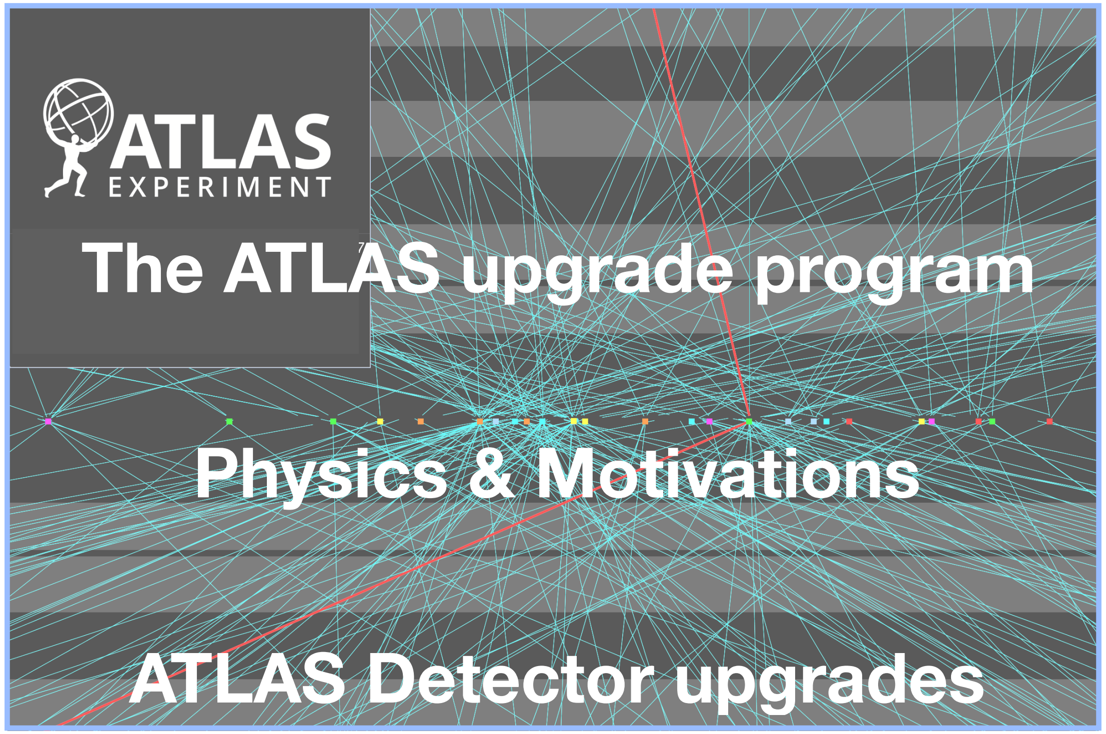
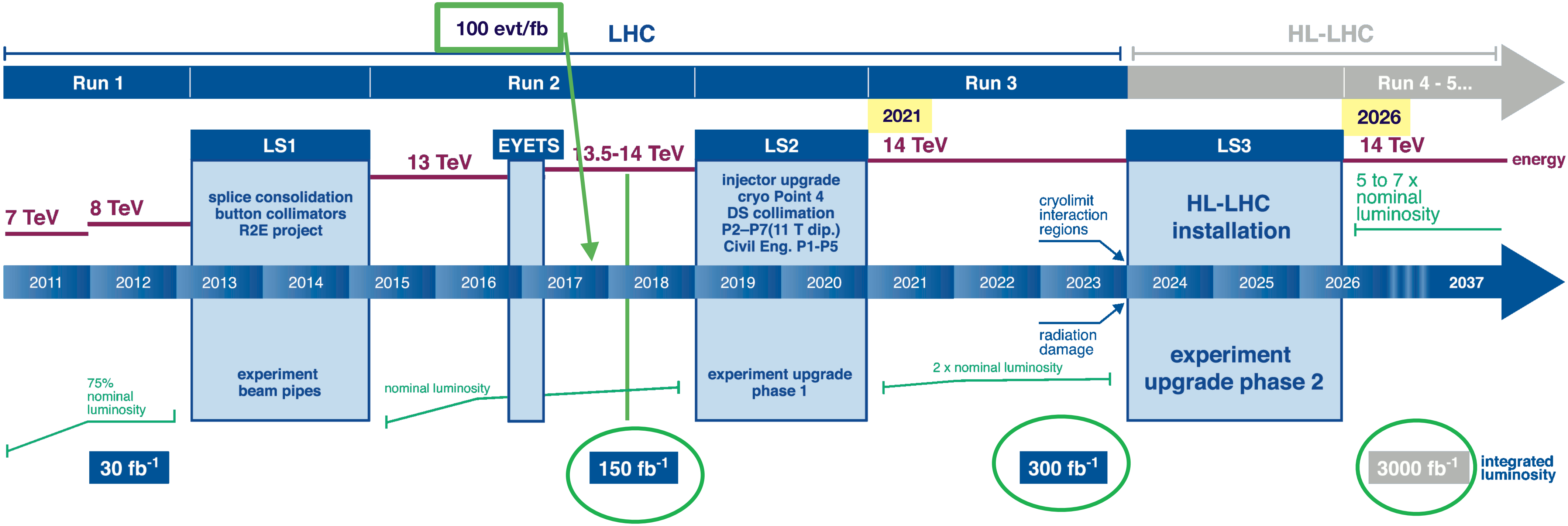


The ATLAS upgrade program

Physics & Motivations

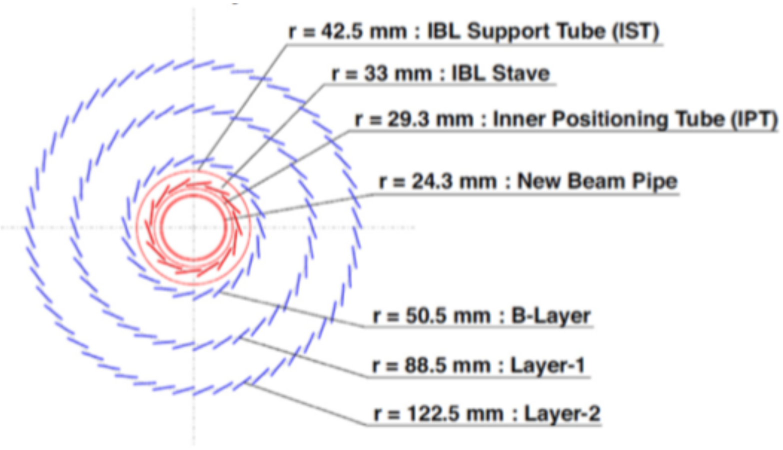
ATLAS Detector upgrades

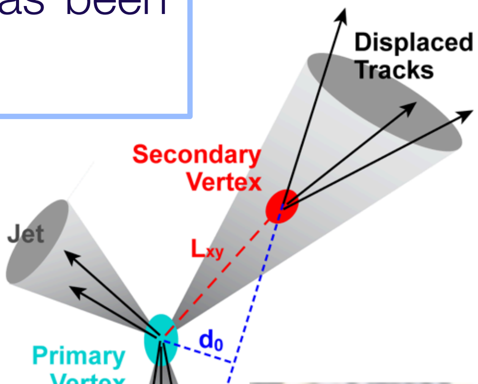


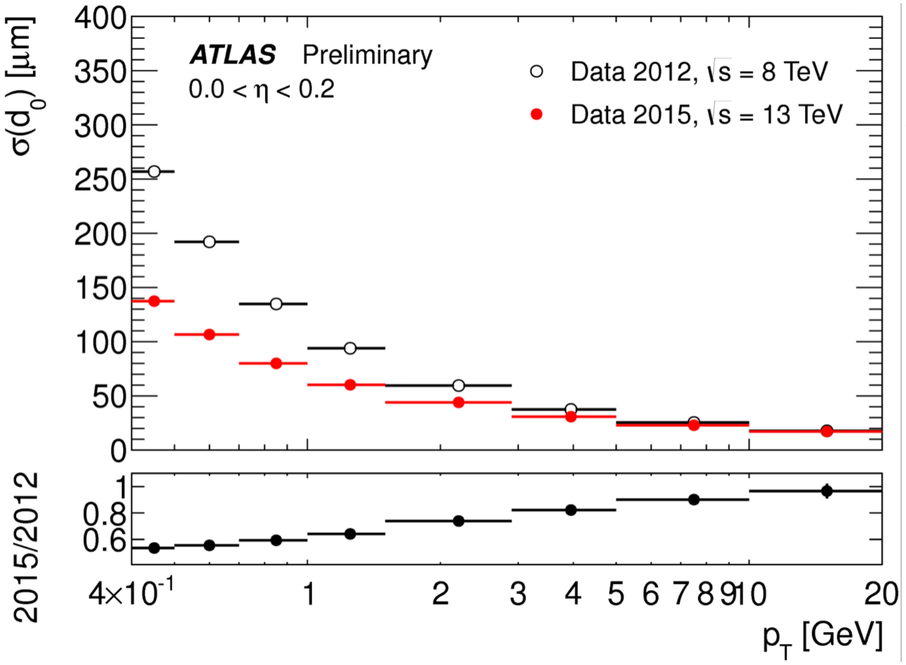
Insertable B-Layer - installed in 2014

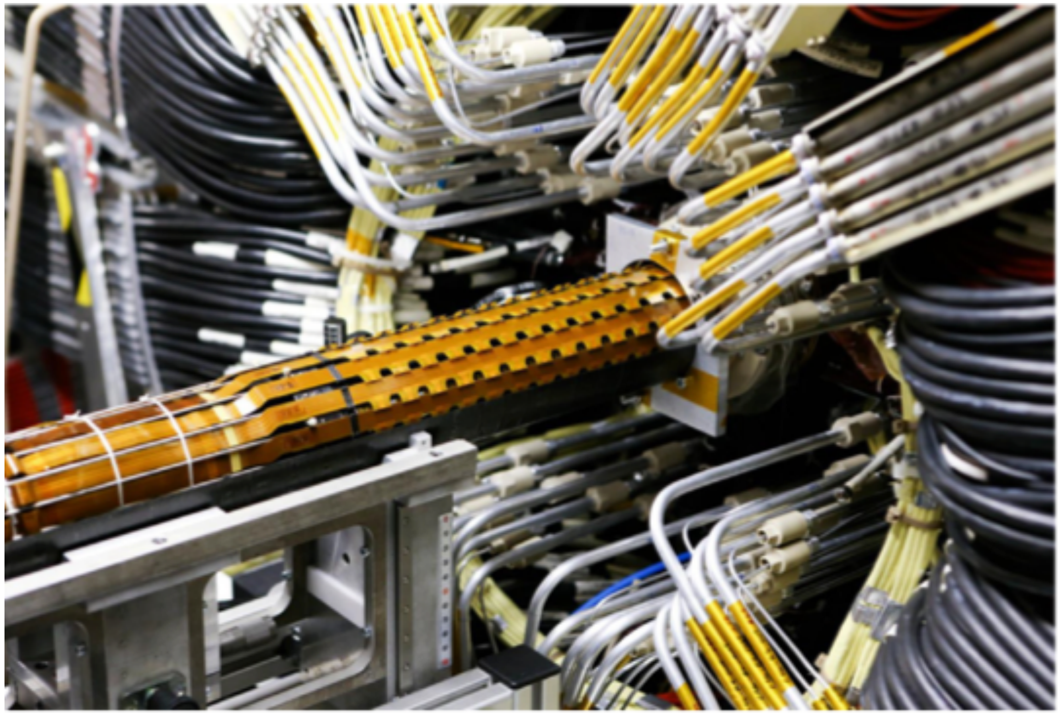
R=33 mm - 10 M channels - 50x250 μm²

After some difficulties in 2015, IBL has been performing very well





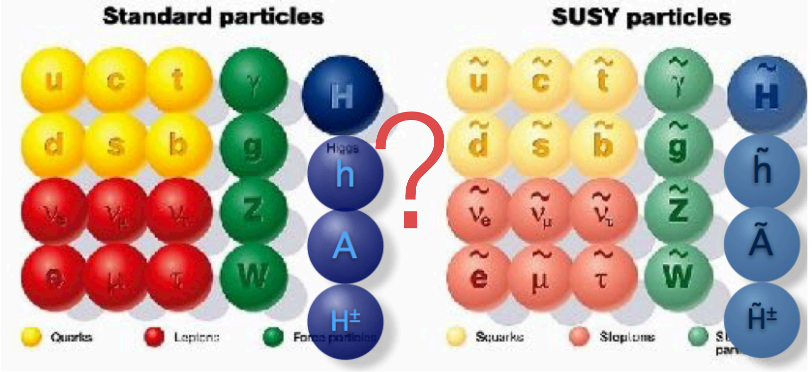




THE MISSION of the LHC

LHC Explore the TeV energy range

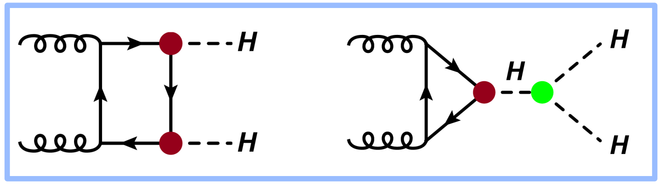
Direct searches for Physics Beyond
the Standard Model at the highest energies



Exploration of the Higgs sector

- Precision measurements of the Higgs boson properties
  - Higgs boson couplings
  - Self coupling
  - New Higgs bosons ?

σ_{HH} ~40 fb



Precision measurements

SMALL CROSS SECTION
HIGH LUMINOSITY

MOTIVATION for HL-LHC upgrade

HL-LHC offers large luminosity needed to cover wide range of physics measurements and searches at the cost of significant challenges to detector systems from increased rates and occupancies.

Keep detector performance for physics at least as good as in run 1 and run 2

Keep acceptable trigger rate with low-p_T thresholds and suppress pile-up up to high $|\eta|$

Machine upgrade

Physics

Radiation

Necessity to upgrade

Computing

Ageing

Technologies

Exiting front-end electronics not qualified for operation at HL-LHC integrated luminosity of 3000 events/fb and needs to be replaced due to radiation exposure.

1 MeV neutron equivalent fluences $1.5\ 10^{16}\ cm^{2}$
Absorbed radiation dose: 11.4 MGy

Benefit from **high performance components** such as larger and faster FPGAs, higher bandwidth transmission links, backplane, network and storage technologies, advance computing.

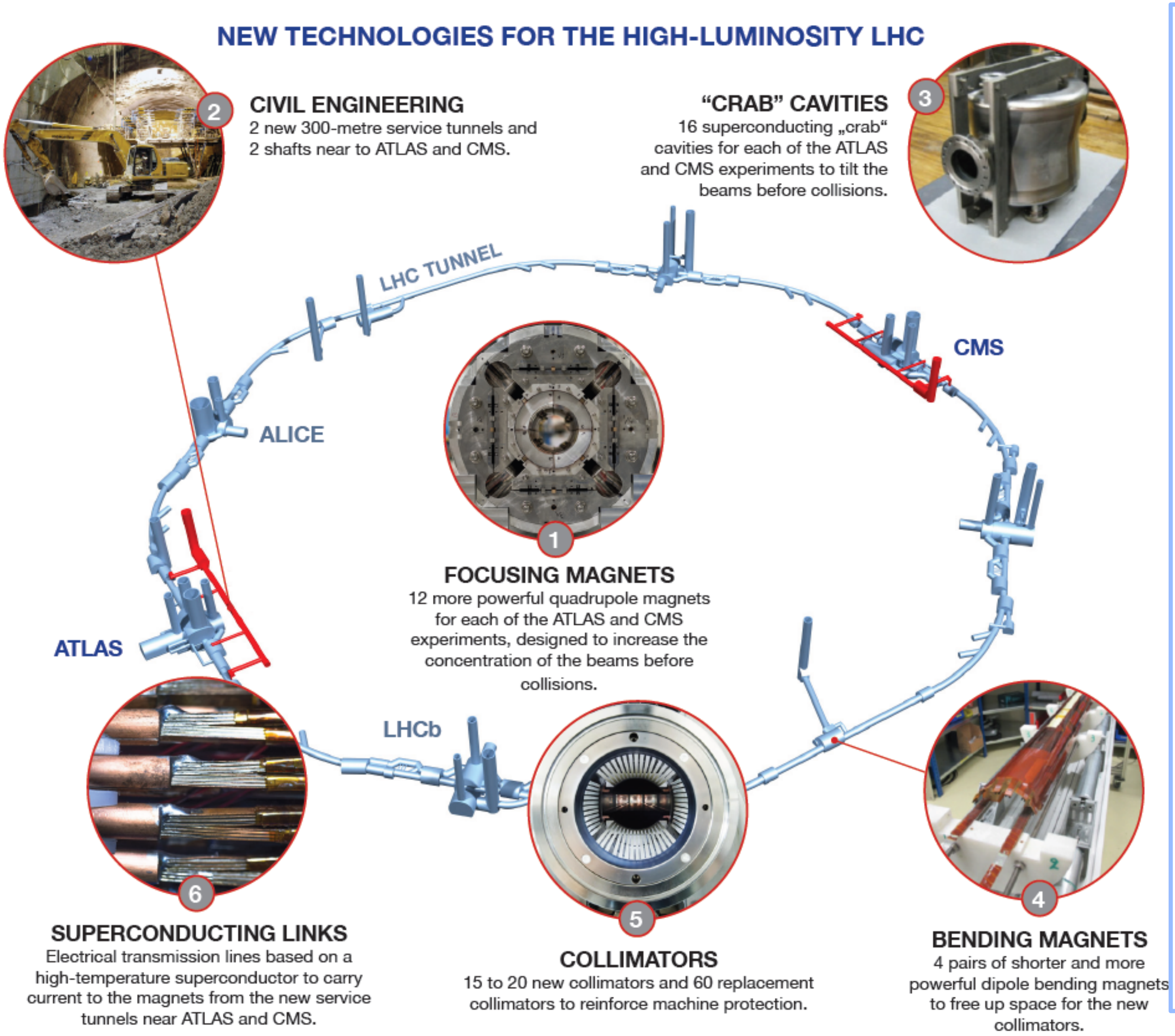
System will be in **operation for more than 20 years** in harsh radiation environnement. Mitigation strategies needed for inaccessible/irreplaceable detector components, e.g. adding new sensitive layers to maintain required performance

Higher trigger rates with longer latencies require revision of readout electronics architecture

Evolving towards free-running scheme where all data are streamed off detector.

This allows for further upgrade for trigger with new off-detector electronics.

The High Luminosity LHC



NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC

CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

Innovative technologies

Superconducting magnets materials

niobium-titanium (NbTi) up to 9-10 Tesla → niobium-tin (Nb$_3$Sn) reaching 12-13 Tesla → double magnet aperture of dipoles and quadrupoles

Crab cavities

rotation of the beam by providing a transverse deflection of the bunches → to increase luminosity at collision points and to reduce beam-beam parasitic effects

New magnesium-diboride-based (MbB$_2$) **superconding cables**

from 20 to 100 kA → move power converters from the LHC tunnel to new service gallery

>1.2 km (~5%) of current ring to be replaced with new components

From LHC to HL-LHC

$$L = \frac{1}{4\pi}\underbrace{(f_{rev} n_b N_b)}_{\text{maximize total beam current}} \underbrace{\frac{N_b}{\varepsilon_N}}_{\text{maximize brightness (injectors \& beam-beam limit)}} \frac{\gamma}{\beta^*} R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

compensate reduction factor R

crossing angle

hourglass effect

maximize energy & minimize β*

Upgrade of several components of the LHC and injector

New super-conducting triplet: **lower β***

Injector upgrade

Increased **beam charge**

Luminosity levelling

High availability

Aim at 3000 events/fb (4000 events/fb)

Parameter	Nominal LHC [Design Report]	Nominal HL-LHC 25ns [standard]	[BCMS]	[8b4e]
Beam energy in collision [TeV]	7	7	7	7
Number of protons per bunch [$\times 10^{11}$]	1.15	2.2	2.2	2.3
n_b	2808	2748	2604	1968
Number of collisions in IP1 and IP5	2808	2736	2592	1960
Beam current [A]	0.58	1.09	1.03	0.82
crossing angle [μrad]	285	590	590	554
beam separation [σ]	9.4	12.5	12.5	12.5
$\beta *$ [m]	0.55	0.15	0.15	0.15
ϵ_n [μm]	3.75	2.50	2.50	2.2
ϵ_L [eVs]	2.5	2.5	2.5	2.5
Levelled luminosity [$\times 10^{34}\text{cm}^{-2}\text{s}^{-1}$]	-	5.32	5.02	5.03
Events / crossing	27	140	140	140
Levelling time [hours]	-	8.3	7.6	9.5

Configuration	$\mathcal{L}_{\text{inst}}$ [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	$\langle\mu\rangle$	$\int \mathcal{L}$ per year [fb^{-1}]
Baseline	5	140	250
Ultimate	7.5	200	>300

Increased pile-up

from **20** (LHC nominal) via **60** (LHC today)

to **140** (HL-LHC baseline) or even **200** (HL-LHC ultimate) with L=7.10^{34}Hz/cm^2

Triggering on low-p_T objects for precision physics

Low occupancy detectors, highly segmented

The PILE-UP CHALLENGE

ATLAS was designed to handle a level of pile-up with <μ>=20.

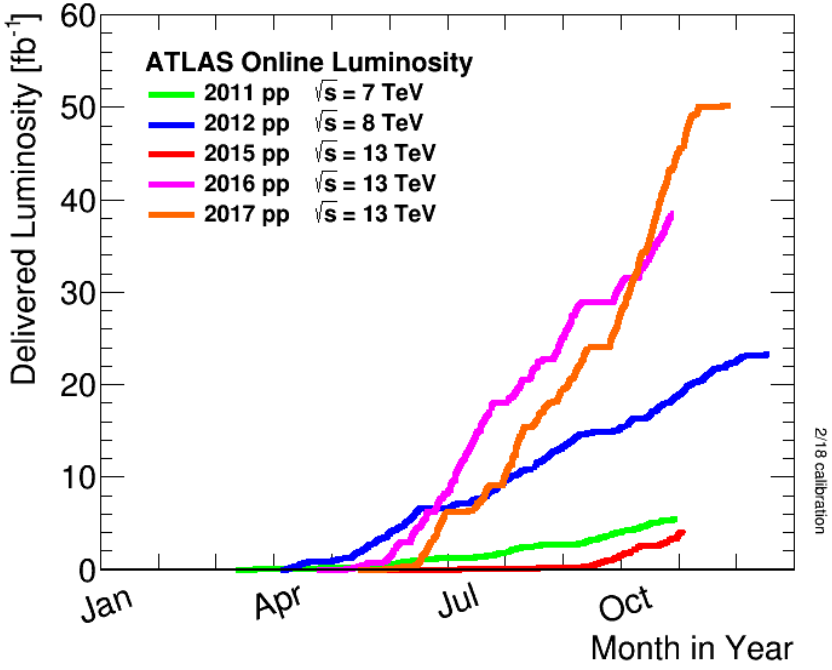
In 2017, the level of pile-up largely exceeded the design value

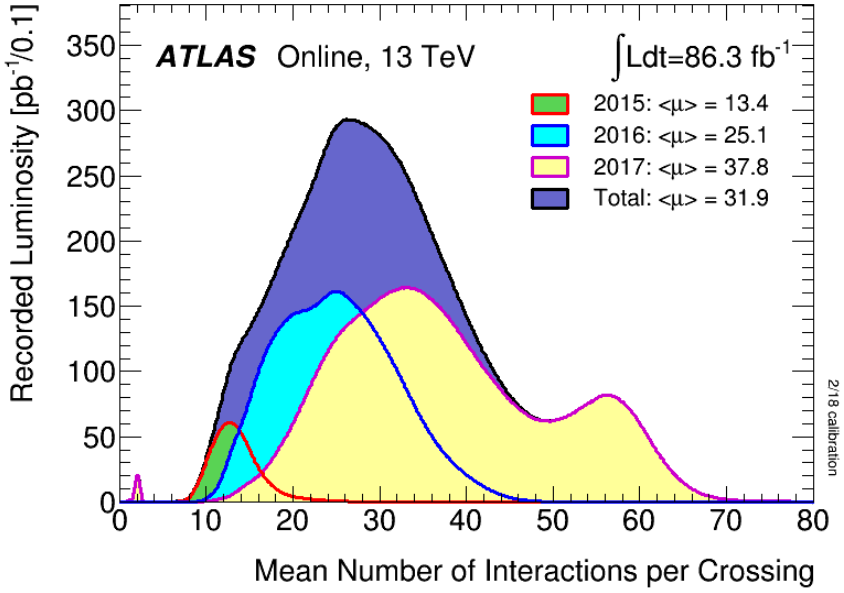
<μ>=37.8 events/BC

μ_{max}~70 events/BC

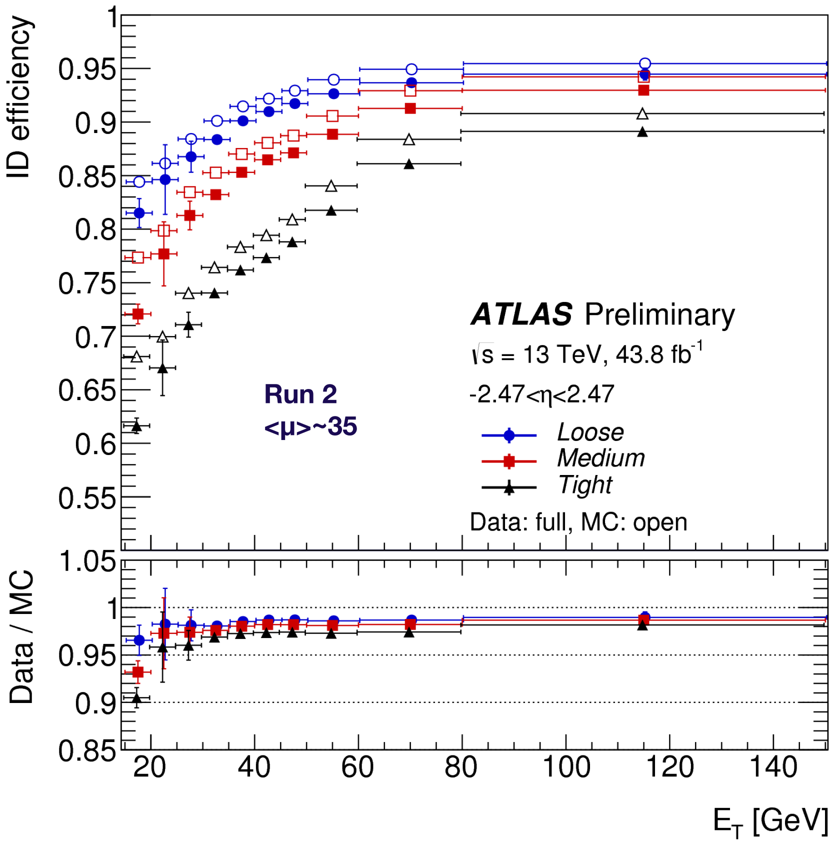
ATLAS has developed an efficient strategy to mitigate the impact of pile-up in event reconstruction and physics analysis.

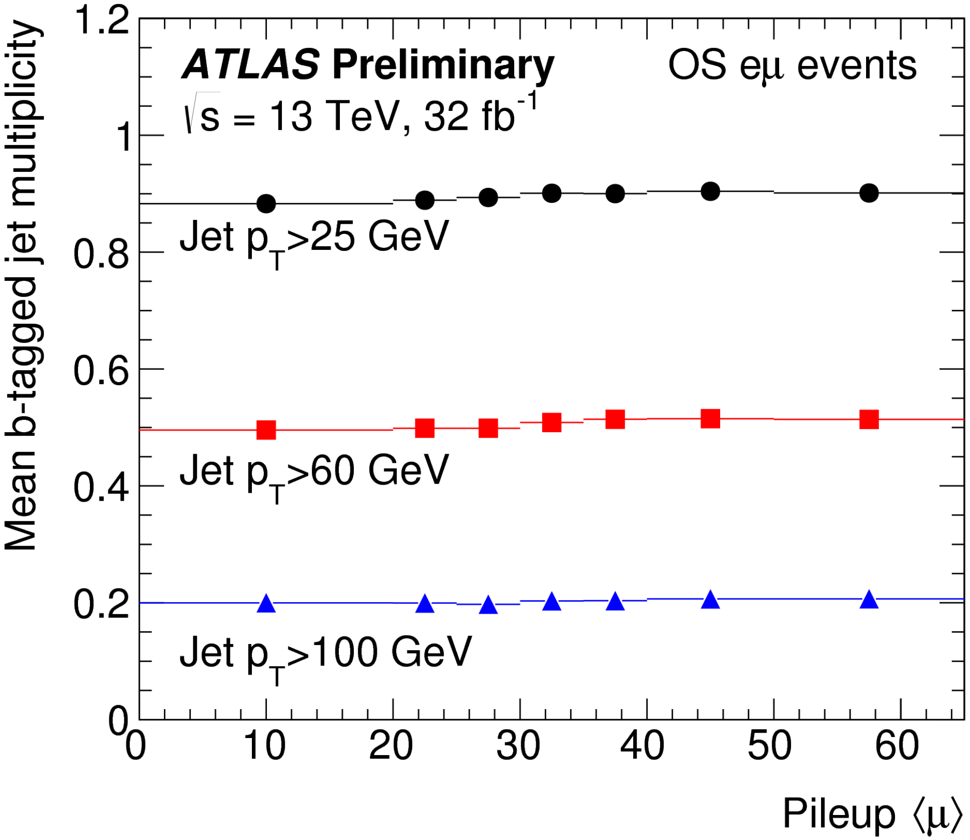
Essential expertise towards detector design for HL-LHC.





The PILE-UP CHALLENGE: PERFORMANCE at HIGH PILE-UP





Electron reconstruction

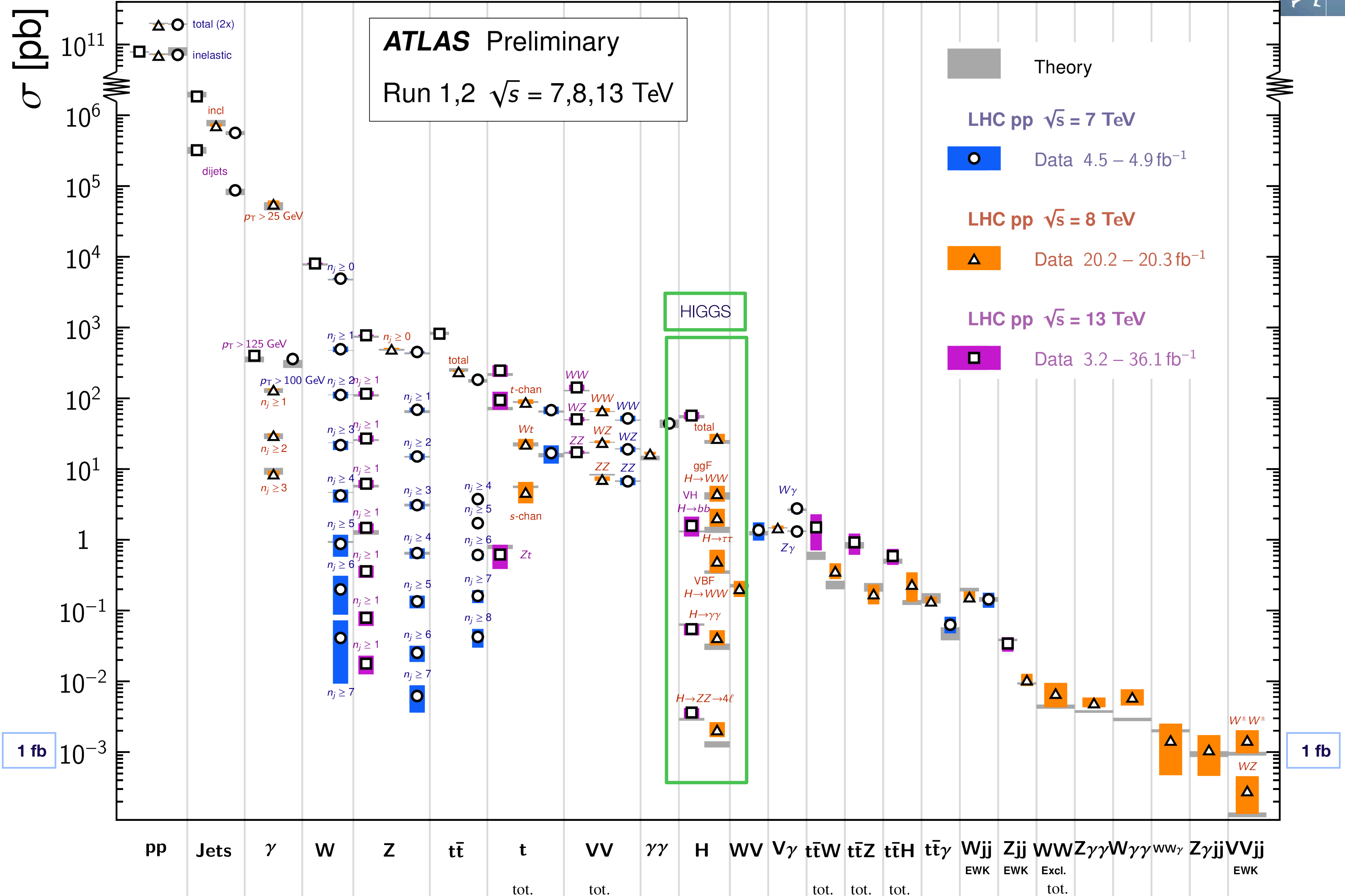
- p_T dependence tracked by Monte Carlo
- Lower efficiency in data w.r.t MC
  - known mis-modelling, differences in shower shapes

Flavour tagging

- Mean number of b-tagged jets on opposite-sign eμ events not affected by pileup

Standard Model Production Cross Section Measurements

Status: March 2018



The main proton–proton physics goals in a nutshell

Run 1 (8 TeV)

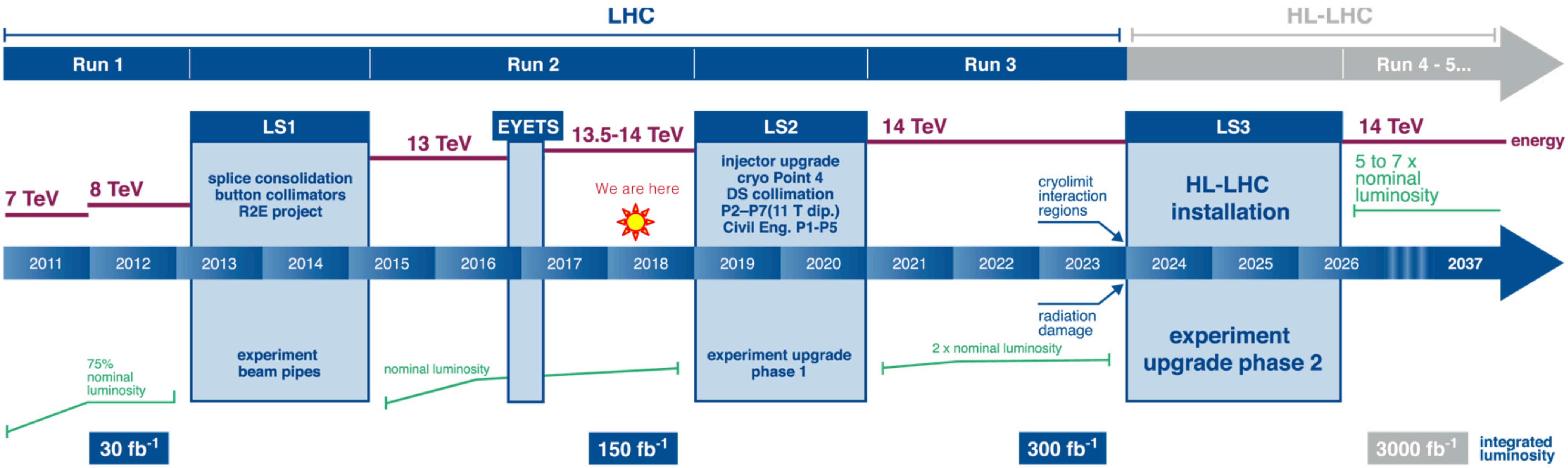
- Discovery of Higgs boson
- Searches for additional new physics (negative)
- Observation of rare processes, such as $B_s \rightarrow \mu\mu$
- Precision measurements of Standard Model processes
- Study of *CP* asymmetries in B_s sector

Run 2 & 3 (13–14 TeV)

- Searches for new physics
- Improved measurements of Higgs couplings in main channels
- Consolidation / observation of Higgs channels
- Measurement of rare Standard Model processes & more precision
- Improved measurements of rare *B* decays and *CP* asymmetries

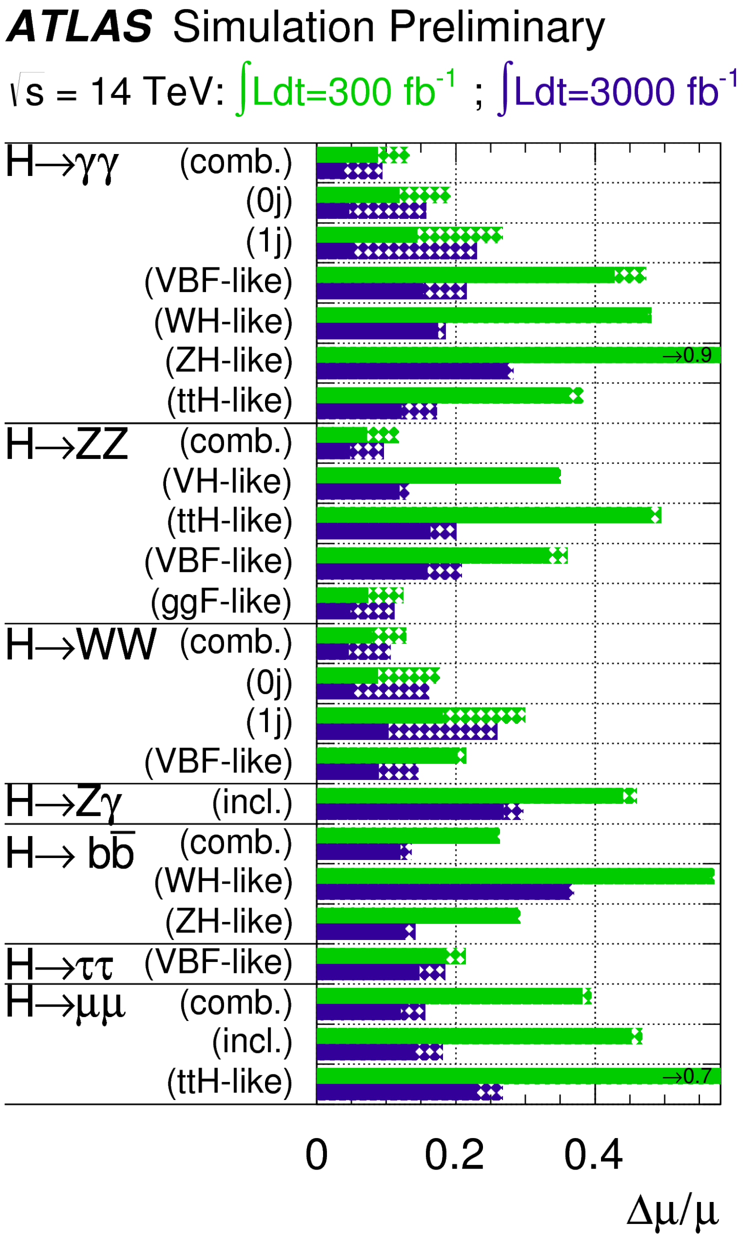
HL-LHC (14 TeV)

- Precision measurements of Higgs couplings
- Observation of very rare Higgs modes
- Ultimate new physics search reach (on mass & forbidden decays, eg, FCNC)
- Ultimate SM & HF physics precision for rare processes



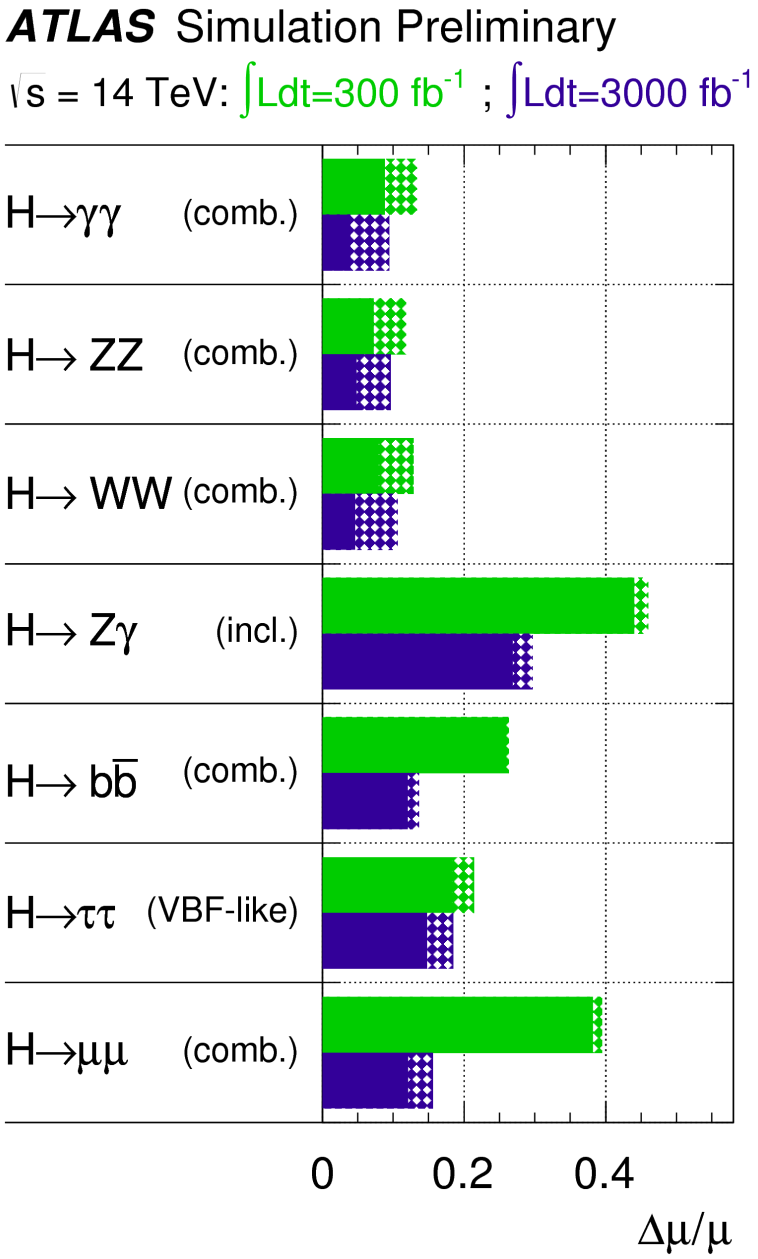
HIGGS BOSON COUPLINGS at HL-LHC

ATL-PHYS-PUB-2014-016



300, 3000 events/fb
<μPU>=140

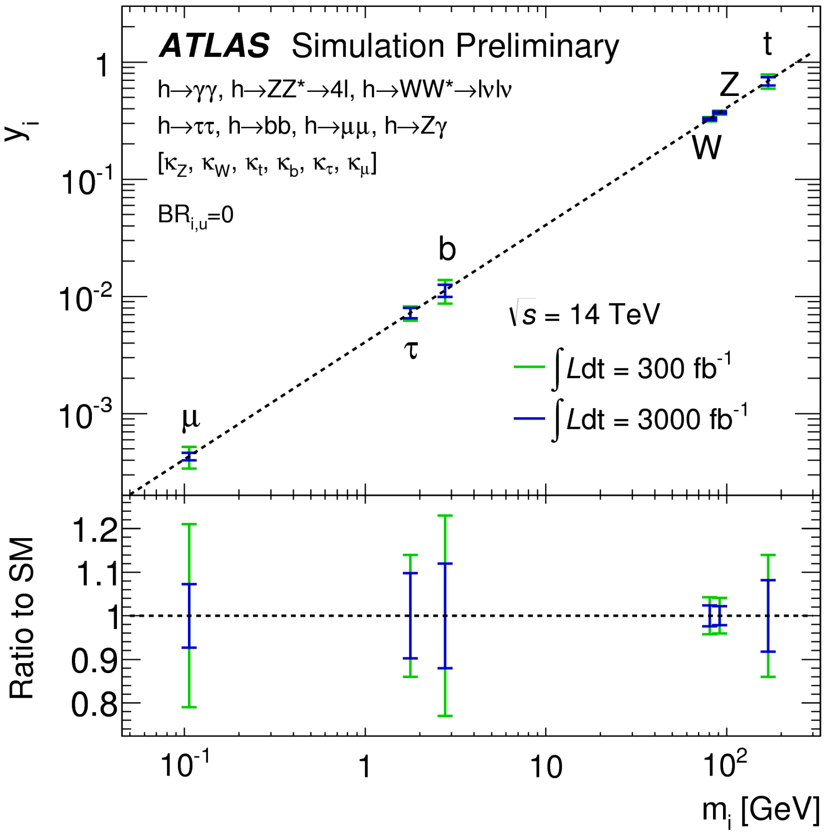
▨ Theoretical uncertainty



Signal strength $\mu=\sigma/\sigma_{SM}$

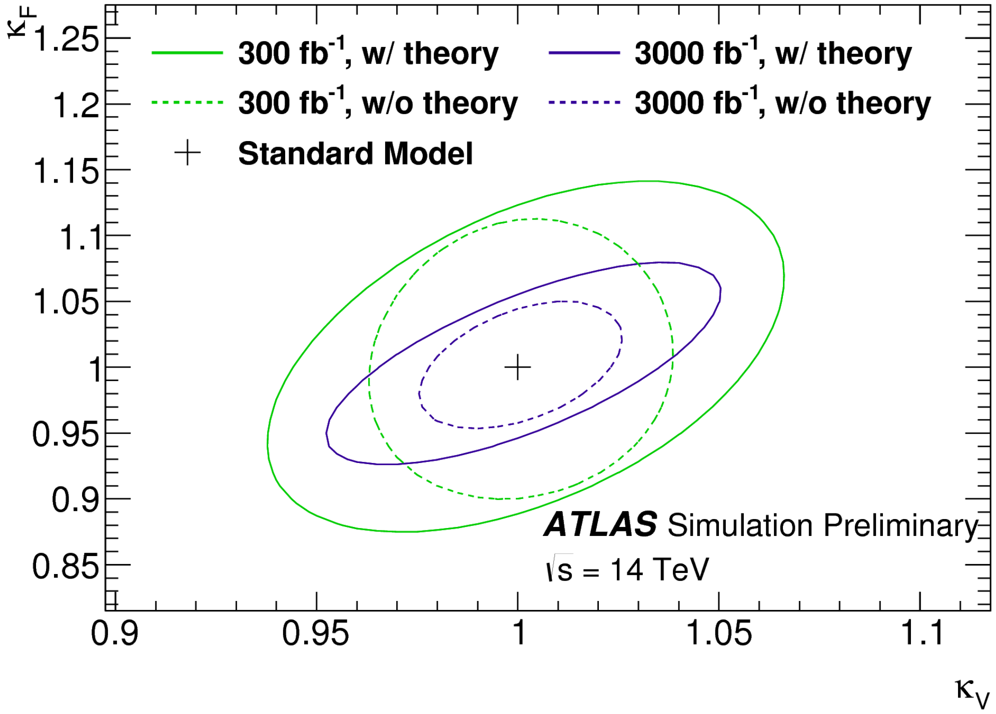
HIGGS BOSON COUPLINGS at HL-LHC

ATL-PHYS-PUB-2014-016



300, 3000 events/fb

<μ_{PU}>=140



With 3000 events/fb, precision on Higgs boson couplings to

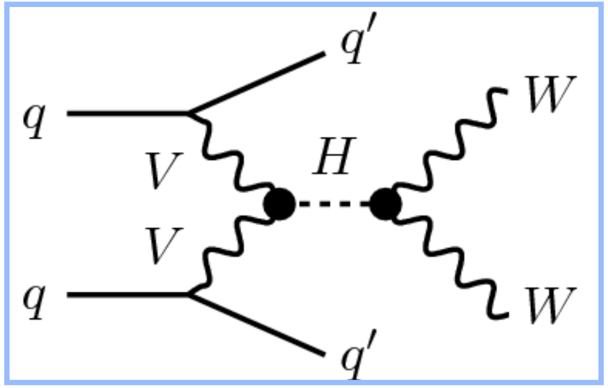
W,Z : 3%

μ : 7%

t, b,τ : 8-12%

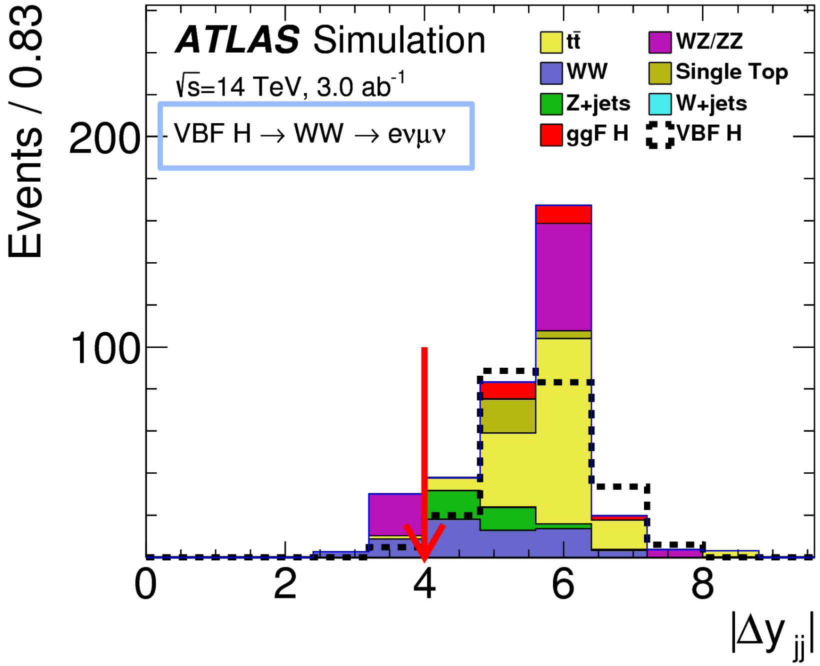
VECTOR BOSON FUSION at HL-LHC

ATL-PHYS-PUB-2016-008
ATL-PHYS-PUB-2016-018



3000 events/fb
<μ_{PU}>=140, 200

Look for forward jets with p_T>30 GeV with
Higgs boson decay products between jets



After event selections in 3000 events/fb

ZZ **190** signal events and **330** background

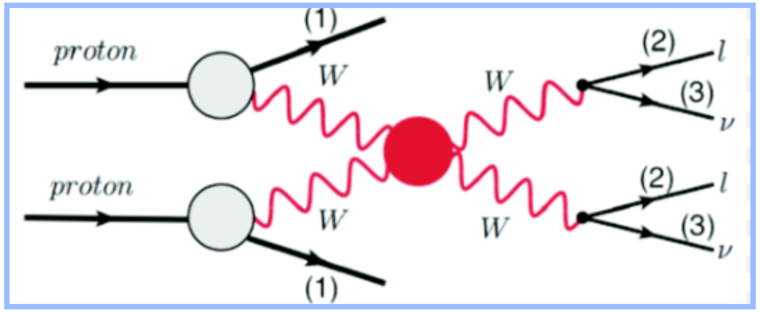
WW **200** signal events and **410** background

Results are presented with different assumptions on systematic uncertainties (full or none)

	ZZ <μ_{PU}>=200 FULL	ZZ <μ_{PU}>=200 NONE	WW <μ_{PU}>=200 FULL	WW <μ_{PU}>=200 NONE
Δμ	0.18	0.15	0.20	0.14
Significance	7.2 σ	10.2 σ	5.7 σ	8.0 σ

VECTOR BOSON SCATTERING at HL-LHC

ATL-PHYS-PUB-2013-006
LHCC-G-166

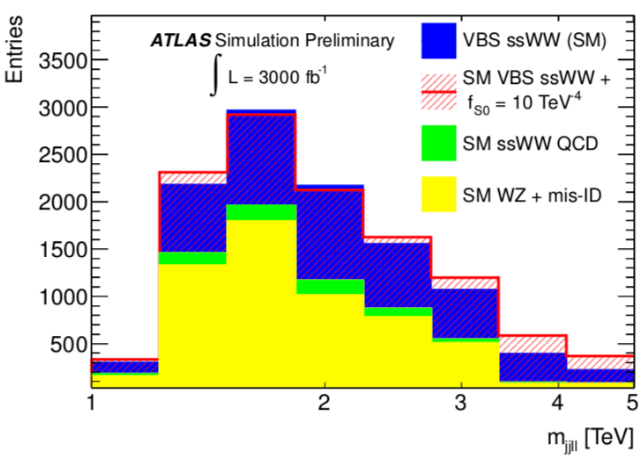


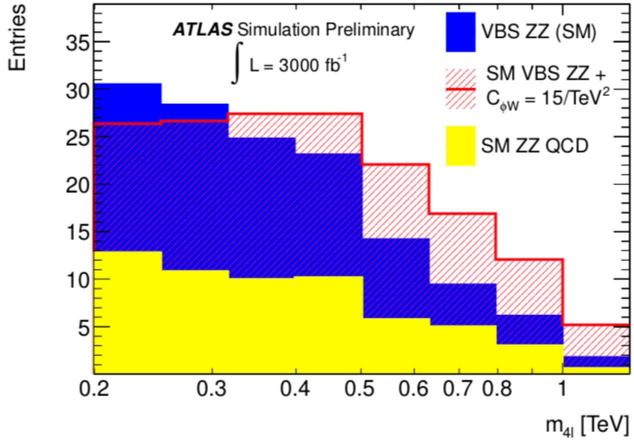
3000 events/fb
<μ_{PU}>=140, 200

Sensitive test of the vector boson vertices in the standard model.

At HL-LHC, with 3000 events/fb

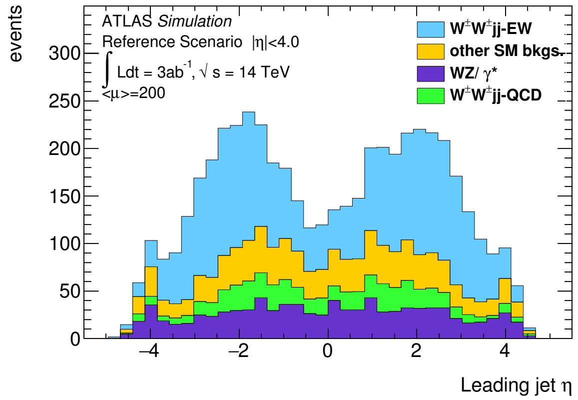
- Clean observation of the W±W±, ZZ and WZ scattering above backgrounds
- Sensitive to dimension-8 operators at scales of ~1 TeV

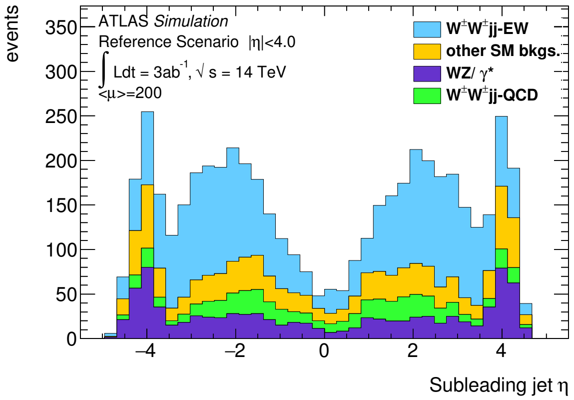




Significance of electroweak **W±W±jj** production at **11σ**

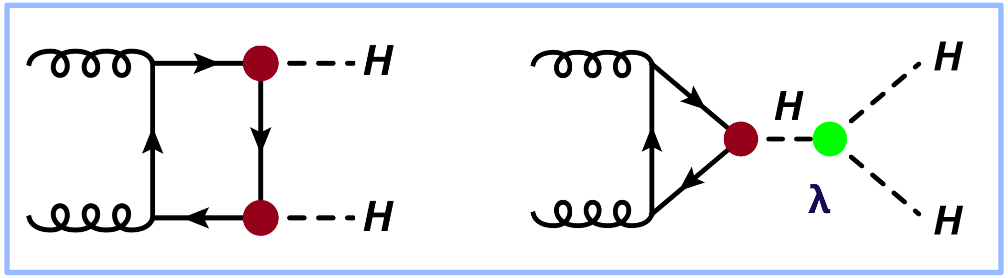
Precision on cross section **Δσ/σ=5.9%**



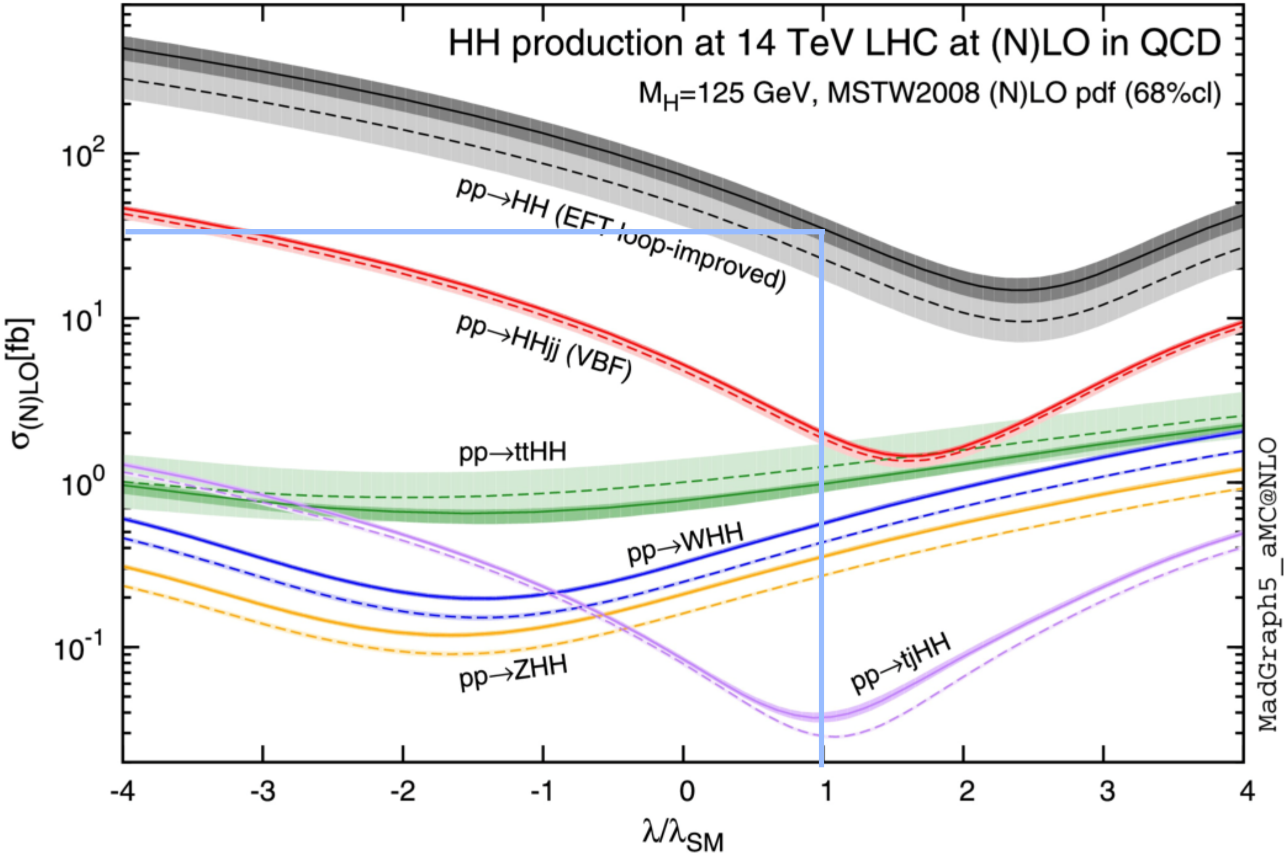


DI-HIGGS PRODUCTION at HL-LHC

Phys.Lett.B732(2014) 1420-149



σ_{HH} ~40 fb



Probe the nature of the Higgs Boson Self Coupling

DI-HIGGS PRODUCTION at HL-LHC: HH→bbbb

ATL-PHYS-PUB-2016-024

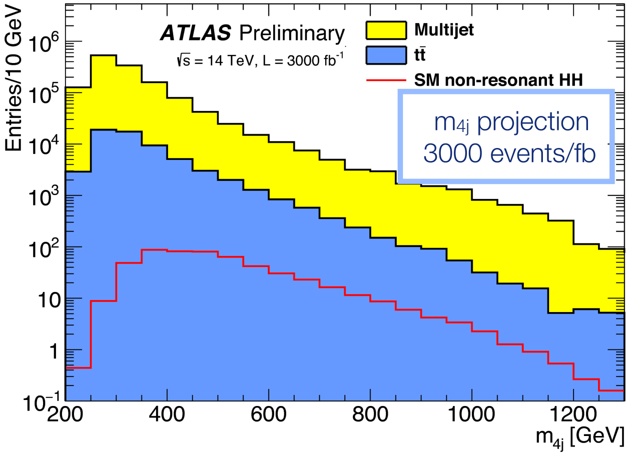
Main background to HH→bbbb production is multi jet QCD production

Extrapolation from Run 2 results

Assume the Run 2 detector, trigger and flavour tagging, not yet taking into account the expected pile-up at HL-LHC

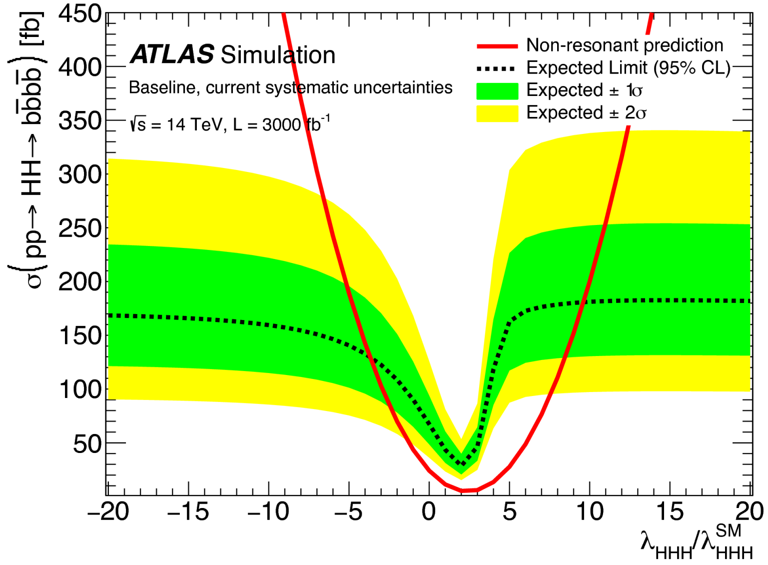
Run 2 trigger threshold:

$p_T^{jet}>40$ GeV → $p_T^{jet}>75$ GeV at HL-LHC



m_{4j} projection
3000 events/fb

	$p_T^{jet}>75$ GeV FULL systematic uncert.	$p_T^{jet}>75$ GeV statistical uncert. ONLY	$p_T^{jet}>40$ GeV FULL systematic uncert.	$p_T^{jet}>40$ GeV statistical uncert. ONLY
λ_{HHH}	$-7.4<\lambda/\lambda_{SM}<14$	$-3.4<\lambda/\lambda_{SM}<12$	$-4.1<\lambda/\lambda_{SM}<8.7$	$-1.2<\lambda/\lambda_{SM}<8$
σ/σ_{SM} excluded at 95% CL	11.5	2.0	5.2	1.5



$p_T^{jet}>40$ GeV
Full systematic
uncertainty

DI-HIGGS PRODUCTION at HL-LHC: HH→bbγγ

ATL-PHYS-PUB-2014-019
Phase-II Upgrade ITk-pixel TDR

Two photons with E_T>30 GeV and 123<$m_{\gamma\gamma}$<128 GeV with $|\eta_\gamma|$<2.37

Two b-tag jets with p_T>30 GeV ($\varepsilon_{b\text{-tag}}$=70%) and 100<$m_{bb}$<150 GeV with $|\eta|$<2.5

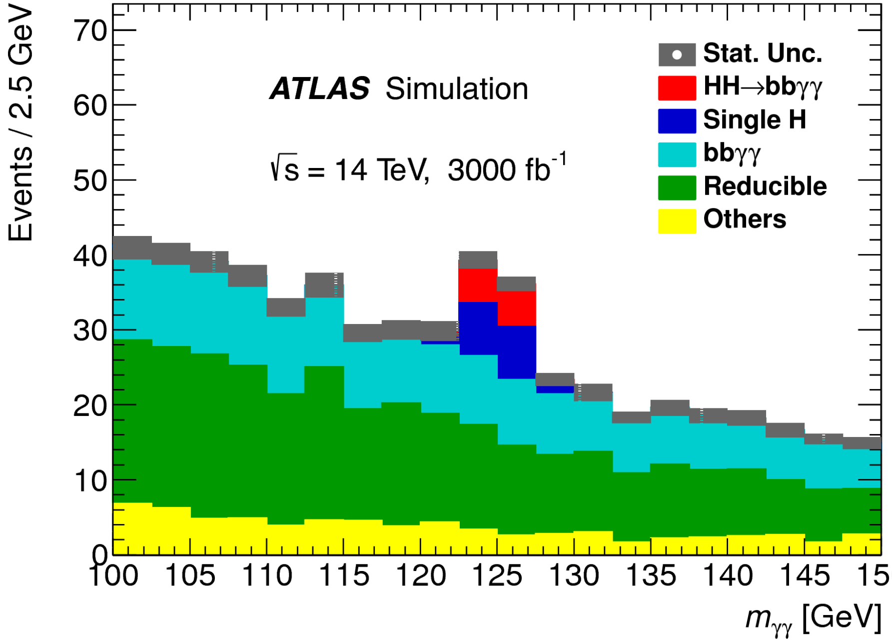
p_T^{bb}>110 GeV & $p_T^{\gamma\gamma}$>110 GeV

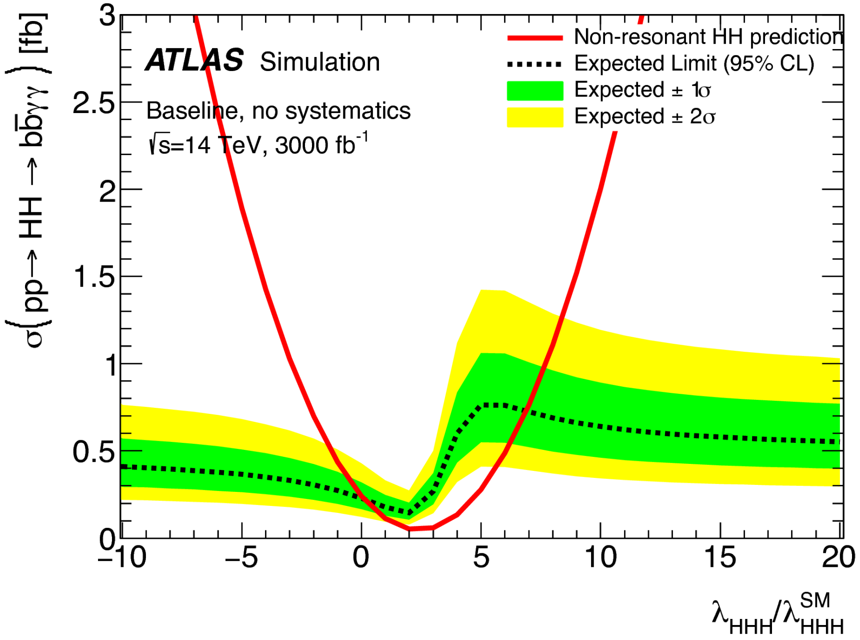
N_{jets} < 6 with p_T>25 GeV (to reduce tt background)

After selection: **11 signal events, 65 background**

Significance (no systematic error - small): **1.5 σ**

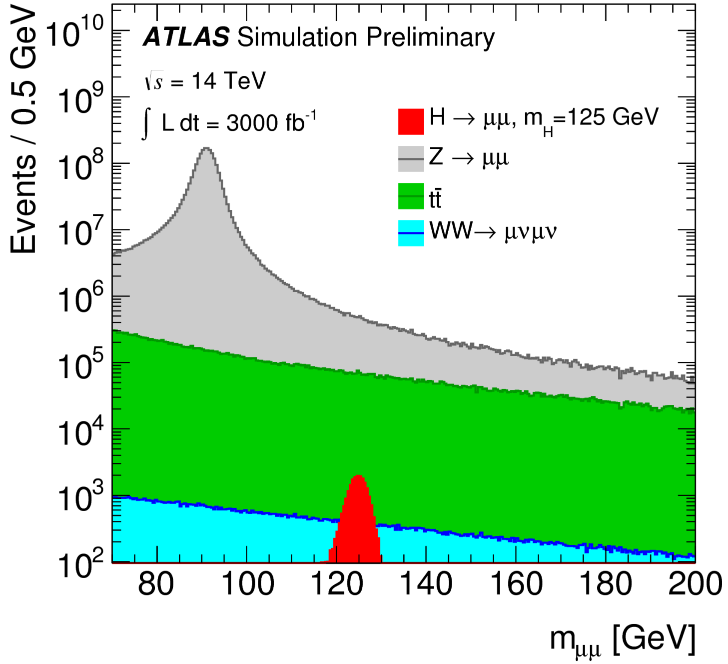
0.2<λ/λ_{SM}<6.9

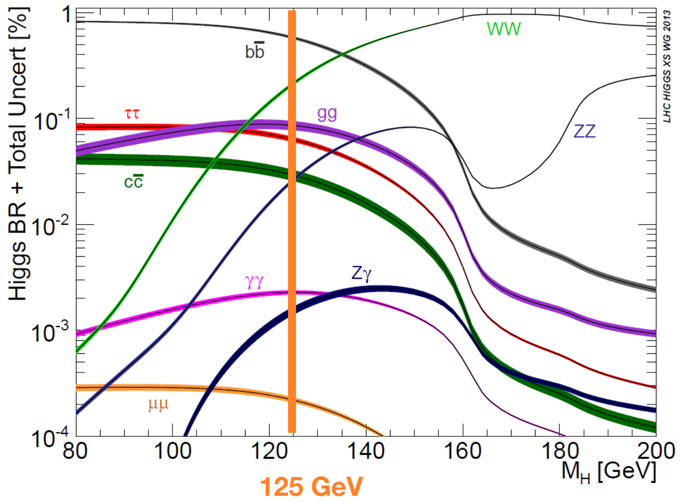


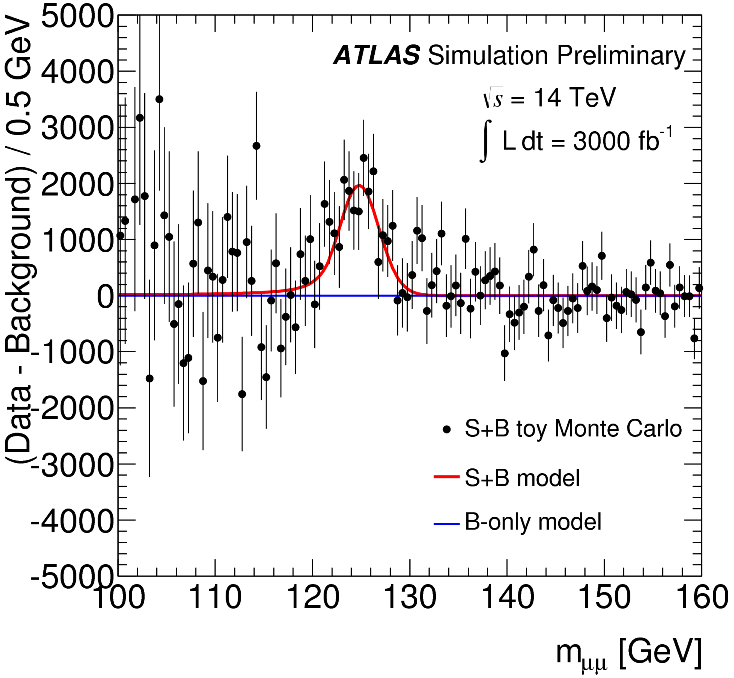


HIGGS BOSON DECAY to $\mu^+\mu^-$ at HL-LHC

ATL-PHYS-PUB-2013-014







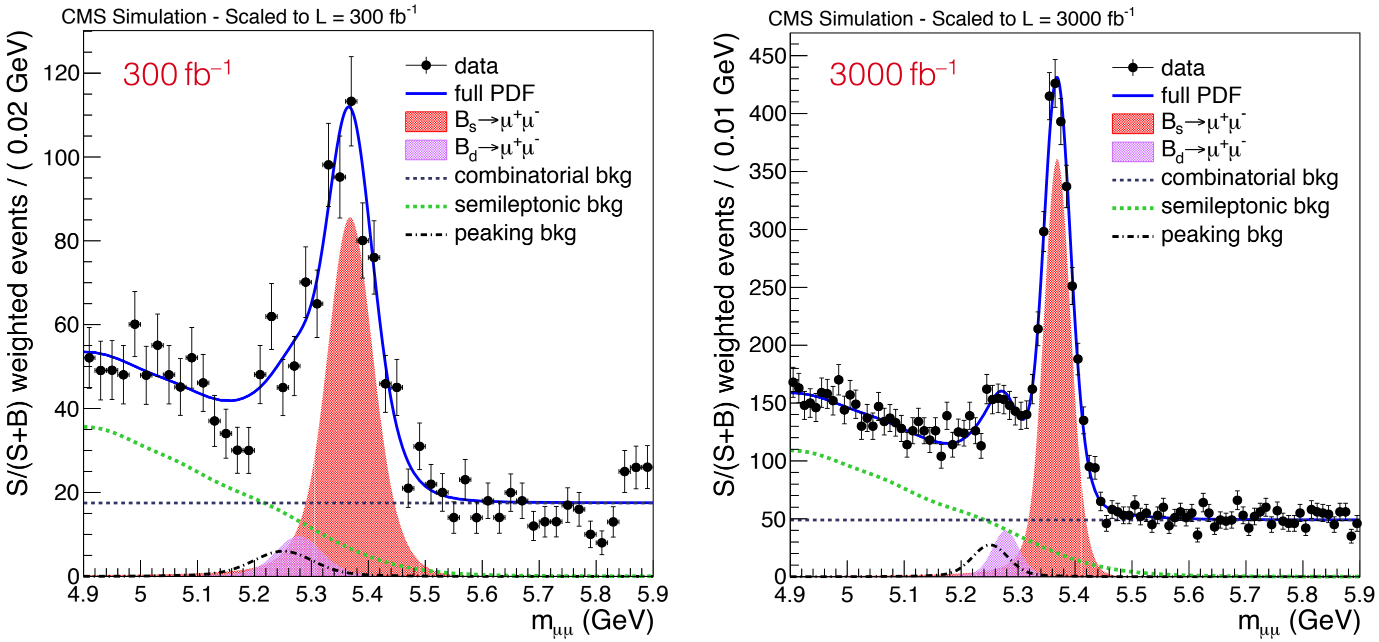
$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
$\Delta^{\mathrm{sys}}_{Bkg}$ (model)	68	110
$\Delta^{\mathrm{sys}}_{Bkg}$ (fit)	190	620
$\Delta^{\mathrm{stat}}_{\mathrm{S+B}}$	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

SUMMARY of HL-LHC HIGGS BOSON RESULTS

Channel	Result	HH channel	Result
VBF $H \to W^+W^-$	$\Delta\mu/\mu$=14 to 20%	$HH \to bb\tau\tau$ (FULL uncertainties)	0.6 σ $-4<\lambda_{HHH}/\lambda_{SM}<12$
VBF $H \to ZZ \to 4l$	$\Delta\mu/\mu$=15 to 18%		
ttH, $H \to \gamma\gamma$	$\Delta\mu/\mu$=17 to 20%	$HH \to bbbb$ ($p_T^{jet}>75$ GeV) (FULL uncertainties)	$-3.4<\lambda_{HHH}/\lambda_{SM}<12$
VH, $H \to \gamma\gamma$	$\Delta\mu/\mu$=25 to 35%		
off-shell $H \to ZZ \to 4l$	$\Delta\mu/\mu$=14 to 50% $\Gamma_H=4.2^{+1.5}_{-2.1}$ MeV	$HH \to bb\gamma\gamma$ (statistical uncertainties only)	1.5 σ $0.2<\lambda_{HHH}/\lambda_{SM}<6.9$
$H \to Z\gamma$	$\Delta\mu/\mu$=30% 3.9σ	ttHH, $HH \to bbbb$ (statistical uncertainties only)	0.35 σ
$H \to J/\psi\ \gamma$	BR<44×10^{-6} @ 95% CL		

Very rare decays

$B_s \rightarrow \mu\mu$

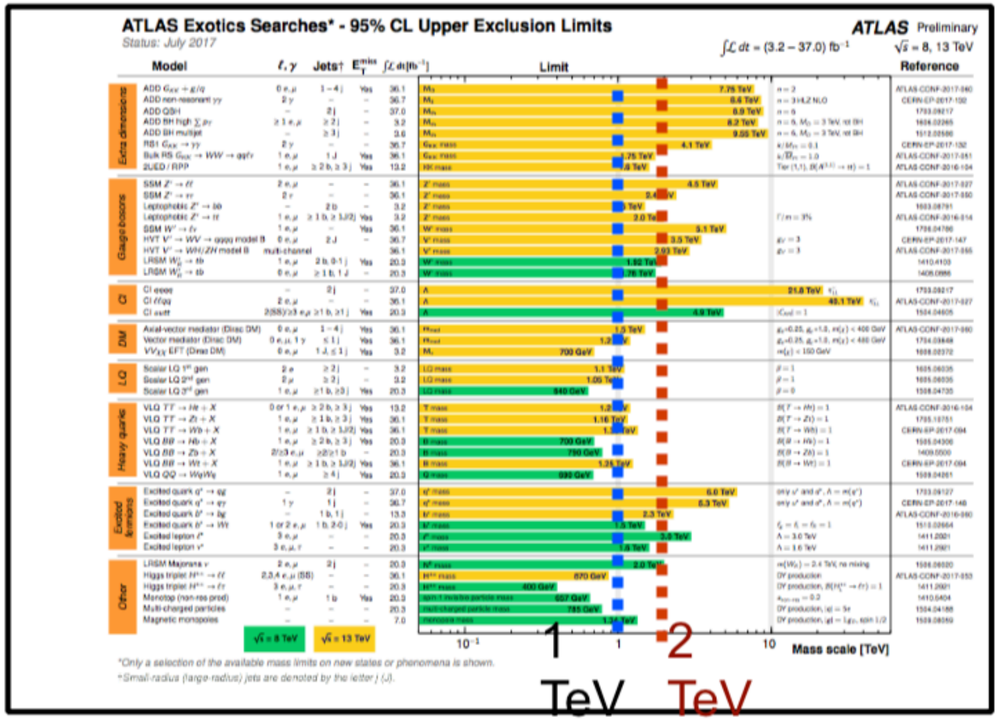


Prospective study by CMS for the rare $B_s \rightarrow \mu\mu$ decay

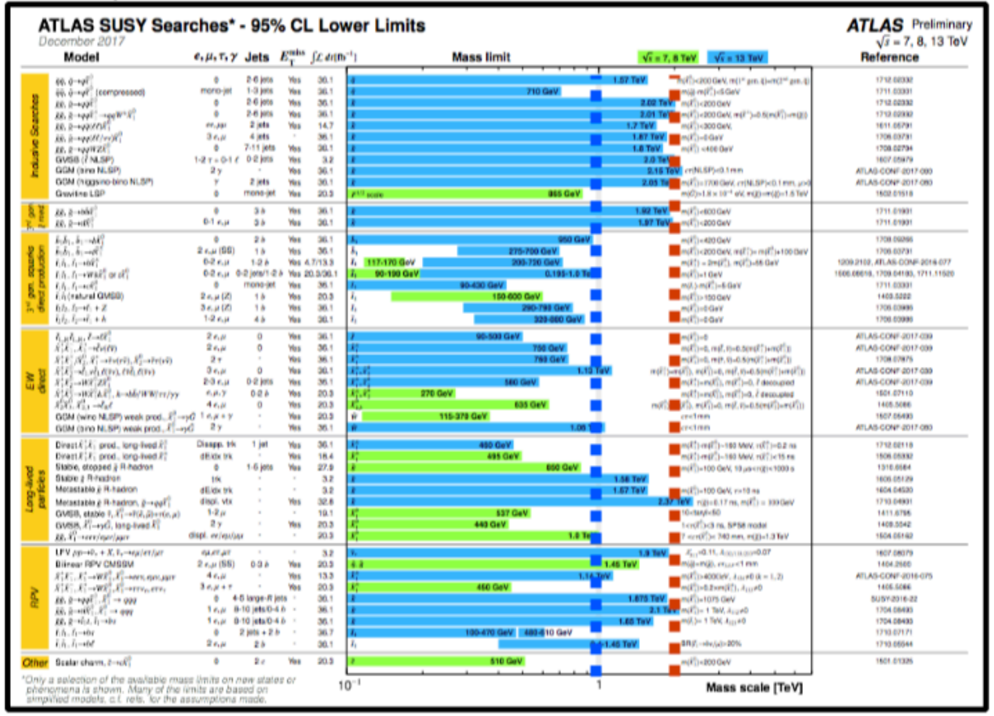
CMS-PAS-FTR-13-022

SEARCHES at the ENERGY FRONTIERE

Exotics



Supersymmetry



ATL-PHYS-PUB-2013-003, 2014-007

ATLAS Mass reach for Exotic signatures

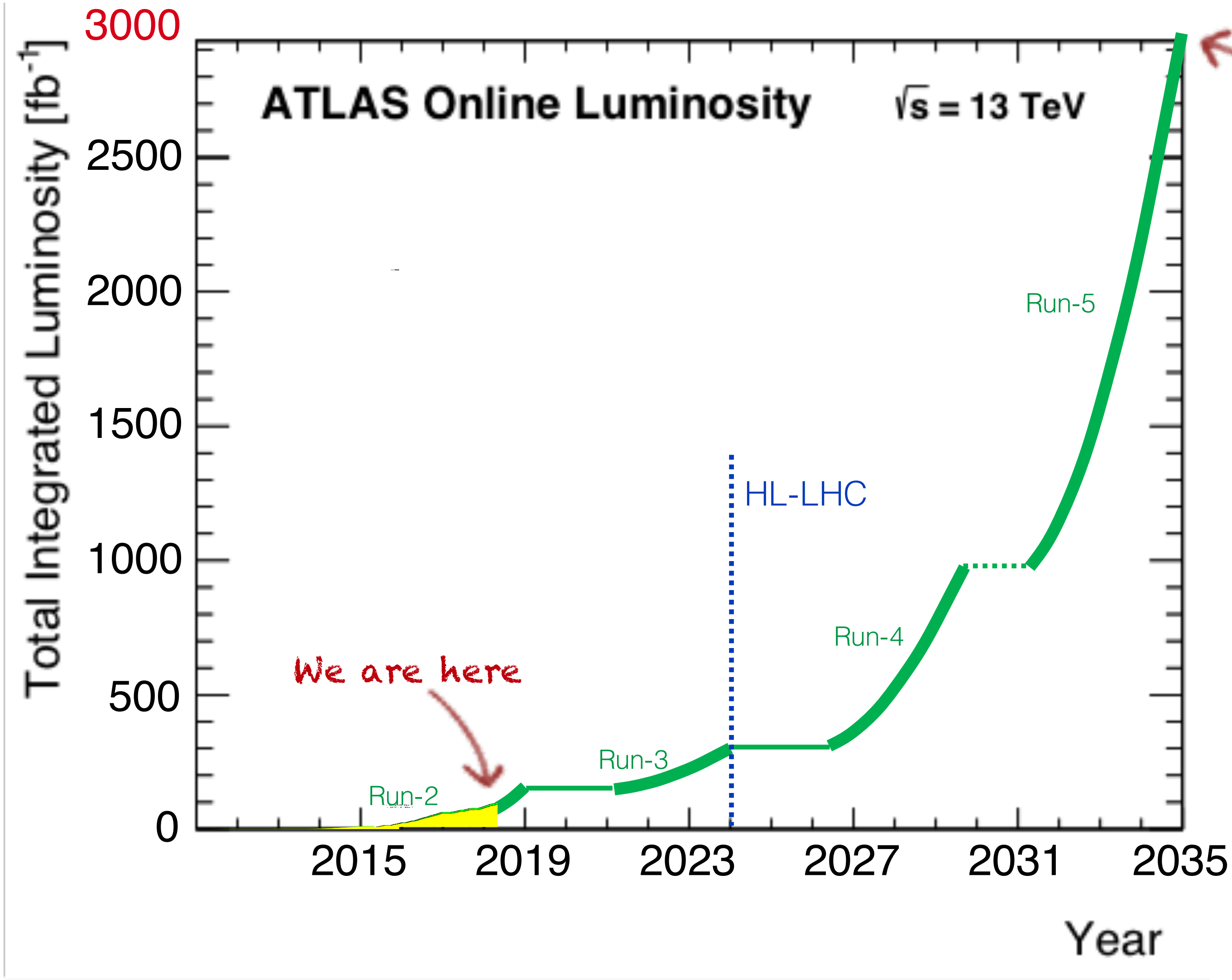
ATLAS @14 TeV	Z' → ee SSM 95% CL limit	g_{KK} → t t RS 95% CL limit	Dark matter M* 5σ discovery
300 fb^{-1}	6.5 TeV	4.3 TeV	2.2 TeV
3000 fb^{-1}	7.8 TeV	6.7 TeV	2.6 TeV

ATL-PHYS-PUB-2014-010 , 2013-011, 2015-032

ATLAS Mass reach for SUSY particles

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

Luminosity increase



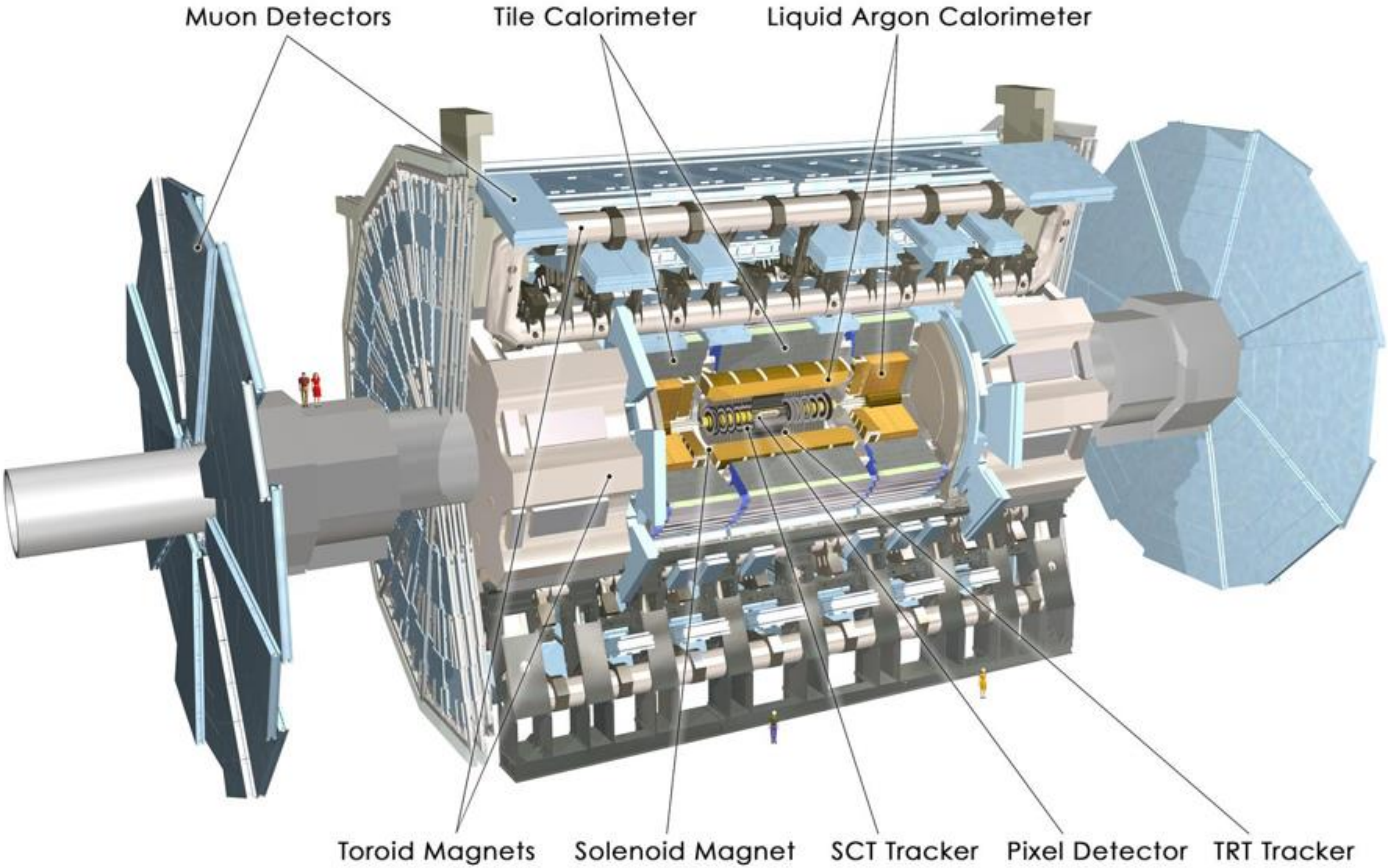
We are here

We will be going here

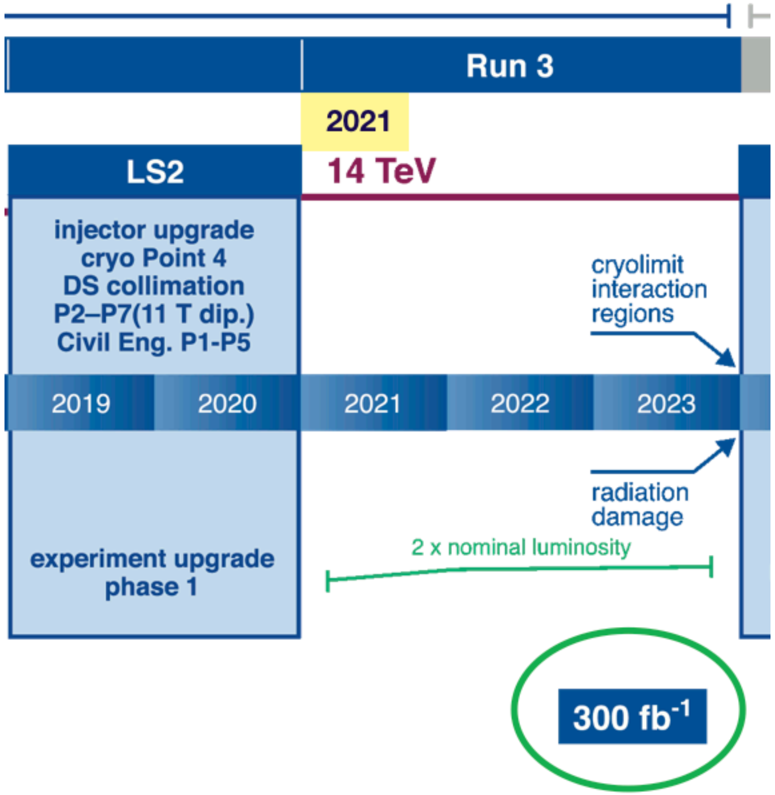
Possibly up to 4 ab^{-1}

© P. Ferreira da Silva at Moriond EW, 2016

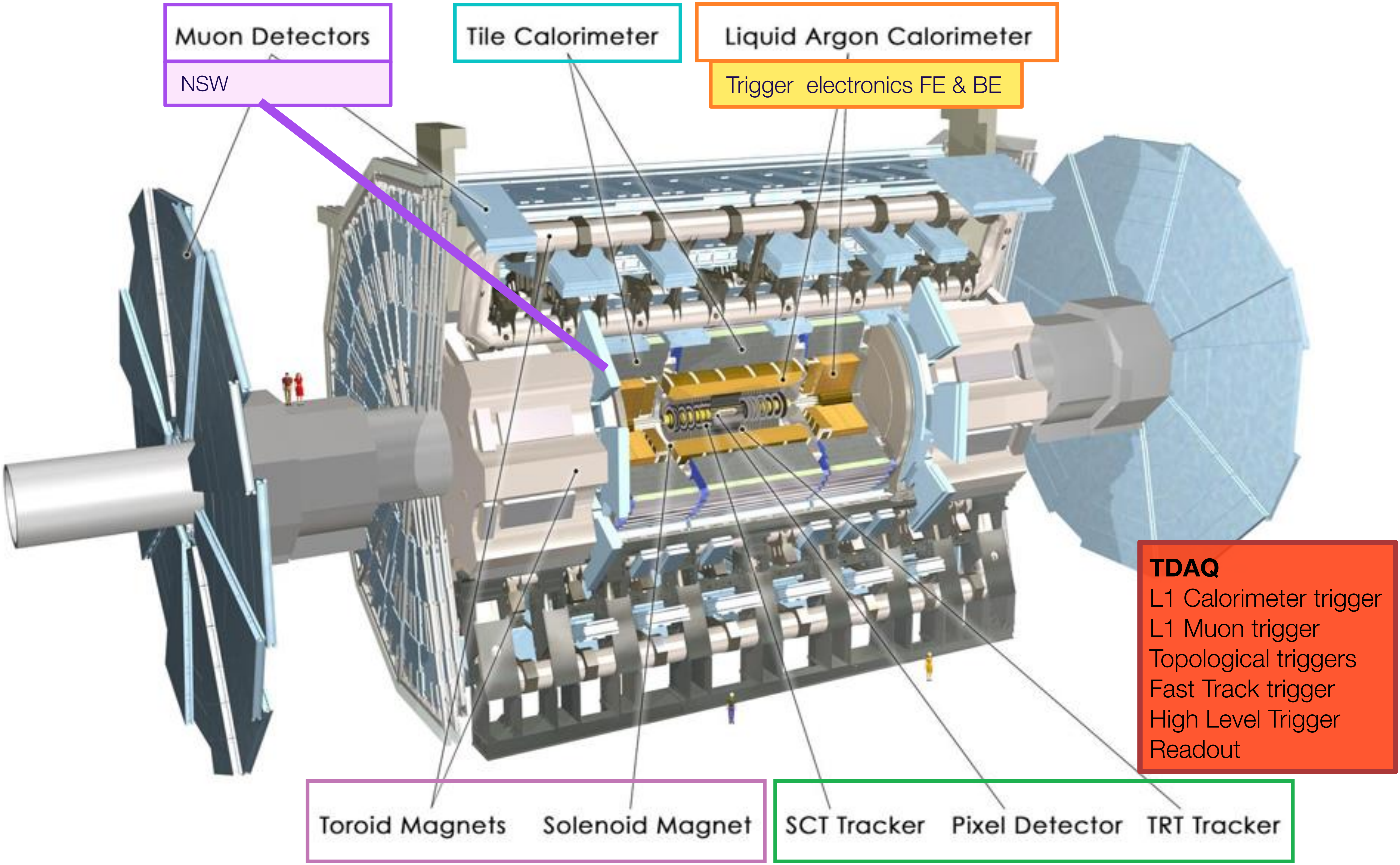
The ATLAS detector



PHASE-I UPGRADE
LAr
Muons - New Small Wheel
TDAQ



The ATLAS detector: Phase-I upgrades



Muon Detectors

NSW

Tile Calorimeter

Liquid Argon Calorimeter

Trigger electronics FE & BE

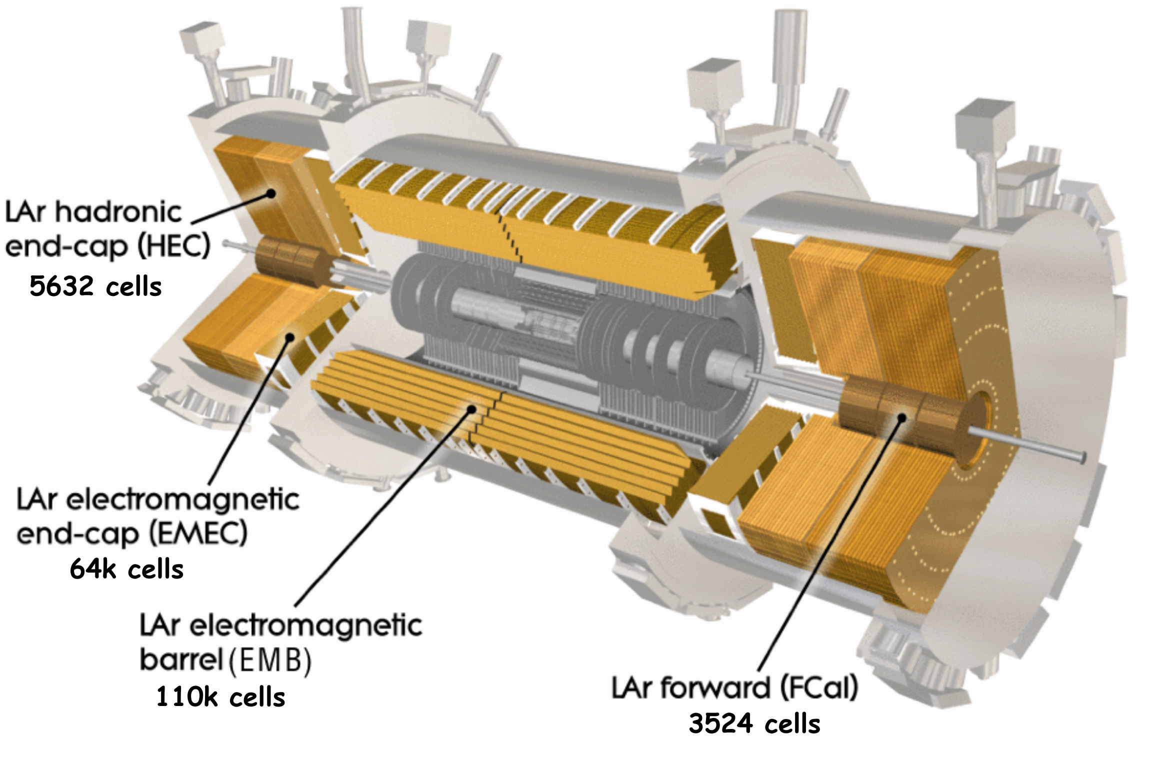
TDAQ
L1 Calorimeter trigger
L1 Muon trigger
Topological triggers
Fast Track trigger
High Level Trigger
Readout

Toroid Magnets Solenoid Magnet

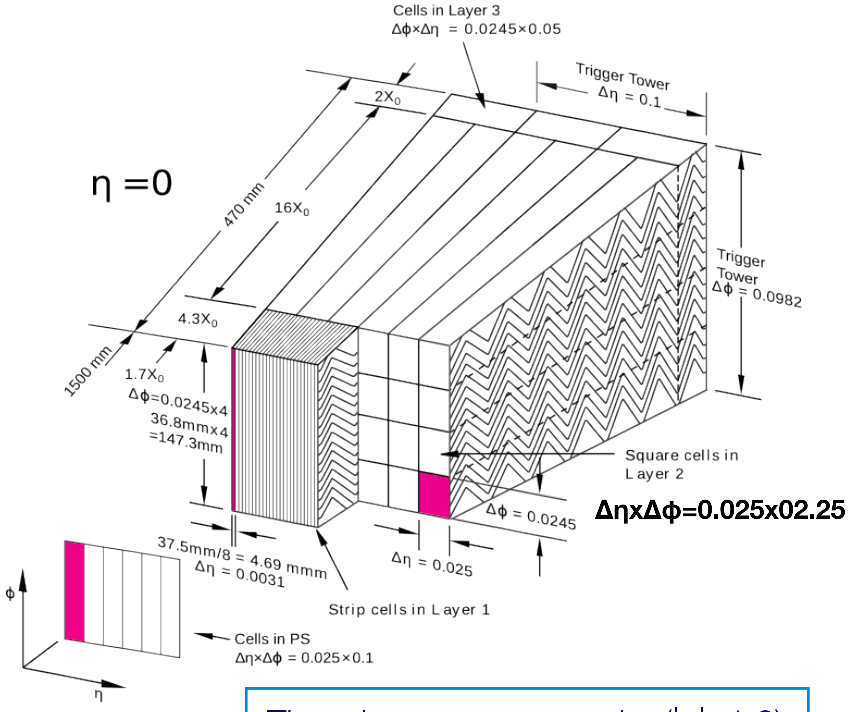
SCT Tracker Pixel Detector TRT Tracker

The ATLAS Liquid Argon Calorimeter

LAr calorimeters are expected to continue to operate reliably during the HL-LHC data taking period

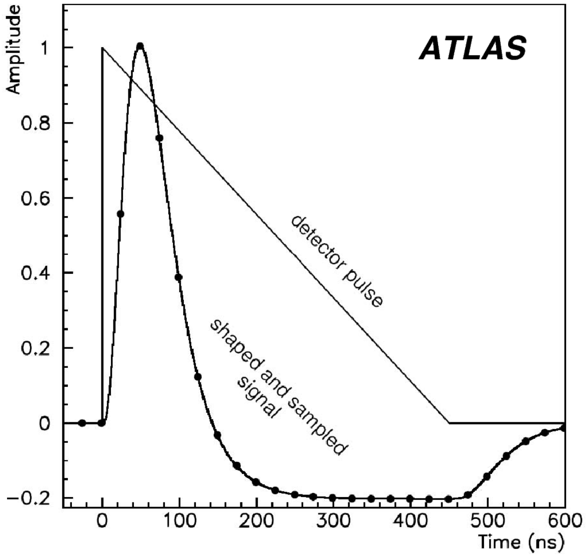


Fine grained LAr sampling calorimeter: 182468 cells
Dynamic range **~50 MeV to 3 TeV**



ΔηxΔϕ=0.025x02.25

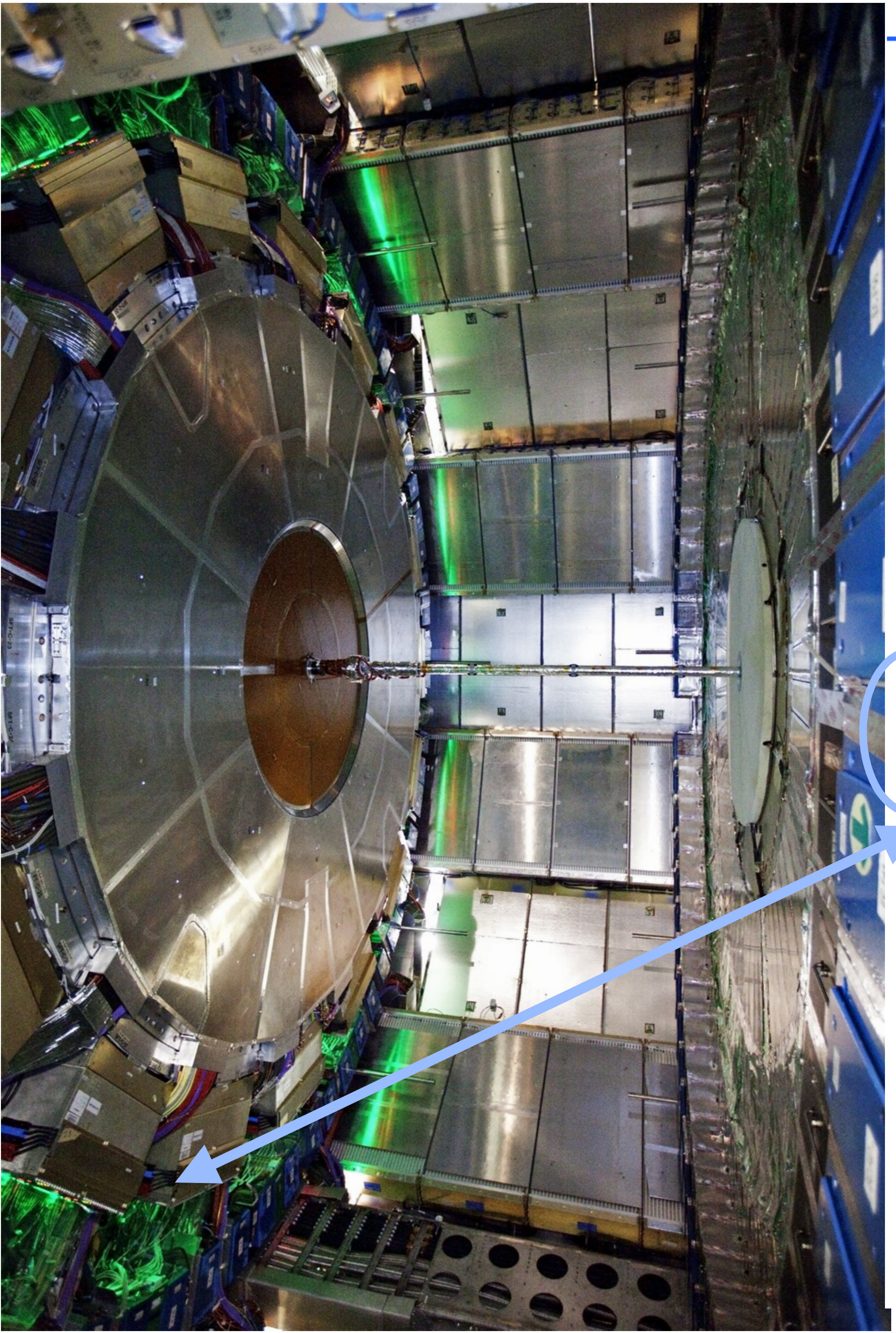
Three layers + presampler (|η|<1.8)

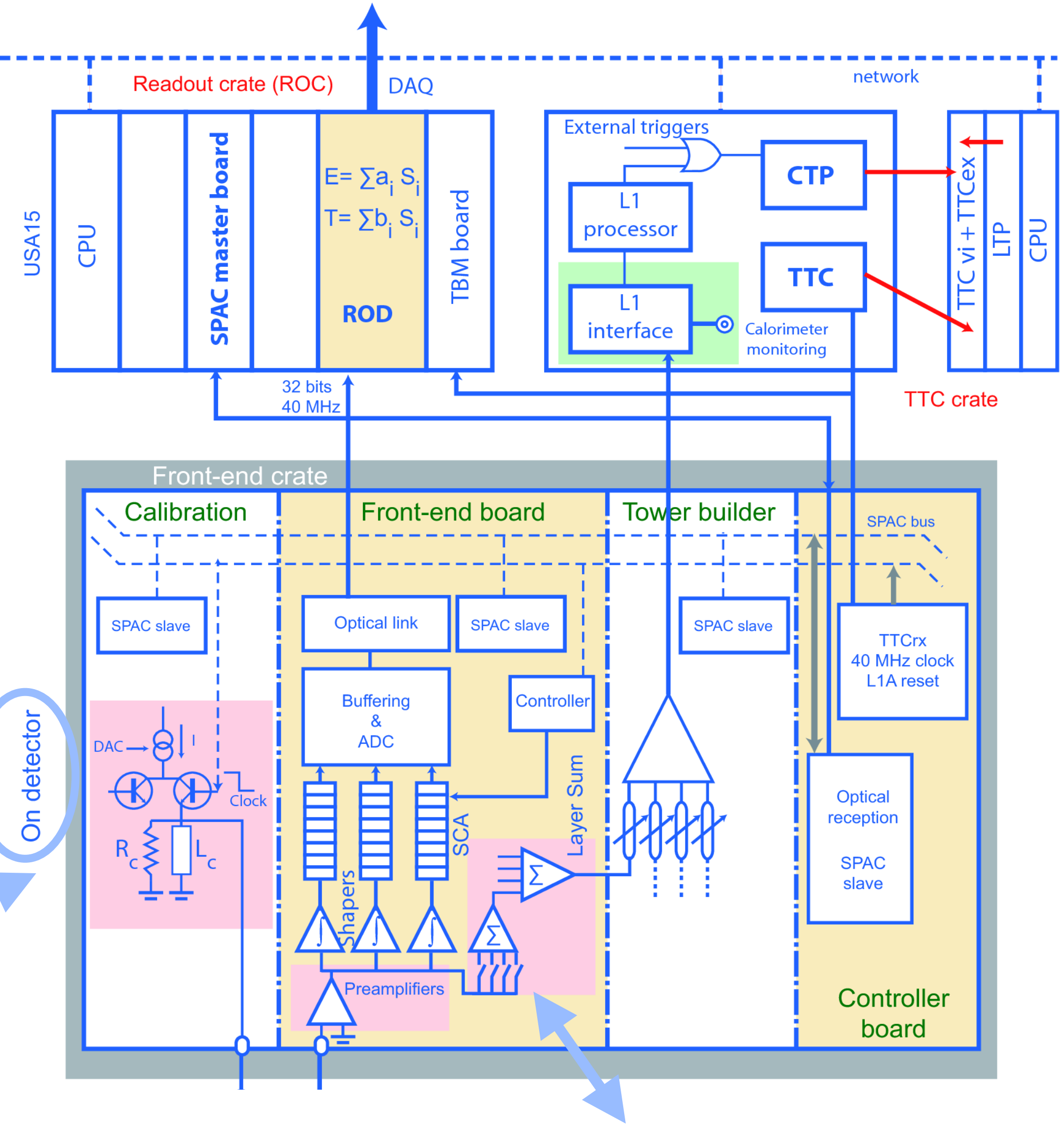


Triangular ionisation pulse amplified, shaped and sampled at **40 MHz**
Trigger sums built on frontend boards and Trigger board
Three gain scales
4 samples digitised by **12-bit ADC** upon L1 accept

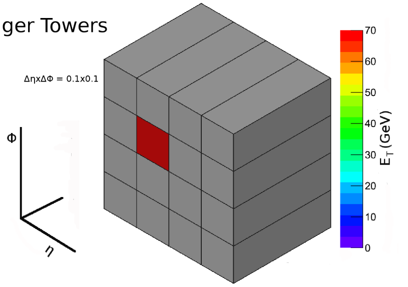
Online **energy reconstruction** at **100 kHz** in DSP based backend electronics

Liquid Argon Calorimeter Readout Electronics



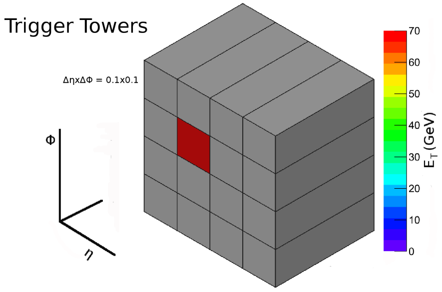


Trigger Towers

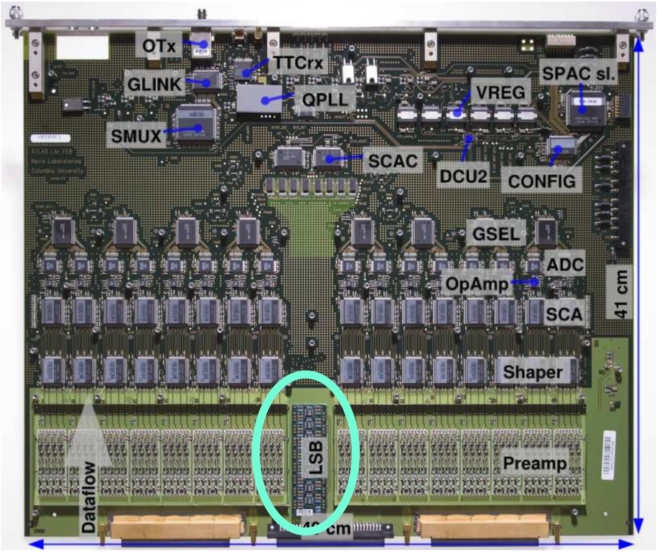


Trigger Towers
Δη x Δϕ = 0.1x0.1

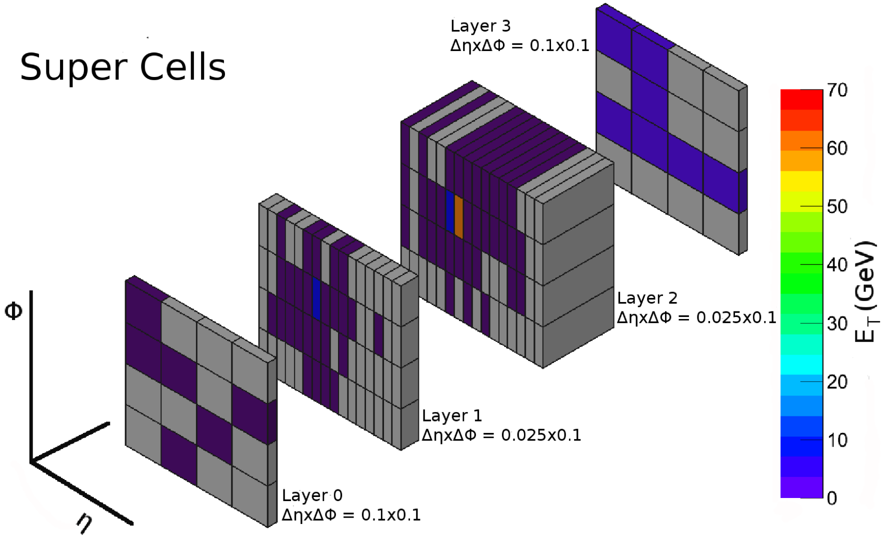
Liquid Argon Phase-I Upgrade: improved trigger



N J Buchanan et al 2008 JINST 3 P03004 (Fig. 17)



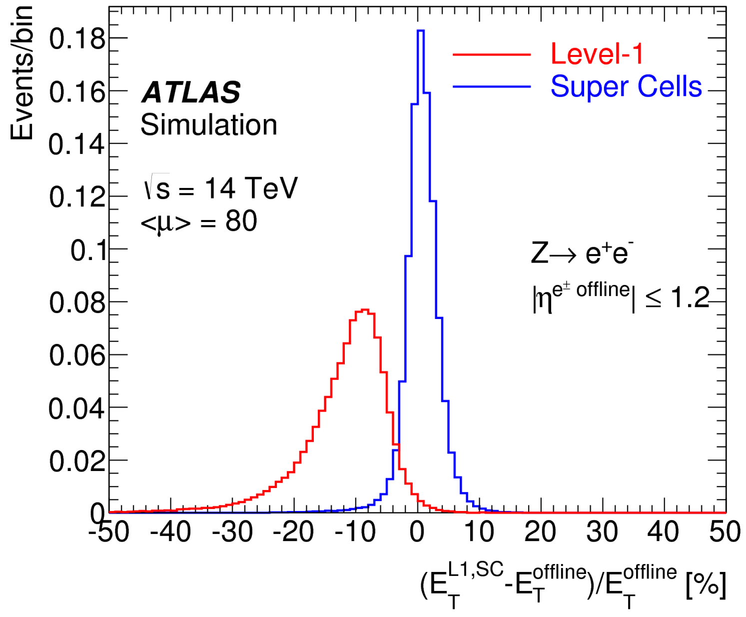
ATLAS Liquid Argon Calorimeter Phase-I Upgrade TDR

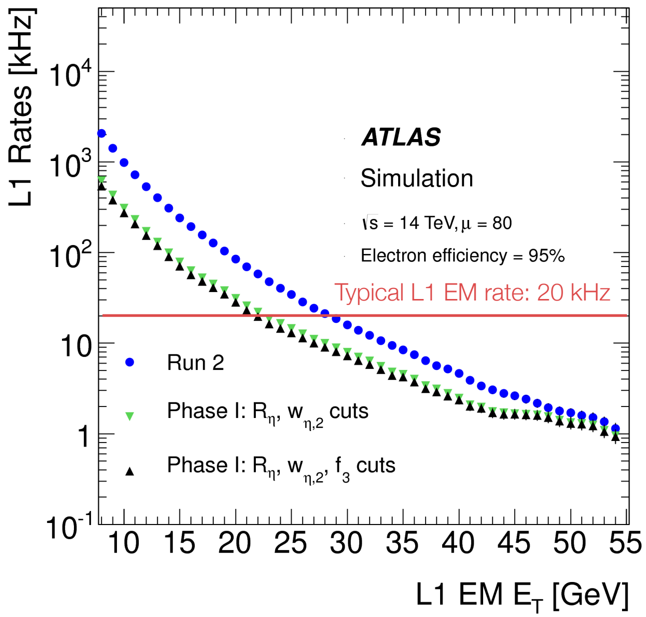


~3000 Trigger Towers

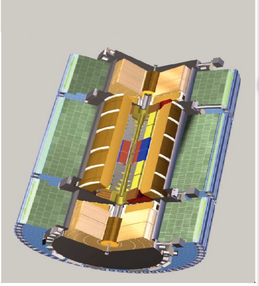
Increase granularity on the trigger path by removing some sums on frontend board.

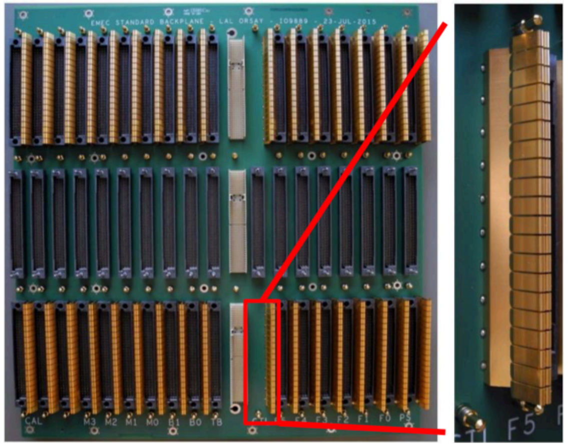
~34000 Super Cells



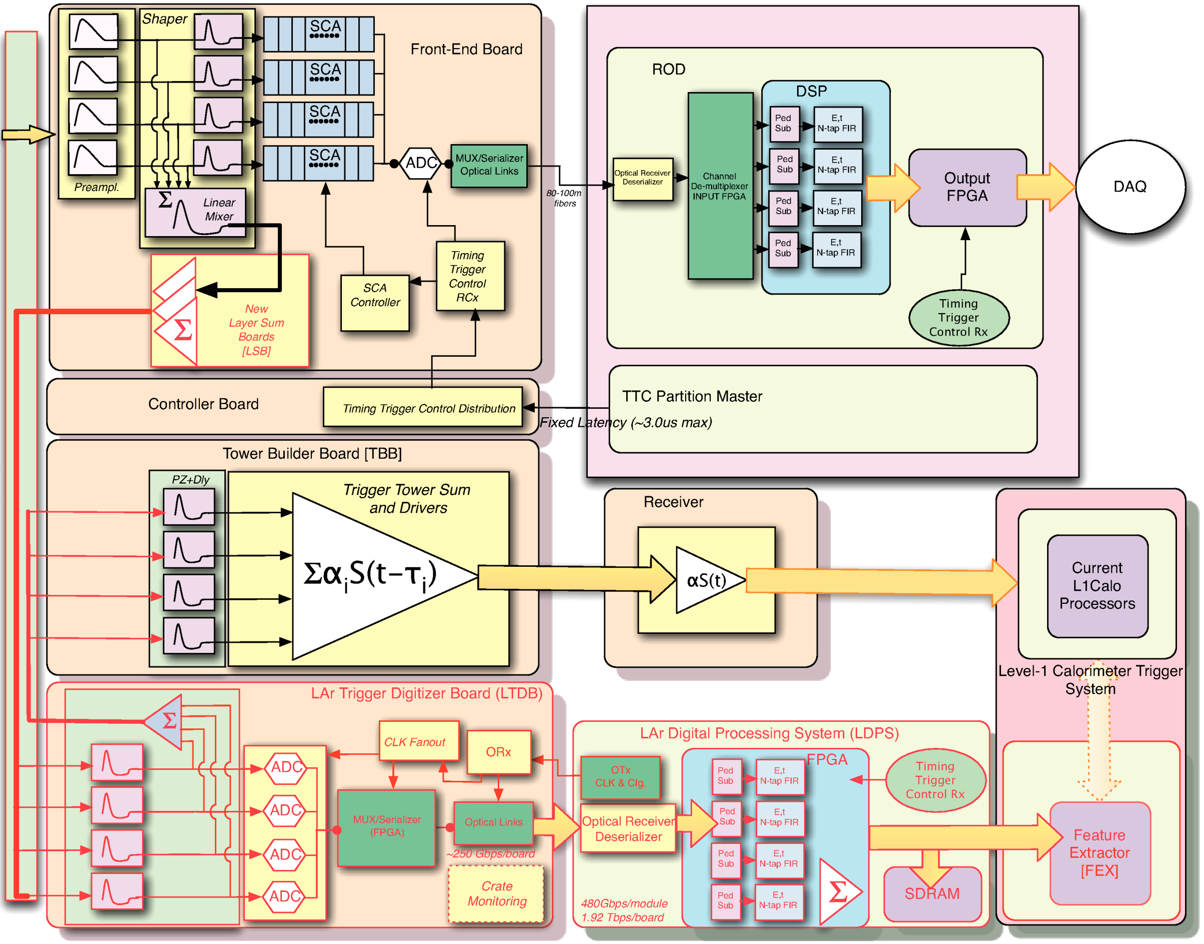


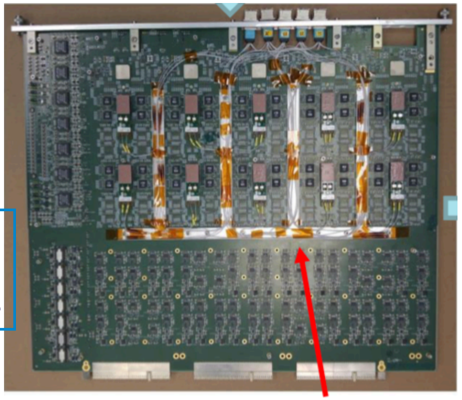
Liquid Argon Phase-I Upgrade: improved trigger





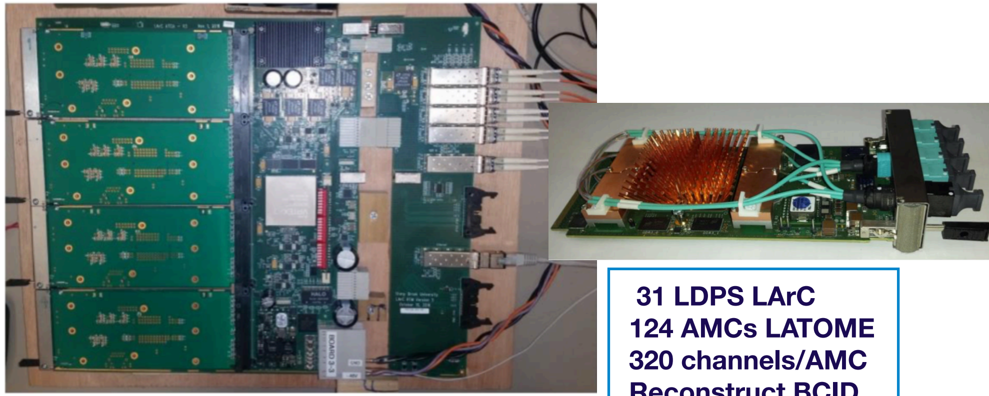
56 baseplanes





Pre-production LTDB with fiber trough

124 LTDB
320 channels/board
Digitise signals at 40 MHz



31 LDPS LArC
124 AMCs LATOME
320 channels/AMC
Reconstruct BCID, E_T at 40 MHz

LAr Phase-I demonstrator

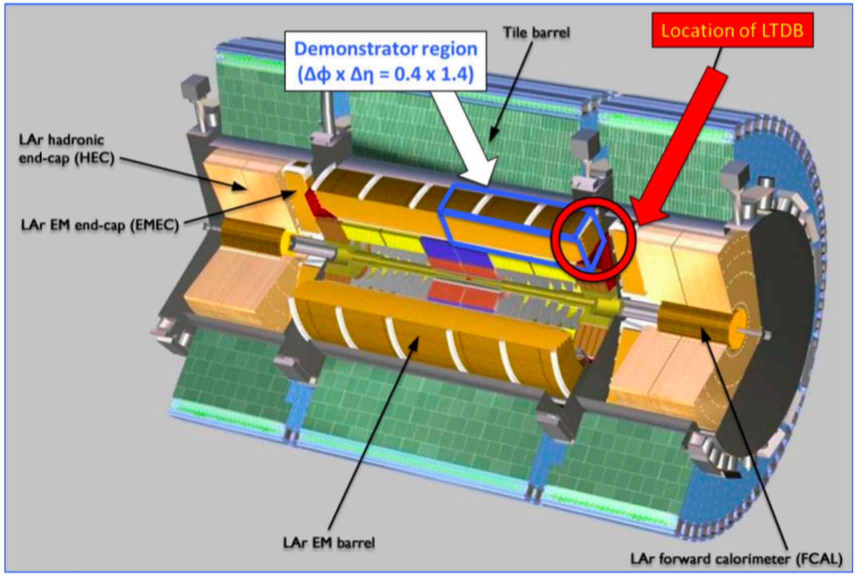
Pre-prototypes with coverage of ΔηxΔφ=1.5x0.4 installed in 2014

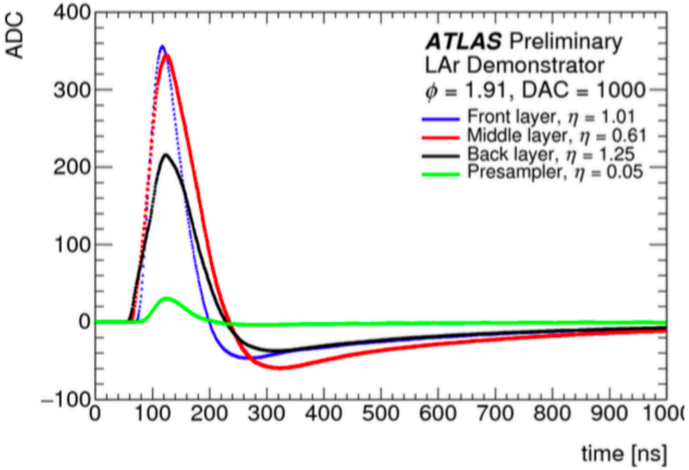
Demonstrate the feasibility and robustness of the system

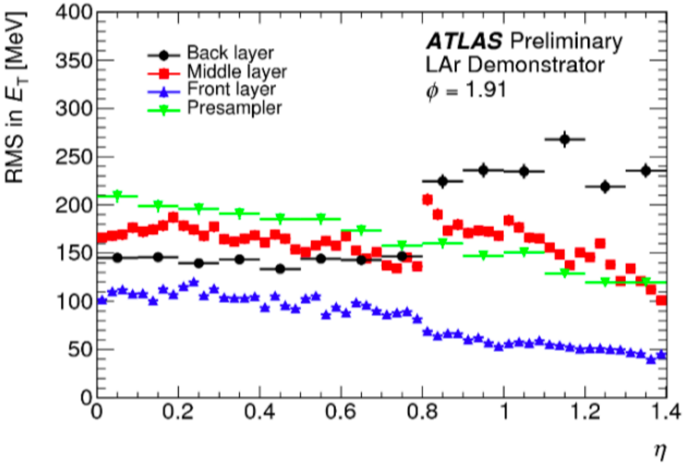
Collecting data during LHC Run 2, parasitically
System being updated with pre-production boards

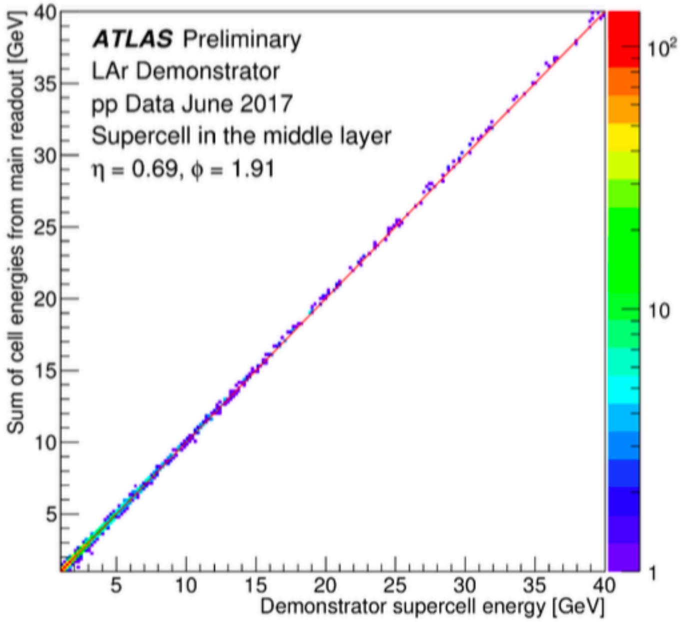
Validation of energy computation by comparing to the main readout system

Study of pulse shape and noise level

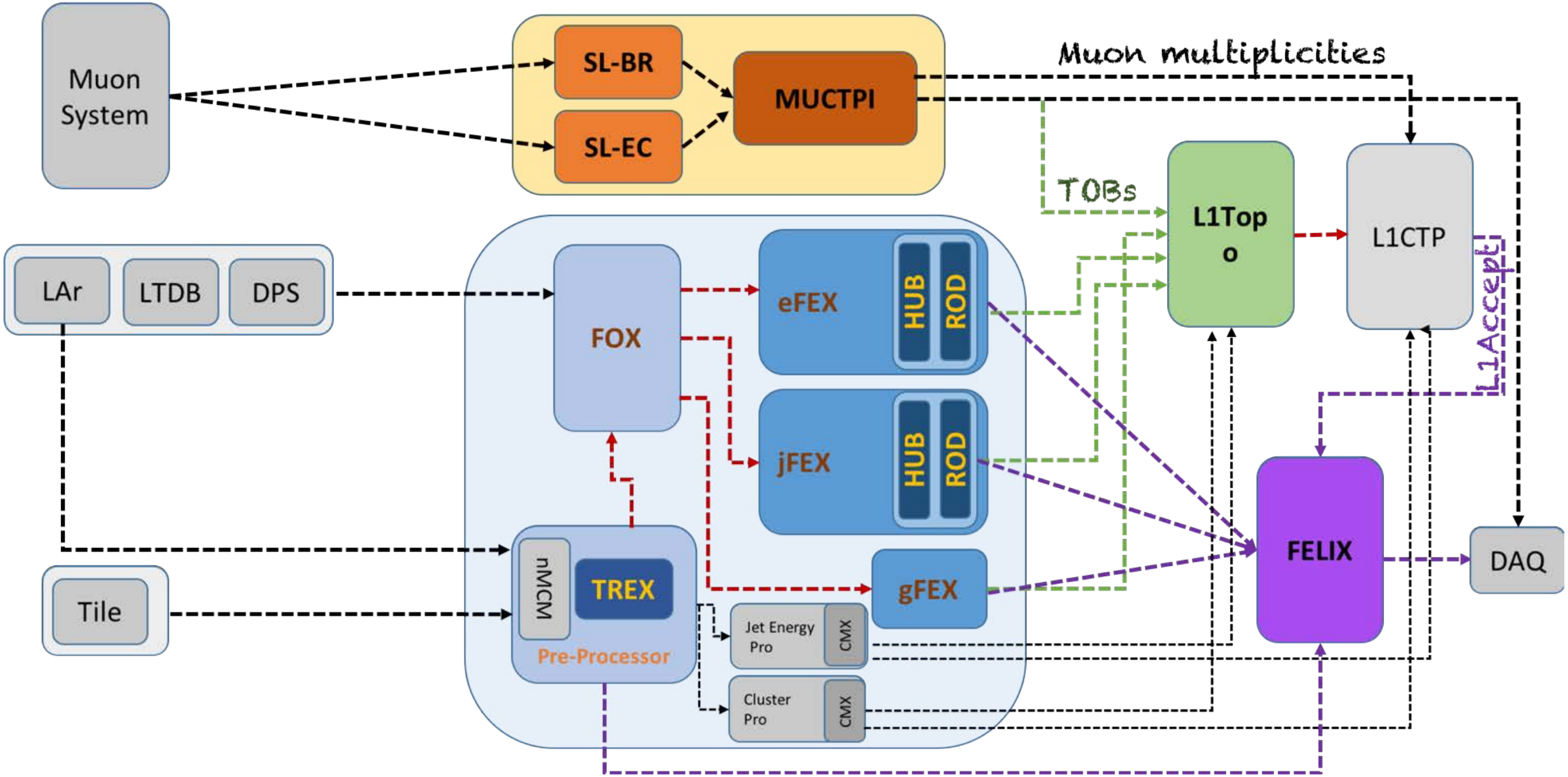




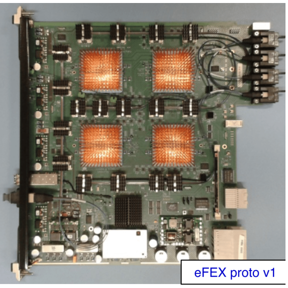


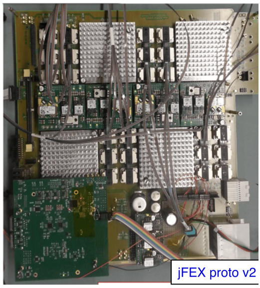


TDAQ upgrade

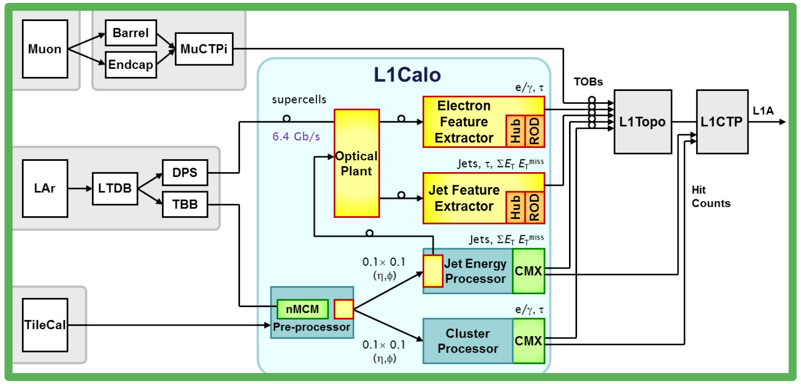


Trigger-DAQ Phase-I Upgrade


eFEX proto v1

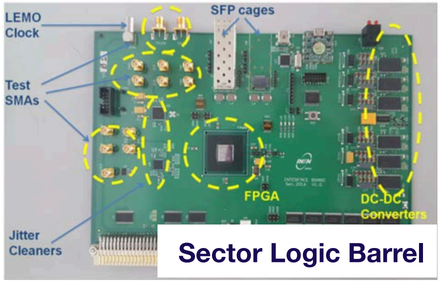

jFEX proto v2


gFEX proto v3b

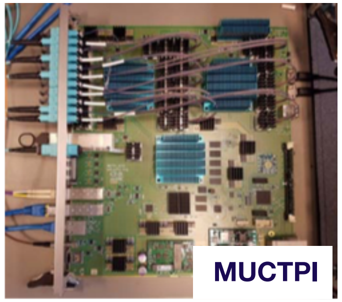


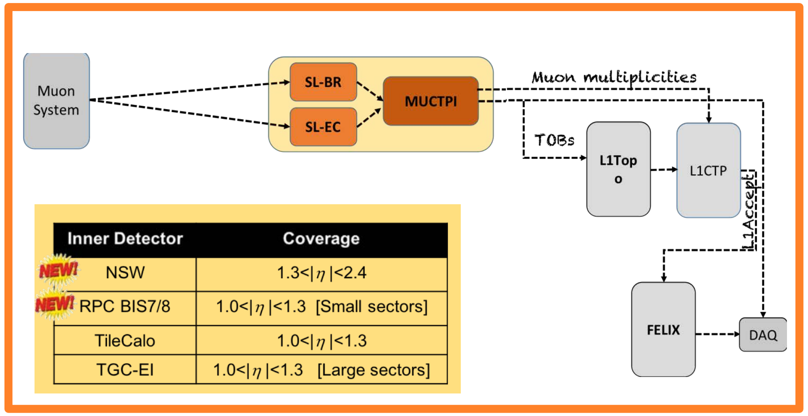
Improved LAr calorimeter segmentation for L1

eFex, jFex, gFex….



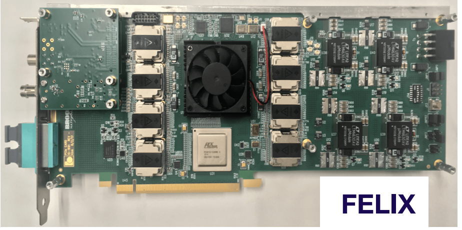
Sector Logic Barrel

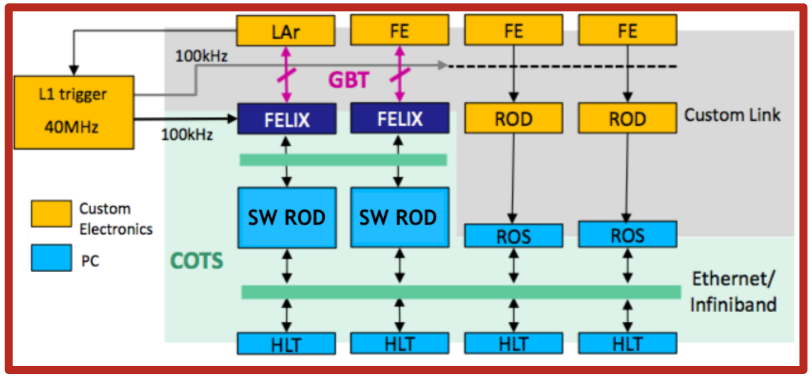

MUCTPI



Inner Detector	Coverage
NEW! NSW	1.3<|η|<2.4
NEW! RPC BIS7/8	1.0<|η|<1.3 [Small sectors]
TileCalo	1.0<|η|<1.3
TGC-EI	1.0<|η|<1.3 [Large sectors]

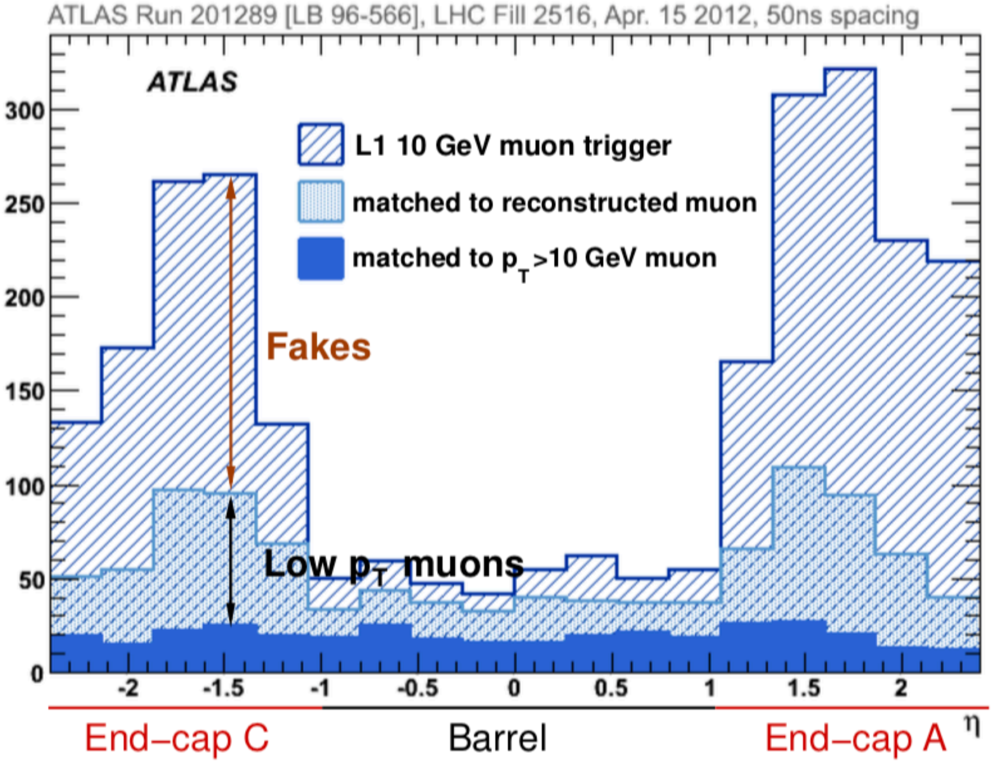
New Small Wheel for improvement background rejection at L1

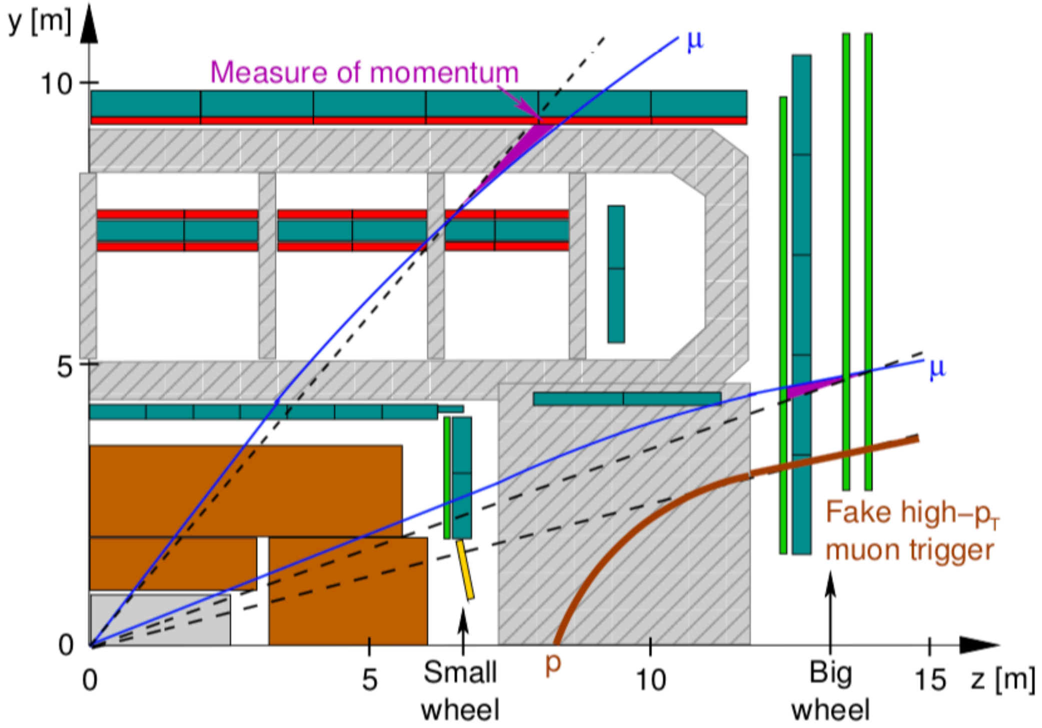

FELIX



FELIX board

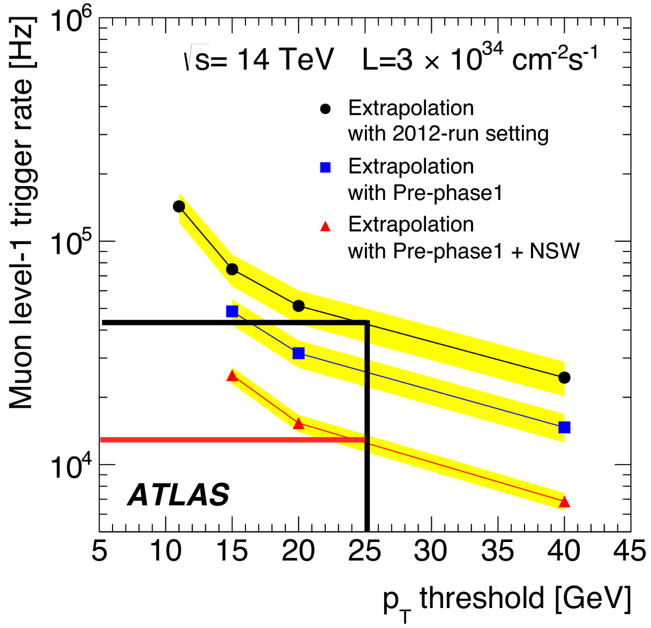
Sources of Level 1 muon trigger at LHC



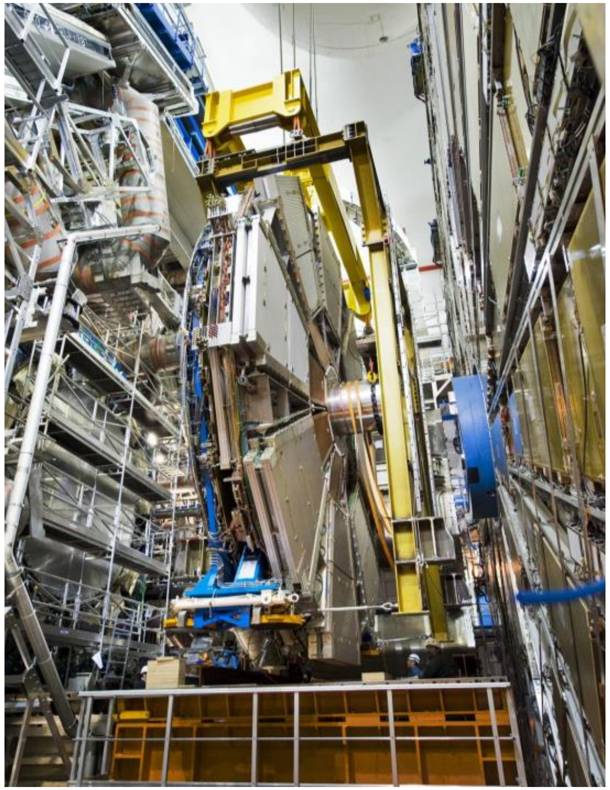


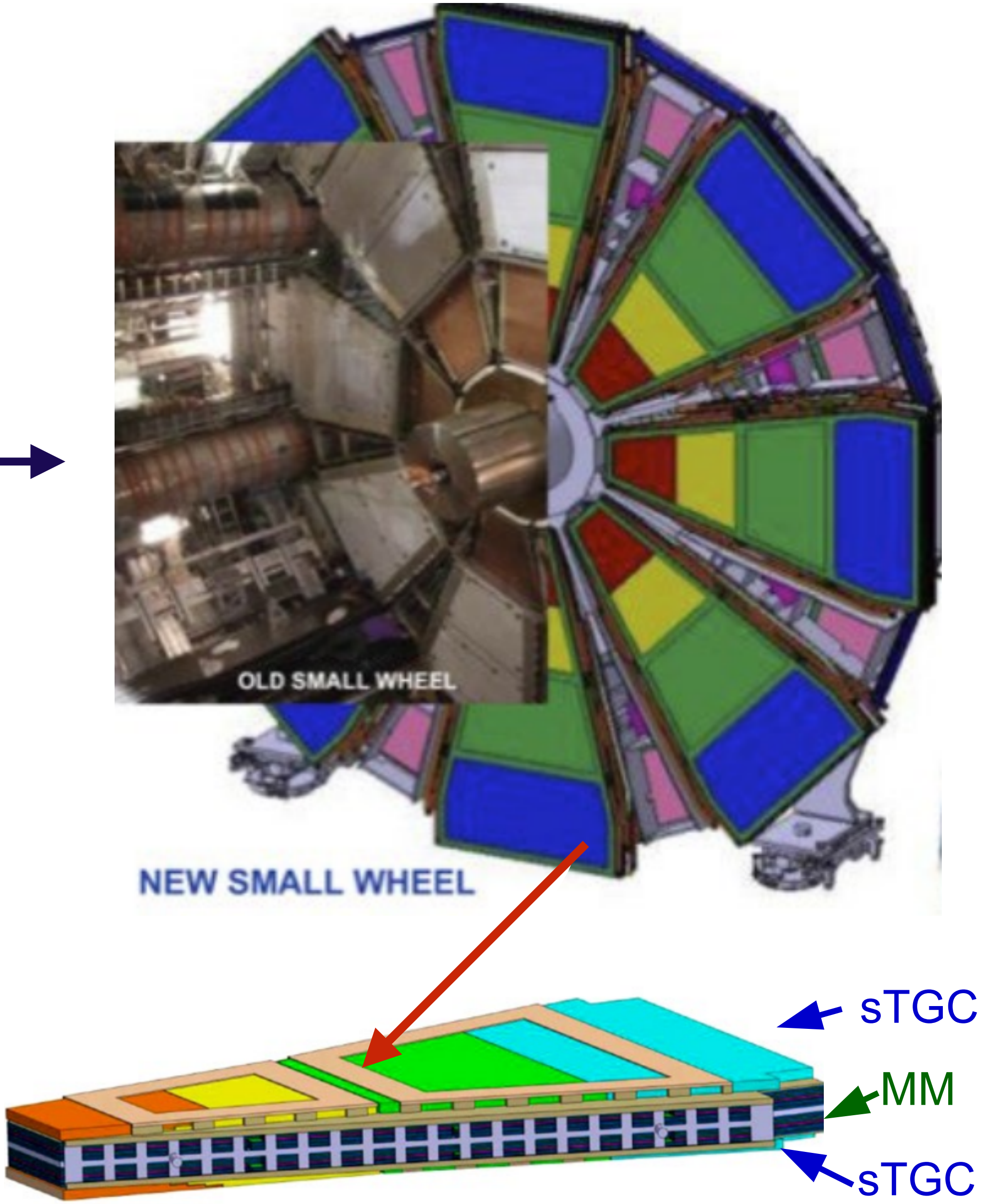
Muon trigger rate dominated by **fake** triggers in the endcaps caused by **charged particles not emerging from the interaction point.**

Real muon triggers contaminated with sub-pT-threshold muon due to the reduced momentum resolution caused by the moderate spatial resolution of the trigger chambers,



New Small Wheel



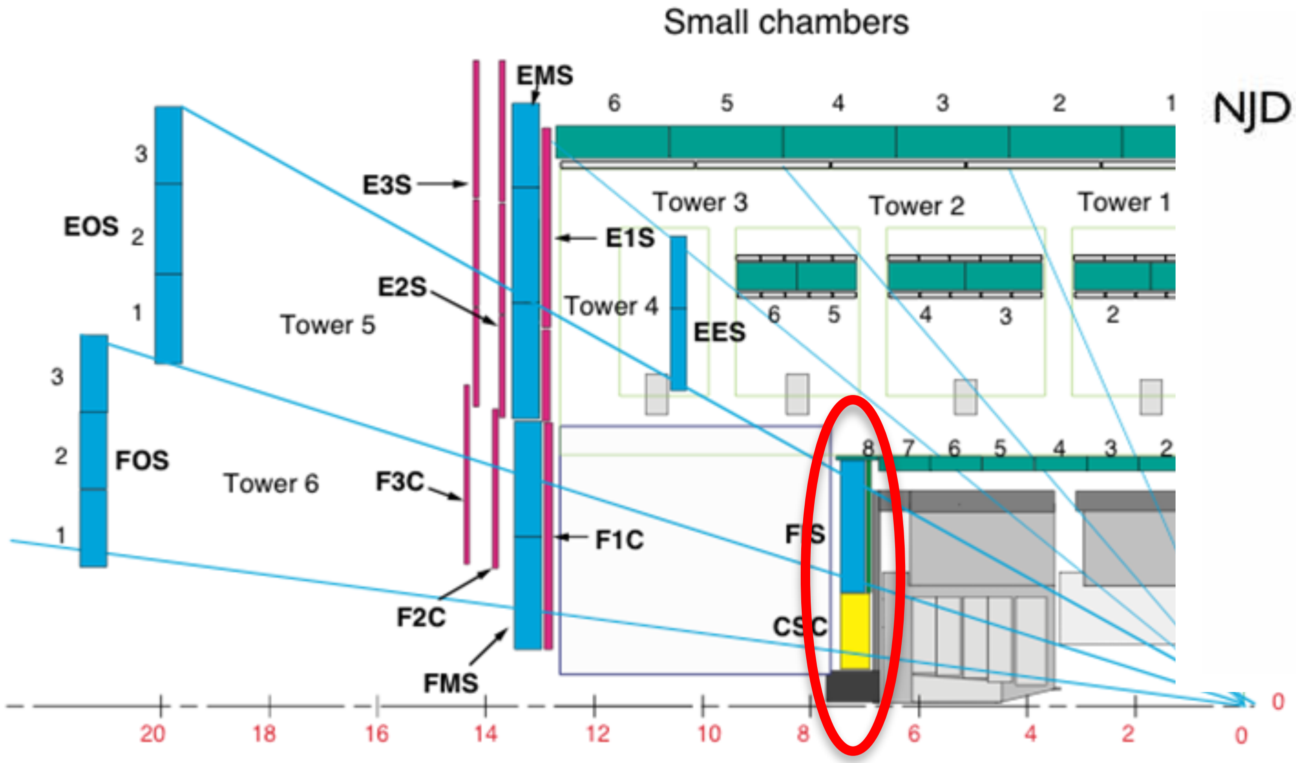


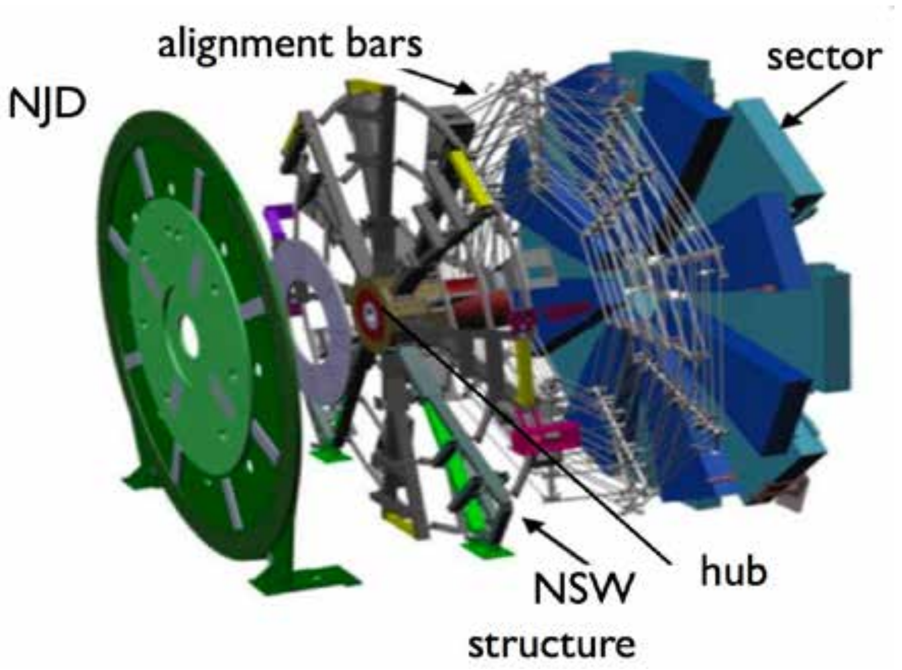
Replace muon small wheels with improved trigger capability: **<1mrad** angular resolution and associated trigger vector capability

2 sTGC quadruplets for trigger, bunch id and vector tracking with **<1mrad** resolution

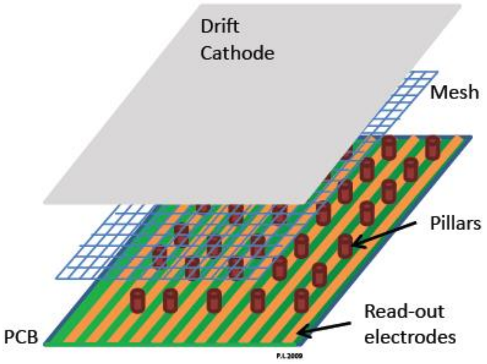
2 MicroMegas for quadruplets for tracking with resolution **<100μm**

New Small Wheel in construction

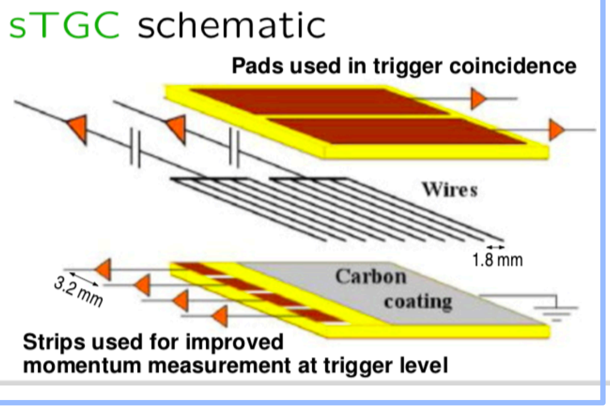




Micromegas



small Thin Gap Chambers (sTGC)



FINAL ADJUSTMENTS for PRODUCTION - VERY INTENSE CONSTRUCTION PERIOD AHEAD of US for INSTALLATION DURING LS2

PHASE-II UPGRADE

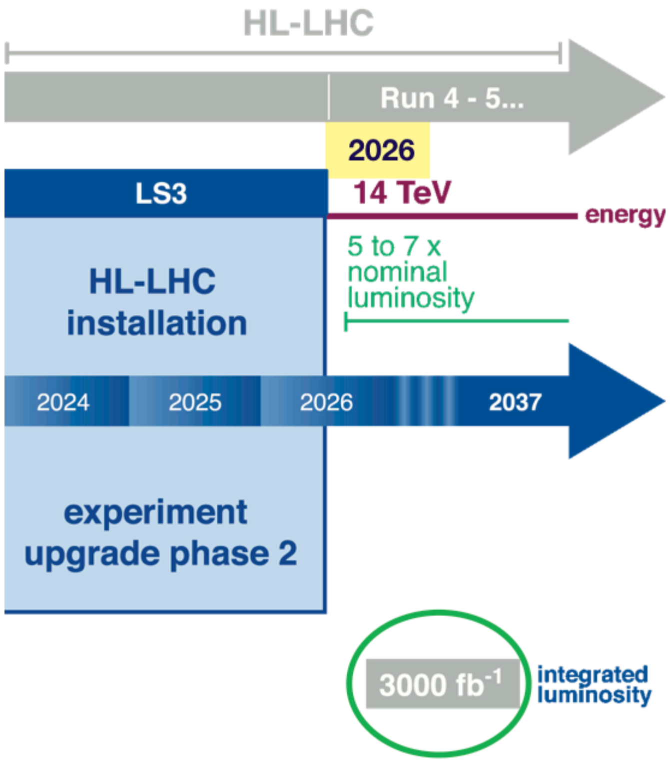
Inner Tracker

Calorimeters

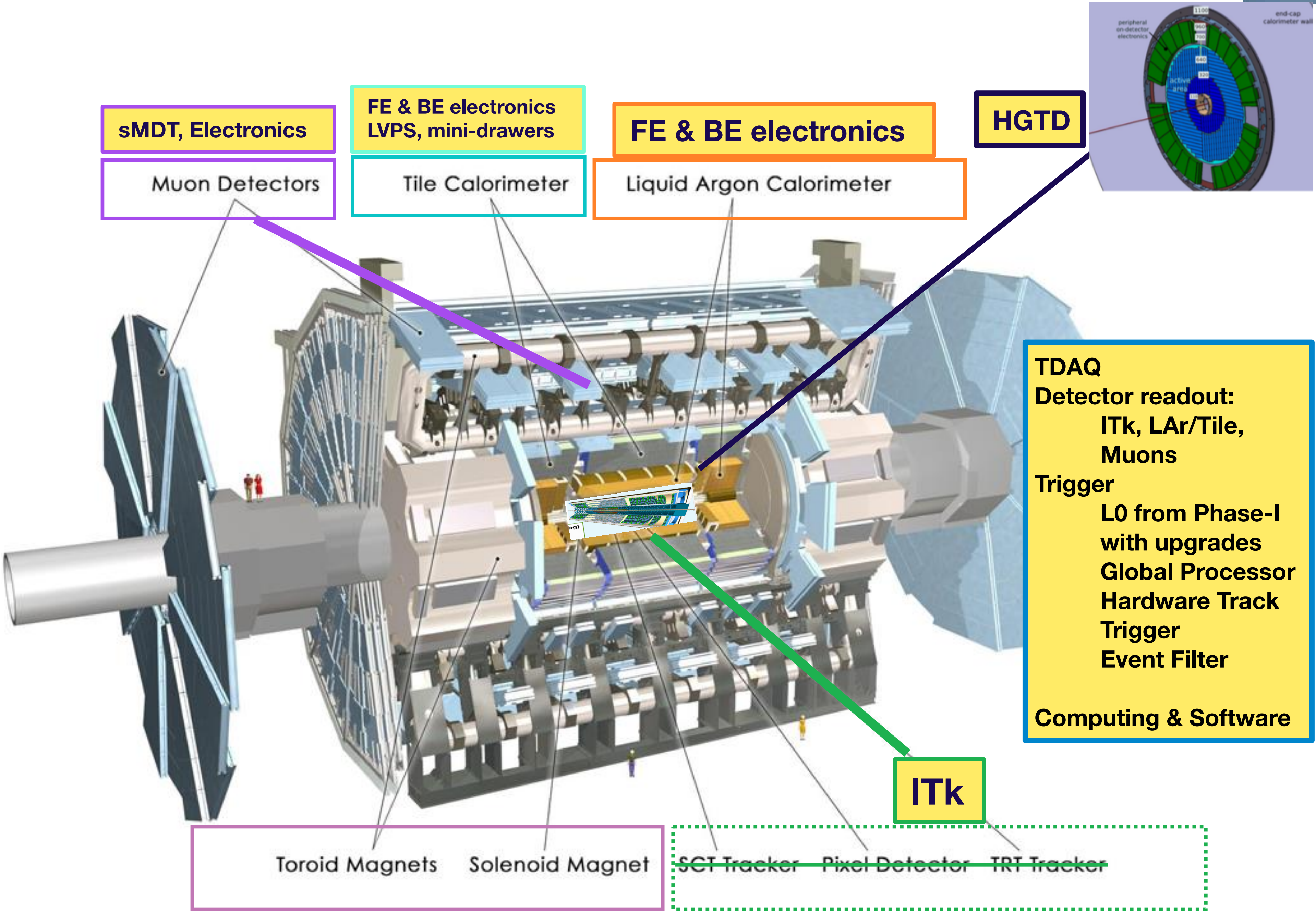
Muon System

TDAQ

High Granularity Timing Detector



The ATLAS detector: Phase-II upgrades



sMDT, Electronics

FE & BE electronics
LVPS, mini-drawers

FE & BE electronics

HGTD

ITk

TDAQ
Detector readout:
- **ITk, LAr/Tile, Muons**

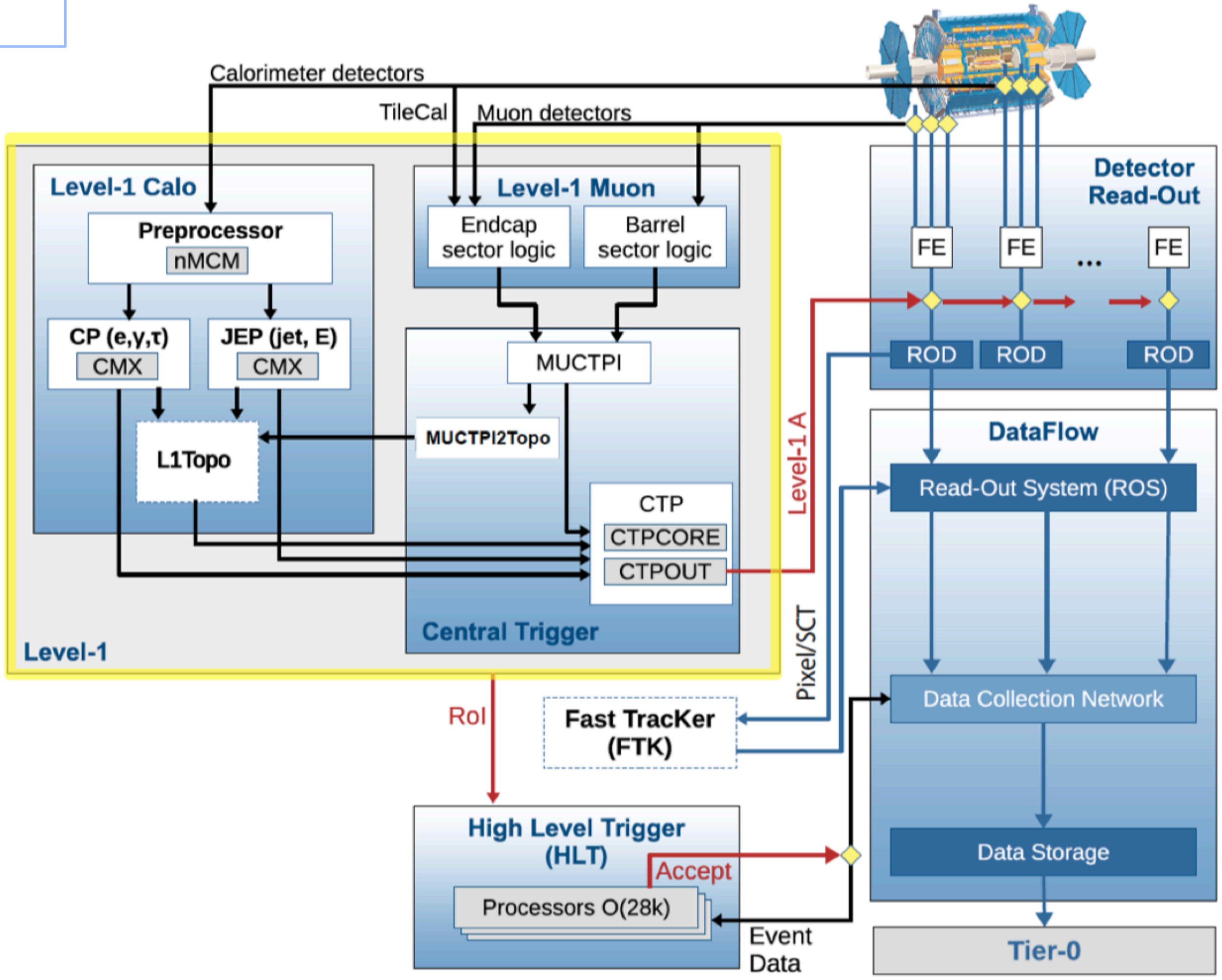
Trigger
- **L0 from Phase-I with upgrades**
- **Global Processor**
- **Hardware Track Trigger**
- **Event Filter**

Computing & Software

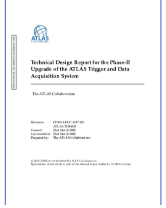
Trigger/DAQ upgrade for HL-LHC

Changes in the readout system have strong implications in the upgrade detector and electronics design.

Rate Latency	Run 2	Run 3 Phase I	Run4 Phase II
Level 0	-	-	1-4 MHz 6-10 μs
Level 1	100 kHz 2.5 μs	100 kHz 2.5 μs	400-800 kHz 35 μs
HLT	1kHz	1kHz	10 kHz



Trigger and Data Acquisition



Trigger/DAQ

Submission: Dec 2017
Approval: April 2018

Level-0 Trigger System 10 μs

Identify physics objects

Compute event level quantities

Send L0A to sub-systems

Data transmitted at 1MHz to FELIX

DAQ system

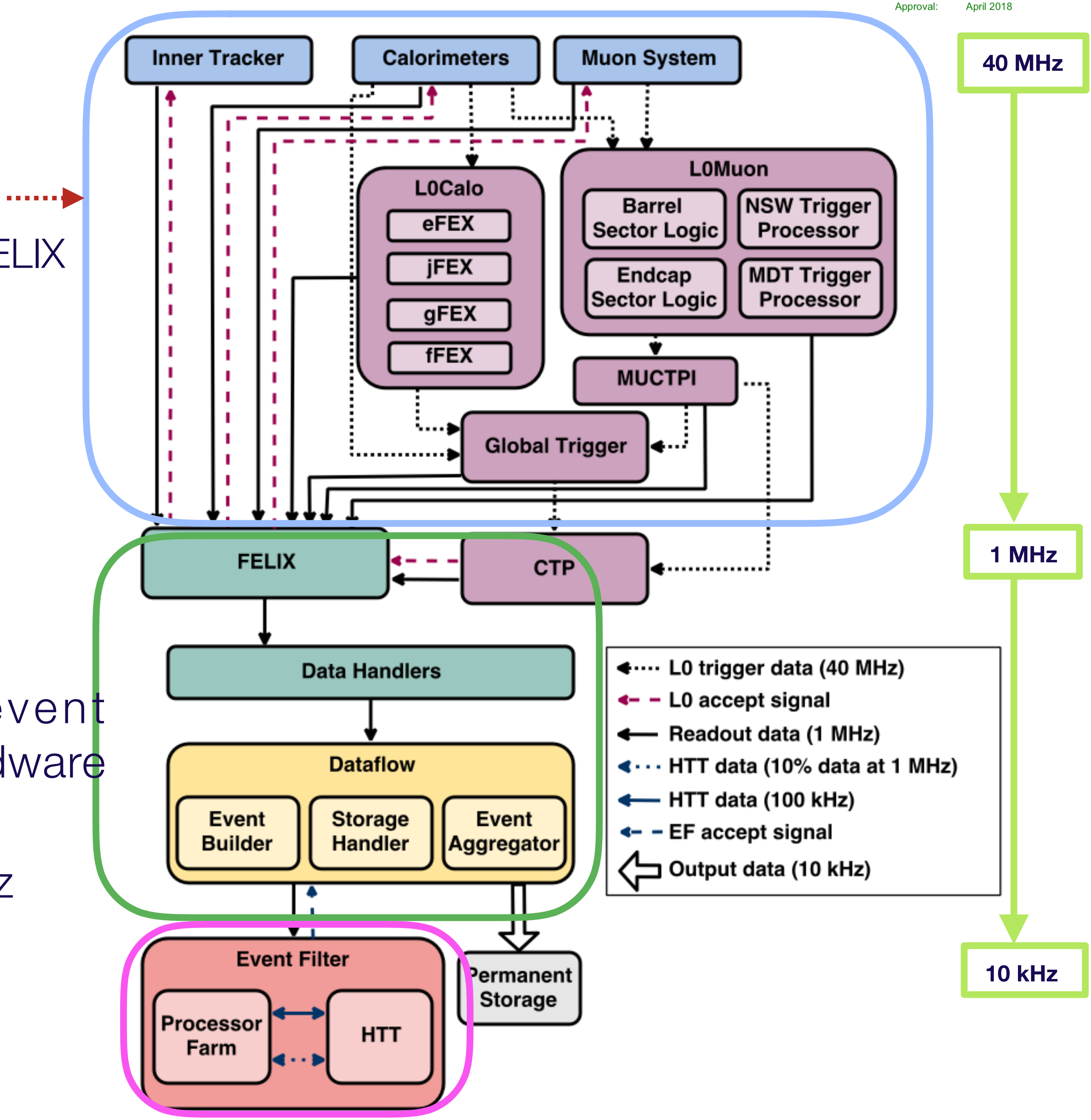
Event builder

Transmit events to

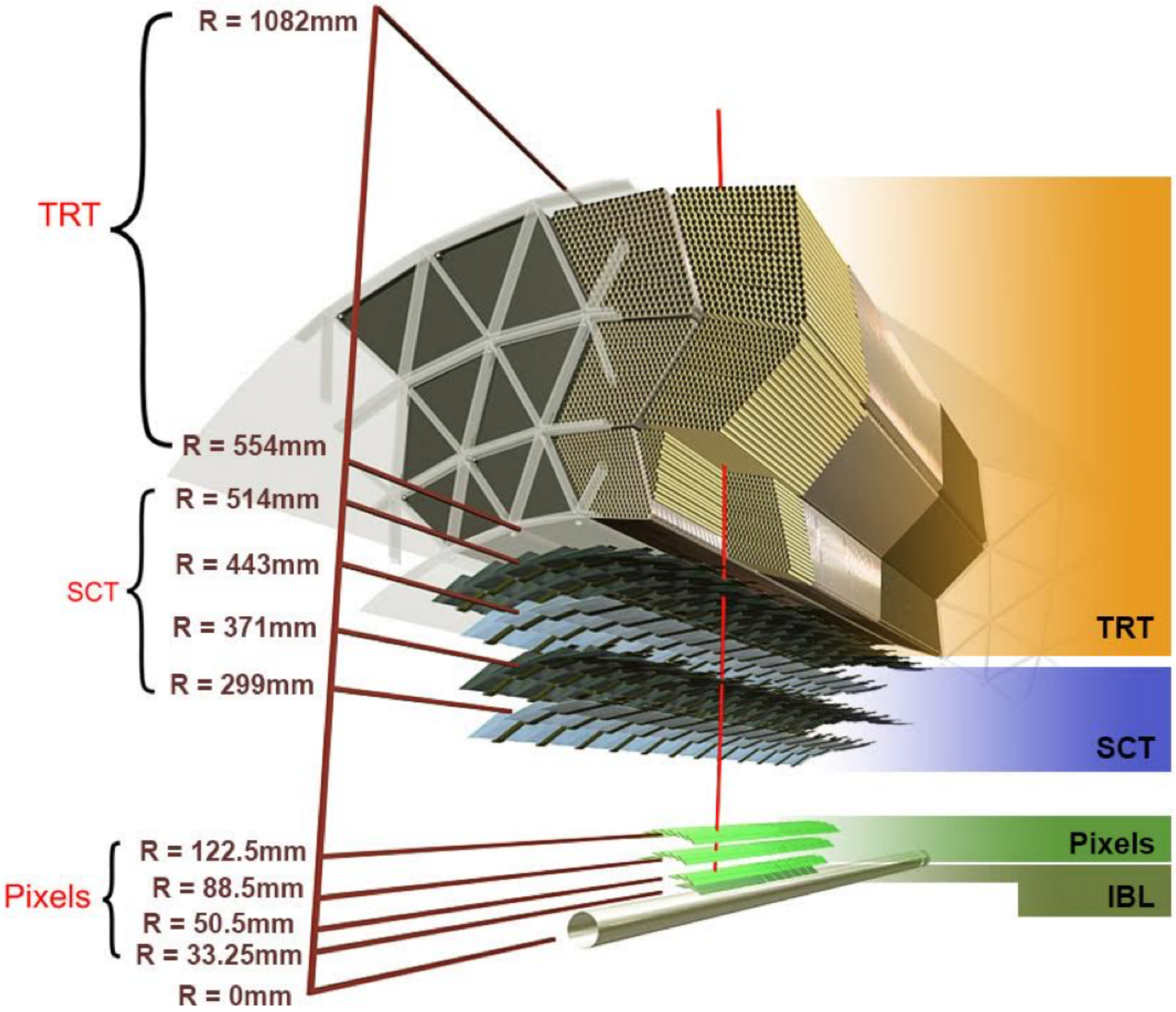
Event Filter System

Decision based on event reconstruction and Hardware Track Trigger

Output to storage at 10 kHz



The ATLAS INNER DETECTOR



Pixels 90
Strips 6
TRT 0.3
} 10^6 channels

$|\eta|<2.5$

pixel

IBL 50x250 μm^2

σ_{hit}=10/70 μm Rϕ/z

pixels 50x400 μm^2

σ_{hit}=10/115 μm Rϕ/z

SCT

pitch 60-80 μm; length ~ 6cm

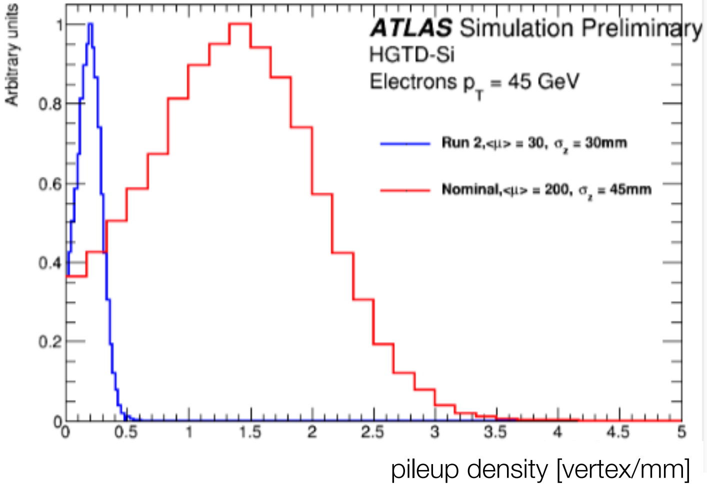
σ_{hit}=17/580 μm Rϕ/z

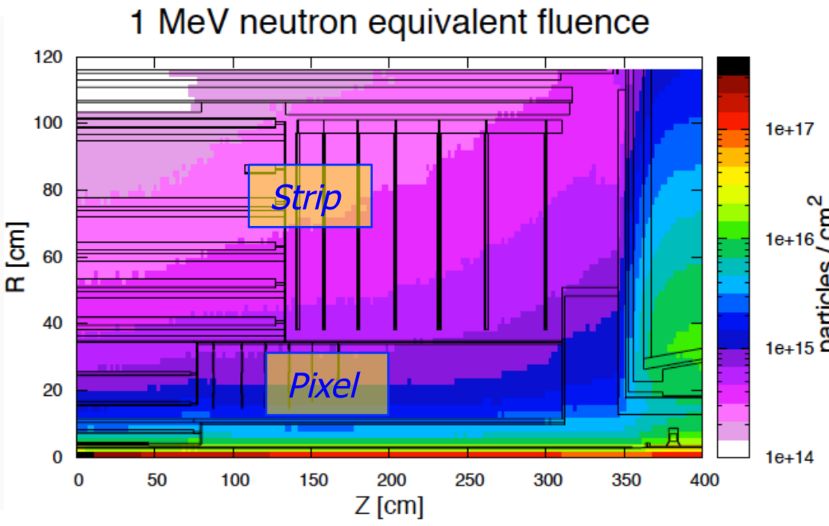
TRT

σ_{hit}=130 μm

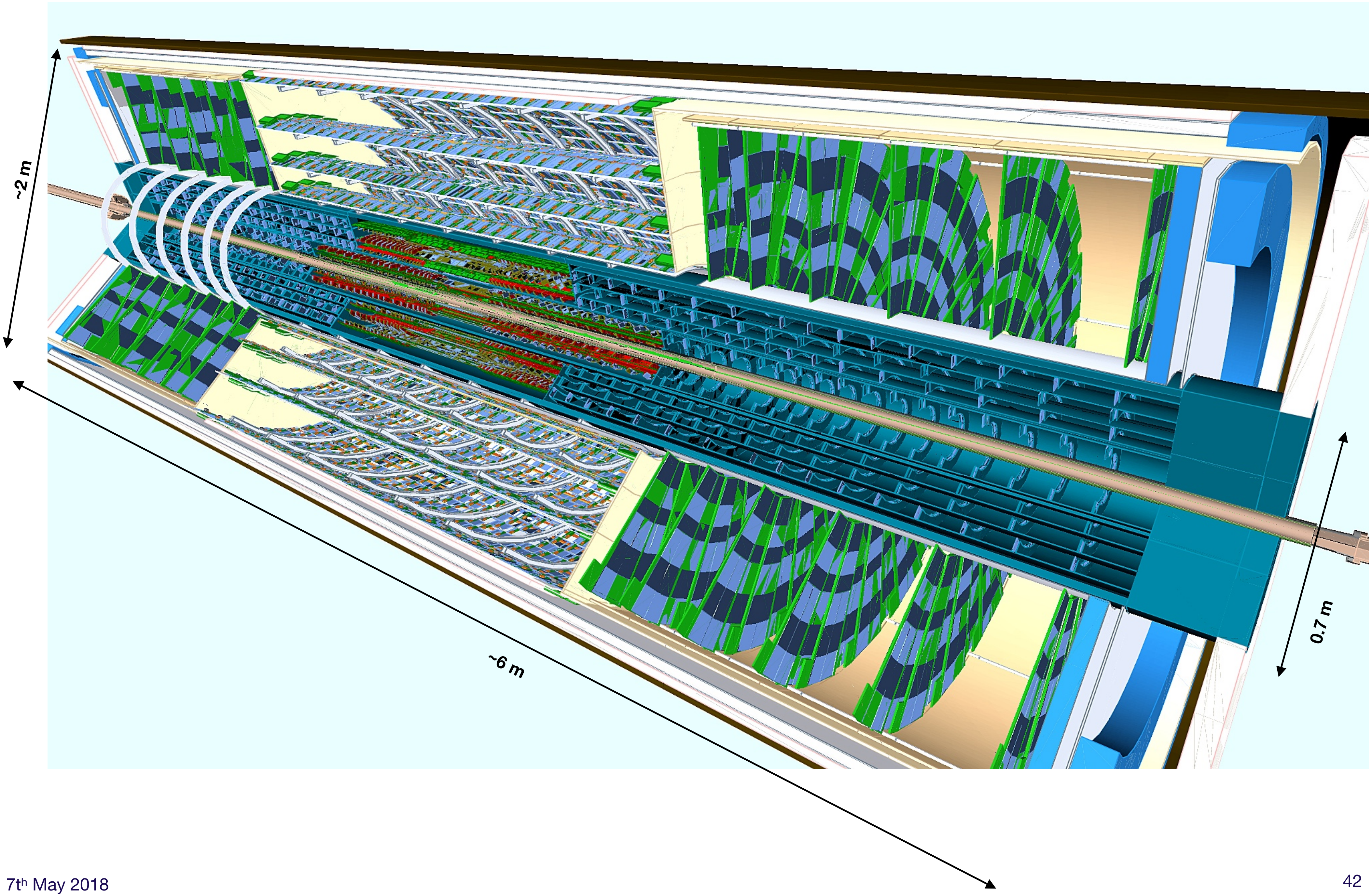
ATLAS Inner Tracker -ITk- for HL-LHC

200 pile-up events	occupancy	high granularity, material
10^{16} neq/cm^2, 10 MGy	conception, tests	modularity
3000 events/fb	2026-2037	robust
VBF/VBS	Increased η coverage	|η|<4





ATLAS Inner Tracker -ITk- for HL-LHC



ITk HOME

ITk: The new ATLAS Inner Tracker

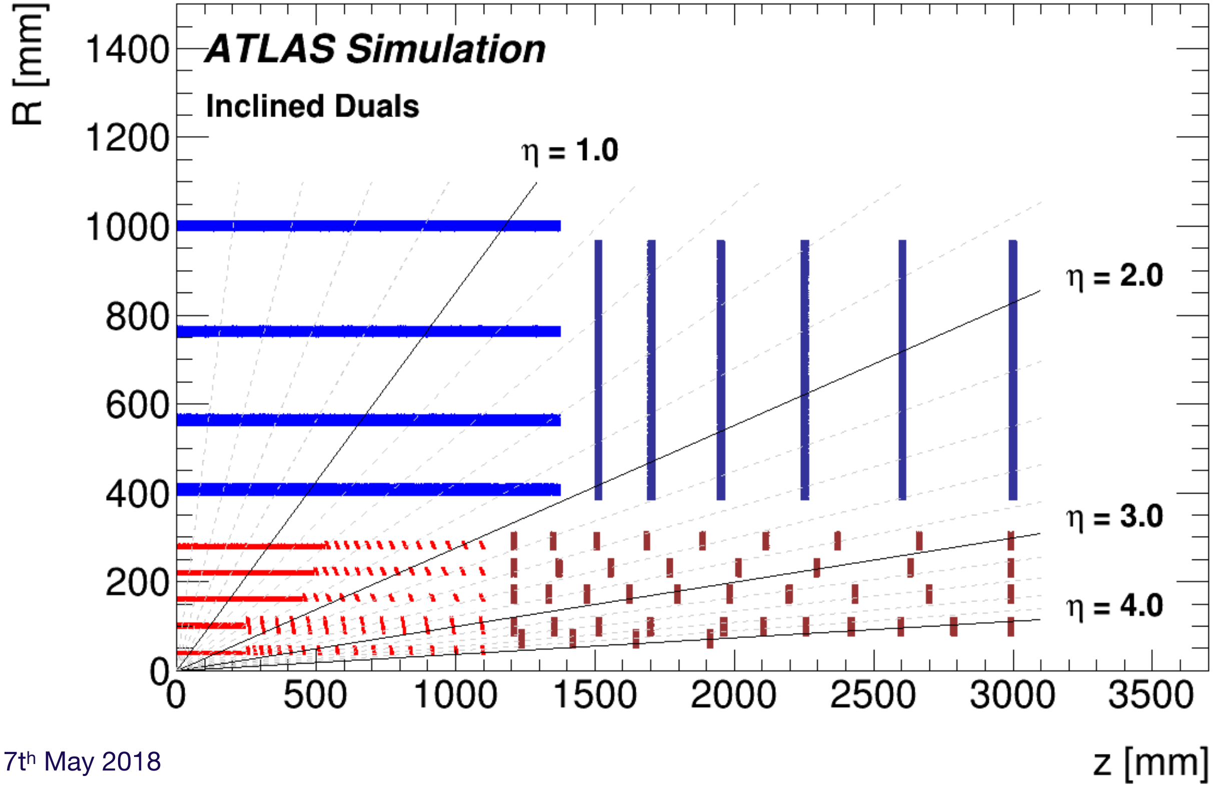
Motivation

Replacement of the central tracking detector in ATLAS.

Essential to manage the higher track densities at the anticipated luminosities. Essential to adapt the detector technologies to the higher radiation levels

Layout has converged on a **silicon pixel** (5 layers in the barrel, confined to a cylinder of R=34.5 cm around the beam pipe) + a **silicon strip** system (4 oute layers in the barrel).

Extension of η coverage to 4.0: requires novel technical advances



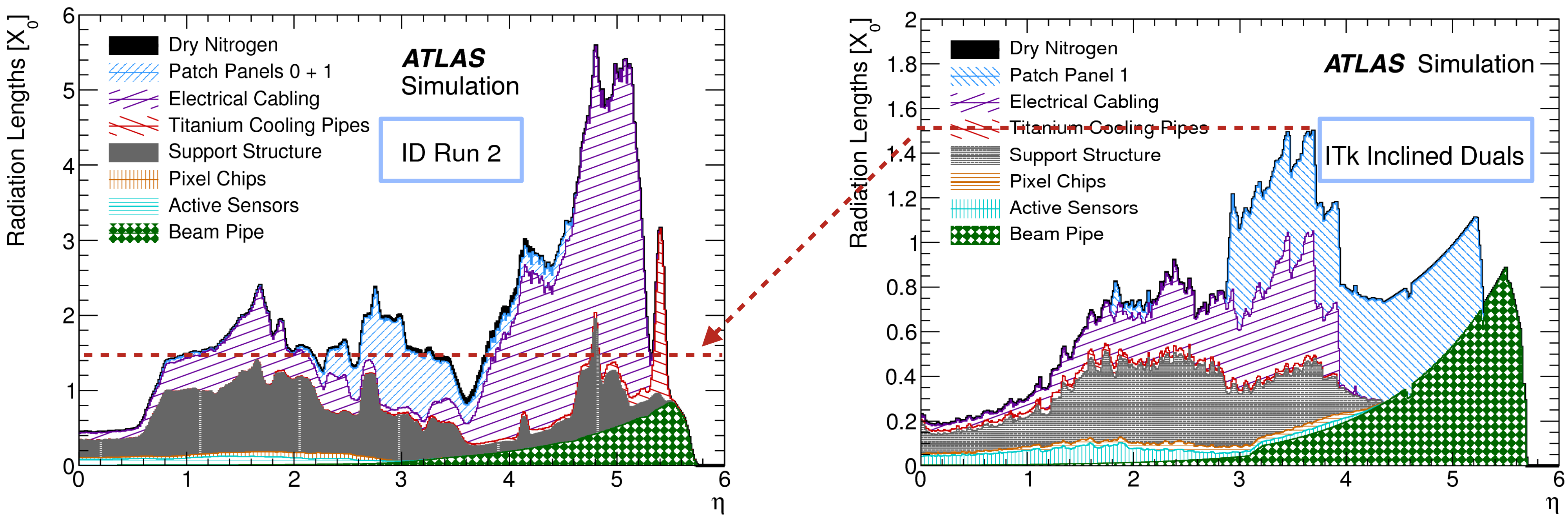
Pixels 600
Strips 70
} 10^6 channels

|η|<4.0

Pixel 25x100 or 50x50 μm²

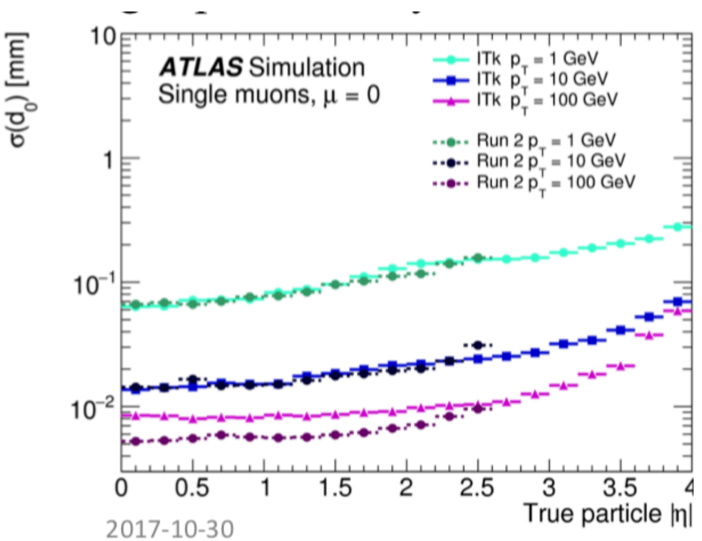
Strips 75μm pitch; length ~10 cm

ITk - MATERIAL

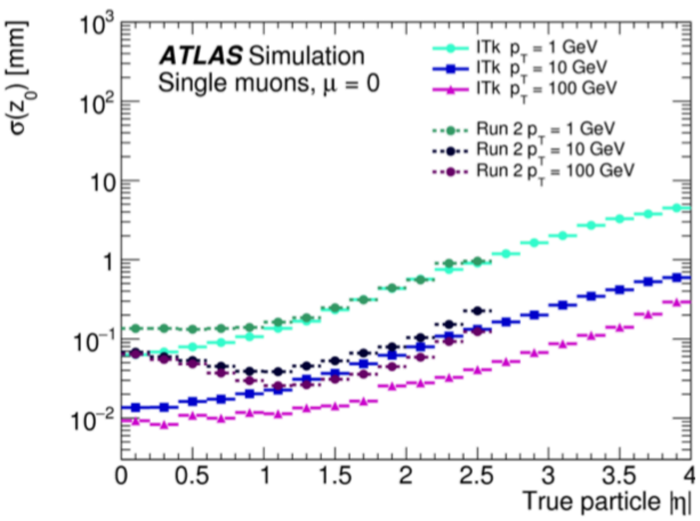


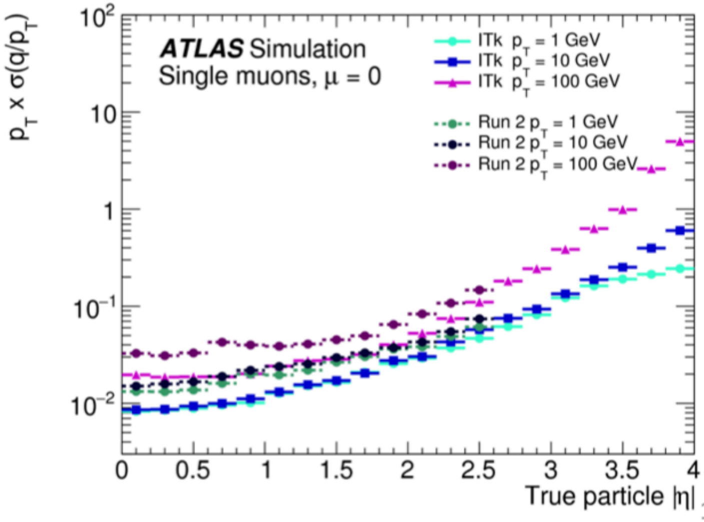
Thinner sensors
Improved (modern) material structure
Titanium tubes for cooling
Sensors inclined in extended barrel section

ITk - PERFORMANCE



2017-10-30





Excellent capability to resolve the position and momentum

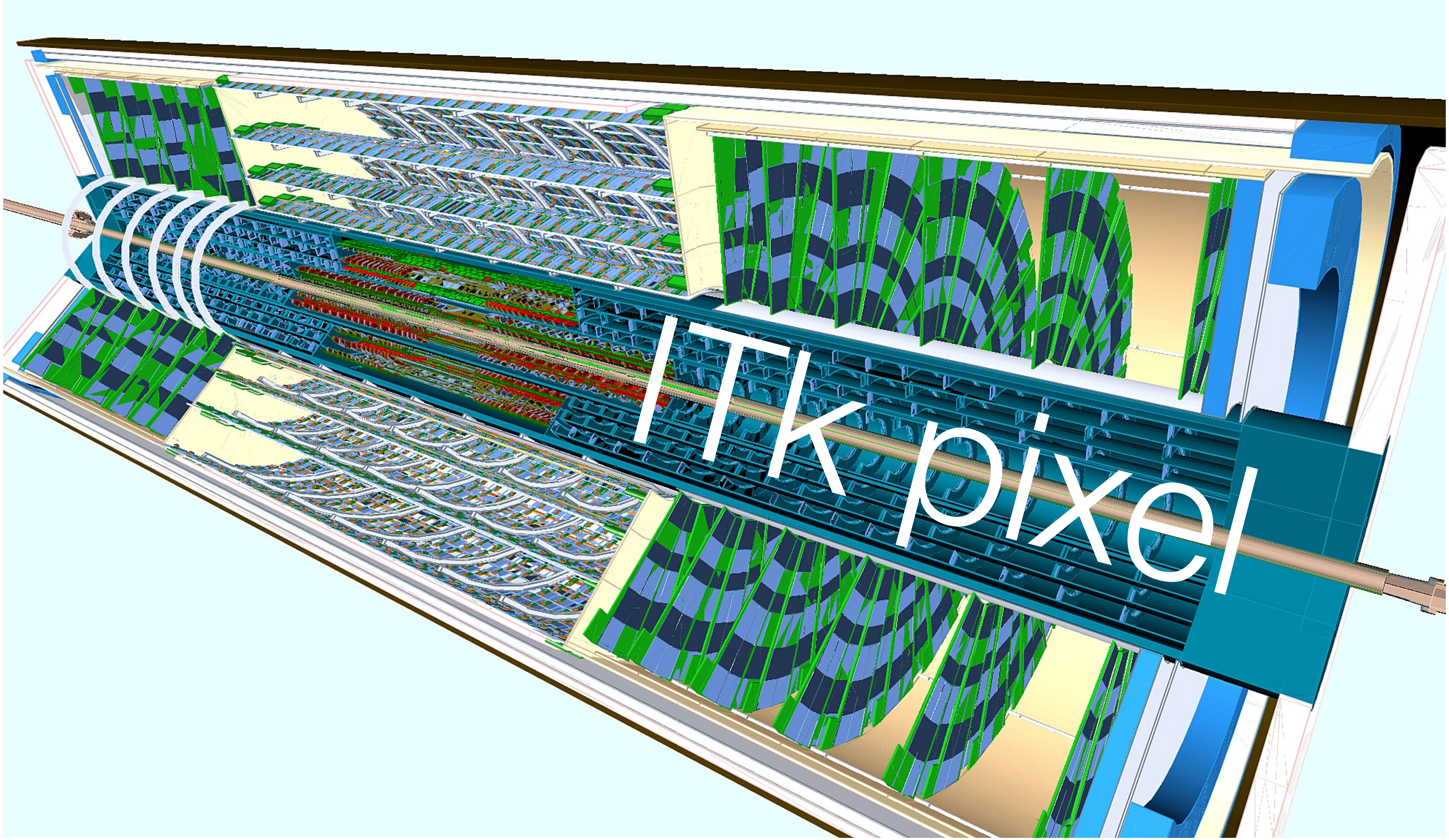
Transverse impact parameter (IP) resolution d_0 similar to current ID

- Run-2 performance better at very high momentum due to analog clustering calibration while such calibrations are not yet ready for ITk
  - ITk with analogue clustering expected to provide similar resolution as for the current ID

Significant improvements in the longitudinal IP resolution z_0.

- Reduction of pixel pitches from 250/400 μm to 50 μm for ITk.

Momentum resolution substantially improved by high precision measurements along the full track length provided by the full silicon tracker


ITk pixel

ITk- pixels

The TDR baseline design was defined aiming at

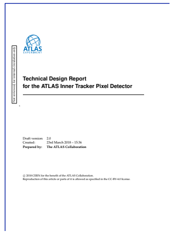
> **5 hits** close to the interaction point with high granularity and accuracy **~10 µm**

> **9 precision hits** over the full acceptance (-4<η<4) and up to R~1m

Minimisation of material over the full η acceptance

Best physics reach: good b-tagging, efficient reconstruction in dense jets and in high pile-up environnement, precise track & vertex measurements

Short barrel followed by inclined modules and the by disks (of different coverage: a measurement layer is not necessarily coplanar)



Not reviewed, for internal circulation only

Technical Design Report
for the ATLAS Inner Tracker Pixel Detector

Draft version: 2.0
Created: 23rd March 2018 – 15:36
Prepared by: The ATLAS Collaboration

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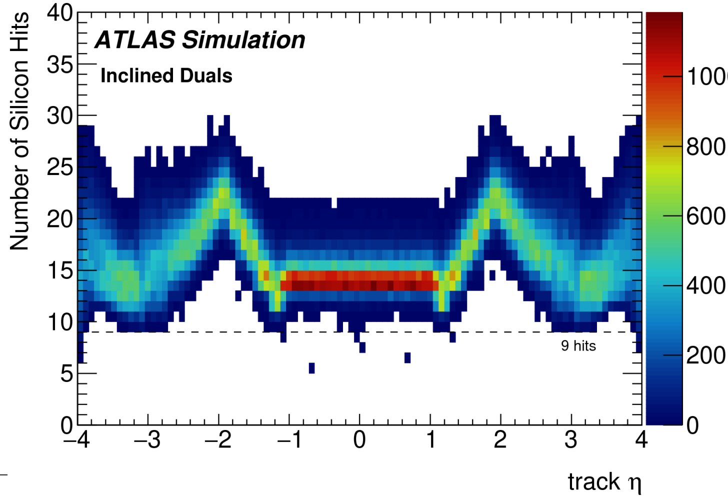
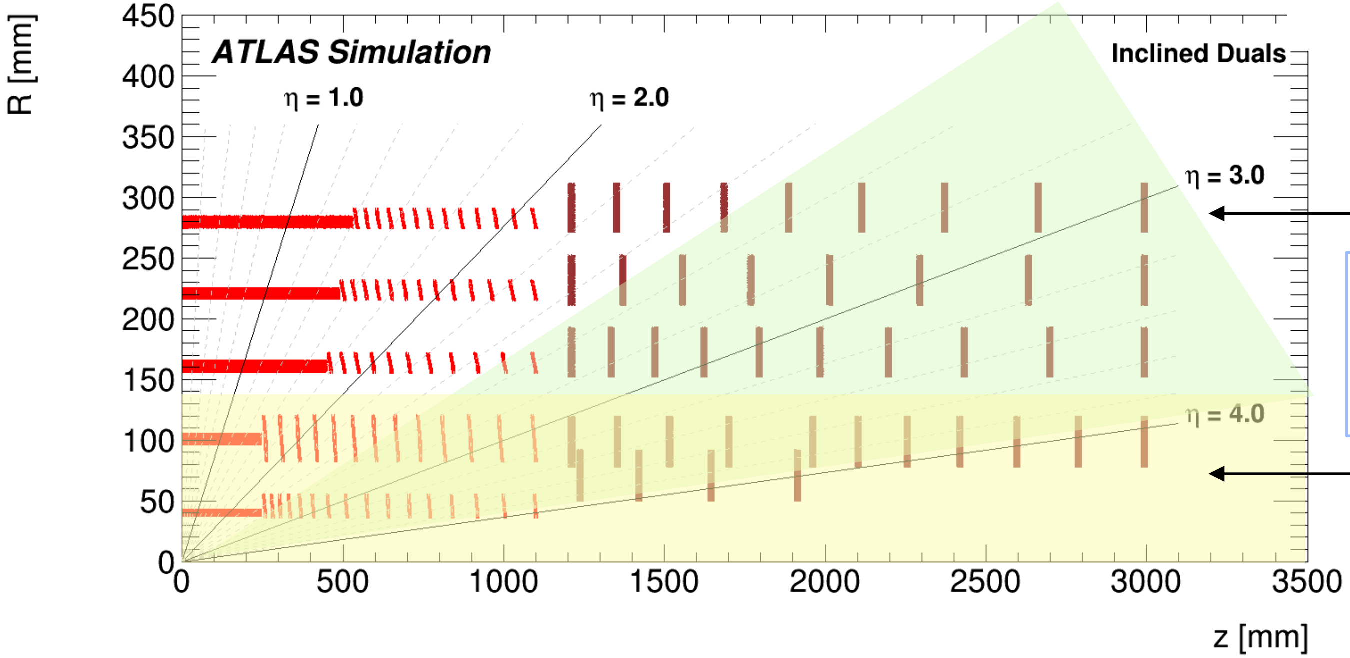
ITk pixel tracker

Submission: Dec 2017
Approval: April 2018





Additional η coverage

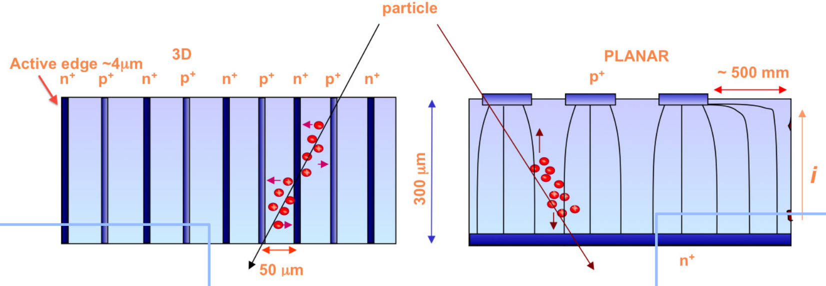
Active area: 12.7 m²
pixel size: 50x50 (or 25x100) µm²
Number of modules: 10276
Number of FE chips: 33184
Number of channels: ~500 10⁶

Insertable inner layers

ITk - pixels sensors

Sensor technology must be tailored to the radiation environnement (and financial constraints)

The baseline for ITk-pixel is **3D** for the innermost layer(s) and **planar** elsewhere.



3D sensors

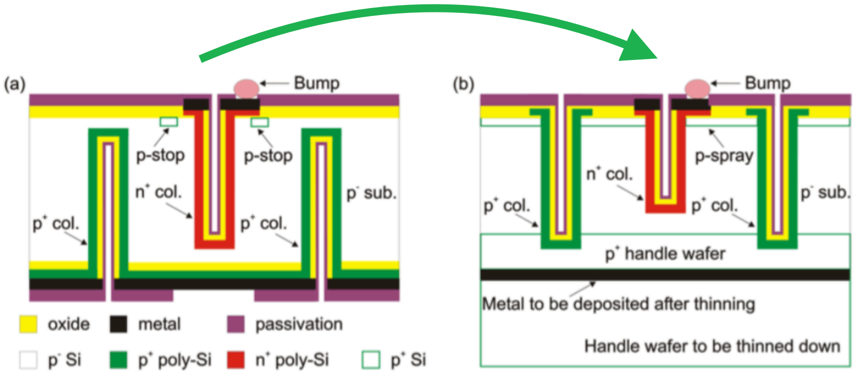
Used in IBL and performing well
An improved design has been developed for ITk-pixel:

- More rad-hard and less power consumption
- To increase yield, a single side process has been studied and implemented

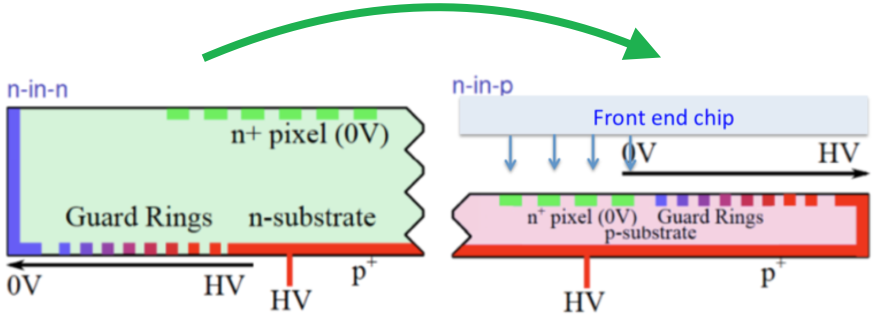
Plannar sensors

Well proven and understood technique, but must simplify production to decrease cost (n-in-p = single sided process)
An improved design has been developed for ITk-pixel:

- More rad-hard and less power consumption
- To increase yield, a single side process has been studied and implemented



G.F. Dalla Betta et al. PoS (Vertex 2016) 028

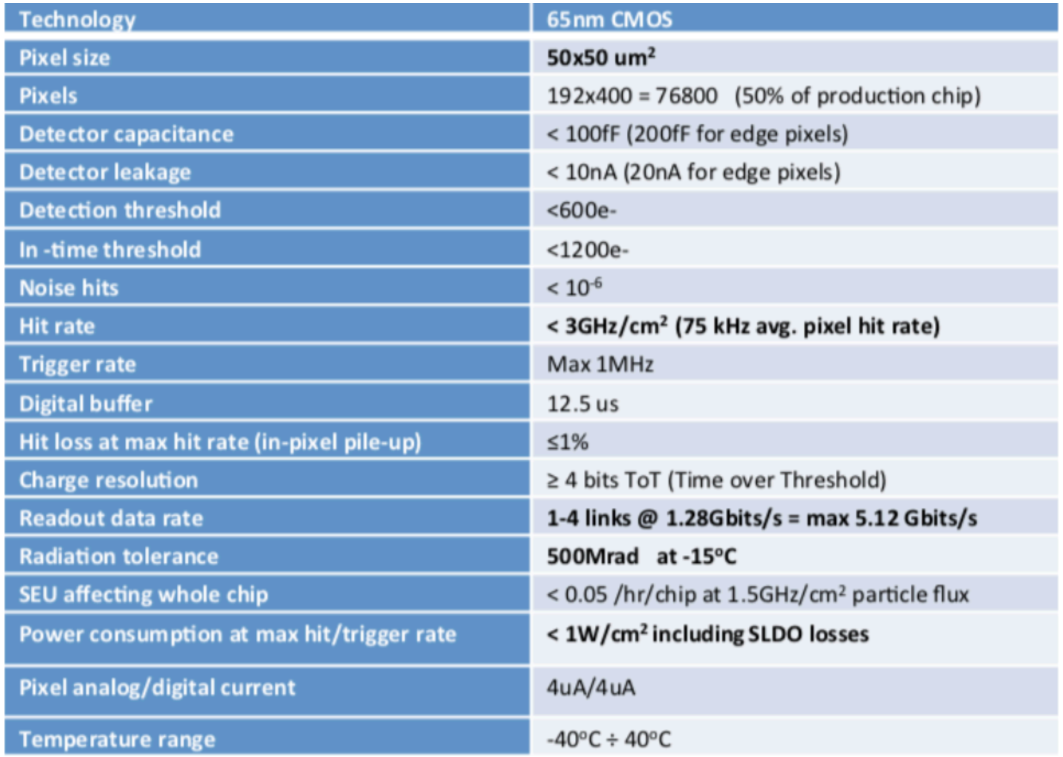


ATLAS Inner Tracker -ITk- for HL-LHC - pixels frontend electronics

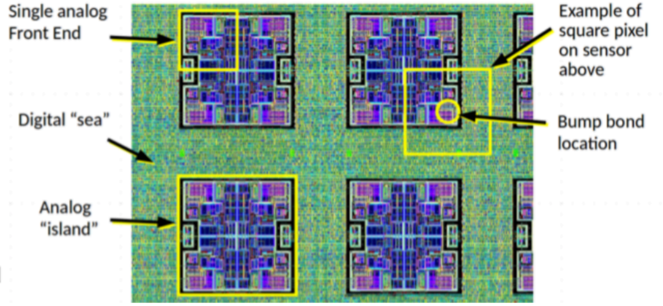
Synergic development with CMS (RD53) to design FE pixel ASIC for HL-LHC.

Main characteristics

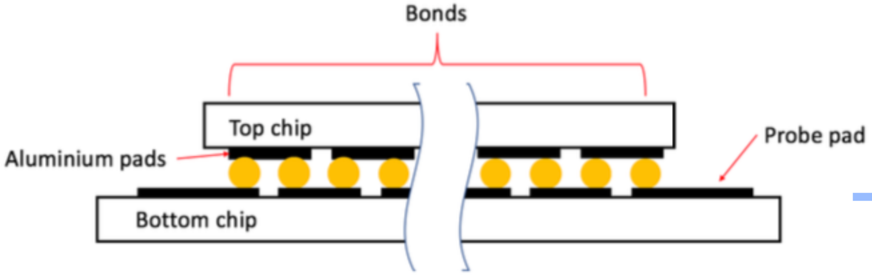
- Increased radiation hardness using 65nm technology in TSMC
- Smallest pitch for hybrid LHC application so far, 50x50 μm^2 (possibility for 25x100 μm^2)
- Highest data rate achievable per ASIC: 5Gbps



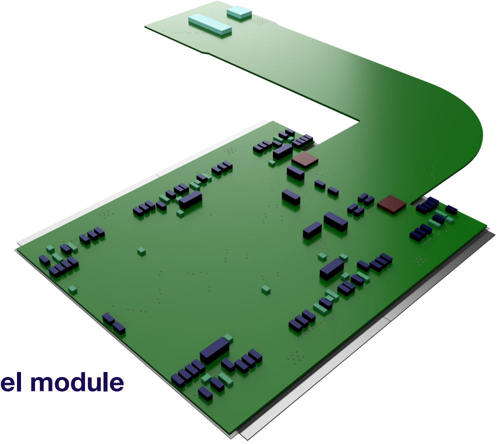
Technology	65nm CMOS
Pixel size	**50x50 um^2**
Pixels	192x400 = 76800 (50% of production chip)
Detector capacitance	< 100fF (200fF for edge pixels)
Detector leakage	< 10nA (20nA for edge pixels)
Detection threshold	<600e-
In -time threshold	<1200e-
Noise hits	< 10^{-6}
Hit rate	**< 3GHz/cm^2 (75 kHz avg. pixel hit rate)**
Trigger rate	Max 1MHz
Digital buffer	12.5 us
Hit loss at max hit rate (in-pixel pile-up)	≤1%
Charge resolution	≥ 4 bits ToT (Time over Threshold)
Readout data rate	**1-4 links @ 1.28Gbits/s = max 5.12 Gbits/s**
Radiation tolerance	**500Mrad at -15°C**
SEU affecting whole chip	< 0.05 /hr/chip at 1.5GHz/cm^2 particle flux
Power consumption at max hit/trigger rate	**< 1W/cm^2 including SLDO losses**
Pixel analog/digital current	4uA/4uA
Temperature range	-40°C ÷ 40°C



ITk-pixel: from sensors to construction

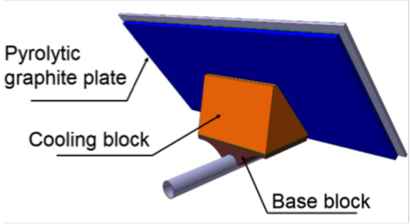


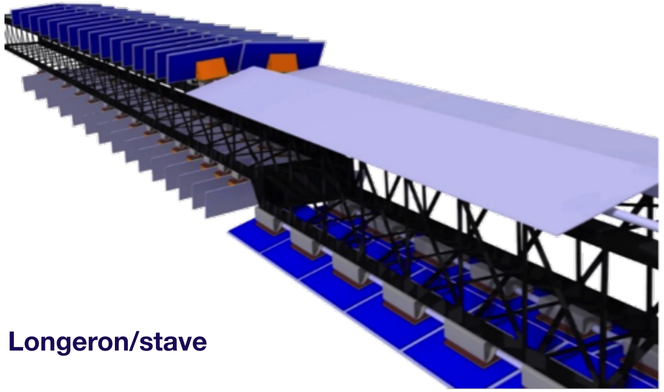
Hybrid Sensor+Readout chip



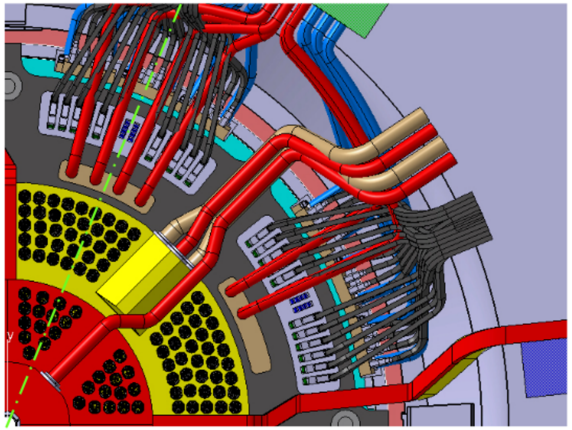
pixel module

Prepared for assembly

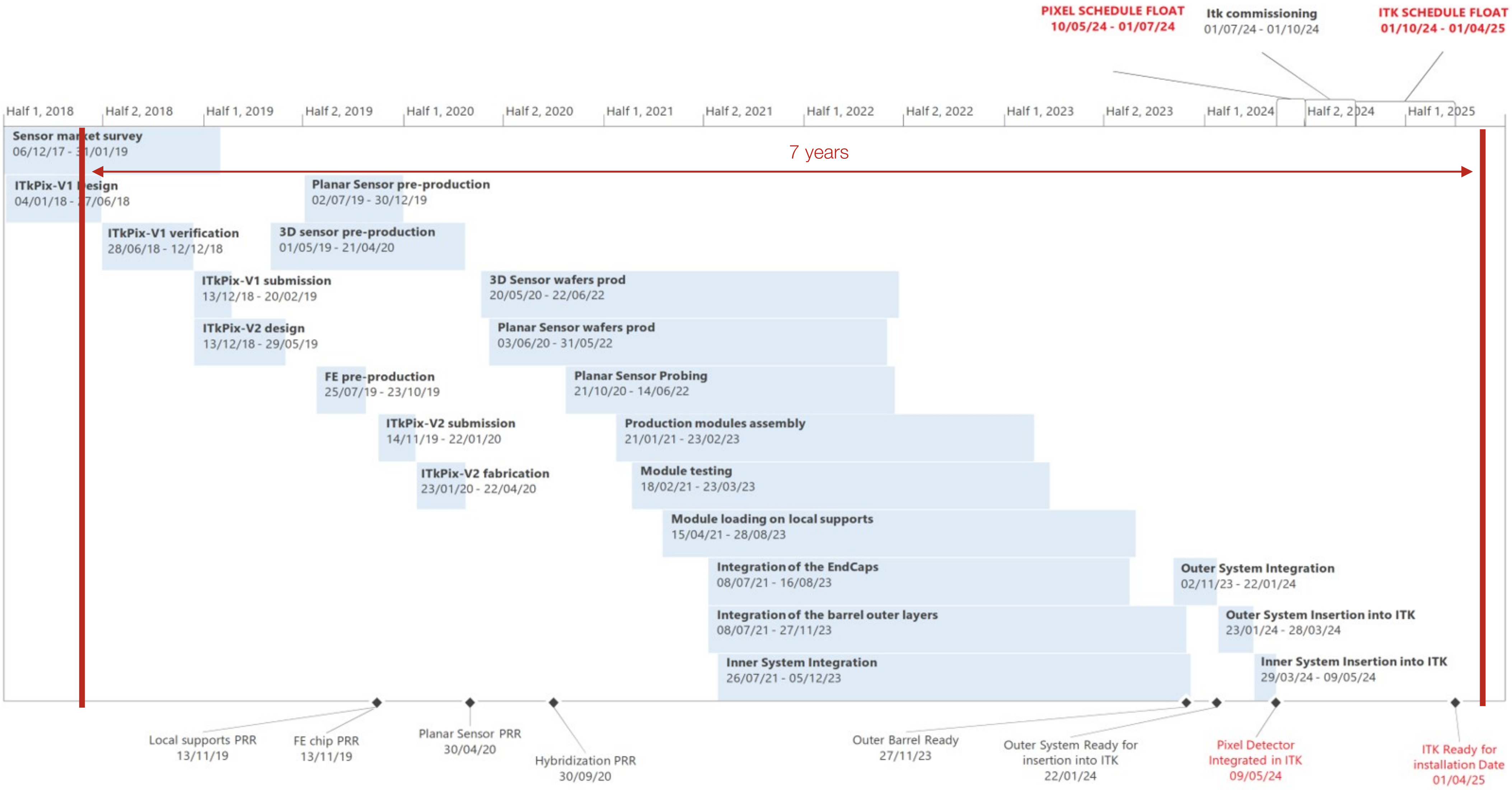




Longeron/stave



ATLAS Inner Tracker -ITk- for HL-LHC - pixel schedule



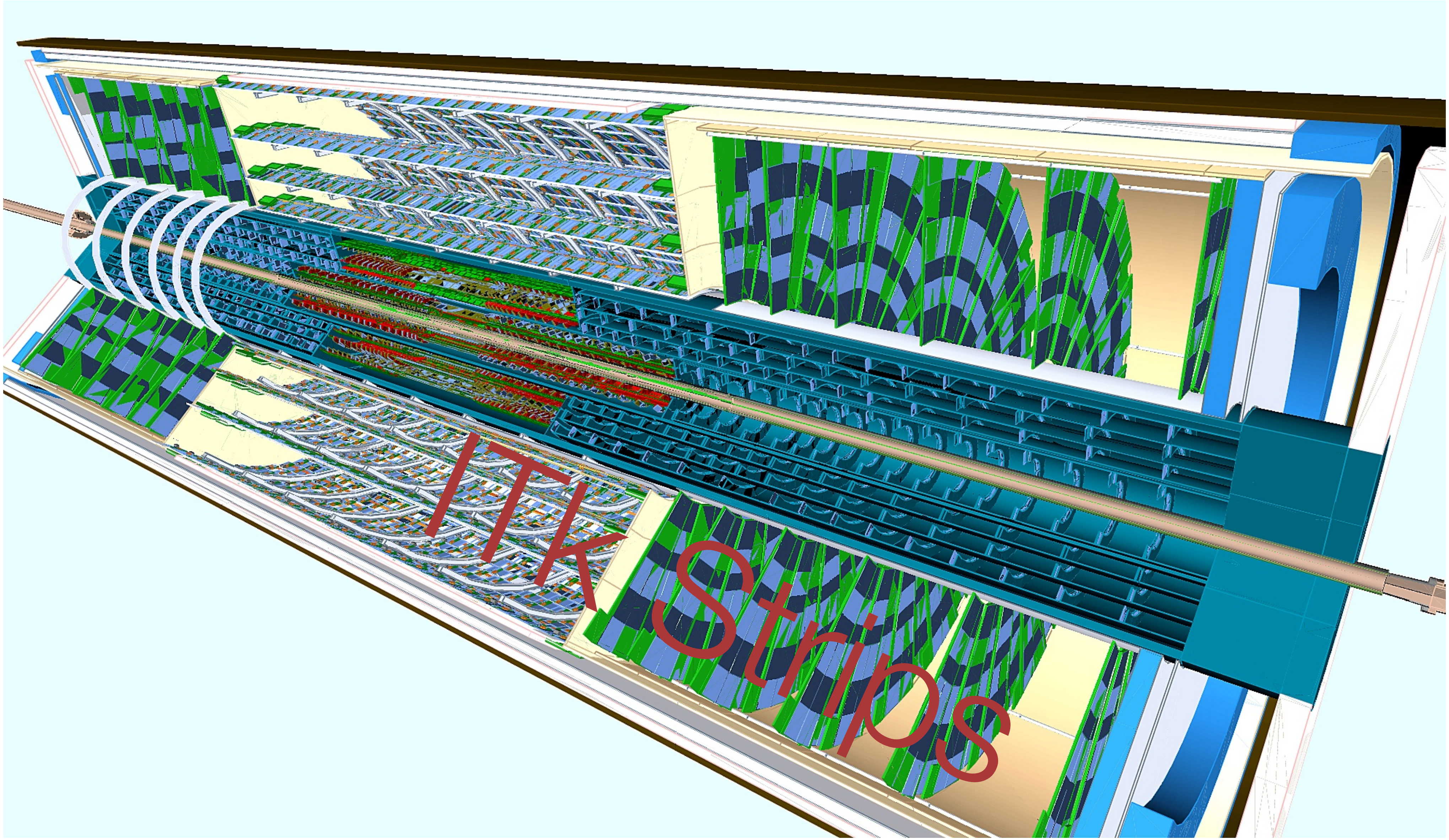
PIXEL SCHEDULE FLOAT 10/05/24 - 01/07/24

Itk commissioning 01/07/24 - 01/10/24

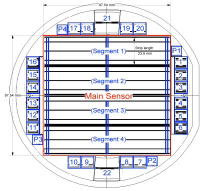
ITK SCHEDULE FLOAT 01/10/24 - 01/04/25

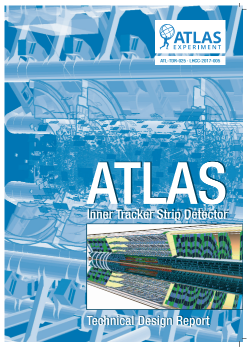
Task	Dates
Sensor market survey	06/12/17 - 31/01/19
ITkPix-V1 Design	04/01/18 - 27/06/18
Planar Sensor pre-production	02/07/19 - 30/12/19
ITkPix-V1 verification	28/06/18 - 12/12/18
3D sensor pre-production	01/05/19 - 21/04/20
ITkPix-V1 submission	13/12/18 - 20/02/19
3D Sensor wafers prod	20/05/20 - 22/06/22
ITkPix-V2 design	13/12/18 - 29/05/19
Planar Sensor wafers prod	03/06/20 - 31/05/22
FE pre-production	25/07/19 - 23/10/19
Planar Sensor Probing	21/10/20 - 14/06/22
ITkPix-V2 submission	14/11/19 - 22/01/20
Production modules assembly	21/01/21 - 23/02/23
ITkPix-V2 fabrication	23/01/20 - 22/04/20
Module testing	18/02/21 - 23/03/23
Module loading on local supports	15/04/21 - 28/08/23
Integration of the EndCaps	08/07/21 - 16/08/23
Outer System Integration	02/11/23 - 22/01/24
Integration of the barrel outer layers	08/07/21 - 27/11/23
Outer System Insertion into ITK	23/01/24 - 28/03/24
Inner System Integration	26/07/21 - 05/12/23
Inner System Insertion into ITK	29/03/24 - 09/05/24

Milestone	Date
Local supports PRR	13/11/19
FE chip PRR	13/11/19
Planar Sensor PRR	30/04/20
Hybridization PRR	30/09/20
Outer Barrel Ready	27/11/23
Outer System Ready for insertion into ITK	22/01/24
Pixel Detector Integrated in ITK	09/05/24
ITK Ready for installation Date	01/04/25


ITk Strips

ATLAS Inner Tracker -ITk- for HL-LHC - **Strips**





ATLAS EXPERIMENT
ATL-TDR-025 · LHCC-2017-005

ATLAS
Inner Tracker Strip Detector
Technical Design Report

ITk strip tracker

Submission:	Dec 2016
Approval:	June 2017

Key components

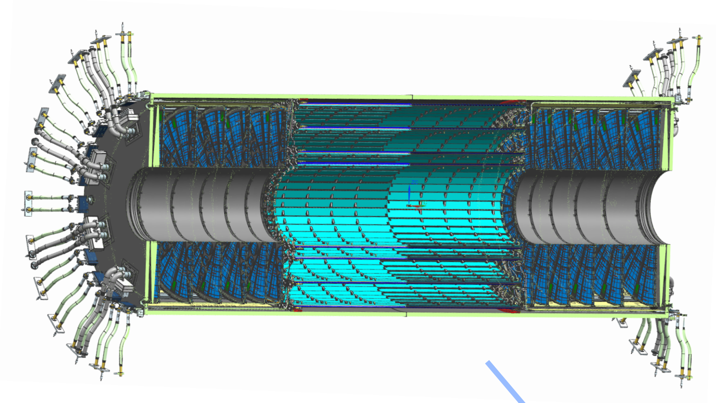
- Sensors
- ASICS
- Optoelectronics

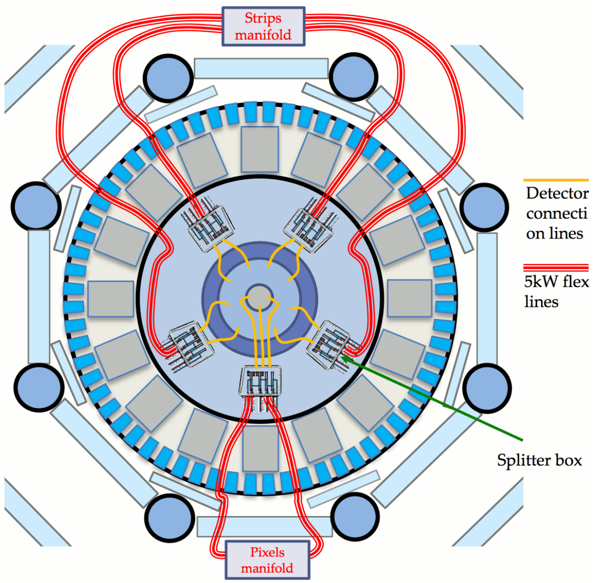
System construction

- Modules
- Staves/petals
- Structures

System

- Powering
- Reliability





ATLAS Inner Tracker -ITk- for HL-LHC - Strips Sensors

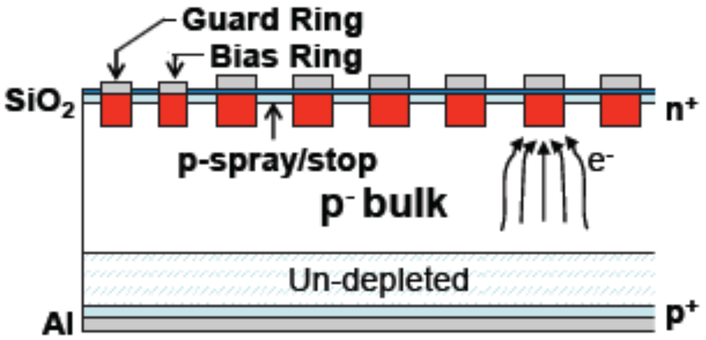
Type n-in-p (SCT p-in-n)

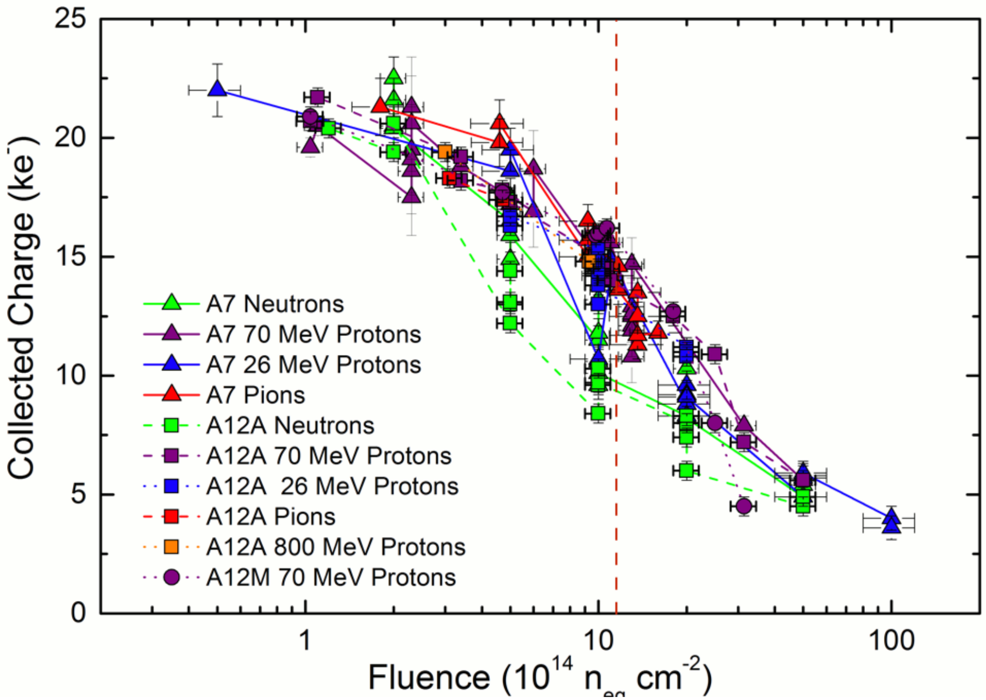
Signal is mainly from electrons (faster than holes)

Depletes from junction: can operate under-depleted

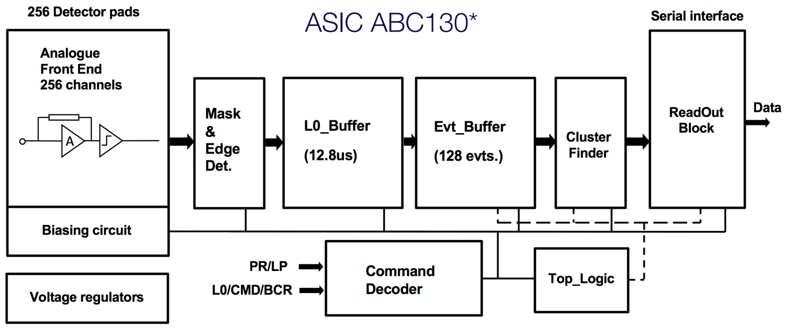
Cheaper than n-in-n

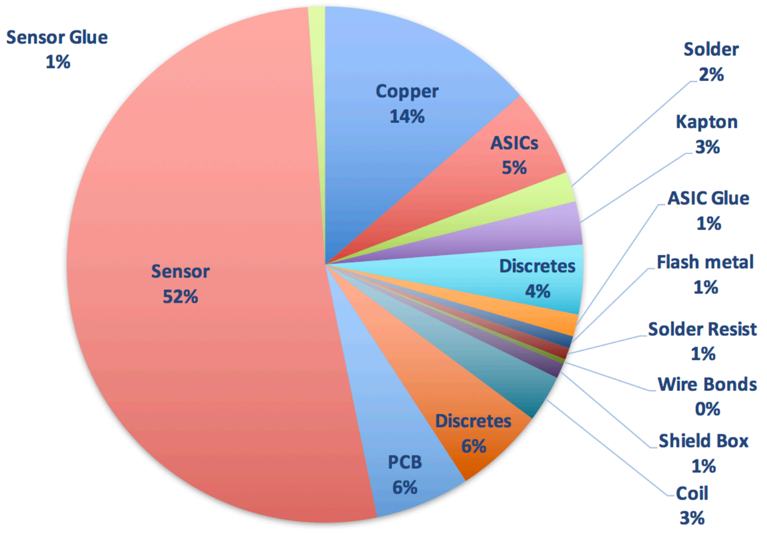
Sufficient signal for maximum strip fluence.



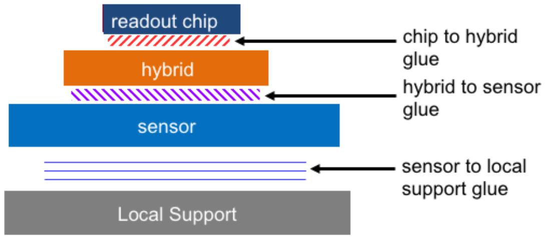


ATLAS Inner Tracker -ITk- for HL-LHC - Strips Module

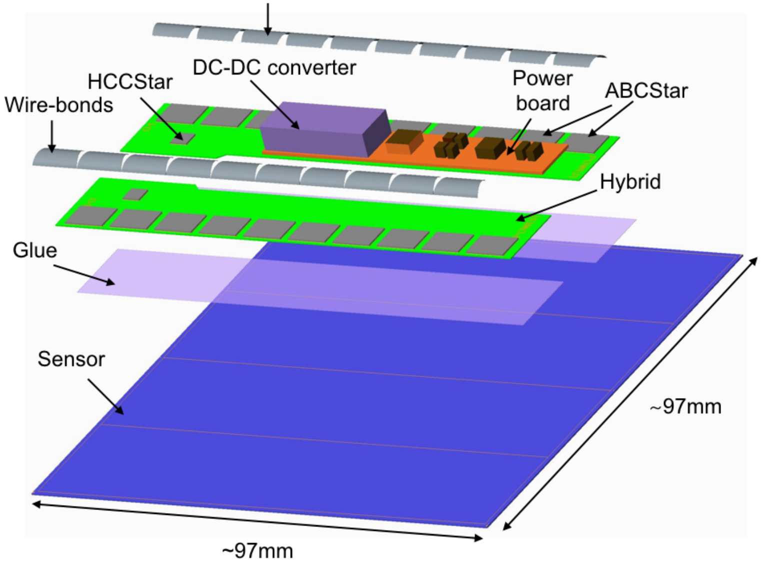




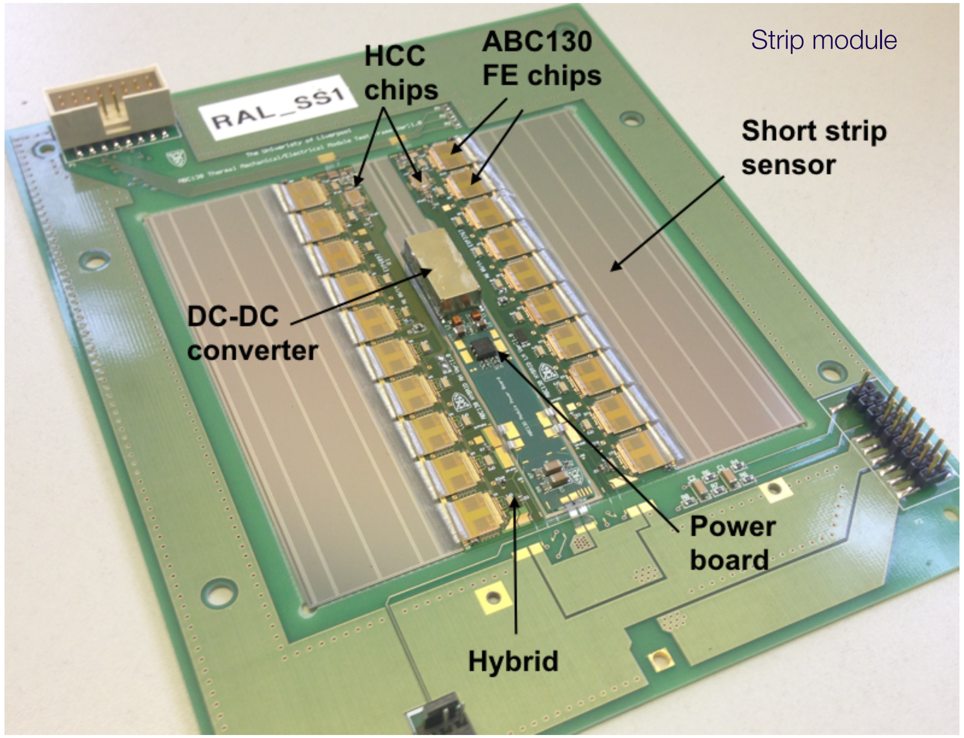
18k modules
25k hybrids
234k ADC130*
60M channels



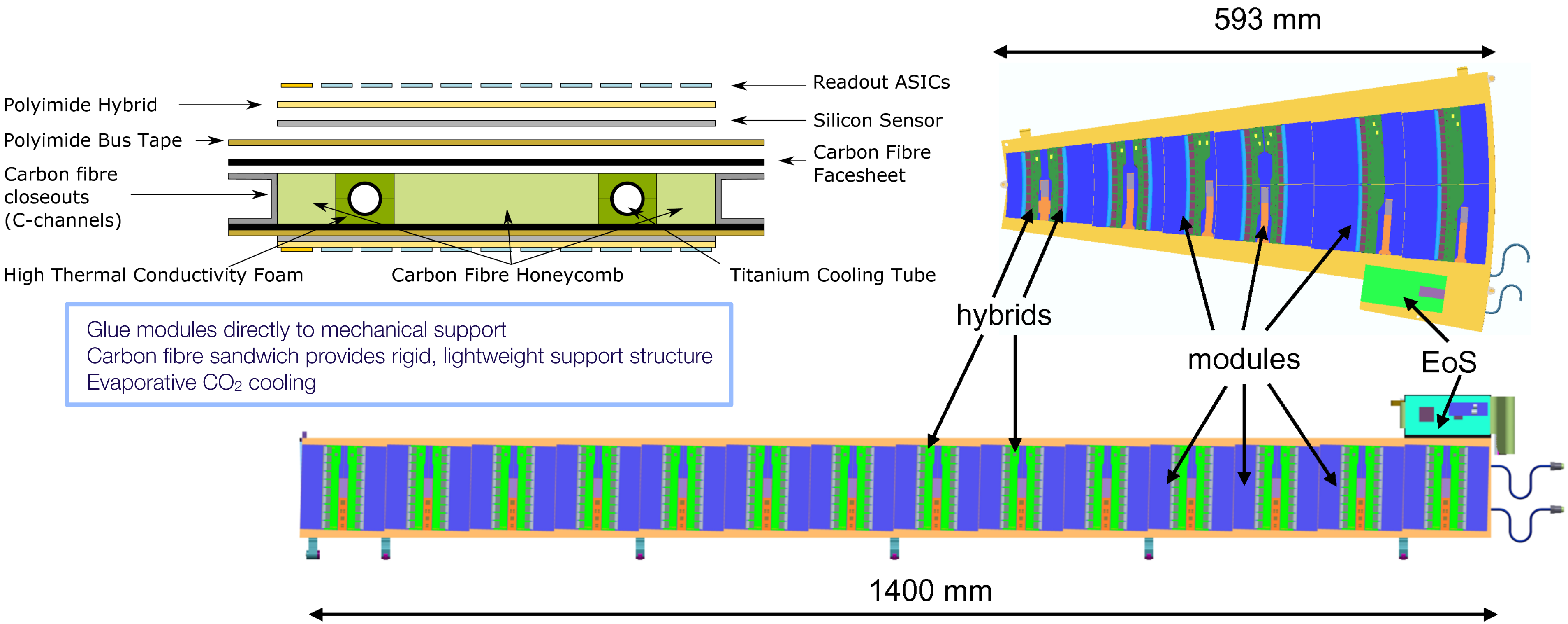
Strip module



Strip module



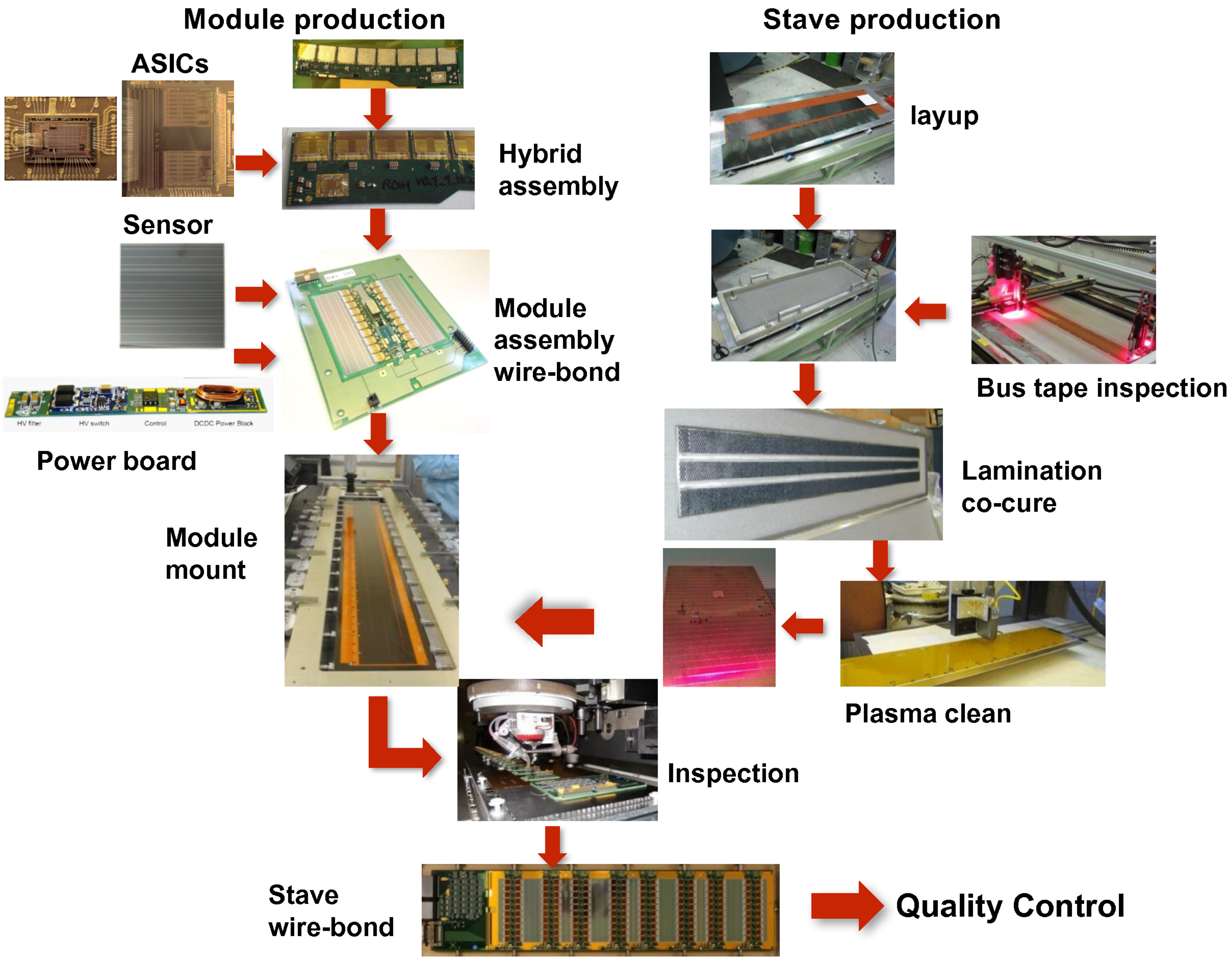
ATLAS Inner Tracker -ITk- for HL-LHC - Strips staves



Glue modules directly to mechanical support
Carbon fibre sandwich provides rigid, lightweight support structure
Evaporative CO_2 cooling

- Modules are rotated for stereo reconstruction
- Opposite stereo angle for modules on bottom of stave
- Services
  - Bus tape provides LV/HV and data transmission to/from *End of Stave* (EoS)
  - Embedded cooling tubes
  - EoS optoelectronics: data to/from counting room

ATLAS Inner Tracker -ITk- for HL-LHC - Strips Construction



Module production

ASICs

Hybrid assembly

Sensor

Module assembly wire-bond

Power board

Module mount

Stave production

layup

Bus tape inspection

Lamination co-cure

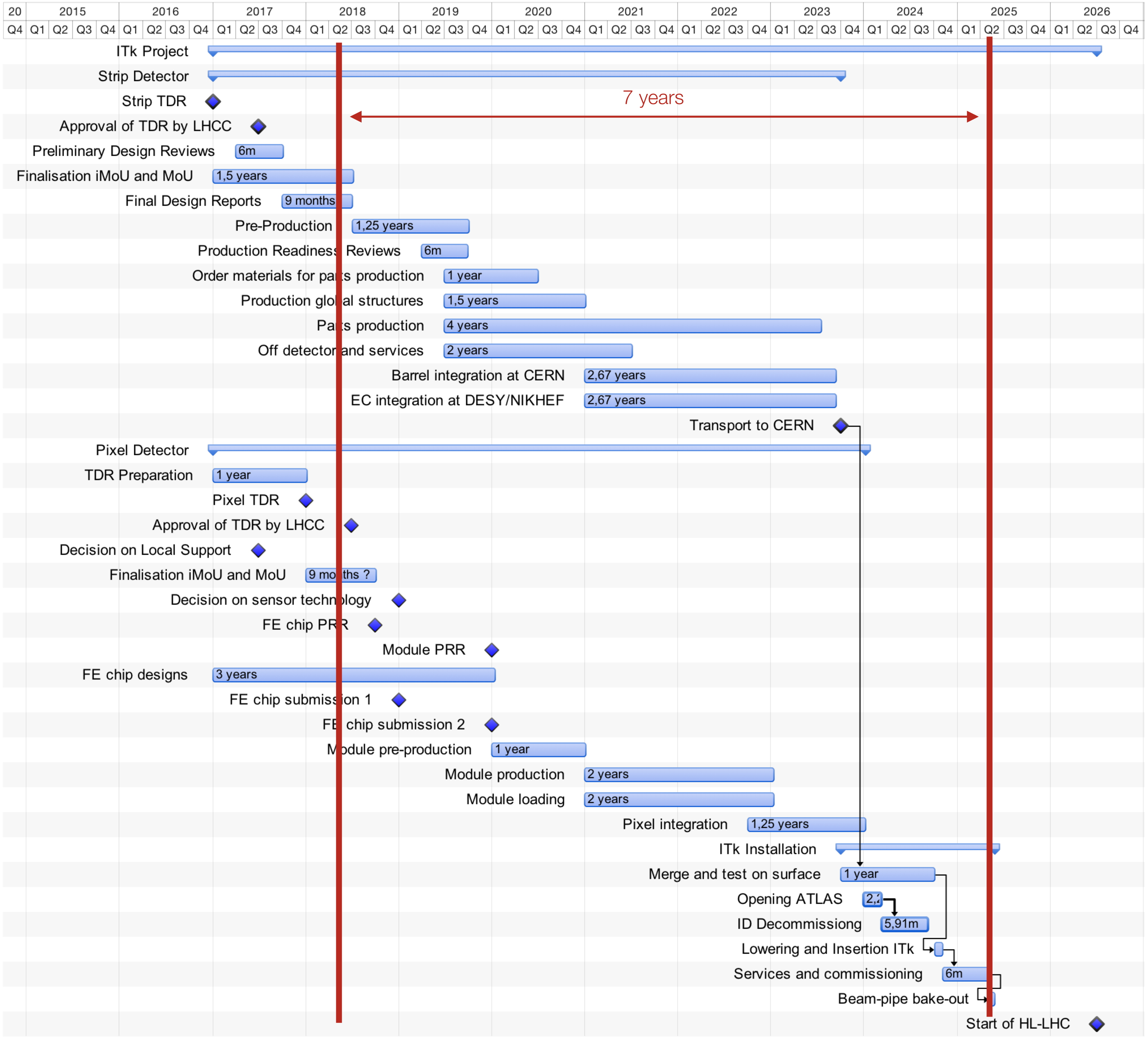
Plasma clean

Inspection

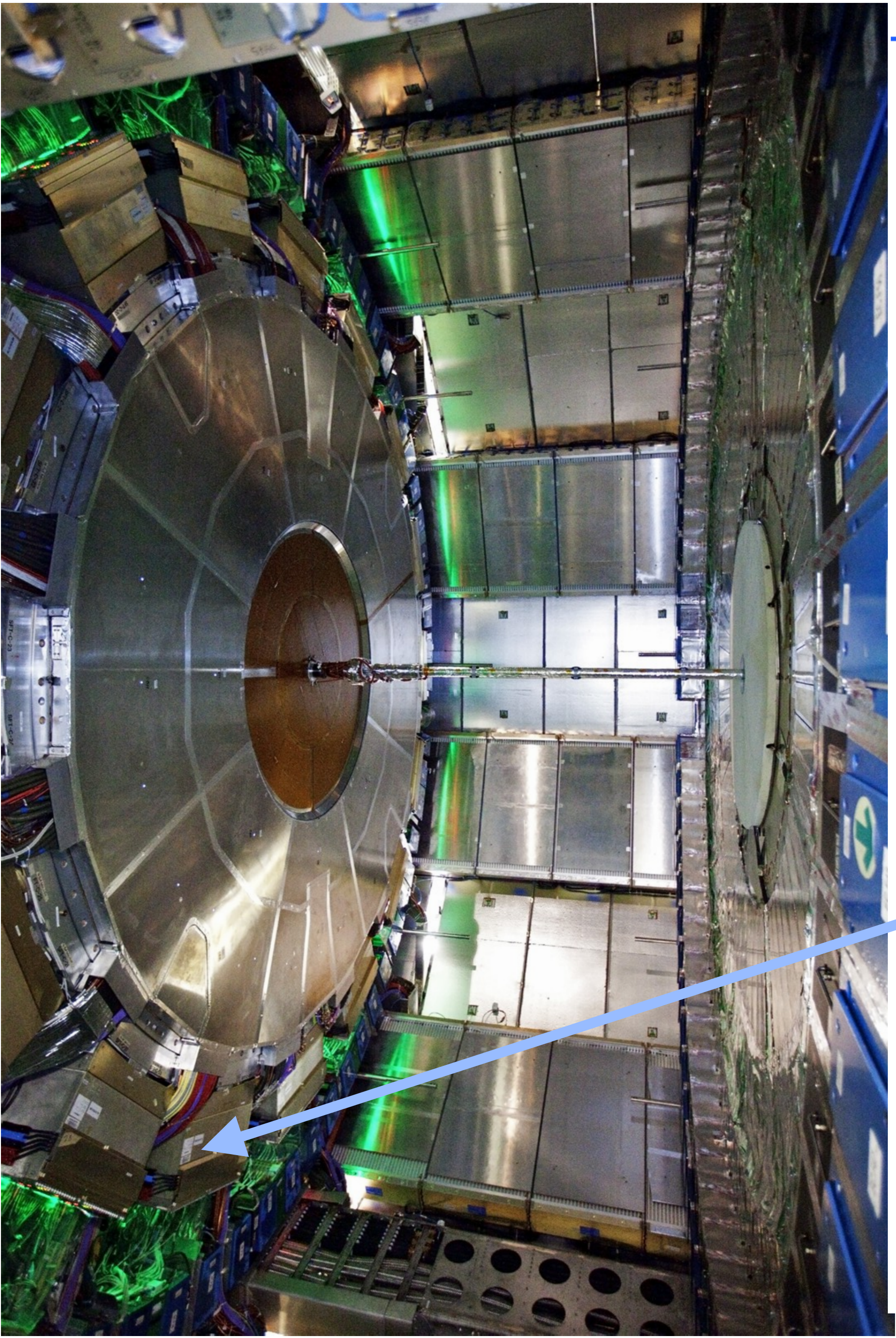
Stave wire-bond

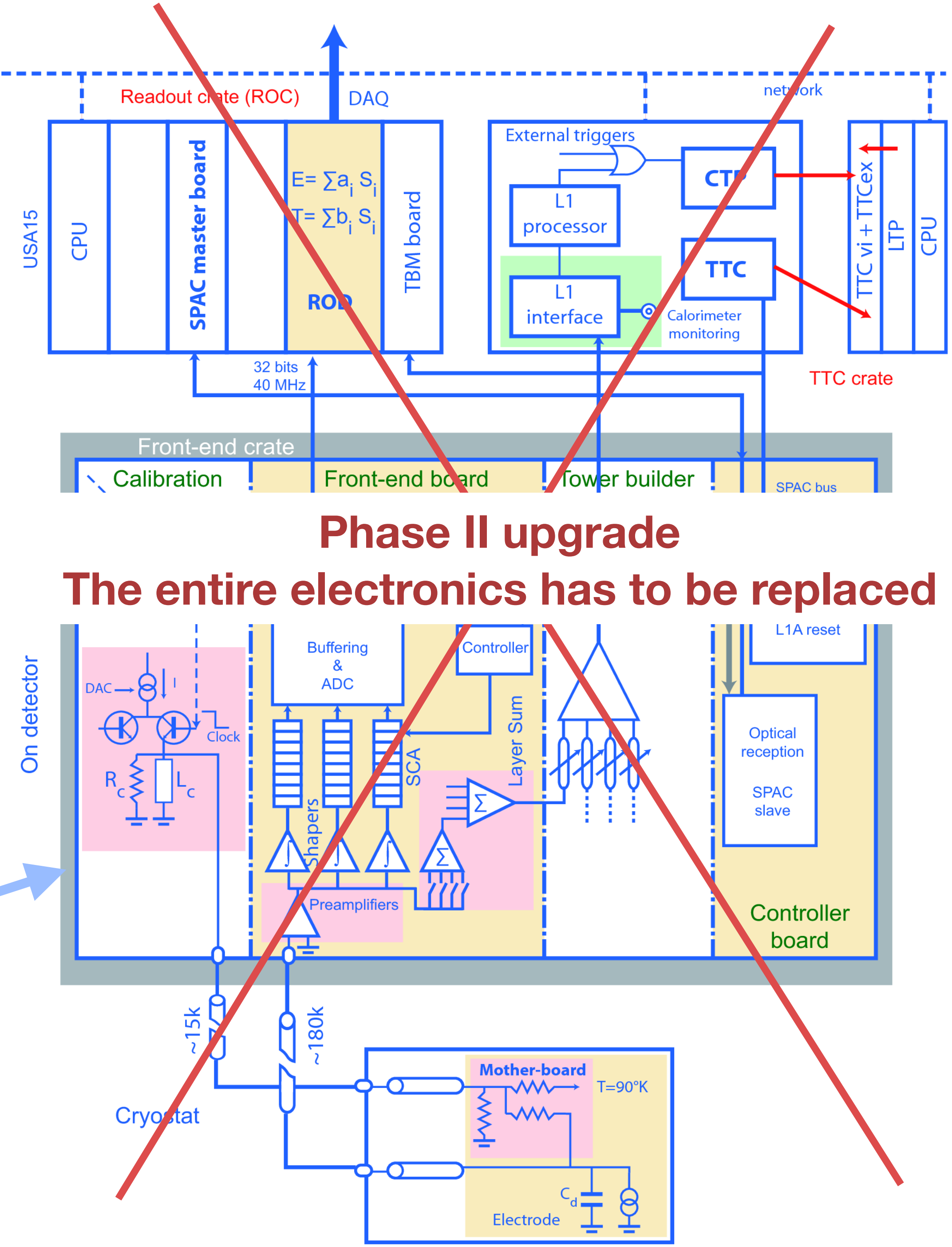
Quality Control

ATLAS Inner Tracker -ITk- for HL-LHC - Strips schedule



Liquid Argon Calorimeter Readout Electronics





Phase II upgrade

The entire electronics has to be replaced

Liquid Argon Phase-II Upgrade - WHY ?

The frontend electronics was qualified to sustain radiations up to ~700 evts/fb

- At HL-LHC expect to accumulate 3000 (up to 4000) evts/fb

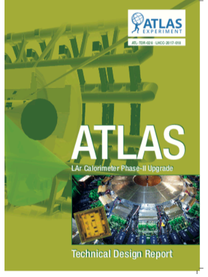
In 2025 the electronics will be 20 years old

- Processes used for fabrication are no more available.

Current LAr electronics readout incompatible with the planned upgrade of the Trigger/DAQ system,

The frontend on-detector electronics as well as the backend off-detector electronics will be replaced for HL-LHC.

Liquid Argon calorimeter Phase-II electronics upgrade



Liquid Argon Calorimeter

Submission: Sep 2017
Approval: March 2018

Dynamic range

from MIP to multi-TeV: 16 bits

2-gain system, **14-bit** ADC

Linearity

~1‰ up to ~300 GeV

few % at high energies

TDAQ

Compatibility with 10/35 μs buffer

1.7 μs latency for L0 input

Noise: electronics + pile-up

electronics noise < MIP signal for calibration

reduction of out-of-time pile-up

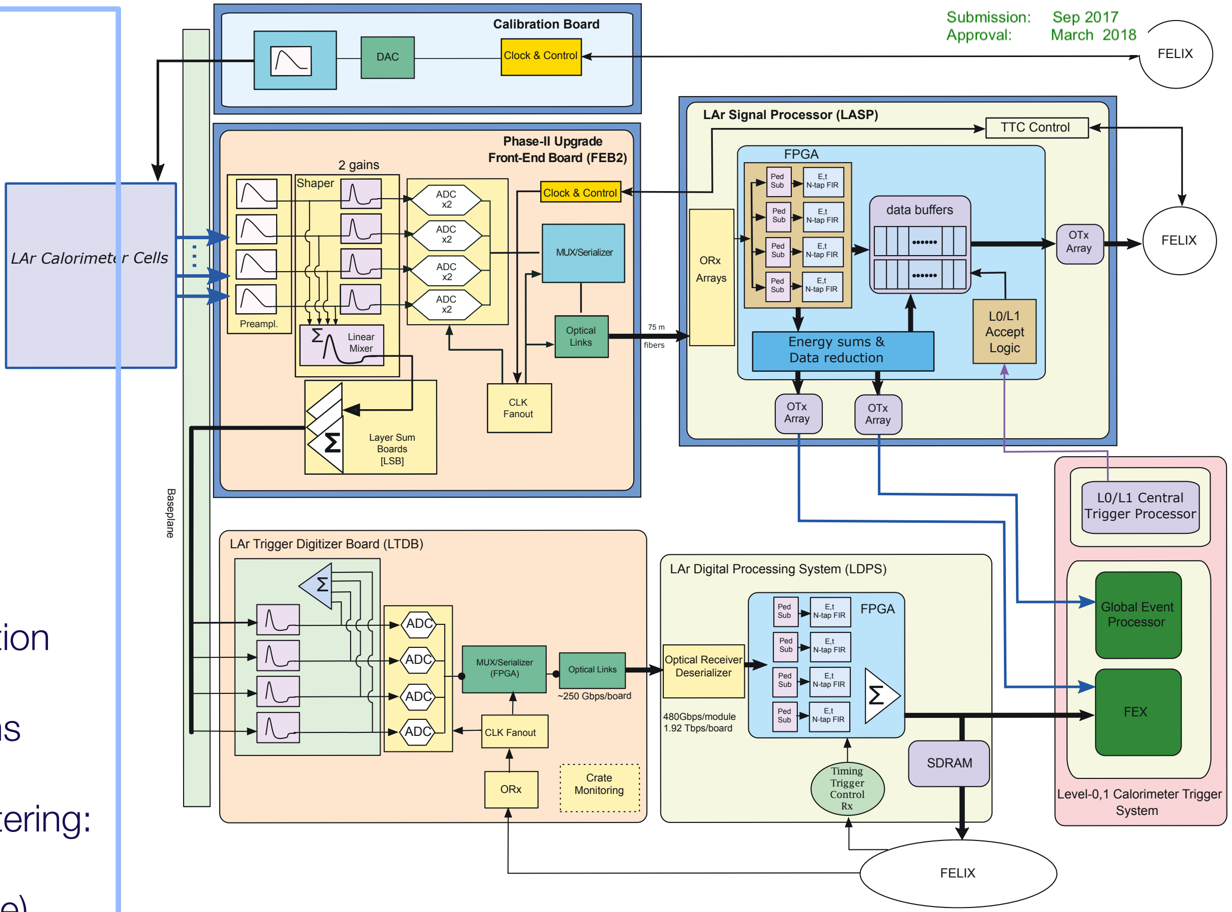
with complex digital filtering algorithms

optimise analog shaper characteristics

to minimise total noise deter digital filtering:

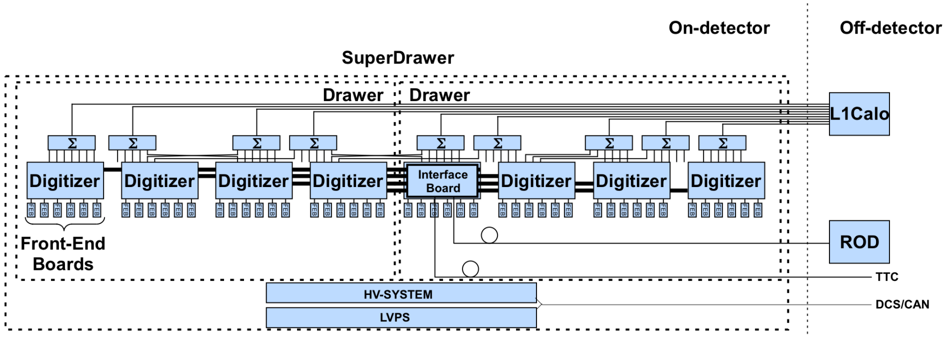
baseline CR-(RC)^2 shaping,

13 ns shaping time (programmable)

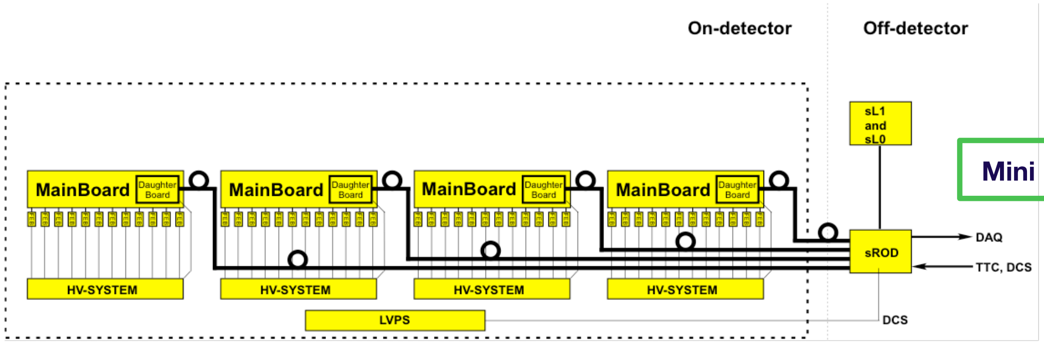


2 LV power systems
130 calibration boards
1524 frontend boards FEB2
372 LAr Signal processor units

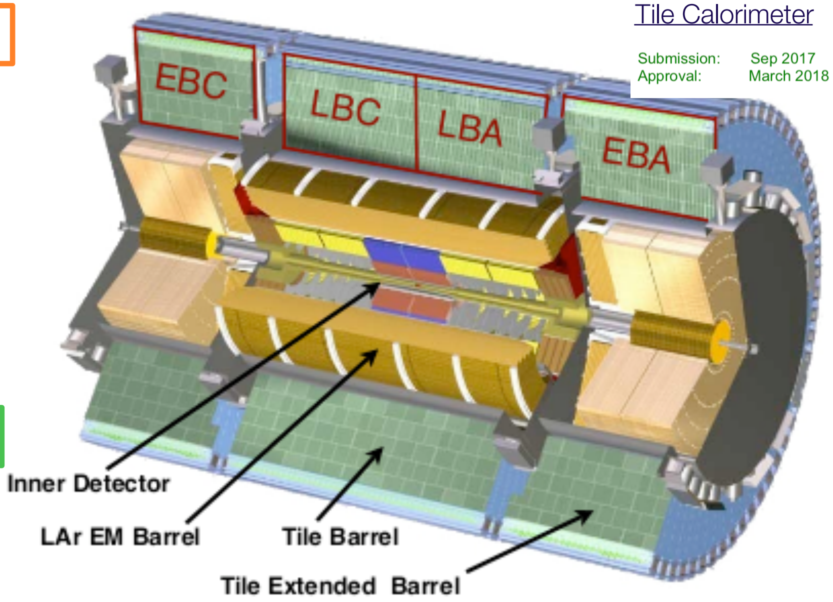
Tiles calorimeter Phase-II electronics upgrade

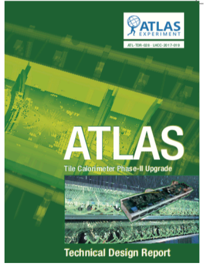


Super Drawers



Mini Drawers

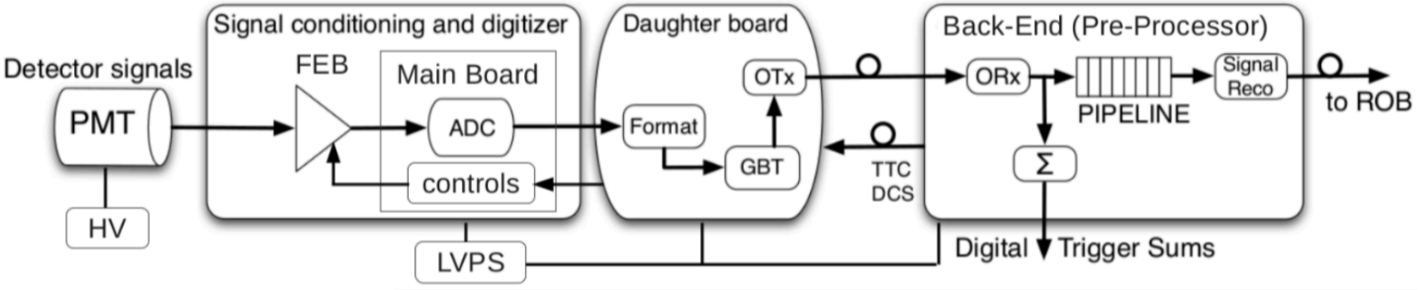




Tile Calorimeter

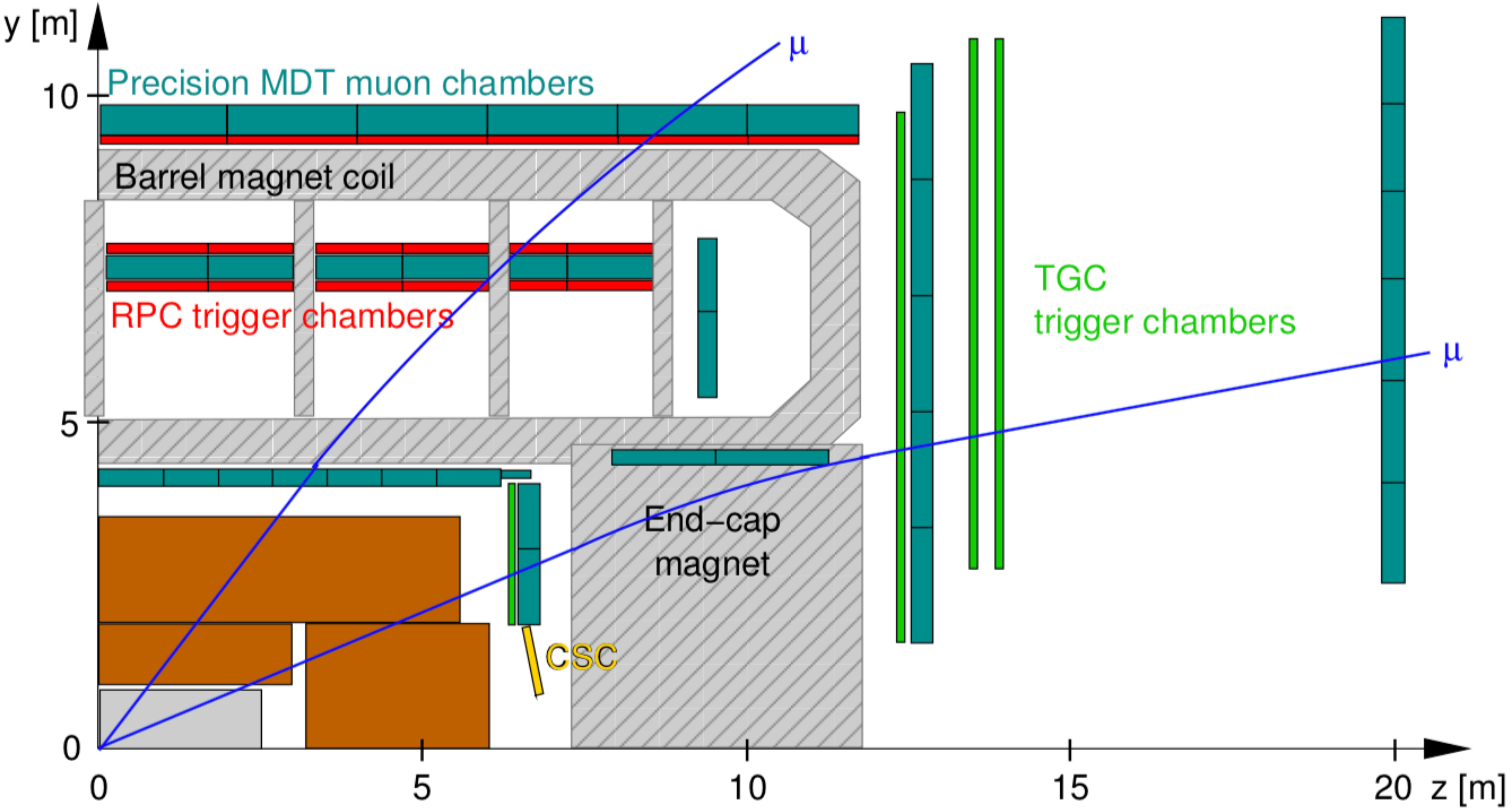
Submission: Sep 2017
Approval: March 2018

PMT at HL-LHC: some will be replaced
FE electronics
LVPS in USA15
BE electronics



Muon system

The ATLAS Muon system at LHC



Fast trigger chambers: RPC, TGC

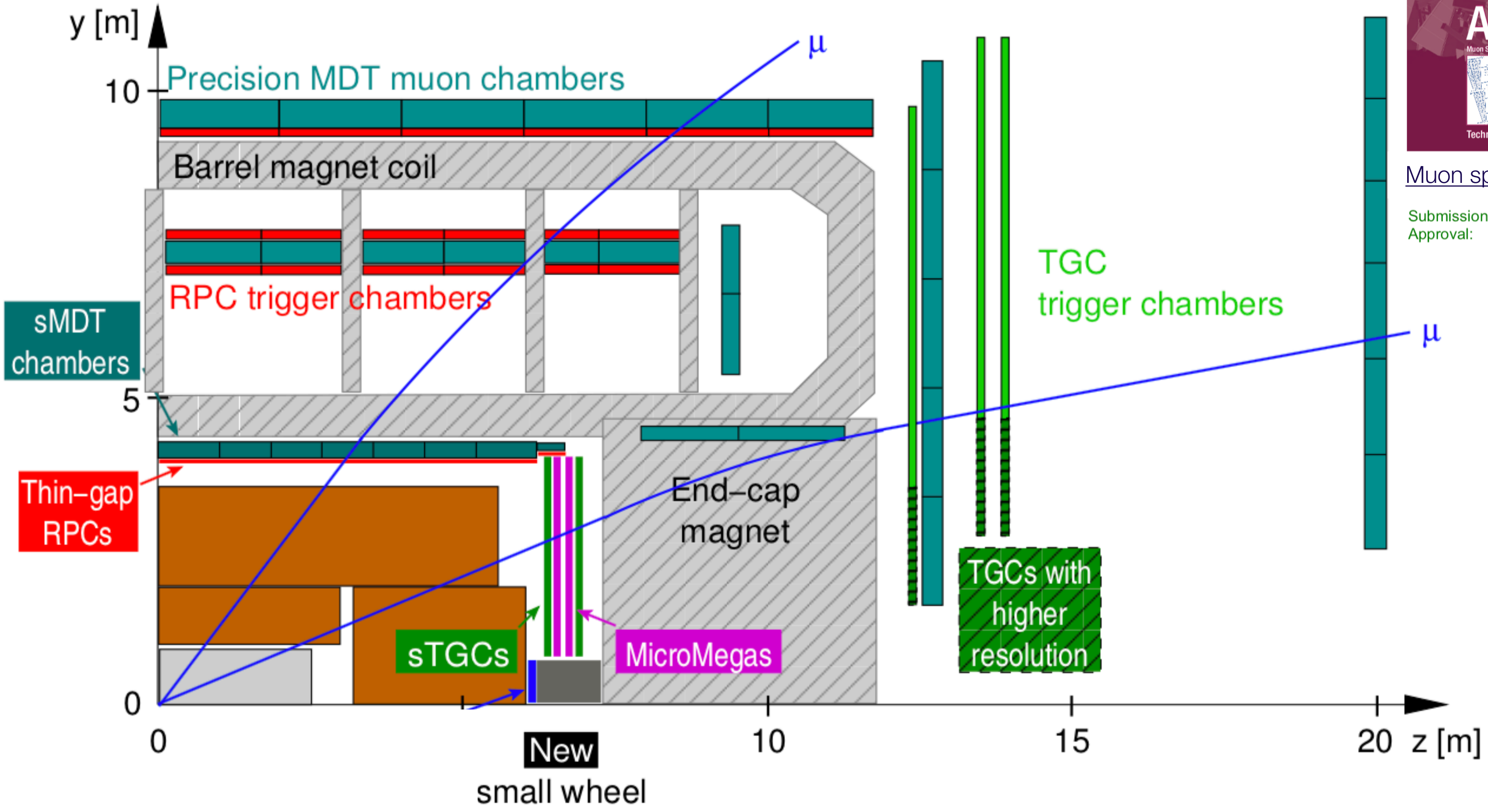
<10ns time resolution, moderate spatial resolution ~ mm-cm

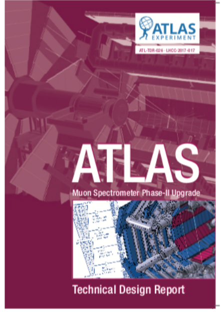
High-resolution tracking detectors: CSC, MDT (40 μm spatial resolution)

Optical alignement system with 50 μm resolution

|η|<2.7

The ATLAS muon system at the HL-LHC





Muon spectrometer

Submission: July 2017
Approval: Dec 2017

New Small Wheel

New TGCs with high resolution to cope with background at |η|~ 2.7

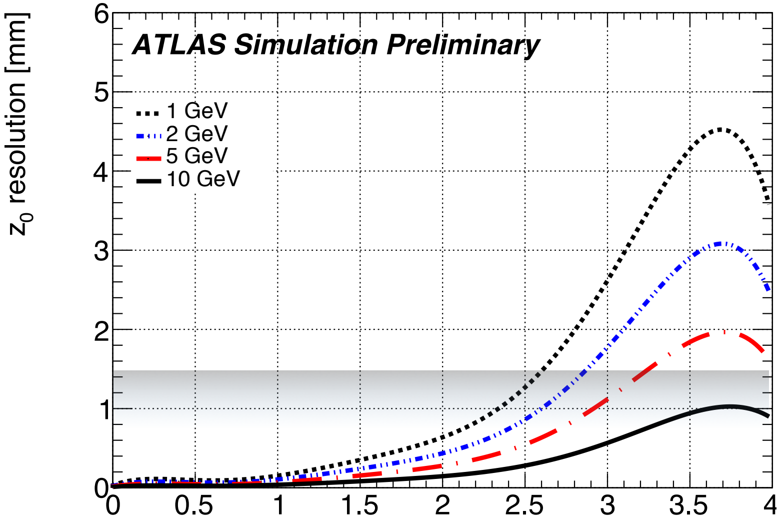
New thin-gap RPCs to close acceptance gaps of the barrel muon trigger

New sMDT chambers to free space for new RPCs

New on- and off-chamber electronics for new trigger architecture

High Granularity Timing Detector

HGTD Technical Proposal
Submitted to LHHC

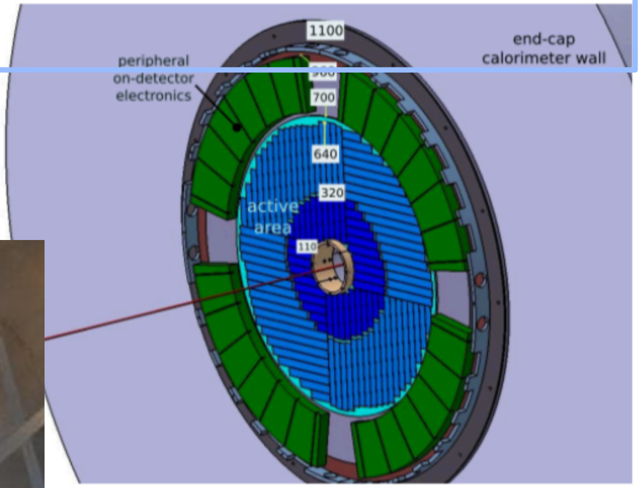


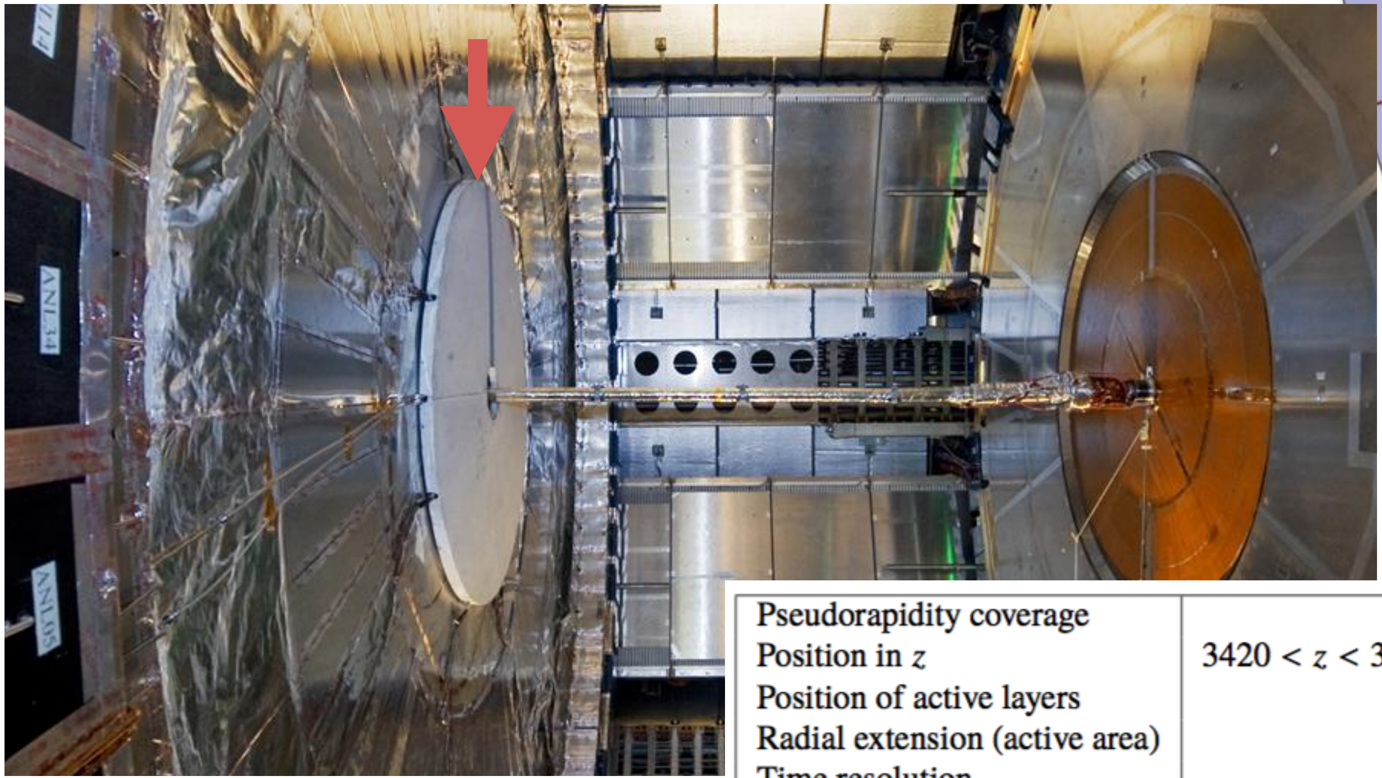
Z_0 resolution degrade with η

Including a high resolution time measurement allows to separate vertices

HGTD designed to have a time resolution of ~30 ps per track and resolve vertices inside the collision region (175 ps RMS)

New LGAD technology





Pseudorapidity coverage	$2.4 < \|\eta\| < 4.0$
Position in z	$3420 < z < 3545$ mm including 50 mm of moderator
Position of active layers	$3435 < z < 3485$ mm
Radial extension (active area)	110–1100 mm (120 mm–640 mm)
Time resolution	30 ps per track

25 years

1990 - ECFA Aachen meeting: Physics, detector, machine (H→ϒϒ ?)

1992 - ATLAS Letter of Intend

2 metre accordion module with fast readout

1994 - ATLAS Technical Proposal

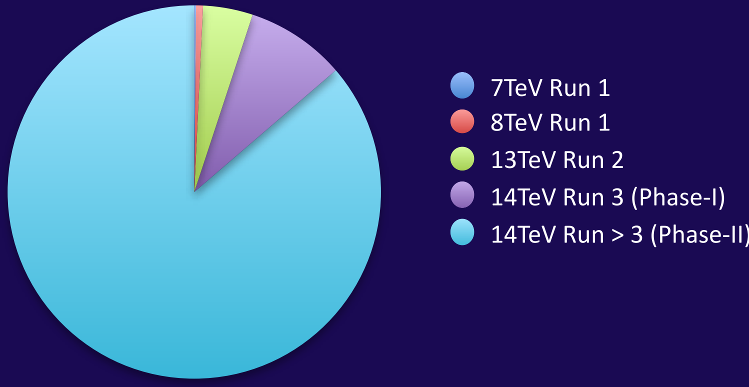
Spanish fan - Endcap accordion prototype

1996 - 2000 - ATLAS Technical Design Reports

Modules Zero and R&Ds, testbeam, testbeam, testbeam

2000 ATLAS Memorendum of Understanding

Cavern & detector construction starts



2003-2004 ATLAS detector starts to go down

ATLAS combined testbeam

2006-2007 ATLAS continues installationFirst cosmic muons data taking

2008 - LHC incident / **2009** First collisions

More cosmic muons + 0.9 TeV + 2.76 TeV pp collisions

2010 ~35 evts/pb pp collisions at √s=7 TeV & Pb-Pb collisions

2011 ~ 5 evts/fb pp collisions at √s=7 TeV & Pb-Pb collisions

2012 ~ 20 evts/fb pp collisions at √s=8 TeV - The Higgs boson is discovered m_H ~125 GeV

2013 - p-Pb collisions and start of a two years Long Shutdown

2013-2014 Long Shutdown 1: **IBL installed**

2015-2018 LHC Run-2 ~80 evts/fb at √s=13 TeV so far

End 2018 Run 1 + Run 2 Towards **160/fb**

---

20 years

2019-2020 Long shutdown 2: New Small Wheel, **LAr trigger**, TDAQ, **FTK**

2021-2023 LHC Run 3 +150 evts/fb for ~300 evts/fb total

2024-2026 Long shutdown 3: ITk, LAr electronics, Tiles, μ-system, TDAQ, HGTD

……. **2037** with 3000 evts/fb

CONCLUSIONS - OUTLOOK

A bright futur for ATLAS

ATLAS is engaged in several upgrades

- Maintain trigger capability for **low p_T objects**
- Replace detectors as pile-up and radiation increase, preserving or improving detector performance
- Include new detector (e.g. HGTD) to improve pile-up rejection and gain redundancy

2014 Insertable B-layer

2017-2018 Fast TracK Trigger being commissioned

2019-2020 - LS2 Mainly trigger upgrade

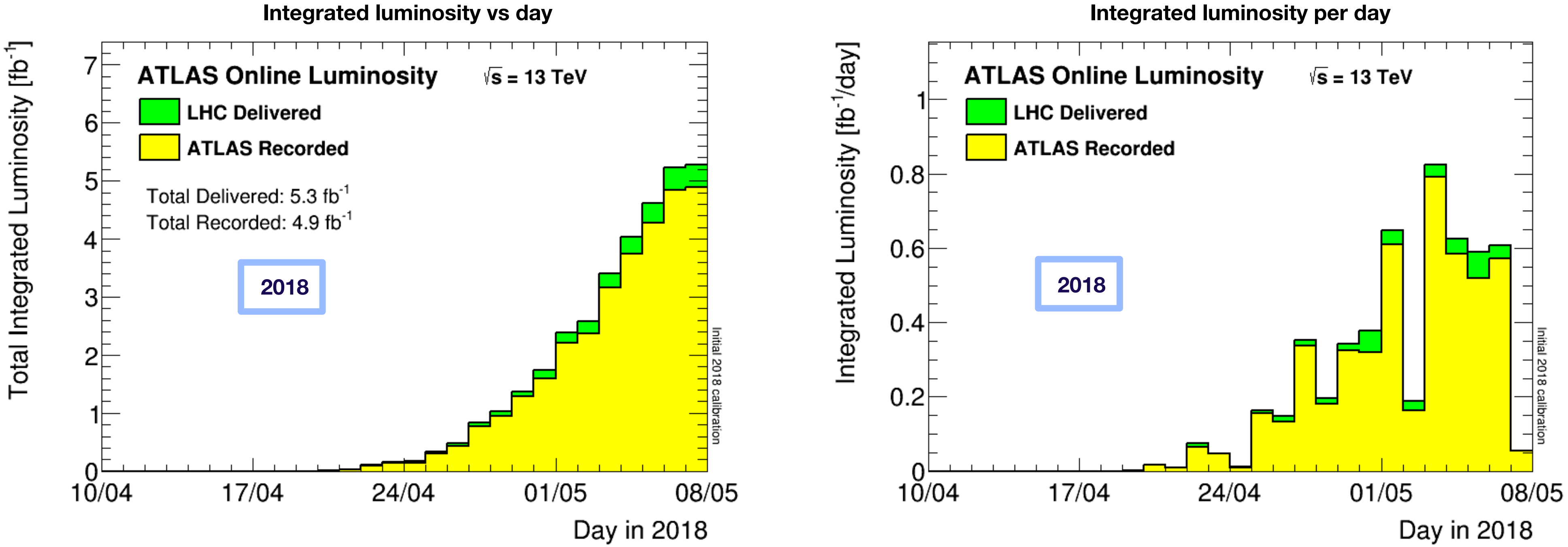
- New Small Wheel
- LAr trigger upgrade
- TDAQ upgrade

2024-2025 - LS3 Replace detectors and electronics when necessary

- Inner tracker ITk
- LAr & Tiles electronics + Tiles mini-drawers
- Muon chambers improvement
- TDAQ

And an exiting present in addition

ATLAS Today



In two weeks (still LHC ramp-up), more data accumulated than in 2015!

Data taking efficiency in 2018: **~93%**

ATLAS Run Coordinator: Masaya Ishino

BACKUP

TRIGGER at HL-LHC: example menu

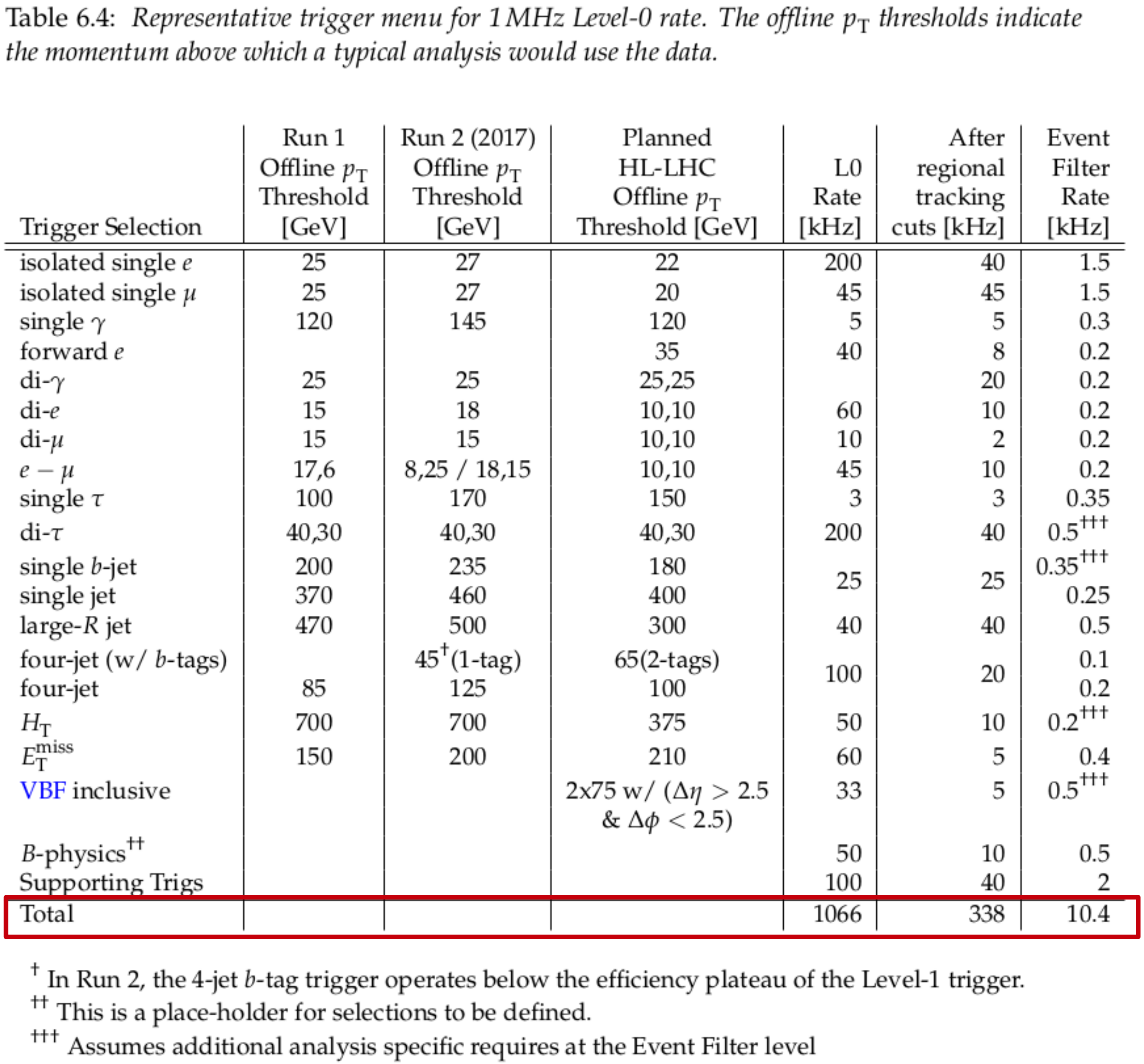


Table 6.4: *Representative trigger menu for 1 MHz Level-0 rate. The offline p_T thresholds indicate the momentum above which a typical analysis would use the data.*

Trigger Selection	Run 1 Offline p_T Threshold [GeV]	Run 2 (2017) Offline p_T Threshold [GeV]	Planned HL-LHC Offline p_T Threshold [GeV]	L0 Rate [kHz]	After regional tracking cuts [kHz]	Event Filter Rate [kHz]
isolated single e	25	27	22	200	40	1.5
isolated single μ	25	27	20	45	45	1.5
single γ	120	145	120	5	5	0.3
forward e			35	40	8	0.2
di-γ	25	25	25,25		20	0.2
di-e	15	18	10,10	60	10	0.2
di-μ	15	15	10,10	10	2	0.2
$e-\mu$	17,6	8,25 / 18,15	10,10	45	10	0.2
single τ	100	170	150	3	3	0.35
di-τ	40,30	40,30	40,30	200	40	0.5[†††]
single b-jet	200	235	180	25	25	0.35[†††]
single jet	370	460	400			0.25
large-R jet	470	500	300	40	40	0.5
four-jet (w/ b-tags)		45[†](1-tag)	65(2-tags)	100	20	0.1
four-jet	85	125	100			0.2
H_T	700	700	375	50	10	0.2[†††]
E_T^{miss}	150	200	210	60	5	0.4
VBF inclusive			2x75 w/ ($\Delta\eta > 2.5$ & $\Delta\phi < 2.5$)	33	5	0.5[†††]
B-physics[††]				50	10	0.5
Supporting Trigs				100	40	2
Total				1066	338	10.4

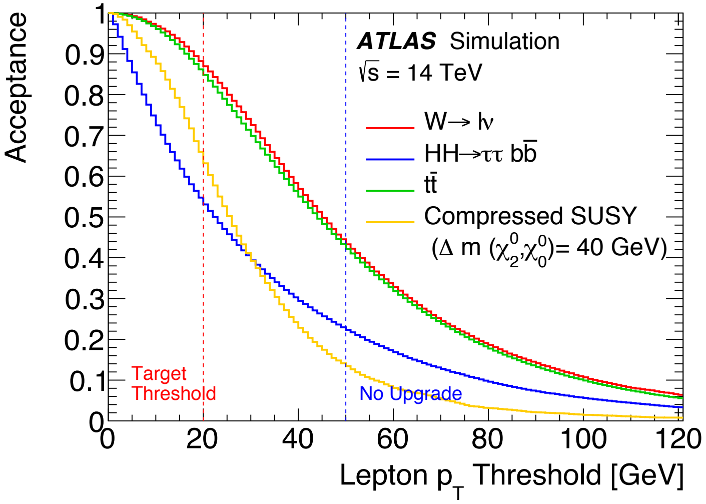
[†] In Run 2, the 4-jet b-tag trigger operates below the efficiency plateau of the Level-1 trigger.

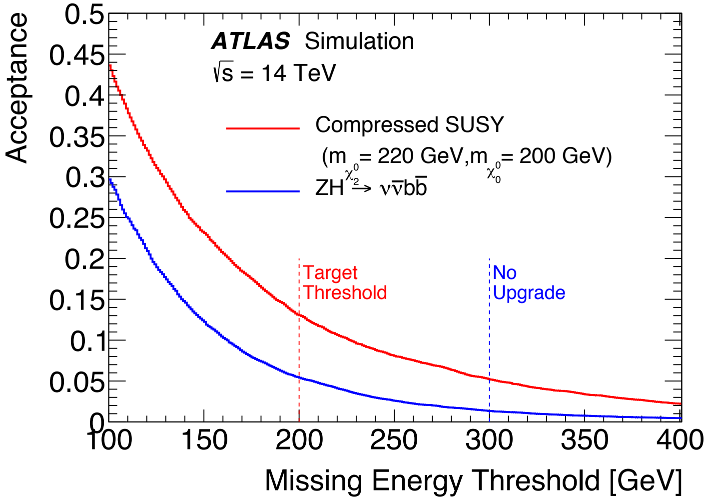
[††] This is a place-holder for selections to be defined.

[†††] Assumes additional analysis specific requires at the Event Filter level

TRIGGER for RUN-4

Preserve or improve low p_T threshold for high precision physics





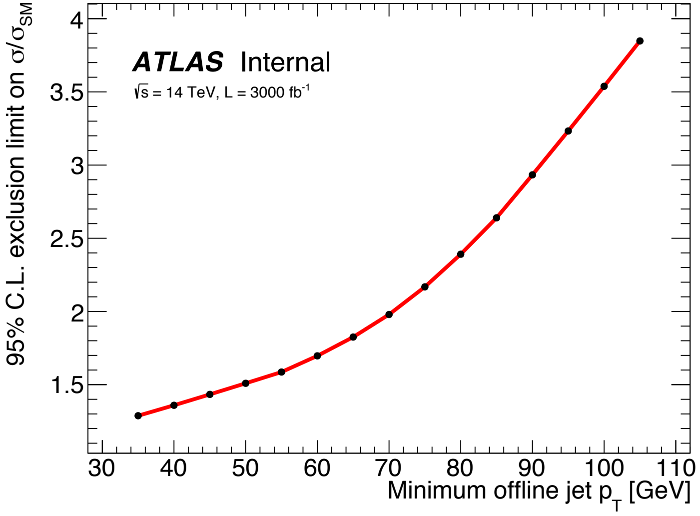


Figure 2.9: Expected 95% C.L. upper limit on the cross-section ratio $\sigma(HH \to 4b)/\sigma(HH \to 4b)_{SM}$ as a function of the minimum p_{T} requirement applied to the fourth-leading jet, assuming that systematics are not a strong limitation on the result. Results with systematics show similar trigger impacts. For a more detailed discussion, see Section 6.13.