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Rebeca Gonzalez Suarez (Uppsala University)

A HARDWARE TRACK TRIGGER FOR ATLAS AT THE HL-LHC

The Large Hadron Collider

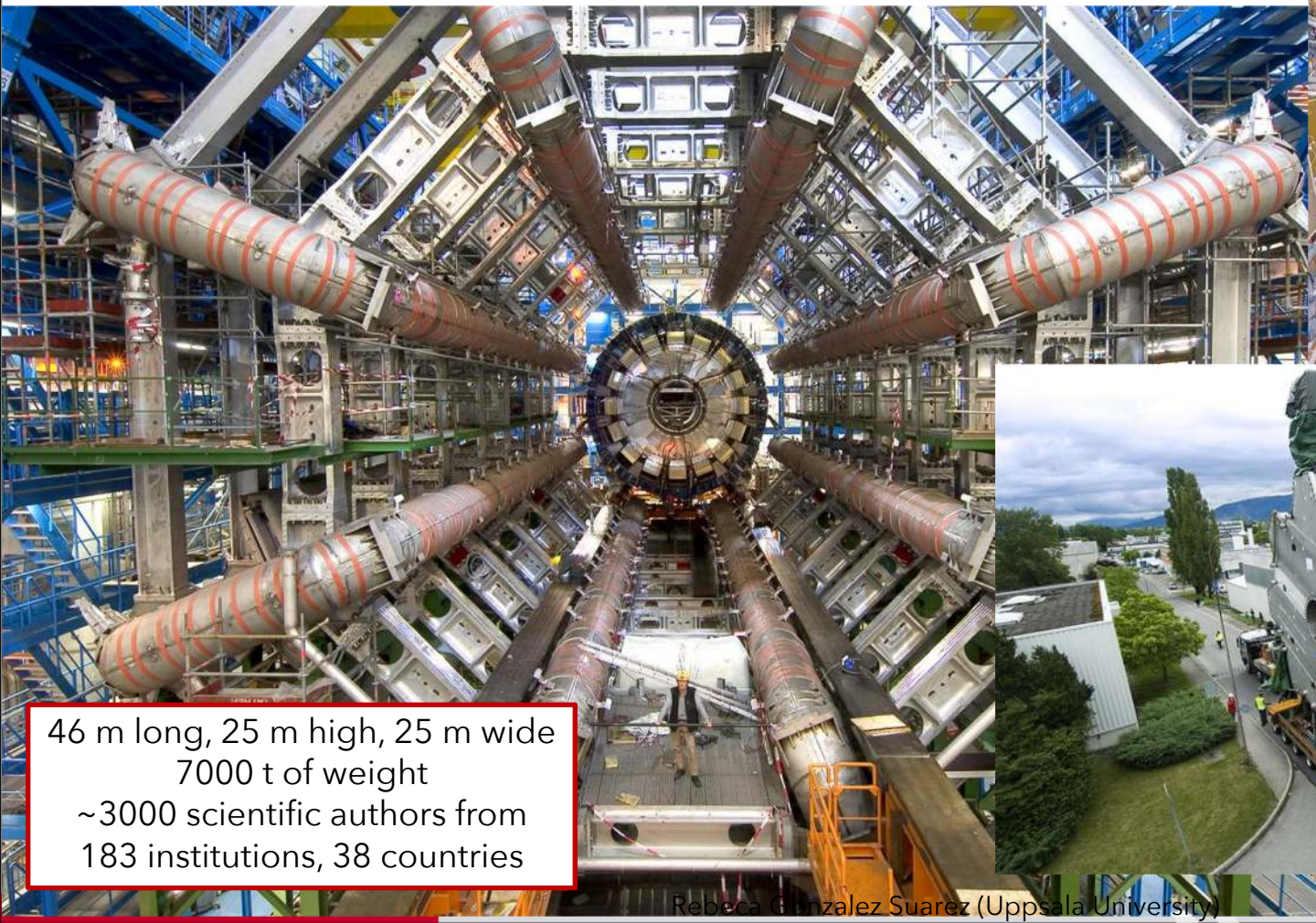
- The LHC is the largest, most energetic particle collider ever built
- Collides mostly protons (also heavy ions)

The LHC experiments

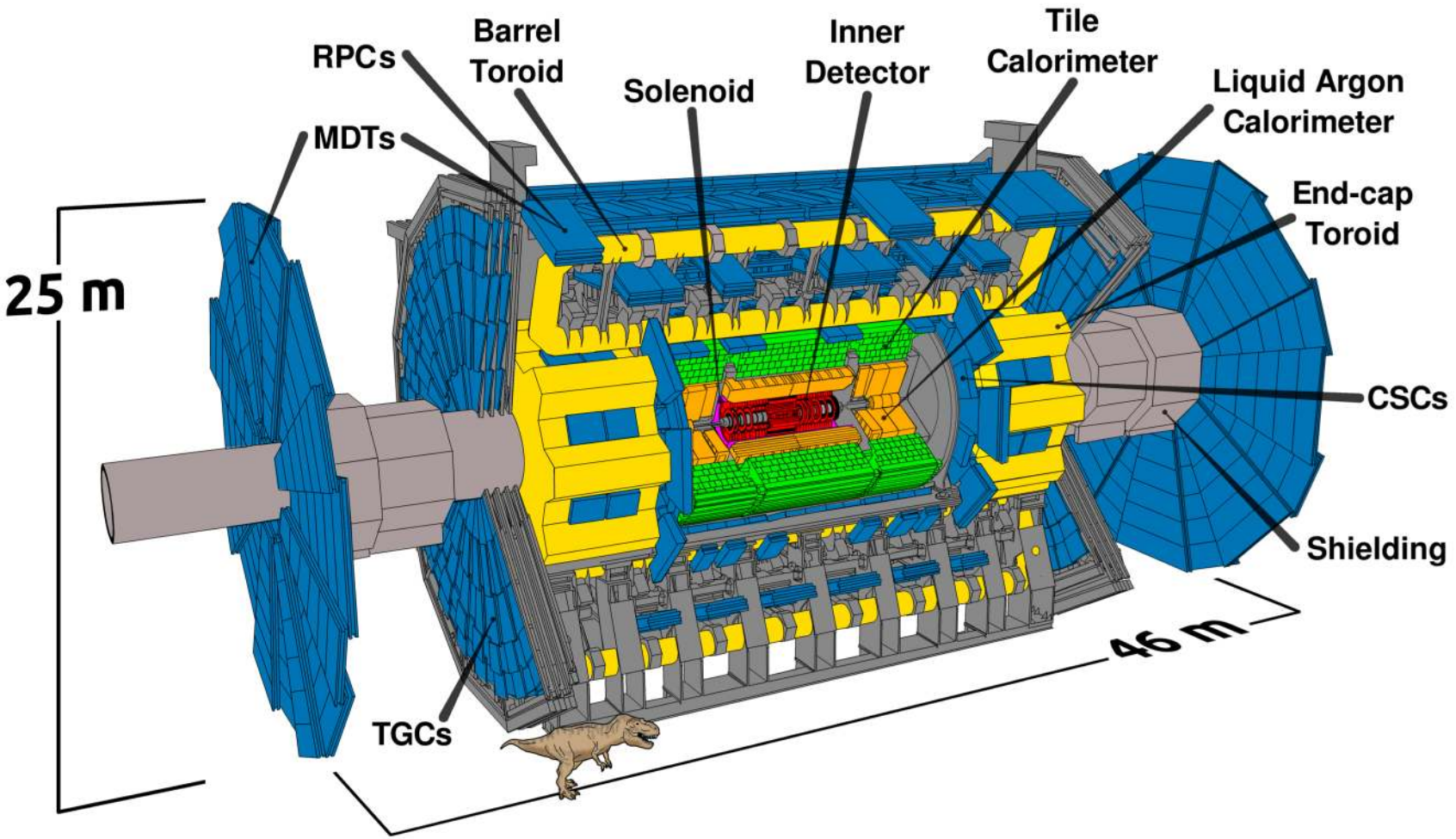
- The LHC has 4 experiments:
  - CMS and ATLAS (that are HUGE all-purpose) and LHCb and ALICE (which are smaller and dedicated)

ATLAS

- ATLAS is the biggest of them all
  - In fact it is the biggest detector of its kind



46 m long, 25 m high, 25 m wide
7000 t of weight
~3000 scientific authors from
183 institutions, 38 countries


RPCs
Barrel Toroid
Solenoid
Inner Detector
Tile Calorimeter
Liquid Argon Calorimeter
MDTs
End-cap Toroid
25 m
CSCs
Shielding
46 m
TGCs

Currently: 2^{d} long shutdown

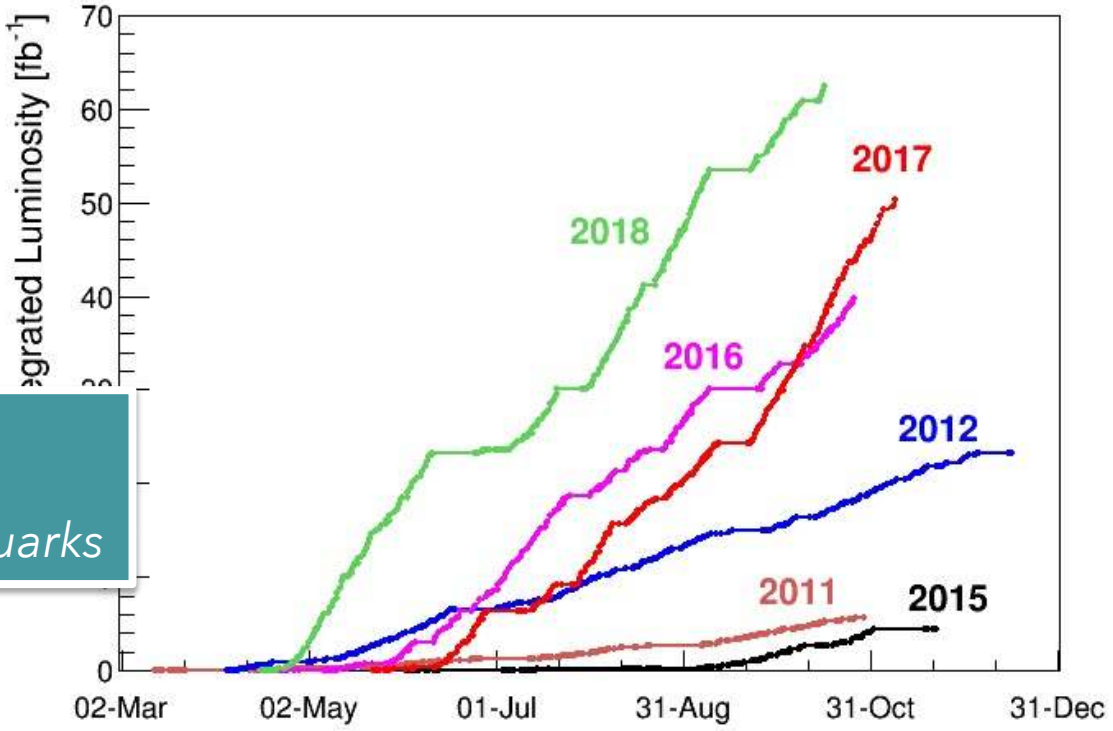
- Time for maintenance and upgrade before the last LHC run

A decade of collisions

- After quite a bumpy start in 2008, at the end of 2009 we had beams back at the LHC, and the first 7TeV collisions came in spring 2010

A decade of data

- Run-1 (2010-2012)
  - **~5fb^{-1}** of pp collisions at 7TeV and **~20fb^{-1}** at 8TeV
- Run-2 (2015-2018)
  - **~150fb^{-1}** of pp collisions at 13TeV



Roughly, per big experiment
- *8M of Higgs bosons*
- *178M of events with top quarks*

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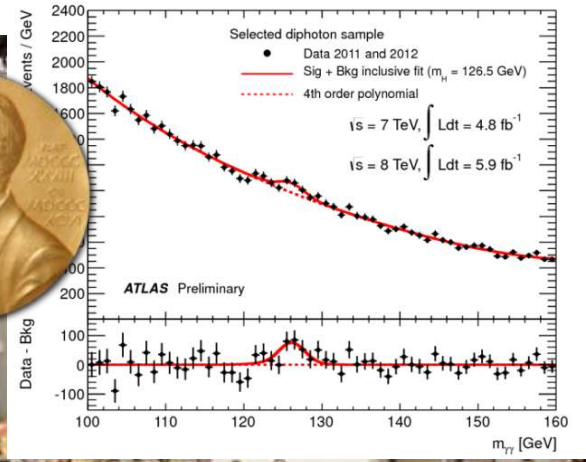
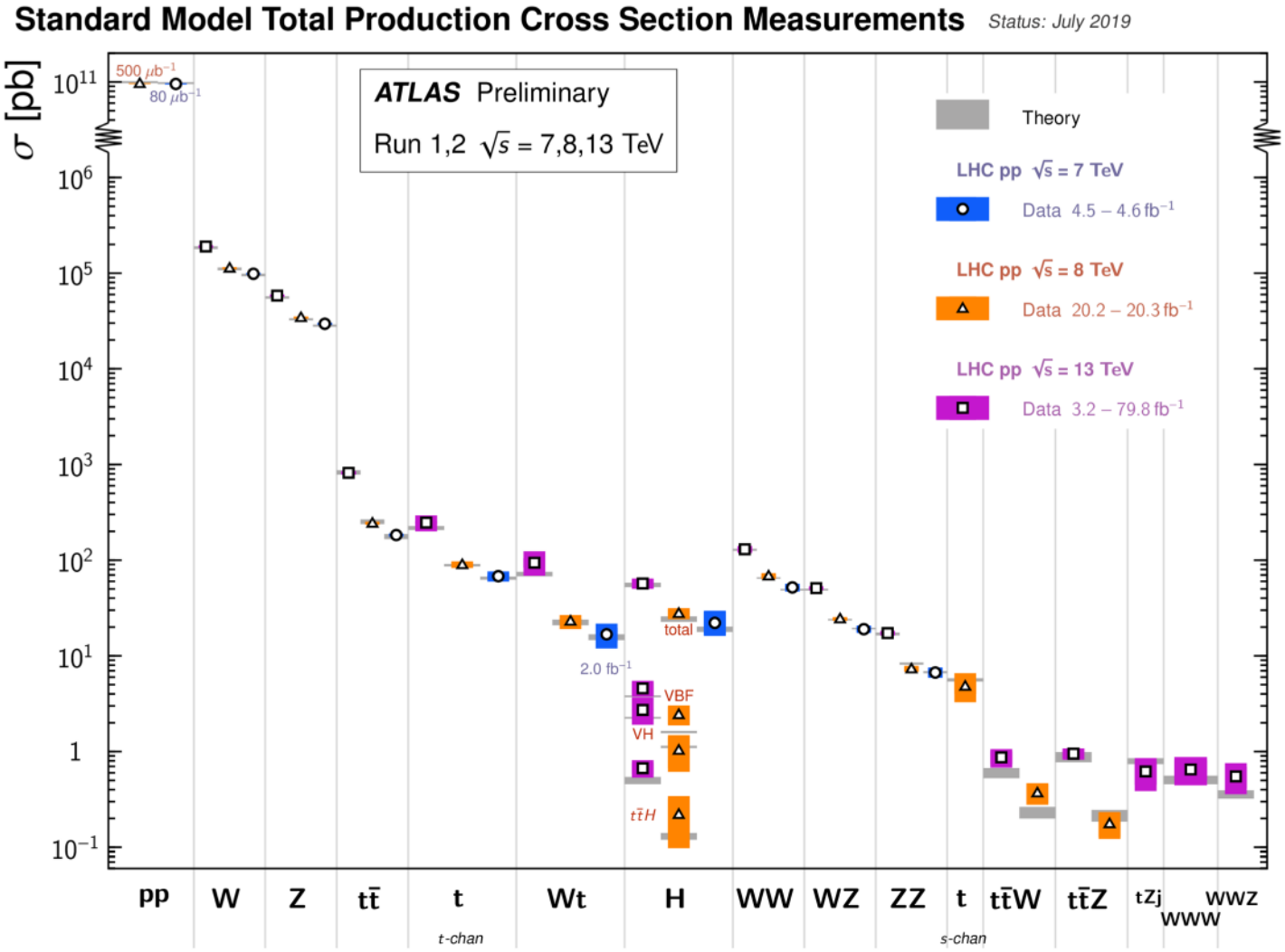
A breakthrough discovery

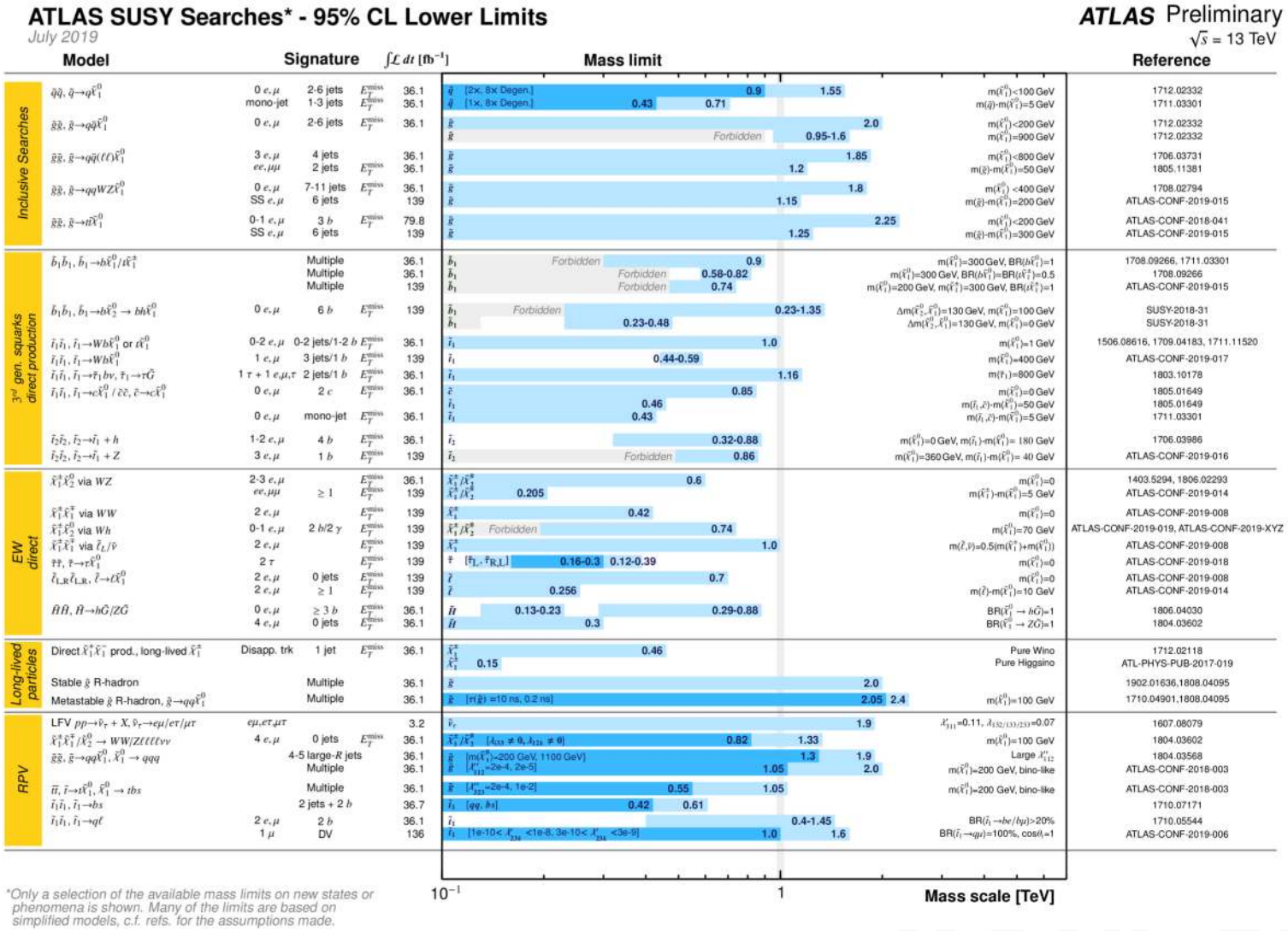


The ~~Higgs~~ Brout-Englert-Higgs boson!

A triumph


Standard Model Total Production Cross Section Measurements
Status: July 2019
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
σ [pb]
500 μb⁻¹
80 μb⁻¹
2.0 fb⁻¹
total
VBF
VH
tt̄H
pp
W
Z
tt̄
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
tt̄W
tt̄Z
tZj
WWW
WWZ

And searches



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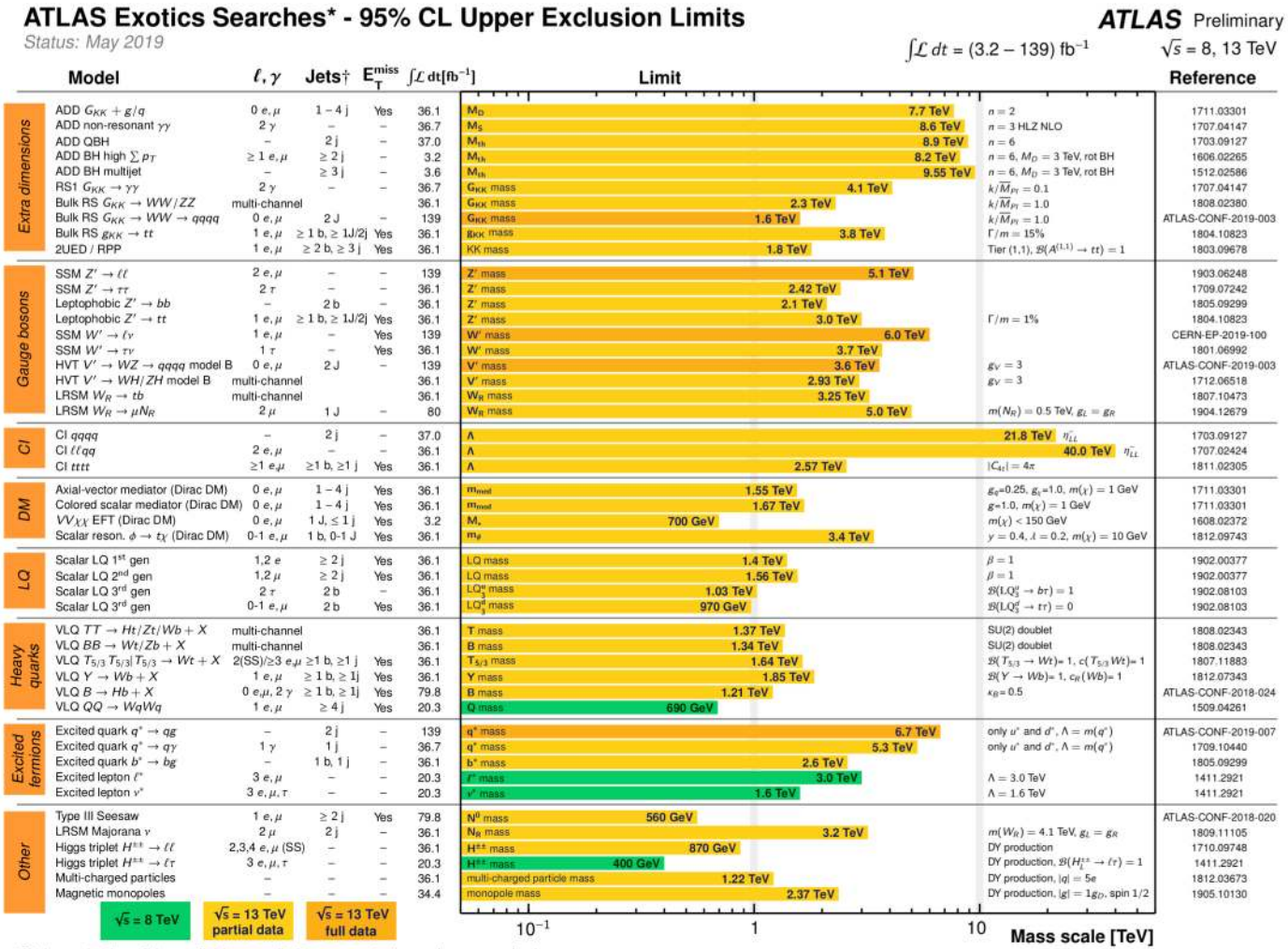
MANY searches



- Our picture of the SM is close to be complete
  - No significant deviations from its predictions have been observed at the LHC so far
- After the Higgs:
  - no other new particles found yet

Are we done?

Absolutely not!

"The easy elementary particle questions were answered thirty and forty years ago"

Martin Lewis Perl
Nobel Prize for the discovery of the tau lepton in 1995
*Phys. perspect. (**2004**) 6: 401*

Time to work on the hard questions

- The SM has been extremely successful in the last 60 years
- But it still falls short in different areas, including but not limited to:
  - **Lack of description for gravity at a fundamental level**
  - **No explanation for neutrino masses**
  - **No explanation for fermion mass structure**
  - **No reason for exactly three generations**
  - **No explanation for the baryon asymmetry of the Universe**
  - **Does not include Dark Matter**
  - **Or Dark Energy**
  - The hierarchy problem…. (infinite dots)
- **There has to be something else!**

How to find new physics?

- We have to keep searching
- We have to keep measuring with high precision

- For this we need new colliders
  - The LHC took ~30 years from proposal to physics

A Few options on the table

- **e+e- linear**
  - International Linear Collider ILC (20 km, 250 GeV) (2024-2033)
  - Compact LInearCollider CLIC (11 km, 380 GeV) (2026-2032)
- **e+e- circular**
  - FCC-ee (100 km up to 400 GeV) (2029-2039)
  - CepC (100 km 240 GeV) (2022-2030)
- **pp circular**
  - HE-LHC (27 km, 27 TeV) (2036-2042)
  - FCC-hh (100 km, 100TeV) (2029-2043)
  - SppC (100 km, 75 TeV)
- **μ+μ- circular**
  - arXiv:1502.02042 arXiv:1901.06150 (2028-2035)
- **Plasma Colliders ?**

Nothing here is real yet
Only proposals!!!

Where are we going?

- Long term we do not know yet…
- But in the **``short''** term we actually have a plan

The HL-LHC

- Run-3: to start in 2021, will give ~300fb^{-1} at 14TeV (new $\sqrt{s}$)
  - it will be **the last run of the LHC as we know it**

- **After RUN-3**
  - **High Luminosity LHC (HL-LHC) upgrade of the LHC**
    - instantaneous luminosities 5x than the nominal value

    → data samples larger by one order of magnitude

  - Run-4, (HL-LHC) will start by ~ 2026
    - HL-LHC will run at least a decade
    - ~3000 fb^{-1} at 14TeV

The HL-LHC

- 5 years of design study and R&D followed by 10 years of developments, prototyping, testing and implementation (**ongoing**)

- Timeline of the project dictated by:
  - critical components of the accelerator reaching the end of their lifetime due to radiation damage
  - **crucial to enable operation of the collider beyond 2025**

- HL-LHC will rely on Innovative technologies
  - 11-12 T superconducting magnets, compact superconducting crab cavities, new technology for beam collimation, high-power, loss-less superconducting links….
  - All the info: HL-LHC Technical Design Report , HL-LHC book

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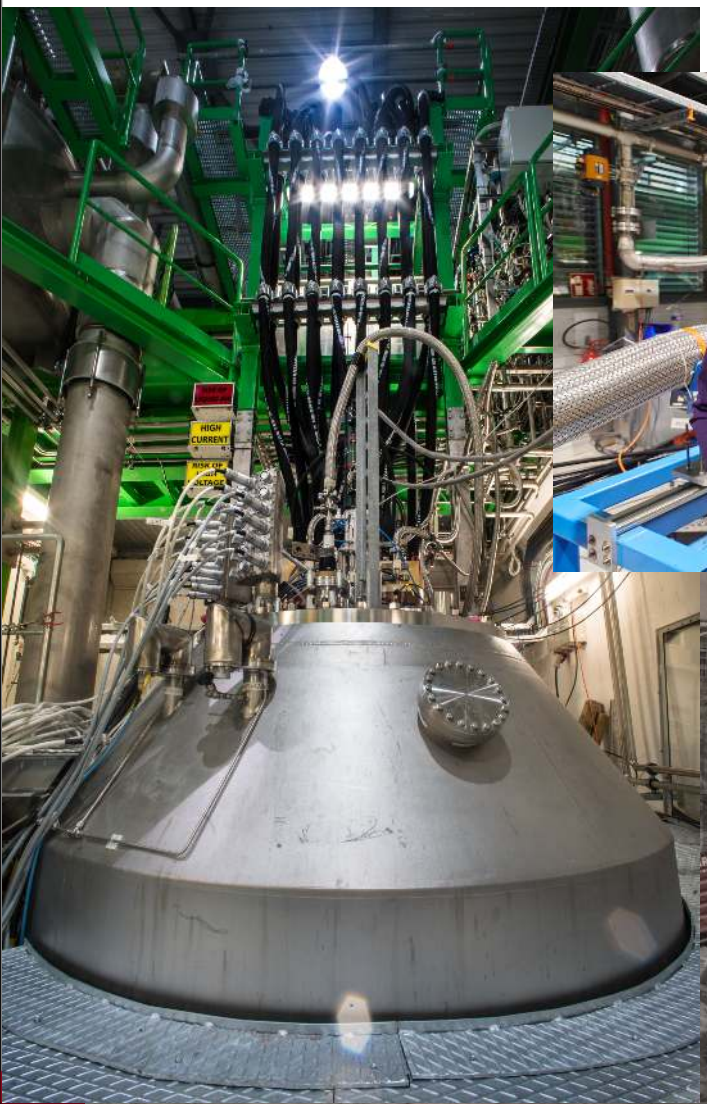
Work is already ongoing



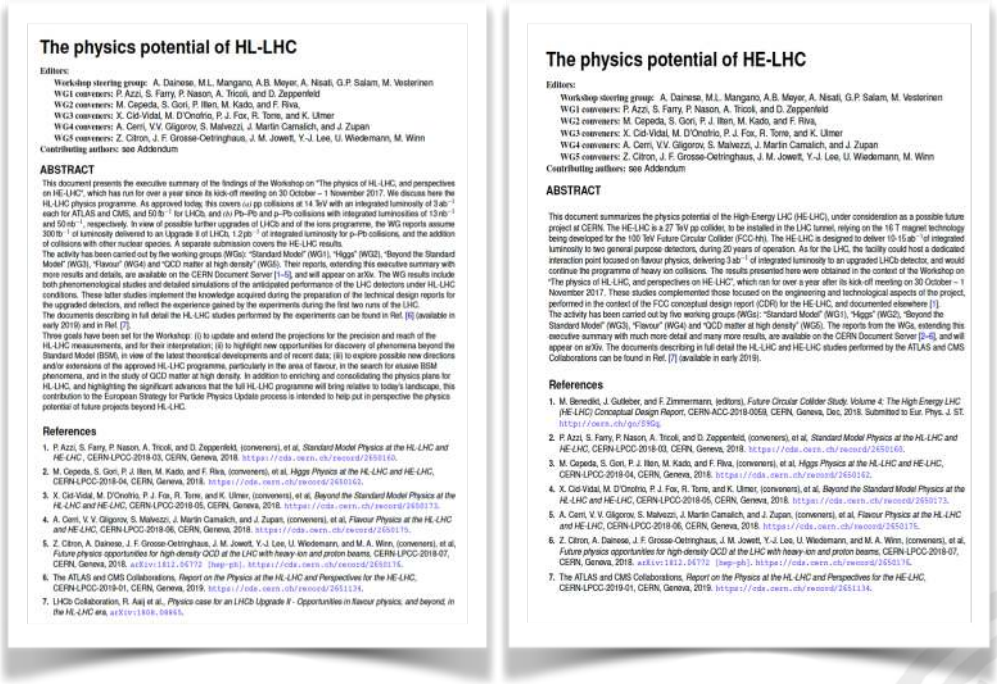
LIEBHERR

The physics

- At the HL-LHC we will have more data
  - We will keep probing SM processes, with higher precision
    - Higher chance to find deviations with respect to the predictions
  - We will test still unexplored areas --**especially low cross section processes**
    - The HL-LHC will be our first shot to understand double Higgs production
  - The opportunity to directly discover new particles and phenomena will also increase

If you want to know more…

Slide from María Cepeda



The physics potential of HL-LHC

Editors:

Workshop steering group: A. Dainese, M.L. Mangano, A.B. Meyer, A. Nisati, G.P. Salam, M. Vesterinen

WG1 conveners: P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld

WG2 conveners: M. Cepeda, S. Gori, P. Ilten, M. Kado, and F. Riva,

WG3 conveners: X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer

WG4 conveners: A. Cerri, V.V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan

WG5 conveners: Z. Citron, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, M. Winn

Contributing authors: see Addendum

ABSTRACT

This document presents the executive summary of the findings of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC", which has run for over a year since its kick-off meeting on 30 October – 1 November 2017. We discuss here the HL-LHC physics programme. As approved today, this covers (a) pp collisions at 14 TeV with an integrated luminosity of 3 ab^{-1} each for ATLAS and CMS, and 50 fb^{-1} for LHCb, and (b) Pb–Pb and p–Pb collisions with integrated luminosities of 13 nb^{-1} and 50 nb^{-1}, respectively. In view of possible further upgrades of LHCb and of the ions programme, the WG reports assume 300 fb^{-1} of luminosity delivered to an Upgrade II of LHCb, 1.2 pb^{-1} of integrated luminosity for p–Pb collisions, and the addition of collisions with other nuclear species. A separate submission covers the HE-LHC results.

The activity has been carried out by five working groups (WGs): "Standard Model" (WG1), "Higgs" (WG2), "Beyond the Standard Model" (WG3), "Flavour" (WG4) and "QCD matter at high density" (WG5). Their reports, extending this executive summary with more results and details, are available on the CERN Document Server [1–5], and will appear on arXiv. The WG results include both phenomenological studies and detailed simulations of the anticipated performance of the LHC detectors under HL-LHC conditions. These latter studies implement the knowledge acquired during the preparation of the technical design reports for the upgraded detectors, and reflect the experience gained by the experiments during the first two runs of the LHC.

The documents describing in full detail the HL-LHC studies performed by the experiments can be found in Ref. [6] (available in early 2019) and in Ref. [7].

Three goals have been set for the Workshop: (i) to update and extend the projections for the precision and reach of the HL-LHC measurements, and for their interpretation; (ii) to highlight new opportunities for discovery of phenomena beyond the Standard Model (BSM), in view of the latest theoretical developments and of recent data; (iii) to explore possible new directions and/or extensions of the approved HL-LHC programme, particularly in the area of flavour, in the search for elusive BSM phenomena, and in the study of QCD matter at high density. In addition to enriching and consolidating the physics plans for HL-LHC, and highlighting the significant advances that the full HL-LHC programme will bring relative to today's landscape, this contribution to the European Strategy for Particle Physics Update process is intended to help put in perspective the physics potential of future projects beyond HL-LHC.

References

1. P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld, (conveners), et al., *Standard Model Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-03, CERN, Geneva, 2018. https://cds.cern.ch/record/2650160.
2. M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al., *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, CERN, Geneva, 2018. https://cds.cern.ch/record/2650162.
3. X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer, (conveners), et al., *Beyond the Standard Model Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-05, CERN, Geneva, 2018. https://cds.cern.ch/record/2650173.
4. A. Cerri, V. V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan, (conveners), et al., *Flavour Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-06, CERN, Geneva, 2018. https://cds.cern.ch/record/2650175.
5. Z. Citron, A. Dainese, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, and M. A. Winn, (conveners), et al., *Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams*, CERN-LPCC-2018-07, CERN, Geneva, 2018. arXiv:1812.06772 [hep-ph]. https://cds.cern.ch/record/2650176.
6. The ATLAS and CMS Collaborations, *Report on the Physics at the HL-LHC and Perspectives for the HE-LHC*, CERN-LPCC-2019-01, CERN, Geneva, 2019. https://cds.cern.ch/record/2651134.
7. LHCb Collaboration, R. Aaij et al., *Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*, arXiv:1808.08865.

The physics potential of HE-LHC

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Contributing authors: see Addendum

ABSTRACT

This document summarizes the physics potential of the High-Energy LHC (HE-LHC), under consideration as a possible future project at CERN. The HE-LHC is a 27 TeV pp collider, to be installed in the LHC tunnel, relying on the 16 T magnet technology being developed for the 100 TeV Future Circular Collider (FCC-hh). The HE-LHC is designed to deliver 10-15 ab^{-1} of integrated luminosity to two general purpose detectors, during 20 years of operation. As for the LHC, the facility could host a dedicated interaction point focused on flavour physics, delivering 3 ab^{-1} of integrated luminosity to an upgraded LHCb detector, and would continue the programme of heavy ion collisions. The results presented here were obtained in the context of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC", which ran for over a year after its kick-off meeting on 30 October – 1 November 2017. These studies complemented those focused on the engineering and technological aspects of the project, performed in the context of the FCC conceptual design report (CDR) for the HE-LHC, and documented elsewhere [1].

The activity has been carried out by five working groups (WGs): "Standard Model" (WG1), "Higgs" (WG2), "Beyond the Standard Model" (WG3), "Flavour" (WG4) and "QCD matter at high density" (WG5). The reports from the WGs, extending this executive summary with much more detail and many more results, are available on the CERN Document Server [2–6], and will appear on arXiv. The documents describing in full detail the HL-LHC and HE-LHC studies performed by the ATLAS and CMS Collaborations can be found in Ref. [7] (available in early 2019).

References

1. M. Benedikt, J. Gutleber, and F. Zimmermann, (editors), *Future Circular Collider Study. Volume 4: The High-Energy LHC (HE-LHC) Conceptual Design Report*, CERN-ACC-2018-0059, CERN, Geneva, Dec, 2018. Submitted to Eur. Phys. J. ST. http://cern.ch/go/89Gq.
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3. M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al., *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, CERN, Geneva, 2018. https://cds.cern.ch/record/2650162.
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SM & TOP - CERN-LPCC-2018-03

Higgs - CERN-LPCC-2018-04

BSM - CERN-LPCC-2018-05

Flavor - CERN-LPCC-2018-06

Heavy Ions - CERN-LPCC-2018-07

The ATLAS Phase-I Upgrade

- ATLAS is being upgraded as we speak (and so has been previously)

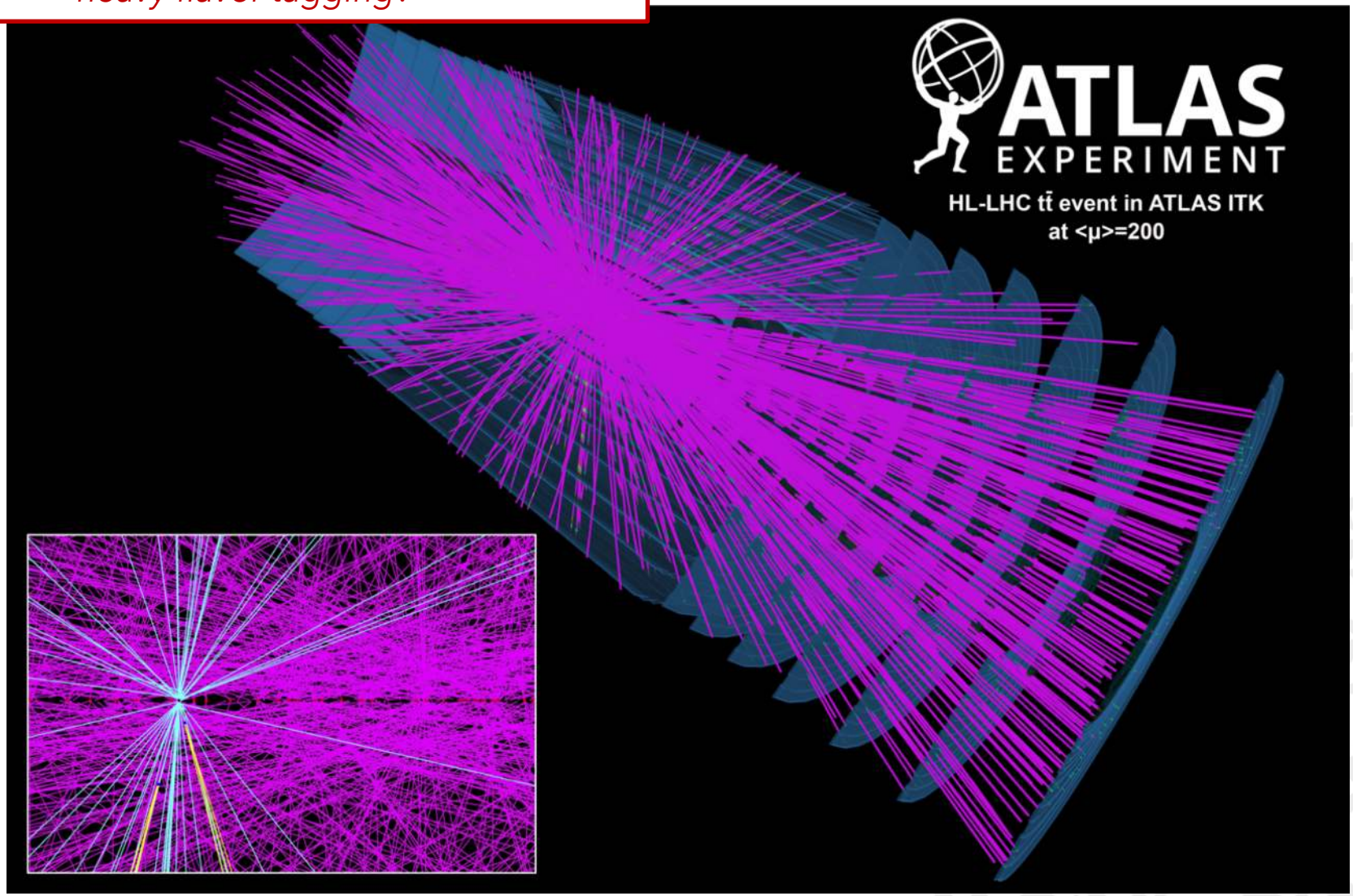
The ATLAS upgrade for the HL-LHC

- The largest changes to ATLAS will come with the **Phase-II** upgrade, the one that will prepare it for the HL-LHC
- The detectors will have to handle
  - higher particle densities → increased occupancies
  - higher radiation levels
- Reconstructing what happens in a collision at the HL-LHC will be EXTREMELY challenging
  - very high pile-up, luminosity 7.5x design
    - ~200 pp collisions are expected every 25 ns

      (~36-37 in Run-2)
    - with just 1/200 of those being interesting…

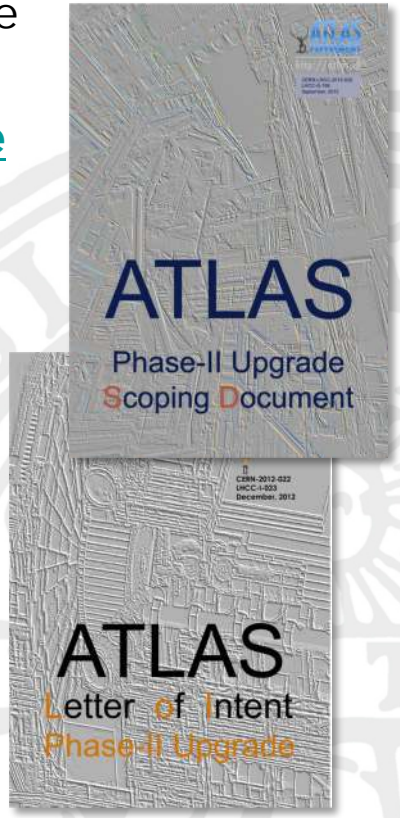
- *How to maintain the performance in*
  - *vertex and track reconstruction?*
  - *lepton identification?*
  - *heavy flavor tagging?*

It will look like this

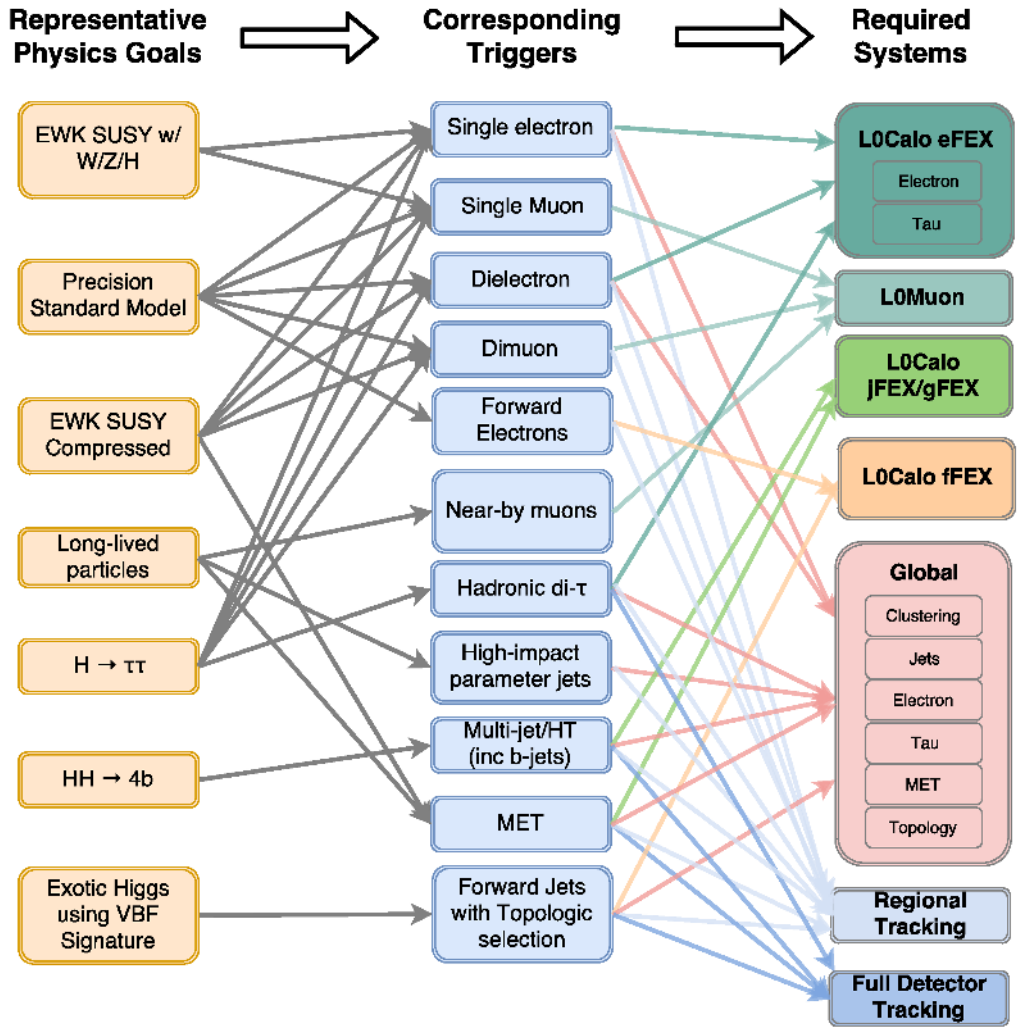


Detector challenges

- Three major detector upgrades:
  - complete replacement of the **inner tracking** system
  - new **radiation-tolerant read-out electronics** for the tracking, calorimeter and muon systems
  - **Trigger and Data Acquisition (TDAQ) architecture**

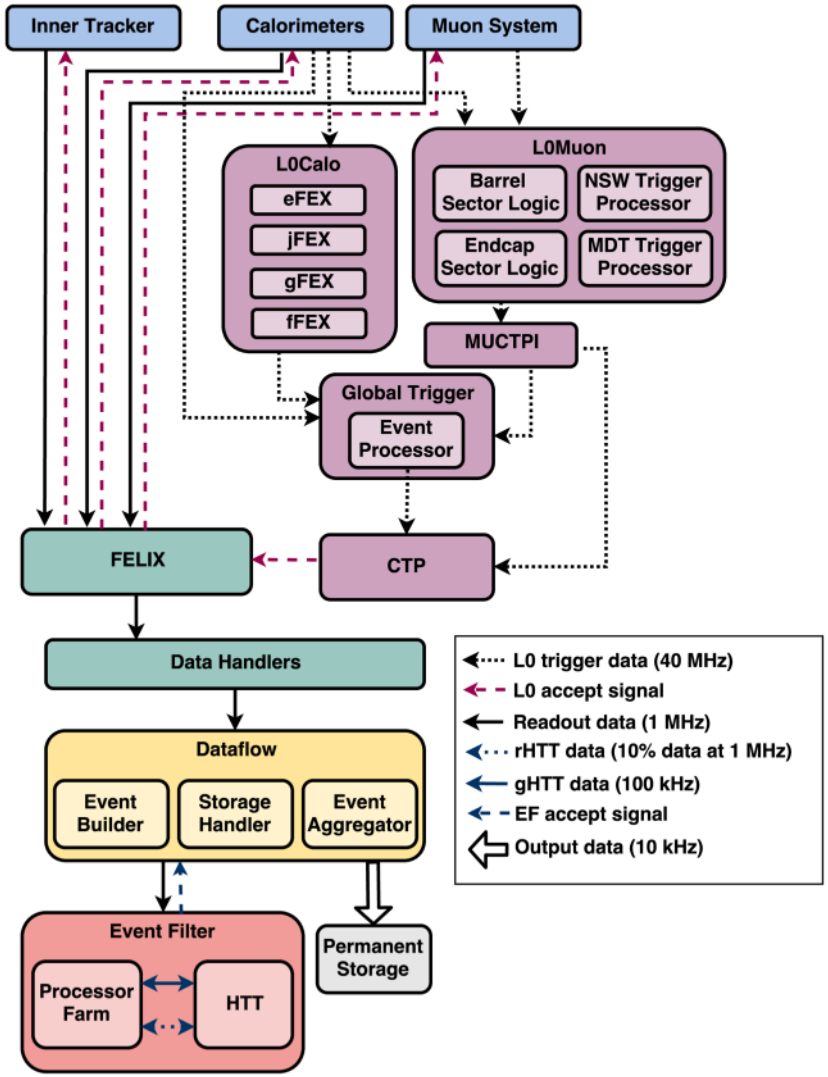


Trigger matters



- Physics goals of the HL-LHC ⟷ hardware systems
- ATLAS will run a single level trigger (L0) at 1MHz
  - 10 x the Run-3 rate
- In order to facilitate this flow the TDAQ should adapt

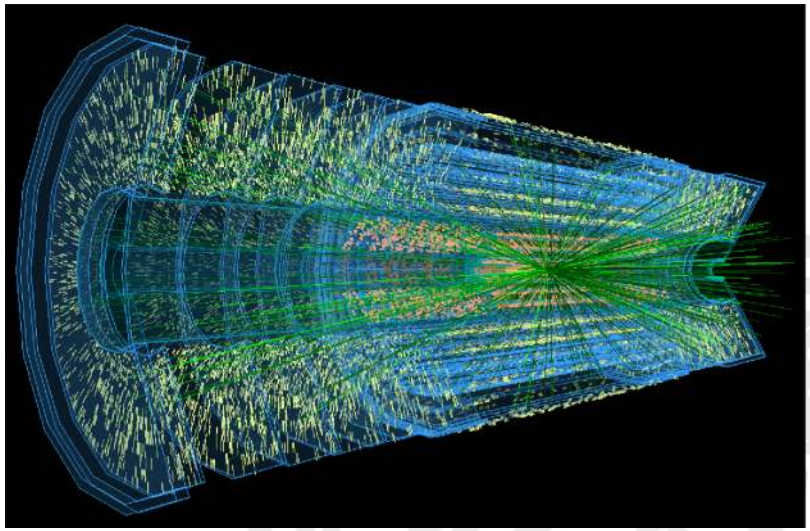
Phase-II upgrade of the TDAQ



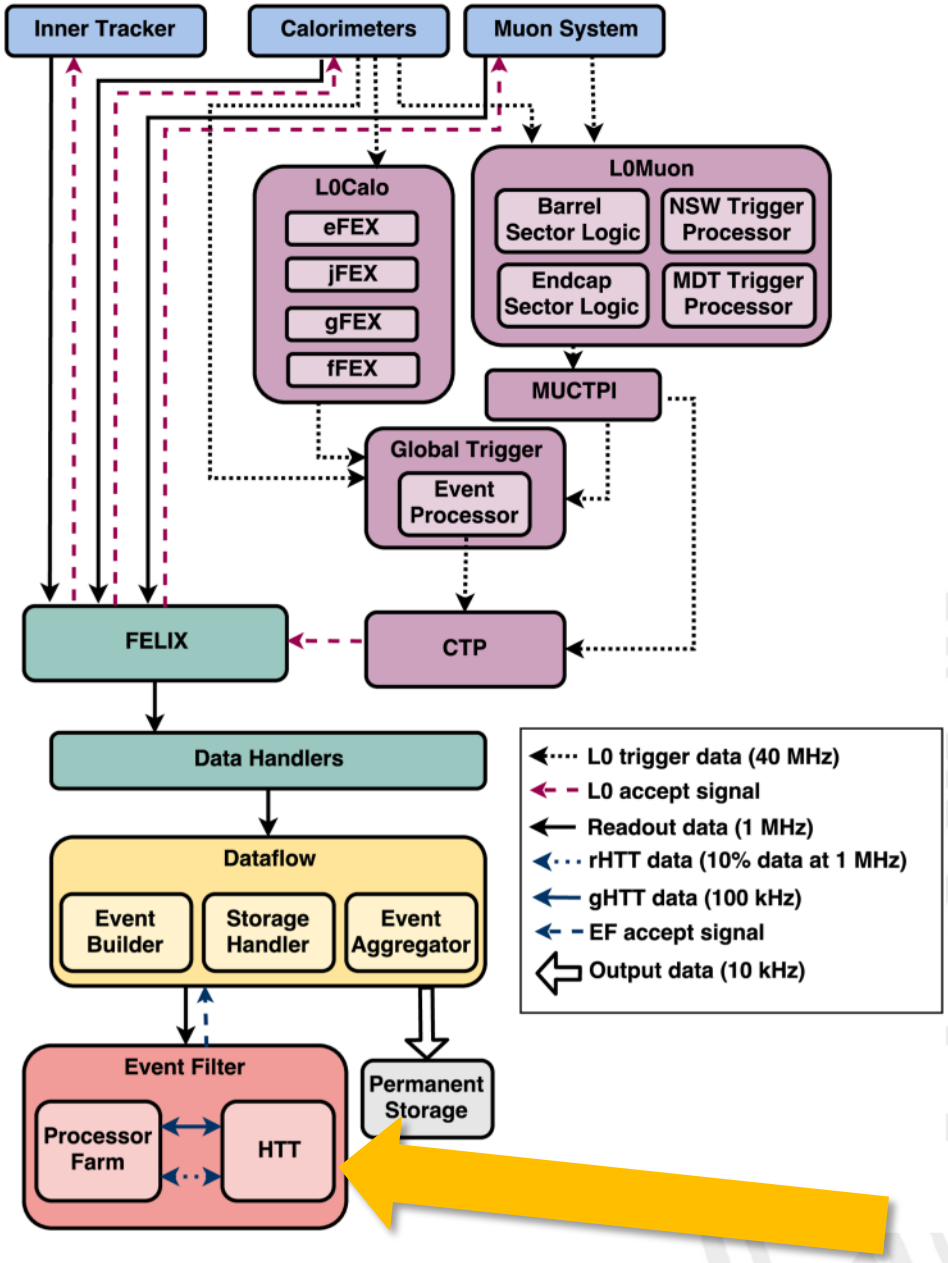
- Baseline configuration:
  - single Level-0 hardware trigger
  - read-out rate of 1MHz
  - maximum latency of 10 μs
- Level-0 trigger decision done using information from the calorimeter and muon detector systems
- All ATLAS upgrade projects are designed also for an evolved, so-called "L0/L1" architecture

Tracking for Trigger

- Charged particle reconstruction in high-pileup conditions → clear challenge for the trigger
- To use of information from the tracking as early as possible in the trigger selection
  - central to the new ATLAS TDAQ



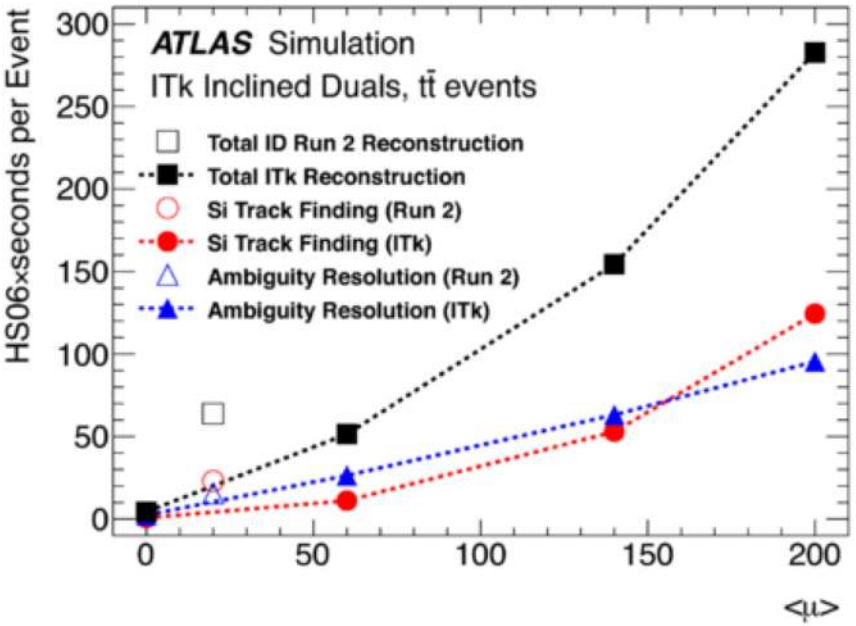
- What is the plan?
  - A **hardware-based system (HTT)** based on custom AM ASICs for pattern recognition and FPGAs for track reconstruction/fitting
  - tracking done directly in hardware


Inner Tracker
Calorimeters
Muon System
L0Calo
eFEX
jFEX
gFEX
fFEX
L0Muon
Barrel Sector Logic
NSW Trigger Processor
Endcap Sector Logic
MDT Trigger Processor
MUCTPI
Global Trigger
Event Processor
FELIX
CTP
Data Handlers
Dataflow
Event Builder
Storage Handler
Event Aggregator
Event Filter
Processor Farm
HTT
Permanent Storage
L0 trigger data (40 MHz)
L0 accept signal
Readout data (1 MHz)
rHTT data (10% data at 1 MHz)
gHTT data (100 kHz)
EF accept signal
Output data (10 kHz)

Why a dedicated hardware system?

- Technologically more risky than CPU but:
  - **Efficient use of resources**
    - In-house expertise in ATLAS
  - **Potential for short latency**
    - O (100 μs) latency for full tracking → 10^4 times faster than CPU!
  - **Lower power budget**
  - Less demanding space requirements wrt to other technologies
  - Cost-effectiveness
    - Independence of its cost from the commodity computing market
  - Capability to evolve it for use in the hardware-based Level-1 trigger
    - "L1Track" running on data stream with regional tracking at 4MHz

But it really boils down to this



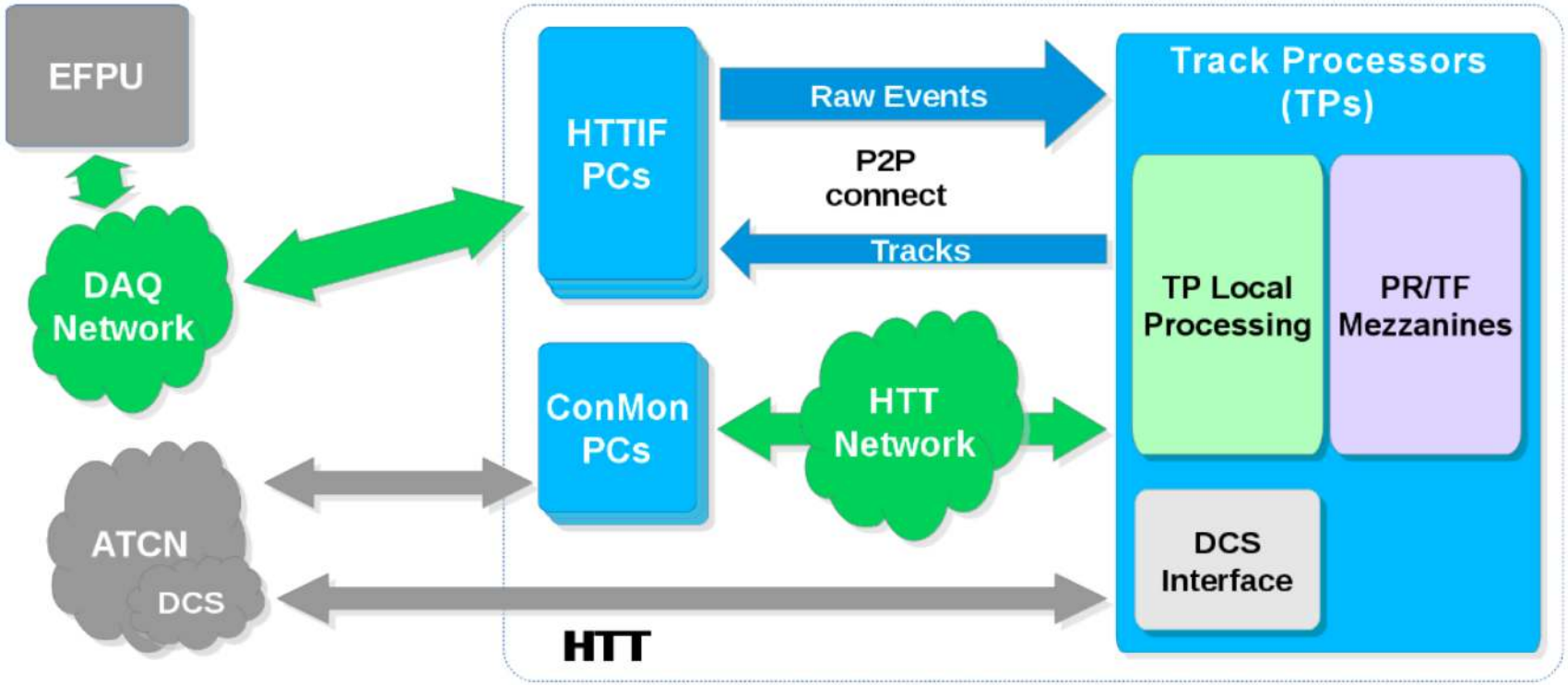
CPU time required to reconstruct a tt event in the ITk with different levels of average pile-up

- Tracking is the most computing-intensive reconstruction algorithm in the trigger system, so if you want to use tracks in the trigger:
  - **Offloading to hardware frees CPU time**

Detector, Pile-up	Cluster Finding	Space Points	Si Track Finding	Ambiguity Resolution	TRT+Back Tracking	Primary Vertex	Total ITk/ID
ITk, 200	26	24	124	96	-	6	283
Run 2, 20	1.5	0.7	23	15	19	0.5	64

What will HTT do?

- Massive co-processor to CPU farm (EF), **tracking on request**
- Event-data provided by EF Processing Unit (EFPU)
- **HTT will return tracks**

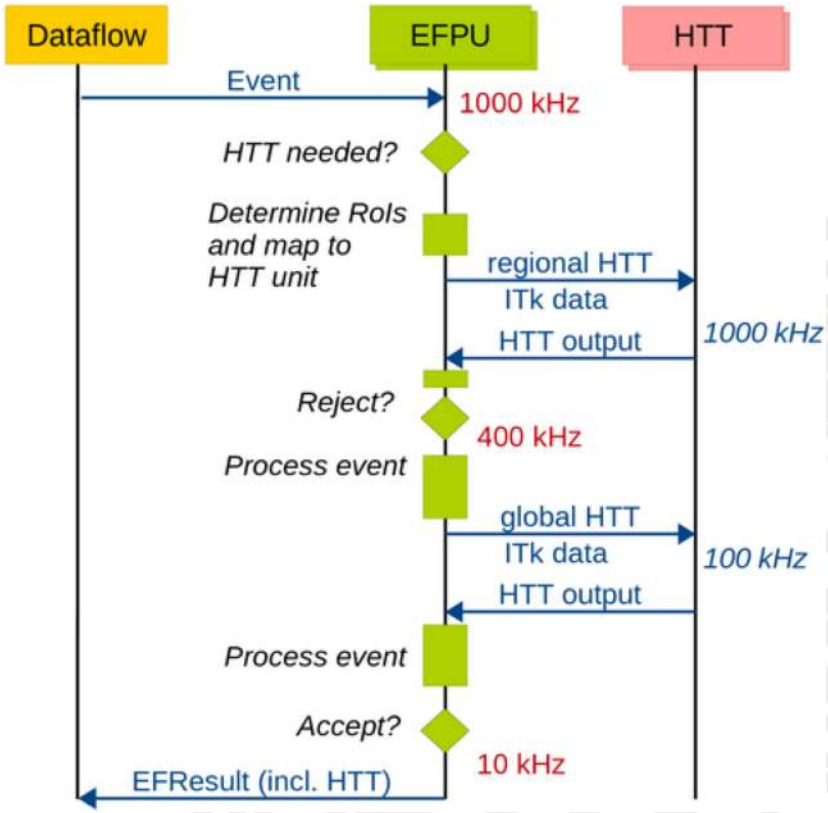


Regional and Global tracking

- It will act in two ways:

- Regional Tracking (rHTT)
  - first stage, $p_T > 2$ GeV
  - 10% of the ITk data, around L0 RoIs
  - reducing the rate < 350kHz

- Global Tracking (gHTT)
  - second stage, $p_T > 1$GeV
  - High precision, full detector
  - Further reducing the rate, up to 100kHz



Design phase

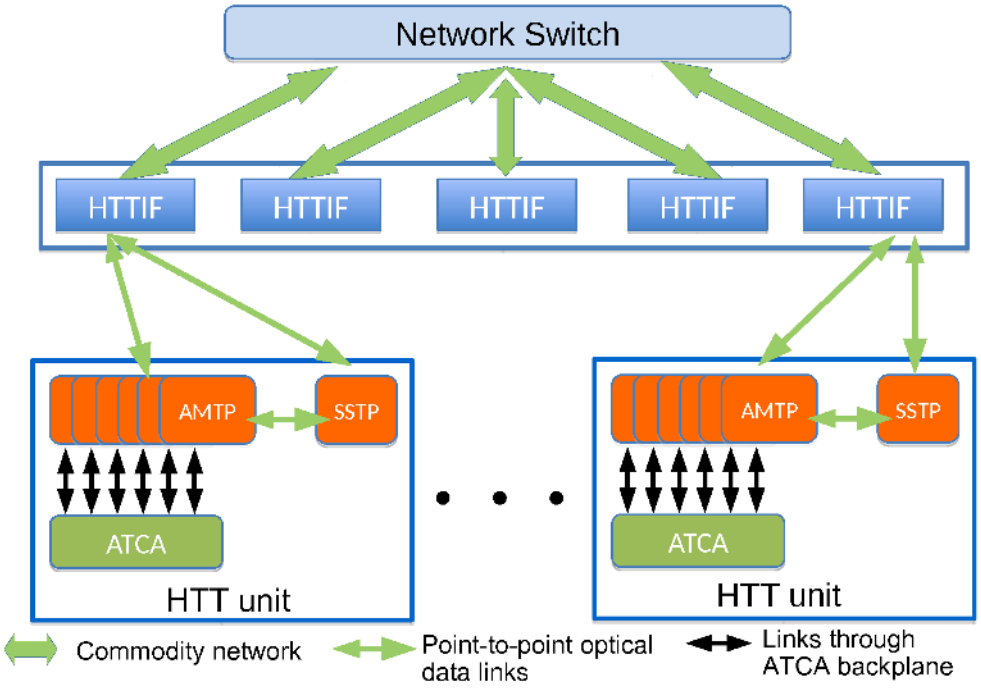
- The HTT is currently in design phase
- Simpler, more homogeneous system than FTK
  - applying FTK experience

Flexible, parallelized, modular, able to evolve

- Challenges: Power budget and data flow

HTT system

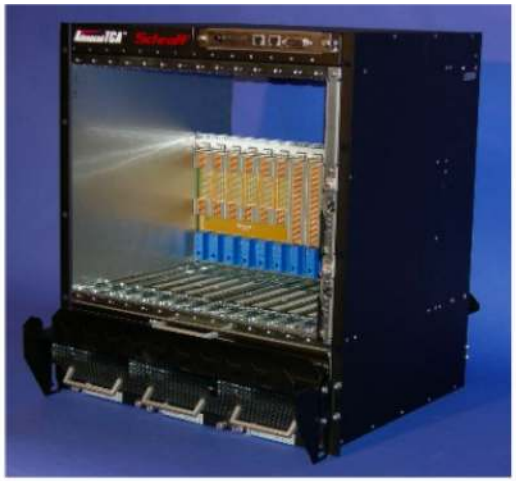
- 48 independent HTT units, each tracking for **specific η × φ region**
- One HTT unit → one ATCA shelf
- Common Tracking Processor (TP) boards, 2 configurations



- 1st stage track, **AMTP**
  - TP board with Pattern Recognition Mezzanine (PRM)
  - AM ASICs
- 2d stage track, **SSTP**
  - TP board with Track Fitting Mezzanine (TFM)
  - FPGAs
- interface with EF processors
  - HTTIF, PC-based

Baby pictures of the hardware

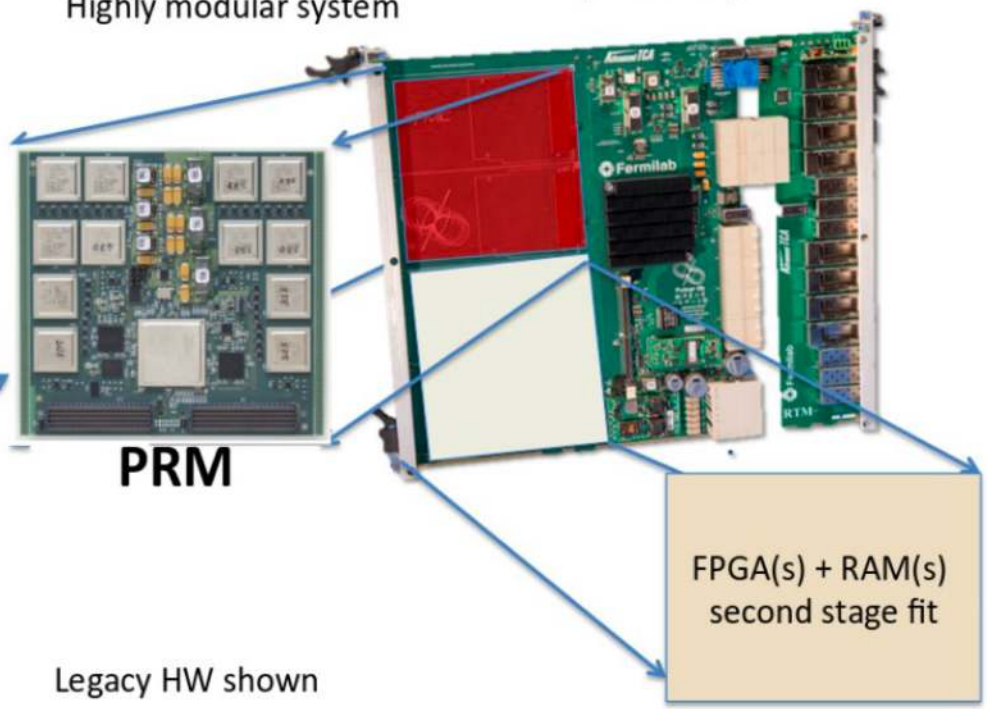
It may not look the same when it grows up!



HW model

Highly modular system

AMTP & SSTP
(same HW)



AM chip

x16

PRM

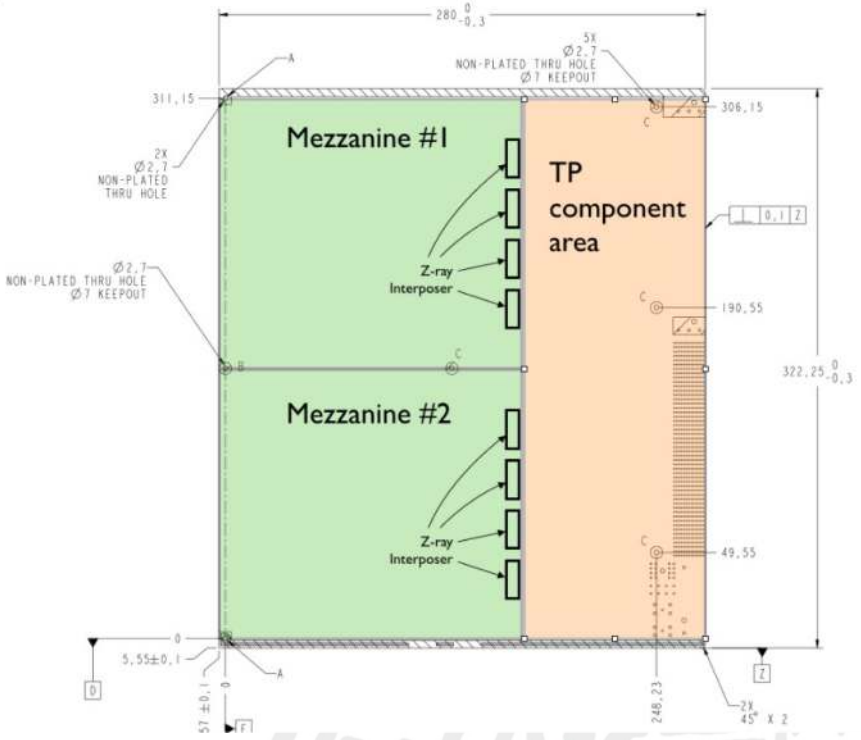
FPGA(s) + RAM(s)
second stage fit

TFM

Legacy HW shown

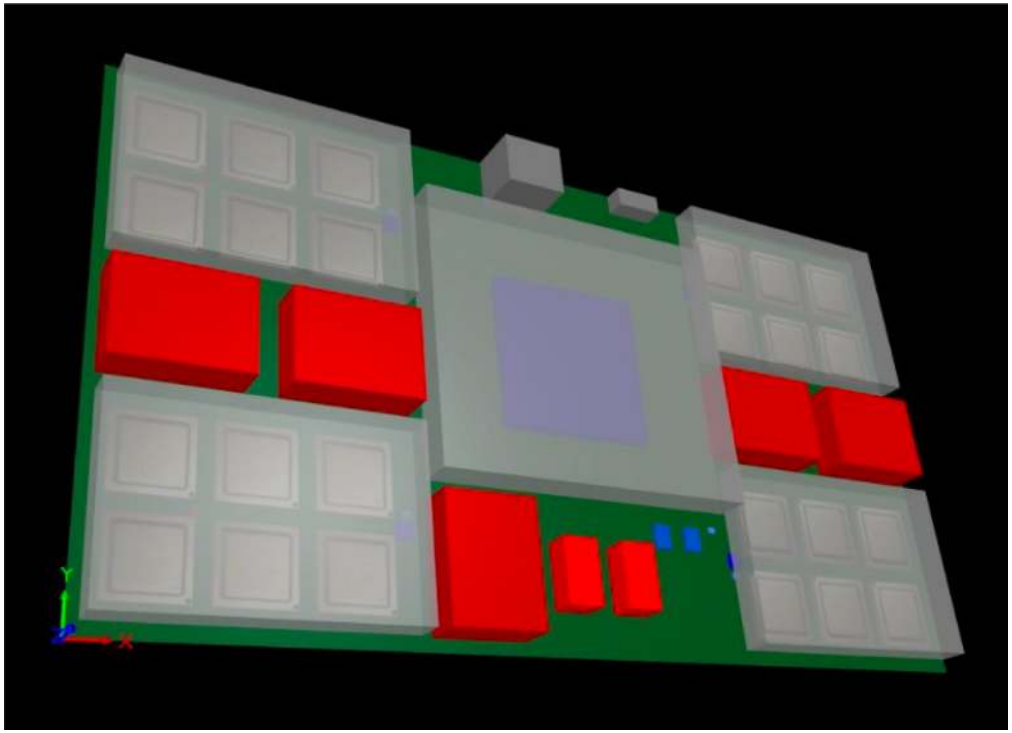
Tracking processor (TP) board

- High-Bandwidth motherboard
  - data communication to /from HTTIF and mezzanine cards
  - data sharing
  - specific algorithms (clustering, duplicates removal)
- Used in both
  - AMTP
    - Pattern Recognition Mezzanine
  - SSTP
    - Track fitting mezzanine
  - High power dissipation, cooling of the electronics must be maximized



- *2 small mezzanines or 1 large mezzanine*
- *10 Gbps links*
- *Large FPGA*
- *SoC (**System on a chip**) to support DCS and monitoring*
- *ATCA support*

Pattern Recognition mezzanine (PRM)



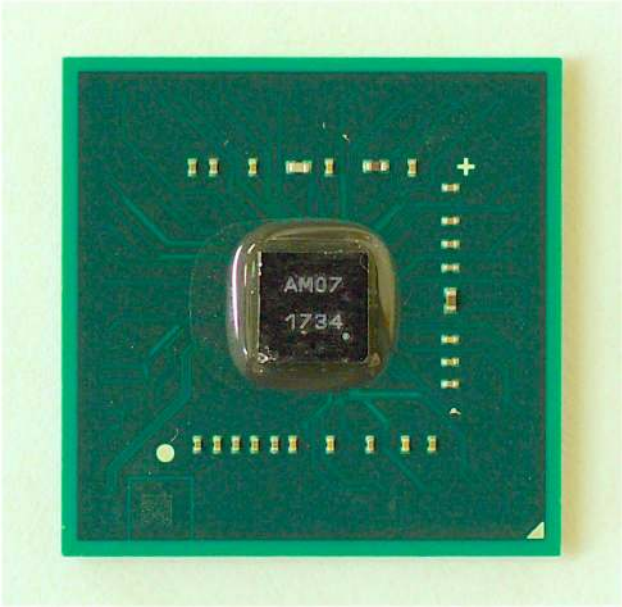
- *4 Blocks of 6 AM-ASICs (9.2M patterns/PRM)*
- *One large FPGA for data sharing and algorithms*
- *High Speed Lines (10 Gbps)*

DC/DC converters + passive elements (red blocks)
heatsinks (in gray)

- Single board occupying full width of TP
  - 1 mezzanine
- 24 Associative Memory (AM) application-specific integrated circuits (ASICs)
  - 4 groups of 6
- I/O bandwidth: 10 Gbps
- Peak cluster rate/layer: 250MHz
- Fit rate: 1GHz
- Performs first level fitting (8-layers)

AM09 ASICS

- Low power, small size
  - high density of chips on board
- AM09:
  - production version for HTT
  - Evolution of FTK AM06
  - Simulation predicts better energy efficiency, improving # of patterns, I/O bandwidths
- 384k patterns/chip
  - 3 times more in same area than previous production version AM06
- Estimate of power consumption
  - P = 1W+ < input rate > * 0.05W/MHz
- Submission planned in 2020



Current understanding of AM07 tests and AM08 simulations shows that AM09 will be within the allocated budget both in terms of area and power consumption

Why ASICs for pattern matching?

- ASICs are:
  - more complicated to develop than FPGAs
  - Non reprogrammable

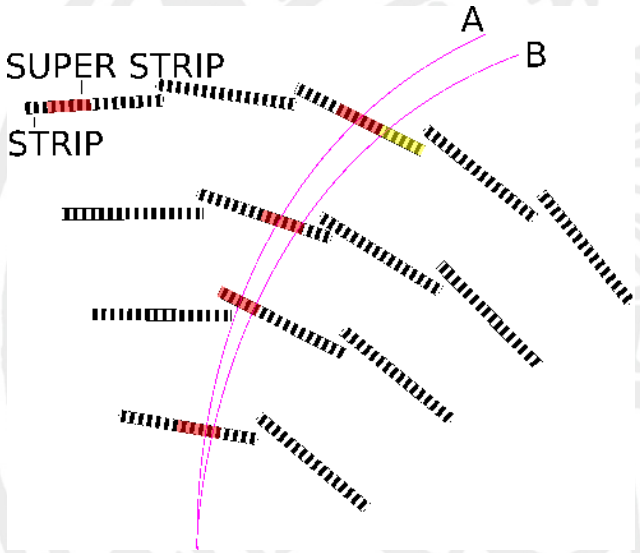
  BUT

  - They provide high performance
  - Cheaper than FPGAs -at a larger scale
  - In a small size
  - With low power consumption

- And the last two points are key to the HTT design

The HTT in action

- **AMTP:**
  - Receives request with data from EF (via HTTIF)
    - groups of ITk hits
  - sends clusters to PRM
- **PRM:**
  - convert clusters into patterns of Super Strips
  - patterns are matched to precomputed patterns
  - Matched patterns → roads
  - roads → cluster combinations
  - cluster combinations sent back to AMTP



- **AMTP:**
  - If rHTT request:
    - **1st stage tracking**
      - Processing the matched hit combinations with linearized track-fitting algorithms
    - **tracks and clusters returned to EF (END)**
  - If gHTT request:
    - **2d stage tracking**
    - tracks and clusters sent to **SSTP** (FPGAs)

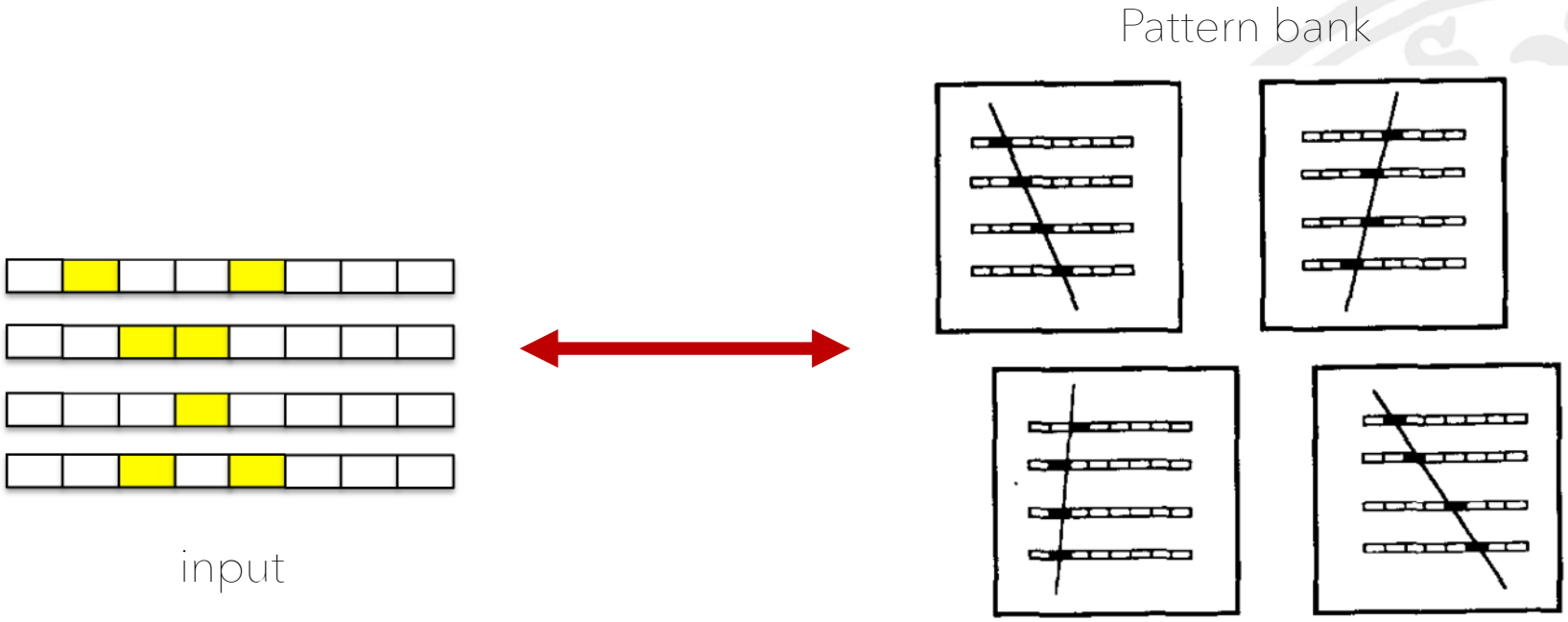
Track Fitting Mezzanine (TFM)

- **SSTP**
  - Receives tracks and clusters from 1st stage fitting for 2d stage fitting (gHTT)
  - **TFM**
    - Extrapolates tracks into remaining ITk layers, finds nearby hits
      - if a pixel hit is missing, the hit is guessed
    - Performs **full fit** of hit combinations
    - Output: hits and track parameters
      - **to SSTP, and from them to the EF (DONE)**

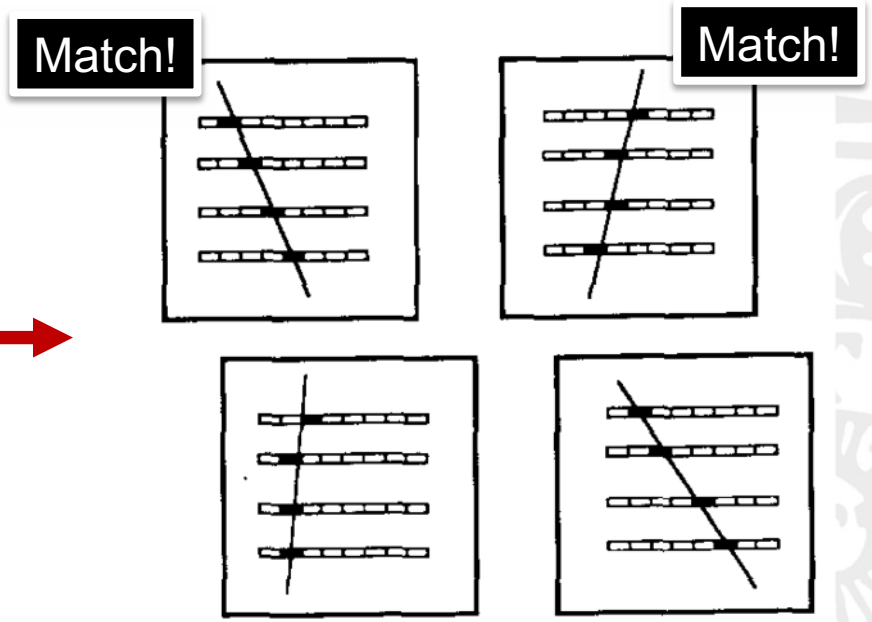
This is done in one large FPGA with high-speed links to TP
Similar connectors and heat sinks as PRM
Power within limits (nominal power = 76W; maximum power = 92W)

Track filtering

- The HTT will then do two things
  1. **Track-filtering:**
     - pattern-recognition with AM ASICs
     - pre-calculated patterns of 8-layer hits



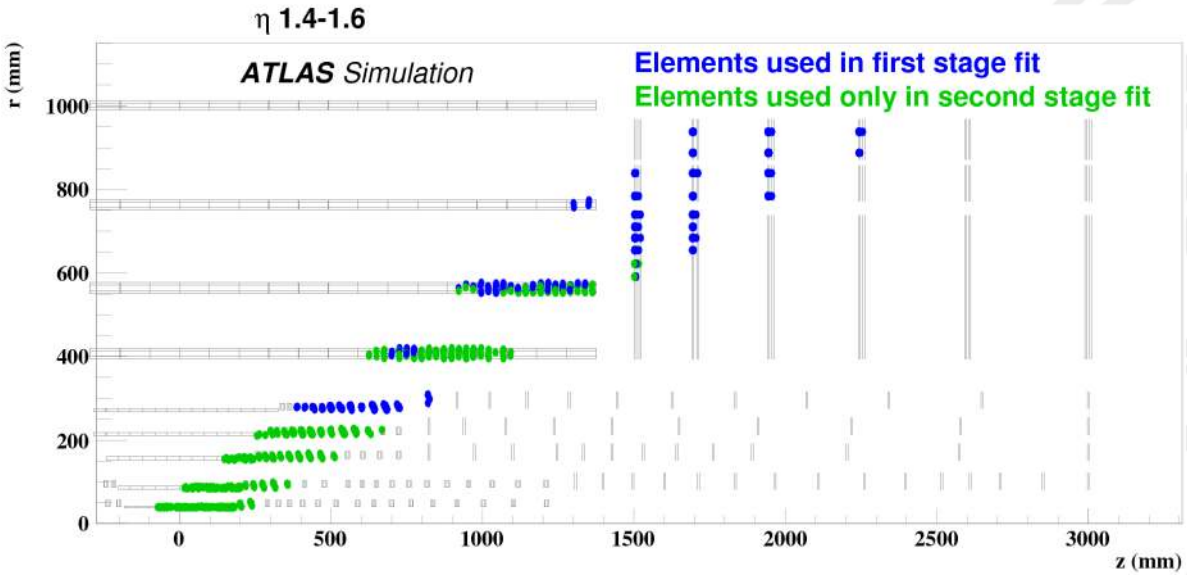
Pattern banks



Track fitting

2. Track-fitting:

- fit algorithms in FPGAs:
  - 1st stage:
    - 8 layers (rHTT)
  - 2nd stage:
    - 14 layers (gHTT), using rHTT as input



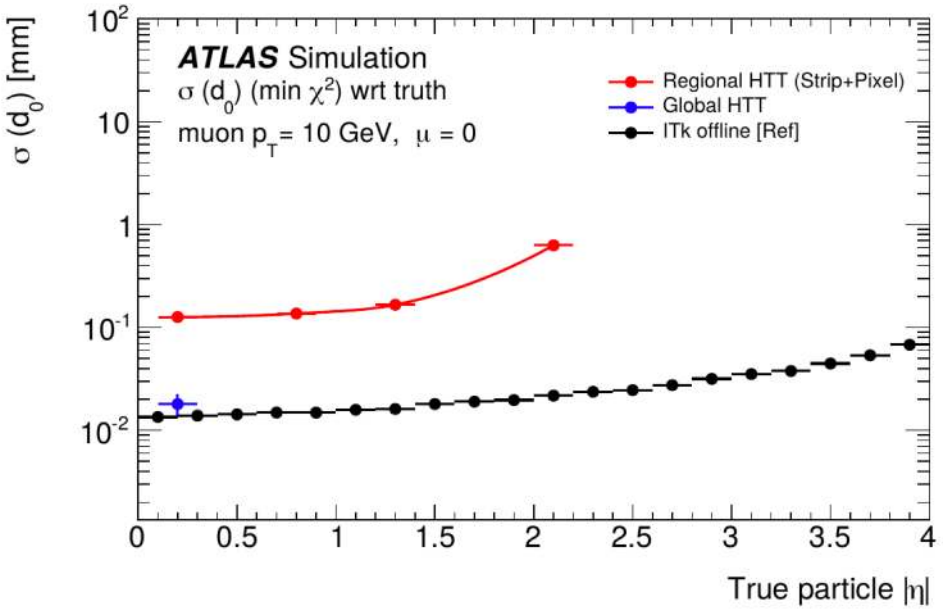
Figures

- Size (and processing rates) depend on p_T threshold
  - Number of patterns for 0.2x0.2 η-φ regions
    - p_T > 2 GeV , 2M (**rHTT**) 1 MHz 10% data
    - p_T > 1 GeV: 3.75M (**gHTT**) 100 kHz
      - p_T > 4 GeV , 1M (L1Track) ≤ 4 MHz
- **98% efficiency for μ p_T >10 GeV (95% for p_T > 1 GeV)**

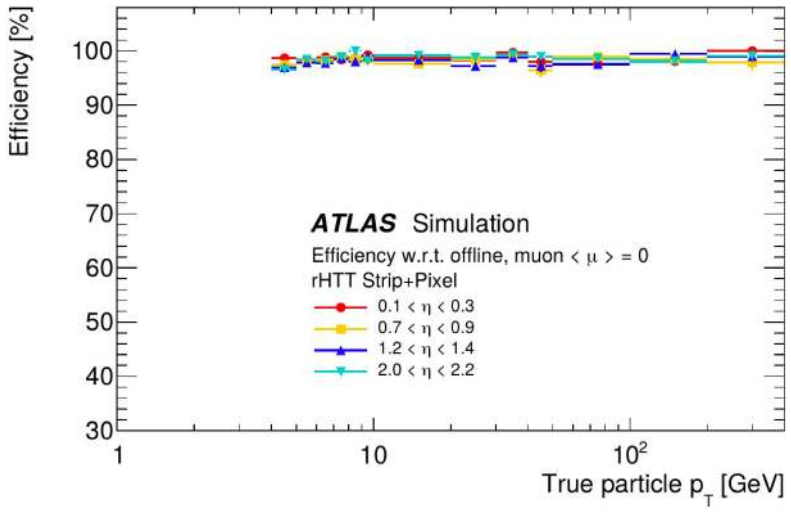
- Required HTT CPU time --from the TDR
  - rHTT: **13 HS06**
  - gHTT: **27 HS06**
  - **> 270 HS06/event** for full-event tracking if done in software
- **Without the HTT, the nominal tracking requirements would require ~10x CPUs**

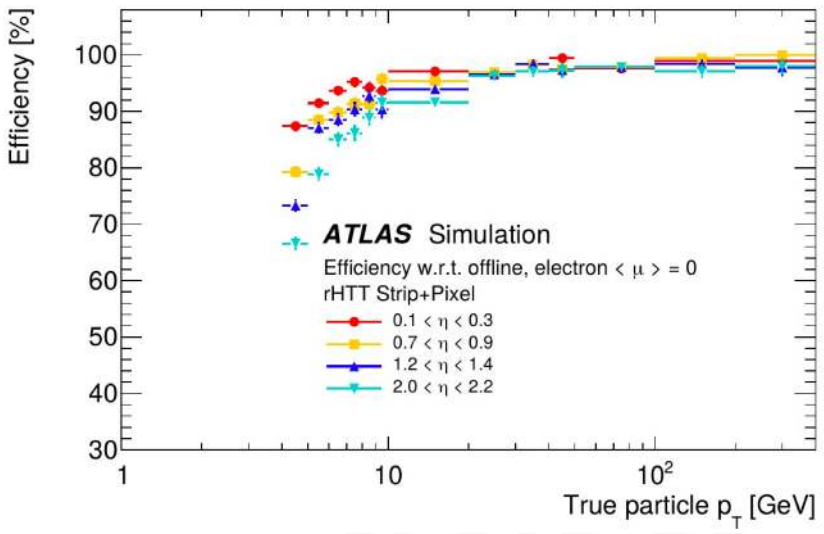
Track fitting performance

- rHTT and gHTT have different performance
- 1st stage track fitting
  - z_0 and d_0 performances limited
- 2nd stage track fitting
  - using all ITk layers
  - **near offline quality**



Tracking efficiency

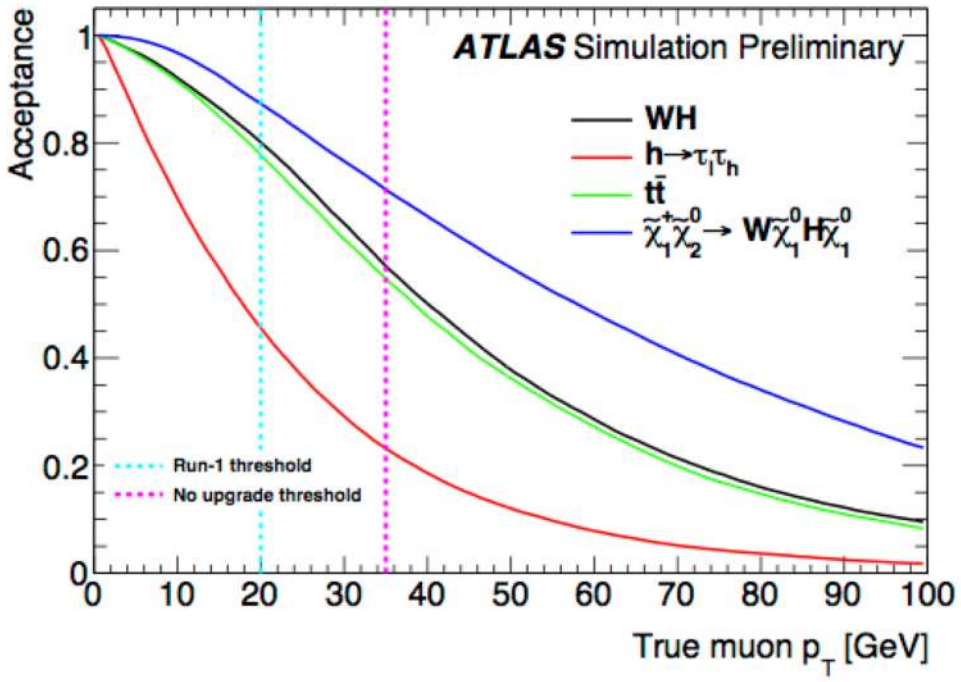




- Tracking efficiency over the full p_T range:
  - flat for muons/pions
  - electron efficiency drops for $p_T < 10$ GeV --Bremsstrahlung
- Over eta:
  - similar efficiency for muons and pions in all studied regions
  - performance on electrons worsens at high eta due to increase in material

Physics acceptance

- The Higher rates at the HL-LHC mean higher thresholds
  - But we do not want high thresholds



Signal acceptance as a function of generated muon p_T for various signal samples at 14 TeV with one muon in the final state.

How can HTT help?

- In many ways
  - Better p_T resolution for rejecting low- p_T leptons
  - Number of tracks requirement
  - Track isolation
  - Dilepton requiring same vertex
  - Spot muons from b-quarks
  - spot jets faking e/gamma
  - SV finding for btag
  - PU suppression using vertices and tracks
  - ready to use tracks for particle flow (p_T>1GeV)
  - …

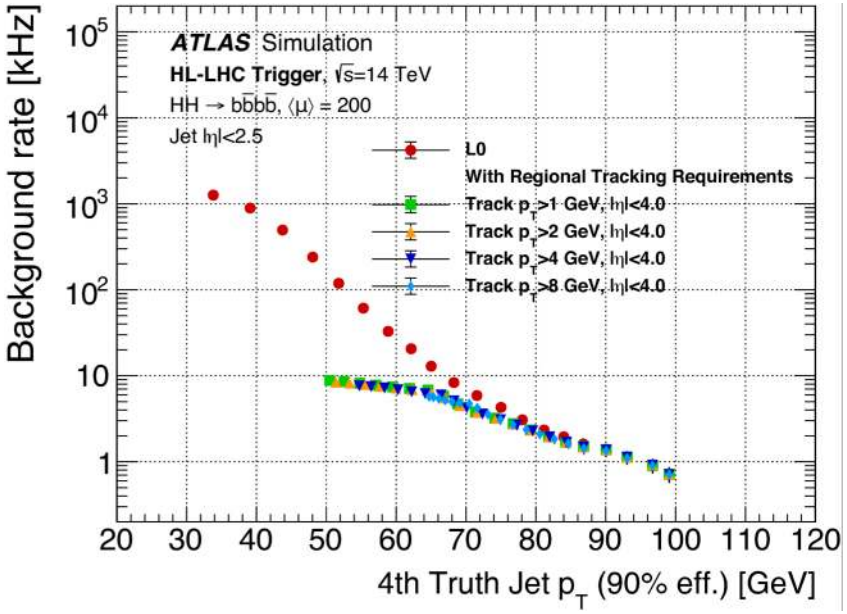
Trigger objects

Preliminary trigger objects in baseline L0-only system

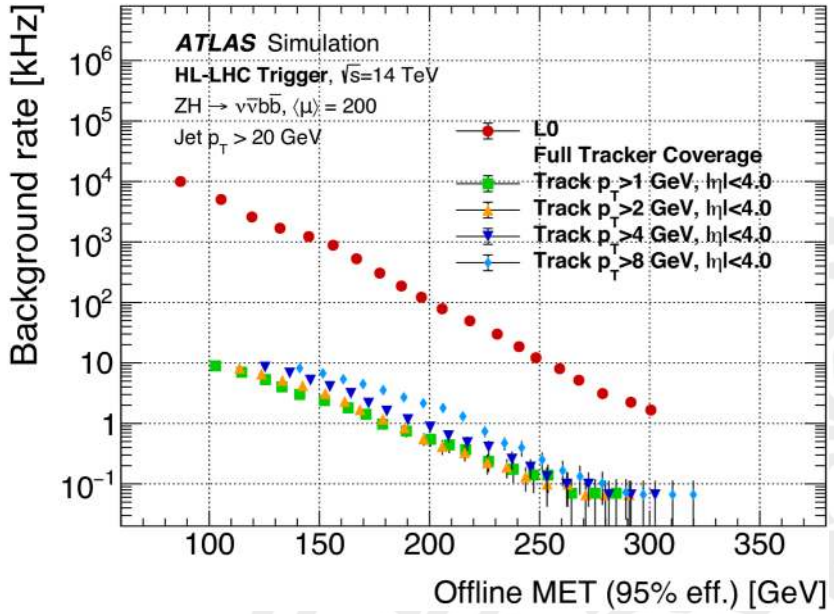
Trigger Selection	Run 1 Offline p_T Threshold [GeV]	Run 2 (2017) Offline p_T Threshold [GeV]	Planned HL-LHC Offline p_T Threshold [GeV]	L0 Rate [kHz]	After regional tracking cuts [kHz]	Event Filter Rate [kHz]
isolated single e	25	27	22	200	40	1.5
isolated single μ	25	27	20	45	45	1.5
single γ	120	145	120	5	5	0.3
forward e			35	40	8	0.2
di-γ	25	25	25,25	20	20	0.2
di-e	15	18	10,10	40	10	0.2
di-μ	15	15	10,10	10	5	0.2
$e-\mu$	17,6	8,25 / 18,15	10,10	45	10	0.2
single τ	100	170	150	3	3	0.35
di-τ	40,30	40,30	40,30	200	40	0.5†††
single b-jet	200	235	180	25	25	0.35†††
single jet	370	460	400			0.25
large-R jet	470	500	300	40	40	0.5
four-jet (w/ b-tags)		45†(1-tag)	65(2-tags)	100	20	0.1
four-jet	85	125	100			0.2
H_T	700	700	375	50	10	0.2†††
E_T^{miss}	150	200	210	60	5	0.4
VBF inclusive			2x75 w/ ($\eta > 2.5$ & $\phi < 2.5$)	33	5	0.5†††
B-physics††				50	10	0.5
Supporting Trigs				100	40	2
Total				1066	341	10.4

† In Run 2, the 4-jet b-tag trigger operates below the efficiency plateau of the Level-1 trigger.
†† This is a place-holder for selections to be defined.
††† Assumes additional analysis specific requires at the Event Filter level

Trigger rates



Rate for a four-jet trigger requiring the jets to be consistent with a common vertex using rHTT



Rate vs offline E_T^{miss} at which the trigger is 95% efficient for a E_T^{miss} trigger which includes track information in the Event Filter using gHTT

How can HTT help?

- In many ways
  - Better p_T resolution for rejecting low- p_T leptons
  - Number of tracks requirement
  - Track isolation
  - Dilepton requiring same vertex
  - Spot muons from b-quarks
  - spot jets faking e/gamma
  - SV finding for btag
  - PU suppression using vertices and tracks
  - ready to use tracks for particle flow (p_T>1GeV)
  - …
- **Dedicated signatures:**
  - Specific triggers for Dark Matter searches, **displaced signatures** …

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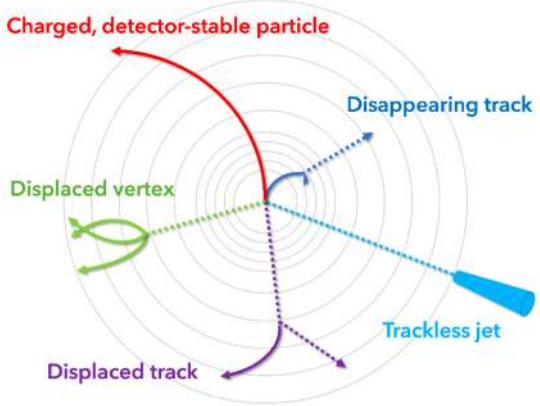
hour.

arXiv:1907.09846 (sub to JINST)

- Recent paper investigating the potential of reserving resources for displaced signatures in the HTT
  - To catch a long-lived particle: hit selection towards a regional hardware track trigger implementation



- Adding displaced patterns in the banks (2 scenarios: 10% and 20%)
- Alternative to pattern matching in ASICs: Hough transform
- **We do not affect negatively our ability to identify prompt tracks, while boosting our ability of "seeing" LLP**

Summary

- If we want to meet the physics goals of ATLAS at HL-LHC
  - Track information at trigger level can help
- A Hardware Tracking Trigger (HTT) system is proposed
  - regional and global tracking
  - can be reconfigured to an evolved system
- **System in design phase**
  - Plans described in 2018 TDAQ TDR
  - Homogeneous system that will deliver high tracking efficiency and ~off-line quality track parameters
- It does not come without challenges (power budget and dataflow limits) but it will provide important physics benefits!
  - Much is still to be decided and many studies to be done, but the future looks bright! (at least very luminous!)

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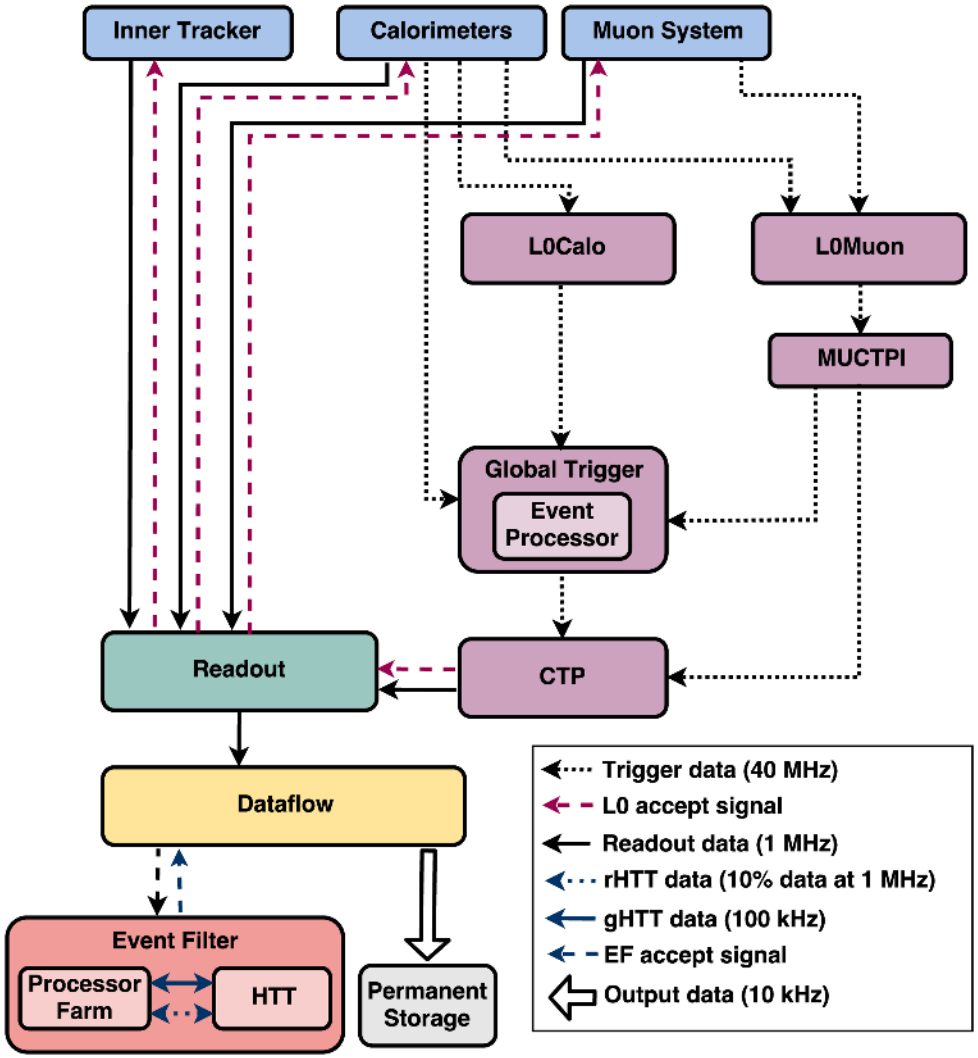
BACKUP

Evolved TDAQ scenario



- In the "L0/L1" architecture part of HTT is used in low-latency mode
  - L1Track
  - rate of up to 4MHz
  - a few micro-seconds latency
  - regional-HTT (L1Track)
  - global-HTT (gHTT)
- very stringent requirements on latency budget and dataflow rates

PRM extra info

- work ongoing:
  - firmware development, power scheme, selection of components
- Number of ASICs/board limited by power and space density on board
  - Could be reduced from 24 to 20
- Evaluating impacts on load of FPGA

- Choice of the FPGA
  - candidate (Intel® Stratix® 10) with High Bandwidth Memory (HBM) for accessing fit constants
    - challenge for the evolved scenario
    - investigating other track-fit techniques

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AM chips

Chip name	Transistor count	Year	Brand	Technology	Area
Core 2 Duo Conroe	291,000,000	2006	Intel	65 nm	143 mm²
Itanium 2 Madison 6M	410,000,000	2003	Intel	130 nm	374 mm²
Core 2 Duo Wolfdale	411,000,000	2007	Intel	45 nm	107 mm²
AM06	**421,000,000**	**2014**	**AMteam**	**65 nm**	**168 mm²**
Itanium 2 with 9 MB cache	592,000,000	2004	Intel	130 nm	432 mm²
Core i7 (Quad)	731,000,000	2008	Intel	45 nm	263 mm²
Quad-core z196[20]	1,400,000,000	2010	IBM	45 nm	512 mm²
Quad-core + GPU Core i7 Ivy Bridge	1,400,000,000	2012	Intel	22 nm	160 mm²
Quad-core + GPU Core i7 Haswell	1,400,000,000	2014	Intel	22 nm	177 mm²
AM09	**1,684,000,000**	**2019**	**AMteam**	**28 nm**	**150 mm²**
Dual-core Itanium 2	1,700,000,000	2006	Intel	90 nm	596 mm²

Total estimated components

- Current estimated size:
  - 48 (AMTP)+8 (SSTP) ATCA shelves, with 12 blades/shelf
  - 13824 ASICs
  - 1440 FPGAs
  - > 1400 cards
  - > 5.3 G patterns
- The size of the system ~ processing power density per board

Item	Number
Number of HTTIF PCs	24
Number of ATCA shelves for AMTP	48
Number of AMTP blades per shelf	12
Number of AMTP blades per HTTIF	24
Total number of AMTP	576
Number of PRM per AMTP	1
Total number of PRM	576
Number of AM ASIC per PRM	24
Total number of AM ASIC	13824
Number of ATCA shelves for SSTP	8
Number of SSTP blades per shelf	12
Number of SSTP blades per HTTIF	4
Total number of SSTP	96
Number of TFM per SSTP	2
Total number of TFM	192
Number of ConMon PCs per ATCA shelf	1
Total number of ConMon PCs	56

	HTT
rHTT minimum track p_T	$2\,GeV$
rHTT Input rate	1 MHz @ 10%
gHTT minimum track p_T	$1\,GeV$
gHTT Input rate	100 kHz
Number of HTTIF	48 (to be revisited)
Number of ATCA shelves for AMTP	48
Total number of AMTP	576
Total number of AM chips	18432
Number of ATCA shelves for SSTP	8
Total number of SSTP	96
Power estimate per TP	300 W

	HTT
Number of HTTIF	24
Number of ATCA shelves for AMTP	48
Number of AM/SSTP boards per shelf	12
Total number of AMTP	576
Number of PRM per AMTP	2
Total number of PRM	1152
Number of AM ASIC per PRM	12
Total number of AM ASIC	13824
Number of ATCA shelves for SSTP	8
Total number of SSTP	96
Number of TFM per SSTP	2
Total number of TFM	192

Dataflow and power estimates

AMTP main card (including DC/DCs)	100 W
PRM FPGA	30 W
PRM 12 AM ASIC	50 W
PRM others (RAMs, IO fanout, DC/DC)	25 W
Total/AMTP	310 W
SSTP main card (including DC/DCs)	100 W
TFM 2 x FPGA	75 W
TFM others (RAMs, IO fanout, DC/DC)	25 W
Total/SSTP	300 W

	rHTT/event	gHTT/event	HTT rate	available
# Cluster /PRM (layer average)	200	260	46 MHz	60 MHz
# Roads/PRM	170	270	45 MHz	400 MHz
# Constants read/PRM	90	140	23 MHz	30 MHz
Fits/PRM	1500	2250	400 MHz	1 GHz
Tracks after χ^2/PRM	80	280	36 MHz	
Tracks after HitWarrior/AMTP	10	35	4.5 MHz	
rHTT output bandwidth /AMTP	640 Mb/s			
<Tracks after HitWarrior>/AMTP	7	20	2.6 MHz	
Total output bandwidth	250 Gb/s	750 Gb/s	1 Tb/s	
Average event size	30kB	900kB		

System performance

- The system has been fully simulated for p_T>4 in 4 eta regions
- One eta region has been studied for p_T > 1,2 and 4 GeV

η range	muon eff.	mean matches pile-up	99% interval matches in pile-up
$0.1 < \eta < 0.3$	99.1%	31	151
$0.7 < \eta < 0.9$	99.2%	21	93
$1.2 < \eta < 1.4$	98.8%	42	159
$2.0 < \eta < 2.2$	98.7%	10	56

particle	min p_T	Eff. (%)	# roads	# fits	# tracks $\chi^2 < 40$	# tracks HitWarrior	# fit constants
muon	1 GeV	99.5	144	1115	55	4.6	73
muon	2 GeV	99.1	79	586	23	1.9	40
muon	4 GeV	99.2	48	313	16	1.2	23
jets	1 GeV		195	1519	77	6.2	97
jets	2 GeV		104	804	29	2.4	52
jets	4 GeV		51	344	13	1.1	26
min-bias	1 GeV		110	842	38	3.6	58
min-bias	2 GeV		48	359	6	0.8	27
min-bias	4 GeV		21	133	1	0.2	12

HitWarrior: Duplicate removal run in TP. Identifies tracks that share more than a given number of hits. The threshold can be tuned to give high efficiency and low number of duplicates.

Dataflow summary

	rHTT/event	gHTT/event	HTT rate	available
# Cluster /PRM (layer average)	200	260	46 MHz	60 MHz
# Roads/PRM	170	270	45 MHz	400 MHz
# Constants read/PRM	90	140	23 MHz	30 MHz
Fits/PRM	1500	2250	400 MHz	1 GHz
Tracks after χ^2/PRM	80	280	36 MHz	
Tracks after HitWarrior/AMTP	10	35	4.5 MHz	
rHTT output bandwidth /AMTP	640 Mb/s			
<Tracks after HitWarrior>/AMTP	7	20	2.6 MHz	
Total output bandwidth	250 Gb/s	750 Gb/s	1 Tb/s	
Processed event size	30kB	900kB		
Average event size	30kB	250kB		

	Needed per event	Capability per event
# of clusters/TFM (max layer)	580	5000
# of clusters/TFM (average)	380	5000
Cluster rate/TFM (max layer)	58 MHz	500 MHz
Cluster rate/TFM (average)	38 MHz	500 MHz
# of roads/TFM	48	120
#of constant sets read/TFM		
Extrapolator	192	500
Fitter	100	230
Fits/TFM	260	600
<Tracks after HitWarrior>/SSTP	30	
Total output bandwidth	200 Gb/s	
Average event size	250kB	