ATLAS Upgrades: a challenge for the next Decades

G. AIELLI

UNIVERSITY AND INFN OF ROMA TOR VERGATA

ON BEHALF OF THE ATLAS COLLABORATION

6th International Workshop on High Energy Physics in the LHC Era

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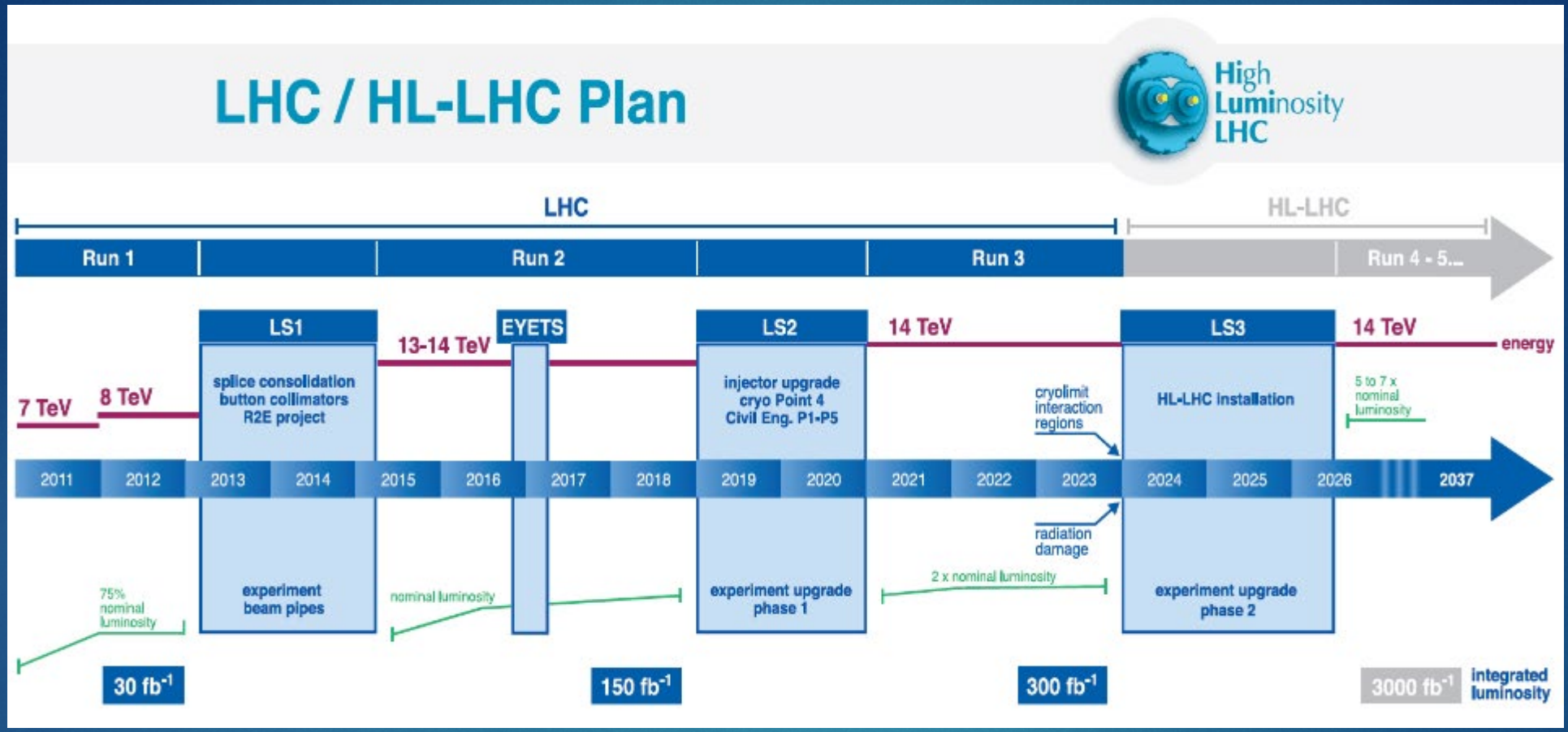
Overview of the challenge



European Strategy for Particle Physics

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030"

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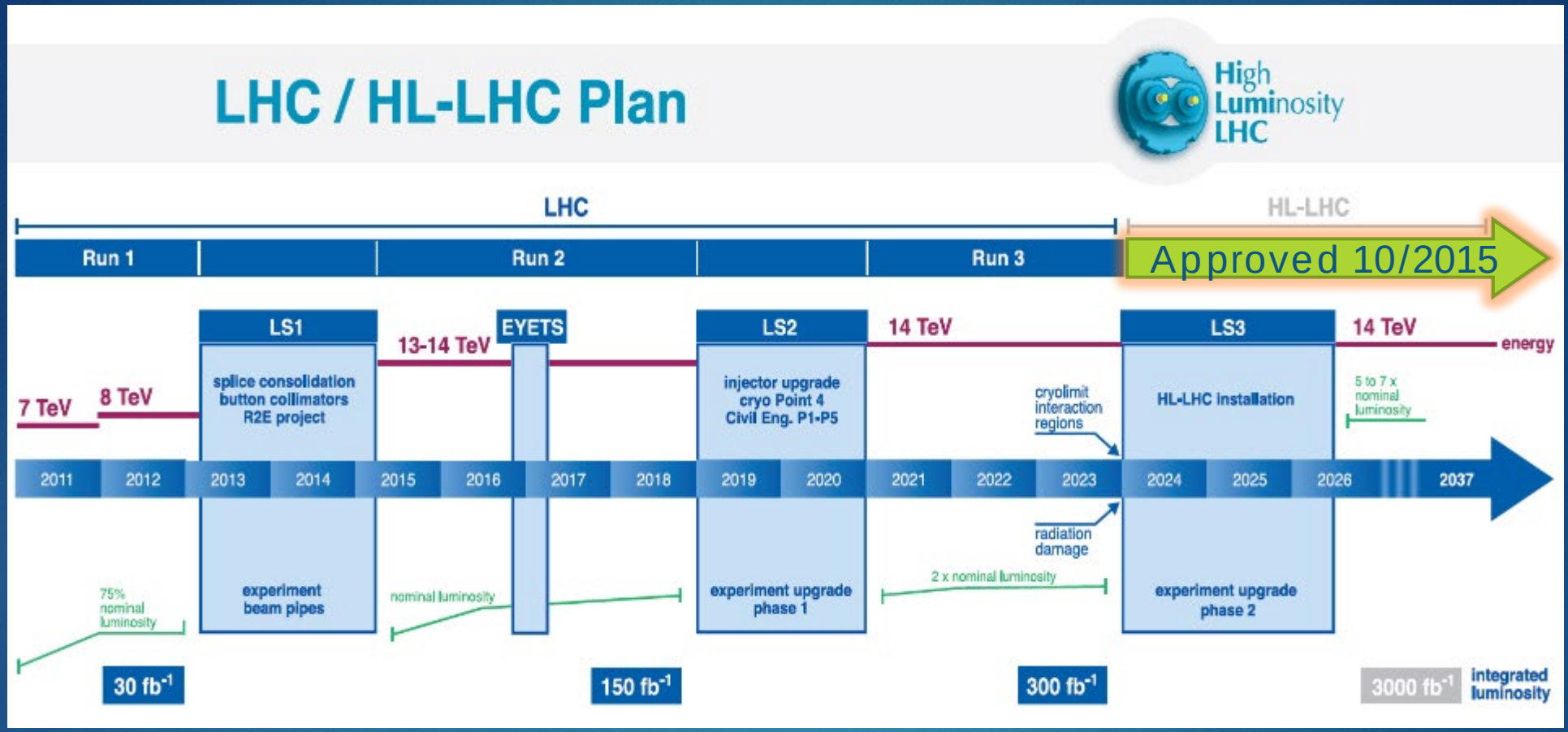

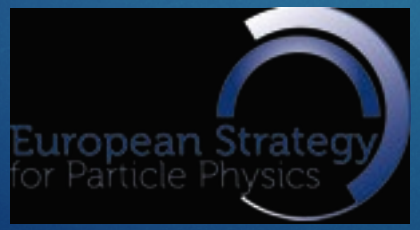

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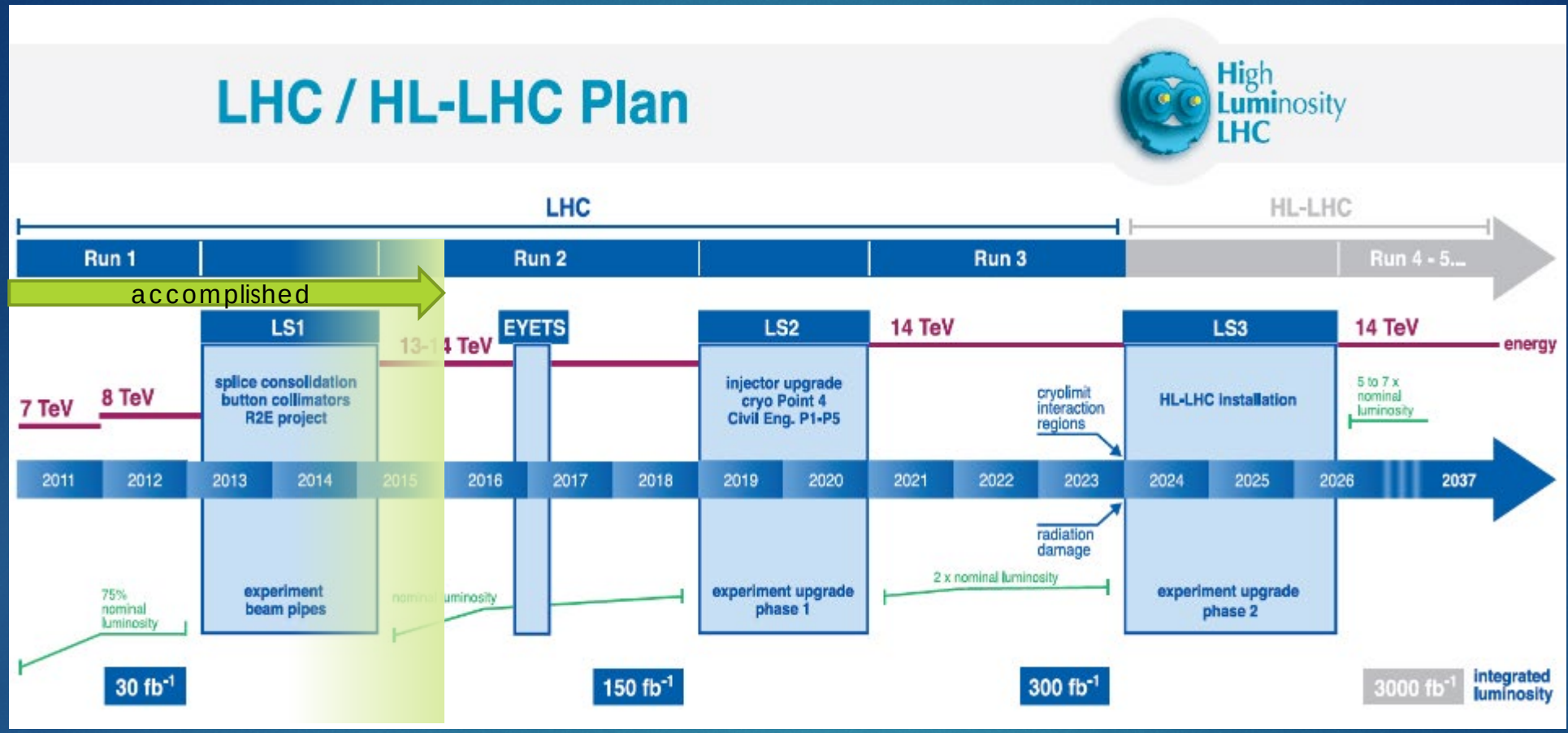

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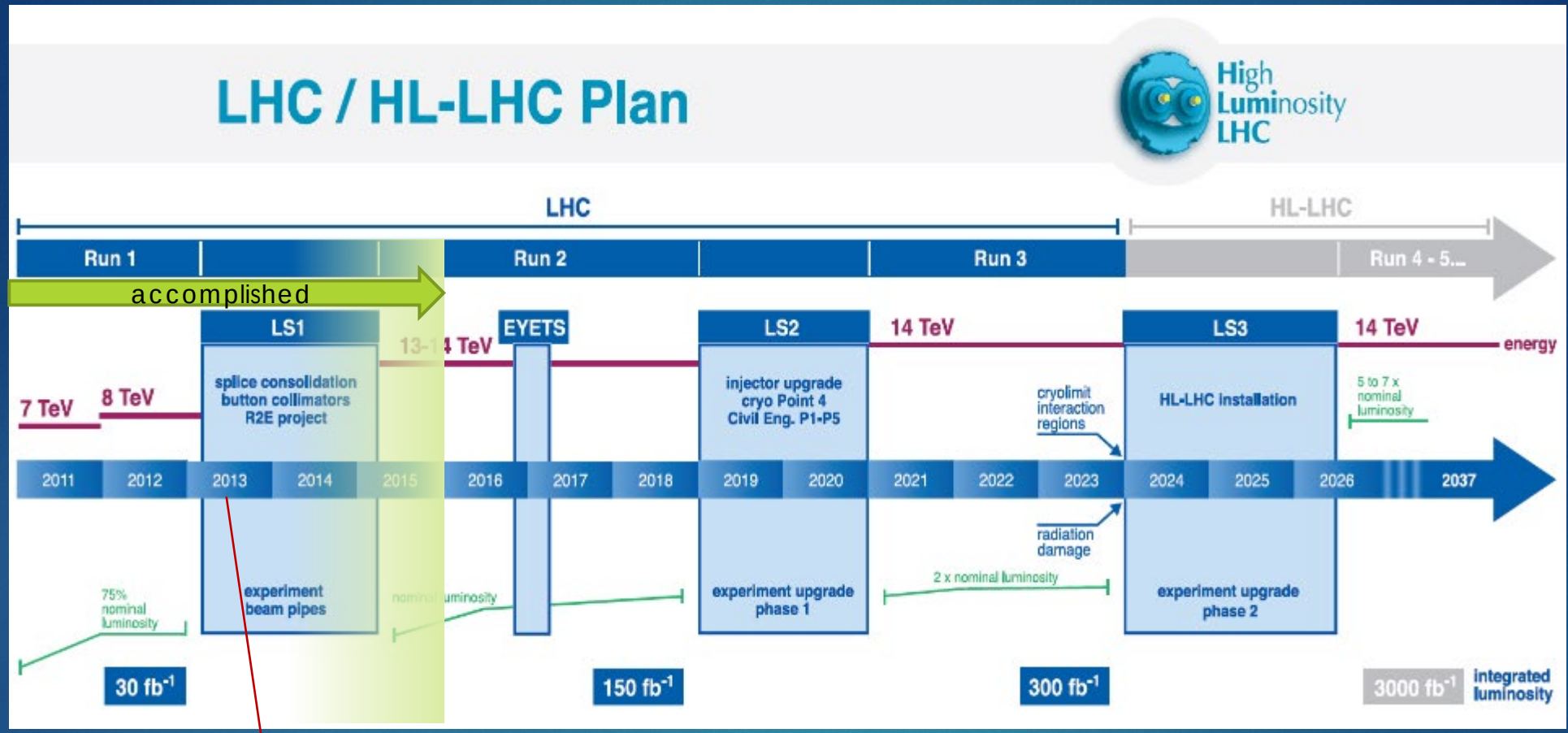

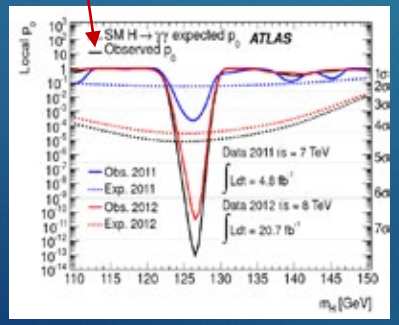

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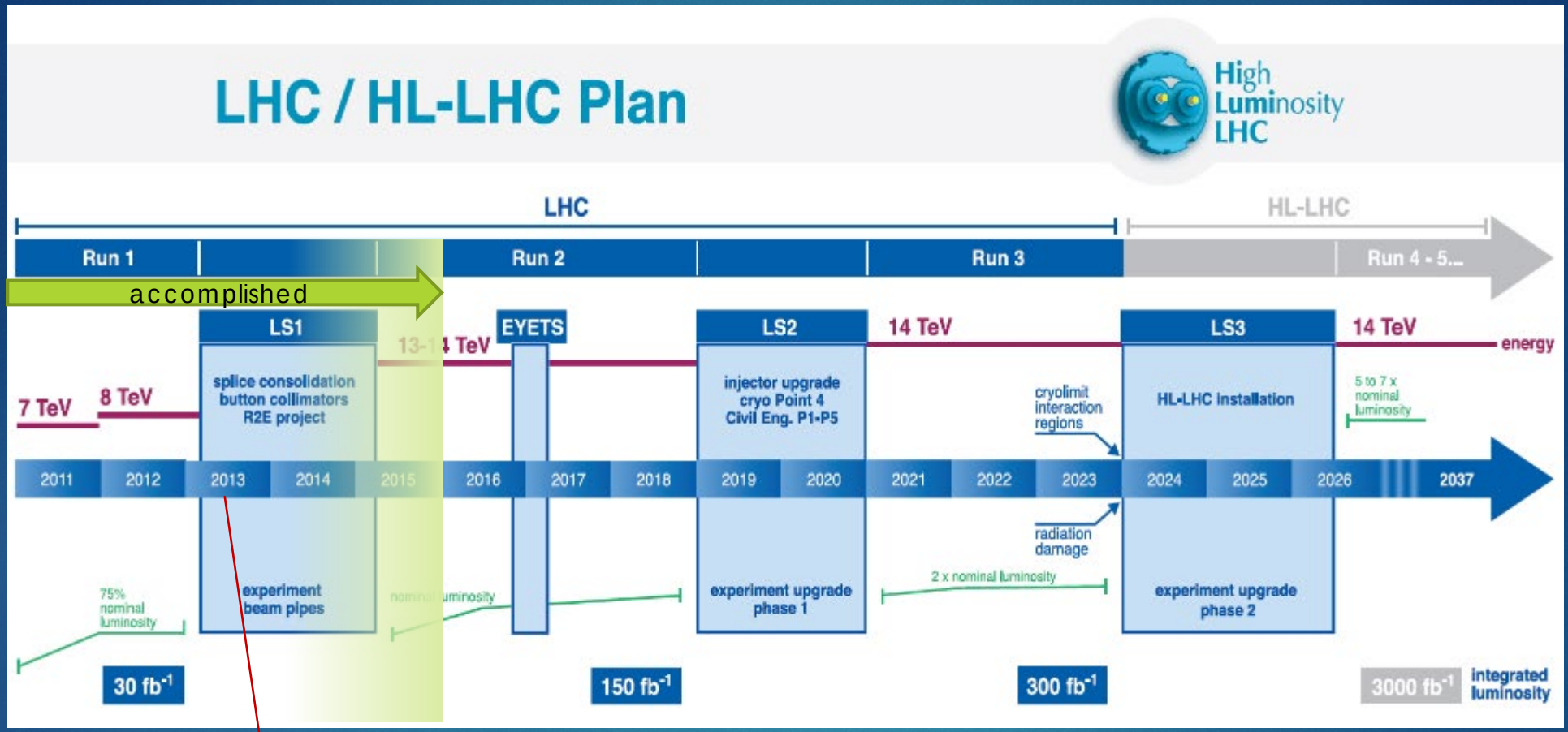
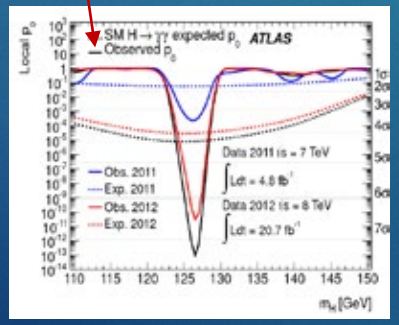




… after just 1% of the final integrated luminosity at about 1/2 of the full energy…

Most of the discovery potential still to be used:

- ~10 x sensitivity + ~2 x Energy

The ATLAS system today

Muon spectrometer

(mTrigger/tracking and Toroid Magnets)

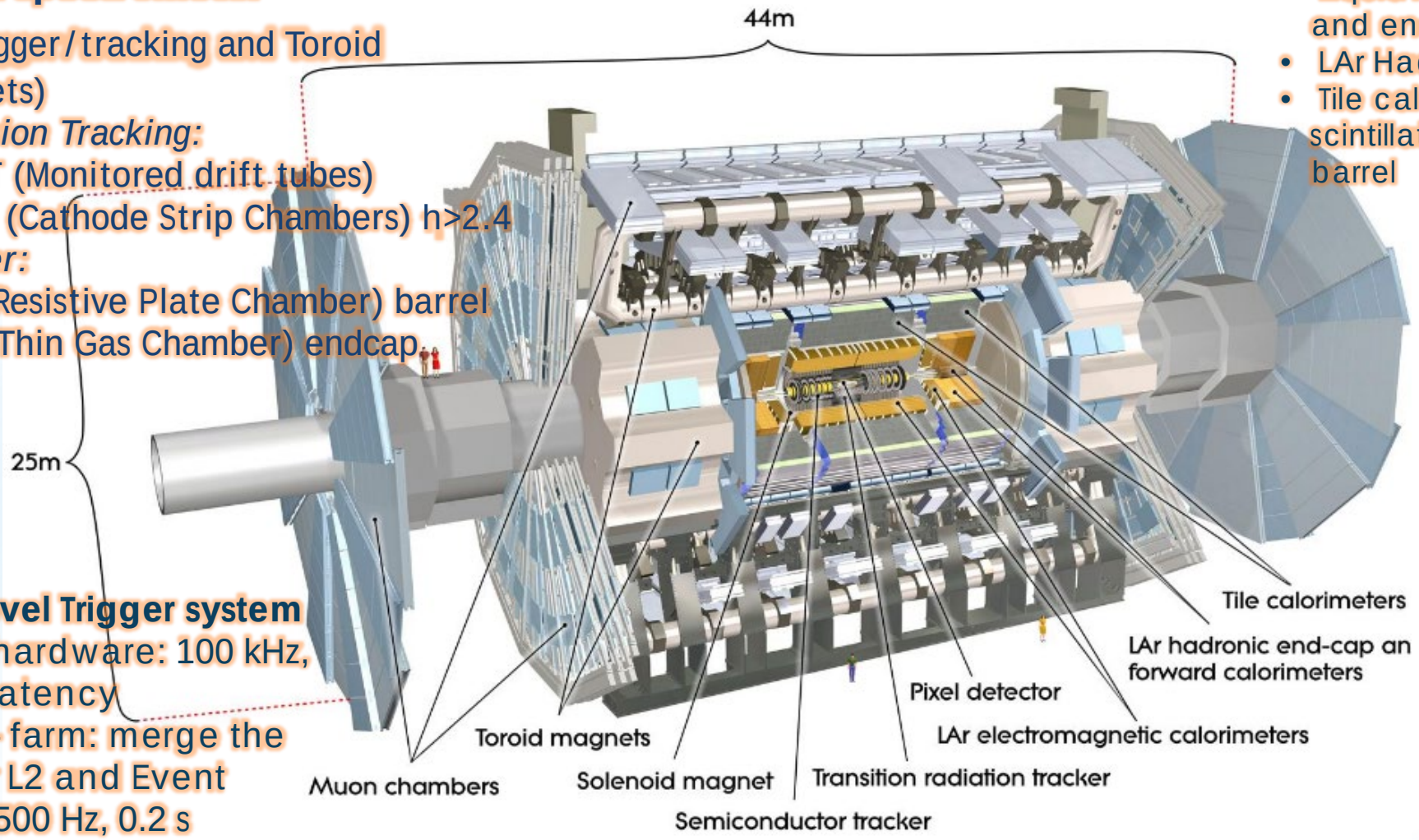
Precision Tracking:

- MDT (Monitored drift tubes)
- CSC (Cathode Strip Chambers) h>2.4

Trigger:

RPC (Resistive Plate Chamber) barrel

TGC (Thin Gas Chamber) endcap



Two Level Trigger system

- L1 – hardware: 100 kHz, 2.5 ms latency
- HLT – farm: merge the former L2 and Event Filter 1500 Hz, 0.2 s latency

Calorimeter

EM and Hadronic energy

- Liquid Ar (LAr) EM barrel and endcap
- LAr Hadronic end-cap
- Tile calorimeter (Fe-scintillator) hadronic barrel

Inner Detector (ID)

Tracking

2T Solenoid Magnet

- Silicon Pixels 50 x 400 m^2
- Silicon Strips (SCT)

40 mrad stereo strips

- Transition Radiation Tracker (TRT)

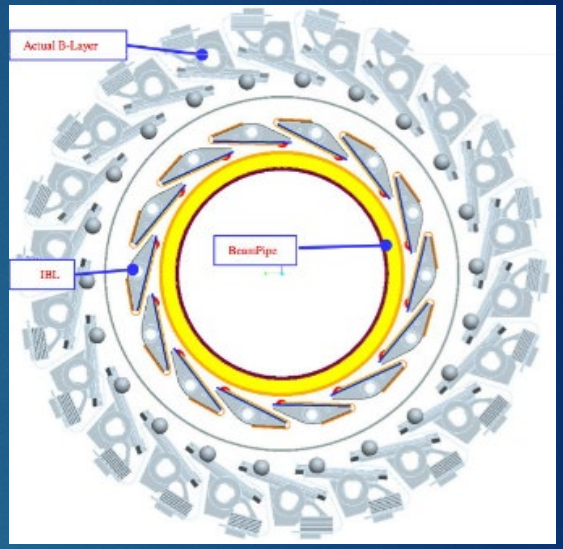
up to 36 points/track

Phase-0 how we prepared for Run2

The Upgrade has already started

Inner Detector

- 4th innermost layer of pixels à good performance at higher occupancy.
- Inserted at innermost radius. The first measurement is at 33 mm from the beam vs. the former 50 mm

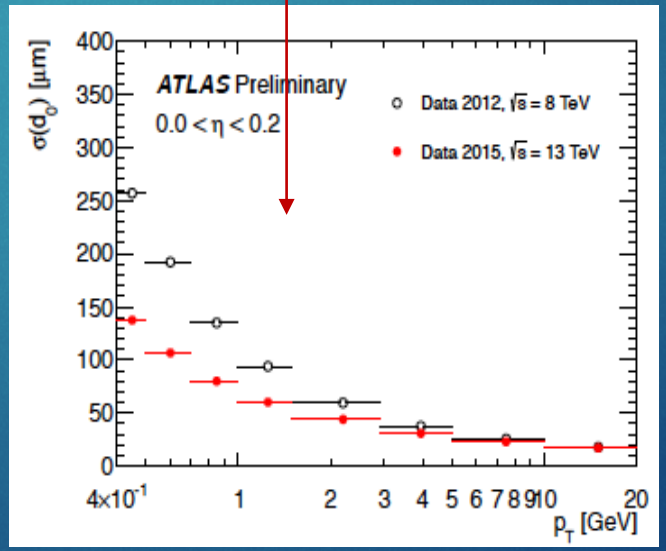


Infrastructure

- New Beam Pipe and muon shielding à lower background Rate

...and more:

- ATLAS Forward Physics (AFP), proton det. at ±210 m
- One arm out of 4 shall be installed within 2016



New technology toward future upgrades

- New electronics in 130 nm CMOS process with new, more rad-hard, architecture.
- First large-scale 3D detector (25% 3D, 75% n-in-n planar).
- CO2 cooling (was C_3F_8).

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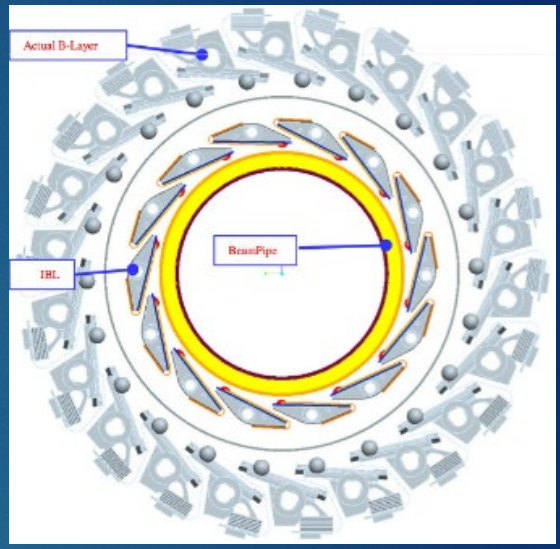

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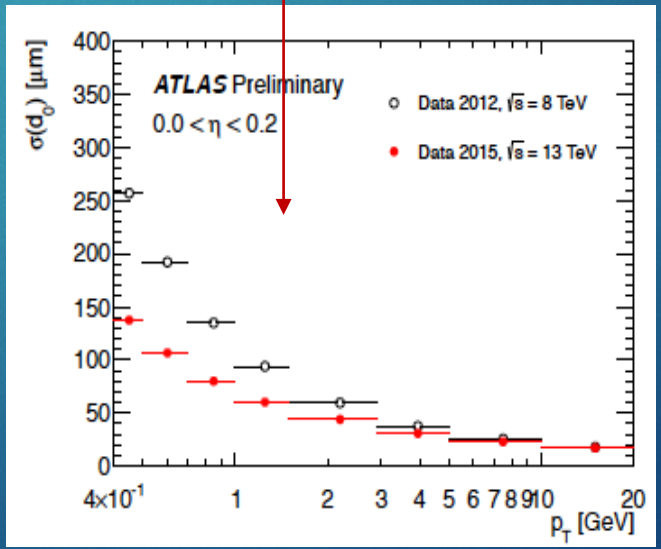

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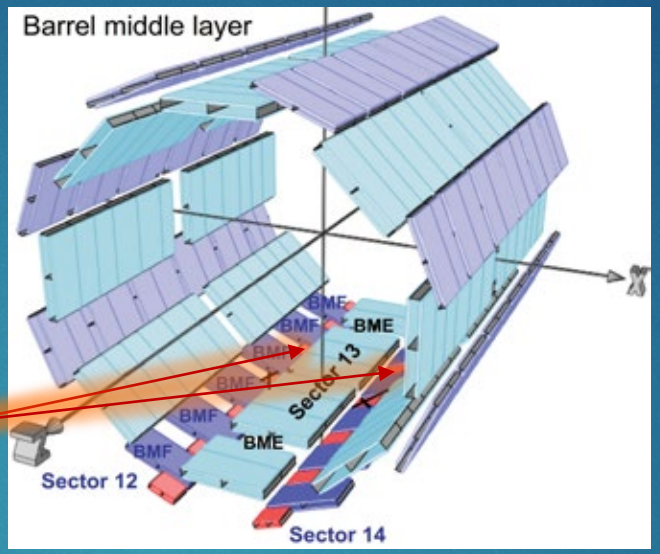
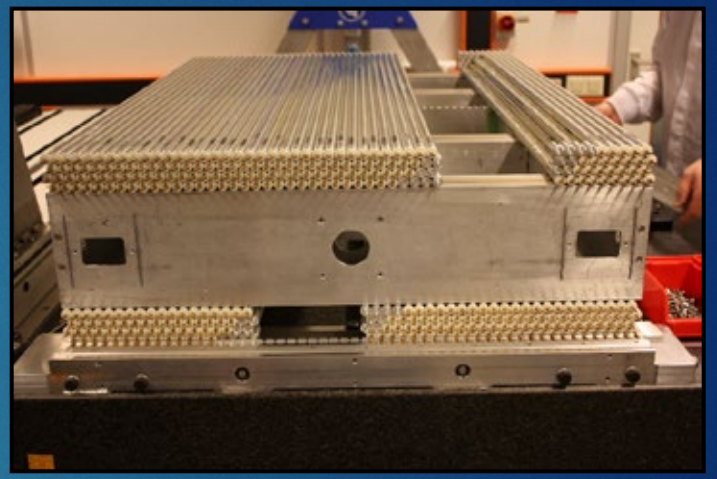
Muon consolidation

extended muon coverage in the feet region

- New tracking chambers in the middle barrel done with sMDTs 15 mm tubes (installation in 2016)
- Doubling of the RPC high pT chambers in the feet region





before

after

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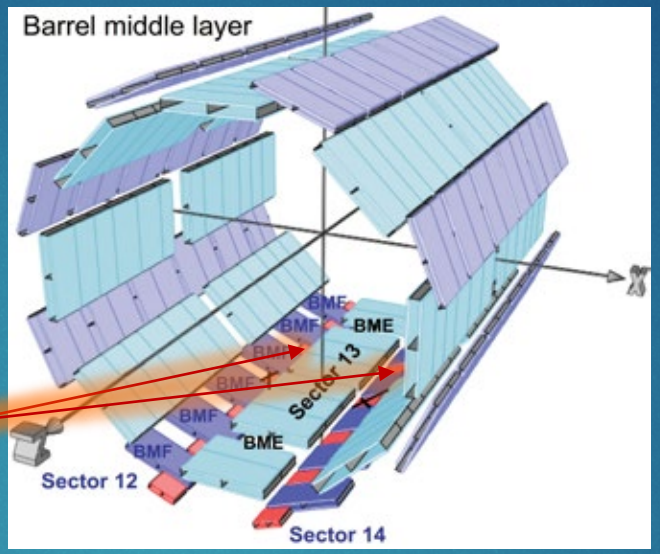

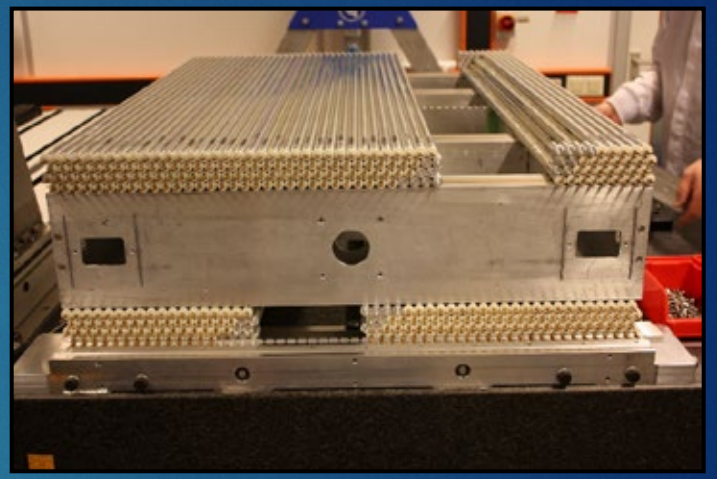

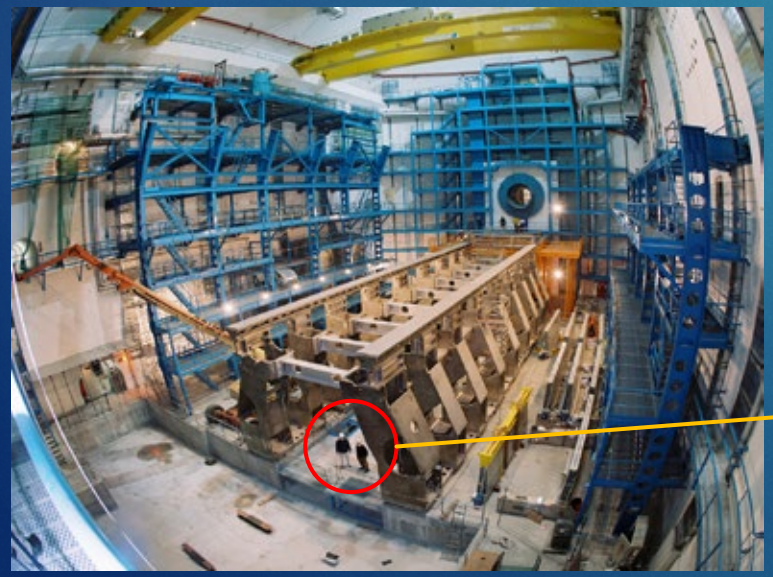

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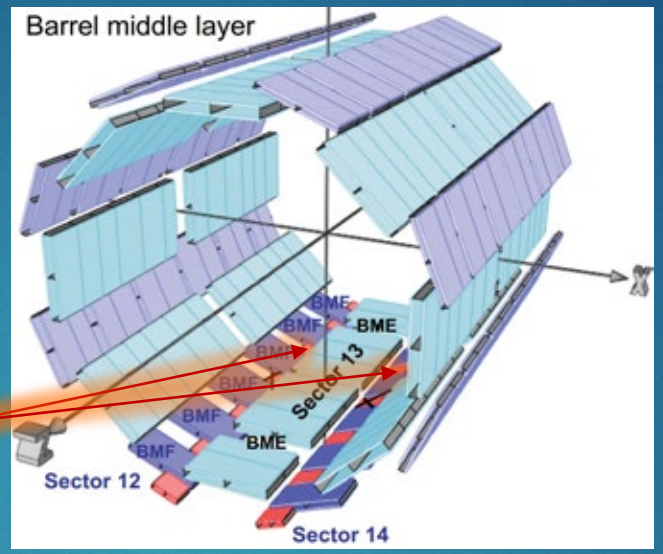
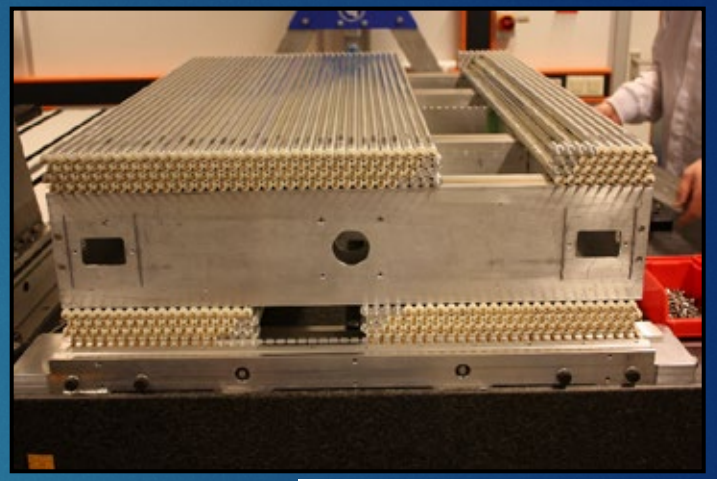
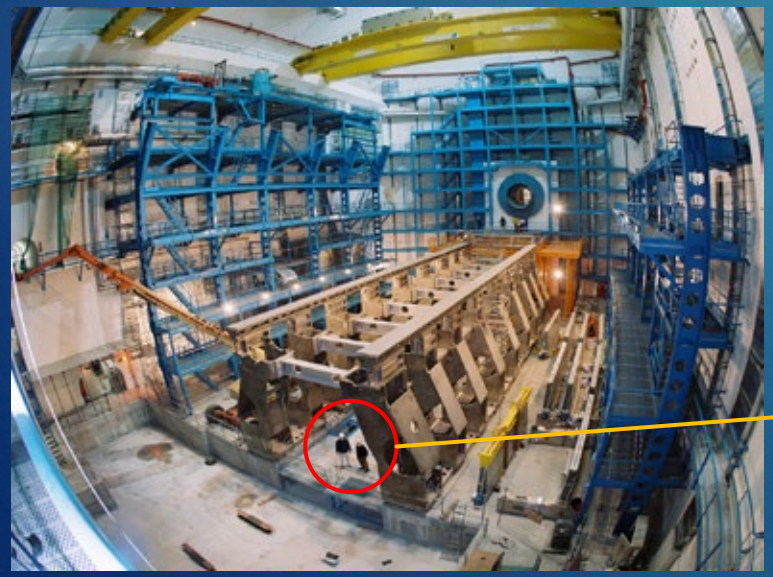
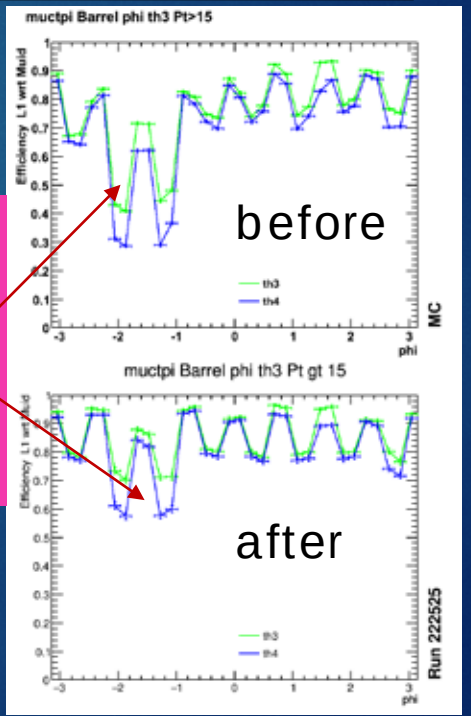






Muon feet region

Feet region Already operative: improved acceptance



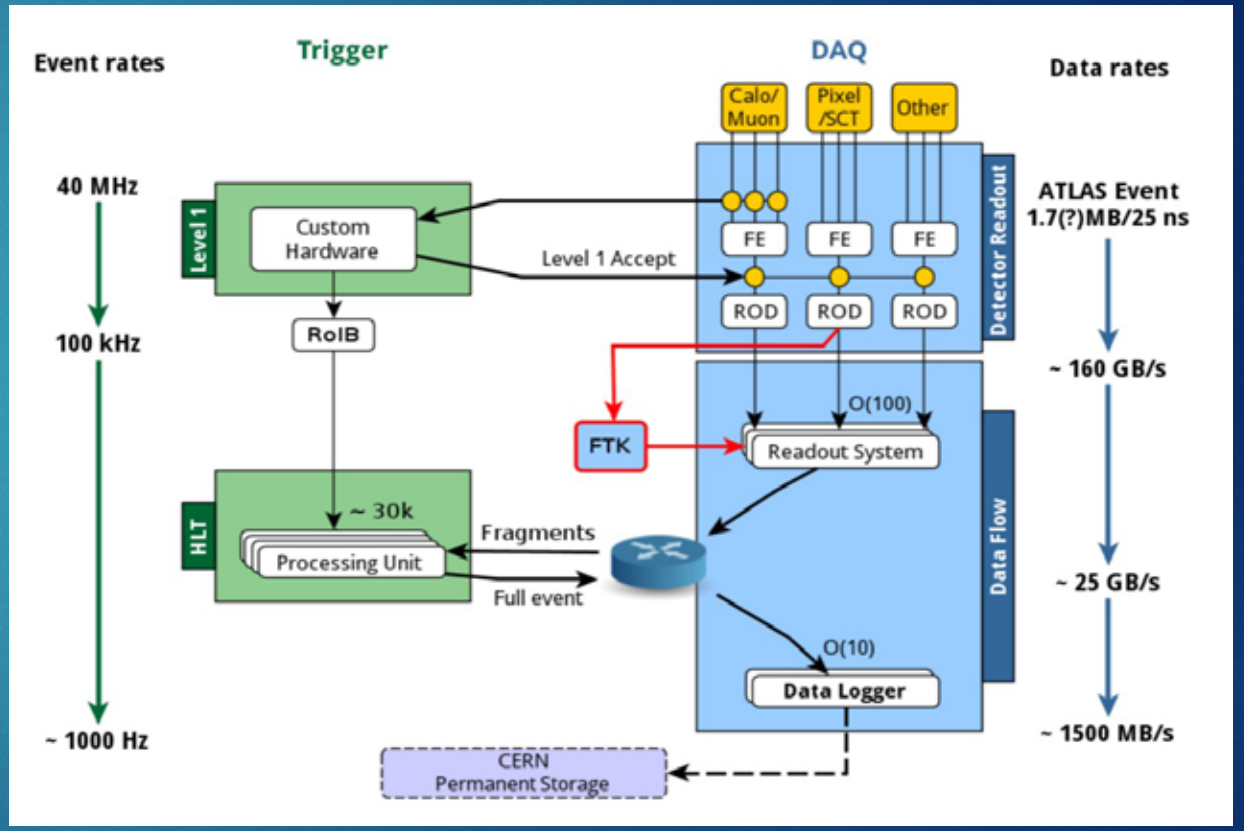
The new Trigger DAQ concept

L1 Topo

- Topological (multi-object) Input trigger objects from L1Calo and L1Muon
- being commissioned in 2015
- Central Trigger Processor (CTP) upgraded

DAQ

- New Central Trigger Processor
- New system based on 2 levels only: L1 and HLT
- HLT merge the former L2 and Event Filter
- Increase max L1 rate from 75 to 100kHz
- HLT in software with 0.2 s of processing time. Higher output rate (limited by storage capacity to 1.1--1.5 kHz



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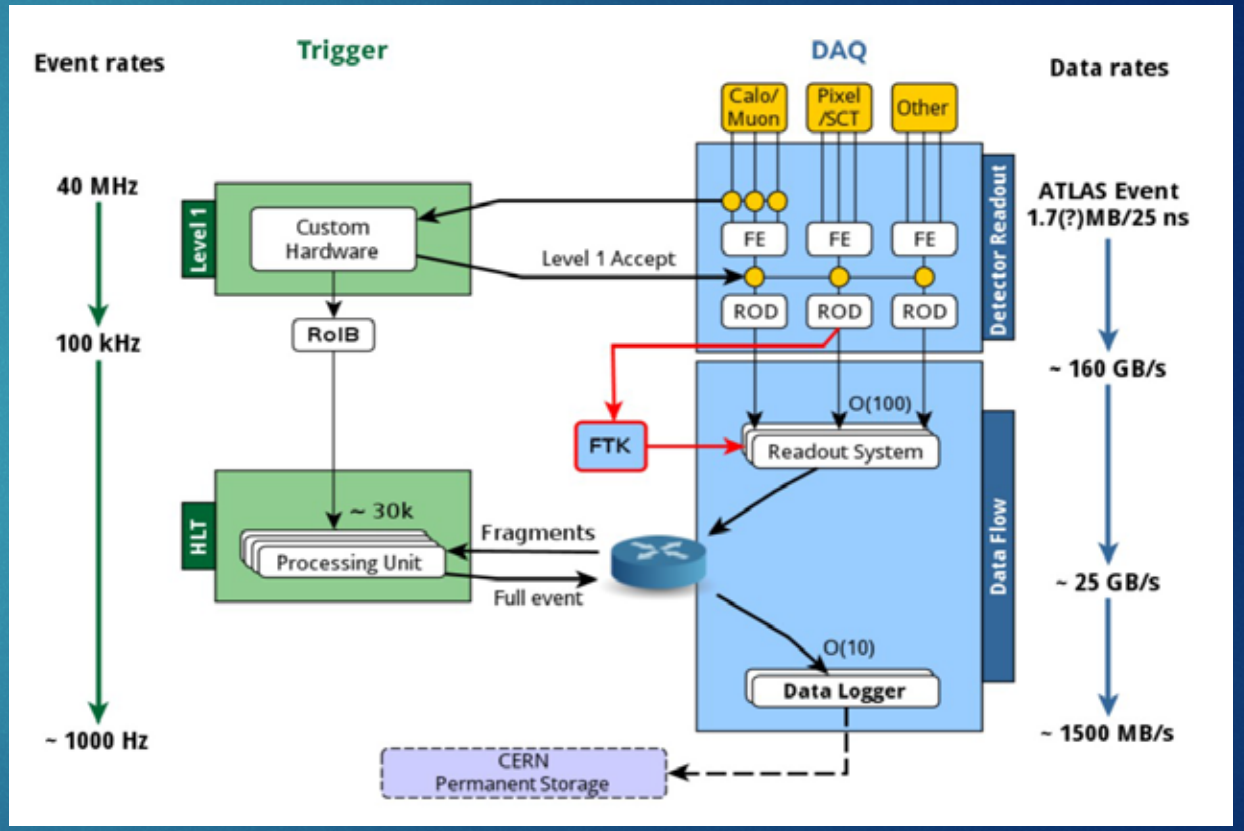
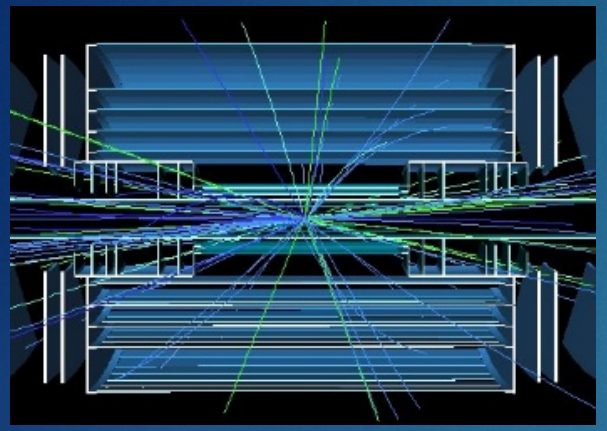


Future challenges and strategies

(ATLAS was designed for LHC: $L=10^{34}$ $cm^{-2}s^{-1}$ (plus safety margins))

[Now we expect 7 x instantaneous and 10 x integrated luminosity]

PILEUP: from ~30 à >200 proton collisions/BC



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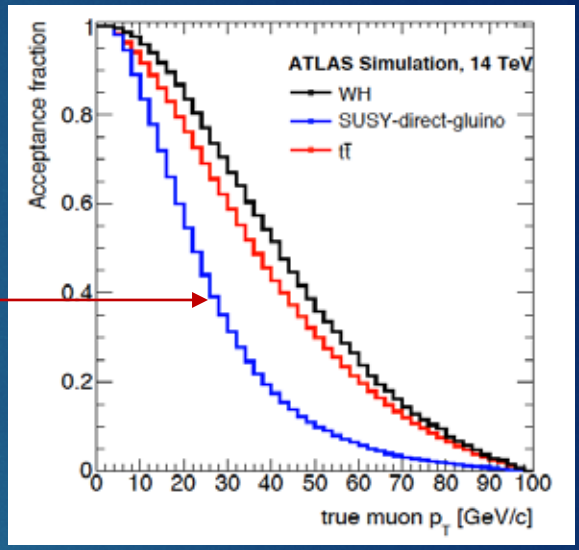

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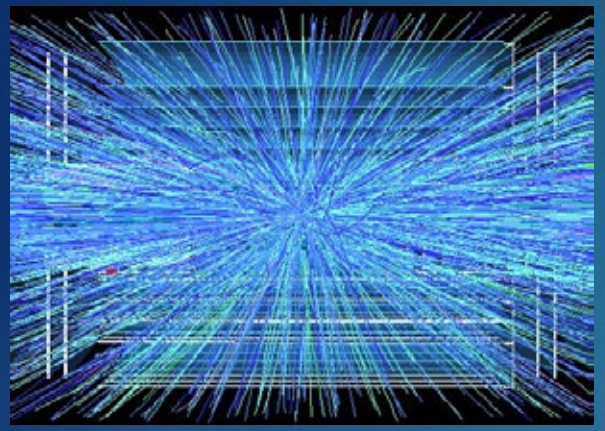

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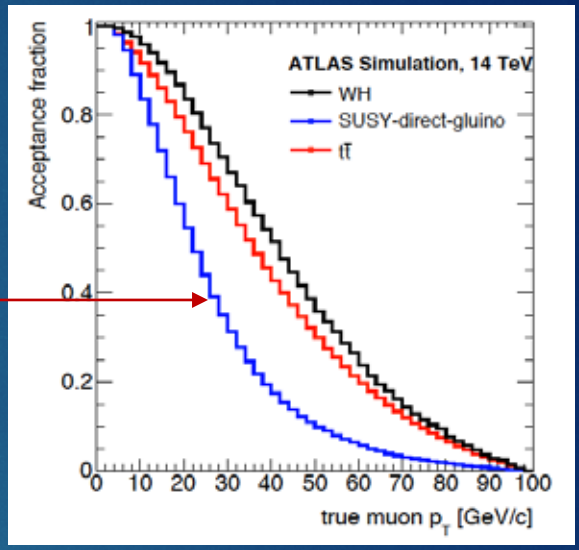

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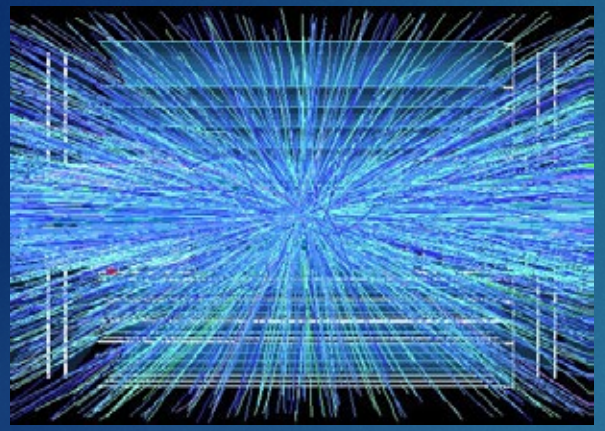

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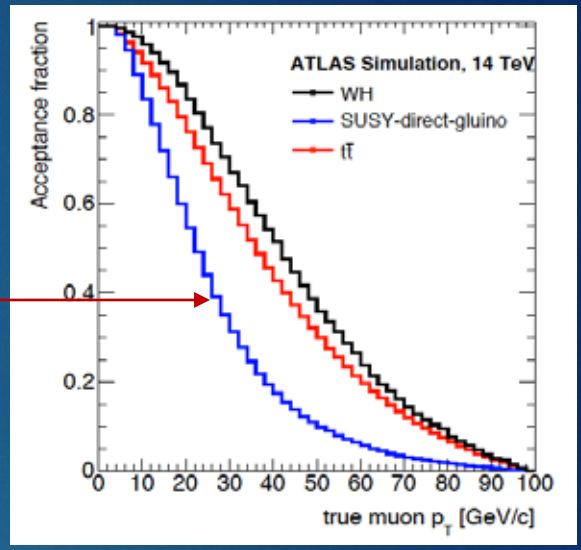

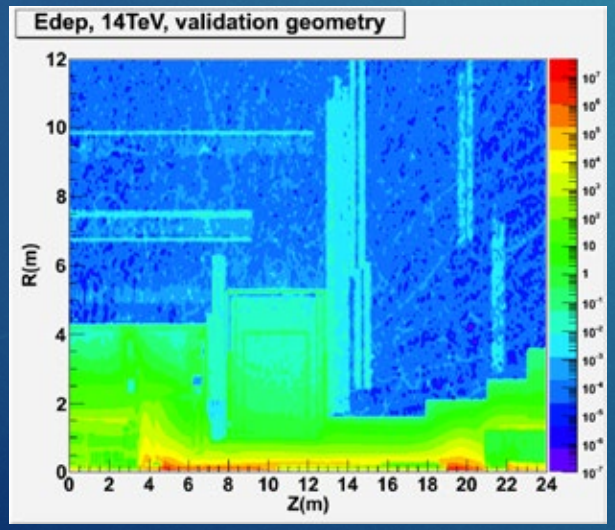

Cavern background rates: 7x10^{34} $cm^{-2}s^{-1}$ Luminosity 14 TeV Energy à large increase, unevenly distributed

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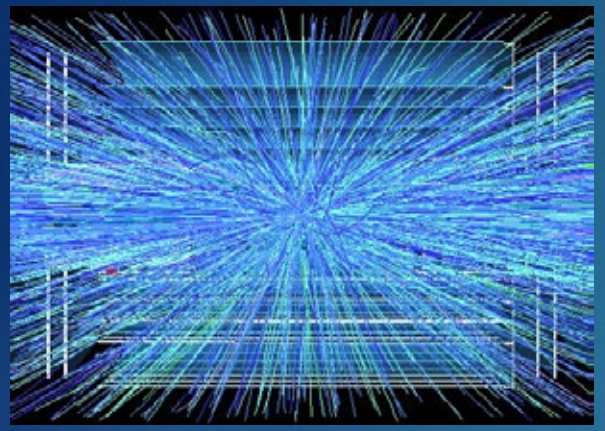

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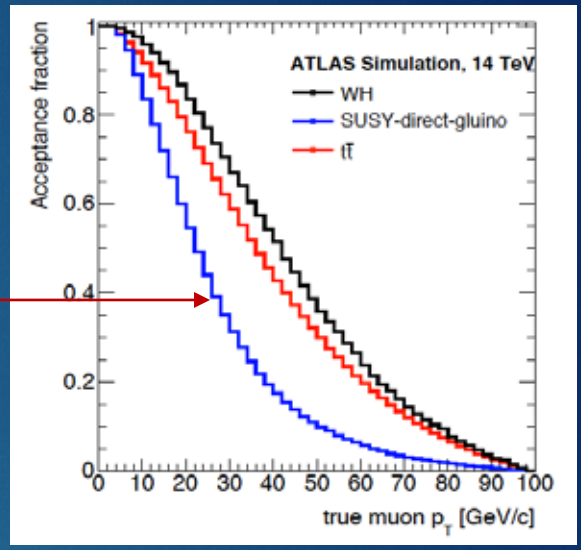

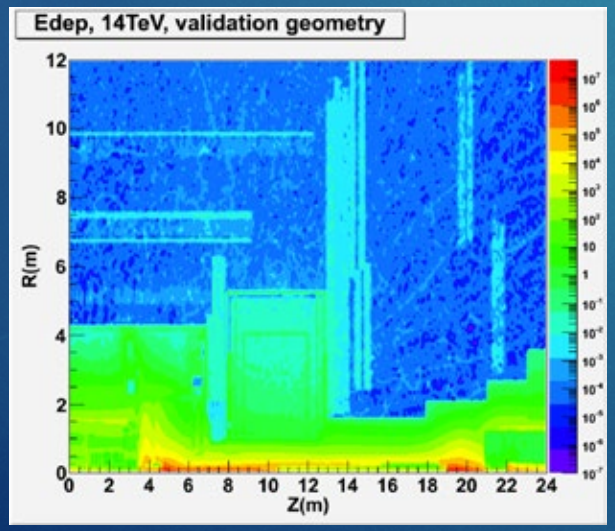

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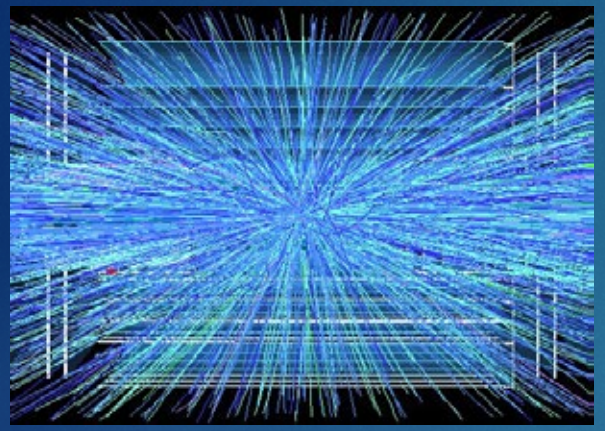

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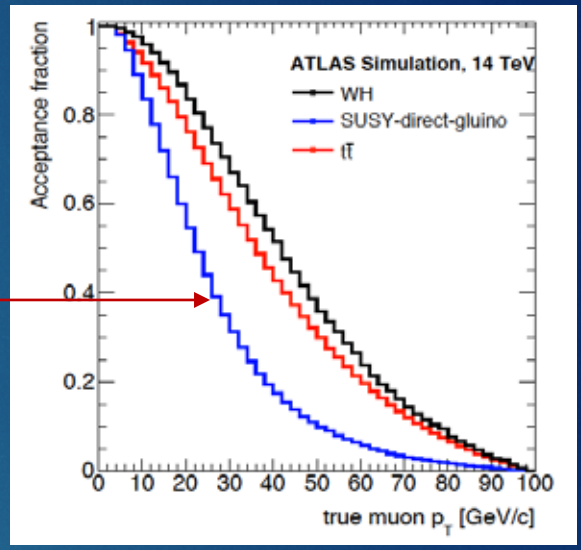

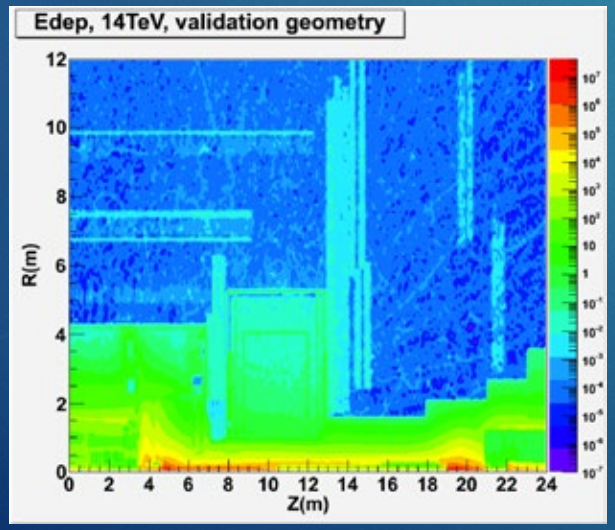

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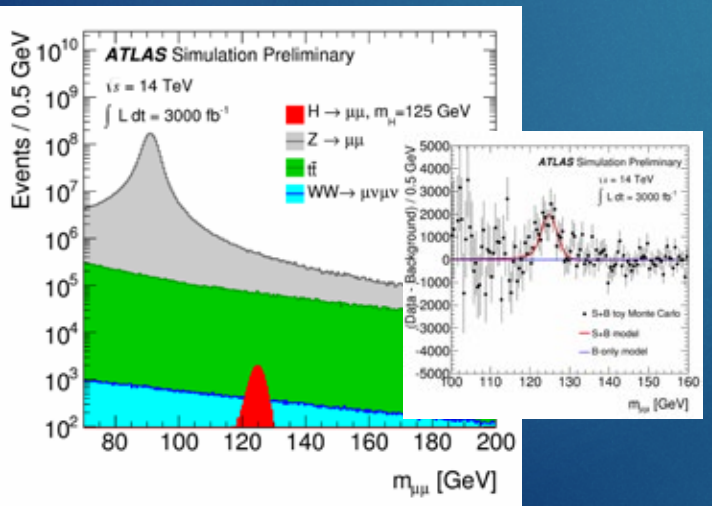
- **Strategy**: replace/refurbish/add detectors to share the load and increase redundancy

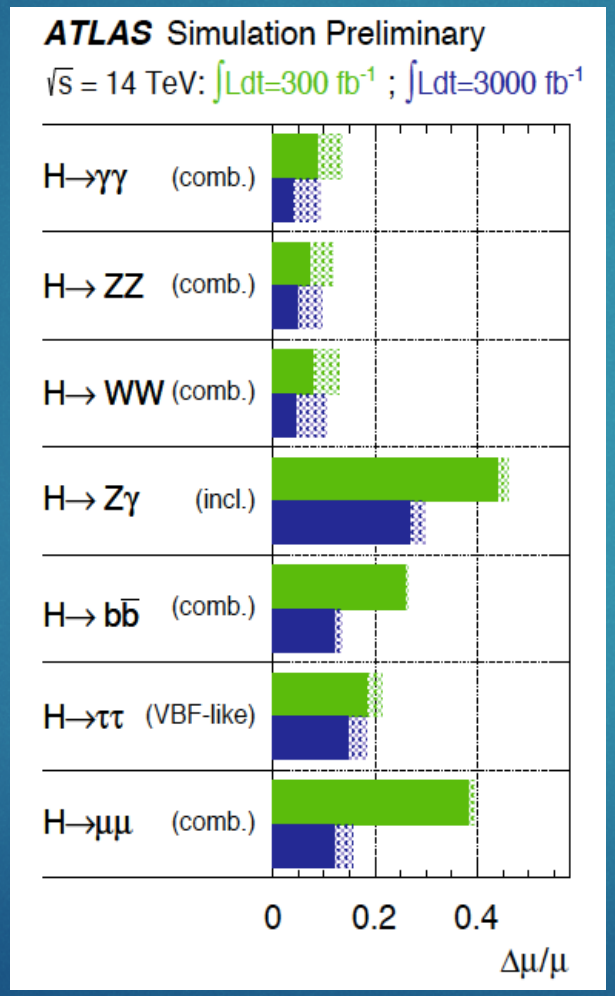
Direct motivation for this challenge (I)

What could we do with 10 x sensitivity and 2 x energy?

(a few examples)

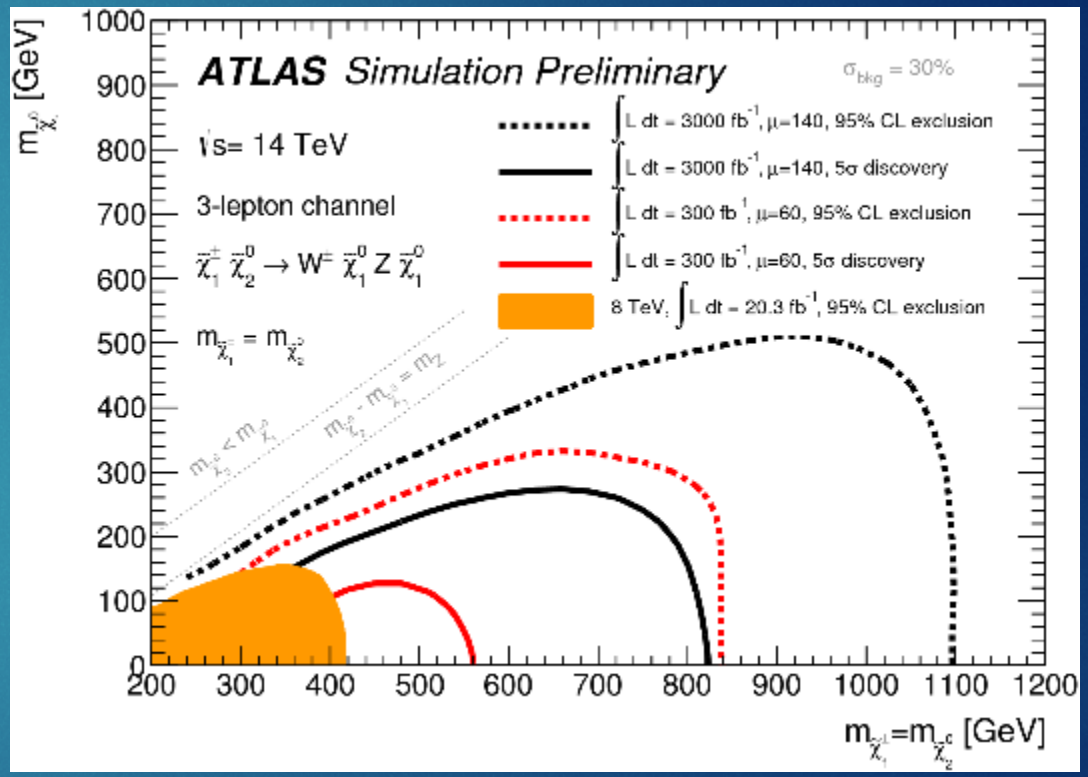
- improvements in Higgs precision measurements
- access to rare processes:
  - H→gg 100 evts S/B=0.2
  - ttH→μμ 30 evts S/B~1
- Higgs self-coupling in SM accessible at HL-LHC.





Relative signal strength

SUSY particles searches significantly extended in Run 3 and the HL-LHC



Direct motivation for this challenge (II)

What could we do with 10 x sensitivity and 2 x energy?

(… ATLAS is conceived as a discovery experiment)

We are eager of more statistics
to investigate objects like this…

Some local excess observed

- Local significance 3.6 s
- Global significance 2,0 s

Need for statistics…

And even higher discovery potential

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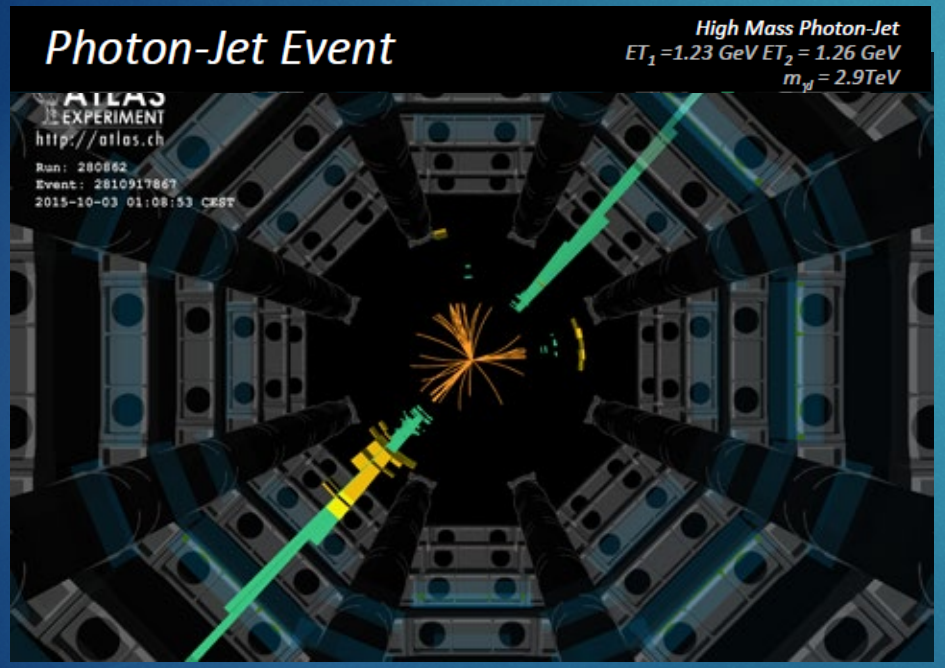

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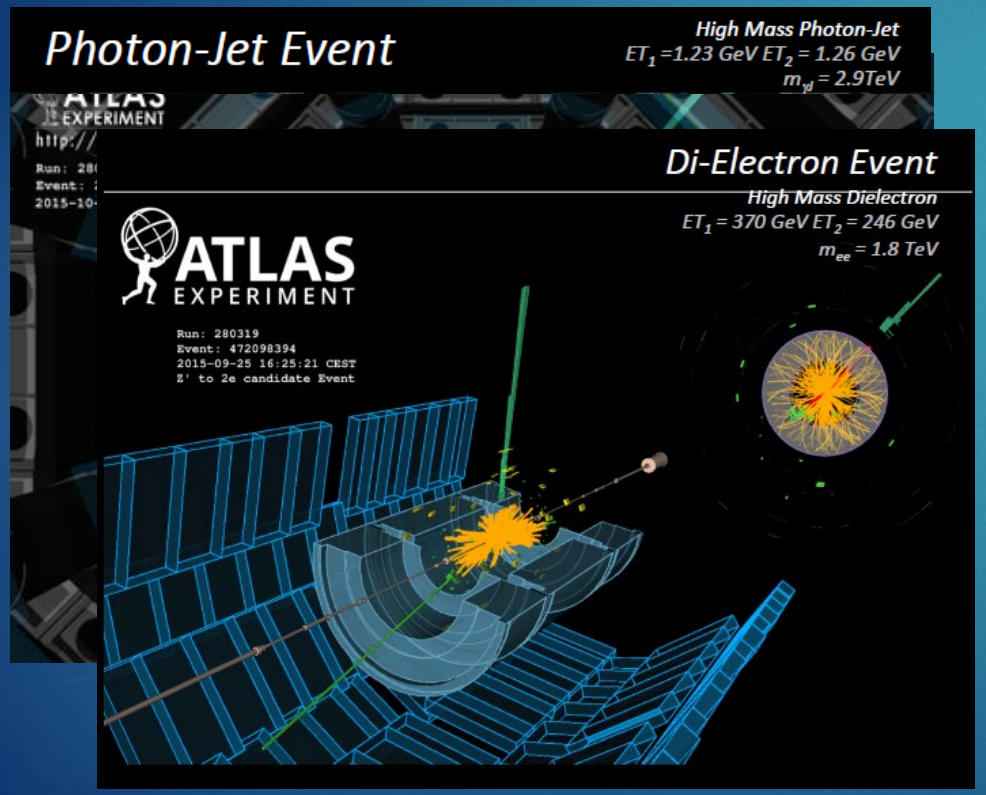

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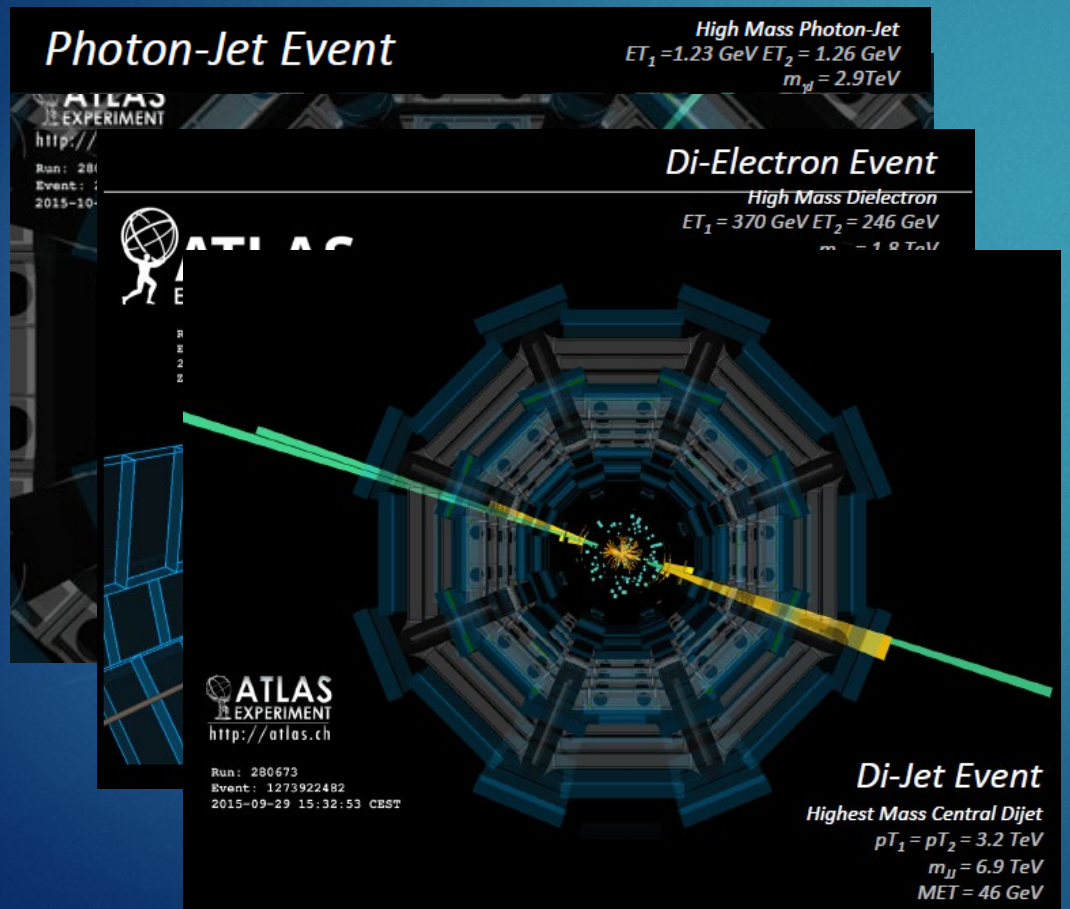

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And even higher discovery potential

Direct motivation for this challenge (II)

What could we do with 10 x sensitivity and 2 x energy?

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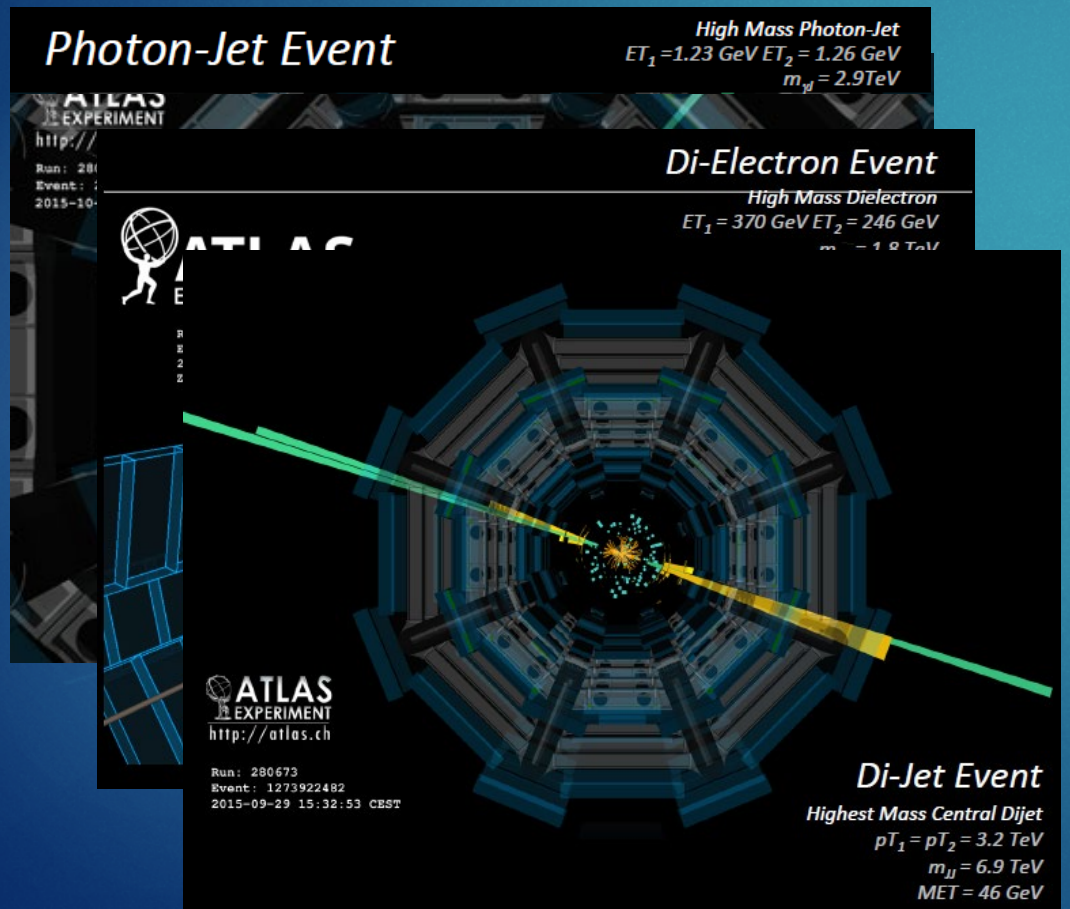

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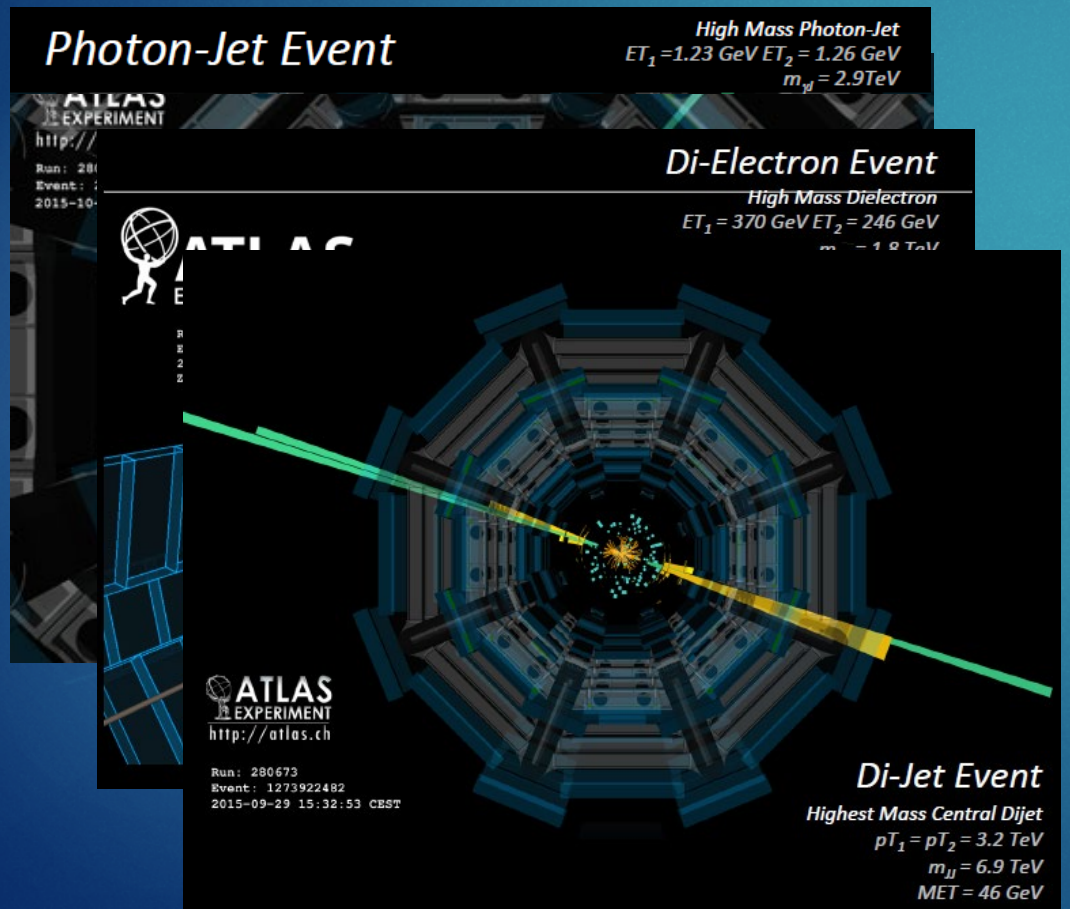

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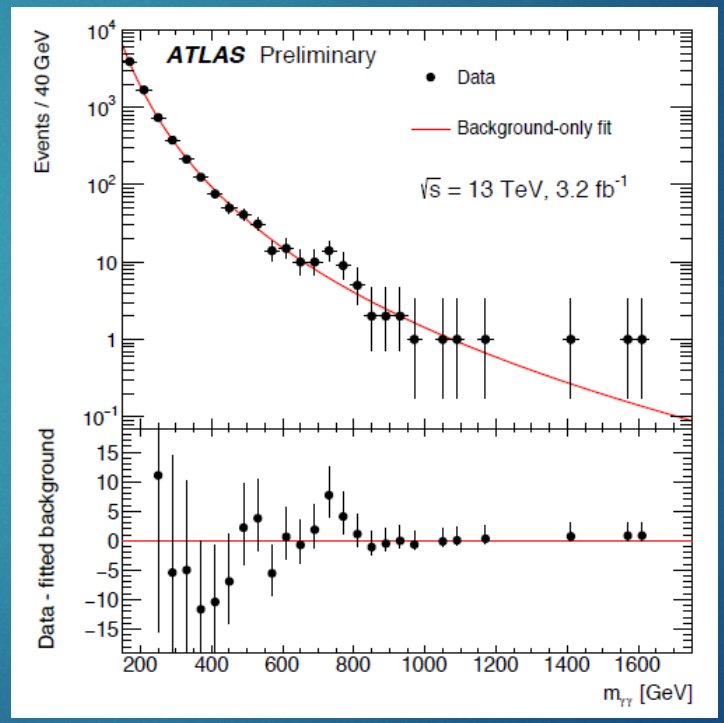

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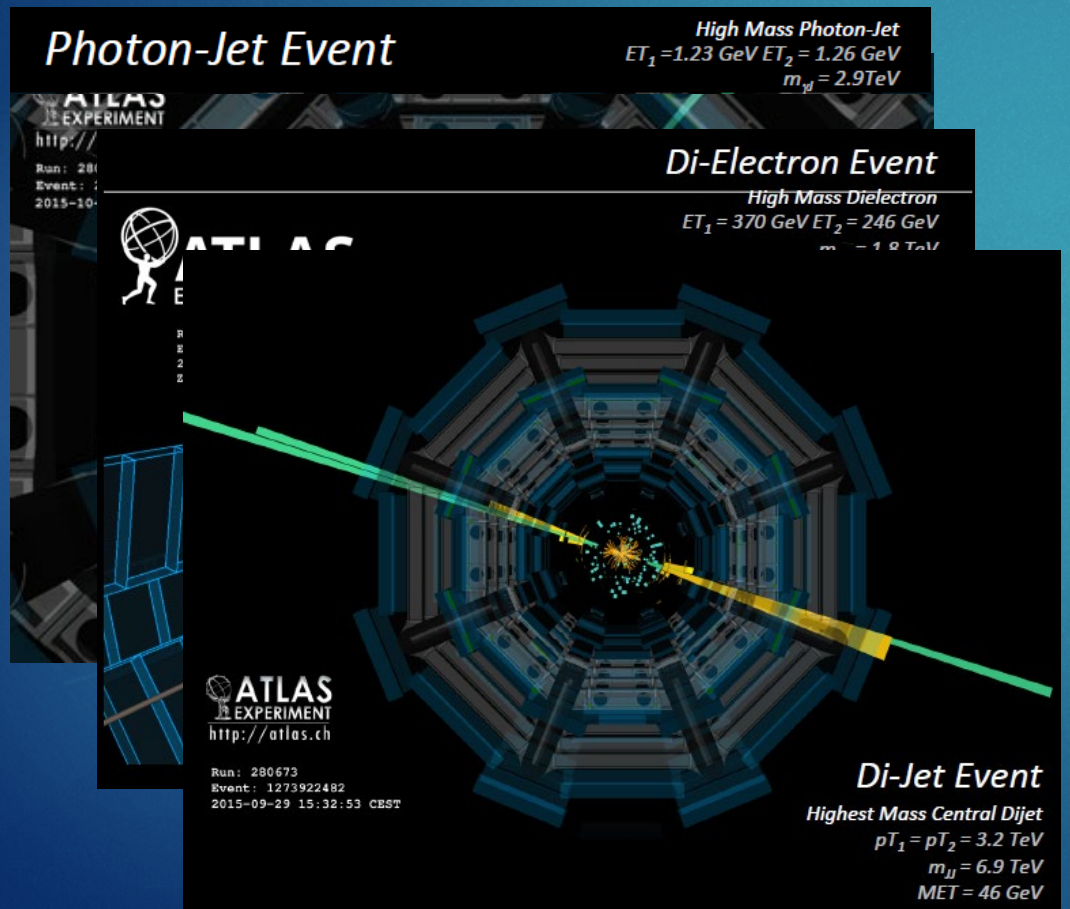

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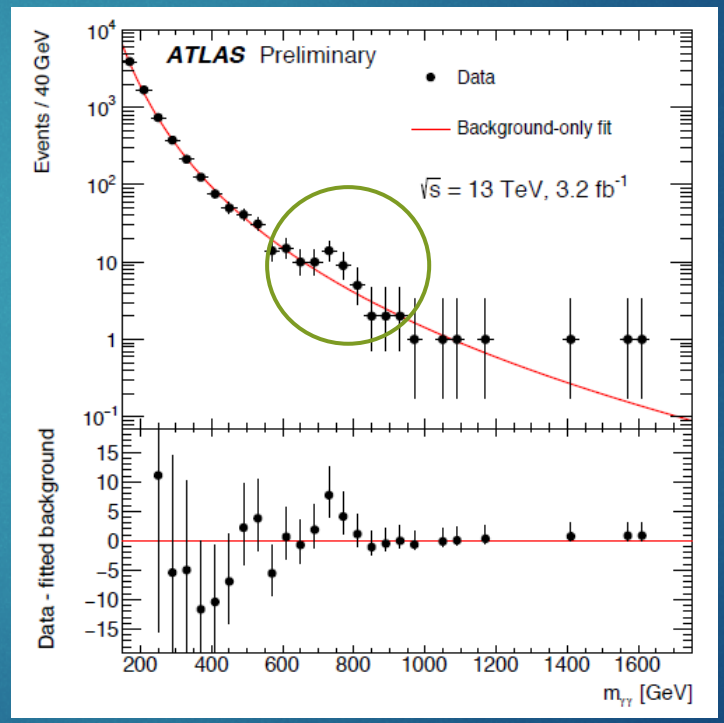

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Strategic approach for this challenge [Time…]

Challenge against time…

- Detector degradation and ageing à inject new technologies
- Developer community need to transfer knowledge to the next generation
- Develop HL-LHC detectors not forgetting what will come NEXT

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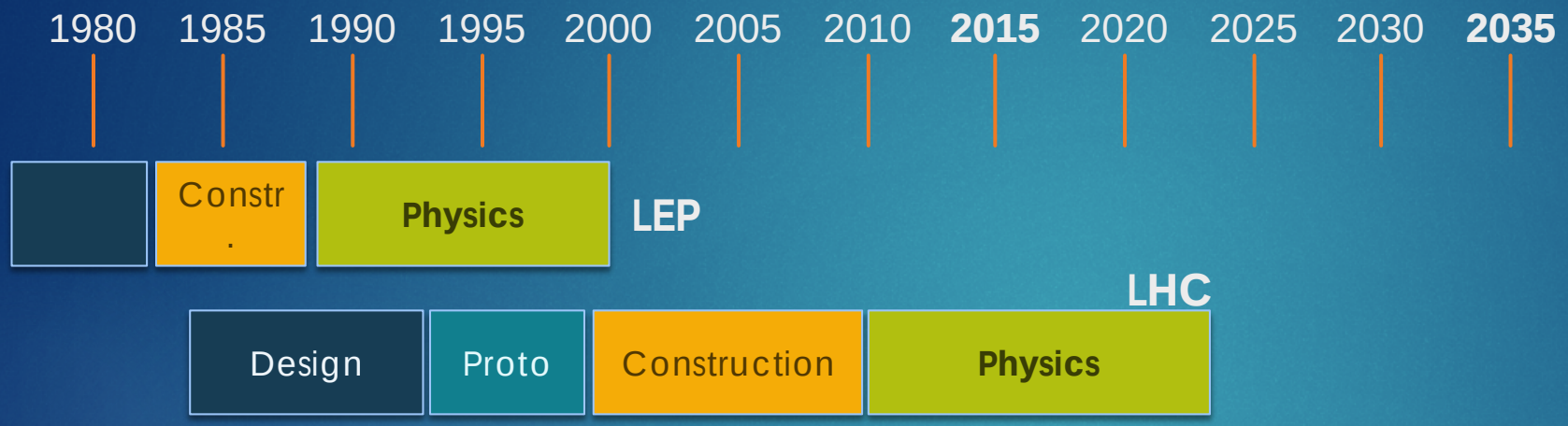

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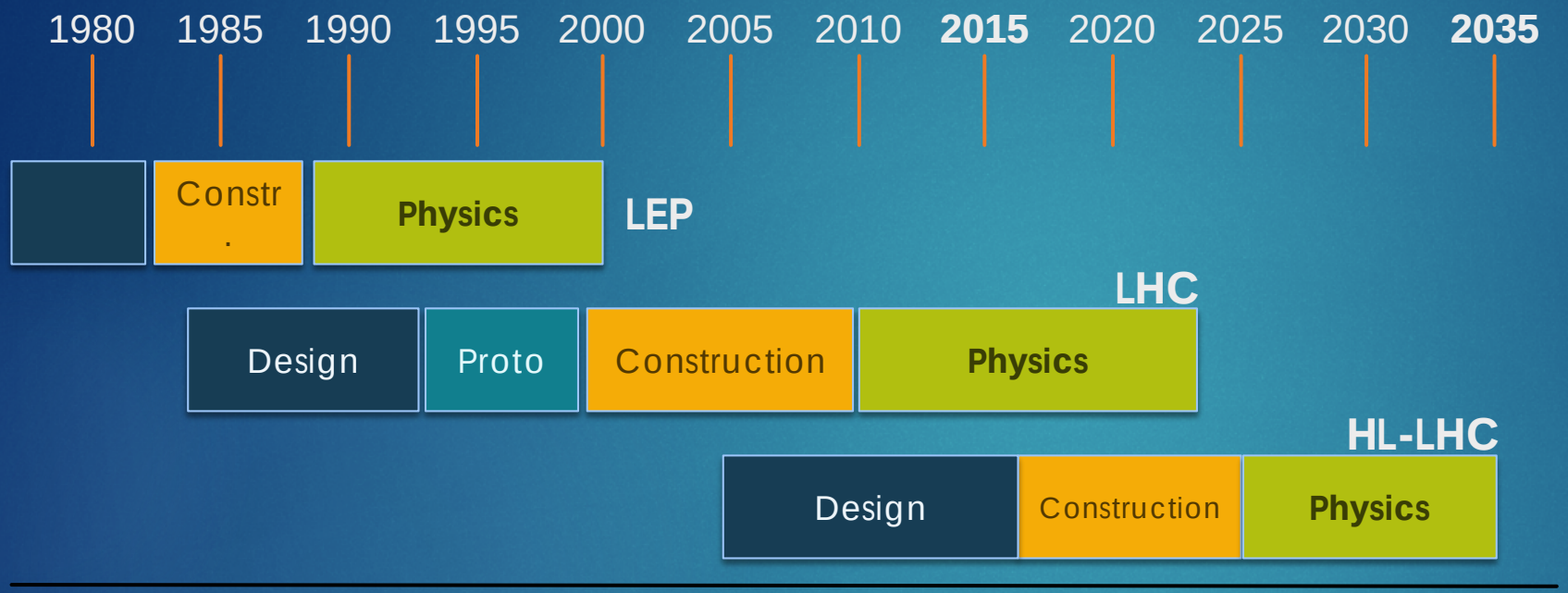

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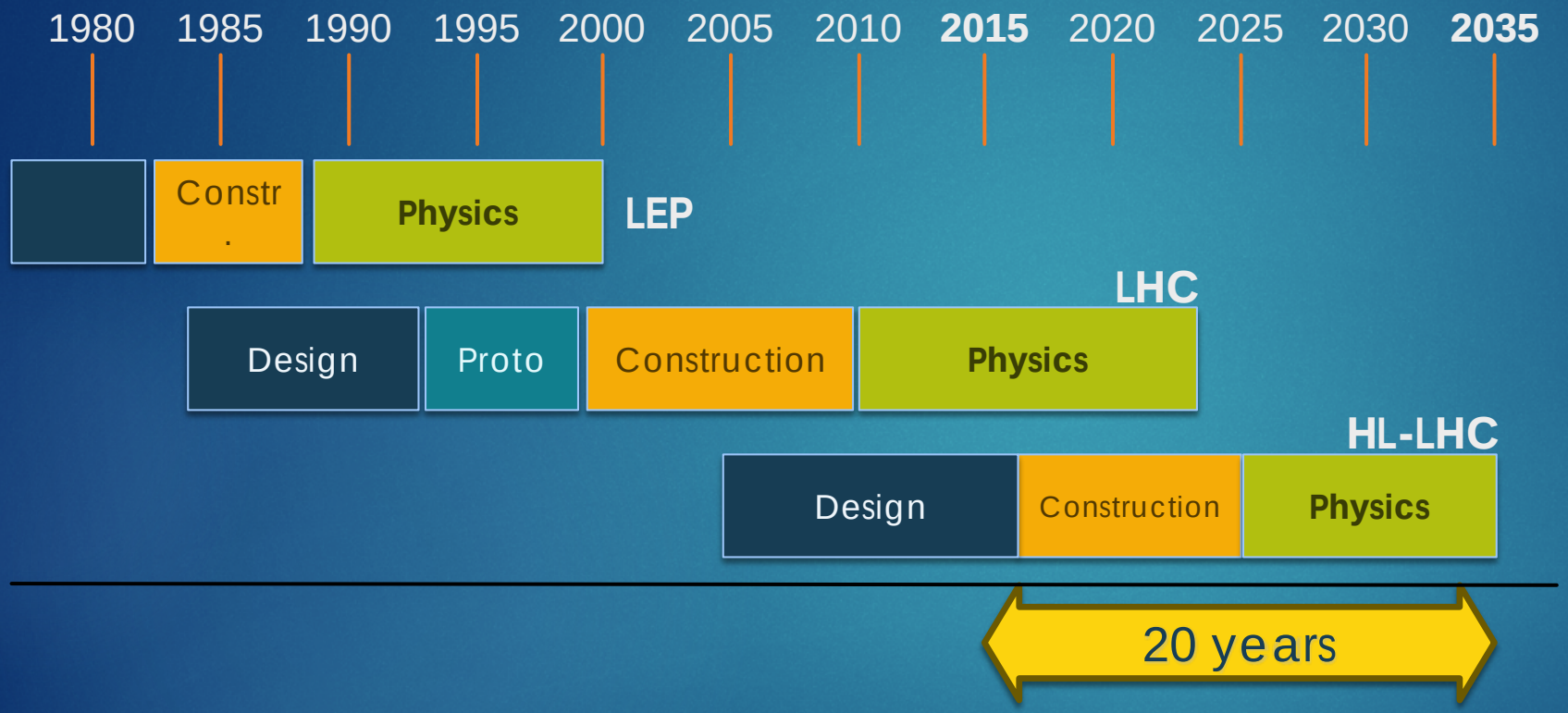

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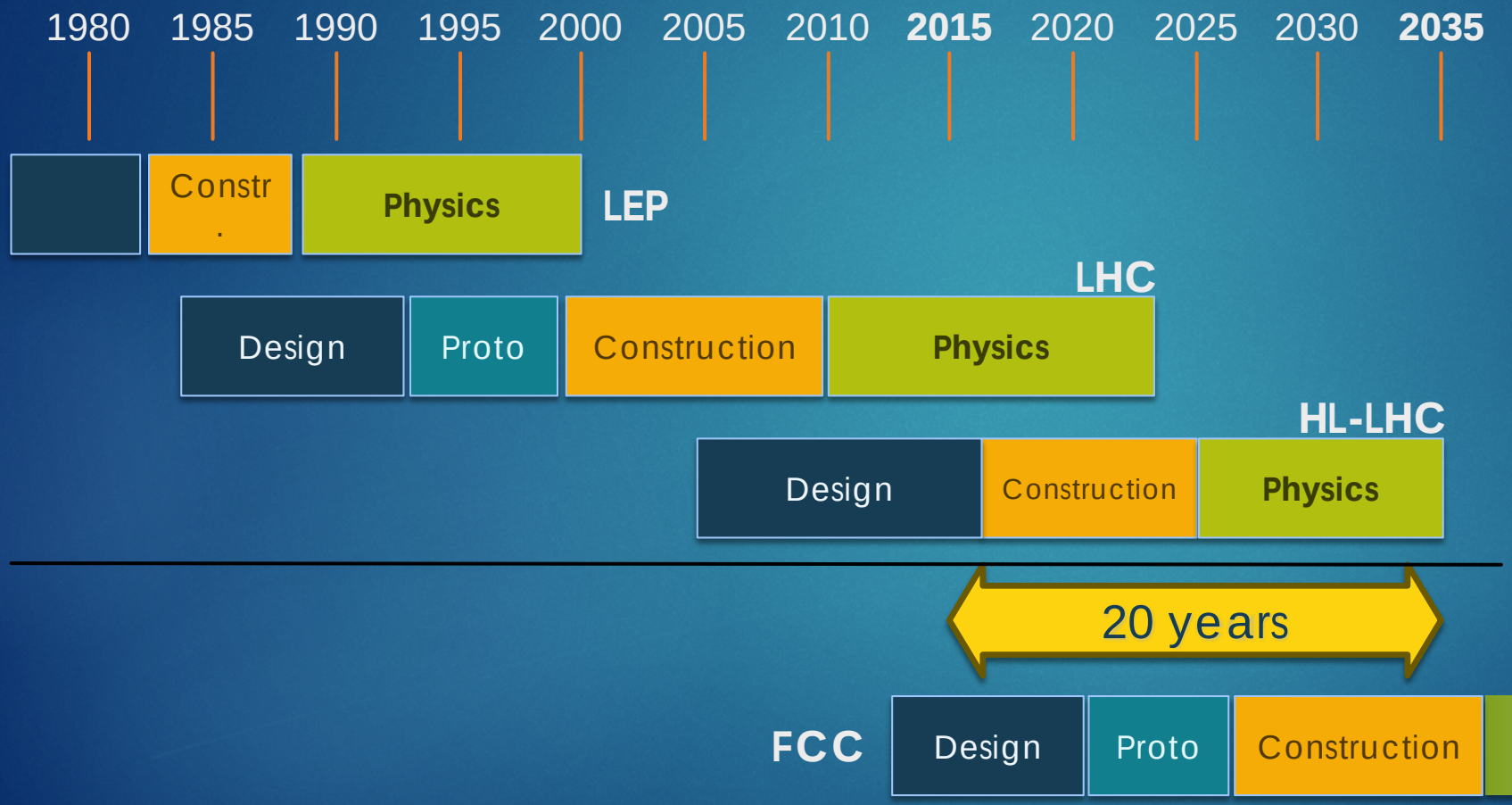

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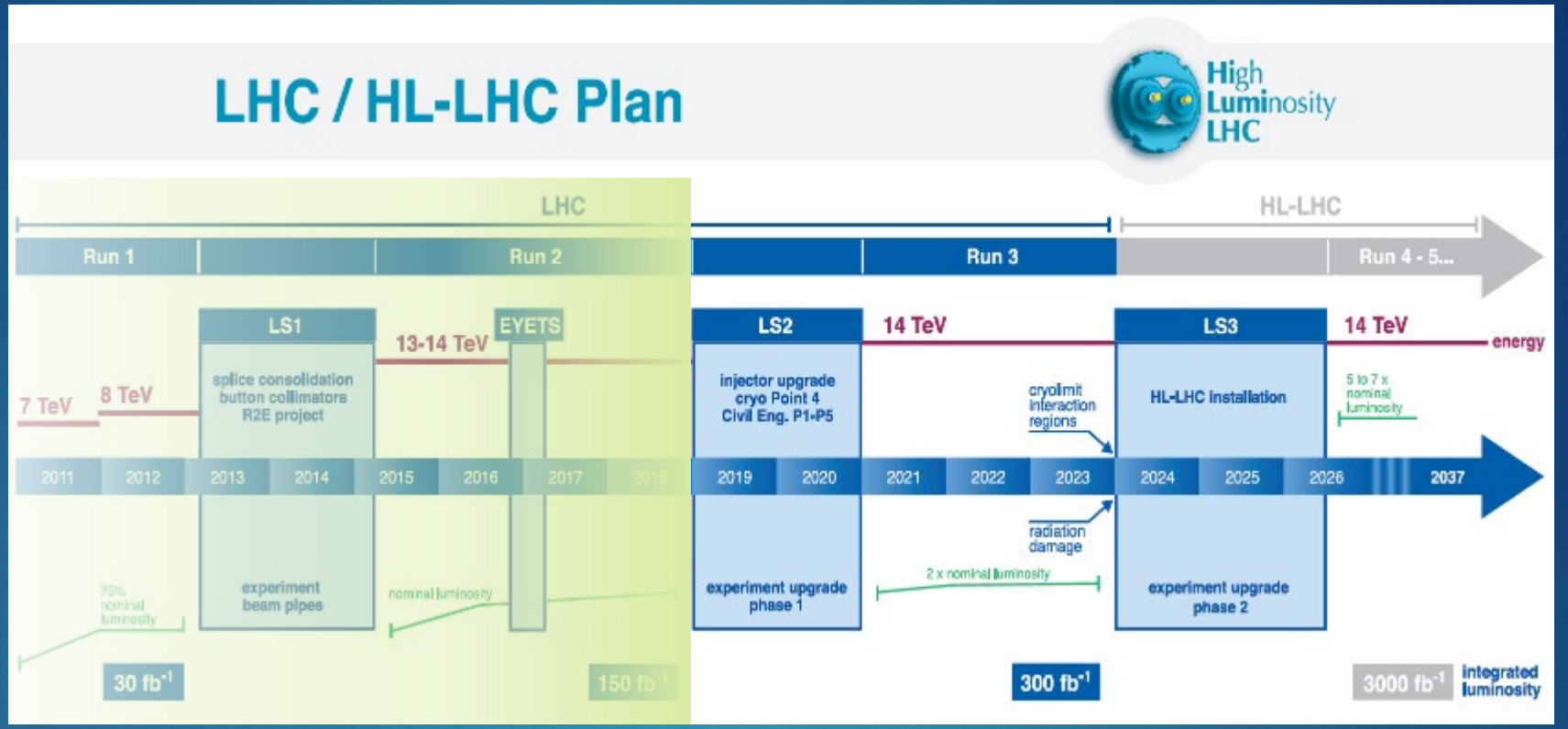
- Develop HL-LHC detectors not forgetting what will come NEXT

Atlas Phase-1 upgrade for RUN3

- Relevant changes on LHC injectors to reach up to 2 x the nominal luminosity
- Several major upgrades on ATLAS



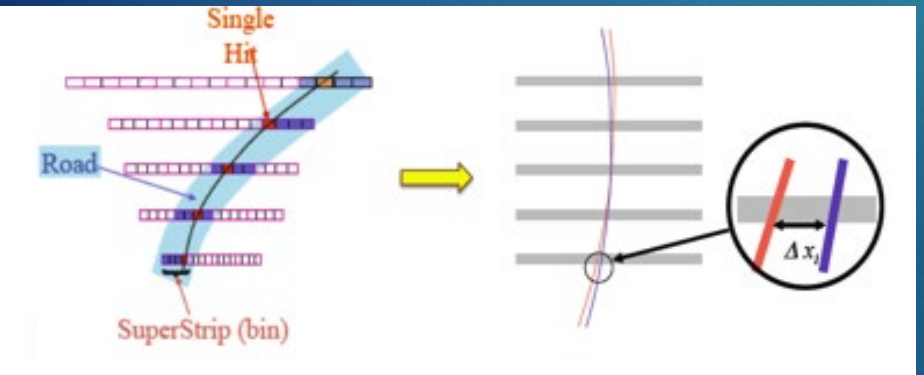
ATLAS detector will be upgraded accordingly:

- Fast Track Trigger at “Level 1.5”!
- L1 Calo supercells à enahnced Trigger
- New Small Wheels for the forward muon
- BIS78 for the transition region

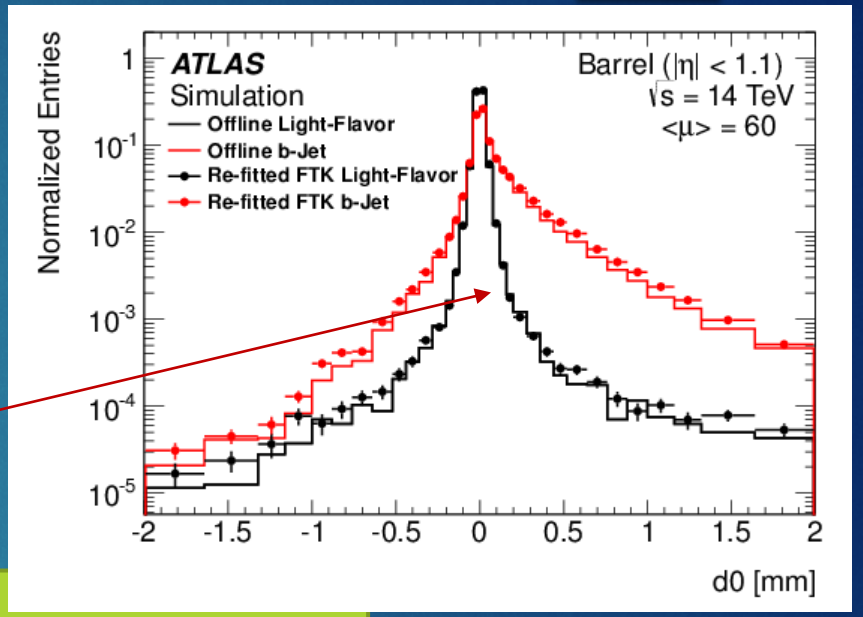
Fast TracK Trigger (FTK)

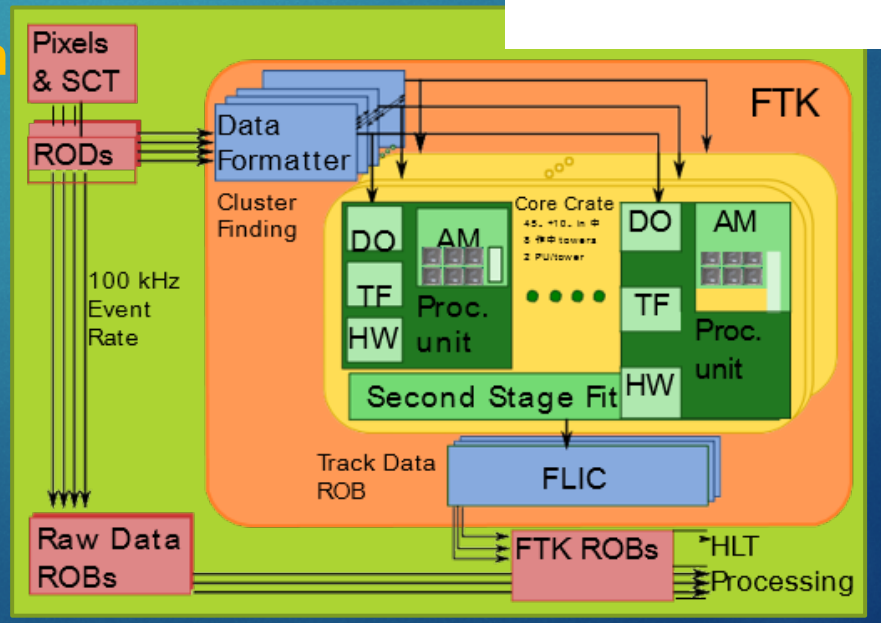
Dedicated, hardware-based track finder maintain efficiency and low thresholds in high pileup environment.

- Clean up of calo-based single lepton triggers
- constrain multi-object triggers to the same vertex.
- Runs after L1 and provides full-event tracking input for L2 from strips and pixels
  - Hit pattern matching using Associative Memory
  - Linear fitting of full resolution hits in FPGAs
- Global track with **near offline resolution**
  - Event rate < 100 kHz
  - Latency < 100μs
  - L2 full track reconstruction $O(100ms)$



Light jet rejection using FTK compared to offline reconstruction



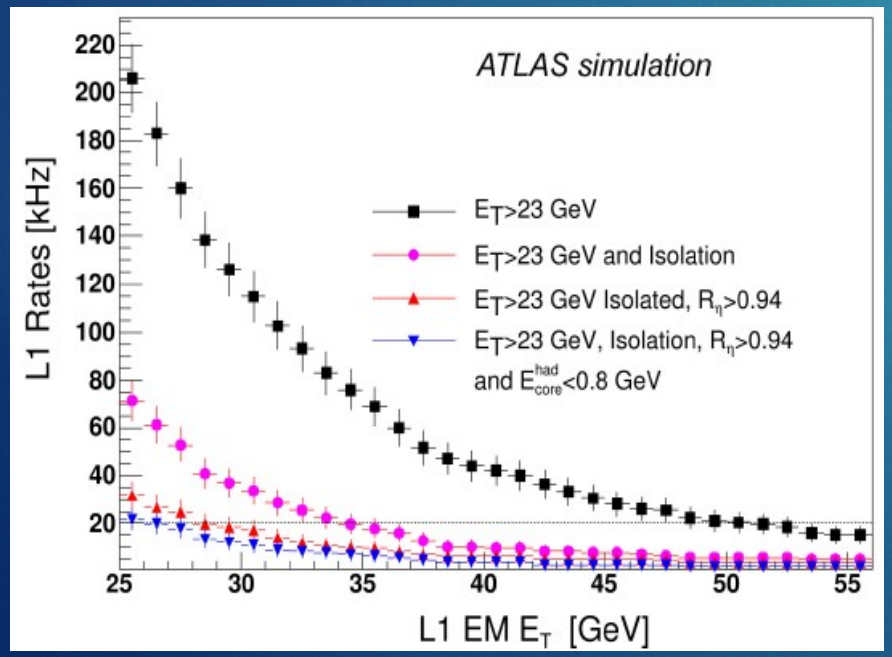


FTK will be integrated in run 2 with full eta coverage for mu up to 40 installed by end 2016

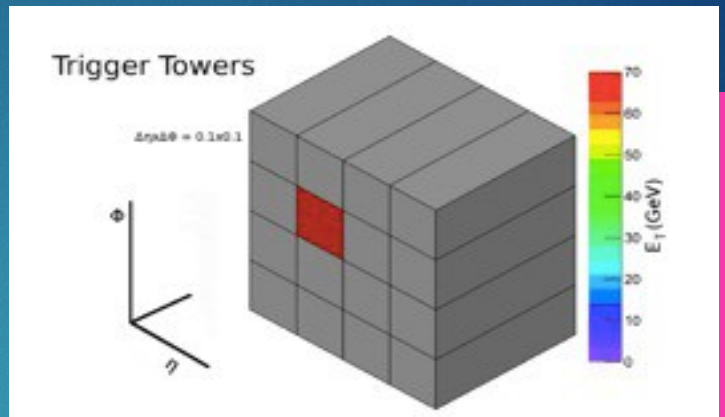
Level 1 Calorimeter trigger Upgrade

New Level-1 trigger electronics

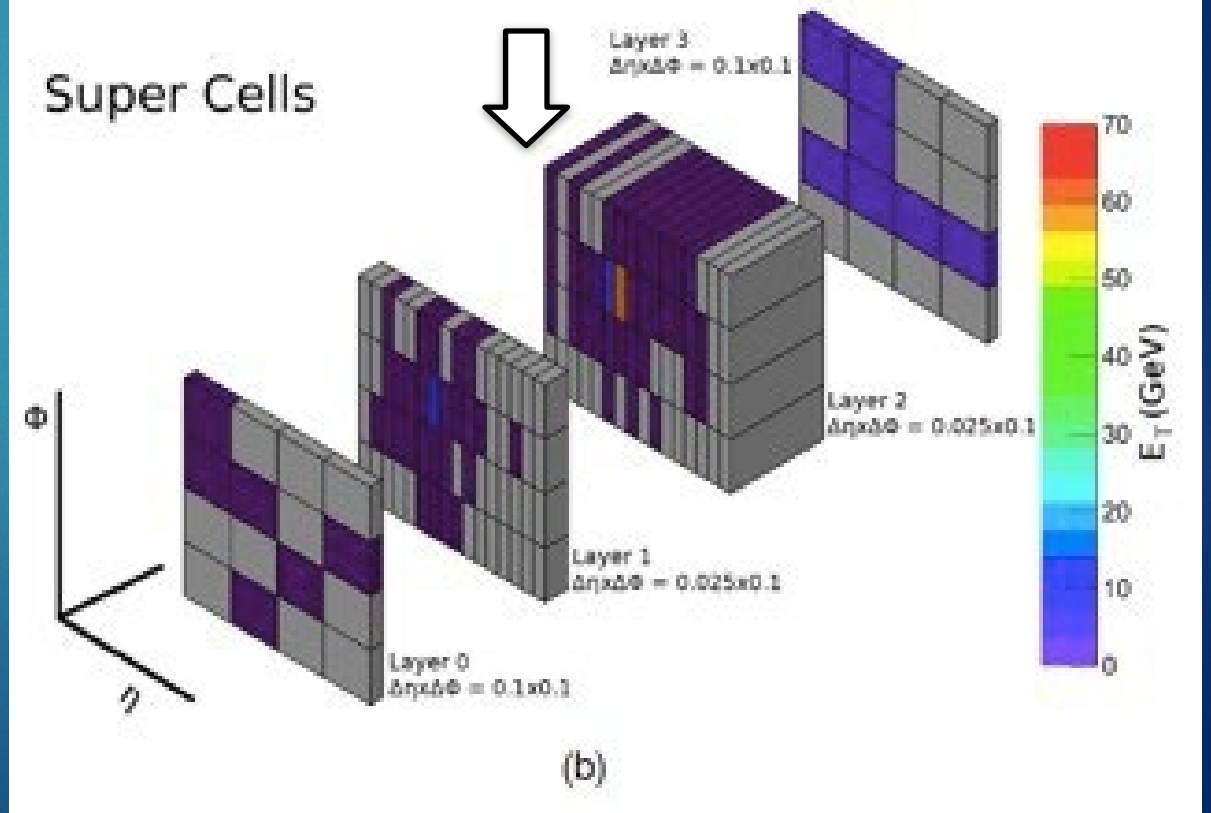
- finer granularity for Level-1 trigger decision
  - 10 super-cells instead of 1 trigger tower
  - Feature Extraction Modules (FEX) in trigger path.
- low pT threshold à high Lvl1 efficiency
- More segmentation in h and in layer depth.



- Better Level1 trigger electron reconstruction isolation, energy resolution.



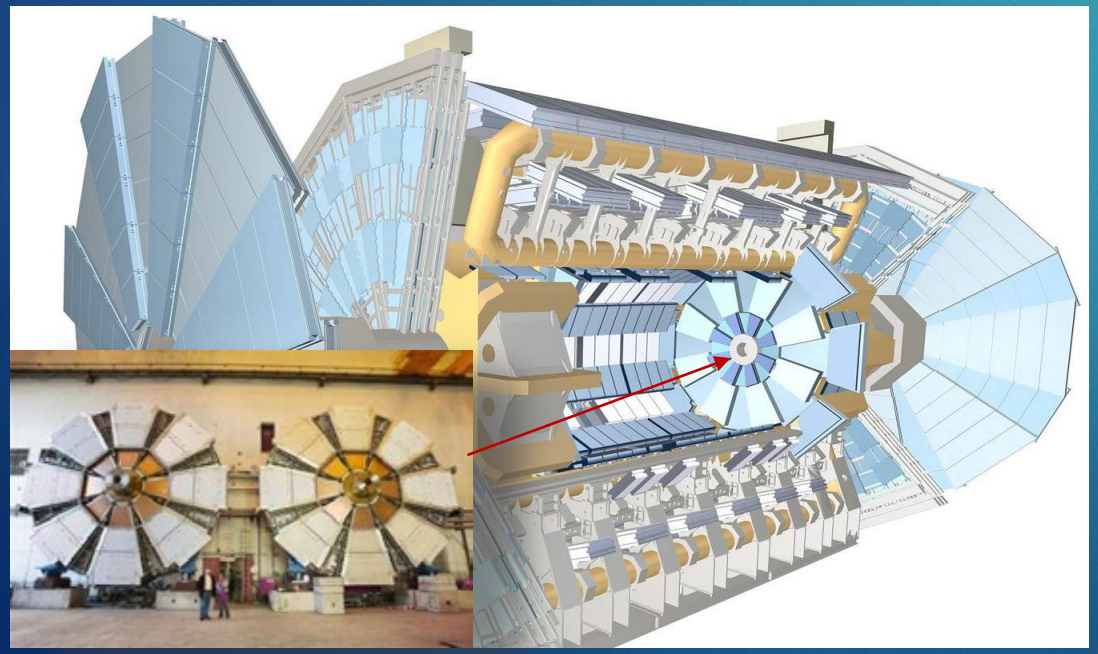
Forward compatible with Phase-2 Upgrade.

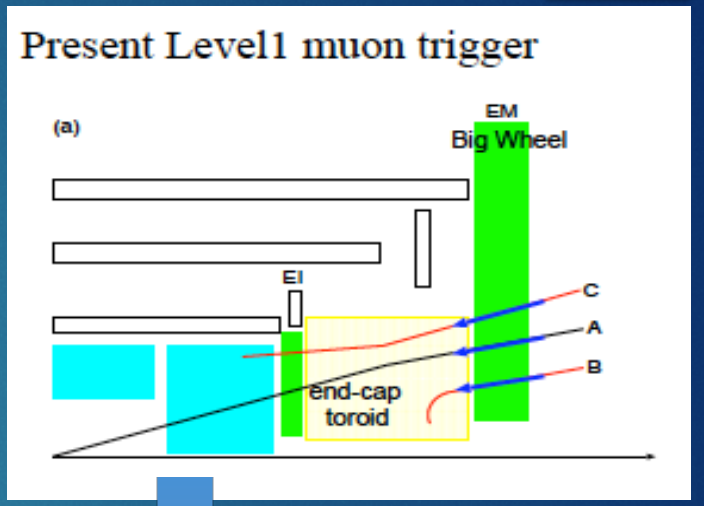


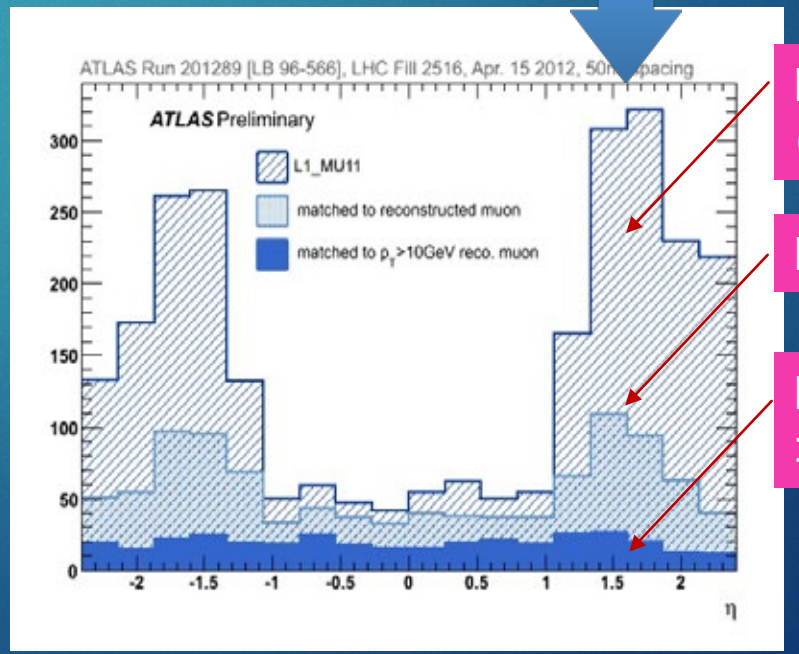
New Small Wheels

Two motivations to replace the Small Wheels:

- The precision chamber efficiency drops with high rates as luminosity goes above design value.
- L1 muon trigger rate (based on Big Wheels) dominated by fake triggers in the end-caps (not coming from the IP).







LVL1 muons >11 GeV/c

Reconstructed muons

Reconstructed muons >11 GeV/c

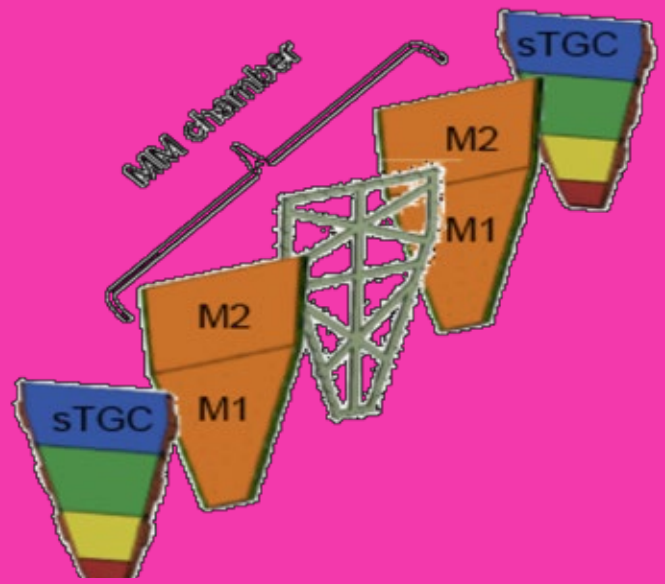
New Small Wheels technology

MicroMegas (area of 1200 m² distributed on 8 layers)

- Space resolution < 100 μm
- High granularity -> track separation
- High rate capability due to small gas gain

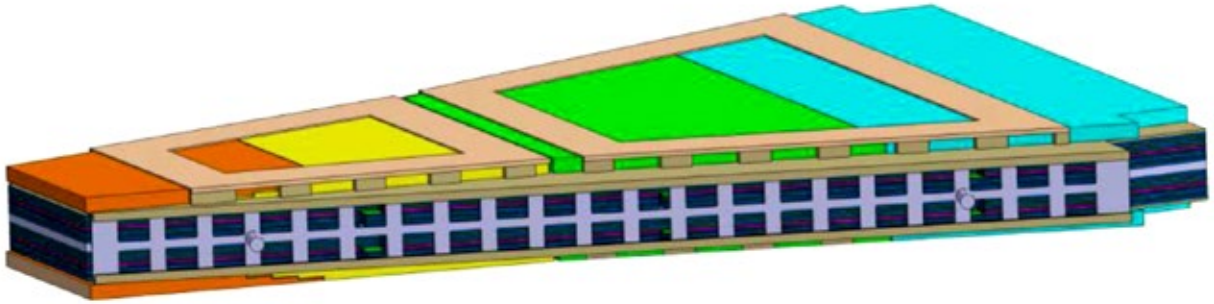
Thin Gap Chambers (sTGC) (area of 1200 m² distributed on 8 layers)

- Space resolution < 100 μm
- Bunch ID with good timing resolution to suppress fakes
- Track vectors with < 1 mrad angular resolution



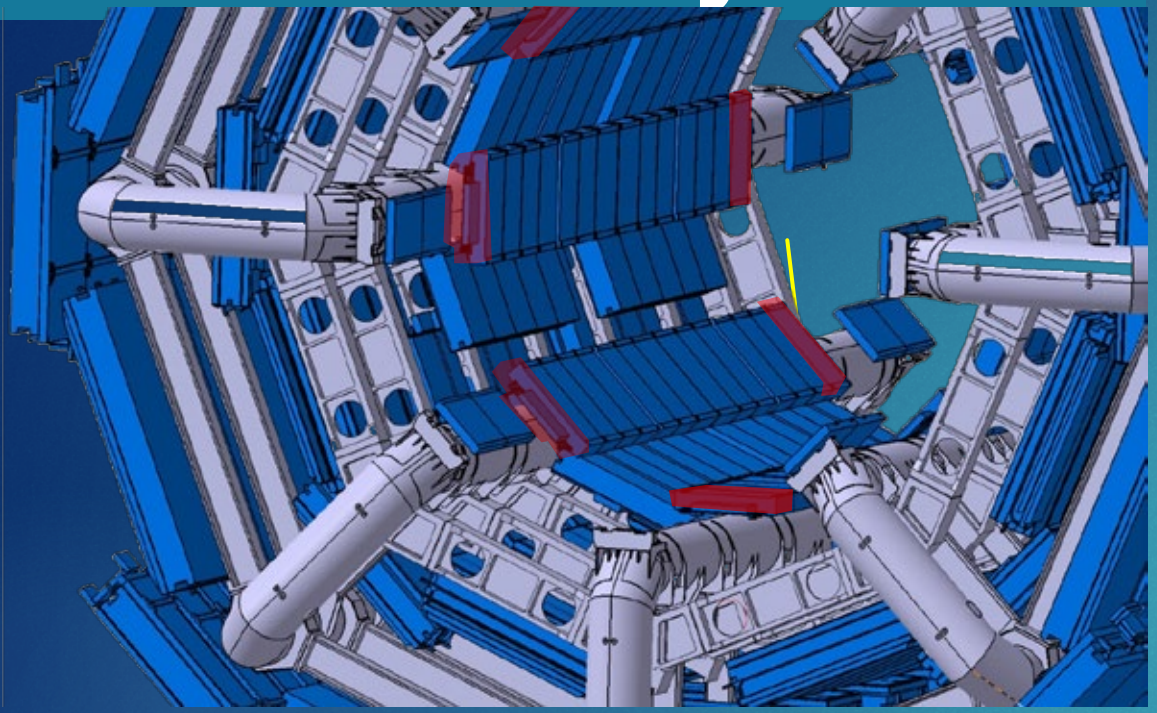
Redundant solution

- **sTGC as primary trigger**
- **MM as primary tracker**



sTGC
MM
sTGC

The BIS78 system



Motivation

provide NSW like performance
in the 1<|h|<1.3 region.

- 22% of the total Lvl1 rate would be concentrated in this region without intervention
- Suppress fake muons
- Lvl1 momentum threshold sharpening
- **It's a pilot for the BI upgrade in phase-2**

LAYOUT (thinner is better)

- 16 muon stations replacing the 32 present ones
  - one sMDT with halved diameter tubes
  - two RPC triplets with halved gas gap

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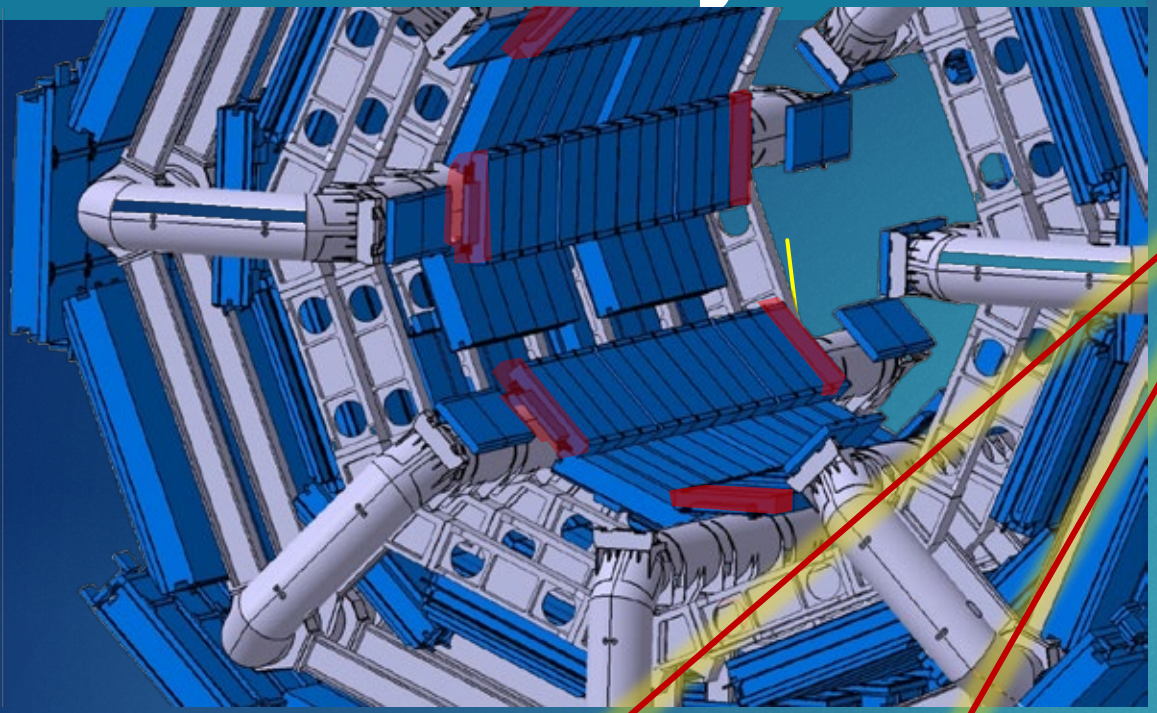

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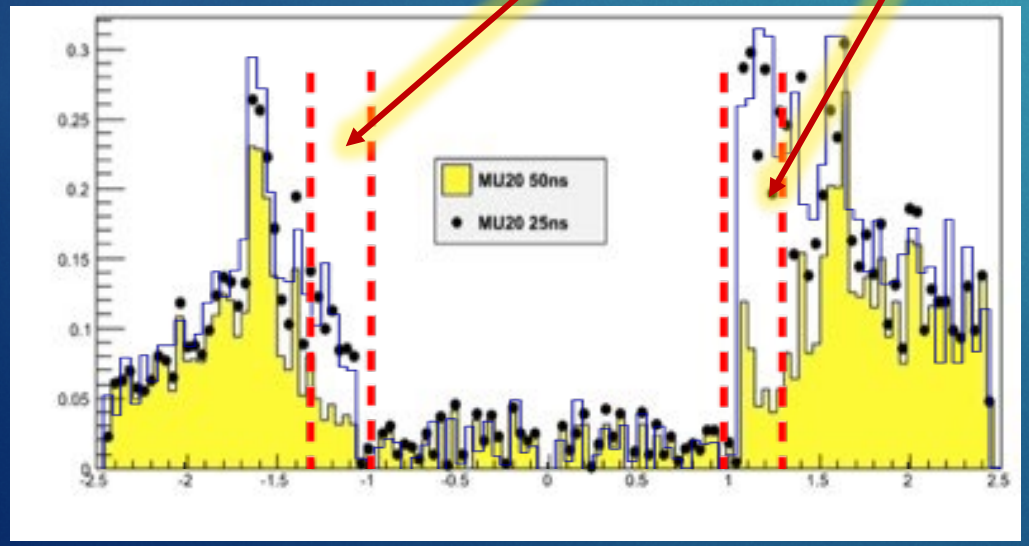

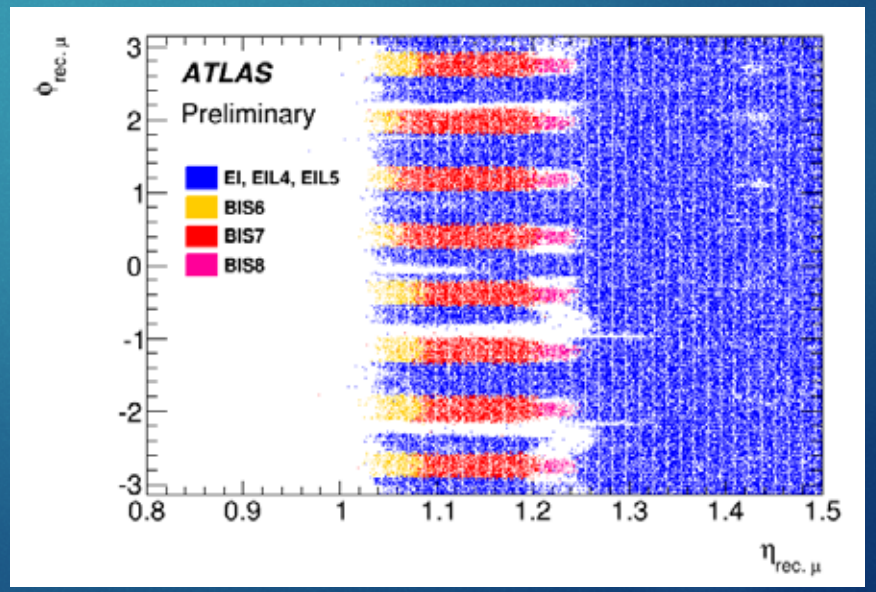

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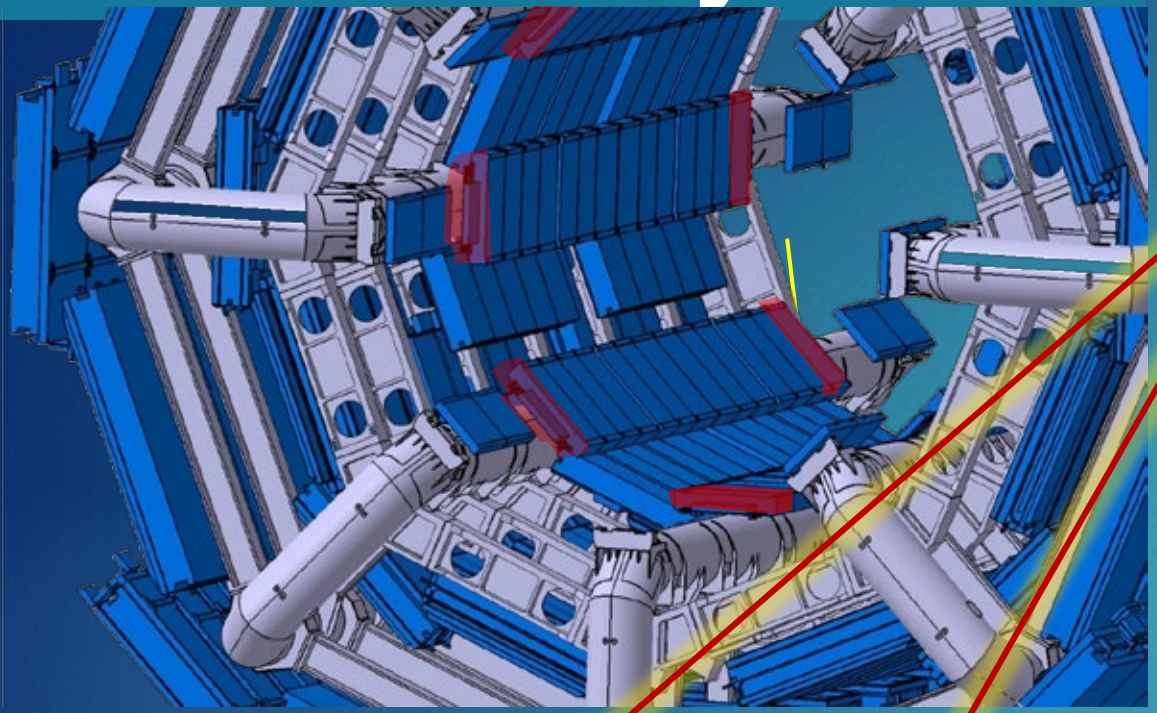

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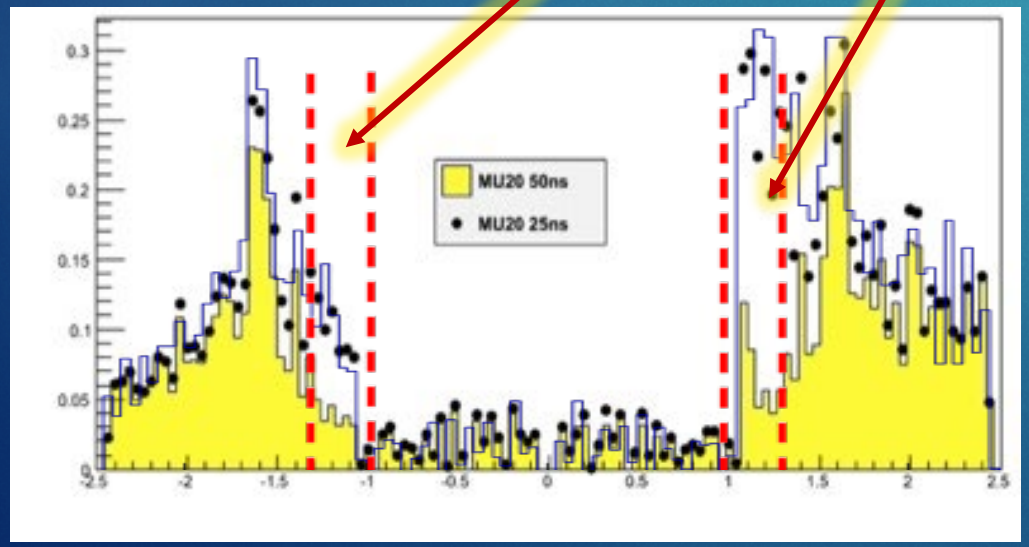
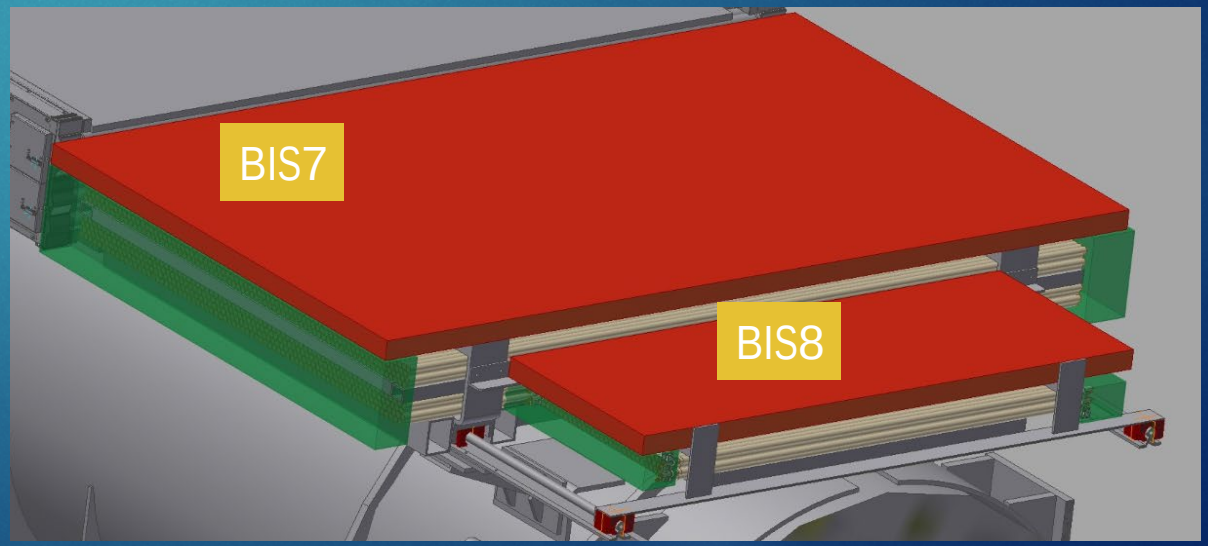
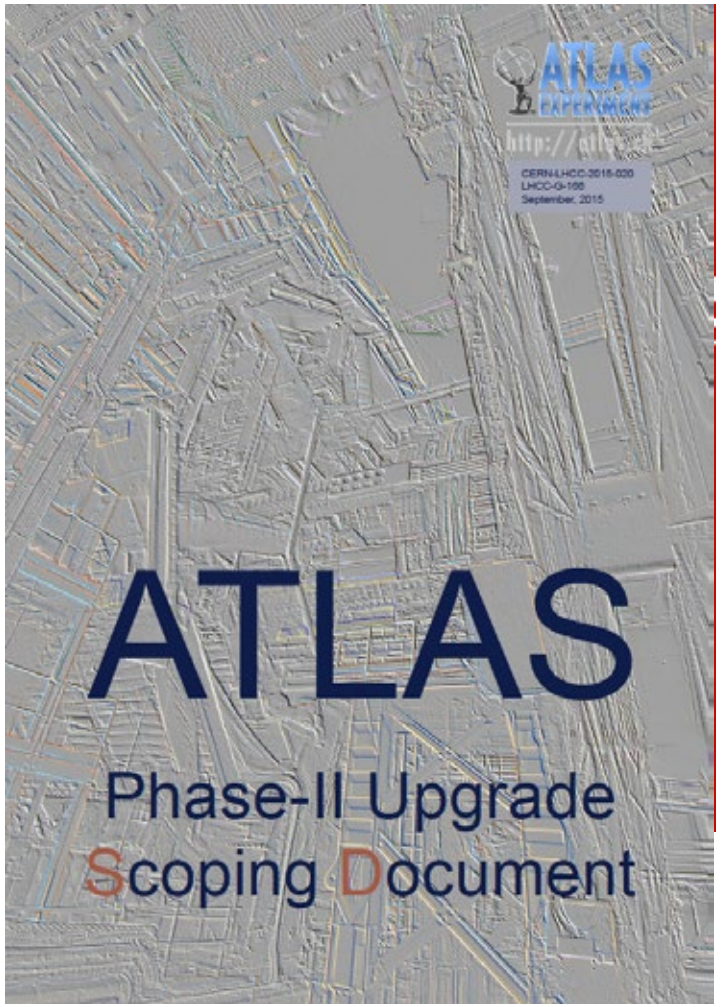




Phase2 upgrade

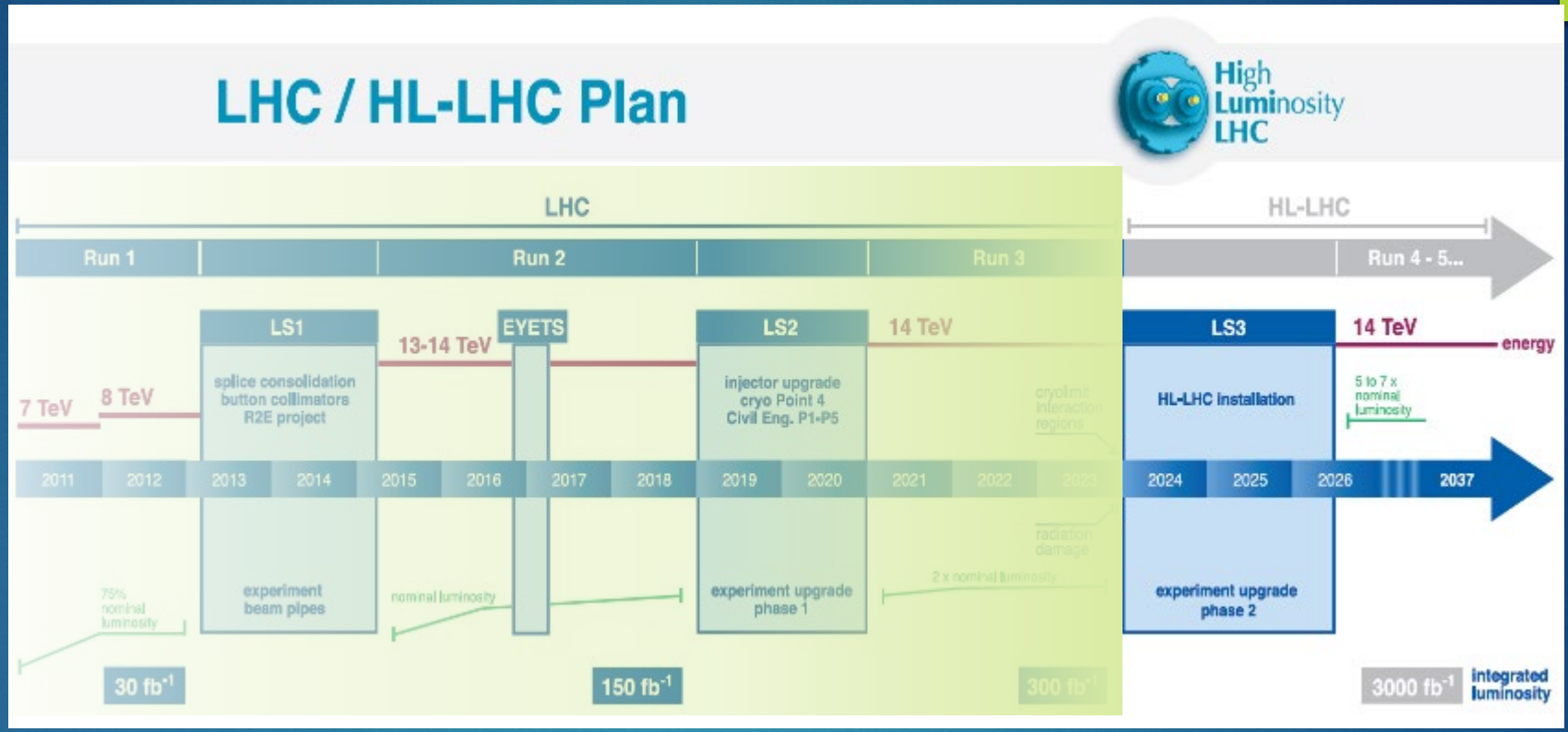


Phase2 upgrade

Withstanding the ultimate HL-LHC performance
with an aged and obsolescing detector
And one eye on future colliders
...keep calm and upgrade...

Atlas Phase-3 upgrade for RUN4

- 7 x luminosity
- The detector core is mostly the same old one
- Very deep upgrade plan is needed



BIG CHANGES

- New Inner Detector with L1 track
- New Trigger DAQ with L0 trigger
- Replace Tile and Lar calo electronics
- Possible timing layer for high h region

…and more:

- Inner Barrel RPCs as 4th trigger layer
- Muon trigger and RO electronics
- possible tracker/muon extension to eta=4

New trigger schema

New design of hardware trigger:

Move part of the High Level Trigger (HLT) reconstruction into the early stage of trigger

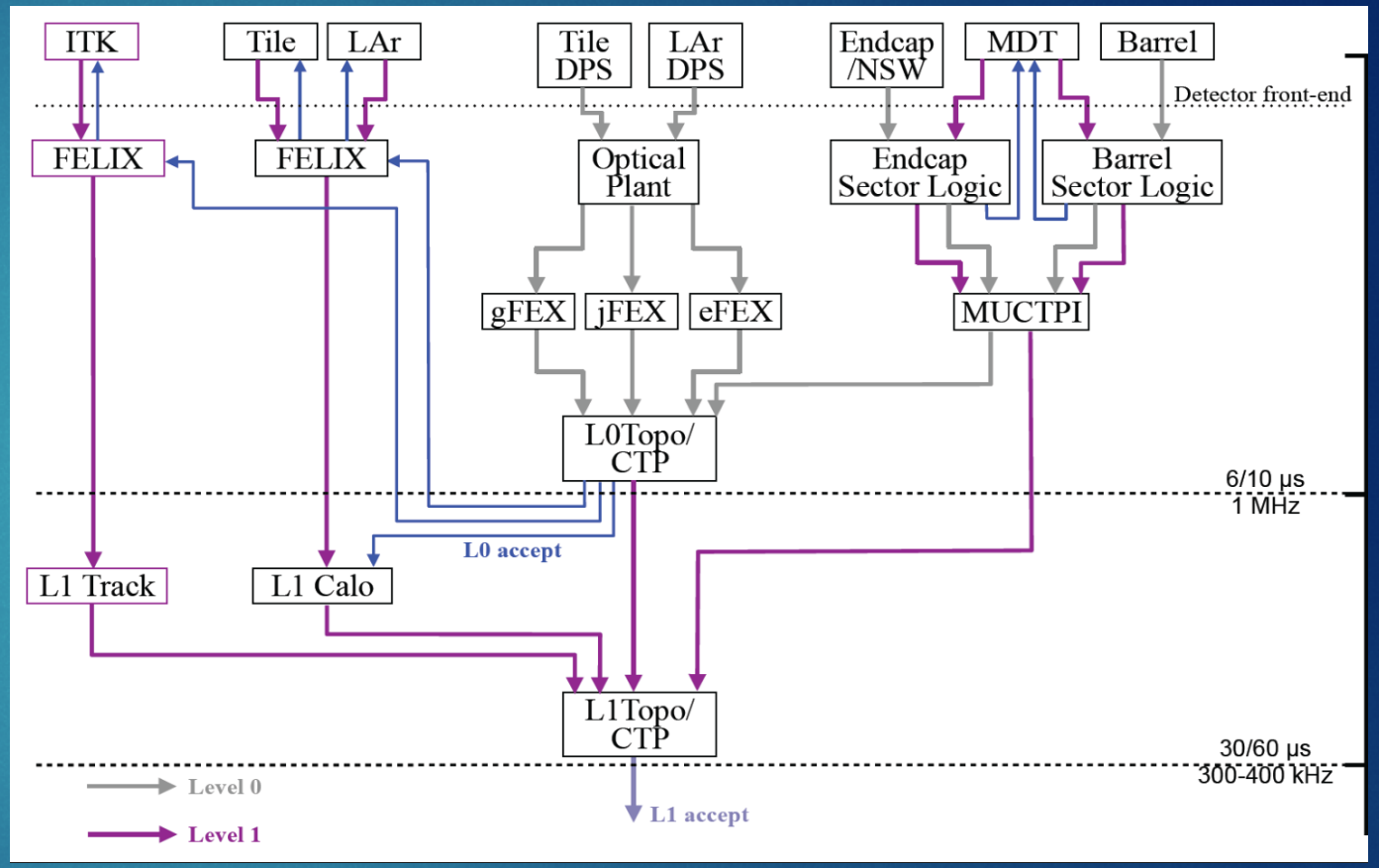
- Goal: keep thresholds on pT of triggering leptons and L1 trigger rates low

Triggering sequence

- L0 trigger (Calo/Muon) reduces rate within ~6 μs to 1 MHz and defines RoIs
- L1 track trigger extracts tracking info inside RoIs from readout electronics

Challenge:

- Finish processing within the latency constraints
- Requires changes to electronics feeding trigger system



Level-0 Calo + Muon
Latency ~6 μs, rate ~1 MHz.
Define RoIs for L1.

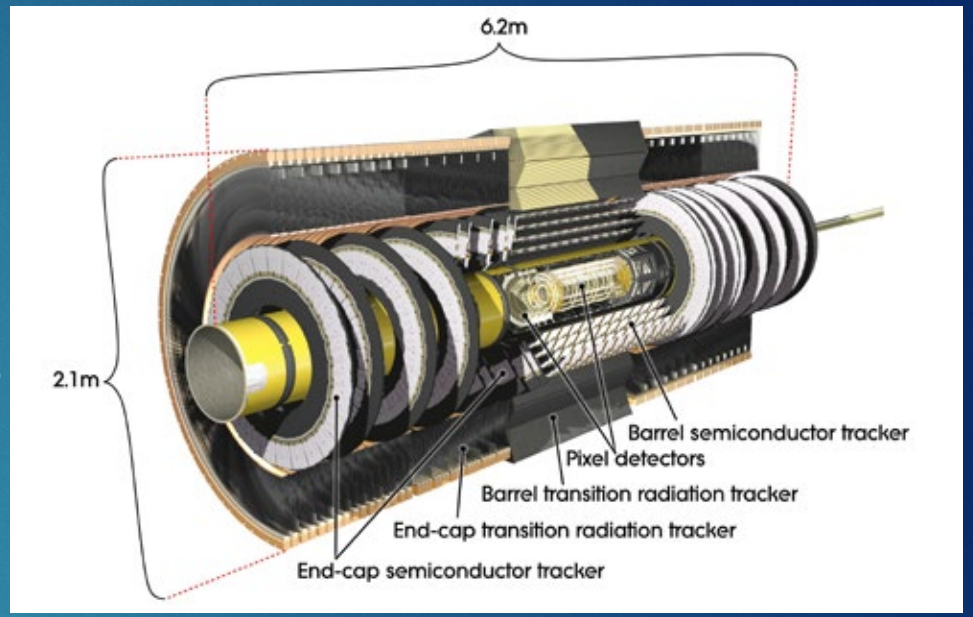
Level-1 Calo + Muon
Latency ~20 μs, rate ~400 kHz.
All data are moved off detector.

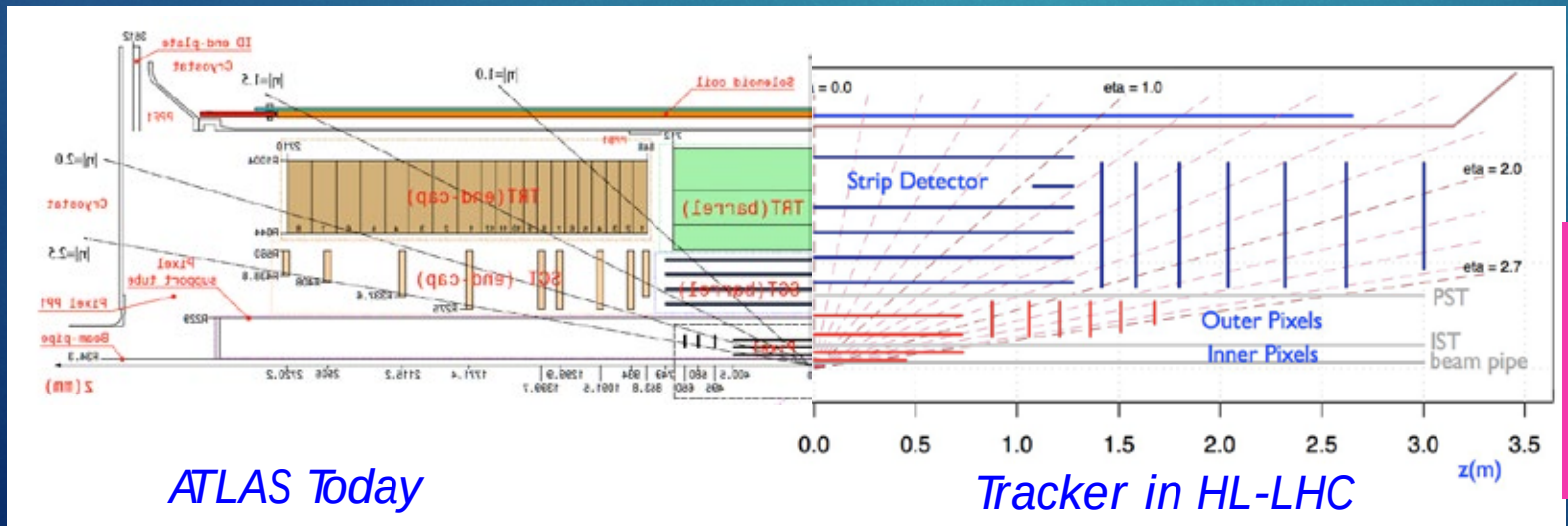
Brand new Inner Tracker Detector ITk

- Present tracker limitations for Phase-II
  - Progressive radiation damage à efficiency loss
  - excessive occupancy in the Transition Radiation Tracker.
  - Readout bandwidth limitation à need of higher granularity and larger bandwidth to operate at larger pile-up.
- Complete replacement with an all-silicon tracker.

  Reduce material in the tracking volume à Improve at low pT
  - Reduce rates of nuclear interaction à lower background

  Reduce average pitch à lower pileup effect
  - Improve performance at high pT





ATLAS Today *Tracker in HL-LHC*

	Si area	Channels
Pixel	8.2 m^2	638×10^6
Strip	190 m^2	71×10^6

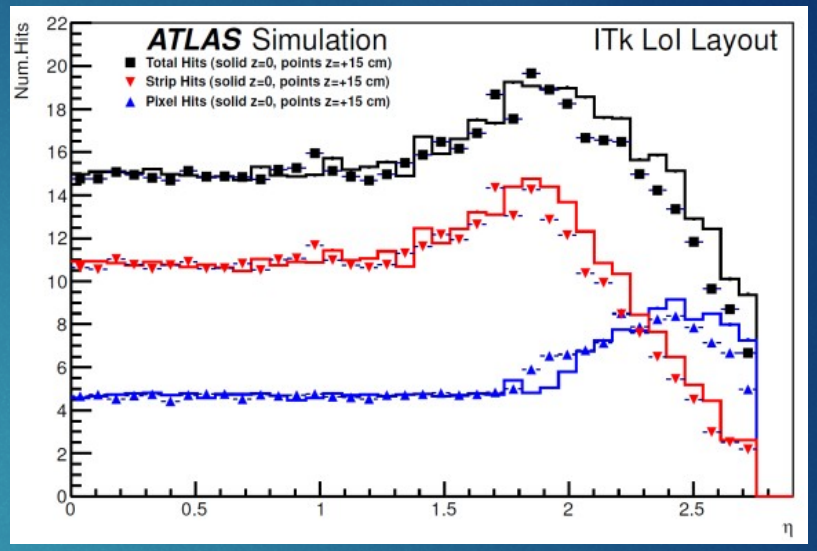
Investigating improved layouts:
- 5 pixel and 4 strip layers
- potential coverage to eta=4

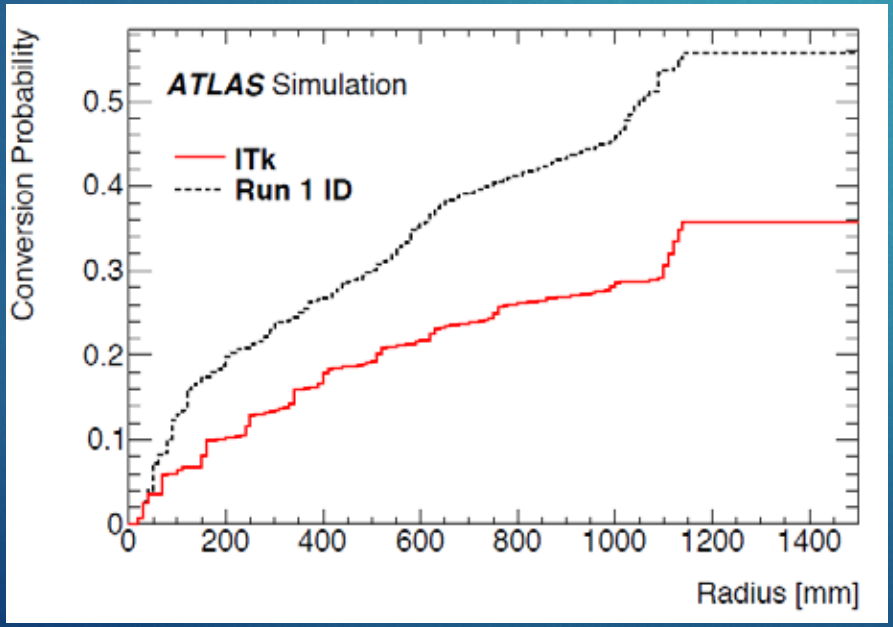
Final decision by ~mid-2016.

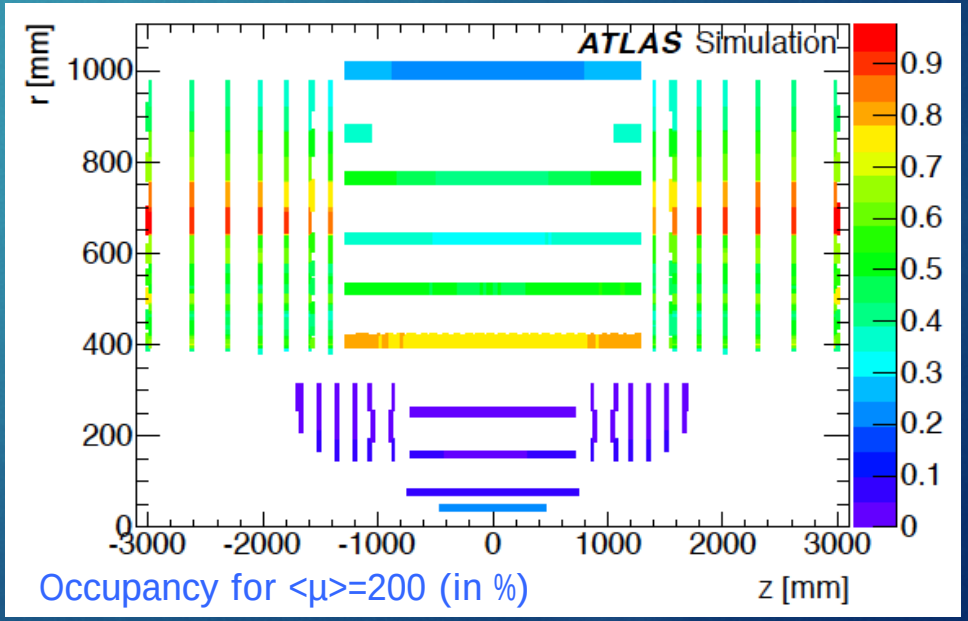
Inner Tracker Performance

LoI Layout allows performance studies

- Robust tracking with at least 11 hits/ track for |h|<2.5
- Occupancy < 1% for <μ>=200
- Reduced material (factor 5 for |h|<1) with respect to current ID







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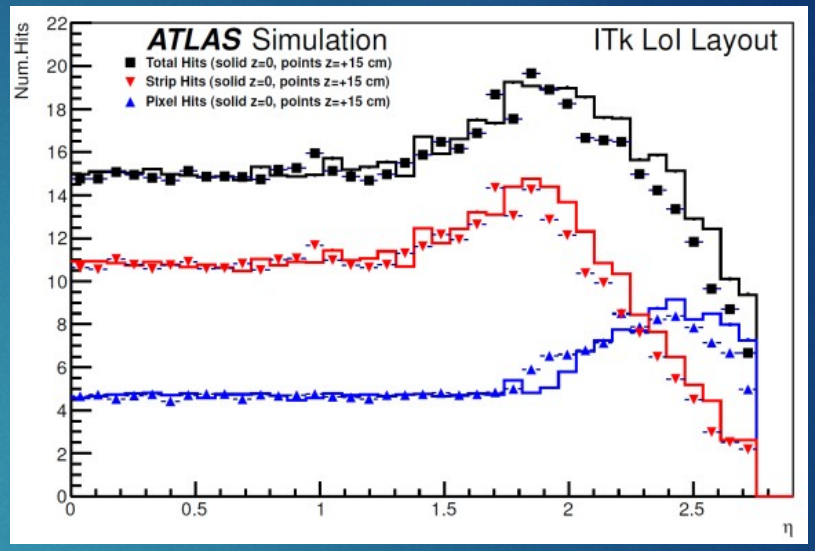
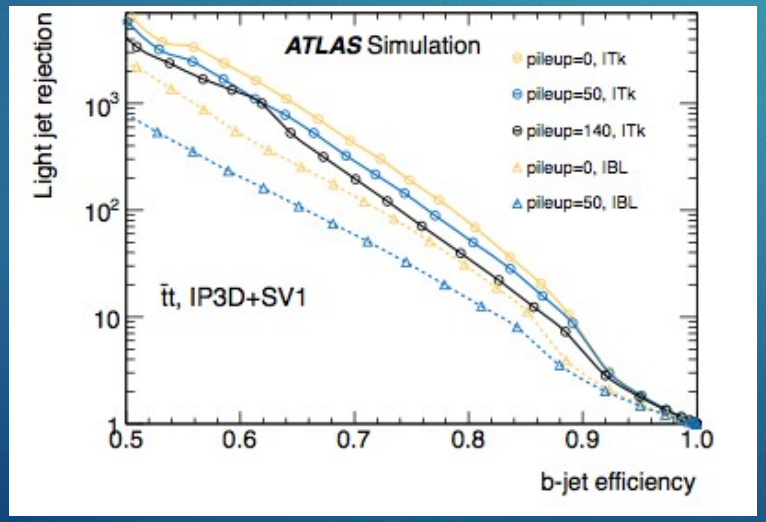
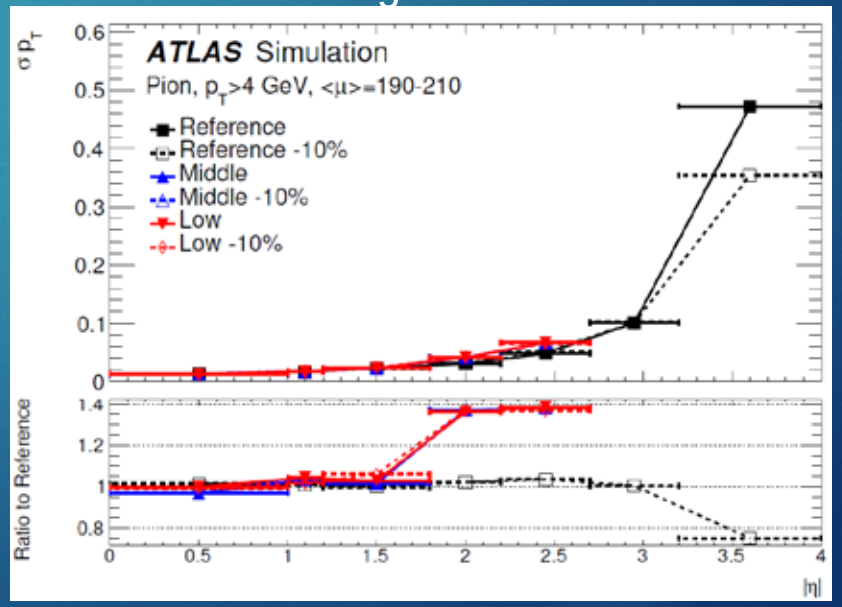


Performances

- b-tagging performances better with ITK compared to ID+IBL with <μ>=0
- Significant improvement (x2) momentum resolution due to the longer level arm and more precise hit position.





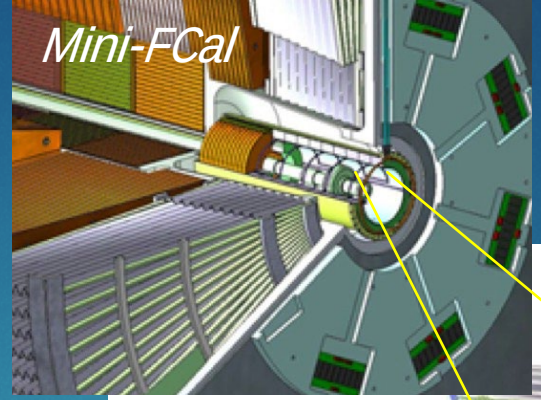
Calorimeters

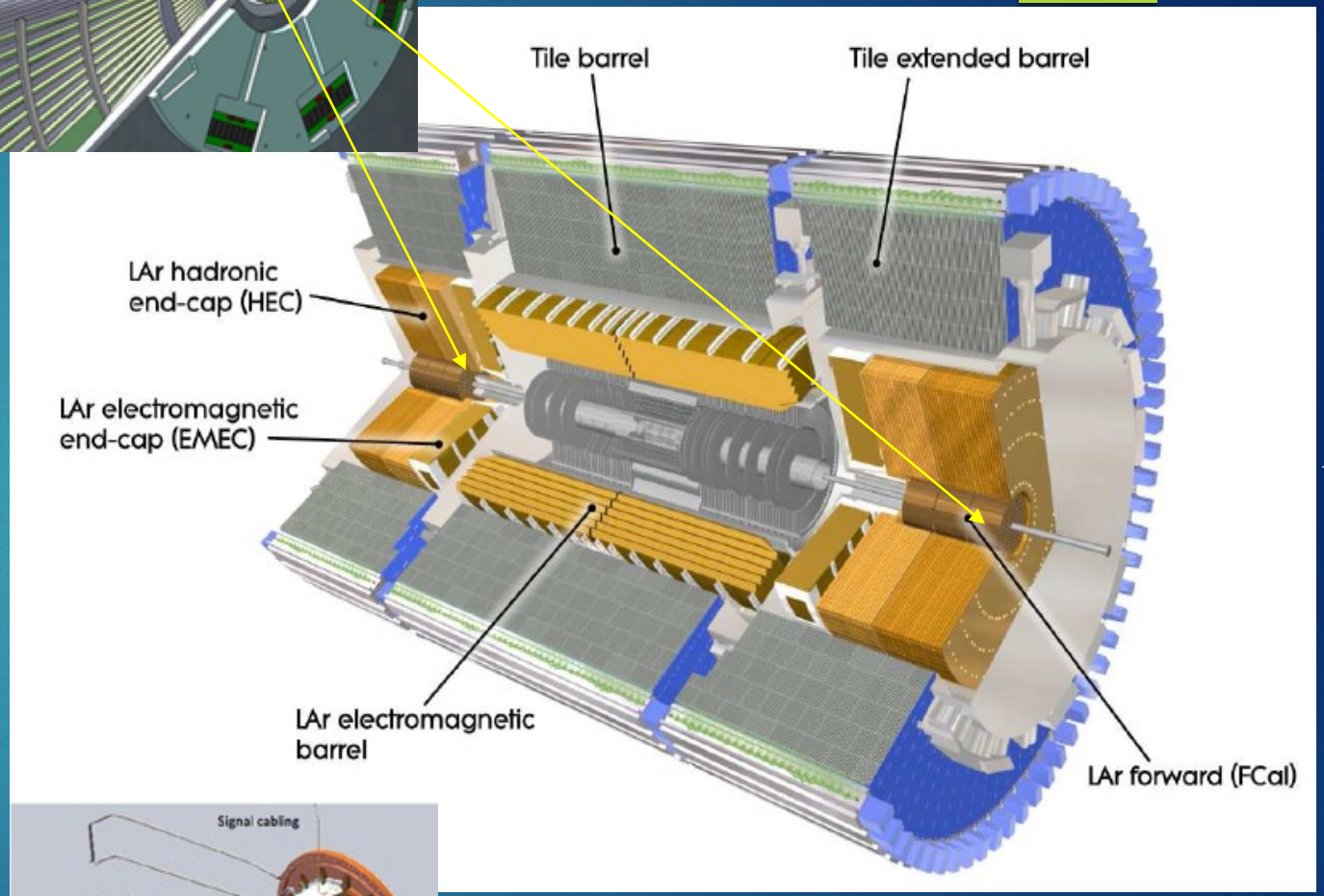
Lar and Tile Calorimeters (EM and Hadronic)

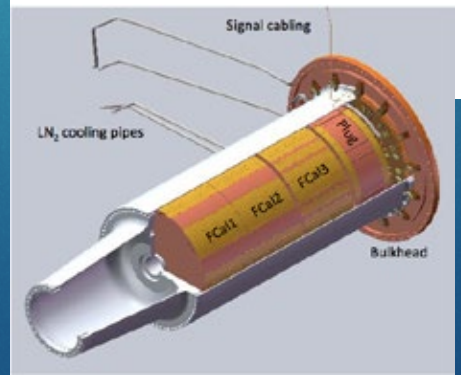
- Full replacement of front-end and back-end electronics due to higher radiation levels
- New read-out architecture:
  - Full digitization and transmission of data at 40MHz . Digital information to level L1/L0
  - compliance with Phase-2 L0/L1 trigger rates and latencies.

Replace Forward calorimeter (FCal)

new sFCAL in cryostat or miniFCAL in front of cryostat if required by Physics or if the FCAL will degradate excessively





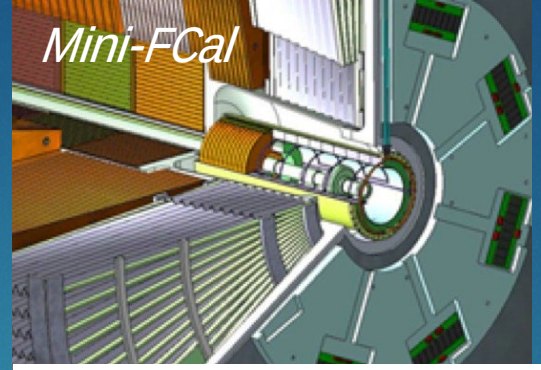


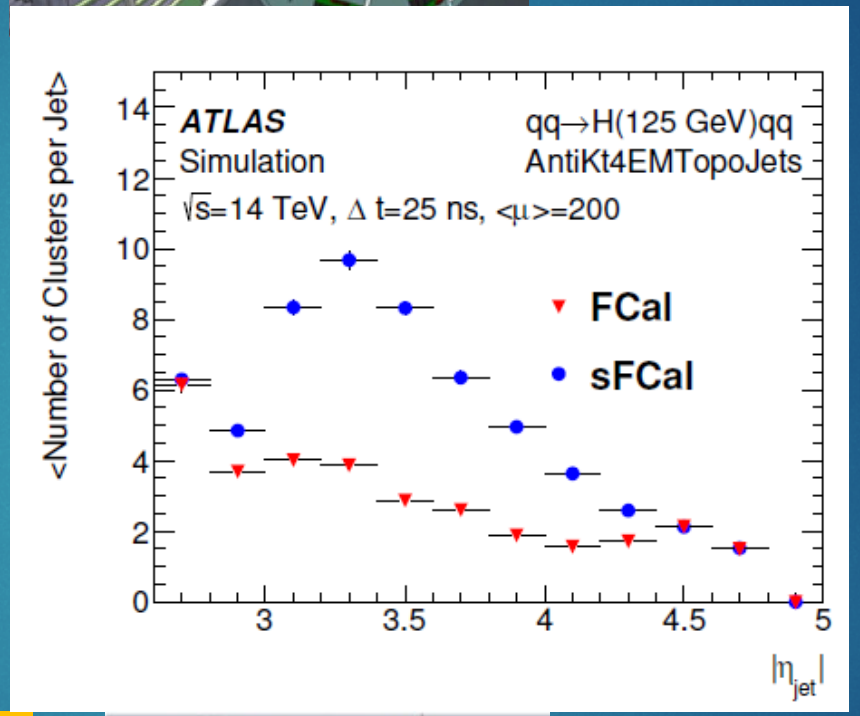
Based on Liquid Argon technique
But with smaller (≈100 μm) Lar gaps

Calorimeters

Lar and Tile Calorimeters (EM and Hadronic)

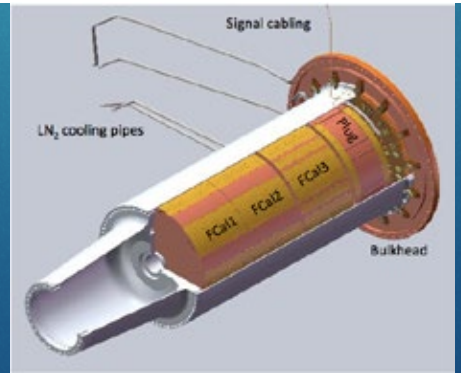
- Full replacement of front-end and back-end electronics due to higher radiation levels
- New read-out architecture:
  - Full digitization and transmission of data at 40MHz . Digital information to level L1/L0
  - compliance with Phase-2 L0/L1 trigger rates and latencies.





Replace Forward calorimeter (FCal)

new sFCAL in cryostat or miniFCAL in front of cryostat if required by Physics or if the FCAL will degradate excessively

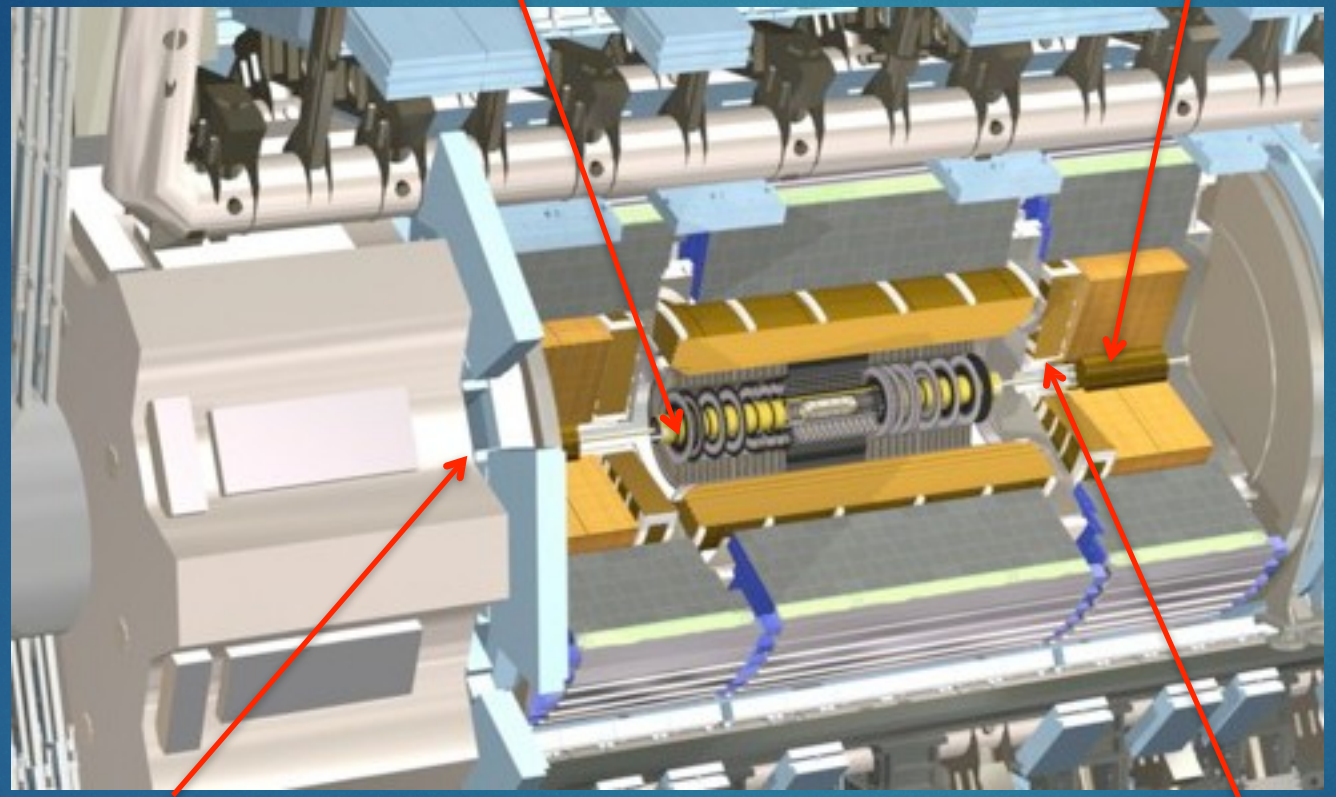


Based on Liquid Argon technique
But with smaller (≈100 μm) Lar gaps

Moving toward larger h

Extend ITK tracker to η = 4.0: different pixel layouts/performance (extended IBL, disks, rings, pixel granularity,...)

sFCal with improved segmentation and reduced pulse length in 3.1<η<4.9



Trigger w/ fwd tracking:
- L0/L1 capabilities
- vertex information

Muon spectrometer options for 2.7<η<4.0:
- 1 pixelated tag chamber before EC toroid

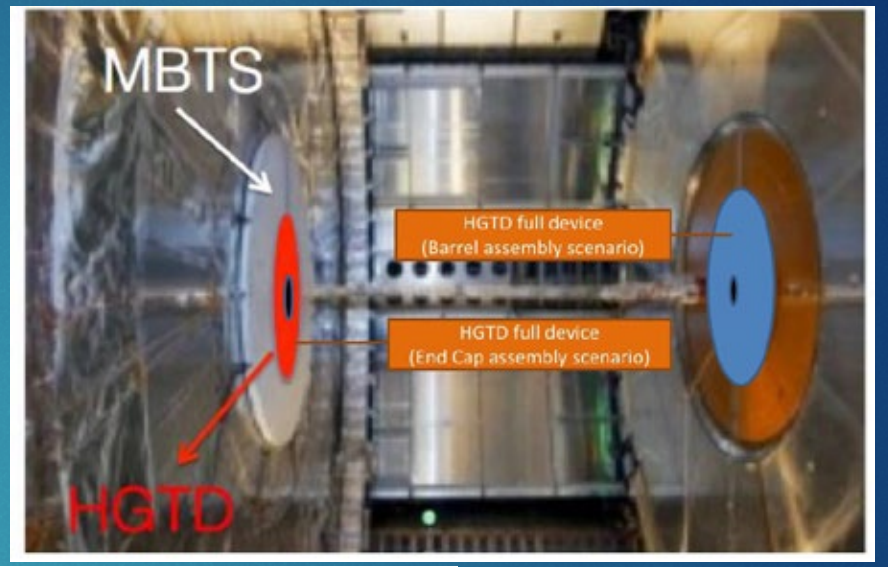
Segmented timing detectors in front of EMEC/FCAL in 2.5<η<4 (MBTS location): (~100mm;~10ps)

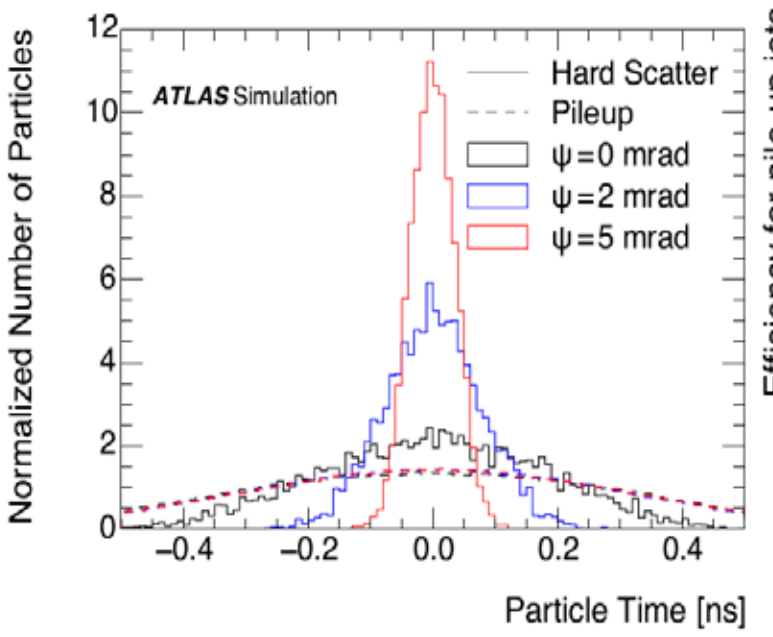
Example: Highly Granular Timing Detectors

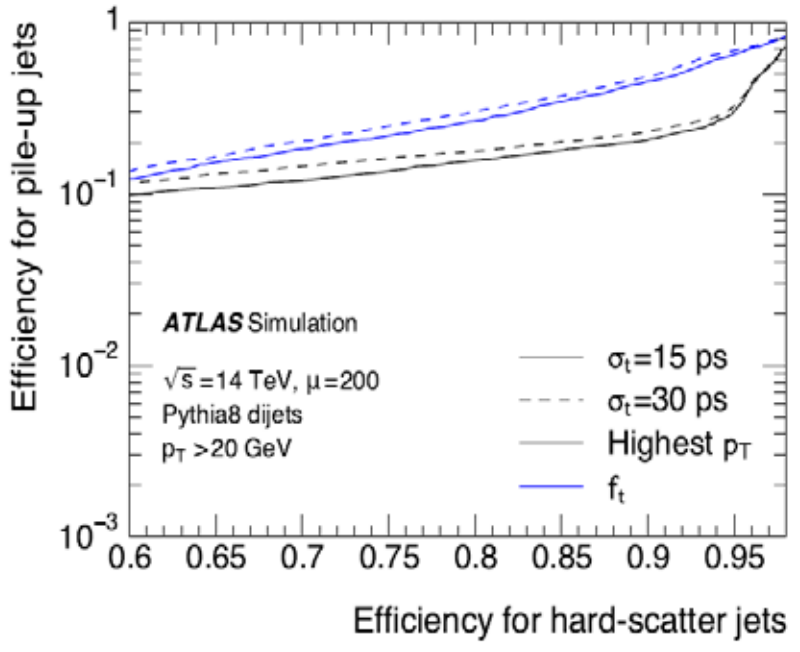
HGTD is being considered for insertion between barrel and Endcap

- Envelope in z, 6 cm
- $2.4 < |\eta| < 4.1$
- $O(300\,\text{k})$ readout cells ~ $5 \times 5\,\text{mm}^2$
- aim is PileUp suppression by separating Hard Scatter jets (narrow time distribution) from Pile-Up jets (broad time distribution)
- might even serve as new L0Time trigger

Important R&D needed to achieve a performance of ≤ 30 ps which is an appropriate goal







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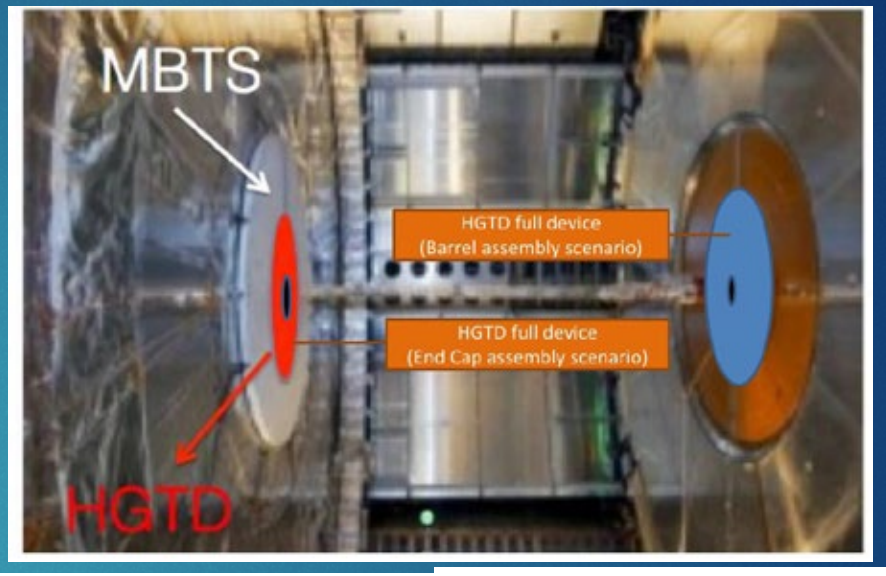
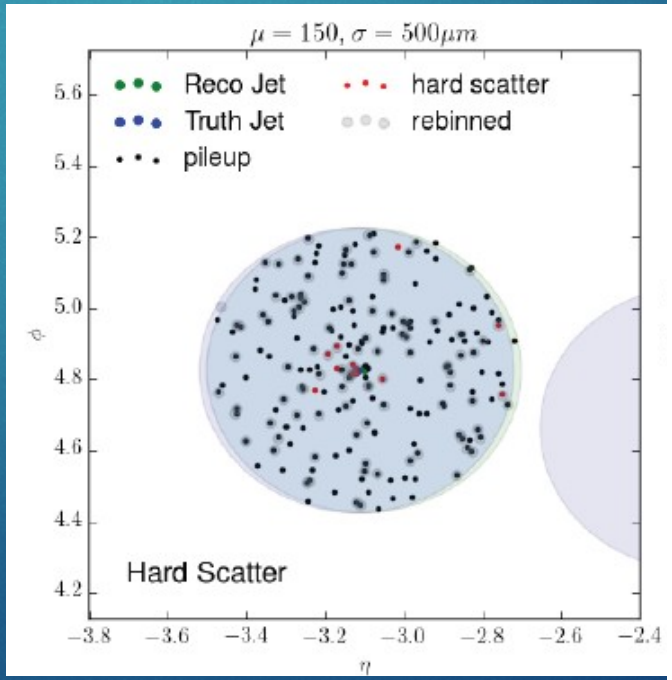
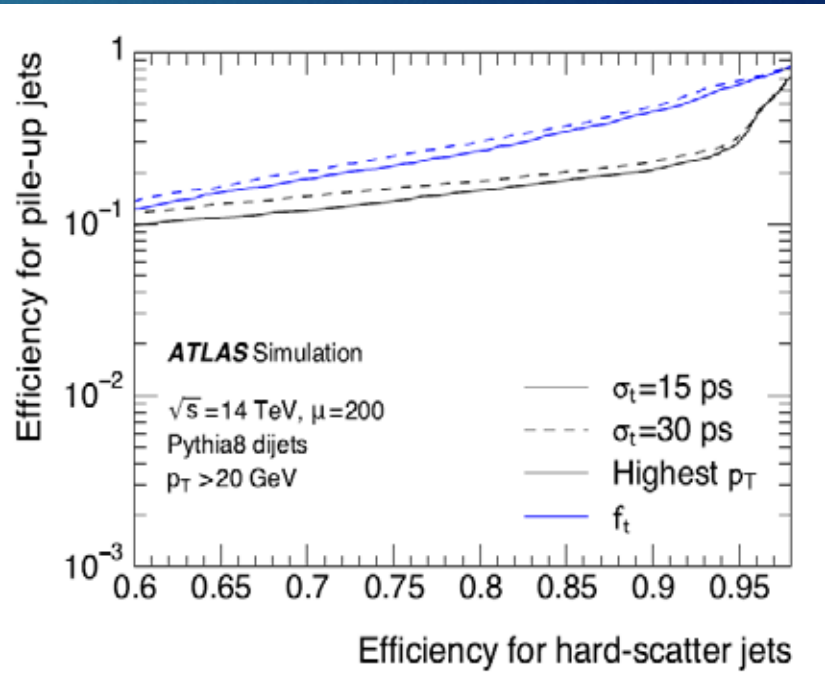




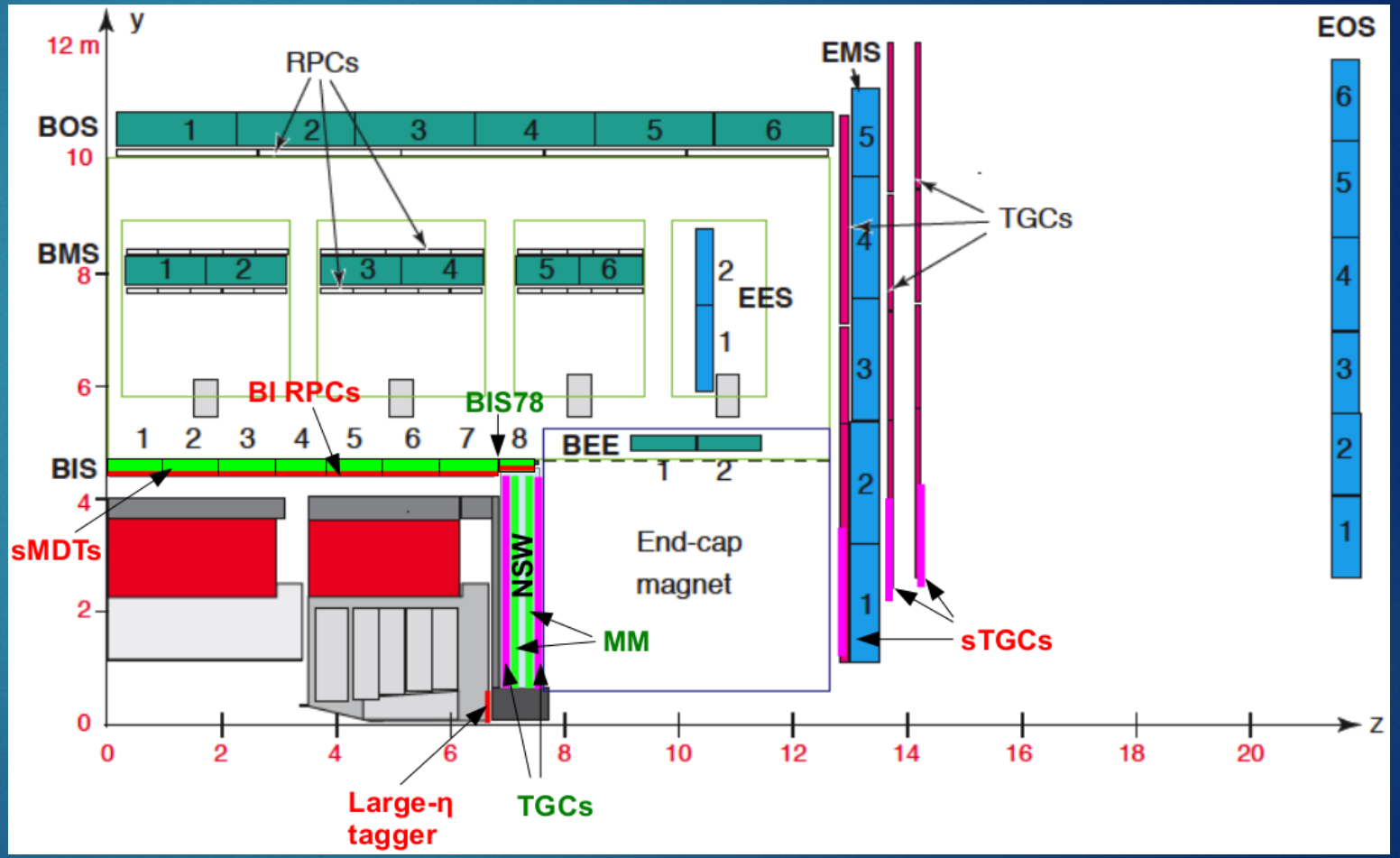


Muon upgrades for Phase 2

A crucial step is taken in Phase 1 to strengthen the high h region(1.05<h<2.7)

In the Phase-2 scoping document the residual problem are addressed

- Barrel region: a new inner barrel RPC triplet layer (BI)
  - Sustain the original RPC performance by Increasing the redundancy
  - Recuperate ~20% of geometrical acceptance
- Replace the TGCs at high h
- New on chamber and off chamber electronics for both RPCs and MDTs
- Large h tagger proposal



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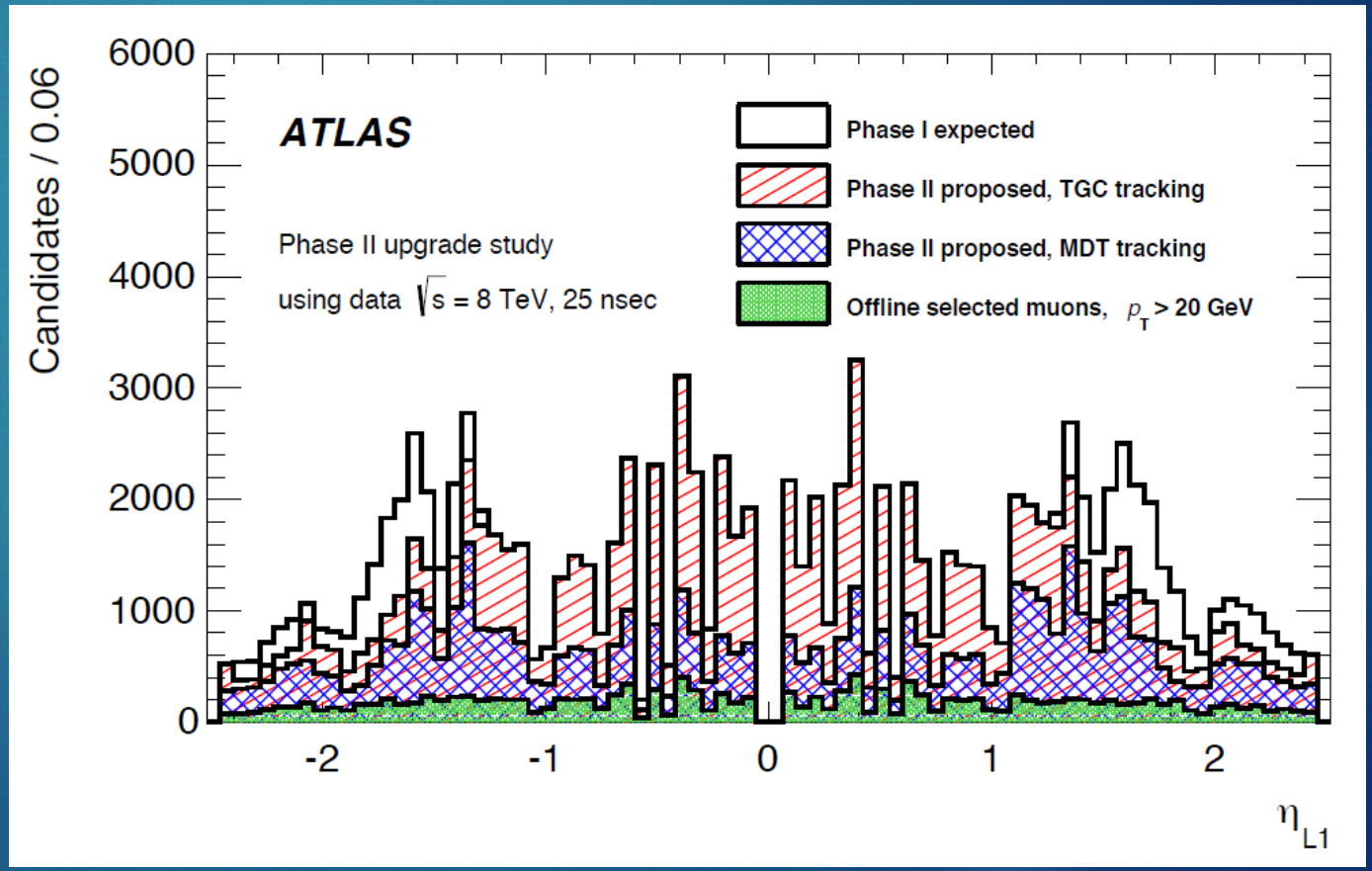
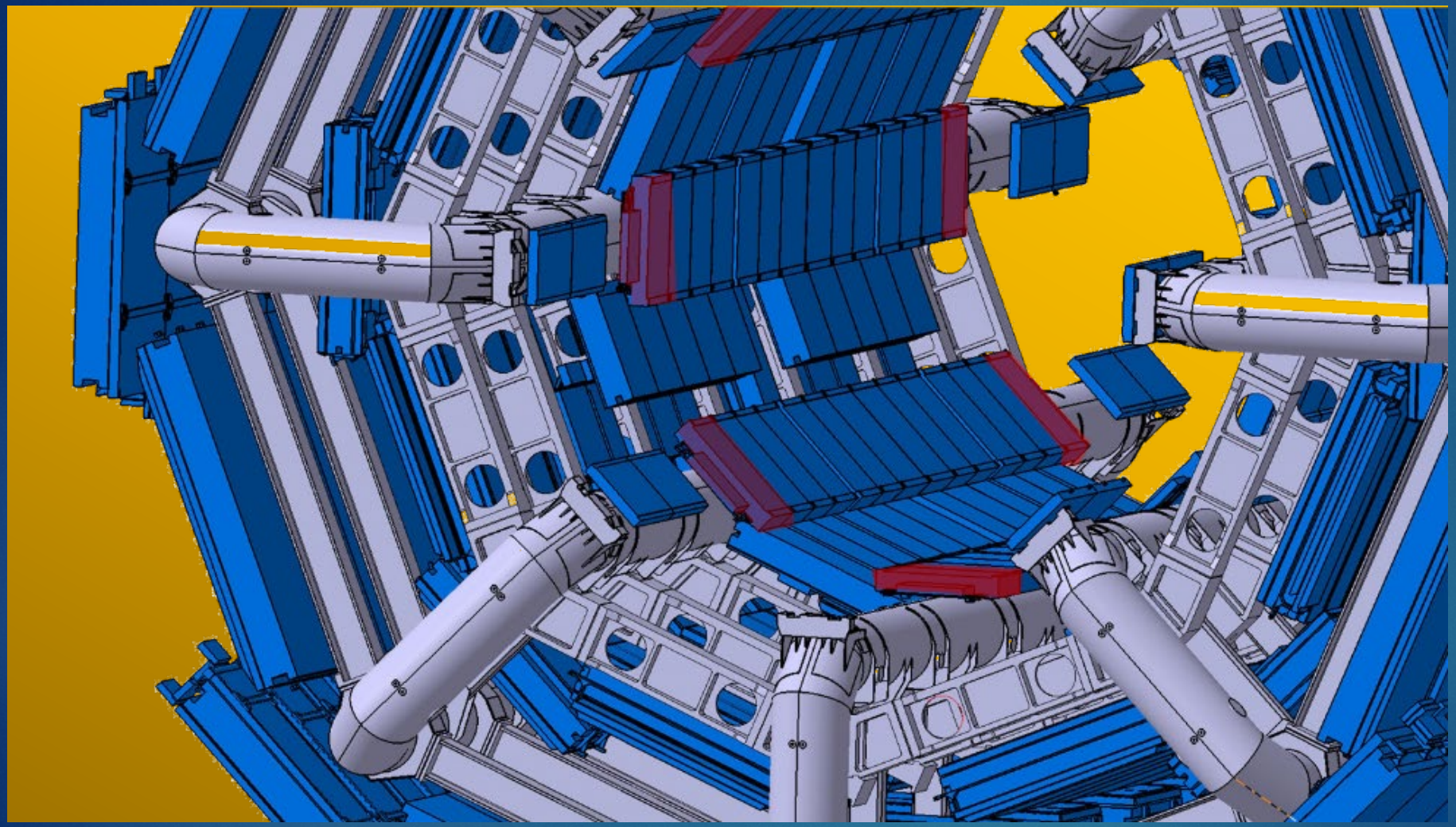


BI New RPC layer (BIS78 as a pilot)



- A layer of RPC triplets in the Inner Barrel can operate in stand alone
- Extends the lever arm x 2 à higher momentum selectivity
- Can cover the barrel acceptance holes

Present limitation of ATLAS RPCs:

- Out of specs for HL-LHC
- Lower performance for the detector elements
- Need additional layers to increase redundancy

A new RPCs generation

- work at 15 kHz/cm^2
- Time resolution 0.4 ns, down to 0.2 ns can be done

Alternative proposal based on MMGAS had been also presented

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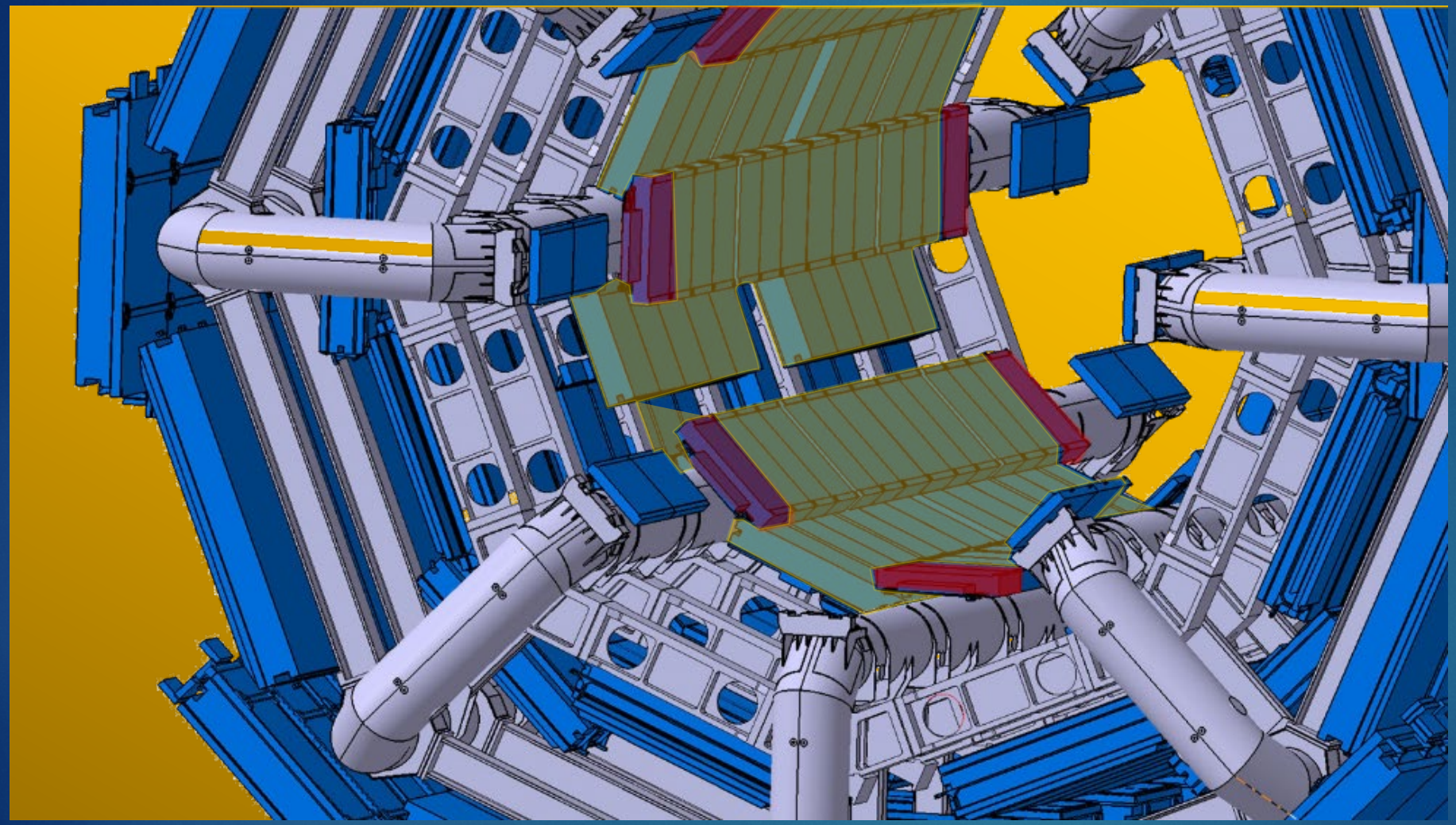

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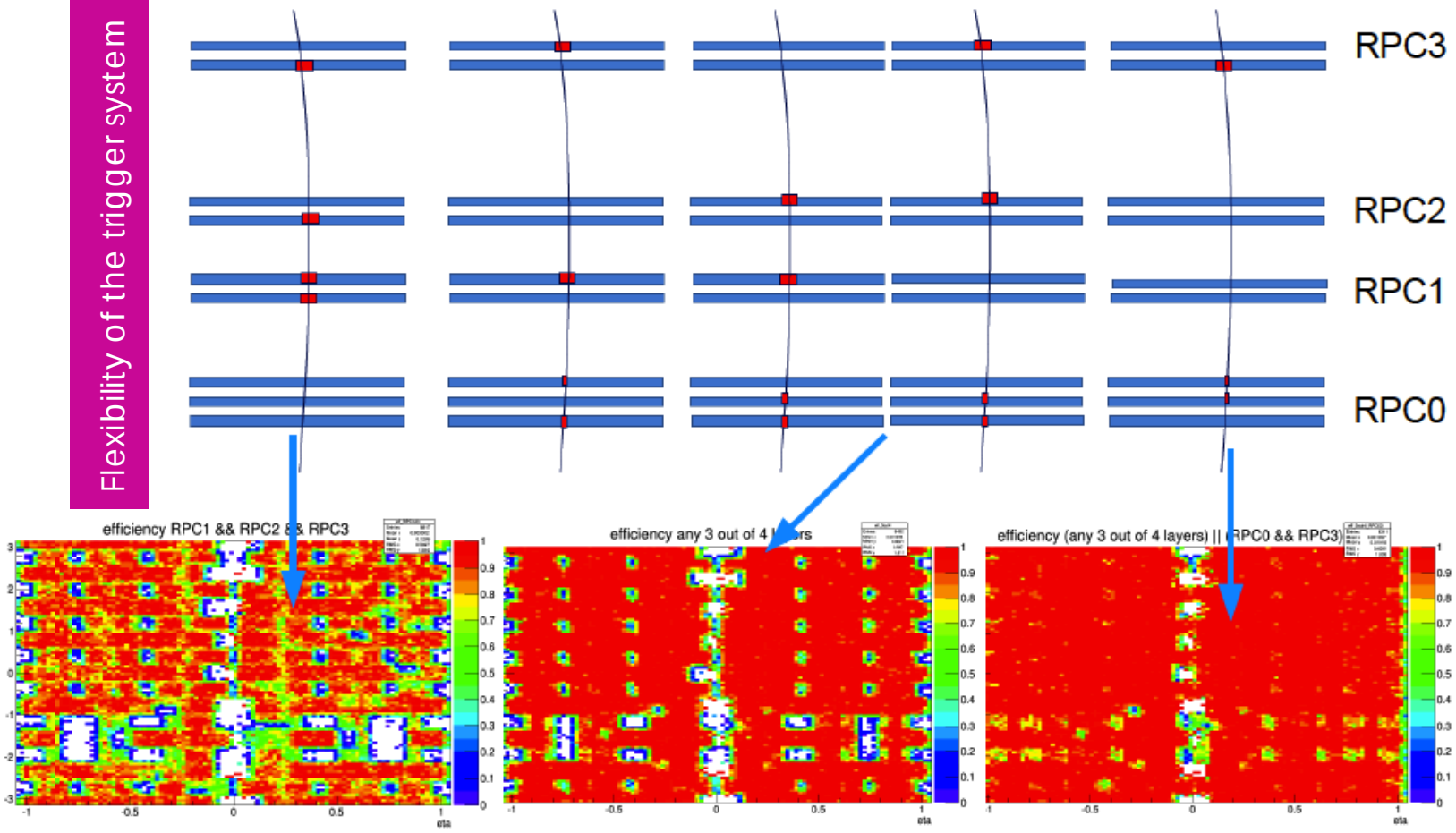
BI+ old RPC trigger acceptance

Requirement	rpc1 && rpc2 && rpc3	BI && (rpc1||rpc2) && rpc3	any 3 out of 4 layers	(any 3 out of 4) || (inner&&outer)
Acceptance wrt muid	73%	82%	88%	96%

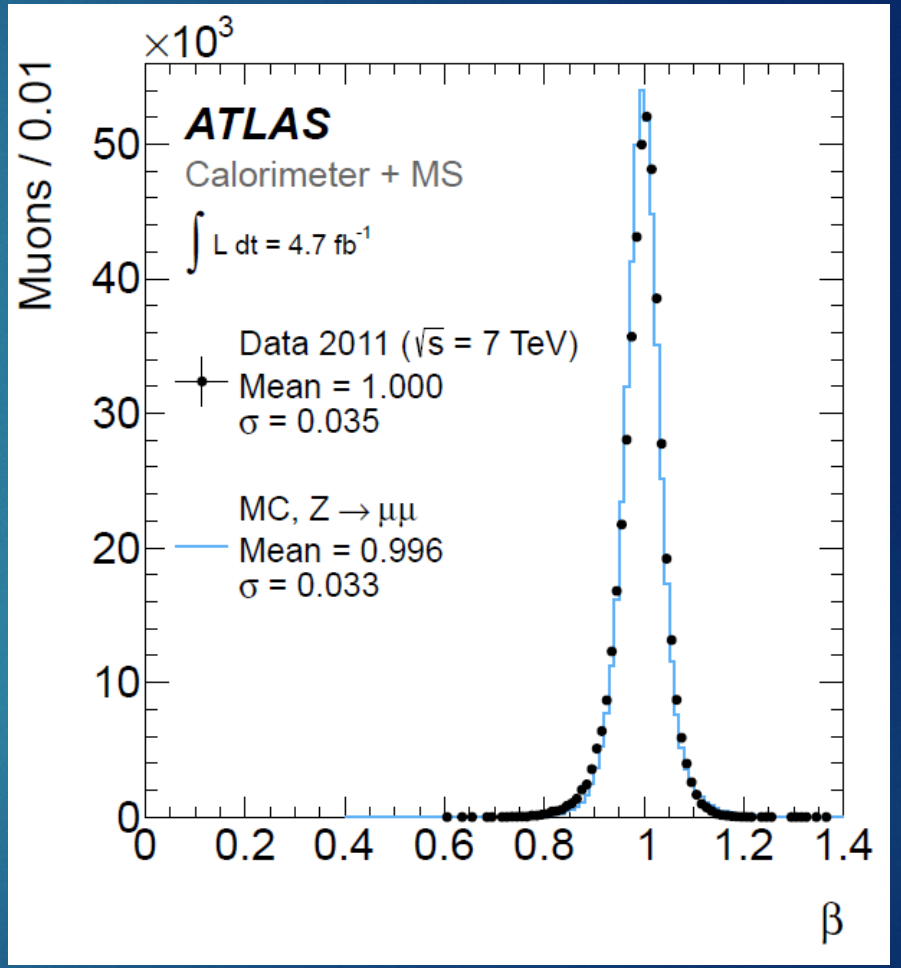
Flexibility of the trigger system



Extending the discovery potential

CERN-PH-EP-2012-236 arXiv:1211.1597v2 [hep-ex] 25 Mar 2013

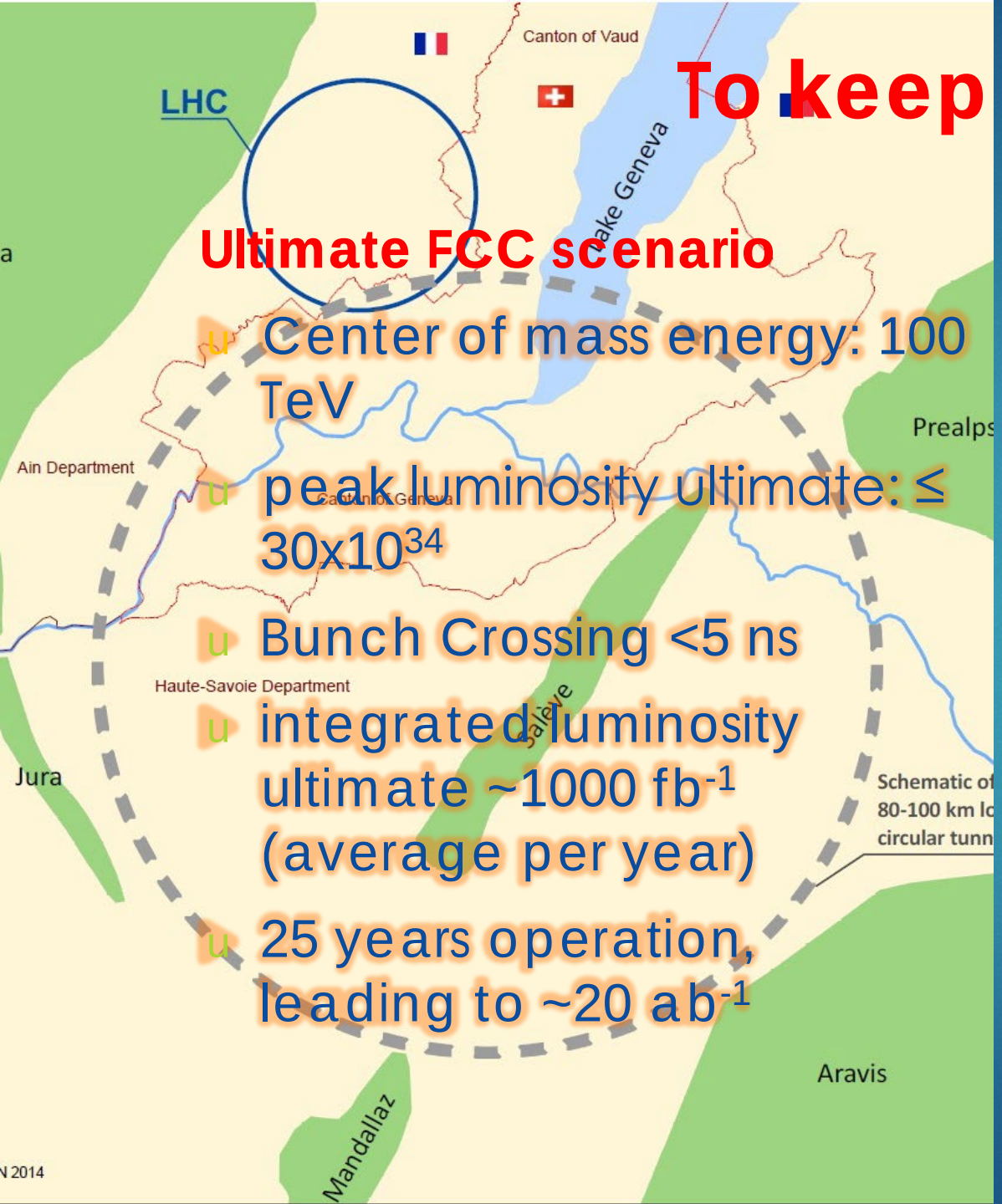
- **Search for heavy à slow charged particles**
  - **Triggered with a single muon or missing transverse momentum**
  - **Selected offline by measuring β**
  - Present ATLAS combined resolution in β is 3,5%
  - BI RPCs + new electronics on the present system can improve by a **factor of ~5 (limited to the barrel…)**
  - the **S/N** can be enriched by introducing a **trigger on β**
- **Search for displaced vertexes**
  - The main problem is the pileup and the eventuality that the decay falls in the next BC.
  - Under heavy pileup the crucial feature is to label in time the segments to select the hits compatible with a slow track to associate it to the correct BC
  - **The presented system would the ideal tool to boost this type of searches (time resolution + pileup immunity)**



Conclusions

- **Atlas upgrade program** is well defined and tailored to the LHC physics needs in the **next decades**
- **Phase-0 is achieved**, **Phase-1** projects and almost all in the FDR phase, **toward** the Module-0 and **the production**.
- **Phase-2** LOI and scoping documents have been approved. Several project are ongoing covering **all the detector aspects**
- **New** concept of **Trigger DAQ** is also envisaged for Phase-2
- Recent **electronics advances** are making the **high time granularity** a real possibility, which will be more and more crucial with the **increasing pileup**
- The **developers community** is aware that the **next** generation experiments will **inherit** much from **HL-LHC detectors**

Backup slides



To keep in mind for the future

Ultimate FCC scenario

- Center of mass energy: 100 TeV
- peak luminosity ultimate: ≤ 30×10^{34}
- Bunch Crossing <5 ns
- integrated luminosity ultimate ~1000 fb^{-1} (average per year)
- 25 years operation, leading to ~20 ab^{-1}

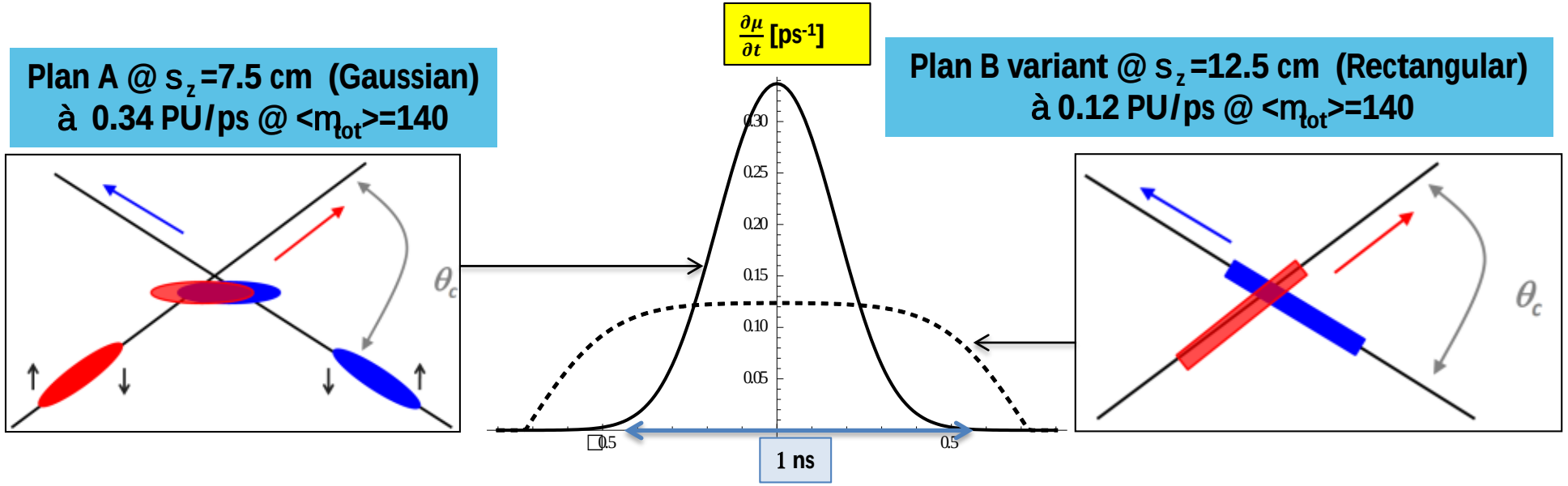
Consequence on detectors

- Boosted objects à up to h=6 coverage
- High pileup and fast BC à very fast and granular detectors
- Momentum resolution ≈15% at pT=10TeV
- ~1ns sharp BCID
- Particle flow capability for calorimeters with high granularity 25 mrad^2
- Fine timing against pileup à < 100 pS

Sensitivity to bunch length & bunch shape (3/3)

à Peak **time density** of vertices**: net gain**

- For longer r.m.s. bunch length
- Even more for rectangular bunches and Plan B (with non-zero Piwinsky angle)



In the best case, still 1.2 pile-up every 10 ps

(and loosing ~10% of integrated performance via the geometric loss factor)

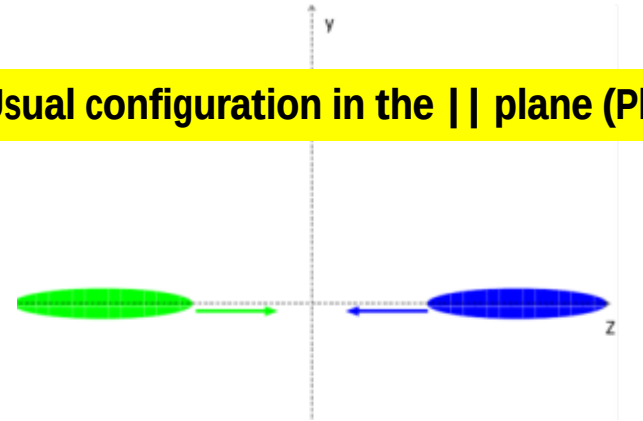
Is it really usable??

The ``crab-kissing'' (CK) scheme (1/5)

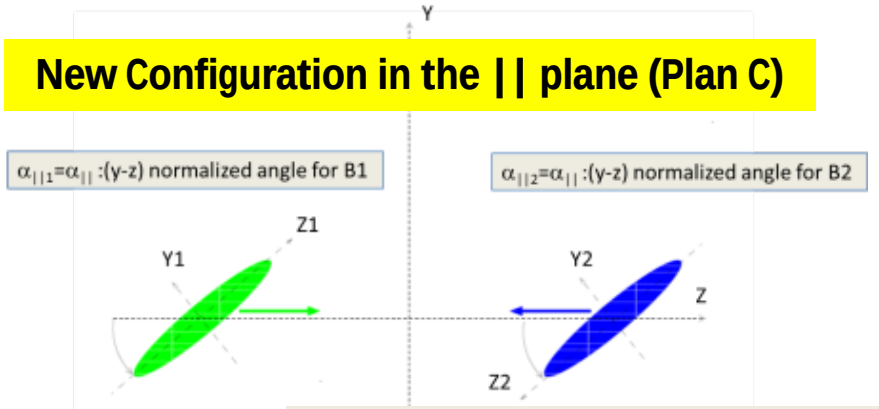
à Transposing to the **line density** the nice behavior which is observed for the **time density vs. bunch length and bunch shape …**

- **Crab-cavities in the || plane (in anti-phase for beam1/2, and flat optics for efficiency)**

Usual configuration in the || plane (Plan A/B)



New Configuration in the || plane (Plan C)



Typical "Time Piwinsky angle" of **100-150 mrad**

- **.. A tool for shrinking the collision time,** hence leveling the lumi, and much more !

a) Gaussian Bunch profile (no 800 MHz) à lumi leveling at "mitigable" z-density

b) Rectangular Bunch profile (800 MHz) à lumi leveling at strongly reduced z-density

c) Reduced BB tune shift in ALL cases (not discussed)