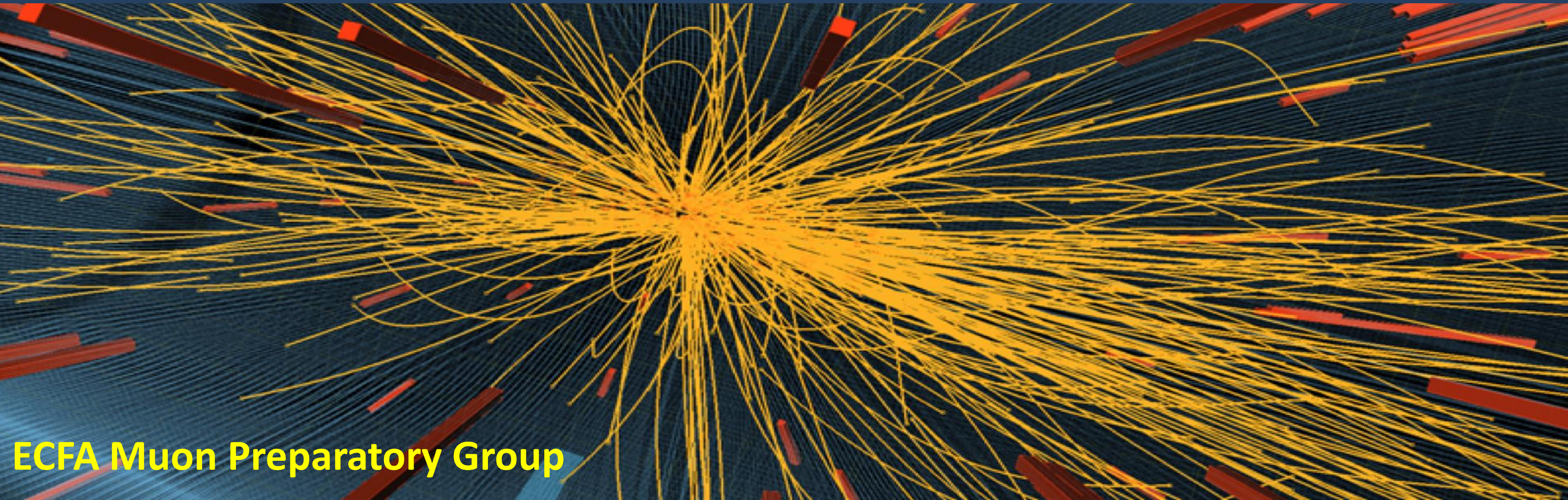
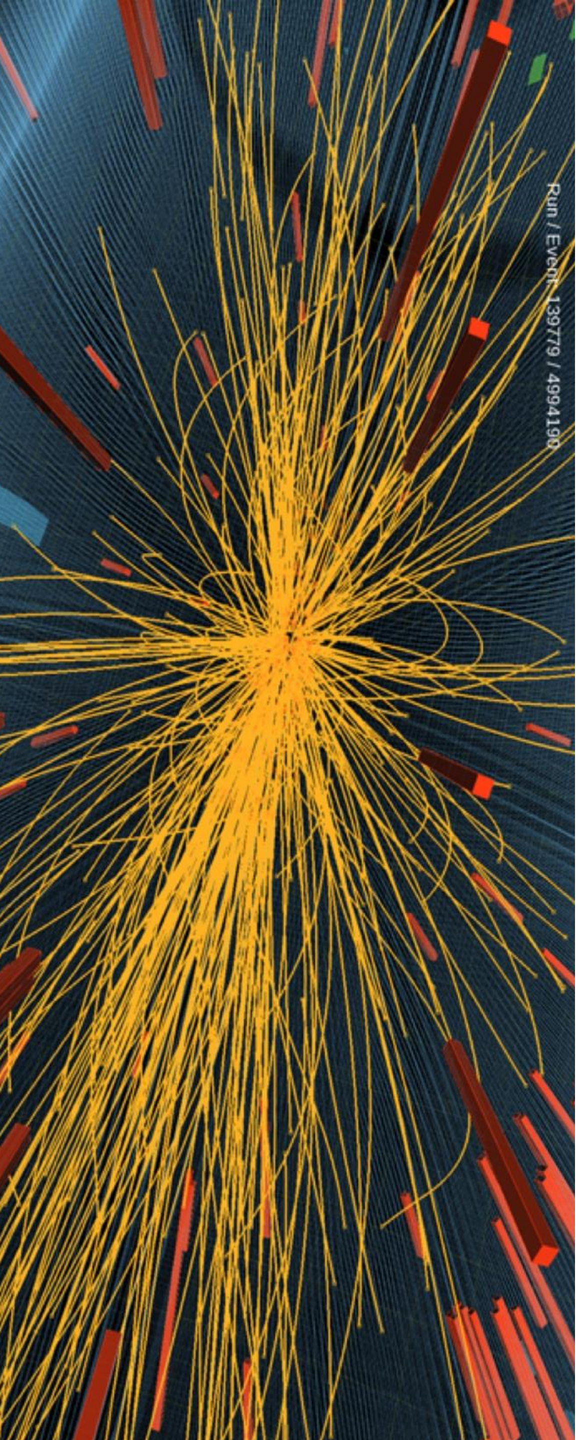
Challenges for Muon Detection and Triggering at High Luminosity

Kerstin Hoepfner, RWTH Aachen, III. Phys. Inst. A

With input from: Alexei Safonov (CMS), Pascal Dupieux (ALICE), Peter Kluit (ATLAS), Giacomo Graziani (LHCb)

HL-LHC ECFA Workshop, Aix-les-Bains, 1-3 Oct 2013





AGENDA

Muon Preparatory Group

Challenges for Muon Detection and Triggering in the HL-LHC Environment

Kerstin Hoepfner

Longevity and Expected Performance of the Existing Muon Systems

Paolo Iengo

Muon detector readout and trigger electronics upgrades for the HL-LHC

Masaya Ishino

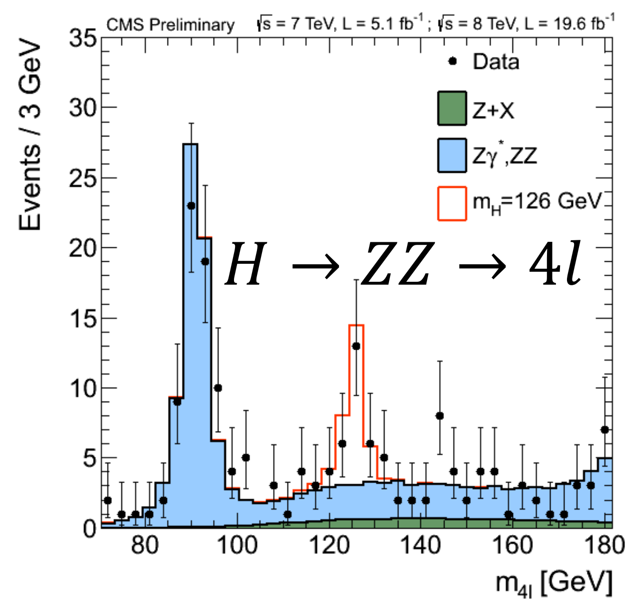
Novel Gaseous Detector and Technology R&D

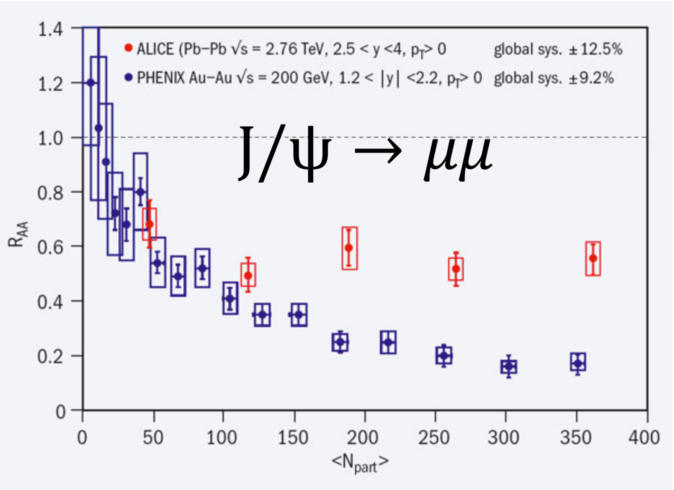
Marcello Abbrescia

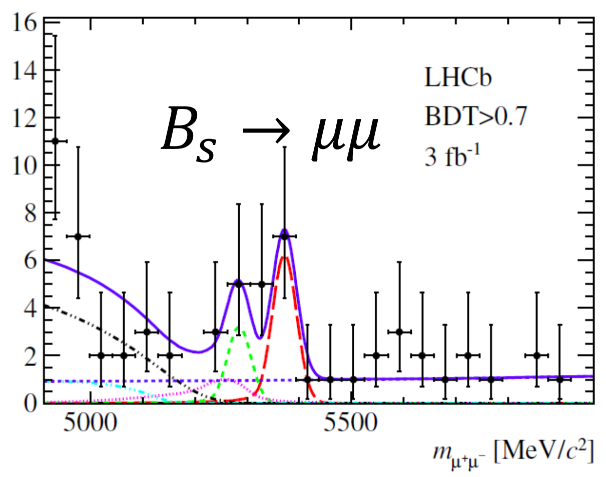
Muon Detection at the LHC

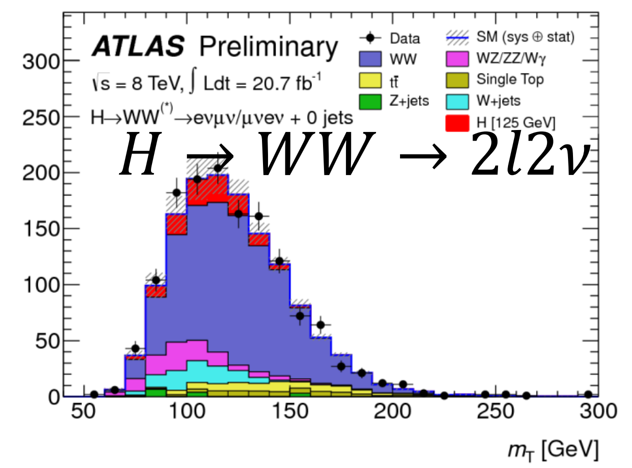
The "Big Four" at the LHC:

- So different in physics programs, detector designs and technologies
- Yet so similar in their reliance on robust muon triggering and detection in reaching their physics goals







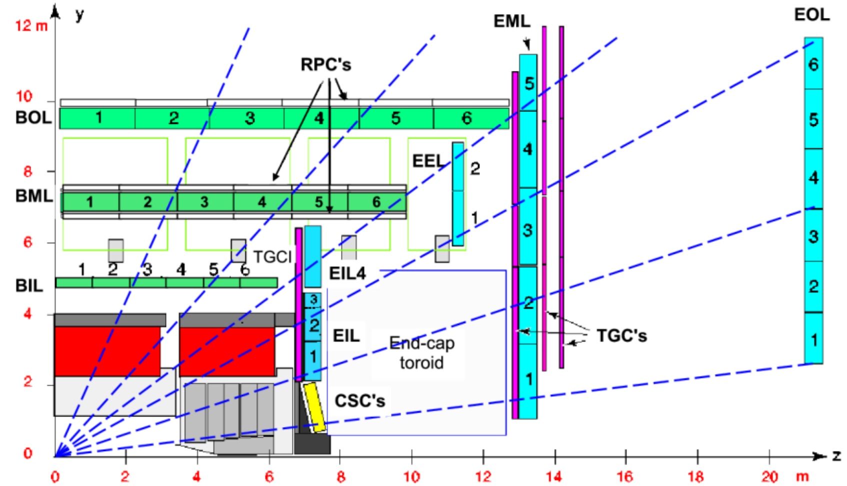


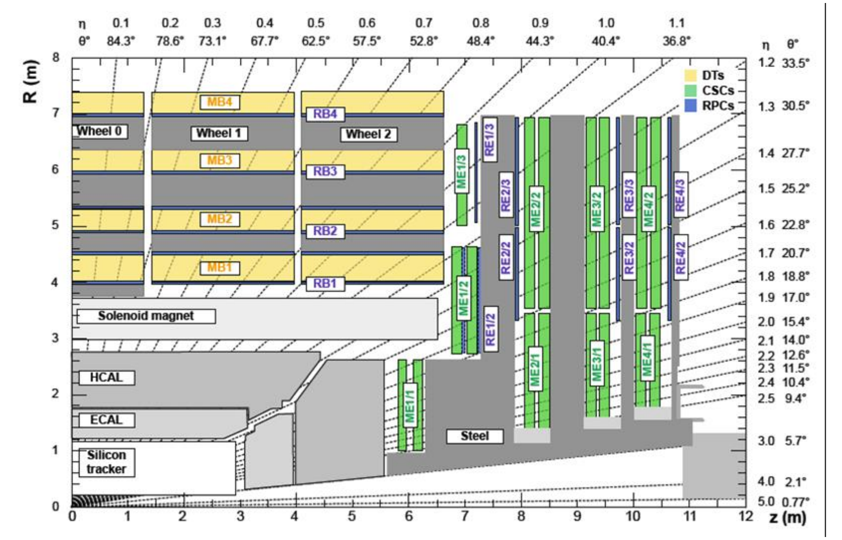
CMS and ATLAS

Highly hermetic and redundant muon systems

- ATLAS:
  - Drift tubes (MDT) up to η=2.7 with spatial resolution ~80 μm measuring bending
  - Cathode-strip chambers (CSC) in the region 2.0<|η|<2.7 for high rates
  - Resistive plate chambers (RPC) for triggering and second coordinate in the barrel |η|<1.0
  - Thin gap chambers (TGC) for triggering and second coordinate in the forward

- CMS:
  - Drift tubes (DT) to η~1.2
  - CSC Endcaps 1.0<|η|<2.4
  - RPCs to ensure adequate redundancy
  - Trigger coverage up to |η|=2.4. Typical threshold of p_T~20-25 GeV for inclusive muon trigger



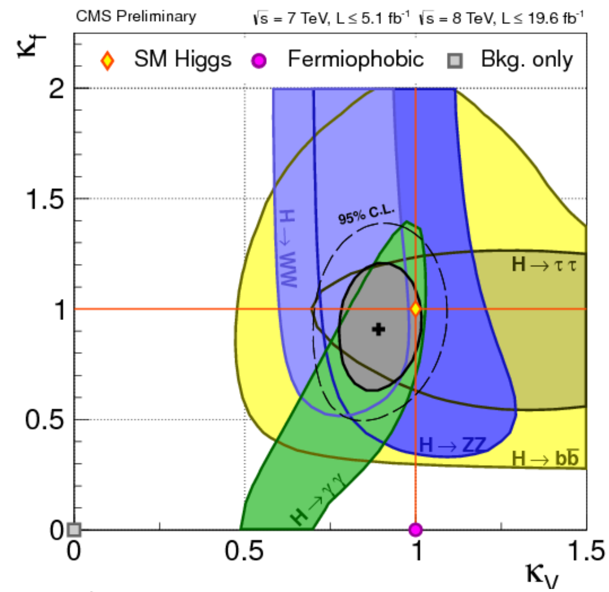


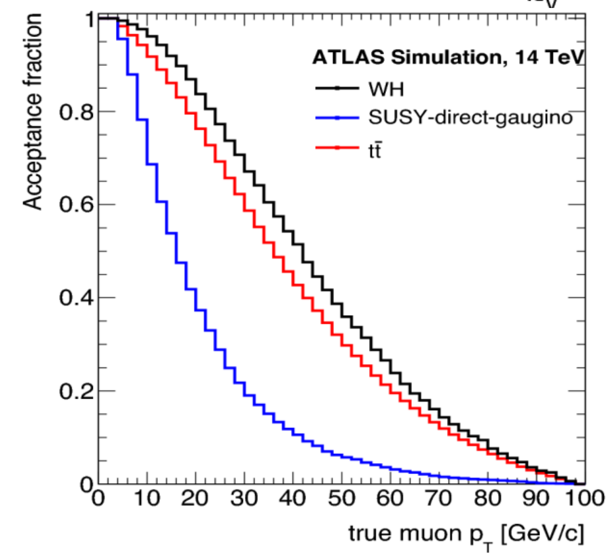
CMS & ATLAS at HL-LHC

- **Robust muon triggering** and identification are major discovery drivers at the LHC:
  - Critical for precision Higgs measurements of both bosonic and fermionic couplings
  - SUSY: need access to low p_T muons
  - New heavy particles: O(TeV) muons

- Relative impact increases at high luminosity
  - Muons are least affected by collective effects of occupancy, e.g. trigger rates grow only linearly with luminosity

- Focus on maximizing the potential of large datasets to be collected at HL-LHC
  - Maintain current performance (η, p_T)
  - Seek acceptance gains where possible

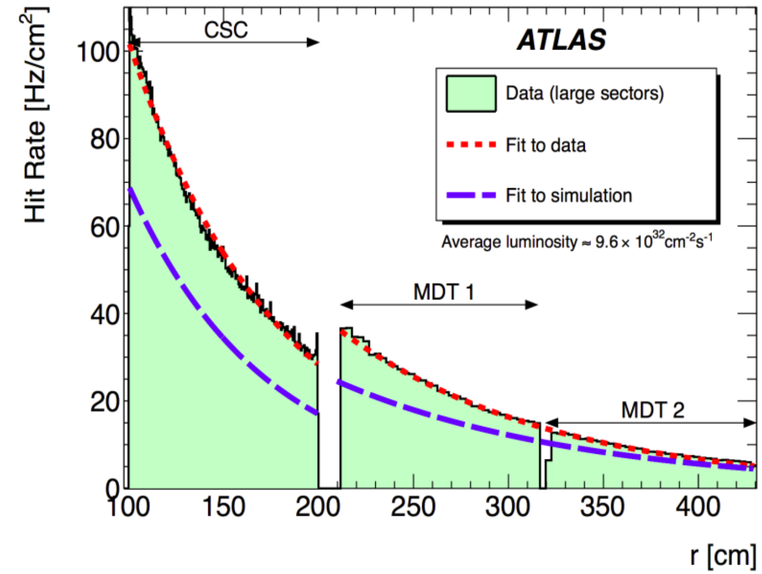




CMS and ATLAS: Common Challenges

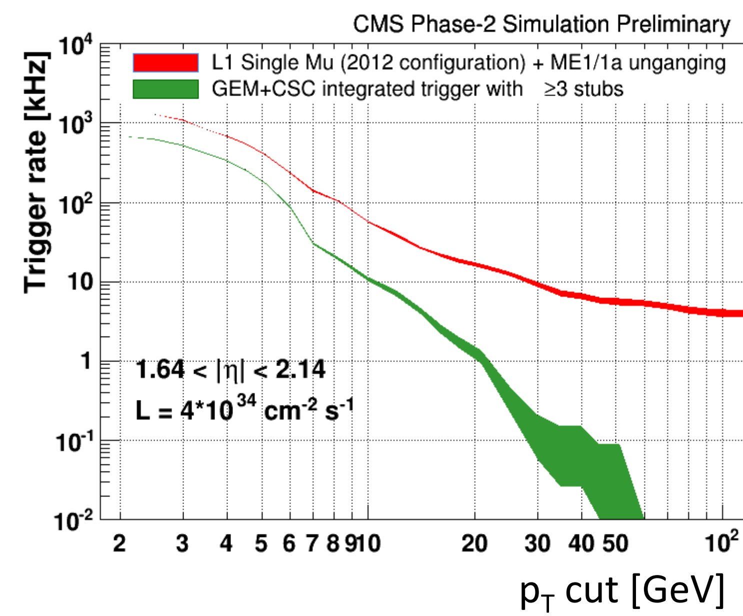
High luminosity can adversely affect muon system performance

- Forward region $|\eta| \geq 2.0$ especially challenging
  - Rate in 10's of kHz/cm^2 and higher towards higher η
- Reduced resolution and longevity issues (see talk by Paolo)
- New requirements often exceed capabilities of the existing electronics (see talk by Masaya)



Trigger rate increases

- Even if scales linearly with instantaneous luminosity, the rates get too high

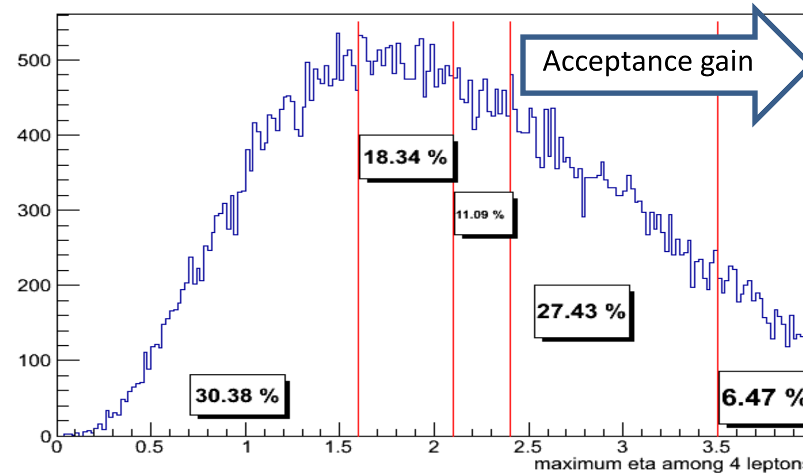


Forward Region Challenges

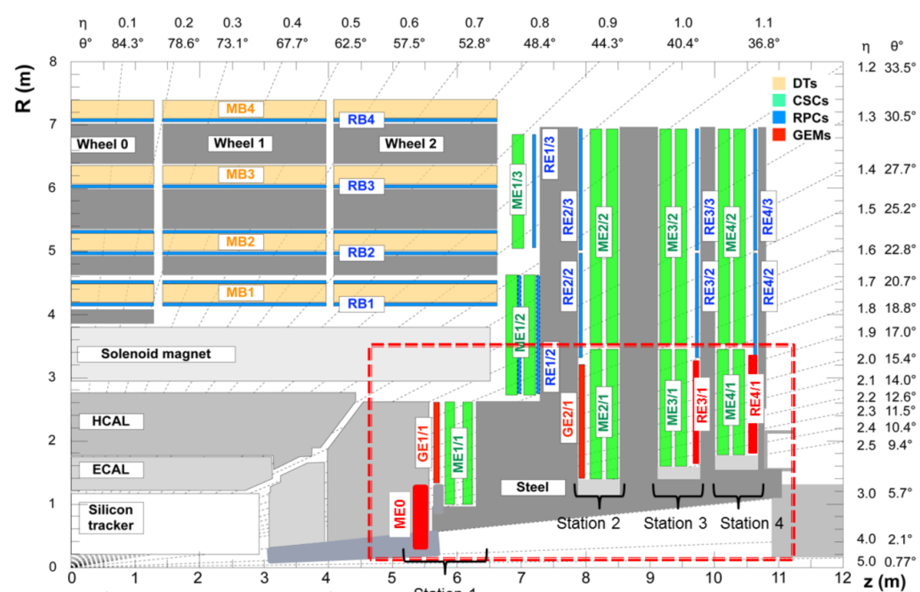
Very forward region is one place to gain physics acceptance

Present CMS muon system: offline and trigger coverage to $|\eta|=2.4$

- **Challenge in region $1.6<|\eta|<2.4$**
  - Highest background rates yet least redundancy, most vulnerable at high luminosity
  - Challenging B-field topology
- Even more so **at $|\eta|>2.4$**

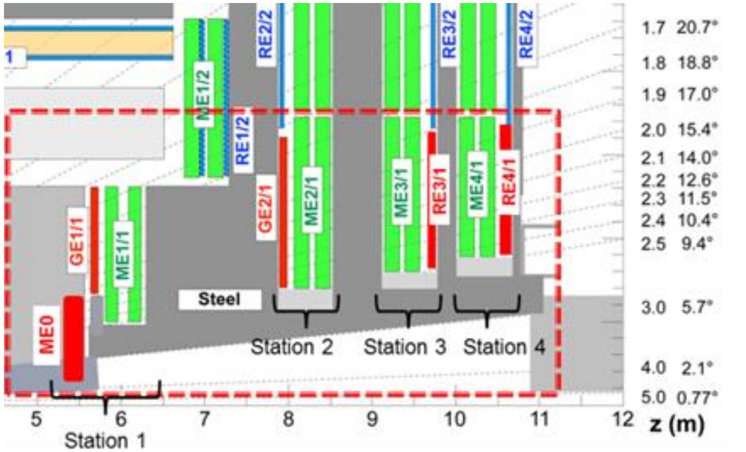


$H\rightarrow ZZ\rightarrow 4\mu$: acceptance increase $60\% \rightarrow 94\%$ if $\eta_{max}=2.4\rightarrow 4.0$



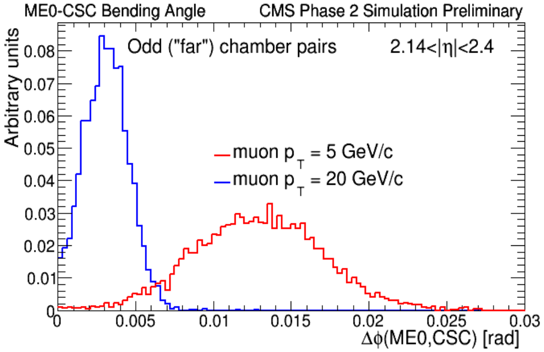
Forward Trigger Challenges

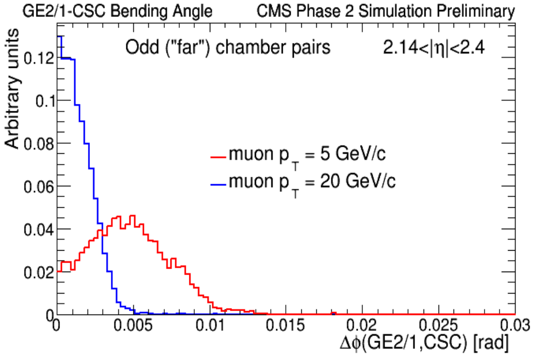
- **Not loosing trigger coverage is key**
  - p_T mismeasurements drive trigger rate
  - Level-1 track trigger helps, but has reduced performance in the high eta "corner"
- **Large rate reduction using bending angle**
  - Need good spatial resolution and rate capability
  - Larger lever arms using new detectors and existing CSC chambers in the same station
  - Must measure bending angle in station 1



Two regions:

- Lower eta 1.6<|η|<2.1: a new GEM station GE1/1, install in LS2
- Higher eta 2.1<|η|<2.4: even larger challenge
  - Upper part of ME0 in trigger (paired w/ CSC ME-1/1)
  - GEM station GE2/1
  - Improved RPC (iRPC) stations RE3/1 and 4/1
  - See talk by Marcello for detector technologies



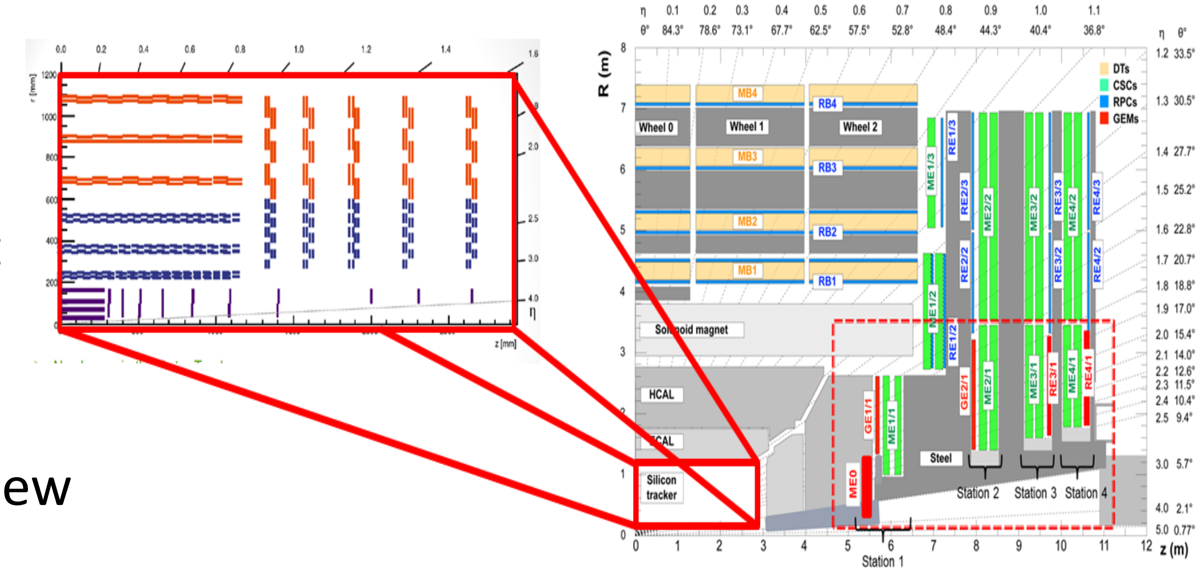


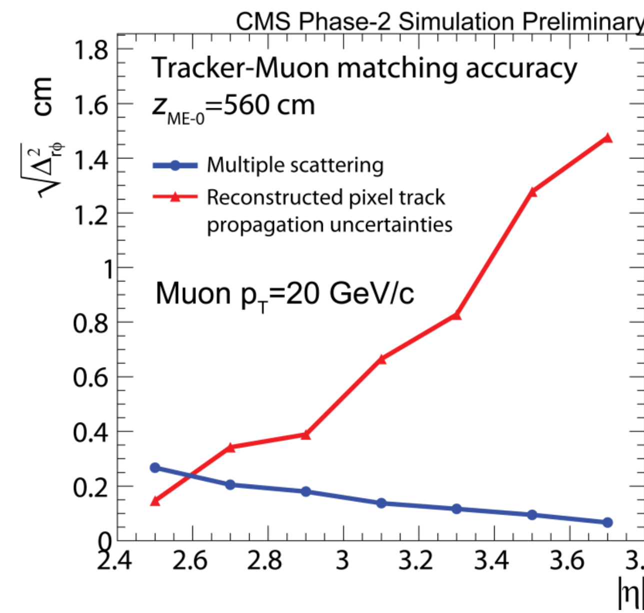
Else radial B-field and multiple scattering quickly diminish discrimination

Expect x5-10 rate reduction with new detectors

Forward Muon Extension

- **Extend offline muon coverage to |η|=4**
  - ME0: small area, but nearly doubles CMS muon coverage
  - Can be optionally integrated into the new forward calorimeter
- **Match muon "stubs" and forward pixel extension tracks**
  - ME0 is a multi-layer detector to suppress neutron backgrounds
- **High efficiency and low fake rate**
  - Resolution is good enough and multiple scattering is low enough in ME0
  - Muon system can improve momentum measurement



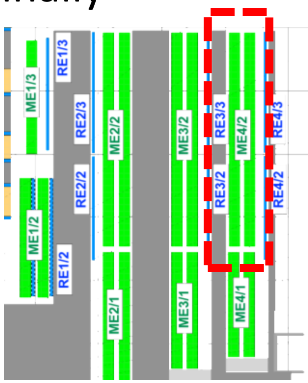


LS1: Detector consolidation

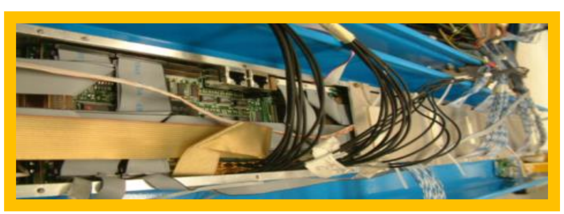
LS2: Anticipated phase-2 upgrades

LS3: HL upgrades

Install originally planned ME4/2 + RE4/2

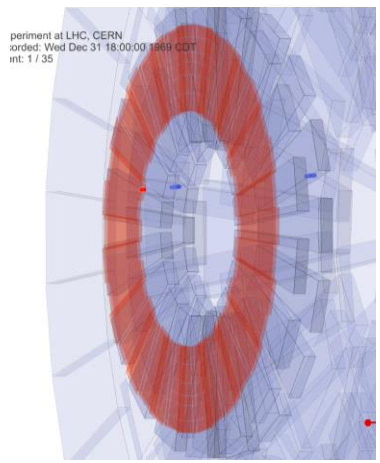


Partially move DT electronics from detector to cavern and redesign in uTCA technology.



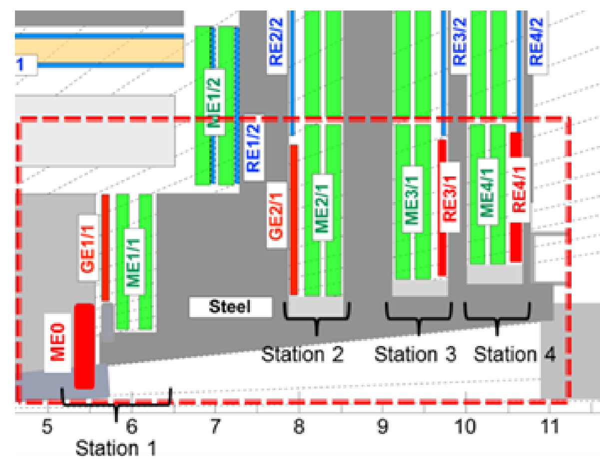
Upgrade ME1/1 electronics.

Installation of GE1/1 Combined CSC+GEM trigger



Muon trigger: Additional detectors in forward region of all 4 stations

Rapidity extension of tracker, calo, muon to |η|~4

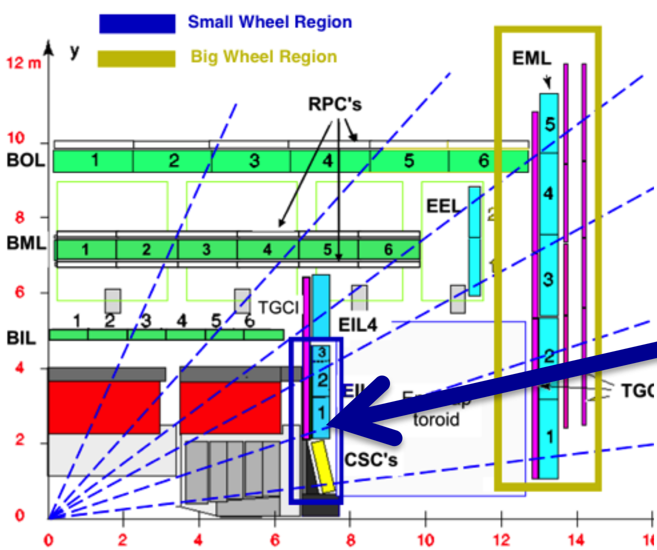


Redesign of DT on-chamber electronics

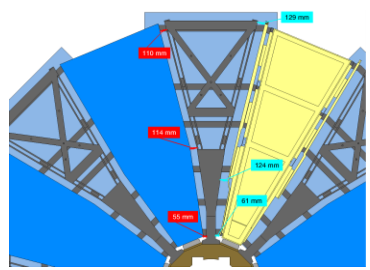
ATLAS Endcap Detector Challenges

Higher rates and occupancies become critical after LS2 in the endcap region at low radii.

→ **Add New Small Wheel (NSW)** with finer granularity for lower occupancies and more capabilities to reduce the backgrounds.

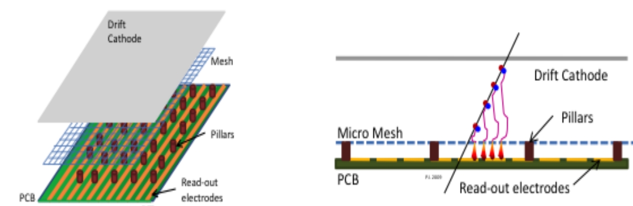


Current detector and location of the NSW

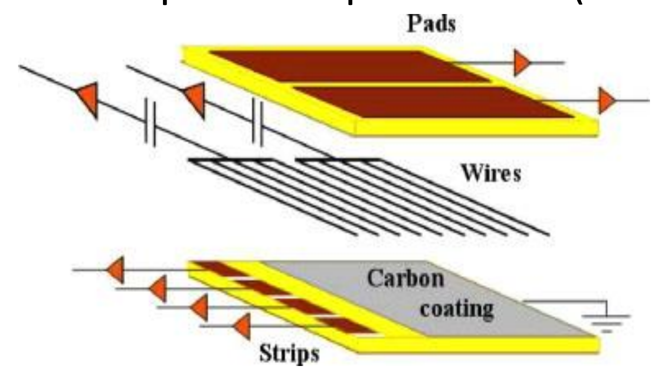


NSW containing MMs and sTGCs detectors

Micromegas (MM)



small-strip Thin Gap Chamber (sTGC)



Detector technologies discussed by Marcello

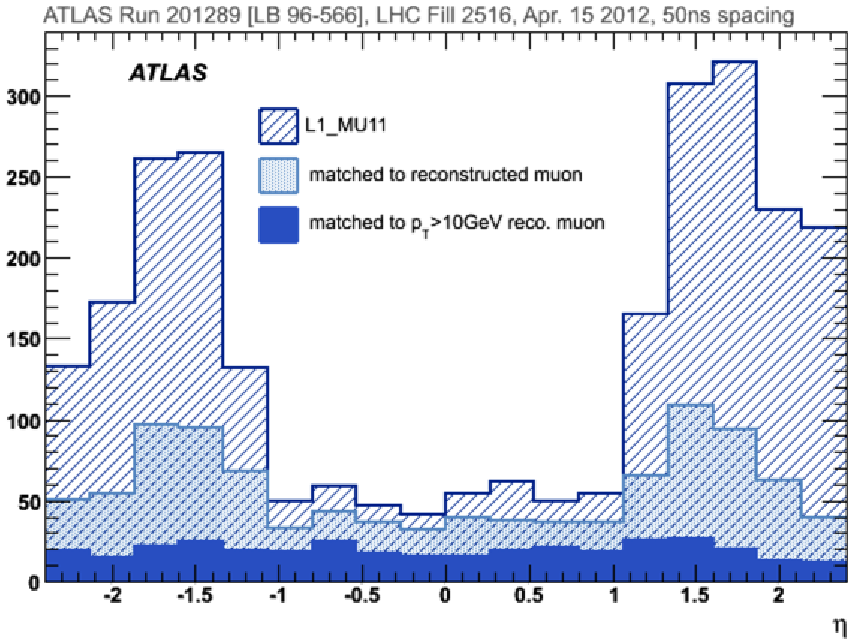
Endcap Trigger Challenges

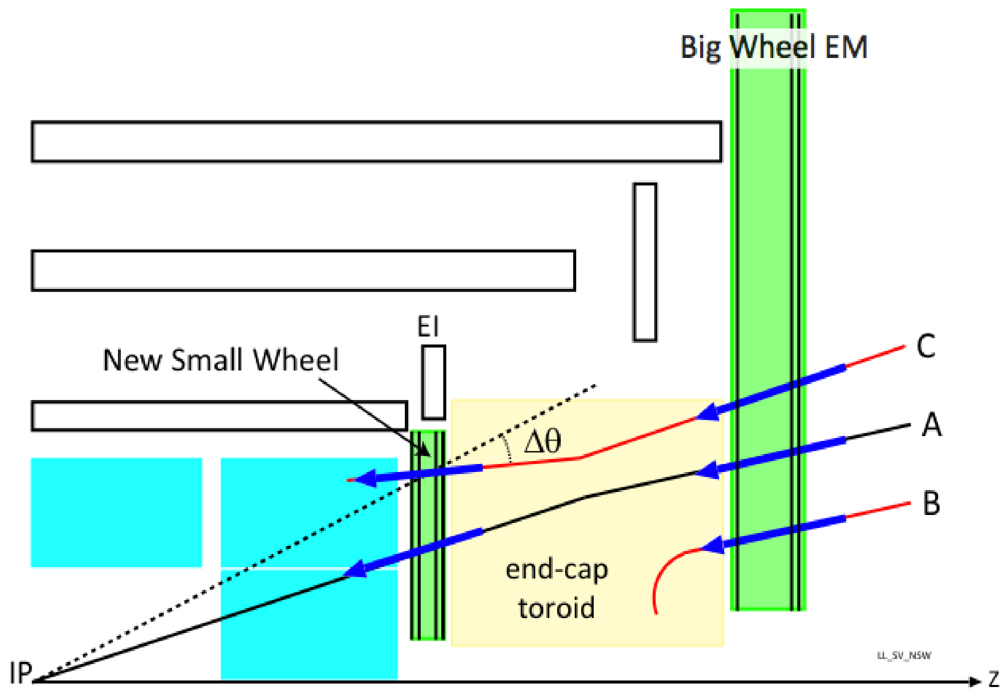
Efficient triggering at increasing luminosities:

Reduce fake triggers in endcaps to keep a manageable L1 trigger rate

→ by reducing significantly the unmatched low momentum particles.

The current endcap trigger only uses the direction and position in the Big Wheel. Significant reduction with the new small wheel (NSW) by adding its measurement of direction and position.

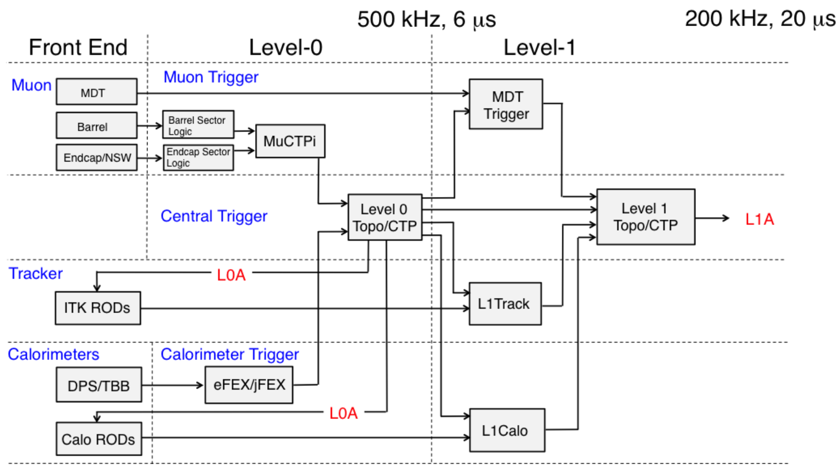


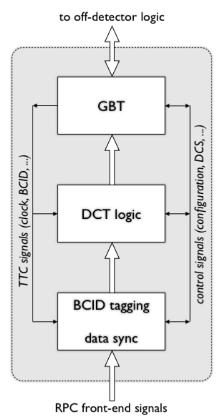


High Luminosity Challenges

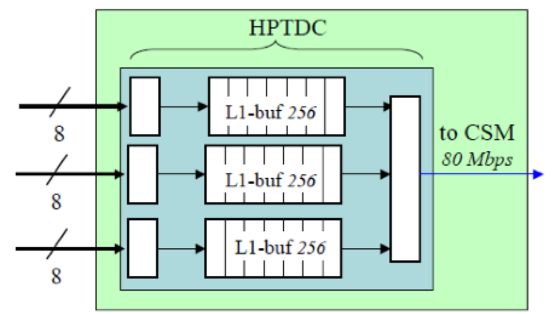
New triggering scheme will be implemented for HL-LHC implying a level 0 trigger and more sophisticated level 1 trigger algorithms.

The trigger electronics for the RPCs and TGCs will be upgraded to cope with larger latencies.





See electronics talk



Full capabilities of the NSW detectors exploited to **sharpen the trigger threshold in endcaps.**

Offline combined muon **reconstruction** will be extended down to **$|\eta| = 2.7$** using the upgraded ATLAS Inner Tracker.

ATLAS EXPERIMENT

LS1 | Nominal lumi ~14 TeV | LS2 | 2 x lumi ~14 TeV 300 fb^{-1} | Phase 1 | Phase 2 | $\langle L \rangle = 5\times10^{34}$ cm^{-2}s^{-1} 3000 fb-1

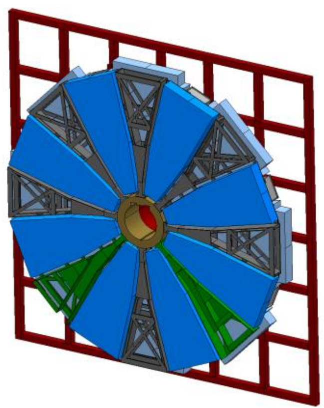
2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

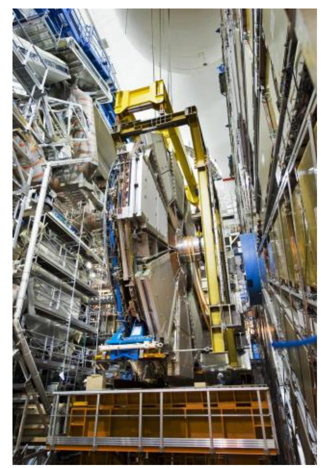
LS1: Detector consolidation

Installing originally planned EE chambers in barrel-endcap region

LS2: Installation of NSW and other upgrades

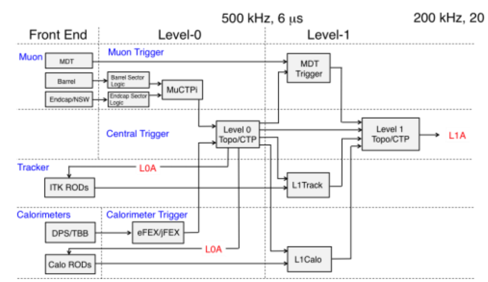
Installation of New Small Wheel and smaller upgrades





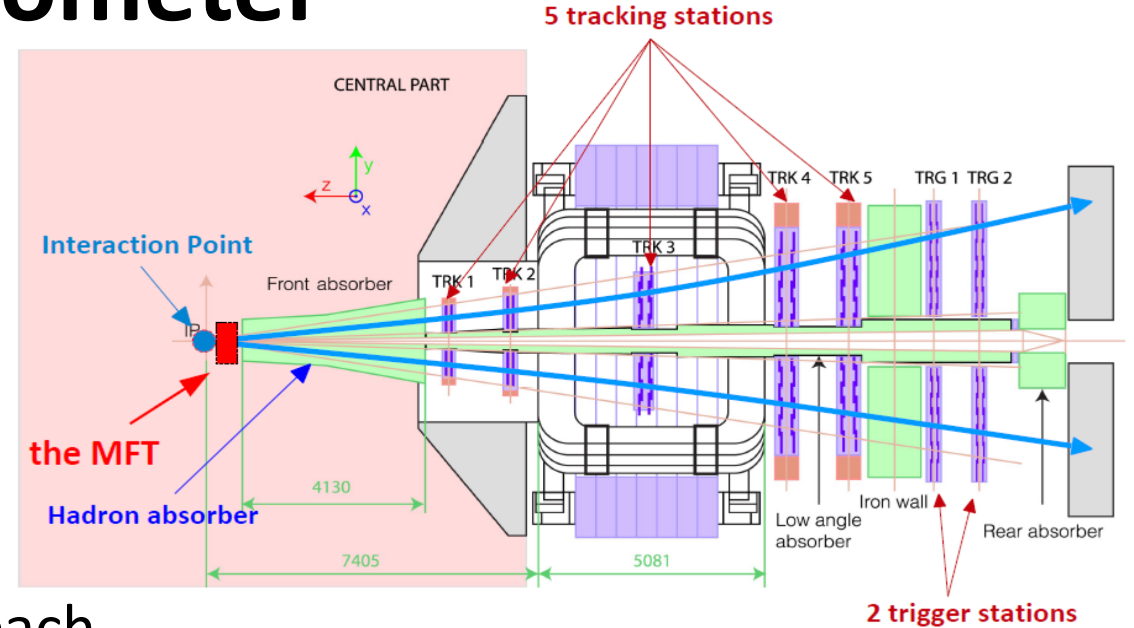
LS3: HL upgrades

Redesign of trigger architecture and electronics, for RPC, TGC and MDT

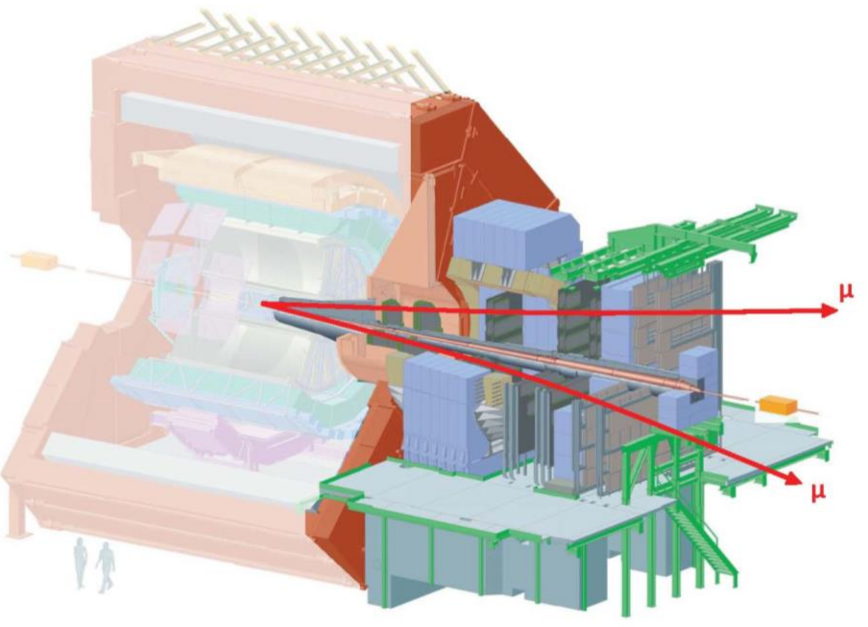


Muon Spectrometer

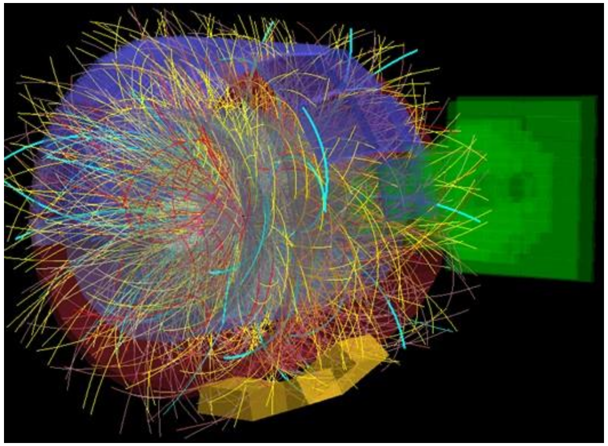
- One arm forward muon spectrometer
  - Acceptance $2.5 < \eta < 4.0$
  - 17 m long



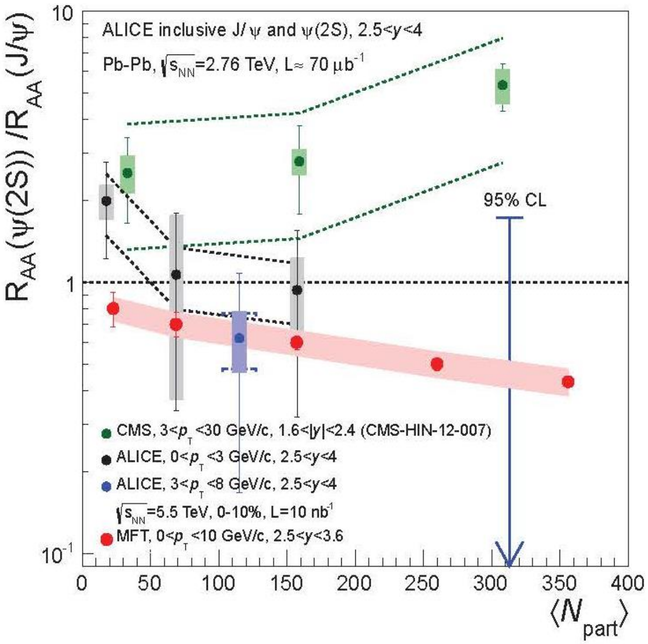
- Tracking = 5 TRK stations, each with 2 planes of cathode pad/strip chambers
  - High spatial resolution ~70 μm
- Trigger = 4 planes of single gap RPCs
  - Typical threshold on single muons of p_T~1 GeV



Upgrade Physics

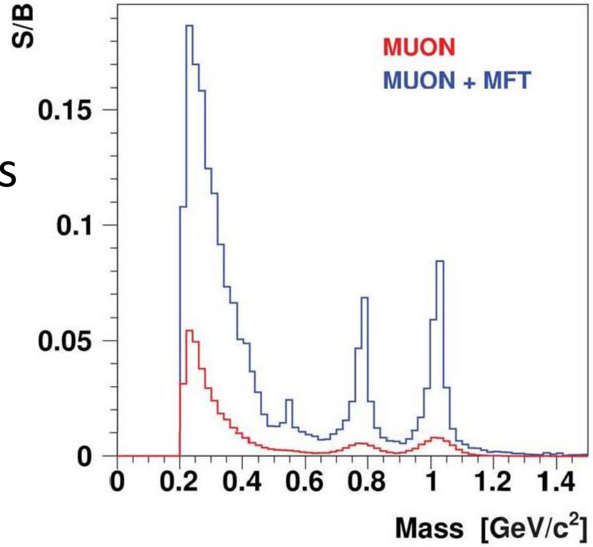


Study Quark Gluon Plasma (QGP) properties at high temperature with rare probes produced in heavy ion (Pb-Pb) collisions



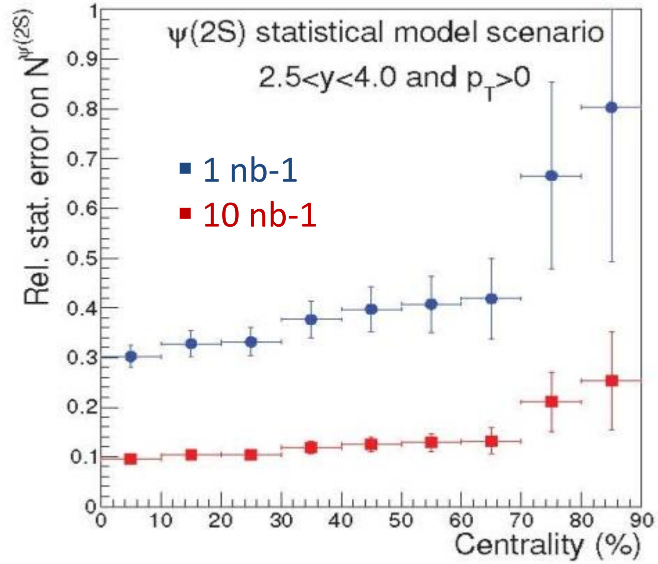
High-precision measurements of

- Quarkonium states to μμ down to p_T=0
- Open heavy flavor prod & flow
- Low mass vector mesons to study chiral nature of the phase transition



→ **Soft muons, record maximum number with accurate p_T meas.**

Challenges and goals for HL operation



- Total integrated luminosity in Pb-Pb ~10 nb^{-1}
- Max Pb-Pb collision rate of 100 kHz = One order of magnitude above present design

→Goal: readout at 100 kHz => no more specific muon trigger

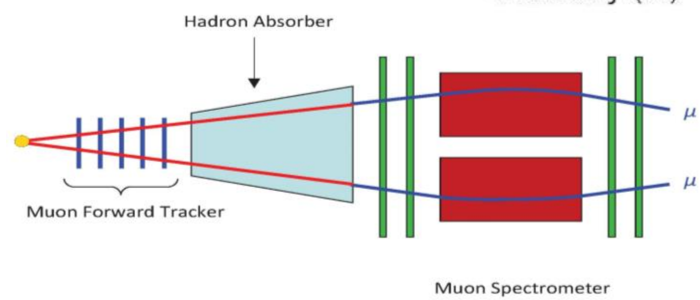
See electronics talk

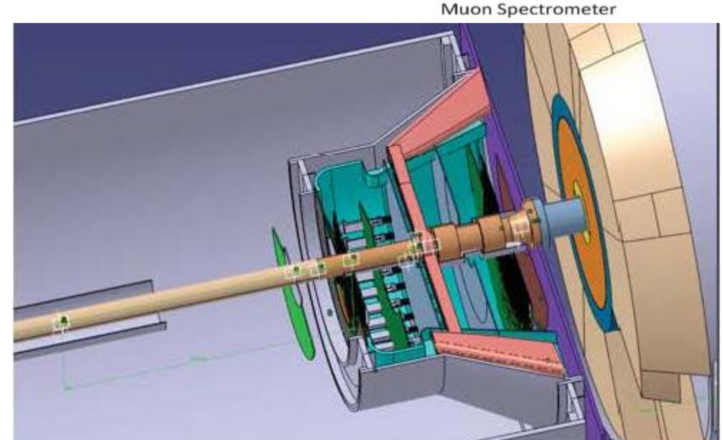
→ p_T measurement:

Present limitation: **blind to details of vertex region** because of hadron absorber =>

Addition of a detector based on pixel CMOS sensors (the Muon Forward Tracker, MFT) in the Muon Spectro acceptance for improving the muon physics capabilities

- Reconstruction of secondary vertices
- Background reduction
- Better mass resolution



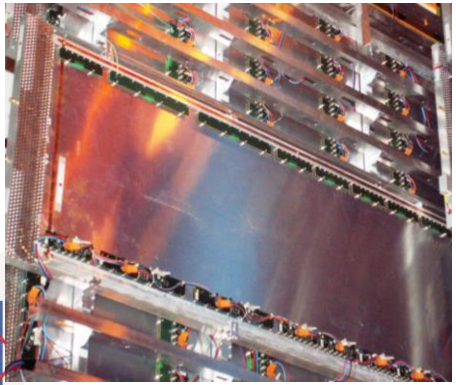


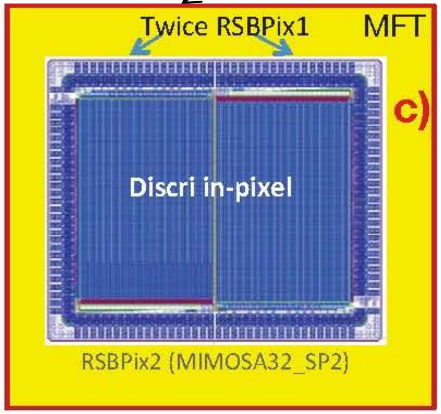
LS1: Detector maintainance

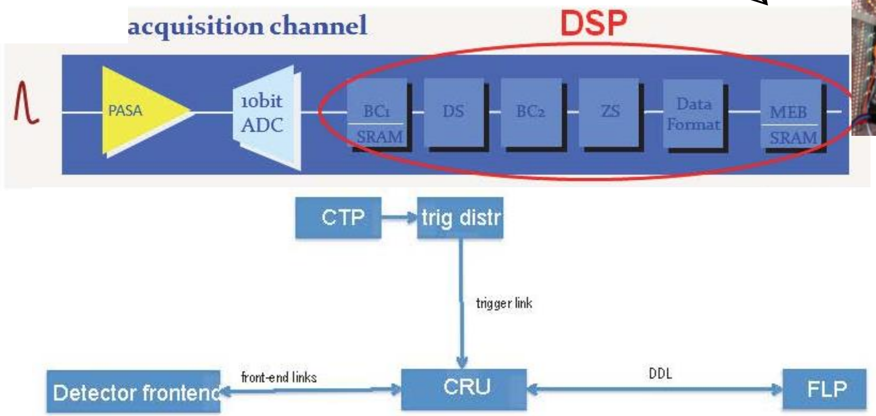
Some repairs

LS2: Upgrade phase-1

- **Replace readout electronics** with new dead-time-free chip with 10 MHz continuous sampling
- Addition of the **MFT** (pixel CMOS)



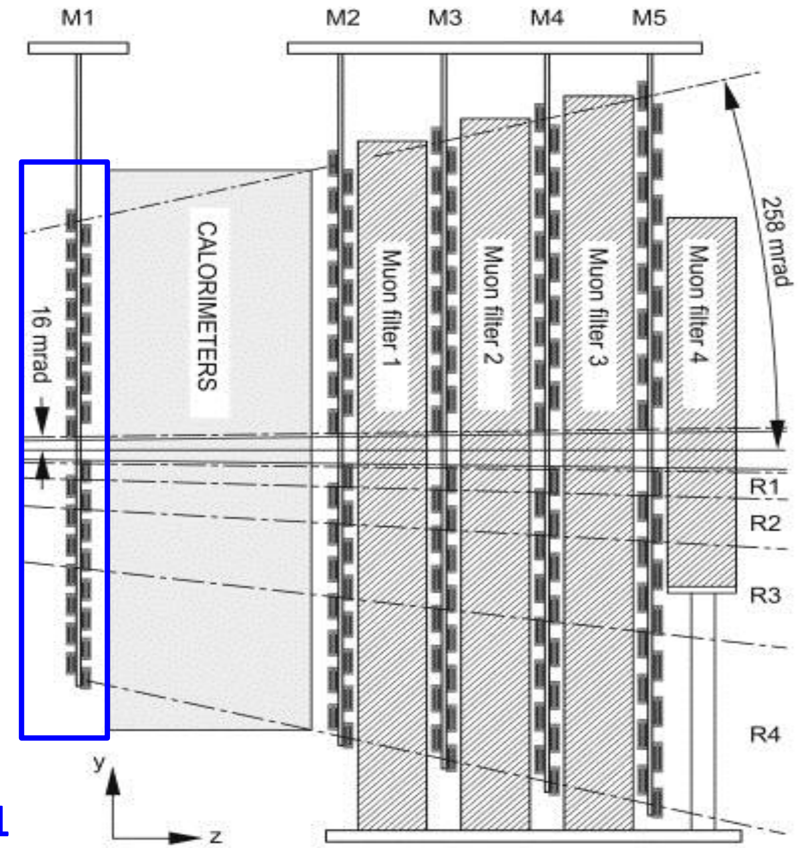




Muon System

One arm spectrometer covering very
high rapidity 1.8< η <4.9

- Requirements:
  - station efficiency > 99%
  - time resolution < 5 ns
- Technology:
  - MWPC in most regions,
  - Triple GEM detectors in inner region of M1



First Station M1
(only used for L0 muon trigger)

In run-1 operated up to 4×10^{32} $cm^{-2}s^{-1}$

- Average rates in most irradiated region (detector):
  - 120 (260) kHz/cm^2 (M1)
  - 60 (90) kHz/cm^2 (M2-M5)

- Upgrade conditions:
  - (scheduled from 2019, after LS2)
  - L=1 to 2 x 10^{33} $cm^{-2}s^{-1}$
  - (independent of LHC upgrade!)
- Aim is to collect 70 fb^{-1}

Challenges

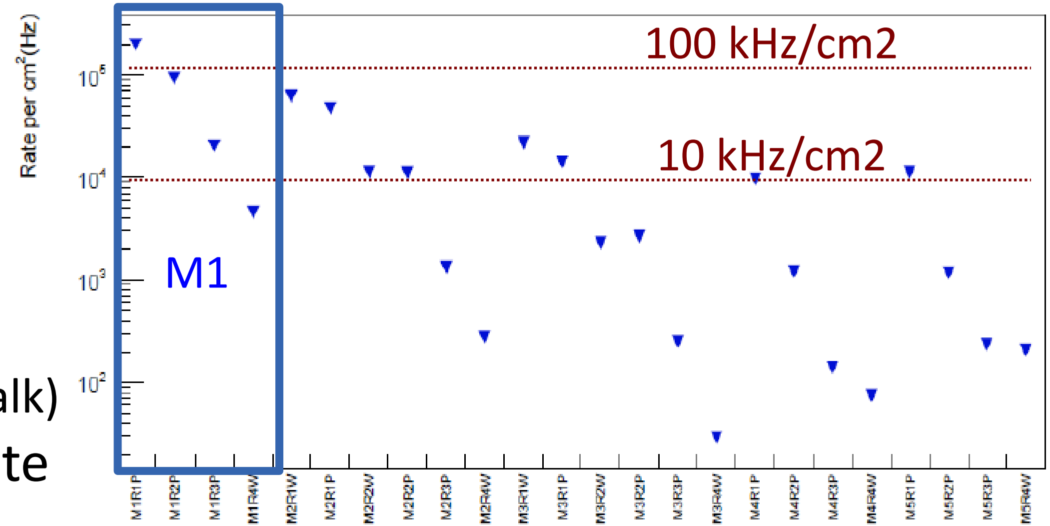
Goal: Maintain performance at higher luminosity

- **Rate increase** critical for M1
  but station not needed anymore (trigger redesigned, see trigger talk)
- For the inner region of M2, rate (>1 MHz/channel at highest lumi) and integrated charge beyond safety limits in the long term

→ **New detectors after LS3**

- **Readout will saturate.**
  Measures:
  - New FE chip for new detectors
  - Increased number of off-detector digital channels

Average rates per region @10^{33}



- Present **trigger**, with L0 level based on standalone calorimeter and muon response, not suited for higher luminosity
  - New trigger capable of full event reconstruction up to 40 MHz
  - Implies redesign and replacement of all off detector readout boards

See electronics talk

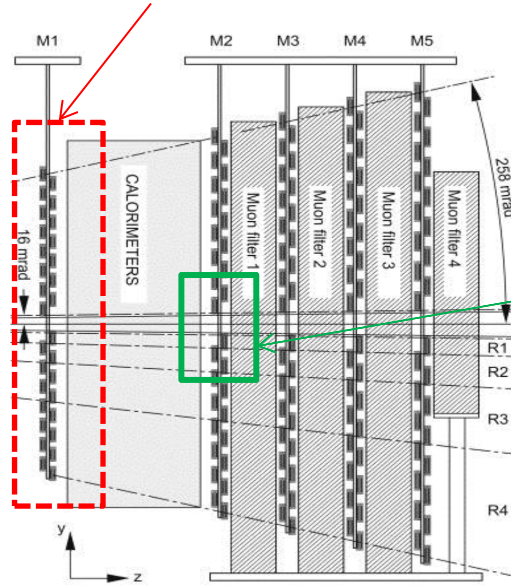
LS1: Detector maintainance

Replace few damaged detectors and FE boards (< 1%)

LS2: Upgrade phase-1

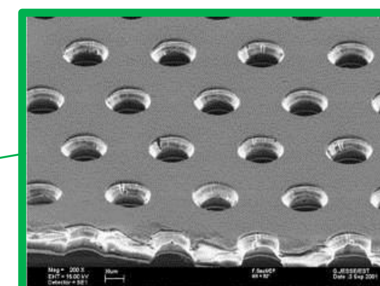
Install new 40 MHz compliant DAQ and control boards, with increased number of channels.

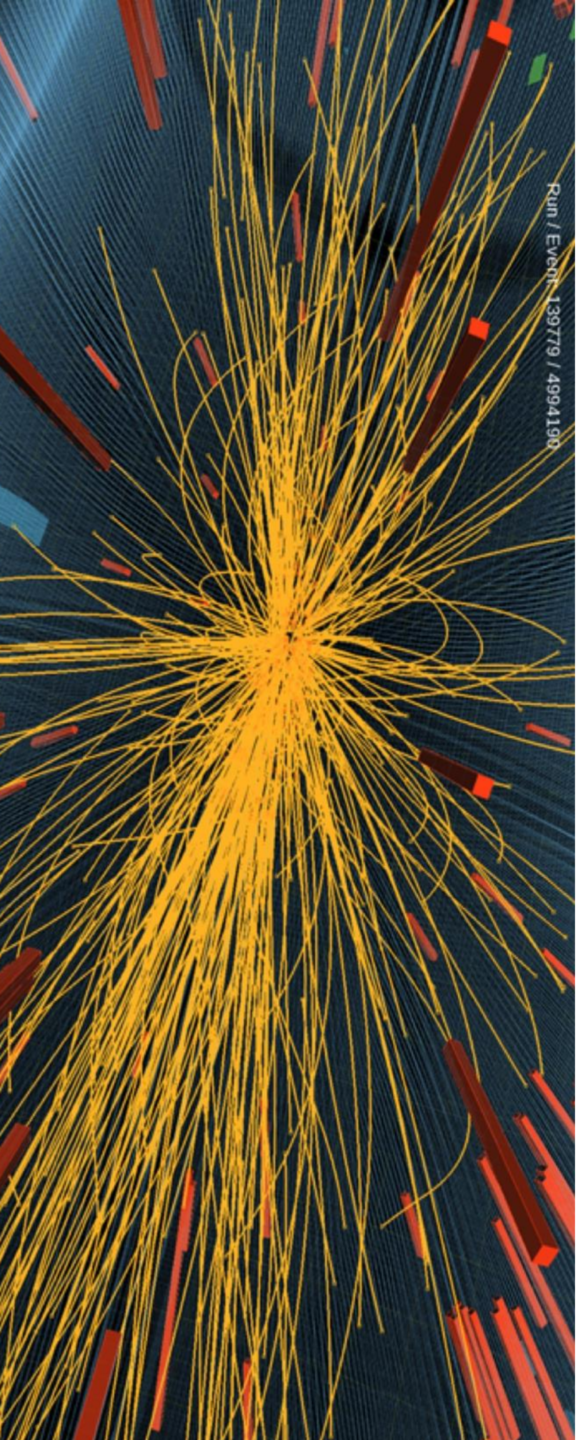
M1 station removed.



LS3: Upgrade phase-2

Install new GEM detectors in inner part of **station M2**





SUMMARY

- Muon detection plays a **key role in physics programs** of all four experiments
  - Clean physics signatures and low backgrounds
- The impact at **high luminosity** can become even larger
  - Muon systems suffer the least from non-linear effects of high luminosity. Muon trigger rates scale better with luminosity that for most other systems.
- All four experiment have a reasonably **clear understanding** of what needs to be done
- But **challenges are significant** and continued good performance of muon systems should not be taken for granted

More details in the following muon talks!