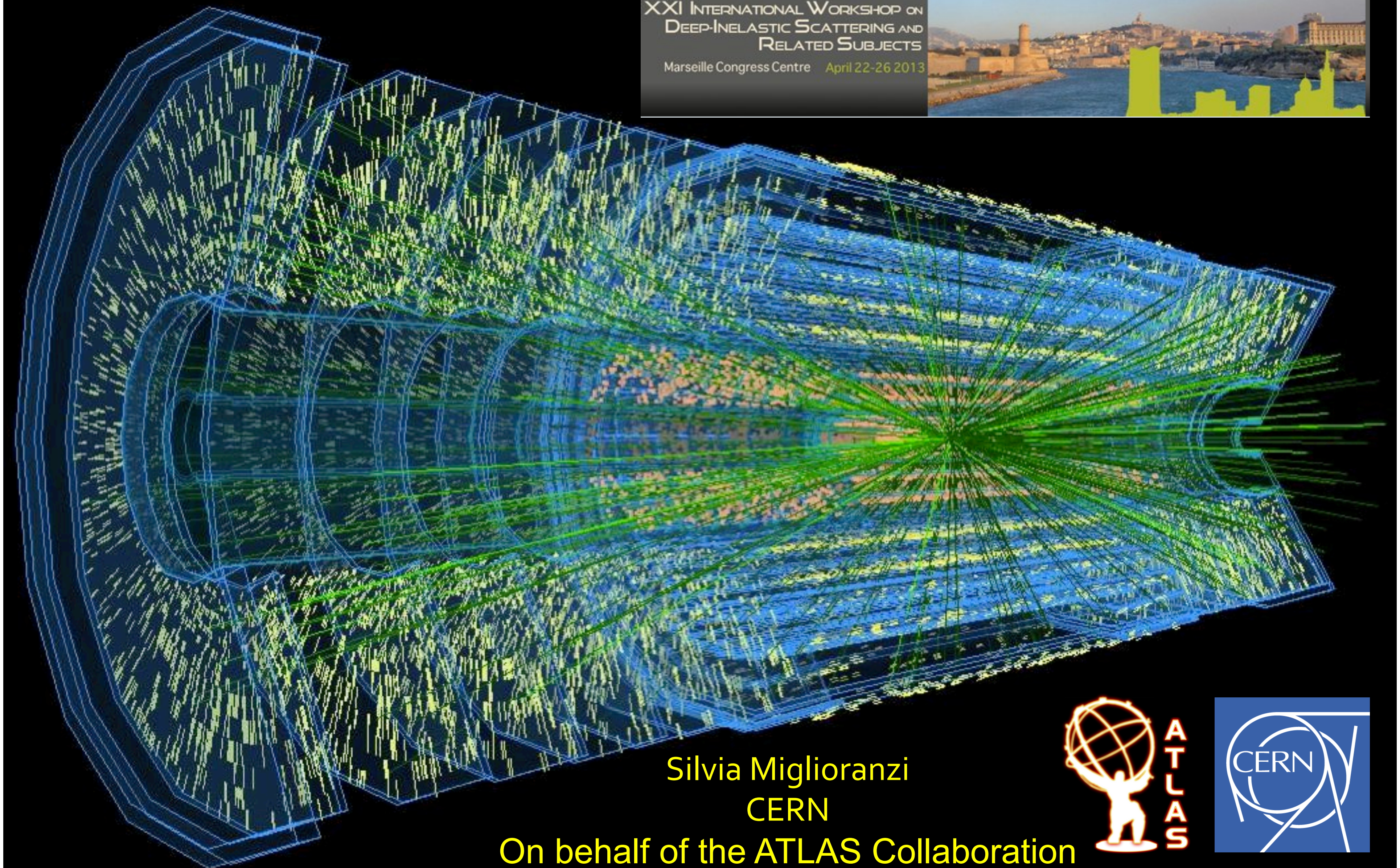
ATLAS Upgrades Towards the High Luminosity LHC: extending the discovery potential

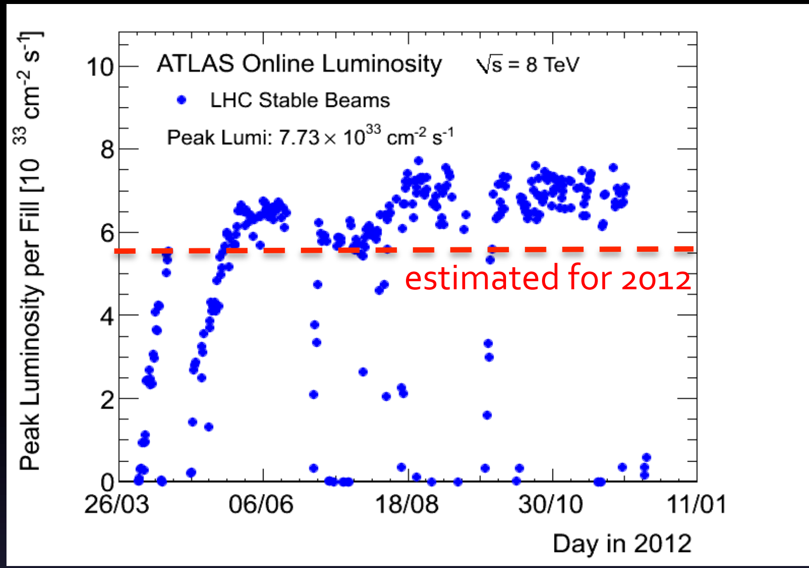
XXI International Workshop on Deep-Inelastic Scattering and Related Subjects
Marseille Congress Centre April 22-26 2013



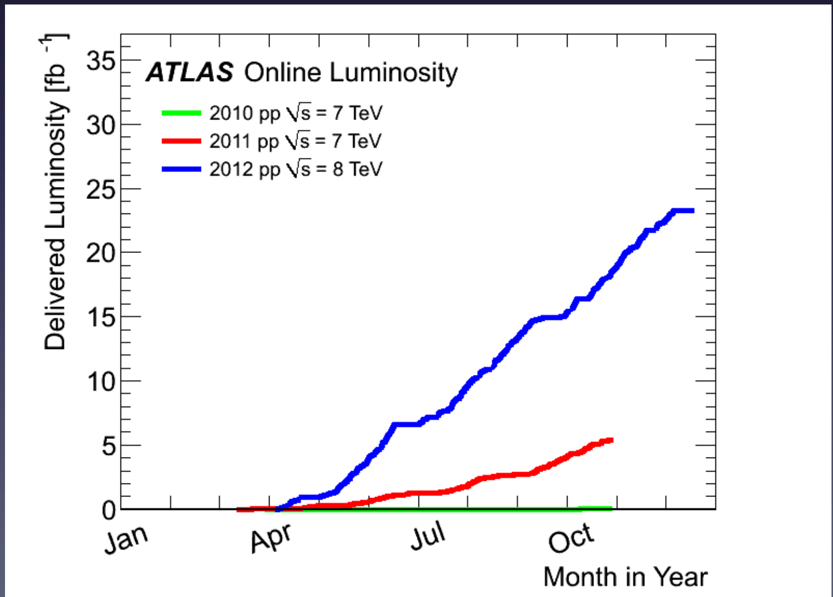
Silvia Miglioranzi
CERN
On behalf of the ATLAS Collaboration

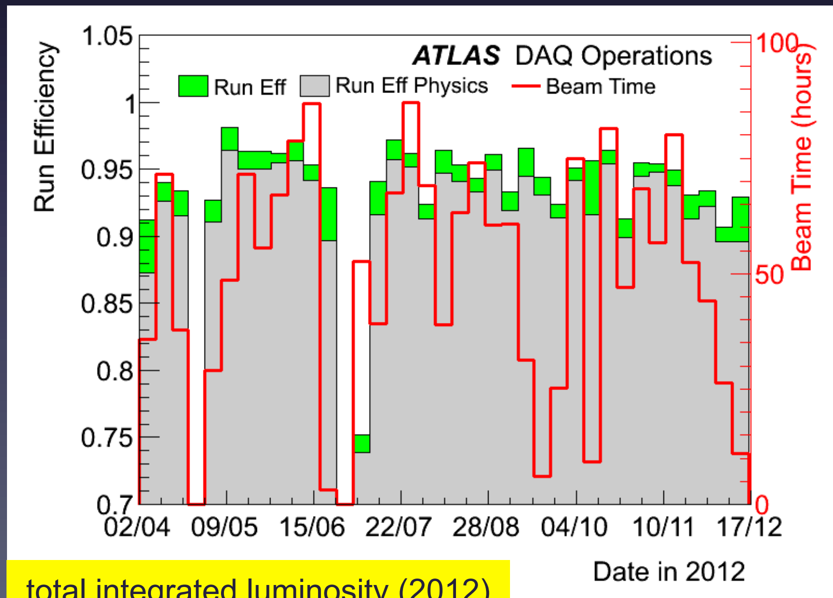
LHC and ATLAS performances in 2012

Outstanding LHC performances during 2012



- ATLAS data taking efficiency ~94%
  dominated by detector dead time
- peak luminosity routinely over 7.5 $10^{33} cm^{-2}s^{-1}$



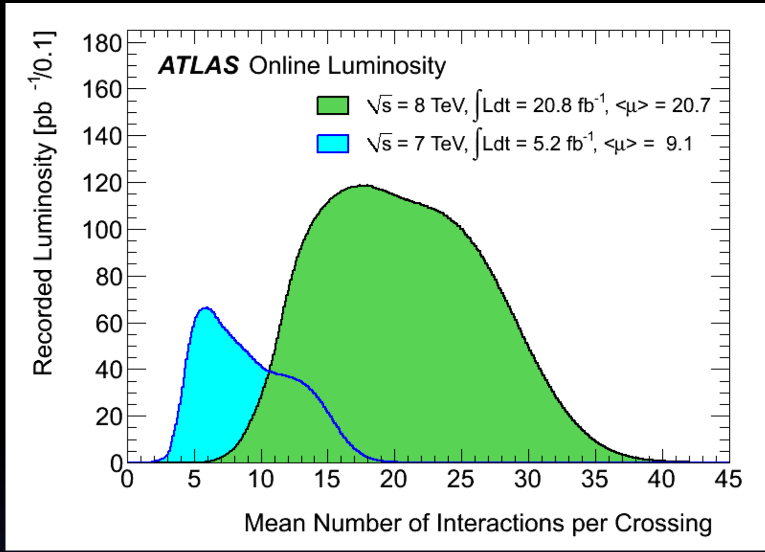


total integrated luminosity (2012)
delivered: 23.3 fb^{-1}
recorded: 21.7 fb^{-1}

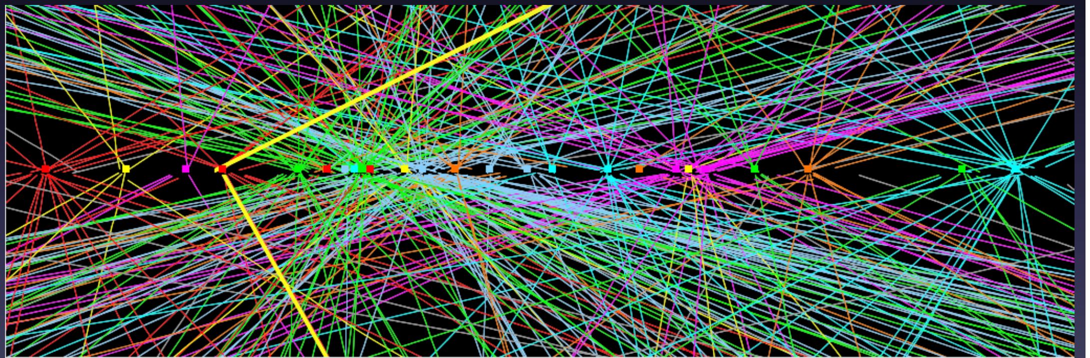
ATLAS performances in 2012

It was a success despite difficult conditions

- the expected in time pile up (PU) at design luminosity ($1 \times 10^{34} cm^{-2}s^{-1}$) was 23
  (25ns bunch spacing)
- in 2012 peak μ regularly over 35
  (50ns bunch spacing)



Z→ μμ with 25 reconstructed vertices



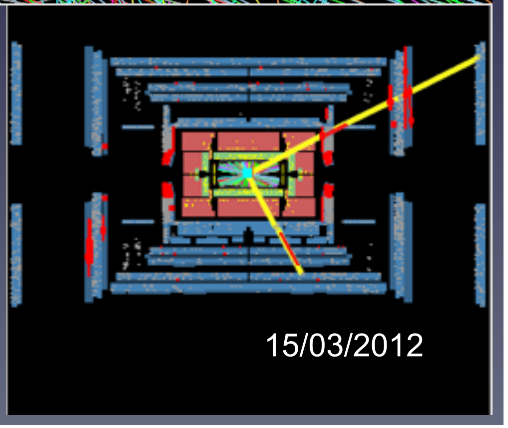
Inner Detector
- high reconstruction efficiency (~99% for muons)
- vertex reconstruction performing well

Calorimeters (e/γ performance)
- electron energy response and photon conversion reconstruction showed excellent stability w.r.t. increasing PU

Calorimeters (Jet/Etmis performance)
- missing Et reconstruction performing well
- stable resolution performance

Particle Identification
- identification efficiency quite robust against PU

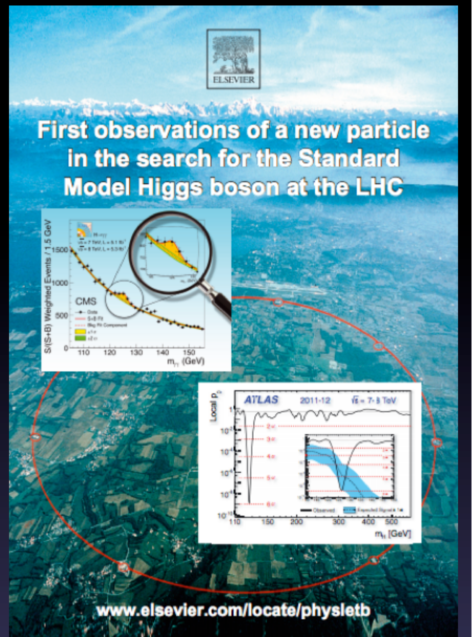
Trigger
- developed algorithms are robust against-pile up



Why Upgrade?

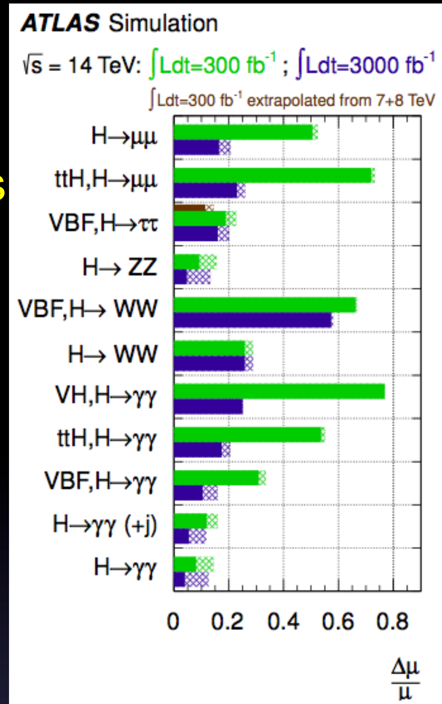
Physics programme at LHC only begun with √s= 7-8 TeV collisions

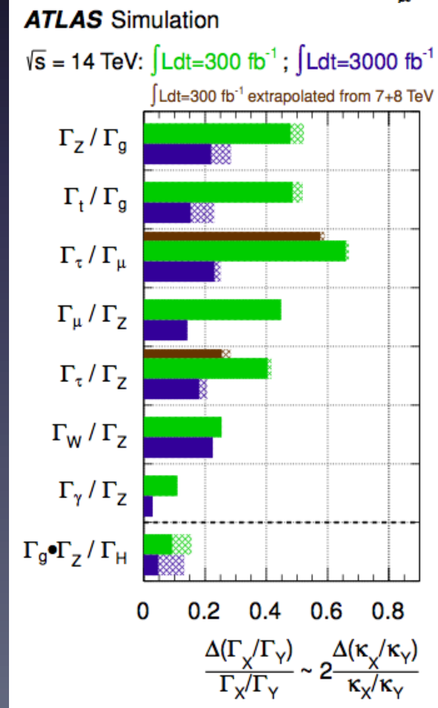
After 4th July 2012…



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 at 5-15% level





Higgs self-coupling in SM becomes accessible only at HL-LHC luminosity

Probing new Physics

- SUSY and other New Physics beyond SM
- enhancements in vector boson scattering amplitudes
- rare processes such as FCNC decays of top accessible to 10^{-5}

details on the Physics case in the European Strategy Meeting (Sept. 2012, Kracow)
http://indico.cern.ch/conferenceDisplay.py?confId=182232

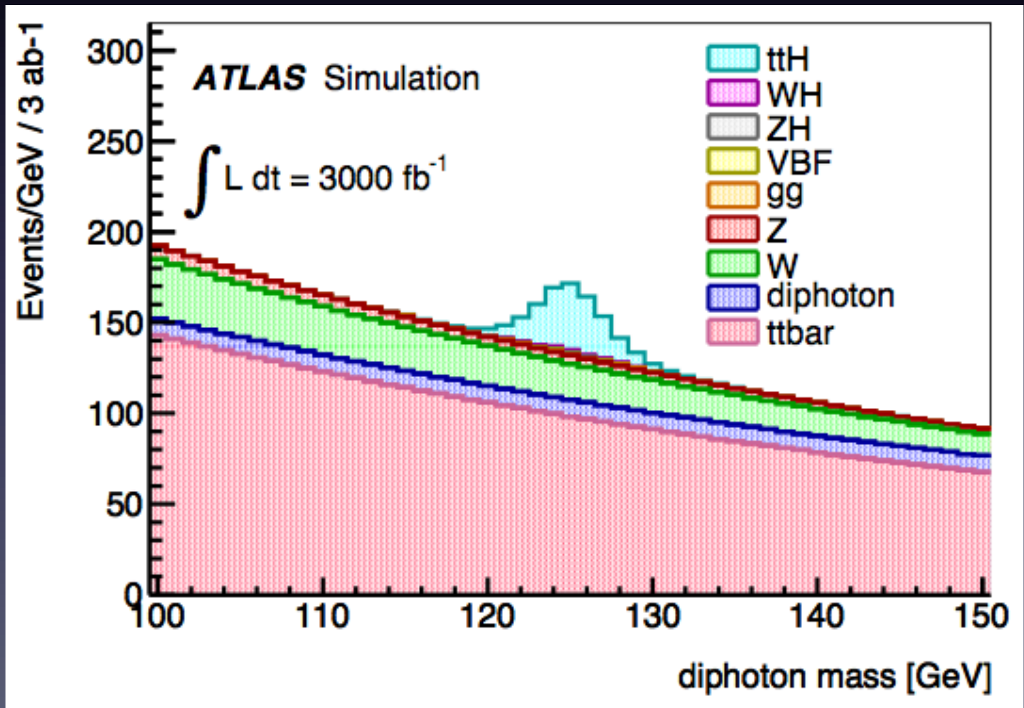
S. Miglioranzi

Precision measurements of Higgs couplings

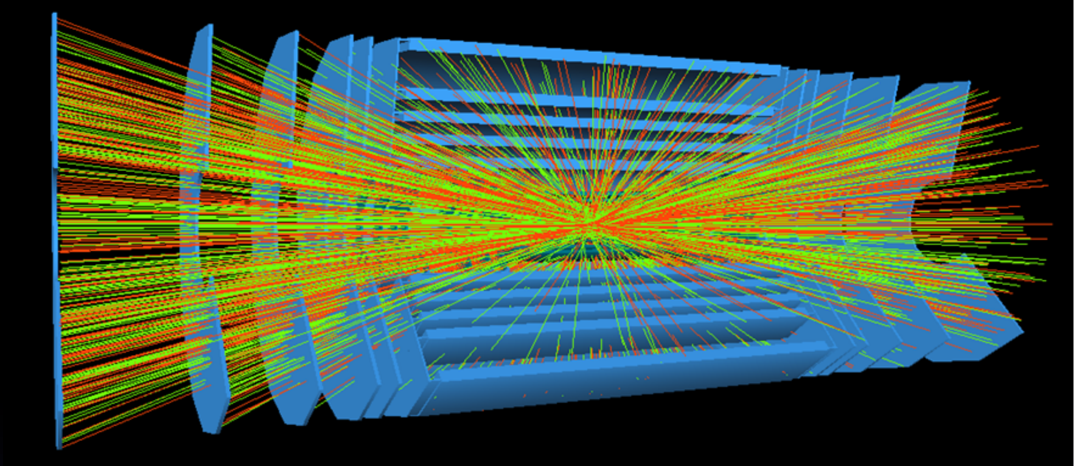
final states targeted to measure couplings (that have low signal rate at LHC):

$t\bar{t}H$ (with H→ γγ)

- allows precise measurement of top-Yukawa coupling
- cleanest signal (w.r.t WH/ZH) → S/B ~20%
- S/√B ~6 with 3000 fb^{-1} (x2 better than 300 fb-1)



Detector Challenges



baseline of the future Inner Detector traversed by an event with 230 Pile Up

Peak luminosity → 1 to $5 \times 10^{34} cm^{-2} s^{-1}$

- higher trigger rate
  → need improved triggers rather than simply raising thresholds globally

Multiple interactions per crossing → <140>

- higher detector occupancy
- increasing reconstruction complexity

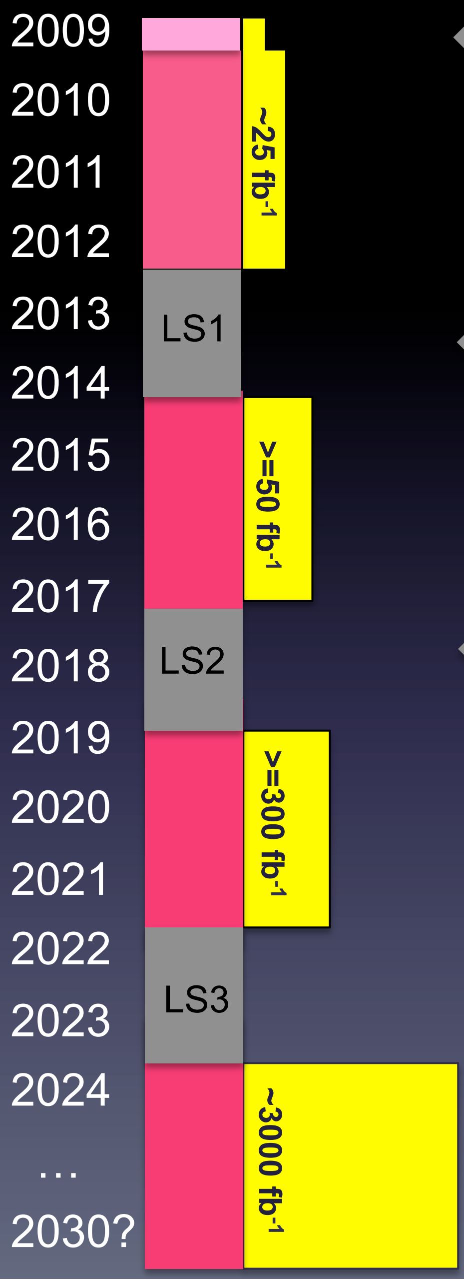
Increasing fluences → $>10^{16} n_{eq}/cm^2$ close to the beam pipe

- increased radiation damage
- increased activation of materials

Aging electronics (obsolete technology)

Distribution and Analysis of data sets recorded at 5-10kHz over a world wide computing infrastructure

LHC Upgrade schedule



LHC startup, $\sqrt{s}$= 900 GeV
$\sqrt{s}$=7~8 TeV, $L=6\times10^{33}$ cm^{-2} s-^{1}, bunch spacing 50 ns

Go to design energy, nominal luminosity
$\sqrt{s}$ = 13~14 TeV, $L \sim 1\times10^{34}$ cm^{-2} s^{-1}, bunch spacing 25 ns
Phase-0

Injector and LHC Phase-1 upgrade to full design luminosity
$\sqrt{s}$ = 14 TeV, $L \sim 2\times10^{34}$ cm^{-2} s^{-1}, bunch spacing 25 ns
Phase-I

HL-LHC Phase-2 upgrade, IR, crab cavities
$\sqrt{s}$ = 14 TeV, $L = 5\times10^{34}$ cm^{-2} s^{-1}, luminosity leveling
Phase-II

Phase 0: 2013/14 (LS1)

LHC

18 months shutdown

- consolidation of the superconducting circuits
  issues identified – improvements and upgrades planned
- replace/repair superconducting splices for (almost) design energy (13TeV) and nominal ($10^{34} cm^{-2} s^{-1}$) luminosity → 50 fb^{-1}

ATLAS

detector consolidation

- new Al beam pipe
- new evaporative Inner Detector cooling plant
- new Low Voltage calorimeter power supplies
- power network, magnet cryogenics, services…
- completion of the Muon system
  new chambers in the muon spectrometer to improve geometrical acceptance (extension $1<|\eta|<1.3$)
- additional neutron shielding in endcap toroid

detector upgrade

- Insertable B-Layer
- new Pixel Service Quarter Panels (nSQP)
- Diamond Beam Monitor (DBM)

Insertable B Layer (IBL)

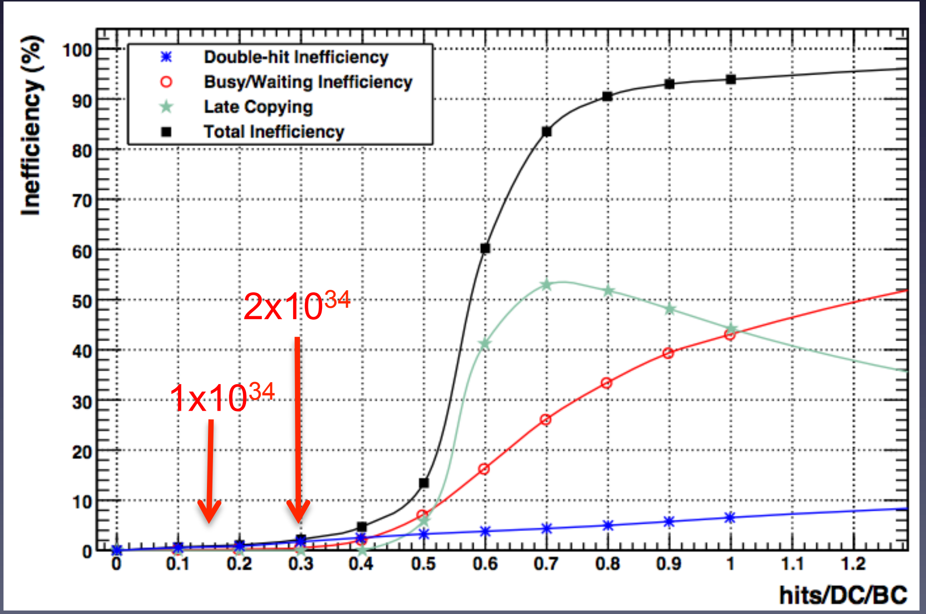
additional (4^{th}) pixel layer closer to IP

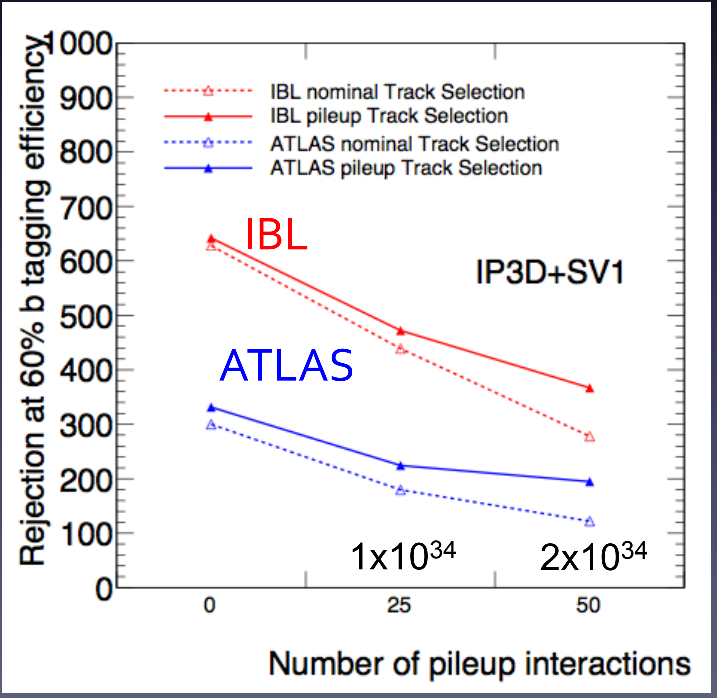
Physics motivation

- robust tracking in case of failures in the current pixel system
- from L = 2×10^{34} cm^{-2}s^{-1} b-tagging efficiency will start to degrade
- improves impact parameter resolution, vertexing, τ-reconstruction at high pile-up

Light jet rejection

occupancy B layer (current innermost layer)

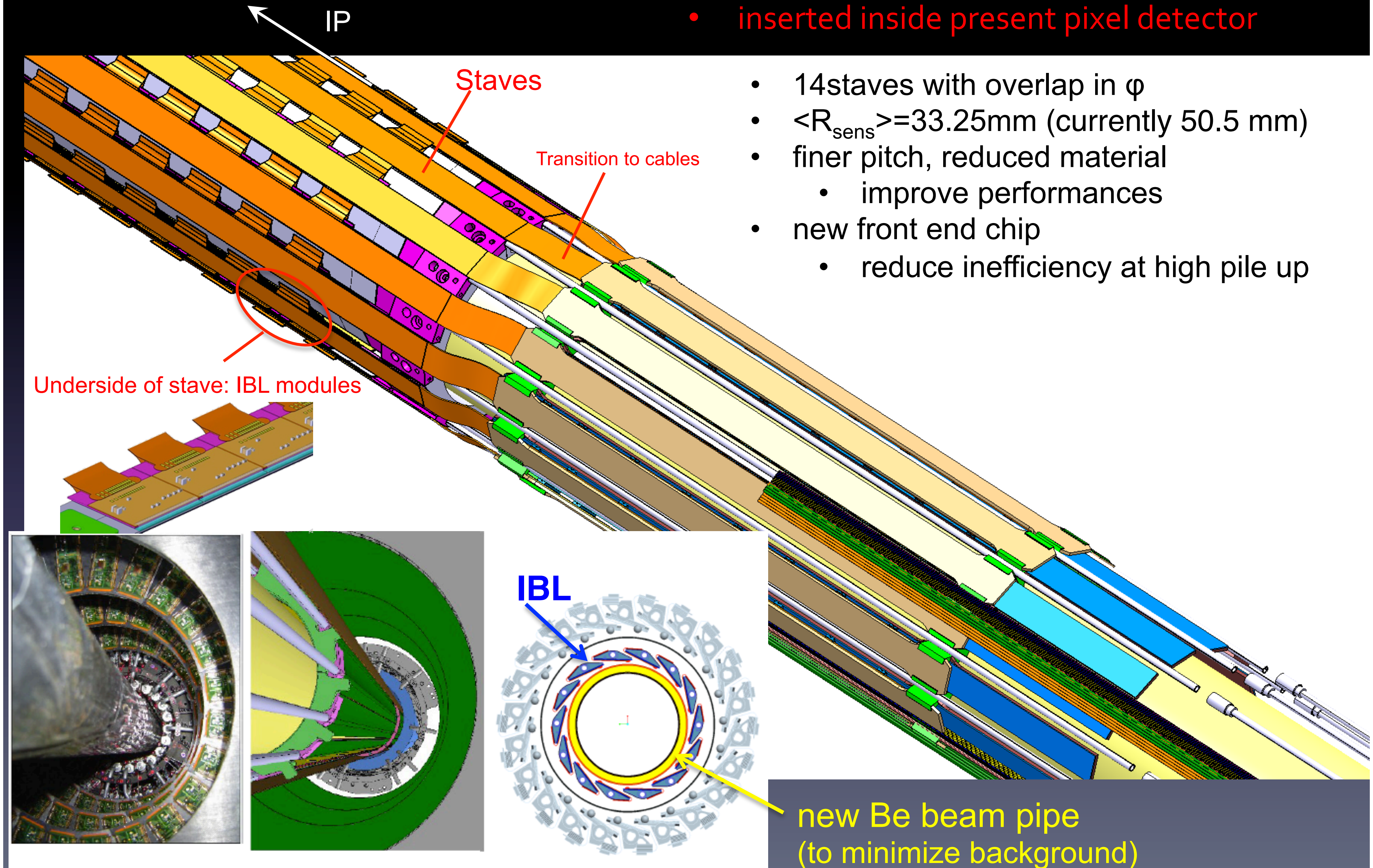




Insertable B Layer (IBL)

- built around a new thinner beam pipe
- inserted inside present pixel detector

- 14staves with overlap in φ
- $<R_{sens}>$=33.25mm (currently 50.5 mm)
- finer pitch, reduced material
  - improve performances
- new front end chip
  - reduce inefficiency at high pile up

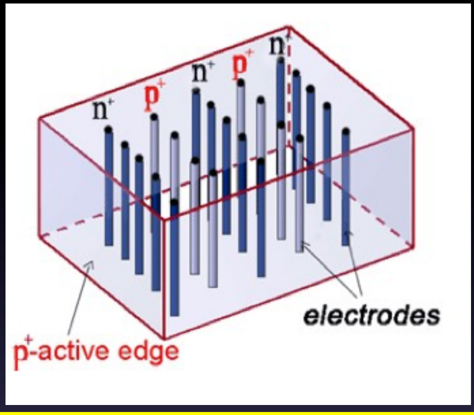


IBL layout

Technology step towards HL-LHC

2 different sensor technologies:

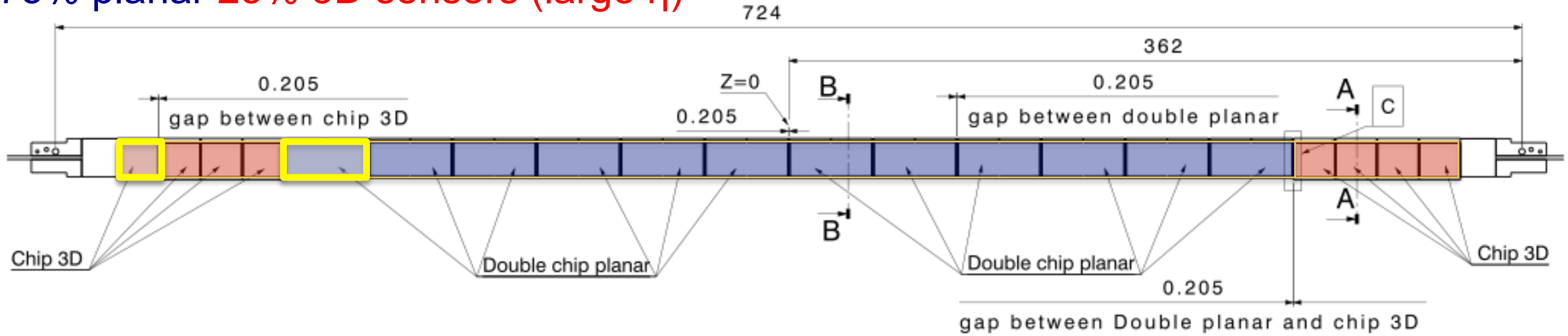
- double chip (DC) modules with 2 FE-I4 and 1 planar n-in-n sensor tile
- single chip (SC) modules with 1 FE-I4 and 1 n-in-p 3D sensor tile



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**

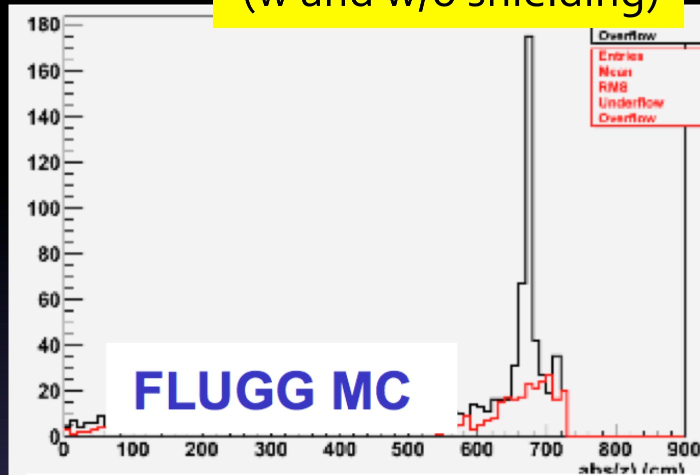
75% planar 25% 3D sensors (large η)

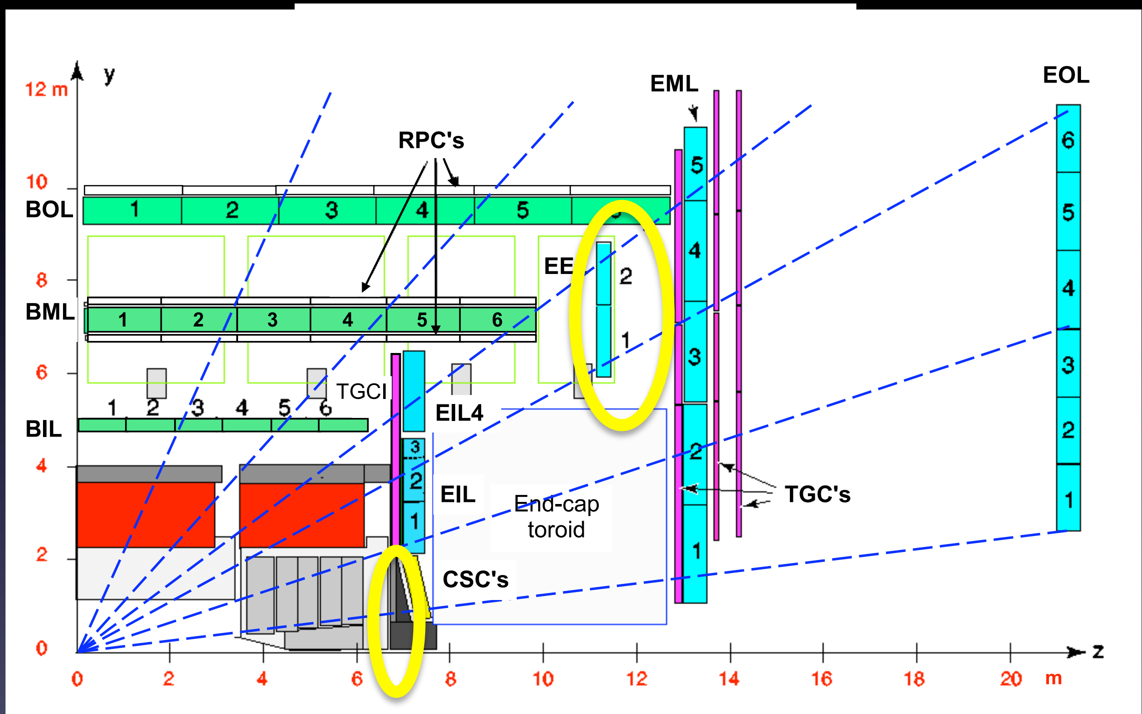


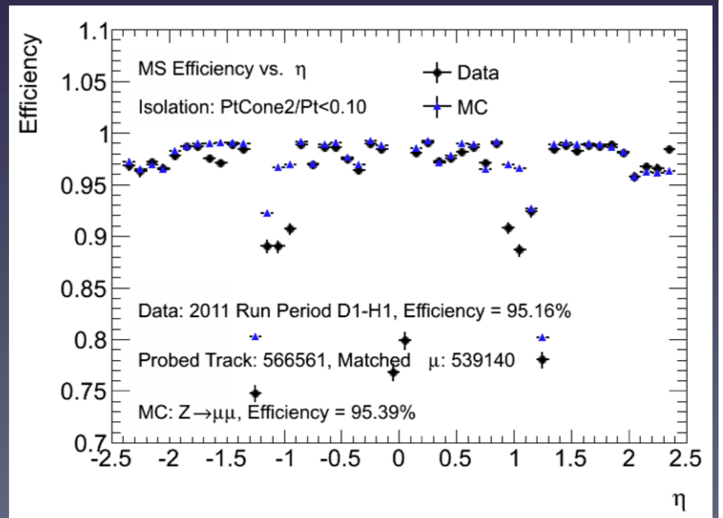
Muon System

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

beam interaction hits (w and w/o shielding)







- Endcap Extension (EE) Muon Chambers
  - installation of 52 of 62
  - address low efficiency in the region 1.0<|η|<1.3

S. Miglioranzi

Phase-I: 2017/2018 (LS2)

14 months shutdown

LHC

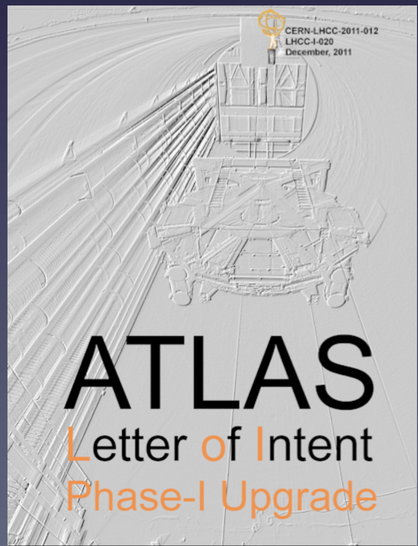
- consolidation of injector chain, collimators
- peak luminosity $2x10^{34}cm^{-2}s^{-1}$ → $300fb^{-1}$ @ 14TeV

ATLAS

detector upgrade

- New Small Wheels for the forward muon spectrometer
- Fast Track Trigger at "Level 1.5"
- Higher granularity in L1 Trigger for calorimeter
- Topological L1 Trigger processors
- Central Trigger Processor (CTP) upgrades
- New forward diffractive physics detectors (AFP)

all upgrades should be compatible with Phase-II



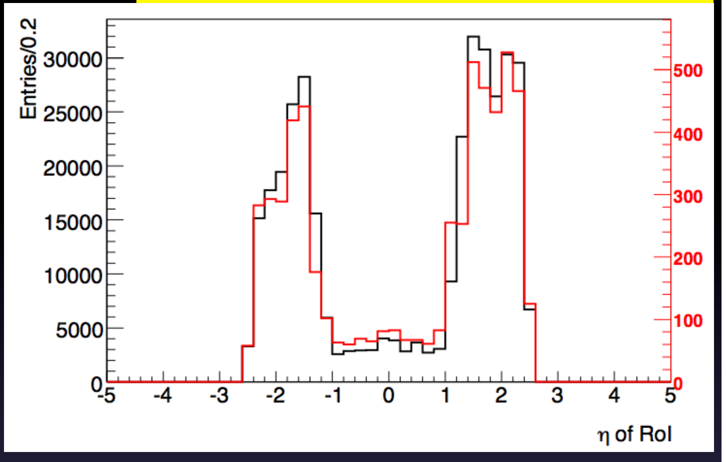
Phase-I LoI: https://cds.cern.ch/record/1402470?ln=en

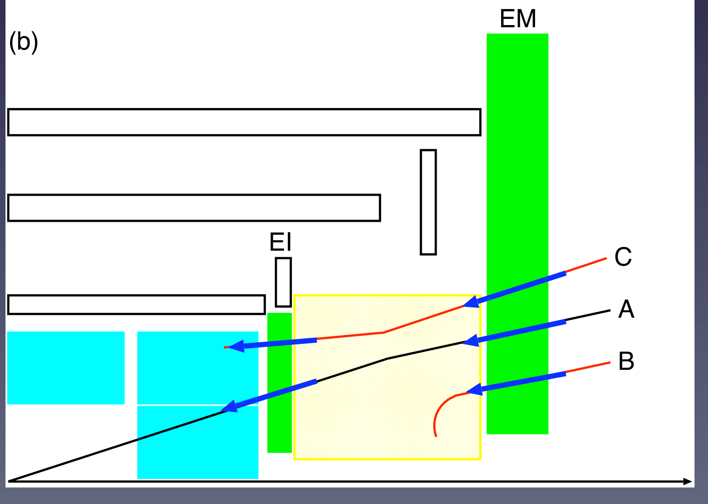
New Muon Small Wheels (NMSW)

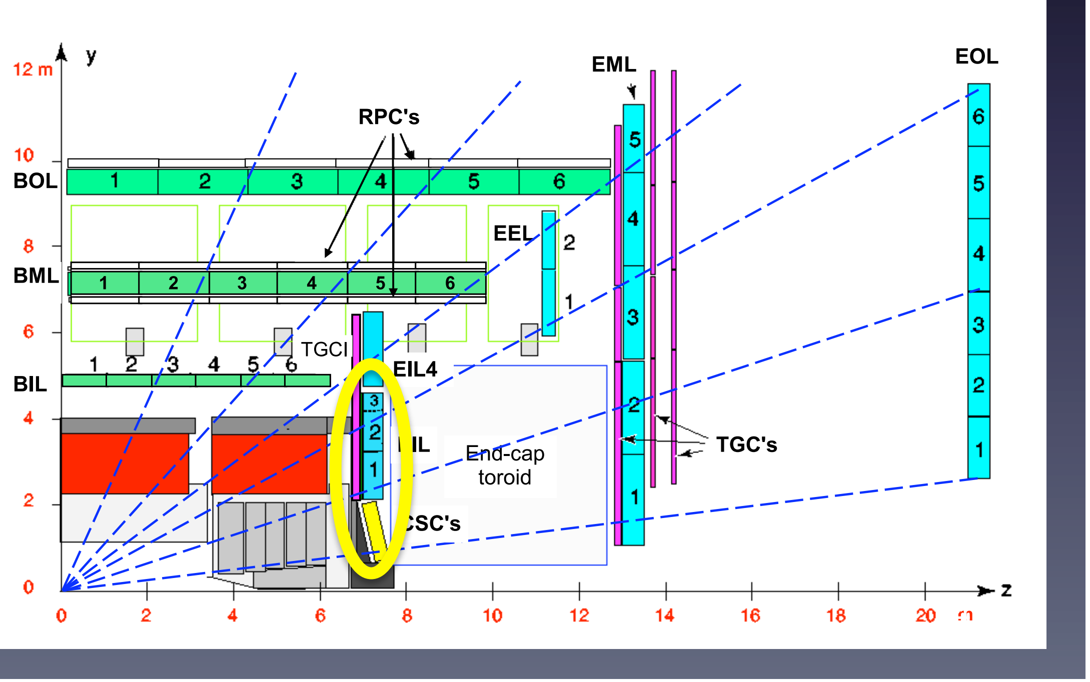
Forward (1.2<|η|<2.4) muon small wheel with improved trigger capability

- high rates in muon system from cavern background, especially in forward region
- aim to maintain high trigger efficiency for low Pt leptons w/o raising thresholds
- idea is to kill the fake trigger by requiring an IP pointing segment (< 1 mrad angular resolution) in small wheel
- equipped with precision tracker working up to the ultimate luminosity

L1 trigger rate with $p_t(\mu)$>20GeV

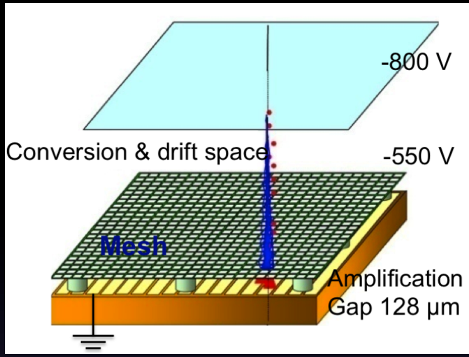






New Muon Small Wheels (NMSW)

Precision chambers combine sTGC and micromegas technologies for robustness to Phase-II luminosities



4+4 layers of MicroMegas (MM) for precision tracking

- planar drift electrode
- gas gap of a few mm thickness, acting as ionization and drift region
- thin metallic mesh at 128 μm distance from the read-out electrode
  → gas amplification region

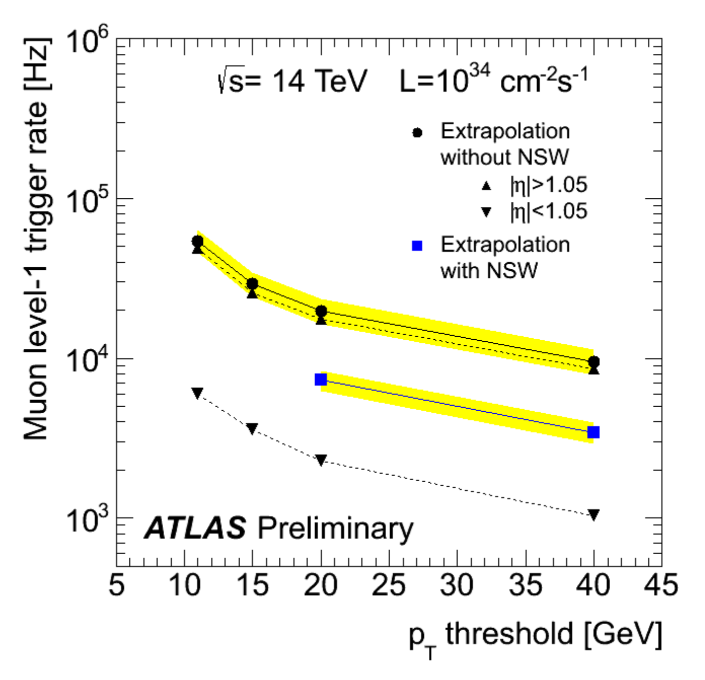
4+4 layers of Thin Gap Chambers (TGC) for trigger

- new version with reduced cathode resistivity for higher rate capabilities

- expected x3 reduction in trigger rate for pt(μ)>20 GeV at Level1 with NMSW at 10^{34} $cm^{-2}s^{-1}$

Acceptance for WH (W→μν) using single μ trigger
And corresponding trigger rates

Trigger	Efficiency (%)	Rate (kHz)
$p_T(\mu) > 20$ GeV	82	40
$p_T(\mu) > 40$ GeV	50	15
$p_T(\mu) > 20$ GeV with NSW	78	18

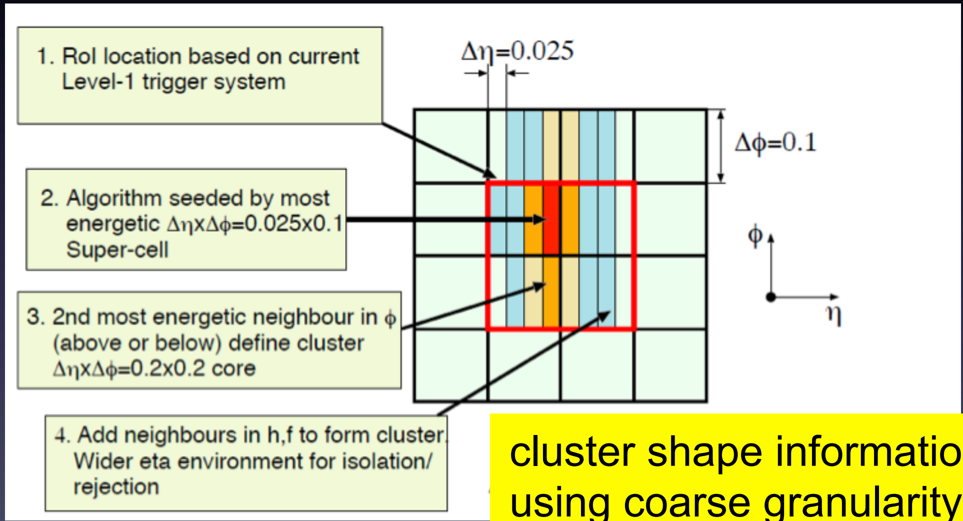


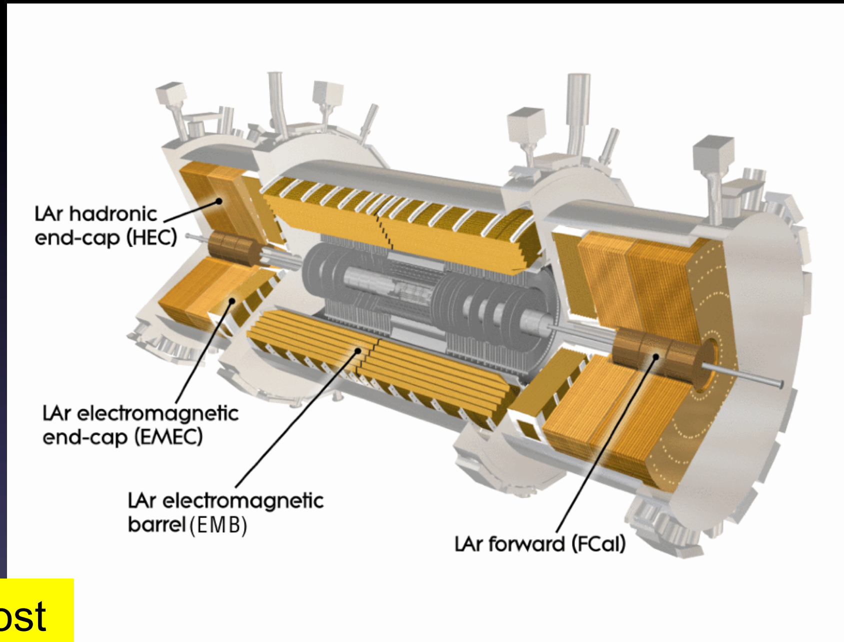
Calorimeter Level 1 Trigger

Goal: maintain high efficiency for Level-1 triggering on low PT objects (here electrons and photons)

The current Level 1 EM calorimeter trigger uses:

- E_t thresholds based on $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ trigger towers
- no fine grained EM sampling level info available at level1 trigger to compute shower shapes





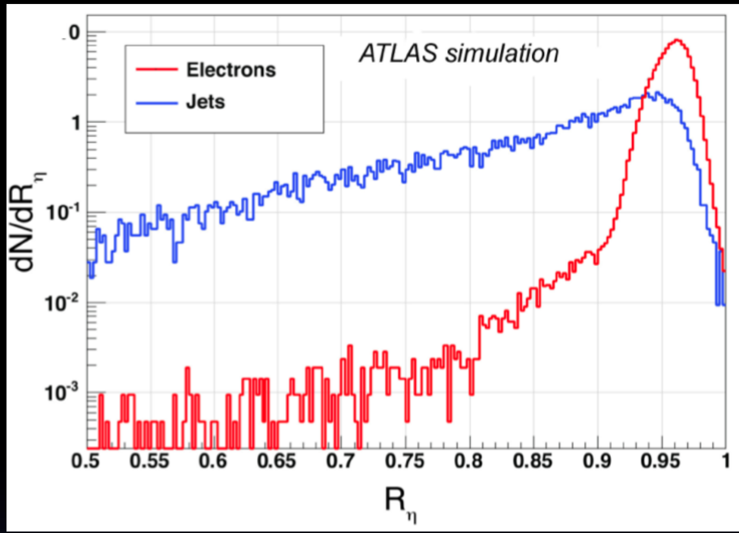
cluster shape information lost using coarse granularity

LAr calorimeter: changes to the front-end electronics to exploit finer granularity

- computation of lateral and longitudinal shower shapes
- preserve un-prescaled single electron triggers at E_t~25 GeV for LHC operation beyond the nominal design ($>10^{34} cm^{-2} s^{-1}$)

Calorimeter Level 1 Trigger

The use of shape cuts at Level 1 reduces trigger rates keeping high physics acceptance

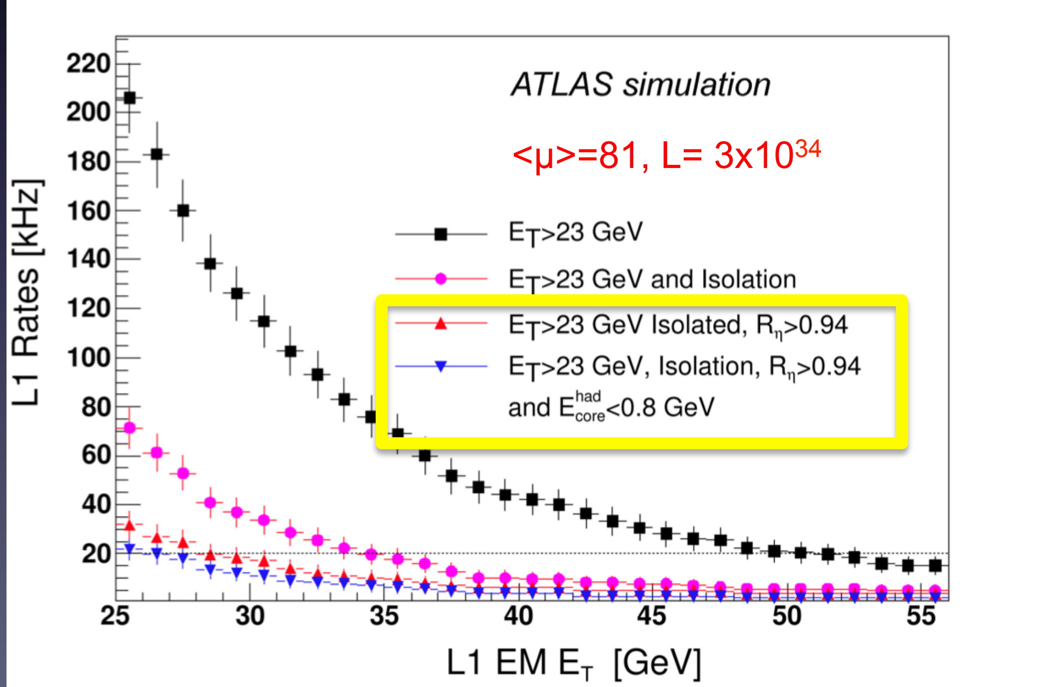


R_η parameter for electrons and jets defined as the ratio of the energy in the 3x2 over the energy in the 7x2 clusters of the 2nd layer of the EM calorimeter

Acceptance for WH using single e trigger and corresponding trigger rates

Level 1 trigger	Eff_{WH}(%)	Rate (kHz)
E_T (EM) > 35 GeV	73	54
E_T (EM) > 35 GeV and isolation	71	16
E_T (EM) > 35 GeV and isolation and shape cuts	71	6.5
E_T (EM) > 23 GeV and isolation and shape cuts	88	23

electron rate vs E_T threshold



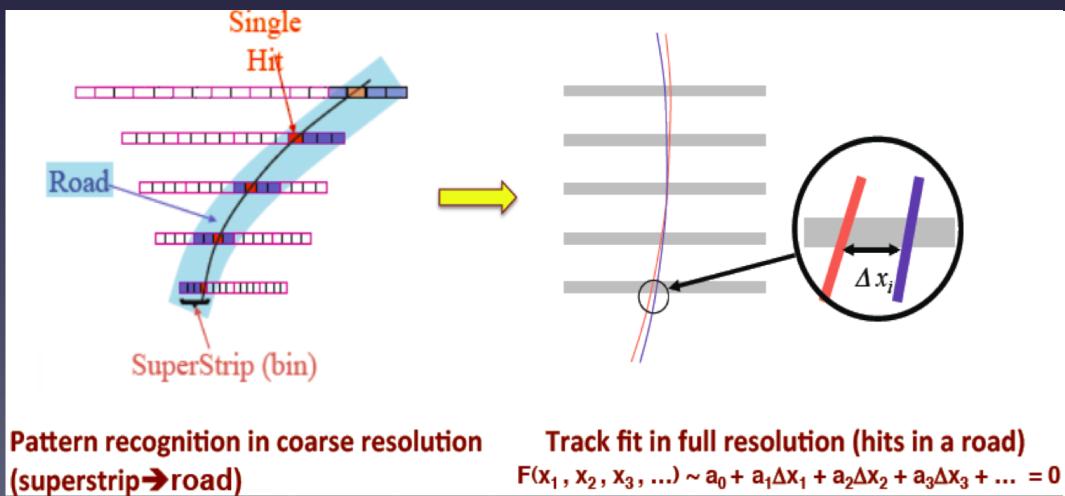
Fast Track Trigger (FTK)

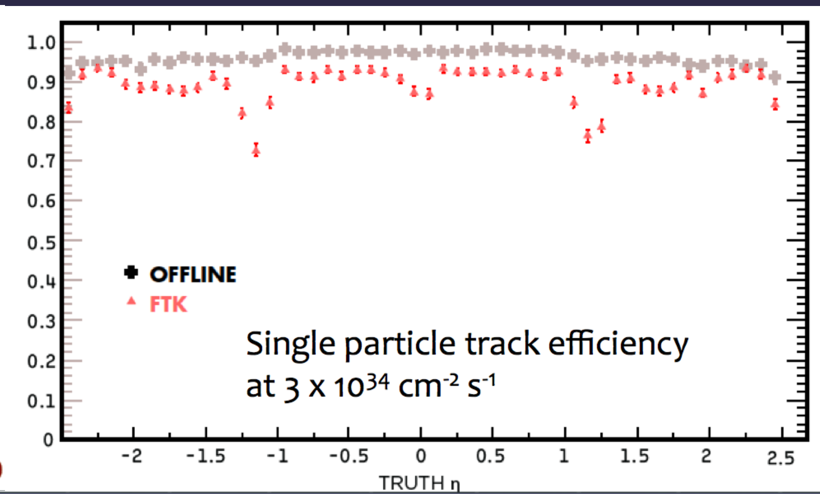
FTK provides a "Level 1.5" track trigger (~25μs) as input to Level 2 with track reconstruction with offline precision

- descendant from the CDF Silicon Vertex Trigger (SVT)
- input from Pixel (including IBL) and SCT
- data in parallel to normal read out
- allows improved object identification using track matching, lepton isolation, vertexing, b-tagging and τ-reconstruction

two steps process:

1) real hit patterns matches to 10^9 pre-stored patterns in associative memory
2) subsequent linear fitting in FPGAs, yelding precise track information





Phase-II: 2021/2022 (LS3)

18 months shutdown

LHC

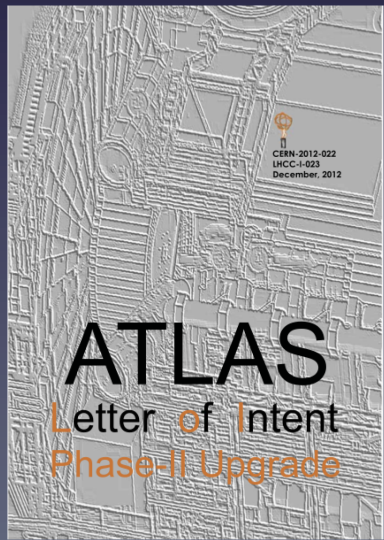
- prepare for luminosity leveling
- peak luminosity $5x10^{34}cm^{-2}s^{-1}$ (leveled), considered up to $7x10^{34}cm^{-2}s^{-1}$ (<μ>=200) for safety
  → 3000 fb^{-1} @ 14TeV

ATLAS

detector upgrade

- replacement of the entire Inner Detector
- LAr and Tile calorimeter electronics upgrades
- possible upgrade of Forward Calorimeters
- upgrade of Muon system
  - Muon Barrel and Large Wheel trigger electronics
  - possible upgrades of TGCs in Inner Big Wheels
- forward detector upgrade
- Target Absorber Secondaries (TAS) and shielding upgrade
- implementation of L1 track trigger
- TDAQ upgrade
- software and computing
- various infrastructure upgrades
- common activities (installation, safety, …)

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

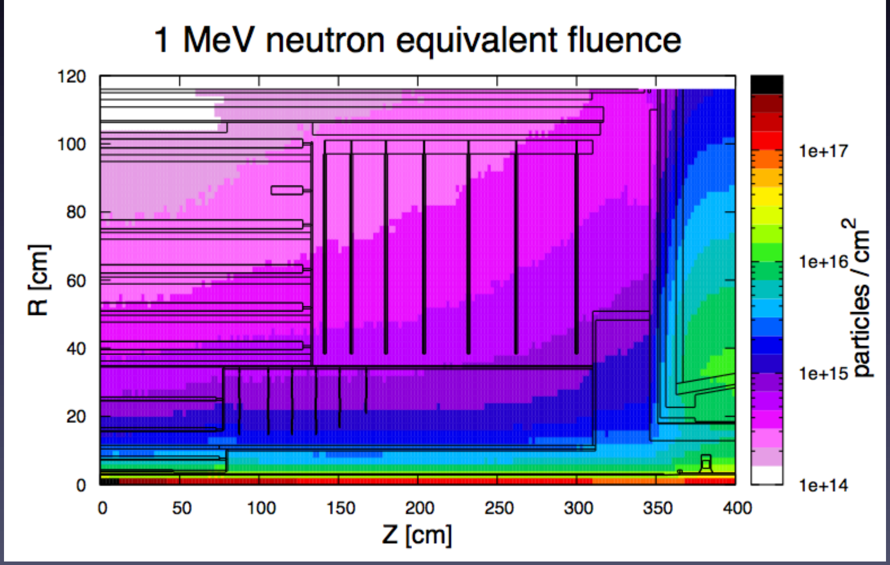


Inner Tracker for HL-LHC

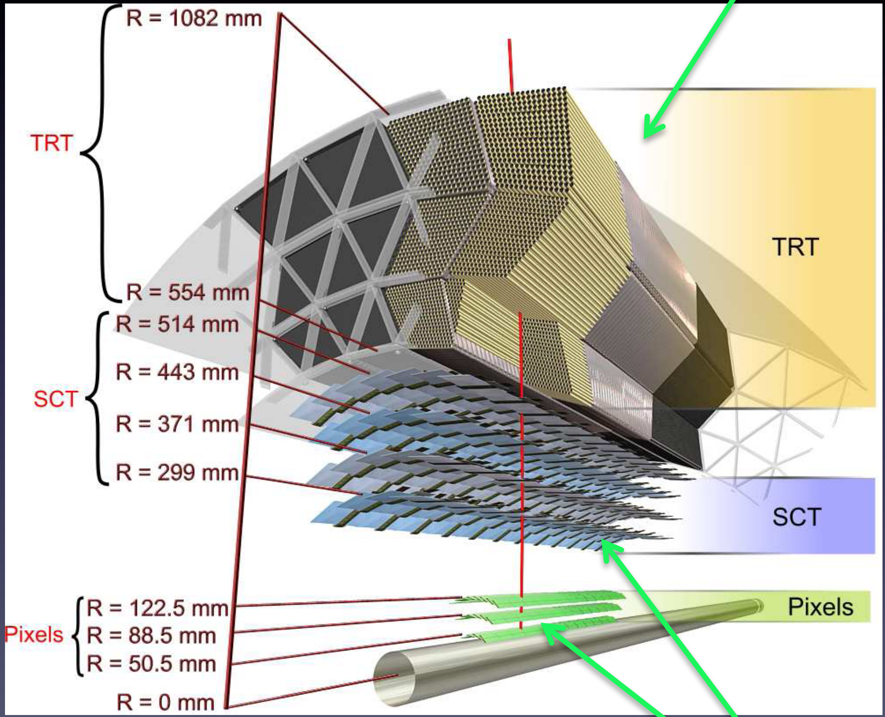
Limitations of the current ID (detector designed for $1x10^{34}$ / 700 fb^{-1}):

- radiation damage
  - increased leakage currents and deteriorating performances at $5x10^{34} cm^{-2} s^{-1}$
- bandwidth saturation
- occupancies

expected fluence at 14 TeV (3000 fb^{-1})



occupancy in the TRT tubes ~ 50 %
several % in strips

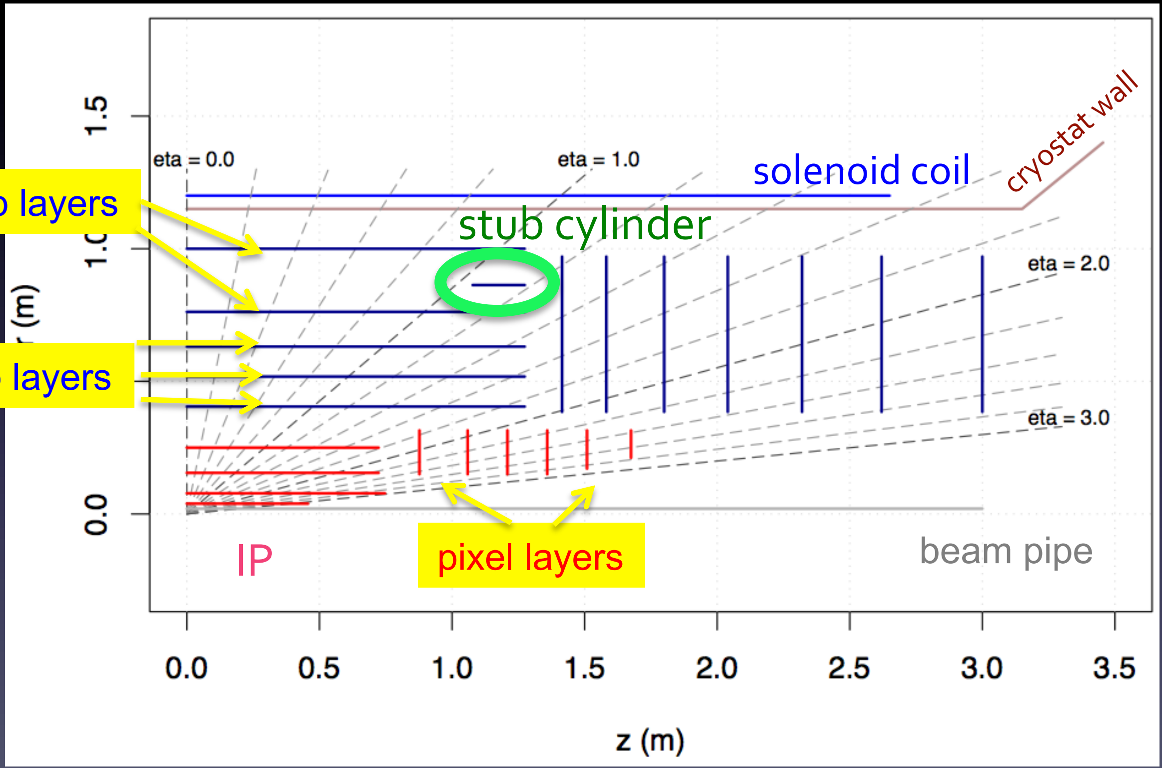


data rates in several layers beyond readout capacity

Inner Tracker for HL-LHC

Classical layout with barrel cylinders and endcap disks

- optimizes use of the available space, within engineering constraints
- used to establish baseline performance and cost
- no special triggering layers



Strips (74M channels)

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

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 technology

total of 14 hits with full coverage to η=2.5

- Pixels to η<2.7 (forward muon ID)

minimize gaps in coverage

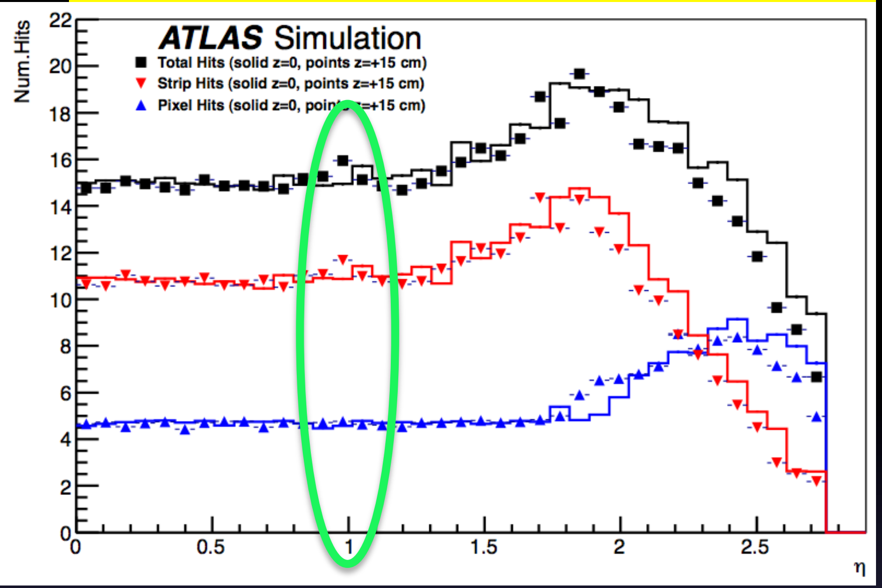
- last strip disk at z=3m, last pixel layer at 25-30cm (improve double track resolution)
- small "stub" layer in barrel

Inner Tracker for HL-LHC

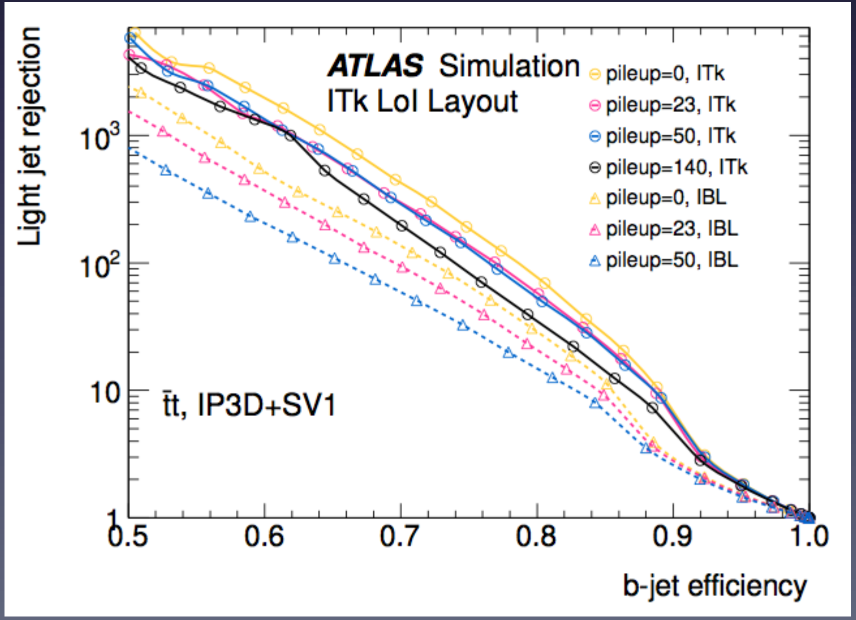
- maximize coverage uniformity
  barrel-endcap region hit coverage
  → stub cylinder

- good momentum resolution across whole η range

hits on muon tracks with pt>5 GeV vs η



the tracker re-design will mitigate the effects of increased pile-up



<μ> = 140 → btagging performance of LoI layout is better than ATLAS+IBL layout (Phase 0) with no pile-up

L1 Trigger

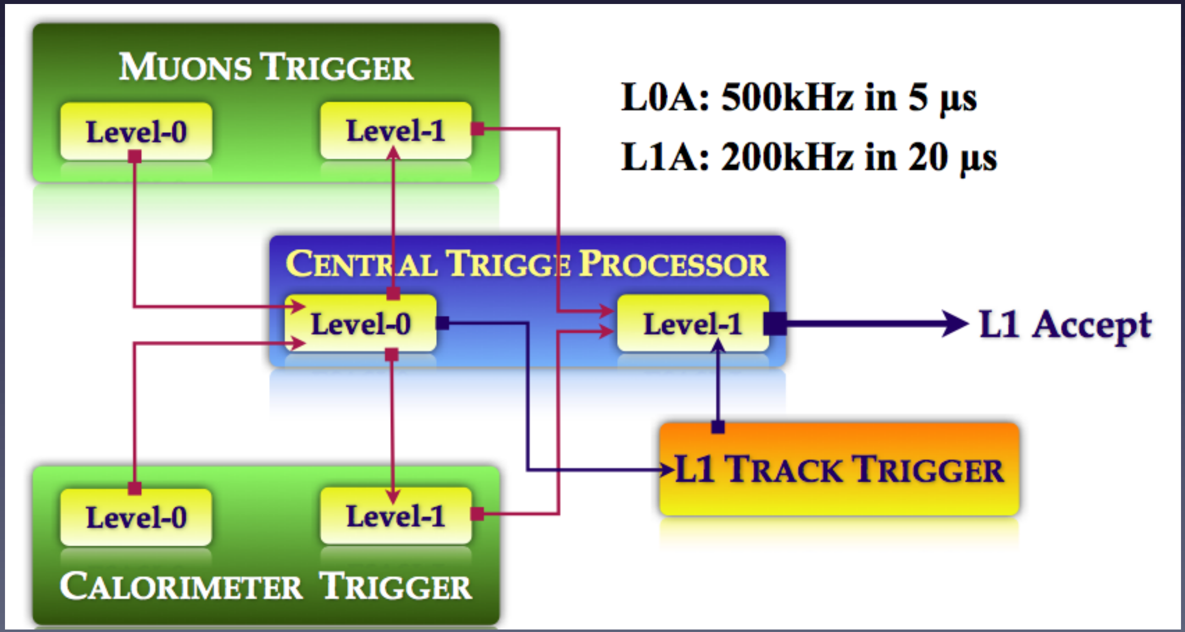
L1 Track Trigger: introduce inner tracker into L1 trigger to improve selectivity

potential great benefit adding tracking information

- reduce single lepton trigger rates combining Inner Tracker info with:
  - MUON: after nMSW in Phase-I → precision chambers info in the trigger
  - CALO: possible use of detectors full granularity at L1 in Phase-II
- can improve τ-identification and b-tagging

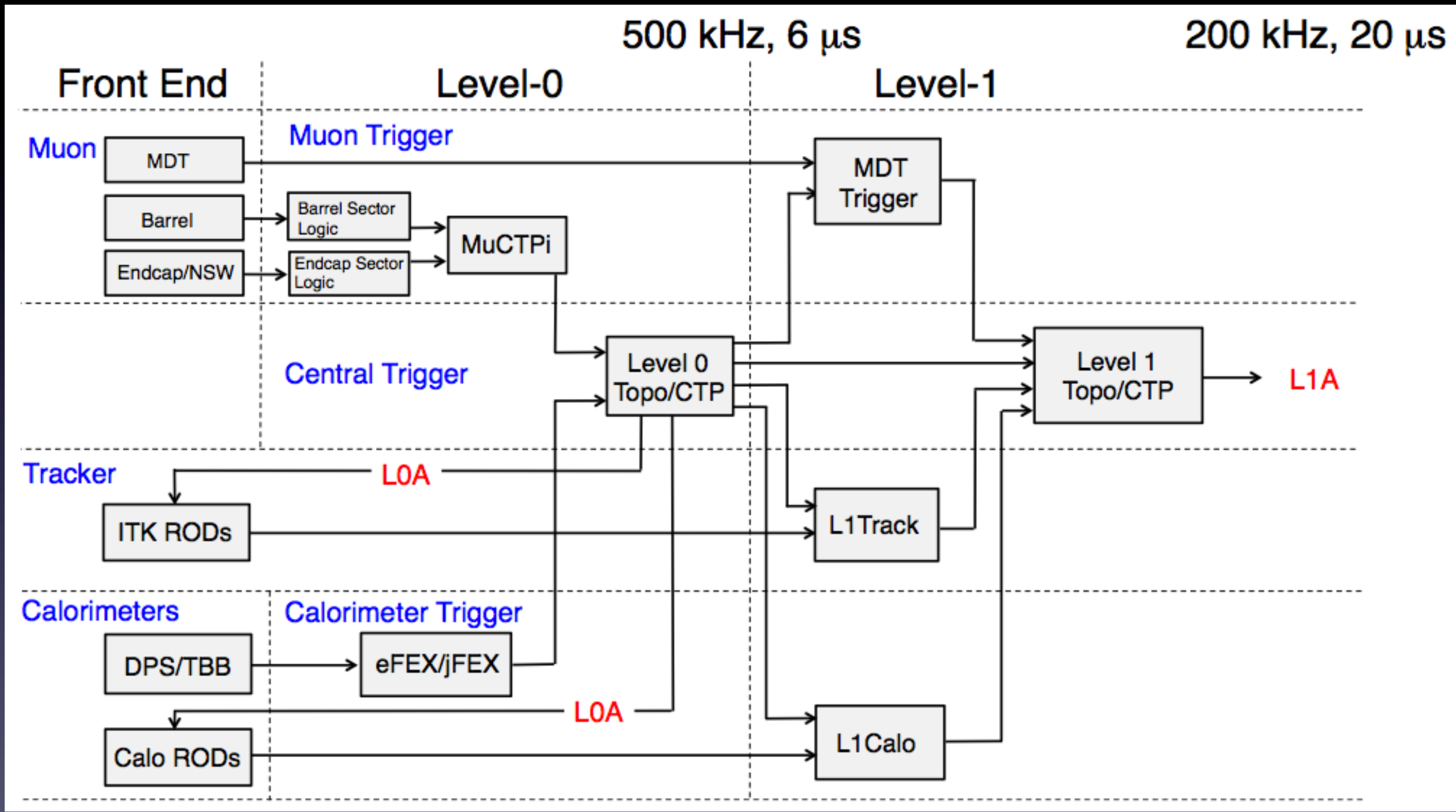
.. but it introduces complexity and needs longer processing time

- increase the Level-1 latency (~20 μs)
- present single-stage L1 trigger scheme could evolve into a 2-level trigger



TDAQ

Redesign of Trigger/TDAQ layout to cope with high rates and latencies at $5x10^{34}cm^{-2}s^{-1}$
low P_T lepton trigger thresholds → essential for maximizing physics acceptance



Summary

ATLAS is actively pursuing a series of upgrades to ensure continued detector efficiency and consequently optimal physics acceptance with increasing luminosity

- additional Pixel layer and other detector consolidation during this shutdown (2013/1014)
- major upgrades to improve Trigger capabilities during Phase-I shutdown (2018)
- replacement of the Inner Tracker, Forward Calorimeter, Electronics and Trigger/DAQ during the Phase-II shutdown (2022)

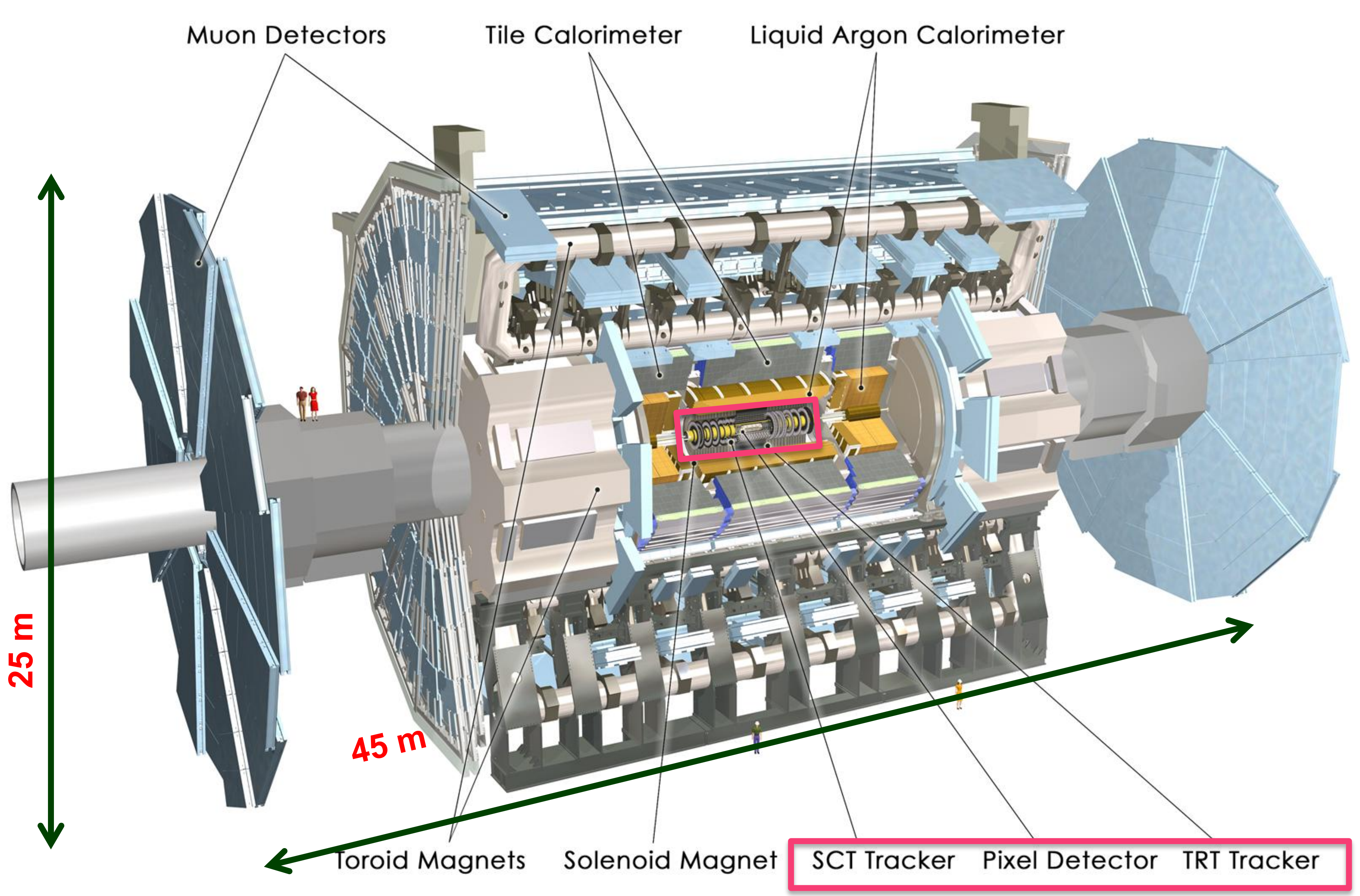
Graduated upgrade program to build on experience to improve our detector and equip it to run at up to 5 times the design luminosity ($5x10^{34}cm^{-2}s^{-1}$)

These upgrades are essential to exploit the Physics potential at the LHC

- to preserve performance while luminosity increases
- in several cases we can improve / extend the performance

backup

The ATLAS detector

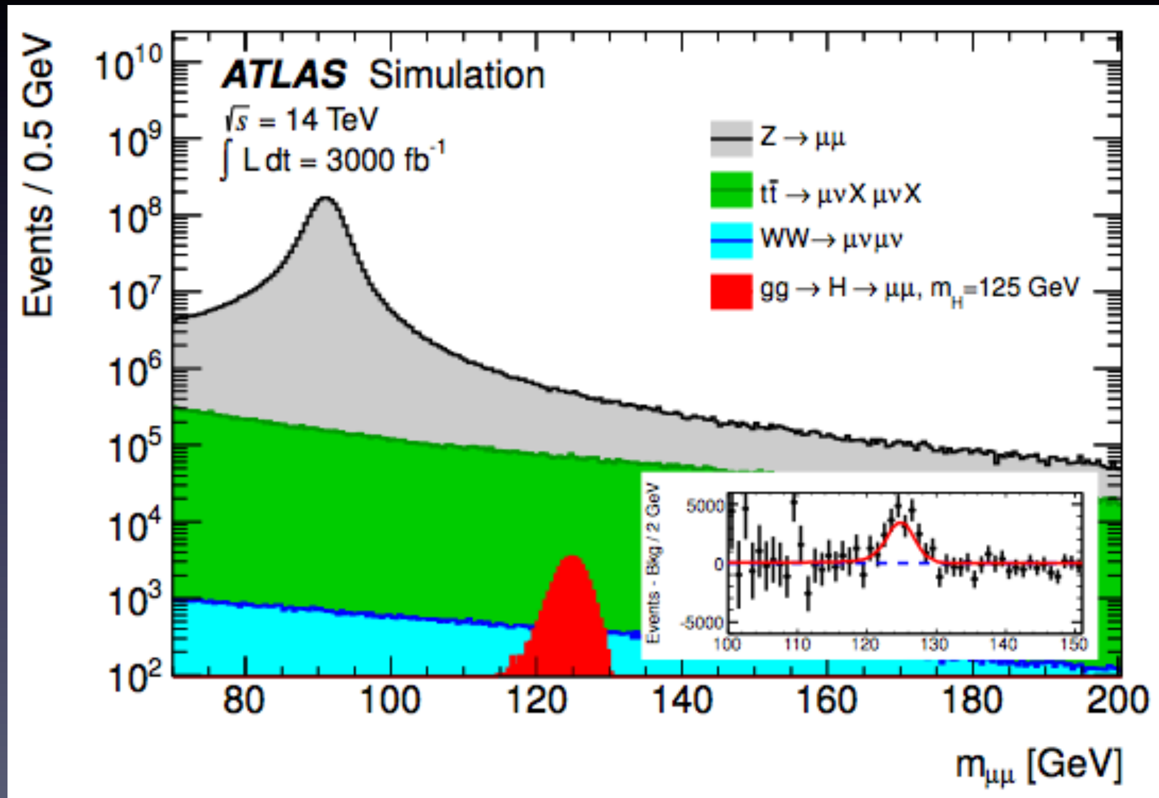


Precision measurements of Higgs couplings

final states targeted to measure couplings (that have low signal rate at LHC):

H→ μμ

- S/B ~0.2%
- 6σ signal significance with 3000 fb^{-1}

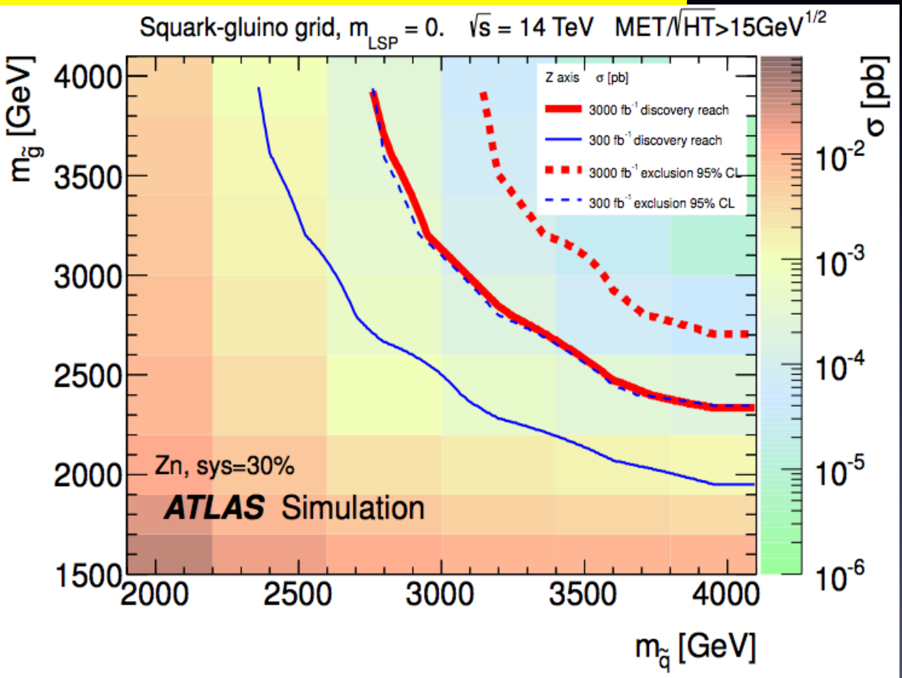


Searches for New Physics

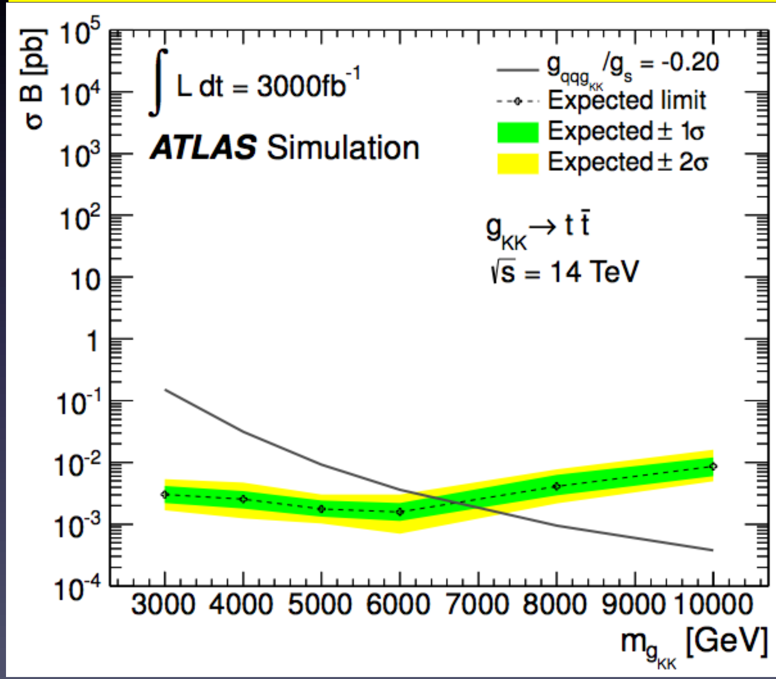
Unique opportunity at LHC to extend the reach for New Physics searches beyond the SM

… and in the event of discovery → precision measurements characterizing its properties

95% exclusion limits in $m_{\tilde{g}}$-$m_{\tilde{q}}$ grid assuming m_{LSP} = 0 with 3000 fb^{-1}



search for ttbar resonances from g_{KK}→ttbar
→limits extended to ~7 TeV with 3000 fb^{-1}



SM still not sufficient to explain the Higgs mass: there should be something else beyond SM…

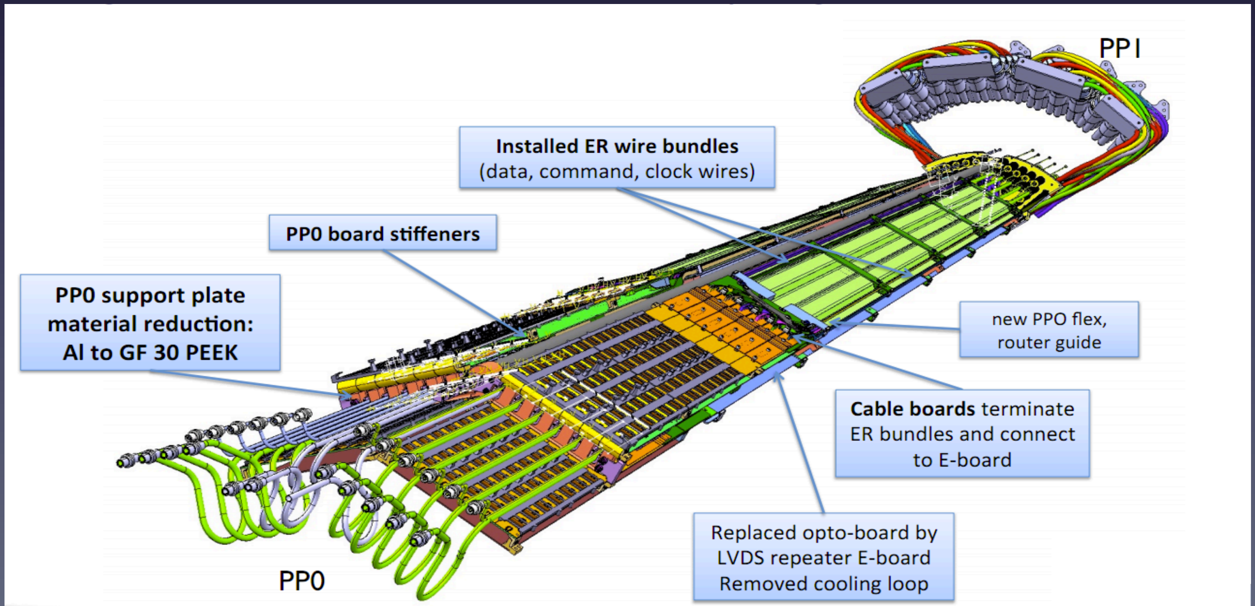
Further Pixels upgrades

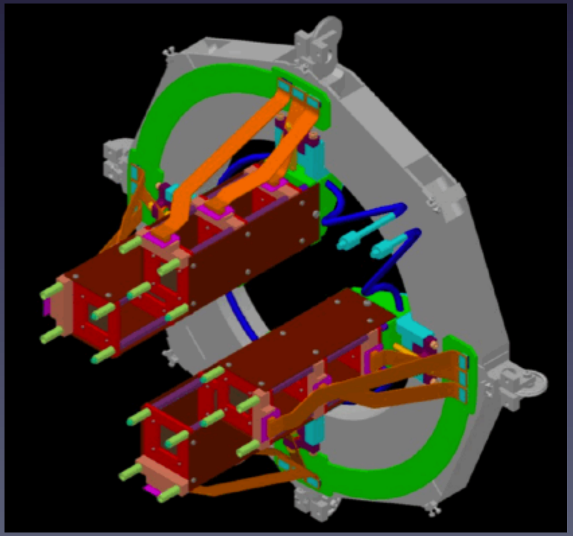
nSQP will replace current Pixel services (project was fully approved last January)

- 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)
- redundant and safer location for fibers transmitters
- material transparency optimization
- doubling of the readout bandwidth in view of $L_p = 2 \times 10^{34}\ cm^{-2}s^{-1}$

Diamond Beam Monitor attached to nSQP

- uses diamond detectors produced for IBL trials
- will provide very fast monitoring of beam in high rate environment

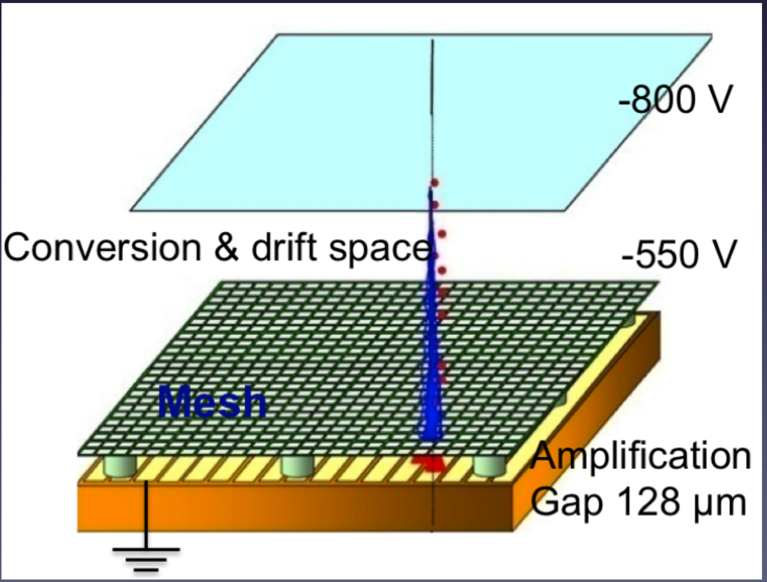


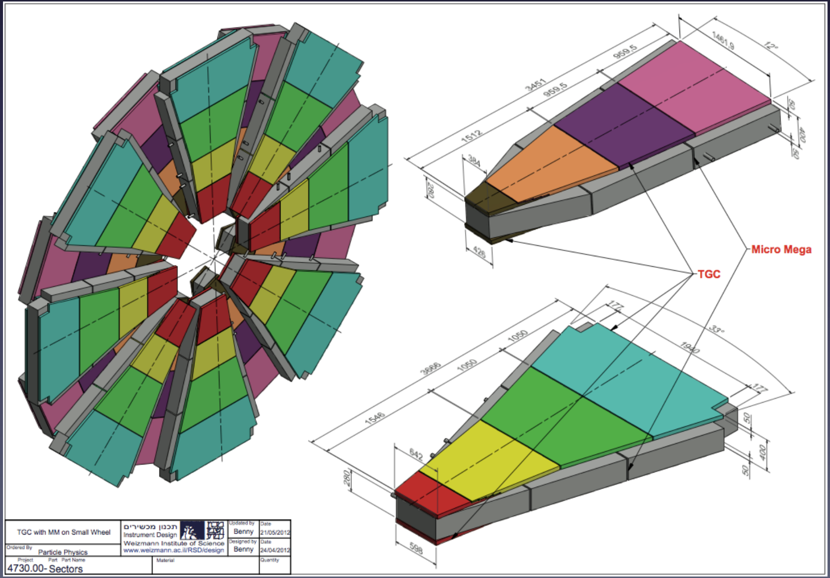


NMSW technology

Precision chambers combine sTGC and micromegas technologies for robustness to Phase-II luminosities

- 4+4 layers of MicroMegas (MM) for precision tracking
  - planar drift electrode
  - gas gap of a few mm thickness, acting as ionization and drift region
  - thin metallic mesh at 128 μm distance from the read-out electrode
    → gas amplification region
- 4+4 layers of Thin Gap Chambers (TGC) for trigger
  - new version with reduced cathode resistivity for higher rate capabilities



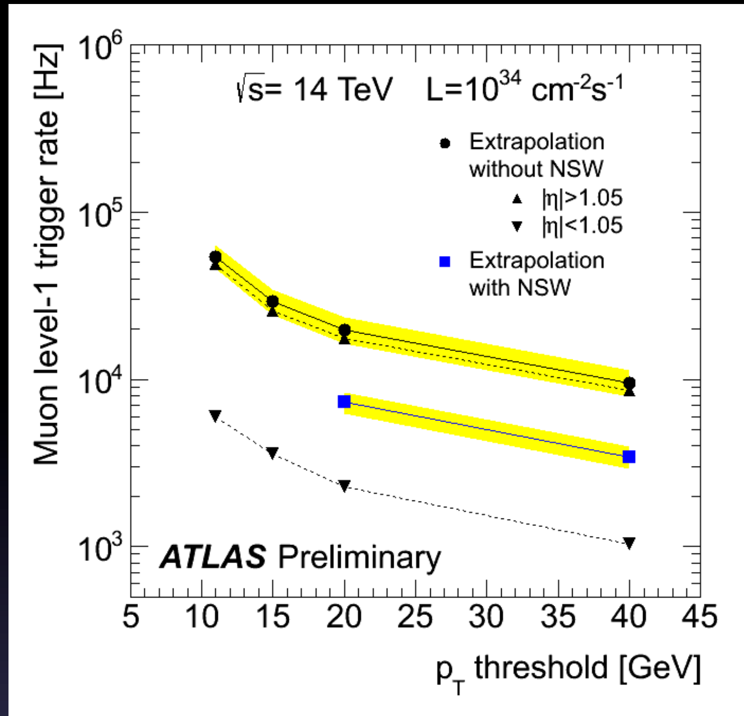


New Muon Small Wheels (NMSW)

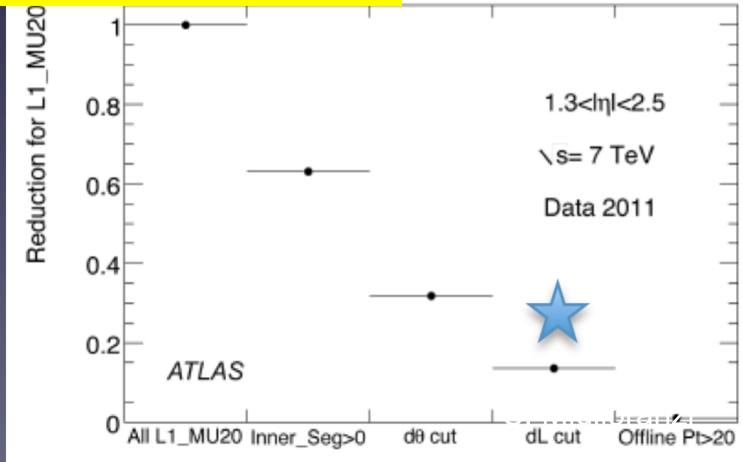
- expected x3 reduction in trigger rate for pt(μ)>20 GeV at Level1 with NMSW at 10^{34} $cm^{-2}s^{-1}$

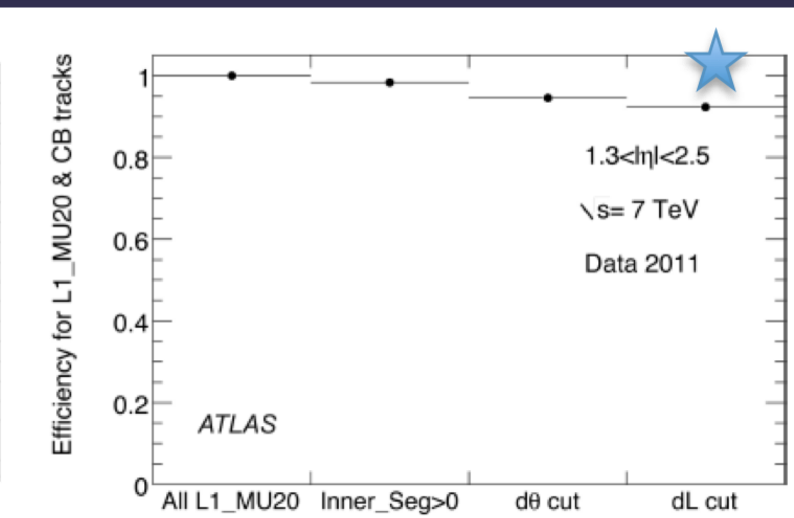
Acceptance for WH (W→μν) using single μ trigger
And corresponding trigger rates

Trigger	Efficiency (%)	Rate (kHz)
$p_T(\mu) > 20$ GeV	82	40
$p_T(\mu) > 40$ GeV	50	15
$p_T(\mu) > 20$ GeV with NSW	78	18



nMSW segment matches in (η−φ) to the triggering segment ★
→ order of magnitude rate reduction





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

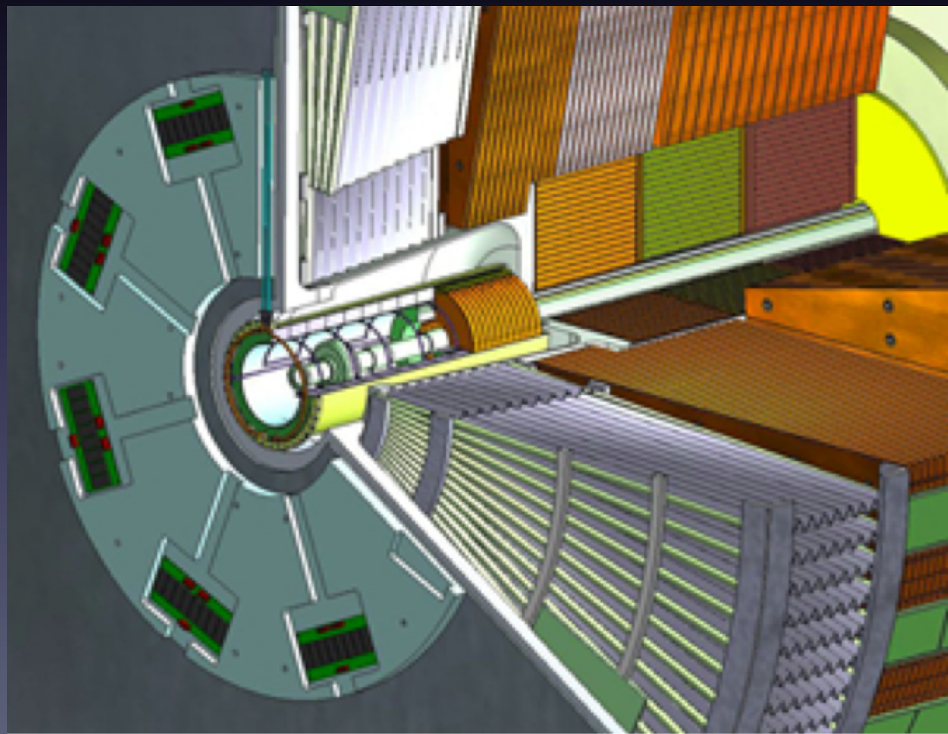
Current Forward Calorimeter ($3.2<|\eta|<4.9$) not designed for $L>10^{34} cm^{-2} s^{-1}$

- 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



S. Miglioranzi

TDAQ Phase-I Upgrade

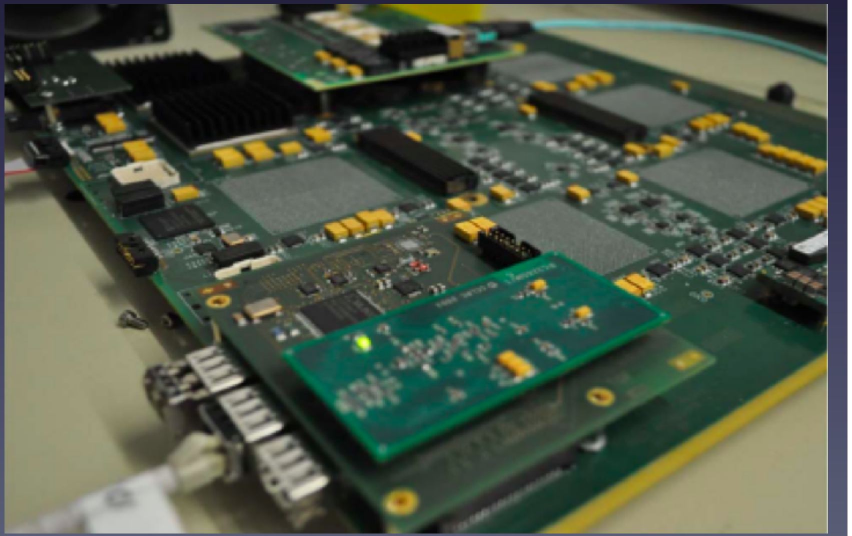
The current L1 trigger has been running extremely efficiently – however it is approaching its design limit (10^{34})

L1 Topological processor

- new topological event selection capability
- FPGAs based implementation
- Inputs:
  - pre-Phase-I : L1 Calo + L1 Muon coarse granularity info
  - Phase-I : data from new L1 Calo digital processor
    + full granularity info from upgraded L1 Muon

Central Trigger Processor (CTP)

- increased number of inputs: 160 → 512
- Increased of trigger items
  (combination, flexibility) : 256 → 512



HLT bandwidth

- increased number of nodes and connectivity