ATLAS Upgrades Towards the High Luminosity LHC: Extending the Discovery Potential

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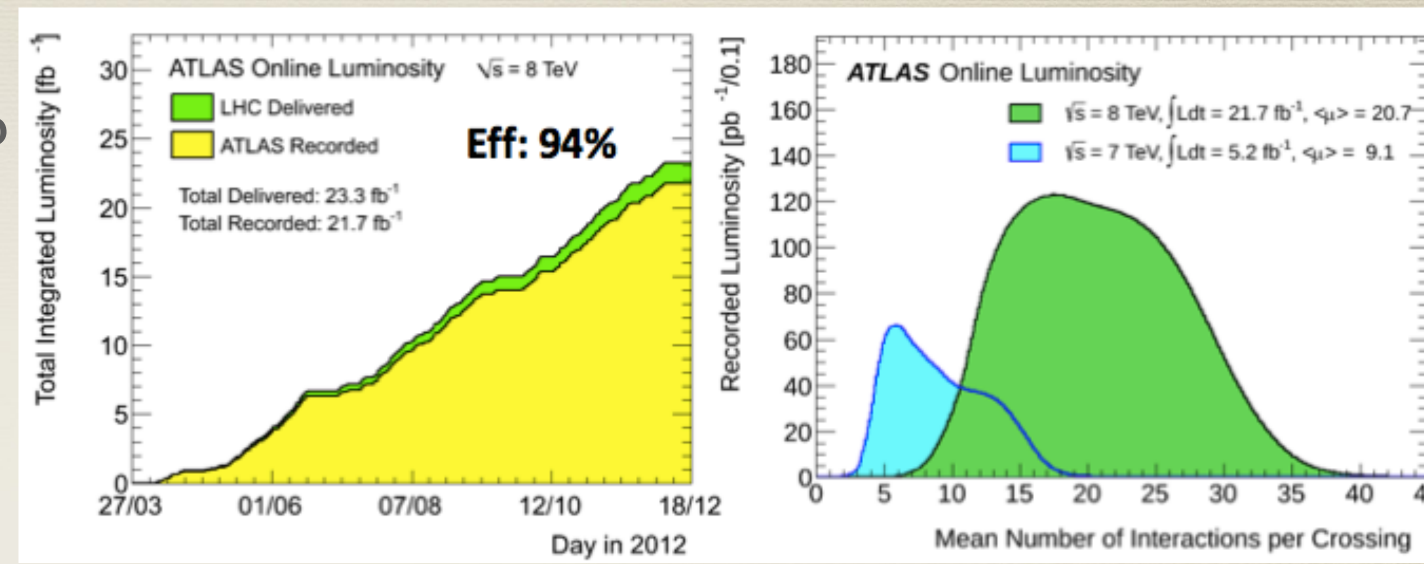
on behalf of the ATLAS collaboration

DIS 2014 - Warsaw

Performance of ATLAS in Run I

* Before data-taking, expected in-time pileup (PU) was 23 (25ns BS (bunch spacing), design luminosity).
* In 2012, average PU was regularly over 30 (50ns BS)
* **Inner Detector:**
  - ✓ High reconstruction efficiency
  - ✓ Vertex reconstruction performing well
* **e/γ performances:**
  - ✓ Electron energy response and photon conversion reconstruction show excellent stability versus increasing pileup.



* **Jet/E_T^{Miss} performances:**
  - ✓ E_T^{Miss} reconstruction is performing well
  - ✓ Stable resolution performances
* **Particle Identification:**
  - ✓ Identification efficiency is robust against pileup
* **DAQ and trigger:**
  - ✓ Developed algorithms are robust against pileup
  - ✓ 21.7 fb^{-1} recorded by ATLAS (94% DAQ efficiency)

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.

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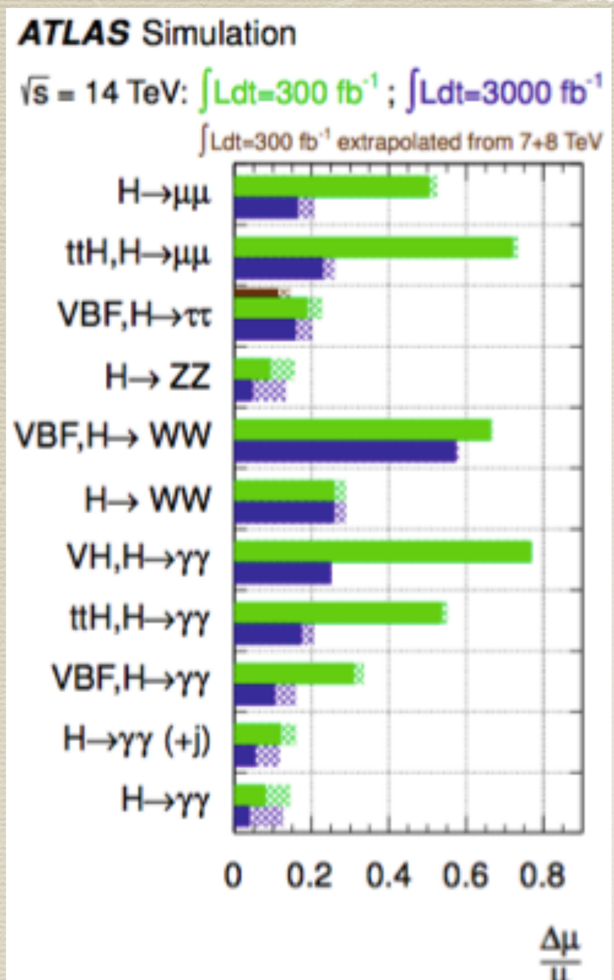

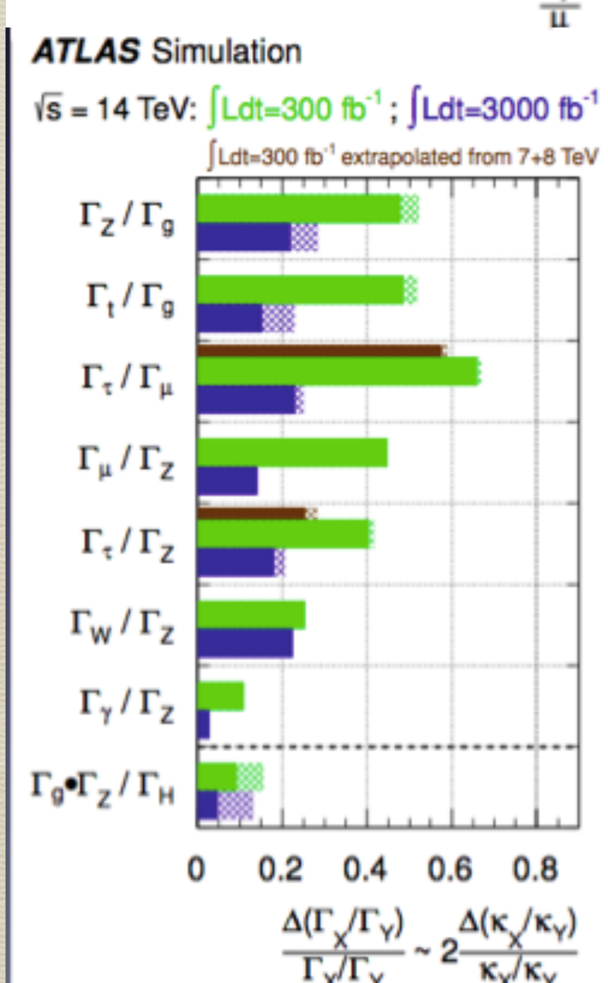

Motivation for an upgrade

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

European Strategy for Particle Physics

* **Higgs boson precision measurements:**
  * Expected uncertainties on signal strength reduced by a factor of 2-3 with HL-LHC.
  * Ratio of partial widths to measure ratios of couplings and probe New Physics.
  * SM Higgs rare decays and processes, e.g. H → μμ, and ttH can be measured.
* **Higgs self-coupling in SM accessible only at HL-LHC.**
* **Probing New Physics:**
  * SUSY and other New Physics beyond SM.
  * Enhancements in vector boson scattering amplitudes.
  * Rare processes, e.g. FCNC decays from top accessible to 10^{-5}.

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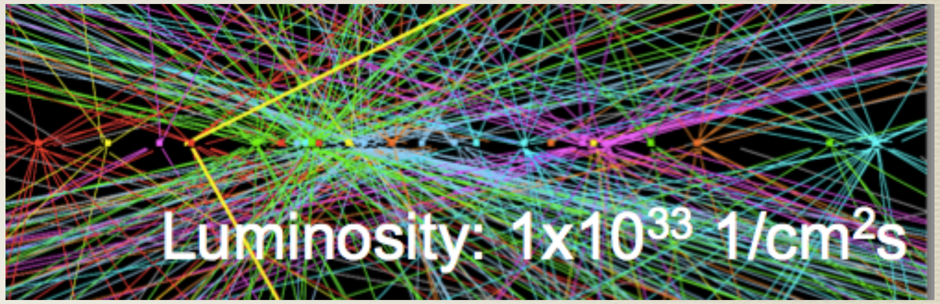
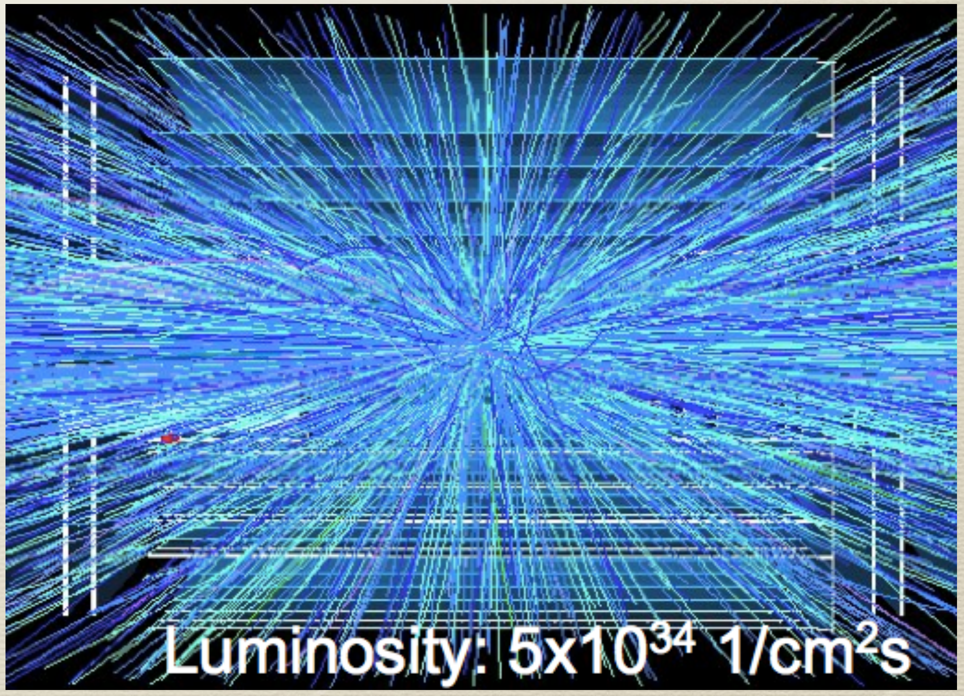
The challenge

* Higher instantaneous luminosity means that more protons will collide in one event:
  * Pileup could reach up to 200 collisions per event.
  * Increased occupancy and saturation of available data transmission bandwidth.
  * Triggers rates cannot increase in line with luminosity so greater selectivity required to preserve efficiency.
* Higher integrated luminosity means higher total particle flux through detector:
  * Increased radiation damage (especially in inner layers).
  * Increased activation of the materials.
* The goal is to achieve the same (or better) performances (resolution, ...) at HL-LHC as at LHC, despite the large increase of event rate.





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LHC roadmap

From LHCC Open meeting, 03.12.2013

LHC roadmap

From LHCC Open meeting, 03.12.2013

LHC roadmap

Last update - December 2013

Year			Run	Integrated luminosity
2009		LHC startup, √s 900 GeV		
2010–2012		$\sqrt{s}$=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns	Run 1	~25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity - Phase 0		
2015–2018		$\sqrt{s}$=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 2	~75-100 fb^{-1}
2019	LS2	Injector + LHC Phase I upgrade to ultimate design luminosity		
2020–2022		$\sqrt{s}$=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 3	~350 fb^{-1}
2023–2024	LS3	HL-LHC Phase II upgrade: Interaction Region, crab cavities?		
2025 … 2035?		$\sqrt{s}$=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling		~3000 fb^{-1}

Now !

From LHCC Open meeting, 03.12.2013

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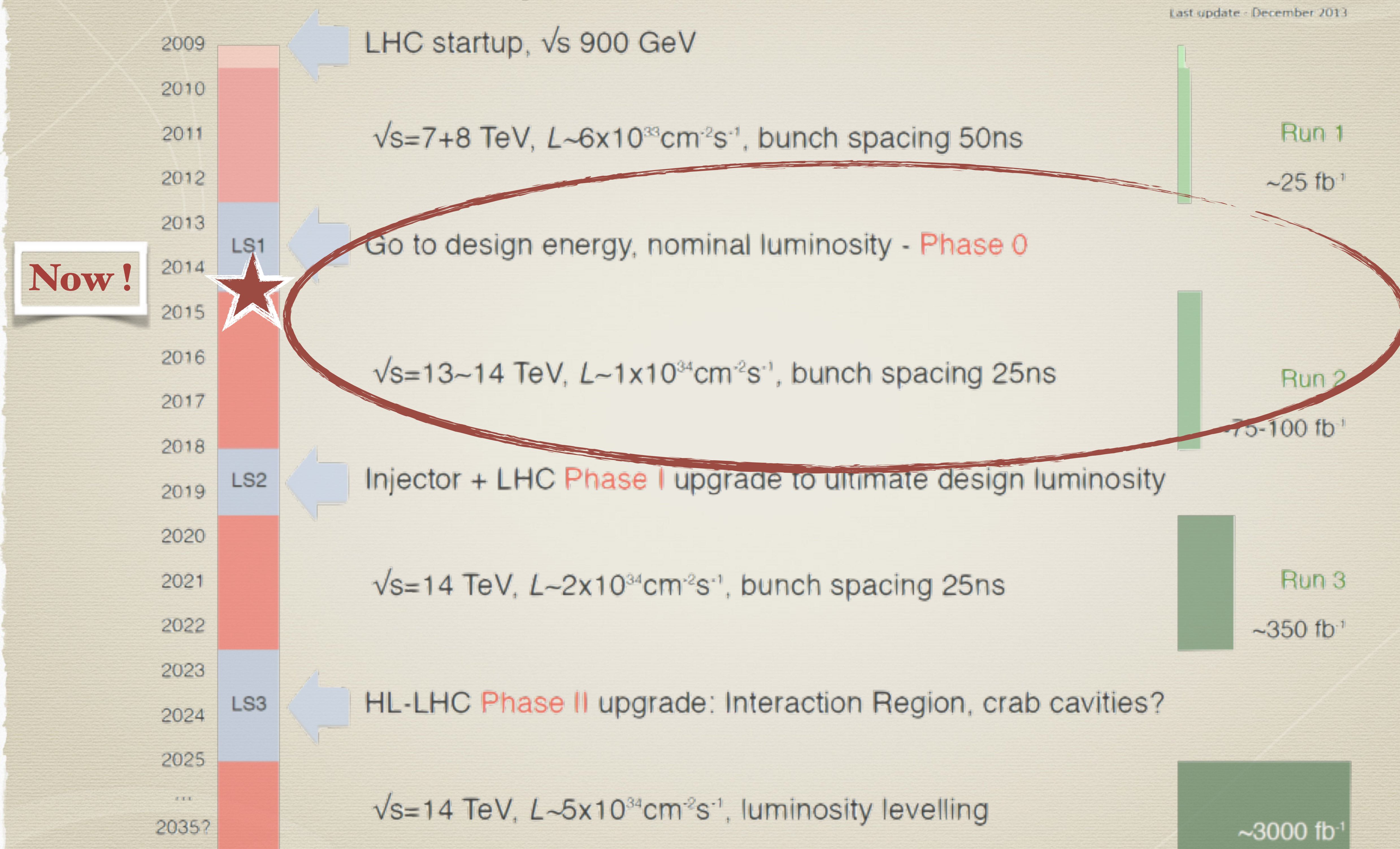
LHC roadmap



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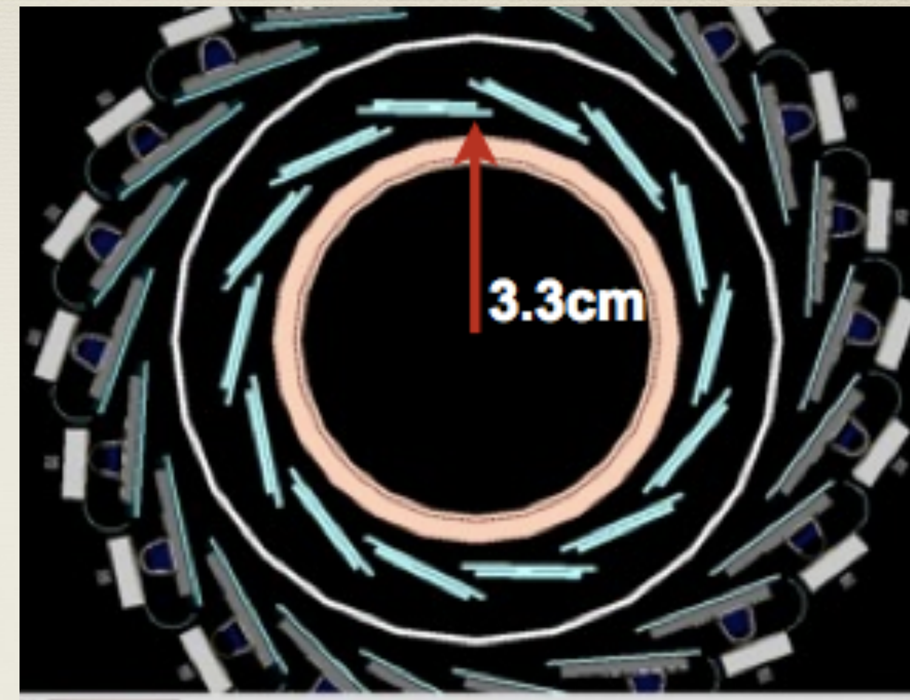
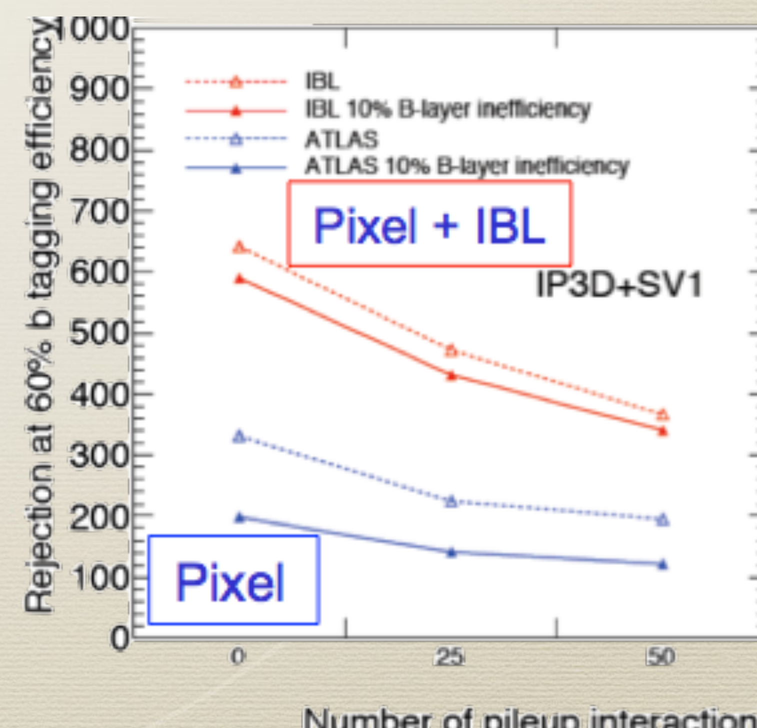
Ongoing: Phase 0

* Long Shutdown 1: duration 18 months
* **LHC upgrades:**
  * Run 2 (2015-2018): $\sqrt{s}$=13-14 TeV, L~1.10^{34} cm^{-2}s^{-1} , <μ>~27, @ 25ns (start at 50ns), ~75-100 fb^{-1} expected
  * Consolidation of superconducting circuits
  * Replace/repair superconducting splices for 13 TeV energy and nominal peak luminosity
* **ATLAS upgrades:**
  * Insertion of an additional 4th pixel layer : Insertable B-Layer (IBL), Diamond Beam Monitor (DBM)
  * Completion of Muon Spectrometer Chambers added to improve acceptance for 1.0 <|η|< 1.3 (Endcap Extension (EE) Muon Chambers)
  * New Pixel Service Quarter Panels (nSQP)
  * Usage of outer most layer of Tile Calorimeter for L1 Muon trigger
* **ATLAS consolidation:**
  * New Al/Be beam pipe
  * New evaporative Inner Detector cooling plant
  * New Low Voltage Power Supplies for the calorimeters
  * Power network, magnet cryogenics, services

Phase 0: Insertable B Layer (IBL)

* Physics motivations:
  * From $L = 2.10^{34}$ cm^{-2}s^{-1} b-tagging efficiency will start to degrade.
  * Robust tracking in case of failures in the current pixel system.
  * Improves impact parameter resolution, vertexing, τ-reconstruction at high pileup.
  * Replace beam pipe.
* Insertable B-Layer (IBL)
  Additional pixel layer as innermost tracking layer
  * Important ingredient for low mass, rad-hard construction: 2 cm x 2 cm FE-I4 Pixel Chip, 130 nm CMOS process.
  * Sensors: planar pixel sensors and 3D.
  * Installation of IBL in the pixel detector, in the pit: May 2014.
  * Will stay until Phase-II (~7 years).

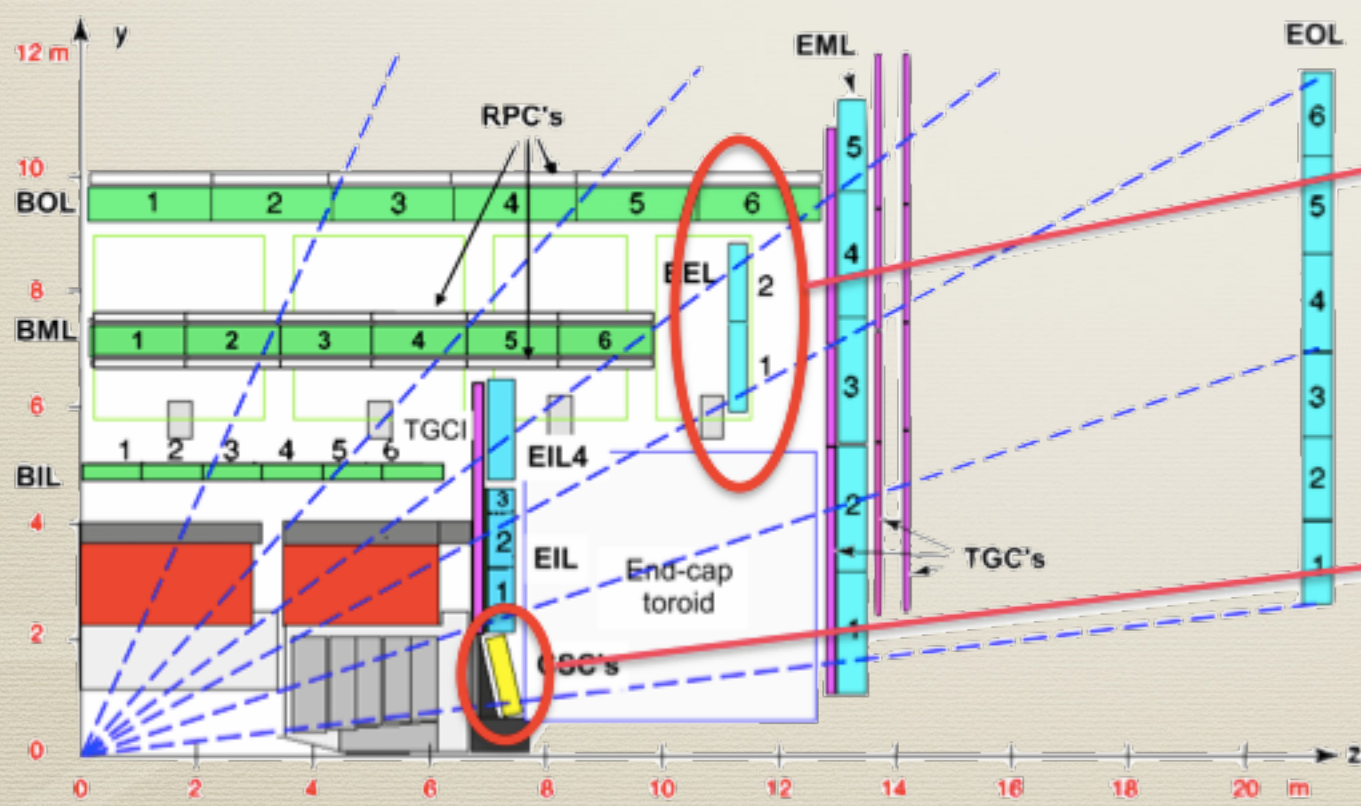


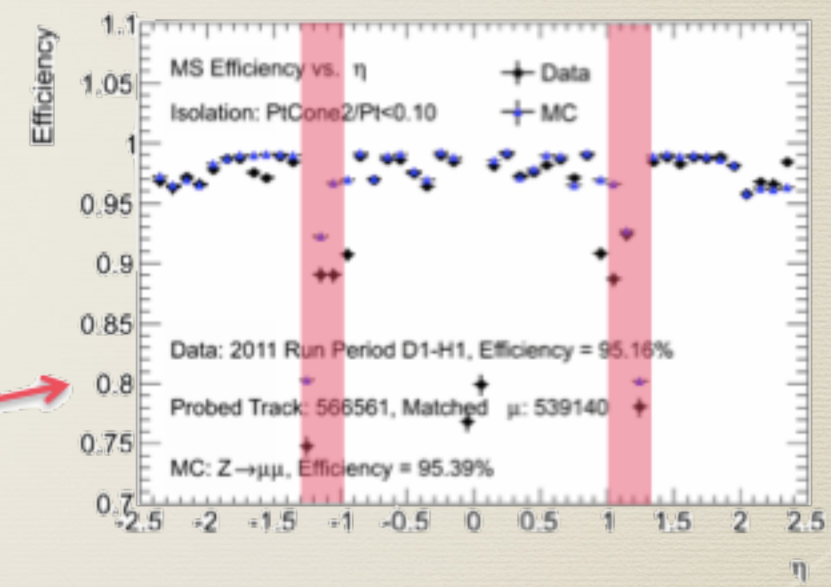


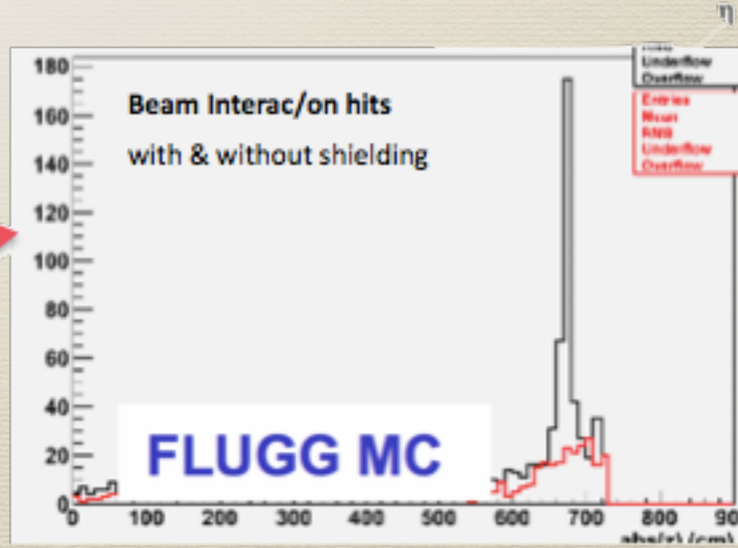
- Reduced material budget: 0.015 X_0
- Coverage: z = 60cm, |η| < 2.5
- Sensors @33mm (now@50.5mm)
  => smaller beam pipe (29 -> 25mm)
- 14 staves with phi overlap
- No eta overlap due to clearance
  => minimize modules edge

Phase 0: Muon chambers

- Endcap Extension (EE) Muon Chambers
  - Installation of the chambers to address low efficiency in the region 1.0<|η|<1.3
  - Need to bring Muon Small Wheel (9m diameter) on the surface out of the way of the IBL
  - New shielding at 7m : gap between forward calorimeter and shielding disk







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LHC roadmap

From LHCC Open meeting, 03.12.2013

ATLAS upgrades - Phase 1

* **LHC (after LS2: duration ~ 18 months, 2018-2019)**
  * Run 3 (2020-2022): $\sqrt{s}$=14 TeV, L~2-3.10^{34} $cm^{-2}s^{-1}$, $\langle\mu\rangle$~50-80, @ 25 ns, ~300 fb^{-1} expected
  * Consolidation of injection chain, collimators
* **ATLAS upgrades:**
  * Fast Track Trigger at "Level 1.5"
  * Higher granularity and precision in L1 Trigger for calorimeter
  * New Small Wheels for the forward muon spectrometer
  * Topological (multi-object) L1 Trigger processors
  * Central Trigger Processor (CTP) upgrades
  * ATLAS Forward Physics (AFP), proton det. at ±210 m

Phase-I Upgrades should be forward compatible with Phase-II

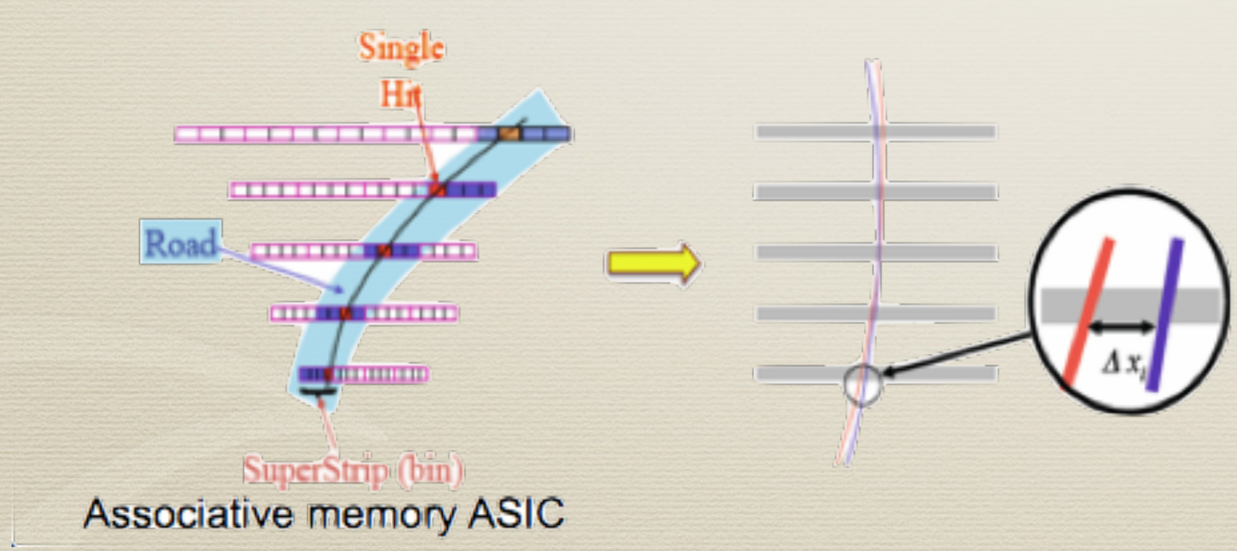
In 2013, 4 TDRs for Phase-I construction projects were prepared within ATLAS, approved by CB and endorsed at the LHCC meeting (December 2013)

Fast track trigger

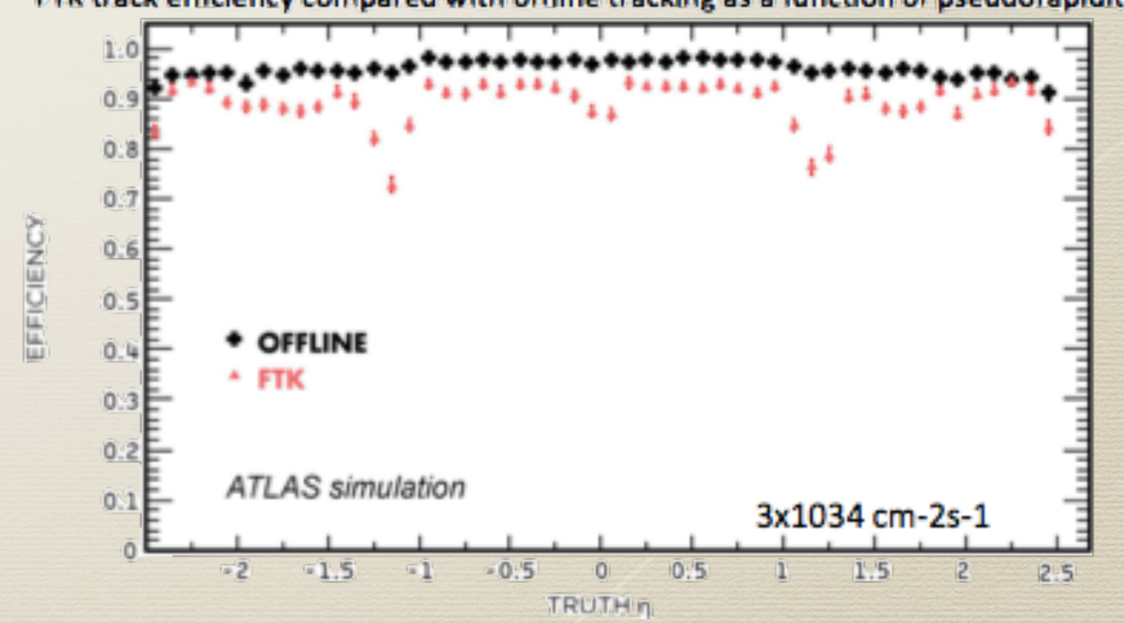
* **Motivation: Track information at the start of Level 2.**
* Dedicated, hardware-based track finder (based on CDF Silicon Vertex Triggering development)
  * Runs after the first level trigger on duplicated Si-detector read-out links
    Provides tracking input for the level-2 trigger for the full event
    * not feasible with software tracking at L2
  * Finds and fits tracks (~ 25 μs) in the ID silicon layers at an "offline precision"
* Processing performed in two steps:

hit pattern matching to pre-stored patterns (coarse)

subsequent linear fitting in FPGAs (precise)



FTK track efficiency compared with offline tracking as a function of pseudorapidity



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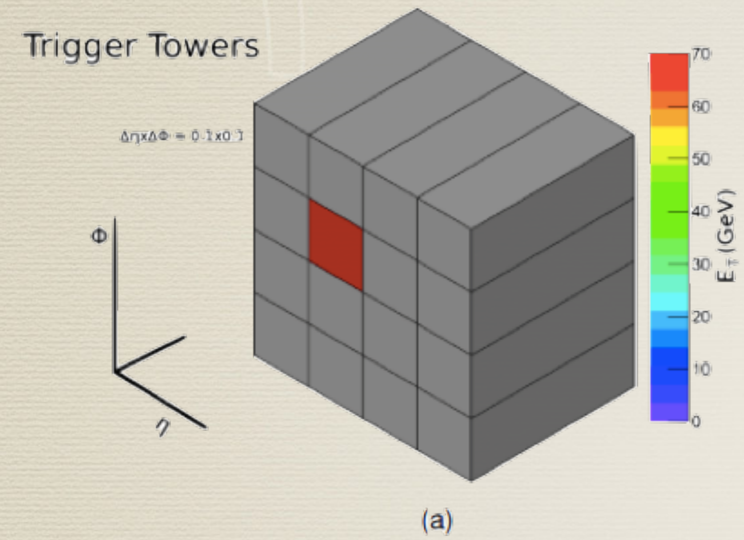
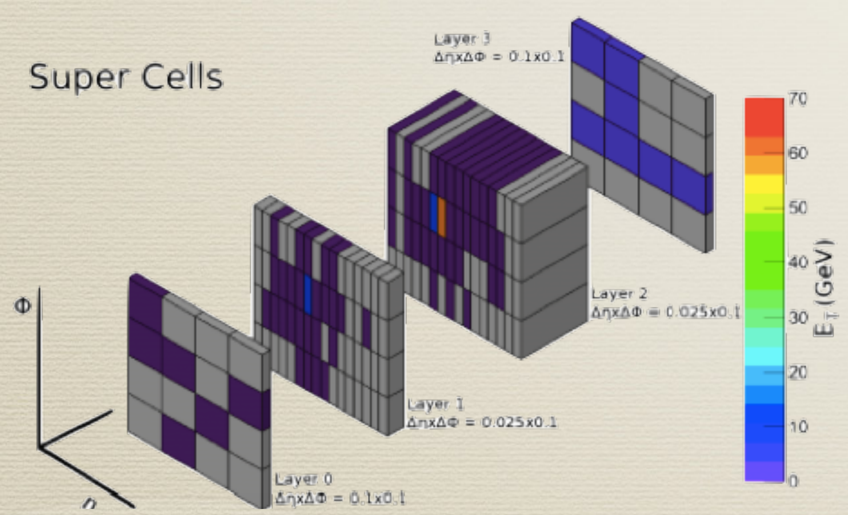
L1 trigger for calorimeter

Motivation: maintain high efficiency for Level-1 triggering on low P_T objects (electrons-photons)

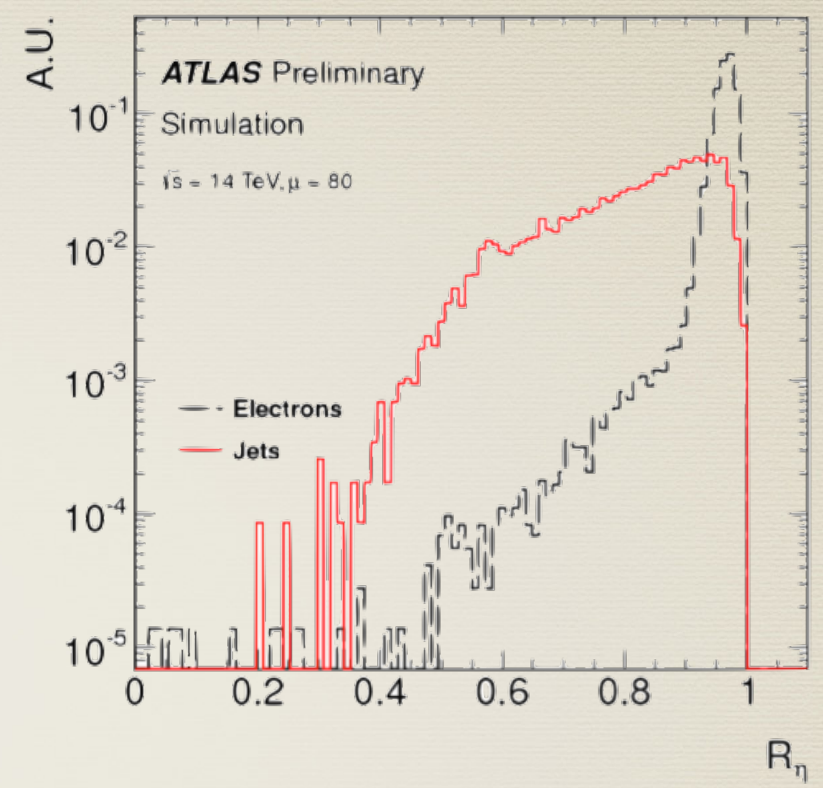




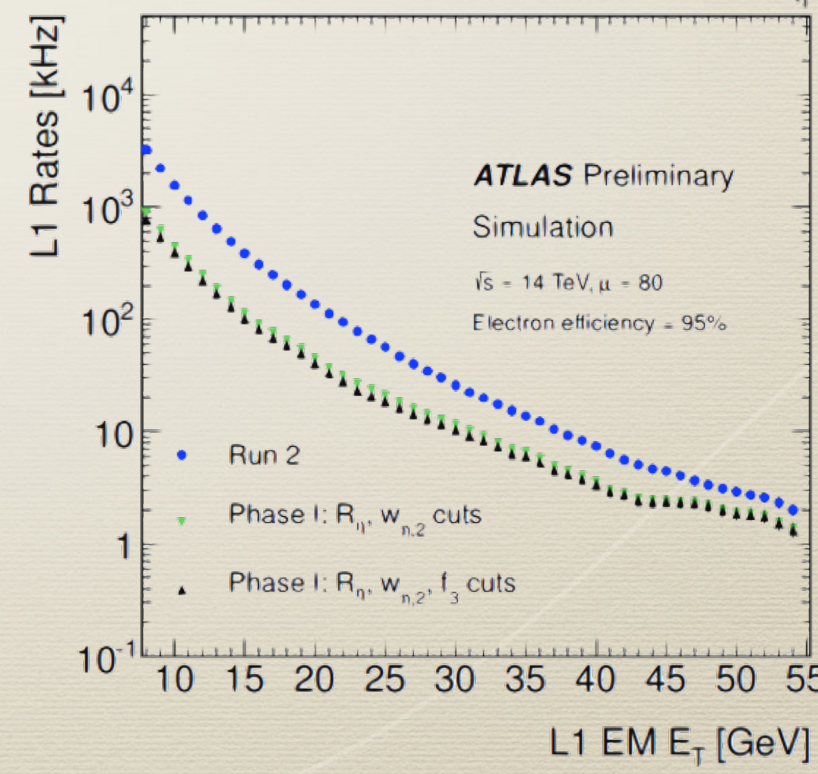
* The current Level 1 EM calorimeter trigger uses:
    * E_T thresholds based on η x ϕ=0.1 x 0.1 trigger towers
    * No fine-grained EM sampling info available at L1 trigger to compute shower shapes
* LAr calorimeter Upgrade : changes on the front-end electronics to exploit finer granularity:
    * Computation of lateral and longitudinal shower shapes
    * Improve granularity of trigger for better discrimination between electrons and jets
    * Requires new trigger electronics located in replacement trigger daughter boards for the Front End boards.

L1 trigger for calorimeter

* New trigger readout architecture for LAr, forward and backward compatibility:
  * On-detector : New layer sum and digitizer boards (LTDB)
  * Off-detector: Digital Processing System (DPS) and Feature Extractor in L1Calo.



* Better shower-shape discrimination:
  * lower EM threshold by ~ 7 GeV at the same rate
* In addition significantly improved resolution
  * lower EM threshold by another few GeV at same rate



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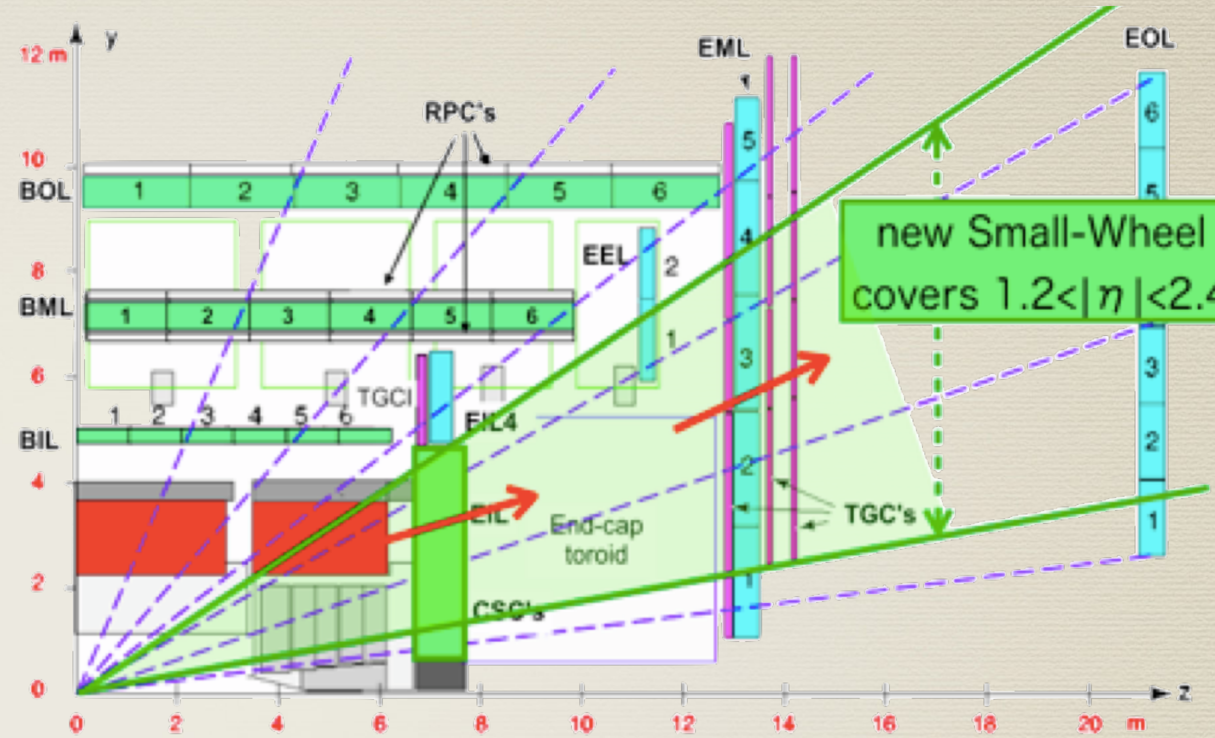
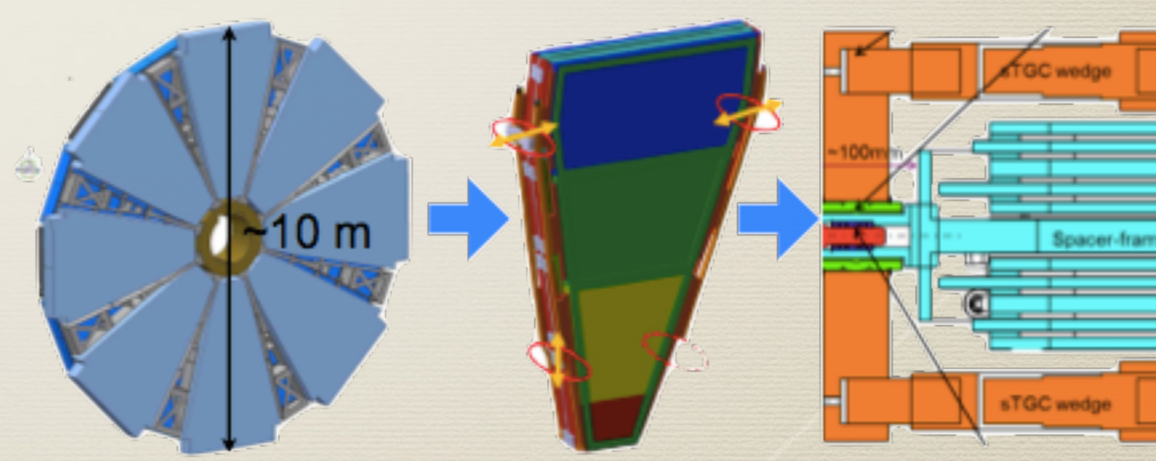
New Muon Small Wheels

* Consequences of luminosity rising beyond design values for forward muon wheels:
  * Degradation of the tracking performance (efficiency / resolution)
  * L1 muon trigger bandwidth exceeded unless thresholds are raised

* Replace Muon Small Wheels with New Muon Small Wheels:
  * Improved tracking and trigger capabilities
  * Position resolution < 100 μm
  * IP-pointing segment with σ_θ~ 1 mrad
  * Meets Phase-II requirements:
    * compatible with <μ>=200, up to $L \sim 7.10^{34}\ cm^{-2} s^{-1}$

* Technology: MicroMegas and strip Thin Gap Chambers (sTGC)





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LHC roadmap

From LHCC Open meeting, 03.12.2013

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ATLAS

Goals for HL-LHC

Physics

Study EWSB Mechanism	precision meas's of Higgs couplings (5-30%), Higgs self-coupling
Probe for signatures of New Physics	SUSY, Extra Dimensions, ...
Measure rare decay modes	Higgs, B, top, ...

Detector Requirements

Example Physics/Detector Motivation	**Requirement**
complex SUSY cascades	Trigger & reconstruct low p_T e/μ
$H \rightarrow \tau\tau$	Trigger on τ's
High-mass gauge bosons	Good lepton e/μ momentum resolution at high p_T
Complex SUSY cascades	Identify Heavy Flavors
Resonances in top pairs, W, Z, H	Reconstruct leptons & b's in boosted topologies
VBF, Missing ET	Preserve acceptance in forward region
Efficient tracking with small fake rates	Radiation Tolerance and Granularity
Impacts Front End electronics	Compatibility with new trigger system

Hal Evans

Goals for HL-LHC

Physics

Study EWSB Mechanism	precision meas's of Higgs couplings (5-30%), Higgs self-coupling
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Impacts Front End electronics	Compatibility with new trigger system

Improved trigger inputs and algorithms and increased detector coverage

New detector technologies required

Hal Evans

ATLAS upgrades - HL-LHC

* **LHC (after LS3: duration - 30 months, 2023-2025)**
  * prepare for luminosity levelling
  * peak luminosity $5.10^{34}cm^{-2}s^{-1}$ (levelled), considered up to $7.10^{34}cm^{-2}s^{-1}$ (<μ>=200) for safety, ~3000 fb^{-1} @ 14TeV
* **ATLAS upgrades:**
  * All new Tracking Detector
  * Level-1 track trigger
  * Calorimeter electronics upgrades
  * Upgrade muon trigger system
  * Possible changes to the forward calorimeters

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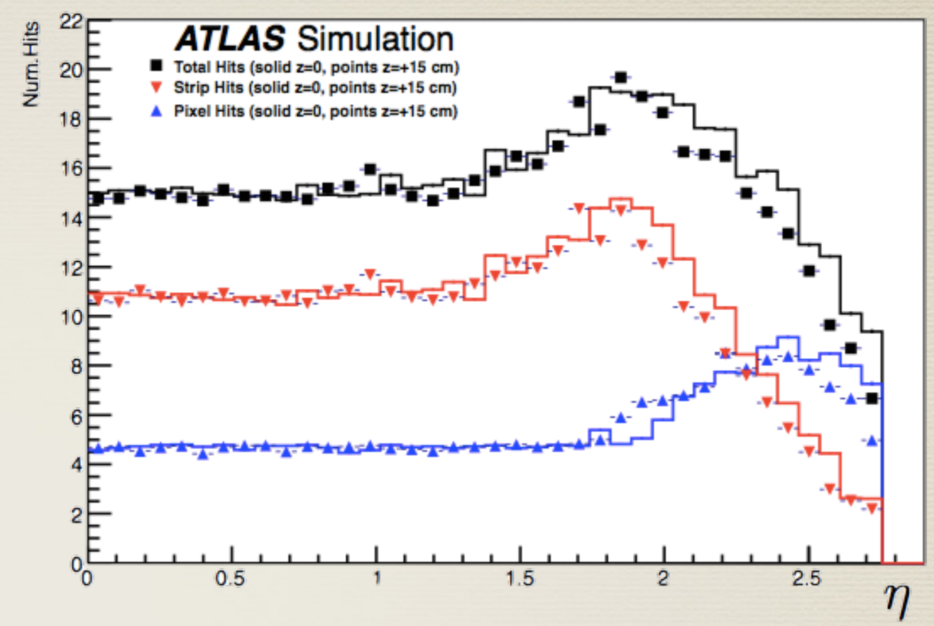
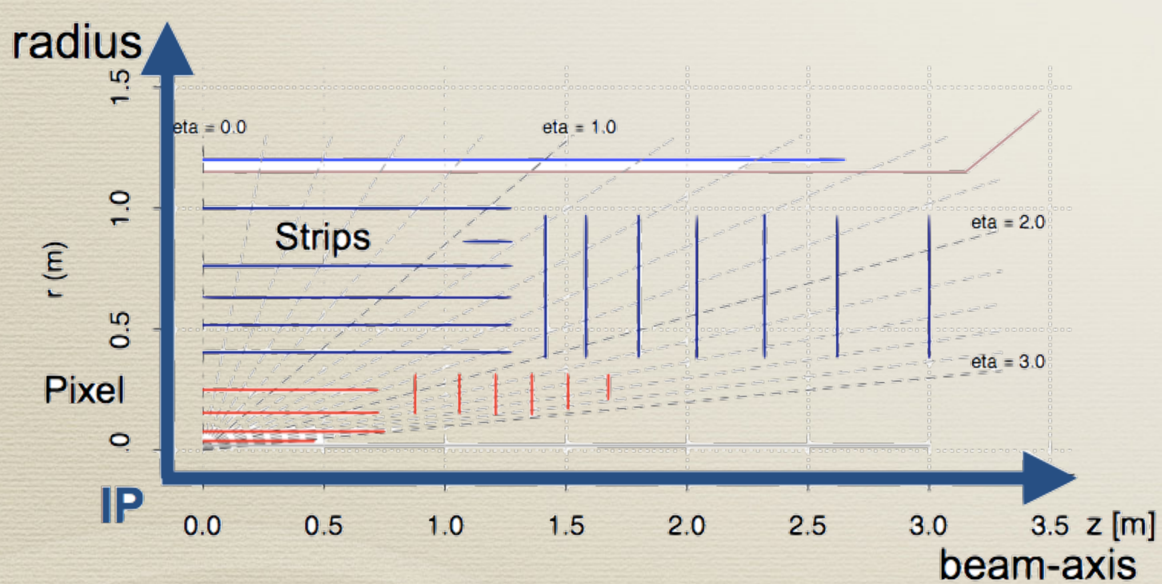
Inner TracKer (ITK)

Current Inner Detector - designed to operate for 10 years at $L=1.10^{34}\ cm^{-2}\ s^{-1}$ with $<\mu>=27$, @25ns, L1=100 kHz

* Limiting factors at HL-LHC ($L=5.10^{34}\ cm^{-2}\ s^{-1}$, $<\mu>=140$, 3000 fb^{-1}):
  * Bandwidth saturation (Pixels, SCT)
  * Increased occupancies (TRT, SCT) – up to 100% in TRT
  * Radiation damage (Pixels, SCT designed for 400 (700) fb^{-1})

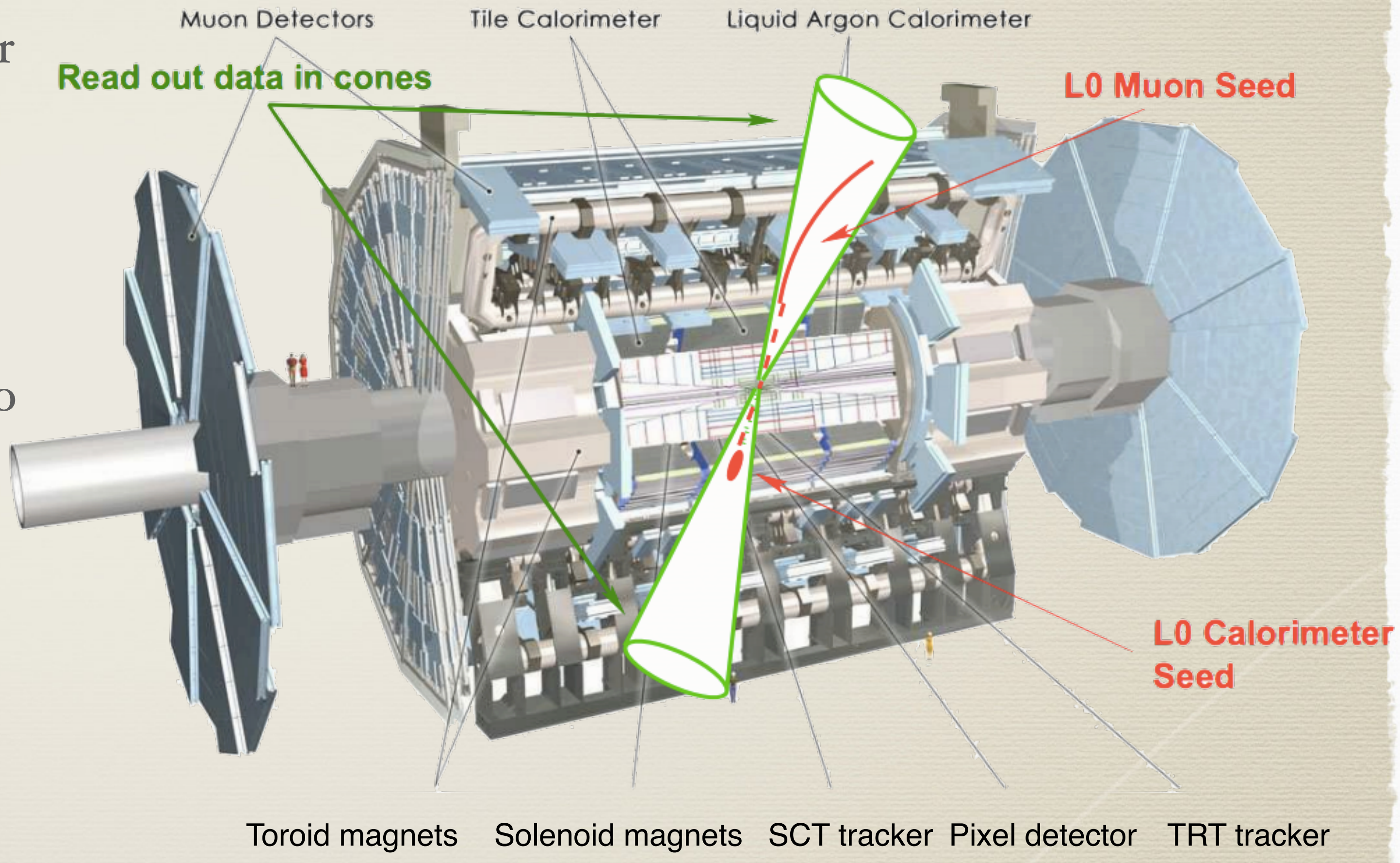




* Biggest changes compared to current tracker:
  * pixels system extends out to larger radii
  * more pixel hits in forward direction to improve tracking
  * smaller pixels and short inner strips to increase granularity
  * outer active radius slightly larger to improve momentum resolution
  * Remove Transition Radiation Tracker (TRT) as occupancy is too high during HL-LHC
  * Install new all-silicon tracker with pixels and strips
  * Granularity increases by a factor 4

L1 track trigger

* Adding tracking information at Level-1 (L1)
  * Move part of the "offline" 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 ≥ 500 kHz and defines RoIs
  * L1 track trigger extracts tracking info inside RoIs from detector FEs
* Challenge
  * Finish processing within the latency constraints
* Requires changes to detector FE electronics feeding trigger system



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Summary

The ATLAS collaboration developed a detailed program to reflect the changes in the LHC conditions towards the HL-LHC, characterised by high track multiplicity and extreme fluences.

We aim at:

* maintaining/improving the present detector performance.
* ensuring optimal physics acceptance as the instantaneous luminosity increases.

The major ATLAS upgrades include:

Phase 0

New Inner Pixel Layer
Detector consolidation

Phase 1

Improve L1 trigger capabilities to cope with higher rates
Improve Muon system with nMSW

Phase 2

Prepare for 200 pileup events
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics

An exciting new chapter is beginning !

Now !

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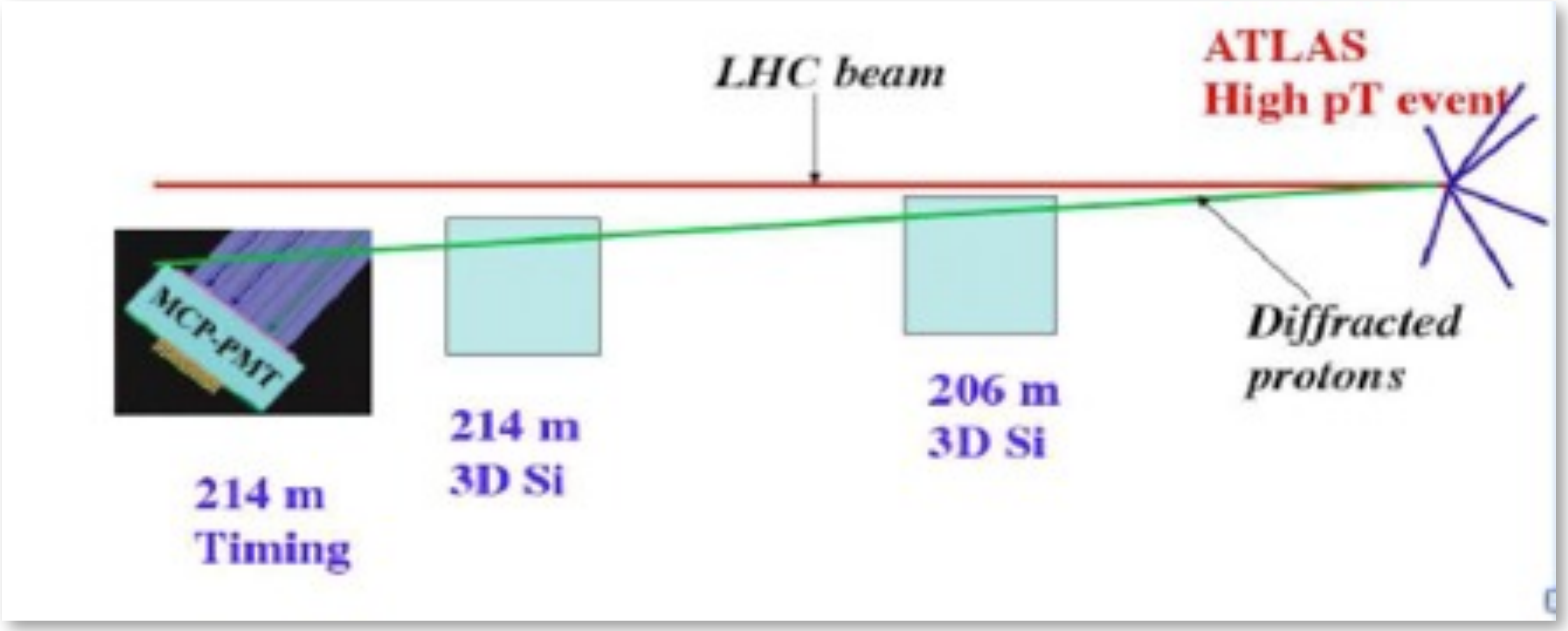
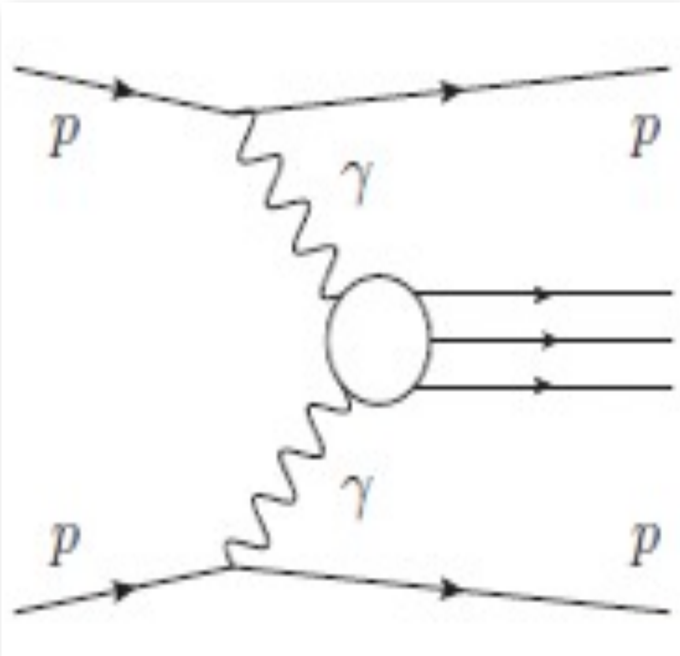
Backup

ATLAS Forward Physics (AFP)

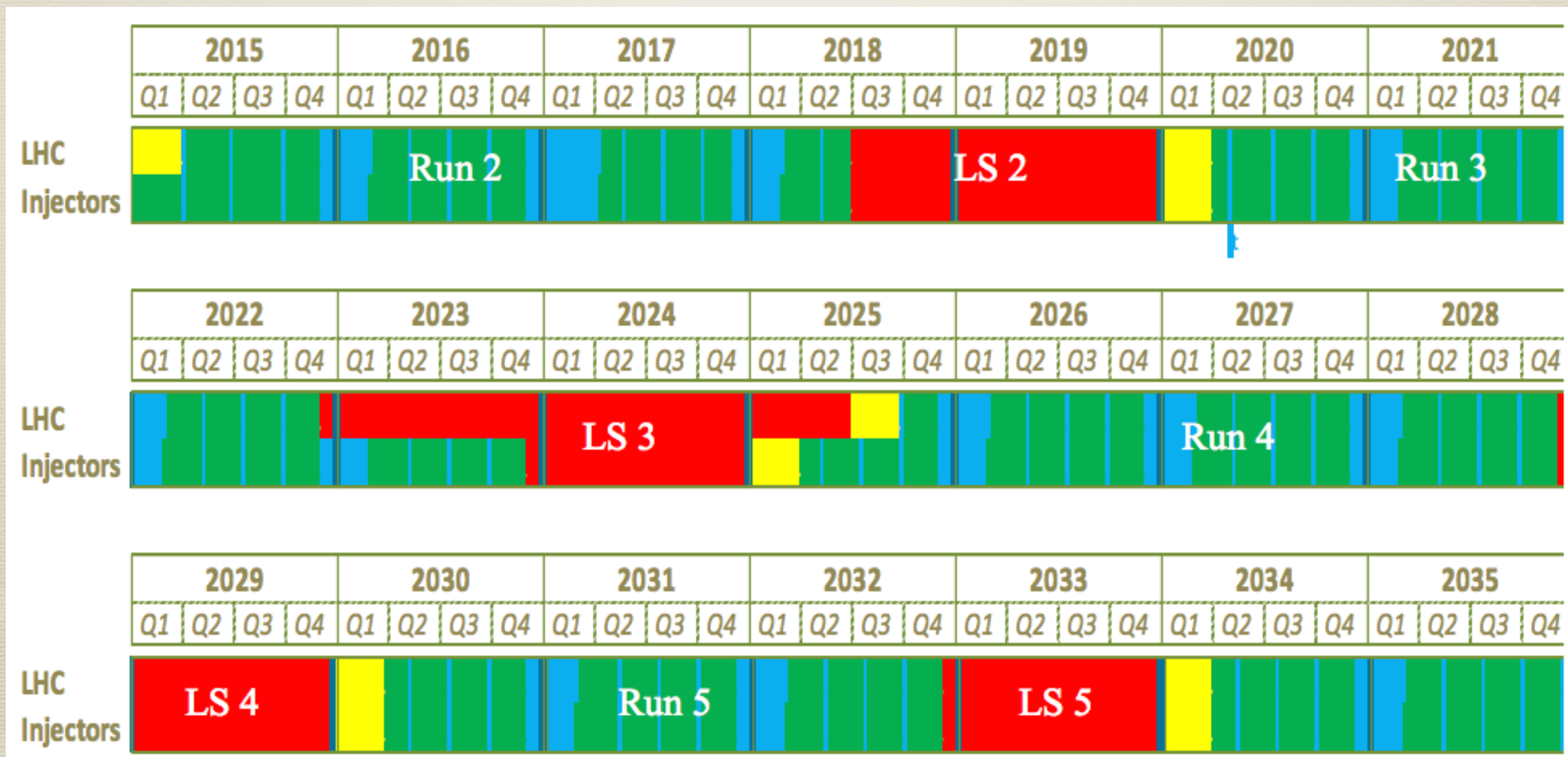
* Tag and measure scattered protons at +/- 210m
  * Link to system triggered in central ATLAS
  * Radiation-hard edgeless 3D silicon developed in IBL context
  * 10ps timing detector for association with high pT primary vertex
  * Probe hard diffractive physics and central exclusive production of heavy systems/particles





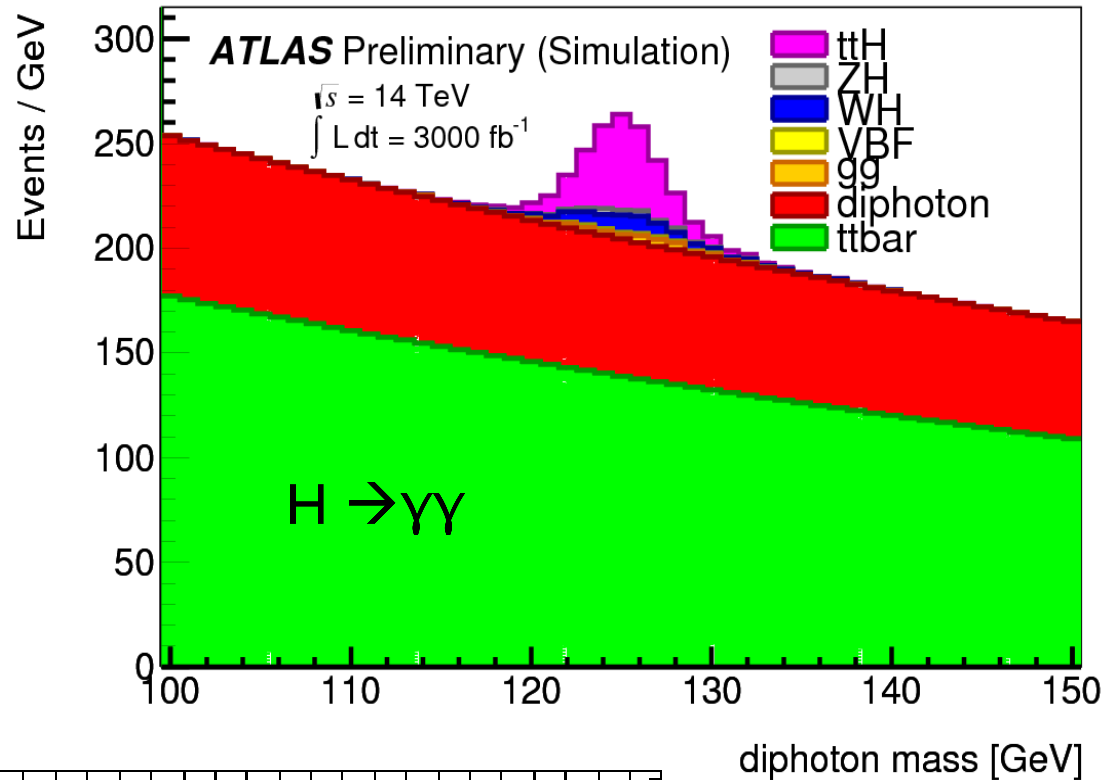
New LHC schedule beyond LS1

* LS2 Starting in 2018 (July) 18 months + 3 months BC (BC: Beam Commissioning)
* LS3 Starting in 2023 30 months + 3 BC
  Injectors: in 2024 13 months + 3 BC



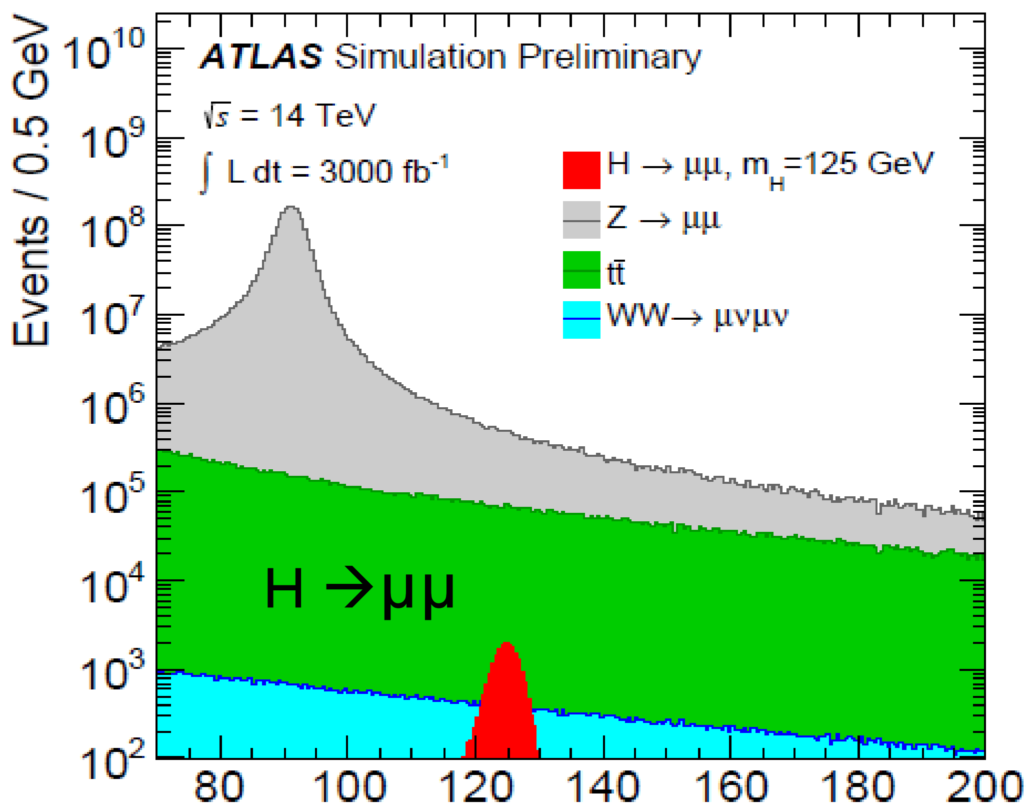
Higgs rare process/Decay projections

Signals only accessible with 3000 fb^{-1} with errors limited by statistics



ttH production with H →γγ

- Direct access to Higgs-top coupling.
- Today's sensitivity (30 fb^{-1}): 6xSM cross-section
- With 3000 fb^{-1}: expect 200 signal events > 5σ
- Higgs-top coupling can be measured to about 10%

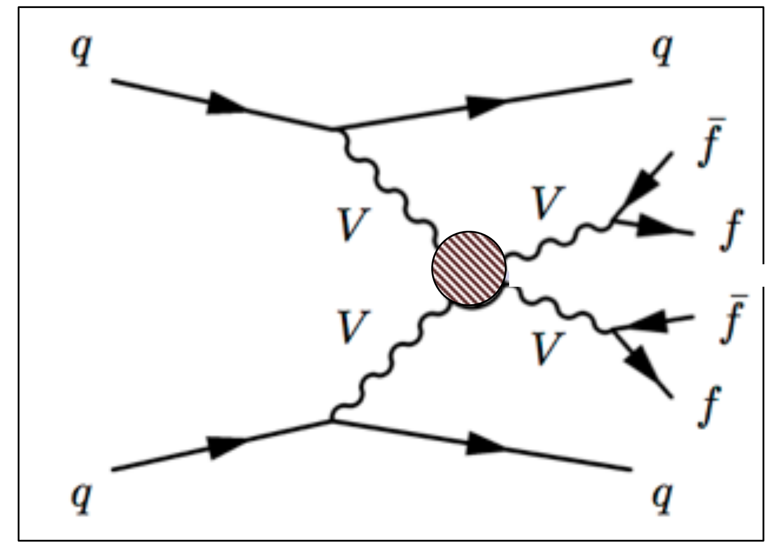


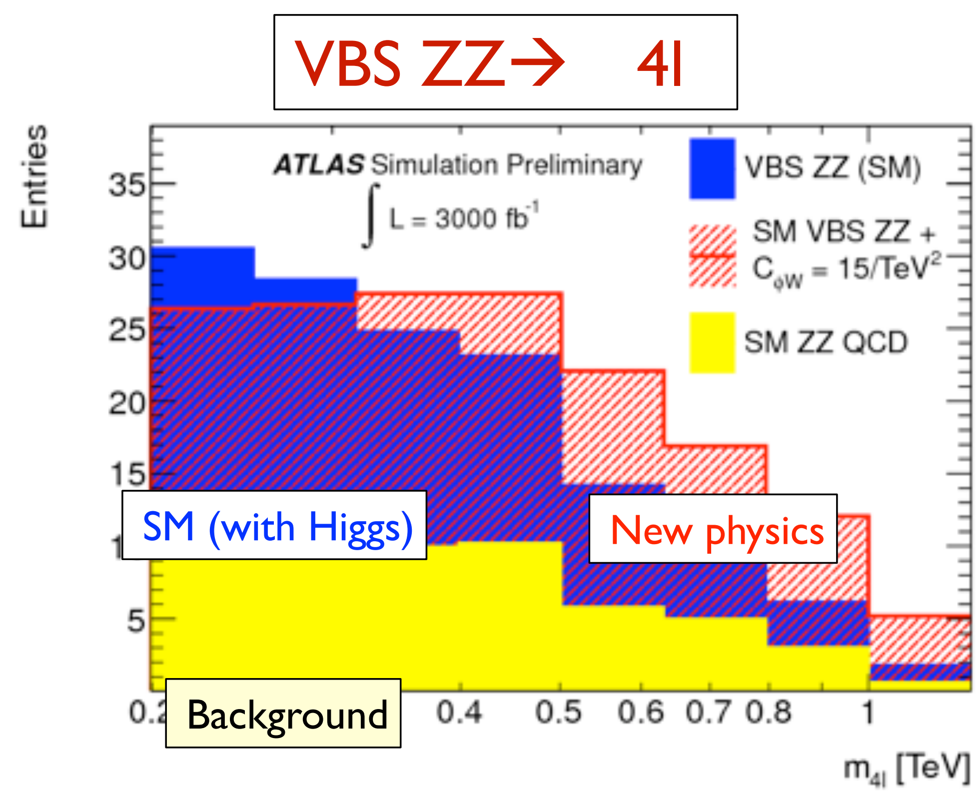
H →μμ

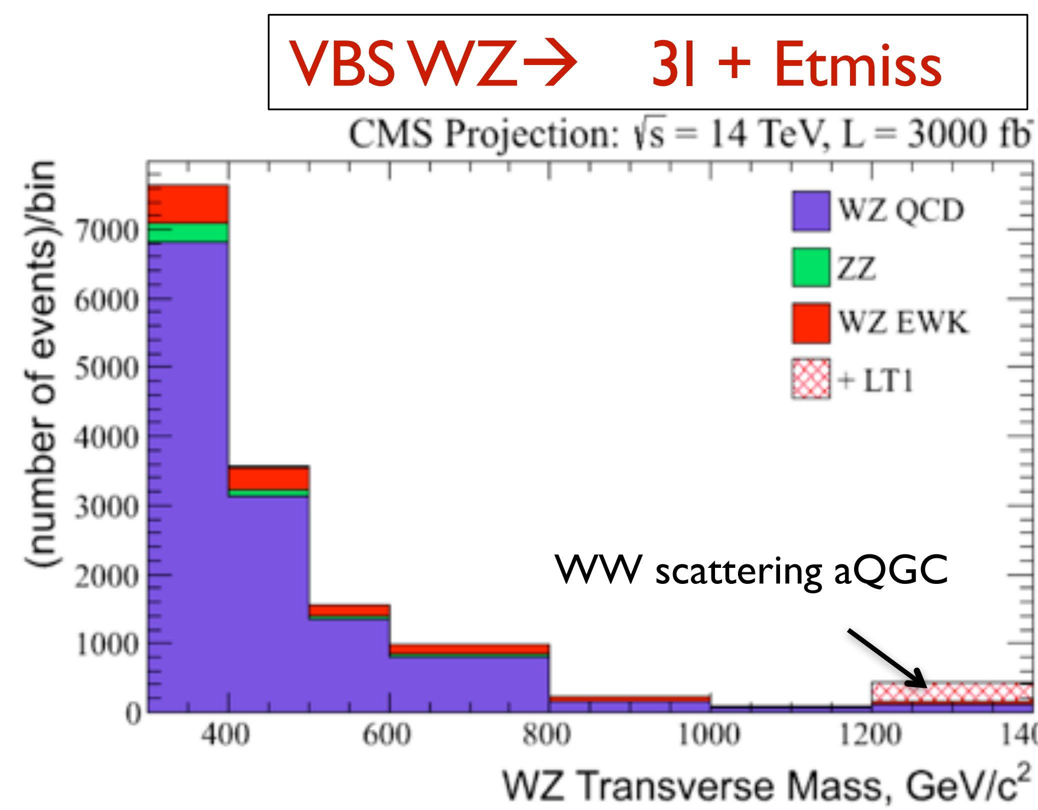
- Gives direct access to Higgs couplings to fermions of the second generation.
- Today: 8xSM cross section
- With 3000 fb^{-1} expect 17000 signal events and 7 σ significance
- Higgs-muon coupling can be measured to about 10%

Vector Boson Scattering

- Not yet observed - test of Higgs role in cancelling VBS divergence in SM can be measured to 30% (10%) with 300 (3000) fb-1
- If new physics exists: sensitivity to anomalous triple or quartic couplings increases by factor of ~ 2 between 300 and 3000 fb-1







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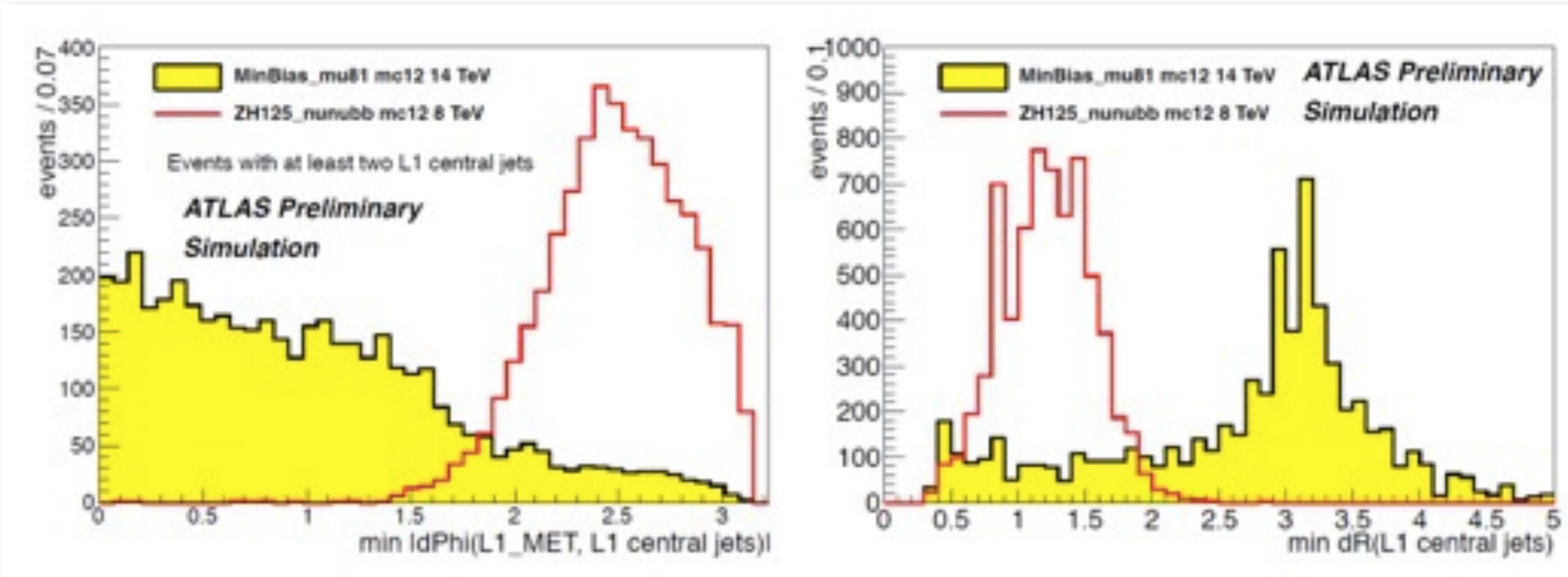
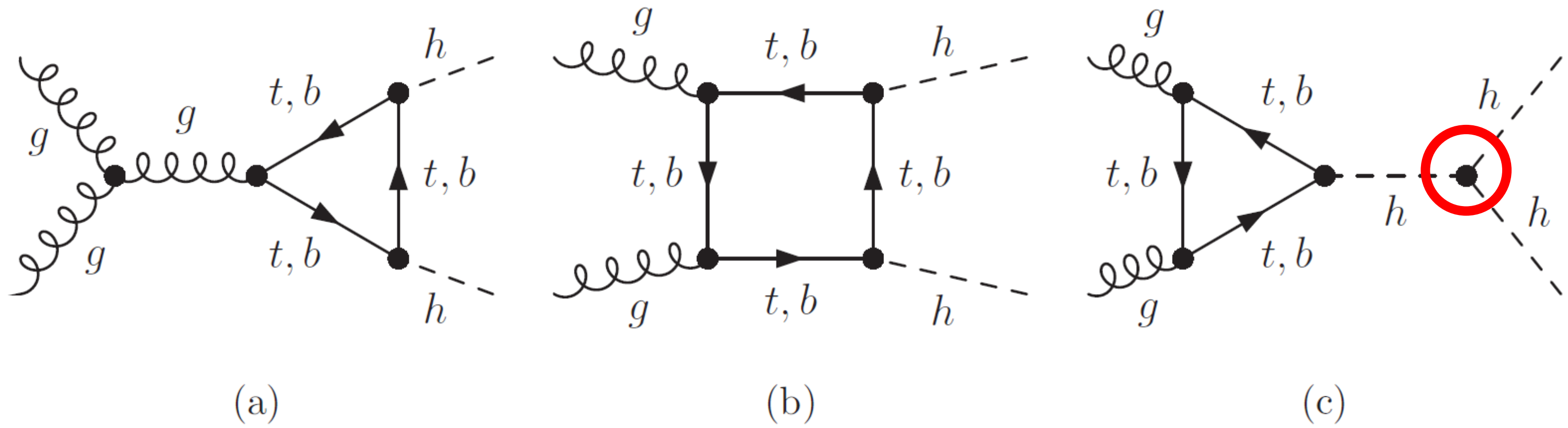
Level-1 Topological Trigger



Example: exploit characteristic location of pile-up jets wrt E_T^{miss} vector

- In Phase-I, ***ZH*** → ***vvbb*** with 160 GeV E_T^{miss} trigger (XE40) would exceed total L1 rate due to pile-up jets faking missing energy
  - Increasing threshold rapidly costs signal efficiency
- Combination with inclusive jet trigger brings rate down to ~10 kHz (still too high)
- L1Topo: cut on azimuthal distance between jet and *E*Tmiss (Δ*φ* > 1) reduces rate by ~45% with negligible loss in signal efficiency
  - radial distance (Δ*R*) cut could be used to further reduce rate

Higgs self-coupling measurement



- In order to determine the parameters of the SM completely, a measurement of the Higgs self-coupling is essential
  - Higgs potential and the EWSB mechanism
- Measurement of double Higgs production
- Destructive interference between diagrams with triple Higgs coupling and other diagrams

	σ_{HH} **(fb)**
$\lambda = 0$	71
$\lambda = \lambda_{SM}$	34
$\lambda = 2 \cdot \lambda_{SM}$	16

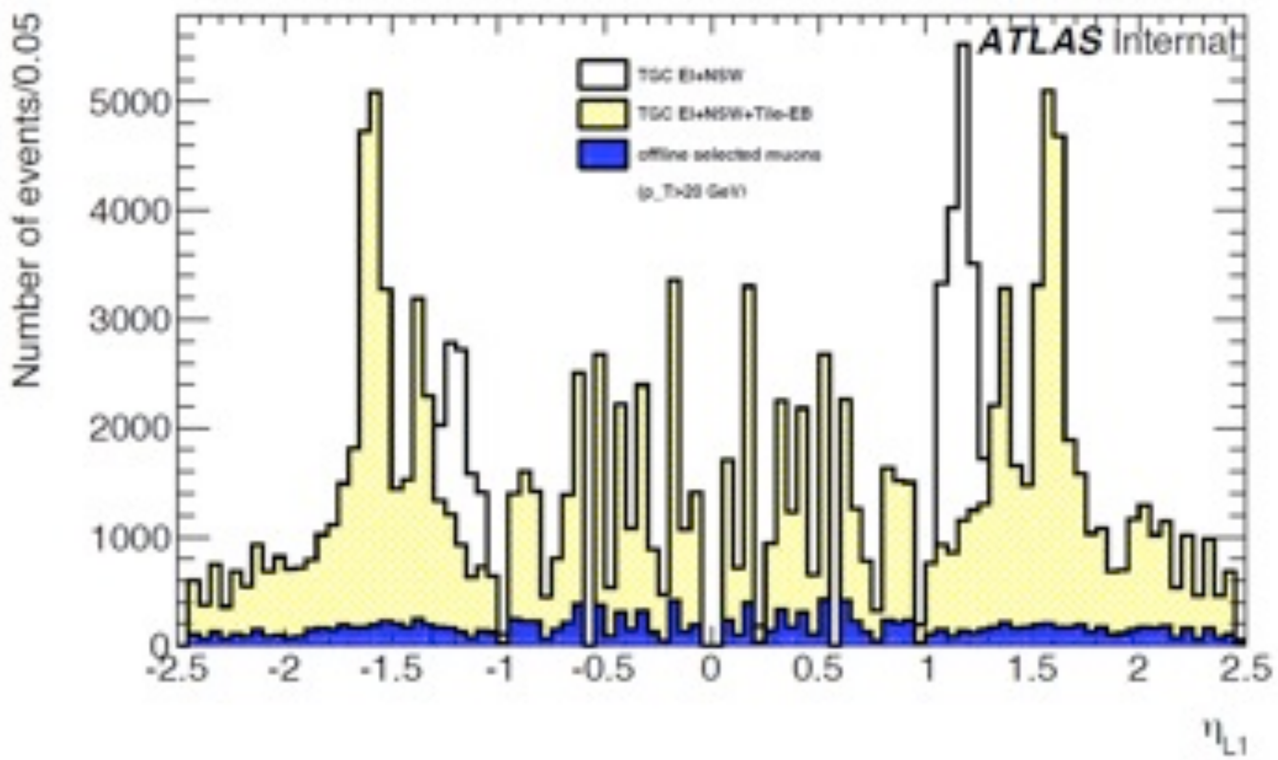
Double Higgs production yields

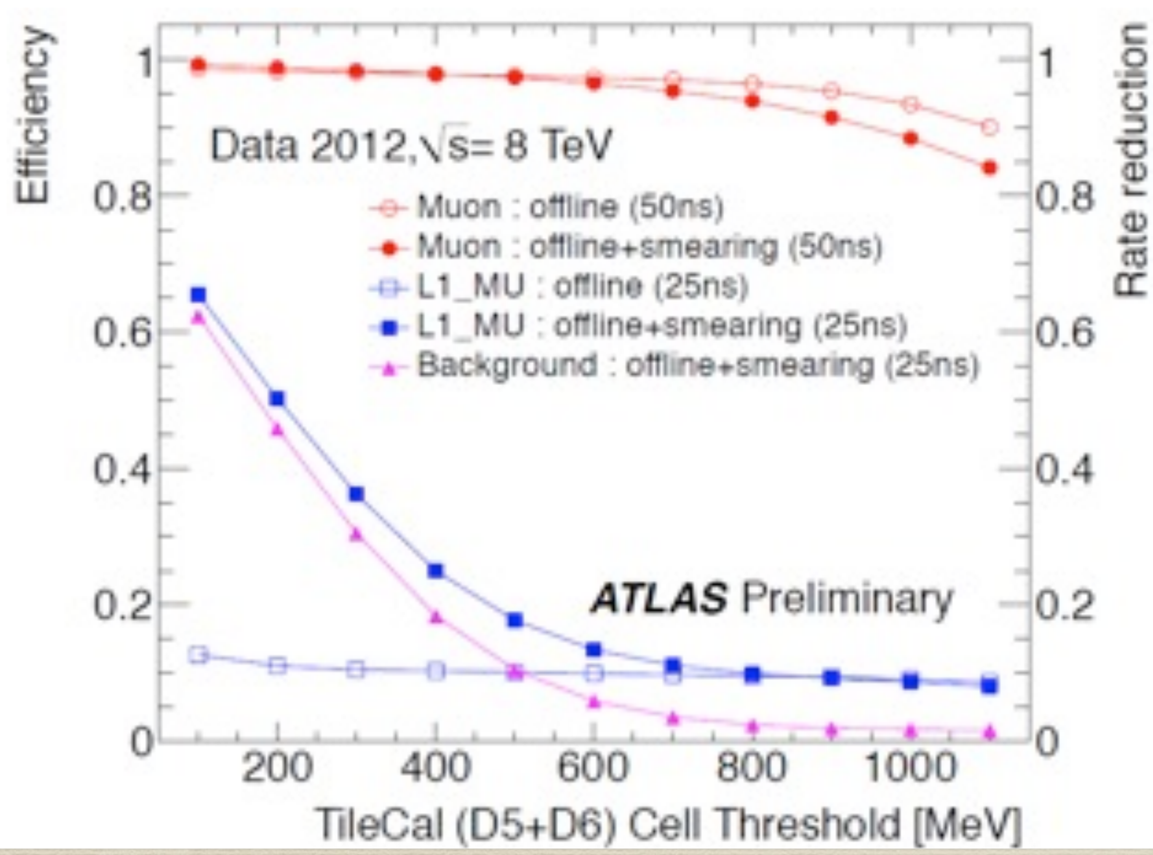
Event yields of various channels

Decay channel	Branching ratio (%)	Yield with 3 ab^{-1}
$b\bar{b}b\bar{b}$	33.4	34,000
$b\bar{b}W^+W^-$	25.0	25,500
$b\bar{b}\tau\tau$	7.36	7,500
$W^+W^-W^+W^-$	4.66	4,750
$b\bar{b}ZZ$	3.09	3,150
ZZW^+W^-	1.15	1,170
$b\bar{b}\gamma\gamma$	0.26	265

- Very challenging due to low yield and contributions from irreducible backgrounds ($t\bar{t}H, ZH,$ etc.)
- Ongoing studies suggest some sensitivity to constrain the triple Higgs coupling
- Also, several phenomenological papers suggest this possibility

Muon Trigger: Tile coincidence





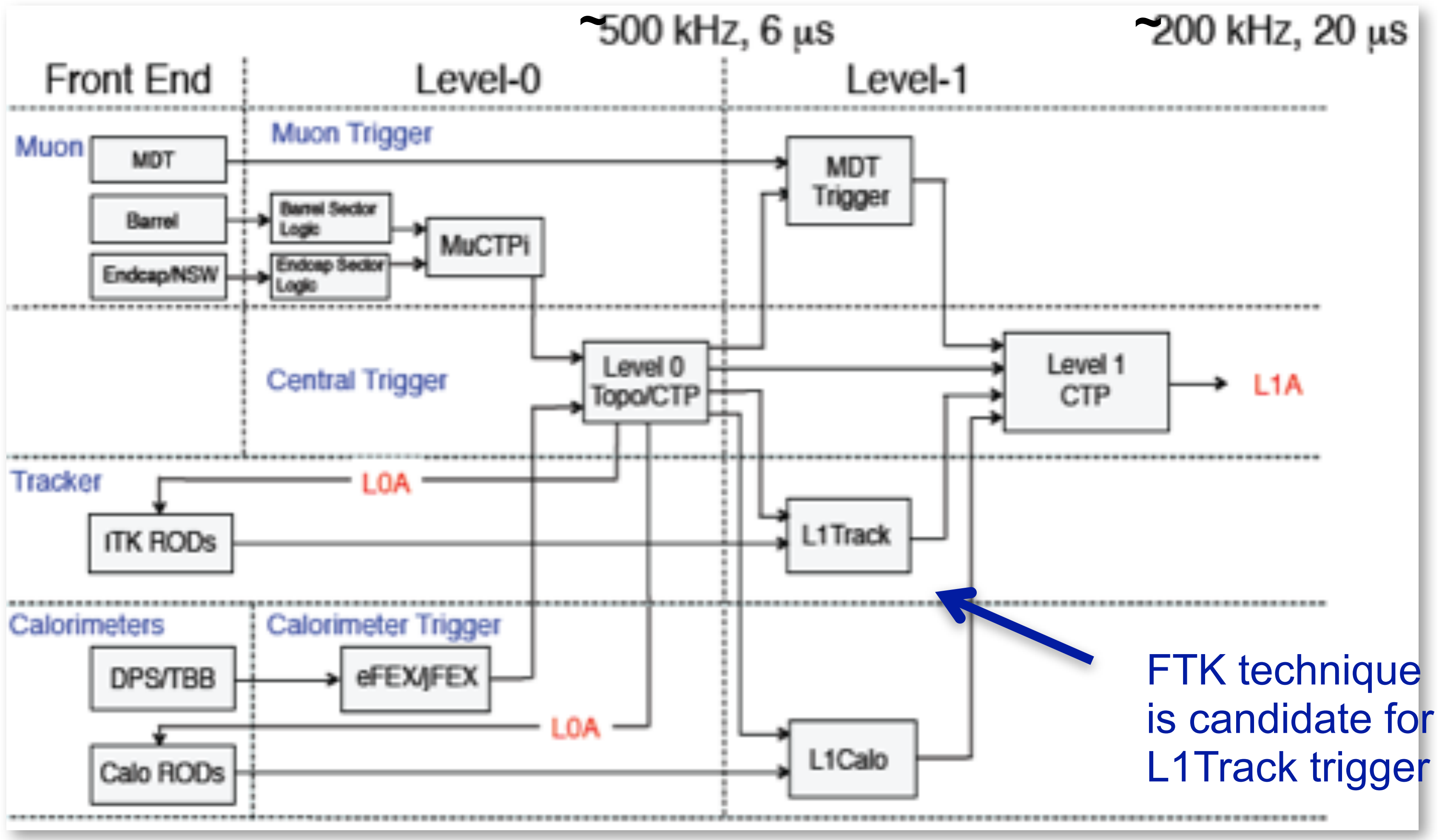
- Main source of fake triggers are low-momentum protons emanating from endcap toroid and shielding
  - 1.0 < |η| < 1.3 region of Big Wheel TGC not covered by the NSW
- Use hadronic TileCal extended barrel (D-layer) for trigger coincidence
  - Energy resolution smeared by electronics noise in Level-1 read-out path lowers efficiency above 500 MeV
- Tile Muon coincidence reduces rate by 82% at that threshold

Trigger system architecture

- New design for Phase II
  - 2-level system, Phase-I L1 becomes Phase-II L0, new L1 includes tracking
  - Make use of improvements made in Phase 1 (NSW, L1Calo) in L0
  - Introduce precision muon and inner tracking information in L1
    - Better muon pT resolution
    - Track matching for electrons,…
  - Requires changes to detector FE electronics feeding trigger system

Will also have new timing/control links and LHC interface system

Level-0
Rate ~ 500 kHz, Lat. ~6 μs
Muon + Calo
Level-1
Rate ~200 kHz, Lat. ~20 μs
Muon + Calo + Tracks



FTK technique is candidate for L1Track trigger

Diane Cinca

ATLAS Silicon Strip tracker

* Outer tracker is a silicon strip detector with n-in-p sensors:
  * 5 barrel layers, 7 discs EC, “stubs”
* Double-sided layers with axial strip orientation and rotated by 40mrad on other side (z-coordinate)
  * Short (23.8 mm) and long strips (47.8 mm) with 74.5 µm pitch in barrel
  * End-Cap with radial strips of different pitch (6 different module designs)
* Silicon Modules directly bonded to a cooled carbon fibre plate.
* A sandwich construction for high structural rigidity with low mass.
* Services integrated into plate including power control and data transmission.