TRIGGERING AT ATLAS

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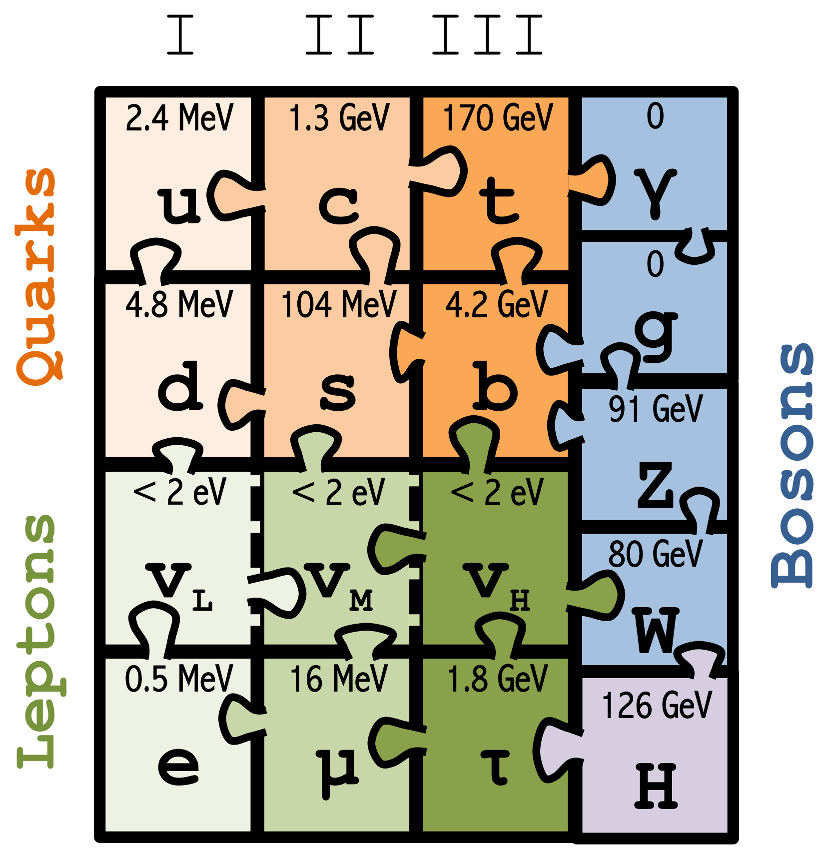
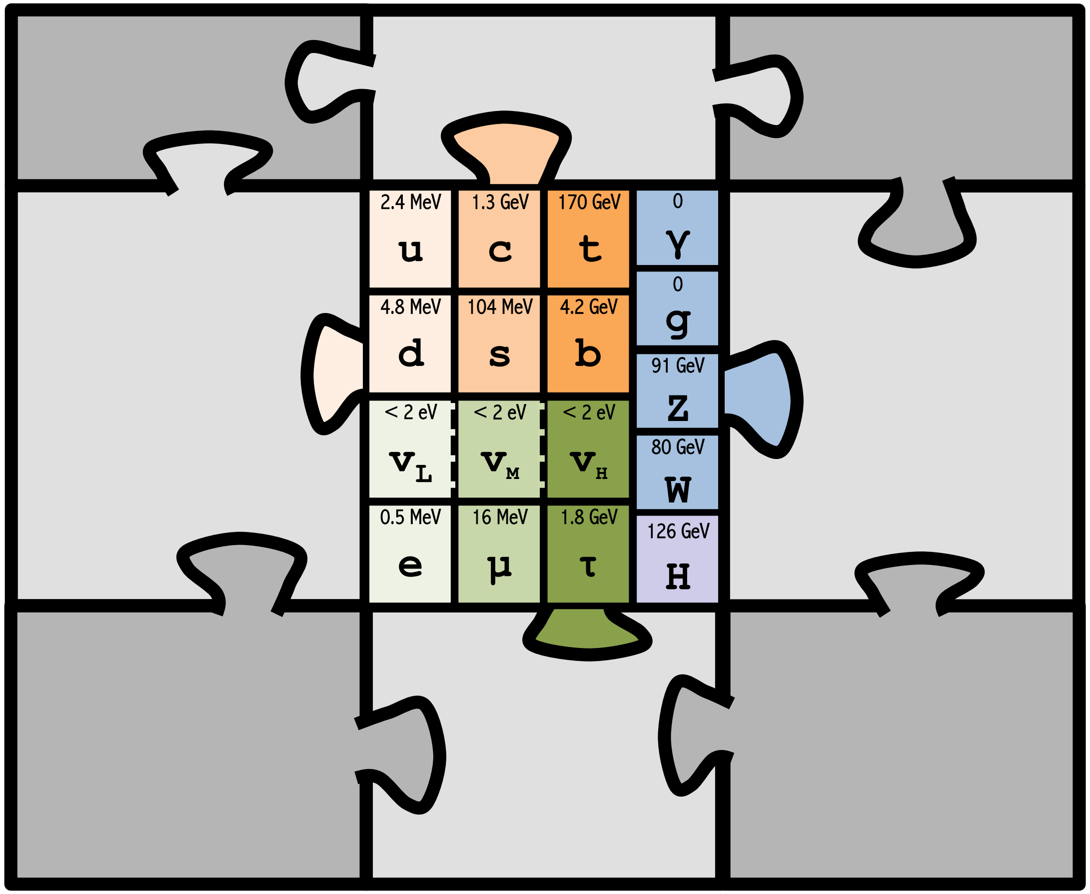
SEMINAR AT LAL, ORSAY

20 JANUARY 2017

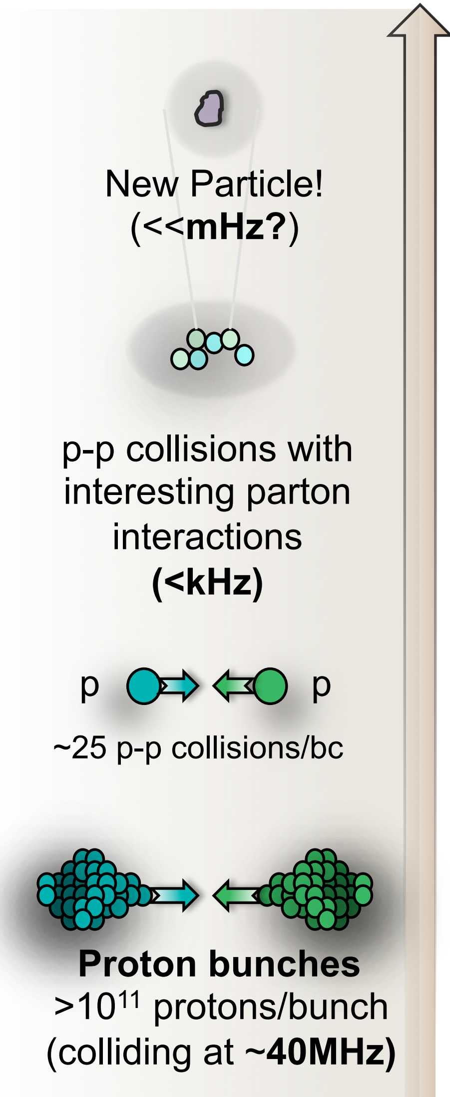
THE STANDARD MODEL

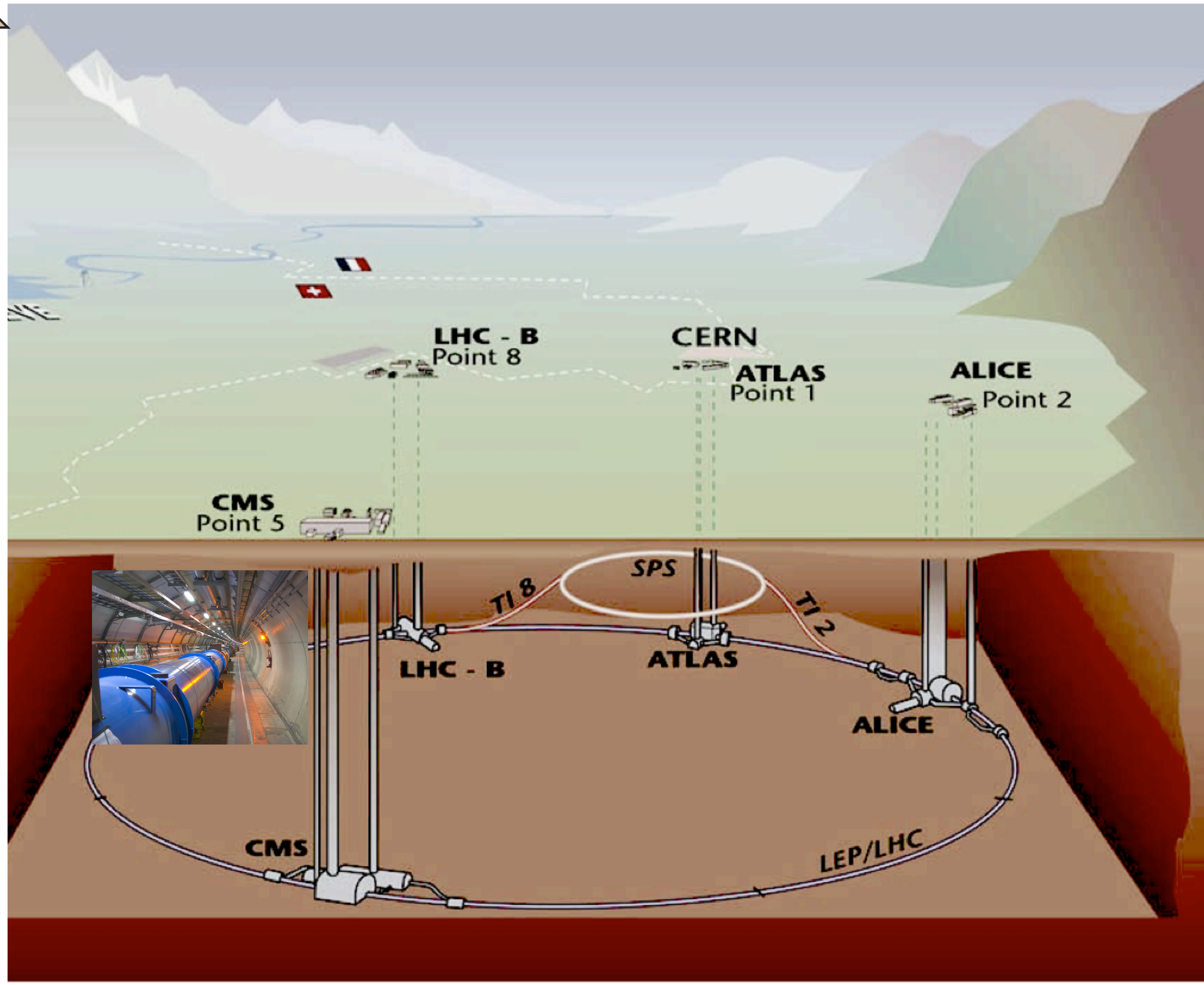


...ONE PIECE IN THE PUZZLE



THE LARGE HADRON COLLIDER





THE LARGE HADRON COLLIDER

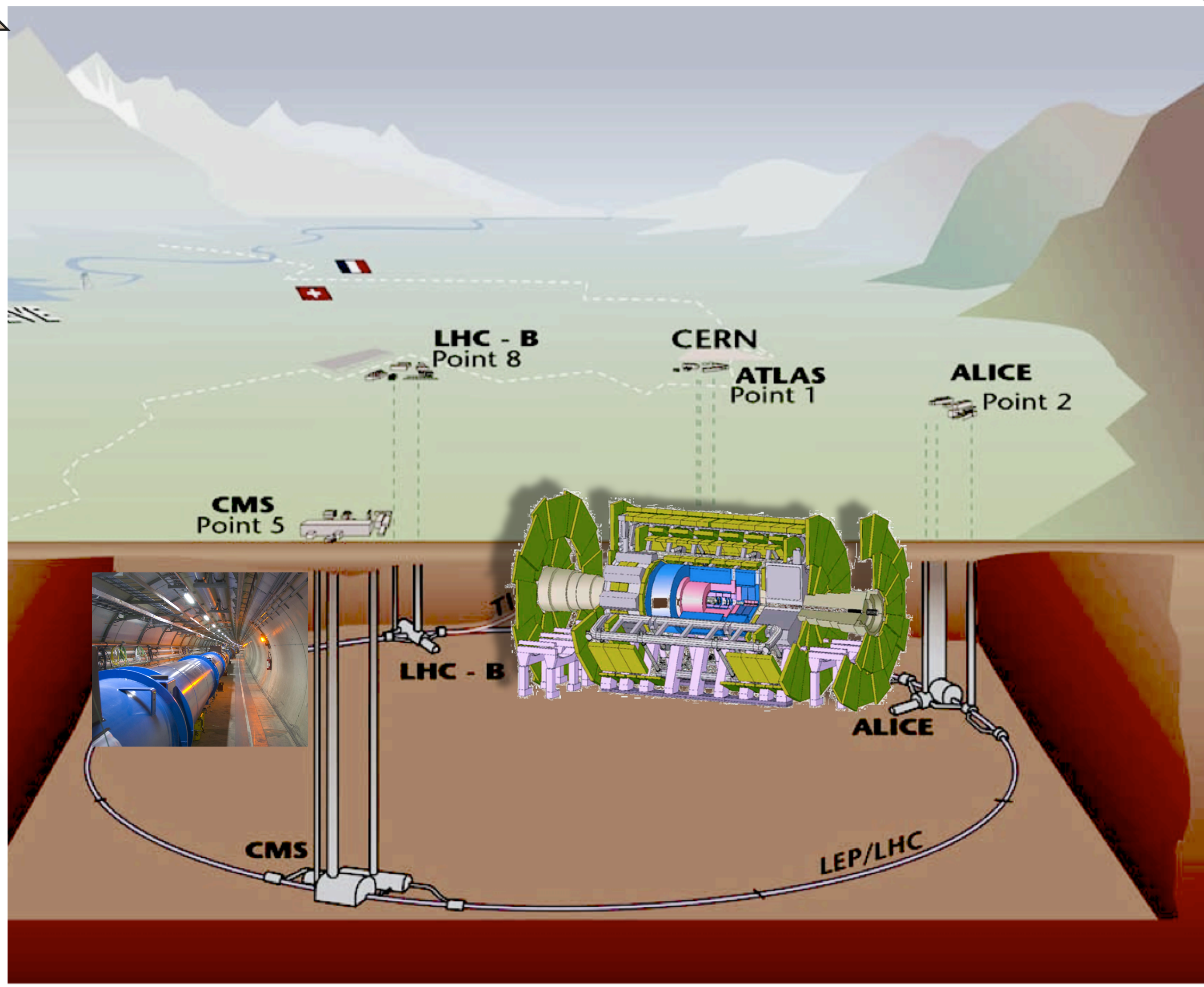
New Particle!
(<<**mHz?**)

p-p collisions with interesting parton interactions
(<kHz)

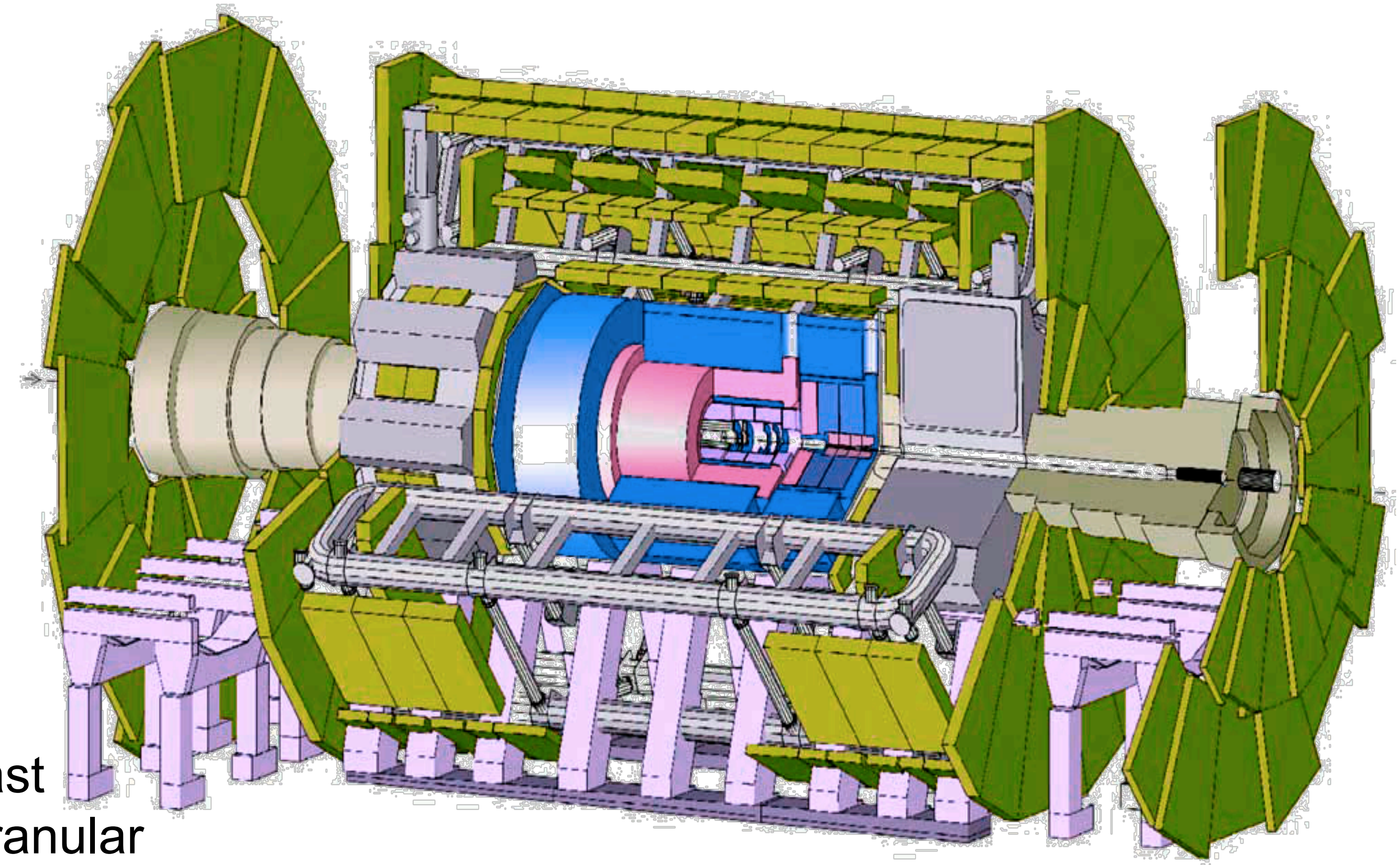
p p

~25 p-p collisions/bc

Proton bunches
$>10^{11}$ protons/bunch
(colliding at ~**40MHz)**

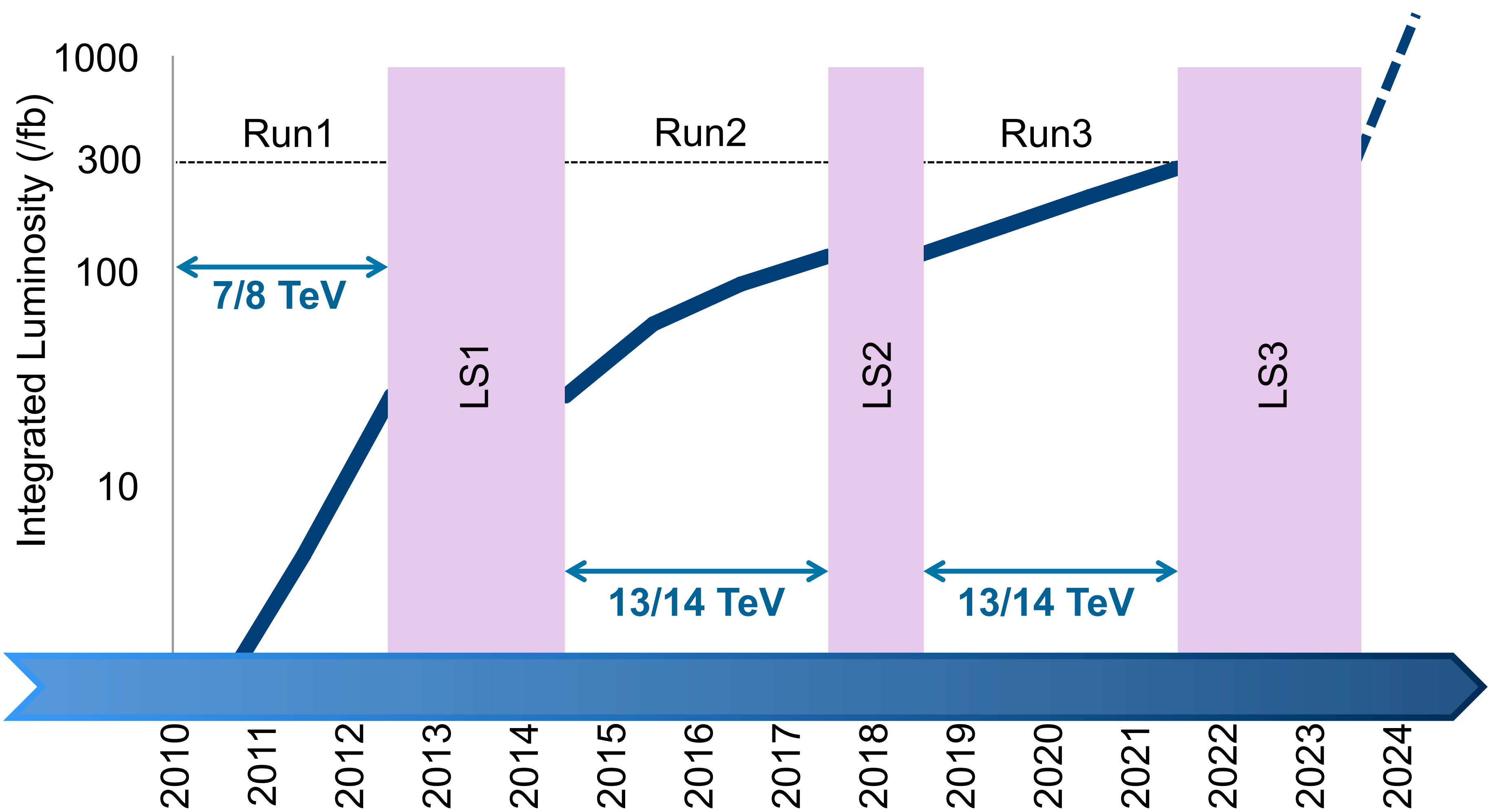


THE ATLAS DETECTOR



- ✓ Fast
- ✓ Granular
- ✓ Resistant to radiation

RUN1, RUN2 AND BEYOND

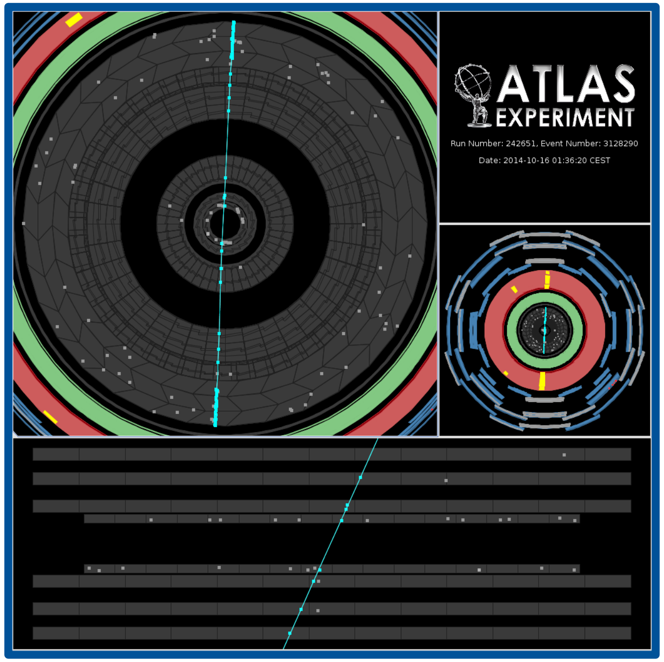


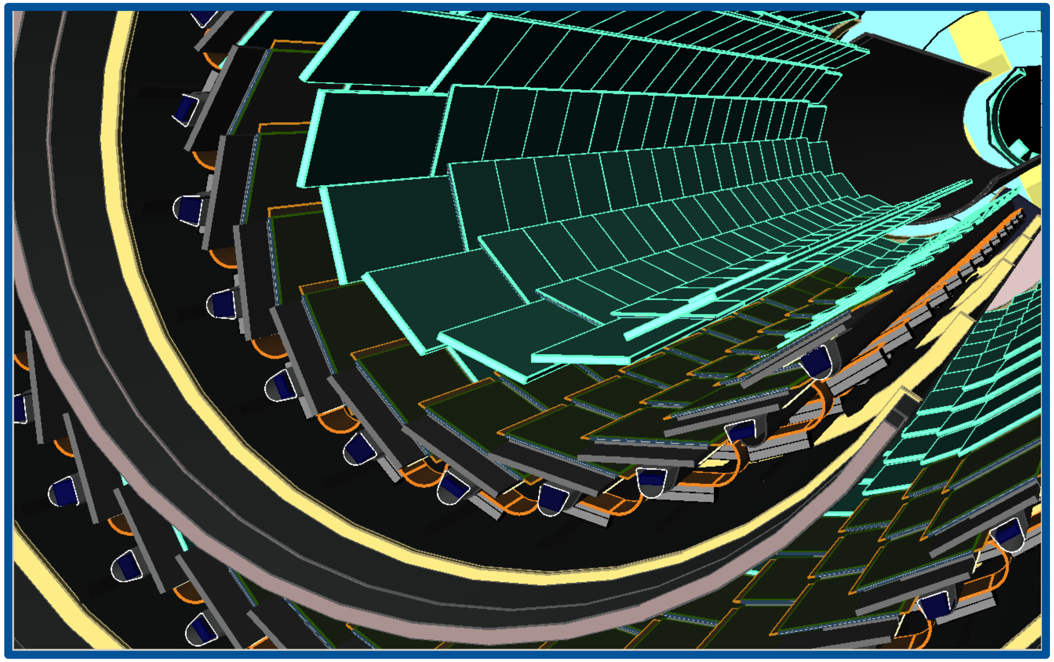
ATLAS POST-RUN1

Detector extensions

Trigger upgrade

Clever ideas for better object reconstruction





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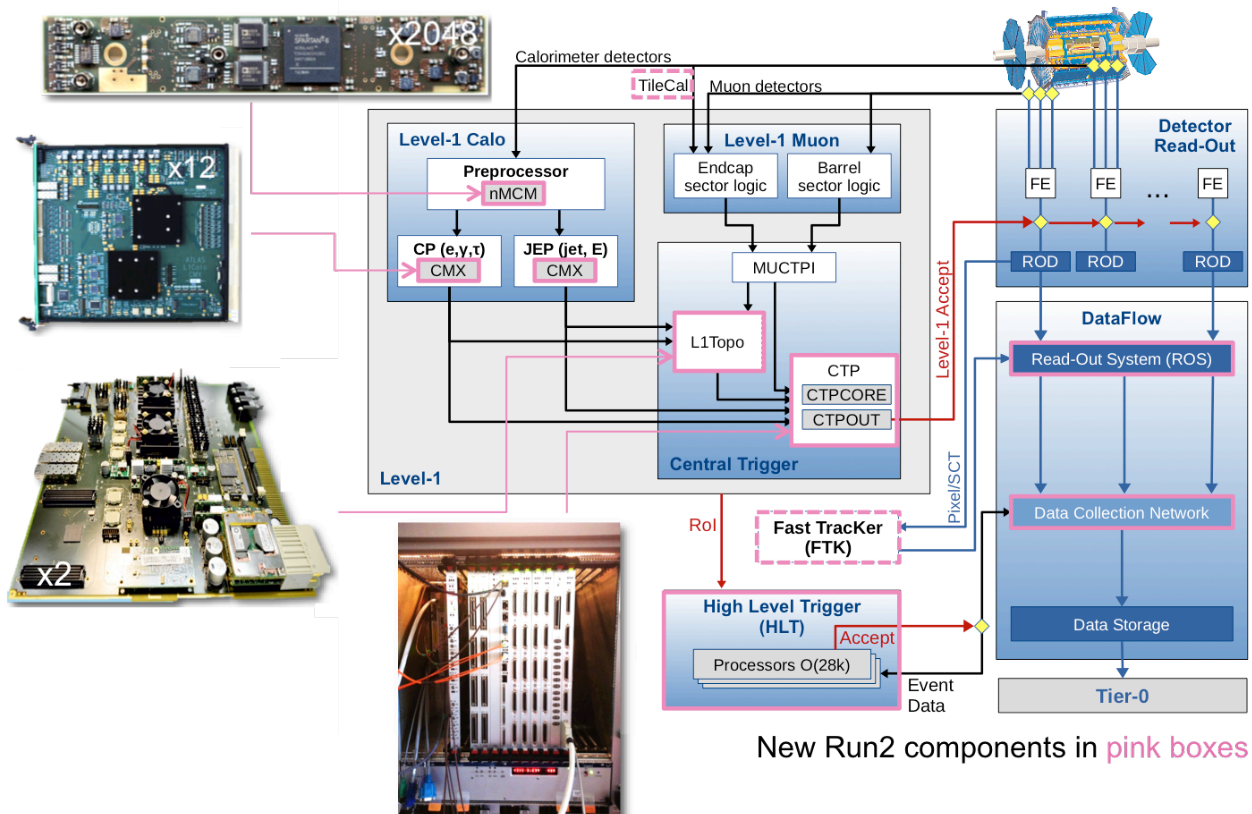
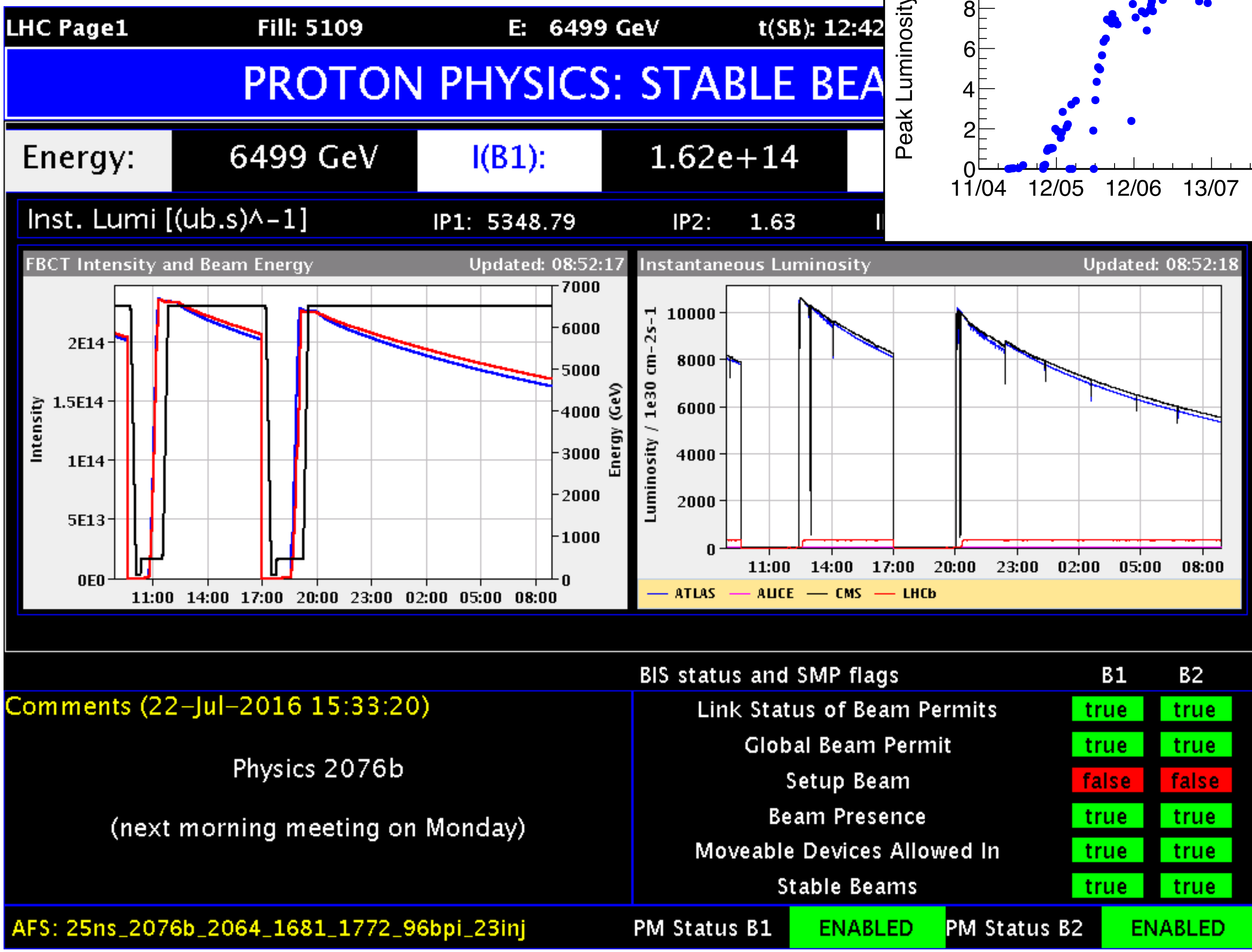
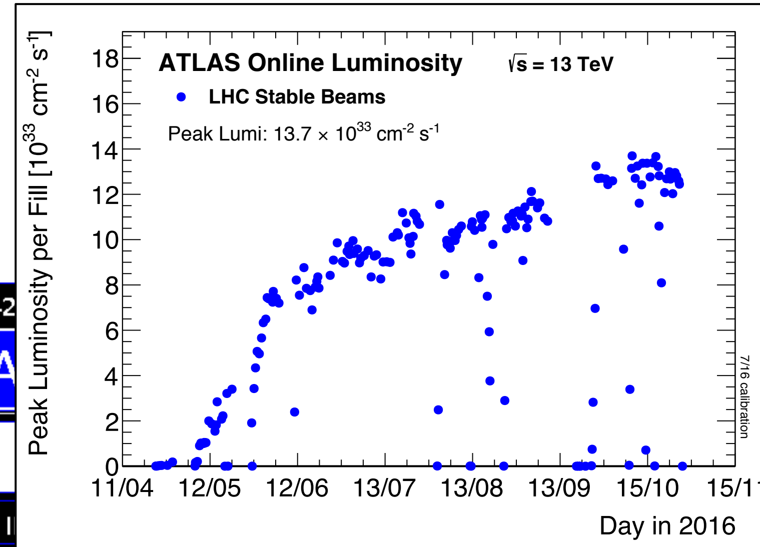


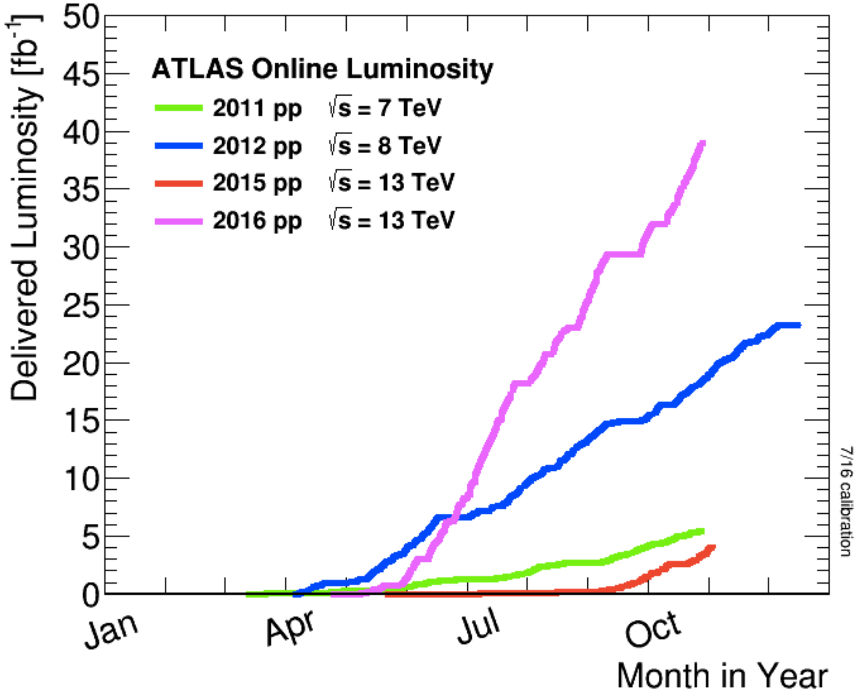
New Run2 components in pink boxes

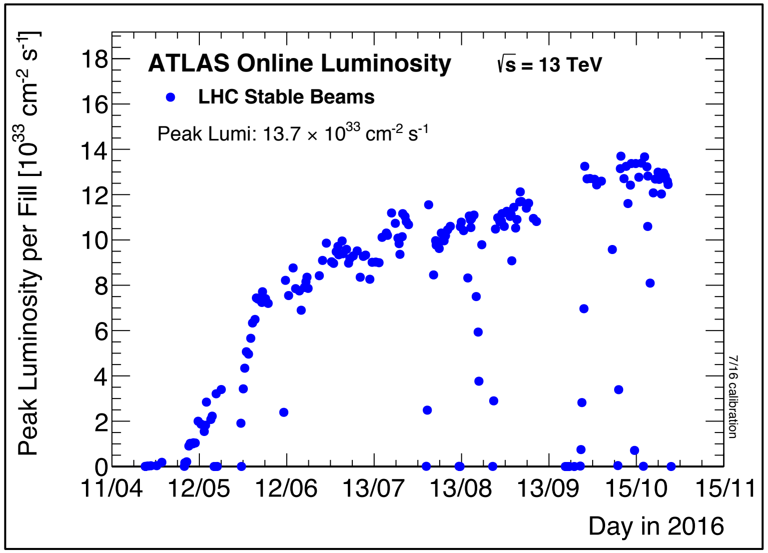
LHC OPERATIONS

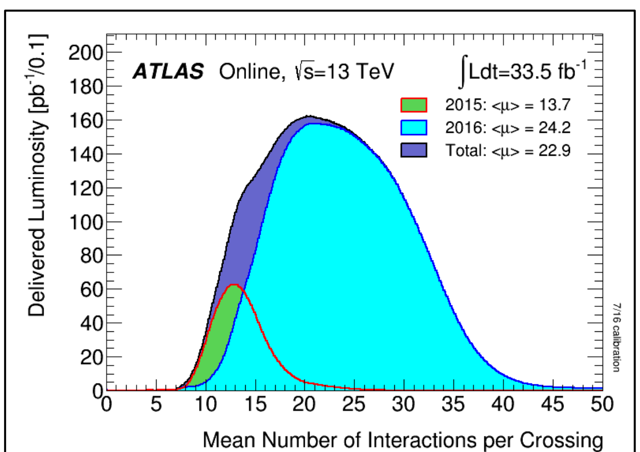


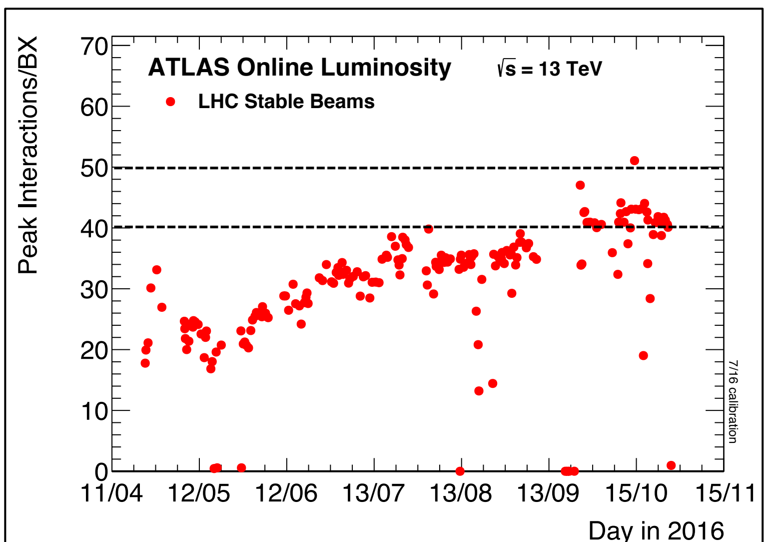


LHC OPERATIONS & ATLAS



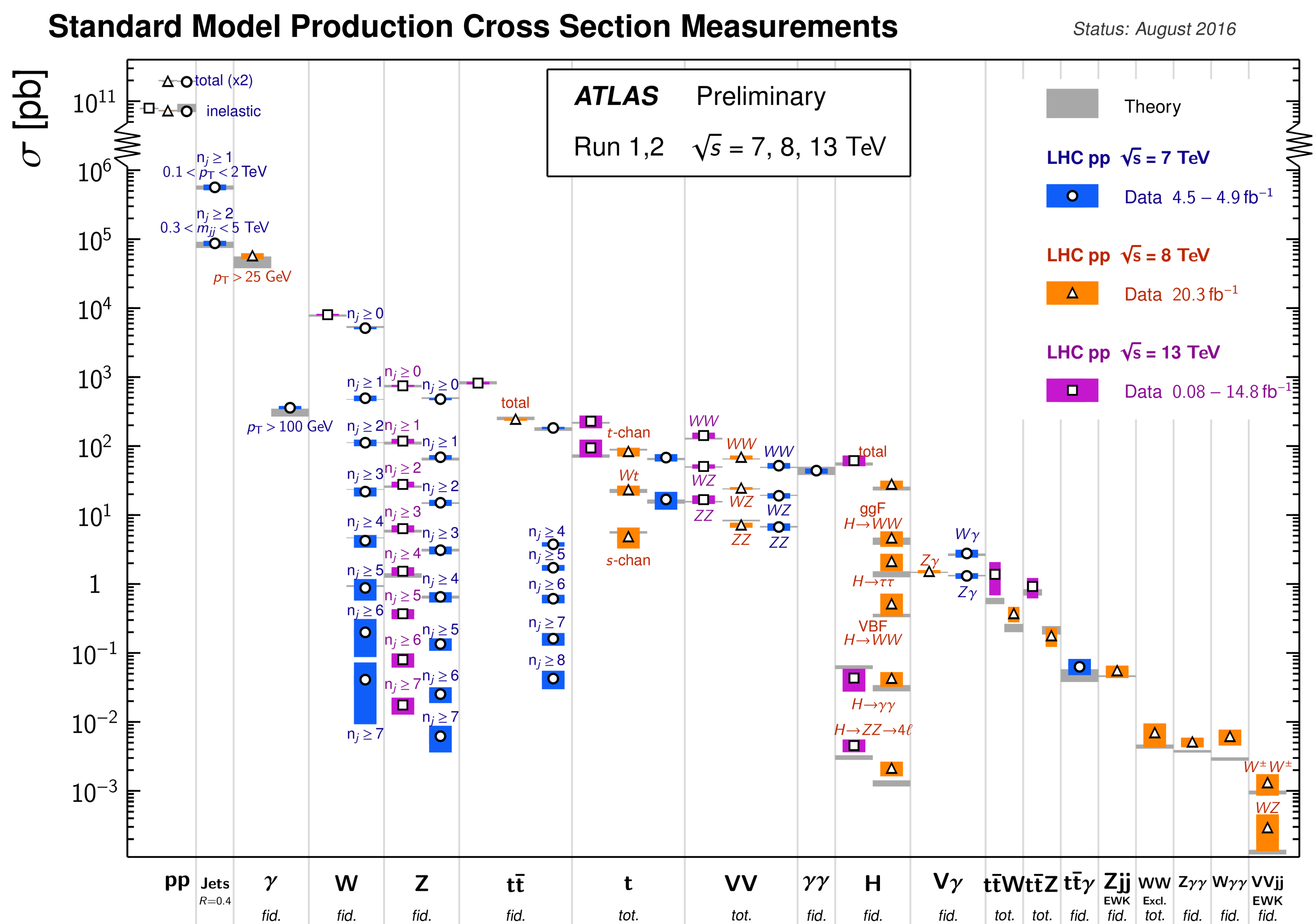






- **Why “trigger”?**
- **The trigger system in ATLAS run2.**
  - including trigger performance and new ideas for 2017 (and beyond).
- **Trigger menus.**
  - and what to expect for the future.
- **Beyond run2…**

THE STANDARD MODEL



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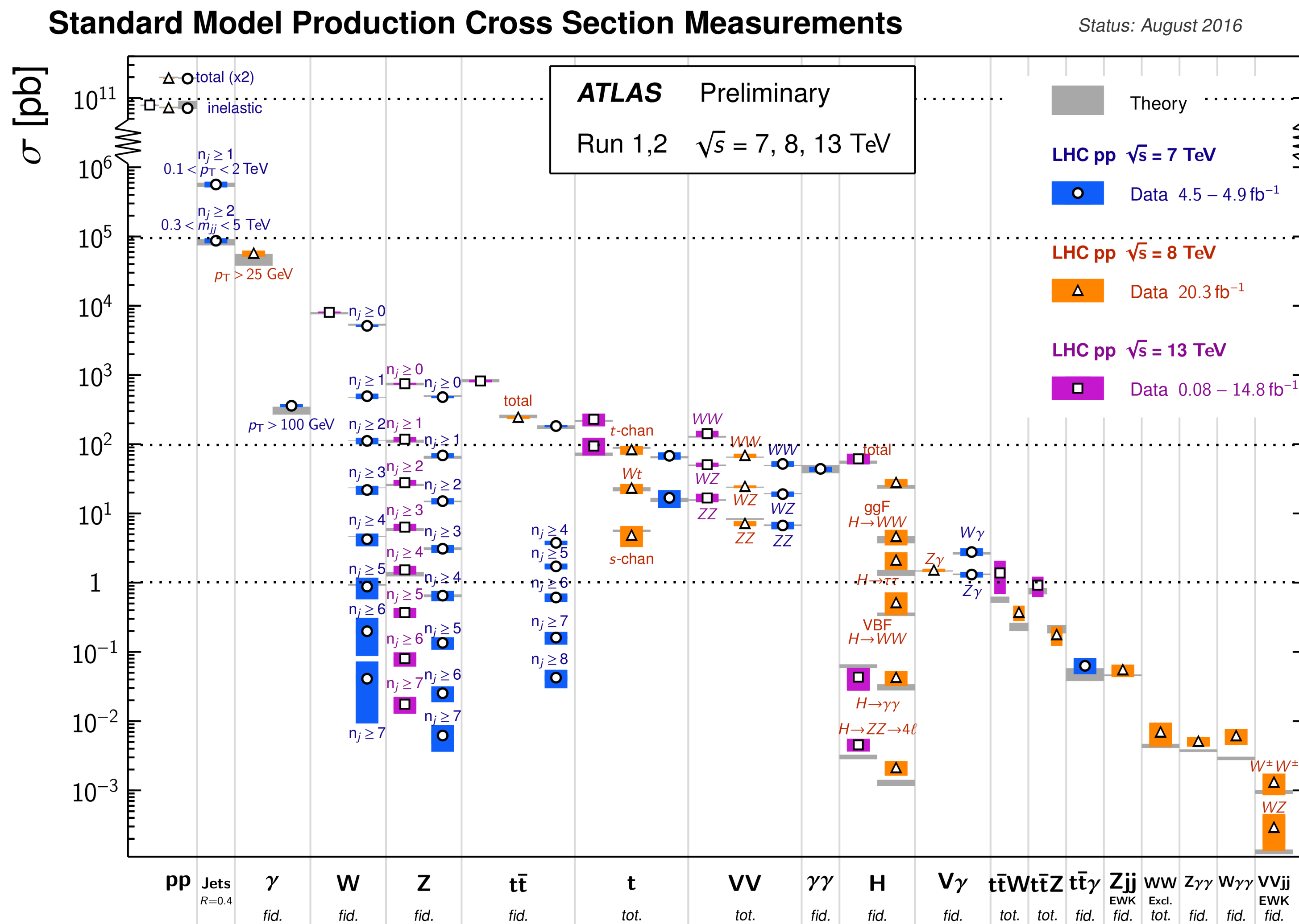


Event Rate

$L_{inst} = 10^{34}/cm^2s$

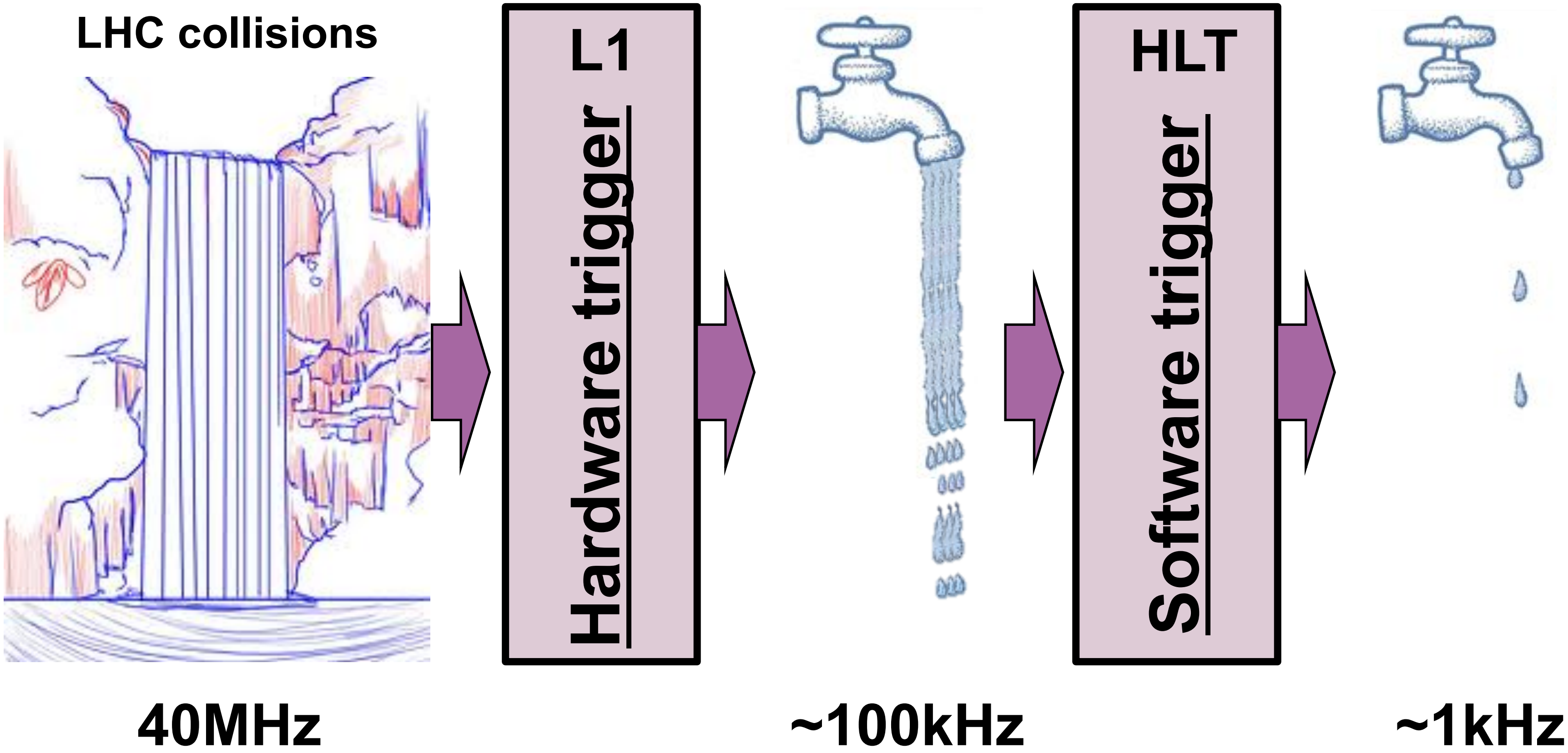
1 GHz

1 kHz

1 Hz

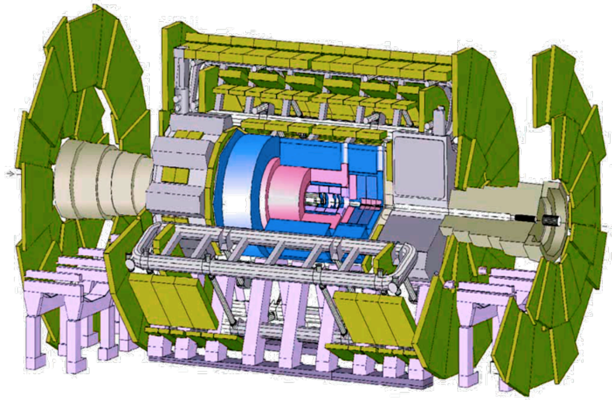
10^{-2} Hz

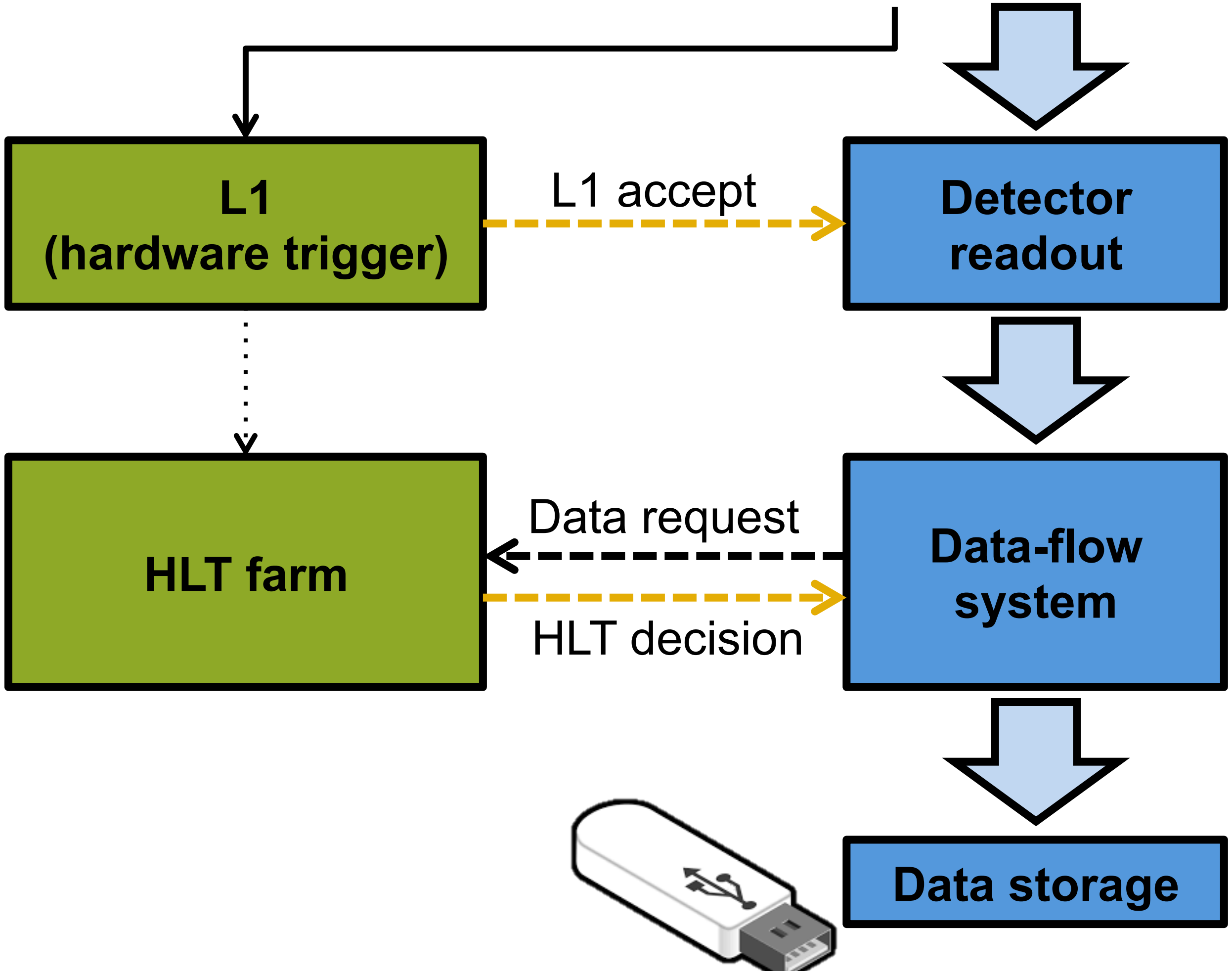
Viable SUSY & other exotics


LHC collisions
L1
Hardware trigger
HLT
Software trigger
40MHz
~100kHz
~1kHz

THE DATA ACQUISITION

Simplified





In 2016

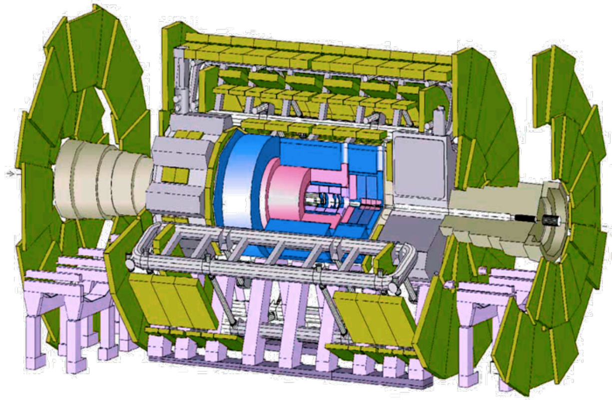
40 MHz
13 TeV

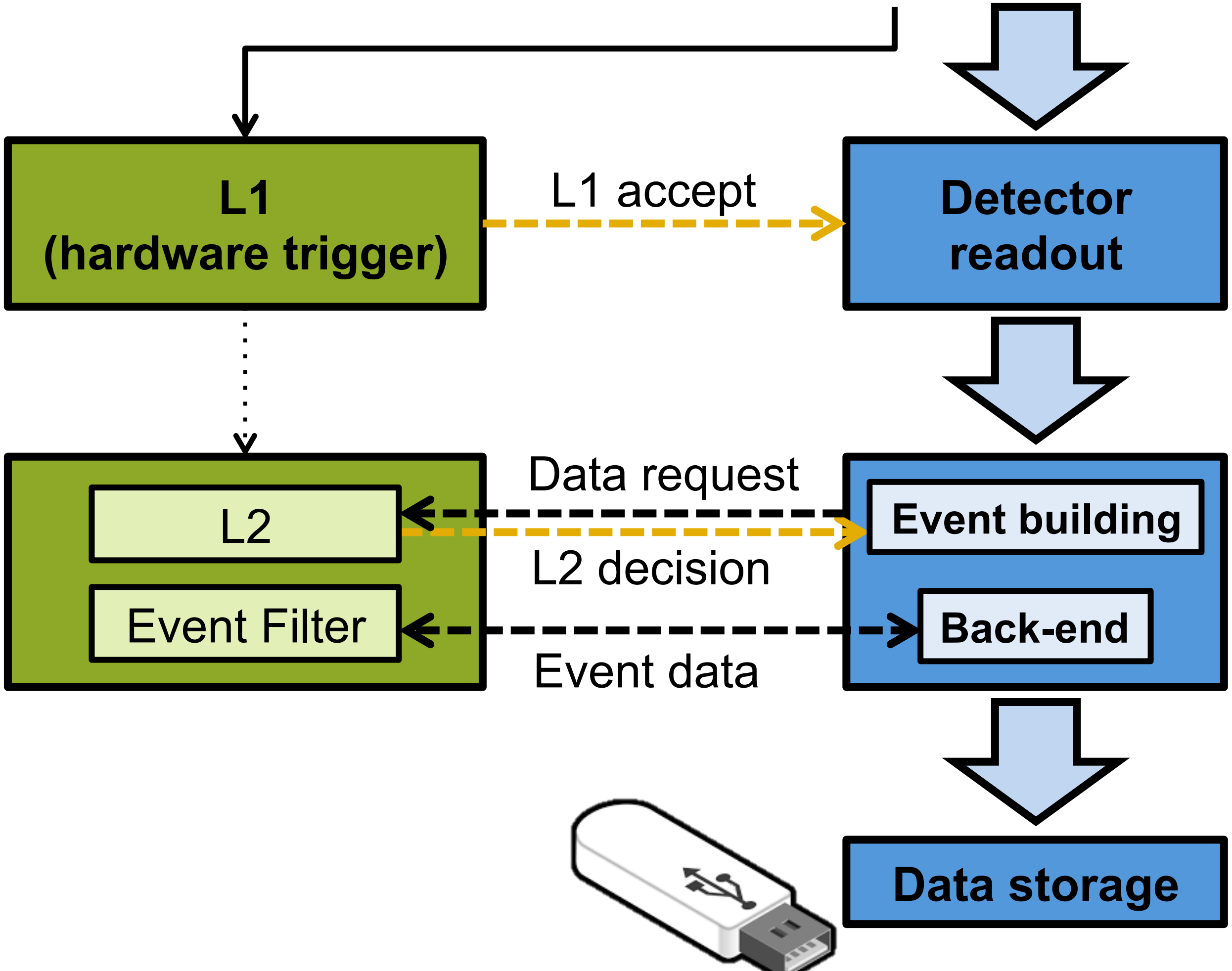
L1 accept
~ 90 kHz

Storage
1 kHz

THE ATLAS DATA ACQUISITION

Simplified





In 2012

20 MHz
8 TeV

L1 accept
70 kHz

L2 requests
25 kHz

Event building
6.5 kHz

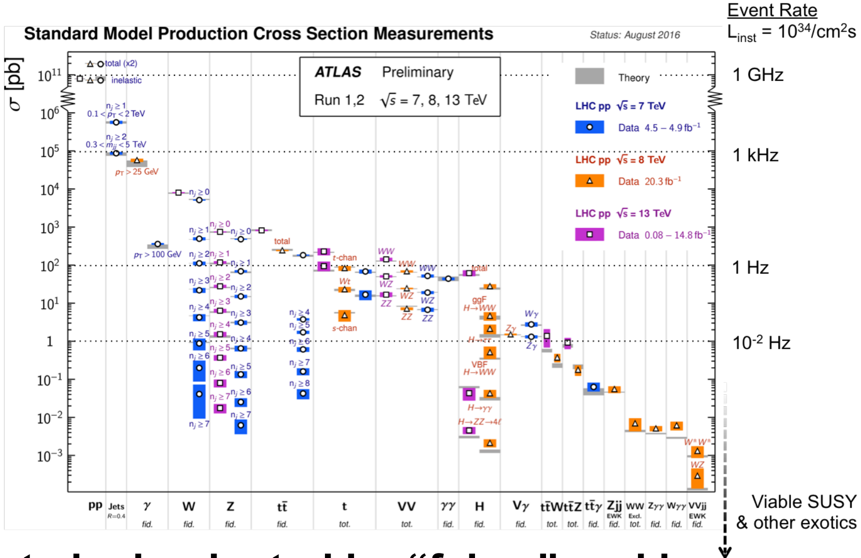
Storage
600 Hz

THE DATA

Triggering Challenge

Maintain a rich acceptance in physics (including unknown new phenomena!) while respecting the limitations of

- **Detector readout**
- **DAQ system & HLT**
- **Computing system**



and knowing that the event rate is dominated by "fakes" and is significantly affected by pile-up.

➔ **Find ways to reduce fakes and improve robustness to pile-up, respecting the limitations imposed by various systems.**

➔ **Various upgrades and new features introduced in DAQ, L1 and HLT.**

➔ **Key feature: robustness; events that are not triggered are lost forever.**

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L1 accept
~ 90 kHz

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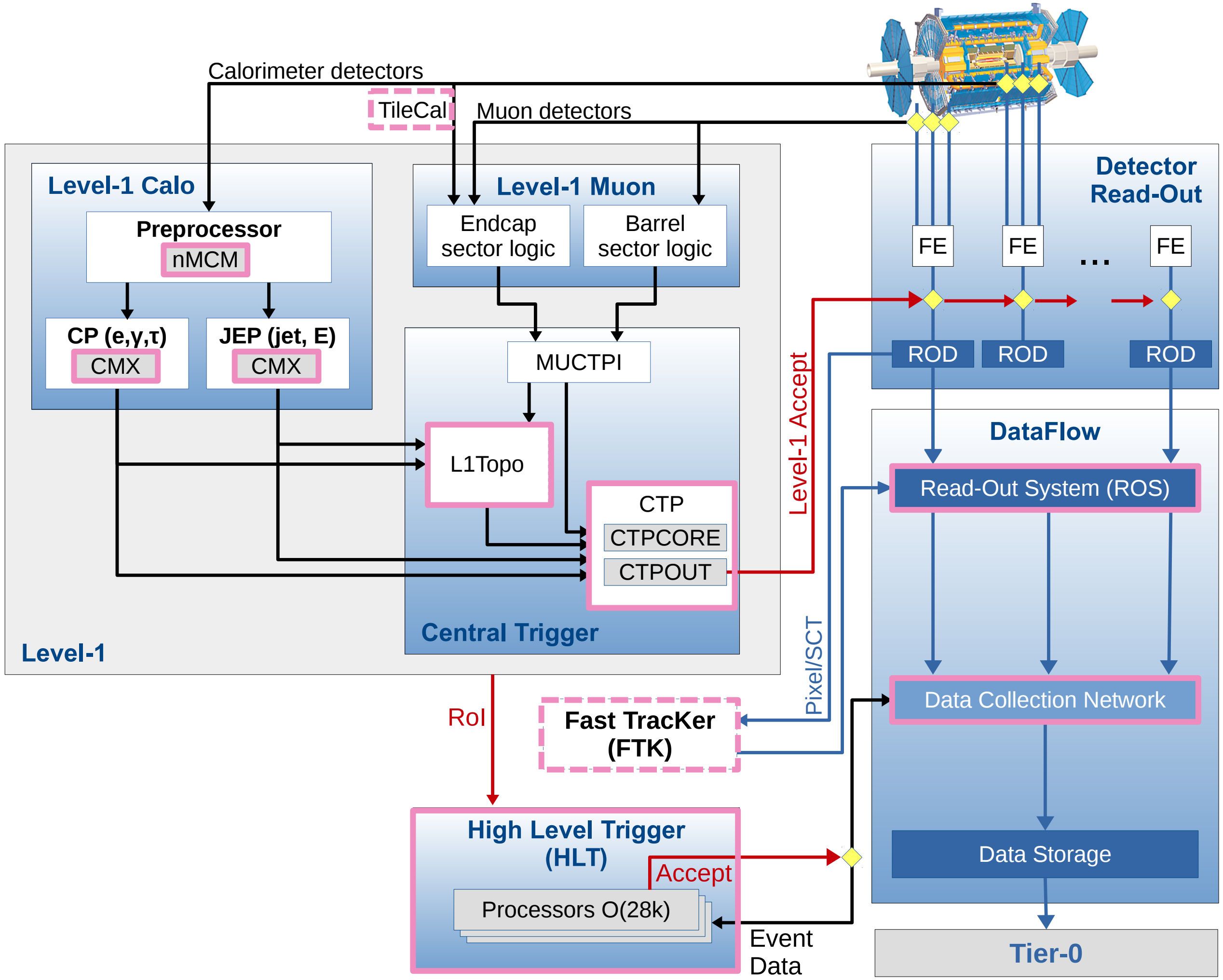
THE ATLAS TRIGGER SYSTEM



New Run2 components in pink boxes

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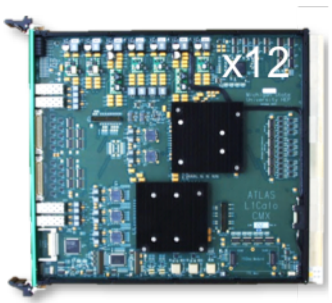

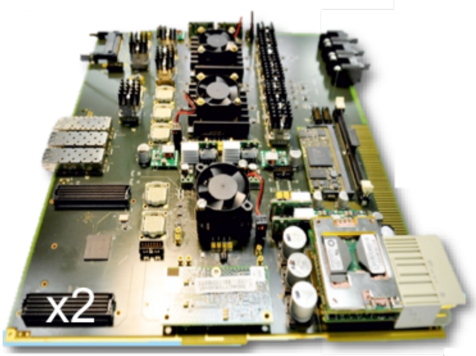

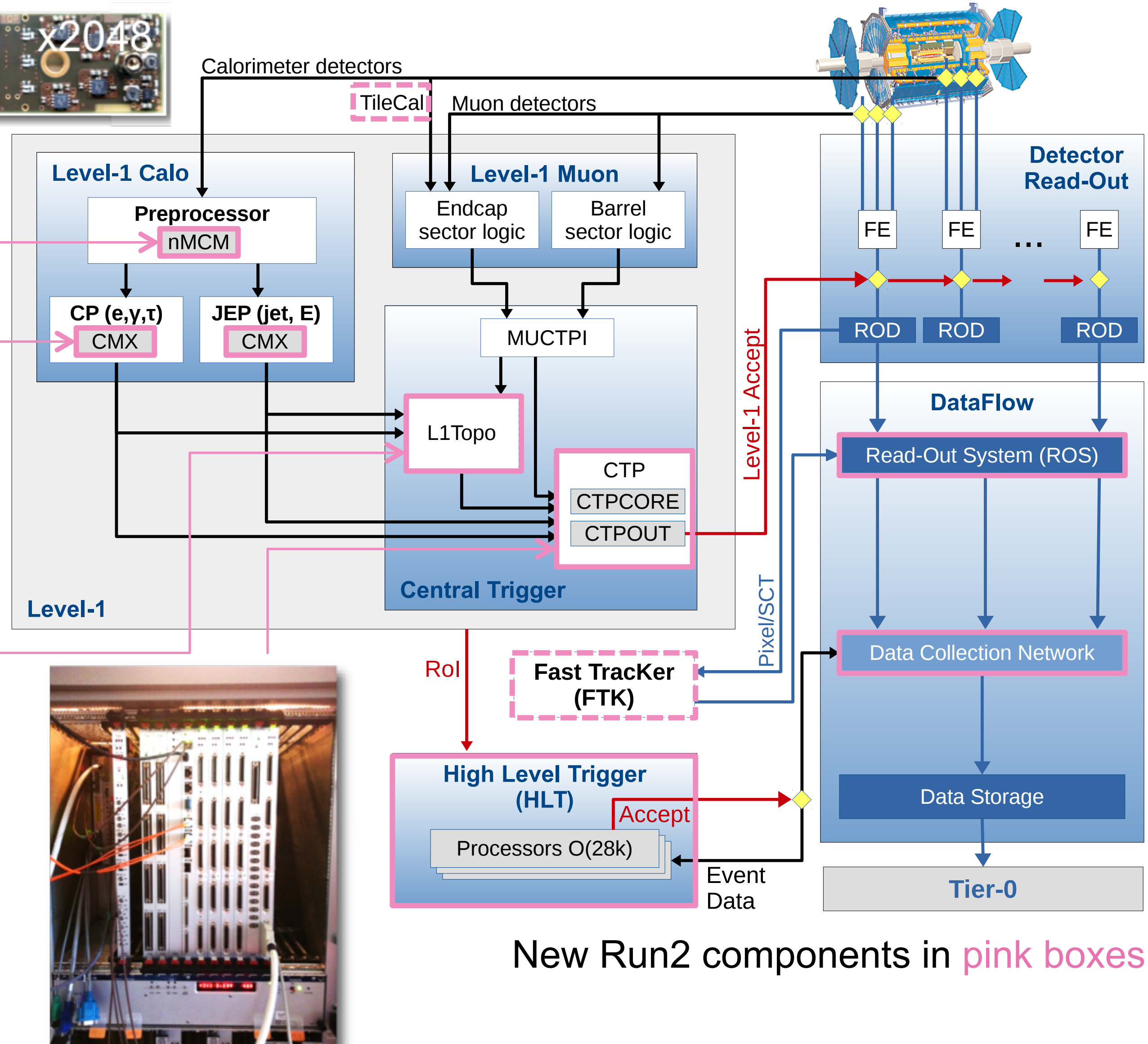

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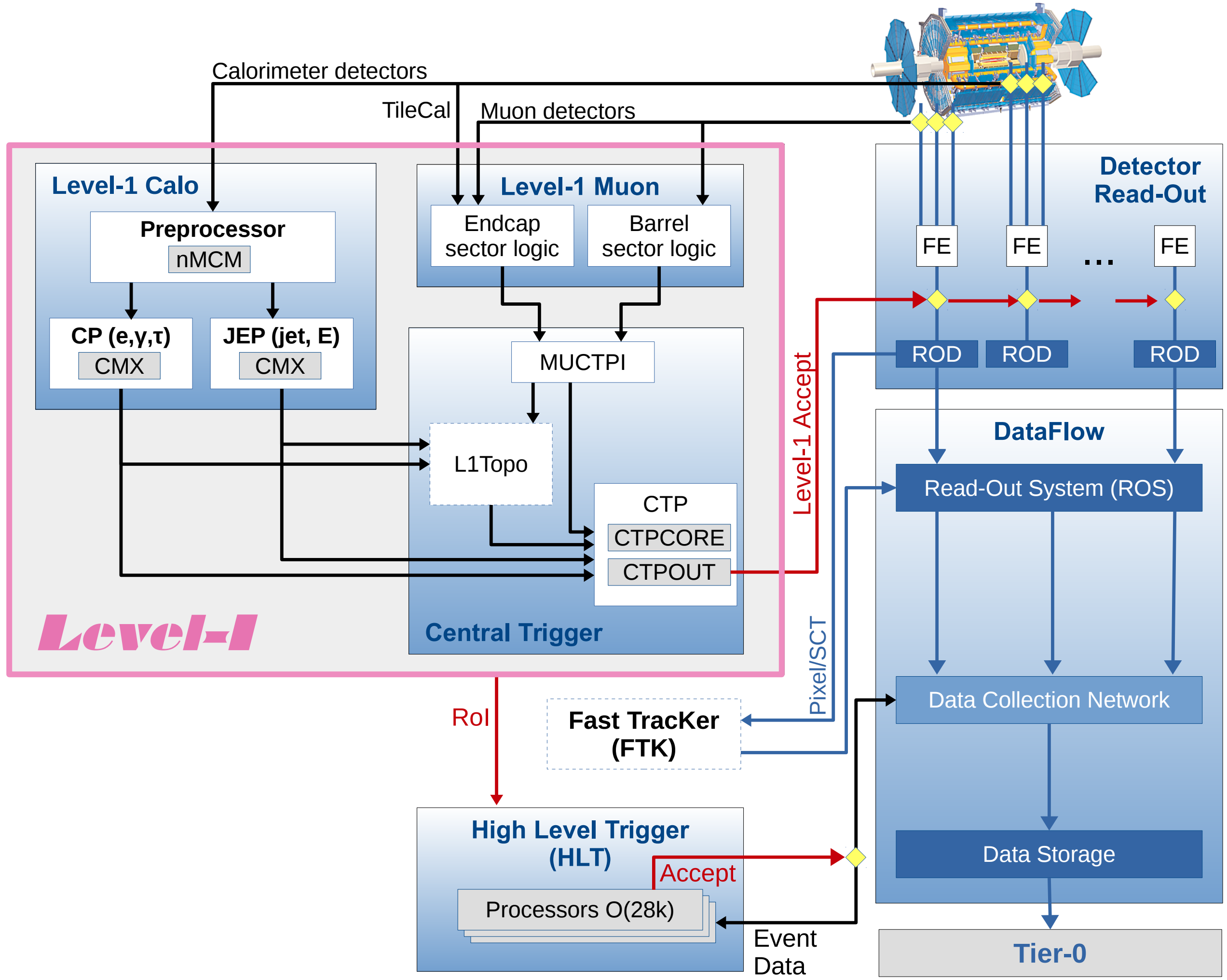
THE ATLAS TRIGGER SYSTEM

Level-1

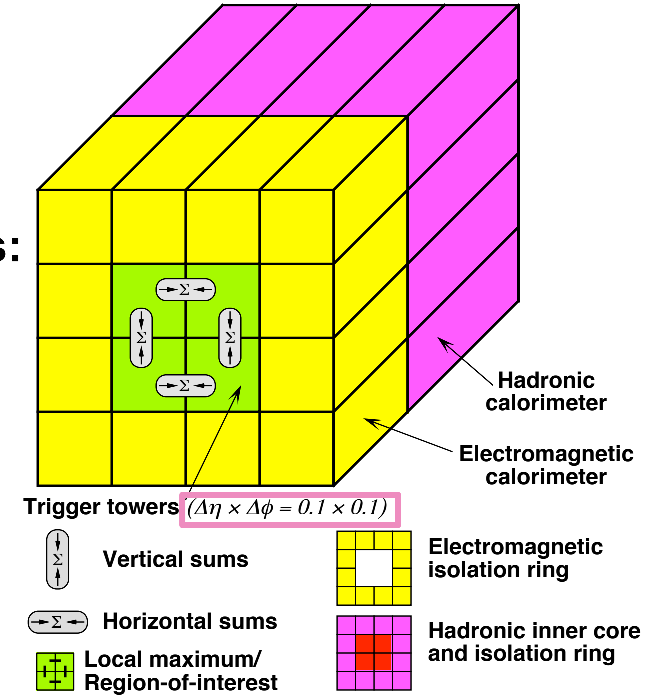
L1Calo
L1Muon
L1Topo
CTP

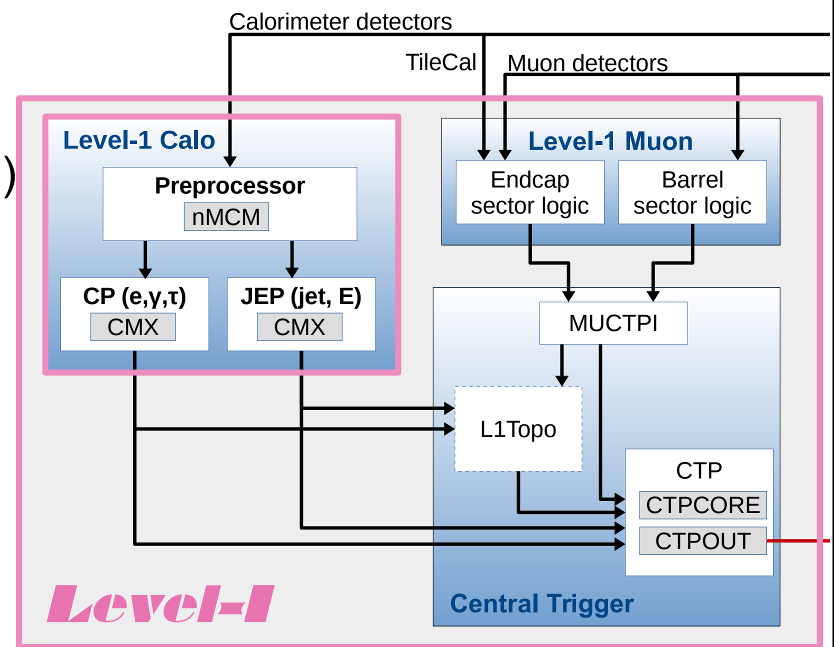


L1CALO

Reconstructs energy depositions in the calorimeters: electrons & photons, taus, jets and MET.

- **Preprocessor** UPGRADED FOR RUN2
  - Data Digitization and Timing definition
  - Bunch-crossing ID
  - Noise suppression and Pedestal correction
  - Calibration
- **Processors** UPGRADED FOR RUN2
  - Cluster algorithms
  - Isolation
  - Identification of “TOBs” (trigger objects)
- **Common Merger Modules** NEW FOR RUN2
  - Eta-dependent thresholds
  - TOBs to L1Topo





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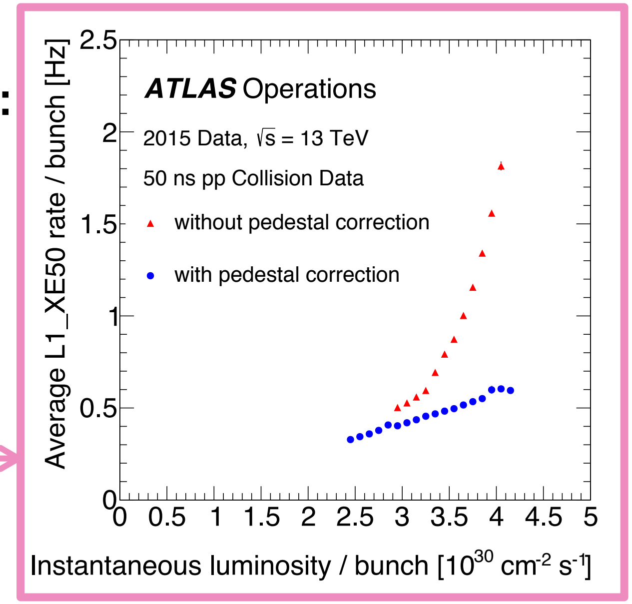
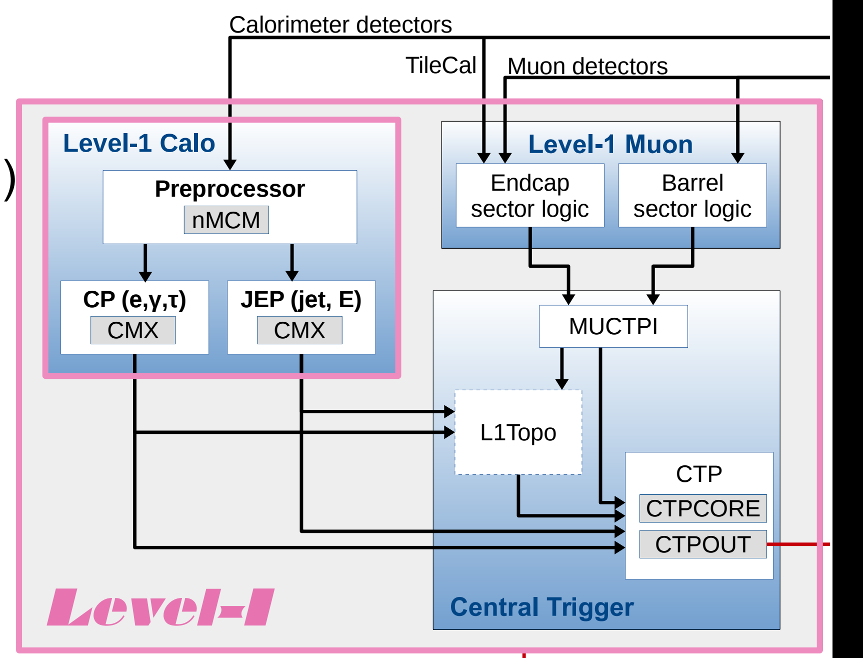
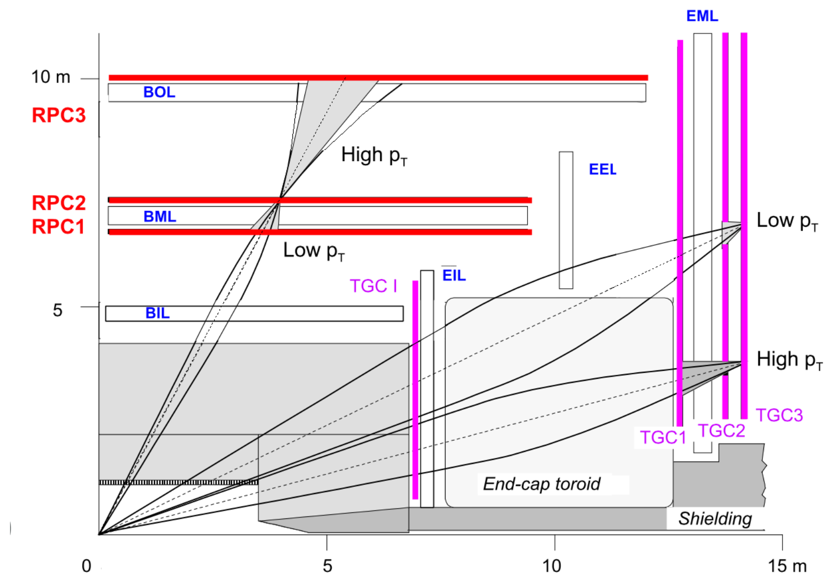
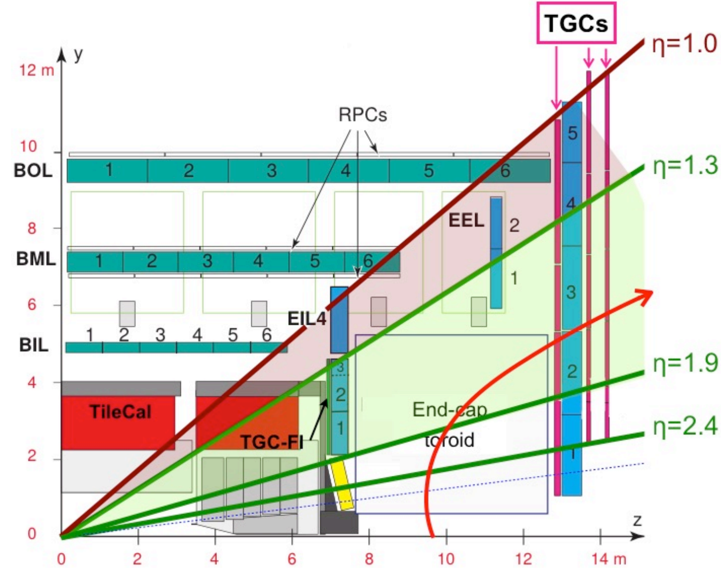




L1MUON





Reconstructs muons.

- **Barrel (RPC, |η|<1.05)**

NEW IN 2016

  - Extra coverage increases acceptance (few %).

- **Endcap (TGC, 1.05<|η|<2.4)**
- **Two- (low-pT) and three-station coincidence.**

NEW FOR RUN2

  - Extra coincidence between specific chambers reduces fakes (up to 60%).

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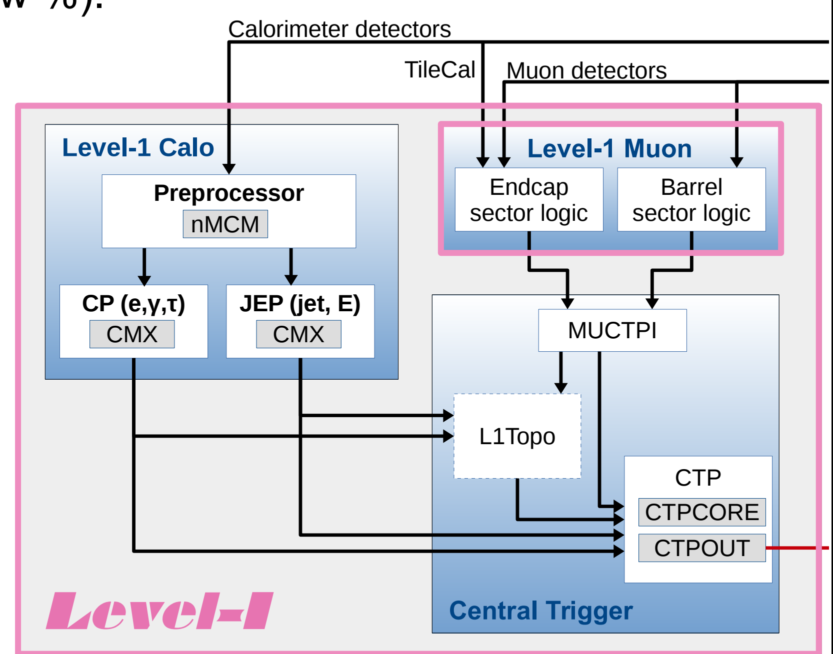
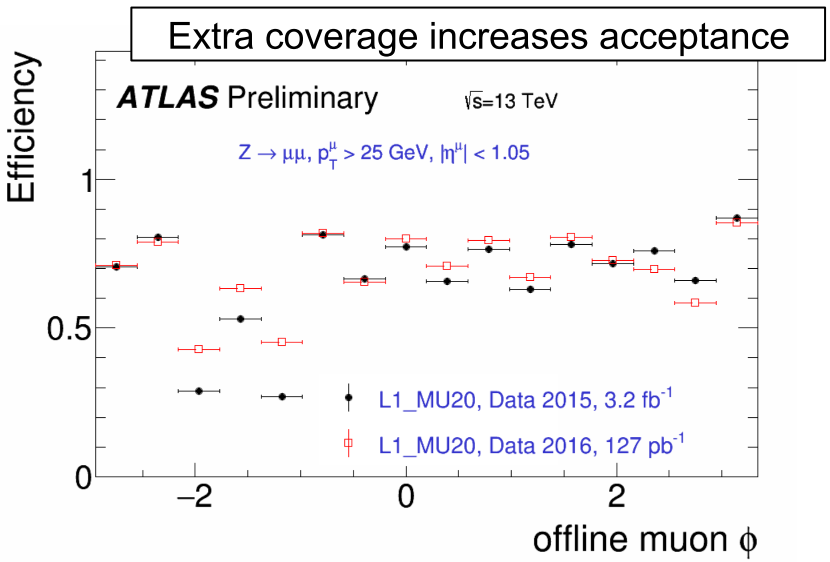
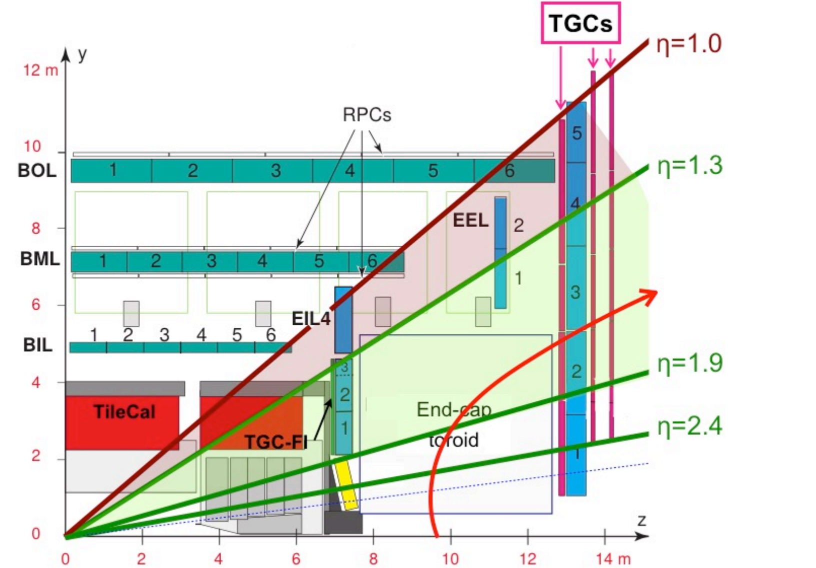
  - Moving for MU4 the two-station coincidence to three-station in the phi-direction reduces fakes significantly.

- **No pT measurement. Only threshold passed (and multiplicities).**







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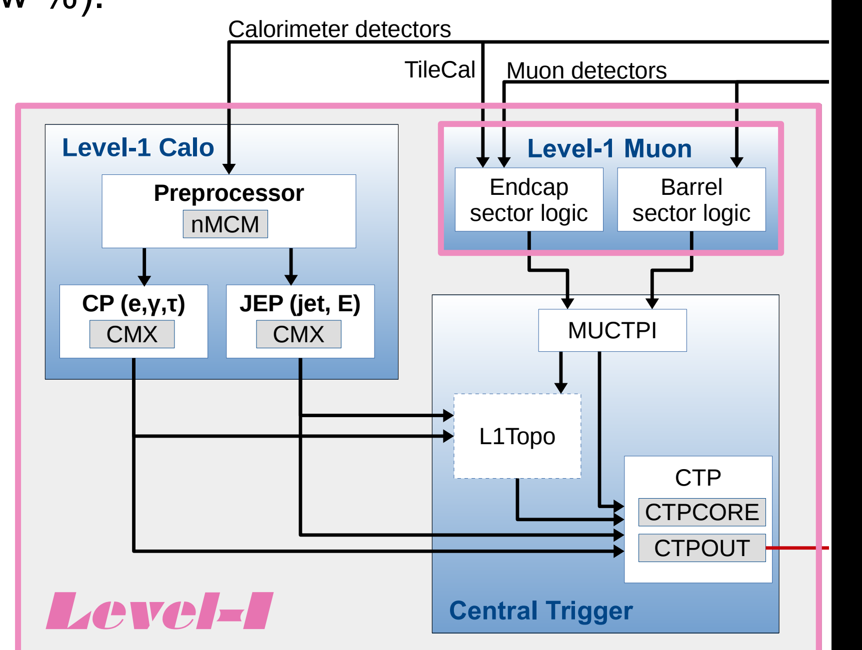

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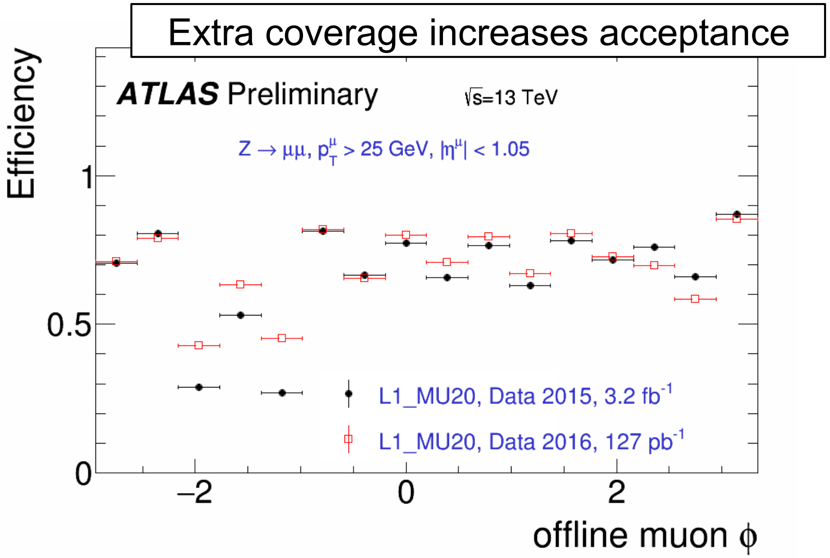

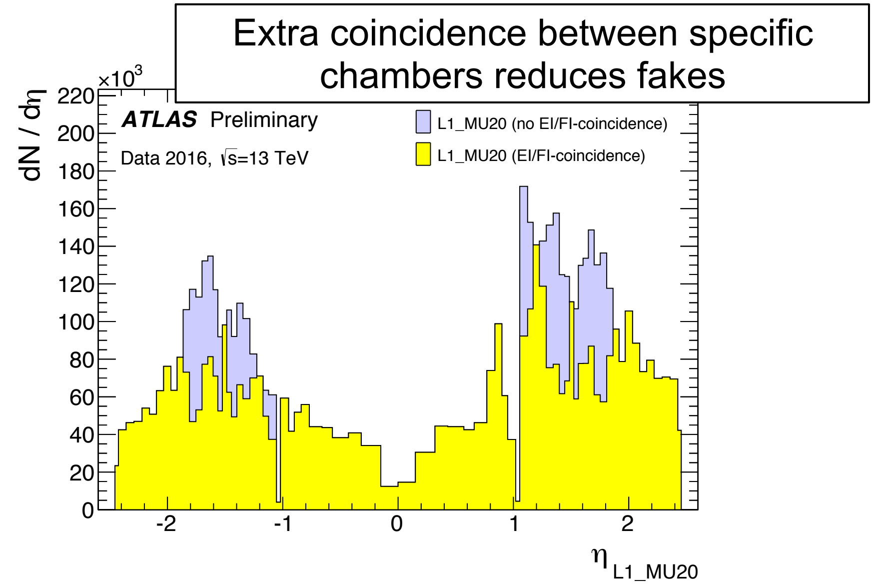

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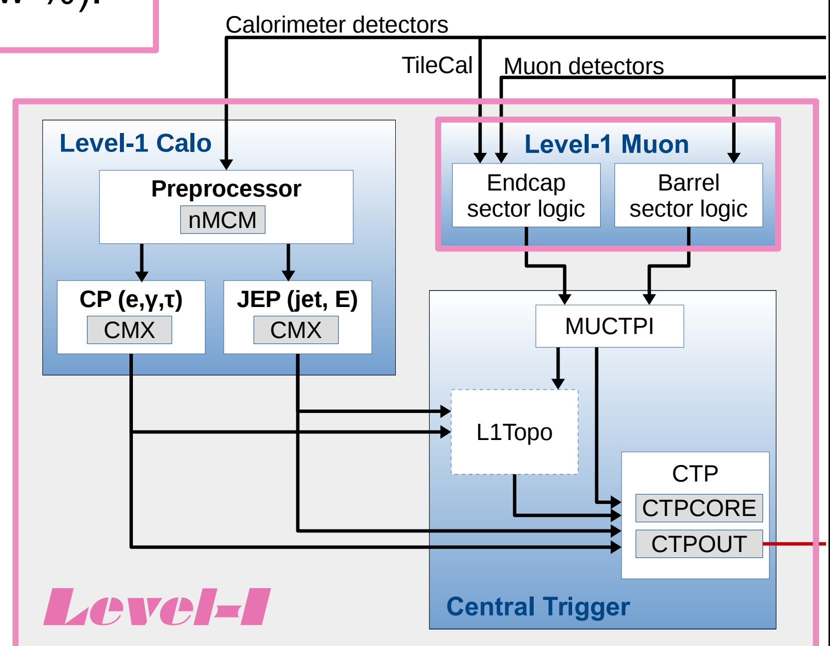

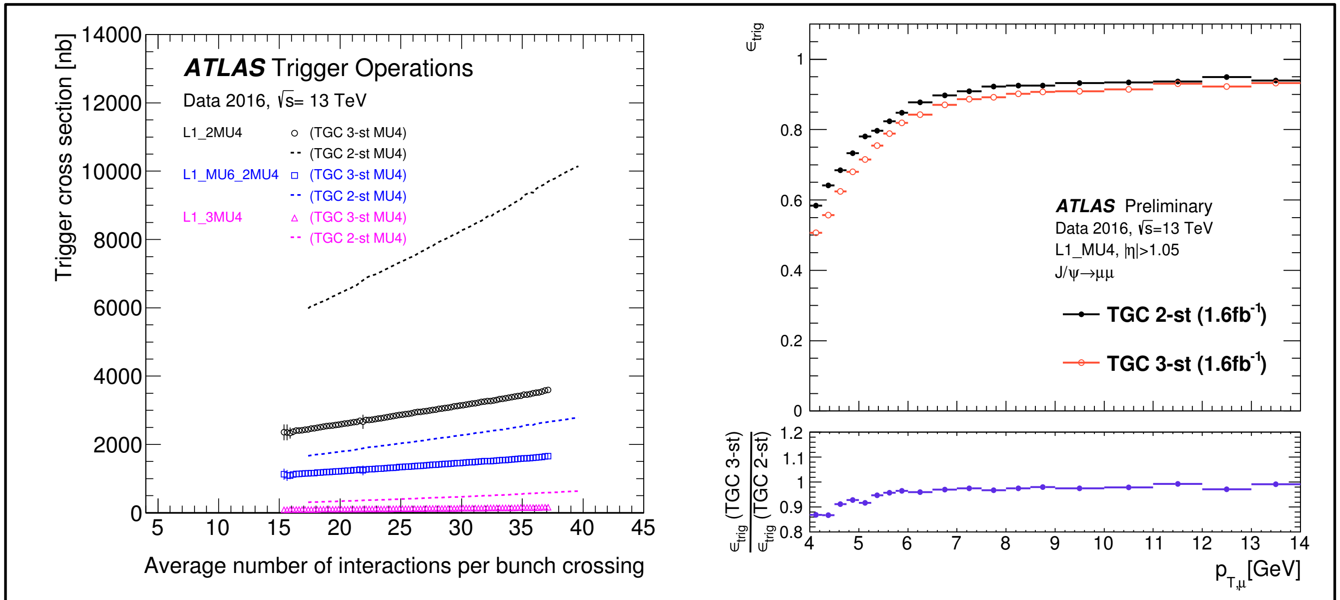

Moving for MU4 the two-station coincidence to three-station in the phi-direction reduces fakes significantly for minimal efficiency loss.

L1MUON

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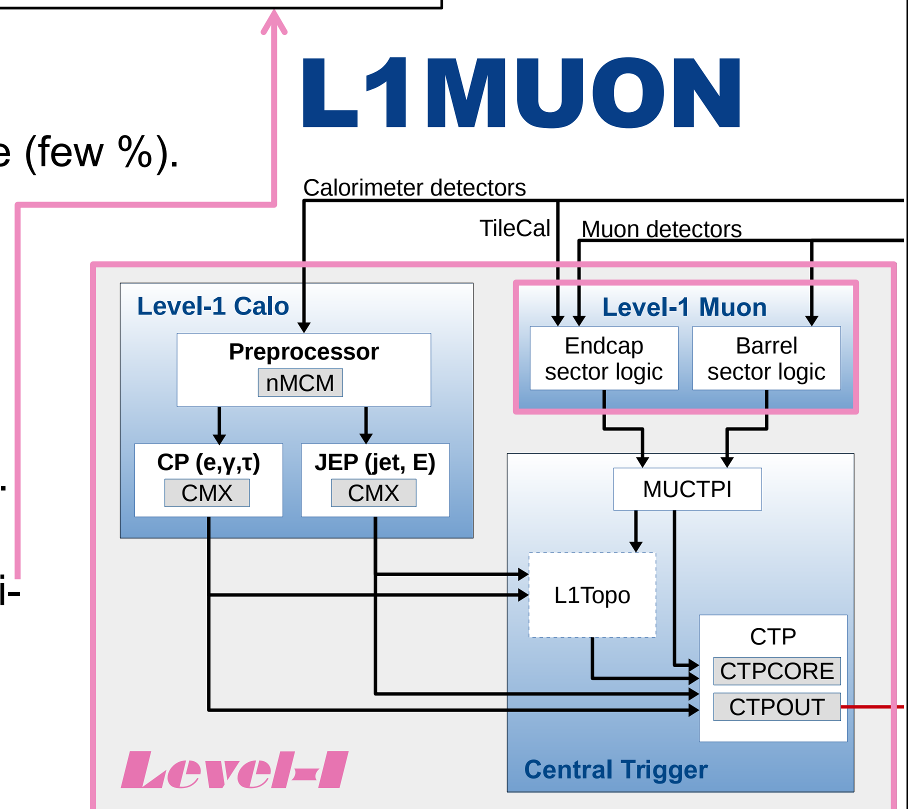
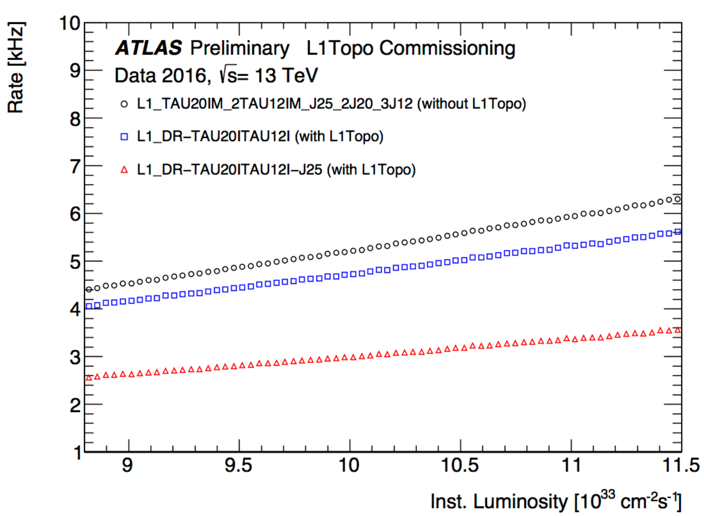
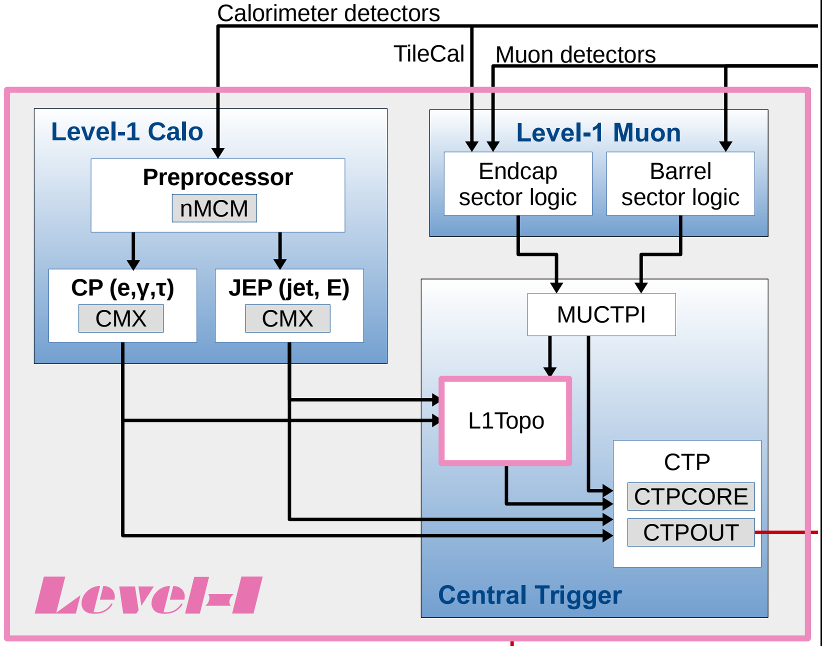


L1TOPO New in 2016 – a major milestone

Combines information from L1Calo and/or L1Muon into variables that are used for additional L1 selections.

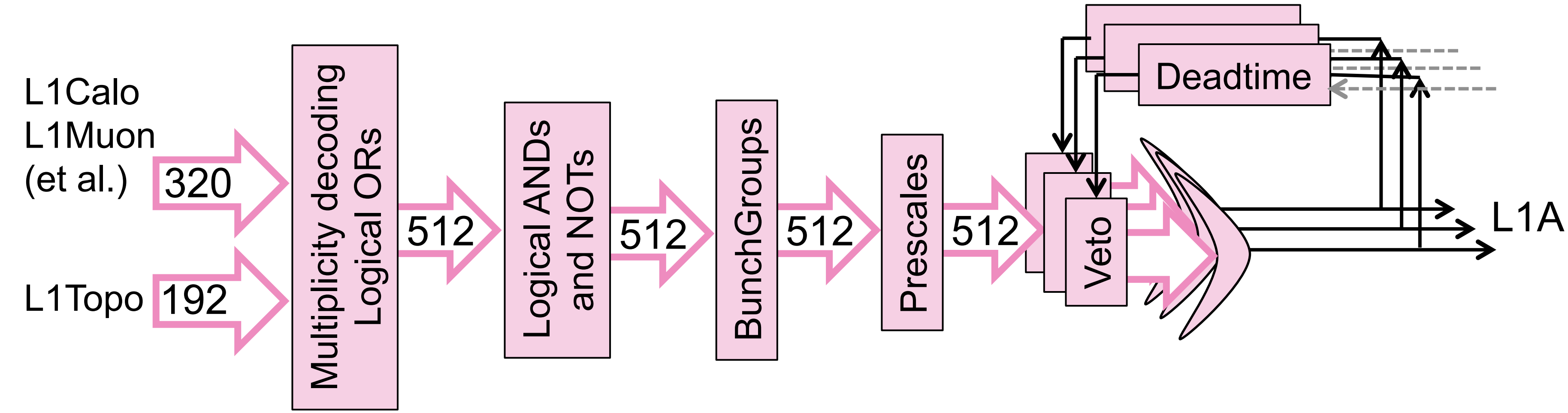
- Topological/angular selections, kinematic selections, sums.
- Significant rate reduction, increased signal purity, no impact in physics acceptance.
- A key feature for high-luminosity running!
- Main use cases in 2016: H→ττ and B-physics.
- **New crucial feature introduced in 2015, in commissioning till mid-2016. In "active" mode since September 2016.**





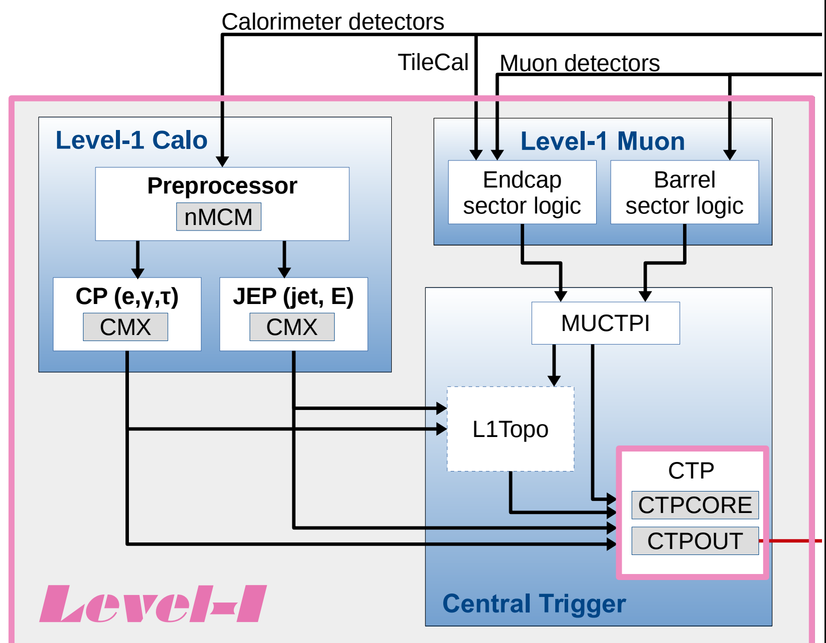
CENTRAL TRIGGER PROCESSOR

UPGRADED FOR RUN2

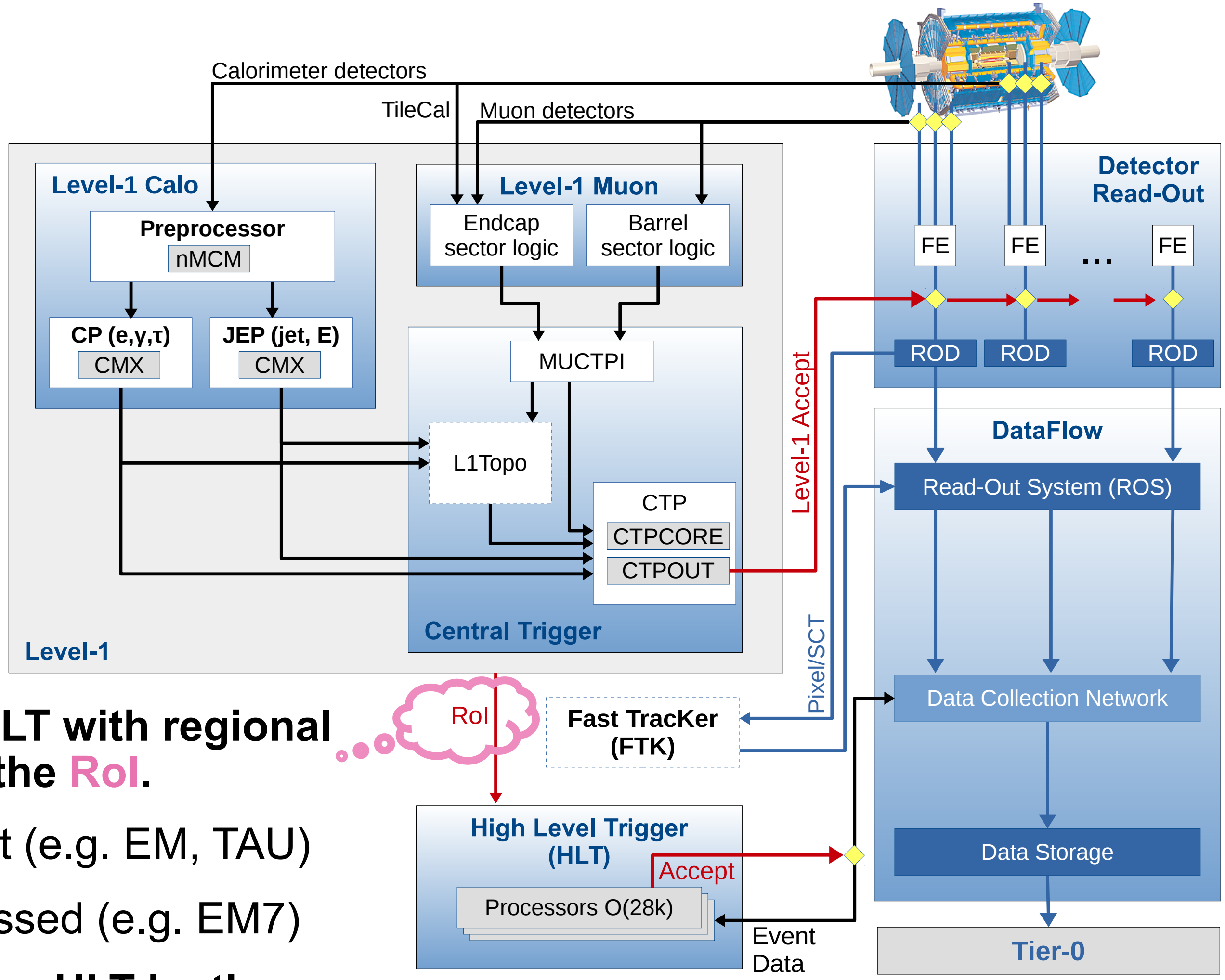


Time-aligns the trigger signals, provides the final trigger decision (L1A).

- **Bunchgroup** defines which bunch of the 3564 possible LHC bunches the trigger is active on.
- **Prescale** factor N means that 1/N events is accepted.
- **Trigger deadtime:**
  - Simple; number of bunches the trigger waits before a new L1 accept.
  - Complex; restricts the number of L1 accepts in a given period.



REGIONS OF INTEREST (RoI)



Level-1 feeds the HLT with regional information (η×φ), the RoI.

- Per type of object (e.g. EM, TAU)
- Per threshold passed (e.g. EM7)

Made available to the HLT by the "RoI-builder" (RoIB).

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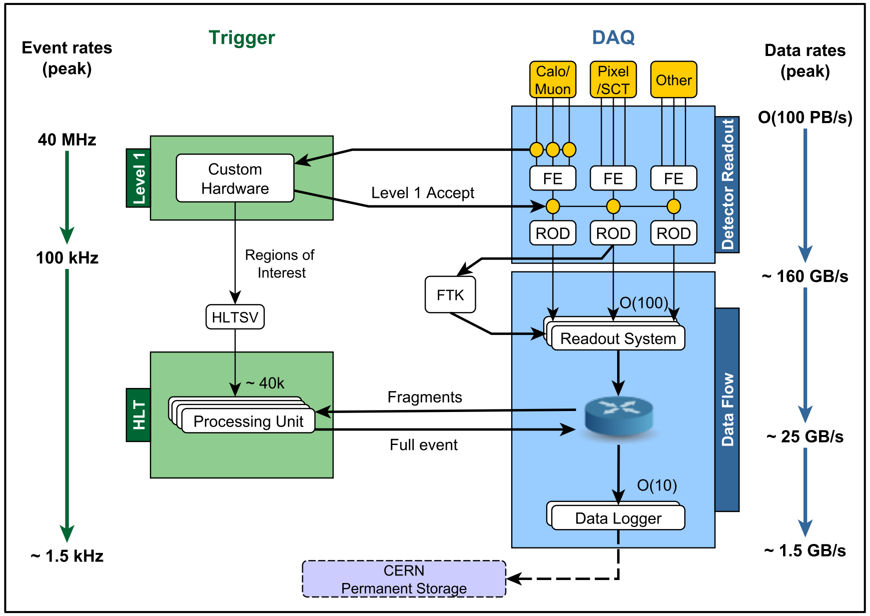


HLT INFRASTRUCTURE

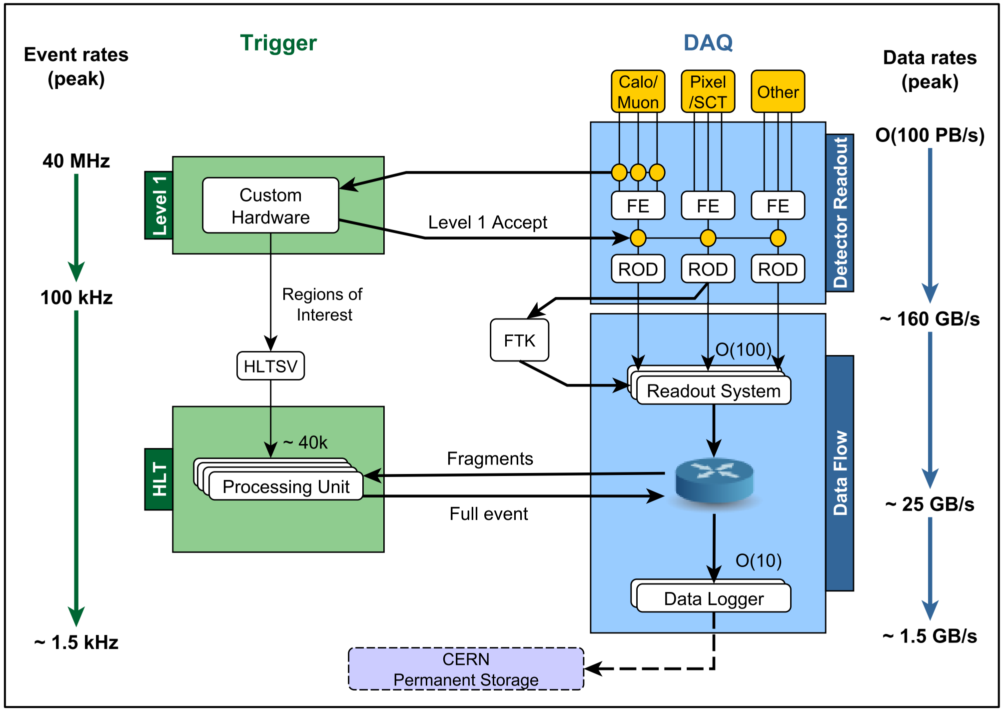
Large commercial PC farm installed in the surface building above ATLAS.

- Typical HLT node: 2x12-core Intel Xeon Haswell, 96 cores / box. 48 GB RAM, 10Gb Ethernet, 4 motherboards in 2U box.

Required number of cores:

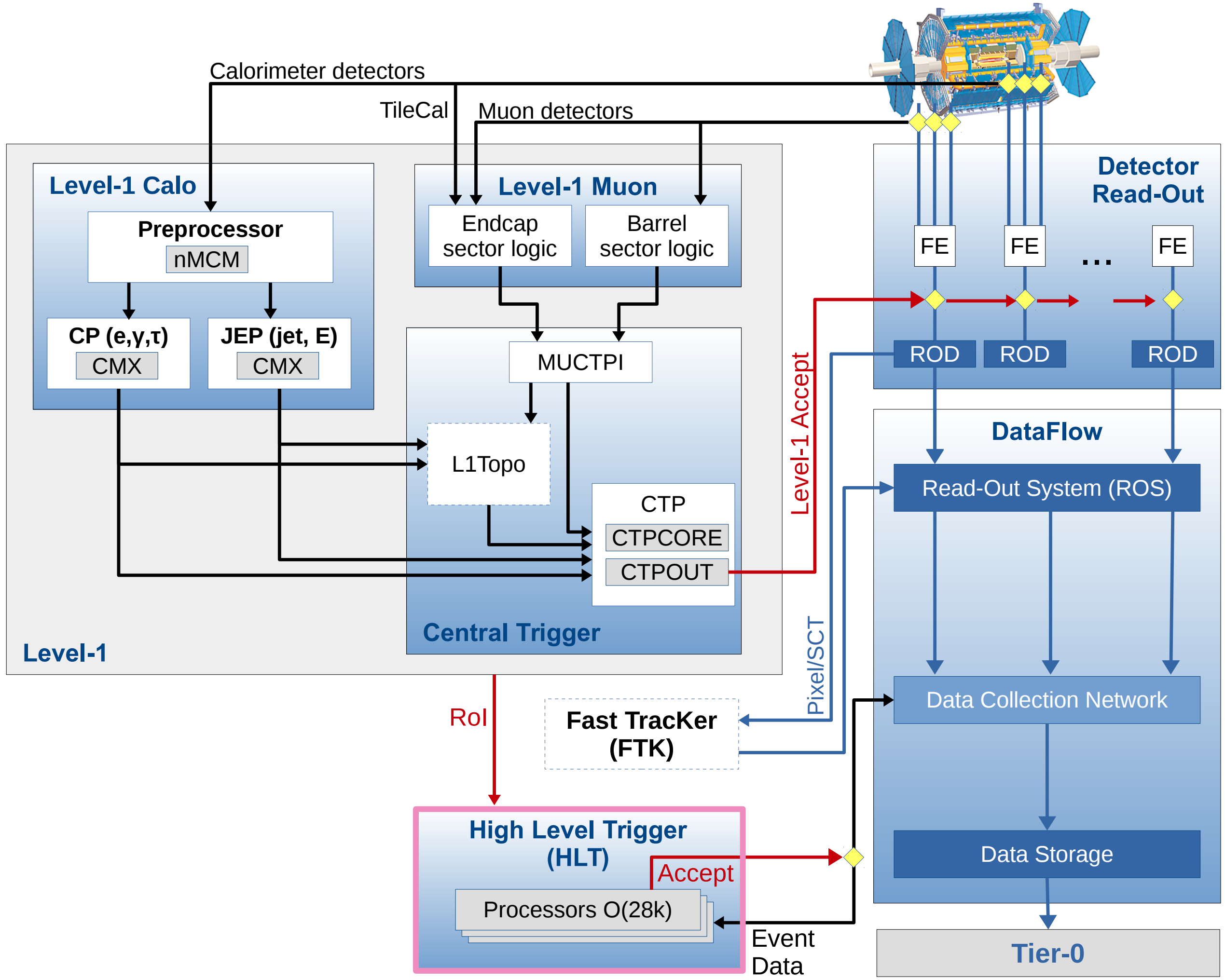
input rate × <processing time>

- E.g: 100kHz x 300ms = 30K cores. Outliers in processing time absorbed by buffers.
- Events are processed independently in these cores.



THE ATLAS TRIGGER SYSTEM

HLT



HLT "CHAINS"

HLT software very similar to the offline reconstruction software; ideally, "identical".

- Except… offline reconstruction takes > 10s / events. The HLT only has << 1s!

Trigger reconstruction works in steps.

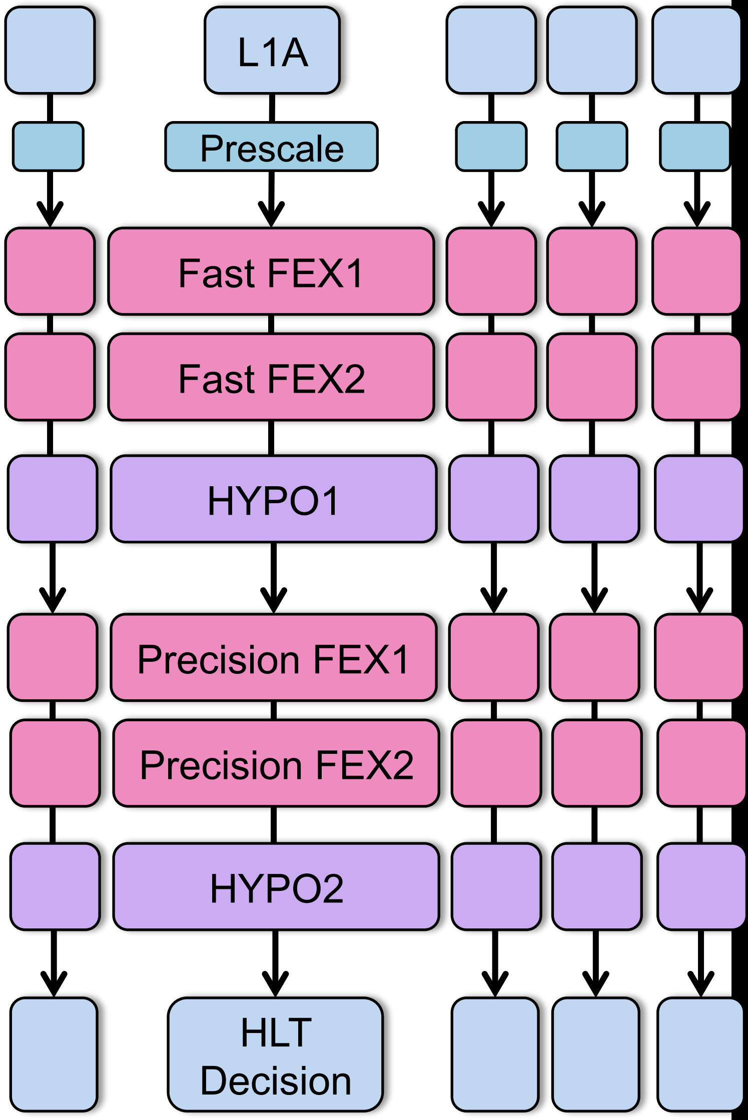
→ **Fast** (often trigger specific) reconstruction, mostly at RoIs.

→ **Precision** reconstruction, with full detector available.

→ Stop chain processing as soon as a step fails; stop event processing as early as possible.

Two types of algorithms:

- "Feature Extraction" (**FEX**) algorithms that build objects (e.g. tracks and clusters). Are (should be) the slowest; we make sure they run once per event.
- "Hypothesis" (**HYPO**) algorithms that apply selection cuts (e.g. track pT, invariant mass).



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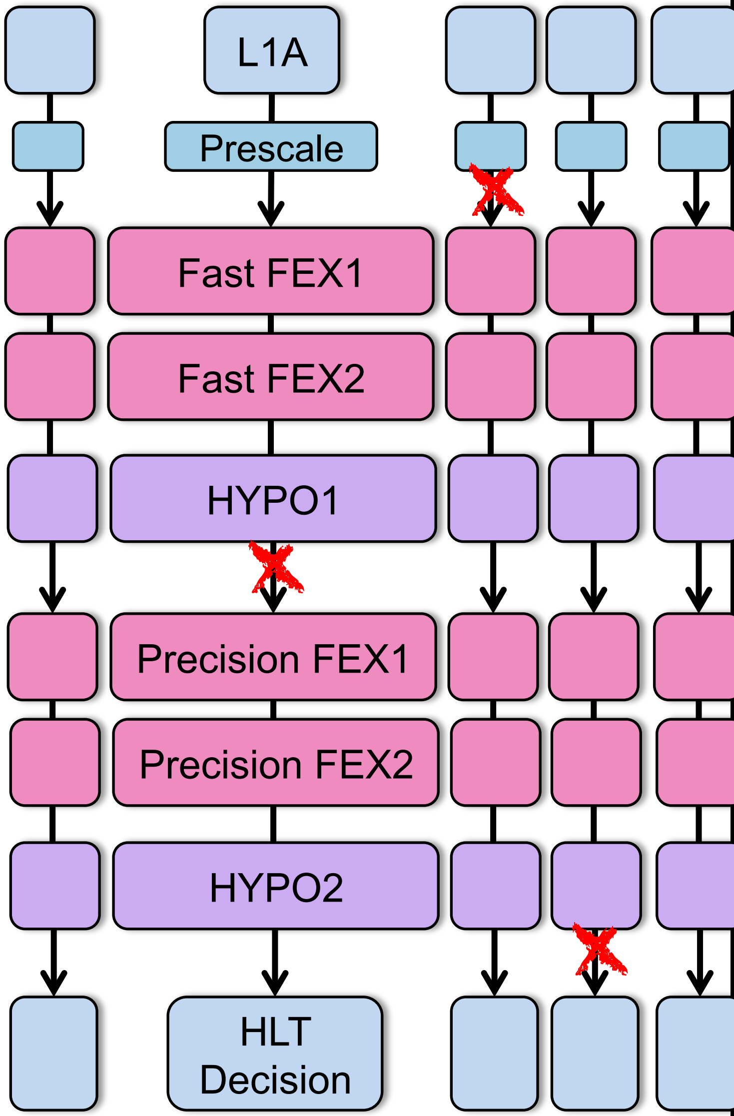
Two types of algorithms:

- "Feature Extraction" (**FEX**) algorithms that build objects (e.g. tracks and clusters). Are (should be) the slowest; we make sure they run once per event.
- "Hypothesis" (**HYPO**) algorithms that apply selection cuts (e.g. track pT, invariant mass).



STREAMING

- Event gets accepted if any trigger passes (HLT decision positive).
- Streaming is based on trigger decisions.
- The Raw Data physics streams are generated at the HLT output level.

Debug Streams

events for which a trigger decision has not been made, because of failures in parts of the online system

Mostly recovered and fed back to analysis.

Physics Streams

data for physics analyses

Express Stream

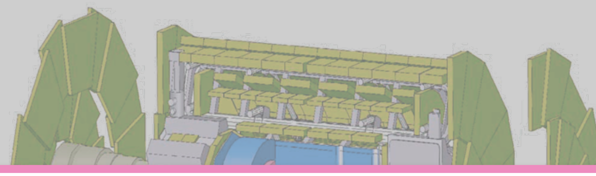
full events for fast reconstruction

Data scouting

Contains HLT objects; used for trigger-level analysis

Calibration Streams

events delivering the minimum amount of information for detector calibrations at high rate

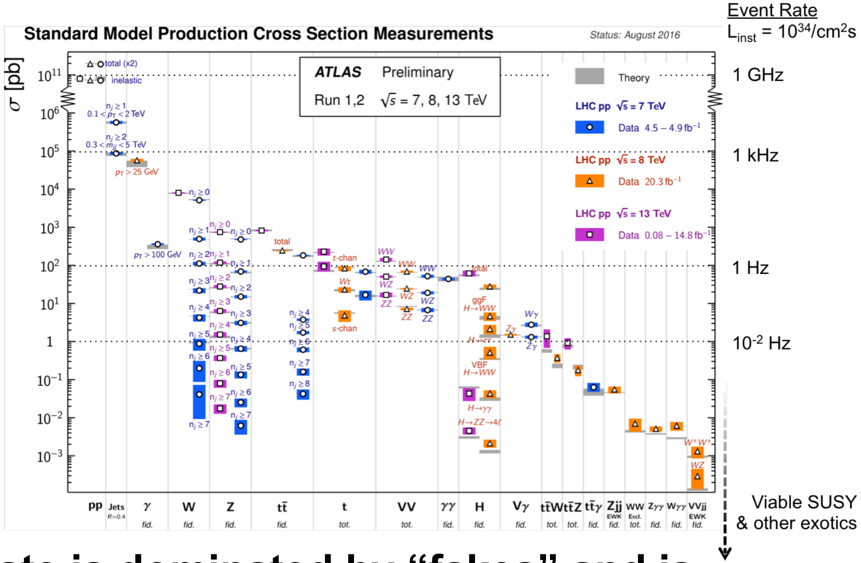


THE DATA

Triggering Challenge

Maintain a rich acceptance in physics (including unknown new phenomena!) while respecting the limitations of

- **Detector readout**
- **DAQ system & HLT**
- **Computing system**



and knowing that the event rate is dominated by "fakes" and is significantly affected by pile-up.

➔ **Find ways to reduce fakes and improve robustness to pile-up, respecting the limitations imposed by various systems.**

➔ **Various upgrades and new features introduced in DAQ, L1 and HLT.**

➔ **Key feature: robustness; events that are not triggered are lost forever.**

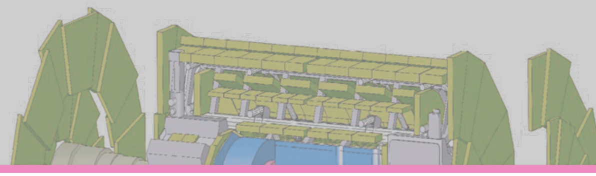
In 2016

40 MHz
13 TeV

L1 accept
~ 90 kHz

Storage
1 kHz

THE DATA



Triggering Challenge

Maintain a rich acceptance in physics (including unknown new phenomena!) while respecting the limitations of

- **Detector readout**

  max ~ 90 kHz

- **DAQ system & HLT**

  CPU: average ~ 300ms, Data bandwidth: average ~ 3GB/s

- **Computing system**

  average ~ 1 kHz

- **2016 limitations.**
- **2017 will see improvements in detector readout and data bandwidth at least.**

and knowing that the event rate is dominated by "fakes" and is significantly affected by pile-up.

➔ **Find ways to reduce fakes and improve robustness to pile-up, respecting the limitations imposed by various systems.**

➔ **Various upgrades and new features introduced in DAQ, L1 and HLT.**

➔ **Key feature: robustness; events that are not triggered are lost forever.**

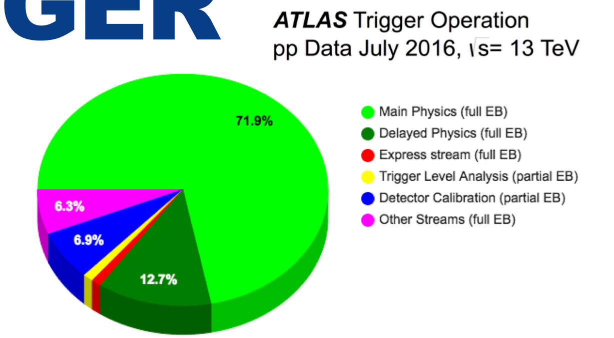
In 2016

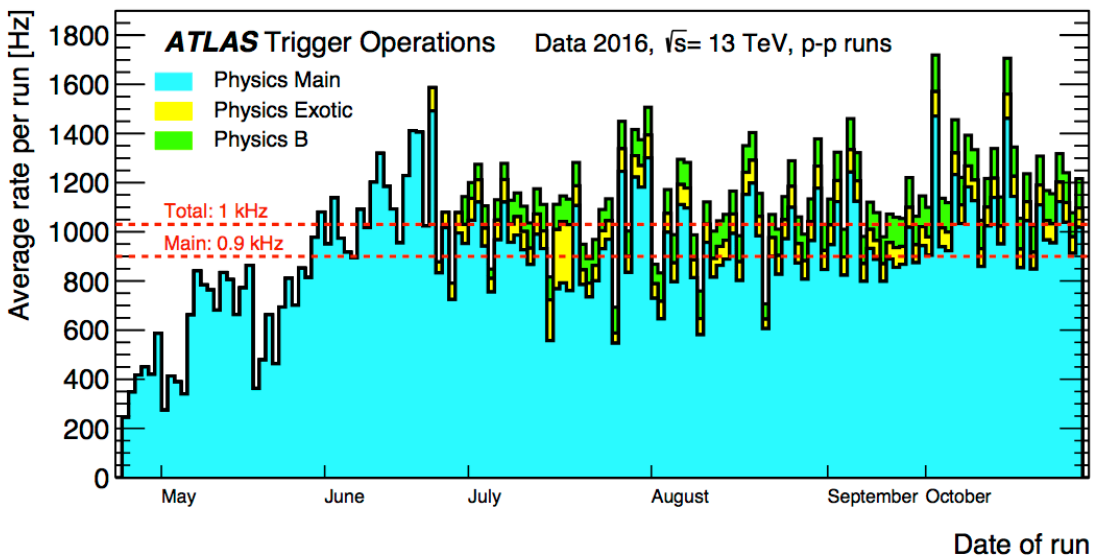
40 MHz
13 TeV

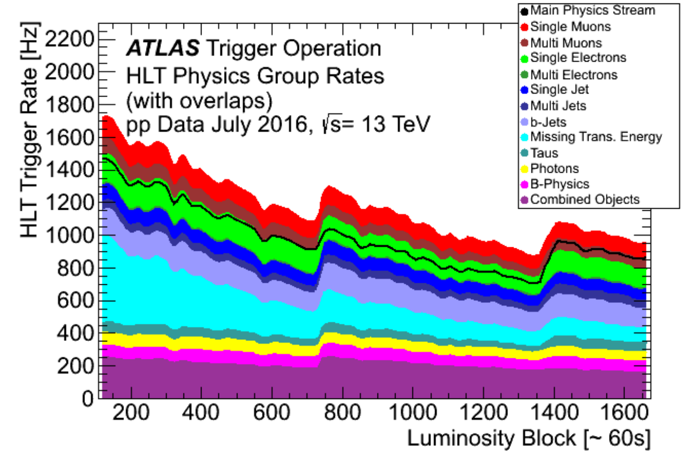
L1 accept
~ 90 kHz

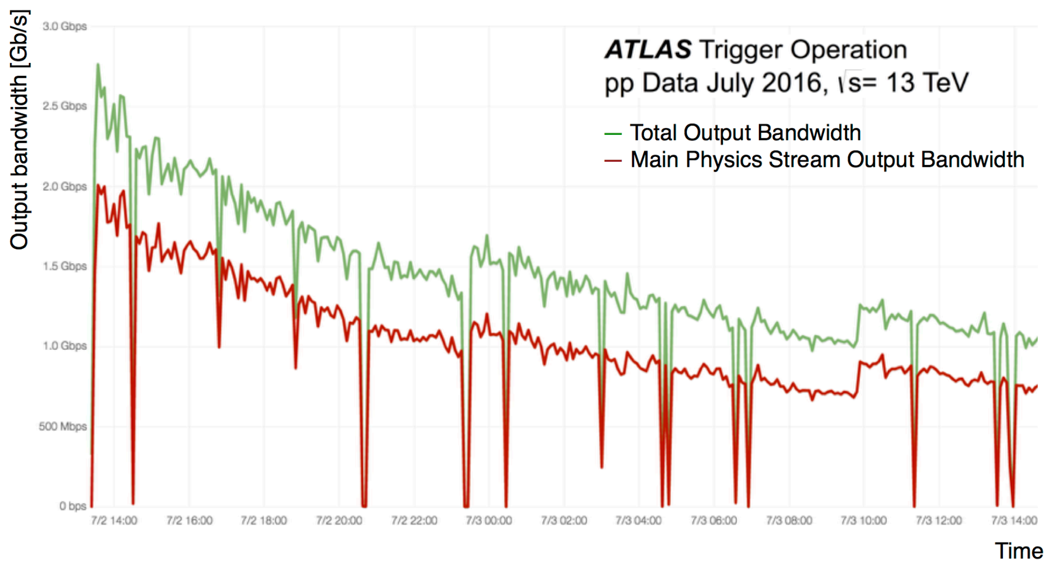
Storage
1 kHz

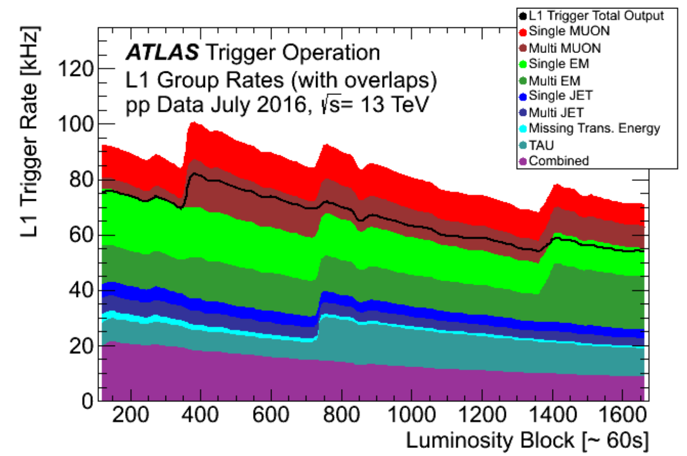
OPERATING THE TRIGGER



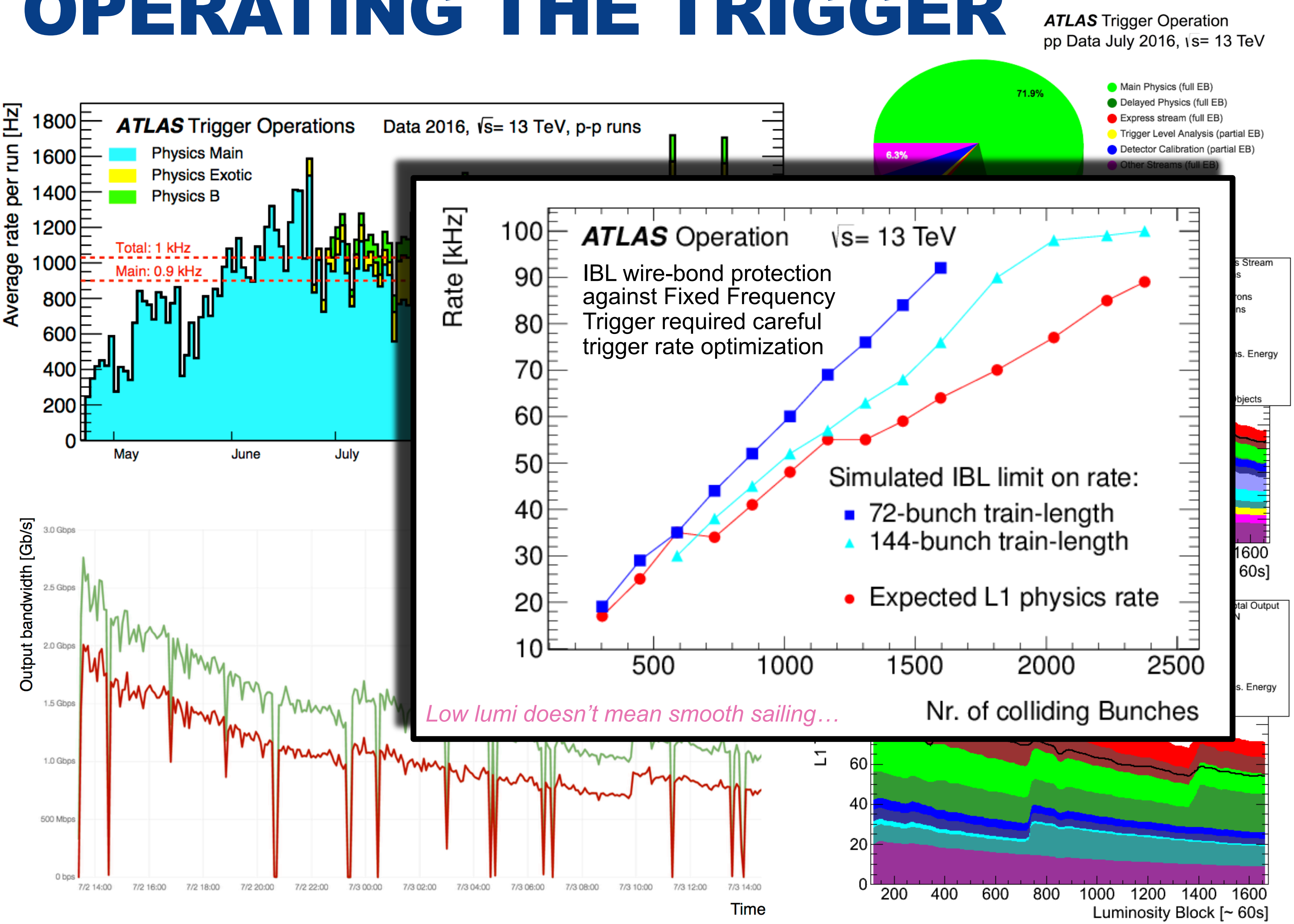




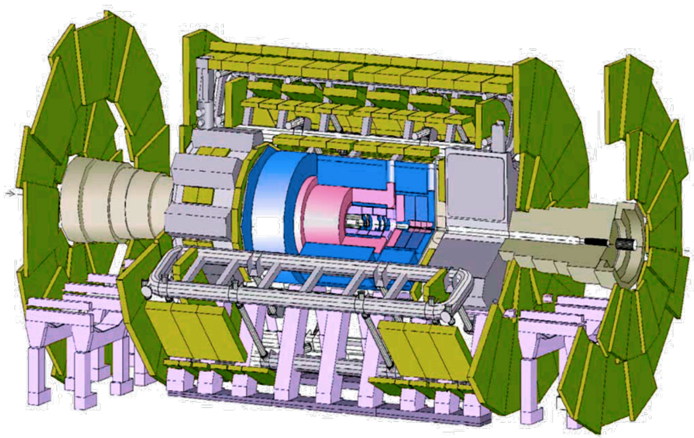


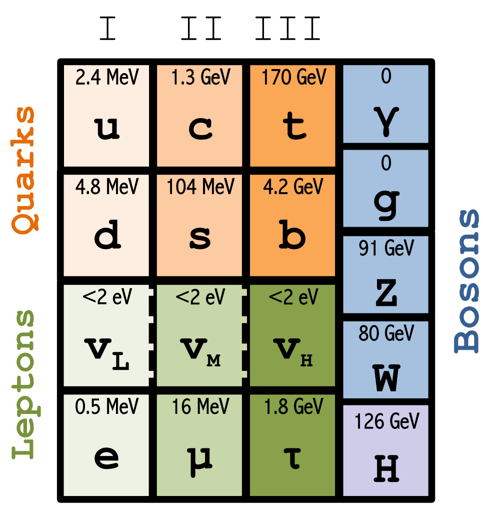


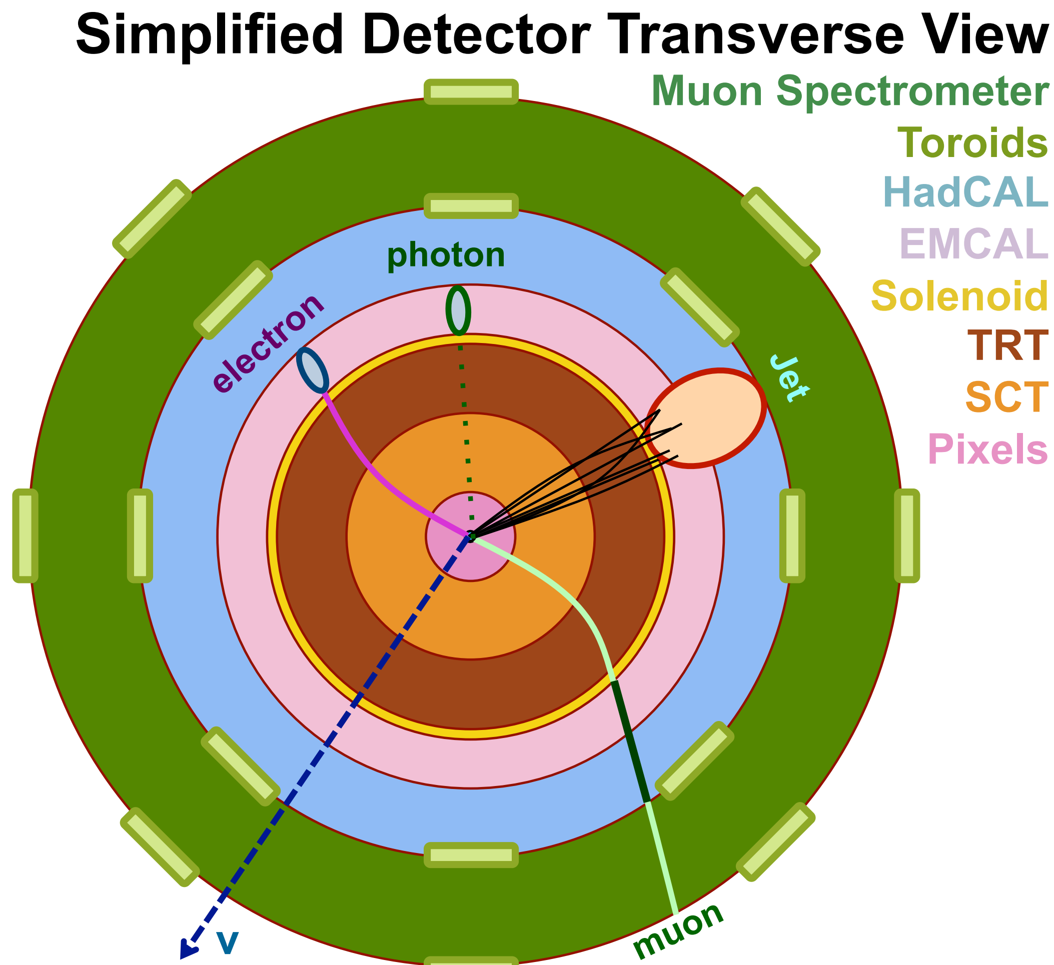
OPERATING THE TRIGGER



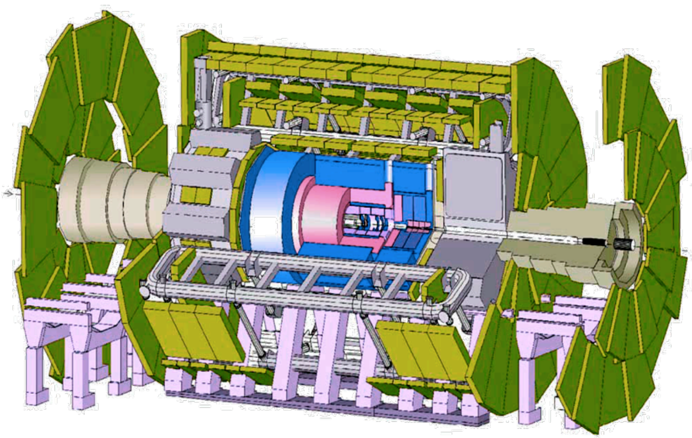
TRIGGER SIGNATURES

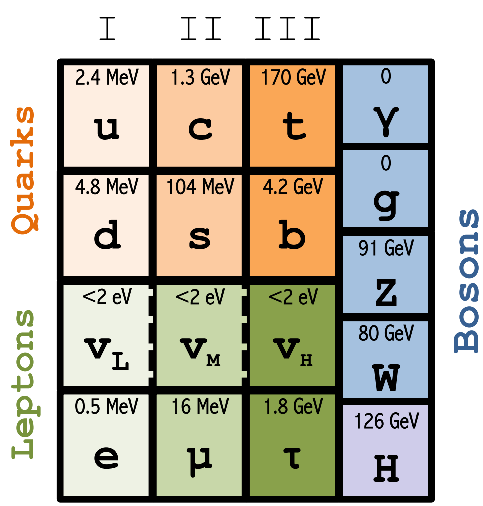




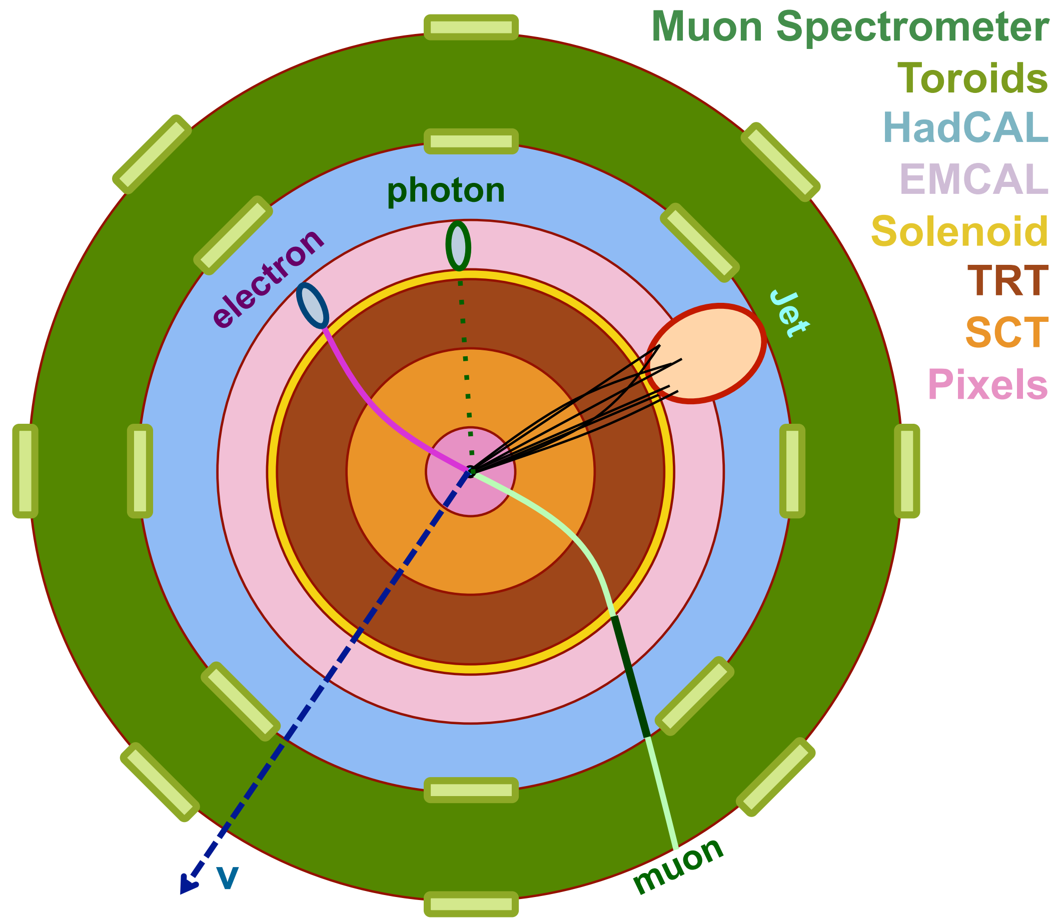


TRIGGER SIGNATURES





Simplified Detector Transverse View



NEW FOR RUN2: Software had to be adjusted (pretty much everywhere) in view of the merged HLT!

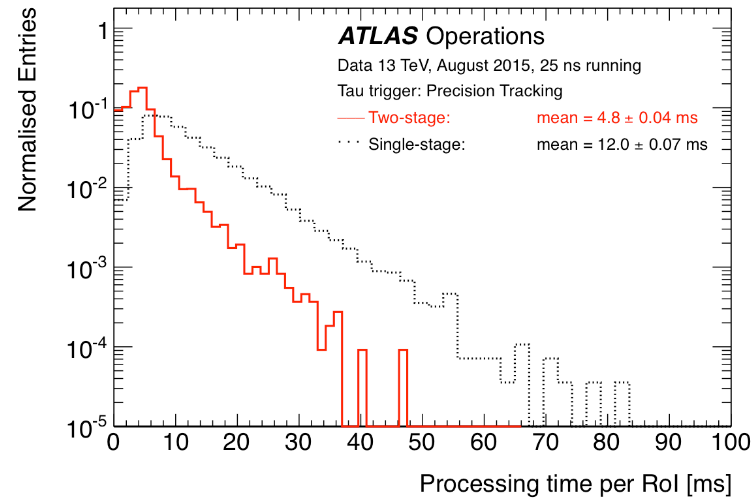
COMMON: INNER DETECTOR TRACKING

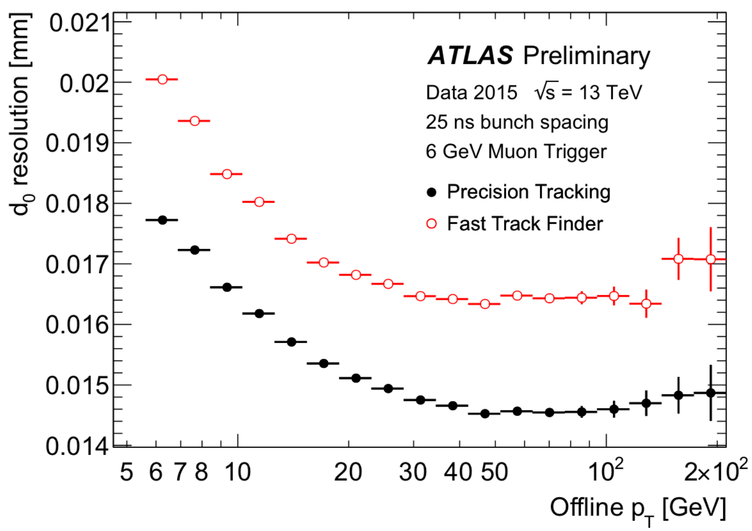
Tracking is used in pretty much all objects reconstructed at the trigger (as is the case for offline).

- Muons, electrons, taus, b-jets and jets, MET, b-physics, minbias. And also, in beamspot and cosmic triggers.

The offline tracking runs in the complete detector, once per event. In the HLT this is not possible (CPU / DAQ).

- To reduce network traffic and the time available to read out the detector, data are read out only from the RoIs.
- The ID Trigger then takes this local data and reconstructs tracks within the RoI only.
- Each RoI in an event is (usually) processed independently.





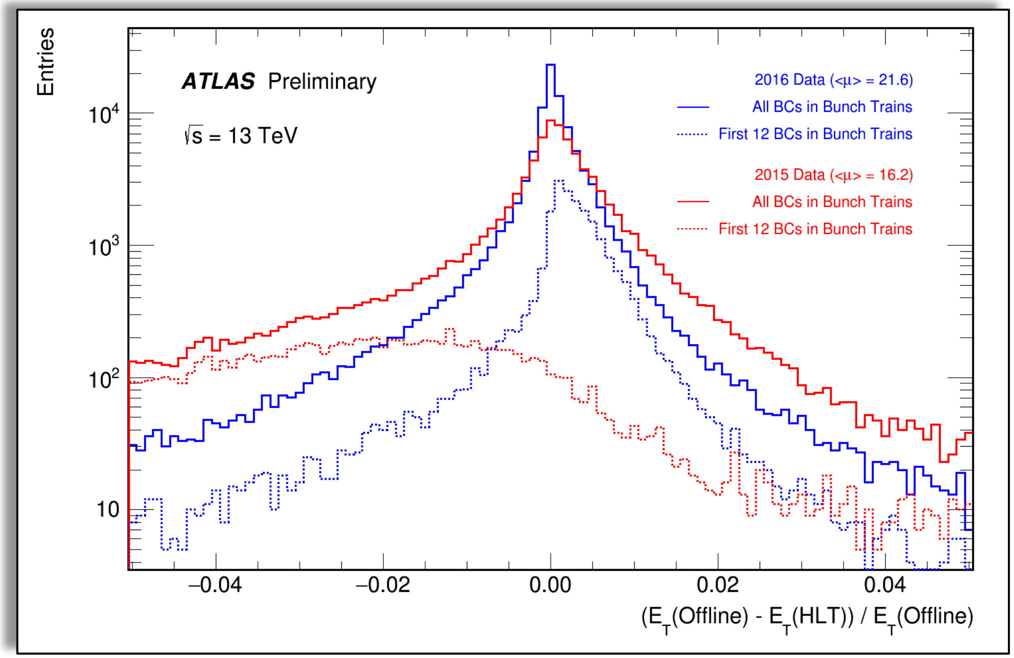
COMMON: HLT CALO CLUSTERING

Reconstructs calorimeter data at the HLT.

- For electrons, taus, jets, MET.
- Exists in RoI-based version (used in electrons and taus) and Full-scan version (used in jets and MET).

Data is unpacked to calorimeter cells from where clusters are built.

Pile-up corrections: train structure and bunch to bunch luminosity variations can create significant energy shifts which are mitigated by BCID dependent average pileup correction. Offline since a while, online since 2016.



ELECTRON / PHOTON

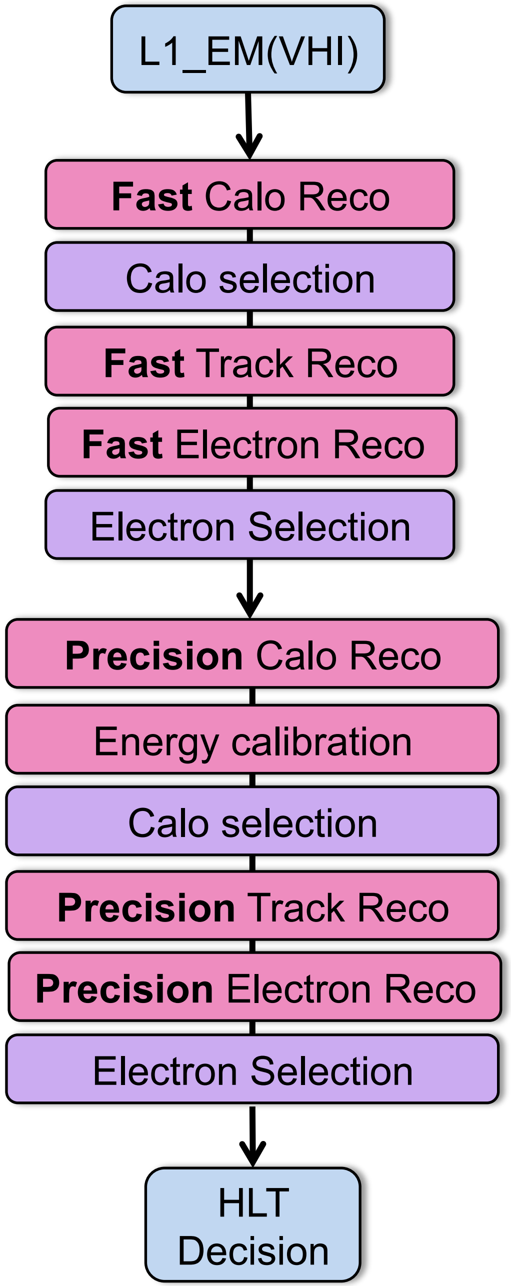
At L1:

- Analyse regions of 4x4 trigger tower.
- Cut on transverse energy threshold; eta-dependent; apply hadronic core isolation; and electromagnetic isolation.

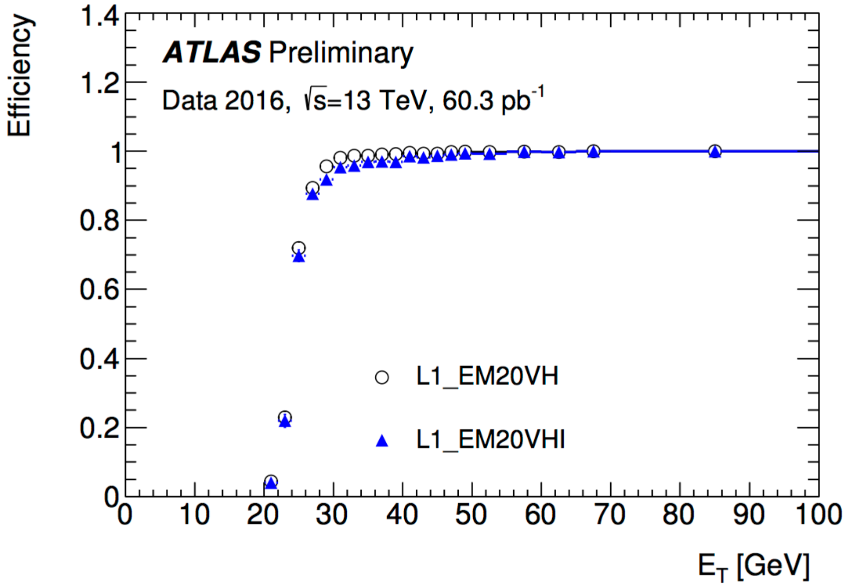
At HLT:

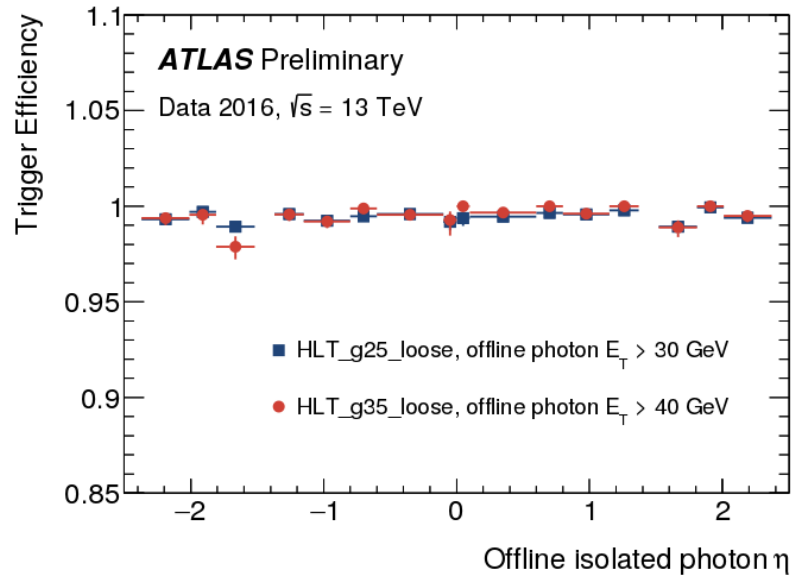
- **Photon** is an energy cluster (no requirement on track).
- **Electron** is an energy cluster matched to a pT > 1GeV track.
- Reconstruction is fully RoI-based.
- Energy calibration based on a multivariate analysis technique.
- Electron identification relies on a likelihood technique.

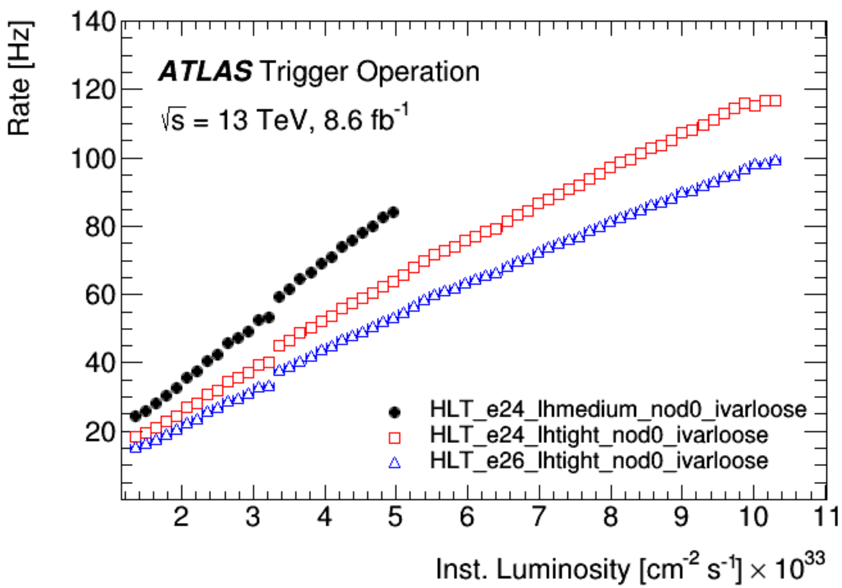
Just like offline

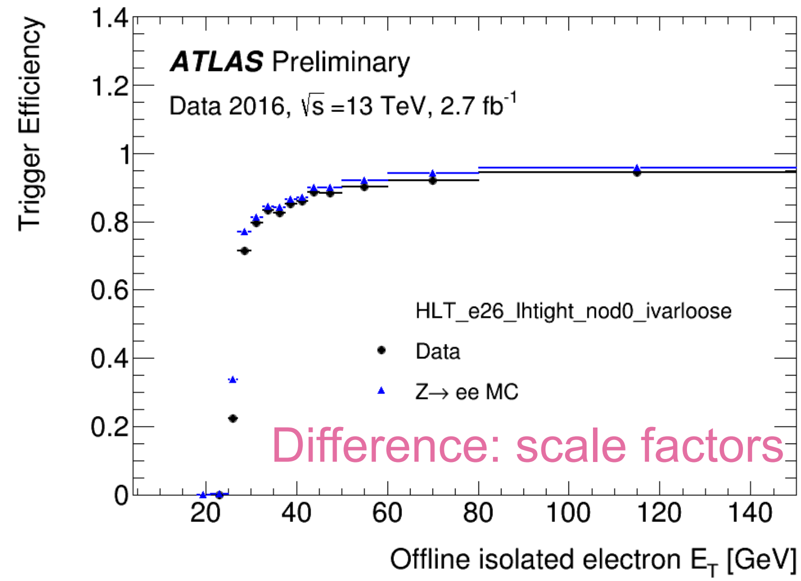


ELECTRON / PHOTON



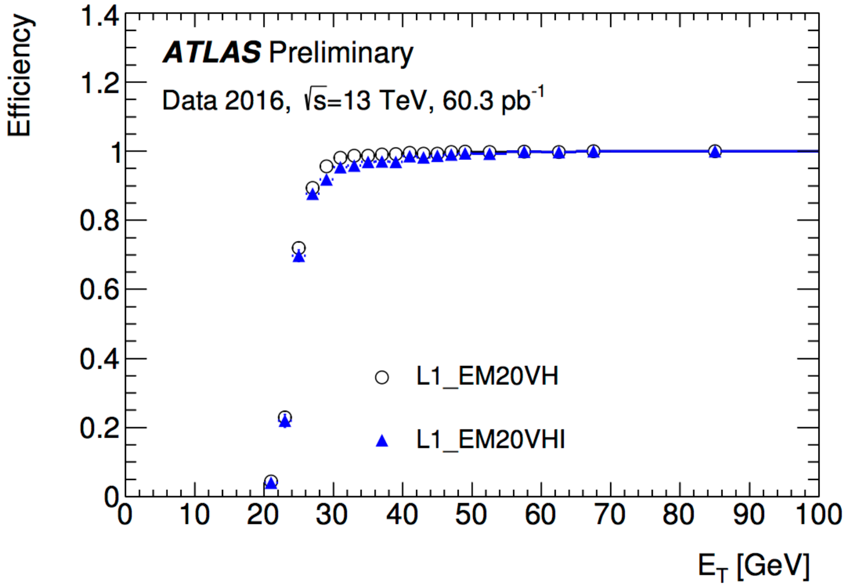


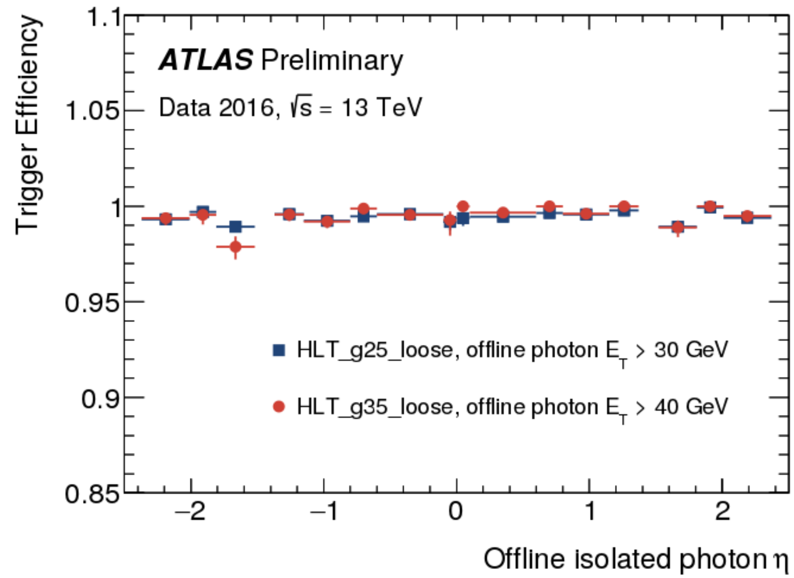


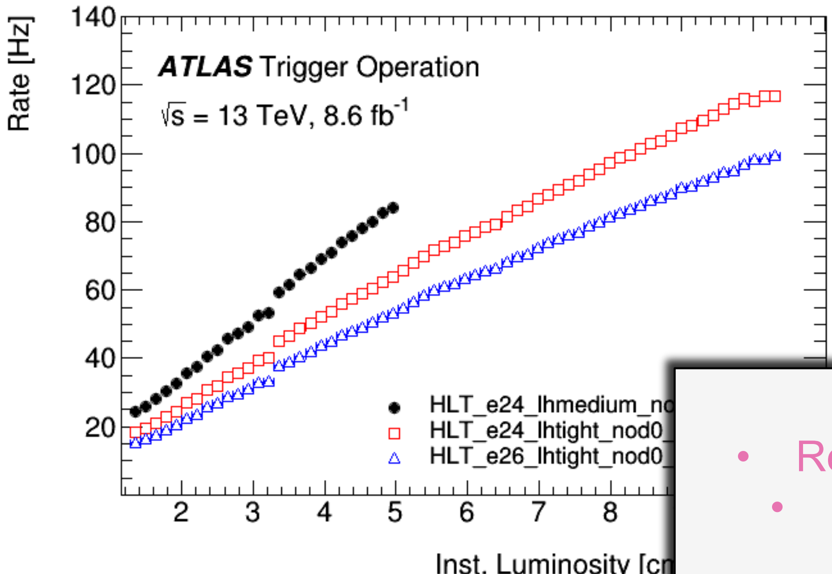


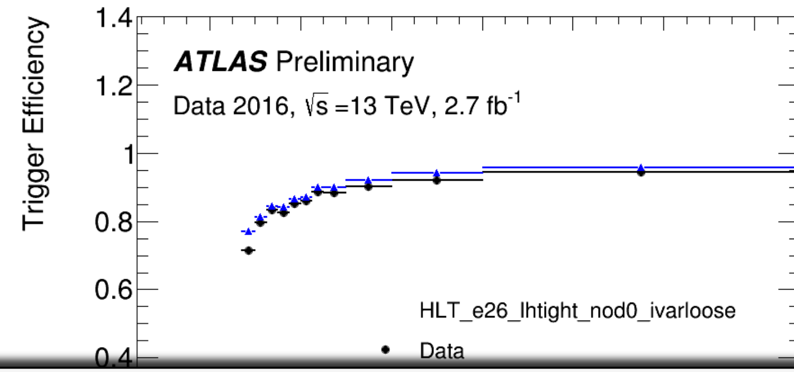
Difference: scale factors ‼

ELECTRON / PHOTON







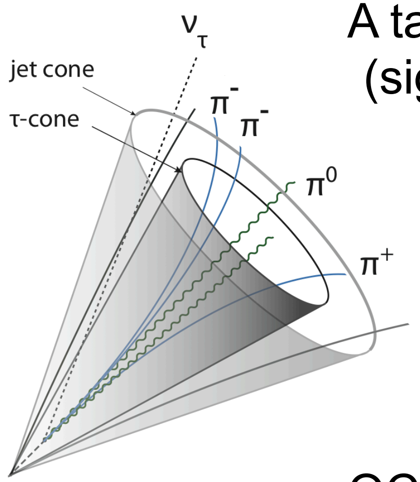


NEW IN 2017:

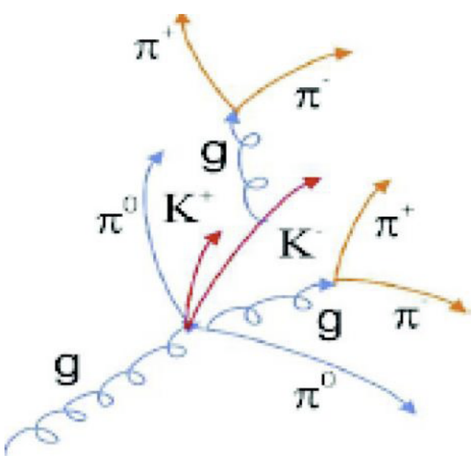
- Render electron identification more robust to pileup;
- Bring electron online ID closer to offline (tracking);
- Add photon isolation.

TAU

A tau jet (signal)



…vs a QCD jet (background)

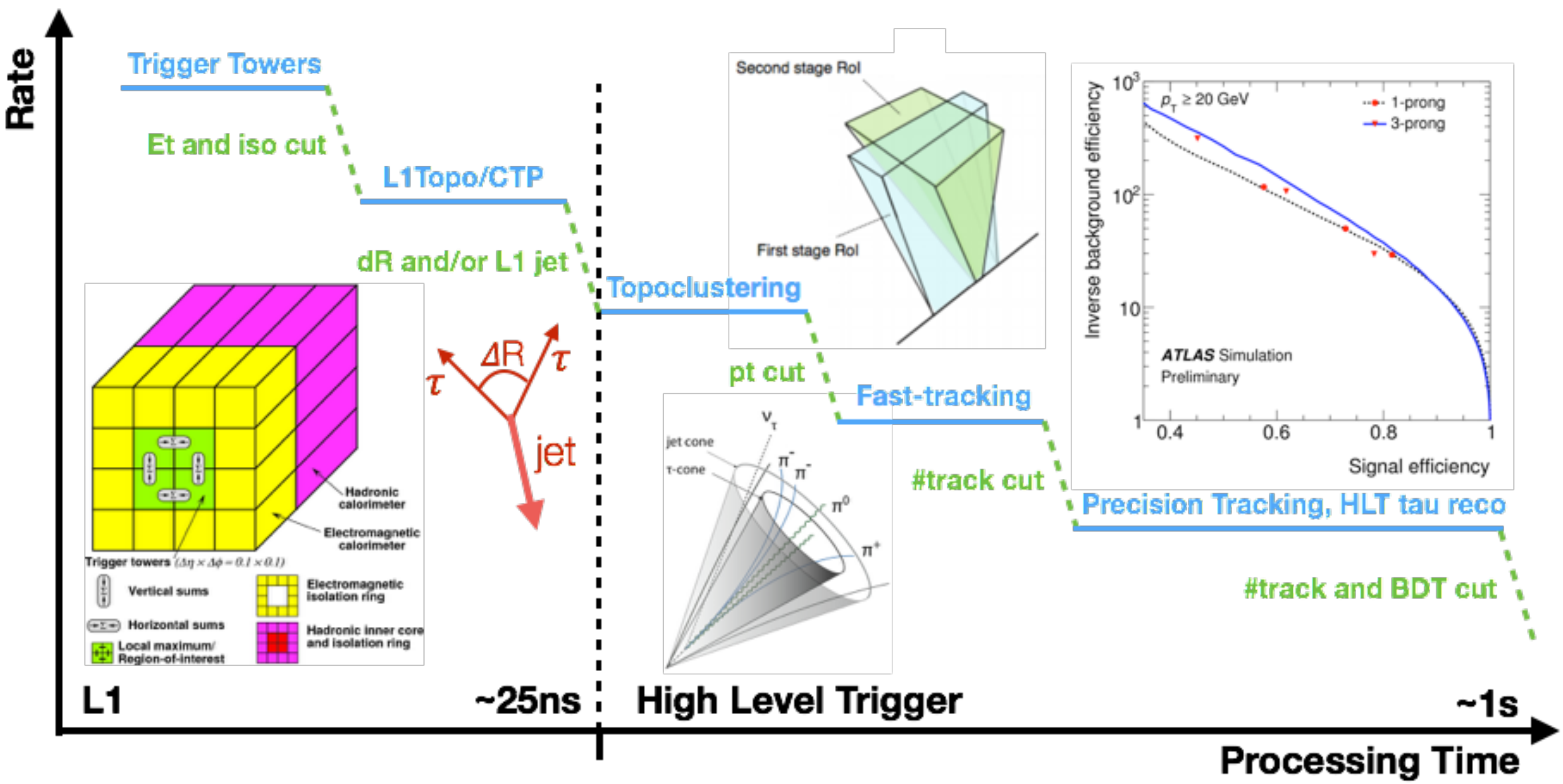


Tau Decay Mode			B.R.
Leptonic		$\tau^\pm \rightarrow e^\pm + \nu + \nu$	17.8%
		$\tau^\pm \rightarrow \mu^\pm + \nu + \nu$	17.4%
Hadronic	1-prong	$\tau^\pm \rightarrow \pi^\pm + \nu$	11%
		$\tau^\pm \rightarrow \pi^\pm + \nu + n\pi^0$	35%
	3-prong	$\tau^\pm \rightarrow 3\pi^\pm + \nu$	9%
		$\tau^\pm \rightarrow 3\pi^\pm + \nu + n\pi^0$	5%
Other			~5%

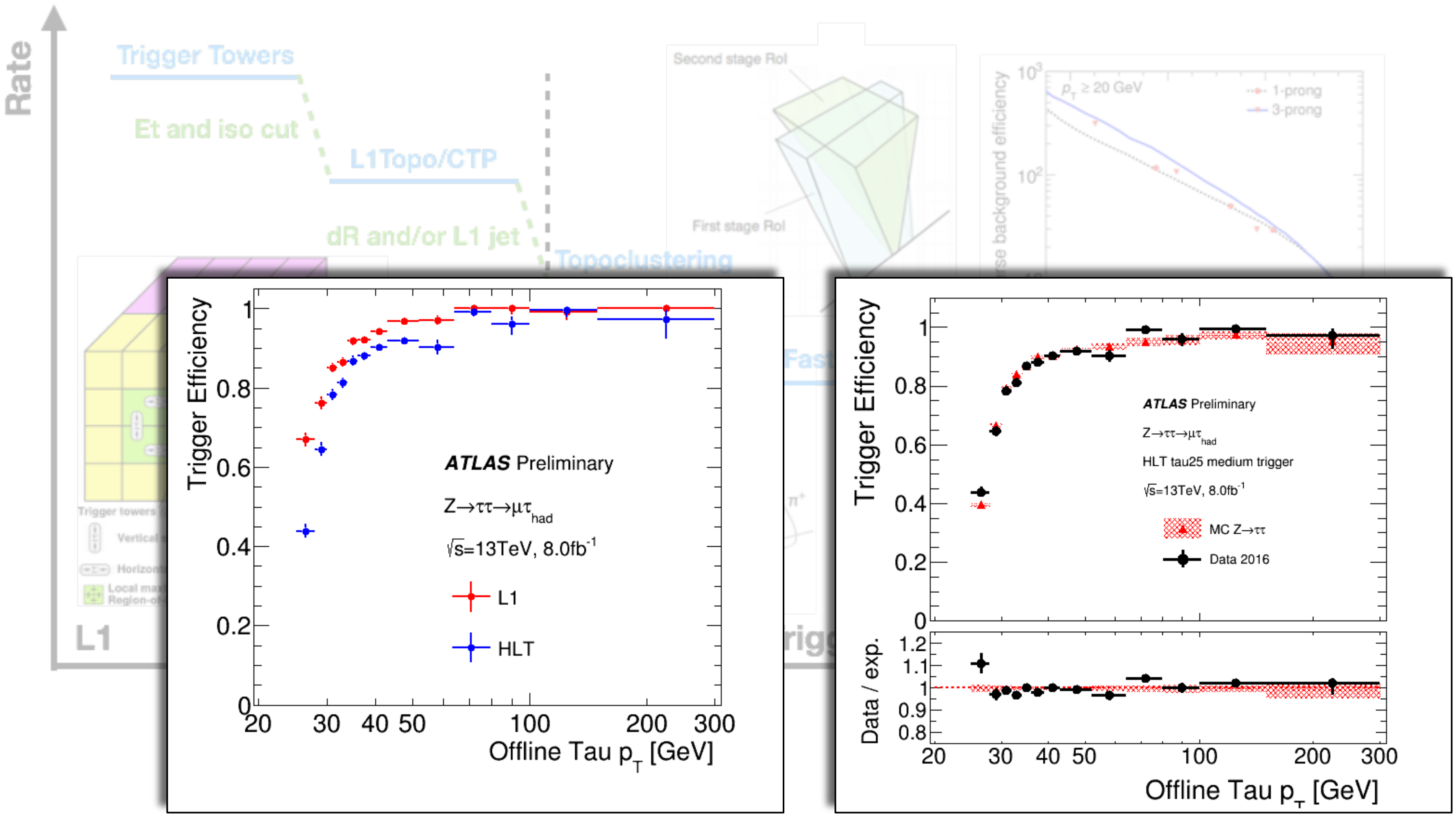
Variable	Offline		Trigger	
	1-track	3-track	1-track	3-track
f_{cent}	•	•	•	•
f_{track}	•	•	•	•
R_{track}	•	•	•	•
$S_{\mathrm{leadtrack}}$	•		•	
$N^{\mathrm{iso}}_{\mathrm{track}}$	•		•	
ΔR_{Max}		•		•
$S^{\mathrm{flight}}_{\mathrm{T}}$		•		•
m_{track}		•		•
$m_{\pi^0+\mathrm{track}}$	•	•		
N_{π^0}	•	•		
$p_{\mathrm{T}}^{\pi^0+\mathrm{track}}/p_{\mathrm{T}}$	•	•		

arXiv:1412.7086

TAU

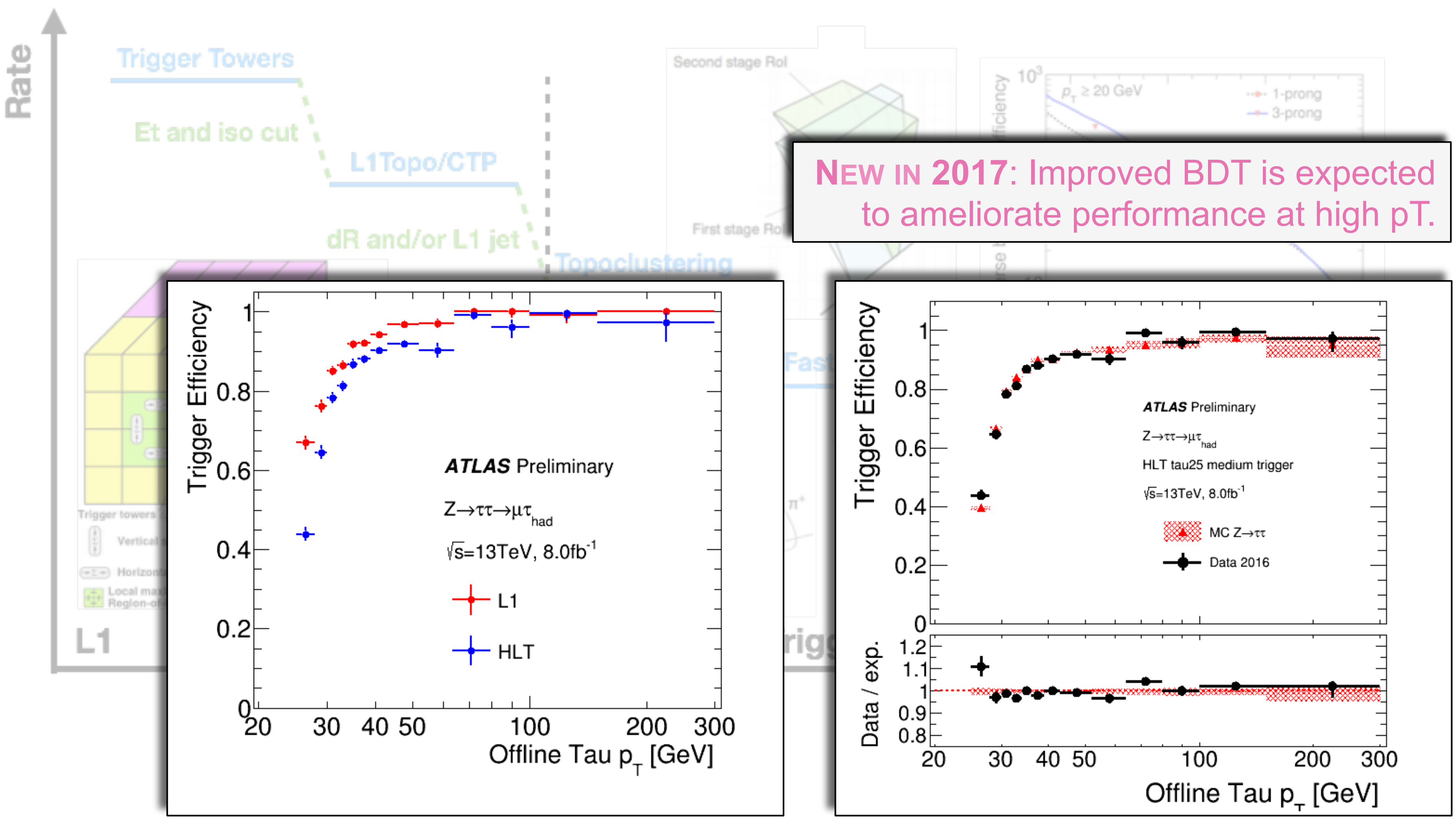

Rate
Trigger Towers
Et and iso cut
L1Topo/CTP
dR and/or L1 jet
Topoclustering
pt cut
Fast-tracking
#track cut
Precision Tracking, HLT tau reco
#track and BDT cut
Hadronic calorimeter
Electromagnetic calorimeter
Trigger towers
Vertical sums
Horizontal sums
Local maximum/ Region-of-interest
Electromagnetic isolation ring
Hadronic inner core and isolation ring
ΔR
τ
τ
jet
Second stage RoI
First stage RoI
jet cone
τ-cone
Inverse background efficiency
Signal efficiency
1-prong
3-prong
ATLAS Simulation Preliminary
L1
~25ns
High Level Trigger
~1s
Processing Time

TAU



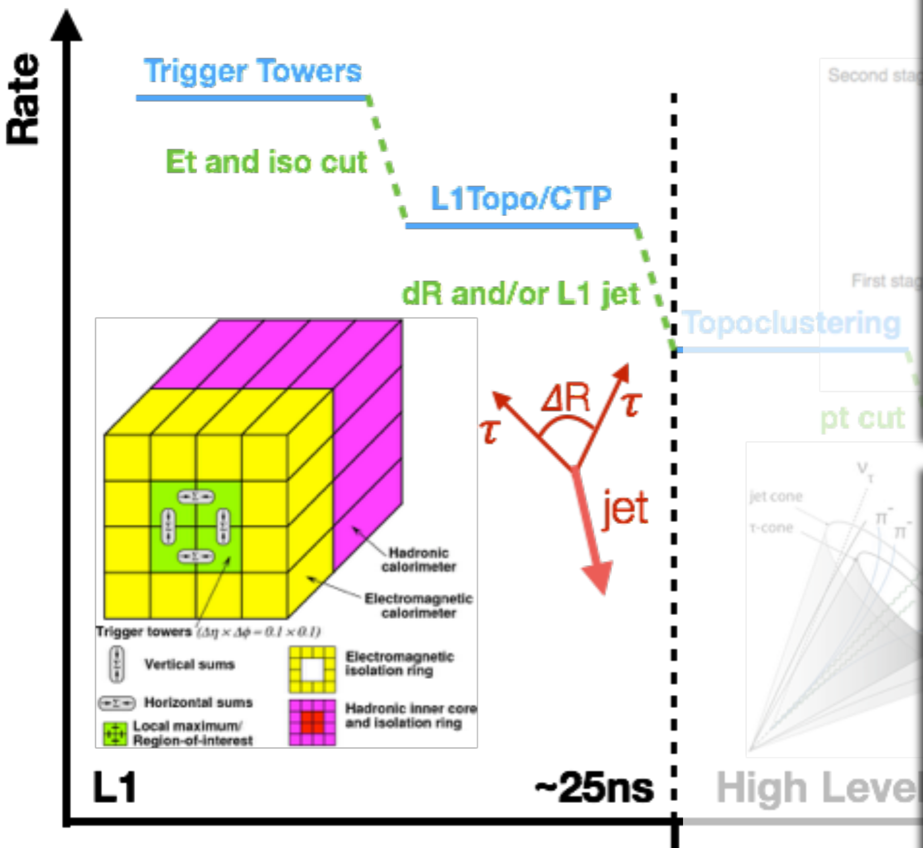
Rate
Trigger Towers
Et and iso cut
L1Topo/CTP
dR and/or L1 jet
Topoclustering
L1
Trigger Efficiency
ATLAS Preliminary
Z→ττ→μτ_had
√s=13TeV, 8.0fb-1
L1
HLT
Offline Tau p_T [GeV]
Trigger Efficiency
ATLAS Preliminary
Z→ττ→μτ_had
HLT tau25 medium trigger
√s=13TeV, 8.0fb-1
MC Z→ττ
Data 2016
Data / exp.
Offline Tau p_T [GeV]

TAU

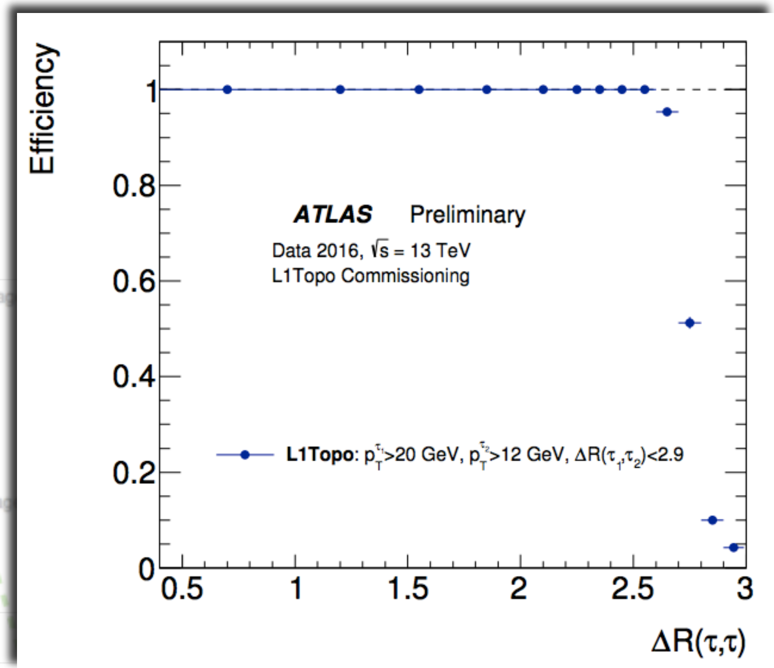


New in 2017: Improved BDT is expected to ameliorate performance at high pT.

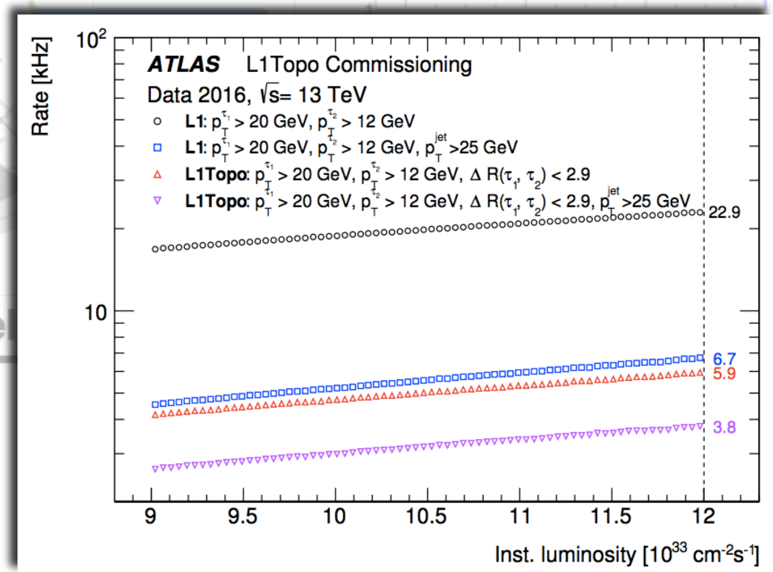
TAU – L1TOPO!



Rate
Trigger Towers
Et and iso cut
L1Topo/CTP
dR and/or L1 jet
Topoclustering
pt cut
Hadronic calorimeter
Electromagnetic calorimeter
Trigger towers
Vertical sums
Electromagnetic isolation ring
Horizontal sums
Hadronic inner core and isolation ring
Local maximum/ Region-of-interest
ΔR
τ
τ
jet
L1
~25ns
High Level

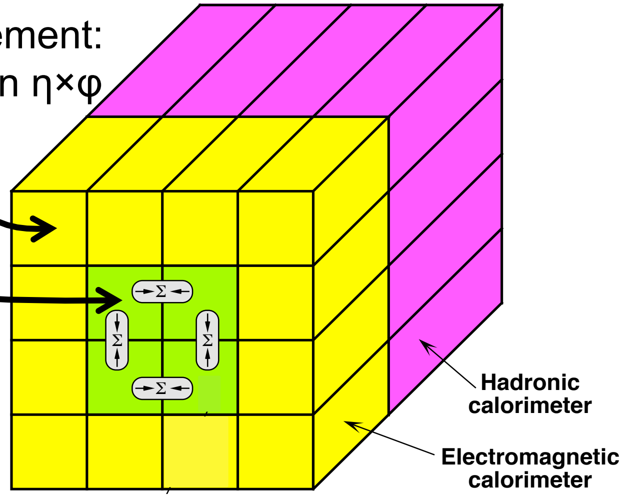


Efficiency
ATLAS Preliminary
Data 2016, √s = 13 TeV
L1Topo Commissioning
L1Topo: $p_T^{\tau_1}$>20 GeV, $p_T^{\tau_2}$>12 GeV, ΔR(τ1,τ2)<2.9
ΔR(τ,τ)

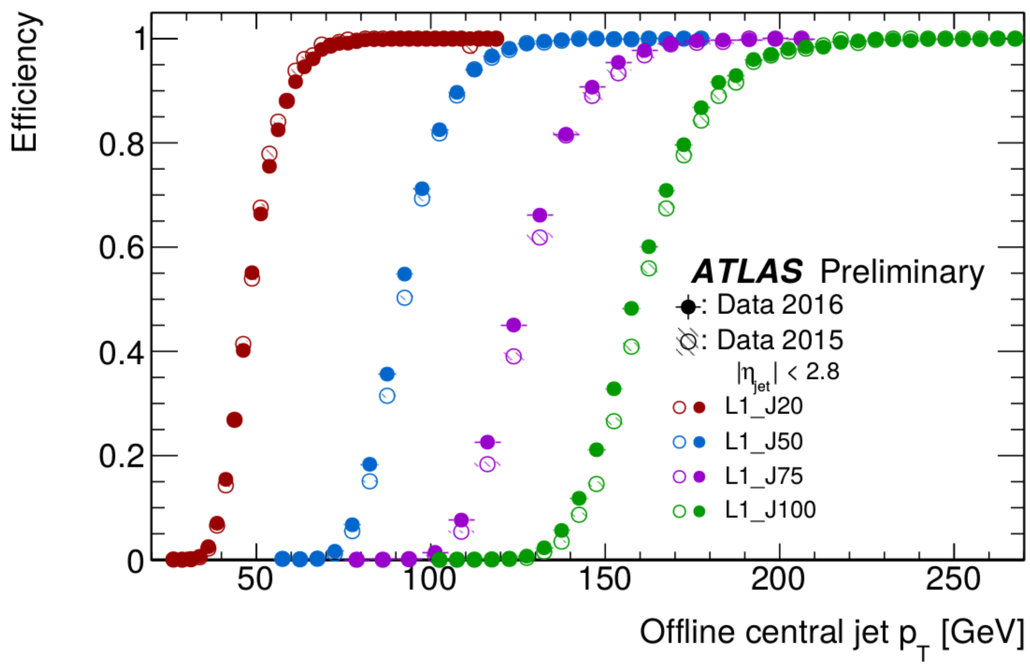


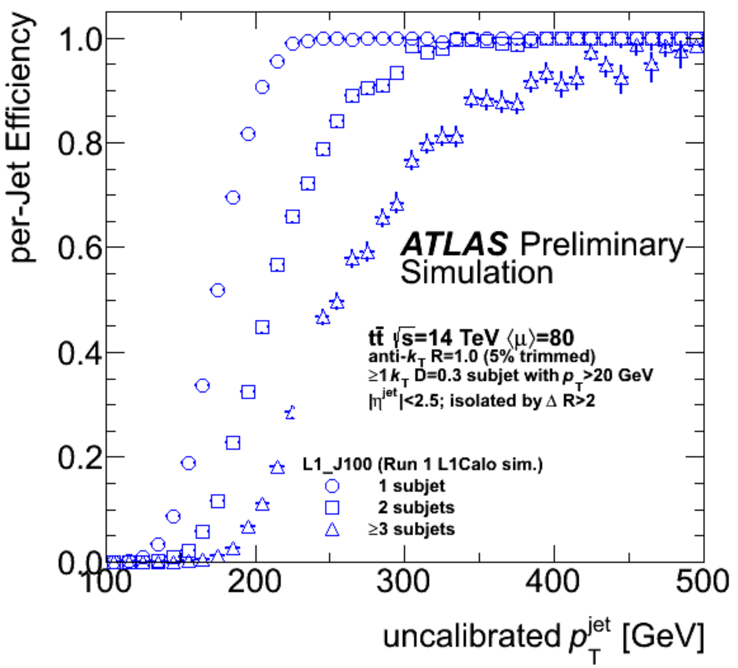
Rate [kHz]
ATLAS L1Topo Commissioning
Data 2016, √s= 13 TeV
L1: $p_T^{\tau_1}$ > 20 GeV, $p_T^{\tau_2}$ > 12 GeV
L1: $p_T^{\tau_1}$ > 20 GeV, $p_T^{\tau_2}$ > 12 GeV, p_T^{jet} >25 GeV
L1Topo: $p_T^{\tau_1}$ > 20 GeV, $p_T^{\tau_2}$ > 12 GeV, Δ R(τ1, τ2) < 2.9
L1Topo: $p_T^{\tau_1}$ > 20 GeV, $p_T^{\tau_2}$ > 12 GeV, Δ R(τ1, τ2) < 2.9, p_T^{jet} >25 GeV
22.9
6.7
5.9
3.8
Inst. luminosity [10^{33} cm^{-2}s^{-1}]

JETS L1



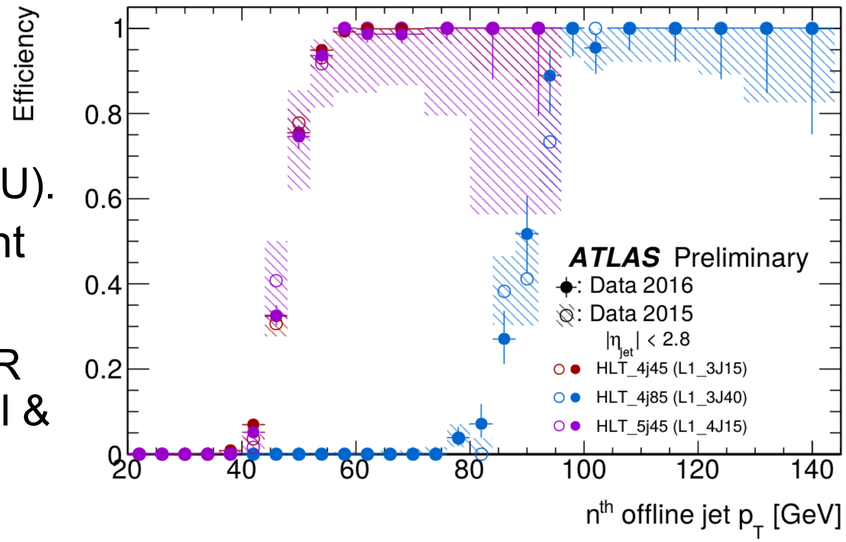
- Built from 4×4 jet elements
  - using a sliding window algorithm
- Pile-up suppression had a huge impact in low-pT
- Very good performance; inefficiencies in close-by mutlijets / fat jets

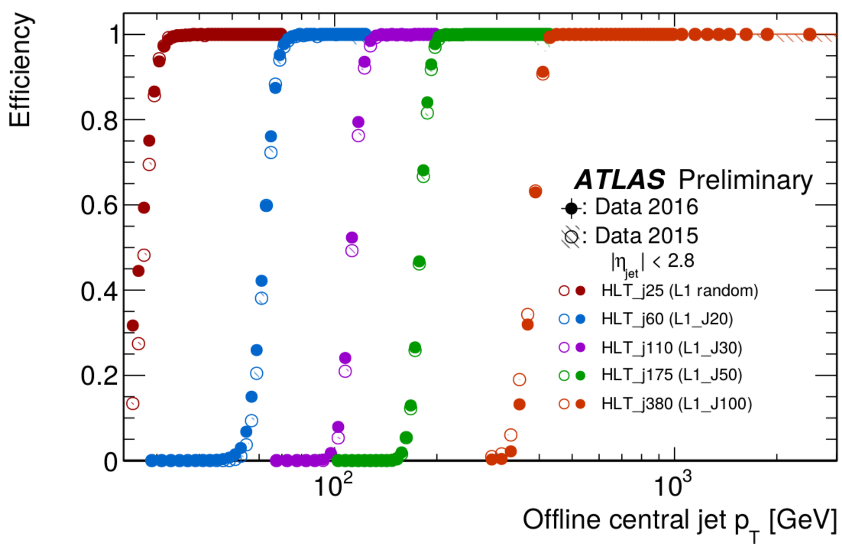


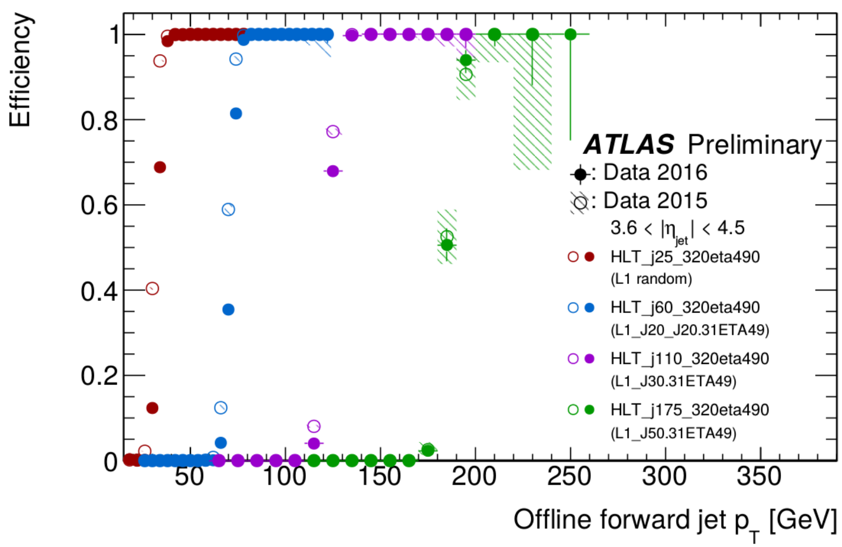


JETS HLT

- Very similar to offline jets, since full-scan topoclustering is used at the HLT.
  - Exception: tracking. Too expensive (CPU).
- Several types of jets exist to cover different uses.
  - Single jets, multijets, reclustered large-R jets, large-R topocluster jets, H_T, central & forward jets …
  - Corrected using “Jet Areas”; MC-based calibration.



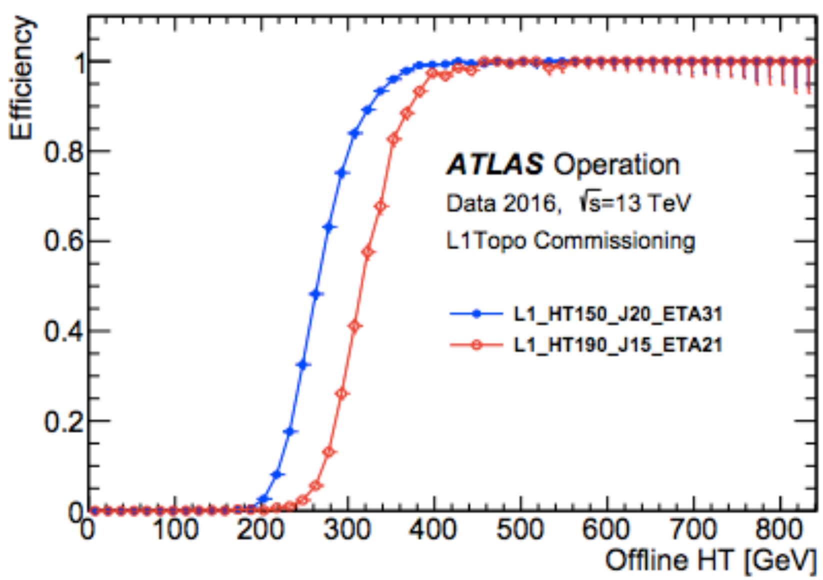


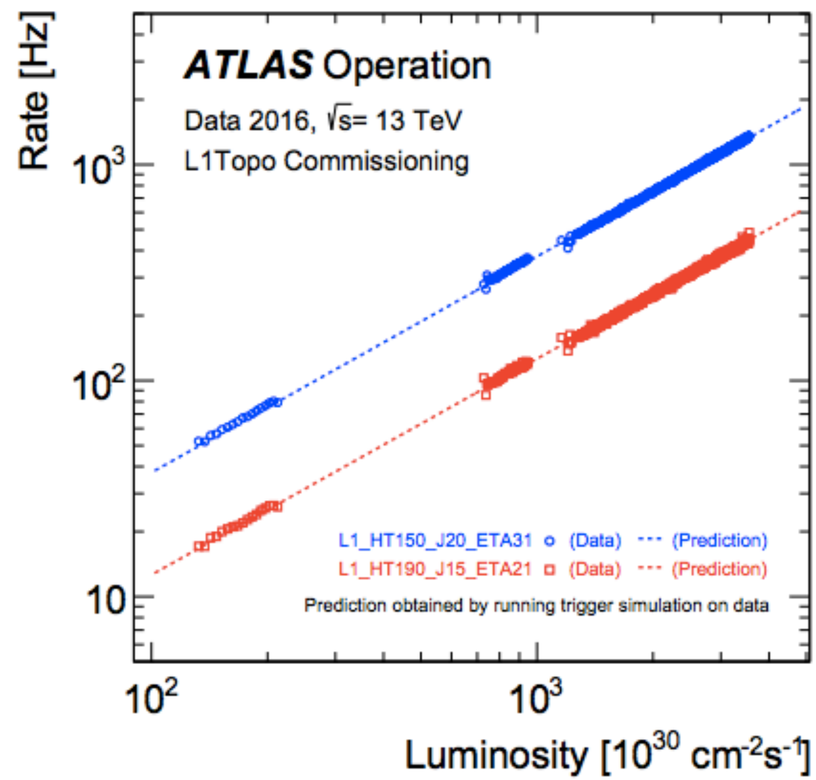


FAT JETS & L1TOPO

- Currently fat jet triggers use single narrow jet seed at L1.
- Prospects for reseeding fat jet triggers in 2017.
- Other envisaged improvements include substructure and top / boson tagging.

NEW IN 2017





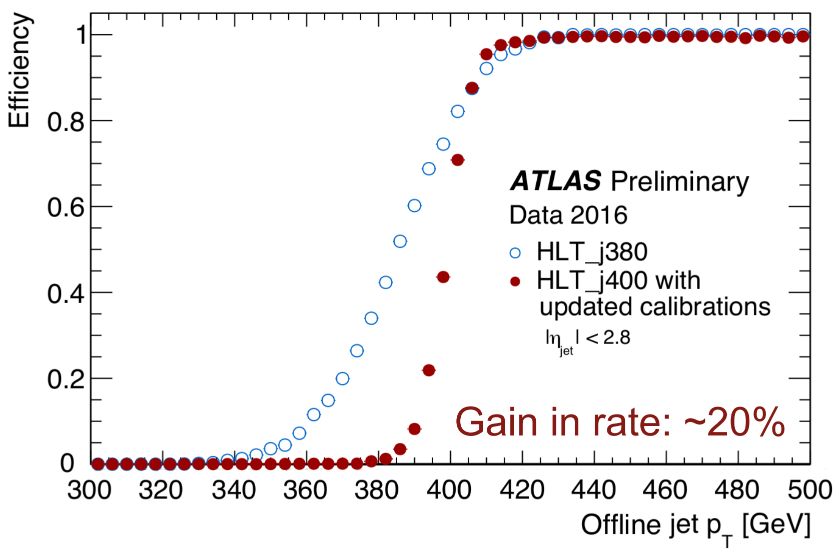
JETS: FURTHER IMPROVEMENTS

Utilize more appropriate noise cuts in topo-clustering algorithm.

Jet Calibration: bringing online jets closer to offline.

NEW IN 2017

- In 2016 we had MC-based calibrations on top of jet areas corrections.
- In 2017 we envisage:
  - Updated MC-based calibrations.
  - Calo term of “Global sequential calibration” (GSC) – default offline.
  - Track term of GSC – for triggers where tracking run in RoIs.
    - Tracking is expensive; consider it when already done for b-jets.
    - (Then, add GCS to b-jets.)
  - *In situ* eta inter-calibration.



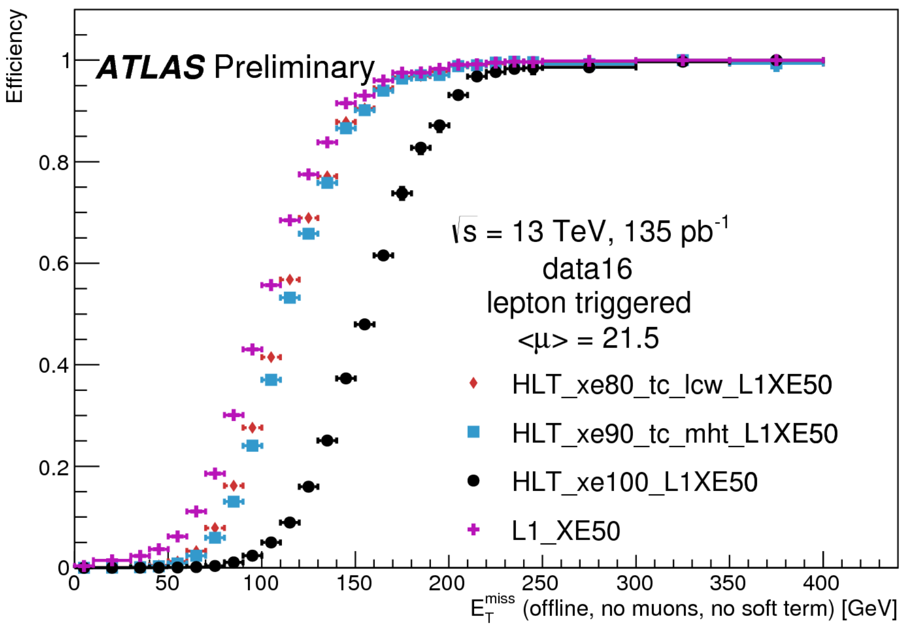
MISSING E_T

At L1:

- **Sum all jet elements to obtain E_{Tx} and E_{Ty} components, from where E_T is calculated.**
- **Pile-up suppression has been essential.**
  - Needs adjustment for large steps in pile-up.

At HLT:

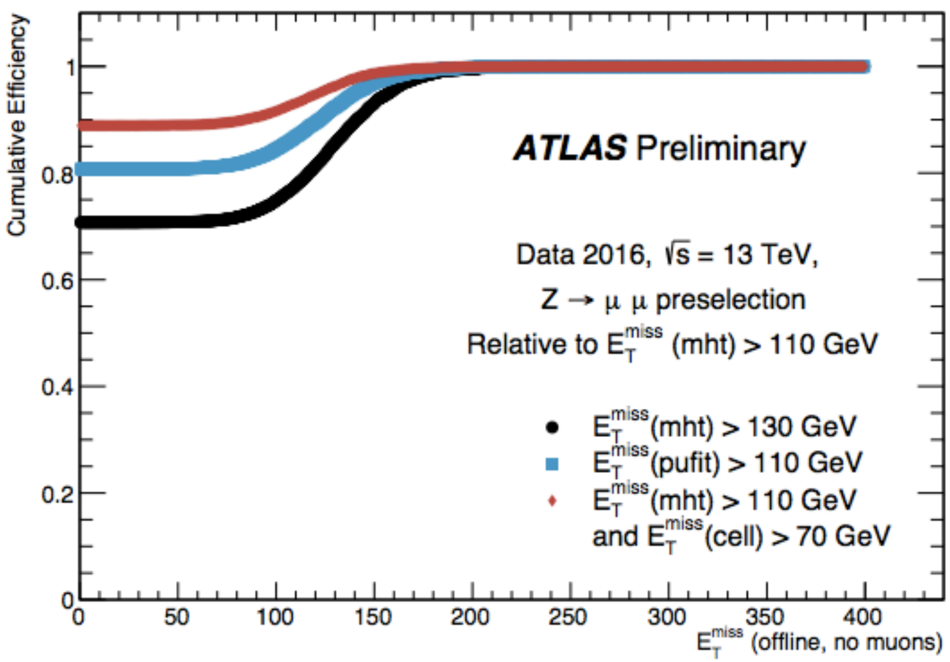
- **One of the few areas where offline ME_T doesn't quite work at the trigger.**
  - Requires proper reconstruction and calibration of all objects in the event.
- **Various trigger alternatives:**
  - Cell ME_T (2015 default)
  - Missing H_T (2016 default)
  - Cell ME_T + Missing H_T
  - Topocluster based ME_T, including with pile-up suppression

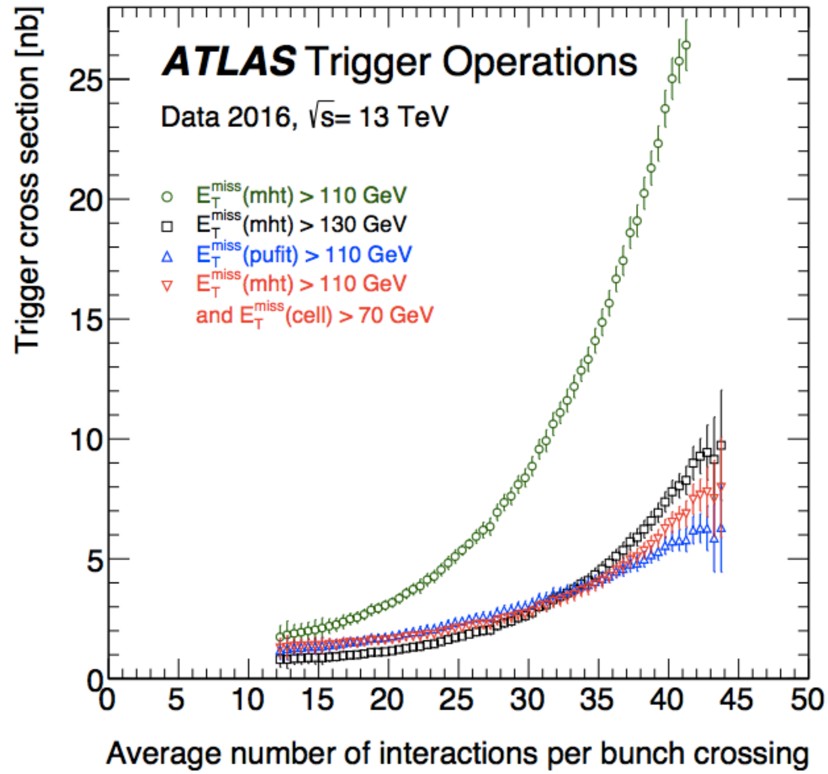


IMPACT OF PILEUP – ME_T

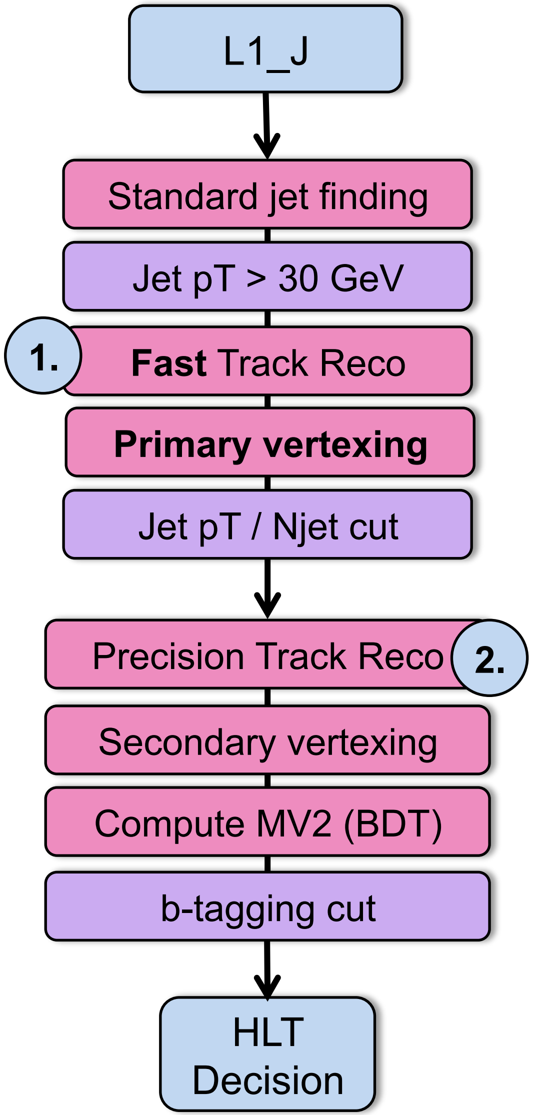
- ME_T triggers significantly hit by pileup in 2016;
  - threshold increase was unavoidable; didn't yet compromise physics.
- Workaround for higher luminosities in place:
  - **Cell ME_T + Missing H_T**
  - **Pile-up suppression algorithm ("PU Fit").**
- Further RnD in progress:
  - **Use tracking to reduce pileup effect.**

NEW IN 2017





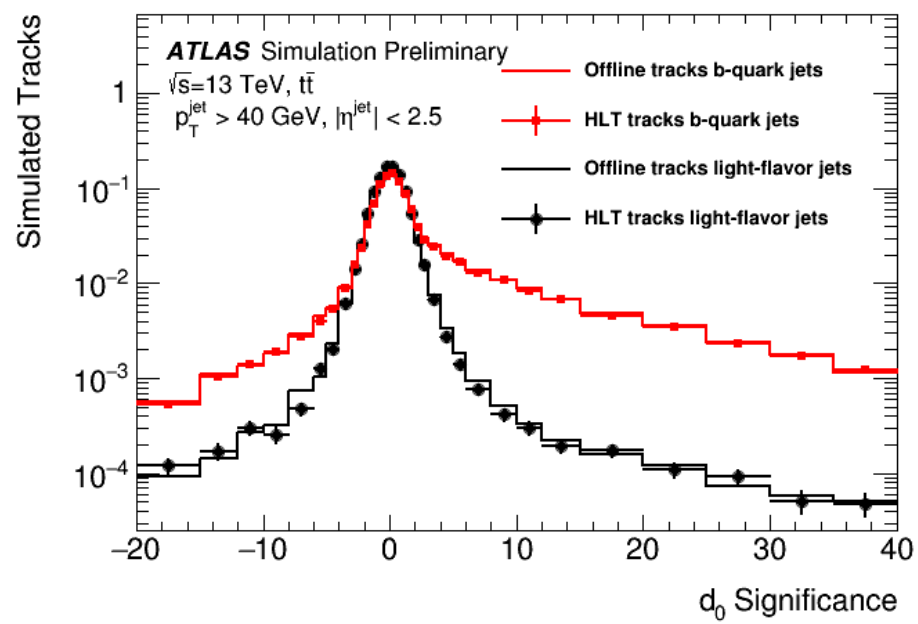
B-JETS



Use dedicated Primary Vertex (PV) finding and a BDT (similar to offline) to select b-jets against c- and light-jets.

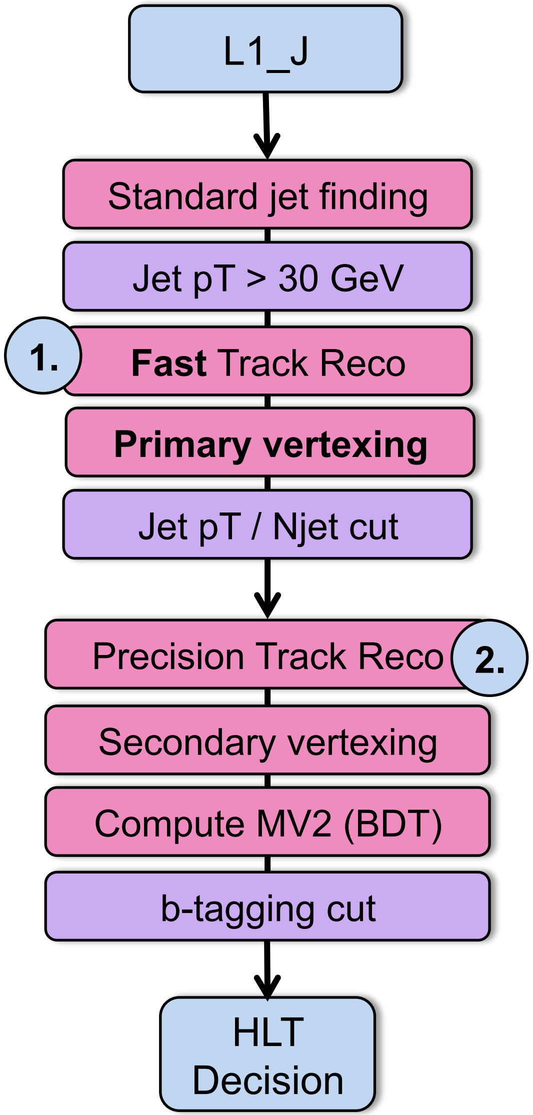
1. Run tracking within jet RoIs for PV reco.

2. Run tracking within wider cone for secondary vertex finding.



B-JETS

NEW IN 2017:
add GSC calibration



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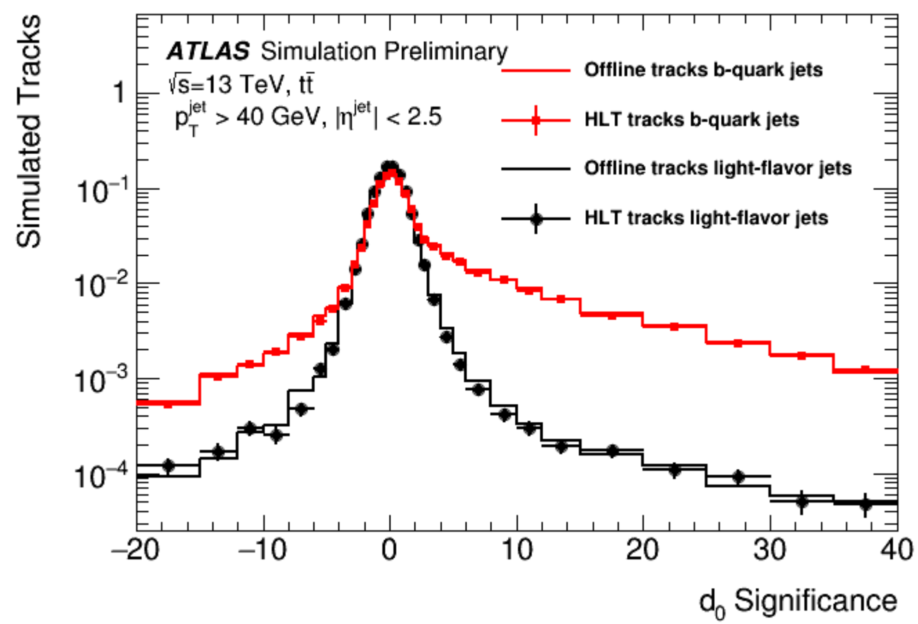
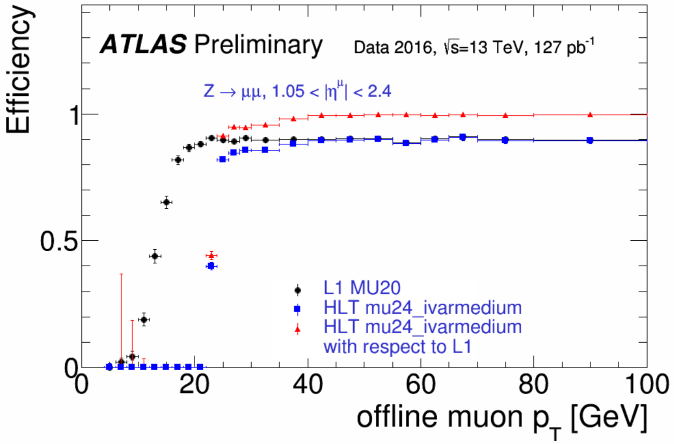
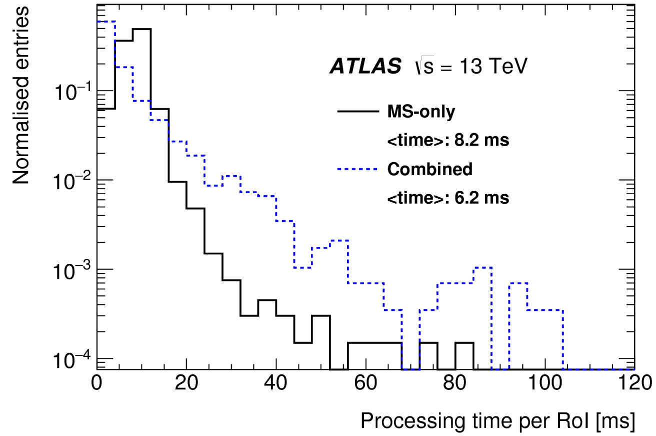
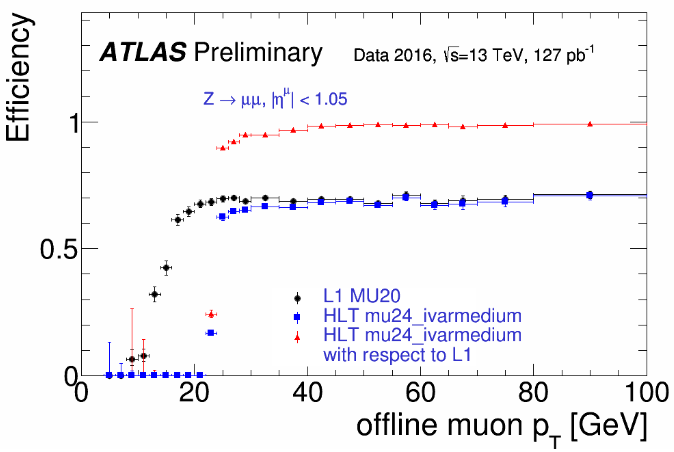
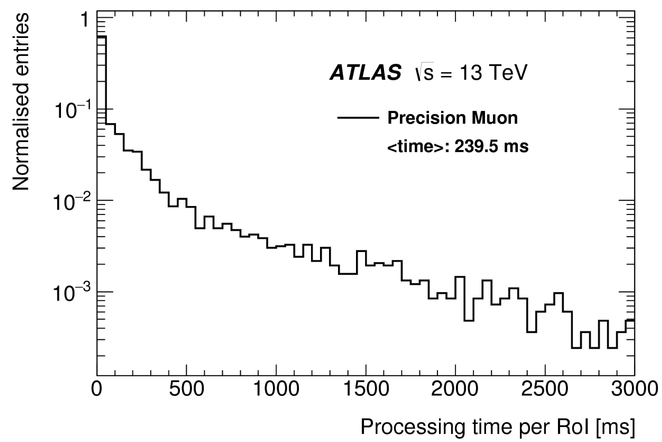


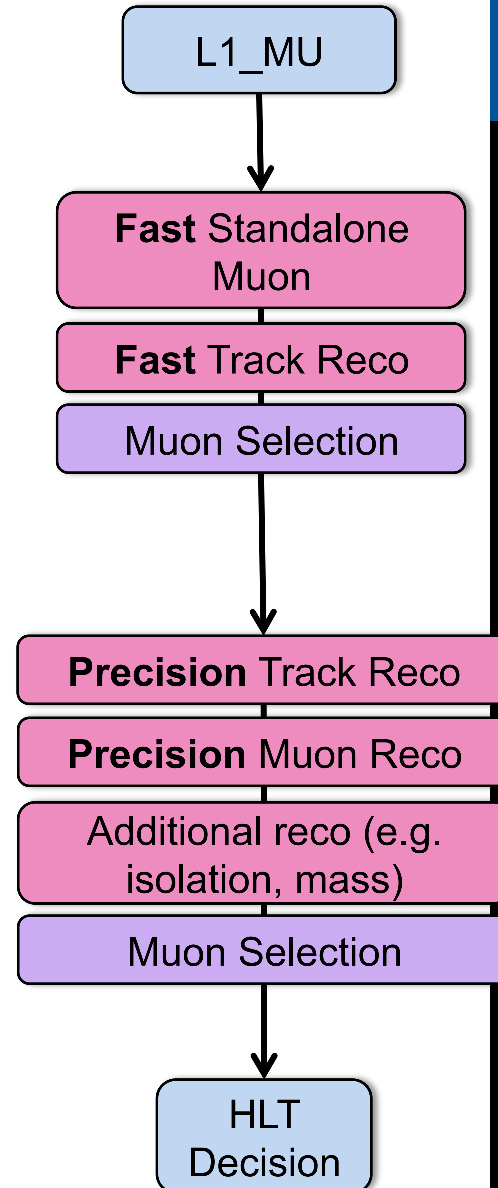
MUON







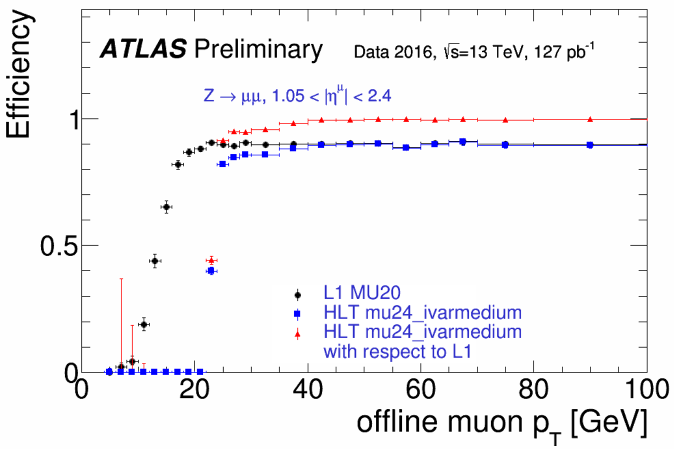


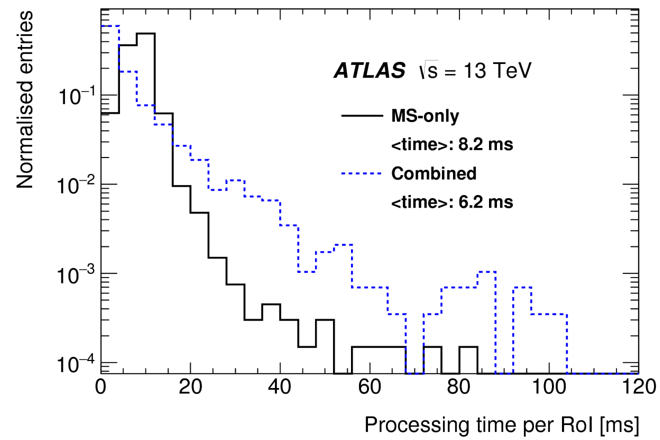


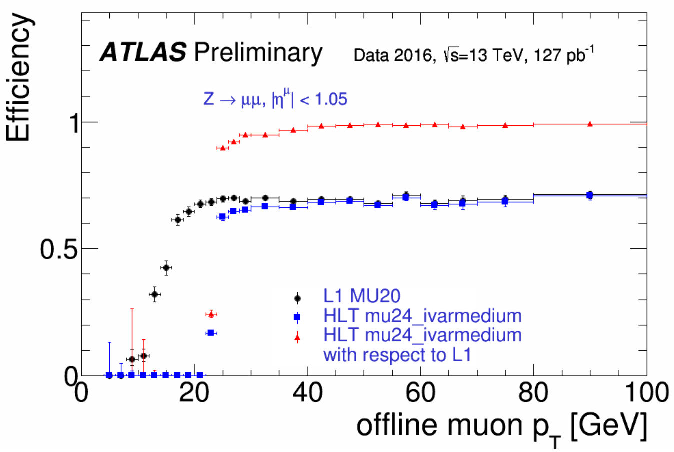
At L1 :
- Single or multi-muon selections (see earlier)

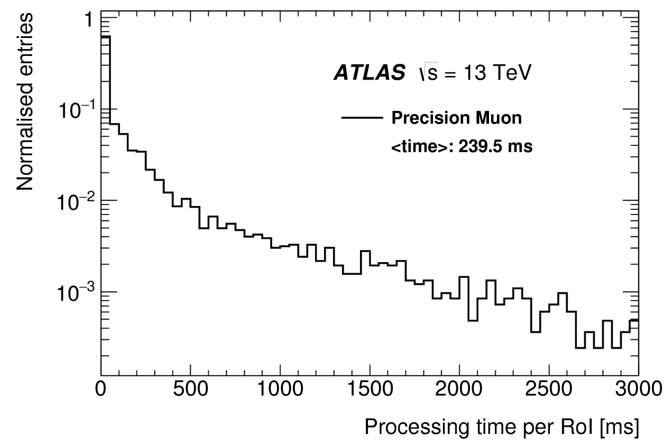
At HLT :
- Single muon triggers are RoI-based.
- Full-scan muon (no RoI-based) option exists; high efficiency & low pT.

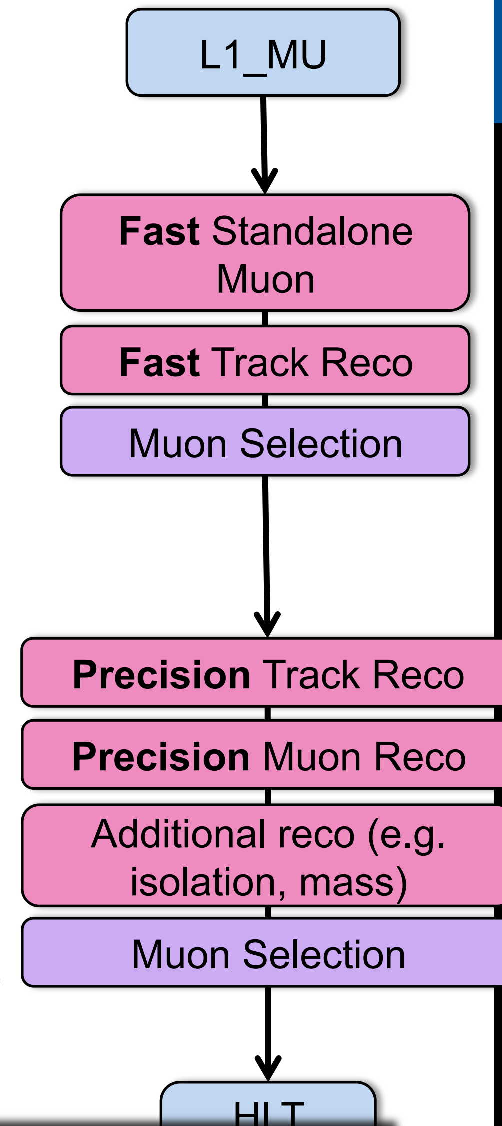
MUON











At L1 : • Single or multi-muon selections (see earlier)

At HLT : • Single muon triggers are RoI-b

• Full-scan muon (no RoI-based)

New in 2017:

- Add calorimeter isolation (as offline).
- Introduce late muon selection!

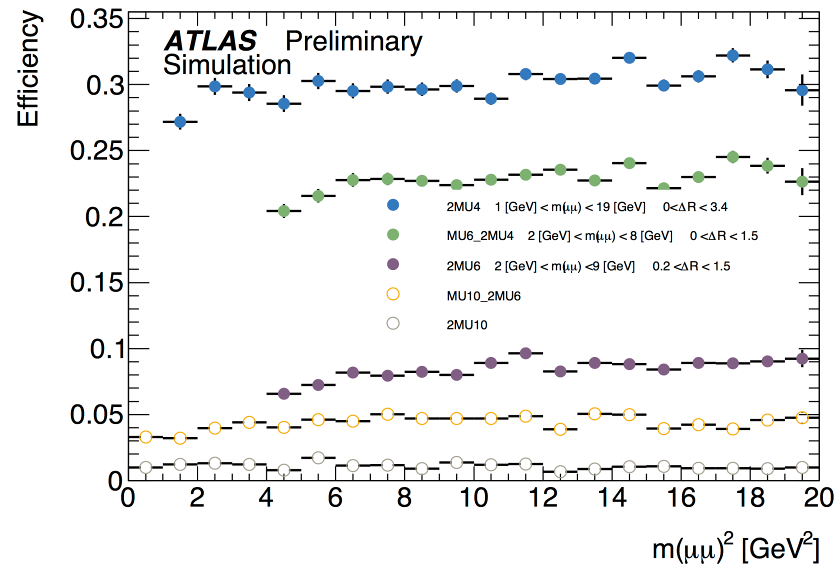
B-PHYSICS

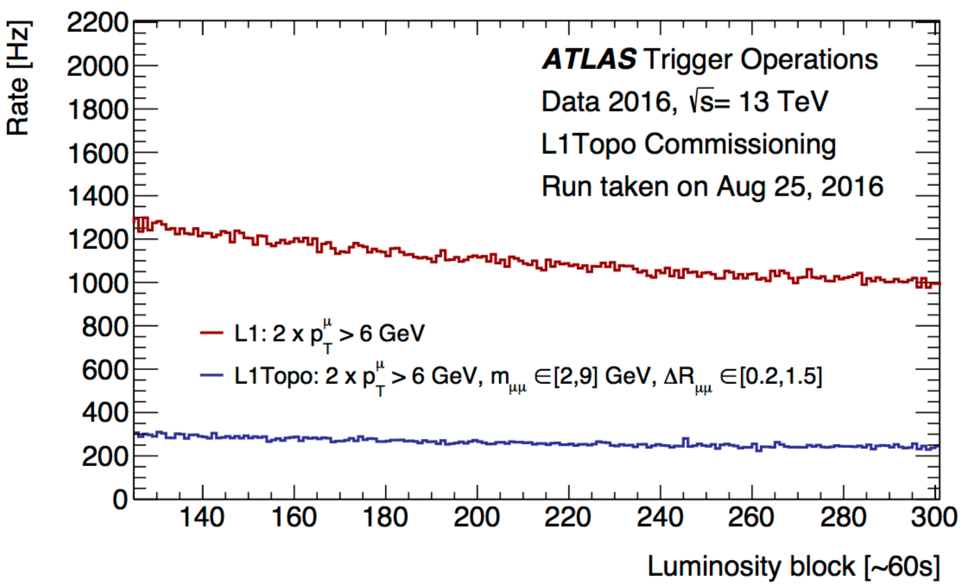
Triggers based in very low-pT muons.

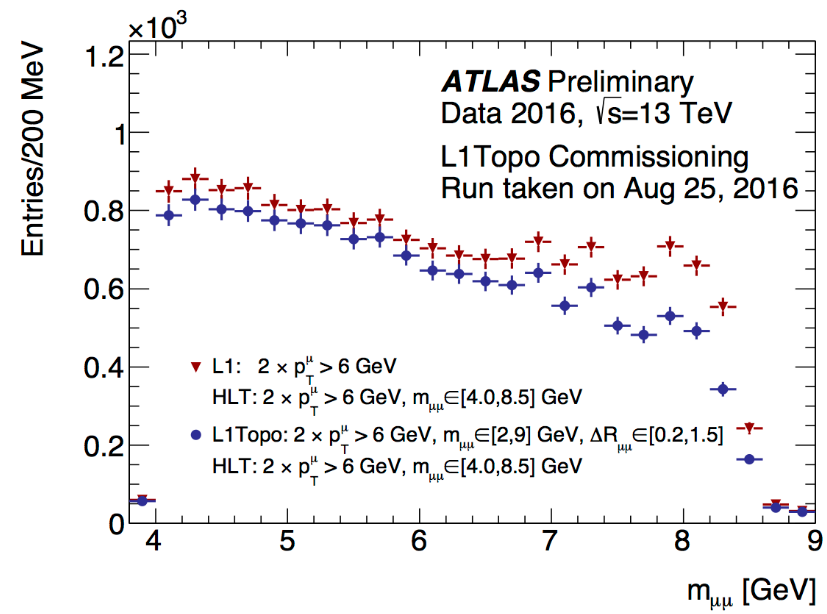
Challenges:

- L1 rates push thresholds high.
- Increased CPU needs due to low-pT muon combinatorics..

Key users of L1Topo!





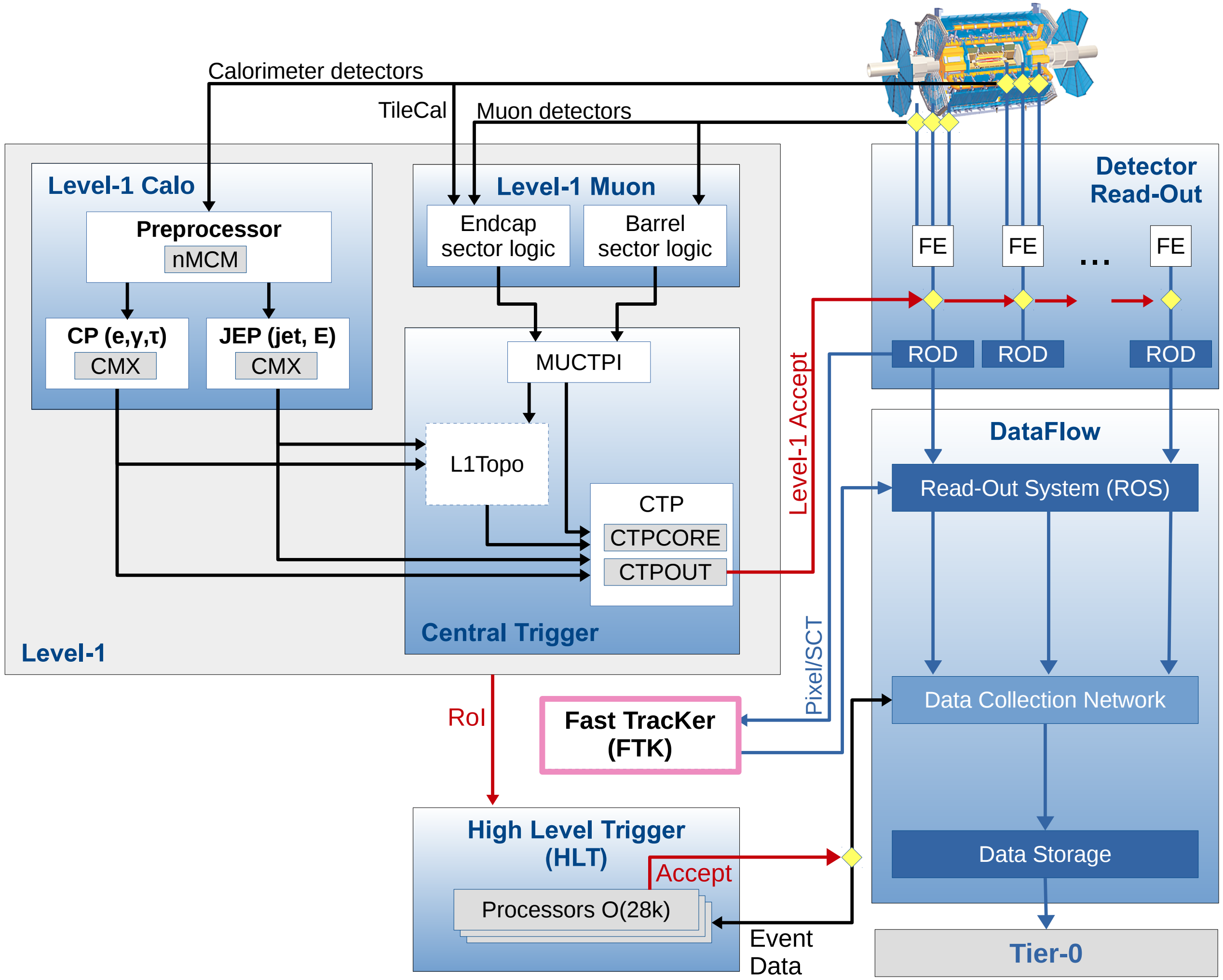


THE NEW
FAST TRACK
TRIGGER

THE ATLAS TRIGGER SYSTEM

FTK

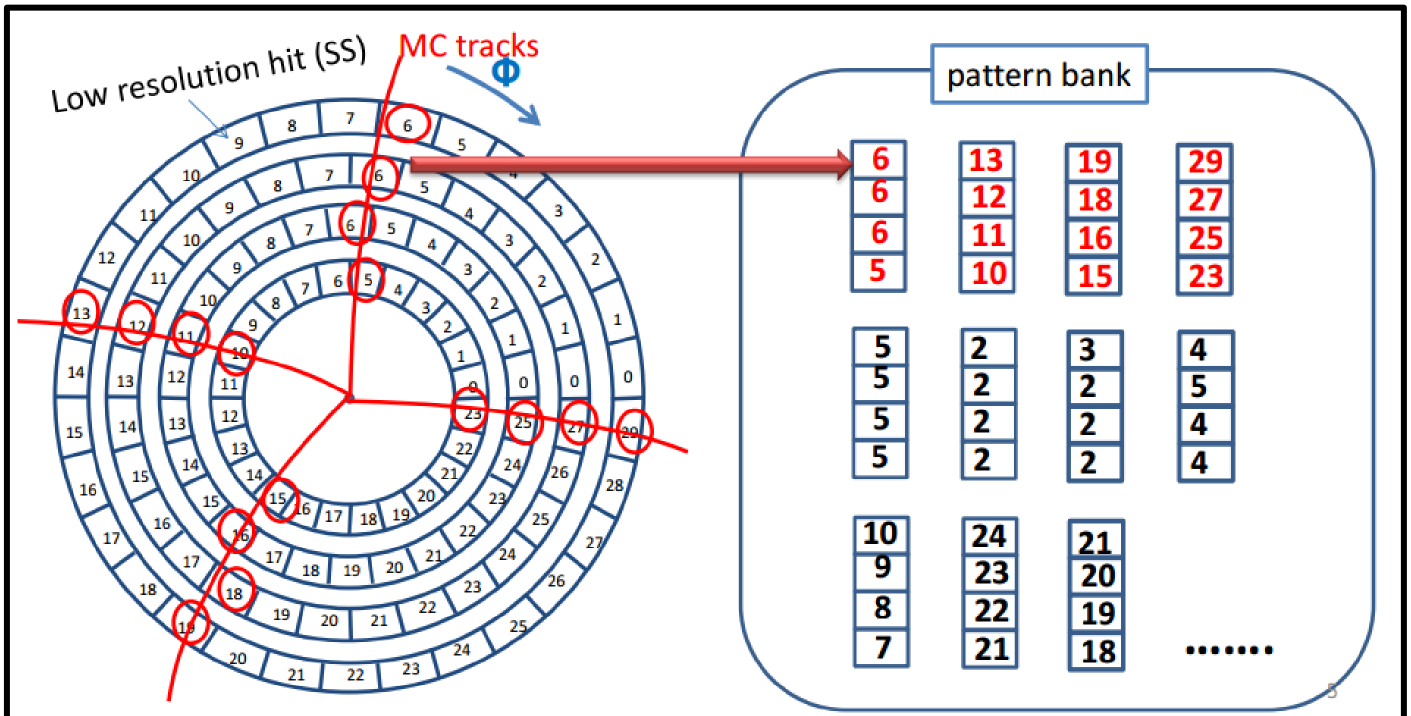
NEW
UNDER COMMISSIONING



FAST TRACKER – FTK

A hardware system that provides (at L1 rate) "full-scan" tracks and associated hits to the HLT (which cannot afford running full-scan track reconstruction high rate).

- Based on pattern matching. Pattern banks generated using MC simulation. More than 50 billion tracks used for ~ 1 billion patterns.



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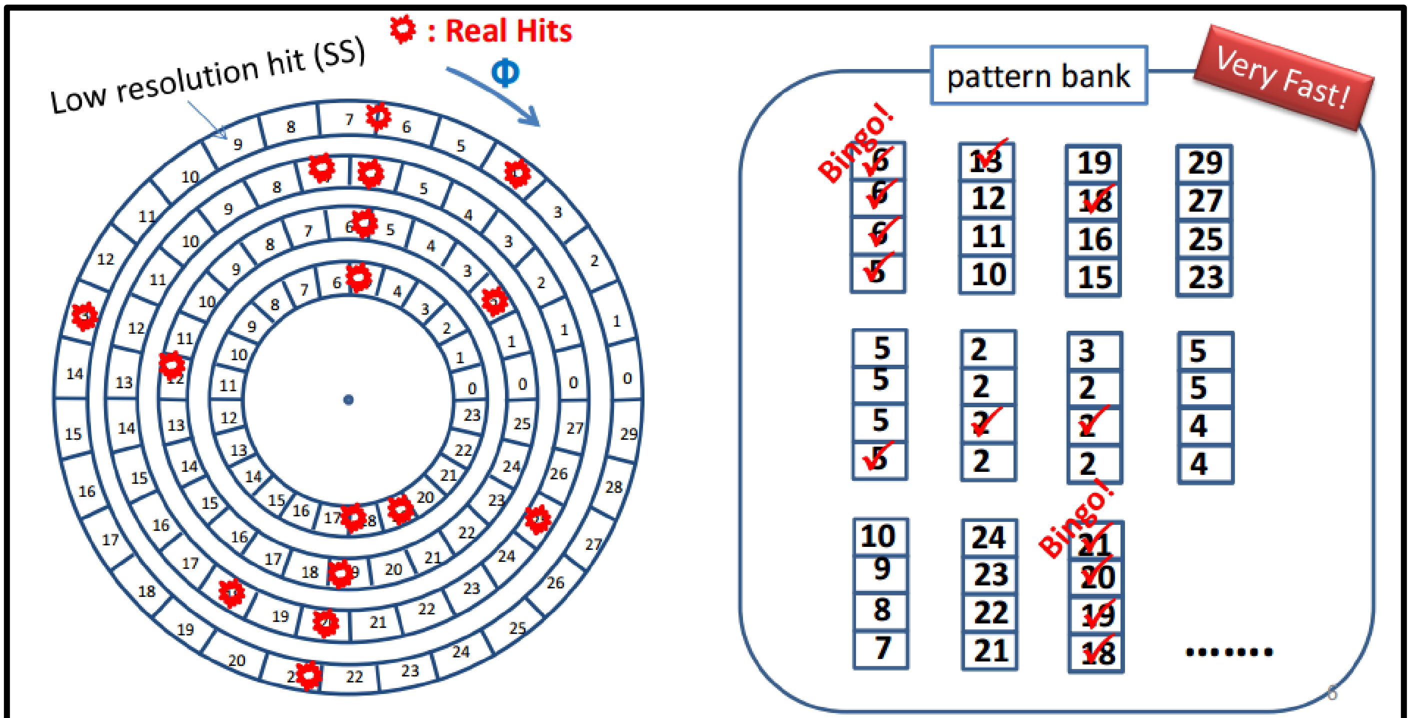

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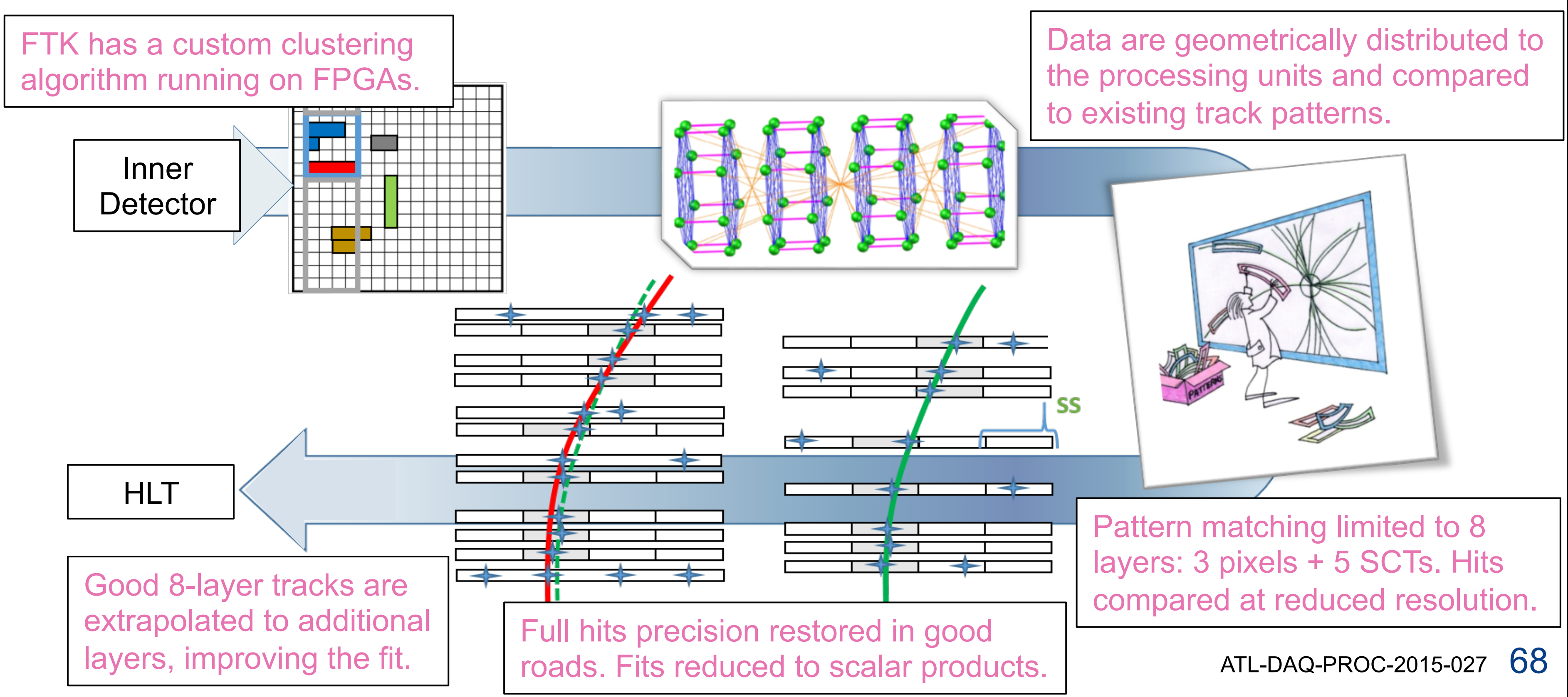
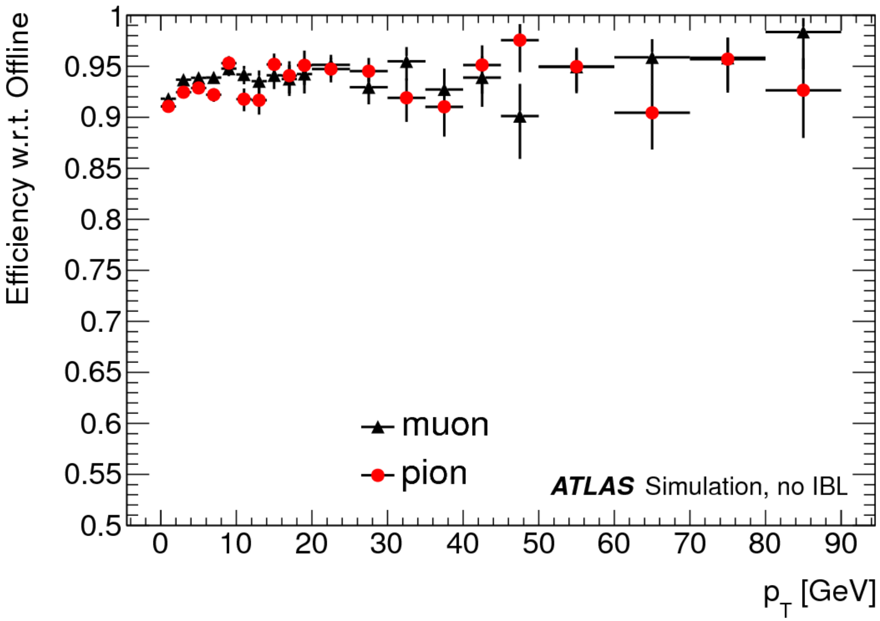
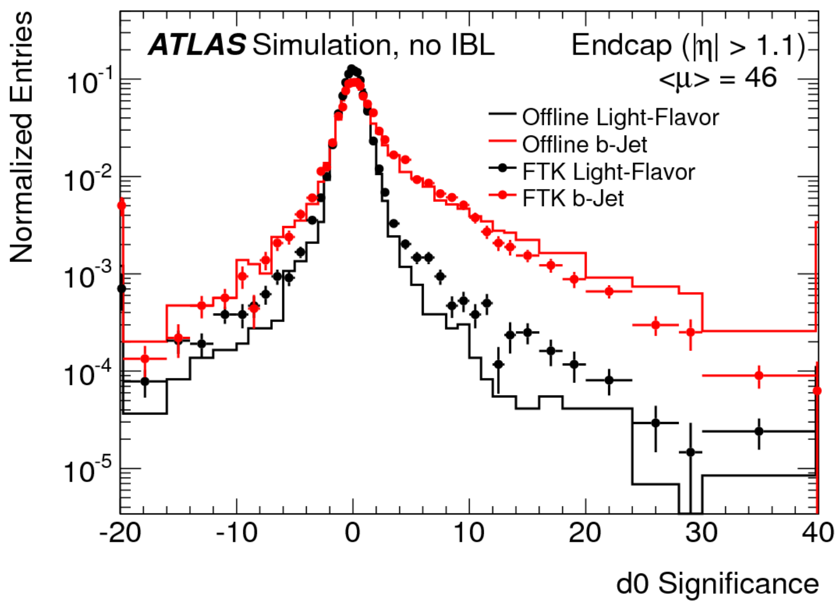


FAST TRACKER – FTK

A hardware system that provides (at L1 rate) “full-scan” tracks and associated hits to the HLT (which cannot afford running full-scan track reconstruction high rate).

- Based on pattern matching. Pattern banks generated using MC simulation. More than 50 billion tracks used for ~ 1 billion patterns.
- The HLT has now available tracks of pT > 1GeV.





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2013-007/index.html

FTK IN THE TRIGGER

Lots of potential for signatures that already use tracks (e.g. taus and bjets)**, and others that don't yet** (e.g. jets and MET)**.**

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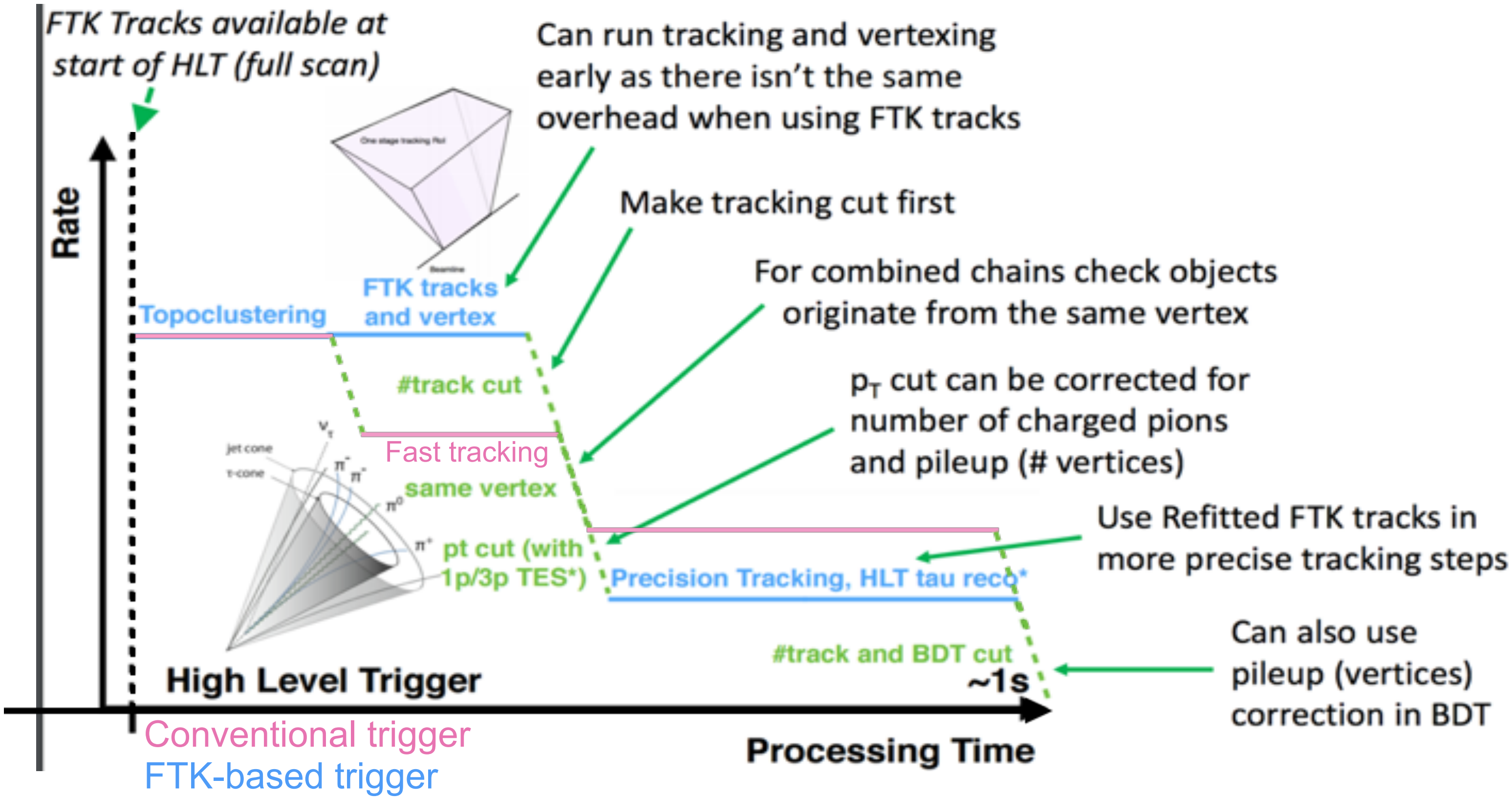

FTK IN THE TRIGGER

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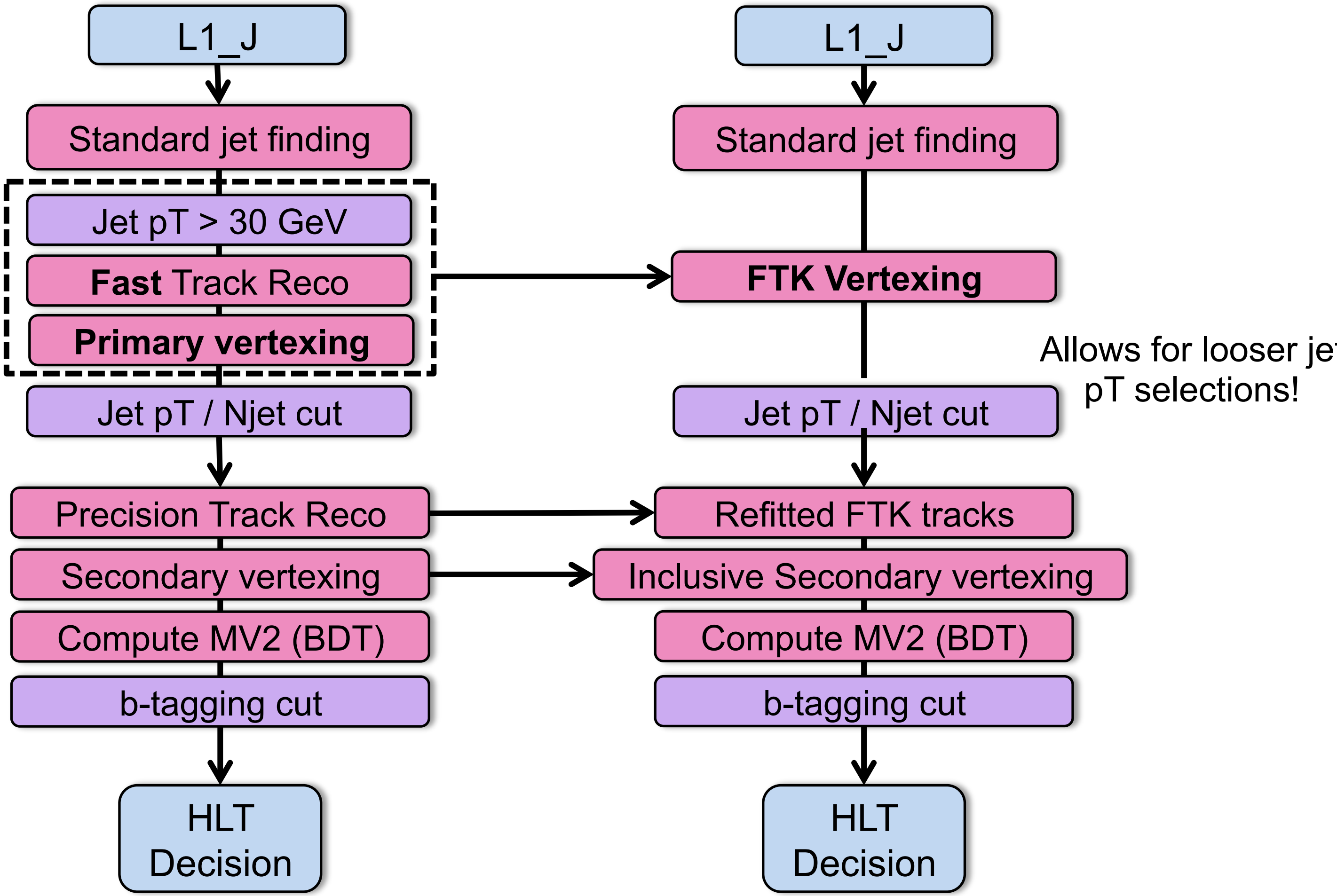
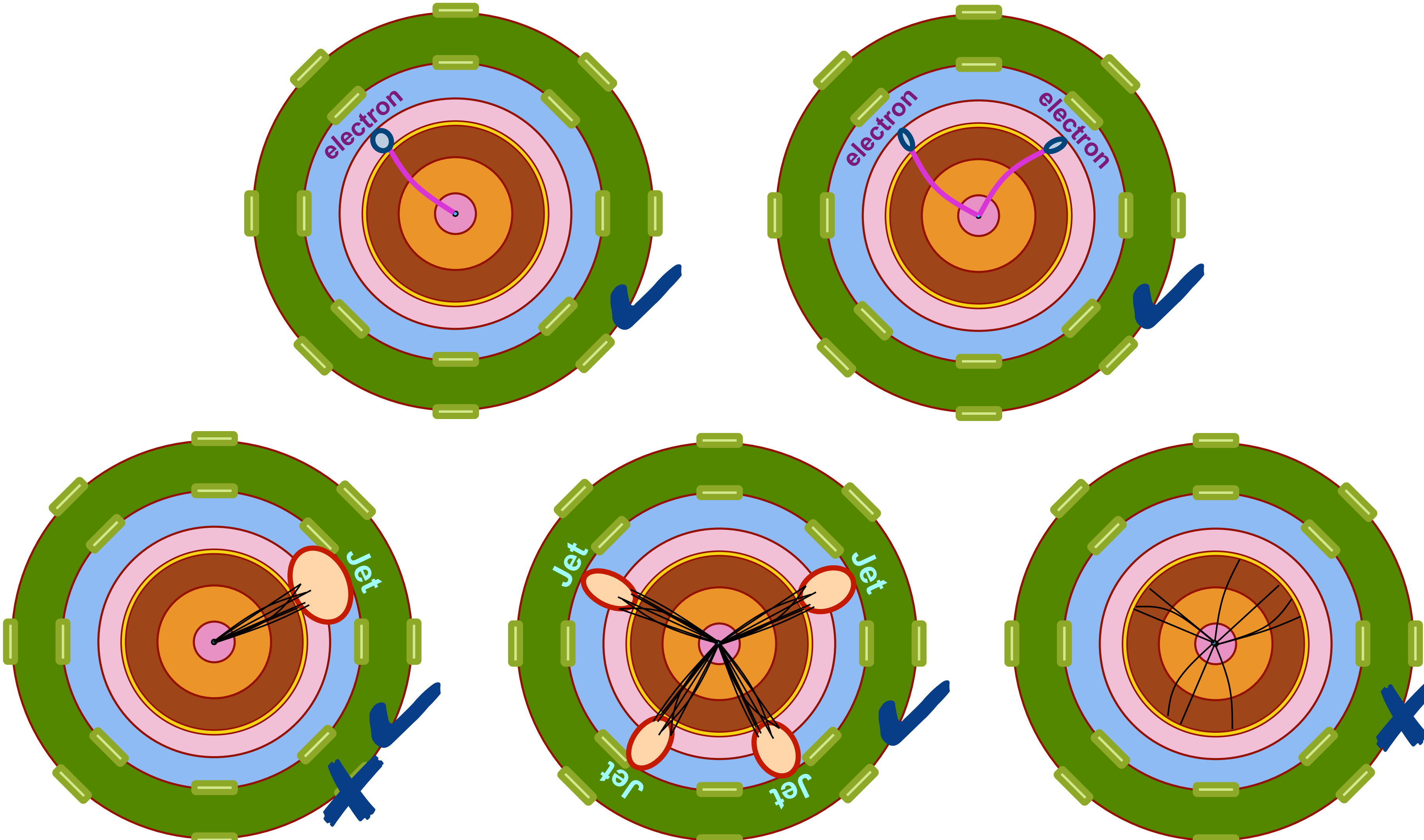


TRIGGERING ON PHYSICS



TRIGGER MENU

About 1.5k HLT selections seeded by about 400 different Level-1 items.

- Primary triggers, usually unprescaled;
- Support and background triggers, usually prescaled;
- Alternative triggers, using different algorithms;
- Backup triggers, using tighter selections;
- Calibration triggers, usually providing partially built events.

Maintained menu items and prescale strategy pretty stable through out 2015 data taking and 2016 data taking, to ensure continuity of trigger selections for physics analyses.

Year	2012		2015		
$\sqrt{s}$	8 TeV		13 TeV		
Peak luminosity	$7.7 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$		$5.0 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$		
	p_{T} threshold [GeV], criteria				
Category	L1	HLT	L1	HLT	Offline
Sing					
Sing					
Sing					
Sing					
Sing					
Sing					
$E_{\mathrm{T}}^{\mathrm{mis}}$					
Diel					
Dim					
Elec					
Diph					
Dita					
Tau,					
Tau, muon	8, 10	20, 15	12i(+jets), 10	25, 14	30, 15
Tau, $E_{\mathrm{T}}^{\mathrm{miss}}$	20, 35	38, 40	20, 45(+jets)	35, 70	40, 180
Four jets	4×15	4×80	3×40	4×85	95
Six jets	4×15	6×45	4×15	6×45	55
Two b-jets	75	35b,145b	100	50b,150b	60
Four(Two) (b-)jets	4×15	2×35b, 2×35	3×25	2×35b, 2×35	45
B-physics (Dimuon)	6, 4	6, 4	6, 4	6, 4	6, 4

TRIGGER MENU

Year	2012		2015		
$\sqrt{s}$	8 TeV		13 TeV		
Peak luminosity	$7.7 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$		$5.0 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$		
	p_{T} threshold [GeV], criteria				
Category	L1	HLT	L1	HLT	Offline
Single electron	18	24i	20	24	25
Single muon	15	24i	15	20i	21
Single photon	20	120	20	120	125
Single tau	40	115	60	80	90
Single jet	75	360	100	360	400
Single *b*-jet	n/a	n/a	100	225	235
$E_{\mathrm{T}}^{\mathrm{miss}}$	40	80	50	70	180
Dielectron	2×10	2×12,loose	2×10	2×12,loose	15
Dimuon	2×10	2×13	2×10	2×10	11
Electron, muon	10, 6	12, 8	15, 10	17, 14	19, 15
Diphoton	16, 12	35, 25	2×15	35, 25	40, 30
Ditau	15i, 11i	27, 18	20i, 12i	35, 25	40, 30
Tau, electron	11i, 14	28i, 18	12i(+jets), 15	25, 17i	30, 19
Tau, muon	8, 10	20, 15	12i(+jets), 10	25, 14	30, 15
Tau, $E_{\mathrm{T}}^{\mathrm{miss}}$	20, 35	38, 40	20, 45(+jets)	35, 70	40, 180
Four jets	4×15	4×80	3×40	4×85	95
Six jets	4×15	6×45	4×15	6×45	55
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B-physics (Dimuon)	6, 4	6, 4	6, 4	6, 4	6, 4

TRIGGER MENU

Year	2012		2015 2016		
$\sqrt{s}$	8 TeV		13 TeV		
Peak luminosity	$7.7 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$		$5.0 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$ $1.2\times10^{34}\,\text{cm}^{-2}\text{s}^{-1}$		
	p_{T} threshold [GeV], criteria				
Category	L1	HLT	L1	HLT	Offline
Single electron	18	24i	20 22i	24 26i	25 27i
Single muon	15	24i	15 20	20i 26i	21 27i
Single photon	20	120	20 22i	120 140	125 145
Single tau	40	115	60	80 160	90 170
Single jet	75	360	100	360 380	400 420
Single b-jet	n/a	n/a	100	225	235
$E_{\text{T}}^{\text{miss}}$	40	80	50	70 110	180 200
Dielectron	2×10	2×12,loose	2×10 15	2×12,loose 17	15 18
Dimuon	2×10	2×13	2×10	2×10 14	11 15
Electron, muon	10, 6	12, 8	15, 10	17, 14	19, 15
Diphoton	16, 12	35, 25	2×15	35, 25	40, 30
Ditau	15i, 11i	27, 18	20i, 12i	35, 25	40, 30
Tau, electron	11i, 14	28i, 18	12i(+jets), 15	25, 17i	30, 19
Tau, muon	8, 10	20, 15	12i(+jets), 10	25, 14	30, 15
Tau, $E_{\text{T}}^{\text{miss}}$	20, 35	38, 40	20, 45(+jets)	35, 70	40, 180
Four jets	4×15	4×80	3×40	4×85 100	95 110
Six jets	4×15	6×45	4×15	6×45 w/ η cuts	55
Two b-jets	75	35b,145b	100	50b,150b	60
Four(Two) (b-)jets	4×15	2×35b, 2×35	3×25	2×35b, 2×35	45
B-physics (Dimuon)	6, 4	6, 4	6, 4	6, 4 6, 6	6, 4

TRIGGER MENU

Category	2012 L1	2012 HLT	2015 **2016** L1	2015 **2016** HLT	2015 **2016** Offline	(Examples) HLT Rate (Hz)
Year	2012		2015 **2016**			
$\sqrt{s}$	8 TeV		13 TeV			
Peak luminosity	$7.7 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$		$5.0 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ **$1.2\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**			
	p_{T} threshold [GeV], criteria					
Category	L1	HLT	L1	HLT	Offline	
Single electron	18	24i	20 22i	24 26i	25 27i	130 130
Single muon	15	24i	15 20	20i 26i	21 27i	130 130
Single photon	20	120	20 22i	120 140	125 145	
Single tau	40	115	60	80 160	90 170	
Single jet	75	360	100	360 380	400 420	
Single *b*-jet	n/a	n/a	100	225	235	
$E_{\mathrm{T}}^{\mathrm{miss}}$	40	80	50	70 110	180 200	55 230
Dielectron	2×10	2×12,loose	2×10 15	2×12,loose 17	15 18	
Dimuon	2×10	2×13	2×10	2×10 14	11 15	
Electron, muon	10, 6	12, 8	15, 10	17, 14	19, 15	
Diphoton	16, 12	35, 25	2×15	35, 25	40, 30	
Ditau	15i, 11i	27, 18	20i, 12i	35, 25	40, 30	
Tau, electron	11i, 14	28i, 18	12i(+jets), 15	25, 17i	30, 19	
Tau, muon	8, 10	20, 15	12i(+jets), 10	25, 14	30, 15	
Tau, $E_{\mathrm{T}}^{\mathrm{miss}}$	20, 35	38, 40	20, 45(+jets)	35, 70	40, 180	
Four jets	4×15	4×80	3×40	4×85 100	95 110	
Six jets	4×15	6×45	4×15	6×45 w/ η cuts	55	12 18
Two *b*-jets	75	35b,145b	100	50b,150b	60	
Four(Two) (*b*-)jets	4×15	2×35b, 2×35	3×25	2×35b, 2×35	45	
B-physics (Dimuon)	6, 4	6, 4	6, 4	6, 4 6, 6	6, 4	

TRIGGER MENU

Year	2012		2015 2016			(Examples)
$\sqrt{s}$	8 TeV		13 TeV			HLT Rate
Peak luminosity	$7.7 \times 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$		$5.0 \times 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ $1.2\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$			(Hz)
	p_{T} threshold [GeV], criteria					
Category	L1	HLT	L1	HLT	Offline	
Single electron	18	24i	20 22i	24 26i	25 27i	130 130
Single muon	15	24i	15 20	20i 26i	21 27i	130 130
Single photon	20	120	20 22i	120 140	125 145	
Single tau	40	115	60	80 160	90 170	
Single jet	75	360	100	360 380	400 420	
Single b-jet	n/a	n/a	100	225	235	
$E_{\mathrm{T}}^{\mathrm{miss}}$	40	80	50	70 110	180 200	55 230
Dielectron	2×10	2×12,loose	2×10 15	2×12,loose 17	15 18	
Dimuon	2×10	2×13	2×10	2×10 14	11 15	
Electron, muon	10, 6	12, 8	15, 10	17, 14	19, 15	
Diphoton	16, 12	35, 25	2×15	35, 25	40, 30	
Ditau	15i, 11i	27, 18	20i, 12i	35, 25	40, 30	
Tau, electron	11i, 14	28i, 18	12i(+jets), 15	25, 17i	30, 19	
Tau, muon	8, 10	20, 15	12i(+jets), 10	25, 14	30, 15	
Tau, $E_{\mathrm{T}}^{\mathrm{miss}}$	20, 35	38, 40	20, 45(+jets)	35, 70	40, 180	
Four jets	4×15	4×80	3×40	4×85 100	95 110	
Six jets	4×15	6×45	4×15	6×45 w/ η cuts	55	12 18
Two b-jets	75	35b,145b	100	50b,150b	60	
Four(Two) (b-)jets	4×15	2×35b, 2×35	3×25	2×35b, 2×35	45	
B-physics (Dimuon)	6, 4	6, 4	6, 4	6, 4 6, 6	6, 4	

TRIGGER MENU

Year	2012		2015 **2016**			(Examples) HLT Rate (Hz)
$\sqrt{s}$	8 TeV		13 TeV			
Peak luminosity	$7.7 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$		$5.0 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ **$1.2\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**			
	p_{T} threshold [GeV], criteria					
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Single photon	20	120	20 22i	120 140	125 145	
Single tau	40	115	60	80 160	90 170	
Single jet	75	360	100	360 380	400 420	
Single b-jet	n/a	n/a	100	225	235	
$E_{\mathrm{T}}^{\mathrm{miss}}$	40	80	50	70 110	180 200	55 230
Dielectron	2×10	2×12,loose	2×10 15	2×12,loose 17	15 18	
Dimuon	2×10	2×13	2×10	2×10 14	11 15	
Electron, muon	10, 6	12, 8	15, 10	17, 14	19, 15	
Diphoton	16, 12	35, 25	2×15	35, 25	40, 30	
Ditau	15i, 11i	27, 18	20i, 12i	35, 25	40, 30	
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Tau, muon	8, 10	20, 15	12i(+jets), 10	25, 14	30, 15	
Tau, $E_{\mathrm{T}}^{\mathrm{miss}}$	20, 35	38, 40	20, 45(+jets)	35, 70	40, 180	
Four jets	4×15	4×80	3×40	4×85 100	95 110	
Six jets	4×15	6×45	4×15	6×45 w/ η cuts	55	12 18
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Four(Two) (b-)jets	4×15	2×35b, 2×35	3×25	2×35b, 2×35	45	
B-physics (Dimuon)	6, 4	6, 4	6, 4	6, 4 6, 6	6, 4	

TRIGGER MENU

Year	2012		2015 **2016**			(Examples)
$\sqrt{s}$	8 TeV		13 TeV			HLT Rate
Peak luminosity	$7.7 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$		$5.0 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ $1.2{\times}10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$			(Hz)
	p_T threshold [GeV], criteria					
Category	L1	HLT	L1	HLT	Offline	
Single electron	18	24i	20 22i	24 26i	25 27i	130 130
Single muon	15	24i	15 20	20i 26i	21 27i	130 130
Single photon	20	120	20 22i	120 140	125 145	
Single tau	40	115	60	80 160	90 170	
Single jet	75	360	100	360 380	400 420	
Single b-jet						
$E_\mathrm{T}^\mathrm{miss}$						
Dielectron						
Dimuon						
Electron, muon						
Diphoton						
Ditau						
Tau, electron						
Tau, muon						
Tau, $E_\mathrm{T}^\mathrm{miss}$						
Four jets						
Six jets	4×15	6×45	4×15	6×45 w/ η cuts	55	12 18
Two b-jets	75	35b,145b	100	50b,150b	60	
Four(Two) (b-)jets	4×15	2×35b, 2×35	3×25	2×35b, 2×35	45	
B-physics (Dimuon)	6, 4	6, 4	6, 4	6, 4 6, 6	6, 4	

Trigger menu made generic enough to cover multiple analyses; dedicated triggers don't necessarily save rate, they add many times unique rate.
Still, there are many "dedicated" and highly selecting triggers
- E.g. soft lepton & jet & MET for highly compressed RPC SUSY.

Common reminder:
- the trigger is the first step in an analysis selection and needs to be well thought of!

GETTING MORE PHYSICS OUT

A flash-back to 2012; the SUSY paradigm.

Dedicated SUSY triggers in 2012

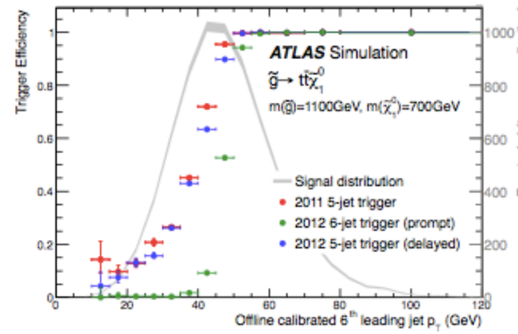
Selection	EF trigger election	EF Avrg Rate (Hz) $L_{\rm avrg}$=5e33/cm^{2}s
Single jet & E_T^{miss}	Jet p_T >145 GeV & EF-only E_T^{miss} >70 GeV	8
Single jet & E_T^{miss} & $\Delta\phi$(jet,E_T^{miss})	Jet p_T >80 GeV & E_T^{miss} >70 GeV & $\Delta\phi$ >1.0	8
H_T	>700 GeV	8
Single electron & E_T^{miss}	Electron p_T >25 GeV & EF-only E_T^{miss} >35 GeV	26
Single muon & single jet & E_T^{miss}	Muon p_T >24 GeV & jet p_T >65 GeV & EF-only E_T^{miss} >40 GeV	15
Single photon & E_T^{miss}	Photon p_T >40 GeV & EF-only E_T^{miss} >60 GeV	5
3 electrons	p_T > 18, 2×7 GeV	<1
3 muons	p_T > 18, 2×4 GeV	<1
3 electrons & muons	p_T > 2×7 (e), 6 (μ) GeV	<1
	p_T > 7 (e), 2×6 (μ) GeV	<1

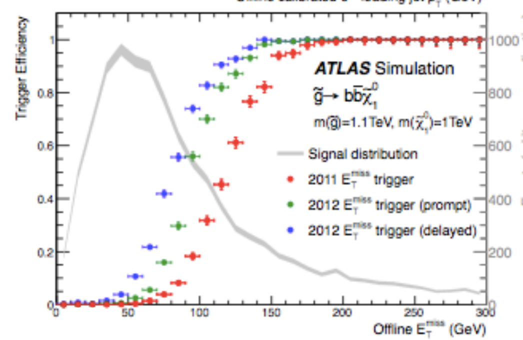
- The $\Delta\phi$ selection is applied at EF, between the E_T^{miss} and the two leading jets >45 GeV.
- H_T is defined as the sum of jets above 45 GeV, and is calculated in events that already satisfied the requirement of a leading jet >145 GeV.
- For the muon & jet & E_T^{miss} trigger, two versions are available, one without muon corrections in the E_T^{miss} and one with (this latter was introduce during the data taking).

SUSY delayed stream

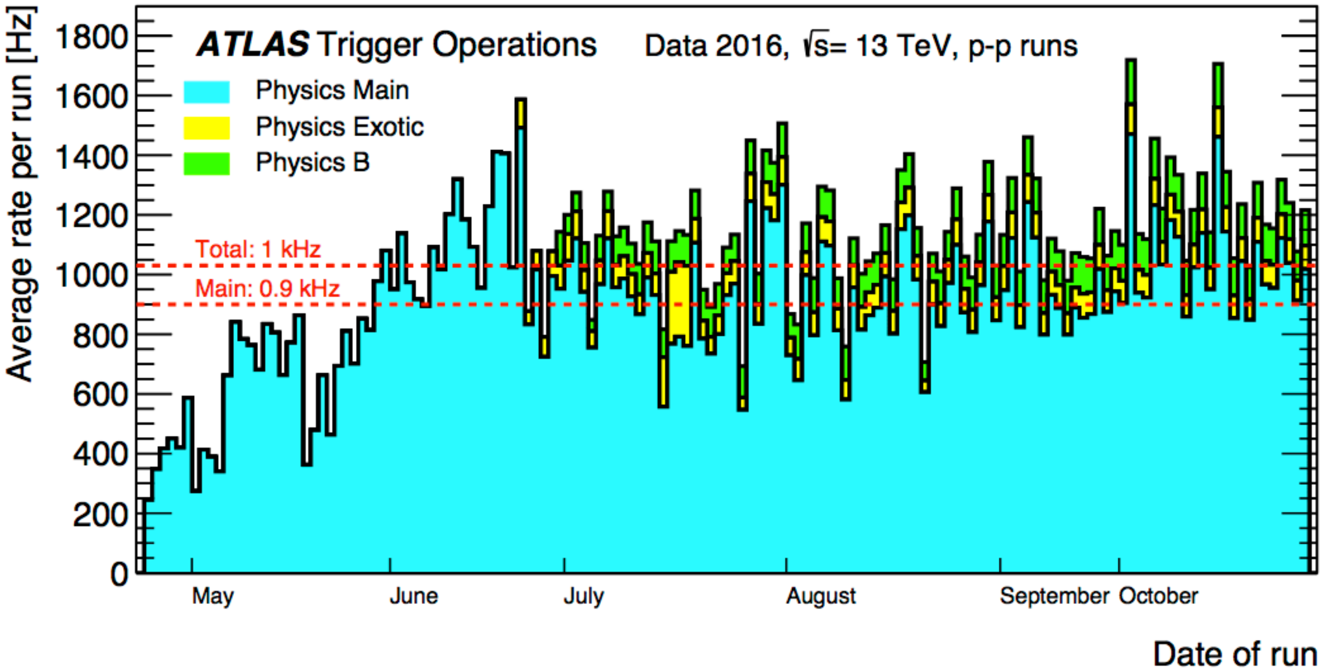
⇒ Data not prompty reconstructed

Signature	EF trigger Selection Prompt	EF trigger Selection Delayed
Multi-jets	4×80 GeV	4×65 GeV
	5×55 GeV	5×45 GeV
	6×45 GeV	
H_T	700 GeV	500 GeV
Jet ($R = 1.0$)	460 GeV	360 GeV
E_T^{miss}	80 GeV	60 GeV





DEDICATED STREAMING IN 2016



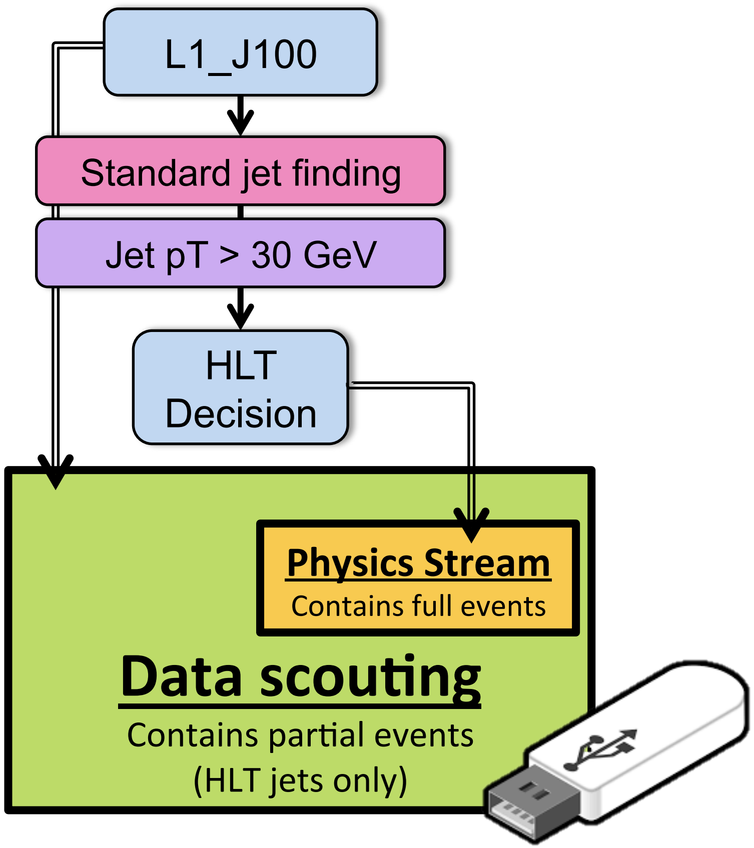
Message:

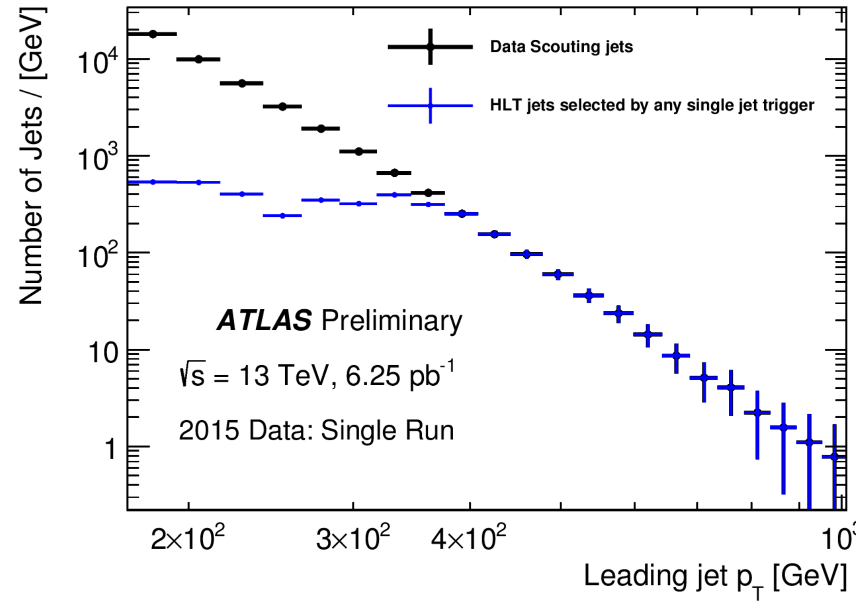
a lot of flexibility is available at the trigger if there is a good use case for it!

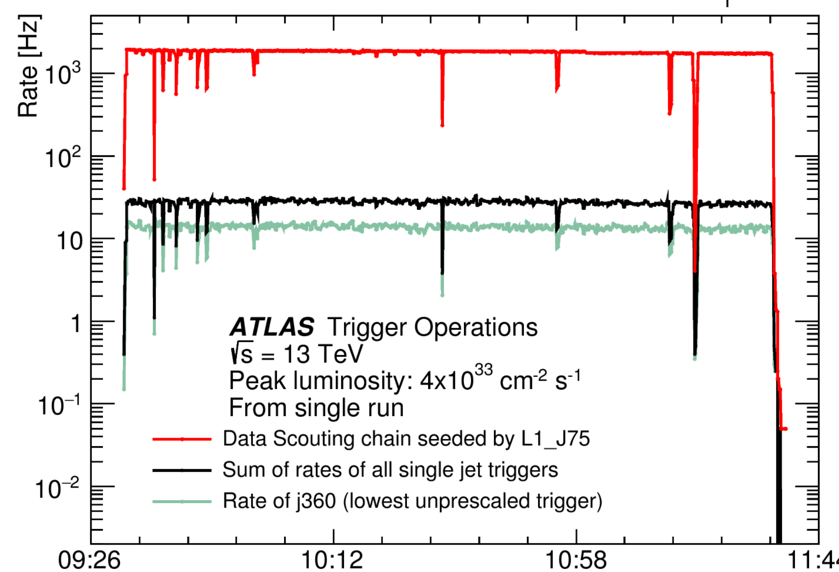
DATA "SCOUTING" aka "Trigger-Level Analysis" (TLA)

Make available higher rate of jetty events by skipping the full detector information

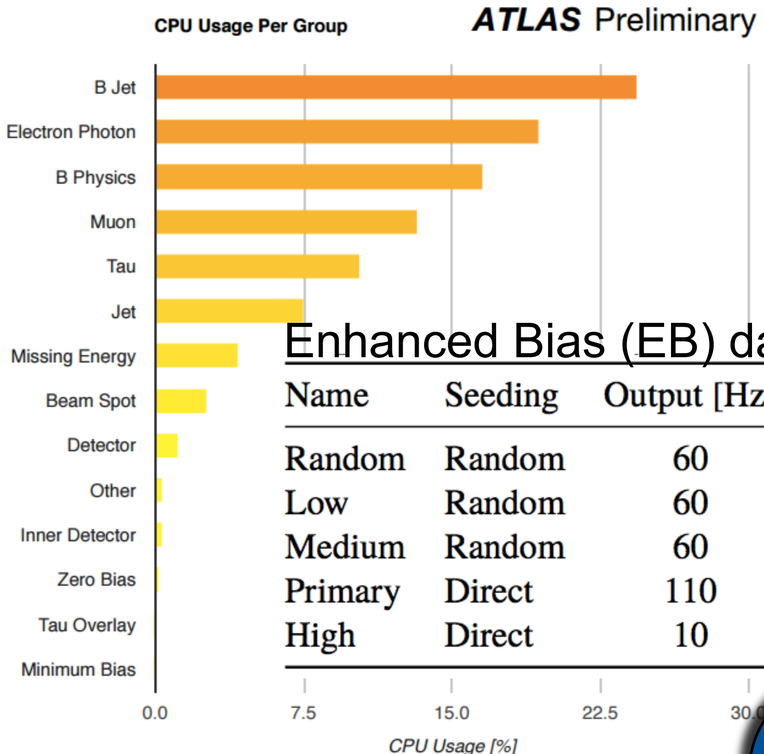
- **save HLT jets only.**
- <5% of full event size. *1kHz of such partial events corresponds to < 50Hz of full events.*





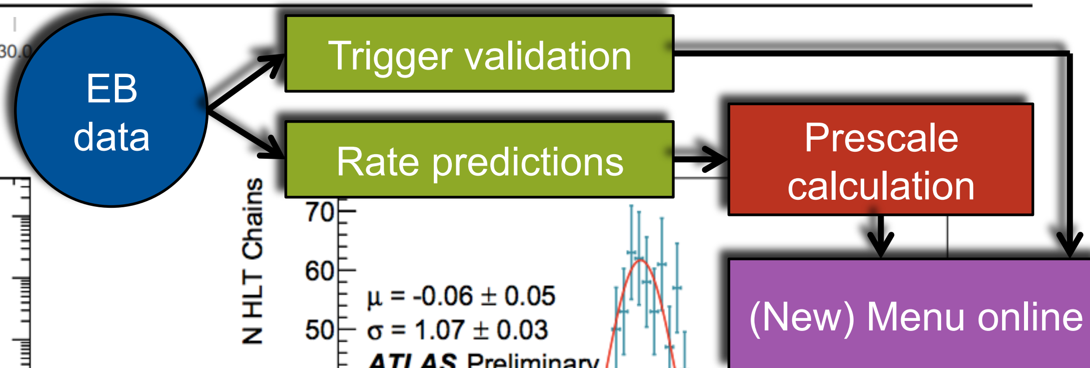


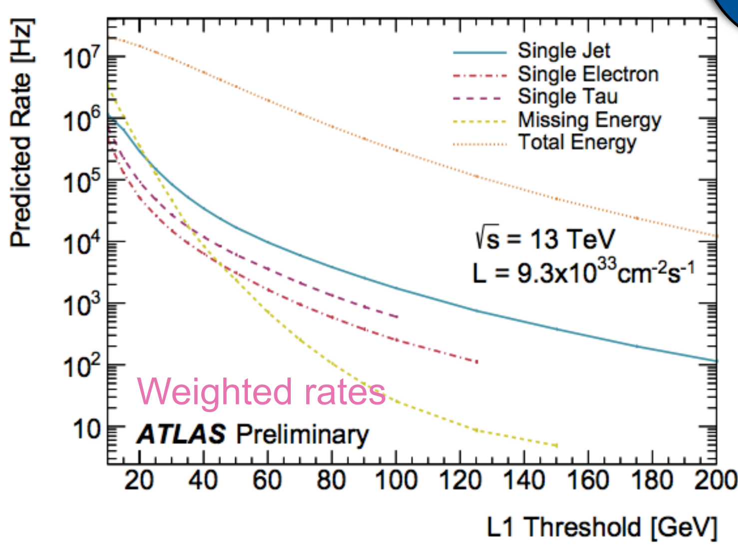
PREDICTING MENU RESOURCES

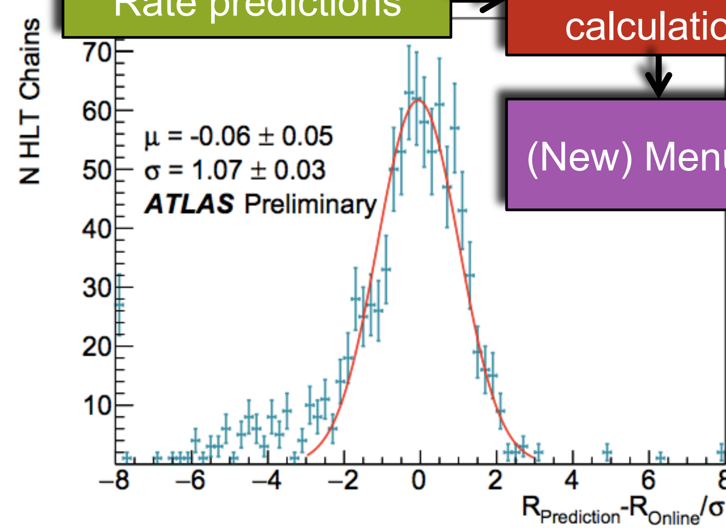


Enhanced Bias (EB) dataset

Name	Seeding	Output [Hz]	Input Range [kHz]	E.g. Items	E.g. HLT Prescale
Random	Random	60	> 500	Random	Fixed
Low	Random	60	50–500	MU6, JET15, 2×EM7	4
Medium	Random	60	20–50	TAU30, EM18, 3×JET15	1
Primary	Direct	110	0.1–20	TAU60, MU20, XE50	350
High	Direct	10	< 0.1	JET400, XE80	4







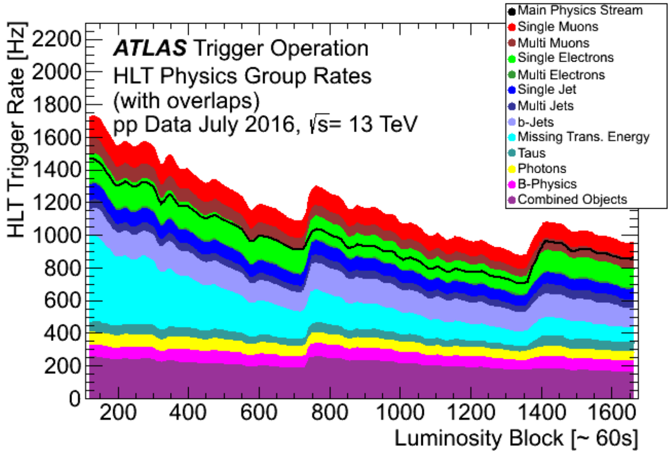
PRESCALING STRATEGY

Prescale changes ensure no bandwidth goes wasted and special requirements for datasets get collected.

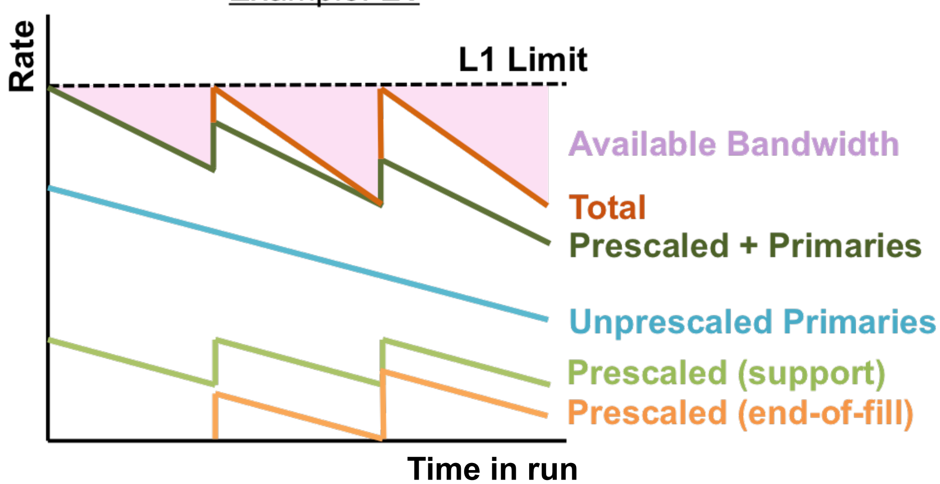
Important difference between L1 and HLT:

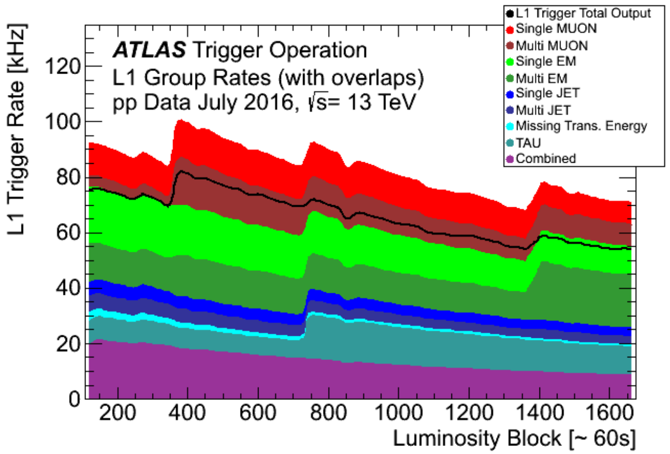
- At L1 we need to watch out for peak rates.
- At the HLT we need to watch out for average rates (primarily).

Usual strategy: single primaries through out a data period; end-of-fill primaries upon request only.



Example: **L1**





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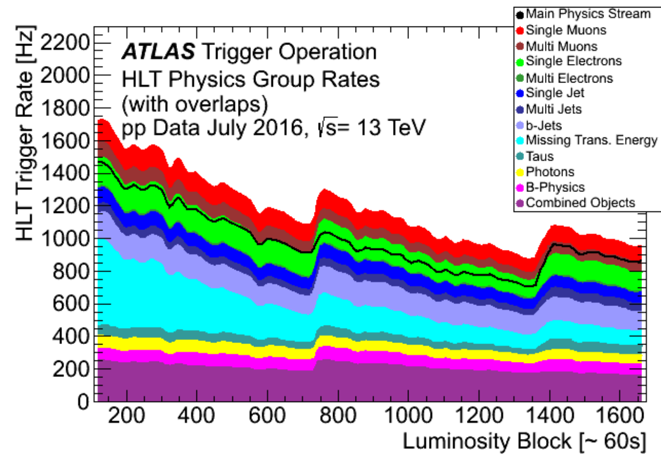
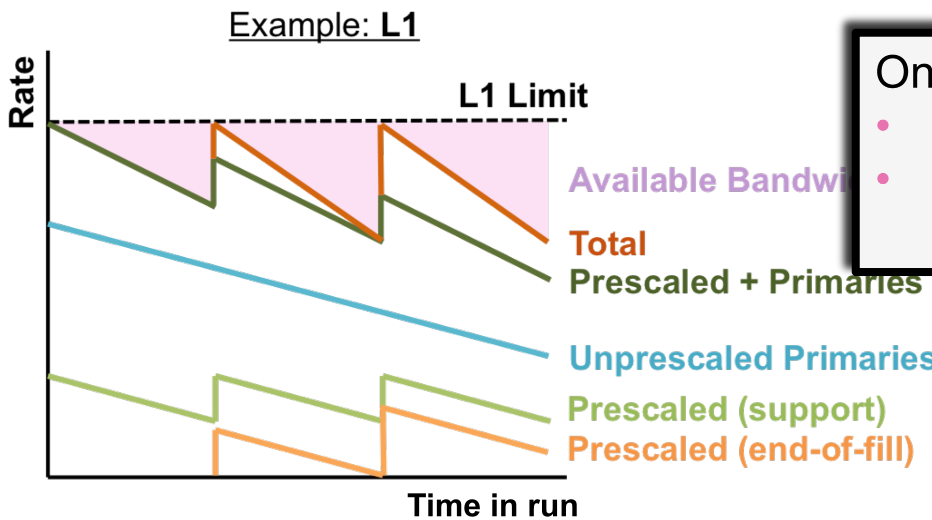
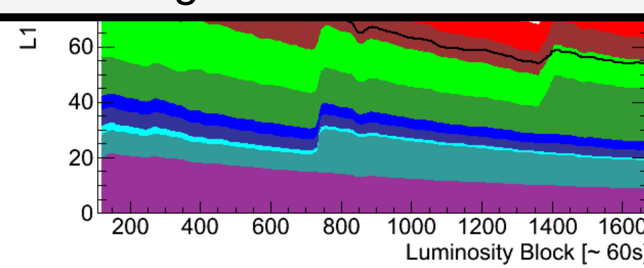




On top of standard operations:

- Special prescale sets for special runs.
- "Emergency" prescale sets addressing special running conditions..



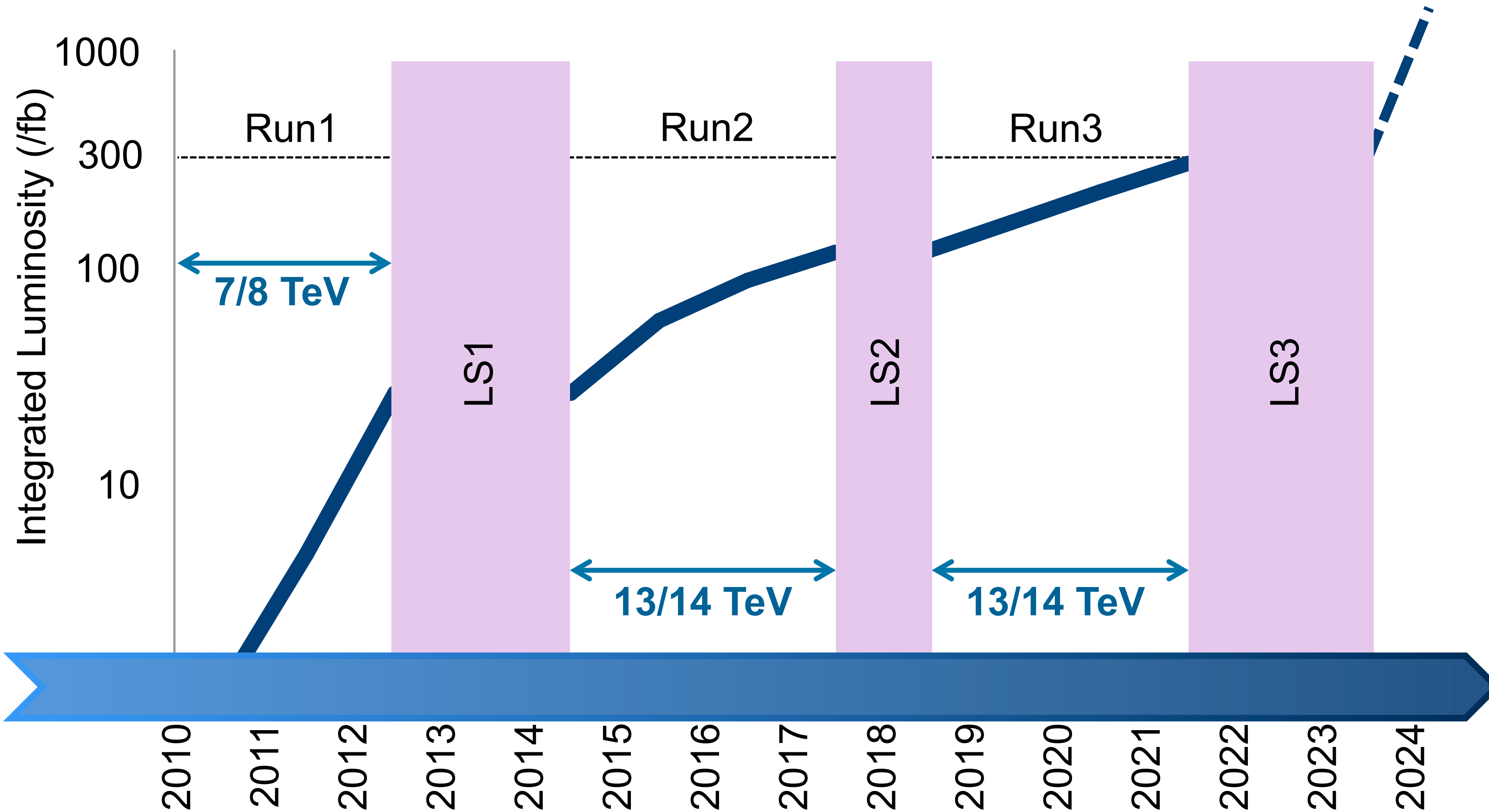
WHAT TO EXPECT IN 2017

Year	Peak Lumi	Peak μ	L1 output	HLT output
2016	1.4e34	~40	90kHz peak	1.5kHz peak, 1kHz avg
2017	2e34	~60	100kHz peak	

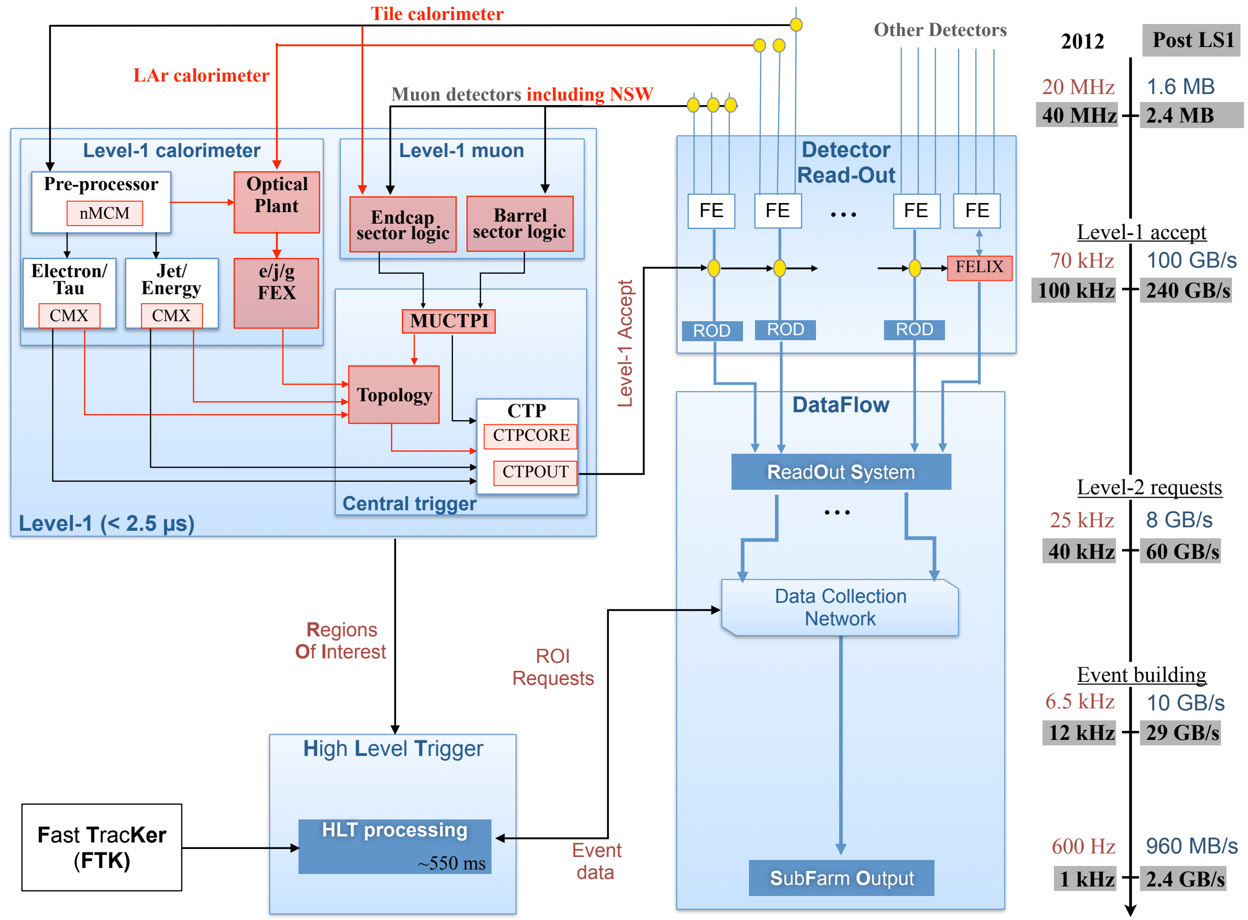
- **Generally, tighter selections at higher luminosity if rate reduction is necessary.**
  - Generic signatures are most favorable to keep unchanged.
- **Dedicated low-rate and analysis-specific triggers to be added depending on impact.**
  - E.g. triggers for LLPs (is an HLT displaced vertex trigger possible?)
- **Now that it is commissioned, make better use of L1Topo!**
  - E.g. late muons, fatter or narrower jets, $\Delta\varphi(\text{jet},ME_T)$
- **Commission FTK to use in physics asap!**
- **…and figure out how to best cover difficult or uncovered phase space.**
  - E.g. compressed SUSY phase-space, RPV SUSY.

FURTHER IN THE FUTURE…

RUN1, RUN2 AND BEYOND



PHASE I

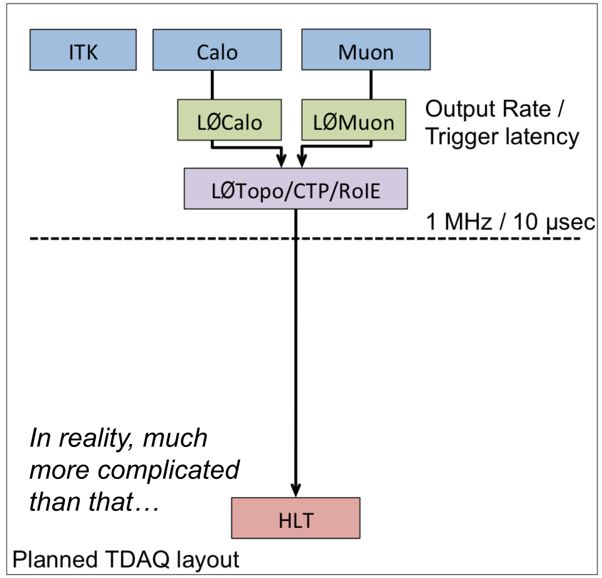


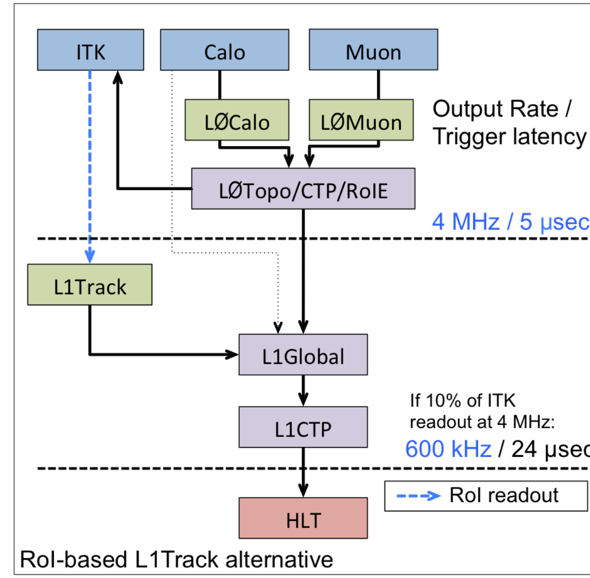
- Full-functional prototypes are being built and tested. First system tests started.
- Aim to complete pre-production by Q3-2017 & complete production by Q3-2018.

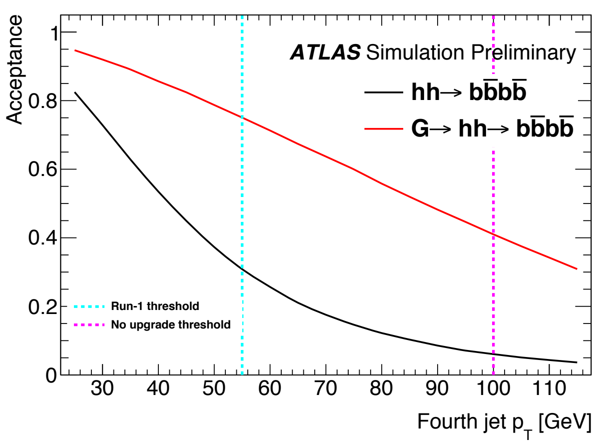
- Extremely important upgrade: software upgrade for the whole of ATLAS. The HLT is obviously following with major changes. More robust code, closer online to offline.

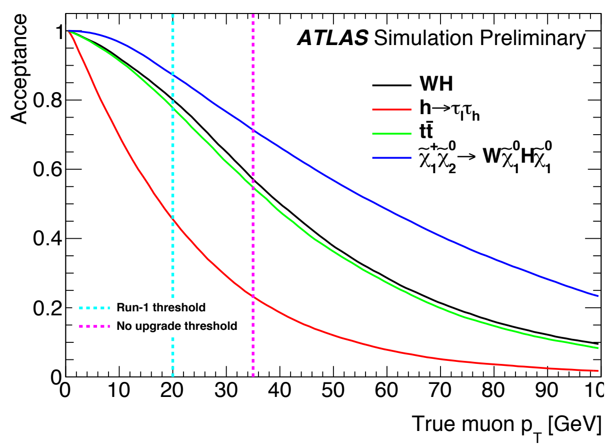
PHASE II

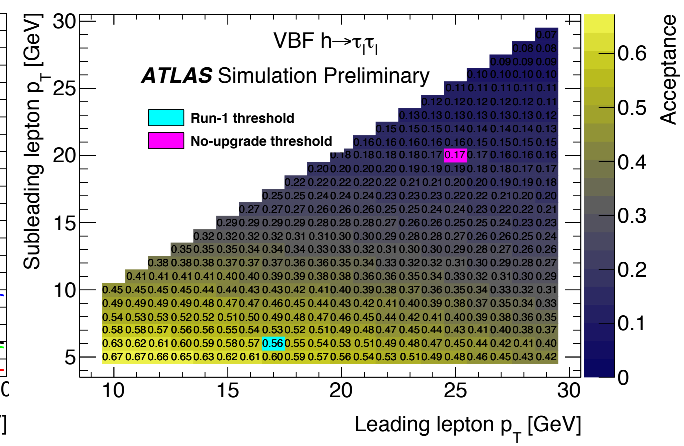
- Very active area with lots of new ideas and developments.
- Two architectures being discussed.
- Huge potential for improvements in otherwise compromised phase-space.











PHASE II

- Very active area with lots of new ideas and developments.
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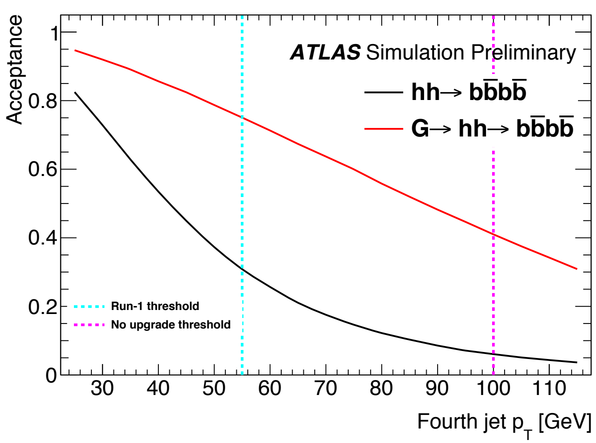
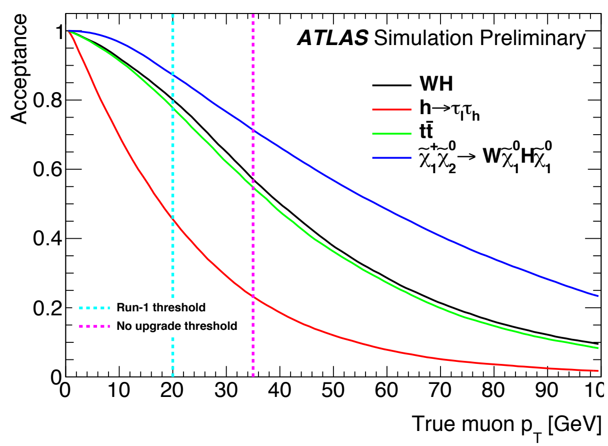
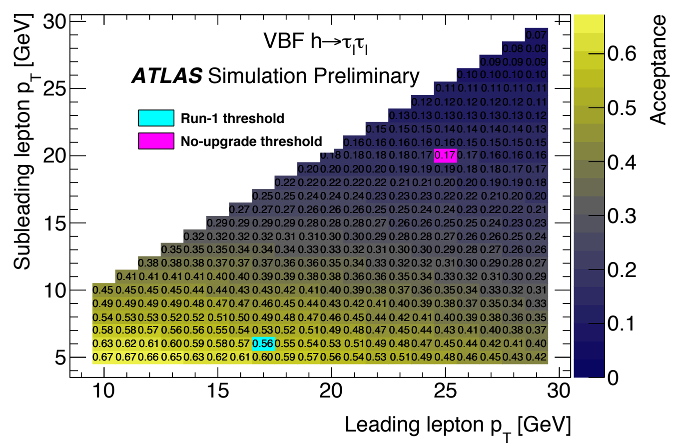
Item	Run 1 Offline p_T Threshold [GeV] $L = 8 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Run 2 Offline p_T Threshold [GeV] $L = 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Run 3 Offline p_T Threshold [GeV] $L = 3 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Run 4 Offline p_T Threshold [GeV] $L = 7.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
isolated single e	25	32	32	22
forward e	N/A	N/A	N/A	35
single γ	120	150	120	120
single μ	25	27	25	20
di-γ	25	35,25	25	25
di-e	17	20	19	15
di-μ	12	15	12	11
$e-\mu$	17,6	20,13	17,12	15
single τ	100	180	180	150
di-τ	40,30	40,30 + jet>50	40,40 + jet>50	40,30
single jet	200	200	200	180
large-R jet				375
four-jet	55	70	60	75
H_T			400	500
E_T^{miss}	120	200	200	200
jet + E_T^{miss}	150,120	150,180	150,150	140,125

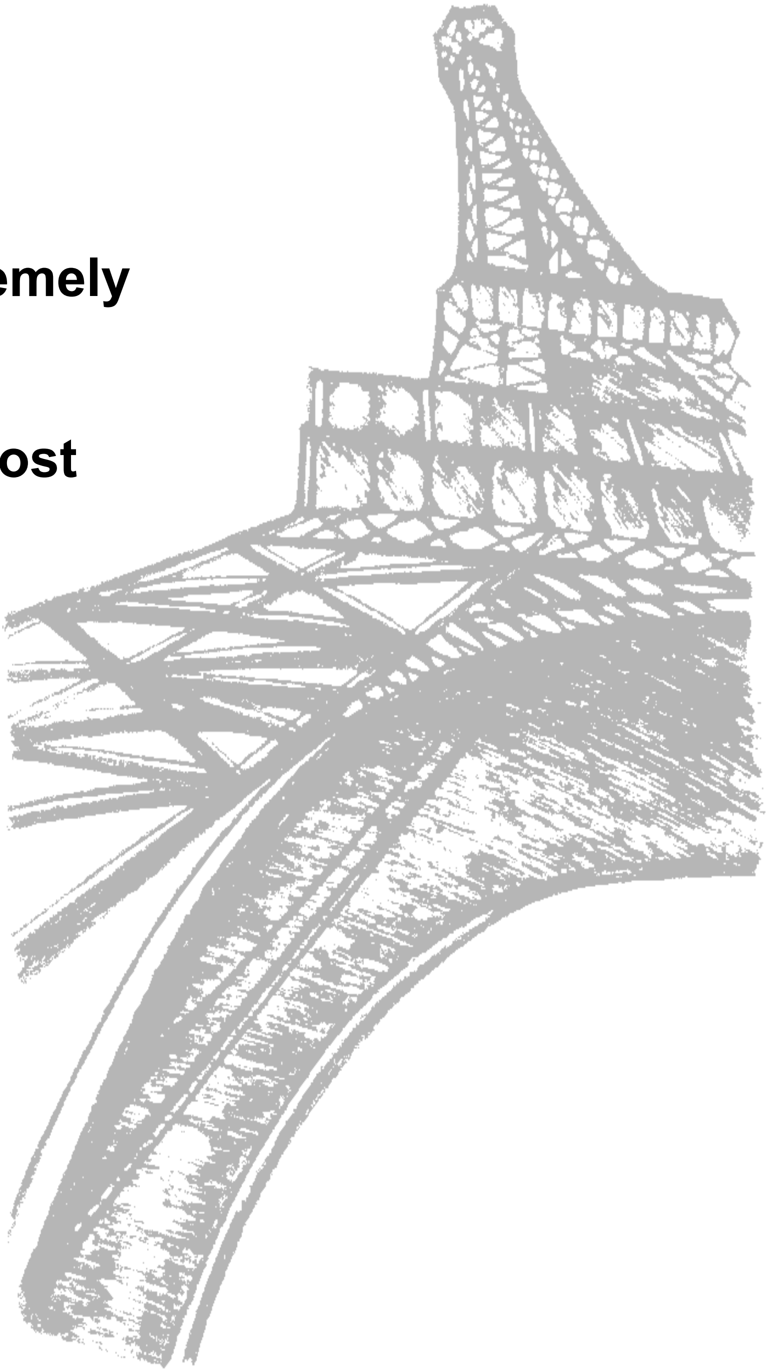






OUTLOOK

- The ATLAS trigger system is an extremely complicated, yet very robust system.
- Events that are not triggered on are lost forever.
- Improving trigger selections directly improves physics potential.
- Huge potential for improvements in the rest of run2.
- Exciting prospects for the future, with room for new ideas and R&D.
- Thrilling times ahead in the trigger community!



EXTRAS

EFFICIENCY MEASUREMENTS

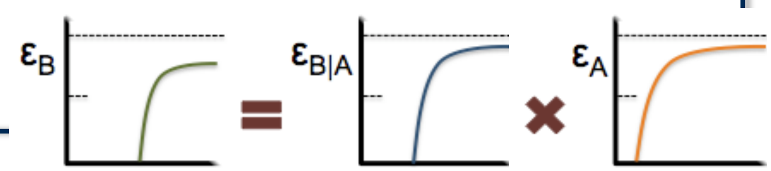
Tag and Probe

Using a single-object inclusive trigger, select one object triggered online and study the trigger response of the second object, not used in the online selection.

- e.g. $Z \rightarrow \tau\tau$ events

Bootstrap method

- The efficiency, ε_B, of a trigger chain B, with threshold higher than a chain A, can be determined in a sample triggered by A (provided that ε_A is measurable): $\varepsilon_B = \varepsilon_{A|B} \times \varepsilon_A$.
- e.g. B: tau50_loose & A: tau16_loose



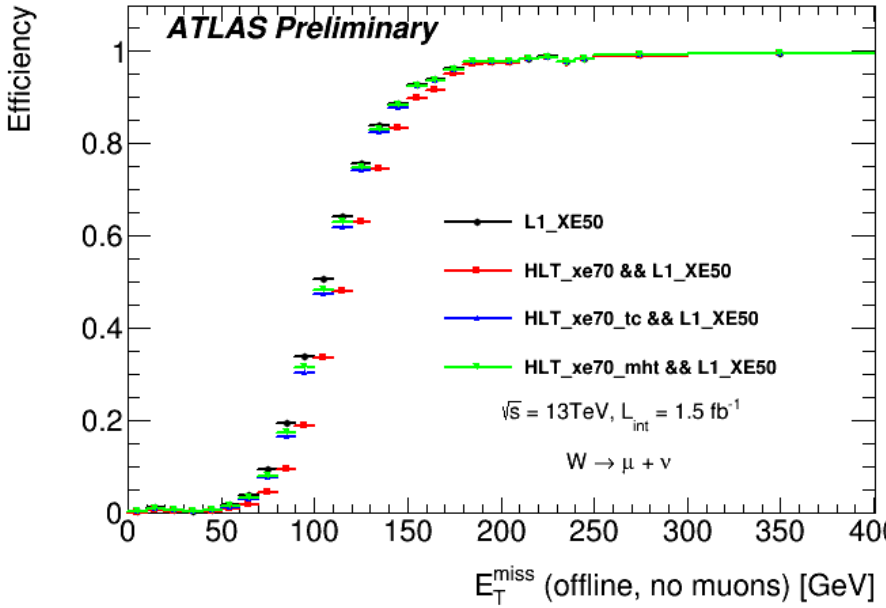
JETS – CALIBRATION

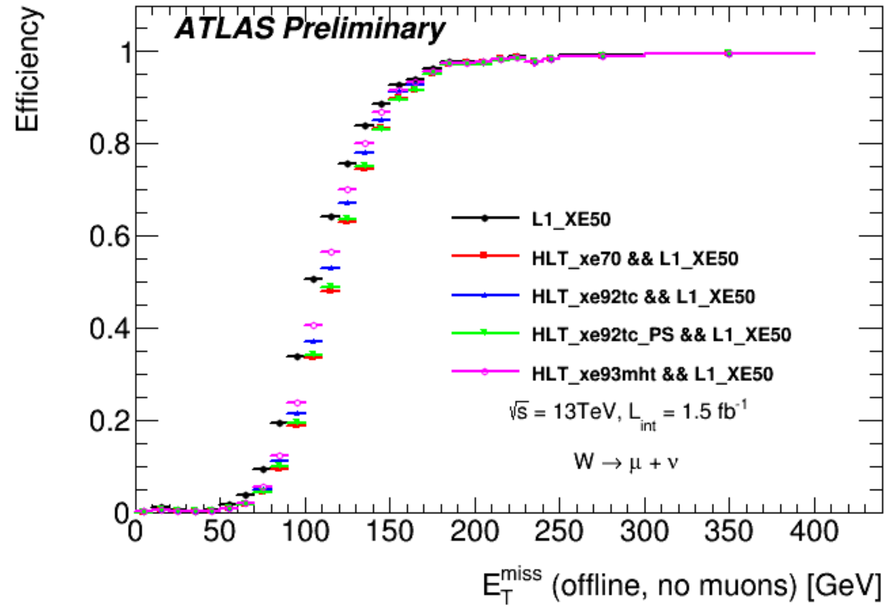
- Different calibrations are one of the main online/offline differences
  - Harmonizing calibration improves HLT/offline resolution
  - Large gains when adding more steps for 2017 (next slide)

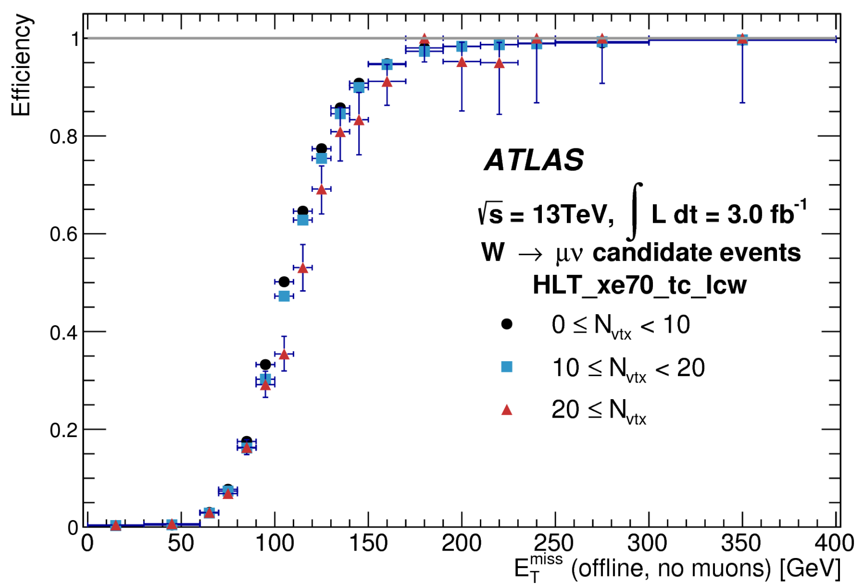
Offline calibration $R = 0.4$ jets	Trigger calibration 2016	2017	Comments
EM/LC topoclusters	✓	✓	
Origin correction	✗	✗	No tracks to find PV0
Jet area subtraction	✓	✓	
Residual pileup offset	✗	✗	No tracks to count PVs
etaJES (MC15)	MC12	MC15	
GSC (calo)	✗	✓	
GSC (track)	✗	✗✓	Active in some 2017 triggers
GSC (punch-through)	✗	✗	Negligible trigger impact
In situ calibration	✗	✓	

(from Steven Schramm)

MISSING E_T – MORE PLOTS







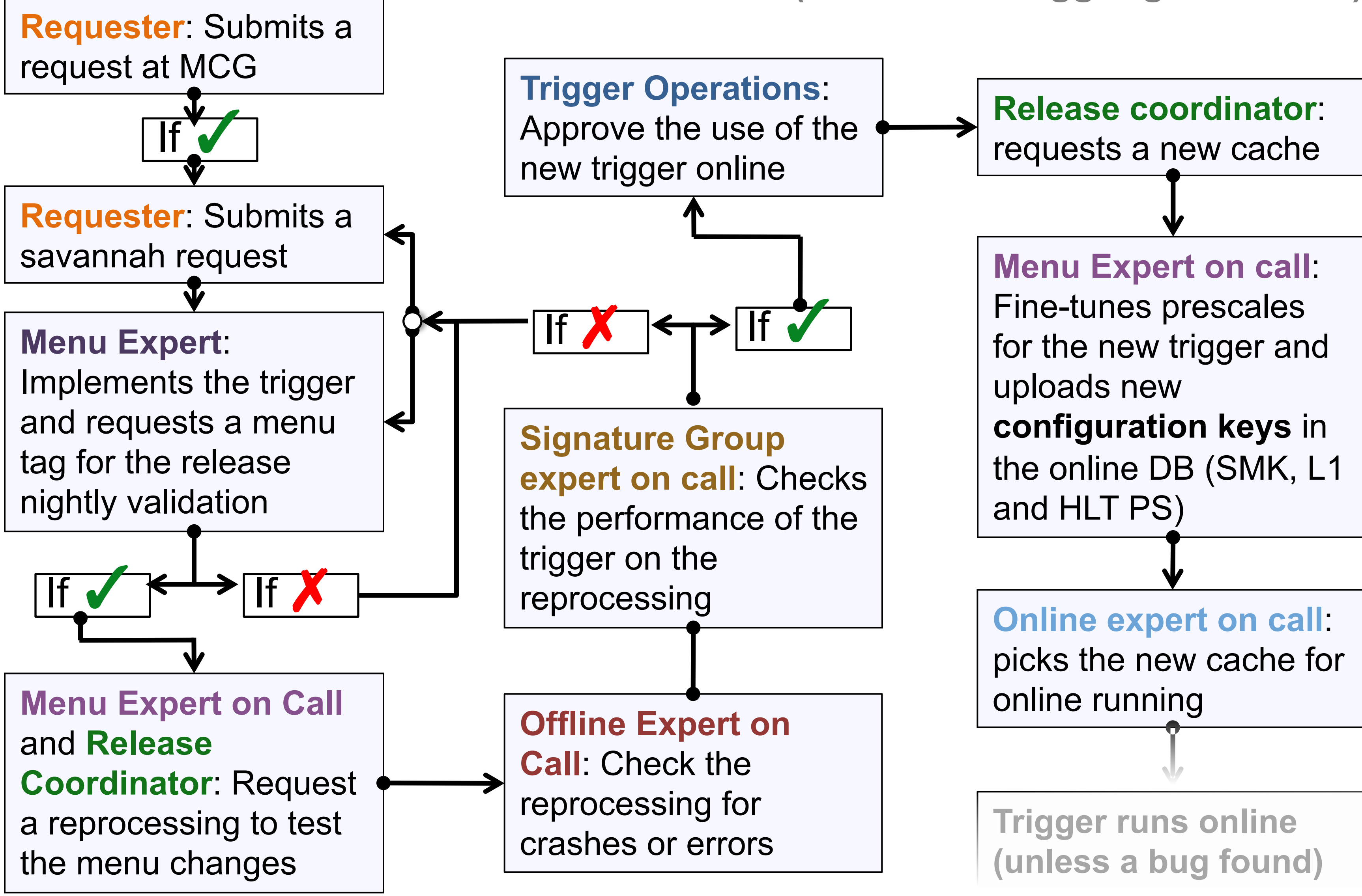
TRIGGER MENU - COMPARISON

Trigger	Typical offline selection	Trigger Selection: Level-1 (GeV)	Trigger Selection: HLT (GeV)	Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
				$L = 5 \times 10^{33}$ cm^{-2}s^{-1}	
Single leptons	Single iso μ, $p_T > 21$ GeV	15	20	7	130
	Single e, $p_T > 25$ GeV	20	24	18	139
	Single μ, $p_T > 42$ GeV	20	40	5	33
	Single τ, $p_T > 90$ GeV	60	80	2	41
Two leptons	Two μ's, each $p_T > 11$ GeV	2×10	2×10	0.8	19
	Two μ's, $p_T > 19, 10$ GeV	15	18, 8	7	18
	Two loose e's, each $p_T > 15$ GeV	2×10	2×12	10	5
	One e & one μ, $p_T > 10, 26$ GeV	20 (μ)	7, 24	5	1
	One loose e & one μ, $p_T > 19, 15$ GeV	15, 10	17, 14	0.4	2
	Two τ's, $p_T > 40, 30$ GeV	20, 12	35, 25	2	22
	One τ, one μ, $p_T > 30, 15$ GeV	12, 10 (+jets)	25, 14	0.5	10
	One τ, one e, $p_T > 30, 19$ GeV	12, 15 (+jets)	25, 17	1	3.9
Three leptons	Three loose e's, $p_T > 19, 11, 11$ GeV	15, 2×7	17, 2×9	3	< 0.1
	Three μ's, each $p_T > 8$ GeV	3×6	3×6	< 0.1	4
	Three μ's, $p_T > 19, 2 \times 6$ GeV	15	18, 2×4	7	2
	Two μ's & one e, $p_T > 2 \times 11, 14$ GeV	2×10 (μ's)	2×10, 12	0.8	0.2
	Two loose e's & one μ, $p_T > 2 \times 11, 11$ GeV	2×8, 10	2×12, 10	0.3	< 0.1
One photon	one γ, $p_T > 125$ GeV	22	120	8	20
Two photons	Two loose γ's, $p_T > 40, 30$ GeV	2×15	35, 25	1.5	12
	Two tight γ's, $p_T > 25, 25$ GeV	2×15	2×20	1.5	7
Single jet	Jet ($R = 0.4$), $p_T > 400$ GeV	100	360	0.9	18
	Jet ($R = 1.0$), $p_T > 400$ GeV	100	360	0.9	23
E_T^{miss}	$E_T^{miss} > 180$ GeV	50	70	0.7	55
Multi-jets	Four jets, each $p_T > 95$ GeV	3×40	4×85	0.3	20
	Five jets, each $p_T > 70$ GeV	4×20	5×60	0.4	15
	Six jets, each $p_T > 55$ GeV	4×15	6×45	1.0	12
$b-$jets	One loose b, $p_T > 235$ GeV	100	225	0.9	35
	Two medium b's, $p_T > 160, 60$ GeV	100	150, 50	0.9	9
	One b & three jets, each $p_T > 75$ GeV	3×25	4×65	0.9	11
	Two b & two jets, each $p_T > 45$ GeV	3×25	4×35	0.9	9
$b-$physics	Two μ's, $p_T > 6, 4$ GeV plus dedicated b-physics selections	6, 4	6, 4	8	52
Total				70	1400

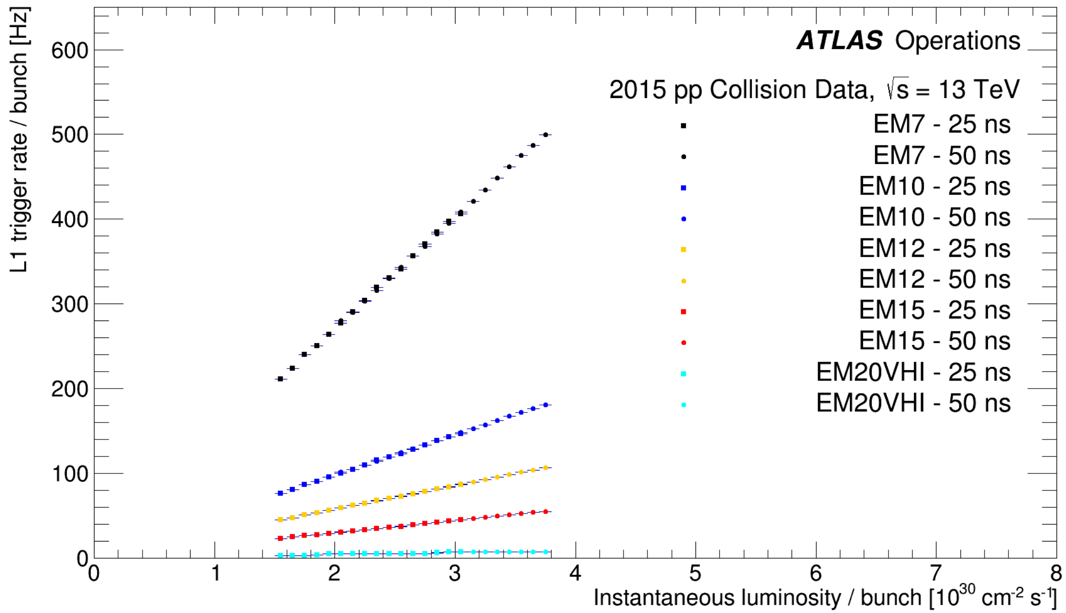
Trigger	Typical offline selection	Trigger Selection: Level-1 (GeV)	Trigger Selection: HLT (GeV)	Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
				$L = 1.2 \times 10^{34}$ cm^{-2}s^{-1}	
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	13	133
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	20	133
	Single μ, $p_T > 52$ GeV	20	50	13	48
	Single e, $p_T > 61$ GeV	22 (i)	60	20	13
	Single τ, $p_T > 170$ GeV	60	160	5	15
Two leptons	Two μ's, each $p_T > 15$ GeV	2×10	2×14	1.5	21
	Two μ's, $p_T > 23, 9$ GeV	20	22, 8	13	30
	Two loose e's, each $p_T > 18$ GeV	2×15	2×17	8	7
	One e & one μ, $p_T > 8, 25$ GeV	20 (μ)	7, 24	13	2
	One loose e & one μ, $p_T > 18, 15$ GeV	15, 10	17, 14	1.5	2.6
	Two τ's, $p_T > 40, 30$ GeV	20 (i), 12 (i) (+jets)	35, 25	6	35
	One τ & one isolated μ, $p_T > 30, 15$ GeV	12 (i), 10 (+jets)	25, 14 (i)	1.5	7
	One τ & one isolated e, $p_T > 30, 18$ GeV	12 (i), 15 (i) (+jets)	25, 17 (i)	3	9
Three leptons	Three loose e's, $p_T > 18, 11, 11$ GeV	15, 2×8	17, 2×10	15	< 0.1
	Three μ's, each $p_T > 7$ GeV	3×6	3×6	0.1	3
	Three μ's, $p_T > 21, 2 \times 5$ GeV	20	20, 2×4	13	4
	Two μ's & one loose e, $p_T > 2 \times 11, 13$ GeV	2×10 (μ's)	2×10, 12	1.5	0.2
	Two loose e's & one μ, $p_T > 2 \times 13, 11$ GeV	2×8, 10	2×12, 10	1.1	0.1
One photon	One loose γ, $p_T > 145$ GeV	22 (i)	140	20	30
Two photons	Two loose γ's, $p_T > 40, 30$ GeV	2×15	35, 25	8	40
	Two tight γ's, $p_T > 27, 27$ GeV	2×15	2×22	8	16
Single jet	Jet ($R = 0.4$), $p_T > 420$ GeV	100	380	3	38
	Jet ($R = 1.0$), $p_T > 460$ GeV	100	420	3	35
E_T^{miss}	$E_T^{miss} > 200$ GeV	50	110	6	230
Multi-jets	Four jets, each $p_T > 110$ GeV	3×50	4×100	0.4	18
	Five jets, each $p_T > 80$ GeV	4×15	5×70	3.5	14
	Six jets, each $p_T > 70$ GeV	4×15	6×60	3.5	5
	Six jets, each $p_T > 55$ GeV, $\|\eta\| < 2.4$	4×15	6×45	3.5	18
$b-$jets	One b ($\epsilon = 60\%$), $p_T > 235$ GeV	100	225	3	24
	Two b's ($\epsilon = 60\%$), $p_T > 160, 60$ GeV	100	150, 50	3	20
	One b ($\epsilon = 70\%$) & three jets, each $p_T > 85$ GeV	4×15	4×75	3.5	19
	Two b ($\epsilon = 60\%$) & one jet, $p_T > 65, 65, 110$ GeV	2×20, 75	2×55, 100	2.7	25
	Two b ($\epsilon = 60\%$) & two jets, each $p_T > 45$ GeV	4×15	4×35	3.5	56
$b-$physics	Two μ's, $p_T > 6, 6$ GeV plus dedicated b-physics selections	6, 6	6, 6	4.7	20
Total				85	1500

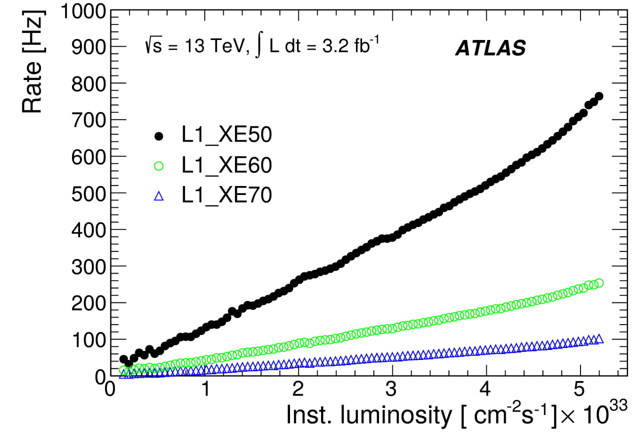
TRIGGER SNAKES AND LADDERS

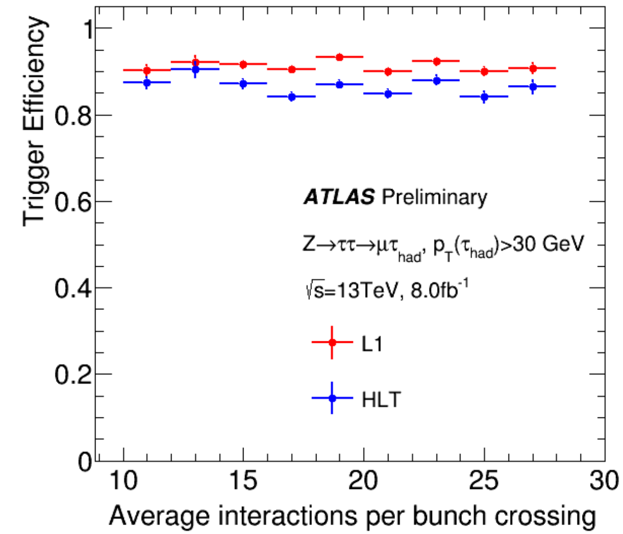
(How a new trigger goes online)



IMPACT OF PILEUP



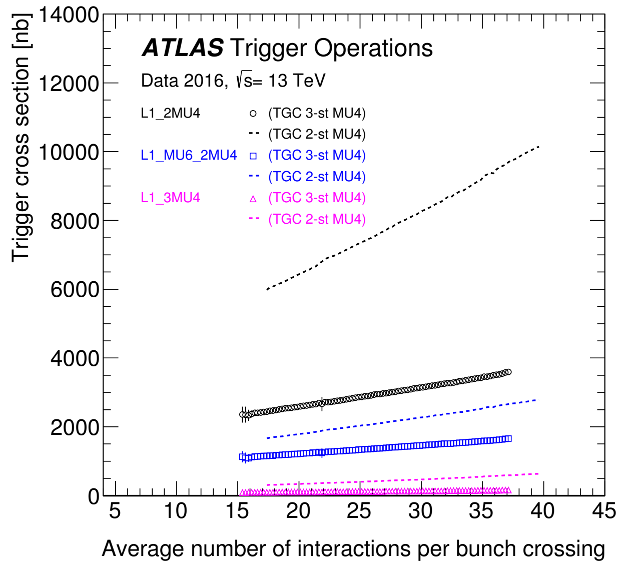


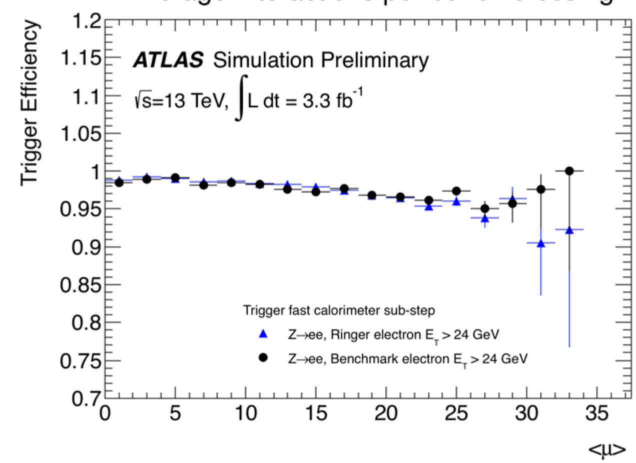


Generally both L1 and HLT reconstruction made robust to pile-up.

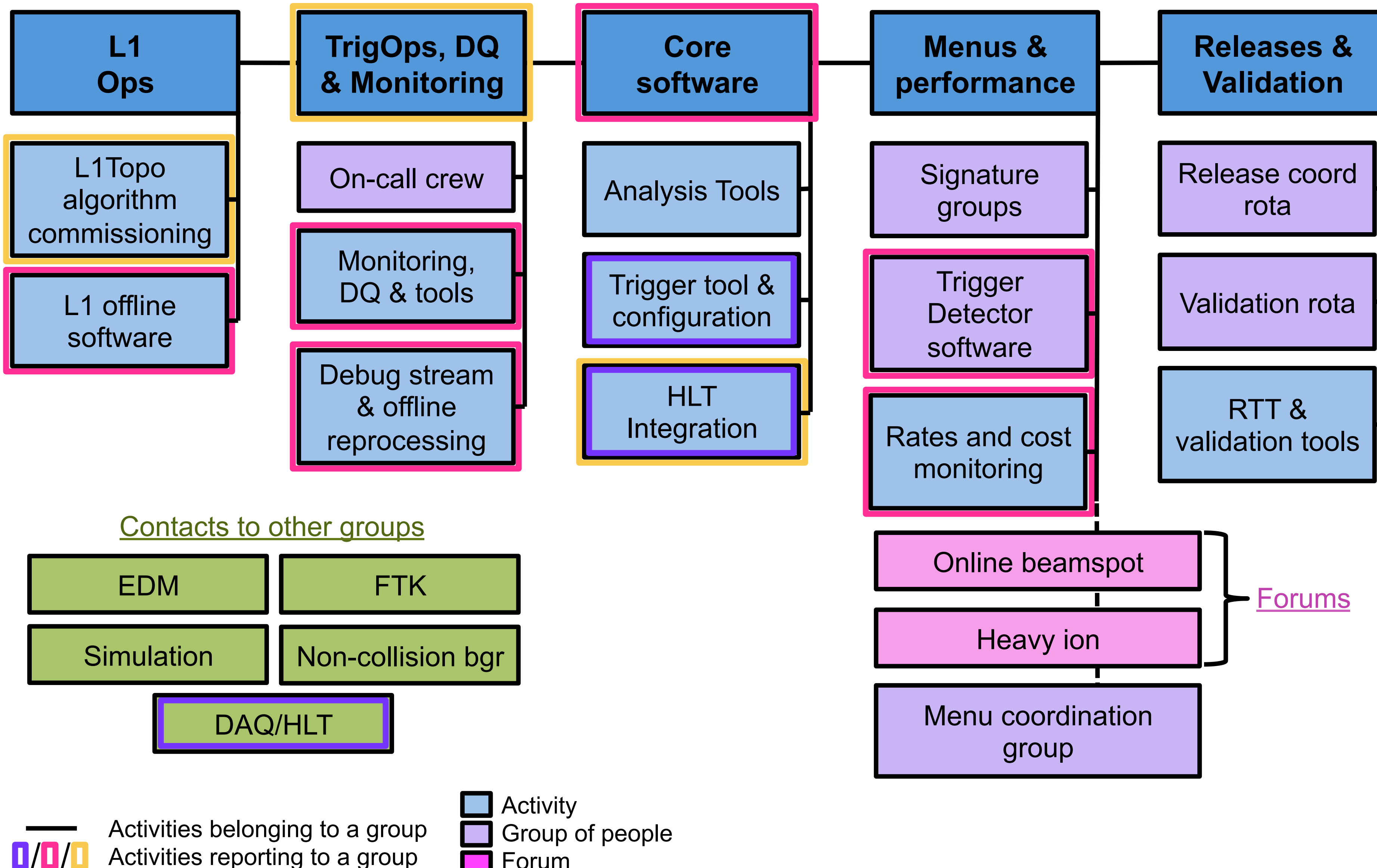
- Huge effort in finding ways to mitigate the problem.
- At the HLT: tracking helps!

Still fighting for ME_T…





TRIGGER ORGANIZATION



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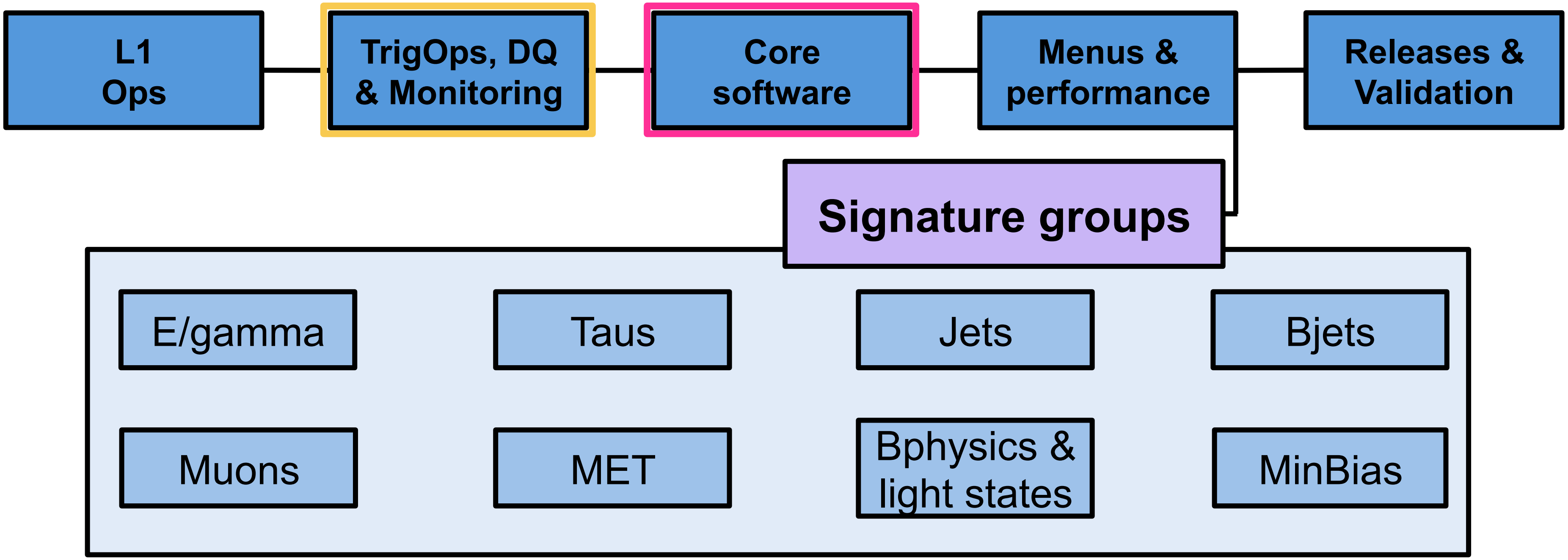
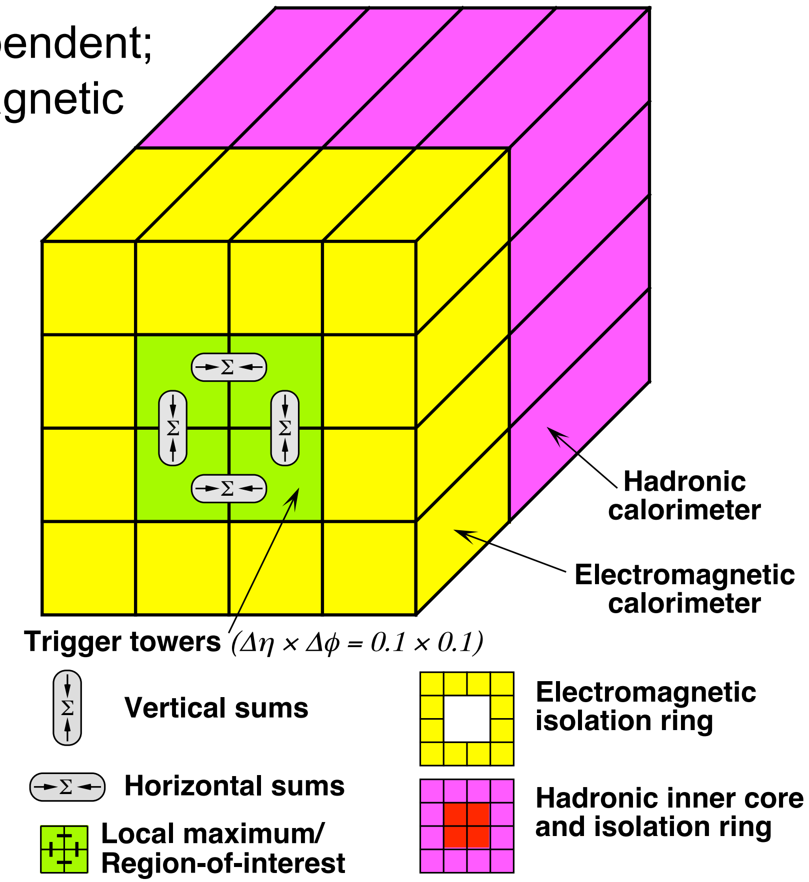


ELECTRON / PHOTON

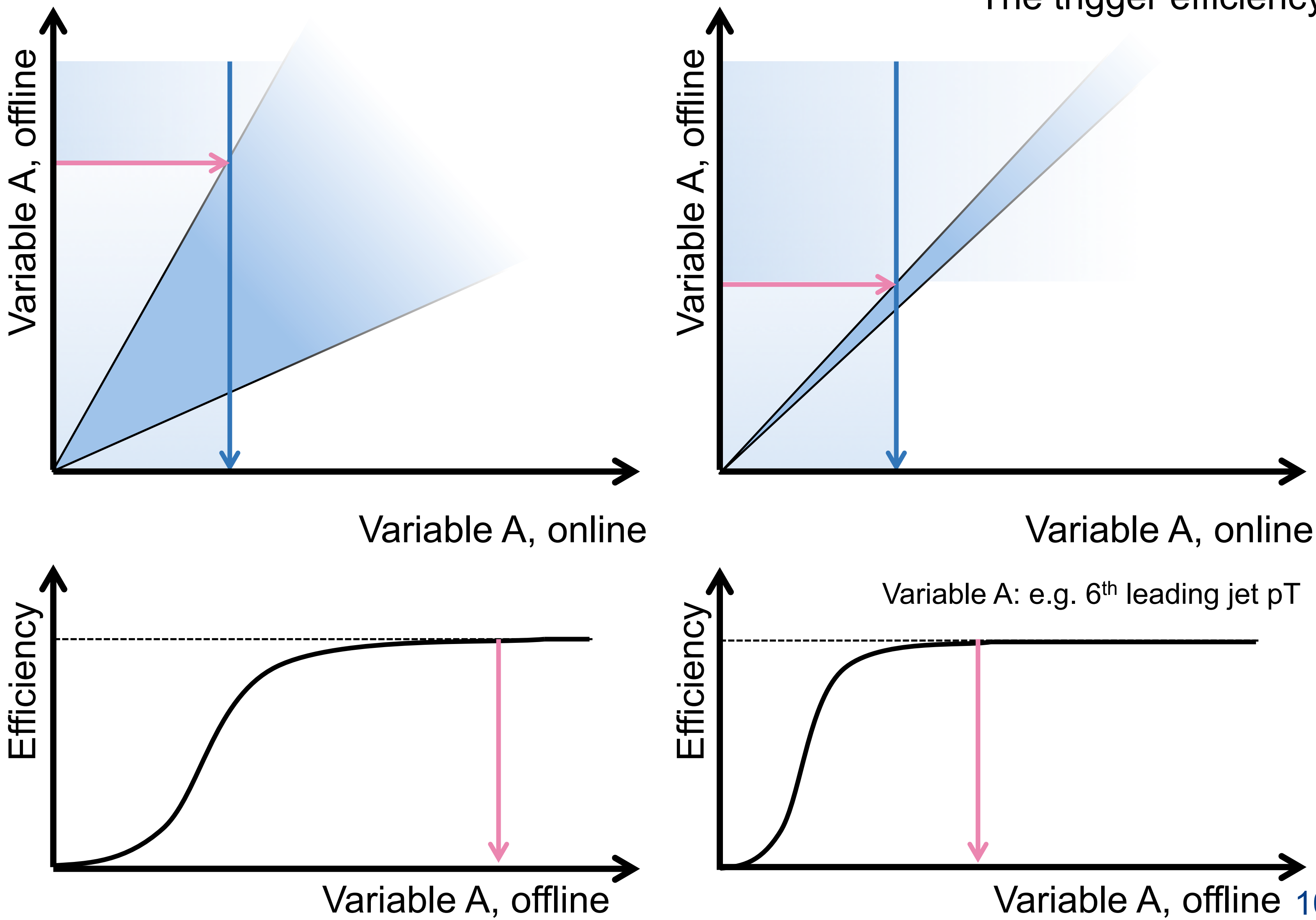
At L1:

- Analyse regions of 4x4 trigger tower.
- Cut on transverse energy threshold; eta-dependent; apply hadronic core isolation; and electromagnetic isolation.

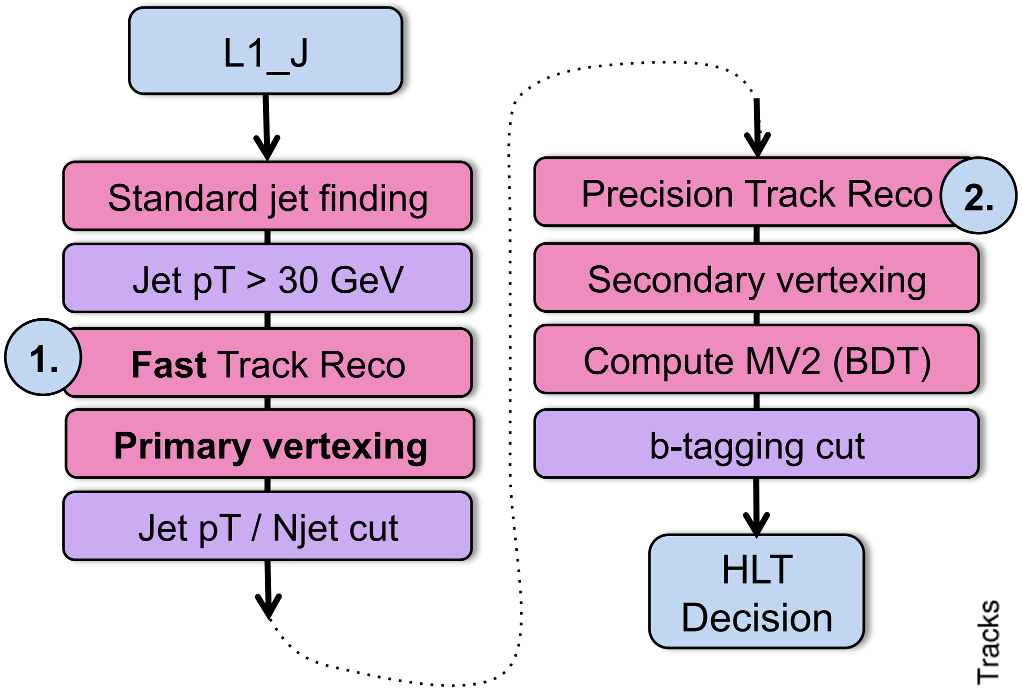


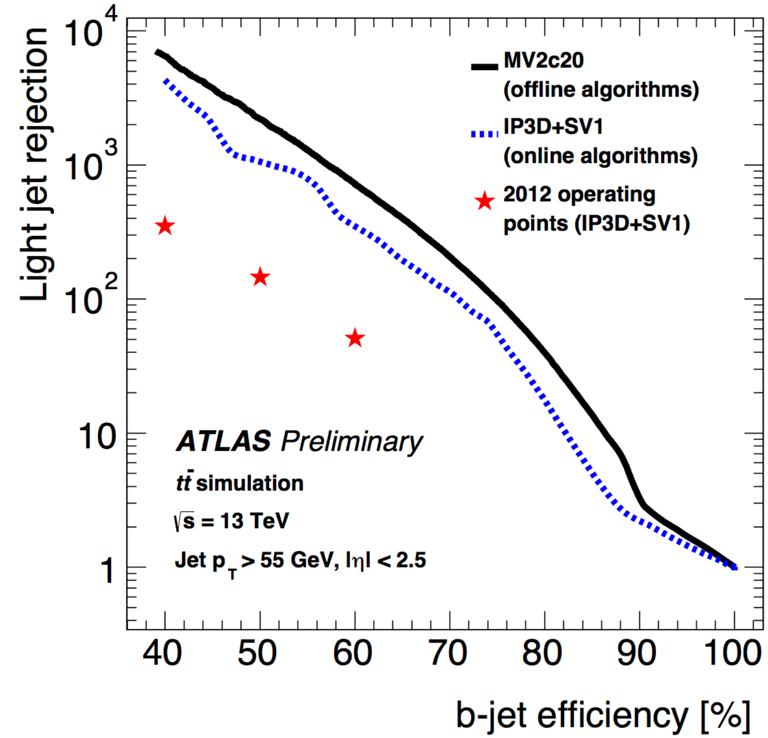
AN IMPORTANT FIGURE OF MERIT

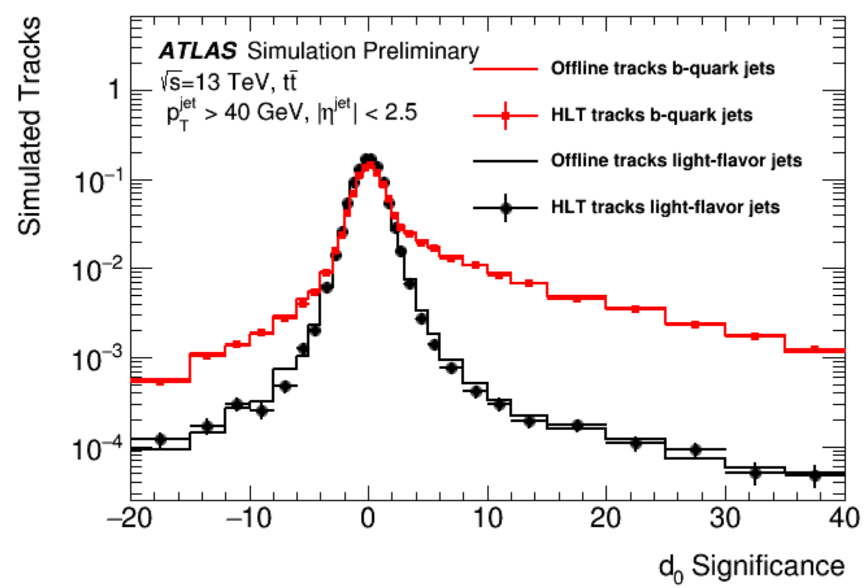
The trigger efficiency



B-JETS



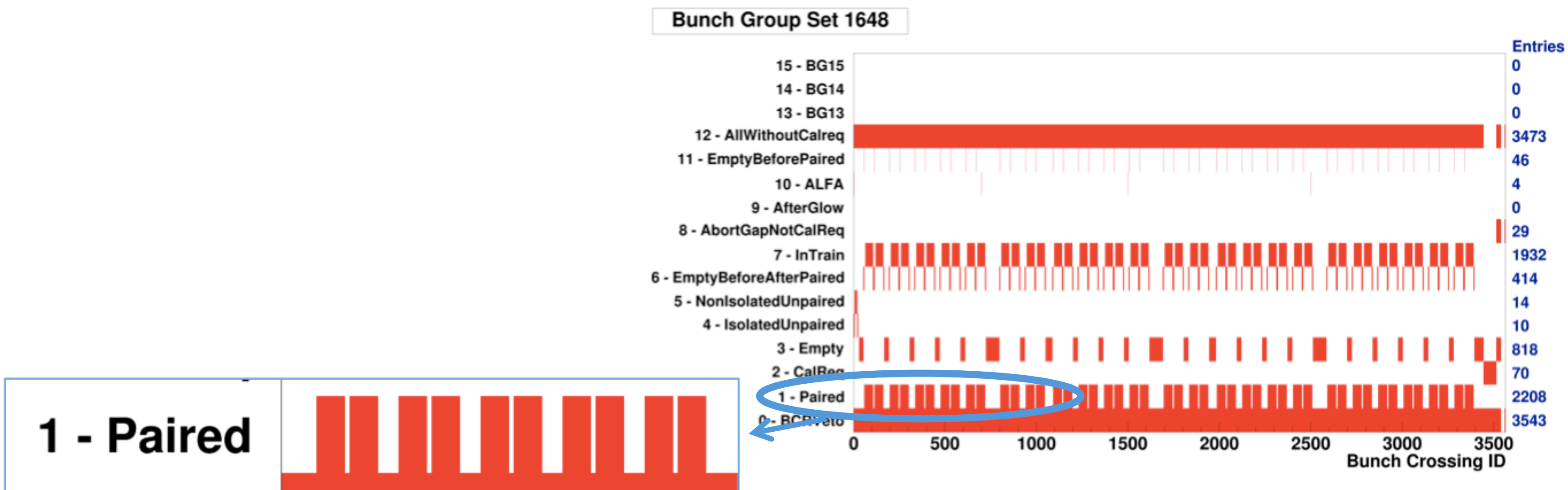




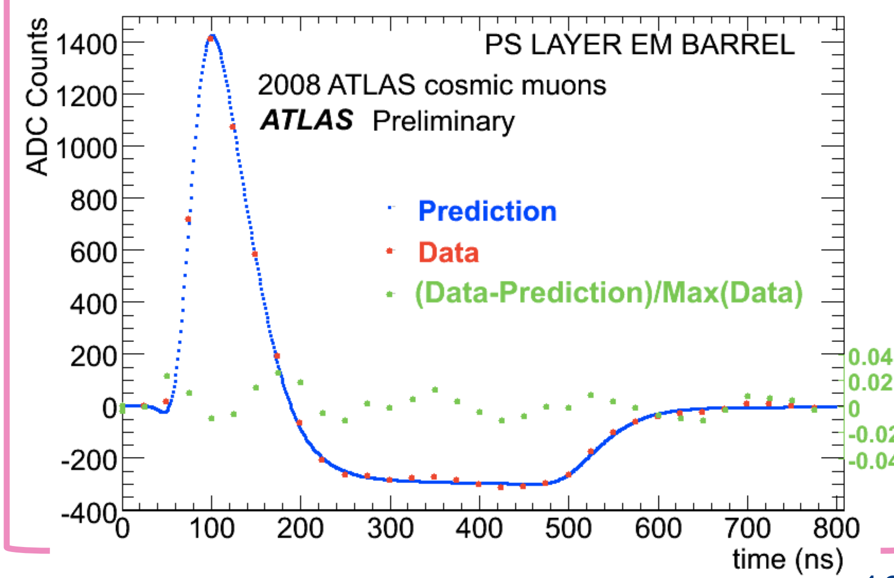
Use dedicated Primary Vertex (PV) finding and a BDT (similar to offline) to select b-jets against c- and light-jets.

1. Run tracking within jet RoIs for PV reco.
2. Run tracking within wider cone for secondary vertex finding.

BUNCHGROUP



- E.g. “paired” BCIDs: 60-107, 116-163, 199-246, etc.
- Colliding BCIDs spaced by 25ns within a “train” of proton bunches.
- Detector readout can be larger than 25ns (sub-detector dependent)...



COMMON: HLT CALO CLUSTERING

Reconstructs calorimeter data at the HLT.

- For electrons, taus, jets, MET.
- Exists in RoI-based version (used in electrons and taus) and Full-scan version (used in jets and MET).

Data is unpacked to calorimeter cells from where clusters are built.

Pile-up corrections: train structure and bunch to bunch luminosity variations can create significant energy shifts which are mitigated by BCID dependent average pileup correction. Offline since a while, online since 2016.

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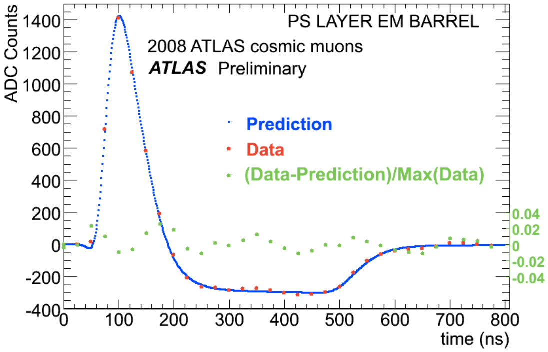

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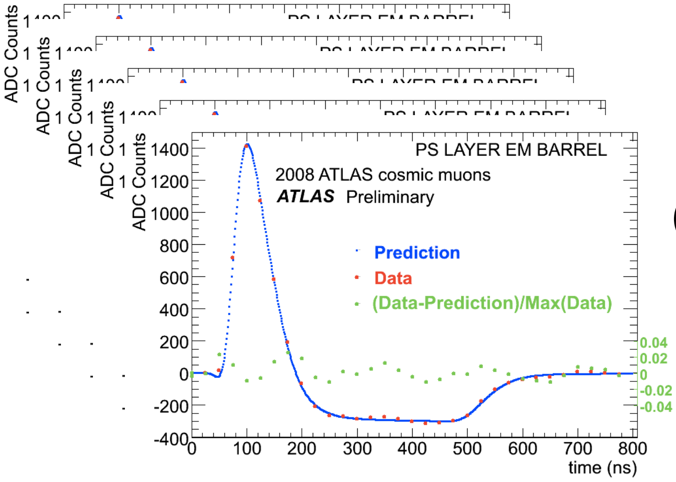

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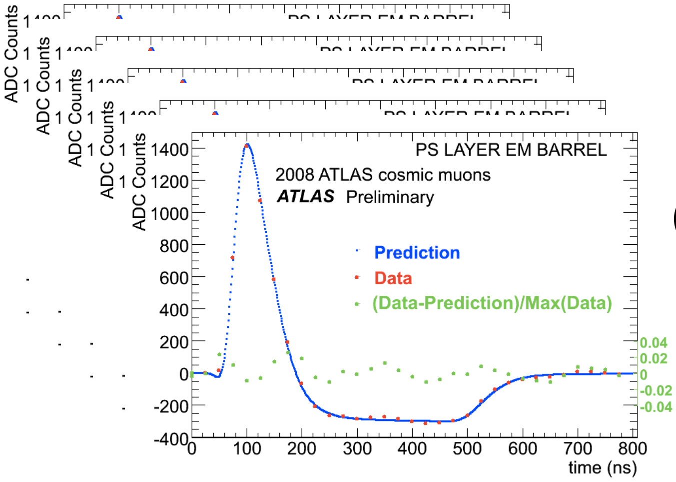
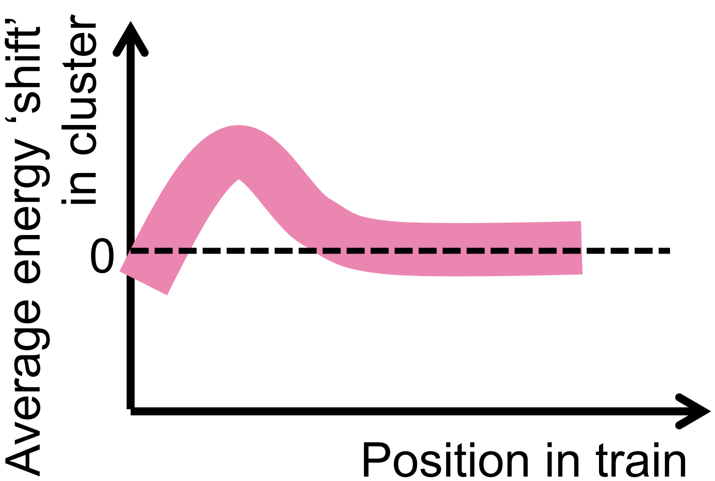
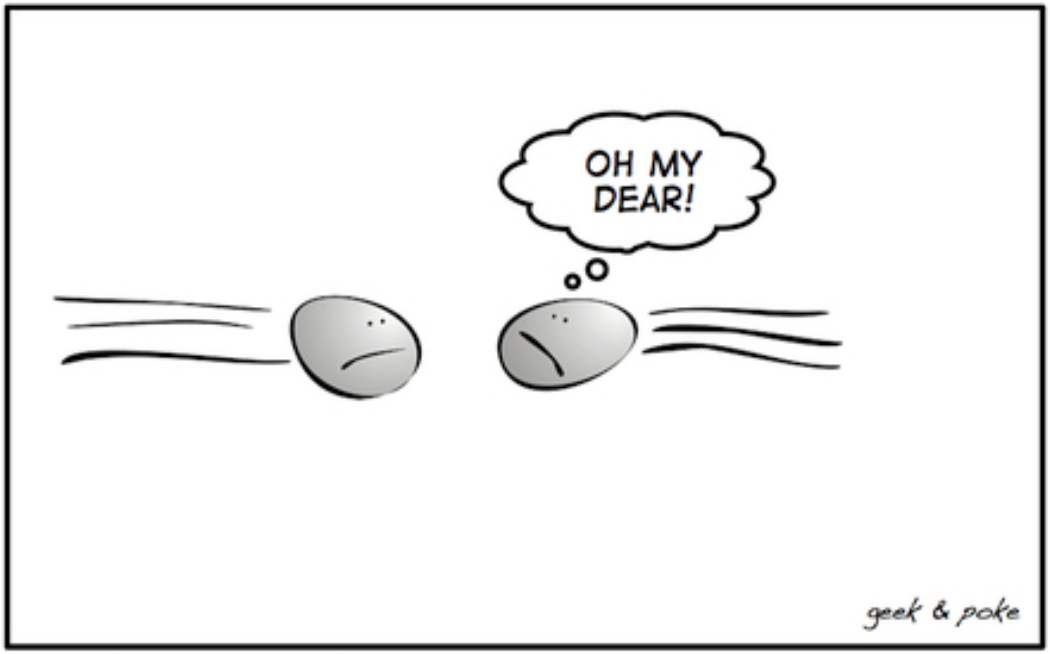
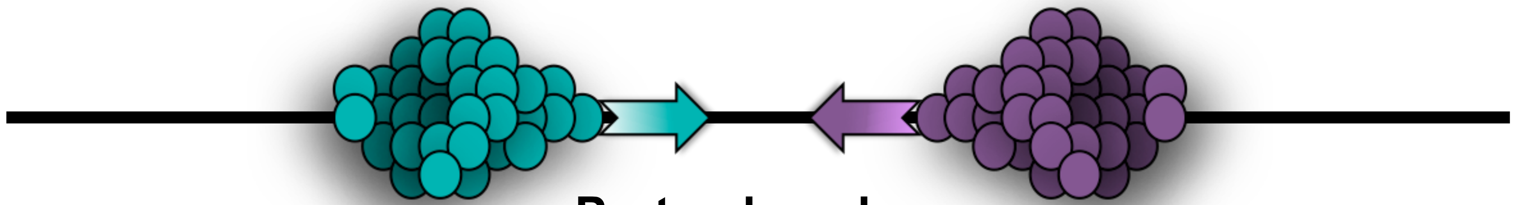






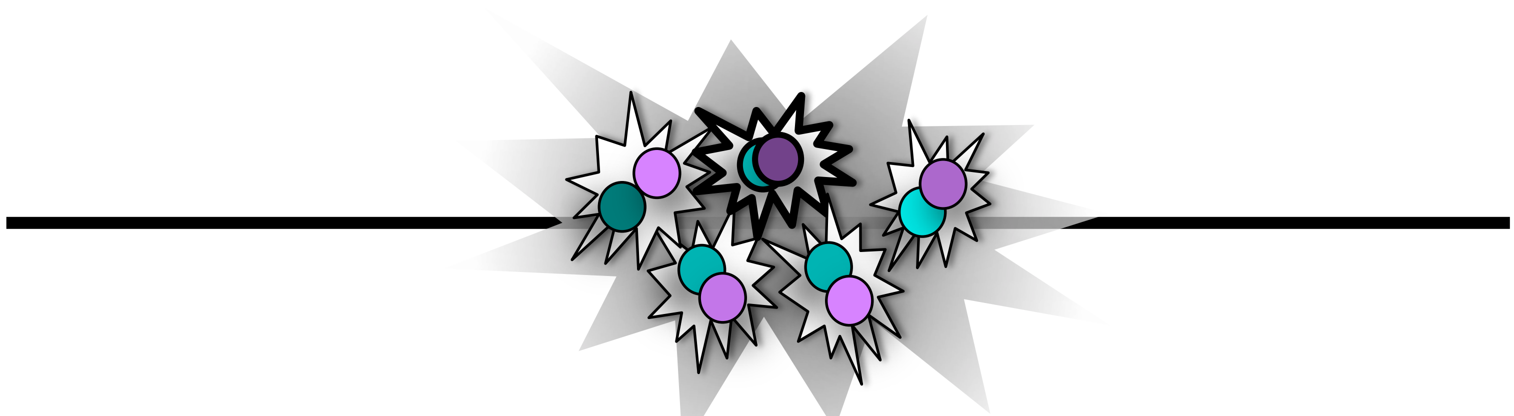
LATELY INSIDE THE LHC:
2 PROTONS 0.0000000000000000001 SEC BEFORE THE COLLISION



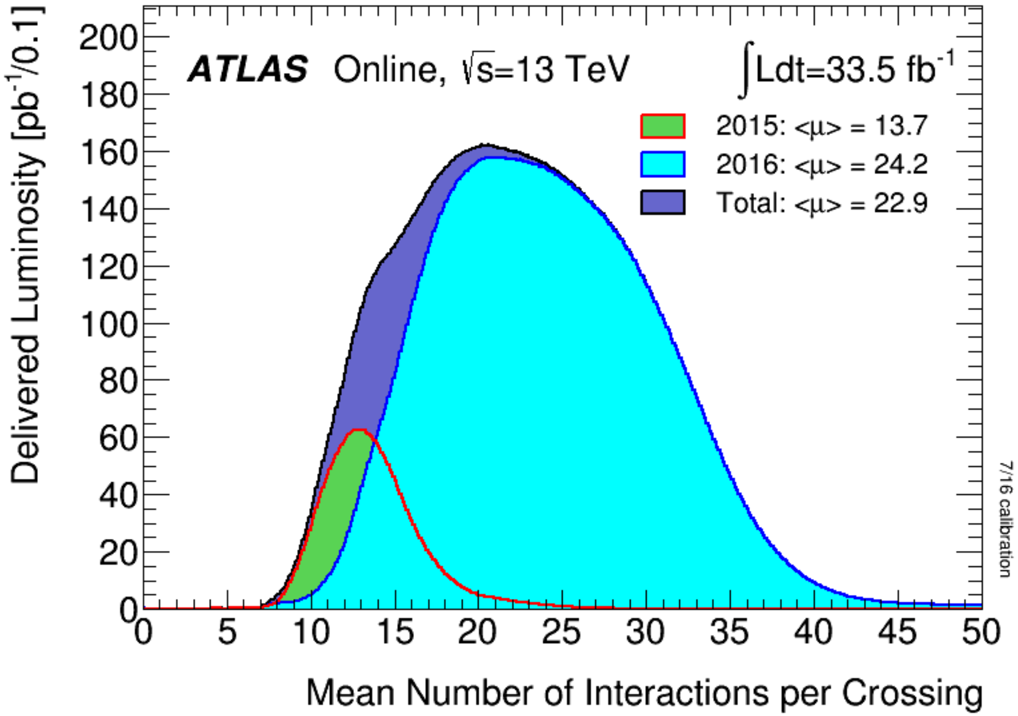
Proton bunches

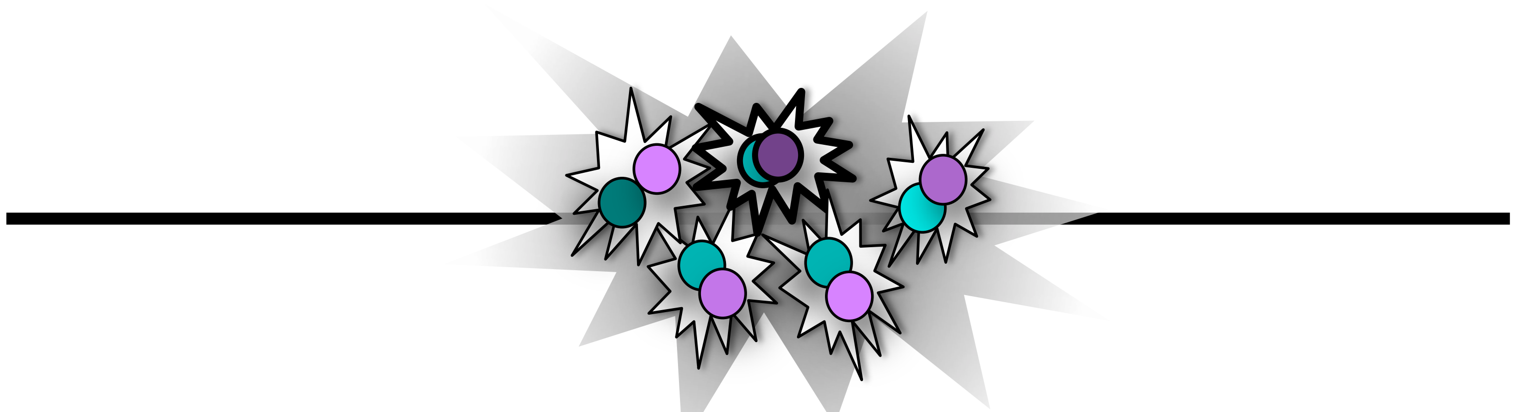
>10^{11} protons/bunch

(colliding at ~**40MHz in run2)**



~25 p-p collisions / bunch crossing





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