2nd CHIPP Workshop on Detector R&D
12, 13 September, 2013

ATLAS Upgrades

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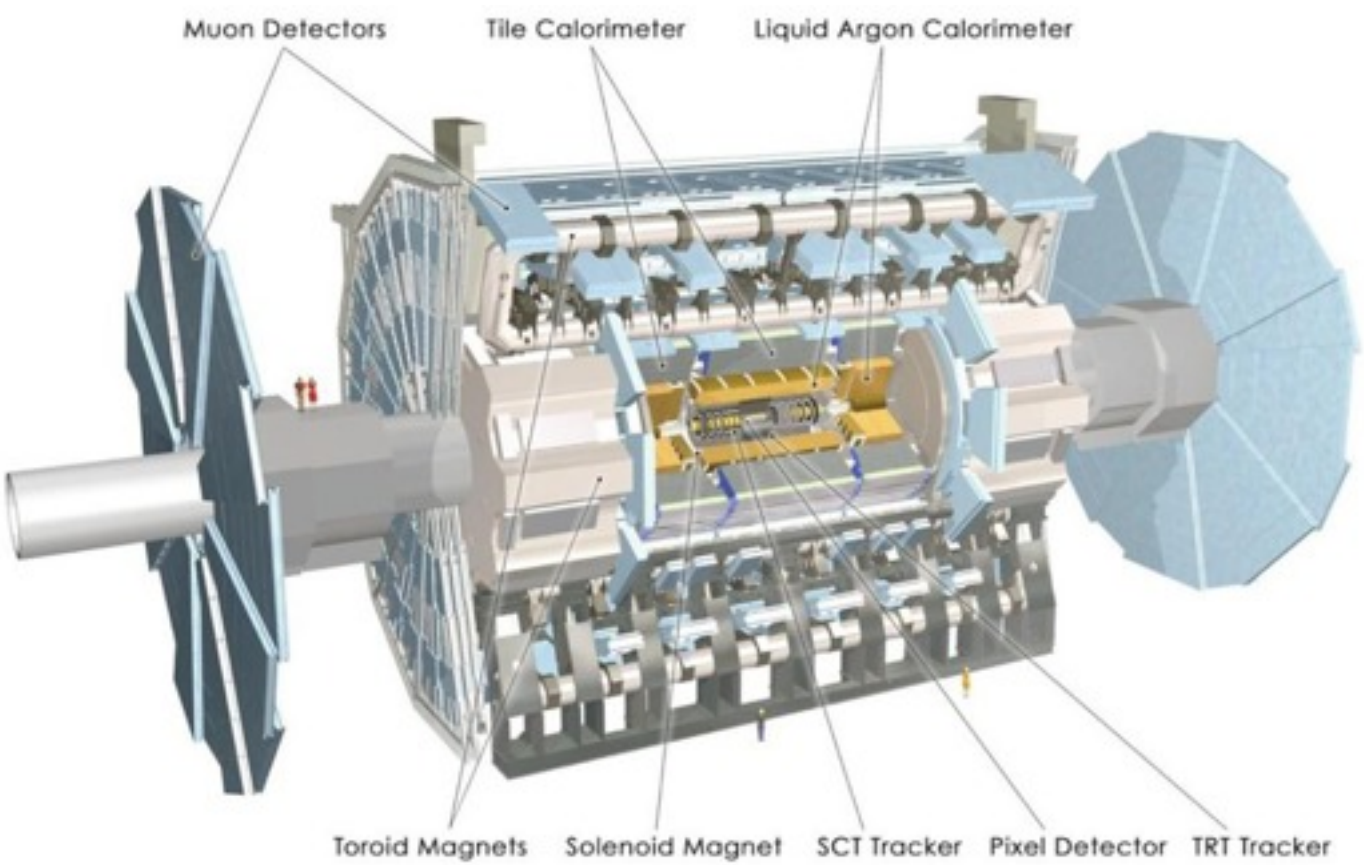
Université de Genève

ATLAS



- Outstanding LHC performance in 2012 run: 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% efficiency)
- Main challenge: higher number of pile-up events (**$<\mu>$~35**)

Motivation for HL-LHC 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**.*"

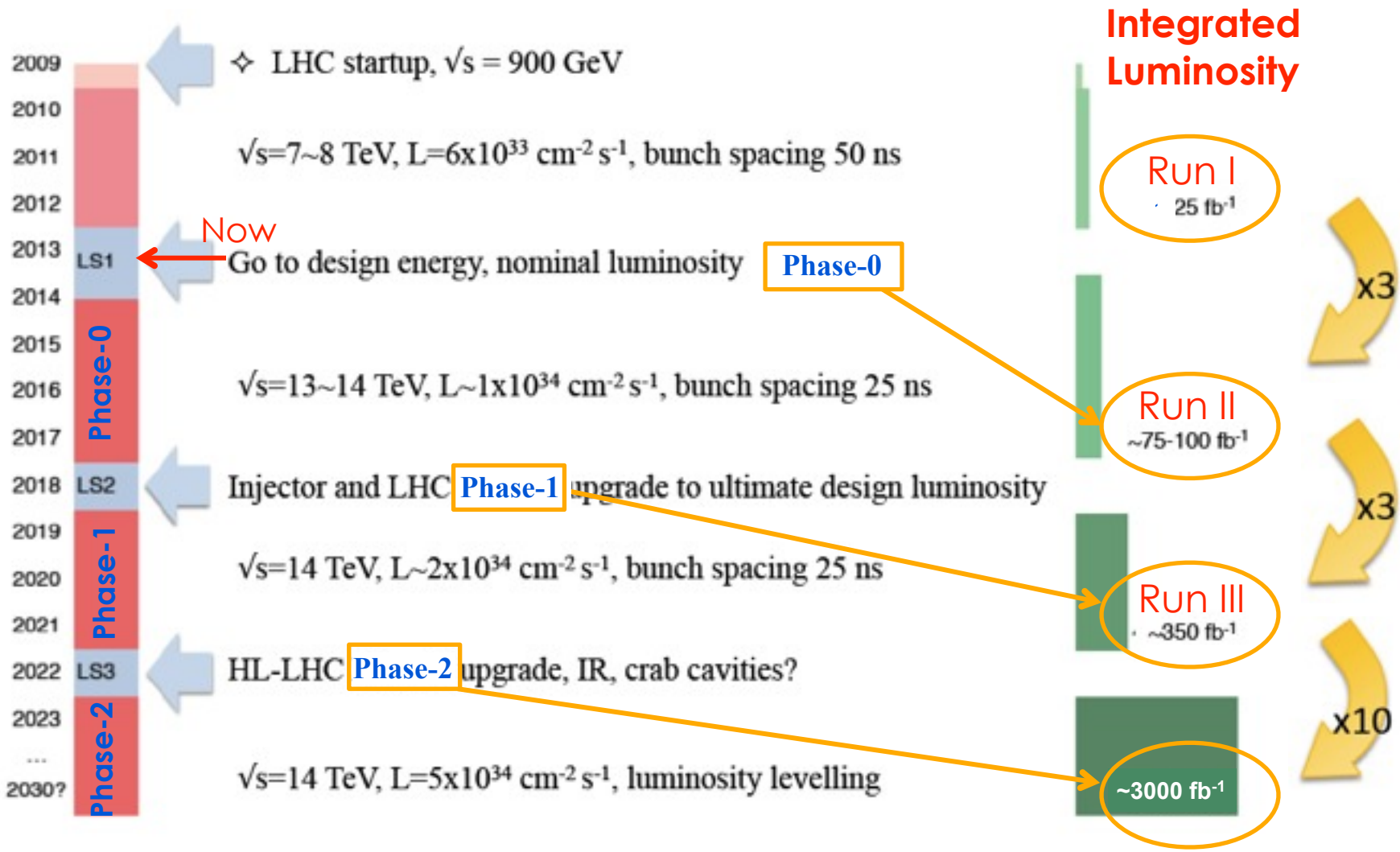
➢ **Physics prospects** with High-Luminosity LHC at ATLAS:

- **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
    - $HH \to bb\gamma\gamma$, $HH \to bb\tau\tau$

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

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

LHC (present) roadmap

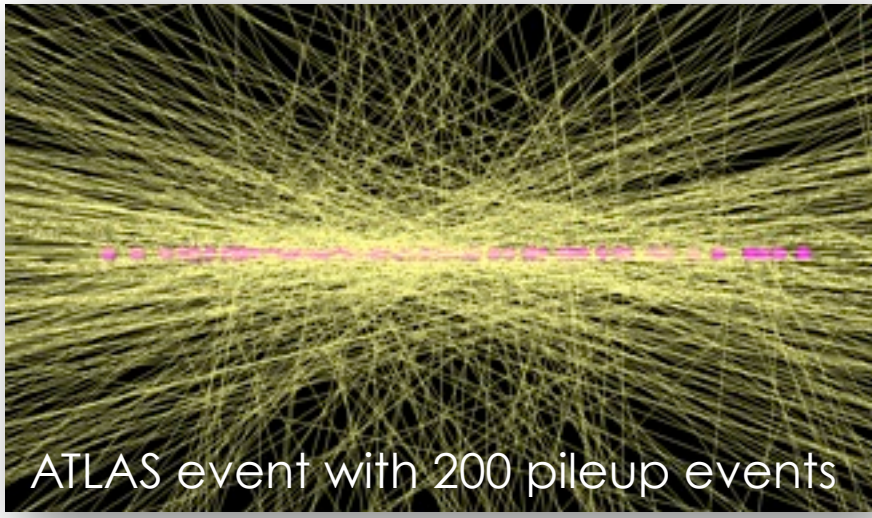


HL-LHC Upgrade Challenges

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

Detector challenges:

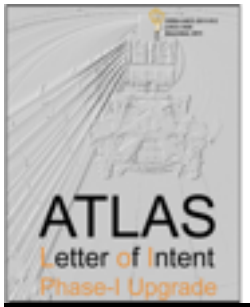
- Expected ***peak luminosity*** → from 1×10^{34} to **$5 \rightarrow 7 \times 10^{34}$ cm^{-2}s^{-1}**
  higher particle fluxes, larger event sizes, higher trigger rate
  ➡ **improved triggers** needed
- *Multiple interactions per bunch crossing* – ***"pileup"*** → up to **μ=<200>**
  higher detector 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 event with 200 pileup events

ATLAS Upgrades

CERN-LHCC-2010-013

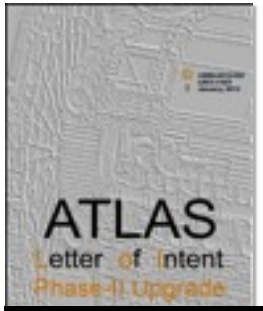
Phase-0
13/14 TeV
100 fb^{-1}/3years
2015-2017



LoI
Phase-I

https://cds.cern.ch/record/1402470

Phase-I
14 TeV
300 fb^{-1}/3years
2019-2021



LoI
Phase-II

https://cds.cern.ch/record/1502664

Phase-II
14 TeV
3000 fb^{-1}/10 years
2023-2033

- Insertable B-Layer

- Fast TracK trigger
- Muon New Small Wheel
- Calorimeter em trigger
- Trigger and DAQ

- ATLASForwadProton (AFP)

- New inner tracker
- New L0/L1 trigger
- TDAQ
- Calorimeters readouts
- Muon trigger electr. (barrel+LW)
- Software & Computing

Phase-0

ATLAS **Phase-0** upgrade

LHC:

- Shutdown of 18 months (2013-2014)
- Consolidate SC splices for **design energy** ($\sqrt{s}$ = 14 TeV) and **luminosity** ($10^{34}cm^{-2}s^{-1}$). Expect **L_{int} = ~75-100 fb^{-1}**

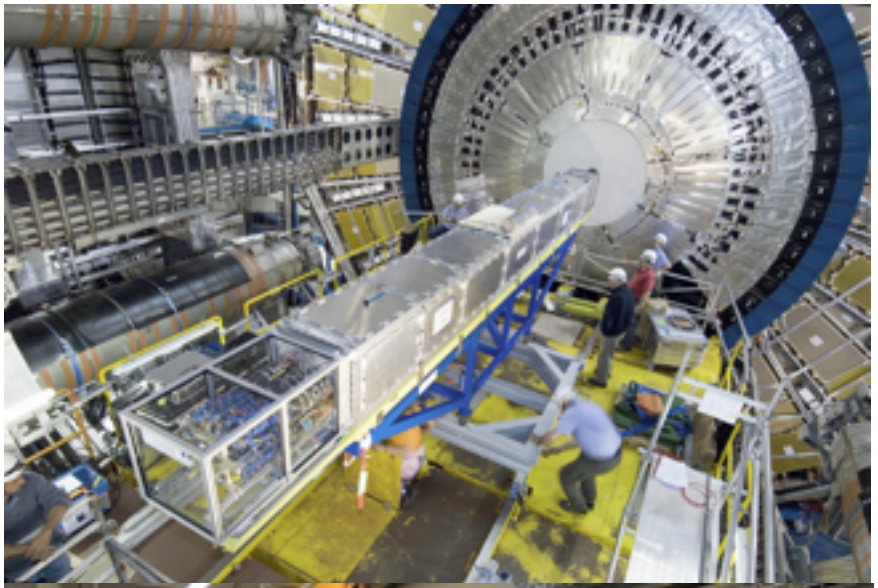
ATLAS: prepare for optimal data taking at design luminosity

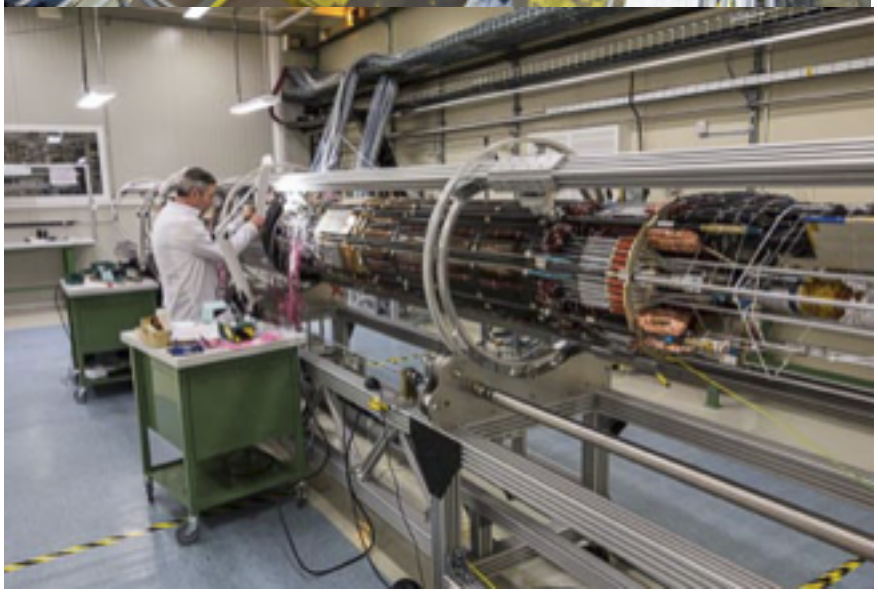
Detector upgrades:

- Insertable Barrel Layer **(IBL)**: pixel 4th layer ⬅ **ATLAS-Switzerland**
  - New small radius central **Beryllium beampipe**
  - New Service Quarter Panels (**NSQP**): Improved pixel services layout
  - Diamond Beam Monitor (**DBM**)
- New chambers in the **muon** spectrometer, to improve geometrical coverage
- New **Aluminum beam pipes** (to prevent activation and reduce backgrounds)

+ series of **detector consolidation**

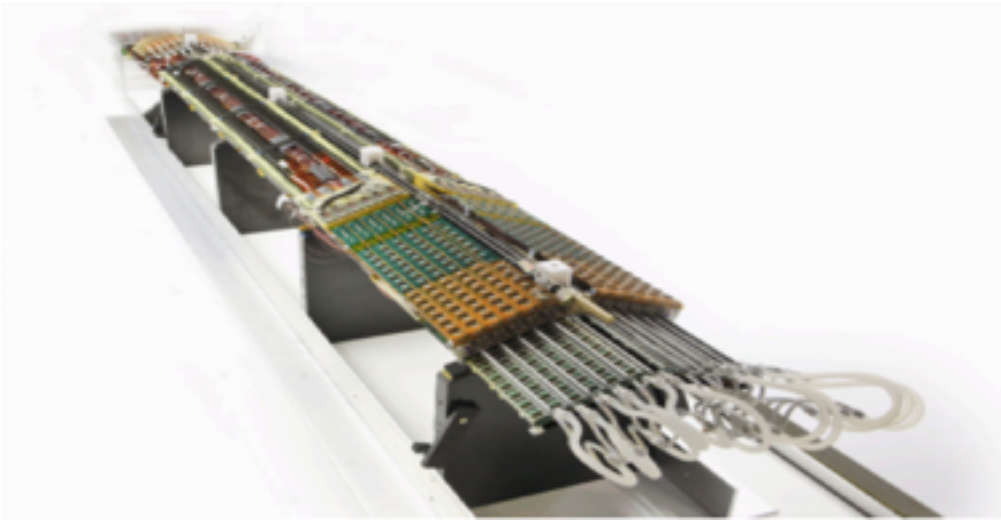
ATLAS PIXEL detector upgrade



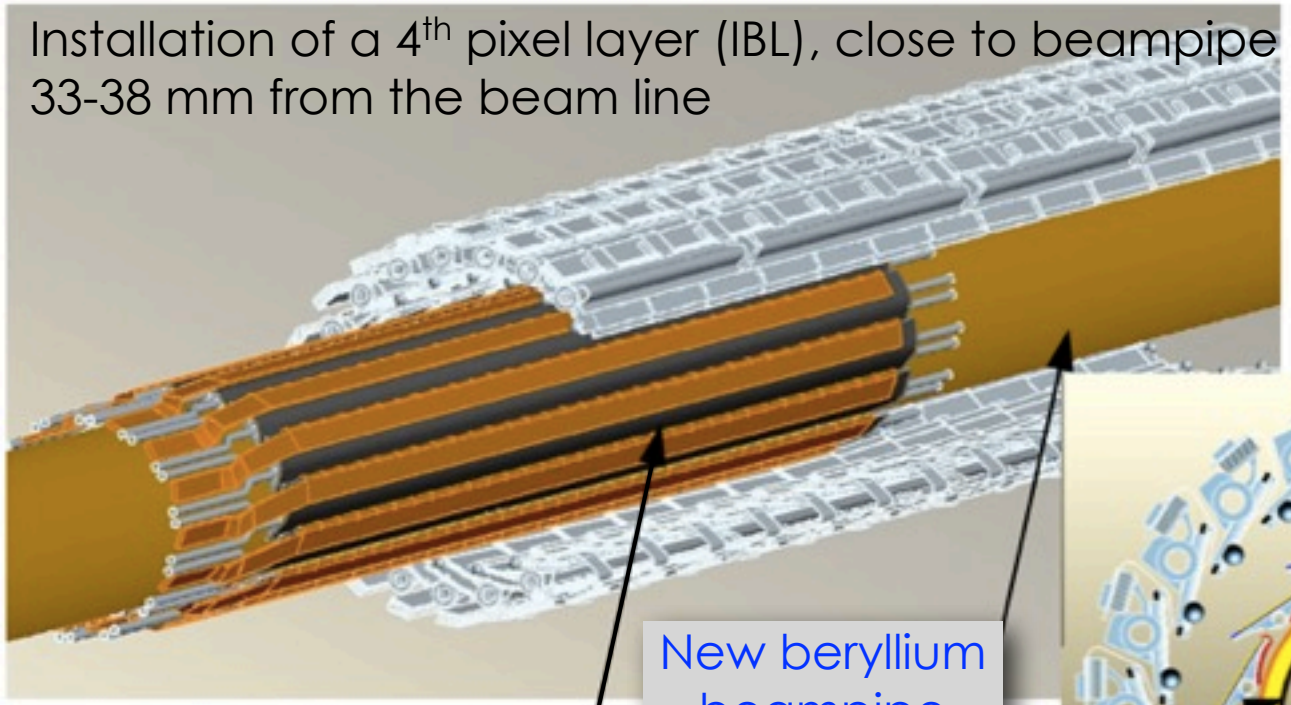


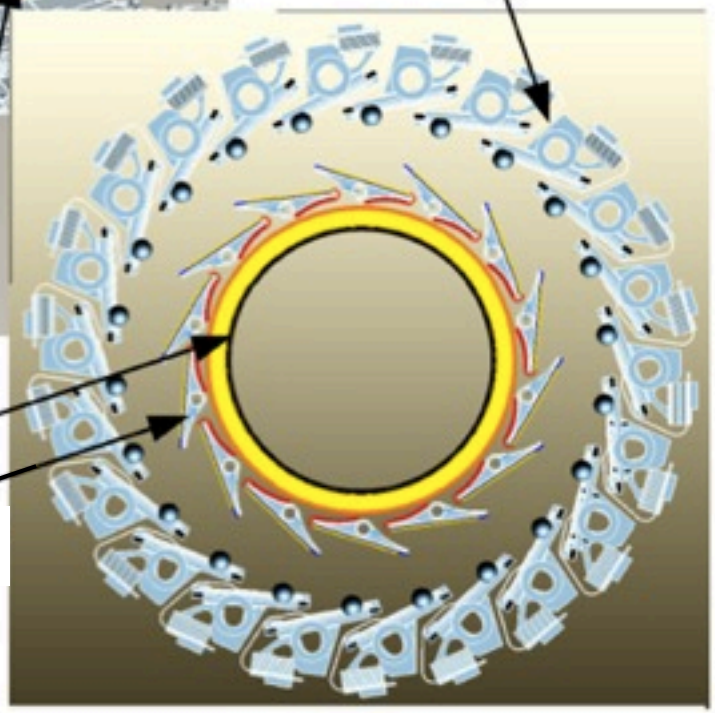
Need to cure progressive radiation damage and mitigate inefficiencies due to pile-up effects.

- ➡ Replacement of service distribution panels, to cure malfunctioning channels, increase accessibility and bandwidth.



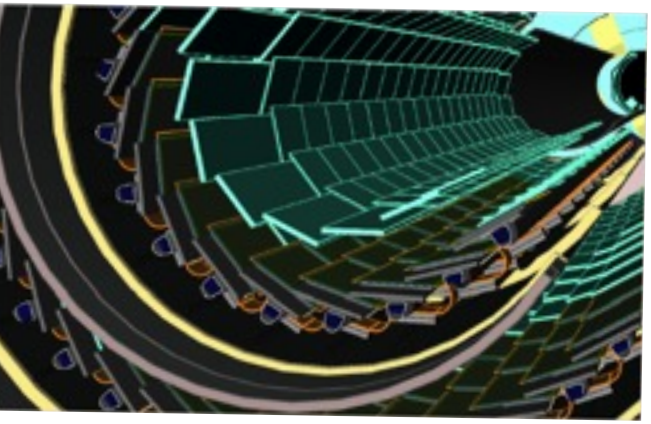
The ATLAS Insertable B-Layer





Present beampipe through present B-layer

The ATLAS IBL



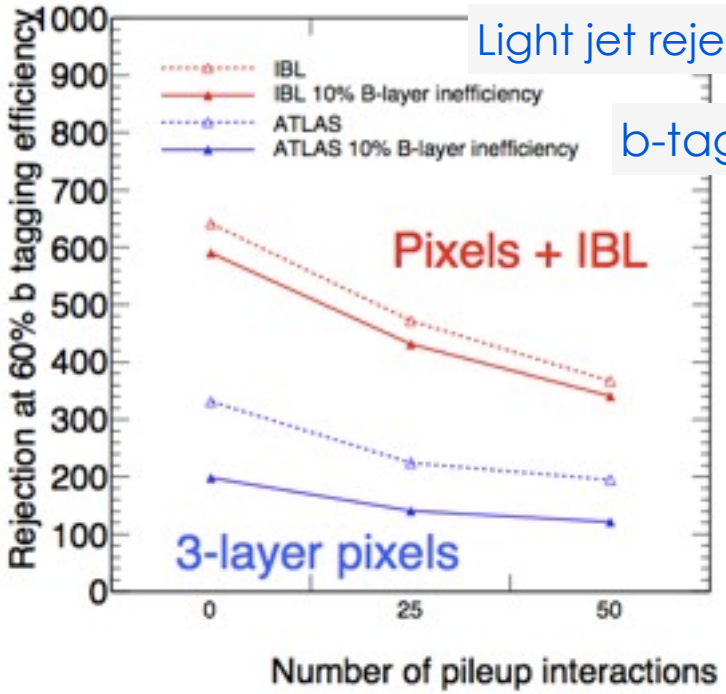
A new, 4th pixel layer between the innermost Pixel (B-)layer and the beam pipe

- Smaller pixels (50x400 μm → 50x250 μm)
- Technology: planar and 3D Si sensors
- New readout chip: FE-I4 Pixel Chip in 130nm CMOS

Improves:

- tracking
- vertex resolution
- secondary vertex finding
- b-tagging
- tau reconstruction

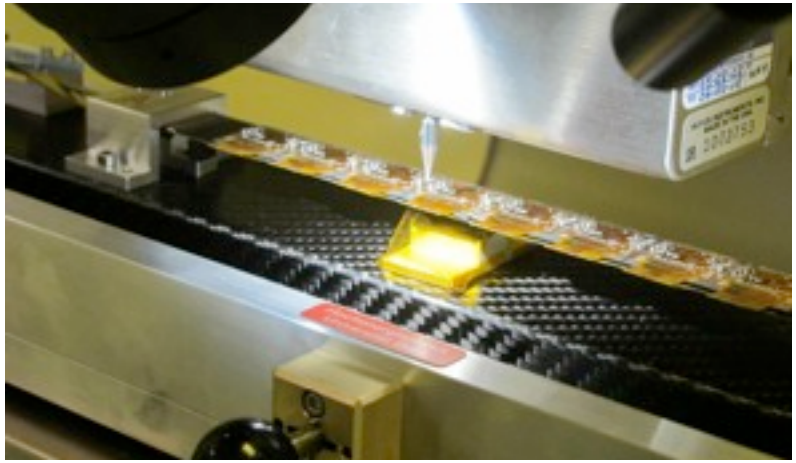
at high pileup



The ATLAS IBL

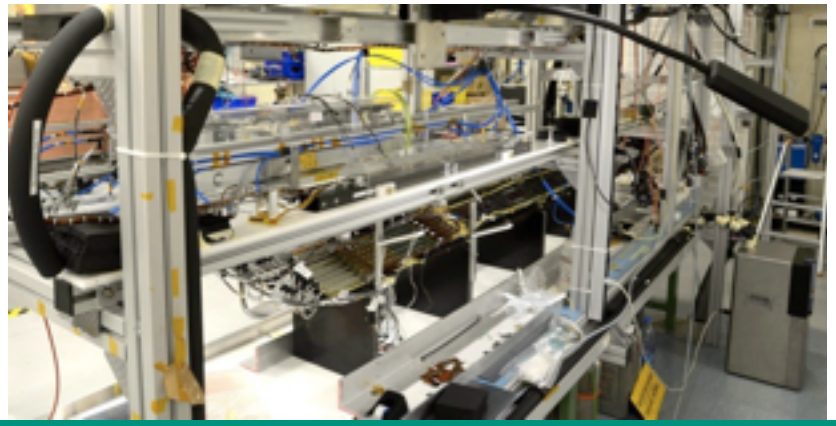
Didier Ferrere (UniGE)
Pixel deputy project leader, in charge of IBL

Construction and tests of staves at UniGE (UniGE + UniBE)



Optical readout (UniBE)

Integration and tests at CERN
(CERN, UniBE, UniGE)

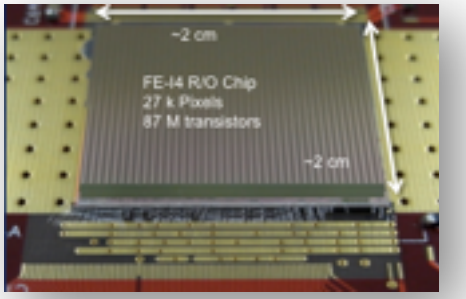


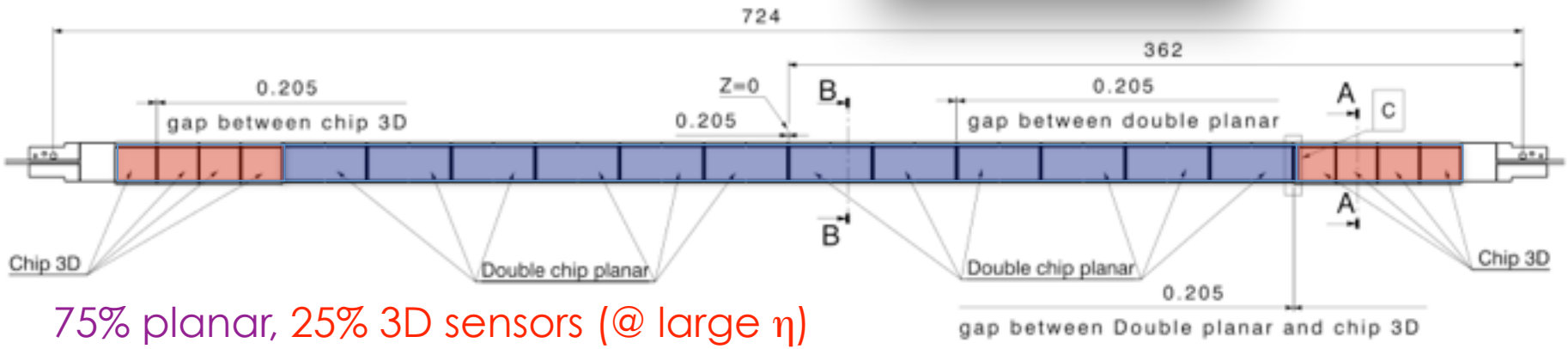
IBL Stave loading at UNIGE: Status

FE-I4chip (16.8x20 mm^2)

336x80 pixels (50μm x 250 μm)

27k channels, 87M transistors





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

- 10 staves loaded with all components and fully tested
  - perfectly working → delivered at CERN
- Need a total of 14
  - will build 18-20

Phase-I

ATLAS **Phase-I** Upgrade

LHC:

- Shutdown of 14 months (**2018-19**)
- Consolidation of injector chain; collimators
- Double the design peak luminosity to **$2\text{-}3\times10^{34}$ cm^{-2}s^{-1}**
- Expect total of **L_{int} = ~300 fb^{-1}** at $\sqrt{s}$ = 14 TeV by end 2021

ATLAS:

1. Continue to require **LVL1 single-lepton** trigger thresholds of p_T ~ 20 GeV, even with pileup <μ> ≈ 50-75 ⇒ preserve **trigger acceptance** of design lumi
2. Keep acceptances high and similar between barrel and forward
3. Retain **sensitivity** to BSM physics with as little model dependence as possible

Detector upgrade projects:

- New Muon Small Wheels
- New Calorimeter Trigger Tower Builders (higher granularity at the trigger)
- Fast TracKer (**FTK**): input to LVL2 trigger ⬅ **ATLAS-Switzerland**
- Trigger/DAQ upgrades (various)
- Consolidation and upgrades to the **Pixel readout** ⬅ **ATLAS-Switzerland**

One (to be approved) addition

- **AFP**: Forward Proton detector at ±210m

Components installed in Phase-I must be **compatible with Phase-II** running

ATLAS Phase-I: the **FTK**

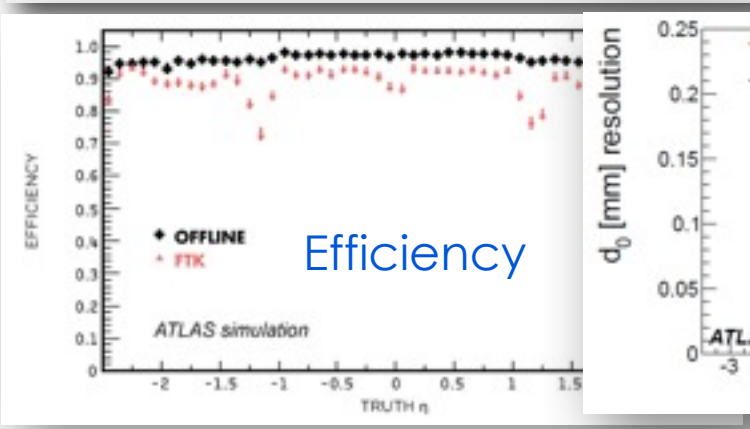
Effective triggering at high luminosity is extremely challenging

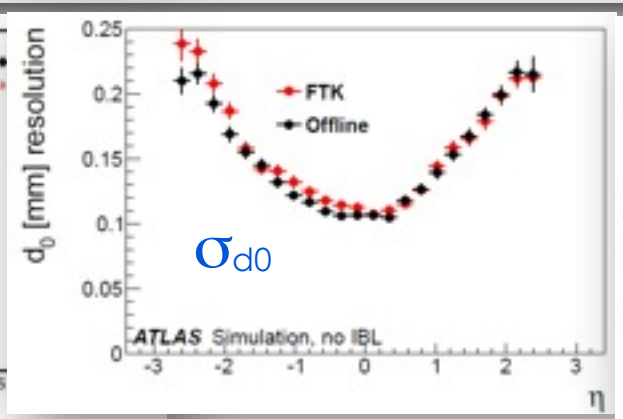
➡ especially for triggers that require track reconstruction

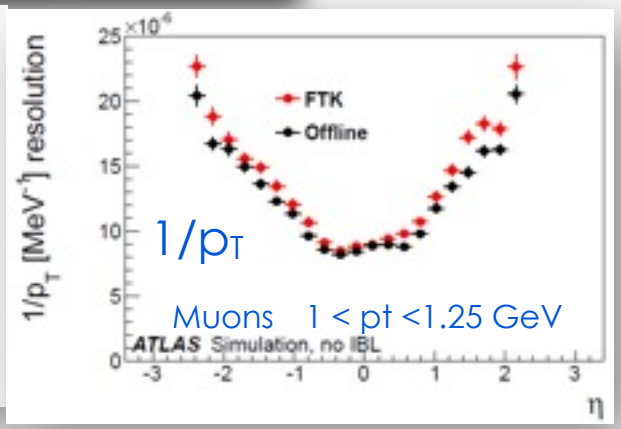
- **F**ast **T**rac**K** trigger (**FTK**) – a dedicated, *hardware-based* track finder, an input for L2
  - Finds and fits tracks (~ 25 μs) in the ID silicon layers (incl. IBL) at an "offline precision", for events passing L1
  - Processing performed in two steps
    1. hit pattern matching to 10^9 pre-stored patterns (coarse)
    2. subsequent linear fitting in FPGAs (precise)
  - Inspired by the CDF Silicon Vertex Trigger (SVT)
  - Major improvement for **b-tagging**, **τ ID**, **lepton isolation**

ATLAS Trigger

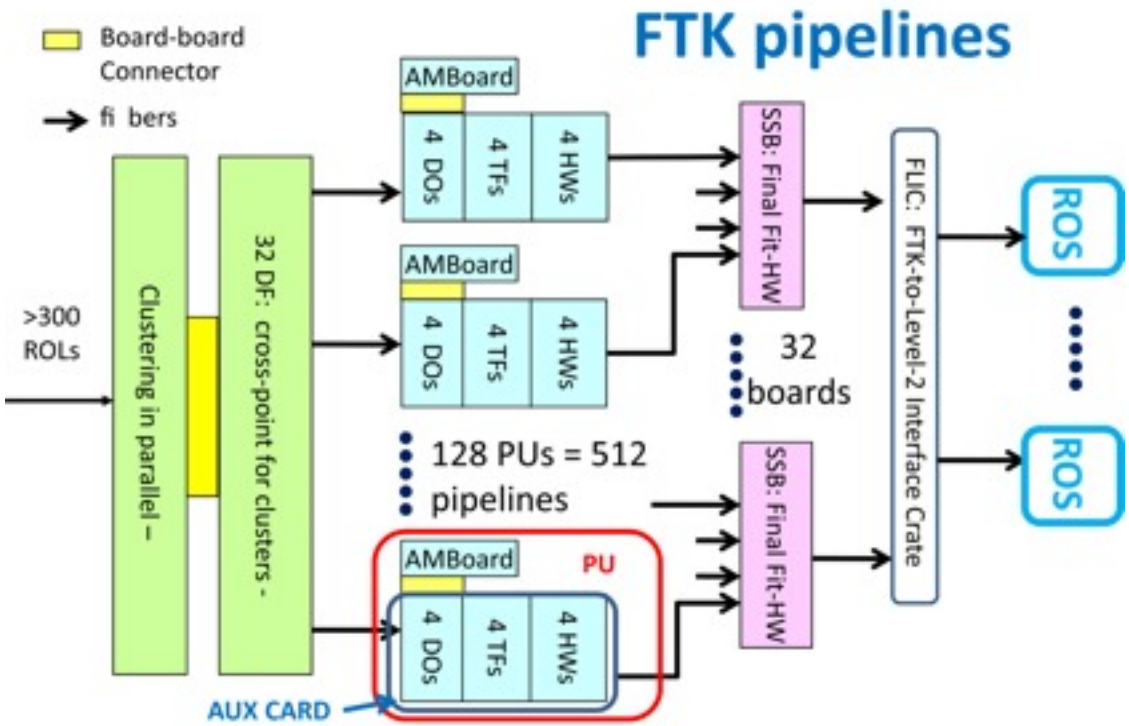
- Level-1 (L1): hardware based (~50 kHz)
- Level-2 (L2): software based, full granularity data (~5 kHz)
- Event Filter: software trigger (~500 Hz)



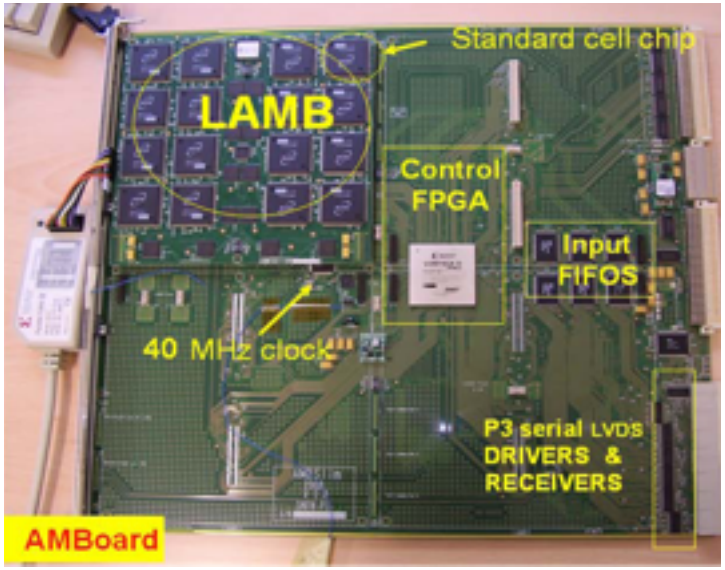




ATLAS Phase-I: the **FTK**



- Massively parallel pattern recognition using an Associated Memory built in custom ASIC chips (AMchips, 16400 in total)
- Data driven pipelines connected by thousands of high speed serial links at 2Gb/s



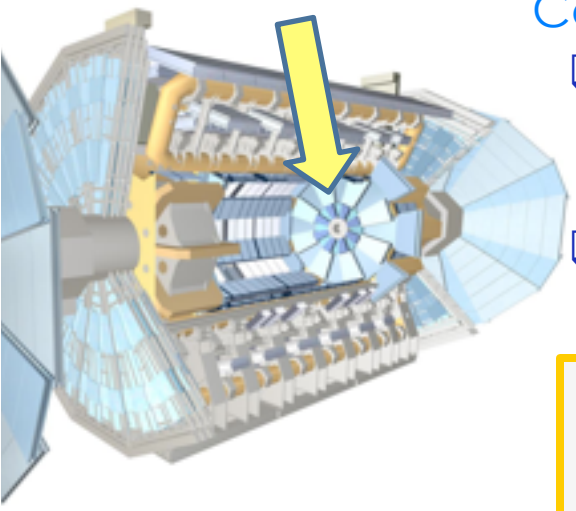
Geneva contributions

UNIVERSITÉ DE GENÈVE

- Production of the AMB-LAMB: boards that house the AMchips and control the data flow through them
- System integration and vertical slice test at the experiment

ATLAS Phase-I: the Muon NSW

$1.3 < |\eta| < 2.7$

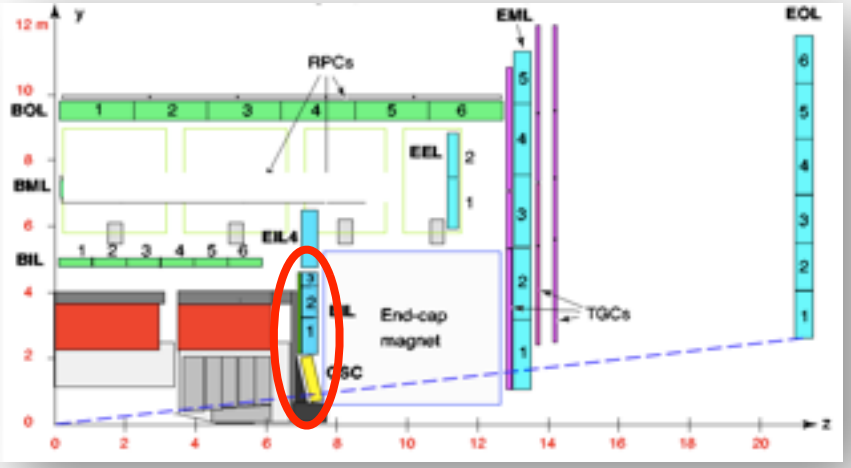


At Phase-1(2): increase of the cavern background rates

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
- Rate of L1 muon triggers exceeds available bandwidth **unless thresholds raised**

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



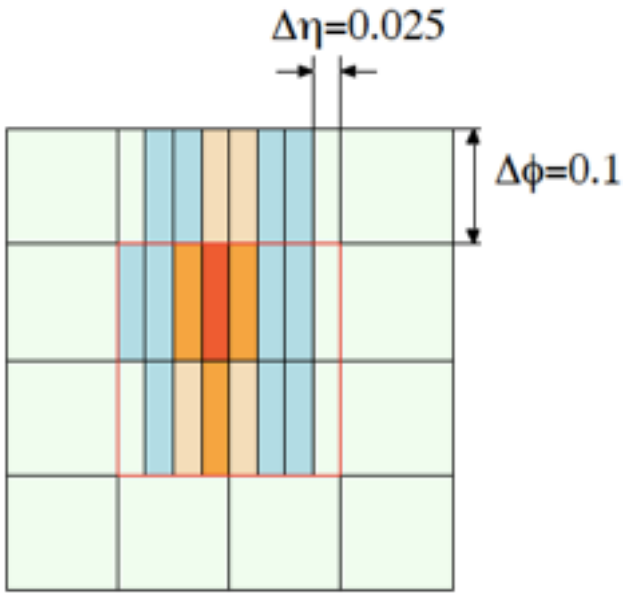
- Composed of gas chambers of higher precision and robustness, assuring:
  - ➡ position resolution < 100 μm
  - ➡ reduction of fake triggers by using **IP-pointing segment** (σ_θ**~ 1 mrad**)
  - ➡ higher rate capabilities (up to L~5x10^{34})

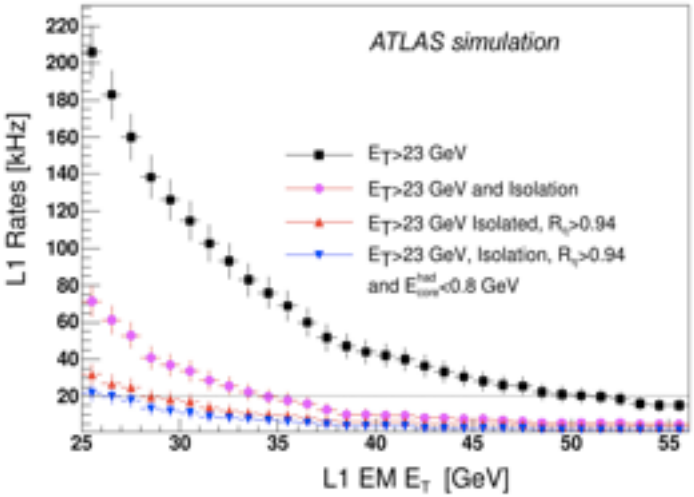
Technology: **MicroMegas** and **sTGCs**

ATLAS Phase-I: Calorimeter Trigger

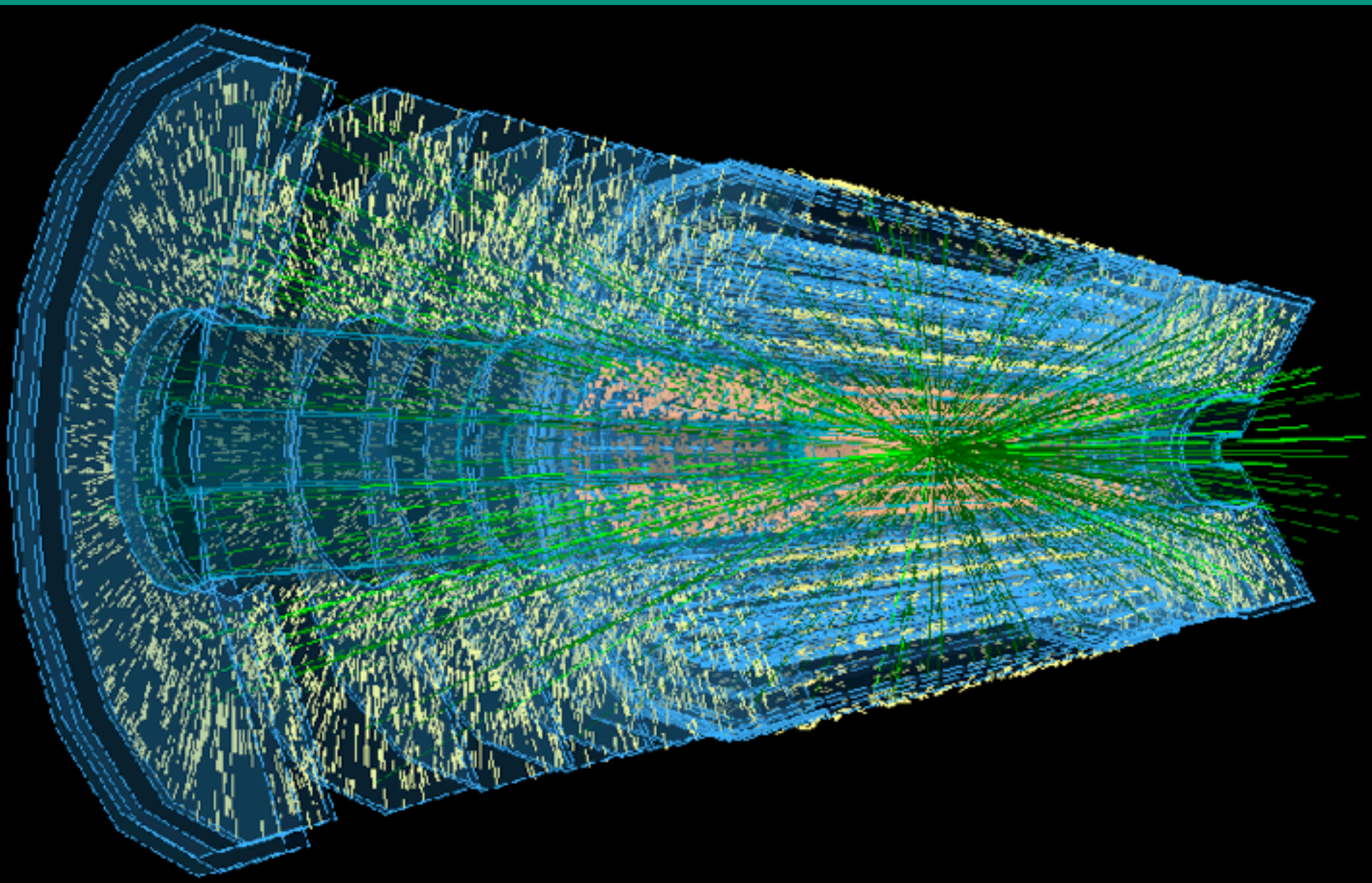
The **granularity of the EM L1 trigger** will be increased, to exploit shower longitudinal and transverse shapes

- ➡ Better electron-jet separation
- ➡ Allow **un-prescaled single electron triggers at E_T ~ 25 GeV** above L = 10^{34} $cm^{-2}s^{-1}$
- ➡ Together with an update of the central L1 trigger processor, **topological L1 triggers** will be available.





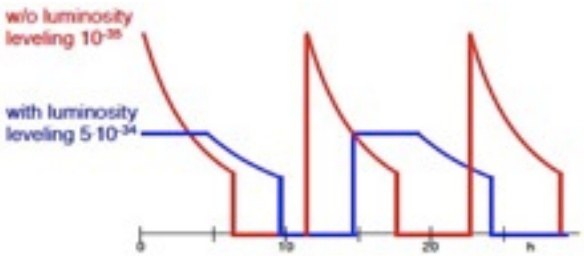
ATLAS **Phase-II** Upgrade



ATLAS **Phase-II** Upgrade

HL-LHC (not yet approved):

- 18 months shutdown in **2022-23** to prepare for inst. luminosity at **5-7×10^{34}cm^{-2}s^{-1}**
- Integrated luminosity **3000 fb^{-1}** after **10 years**
- **Average pileup: <μ> ~ 140-200 int/bx**
- **Levelling:** larger int. lumi & smaller pileup →



ATLAS Phase-II:

- Prepare ATLAS for up to 200 int/bx (7x10^{34} cm^{-2}s^{-1}) and up to 3000 fb^{-1}
  ➡ integrated **radiation levels, particle densities, trigger.**
- **Main activity**: construction of a **new, all silicon tracking detector**. Collaboration already very active with R&D, prototypes and engineering work.
- Be able to trigger on 20 GeV single muons or electrons (e.g. for Higgs):

Trigger upgrades
- ❑ TDAQ upgrade
- ❑ Implementation of L1 Track Trigger

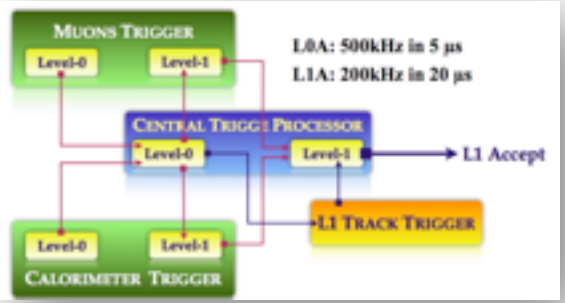
Calorimeter upgrades
- ❑ New LAr, Tile and HEC readouts
- ❑ Possible upgrade of FCal

Muon system upgrades
- ❑ Barrel and Large Wheel trigger electronics
- ❑ Possible upgrades of TGCs in Inner Big Wheels

Software & Computing upgrades

ATLAS Phase-II: L1 track trigger

- Adding tracking information at Level-1 (L1)
  - Move part of High Level Trigger (HLT) reconstruction into L1
  - Goal: keep lepton-p_T trigger thresholds 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

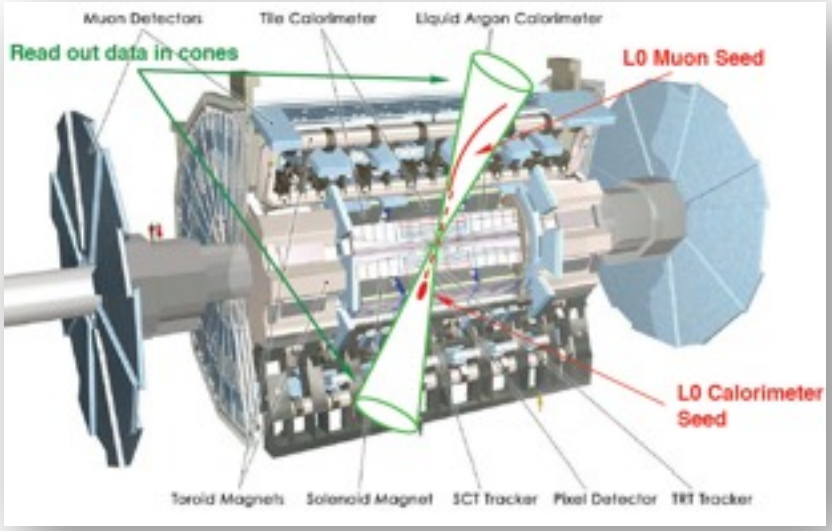


ATLAS RoI Trigger:

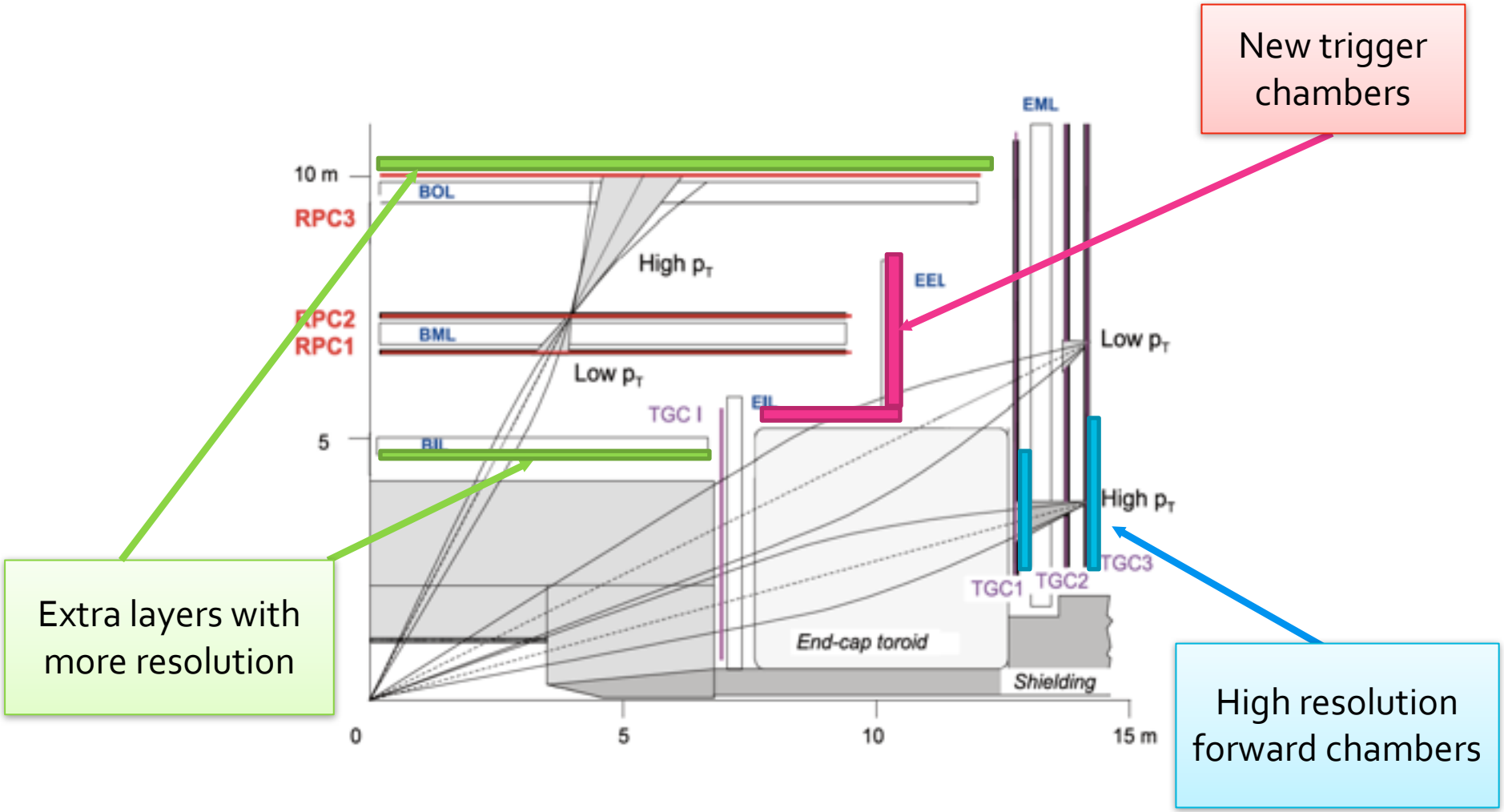
Improve calo and muon trigger granularities (already in Phase-I)

➡ New Level-0 trigger within 5μs uses calo and muon systems to reduce the rate from 40 MHz to ~ 500kHz and define RoIs

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



ATLAS Phase-II: Muon Spectrometer



ATLAS Phase-II: the new tracker

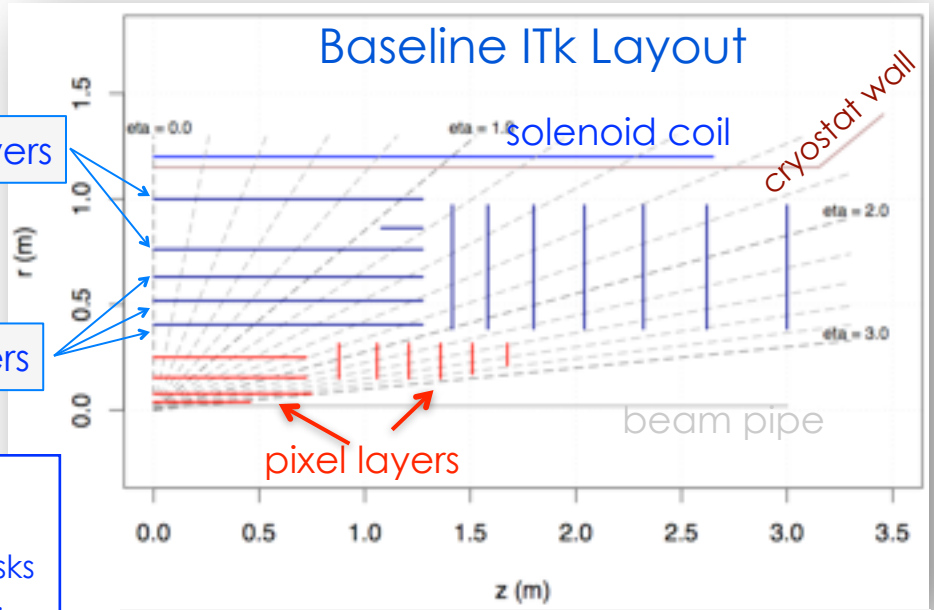
- Current Inner Detector (ID) - designed to operate for 10 years at $L=1\times10^{34}\ cm^{-2}s^{-1}$ with $<\mu>=23$, L1=100kHz
- Limiting factors at HL-LHC
  - Bandwidth saturation in Pixels and SCT
  - Increased occupancies in TRT and SCT
  - Radiation damage for Pixels (SCT) designed for 400 (700) 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

long strip layers

short strip layers



Pixels (638M channels)

- 4 barrel layers + 6 FWD disks
- inner 2 layers, replaceable: 25μm × 150μm
- outer 2 layers: 50μm × 150μm

Strips (74M channels)

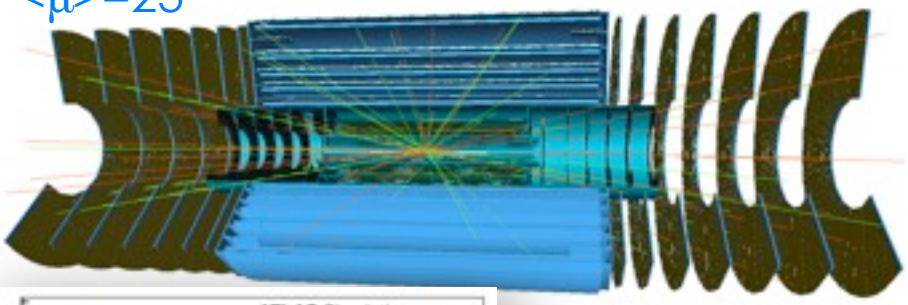
- 5 barrel layers + 7 FWD disks
- stub layer for overlap region
- 2 Si sensors at 40 mrad

all silicon tracker, 14 hits

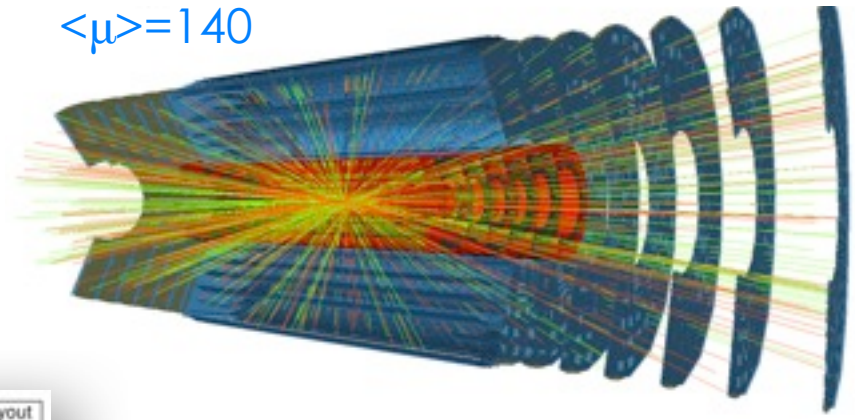
➡ robust tracking @ $<\mu>=140$ for $\eta<2.5$

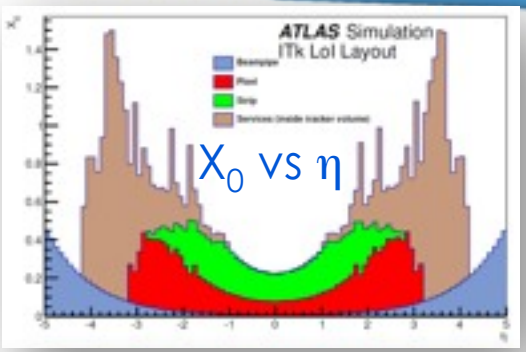
ATLAS Phase-II Upgrade: ITk Performance Studies

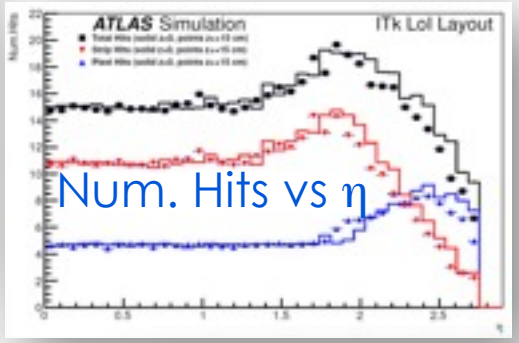
<μ>=23

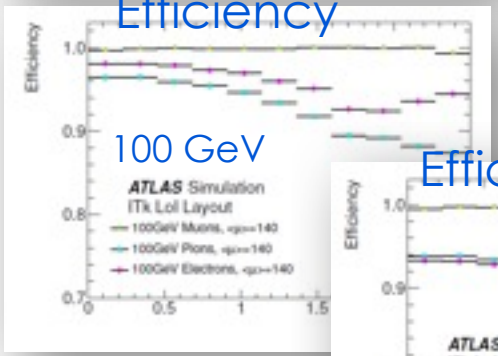


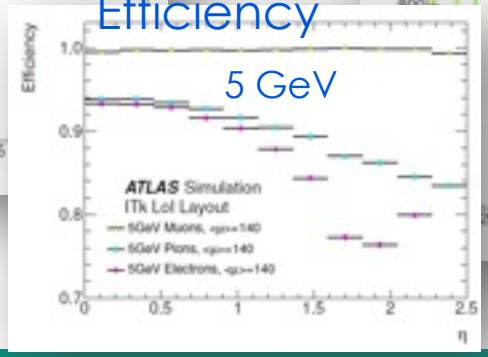
<μ>=140

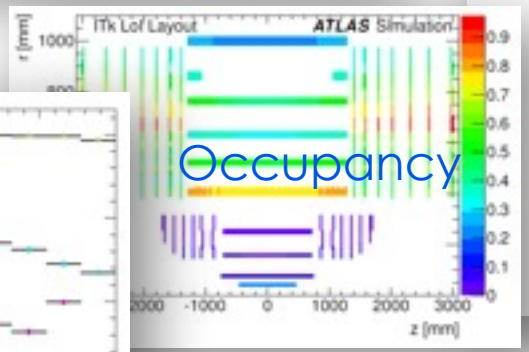


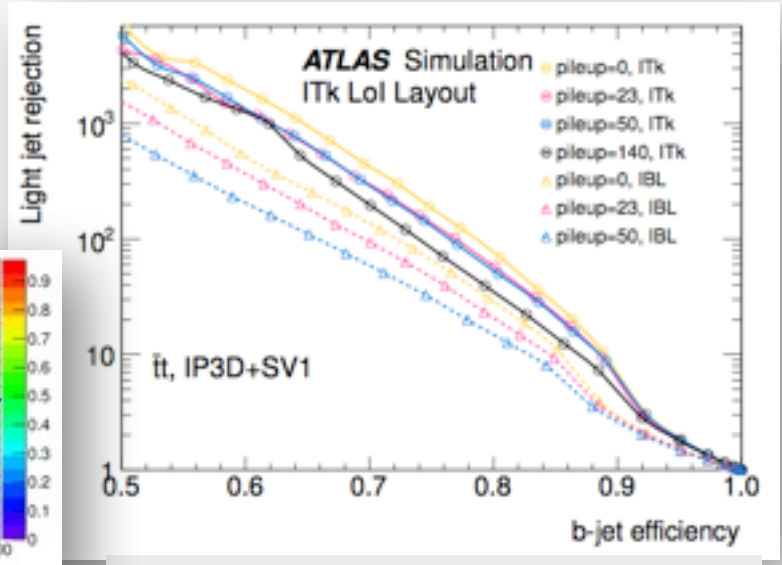












b-tagging: ITk with <μ>=140 better than ATLAS+IBL with <μ>=0

ATLAS Phase-II: the new tracker

- **Baseline layout design**:
  - Pixel size 25/50×150 μm^2 (now 50×400/250 μm^2)
    ➡ better **two-track separation** for boosted bottom quark jets
  - Less material, thinner sensors (<150 μm)
    ➡ improved **p_T resolution**
  - Pseudorapidity range up to η = 2.7
    ➡ to **match muon acceptance**

- **ATLAS-Switzerland**: important involvement in ITk (as it was for the present tracker). Under discussion:
  - **Strips** (UniGe proponent of one of the 2 designs)
  - **Pixels**
  - R&D on **HV-CMOS** started

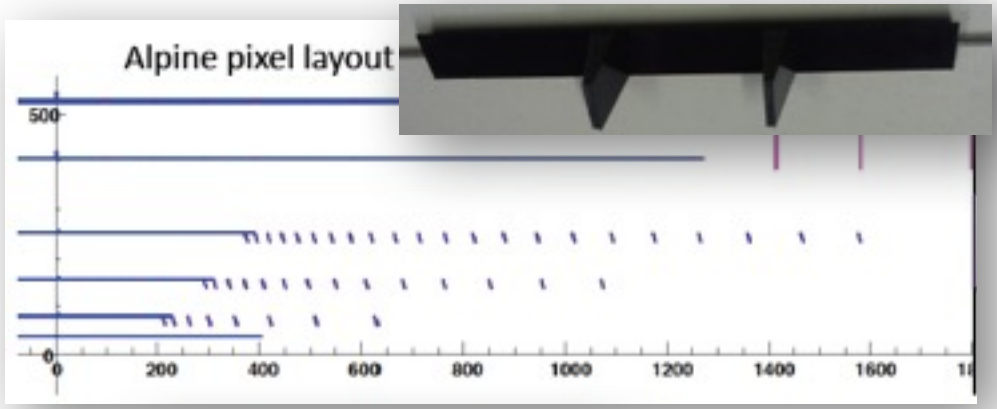
- Baseline layout used for detailed perf. & physics studies at HL-LHC
  - Not frozen in stone, neither layout nor technology
  - e.g.: physics case for extending the ITk in the forward direction?

ATLAS Phase-II tracker: Layout Variants

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

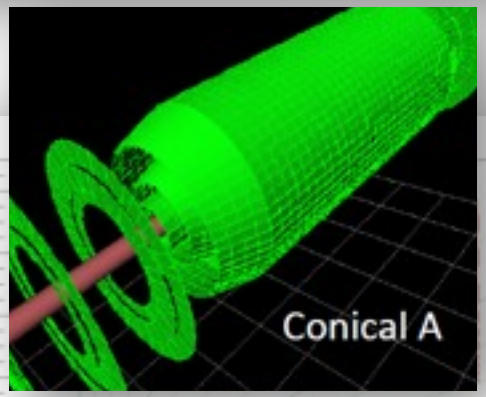
Alpine pixels

- 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***



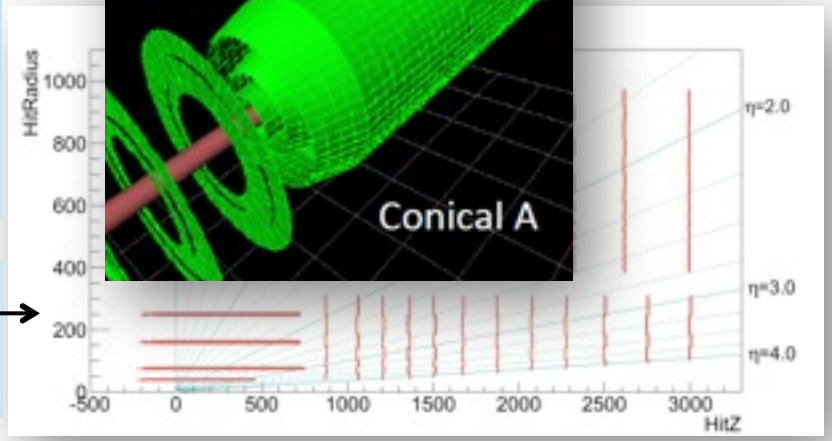
Conical pixels

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



Very Forward pixels

- Extends tracking to | η | ~ 4



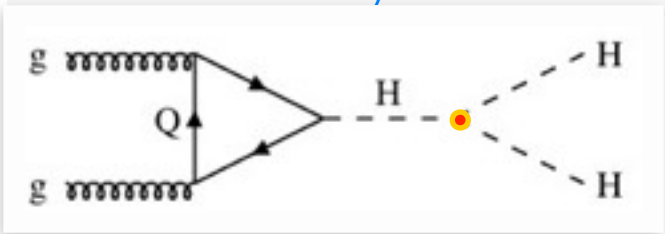
Summary

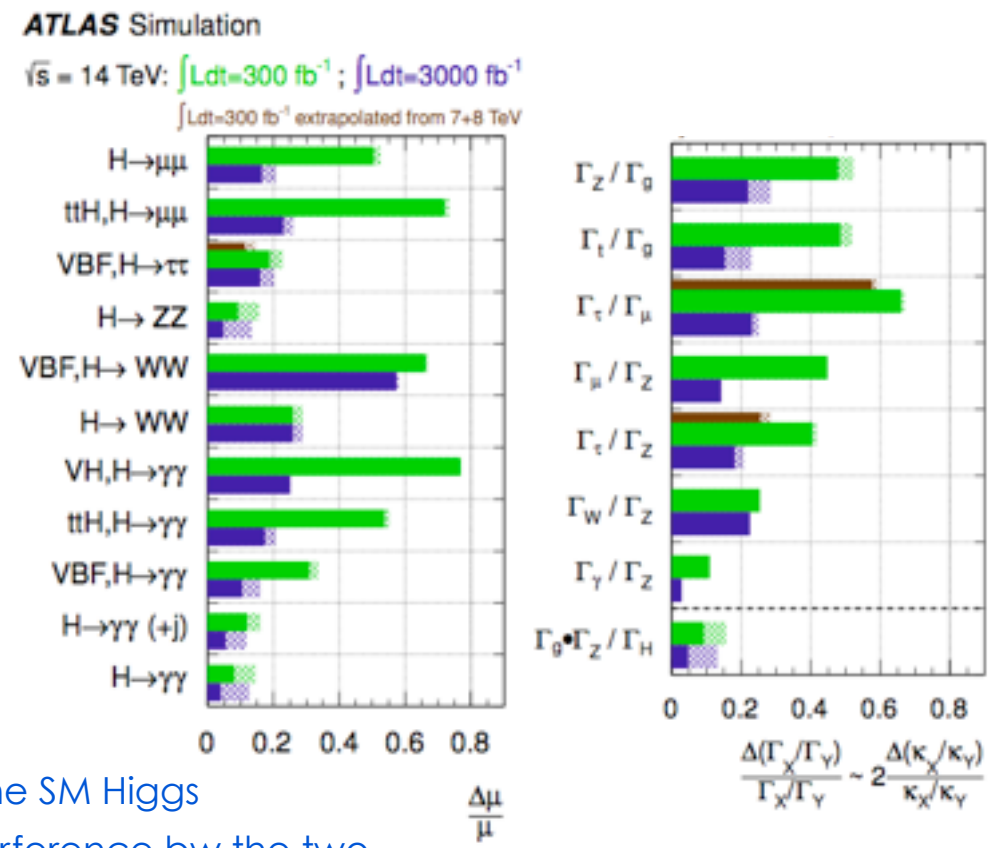
- ATLAS collaboration has devised a detailed **3-phase program** to reflect the changes in the LHC conditions towards the HL-LHC, characterized by high track multiplicity and extreme fluences, with intention to:
  - ***maintain/improve the present detector performance***, *ensuring optimal physics acceptance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

- The foreseen, major ATLAS upgrades include:
  - **Phase-0** (2013/2014 LHC shutdown)
    - Installation of a new, 4th 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 10 more years

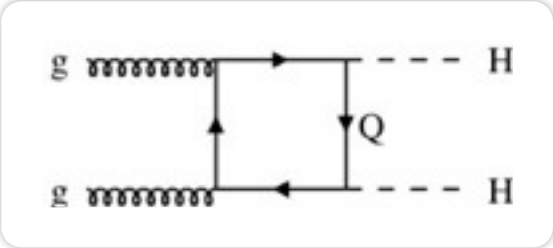
Higgs Prospects at the HL-LHC

- 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



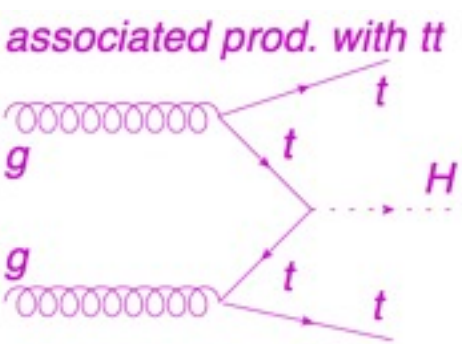


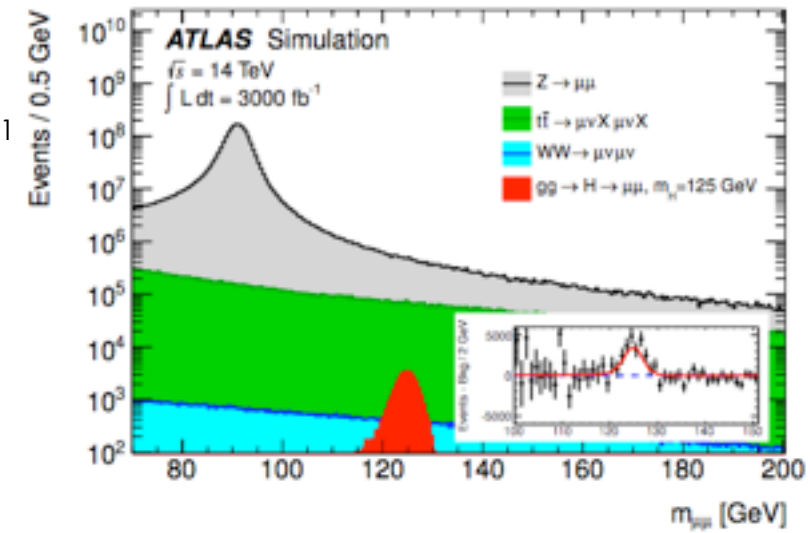
- Self-interaction is a fundamental property of the SM Higgs
- Higgs pair production includes destructive interference bw the two diagrams
- ATLAS HH→bbγγ yields ~2σ significance with 3000 fb-1 (*preliminary*)
- Combining with HH→bbττ, + CMS, it is believed that it is possible to reach a 30% or 40% precision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



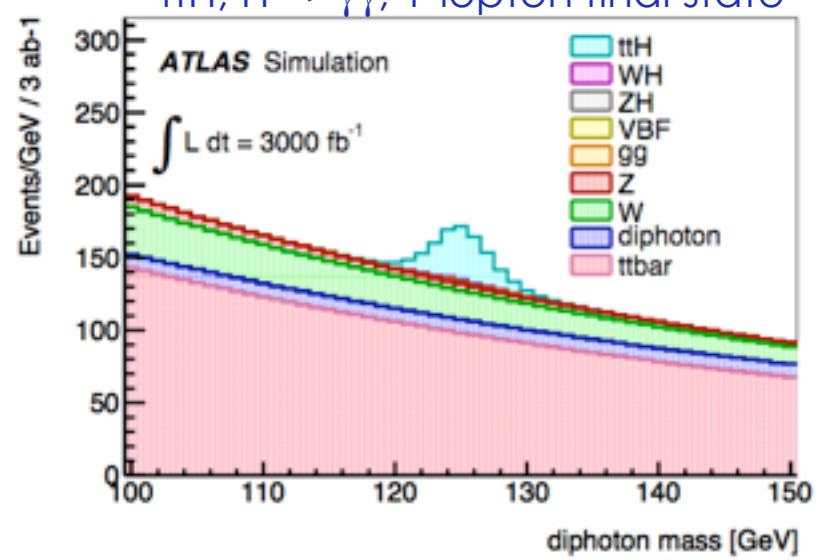
Rare Higgs processes at HL-LHC

- $H \rightarrow \mu\mu$
  - ATLAS expect >6σ significance with 3000 fb^{-1}
- ttH - allows precise measurement of top-Yukawa coupling
  - ttH, $H \rightarrow \gamma\gamma$
    - >100 signal events @ 3000 fb^{-1}
    - S/B ~20%
  - ttH, $H \rightarrow \mu\mu$
    - Only ~30 signal events but S/B~1 with 3000 fb^{-1}





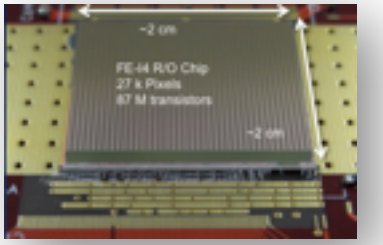
ttH, $H \rightarrow \gamma\gamma$, 1-lepton final state

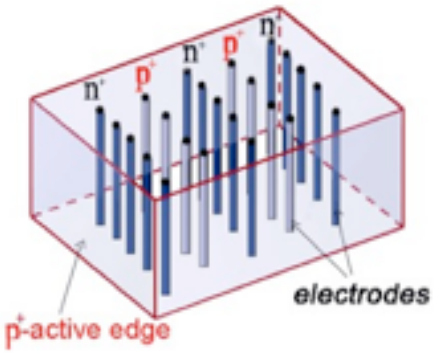


IBL

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



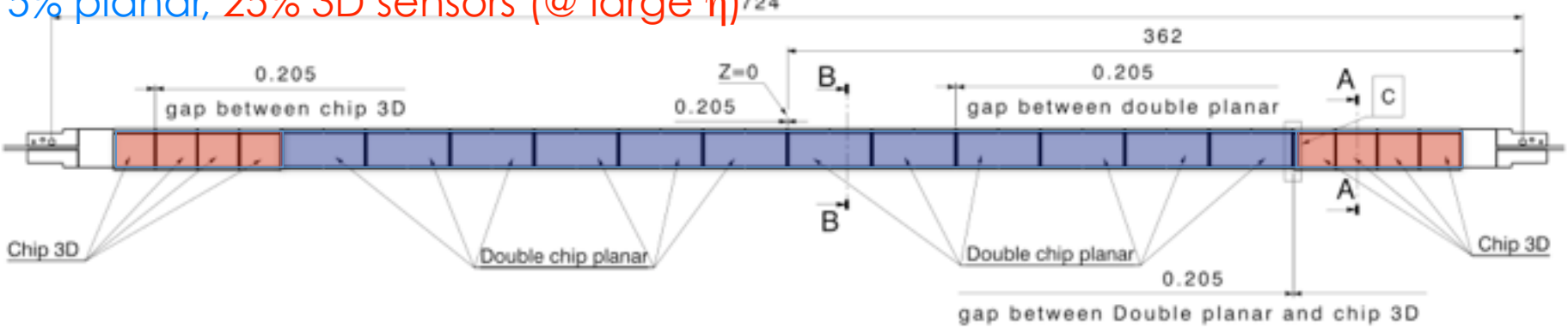


Planar sensor	3D sensors
200 µm thickness	230 µm thickness
inactive edge <250 µm (minimize gaps in η , no overlap)	inactive edge 200 µm
low Q generated after irradiation → low threshold operation and high HV	low depletion voltage (<180V) even after high doses
cheaper and easier to fabricate	**electrode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

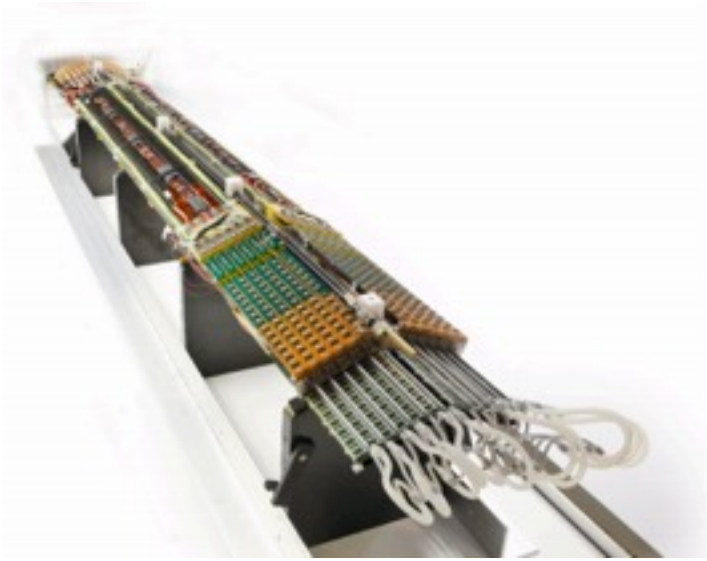
FE-I4chip (16.8x20 mm^2)

336x80 pixels (50µm x 250 µm)

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



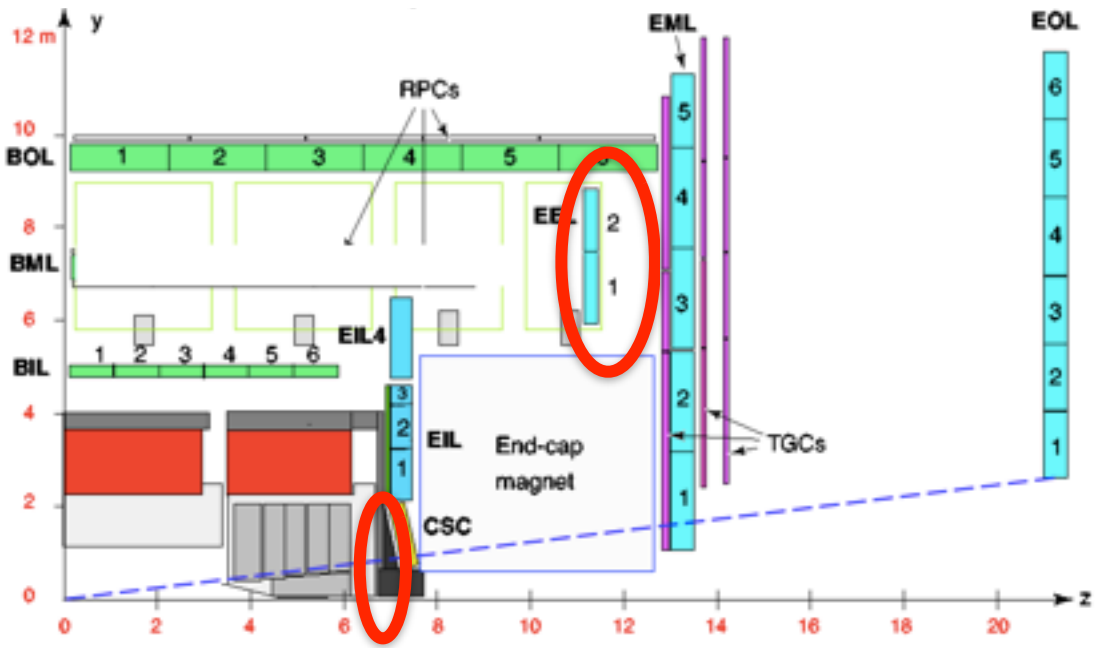
New Service Quarter Panels



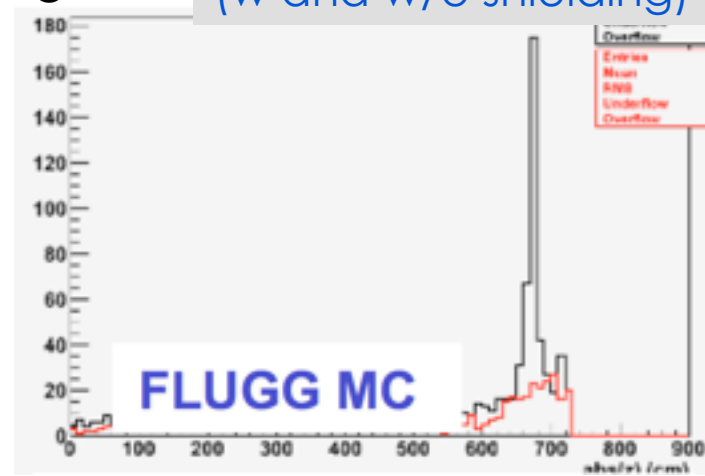
- nSQP will replace current Pixel services
- opto-boards on the panels will be replaced with e-boards connected to new opto-boards outside the Pixel detector volume (easier access for optical link replacement)
- Also: repair of Pixel RO channels, redundant links, faster
- Diamond Beam Monitor attached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

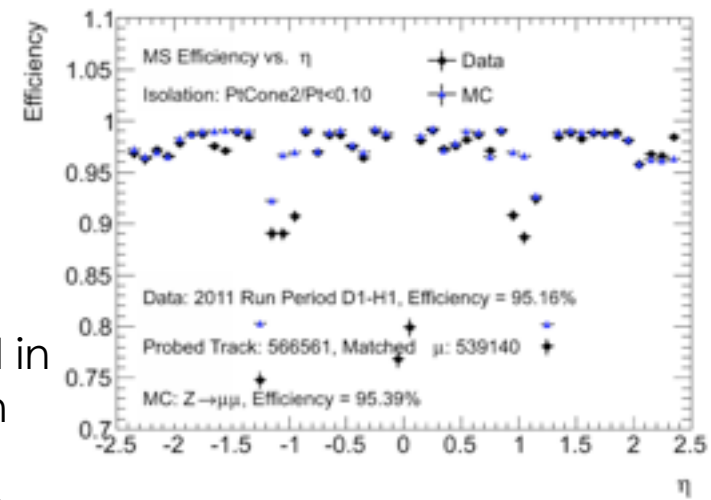
Endcap Extension (EE) Muon Chambers

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



beam interaction hits (w and w/o shielding)





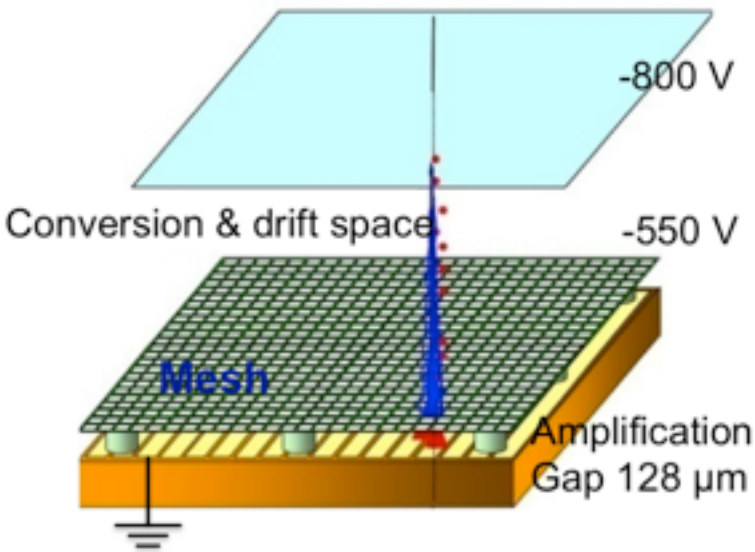
- Endcap Extension (EE) Muon Chambers
  - Finish installation of the EE muon chambers staged in 2003 + additional muon chambers in the feet (with new electronics) and elevators region
  - Addresses low efficiency in the region $1.0<|\eta|<1.3$

New Muon Small Wheels (NSW)

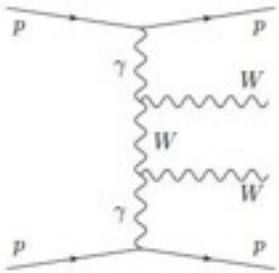
- Precision chambers combine small-strip TGCs and MicroMegas technologies for robustness to Phase-II luminosities
- **sTGC** (small-strip Thin Gap Chambers): reduced cathode resistivity of 100kΩ/square
  → *rate capability has been increased* substantially up to 30kHz/cm2
- **MicroMegas** (MM)

–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



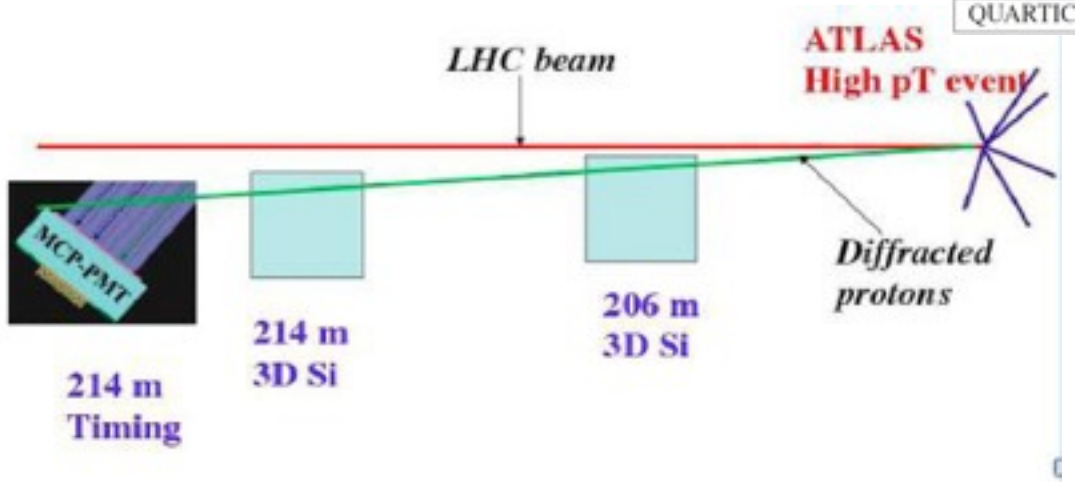
ATLAS Forward Proton (AFP)



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 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



Calorimeter Upgrades

- 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 ($3.2<|\eta|<4.9$) not designed for $L>10^{34}cm^{-2}s^{-1}$

when 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