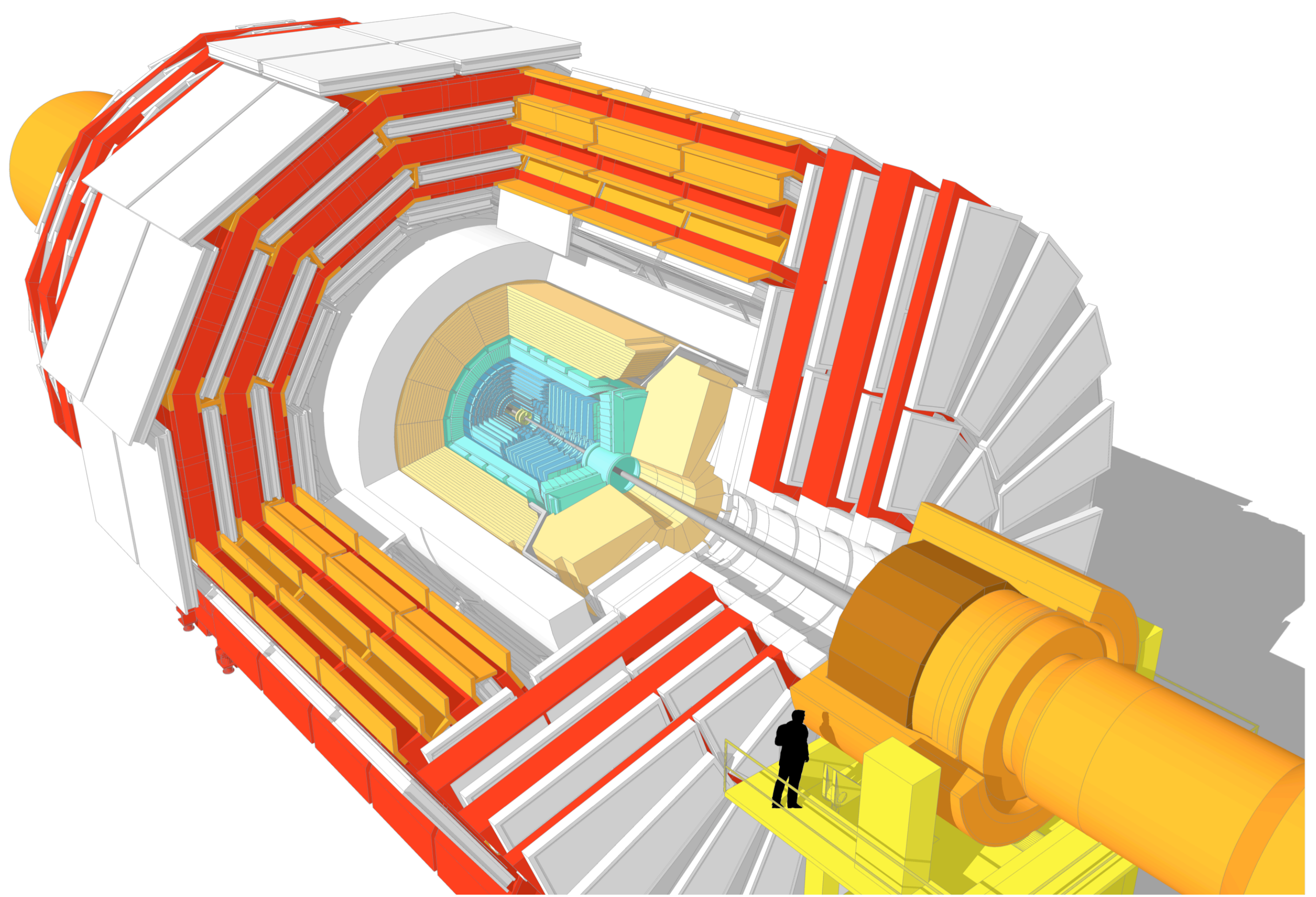
INTRODUCTION TO HL-LHC & CMS PHASE 2

PPAP 2019

12TH SEPTEMBER 2019

SUDAN PARAMESVARAN (UNIVERSITY OF BRISTOL) ON BEHALF OF CMS UK

(MANY THANKS TO MONICA D'ONOFRIO FOR VERY HELPFUL SUGGESTIONS ON HL-LHC PHYSICS)

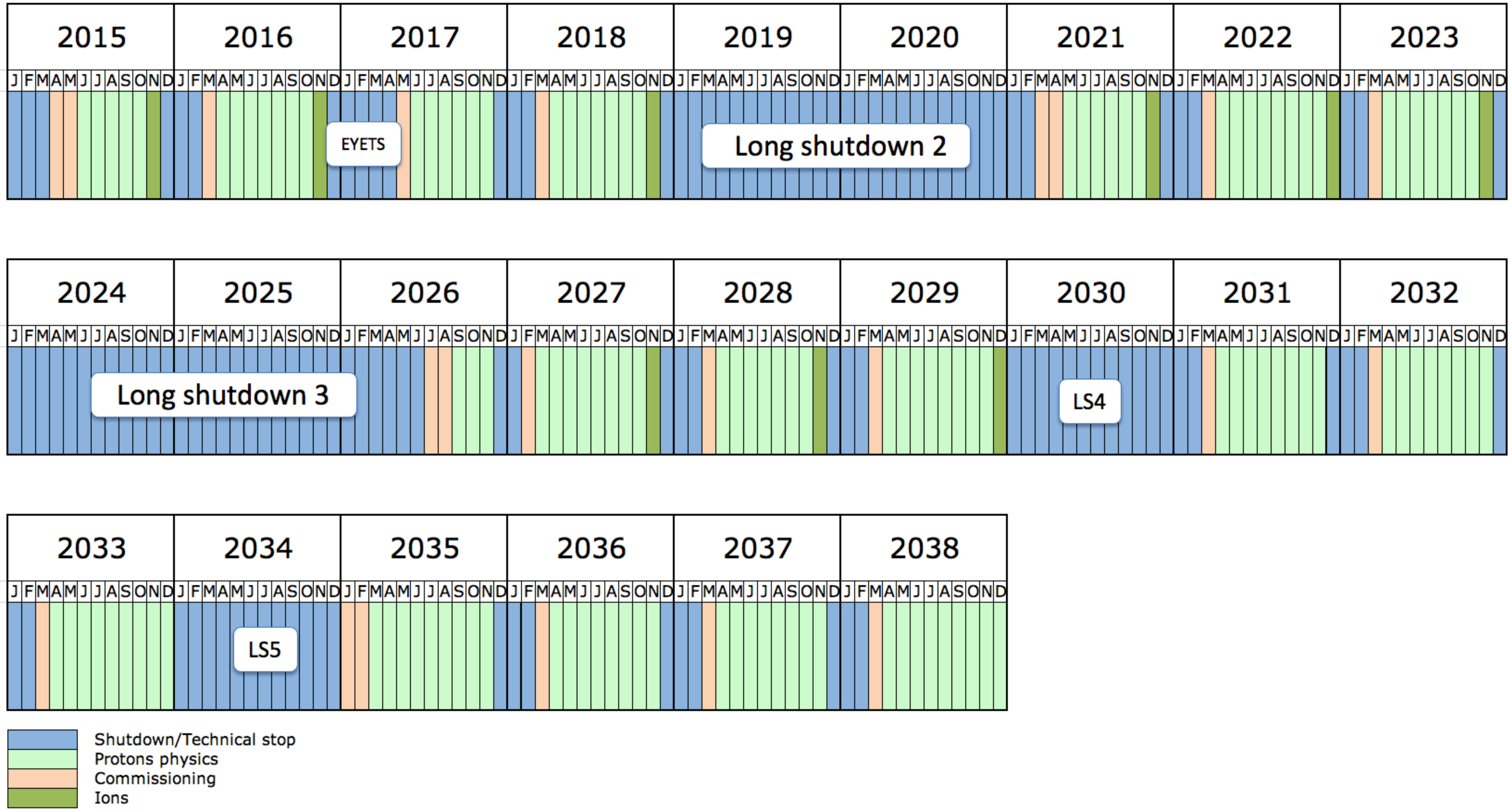


TOPICS TO DISCUSS IN VIEW OF HIGH-LUMINOSITY LHC

- HL-LHC
  - Goals/Timeline
  - Physics reach
- CMS HL-LHC (Phase 2) program
  - Common technology
  - L1 Trigger
  - Tracker
  - ECAL/ HGC

HL-LHC

HL-LHC TIMELINE



HL-LHC GOALS

Goal of HL-LHC as fixed in 2010

From FP7 HiLumi LHC Design Study application

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult} \cong 7.5\ 10^{34}$ cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult} \sim 4000$ fb^{-1}**

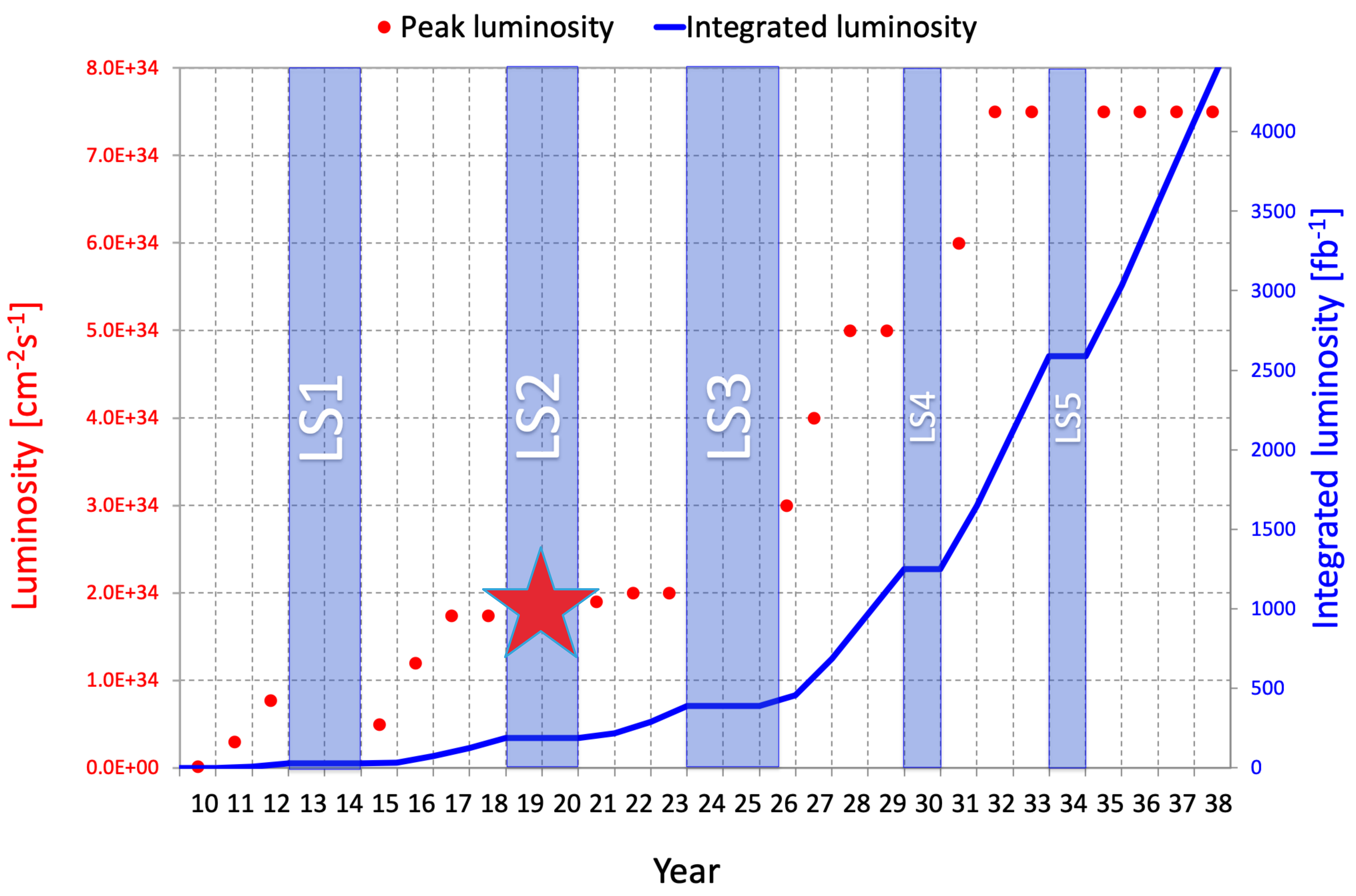
LHC should not be the limit, would Physics require more...

Project approved by CERN Council in June 2016

HiLumi HL-LHC PROJECT

Lucio Rossi - 8th HiLumi Collaboration Meeting 2018

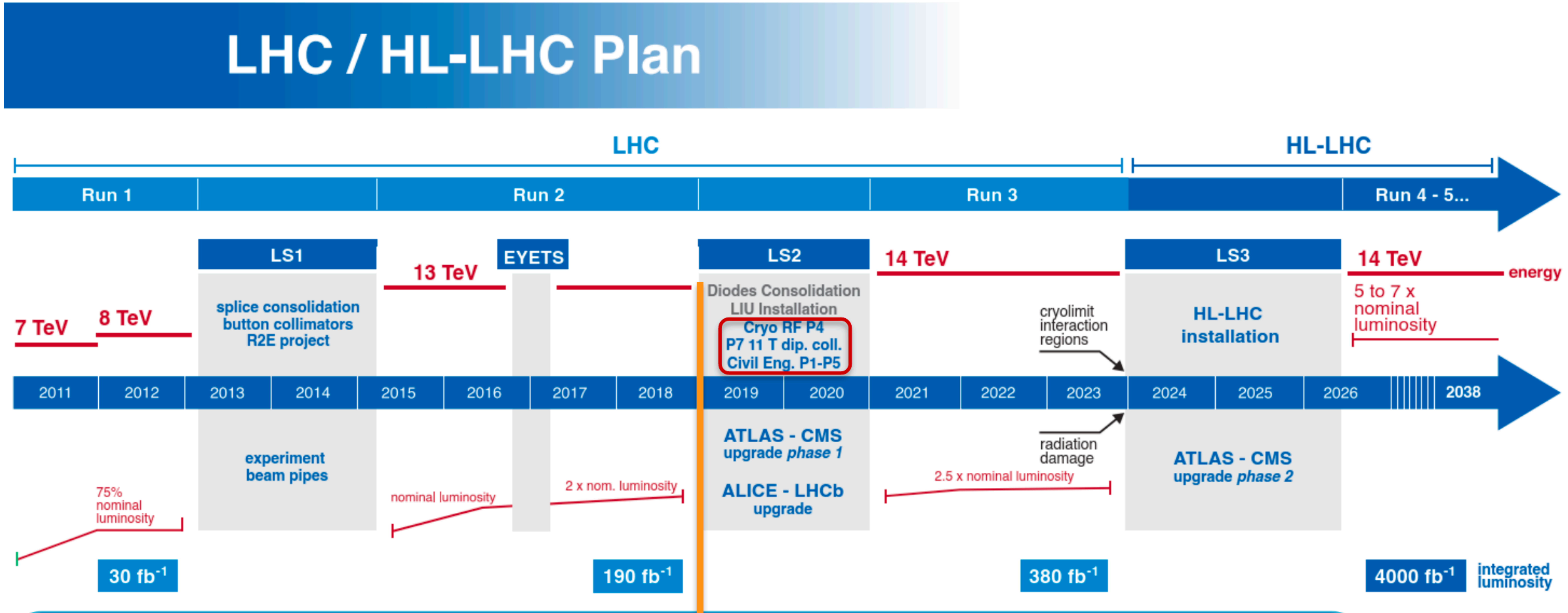
HL-LHC TIMELINE - ULTIMATE PERFORMANCE



HL-LHC PARAMETER ESTIMATES

Parameters	Nominal LHC (Design report)	LHC 2018 max values	HL-LHC (standard)	HL-LHC 8b+4e[12]	HL-LHC (Ultimate)
Beam energy in collision [TeV]	7	6.5	7	7	7
N_b	1.15E+11	1.15E+11	2.2E+11	2.2E+11	2.2E+11
n_b	2808	2556	2760	1972	2760
Number of collisions in IP1 and IP5 [1]	2808	2544	2748	1967	2748
N_{tot}	3.2E+14	2.9E+14	6.1E+14	4.3E+14	6.1E+14
beam current [A]	0.58	0.52	1.1	0.79	1.1
x-ing angle [μrad]	285	320 ==> 260	500	470[10]	500
beam separation [σ] [11]	9.4	10.3 ==> 6.8	10.5	10.5[10]	10.5
β^* [m]	0.55	0.30 ==> 0.25	0.15	0.15	0.15
ε_n [μm]	3.75	2 ==> 2.5	2.50	2.20	2.50
r.m.s. bunch length [m]	7.55E-02	8.25E-02	7.61E-02	7.61E-02	7.61E-02
Total loss factor R0 without crab-cavity			0.342	0.342	0.342
Total loss factor R1 with crab-cavity [13]			0.716	0.749	0.716
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}] [13]			1.70E+35	1.44E+35	1.70E+35
Luminosity [cm^{-2} s^{-1}] or Leveling luminosity for HL-LHC	1.00E+34	2.00E+34	5.0E+34[5]	3.82E+34	7.5E+34[5]
Events / crossing (with leveling and crab-cavities for HL-LHC) [8]	27	55	131	140	197
Peak line density of events [event/mm] (max over stable beams)	0.21	0.38	1.3	1.3	1.9
Leveling time [h] (assuming no emittance growth) [8, 13]	-		7.2	7.2	3.5

HL-LHC PROGRESS



HL-LHC established in summer 2010 in view of FP7-Hilumi LHC DS
Installation of equipment will start in 2024 and HWC in 2026; today Oct. 2018 we are
HALF WAY through the project duration!

HL-LHC PHYSICS REACH

UK INPUT TO HL-LHC PHYSICS

- Since 2017, there has been a joint LHC experiments + theorists effort to update and document systematically the physics programme for HL-LHC.
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop
- This served as input to the update of the European Strategy of Particle Physics
- Broken down into 5 areas: SM, Higgs, BSM, Flavour, Heavy Ion
- **UK has been heavily involved in this process from the start and occupied leading roles in four of these five groups**
  - **Convenor roles in SM, Higgs, BSM, Flavour**
  - **Also UK role in overall steering group**

UK INPUT TO HL-LHC PHYSICS

- UK also strongly represented through the actual analyses that form the bulk of the reports.
  - e.g W mass, $\sin^2\theta_{\text{eff}}$, Higgs combination, trilinear coupling, SUSY searches, resonances, B-physics
- As such a huge amount of UK input has gone into the summary document that was submitted to the European Strategy

UK convenors

The physics potential of HL-LHC

Editors:

Workshop steering group: A. Dainese, M.L. Mangano, A.B. Meyer, A. Nisati, G.P. Salam, M. Vesterinen
WG1 conveners: P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld
WG2 conveners: M. Cepeda, S. Gori, P. Ilten, M. Kado, and F. Riva,
WG3 conveners: X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer
WG4 conveners: A. Cerri, V.V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan
WG5 conveners: Z. Citron, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, M. Winn
Contributing authors: see Addendum

ABSTRACT

This document presents the executive summary of the findings of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC", which has run for over a year since its kick-off meeting on 30 October – 1 November 2017. We discuss here the HL-LHC physics programme. As approved today, this covers *(a)* pp collisions at 14 TeV with an integrated luminosity of 3 ab^{-1} each for ATLAS and CMS, and 50 fb^{-1} for LHCb, and *(b)* Pb–Pb and p–Pb collisions with integrated luminosities of 13 nb^{-1} and 50 nb^{-1}, respectively. In view of possible further upgrades of LHCb and of the ions programme, the WG reports assume 300 fb^{-1} of luminosity delivered to an Upgrade II of LHCb, 1.2 pb^{-1} of integrated luminosity for p–Pb collisions, and the addition of collisions with other nuclear species. A separate submission covers the HE-LHC results.
The activity has been carried out by five working groups (WGs): "Standard Model" (WG1), "Higgs" (WG2), "Beyond the Standard Model" (WG3), "Flavour" (WG4) and "QCD matter at high density" (WG5). Their reports, extending this executive summary with more results and details, are available on the CERN Document Server [1–5], and will appear on arXiv. The WG results include both phenomenological studies and detailed simulations of the anticipated performance of the LHC detectors under HL-LHC conditions. These latter studies implement the knowledge acquired during the preparation of the technical design reports for the upgraded detectors, and reflect the experience gained by the experiments during the first two runs of the LHC. The documents describing in full detail the HL-LHC studies performed by the experiments can be found in Ref. [6] (available in early 2019) and in Ref. [7].
Three goals have been set for the Workshop: (i) to update and extend the projections for the precision and reach of the HL-LHC measurements, and for their interpretation; (ii) to highlight new opportunities for discovery of phenomena beyond the Standard Model (BSM), in view of the latest theoretical developments and of recent data; (iii) to explore possible new directions and/or extensions of the approved HL-LHC programme, particularly in the area of flavour, in the search for elusive BSM phenomena, and in the study of QCD matter at high density. In addition to enriching and consolidating the physics plans for HL-LHC, and highlighting the significant advances that the full HL-LHC programme will bring relative to today's landscape, this contribution to the European Strategy for Particle Physics Update process is intended to help put in perspective the physics potential of future projects beyond HL-LHC.

HIGGS PHYSICS – NEW REGIME OF UNDERSTANDING

- Higgs SM couplings will be measured to the percent level
- Large statistics will particularly help with complex final states

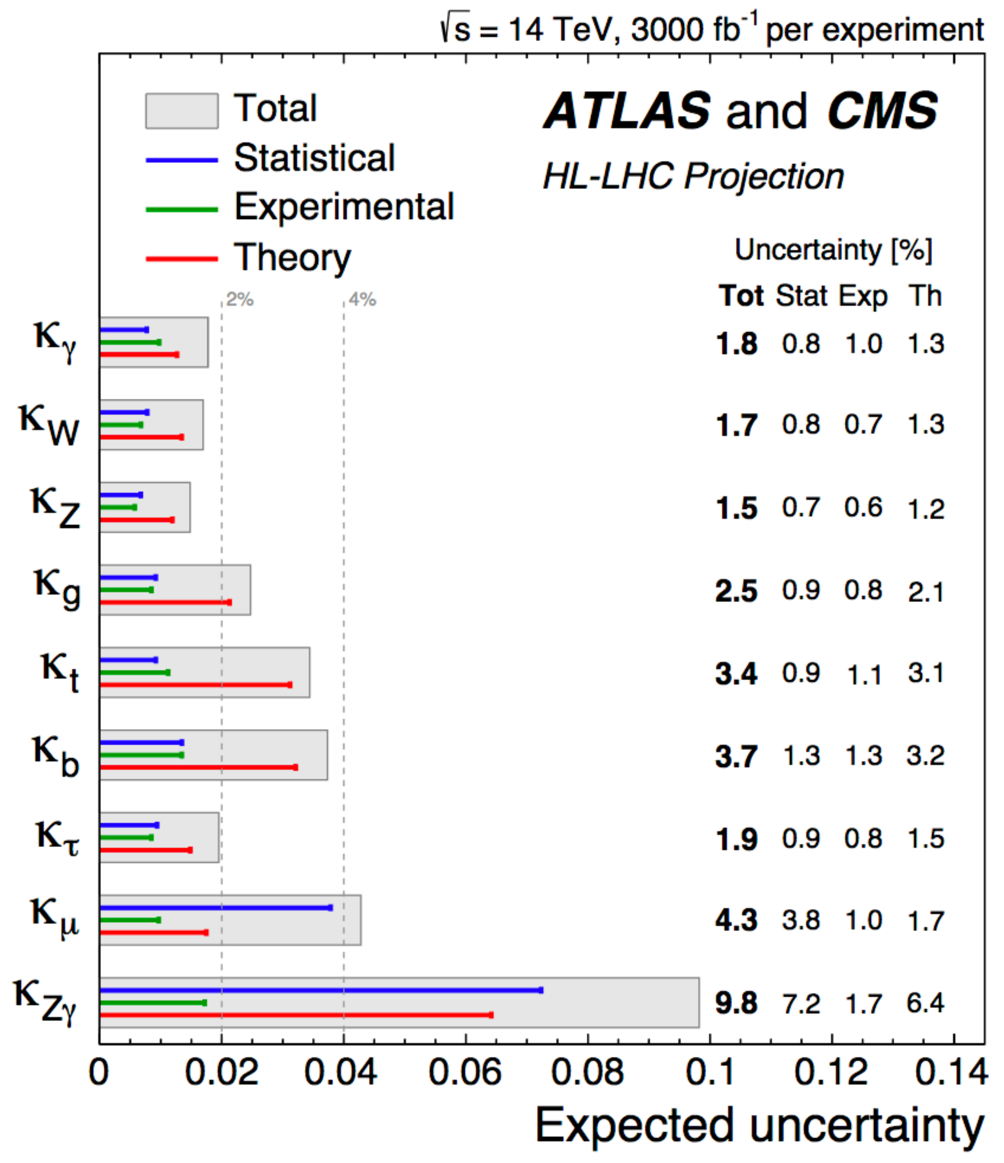
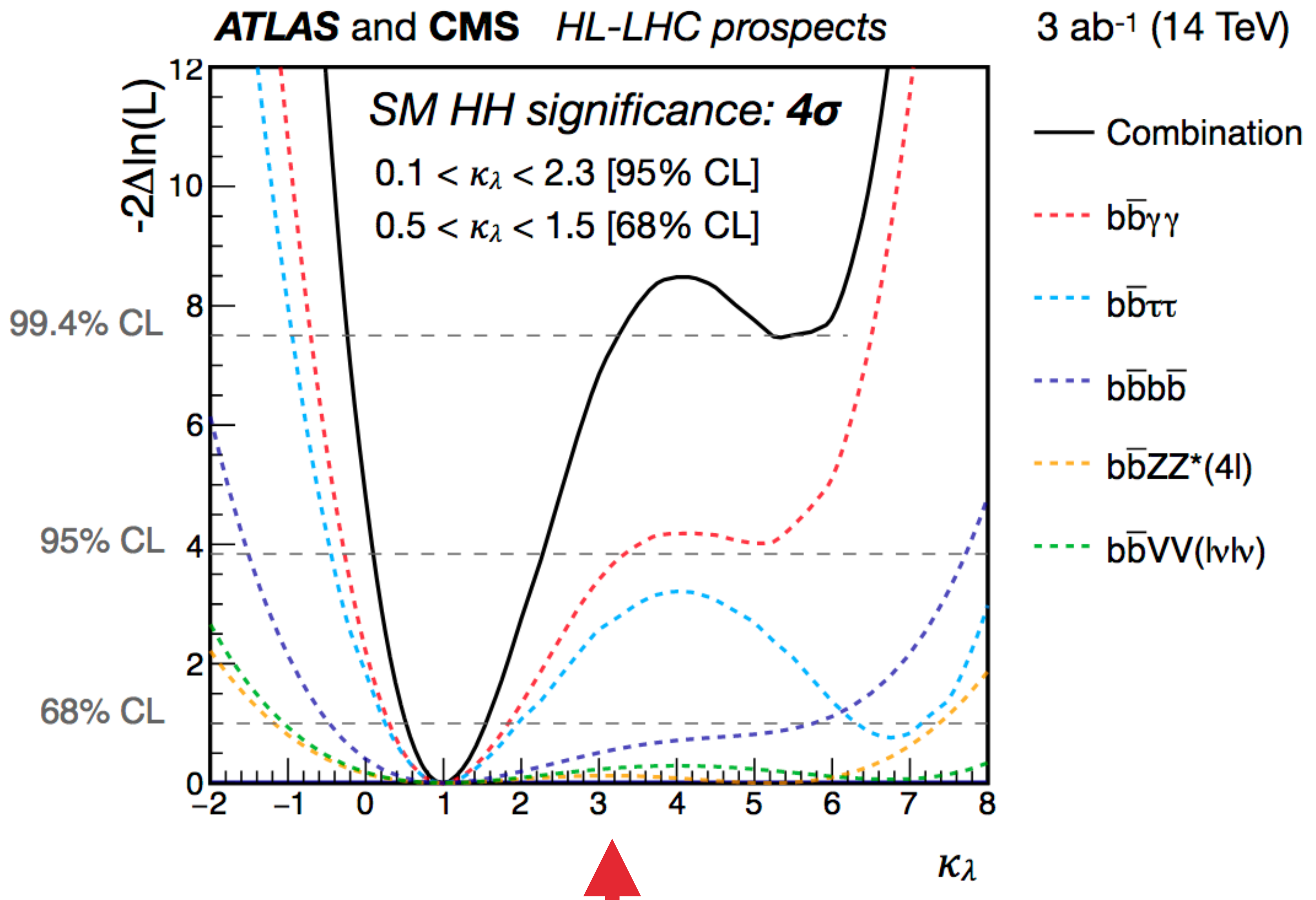
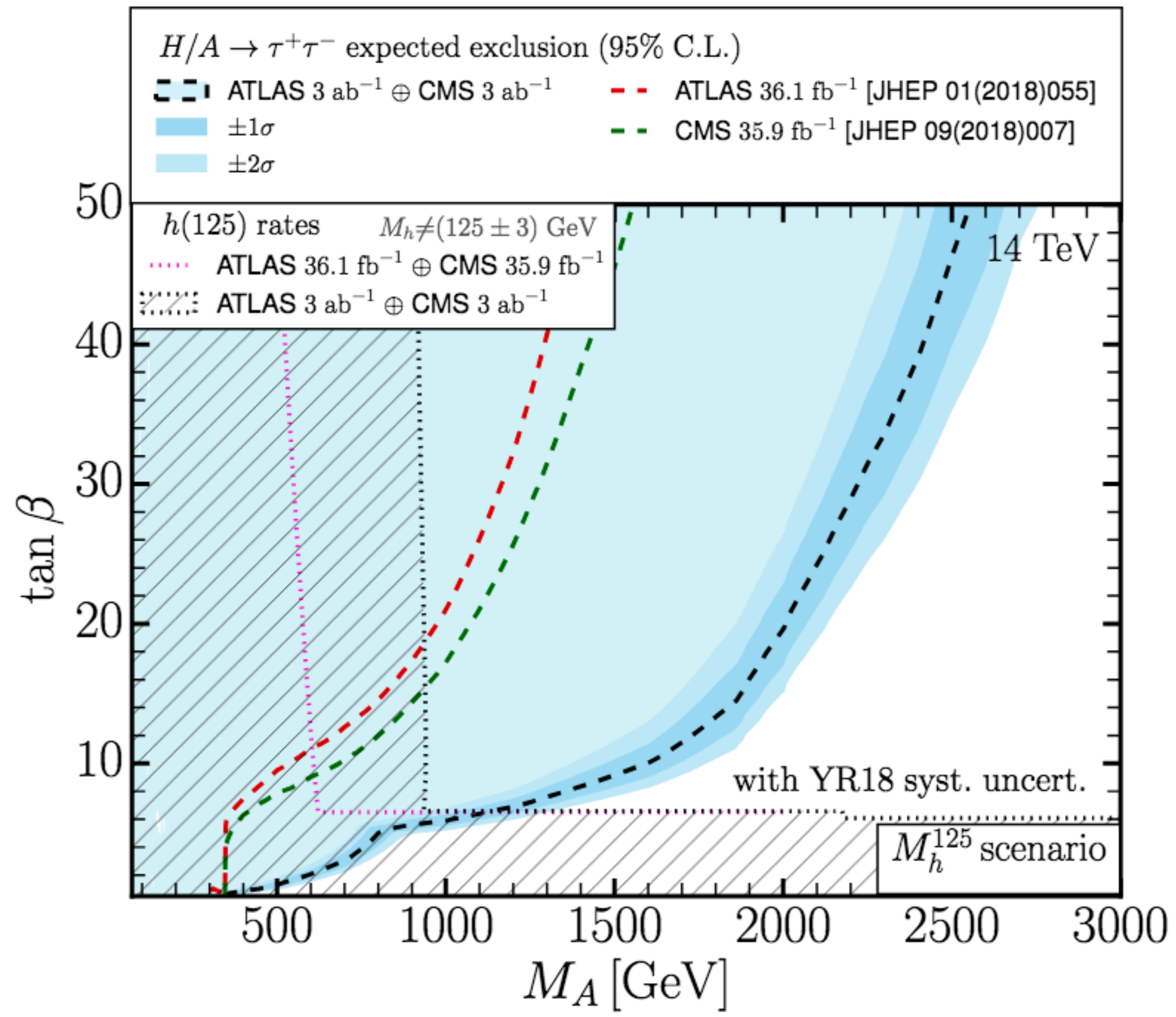


Figure 1. Projected uncertainties on κ_i, combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red). From Ref. [2].



- Assuming SM Higgs self-coupling $\boldsymbol{\lambda}$ - ATLAS and CMS project sensitivity of 3σ each, 4σ combined,.

- Large statistics will improve sensitivity to new Higgs bosons.
- One example decaying to $\boldsymbol{\tau\tau}$ will have reach up to 2.5 TeV for tan β > 50.

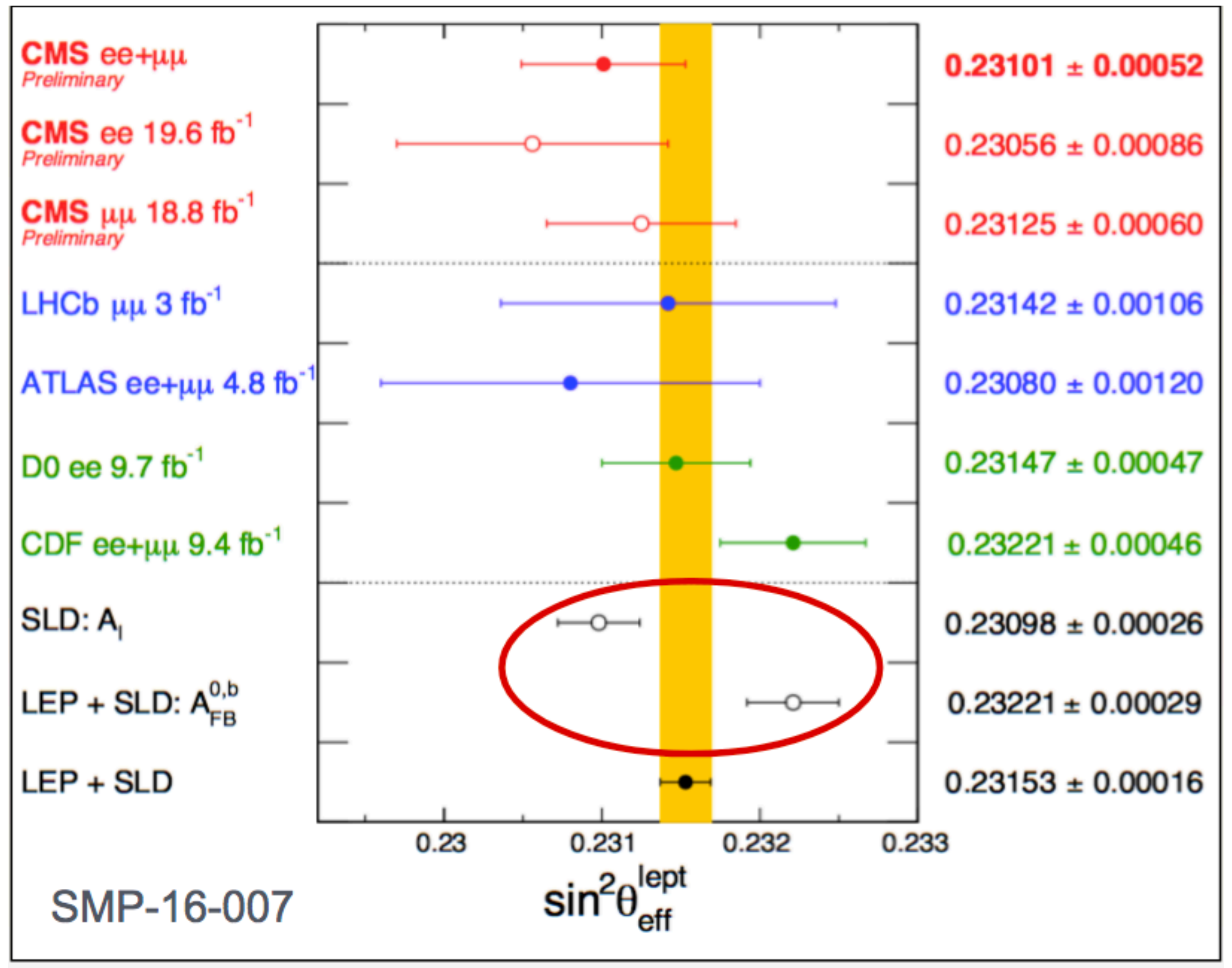


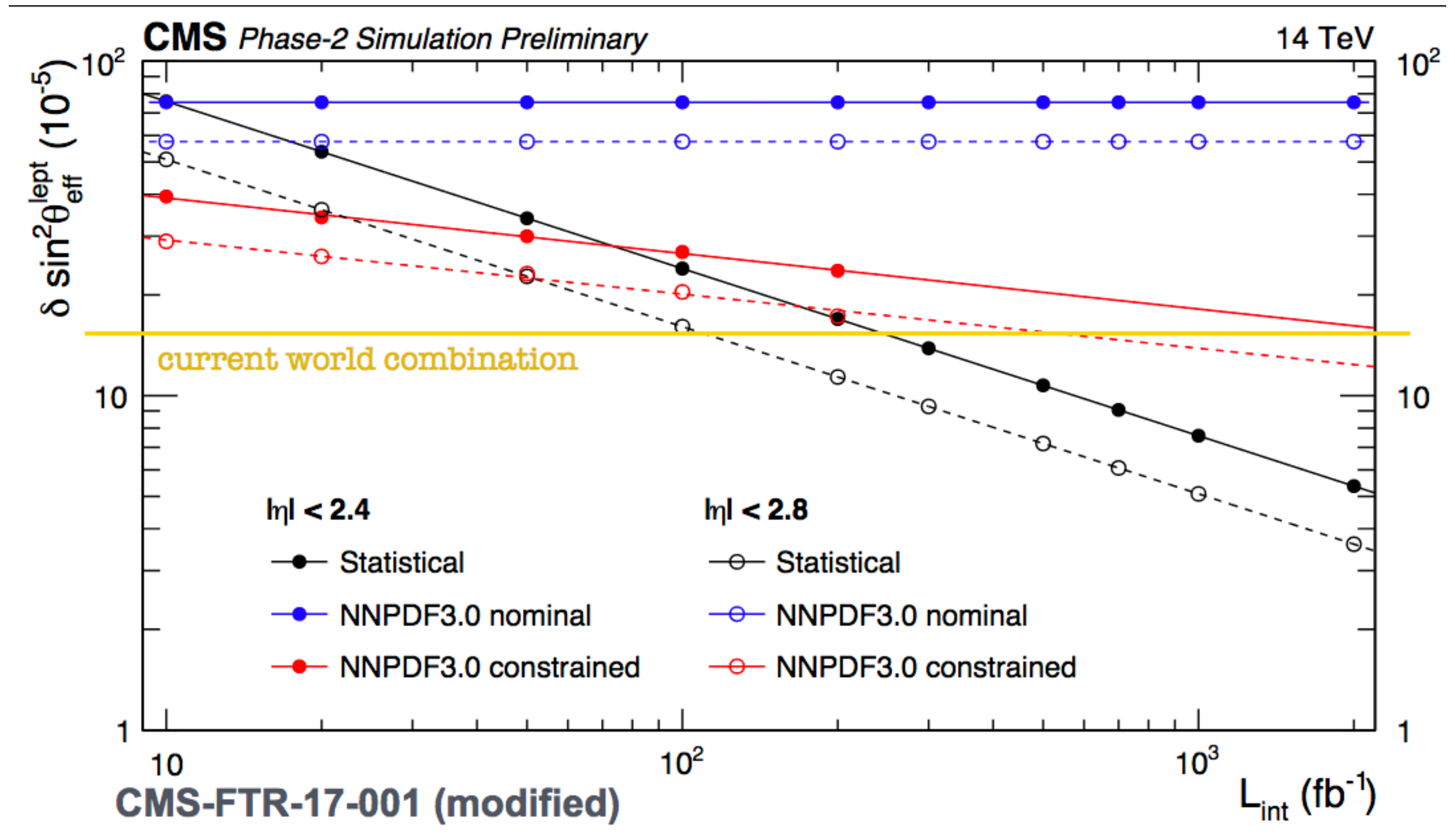
STANDARD MODEL – PUSHING THE PRECISION

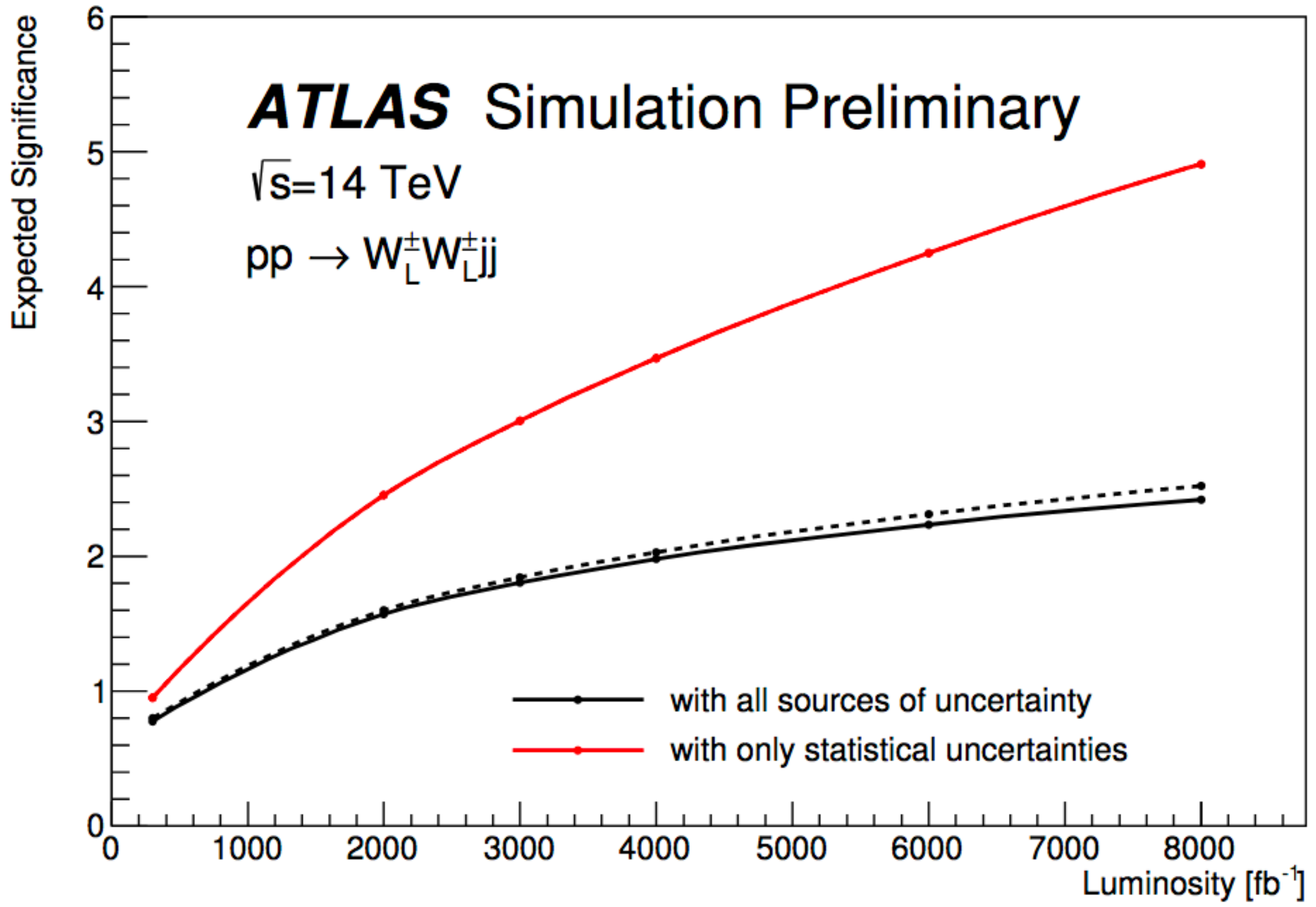
- Obtaining the most precise measurement of the weak mixing angle: $\sin^2\theta_{eff}$
  - Most precise measurements to date from LEP and SLD but differ by 3 s.d.

- **With ATLAS, CMS and LHCb should be able to achieve better than 5.10^{-5}**

- Huge luminosities will give rise to EW multiple boson production not yet accessible at the LHC.
- Sensitivity to new physics i.e anomalous EW couplings
- Extraction of longitudinal polarisation components to same-sign WW scattering should give 3σ evidence (CMS+ATLAS)

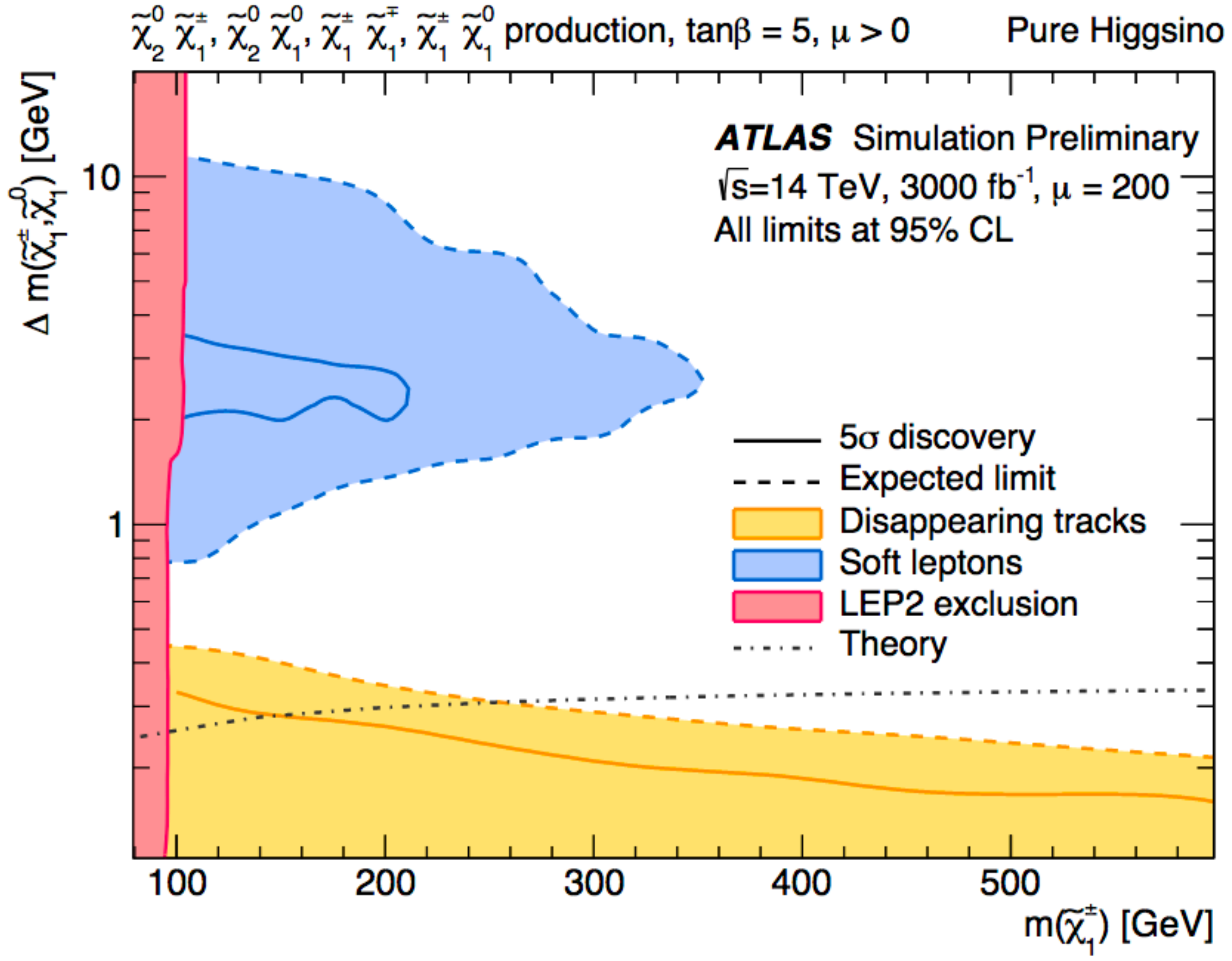


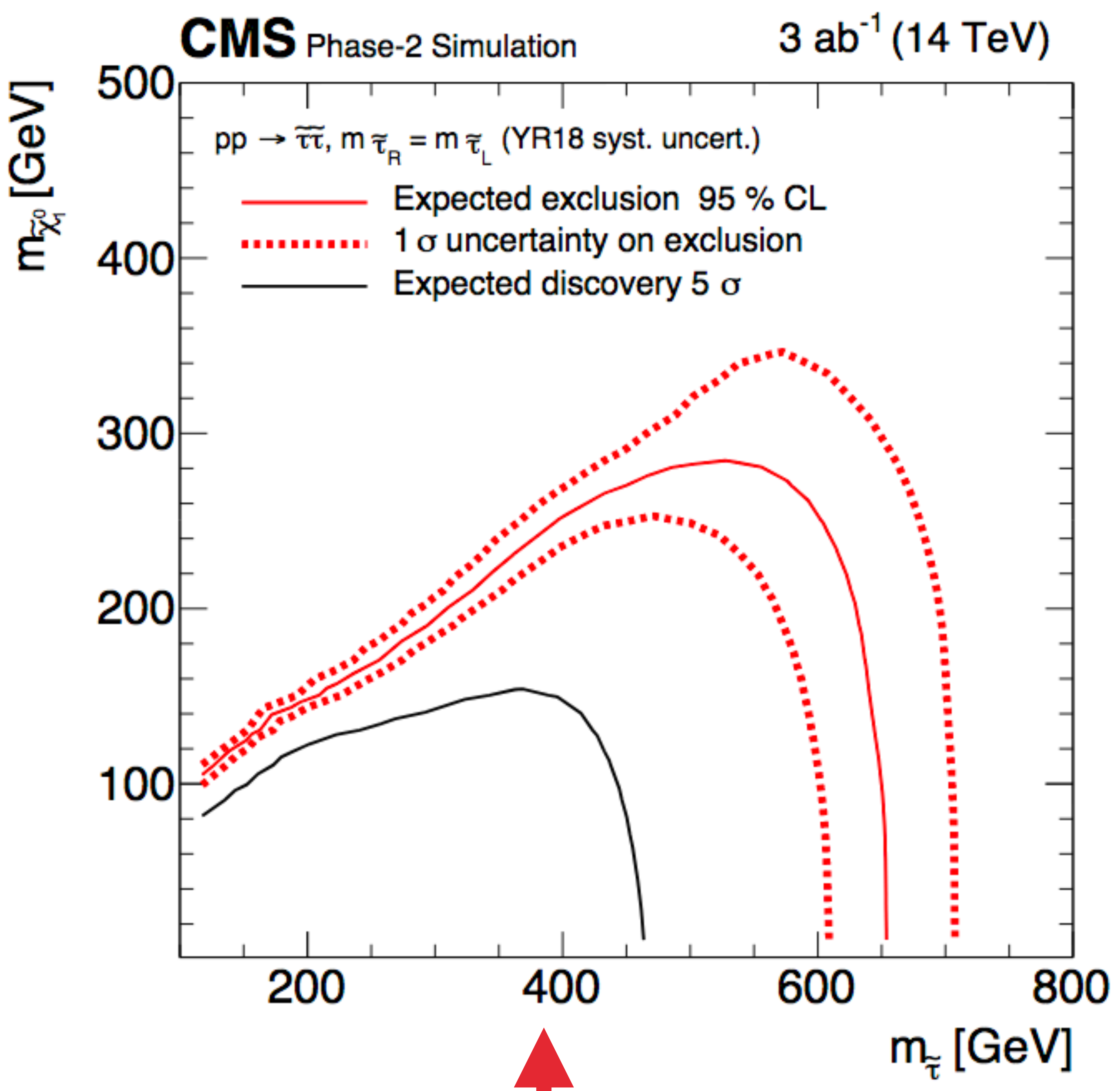




BSM PHYSICS – MAXIMISING DISCOVERY POTENTIAL

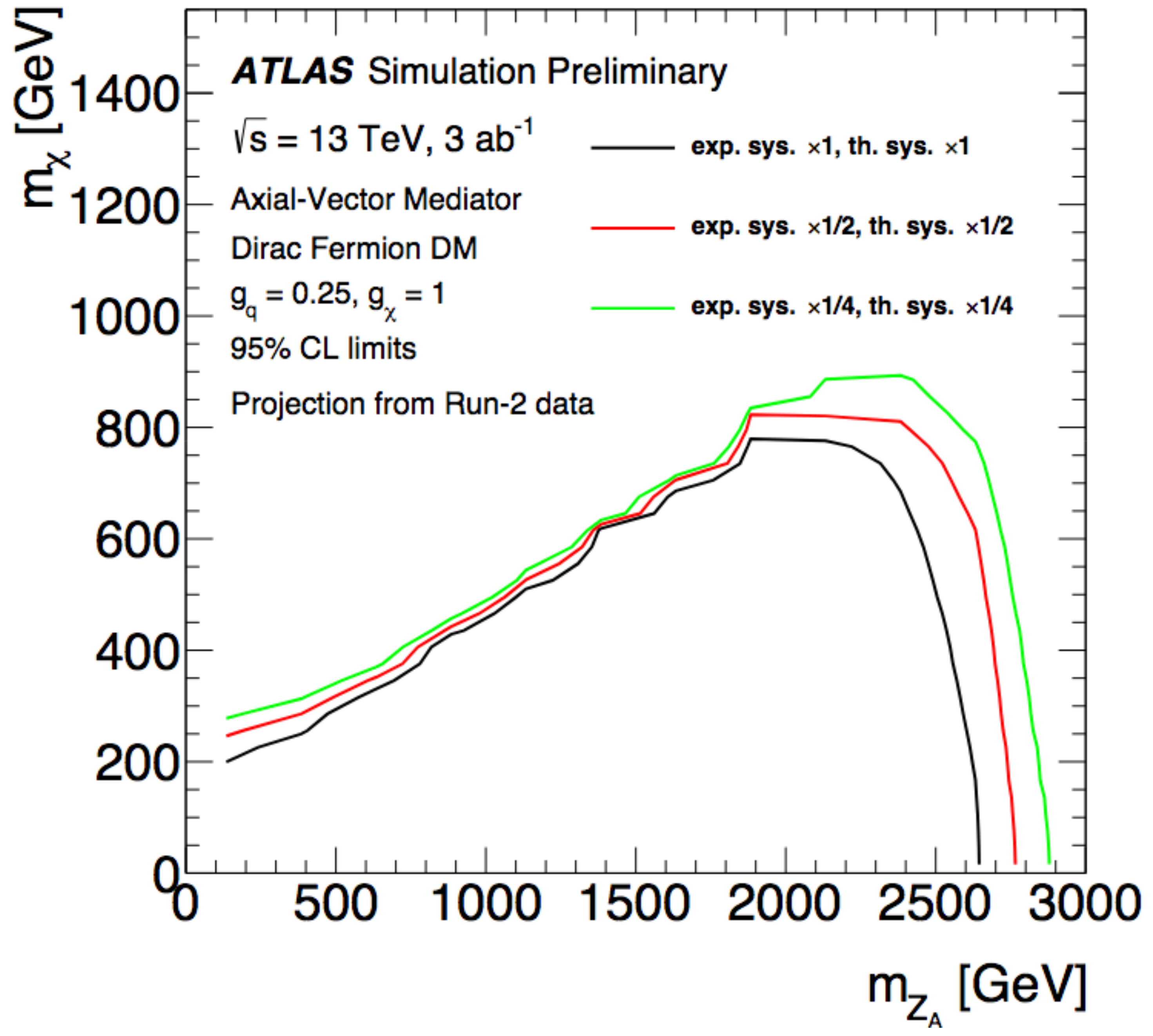
- Huge increase in sensitivity to SUSY signatures.
- E,g. Compressed SUSY models where difference in mass between new particles is small have barely been covered so far.
- With HL-LHC will significantly extend our reach





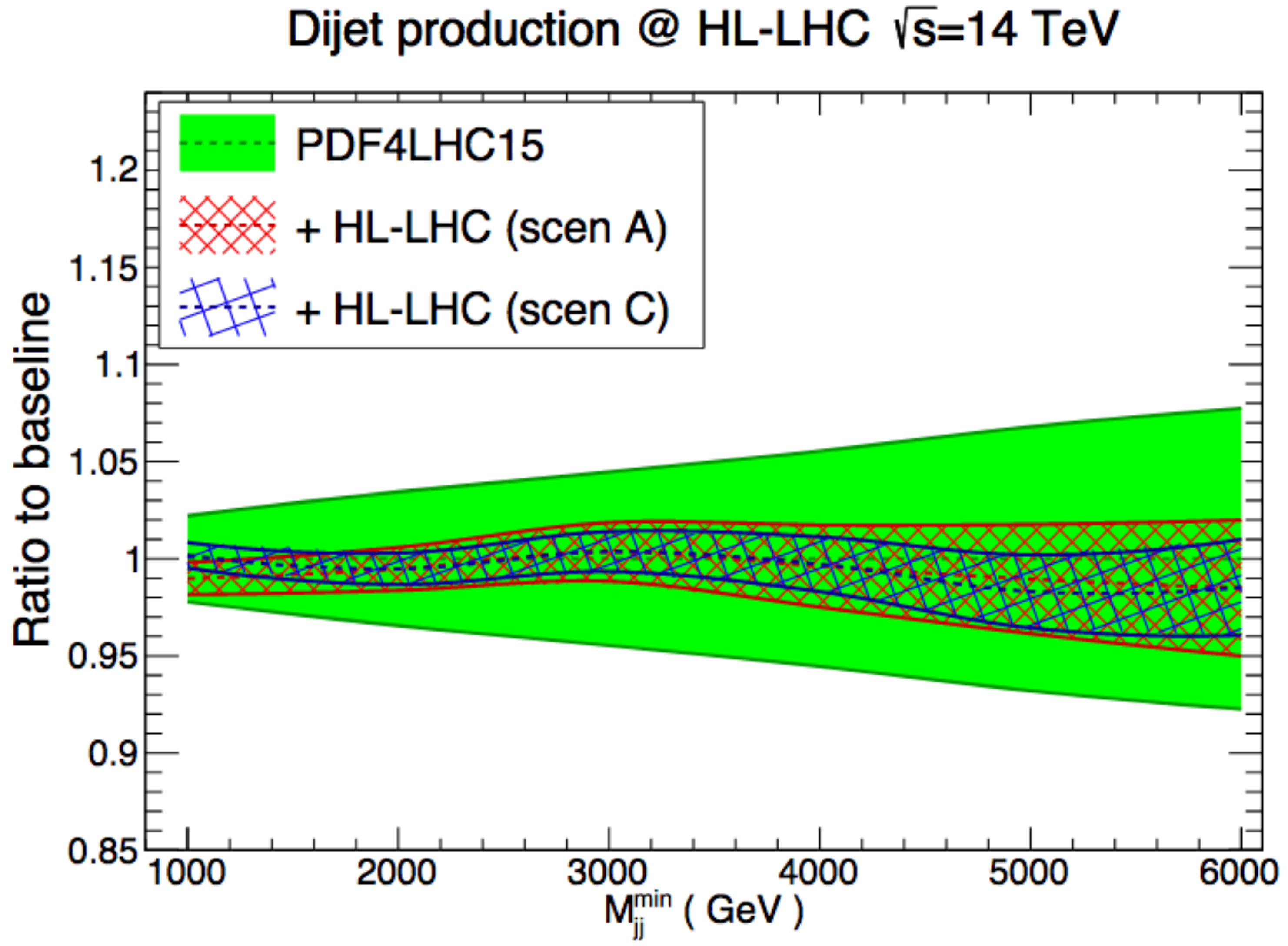
- Currently challenging scenario = di-stau production
- Only excluding ~ 100 GeV currently
- Will be able to reach ~500 GeV for discovery at HL-LHC

- In searches for Dark Matter will have much improved discovery reach - on the order of a ~ TeV for a key search using the monojet + missing energy signature



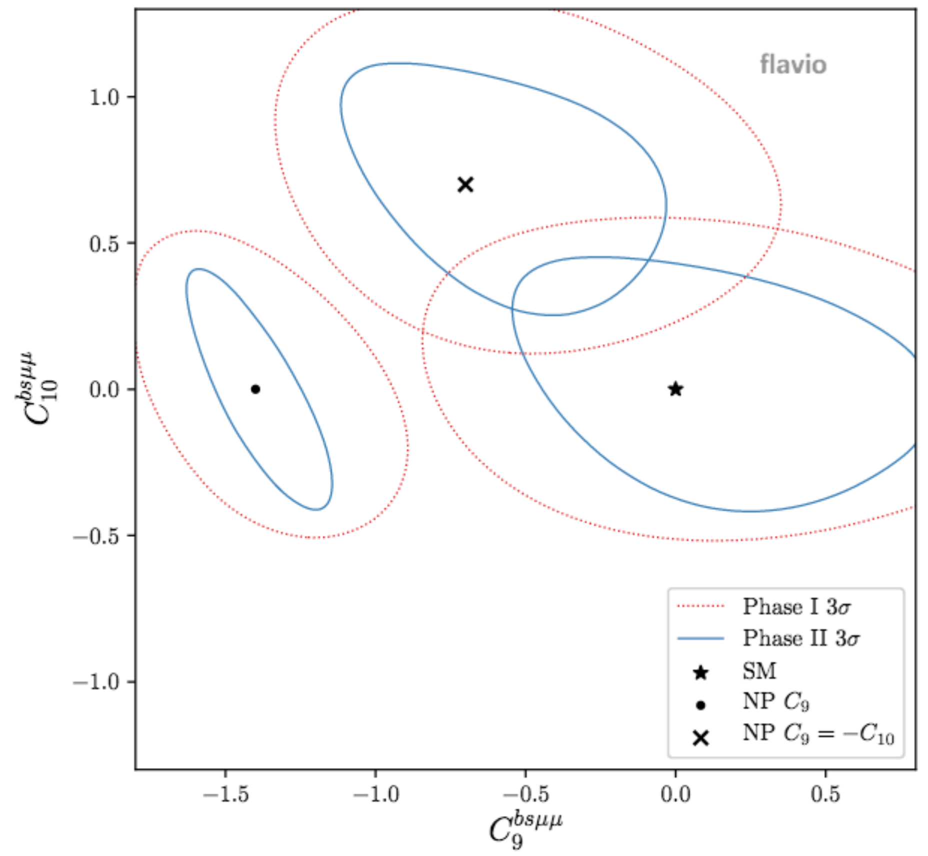
MANY OTHER IMPORTANT PHYSICS GOALS!!

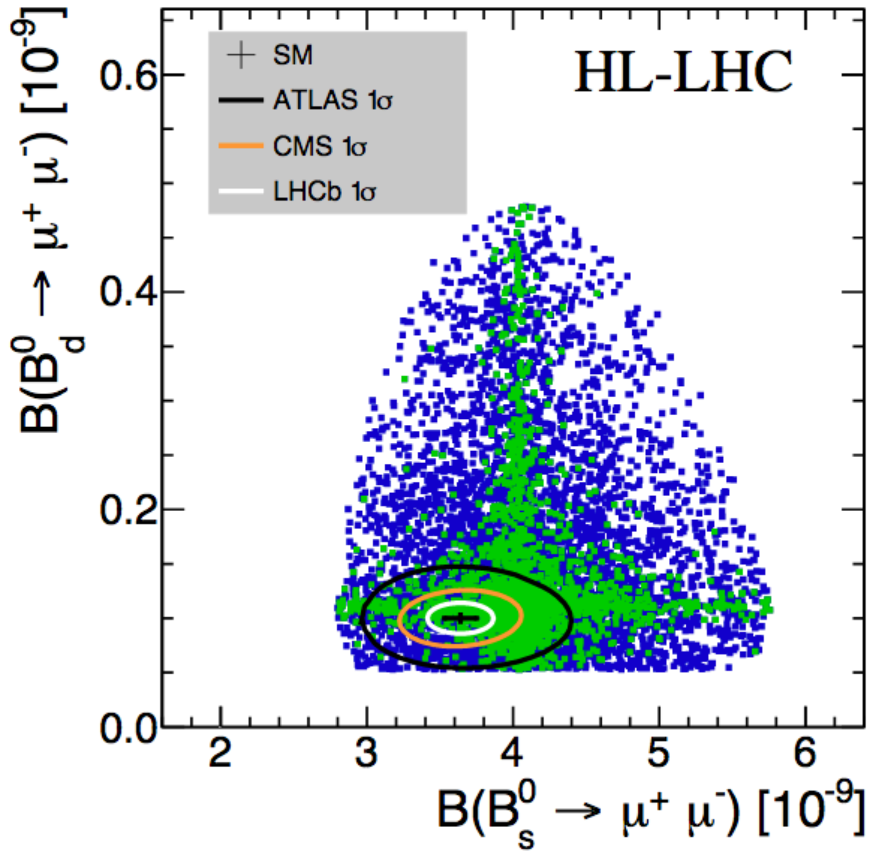
- Reducing errors significantly on PDFs - will feed in to improved theoretical predictions to help SM and BSM physics

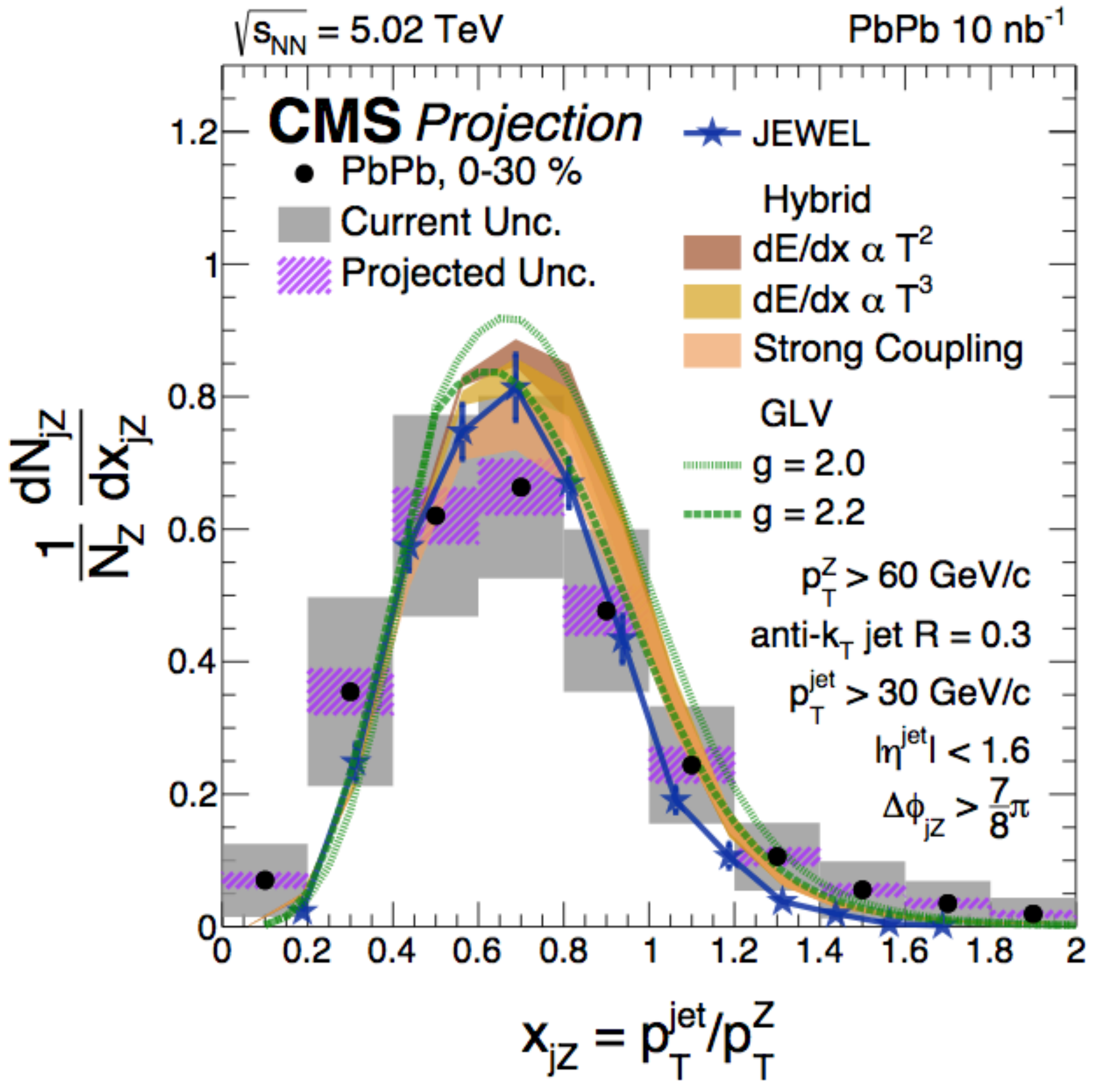


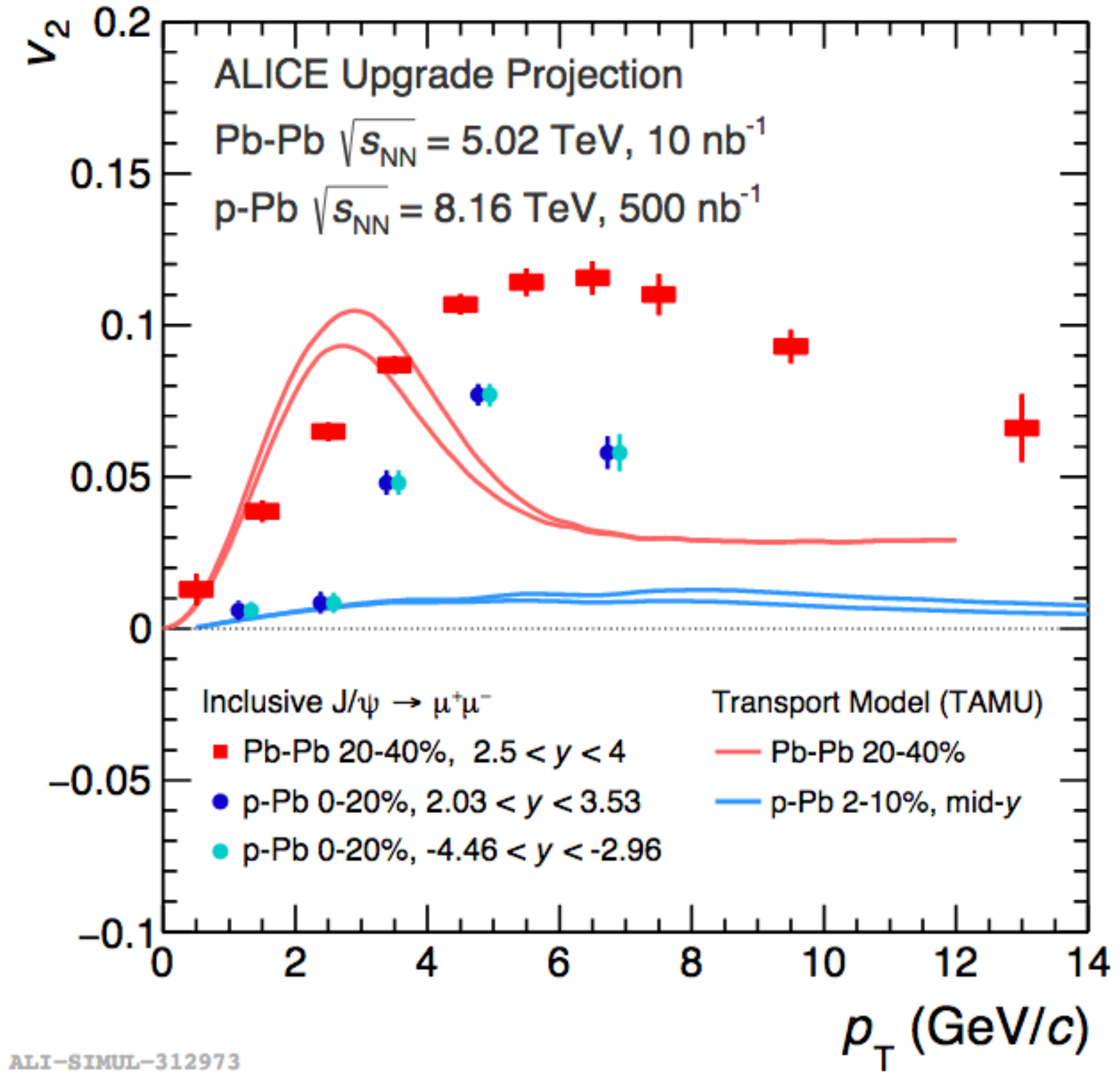
- Flavour physics: pushing FCNC measurements (stats limited), extremely sensitive probe to New Physics.
- Heavy Ion physics: microscopic structure of the Quark-Gluon Plasma, with much reduced uncertainties

combined ATLAS, CMS, LHCb









CMS PHASE 2

OVERALL PICTURE

CMS HL-LHC Upgrade

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
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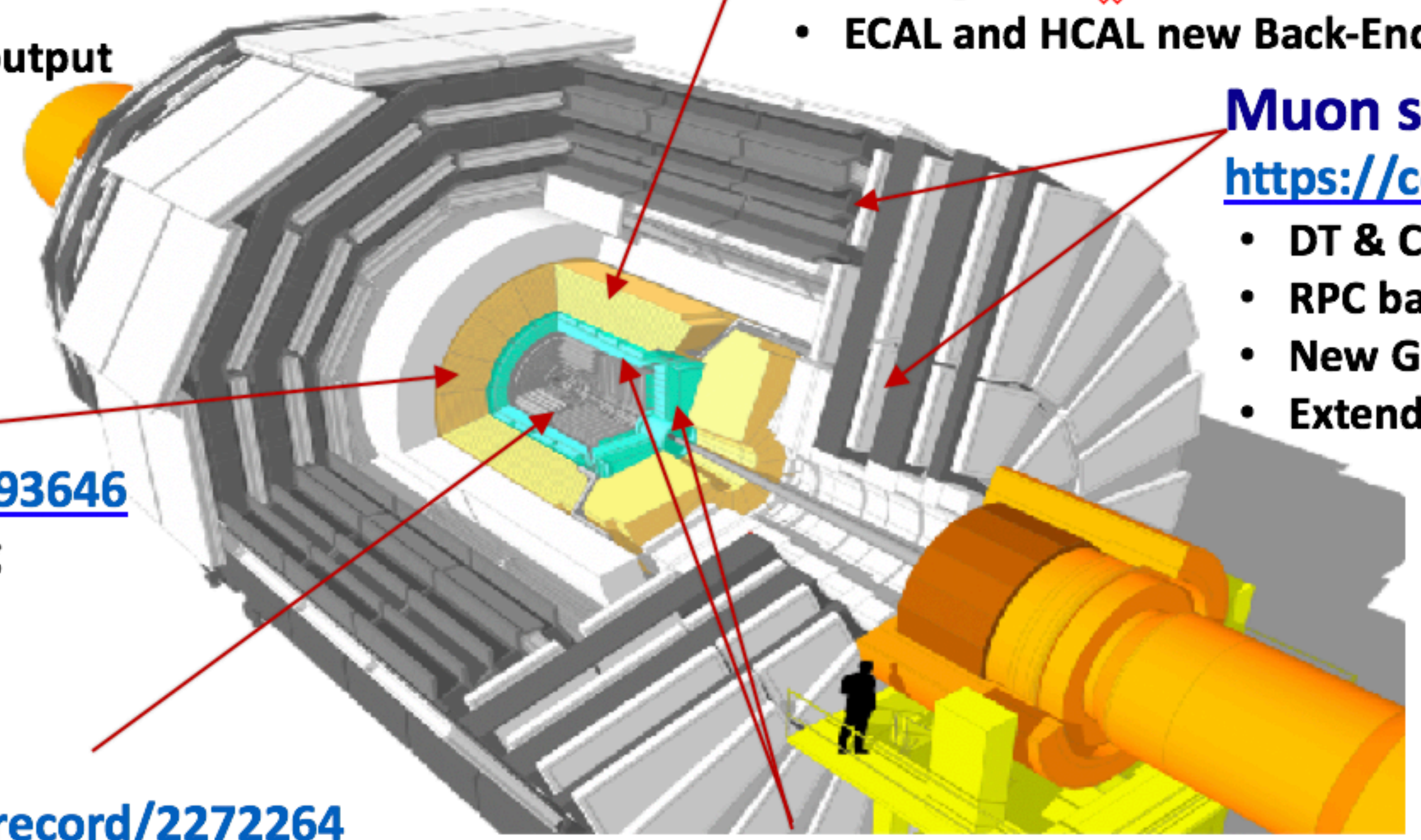
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity

OVERALL PICTURE – UK

CMS HL-LHC Upgrade

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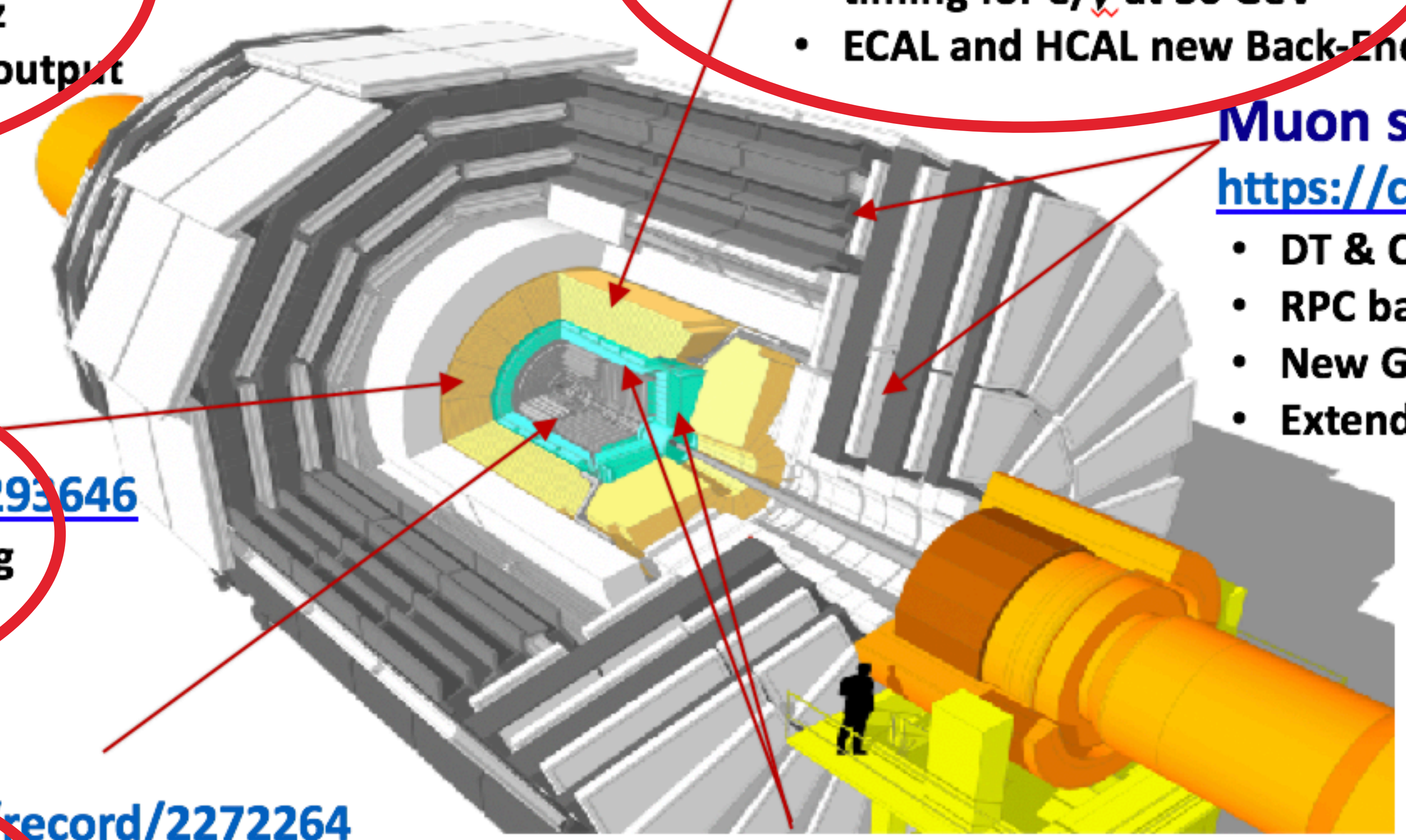

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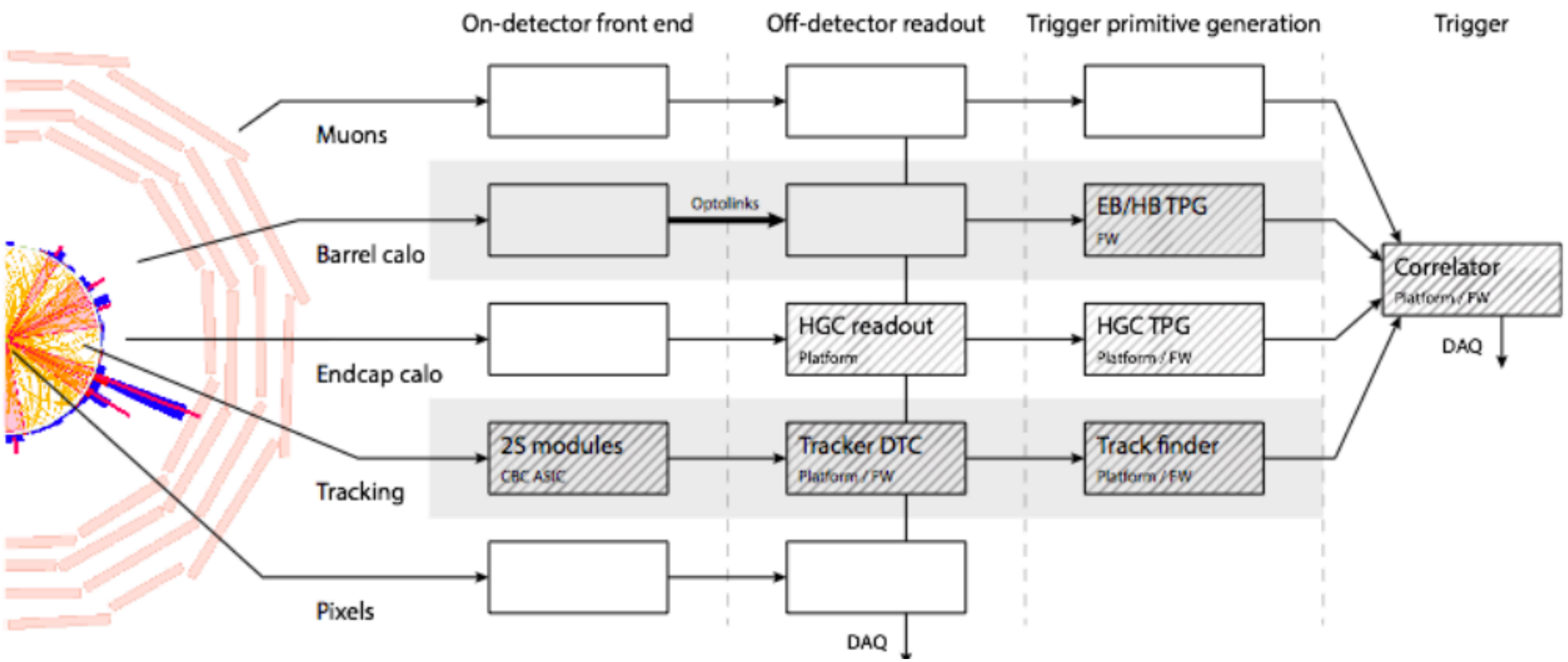
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity

OVERALL PICTURE – UK

- Strategy to build on success of original and Phase 1 UK-led projects
- Create common technology work package
- Maintain intellectual lead in all areas we participate in



CMS UK UPGRADE: COMMON TECHNOLOGY – SERENITY

Prototype ATCA card to provide back-end electronic services for CMS

- Flexible, dual FPGA card
- Flexible, pluggable FPGA units

Small production of 15 cards

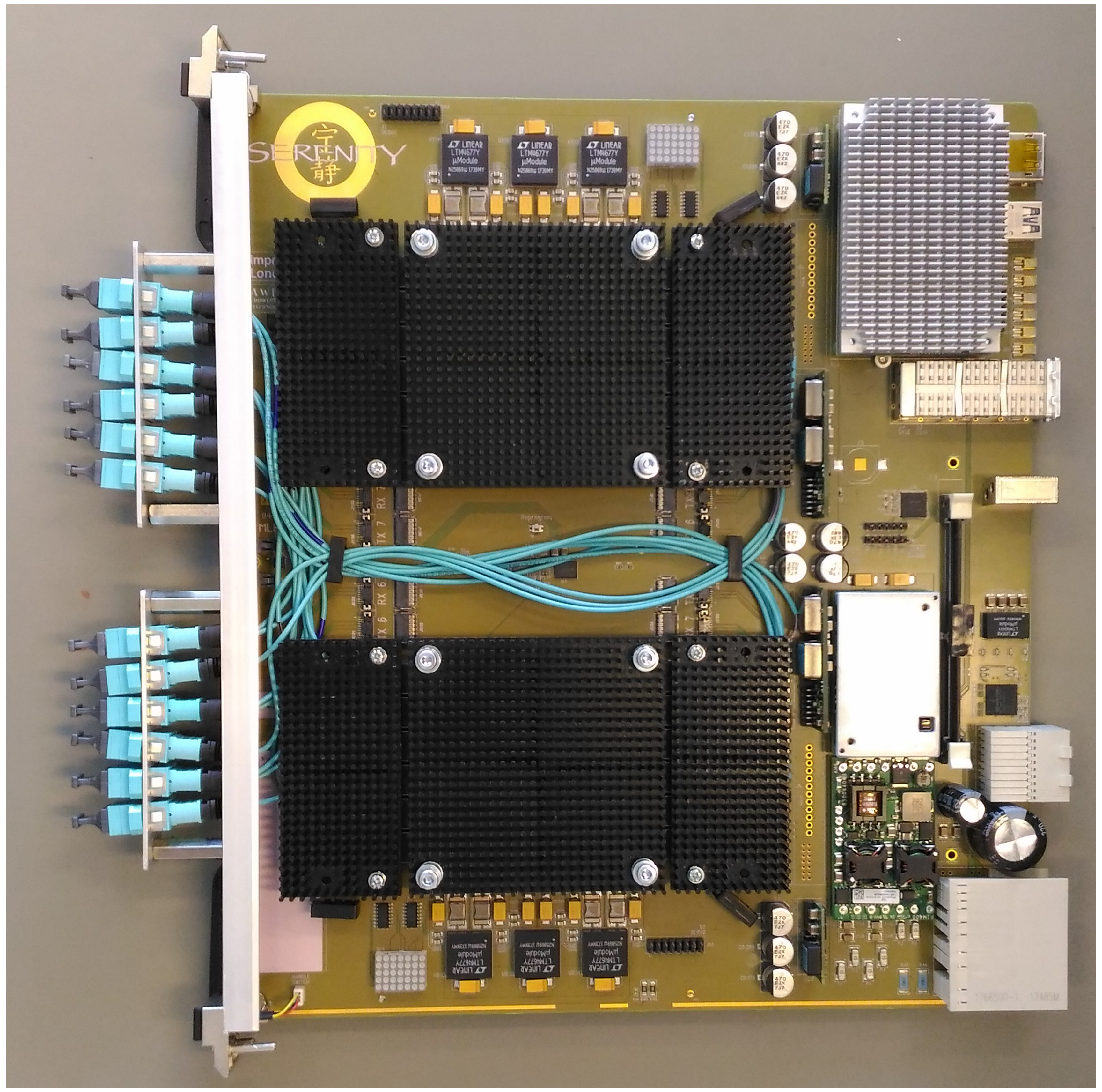
- 9 delivered with 6 more on the way.
- For use in Calorimeter, Trigger & Tracker

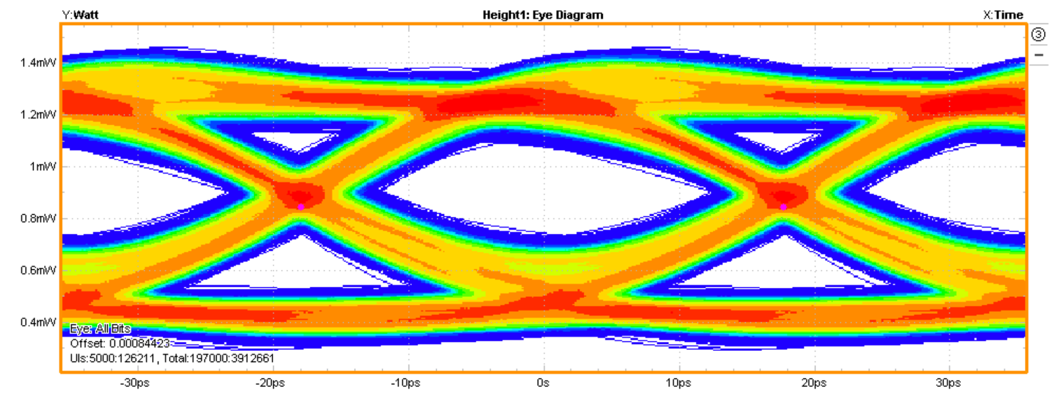
Focus has now shifted

- Completing infrastructure firmware & software
- Integrating application specific payload firmware
- System integration
- Documentation
  - http://cern.ch/serenity

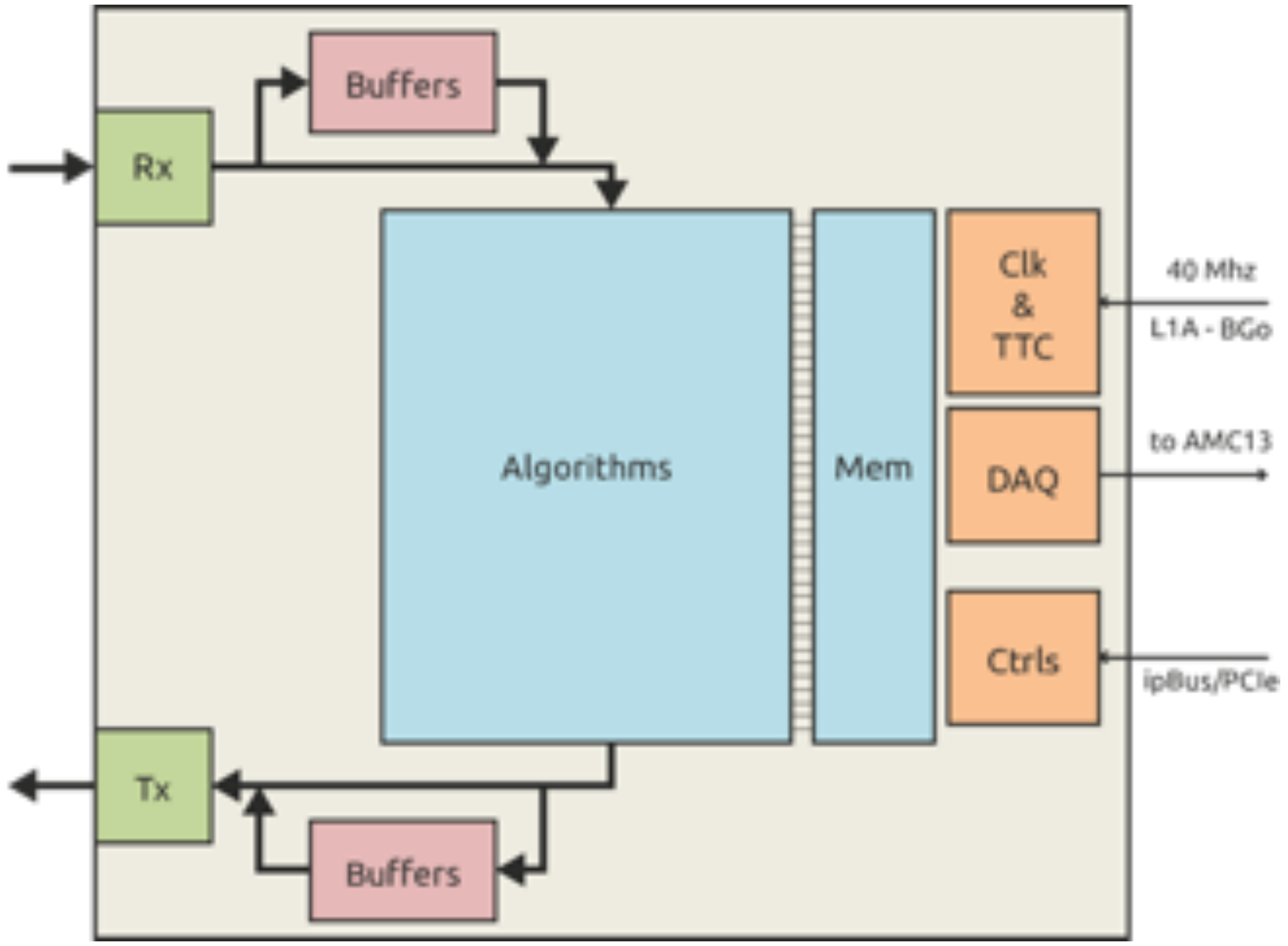
7Tb/s: 288 fibres @ 25Gb/s via 12x MTP24s

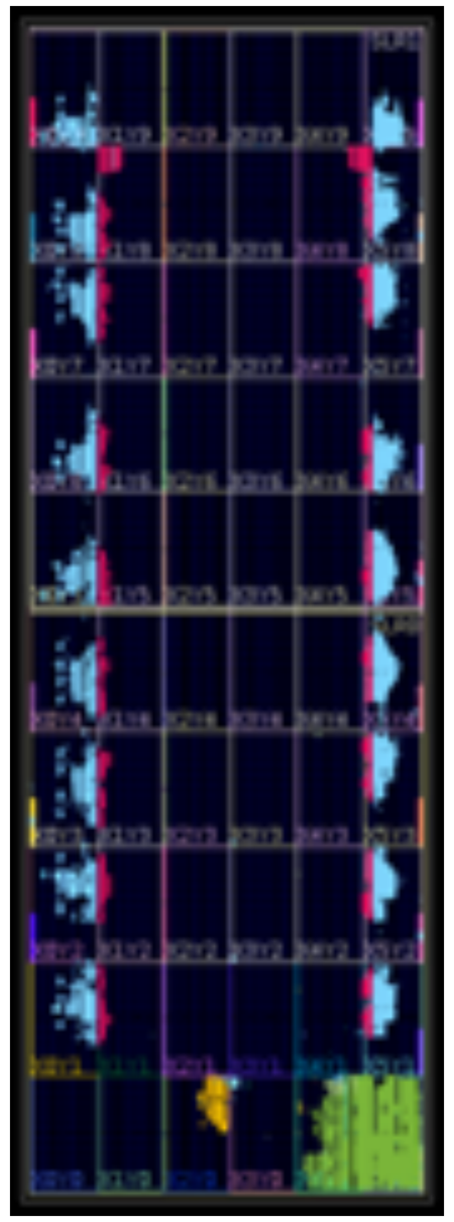
Feeds directly into all other UK upgrade projects





CMS UK UPGRADE: COMMON TECHNOLOGY –NEXT STEPS





Infrastructure firmware & software provides common services

- •Communication,
- •Fast Control & Feedback (trigger, timing, throttle)
- •SerDes Links (aligned, fixed, low latency)
- •Providing input & output buffering
- •DAQ path

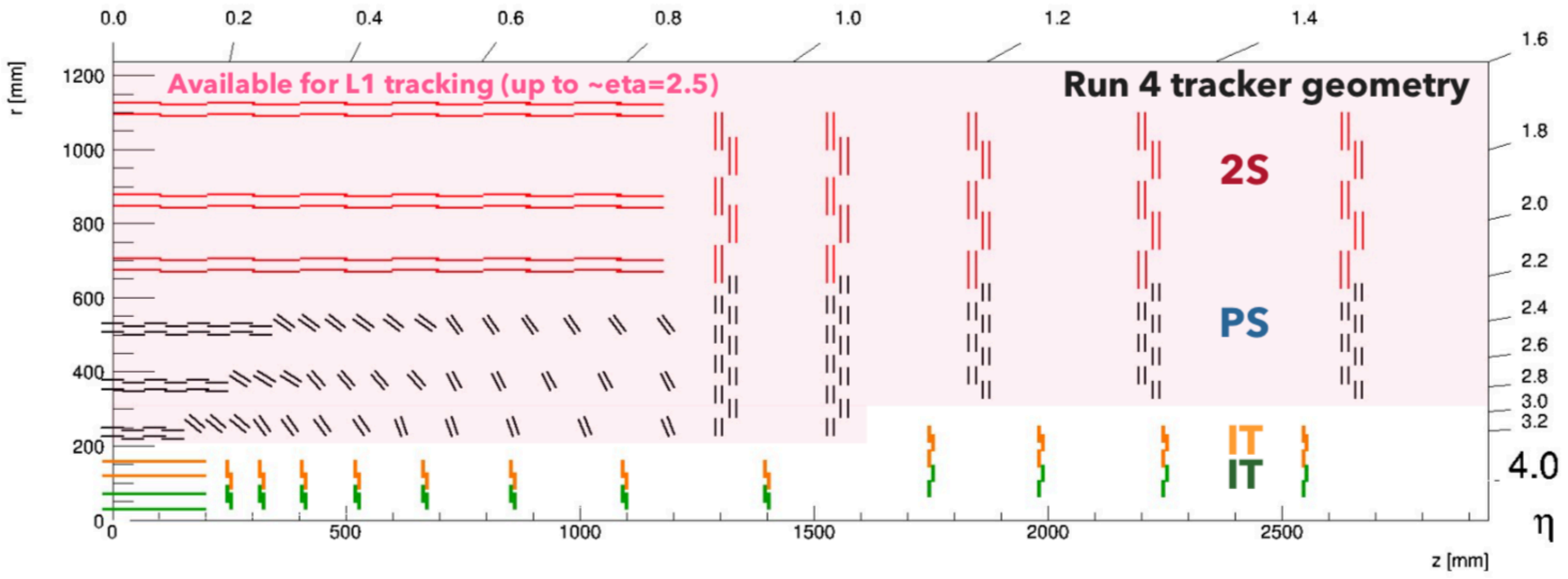
Challenge now will move to

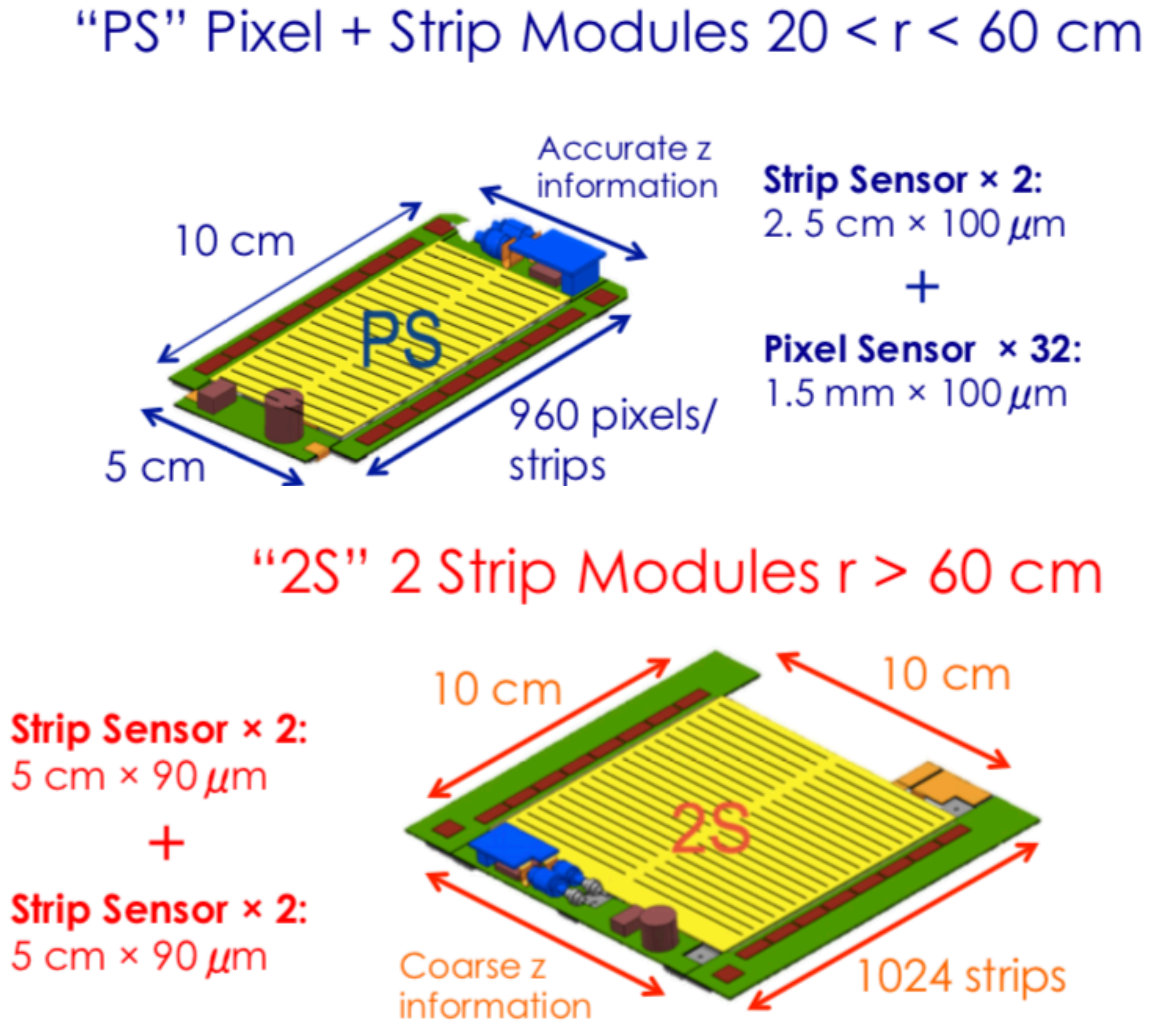
- Delivering system, rather than a few individual cards.
- Procurement of 100s of cards.
    - **Multi-million CHF purchase.**
- **Significant quality assurance task.**
- Looking towards next iteration of the card, particularly production aspects

Commissioning Phase

- Still several years away, but planning for this is already starting

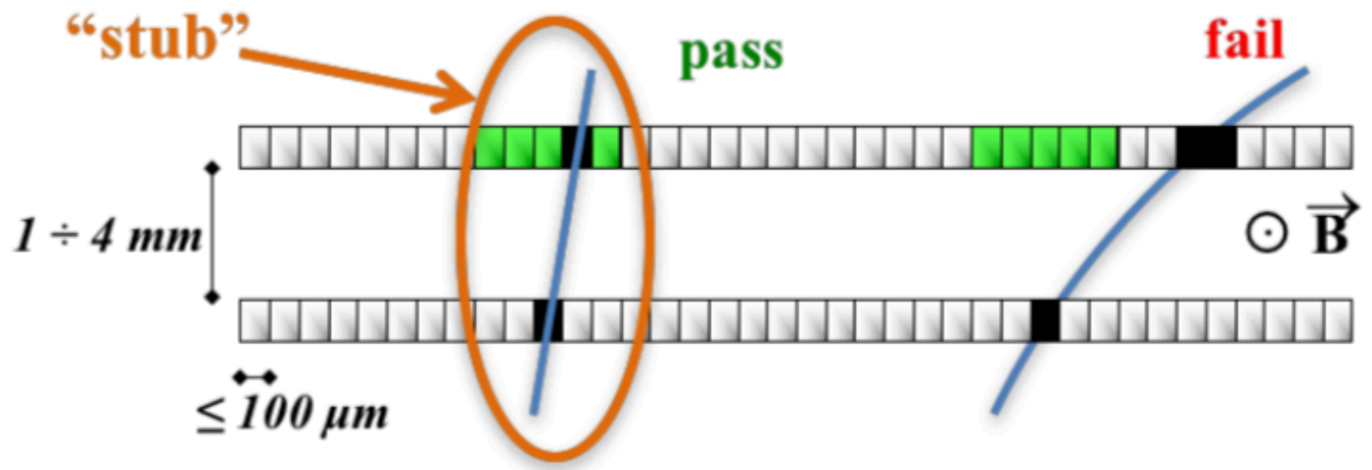
CMS UK UPGRADE: TRACKER





<u>Two key areas of UK involvement:</u>

- Developed concept of "p_T" modules to discriminate high p_T tracks - including leading design and production of readout ASIC to be used in the outer layer "2S" modules (CBC)



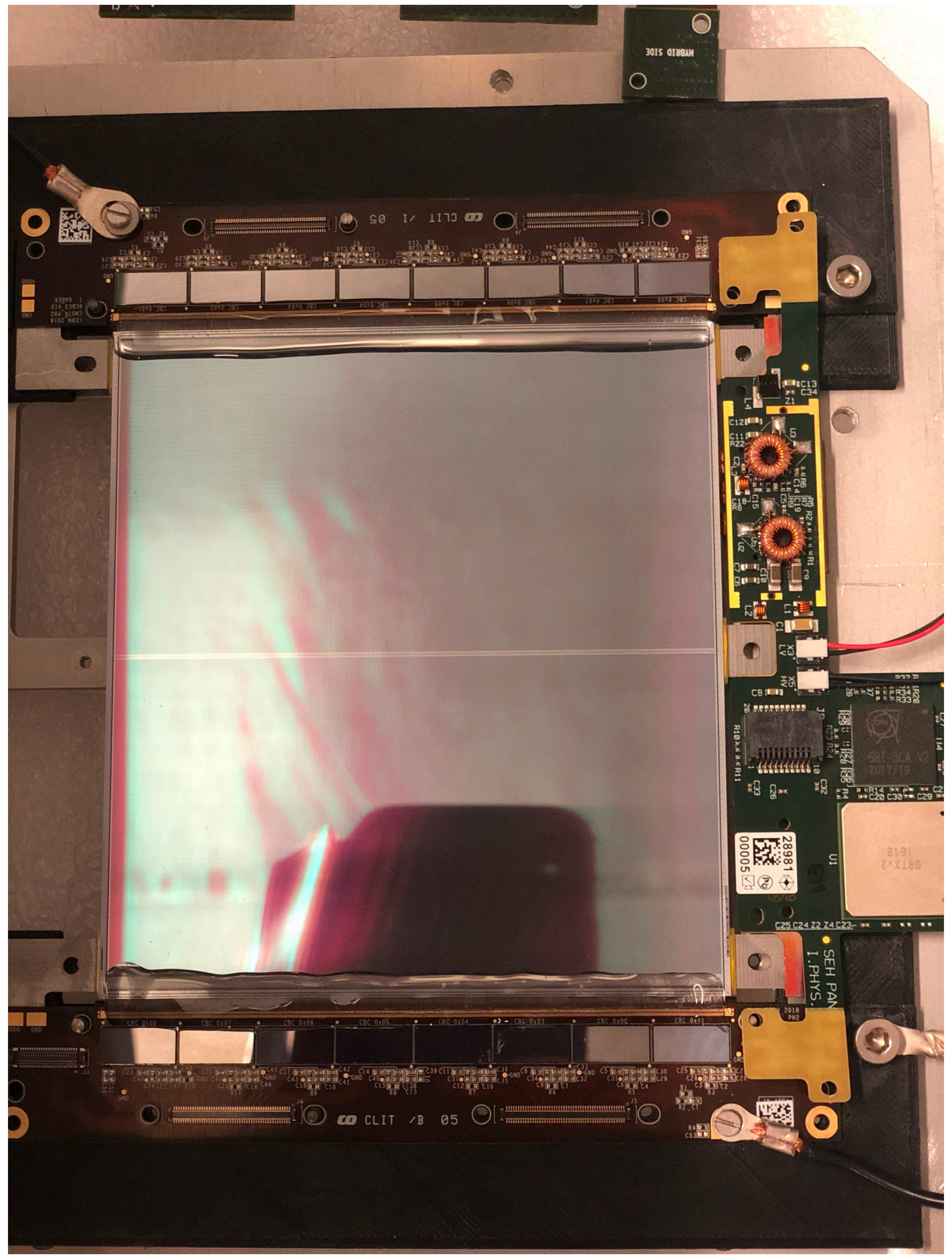
- Developed and led all-FPGA solution to provide tracking information to L1 trigger at 40 MHz

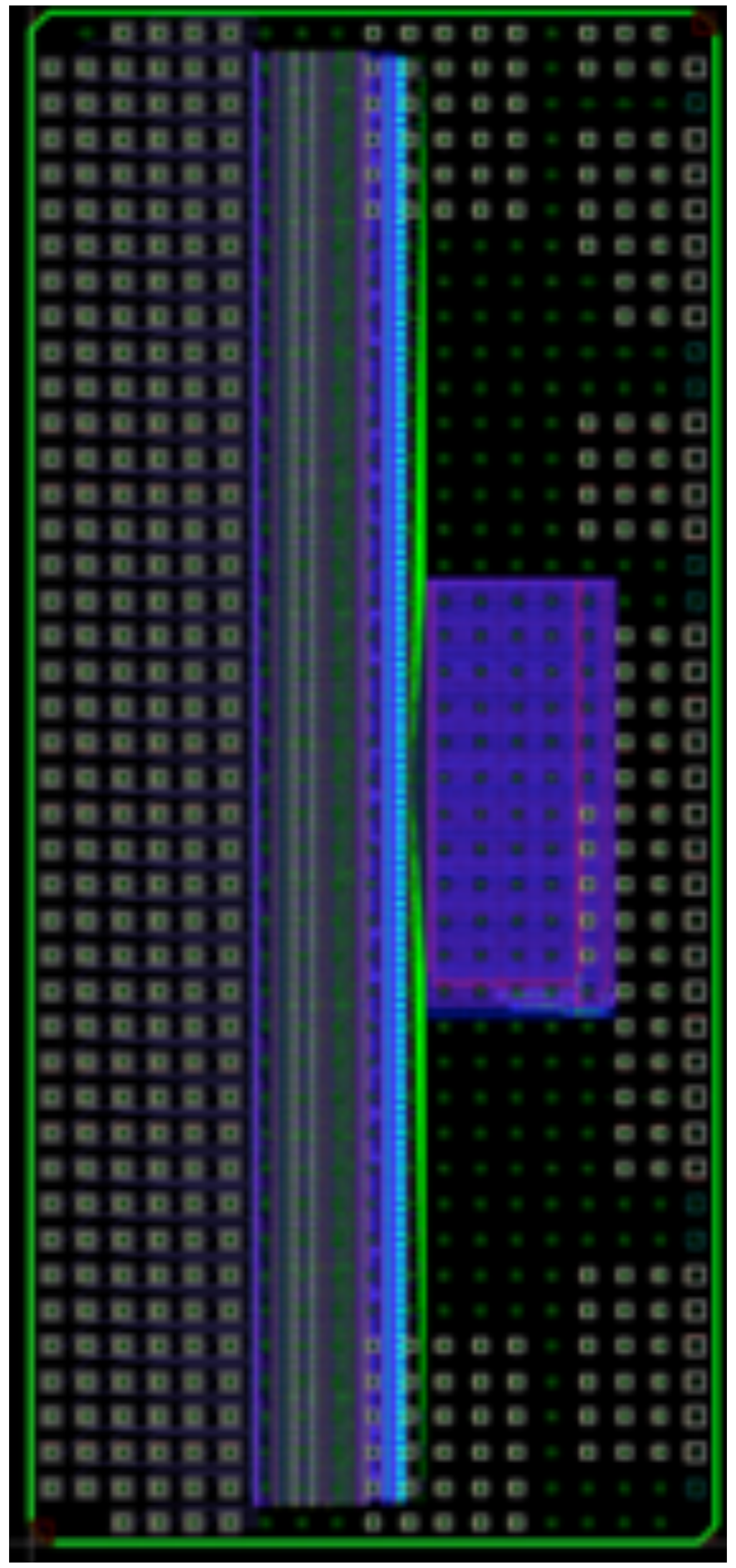
CMS UK UPGRADE: TRACKER FRONT-END

CMS Binary Chip (CBC)

- Front-End read-out ASIC for “2S” modules. 130nm CMOS.
- 254 Channels @ 320 MHz readout, latency 12.8 us
- CBC development is now complete.
- 24 CBC3.1 wafers have been received to evaluate for production yield, another 24 expected next month.

These are the final pre-production orders, and then would move on to large scale module assembly





CMS UK UPGRADE: TRACK-FINDING FOR L1 TRIGGER

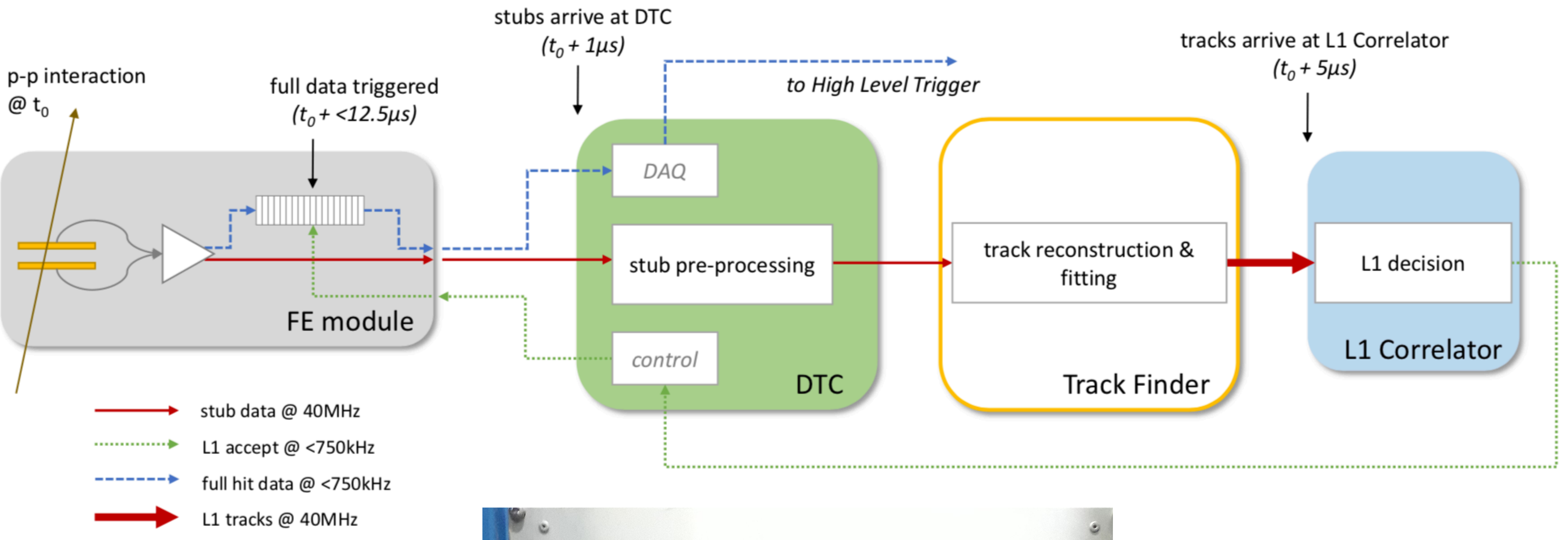
UK lead:

- Developing concept of L1 Track-Trigger
- Implementing all-FPGA working solution including SW/FW/HW demonstrator

- For overall project UK has responsibility for Data, Trigger & Control card (DTC), and for developing Track-Finding algorithms

Current status:

- Preliminary firmware for stub processing in DTC completed and running at 360 MHz
- TMTT L1 Tracking algorithm run on Serenity at 320 MHz
- Hybrid algo with US contribution working in software, being translated to firmware via HLS
- Integration tests at CERN scheduled to start this month

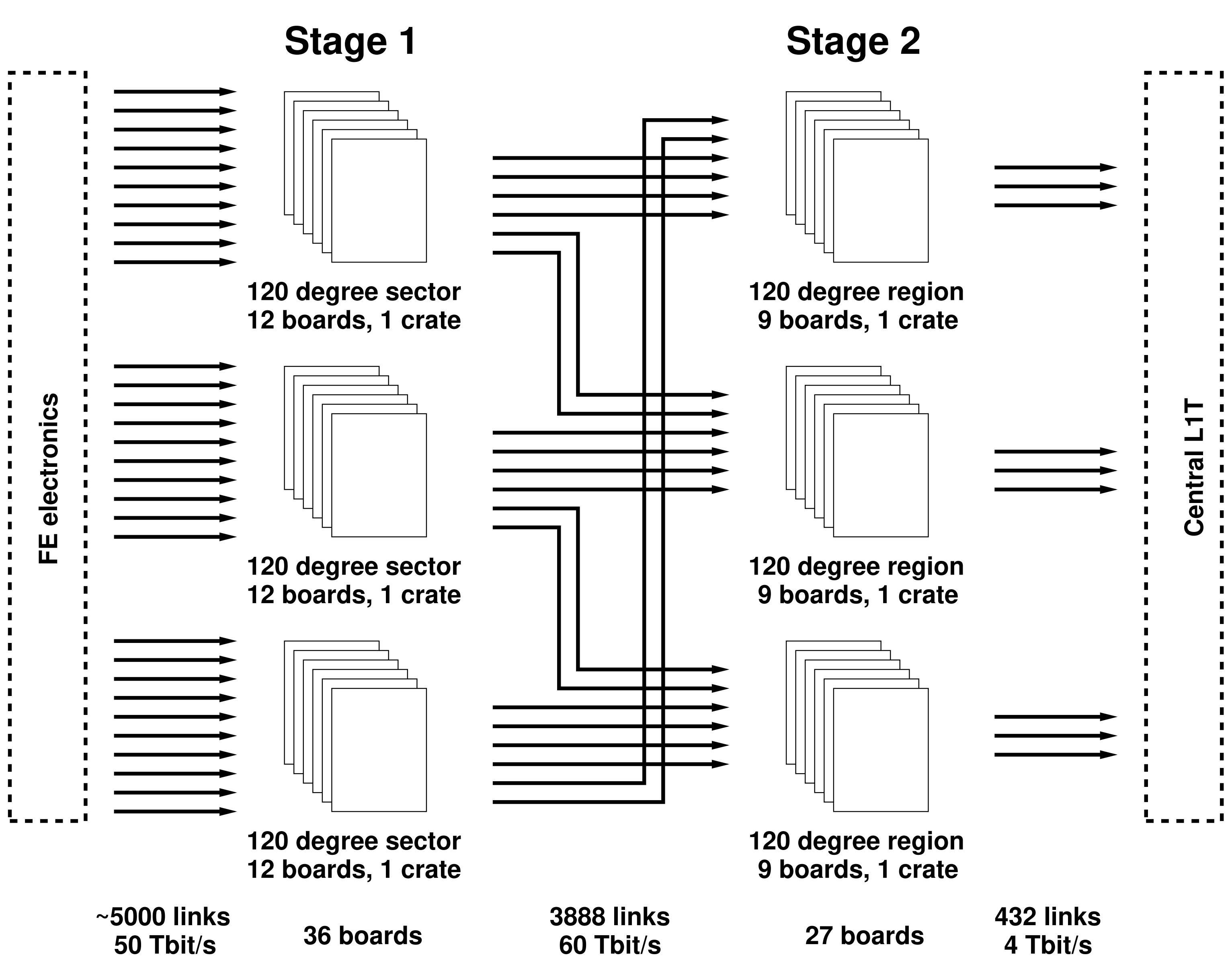


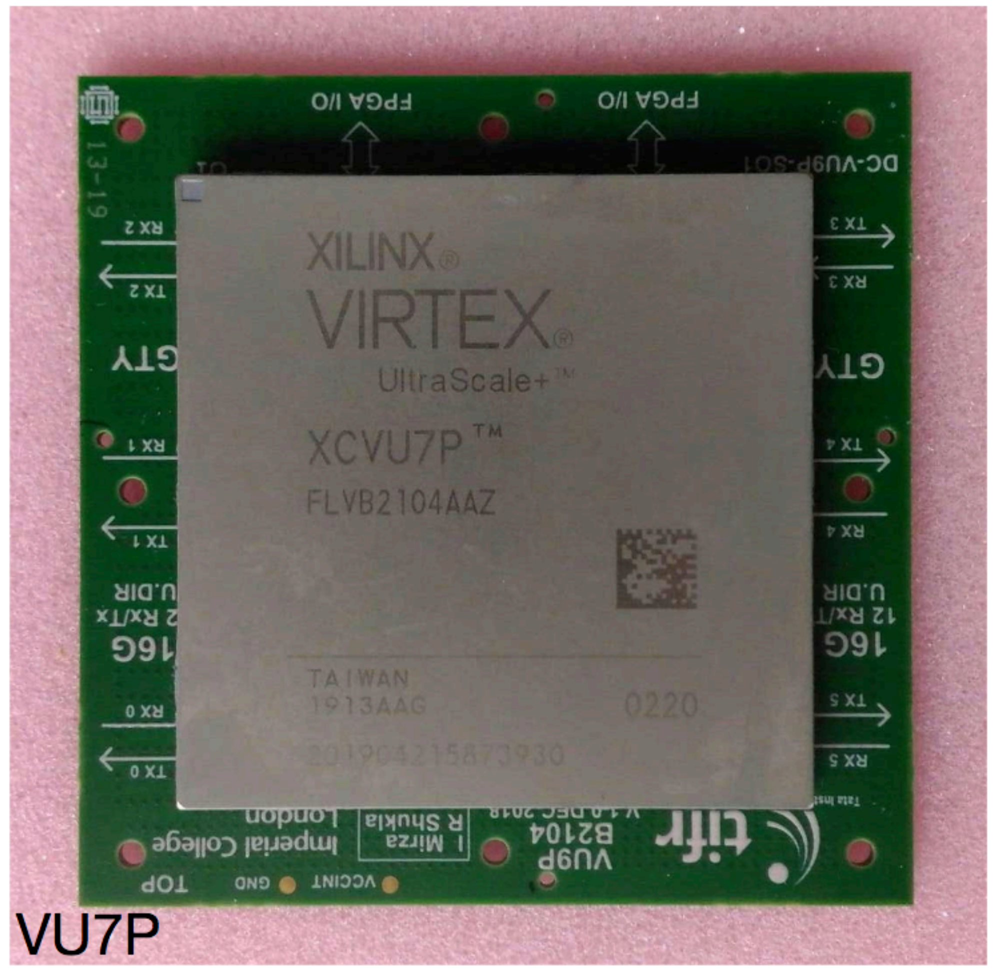
CMS UK UPGRADE: HIGH-GRANULARITY CALORIMETER

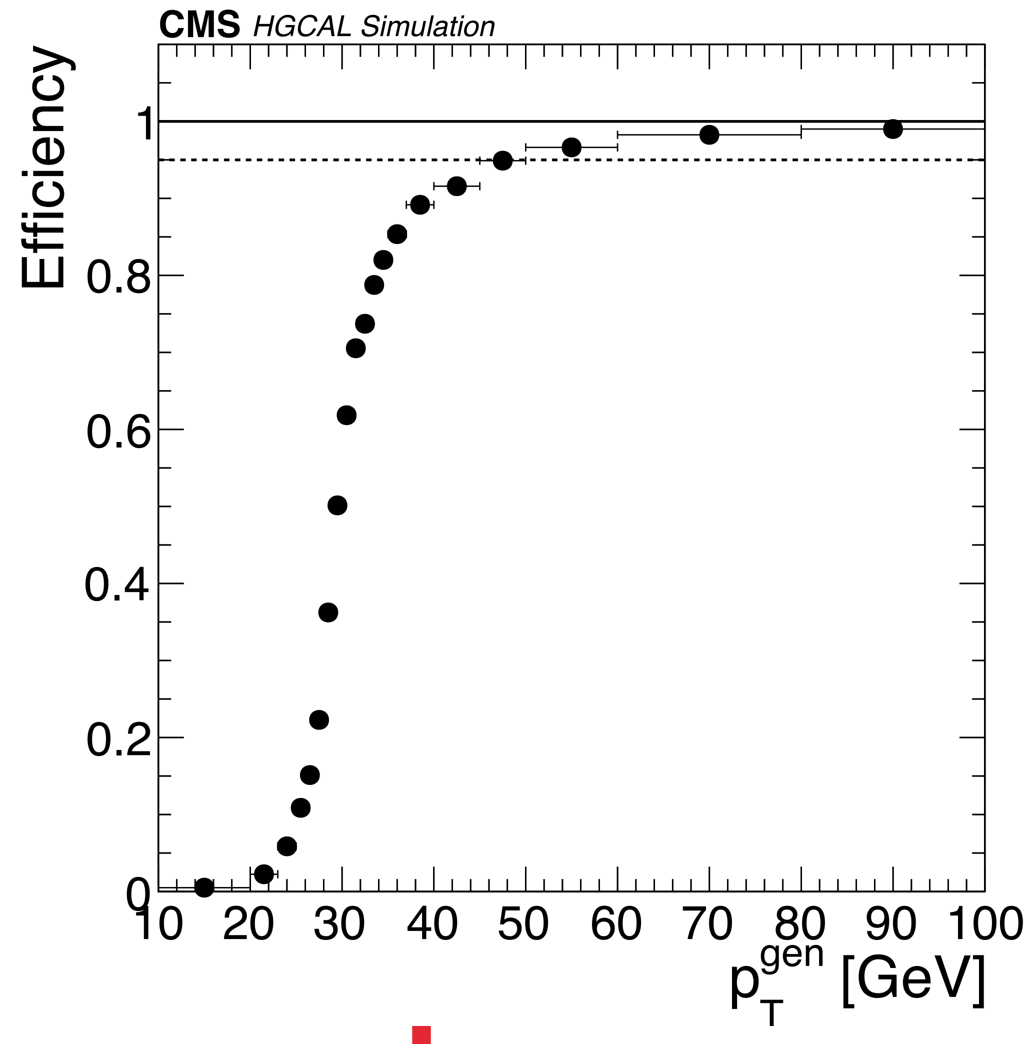
Key areas of UK involvement:

- UK developed and led the concept of new paradigm in calorimetry.
- Leading role in Trigger primitive development and electronics, and simulation

TP Architecture for one end-cap





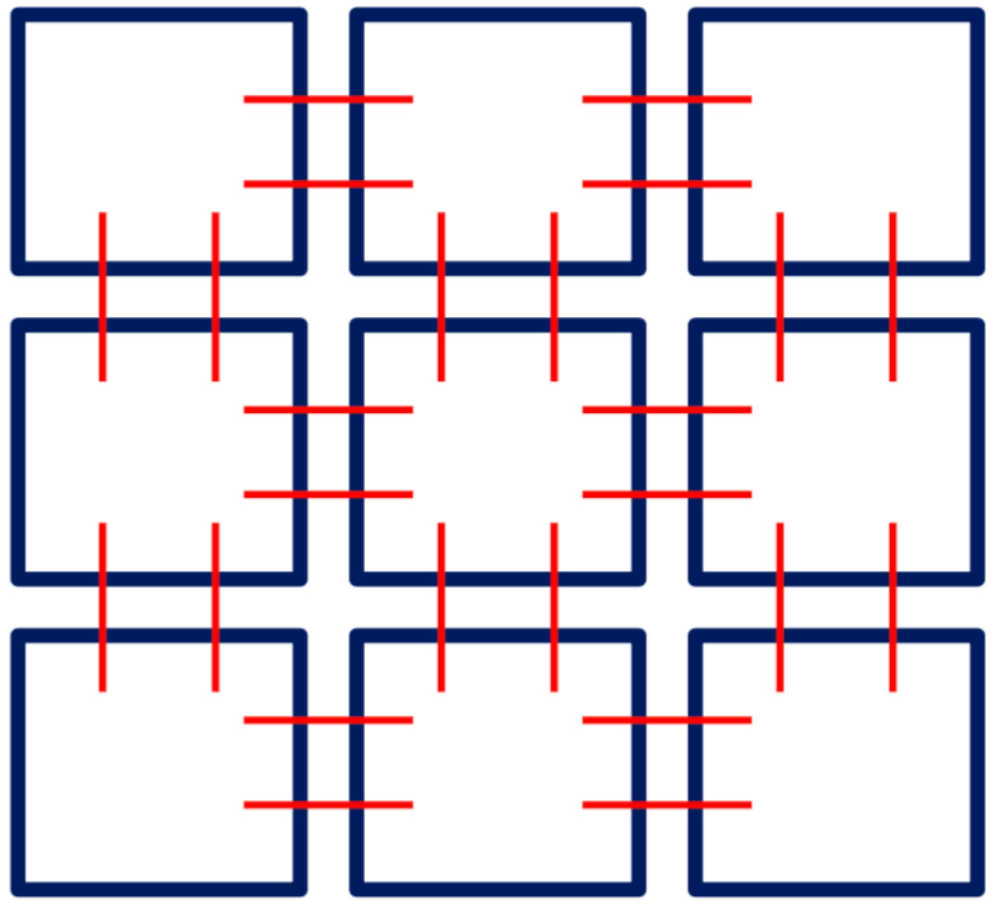


- Large and complex project pushing technology to the limit
- Huge number of trigger channels
- Very high data occupancy.
- However simulation shows excellent efficiency and resolution can be achieved.

CMS UK UPGRADE: BARREL CALORIMETER

Key areas of UK involvement:

- Trigger primitive software and firmware for upgraded ECAL barrel
- Optical fibre routing

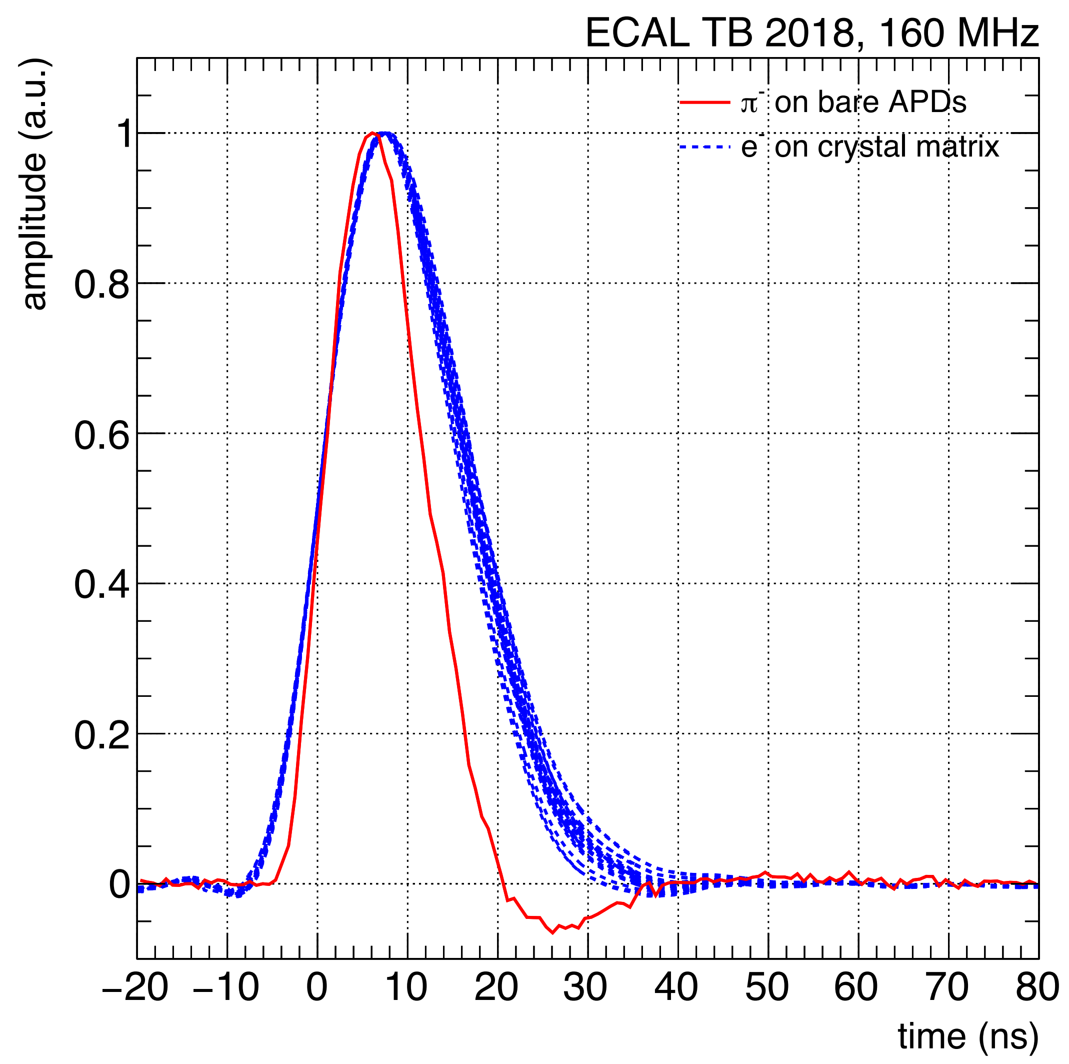


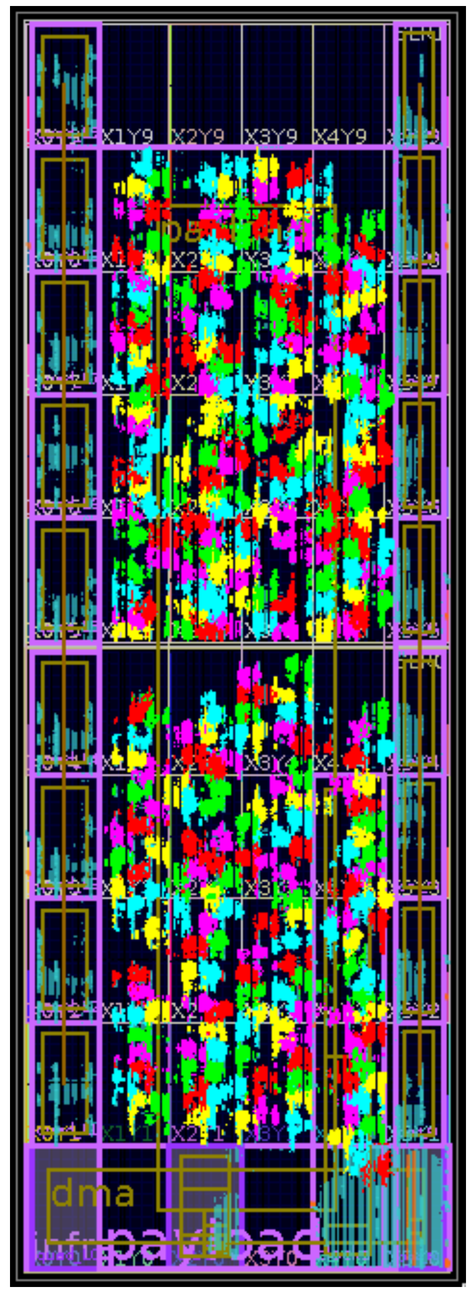
Developed preliminary ECAL crystal sharing scheme based on Barrel Calorimeter TDR design

sharing of crystal data between 216 trigger processor FPGAs serving 36 ECAL Barrel supermodules

using technology developed for CMS Phase 1 Calorimeter Trigger upgrade

Now being revised with an updated and expanded sharing scheme





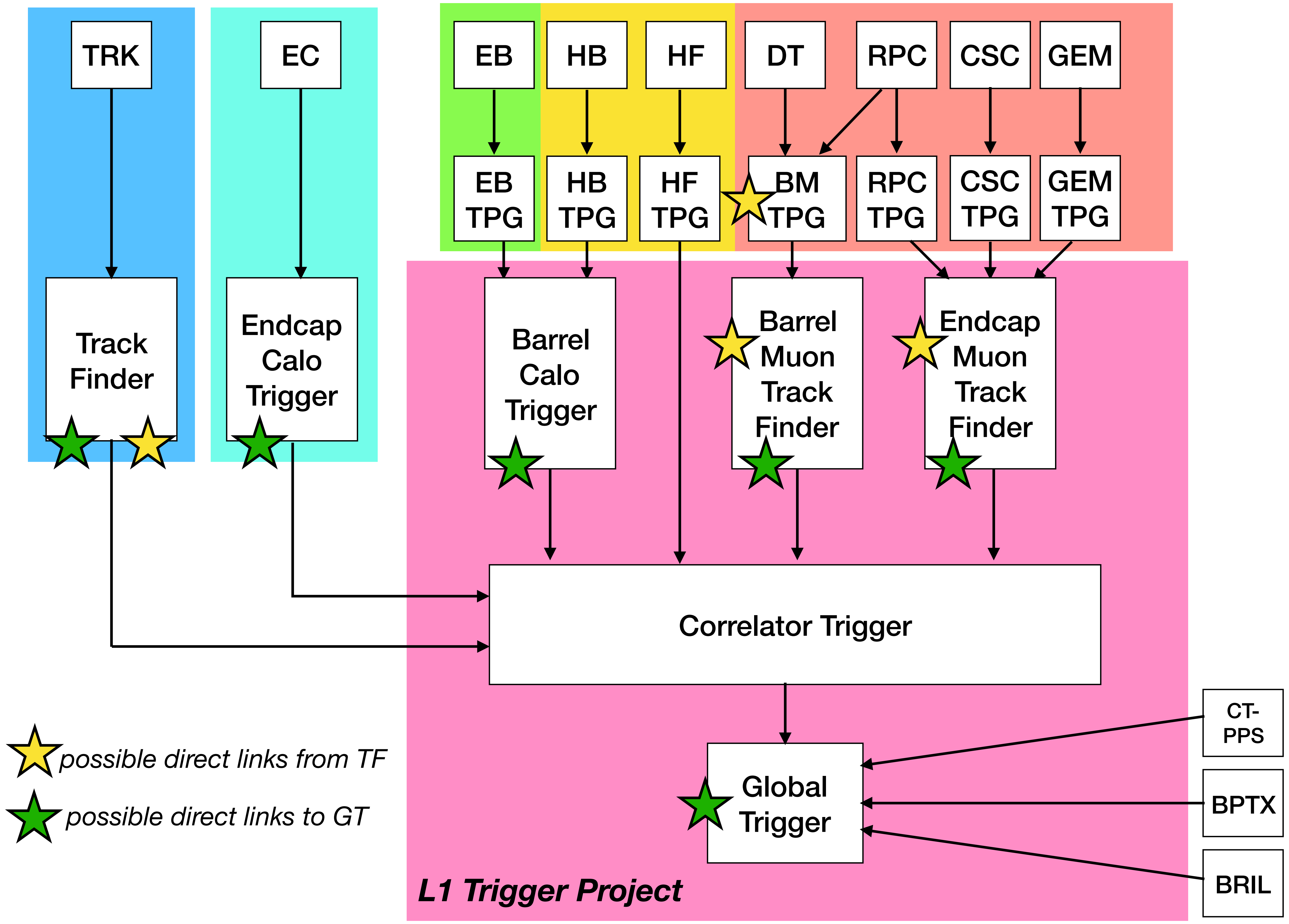
Developed first version of ECAL trigger primitive firmware to reject direct signals ("spikes") in APD photodetectors

based on differences in pulse shapes between spike and electron/photon signals

Now updating algorithm to optimise FPGA resource usage and developing emulator software

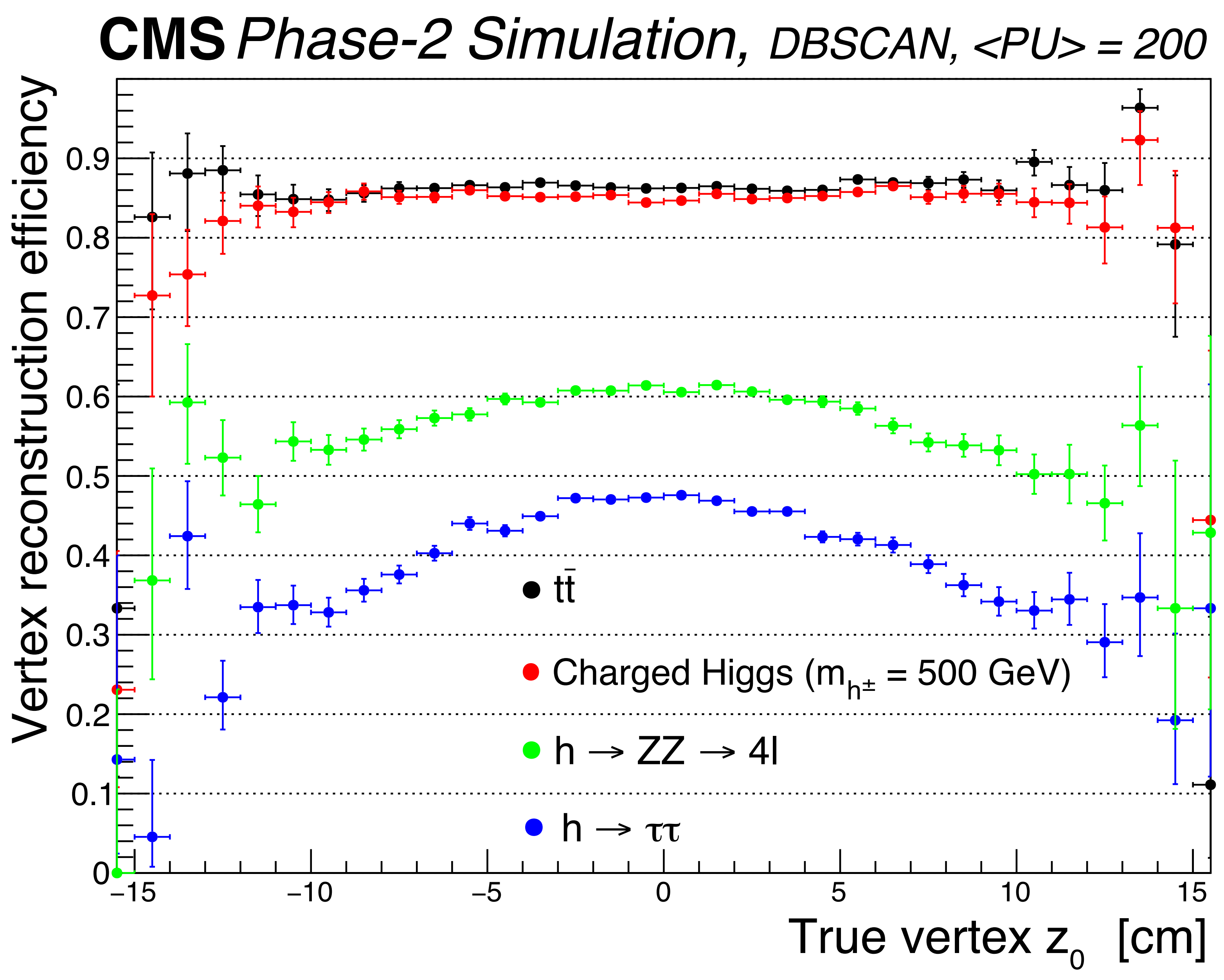
CMS UK UPGRADE: L1 TRIGGER

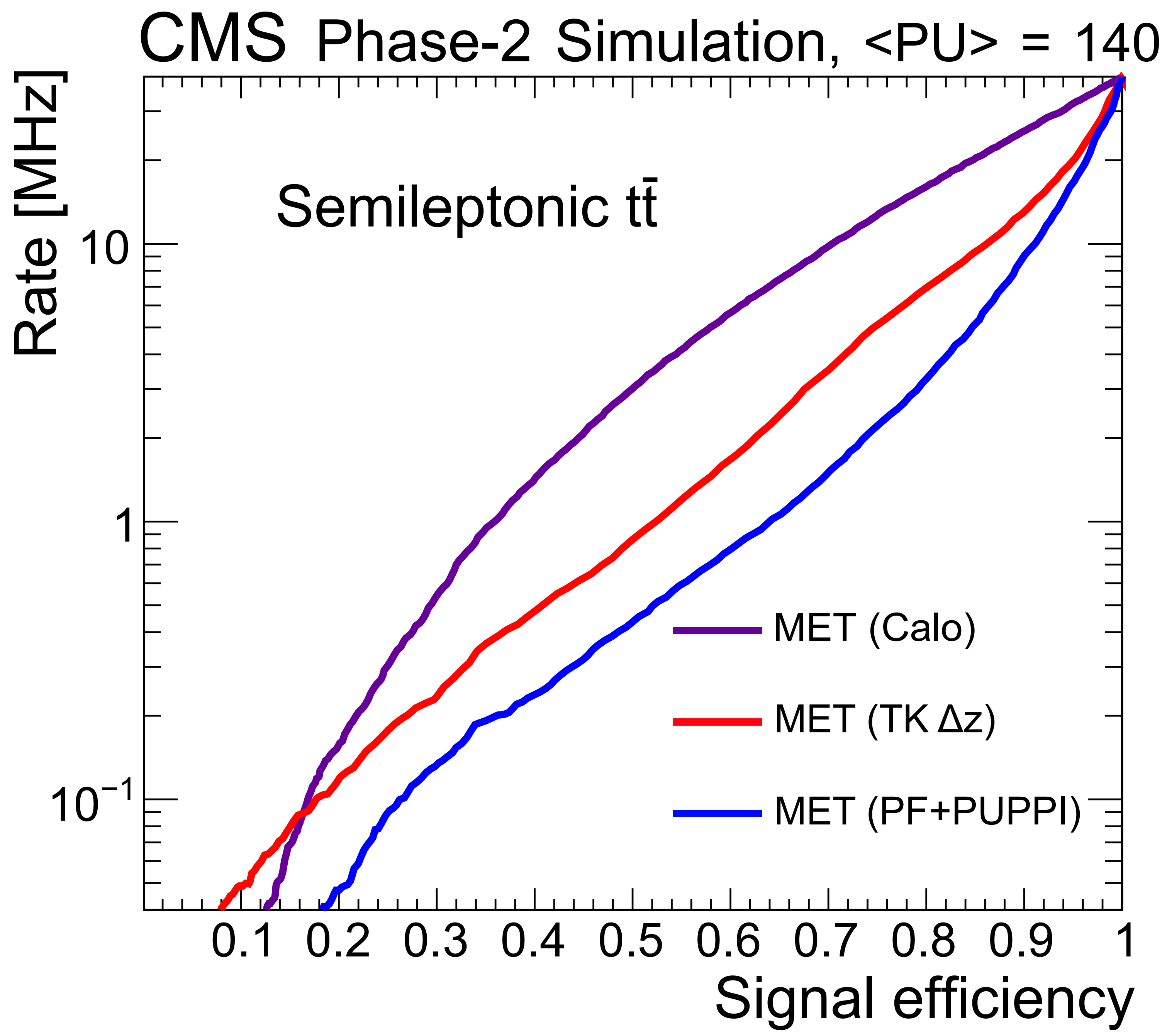
- L1T will receive data from all sub-detectors, inc tracking
- Increased readout capability
  - L1 rate < 750kHz
  - L1 latency < 12.5us
- Full replacement of L1T system
  - Xilinx Ultrascale/+ FPGAs
  - Link speeds up to 25Gb/s
- Aim to maintain current L1 trigger thresholds through to HL-LHC



CMS UK UPGRADE: L1 TRIGGER

- Reconstruct physics objects using ***particle-flow*** techniques
    - Receive tracks, clusters, muon stubs
    - Identify vertices
    - Identify particle candidates
    - Reconstruct jets, taus, electrons, photons, energy sums etc.
- Demonstrator programme based on Serenity hardware well underway
    - Rapid algorithm prototyping using Vivado HLS





CMS UK UPGRADE: SUMMARY

- HL-LHC provides an unrivalled opportunity to advance the collider physics program massively.
- A wealth of studies have already been done to prepare for Physics exploitation - and techniques/tools will improve in the next years to stay on the cutting edge
- CMS UK Phase 2 program is well underway- involved in the key CMS projects in mission-critical roles.
    - In addition developed many of the concepts that underpin the CMS Phase 2 detector
- Will continue to punch above our weight and ensure CMS UK remains an essential contributor to CMS