Triggering And Data Acquisition in High Energy Physics

for the Heidelberg GK BSM
Lecture 2/3

22nd November 2017

by
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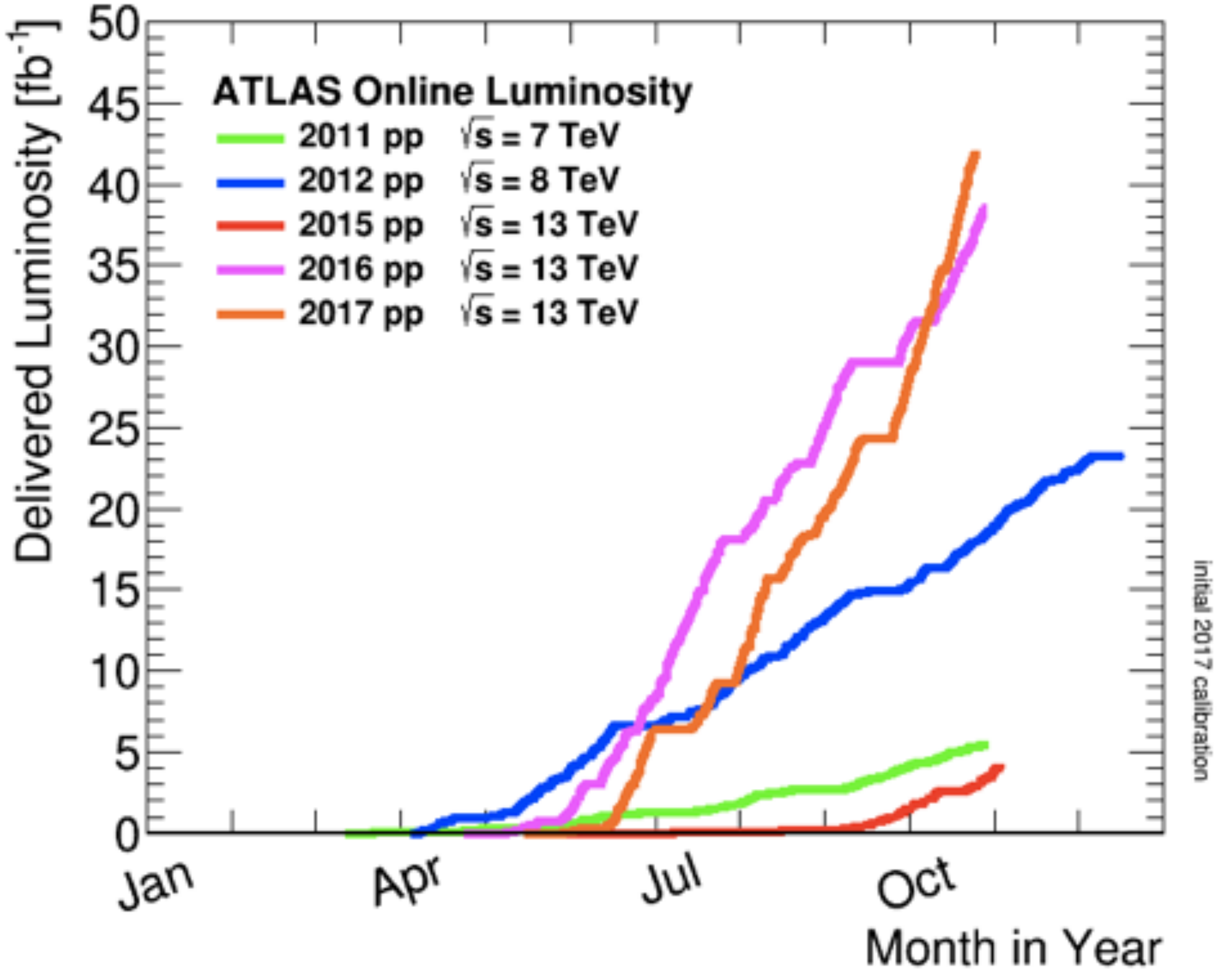
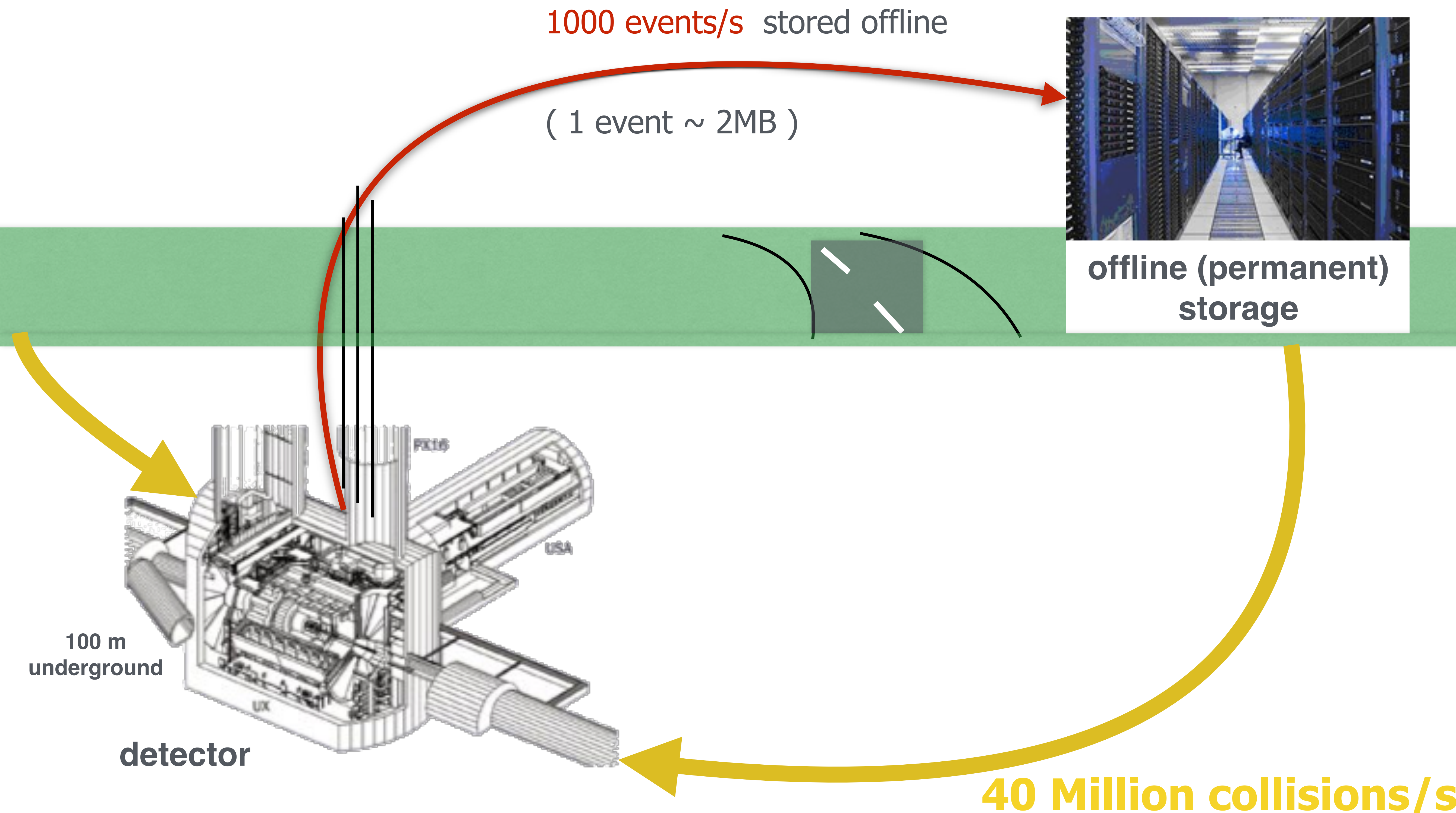
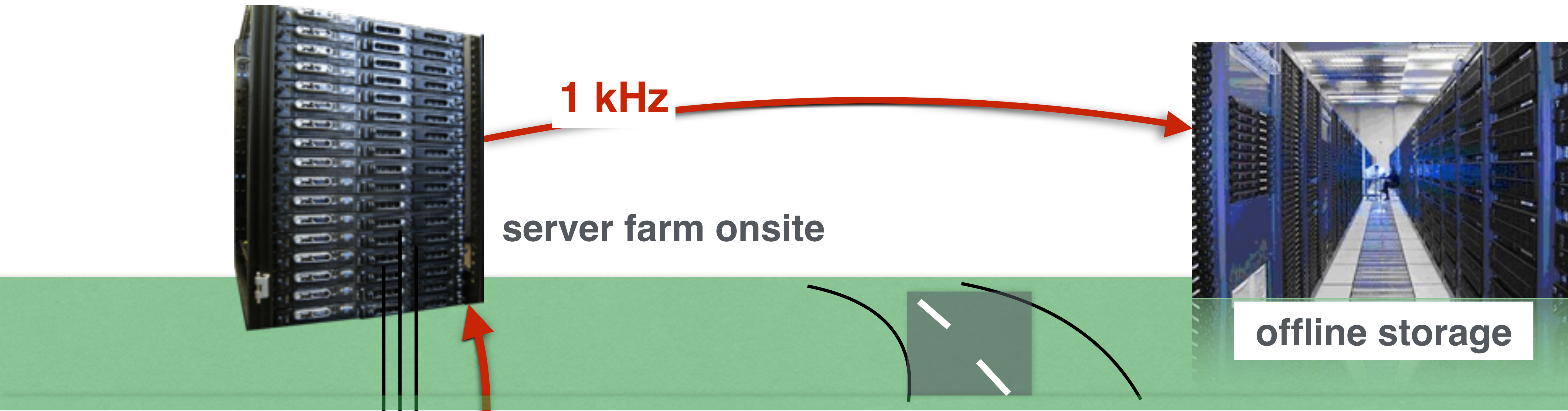


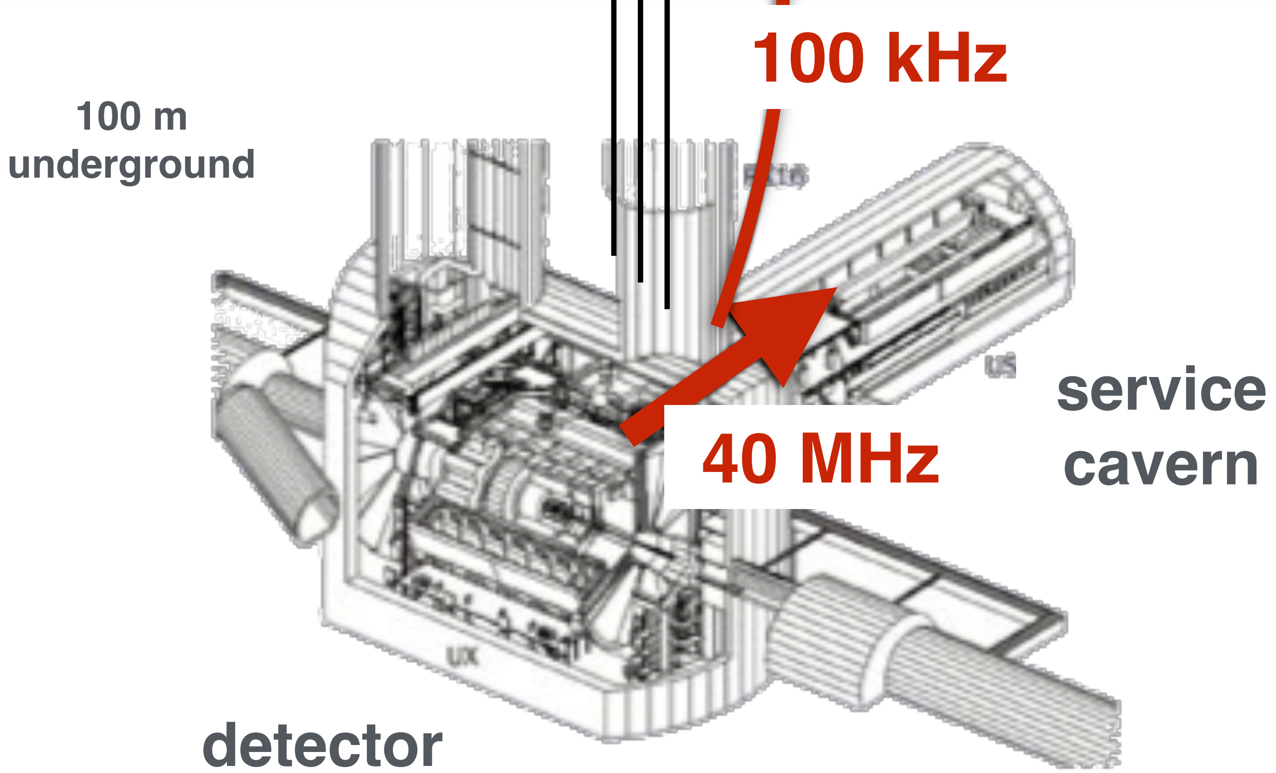
- **Lecture 2 (today):**
  - Trigger challenges for general-purpose detectors at the LHC and how to do a dijet bumphunt for dark matter.

Recap: Data recording with ATLAS at the LHC



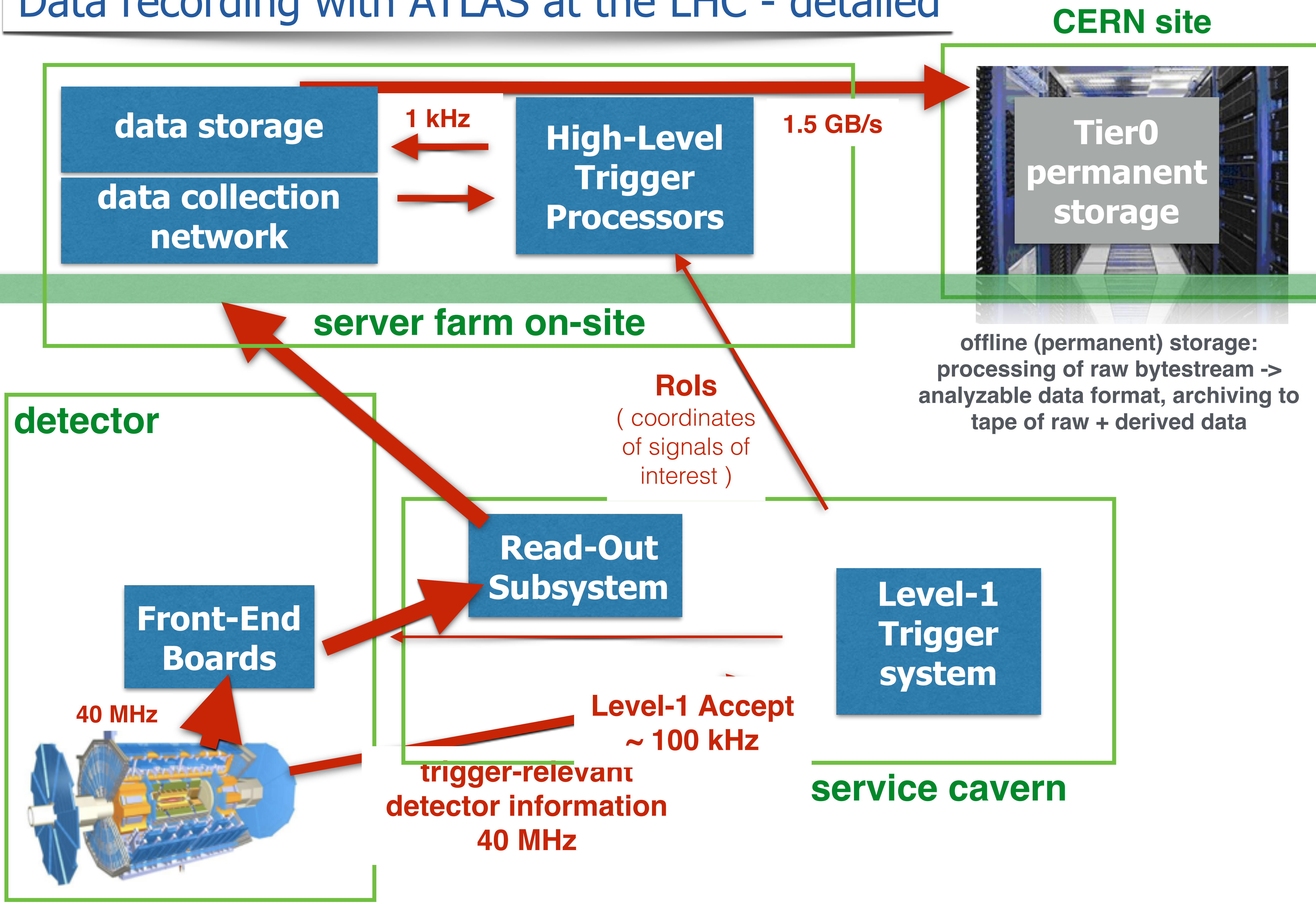
Recap: Data recording with ATLAS at the LHC



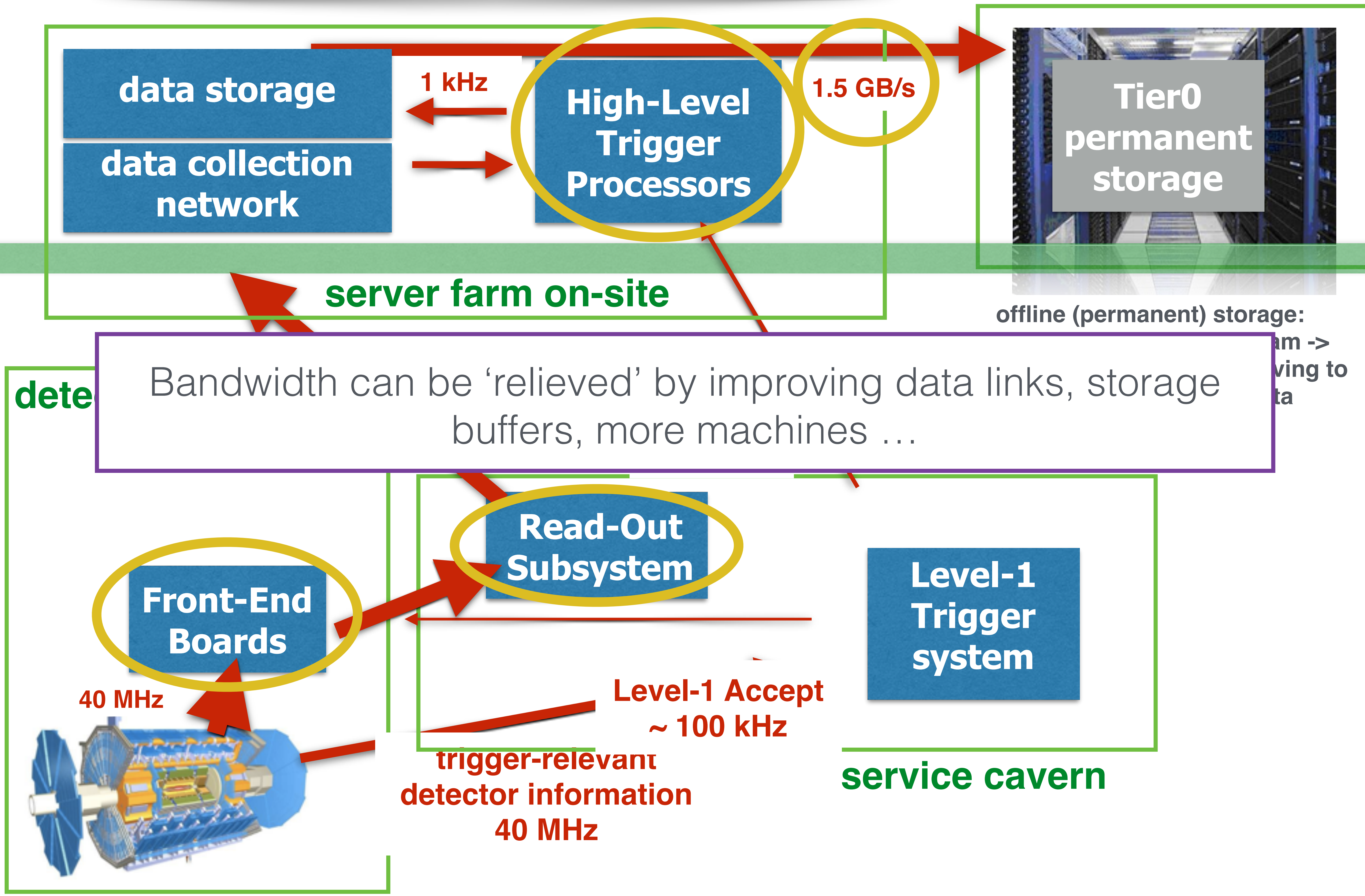


Events are not randomly selected; ATLAS filters events using a <u>multi-level trigger</u> to select 'interesting' over 'boring' events..

Data recording with ATLAS at the LHC - detailed

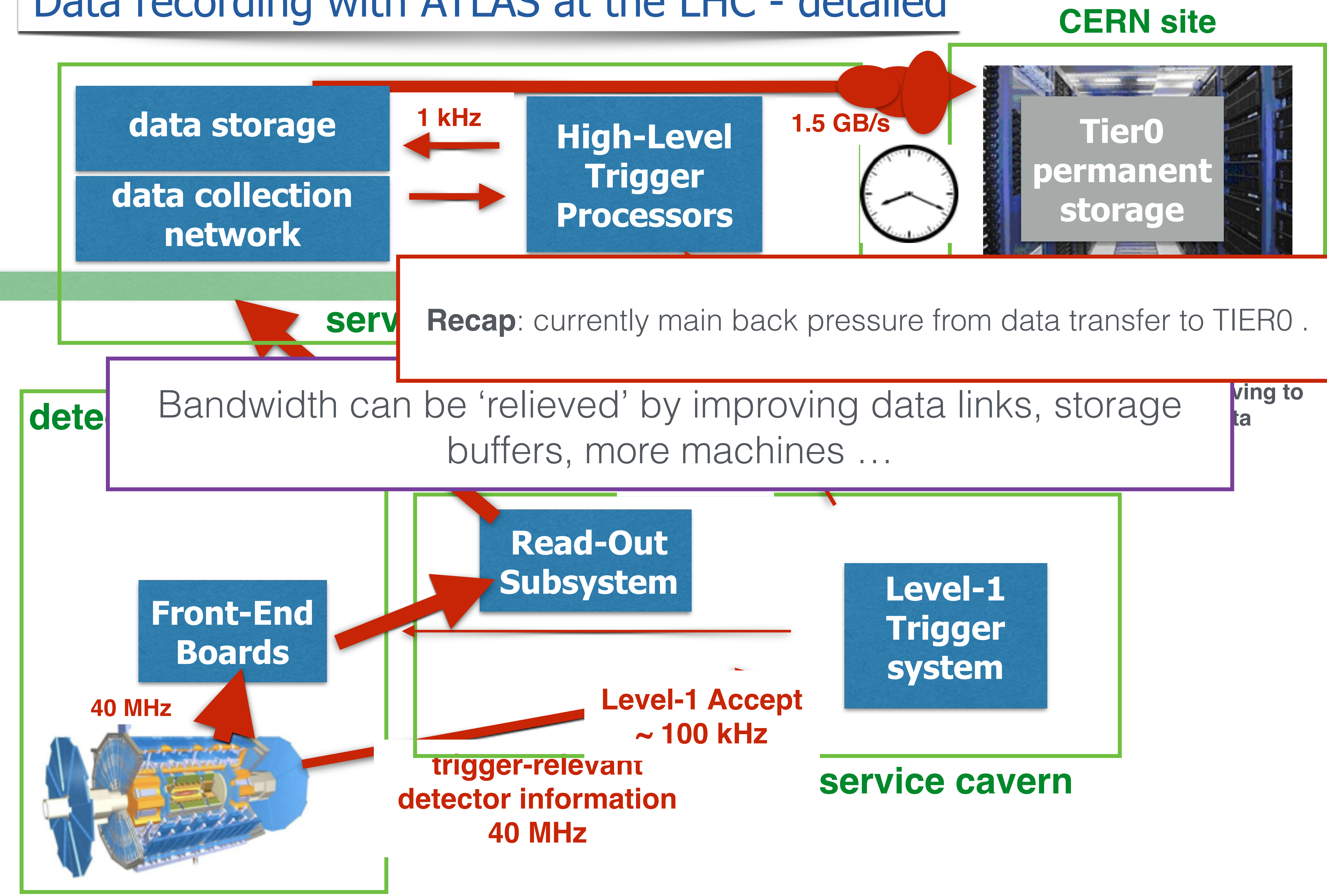


Data recording with ATLAS at the LHC - detailed



Bandwidth can be ‘relieved’ by improving data links, storage buffers, more machines …

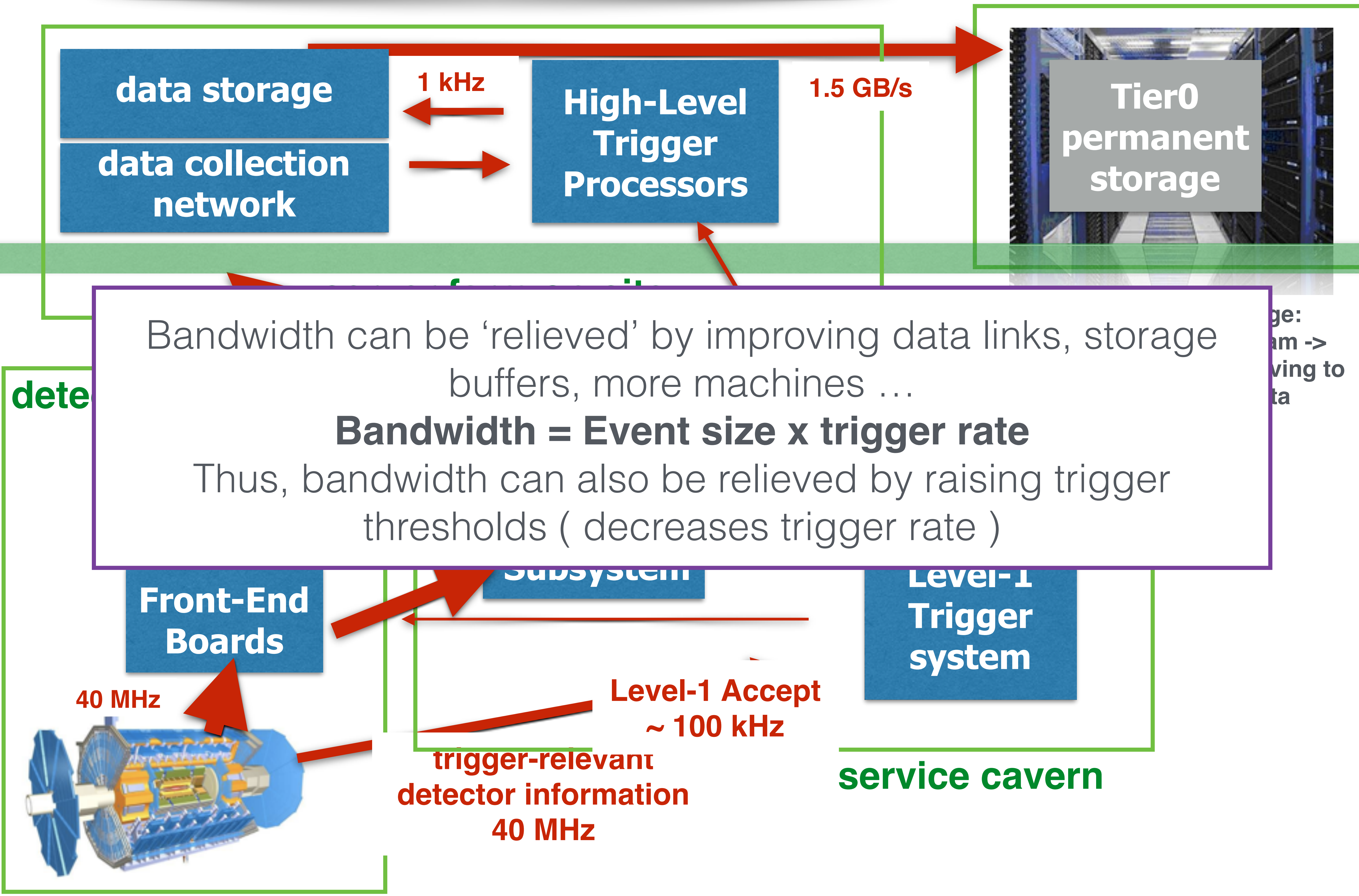
Data recording with ATLAS at the LHC - detailed



Recap: currently main back pressure from data transfer to TIER0 .

Bandwidth can be 'relieved' by improving data links, storage buffers, more machines …

Data recording with ATLAS at the LHC - detailed



Bandwidth can be ‘relieved’ by improving data links, storage buffers, more machines …

Bandwidth = Event size x trigger rate

Thus, bandwidth can also be relieved by raising trigger thresholds (decreases trigger rate)

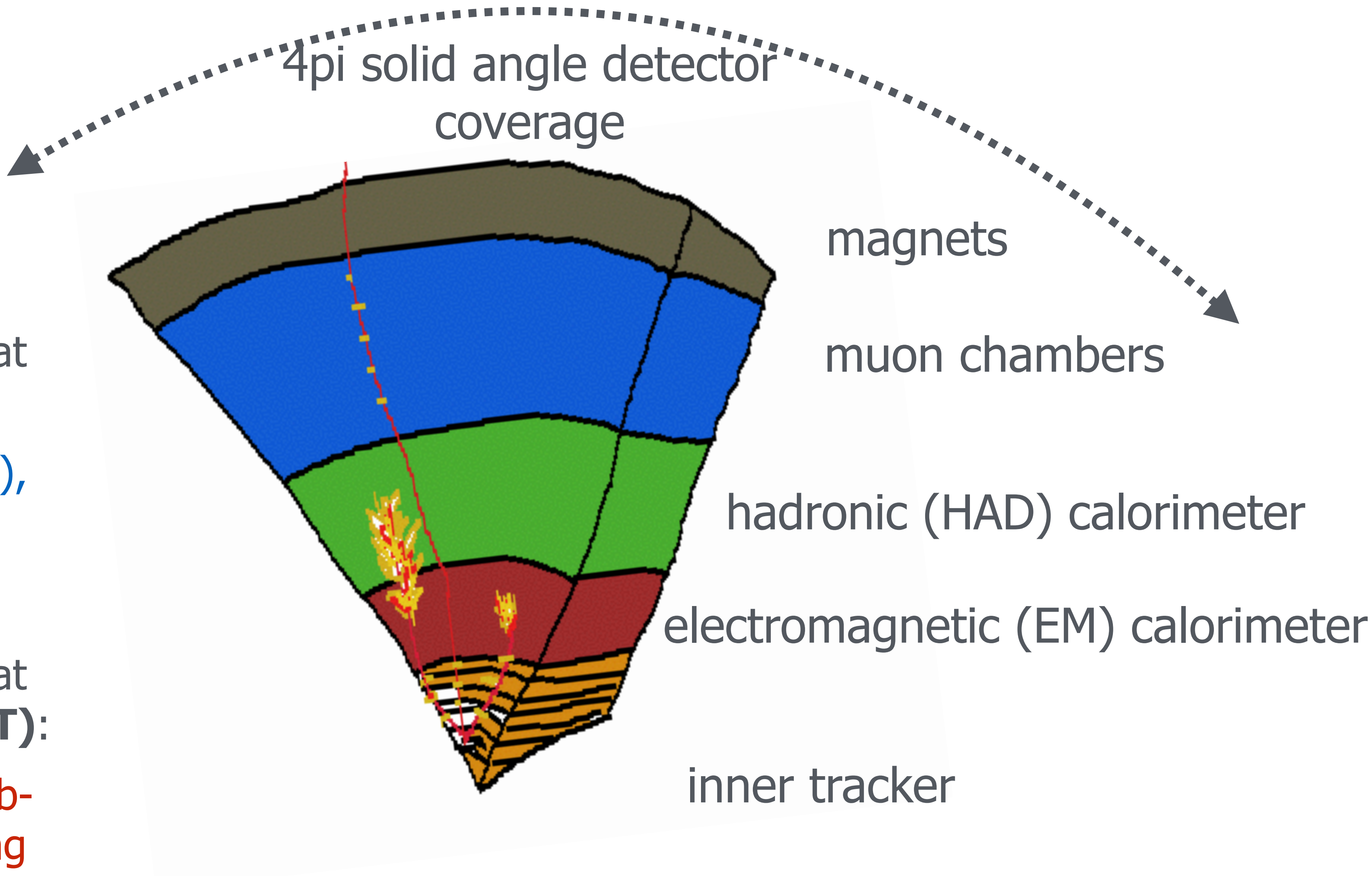
Recap: hermetic detector design

Types of trigger objects at **Level 1 Trigger (L1)**:

EM (electrons + photons), JETS, MUONS, TAUs, MISSING ENERGY …

Types of trigger objects at **High Level Trigger (HLT)**:

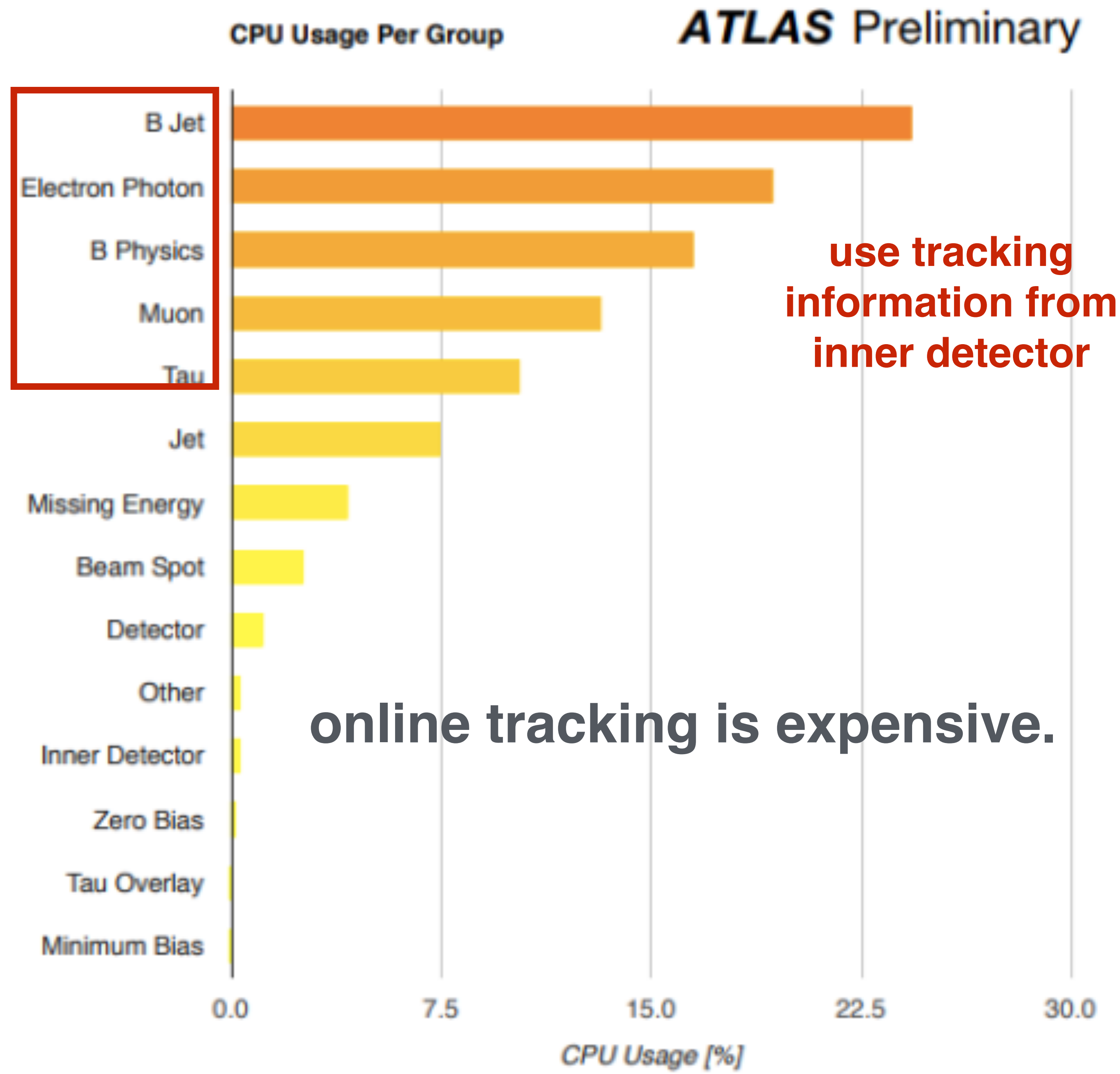
electrons, photons, jets, b-jets, muons, taus, missing energy …



Which subdetectors are most CPU intensive ?

main central subdetectors

	subdetector	# of channels
	pixels	92 million
inner tracker	silicon strips	6.3 million
	transition radiation tracker	350000
calorimeters	LAr Central (EM) Calorimeter	170000
	Tile Central (HAD) Calorimeter	5200
muon chambers	Muon Drift Chambers	357000
	Muon Resistive Plate Chamber Triggers	383000



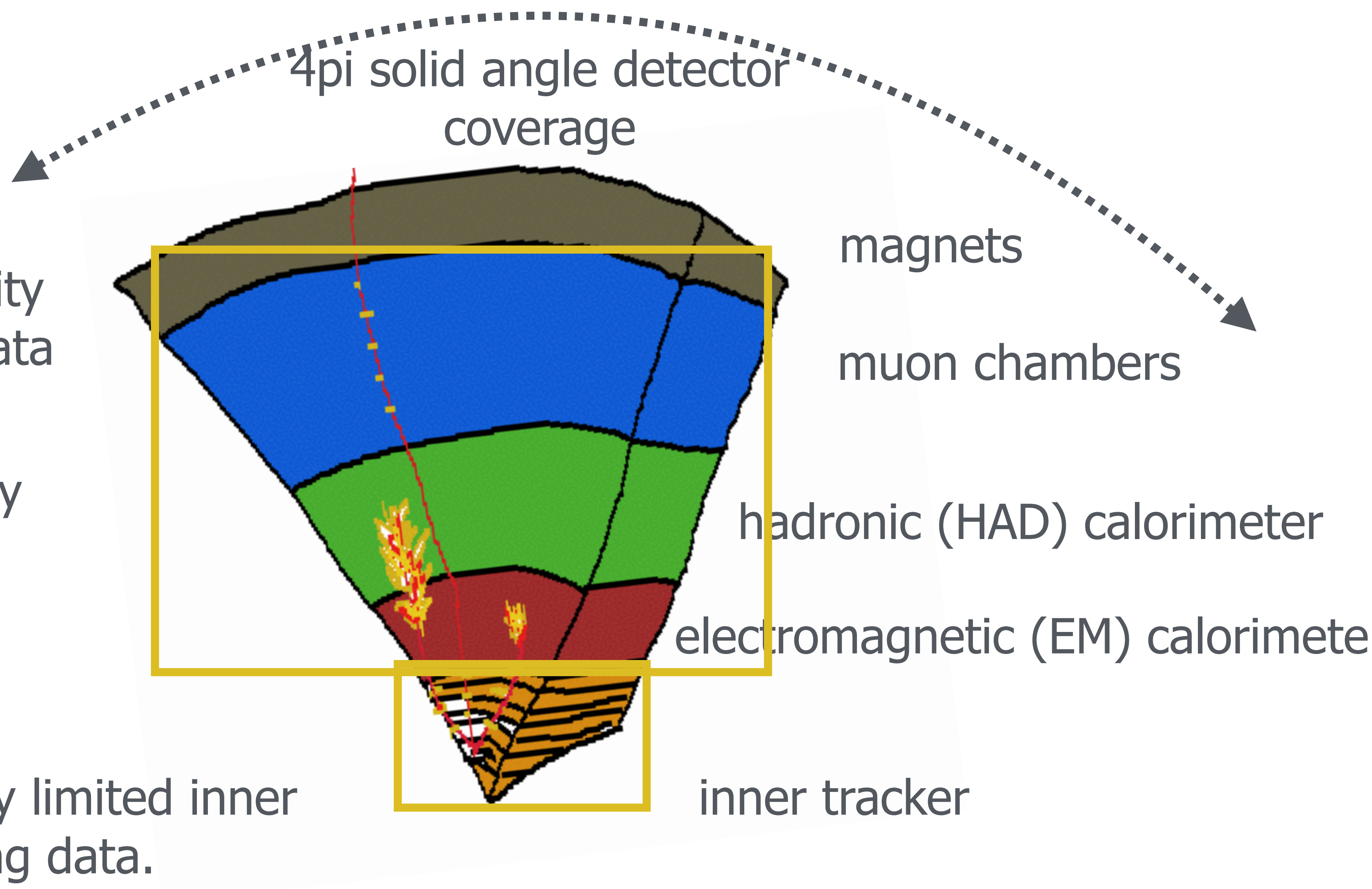
CPU usage at the High Level Trigger

Subdetectors and triggering

L1 uses coarse granularity calorimeter and muon data

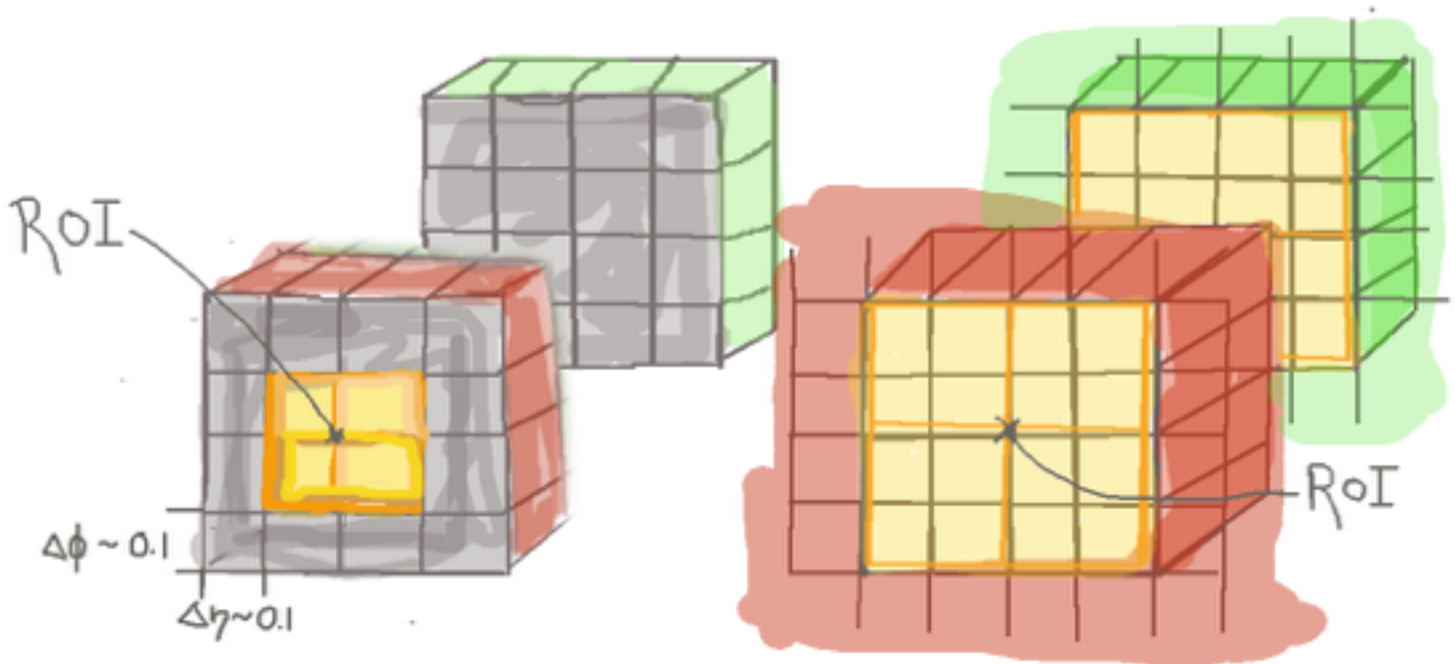
HLT uses full granularity calo and muon data

HLT uses only limited inner tracking data.



Construction of Trigger Objects: Central Electrons/Photons, Jets

Level-1 reconstruction



- Each trigger tower is the energy sum of all calorimeter cells within eta x phi projection 0.1x0.1.

EM trigger object:

- identified within 4x4 trigger tower (TT) window
- E threshold: max sum ET of 2x1 elements in core of window
- HAD threshold: sum ET veto on 4x4 towers in HAD layer.
- Iso threshold: sum ET veto on surrounding 12 towers in EM and HAD layer.
- Region-of-Interest (RoI) coordinates from 2x2 core center.

JET trigger object:

- identified within 4x4, 6x6 or 8x8 TT window across EM and HAD layers.
- reconstruct jets elements from 2x2 TT
- E threshold: max sum ET of 4 (EM) + 4 (HAD) Jet Elements (8x8+ 8x8 TTs) within window
- RoI coordinates from 4x4 core center.

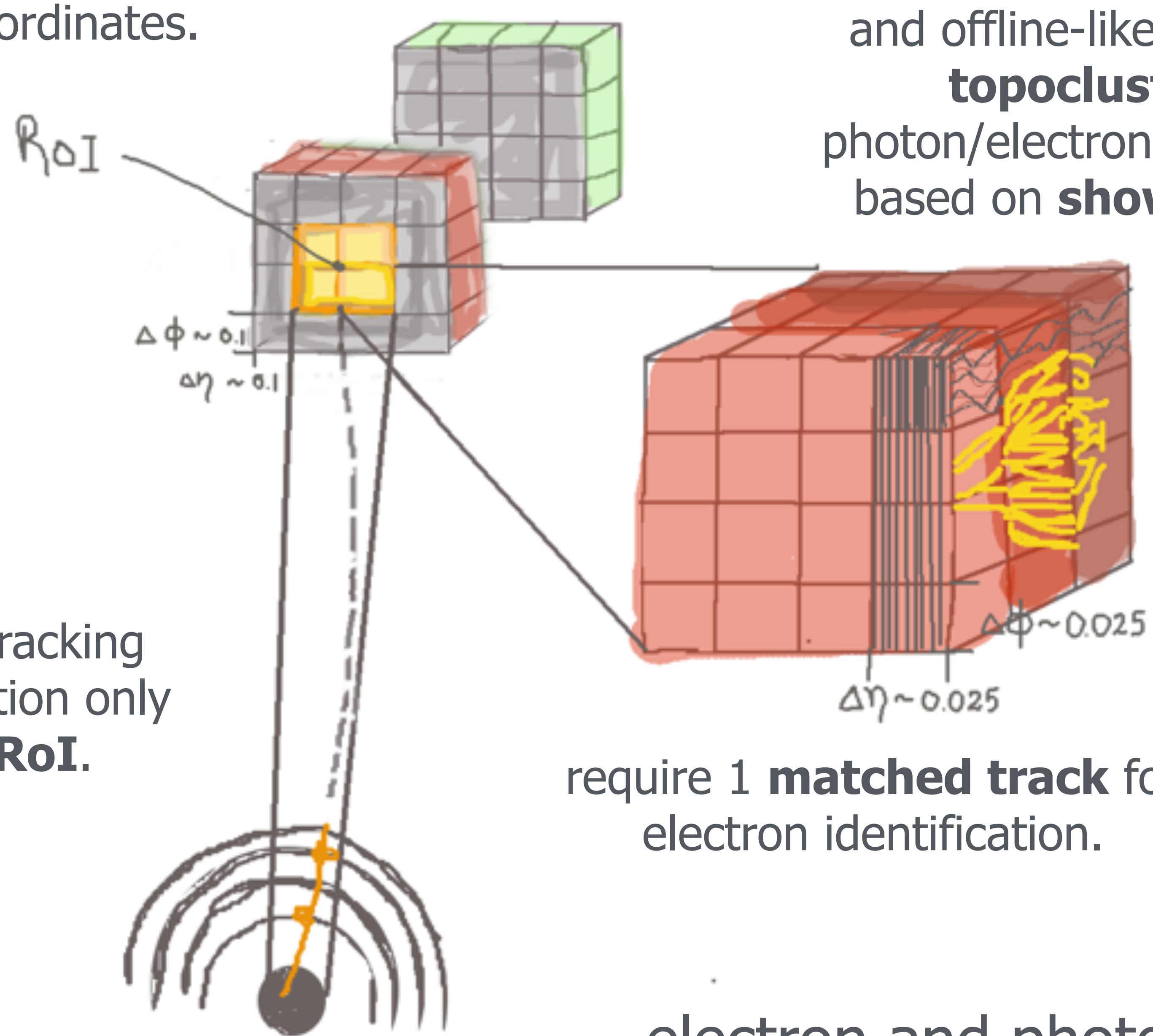
EM and JET reconstruction at L1

Construction of Trigger Objects: Electrons & Photons

HLT reconstruction

Level-1 seed provides RoI coordinates.

energy clustering using **full calorimeter granularity**, and offline-like algorithms: **topoclustering**. photon/electron identification based on **shower shape.**



- EM and HAD calorimeters: 3 layers each.
- Cells of varying granularity, cells in central layer span 0.025x0.025 in etaxphi. (1 TT ~ 4x4 cells from central layer)

perform tracking reconstruction only within **RoI**.

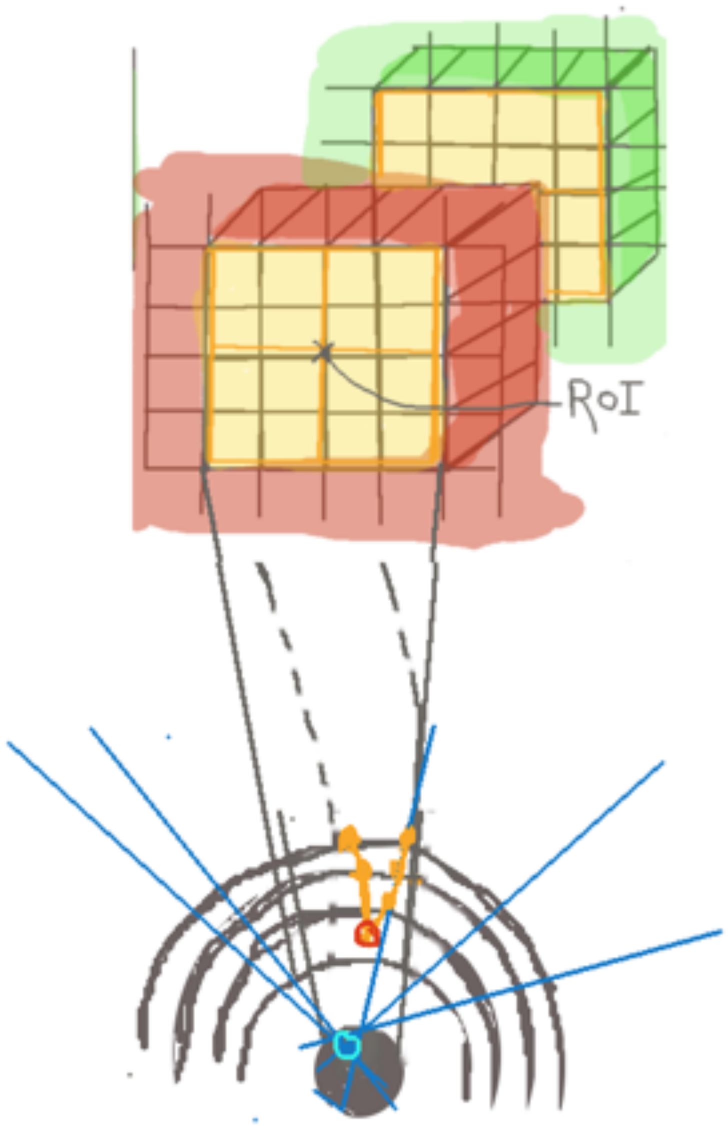
require 1 **matched track** for electron identification.

electron and photon reconstruction at HLT

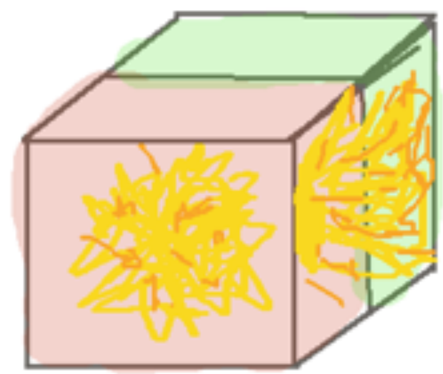
Construction of Trigger Objects: Jets & b-jets

HLT reconstruction

HLT jets are reconstructed using **full-granularity** calorimeter info + offline-like algorithms: **anti-kT jet reco.**



Primary vertex position roughly reconstructed based on fast track reco in all jet RoIs, and online beamspot algorithm.



- b-tagging not performed on every jet; requires L1+HLT jet seed, e.g. HLT_j175_bmv2c1040_split_L1J100 (requires Level-1 Jet > 100 GeV + HLT jet > 175 GeV, which after online calibration has pT > 225 GeV)

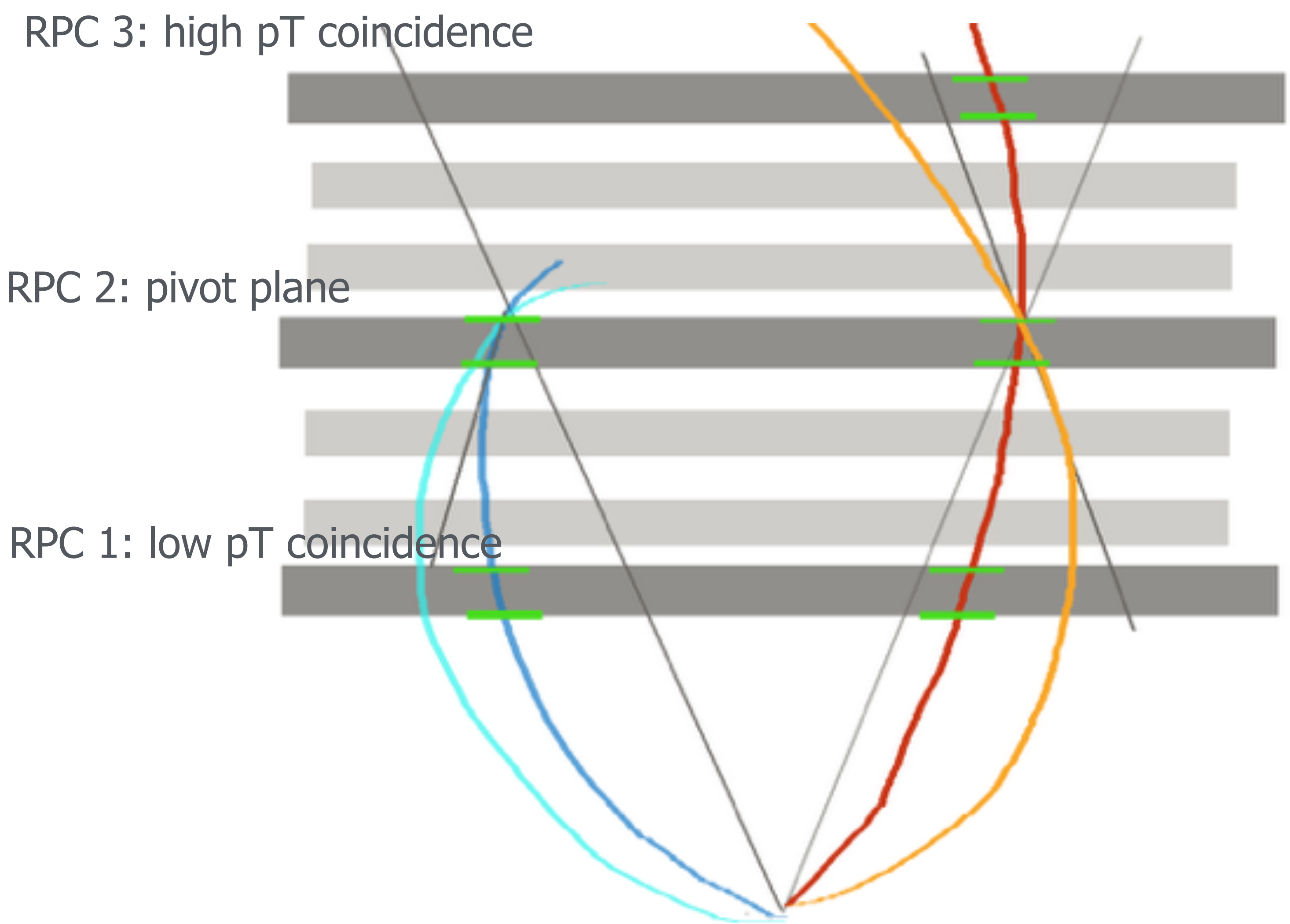
HLT jets are b-tagged, based on :

- secondary vertex reconstruction from tracks within jet RoI
- multivariate algo, same as in offline, to exploit b-jet properties (large impact parameters, large b-hadron mass)

b-taggin at HLT

Construction of Trigger Objects: Central Muons

Level-1 reconstruction

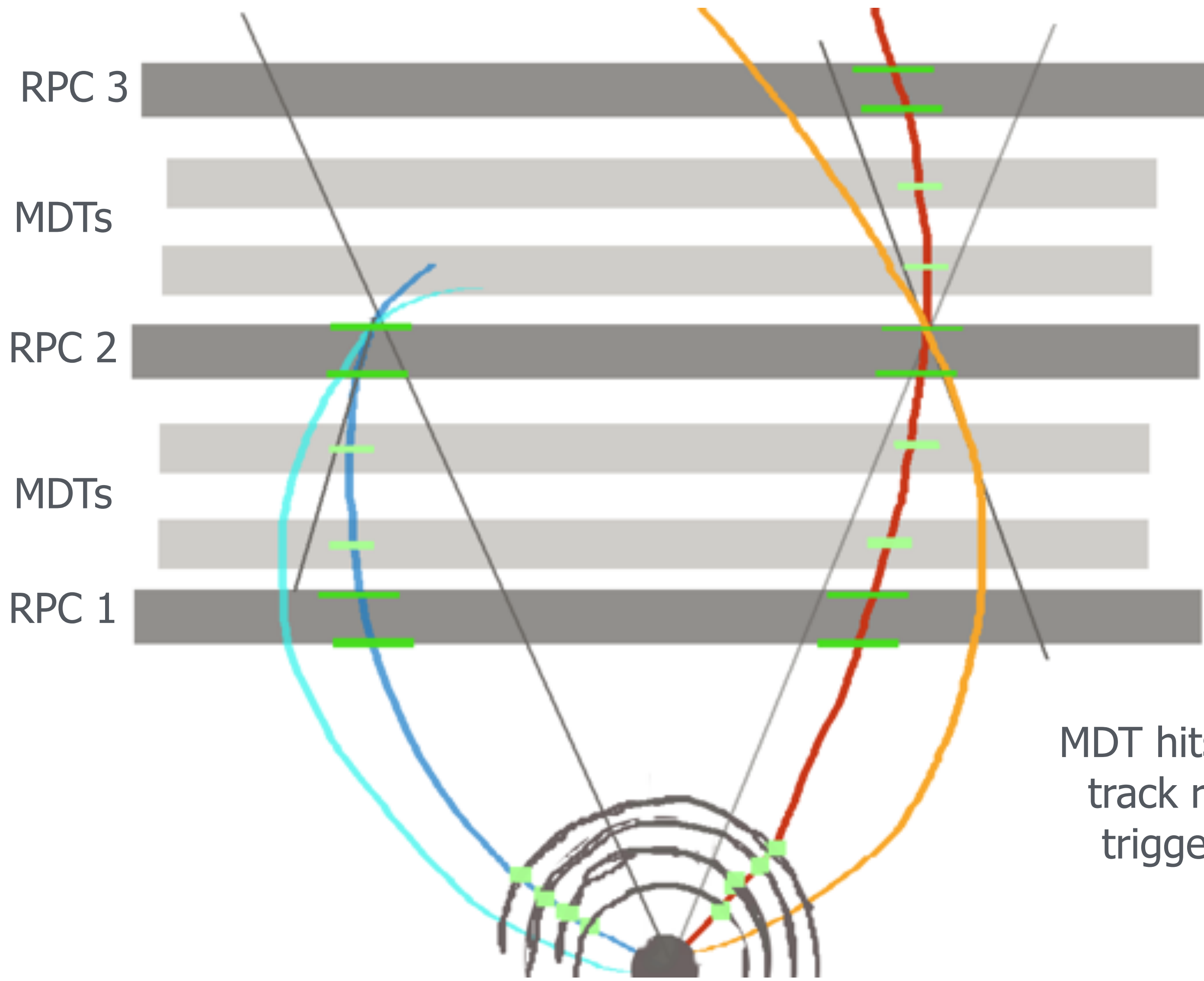


- Resistive Plate Chambers (RPC) are used for triggering based on coincidence hits within trigger window.
- low pT muons triggered by coincidence hits in RPC 1 + 2 planes.
- high pT muons triggered by coincidence hits in RPC1 + 2 and RPC 2 + 3.

Muon reconstruction at L1

Construction of Trigger Objects: Central Muons

HLT reconstruction



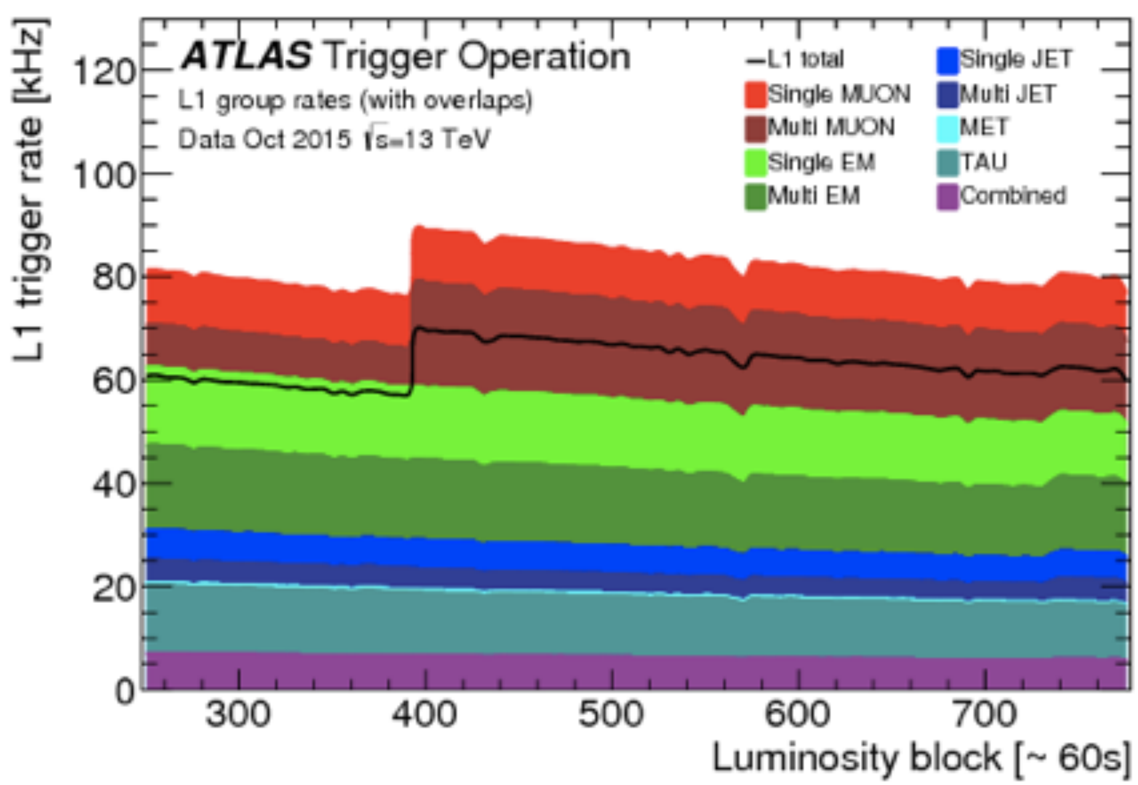
- Resistive Plate Chambers (RPC) are used for triggering
- Muon Drift Chambers (MDT) provide precision data.

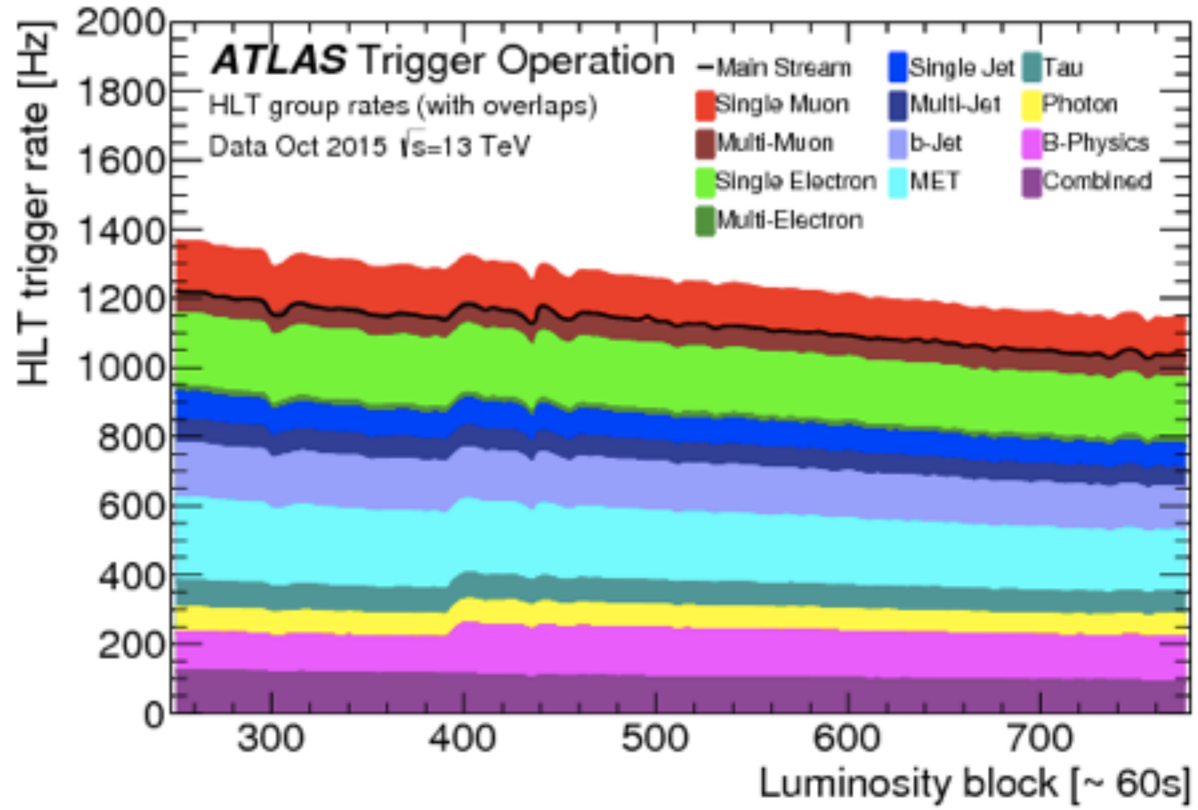
MDT hits within L1 RoI from RPC used for muon track reconstruction (offline-like algorithm): triggers for muons originating outside inner tracker.

MDT muon tracks extrapolated to inner detector hits to form combined tracks: triggers for muons from interaction vertex.

Muon reconstruction at HLT

Bandwidth needs to be shared between all trigger types …





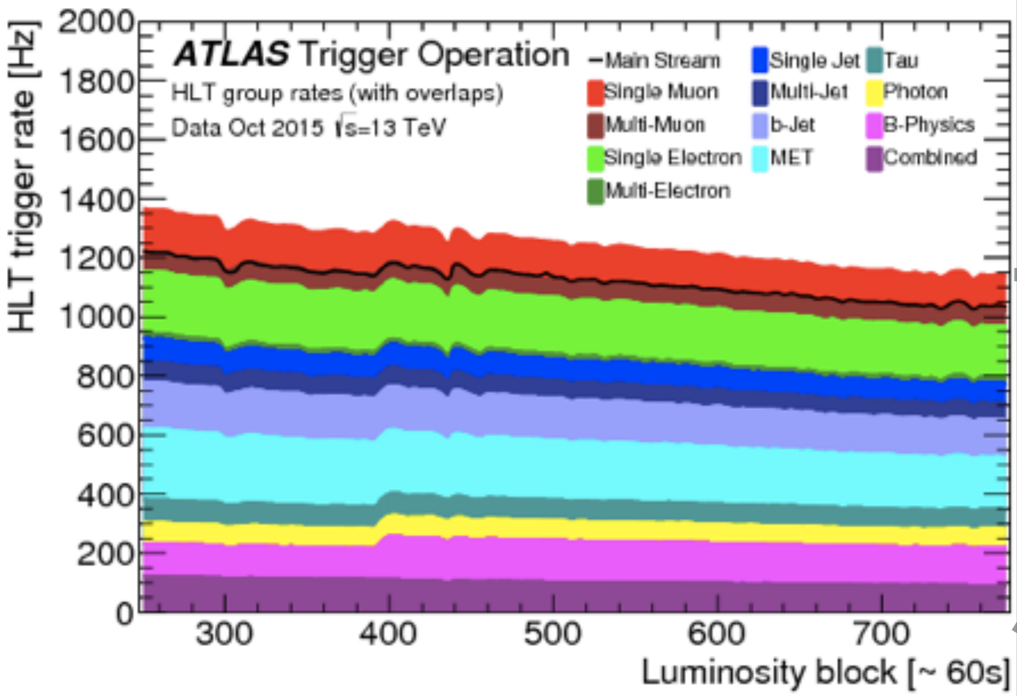
Level 1 Trigger (L1):

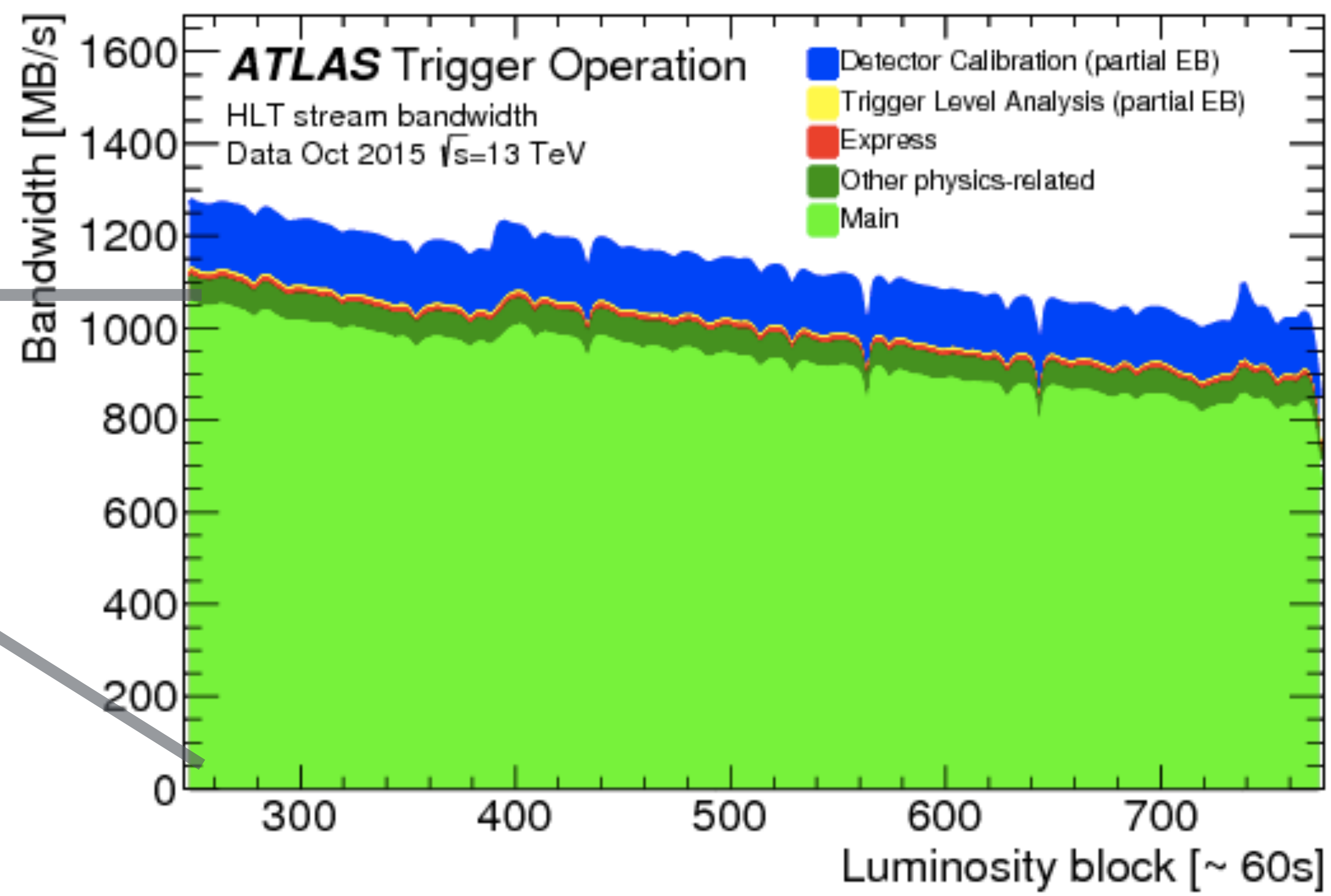
EM (electrons + photons), JETS, MUONS, TAUs, MISSING ENERGY, + multi object triggers + combined triggers

High Level Trigger (HLT):

electrons, photons, jets, b-jets, muons, taus, missing energy, + multi object triggers + combined triggers.

…. as well as with other data streams.





main data streams:

- Physics Main: data used for physics searches
- Calibration: data used for offline calibration
- Express: subset of physics main, reconstructed promptly for monitoring
- 'other physics related': for physics performance studies.

Trigger Menu is carefully put together prior to data taking.

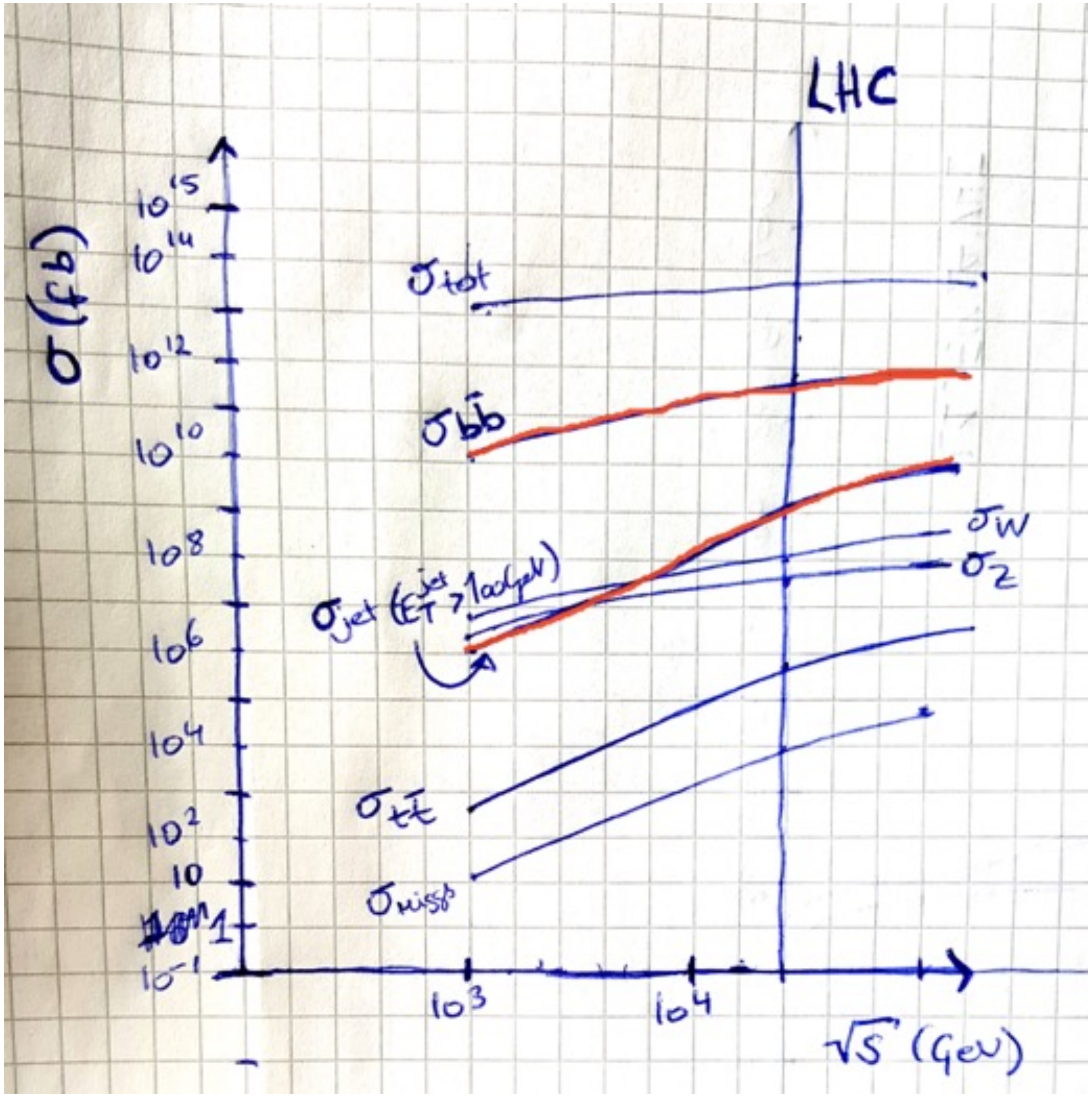
The ATLAS Trigger Menu

Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 1.2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	
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
One photon	One loose γ, $p_T > 145$ GeV	22 (i)	140	20	30
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
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	$2 \times 20, 75$	$2 \times 55, 100$	2.7	25
	Two b ($\epsilon = 60\%$) & two jets, each $p_T > 45$ GeV	4×15	4×35	3.5	56

- lower thresholds translate to higher rate.
- Large fraction of rate given to lepton triggers. e.g., compare:
  - lowest HLT tight electron trigger (at 26 GeV): 133 Hz
  - lowest single jet trigger (at 380 GeV): 38 Hz.

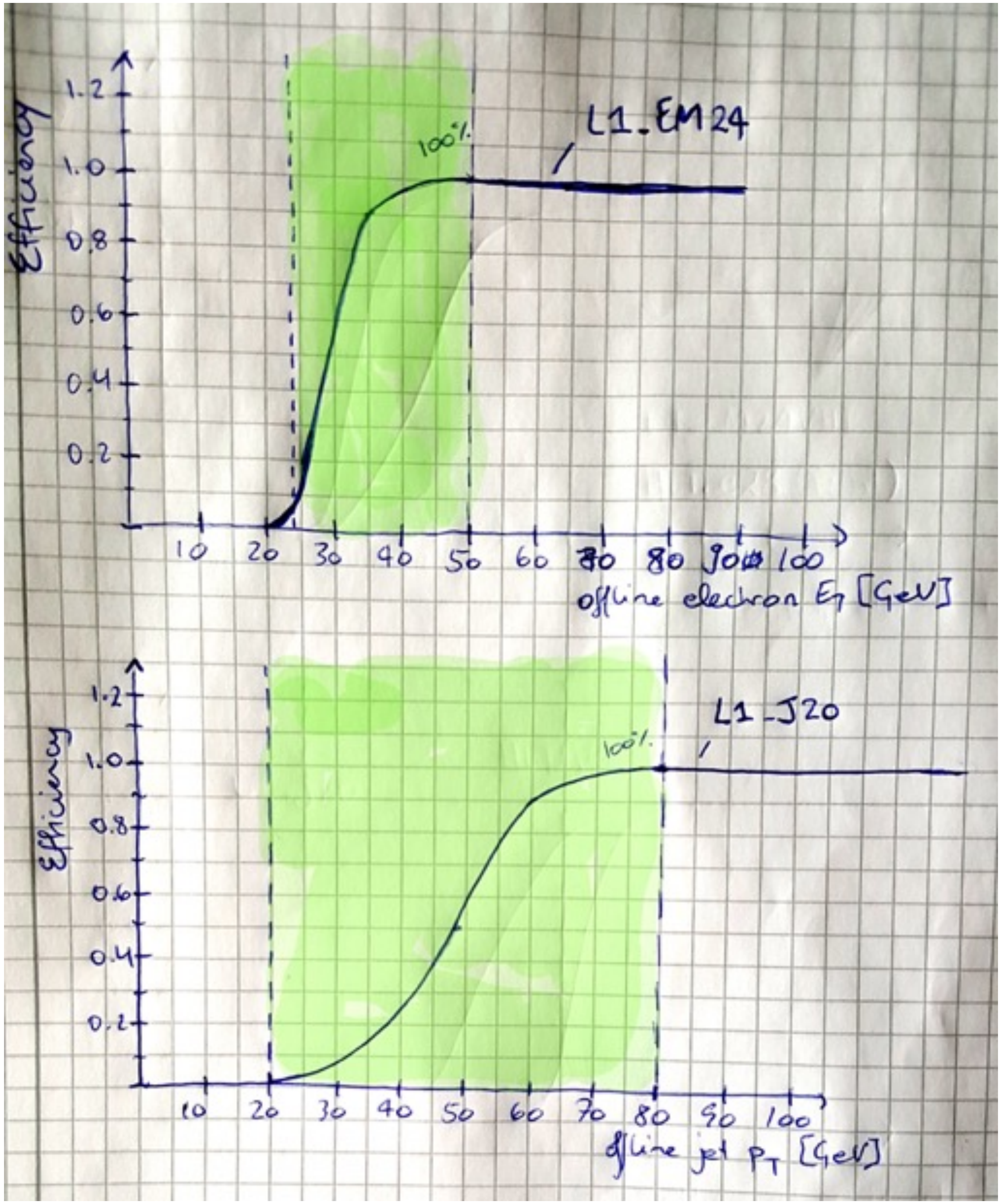
ATLAS trigger menu designed to be a good lepton trigger.
Why ? Because triggering on jets is challenging at a hadron collider.

Why jets are challenging: Reason 1



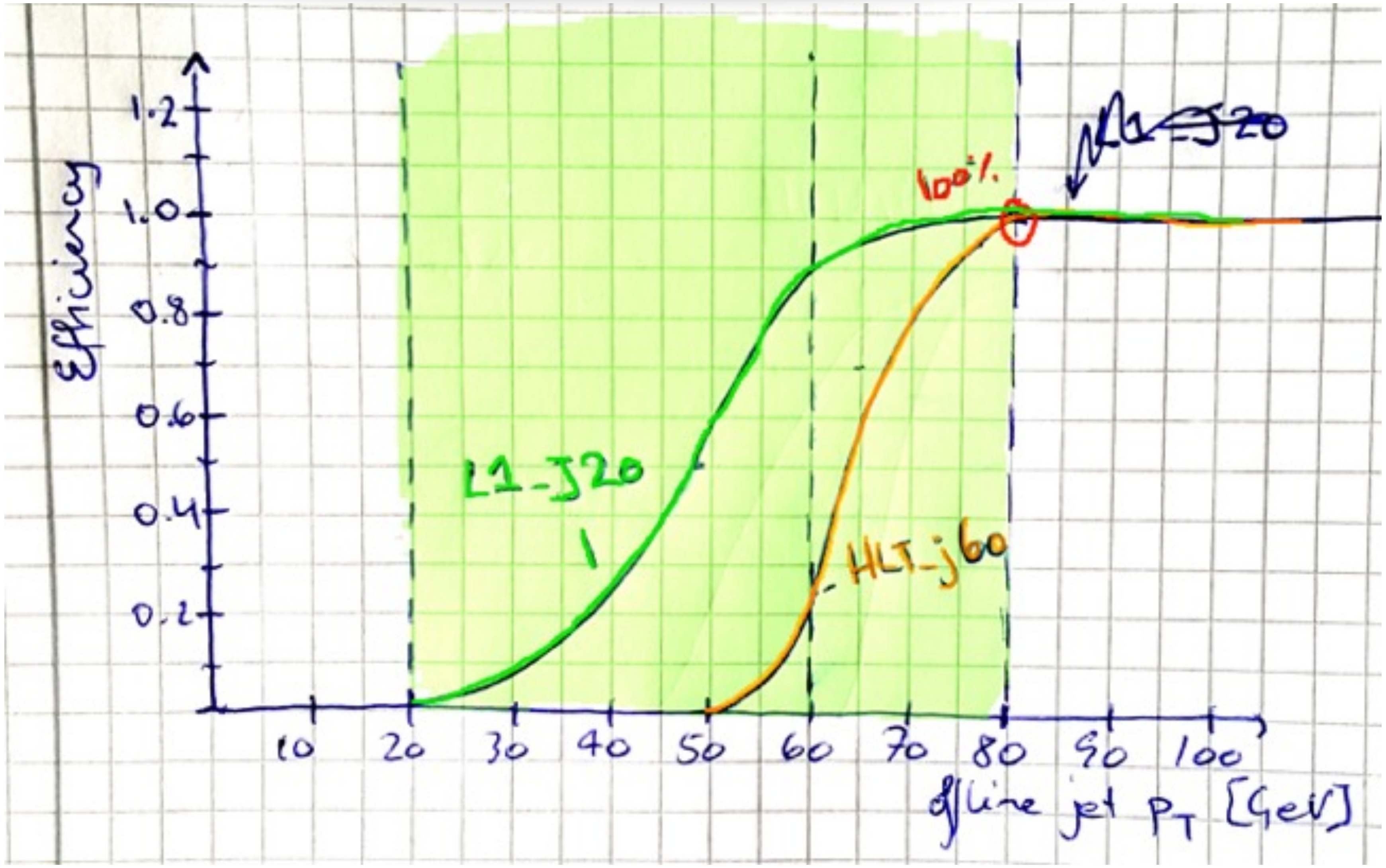
- jet processes are the dominant processes at hadron colliders by several orders of magnitude -> results in most events being very boring (if you don't care about parton distributions)
- If your signal signature is 1 or more jets , main background is QCD multijets: *very* small signal-to-noise ratio.
- Furthermore: QCD multijet background not well understood - background estimation tricky due to poor modelling.

Why jets are challenging: Reason 2



- Jet energy measurements suffer in resolution due to the non-compensating nature of the calorimeters and the fluctuating sampled energy within a jet depending on its electromagnetic content.
- Electromagnetic showers from electrons and photons are on the other hand fully sampled, and only suffer through energy loss to dead/inactive material.
- The 'trigger turn-on' (a curve defining the efficiency of a trigger as function of the offline 'true' energy of object) of Level-1 Jets rise to 100% efficiency more slowly, or over a larger energy range, compared to the turn-on of Level-1 EM triggers.

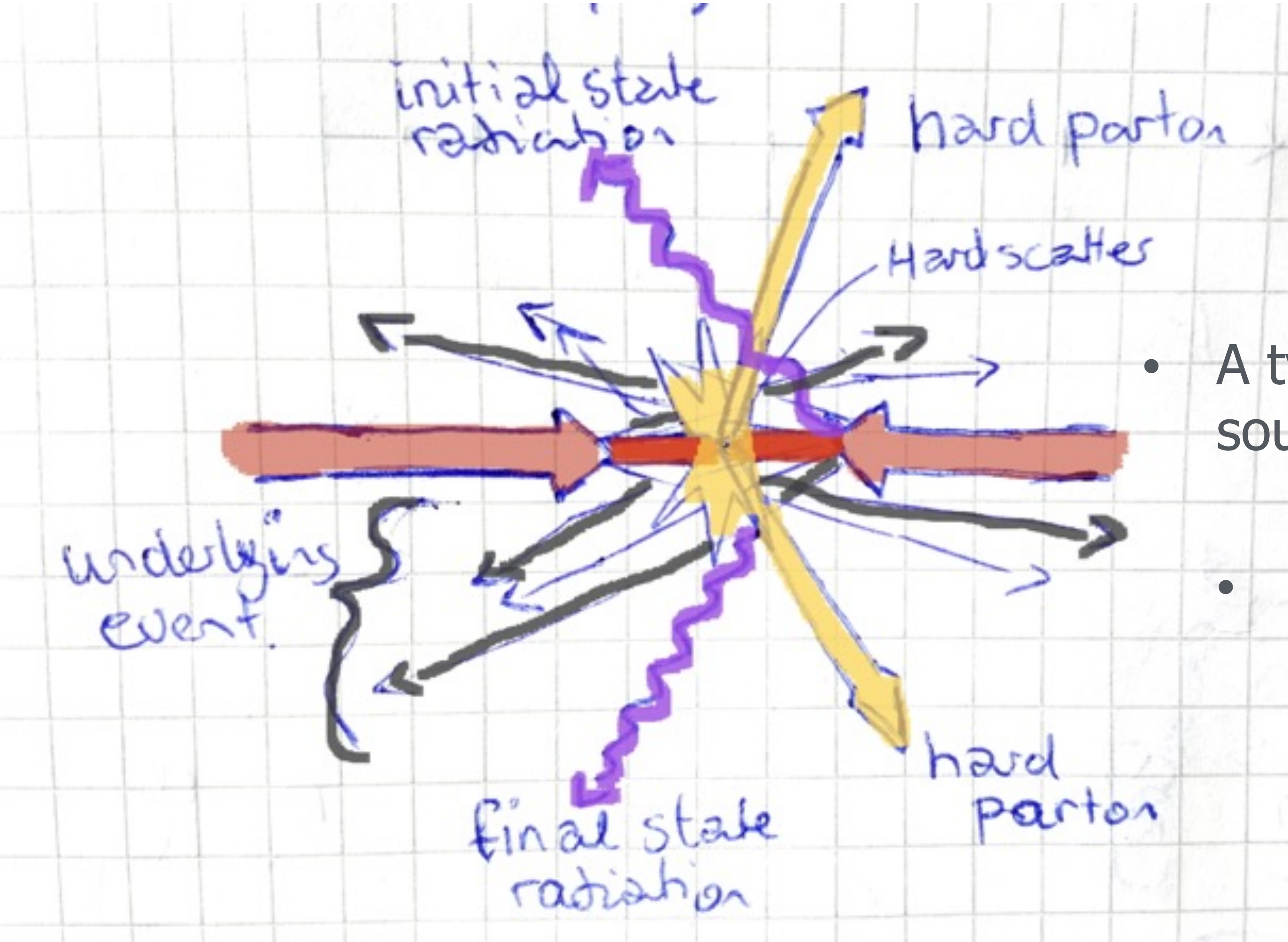
Why jets are challenging: Reason 2



- Every HLT trigger is seeded by an L1 trigger. An HLT trigger threshold is based on the point at which the L1 seed is fully efficient (as well as keeping within rate limits).

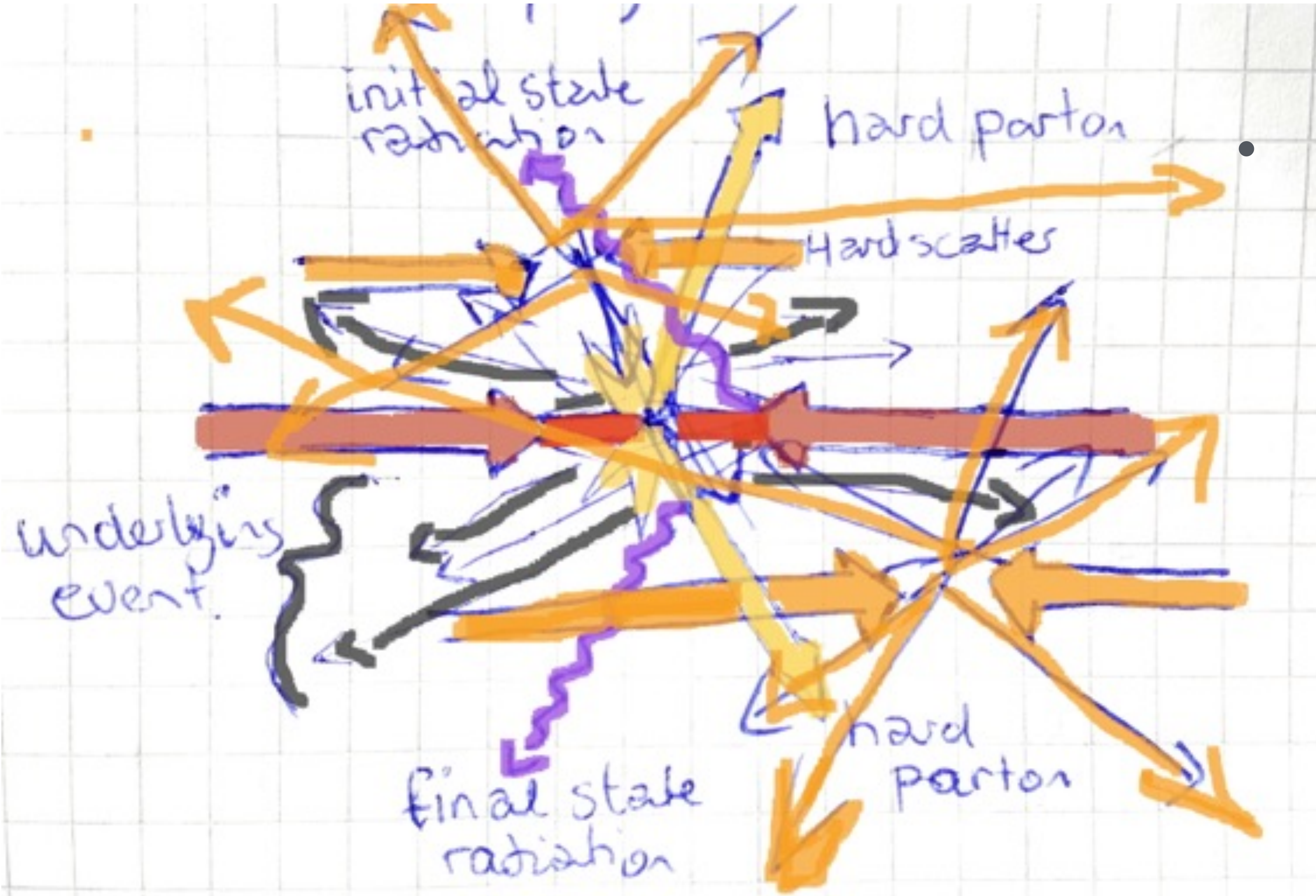
- The slow turn-on of L1 Jet triggers means HLT jet triggers use a higher threshold.

Why jets are challenging: Reason 2



- A typical event will have many sources of jet activity:
  - initial state radiation, final state radiation, underlying event

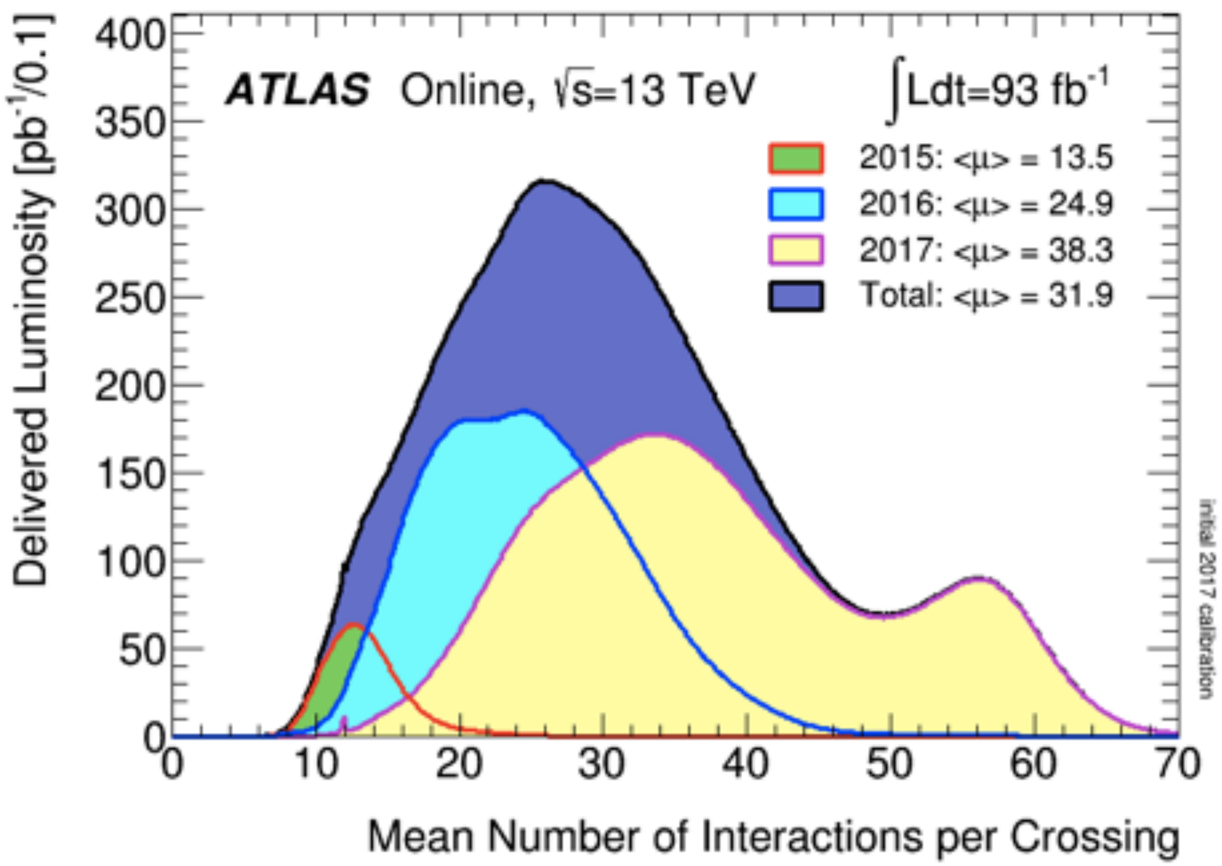
Reason 3: Pile-up Jets



- A typical event will have many sources of jet activity:
  - initial state radiation, final state radiation, underlying event
  - as well as **pile-up:** interactions from other protons in the same interacting bunch.

- Jet triggers very sensitive to pile-up jet activity:
  - energy from pile-up activity contribute to jet energies, so that triggers are more likely fired.

Reason 3: Pile-up Jets

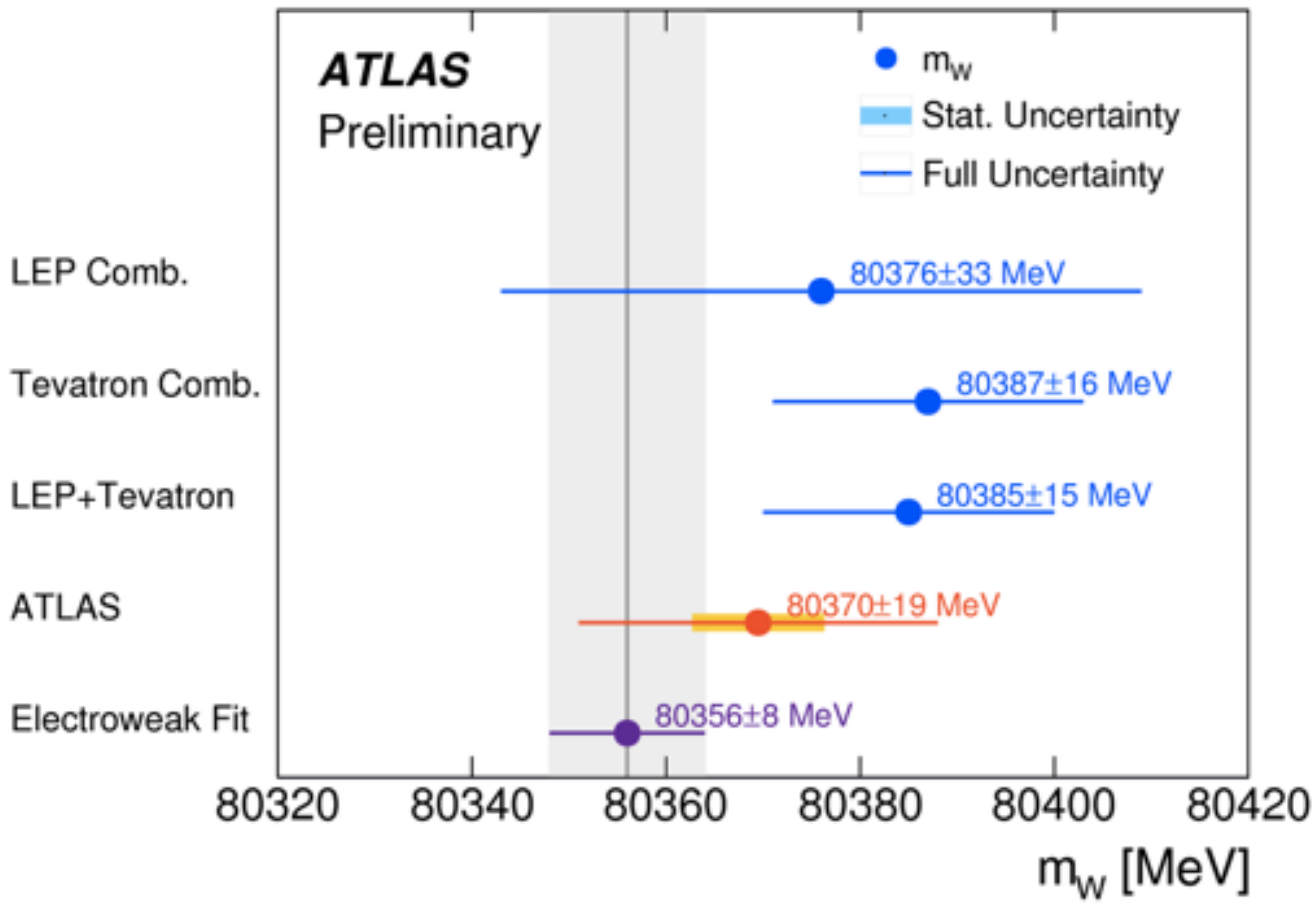


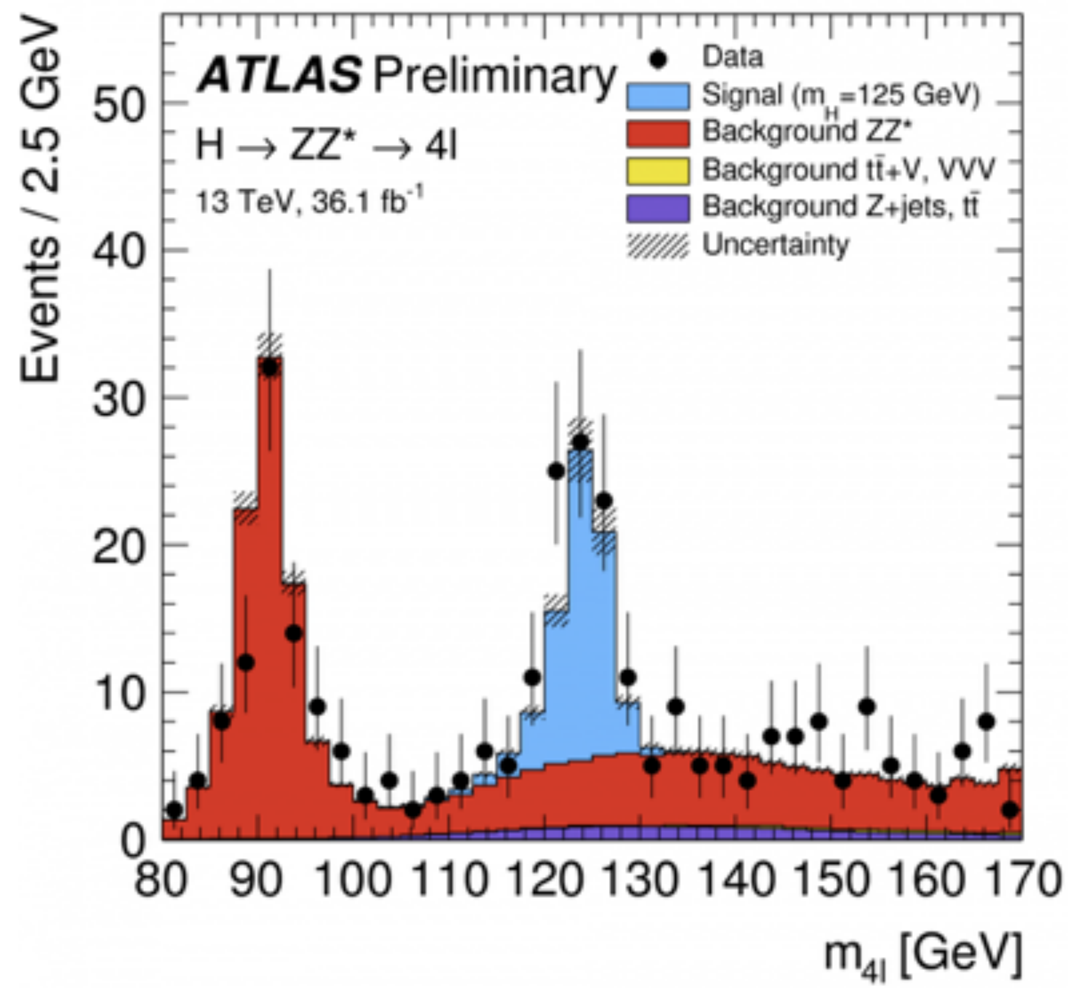
Lowest HLT jet trigger thresholds

year	jet energy [GeV]
2015	360
2016	380
2017	450

- LHC has been increasingly raising the instantaneous luminosity of collisions, which increases the average number of interactions within a collision.
- This has been the main reason why jet trigger thresholds increase every year.

ATLAS precision measurements based on lepton physics: some examples





- precision measurement of the W boson mass (arXiv:1701.07240)

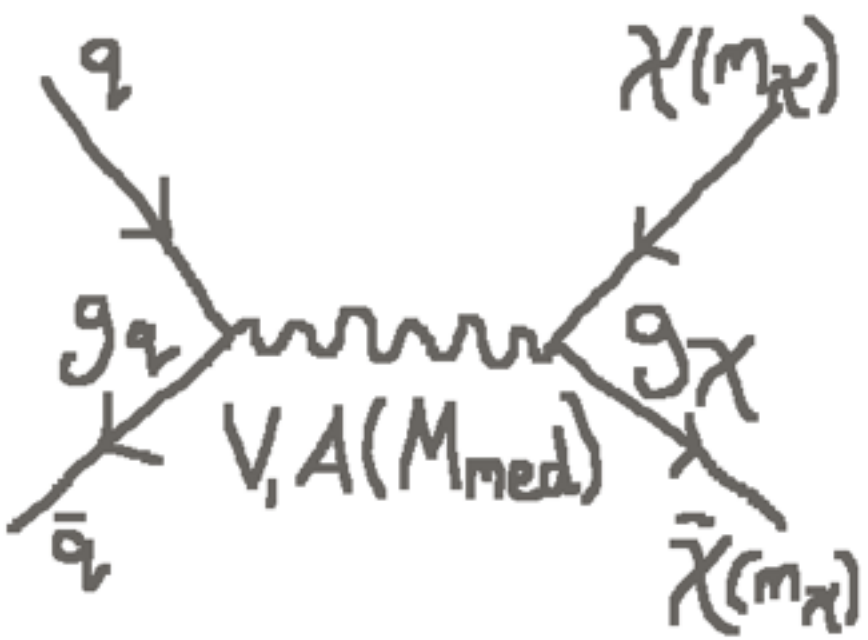
- inclusive and differential cross-section measurements with H->ZZ*-> 4 leptons (ATLAS-CONF-2017-032)

ATLAS Trigger Menu Summary

- Triggering is interesting business, because there are necessarily biases as we need to be highly selective when we can only record 0.0025% of delivered events.
- ATLAS trigger menu priorities high pT items, and general signatures (single object triggers).
- ATLAS trigger menu has a heavy focus on lepton triggers. This is because
  - Triggering on jets is challenging: large background, weaker turn-on curves and sensitive to pile-up.
  - Electromagnetic signatures are much cleaner.
- This has allowed some really nice precision measurements and strong constraints for SUSY/DM leptonic signatures.
- Next up: How does one deal with the jet challenge and continue improving jet searches at ATLAS ?

Physics Case: Dark matter in dijets

- We do not know what dark matter looks like.
- Thus far there has been no evidence of dark matter at colliders.
- Search strategy: search for a **generic signal** of a **simplified dark matter model**, without getting entangled in complexities of the full theory at energies not accessible to the collider.
- A simple DM model contains following parameters:

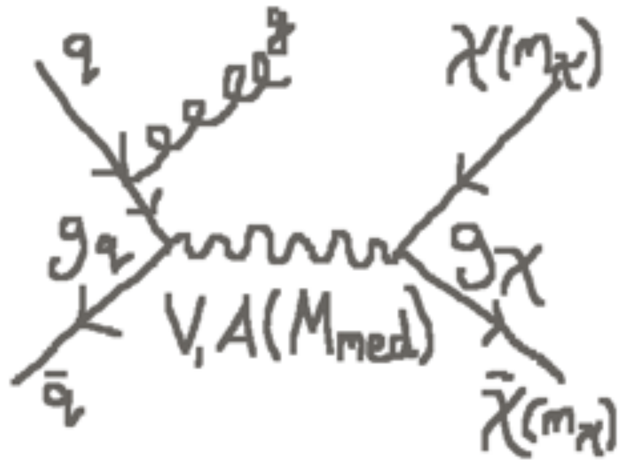


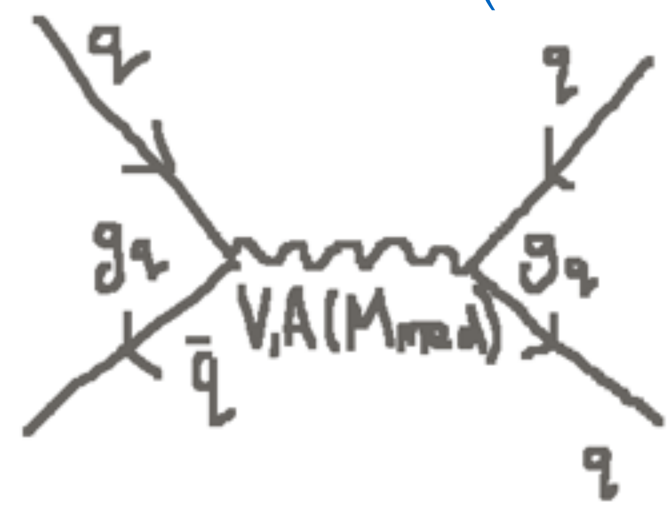
- **m_χ**: mass of dark matter particle.
- **M_{med}**: or Z′, mass of vector or axial vector mediator particle with couplings to dark sector as well as Standard Model sector.
- **g_q** : mediator coupling to SM fermions (quarks only if leptophobic mediator).
- **g_χ**: mediator coupling to dark matter particle.

Physics Case: Dark matter in dijets

- Looking at s-channels

probed parameters:
Z' (mediator) mass and g_q



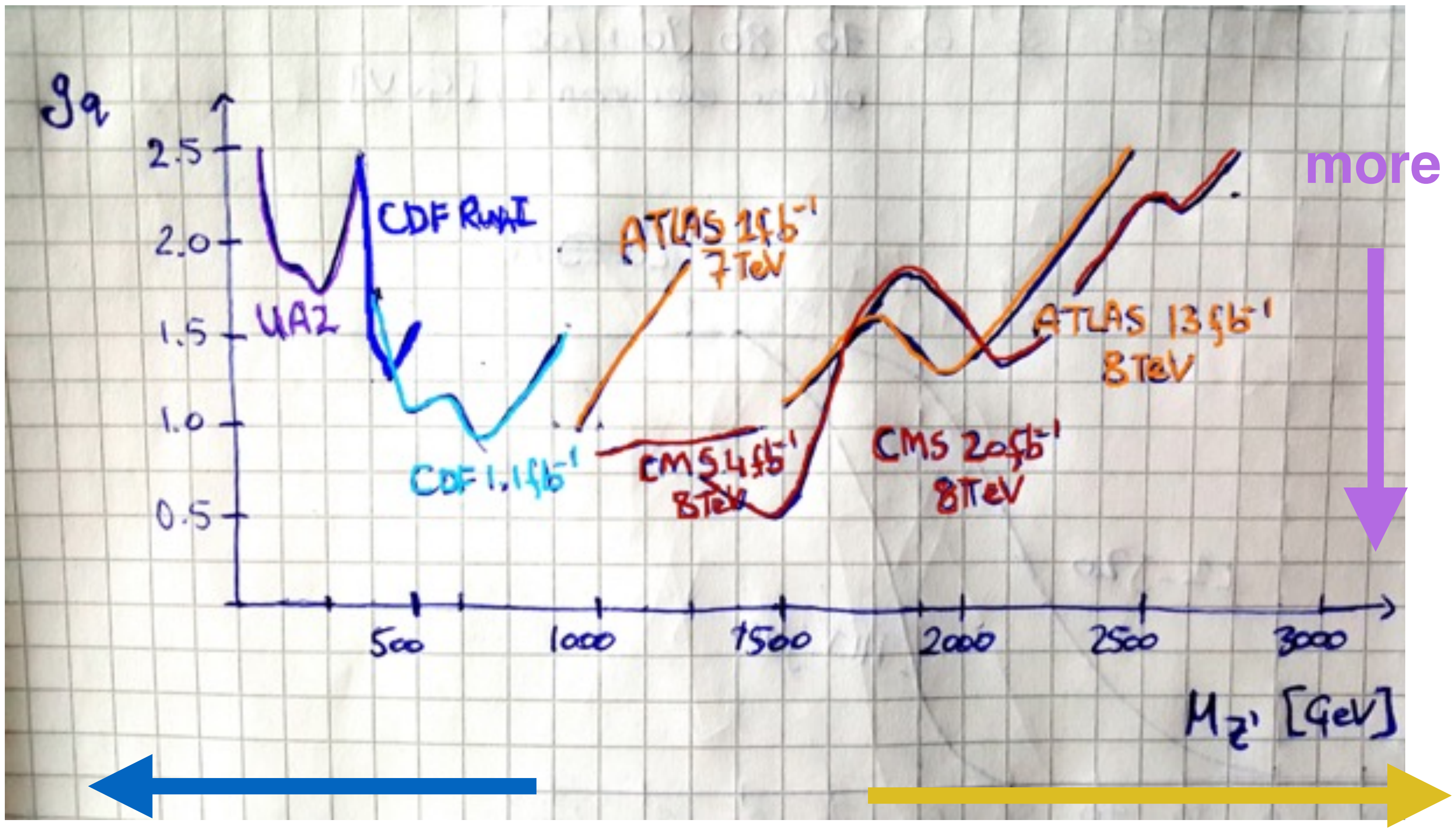


- We can look for dark matter decay products, e.g. mono-jet + missing energy
- We can look for SM decay products, e.g. dijets.

here, we focus on this

- There is nothing special about 2 jets in an event at a hadron collider: QCD multijet production dominates and is an irreducible background, ranging across entire pT range. We know it is smoothly falling with pT.
- The s-channel coupling will however provide a narrow resonance at the mediator mass.
- strategy: search for a tiny but significant (larger than statistical uncertainty) fluctuation in the smooth QCD background, which could corresponds to a narrow signal.

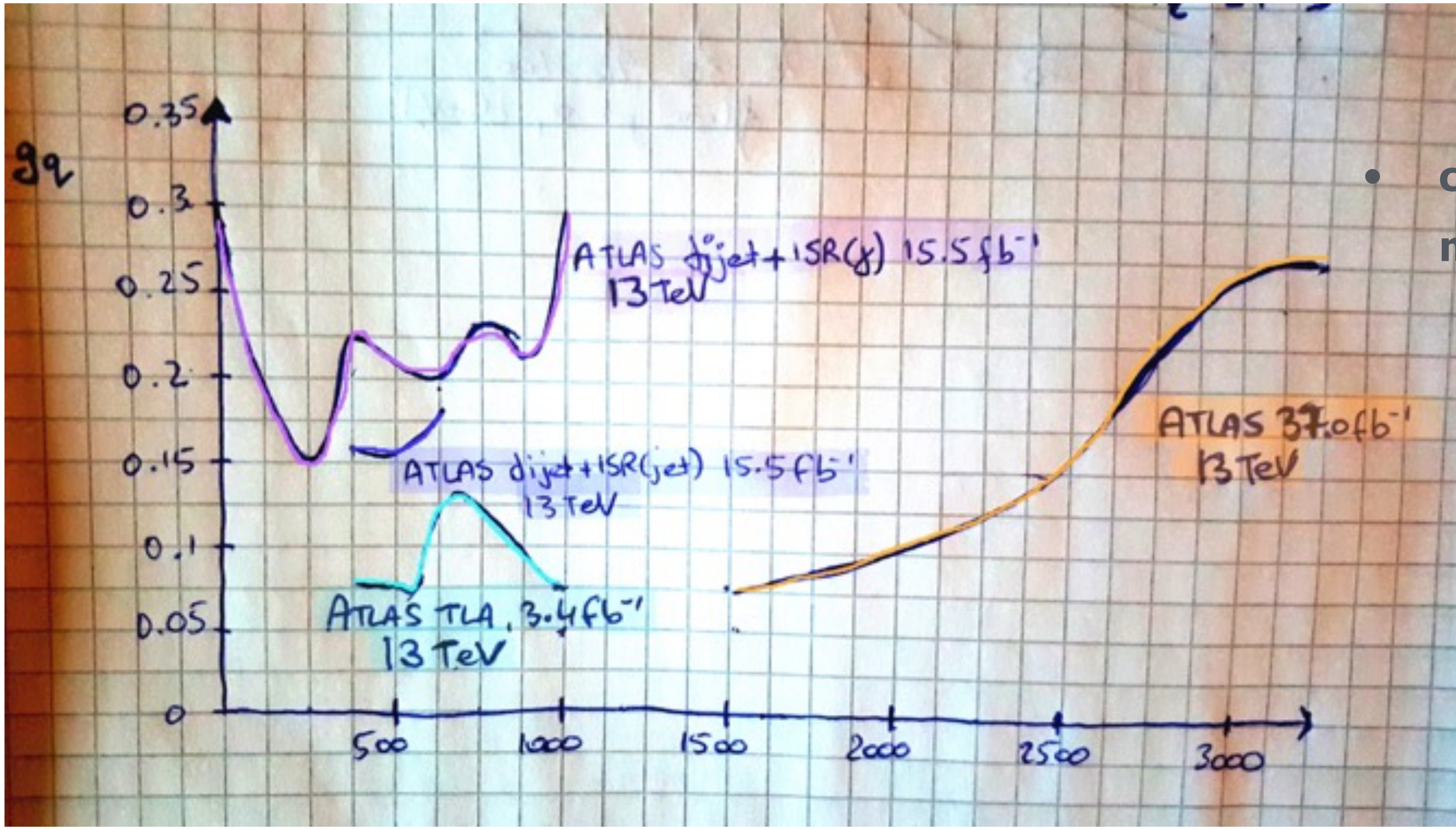
Z′ constraints from dijet searches prior to LHC Run 2



- **coupling-mass limit plot of a Z′ mediator:**
  - tighter limits are set by collecting more data
  - limits at higher masses are set with higher colliding energies
  - limits at lower masses are set by lower trigger thresholds.

- Prior to the LHC, previous experiments have conducted dijet resonance searches, setting limits on couplings to Z′ of mass between ~ 80 - 1000 GeV
- ATLAS and CMS set further limits at masses ~ 1000 + GeV.
- The higher jet thresholds at LHC experiments meant, despite greater statistics, lower Z′ masses were being left unprobed.

Z′ constraints in LHC Run 2

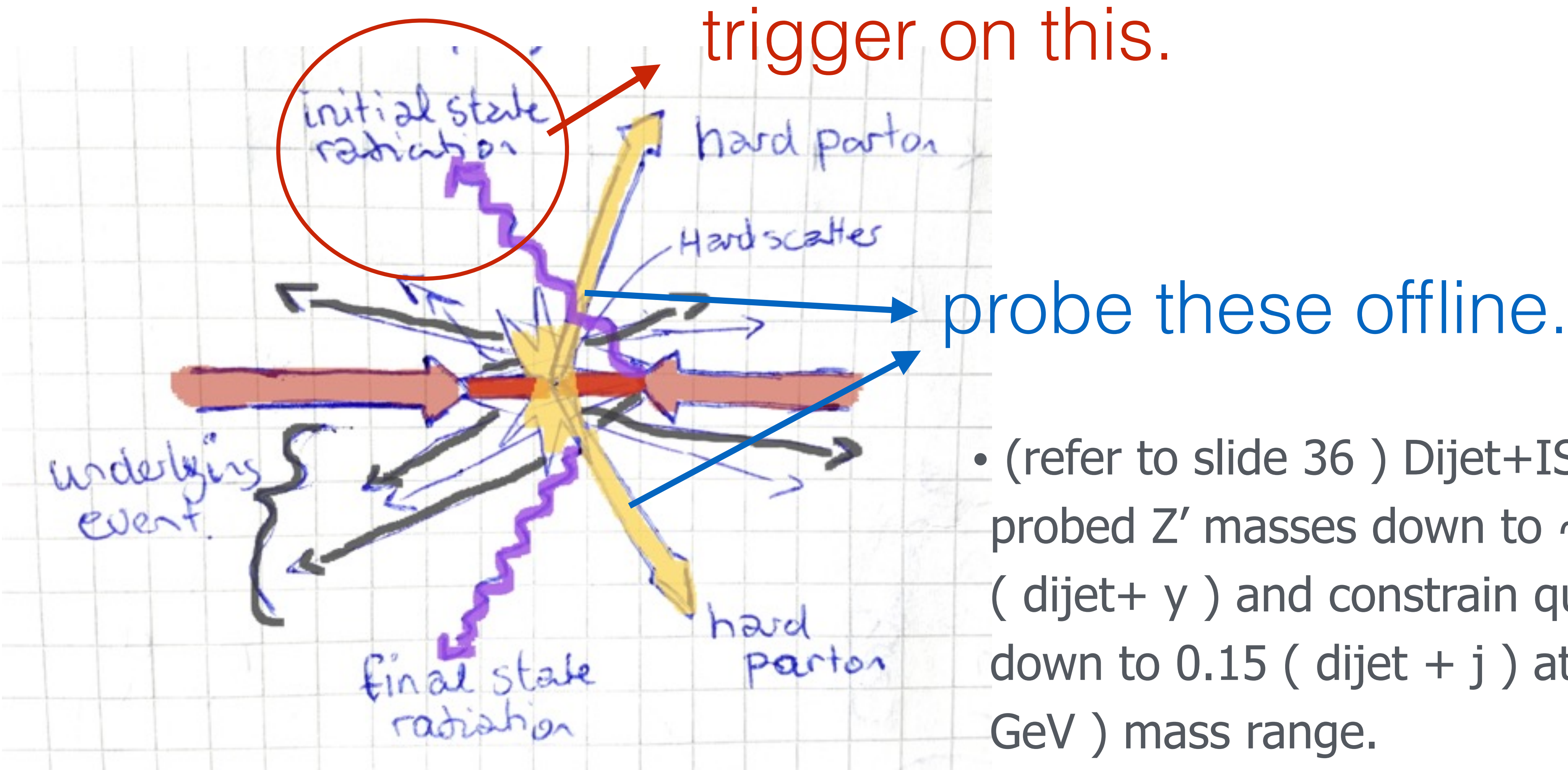


- **coupling-mass limit plot of a Z′ mediator, ATLAS results Run 2**

- In Run 2, in order to cover low mass range and exploit the high statistics at the LHC, new methods were employed by CMS and ATLAS:
  - Dijet + ISR
  - Trigger Object Level Analysis (TLA): Analysis on trigger jets.

Probing low dijet masses: Dijet + ISR

- **idea**: make use of other signals in event, such as **initial state radiation**.
- trigger on gamma radiation:
  - low photon trigger threshold - extend to very low mass range.
- trigger on gluon radiation:
  - higher statistics compared to gamma radiation - tighter limits
  - higher trigger threshold - extension to low mass not as low.



- (refer to slide 36) Dijet+ISR method has probed Z′ masses down to ~170 GeV (dijet+ γ) and constrain quark couplings down to 0.15 (dijet + j) at low (< 500 GeV) mass range.

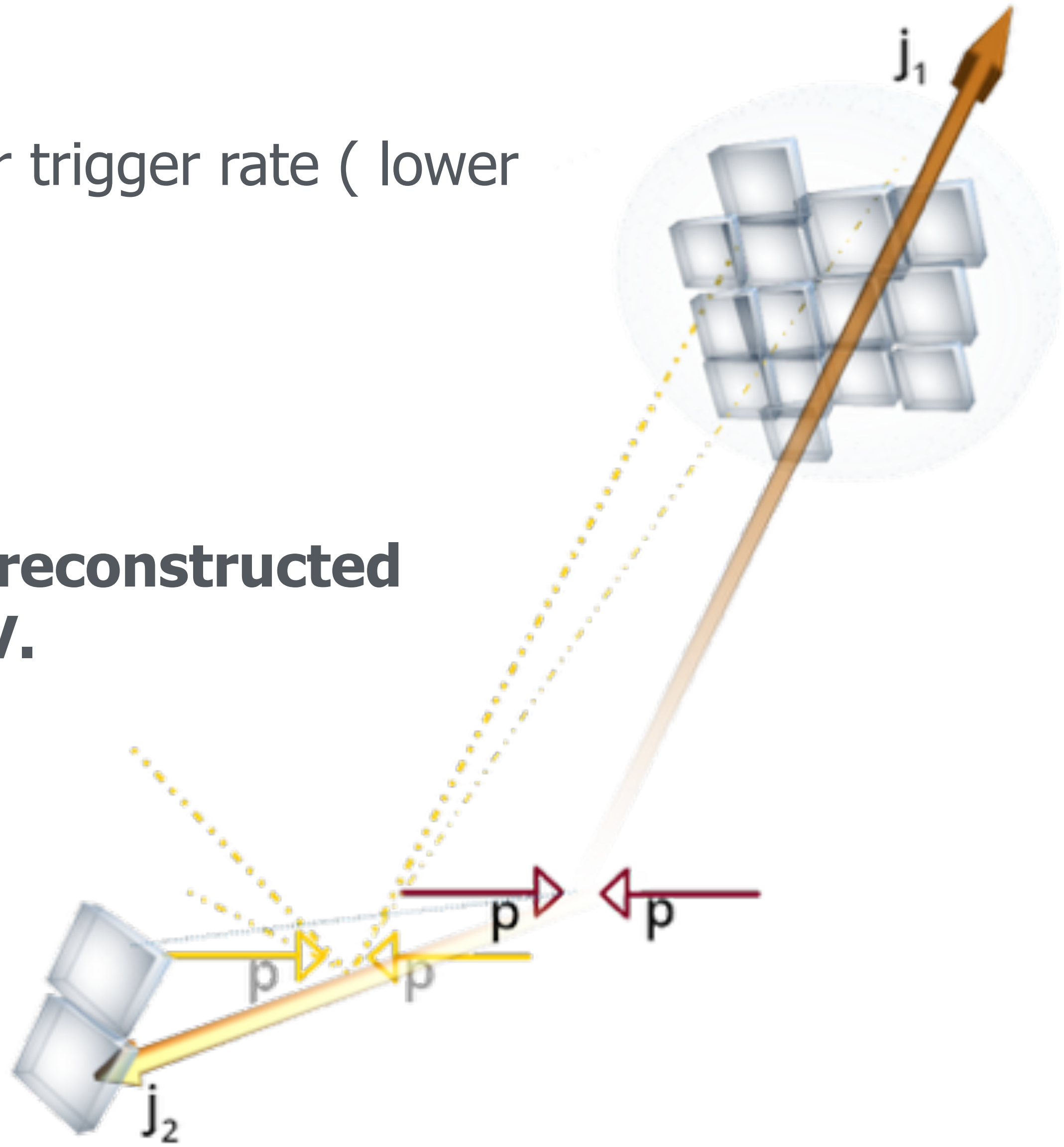
Probing low dijet masses: TLA

- **Idea**: only save what we need for a dijet search in order to reduce event size, as

Bandwidth = Event size x trigger rate

- smaller event size means can allow higher trigger rate (lower threshold).
- Info that is saved (basically):

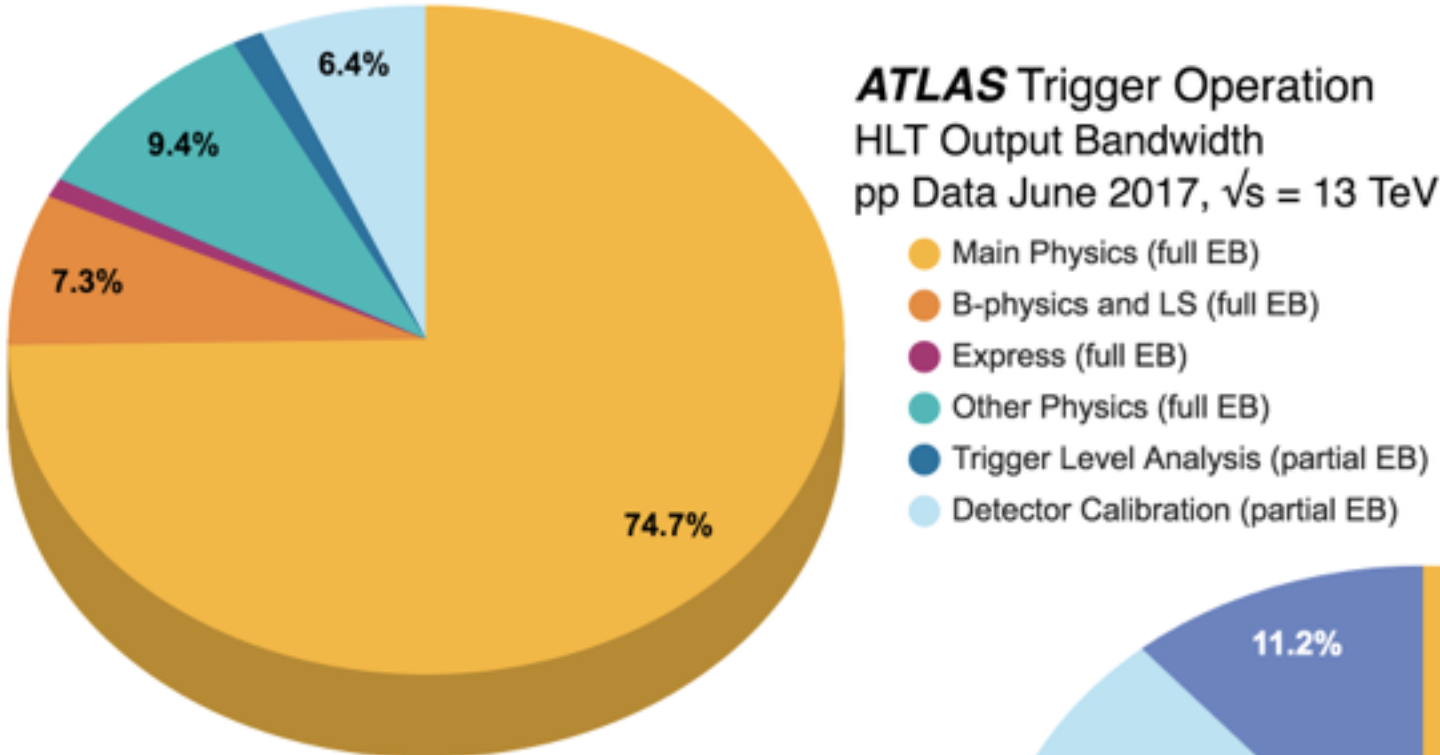
four-momenta of all HLT-reconstructed jets > 20 GeV.



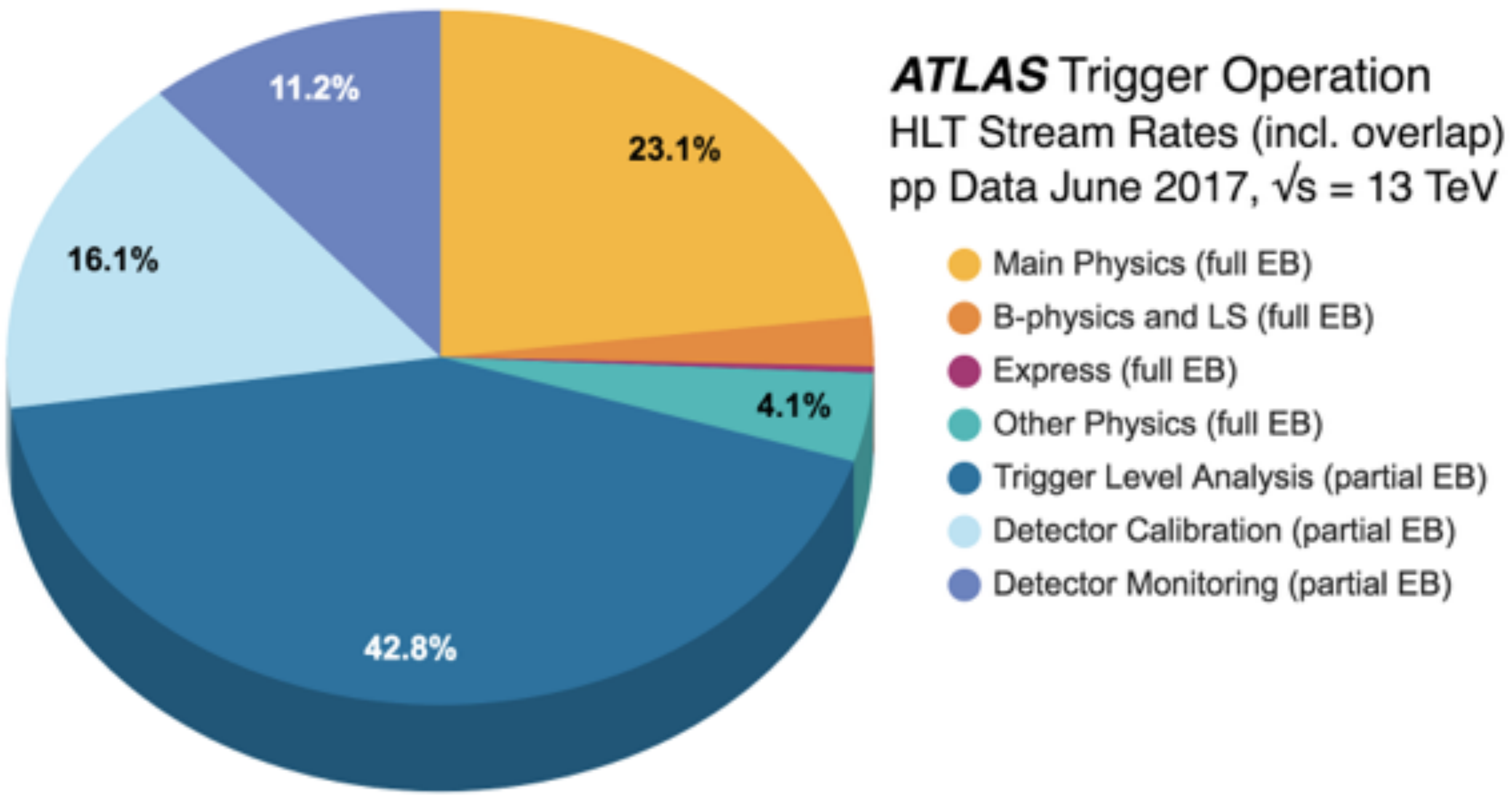
- This method is known as the Trigger Object Level Analysis (TLA)

Probing low dijet masses: TLA

- Event size of a Physics Event: **~ 2MB** ; Event size of a TLA event: **~ 10 kB**.

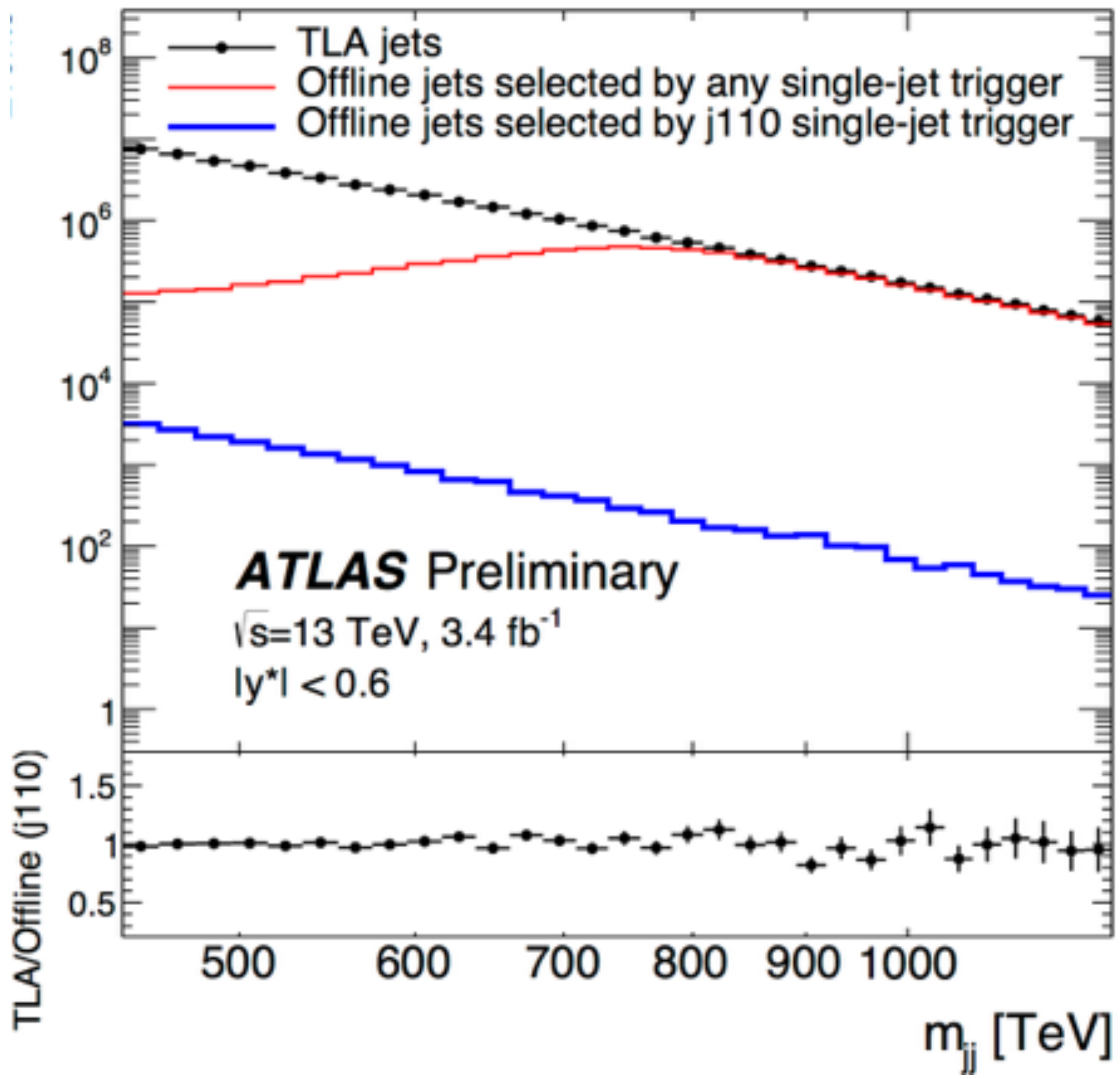


- Due to the small event size, the TLA stream occupies less than the 5% of the total bandwidth.



- Because of the small bandwidth, TLA can operate at a larger rate, allowing it to seed straight off the lowest Level-1 Jet trigger.

Probing low dijet masses: TLA



- seeding based on lowest L1 Jet trigger: accept all events that contain a Level-1 Jet > 100 GeV.
- TLA regains all the statistics that are lost from throttling HLT jet triggers.
- one disadvantage: no tracking info for offline calibration, thus TLA HLT jets poorer energy resolution than offline jets.

- (refer to slide 36) TLA method has probed Z' masses down to ~420 GeV and constrained quark couplings down to ~0.08.

Probing further ?

- TLA exploits full LHC stat power, however it is still limited by the lowest Level-1 jet trigger threshold.

- Pile-up conditions have pushed also Level-1 thresholds higher.

Lowest L1 jet trigger thresholds

year	jet energy [GeV]
2015	75
2016	100
2016	100

- How can one probe masses even further with full statistics ?
  -> Next week's lecture !

further reading

- Details on simplified Dark Matter benchmark models (vector, axial-vector, mixed mediators): https://arxiv.org/pdf/1507.00966.pdf

- Coupling-mass mapping of dijet resonance searches: https://arxiv.org/abs/1306.2629

- TLA CONF note: http://inspirehep.net/record/1470774