LHC Detector Upgrade Plans

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Particle Detectors and Instrumentation UK

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Disclaimer

- Very limited time
  → selection to personal taste
- Largely restrict to PHASE 2 upgrades
- A lot of great ongoing work in ATLAS, CMS & LHCb
  → impossible to do proper justice in 25 min
- Apologies for any omissions & a slight ATLAS bias
- Updated version of HEPP talk
  https://indico.shef.ac.uk/indico/event/1/contribution/16/material/slides/0.pdf

LHC Upgrade: HL-LHC

High Luminosity Large Hadron Collider

- Luminosity:

  300 fb^{-1} → 3-4000 fb^{-1}

- Inst. Luminosity:

  $L > 1.4 \times 10^{34}\ cm^{-2}\ s^{-1}$

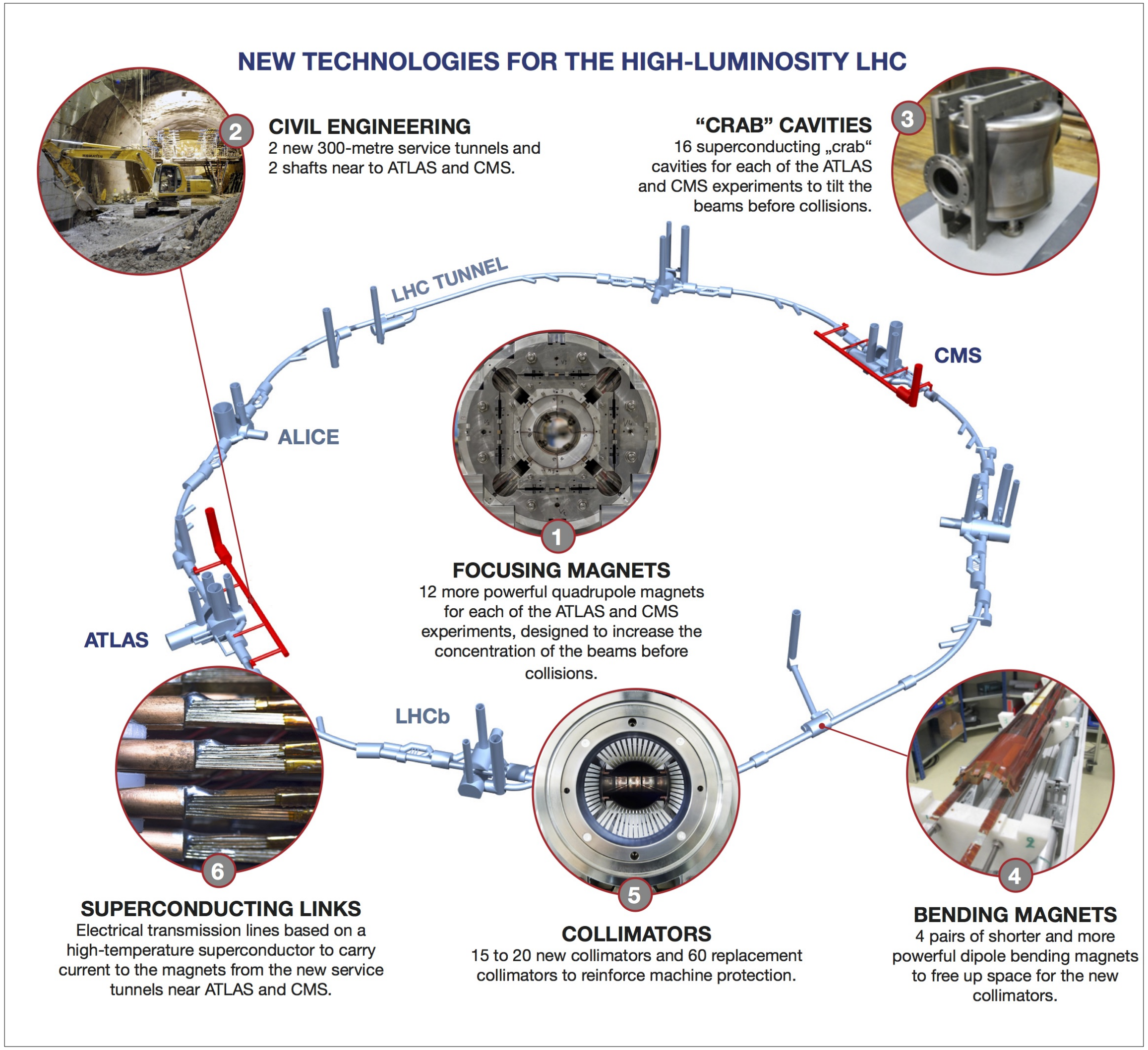
  ↓

  $L = 7 \times 10^{34}\ cm^{-2}\ s^{-1}$

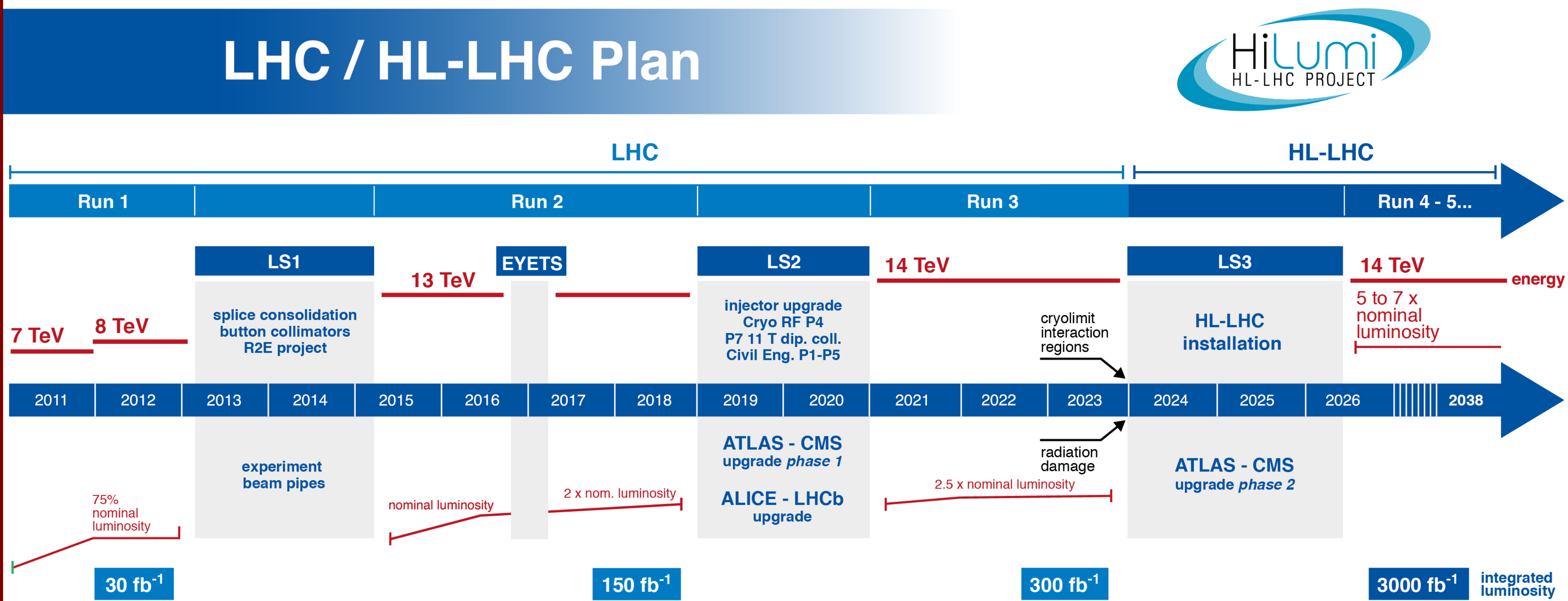
Luminosity leveling

- Pile-up collisions:

  40 → 140/200



HL-LHC Schedule



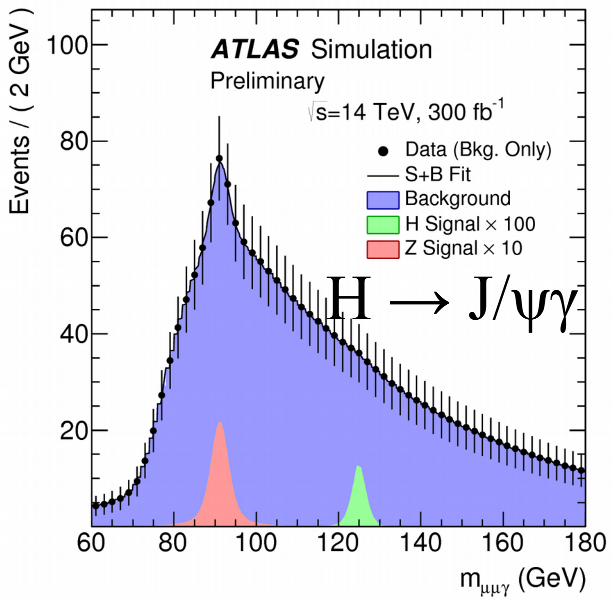
Funded/under way:
ATLAS/CMS/LHCb
Phase I

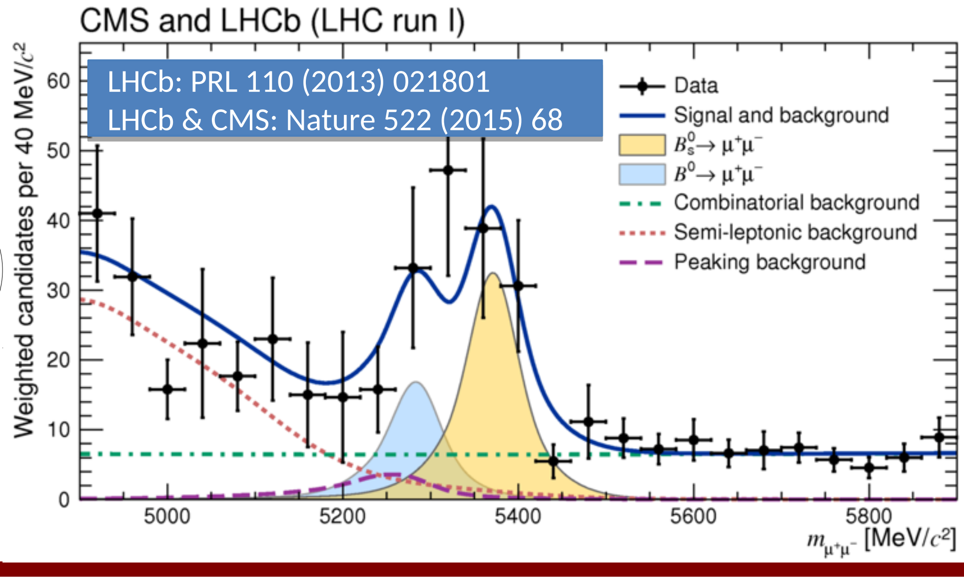
ATLAS/CMS
Phase II

LHCb
Phase II

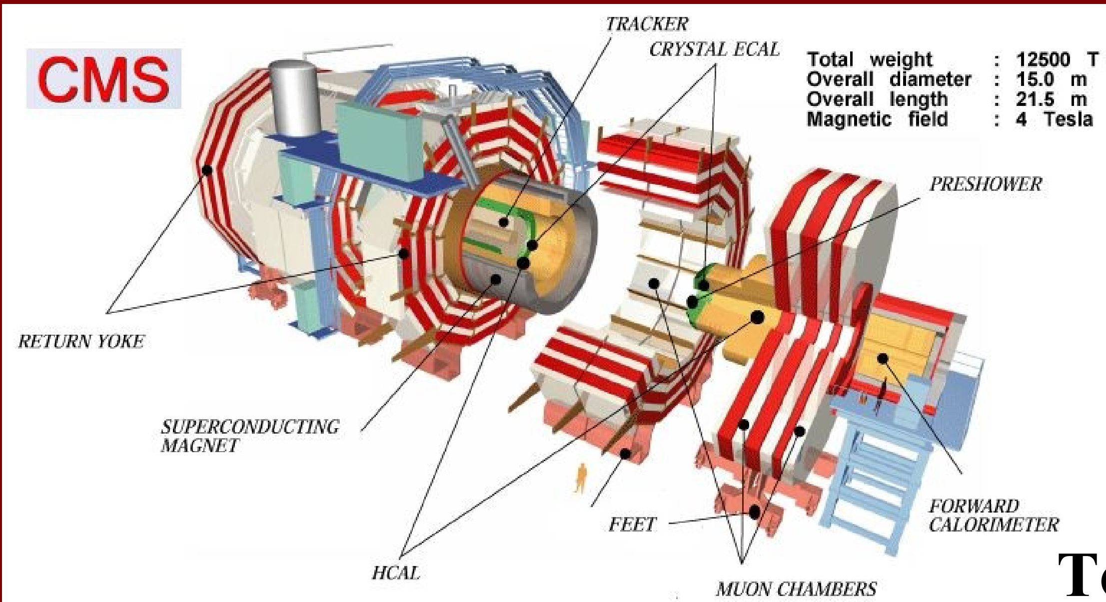
Physics Motivations

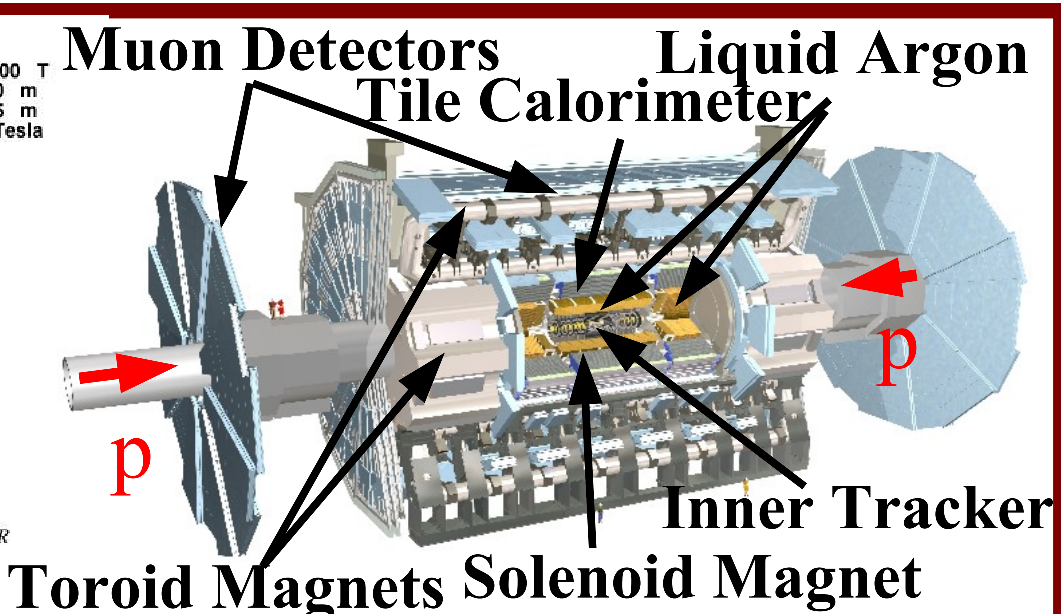
- Higgs precision measurements
  - Fermion couplings
  - Rare decays
- Higgs self coupling
- Understanding CP Violation
- Dark Matter
- New Physics Searches
  - Direct
  - Indirect (Loops!)
- Exclude SUSY models

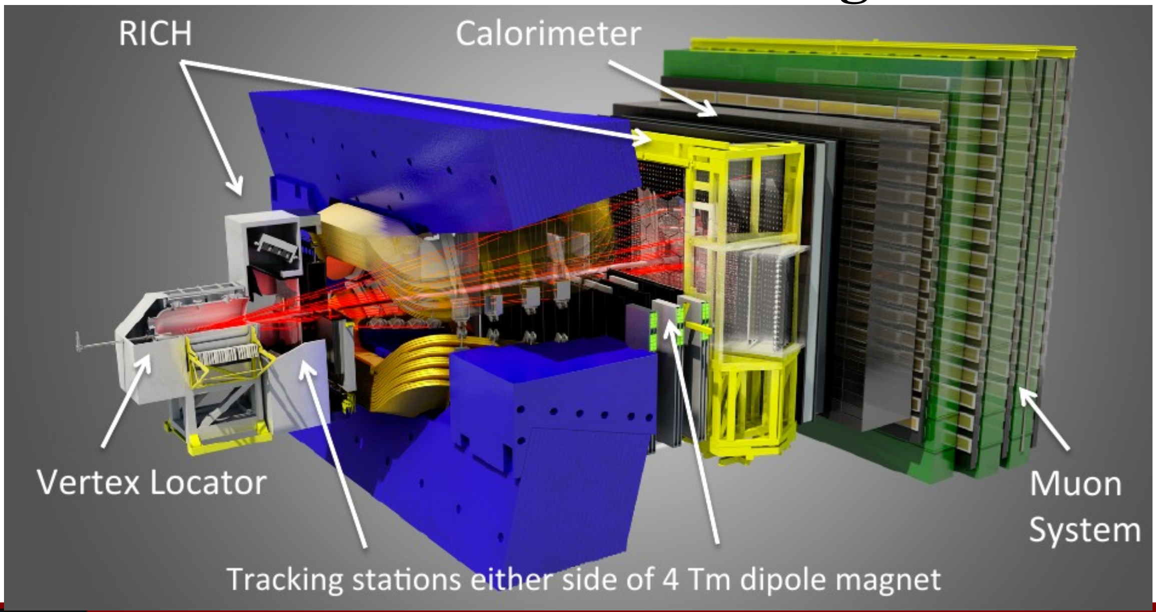




Current LHC Detectors

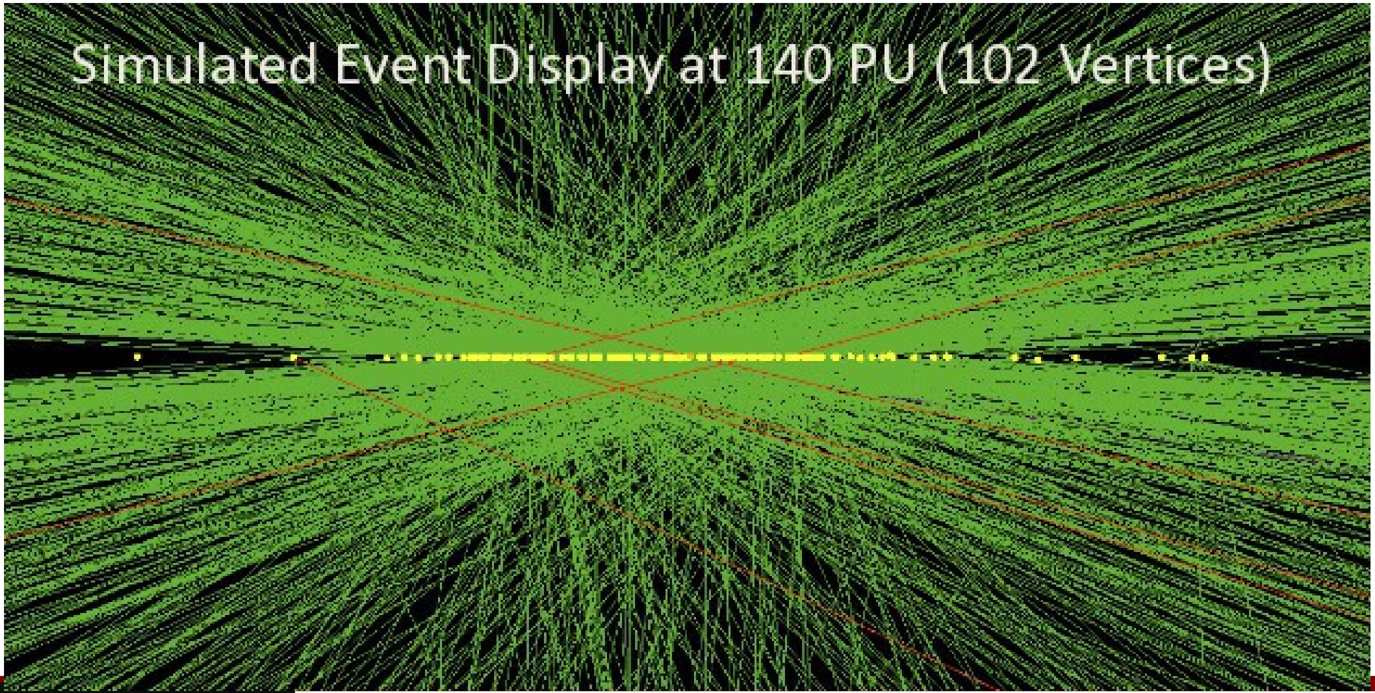






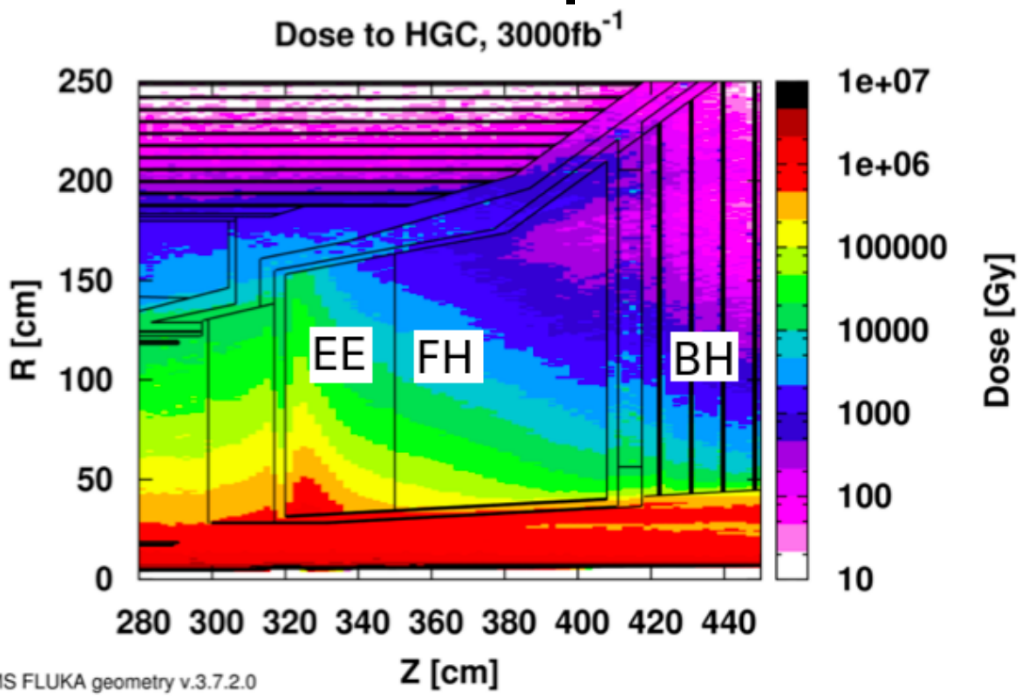
Detector challenges

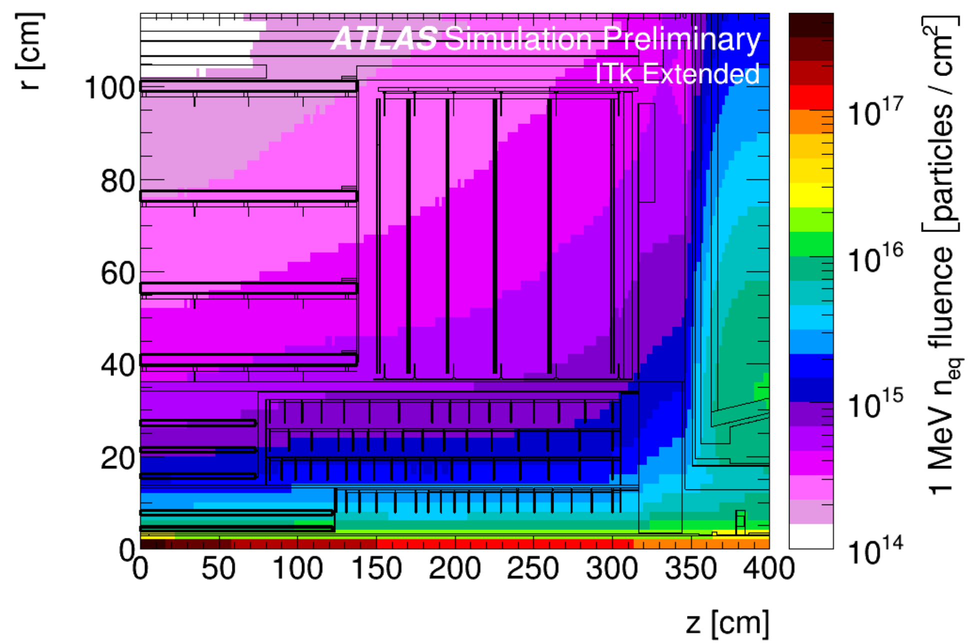
- Accelerator conditions
  - High rate
    → readout speed/buffers
    → fast data selection/trigger
  - High occupancy → Granularity
    - 40 interactions → 140 !



Detector challenges: radiation

- Radiation hardness
  - Pixel region
    - Up to $2\text{x}10^{16}\ n_{eq}\ cm^{-2}$
    - Up to 10 MGy

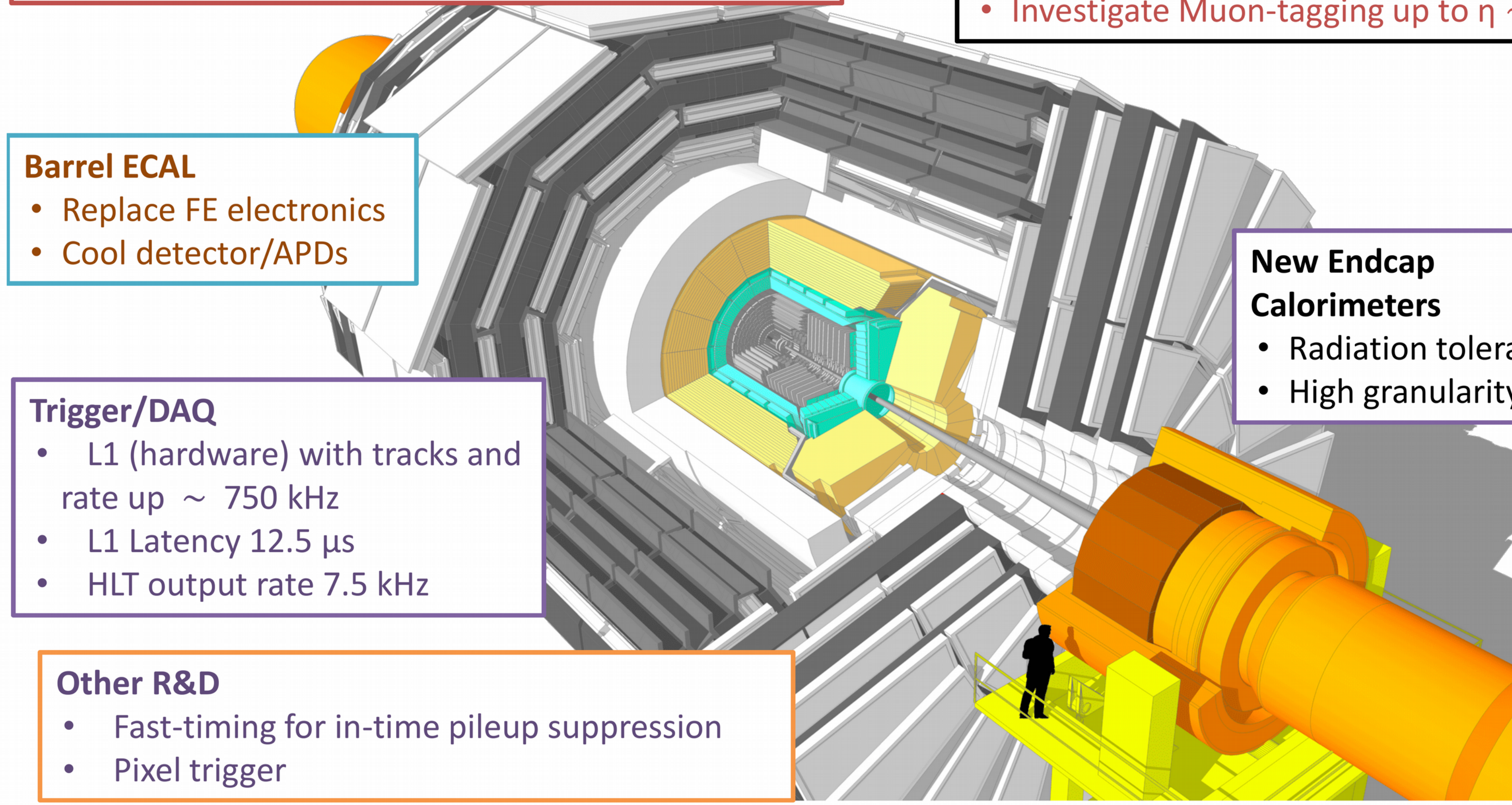




CMS Upgrade Overview

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3



Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

New Endcap Calorimeters
- Radiation tolerant
- High granularity

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

Other R&D
- Fast-timing for in-time pileup suppression
- Pixel trigger

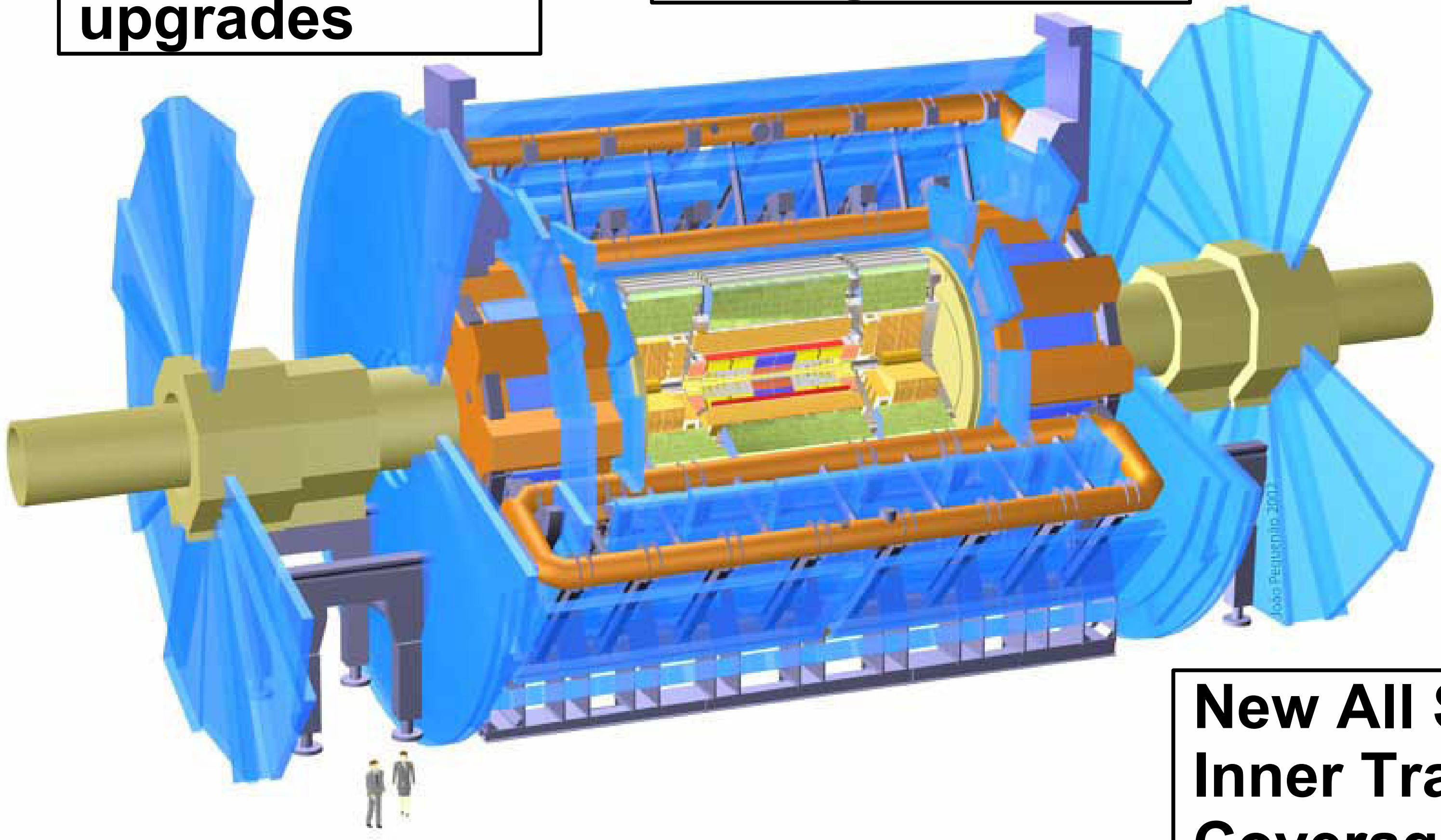
ATLAS Upgrade Overview

New faster Muon readout
Minor chamber upgrades

Upgraded faster Calo readout
Timing options

Upgraded Trigger/DAQ System

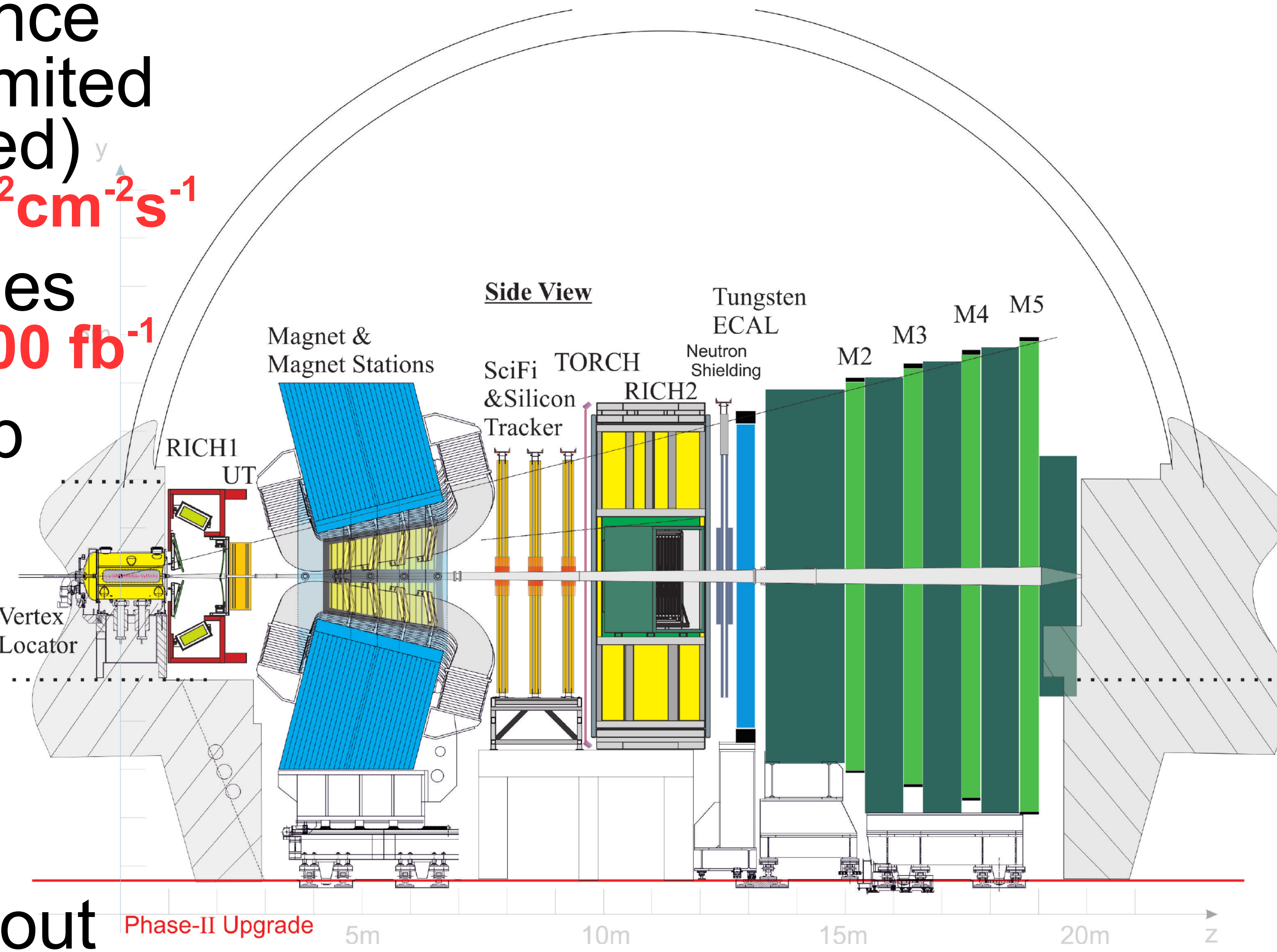
Global TP
L1track
FTK++



New All Silicon Inner Tracker
Coverage up to $\eta \sim 4$

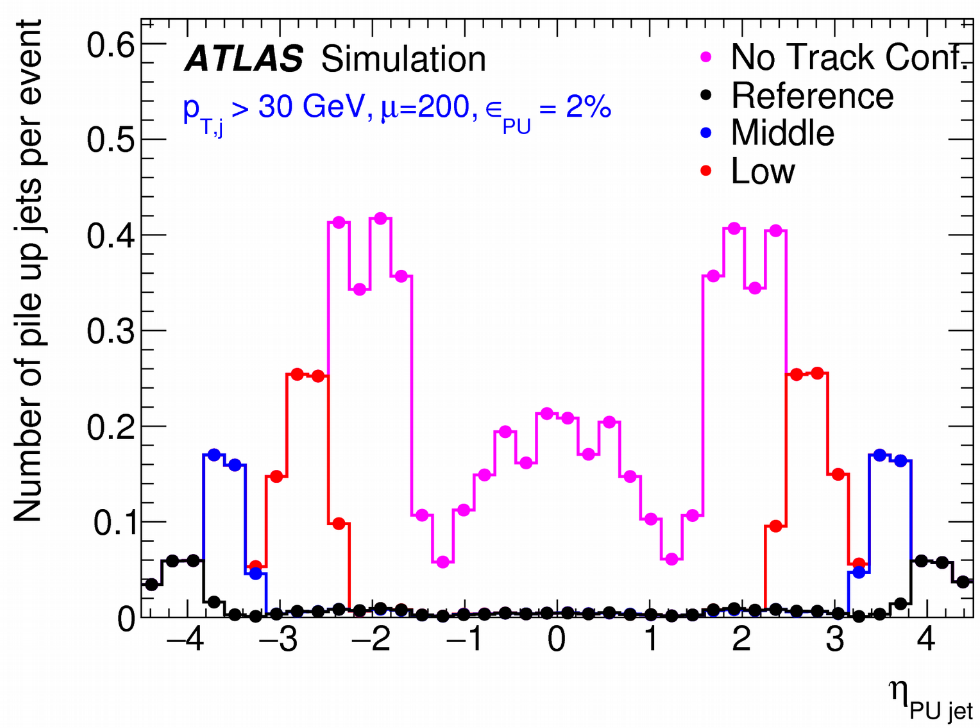
LHCb Upgrade Overview

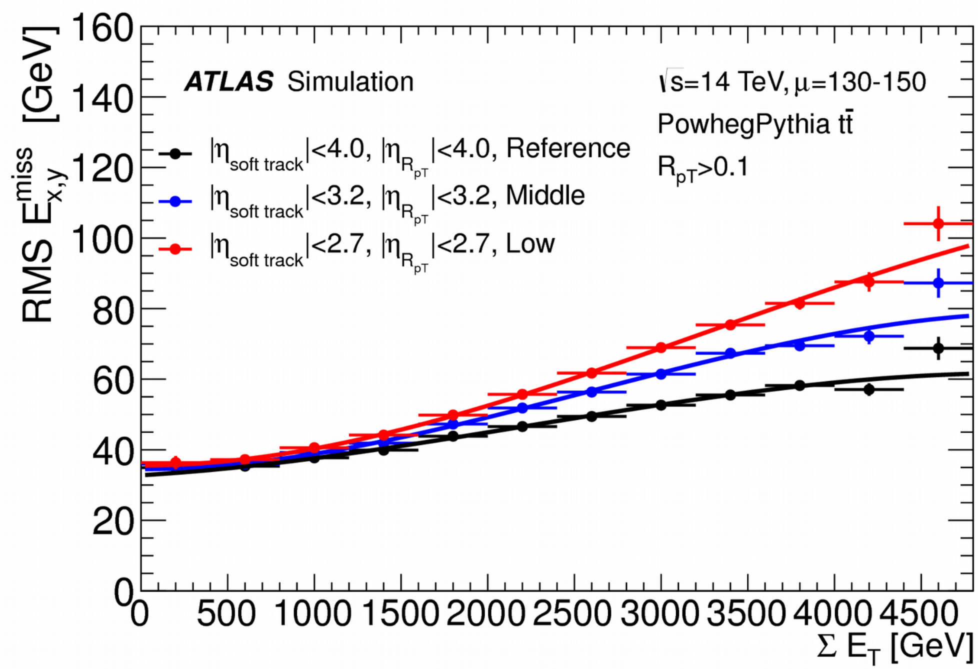
- LHCb performance NOT machine limited (luminosity leveled)
  $4 \rightarrow 20 \rightarrow 200 \times 10^{32} cm^{-2} s^{-1}$
- Detector upgrades
  $8\ fb^{-1} \rightarrow 50\ fb^{-1} \rightarrow 300\ fb^{-1}$
- Show both LHCb Phase I & II
- New Velo
- Tracker
- Particle ID RICH/TORCH
- Muon/Calo readout
- Smaller ECAL cells



Detector trends

- High granularity silicon trackers
  - ATLAS, CMS & LHCb
- ATLAS/CMS: Large eta (η~4) tracking coverage
  - → Improved MET resolution



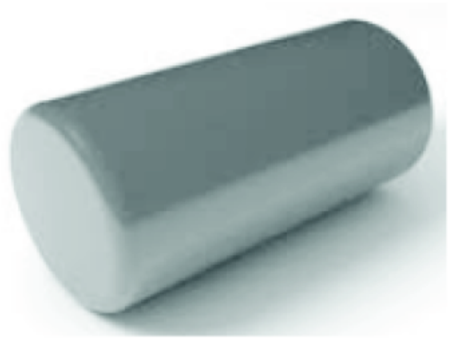


Detector trends: tracker geometry

Ideally: constant track density (pixel occupancy) in all sensors
The track density is constant in eta at LHC

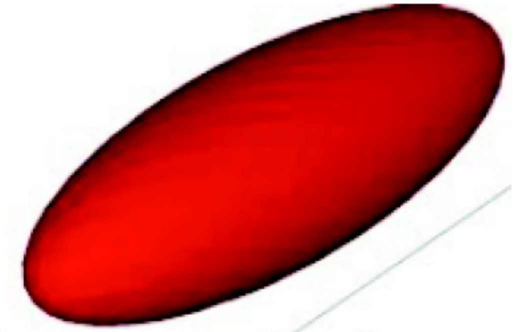
- up to phase space limit, which is above eta 2.5 for many processes of interest

Achieved on a cylindrical surface -> barrel-only layout?



Ideally tracks coming from the I.P. should cross the sensors perpendicularly (to minimize material and minimize number of sensors needed)

- This condition implies a spherical surface for point source, ellipsoid for the LHC beam spot



Transverse momentum accuracy should be constant in eta

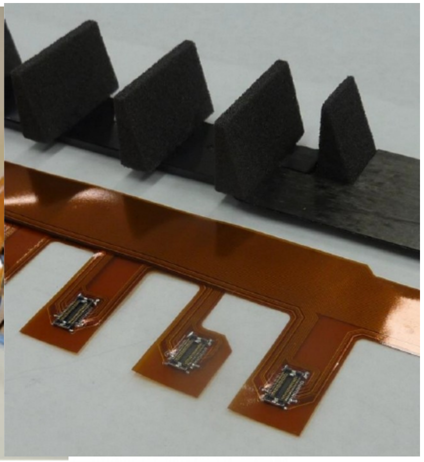
- the B field integral along tracks should be constant
- In a solenoidal field this implies cylindrical layers, constatnt radial lever arm
- Reminder: the momentum accuracy is proportional to the square of the radial lever arm

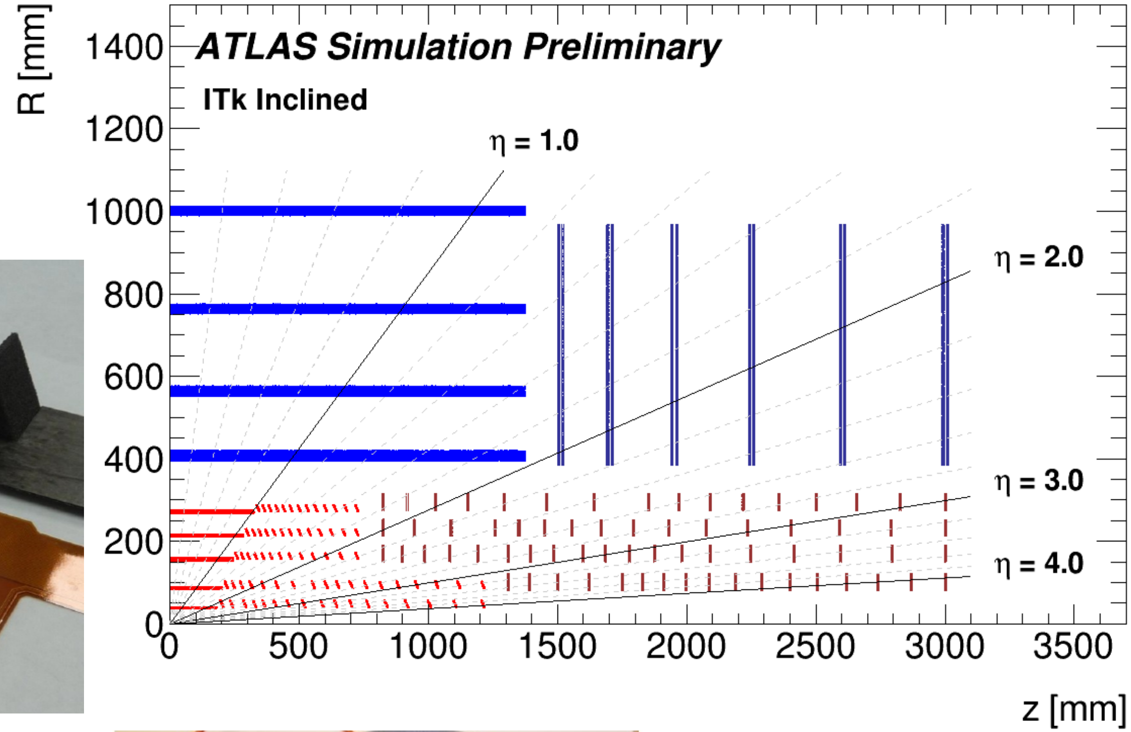
4

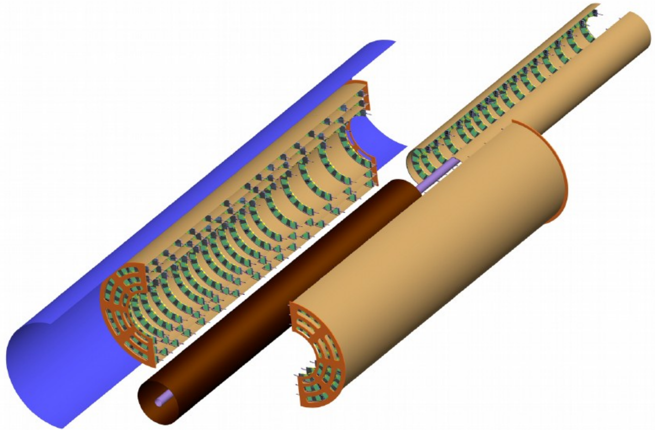
T.Todorov, October 2011

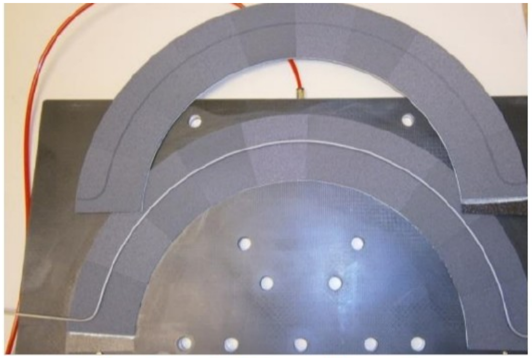
ATLAS: Tracker Upgrade

- Inclined pixel layout
- Endcap Rings

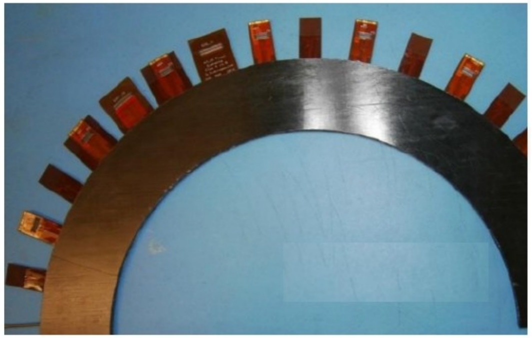








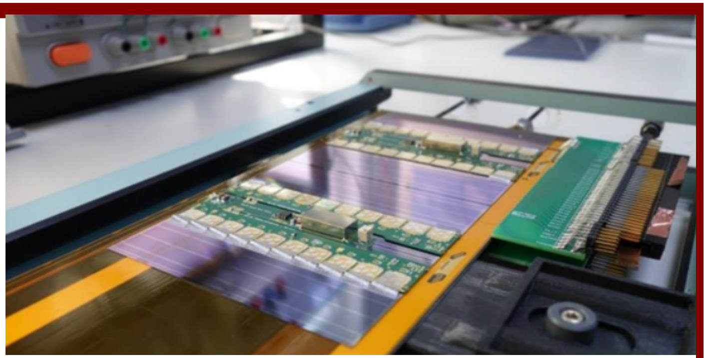
Titanium CO2 cooling pipe embedded in ring.

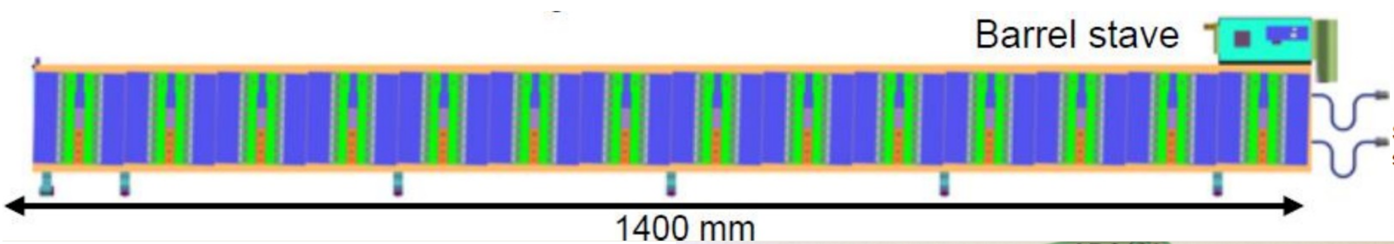


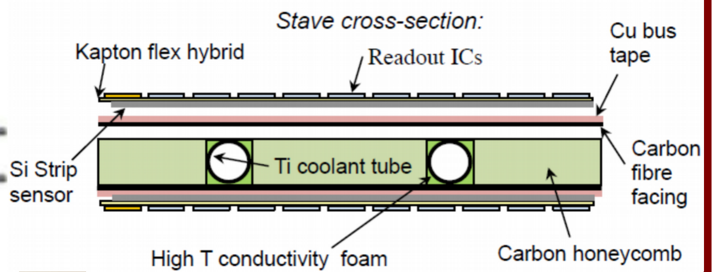
Electrical services (flex) embedded in ring.

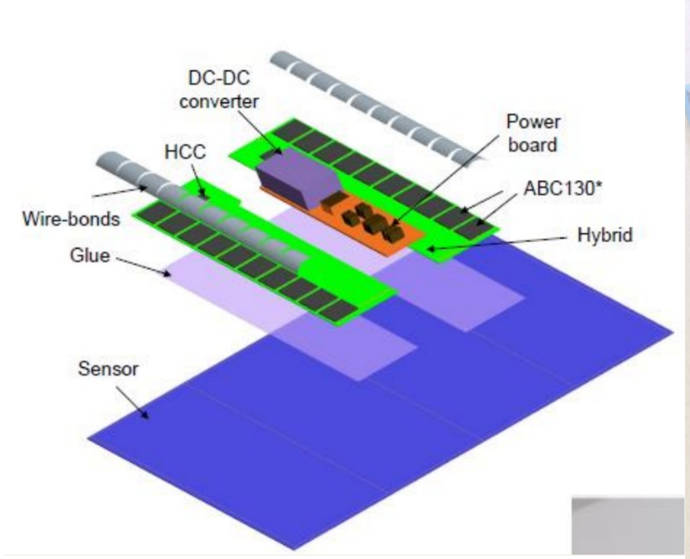
ATLAS: Tracker Upgrade

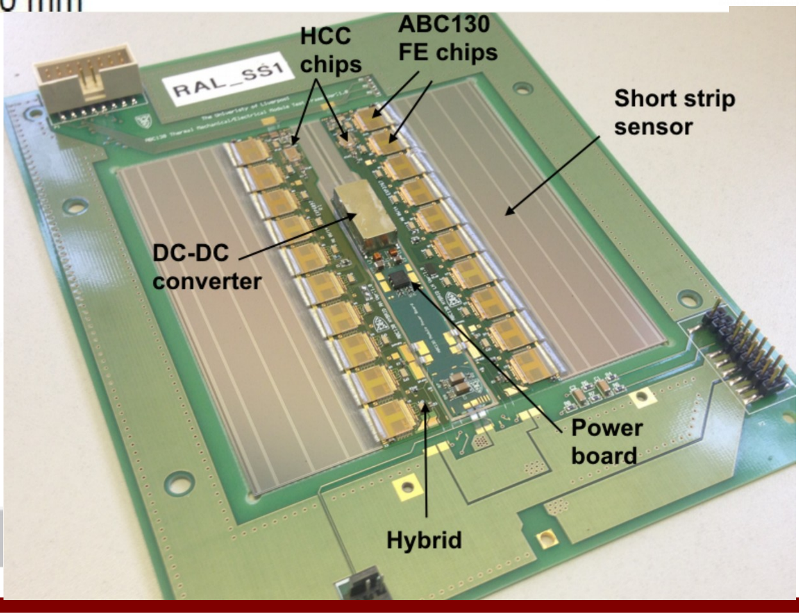
- Strip tracker: pitch 75.5 μm
- Short & long strips 24.1/48.2mm
- L0/L1 deep buffers
- Powered with DC-DC converters

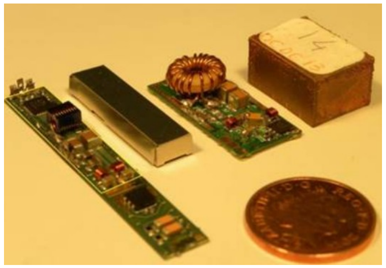




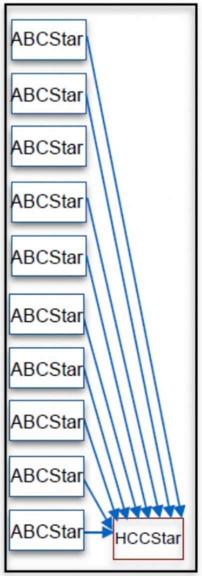








DC-DC converter

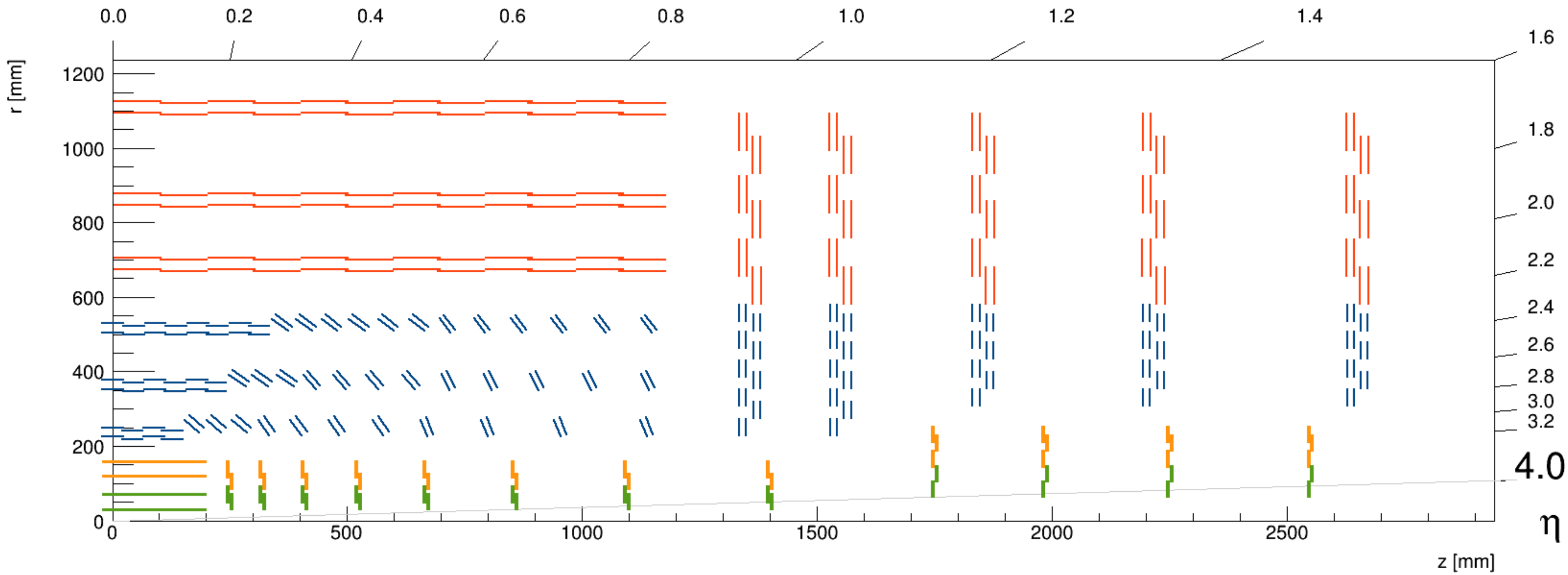


CMS: Tracker Upgrade

- 'Tilted' inner parts of Outer Tracker
- Double sided modules

  2S (strip-strip)

  PS (pixel-strip)



Detector trends

- ATLAS/CMS Pixel readout chip development: RD53

- Pitch:
  50 x 50 μm²
- supports also 25 x 100 μm² pixels
- RD53A chip (400x192 pixels) submitted on 31.08.2017!

RD53 ASIC 65 nm

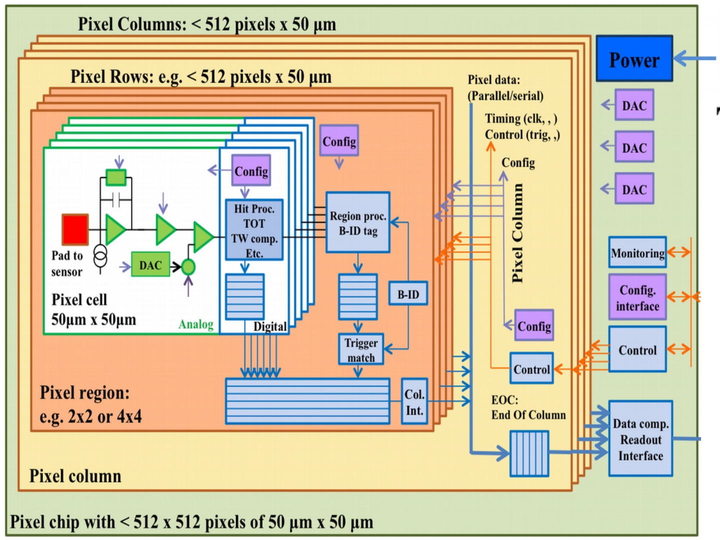
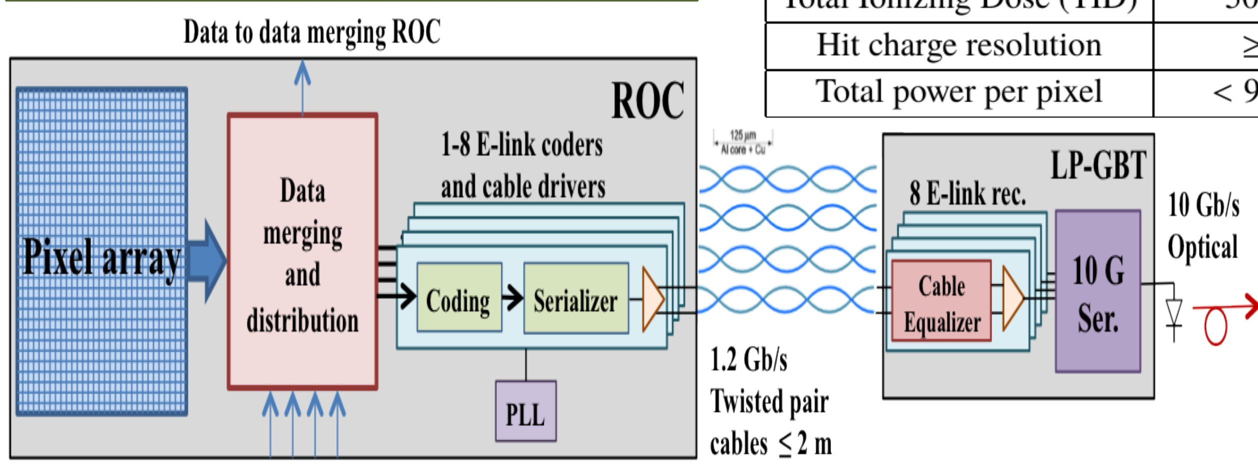


Table 1. Summary of RD53A main specifications.

SPECIFICATION	VALUE
Pixel cell	$50 \times 50\ \mu m^2$
leakage current	< 10 nA per Pixel
Pixel hit rate	3 GHz/cm²
Dead Time loss	< 1 %
Trigger rate / latency	1 MHz/12.5 μs
Low In-time Threshold	< 1200 e^-
Total Ionizing Dose (TID)	500 Mrad
Hit charge resolution	≥ 4-bit
Total power per pixel	< 9–10 μW



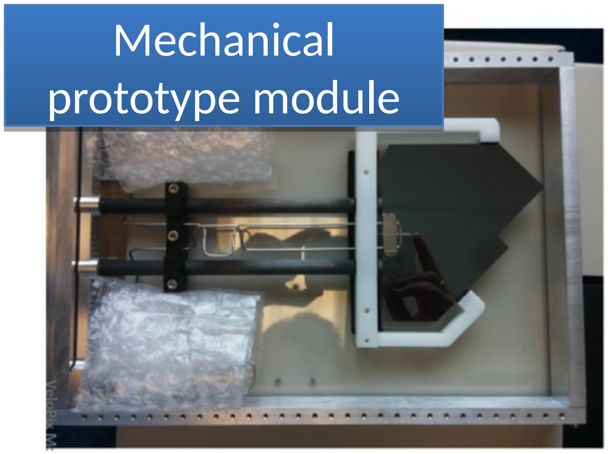
Phase I Velo Upgrade

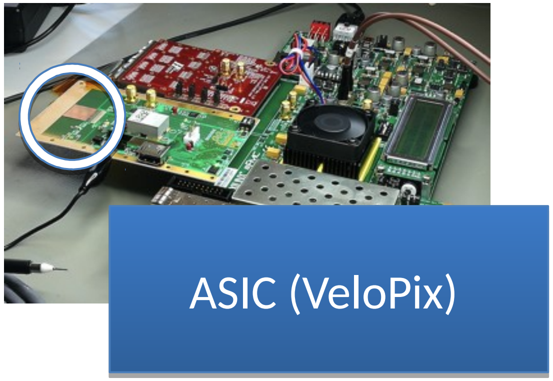
- 55 x 55 μm^2 Pixel sensors
- 26 x modules 2 retractable halves
- 4 sensors/module
- 5.1 mm from beam
- Dose:

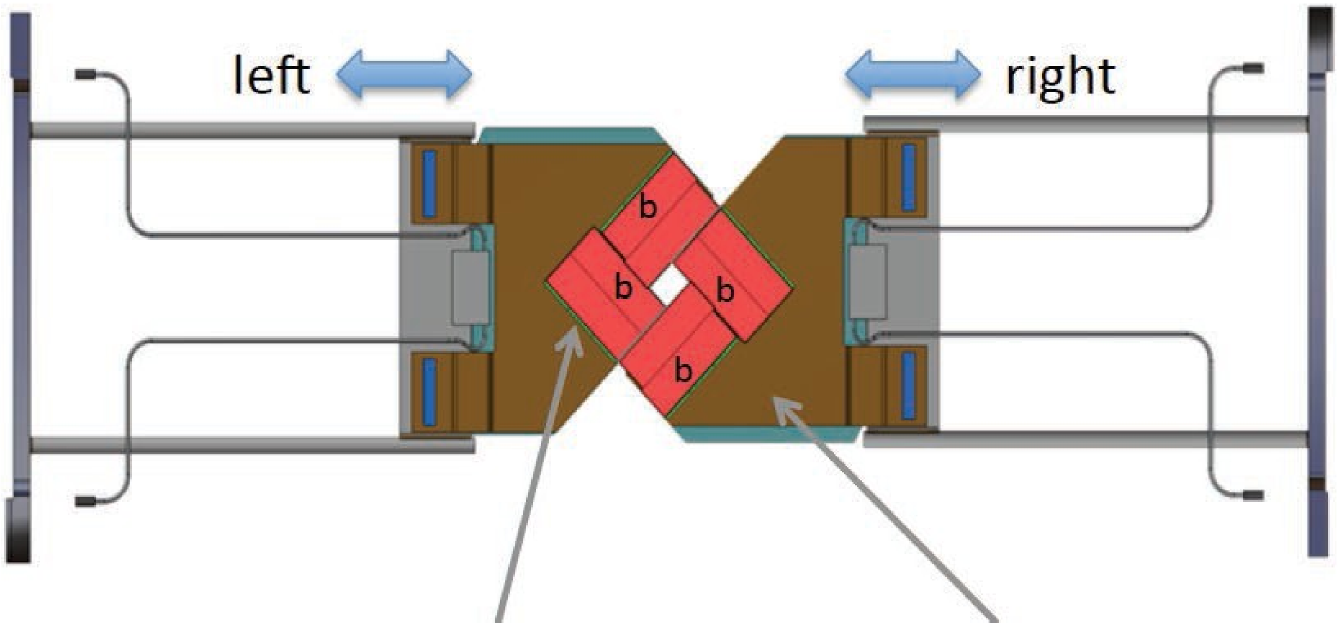
$8x10^{15}$ n_{eq} cm^{-2}

- VeloPix Chip:

20Gbit/s output

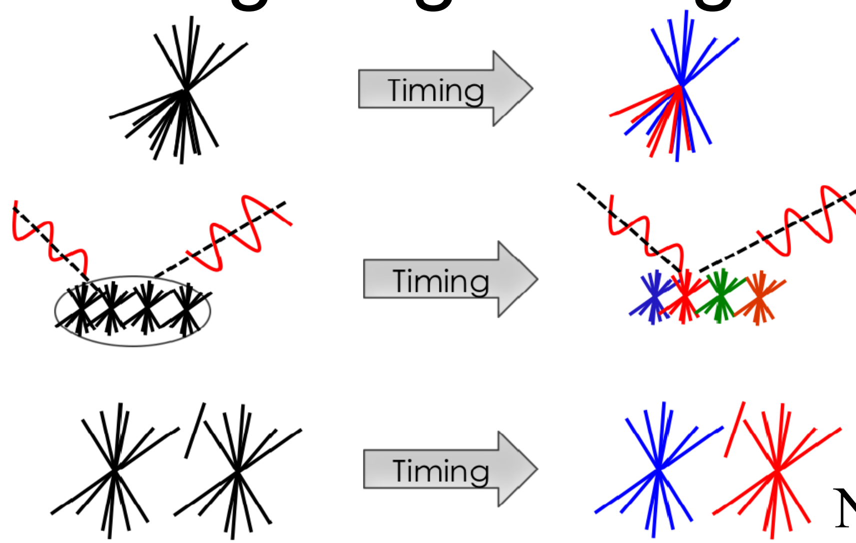




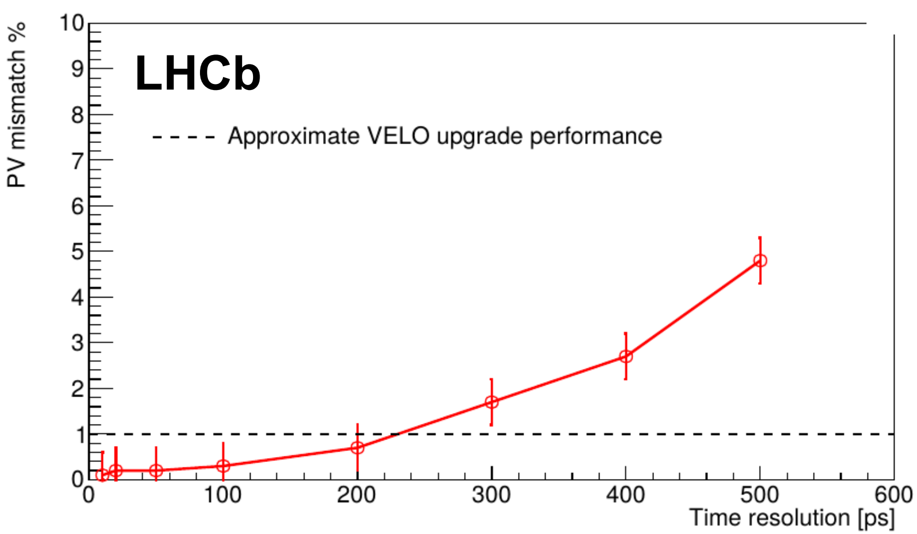


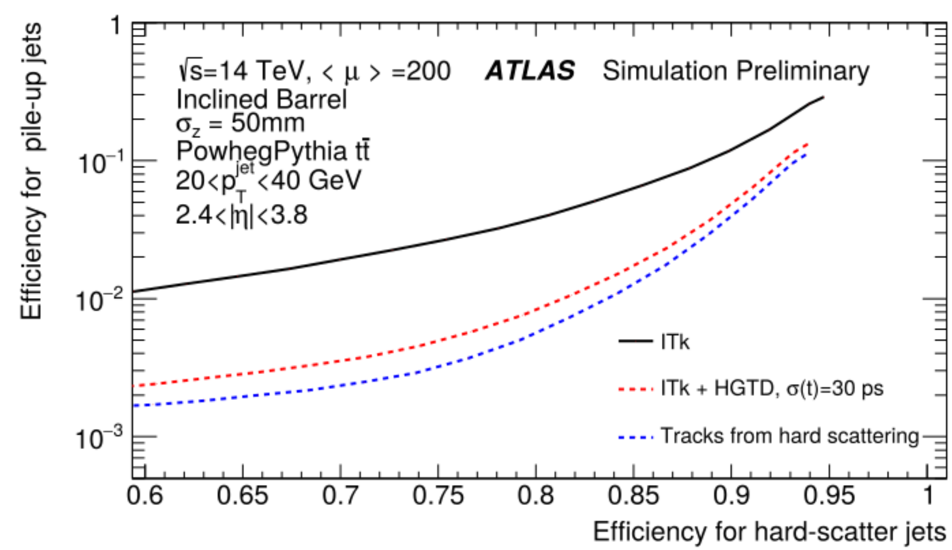
Detector trends: Timing

- R&D: Experiments are investigating Timing detectors
  - Pile up reduction
  - Photon association
  - Association of displaced tracks



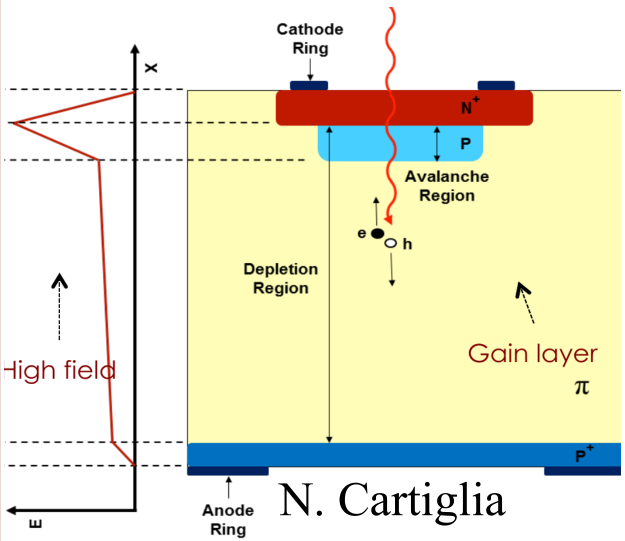
N. Cartiglia





Detector trends: Timing

- R&D: use Low Gain Avalanche Diodes (LGAP)
- timing optimised: UltraFastSiliconDetectors (UFSD)



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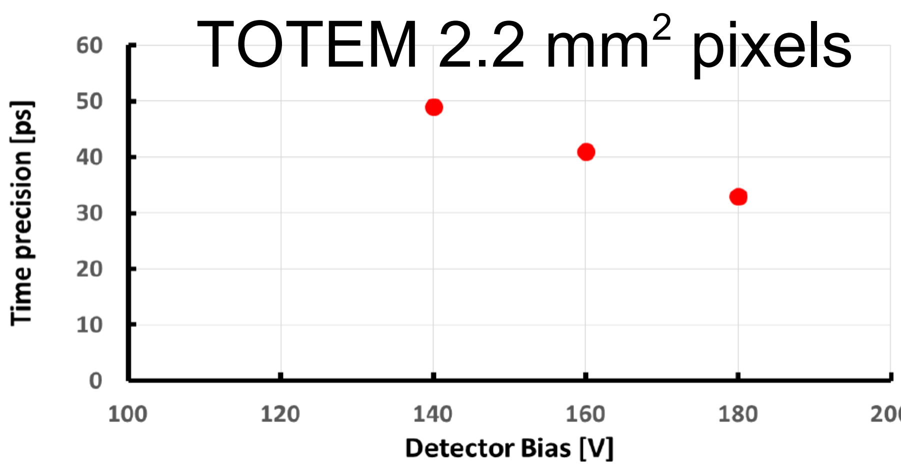
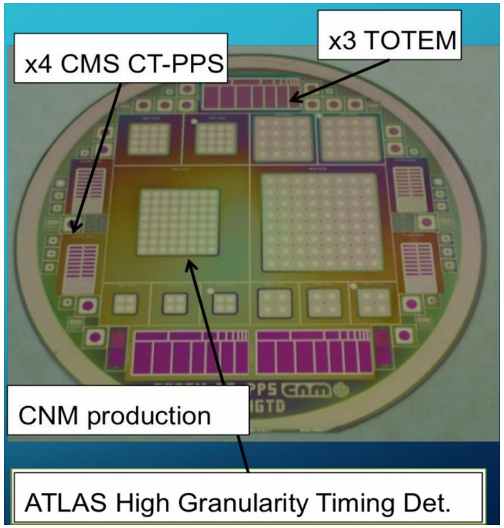
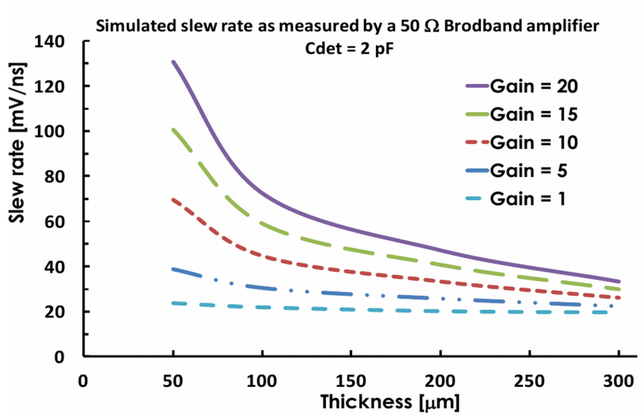
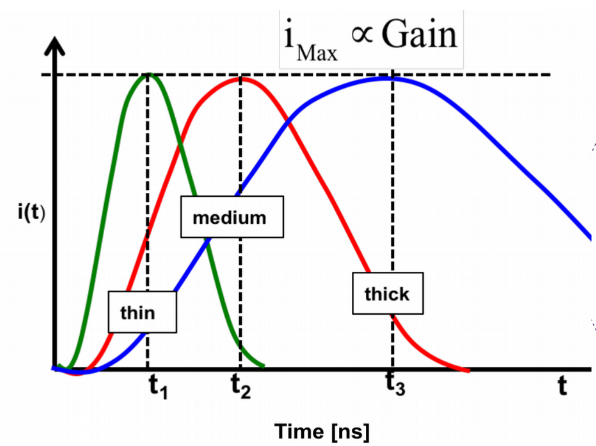
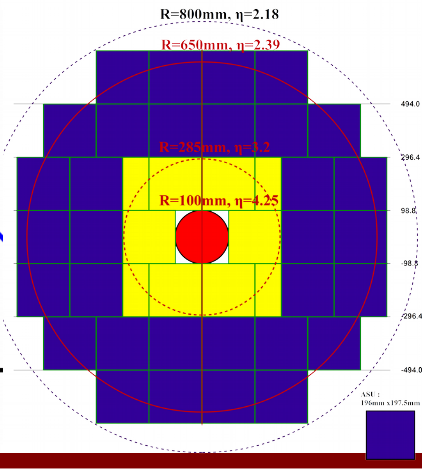
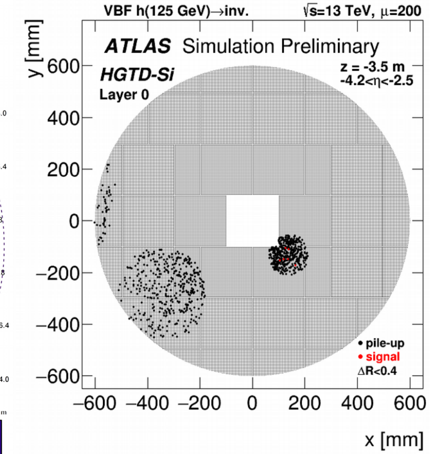












Detector trends

- R&D:
  - HVCMOS/HRCMOS
  - High voltage/High resistivity
  - Underlying technology
    Non-HEP specific

    → cost savings
  - Integration possibilities
    - Smaller pixels
    - Monolithic devices
    - Thinner devices
  - 3D sensors

    See C. DaVia's Talk

See D. Bortoletto's/L. Gonella's Talks

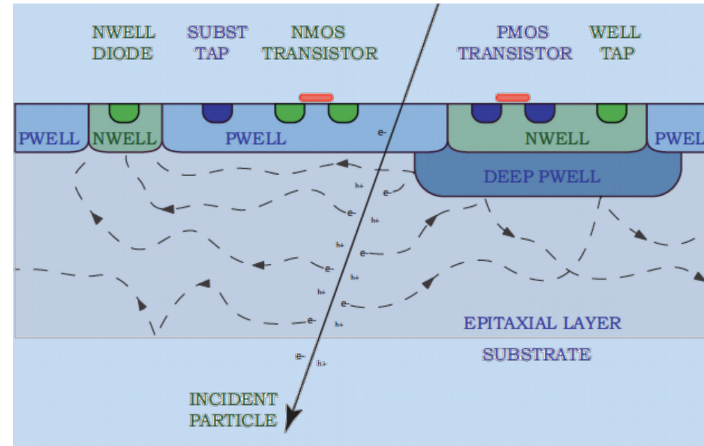
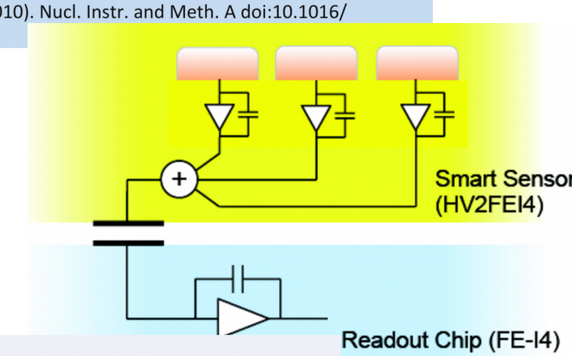
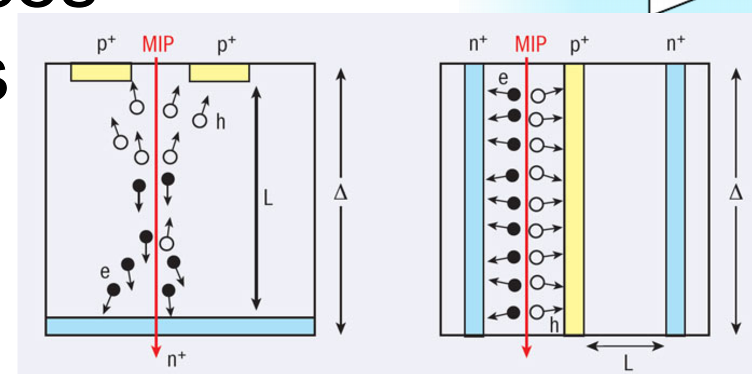


Figure Stanitzki, M. (2010). Nucl. Instr. and Meth. A doi:10.1016/j.nima.2010.11.166

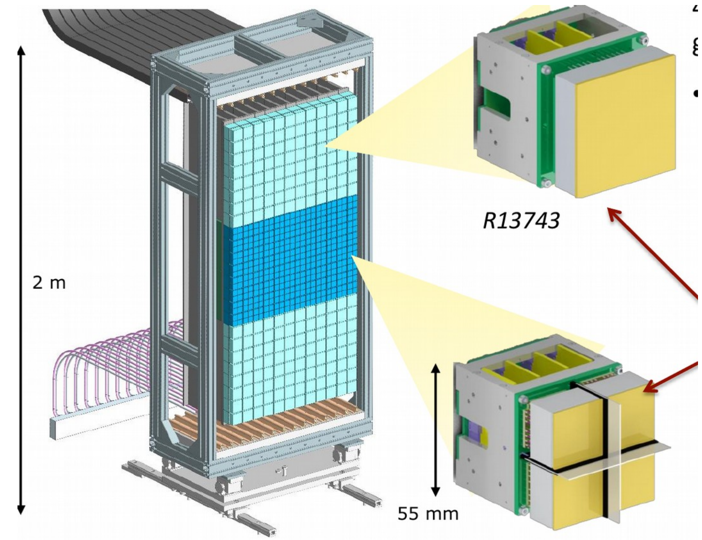




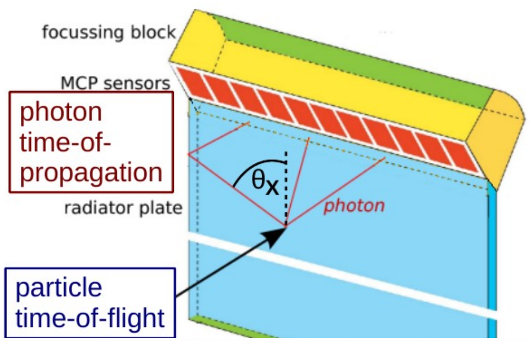
Particle ID: Kaon/pion

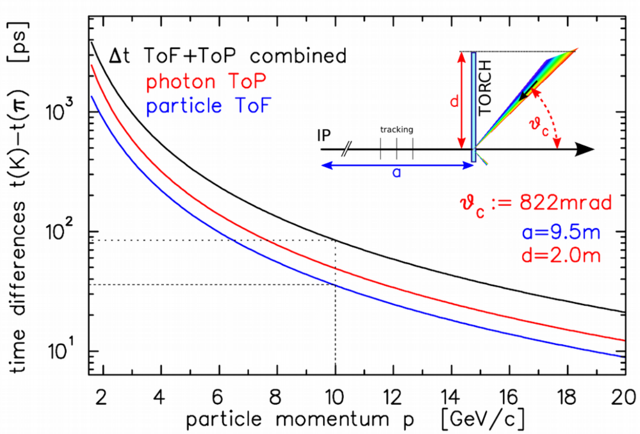
- Ring Imaging CHerenkov/RICH PHASE I:
  - larger Cherenkov rings → reduced occupancy
  - higher granularity faster readout Multianode PMTs
- TORCH concept for PHASE II

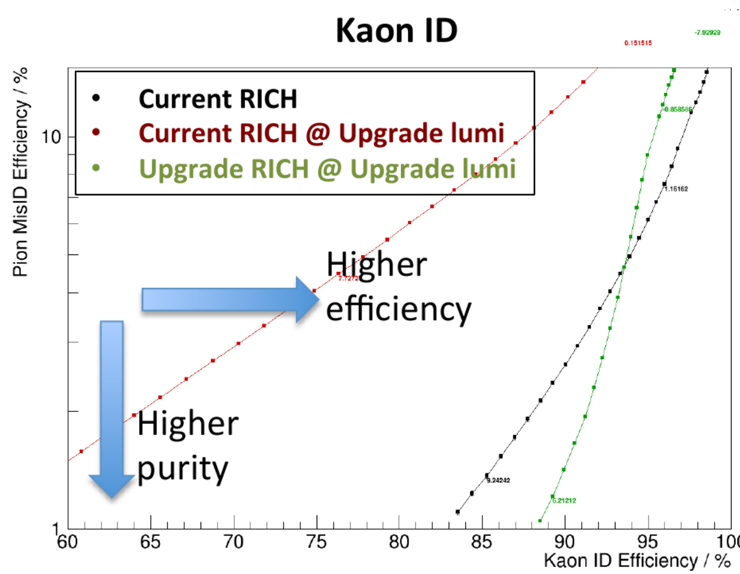
  Timing of internally Reflected CHerenkov Light

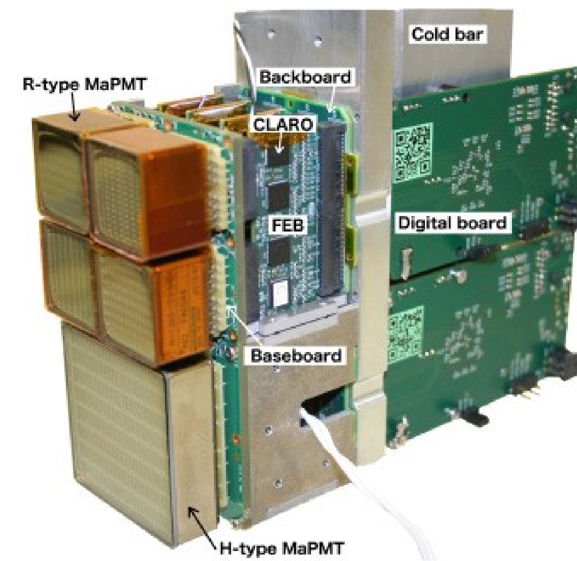


Photosensitive plane of the RICH-2 detector



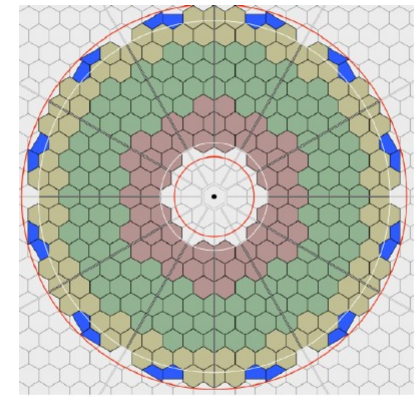


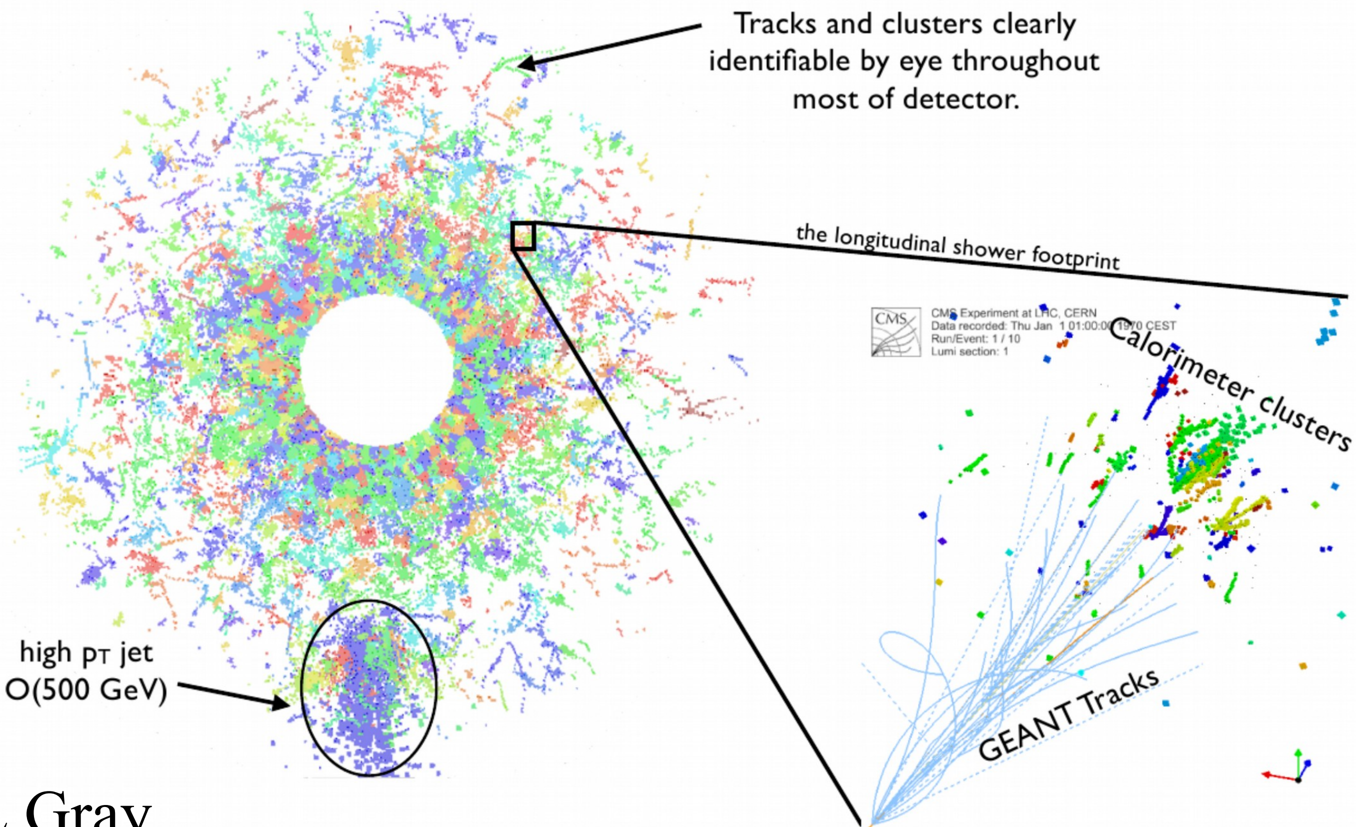




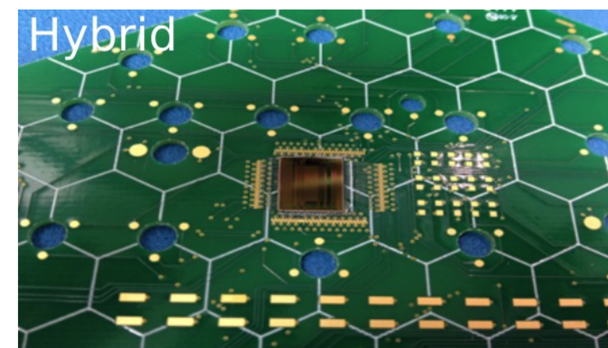
Detector trends: CMS HGCAL

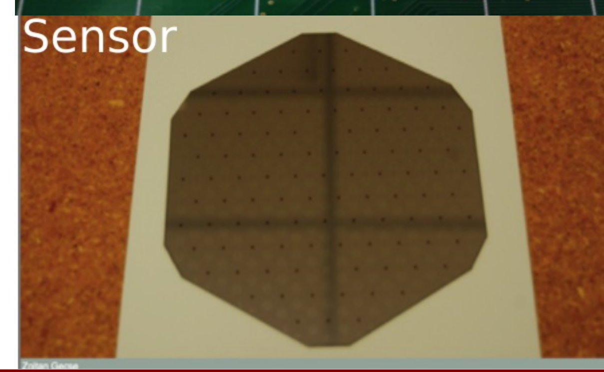
High granularity Calorimeter using silicon sensors
→ perfect particle flow!





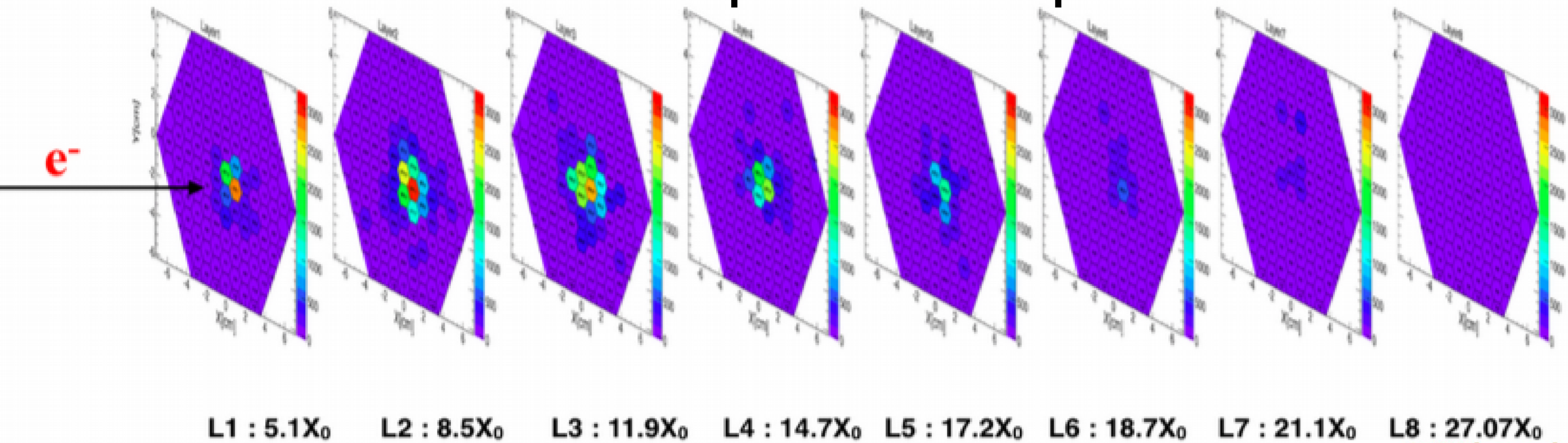
L.Gray



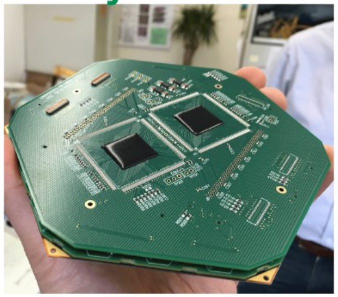


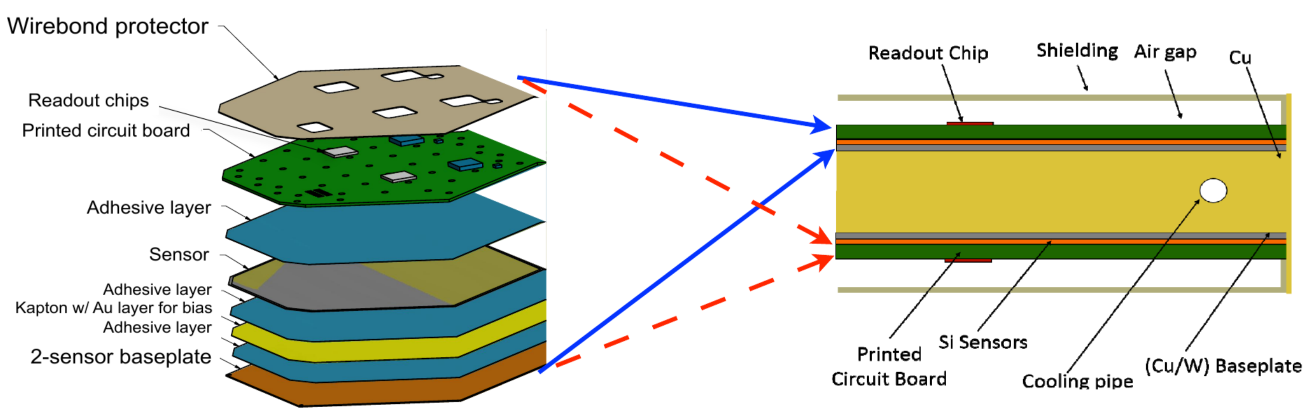
Detector trends: CMS HGCAL

High granularity Calorimeter using silicon sensors
→ measure shower depth/development



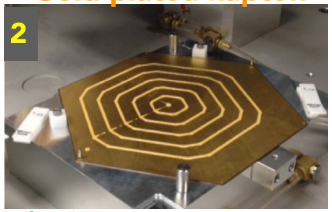
Full module with double-layer PCB readout



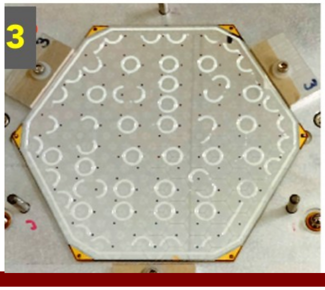


CuW baseplate

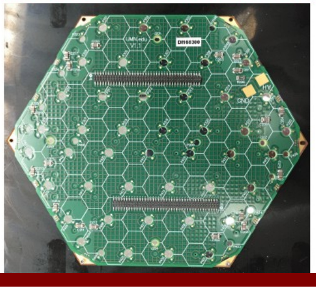
Gold plated kapton



Silicon sensor

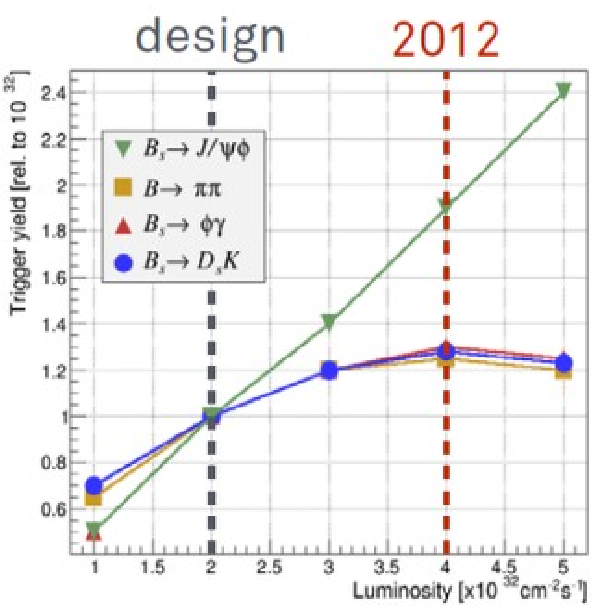


1st PCB wire-bonded to sensor



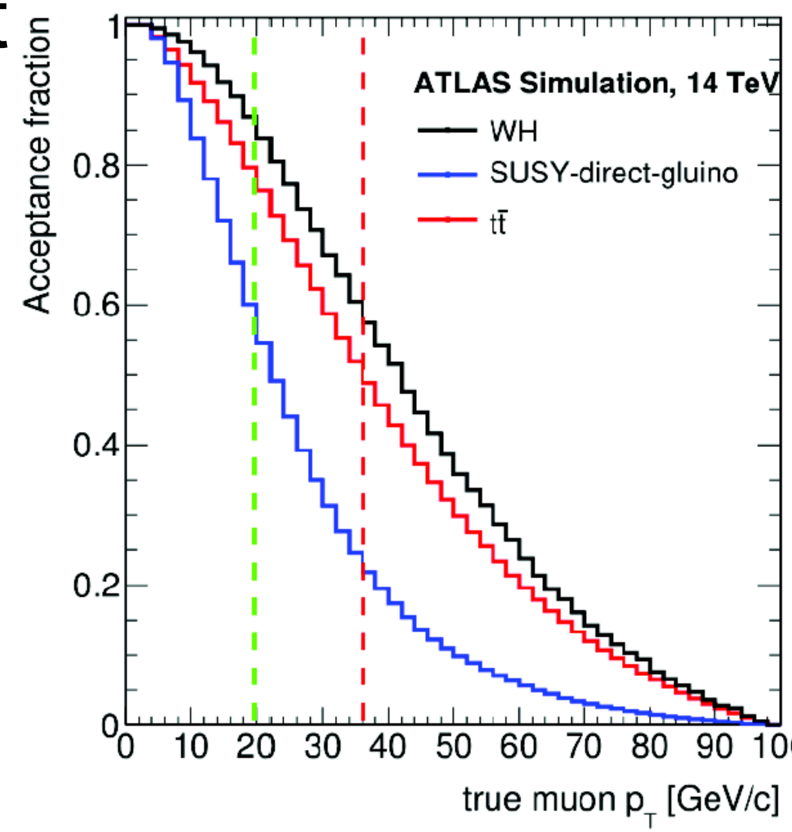
Detector trends

- Improve readout speed and trigger sophistication to keep more physics of interest
  - ATLAS & CMS track trigger
  - LHCb 40 MHz readout



Leptonic

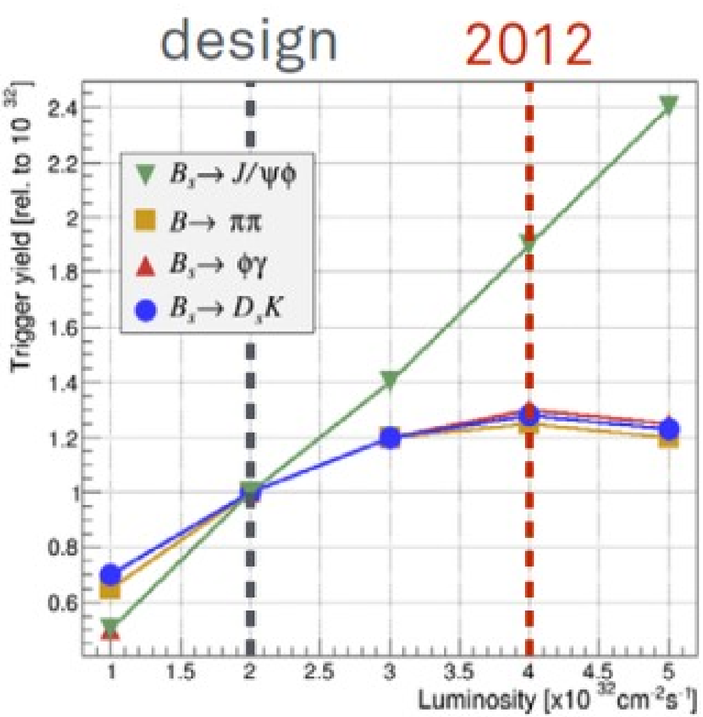
Hadronic



Signatures: W,Z
Need low thresholds!

Readout upgrade

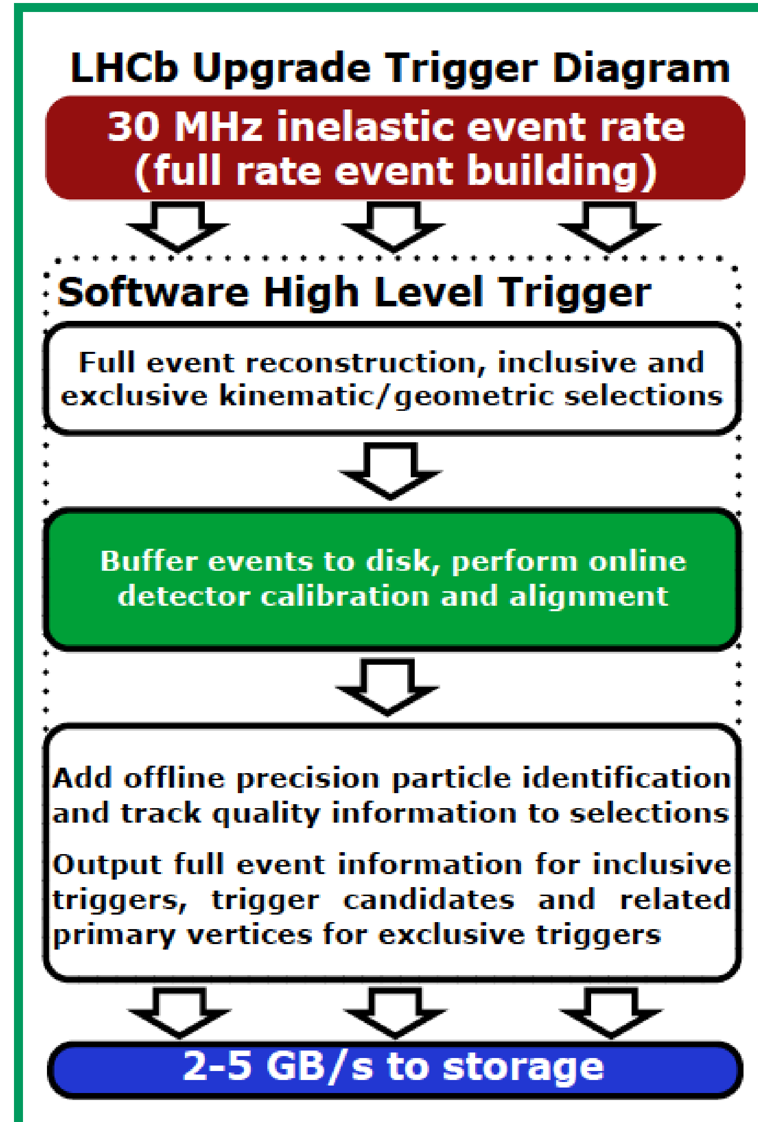
- Hadronic triggers saturate
  → bandwidth limited
- Increase in lumi
  → increase in threshold



Leptonic

Hadronic

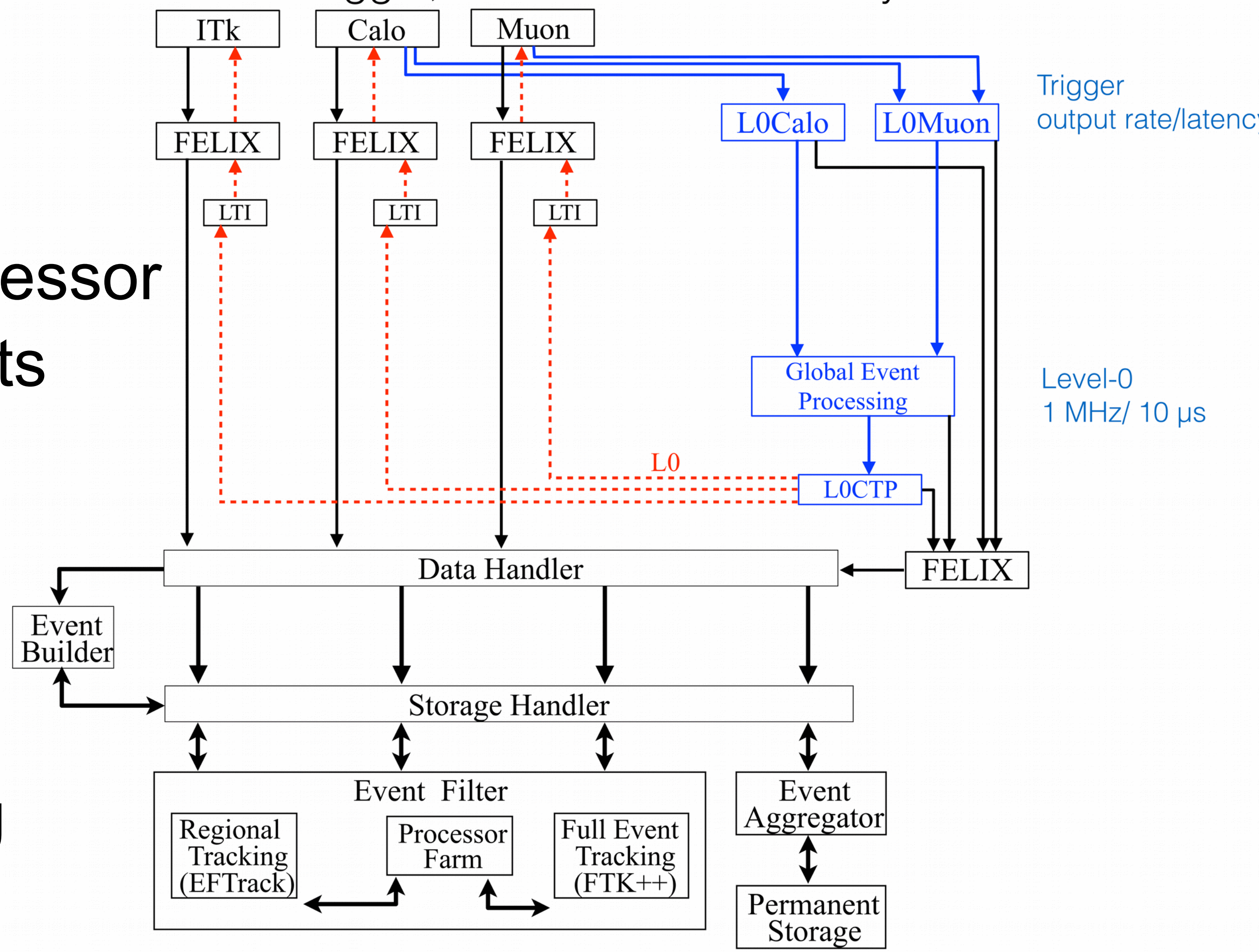
PHASE II:
200×10^{32} cm^{-2}s^{-1}



ATLAS: Trigger/DAQ upgrade

- Single level hardware trigger, Event Filter and DAQ system

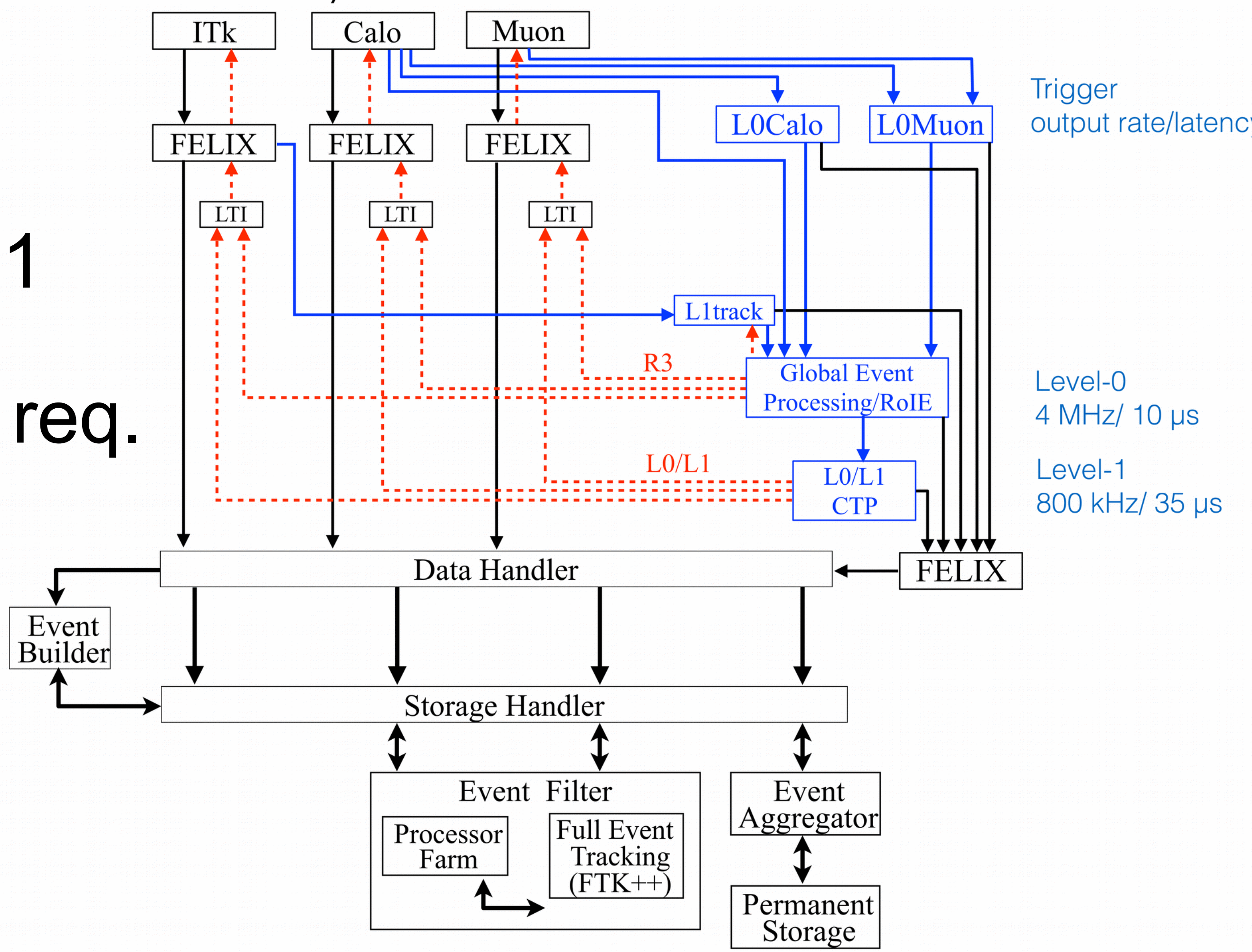
- 1 MHz readout at lowest level
- Upgraded "Global" EventProcessor
- Regions of Interests
  - Calo
  - Muons
- Regional Tracking
  - EFTrack
- Full Event Tracking
  - FTK++

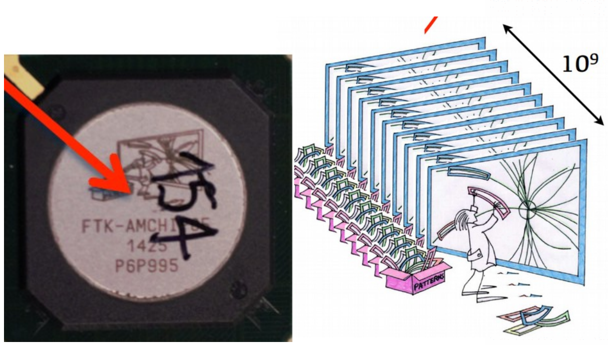


ATLAS: Trigger/DAQ upgrade

- Evolved to a low-latency level-0 – level-1

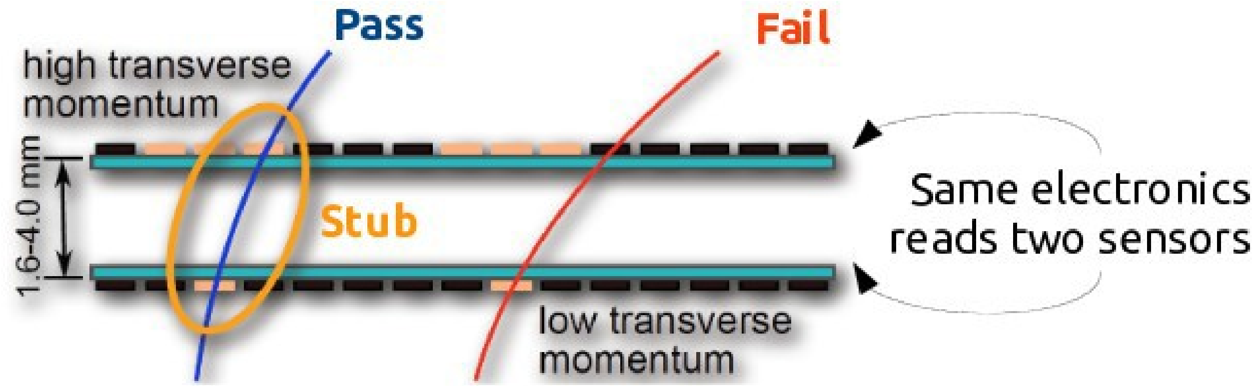
- Allow for 4 MHz capabilities
- Two stages L0/L1
- R3, regional readout req.
- AM based Track Trigger



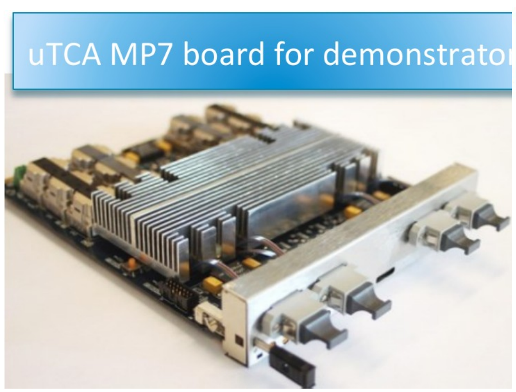


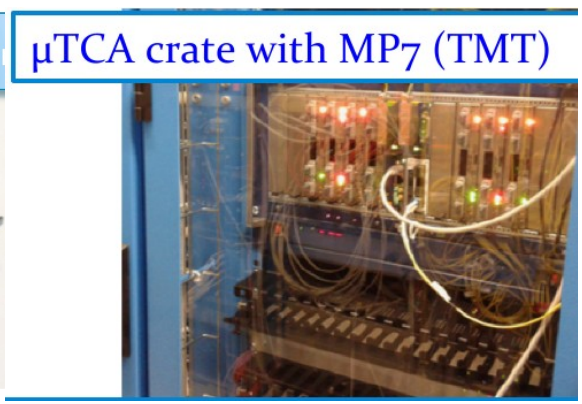
CMS Track Trigger

- Use double layers

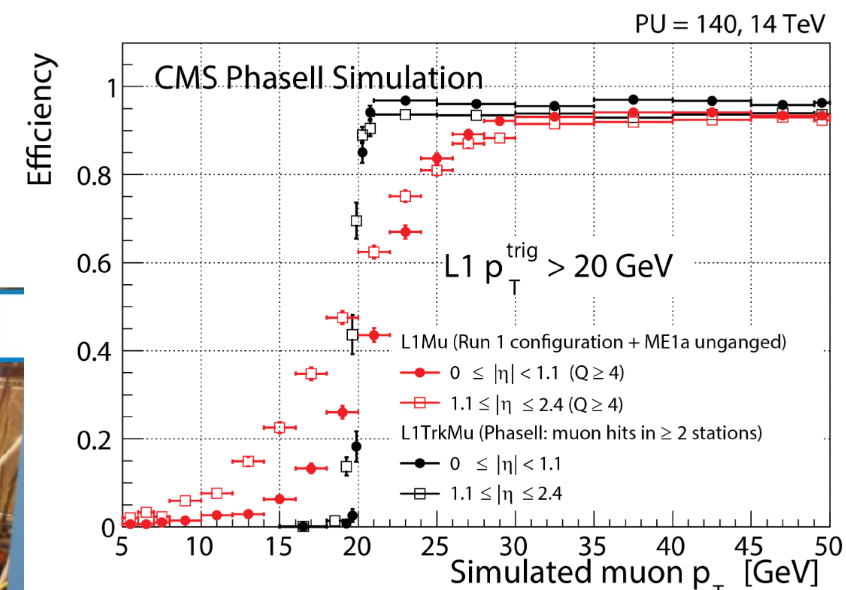


- Stub seeding
- Several approaches
  - Time multiplexing
  - FPGA based
  - Associative Memory based





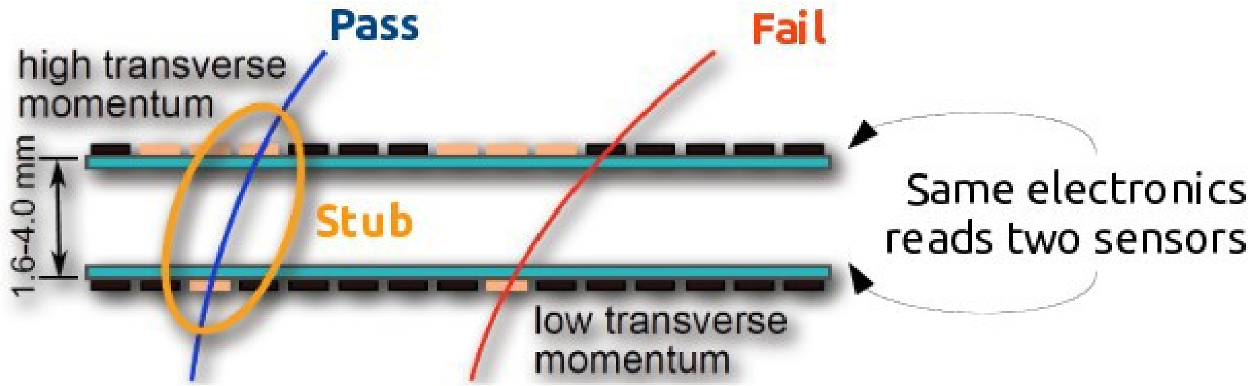
See T. James/S.Summers Talks

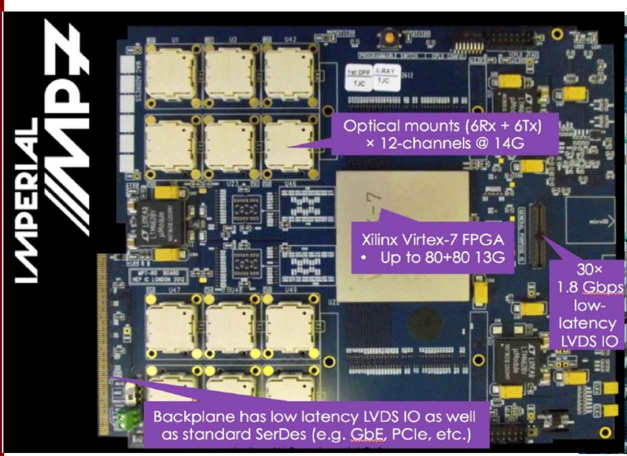


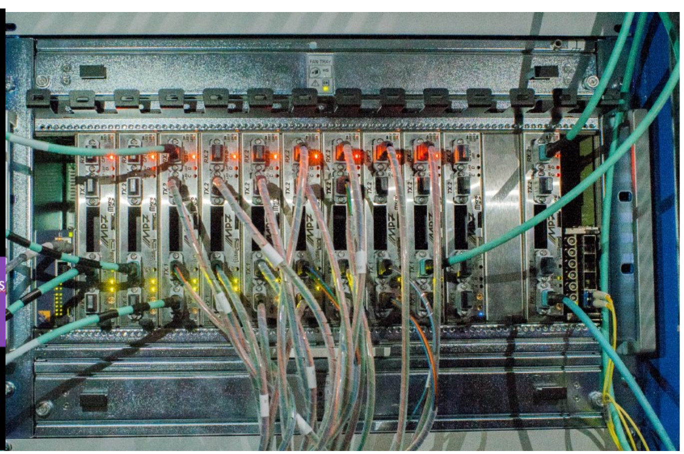
Sharp muon threshold, keeps trigger rate acceptable

CMS Track Trigger

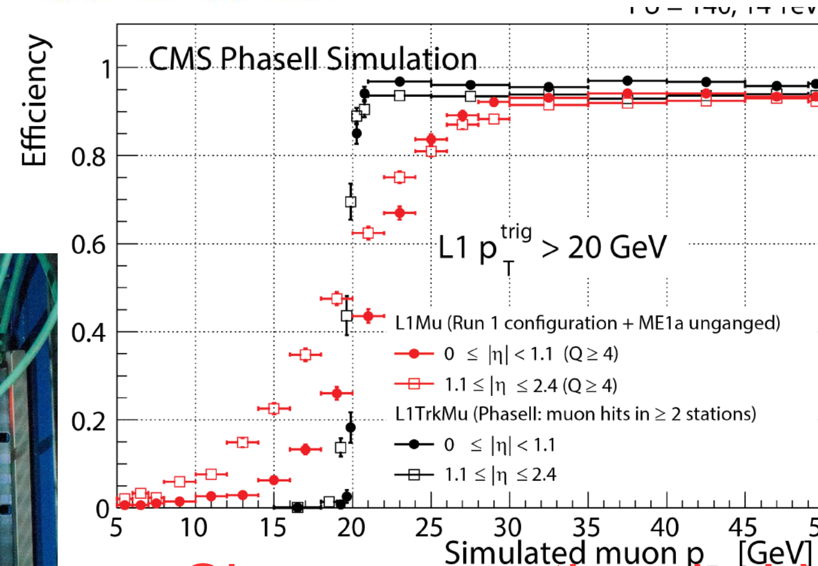
- Use double layers
- Stub seeding
- Several approaches
  - Time multiplexing
  - FPGA based
  - Associative Memory based







T. James

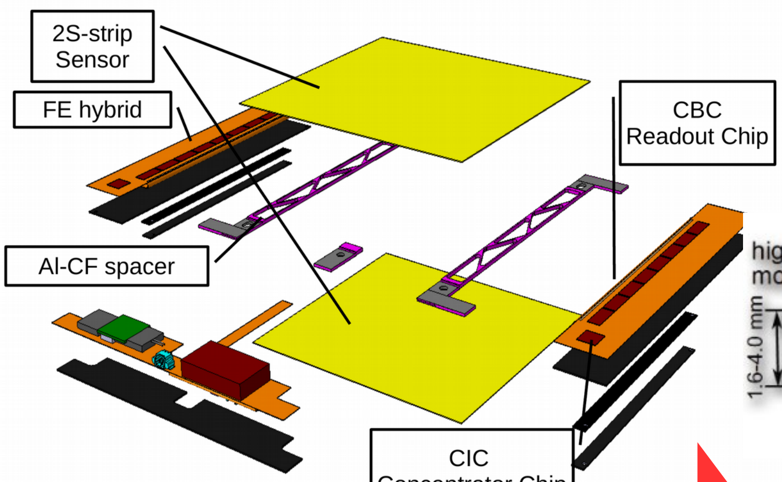


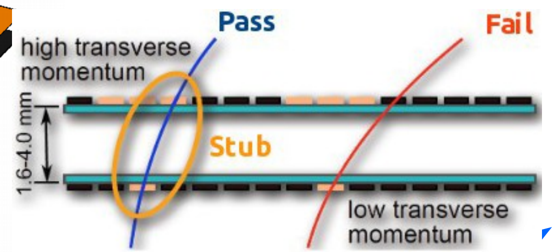
Sharp muon threshold, keeps trigger rate acceptable

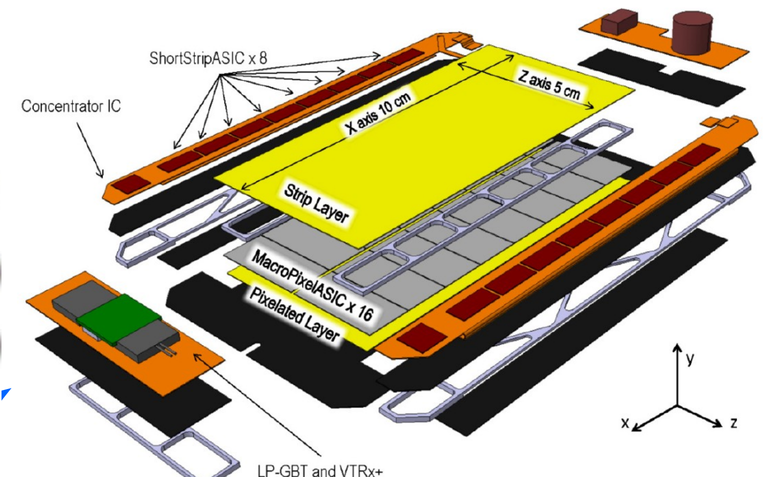
CMS Track Trigger

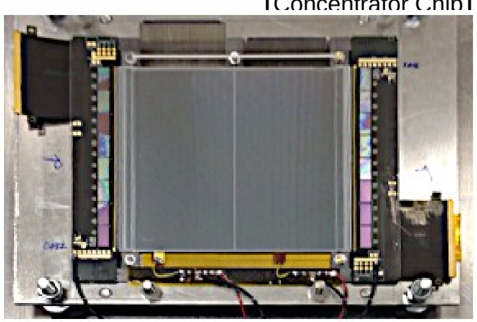
- 2S: strip-strip
- 5cm x 90μm double strips
- Separated by 1.6/4mm

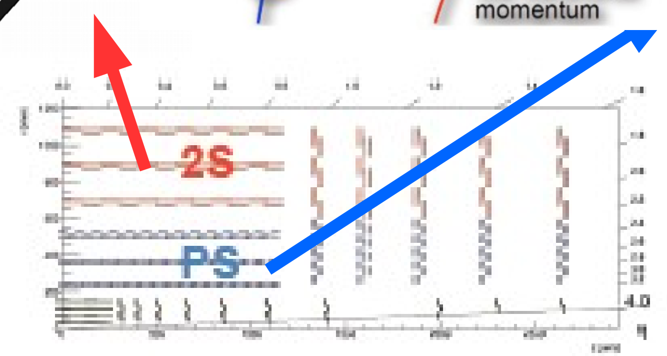
- PS: pixel-strip
- 2.5cm x 100μm short strips
- 1.5mm x 100μm pixels
- Separated by 1.6-4mm

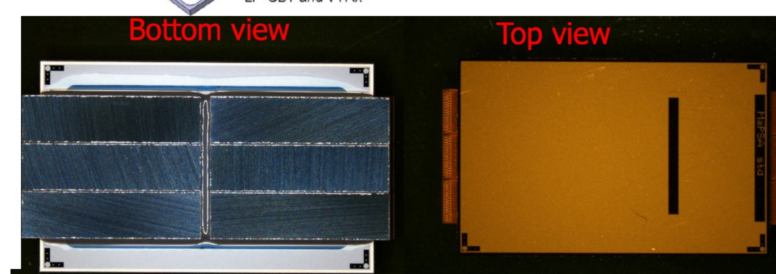






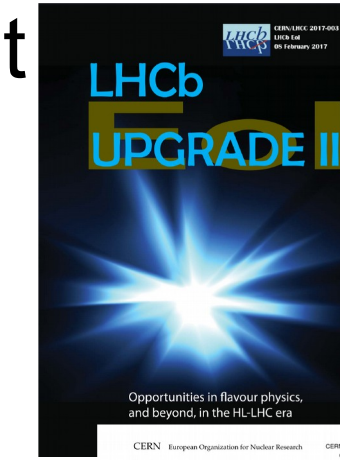




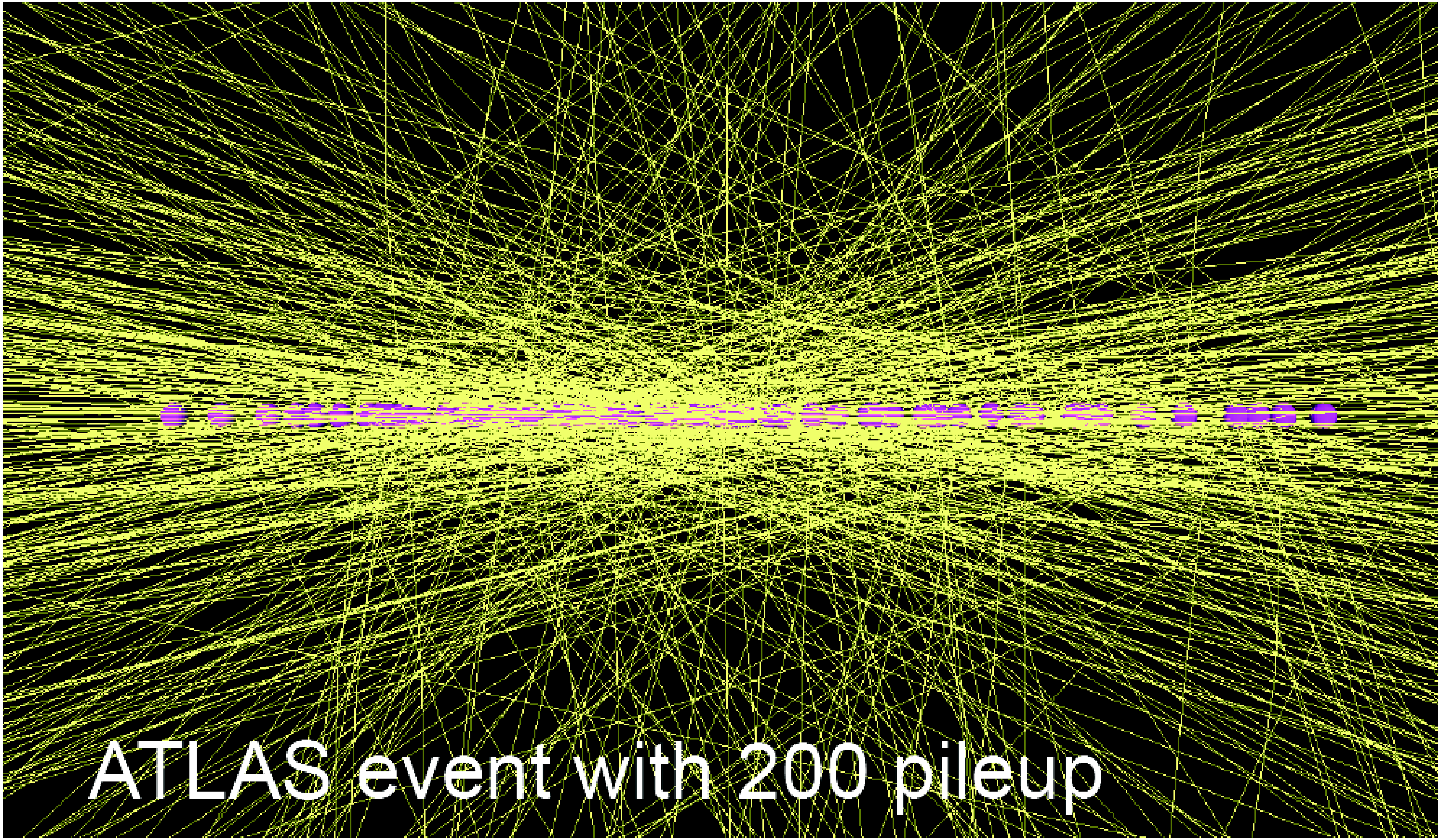


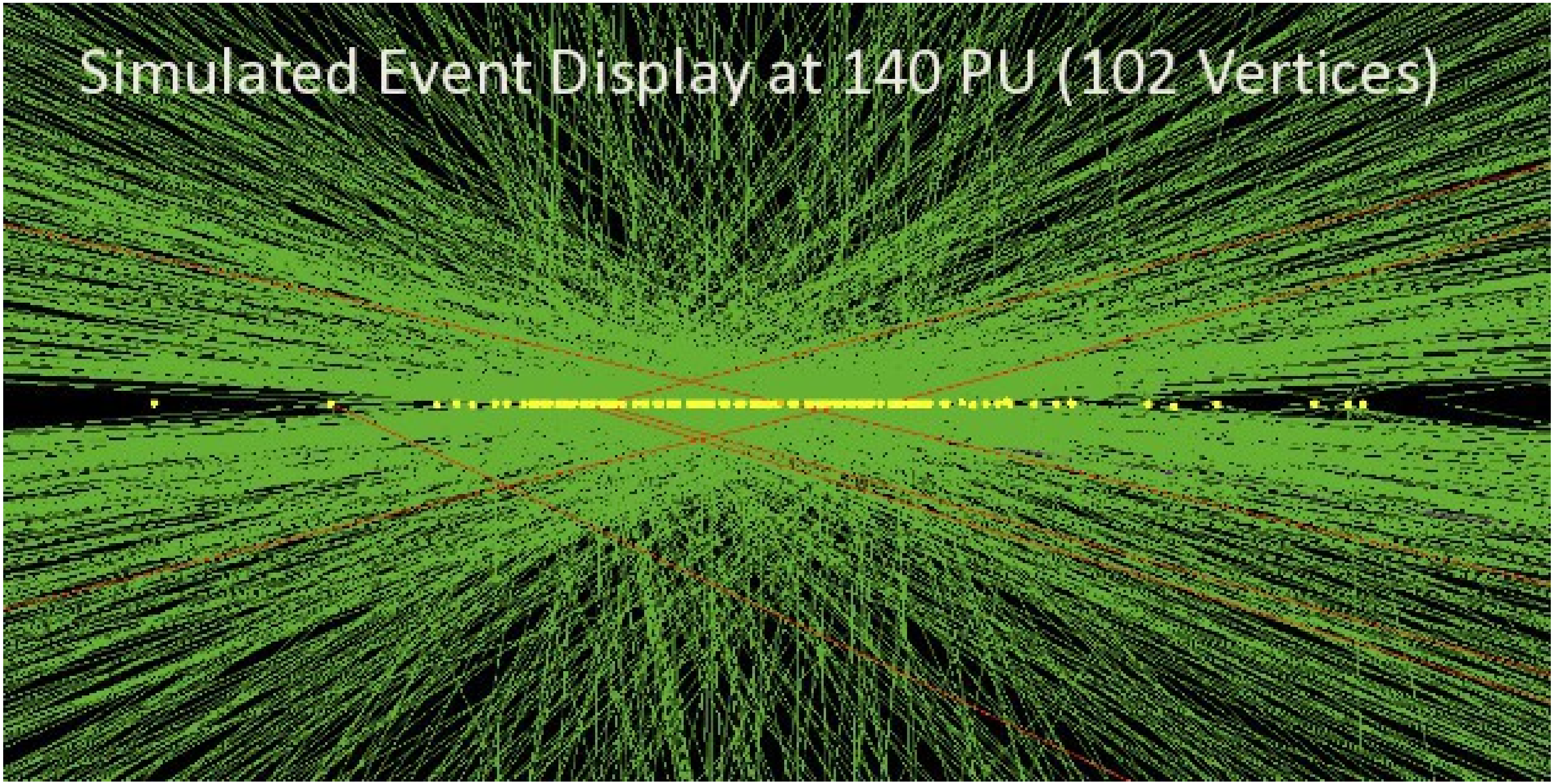
Documentation

- A number of new documents of interest
- LHCb Upgrade II CERN-LHCC-2017-003
  - http://cds.cern.ch/record/2244311
- Phase-2 CMS Upgrade Technical Proposal
  - http://cds.cern.ch/record/2020886/files/LHCC-P-008.pdf
- Phase-2 CMS Upgrade Scope Document
  - http://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf
- Phase-2 CMS Upgrade of the CMS Tracker in prep
- Phase-2 ATLAS Strip TDR CERN-LHCC-2017-005
  - https://cds.cern.ch/record/2257755
- Phase-2 ATLAS Scoping Document
  - https://cds.cern.ch/record/2055248
- Phase-2 ATLAS Pixel TDR in preparation



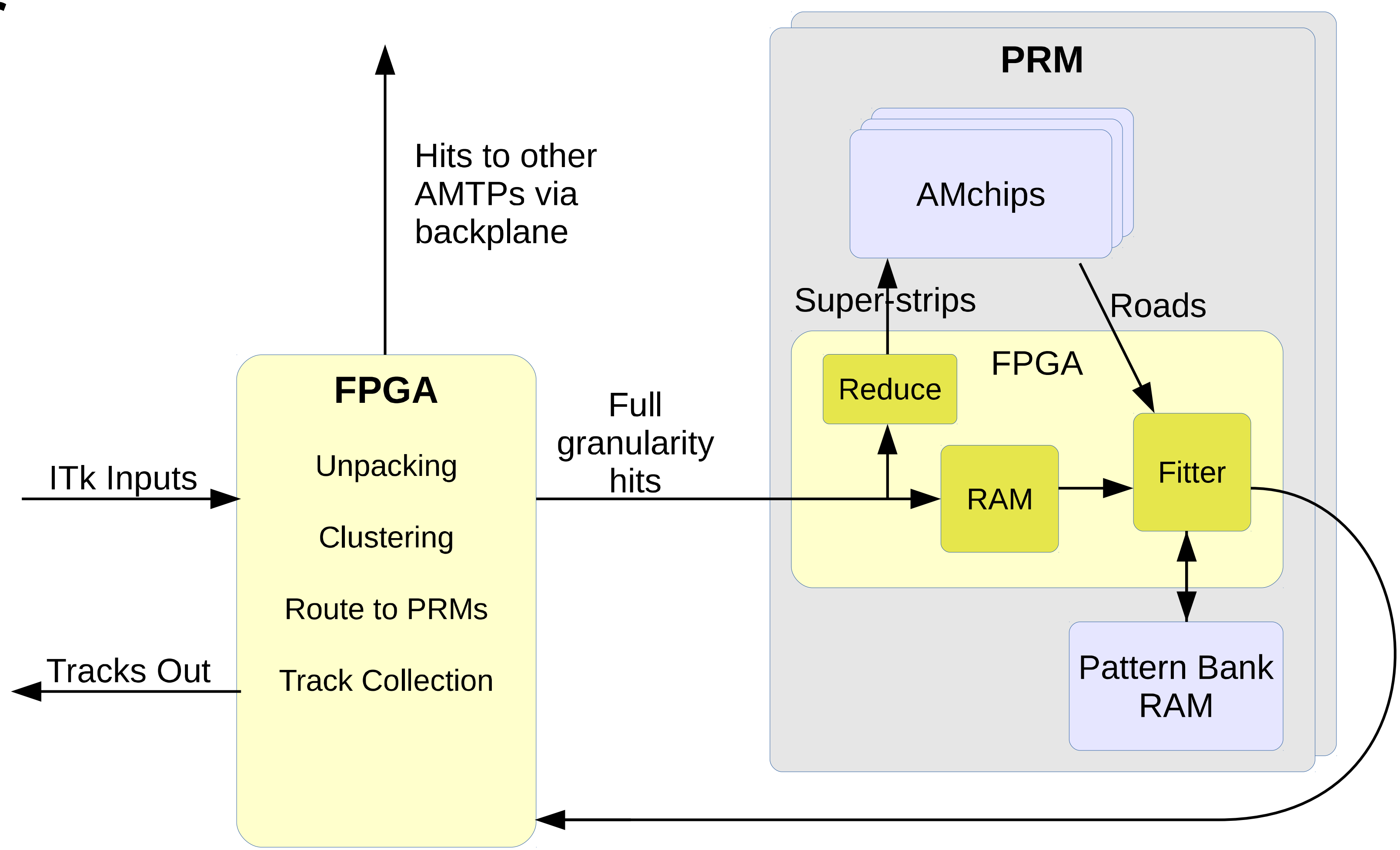
Bonus Slides

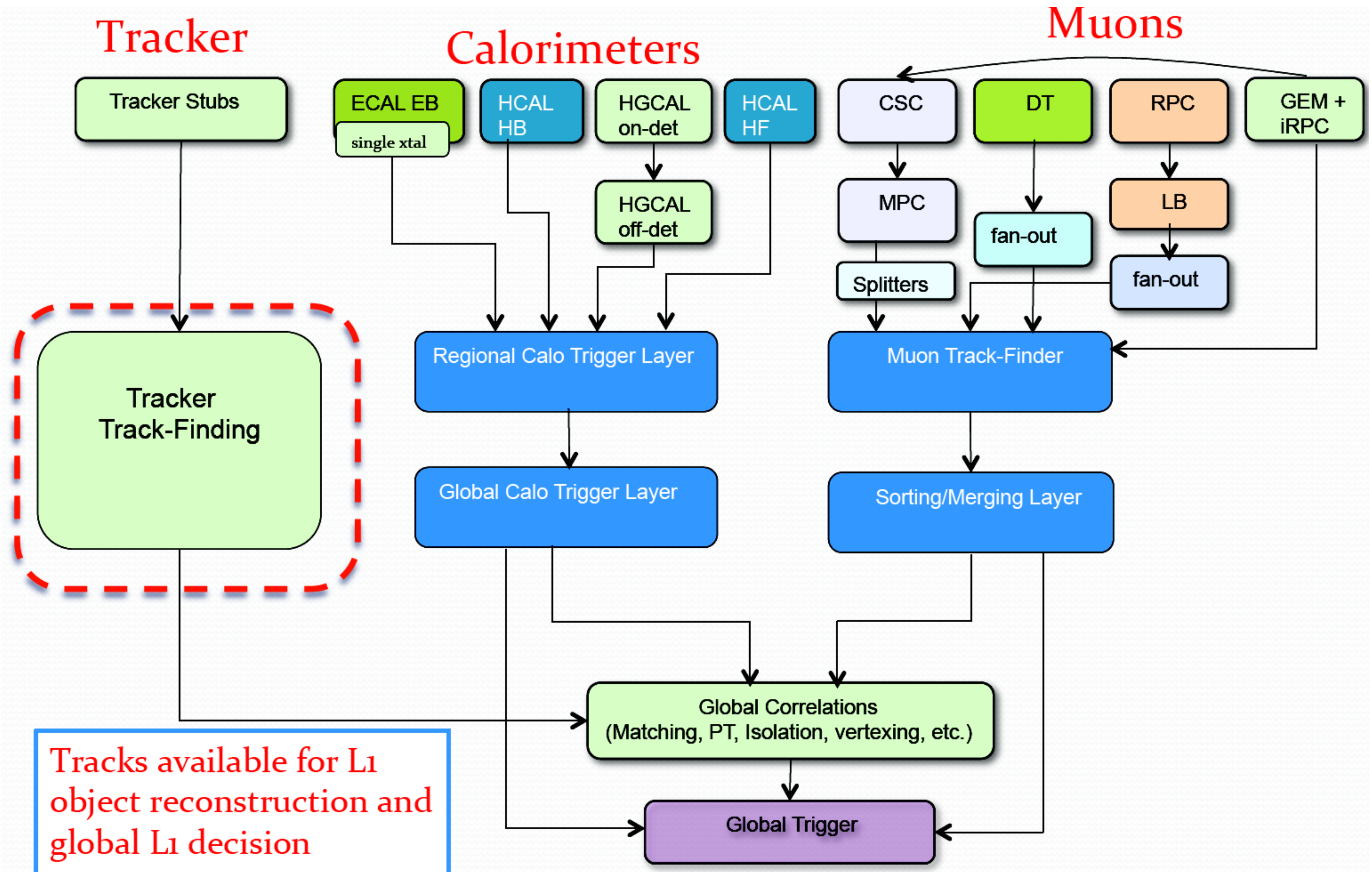

ATLAS event with 200 pileup


Simulated Event Display at 140 PU (102 Vertices)

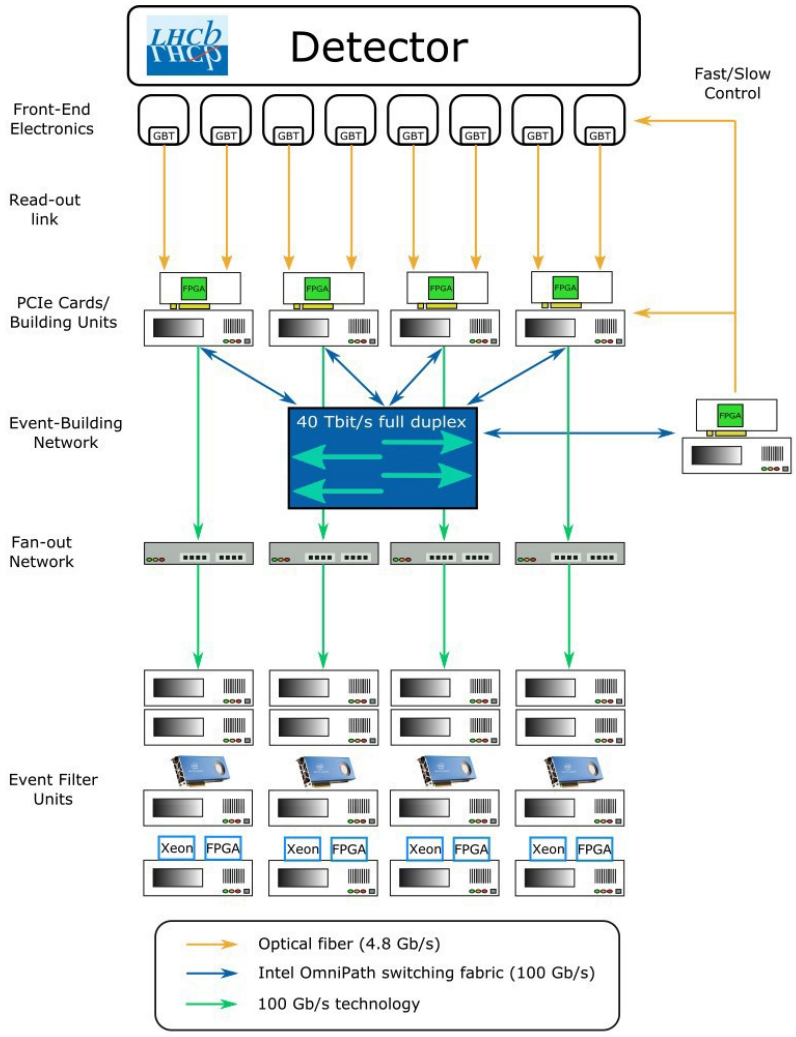
ATLAS: Track Trigger

- Trigger
- Tracker
-

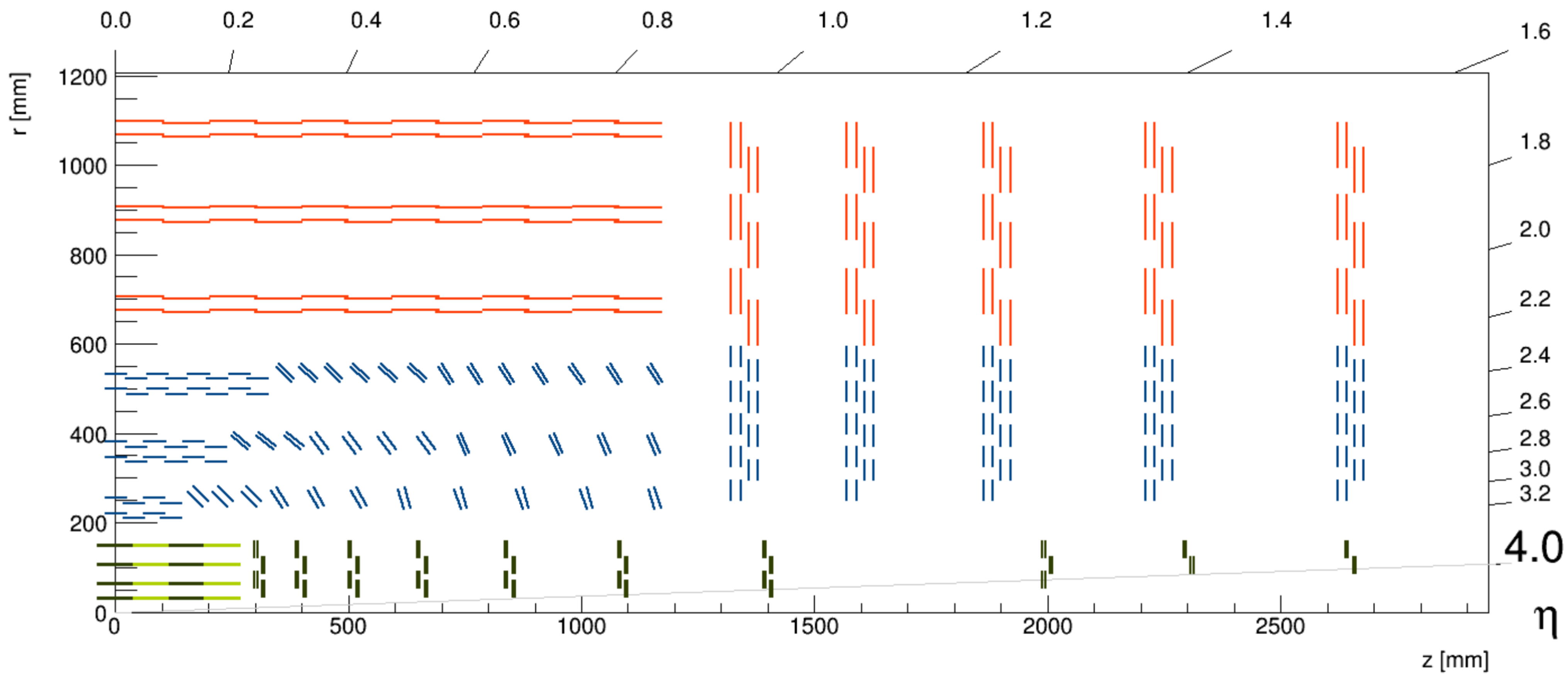




Tracks available for L1 object reconstruction and global L1 decision

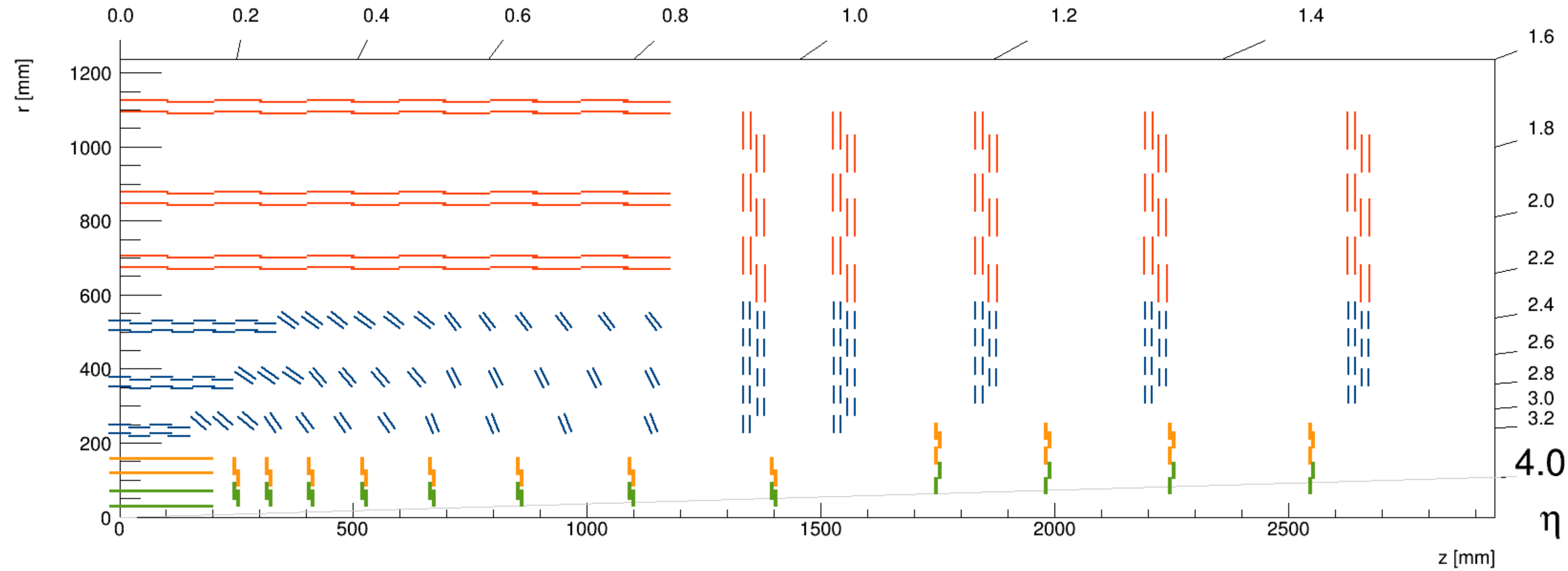

Detector
Fast/Slow Control
Front-End Electronics
GBT
Read-out link
PCIe Cards/ Building Units
FPGA
Event-Building Network
40 Tbit/s full duplex
Fan-out Network
Event Filter Units
Xeon
FPGA
Optical fiber (4.8 Gb/s)
Intel OmniPath switching fabric (100 Gb/s)
100 Gb/s technology

CMS



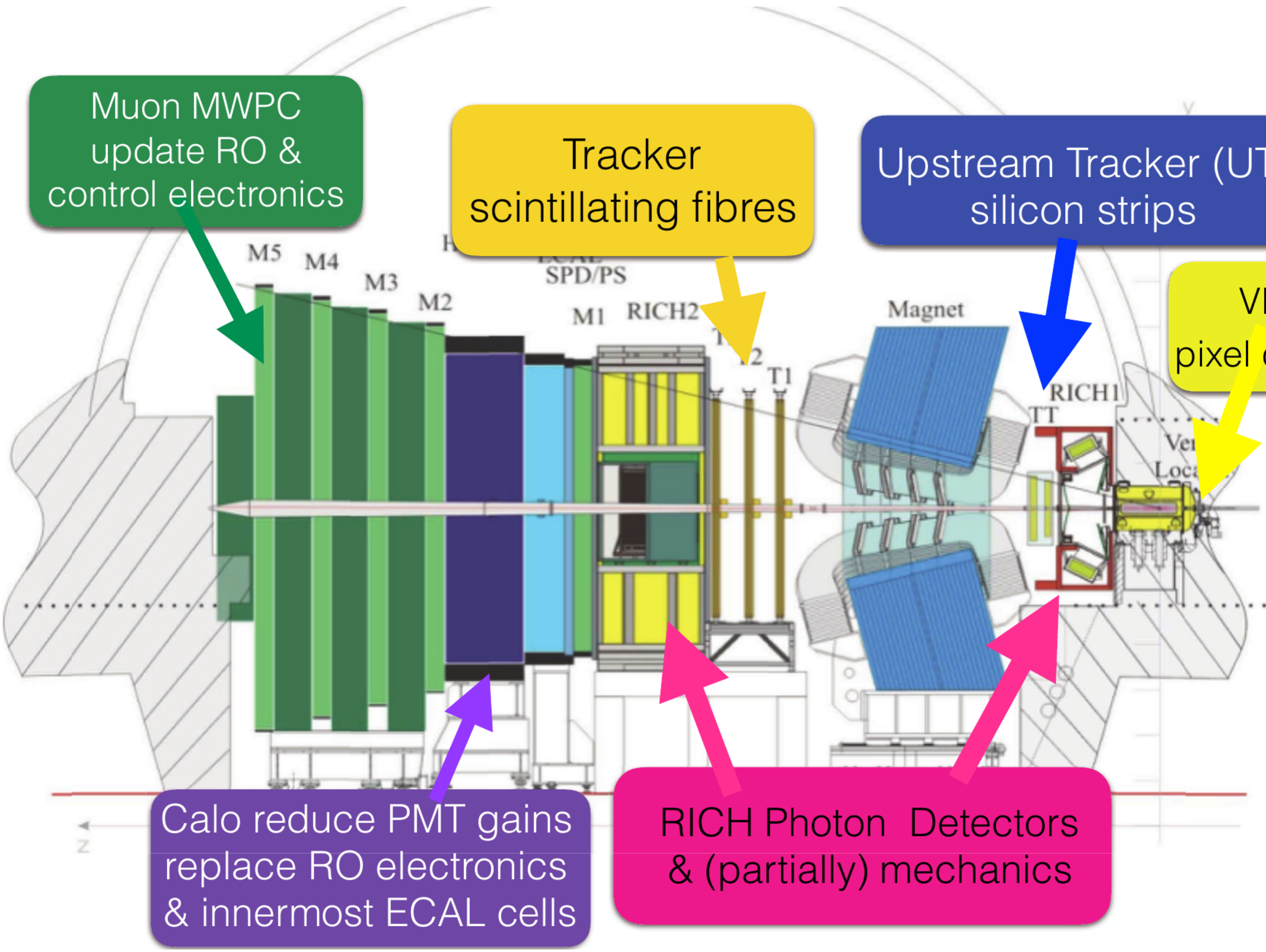
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
4.0
η
r [mm]
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
z [mm]

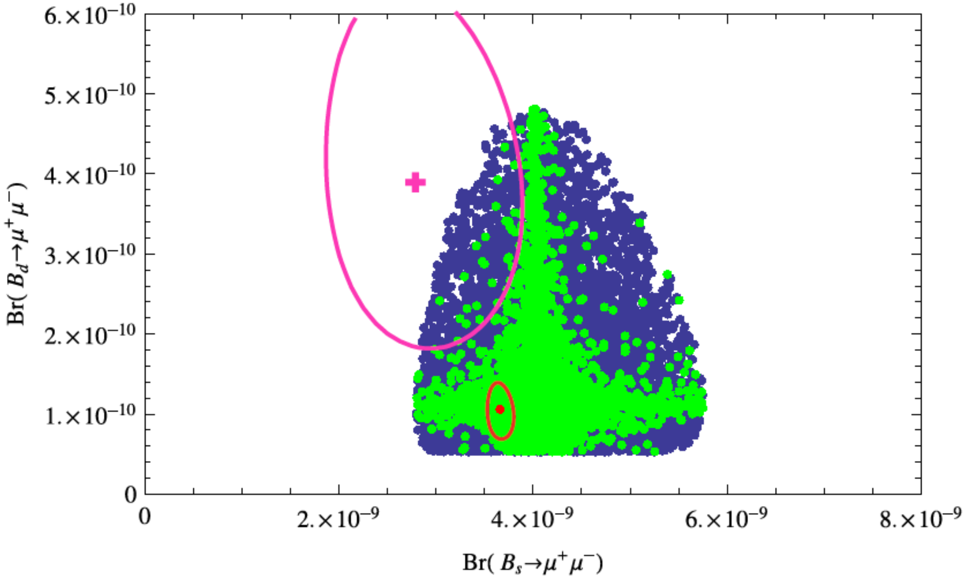
CMS

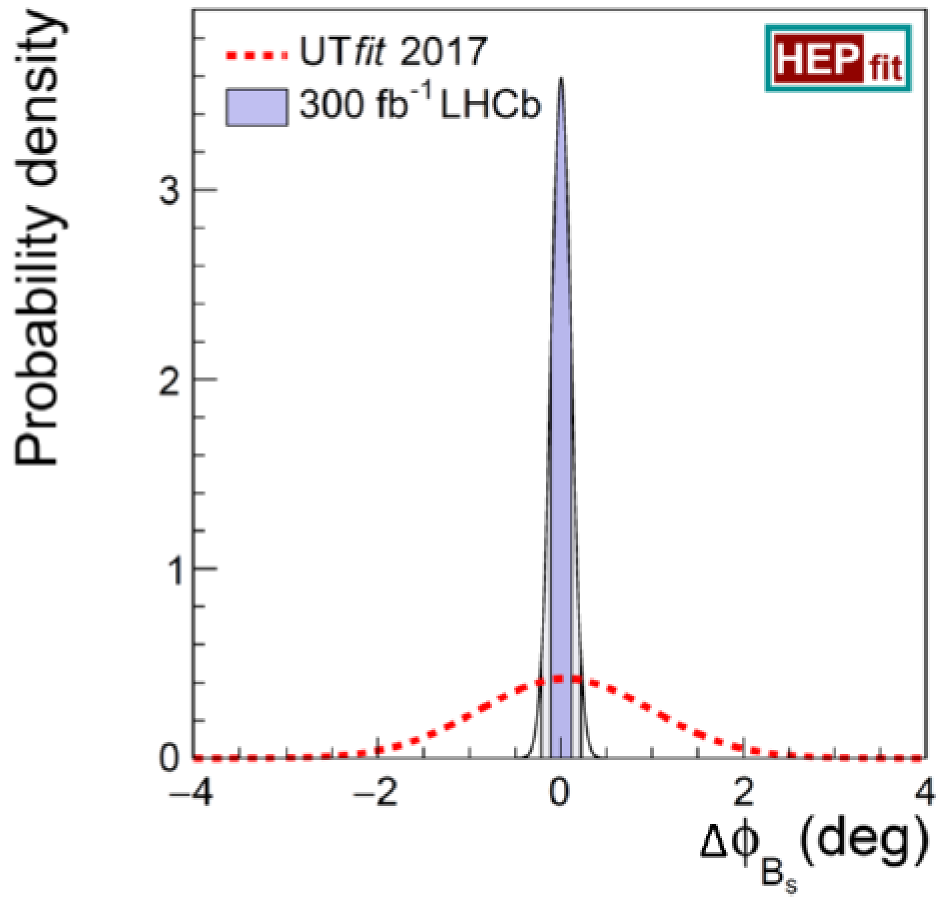

0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
4.0
η
r [mm]
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
z [mm]

LHCb Upgrade Overview

- Trig
- Tra
-

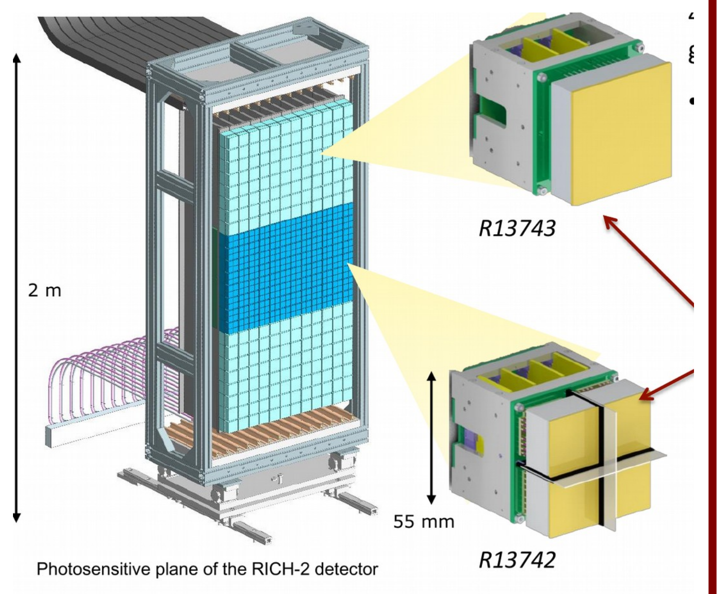


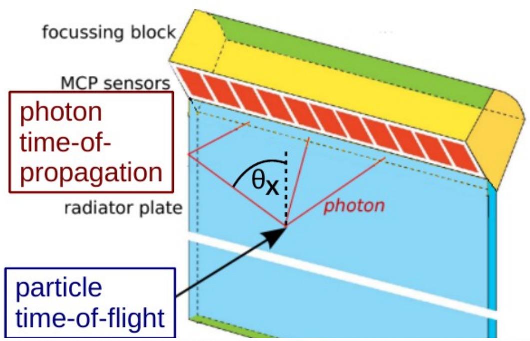

6. × 10⁻¹⁰
5. × 10⁻¹⁰
4. × 10⁻¹⁰
3. × 10⁻¹⁰
2. × 10⁻¹⁰
1. × 10⁻¹⁰
0
0
2. × 10⁻⁹
4. × 10⁻⁹
6. × 10⁻⁹
8. × 10⁻⁹
Br($B_d \to \mu^+\mu^-$)
Br($B_s \to \mu^+\mu^-$)

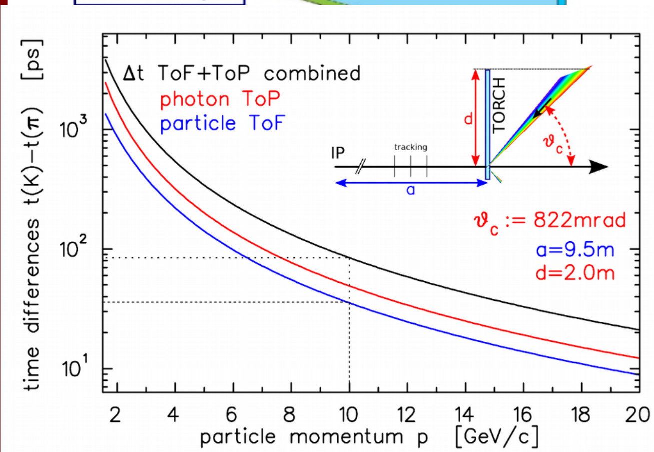

UTfit 2017
300 fb-1 LHCb
HEPfit
Probability density
3
2
1
0
−4
−2
0
2
4
$\Delta\phi_{B_s}$ (deg)

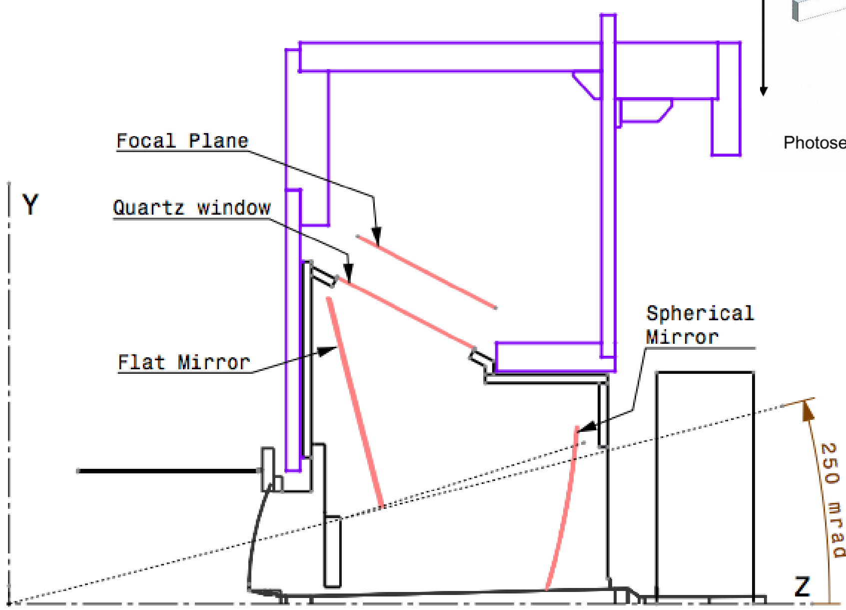
Particle ID: Kaon/pion

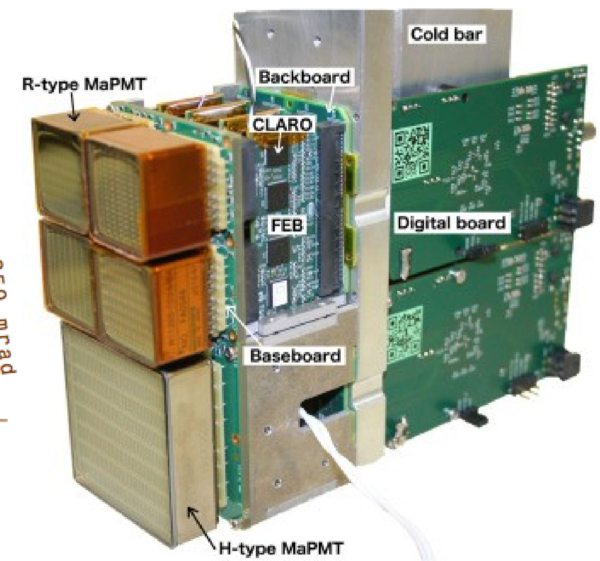
- Ring Imaging CHerenkov/RICH PHASE I:
  - larger Cherenkov rings → reduced occupancy
  - higher granularity faster readout Multianode PMTs
- TORCH concept for PHASE II
  Timing of internally Reflected Cherenkov Light











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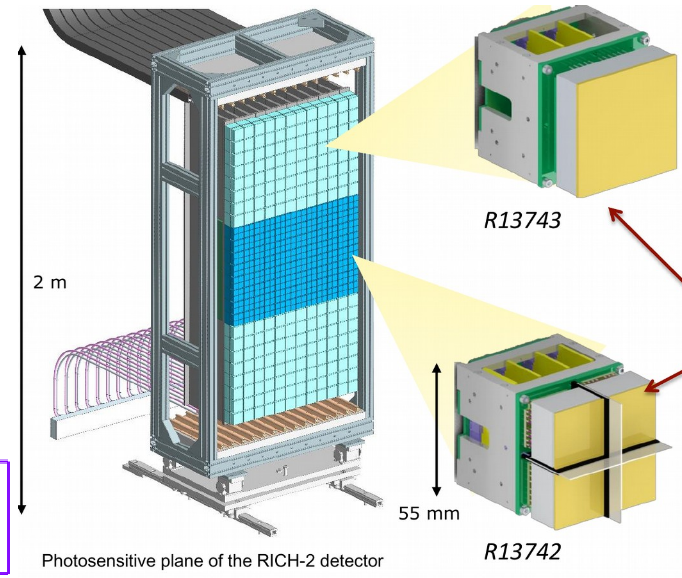

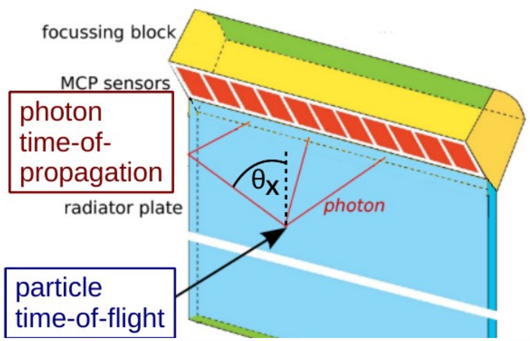

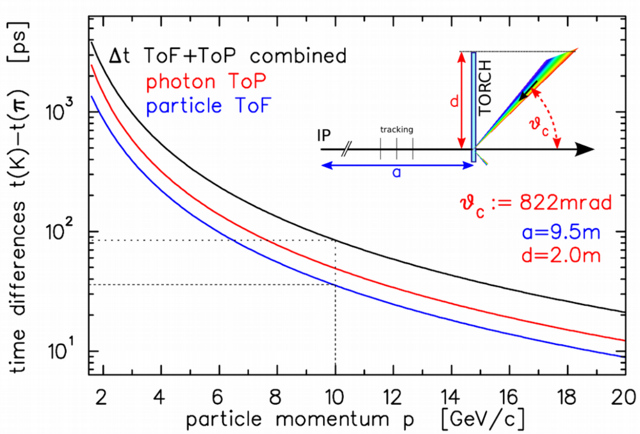

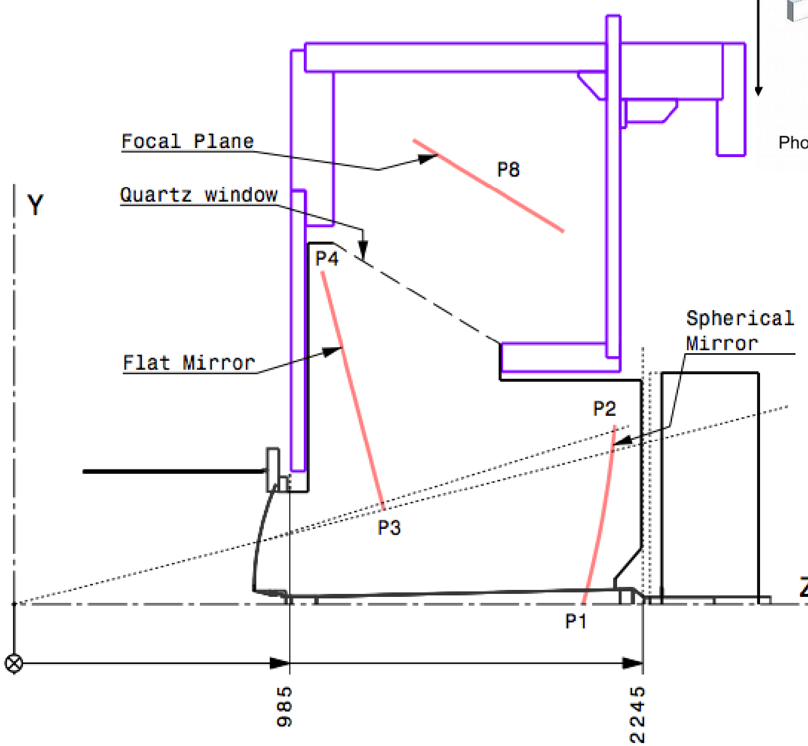

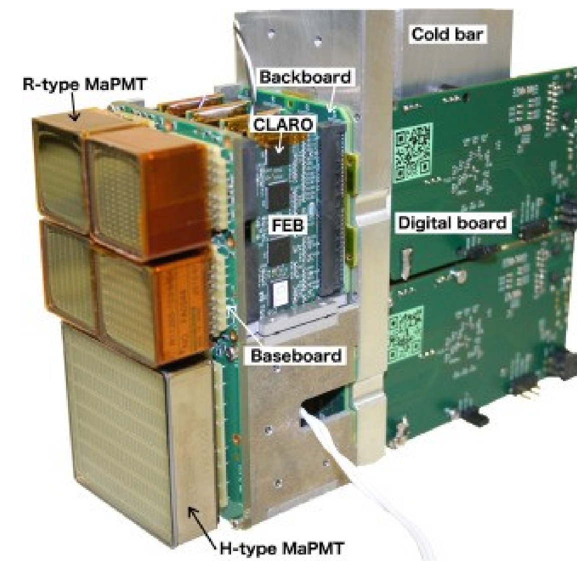

Particle ID: Kaon/pion

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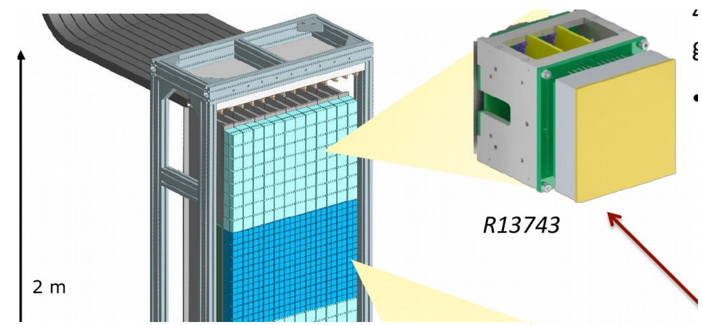
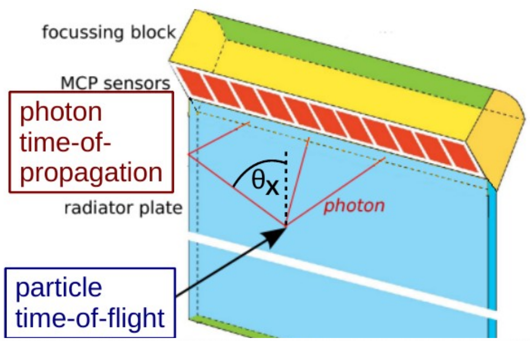
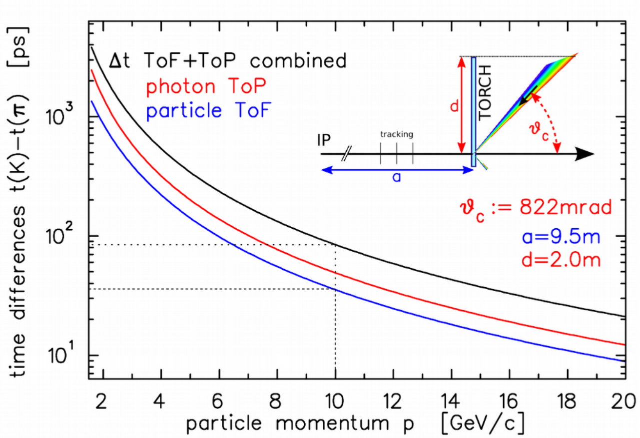
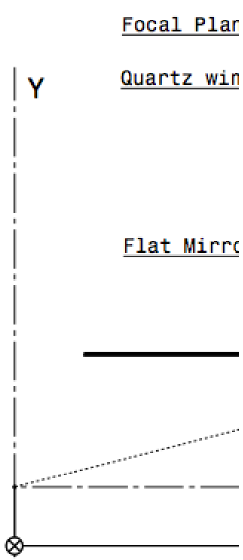
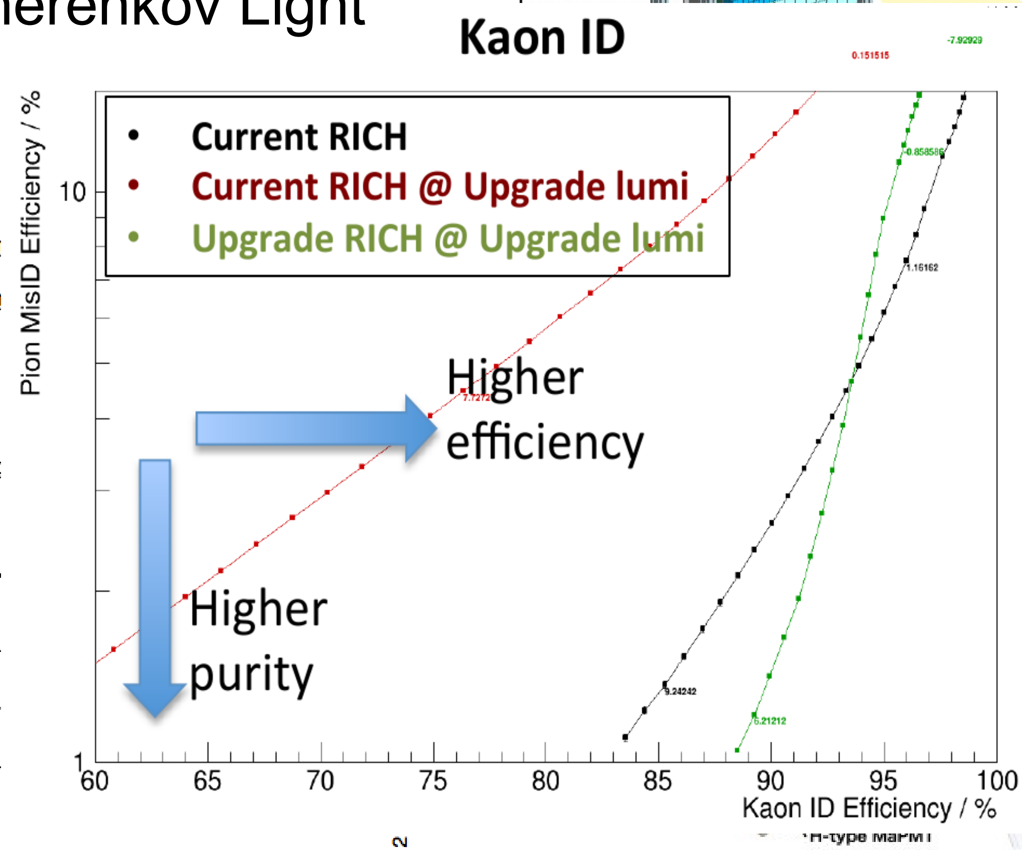








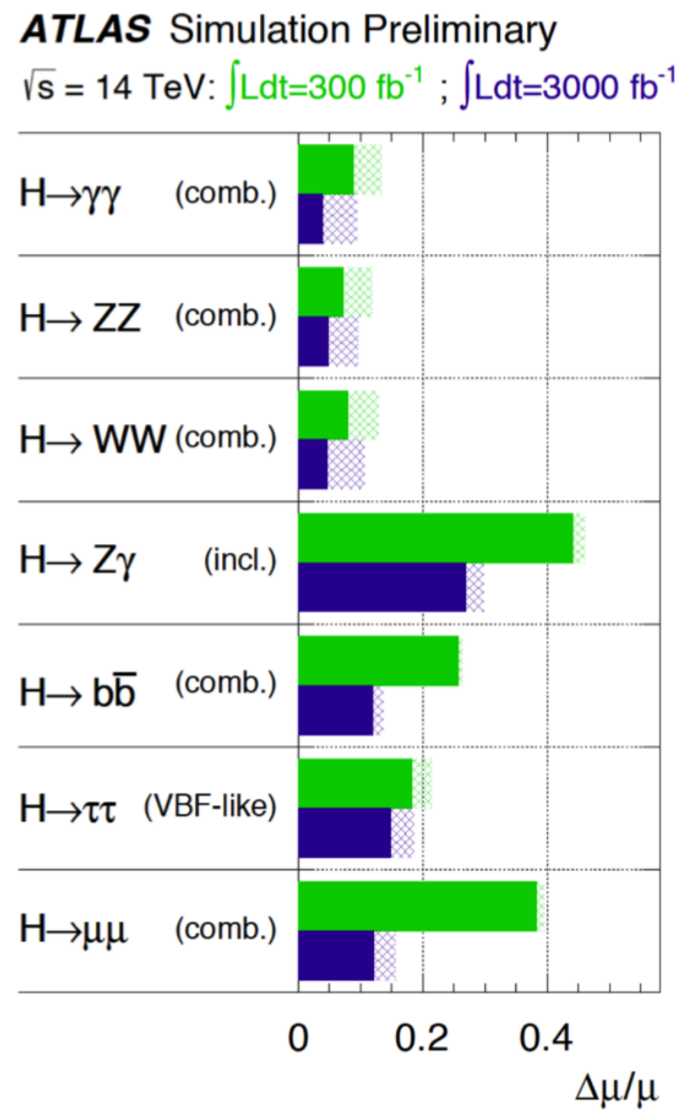


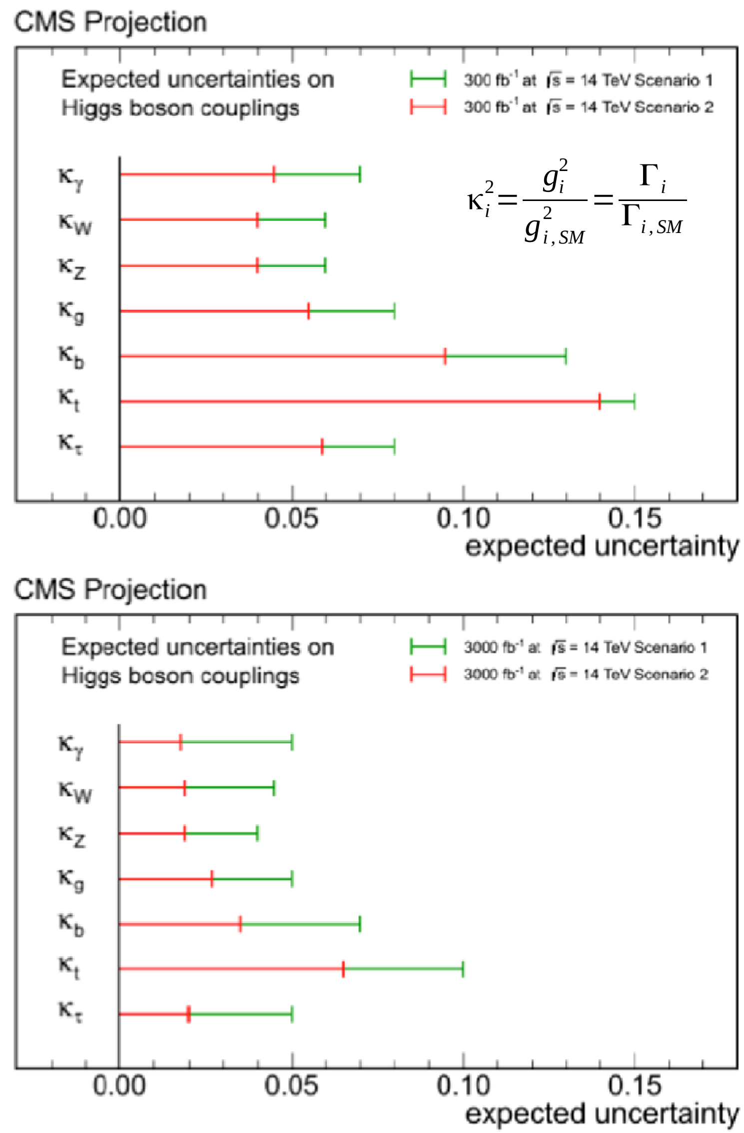
Physics Motivations: Higgs

- Is the observed particle really THE Higgs?
  - Couplings to Fermions/Bosons
  - Rare decays
  - Couplings to all 3 families …..

    → first hints into mass/family hierarchy ???
- Does the Higgs break EW symmetry?
  - Higgs self couplings → Higgs potential
  - WW-scattering

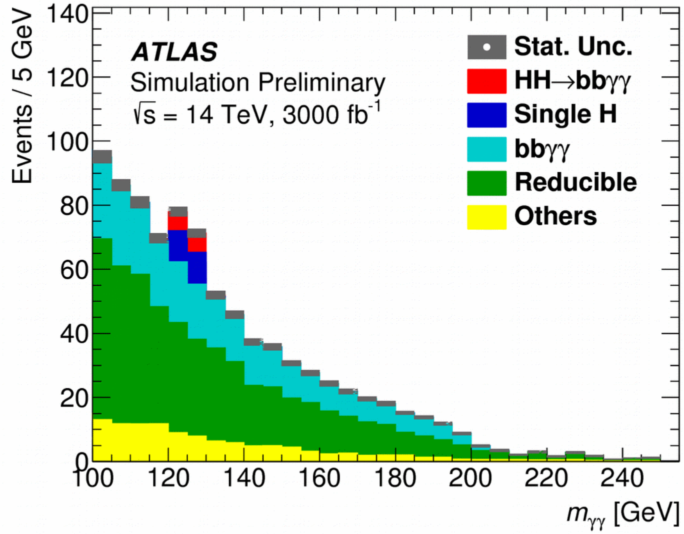
Physics Motivation: Higgs couplings

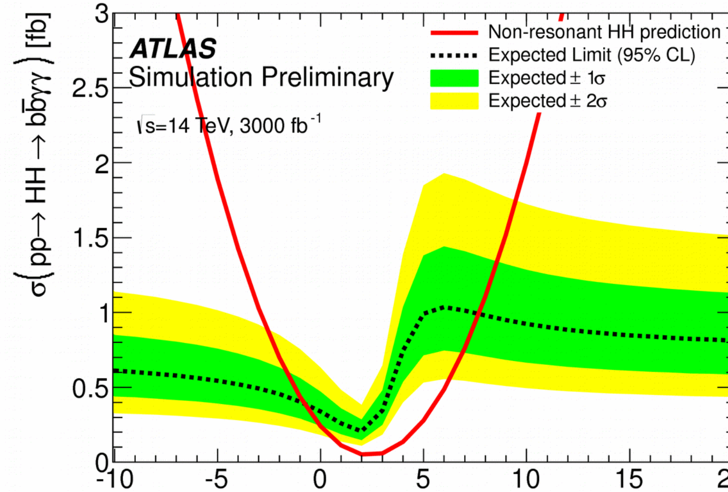




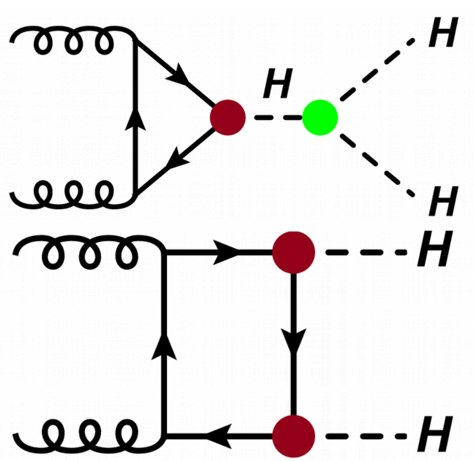
Physics Motivation: HH

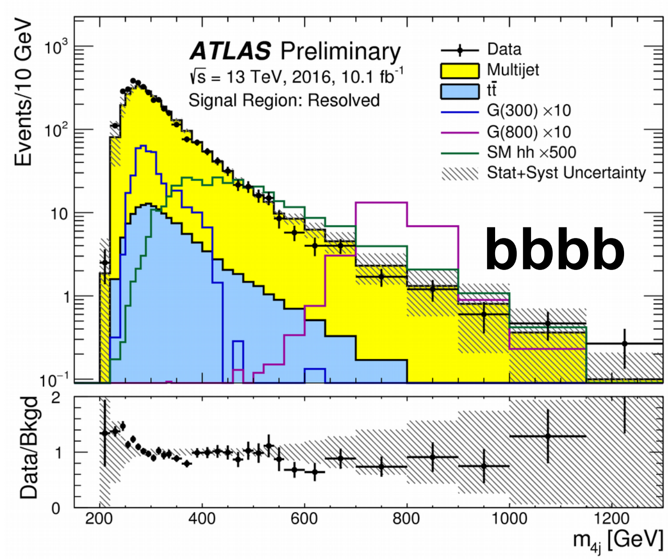
- H self coupling
  - bbγγ
  - bbbb
  - bbττ
  - bbVV

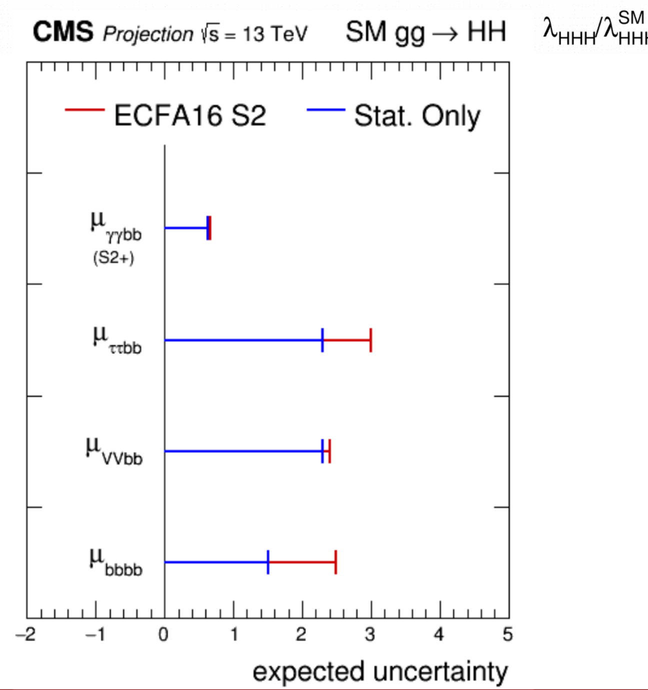




- Higgs potential
- New Physics

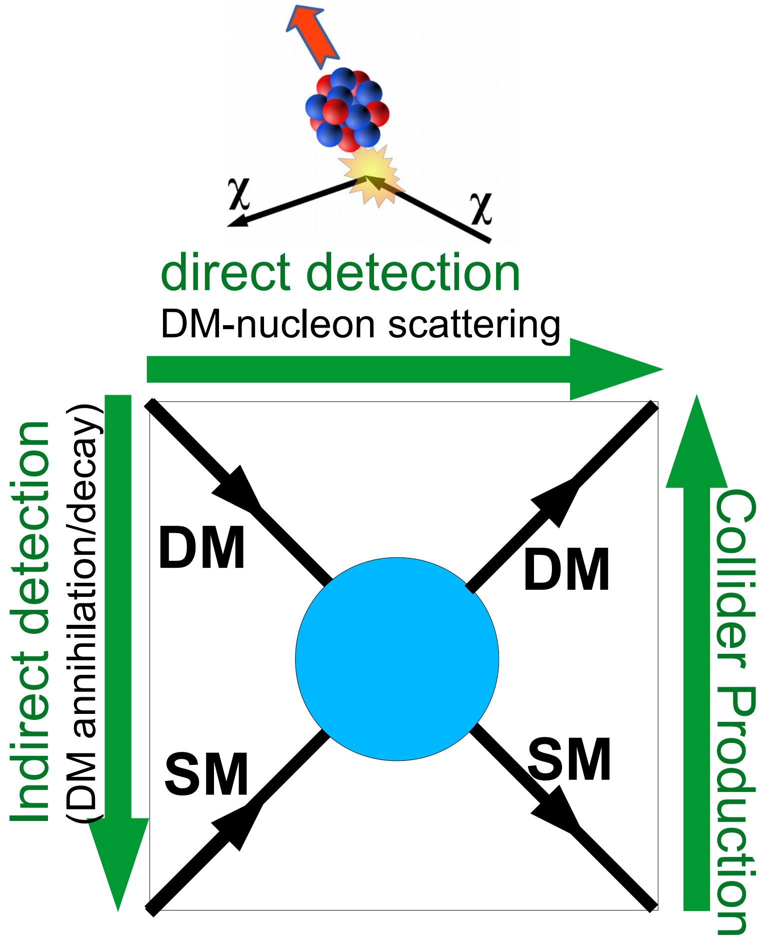






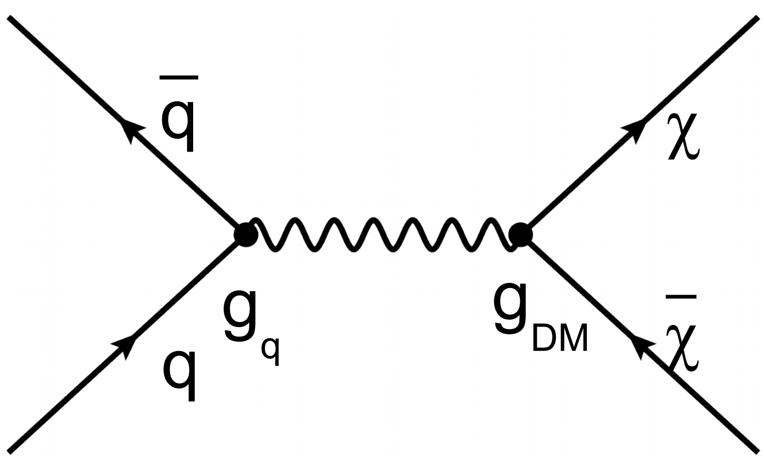
Physics Motivations: Dark Matter

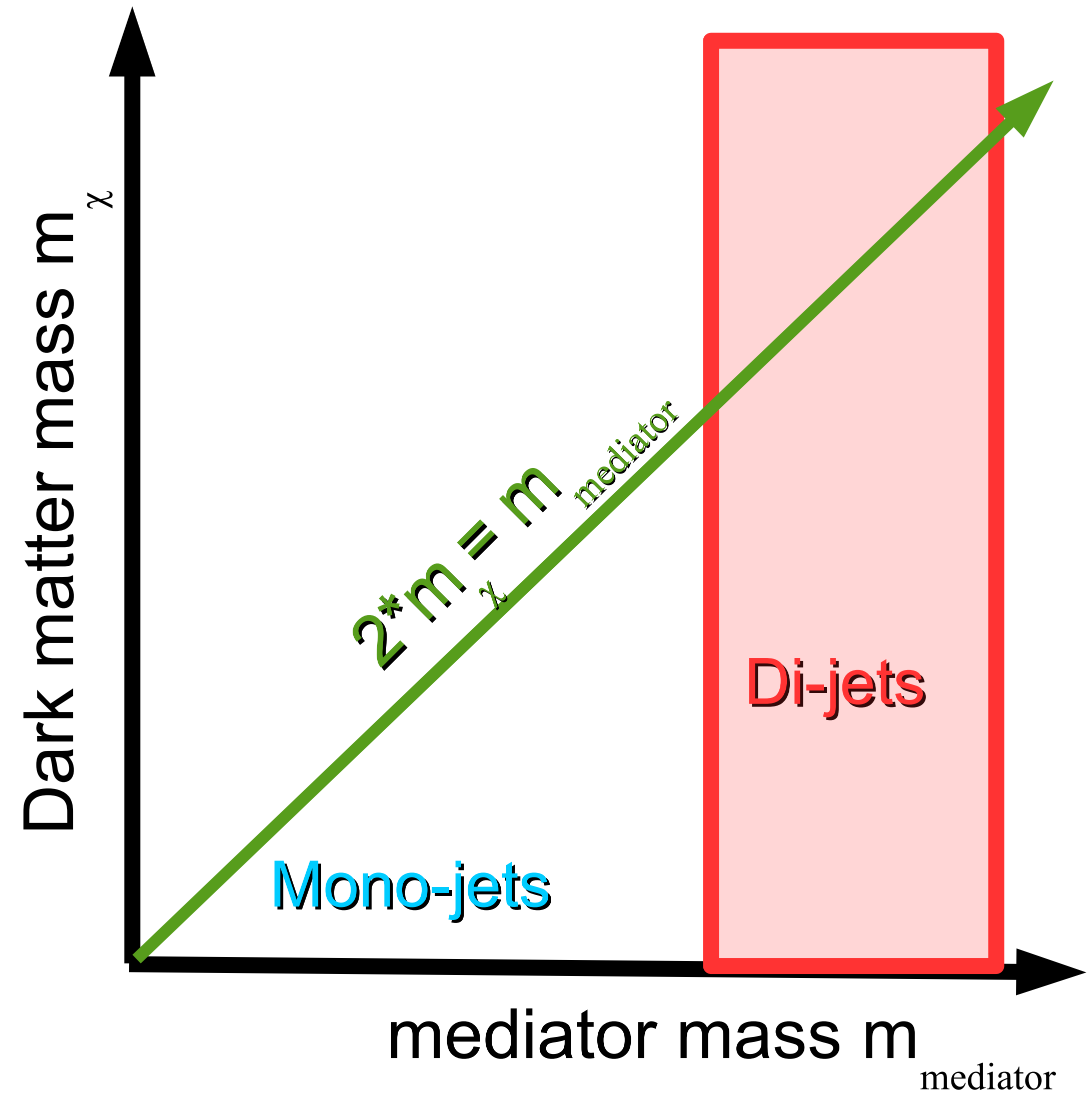
- Don't know what makes up most of the Universe
- LHC searches can provide complimentary information



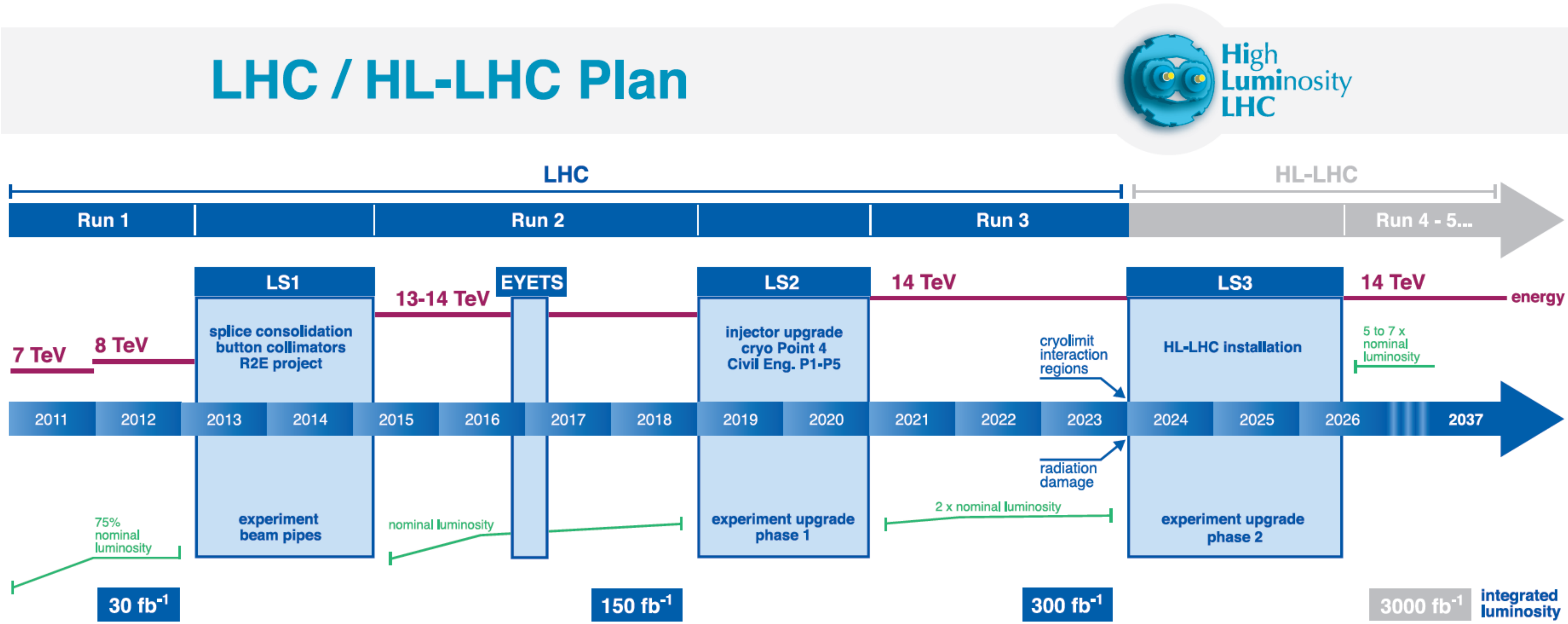
Physics Motivations: Dark Matter

- Direct searches
  - X + missing E_T
- Mediator constraints
  - Resonance searches





HL-LHC Schedule 2016



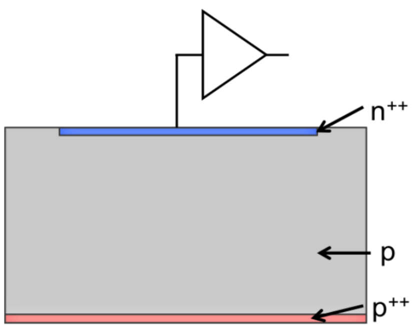
Funded/under way:
ATLAS/CMS/LHCb
Phase I

ATLAS/CMS
Phase II

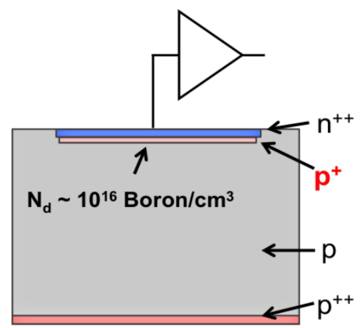
LHCb
Phase II

Detector trends: Timing

- R&D: use Low Gain Avalanche Diodes (LGAP)
- timing optimised: UltraFastSiliconDetectors (UFSD)



Traditional silicon detector



Low gain avalanche detectors