ATLAS & CMS UPGRADES ON TRACKING & TDAQ

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UNIV. OF GENEVA

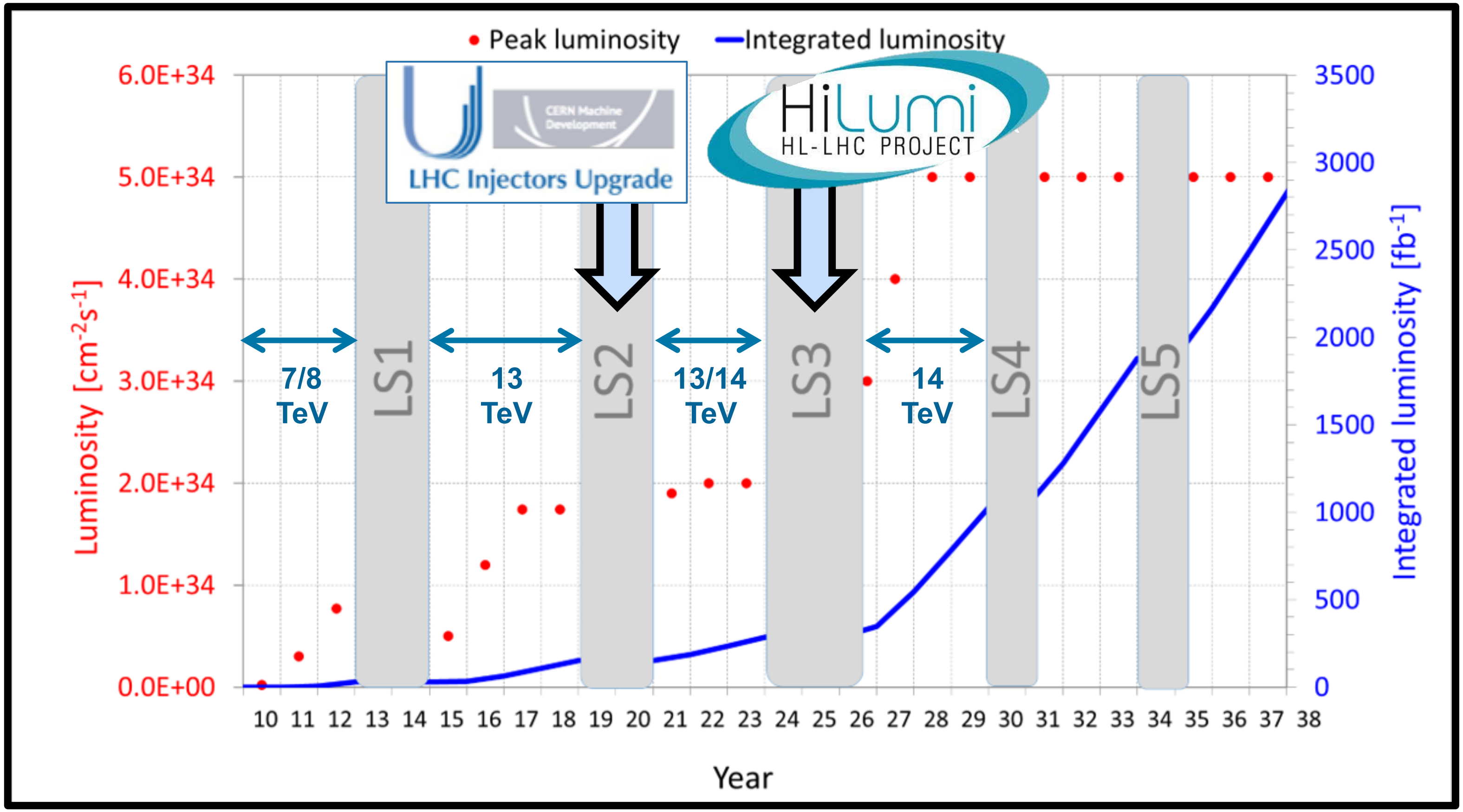
JUNE 2018

CONTENTS

- General landscape of the ATLAS and CMS upgrades
- Tracking and TDAQ
  - Status of current upgrades for Run3
  - Prospects for the HL-LHC: the focus of this talk!

LHCP Bologna 2018

THE LHC LIFETIME



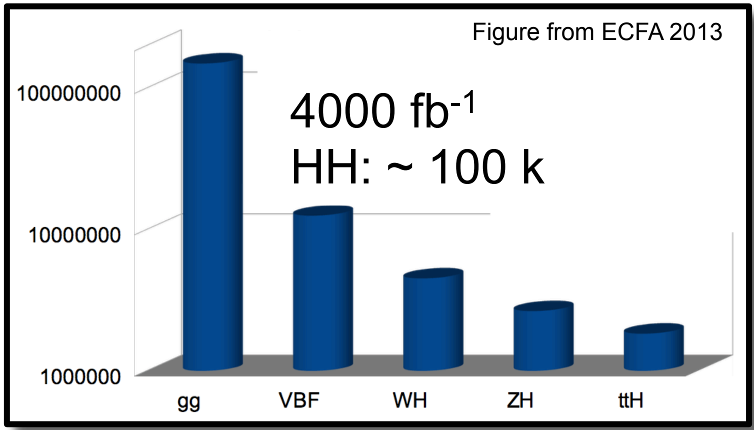
PHYSICS PROGRAM AT THE (HL-)LHC

Extended sensitivity for Beyond the Standard Model Physics:

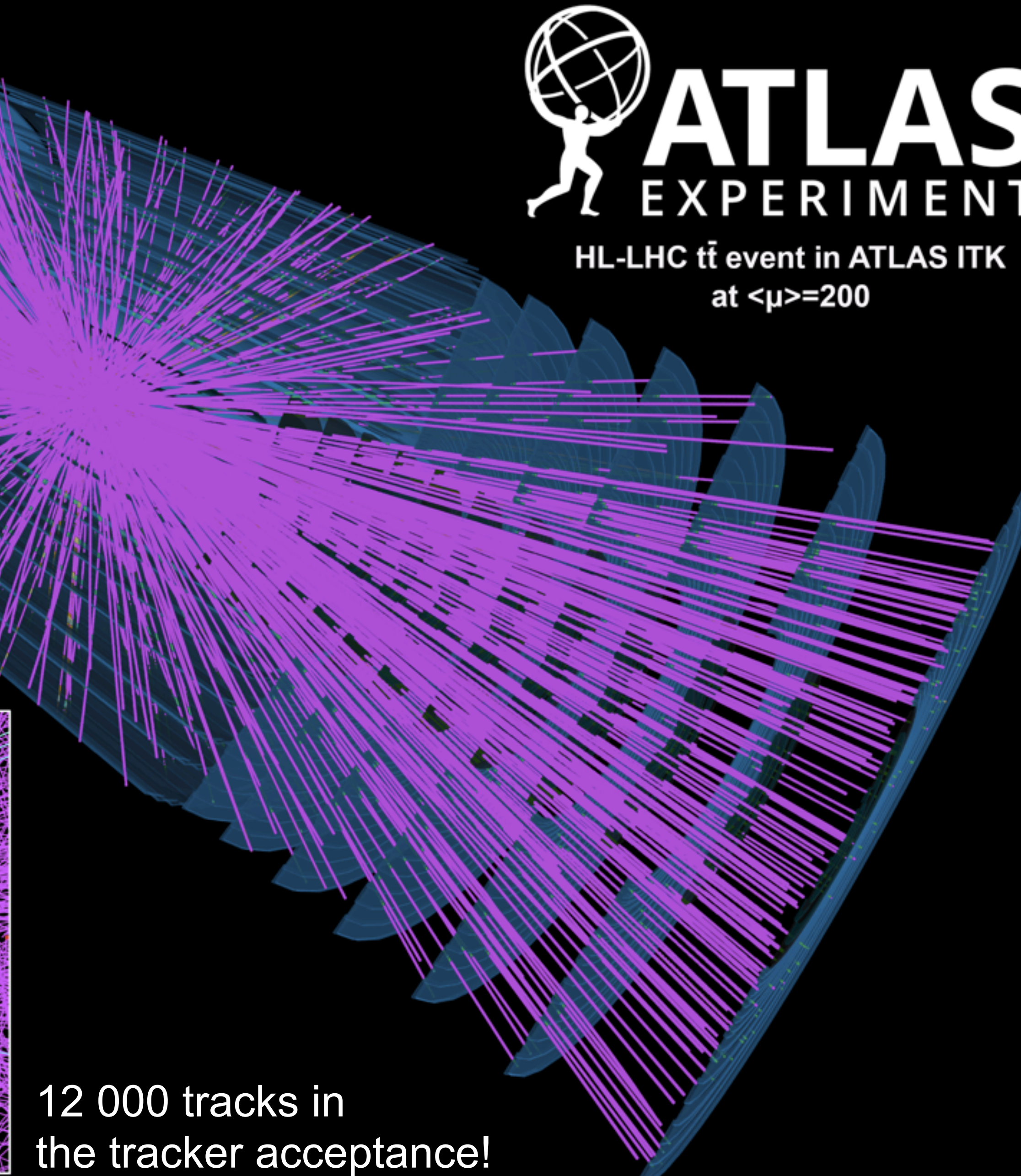
- New TeV-scale physics could be discovered or very strongly disfavored

Higgs Boson Program a major component, main measurements:

- Higgs couplings
- Higgs self-coupling
- Higgs differential distributions
- Rare Higgs decays
- Heavy Higgs searches

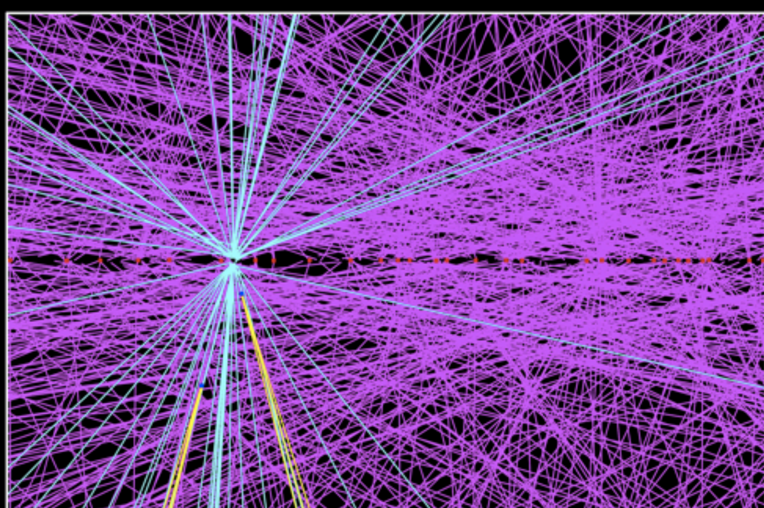


Support a rich program in Standard Model and Flavor Physics.



ATLAS EXPERIMENT

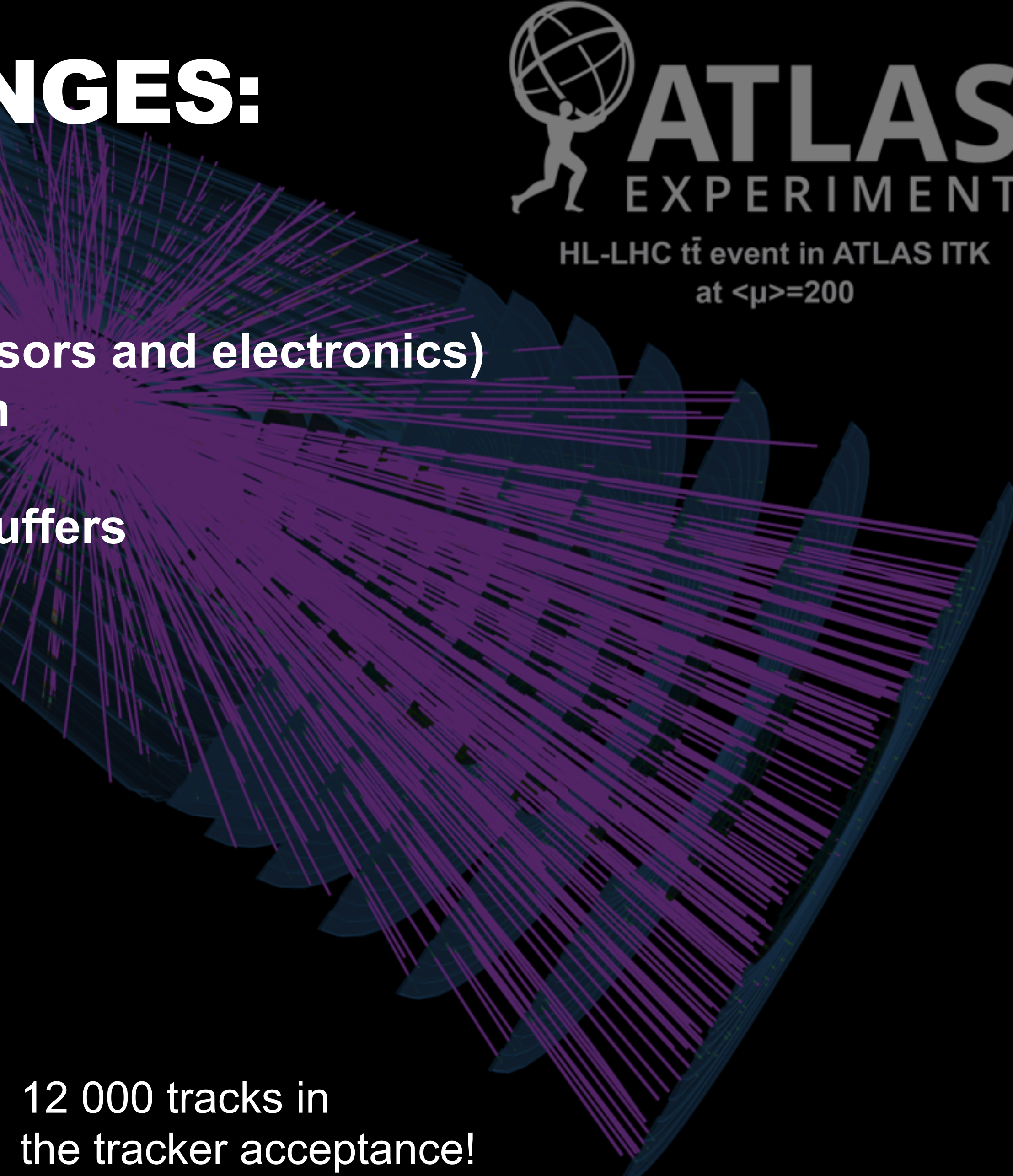
HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$



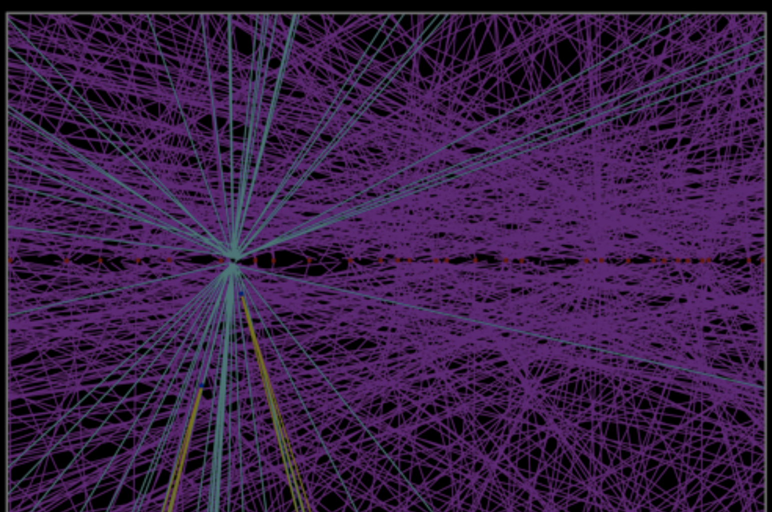
12 000 tracks in
the tracker acceptance!

THE CHALLENGES: TRACKING

- Radiation hardness (sensors and electronics)
- Large readout bandwidth
- Low detector occupancy
- Fast readout and deep buffers



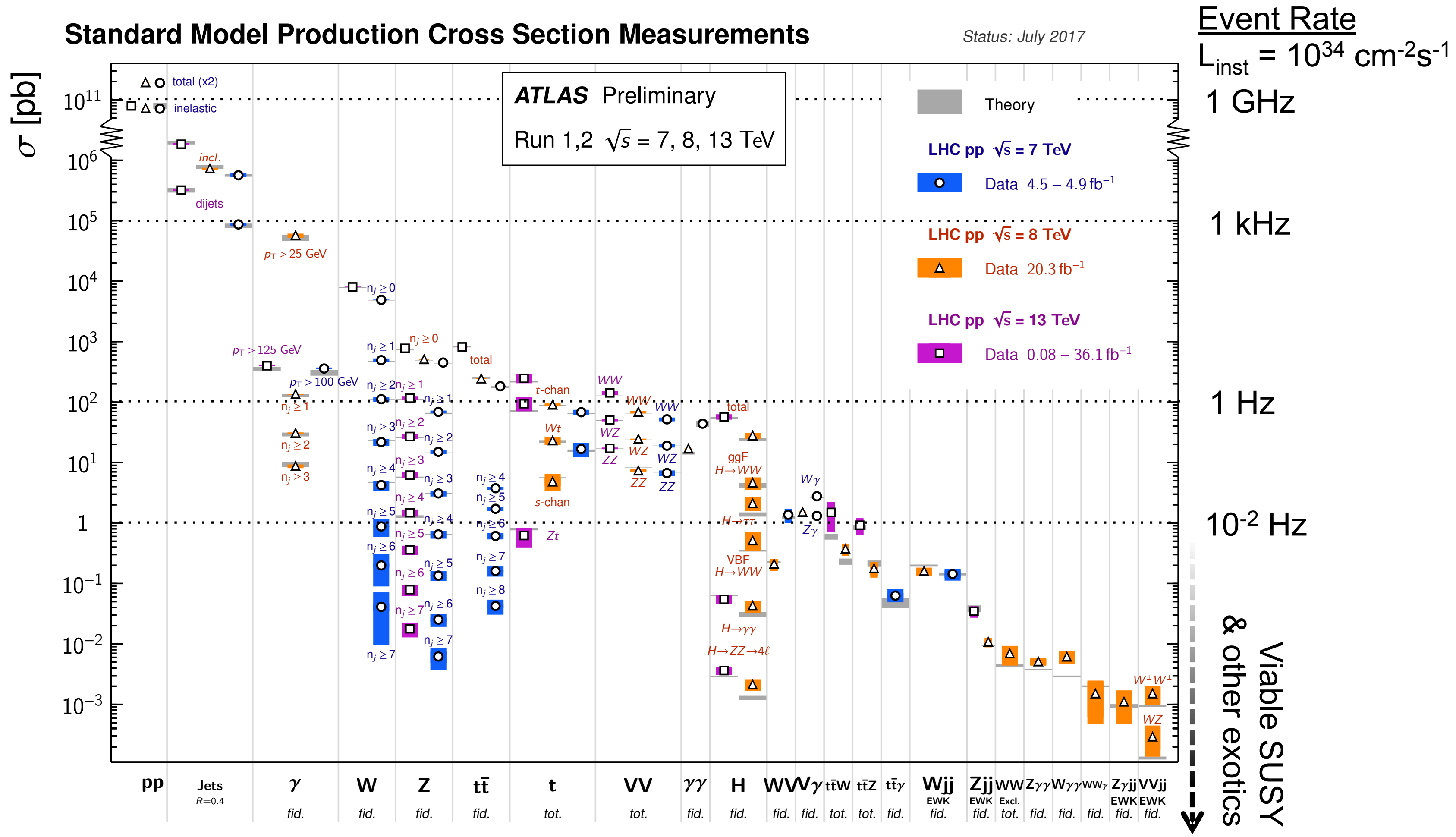
HL-LHC $t\bar{t}$ event in ATLAS ITK at <μ>=200



12 000 tracks in the tracker acceptance!

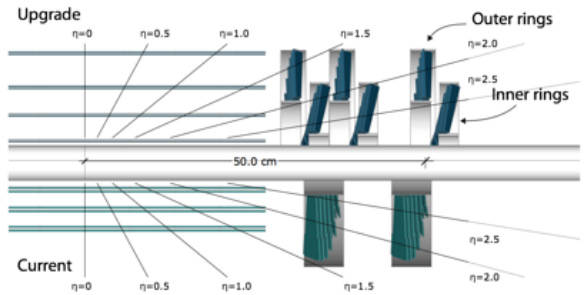
THE CHALLENGES: TRIGGER / DAQ

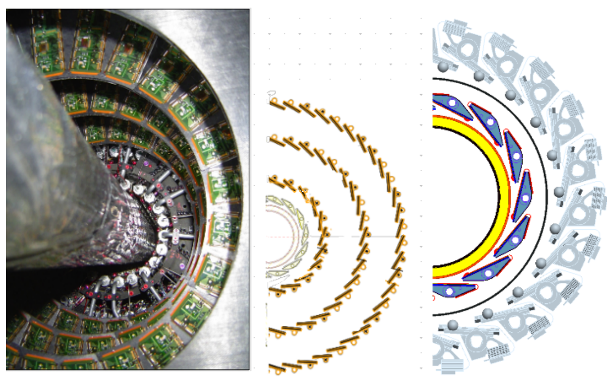
- Unprecedented instantaneous luminosity leads to large rates.
- High pile-up leads to non-linear scaling of rates with luminosity.
- High detector occupancy leads to limitations in detector read-out.



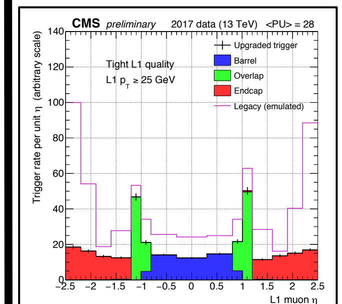
UPGRADES SO FAR (FOR OR DURING RUN2)

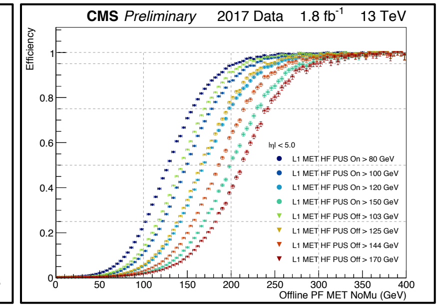
Tracking

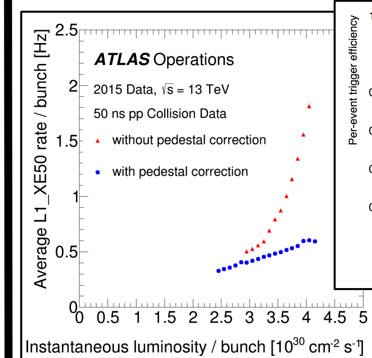


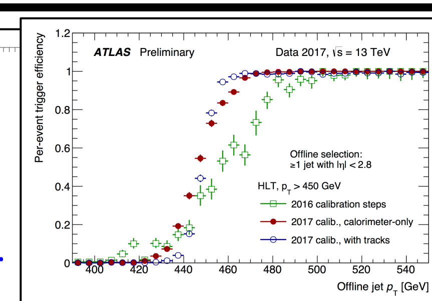


Trigger / DAQ









Common key aspects

Tracking:

- Increase granularity to improve tracking and vertexing performance.
- Improve stability of read-out system to higher occupancy (luminosity).

Trigger / DAQ:

HW:
- Robust pile-up treatment.
- Reduction of fakes.
- Topological selections.

SW:
- Better CPU usage.
- Maximize output bandwidth.

Lessons learned

We can very successfully upgrade our systems! But also…
Things do take long and things can go wrong.

UPGRADES FOR RUN3

	Tracking	Trigger / DAQ
CMS	✗	• No major upgrades. • Muon and calorimeter detector upgrades will improve trigger performance.
ATLAS EXPERIMENT	✗	**Major system upgrade** • Read-out changes to follow detector upgrades (FELIX). • Upgrade all components of HW trigger and introduce new functionality (& physics potential). • New hardware fast tracker (FTK) to become operational. **Status** • Good progress despite some delays. • Hardware is now in final production, testing ongoing. • Full system under commissioning.

✗: Only maintenance and operational tasks foreseen.

See also parallel talk of D. Rohr.

UPGRADES FOR HL-LHC

	Tracking	Trigger / DAQ
CMS	• Si-strip and pixels replaced to increase granularity & functionality. • Design for tracking in **HW trigger**. • Covering up to η=3.8.	• **Tracks** in HW trigger at 40 MHz for 750 kHz **pflow-like selection rate**. • SW selection output 7.5 kHz. **Aim:** trigger on selections as close as possible to offline.
ATLAS EXPERIMENT	• Complete replacement of Inner Detector with all-silicon tracker of high granularity. • Covering up to η=4.0.	• Full granularity detector data into HW trigger for 1 MHz selection rate. • **HW tracking for trigger** available for SW selections. • SW selection output 10 kHz.
Status	• TDRs produced by both experiments.	• TDR produced by ATLAS, interim reports by CMS.

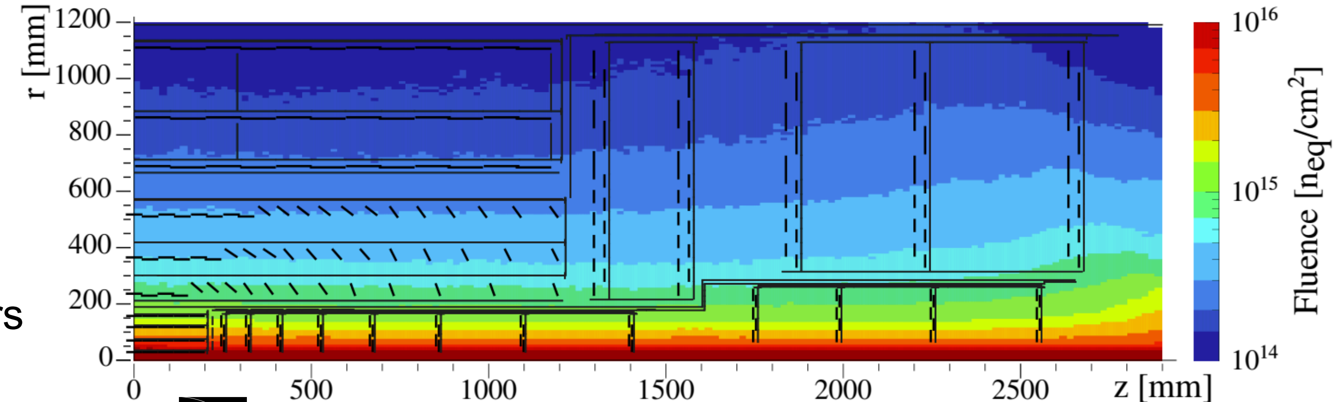
TRACKING AT HL-LHC

CMS Tracker TDR: CERN-LHCC-2017-009

ATLAS Tracker TDRs: CERN-LHCC-2017-005, CERN-LHCC-2017-021

FLUENCES AND MATERIAL

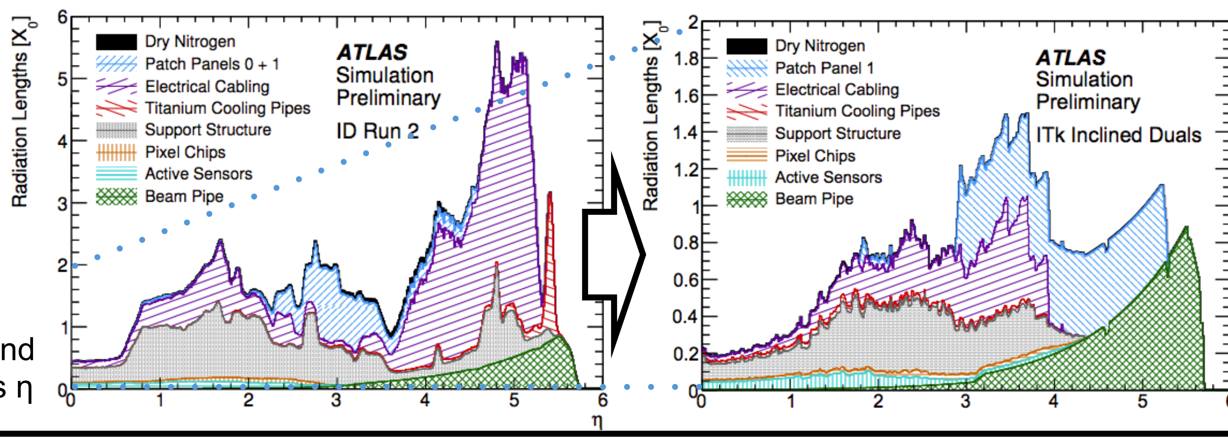
- Radiation hard materials required to sustain enormous particle fluence.
  - Design to accommodate radiation damage; e.g. must assume that inner two ATLAS Pixel layers are replaceable!



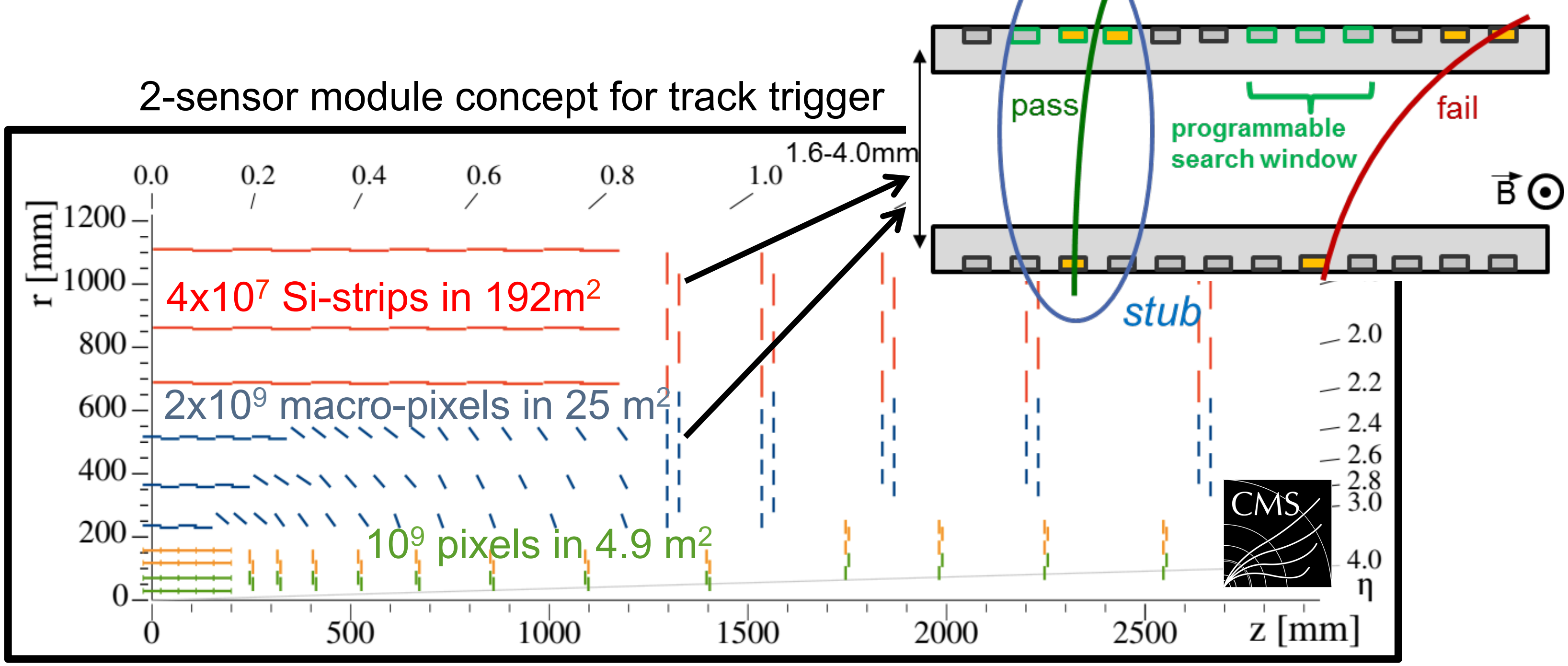
Integrated particle fluence in 1 MeV neutron equivalent per cm^2

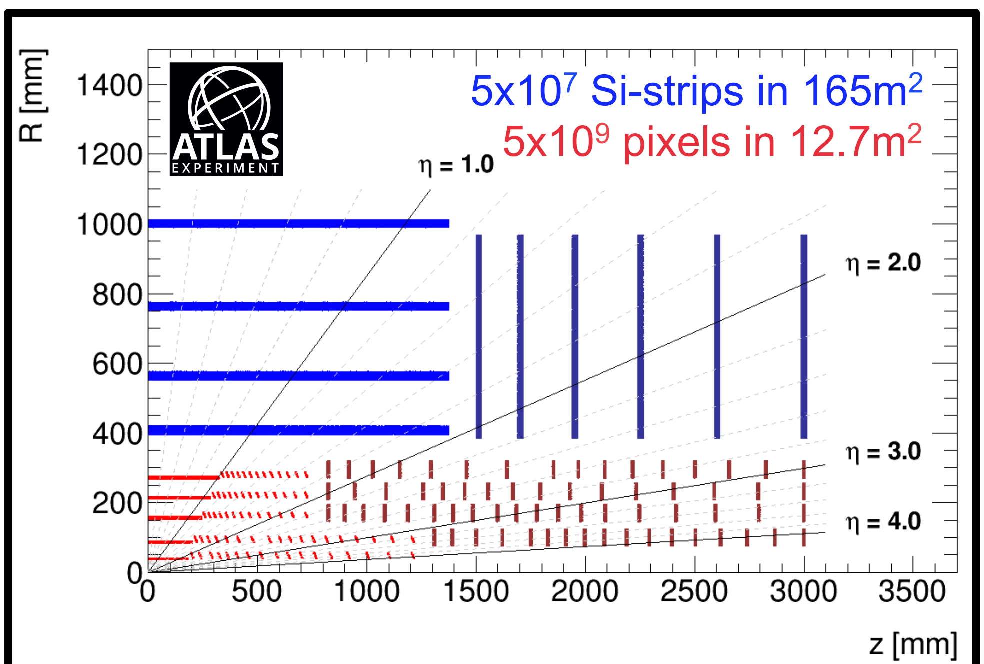
- All design choices aimed at reducing the material budget in both the acceptance region and the forward region.
  - Thin sensors and electronics, CO_2 evaporative cooling, serial powering.

Comparison between Run2 and Phase II of radiation length vs η



TRACKERS

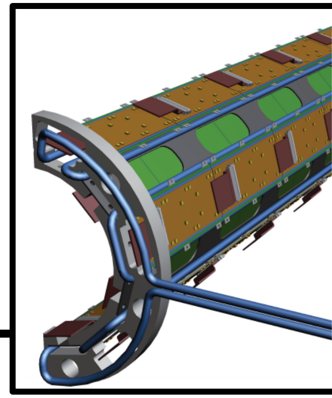


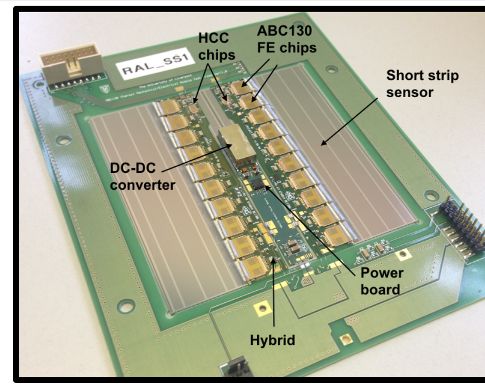


	ATLAS EXPERIMENT	CMS
Strips		
Pitch (μm)	70-85	90-100
Length (cm)	2.5-8	2.5-5
Thickness (μm)	300	200
Macro-pixel length (mm)	-	1.5
Pixels		
Size (μm²)	50x50 or 25x100	
Thickness (μm)	≤ 150 μm	

SILICON MODULES

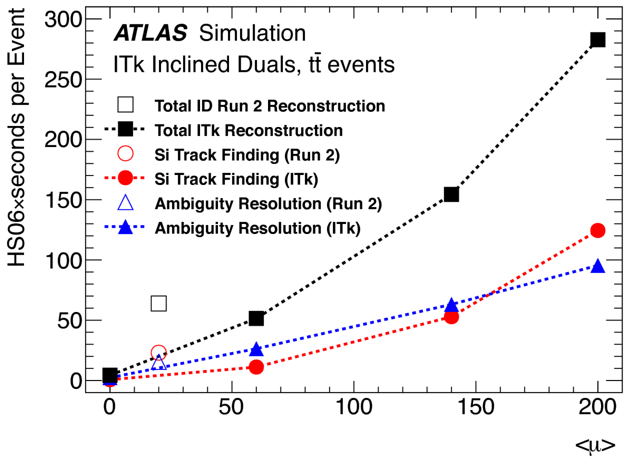
	Pixels	Strips
CMS	• Planar n-in-p • 3D also possible.	• Two sensors back to back. Combination of strip-only and pixel & strip modules. • **Self-contained readout, provide pT measurement at HW trigger.**
ATLAS EXPERIMENT	• Planar n-in-p in outer layers; 3D in inner. CMOS considered for outermost barrel layer.	• Stereo-angle between sensors, on double-sided structure.
Front-end electronics	• Synergic development (RD53). Radiation hard, 65nm.	• ASICs custom made per experiment.



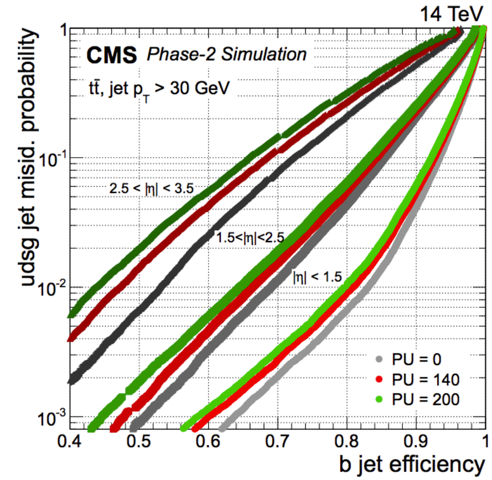


TRACKING ALGORITHMS AND PERFORMANCE

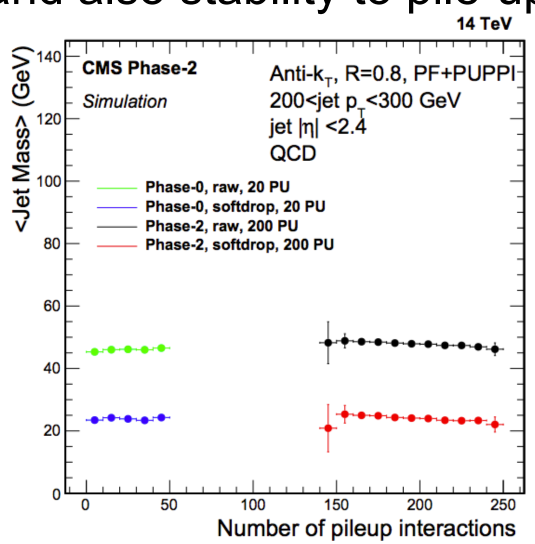
Tracking algorithms updated/rewritten for mu=200, CPU vs μ monitored.



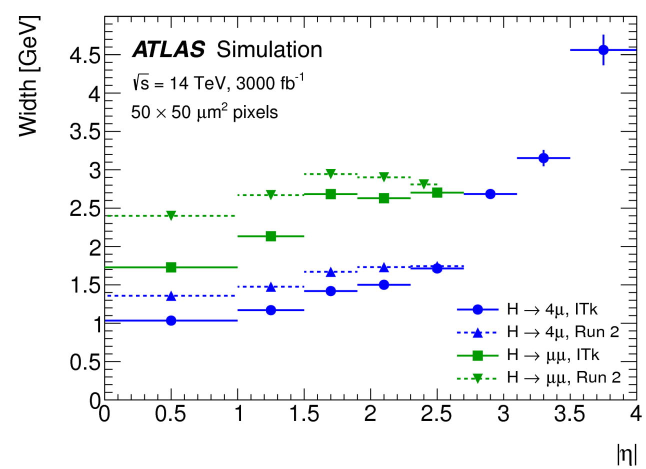
Performance carefully studied evaluating new options (e.g. fwd)...



… and also stability to pile-up.



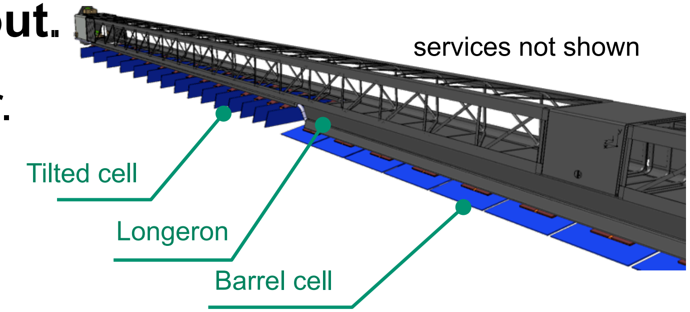
Physics extrapolations and comparisons to Run2 performed.



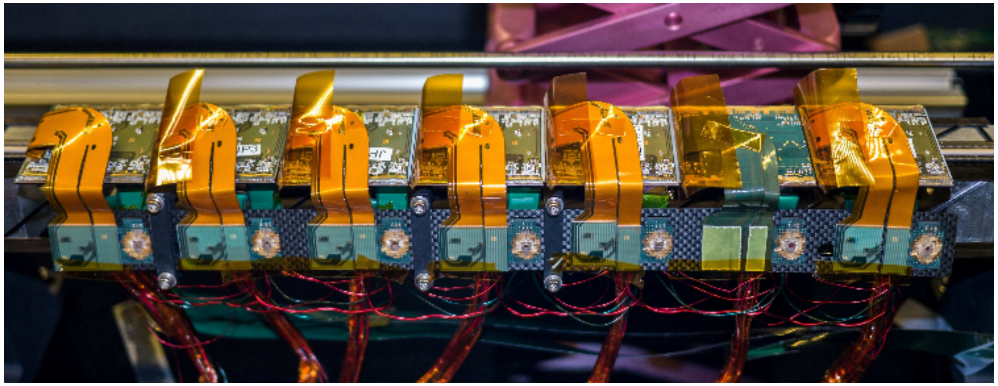
Large variety of studies done. Examples given here.
See also parallel talks of C. Gemme and K. Hoepfner.

PROTOTYPES & DEMONSTRATORS

- **Both ATLAS and CMS are producing prototypes of modules prior to finalisation of design and production.**
  - Tests primarily for long-term operation & radiation hardness.
- **Longer scale demonstrators put in place to test full concept, including challenging mechanics and read-out.**
  - E.g. ATLAS Pixel outer barrel demonstrator.
    - Aims at evaluating and validating the mechanics concept: longeron with 2 cooling lines with flat and inclined modules.

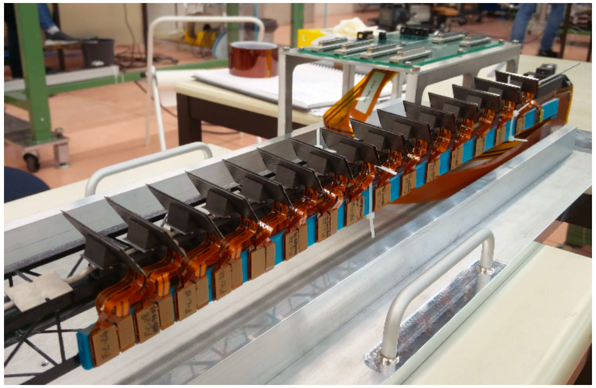


Electrical prototype



7 quad modules on carbon local support structure

Thermal prototype



Required thermal figures of merit achieved

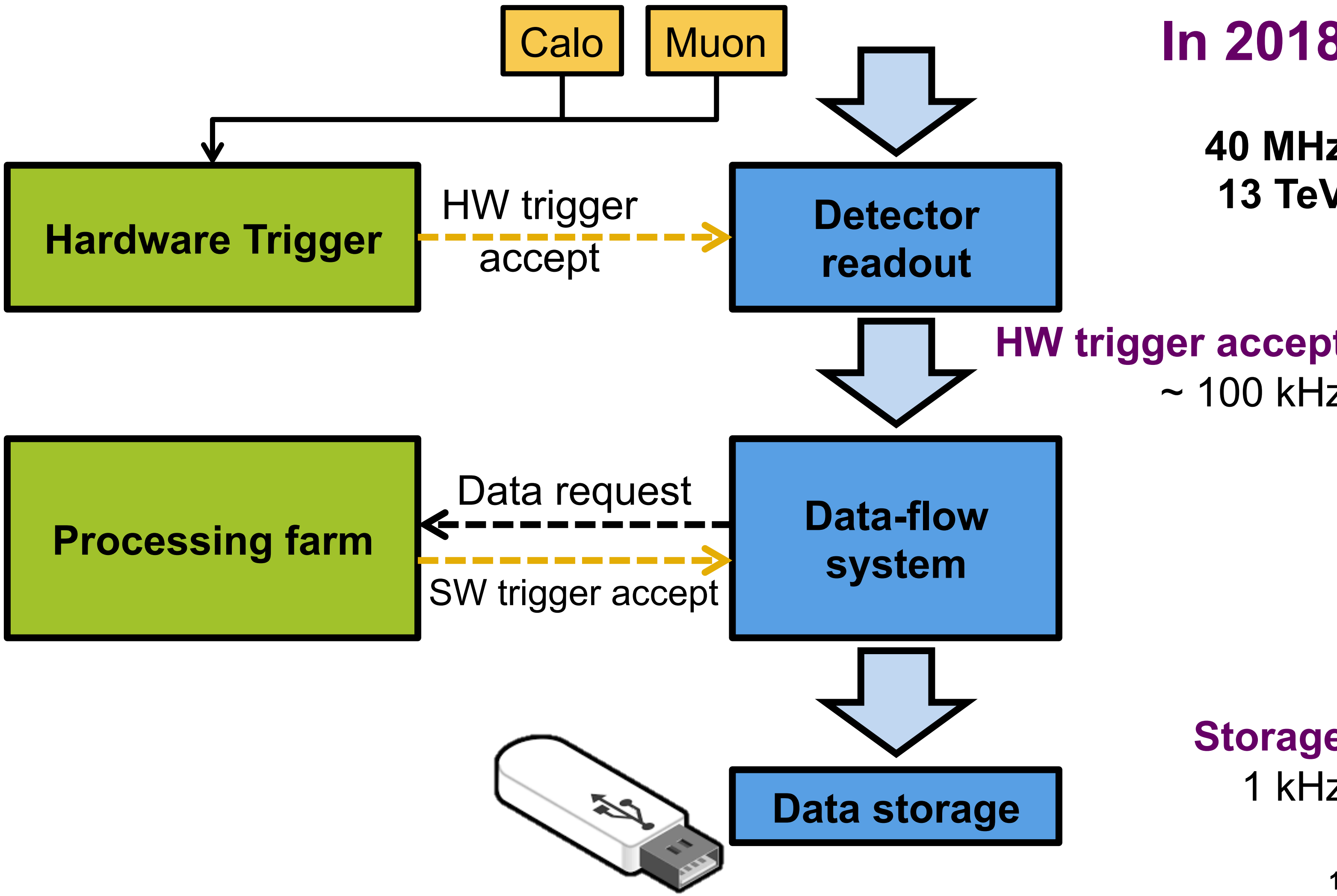
TRIGGER AT HL-LHC

CMS interim reports: CERN-LHCC-2017-013, CERN-LHCC-2017-014

ATLAS TDAQ TDR: CERN-LHCC-2017-020

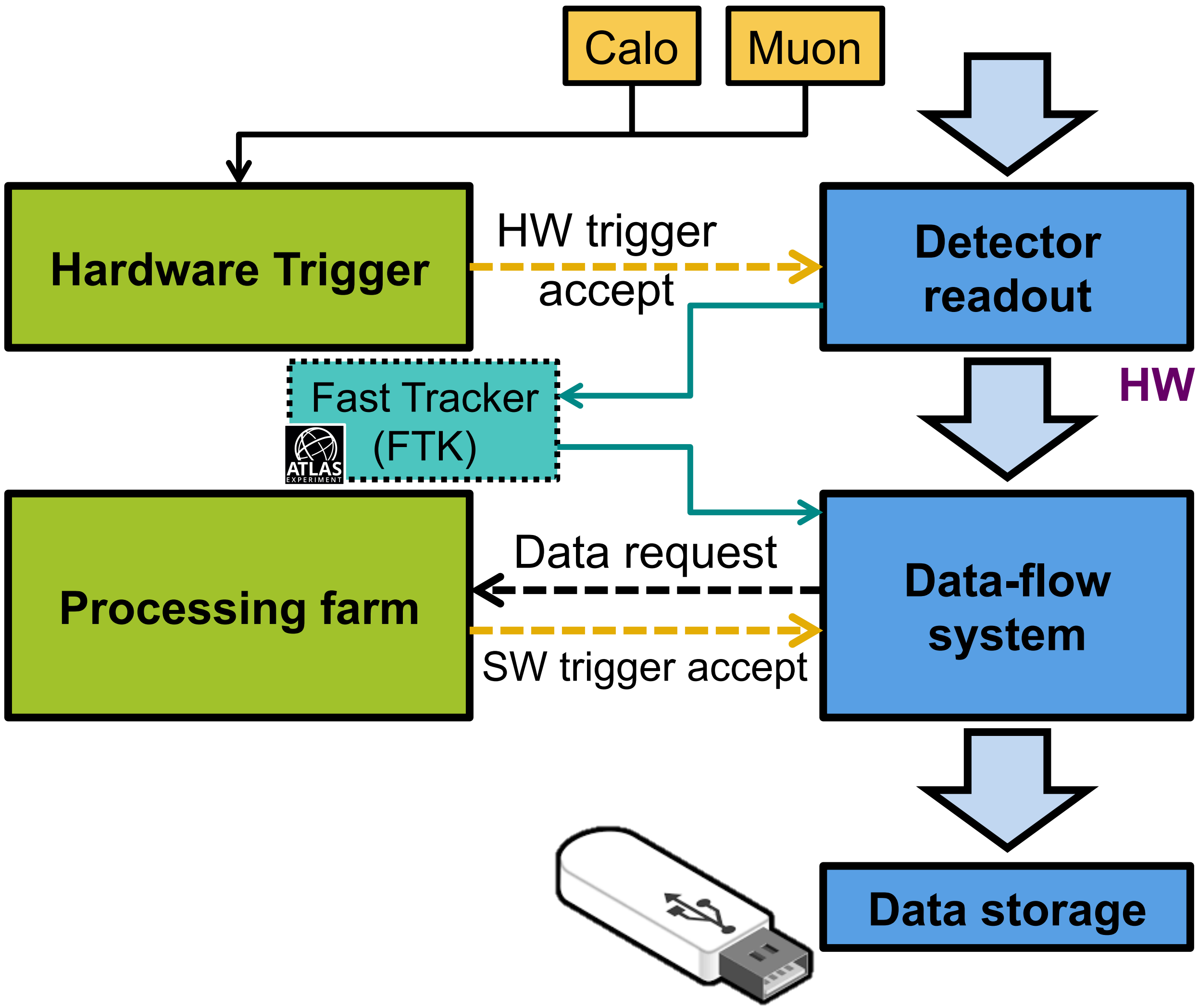
THE TRIGGER & DATA ACQUISITION

Architecture: Very simplified view



THE TRIGGER & DATA ACQUISITION

Architecture: Very simplified view



In Run3

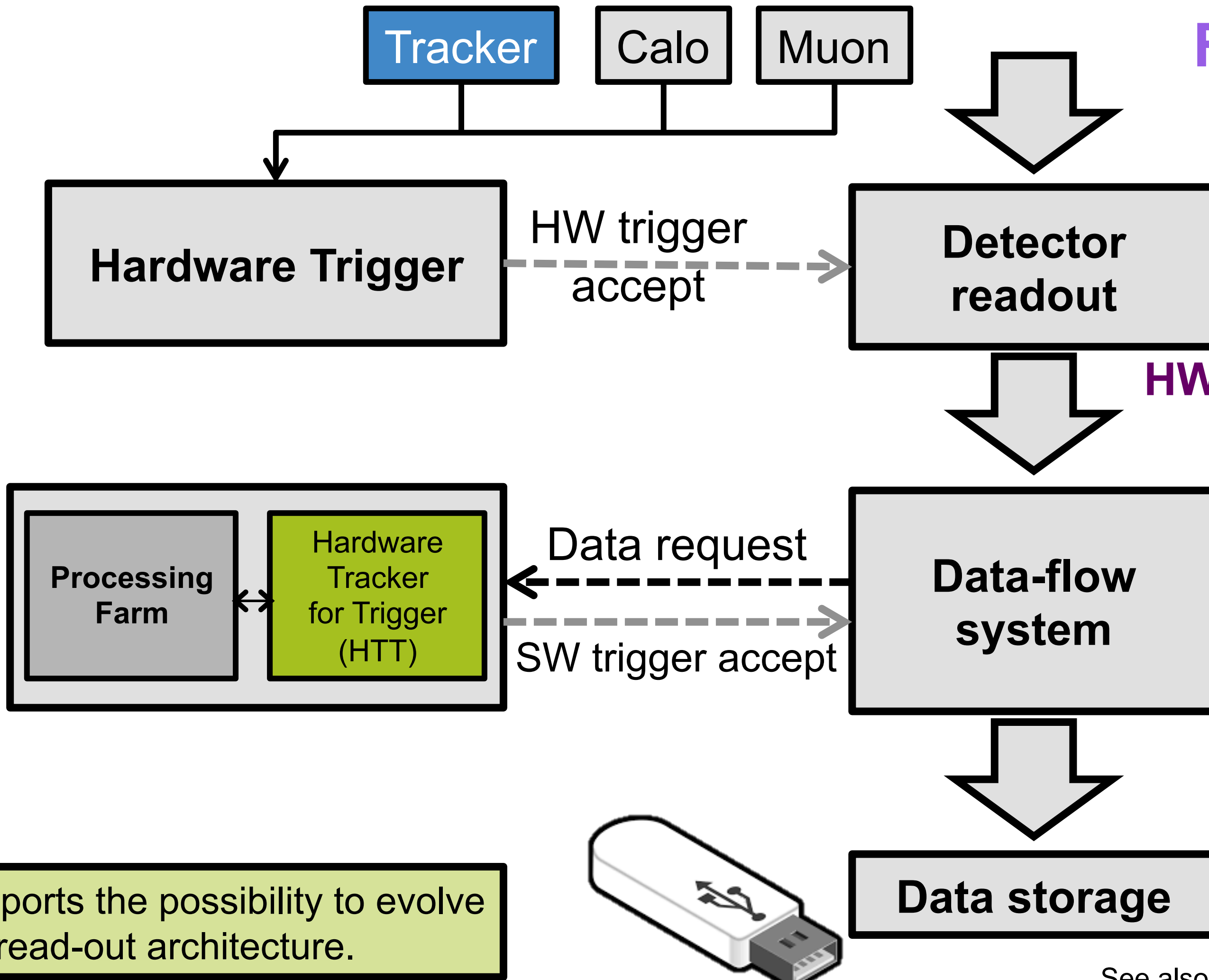
40 MHz
13 TeV

HW trigger accept
~ 100 kHz

Storage
1 kHz

THE TRIGGER & DATA ACQUISITION

Architecture: Very simplified view



For HL-LHC

40 MHz
14 TeV

HW trigger accept
1MHz/750kHz
(10µs/12.5µs)

Storage
10kHz/7.5kHz

ATLAS supports the possibility to evolve to a 4MHz read-out architecture.

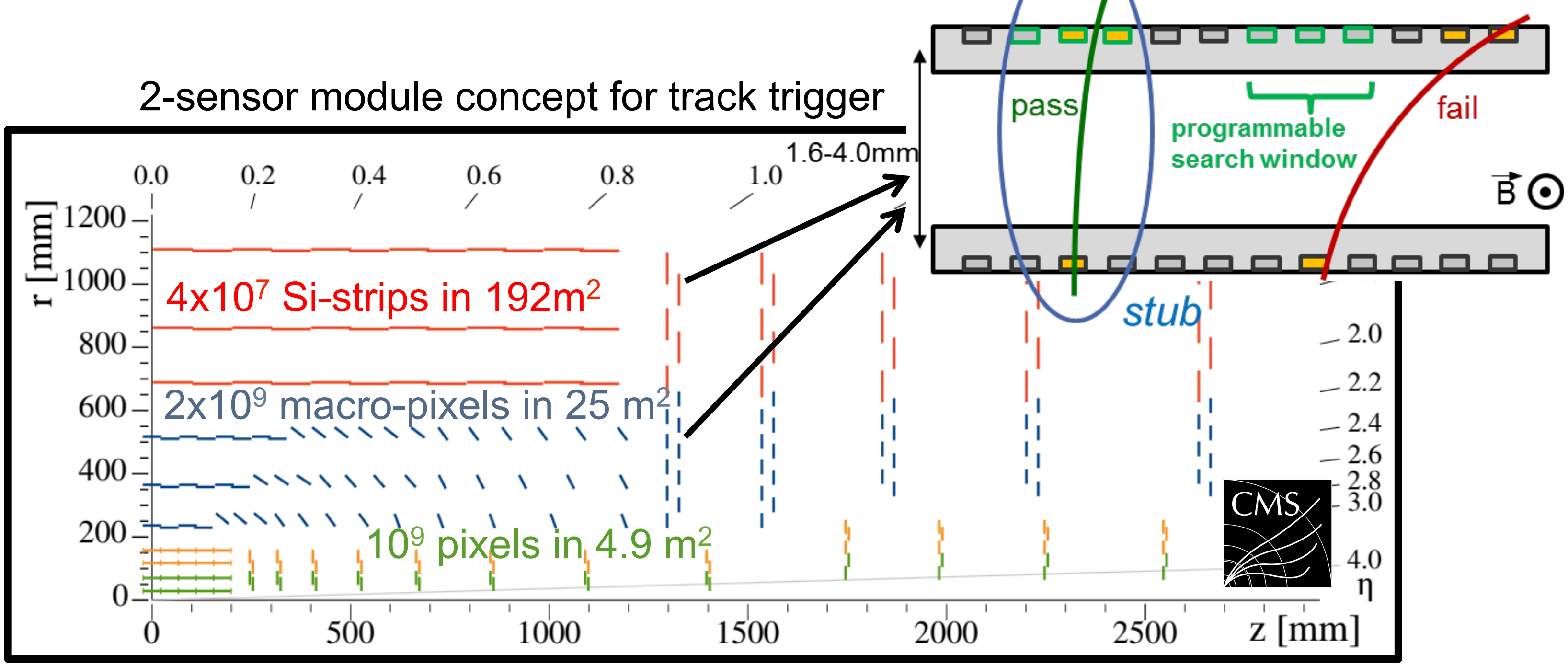
THE TRIGGER & DATA ACQUISITION

Architecture: Very simplified view

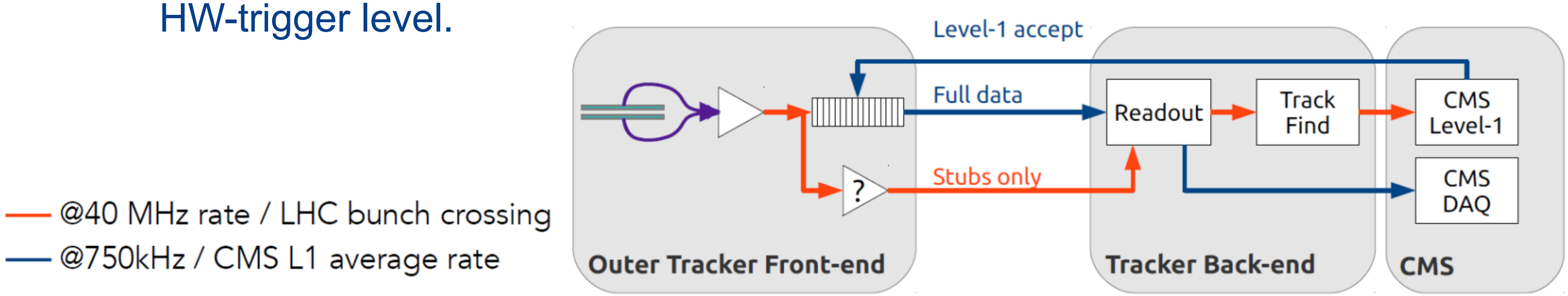
Upgrade highlights

- **Increased latency.**
- **Higher data granularity.**
- **Enhanced processing capability with:**
  - time-multiplexed architectures processing event information from multiple systems.
  - tracking information integrated into the detector and system design.
- **Technologies:**
  - Latest class FPGAs; ATCA crates; GPUs; ML.
  - Trend away from custom boards and ASICs towards firmware and software on commodity hardware (PCs, FPGAs, etc).
- **Major challenges:**
  - Power delivery and thermal management.
  - System integration and management.

TRIGGER TRACKING
THE CMS APPROACH



- Stubs are formed from hit pairs compatible with track pT > 2GeV.
  - **At 40 MHz!** They provide factor 10 data reduction.
- FPGA-based tracking algorithm reduces rate further.
  - Two approaches: (1) Tracklets; (2) Hough-transform plus Kalman-Filter
- Tracks combined with calo & muon signatures to provide HW trigger accept.
  - Gives capability to perform sophisticated selections (e.g. particle-flow) at HW-trigger level.

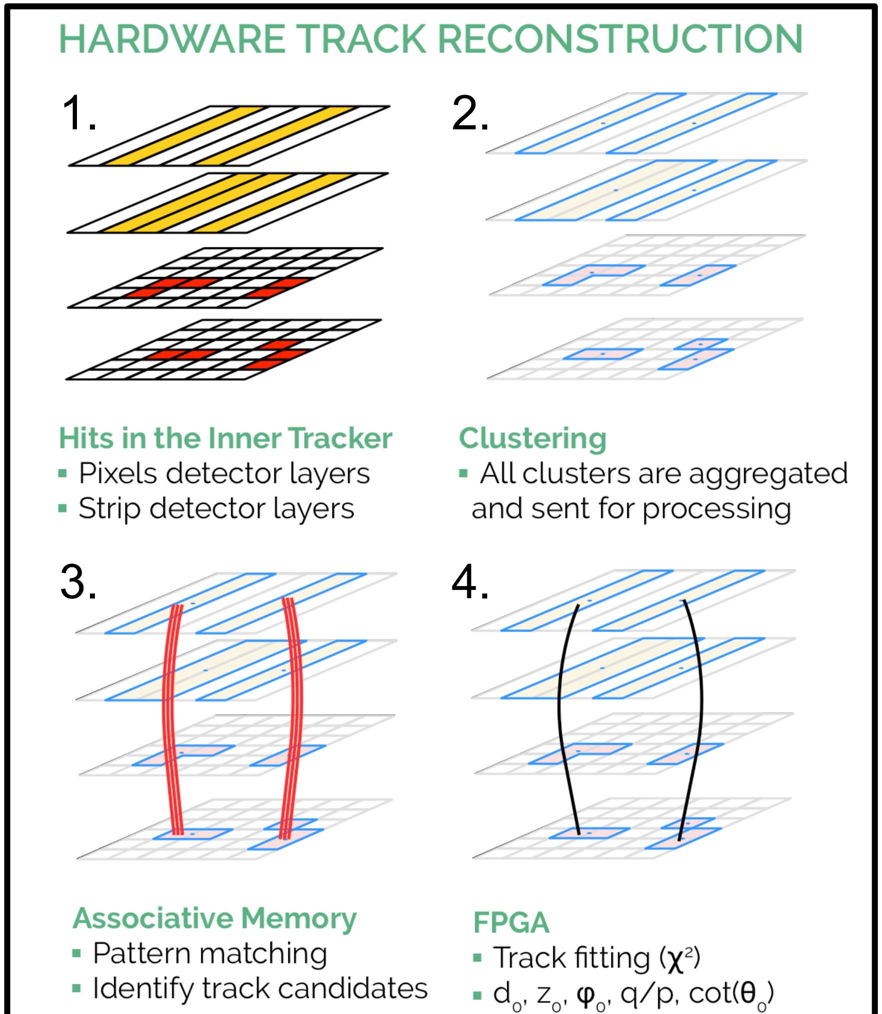


See also parallel talk of M. Trovato.

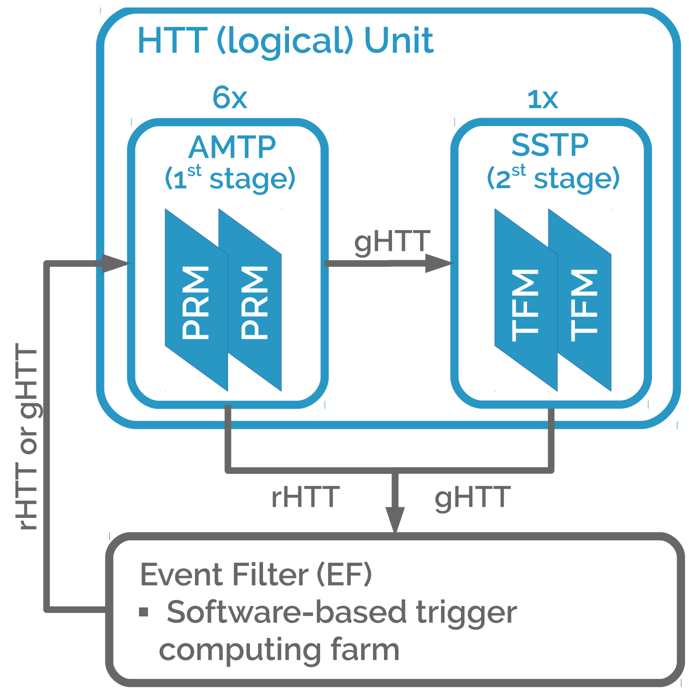
Drawings: A. Dierlamm, S. Mersi

Hardware Tracker for the Trigger (HTT)

- **Regional** (“**rHTT**”, pT > 2 GeV, full η coverage) and **global** (“**gHTT**”, planned for 100kHz input rate, pT > 1 GeV, full η coverage) functionality in the default TDAQ architecture.



- Systems based on the **same hardware**, implemented according to needs.



See also parallel talk of M. Trovato.

Drawings: R. Poggi

TRIGGER MENUS

Objective of HL-LHC menus: ensure thresholds as low or lower than what we currently have, **to allow for EW scale physics.**

- **Achievable thanks to the upgraded systems!**

Trigger Selection offline threshold (GeV)	Run1 ATLAS	Run2 ATLAS	HL-LHC ATLAS	HL-LHC CMS
isolated single e	25	27	**22**	**27**
Isolated single μ	25	27	**20**	**18**
di-γ	25,25	25,25	**25,25**	**22,16**
di-τ	40,30	40,30	**40,30**	**56,56**
four-jet w/ b-jets	45	45	**65**	**72**
HT	700	700	**375**	**350**
MET	150	200	**200**	**TBD**

Just indicative comparison using ATLAS menus. Similar between the two experiments.

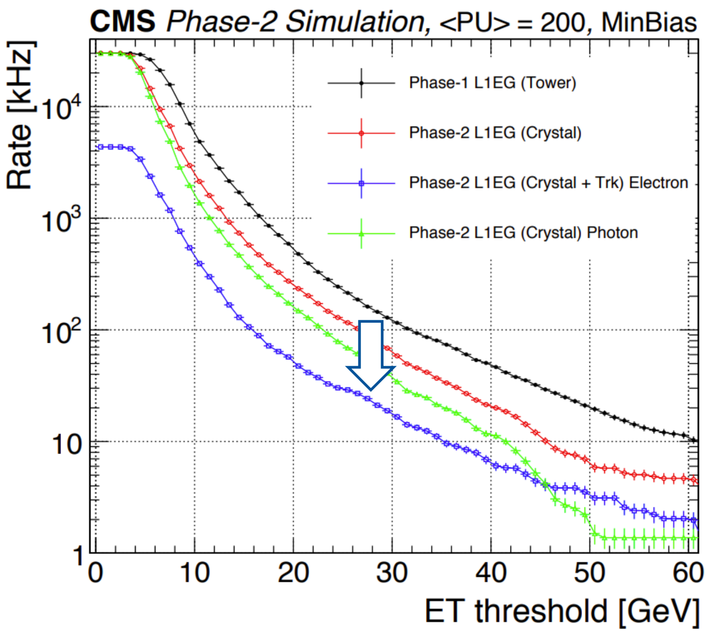
Work in progress towards the TDR (late 2019).

KEY ASPECTS OF TRIGGER PERFORMANCE

Major improvements targeting the very important single lepton triggers.

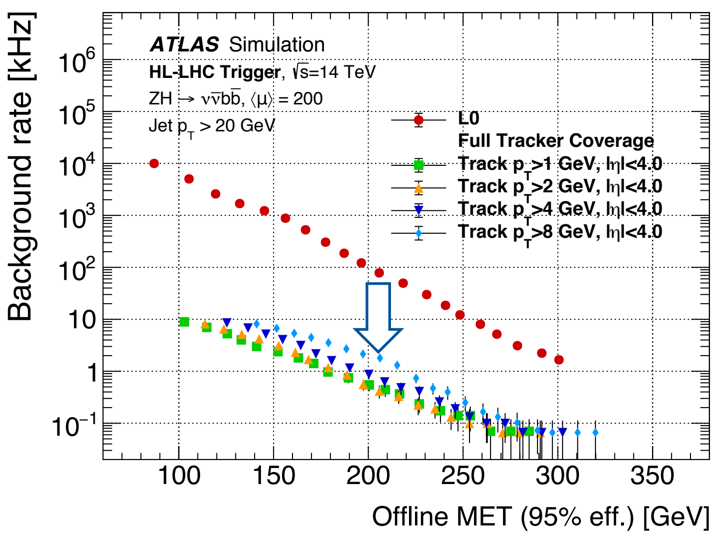
E.g. for electrons at CMS (similar for ATLAS):

- Rate rejection in electron triggers improved by factor > 2 by increasing Calo granularity.
- Significant extra rate reduction for small (<5%) efficiency loss by adding tracking.



Offline-like techniques used for pile-up-prone hadronic triggers, crucial in searches.

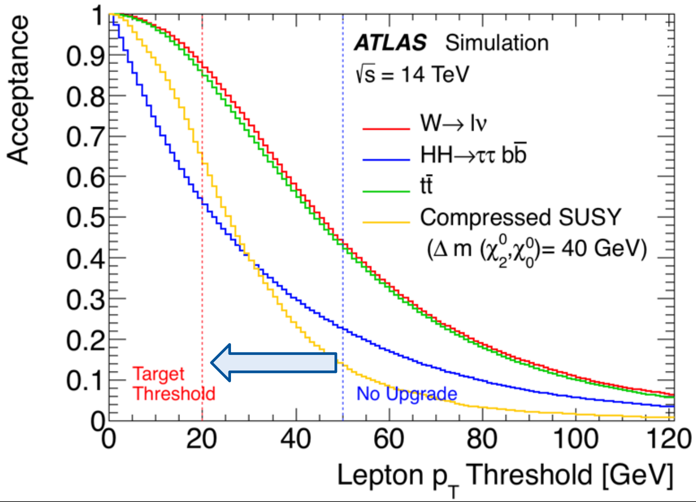
- Impact of Missing Transverse Momentum reconstruction with pile-up subtraction and track-based soft-term: Orders of magnitude reduction in rate for high trigger efficiency.



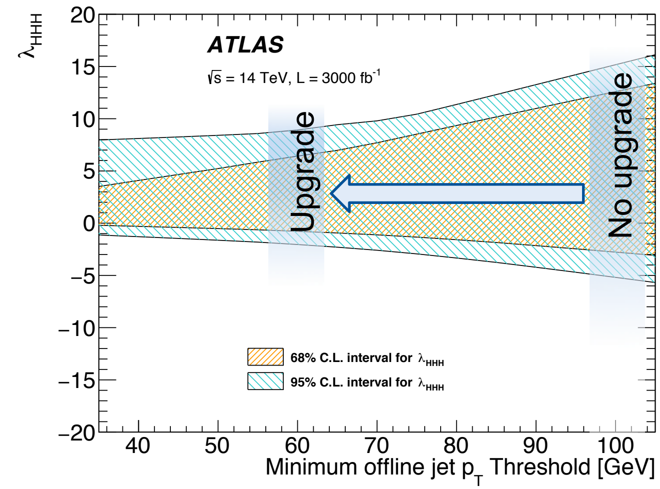
Large variety of studies done. Examples given here.

IMPACT TO PHYSICS POTENTIAL

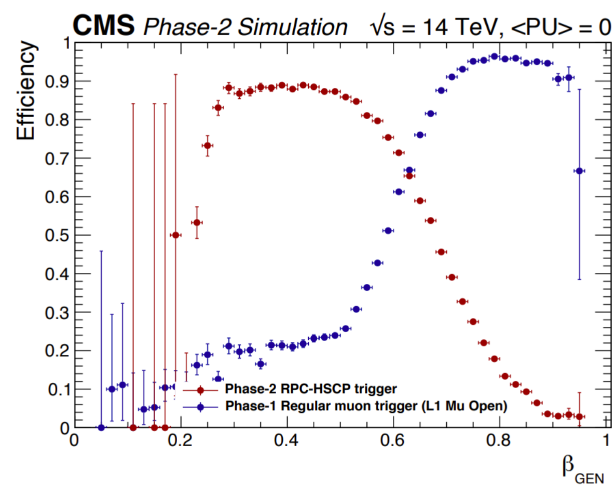
- Impact of lepton trigger pT to acceptance of key processes.



- Impact of multi-jet trigger pT to Higgs self-coupling measurement.



- Impact of muon trigger upgrade to unconventional signatures (e.g. long-lived particles, displaced vertices, lepton-jets, etc): New possibilities open up!
  - E.g. Heavy stable charged particle trigger exploits intrinsic resolution of RPC timing to provide good coverage down to β=0.3.



Large variety of studies done. Examples given here.
See also parallel talks of C. Gemme and K. Hoepfner.

OUTLOOK

The ATLAS and CMS detectors will be upgraded with requirements driven by the physics program priorities and ensure that the experiments will be running with maximal physics potential.

Tracking and trigger upgrades have been presented in this talk.

Ongoing upgrades for Run3 are well underway.

Tracking and trigger are among the most challenging aspects of the HL-LHC upgrades due to the unprecedented data-taking conditions.

Plans have been outlined in Technical Design Reports / Interim documents by both collaborations.

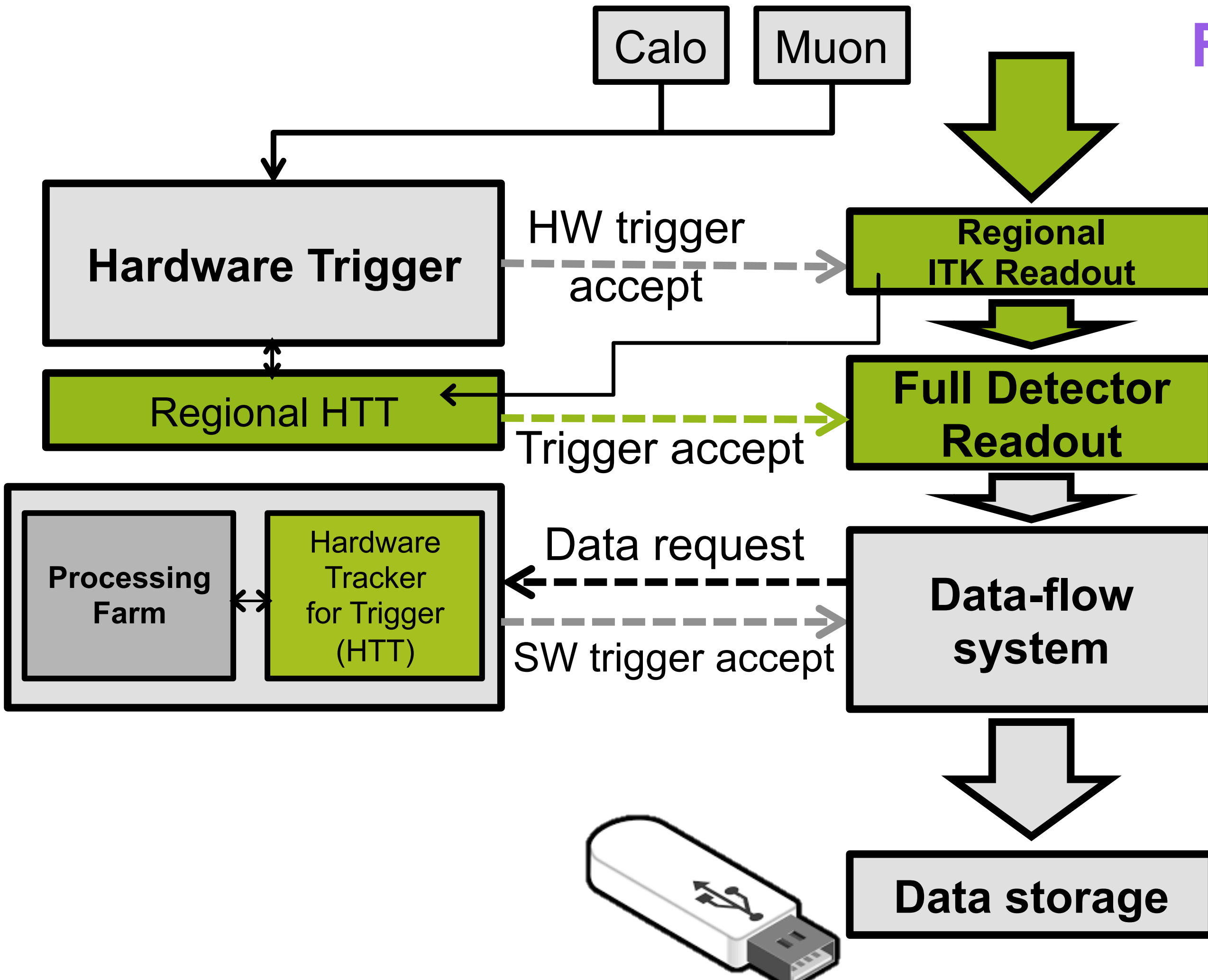
- Details are still being established in many aspects of both tracking and trigger upgrades.
- Demonstrator projects are underway to give confidence on the planned systems.
- Production will follow in early 2020's.
- Lots of exciting work for the ATLAS and CMS tracking & trigger communities!

EXTRAS

THE TRIGGER & DATA ACQUISITION

Architecture: Very simplified view

TDAQ
“Evolved Scenario”



For HL-LHC

40 MHz
14 TeV

“L0” accept
2 – 4MHz

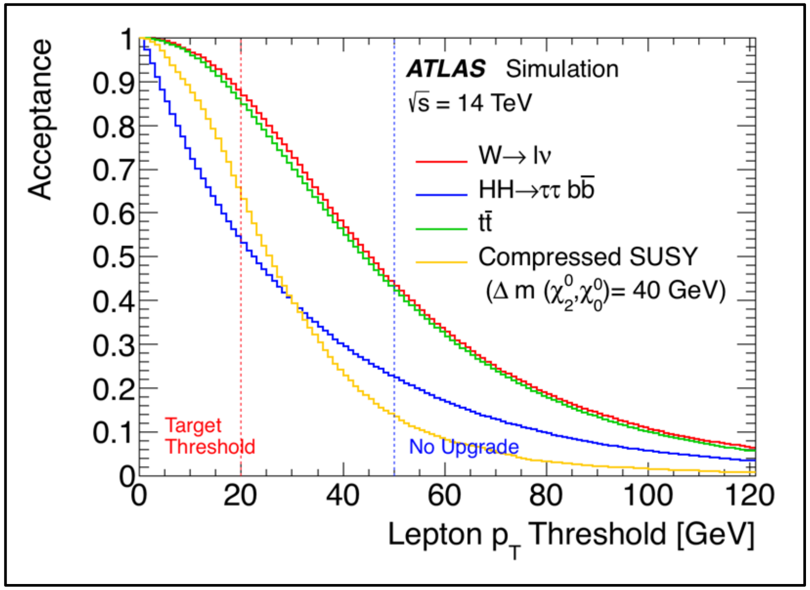
“L1” accept
800 – 600kHz

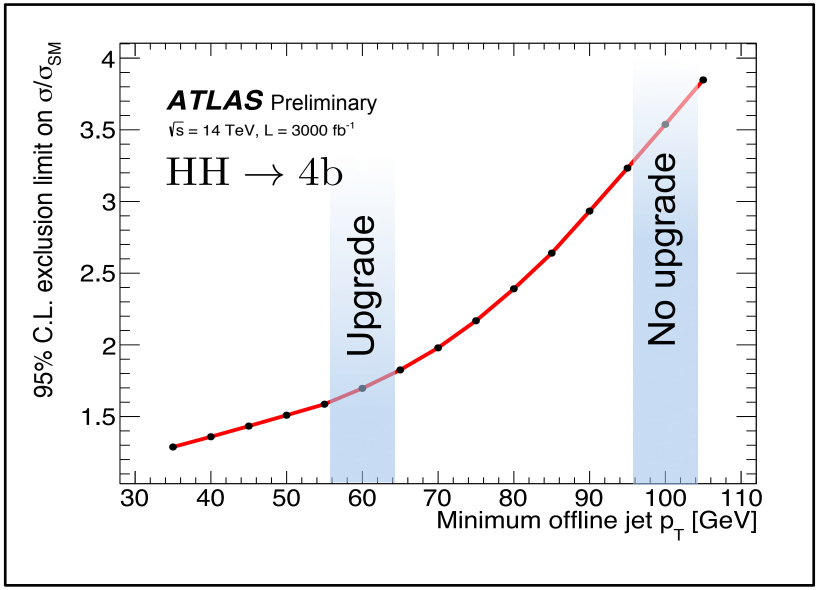
Storage
10kHz

TRIGGER UPGRADE **HIGHLIGHTS**

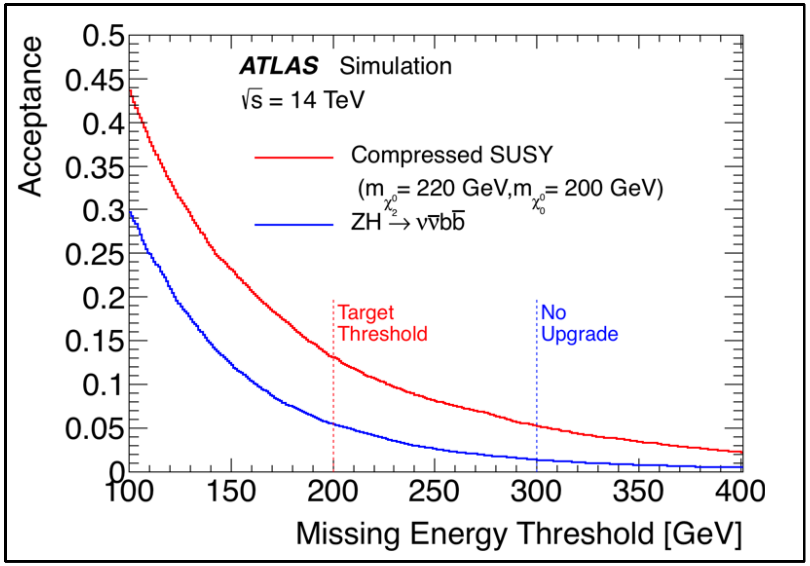
Increased latency	• Allowing for more complex objects, conditions and algorithms (including ML-based algorithms in FPGAs).	
Higher data granularity	• Full granularity for Calo (over noise) and Muons. (ATLAS EXPERIMENT)	• Significant increase over current calorimeters and new tracking information. (CMS)
Processing capability	• New "**Global**" trigger improves calo & muon triggers and provides offline-like calorimeter reco. In the evolved architecture, it includes tracking info. (ATLAS EXPERIMENT)	• New "**Correlator Trigger**" system matches tracking information with fine grain calo and fits muon and track data together. (CMS)
	• More **tracking** information integrated into the systems. • Key feature for pile-up mitigation and offline-like object reconstruction.	
Key technologies	• Latest class FPGAs with High-Bandwidth Memory and large DSP capability. • ATCA crates, multi-gigabit transceivers / optics. • GPUs considered and evaluated for the software trigger farm.	
Key challenges	• Power delivery and thermal management. • System integration.	

EXAMPLE PHYSICS CASES





Figures from TDR Draft

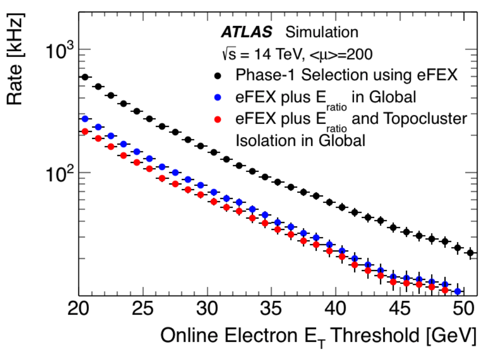


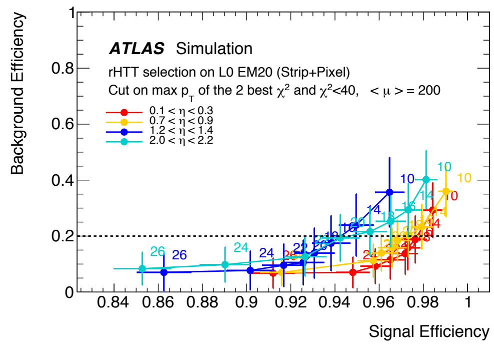
Upgrade leads to significant gains in both acceptance & significance.

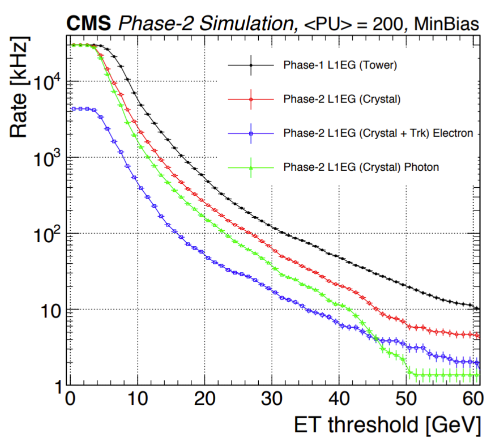
PROJECTED TRIGGER PERFORMANCE

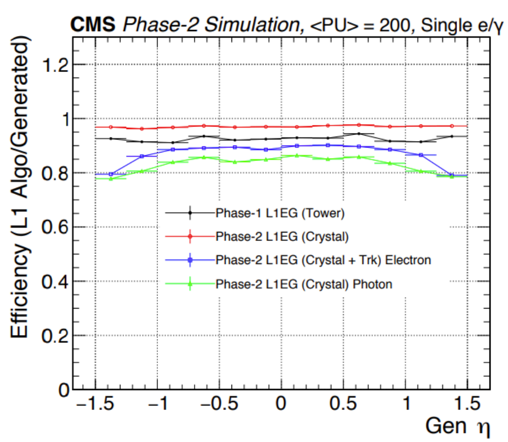
Major improvements targeting the very important single lepton triggers. E.g. for electrons:

- Rate rejection in electron triggers improved by factor > 2 by increasing Calo granularity.
- Significant extra rate reduction for small (<5%) efficiency loss by adding tracking.



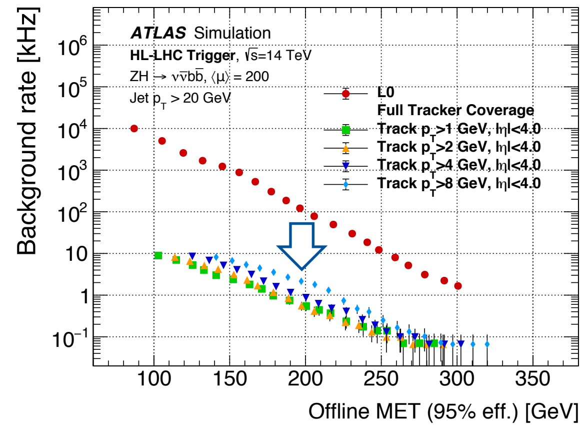


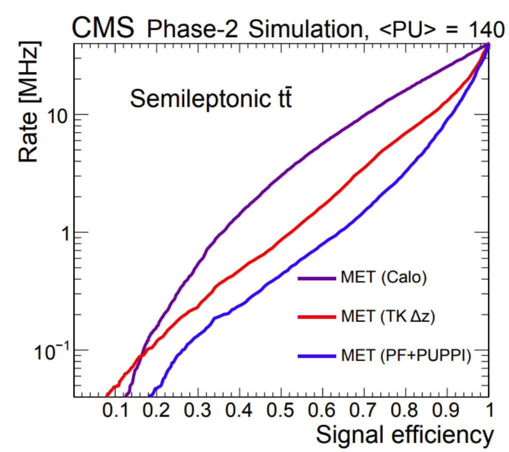




- Offline-like techniques for pile-up prone hadronic triggers, crucial in searches.

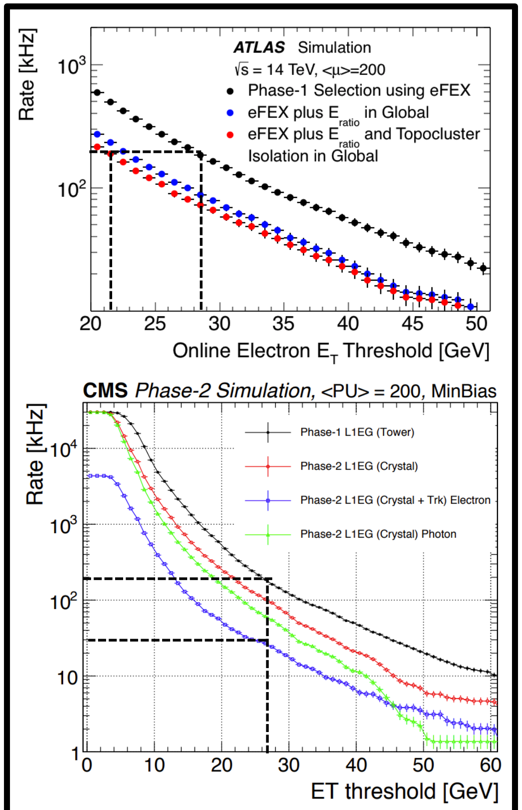
E.g. Missing Transverse Momentum triggers.





Large variety of studies done. Examples given here.

SINGLE ELECTRON TRIGGER COMPARISON



Trigger Selection offline threshold (GeV)	HL-LHC (ATLAS)	HL-LHC (CMS)
isolated single e	**22**	**27**
Allocated Rate (μ=200)	200 kHz (L0)	27 kHz
	50 kHz (after tracking)	

EVOLVED ATLAS MENU

Table 14.12: Prospective additional triggers for an evolved system. The gains for example physics channels are described in the last column.

Signature	Baseline Threshold	Evolved Threshold	Level-0 (kHz)	Level-1 (kHz)	EF before analysis specific cuts (kHz)	Gain
E_T^{miss}	210 GeV	160 GeV	800	80	3	2× acceptance for compressed SUSY model and 2.4× for $ZH \rightarrow \nu\nu bb$
di-τ	40, 30 GeV	30, 20 GeV	800	80	2.2	increased acceptance from 30% to 55% for VBF $H \rightarrow \tau\tau$ and 32% to 54% for $HH \rightarrow bb\tau\tau$
4 jet w/ 2-btags	65 GeV	55 GeV	800	100	0.4	improved limit in $HH \rightarrow 4b$ from 1.85 to 1.65 σ/σ_{SM}
VBF Higgs	75 GeV + topological	60 GeV + topological	280	40	40	increased acceptance from 6.6% to 10% for inclusive VBF Higgs production
Total			2680	300	-	