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

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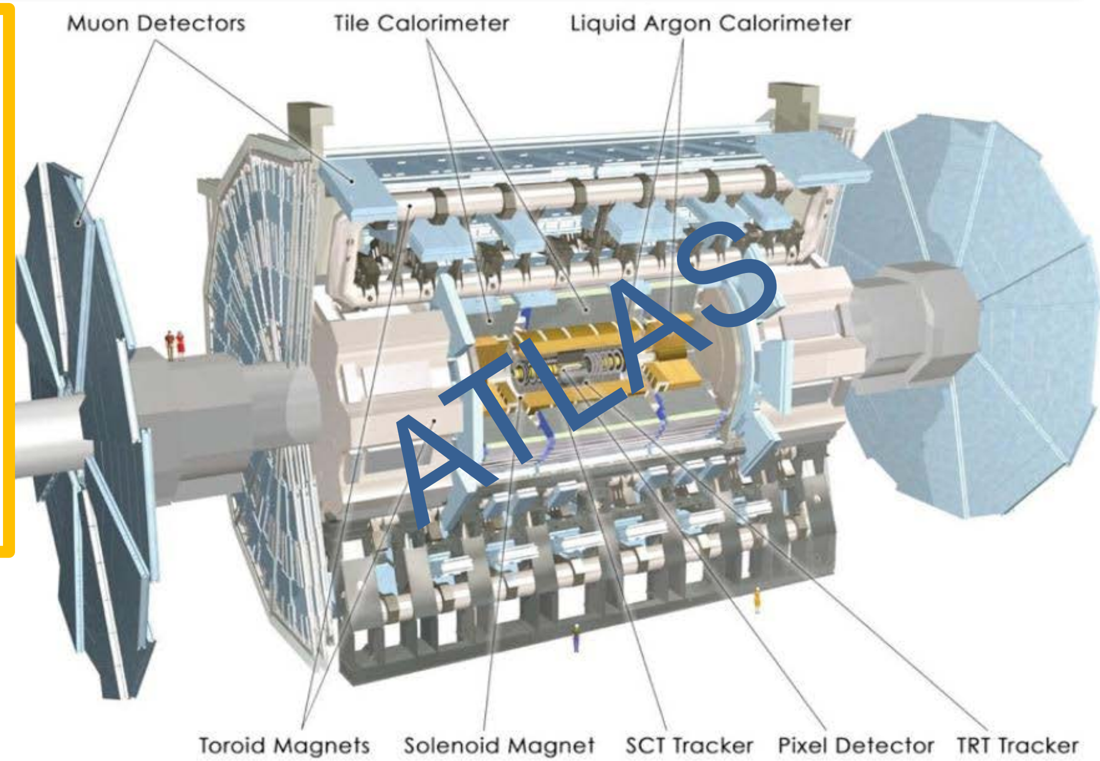
Outline

- Motivation for ATLAS Upgrade(s)
- Timeline & Individual Sub-System Upgrades
  - Phase 0 (consolidation)
  - Phase 1
  - Phase 2 (HL-LHC)
- Summary



⇨ LHC 2012 pp run, $\sqrt{s}$=8 TeV

- Outstanding LHC performance, 23.3 fb^{-1} delivered,
  - Peak luminosity routinely over 7.5 $10^{33}cm^{-2}s^{-1}$
- Excellent ATLAS performance, 21.7 fb^{-1} recorded
  - ~94% data-taking efficiency
    - dominated by detector dead-time
- Main challenge: higher number of pile-up events ($\langle\mu\rangle \sim 35$)

More about the ATLAS performance in I. Riu's talk

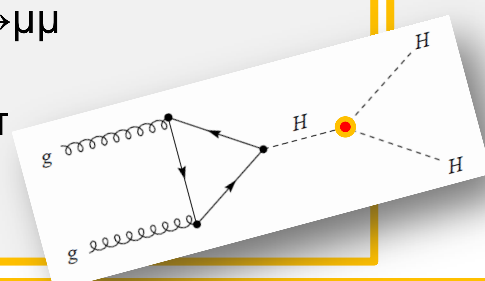
Motivation for ATLAS Upgrade

- European Strategy for Particle Physics:
  https://indico.cern.ch/getFile.py/access?resId=0&materialId=0&confId=217656
  - “The discovery of the Higgs boson is the start of a major program of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this program.”
  - “*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*.”

➤ Physics prospects with High-Luminosity LHC at ATLAS:

- Higgs measurements:
  - Higgs couplings (exp. precision 5-30%)
  - Higgs rare processes
    - $H \to \mu\mu$
    - ttH with $H \to \gamma\gamma$ or $H \to \mu\mu$
  - Higgs self-coupling
    - $HH \to bb\gamma\gamma$, $HH \to bb\tau\tau$

More in N. Konstantinidis’s talk

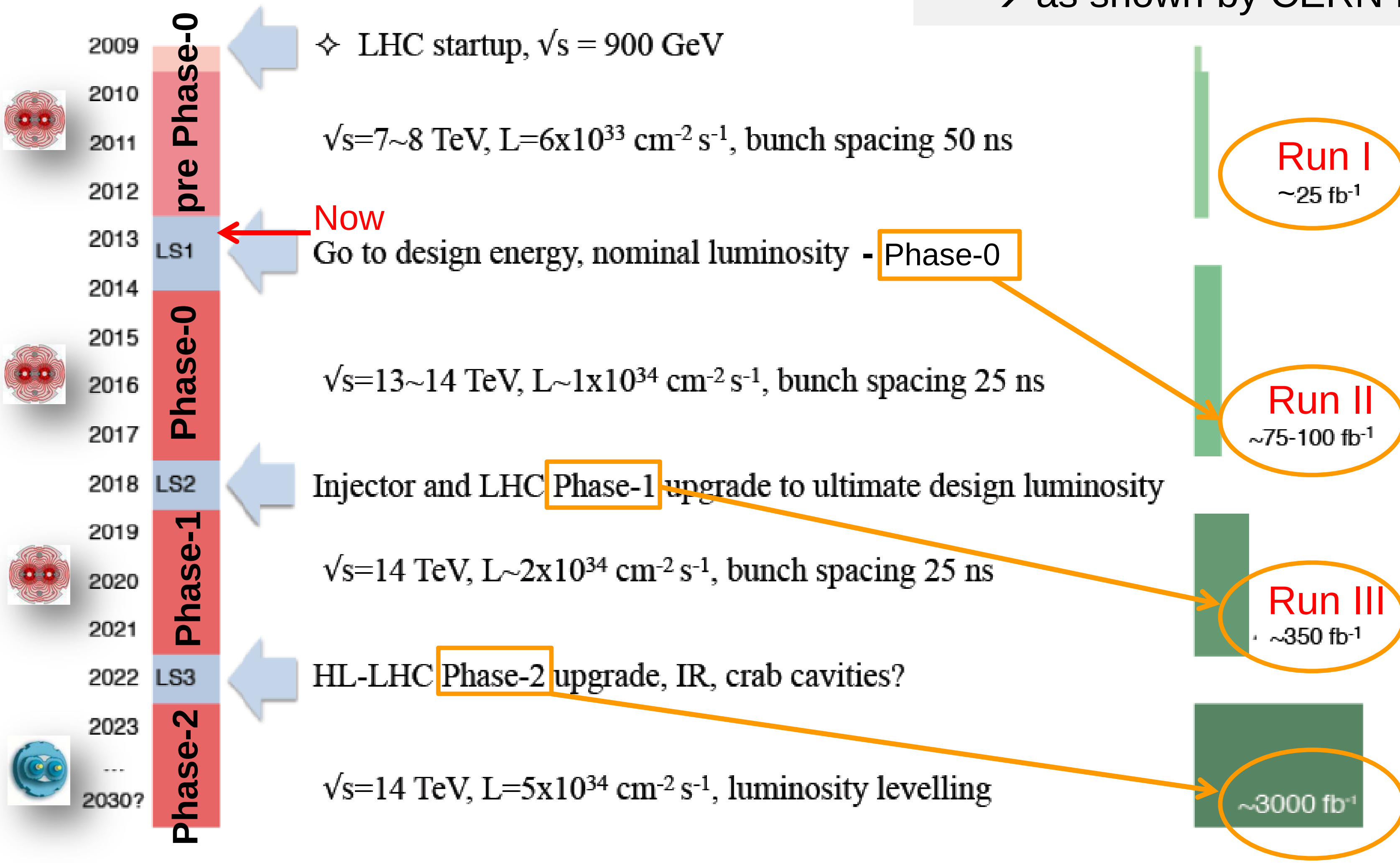


- Vector boson scattering
- BSM physics
  - High mass gauge bosons
  - tt resonances
  - SUSY, Extra dimensions
  - Quark and lepton substructure
  - Dark matter candidate, …

- HL-LHC environment is a great challenge to ATLAS. Upgrades are needed.

LHC Roadmap to Achieve Full Potential

- Foreseen schedule
  → as shown by CERN DG ('13)

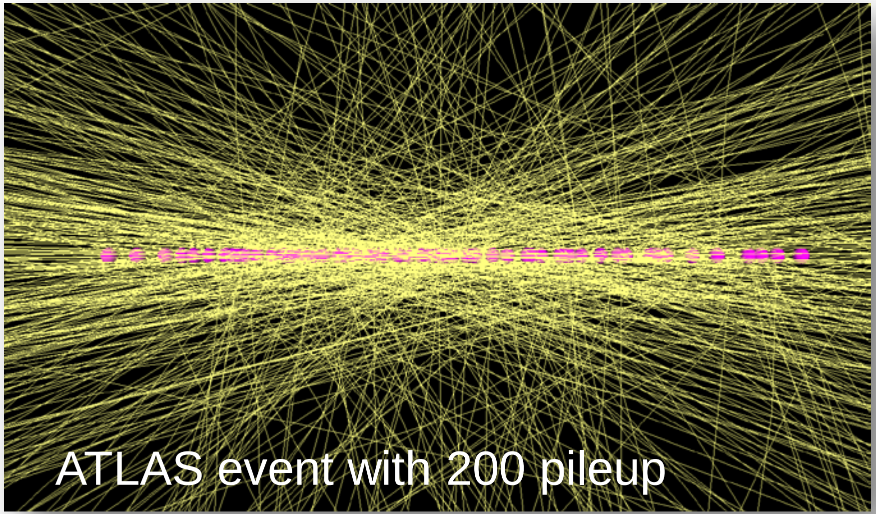


ATLAS Upgrade Program & Challenges

- Upgrades of ATLAS sub-systems are planned in order to maintain or improve the present performance as the instantaneous luminosity increases.
- The upgrades are devised in three phases, following the LHC upgrade periods. The goal is to optimize the physics reach for each LHC run.

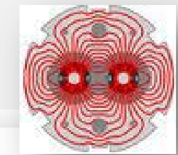
➢ Detector challenges:

- Expected *peak luminosity* → from 1×10^{34} to 5×10^{34} cm^{-2}s^{-1}
  - higher particle fluxes, larger event sizes, higher trigger rate
    - improved triggers needed
- *Multiple interactions per bunch crossing – "pileup"* → up to μ=<200>
  - higher detector occupancy
    - readout limitations
  - increasing reconstruction complexity
- *Increasing fluences* → up to $10^{16} n_{eq}/cm^2$, close to beam pipe
  - increased radiation damage
  - increased activation of materials

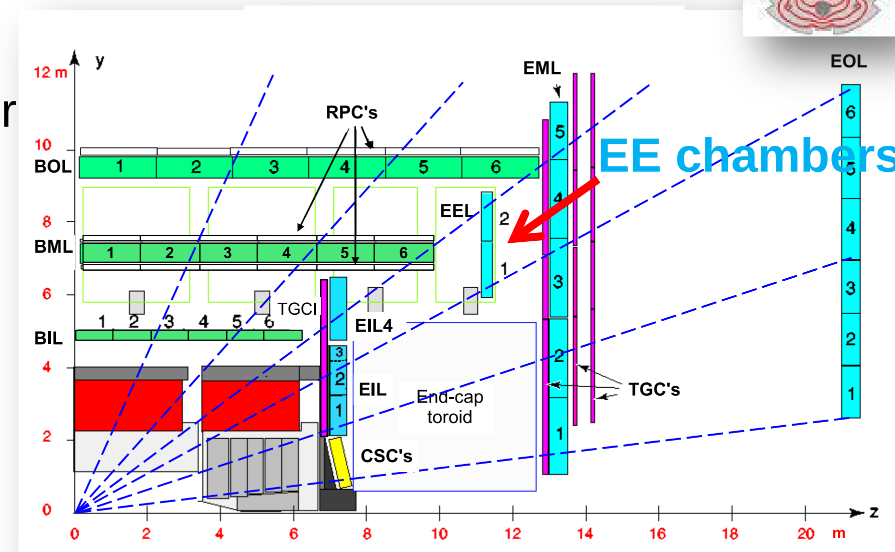


ATLAS Phase-0 Upgrade

- **Phase-0 upgrade** (duration - 18 months, 2013-2014, during the LHC LS1) → **Now!**
  - Run II (2015): $\sqrt{s}$=13-14 TeV, L~1x10^{34} $cm^{-2}s^{-1}$, <μ>~23, @ 25 ns,
  - ~100 fb^{-1} expected



- Detector upgrade
  - Insertion of an additional, 4^{th} pixel layer (Insertable B-Layer, IBL)
  - New Pixel services (nSQP)
  - Completion of Muon Spectrometer
    - Chambers added to improve acceptance for 1.0<|η|<1.3, the so called Endcap Extension (EE) Muon Chambers

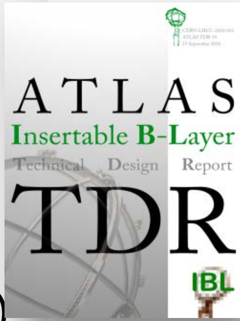


- Detector consolidation
  - New evaporative cooling plant for the Si trackers (Pixel and SCT)
  - New, *Al* (forward region) and *Be* (central region) beam pipes
  - Replace all calorimeter Low Voltage Power Supplies
  - Add additional neutron shieldings (e.g. behind the endcap toroid)
  - Upgrade the magnets cryogenics and decouple toroid and solenoid cryogenics

ATLAS Phase-0: IBL

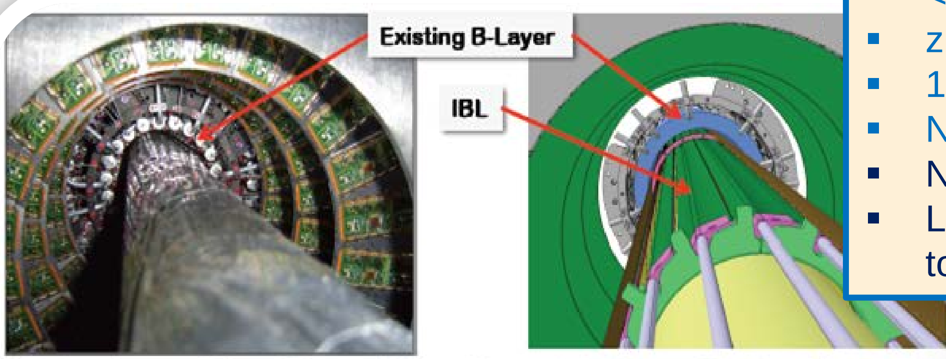
More in Jens Dopke's talk

- Core activity of the ATLAS Phase-0 Upgrade: installation of a new, 4th pixel layer b/w the innermost Pixel (B-)layer and the beam pipe – the **Insertable B-Layer**, **IBL**
  - Smaller pixels (50x400 μm → 50x250 μm)
  - Technology: planner and 3D Si sensors
  - New readout chip (FE-I4 Pixel Chip in 130nm CMOS, 26880 channels)
- New *Be* beam pipe with smaller radius is foreseen, r = 29mm → 25 mm

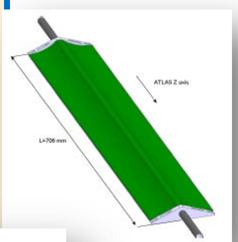


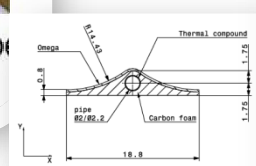
CERN-LHCC-2010-013

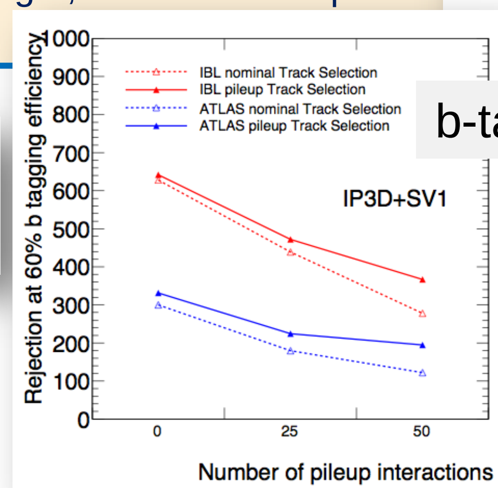
- $\langle r \rangle_{sens}$=33 mm vs. present $\langle r \rangle$ = 50.5 mm
- z coverage = 60 cm, |η| < 2.5
- 14 staves with φ overlap
- No η overlap of modules on stave
- New stave design with carbon foam
- Low material budget; Excellent heat path to cooling pipe



Mission impossible… fit an additional layer in between Pixel and beam-pipe
- Reduce beam-pipe by 4 mm in radius… and make it possible!



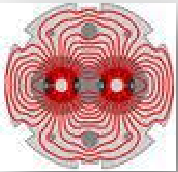




b-tagging

- Compensate for defects in the existing B-layer
- Improves tracking, vertex resolution, secondary vertex finding, b-tagging, τ-reconstruction at high pileup

ATLAS Phase-1 Upgrade

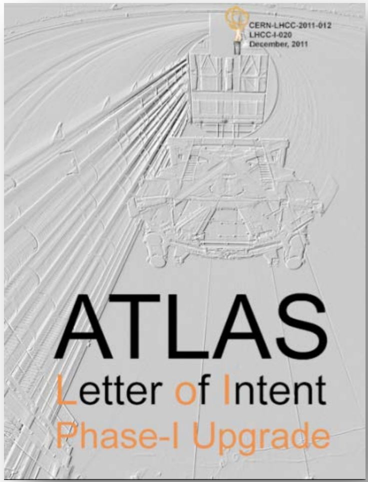


- ❑ **Phase-1 upgrade** (duration - 14 months, 2017-2018, during the LHC LS2)
  - ⇨ ❑ Run III (2018): $\sqrt{s}$=14 TeV, L~2-3x10^{34} $cm^{-2}s^{-1}$, <μ>=55-80, @ 25 ns
    - ❑ ~ 300 fb^{-1} expected

- ❑ Detector upgrades
  - ❑ **N**ew Muon **S**mall **W**heels (**NSW**) for the forward muon spectrometer
  - ❑ Higher precision Level-1 calorimeter trigger (L1Calo)
    - ❑ New front-end readout interface for the LAr to exploit finer granularity
  - ❑ **F**ast **T**rac**K** trigger (**FTK**) - input for Level-2
  - ❑ Topological (multi-object) trigger processors for Level-1
  - ❑ **C**entral **T**rigger **P**rocessor (**CTP**) upgrades

- ❑ New project
  - ❑ New forward diffractive physics detectors at ± 210 m, **A**TLAS **F**orward **P**hysics (**AFP**)

- ❑ All upgrades **compatible** with Phase-2



CERN-LHCC-2011-012

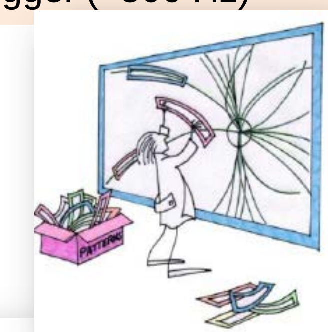
Phase-1 LoI: https://cds.cern.ch/record/1402470?ln=en

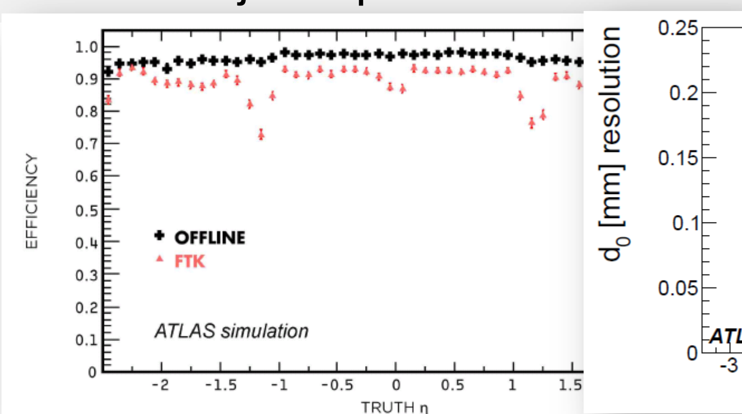
ATLAS Phase-1: FTK

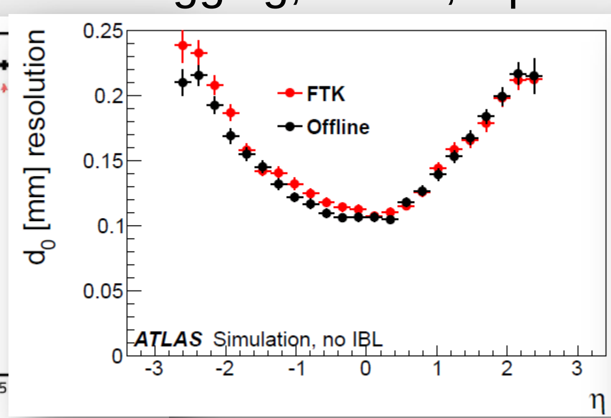
- Effective triggering at high luminosity is extremely challenging
  - especially for triggers that require track reconstruction
- **Fast TracK trigger (FTK)** – a dedicated, *hardware-based* track finder, an input for L2
  - Finds and fits tracks (~ 25 μs) in the ID silicon layers (incl. IBL) at an “offline precision”, for events passing L1
  - Processing performed in two steps
    1. hit pattern matching to 10^9 pre-stored patterns (coarse)
    2. subsequent linear fitting in FPGAs (precise)
  - Inspired by the CDF Silicon Vertex Trigger (SVT)
  - Major improvement for b-tagging, tau ID, lepton isolation

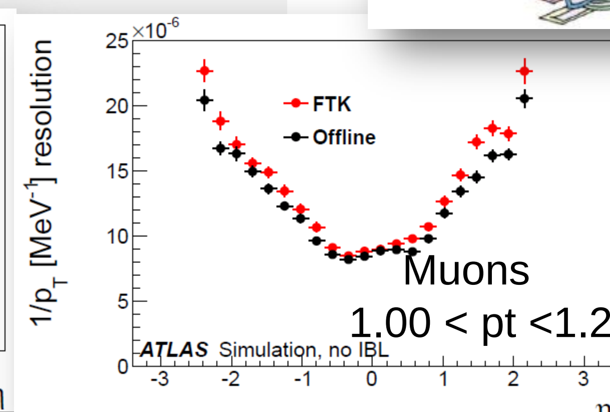
ATLAS Trigger

- Level-1 (L1): hardware based (~50 kHz)
- Level-2 (L2): software based, full granularity data (~5 kHz)
- Event Filter: software trigger (~500 Hz)



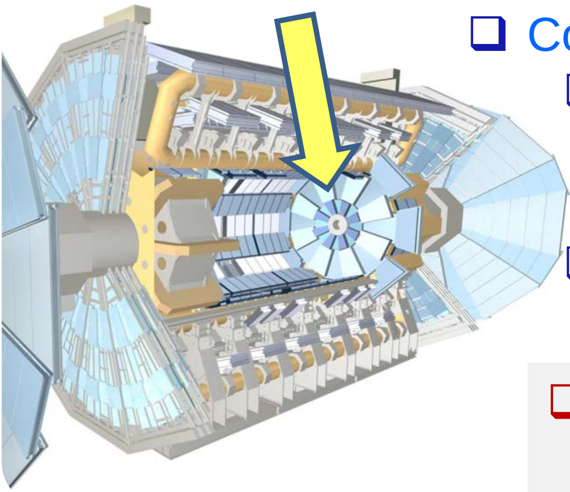






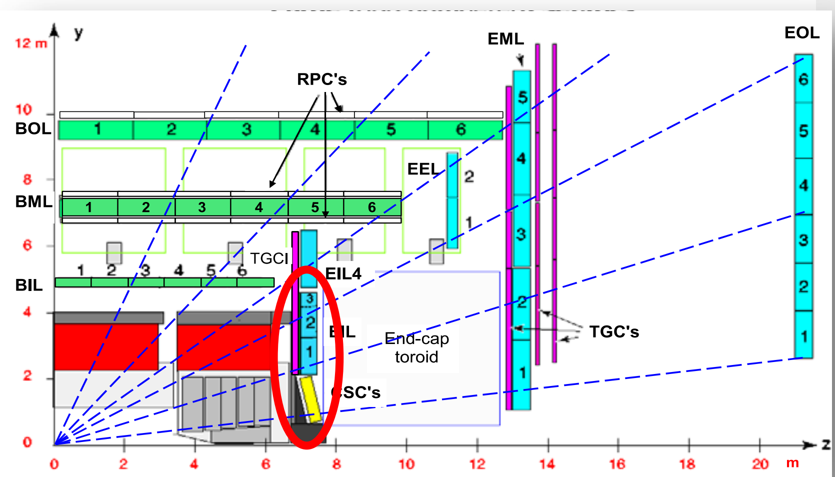
ATLAS Phase-1: NSW

1.3 < | η | < 2.7



- At Phase-1(2) – increase of the cavern background rates
- Consequences for the current fwd Muons (Small Wheels)
  - Substantial degradation of the tracking performance, both in terms of efficiency and resolution for hit rates corresponding to luminosities greater than the design value
  - Rate of L1 muon triggers exceeds available bandwidth unless thresholds raised

- Replace Muon Small Wheels with **N**ew Muon **S**mall **W**heels with improved tracking and trigger capabilities



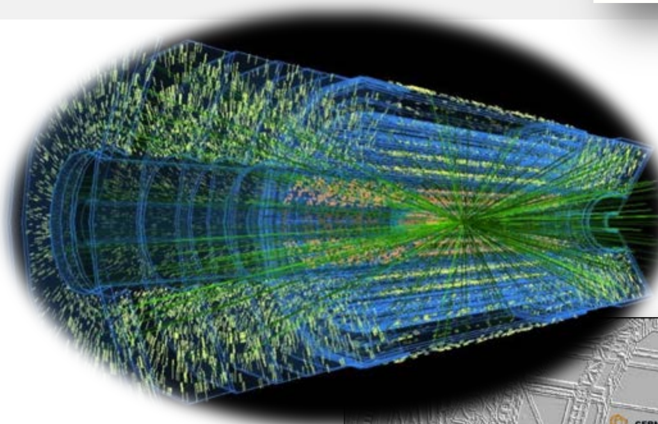
- Composed of gas chambers of higher precision and robustness, assuring:
  - position resolution < 100 μm
  - reduction of fake triggers, 3x reduction of trigger rate for pt(μ)>20 GeV at Level-1, using
    - IP-pointing segment in NSW (σ_θ~ 1 mrad)
  - higher rate capabilities (up to L~5x10^{34} $cm^{-2}s^{-1}$)

- Technology: MicroMegas and sTGCs

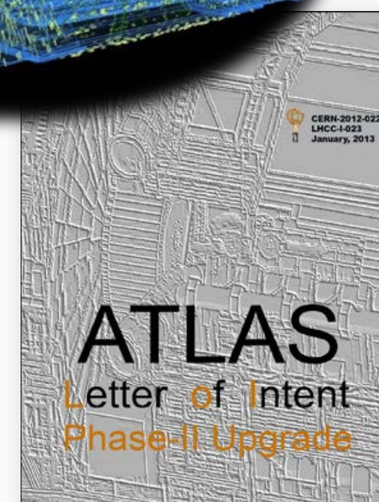
See the talks of M. Bianco and Y. Benhammou

ATLAS Phase-2 (HL-LHC) Upgrade

- **Phase-2 upgrade** (duration ~ 18 months, 2022-2023, during the LHC LS3)
  - ⇨ HL-LHC (~2023): $\sqrt{s}$=14 TeV, L=5x10^{34} $cm^{-2}s^{-1}$ (leveled), up to L=7x10^{34} $cm^{-2}s$
    - <μ>=140 (leveled), up to <μ>=200



- Detector upgrades
  - ⇨ All new Inner Detector → **I**nner **Tr**ac**k**er (**ITk**)
  - Trigger upgrades
    - TDAQ upgrade
    - ⇨ Implementation of L1 Track Trigger
  - Calorimeter upgrades
    - New LAr, Tile and HEC readouts
    - Possible upgrade of FCal
  - Muon system upgrades
    - Muon Barrel and Large Wheel trigger electronics
    - Possible upgrades of TGCs in Inner Big Wheels
  - Software & Computing

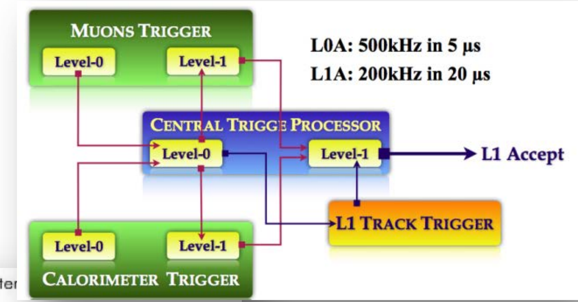


CERN-LHCC-2012-022

Phase-2 LoI: https://cds.cern.ch/record/1502664?ln=en

ATLAS Phase-2 Upgrade: L1 Track Trigger

- Adding tracking information at Level-1 (L1)
  - Move part of High Level Trigger (HLT) reconstruction into L1
  - Goal: keep thresholds on p_T of triggering leptons and L1 trigger rates low
- Options considered:
  - Region of Interest (RoI) based approach with L0 seeding necessary
  - Standalone approach (subset of layers, layout important)
- Challenge: squeeze into existing latency

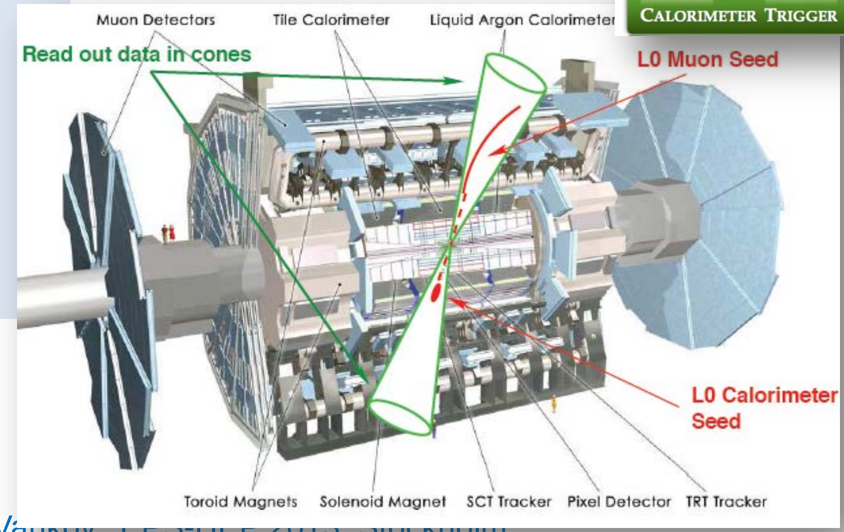


ATLAS – ROI trigger

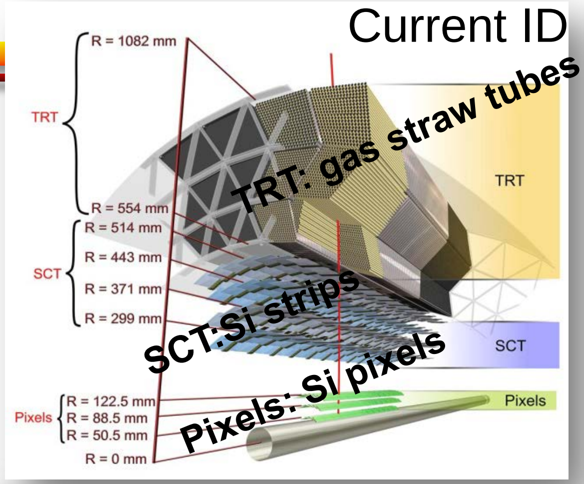
Improve calo and muon trigger granularity (already in Phase 1)

→ New Level 0 trigger within 5 μs uses calorimeter and muon system to reduce the rate from 40 MHz to ≈ 500 kHz and define RoIs

→ Level 1 extracts tracking for just RoIs from detector front-ends



ATLAS Phase-2 Upgrade: New Tracker

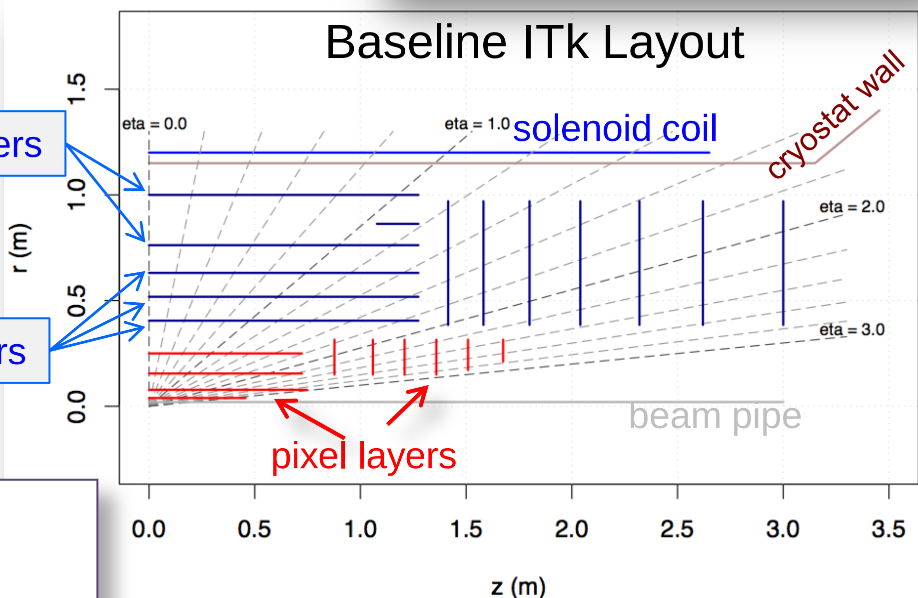


- Current Inner Detector (ID) - designed to operate for 10 years at L=1x10^{34} cm^{-2}s^{-1} with <μ>=23, @25ns, L1=100kHz
- Limiting factors at HL-LHC
  - Bandwidth saturation (Pixels, SCT)
  - Increased occupancies (TRT, SCT)
  - Radiation damage (Pixels (SCT) designed for 400 (700) fb^{-1})

➲ New Inner Tracker for HL-LHC (ITk)
- All-silicon tracker, no TRT
- Higher granularity
- Improved material budget
- Baseline: Layers of Si pixels and micro-strips

Pixels (638M channels)

- 4 barrel layers + 6 fwd disks
- inner 2 layers replaceable:
  25μm x 150μm
- outer Pixel:
  50μm x 150μm
- sensors bump bonded to readout chip using 65nm CMOS



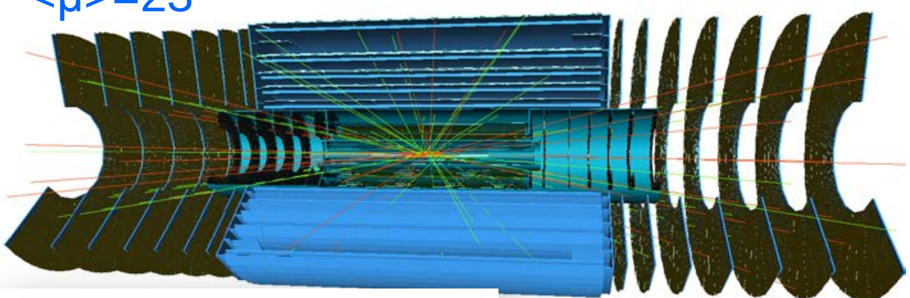
Strips (74M channels)

- 5 barrel layers + 7 fwd disks
- stub layer for overlap region
- 2 Si sensors at 40mrad

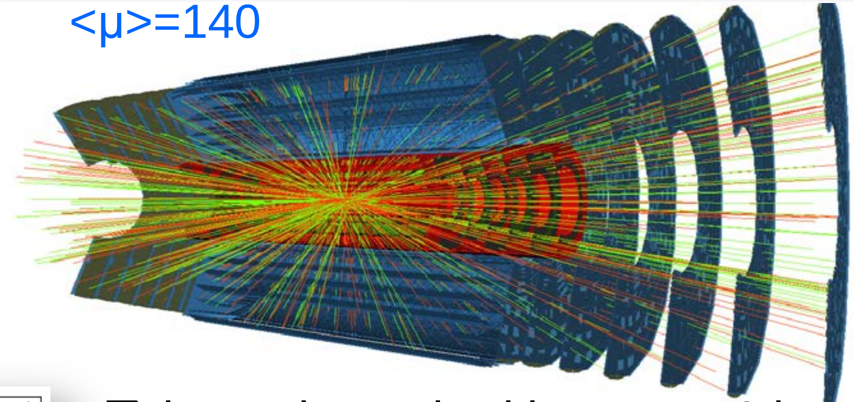
➲ all silicon tracker, 14 hits
- robust tracking @ <μ>=140 for η<2.5

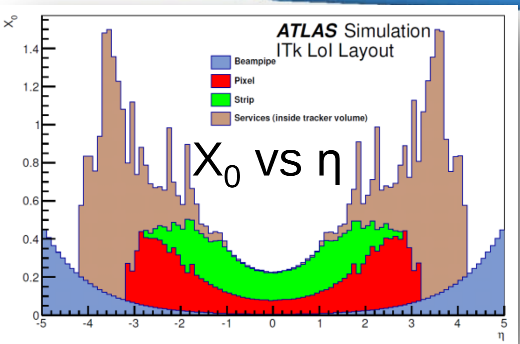
ATLAS Phase-2 Upgrade: New Tracker: Performance Studies

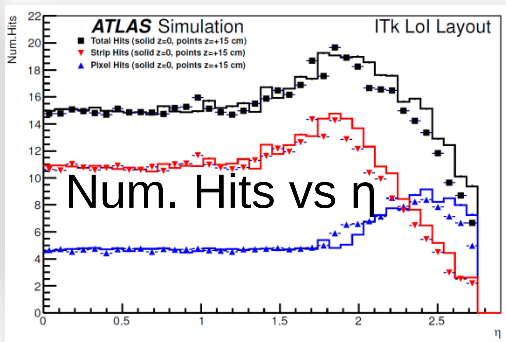
<μ>=23



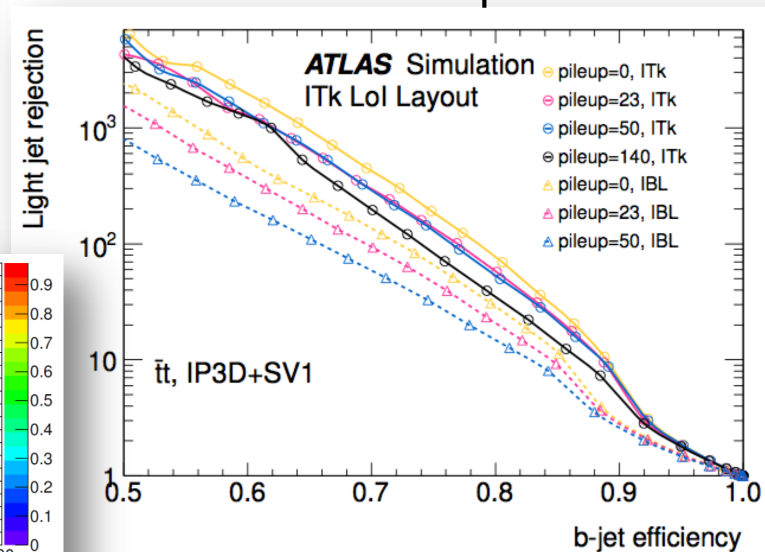
<μ>=140

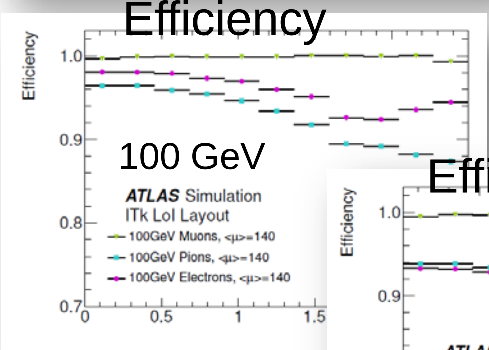


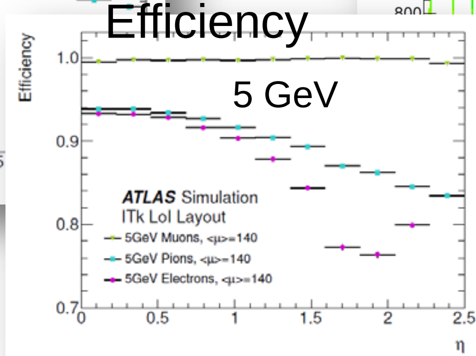


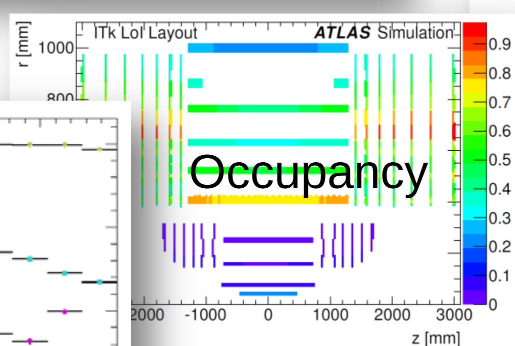


- b-tagging: ITk with <μ>=140 better than ATLAS+IBL with <μ>=0





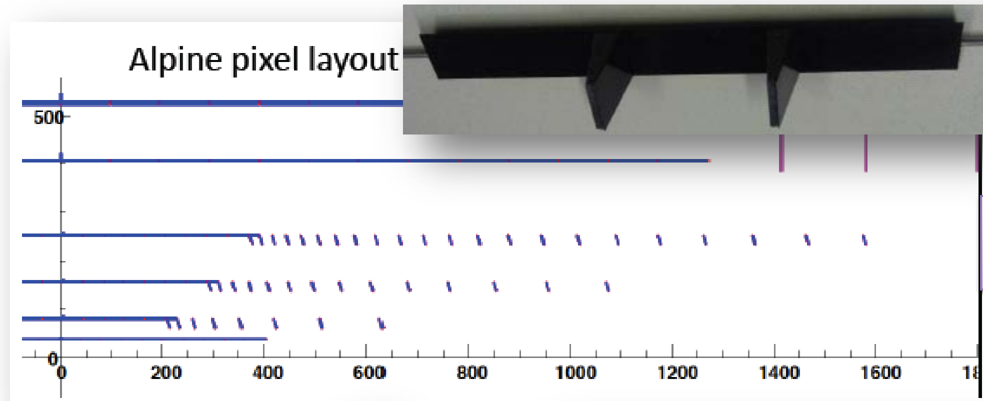




ATLAS Phase-2 Upgrade: New Tracker: Layout Variations

- Alternative layouts being considered which include either a further pixel layer or inclined pixel sensor possibly attached to the same barrels

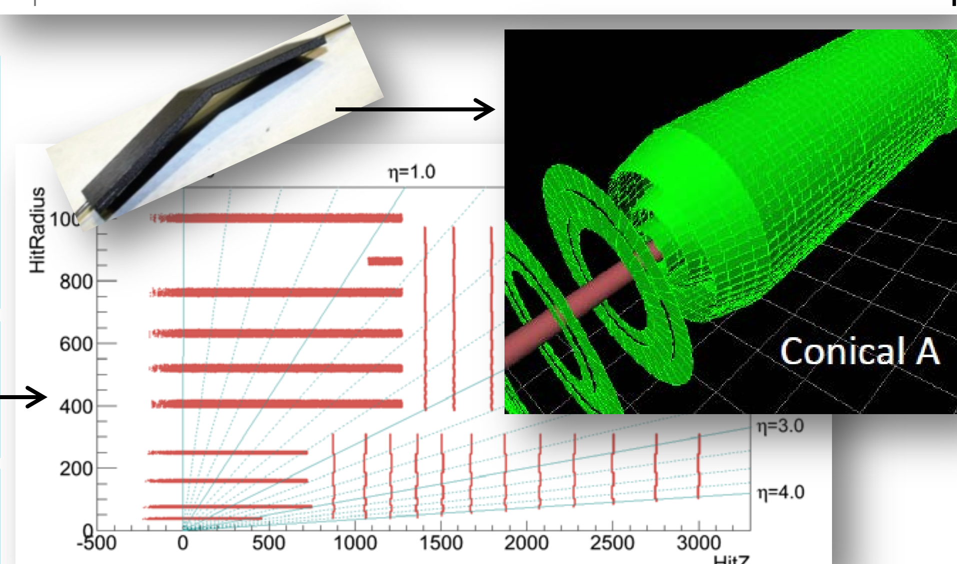
Alpine pixels
- Uses the same stave for barrel and endcap modules
- No barrel-endcap transition region
- Less services material
- Simplified mechanical support
- *Large reduction in sensor area*



Conical pixels
- Uses bent staves on outer barrel pixels
- Improves hermeticity and material in transition region

Very Forward pixels
- Extends tracking to | η | ~ 4

Optimize Si-strip barrels
- Reconfigure layers in the strip detector



Summary

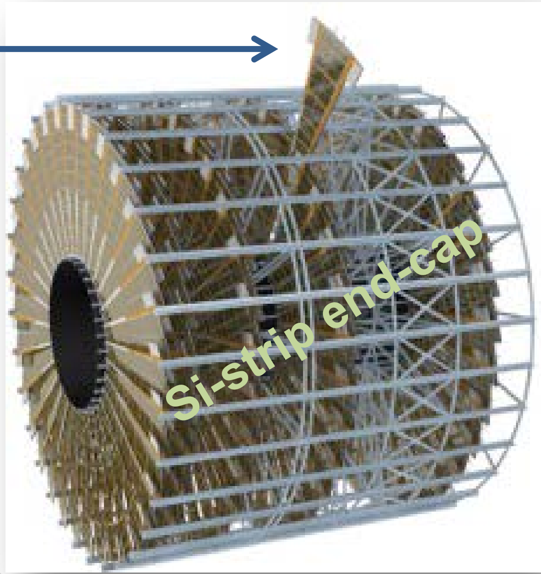
- ATLAS collaboration has devised a detailed, 3-phase program to reflect the changes in the LHC conditions towards the HL-LHC, characterized by high track multiplicity and extreme fluences, with intention to:
  - *maintain/improve the present detector performance, ensuring optimal physics acceptance as the instantaneous luminosity increases*

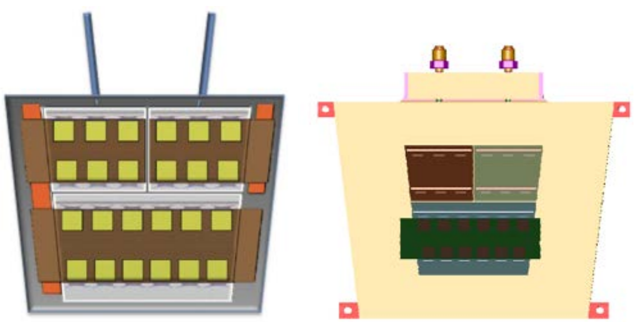
- The foreseen, major ATLAS upgrades include:
  - Phase-0 (2013/2014 LHC shutdown)
    - Installation of a new, 4^{th} pixel layer (IBL)
  - Phase-1 (2016/2017 LHC shutdown)
    - Installation of a New Muon Small Wheels
    - Fast Track Trigger
  - Phase-2 or HL-LHC (2022/23 LHC shutdown):
    - Inner Detector challenged by high radiation & occupancy
    - Build completely new all-silicon ID (pixel and strips)
    - Introducing L1 Track Trigger
    - Prepare the detector for HL-LHC and 8-10 more years
    - Further detector R&D is in progress

Backup

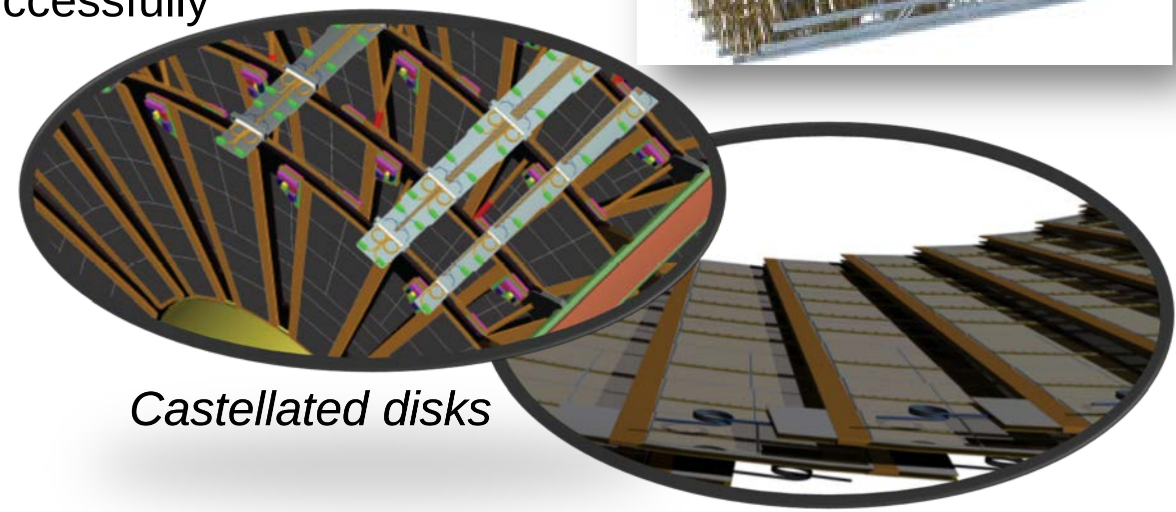
ATLAS Phase-2 Upgrade: New Tracker: R&D

- ❑ LoI proposal: 7 disks per Si-strip end-cap
  - ❑ Many different sensor sizes
  - ❑ Strip length 8.1mm to 58.3mm
  - ❑ 32 "***petals***" per disk
  - ❑ 6 rings of sensors/radial strips
- ❑ ***"Petalet"*** program underway
  - ❑ Double-sided, six-sensor *prototype*
  - ❑ Explore many options
  - ❑ Prototypes sensors & hybrids available
  - ❑ First modules produced successfully





Petalet

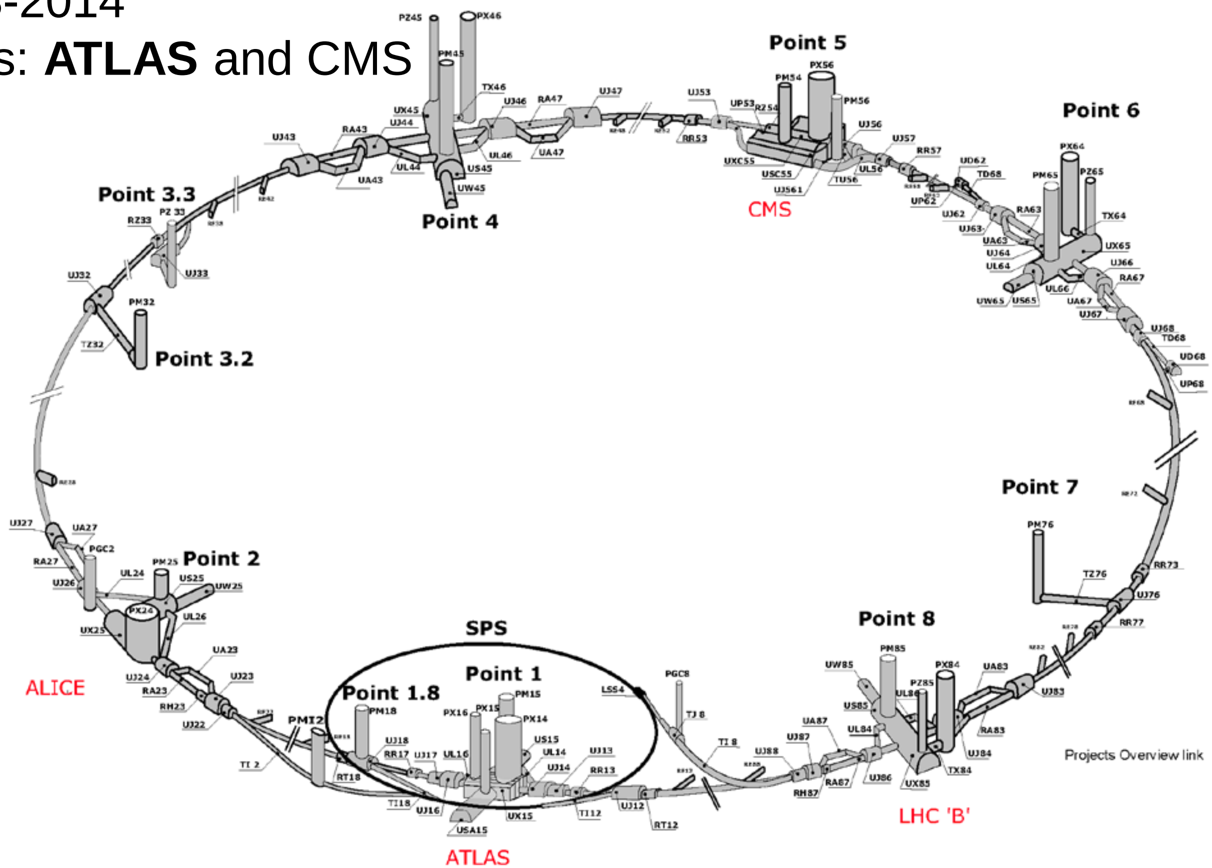


Castellated disks

Turbo fan arrangement

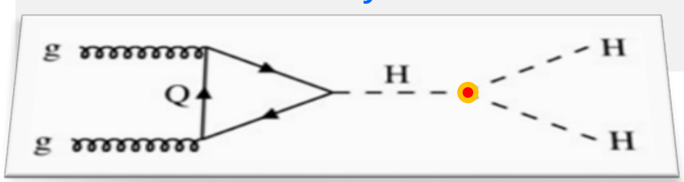
LHC: p-p collider

- Center of mass energy $\sqrt{s}$ = 7 TeV
- $\sqrt{s}$= 8 TeV @ 2012
- $\sqrt{s}$ = 13-14 TeV after 2013-2014
- Multi-purpose experiments: **ATLAS** and CMS

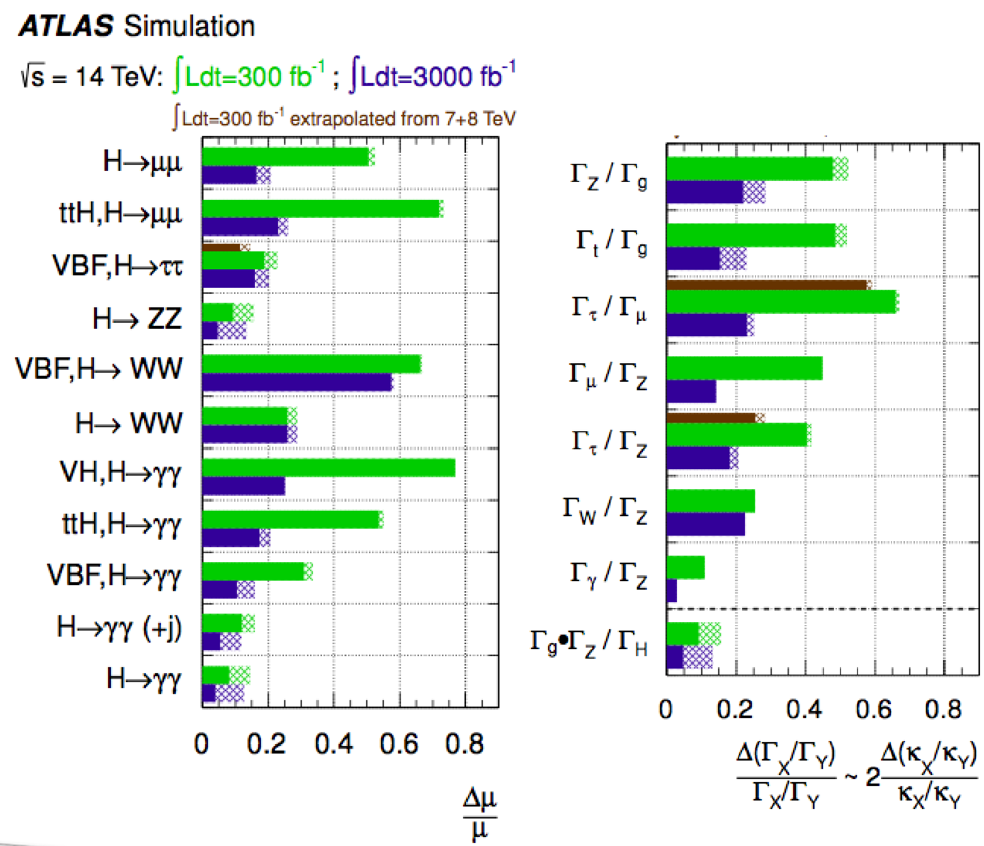


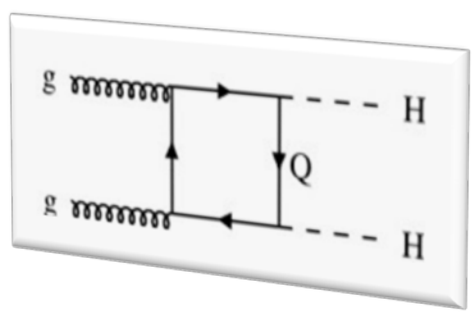
Higgs Prospects @ HL-LHC

- Higgs 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 at 5-15% level
- Higgs self-coupling in SM becomes accessible only at HL-LHC luminosity



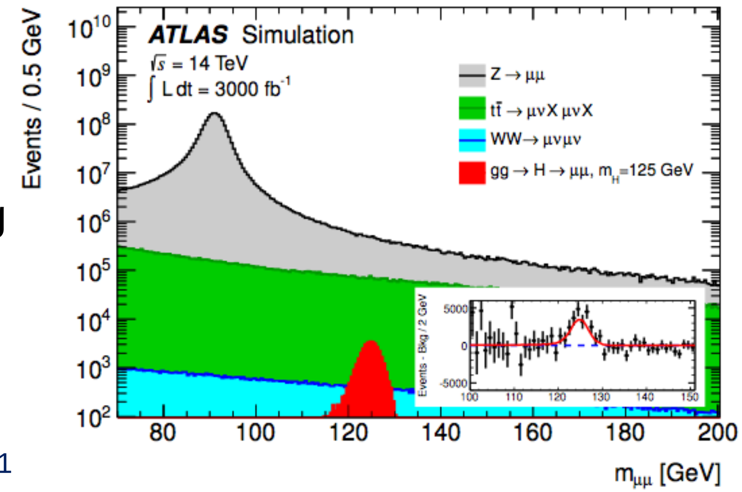
- Self-interaction is a fundamental property of the SM Higgs
- Higgs pair production includes destructive interference bw the two diagrams
- ATLAS HH→bbγγ yields ~2σ significance with 3000 fb-1 (*preliminary*)
- Combining with HH→bbττ, + CMS, it is believed that it is possible to reach a 30% or 40% precision on λ





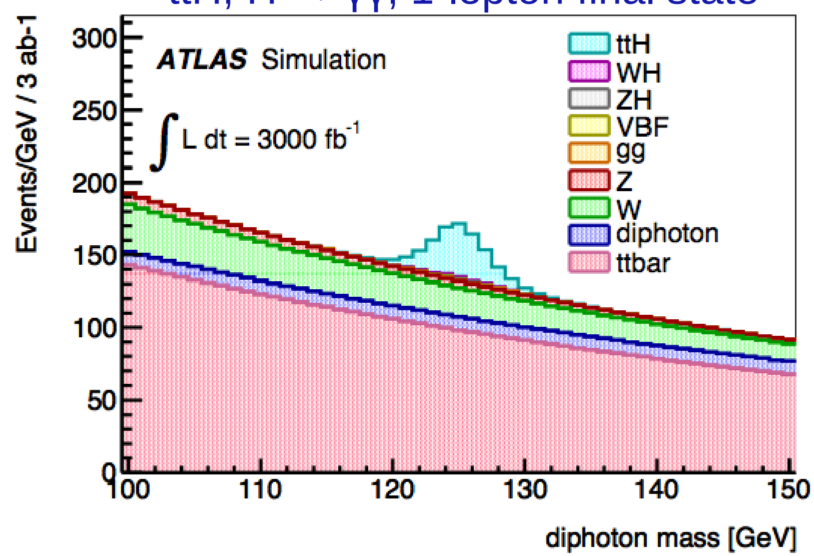
Rare Higgs Processes @ HL-LHC

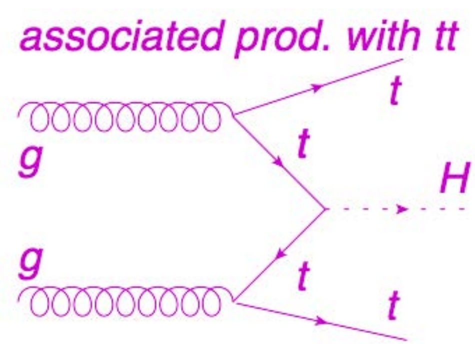
- H → μμ
  - ATLAS expect >6σ significance with 3000 fb-1



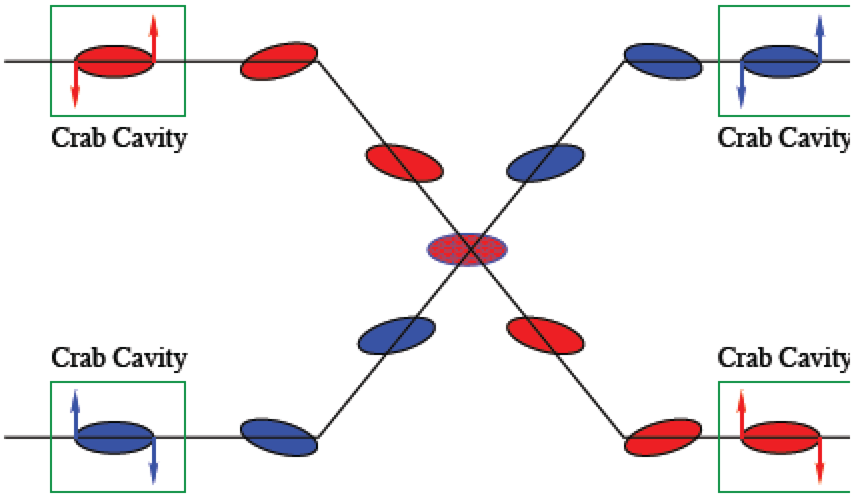
- ttH - allows precise measurement of top-Yukawa coupling
  - ttH, H → γγ
    - >100 signal events @ 3000 fb^{-1}
    - S/B ~20%
  - ttH, H →μμ
    - Only ~30 signal events but S/B~1 with 3000 fb^{-1}

ttH, H → γγ, 1-lepton final state



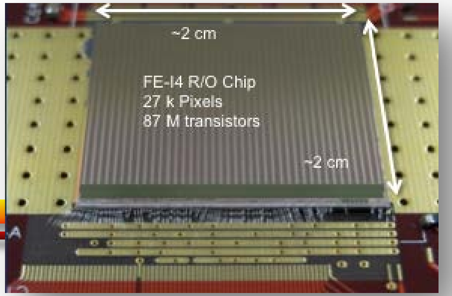


Crab cavities



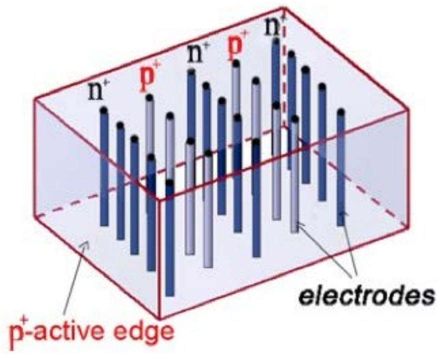
- Allow bunches to meet "head on" even though the beams have a crossing angle

Insertable B-Layer (IBL)



2 different sensor technologies:

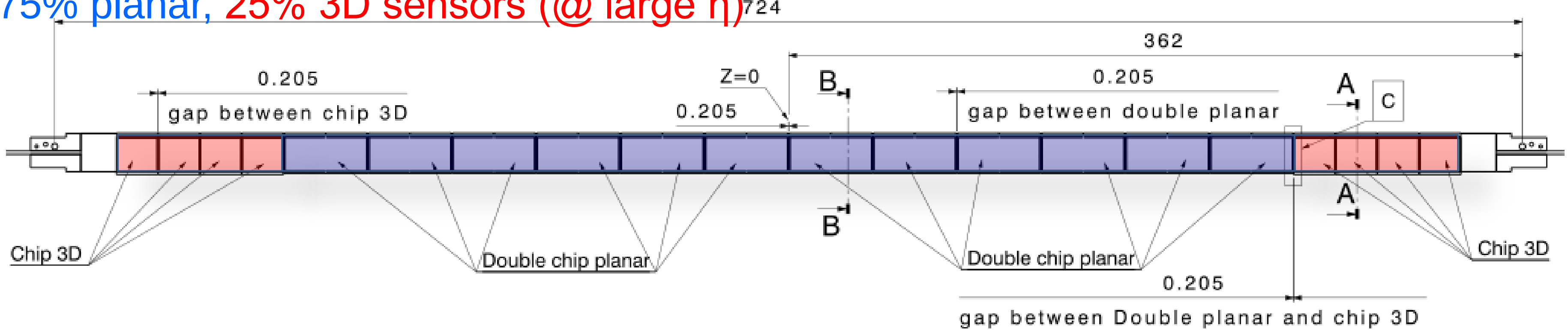
- double chip (DC) modules with 2 FE-I4 and 1 planar n-in-n sensor tile
- single chip (SC) modules with 1 FE-I4 and 1 n-in-p 3D sensor tile



FE-I4chip (16.8x20 mm^2)
336x80 pixels (50µm x 250 µm)

Planar sensor	3D sensors
200 µm thickness	230 µm thickness
inactive edge <250 µm (minimize gaps in η , no overlap)	inactive edge 200 µm
low Q generated after irradiation → low threshold operation and high HV	low depletion voltage (<180V) even after high doses
cheaper and easier to fabricate	**electrode orientation suitable for highly inclined tracks**

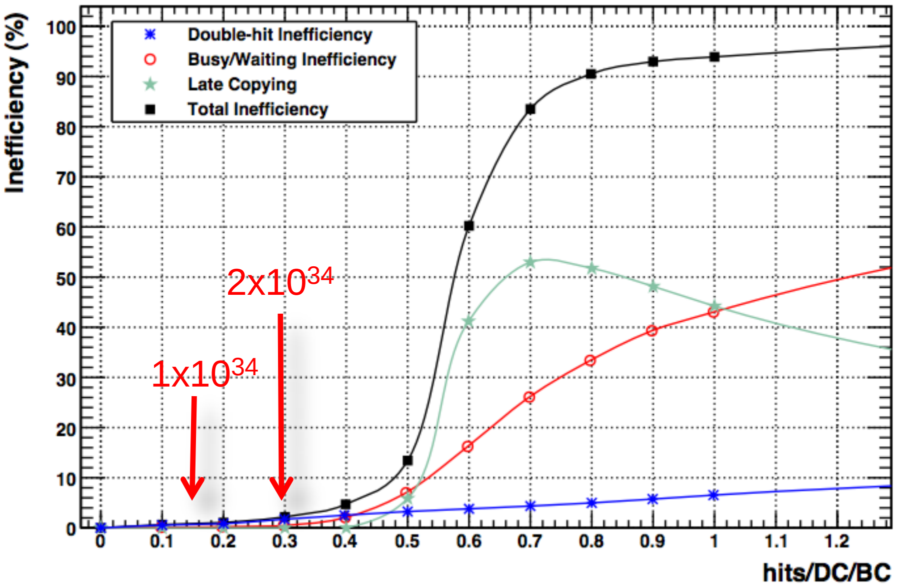
75% planar, 25% 3D sensors (@ large η)



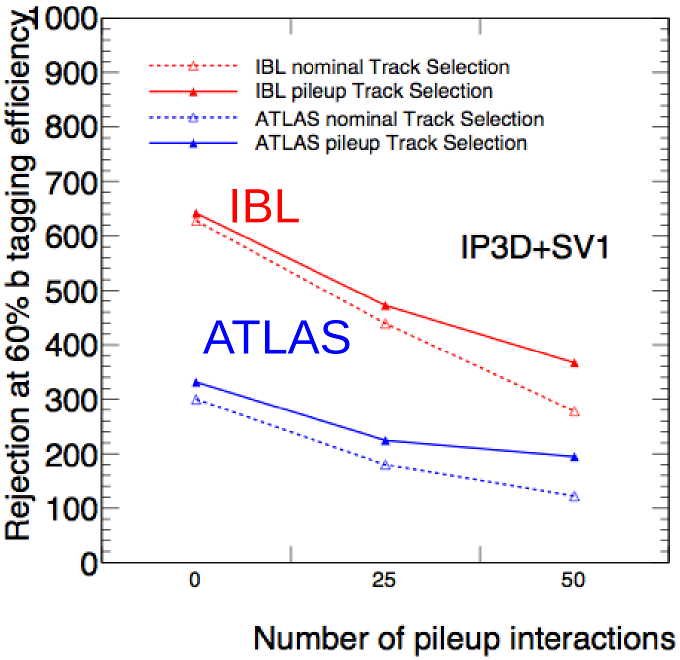
Insertable B-Layer (IBL)

- robust tracking in case of failures in the current pixel system
- from L = $2x10^{34}$ $cm^{-2}s^{-1}$ b-tagging efficiency will start to degrade
- improves impact parameter resolution, vertexing, τ-reconstruction at high pile-up

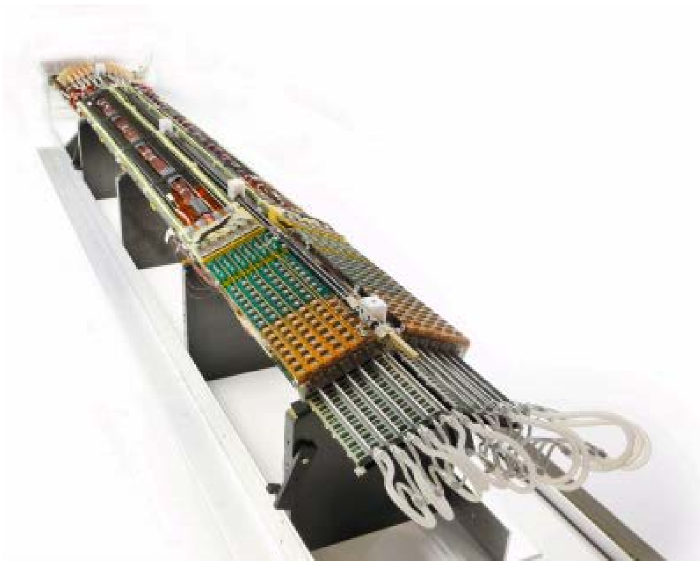
occupancy B layer (current innermost layer)



Light jet rejection



New Service Quarter Panels (nSQP) & DBM

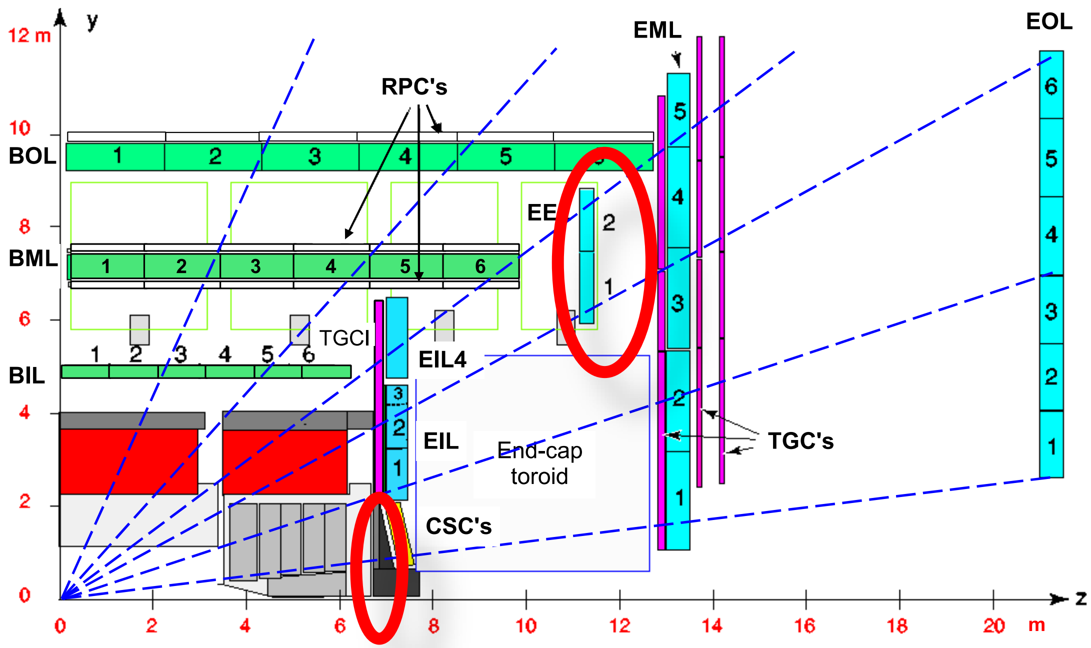


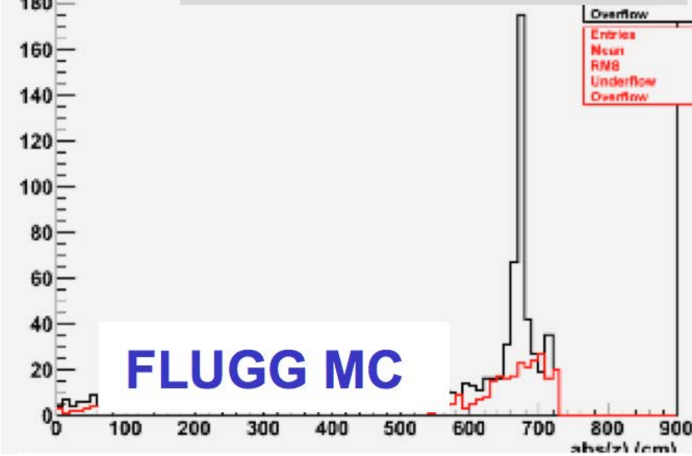
- nSQP will replace current Pixel services
- opto-boards on the panels will be replaced with e-boards connected to new opto-boards outside the Pixel detector volume (easier access for optical link replacement)
- Also: repair of Pixel RO channels, redundant links, faster
- Diamond Beam Monitor attached to nSQP
  - uses diamond detectors produced for IBL trials
  - will provide very fast monitoring of beam in high rate environment

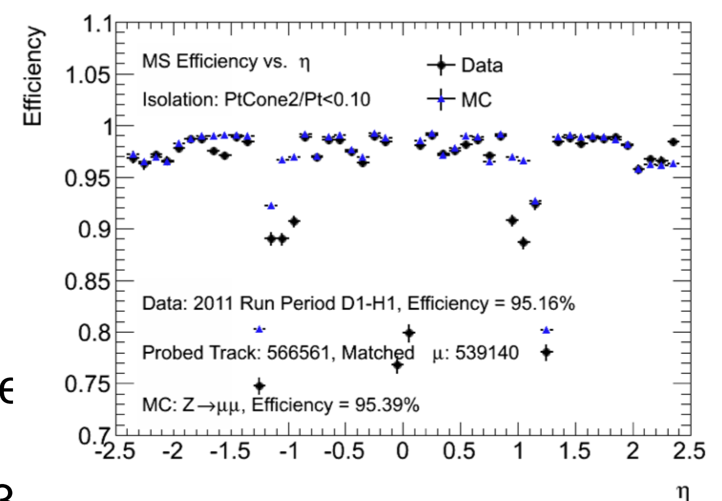
Endcap Extension (EE) Muon Chambers

- new shielding at 7m
  - gap between forward calorimeter and shielding disk

beam interaction hits
(w and w/o shielding)







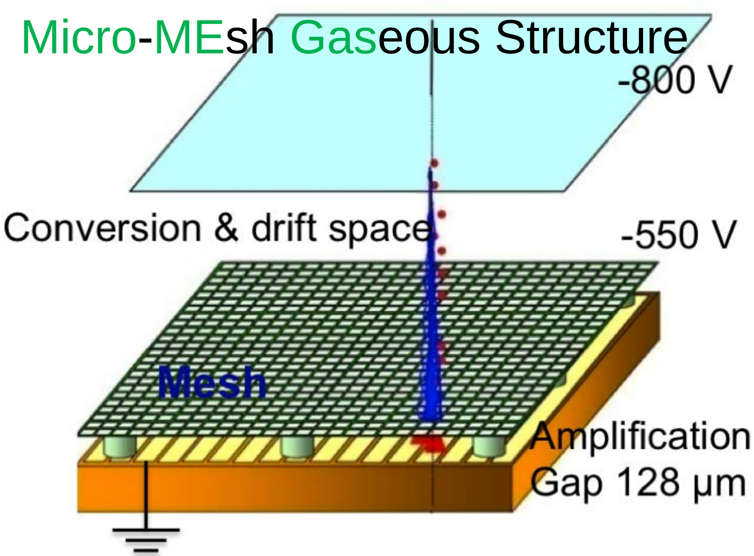
- Endcap Extension (EE) Muon Chambers
  - Finish installation of the EE muon chambers staged in 2003 + additional muon chambers in the feet (with new electronics) and elevators region
  - Addresses low efficiency in the region 1.0<|η|<1.3

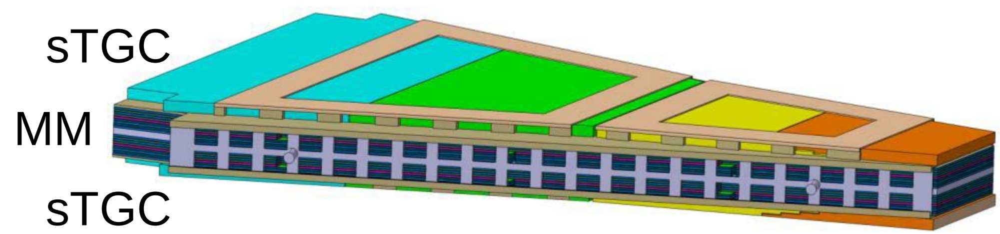
New muon Small Wheel (NSW)

- Precision chambers combine small-strip TGCs and MicroMegas technologies for robustness to Phase-II luminosities
- **sTGC (**small-strip Thin Gap Chambers): reduced cathode resistivity of 100kΩ/square → *rate capability has been increased* substantially up to 30kHz/cm2
- **MicroMegas** (MM)

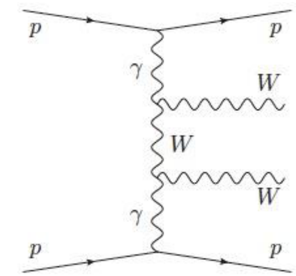
–MM consists of a planar drift electrode, a gas gap of a few mm thickness, acting as ionization and drift region, and a thin metallic mesh at ~100 μm distance from the read-out electrode, creating the gas amplification region

Micro-MEsh Gaseous Structure





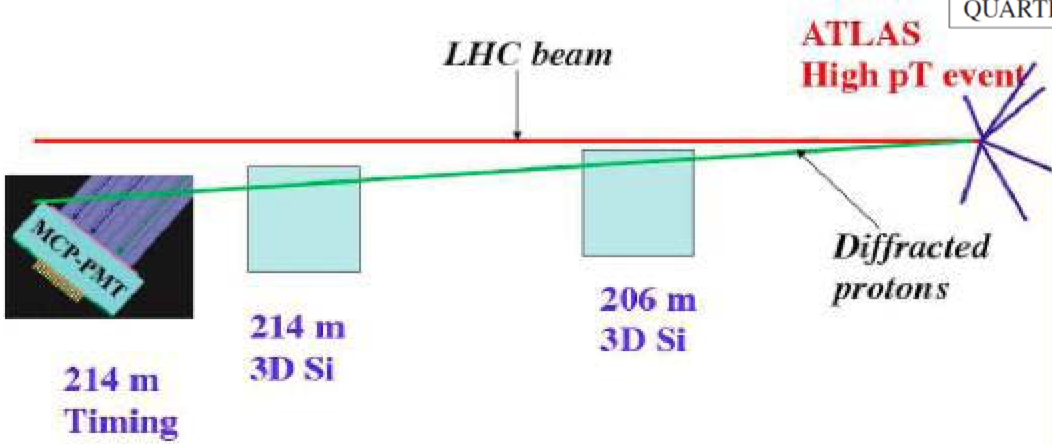
ATLAS Forward Physics (AFP)



Diffractive Physics

- ATLAS Forward Proton (AFP) detectors
  - Tag and measure scattered protons at ± 210m
- Hardware
  - Radiation-hard edgeless 3D silicon developed in IBL context
  - 10ps timing Cerenkov detector for association with high pT primary vertex
  - Probe hard diffractive physics and central exclusive production of heavy particles

Acceptance	Tagged proton momentum loss ξ	$0.02<\xi<0.2$
	Typical di-photon mass acceptance	$300<\sqrt{(\xi_1 \xi_2 s)}<1200$ (GeV)
Si Tracker	Spatial Resolution	$\sim 15\ \mu$m
	Angular Resolution	$\sim 1\ \mu$rad
	Reconstructed Mass Resolution	~ 5 GeV
QUARTIC	Time resolution	<10 ps



Calorimeters

- ❑ EM and Hadronic Calorimeters require no upgrade
- ❑ full upgrade of FE and BE electronics for both Lar EM and Tile Hadronic:
  - ❑ radiation effects and expected flux will deteriorate their performance
- ❑ Hadronic EndCap calorimeter cold electronics designed for 1000 fb^{-1}
  - ❑ assuming safety factors → possible replacement

- ❑ Current Forward Calorimeter (3.2<|η|<4.9) not designed for $L>10^{34}cm^{-2}s^{-1}$

space charge effects cause significant signal deterioration

Option 0
detector unchanged

Option 1
complete replacement of FCAL
smaller LAr gaps (to reduce ion build up /HV drop)
+ better cooling (to avoid overheating)

Option 2
installation small calorimeter in front of current Fcal: Mini-Fcal
→ reduce energy and ionization @ FCal