LHC Upgrade Detector Challenges

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Overview

- First challenge – the schedule
  - LS3 is less than 10 years away and there is much to be done, including putting in place essential resources
  - some of the detector plans are very ambitious
  - enough said…
- Physics motives for upgrades
  - leave this mostly to Pippa in next talk
- Experiment plans - biased, selective coverage
  - **time is too limited to cover everything!**

    apologies in advance
- Recent useful reference material – borrowed heavily
  - ECFA workshops Oct 2013 & 2014 https://indico.cern.ch/event/315626/

I hope Mike Lamont will mostly have covered …

Upgrade schedules

- Planned around essential shutdowns
  - LS1 – currently underway – collisions in 2015
    - upgrade energy to 13-14 TeV
  - LS2 – 18 months 2018-2019
    - collimation, injector and cryogenic upgrades
  - LS3 - 30 months 2023-2025
    - prepare for levelled high-luminosity running
- Experiment upgrades must be adapted to machine
  - some upgrade activities possible in Year End Technical Stops
    - probable extended 2016 YETS for CMS pixel installation
  - ALICE & LHCb in LS2
  - CMS & ATLAS in LS3 – but important intermediate changes

Motives for upgrades

- Many big physics questions outstanding
  - perhaps improving the Higgs precision will be the only way?
    - experimentally challenging – both for detectors and analyses
  - if SUSY is discovered in Run 2, may expect some revision of plans
    - if discoveries are absent should expect further theoretical ideas
- probably unwise to assume today's experimental and theoretical landscape will be static
  - LHC machine and experiments have been running only three years
  - gains from software and analyses have been impressive

- Eventually important parts of detectors will be under great stress
  - radiation damage
  - data volumes and rates
  - performance improvement from technology evolution

Heavy ions in ALICE

- ALICE not strongly represented in the UK, or in this meeting
  - so be very brief
  - Long term programme foreseen in Runs 3 & 4 with upgrade in LS2
- High precision measurements with rare probes at low p_T to study coupling with QGP and hadronisation processes
  - heavy flavour hadrons, quarkonia, low mass dileptons
- requires improved spatial precision and high track efficiency
  - substantial statistics because low S/B
- Two items worthy of note
  - long term involvement in trigger – similar to other UK activities
  - upgraded tracker will utilise very large MAPS system - unique
    - possible because of less demanding environment than other LHC detectors
  - trend to read out more data
    - common to all, as will be seen

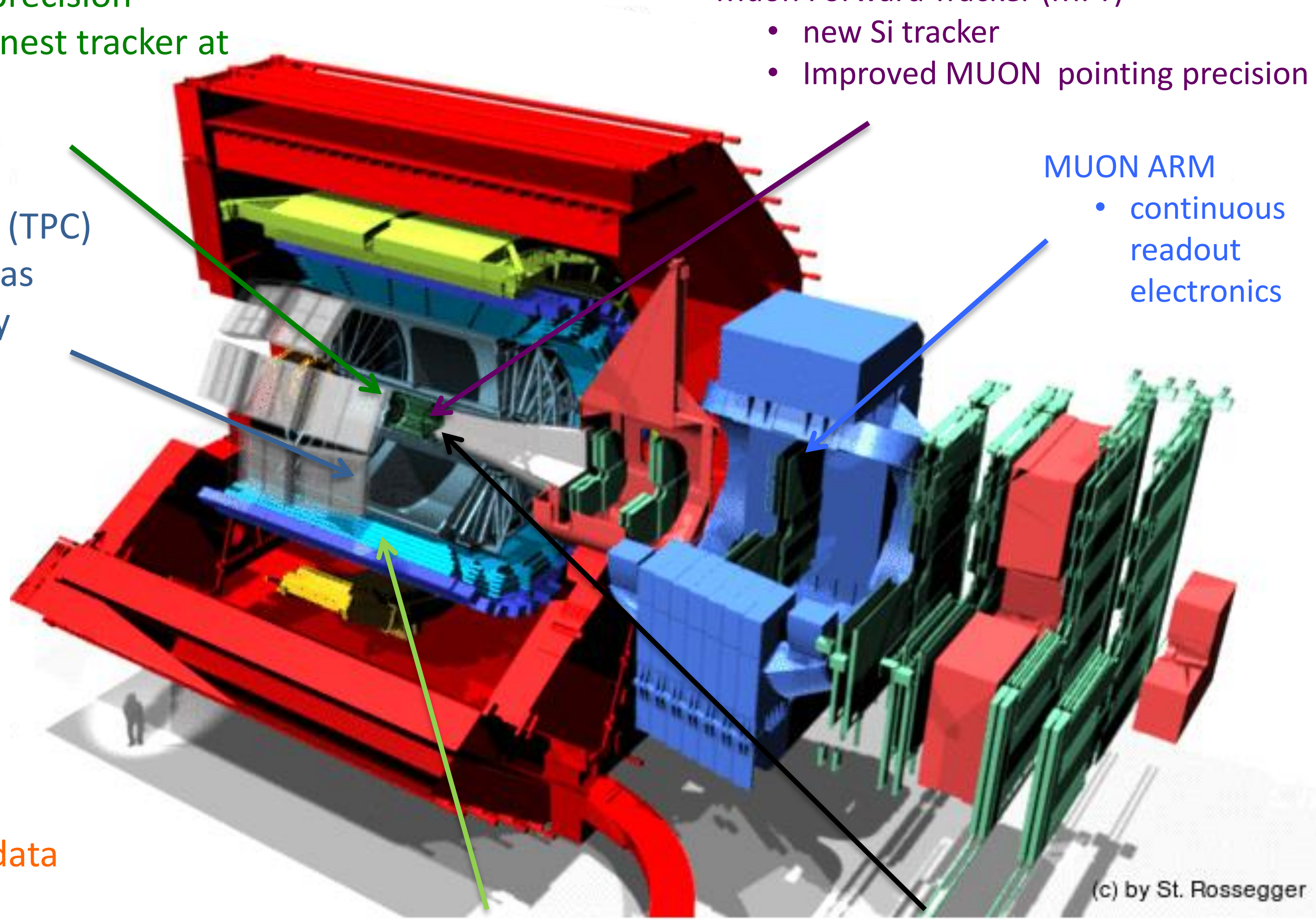
ALICE Upgrade

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- New Micropattern gas detector technology
- continuous readout



New Central Trigger Processor (CTP)

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

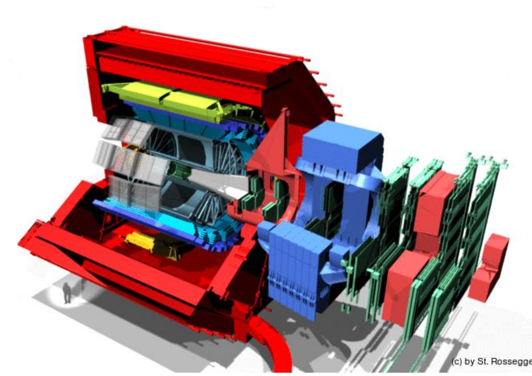
TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

ALICE Upgrade Strategy

Goal:

- High precision measurements of rare probes at low $p_{T,}$ which cannot be selected with a trigger. Target a recorded Pb-Pb luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} events to gain a factor 100 in statistics over the Run1+Run2 programme and
- Significant improvement of vertexing and tracking capabilities

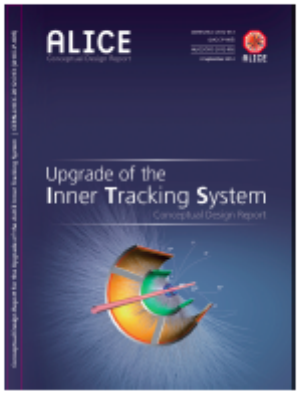


Detector:

- Read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6x10^{27}\ cm^{-1}s^{-1}$) upon a minimum bias trigger
- Perform online data reduction based on reconstruction of clusters and tracks
- Improve vertexing and tracking at low p_T ➔ New Inner Tracking System (ITS)

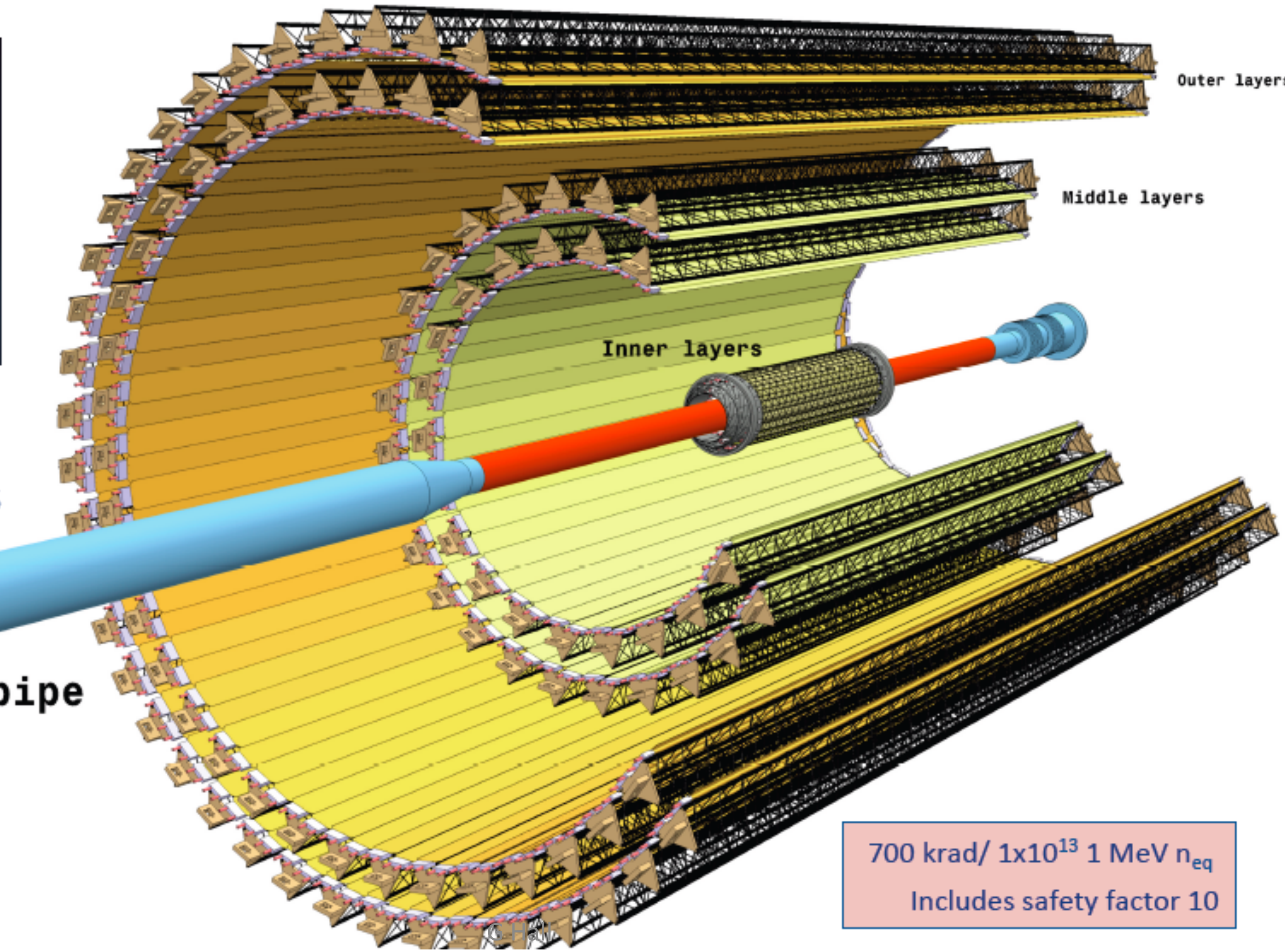
New ITS Layout

25 G-pixel camera
(10.3 m²)



CDR – LHCC-2012-013

7 layers of MAPS



Radial coverage
22 – 406 mm

700 krad/ 1×10^{13} 1 MeV n_{eq}
Includes safety factor 10

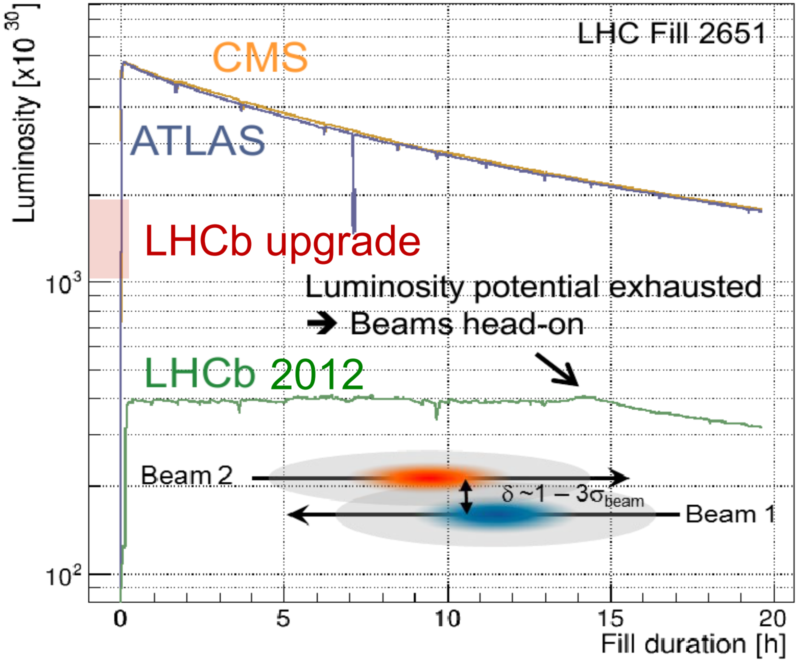
LHCb

Can do something in future which CMS and ATLAS cannot: read out all the data at 40 MHz

- to capture high statistics (relatively) modest luminosity is sufficient
- detector is much smaller than CMS & ATLAS
- with more favourable layout to route data

How to increase LHCb statistics significantly

2012 running conditions



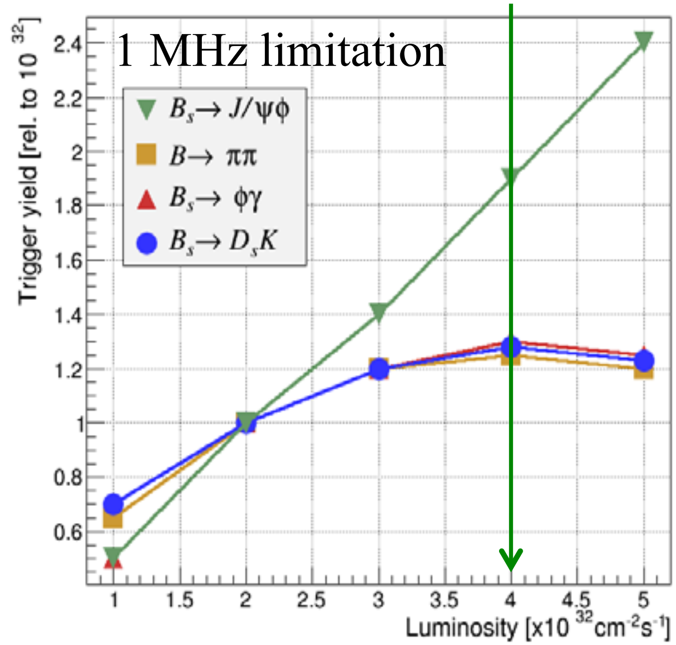
← $1\text{-}2 \cdot 10^{33}$ cm^{-2}s^{-1}

← ~ $4 \cdot 10^{32}$ cm^{-2}s^{-1}

LHCb up to LS2

- running at levelled luminosity of ~ $4 \cdot 10^{32}$ cm^{-2}s^{-1}, pile-up~1
- first level hardware trigger running at ~1 MHz
- record ~3-5 kHz

LHCb 2012



LHCb upgrade

LHCb upgrade

- increase luminosity to a levelled $1\text{-}2 \cdot 10^{33}$ cm^{-2}s^{-1}, pile-up~5
- run fully flexible & efficient software trigger up to 40 MHz
- record ~20 kHz

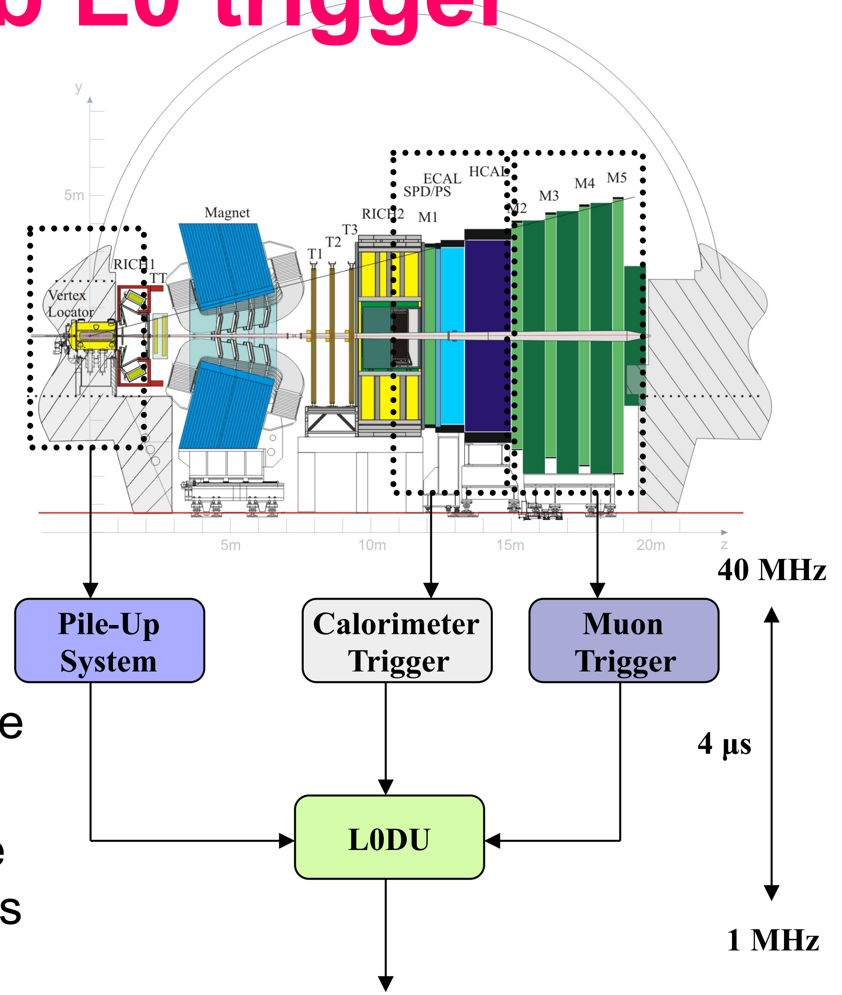
Overview of the LHCb L0 trigger

- <u>**Composed of four custom processors:**</u>
  - L0 Calorimeter trigger
  - L0 Muon trigger
  - L0 Pile-Up system
  And
  The Level 0 Decision Unit (L0DU)

- Reduce the data flow down to 1 MHz for the next trigger level

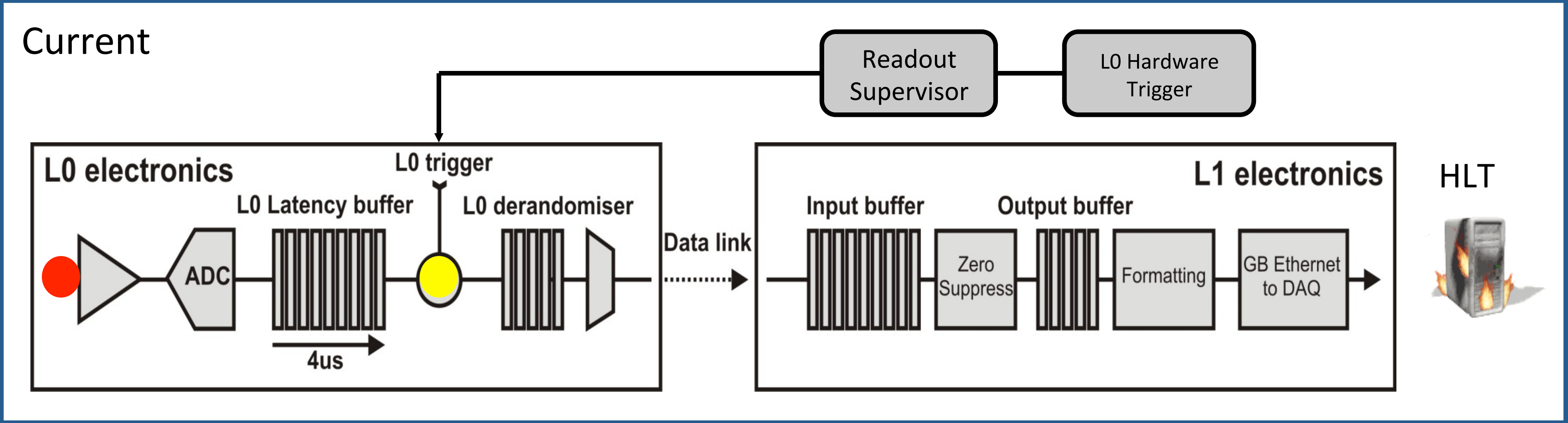
- System fully synchronous, pipeline architecture
  => each event is processed
  => a decision is produced every 25 ns and the system is able to generate consecutive triggers

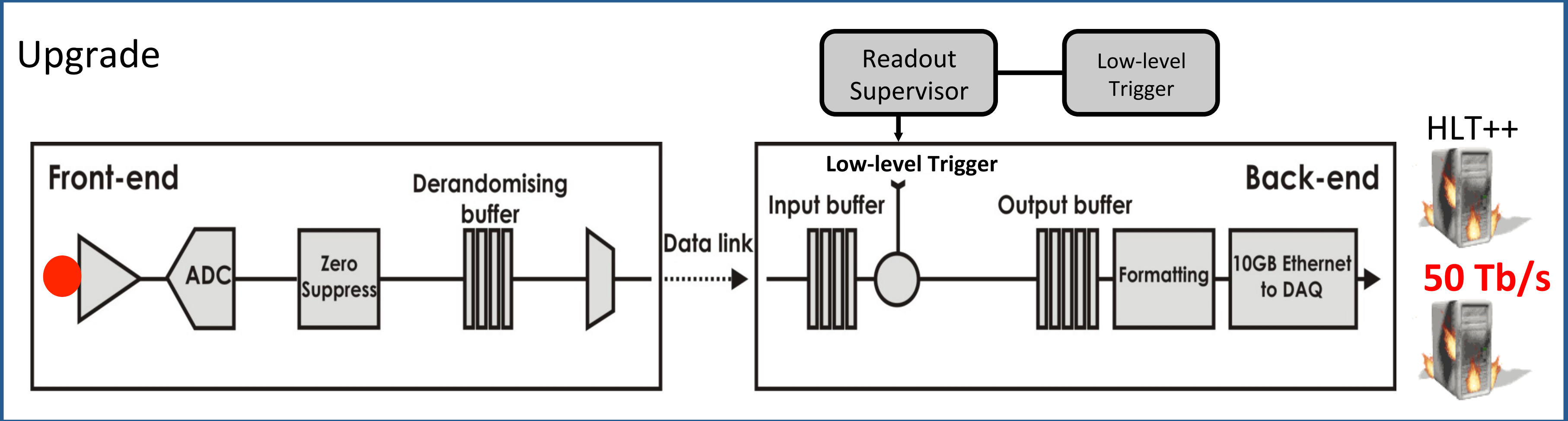
- **A physics algorithm is applied to select events** and to deliver the L0DU decision



Upgrade architecture

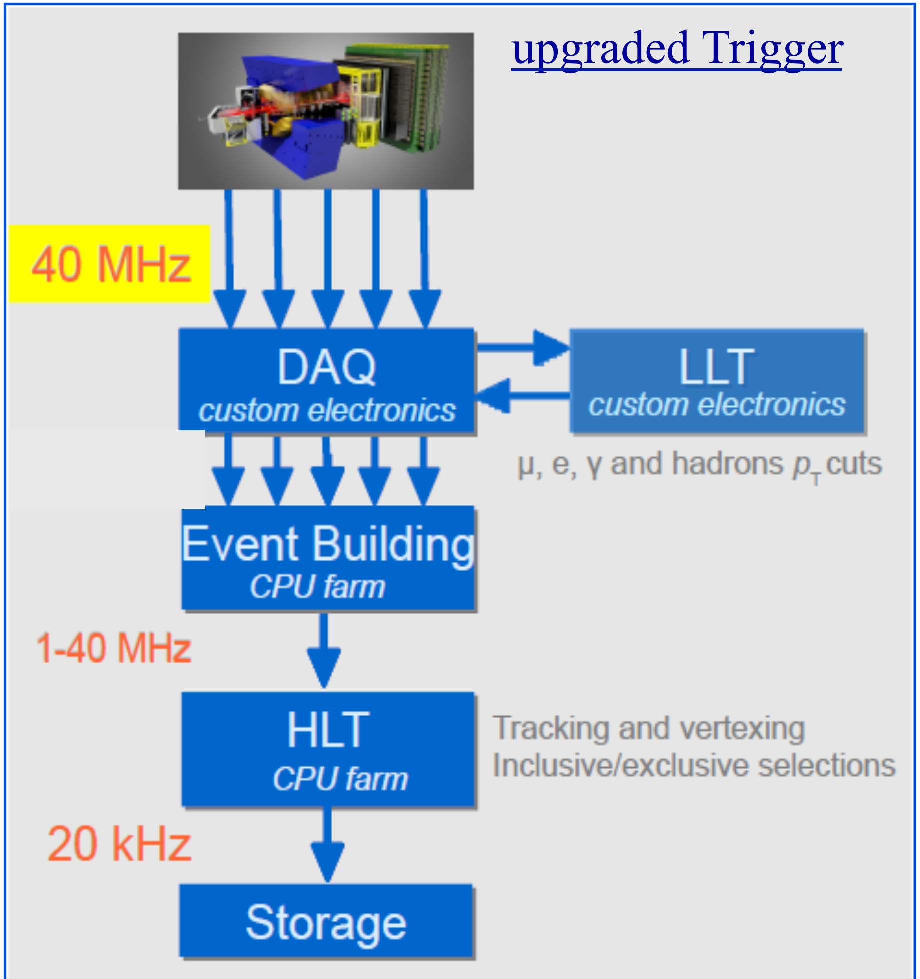
No 'front-end' trigger, Event rate to DAQ nominally 40 MHz



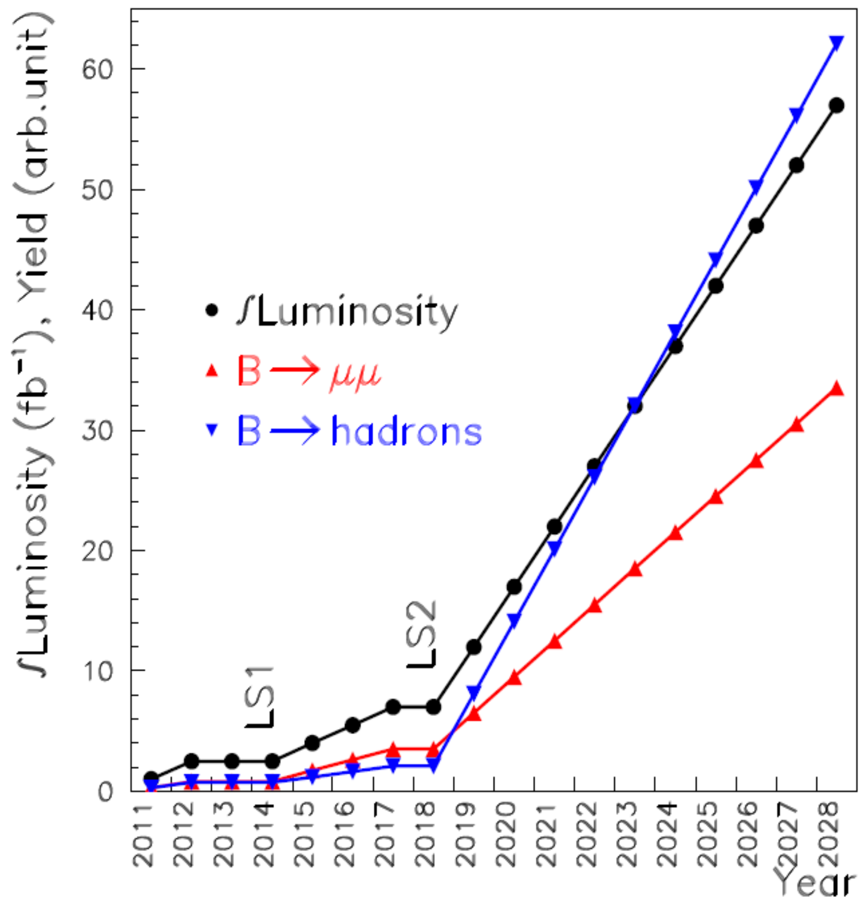


Trigger upgrade

run an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing → increase luminosity and signal yields



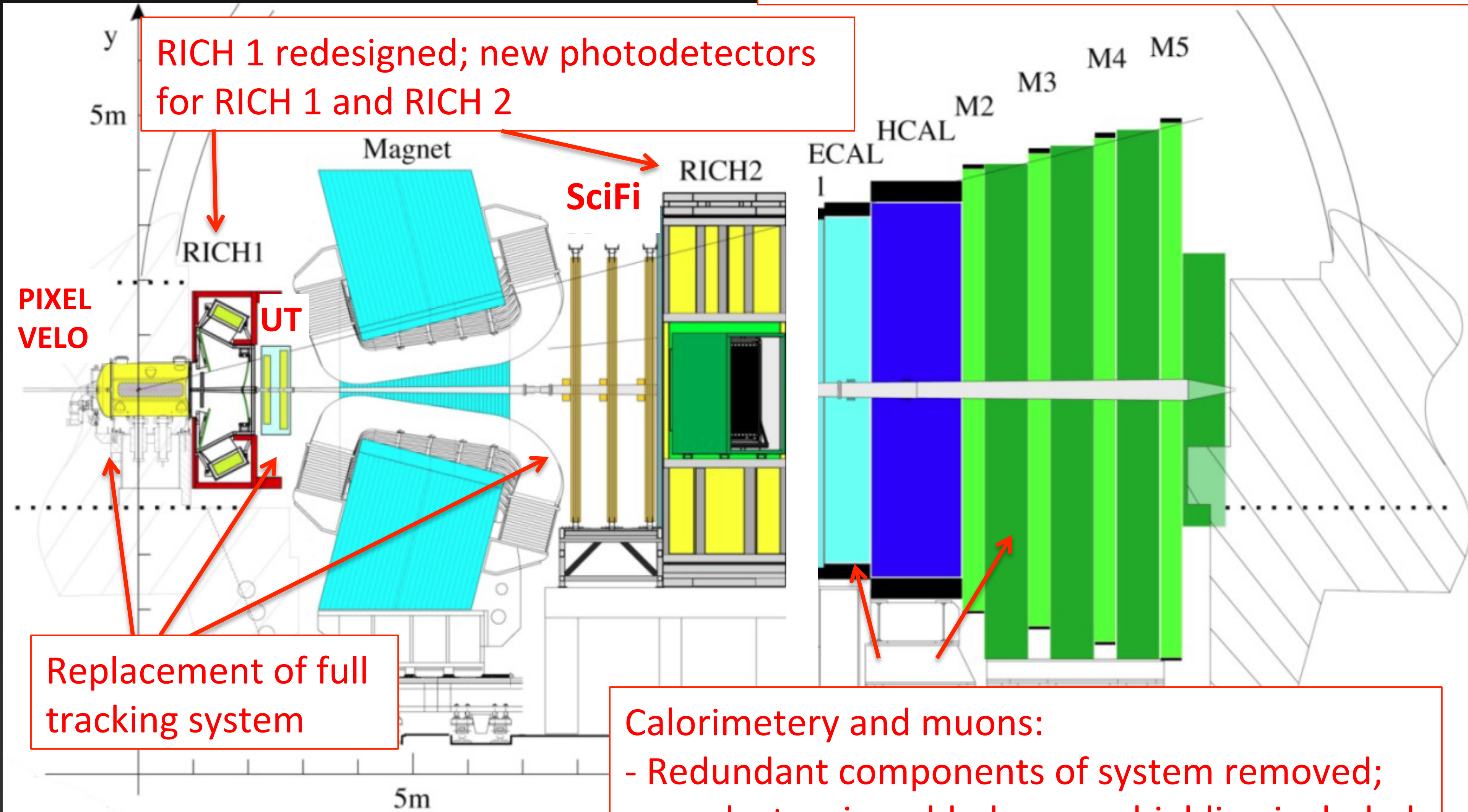
effect on luminosity and signal yields



Upgraded LHCb

All subdetectors are read out at 40 MHz

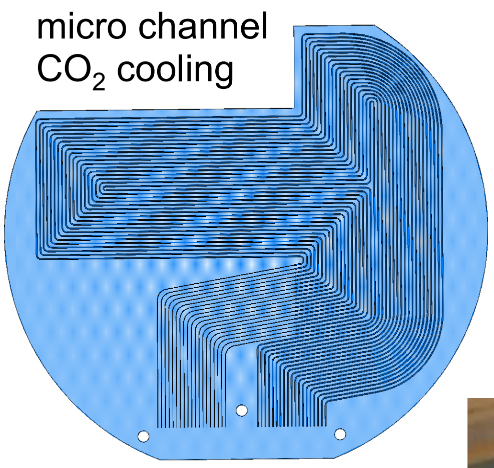
RICH 1 redesigned; new photodetectors for RICH 1 and RICH 2

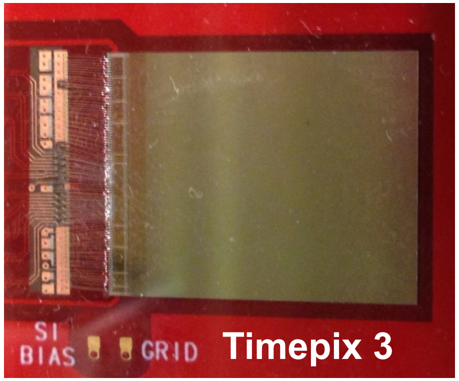


Replacement of full tracking system

Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

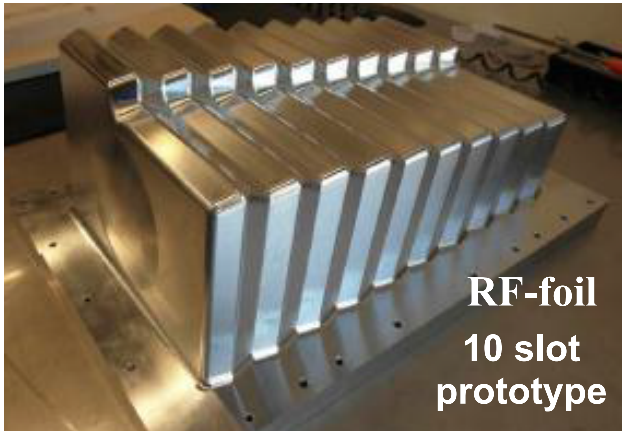
VELO upgrade





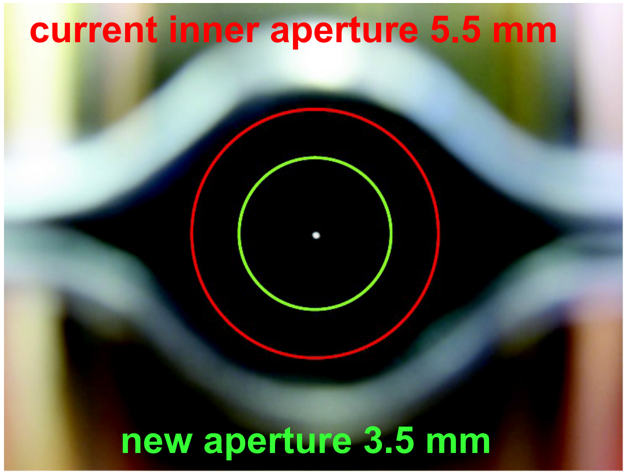
Upgrade challenge:

- ✓ withstand increased radiation
  (highly non-uniform radiation of up to $8 \cdot 10^{15}$ n_{eq}/cm^2 for 50 fb^{-1})
- ✓ handle high data volume
- ✓ keep (improve) current performance
  - ➢ lower material budget
  - ➢ enlarge acceptance



Technical choice :

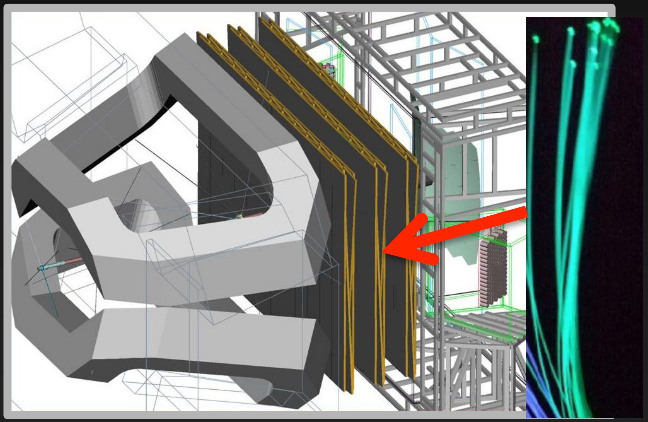
- ✓ 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- ✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - ➢ 130 nm technology to sustain ~400 MRad in 10 years
  - ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
- ✓ replace RF-foil between detector and beam vacuum
  - ➢ reduce thickness from 300 μm → ~150 μm
- ✓ move closer to the beam
  - ➢ reduce inner aperture from 5.5 mm → 3.5 mm



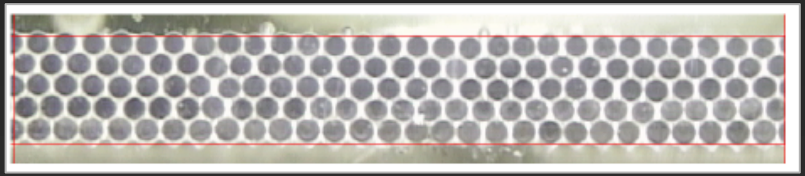
Tracking detectors: Scintillating Fibre tracker

Large scale tracking system based on mats of 2.5m long scintillating fibres of 250µm diameter, readout by SiPMs

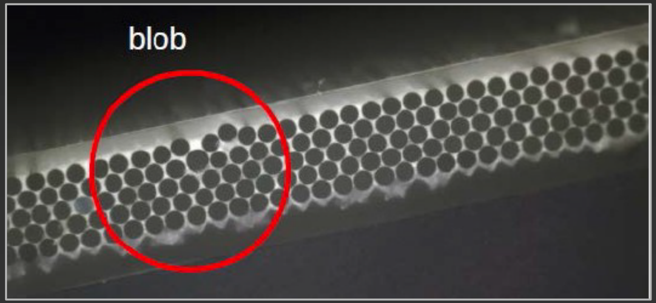
About 10000 km of scintillating fibres ! Fibre quality control is an issue. R&D in strict collaboration with the manufacturers ongoing



1) A good fibre mat and 2) a mat with a fibre with wrong diameter

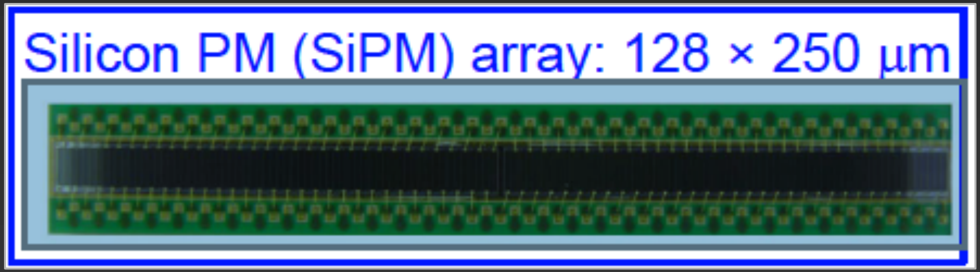


(1)



(2)

Various SiPM vendors and arrangements have been tested and qualified
R&D on SiPM radiation hardness performed: cooling is critical.
Neutron shielding is also important



ATLAS & CMS

Unsurprisingly both experiments expect to encounter challenges in the same regions and focus on the same detectors to upgrade, especially

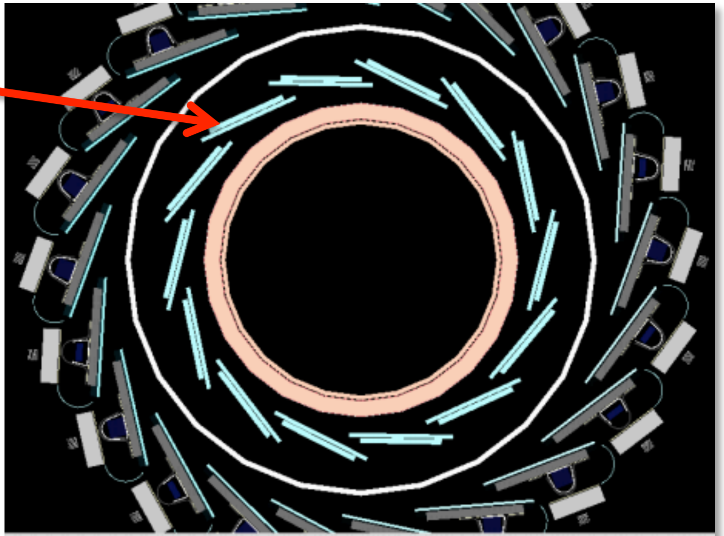
- tracking
- trigger
- forward calorimetry

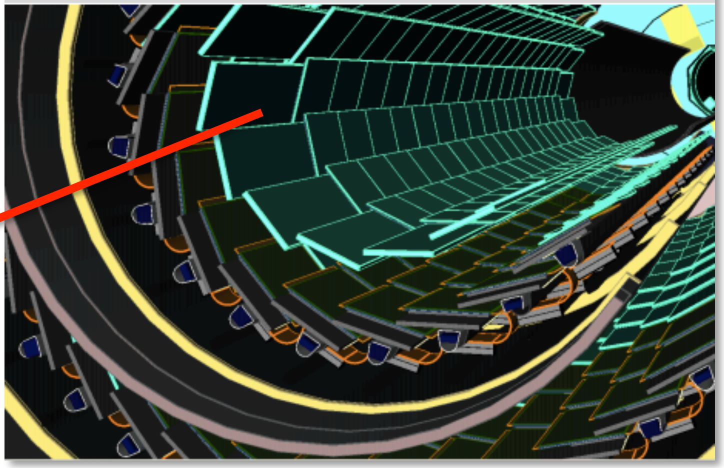
plus some changes which result from new specifications, e.g. latency must be consistent across experiment

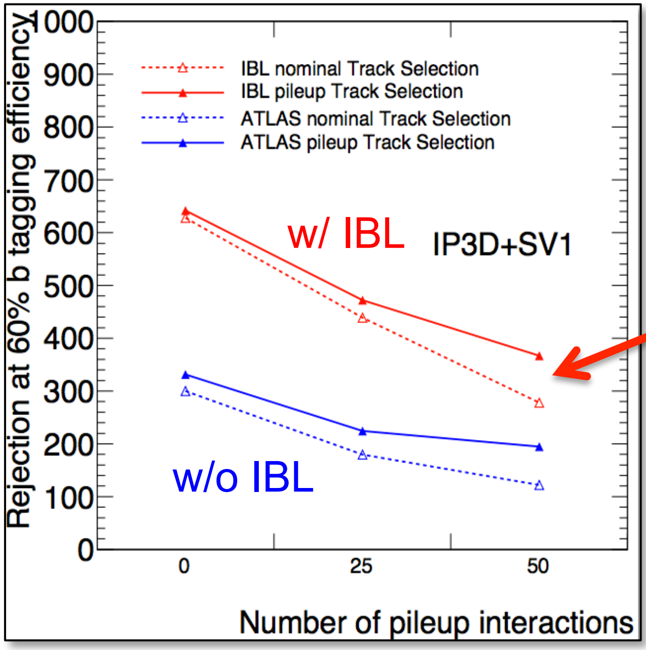
Upgrades have already started, with pixels…

ATLAS Phase-0 upgrades (LS1)

- Insertable B-Layer
  - Installation of IBL in the pixel detector March 2014
  - FE-I4 Pixel Chip, 130 nm CMOS process
  - Will stay until Phase-II

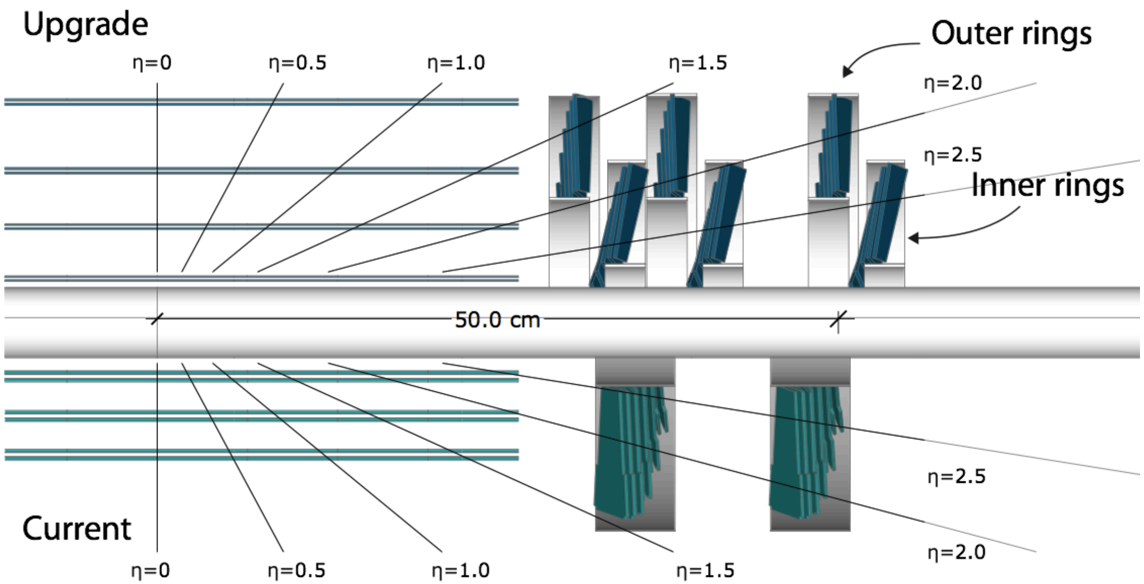


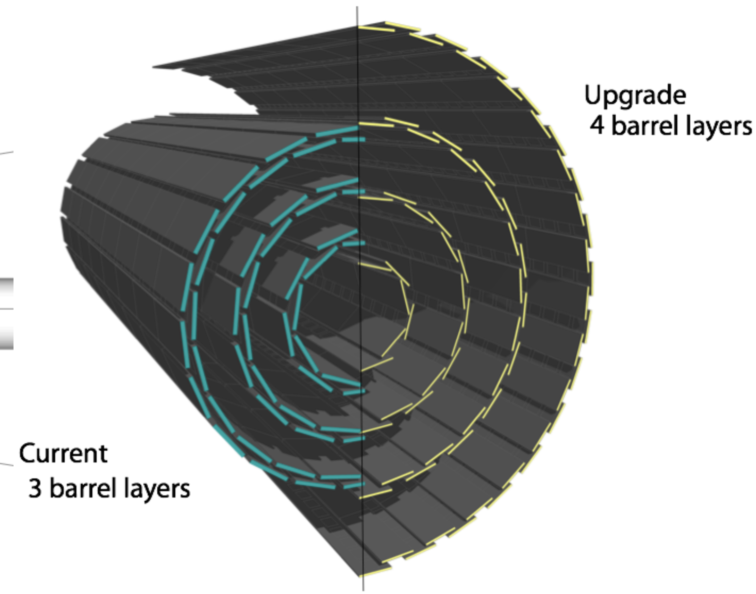




b-tagging rejection vs pile-up

CMS Phase 1 Upgrades – Pixel Detector





Ready to install at end of 2016

- 4 layers / 3 disks
  - 1 more space point, 3 cm inner radius
  - Improved track resolution and efficiency
- Modified readout chip
  - Recovers inefficiency at high rate and PU
- Less material
  - CO_2 cooling, new cabling and powering scheme (DC-DC)
- Longevity
  - Tolerate up to 100 PU and survive to 500 fb^{-1}, with exchange of innermost layer

GPDs: scope of Phase II detector upgrades

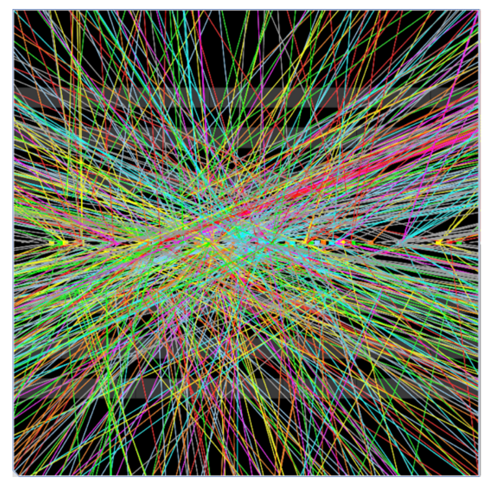
- Most sub-detectors are foreseen to survive to 3000 fb^{-1}
  - with on-going maintenance and refurbishment where possible
- Trackers must be completely replaced
  - radiation damage limits their lifetimes to <500 fb^{-1}
- New tracker readout systems are therefore essential
  - based on more modern technologies, which improve performance
    - though to meet even greater challenges – radiation, occupancy, precision
  - all sub-system readout systems must remain compatible
    - some constraints on tracker changes, and modifications to others
- Triggers must also be substantially upgraded
  - designed for 10^{34} $cm^{-2}s^{-1}$, $\langle N_{ev} \rangle \sim 25$
  - with safety factors – but exploited to maximise acceptance

Basic Requirements For ATLAS and CMS

ttbar event with 140 pile-up events
(ATLAS simulation)

- **Radiation hardness**
  - Ultimate integrated luminosity considered ~ 3000 fb^{-1} (original ~ 400 fb^{-1})
  - Radiation hard sensor material
  - New readout electronics required
- **Granularity**
  - Resolve 140-200 collisions per bunch crossing
  - Maintain occupancy below % level
  - Requires much higher granularity

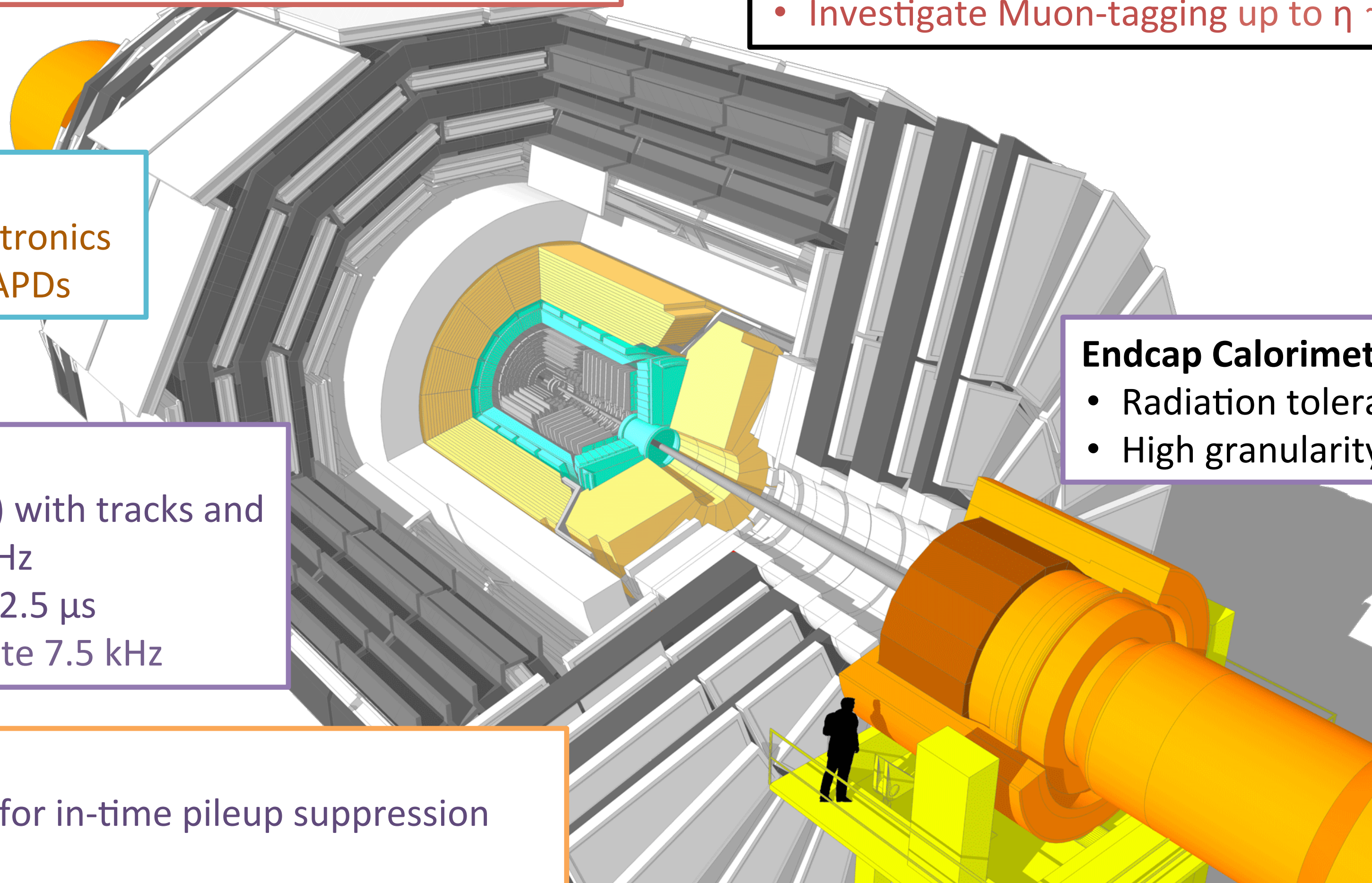
- **Improve tracking performance**
  - Reduce material in the tracking volume
    - Improve performance at low p_t
    - Reduce rates of nuclear interaction, photon conversions, Bremsstrahlung…
  - Reduce average pitch
    - Improve performance at high p_t



CMS upgrade summary

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3



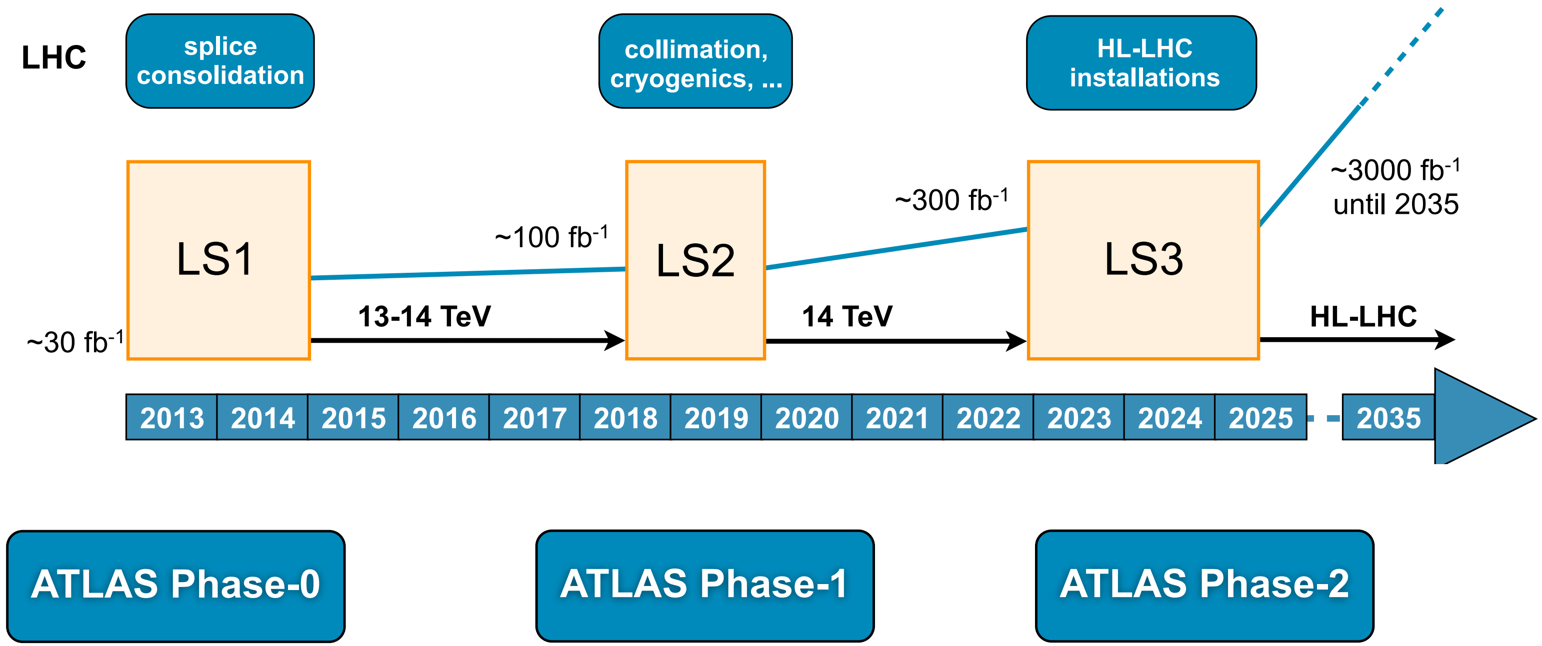
Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

Endcap Calorimeters
- Radiation tolerant
- High granularity

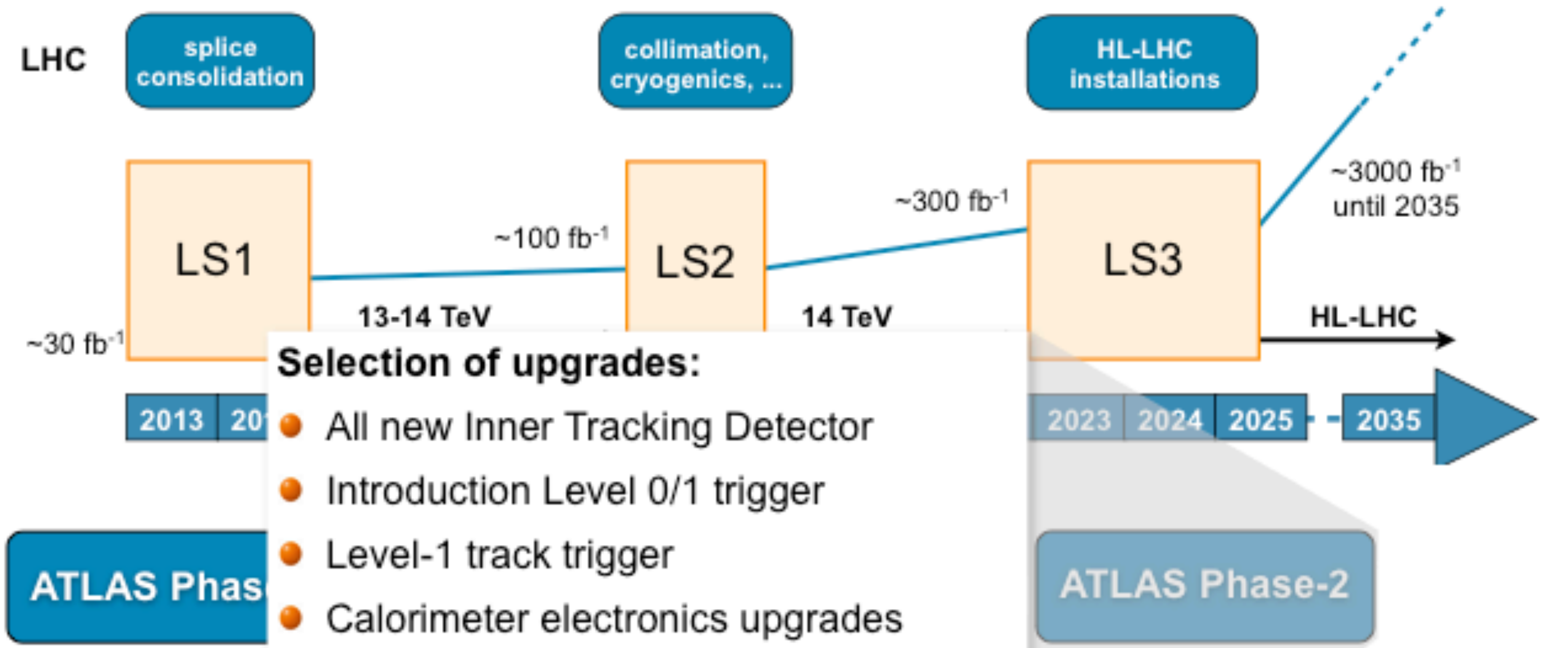
Trigger/DAQ
- L1 (hardware) with tracks and rate up ~750 kHz
- L1 Latency <12.5 μs
- HLT output rate 7.5 kHz

Other R&D
- Fast-timing for in-time pileup suppression
- Pixel trigger

The ATLAS Roadmap



The ATLAS Roadmap



Selection of upgrades:

- All new Inner Tracking Detector
- Introduction Level 0/1 trigger
- Level-1 track trigger
- Calorimeter electronics upgrades
- Upgrade muon trigger system and electronics
- DAQ upgrade
- Enhancements to high-eta region

Need for Tracker replacement

J Mans
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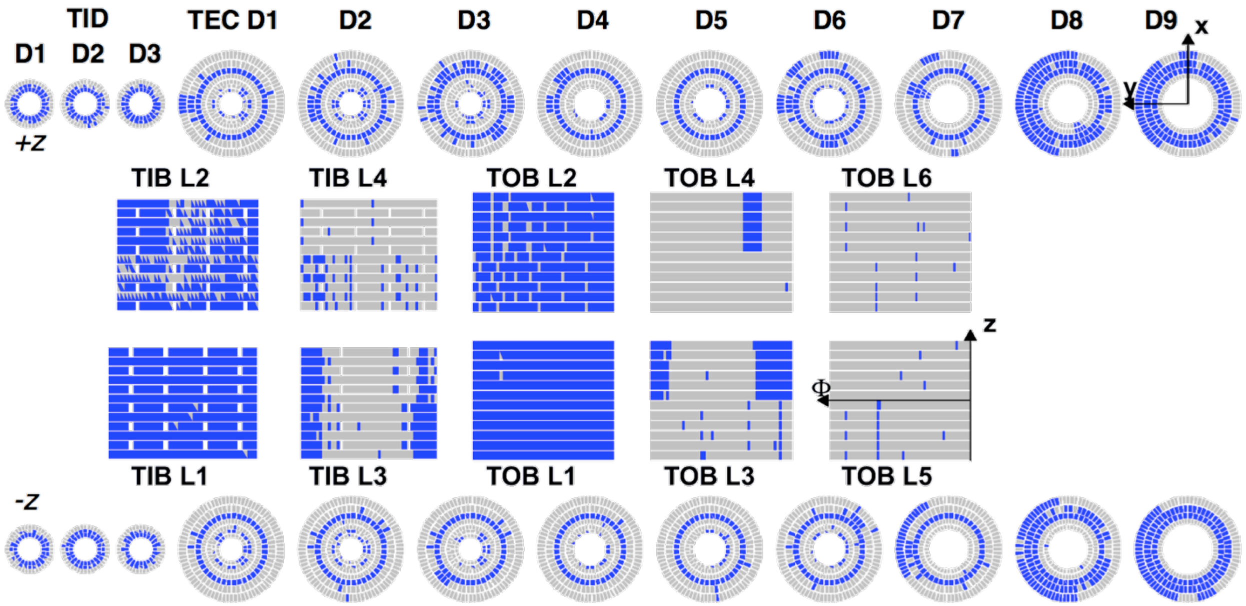
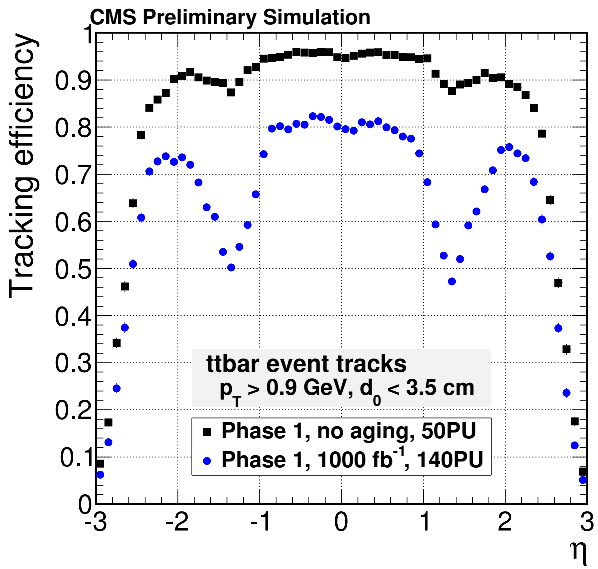
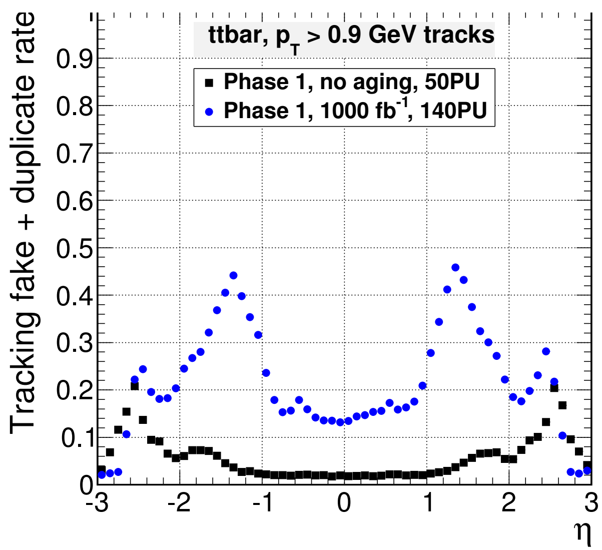






Blue tracker modules are inactive after 1000 fb^{-1} due to very high leakage currents induced by hadron fluence.

Sensors @ HL-LHC

F Hartmann
ECFA 2014

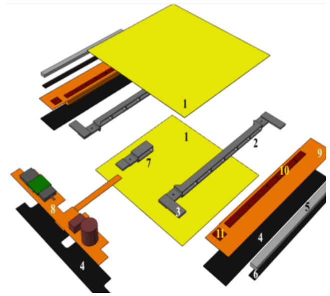
- Extensive R&D campaigns happened in all experiments.
  Baselines defined with options to follow up.
  - For ATLAS and CMS - Outer Tracker well defined
    - **Common ATLAS & CMS Market Survey** for Outer Tracker for AC-coupled sensors
  - More studies necessary for inner pixel
    - Some common ATLAS/CMS wafer submissions planned

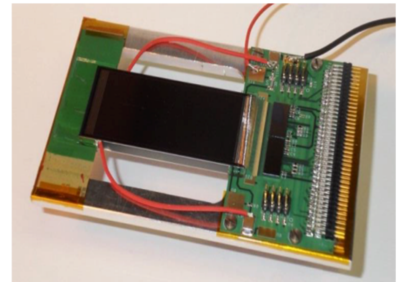
	Strips/strixel baseline	**Pixel <u>outer</u> layers baseline / options**	**Pixel <u>inner</u> layers baseline / options**	**Special**
ALICE	MAPS (Monolithic Active Pixels)			
ATLAS	• **n-in-p planar** FZ 300μm thick AC-coupled • and/or HV-CMOS	• **n-in-p** (n) **planar** • and/or HR/HV-CMOS	• **n-in-n planar** 100-200μm active thickness • and/or HR/HV-CMOS • and/or **3D** • and/or diamonds	
CMS	• **n-in-p planar** FZ 200μm *active* thickness AC- and DC-coupled • and/or MCz (pref) • and/or 300 μm	• **n-in-p planar** 100-200μm active thickness	• **n-in-p planar** 100-200μm active thickness • and/or **3D** sensors	**HGCAL** • p-in-n planar DC-coupled large PAD sensors 100-300μm active thickness (deep diffused) • Or n-in-p (deep diffused)
LHCb	UT **planar n-in-p** • or p-in-n	VELO **planar n-in-p** • or n-in-n		

With ~700m² needs to be factored in the global orders

Layout of silicon tracker with trigger-stub capability

Strip/Strip Modules
90 µm pitch/5 cm length





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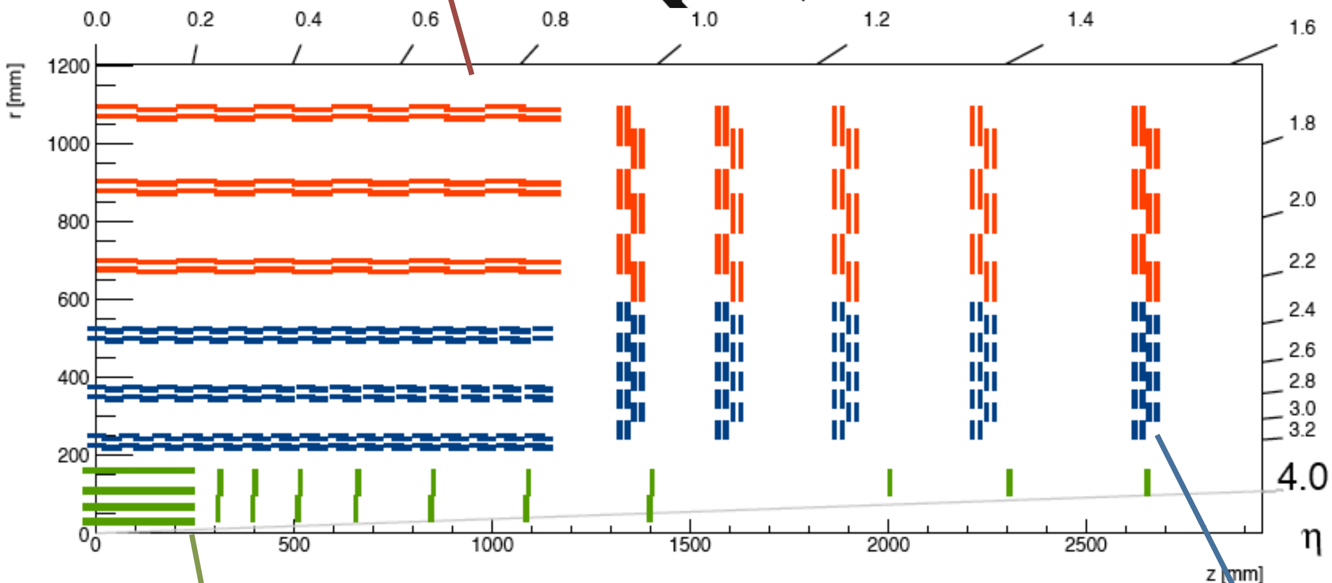
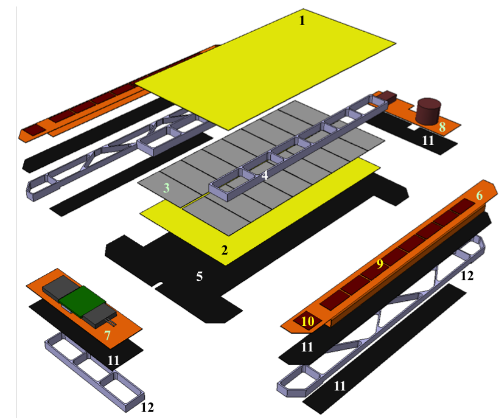
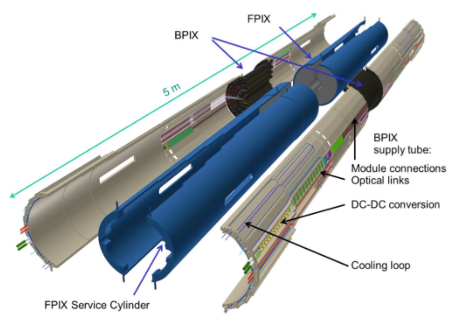




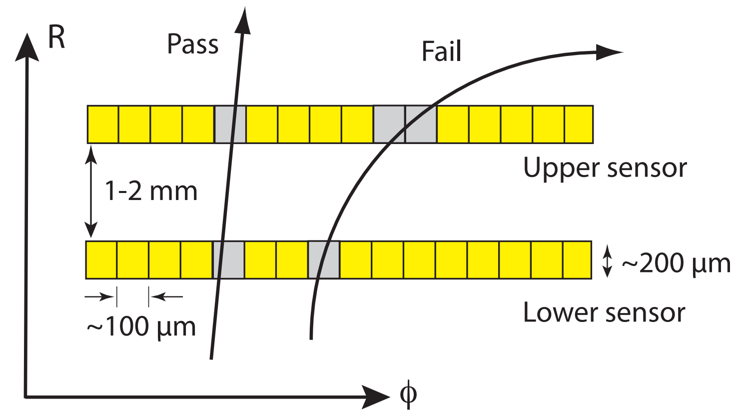
Inner Pixel
Covers up to η=4.0

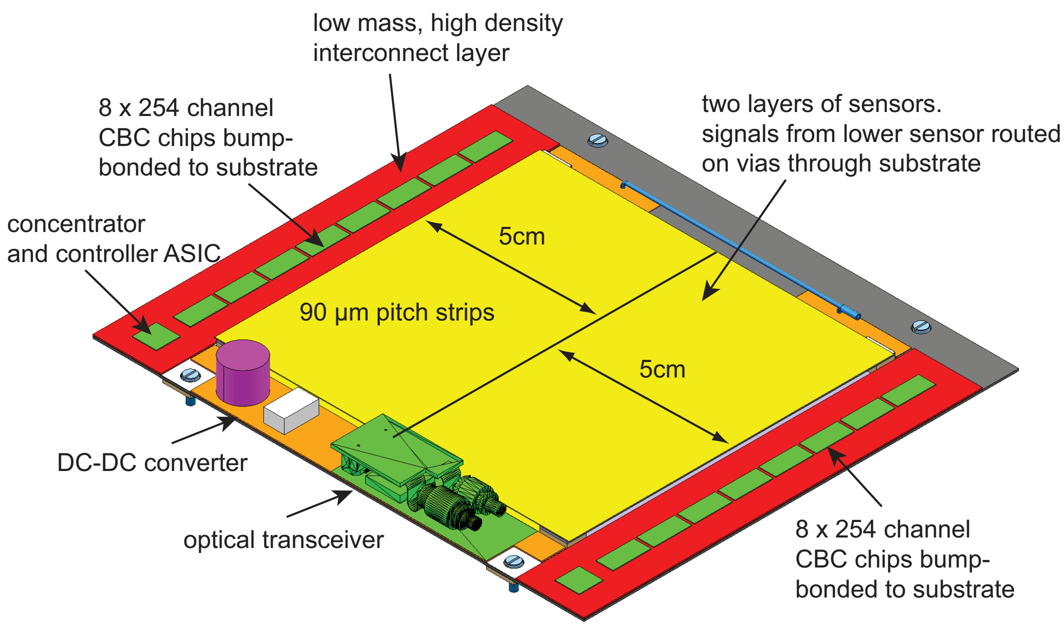


Strip/Pixel Modules
100 µm pitch/2.5 cm length
100 µm x 1.5 mm "macropixels"

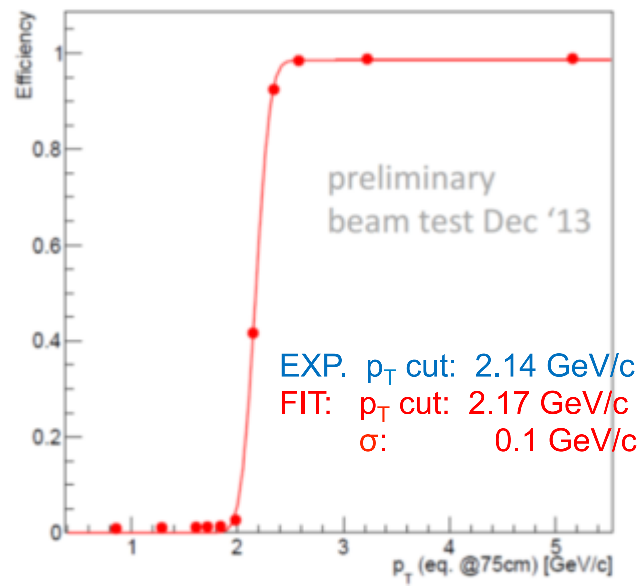
CMS Outer Tracker trigger

- ~15000 modules transmitting
  - p_T-stubs to L1 trigger @ 40 MHz
  - full hit data to HLT @ 0.5-1 MHz





~8400 2S-modules



reconstructed p_T cut of r=75cm layer

Efficiency, resolution and fake rate

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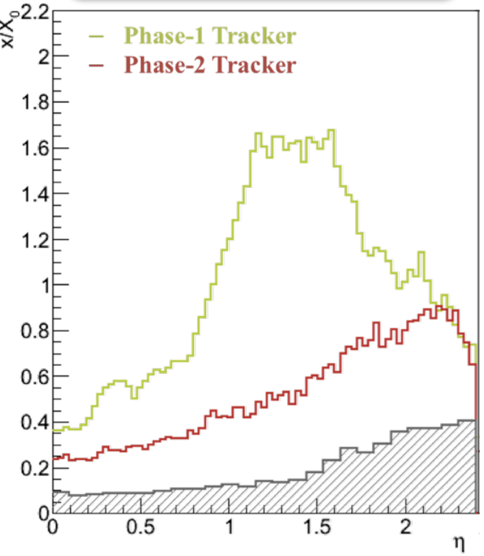
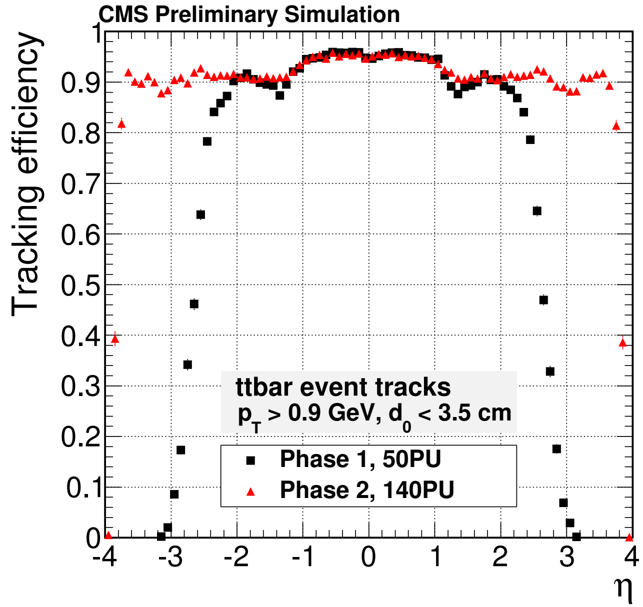
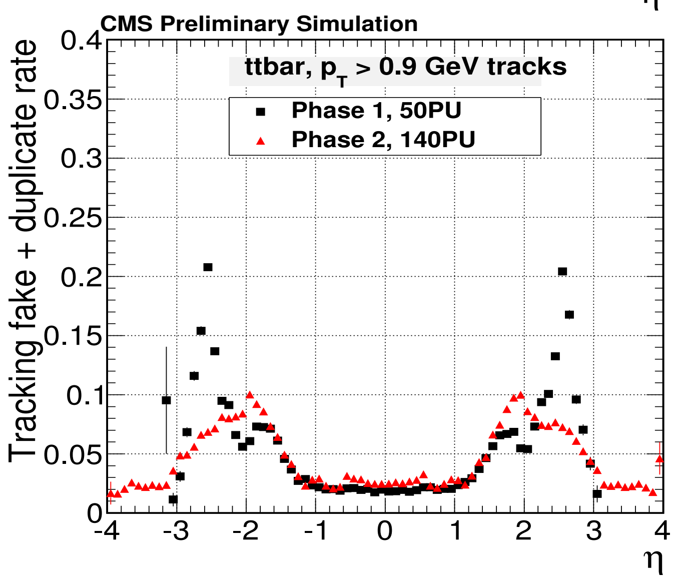
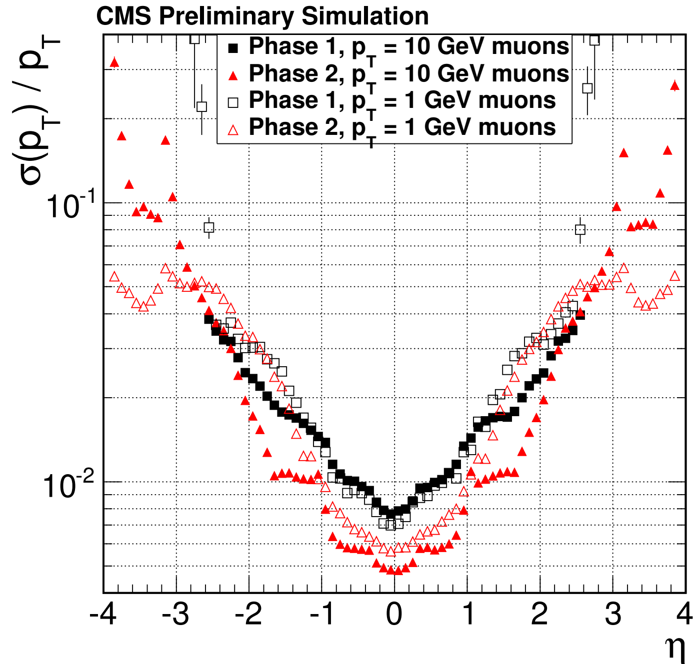
Outer Tracker substantially lighter!







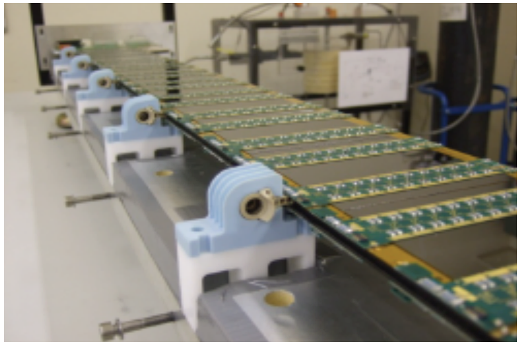


Pixel used in simulation results to date is identical to the Phase 1 Pixel detector with additional forward disks.
Further optimization of pixel parameters for b-tagging and forward track parameter resolution is planned

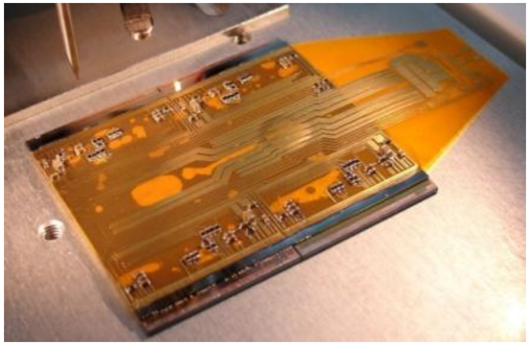
ATLAS New Tracker (LS3)

- Current Inner Detector (ID)
  - Designed to operate for 10 years at $L=1x10^{34}$ $cm^{-2}s^{-1}$ with <μ>=23, @25ns, L1=100kHz
- Limiting factors at HL-LHC
  - Bandwidth saturation (Pixels, SCT)
  - Too high occupancies (TRT, SCT)
  - Radiation damage (Pixels (SCT) designed for 400 (700) fb^{-1})

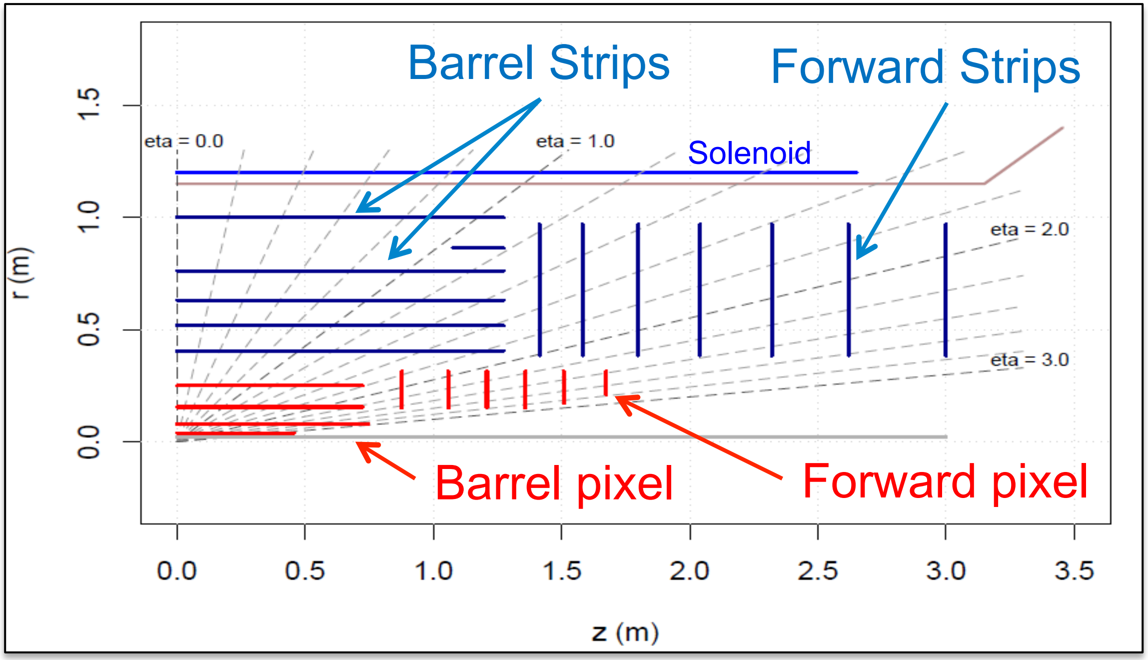
Microstrip Stave Prototype



Quad Pixel Module Prototype



LoI layout new (all Si) ATLAS Inner Tracker for HL-LHC



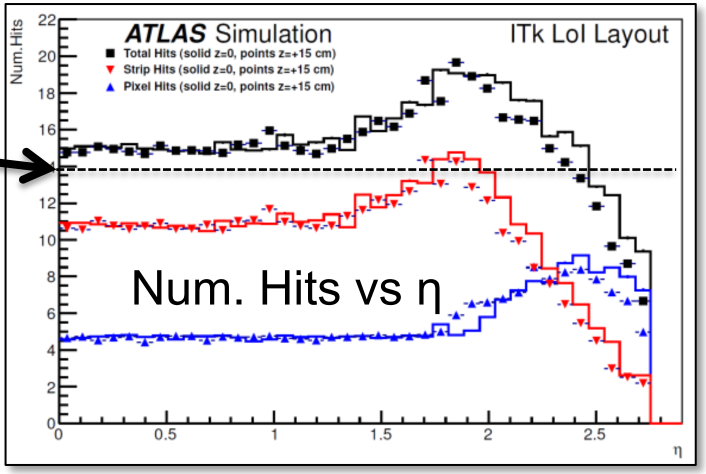
New 130nm prototype strip ASICs in production

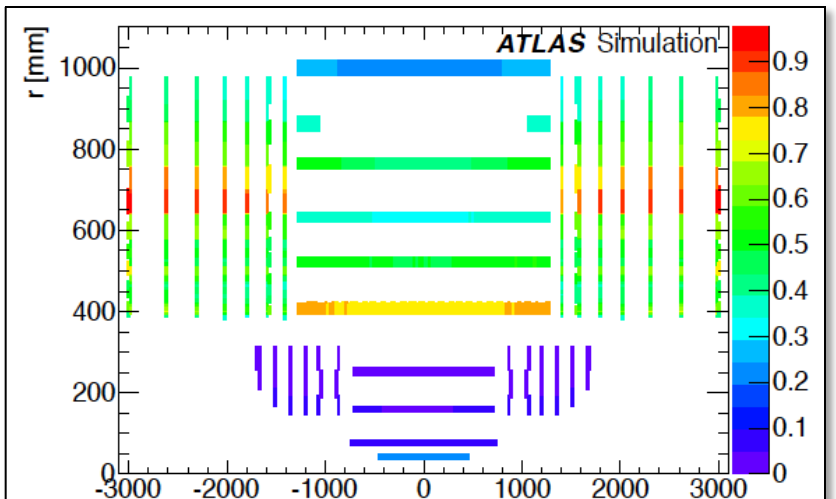
- incorporates L0/L1 logic

Sensors compatible with 256 channel ASIC being delivered

ATLAS New Tracker

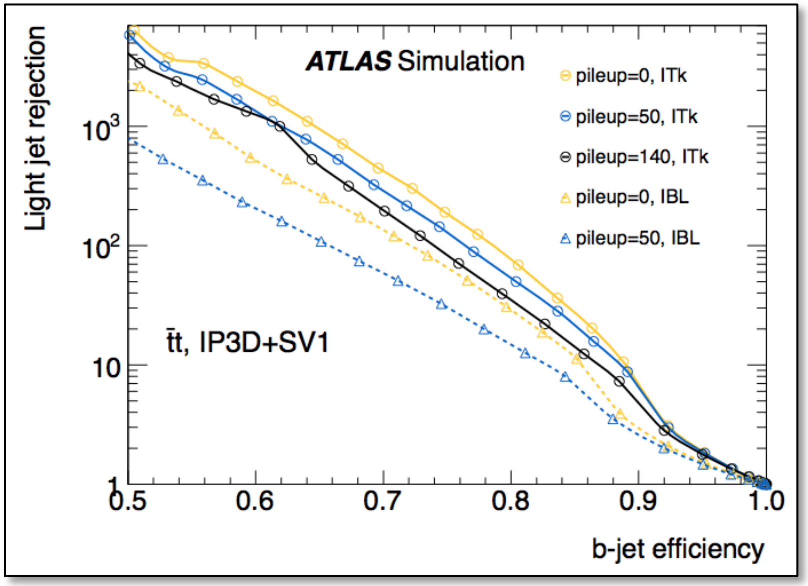
- Studies with LOI layout
  - Robust tracking (14 layers)
  - Occupancy <1% for <μ>=200
  - Reduced material wrt current ID
  - Comparable / better tracking performance at <μ>=200 as current ID at <μ>=0
- Prototypes tested to 2x HL-LHC flux
- Solid baseline design
  - working on optimisation





Occupancy for <μ>=200 (in %)

Light jet rejection, ID (w/IBL) and ITk



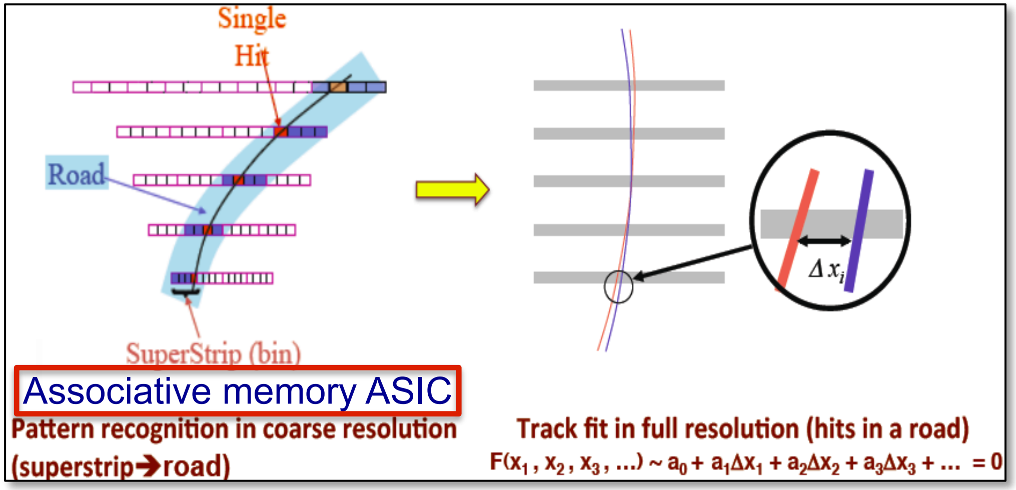
ATLAS Fast TracK Trigger (FTK)

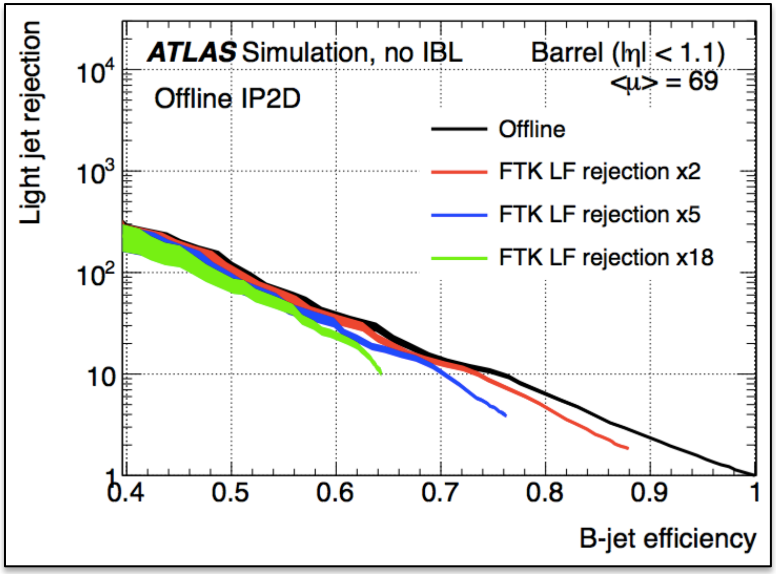
- Dedicated, hardware-based track finder
  - Runs after L1, on duplicated Si-detector read-out links
  - Provides tracking input for L2 for the full event
    - not feasible with software tracking at L2
  - Finds and fits tracks (~ 25 μs) in the ID silicon layers at an "offline precision"

- Processing performed in two steps

hit pattern matching to pre-stored patterns (coarse)

subsequent linear fitting in FPGAs (precise)



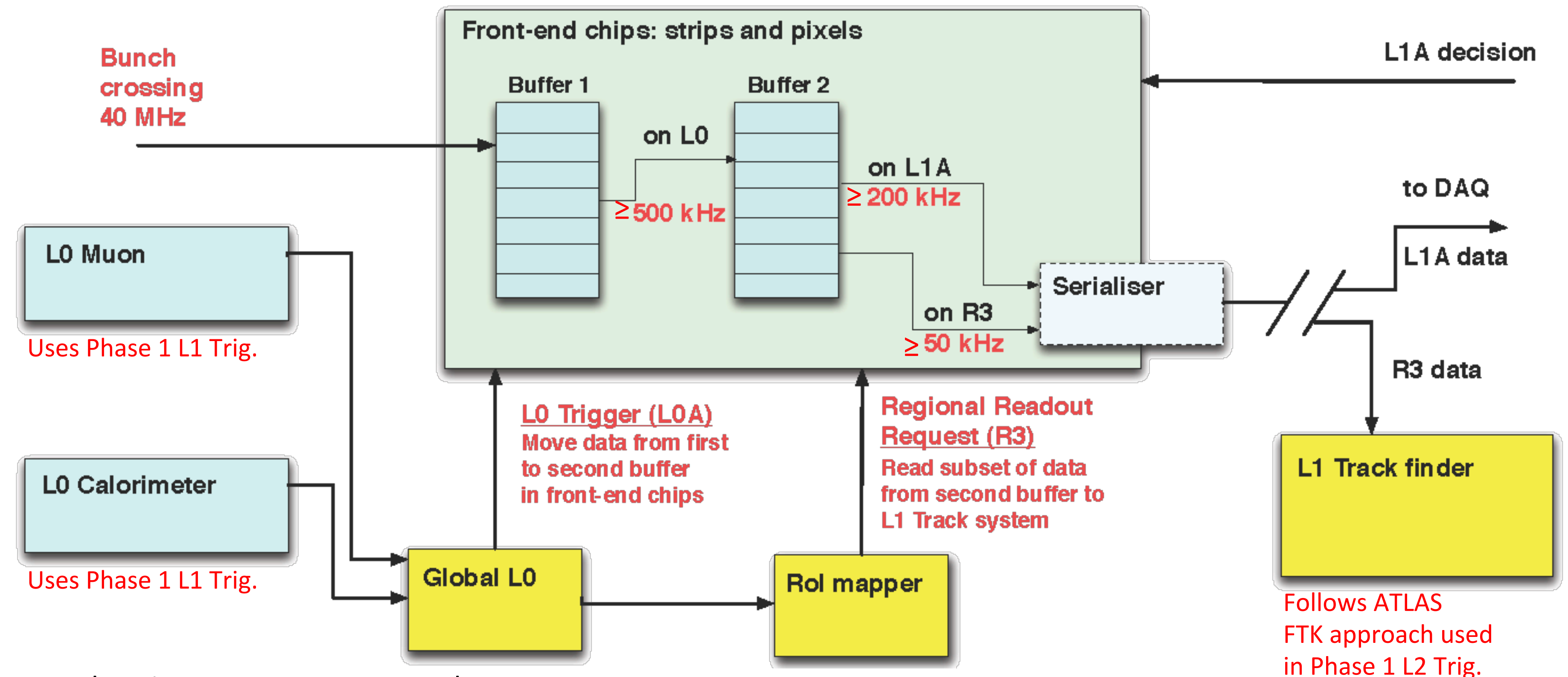


Light jet rejection using FTK compared to offline reconstruction
(further improved by addition of IBL)

Trigger levels

- Not feasible to achieve sufficient data reduction in L1 single step
  - 100 kHz was GPD target
    - but now feasible to increase the rate from technology progress
- When decisions were made on L2, two points of view
  - (custom) hardware processors needed to reduce data volume in ~50ms
  - sufficient computing power would evolve to avoid intermediate level
    - this proved to be correct, partly because of long LHC construction time
- ATLAS and CMS therefore diverged, with future implications
  - CMS must always store data on-detector until L1 decision
    - hardware trigger latency limited by shortest buffer length
    - transfer large data volume quickly to HLT = large BW
  - ATLAS can transfer selected data to L2 buffers
    - potentially much longer trigger latency possible
    - much smaller fraction of data, but more complexity

ATLAS "Double buffer" readout



- Level 0 trigger accept rate ≥ 500 kHz
  - On an L0 accept, copy data from primary to secondary buffer
  - Identify "Regions" in detector (1-10% of the detector on each L0 accept) like L1 RoI
  - Generate "Regional Readout Request" (R3) - modules in "Region" read out subset of their data
- On an L1 accept (≥ 200 kHz), all modules read out event from Secondary buffer
- Since only ~10% of the detector (the "Regions") will be read out on the Level 0 accept,
  R3 request rate for any specific part of the detector will be ≥ 50 kHz

Calorimeters

Barrel systems are expected to continue to function well

but with modified electronics to match changes in latency & rates

(however, not a small effort to access and replace)

Forward calorimetry requires attention because of radiation damage

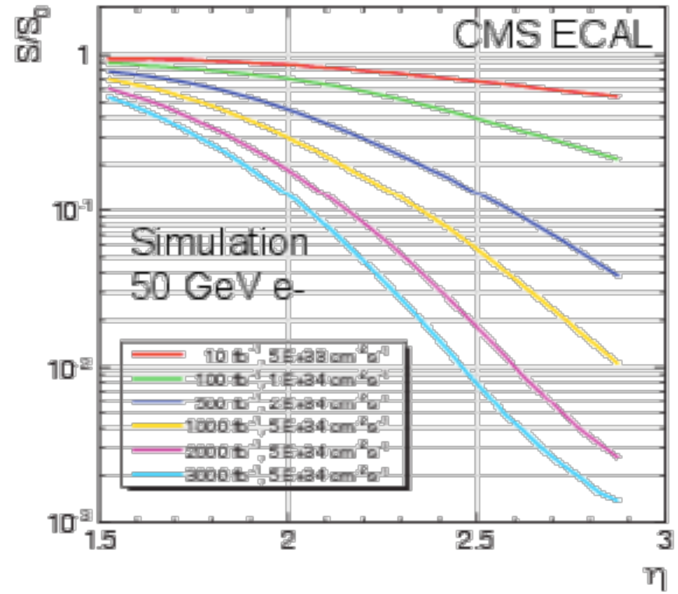
and potential to improve physics performance

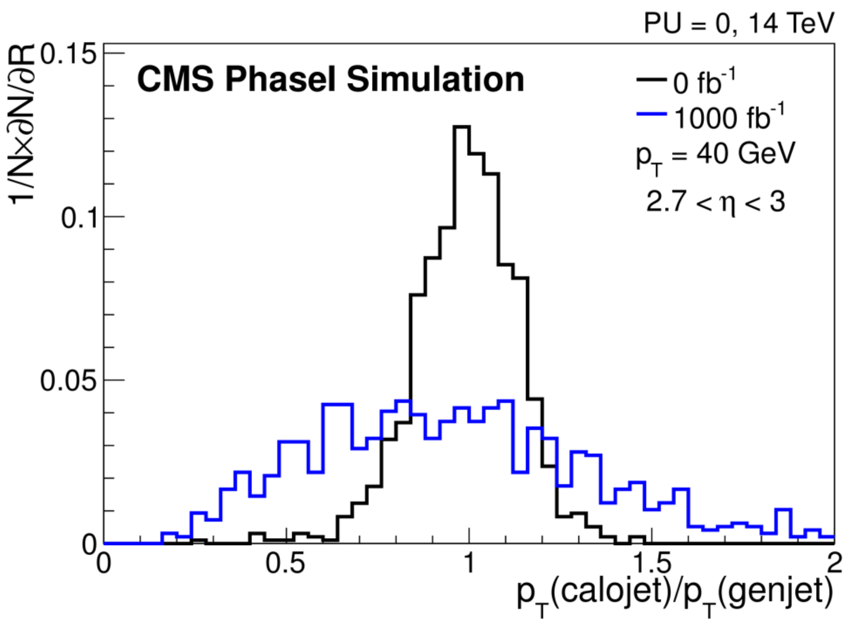
(not yet quantified by simulations)

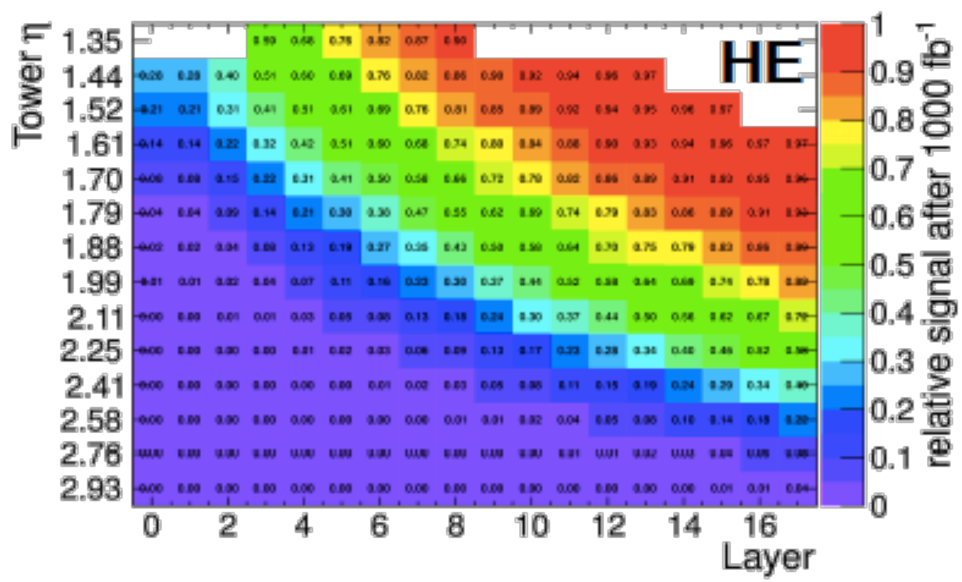
details of new detectors are not yet decided

Replacement of endcap calorimeters

- Required due to radiation-induced signal loss
  - Very significant at high η
  - Particularly important region for VBF Higgs and VBS measurements
- Two concepts under study for endcap calorimetry in Phase 2

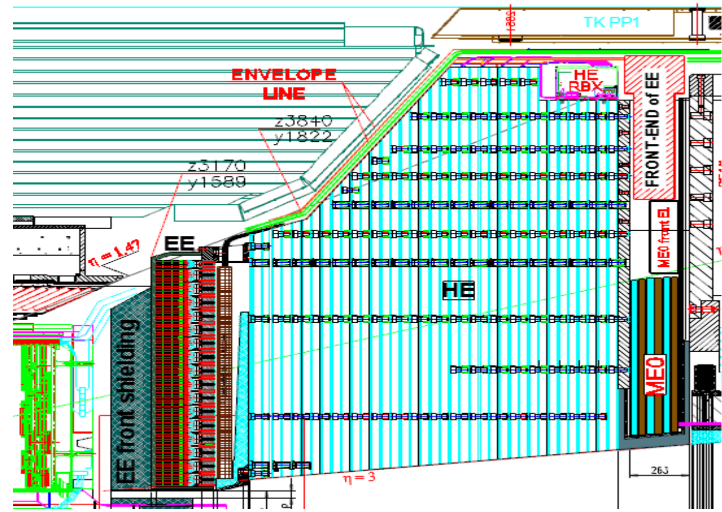


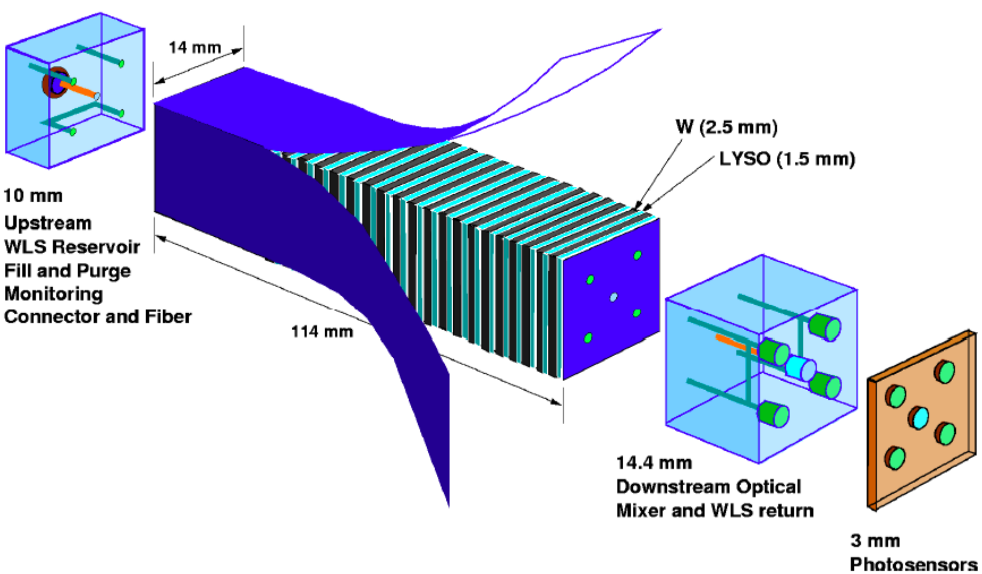


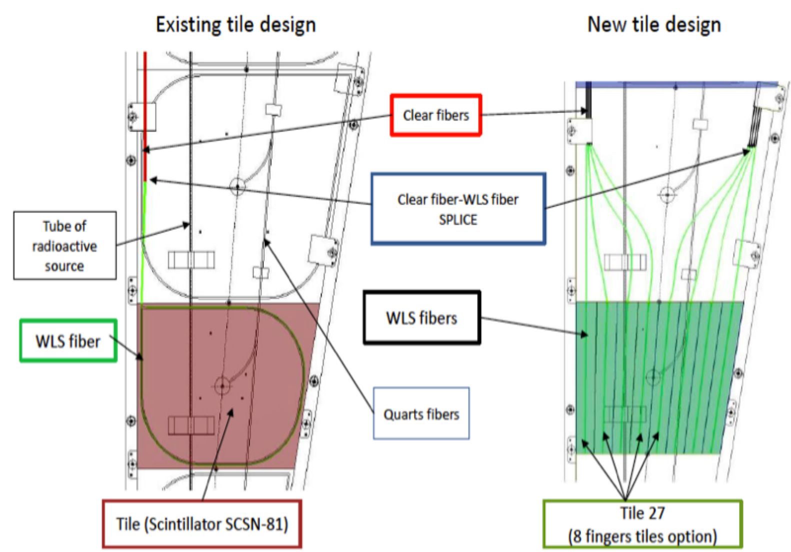


Concept 1: Shashlik

- EM Calorimeter
  - Compact Pb/LYSO Shashlik using WLS based on quartz capillaries and readout using GaInP "SiPMs"
- Hadron Calorimeter
  - Scintillator-based hadron calorimeter with 30% of volume replaced by "finger tiles" and 10% by a solution with higher radiation tolerance

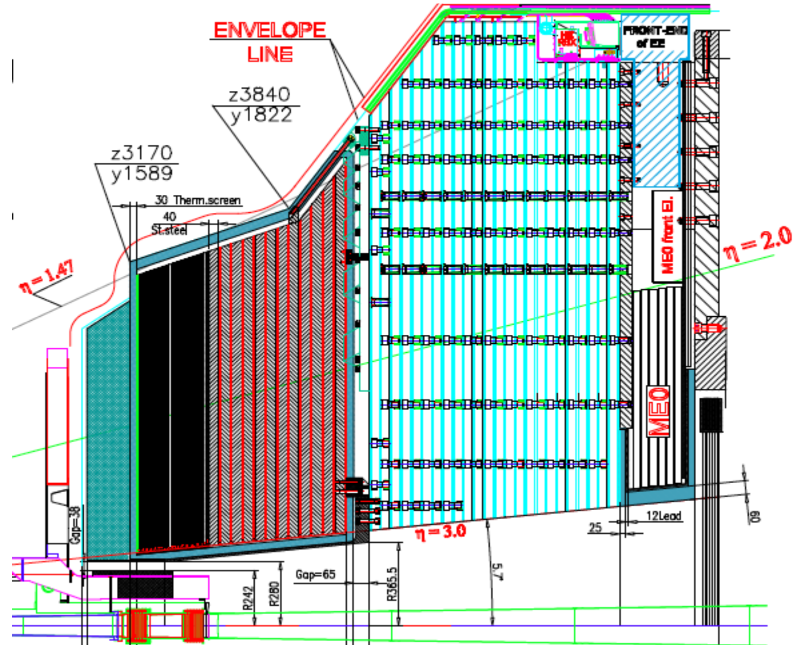


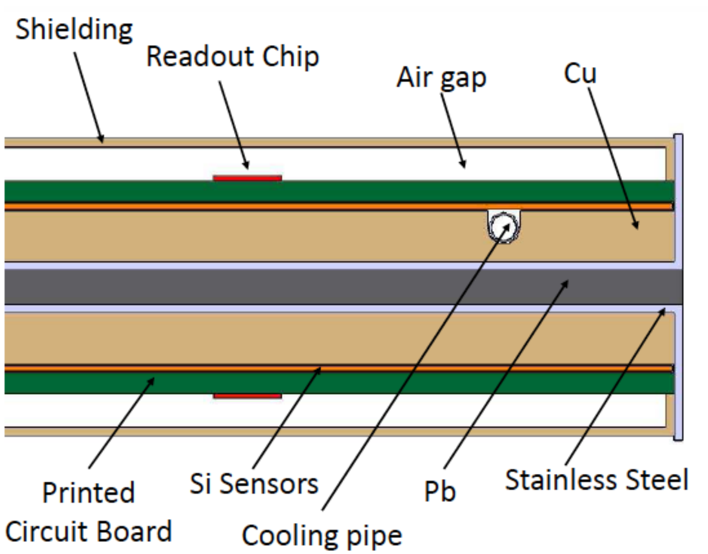


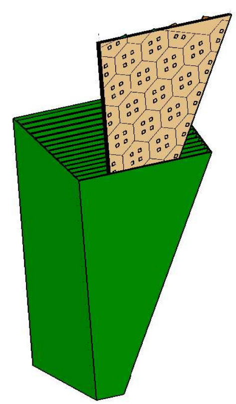


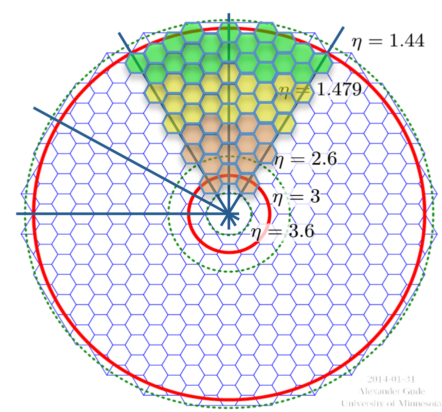
Concept 2: High Granularity Silicon Calorimeter

- Silicon-lead/copper EM (25 X_0, 1λ)and silicon/brass front hadron (3.5 λ) calorimeter
  - 8.7 M channels, pad sizes 0.9 cm^2 or 0.45 cm^2 depending on η
- Scintillator-brass backing calorimeter (5.5 λ, low radiation zone)









J Mans
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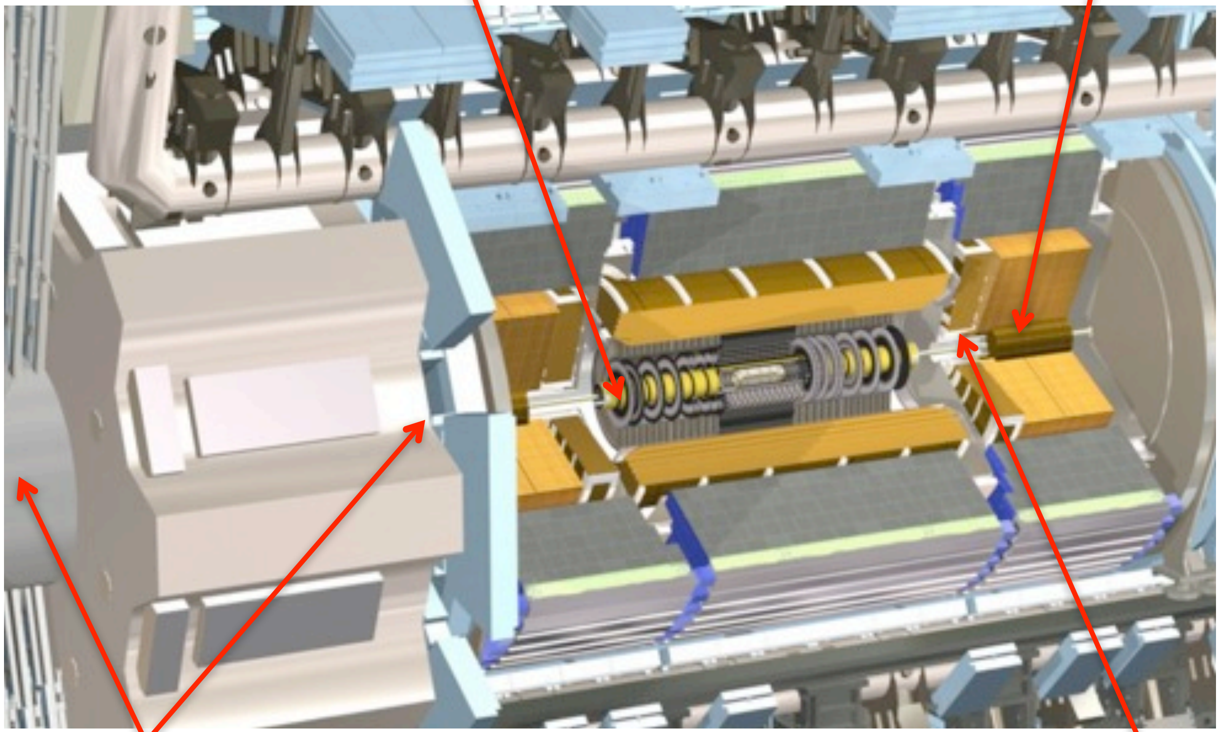
POSSIBLE EXTENSIONS AT LARGE η

Extend ITK tracker to $\eta = 4.0$: different pixel layouts/performance (extended IBL, disks, rings, pixel granularity,…)

sFCal with improved segmentation and reduced pulse length in $3.1<\eta<4.9$



Trigger w/ fwd tracking:
- L0/L1 capabilities
- vertex information

Recommendation in spring 2015 !

Muon spectrometer options for $2.7<\eta<4.0$:
- 1 pixelated tag chamber before EC toroid
- 2 chambers (before/after EC toroid)
- 2 chambers +1.5T warm toroid

Segmented timing detectors in front of EMEC/FCAL in $2.5<\eta<4$ (MBTS location): (~100μm;~10ps)

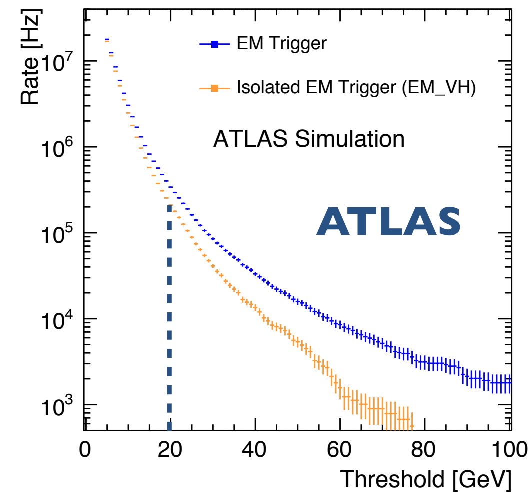
New issues for trigger

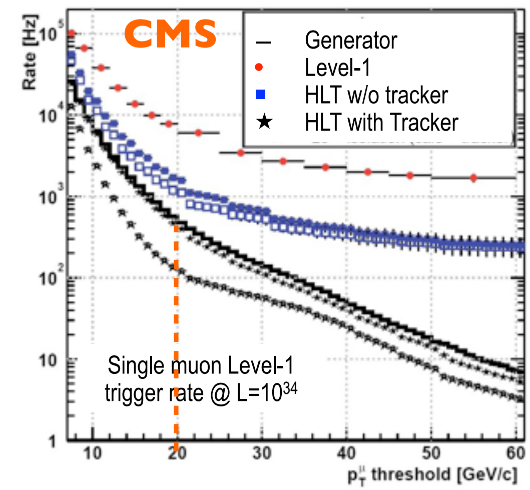
- L ~ 5 x 10^{34} $cm^{-2}s^{-1}$ (levelled) => N_{ev}/BX ~ 140 - 200
- Calorimeters
  - isolation of e/γ/τ degraded by pile-up from π^0 γs and hadrons
  - many more jets, which overlap
- Muon systems
  - increased combinatorial fakes, enhanced by MS (CMS)
- Outcome: much higher rate of L1 triggers
  - usual response is to increase thresholds, which risks physics
  - even worse - raising thresholds does not look effective
- Options to mitigate
  - increase L1 accept rate – and improve performance of HLTs
  - seek new input data to help the trigger decision
    - but only modest improvements expected from gains in μ & Calo systems

New Trigger Schemes Required

- Choice of trigger has direct impact on tracker design
- Tracker input to Level-1 trigger
  - μ, e and jet rates would exceed 100 kHz at high luminosity
  - Increasing thresholds would affect physics performance
    - Muons: increased background rates from accidental coincidences
    - Electrons/photons: reduced QCD rejection at fixed efficiency from isolation

- Add tracking information at Level-1
  - Move part of High Level Trigger reconstruction into Level-1
  - Challenge: squeeze data processing into a few micro seconds





Improvements To Current Triggers

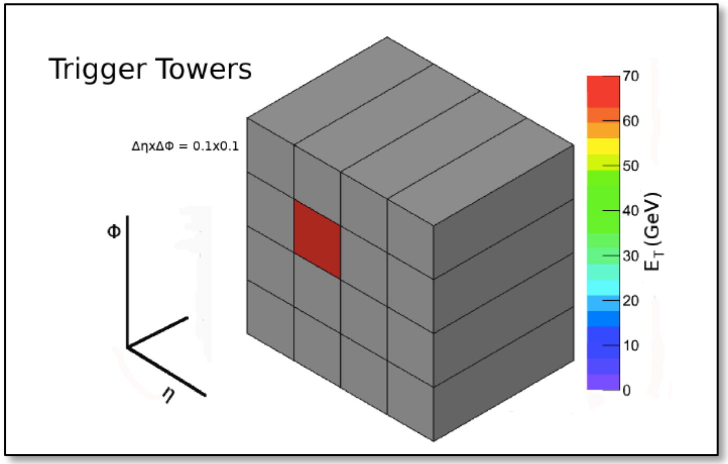
extract further information, where possible, from μ & Calo trigger data

Examples

ATLAS Level-1 calorimeter trigger

Run-1 calorimeter trigger input:
Trigger Towers $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

- Used to calculate core energy, isolation



Run-1 trigger menu
at L_{inst}=3 x 10^{34} $cm^{-2}s^{-1}$

⇩

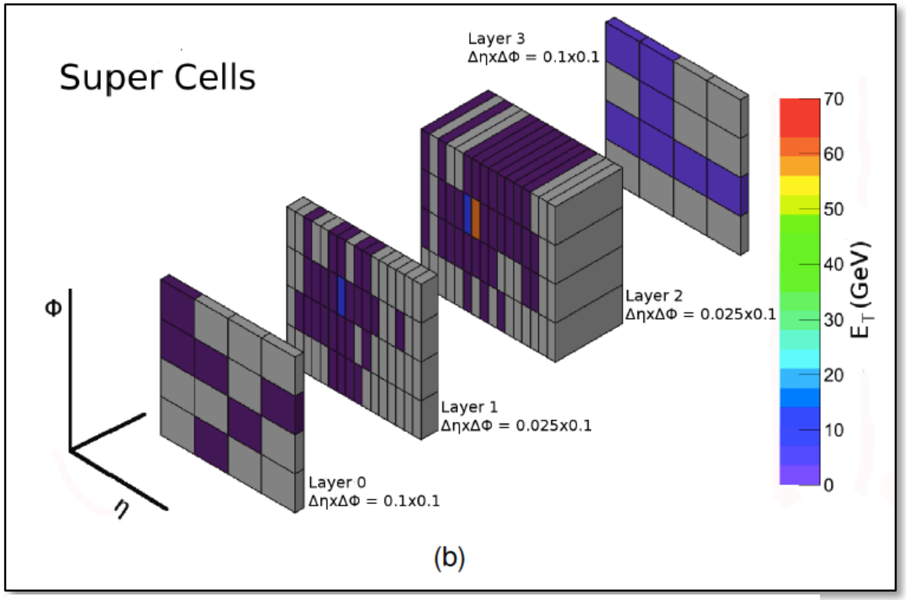
Total rate for EM triggers would be 270 kHz!
(Total L1 bandwidth is 100kHz)

⇨

maintain lower thresholds at an acceptable rate

↑

Provide better granularity and better energy resolution

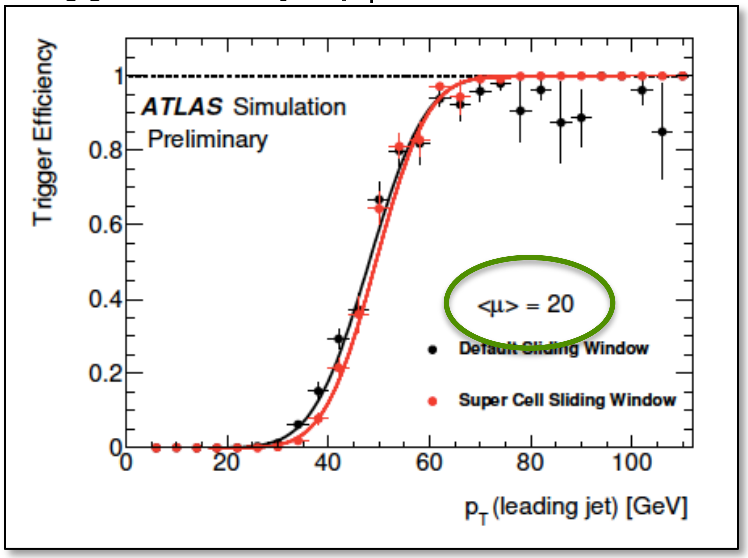


(b)

Complemented by new L1Calo trigger processors eFEX and jFEX

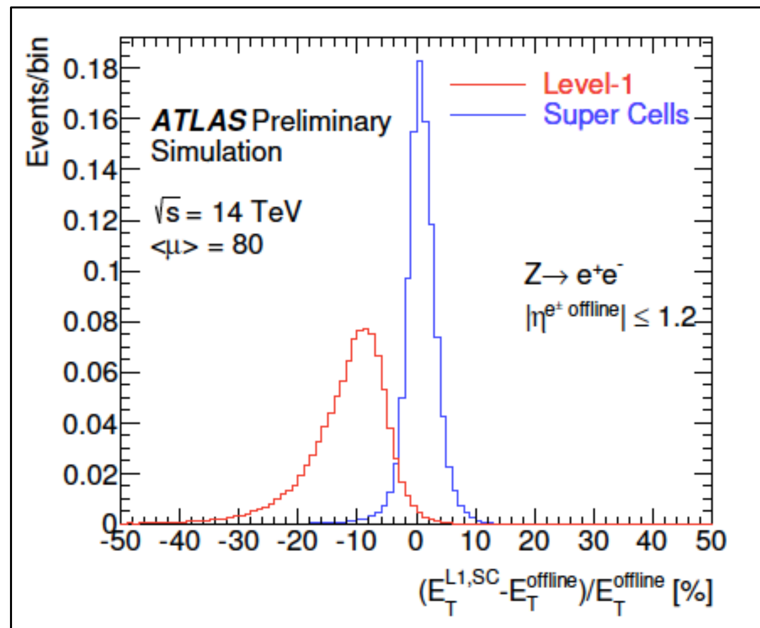
Level-1 calorimeter trigger cont.

Trigger eff. vs jet p_T



Significant degradation of the turn-on curve with pile up (<μ>=80)

- requiring much higher offline threshold (black curve)
- recovered through introduction of super-cells (red curve)



EM Triggers

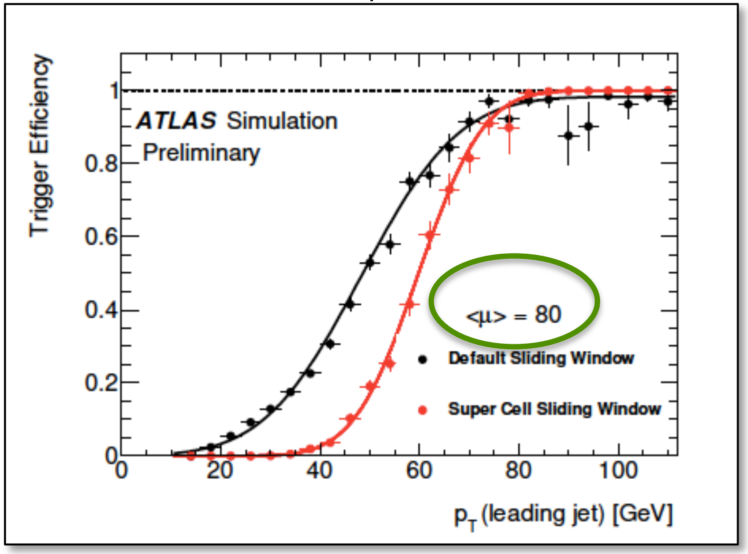
- Better shower shape discrimination
  → lower EM threshold by ~ 7 GeV at same rate
- In addition significantly improved resolution
  → lower EM threshold by another few GeV at same rate

Topological triggering

- Will feed calorimeter trigger input to L1 topological processor (already in Phase-0)

ATLAS Level-1 calorimeter trigger cont.

Trigger eff. vs jet p_T



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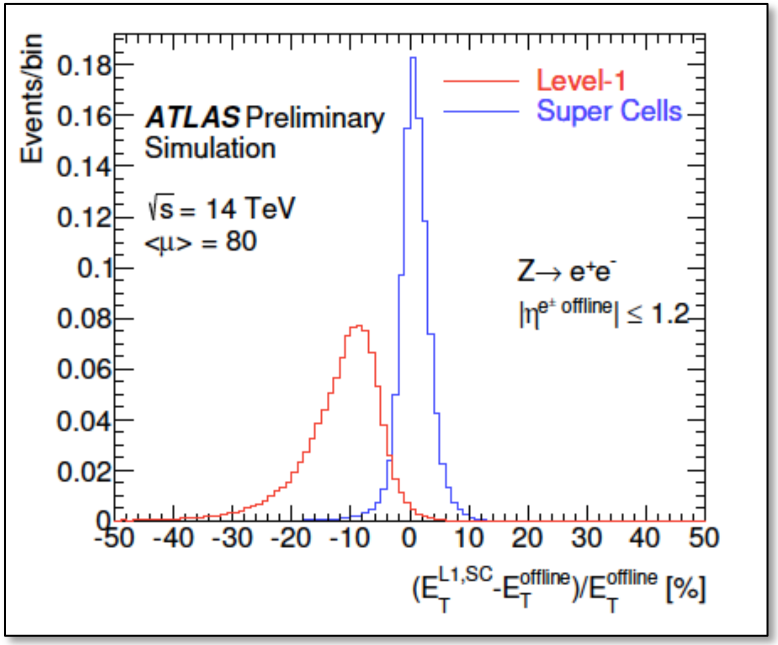

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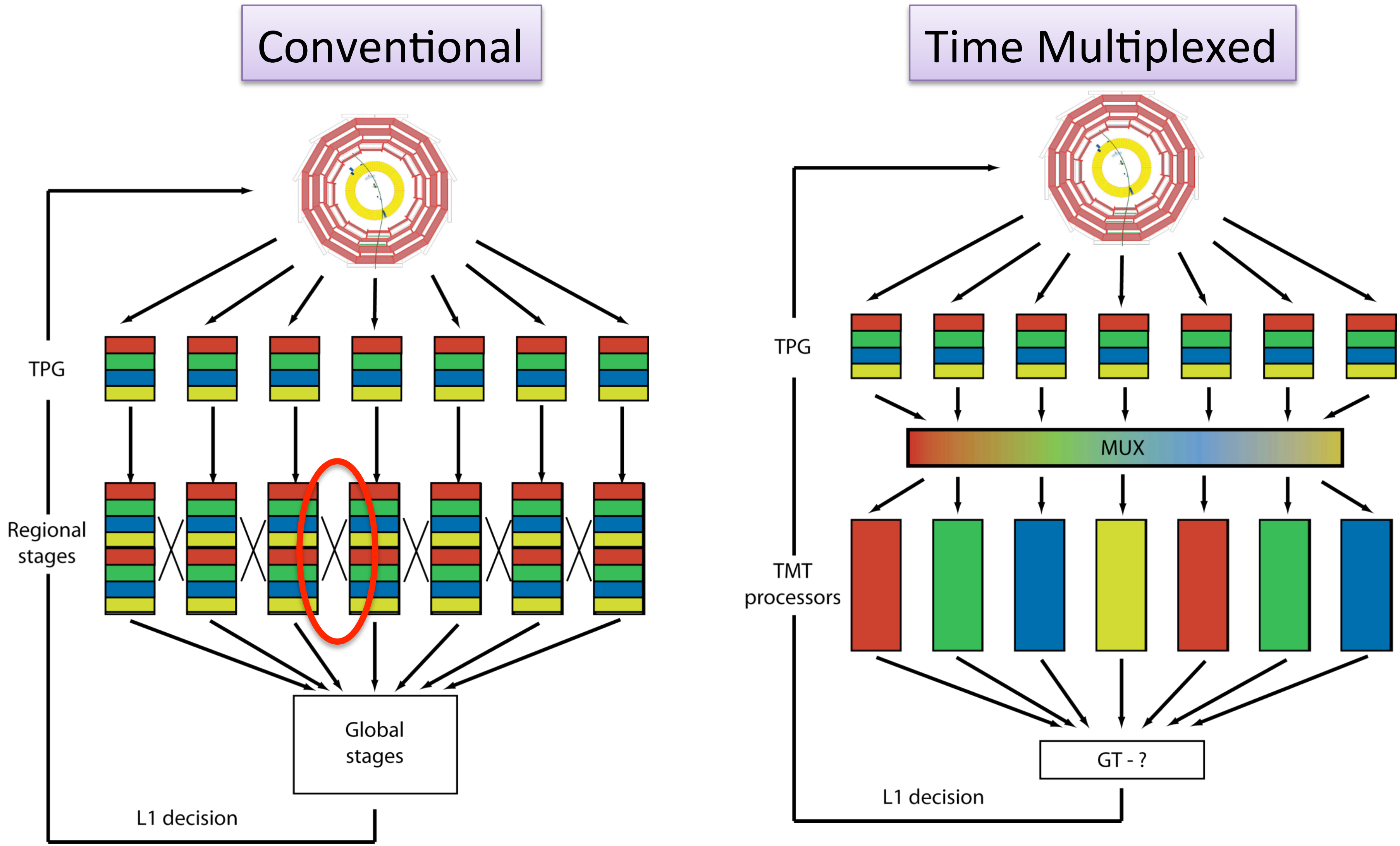
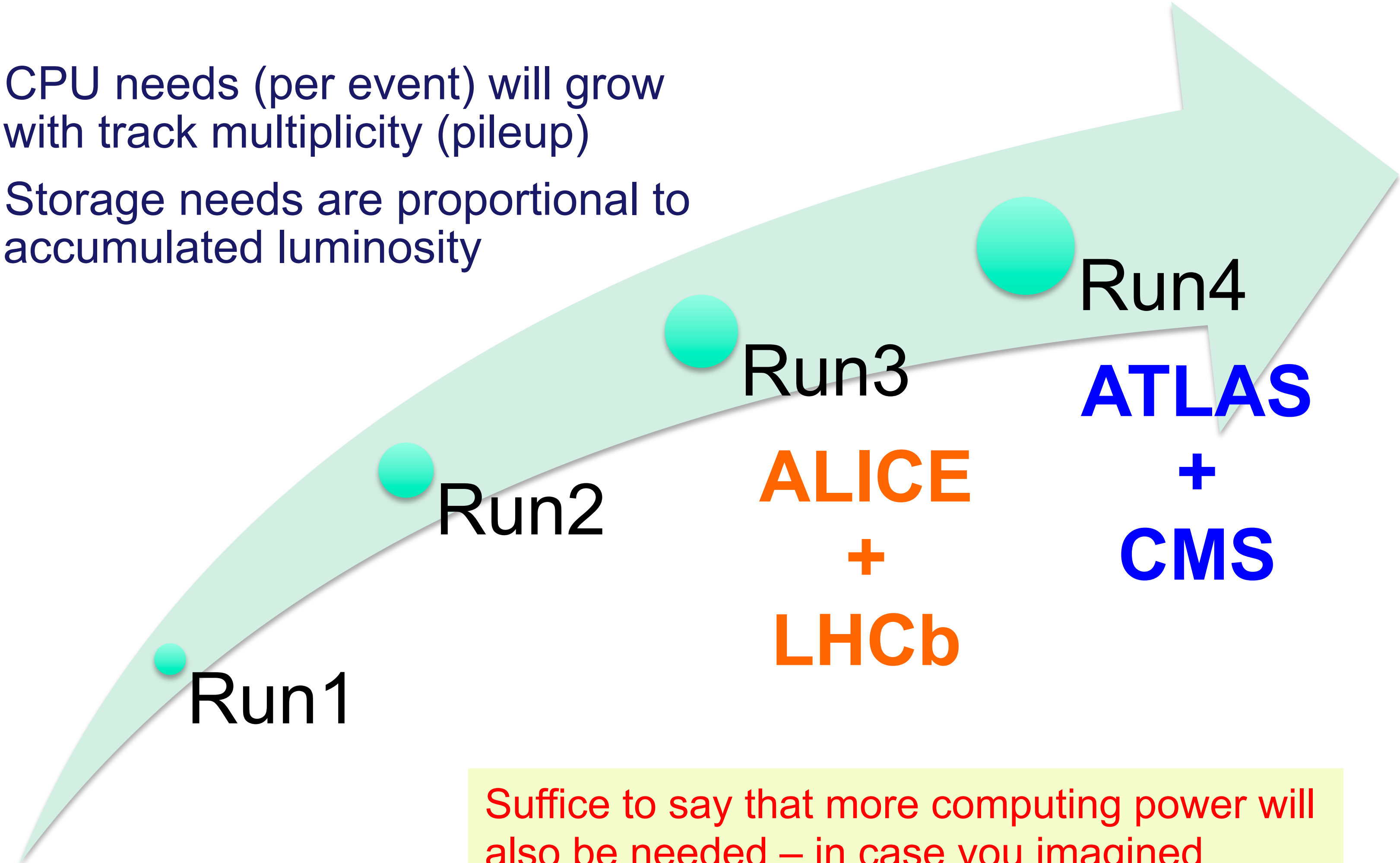
New CMS calorimeter Trigger Architecture



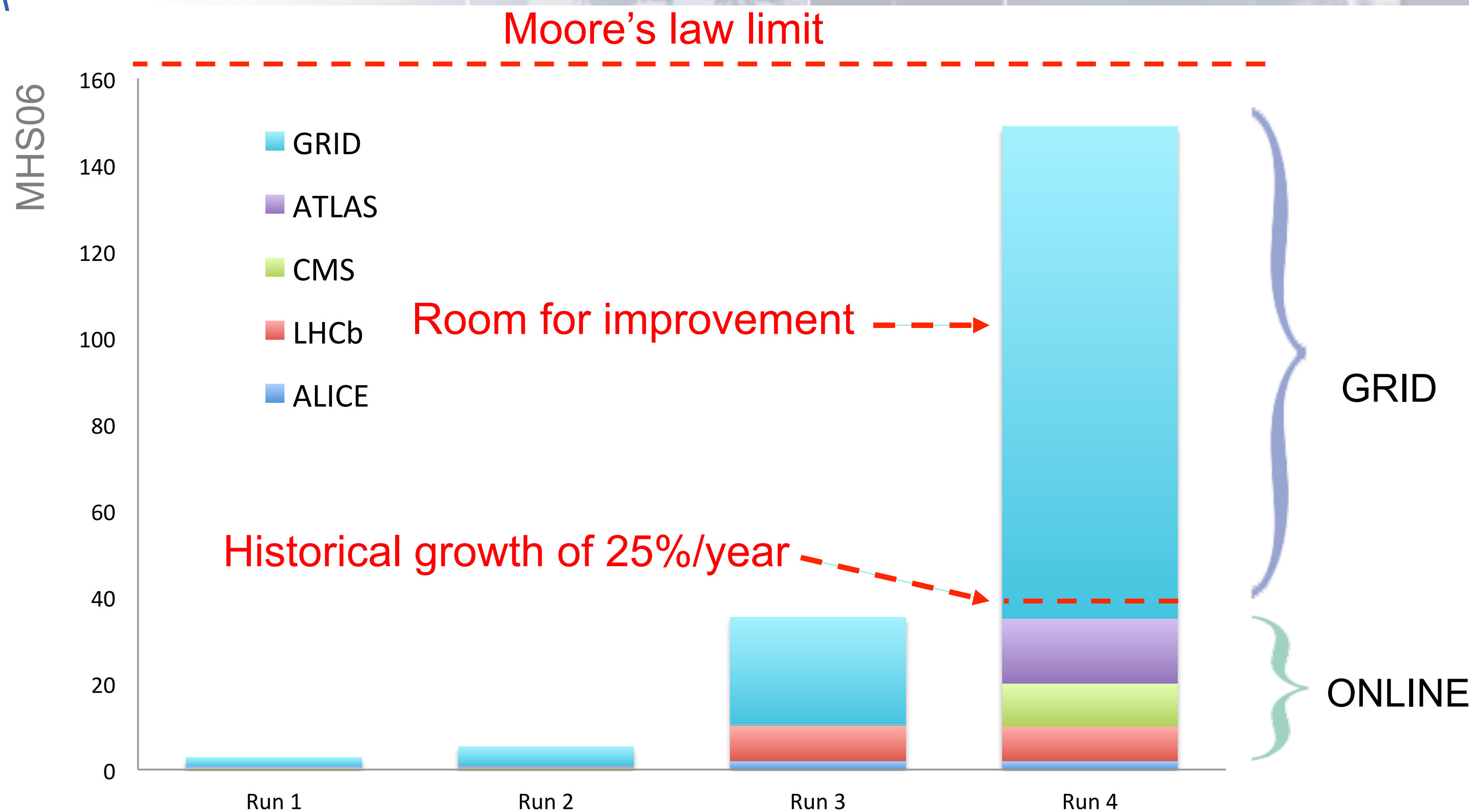
Computing @ HL-HLC

- CPU needs (per event) will grow with track multiplicity (pileup)
- Storage needs are proportional to accumulated luminosity



Suffice to say that more computing power will also be needed – in case you imagined otherwise…

CPU: Online + Offline



- Very rough estimate of new CPU requirements for online and offline processing per year of data taking using a simple extrapolation of current requirements scaled by the number of events.
- Little headroom left, we must work on improving the **performance**.

However…

- The detector upgrades present many technical challenges
  - perhaps some items are only just starting
    - new pixel systems in 65 nm CMOS for Grad radiation levels
    - forward calorimetry – power, radiation environment, new electronics,…
    - …
  - But there are also practical issues to be understood
    - ageing infrastructure
    - careful scheduling
    - financial resources, to match tight schedules
    - activation inside the experiments, where lengthy work is needed
    - human resources…
  - note of caution to be sounded?

W Zeuner
ECFA 2014

Challenges

Personnel

- LS1 has been performed with a large fraction of experts from the construction phase
- A younger generation of experts both for subdetectors and for the central coordination has to be available latest by LS2
- Without ATLAS and CMS will have difficulties to perform LS3
  LS3 will require additional personnel that has to be trained well before
- The complexity of the detectors require considerable training times and some continuity to be operated and upgraded efficiently
- Difficult to attract enough young people, as for career advancement this work is not considered valuable

Summary

- There is much more to learn from bigger data samples
  - Improvements to the detectors and machine will ensure it will be delivering physics for two decades
  - some technologies have come of age during LHC
    - SiPMs, FPGAs, optical links,
  - others still maturing
    - silicon sensors,

- Many of the changes are extremely challenging
  - They will need all the ingenuity of the next generation of physicists to accomplish successfully

BACKUP MATERIAL

Pixel Sensors – Challenges and Synergies

F Hartmann
ECFA 2014

- Evaluation which sensor technology will withstand the radiation at the innermost pixel layer(s).
  - ***Diamond*?** **3D?** **Planar** (would be wonderful because it is simple)?
    - By the way – for planar voltage helps!
    - Is 3D compatible with the small pitch (ratio column radius vs. column depth)
    - Are diamonds available? Is polarization a problem?
- Pitch of 25 μm (baseline is ~50x50 μm^2 or 25x100 μm^2)
  - BB on small sensor pitch 25 μm to demonstrated reliably within industry
    - Cell size? Probably not a problem!
  - Cell isolation? Breakdown voltage?
  - Bias grid – how to? Do we need one?

Synergies
ATLAS & CMS

- Solution for sparking with n-in-p sensors
  - Industry solution? In-house?
- Is there a limit on physical sensor thickness to be assembled with acceptable yield?
  - Bow and bump bonding??

Synergies ATLAS & CMS & LHCb

NB.: Main R&D for strip/strixel layers done – common MS ATLAS&CMS in preparation

Not an HL-LHC baseline

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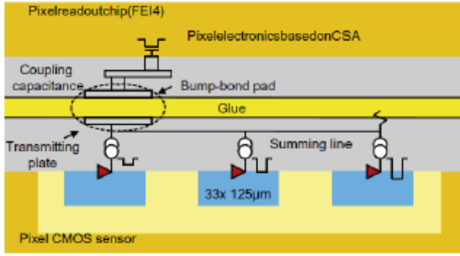
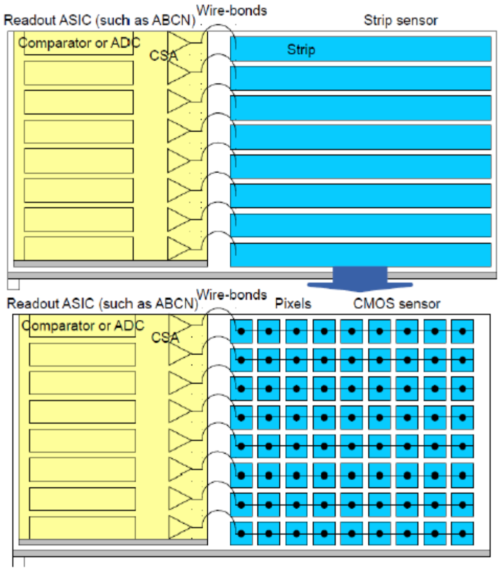
HR/HV-CMOS

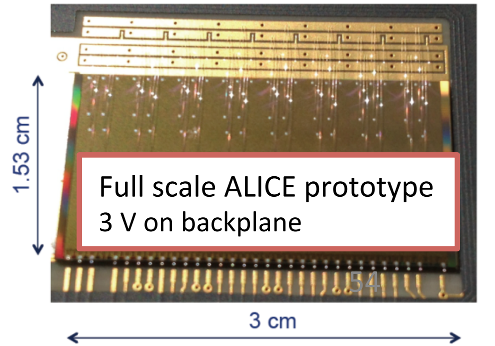


- HR/HV-CMOS is a very appealing and interesting technology.
  - It could solve lots of issues, especially in case of a full monolithic approach
  - Ideas are being evaluated to use it to replace the standard **pixel and/or strip** sensors at lower cost still together with standard CMOS chips
    - 'Standard' CMOS process (but HV) instead of dedicated process
    - Gluing replaces high cost bump bonding in pixel case



- Unfortunately it has not been consequently picked up by a dedicated R&D collaboration some years ago.

- Can the technology be matured in time for HL-LHC?
  - R&D!
  - System changes?
  - Power?
- Potential cost savings to be demonstrated
  - Taking the whole system into account



- ALICE: MAPS is a natural bet for ALICE with the less stringent requirement on radiation tolerance and readout frequency
  - Nice monolithic light weight approach

ALICE baseline

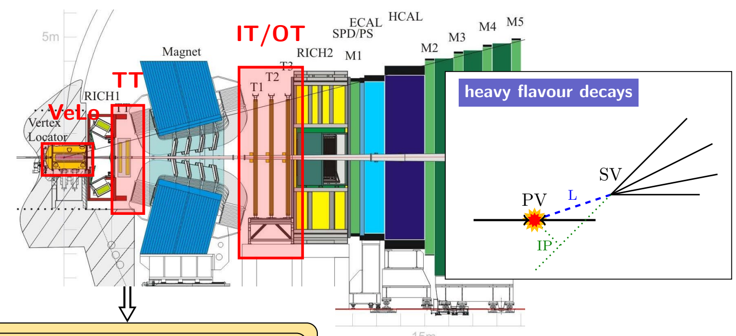
Special case of LHCb

- LHCb can read out entire detector faster than GPDs
  - the detector is much smaller (e.g. tracking ~0.5M chan)
  - then process events in HLT for storage at 5 kHz, event size ~0.1 MB
- 1 MHz is sufficient to allow HLT time to make selection
  - to avoid excessive HLT processing time include pileup veto
    - allows to increase <N_{coll}/BX>, and increase L, thus statistics

Status of the LHCb trigger

HLT1: Add tracking information

- Select high E_T hadrons, $e^\pm$, γ, threshold $E_T > 2.5 - 3.5\,\mathrm{GeV}$
- Efficiency hadronic B-decays $\sim 50\%$, radiative B-decays $\sim 80\%$
- L0 hadron rate $\sim 450\,\mathrm{kHz}$, L0 $e^\pm/\gamma$ rate $\sim 150\,\mathrm{kHz}$
- Momentum resolution $\Delta p/p \sim 20\%$
- Single muon $p_T > 1.5\,\mathrm{GeV}$, dimuon $p_{T,1}p_{T,2} > (1.3\,\mathrm{GeV})^2$
- Efficiency typically $\sim 90\%$ for dimuon channels
- L0 muon rate $\sim 400\,\mathrm{kHz}$



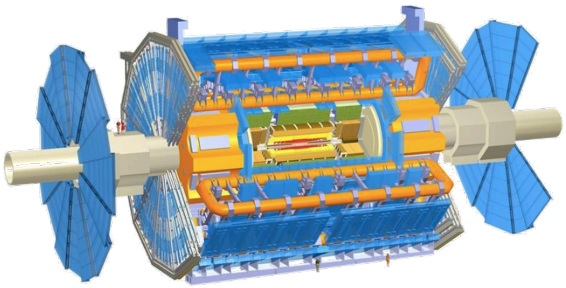
HLT1
Displaced high p_T tracks
70 kHz output rate

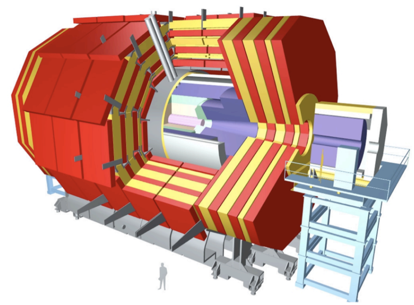
HLT2
Full event reconstruction
Exclusive and inclusive lines

5 kHz to storage
2kHz topo|2kHz charm|1kHz muon

C. Langenbruch (CERN), EPS 2013 — The LHCb trigger system

ATLAS & CMS @ Run 4 (2025)





Level 1 — 0.5 – 1 MHz — Level 1

HLT | HLT

5-10 kHz, 2MB/event | 10 kHz, 4MB/event

Storage | Storage

10-20 GB/s ← PEAK OUTPUT → 40 GB/s

Hardware triggers retained
- but with much higher rate

Why?

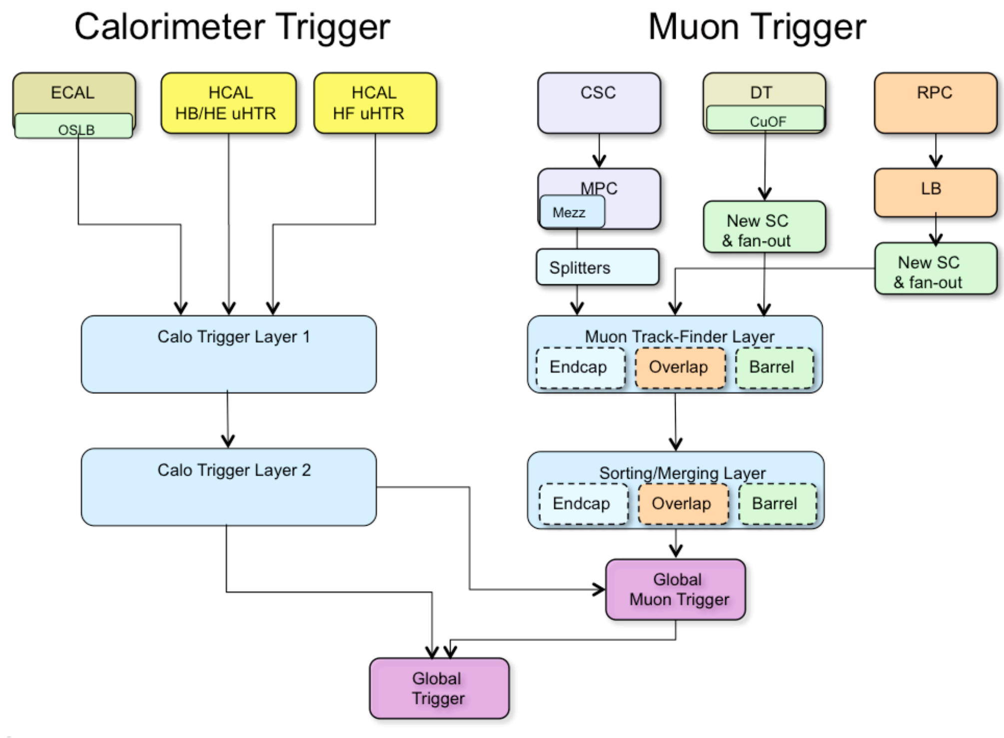
Preserve low trigger thresholds

BW is still insufficient to transmit all data off detector at 40 MHz

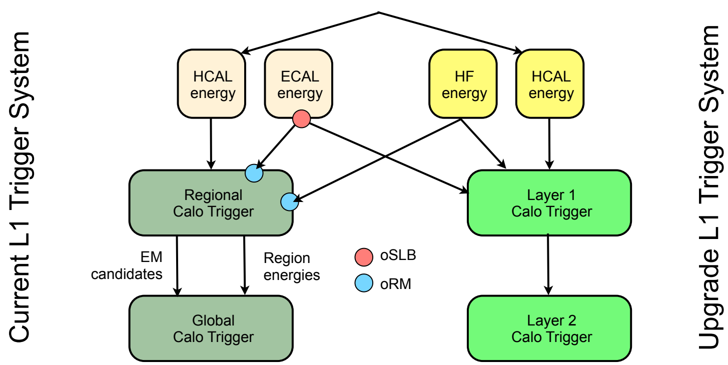
Why?

CMS Phase 1 Upgrade of L1 Trigger

- Hardware based on powerful FPGAs and high bandwidth optics
  - Calorimeter, Muon and Global triggers built with few board types, all using Virtex 7 FPGA
  - Improved algorithms for PU mitigation and isolation
  - Trigger inputs split during LS1 to commission new trigger in parallel to operating system



Level 1 Trigger Upgrade

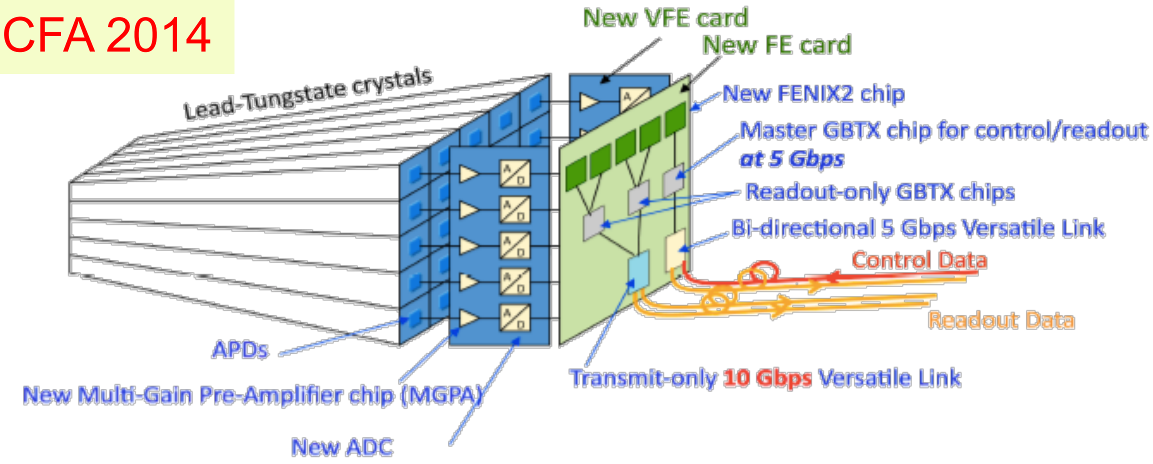


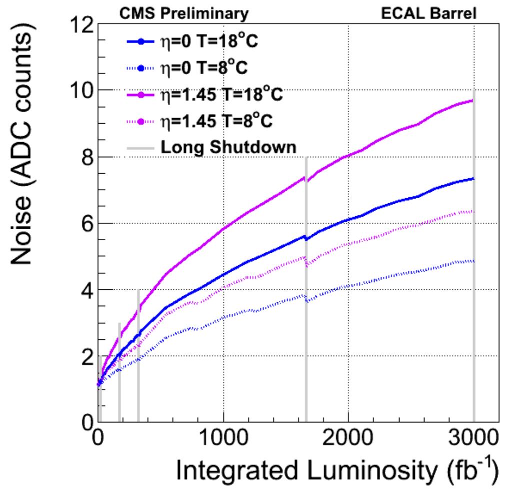
Optical splitting for parallel commissioning, calorimeter trigger

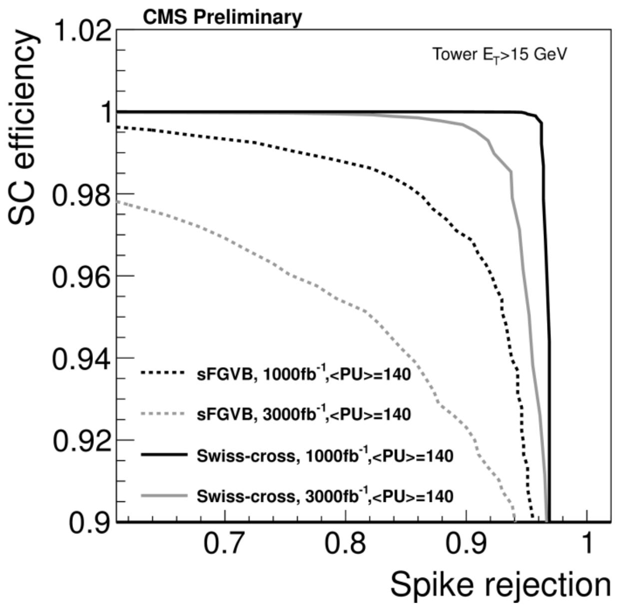
transmit greater granularity calorimeter information = more bits

Barrel electromagnetic calorimeter upgrades

J Mans
ECFA 2014







- New on-detector electronics needed to meet requirements for track trigger latency
- Replacement allows trigger-level readout of each crystal and new shaping to reduce impact of out-of-time pileup and increasing APD noise

Calorimeter

- Tile Calorimeters
  - No change to detector needed
  - Full replacement of front-end and back-end electronics to cope with higher initial event-rates and higher radiation levels
    - New read-out architecture: Full digitisation of data at 40MHz and transmission to off-detector system, digital information to level L1/L0 trigger
- LAr Calorimeter
  - Replace front-end and back-end electronics
    - Ageing, radiation limits, compliance with Phase-2 L0/L1 trigger rates and latencies.
    - Fully digital 40 MHz readout → finest granularity trigger input (L0/L1)
- Replace Forward calorimeter (FCal) if required
  - Install new sFCAL in cryostat or miniFCAL in front of cryostat if significant degradation in current FCAL or if finer granularity mandated by physics requirements at HL-LHC