs couplings

SUSY Kanemura, Tsumura, Yagyu, Yokoya COMPOSITE HIGGS