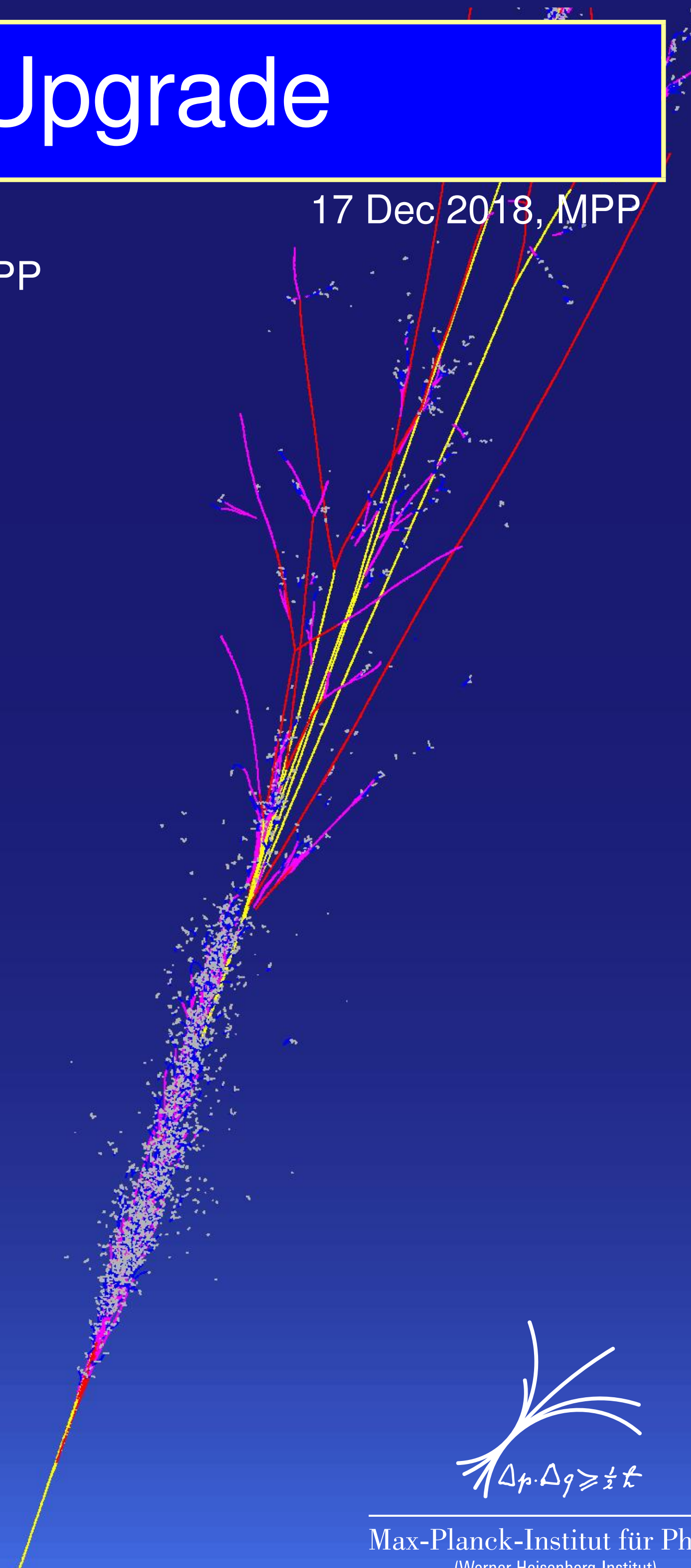
ATLAS Operation & Upgrade

MPP Project Review Sven Menke, MPP München 17 Dec 2018, MPP

on behalf of the ATLAS Group @MPP

- Introduction
- Operation
- Upgrade for HL-LHC
  - Physics motivation
  - Radiation backgrounds
  - Inner tracker
  - Liquid argon calorimeters
  - Muon system
- Summary & Outlook



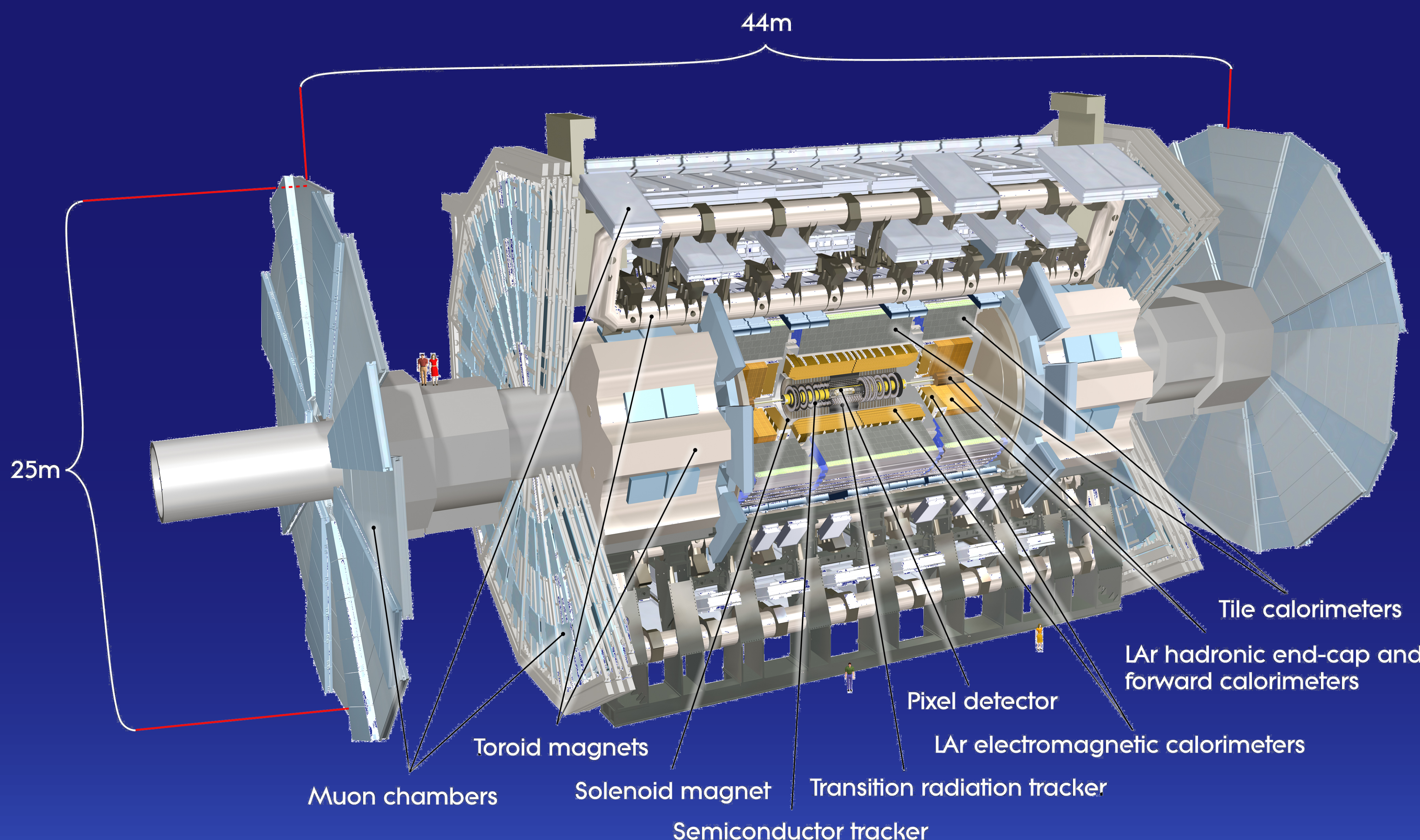
ATLAS EXPERIMENT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Denis Salihagic (1965-2018)

In memory of our dear colleague and friend Denis Salihagic who passed away after long illness on April 2nd 2018

ATLAS



A Toroidal LHC ApparatuS

about 3000 scientific authors from 181 institutions around the world, representing 38 countries from all the world's populated continents

Siggi Bethke (Director)

Muons

Staff
- Hubert Kroha (Project Leader)
- Sandra Kortner (Project Leader, Independent Research Group)
- Oliver Kortner

Active Retiree
- Robert Richter

Post-Docs
- Davide Cieri
- Dominik Duda
- Patrick Rieck
- Zinonas Zinonos

PhD Students
- Katharina Ecker
- Philipp Gadow
- Andreas Hönle
- Johannes Junggeburth
- Dominik Krauss
- Nicolas Köhler
- Stefan Maschek
- Rainer Röhrig
- Korbinian Schmidt-Sommerfeld
- Verena Walbrecht

Master Students
- Catriona Bruce, Šejla Hadžić, Maximilian Klinke, Marian Rendel, Patrick Selle, Maxim Sinner, Makoto Teshima

Bachelor Students
- Florian Henkes, Iris Hydi, Rabea Klaar, Ivan Popov, Nicole Schermer, Justin Skorupa

Calorimetry

Staff
- Sven Menke (Project Leader)
- Teresa Barillari
- Andrey Kiryunin
- Denis Salihagic†

Active Retiree
- Peter Schacht

Post-Docs
- Tom McCarthy
- Margherita Spalla

Inner Detector

Staff
- Richard Nisius (Project Leader)

Post-Docs
- Alessandro LaRosa
- Anna Macchiolo
- Ben Pearson

PhD Students
- Julien Beyer
- Natasha Savić

Master Students
- Meghranjana Chatterjee

Bachelor Students
- Nicolas Baron Perez, Abishek Chikkaballi Ramalingegowda

Computing

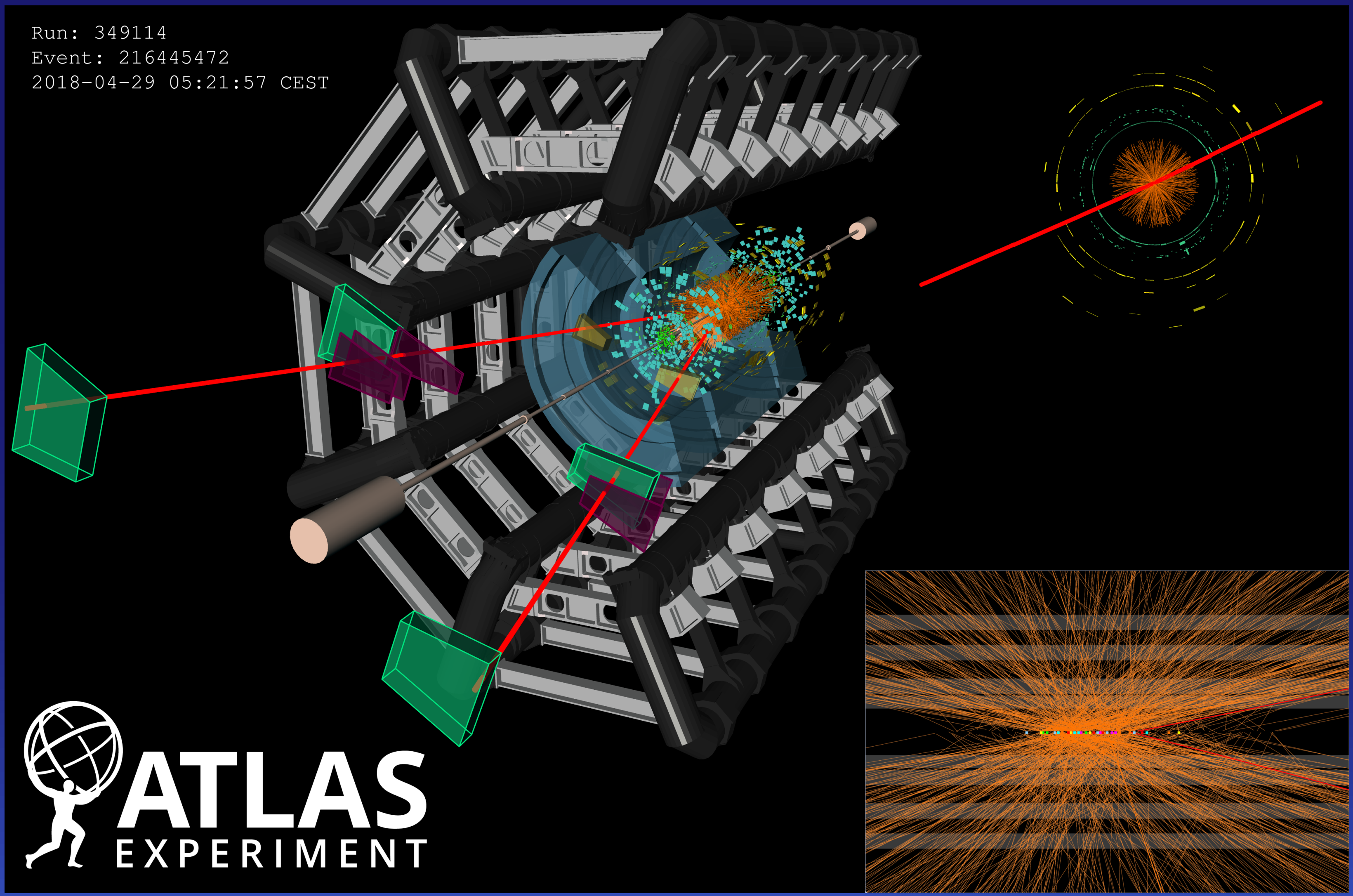
Staff
- Stefan Kluth (Project Leader)
- Stefan Stonjek

Post-Docs
- Daniel Britzger
- Cesare Delle Fratte
- Sergio Tafula
- Andrii Verbytskyi

PhD Students
- Ludovic Scyboz

Operation

- LHC: pp collisions @ $\sqrt{s} = 13\,\text{TeV}$ in 2018
- PbPb collisions @ $\sqrt{s_{\text{NN}}} = 5\,\text{TeV}$ in 2018 with lower luminosity



ATLAS event display from April 2018 with $Z^0 \to \mu^+\mu^-$ candidate ($m_{\mu\mu} = 92.3\,\text{GeV}$) and 28 additional vertices (~ 60 additional pp interactions)

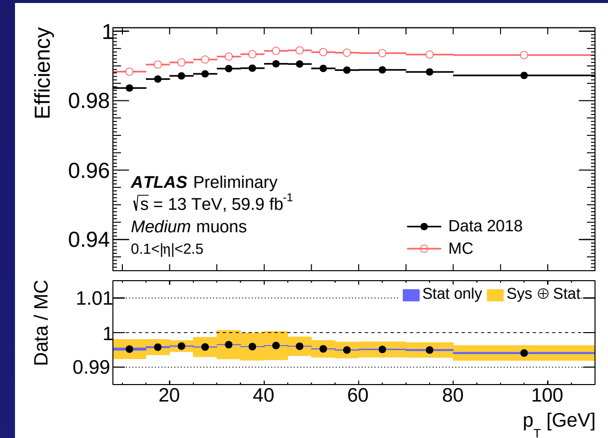
Operation

- ATLAS recorded integrated luminosity $61.7\,\text{fb}^{-1}$ in 2018 @ $\sqrt{s} = 13\,\text{TeV}$

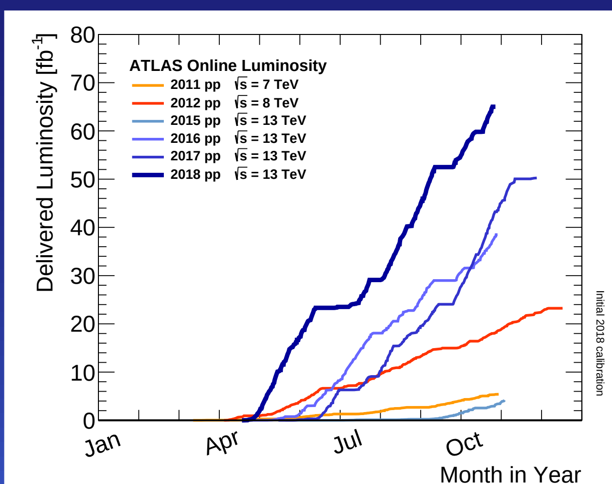
Overall efficiency

ATLAS pp data: April 25-October 24 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.8	100	99.7	100	99.8	99.7	100	100	100	99.6
Good for physics: 97.5% (60.1 fb^{-1})										

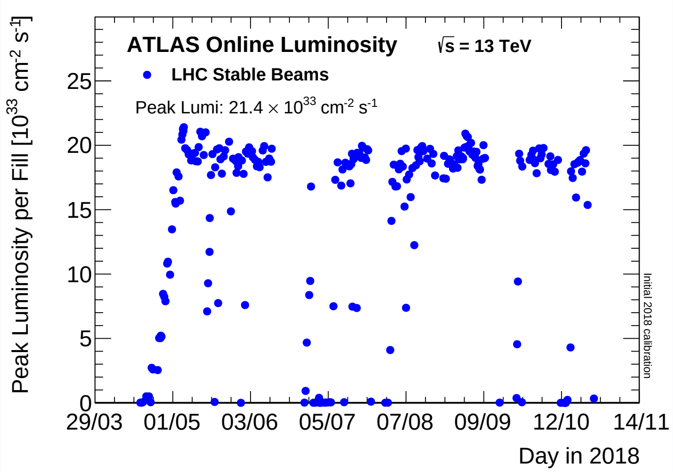
Muon reconstruction efficiency



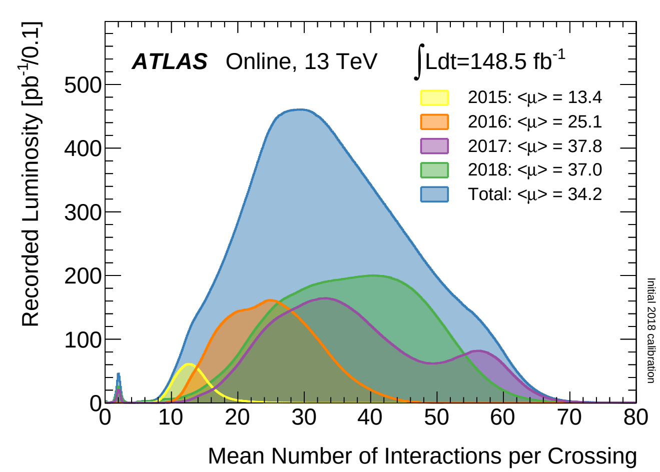
Integrated luminosity



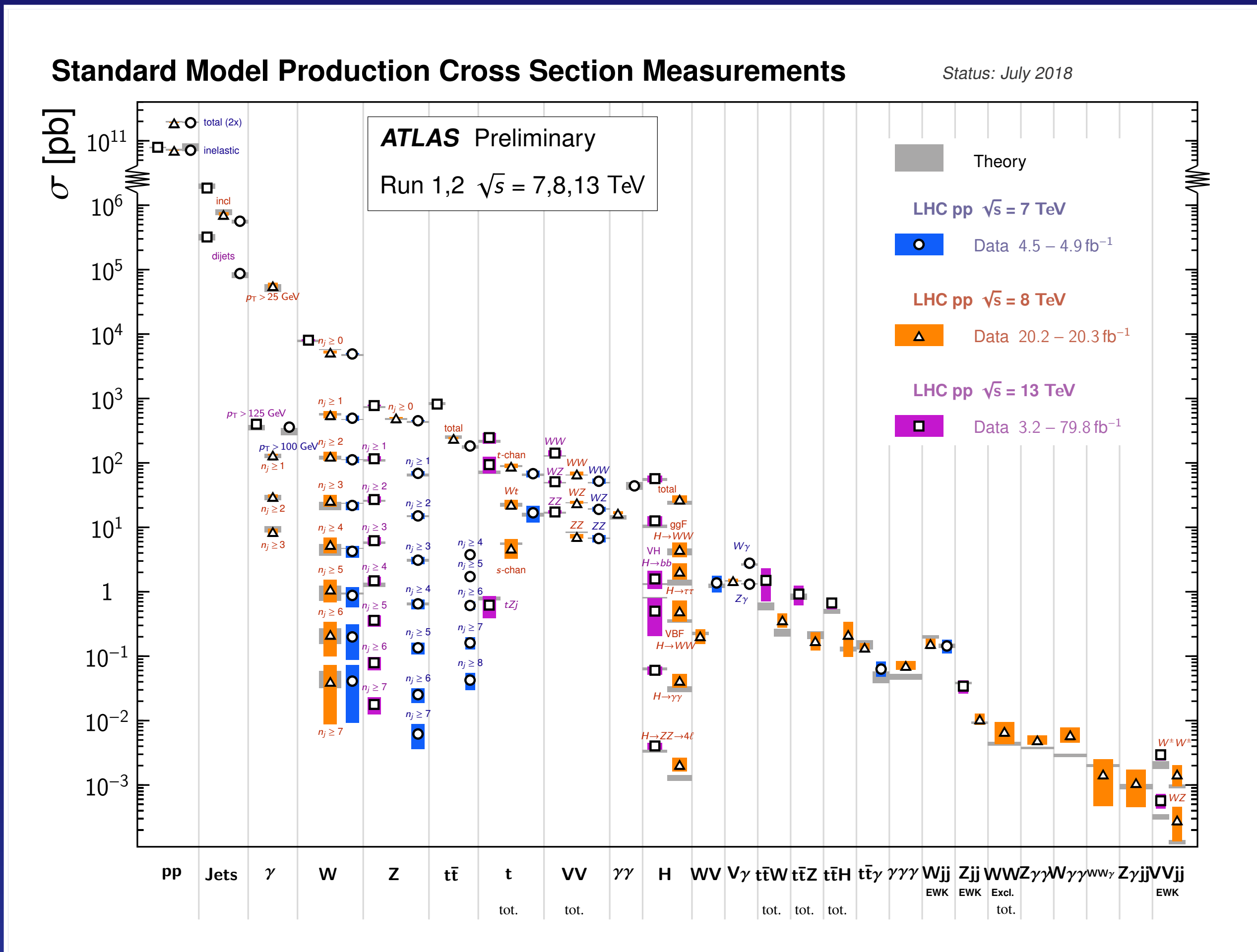
Peak luminosity



Number of interactions per crossing

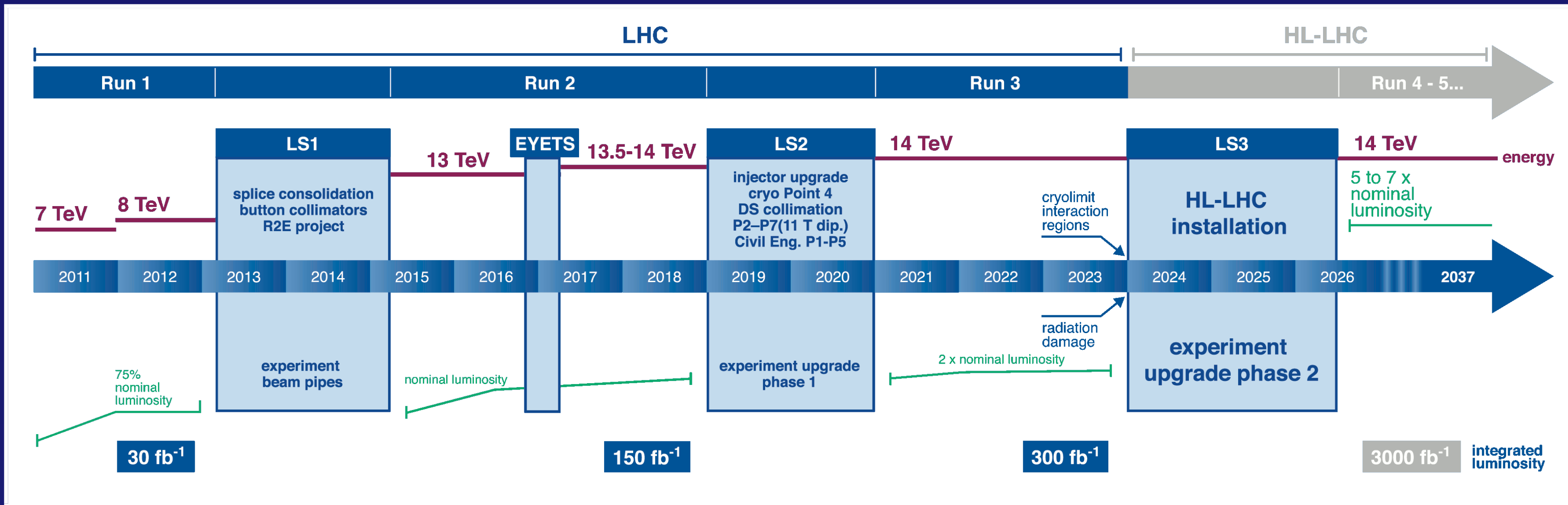


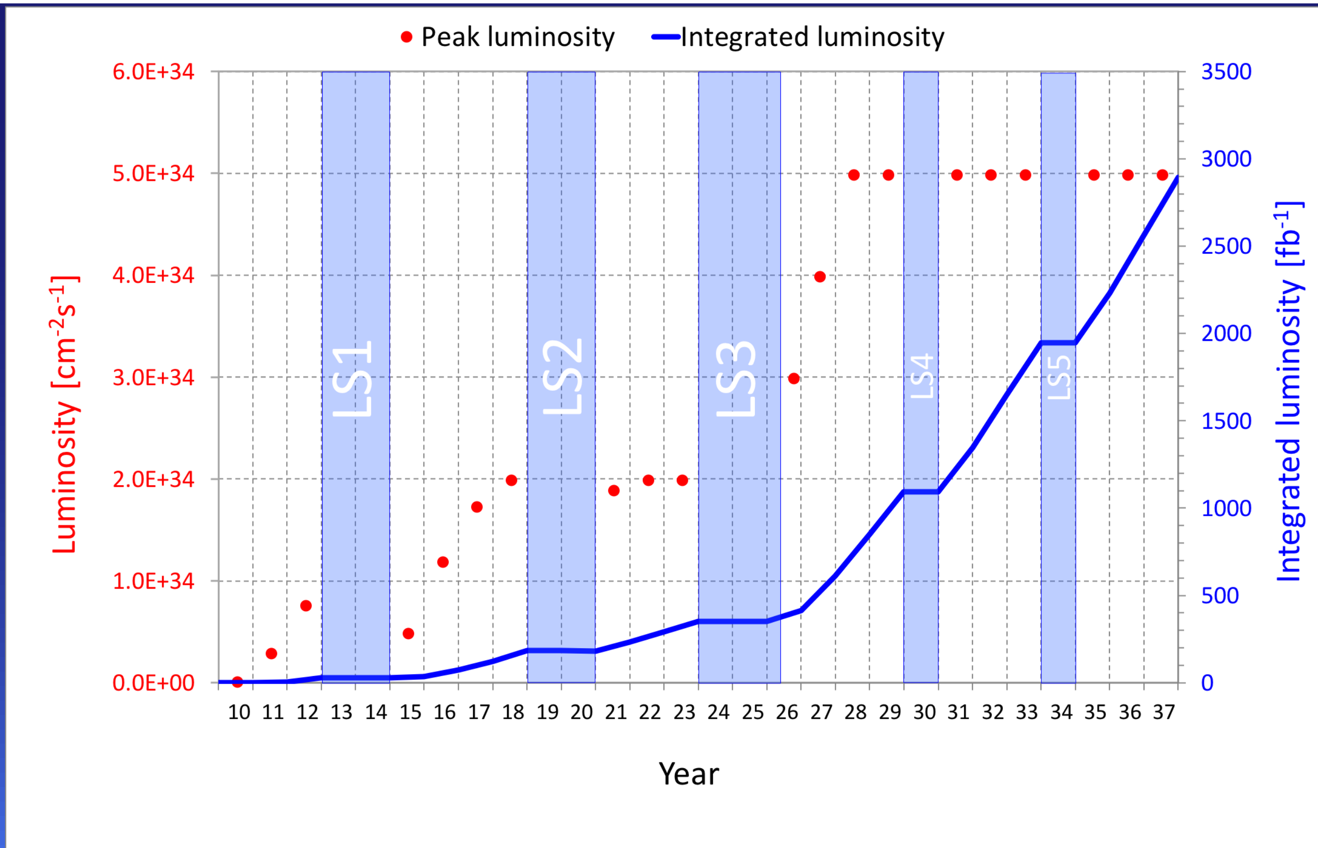
Physics ► Measurements/Searches so far

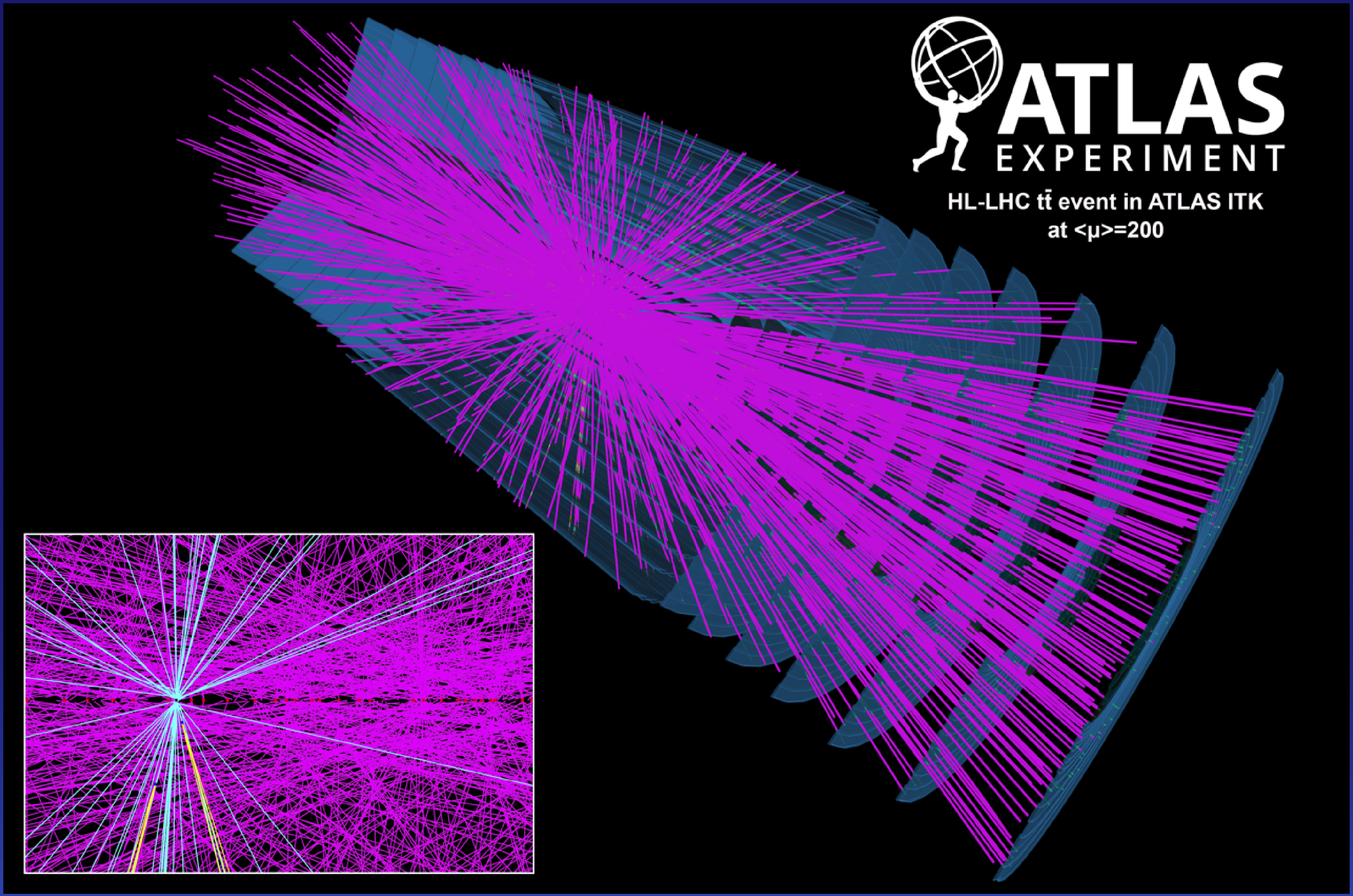


- ► Cross-section measurements down to $\sim 0.5\,\mathrm{fb}$ (left) as examples for ATLAS achievements so far
- ► Discovery of the Higgs-Boson, Measurements of Higgs-boson mass and decay channels
- ► Precision top-quark ($\Delta_m < 500\,\mathrm{MeV}$) and W-boson ($\Delta_m = 19\,\mathrm{MeV}$) mass-measurements
- ► $O(1 - 2\,\mathrm{TeV})$ mass-limits in SUSY searches
- ► Searches for dark-matter and exotic physics beyond the standard model
- ► See presentation on ATLAS physics results by Tom McCarthy

Upgrade ► Road-map to the HL-LHC



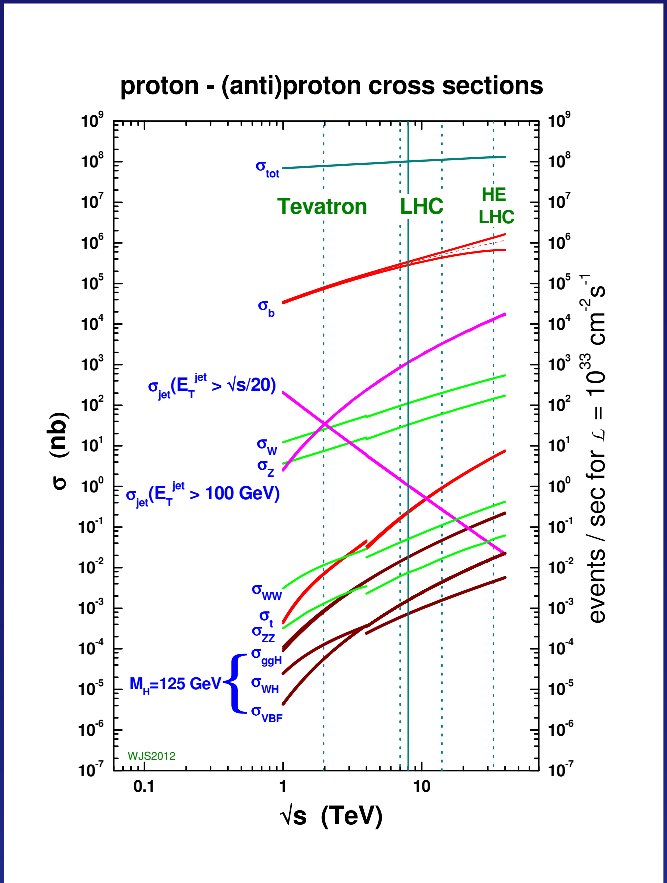


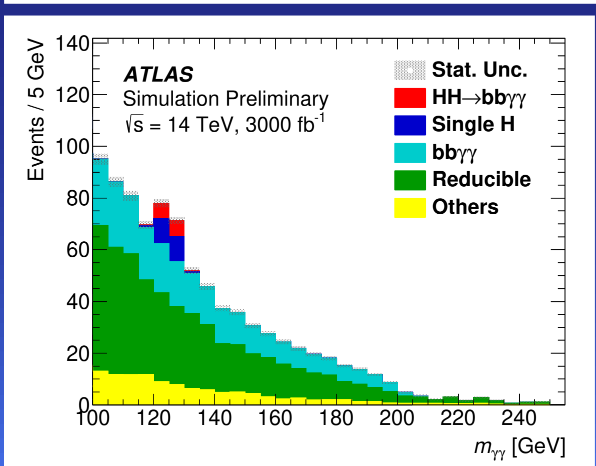


Simulated ATLAS event display at $\sqrt{s} = 14\,\text{TeV}$ with $t\bar{t}$-production (cyan), 2 secondary vertices (yellow) and ~ 200 additional pp-interactions (purple) in the Inner Tracker

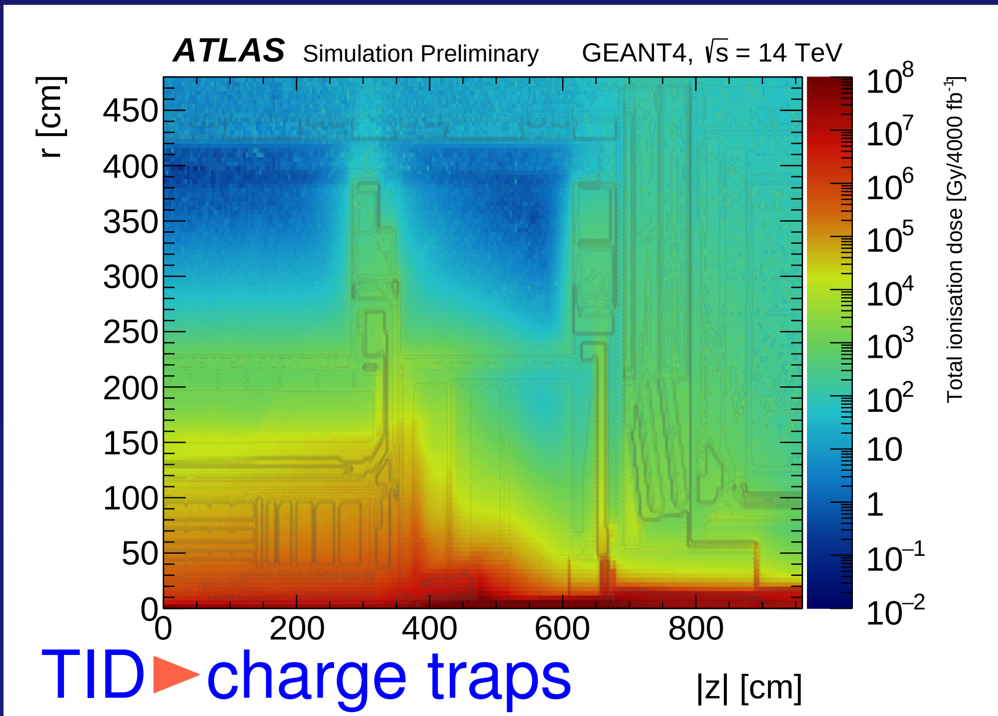
- Run-3 (2021-2023) expect $\sim 150\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 14$ TeV
  - Standard Model
    - $t\bar{t} + X$ production cross-section, precision top-quark mass measurement
  - Higgs
    - Higgs couplings and CP properties, invisible Higgs decays, associate production like $t\bar{t}H$
  - Searches
    - SUSY 4-lepton channels, long-lived particles, dark-matter, di-boson (VH) resonances, lepton-flavour violation
- Run-4 and beyond (2026-2037) expect $\sim 3000\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 14$ TeV in addition:
  - Standard Model
    - VV scattering (to check if $H(125)$ is sufficient for cross-section regularisation), quartic gauge-boson couplings, precision W mass measurement, precision top-quark mass measurement
  - Higgs
    - Higgs self couplings (expect ~ 10 $H(b\bar{b})H(\gamma\gamma)$ events after cuts (right)), Higgs couplings with high precision, rare Higgs decay channels (like $H \to \mu^+\mu^-$)
  - Searches
    - beyond standard model Higgs, resonant HH/VV/di-lepton production, dark-matter, SUSY, dark-energy, ...

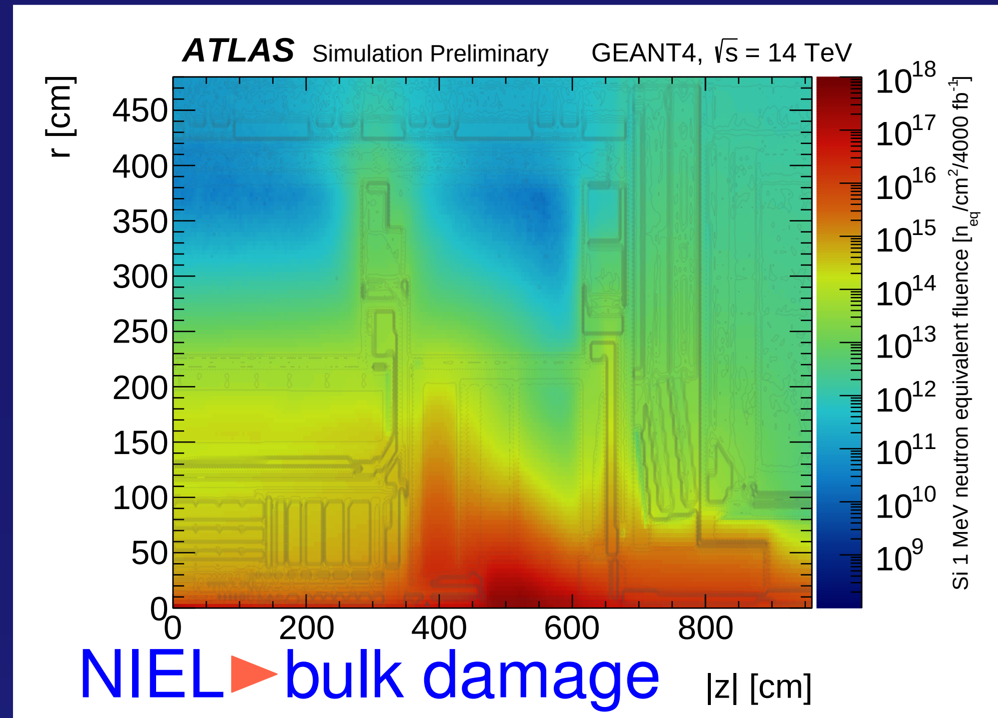
W. J.Stirling†

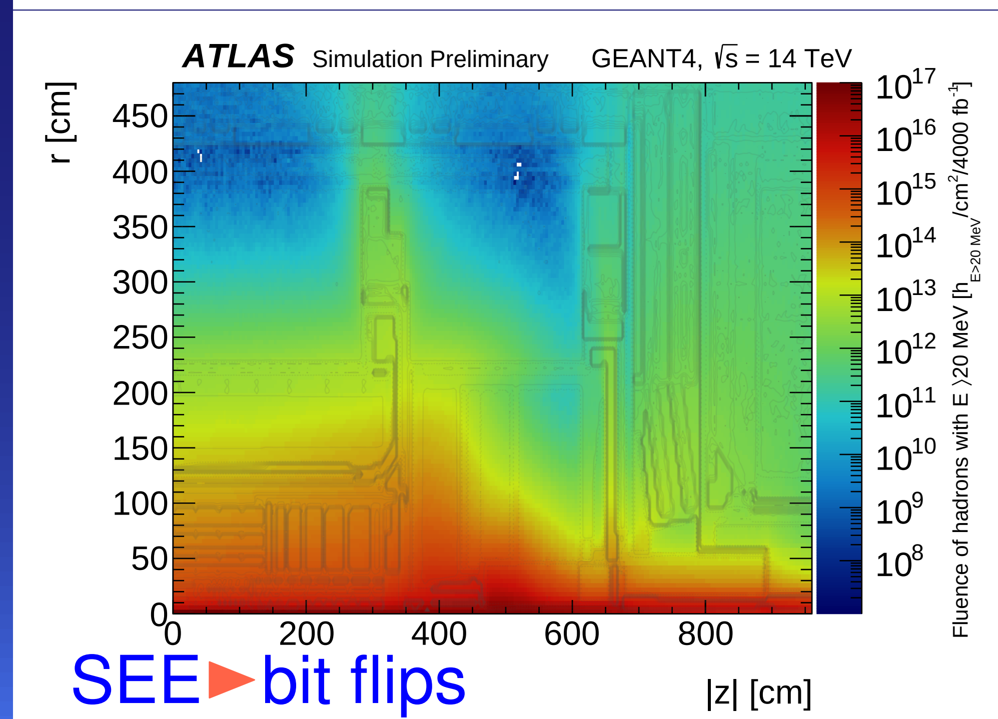




Radiation backgrounds @ HL-LHC



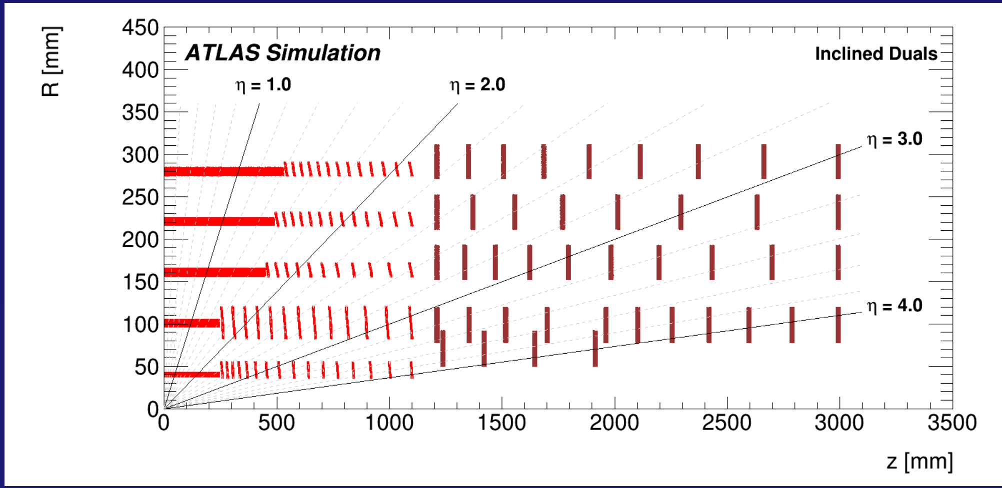




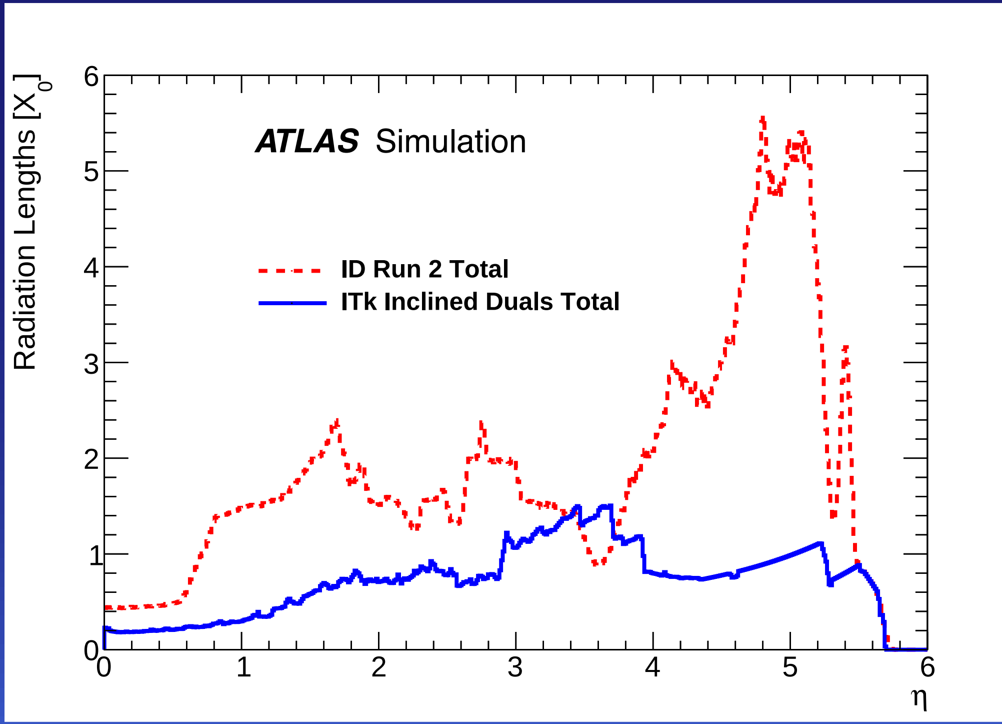
- Current ATLAS detector was designed for pp collisions at $\sqrt{s} = 14$ TeV in the LHC with an integrated luminosity of $1000\ \mathrm{fb}^{-1}$
- For the HL-LHC ATLAS has to stand $3 - 4\times$ that luminosity
- ATLAS now uses Geant4 predictions made by MPP-group for radiation estimates
- Clockwise from top left: Total Ionisation Dose (TID), Neutron Fluence (NIEL), Flux of > 20 MeV hadrons (SEE)

Inner tracker (ITk)

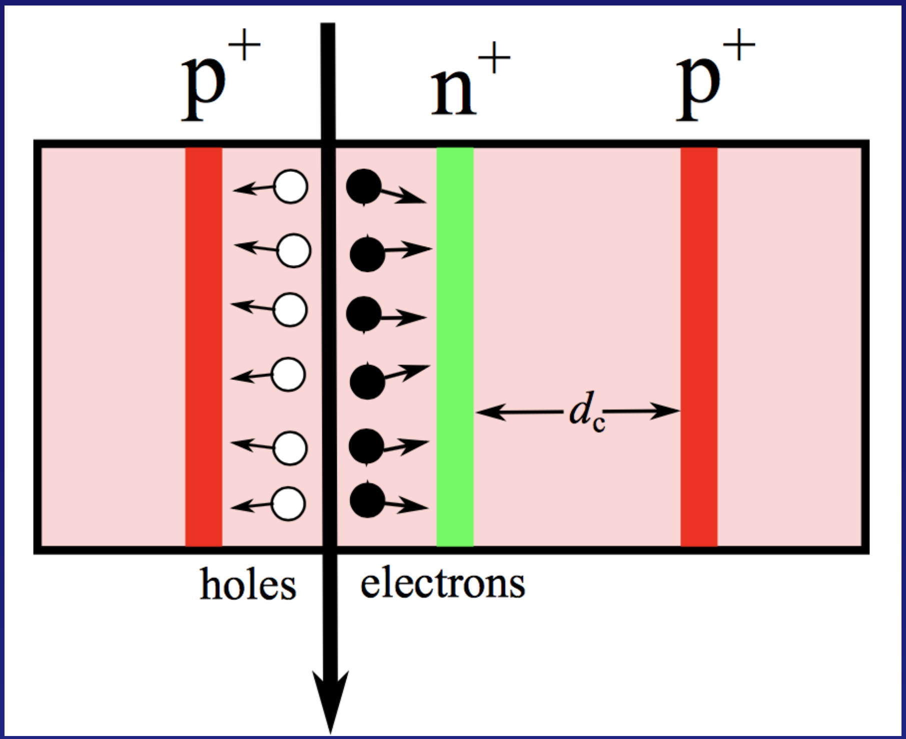
- New ITk pixel layout optimised in 2018
  - 5 pixel layers up to $|\eta| = 4$
  - reduced coverage in z by $\sim$ 15 cm (compared to TDR shown on top right) to make space for HGTD
  - 4-chip modules everywhere except innermost layer
  - two innermost layers are replaceable

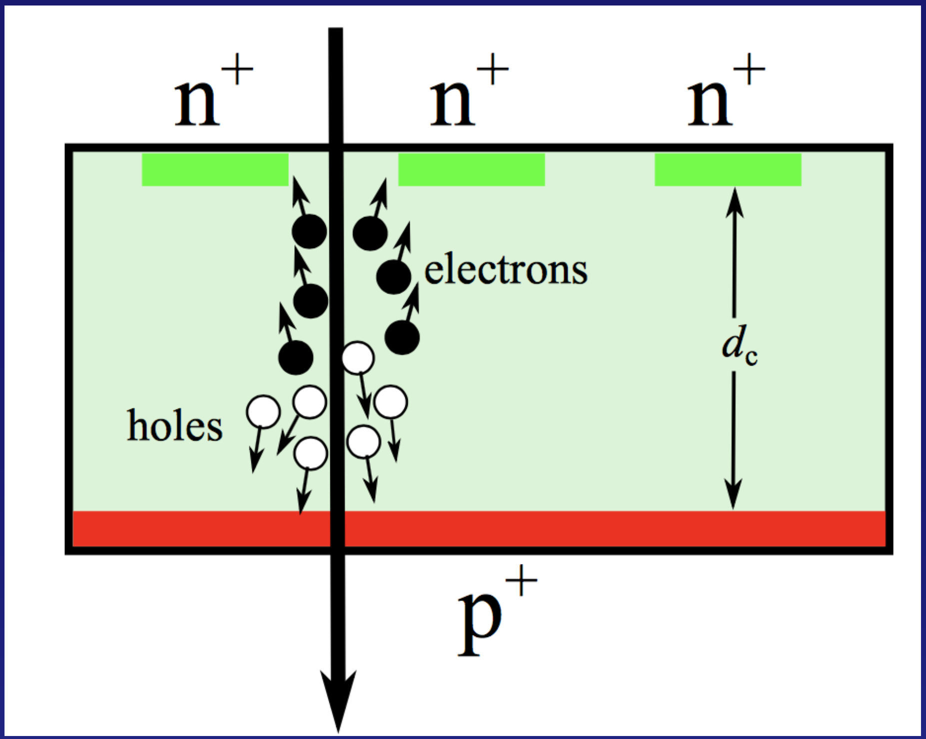


- Main challenges
  - hit rate (up to 0.16% per channel) and radiation hardness (up to $1.3 \times 10^{16}\ n_{eq}/cm^2$ with one exchange)
  - number of modules 9416
  - number of readout channels $\sim 5 \times 10^9$ (either $50 \times 50\ \mu m^2$ or $25 \times 100\ \mu m^2$)
- Total material budget of ITk compared to current Inner Detector (bottom right)
  - much reduced number of X_0
  - better tracker resolution
  - less impact on calorimeters



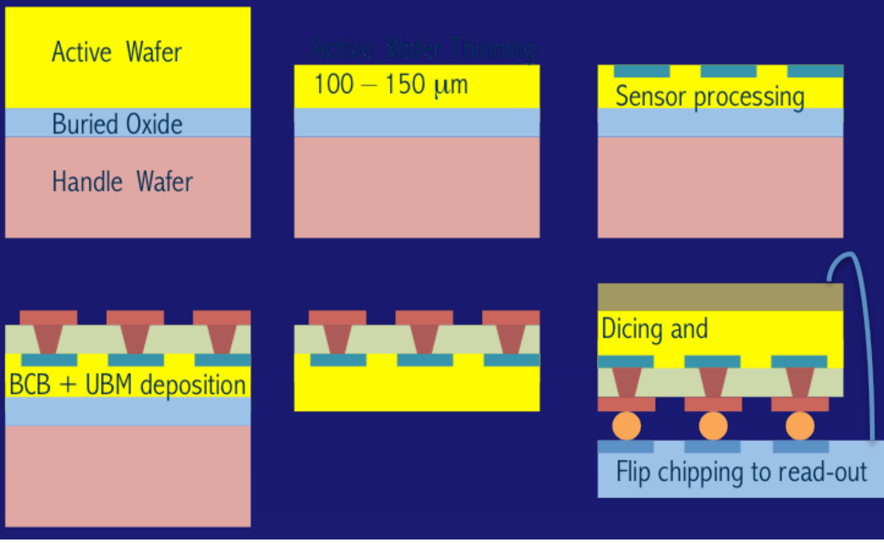
- Sensor technology depends on radiation environment

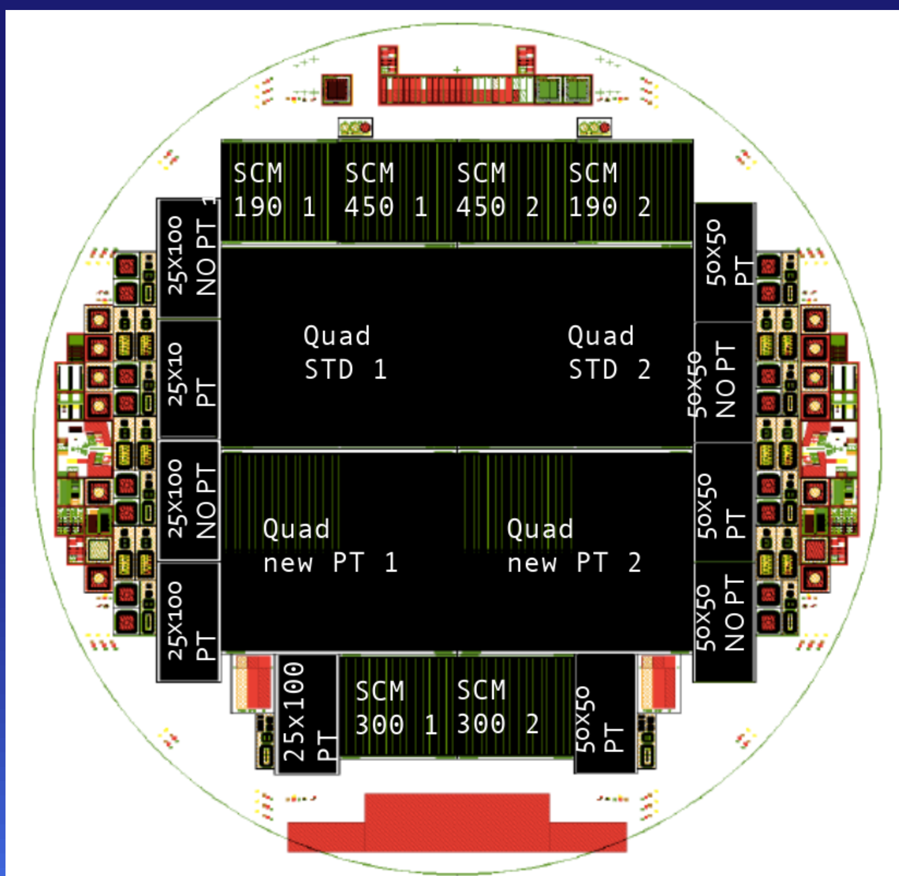




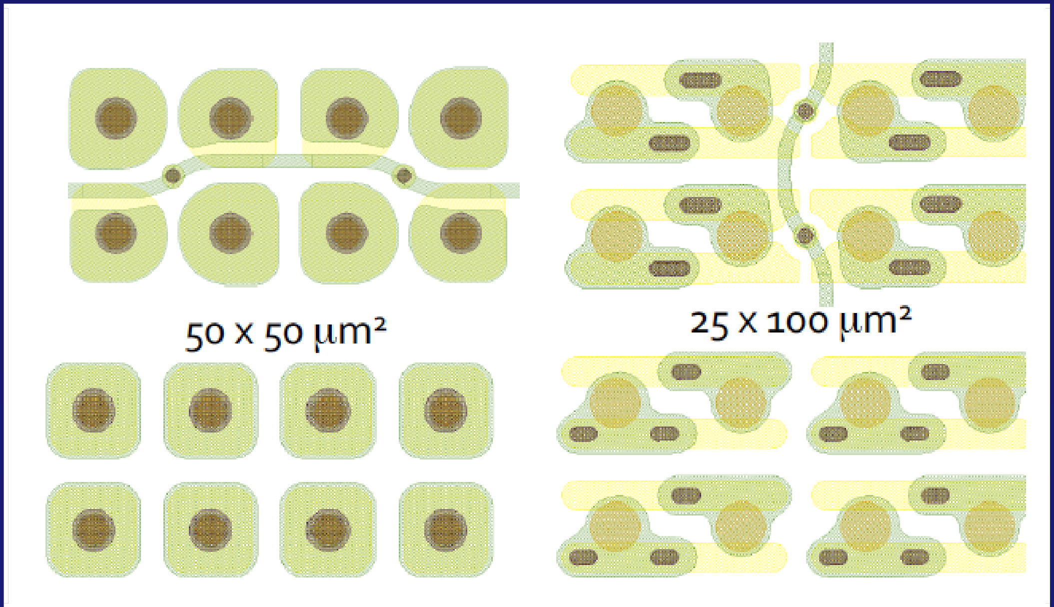
- 3D sensors for innermost layer
  - 150 μm active thickness
  - charge collection with vertical electrodes
  - single-chip sensors for 1– or 2–chip modules
  - exchanged after 2000 fb^{-1} and $1.3 \times 10^{16}\ \text{n}_{\text{eq}}/\text{cm}^2$
- Planar sensors for all other layers
  - 100 μm active thickness in 2$^{\text{nd}}$ layer; 150 μm in outer layers
  - 4-chip sensors
  - Maximum NIEL fluence in 2$^{\text{nd}}$ layer after 2000 fb^{-1}: $4 \times 10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$

ITk ► Pixel sensor production @ HLL

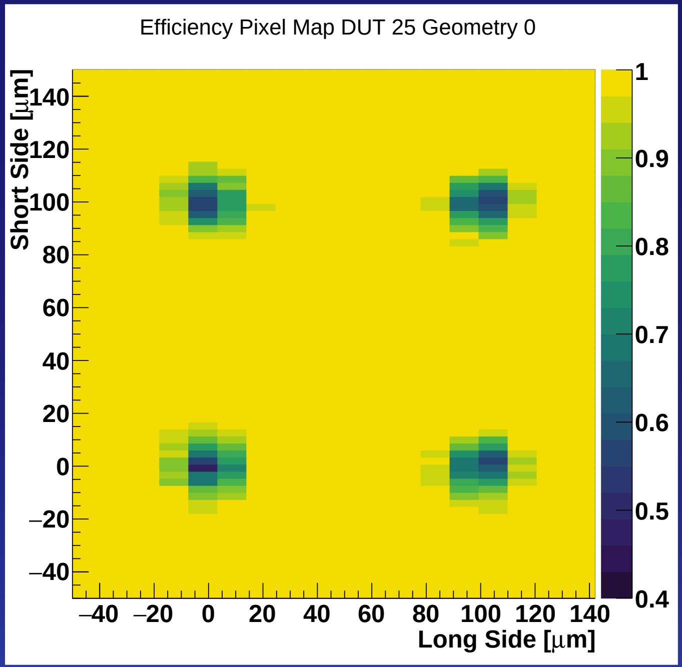




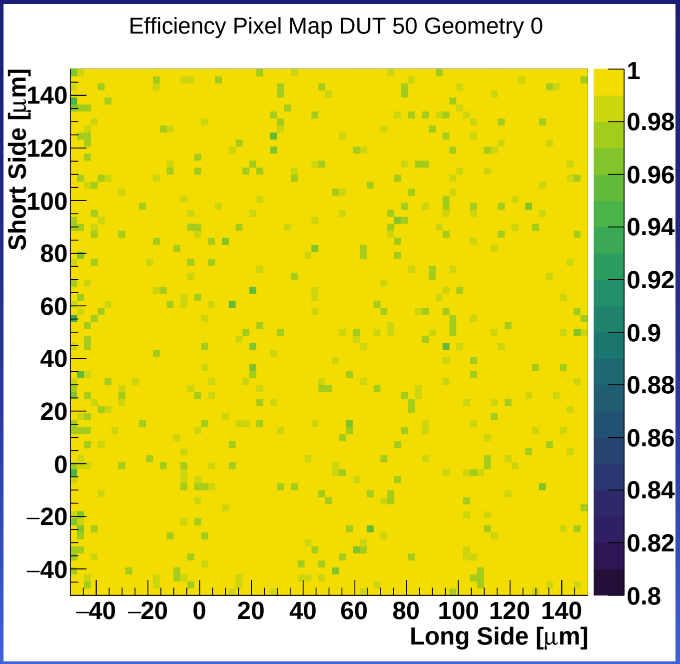
- ► MPP is planning to contribute to second pixel layer with 100 μm thick sensors produced at HLL
- ► Silicon On Insulator (SOI) technology (top) as reliable method to obtain thin sensors
  - HLL sensors (bottom) are at the moment being used by the RD53 Collaboration as reference to decide which version of the analogue stage to select for the future ATLAS/CMS final chips
  - First results in the community on tracking performance of 50×50 and 25×100 μm^2 pixel cells – before and after irradiation – obtained by MPP with HLL sensors
- ► Qualification of the foundries on-going within the ITk pixel sensor market survey
- ► Start of the pre-production planned in the second half of 2019



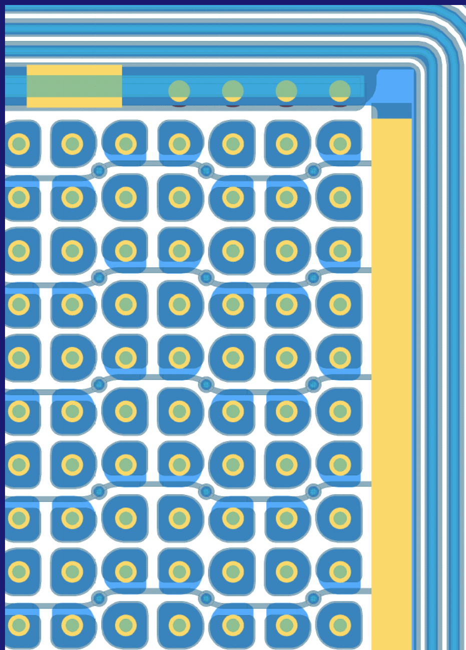
- Different designs implemented to study the possible detrimental effect of the biasing structure (only used for QC before chip interconnection) on the hit efficiency



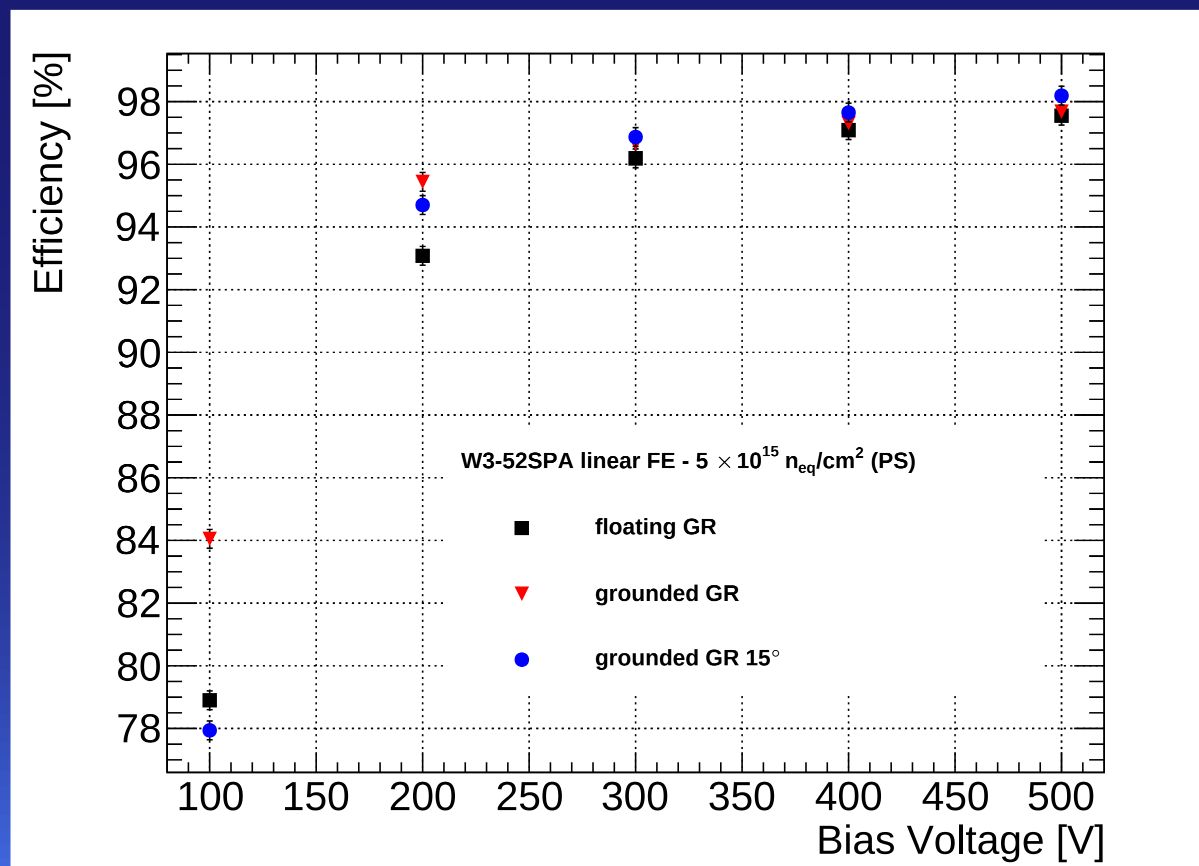
- Bias grid grounded
  - $50 \times 50\ \mu m^2$ pixels
  - Hit efficiency $= 98.5\%$



- No bias grid
  - $50 \times 50\ \mu m^2$ pixels
  - Hit efficiency $= 99.8\%$
  - Note change in z-scale



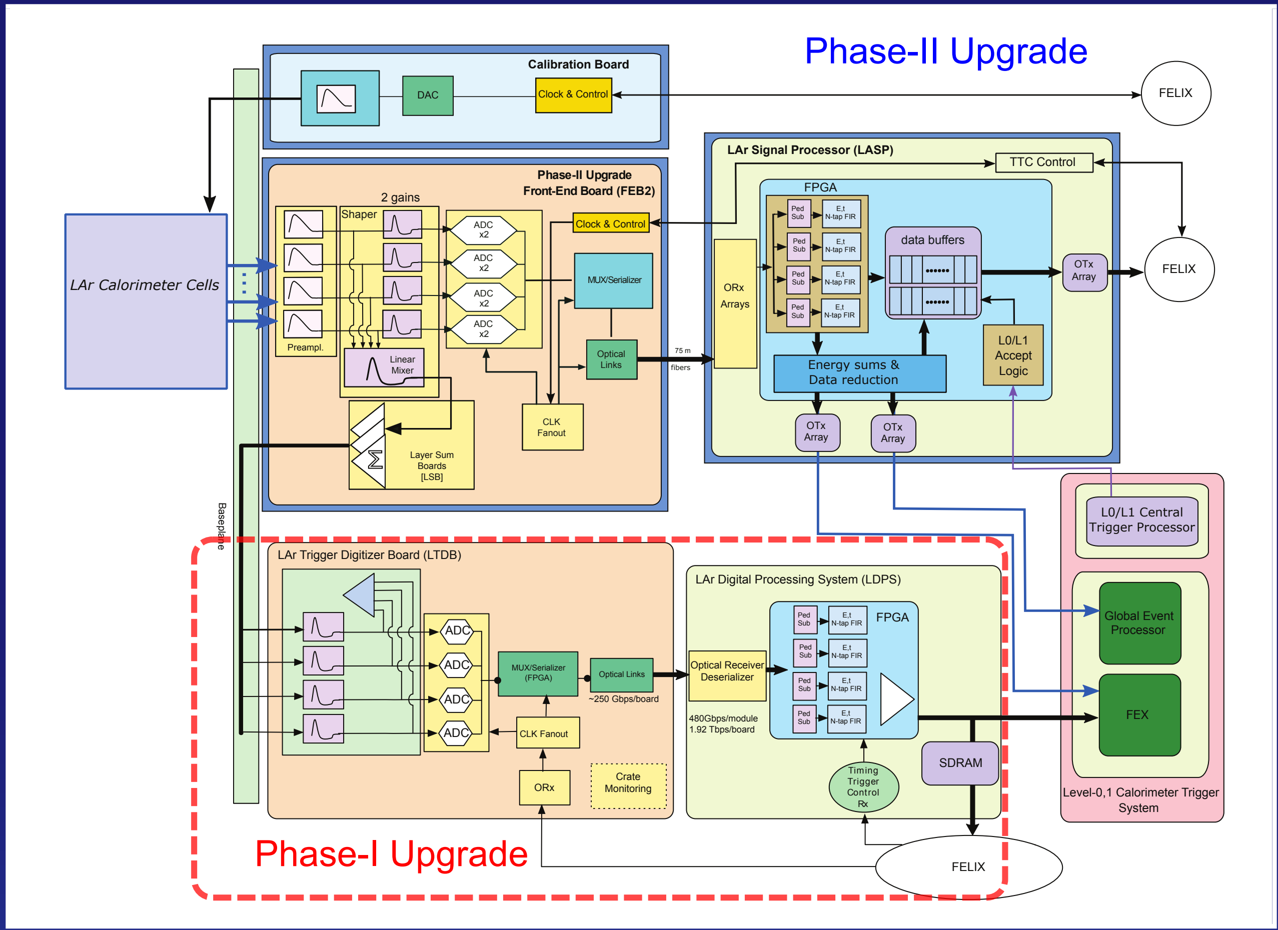
- Developed new design where the implant of the innermost ring can be grounded while the grid for testing is left floating after chip interconnection
- The ring implant intercepts the sensor currents from the sensor edges avoiding the last columns and rows to become noisy



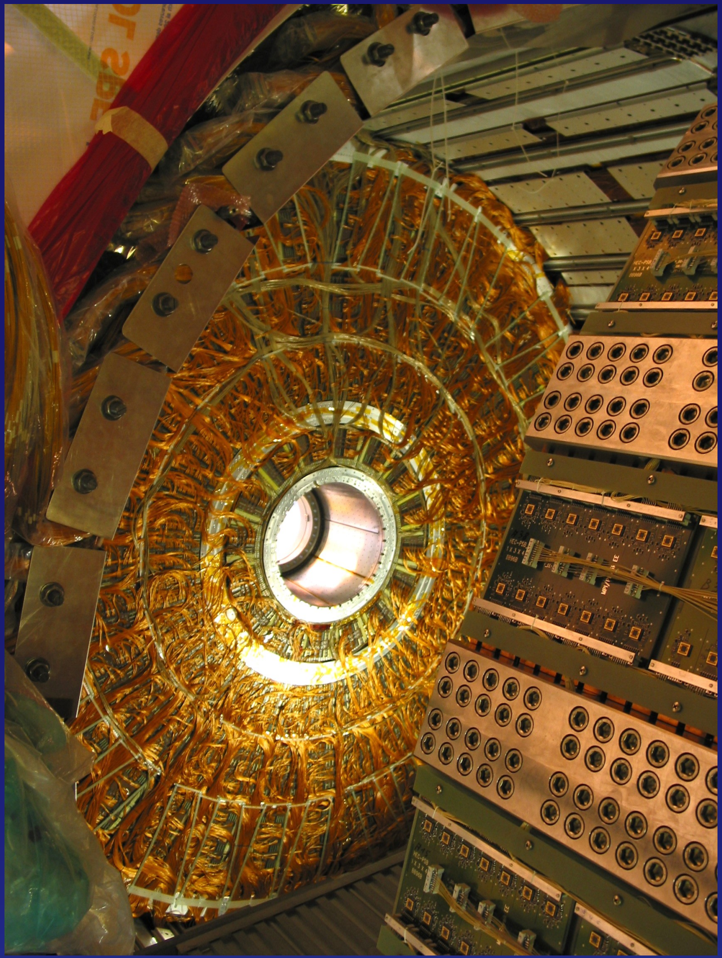
- A good hit efficiency of $\sim 98\%$ is maintained after irradiation to fluences of $5 \times 10^{15}\,n_{eq}/cm^2$

Liquid argon calorimeters (2024–2026)

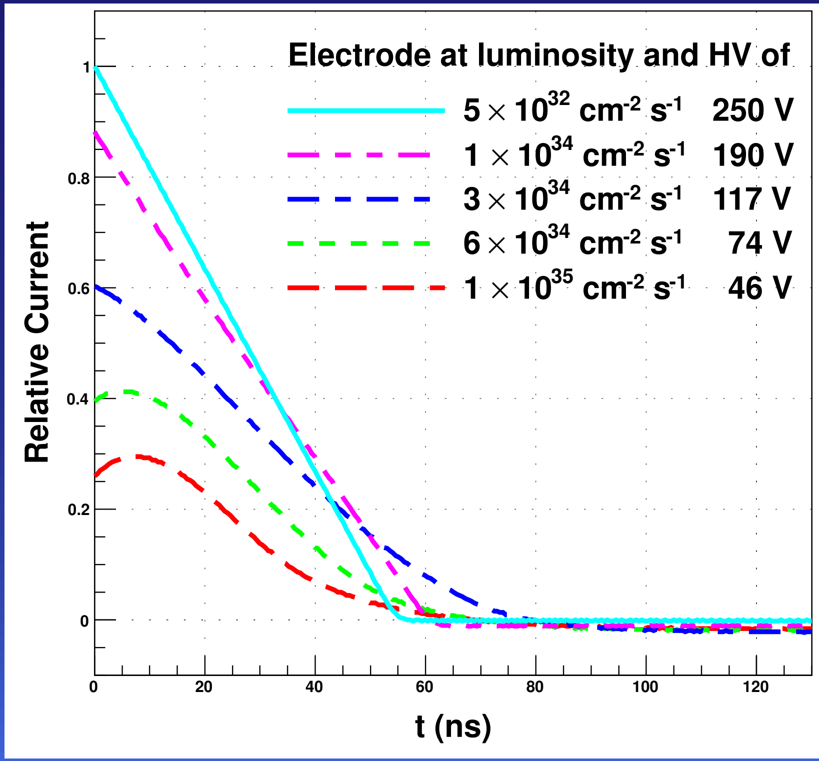
- Calorimeter hardware remains unchanged
  - LAr sampling calorimeters are inherent radiation hard
    - no need to change EMB, EMEC, HEC, FCal
- Readout and trigger electronics changes
  - Phase-I upgrade (2019–2020) for trigger
  - Phase-II upgrade (2024–2026) for readout electronics
    - to meet requirements of new trigger and data-acquisition scheme
    - for more radiation tolerance
    - and because of age ($>$ 30 years)



- Requirements
  - 40 MHz digital readout with 2 gains for all 180 000 cells
  - 16 bit dynamic range over 2 gains avoids gain switching in precision physics region
  - 10 μs Level-0 trigger latency
  - 1 — 4 MHz Level-0 trigger rate



- ► HEC readout electronics
  - GaAs based ASICs stay in cold since we tested them as rad-hard enough
  - need special front-end ASIC since polarity, gain and timing differ from rest of LAr
  - need more radiation-hard new low-voltage power supplies

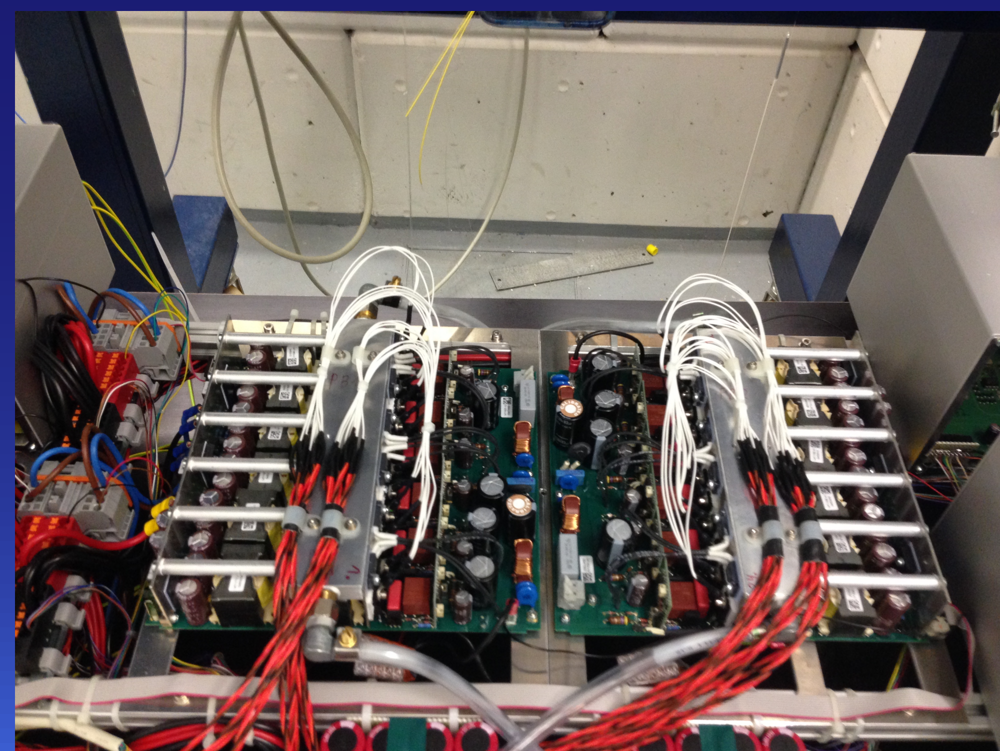


- ► FCal studies
  - signals in FCal will be degraded at HL-LHC (plot to the right) due to
  - large HV currents through protection resistors lowering the HV over the LAr gaps
  - potential build-up of positive argon ions in the gaps destroying the electric field

LAr ► HEC low voltage power supplies

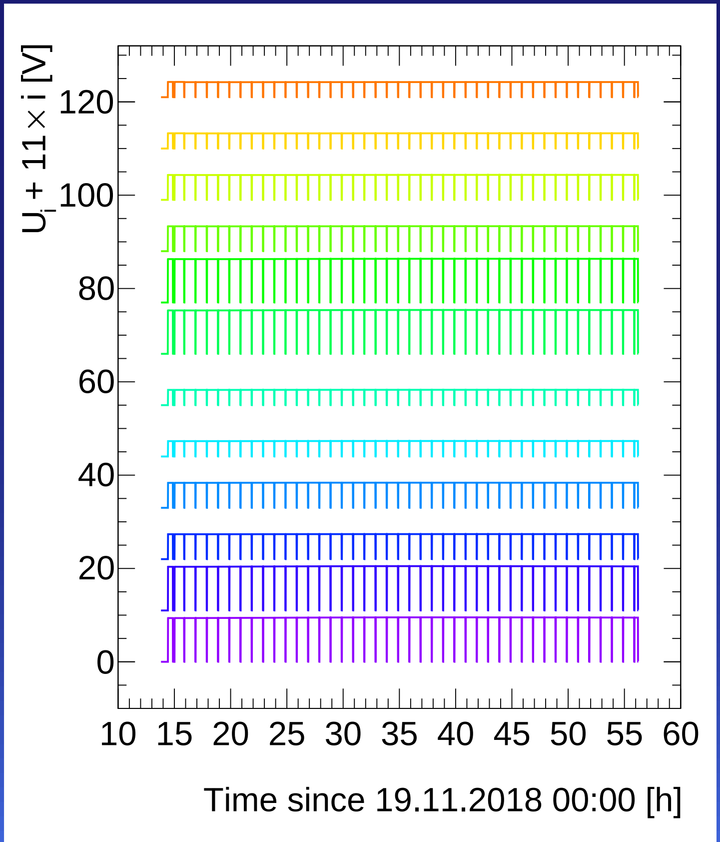
- Power board prototypes
- 2 of the 5 new prototype power boards from Wiener for the Phase-II HEC low voltage power supplies have been tested under Neutron Irradiation at Řež from 10.–12. November 2017
  - passed NIEL levels of at least $5.9 \times 10^{12}\ \mathrm{n_{eq}/cm^2}$
  - this is $10\times$ the max level from Geant4 ($5\times$ over min. SF of 2)

- 2 of the remaining 3 prototypes have been tested for total ionisation dose at the Fraunhofer Institute in Euskirchen from 18.–21. November 2018
- The aim was to reach a TID of $\sim 400\ \mathrm{Gy}$
- From 3D Geant4 simulations the current best estimate of the expected TID after $4000\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 14\ \mathrm{TeV}$ is $\sim 73 \pm 6\ \mathrm{Gy}$



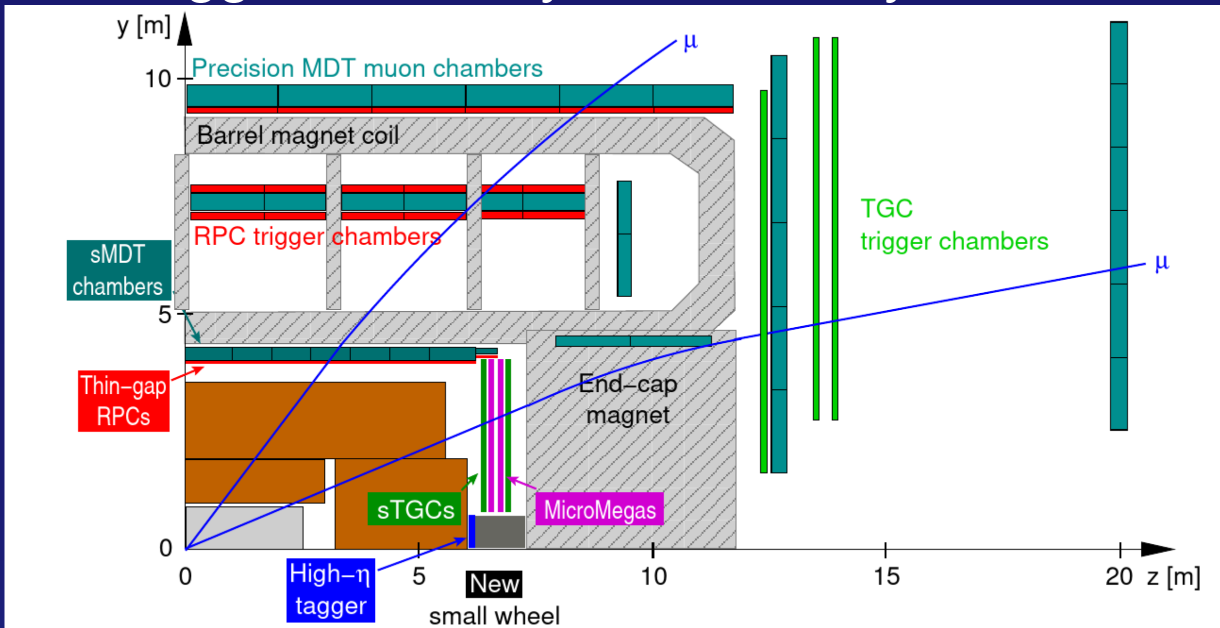
LAr ► HEC low voltage power supplies

- Co-60 source in Euskirchen
  - Hard Gammas from 14.7 TBq Co-60 source in 60 cm distance
    10 Gy/h
- TID Test from November 2018 in Euskirchen
  - Reached > 400 Gy at end of test – with all converters healthy (only 1% change in output voltage) ($5.5\times$ max. Geant4 (3D))
  - top picture shows setup in Euskirchen
  - bottom plot shows the 12 DC/DC converter voltages as function of time (irradiation from $15.5 - 55.5$ h) with hourly dips from the scheduled power cycles
- Next steps
  - FPGA for monitoring and control needs to be tested with neutrons and γs
  - Integration with slow control HW from CERN (ELMB2/ELMB++)
  - Monitoring- and Distribution-boards need to be designed and constructed
  - Design & Construction of Mechanics and Connector-plate



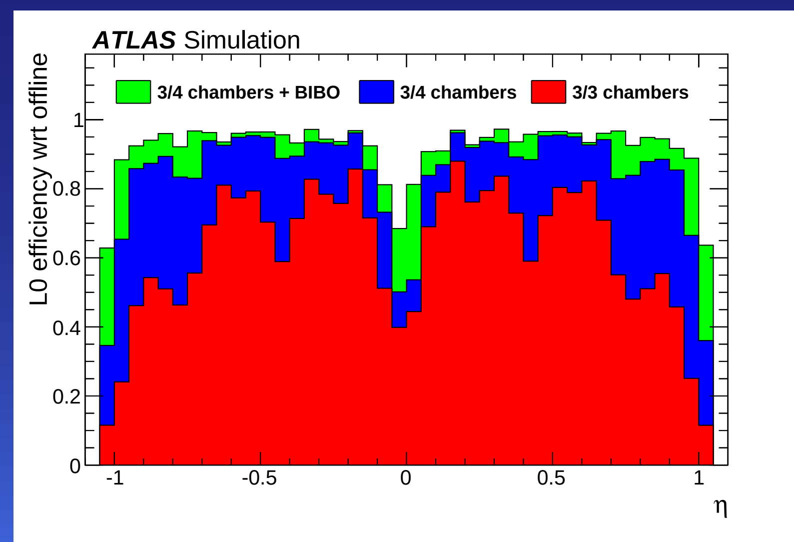
Muon system ► Phase-II upgrades designed and led by MPP (2024–2026)

- Expected degradation of RPC performance at high rates would lower trigger efficiency substantially

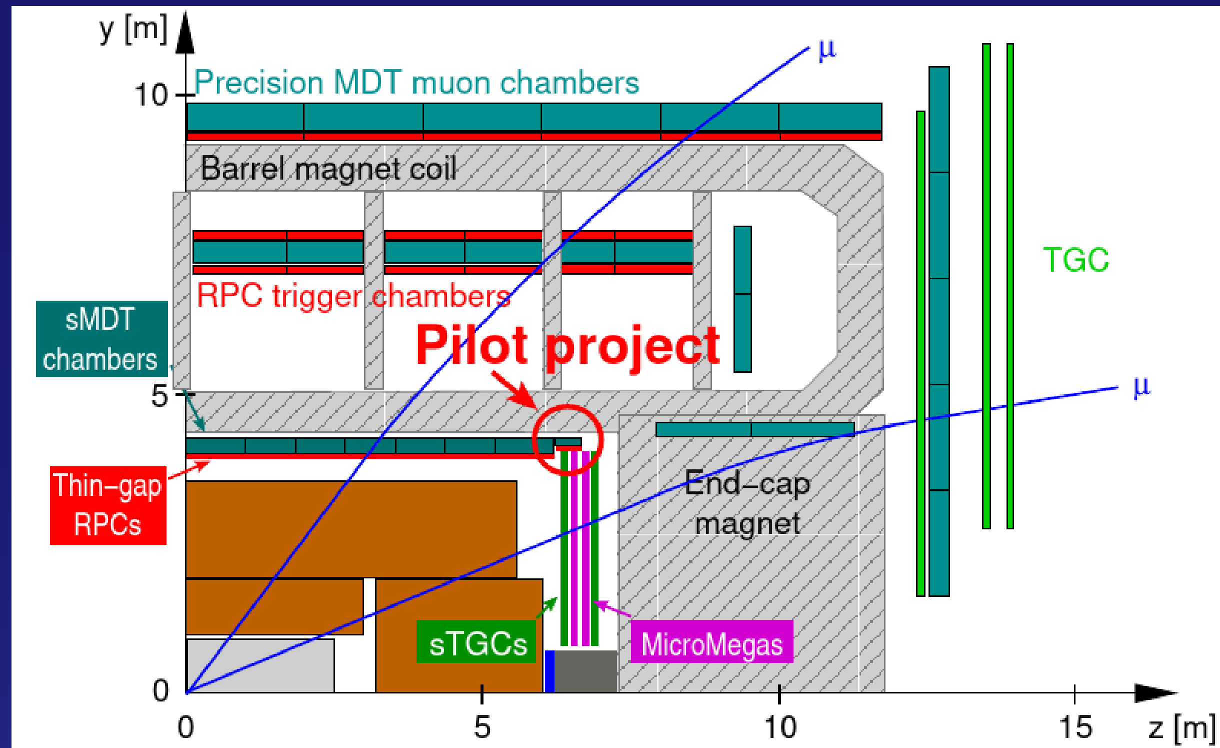


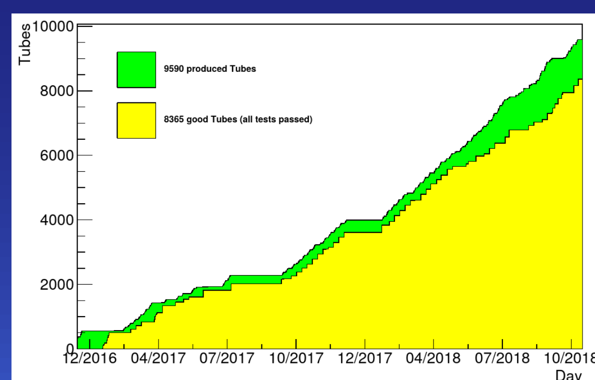
- Thin-gap RPCs
  - mitigate inefficiencies of current RPCs
  - close acceptance gaps of barrel muon trigger
- sMDT chambers
  - freeing space for new RPCs
  - $10\times$ higher background rate capability
- Electronics
  - new on-chamber electronics to master higher rates

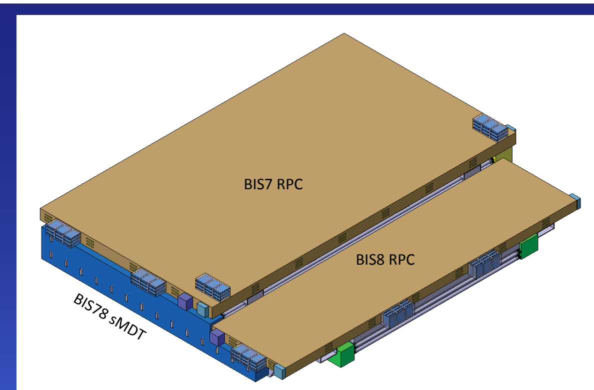
- First-level muon track trigger
  - using MDT chamber information
  - $10\times$ higher selectivity against low $p_\perp$ muons
- Electronics
  - new on- and off-detector electronics for new trigger architecture
- Trigger Efficiency at the HL-LHC (right)
  - Without upgrade: $\sim$ 60% only
  - With sMDTs and new RPCs: $\sim$ 95%



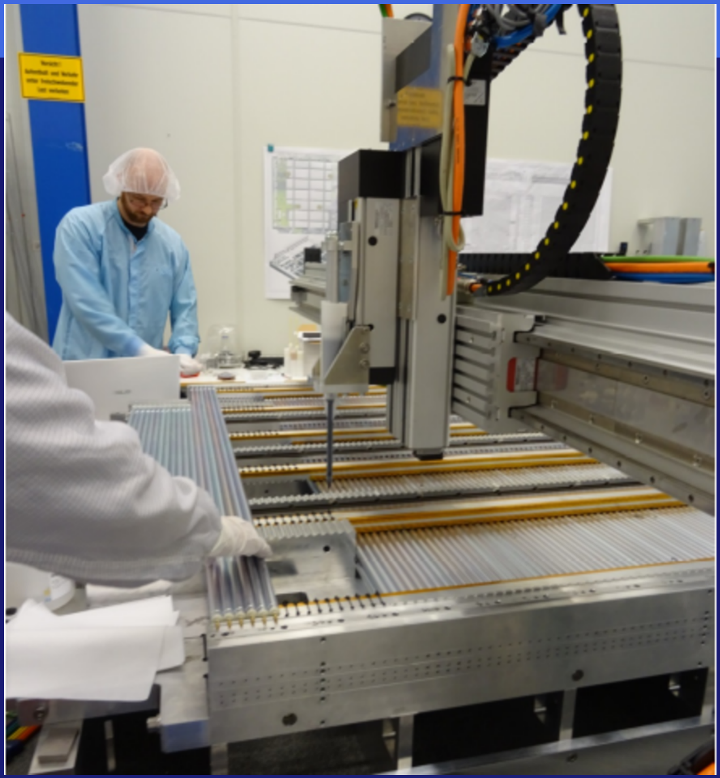
- Installation of 16 new muon stations inside the barrel toroid coils at the boundary to the endcaps (BIS7/8) during LS2 (2019–2020)
- Motivation
  - improving selectivity in barrel-endcap transition region
  - increasing high-rate capability
- Technology
  - integrated sMDT-RPC chambers
  - like for full HL-LHC upgrade
- MPP contributions
  - design and construction of sMDT chambers
    ► production rate 70 — 80 tubes/day with 3 technicians
    ► need until March 2019 to reach ∼ 12000 tubes
  - front-end electronics
  - thin-gap RPC mechanics



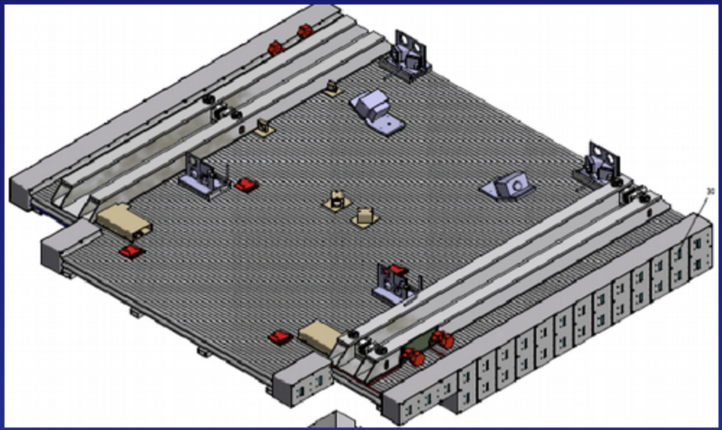


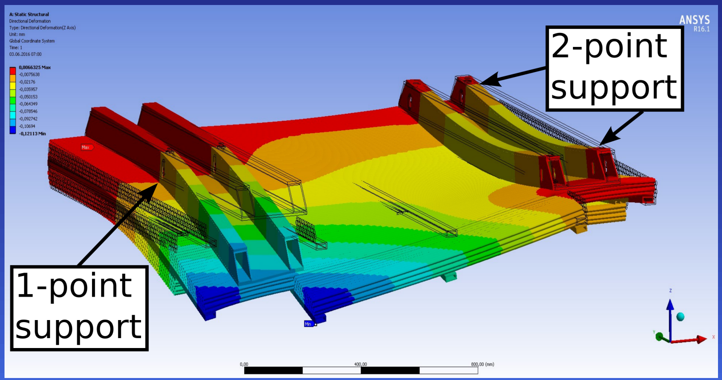


Muon ► sMDT chamber assembly



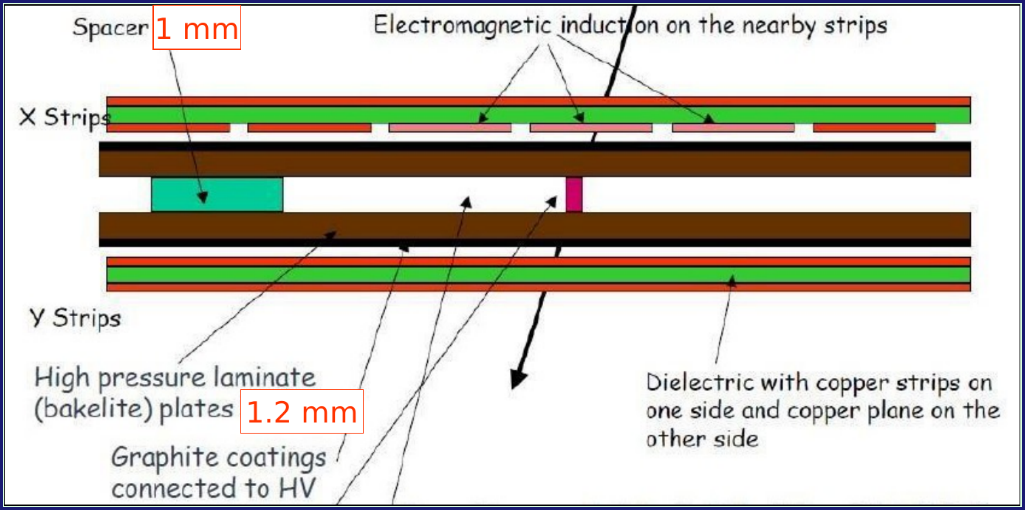
- Complex chamber geometry with alignment and magnetic field sensors (drawing below)
- Tube insertion and chamber gluing (right)
- Assembly of 63% of the chambers in 2018
- Remaining chambers in 2019

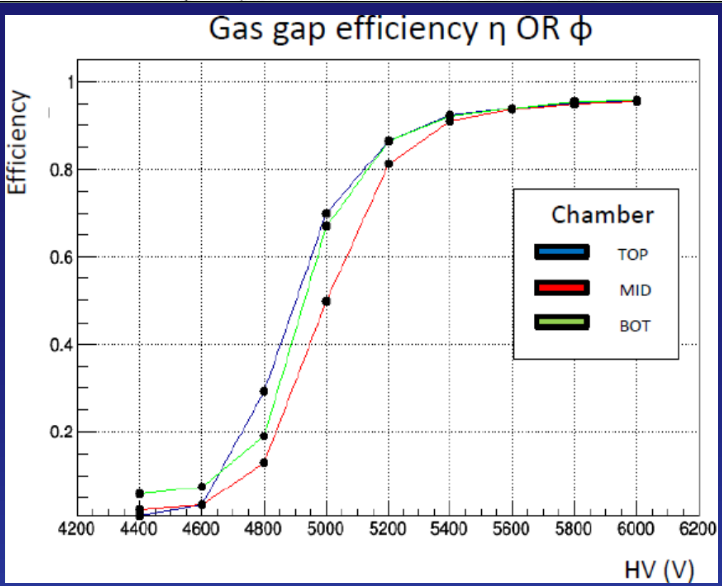




- Measurement of wire positions with feeler gauge on granite table
- Measurement of sagging and torsion angles as function of chamber angle
- Deformations agree with simulation (bottom left)
- Wire positions accurate to $O(10\,\mu\mathrm{m})$

Muon ► Thin-gap RPCs



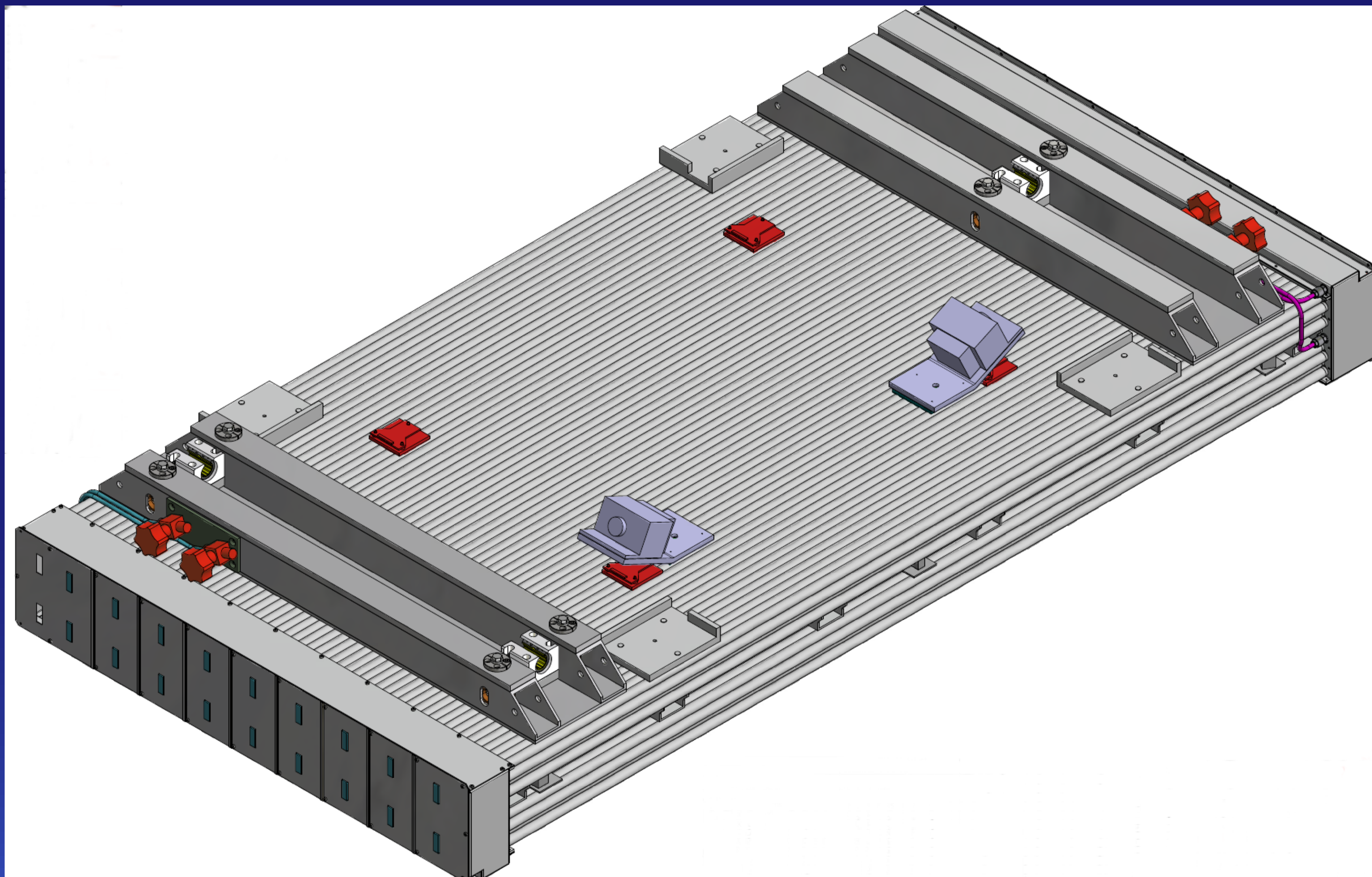


- Twice thinner gas gaps (1 mm) compared to standard RPCs
- Thinner electrodes and highly sensitive amplifiers
- Allows operation at reduced HV (5.8 kV instead of 9.6 kV)
- Rate capability of up to $10\,\mathrm{kHz/cm^2}$
- MPP group has focus on industrialisation of RPC production for HL-LHC and future colliders

- RPC integration with sMDT chamber

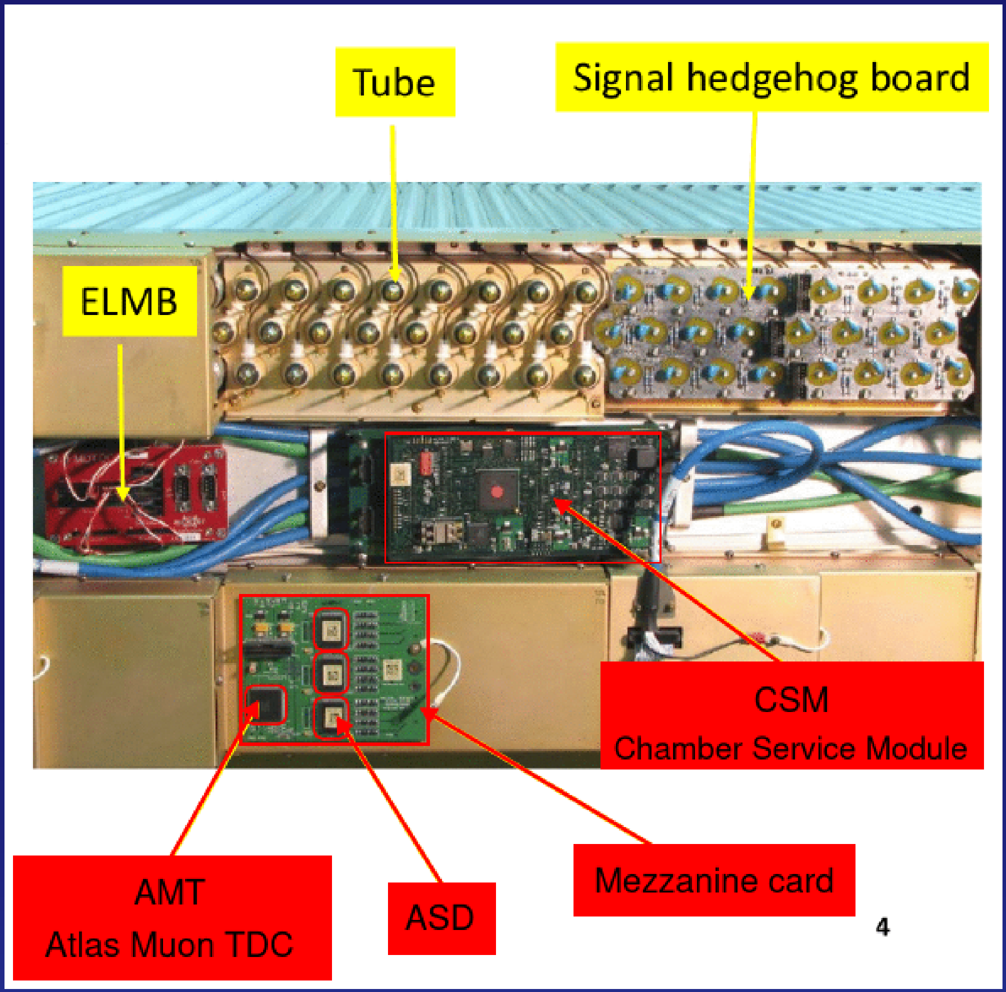
Muon ► sMDT chambers for HL-LHC (2024–2026)

- BIS1-6 chambers very similar to the BIS7/8 sMDT chambers
- Module-0 will be produced by fall 2019



- Production of 48 BIS sMDT chambers in 2020-2022 (compare to 16 BIS7/8 chambers in 2018-2019)

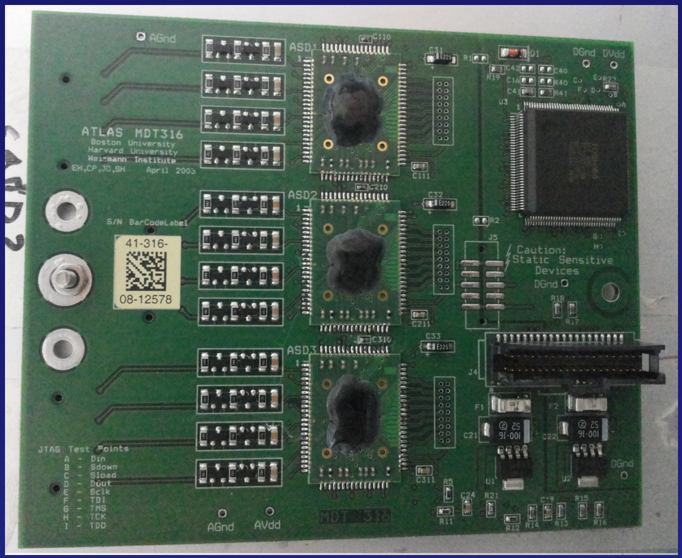
- Current MDT readout electronics
  - readout in groups of 24 tubes
  - passive “Hedgehog” cards with coupling capacitors
  - active part:
    3 Amplifier-Shaper-Discriminator (ASD) chips $\longrightarrow$ TDC
    18 TDCs $\longrightarrow$ Chamber-Service-Module (CSM) $\longrightarrow$ off-detector electronics
- Trigger requirements at HL-LHC
  - first-level trigger rate will increase from 100 kHz to 1 — 4 MHz
  - currents TDCs and CSMs not capable of frequencies above 200 kHz
  - new on-chamber electronics needed for operation at HL-LHC

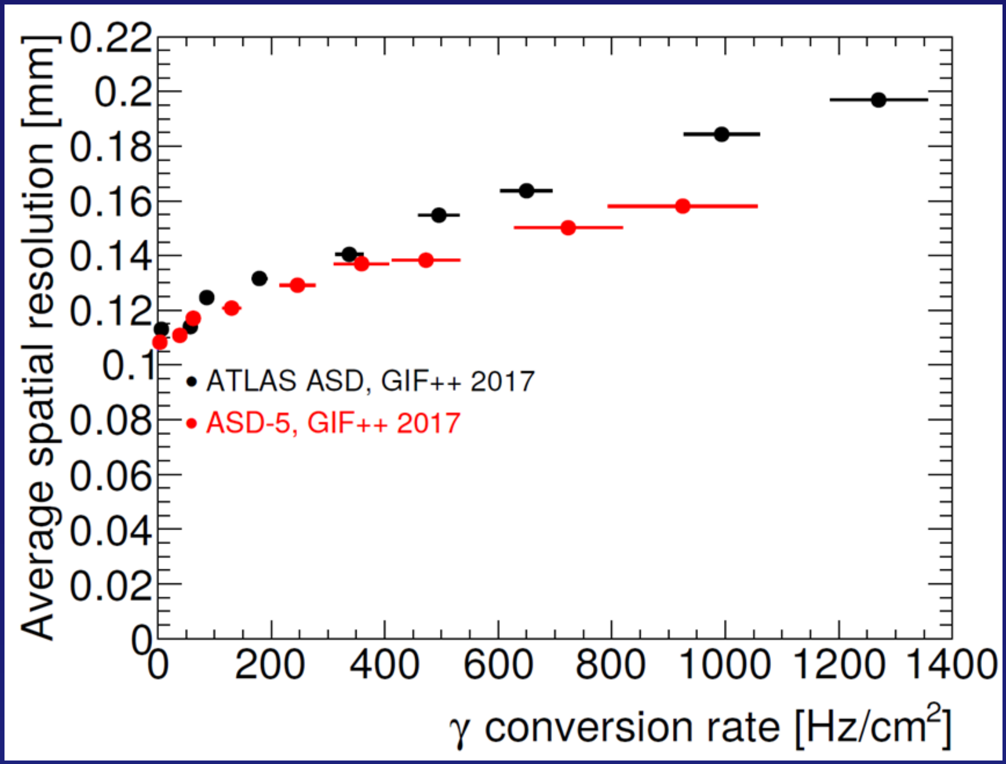


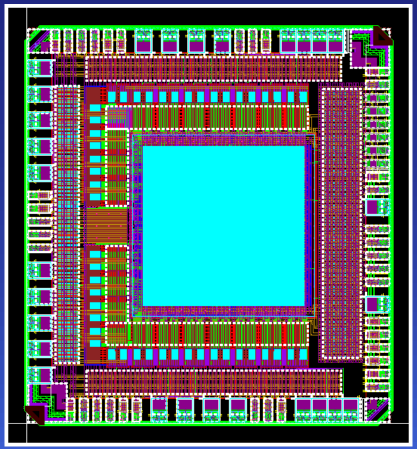
- MPP contributions to new on-chamber MDT electronics
  - design and production of new ASD chip
  - design of new TDC chip in cooperation with Univ. of Michigan, Ann Arbor
  - design of the front-end-electronics-boards with ASDs and TDCs

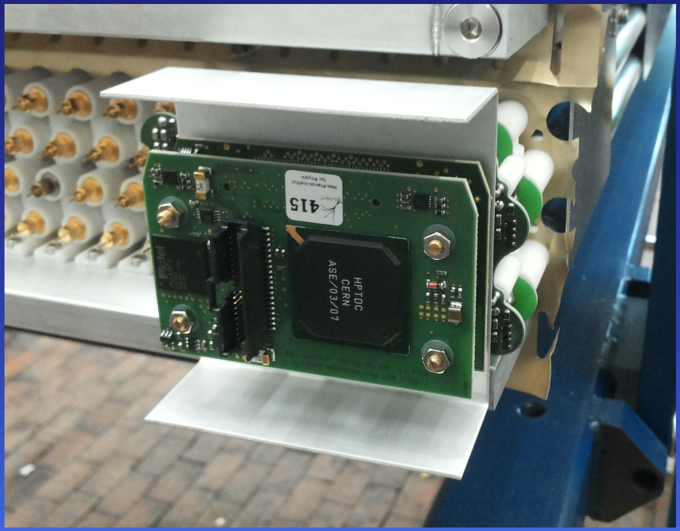
► Test of new ASD chip

- spatial resolution as function of hit rate
- new ASD better than legacy ASD in terms of noise, threshold spread and amplification
  ► new ASD has better spatial resolution





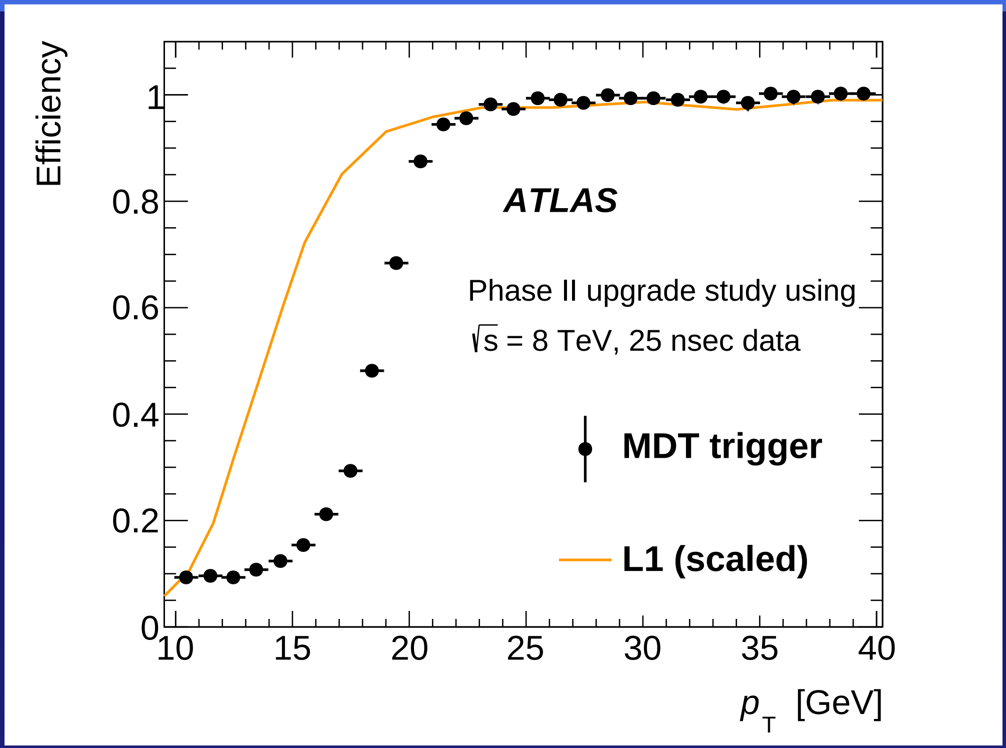




► Test from TDC demonstrator

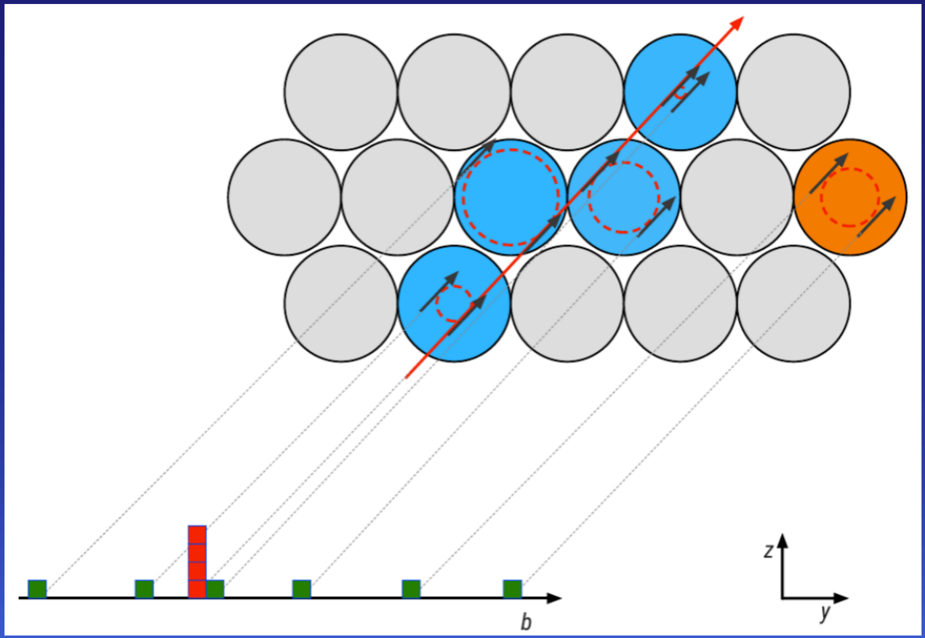
- time resolution as function of TDC channel
- excellent uniformity
- spread is less than ± 40 ps

Muon ► 1st level trigger (2024–2026)



Motivation

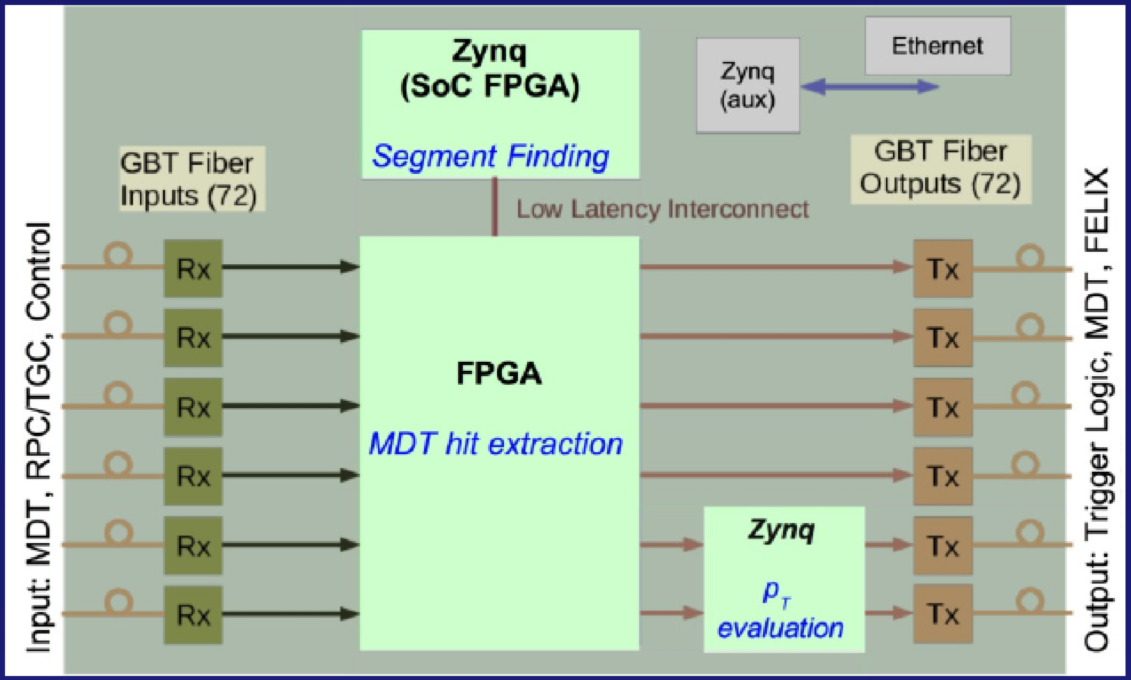
- present 20 GeV 1st level muon trigger (orange line) accepts too many low $p_\perp < 20$ GeV muons due to limited spatial resolution
- including precision MDT information in trigger decision (black points)
  - sharpens turn-on trigger curve
  - reduces trigger rate from 45 — 85 kHz to $\sim$ 15 kHz in the barrel



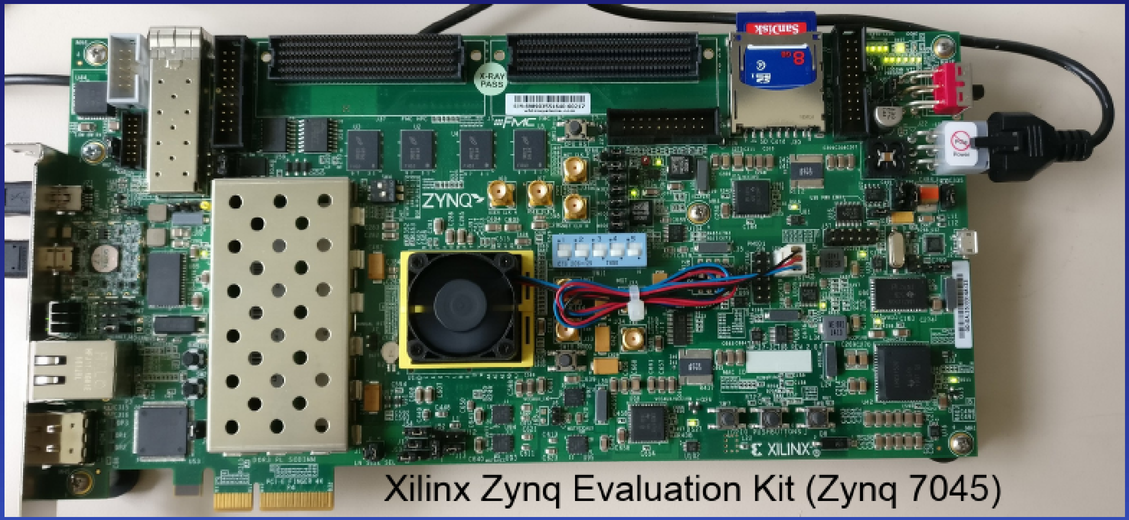
MDT-based trigger algorithm (MPP)

- Compact Segment Finder (left)
- seed track from RPC/TGC trigger
- compute two possible position solutions based on seed slope and measured drift radius for each hit
- fill 1D histograms with position solutions
- final segment fit with hits belonging to maximum only

Muon ► 1st level trigger



- ► Hardware implementation
  - 64 trigger processor boards with FPGA processing units on an ATCA blade
  - Next year: Design and production of the first full-scale demonstrator



Xilinx Zynq Evaluation Kit (Zynq 7045)

- ► Tests of the segment-finding firmware on a Zynq evaluation board
  - Firmware performance validated with software emulation in C++
  - Low resource consumption: only one segment finding Zynq needed for trigger board

Summary & Outlook

- **Operation**
  - 2018 was year with highest integrated luminosity and highest peak luminosity so far
  - Extremely efficient data taking (97.5% good for physics)
  - MPP strongly involved in hardware maintenance, shifts, online and offline software, simulation and analysis
- **Upgrades**
  - 95% of integrated luminosity still to be collected by ATLAS up to end of HL-LHC in 2037
  - Huge upgrade program for ATLAS to improve resolution under much more harsh conditions at the HL-LHC compared to LHC
  - MPP involved in Phase-II upgrades for ITk, LAr calorimeters and Muon system
  - R&D, Irradiation Tests, Design & Construction of Detectors and Electronics
  - Many challenges ahead of us
  - 6 Phase-II TDRs (see below) published in 2018 with major MPP contributions
- **Many thanks to the technical departments for their support!**