Upgrades at the LHC

Nikos Konstantinidis

IOP HEPP & APP 2013 Meeting – Liverpool

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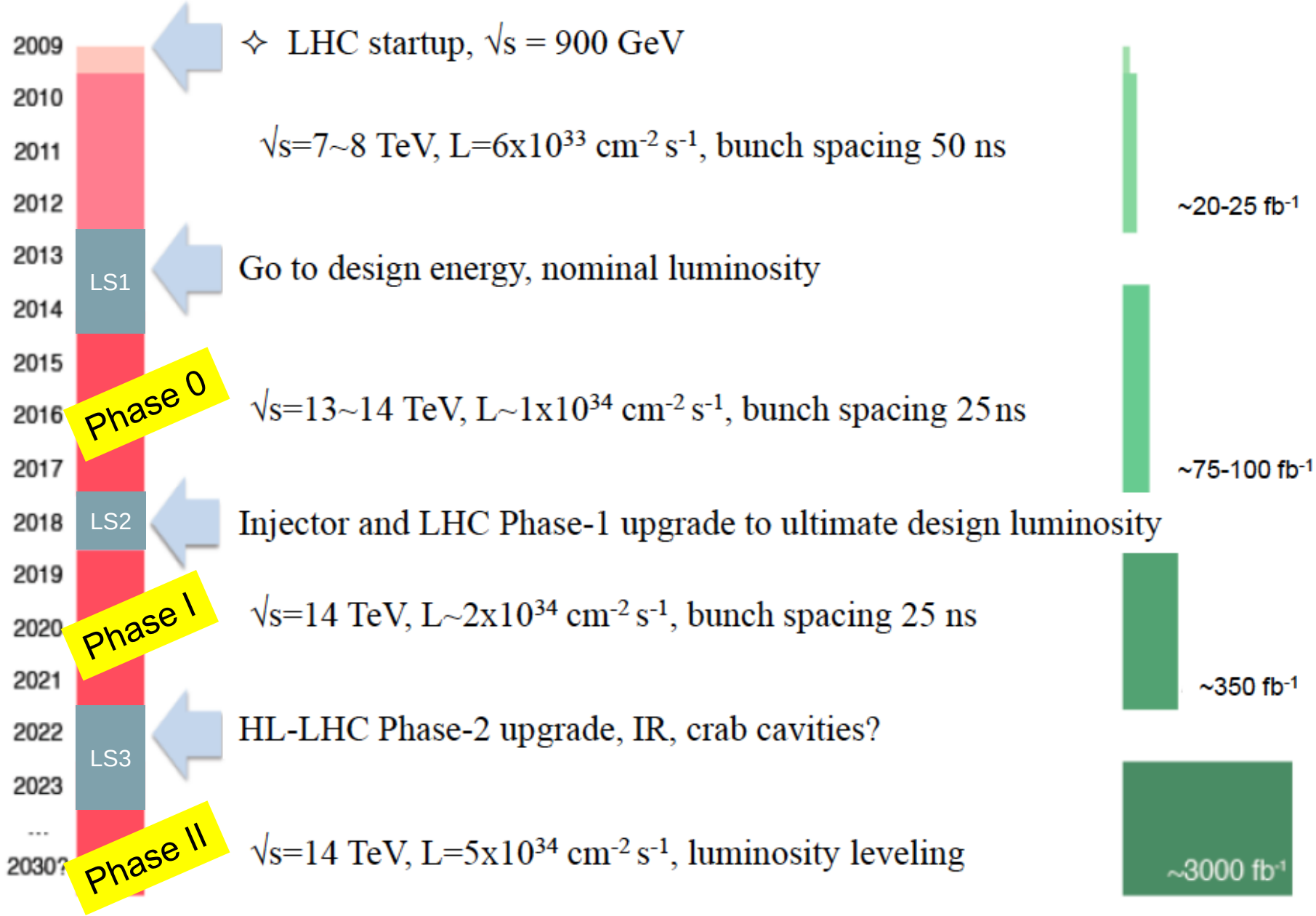
Many thanks to colleagues from the LHC experiments for helping me with this talk, especially David Evans, Geoff Hall, Neville Harnew

Outline

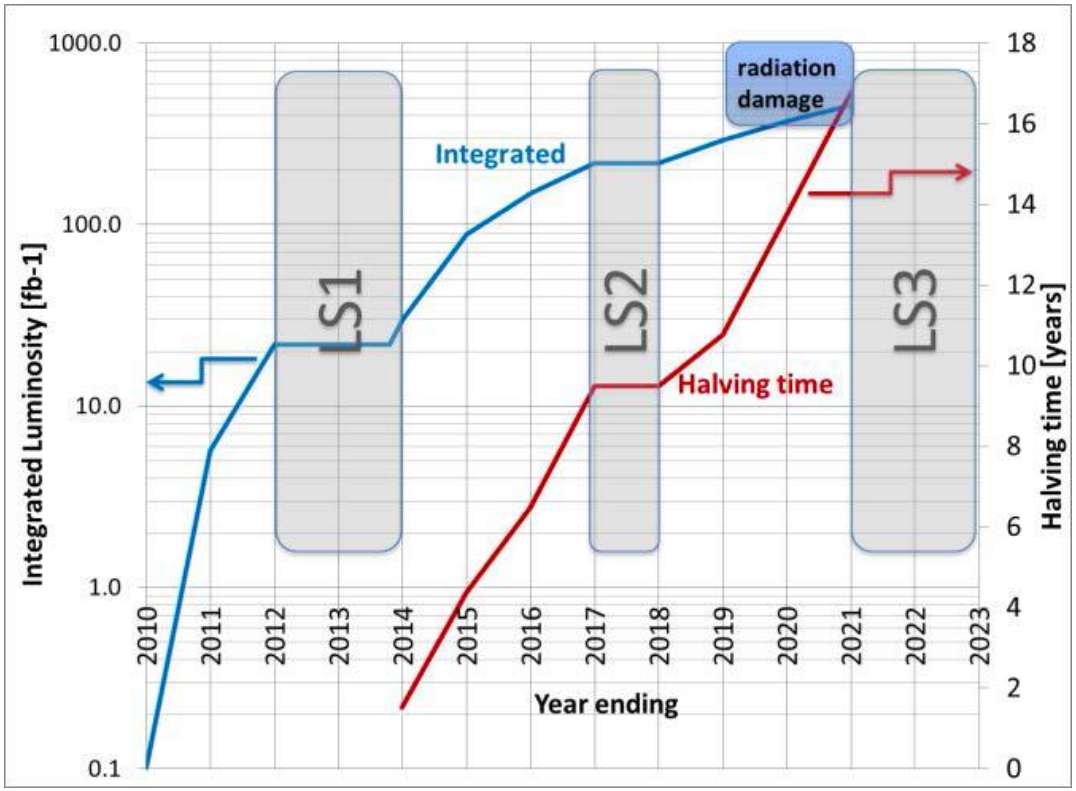
- LHC upgrade timelines
- Science case for up to 3000 fb^{-1} per expt (ATLAS & CMS)
- Challenges, proposed upgrades and ongoing R&D
- LHCb and ALICE upgrades – prospects and R&D
- Conclusions

LHC: The 20-year plan



The science case for 3000 fb^{-1} (I)

- From the luminosity delivery point of view:
  - Optimize shutdown time vs. increased luminosity delivery



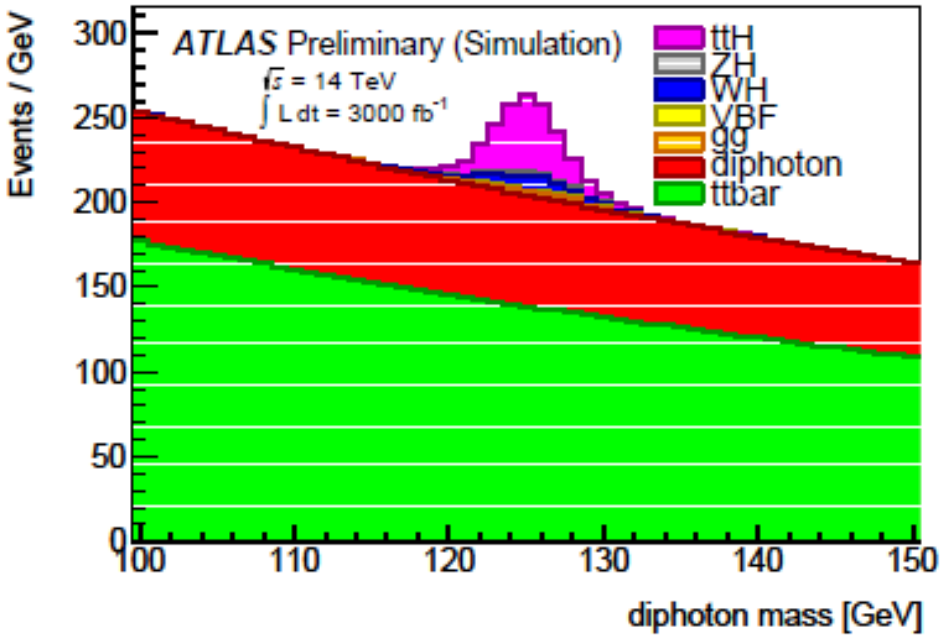
The science case for 3000 fb^{-1} (II)

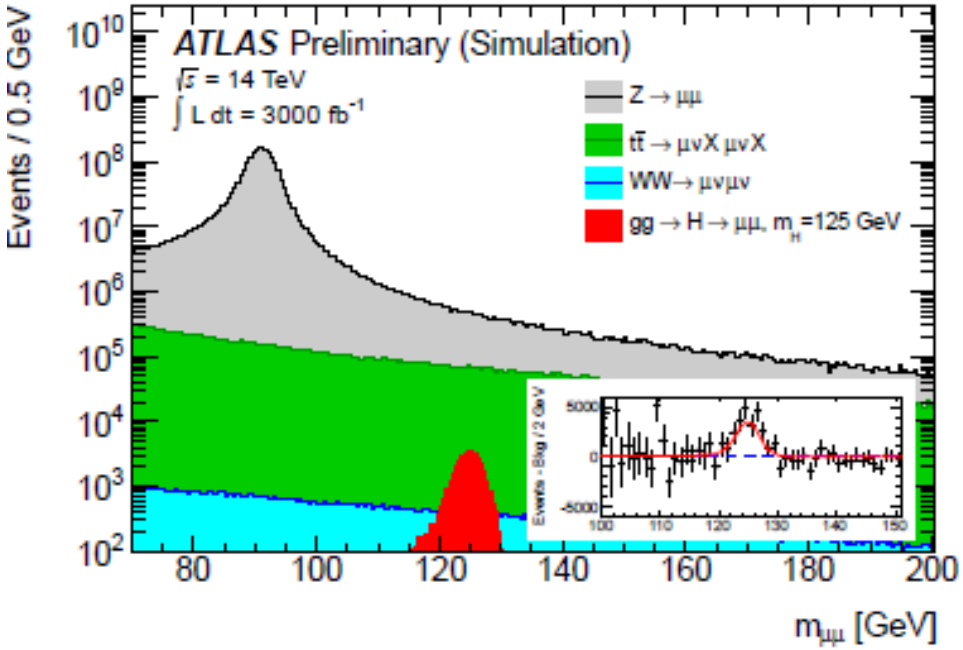
Given that the programme up to 300fb^{-1} is well established, focus on the benefits from 300fb^{-1} to 3000fb^{-1}

- A wealth of physics with ~100 times more data than today
  - High precision measurements of the Higgs properties
  - Rare decays (e.g. $H \rightarrow \mu\mu$, $H \rightarrow HH$ or $t \rightarrow Z/\gamma q$)
  - Thorough exploration of multi-TeV mass range
  - Significant extension of coverage in SUSY parameter space
  - Study properties of new particles that may be discovered

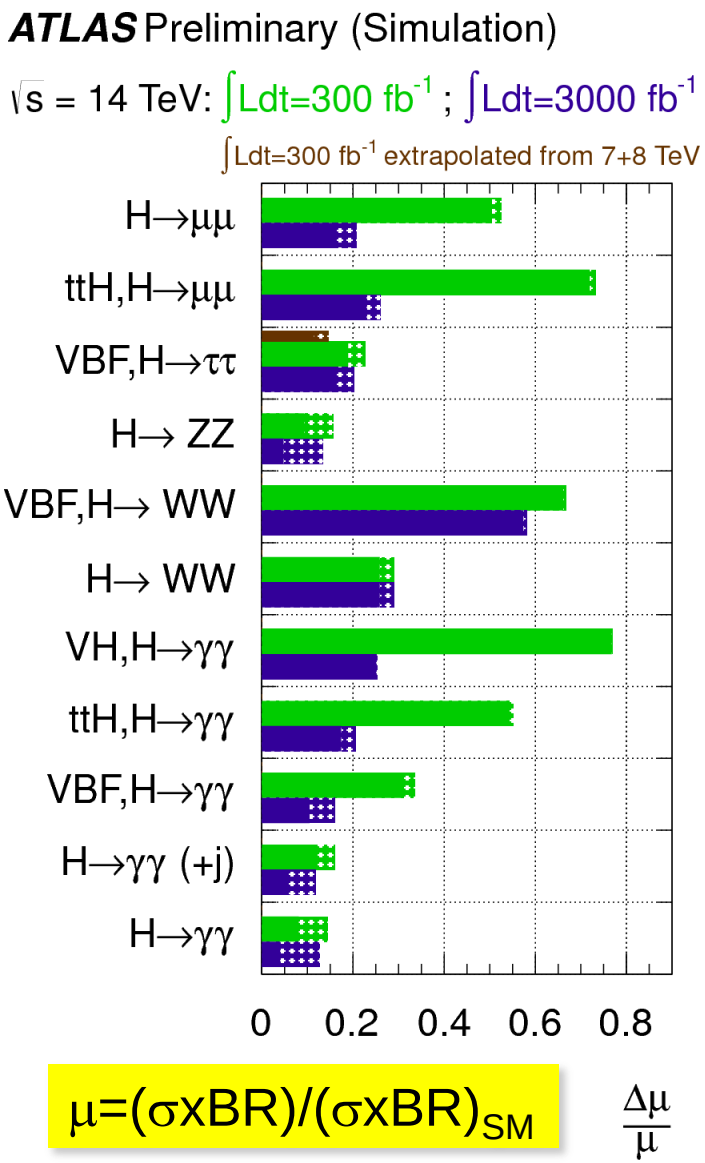
Rare Higgs decays

- ttH with H→γγ allows a cleaner determination of the top Yukawa coupling
- A >6σ H→μμ signal peak
  - Only direct observation of the Higgs coupling to 2nd generation of fermions





Determination of Higgs couplings



$\mu=(\sigma x BR)/(\sigma x BR)_{SM}$

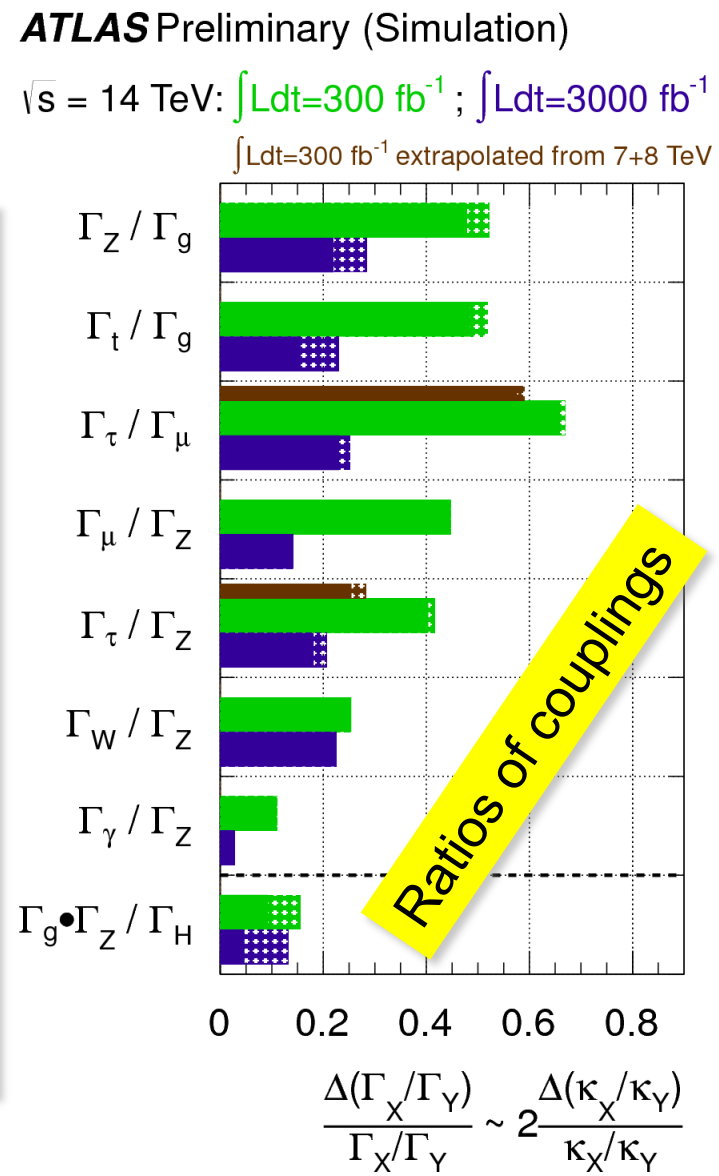
Higher stats

↓

Reduced errors
&
more final states observable

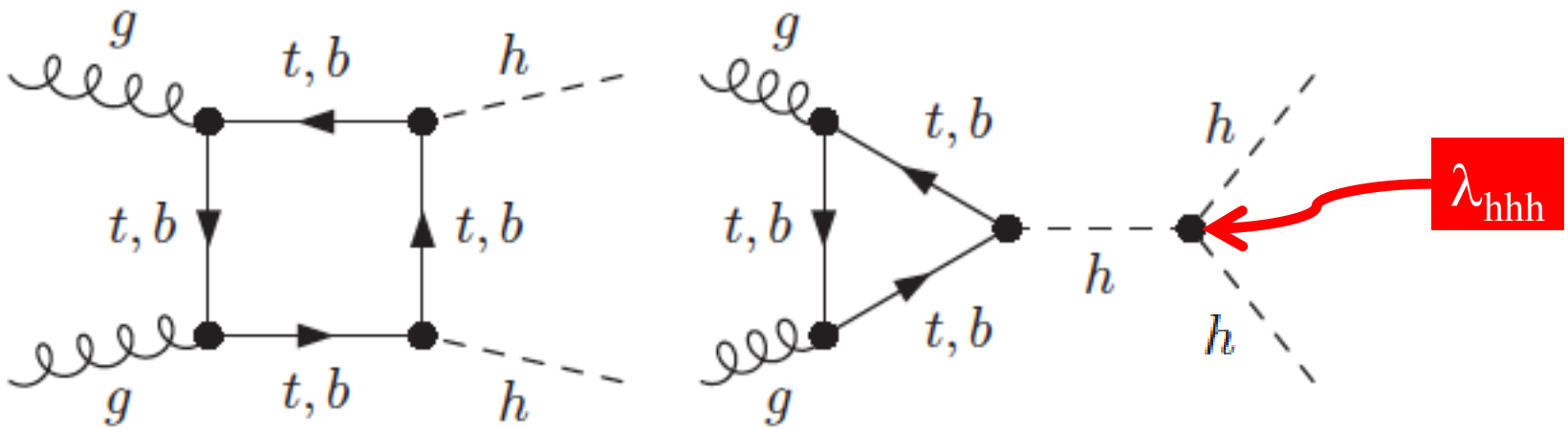
↓

Better prospects for Model independent determination of couplings



$$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y} \sim 2\frac{\Delta(\kappa_X/\kappa_Y)}{\kappa_X/\kappa_Y}$$

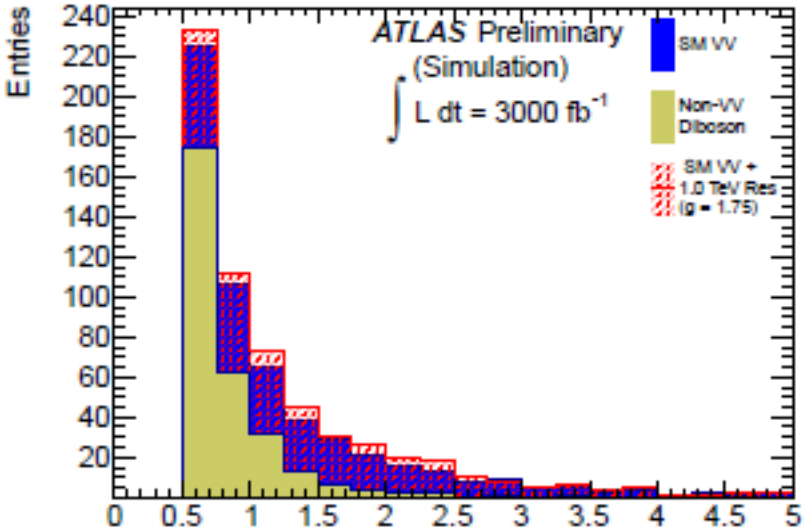
Higgs self-coupling



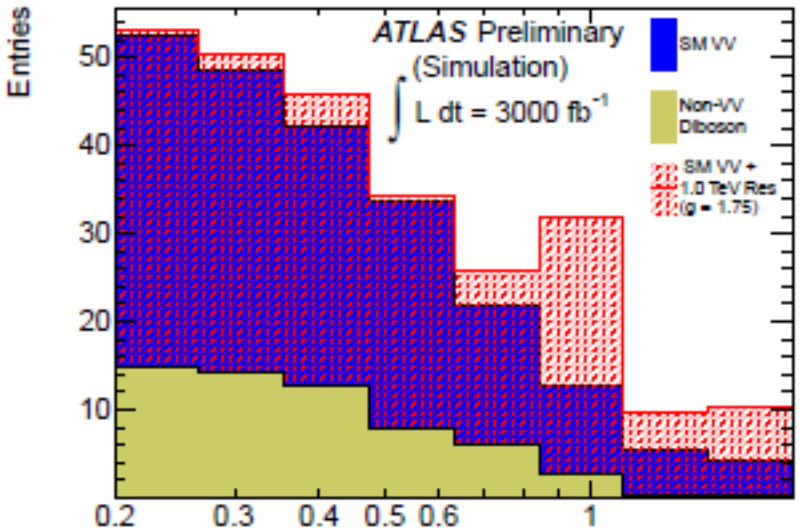
- Hardest measurement in the Higgs sector!
  - But an important consistency check of the EWSB mechanism
- Look for two-higgs final state – destructive interference with diagrams not containing λ_{hhh}
  - For $\lambda_{hhh}=\lambda_{SM}$: σ=34fb, for $0*\lambda_{SM}$($2*\lambda_{SM}$):71fb(16fb)
  - For $\lambda_{hhh}=\lambda_{SM}$, a 3σ observation is possible in the $bb\gamma\gamma$ final state
  - Other promising channels under investigation (e.g. $bb\tau\tau$)

Weak Boson (VV) scattering

- Validate the SM prediction for the VV scattering cross section at high energies in the presence of the Higgs
- Look for new physics, e.g. a new resonance sharing with the Higgs the role of unitarising the $V_L V_L$ scattering amplitude



Invariant mass of forward jets [TeV]



Invariant mass of 4 leptons [TeV]

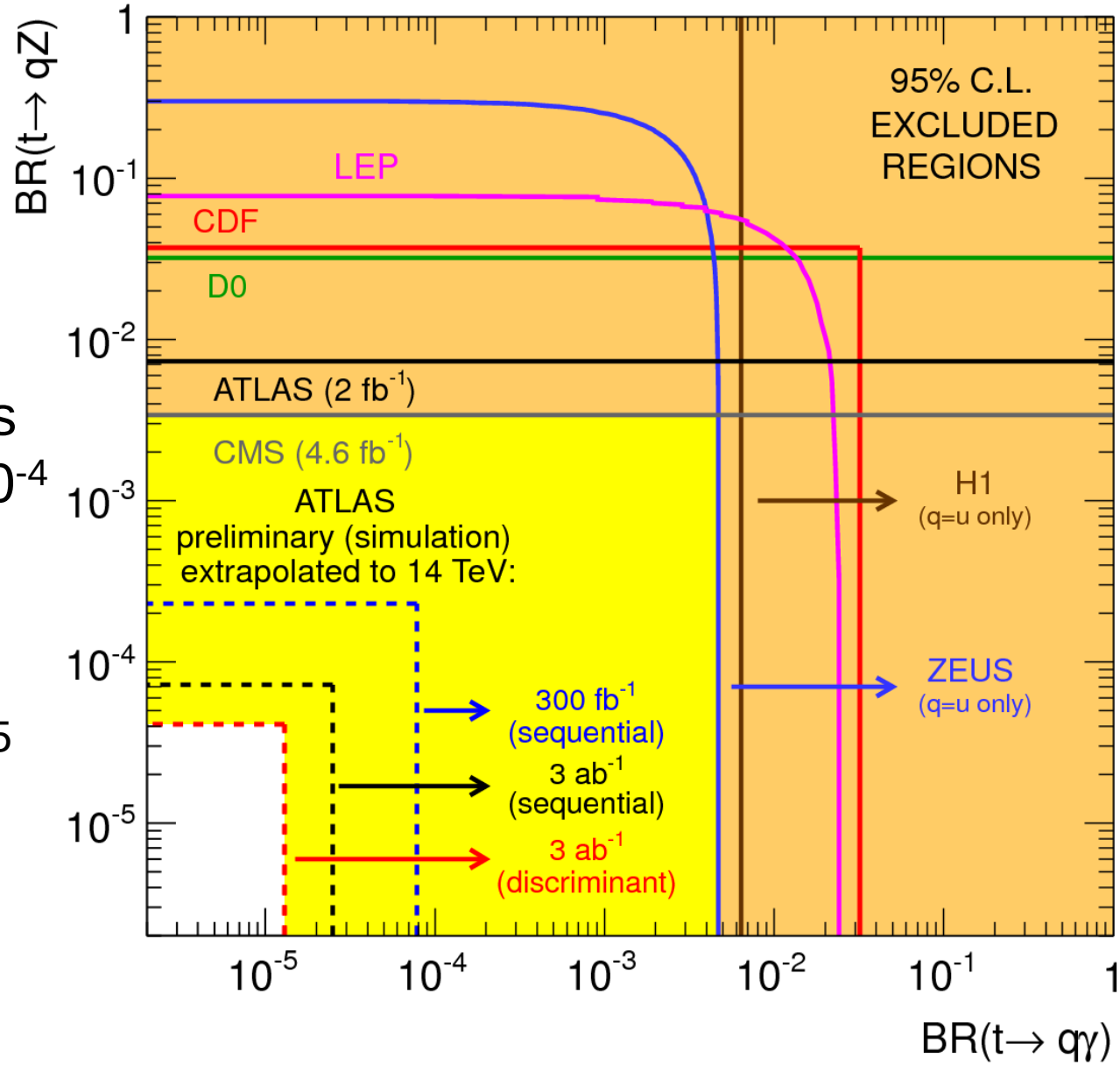
model	300 fb^{-1}	3000 fb^{-1}
$m_{\text{resonance}}$ = 500 GeV, g = 1.0	2.4σ	7.5σ
$m_{\text{resonance}}$ = 1 TeV, g = 1.75	1.7σ	5.5σ
$m_{\text{resonance}}$ = 1 TeV, g = 2.5	3.0σ	9.4σ

Rare decays: FCNC t→Zq, t→γq

In SM, BR ~10^{-12}

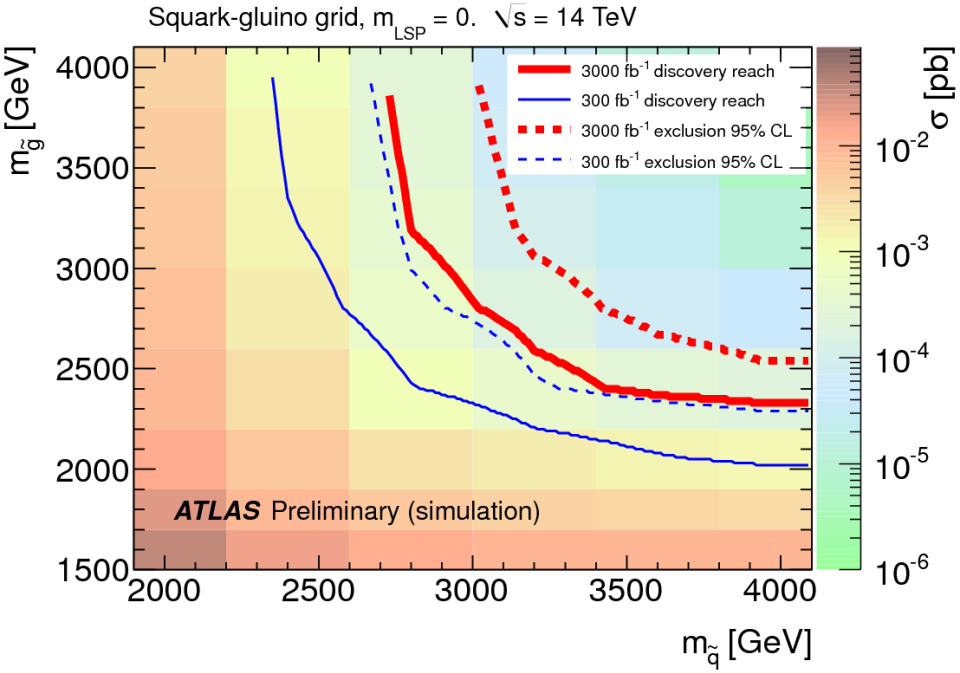
New physics models predict BRs up to ~10^{-4}

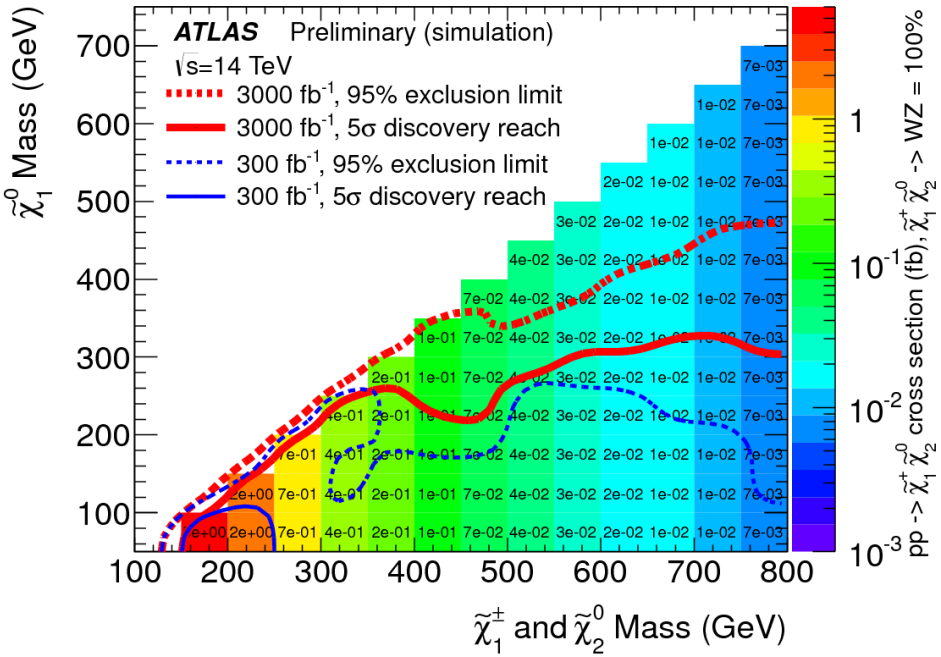
with 3000fb^{-1} sensitivity to BR~10^{-5}



Supersymmetry

- If SUSY is discovered at 14TeV with ~300fb^{-1} by ~2021
  - 3000fb^{-1} vital for characterising the observed signal (masses, spin, couplings…)
- If no SUSY with~300fb^{-1}, extend significantly the reach of searches in the SUSY parameter space
  - Up to ~30% higher masses accessible with 3000fb^{-1}
- If no SUSY signs in 3000fb^{-1}, weak scale SUSY very disfavoured





Other exotic models

- Strongly or weakly produced high mass resonances leading to boosted topologies
  - Main bkg is SM; for a given s/b benefit from increased stats
    - Reach ~2TeV higher masses or ~3 times smaller cross section for same mass

- Heavy partners of W/Z decaying to lepton pairs
  - Sensitivity up by ~20%, approaching masses of 8TeV

model	300 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	6.7 (5.6)
$Z'_{\text{Topcolour}}$	3.3 (1.8)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.6

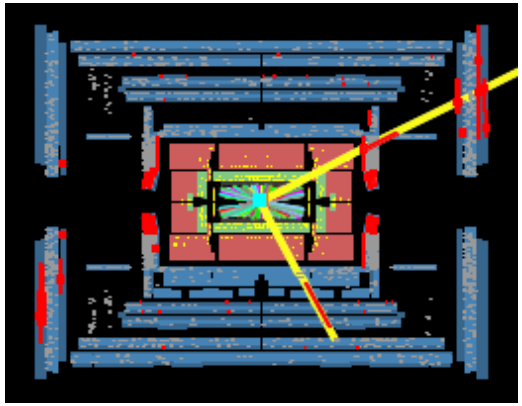
LHC: the only collider to probe directly the multi-TeV energy scale in the 2020s

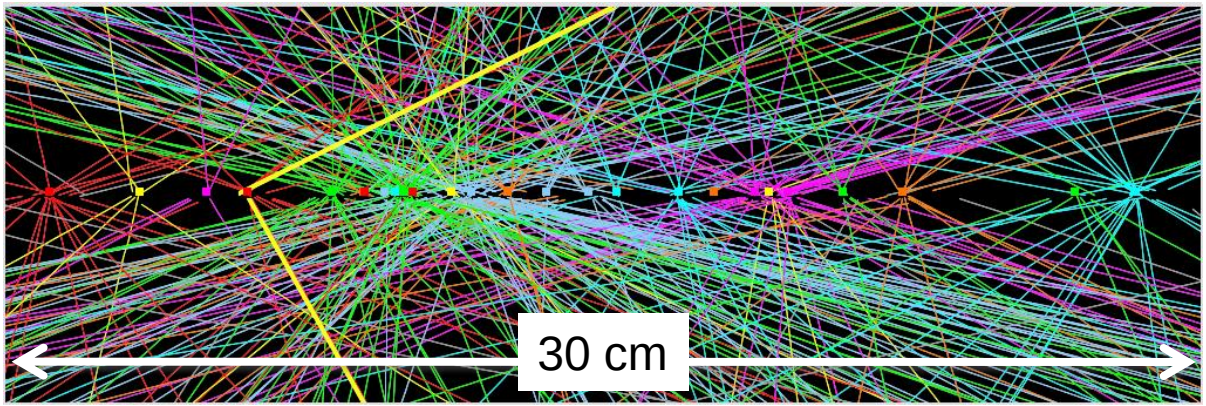
upgrades

The problem with higher luminosity…

- To exploit fully the LHC lumi upgrades, ATLAS and CMS must maintain today's performance
  - …in a much harsher environment: **pile-up**
  - After LS2: ~ 55-80 pp collisions per bunch crossing
  - After LS3: ~140-200 pp collisions per bunch crossing
- Unprecedented challenges for triggering & pat. recognition
- High radiation dose to tracking detector

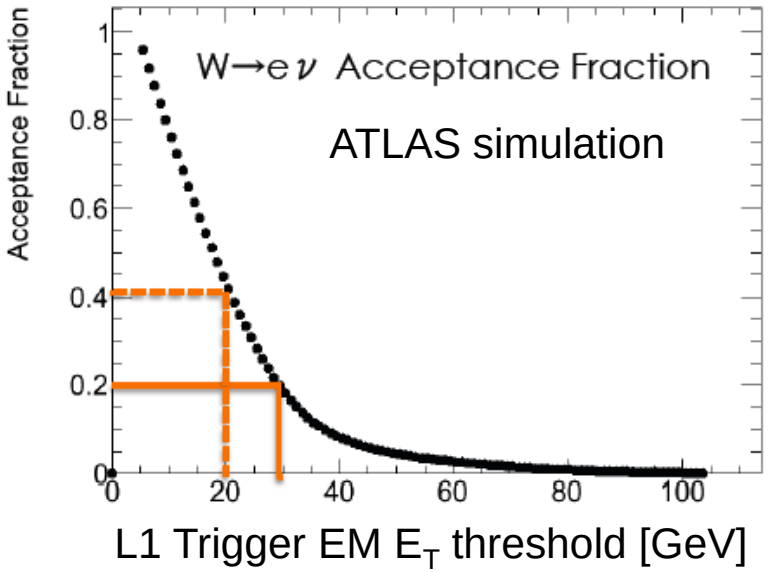
Typical ATLAS event in 2012: $Z \rightarrow \mu\mu$ in 25 pile-up pp collisions



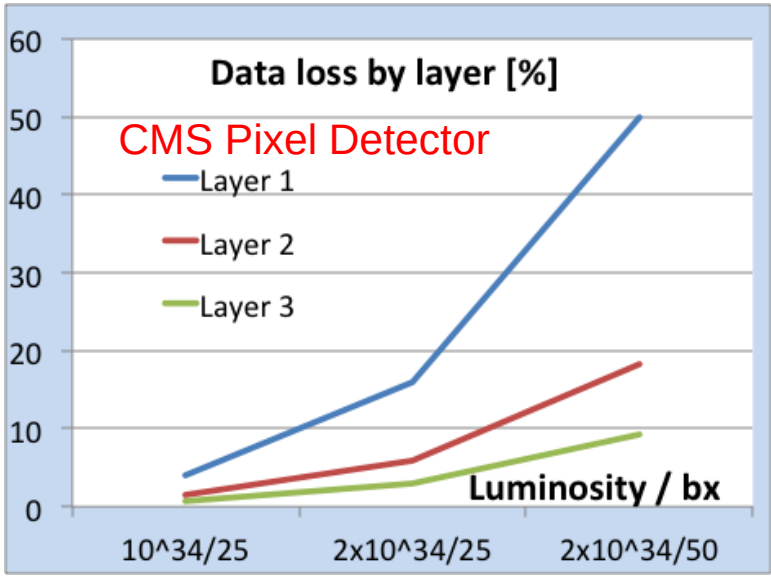


Key challenges

- The trigger challenge (mainly L1)
  - Retain current p_T thresholds, to preserve high efficiency for EW scale objects (W, Z, top, Higgs…)
  - Most of the L1 rate is bkg events (mis-measured, lower p_T objects)
    - Pile-up has a huge impact on rates



- The high occupancy challenge
  - Increased occupancy leads to readout inefficiencies in inner tracking layers
    - Critical for pattern recognition, and particularly for b-jet tagging



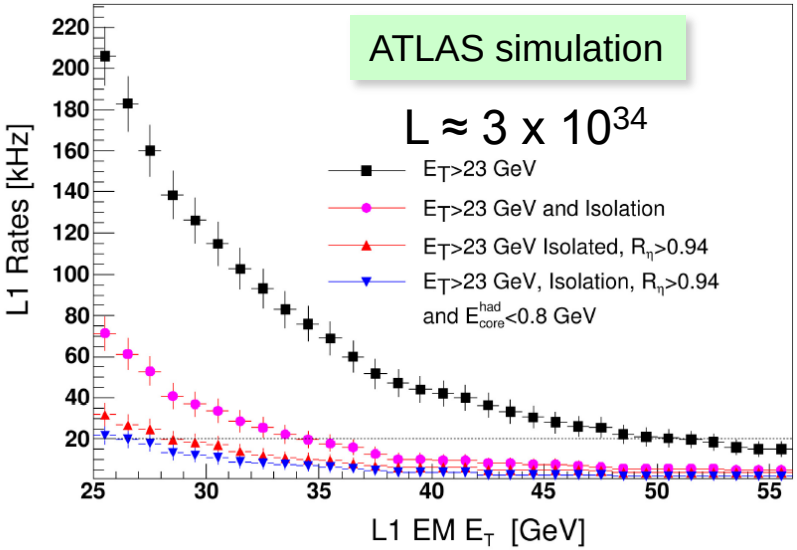
Phase-0/I key upgrades

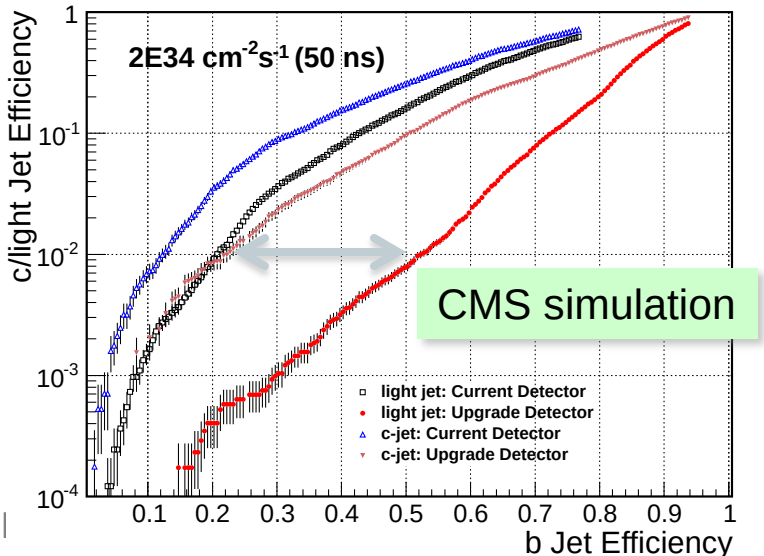
ATLAS:

- New insertable Pixel barrel layer at radius ~3.3cm (in 2014)
- New Muon Small Wheels
- Finer granularity L1 Calo Trigger
- Hardware track reconstruction for L2 trigger (FTK)
- New forward detectors
- High Level Triggers & offline sw
- …

CMS:

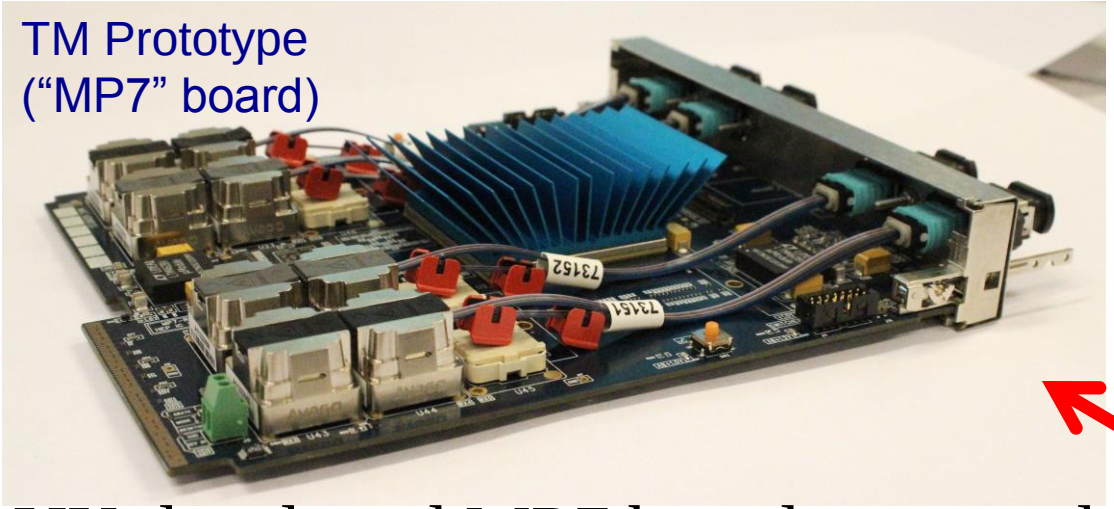
- New, 4-layer Pixel system
- Additional Muon chambers for improved L1 trigger performance (in 2014)
- New L1 Trigger hardware and architecture (2015-16)
- Replace HCAL HPDs with (more robust) Si Photomultipliers
- …



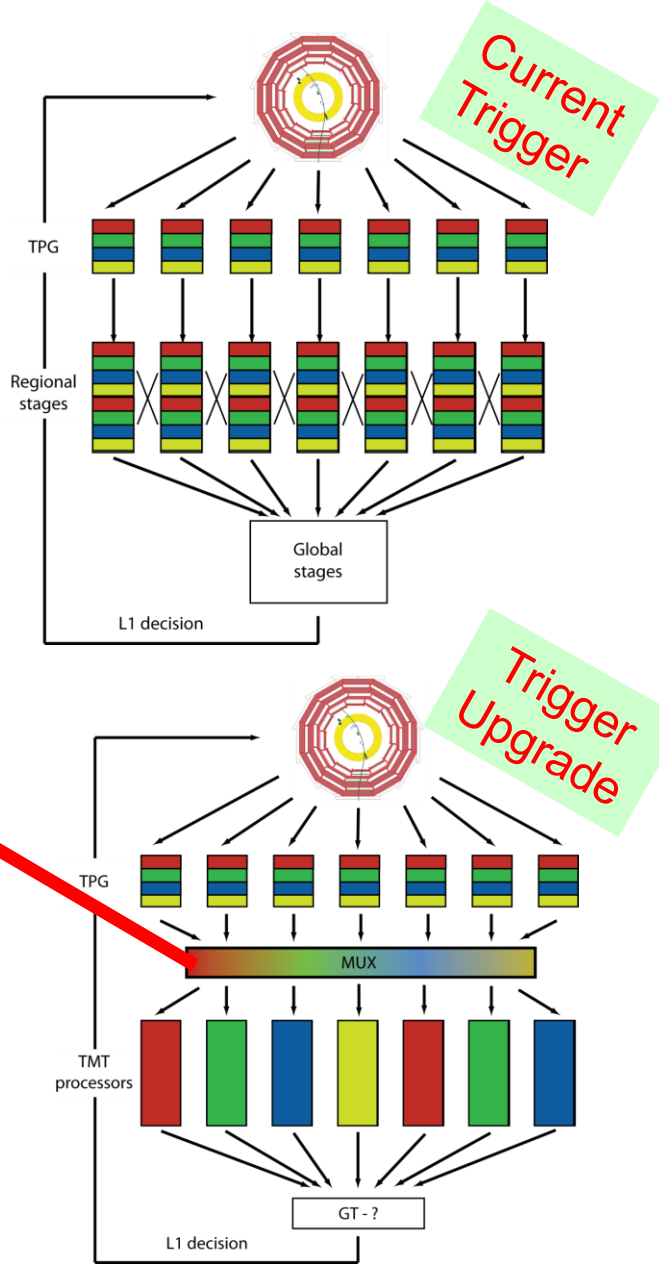


Example – CMS L1 Trigger upgrade

- Use time multiplexing to bring all data e.g. from Calo to a single processor
  - No boundary issues between regions
  - More powerful for global variables



- UK developed MP7 board approved for installation in CMS
  - 1Tb/s - All 96 optical links operating at 10Gb/s simultaneously



Phase-II upgrades

- Possibly up to 200 pp collisions per bunch crossing!
  - Depending on the performance of luminosity levelling
- Both ATLAS and CMS to install new all-silicon trackers
  - Finer granularity, higher readout bandwidth, more radiation hard, newest technologies
    - ATLAS/CMS-UK playing leading role in ongoing R&D
- L1 Triggers need major overhaul to keep thresholds low and really benefit from the luminosity increase
  - Further refinement of L1 Calo/Muon triggers not sufficient
  - Profit from the installation of new trackers to provide tracking info at the L1 Trigger
    - Great idea, but L1 tracking VERY challenging at the LHC!!!

ATLAS-UK tracker upgrade R&D

"Short strips": Lead role in entire programme: hybrid/module/stave design, to powering & readout, to mechanics & integration

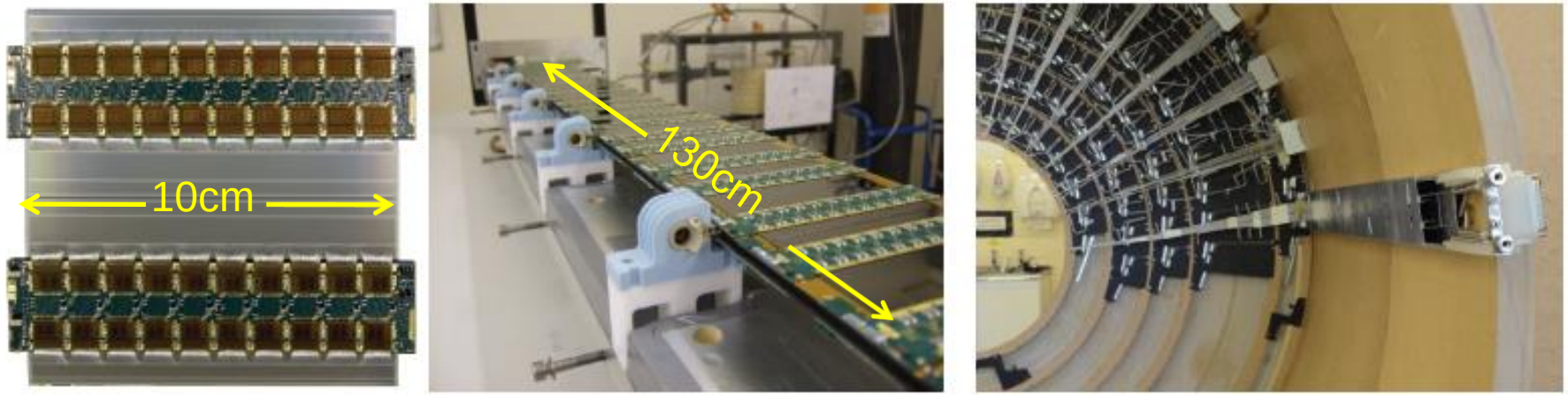
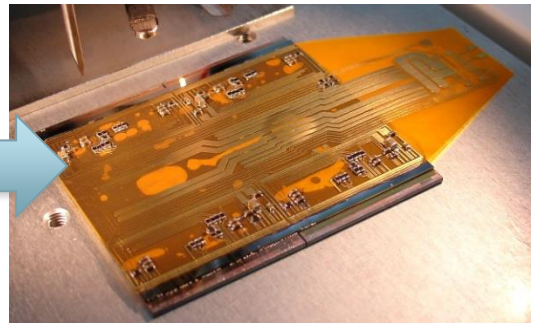
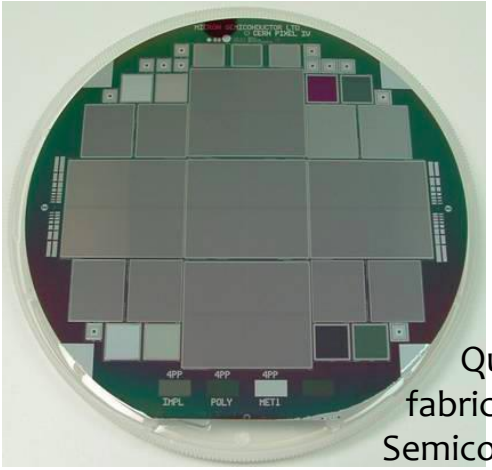


Figure 11: (Left) A strip module with hybrids, (middle) a thermo-mechanical strip stave and (right) the end of the barrel services mock-up

Pixels: Development & construction of forward pixel disks, R&D on sensors

Quad module Prototype (4x4cm^2)

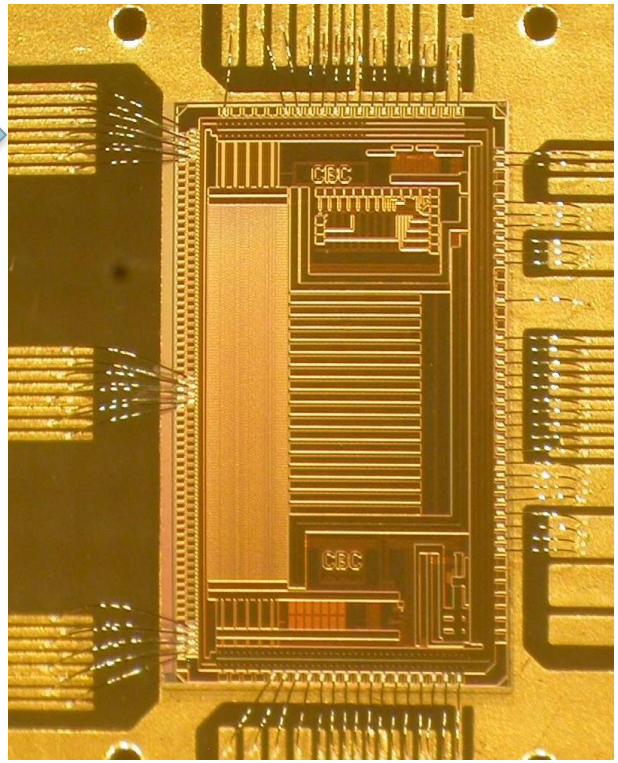




Quad sensor masks fabricated with Micron Semiconductor (UK) Ltd

CMS-UK tracker R&D highlights

- CMS Binary Chip (CBC) for outer tracker readout: 130nm CMOS
  - 128 channel binary ASIC, non-zero suppressed
  - Amplifier, pipeline, memory, logic, control
  - excellent performance, tested in beam with 5cm µstrips



- New iteration, CBC2, produced recently and currently under testing
  - 250 µm pitch, 254 channels
  - Includes track triggering functionality

- Design of modules with track triggering capability

L1 Track Trigger

- Full tracker readout at 40MHz practically impossible
  - EITHER: apply some hit filtering at 40MHz and bring off-detector a very small fraction of data, e.g. only hits from high-pT tracks

CMS

  - OR: L1 in two steps:

ATLAS

    L0: reduce the rate from 40MHz to ~0.5-1MHz using Calo/Muon info

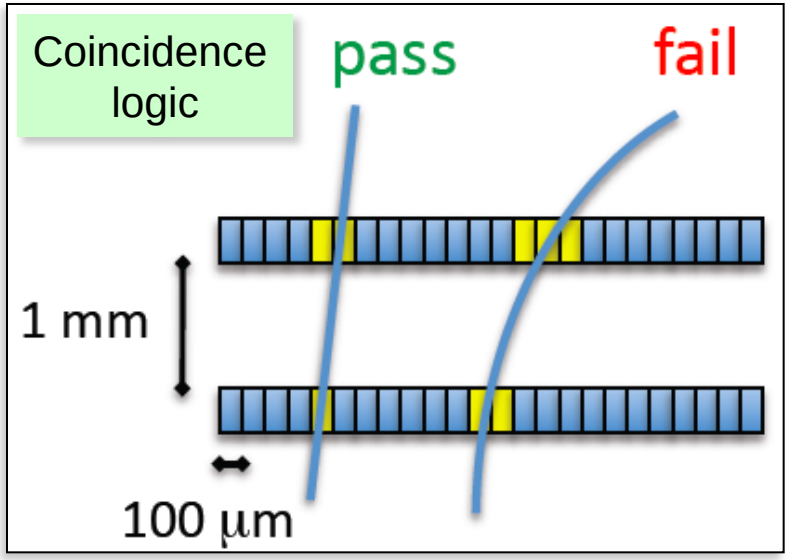
    L1: read out only interesting regions of the tracker at L0 rate for L1 decision

- Optimal choice depends on additional boundary conditions
  - Second option requires increased latency: L0+L1 ~20μs

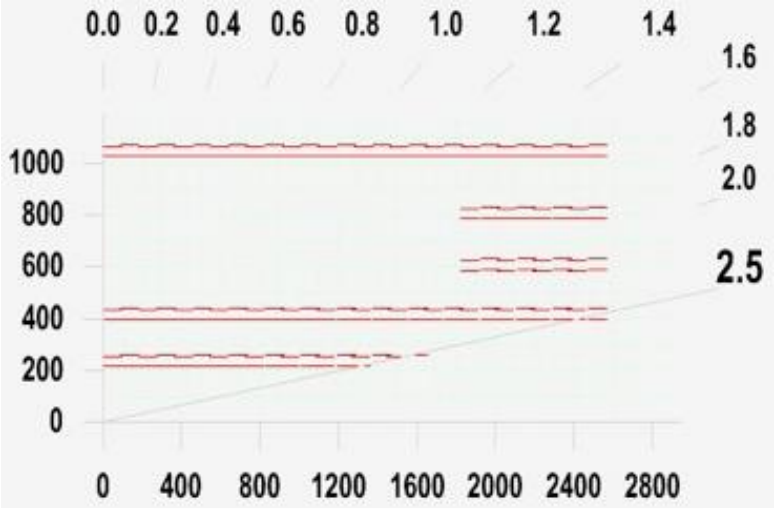
- A lot of R&D – final decisions are yet to be taken

L1 Track Trigger in CMS

- pT filtering in stacked double layers of silicion stri-xels (few mm in z)
  - Coincidence hits read out at 40MHz and combined to form track trigger primitives



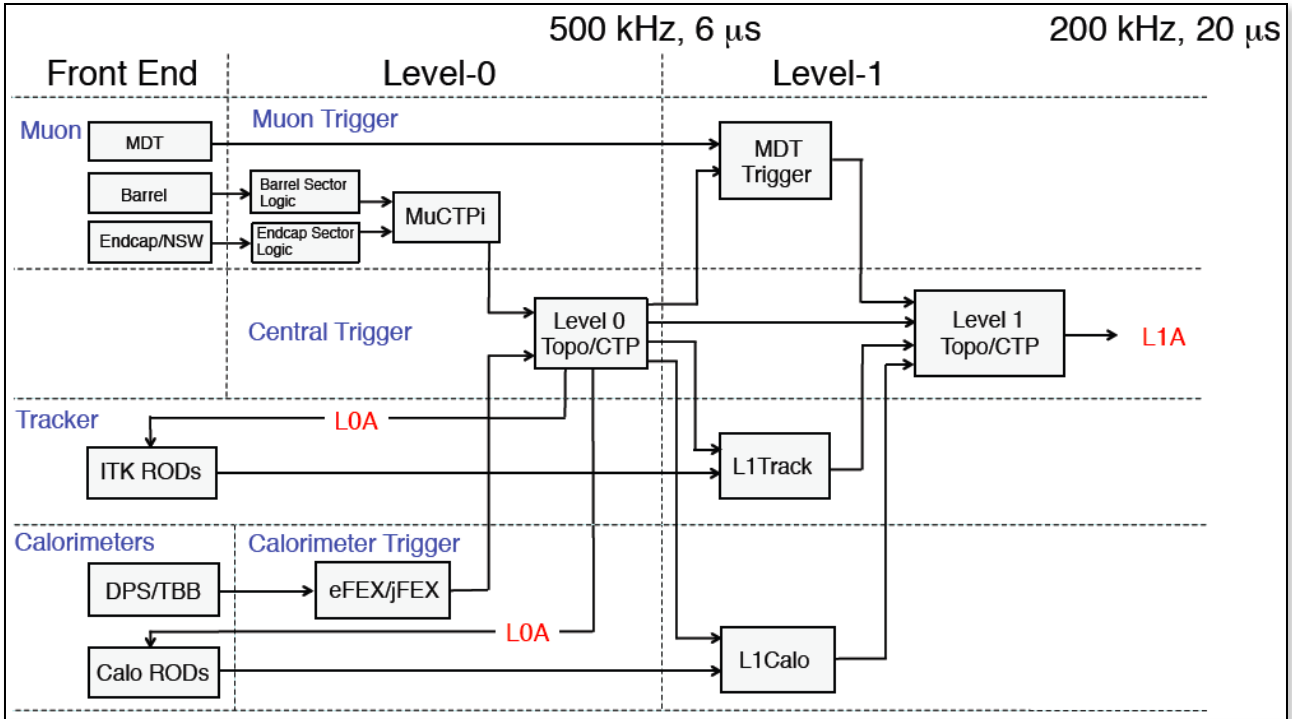
- Major impact on the layout of the tracker



Possible layout of CMS tracker

L0/L1 design for ATLAS Phase-II

- Phase-I L1 trigger (Calo/Muon) becomes Phase-II L0
  - Latency: ~ 5μs; rate: 0.5-1.0MHz, synchronous
- From L0 to L1, bring in tracking and other new information
  - L1Track in Regions of Interest found by L0
    - Read out only ~10% of tracker at L0 rate (takes ~6-7μs)
  - Full granularity Calo and precision Muon chambers
  - Latency ~15μs; rate <200kHz, asynchronous

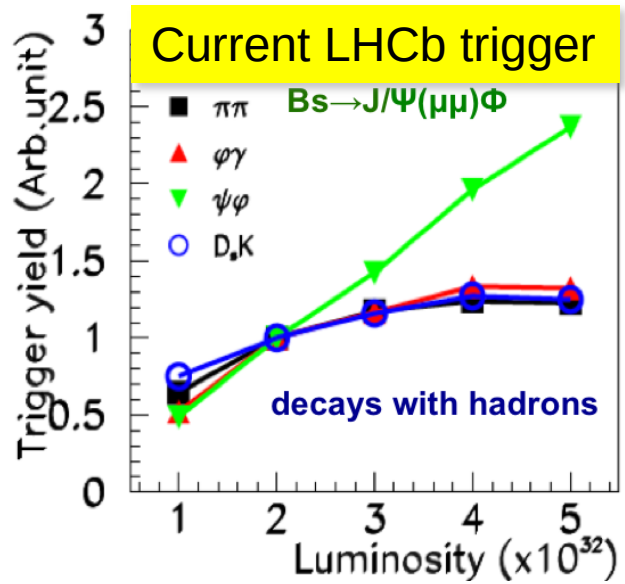


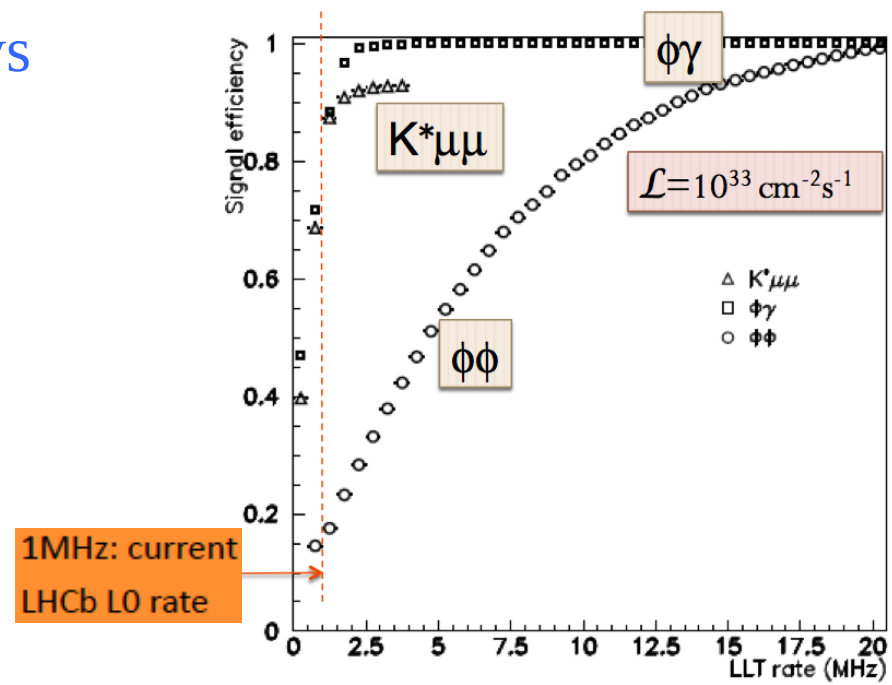
"LHC is a versatile facility used by heavy flavour and heavy ion communities as well"

upgrades

Motivation for the upgrades

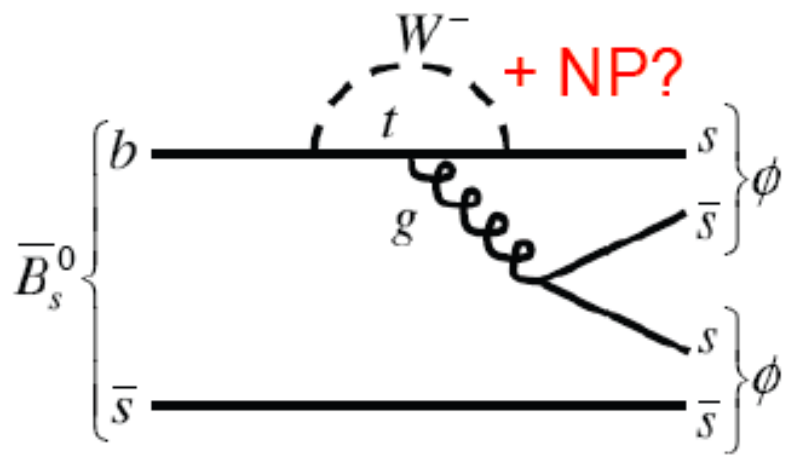
- Run at 1-2e33 (~3-4 times current) with full detector readout at 40MHz and an entirely sw-based trigger
- Expected increase in annual yield
  - x5 in decays with muons
  - more than x10 in hadronic decays
- Upgrade during LS2 in 2018
- Collect 5fb^{-1} /year for 10 years

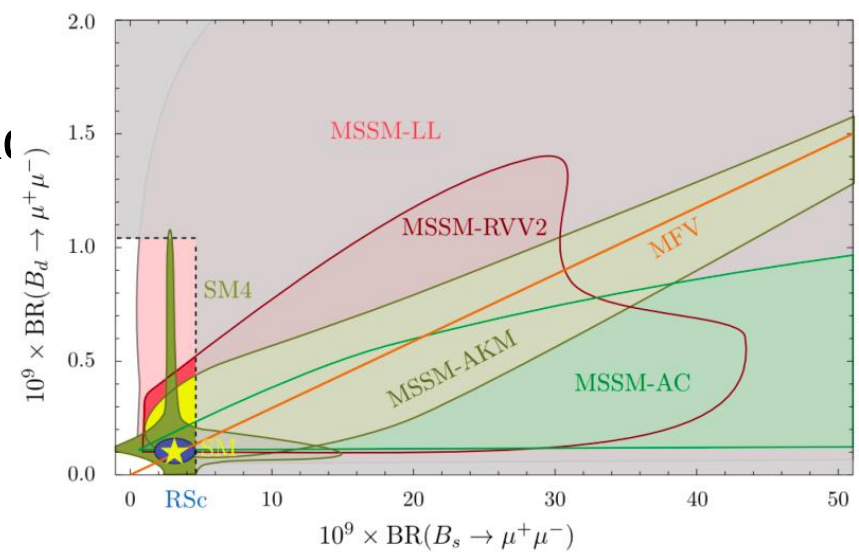




Prospects with upgraded LHCb

- Typical factors of ~3-5 improvement in many key measurements
- CPV phase φ_s: σ~0.03
  - Non-zero φ_S ==> New Physics
- $B_s \to \mu\mu$ measured to10% and $B_d \to \mu\mu$ observed
  - Ratio very sensitive to New Physics
- CKM angle γ measured to ~1° and to 0.2°
- CPV in charm sector
- LFV in tau decays
- …

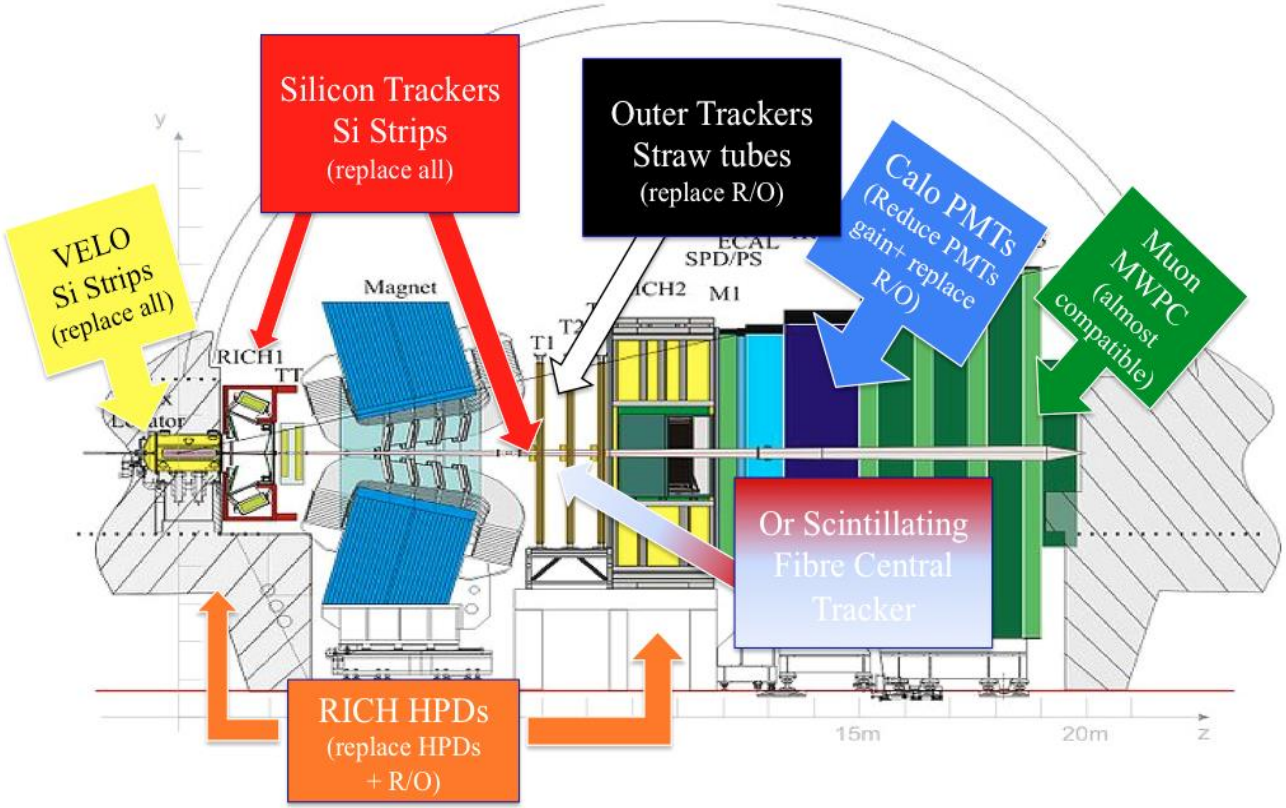




Proposed upgrades

Main changes:

- Replace electronics for 40MHz readout
- Replace silicon trackers to maintain performance with higher radiation and occupancy
- Replace RICH HPDs with Multi analogue PMTs



UK has a leading role in the Si tracker and RICH upgrades

“LHC is a versatile facility used by heavy flavour and heavy ion communities as well"

ALICE

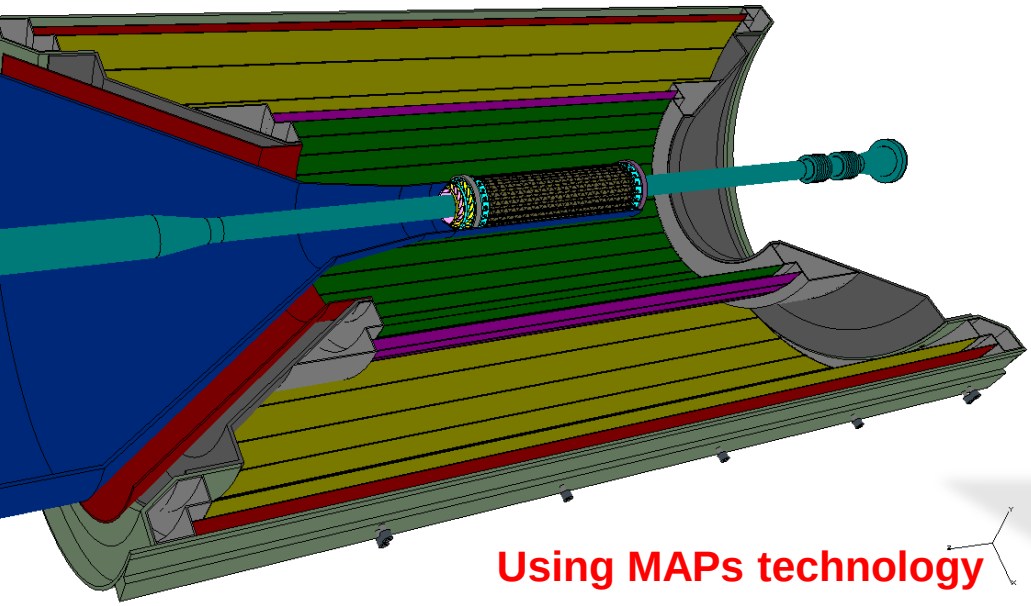
upgrades

Motivation & target for the upgrades

- Primary scope:
  - precision studies of charm, beauty and charmonia
  - low mass lepton pairs and thermal photons
  - gamma-jet and jet-jet with particle
  - heavy nuclear states
- **Operate ALICE at high rate while preserving its uniqueness, superb tracking and PID, and enhance its secondary vertex capability and tracking at low-pT**
- Run at 50kHz Pb-Pb ($L = 6x10^{27}$ $cm^{-2}s^{-1}$), with minimum bias (pipeline) readout (max readout with present ALICE set-up ~500Hz)
  - Gain a factor of 100 in statistics over current programme
  - improve vertexing and tracking at low pt

Planned upgrades

(1) New, smaller radius beam pipe
(2) New inner tracker (ITS) (scope and rate upgrade)
(3) High-rate upgrade for the readout of the
TPC, TRD, TOF, CALs, DAQ/HLT, Muons and Trigger detectors



New ITS (silicon tracker)

Inner Barrel (IB): 3 layers pixels

Outer Barrel: 4 layers pixels (strips)

First det. layer: ~22 mm from IP

Material thickness (IB): 0.3% X_0

Pixels pitch: ~20 μm

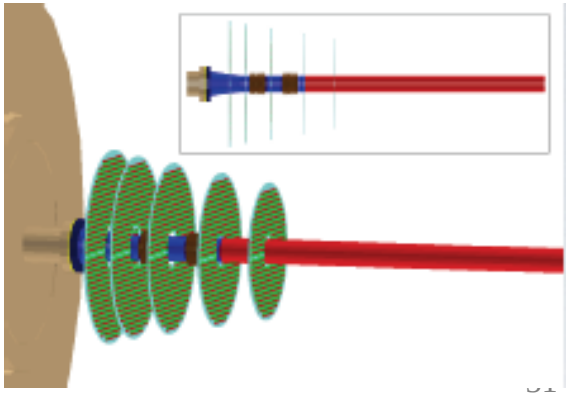
Total surface: ~10 m^2

Using MAPs technology

UK involved in ITS (MAPS R&D) and Trigger.

Muon Forward Tracker

secondary vertex measurement
better background rejection
improved mass resolution



Conclusions

- Massive success of LHC machine and experiments
  - With only ~1% of the ultimate goal of ~3000fb^{-1}
- A rich and exciting programme, well into the 2030s, to
  - Deepen our knowledge of EWSB & the electroweak scale physics
  - Push the energy frontier to the multi-TeV region and beyond through a multitude of direct & indirect searches for New Physics
- Very strong science case for HL-LHC
  - Even stronger following the 125GeV discovery
  - Named top priority by the European Strategy Group
- UK in pole position of an ambitious programme of detector upgrades to cope with the challenges of HL-LHC!