Upgrades for High-Luminosity LHC (HL-LHC)

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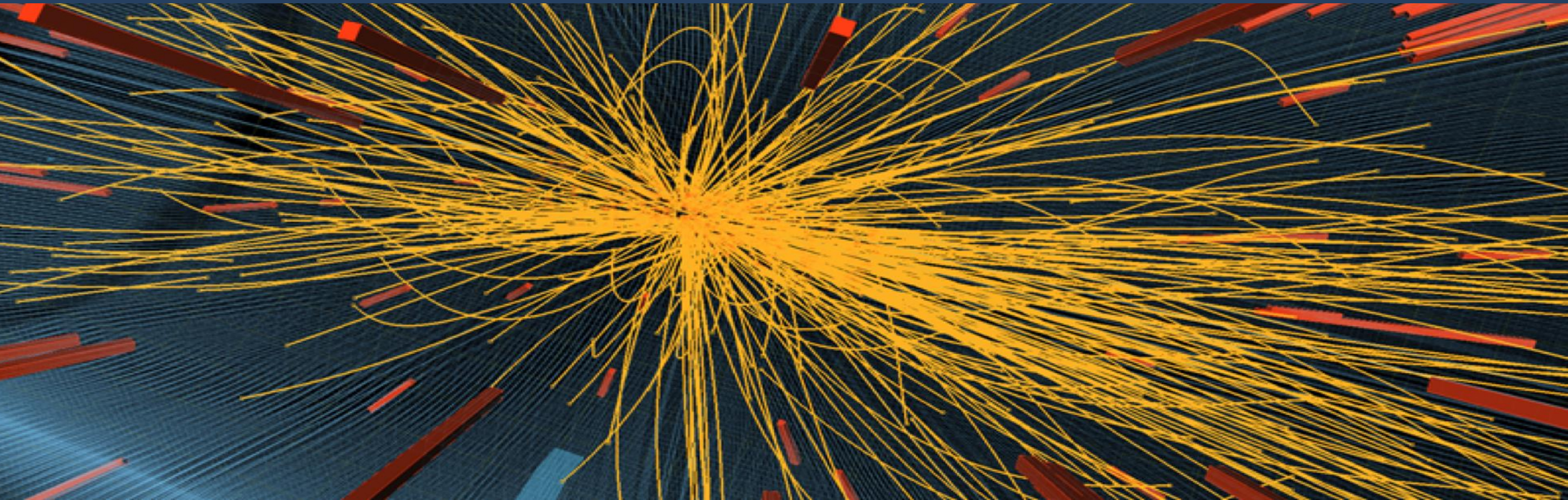
Terascale Introductory School April 2015



Outline

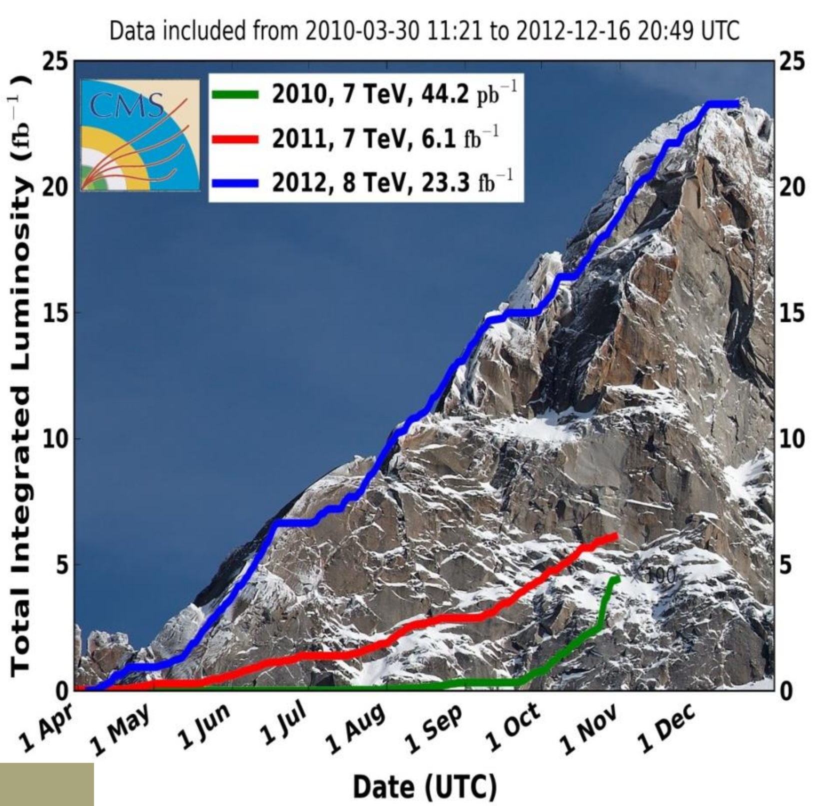
- Why an upgrade?
- Challenges of HL-LHC operation and implications for detectors
- Trigger upgrade to find the “interesting” events
- Tracker upgrades because of radiation damage
- Muon upgrades to extend acceptance and increase granularity
- Calorimeter upgrade (mainly CMS)

LHC very successful so far

Very successful up to now!
Run-1 recorded luminosity of high quality data ~25 fb^{-1}

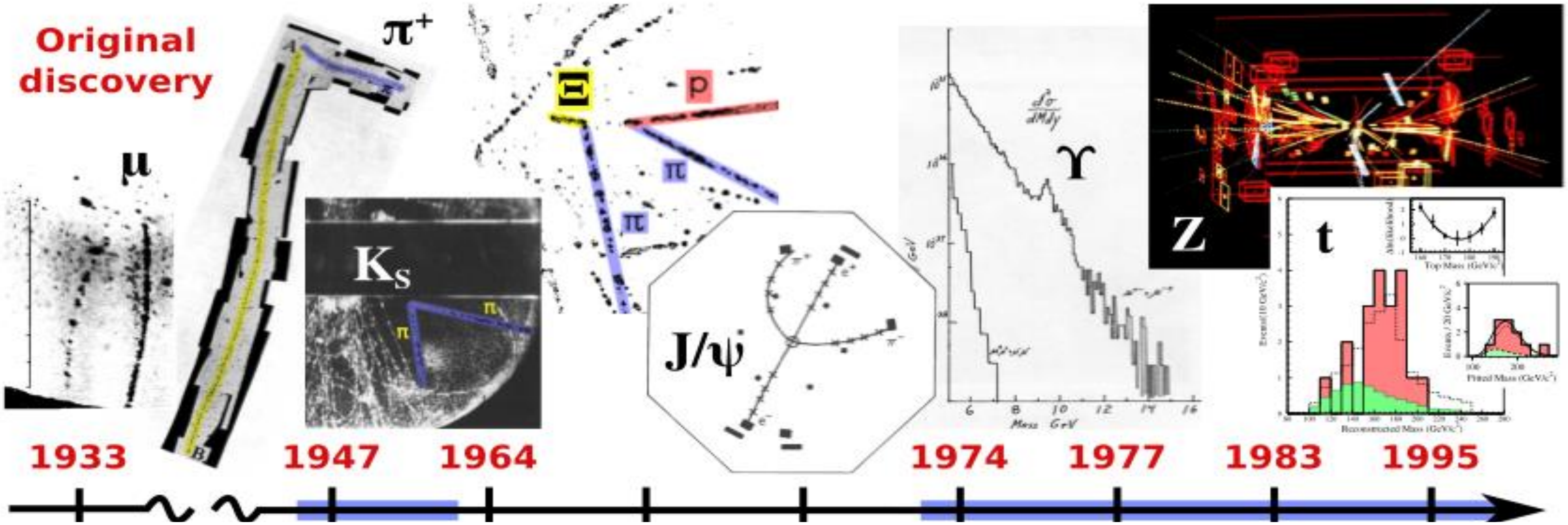
√s (LHC) = 4 x √s (Tevatron)

Published >200 papers per experiment

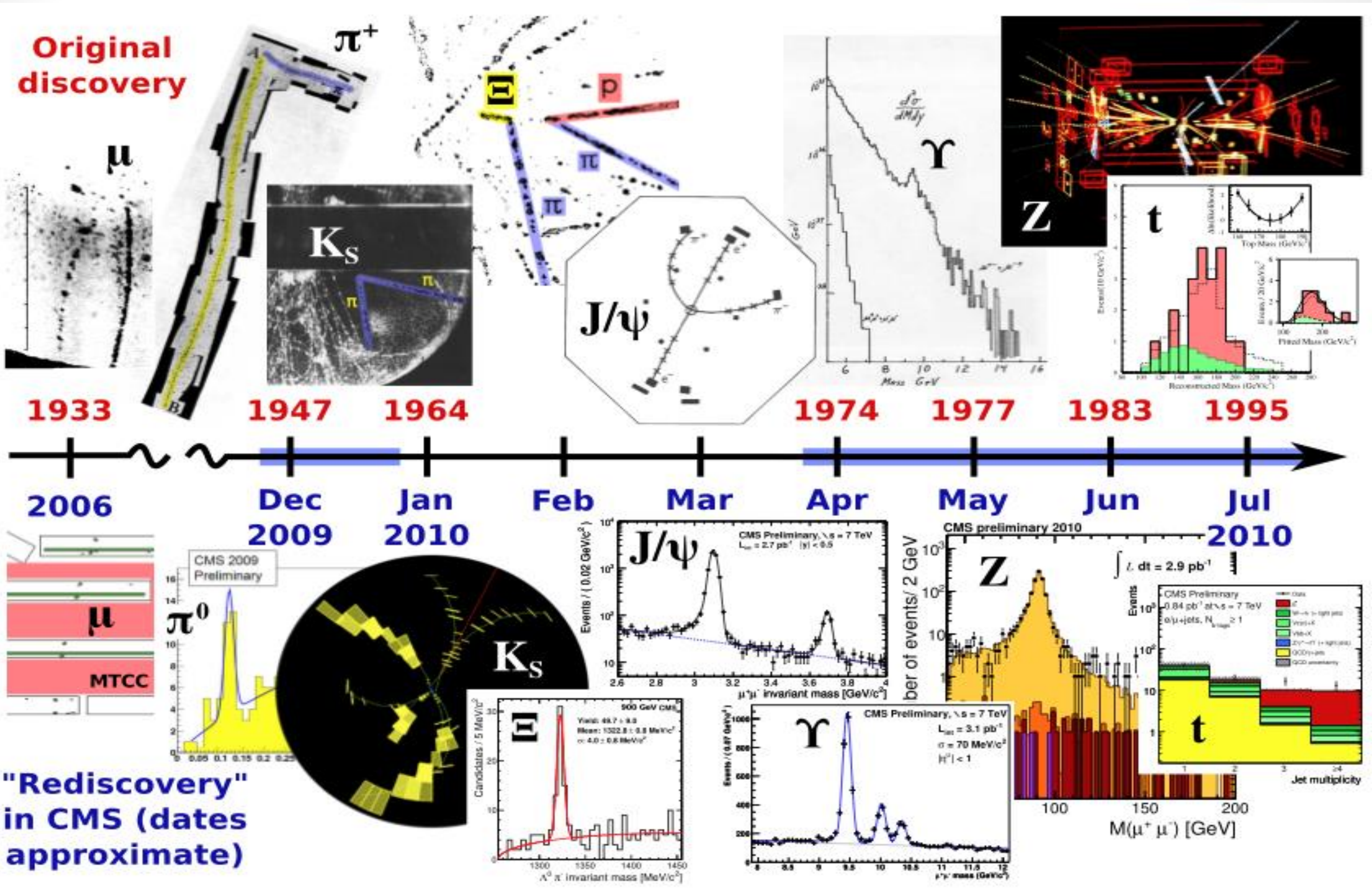


Run period	Center-of-mass	Integr. luminosity
Run-1	√s = 7 - 8 TeV	25/fb
Run-2	√s = 13 TeV	100/fb
Run-3	√s = 14 TeV	300/fb
Phase-II	√s = 14 TeV	3000/fb

At the beginning: Re-discover the Standard Model



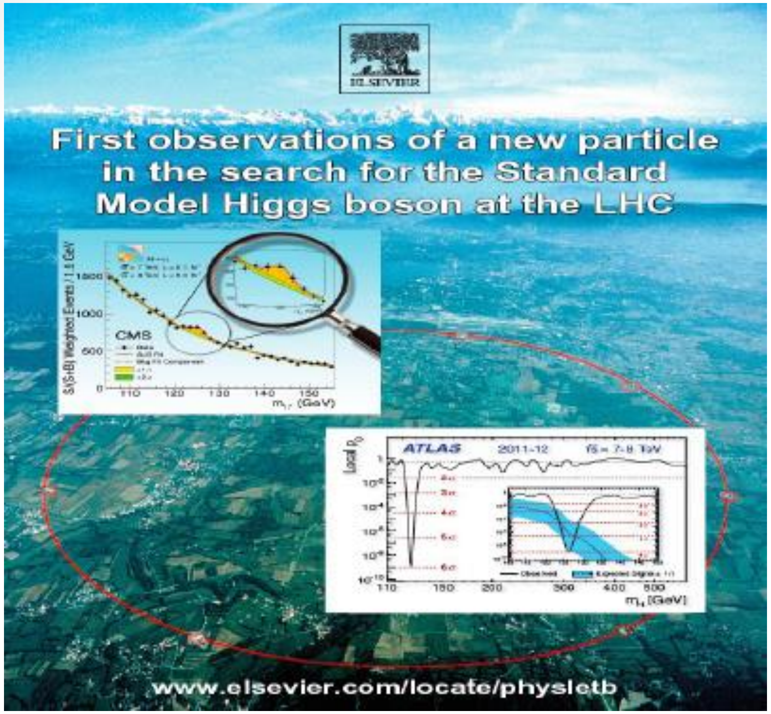
At the beginning: Re-discover the Standard Model



Many precision measurements at the LHC since then

In 2012: Discovery of the Higgs

MISSION ☺ ACCOMPLISHED!



theguardian

The Higgs boson discovery is another giant leap for humankind

Themis Bowcock

The Cern discovery of the Higgs particle is up there with putting man on the moon – something all humanity can be proud of

Wednesday 4 July 2012 12.45 BST

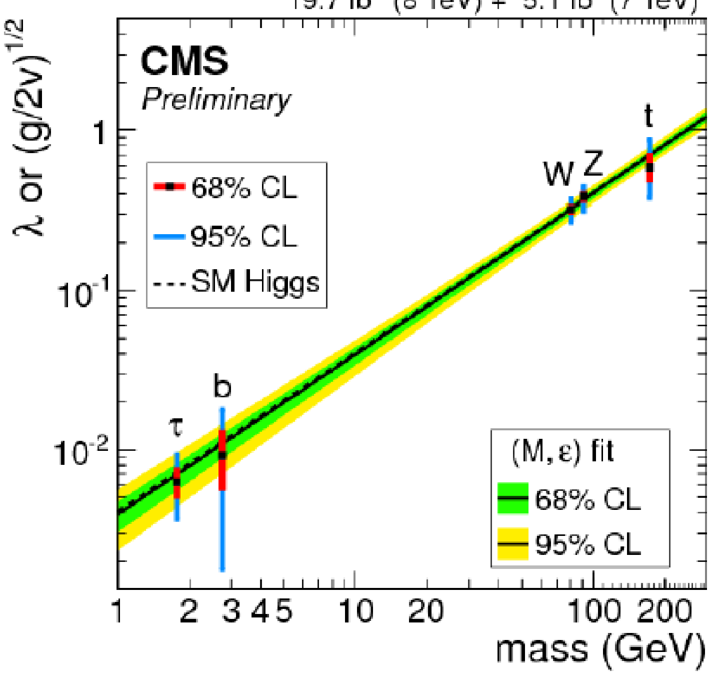
Early this morning, the physicists sat, with the media poised, waiting for two technical seminars from Cern to be delivered. There was only one question we all really wanted answered – would there be enough evidence to prove the Higgs particle had been discovered?

Higgs (BEH) boson is now firmly established

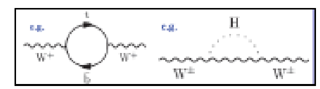
See Higgs lecture

- ✓ M_H ~ 125 GeV
- ✓ Couplings to fermions and to weak bosons (verified to ~10-30% precision) consistent with the minimal scalar sector required for the BEH mechanism
- ✓ Custodial symmetry verified (~ 15% precision) and the existence of a boson with non-universal family couplings established ($\tau\tau$ evidence + no $\mu\mu$ signal)

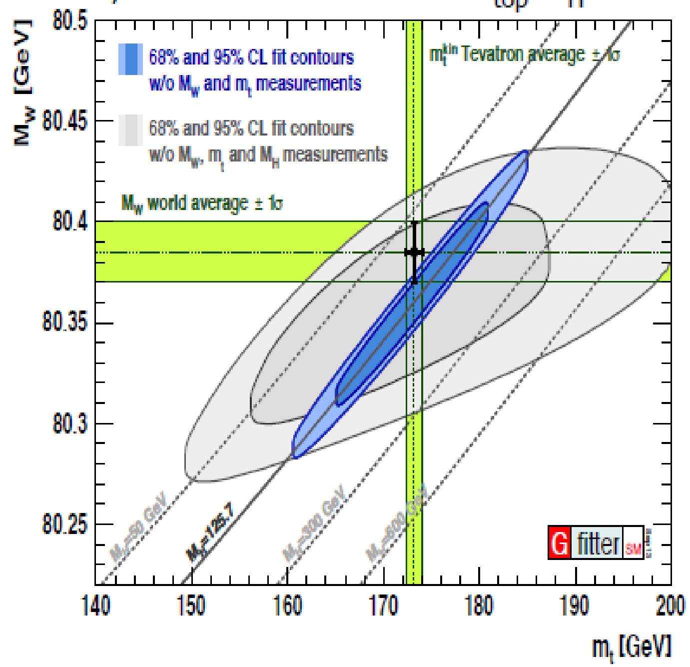
Couplings to fermions and to weak bosons
(verified to ~10-30% precision)



Rad. corrections:

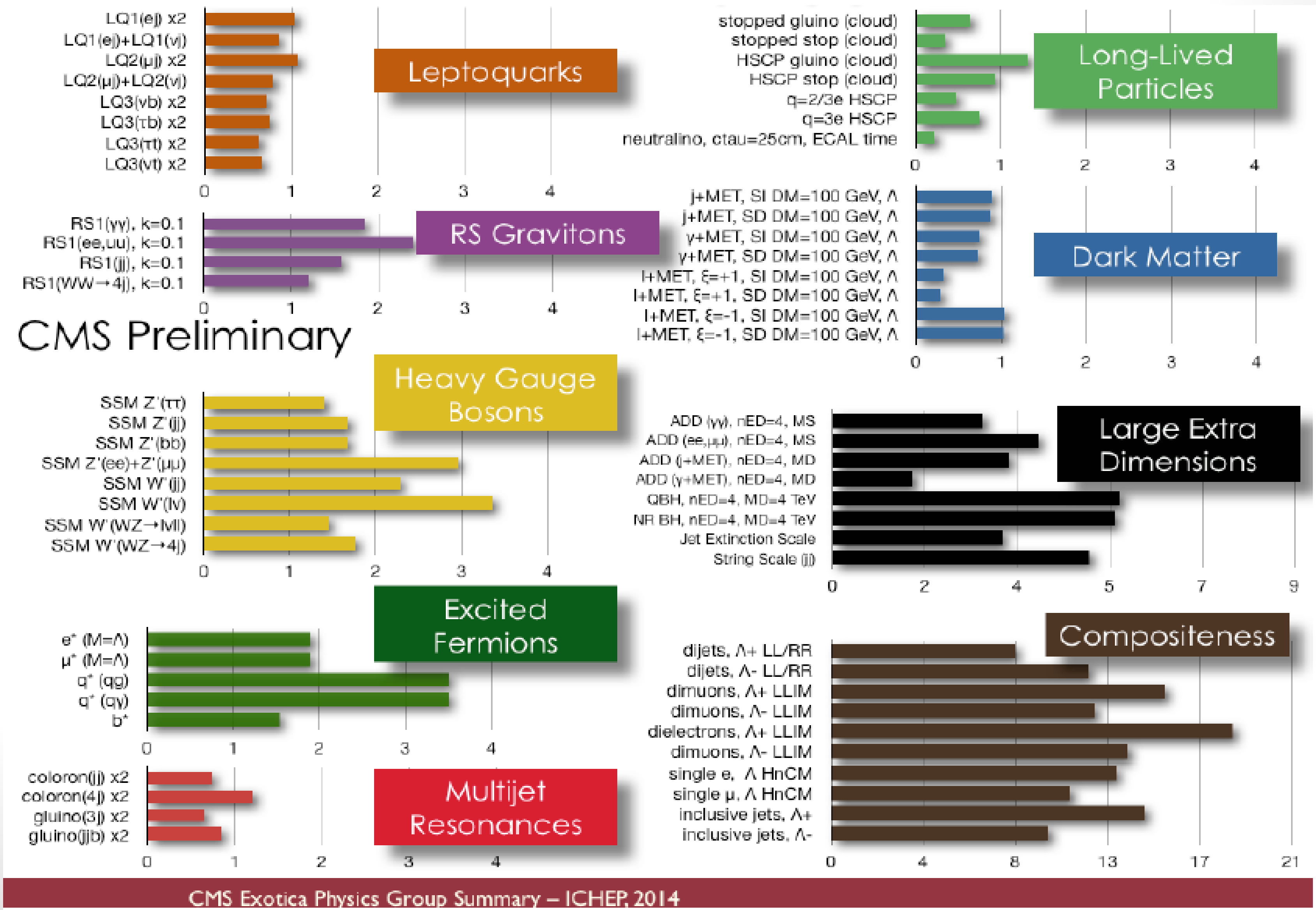


W, Z meas. sensitive to M_{top} M_H



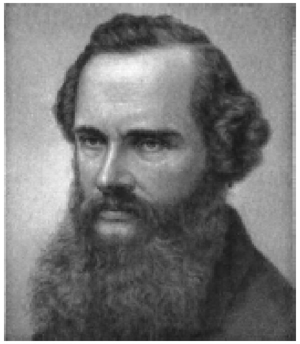
- SM-like Higgs at ~125 GeV is compatible with global EWK data at 1.3σ (p = 0.18)

Many other searches without signal, setting limits in TeV range (Example: CMS Exotica)



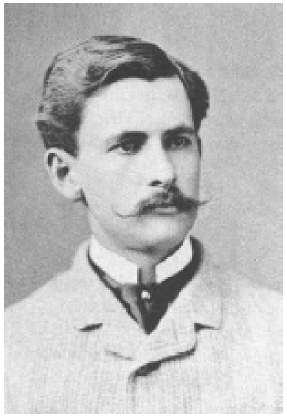
Nothing else?

An Historical Precedent ...



"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"

Lord Kelvin 1900



"The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote ..."

Albert Michelson 1903

And then there was
Relativity, Quantum Mechanics, anti-matter, cosmic microwave background, ...

Physics Beyond the Standard Model?

SM has some open questions. Many models trying to address them.
Experiments will decide which one is implemented by nature.

Guidance by theory, what to look for?
Final state allows different interpretations
Be ready also for the unexpected

Still many open questions

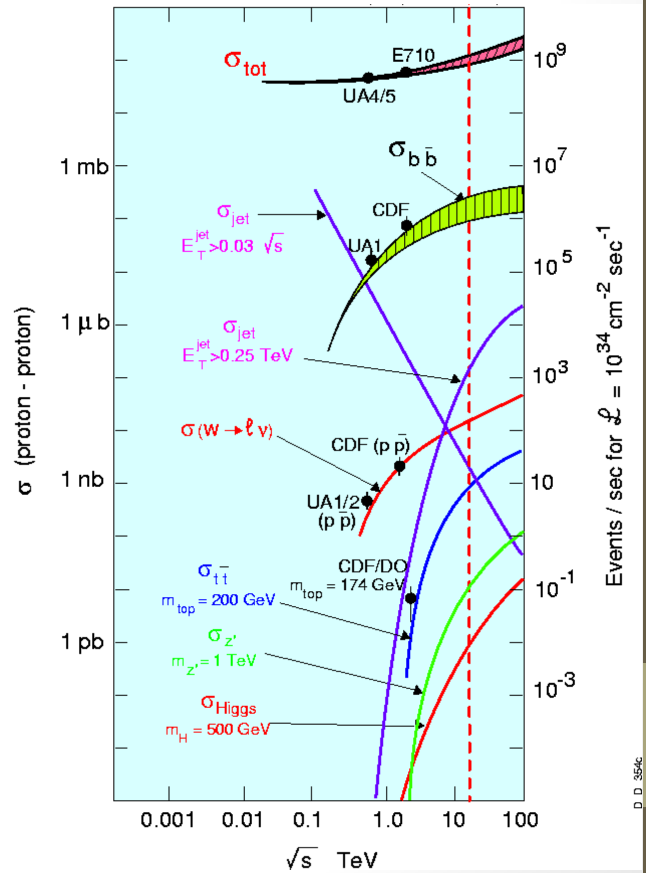
Many models tested so far address just one open question…

- **Hierarchy between EWK and Planck scale?**
- **Are there SUSY or vector-like quarks?**
- **What is the missing dark matter?**
- **Why three generations?**
- **Composite structure of particles?**
- **Others….**

Not just one golden channel to guide detector design.

LHC upgrade options:

- Increase sqrt(s)
- Increase luminosity ← chosen



Something new will have even smaller cross sections


Mission relaunched

Do we need to start already now?

Example CMS

1990 First LHC meeting (Aachen)

1997 Subsystems TDRs

2000 Detector construction started

2004 Cavern completed

2006/07 Physics TDR vol.I & II

2009 Detector completed

2010 Start LHC data taking

2012 Higgs discovery

~ 20 years

Do we need to start already now?

Example CMS

2012/13 Phase-I upgrade TDRs

2015 Phase-II upgrade TDR

20xx Completed R&D

20xx Start detector construction

2025 Start phase-II data taking

~ 10 years

2030? Discovery of dark matter

2035? Discovery of SUSY

LHC/LH-LHC Characteristics

$\sqrt{s_{pp}} = 7\text{-}8$ TeV

Phase 0

2010-2012

$$\int L\,dt \approx 25\,fb^{-1}$$

$\sqrt{s_{pp}} = 13\text{-}14$ TeV

Phase 1

2015-2022

$$\int L\,dt = 300\,fb^{-1}$$

(LS1 + LS2 ≡ consolidation and phase 1 upgrades)

Phase 2

2023-203x

$$\int L\,dt = 3000\,fb^{-1}$$

(LS3 ≡ phase 2 upgrades)

R&D on-going !!!
Installation in LS3 : 2023-2024

Luminosity $$\mathcal{L} = f \cdot k^2 \cdot \frac{n^2}{A}$$

f=frequency

k=number of bunches

n=particles/bunch

A=beam cross section

High luminosity gives access to rare processes and allows precision measurements.

Consequences of high luminosity for detectors

- → Higher rates would imply increased trigger thresholds without upgrade
- → Detector ageing
- → More bandwidth needed

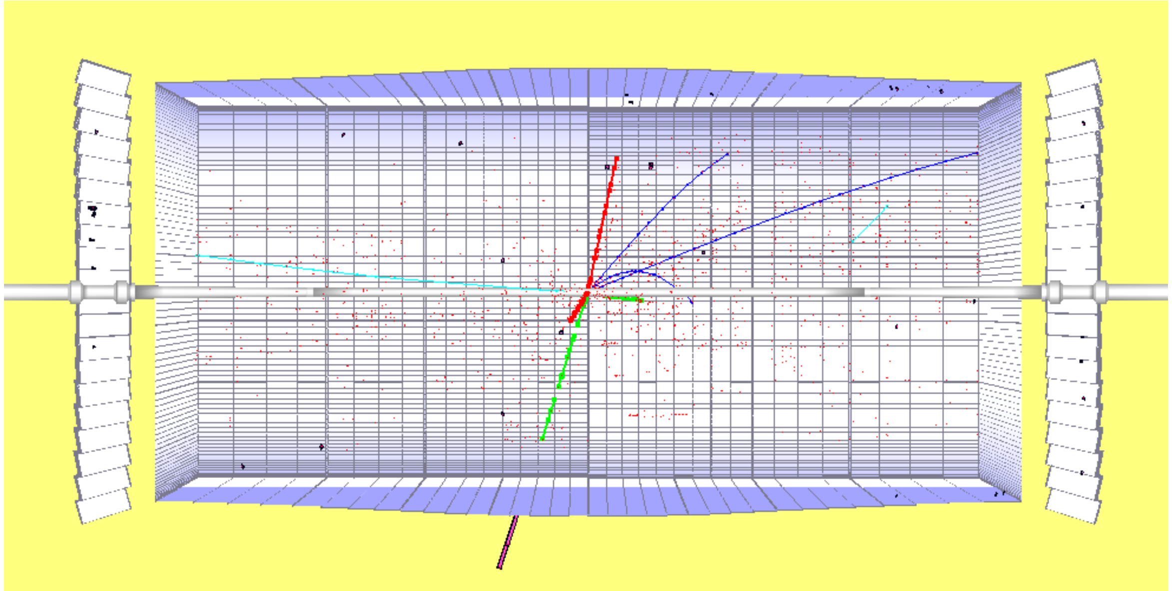
Physics requirements?

	... 2012	2013–2014 (LS 1)	2015–2017	2018–2019 (LS 2)	2020–2022	2023–2025 (LS 3)	+10 (HL-LHC)
			Phase-1	Phase-1	Phase-1		
E_{CM} [TeV]	8	(You are here)	13		13?		13?
L [$cm^{-2}\,s^{-1}$]	7×10^{33}		$\leq 2\times10^{34}$		$\leq 2.5\times10^{34}$		$\approx 5\times10^{34}$
PU	~ 21		≤ 50		≤ 70		≤ 140
∫L.dt [fb^{-1}]	~ 30		≤ 120		< 500		≤ 3000

Higher luminosity results in more pile-up (PU) in detectors.

The price to pay for HL

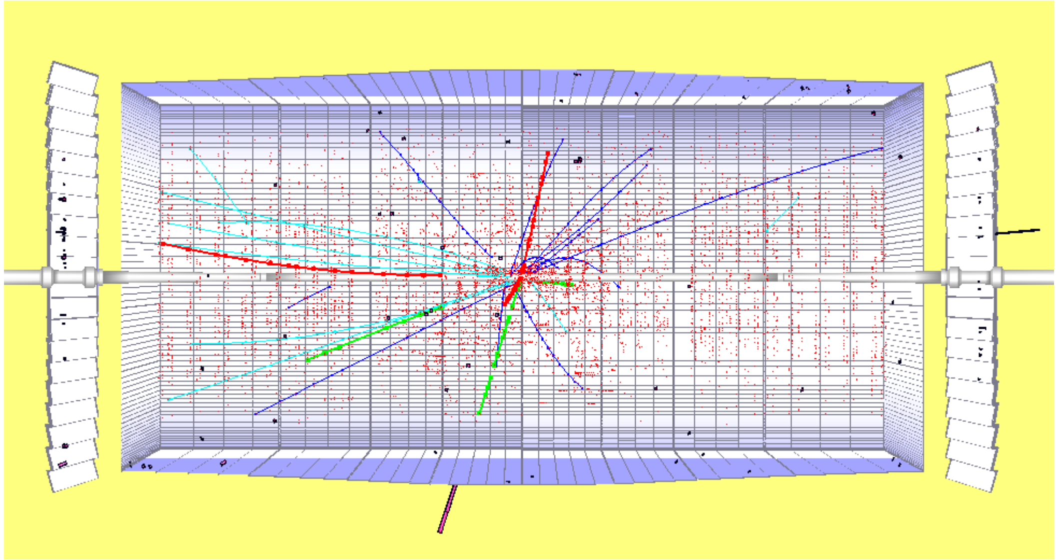
With increasing luminosity more overlapping interactions



L< 10^{32} cm^{-2}s^{-1}
~10^{1} bunches/beam
<= 1 Event/BX

The price to pay for HL

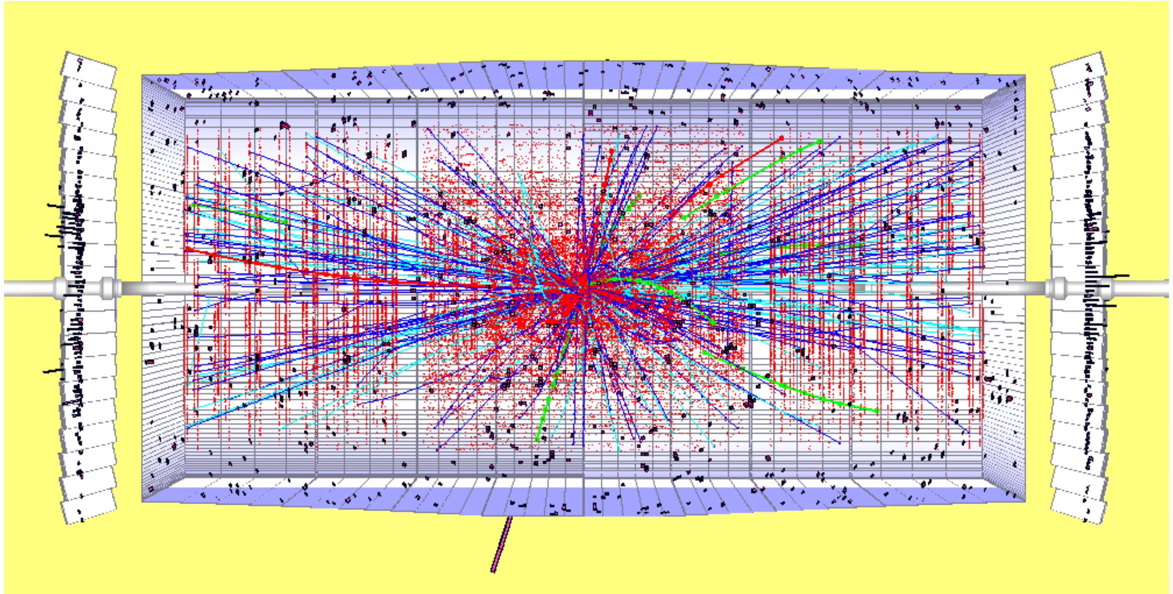
With increasing luminosity more overlapping interactions



L~10^{33} $cm^{-2}s^{-1}$
~10^2 bunches/beam
~2 - 8 Evts/BX

The price to pay for HL

With increasing luminosity more overlapping interactions

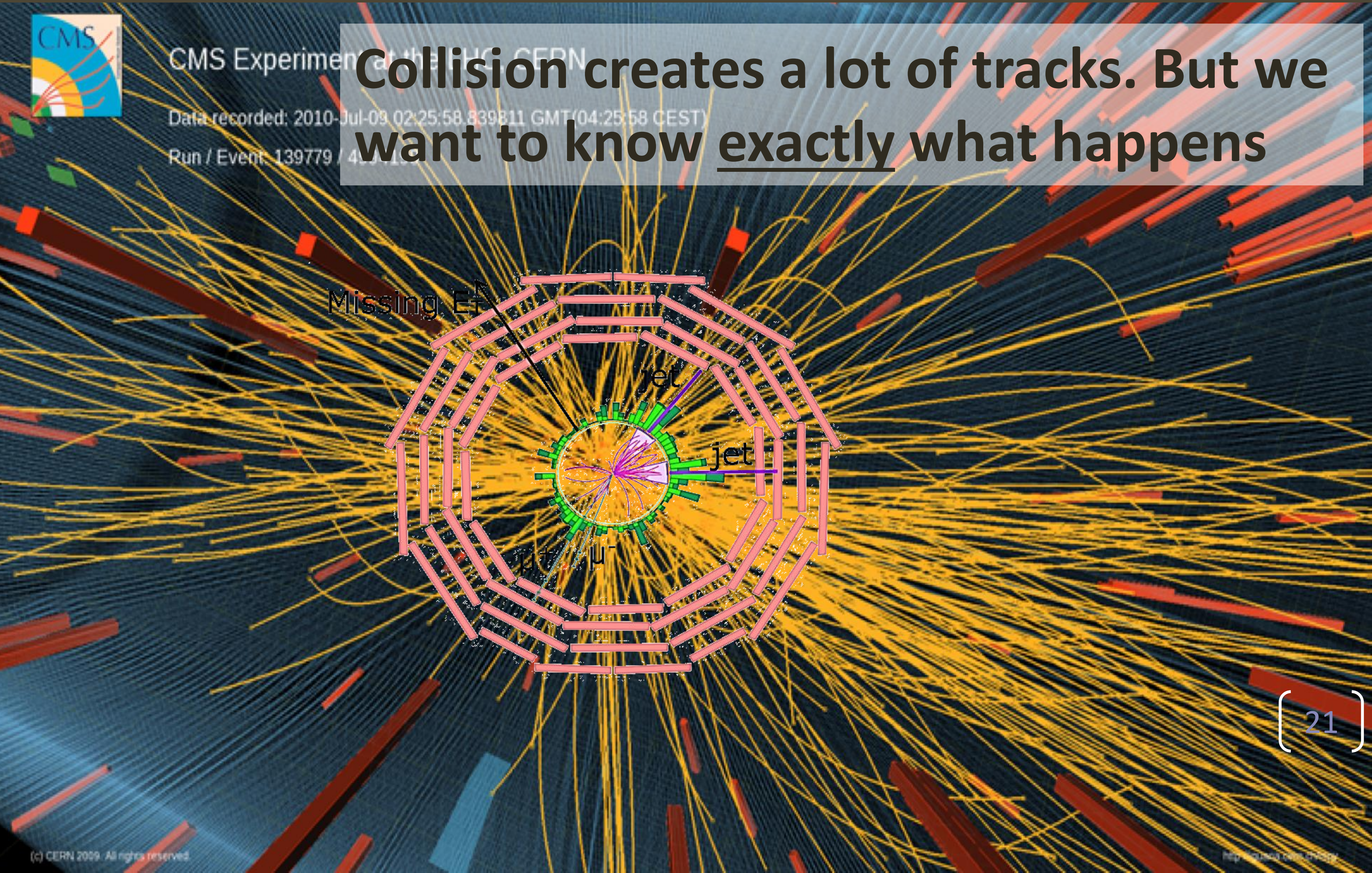


L=10^{34} $cm^{-2}s^{-1}$
~10^3 bunches/beam
~25 Evts/BX

At HL-LHC ~140 Evts/BX

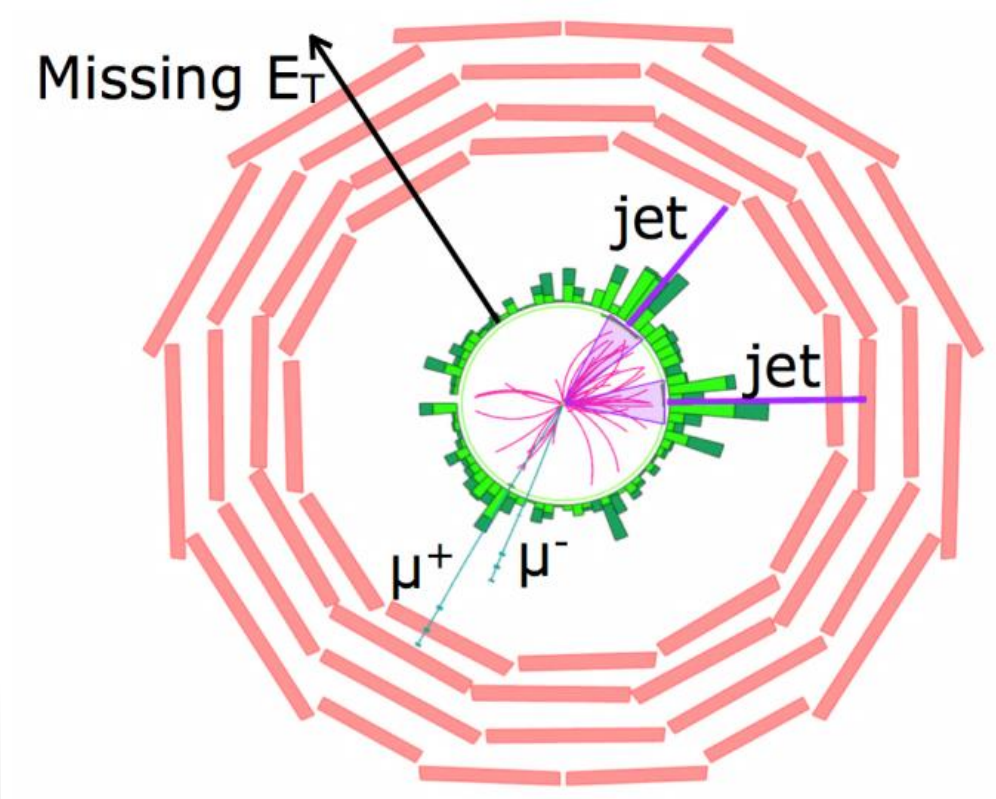
A Typical Collision

Collision creates a lot of tracks. But we want to know exactly what happens



Identifying Particles

Measure final state particles and kinematic reconstruction



To determine:

Momentum and direction of charged particles

Energy measurement

Particle identification

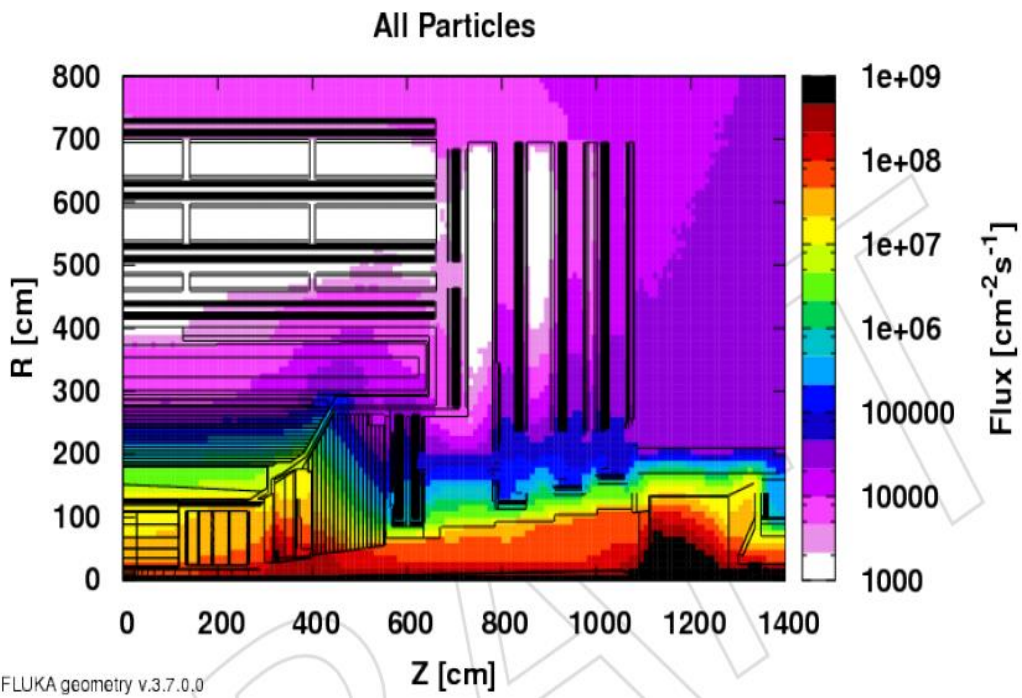
Derived quantities:

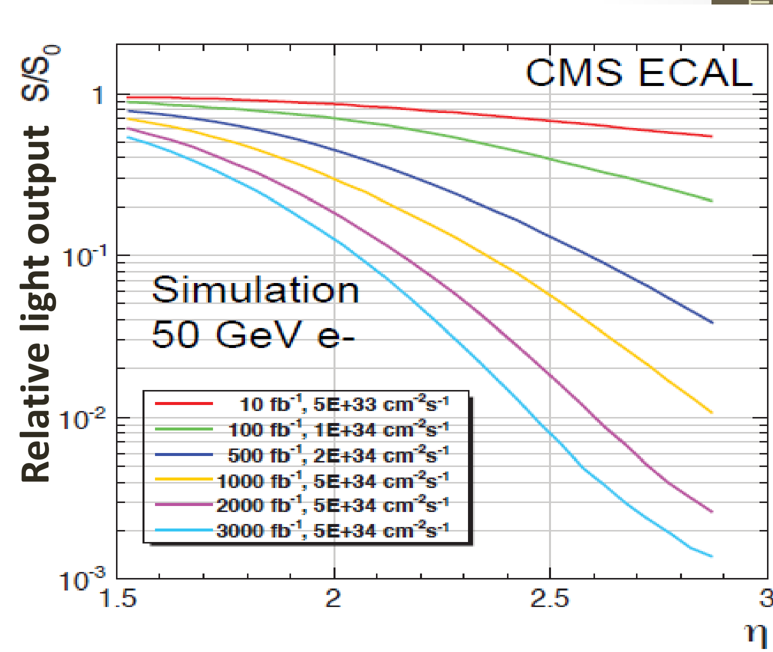
Neutral particles (missing E_T, neutrinos)

Maintain phase-I performance despite harsh environment

Reason #1 for upgrade = radiation damage

Detector will age and performance deteriorate



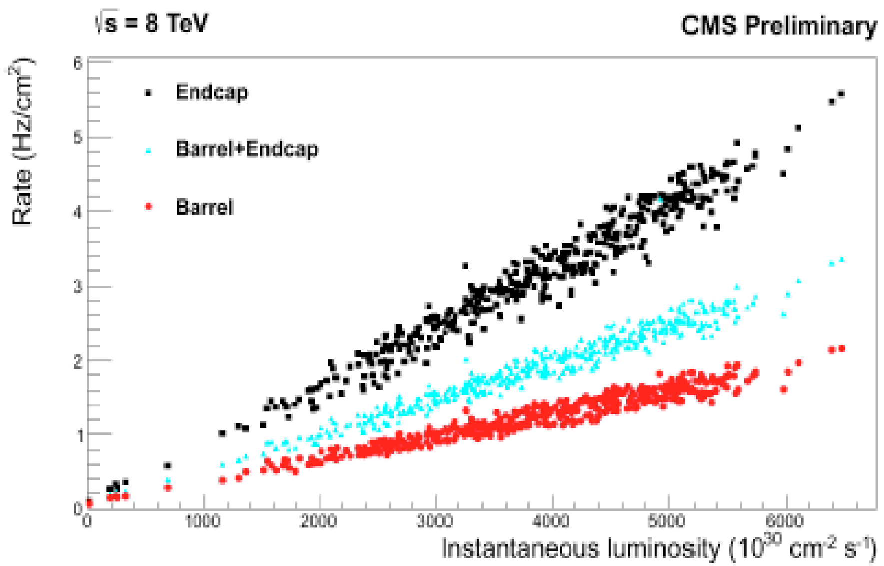


Many high rate testbeam campaigns, aging projections and simulations

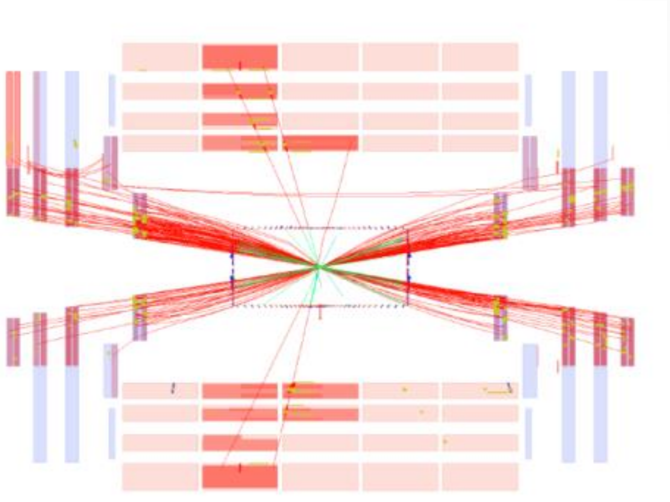
→ Need to replace tracker and forward detectors with radhard material

Reason #2 = high rates

Higher rates, in particular in the forward



RPC backgroound rates vs luminosity



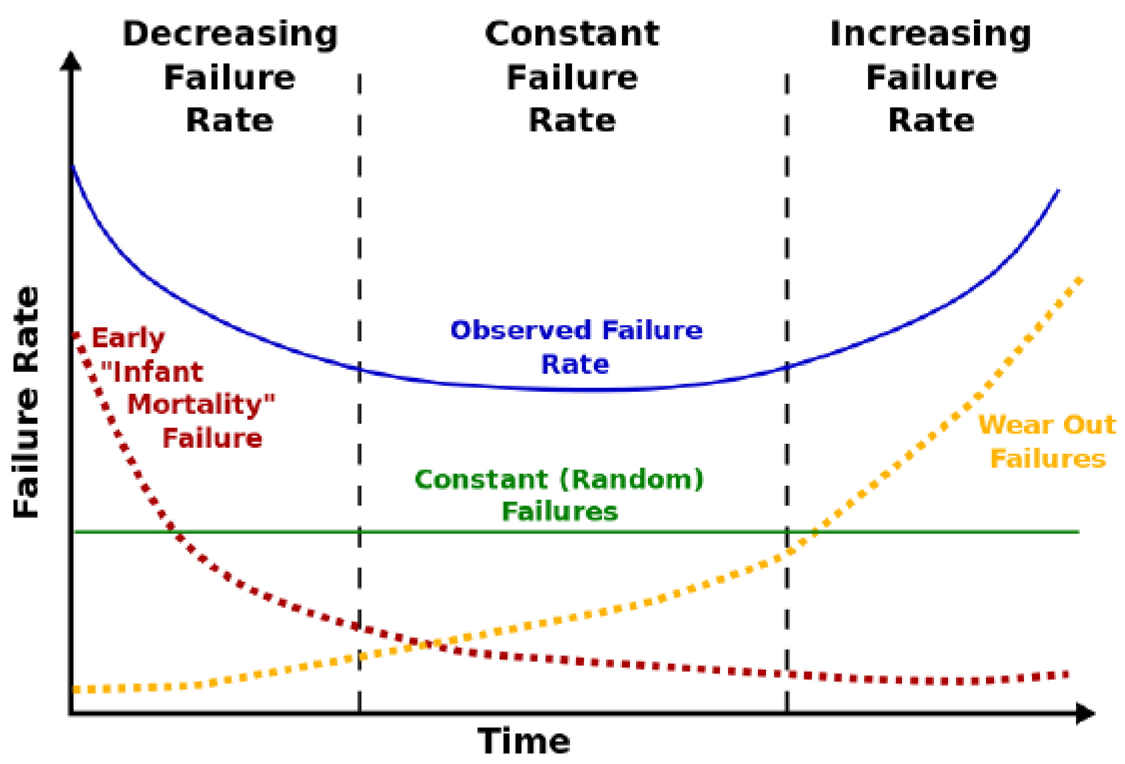
Triggers need to stay efficient (MHz→kHz). Keep trigger thresholds low for Higgs and particles from cascade decays

→ Finer granularity detectors and larger trigger bandwidth

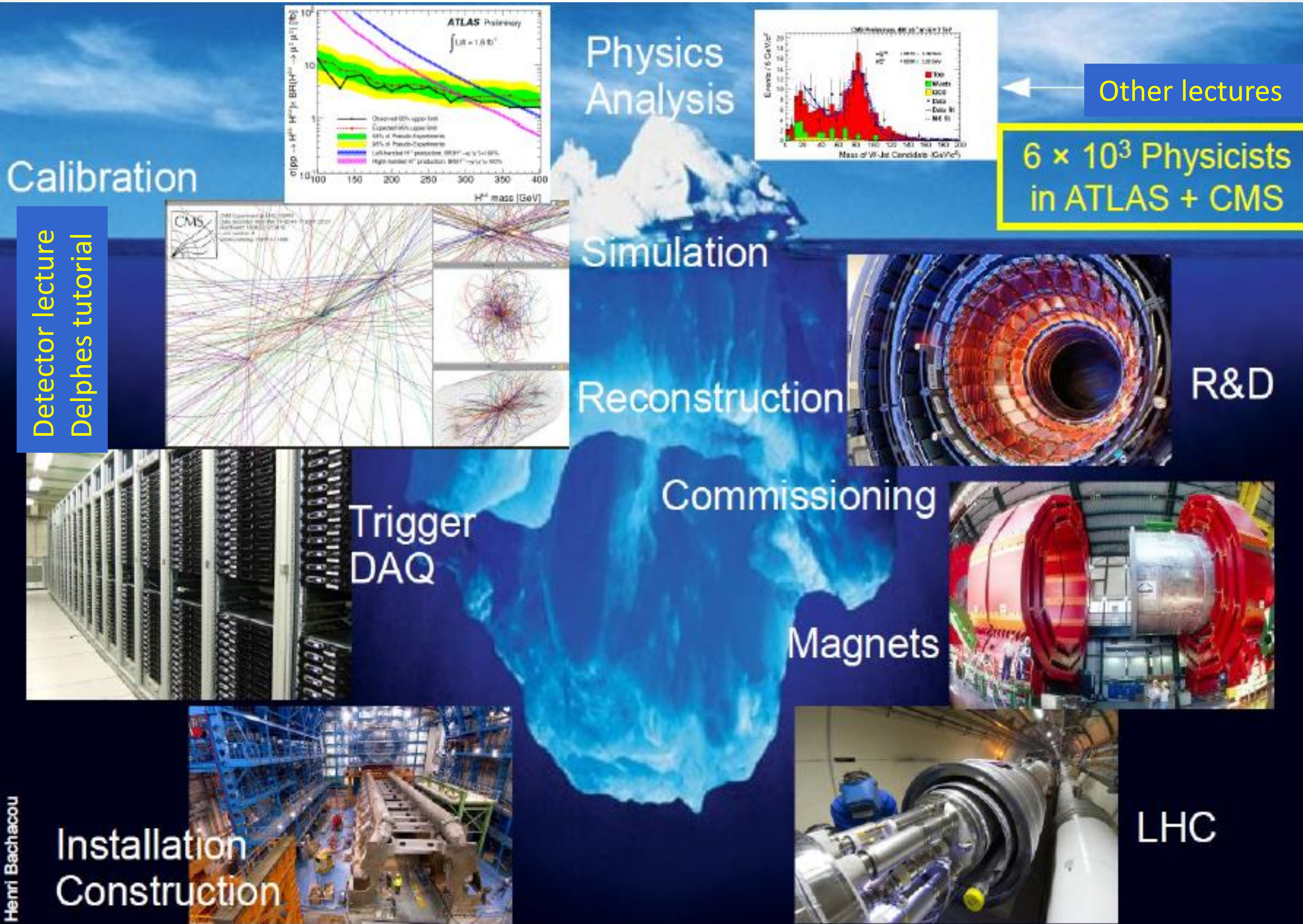
Reason #3 for upgrade = age

By ~2025 detectors are operational for ~20 years. Built in technology from ~30 years ago (in particular electronics and computing)

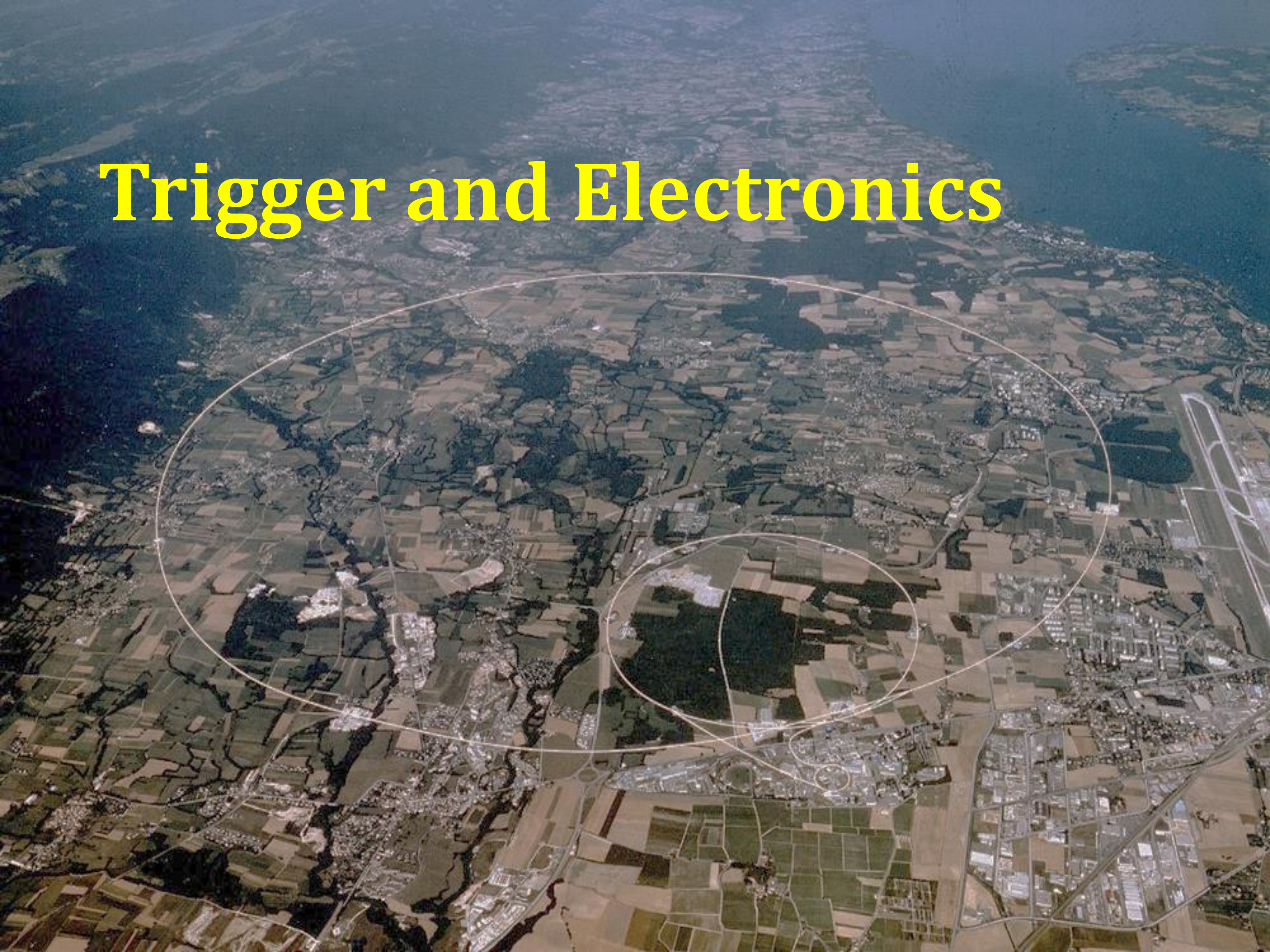
→ Redesign electronics, trigger and DAQ



Now let‘s discuss detectors

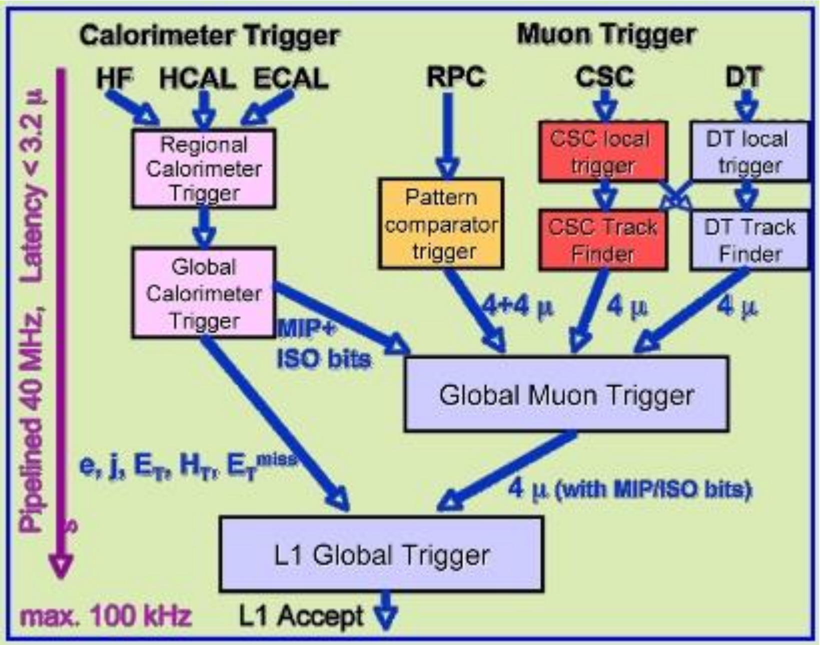


Trigger and Electronics



Selective triggers (ATLAS, CMS) for high rates

- At high luminosity even more background → high efficiency and high purity of triggers.
- High granularity detectors and high rate capability. Detector upgrades to support trigger strategy by providing high-quality input.



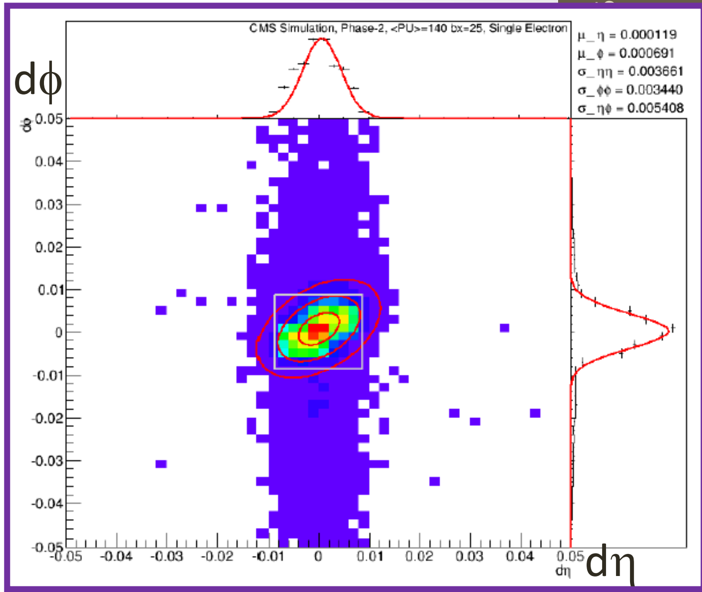
improve purity, reduced fakes, sharper turn-on

Trigger

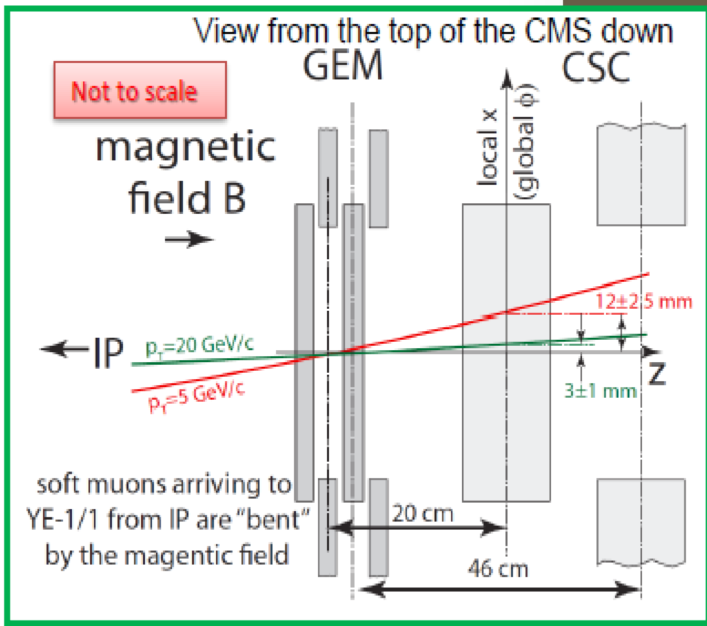
Increase L1 Trigger **latency 3.4 µs → 12.5 µs**

& L1 Trigger **rate 100 kHz → 750 kHz**

- New readout electronics



The trigger challenge: keep the **thresholds** at 5x higher PU. Sharpen **turn-on** curves and reduce **fake** triggers.



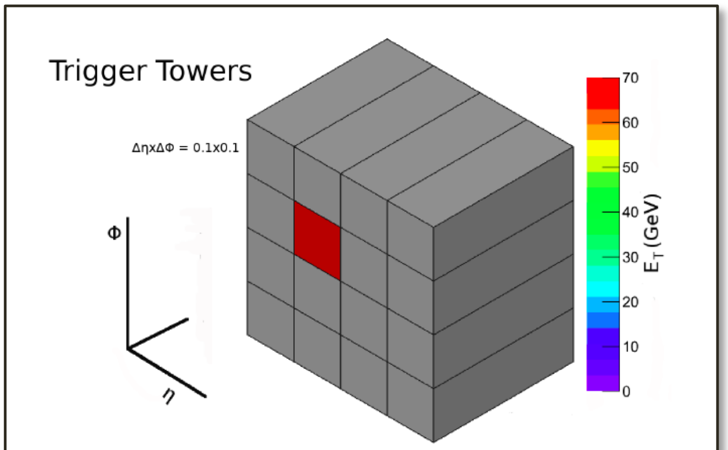
Tools:

- **Single ECAL crystal readout** improves track matching, spike rejection (noise) and timing
- Additional muon detectors (GE1/1) enable **measurement of bending angle** in forward region → reduce mis-measurement
- Tracking information at L1 (tracking trigger)

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 $L_{inst}=3 \times 10^{34}\ cm^{-2}s^{-1}$

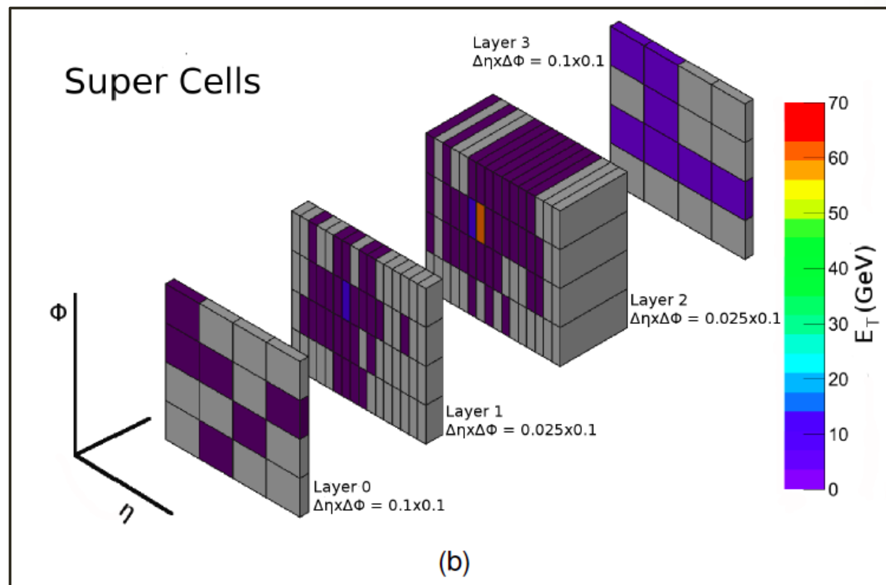
⇩

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

maintain lower thresholds at an acceptable rate

↑

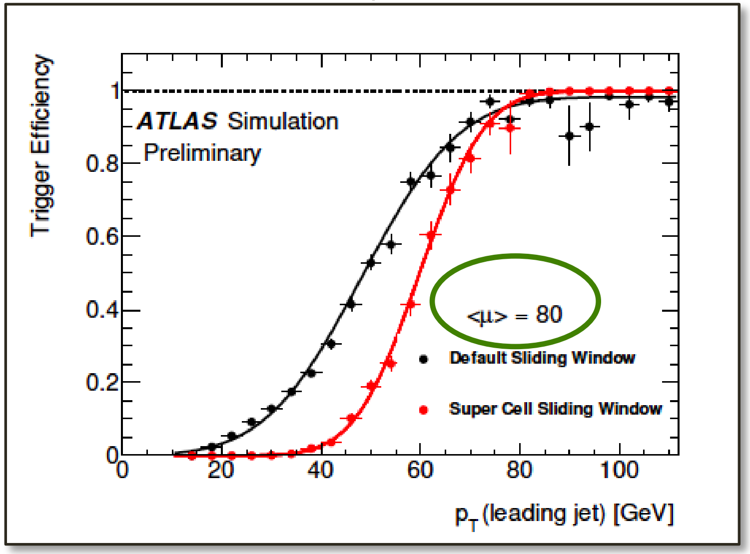
Provide better granularity and better energy resolution



(b)

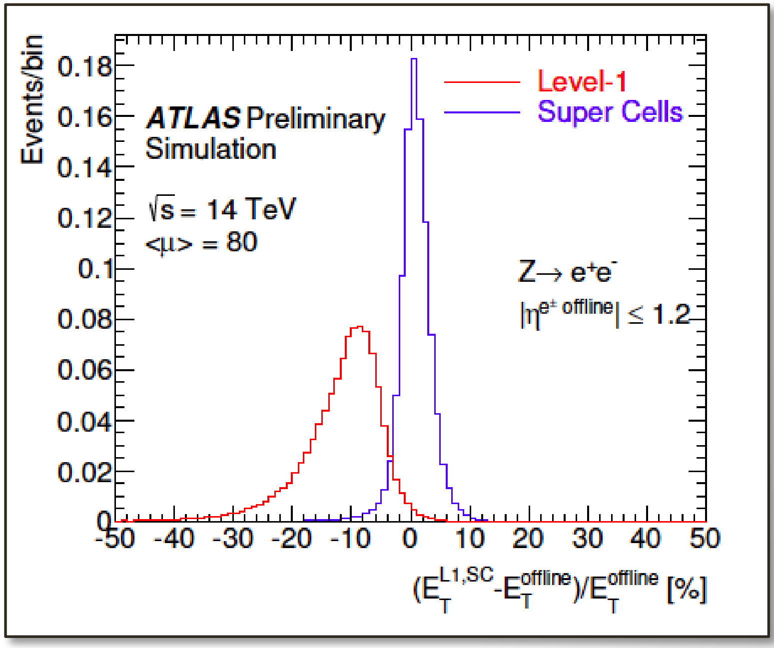
Physics impact

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)



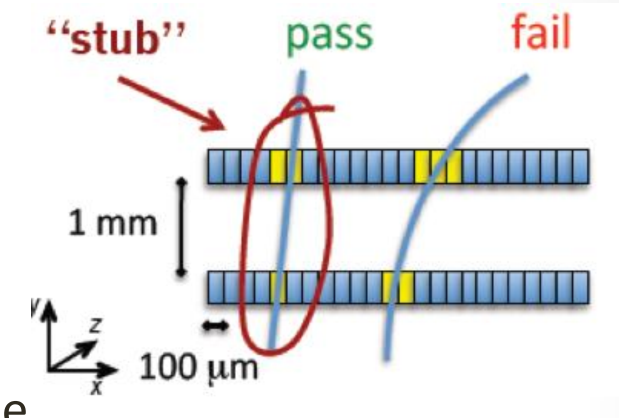
EM Triggers

- 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

CMS phase-II Tracking Trigger

Objective: reconstruct all tracks with p_T>2 GeV **at trigger level**. Identify primary vertex along beam line with ~1mm precision.

B=3.8T

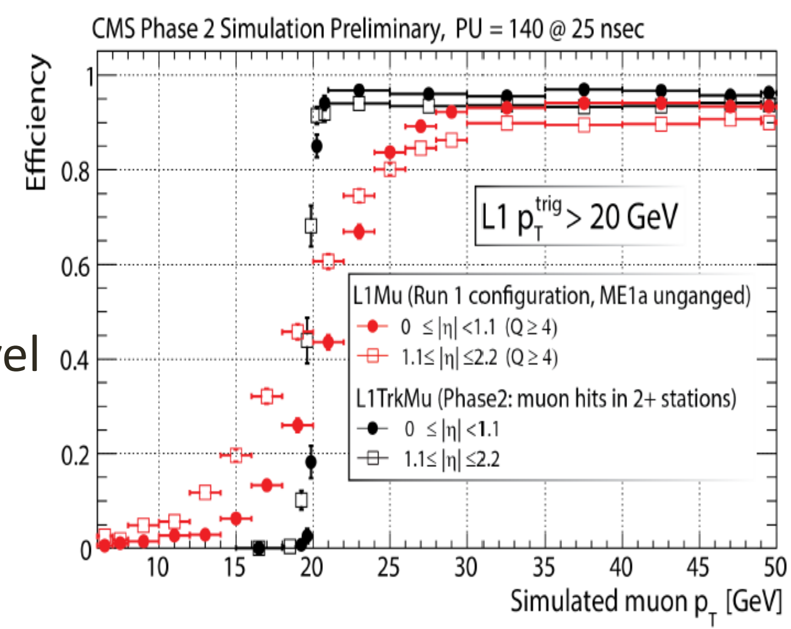


Conceptual design: to implement tracks in hardware trigger (40 MHz)

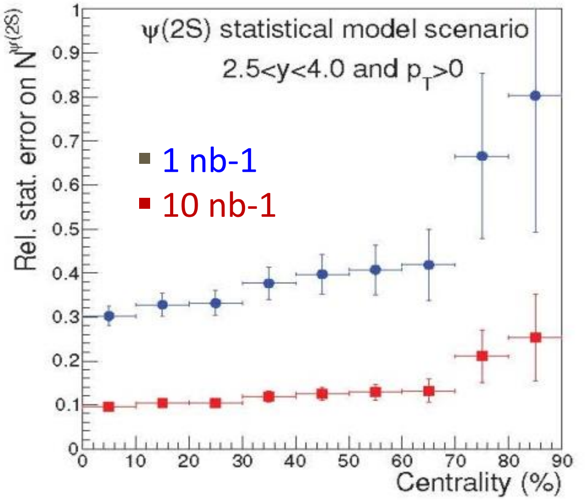
- Correlate hits in two closely-spaced sensors to provide vector ("stub") in transverse plane: angle is a measure of p_T
- Exploit the strong magnetic field of CMS

Physics benefit:

- Threshold can stay roughly at present level
- Sharp trigger turn on



Continuous readout for ALICE Upgrade



Goal:

High precision measurements of rare probes of Pb-Pb collisions at low $p_{T,}$ which cannot be selected with a trigger → Read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. L = $6x10^{27}$ $cm^{-1}s^{-1}$)

- Lower luminosity than ATLAS/CMS but exceeding ALICE design values, about 100x more statistics than run1+2

- Significant improvement of vertexing and tracking capabilities → New Inner Tracking System (ITS)
- Upgrade mainly related to readout and trigger electronics to handle large rates. Other upgrades at smaller scale w.r.t. multi-purpose detectors and mostly in LS2 (no strong correlation to HL-LHC).

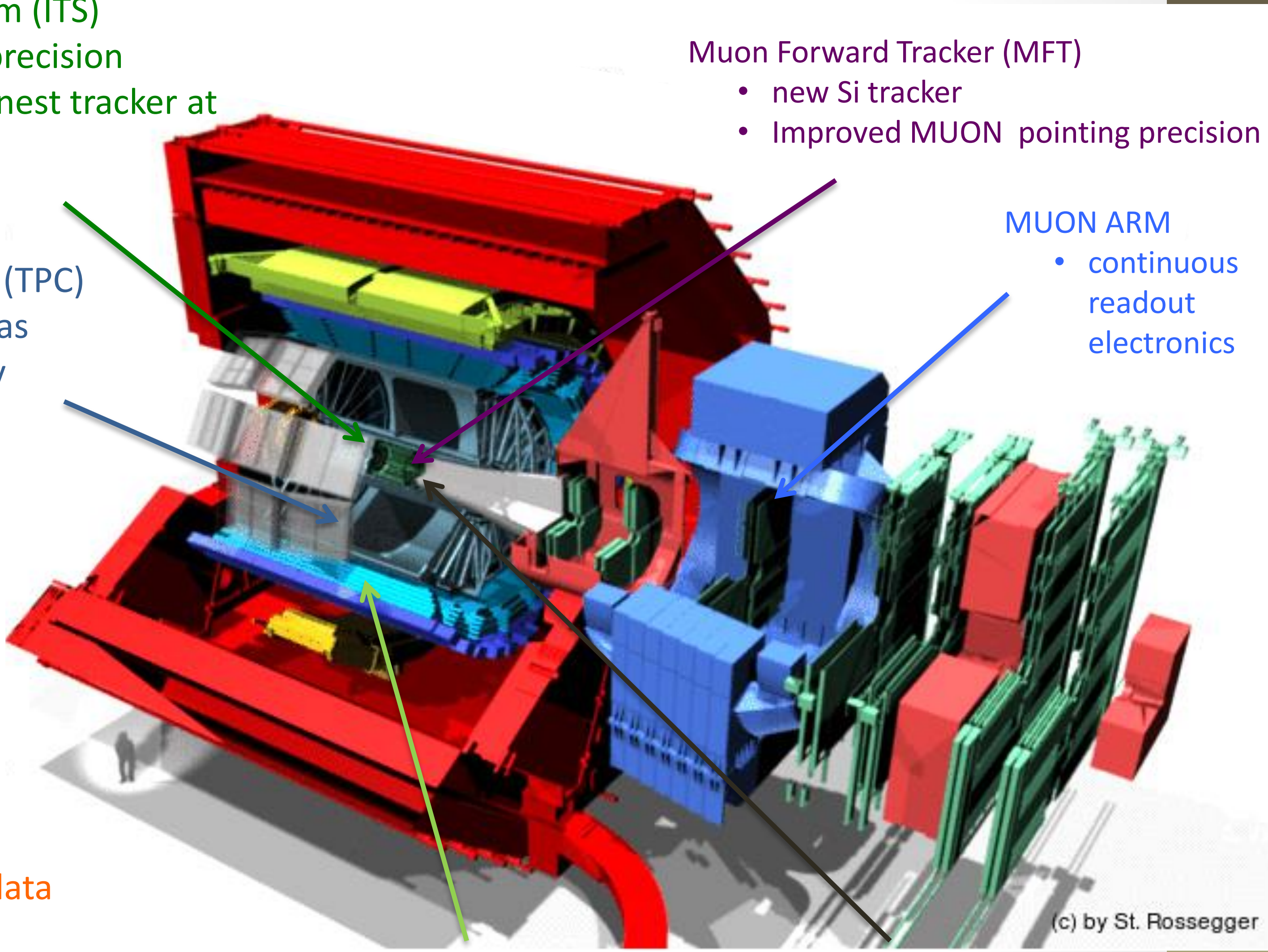
ALICE Upgrade

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 PbPb event rate

TOF, TRD
- Faster readout

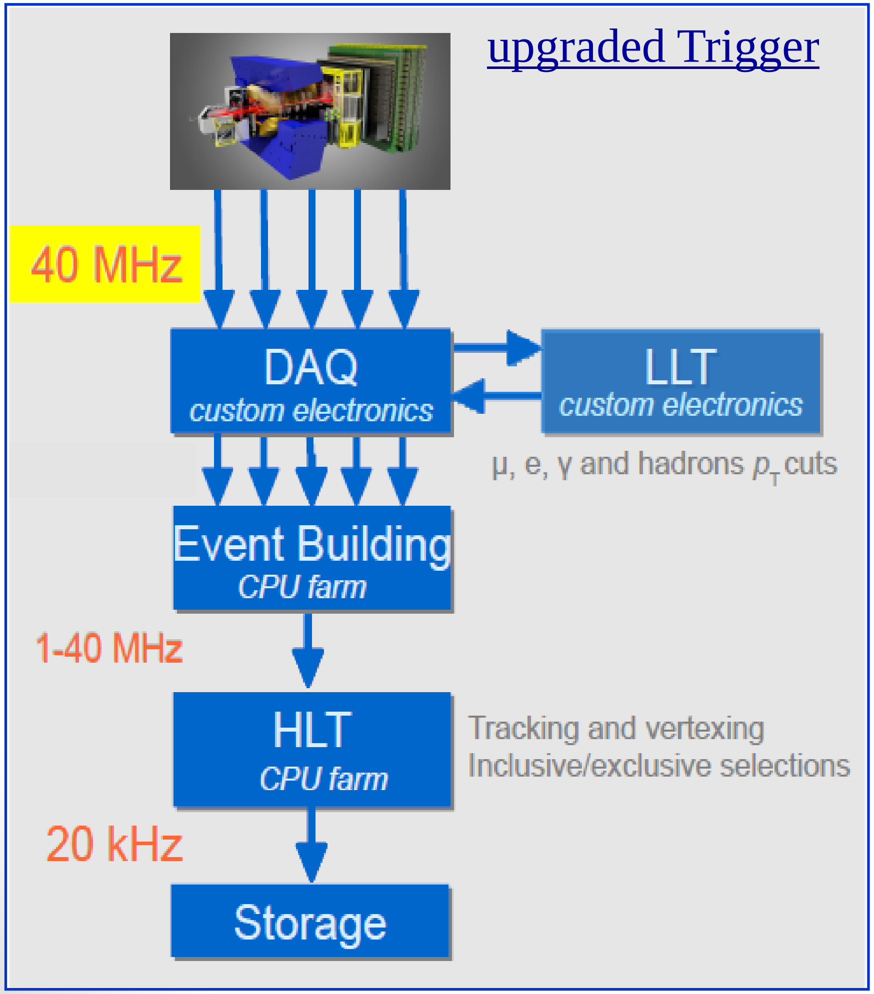
New Trigger Detectors (FIT)

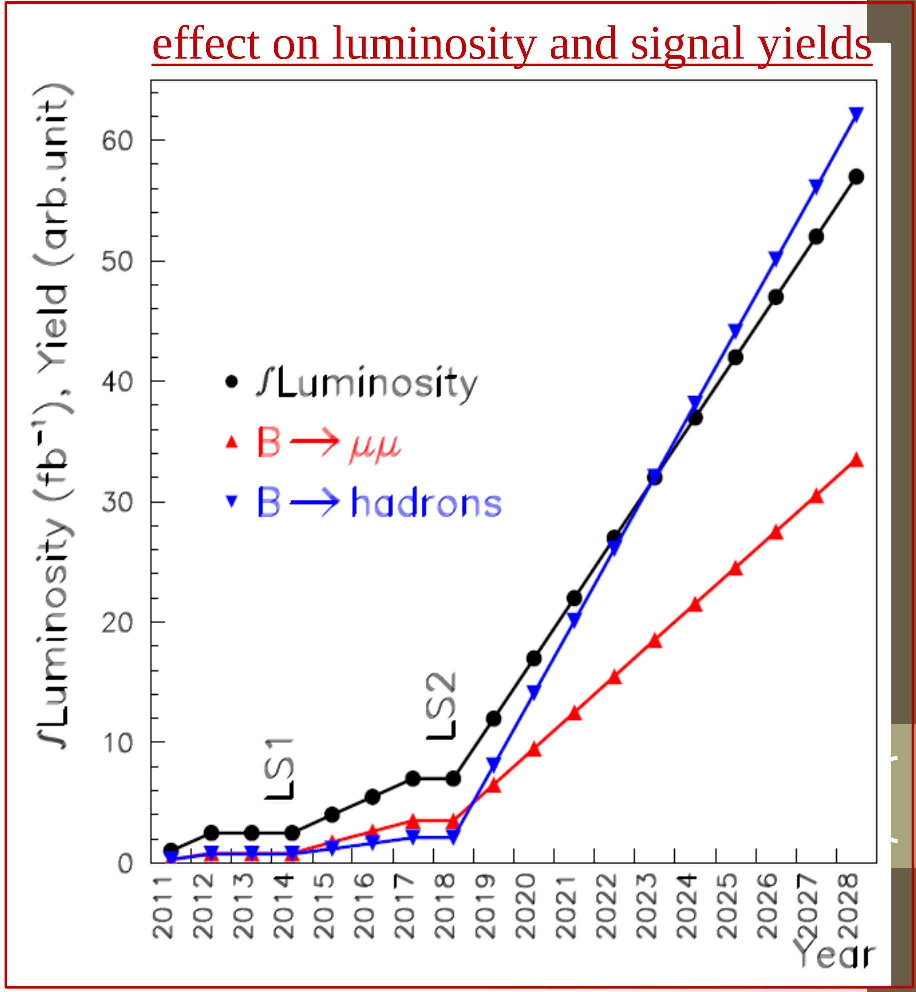
Trigger upgrade

run an efficient and selective software trigger with access to the full detector information at every 25 ns BX crossing

→

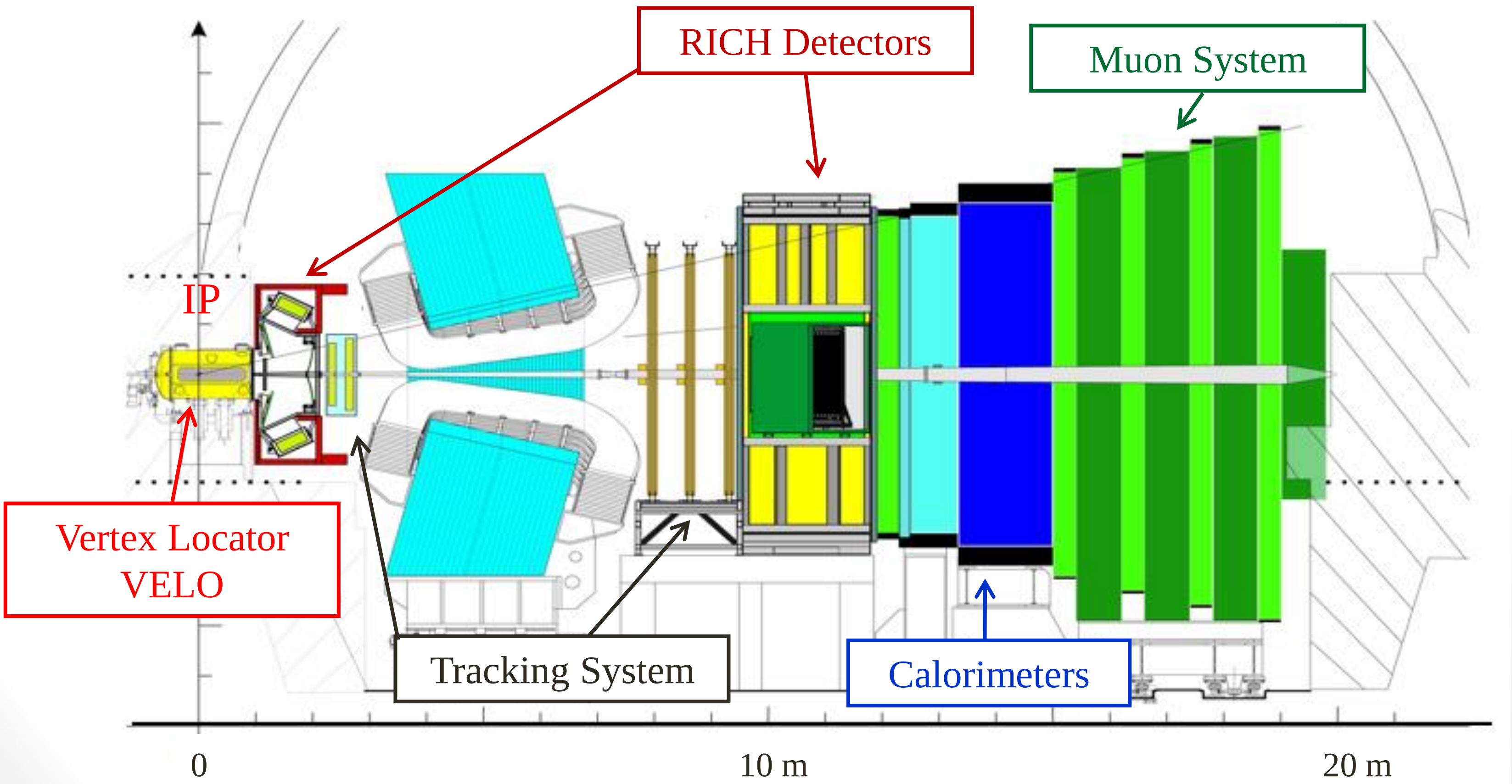
increase luminosity and signal yields





Upgrade to 40 MHz readout

- ✓ upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- ✓ replace complete sub-systems with embedded FE electronics
- ✓ adapt sub-systems to increased occupancies due to higher luminosity
- ➢ keep excellent performance of sub-systems with 5 times higher luminosity and 40 MHz R/O



Multi-purpose experiments to operate at maximum luminosity

High collision rates causing

→ radiation damage to detectors, in particular inner trackers

→ more background, selective triggers

Tracking systems

HL Challenges for tracking systems

1) Radiation, radiation, radiation… causing material damage

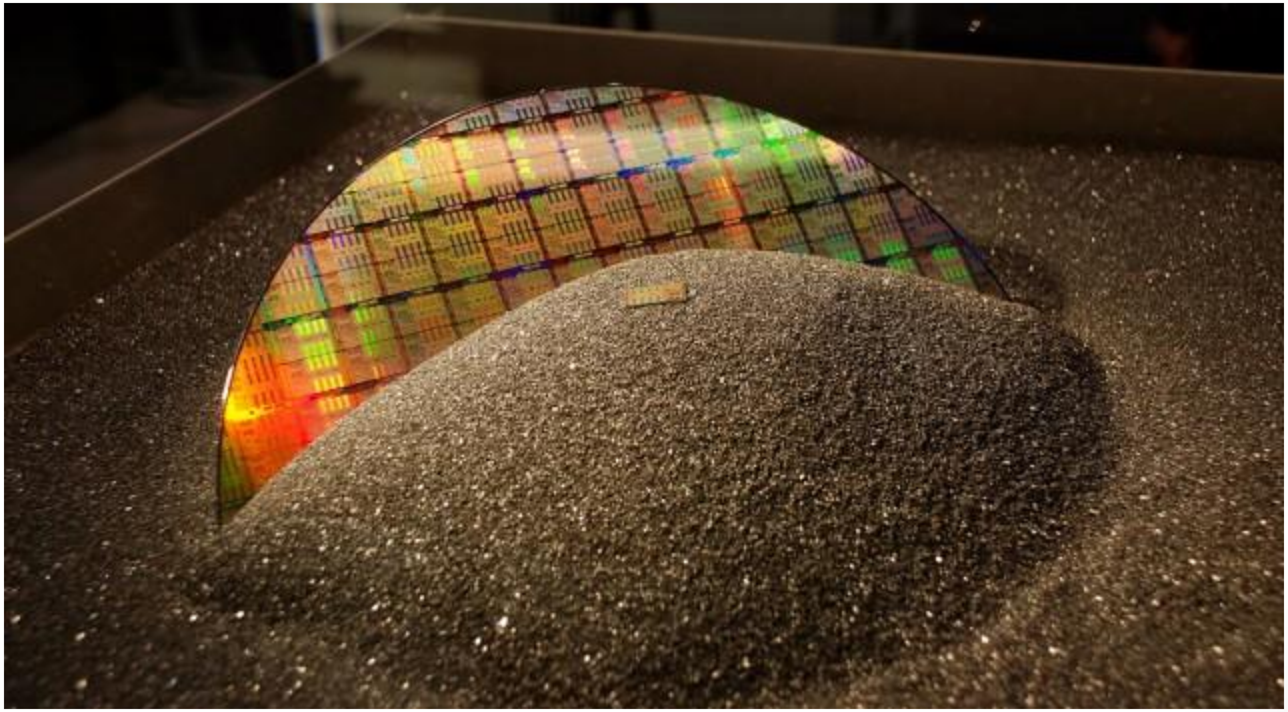
2) Higher occupancies = needs smaller cells

3) Even more background, more selective triggers. Include tracking information in trigger

4) Extending acceptance in the forward to gain physics potential

The material for tracking

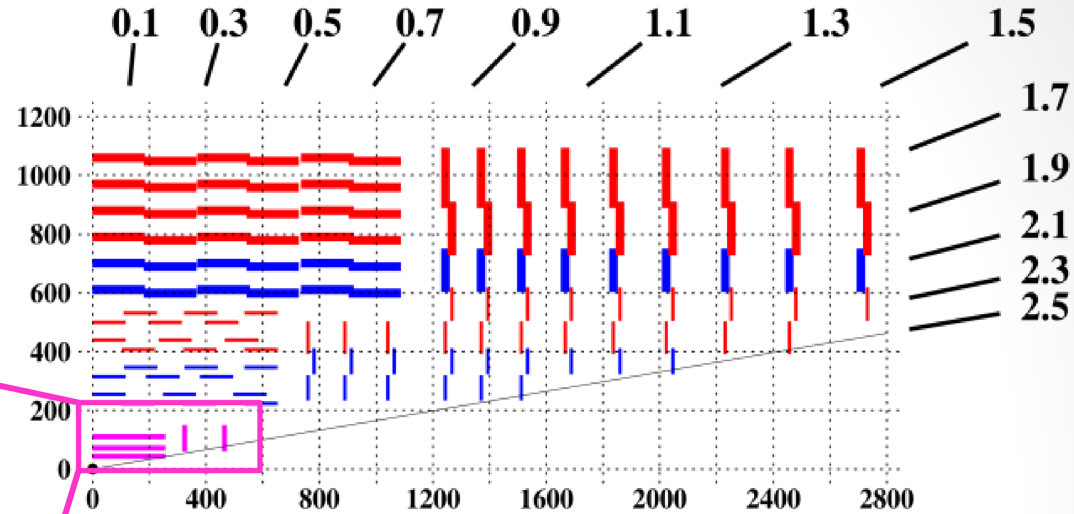
= Silicon



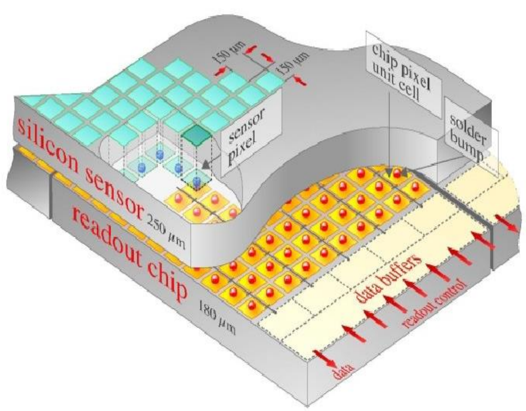
CMS: Present Tracker

See detector lecture

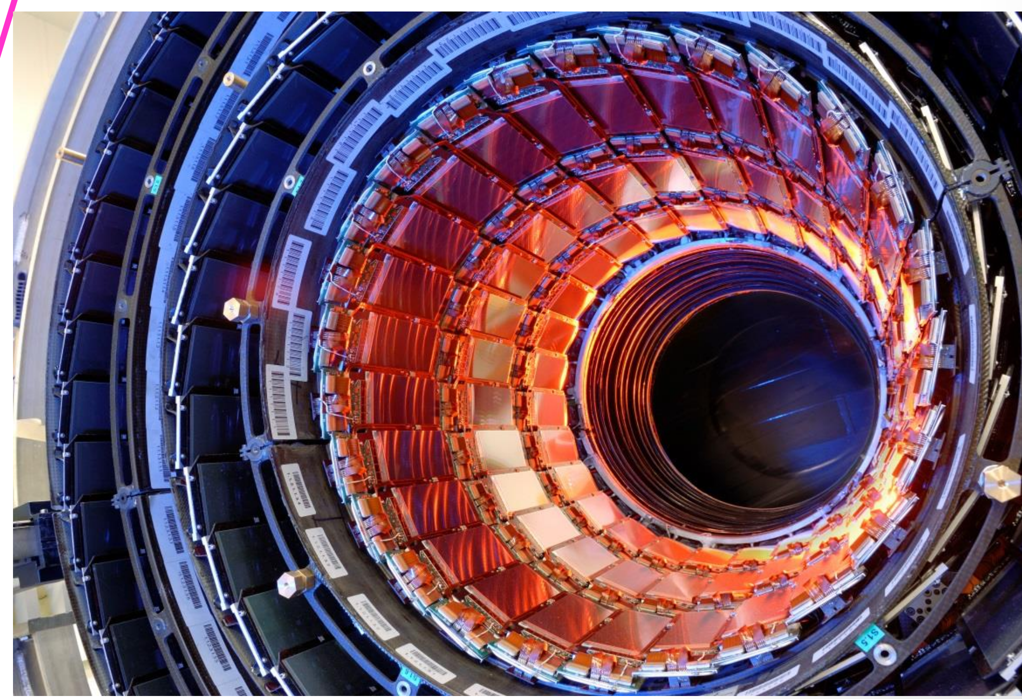
B=3.8T



Pixel detector. Phase-1 replacement end 2016 (150/fb)
Current & Phase1: Planar pixels

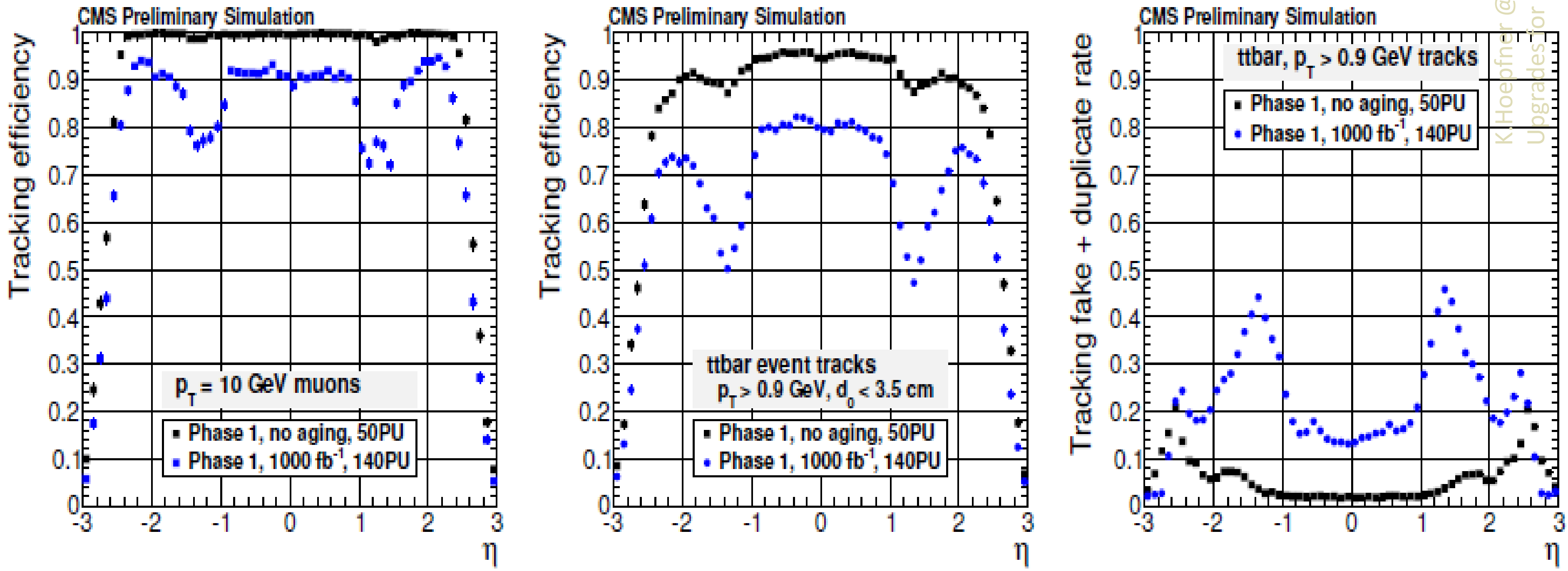


200 m² Silicon strip tracker
Designed to operate
at LHC nominal conditions
(500/fb, PU50)



Performance Degradation of Silicon Tracker

Radiation damage of material causes efficiency loss

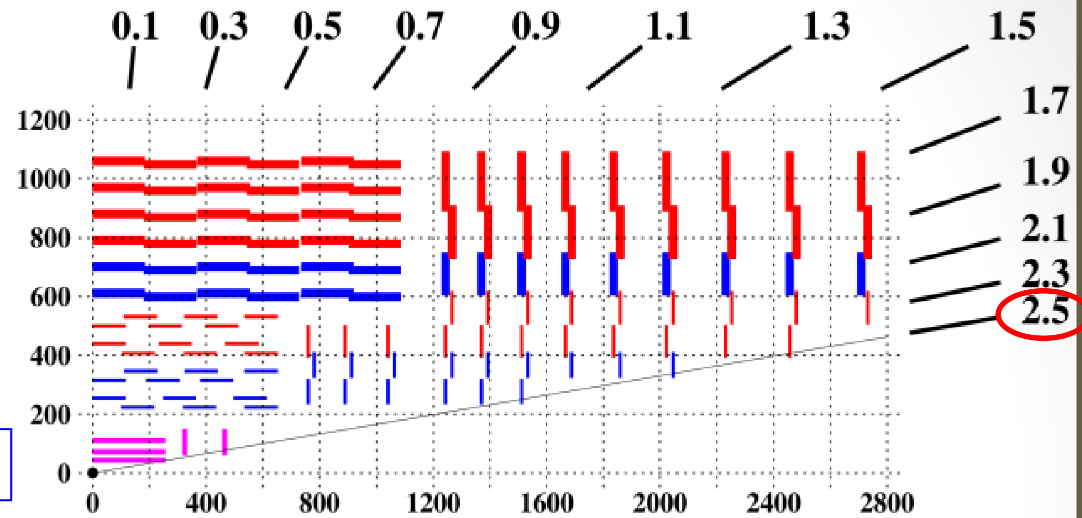


CMS: Present to Upgraded Tracker

CMS Si Tracker today

B=3.8T

Current & Phase1: Planar pixels



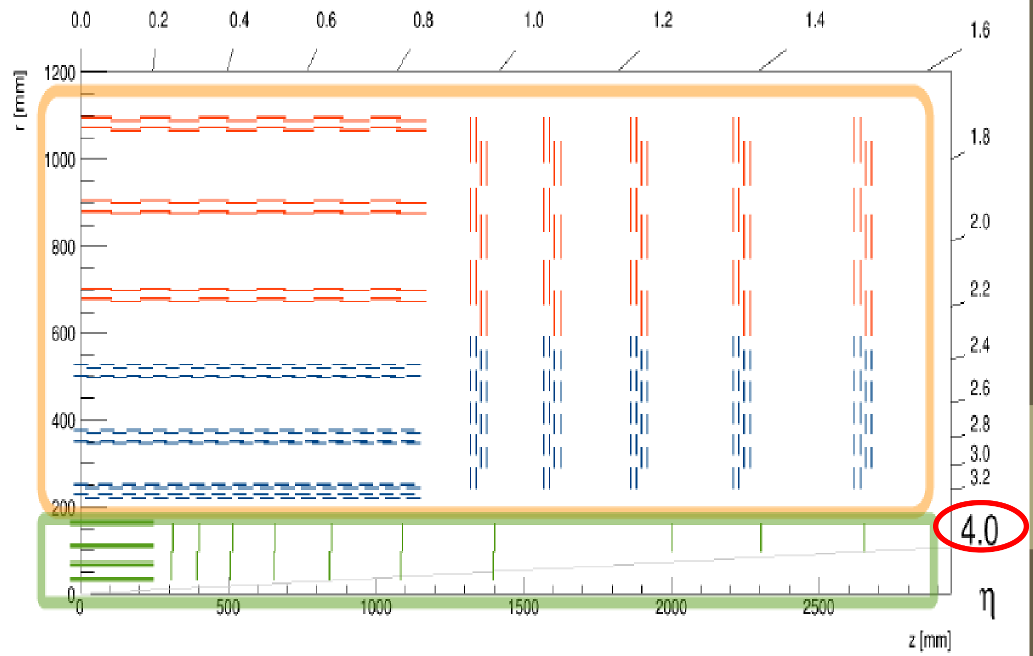
CMS Si Tracker as it could be in 2025

Outer Tracker, new Pt modules
3 more Pixelated layers
5 more Pixelated disks

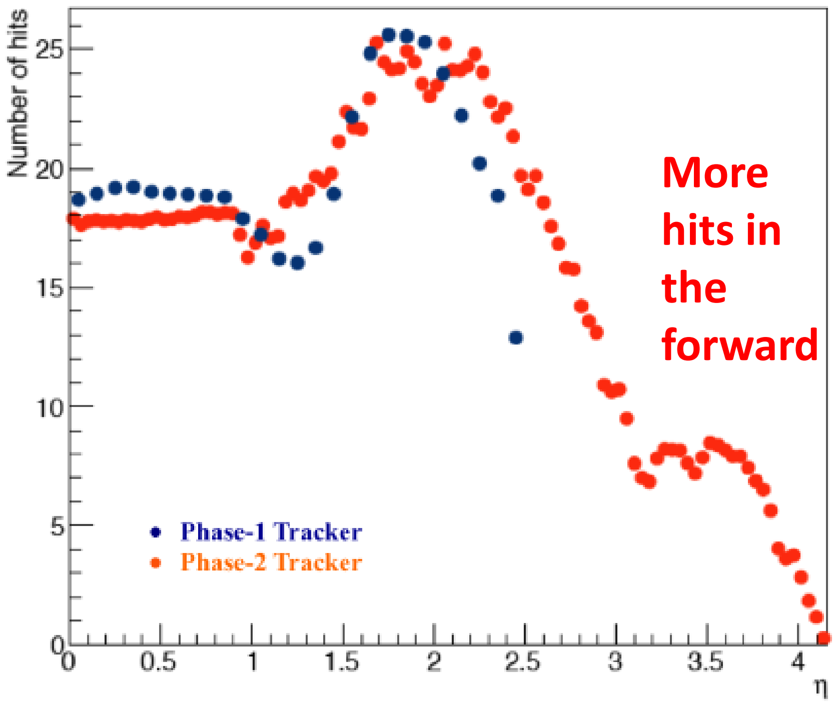
Strip/Strip modules SS
in outer layers

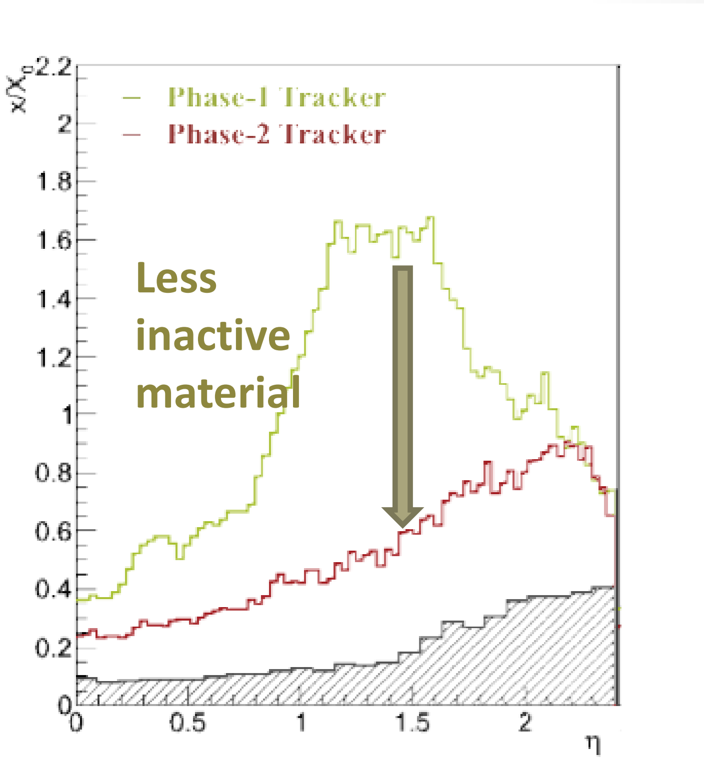
Macro Pixel/Strip modules PS
in inner layers (z-measurement)

Pixel modules, new Disks to η=4
Possible pixel size ~25x100μm^2
Planar or 3D?



Less Tracker Material

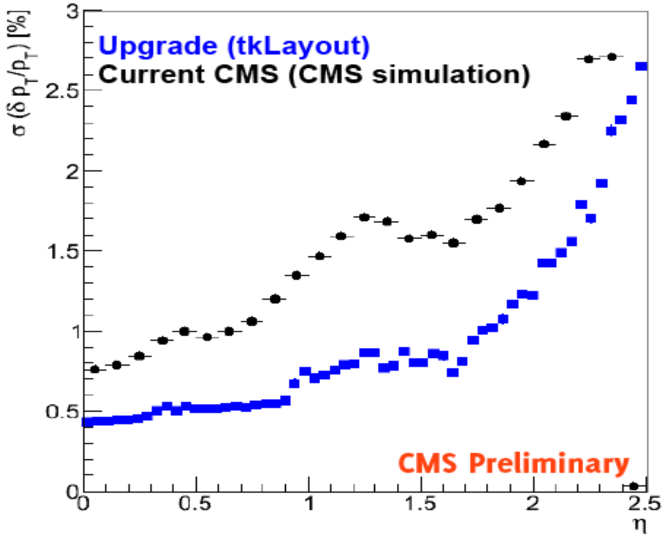




Upgraded Tracker: Lighter, Smarter, Better (acceptance)

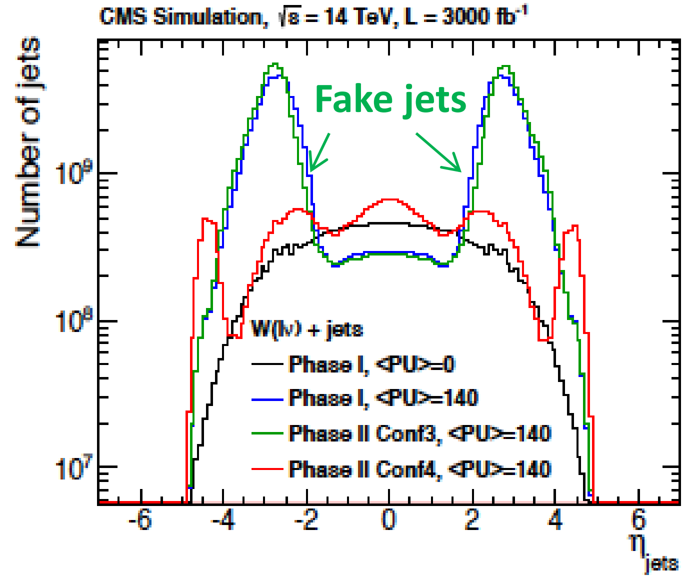
Lighten up DC-DC powering scheme, CO_2 cooling, low mass assemblies, reduced material within tracker volume, thinner sensors

- Physics gain: improved track p_T resolution. Reduced rate of γ conversions.



Larger coverage extend pixel acceptance to |η|~4.0.

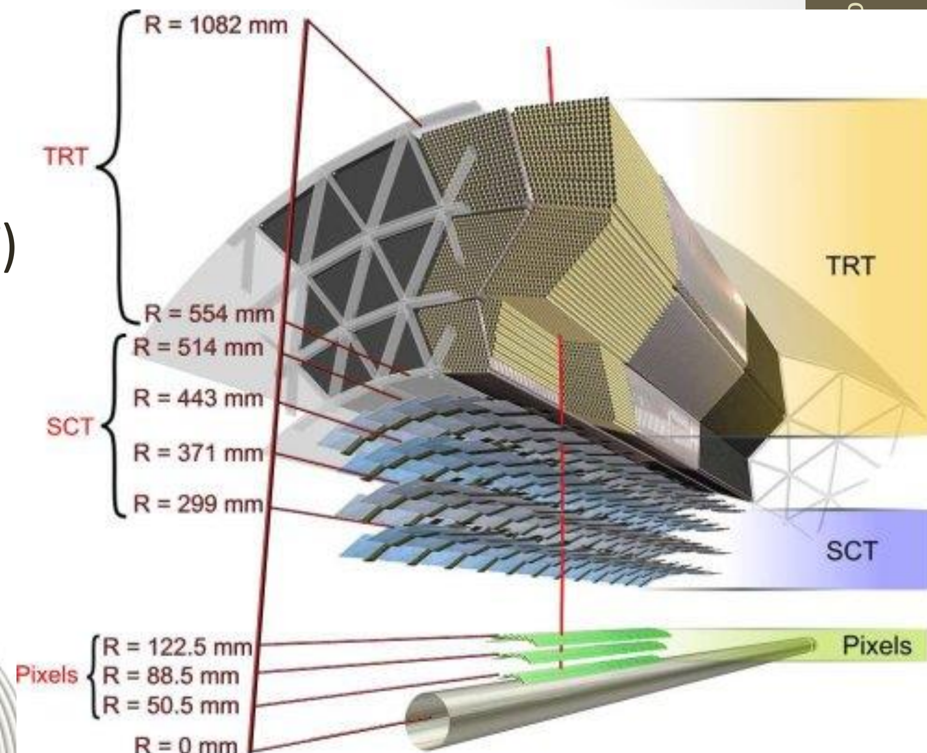
- Physics gain: Reduces fake jets due to PU for VBF physics. Allows to separate signal jets (primary vertex) from PU jets.



ATLAS present tracker

Present Atlas tracker designed for nominal LHC conditions:

- Straw tubes (wire chambers) for tracking and transition radiation (TRT)
- Silicon strips (SCT)
- Pixel vertex detector, rectangular pixels 50 x 400 um^2 (B-field)

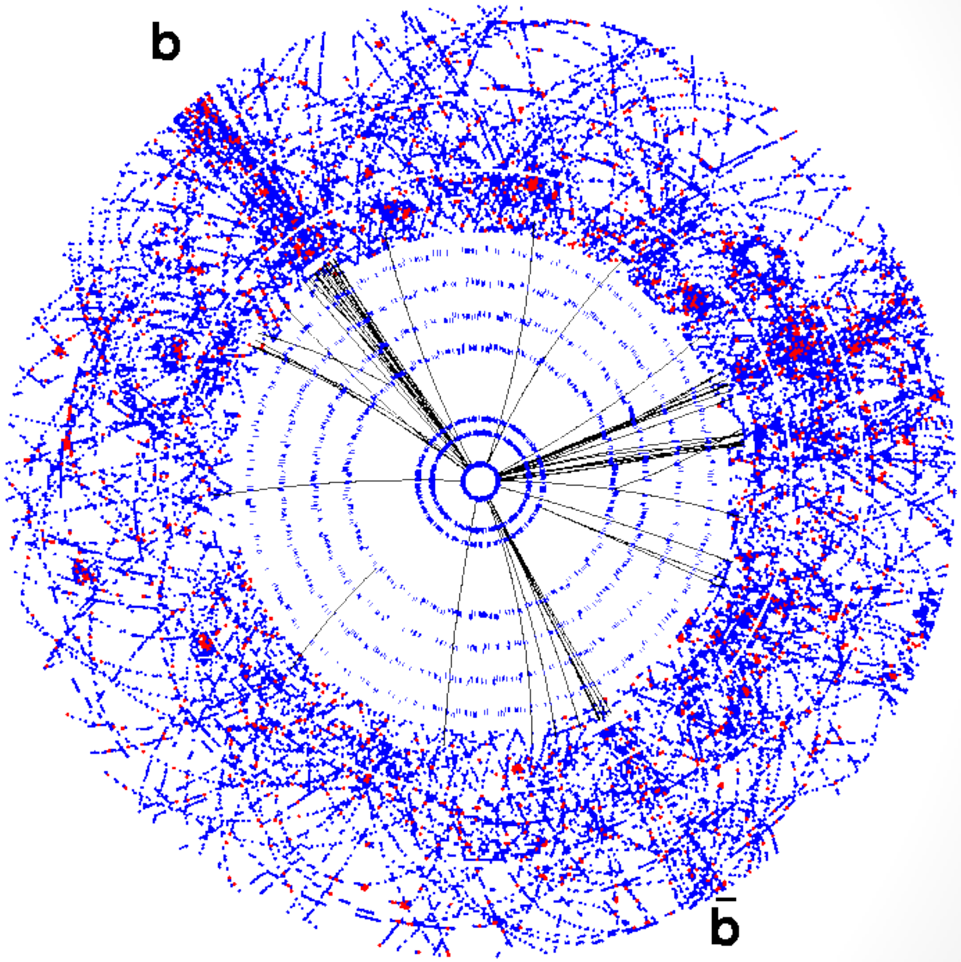


B = 2T (solenoid) for inner detectors

typical accuracy of:
~ 100-150 microns/straw
~ 20-30 micron/silicon strip
~5-15 micron/pixel

Why straw tubes?

- Provides many hits along track → tracking inside jets
- Less radiation length



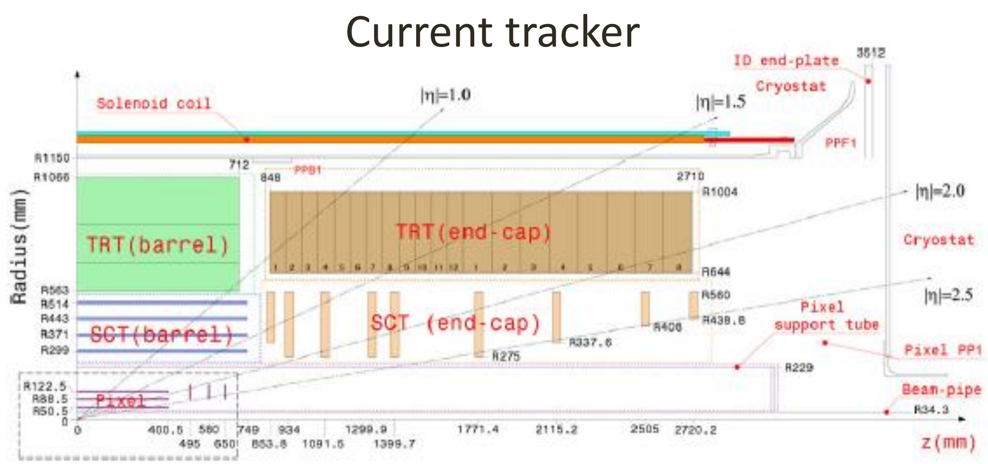
http://www.hep.lu.se/atlas/thesis/egede/thesis-img386.gif

Phase-II tracker upgrade

Complete replacement with a full silicon tracker

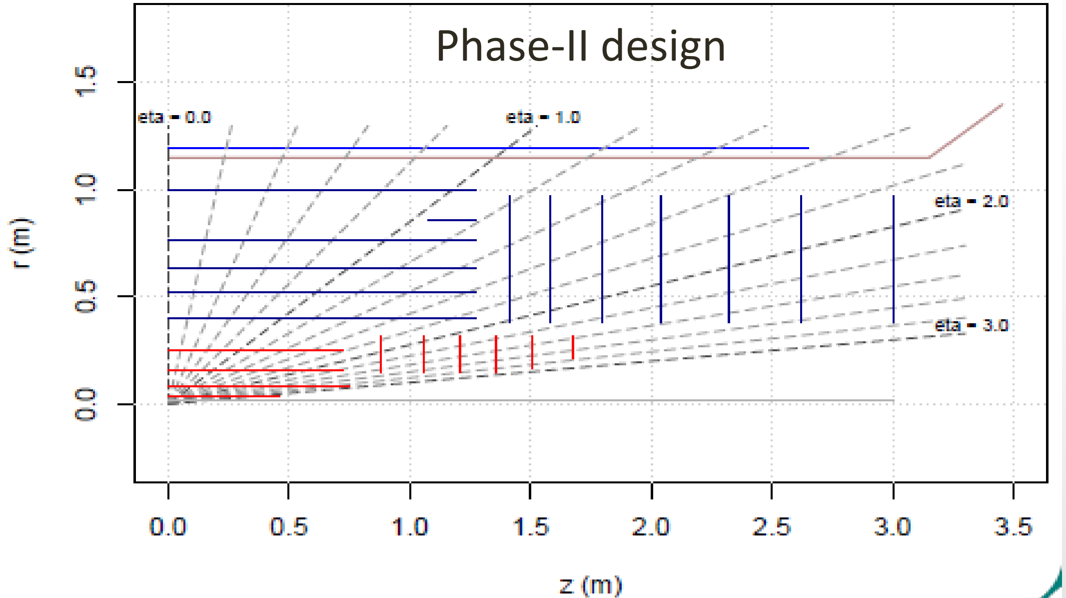
Limiting factors for HL-LHC

- Radiation damage (Pixel, SCT)
- Occupancy
  - Bandwidth saturation (Pixel, SCT)
  - Performance deterioration (TRT)



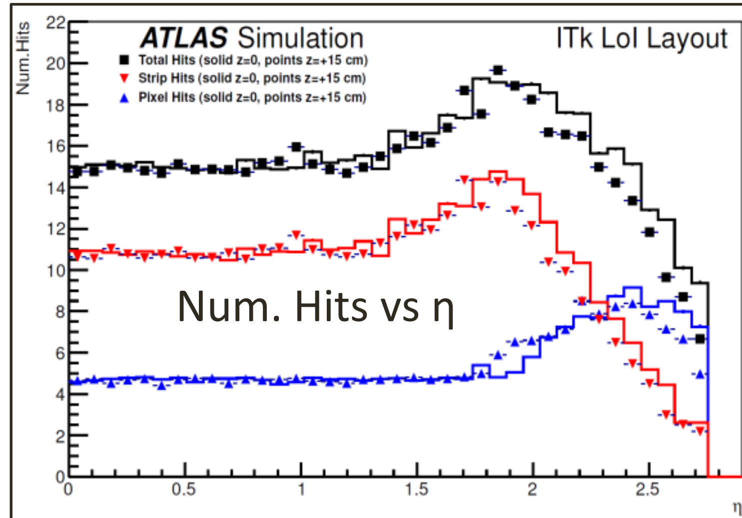
Barrel: 4 pixel + 5 concentric double strip layers

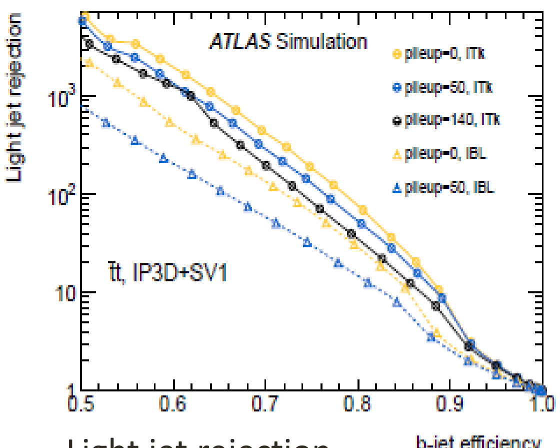
Endcaps: on each side 6 pixel + 7 strip disks



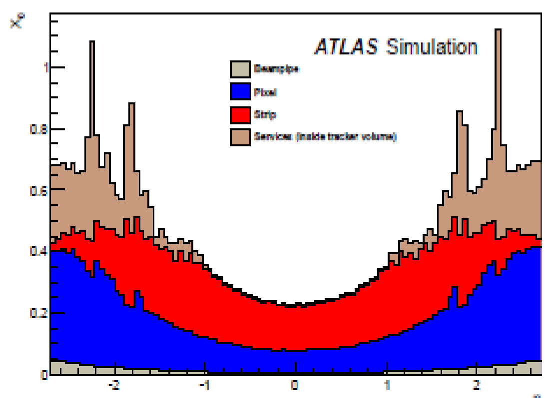
Tracker performance

- Robust tracking (14 hits/track for $|\eta| \lesssim 2.3$)
- Occupancy $< 1\%$ for maximum μ of 200
- Reduced material compared to current ID (less than $0.7X_0$ for $|\eta| \leq 2.7$)
- Maintain and improve detector performance (p_T-resolution, tracking efficiency, two-particle separartion, vertexing, b-tagging) in high-pileup environment

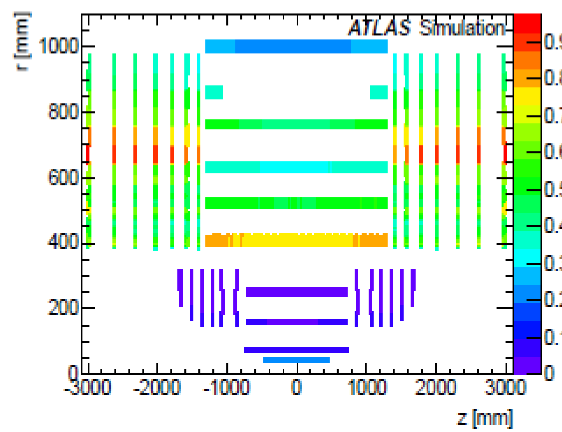




Light jet rejection, ID (w/IBL) and ITk



Radiation length vs η

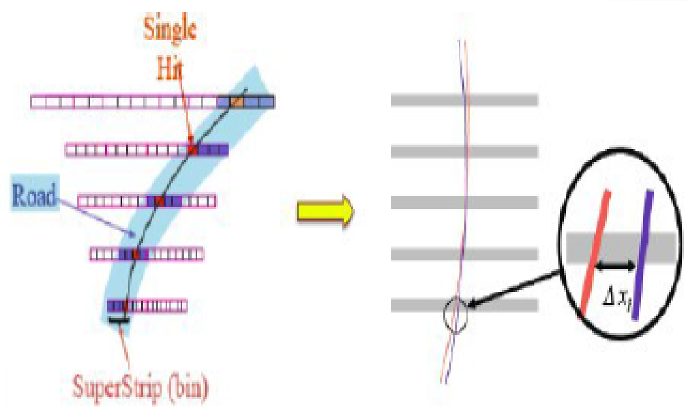


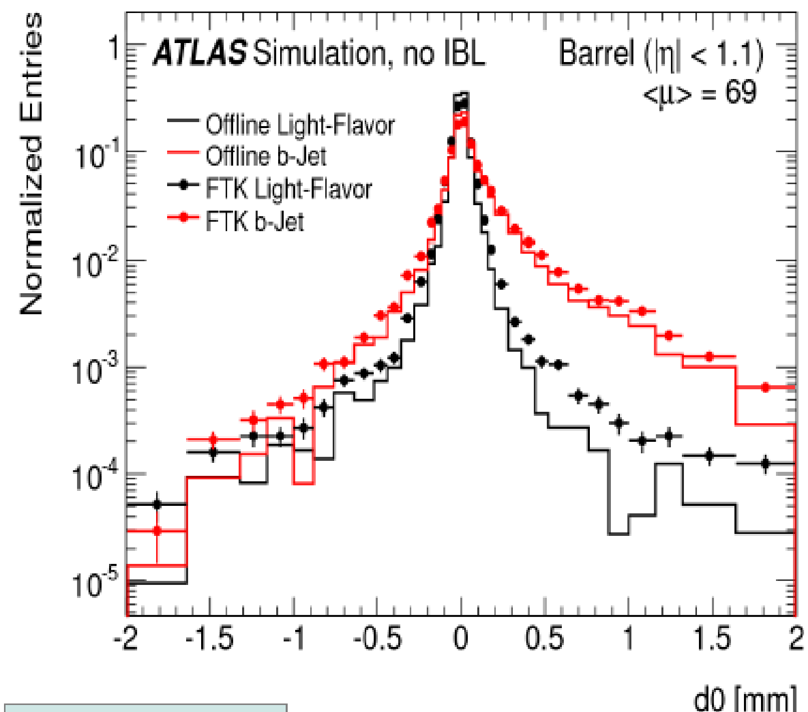
Occupancy for <μ>=200 (in %)

K.Hoepfner @ Terascale intro school 2015
Upgrades for HL-LHC

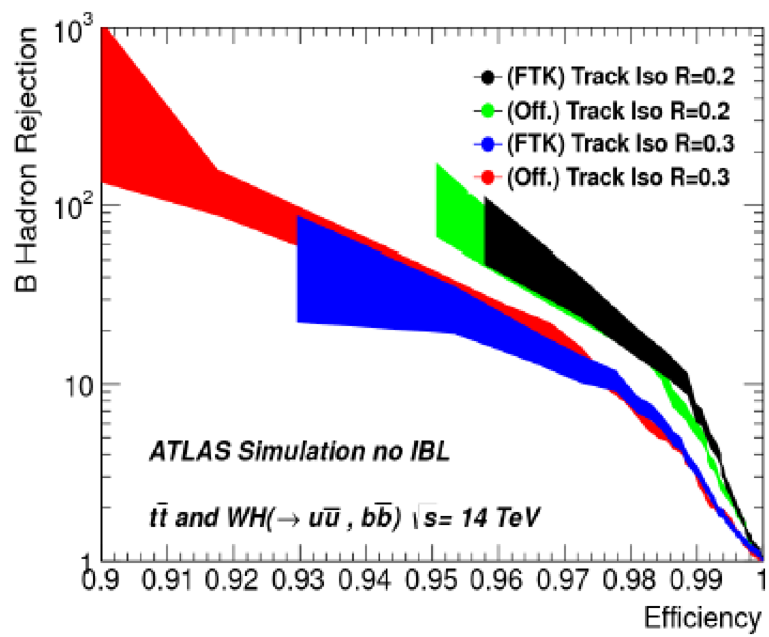
New Fast TracKer (FTK)

- FTK does hardware based si-tracking at start of HLT with near offline quality.
- Providing precision tracking(Pt, d0, btag) for HLT to improve triggers.





CERN-LHCC-2013-007

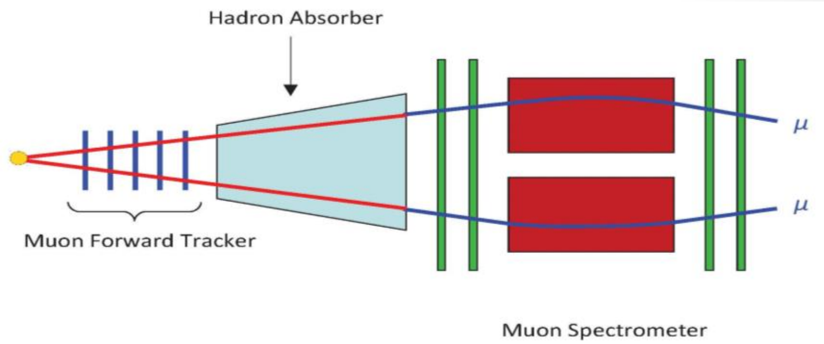


10

Forward Muon Tracker (FMT)

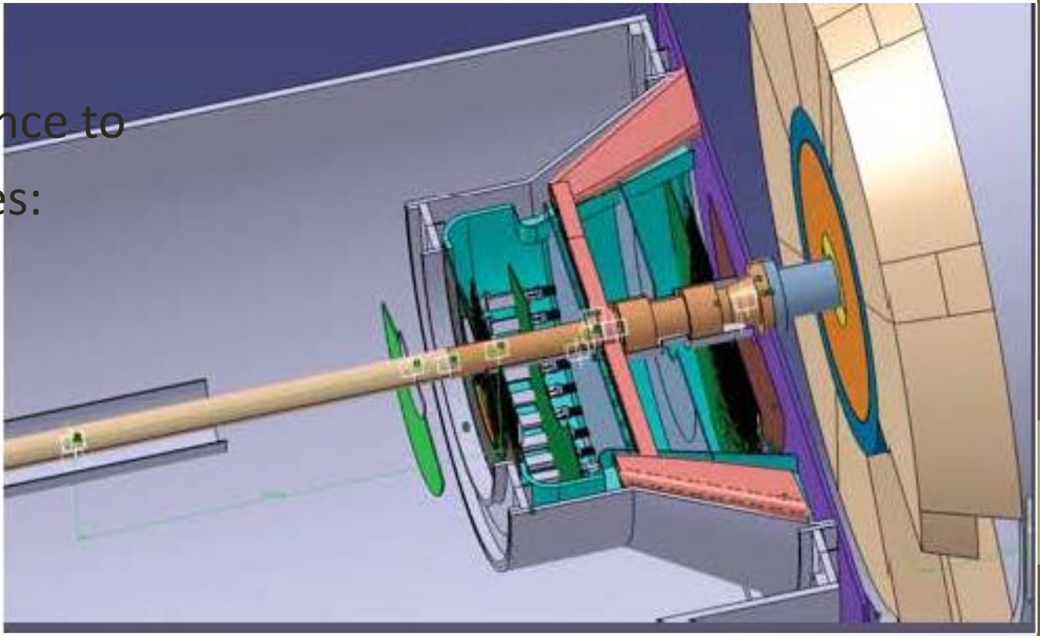
p_T measurement:

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



Upgrade: Addition of a detector based on pixel CMOS sensors (MFT) in the Muon Spectrometer acceptance to improve muon physics capabilities:

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



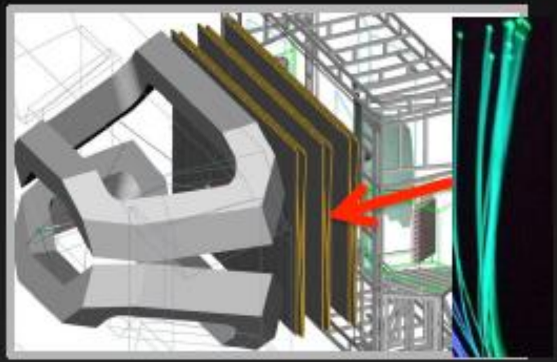
Not only silicon. Renaissance of scintillating fiber technology, now with SiPM readout.

Remember: LHCb operates at lower collision rates

Tracking detectors: Scintillating Fibre tracker

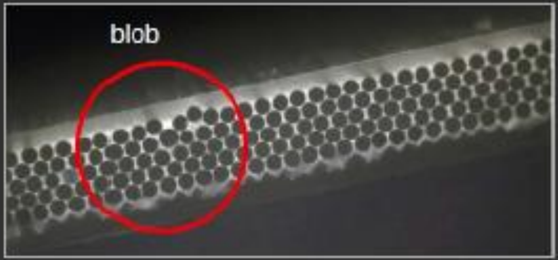
Large scale tracking system based on mats of 2.5m long scintillating fibres of 250µm diameter, readout by SiPMs

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

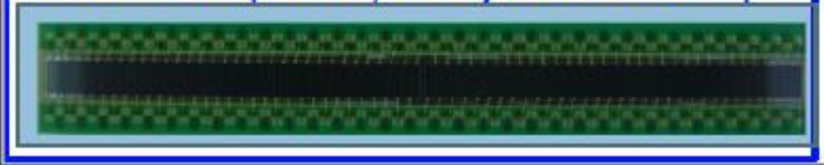
(1)



(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

Silicon PM (SiPM) array: 128 × 250 µm



Muon Systems

Challenges muon system

1) Higher rates in the forward → affects trigger rate, trigger purity, resolving several tracks.

2) Muon channels become even more „golden“ because of their clean signature → robust and efficient muon trigger

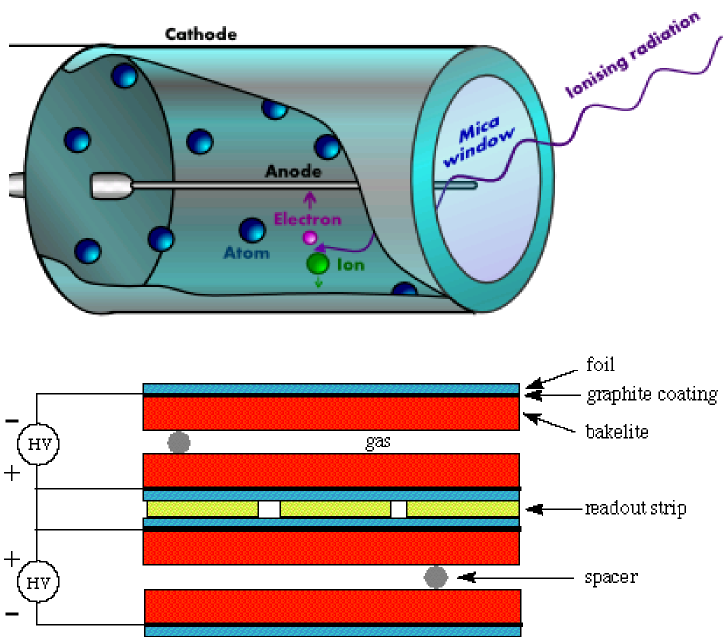
3) Extending acceptance in the forward to gain physics potential. Remember that tracking is already extended.

Avoid rebuilding muon detectors with large areas (construction time >6 years). Possible because of calorimeter shielding.

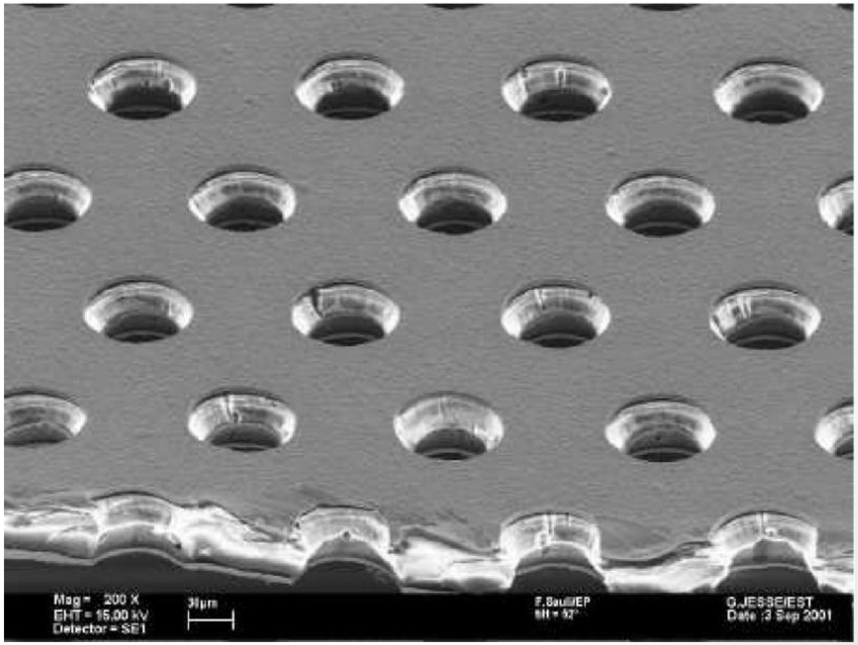
Gaseous detectors with little alternatives. Dedicated R&D accross experiments (RD51, etc.)

Material for (large size) muon systems
= gas-based detectors

Classical: wire chambers of thin spark chambers O(mm)

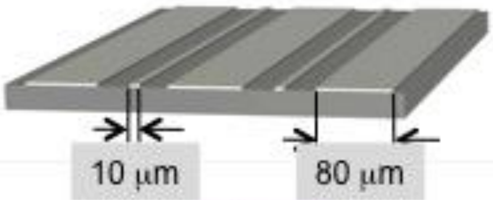


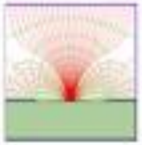
Future: Micro-pattern gas detectors (MPGD) with fine segmentation O(0.1mm)



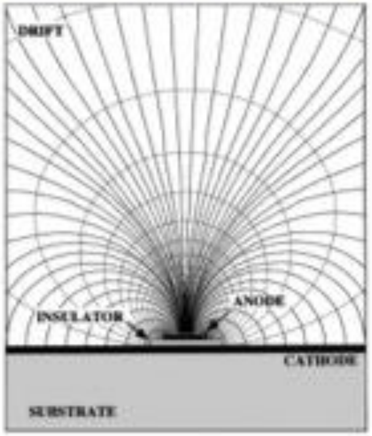
The MPGD Zoo of the 90s

Microstrip Gas Chamber
[A. Oed, NIM A263, 351 (1988)]

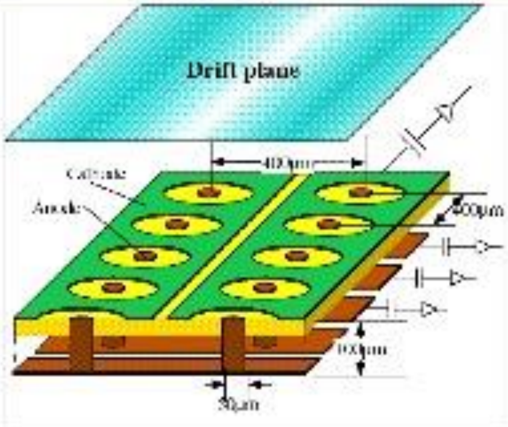




Microgap Chamber (MGC)
[F. Angelini et al., NIM A335, 69 (1993)]

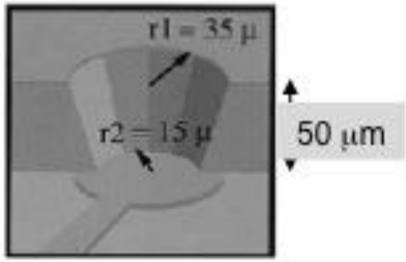


Microdot Chamber
[S.F. Biagi et al., NIM A361, 72 (1995)]

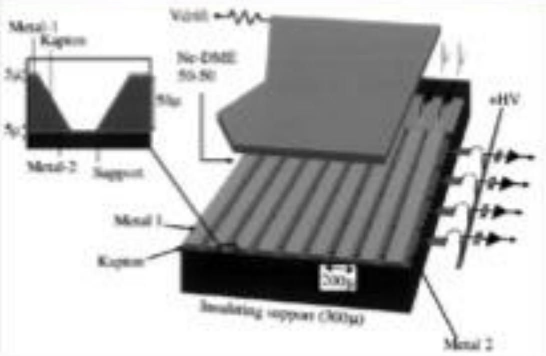


Compteur à Trous (CAT)
[F. Bartol et al., J. Phys. III 6, 337 (1996)]

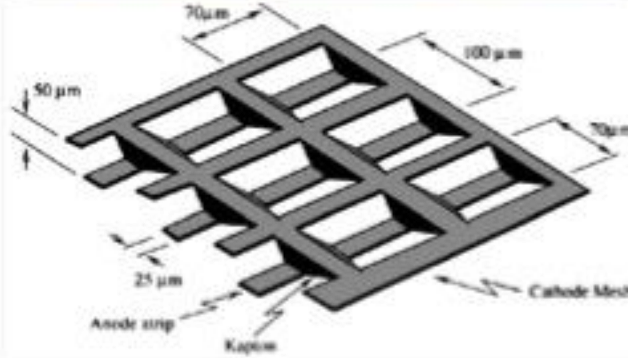
WELL Detector (μCAT)
[R. Bellazzini et al., NIM A423, 125 (1999)]



Micro Groove Counter
[Bellazzini et al., NIM A424, 444 (1999)]



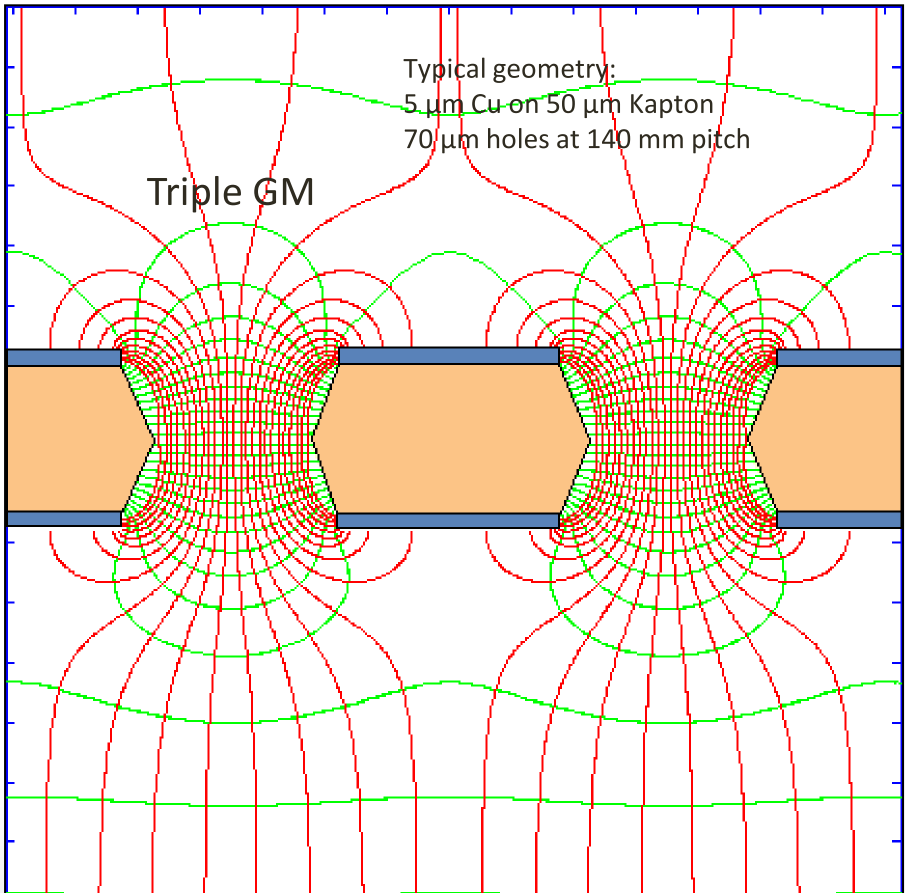
Micro Wire Detector
[B. Adeva et al., NIM A435, 402 (1999)]



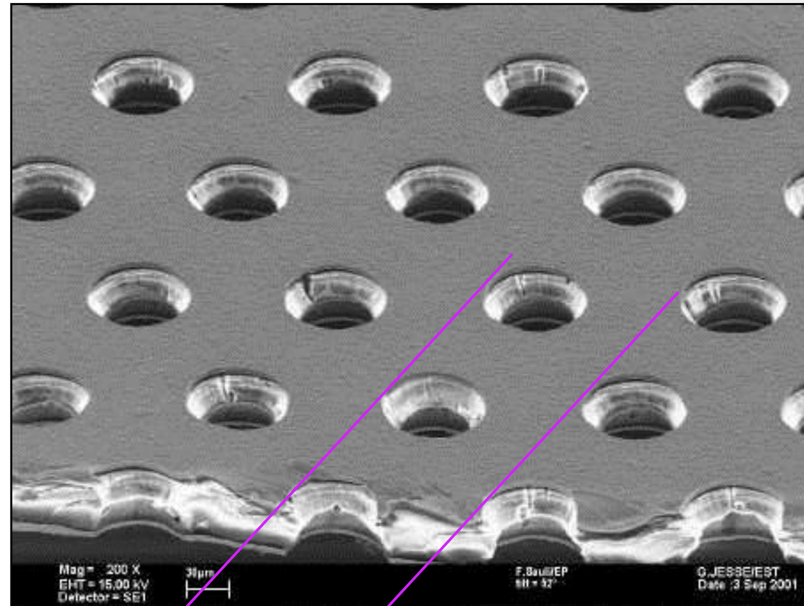
Sauli Sharma Annual Review of Science 1999

Gas Electron Multiplier (GEM)

Thin, metal-coated polymer foil
with high density of holes:

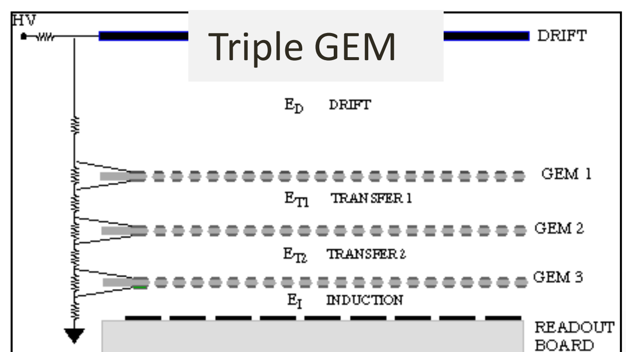


F. Sauli,
Nucl. Instrum. Methods A386(1997)531



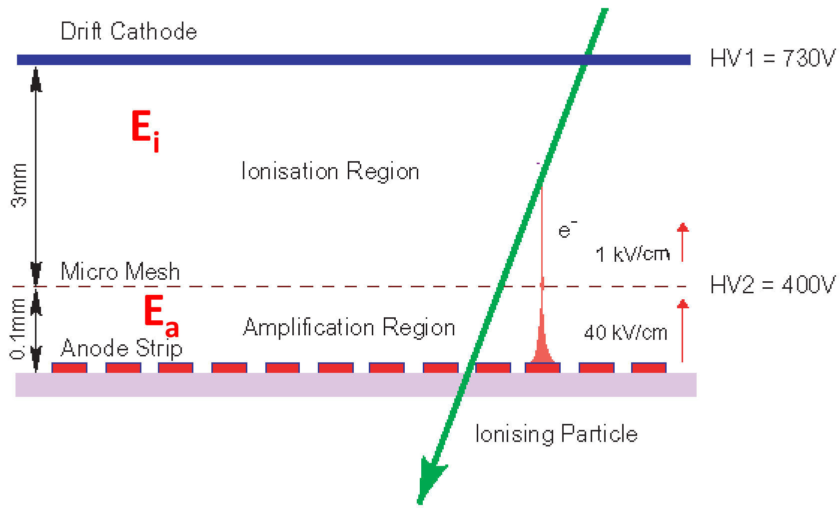
100÷200 µm

Cascaded GEMs permit to attain much larger gains before discharge



C. Buttner et al, Nucl. Instr. and Meth. A 409(1998)79
S. Bachmann et al, Nucl. Instr. and Meth. A 443(1999)464

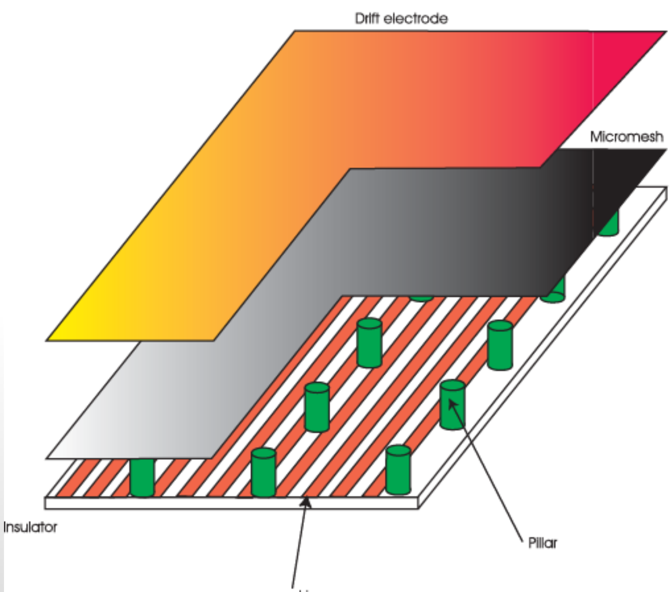
MICROMEGAS (MM): another future technology for gaseous detectors

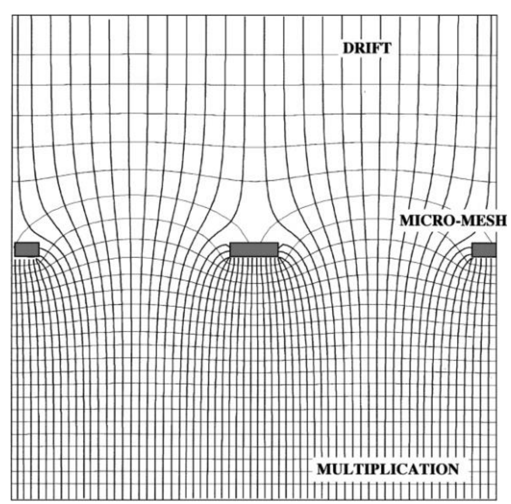


Micromesh Gaseous Structure

[G. Charpak & I. Giomataris et al., NIM A376, 29 (1996)]

- Thin gap parallel plate structure
- Fine metal grid (Ni, Cu) separates conversion (~ 3 mm) and amplification gap (50-100 mm)
- Very asymmetric field configuration: 1 kV/cm vs. 50 kV/cm





→ Fast collection of ions (~ 100 ns)

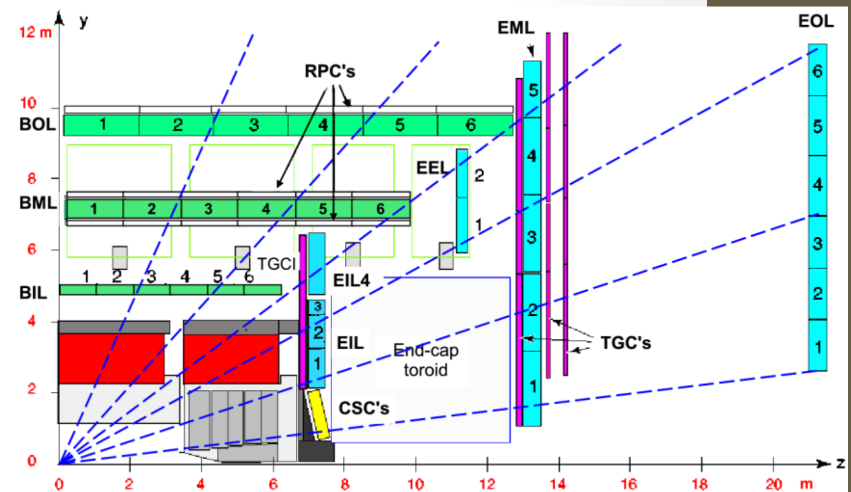
→ Saturation of Townsend coefficient (mechanical tolerances)

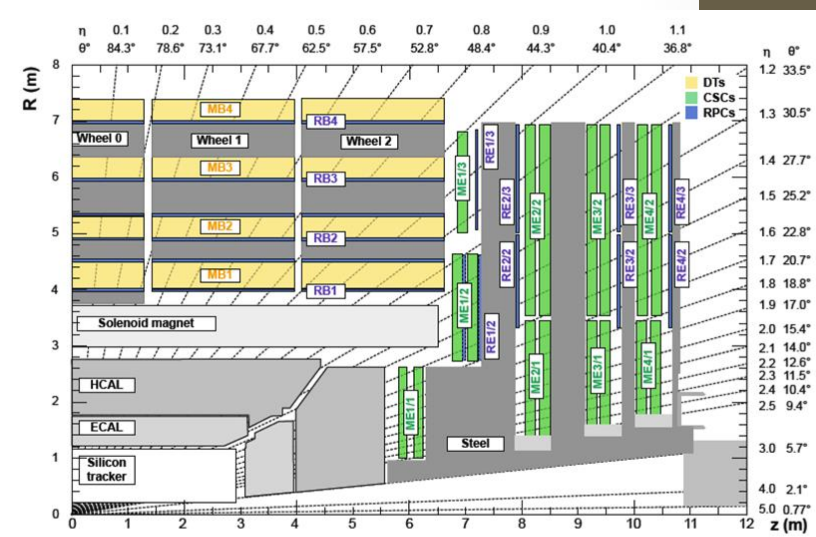
→ good energy resolution

Present CMS and ATLAS

Highly hermetic and redundant muon systems

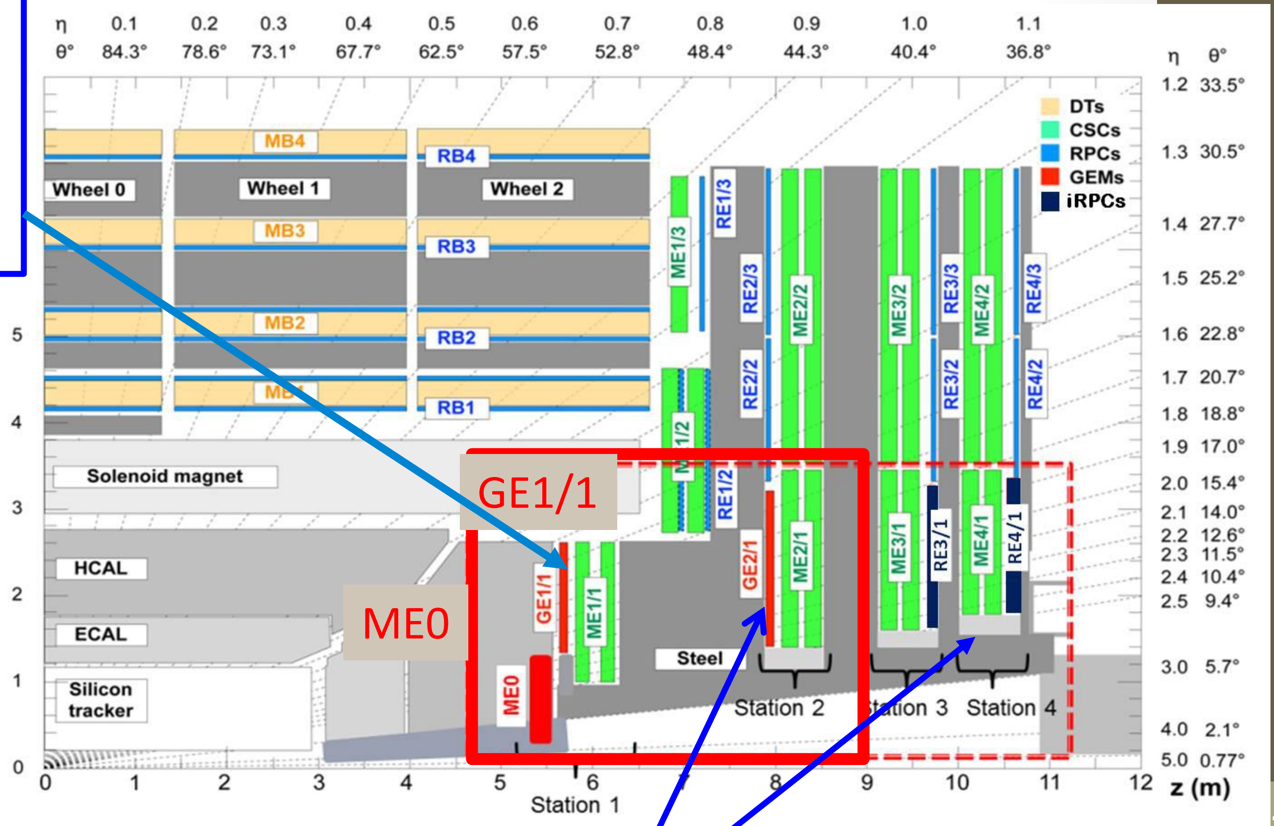
- ATLAS:
  - Drift tubes (MDT) up to η=2.7 with spatial resolution ~80 μm measuring bending
  - Cathode-strip chambers (CSC) in the region 2.0<|η|<2.7 for high rates
  - Resistive plate chambers (RPC) for triggering and second coordinate in the barrel |η|<1.0
  - Thin gap chambers (TGC) for triggering 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: Additional stations in the difficult forward region to address (1)

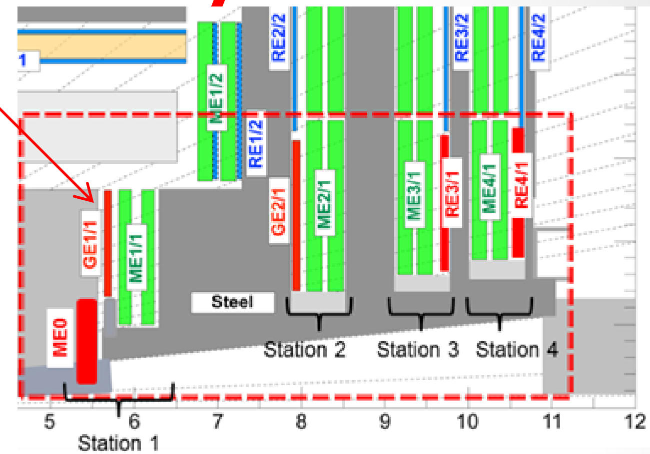
Triple GEM detector (GE1/1): precision chambers to **improve trigger momentum selectivity and reconstruction** already in late LHC phase-1. Installation in LS2 (2018).



Enhance region without redundancy $1.6 < |\eta| < 2.4$ with **maximum rate.**
Technology = GEM (GE2/1) and improved high-rate RPC (RE3/1 and RE4/1)

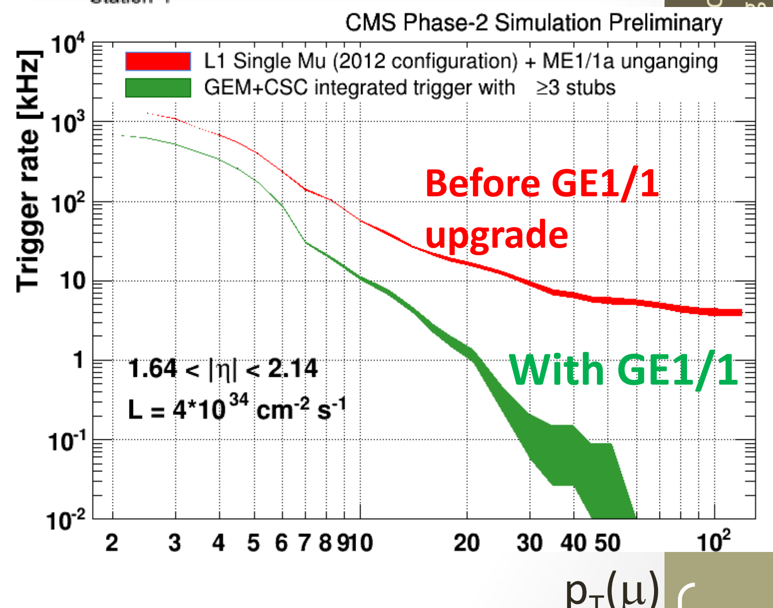
Physics benefit of GE1/1

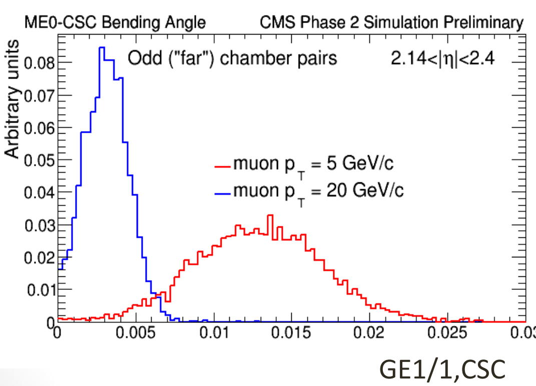
Additional GEM station **(next to ME1/1)**

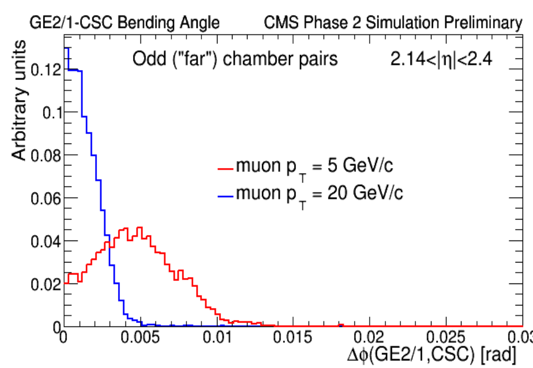


Goal: large reduction of (fake) trigger rate using bending angle

- Need good spatial resolution & rate capability
- Larger lever arms using new detectors and existing CSC chambers in the same station
- Must measure bending angle in station 1







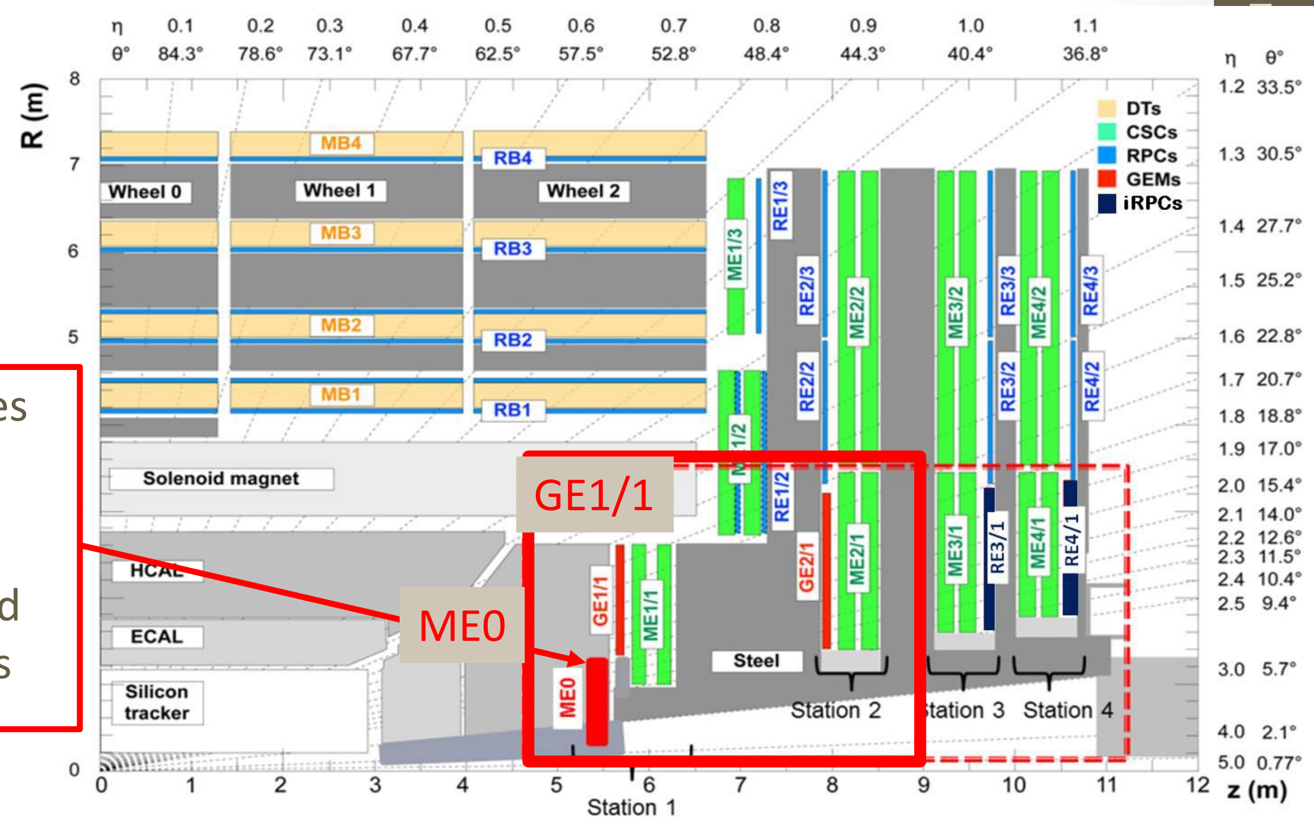
Else radial B-field and multiple scattering quickly diminish discrimination

Expect x5-10 rate reduction with new detectors

CMS: Additional station near calorimeter to extend coverage

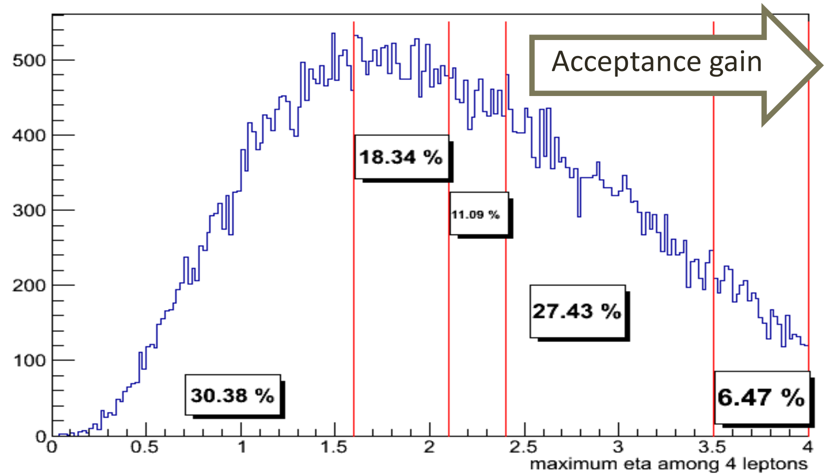
Extended coverage provides muon **tag** in forward region $|\eta|<3$

Several tens of kHz expected
→ GEM technology, 6 layers

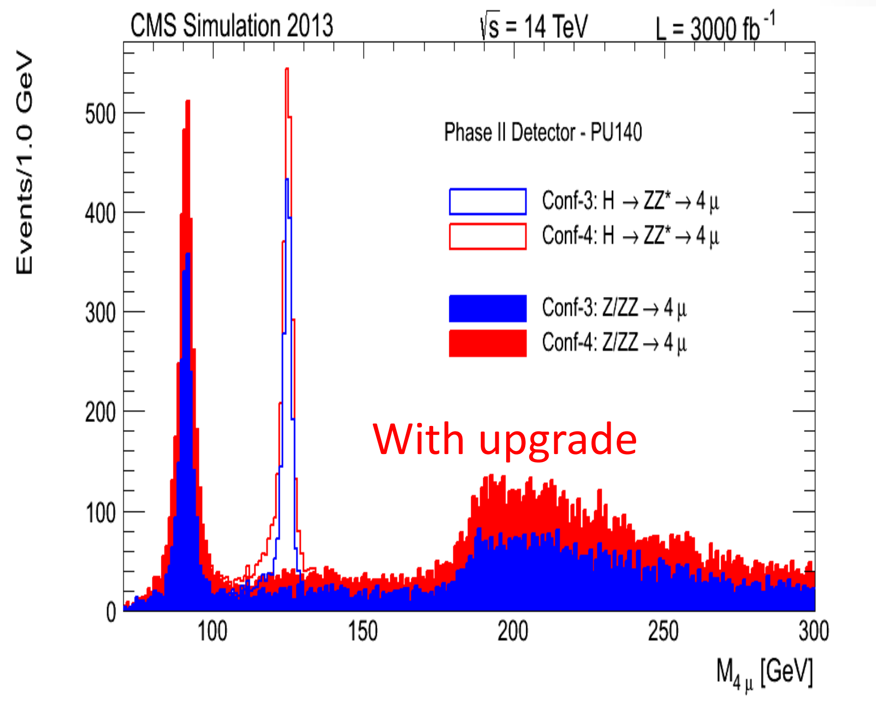


Benefit of Extended Acceptance

Considered extension to |η|~ 4.0 (now 3.0) provides critical benefits for physics, e.g. H → ZZ → 4μ (note: lower mass resolution, also increase in background)

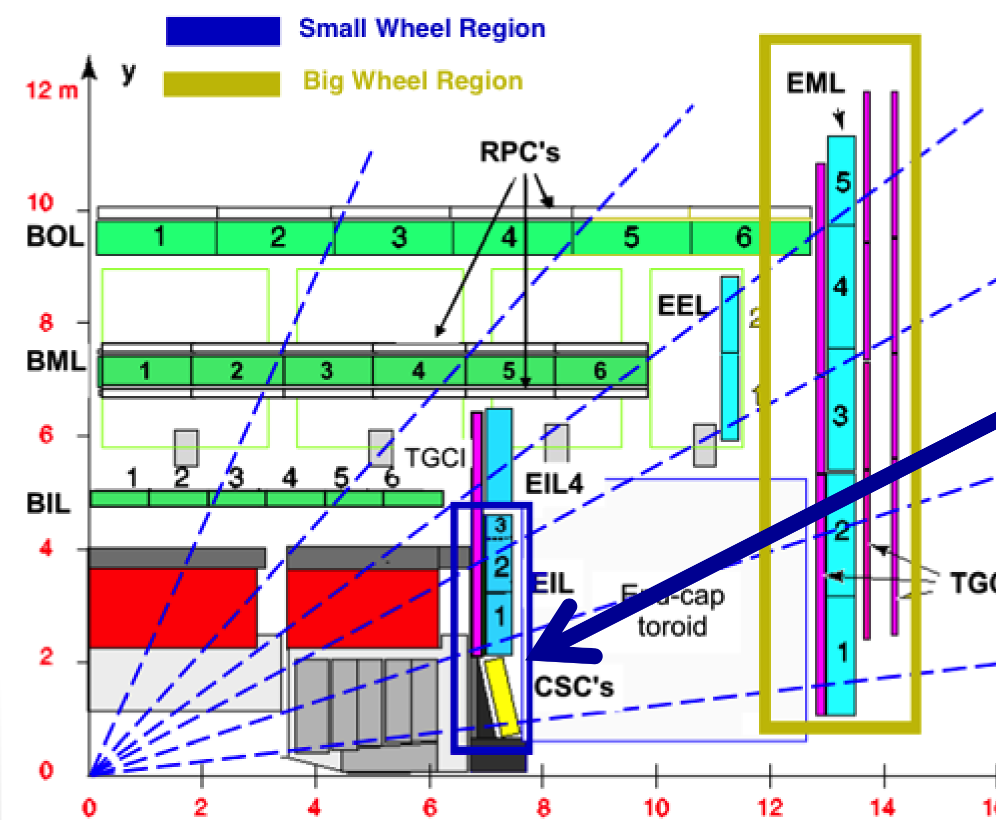


H→ZZ→4μ : acceptance increase 60%→94% if η_{max}=2.4→4.0

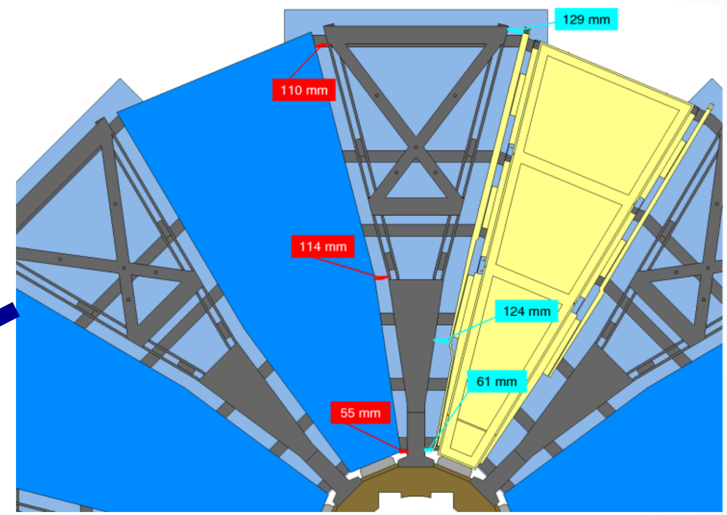


New Small Wheel (NSW)

with finer granularity for lower occupancies and more capabilities to reduce the backgrounds. More punch-through dues to less shielding = more fakes.



Less redundancy with three stations. Again forward region.



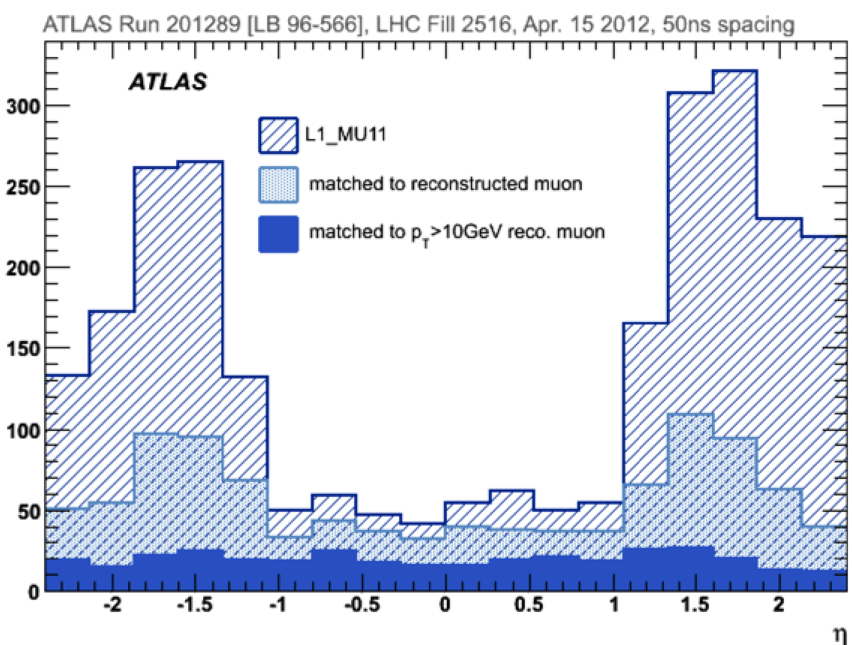
Detector technologies for NSW: Micromegas and small-strip TGCs

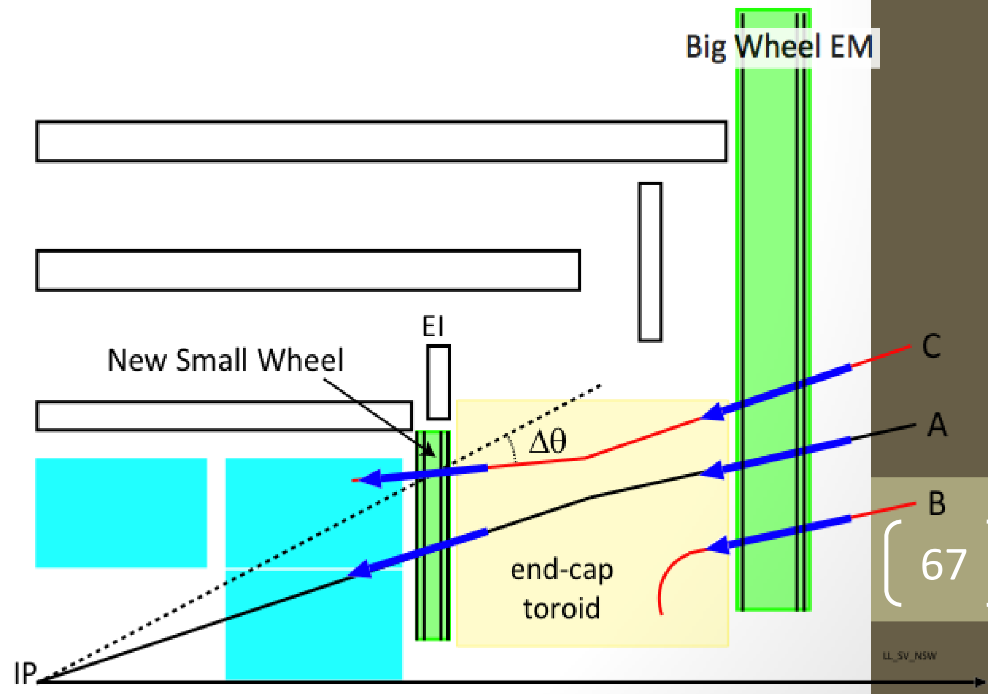
Already in phase-I as consolidation of muon system

Efficient Triggering at high $\mathscr{L}$

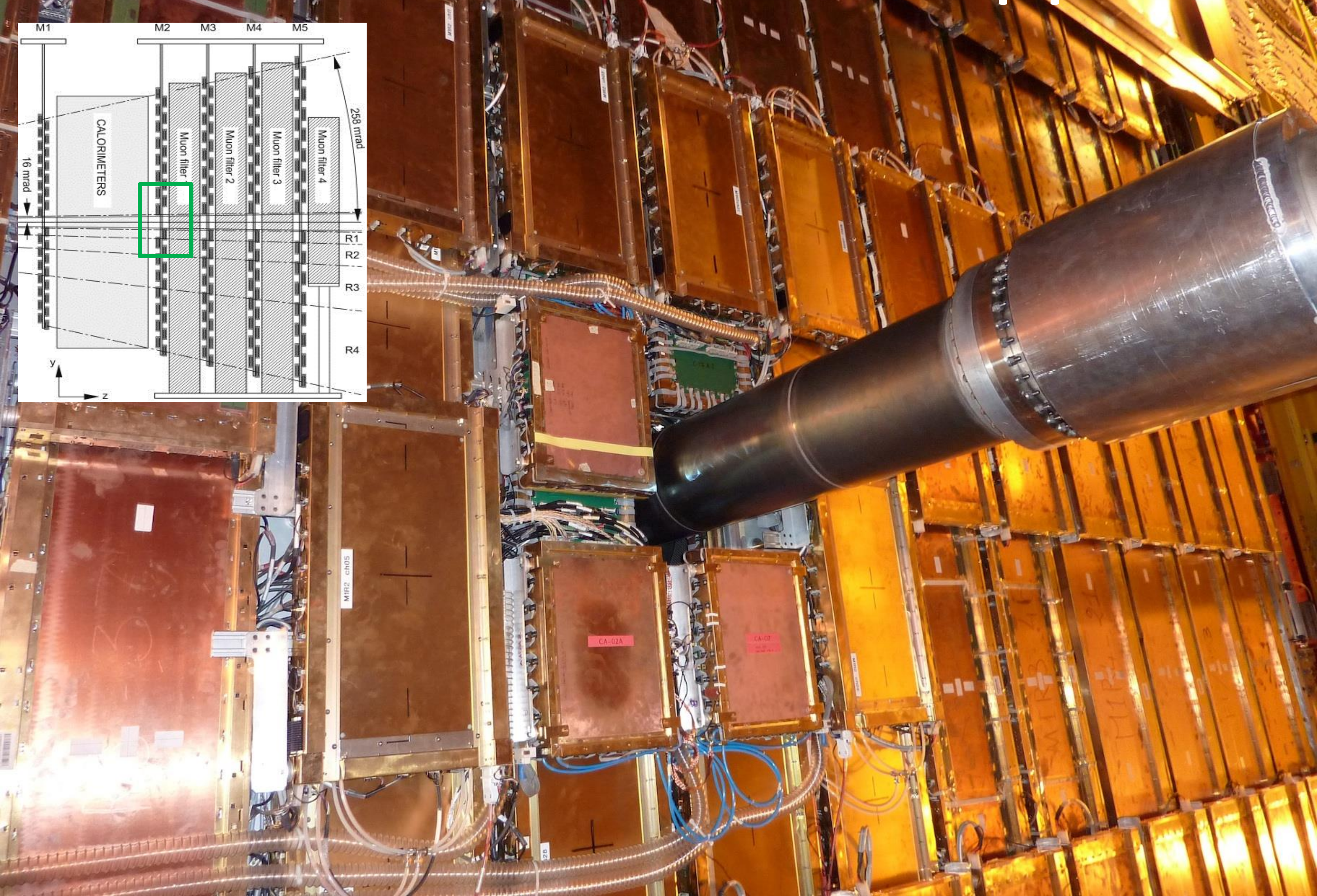
Reduce fake triggers in endcaps to keep a manageable L1 trigger rate → by reducing significantly the unmatched low momentum particles.

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.



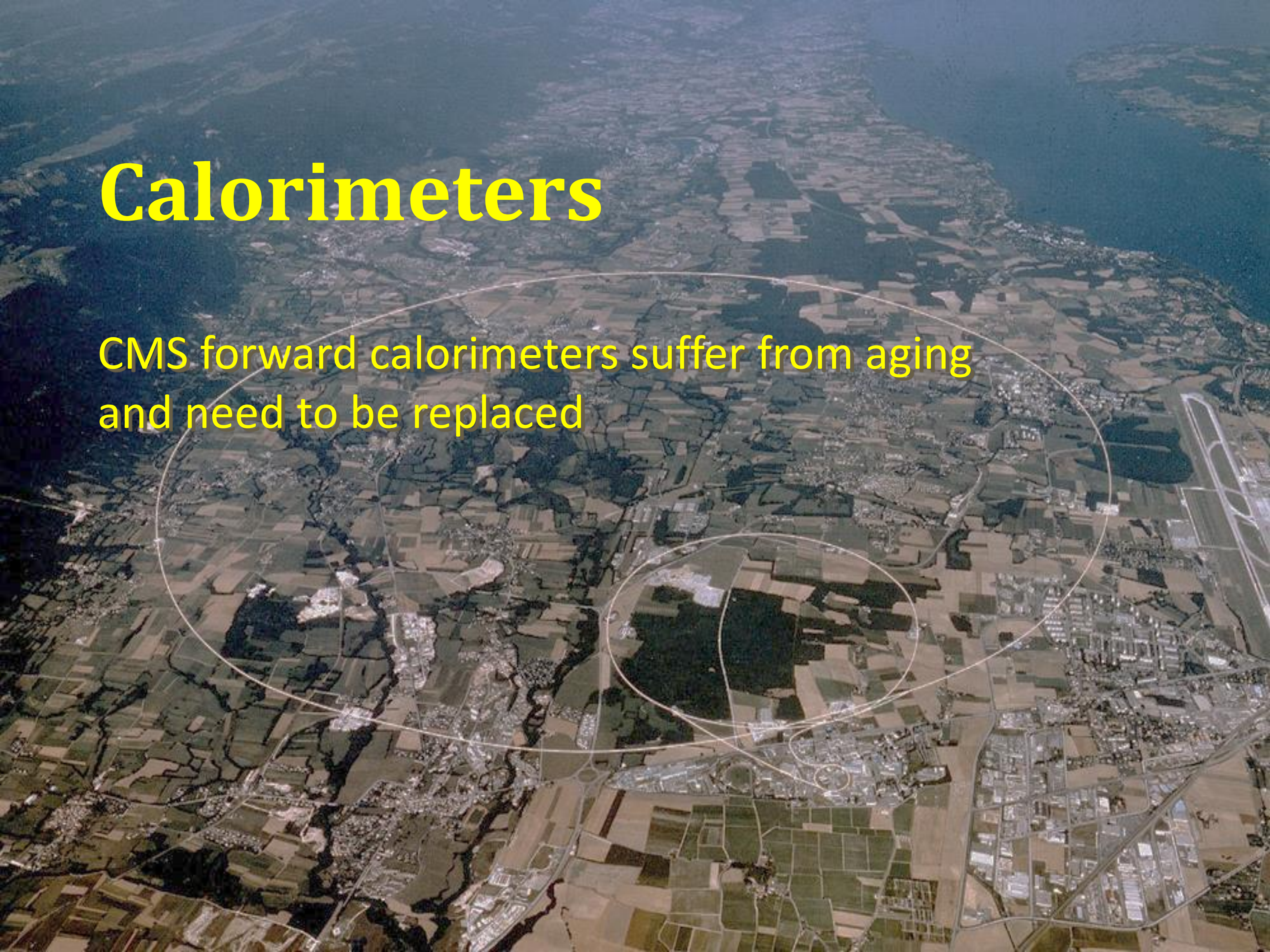


Also LHCb will use GEMs near beampipe



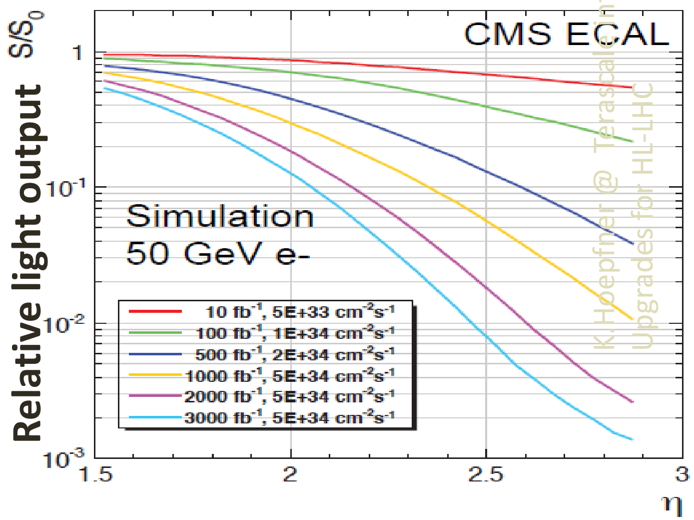
Calorimeters

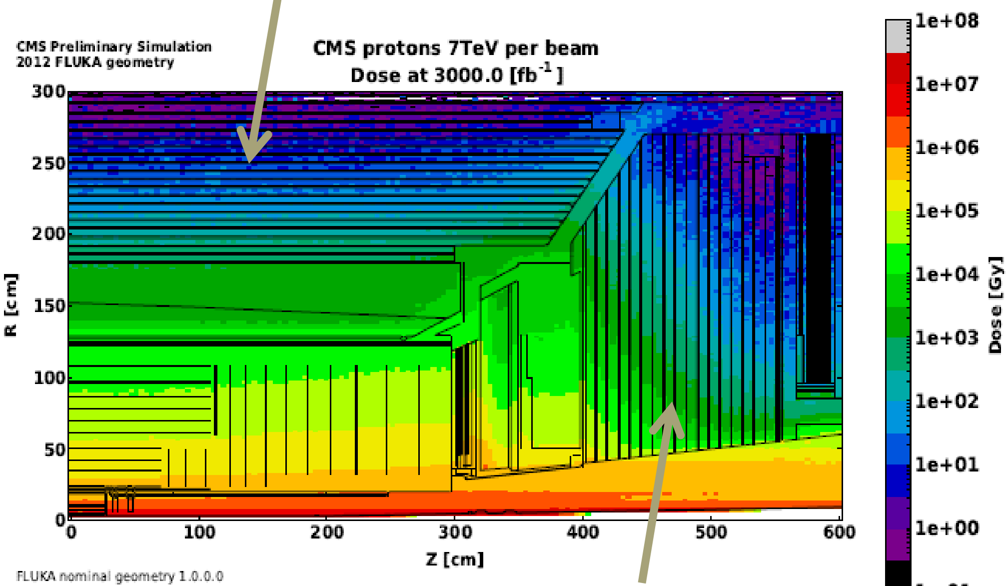
CMS forward calorimeters suffer from aging and need to be replaced

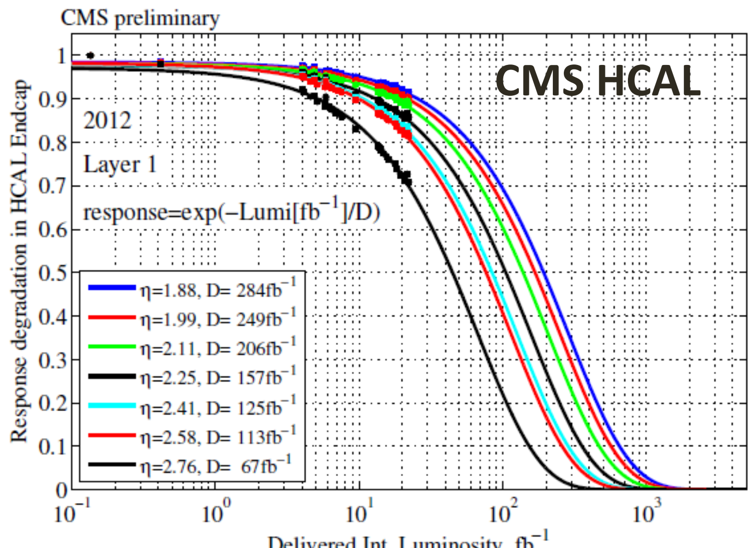


Calorimeters

- At present $PbWO_4$ crystals in ECAL barrel and scintillator-tile HCAL.
- Active detectors can stay in barrel where rad damage is less. Electronics needs replacement to cope with new trigger rates/latency







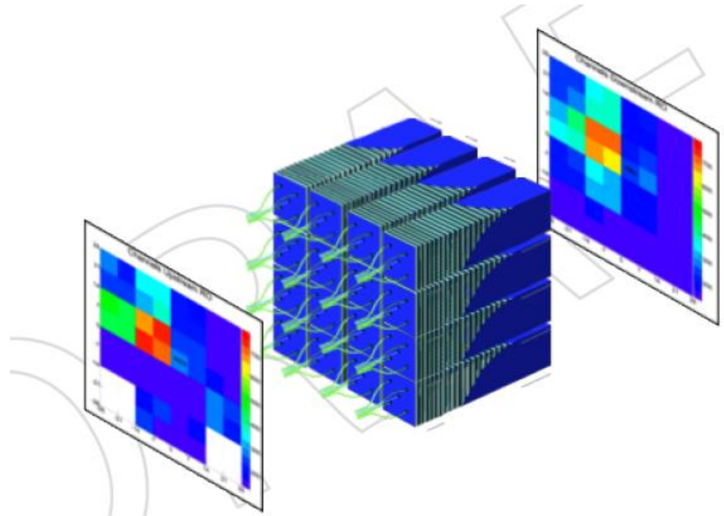
Radiation dose strong function of eta. Variation in forward region by 100.

Two Scenarios for Forward Calorimetry

Need to replace forward calorimeters after 500/fb due to ageing damage

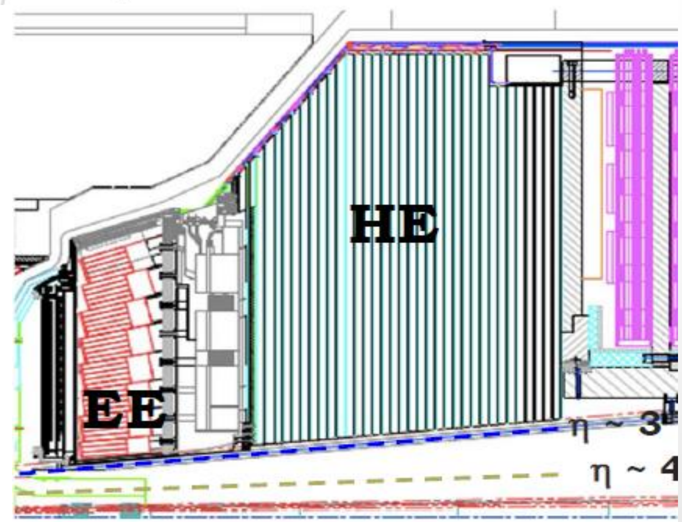
Scenario 1

- Maintain present geometry with ECAL and HCAL stand-alone
- ECAL Endcap in Shashlik design
- HCAL Endcap re-build as radhard



Scenario 2

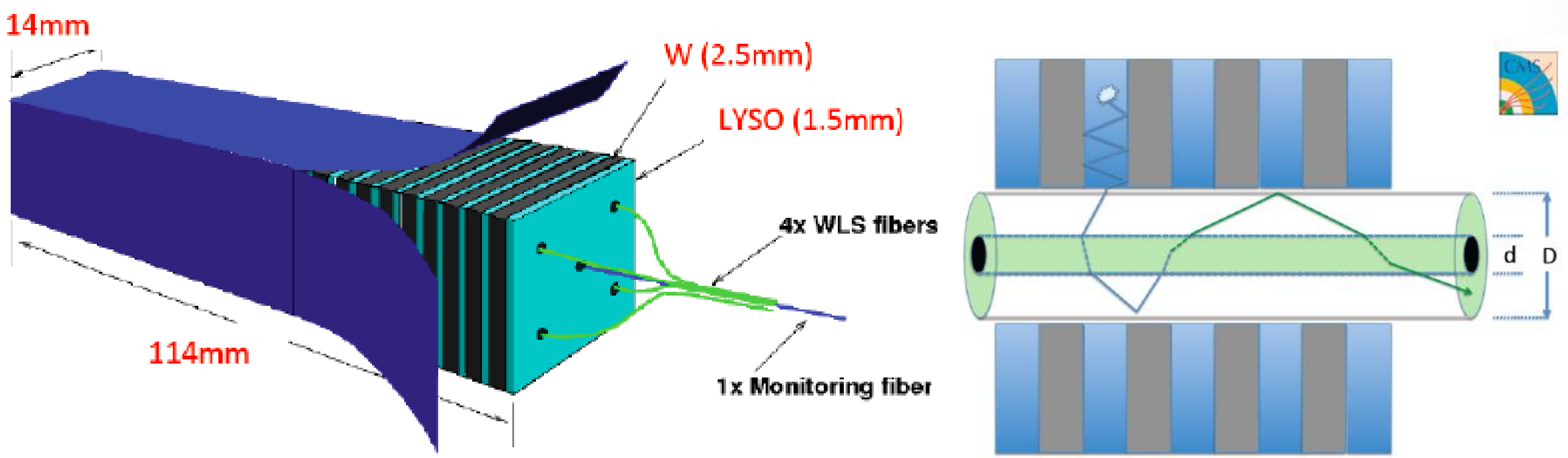
- New integrated design as a High Granularity Calorimeter (HGC)
- Particle flow imaging calorimeter



Scenario 1: Shashlik ECAL

Sampling calorimeter w/out depth segmentation, very compact X_0~25

- Radhard inorganic scintillator. Best performance with LYSO and tungsten & brass as absorber
- Light readout with WLS in shashlik configuration
- Readout with GaInP photosensors (radhard due to larger band gap)



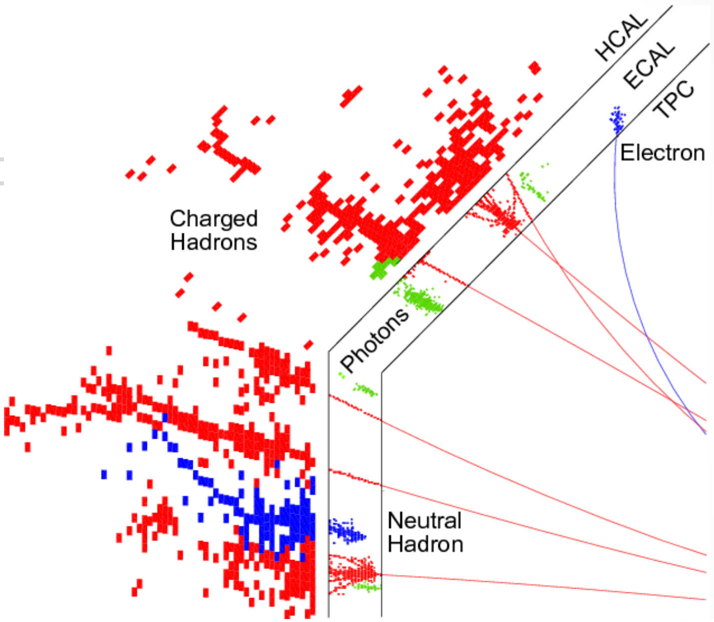
- **Good energy resolution $\Delta E/E = 10\%/\sqrt{E}$**
- Very compact and highest light yield
- Small Moliere radius (14mm) provides **fine granularity** for pile up mitigation (matching with tracker)

Two Scenarios for Forward Calorimetry

Need to replace forward calorimeters after 500/fb due to ageing damage

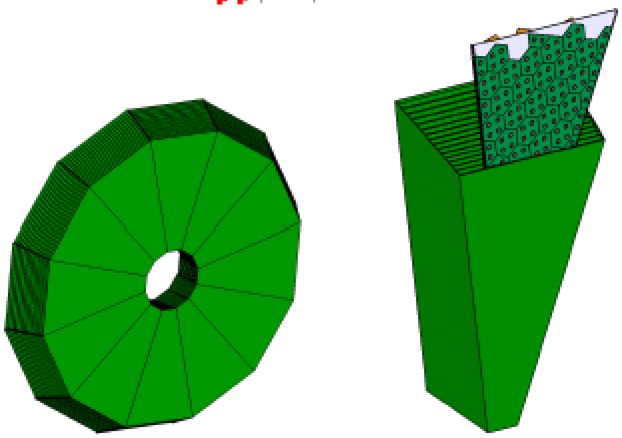
Scenario 1

- Maintain present geometry with EE and HE stand-alone
- EE in Shashlik design
- HE re-build as radhard

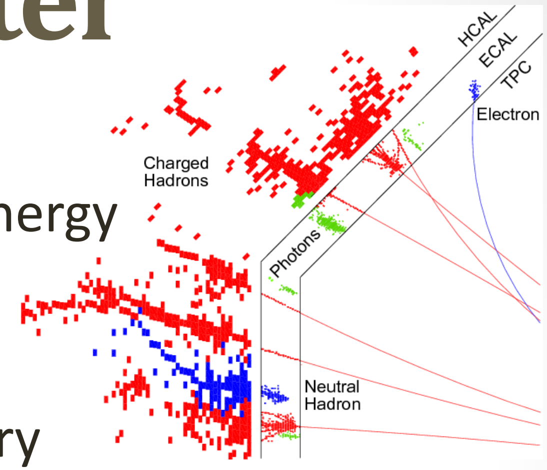


Scenario 2

- New integrated design as a High Granularity Calorimeter (HGC)
- Particle flow imaging calorimeter



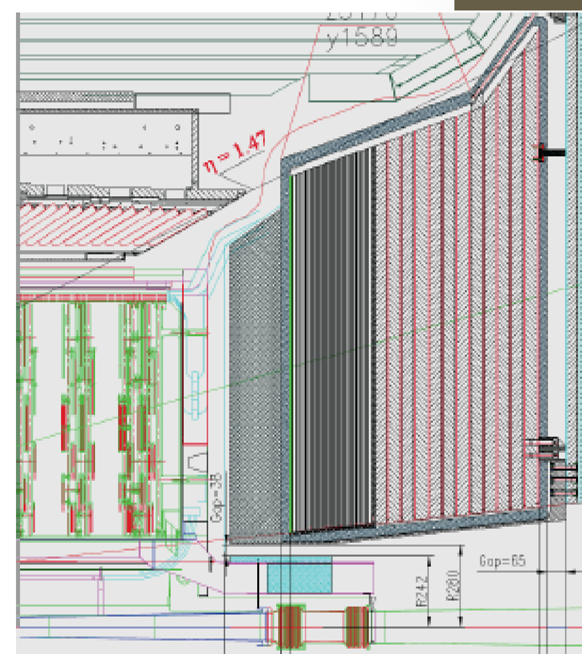
Scenario 2: High-granularity combined calorimeter



High granularity calorimeter (HGCAL) based on ILC/CALICE development. Key point: "visualize" energy flow through fine granularity and longitudinal segmentation.

- Good **resolving power for single particles** in very dense jets. $\Delta E/E = 10\%/\sqrt{E}$

- Planes of Si separated by layers of Pb/Cu or brass
- Exploits developments on Si rad.hardness and price



Structure:

- E-HG: 33 cm, 25 X_0, 1λ, 31 layers. Absorber W/Pb
- H-HG: 66 cm, 3.5λ, 12 layers, Absorber brass
- B(back)-HG as HE re-build 5 λ

Opens up possibility to extend to $|\eta|$~4

High Granularity Calorimeter

Fine depth segmentation

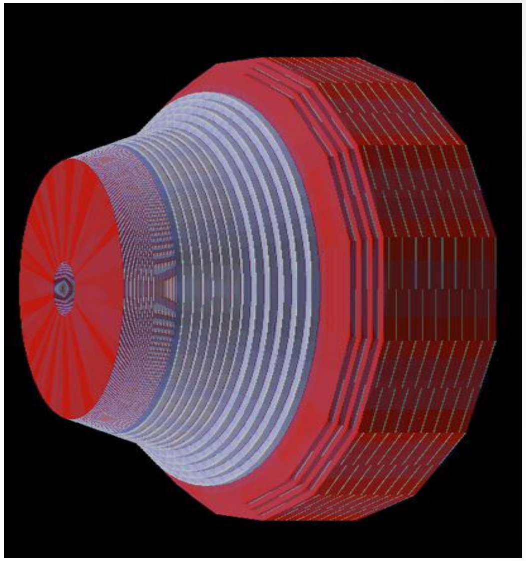
ECAL: ~33 cm, 25 X_{0}, 1λ, 31 layers:

- 11 planes of Si separated by 0.5 X_0 of lead/Cu
- 10 planes of Si separated by 0.8 X_0 of lead/Cu
- 10 planes of Si separated by 1.2 X_0 of lead/Cu

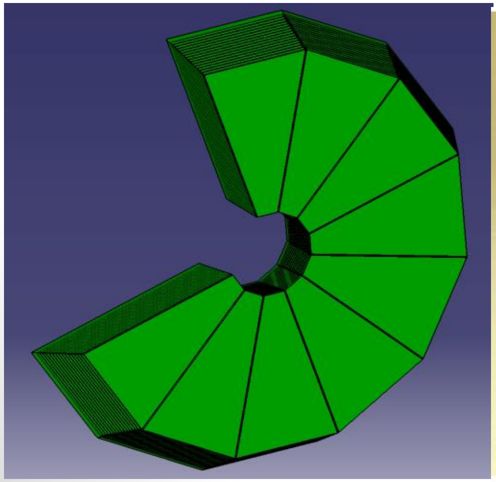
HCAL: ~66 cm, 4λ:

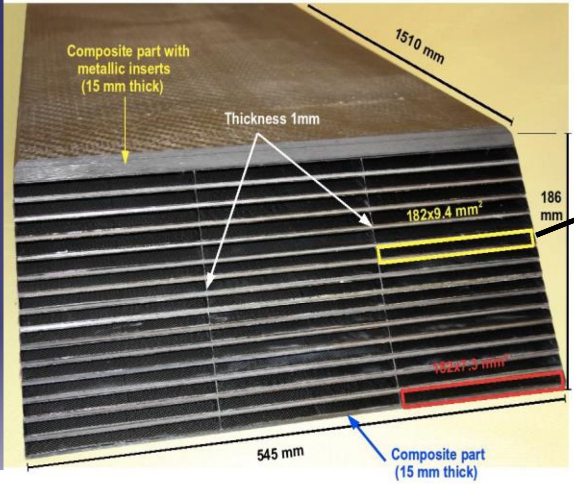
- 12 planes of Si separated by 40 mm of brass

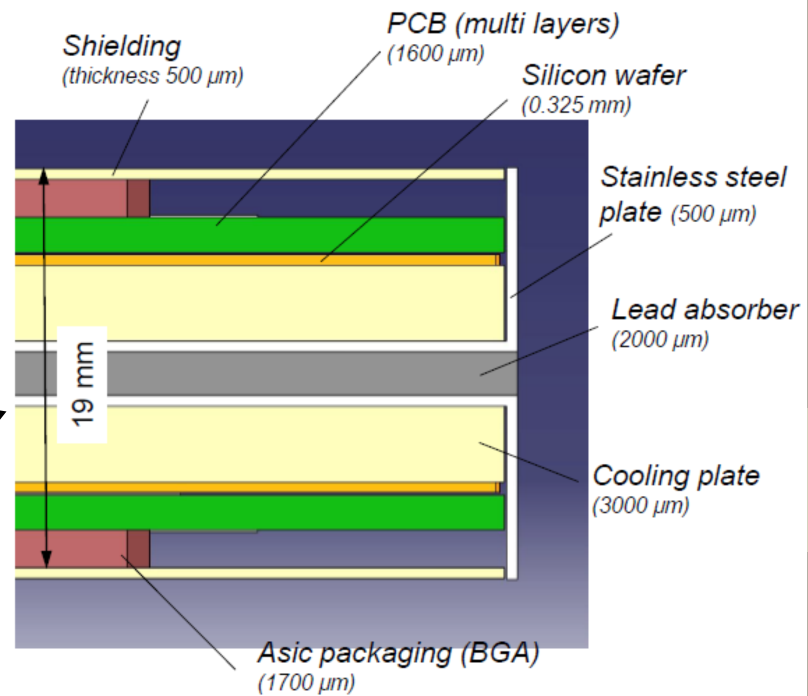
- Fine grain pads 0.9 cm^2 to 1.8 cm^2
- 3.7/1.4 Mch & 420/250 m^2 Si in E/H



Back HCAL as HE re-build 5λ with increased transverse granularity







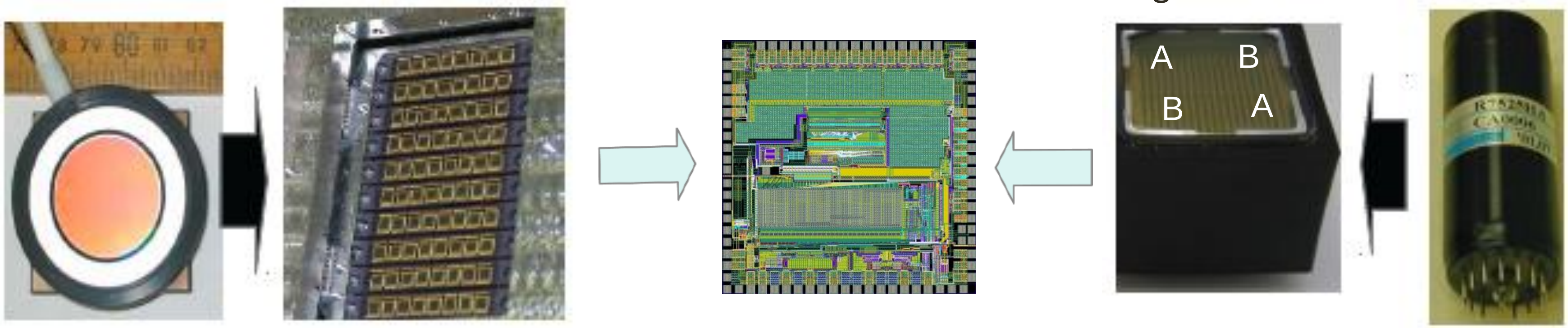
Establish Depth Segmentation

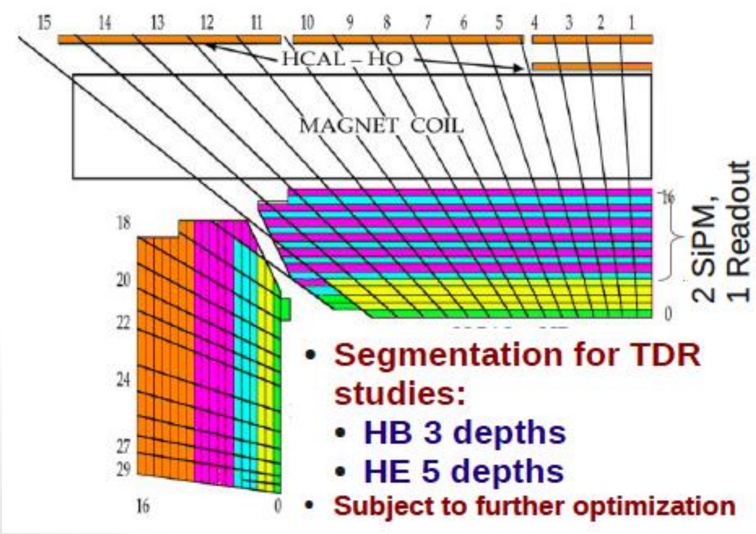
Phase I CMS HCAL Read-Out Upgrades

Replace Photo-transducers to reduce noise & improve performance. Improve with new FE Chip.

HB/HE/HO
From HPD to SiPM's

HF
From single to multi-anode PMT's



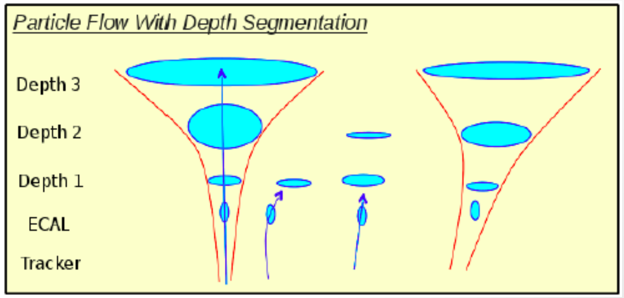


SiPM's to increase HB/HE Depth Segmentation

- Improved PF Hadronic shower localization

Provides effective tool for PU mitigation at HL

- Mitigate radiation damage to scintillator & WLS fibers



Summary

- Why? Solve open questions and find new physics
- Challenges of HL:
  - Radiation, material damage
  - High rates, selective triggers and radiation resistant detectors
- Operation >2025: electronics more than 20 years old
- Substantial trigger upgrades including tracking and finer granularity
- Complete replacement of tracking system
- Several additions to muon systems to increase acceptance

Interested to join?