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Overview of the Tracker Upgrades

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on behalf of ALICE, ATLAS, CMS, and LHCb

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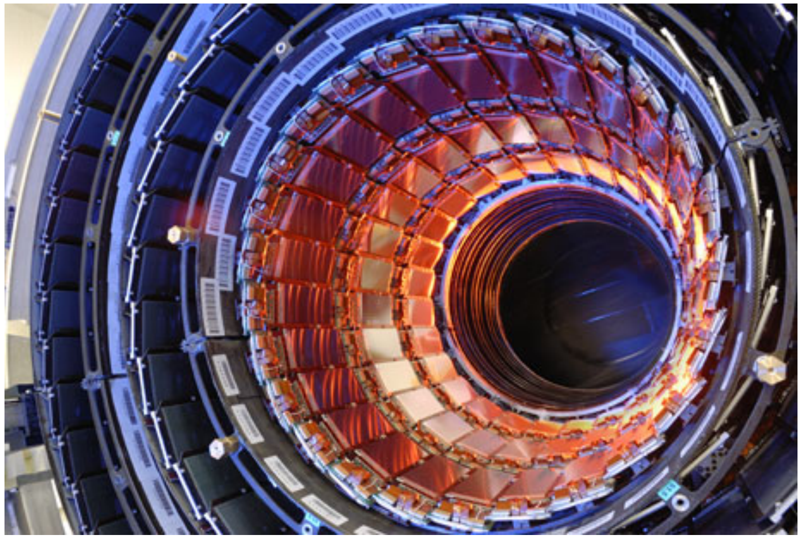
Introduction

- The challenging physics program and environment require excellent tracking capabilities for all four LHC experiments.
  - Current trackers are performing outstandingly well.
- Improvements/replacements of the trackers will be necessary for the running after LS2 and LS3.
- Two main considerations:
  - Bandwidth saturation and occupancy: frontend electronics designed to accomodate occupancies of up to 50 pile-up events.
  - Radiation Damage: Current detectors not designed to withstand the expected fluences beyond LS3.
- All four experiments will upgrade their tracking systems in the next decade
  - LS2: ALICE, LHCb
  - LS3: ATLAS, CMS
- All tracker designs are based on the experiences in building and running the current trackers.



Current CMS Strip Tracker

Performance Improvement

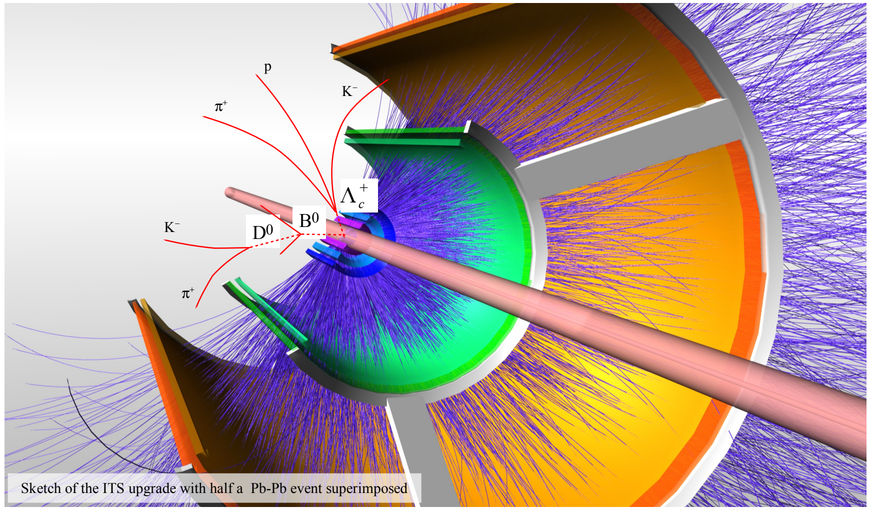
	Increase granularity at large radii	Increase granularity close to the IP (small pixels)	Increase number of pixellated layers	Reduce material
Fast and efficient pattern recognition in high pileup	ATLAS, CMS	ATLAS, ALICE, CMS, LHCb	ALICE, CMS, LHCb	
Improve momentum resolution at low pT				ATLAS, ALICE, CMS, LHCb
Improve momentum resolution at high pT	ATLAS, CMS			
Improve tracking efficiency	ALICE			ATLAS, ALICE, CMS, LHCb
Improve impact parameter resolution		ATLAS, ALICE, CMS, LHCb		
Improve two-track separation		ATLAS, ALICE, CMS, LHCb		
Reduce photon conversions				ATLAS, ALICE, CMS, LHCb

Tracker Upgrades during LS2
ALICE and LHCb

ALICE Tracker Upgrade

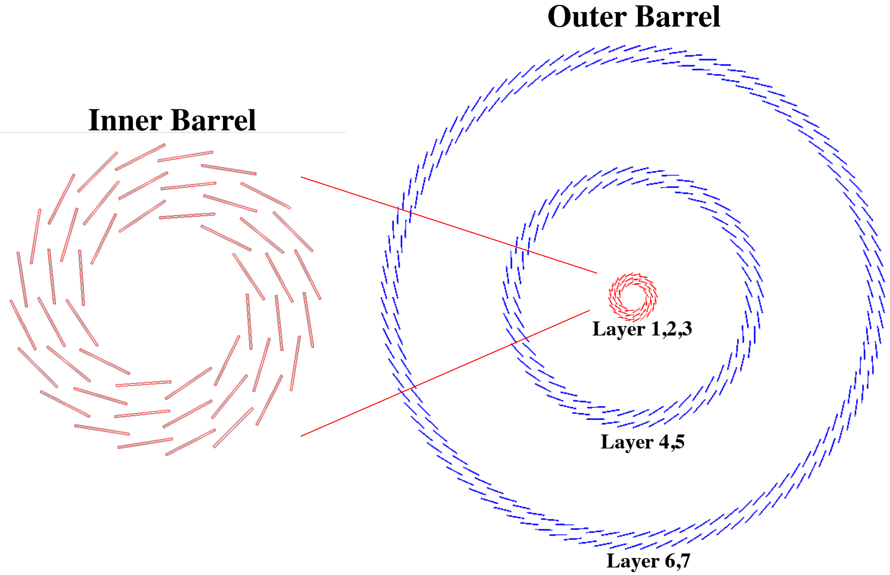
- After LS2 Pb−Pb collisions at 50 kHz expected
- Opens the door for a unique physics program in 10 nb^{-1} regime
- Requires significant upgrade of the inner tracking system (ITS) and time projection chamber (TPC).
- TPC Upgrade: replacement of multi-wire chambers with GEM detectors
  - not covered in this session -> Muon session (Thursday)

- New high-resolution, low material Inner Tracking System (ITS)
  - Measurements closer to interaction point
  - Reduce material budget: 0.003 X0/layer
  - Increase granularity
  - Increase η coverage



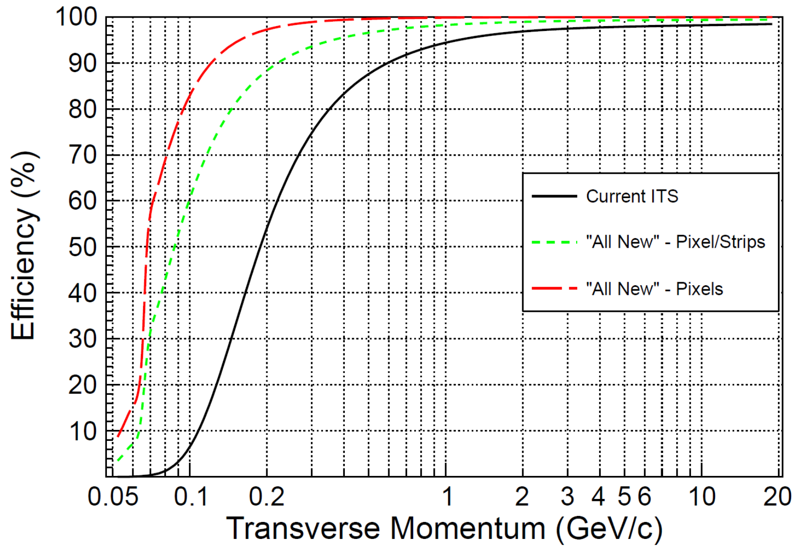
Sketch of the ITS upgrade with half a Pb-Pb event superimposed

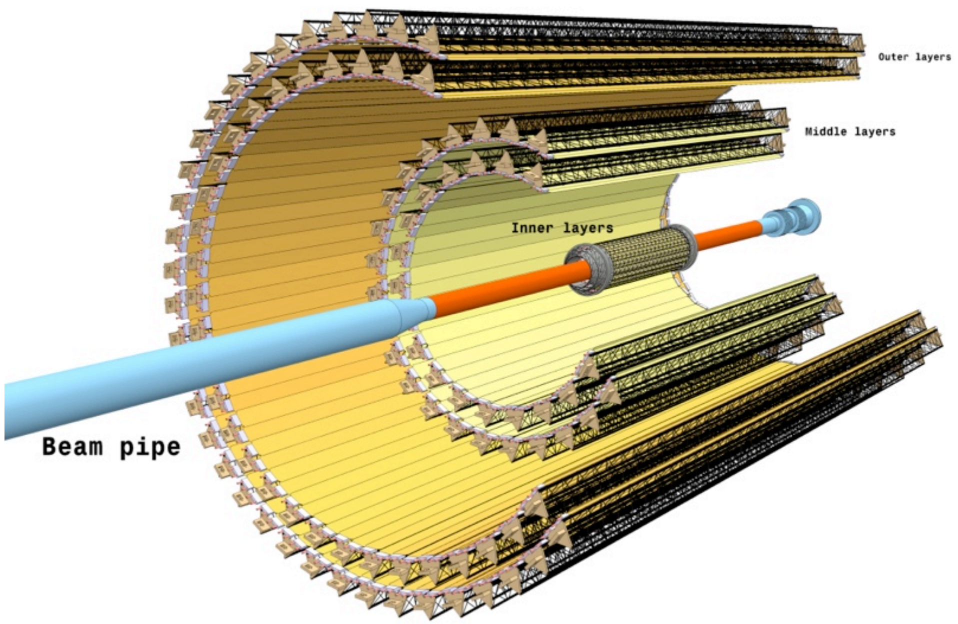
Schematic Layout



ALICE Pixel Detector

- Different options for the layout were studied
- Baseline design
  - 7 layers of monolithic pixel detectors
  - Improved standalone tracking efficiency and pt resolution
- Under investigation: Enable charge amplitude measurement in outer layers for dE/dx measurement -> PID





Option A: 7 pixel layers

Resolutions: $\sigma_{r\varphi}$ = 4 μm, σ_z = 4 μm for all layers

Material budget: X/X_0 = 0.3% for all layers

Option B: 3 layers of pixels + 4 layers of strips

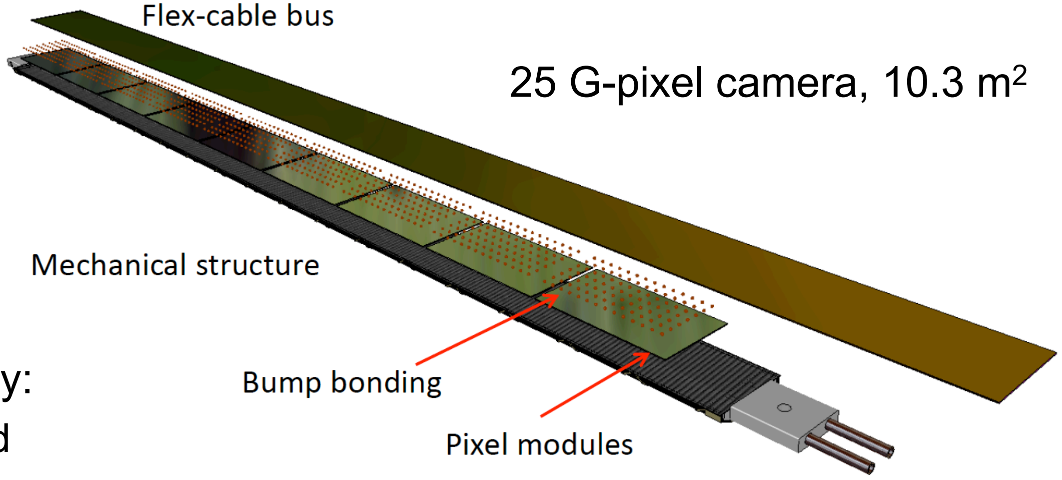
Resolutions: $\sigma_{r\varphi}$ = 4 μm, σ_z = 4 μm for pixels

$\sigma_{r\varphi}$ = 20 μm, σ_z = 830 μm for strips

Material budget: X/X_0 = 0.3% for pixels

X/X_0 = 0.83% for strips

ALICE Pixel R&D

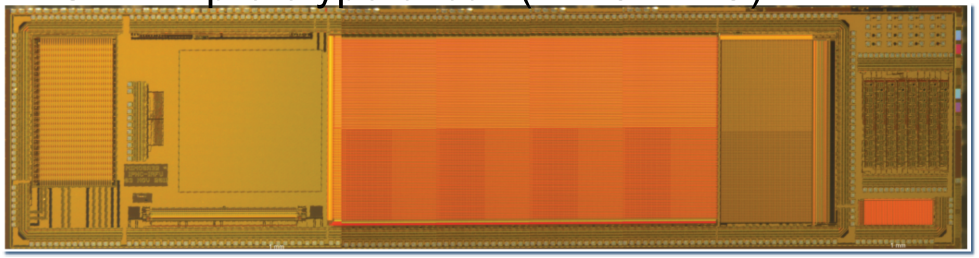


25 G-pixel camera, 10.3 m^2

- Sensor baseline decision: Monolithic pixels for all 7 layers
- Chosen technology is the Tower Jazz Technology
- Three different architectures under study:
  - MISTRAL/ASTRAL (IPHC-IRFU) based on MIMOSA
  - CHERWELL2 (RAL) based on FORTIS and TPAC
  - ALPIDE (CERN-INFN-CCNU)

- Modules/stave:
  - carbon fibre structure
  - cooling
  - sensors
  - polimide printed circuit board

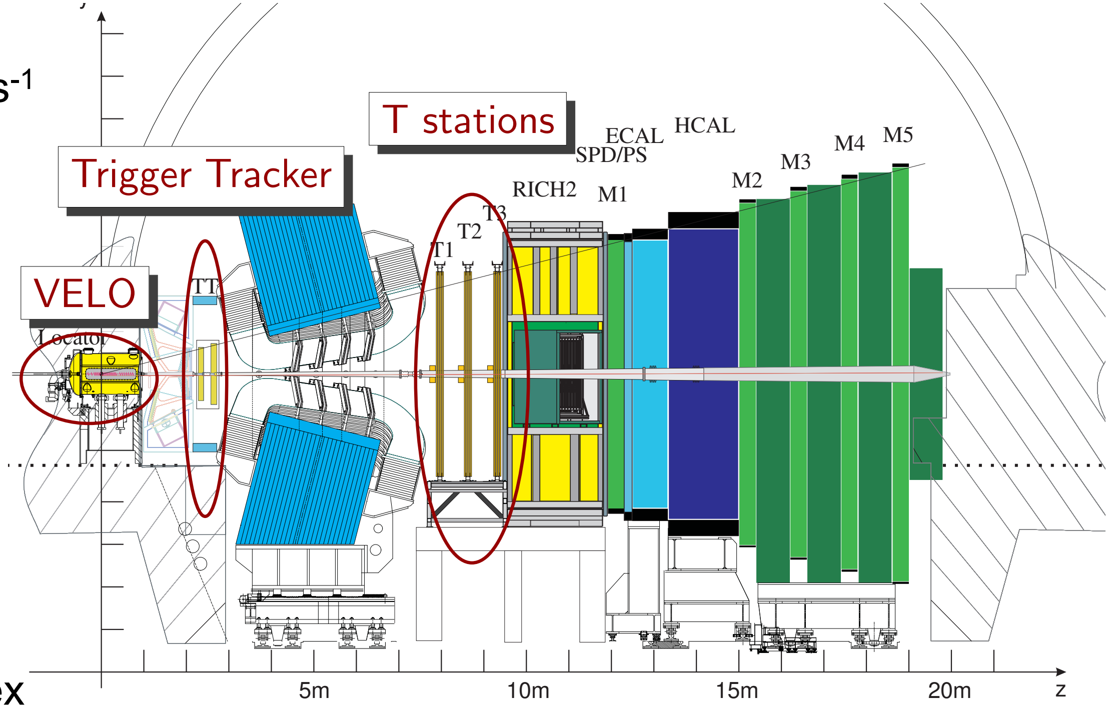
MISTRAL prototype circuit (IPHC-IRFU)



ALPIDE (CERN-INFN-CCNU)

LHCb Tracker Upgrade

- Increase luminosity to L=2x10^{33} cm^{-2}s^{-1} to reach 10fb^{-1} per year
  - Better event selection at 40MHz readout and software trigger
- Event topology is more complex
  - More primary vertices
  - Increased track multiplicity
  - Detector occupancy



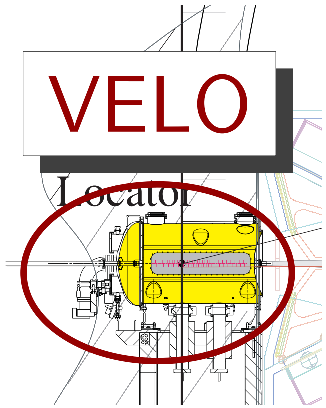
- Excellent momentum, time, and vertex resolution
- Keep or improve current detector performance under more challenging conditions
- Maintain high track efficiency (~90% when p≥5GeV)

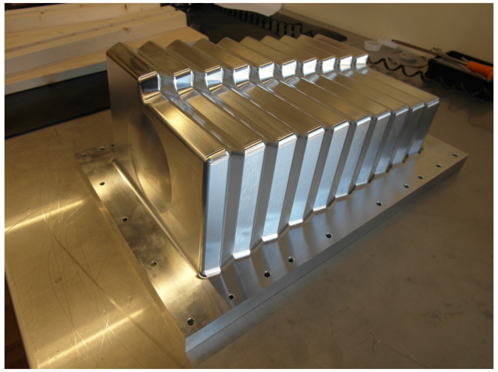
- Planned LHCb tracker upgrades during LS2
  - replace Vertex locator (VELO)
  - Trigger tracker: replace sensors
  - T stations: redesign high occupancy regions
- Upgrade of all electronics to cope with 40MHz readout

LHCb VELO

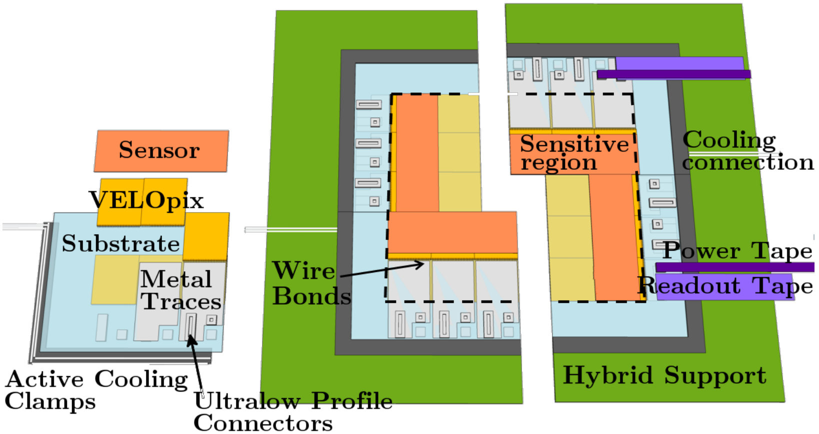
Upgrade challenge :

- Withstand increased radiation
- Close to beam pipe within vacuum
- High data volume
- Keep or improve current performance
  - Lower material budget
  - Enlarge acceptance





RF Foil for new VELO

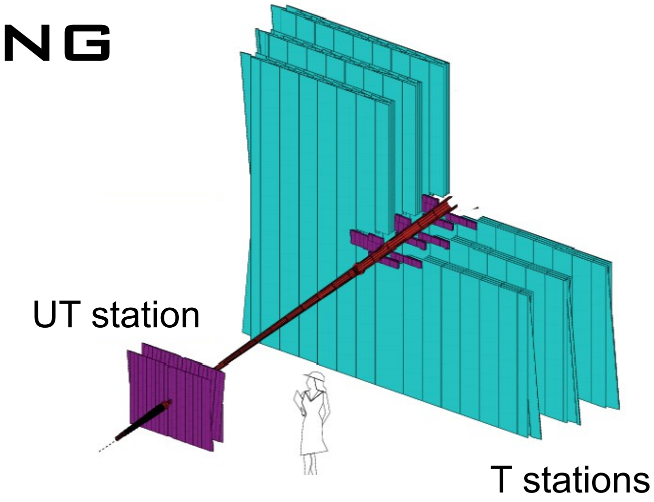


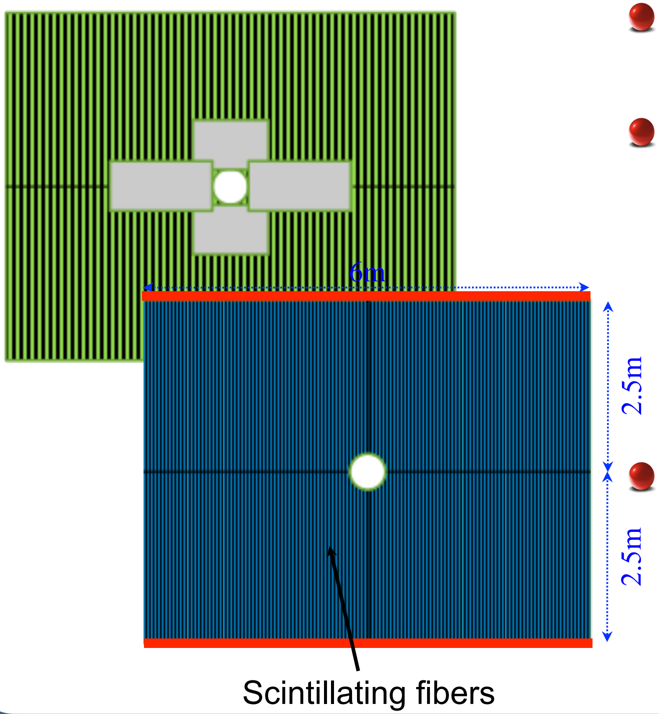
(a) Proposed pixel module

- **Technical choice :**
  - Pixel sensors with micro channels cooling
  - Thickness 300 µm → 150 µm
  - Move closer to the beam : inner aperture 5.5 mm → 3.5 mm
- Hybrid pixel with chip based on Timepix chip
  - 55 µm x 55 µm pixel size, advantageous for pattern recognition
- L-shaped half modules with two blocks of 6 chips
- Several sensor options being investigated

LHCb Downstream tracking

- Upgrade of Trigger Tracker station (UT) in front of magnet
  - Challenges: low mass, cooling and segmentation to reduce occupancy
  - New more granular silicon sensors to cope with occupancy
  - Reduce gaps and minimize material in acceptance





- T stations behind magnet will be upgraded to cope with higher occupancy in inner region
- **Preferred option:**
  - A full scintillating fibre tracker with 2.5m long fibre tracker modules and SiPM readout
  - Challenge: SiPM must be cooled to -40^{o}C for noise reduction (radiation damage, up to 6*10^{11} neq/cm^{2})
  - Fibre inner ends will experience up to 22 kGy, still be OK for LHCb
- **Also considering:**
  - Replace only central part of OT and IT (Si sensors)
  - Other option: enlarge OT hole near beam pipe, and enlarge Silicon Inner Tracker

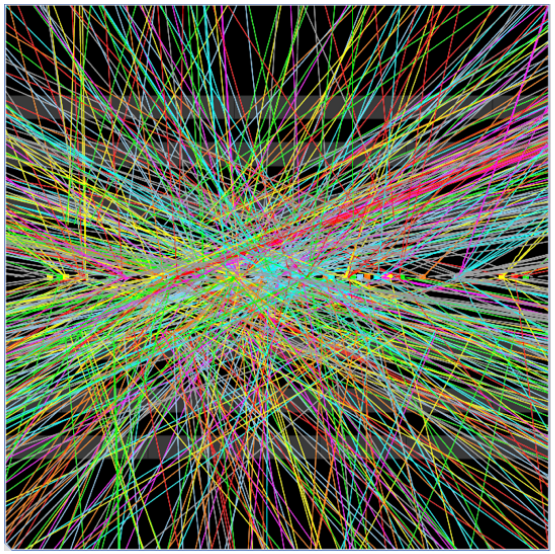
Tracker Upgrades during LS3
ATLAS and CMS

Basic Requirements For ATLAS and CMS


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

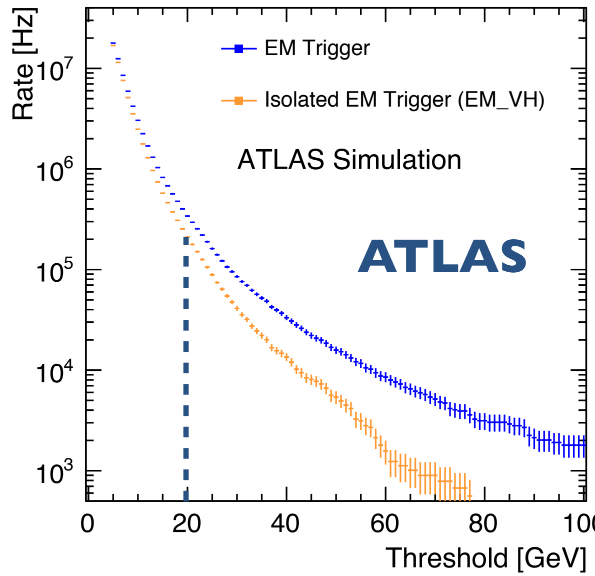
- **Radiation hardness**
  - Ultimate integrated luminosity considered ~ 3000 fb^{-1} (original ~ 400 fb^{-1})
  - Radiation hard sensor material
  - New readout electronics required
- **Granularity**
  - Resolve 140-200 collisions per bunch crossing
  - Maintain occupancy below % level
  - Requires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

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

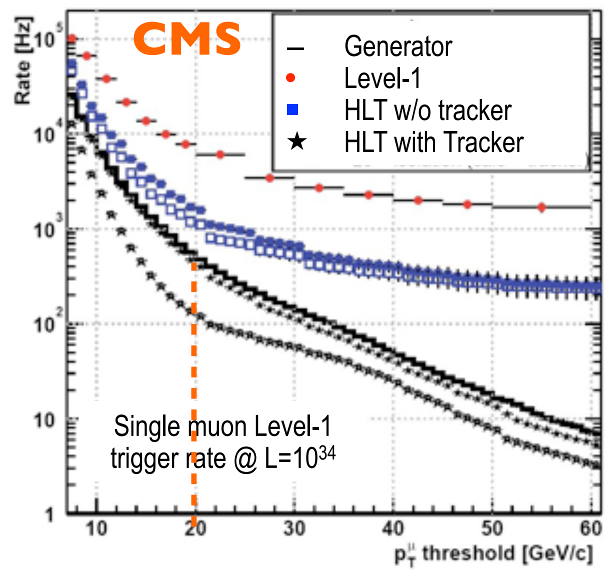


New Trigger Schemes Required

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



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

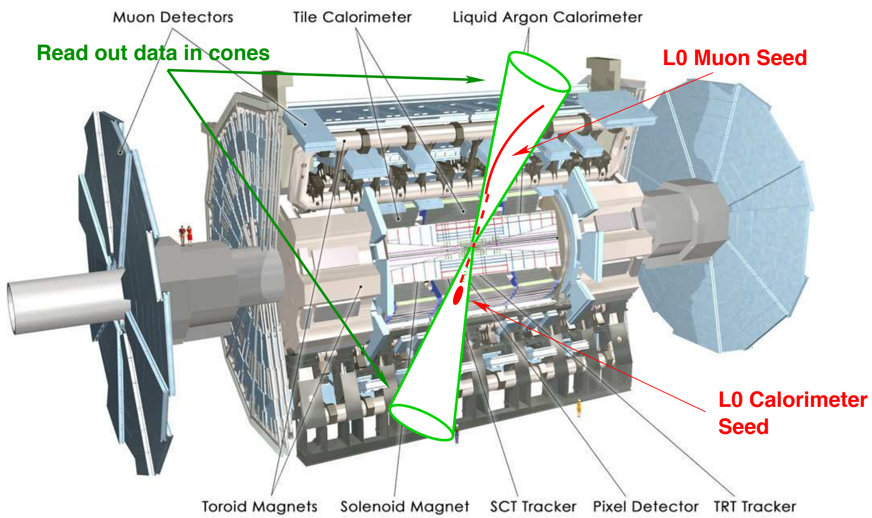


Details: Trigger Session on Thursday

Track Trigger Basic Concepts

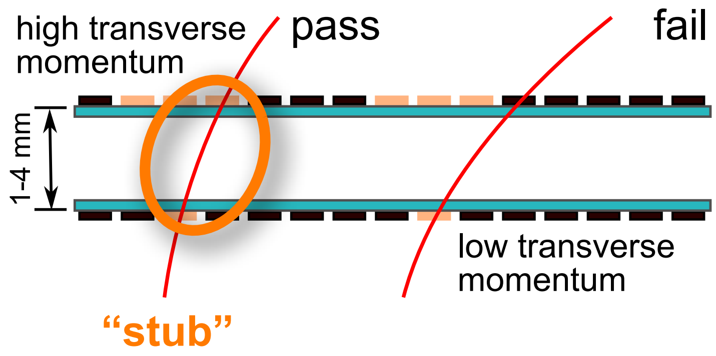
ATLAS - Region of Interest trigger

- Improve calo and muon trigger granularity (already in Phase 1)
- Trigger (L0) within 6 μs uses calorimeter and muon system to reduce the rate from 40 MHz to ~ 500 kHz and define regions of interest (RoIs)
- Further trigger (L1) within latency of 20 μs uses data from tracker front-ends in ROIs to search for high-pt tracks in ROIs
- Approach has little impact on the tracker layout and construction



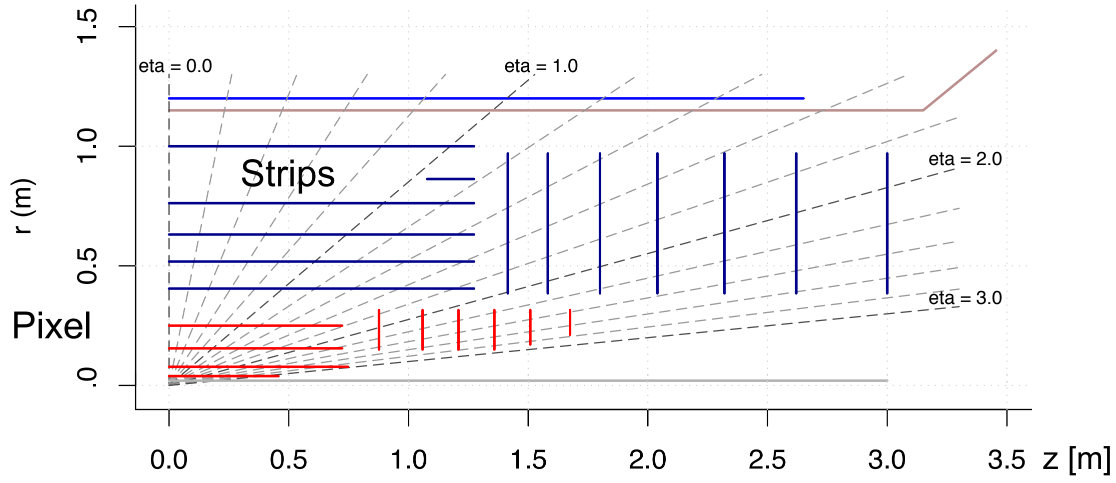
CMS - self seeded trigger

- Take advantage of large magnetic field of CMS
- Goal: reconstruction of high pt tracks > 2GeV
  - Reduction of data volume by factor >10
- Higher p_t objects will be correlated between layers -> form p_t stubs.
- Approach allows for an independent track trigger but has an impact on the layout and construction.



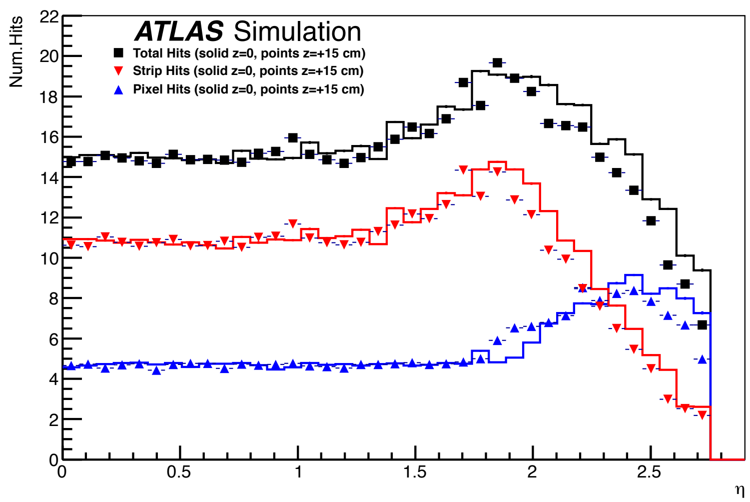
ATLAS Tracker Upgrade

	Silicon Area	Channels [10^6]
Pixel	8.2m^2	638
Strip	193m^2	74

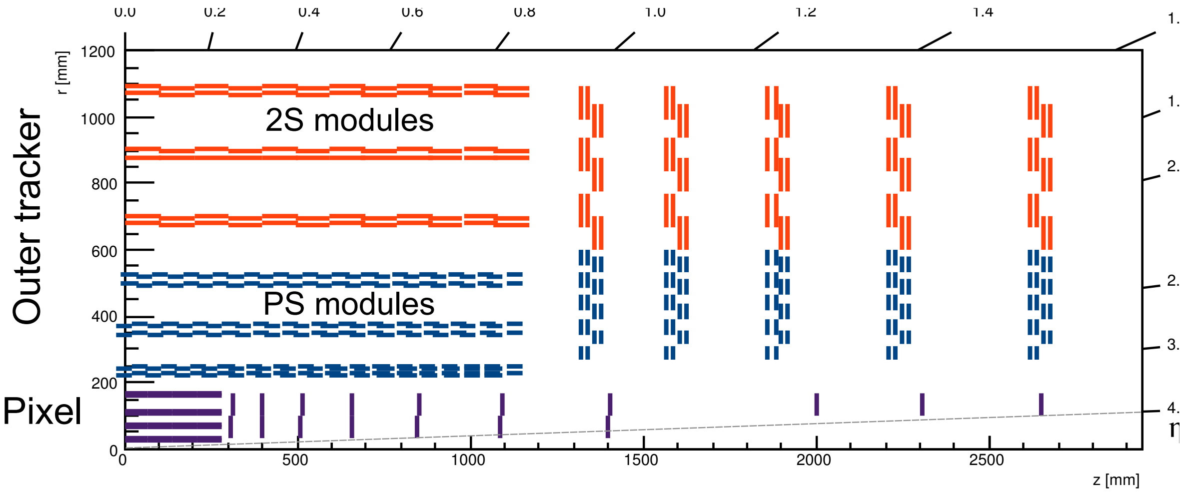


- Remove Transition Radiation Tracker (TRT) as occupancy is too high during HL-LHC
- Install new all-Silicon tracker with pixels and strips
- Granularity increase by factor >4

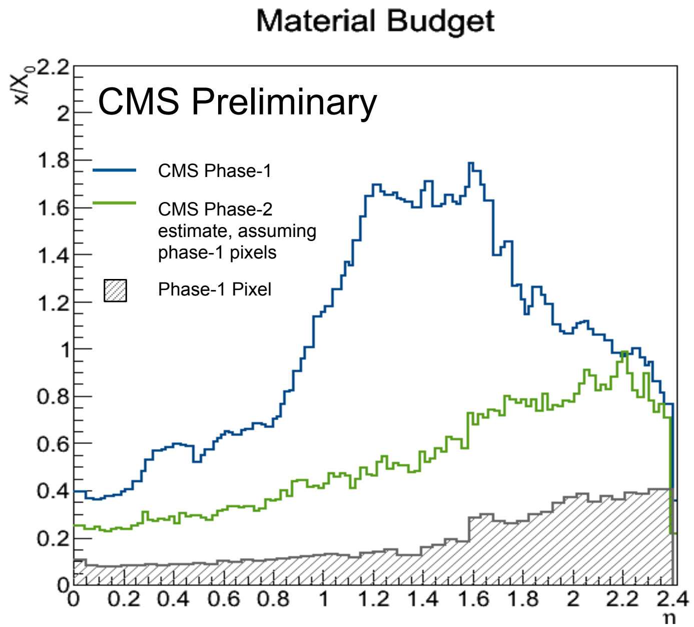
- Baseline layout optimized for tracking performance
  - Full simulation of tracker with LoI layout including service layout
- Biggest changes compared to current tracker:
  - pixels system extends out to larger radii
  - more pixel hits in forward direction to improve tracking
  - smaller pixels and short inner strips to increase granularity
  - outer active radius slightly larger to improve momentum resolution



CMS Tracker Upgrade



In outer tracker two types of pt modules for track triggering

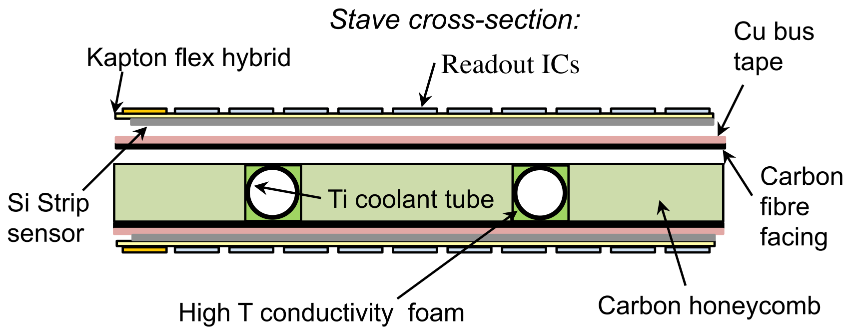


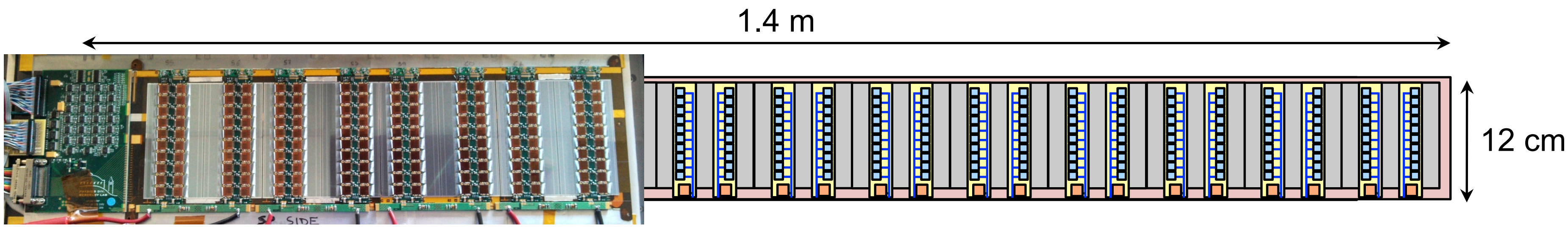
- Granularity in strip sensors x4 compared to current tracker (on average)
- Three more layers of pixellated sensors
  - Unambiguous 3d coordinates – helps track finding in high pile-up
- Modules with p_T discrimination in all outer tracker layers
  - All coordinates available at Level-1 (with cut at ~2 GeV)
  - Powerful pattern recognition for high level trigger (HLT) and offline
- Greatly reduced material in the whole rapidity range
- Tracking resolution improved in all aspects

ATLAS Silicon Strip Tracker

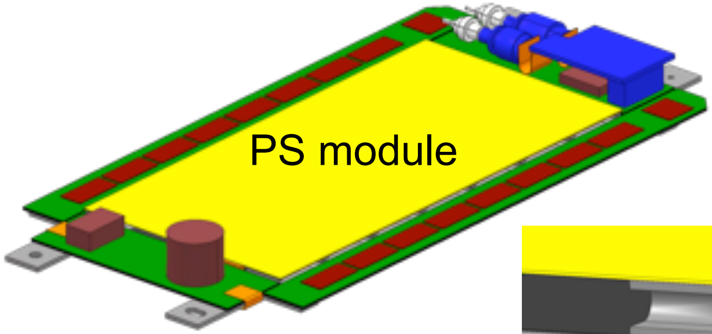
- Outer tracker is a silicon strip detector with n-in-p sensors
  - 5 barrel layers, 7 discs EC, “stubs”
- Double-sided layers with axial strip orientation and rotated by 40mrad on other side (z-coordinate)
  - Short (23.8 mm) and long strips (47.8 mm) with 74.5 µm pitch in barrel
  - End-Cap with radial strips of different pitch (6 different module designs)
- Efforts are directed at low cost

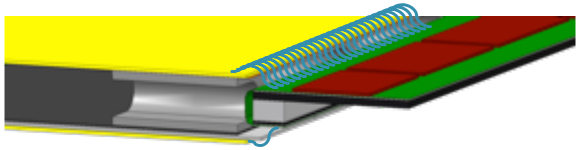
- Silicon Modules directly bonded to a cooled carbon fibre plate.
- A sandwich construction for high structural rigidity with low mass.
- Services integrated into plate including power control and data transmission.
- R&D already in full swing

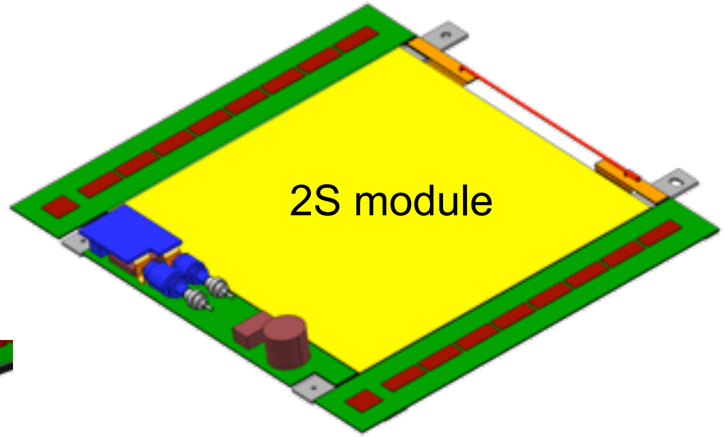




CMS Outer Tracker







- Modules discriminate low-p_T tracks in the FE electronics
- Hybrid is key element: Wire-bonds from the sensors to the hybrid on the two sides
  - FE chips bump-bonded onto hybrid
- Overall 216 m^2 with 47 M strips, 215M long pixels
- All modules send out data for track reconstruction at Level-1

PS Module

- Three inner layer (R>20cm) of Pixel-Strip modules
  - Top sensor: strips 2x25 mm, 100 µm pitch
  - Bottom sensor: long pixels 1.5 mm × 100 µm
- z-information from pixel sensor

2S Module

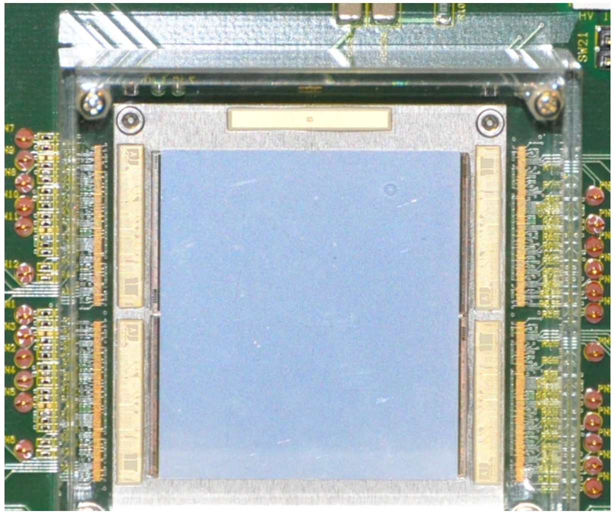
- Three outer layer (R>60cm) of 2-Strip modules
  - Strip sensor 10x10 cm^2 with 2x5cm long strips, pitch of 90 µm
  - light and “simple”
  - no z-information

ATLAS and CMS Pixel Detectors

- The requirement of radiation tolerance is particularly demanding for the Inner Pixel.
- CMS has an extension to high rapidity, ATLAS is also considering that option.
- Current pixel layout based on existing solutions
  - Several more years of R&D should allow the use of more performant technologies.
  - Plan to develop readout ASICs in 65 nm technology -> pixel sizes as small as 25 µm x 100 µm
  - Hybrid pixel approach with planar or 3D sensors under investigation.
  - CMOS technologies emerging and interesting for larger radii.

- R&D progress in many areas:
  - Sensors, FE- development, mechanics, bump bonding, ….
  - **Efforts are directed at low cost**

	ATLAS	CMS
Barrel layers	4	4
End-cap disks	6 (12)	10
Area	8.2 m^2	4.6 m^2



Example: ATLAS quad module (KEK)

Test Infrastructure for Tracking Detectors

Infrastructures: Test Beam

- Most crucial test during R&D phase for tracking detectors are beam based studies
  - efficiency, resolution, high rate tests, radiation tolerance ….

- Ongoing shutdown of PS and SPS difficult for community -> beam time very limited
- HL-LHC demands are resulting in more need for test beam time (high energy beams) and irradiation facilities.

- Test beam facility with 25 ns bunch structure to determine the necessary timing precision for the readout electronics and optimize timing through the entire readout chain.

- High rate tests, possibly with beam particles, are needed with intensities of the order of $2*10^{8}$ particles cm^{2}
  - Irrad4 facility at PS not optimal (facility developed for different scope)
  - Only available high rate facility at Fermilab (http://www-ppd.fnal.gov/FTBF/M03/)

Infrastructures: Irradiation

- Irradiation facilities: need a wide variety of facilities to prove sufficient radiation tolerance of all components
  - Karlsruhe, Ljubljana and CERN PS are most relevant facilities for the silicon detector community
  - Can not replace each other due to their different particle types and energies

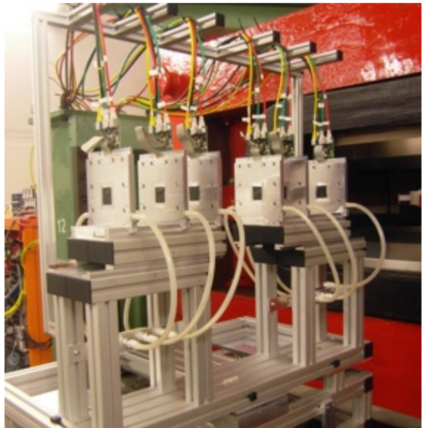
- Upgraded irradiation facility at CERN EAST Area (24 GeV/c protons) will help to cover demands.
- To cover demands additional facilities would be useful:
  - High intensity facility with some hundred MeV pions
  - Reliable and easily accessible proton facility in the 100 MeV range to complement the present irradiation test program.
  - Large area neutron source

Facility	Particles
Birmingham	protons, 27MeV
BNL	gamma 1.17 and 1.33 MeV
CERN	24 GeV/c protons, 1 MeV neutrons
NCSR "Demokritos"	Gamma, protons, neutrons
Paul Scherrer Institut	300 MeV/c pions, Protons 5 to 235 MeV (PIF)
KEK CYRIC	protons, 70MeV
Université catholique de Louvain	neutrons 1 to 70 MeV, protons 10 to 75 MeV, heavy ions
University of Karlsruhe	25 MeV protons
University of Ljubljana	neutrons
Université de Montréal	protons up to 11 MeV, ions up to 5.5 MeV/charge
University of New Mexico	Gamma, Neutrons, Protons
University of Padua	27 MeV protons, 58 MeV Lithium ions, 102 MeV Carbon ions, heavier ions
Uniwersytet Warszawski	heavy ions from 22 to 190 MeV
Uppsala Universitet	protons 500 keV to 10 MeV, ions 1 to 50 MeV

source: http://rd50.web.cern.ch/rd50/

Test Infrastructure

- With EUDET, AIDA and other programs new infrastructure was developed and provided for the community at test beams at CERN and DESY
- Tracking community mostly interested in high energy test beam lines and high resolution test beam telescopes
- Many groups built telescopes with excellent performance.



DESY

Timepix collaboration

- With EUDET/AIDA and other infrastructure programs quiet a lot developments for common tools.
- EUDET telescope family
  - Copies available around the world (currently mostly at DESY)
  - Used by R&D groups from all 4 experiments (and others)
  - Complete reconstruction software available and widely used
  - Good example for common infrastructure
- Timepix telescope
  - Available at SPS
  - Used by LHCb and ATLAS
- Common developments within AIDA for both telescope
- **Continuation of telescope efforts requested from community**
  - More common infrastructures as cold boxes and CO_2 cooling needed

Summary

- The challenging physics program and environment requires excellent tracking capabilities for all four LHC experiments.
- Improvements/replacements of the trackers are mandatory for the running after LS2 and LS3.
- ALICE and LHCb are planning tracker improvements and replacements during LS2
  - ALICE: upgrade of the TPC and full replacement of ITS by CMOS pixel layers
  - LHCb: new VELO, new TT, new T stations

- CMS and ATLAS are planning for full tracker replacements during LS3
  - Both detectors are in the order of $200m^2$ and a combination of pixel and strip layers
  - Trigger choice is driving the main differences in the detector layout and technology solutions

- Challenges in radiation hardness, readout limitations, sensor design are similar for all four experiments
  - Common R&D in this field is very important
  - Details will be shown in the following presentations

- Community expresses need of more test beam time and supports common infrastructure efforts.

Test Beams in The World

Beam lines with beam of energies higher than 100 MeV/c

Test beams* in the world, status June 2013						
Laboratory	**Number of beam lines**	**Particles**	**Energy range**	**Diagnostics etc.**	**Availability**	**Information, contacts & comments**
CERN / PS (CH)	4	p (prim.) e, h, μ (sec.)	24 GeV/c 0.6 - 12 GeV/c	Threshold Cherencov, scintillators, MWPCs, delay wire chambers, scintillators, magnet, movable platform	9 months per year, continous except winter shutdown Duty cycle depends on PS / SPS / LHC operation mode and is typical * PS ~1-3% * SPS: 20-40%	contact beam time request and scheduling: Sps.Coordinator@cern.ch http://spsschedule.web.cern.ch/SPSschedule/pindex.html contact beam lines: sba-physicists@cern.ch http://sba.web.cern.ch/sba/
CERN / SPS (CH)	4	p (prim.) e, h, μ (sec.) e, h (tert.) Pb ions (prim) other ion species (out of fragmentec primary Pb ions)	400 GeV/c 10 - <400 GeV/c 10 - 200 GeV/c 20 - 400 GeV/c proton equivalent (z=1)	delay wire chambers, filament scanners, XEMC calorimeters, Threshold & CEDAR, hodoscopes, magnet, movable platform		
DESY (D)	3	e+, e- (sec.) e- (prim., planned for 201X)	1 - 6 GeV/c 6.3 GeV/c	Trigger systems and beam telescopes, magnet (~1T)	10 months per year, 2014: presumably 8 - 10 months Duty cycle ~ 50%	contact: Testbeam-Coor@desy.de http:// testbeam.desy.de
FERMILAB/FTBF (US)	2	p (prim.) e, h, μ (sec.) h (tert.)	120 GeV/c 1-66 GeV/c 200-500 MeV	Cherencov, TOF, pb-glass calorimeters, MWPC, Si Tracker, see website for more	24 hrs/day 10% duty cycle	contact: FTBF_Co@fnal.gov http://www-ppd.fnal.gov/FTBF/
FERMILAB/MTA (US)	1.00	H^- ions	400 MeV Flux of $1*10^{12}$/minute	SEM for beam flux measurement	T. b. d.	contact: Aria Soha (aria@fnal.gov) Erik Ramberg@fnal.gov
IHEP Bejing (CN)	2	e (prim.) e (sec.) p, π (sec.)	1.1 - 2.5 GeV/c 100 - 300 MeV/c 0.4 - 1.2 GeV/c	MWPC, TOF Cherencov, CAMAC system, platform	Availability: 3 mouths per year, duty cycle depends on BEPCII operation mode	contact: Hu Tao (hut@ihep.ac.cn)

Christoph Rembser

Test Beams in The World

Beam lines with beam of energies higher than 100 MeV/c

Test beams* in the world, status June 2013						
Laboratory	**Number of beam lines**	**Particles**	**Energy range**	**Diagnostics etc.**	**Availability**	**Information, contacts & comments**
IHEP Protvino (RU)	5	p (prim), p, K, π, μ, e (sec.) C-12 (prim)	70 GeV/c 1-45 GeV/c 6-300 GeV/c	Cherenkov, TOF, MWPC	two months per year	contact: Alexandre Zaitsev (alexandre.zaitsev@cern.ch)
KEK / JPARC (JP)	1	p,π,K,e(sec.)	<1GeV/c	Cherenkov, TOF		contact: Masaharu Ieiri (masaharu.ieiri@kek.jp) http://j-parc.jp/researcher/Hadron/en/index.html
KEK / Tsukuba (JP)						Fuji beam line in KEKB main ring unavailable until Super KEKB will resume operation (~2015) http://www.kek.jp/ja/Facility/IPNS/K11BeamLine/
PSI / piE1, piM1, etc. (CH)	2-4	π+-, μ+-, e+-, p	50-450 MeV/c, rate <10^9 sec^{-1} 20nsec structure continuous beam at very high rate		6-8 months per year	beam time allocated by programme committee (twice per year) contact: Peter Kettle (peter.kettle@psi.ch)
PSI / PIF (CH	1	p	5 - 230 MeV/c ax. current 2 - 5 nA, rate <10^9 sec^{-1}, typ. flux 10^8 cm^{-2} sec^{-1} for wide beam, energy, beam spot and flux selectable by user		11 months per year, mostly during weekends	contact: Wojtek Hajdas (wojtek.hajdas@psi.ch)
SLAC (US)	1	e (prim.) e (sec.)	2.5 - 15 GeV/c 1 - 14 GeV/c		Starting July 2012, 9 months per year, 50% duty cycle	contact: Carsten Hast (hast@slac.stanford.edu) https://slacportal.slac.stanford.edu/sites/ard_public/tfd/
SPRING-8, Compton Facility (JP)	1	photons (tagged) +, e- (conversions	1.5 - 3.0 GeV/c 0.4 - 3.0 GeV/c		>60 days per year	contact: Takashi Nakano (nakano@rcnp.osaka-u.ac.jp) http://www.spring8.or.jp/en/

*Beam lines with beams of energies higher than 100 MeV/c

CR, 29 June 2013

Christoph Rembser

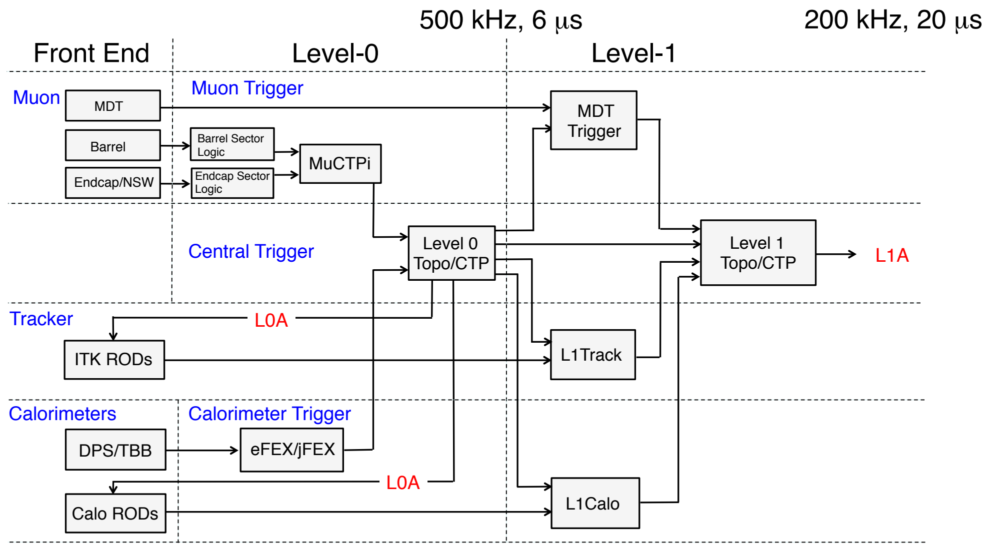
Tracker Upgrades for (HL)-LHC

	ALICE	ATLAS	CMS	LHCb
Tracker	new inner tracker (ITS)	New tracker (pixels and strips)	New tracker (pixels and strips)	new tracker (VELO and outer tracker)
Installation/ Commissioning	LS2(2018)	LS3	LS3	LS2(2018)
Lumi goals	> 10nb^{-1} PbPb > 6nb^{-1} pp	3000 fb^{-1}		> 50nb^{-1} PbPb > 50fb^{-1} pp
Radiation levels	10^{13} neq/cm^2 700 kRad	10^{14} - 3x10^{16} neq/cm^2 10MRad - 1500 MRad		10^{16} neq/cm^2 400 MRad

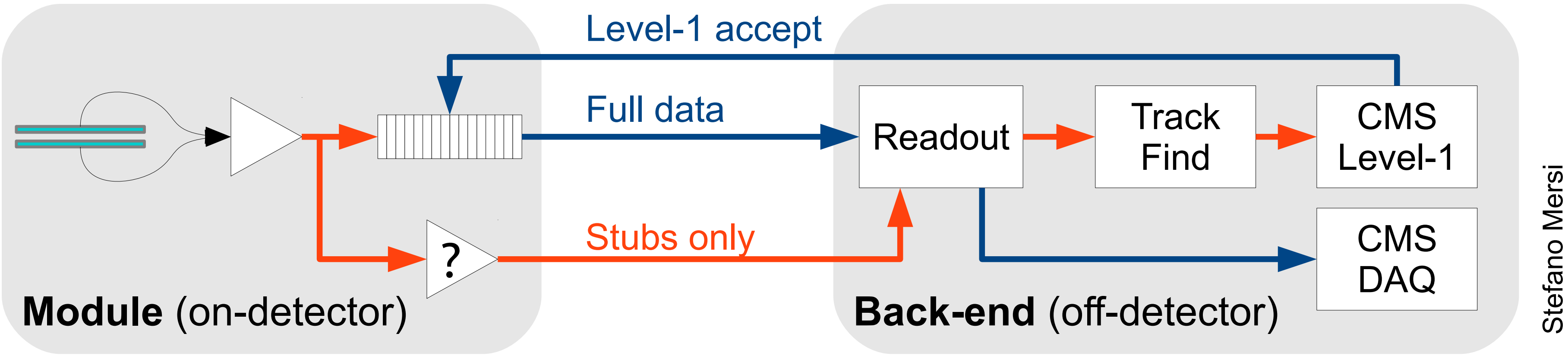
ATLAS Trigger Scheme

- Split Level-0/Level-1 hardware trigger with a total level-1 accept rate of 200 kHz and total latency of 20 µs.
- Level-0 trigger distributes the Level-0 accept at a rate ~500 kHz within 6 µ s.
- Phase-II Level-0 trigger is ~Phase-I Level-1 system and consists of a feature extractor (FEX) based on calorimeter electromagnetic and jet triggers, and the Phase-I Level-1 muon trigger.
- The Level-0 accept is generated by the central trigger system which incorporates topological triggering capability.

- Level-1 system will reduce the rate to 200kHz within an additional latency of 14µs.
- Accomplished by
  - introduction of track information within a Region-of- Interest (RoI)
  - full calorimeter granularity within the same RoI
  - introduction of a refined muon selection based on the use of the MDT information.
- Increased use of offline-like algorithms in the High-Level Trigger (software trigger) with an anticipated readout rate of 510 kHz.

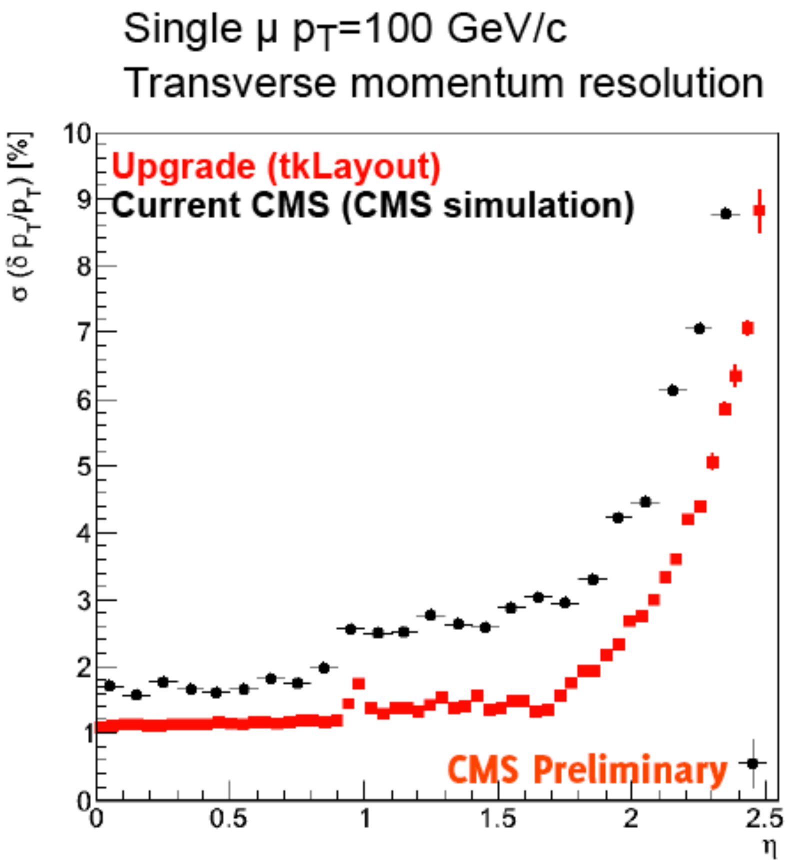


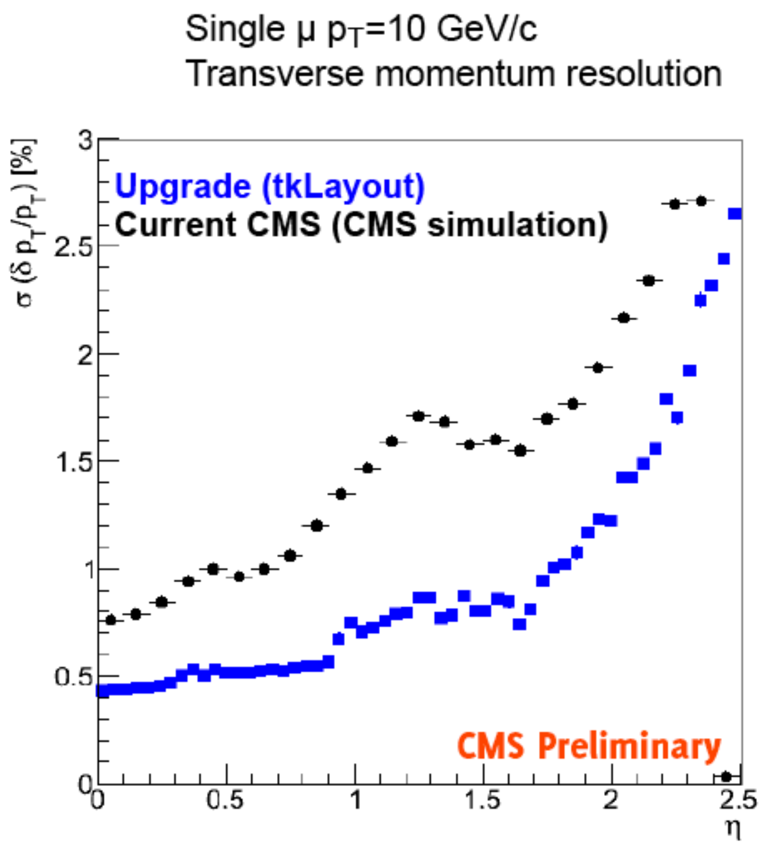
CMS Trigger Scheme



@ 40 MHz – Bunch crossing
@ O(100) kHz – CMS Level-1 trigger

CMS Tracking Resolution Improvement



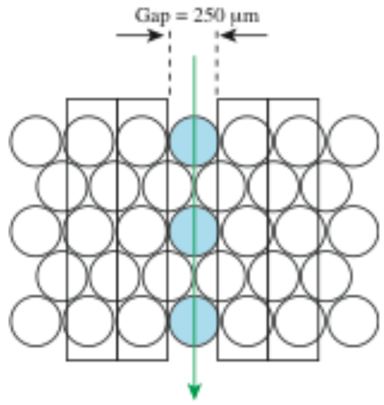


- tkLayout is a tool to evaluate the material budget and tracking resolution of different tracker upgrade designs.
- Plot shows a comparison of the p_T resolution of the current CMS tracker to the expected resolution of the Phase-2 upgrade current baseline for single-muons with p_T=100 and p_T=10 GeV/c

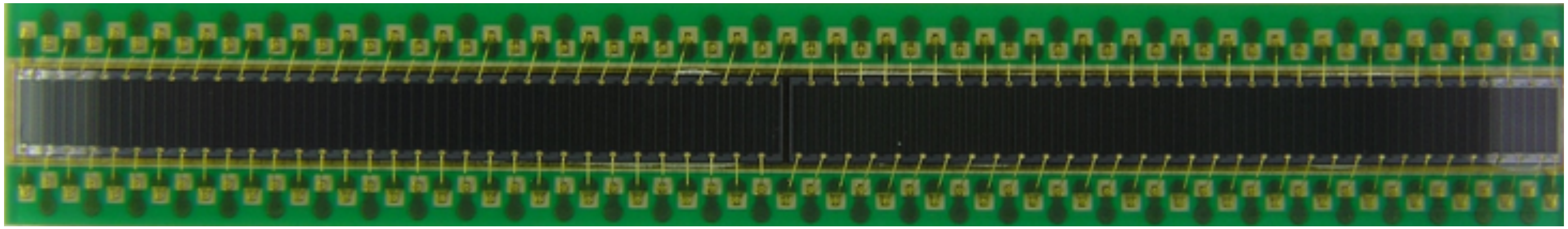
LHCb: Main SciFi detector features

area: 360 m^2
fibre length: 7200 km

- 250µm diameter scintillating fibers
  - arranged in multiple layers for sufficient light collection
- Cover the acceptance with 2.5m long fibers
  - mirror at the center (beam pipe height)
  - light detected outside the acceptance
    ⇒ minimize “inactive” material in the acceptance
  - vertical (x) and stereo (u&v) ⇒ 12 layers



- Readout with multi-channel Silicon photo-multipliers (SiPM)
- Readout: 40MHz front-end electronics



- 0.25 × 1.3 mm^2 channels of 4×20 pixels
- pixel size = 55µm
- 128 (2×64) channels grouped in a an 32mm array