LHC Upgrades
(ATLAS, CMS, LHCb)

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Thanks to the contribution from:
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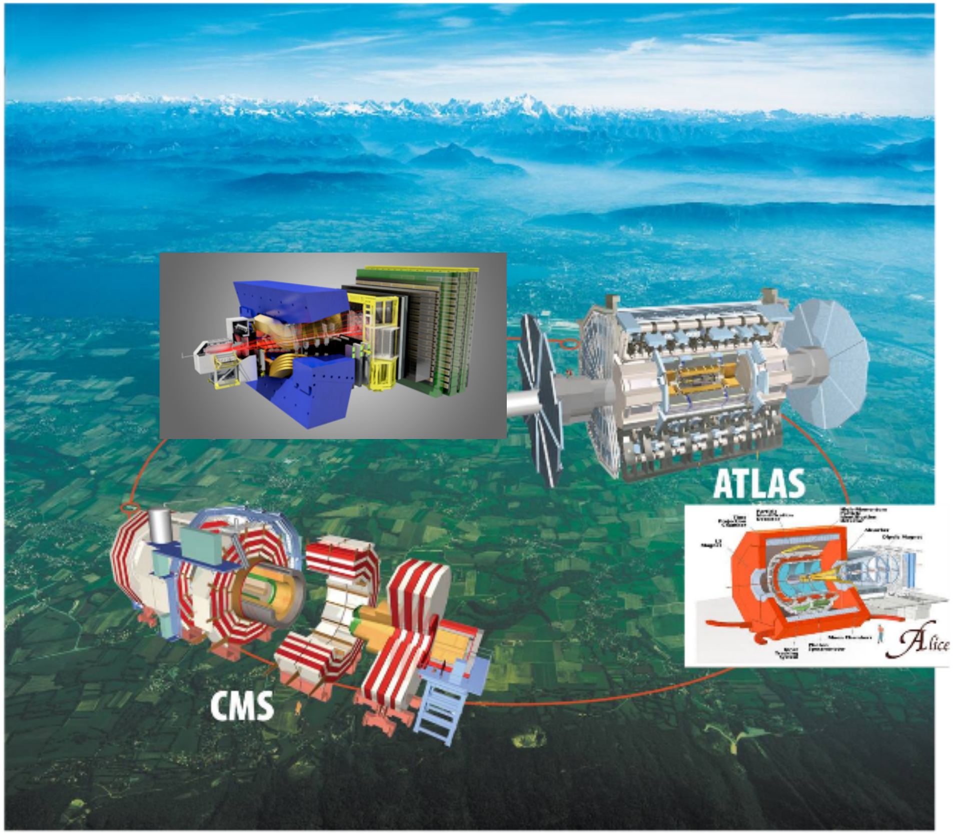
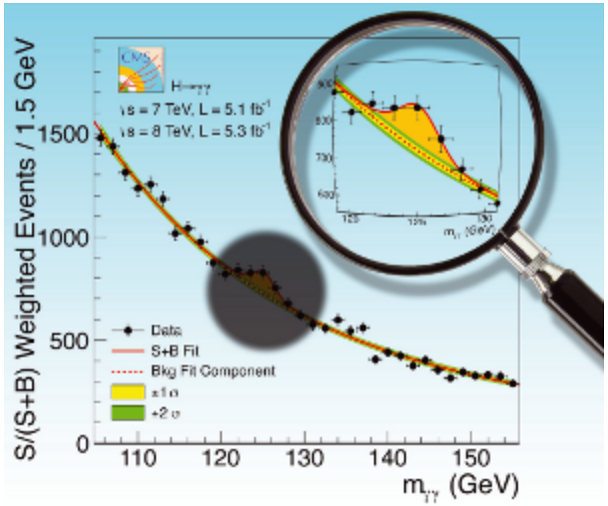
The Large Hadron Collider

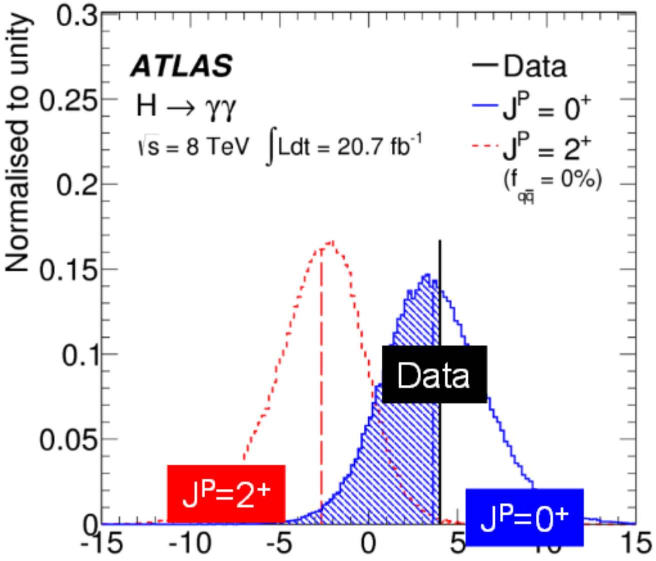
Higgs Boson discovery



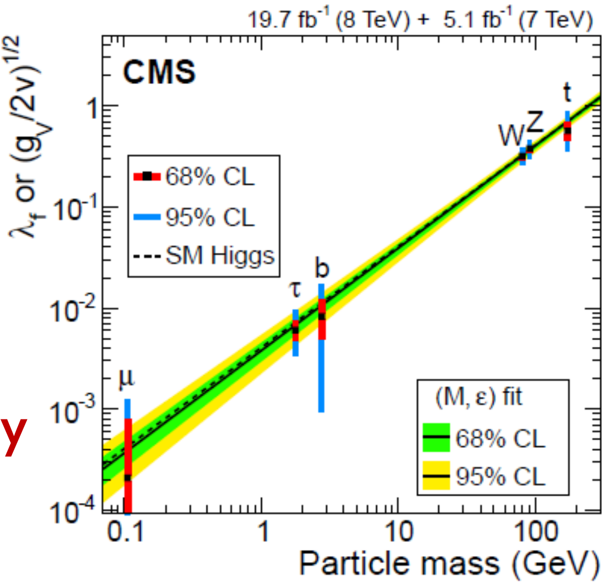


- The Large Hadron Collider (LHC) is one of largest scientific instrument ever built.
- It has been exploring the new energy frontier since 2010.
- Major discovery has been the Higgs boson, but we hope this is the first one of many…

LHC Run I Physics Results

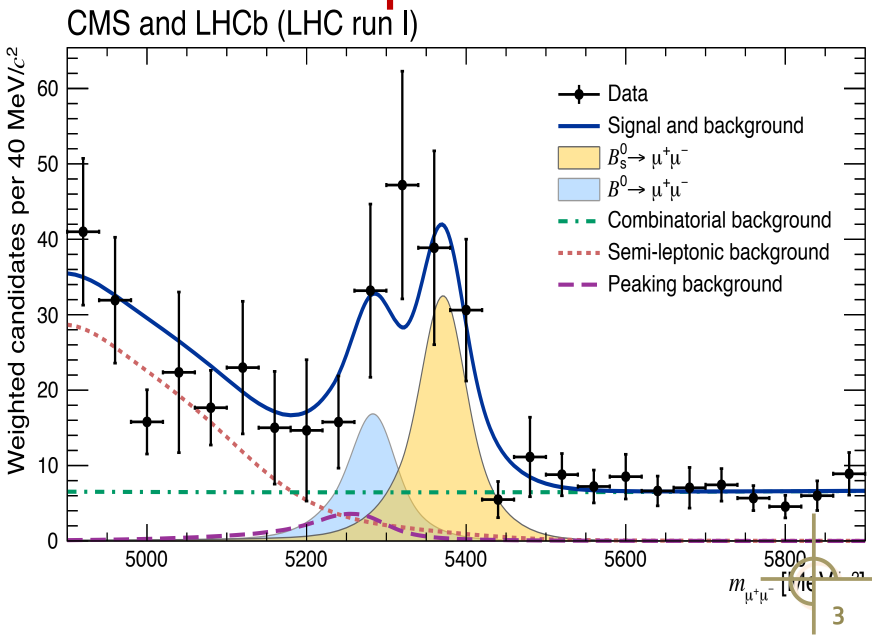


Higgs boson discovery



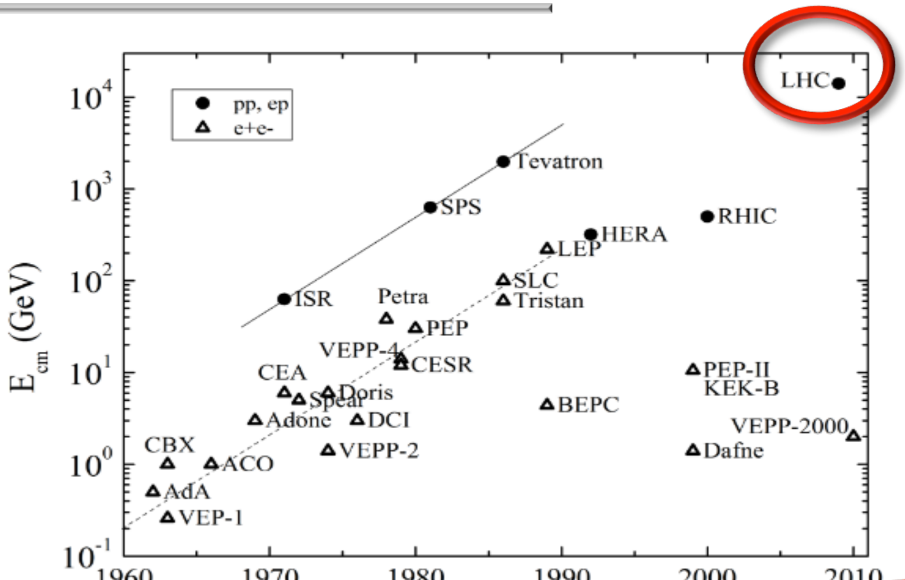
Its spin-parity is $J^P=0^+$

It couples to particles as SM predicts



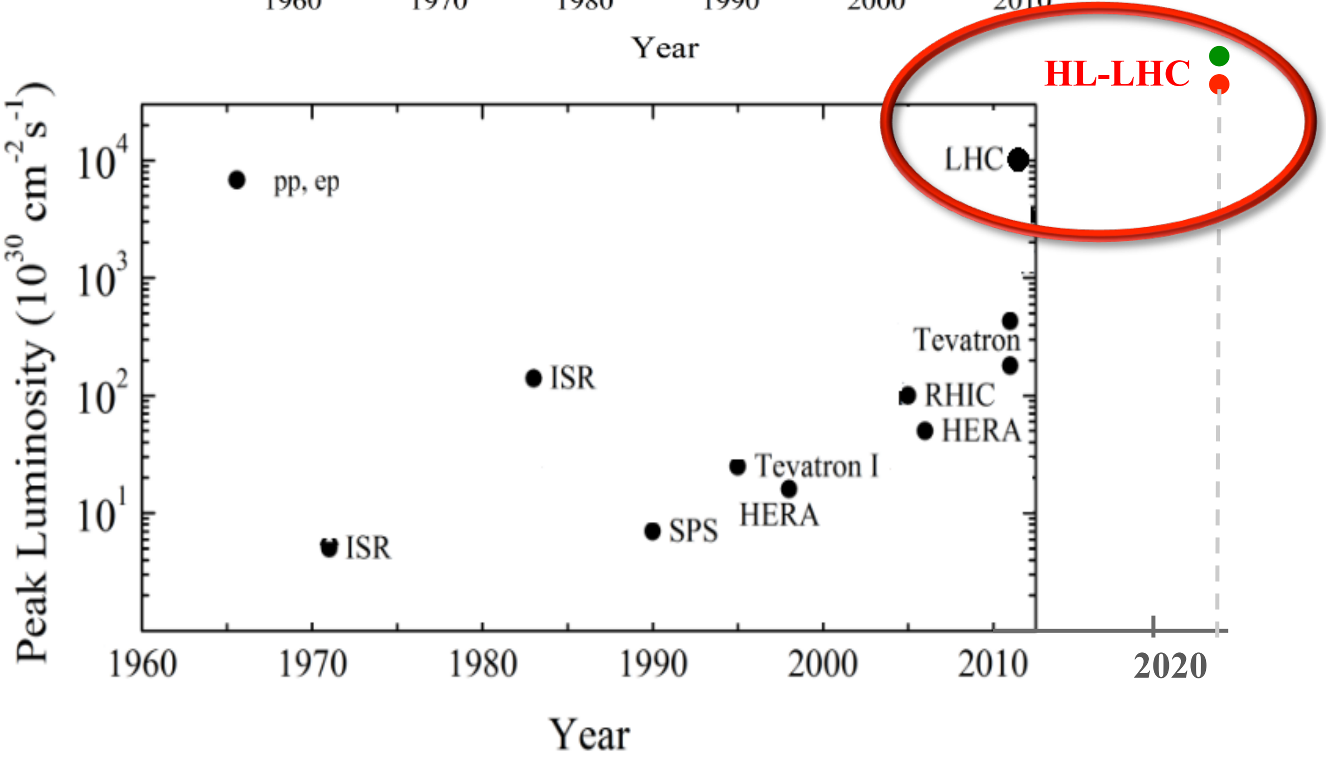
- **Higgs discovery**
- **Rare processes: $B_{s,d}$ →μ μ**
- **Exotic: pentaquarks (or hadronic molecules)**
- **Precise verification of Standard Model**
- **Just started the exploration of the TeV scale (13-14 TeV can bring surprises…)**

The Large Hadron Collider



14 TeV

Energy increase is difficult technologically. Luminosity is "easy"



LHC
10^{34} cm^{-2} s^{-1}
300 fb^{-1}

HL-LHC
5 10^{34} cm^{-2} s^{-1}
3000 fb^{-1}

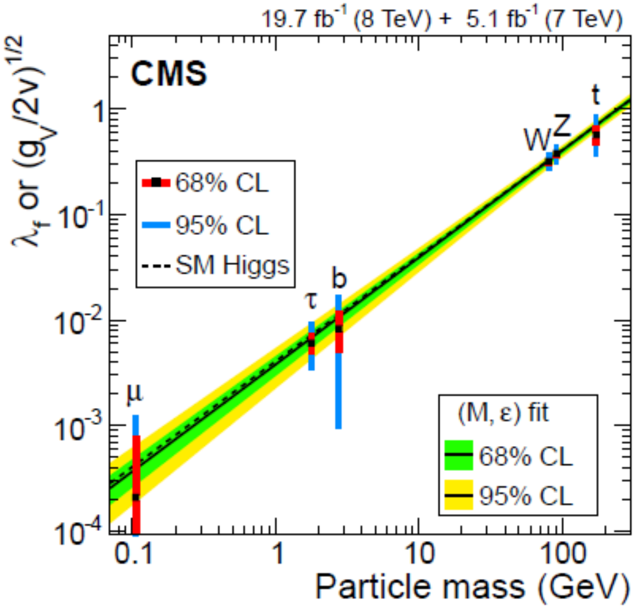
Ultimate
10^{35} cm^{-2} s^{-1}

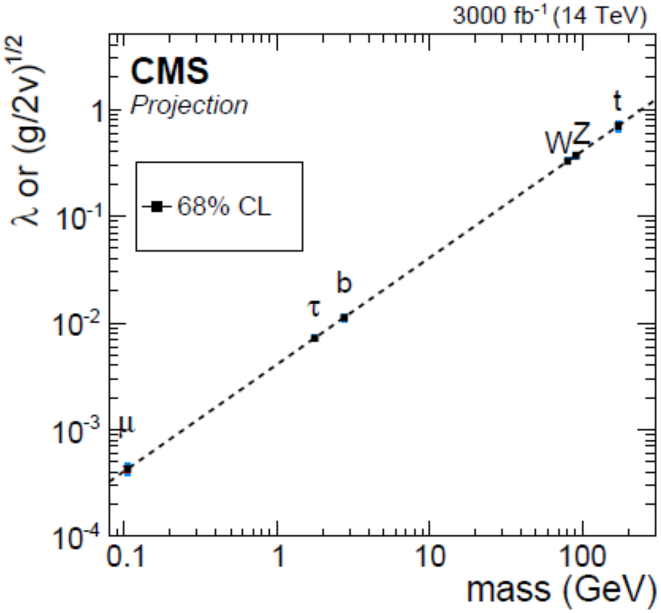
Higgs Case for HL-LHC

HL-LHC is a Higgs factory: 170 Mhiggs/expt!

Facility	LHC	HL-LHC	ILC	ILC LumiUP	CLIC	TLEP (4 IPs)
Energy (GeV)	14,000	14,000	250+500+1000	250+500+1000	350+1400+3000	240+350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10000+1400
N_H ($\times 10^6$)	17	170	0.37	1.05	2.2	3.2

- Higgs as a window to BSM physics:
  - The pattern of corrections to the SM Higgs couplings is different for new physics models
  - Measure as many Higgs couplings to fermions and bosons as precisely as possible:
    - 2 to 10% precision on Higgs couplings ~1.5-2x better than with 300 fb^{-1}
- Evidence of di-Higgs production (about 1.3 σ significance per experiment).
- Measure Higgs self-coupling.





Higgs Case for HL-LHC

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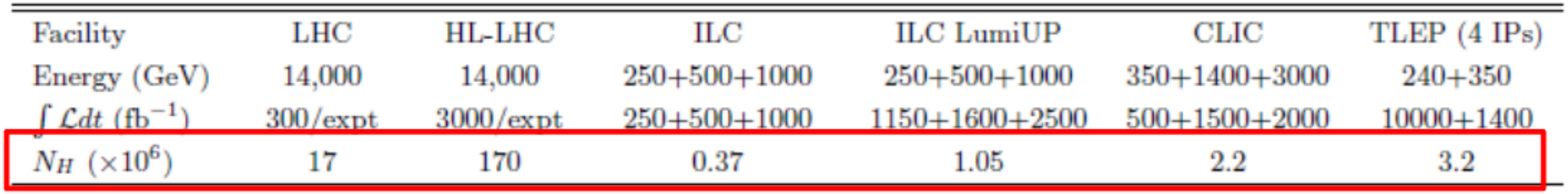

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However...

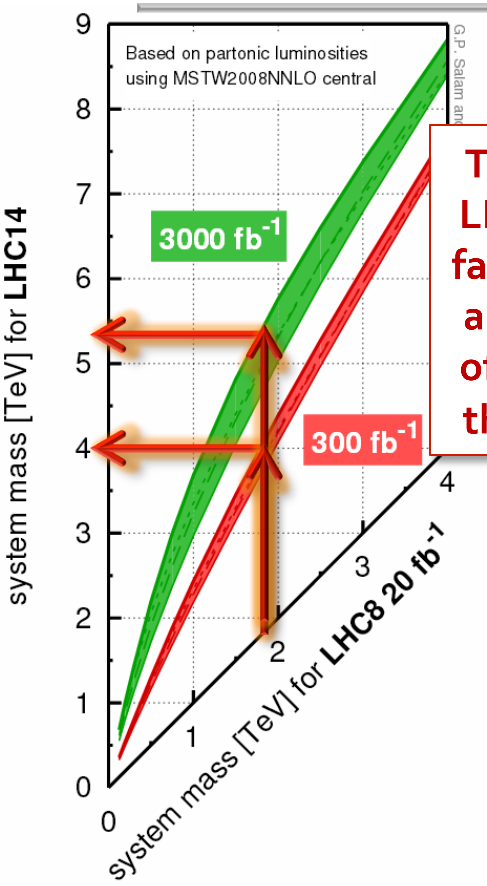
$$\frac{\sigma(pp \to h)}{\sigma(pp)} \sim 10^{-9} \qquad \frac{\sigma(pp \to h)}{\sigma(pp \to Z)} \sim 10^{-3}$$

PU = 140

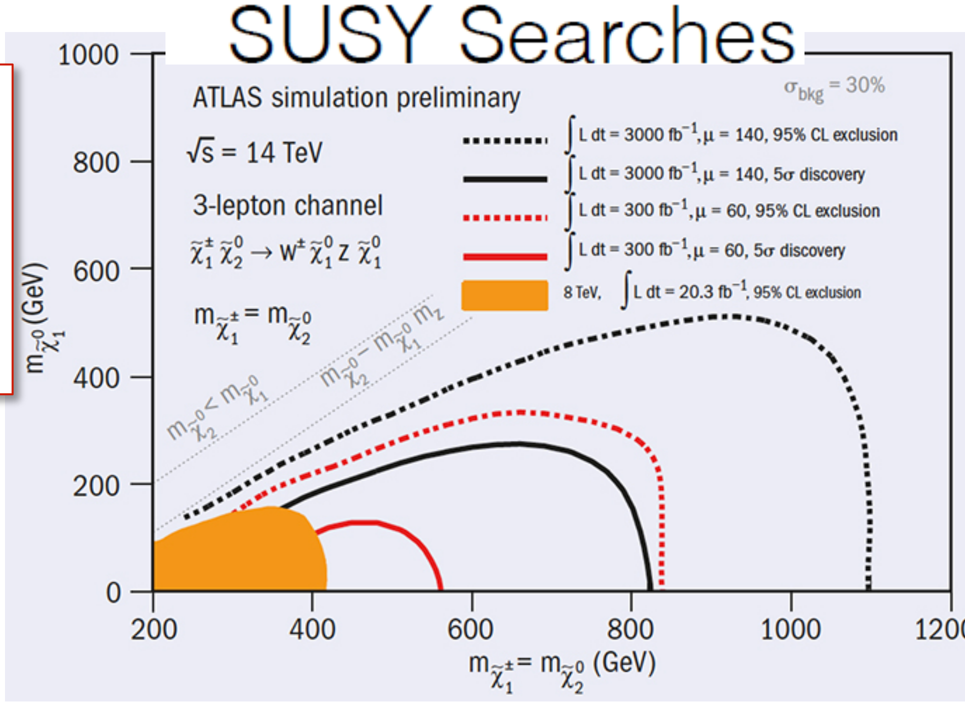
➔**Requires detector upgrades to meet experimental challenges**

Why HL-LHC?

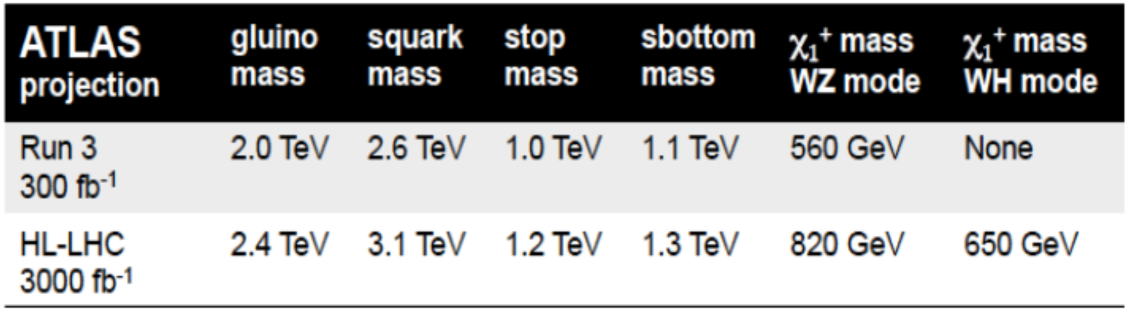
HL-LHC remains *the* energy frontier



The LHC and HL-LHC is the unique facility for indirect and direct search of New Physics in the next decades



Access to small cross section SUSY



ATLAS projection	gluino mass	squark mass	stop mass	sbottom mass	χ_1^+ mass WZ mode	χ_1^+ mass WH mode
Run 3 300 fb^{-1}	2.0 TeV	2.6 TeV	1.0 TeV	1.1 TeV	560 GeV	None
HL-LHC 3000 fb^{-1}	2.4 TeV	3.1 TeV	1.2 TeV	1.3 TeV	820 GeV	650 GeV

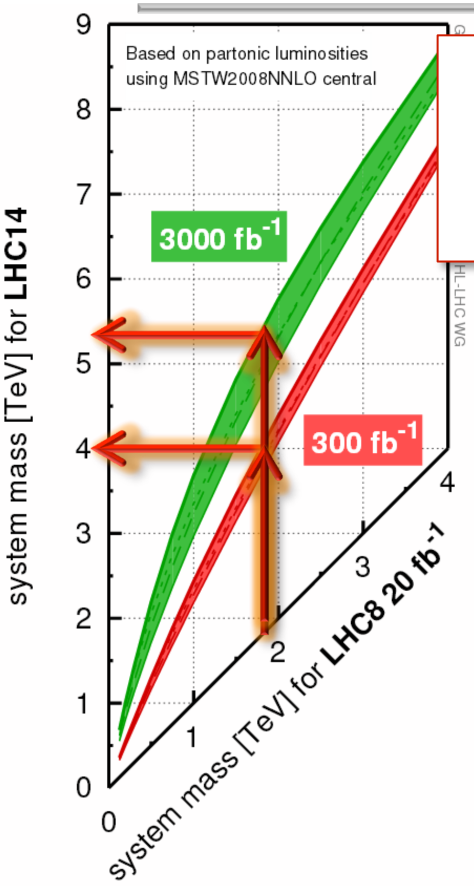
Looking at the parton kinematics:

- LHC pushes the explored region from 2 TeV to 4 TeV
- HL-LHC advances only until 5.5 TeV
  - an e+e- collider with this reach is not on the map

Extended phase space and mass reach coverage

Why HL-LHC?

HL-LHC remains *the* energy frontier



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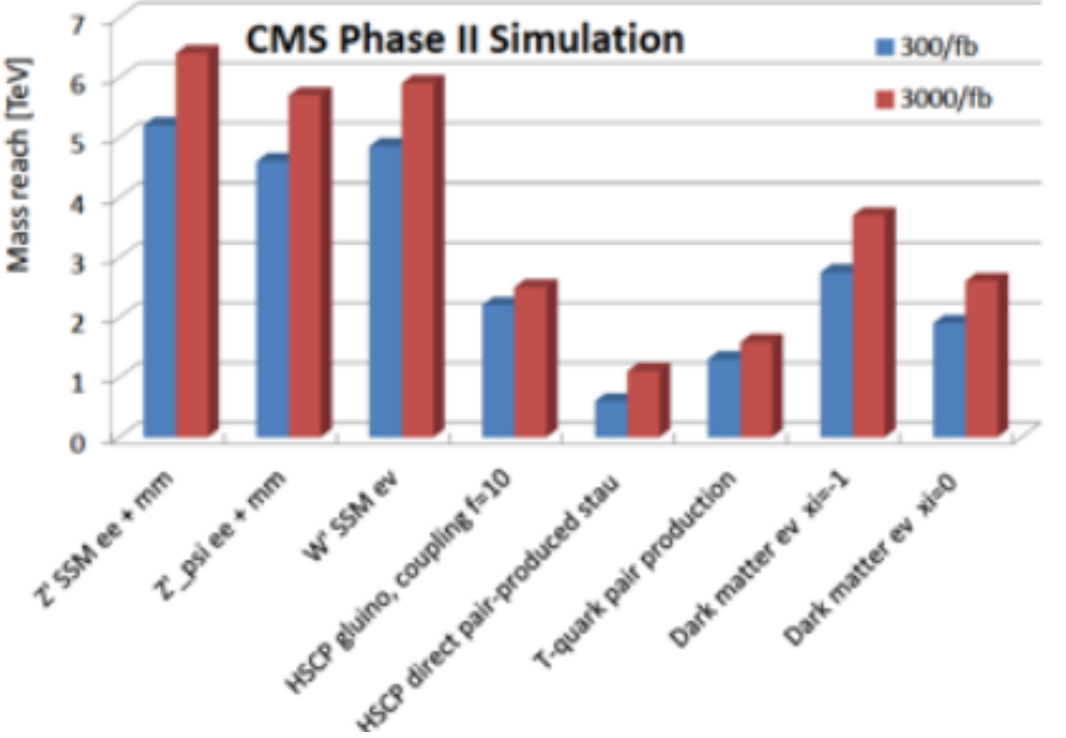
Exotica



Sensitivity to physics Beyond the Standard Model and increased mass range:

- **Search for heavy gauge bosons: W', Z':**
  - **Discovery up to ~6.4 TeV (300 fb^{-1}) and ~ 7.8 TeV (3000 fb^{-1}).**

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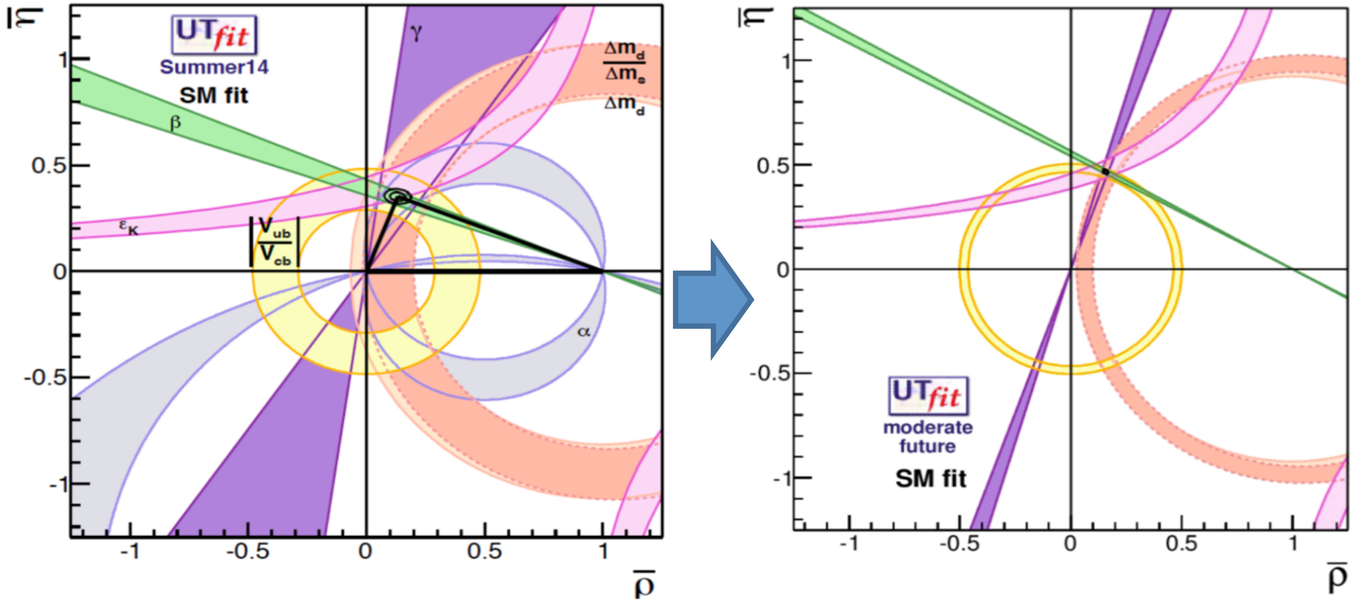
B (and c) system case for HL-LHC

Indirect window on BSM physics through radiative corrections.

1. **Precision test of CKM and the SM**
2. **Rare process, golden example, $B^0 \rightarrow \mu\mu$**
    - **Increased sensitivity through larger stats and better precision**

Also:

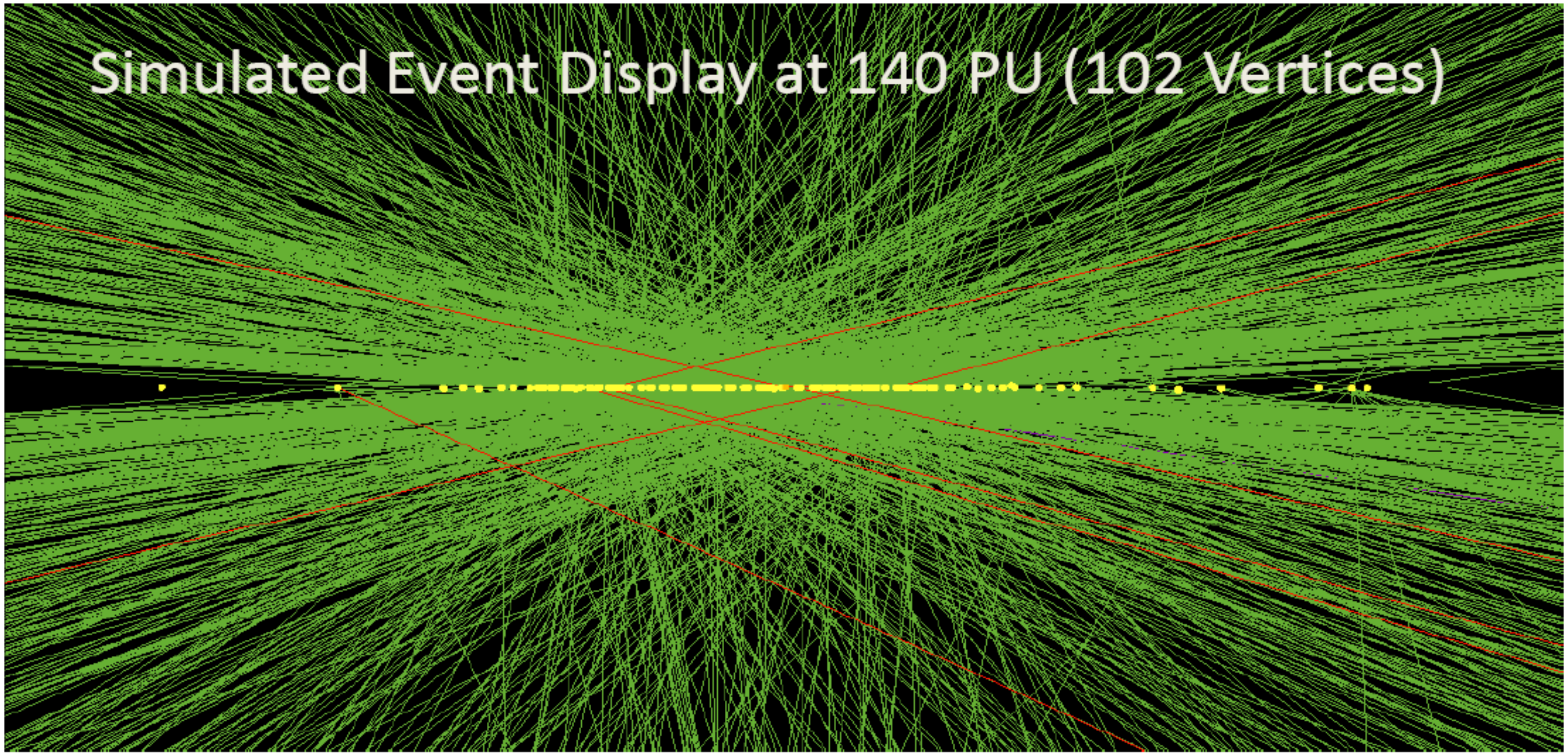
- **Anomalies from LHC running**
    - **~3.7σ in angular distribution of $B^0 \rightarrow K^*\mu\mu$ seen in the 2011 data, confirmed with 3fb-1 .**
- **More precise test of lepton universality of SM coupling**



LHCb results in competition/complementarity with Belle-II from 2018.

Challenges at higher luminosity


Z→μμ event from 2012 data with 25 vertices


Simulated Event Display at 140 PU (102 Vertices)

Luminosity leveling: key for HL-LHC

It is necessary to limit:

- pile-up in the detectors up to 140 (difficult reconstruction) (up to 5 in LHCb)
- the instantaneous luminosity to a factor 5 ((radiation damage on sensors and electronics and high occupancy, rates, bandwidth):
  - ATLAS and CMS : from 10^{34} $cm^{-2}s^{-1}$ LHC -> 5 10^{34} $cm^{-2}s^{-1}$
  - LHCb: from 4 10^{32} $cm^{-2}s^{-1}$ to 2 10^{33} $cm^{-2}s^{-1}$

while

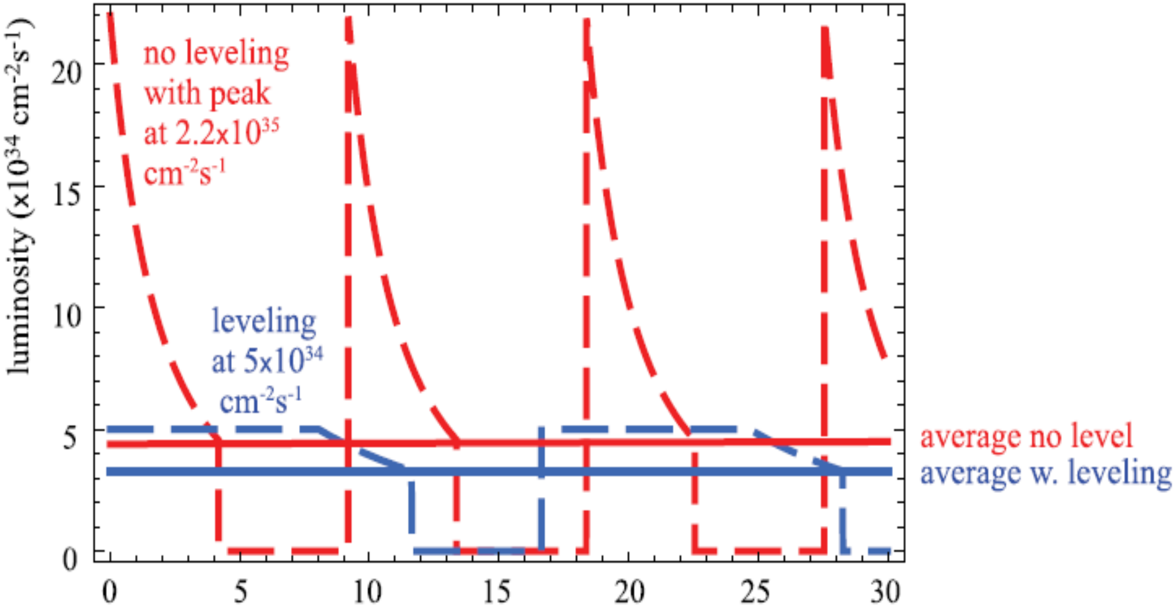
providing up to a factor 10 integrated luminosity

ATLAS and CMS : 300 fb^{-1} (LHC) -> 3000 fb^{-1} (HL-LHC)

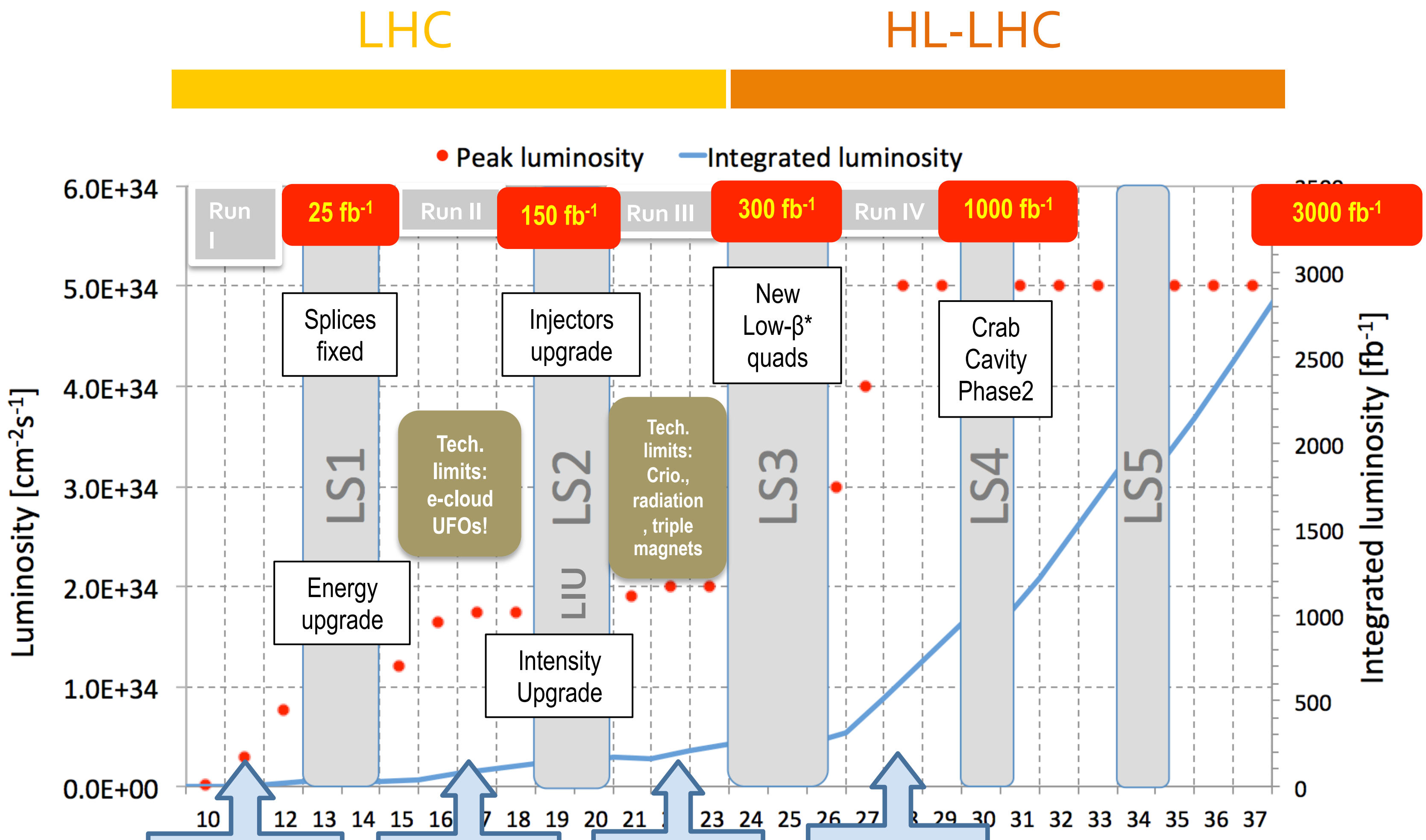
LHCb: 8 fb-1 to > 50 fb-1

HL-LHC upgrade goal: deliver maximum integrated luminosity with lowest possible pile-up density.

Key to HL-LHC: luminosity leveling



LHC / HL-LHC Roadmap



0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
8 TeV
high pile up ~40

1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
13-14 TeV
high pile up ~40

1.5 -2.2 · 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
14 TeV
very high pile up > 60

5-7 10^{34} $cm^{-2}s^{-1}$ levelled
25 ns bunch
14 TeV
very high pile up ~140

LS : Long Shutdown

LHC upgrade goals: Performance optimization

Luminosity recipe (round beams):

$$L = \frac{\gamma \cdot n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot \frac{1}{\sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}}}$$

γ is the proton beam energy in unit of rest mass

n_b is the number of bunches per beam: 2808 (nominal LHC value) for 25 ns bunch spacing

N is the bunch population. $N_{\text{nominal 25 ns}}$: 1.15×10^{11} p (⇒0.58 A of beam current at 2808 bunches)

f_{rev} is the revolution frequency (11.2 kHz)

β^* is the beam beta function (focal length) at the collision point (nominal design 0.55 m)

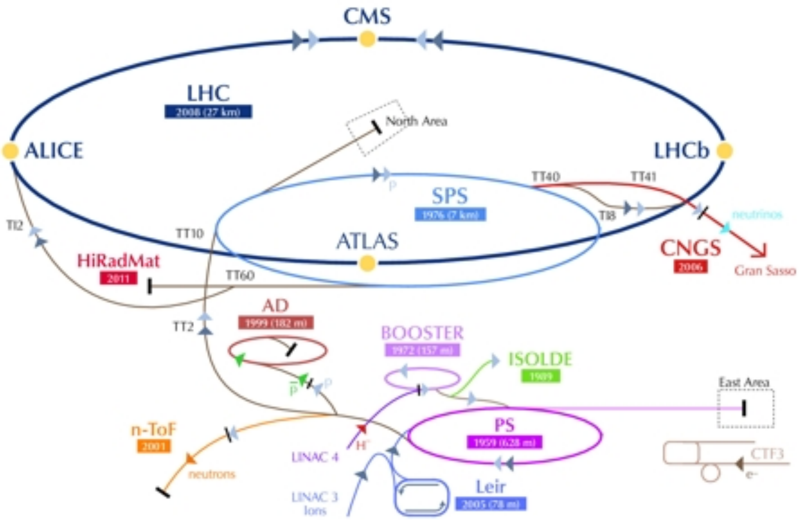
ε_n is the transverse normalized emittance (nominal design: 3.75 μm)

R is a luminosity geometrical reduction factor (0.85 at a β^* of 0.55 m of, down to 0.5 at 0.25 m)

θ_c is the full crossing angle between colliding beam (285 μrad as nominal design)

σ, σ_z are the transverse and longitudinal r.m.s. sizes, respectively

- ○ Maximize bunch intensities => Injector complex
- ○ Minimize beam emittance => LHC Injectors Upgrade (LIU)
- ○ Maximize number of bunches (beam power) => 25 ns



Upgrade foreseen by LS2

Includes Linac 4, PS booster, PS, SPS and heavy ion injector chain

Will allow reaching 2 10^{34} $cm^{-2}s^{-1}$

LHC upgrade goals: Performance optimization

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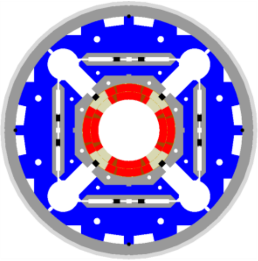
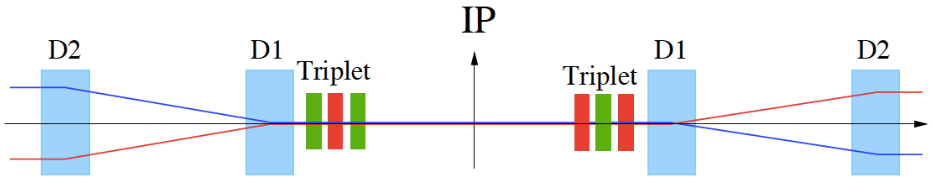
- Minimize beam size (constant beam power) => triplet aperture

US-LARP
MQXF
magnet
design
Based on
Nb_3Sn
technology





Triplet quadrupole magnets will need to be replaced due to radiation

To obtain a small β* new triplet quadrupoles with double aperture => 50% higher magnetic field. (8 T to 12 T peak)

Need a new technology => Nb_3Sn (25 years development)

LHC upgrade goals: Performance optimization

Luminosity recipe (round beams):

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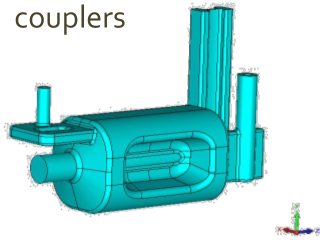
RF Dipole: Waveguide or waveguide-coax couplers



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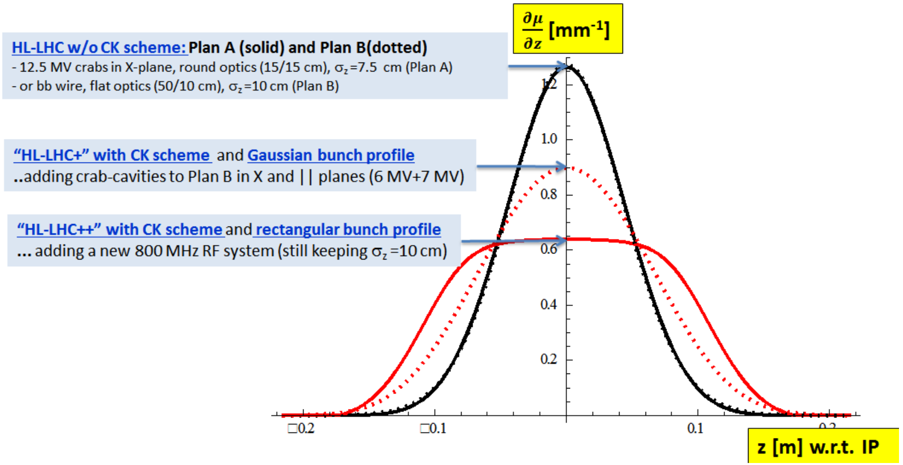
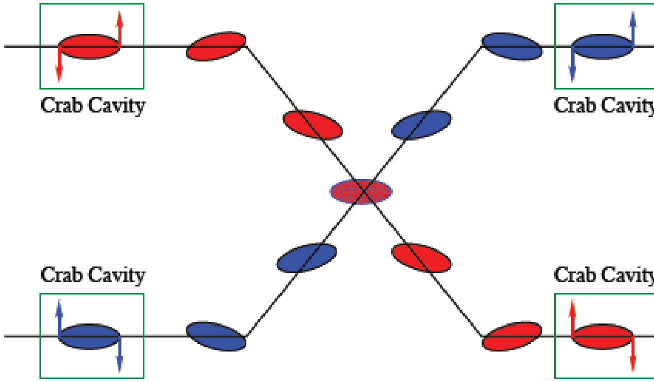
- ○ Compensate for ´F´ : => crab cavities and crab kissing



HL-LHC w/o CK scheme: Plan A (solid) and Plan B(dotted)
- 12.5 MV crabs in X-plane, round optics (15/15 cm), σ_z=7.5 cm (Plan A)
- or bb wire, flat optics (50/10 cm), σ_z=10 cm (Plan B)

"HL-LHC+" with CK scheme and **Gaussian bunch profile**
..adding crab-cavities to Plan B in X and || planes (6 MV+7 MV)

"HL-LHC++" with CK scheme and **rectangular bunch profile**
... adding a new 800 MHz RF system (still keeping σ_z =10 cm)



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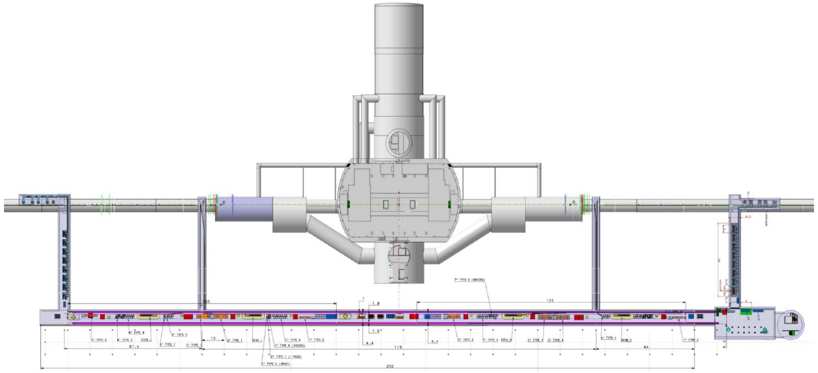

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- Minimize beam emittance => LHC Injectors Upgrade (LIU)
- Maximize number of bunches (beam power) => 25 ns
- Minimize beam size (constant beam power) => triplet aperture
- Compensate for ´F´ : => crab cavities
- Improve machine efficiency => Minimize number of unscheduled beam aborts (radiation protection)

  - Radiation to electronics➔ removal of all electronics from tunnel region
  - e-cloud ➔ beam scrubbing (conditioning of surface)
  - UFOs (Unidentified Falling Objects) ➔ beam scrubbing (conditioning of surface)

LHC upgrade goals: Performance optimization

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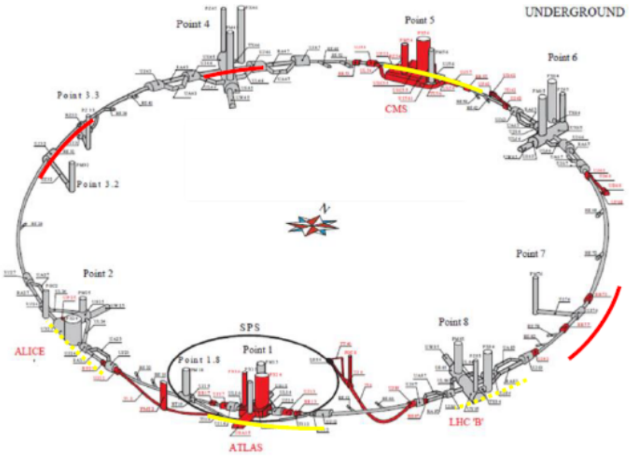

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Major intervention on more than 1.2 km of LHC

Challenges at higher luminosity

Physics in the HL-LHC high luminosity environment is **challenging:**

- Precise measurement of physics objects: leptons (e, μ, τ-lepton), photons, missing transverse energy, jets, b-(c-)quarks over full p_T range
- Accurate reconstruction of complex event topologies: W/Z, top, VBF
- Keep low-p_T lepton triggers despite high rate

Object(s)	Trigger	Estimated Rate No L1Track	With L1Track
e	EM20	200 kHz	40 kHz
γ	EM40	20 kHz	10 kHz
μ	MU20	> 40 kHz	10 kHz
τ	TAU50	50 kHz	20 kHz
ee	2EM10	40 kHz	< 1 kHz
$\gamma\gamma$	2EM10	as above	~5 kHz
$e\mu$	EM10_MU6	30 kHz	< 1 kHz
$\mu\mu$	2MU10	4 kHz	< 1 kHz
$\tau\tau$	2TAU15I	40 kHz	2 kHz
Other	JET + MET	~100 kHz	~100 kHz
Total		**~500 kHz**	**~200 kHz**

ATLAS HL-LHC trigger scenario
based on Phase 1 upgrades

Goal is to improve or at least maintain present physics performance during HL-LHC

present physics performance during HL-LHC

Challenges at higher luminosity

Same physics but…

*** Higher Occupancy:**

* hits on detector elements proportional to the number of interactions, problems of **detectors granularity** and **buffers occupancy**

*** Radiation damage to detectors and electronics:**

* **Peak luminosity**: reduced mean time between failures for SEE (Single Event Effects)

* **Integrated luminosity**: charge trapping in silicon, increased noise and dark current, light absorption in crystals, etc

*** Event pile-up:**

* **Trigger efficiency and purity**, event size, DAQ bandwidth, computing power….

* **Particle and event reconstruction**, missing ET measurement, particle isolation definition, backgrounds to signal processes…

+ aging…

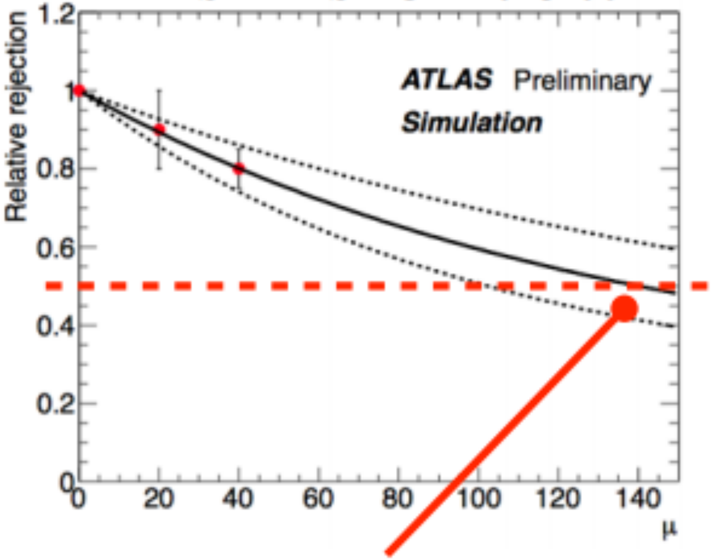
Challenges at higher luminosity

b-tagging @ 140 <PU>

B-tag performances heavily degraded by PU

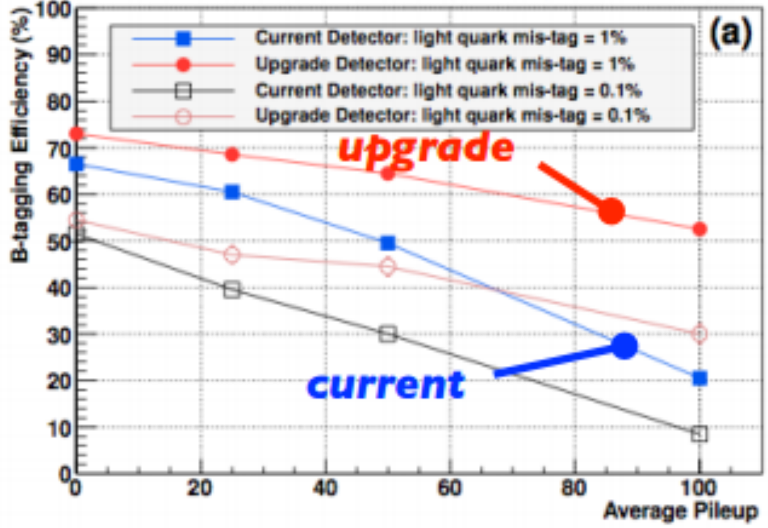
- extra particles, lower tracking efficiency

ATLAS-PHYS-PUB-2013-004



Light-flavour rejection vs μ_{PU} w/o detector upgrade

CMS, NOTE-13-02 (2013)



Pixel upgrade crucial to recover efficiency

- **New trackers and pixels**
- **More powerful trigger schemes:**
  - **track based (CMS,Atlas)**
  - **Pushing the full data payload (LHCb)**

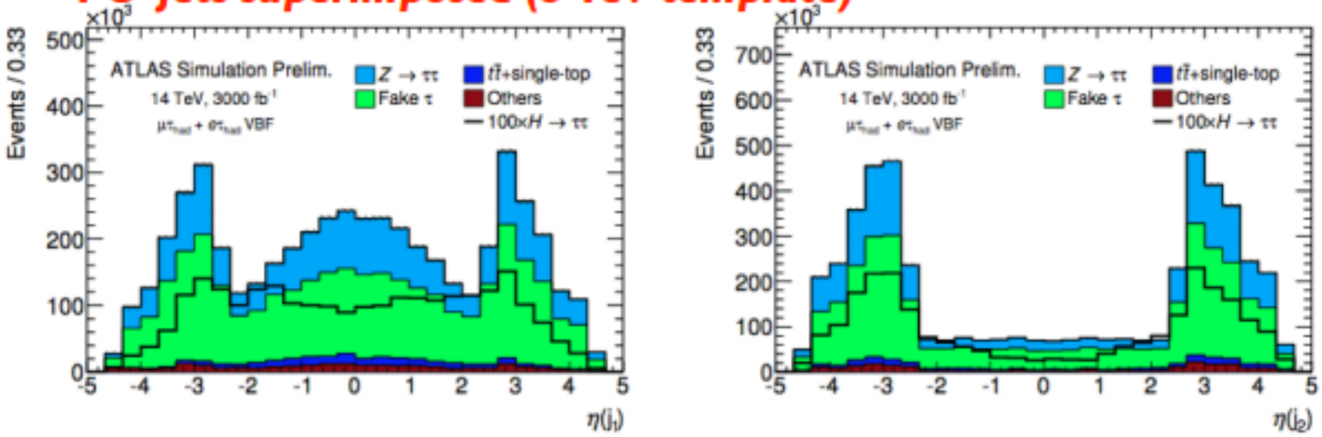
Challenges at higher luminosity

Forward jets@ 140 <PU>

VBF-like selection based on forward/backward di-jet pairs

- fake VBF signature from pile-up jets

PU-jets superimposed (8 TeV template)



	Leading jet	Trailing jet
% of events w/ a PU jet as…	42%	72%

ATL-PHYS-PUB-2014-018 17

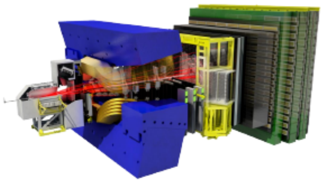
Impact on Δμ from tracker extension:

forward pile-up jet rejection	50%	75%	90%
forward tracker coverage	$\Delta\mu$		
Run-I tracking volume	0.24		
$\|\eta\| < 3.0$	0.18	0.15	0.14
$\|\eta\| < 3.5$	0.18	0.13	0.11
$\|\eta\| < 4.0$	0.16	0.12	0.08

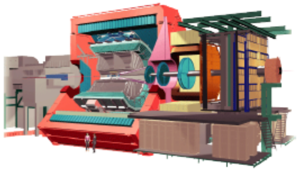
- **Forward extensions**
- **Replace damaged calorimeters**
- **More bandwidth, more granularity more resilient**

LHC detector upgrades

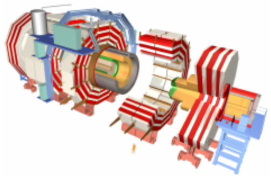
LHCb



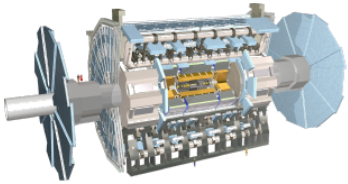
Alice



CMS



ATLAS



	LS1 (2013-2014)	2016-17	LS2 (2019-2020)	LS3 (2024-2025)
ATLAS	-New inner pixel layer -Muon extension	-	-FTK: Fast Tracker Trigger -NSW: New Small Wheels	-New Tracker (ITk) -Tracking Trigger -Muon and calorimeter electronics -Extensions at large η
CMS	-Muon forward -DT elect. -HF and HO photodetectors	-L1 Trigger Upgrade -Pixel	-HCAL electronics	-New Tracker (Tracking Trigger) -Endcap calorimeters replacement -New Muon stations and electronics -Extensions at large η
ALICE	-	-	-Readout 50 kHz -ITS, TPC, MFT	-
LHCb	-	-Real-time align./calib. and reco. -Herschel	-Readout 40 MHz -VELO, RICH, Tracking	-

Tracking
Calorimeter
Muon
Trigger & DAQ

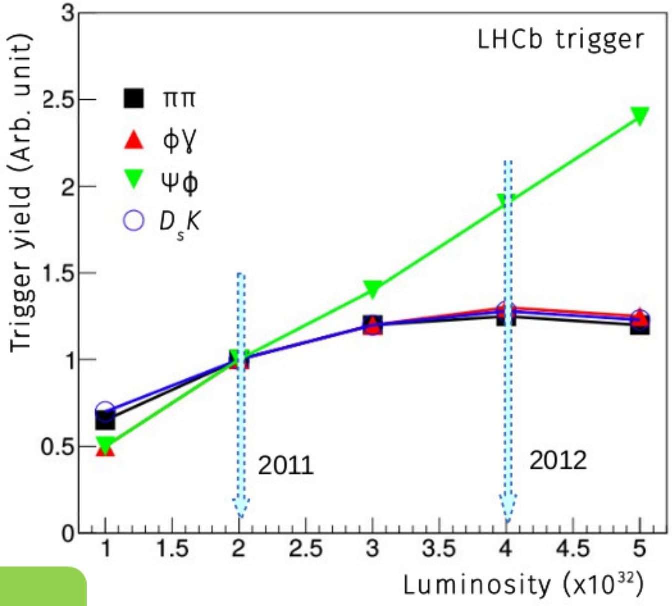
LHCb Upgrade

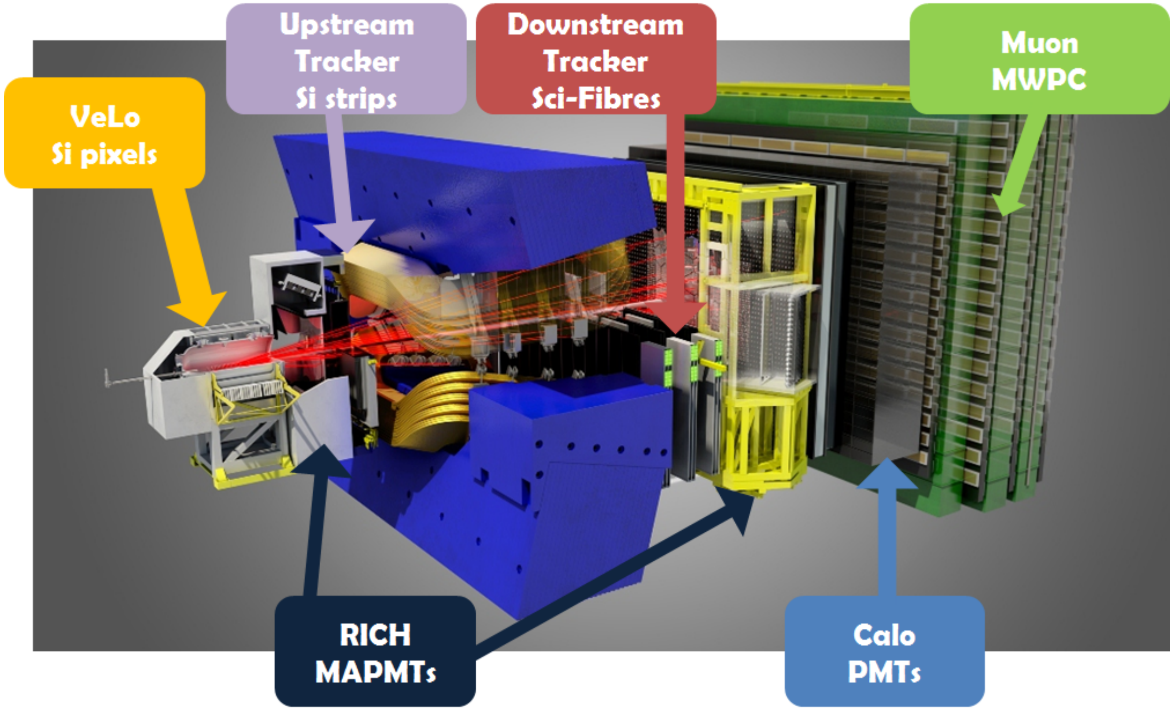
UPGRADE IN LS2 (2019)

- Measurable deviations from SM are still expected but should be small.
- Need to go to very high statistical precision.
- Upgrade essential.

Goal:

- Increase statistic (move to a 40 MHz readout)
- Improve fast tracking and vertexing





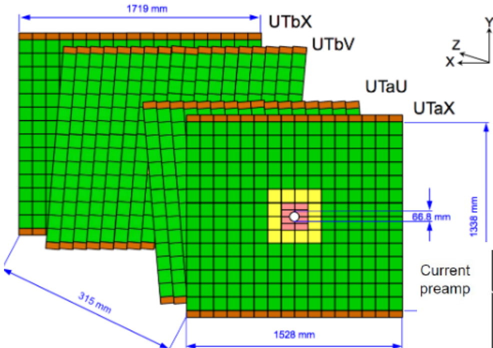
Many hadronic channels saturate due to energy cuts in the trigger => Need to increase the bandwidth

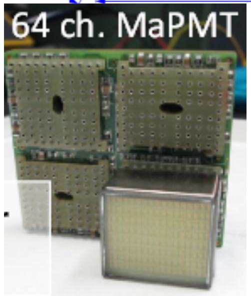
$L_{int} > 50\ fb^{-1}$
$L = 4\ 10^{32}\ cm^{-2}s^{-1} \rightarrow$
$2\ 10^{33}\ cm^{-2}s^{-1}$

LHCb Upgrade

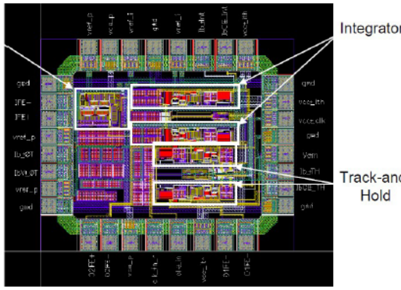
Other upgrades…

- Increase Upstream Tracker granularity in inner region (replacement of Si sensors)
- Replace photodetectors of RICH with 64 multianode PMT
- Replace calorimeters readout @ 40 MHz (ICECAL ASIC) and back-end
- Presshower and SPD removed, most inner ECAL modules could be replaced
- New muon off-detector electronics





ICECAL



TRIGERLESS DETECTOR : 40 MHZ READ-OUT

	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**

Remove existing L0 hardware trigger (1 MHz) and perform trigger in CPU farm (reduction to 20 kHz)

Read out all detector data from all BXs @ 40 MHz

Selection is 100% in software running in PC farm

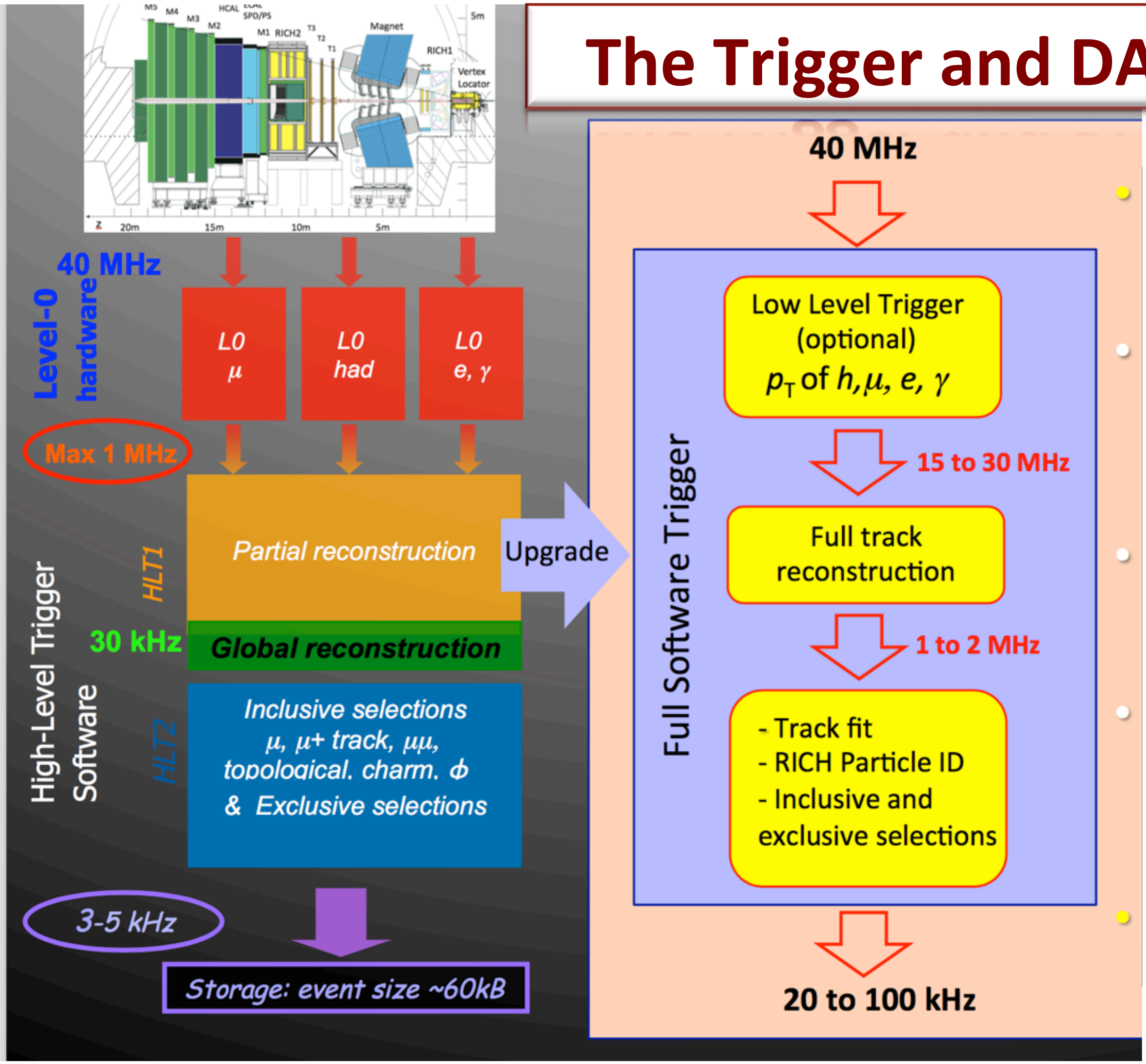
⇒ New front-end electronics (almost all)

New back-end electronics (100%)

New DAQ (100%)

LHCb Upgrade

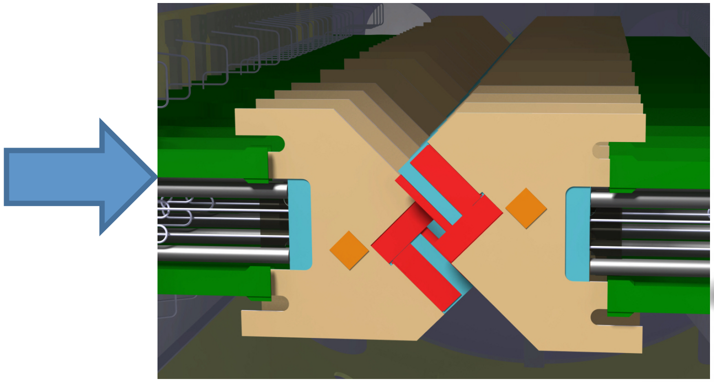
The Trigger and DAQ Upgrade

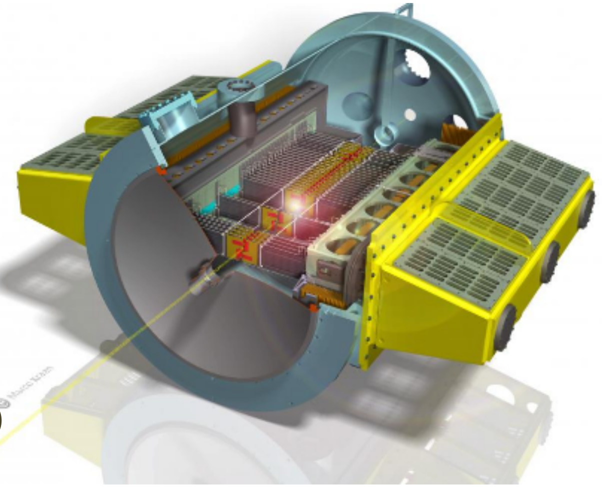


- Full software trigger, 20 kHz output rate
- Efficient and selective use of ALL detector information
- Low Level Trigger (LLT) foreseen in early stage
- LLT output rate increases as trigger farm grows
- 40 Mhz readout rate

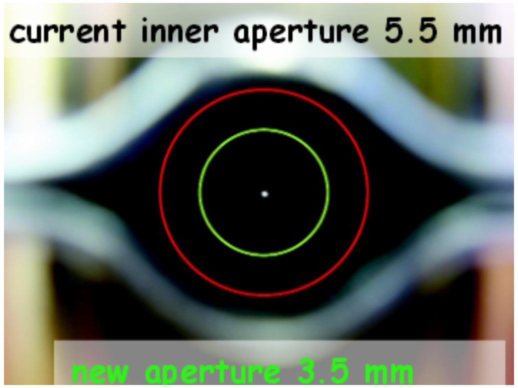
- Real-time alignment and calibration
- Not only a triggerless readout but also to a detector analyzed in real time
- Greatly expand physics reach not only for B-physics and charm but also for low-mass exotic/DM searches.

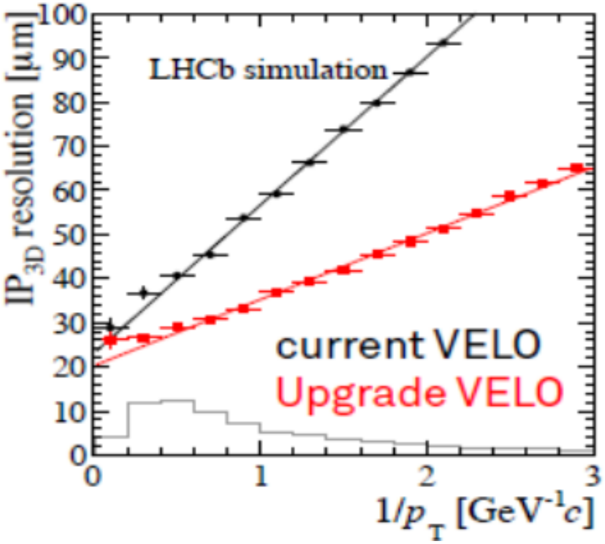
LHCb: VELO (Vertex Locator) Upgrade

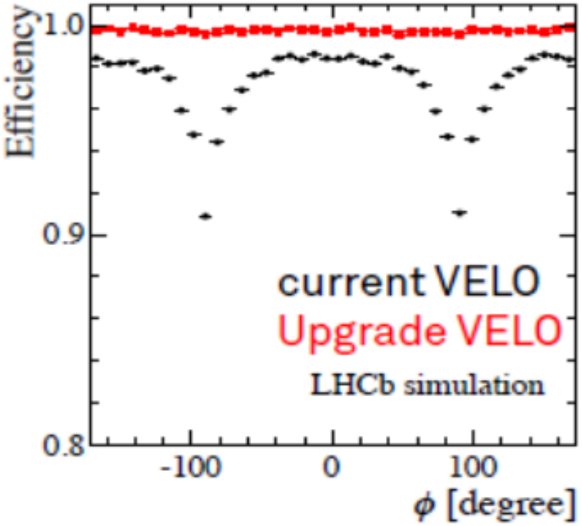




- Increased radiation tolerance, closer to beam (8.1 to 5.1 mm)
- From strips to pixel. Higher granularity: 55x55 μm² pixel sensors (based on Timepix)
- Novel microchannel CO_2 cooling (minimize material)
- Data driven readout at 40 MHz → > 2Tbits/s





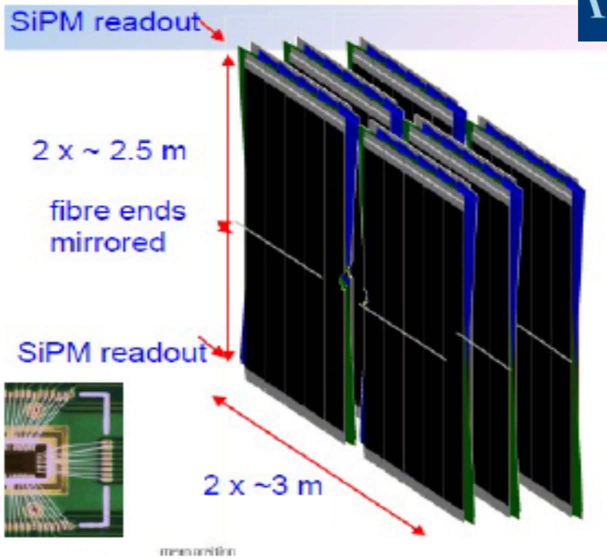


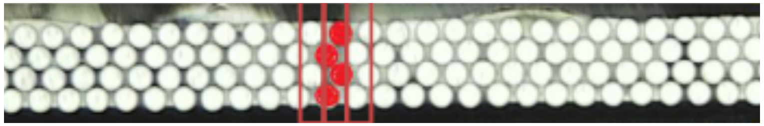
LHCb Upgrade: SciFi

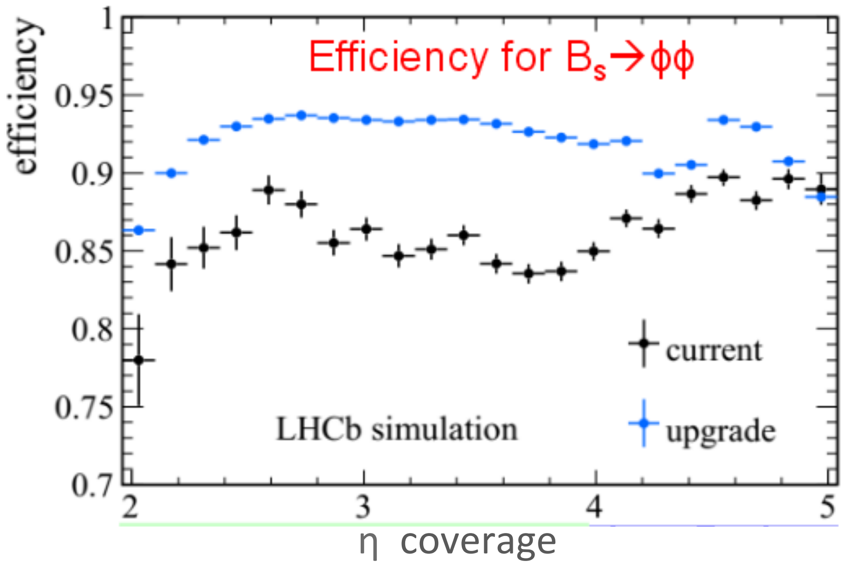
Replace completely straw tube and inner Si strips with Scintillating Fibres (***SciFi***).

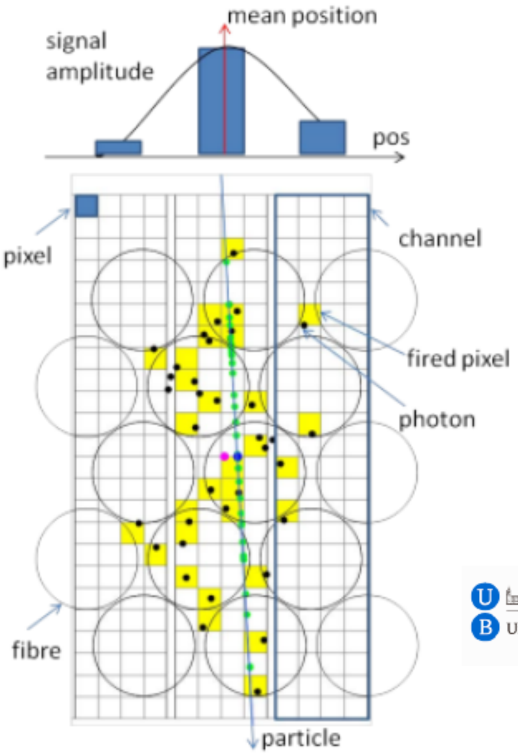
Fast Track reconstruction in trigger.

- 6 layers of 2.5m long fibres with 250 µm diameter (10000 km)
- Straight to 50µm and flat to 200µm over 2.5m.
- SiPM readout. Cooled to -40ºC.

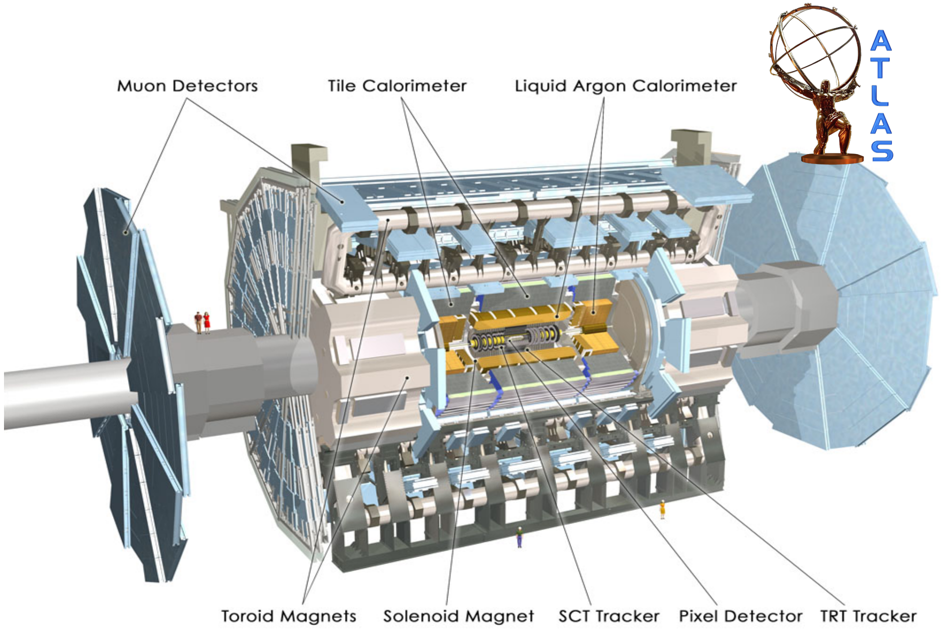








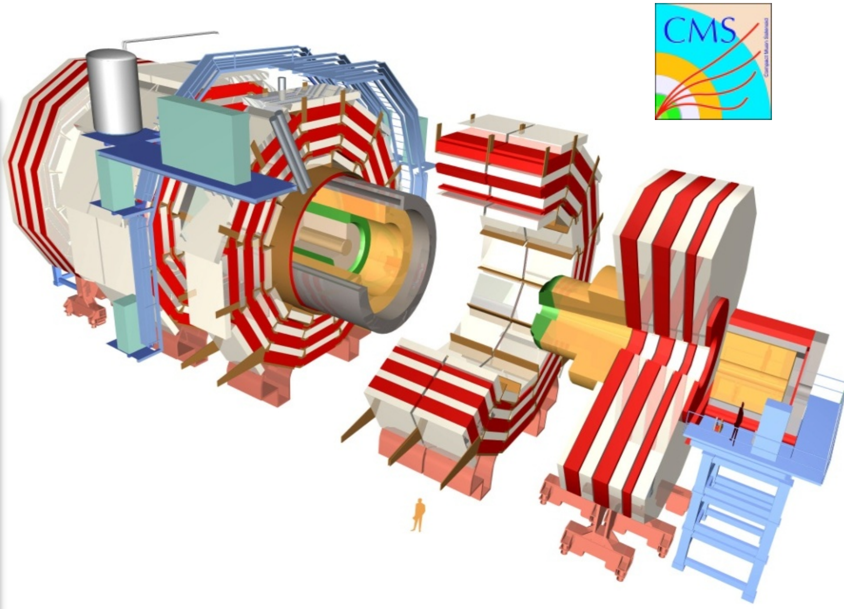
ATLAS and CMS Upgrades



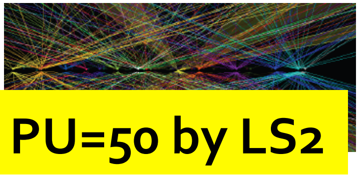
Full upgrade program to cope with increasing luminosity:

Radiation damage, pile-up mitigation, bandwidth limitations, aging…

- ✓ New Trackers and pixels
- ✓ CMS endcap and ATLAS forward calorimeter
- ✓ Forward extension (tracking and muons)
- ✓ Higher granularity wherever possible
- ✓ New electronics almost everywhere with increased bandwidth
- ✓ New trigger systems: include tracker, bring offline algorithms online



ATLAS and CMS Pixel Phase 1 Upgrades

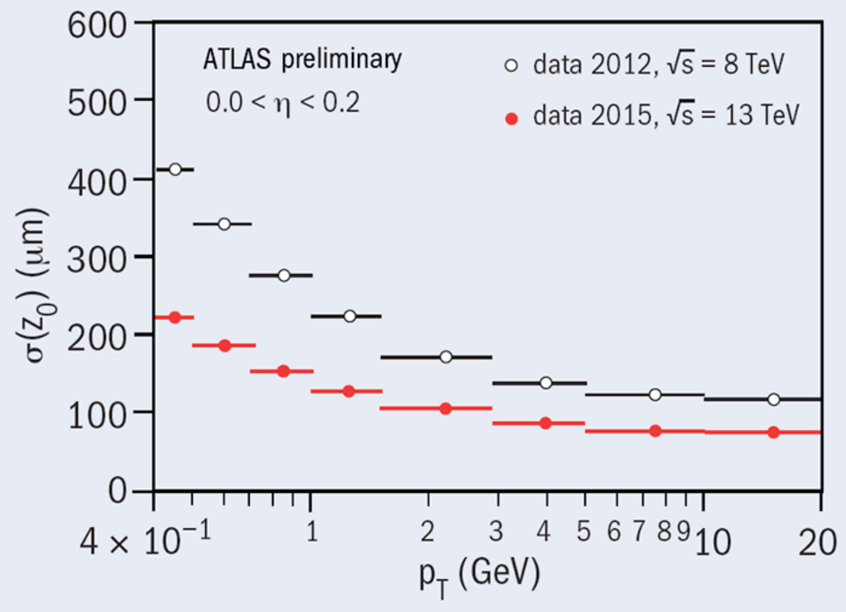


PU=50 by LS2

ATLAS - New Insertable B-layer (IBL)

IN 2014

- Additional 4th pixel layer. Close to interaction point (33 mm)
- 75% thin planar sensors and 3D double side sensors (first time 3D used)
- CO2 cooling
- Reduce the fake tracks arising from random combinations of hits and enhance efficiency of tagging heavy flavour quarks

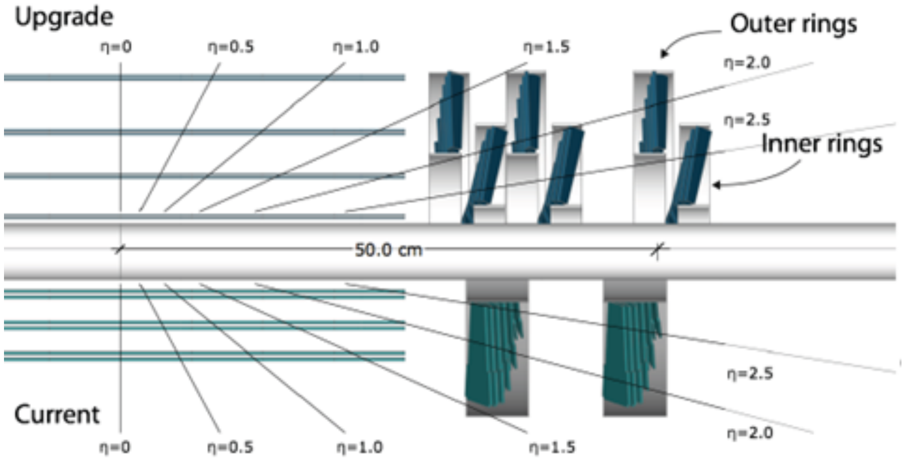


IFAE CNM
Contribute to 10%

CMS - New Pixel

IN 2017

- New beam pipe in 2014
- 4 layers/3 disks
- 3 cm inner radius
- New readout chip: recovers inefficiency at high rate and PU
- Significantly reduced material budget
- CO_2 cooling, DC-DC powering scheme
- Improved track resolution and efficiency
- Improved vertex resolution and b-tagging



ATLAS and CMS Phase 1 Trigger Upgrade

Increase of luminosity forces upgrading present trigger system in order to control the rates maintaining similar thresholds already before LS3

High Precision L1 Calorimeter Trigger

>LS2

- Readout of super-cells in LAr with higher granularity and higher precision

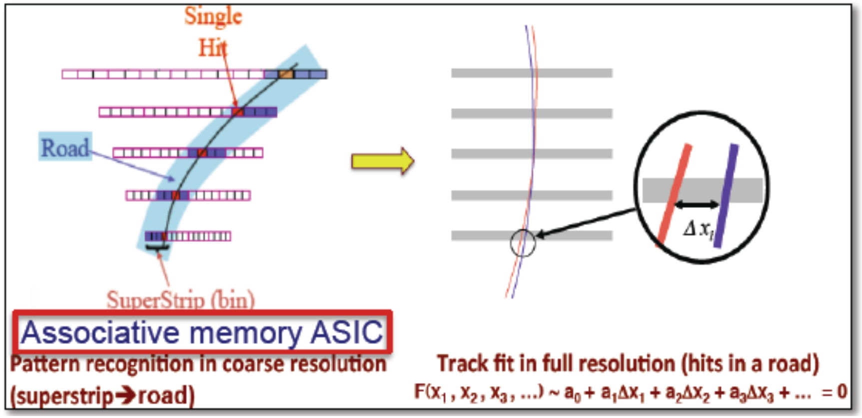
Fast TracKing (FTK) for the Level-2 trigger

- Very fast pattern recognition and track fitting (~ 25 µs) in the ID silicon layers at an "offline precision"
- ATCA and VME electronics. 8000 ASICS, 2000 FPGAs 10 Gb/s links

IN 2017

hit pattern matching to pre-stored patterns (coarse)

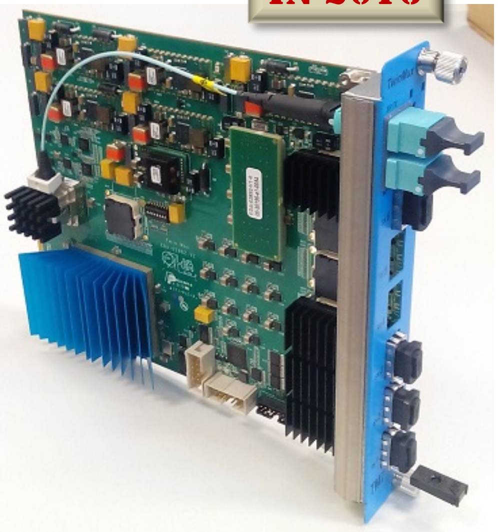
subsequent linear fitting in FPGAs (precise)



New Level1 back-end electronics

- Upgrade of the off-detector electronics using µTCA technologies (powerful FPGAs and high bandwidth optics)
- Allows much improved algorithms for PU mitigation and isolation
- Improve L1 Trigger capabilities to cope with higher rates

IN 2016

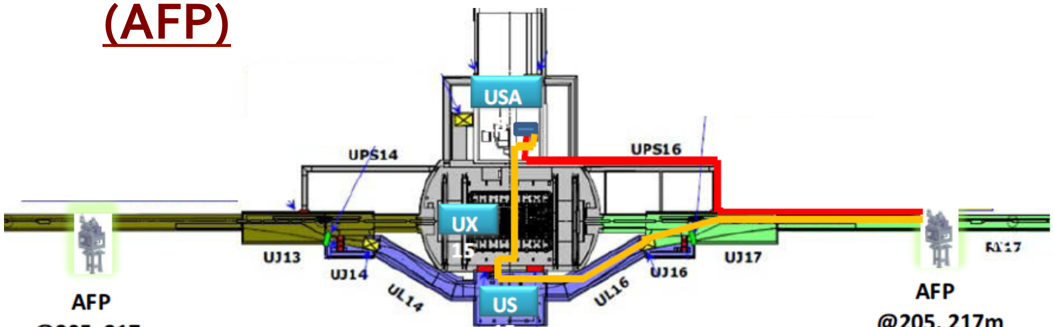


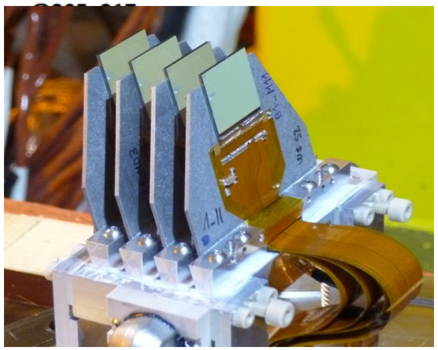
µTCA boards

TwinMux and uROS (U. Padova + Ciemat

ATLAS and CMS Forward Physics

ATLAS Forward Physics (AFP)





IN 2017

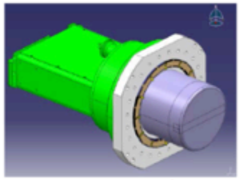
IFAE CNM

- AFP will study events in which intact protons emerge from ATLAS inelastic collisions, with detectors close to the LHC beam at 210 m from the IP
- 4 roman pots in total
- 3D sensors for first AFP phase

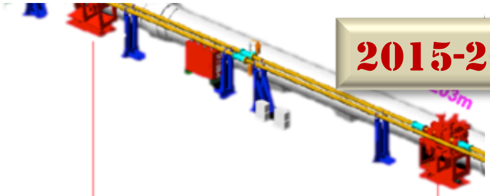
CMS- TOTEM- Proton Precision Spectrometer (CT-PPS)

- Very forward diffractive physics
- Located in the very forward region on both sides of CMS at about 200m from the IP
- Silicon tracking system to measure the position and direction of the protons,
- and a set of Timing counters to measure their arrival time with a precision of the order of 10 ps.

2 new horizontal pots (only 1 during LS1)

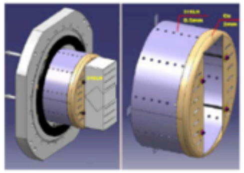


Cylindrical RP for timing detectors



2015-2019

horizontal pots at 203 m and 214 m equipped with **Faraday cages** (RF shields)

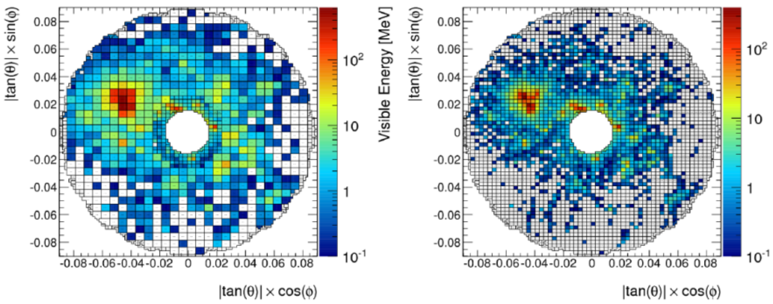


ATLAS Calorimeter Upgrade

PHASE 2 UPGRADES

Fcal -> sFCal upgrade (3.2 < η < 4.9)

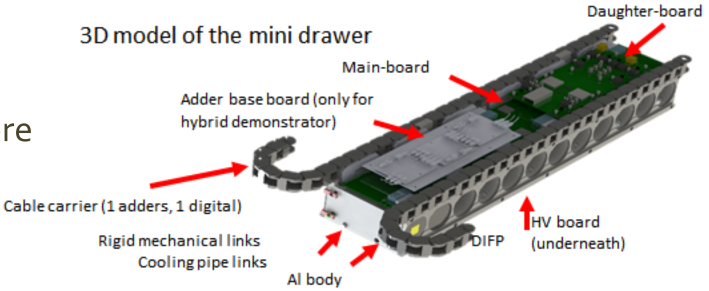
- Higher granularity=> lower pileup noise



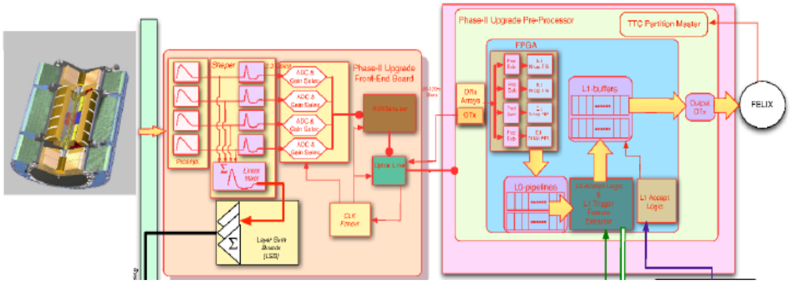
EM and Hadronic calorimeter don't require upgrade

Replace TileCal and LAr electronics in LS3

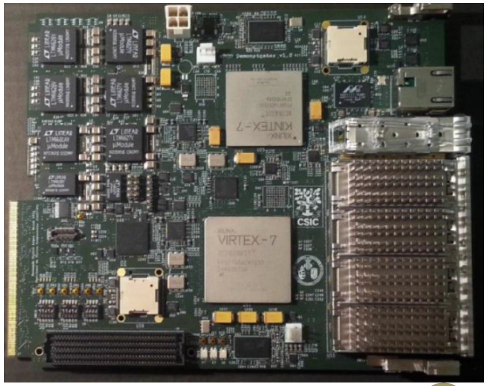
- Replacement due to ageing and radiation tolerance
- Limited on-detector pipelines prevent application of more advanced trigger algorithms
- On-detector digitization of all signals at 40 MHz
- Radiation tolerant chips on detector
- ATCA/uTCA technology in the back-ends



TileCal mini drawer to host new on detector electronics



New LAr on detector, off detector and powering electronics for Phase 2



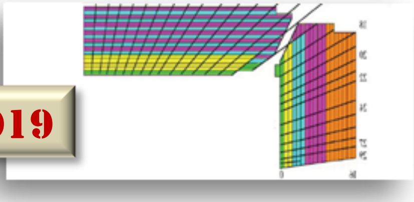
TileCal sROD Demonstrator

CMS Calorimeter Upgrade

Replacement of HCAL electronics < 2019

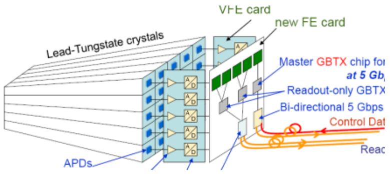
- Replacement of photosensors , on detector and off detector electronics
- Reduce noise, increase depth segmentation and allow timing measurement

<2019



Replacement of ECAL barrel electronics in LS3

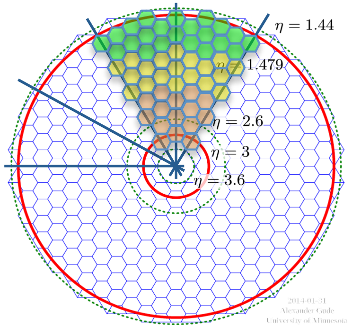
- to accommodate to higher trigger rates and latency
- Implement a 40 MHz continuous read-out



PHASE 2 UPGRADES

New ENDCAP Calorimeter in LS3

- Cannot survive radiation environment
- Silicon based calorimeter for the forwards region.
- Benefiting from CALICE collaboration R&D

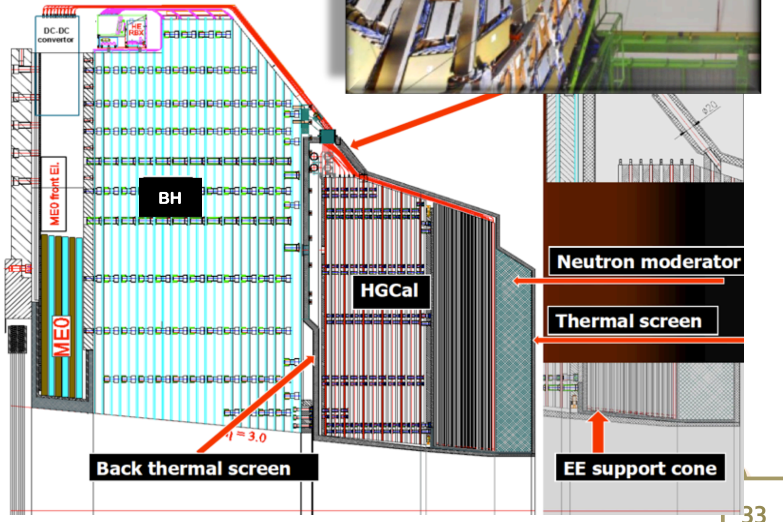


HGCAL: High Granularity Calorimeter with 4D (space-time) shower measurement

- Electromagnetic section (26 X_0, 1.5λ): 28 layers of Silicon-W/Cu absorber
- Front Hadronic section (3.5 λ): 12 layers of Silicon/Brass or Stainless Steel

Back Hadronic Calo. (BH) similar as present HE - radiation tol. - granularity ≃ x4

- BH (5 λ): 12 layers of Scintillator/Brass or Stainless Steel (2 depths readout)



ATLAS Muon Upgrade

Existing detectors are expected to cope with HL-LHC radiation and luminosity though much of the electronics will be replaced.
Weakest parts will be extended.

New Small Wheel (NSW)

IN 2019

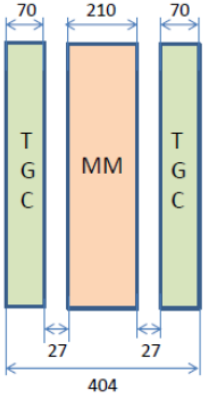
Innermost muon endcap stations |η| >1.3

- **Micromegas** (precision) **& sTGC** (trigger and bunch id) :
  - precision and trigger.
  - Improve pointing , reject fake muons and control rates.
- First large system based on Micromegas (1200 m^2)
- Spatial resolution < 100 µm

Replacement of all muon electronics for Phase 2

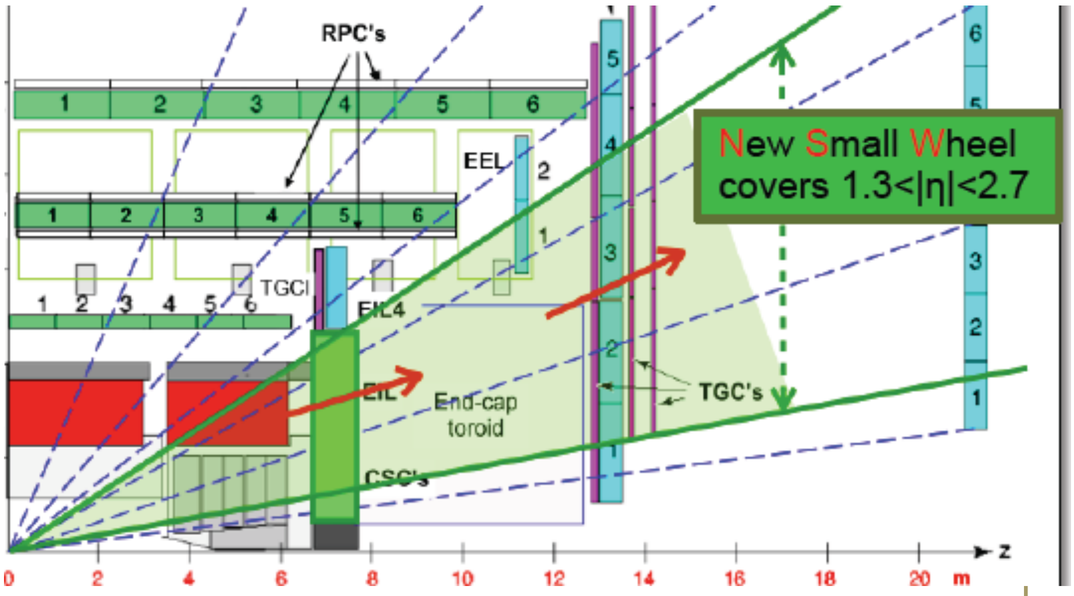
PHASE 2 UPGRADE

- Under study to eliminate limits on the L1 trigger rate and L1 latency. **=> One layer of trigger**
- It could provide the possibility to add RPCs on the innermost layer and allows the use of an RPC-seeded MDT trigger in L0 => sharper p_t thresholds.



Sketch of chamber

MDT -> sMDT

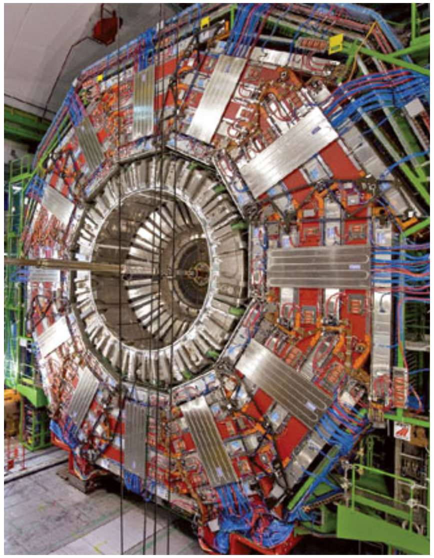


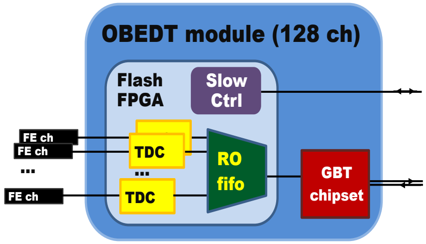
CMS Muon Upgrade

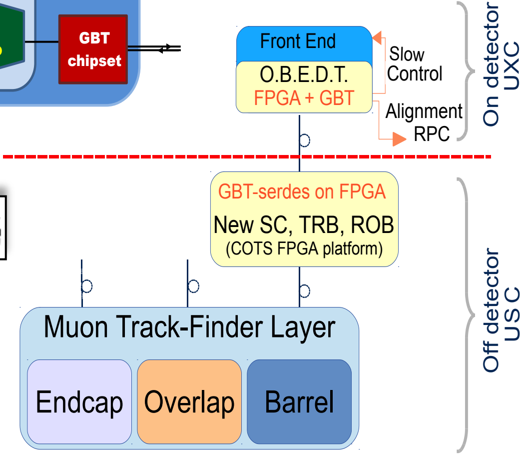
PHASE 2 UPGRADES

New DT on detector electronics (Minicrates)

- Replace all on and off detector electronics
- Implement a 40 MHz continuous readout
- Eliminates bandwidth and latency restrictions
- Improve trigger primitives with offline resolution

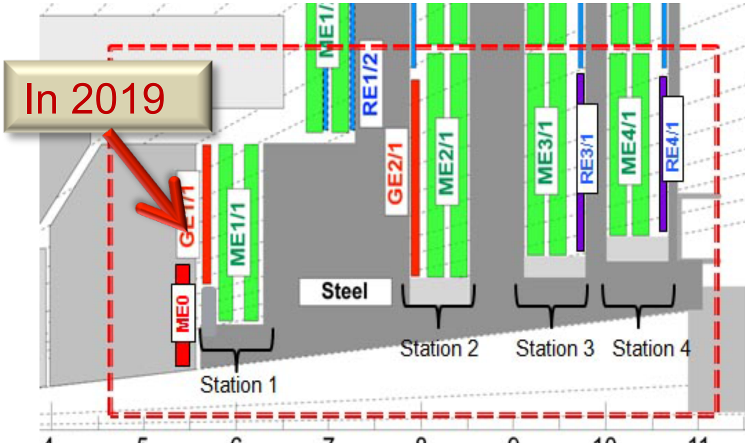


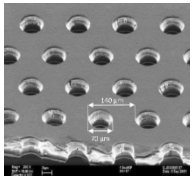



Front End
O.B.E.D.T.
FPGA + GBT
Slow Control
Alignment RPC
On detector UXC
GBT-serdes on FPGA
New SC, TRB, ROB
(COTS FPGA platform)
Off detector USC
Muon Track-Finder Layer
Endcap
Overlap
Barrel

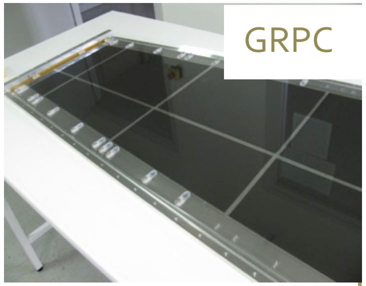
- **New chambers to complete forward region** at 1.6 < η < 2.4 region
  - Pair of triple GEMs in 2 first stations - high rate, and resolution for L1-trigger
  - iRPC in stations 3 and 4 - high rate, and timing resolution to reject background
- **CSC readout replacement**
- **ME0. Coverage up to η = 3**
  - 6 triple GEMs (ME0) for μ-tagging

In 2019





GEM detectors



GRPC

CMS Muon Upgrade

PHASE 2 UPGRADES

New DT on detector electronics (Minicrates)

- Replace all on and off detector electronics
- Implement a 40 MHz continuous readout
- Eliminates bandwidth and latency restrictions

- **New chambers to complete forward region** at 1.6 < η < 2.4 region
  - Pair of triple GEMs in 2 first stations - high rate, and resolution for L1-trigger
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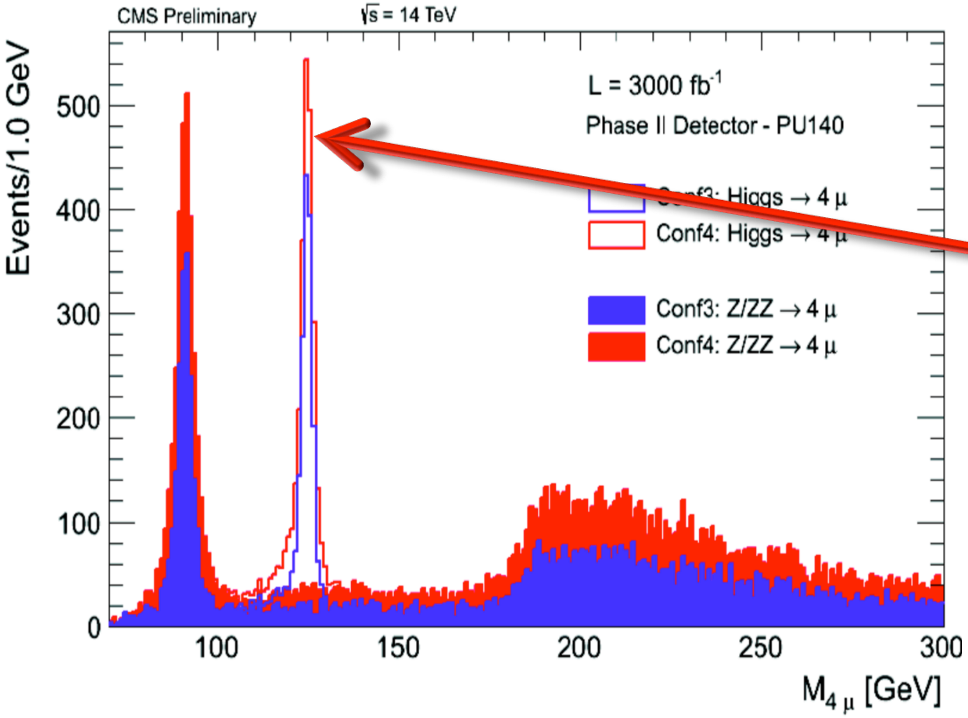
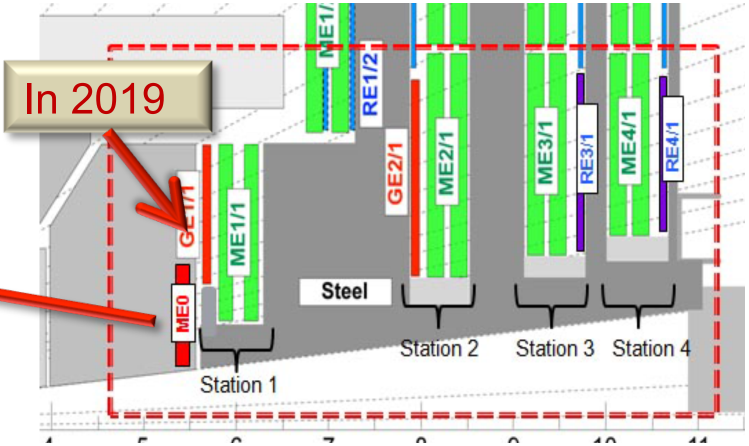




H→ZZ (4μ) without with ME0

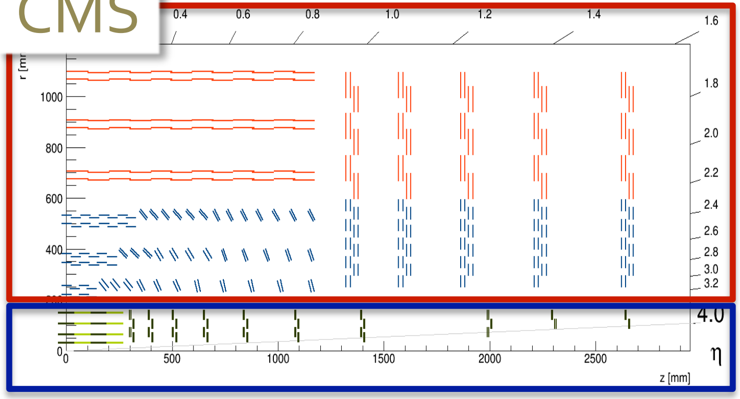
ATLAS and CMS Tracker Upgrade

PHASE 2 UPGRADES

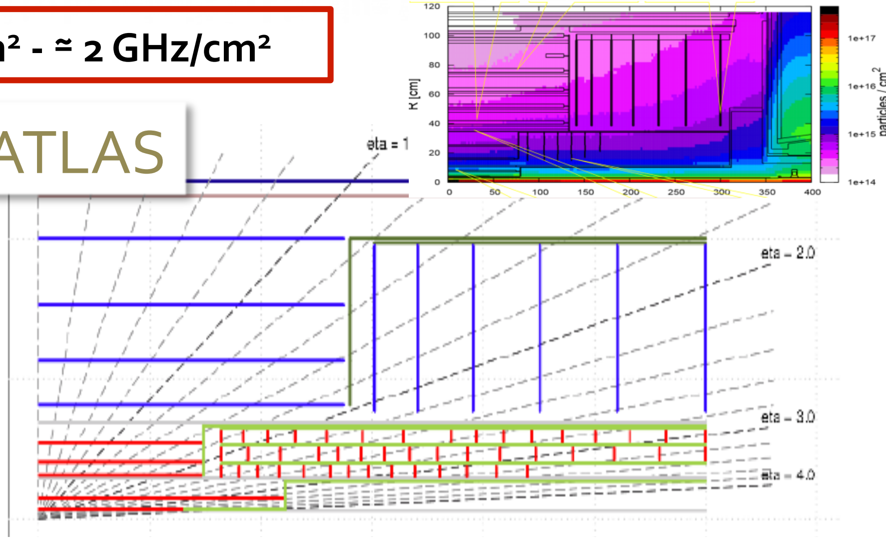
Tracker (and pixel) of both ATLAS and CMS need to be rebuilt in LS3 due to radiation damage

≃ 1 Grad - ≃ 2 x 10^{16} neq/cm^2 - ≃ 2 GHz/cm^2

CMS



ATLAS



CMS Pixel	4.6 m^2	4 layers (B) + 10 disks (E)
CMS Outer	220 m^2	6 layers (B) + 5 disks (E)

ATLAS Pixel	8.2 m^2	4 layers (B) + 6 disks (E)
ATLAS Strip	193 m^2	5 layers (B) + 7 disks (E)

- **More radiation tolerant**
- **Higher Granularity:**
  - 4 to 6 times present Trackers
  - Improved tracking reconstruction efficiency, transverse momentum and impact parameter resolution (higher granularity)
- **Lightness:**
  - Minimize inactive material requires new technologies: DC-DC and serial electronics powering, new CO2 cooling, new materials, etc

IMFP16
4-8 April 2016
Madrid

"LHC Upgrades (ATLAS, CMS, LHCb)"

Cristina Fdez. Bedoya

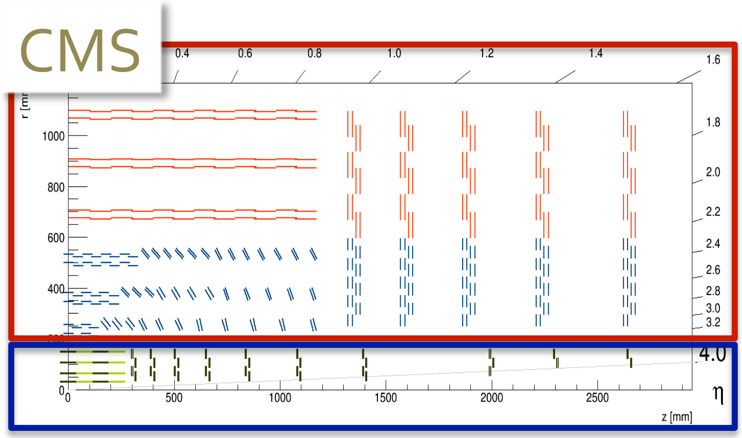
ATLAS and CMS Tracker Upgrade

PHASE 2 UPGRADES

Tracker (and pixel) of both ATLAS and CMS need to be rebuilt in LS3 due to radiation damage

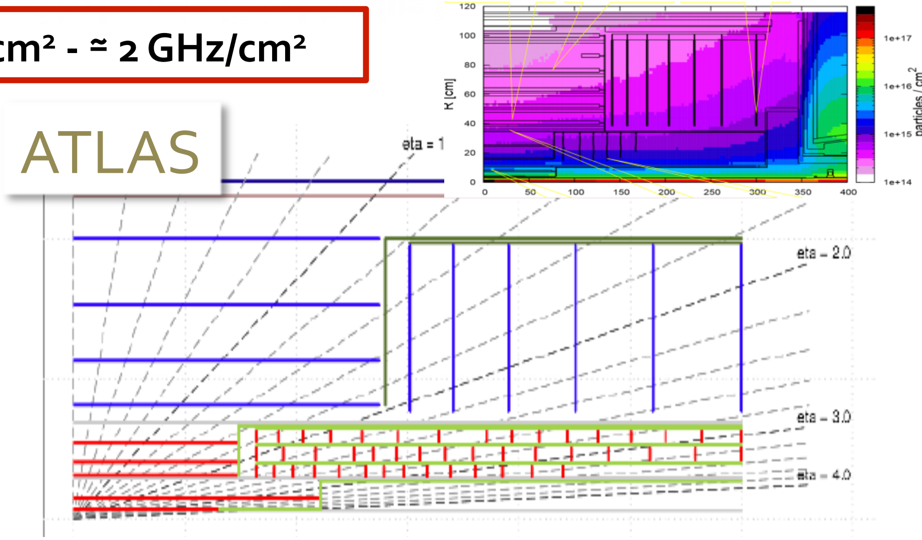
≃ 1 Grad - ≃ 2 x 10^{16} neq/cm² - ≃ 2 GHz/cm²

CMS



CMS Pixel	4.6 m²	4 layers (B) + 10 disks (E)
CMS Outer	220 m²	6 layers (B) + 5 disks (E)

ATLAS



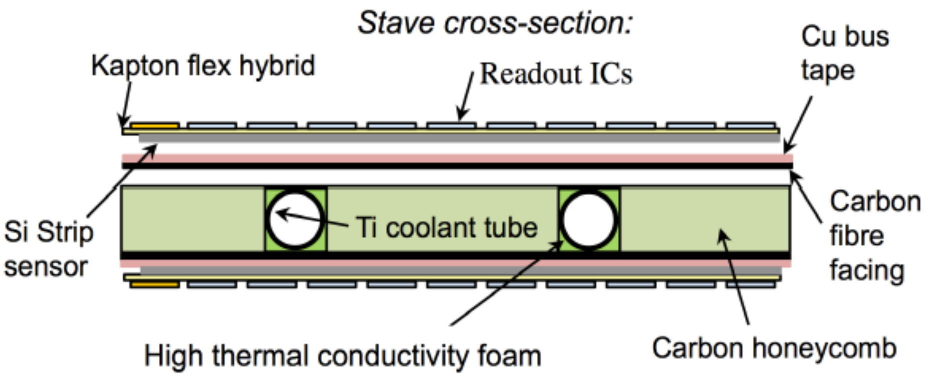
ATLAS Pixel	8.2 m²	4 layers (B) + 6 disks (E)
ATLAS Strip	193 m²	5 layers (B) + 7 disks (E)

- **Include tracking information in the hardware trigger:**
  - Improves lepton energy assignment and isolation, allows association to vertex for PU rejection and multi object triggers
  - Required to maintain low energy trigger thresholds
  - Different designs in ATLAS and CMS
- **Extension of coverage from η ≃ 2.4 to η ≃ 4**
  - Better matching with calorimeter coverage to improve Jet ID and MET tails and resolution, crucial for VBF and VBS jet tagging

EXCELENCIA MARÍA DE MAEZTU

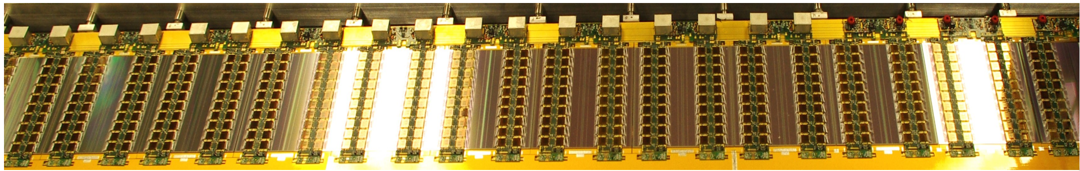
Ciemat

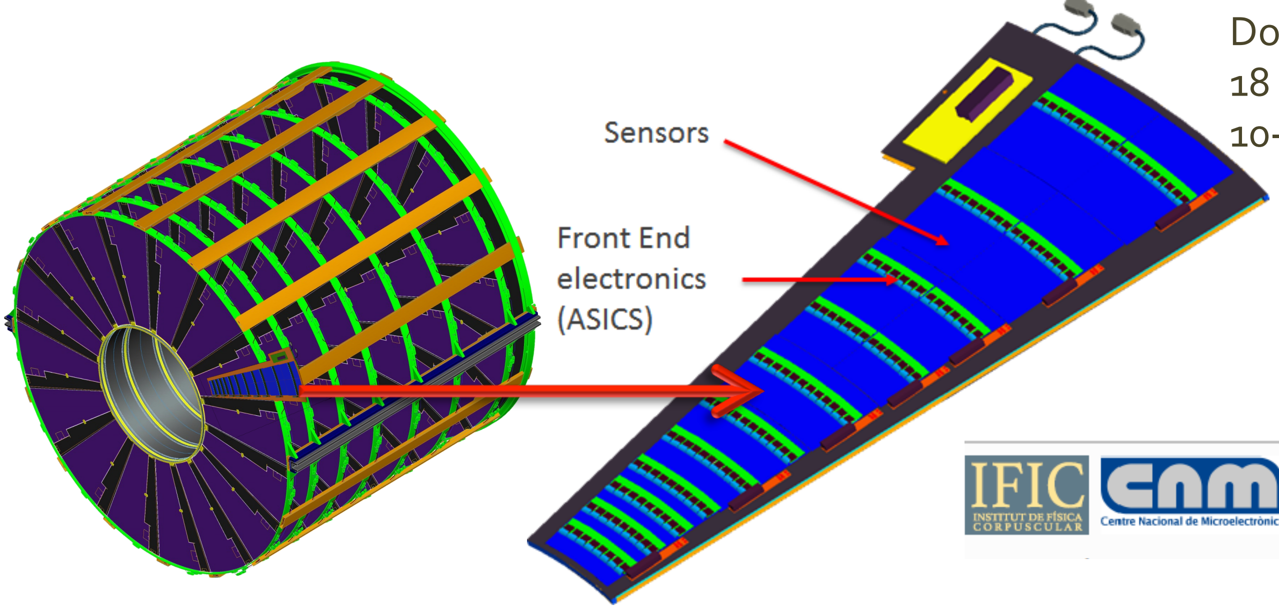
ATLAS Tracker Upgrade



- **Based on Supermodules:** a carbon fiber sandwich with integrated cooling and electronics
- **2 barrel module and 9 endcap modules types**
- Inclined sensors layouts also under study

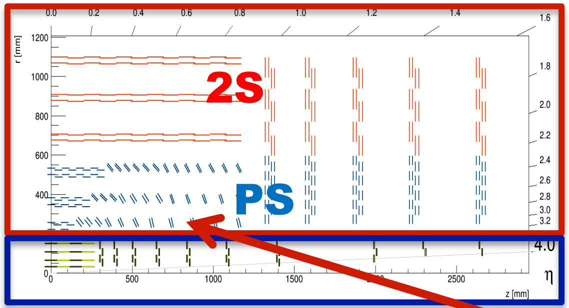
A 12 module long barrel stave.

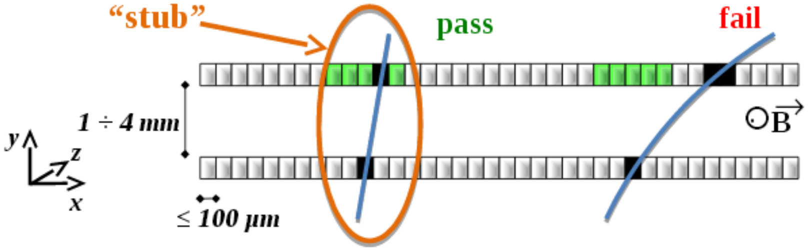




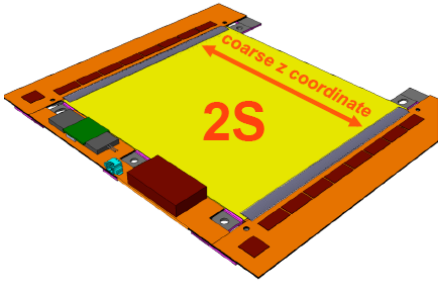
Petals (Endcap)
Double sided object with 18 sensors, 70cm height, 10-20cm width

CMS Tracker Upgrade



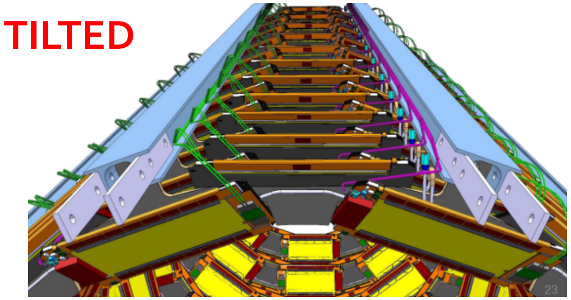


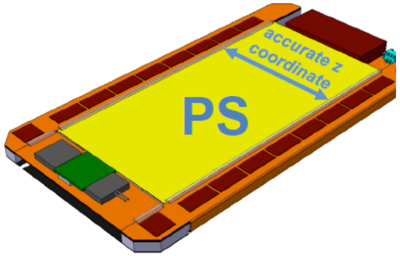
- Measure bending of particles in high B-field
- Threshold of ~ 2 GeV/c data reduction of ~ one order of magnitude



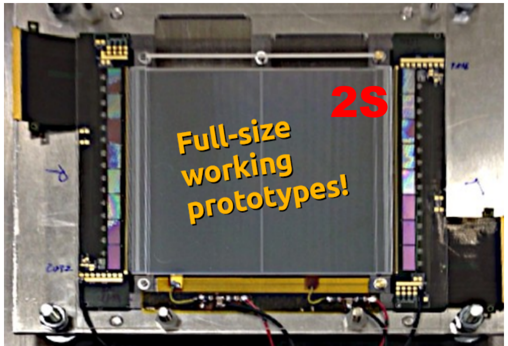
2 Strip sensors
2×1016 Strips: ~ 5 cm × 90 µm
2×1016 Strips: ~ 5 cm × 90 µm
P ~ 5 W
~ 2× 90 cm^2 active area
For r > 60 cm
Spacing 1.8 mm and 4.0 mm

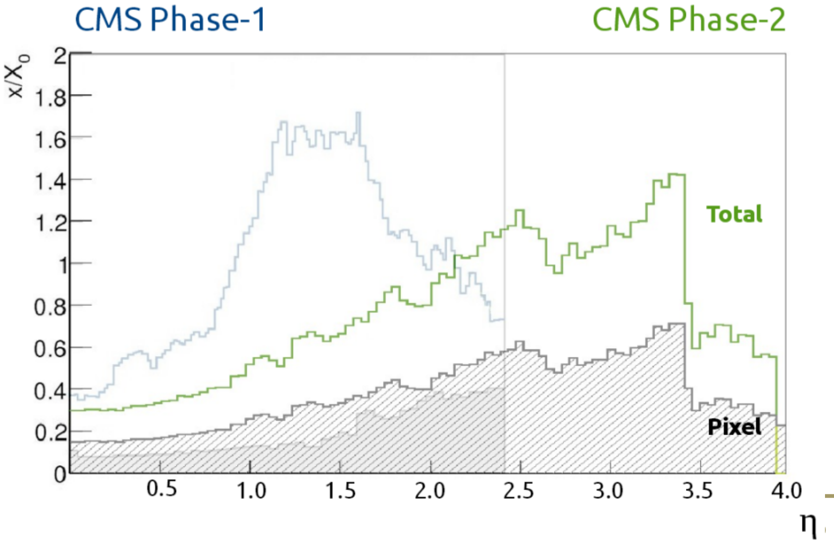
TILTED





Pixel + Strip sensors
2×960 Strips: ~ 2.5 cm × 100 µm
32×960 Pixels: ~ 1.4 mm × 100 µm
P ~ 7 W
~ 2× 45 cm^2 active area
For r > 20 cm
Spacing 1.6 mm, 2.6 mm and 4.0 mm





ATLAS and CMS Pixel Upgrade

PHASE 2 UPGRADES

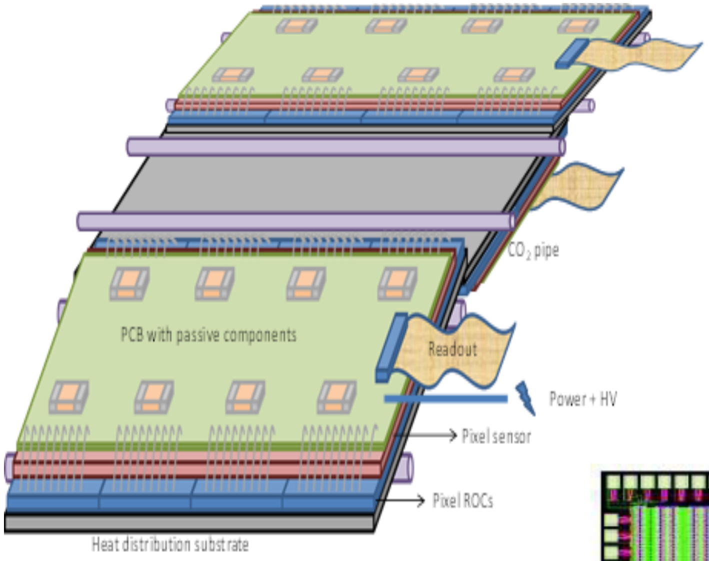
Requirements Need to cope with extremely high hit rates 2 GHz/cm² and extreme radiation tolerance: 2 x 10^{16} neq/cm² , 1Grad (10years)

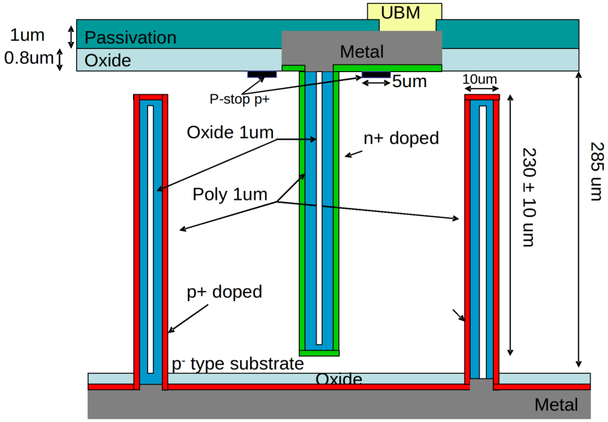
Pixel layouts under definition with **extended forward coverage**

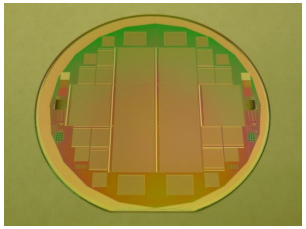
Pixel sensor: Planar and possibly 3D sensors

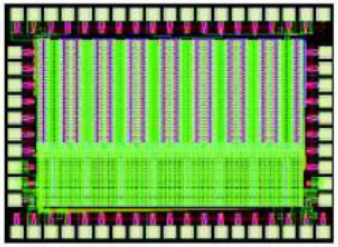
Low mass -> Low power, "exotic" powering system (serial powering)

Common ATLAS+CMS development of **Readout chip in RD53 collaboration**

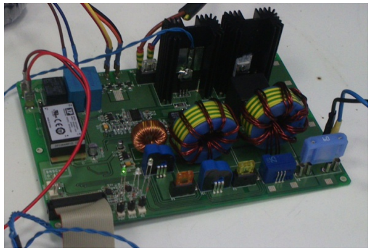








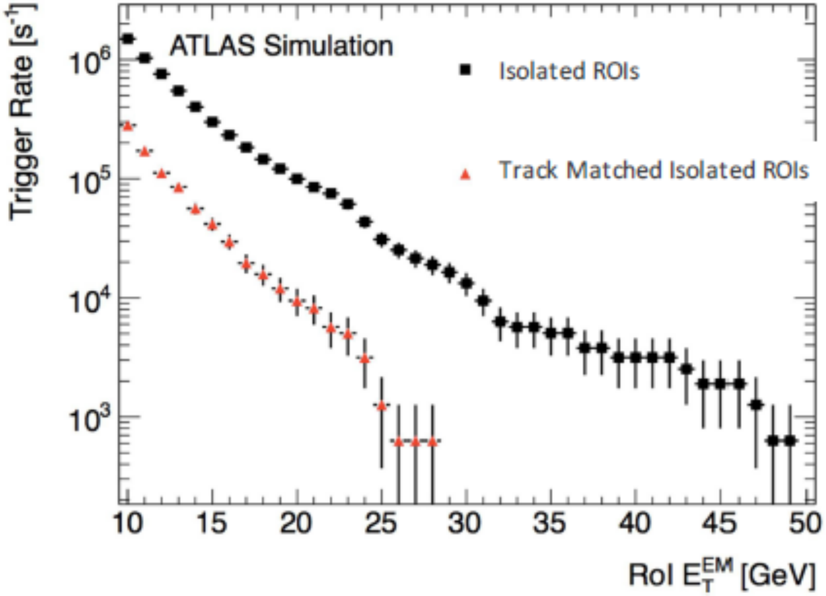
RD53: Test chip in 65nm



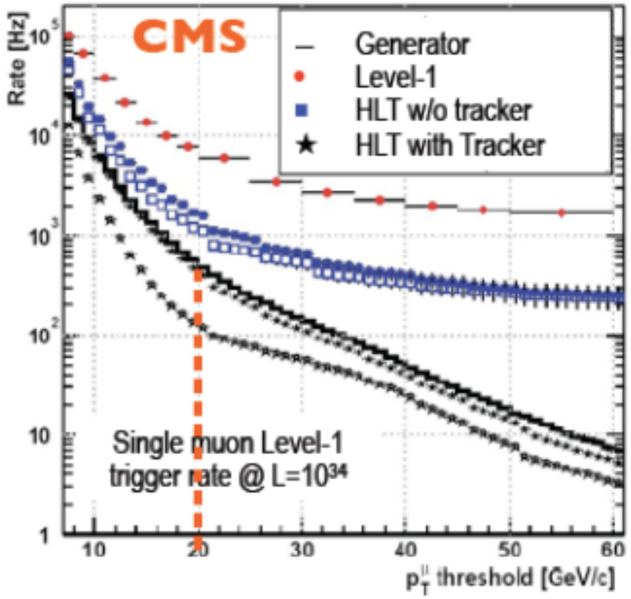
IFCA
Instituto de Física de Cantabria
CNM
Centro Nacional de Microelectrónica CSIC
ITAINNOVA

ATLAS and CMS Track Trigger

- Physics program requires low p_T lepton thresholds similar to Run 1 to get max. benefit from the 3000 fb^{-1}.
- Hardware trigger rates for desired physics come in at around 1 MHz:
  - Setting thresholds to keep total rate to 100 kHz incompatible with physics aims for single leptons would imply 32 GeV electron and 40 GeV muon
- Improvements in L1 Calo and Muon systems not sufficient for achieving manageable rates with acceptable physics.
- **Match tracking information to muon and calorimeter information.**



Single electron trigger rate
@ 1E34 for $\langle\mu\rangle \sim 140$



Single muon trigger rate
@ 1E34 for $\langle\mu\rangle \sim 140$

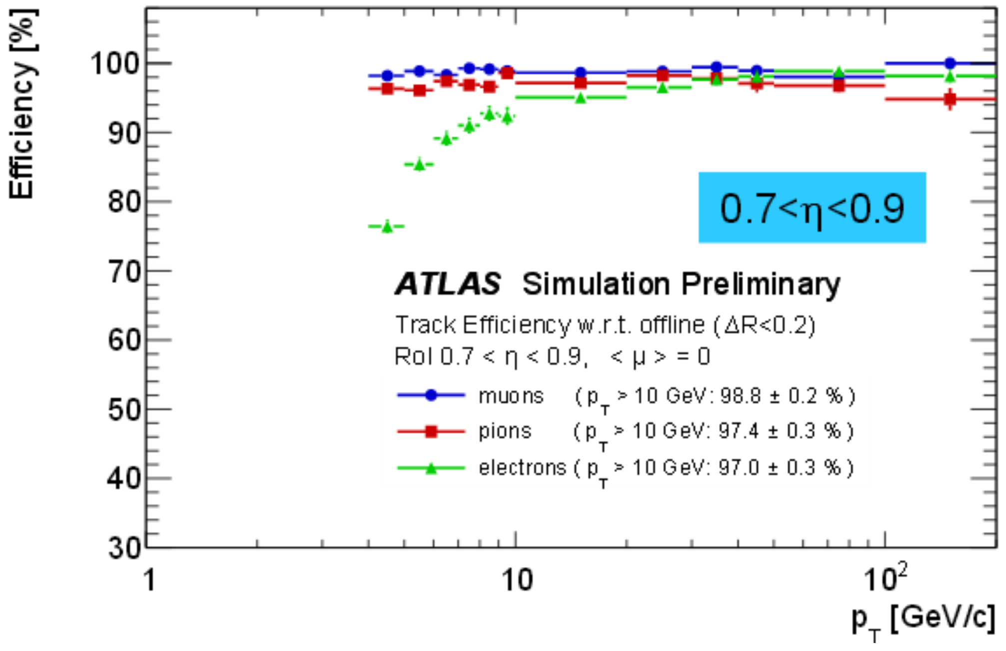
ATLAS Track Trigger

Tracker region of interest selected by Calo/Muon and sent to the trigger.

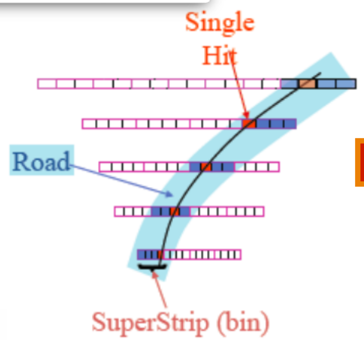
Select tracks above 4 GeV.

Two hardware trigger Levels:

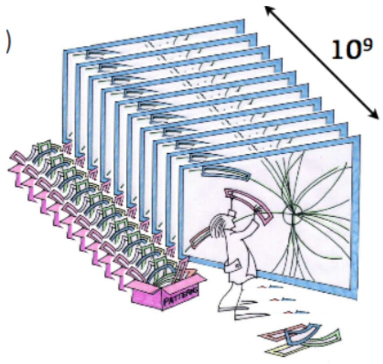
- Level- 0 (Calo+Muon): 1 MHz accept rate, trigger latency 6 μs
- Level – 1 (+ROI Tracker): 400 kHz accept rate, trigger latency 30 μs



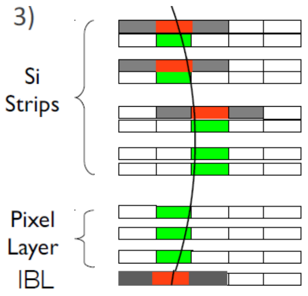
1 MHz Data from Region of Interest (max 10% iTk).



Create hits from clusters in "super strips".



Custom associative memory chips are used to compare hits to O(10^9) patterns simultaneously



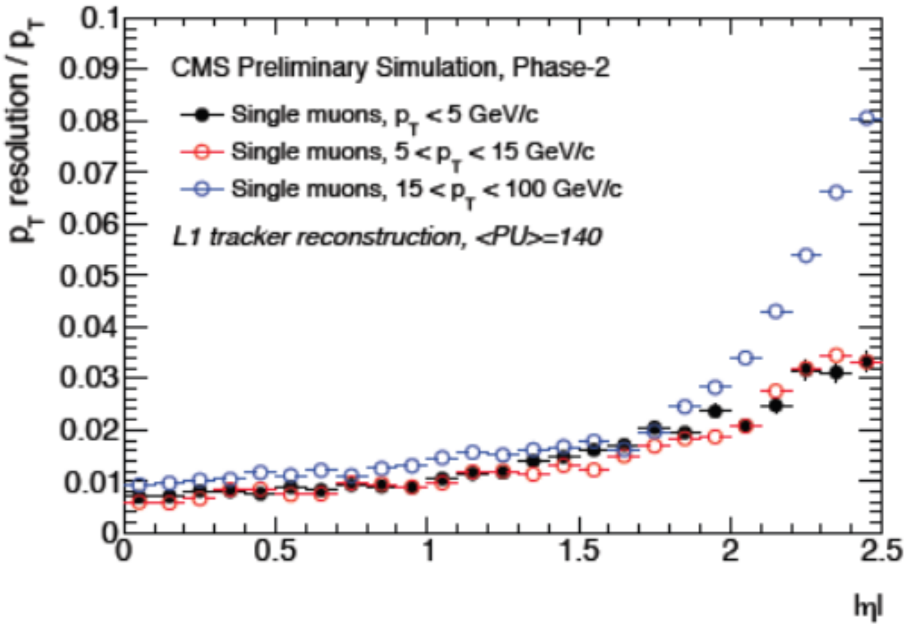
Linearized track fitting (FPGA) Good tracks are sent to next trigger level

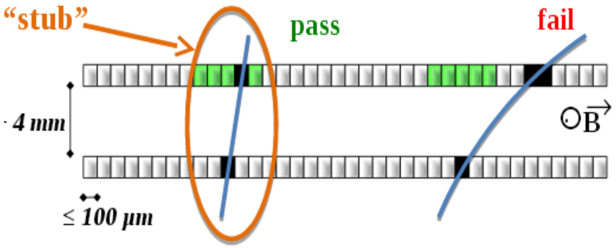
Tracks to L1Global

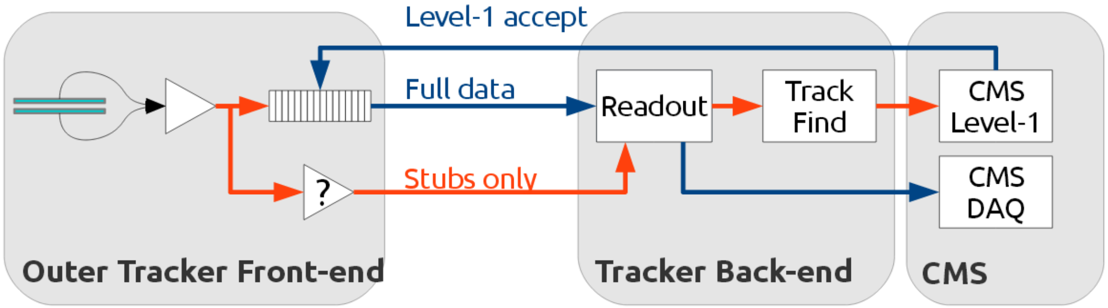
CMS Track Trigger

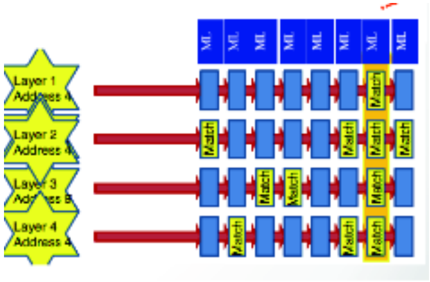
- Only one level of HW trigger (Track Trigger, finer granularity μ & calo.)
- Filtering through Tracker p_t modules to bring off-detector only hits with p_t>2 GeV
- Stubs readout at 40MHz and sent to the L1 Track Trigger electronics.

40 MHz Readout
750 kHz CMS Level-1 trigger

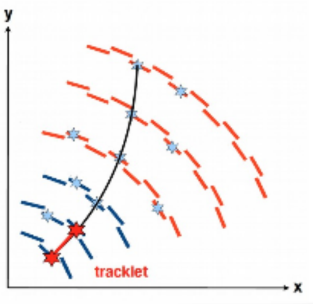




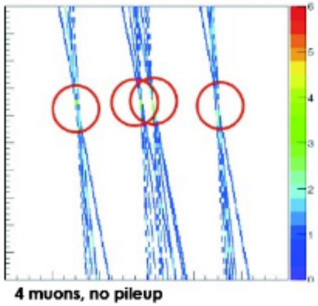

Level-1 accept
Full data
Stubs only
?
Readout
Track Find
CMS Level-1
CMS DAQ
Outer Tracker Front-end
Tracker Back-end
CMS



AM+FPGA



Tracklet



TMT Hough

Track reconstruction in Back-End electronics for L1-Trigger.

Different algorithms considered.

R&D collaborations

Common initiatives that foster developments across experiments

Tracking systems:

- RD42 “Development of Diamond Tracking Detectors for HL-LHC”
- RD50 “Radiation hard semiconductor devices for very high luminosity colliders”
- “Forum on Tracking Detector Mechanics 2013”

Calorimetry

- RD52 “Dual Read-out Calorimetry”
- CALICE collaboration

Muon systems

- RD51 “Micro-Pattern Gas detectors Technologies”

Electronics

- Common Electronics Projects (GBT), ACES
- RD53 “Development of pixel readout integrated circuits for extreme rate and radiation”

Trigger/DAQ/Offline/Computing

- TDAQ teams from experiments
- PH-SFT group

Spanish participation to LHC detector upgrades

Upgrade of the ATLAS IBL Pixel
IFAE
IMB-CNM-CSIC

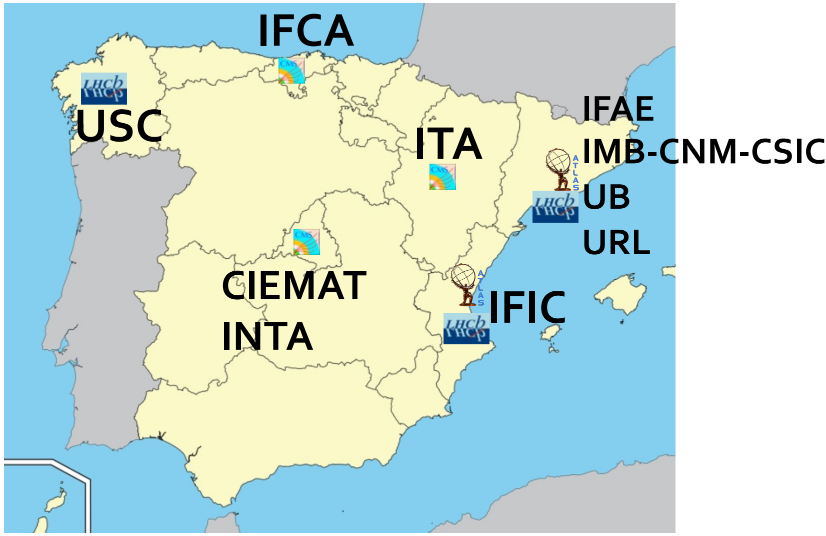
Upgrade of the AFP (forward detector silicon roman pot) at ATLAS
IFAE

Upgrade of the ATLAS forward tracker
IMB-CNM-CSIC
IFIC

Upgrade of the ATLAS TileCal
IFIC
IFAE

Upgrade of the CMS Drift Tubes
CIEMAT

Upgrade of the CMS Tracker (Pixels phase 2)
IFCA
ITA
INTA
IMB-CNM-CSIC
U. Sevilla



Upgrade of the LHCb velo
USC

Upgrade of the LHCb SciFi
UB (Universitat de Barcelona)
IFIC

Upgrade of the LHCb Calorimeter FE
UB
IFIC
URL (La Salle - Universitat Ramón Llull)

Summary

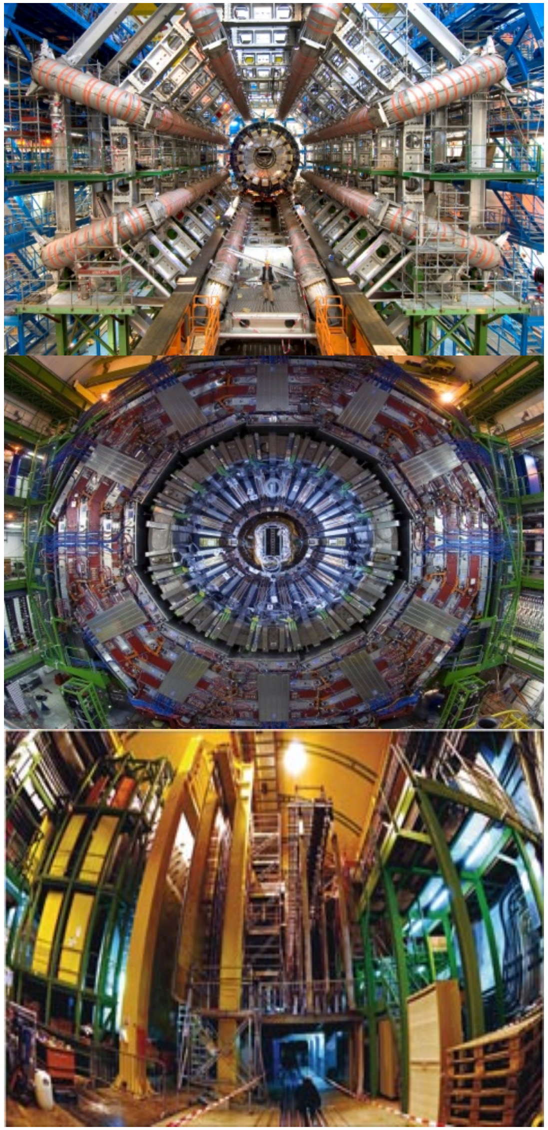
- HL-LHC may not be the cleanest but it is the existing facility where Higgs can be studied in the next years/decades

- Moreover, it has a great discovery potential for new physics

- A high luminosity proton-proton collider is a difficult environment, luminosity increase needs to be matched with better performing detectors

- Technological challenges ahead:
    - High level of radiation
    - High occupancy and pile up
    - High trigger rates

- 2024 seems to be far away but the schedule to perform de described upgrades is tight!



Thank you!

“LHC Upgrades (ATLAS, CMS, LHCb)”

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