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Future upgrades to the LHC

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IOP Institute of Physics

Joint annual HEPP and APP conference

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

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Outline

- Physics motivation
- Accelerator overview
- Detector upgrades
- Summary

LHC Run 1 and Run 2 (so far…)

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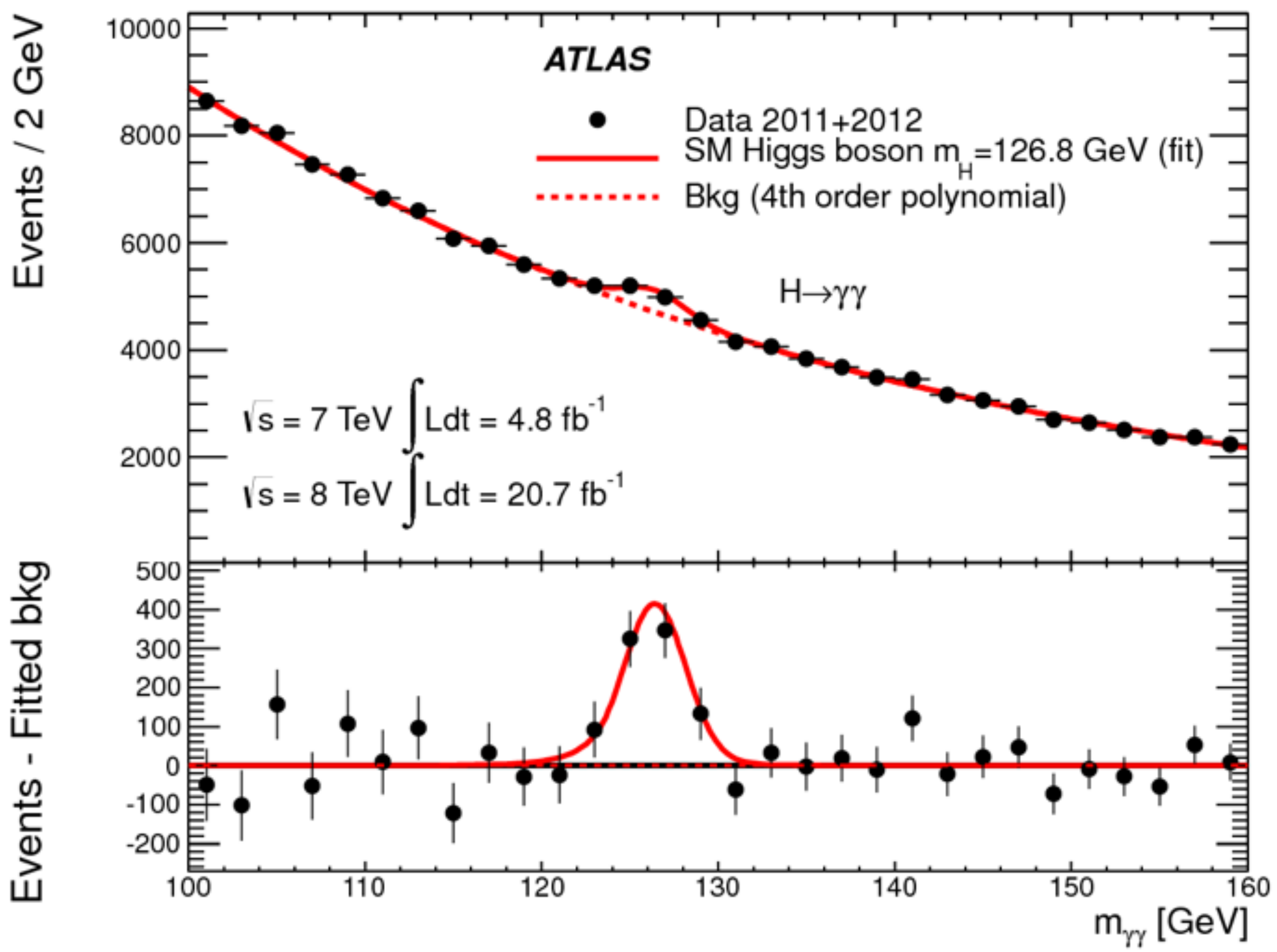
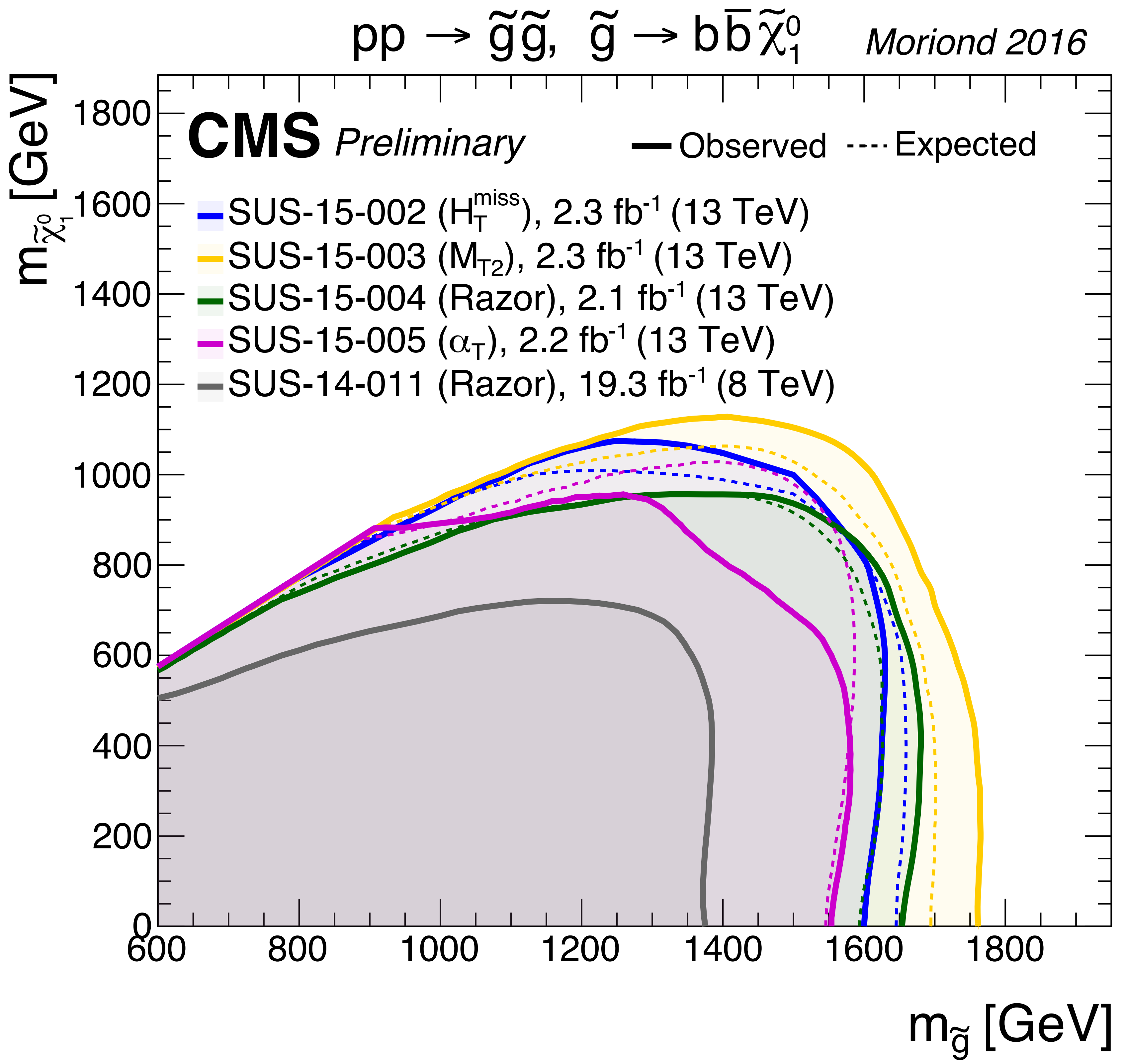
Great success in Run 1…





… and a strong start to Run 2

Future physics: Higgs

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- 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
$H \to \gamma\gamma$	390k
$H \to Z\gamma$	230k
$H \to \mu\mu$	37k
$H \to J/\psi\gamma$	400
HH (all)	121K
$HH \to WWWW$	9200
$HH \to bb\gamma\gamma$	320
$HH \to \gamma\gamma\gamma\gamma$	1

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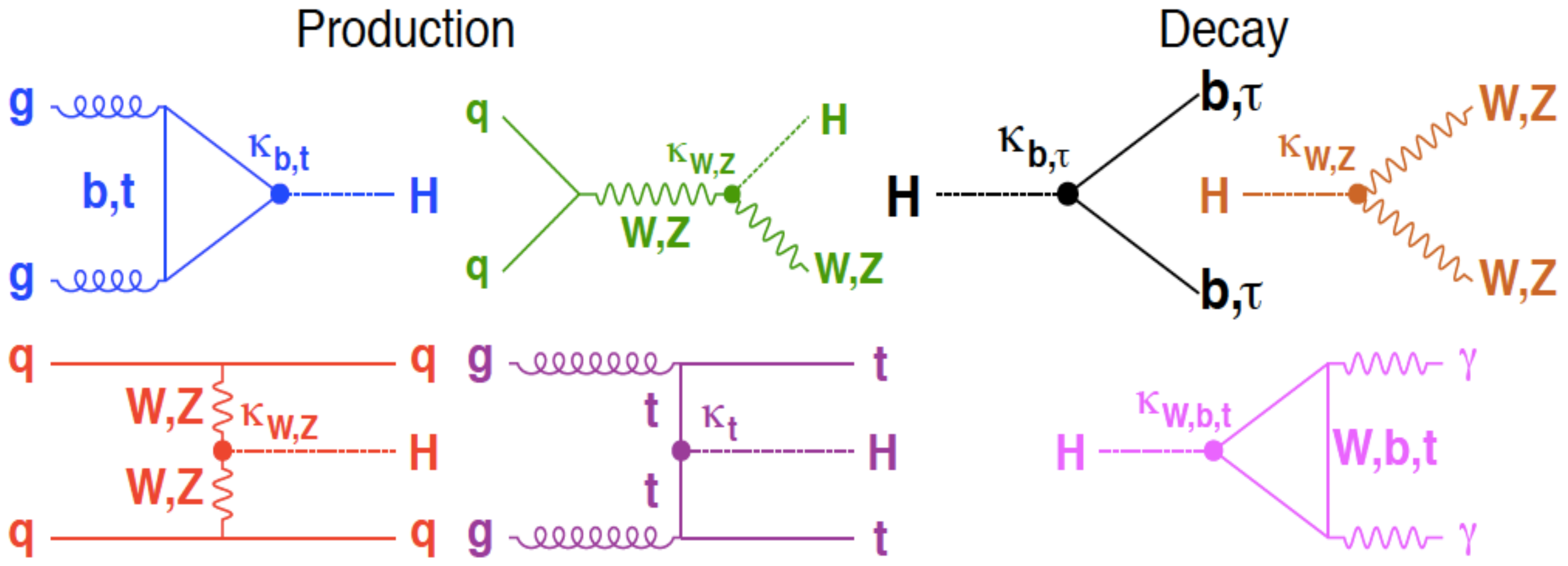
Future physics: Higgs

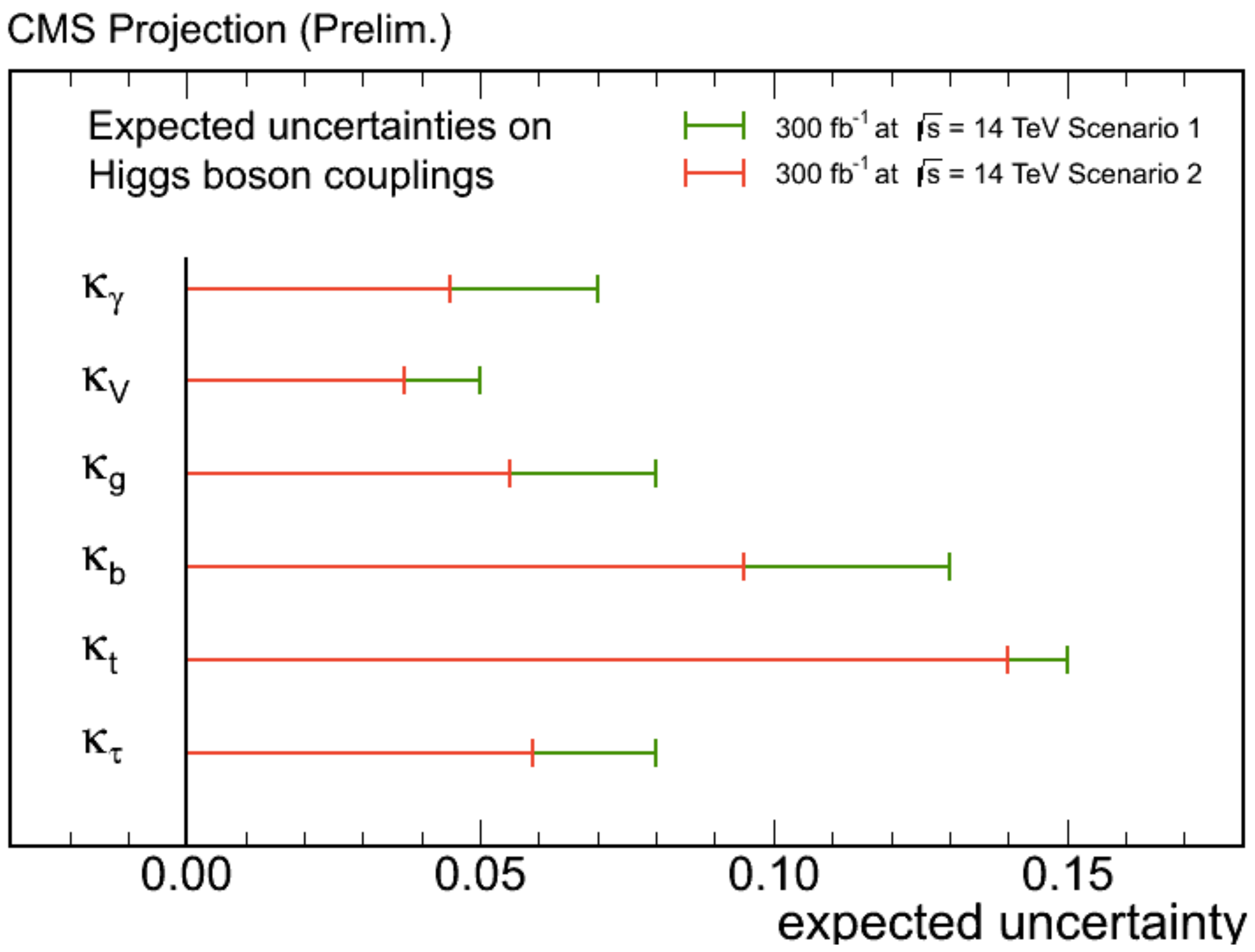
- Measurements of Higgs couplings
  - Answering the question, *is this the SM Higgs?*
  - Express the production and decay of the Higgs in terms of deviation from SM coupling

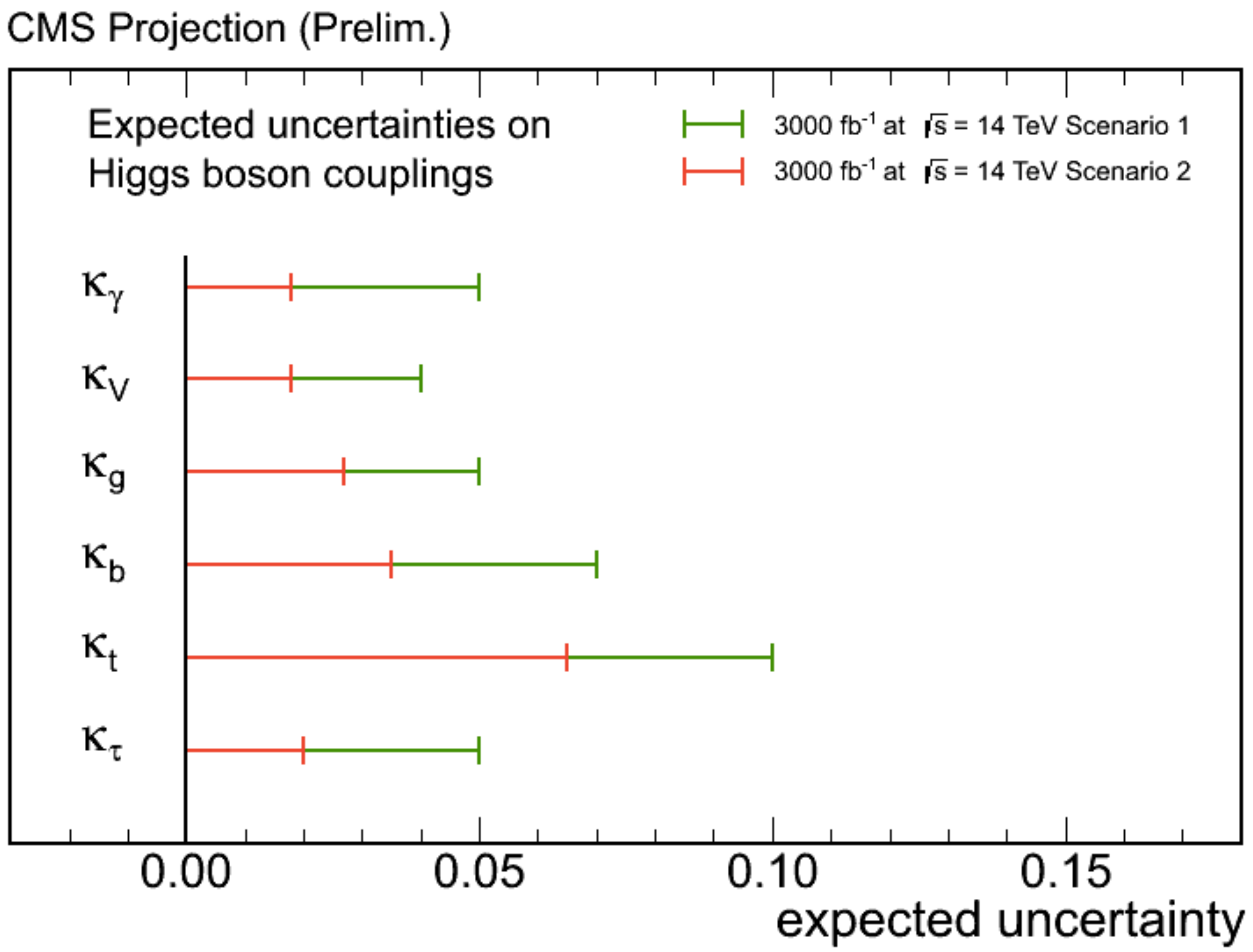


  - Requires great performance across the board
    - Electrons, muons, taus, forward jets, b-tagging, trigger, MET….

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/√L





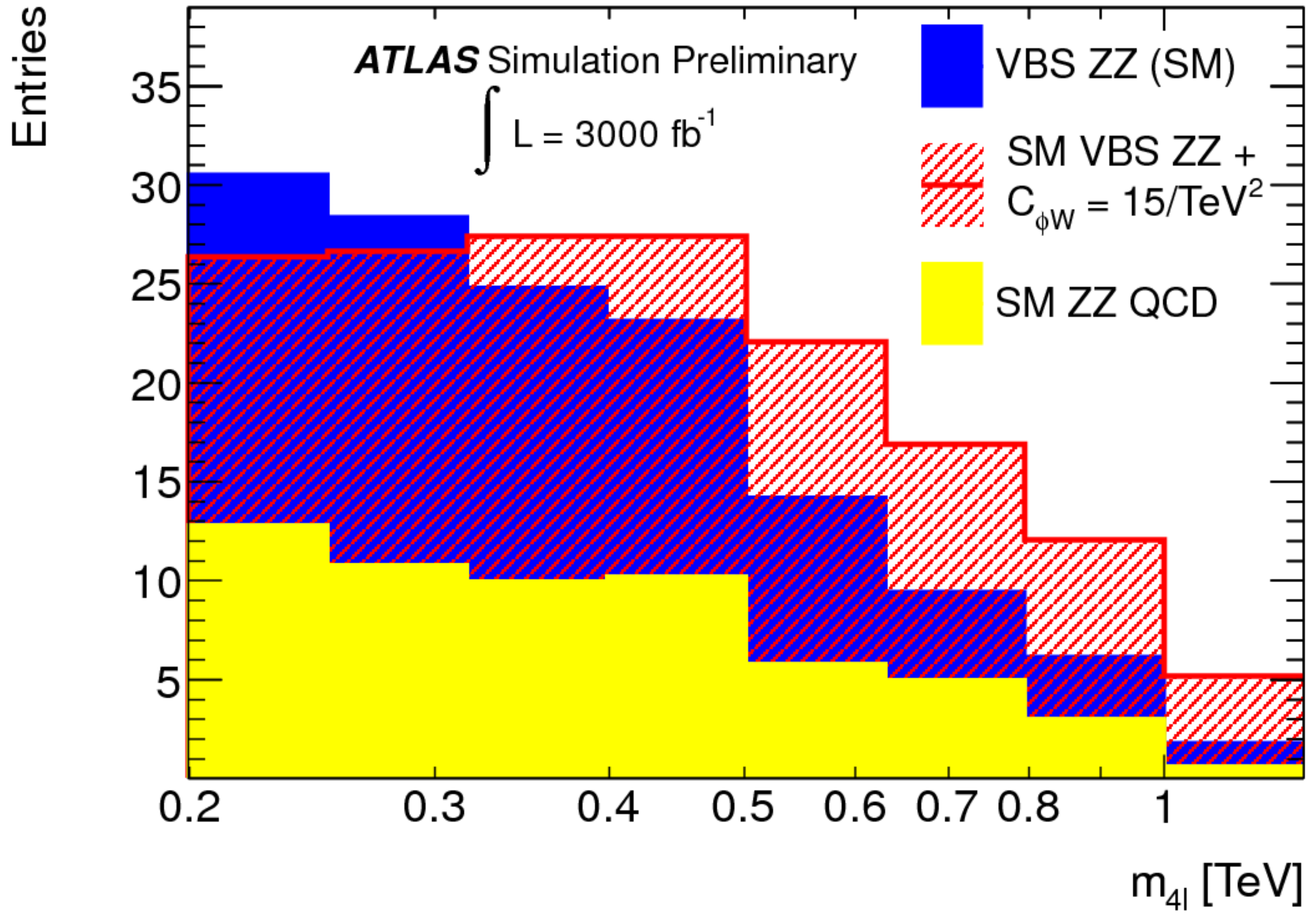
  - Example beyond the Standard Model theories predict up to ~5% deviation

Future physics: VV scattering

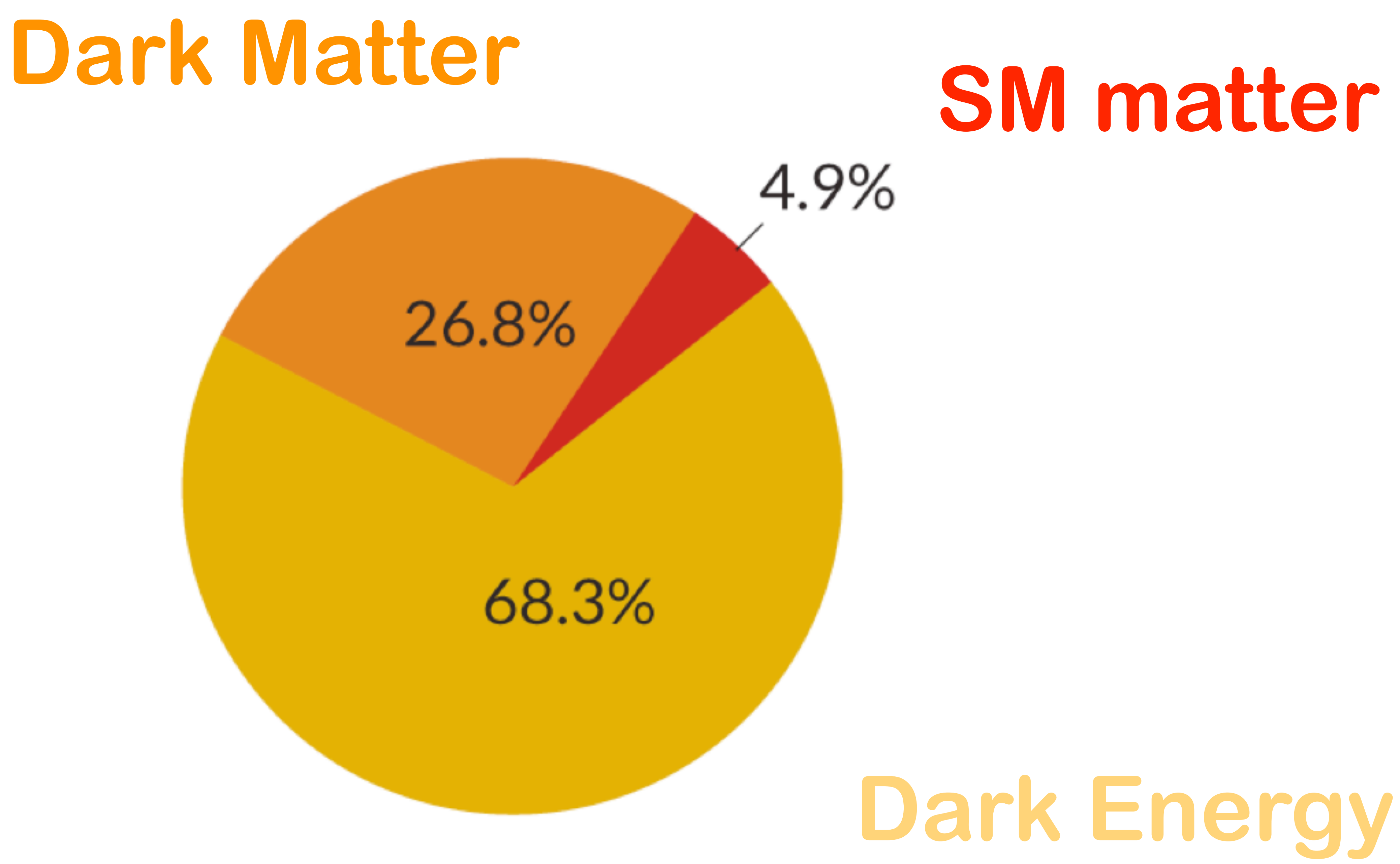
- Without the Higgs VV scattering would violate unitarity
  - Complementary probe of EWSB to direct Higgs measurements

  - 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)
    - …

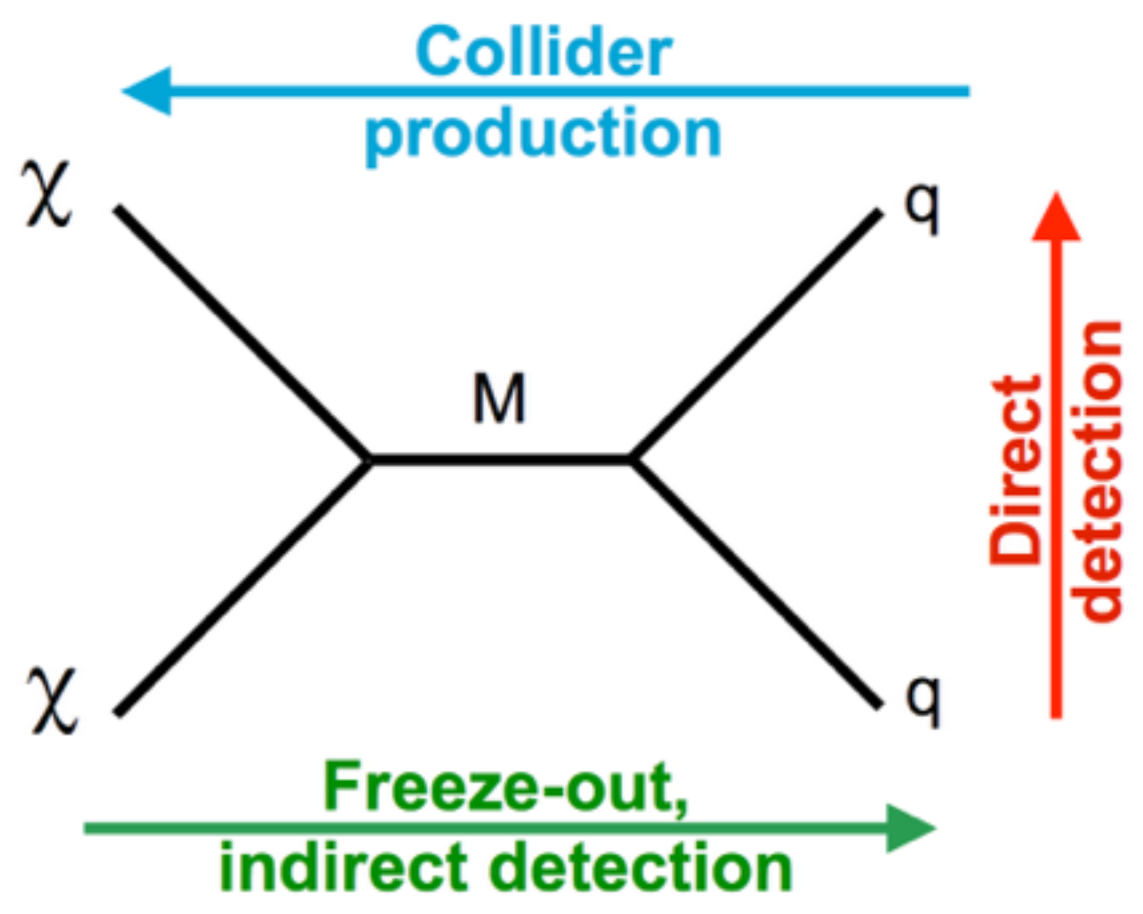


Future physics: Dark Matter



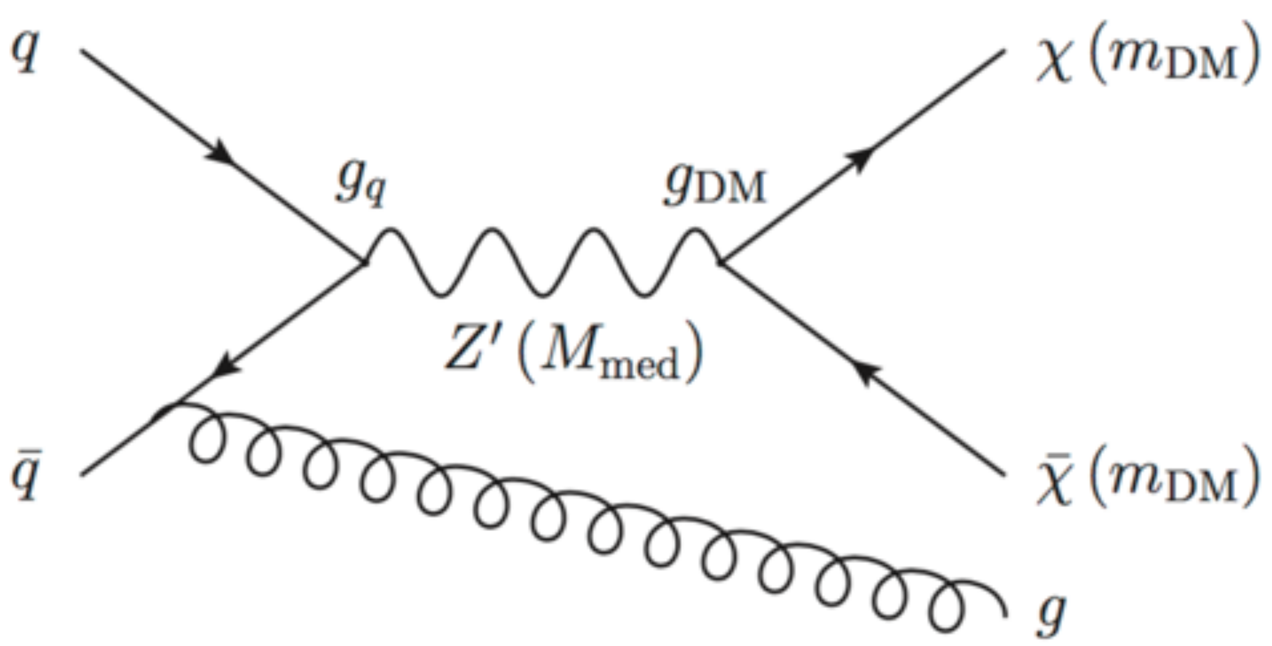
More than 95% of the matter-energy in the Universe is of unknown origin!

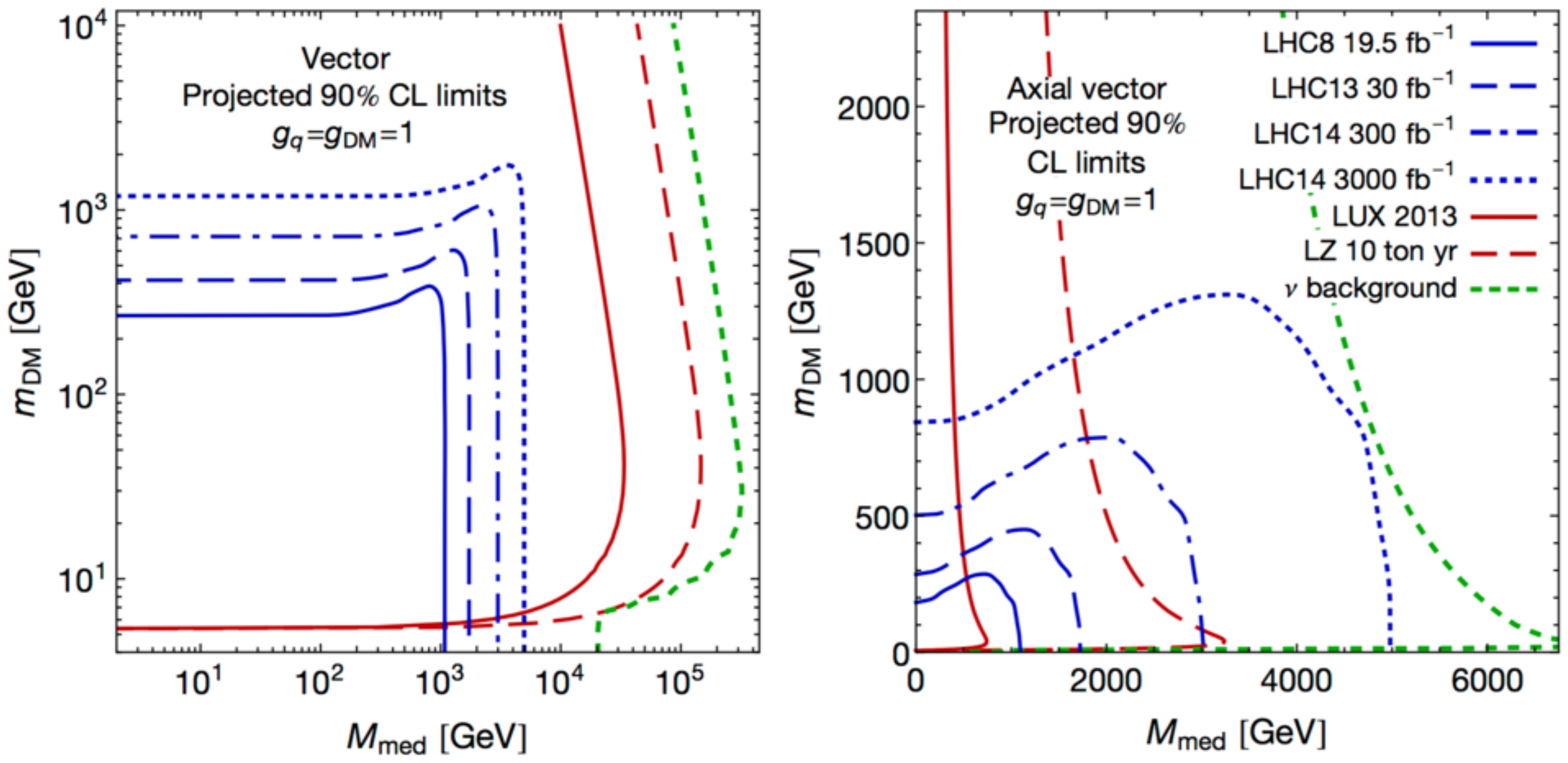
- What can the LHC contribute?
  - Complementary to direct detection experiments and observations



Future physics: Dark Matter

- How do you observe something invisible?
  - Monojet (and other) events





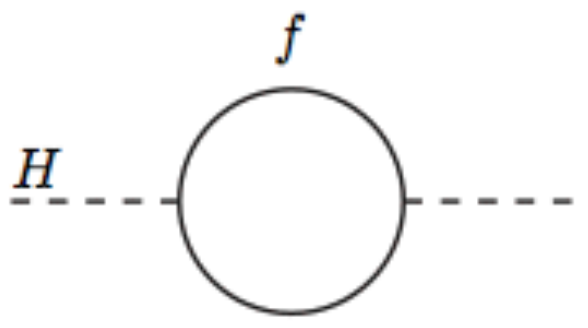
  - Large gains with 300 fb^{-1} to 3000 fb^{-1}

Buchmüller et al.
arXiv:1407.8257

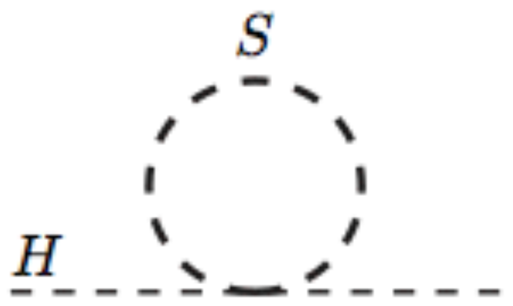
  - Requires excellent performance for jets and missing energy

Future physics: SUSY

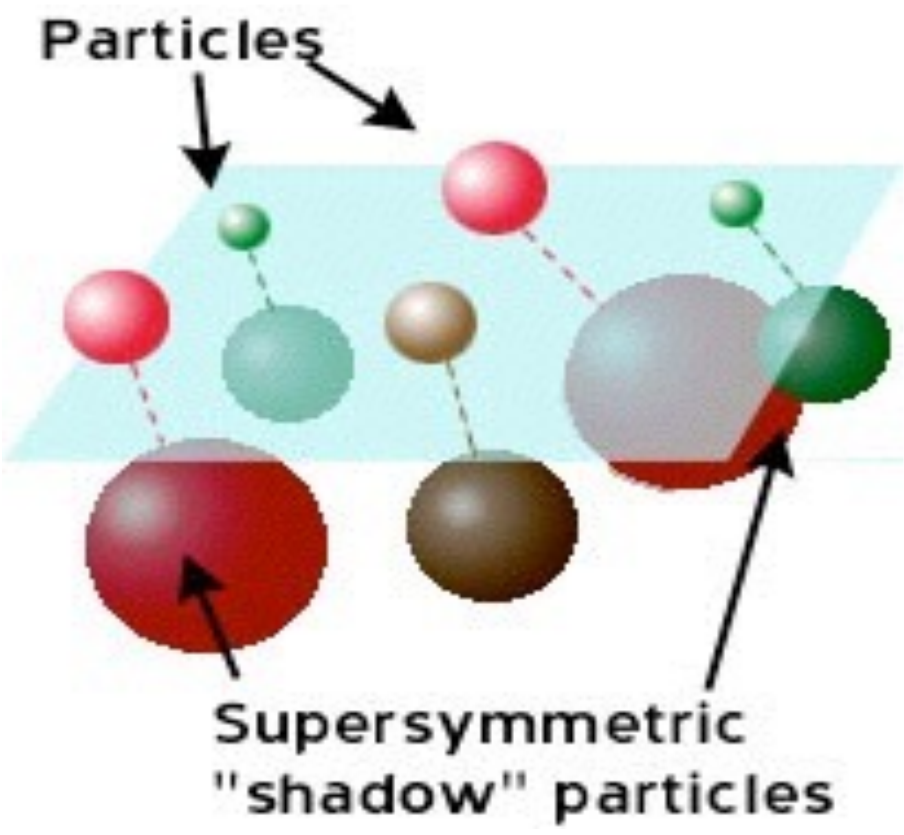
- Why we love supersymmetry…
  - Hierarchy problem



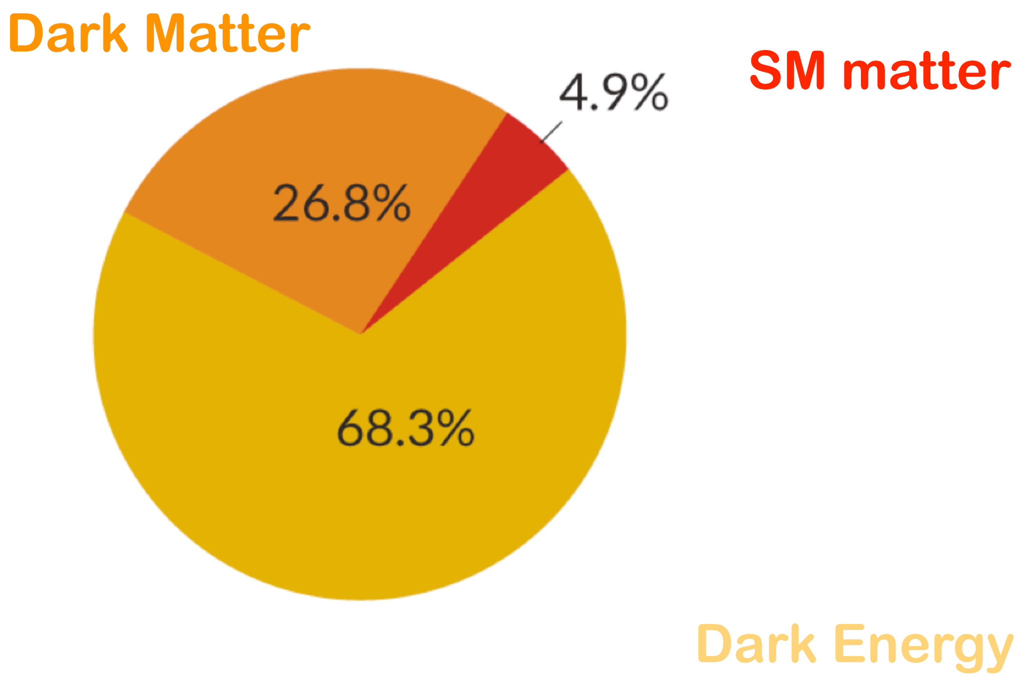
$$\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 ln \frac{\Lambda}{m_f}]$$



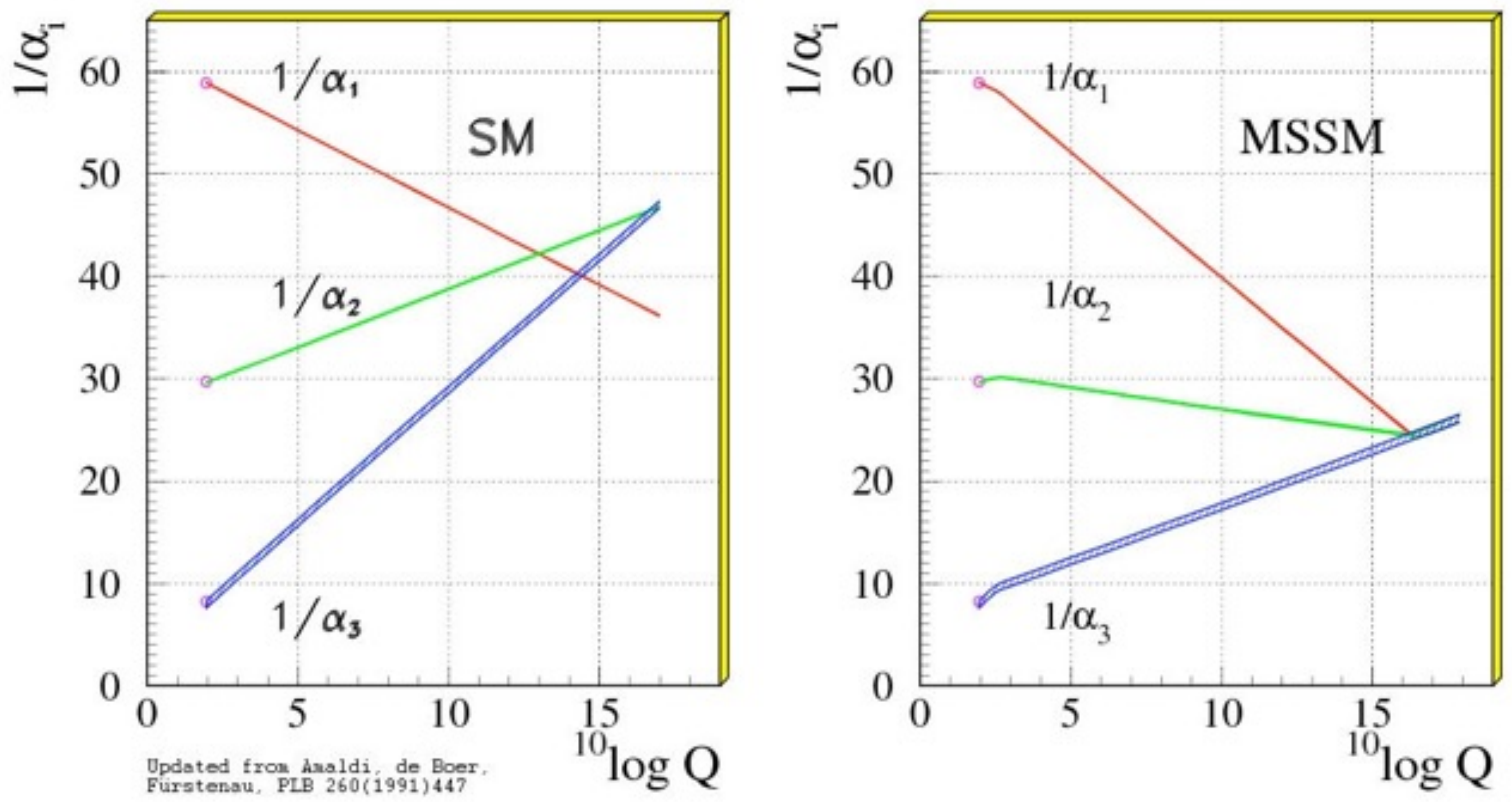
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 ln \frac{\Lambda}{m_S}]$$



  - Dark Matter candidate

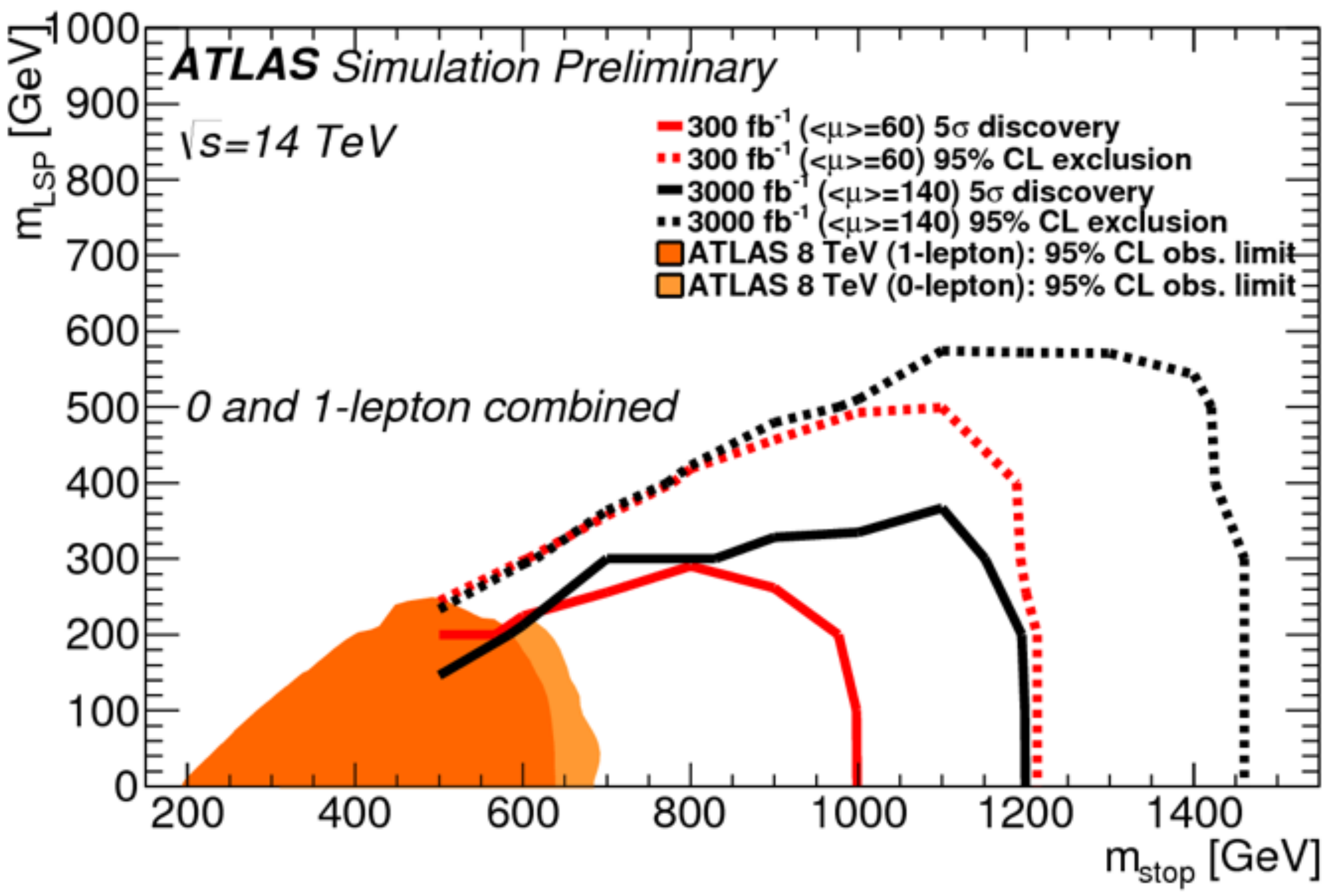


  - Unification

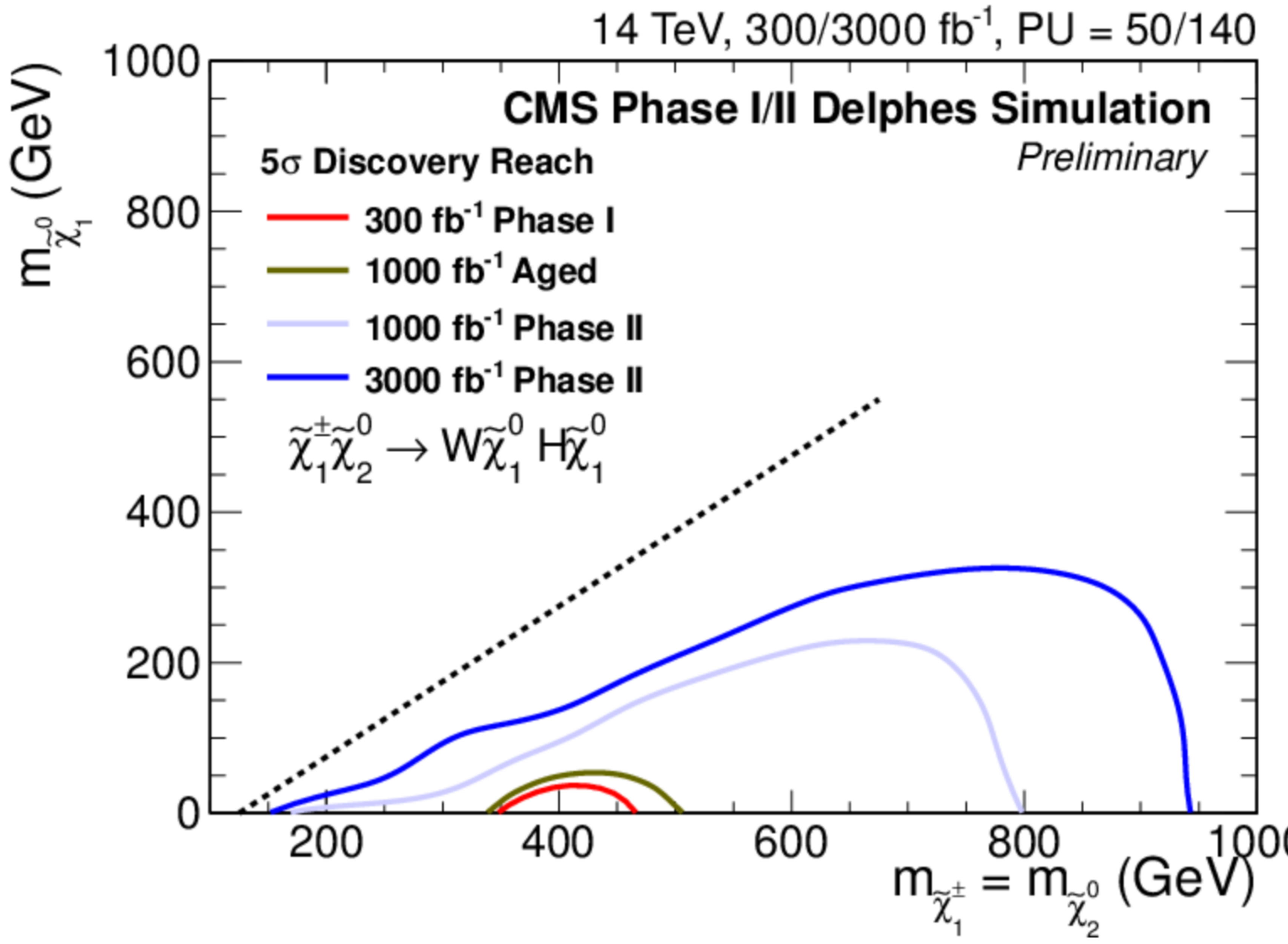


Future physics: SUSY

- Natural SUSY
  - $M_{stop} < \sim 1$ 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



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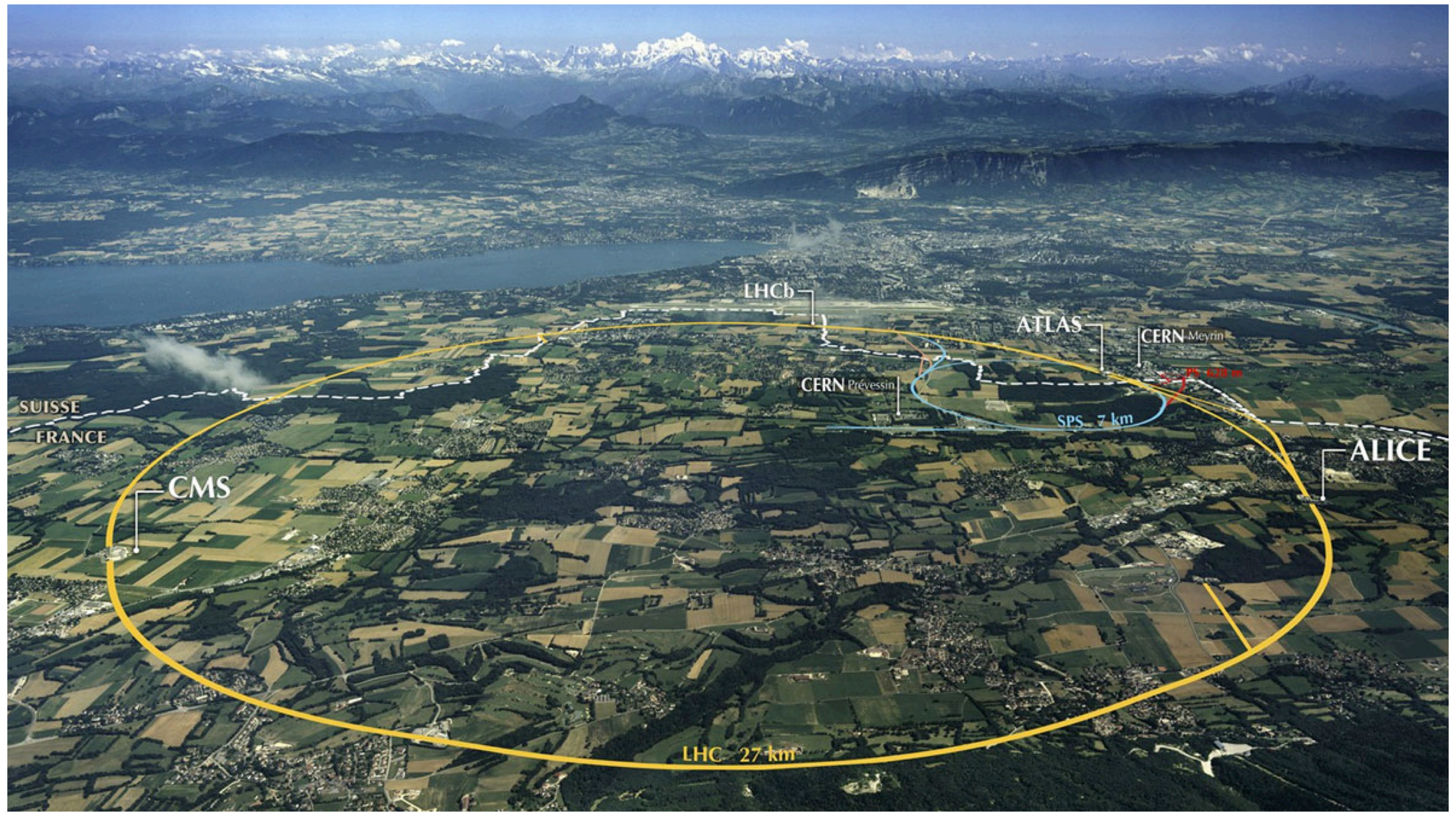
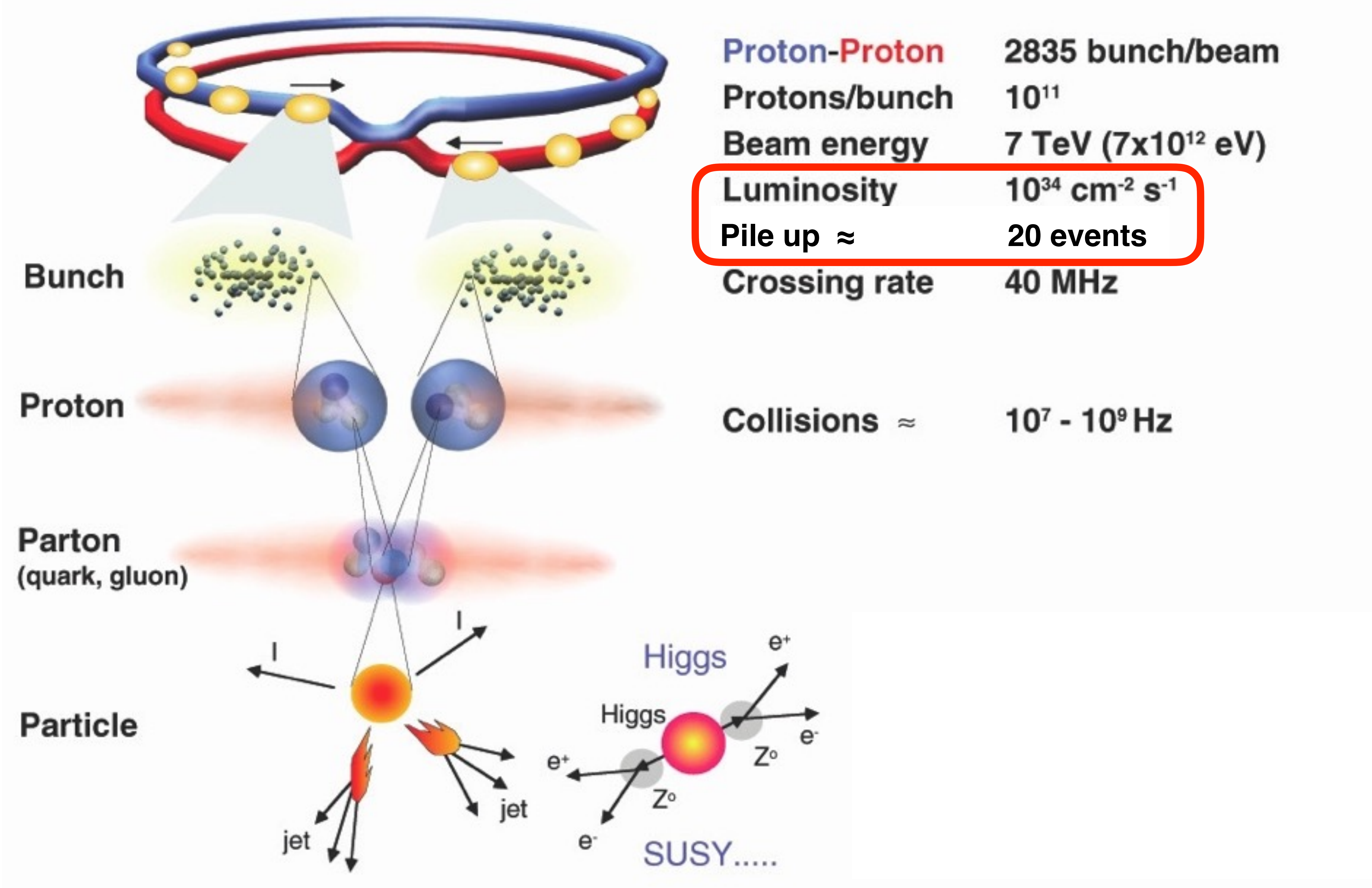
Physics summary

- 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

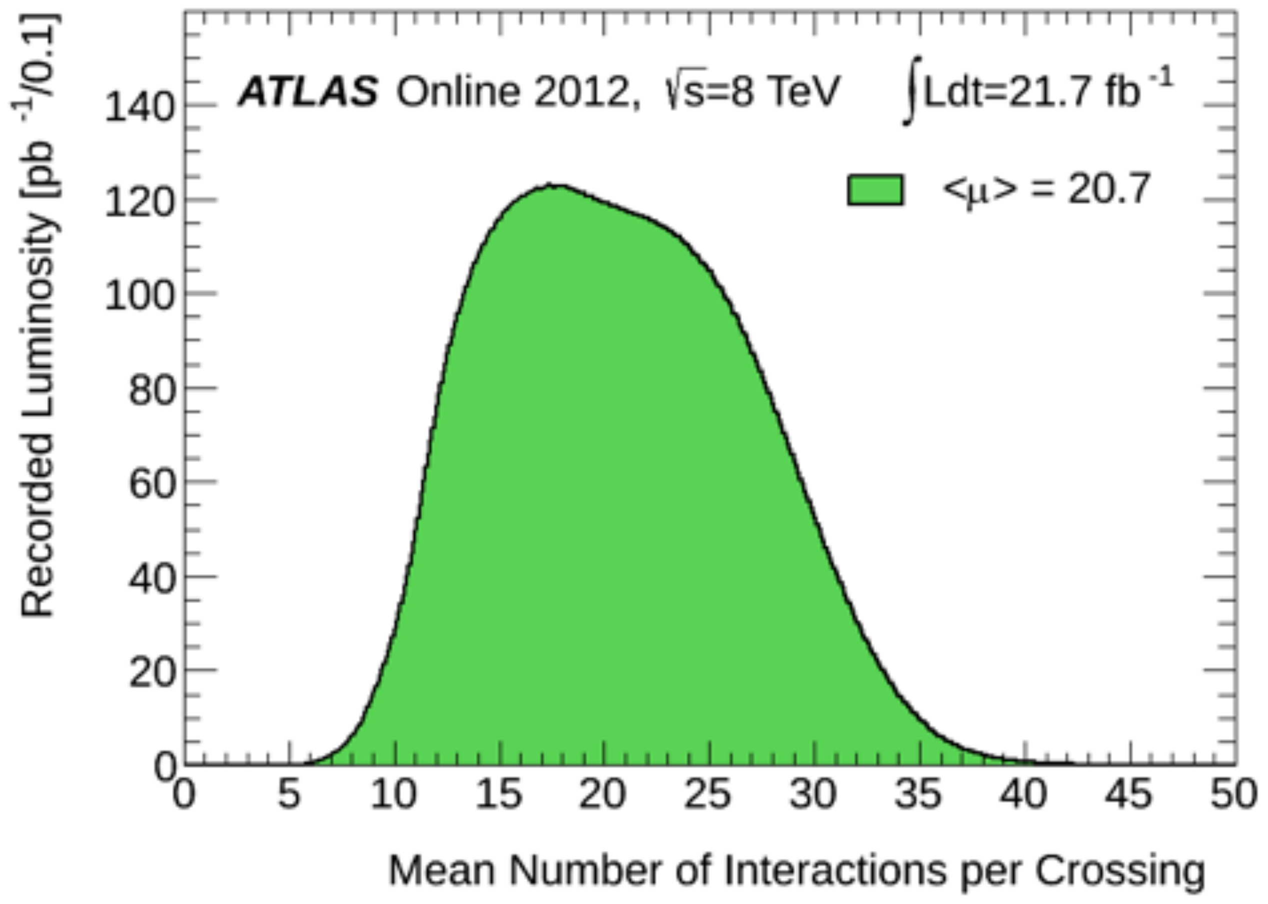
LHC: Introduction



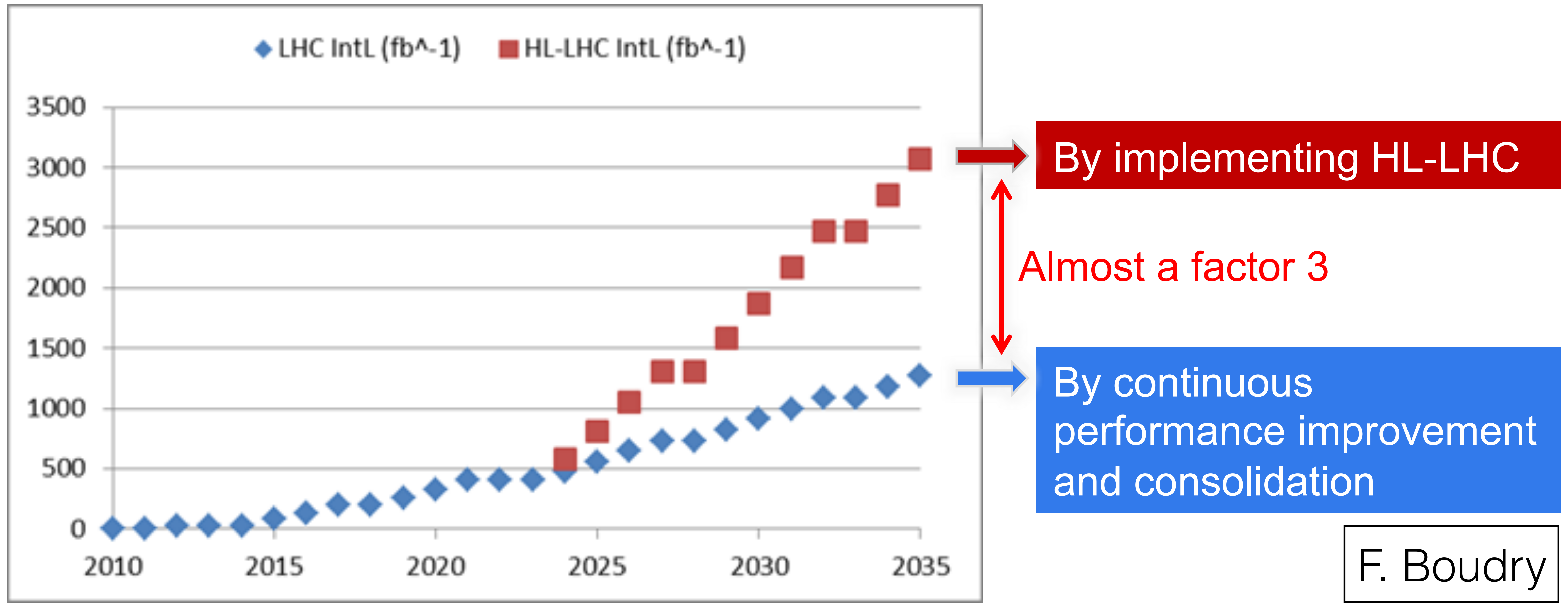


LHC: Running conditions

- Close to design luminosity reached already
  - 7×10^{33} cm^{-2} s^{-1} *vs* 1×10^{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?



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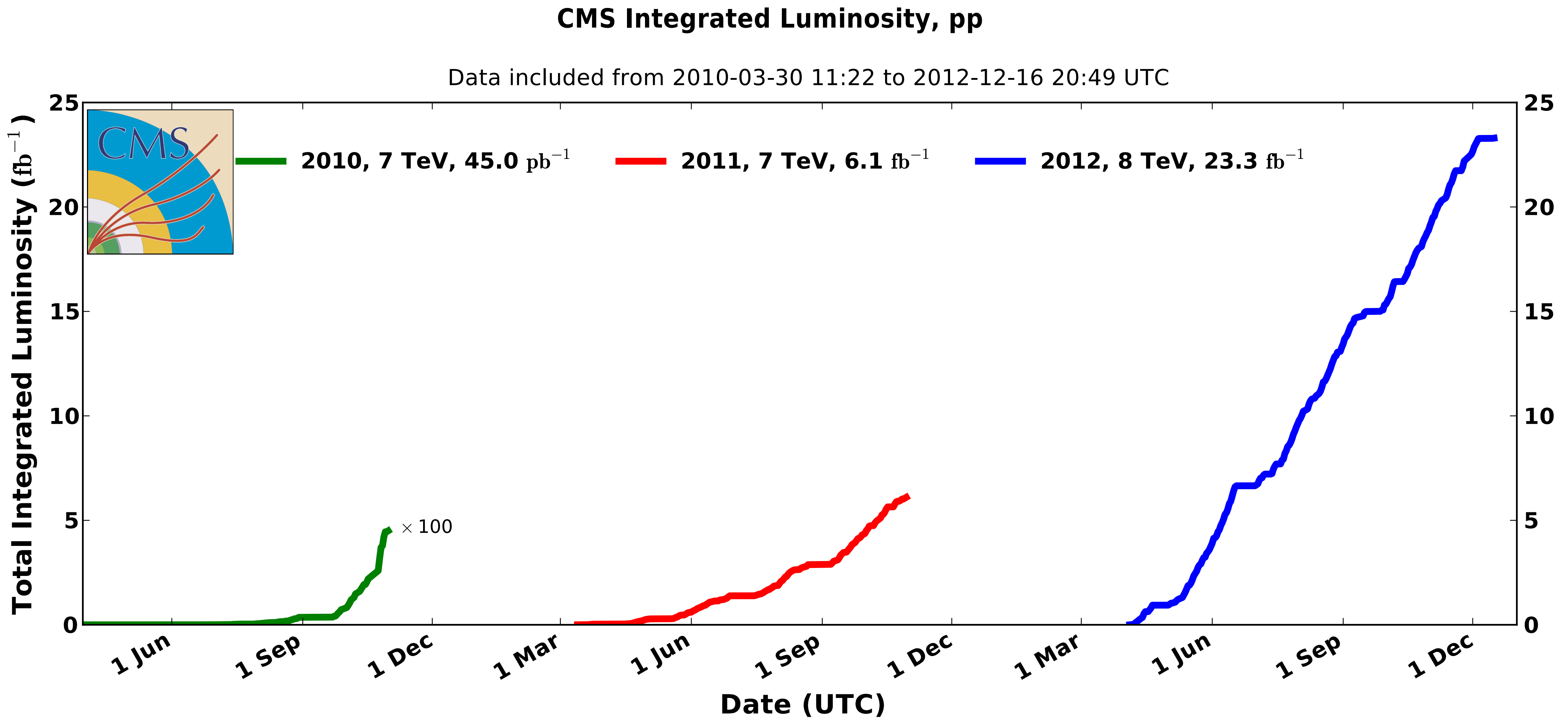
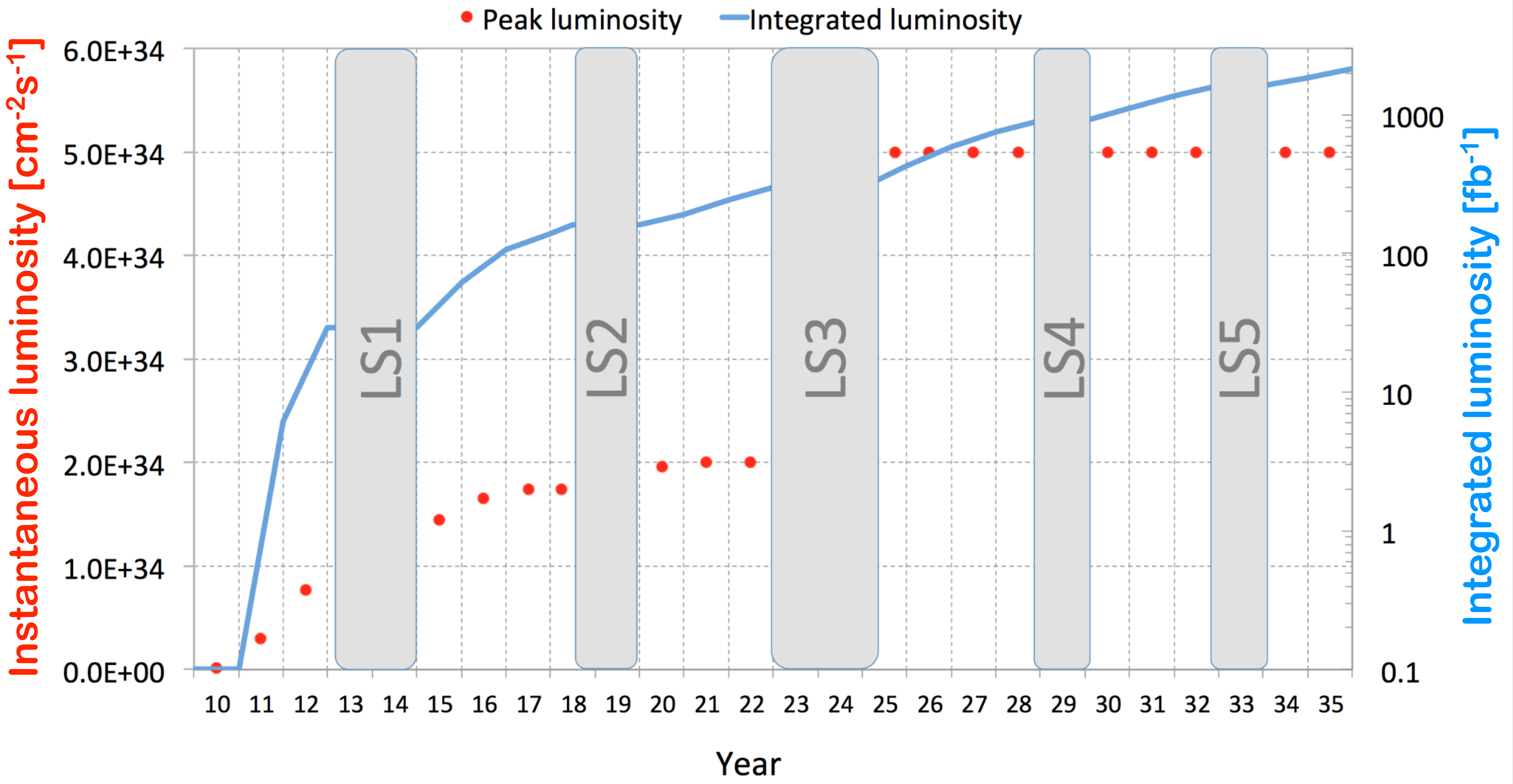
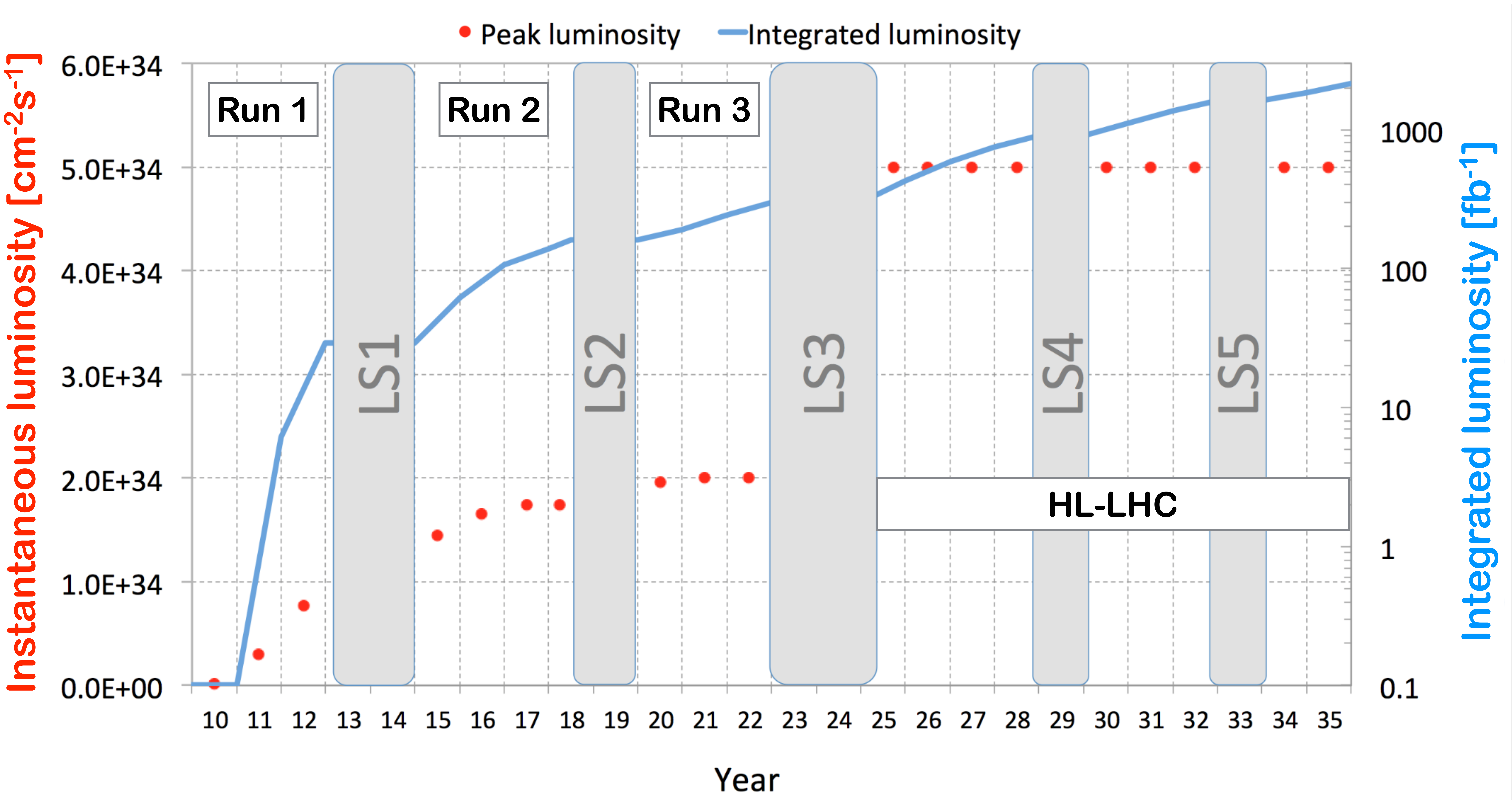


LHC: Future plans



LHC: Future plans



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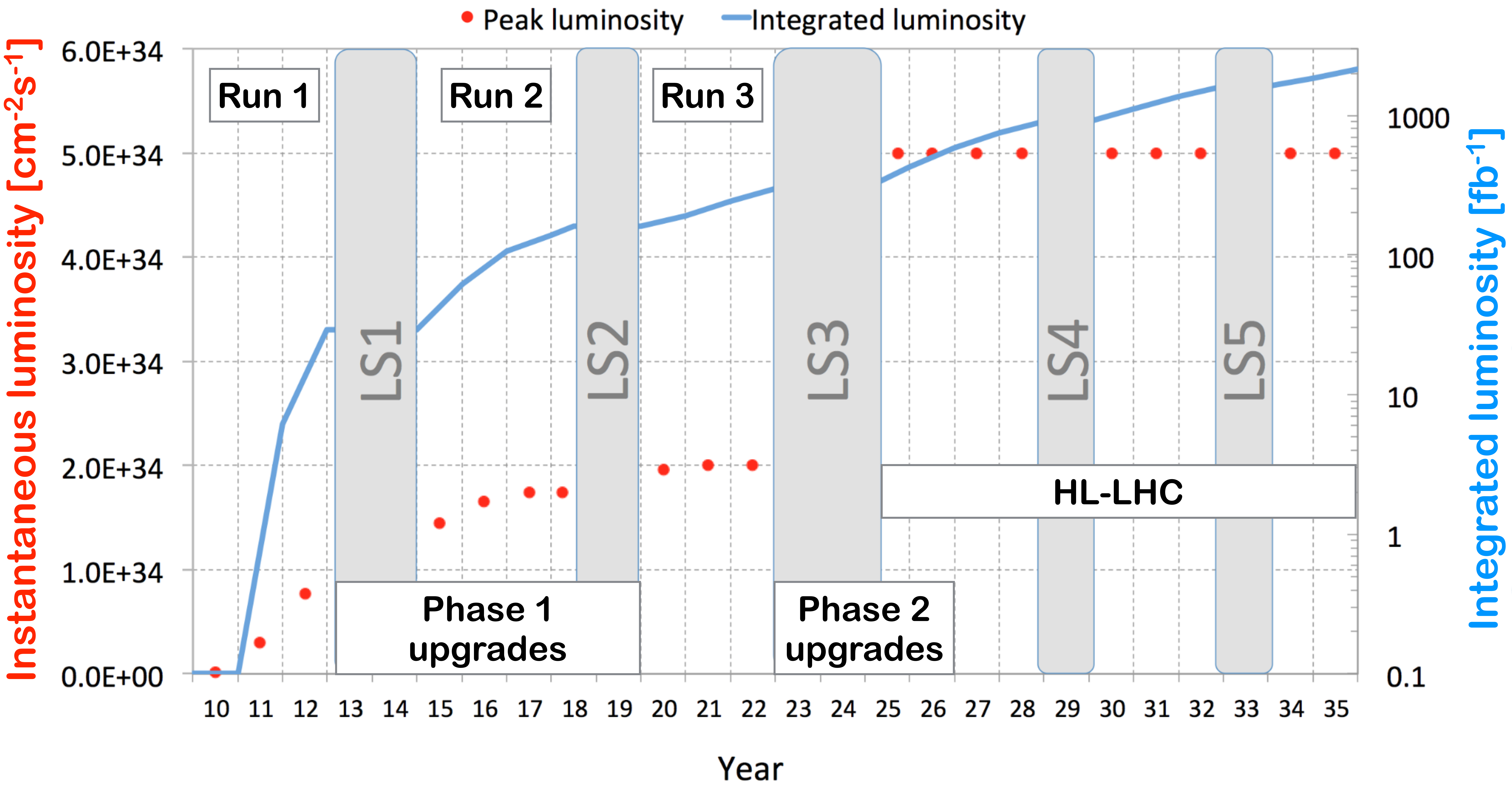

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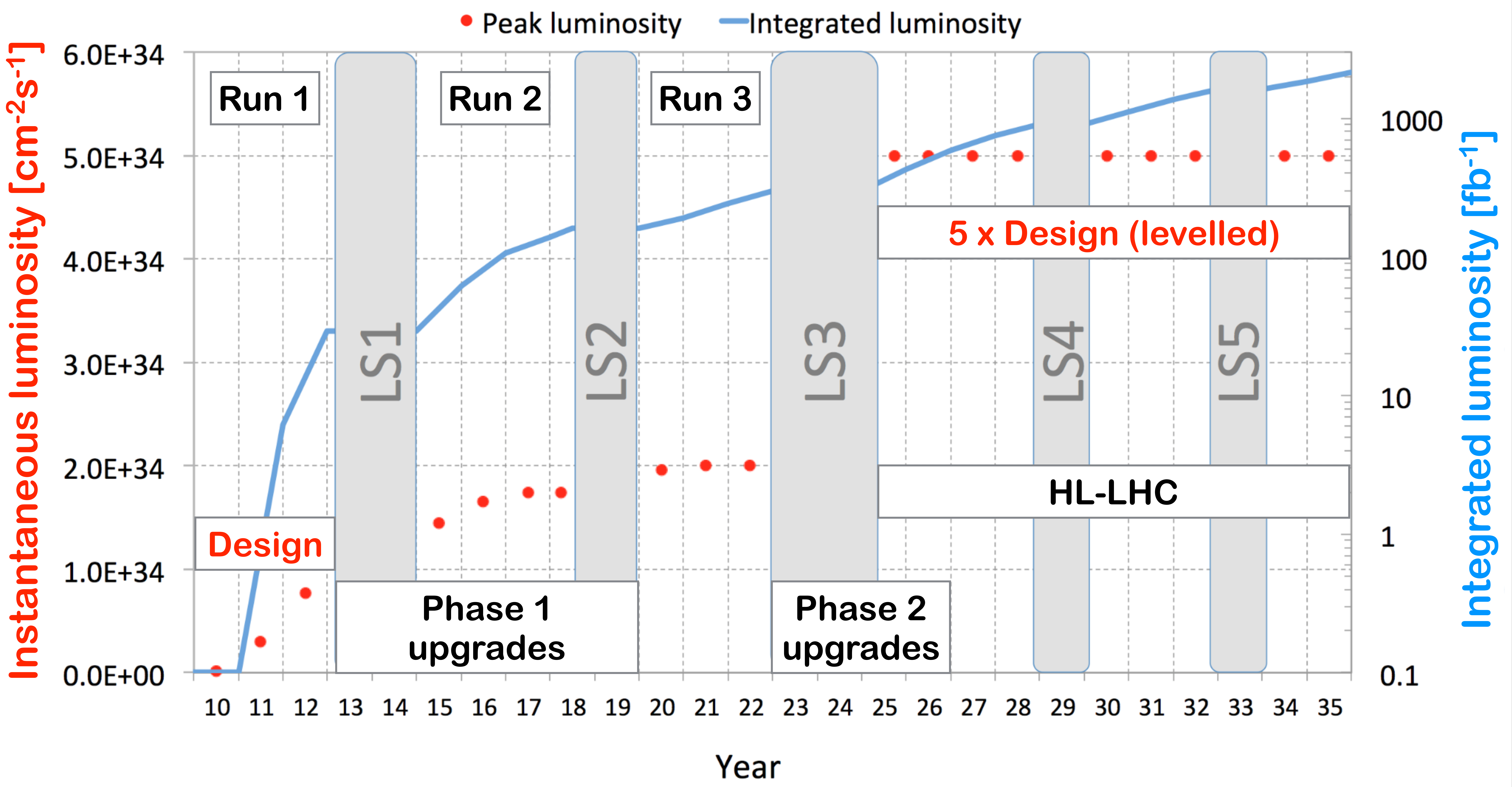
LHC: Future plans



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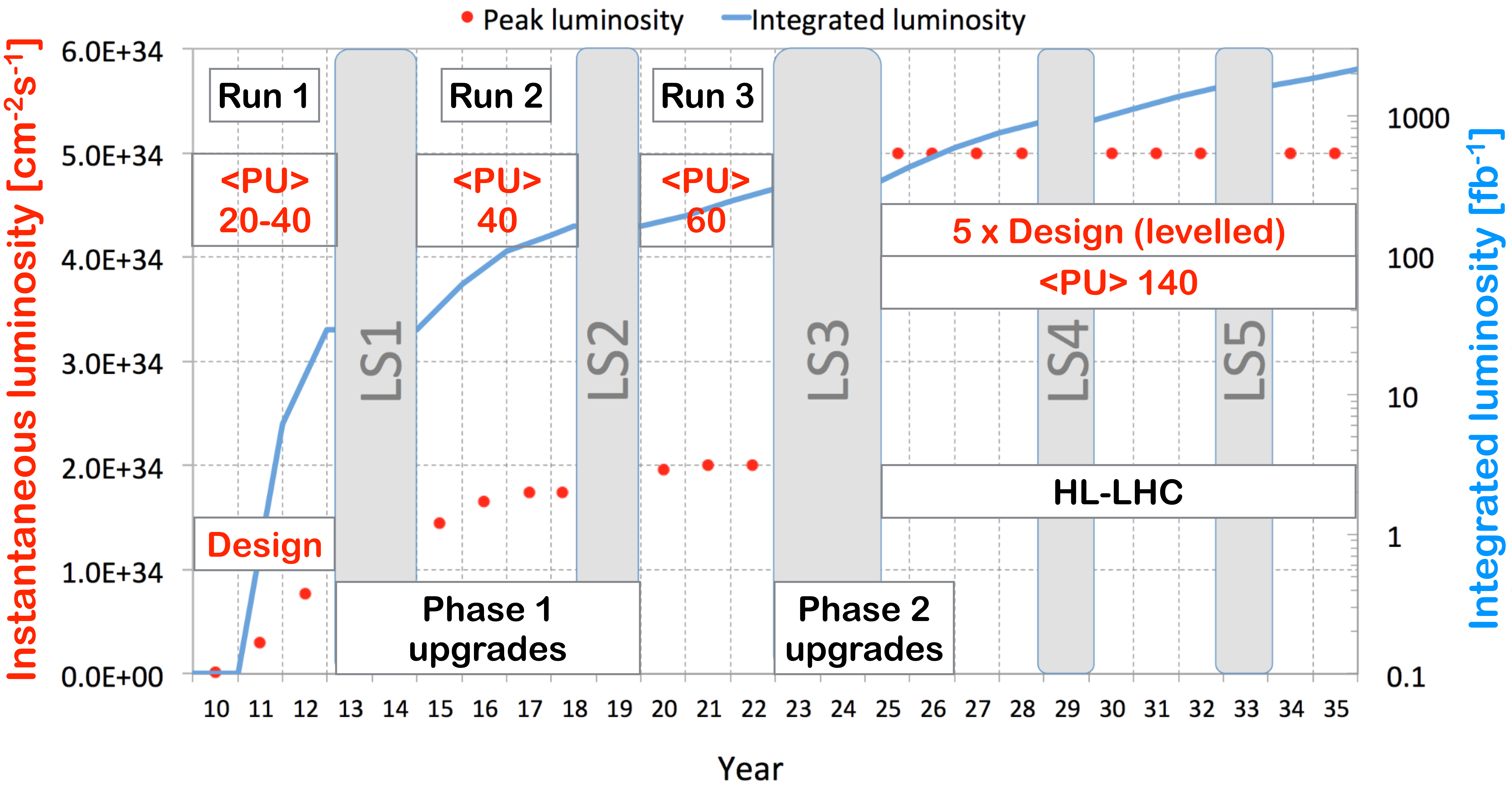
LHC: Future plans



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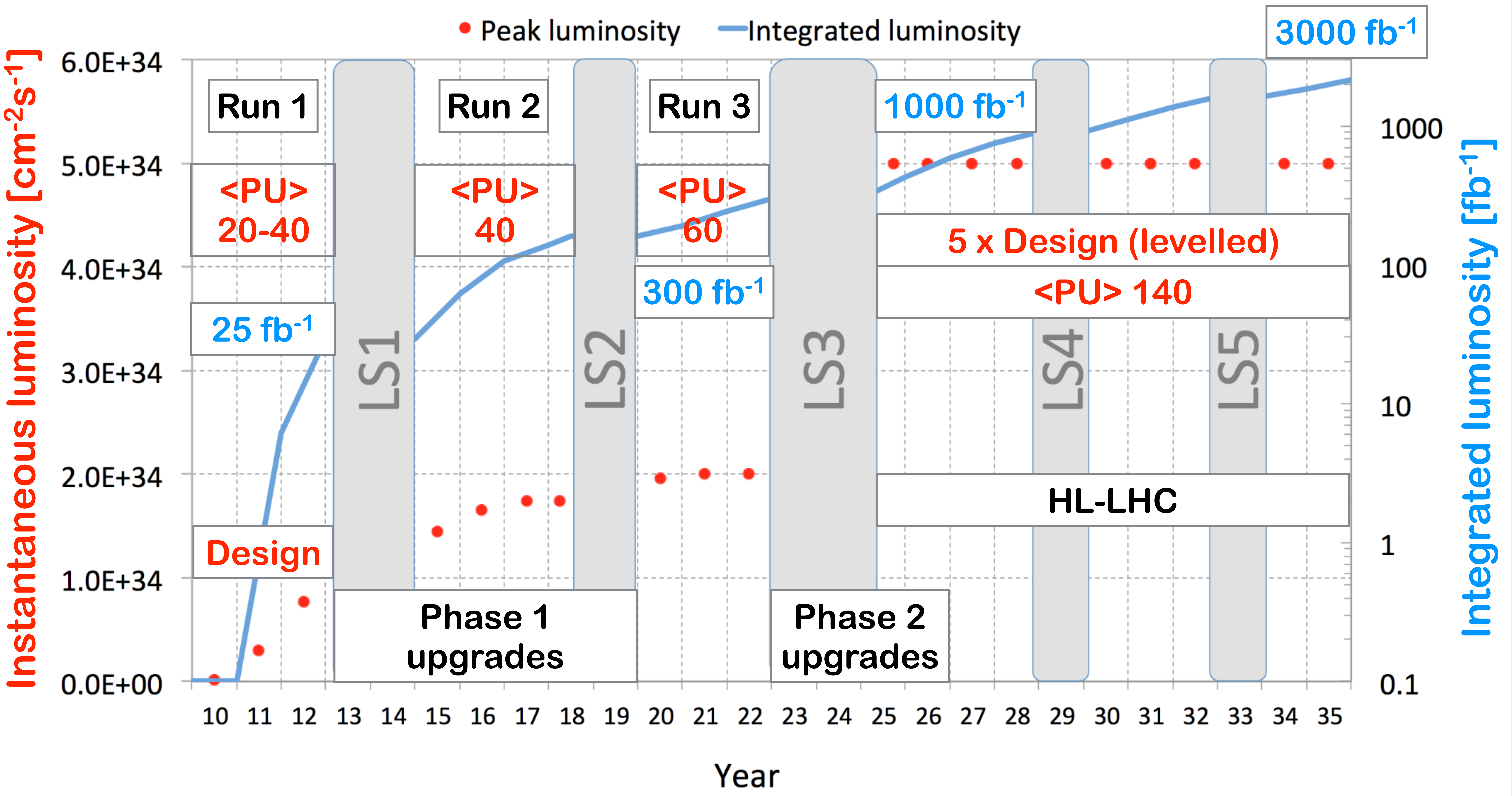
LHC: Future plans



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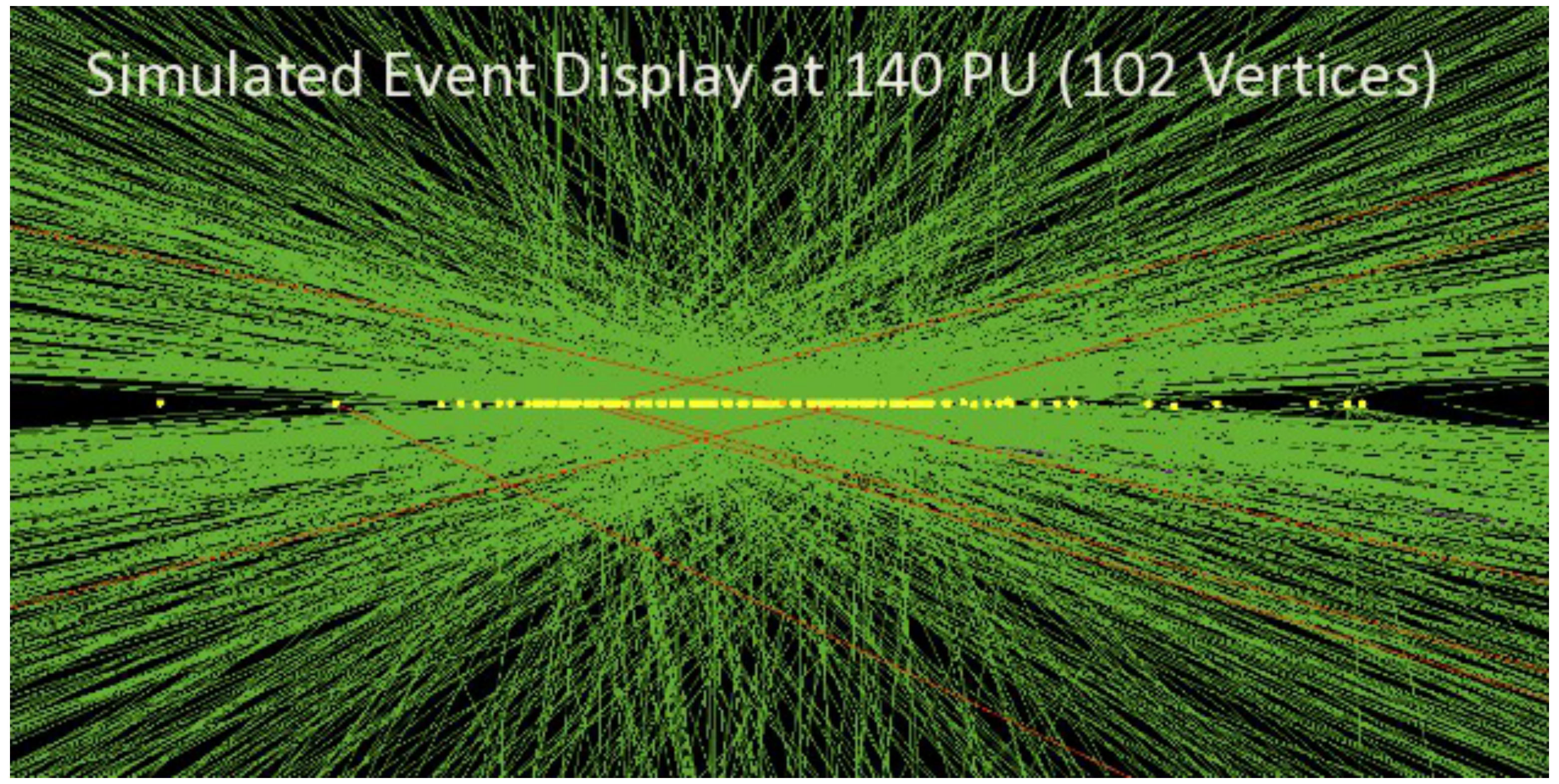
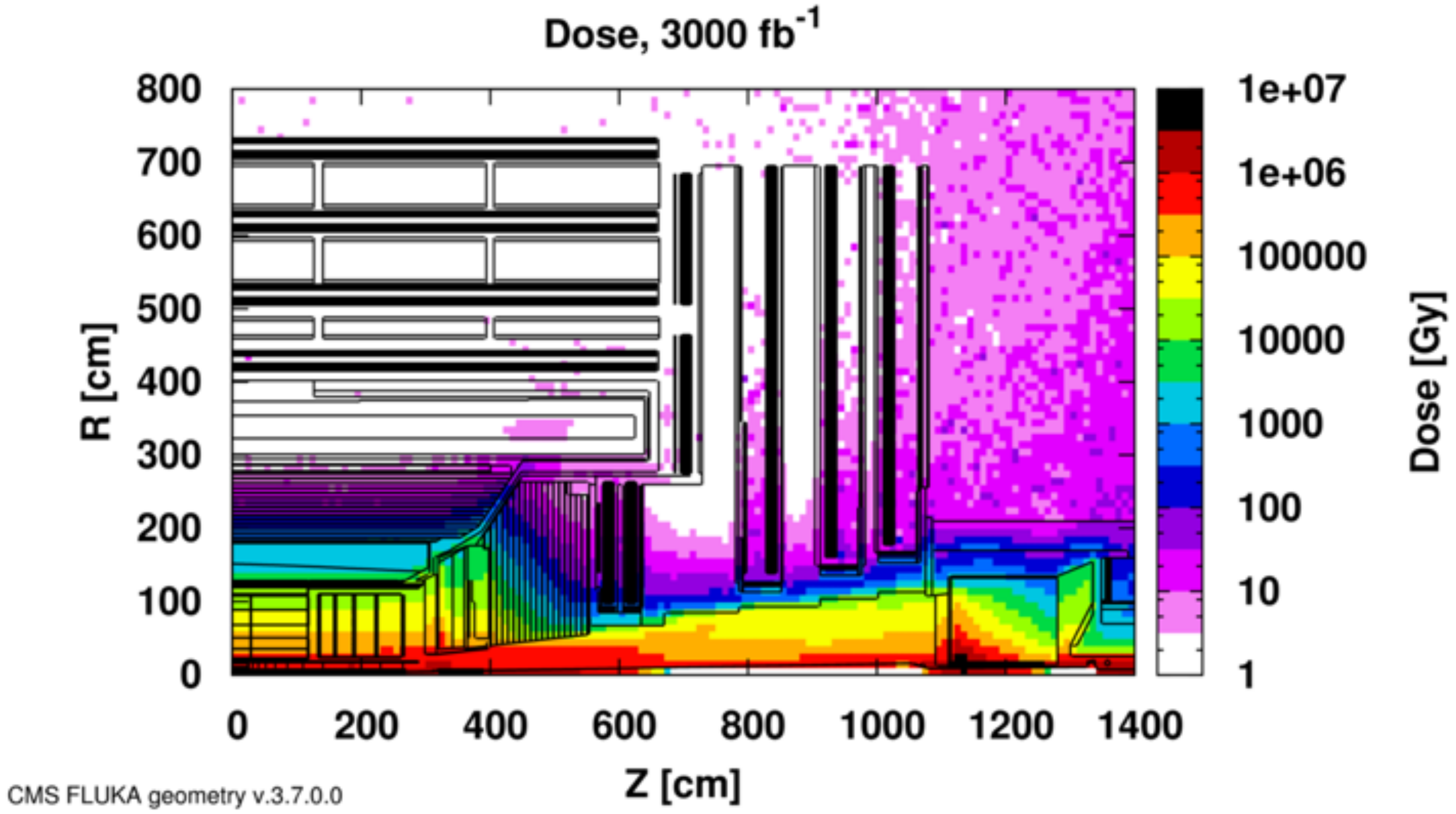
Detector upgrades: challenges

- 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	$W \rightarrow l\nu$ rate
Run1	80 Hz
Run 2	200 Hz
Run 3	400-600
HL-LHC	1KHz

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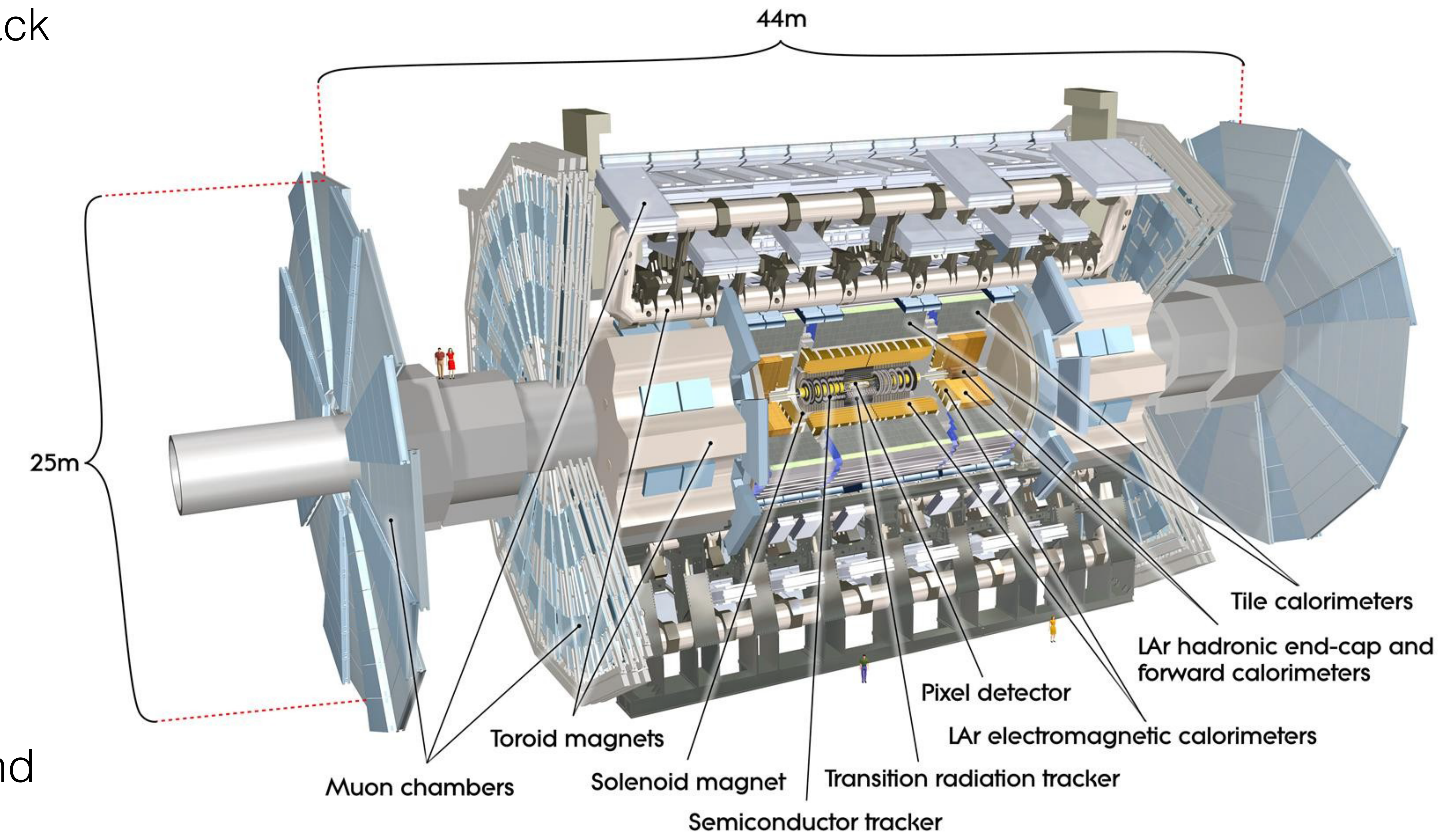
ATLAS: Phase 1 upgrade

- 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



ATLAS: Phase 1 upgrade

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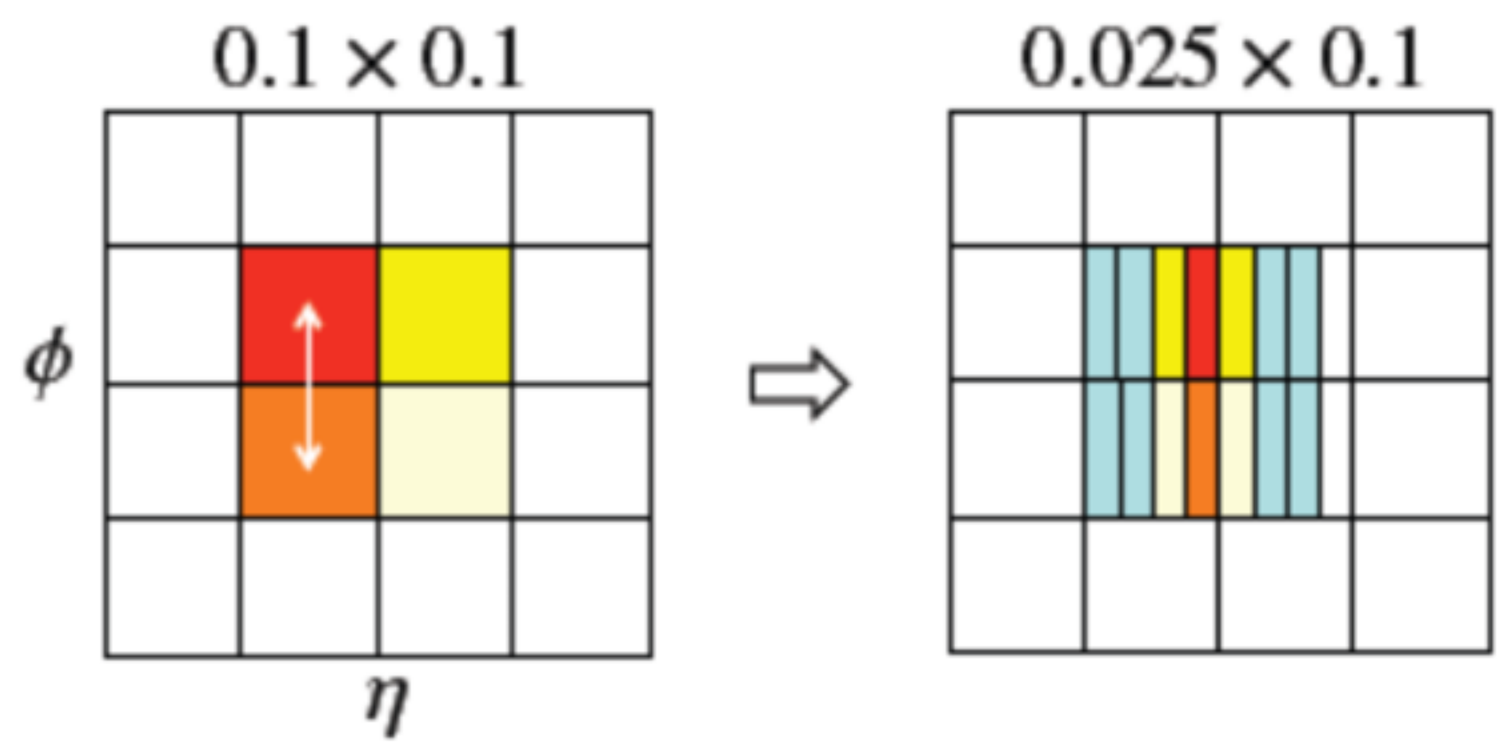
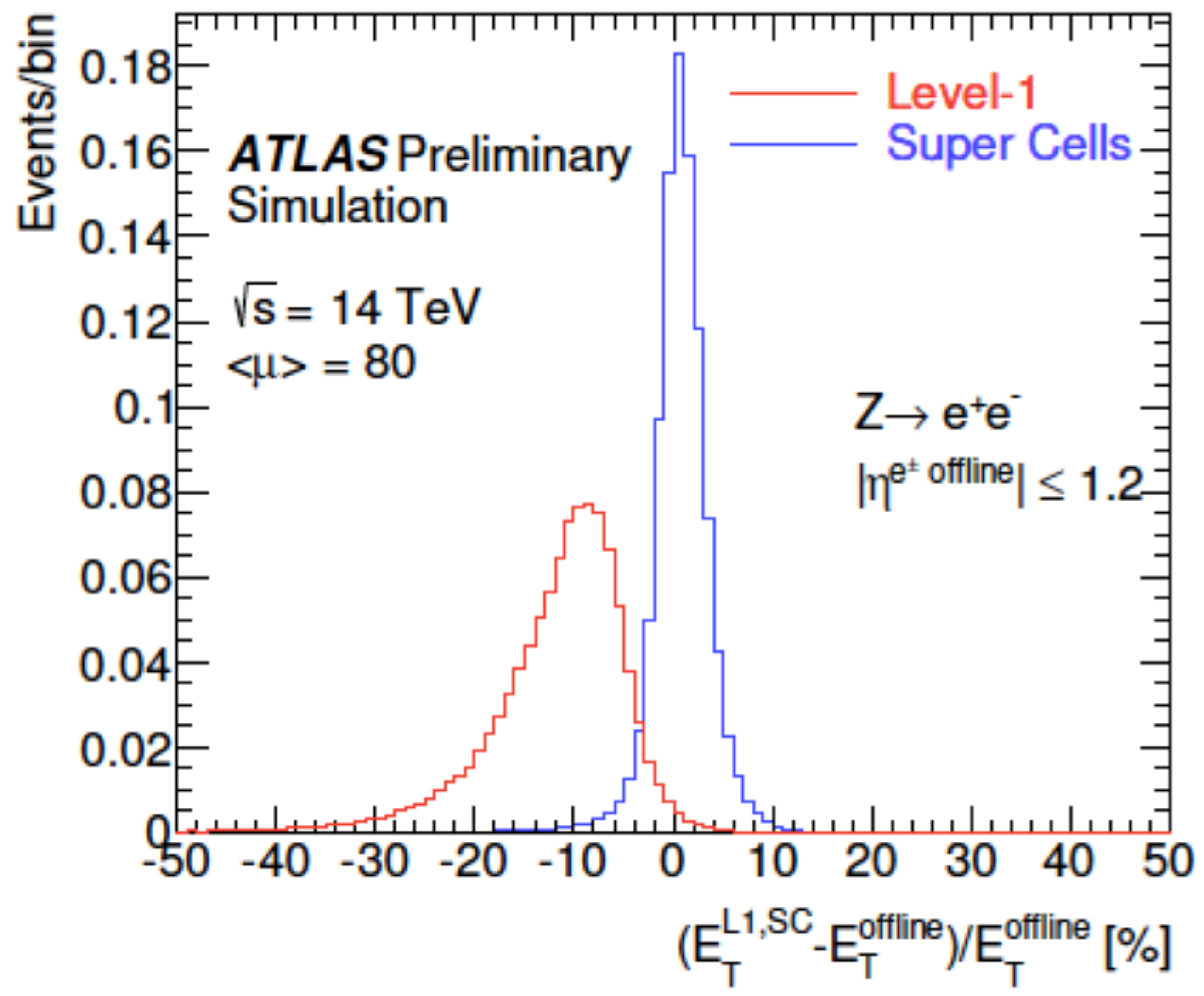
- Level-1 Calorimeter Trigger
  - Upgrade calorimeter electronics will provide finer granularity data to Level-1 trigger in η and depth information
  - Preserve thresholds for single electron trigger at p_T ~ 25 GeV for LHC luminosity increasing to ~2-3x nominal
  - UK developing electron feature extractor and associated readout (ATCA and high speed optical links)





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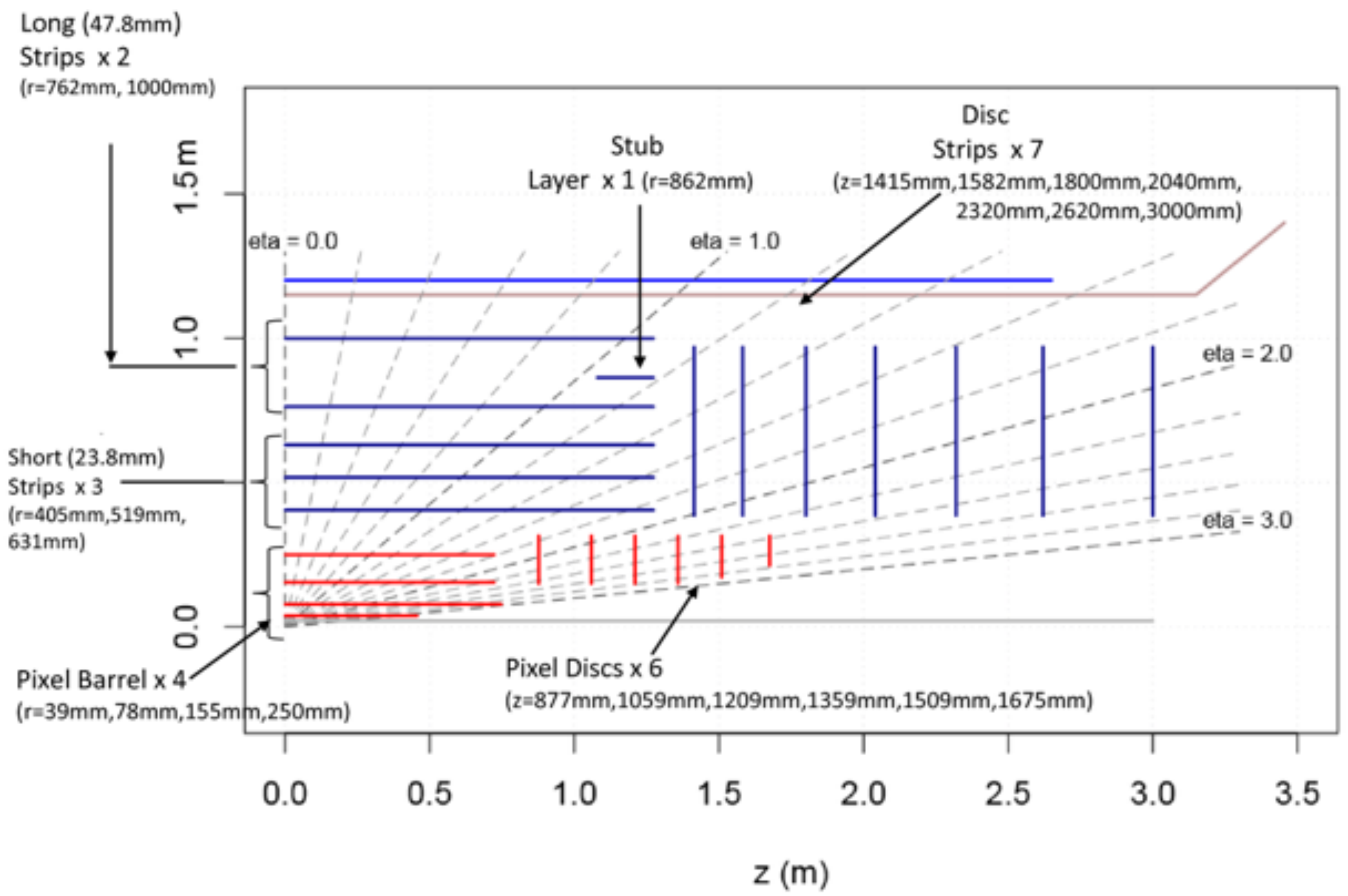
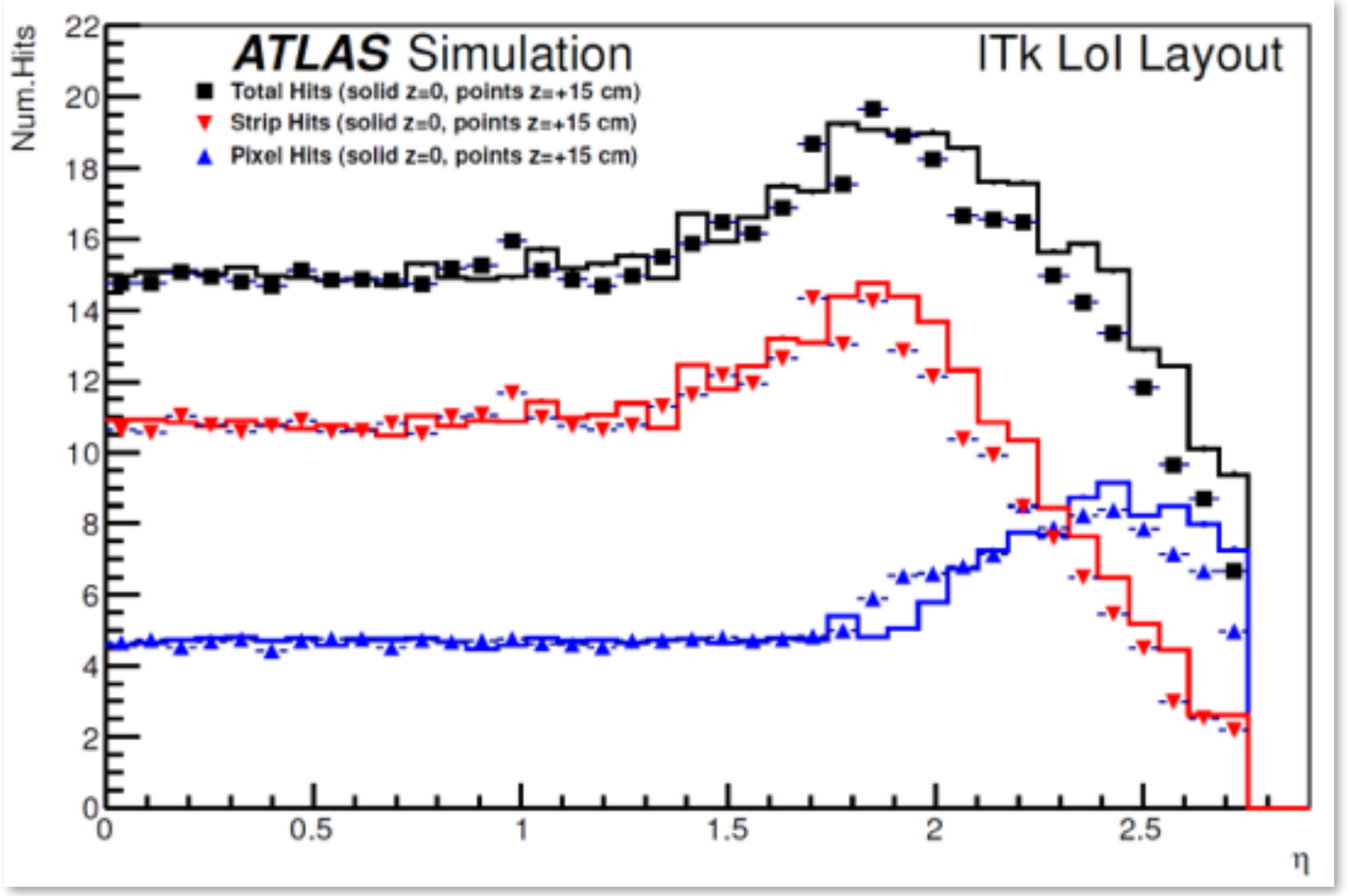
ATLAS: Phase 2 upgrade

- 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 m²)
    - Strip system 5 barrel layers plus 7 disks (~190 m²)
    - Robust tracking with 14 layers →
  - Minimise material budget within tracking acceptance

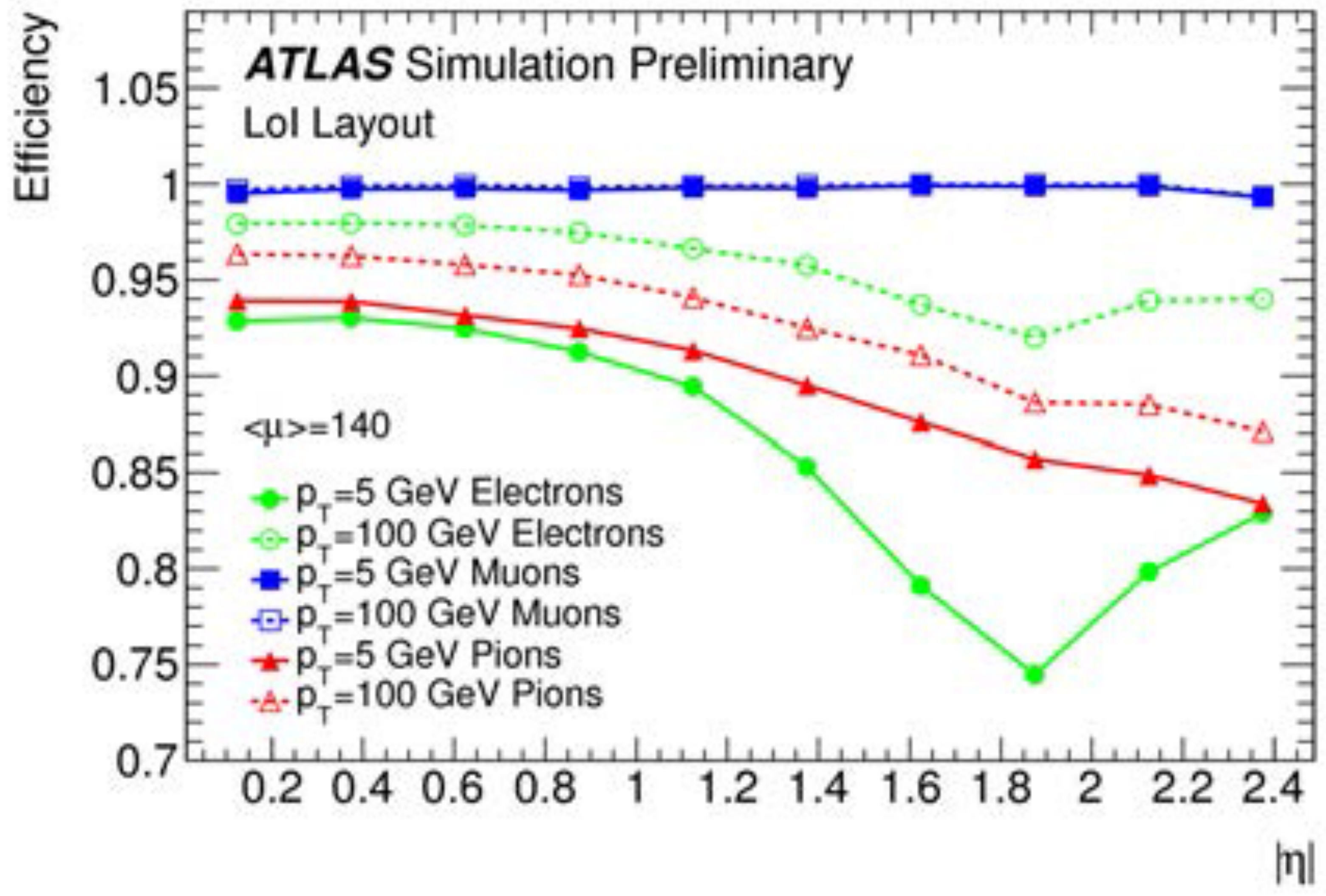




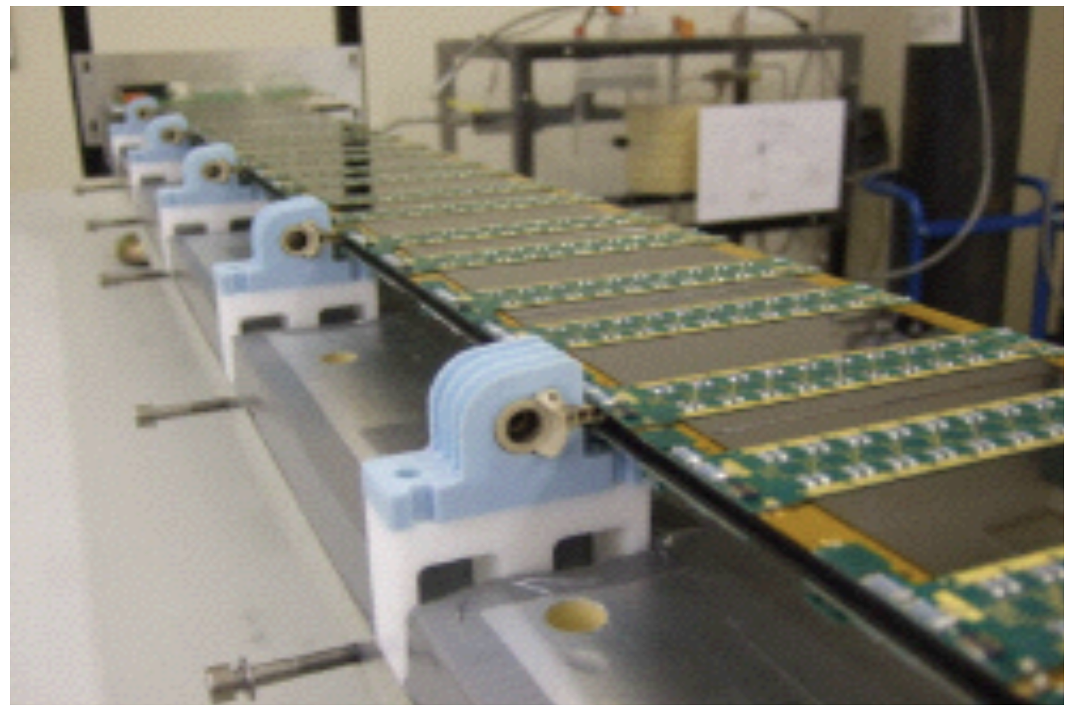
Other layouts with extended η under study

ATLAS: Phase 2 upgrade

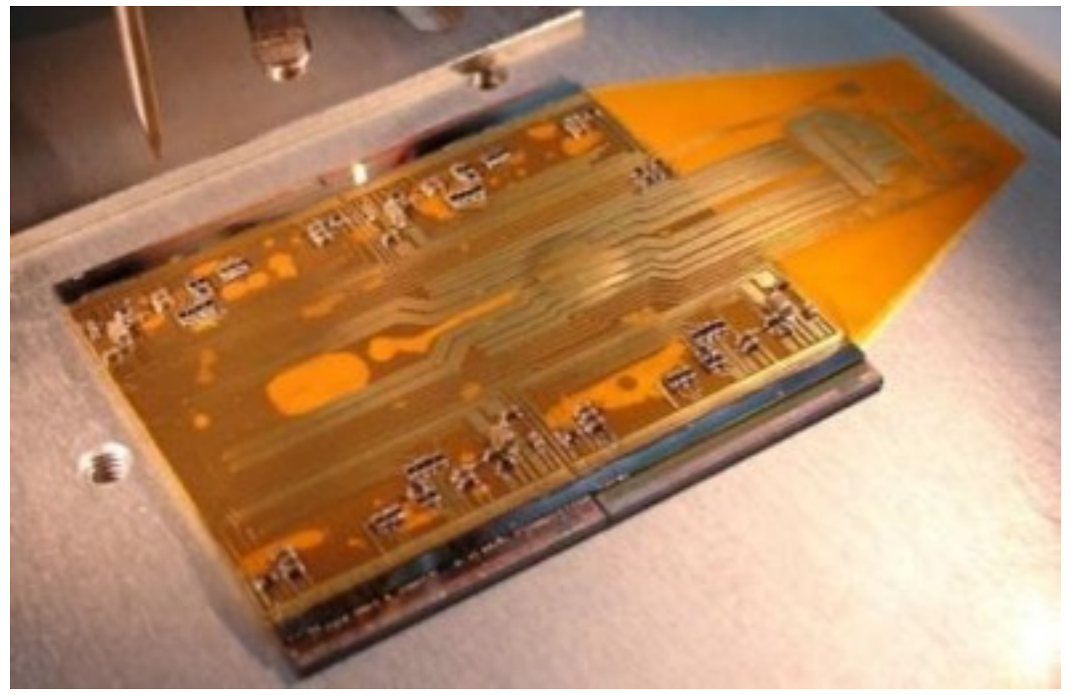
- Sufficient hits on track to maintain high efficiency and combat combinatorics at high pile up
  - Excellent tracking efficiency →
- UK interest in large contribution to new tracker
- Extensive R&D underway for several years



Microstrip Stave Prototype



Quad Pixel Module Prototype



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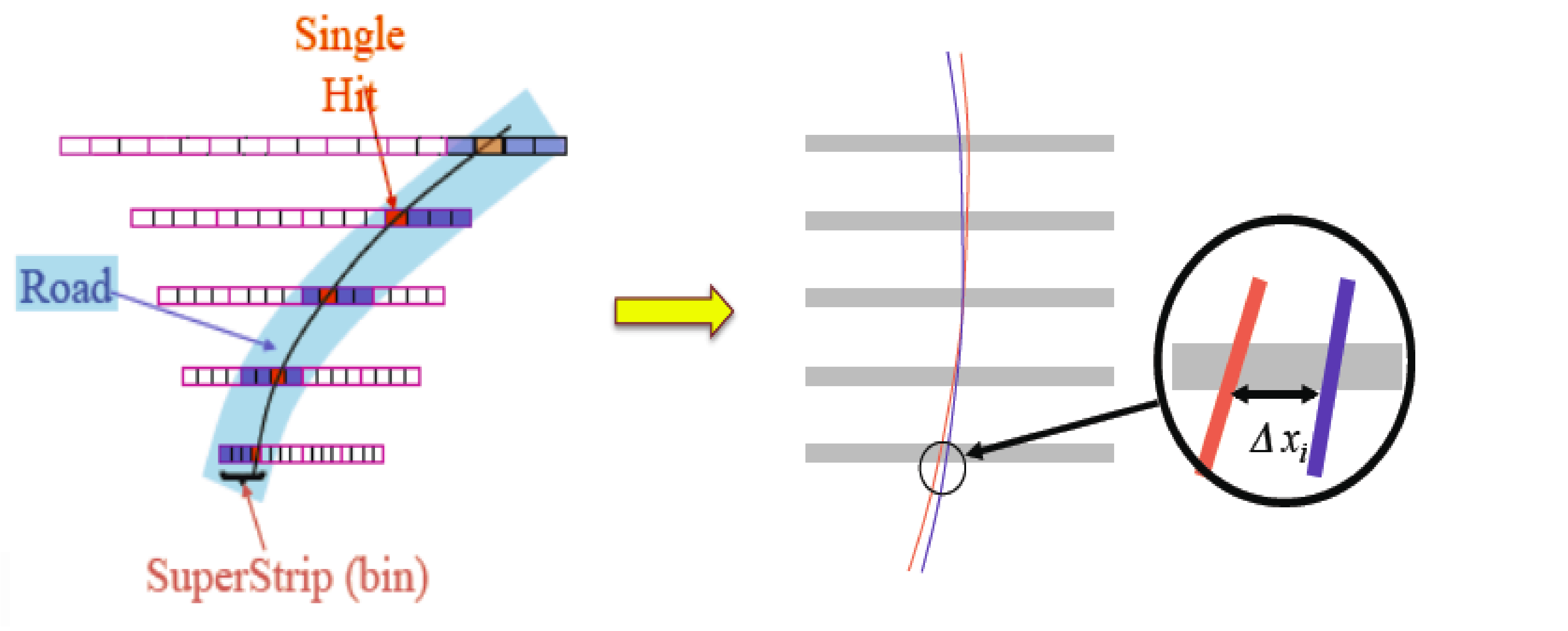
ATLAS: Phase 2 upgrade

- 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

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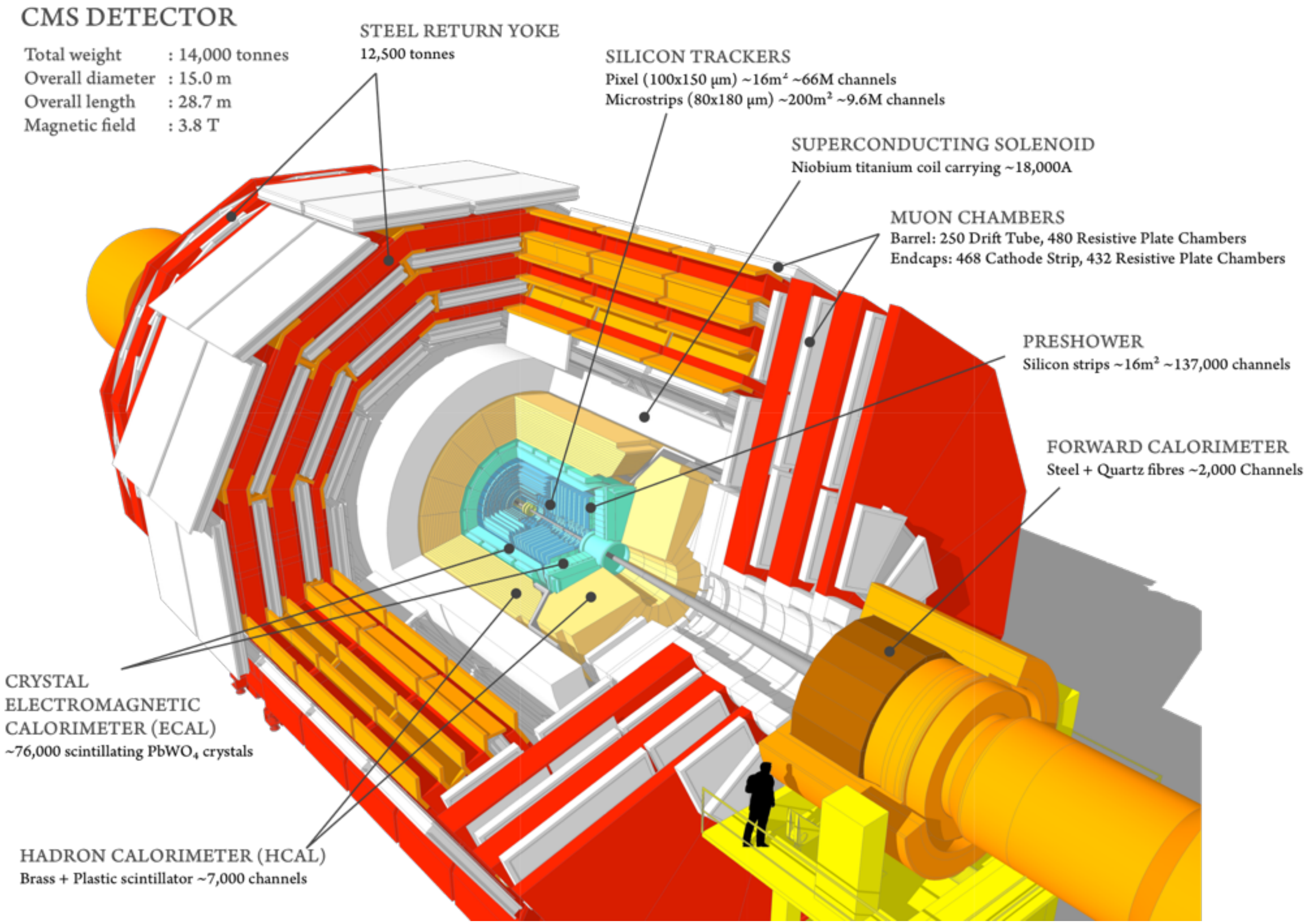
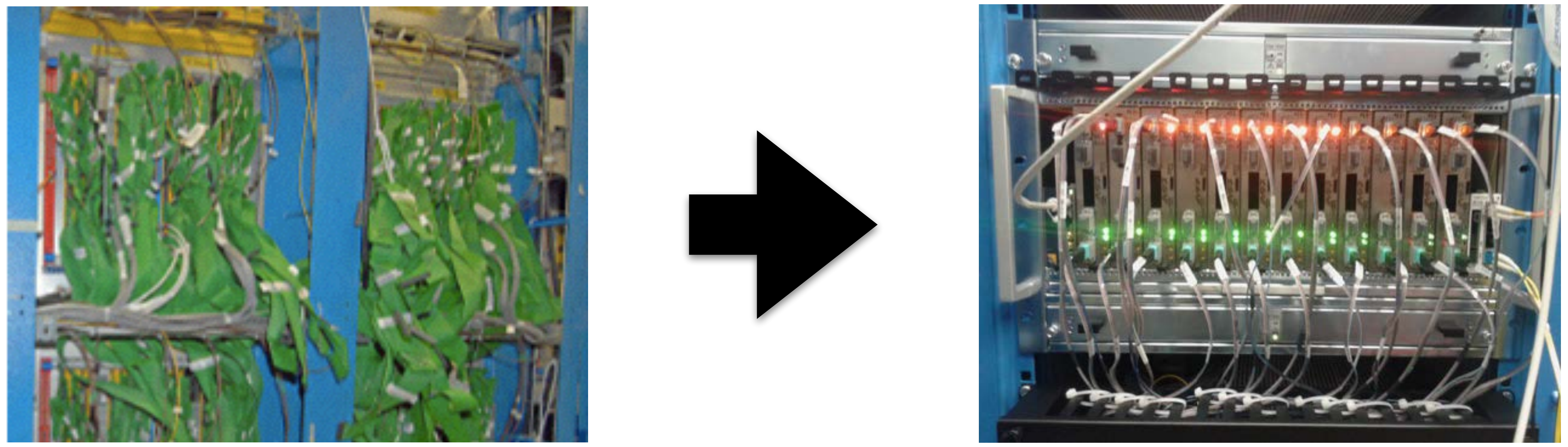
CMS: Phase 1 upgrade

- 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



CMS: Phase 1 Level-1 Trigger upgrade

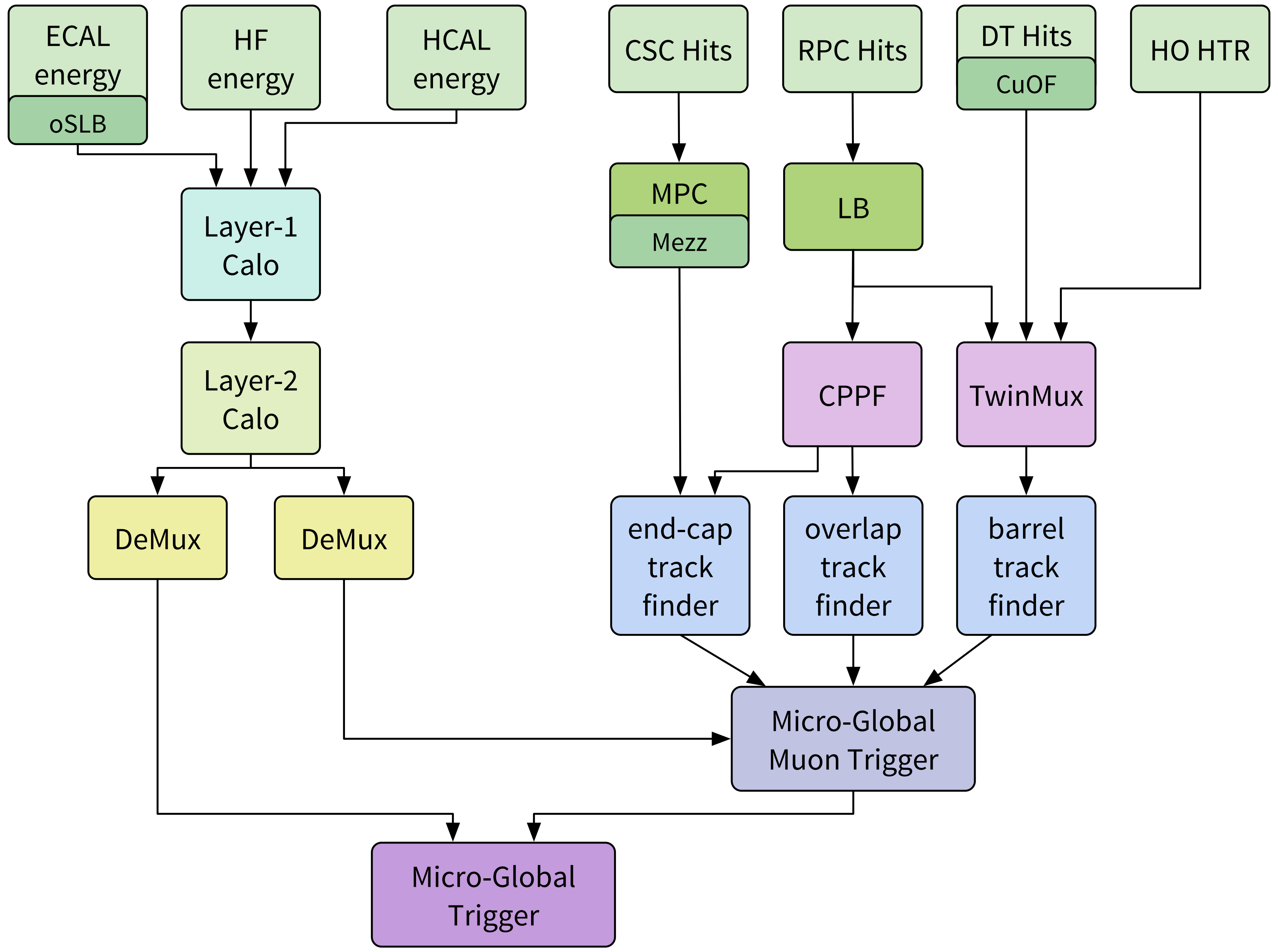
- Replace older VME electronics with latest μTCA (telecoms standard) electronics → latest, powerful processing (FPGAs) and high speed serial links



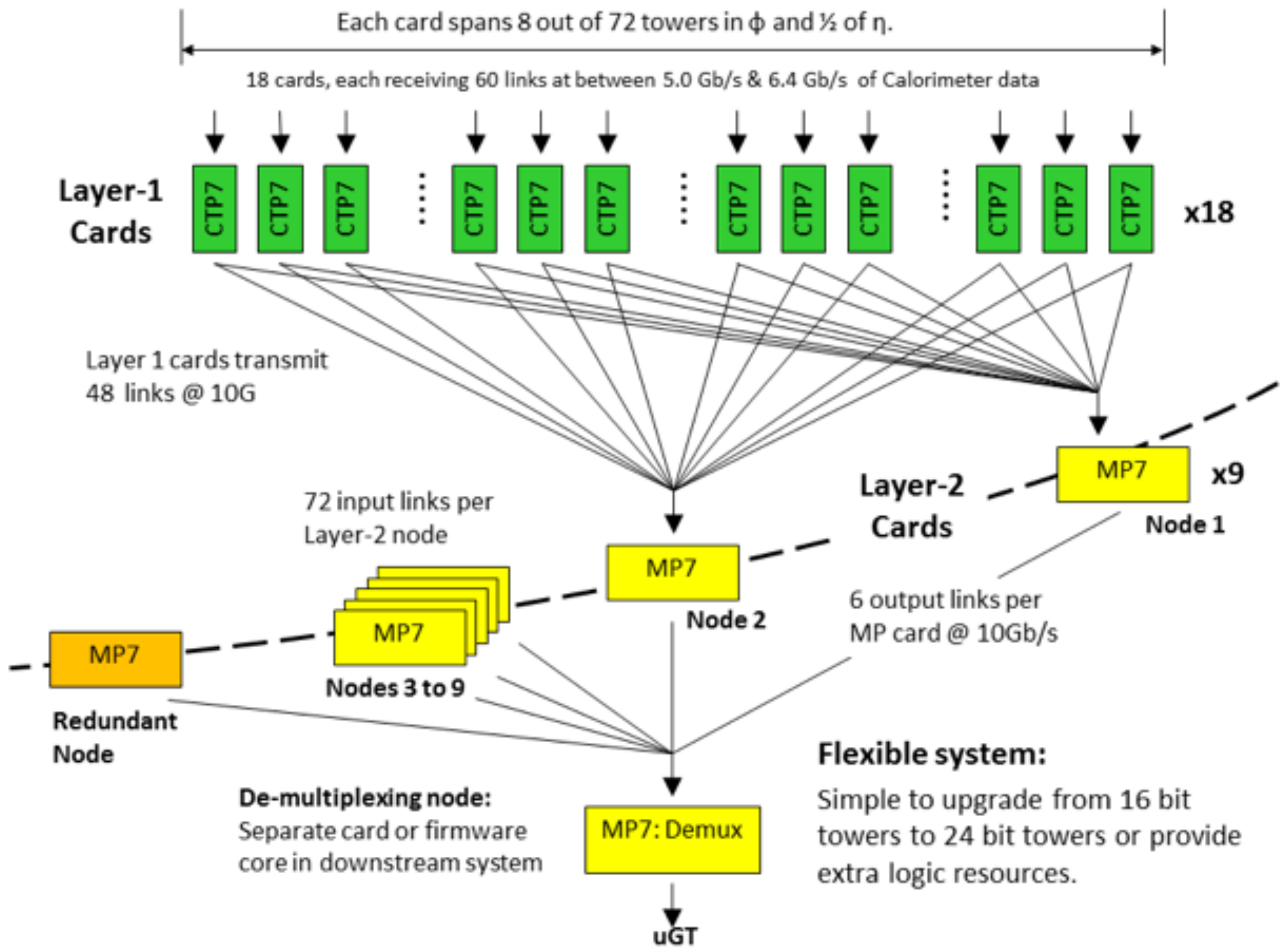
- Replace copper links with optical fibres almost everywhere

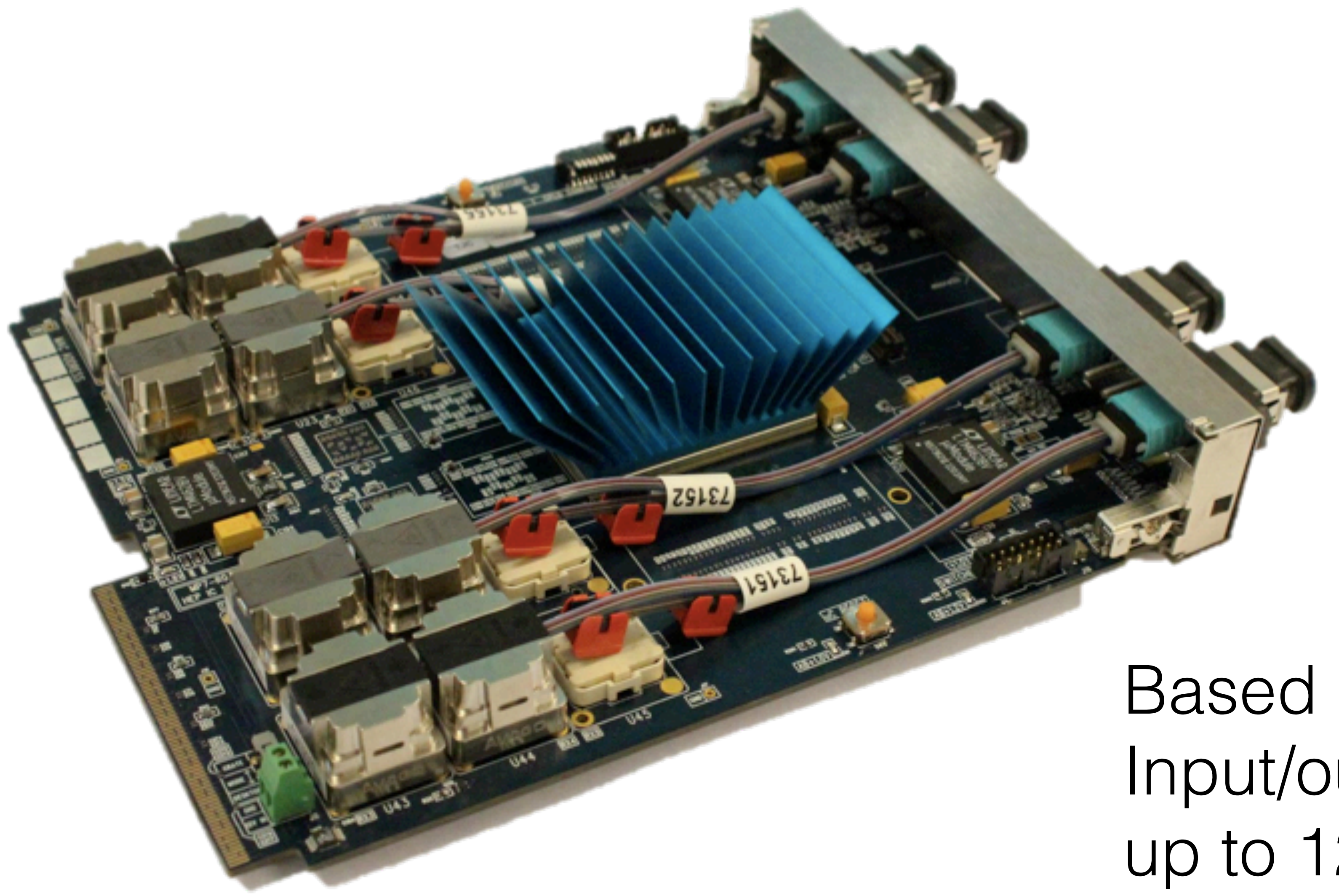
- Earlier merging of detector data in muon system → better reconstruction

- Pile up subtraction in calorimeter system for object energies and isolation energies



CMS: Phase 1 Level-1 Trigger upgrade

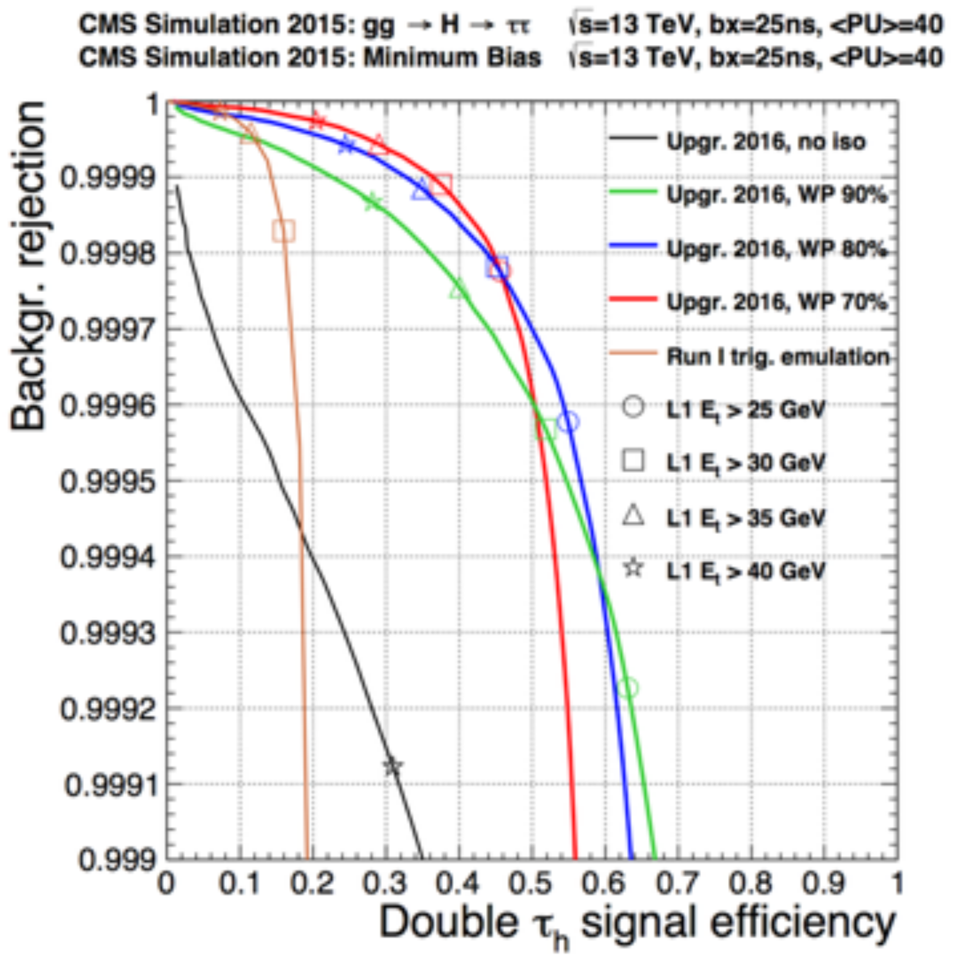


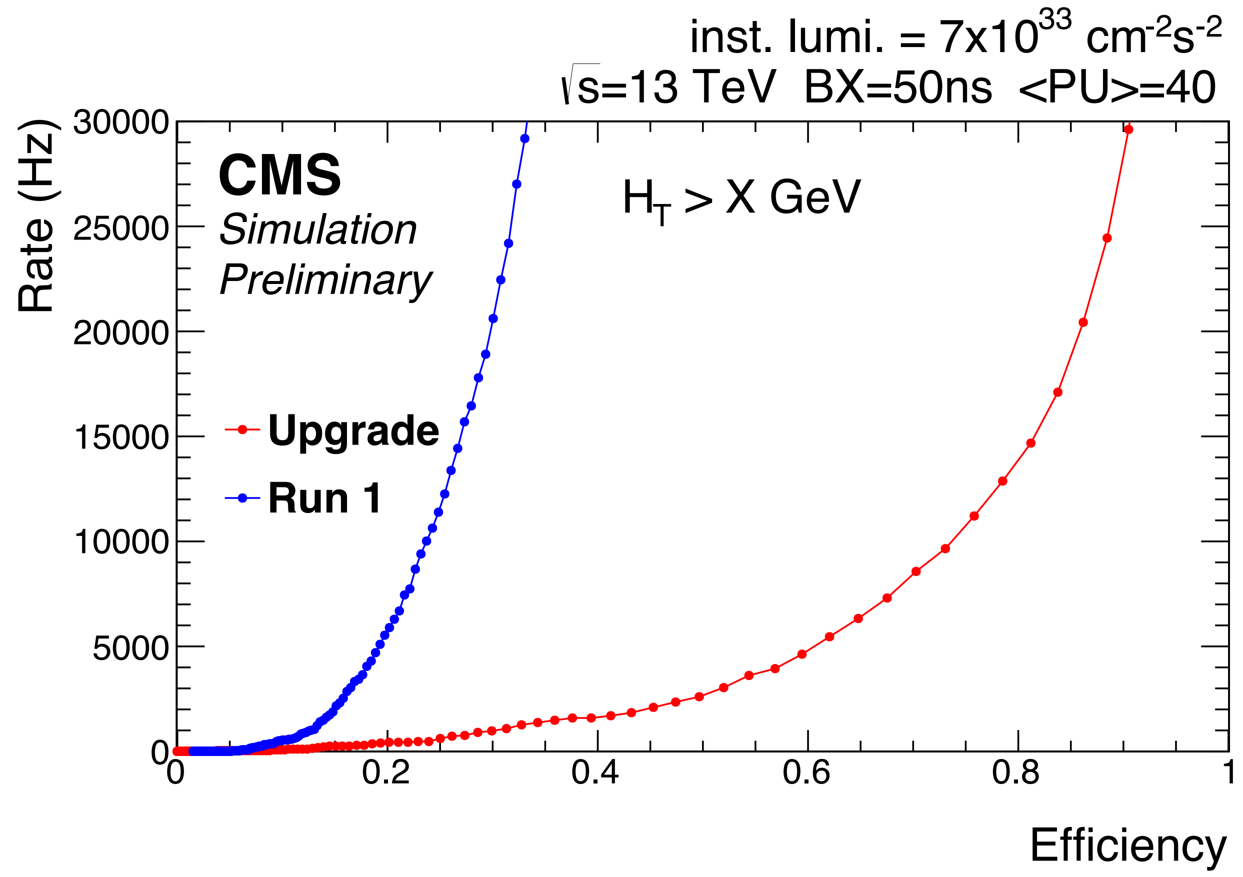


IMPERIAL MP7

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

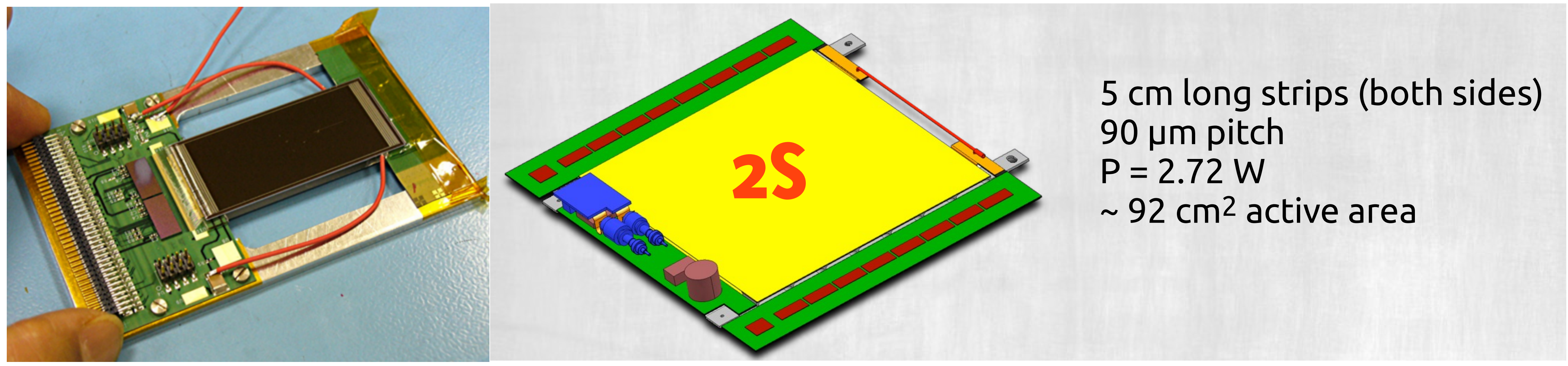
- Higher granularity (tower level)
- One processing FPGA sees the entire detector for one event
  - Seamless coverage of detector
  - Sophisticated algorithms (closer to offline)



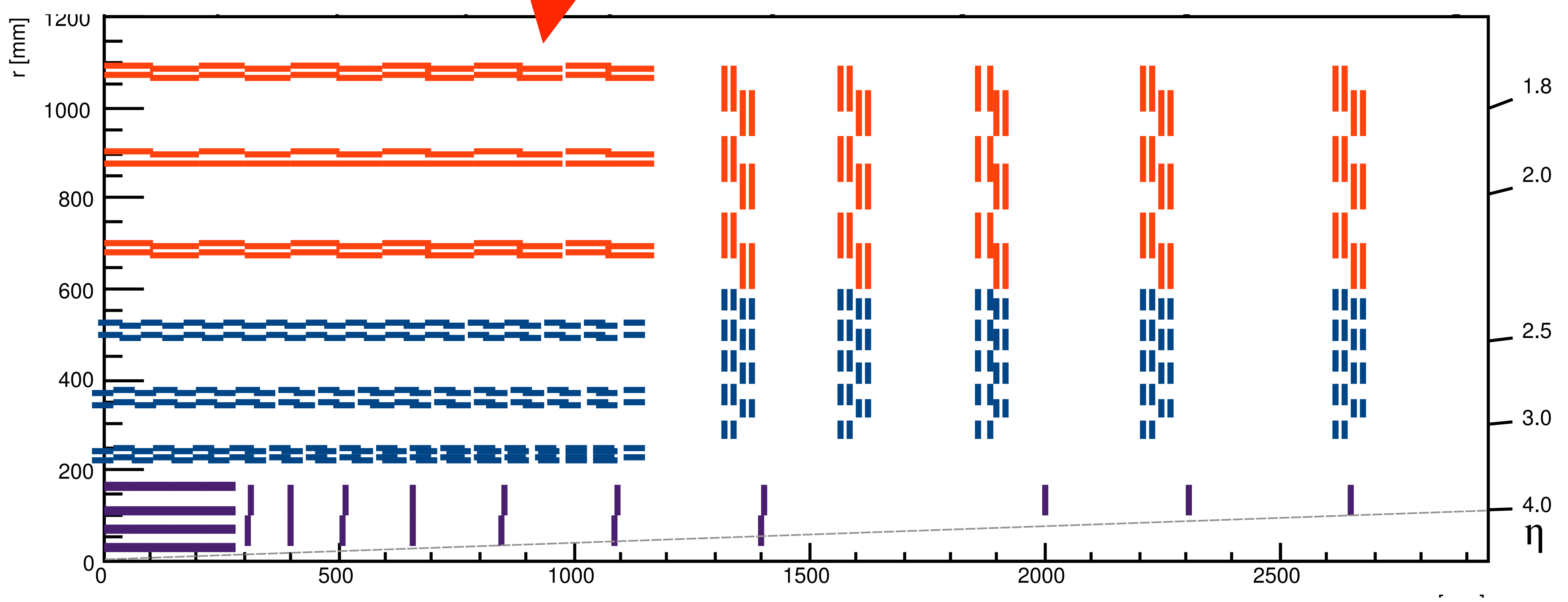


CMS: Phase 2 Tracker upgrade

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

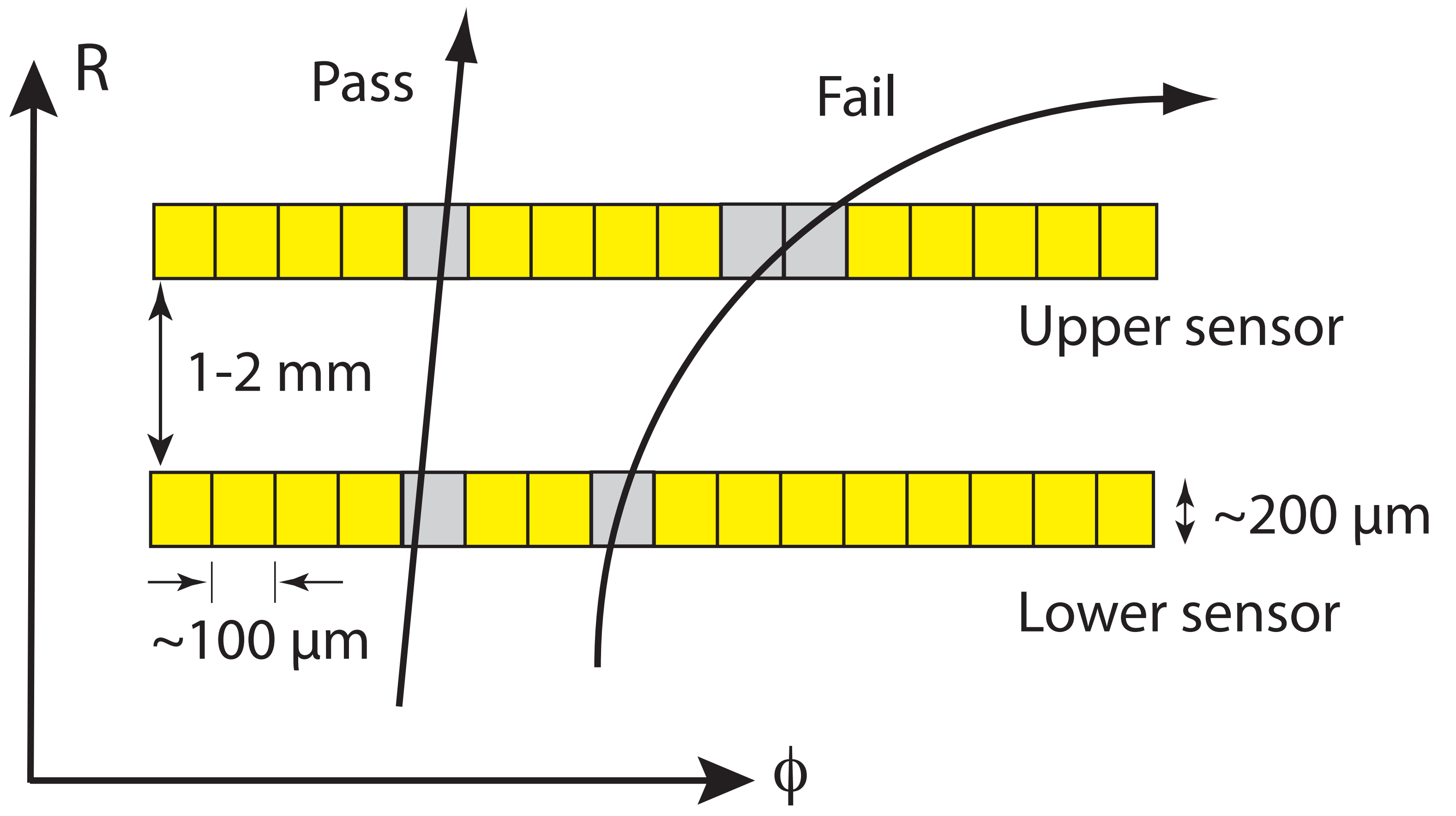


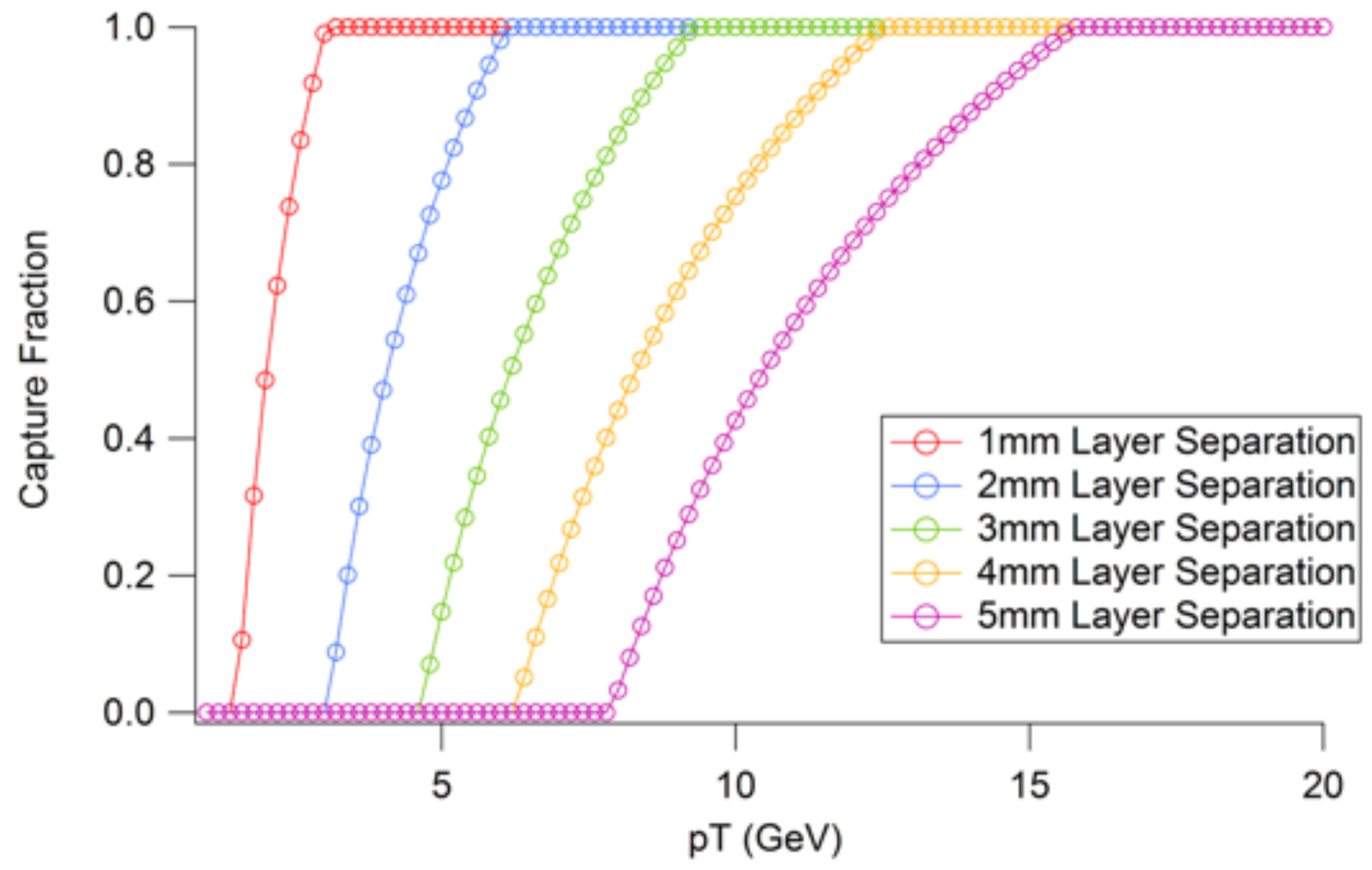
- Outer tracker (UK)
  - High granularity for efficient track reconstruction beyond 140 PU
  - Improved material budget
  - *P_T-modules* to provide trigger for tracks with $P_T \geq 2$ GeV

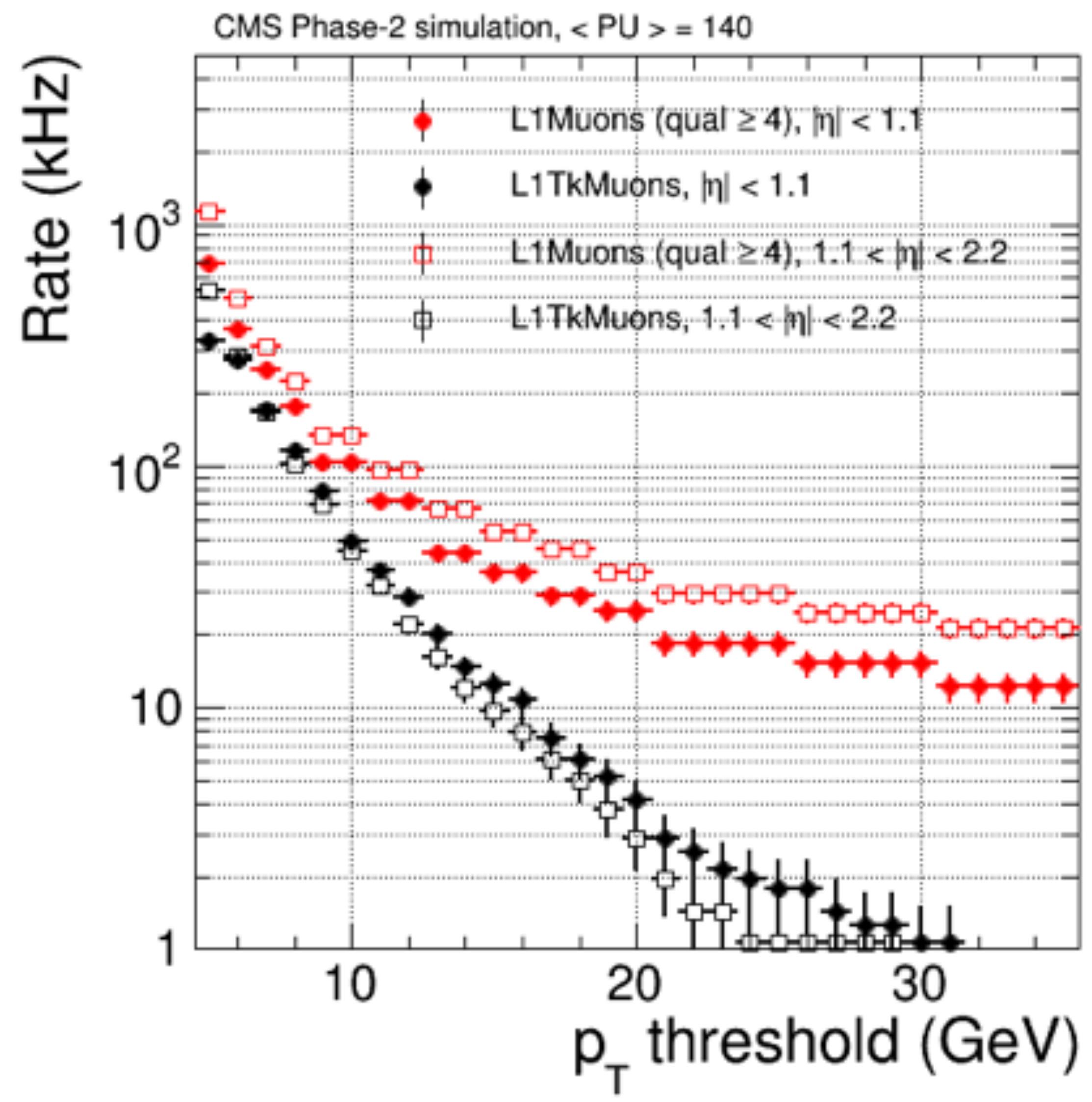


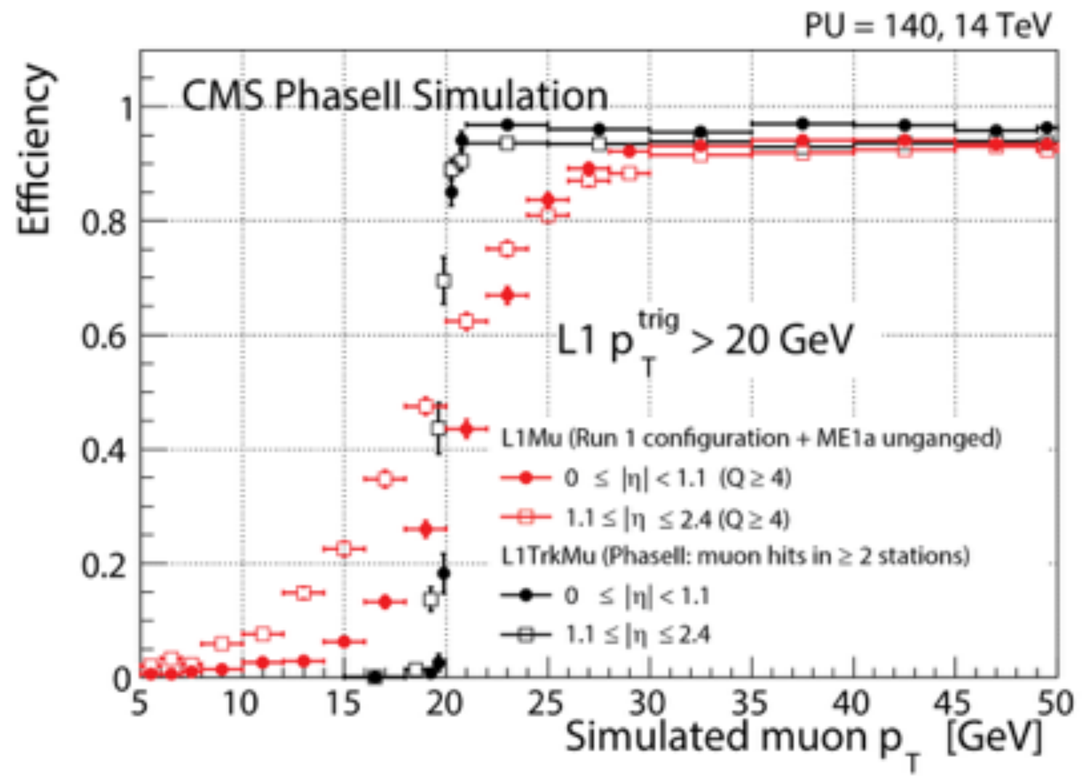
CMS: Phase 2 Tracker upgrade

- 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

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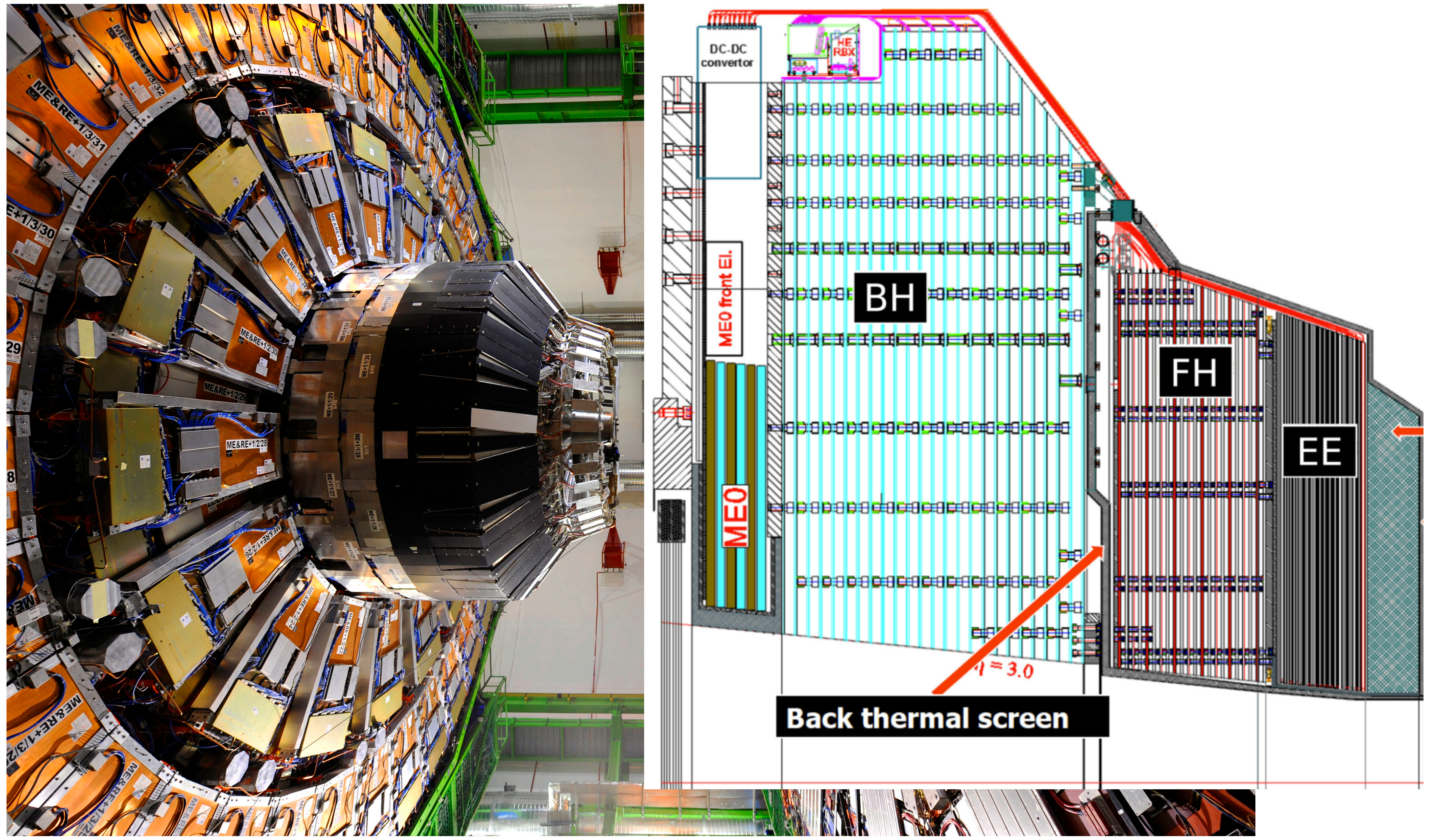
CMS: Phase 2 Calorimeter upgrade

- 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)



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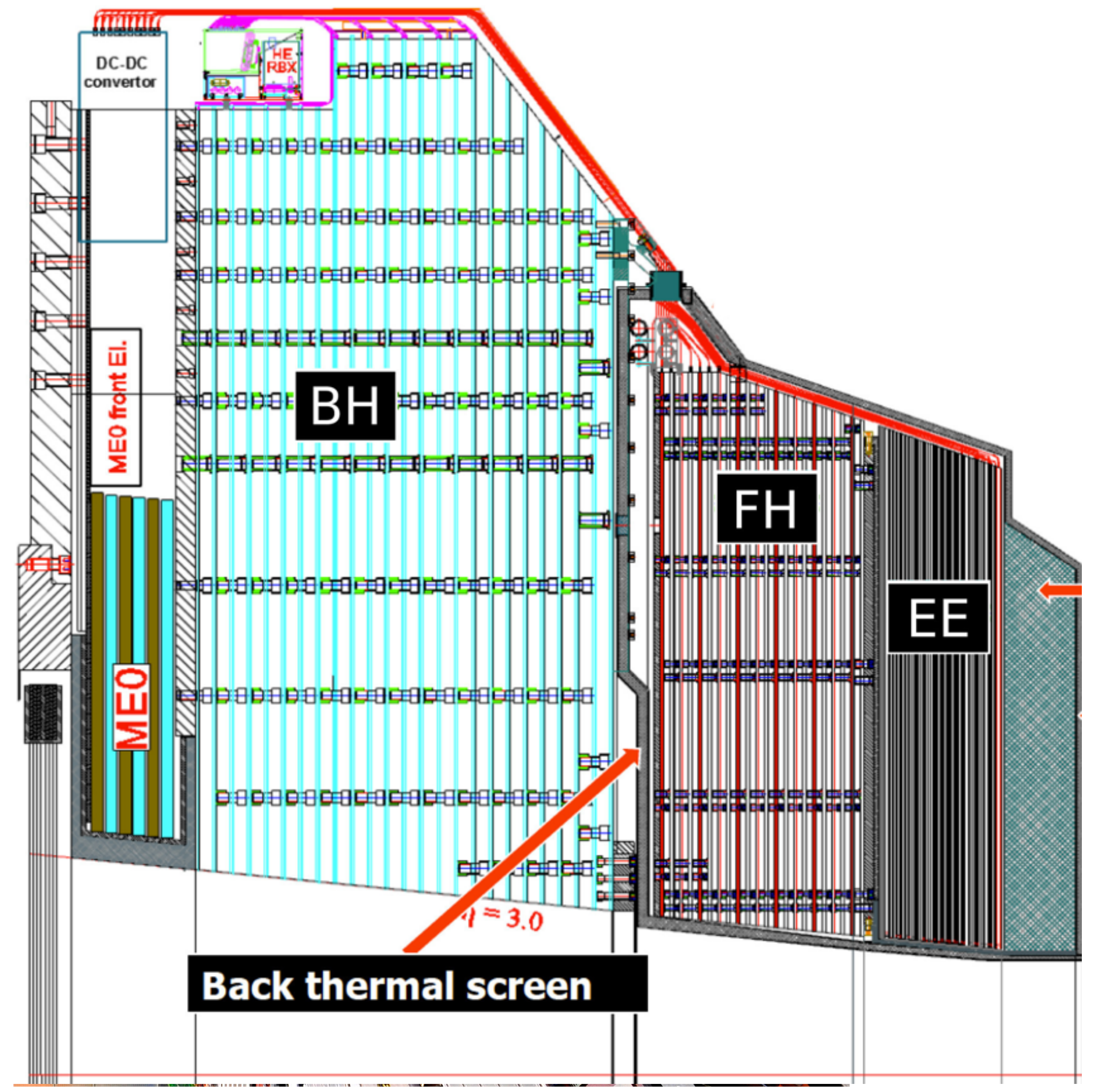
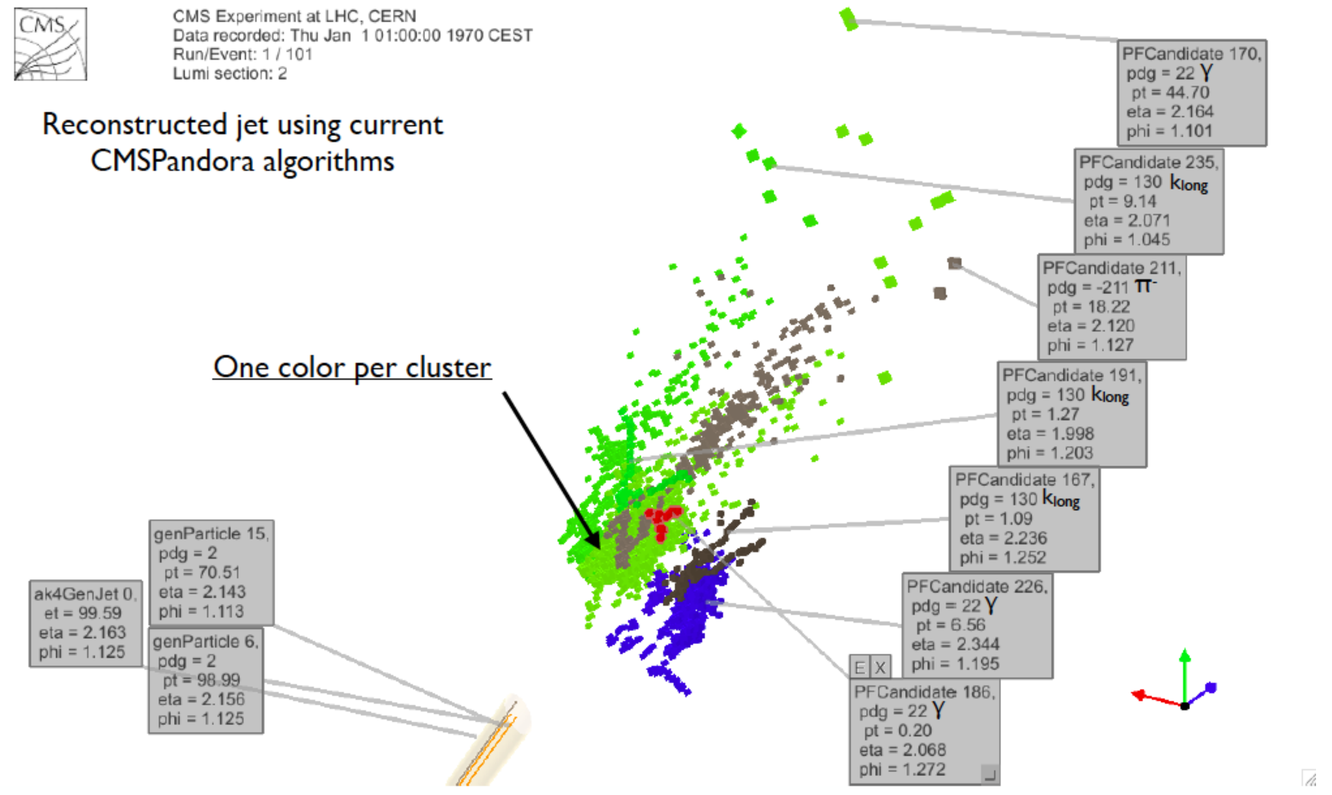
CMS: Phase 2 Calorimeter upgrade

- 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)

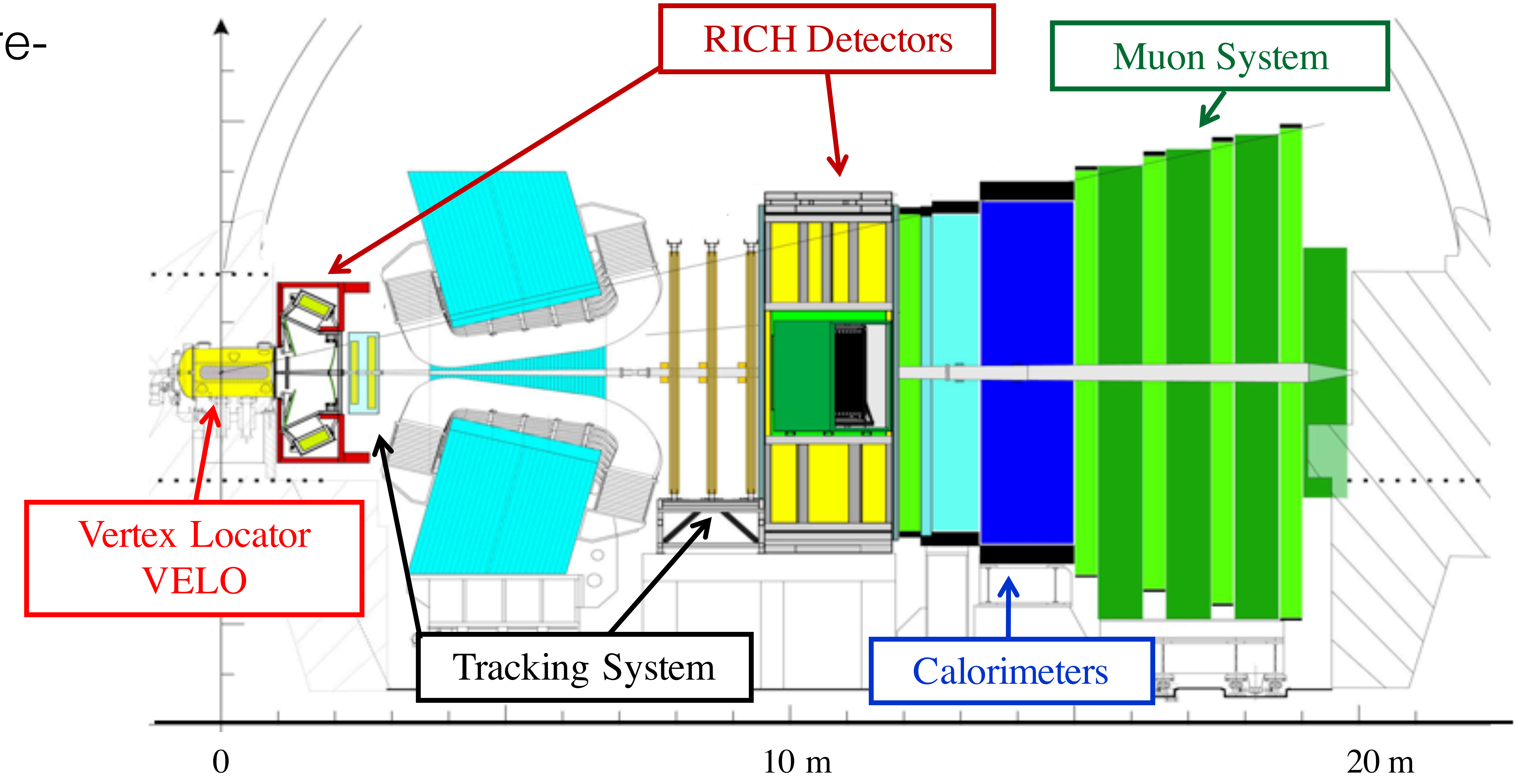


- Major new areas of R&D (UK)
  - Level-1 Trigger, reconstructions algorithms, analogue and digital electronics…



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…



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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

Bibliography

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  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TDR-15-002/index.html
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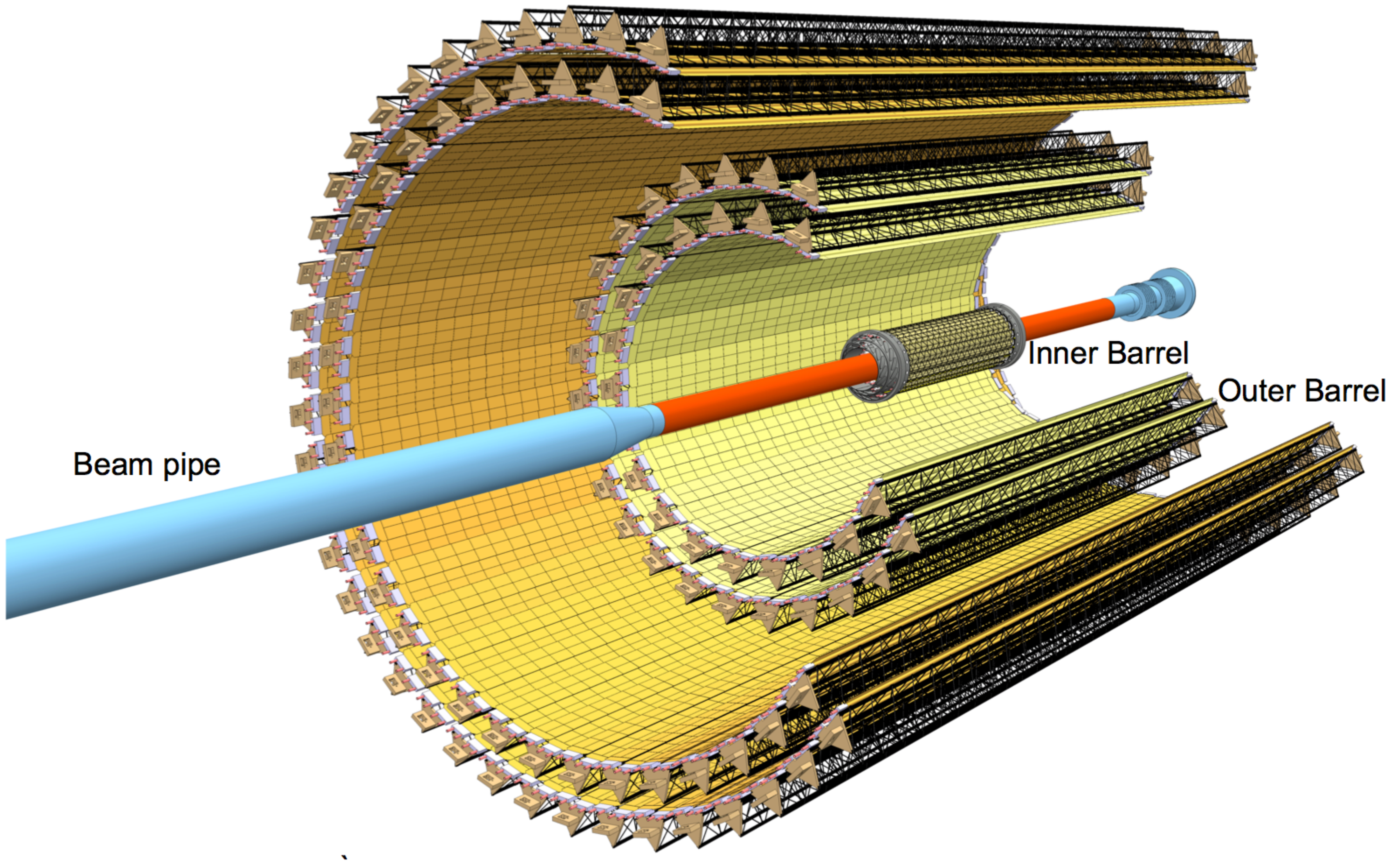
ALICE upgrade

- 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



Higgs couplings

SUSY

Kanemura, Tsumura, Yagyu, Yokoya

COMPOSITE HIGGS