ATLAS experiment trigger menu and operation during heavy-ion data taking

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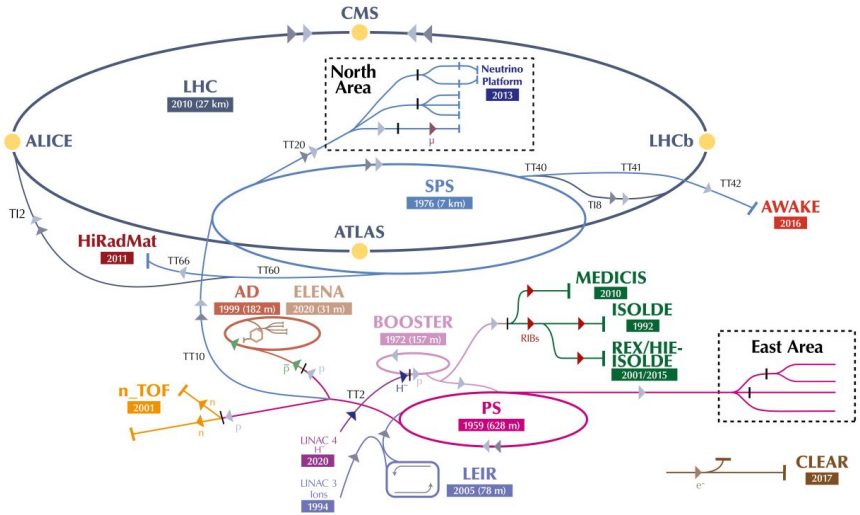
NO1 seminar, 9.12.2025

Outline

- **Ions in LHC** - where, when, why?
- **HI physics program** - pick your favourite physics from our menu!
- **ATLAS and its trigger system** - how it works? why we need it?
- **Advances in HI trigger strategy** - what's new in recent years?
- **HI trigger operations** - challenges and why it's fun

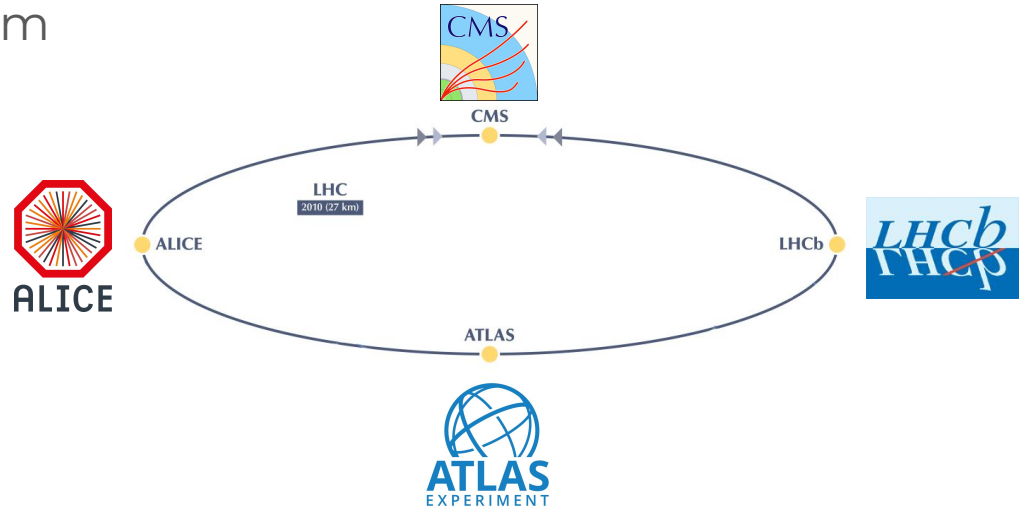
LHC

- LHC is the last one and largest in the CERN accelerator complex
- It uses the infrastructure from previous colliders



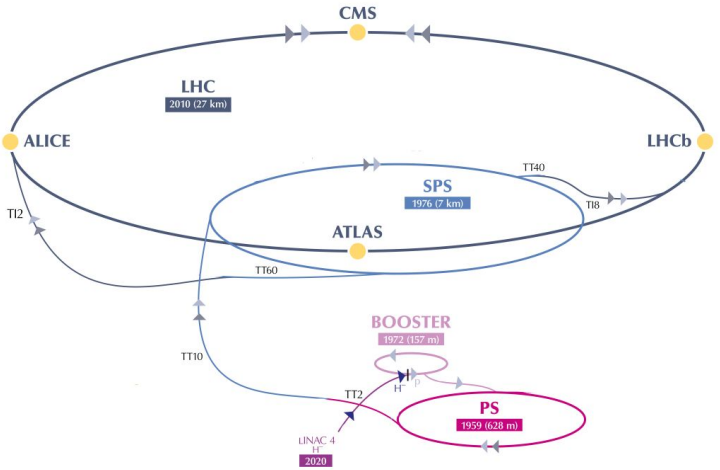
LHC experiments

- LHC is the last one and largest in the CERN accelerator complex
- It uses the infrastructure from previous colliders
- Four big experiments operate at the LHC
  - ATLAS/CMS - with a goal to discover Higgs boson and test SM
  - ALICE - to study ion collisions
  - LHCb - to study CP symmetry breaking



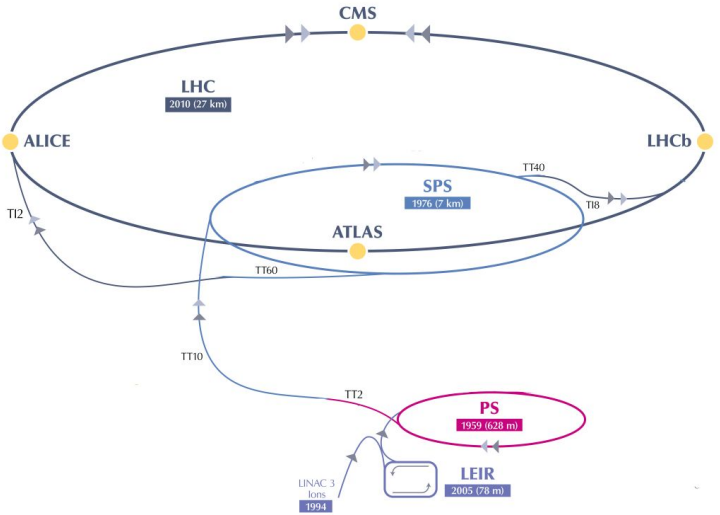
LHC - colliding pp

- Most of the year LHC collides bunches of protons
  - pp collisions possible at very high luminosities, up to **2.4×10^{34} cm^{-2}s^{-1}**
  - allowed to discover Higgs boson and to study its properties
  - a lot of collision data available: precise test of Standard Model and Beyond Standard Model searches performed
  - interest from all four big experiments at LHC



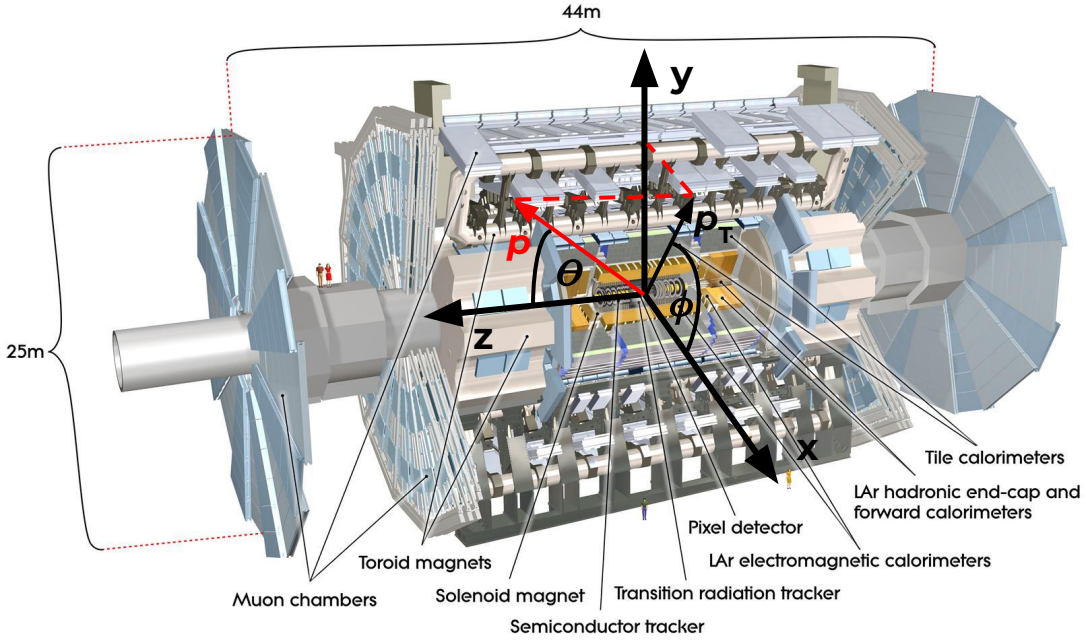
LHC - colliding ions

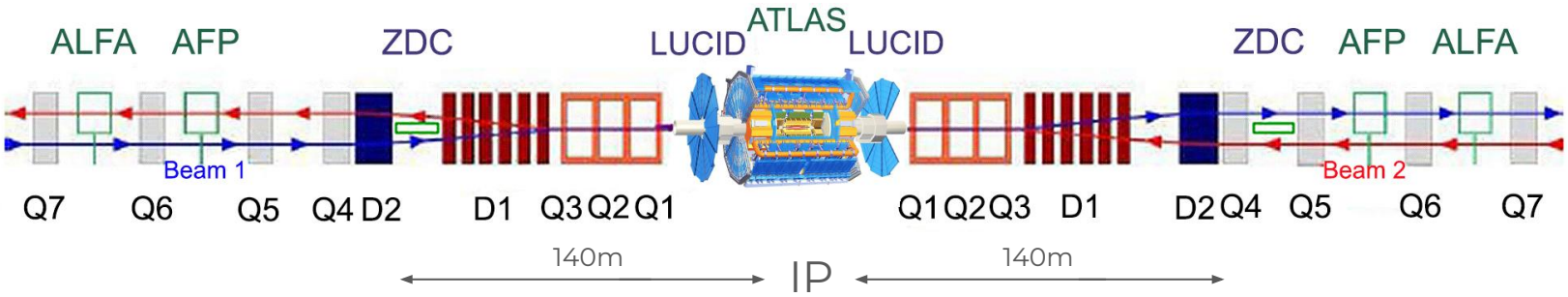
- Few weeks each year are dedicated for ion collisions
  - lower beam energy than in pp - accelerated protons “carry” neutrons
  - lower luminosities than in pp (up to **6.7 x 10^{27} $cm^{-2}s^{-1}$**) - due to lower beam intensities and lower number of bunches
  - typically few weeks at the end of the year
- Primary goal: study properties of quark-gluon plasma (QGP) with Pb+Pb collisions
- Unique capabilities of each large experiment: all involved in heavy-ion data taking
- This year also started program for light ions with O+O and Ne+Ne collisions



ATLAS detector

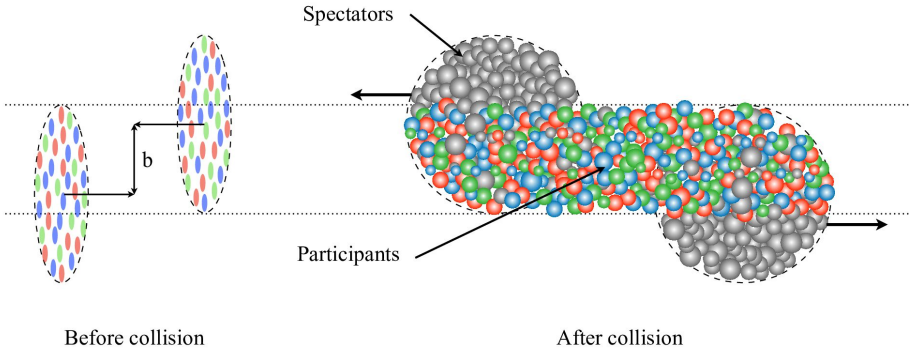
- Large general-purpose detector with almost 4π coverage
  $\eta = -\log(\tan(\theta/2))$
- Inner detector $|\eta|<2.5$
- Muon system $|\eta|<2.7$
- Calorimetry out to $|\eta|<4.9$
- Zero-Degree-Calorimeters (ZDC) capture neutral particles with $|\eta|>8.3$

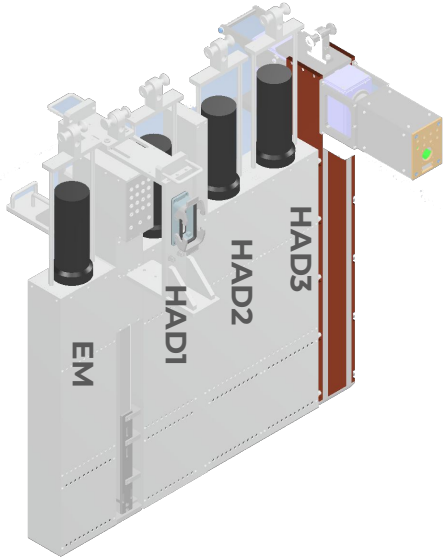




Role of ZDC

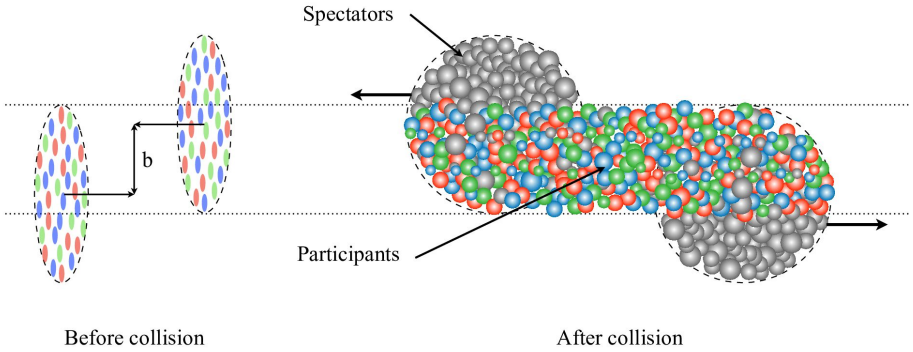
- Ions can collide at various impact parameters - *b*
- Spectator neutrons - outside the overlap region - travel along the beam direction
- ZDC with coverage of $|\eta| > 8.3$ provides information on number of detected spectator neutrons

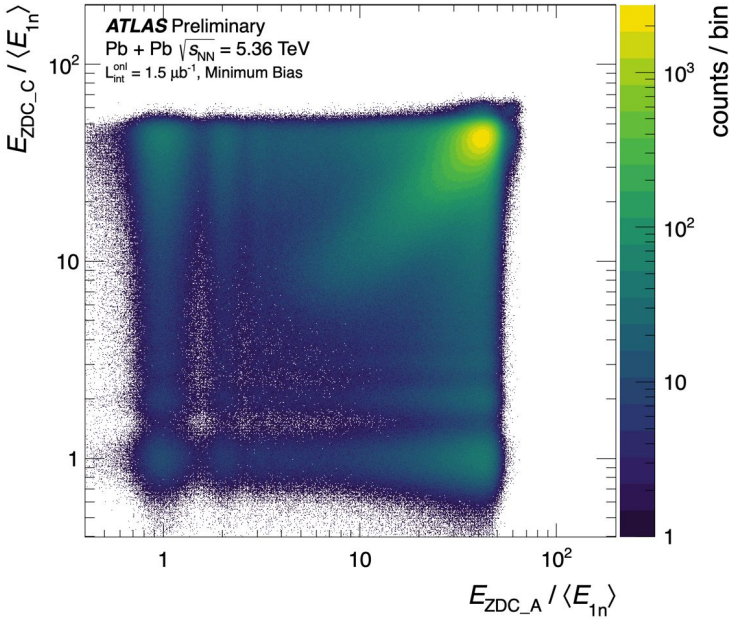




Role of ZDC

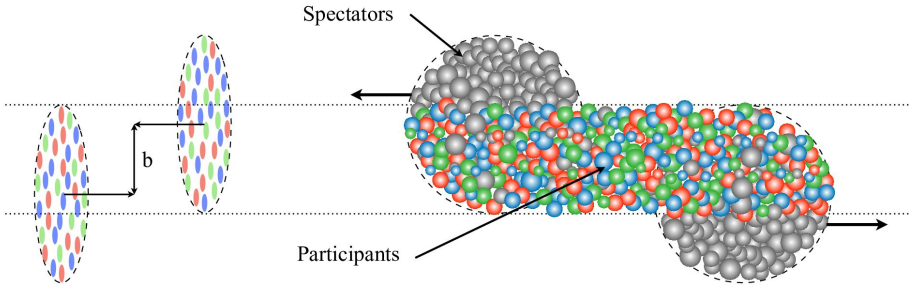
- Ions can collide at various impact parameters - *b*
- Spectator neutrons - outside the overlap region - travel along the beam direction
- ZDC with coverage of $|\eta| > 8.3$ provides information on number of detected spectator neutrons
- Both very large overlap and very smal overlap produce low number of neutrons - can be used in event selection

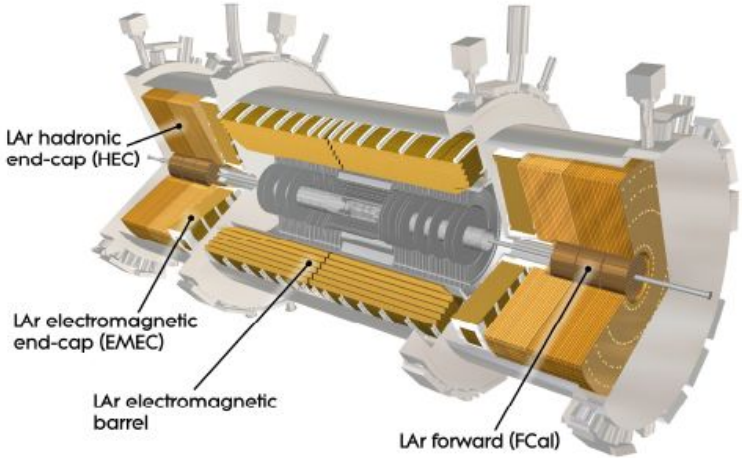




Forward Calorimeters

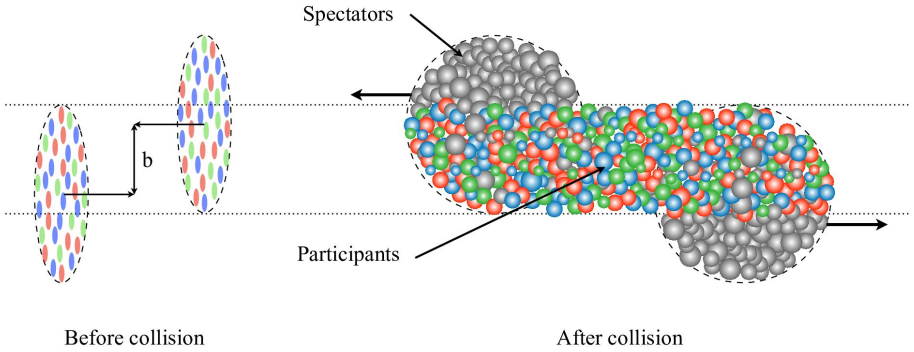
- Forward Calorimeter - FCal covering $3.2 < |\eta| < 4.9$
- Multiple interactions in overlap region - up to thousands of charged particles produced

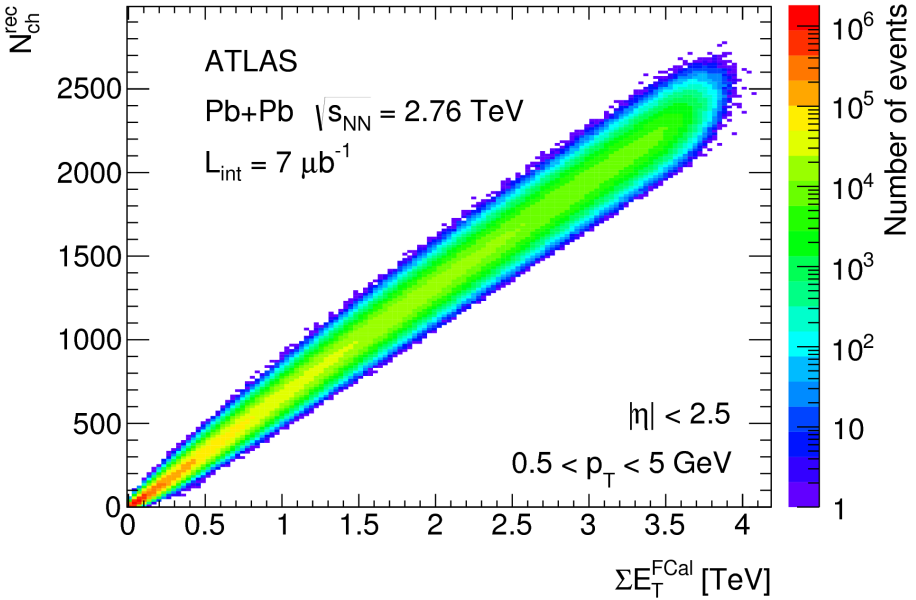




Forward Calorimeters

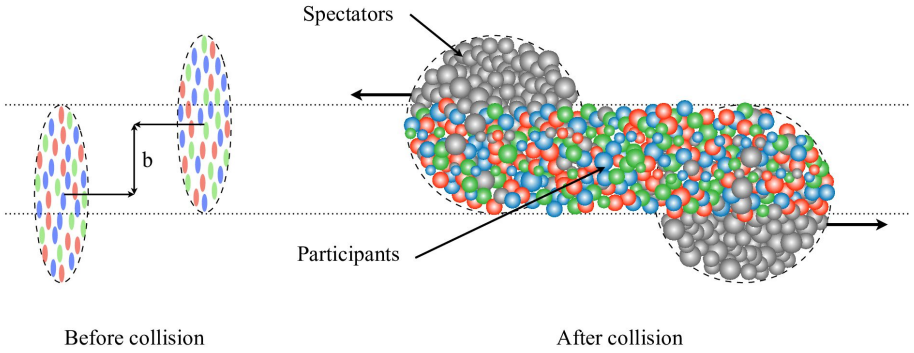
- Forward Calorimeter - FCal covering $3.2 < |\eta| < 4.9$
- Multiple interactions in overlap region - up to thousands of charged particles produced
- Number of charged tracks well correlated with total energy in FCal
- Not biased by presence of hard scattering products

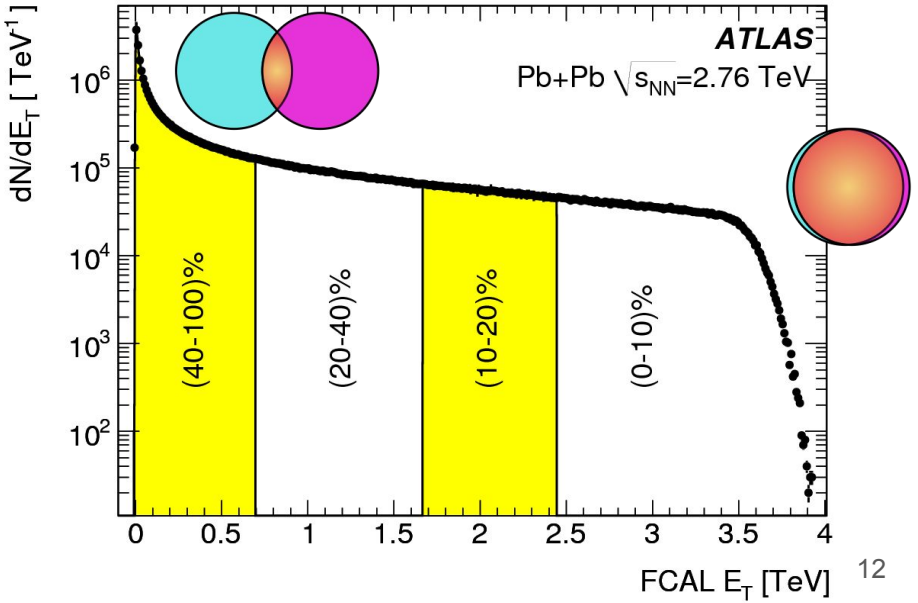




Centrality

- Total energy in FCal is a proxy for event centrality
- Measured using a sample of MinimumBias events
- The more central collisions is, the larger the quark-gluon plasma (QGP) droplet is created

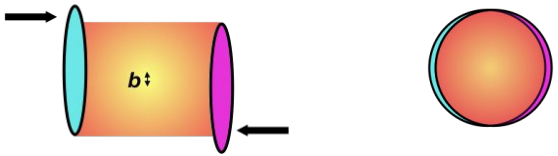


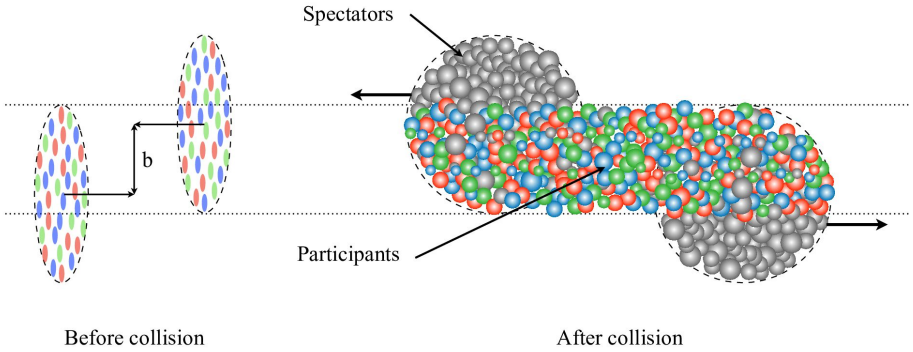


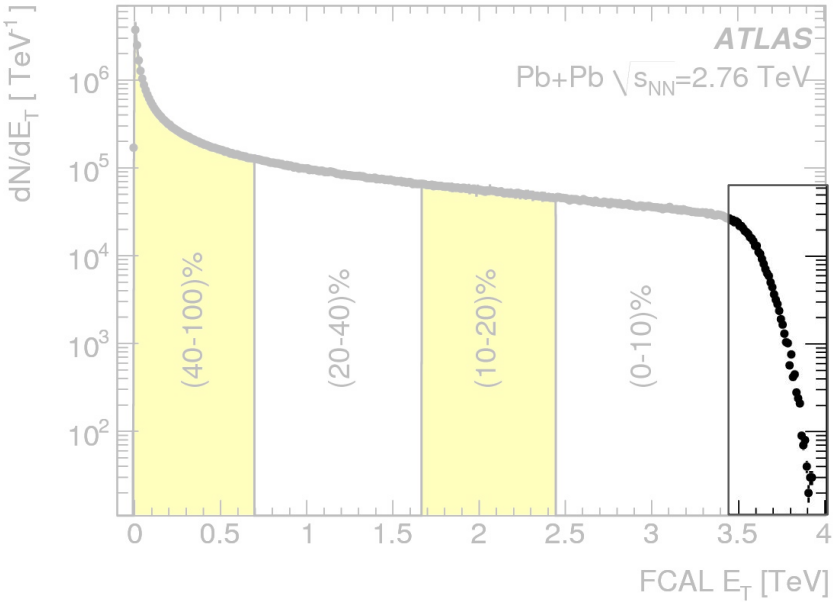
Centrality

- Events can be split into coarse categories in terms of centrality

UCC: ultra-central collisions



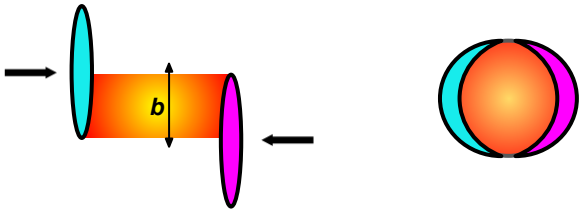


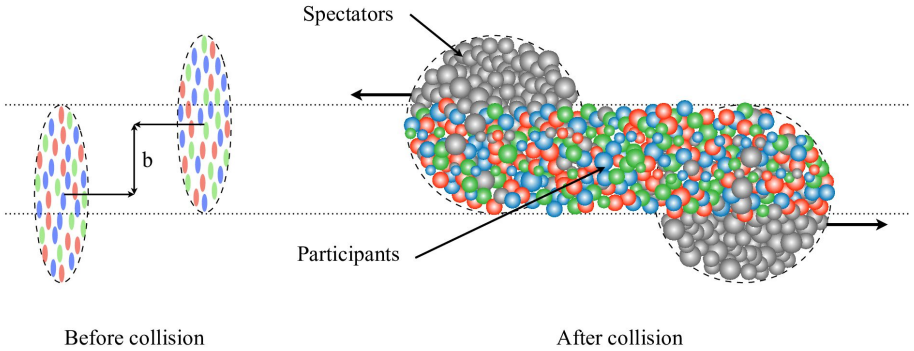


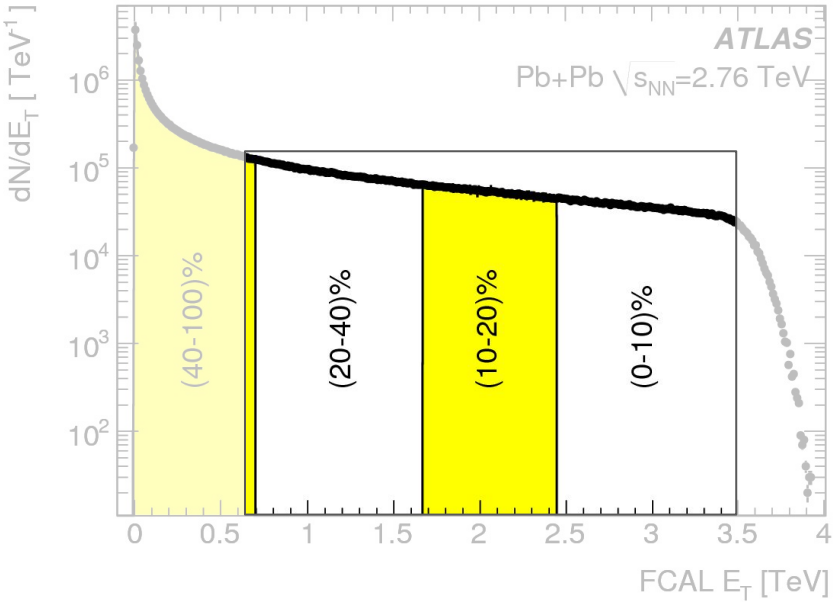
Centrality

- Events can be split into coarse categories in terms of centrality

UCC: ultra-central collisions
CC: central collisions



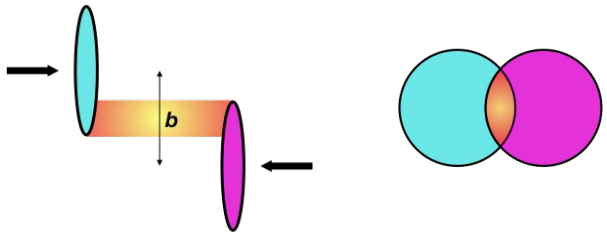


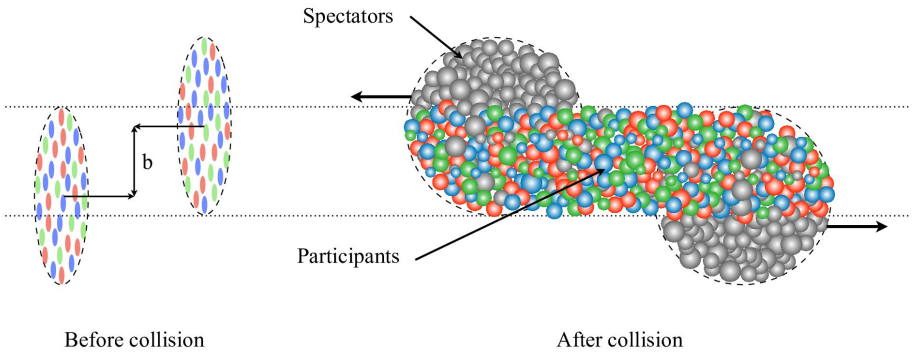


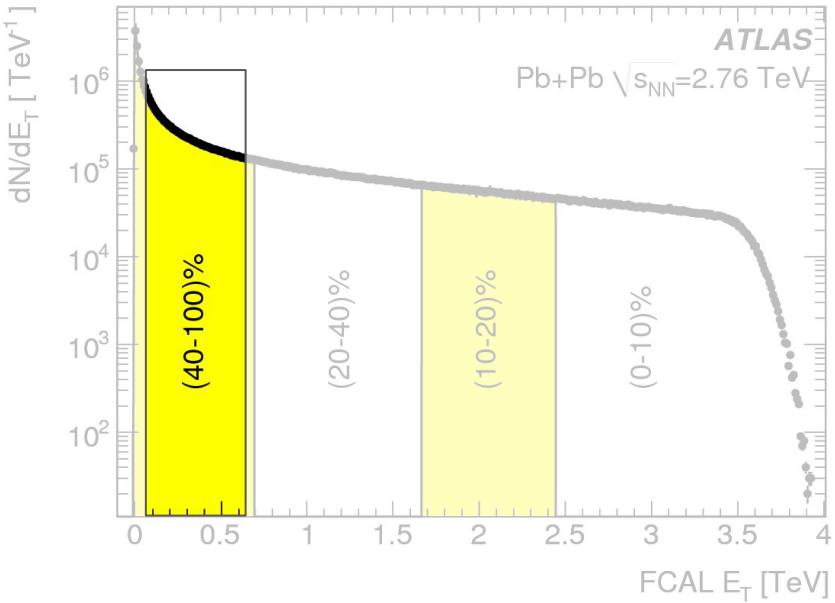
Centrality

- Events can be split into coarse categories in terms of centrality

UCC: ultra-central collisions
CC: central collisions
PC: peripheral collisions



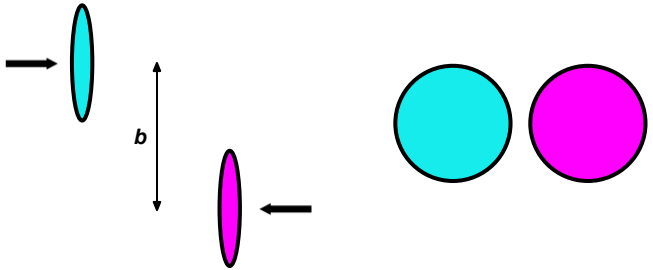


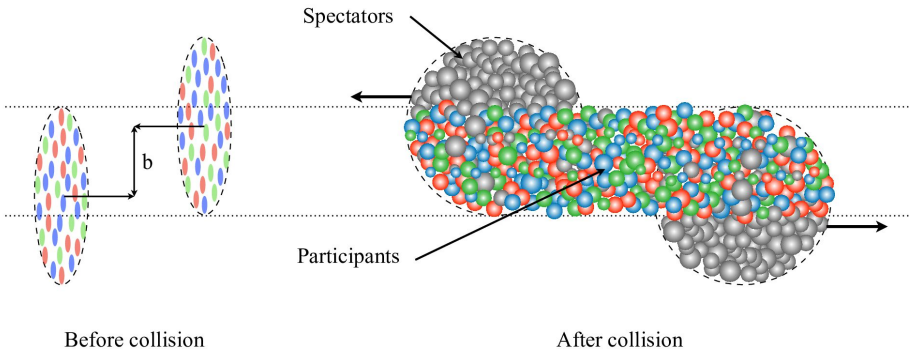


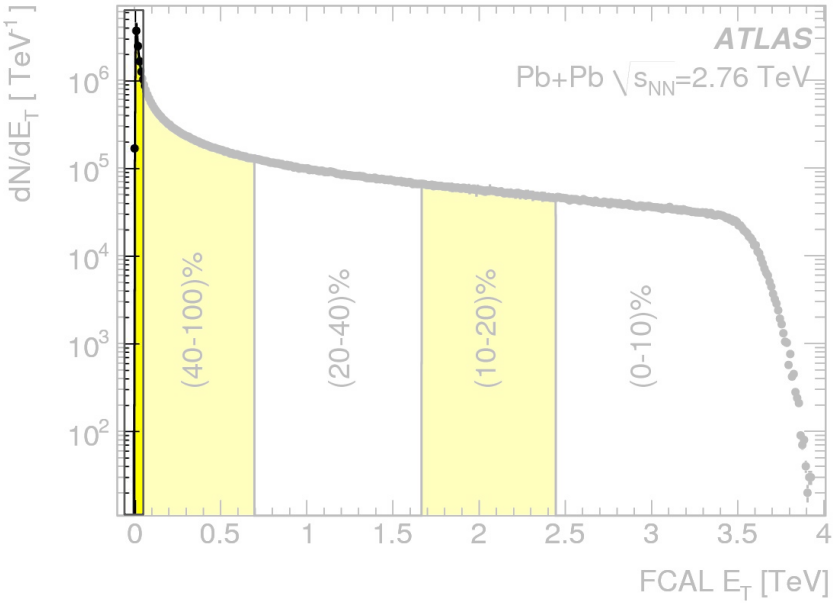
Centrality

- Events can be split into coarse categories in terms of centrality

UCC: ultra-central collisions
CC: central collisions
PC: peripheral collisions
UPC: ultra-peripheral collisions

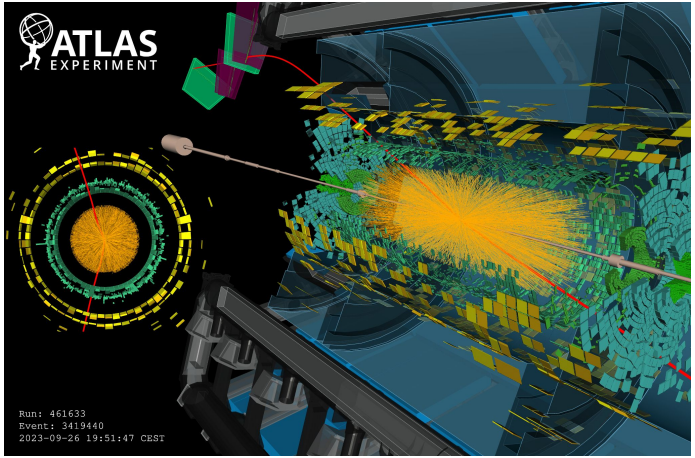




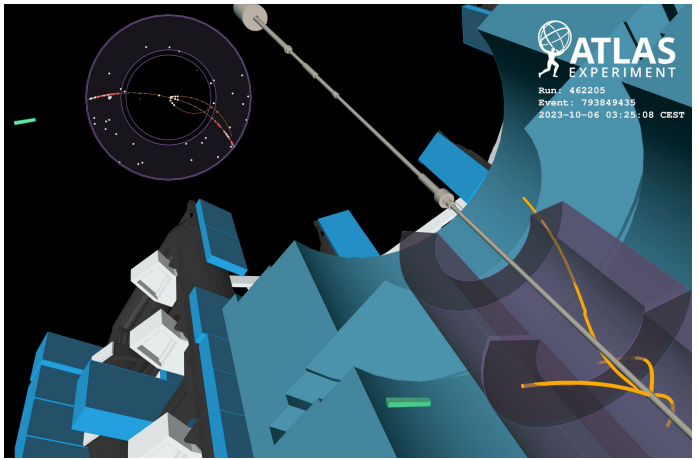


HI physics programme

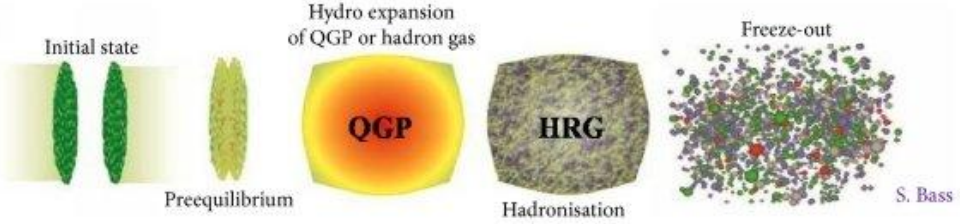
- Bulk properties of QGP
  - soft particle correlations, global properties
- QGP studies with hard-probes
  - W/Z, jets, heavy flavor
- Photon-induced interactions
  - γγ, γ+Pb



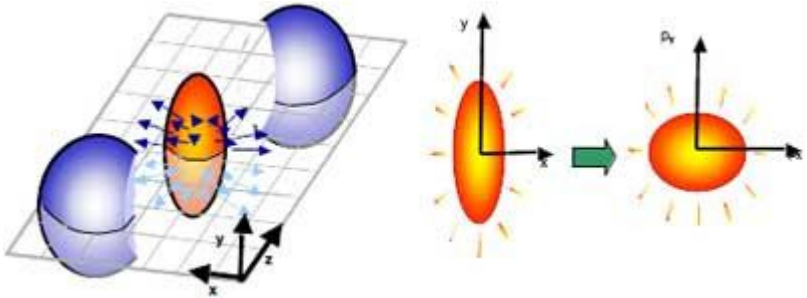
HI collisions push ATLAS to the limits

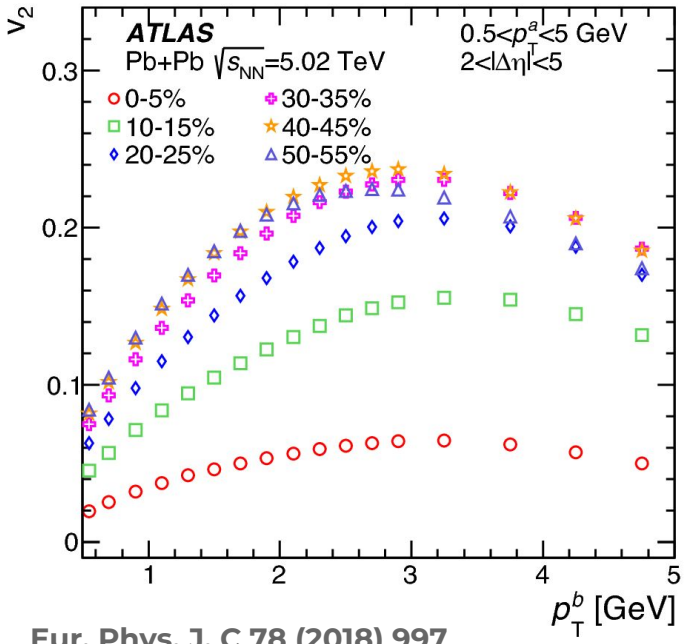


Bulk properties



- Original purpose of HI collisions: study properties of QGP
- Using PC, CC and UCC events
- Interest in all particles (including soft tracks down to 0.5 GeV)

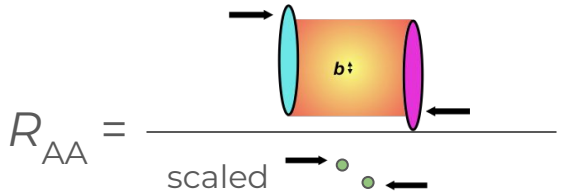


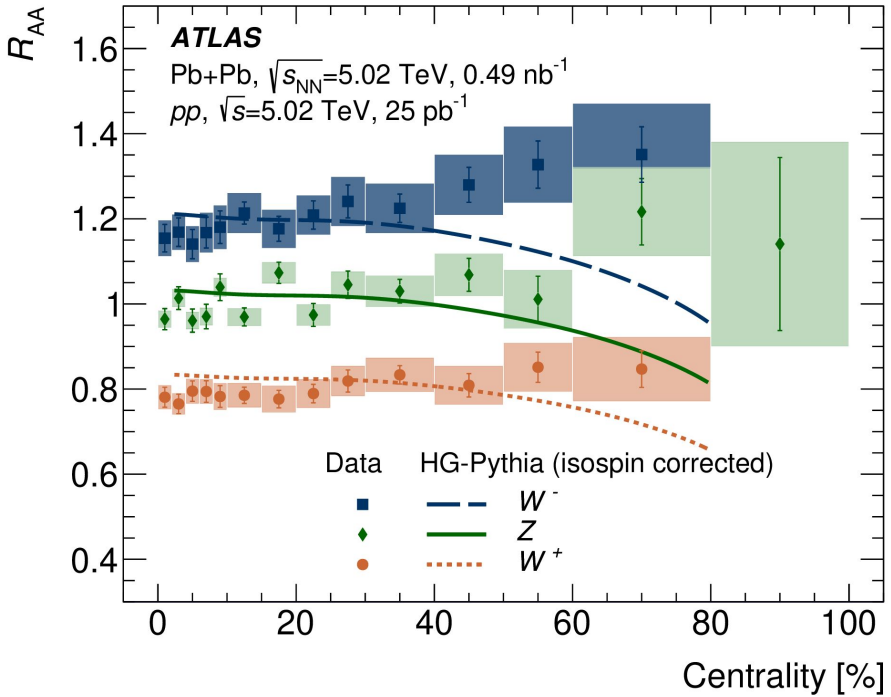


Eur. Phys. J. C 78 (2018) 997

Hard probes

- Interest to select events with jets, electrons, photons, muons at high p_T
- Using PC, CC and UCC events
- Studies of colorless objects
  - W/Z - not modified by QGP

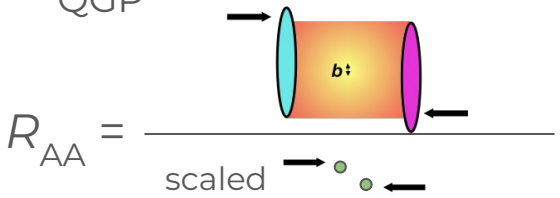


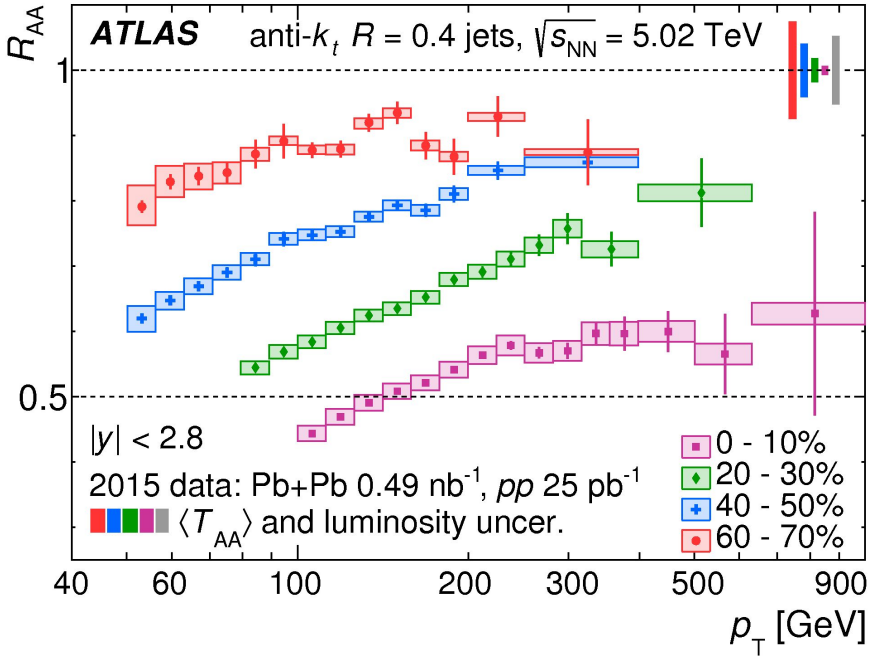


Phys. Lett. B 802 (2020) 135262

Hard probes

- Interest to select events with jets, electrons, photons, muons at high p_T
- Using PC, CC and UCC events
- Studies of colorless objects
  - W/Z - not modified by QGP
- QGP studies with hard-probes
  - jets, heavy flavor - modification of particle spectra by presence of the QGP

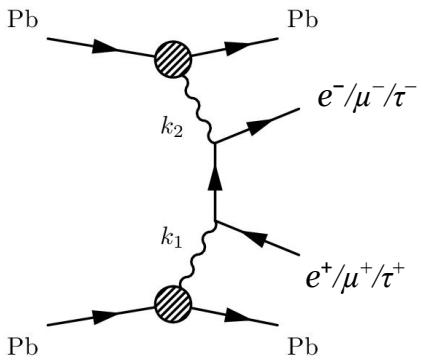


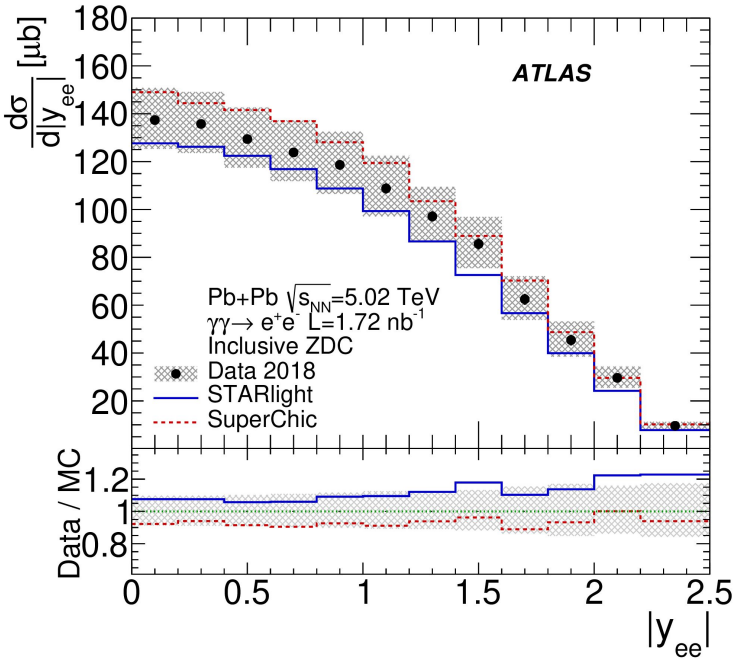


Phys. Lett. B 790 (2019) 108

Photon-induced interactions

- Using UPC events
- Interest in both photon-photon and photo-nuclear interactions
  - γγ: precise tests of photon flux modeling with SM processes, but also BSM searches





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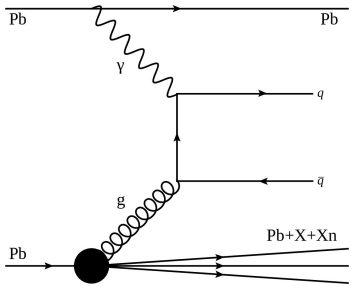
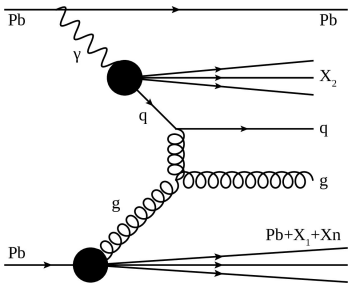
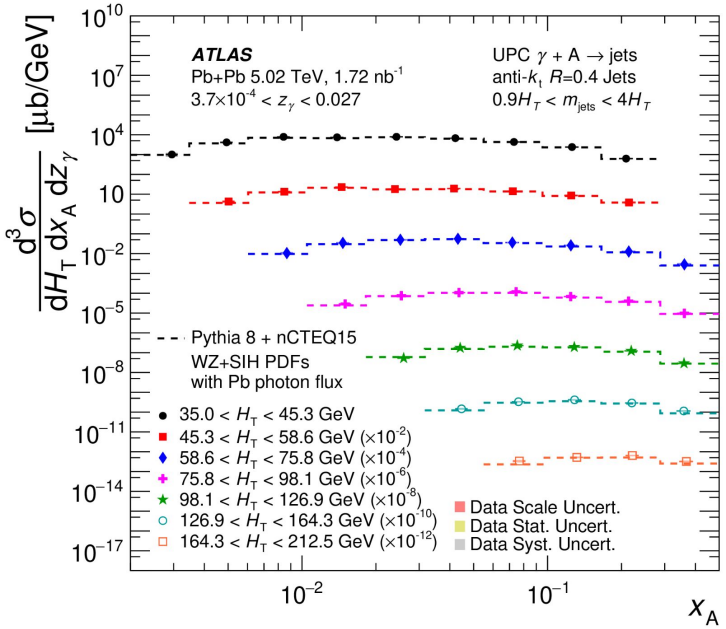
Photon-induced interactions

- Using UPC events
- Interest in both photon-photon and photo-nuclear interactions
  - γγ: precise tests of photon flux modeling with SM processes, but also BSM searches
  - γ+Pb: probing nuclear PDFs, shadowing and saturation phenomena, searches for collective effects







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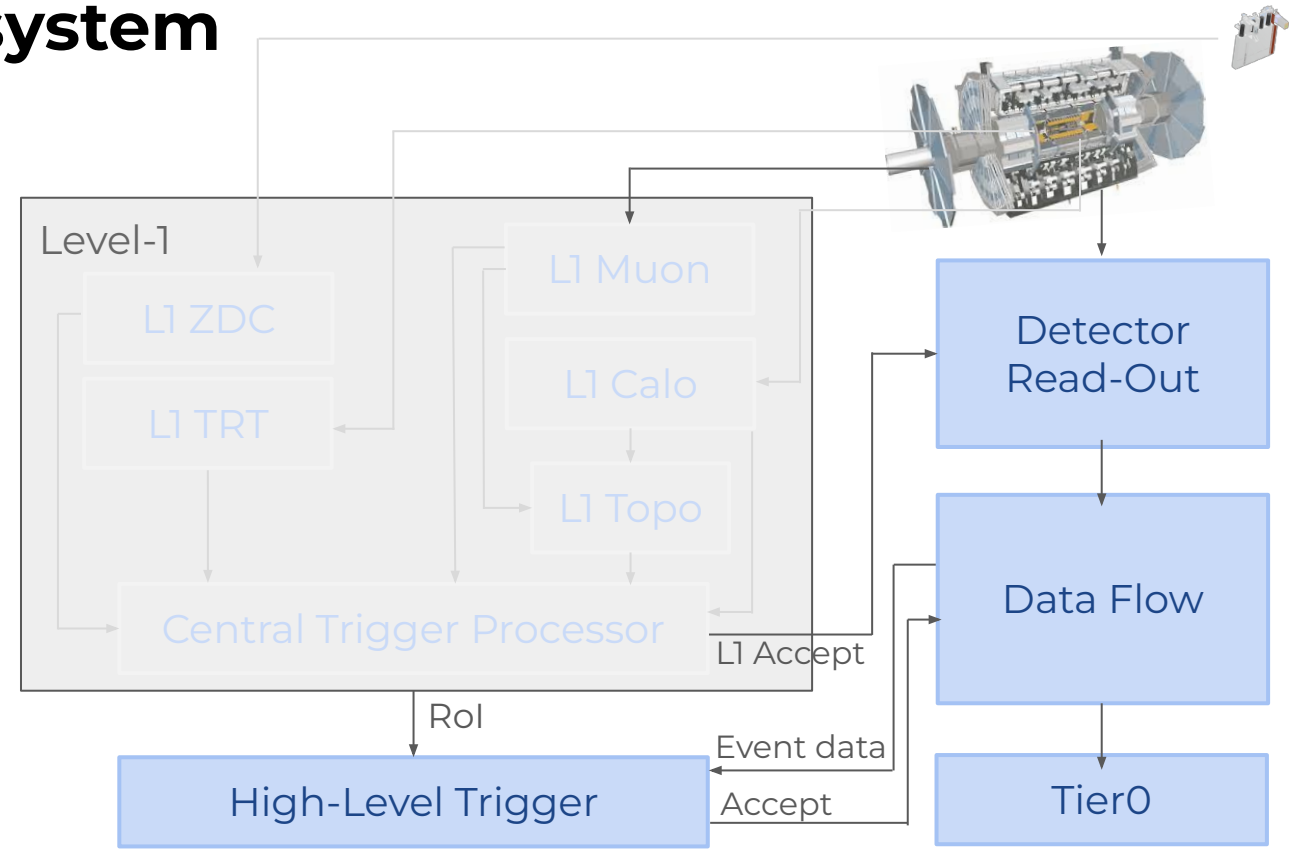
Why ATLAS needs trigger?

- Collisions at LHC every 25 ns for pp, 50 ns for ions
  - event rate is 12-30 MHz
- Amount of data limited by recording bandwidth at about 8 Gb/s
- With current event size recording rate is only about a few kHz
  - need to lower the incoming event rate by 3 to 4 orders of magnitude!
- Which events we should select? How do we select?
- We make decision using the trigger system
  - for every process there is a need for a dedicated trigger chain
  - ideal trigger chain provides high efficiency and high purity

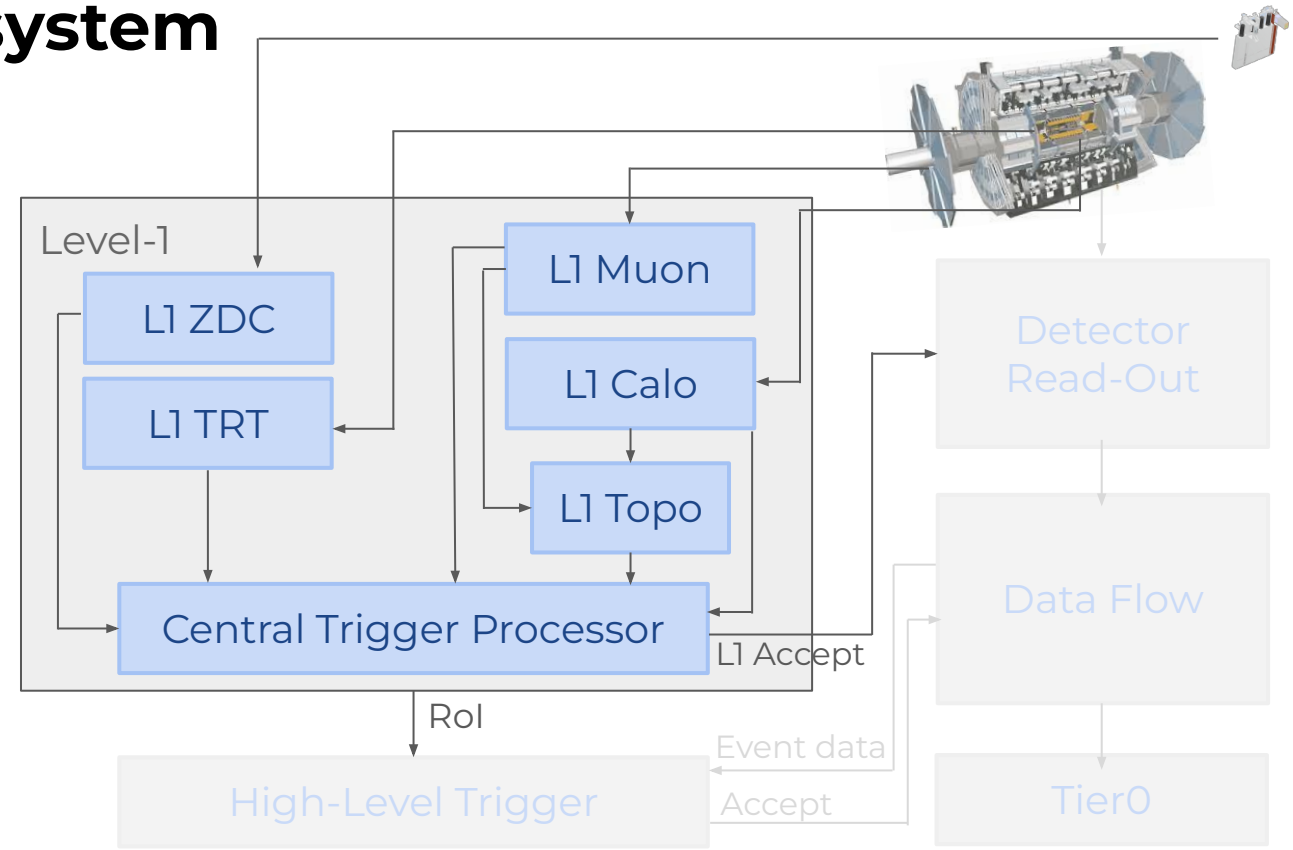
ATLAS trigger system

- Two components: hardware (Level-1, L1) and software (High Level Trigger, HLT)
- L1: up to 512 items
- HLT: no limit in number of algorithms



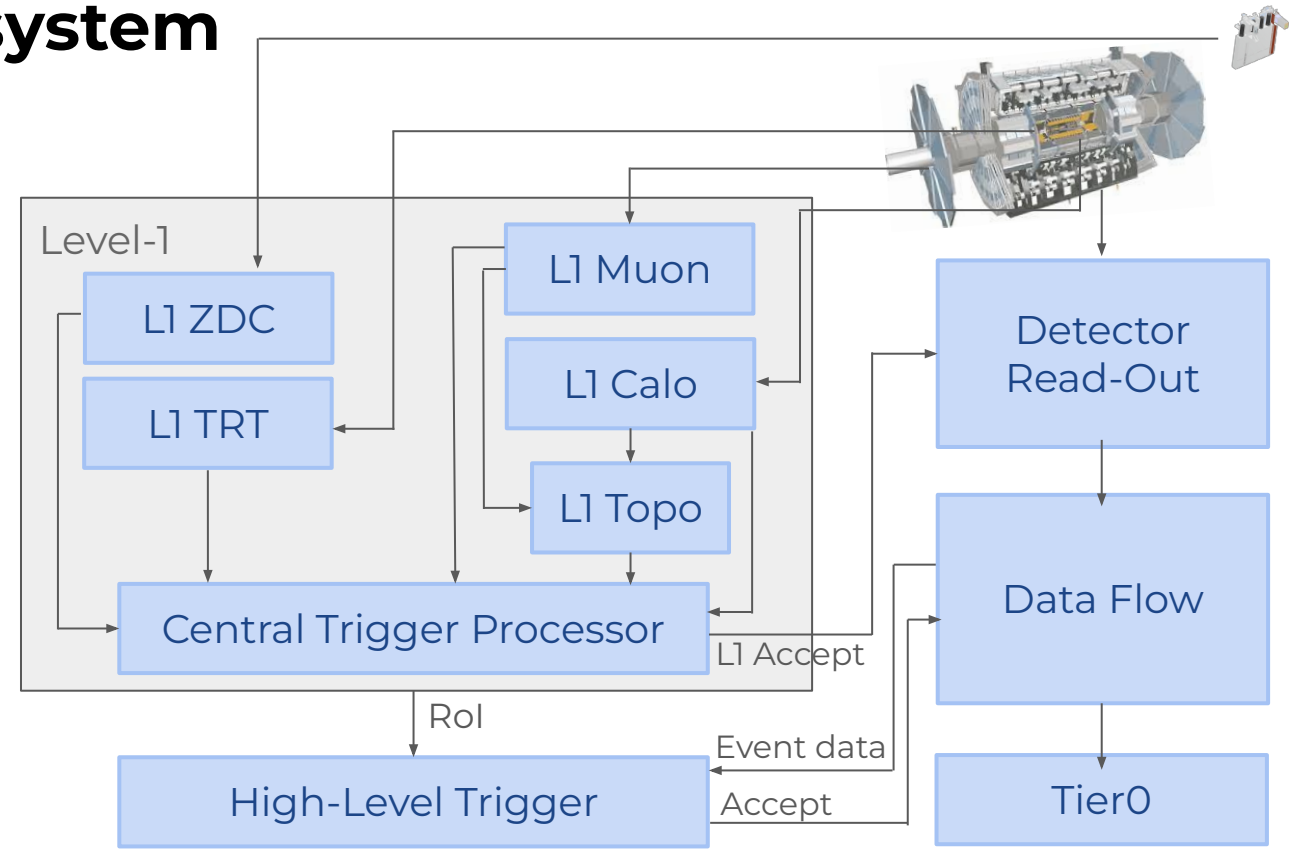
ATLAS trigger system

- At L1: coarse granularity info from calorimeters, muons system, TRT and ZDC,
- L1 output up to 100 kHz
- Topological selections using muons and calo information possible
- Regions of Interest (RoIs) identified around muon, e/gamma, jet L1 objects



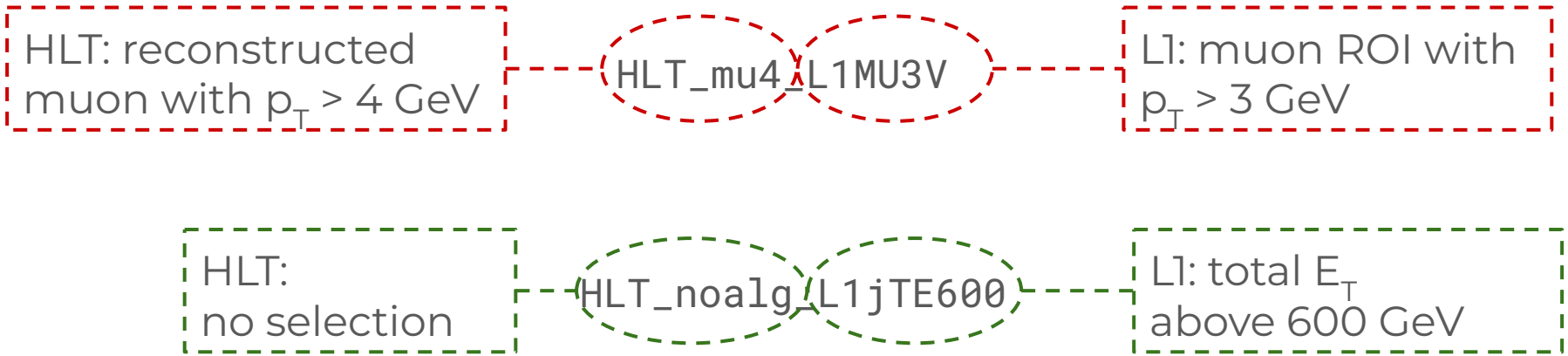
ATLAS trigger system

- At HLT: offline-like reconstruction and selection
- Many processing units available
- Fast reconstruction around RoIs, longer using full detector info
- HLT output at the level of a few kHz



What is trigger chain?

- Sequence of L1 and HLT selections
- Simple examples:



What is trigger chain?

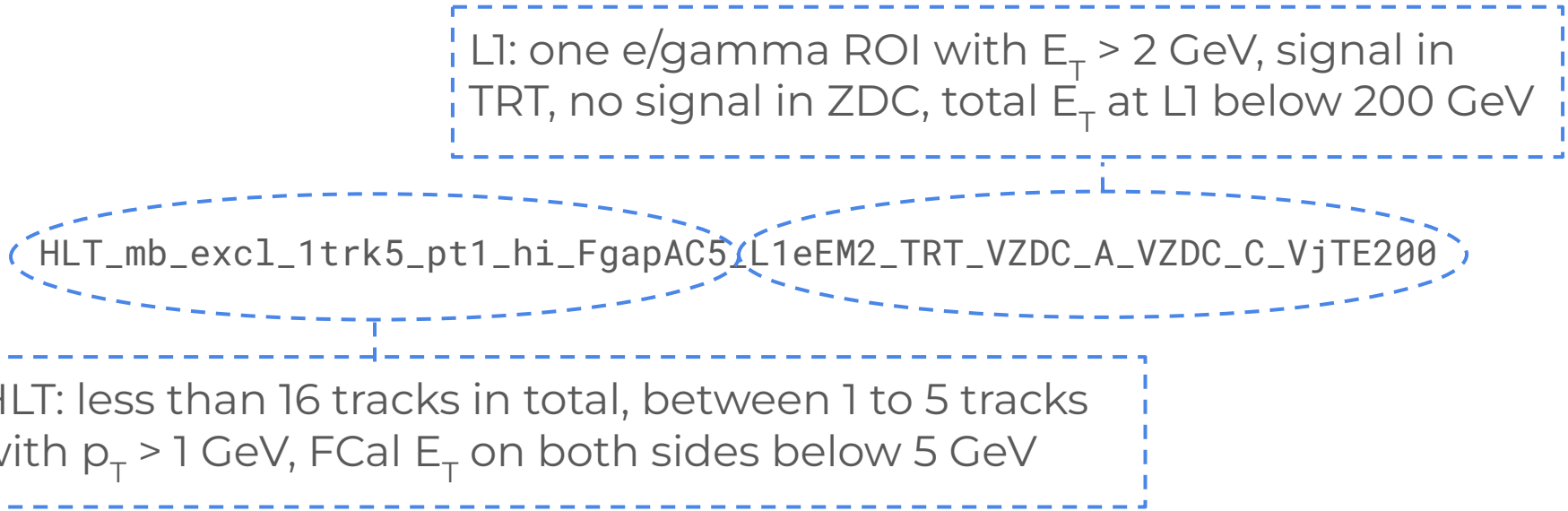
- Sequence of L1 and HLT selections
- More complex example:

L1: one e/gamma ROI with E_T > 2 GeV, signal in TRT, no signal in ZDC, total E_T at L1 below 200 GeV

`L1eEM2_TRT_VZDC_A_VZDC_C_VjTE200`

What is trigger chain?

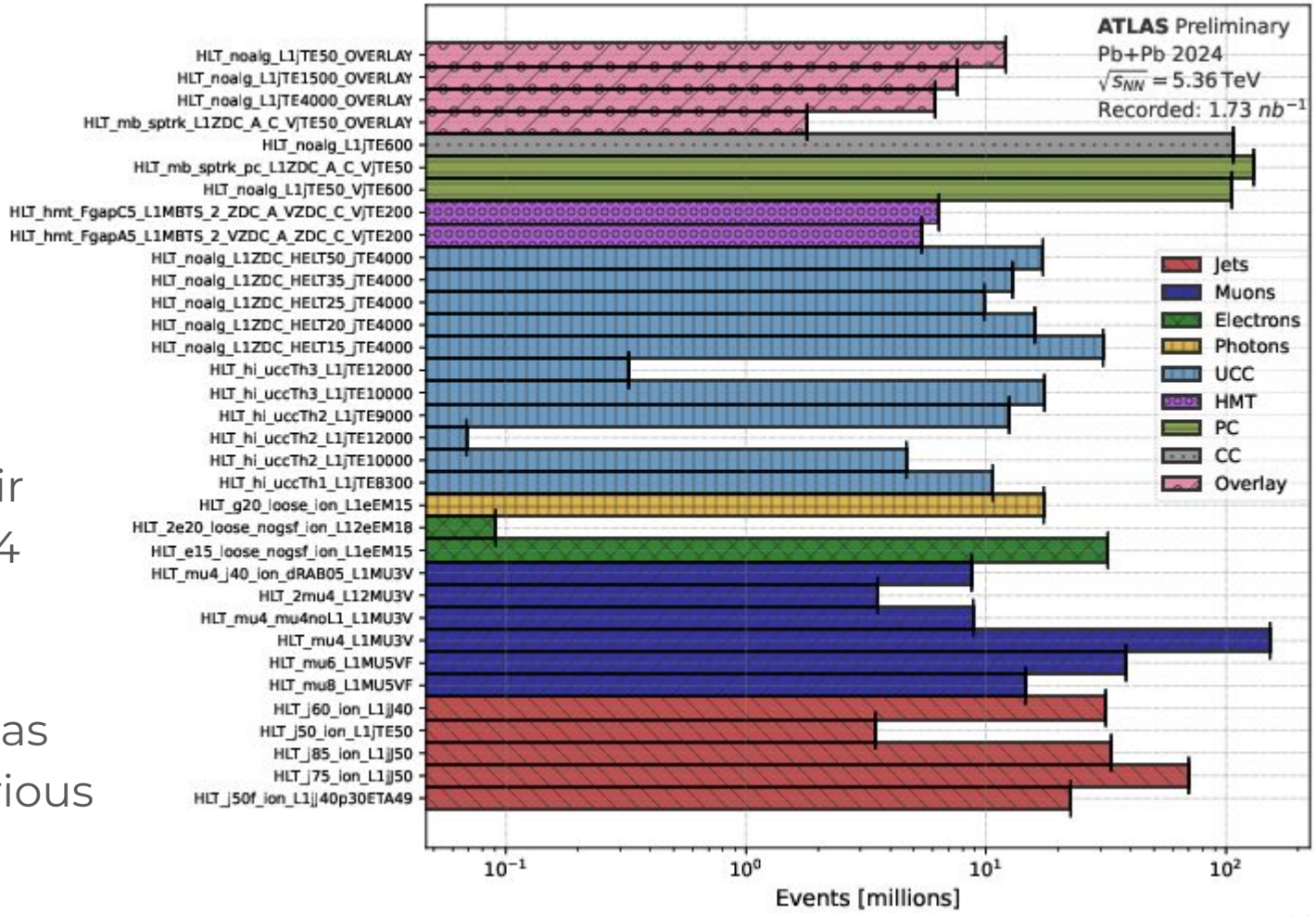
- Sequence of L1 and HLT selections
- More complex example:



Trigger menu

Some selected physics trigger chains with their statistics in 2024

Trigger menu has hundreds of various trigger chains



Trigger menu

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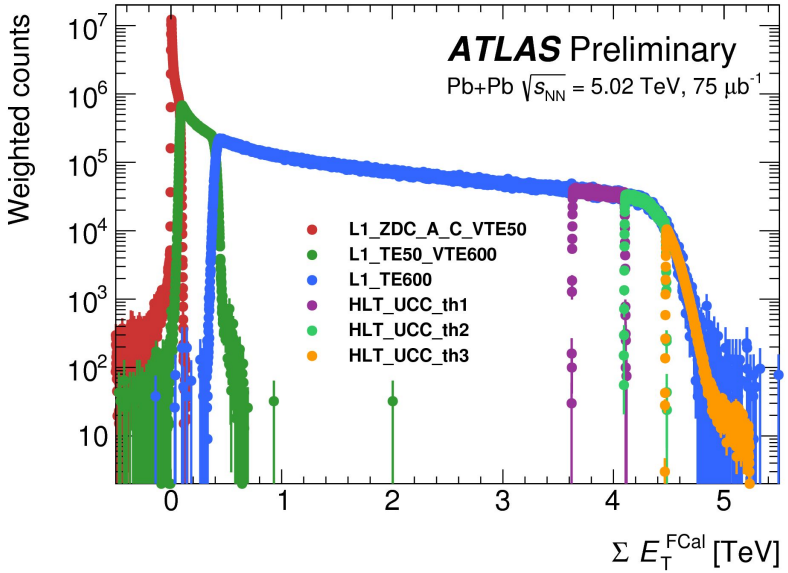
MinBias triggers

- We cannot record all MinBias rate
  - need to select which events we need for further analyses
  - Interest in more central collisions
- MinBias events split based on the total transverse energy at L1 (jTE)
  - to reduce photon-induced rate for low jTE also coincidence in ZDC (ZDC_A_C)
- CC: jTE > 600 GeV
- PC: (50 GeV < jTE < 600 GeV) || (ZDC_A_C && jTE < 50 GeV)
- At least one track required at HLT for most peripheral, no selection at HLT for more central



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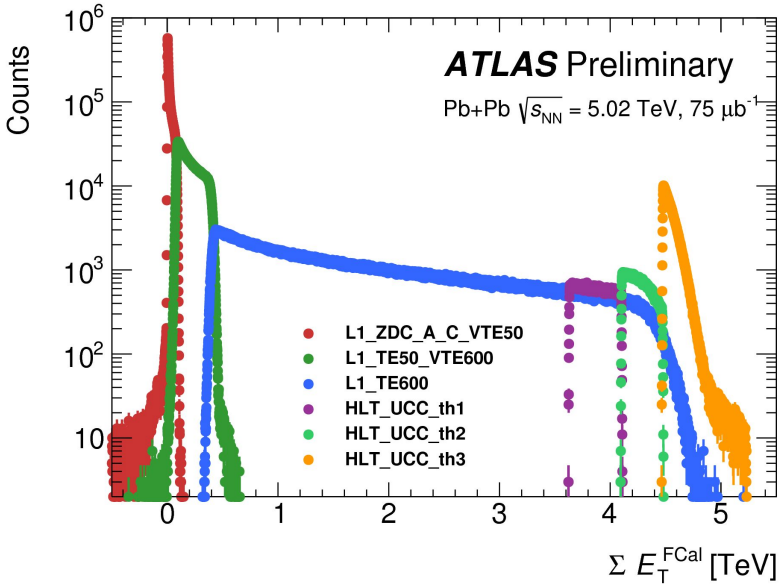
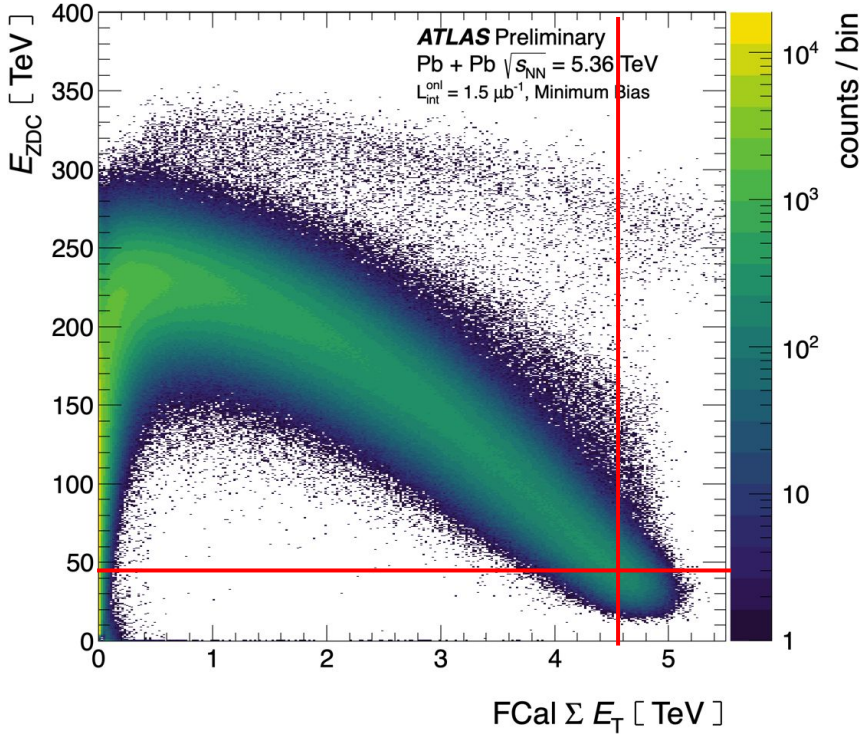
- Relative rate regulated by “prescales” - only fraction of accepted events is recorded



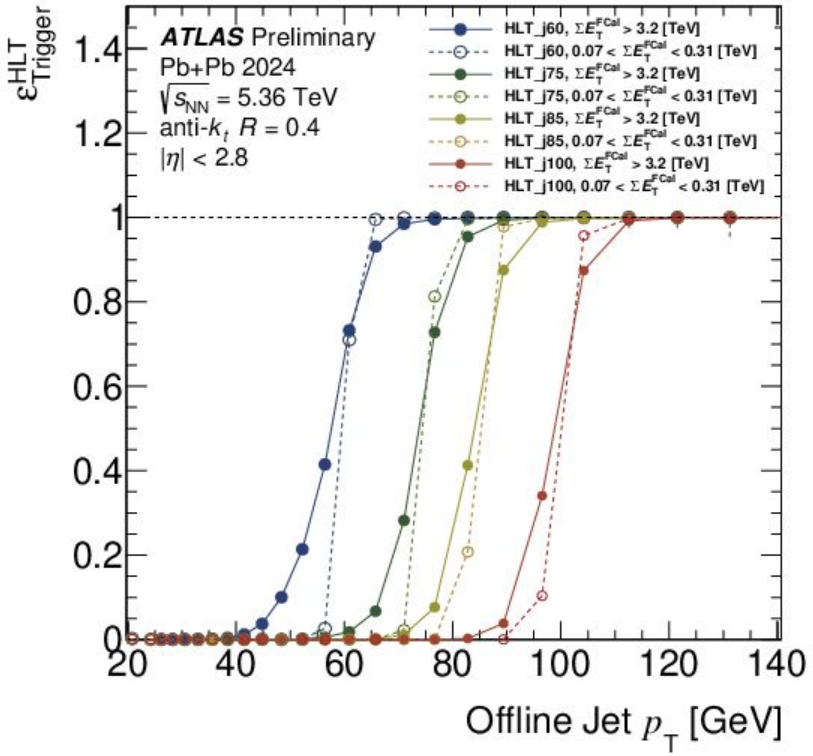
ZDC trigger for UCC

- Most central events - most energy in FCal
  - one approach to select UCC, we use forward jTE > 6600 GeV
- UCC also with low signal in ZDC
  - also needs to veto low forward jTE events
- This approach introduced in 2024
  - selection of the UCC based on initial geometry, complementary to selection in FCal energy



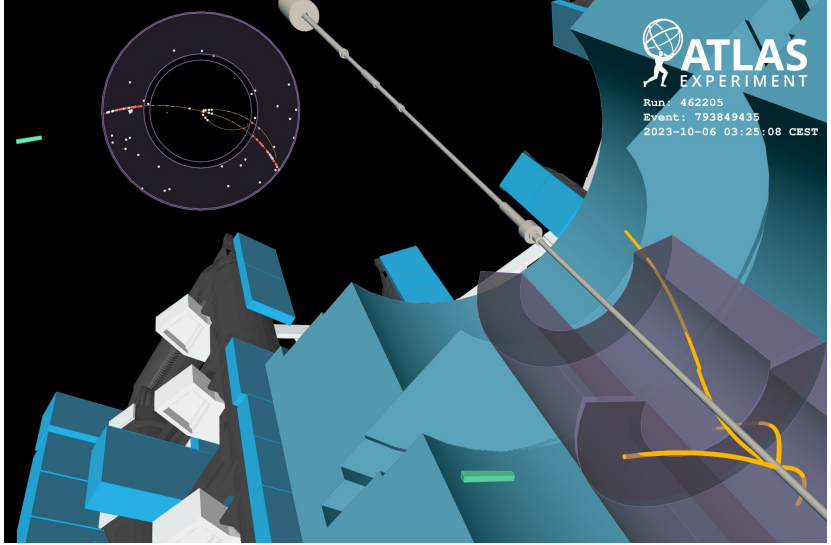
Hard probes triggers

- Interest in recording all high-p_T objects
  - electrons with p_T > 15 GeV
  - photons with E_T > 20 GeV
  - muons with p_T > 4 GeV
  - jets with p_T > 75 GeV
- At L1: dedicated objects, i.e. EM, MU, J
- At HLT:
  - e/gamma & muons - reco around ROIs
  - jets - full scan reco
  - ion version of reconstruction: corrects for underlying event



UPC triggers

- All UPC triggers with L1 total E_T up to 200 GeV
- Photon-photon interactions
  - little signal in central detector
  - mostly no signal in ZDC



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- Photon-photon interactions
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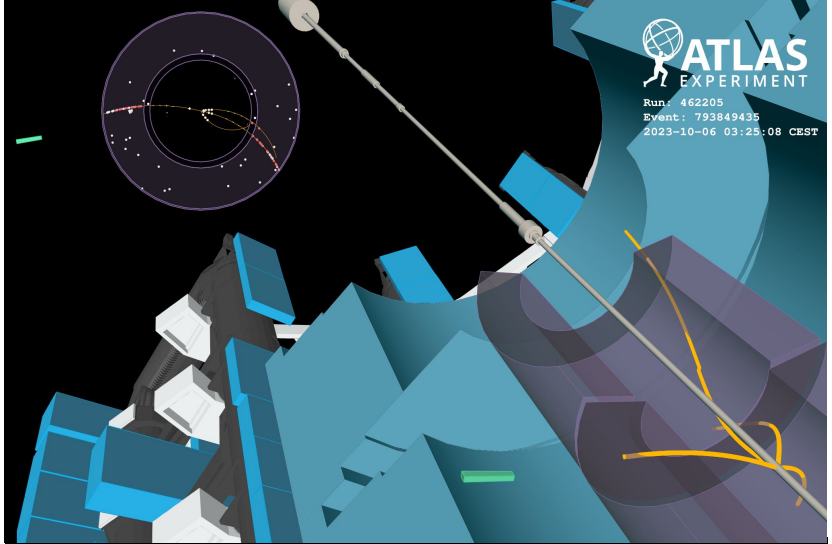
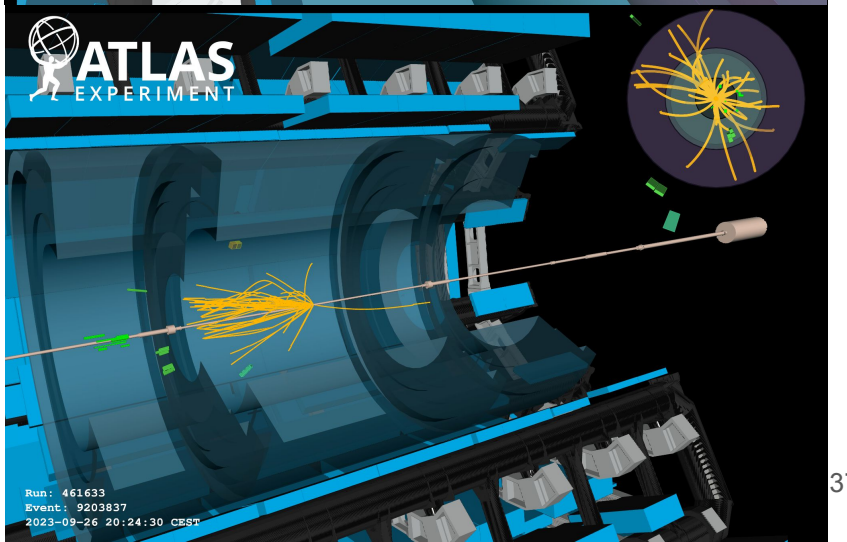
- Photonuclear events
  - more particles in final state
  - typically asymmetric in central detector and in ZDC





UPC triggers

- Interest in low p_T objects:
  - muons with $p_T > 4$ GeV
  - e/gamma with $p_T > 2$ GeV
  - jets with $p_T > 10$ GeV
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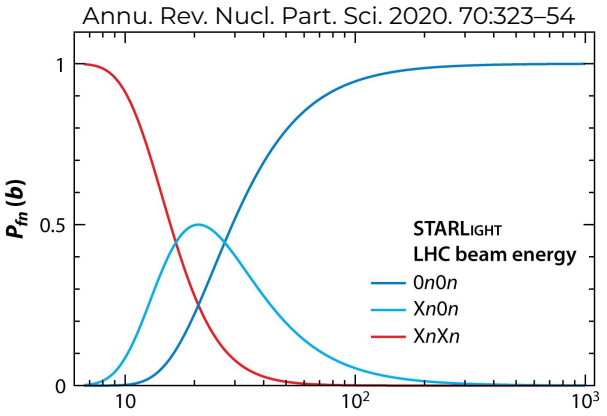
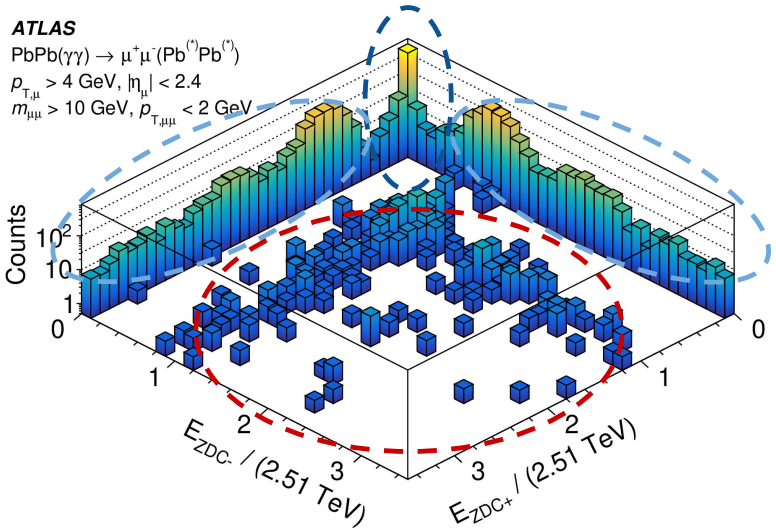
- Typically multiple requirements at L1, often also at HLT
  - resulting in longish trigger chain names...

ZDC trigger for UPC

- Various neutron topologies provide handle on impact parameter
- Extra neutrons in ZDC possible due to additional photon exchange
    - excited nucleon de-excites by neutron emission





ZDC trigger for UPC

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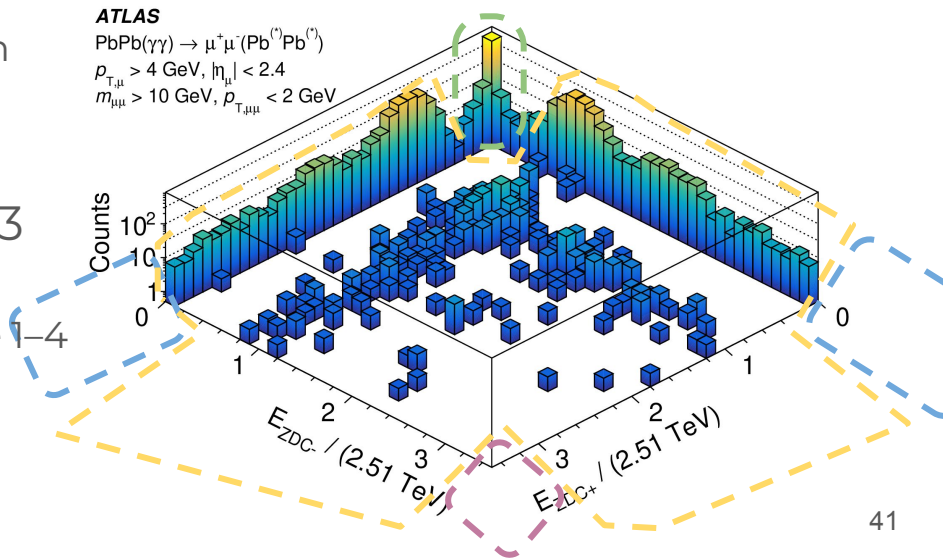
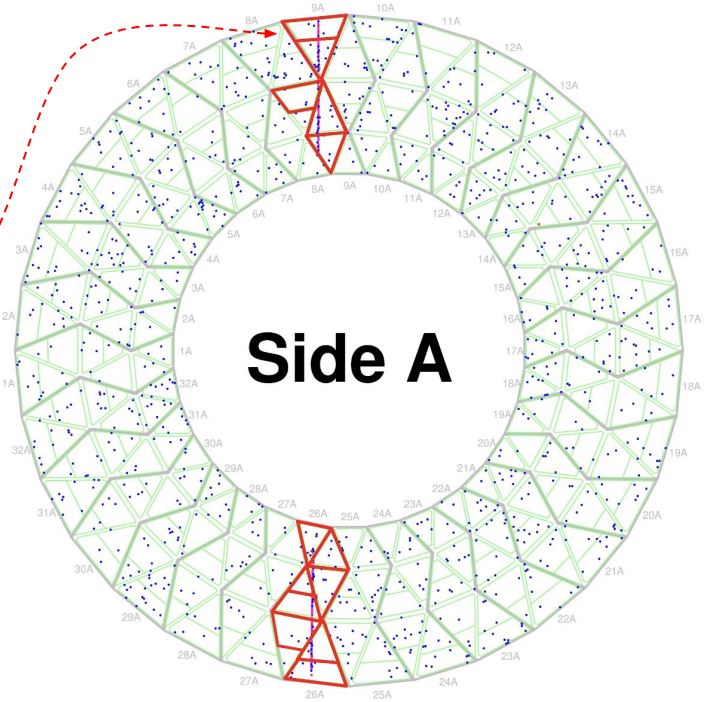
- Extra neutrons in ZDC possible due to additional photon exchange
  - excited nucleon de-excites by neutron emission
- Switched from 2 to 3-bit information in ZDC trigger in 2023
  - Allows for selection on more complex neutron topologies with intermediate 1–4 neutron threshold

>5n	γA 7	γA 2	AA 3
1-4n	γA γγ 6	γA γγ Aγ 1	Aγ 2
0n	γγ 0	γγ Aγ 4	Aγ 5
↑C / A→	0n	1-4n	>5n



TRT trigger - how it works

- TRT - Transition Radiation Tracker
  - outermost tracking detector in ATLAS
  - reaching up to $|\eta|<2.0$
  - helps in e/π discrimination
- TRT split into 288 **segments** providing signal for trigger
  - hit when energy deposited in straws slightly larger than MIP



ATL-INDET-PUB-2009-002

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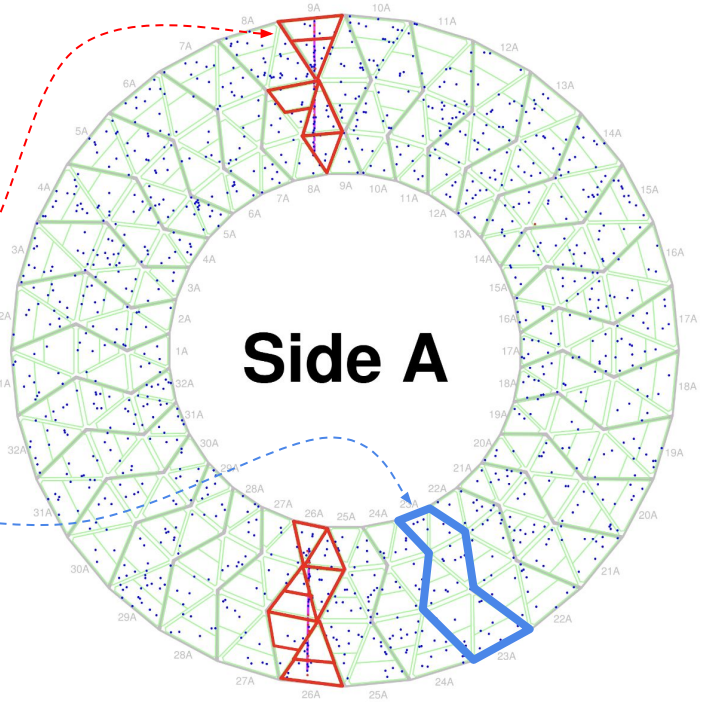

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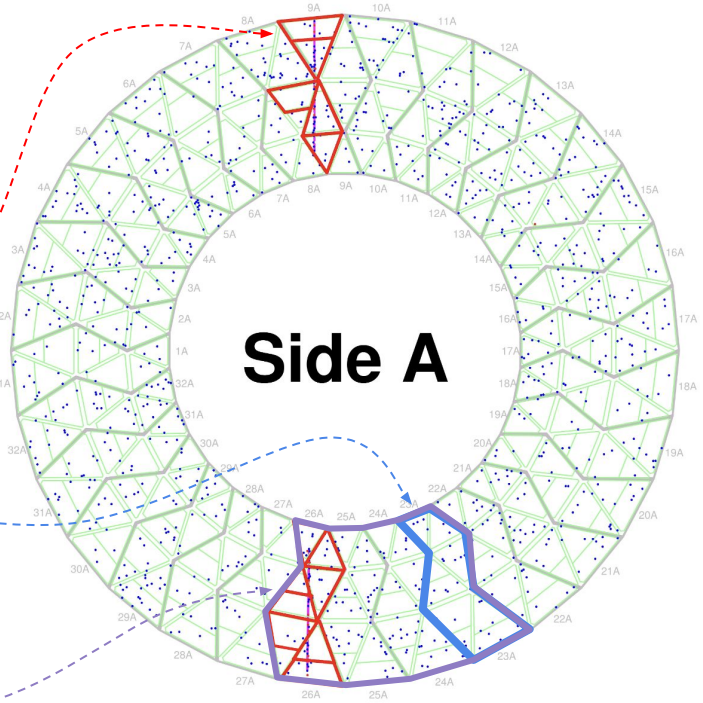
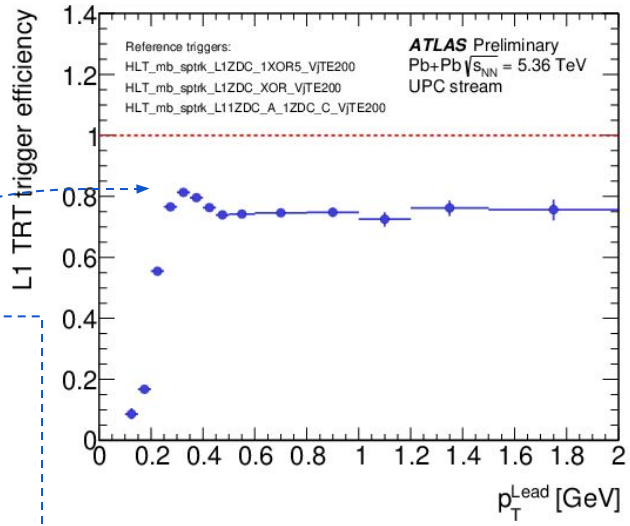
- Segments grouped into **slices** in ϕ, with width of $2\pi/32$
- Event accepted if at least **4 segments** have signal in **4 neighboring slices** in barrel (2 in end-cap)
- Selective L1 trigger for very low-p_T signals - crucial for UPC



ATL-INDET-PUB-2009-002

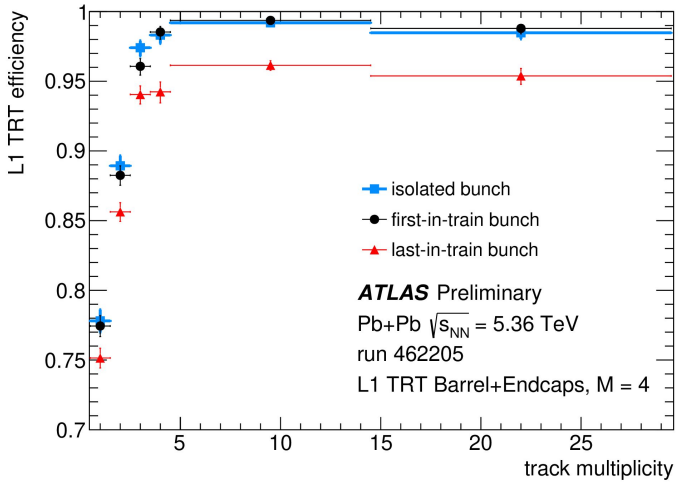
TRT trigger - performance

Efficiency for events with exactly two opposite charge tracks with $p_T > 100$ MeV, $|\eta| < 2$, and $|d_0| < 2$ mm



Bump at 0.3 GeV results from TRT geometry

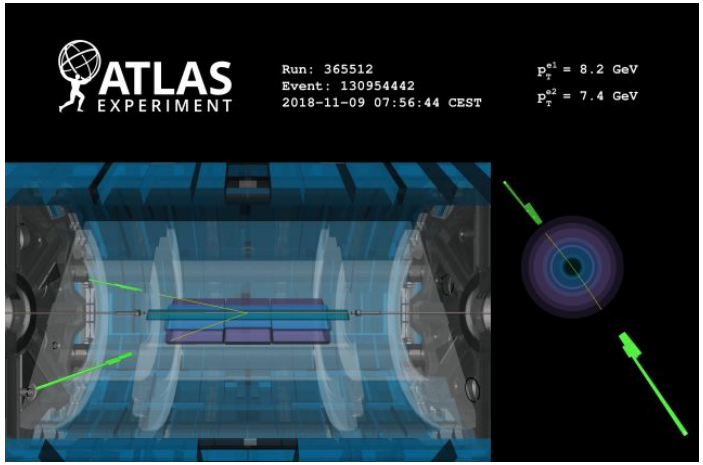
All tracks are required to have $p_T > 100$ MeV, $|\eta| < 2$, and $|d_0| < 2$ mm

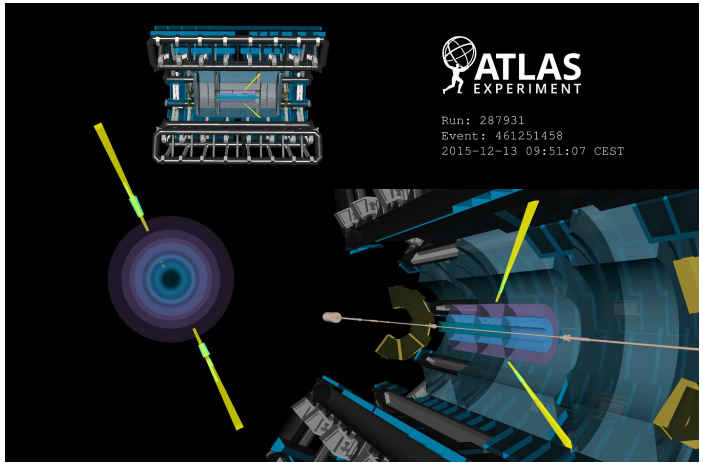


Very high efficiency even at low multiplicities

Topo items in UPC

- Very low p_T of final state particles for many UPC processes
  - Need to have as low as possible E_T requirement at L1
  - However this increases the rate of events a lot
- Exclusive final states with characteristic back-to-back topology
  - using topological selection - large $\Delta\phi$ - to lower the rate
  - alternatively together with loose invariant mass requirement (to further limit noise rate)





Streaming strategy

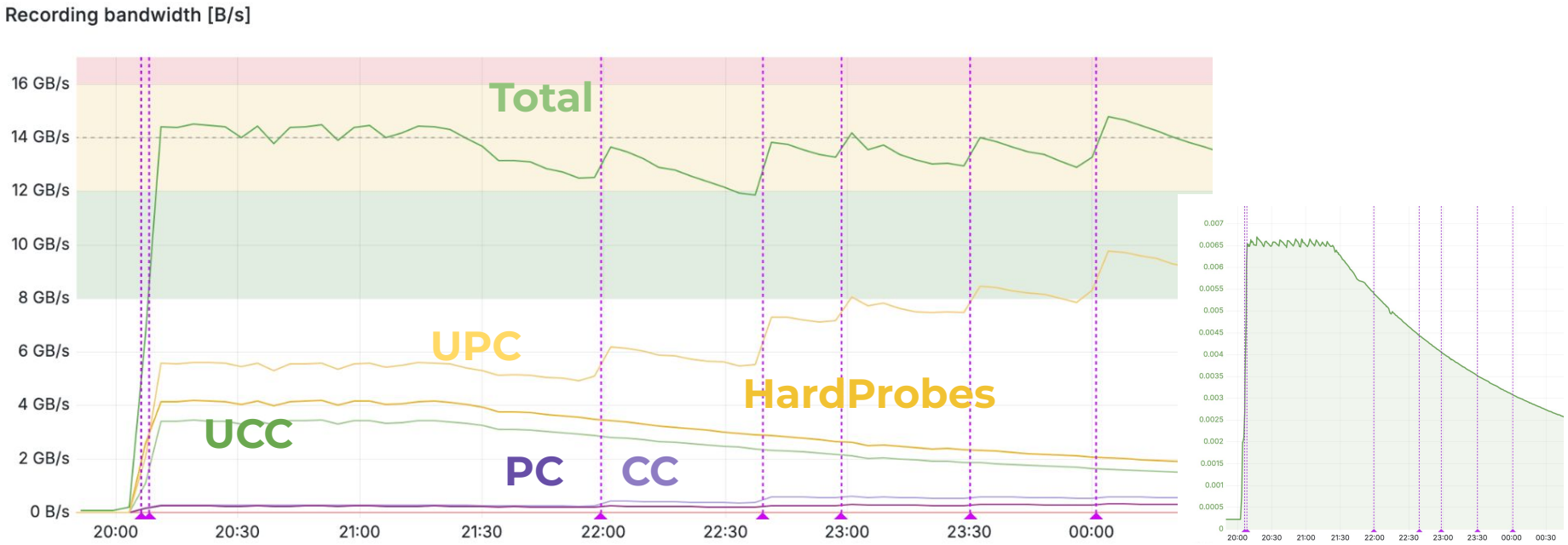
- QGP studies with hard-probes → HardProbes (large event size)
  - W/Z, jets, heavy flavor
- Bulk properties of QGP → MinBias, PC, CC, UCC
  - soft particle correlations, global properties

  MinBiasOverlay → for data overlay
- Photon-induced interactions → UPC (small event size)
  - γγ, γ+Pb

Separate streams → different offline reconstruction

Very important for low-p_T particles!

Recording bandwidth per stream



HardProbes and UCC streams following lumi decay

Others boosted towards end of the fill: UPC - strongly, PC/CC - slightly

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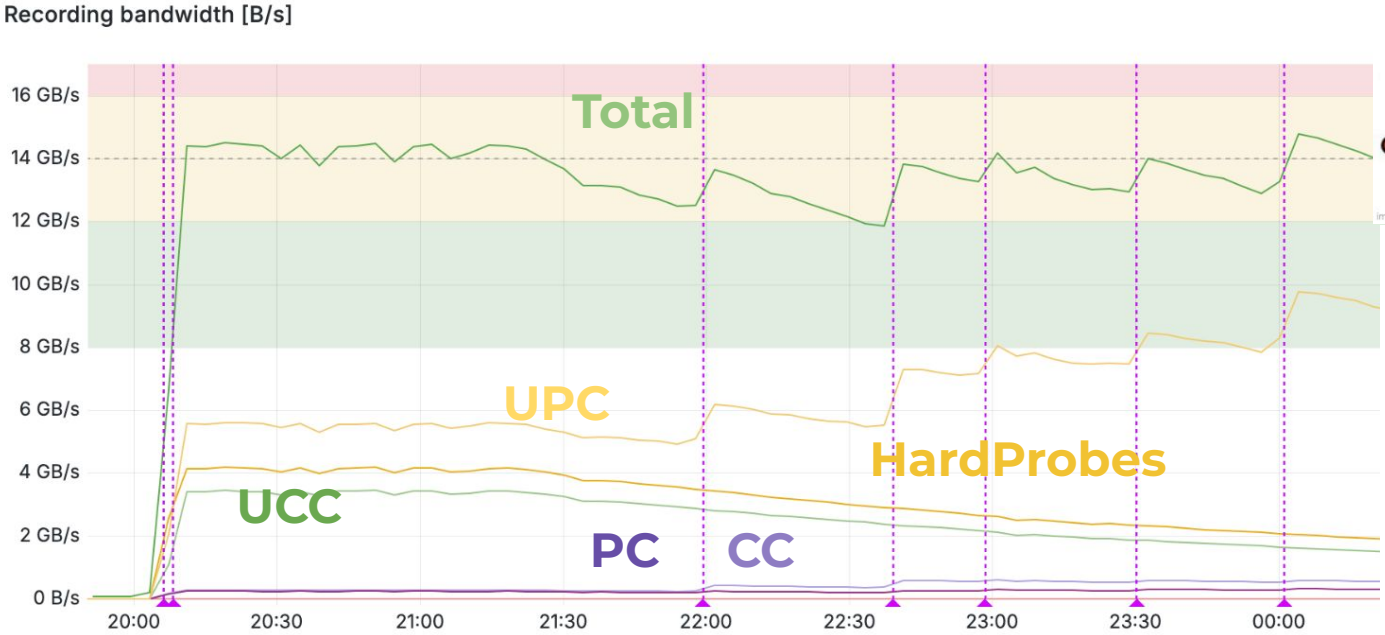

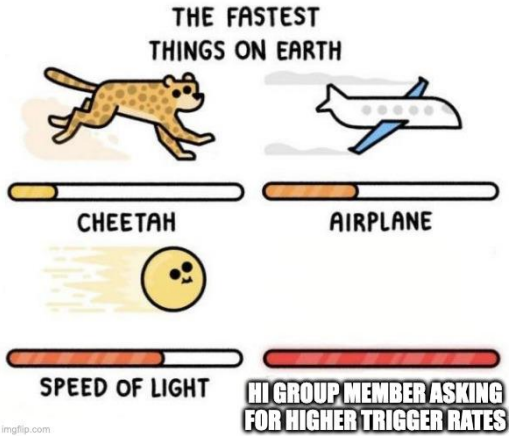

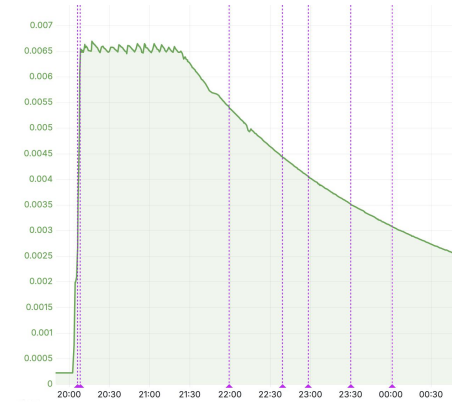

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How to write more data? Let’s play with SFO!

- Data from HLT enters Sub-Farm Output (SFO) system
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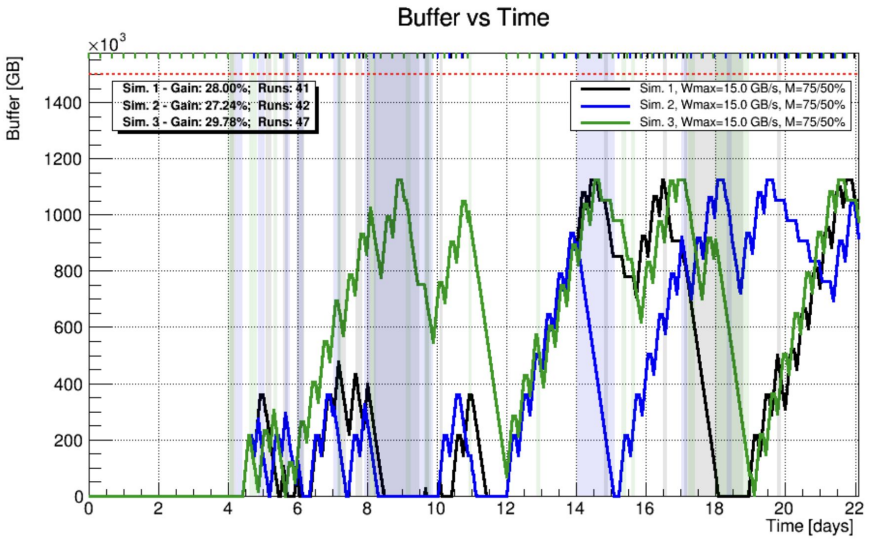
- Simulations suggested up to 30% more data



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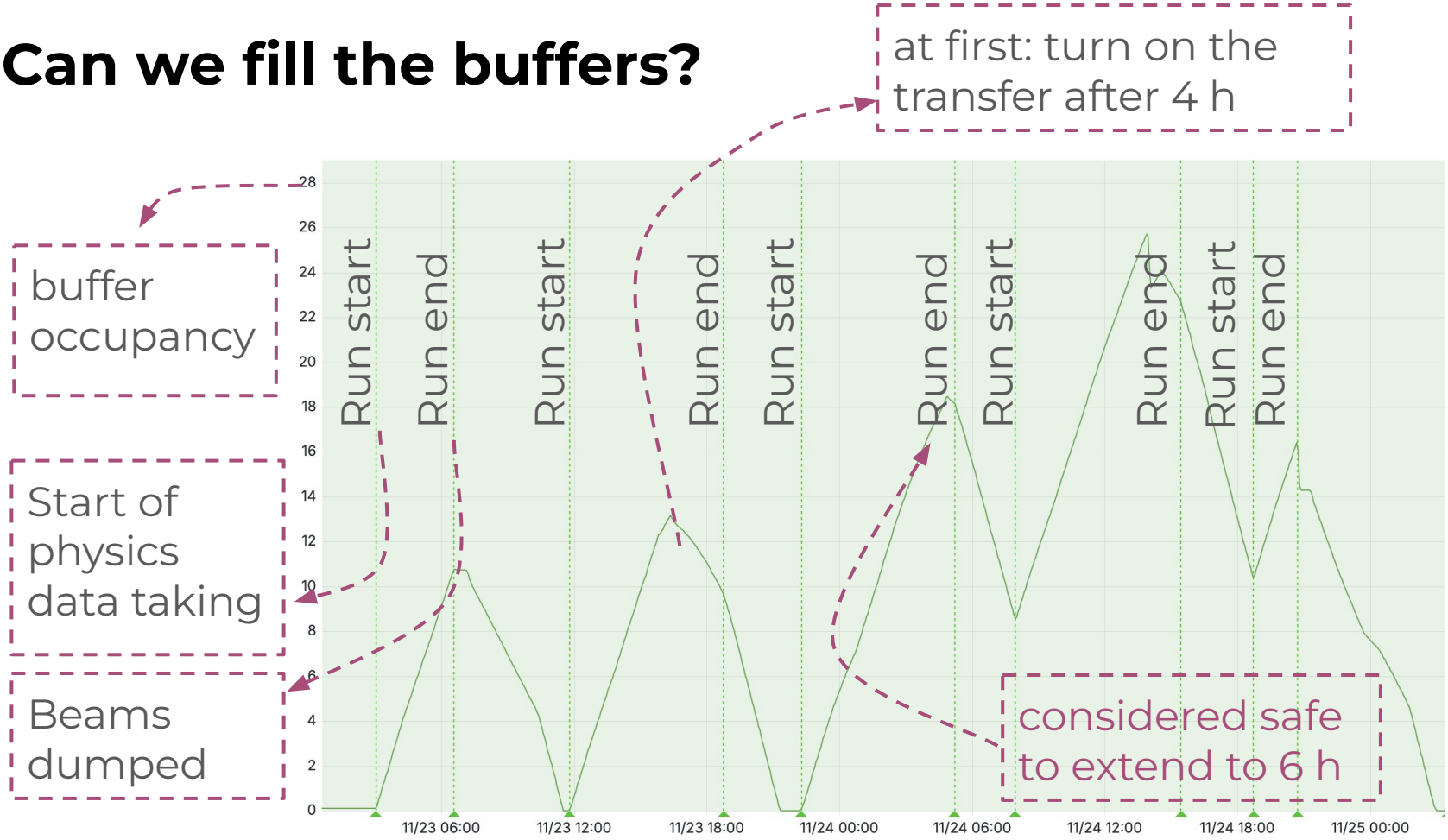

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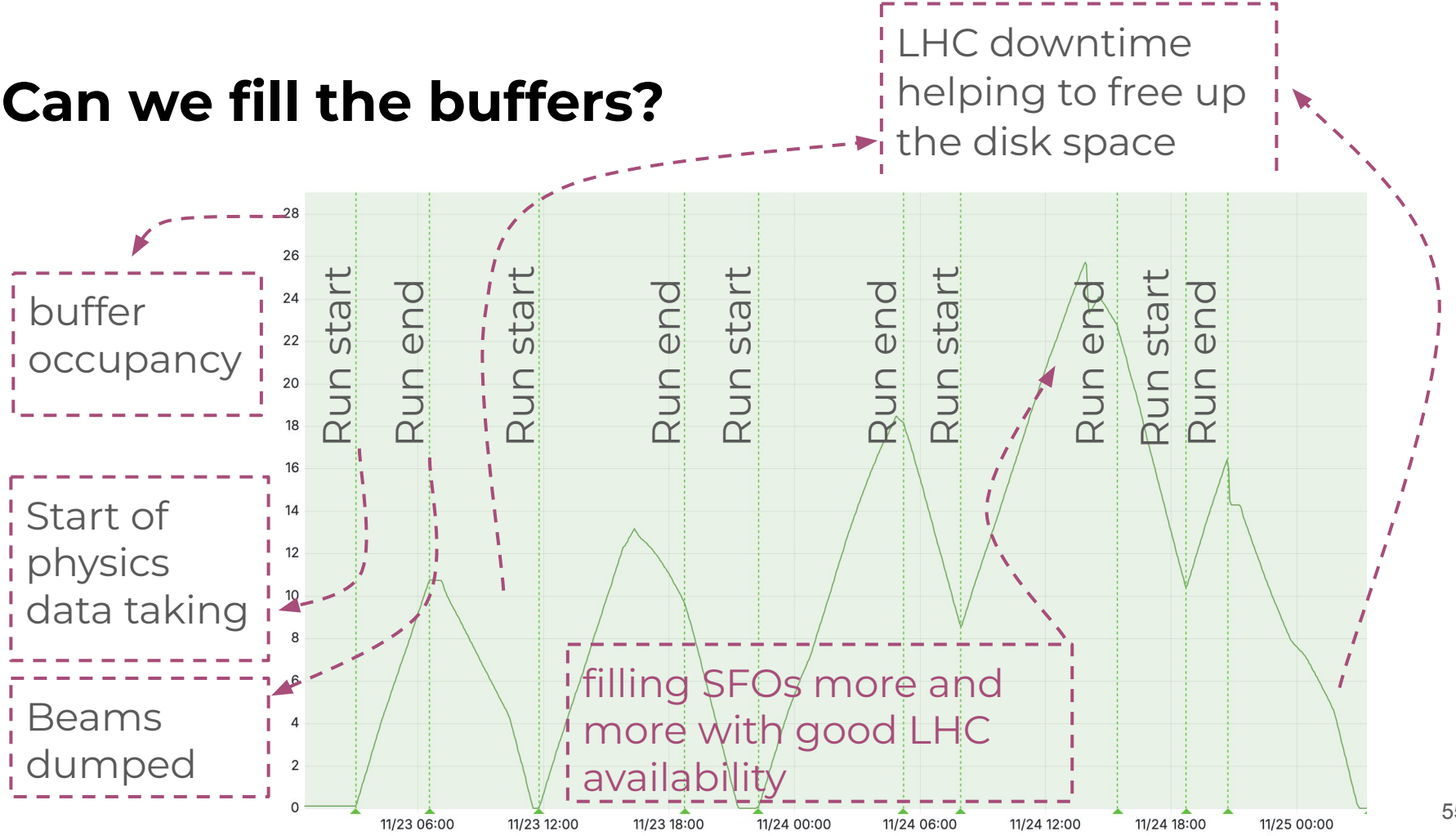

More bunches - more problems?

- In 2023 we moved from 100 ns to **50 ns bunch spacing**
  - Reaching higher luminosities than in 2018
- Caveat: several unwanted effects seen
  - High rate of events with **out-of-time** contributions - noticed in events passing UPC jet triggers

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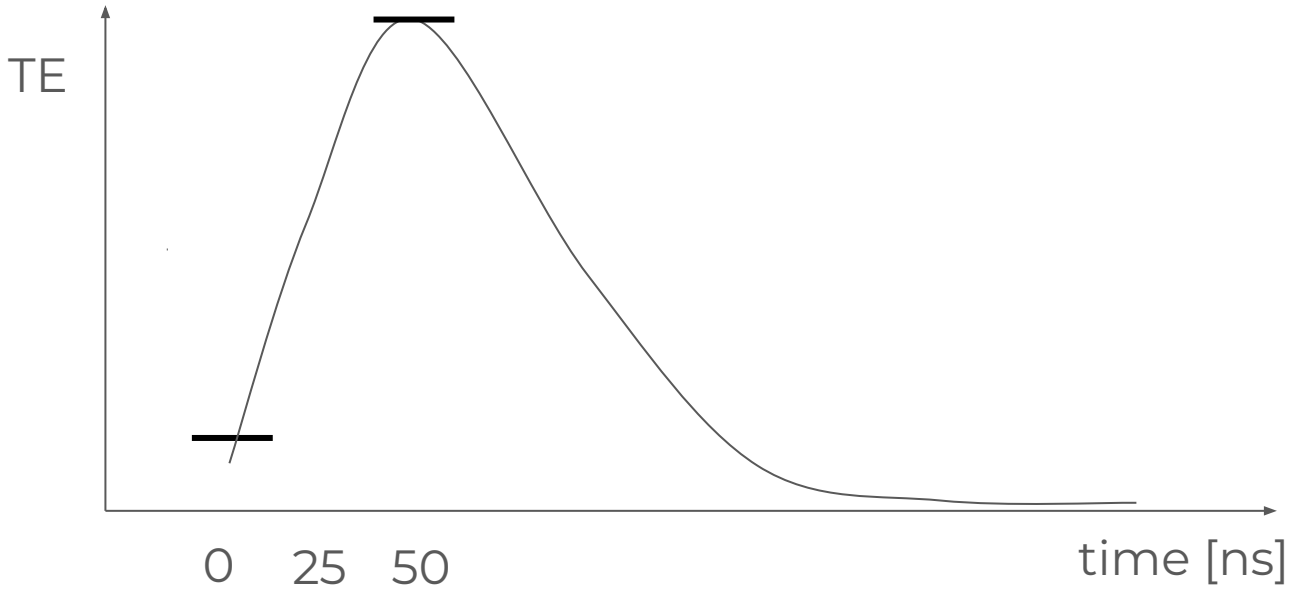
  - High rate of events with **out-of-time** contributions - noticed in events passing UPC jet triggers
  - Accepting more UPC events - potential loss (shadowing) of hadronic events
    - due to ~100 ns time reserved for write-out of accepted event

Shadowing

- Huge calorimeter signal from UCC event is so wide , that 50 ns before it looks like UPC signal
  - related to broad timing distribution for some L1 items



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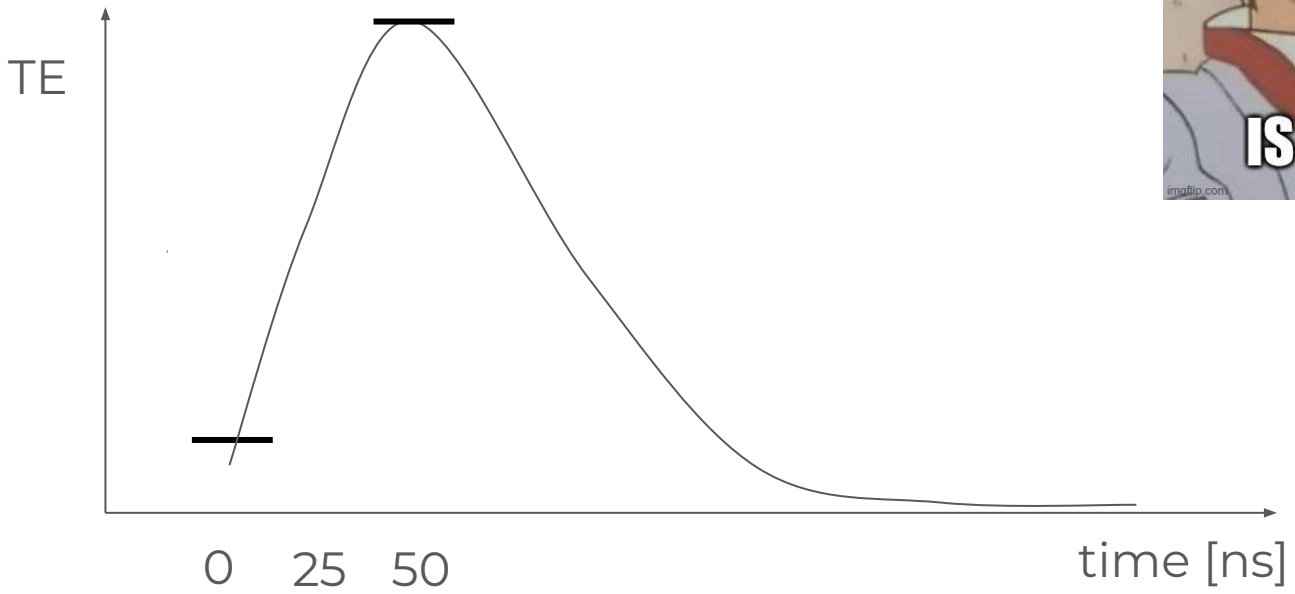

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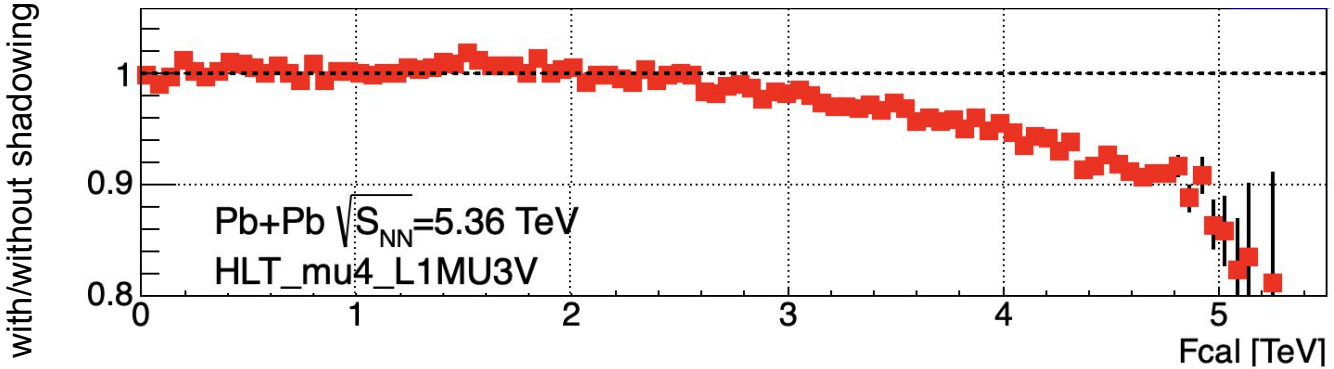
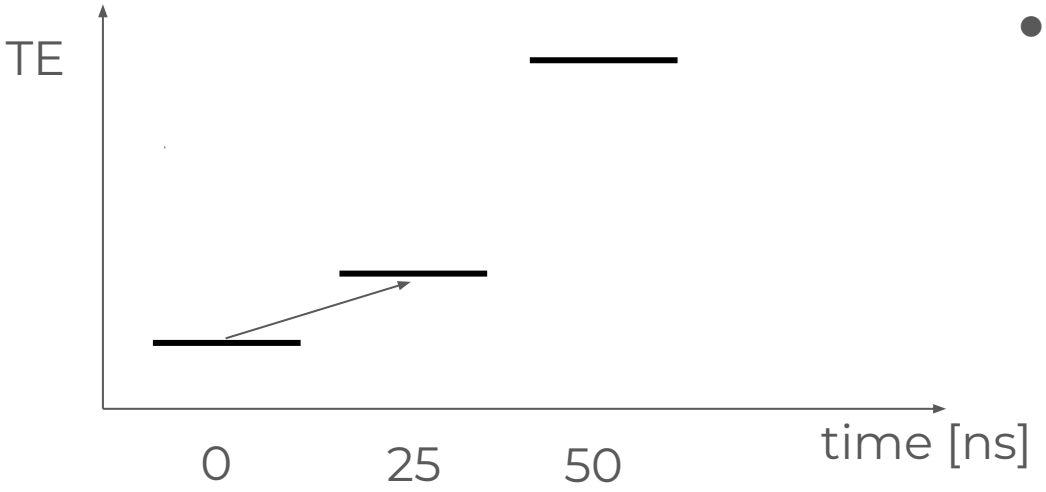
- It was found that the shadowing is centrality dependent, ie UCC events are more frequently shadowed
- Emergency fix by disabling the problematic UPC items



Anti-shadowing items - new TE triggers

- Proper fix with dedicated L1 Topo items
- Exploiting the fact that L1 Topo can “wait” some time before the final decision
- Looking for rising edge of calo response



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  - **TEATIME** - **T**otal **E**nergy **A**nti-**T**rigger for **I**mminent **M**assive **E**vents

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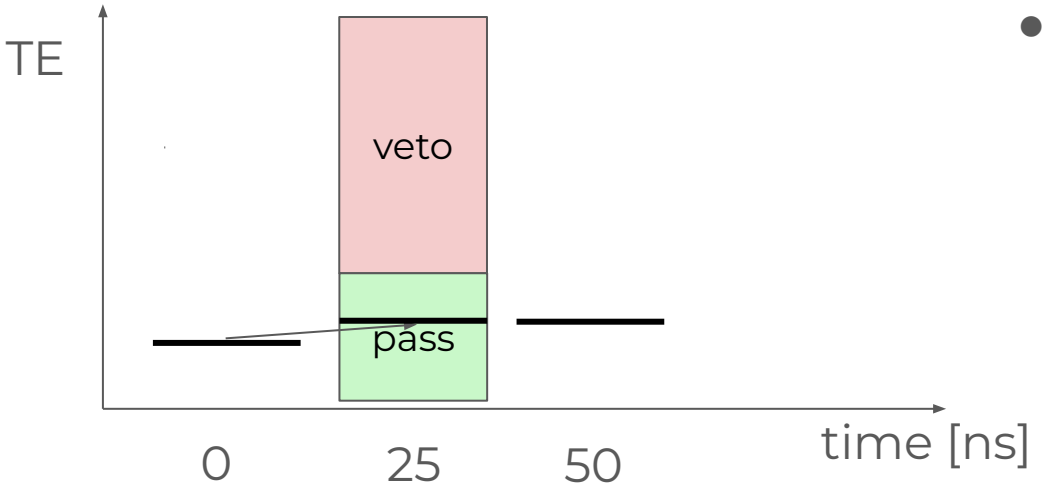

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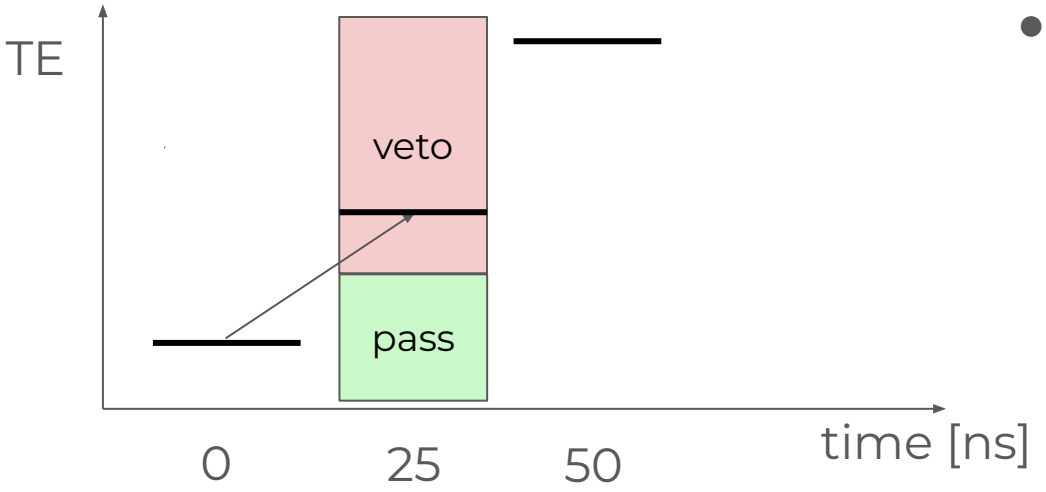

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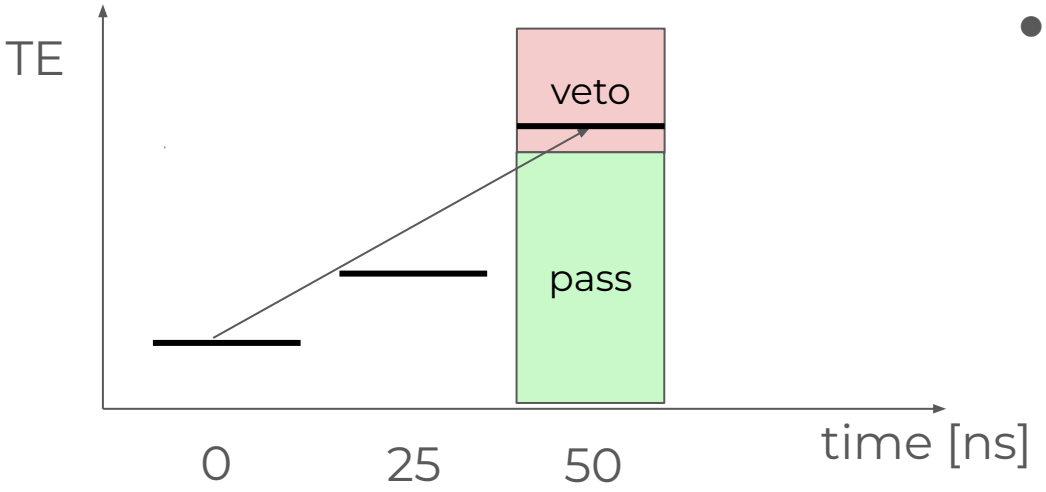

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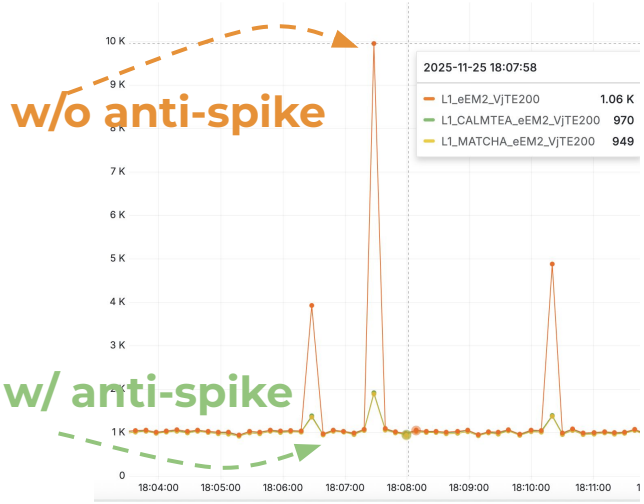
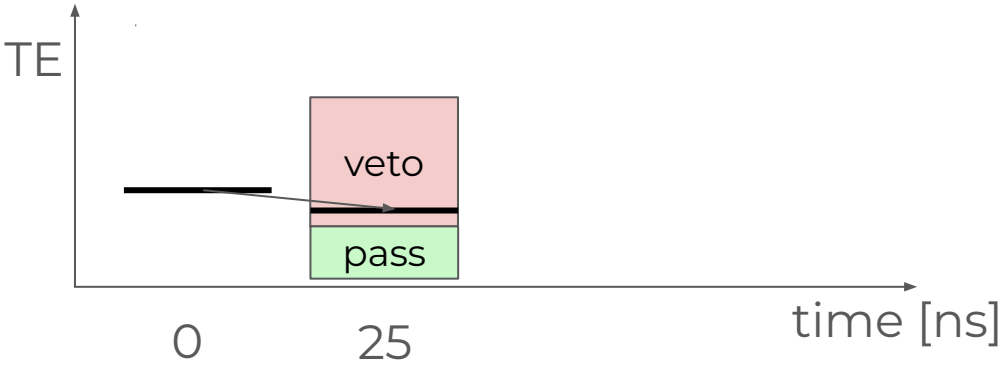
Spin-off: anti-spike items

- TEATIME algorithm also giving possibility to tag “long” lasting activity - noise bursts
- In two flavours:
  - **CALMTEA** - **C**alming **A**lgo for **L**owering **M**isbehaving **T**rigger **E**xcessive **A**ctivity (total E_T)
  - **MATCHA** - **M**itigation **A**gainst **T**riggering on **C**ontinuously **H**igh **A**ctivity (E_T only in barrel)





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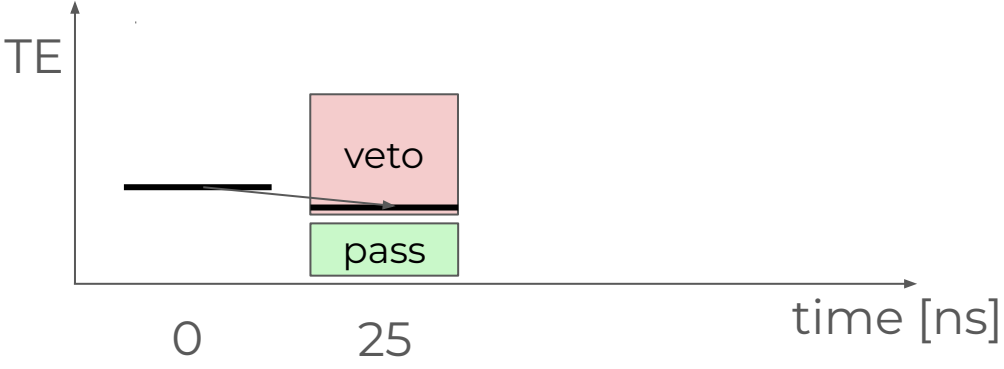
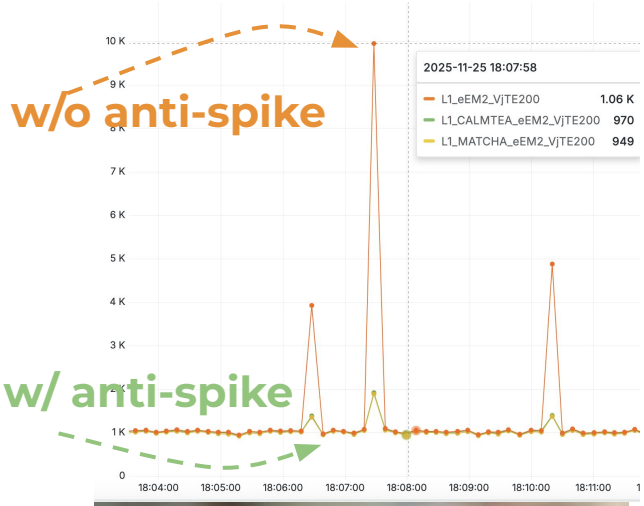
  - **MATCHA** - **M**itigation **A**gainst **T**riggering on **C**ontinuously **H**igh **A**ctivity (E_T only in barrel)





Instead of summary

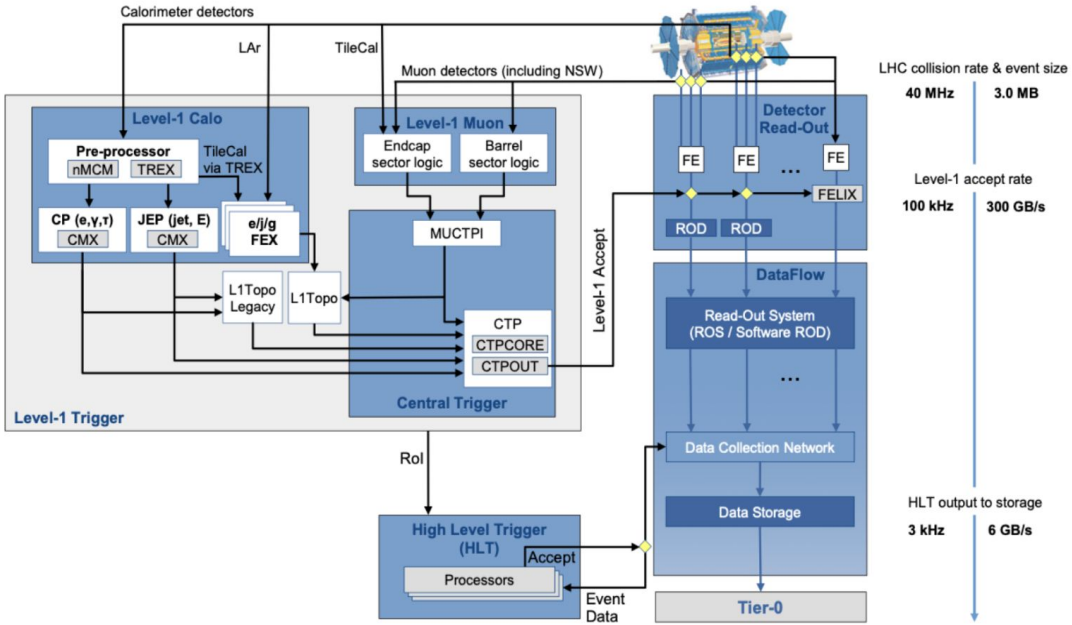
Instead of summary

Instead of summary

Backup

ATLAS trigger system

- LHC collision rate is up to 40 MHz
- In ATLAS experiment the limit for recording rate is at about a few kHz
- Online filtering of the events is done by the trigger system
- It has hardware (Level-1) and software (High LeveL Trigger, HLT) component
  - Coarse granularity information from calorimeters, muons system, TRT and ZDC @ L1, output up to 100 kHz
  - offline-like reconstruction @ HLT, output limited by recording bandwidth



ZDC trigger for UPC

- Various neutron topologies provide handle on impact parameter
- Extra neutrons in ZDC possible due to additional photon exchange
  - excited nucleon de-excites by neutron emission