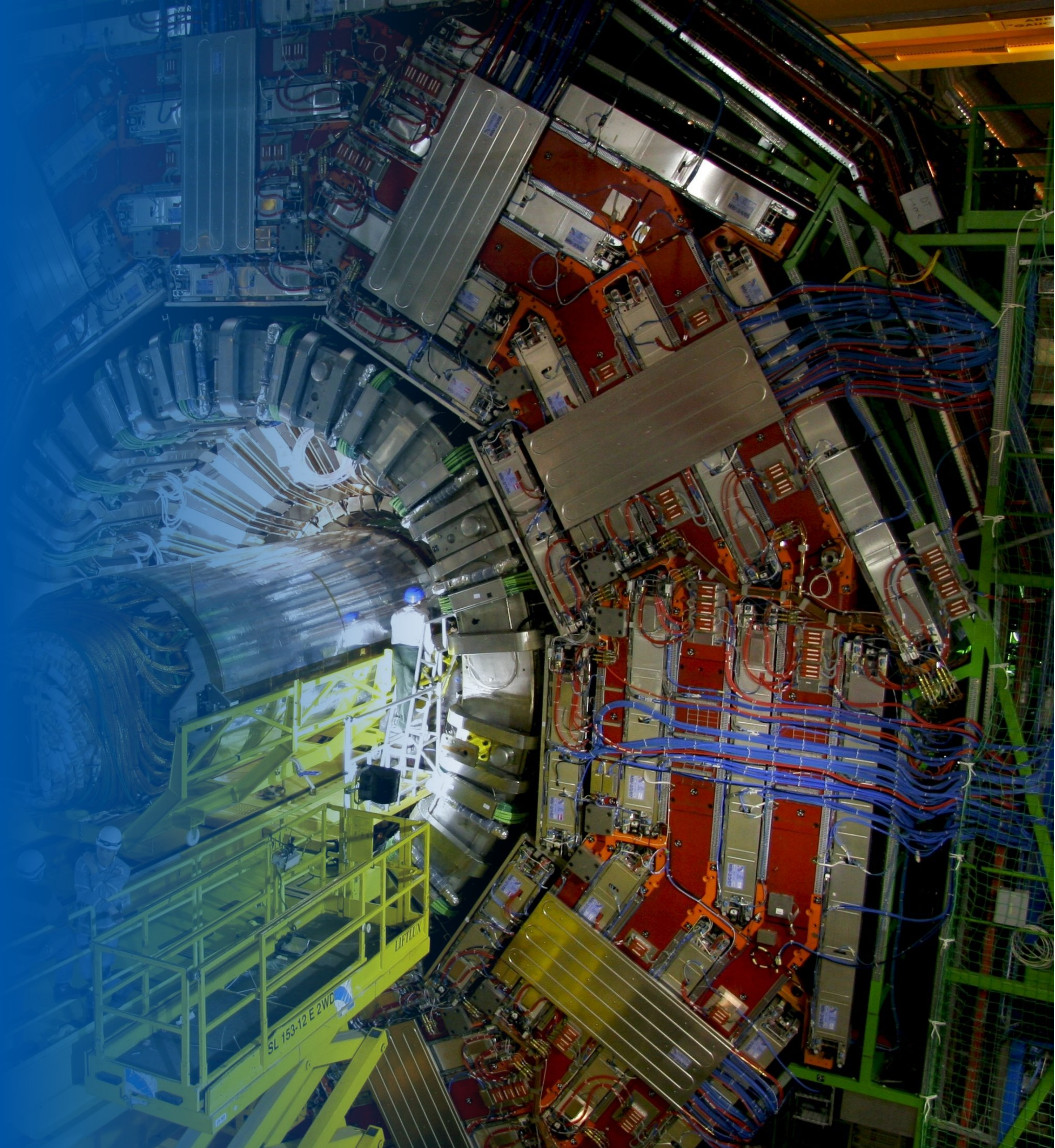
CERN



Trigger and data processing

or

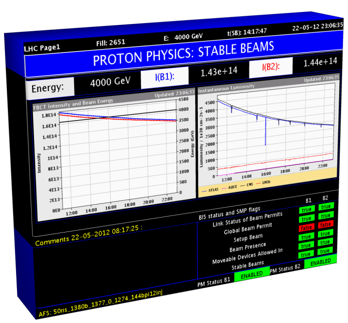
The CMS trigger system

Andrea Bocci - CERN

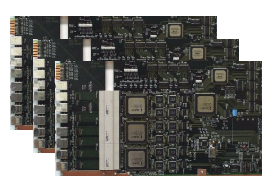
Why do we need a *trigger*?

- the role of the trigger is to
  - reduce the event rate from the LHC collision rate (**~ 15 MHz**) to what can be stored and analysed offline (**~ 400 Hz**)
  - while keeping the **physics reach** of the experiment

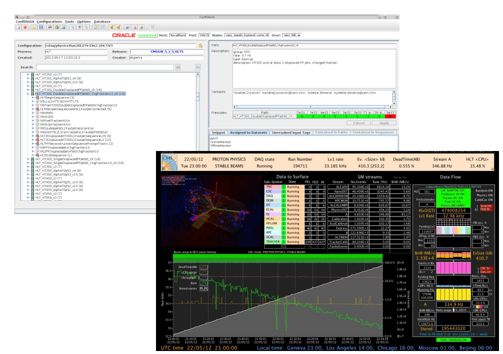
- CMS has been designed with a 2-level trigger system



~15 MHz



100 kHz



400 Hz

Offline

LHC

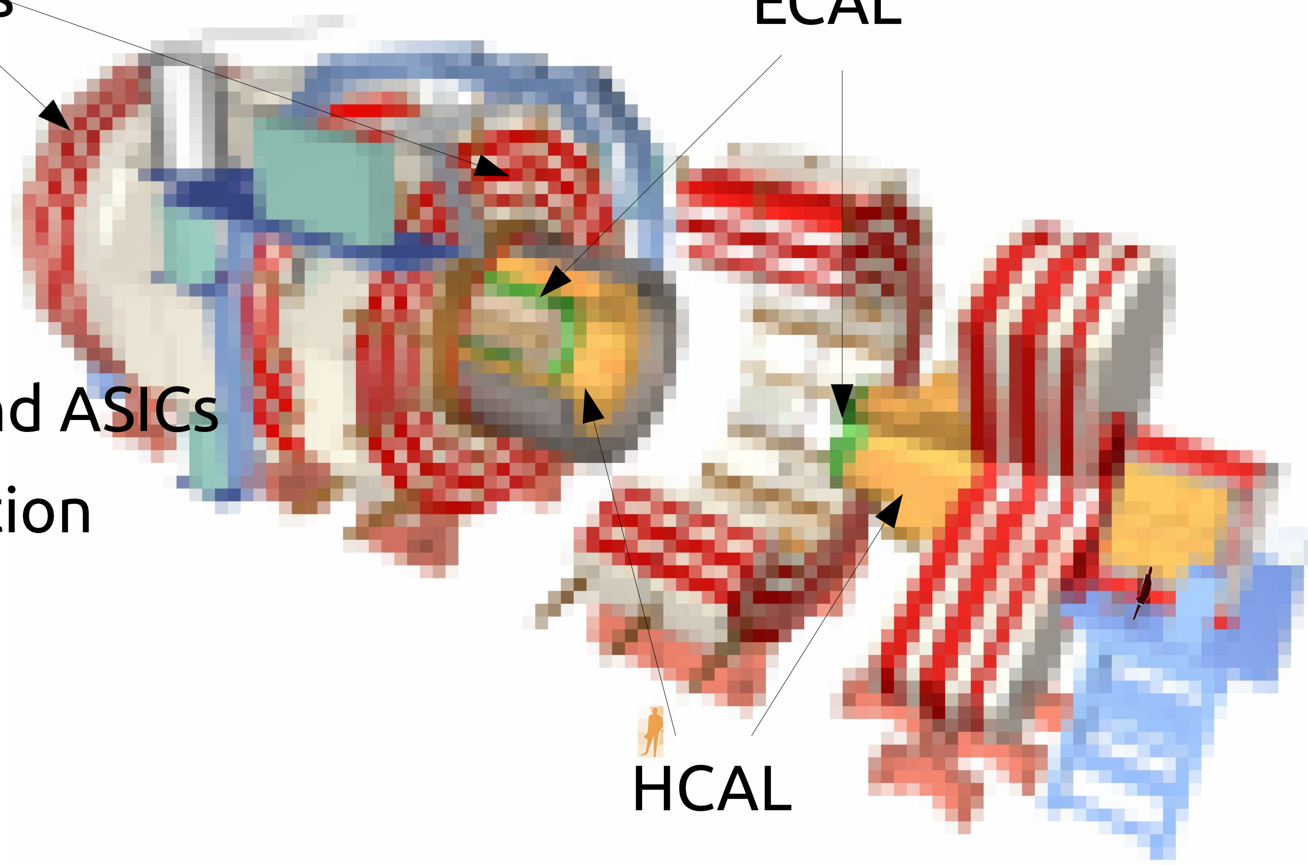
Level 1 Trigger

High Level Trigger

Level 1 Trigger

Level 1 Trigger

- fast readout of the detector, with a limited granularity



- implementation
  - hardware: FPGAs and ASICs
  - synchronous operation
  - 40 MHz LHC clock

- constraints
  - ~4 μs to take a decision
  - 100 kHz maximum output rate

L1 Trigger Objects

- the L1 Trigger reconstructs

Global Muon Trigger

- “stand alone” muon candidates
  - up to 4 candidates from the hits in the muon detectors

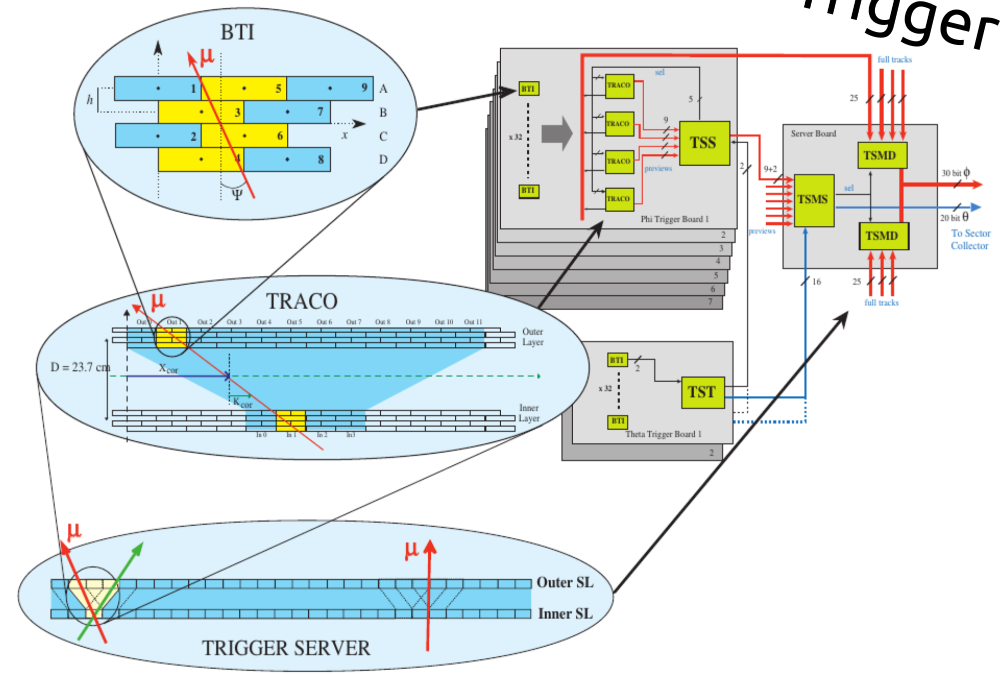
- e/gamma objects: photons or electrons
  - from ECAL deposits
  - including the possibility for a loose calorimetric isolation
- jets
  - up to 4 central, 4 forward, and 4 tau candidates
  - from the calorimetric deposits
- global quantities: MET, HT
  - from the calorimetric deposits

Global Calo Trigger

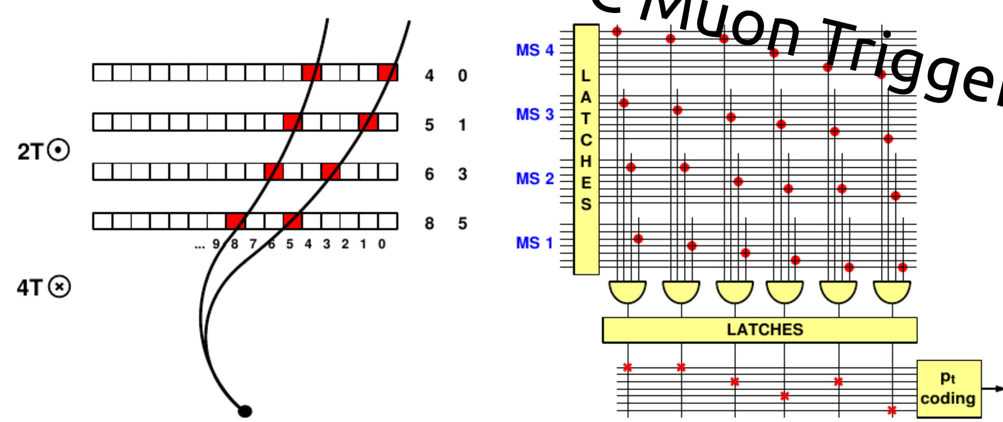
L1 Muon Trigger

- **DT and CSC**
  - track segments are identified in the detectors
  - track finders (DTTF and CSCTF) build muon candidates
  - each candidate is assigned η, φ, p_T and quality
  - **select 4 (DT) + 4 (CSC) candidates**
- **RPC**
  - hits are built into candidates
  - each candidate is assigned η, φ, p_T and quality
  - **select 4 (barrel) + 4 (endcap) candidates**
- **GMT – Global Muon Trigger**
  - combine candidates in the barrel (DT+RPC) and endcap (CSC+RPC)
  - merges or removes duplicates
  - each candidate is assigned η, φ, p_T and quality
  - select **4 leading muon candidates**
    - high quality candidates ued for single muon triggers
    - low quality candidates are used for di-muon and cross-triggers

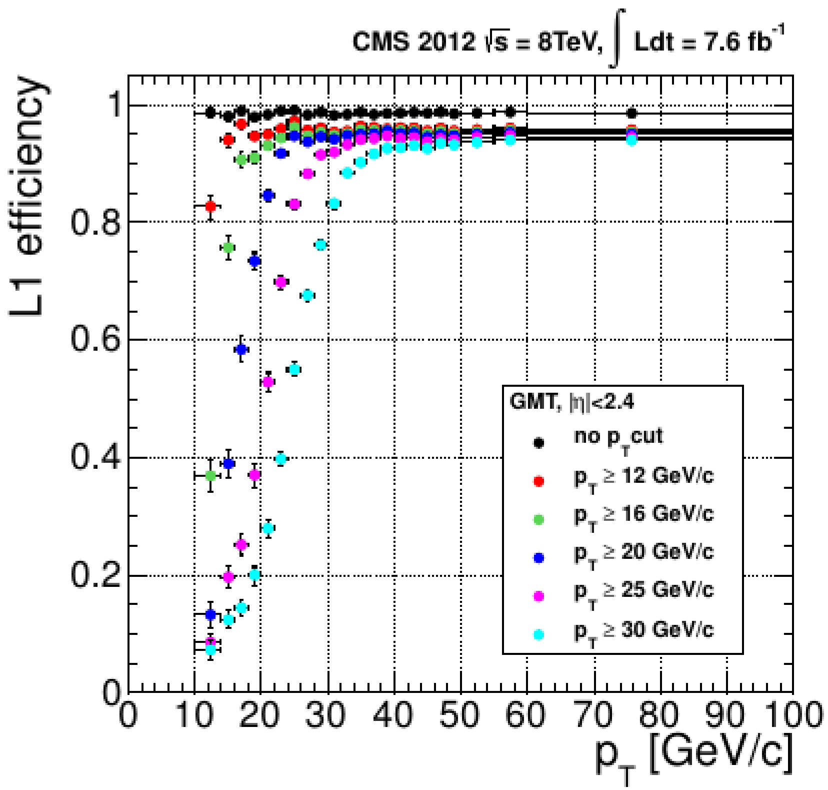
DT Muon Trigger



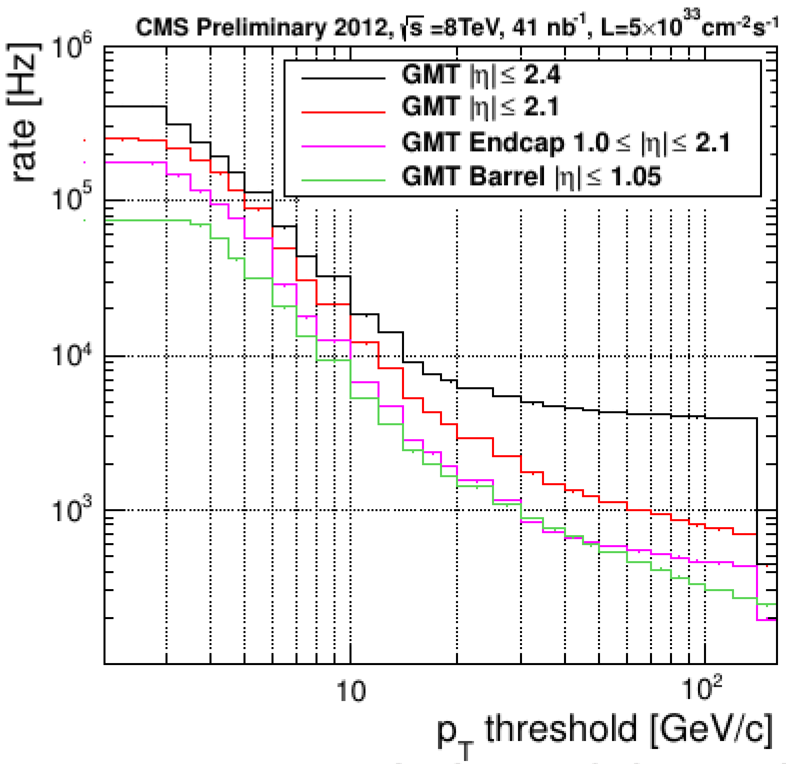
RPC Muon Trigger



L1 Muon Trigger



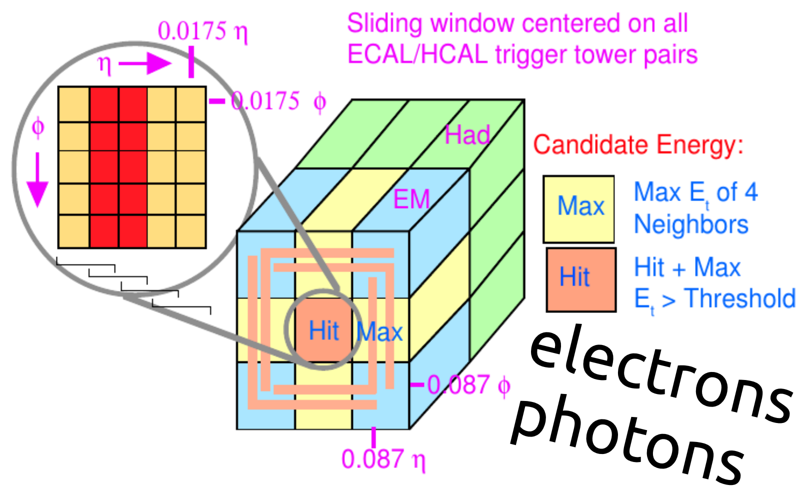
L1 muon efficiency vs.
offline transverse momentum

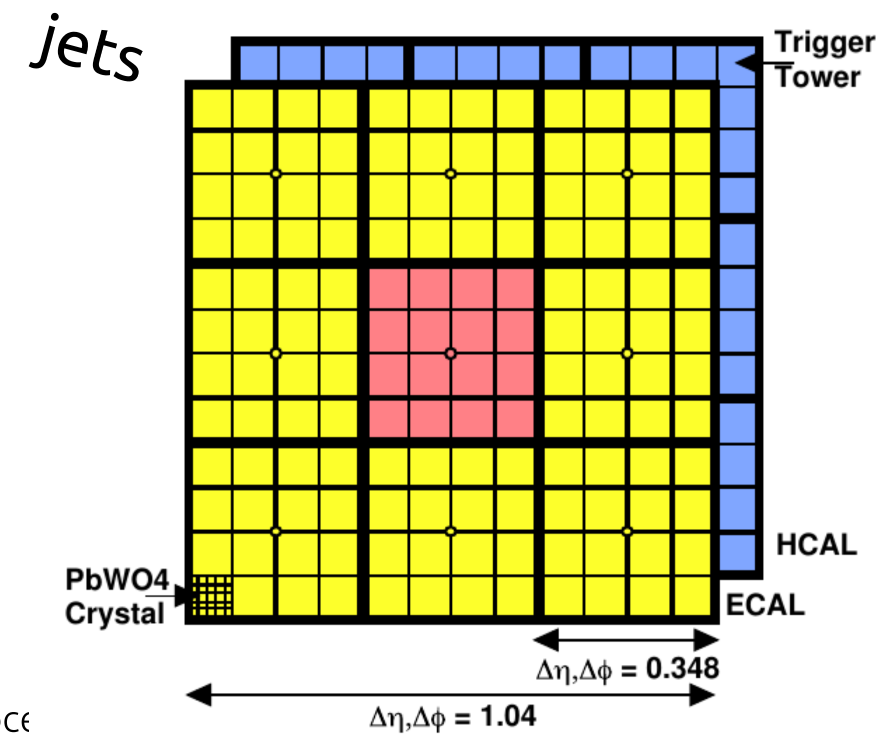


L1 muon rate vs. pT cut

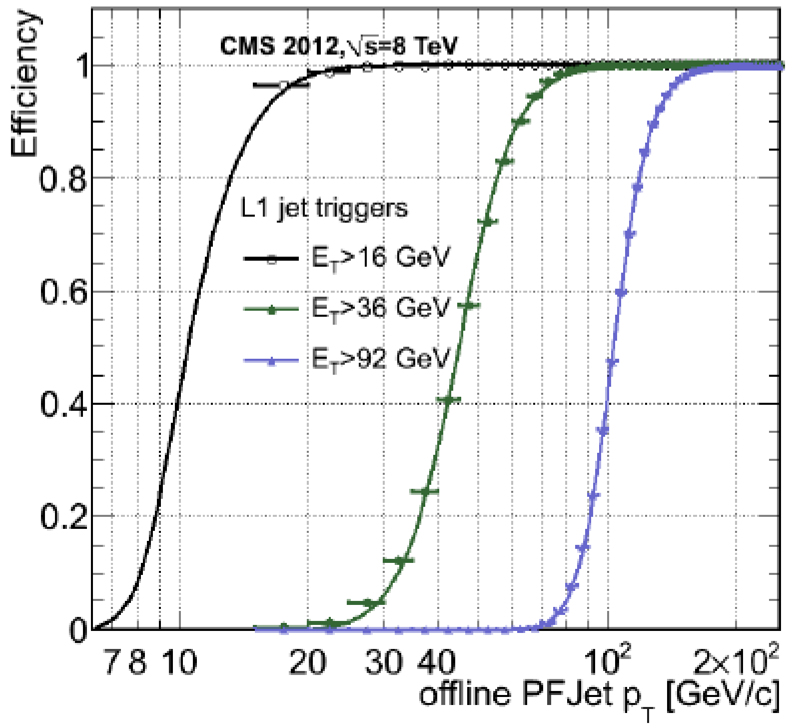
L1 Calo Trigger

- **ECAL trigger primitives**
  - trigger tower: 5x5 crystals
  - ET in each tower
  - reject “spikes”, apply “transparency corrections”
- **HCAL primitives**
  - ET in each tower
- **e/gamma candidates**
  - id based on shower shape, isolation from ECAL and H/E
  - select **4 isolated** and **4 non-isolated** e/gamma candidates
- **jet candidates**
  - calorimeter regions (4x4 towers)
  - sum ET of 3x3 regions
  - tau “veto” based on the number of deposits
  - select **4 forward jets** (|η| > 3), **4 central jets** (|η| < 3, tau veto), **4 tau jets** (|η| < 3, no tau veto)
- **energy sums**
  - **ETT, MET** computed from all trigger towers above threshold
  - **HT, MHT** computed from all jets above threshold

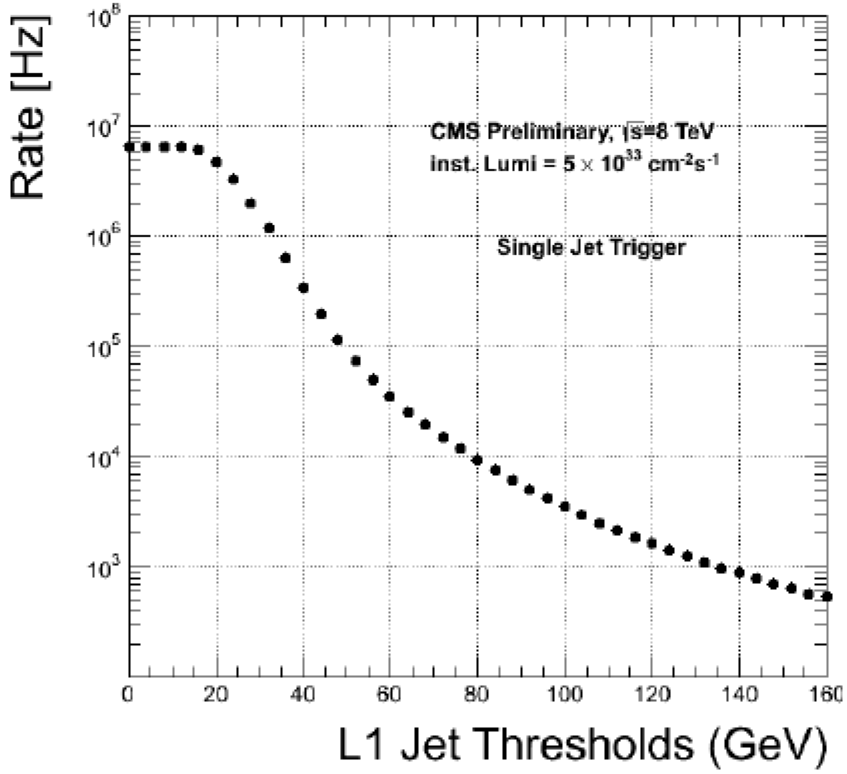




L1 jets

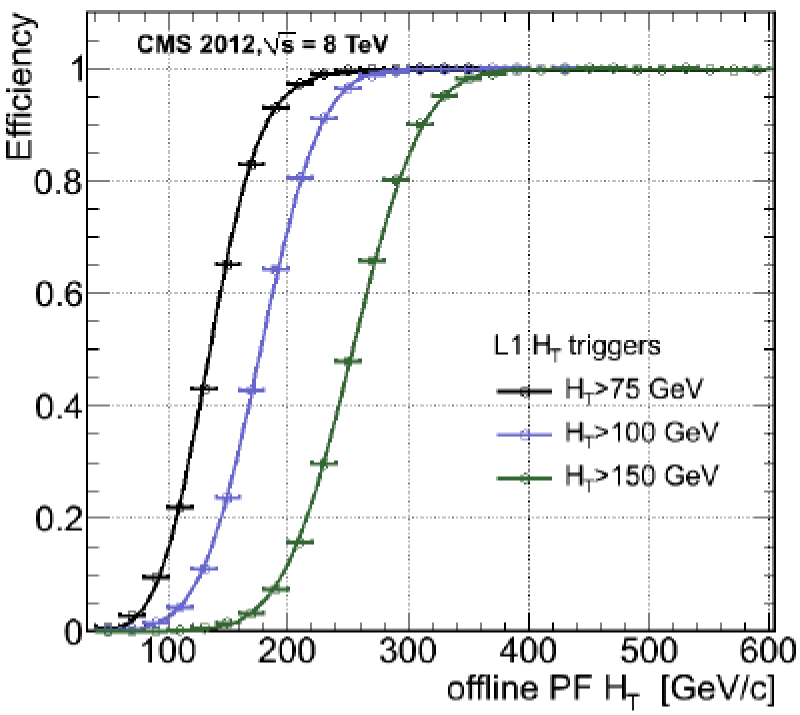


L1 jet efficiency vs.
offline transverse momentum

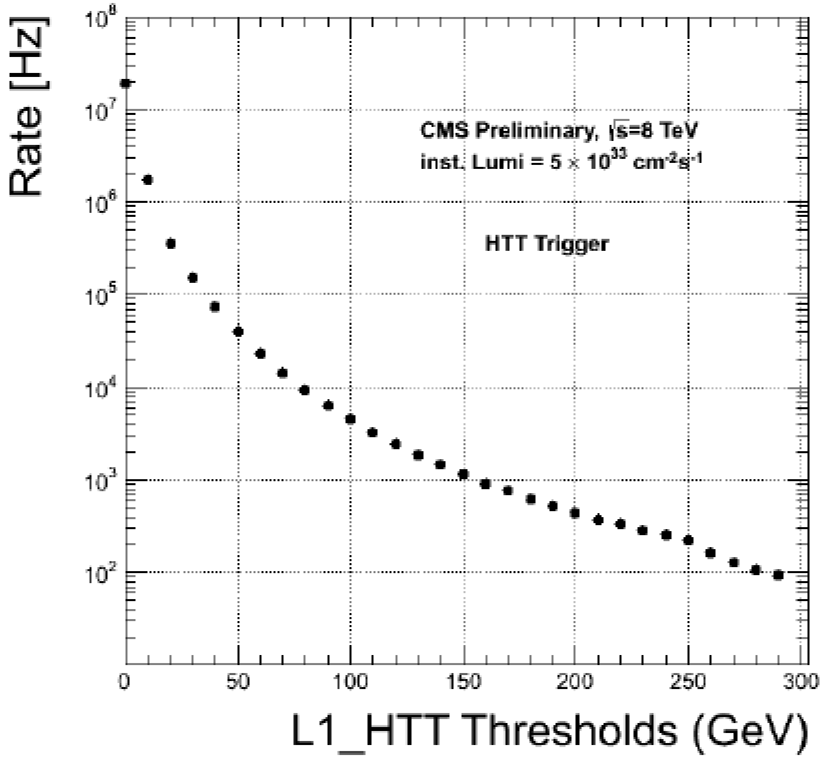


L1 jet rate vs. ET cut

L1 energy sums



L1 HT efficiency vs. offline HT



L1 HT rate vs. cut

L1 Trigger Menu

- L1 Global Trigger
  - reads the candidates from the Muon and Calo triggers
  - define up to 128 algorithms
    - based on the candidates
    - their quality flags
    - and their combinations
  - some random examples
    - L1_SingleMu16
    - L1_IsoEG12er_ETM36
    - L1_TripleJet_68_48_32_VBF

one (or more) muon(s), with pT above 16 GeV

one loosely isolated ECAL deposit, within $|\eta| < 2.1$

together with a missing ET above 36 GeV

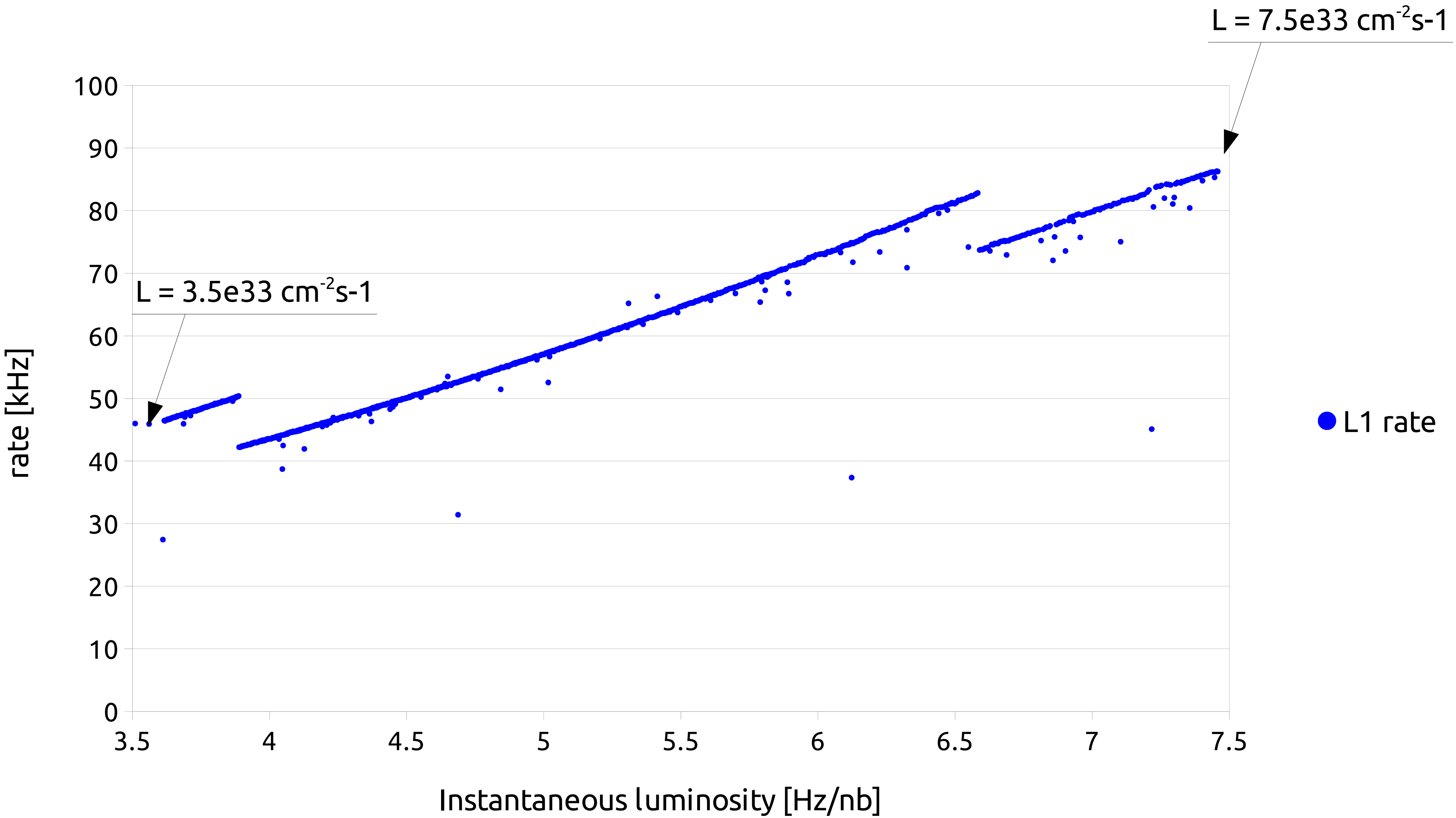
3 jets above different thresholds, in a VBF-like topology

- In 2012: 4 iterations of the L1 menu
  - with minimal changes, remove unused triggers, add cross-triggers, …

(some) L1 thresholds used in 2012

(Unprescaled) Object	Trigger Threshold (GeV)	Physics
Single muon	16 (14 central)	Searches
Double muon	(10, 0) or (10, 3.5)	Standard Model / Higgs
Double muon, tight	(0, 0) or (3, 0)	Quarkonia / B Physics
Single e/gamma	20 or 22	Standard Model / Searches
Single Isolated e/gamma	18 or 20	Standard Model / Searches
Double e/gamma	(13, 7)	Standard Model / Higgs
Muon + Ele x-trigger	(3.5, 12), (12, 7), (5, 6, 6)	Standard Model / Higgs
Single Jet	128	Standard Model
QuadJet	40	Standard Model /Searches
Six Jet	(6 x 45), (4 x 60, 2 x 20)	Searches
MET	40	Searches
HT	150 or 175	Searches

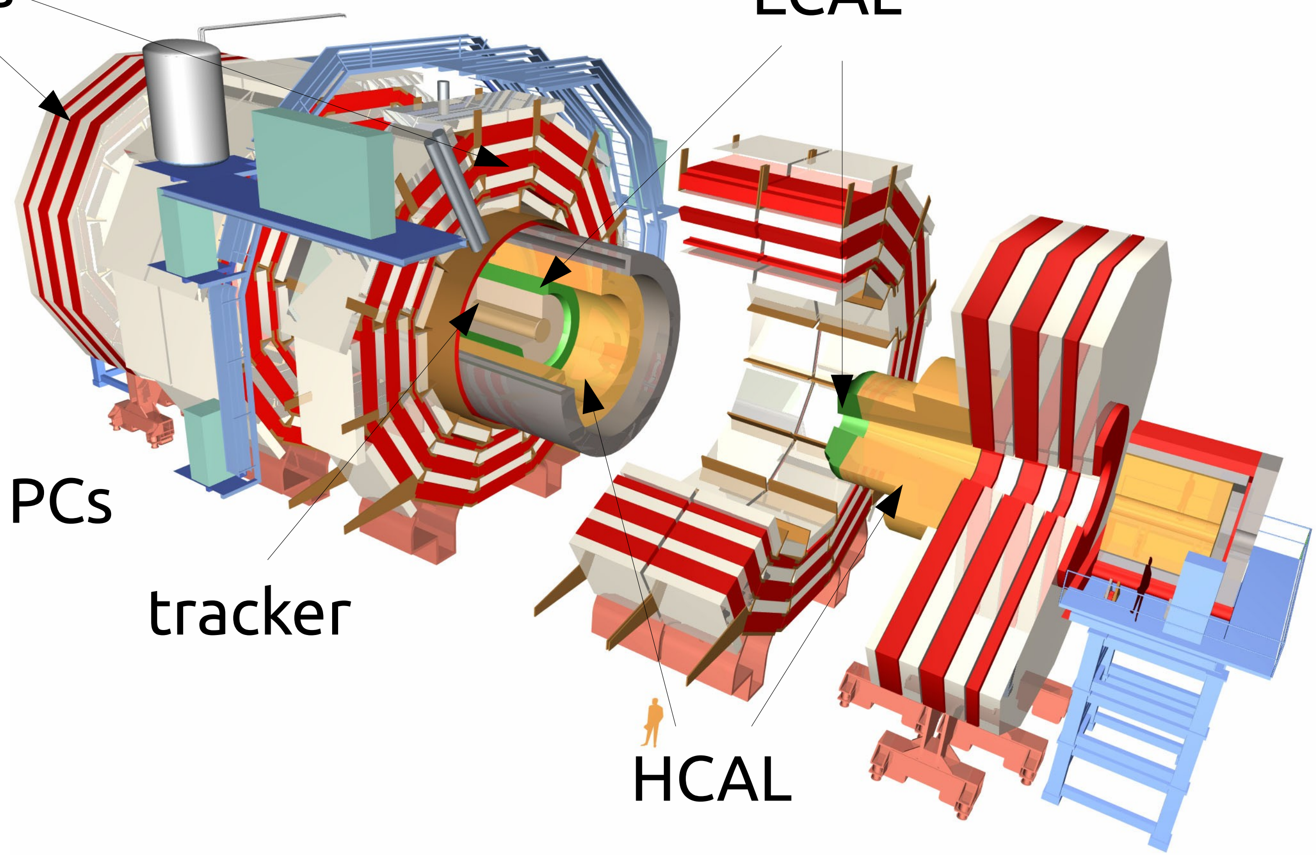
L1 Trigger rate vs. Luminosity



High Level Trigger

High Level Trigger

- full readout of the detector at 100 kHz



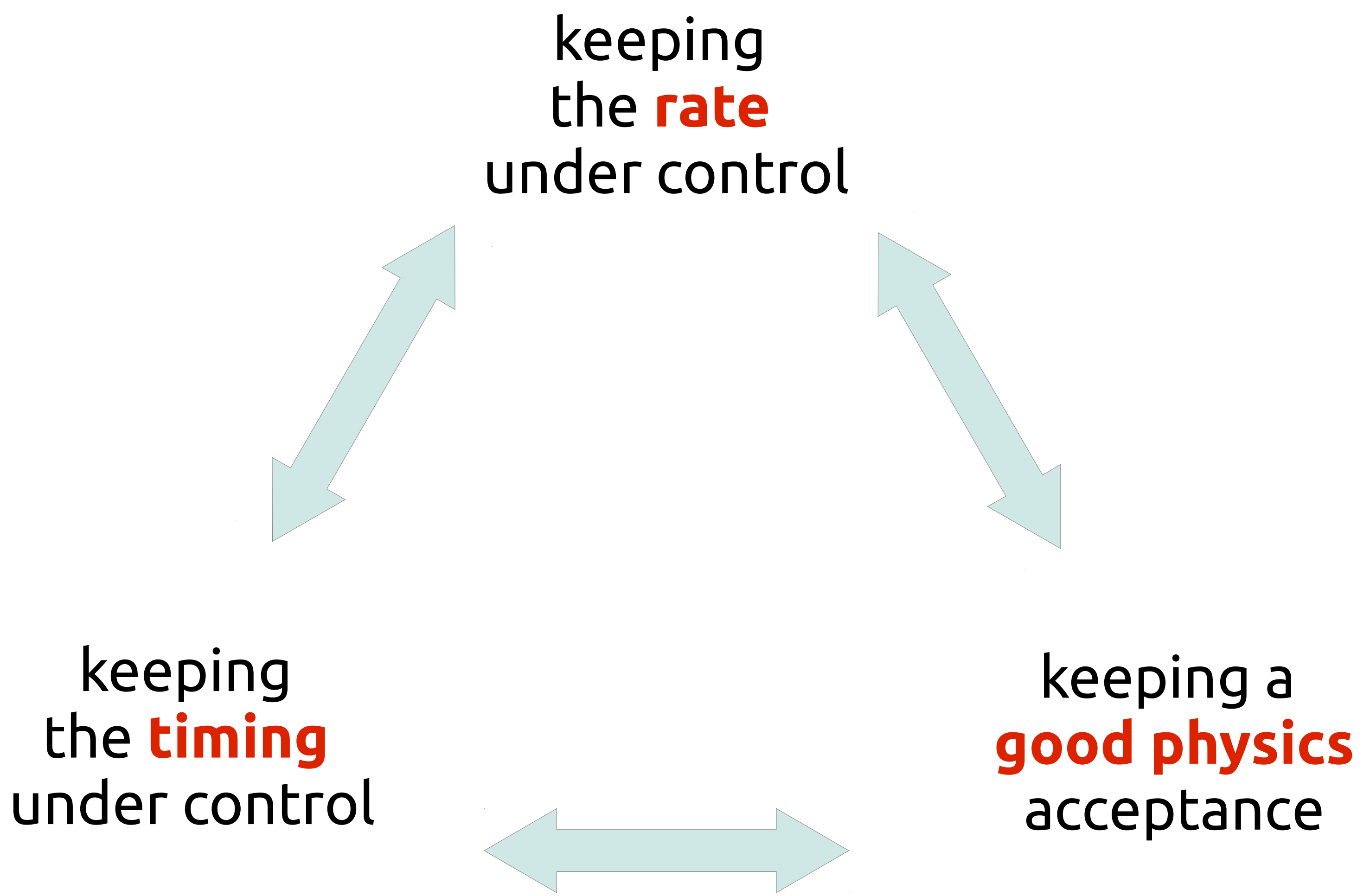
- implementation
    - software: CMSSW
    - runs on commercial PCs
    - quasi-synchronous
- constraints
    - ~200 ms *average* maximum time to take a decision
    - ~400 Hz *average* output rate

High Level Trigger

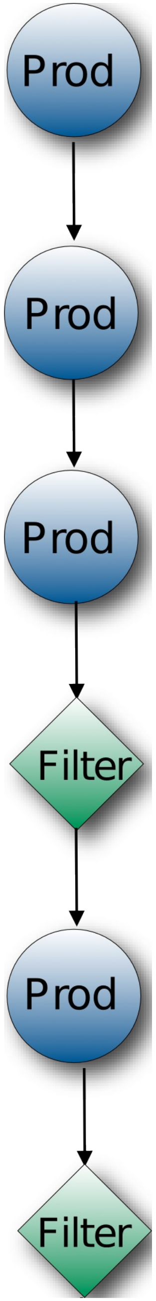
- The High Level Trigger
  - is implemented in software (CMSSW)
    - running the same code used for offline reconstruction and analysis
    - but a very optimised configuration: O(100~1000) faster than offline
  - running on a farm of commercial computers
    - Intel Xeon, from different generations (2008-2012)
    - O(13'000) cpu cores, O(20'000) processes
  - over the full detector information
    - but take advantage of regions of interests to speed up the reconstruction

the challenge

- the trigger needs to find a compromise between …



online reconstruction

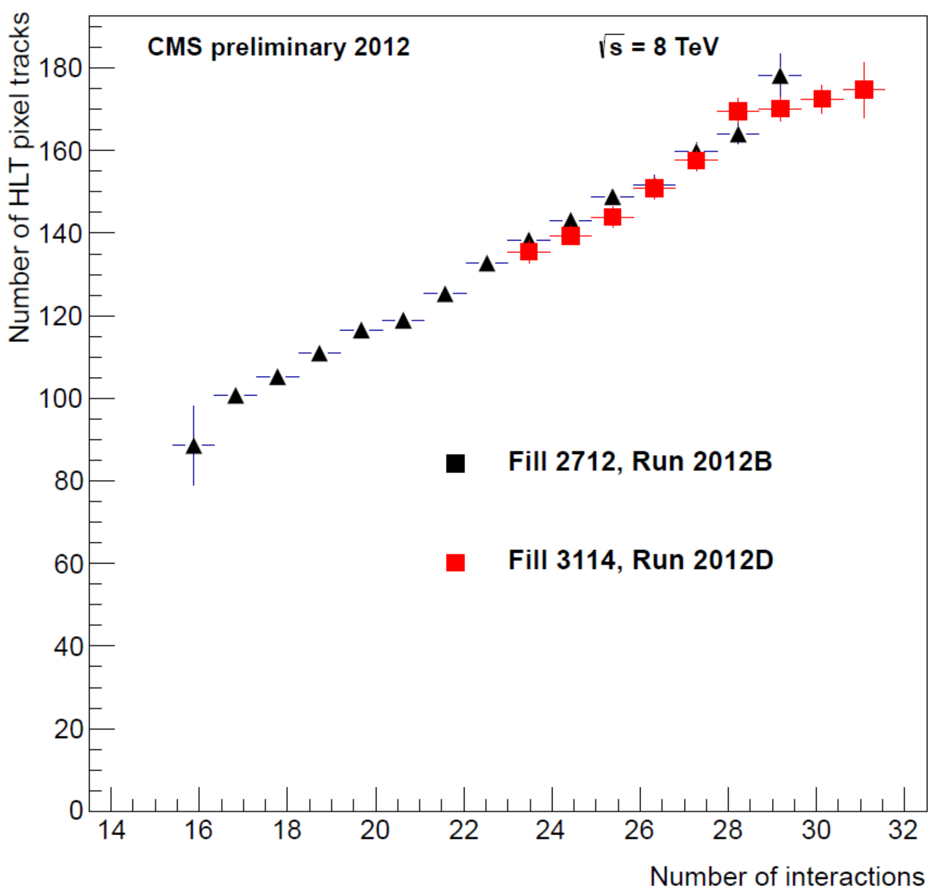


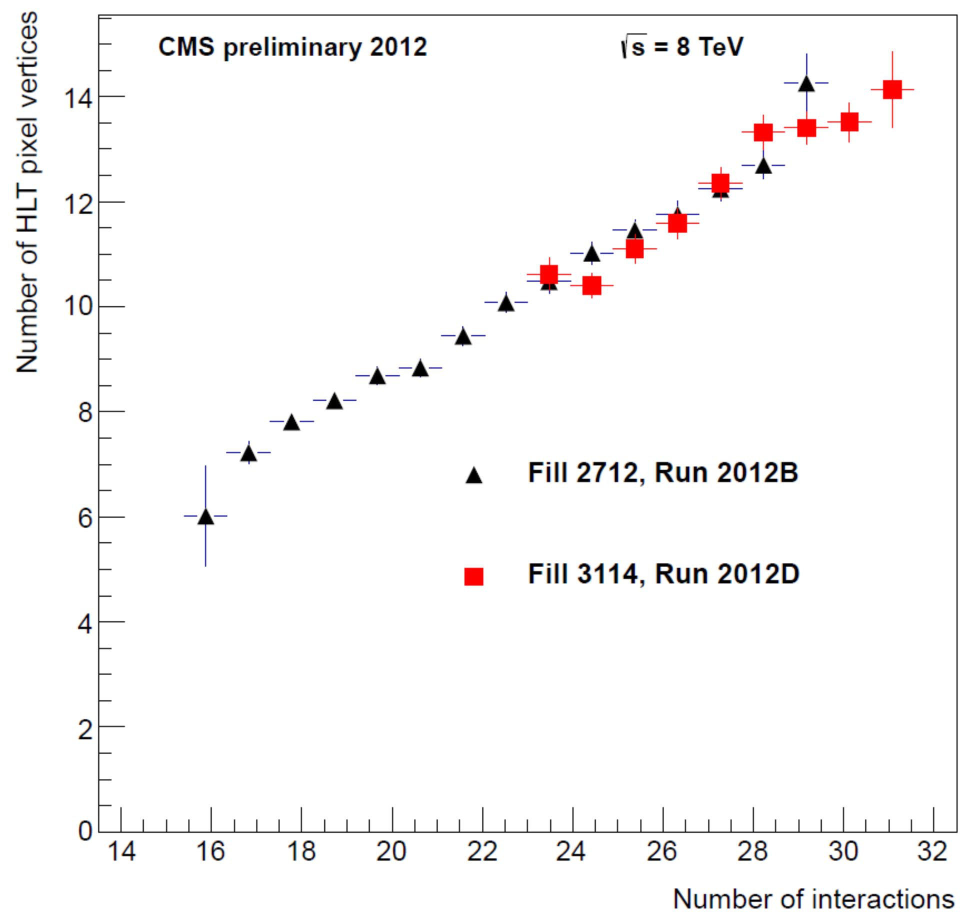
- the HLT uses many "tricks" to speed up the online reconstruction
  - remember – the limit is the **average** processing time per event
  - modular approach to reconstruction and filtering
    - reconstruct the **fastest object first**
      - L1 muon → L2 muon → L3 muon
      - L1 jet → "calo" jet → tracking and particle flow jet
    - **reject an event as soon as possible**
  - only look at what is really needed
    - **regional "unpacking" and reconstruction**
      - read the detector data around L1 objects
      - reconstruct tracks inside jets, or around leptons
  - keep combinatorics under control
    - **reject pile-up**, limit the number of candidates being evaluated

online reconstruction

- muons
  - "L2" stand alone muons
  - "L3" global muons
  - tracker-based isolation
- photons
  - based on ECAL superclusters
  - calorimeter-based id and isolation, tracker-based isolation
- electrons
  - match ECAL superclusters, pixel tracks, and full tracking
  - calorimeter-based id and isolation, tracker-based id and isolation
- taus
  - particle flow reconstruction
- jets, MET, HT
  - calorimteric jets and MET
  - particle flow-based jets and MET
- b-tagging
  - jets, full tracking
  - secondary vertex reconstruction
- but also
  - razor, α_T, dE/dx, …

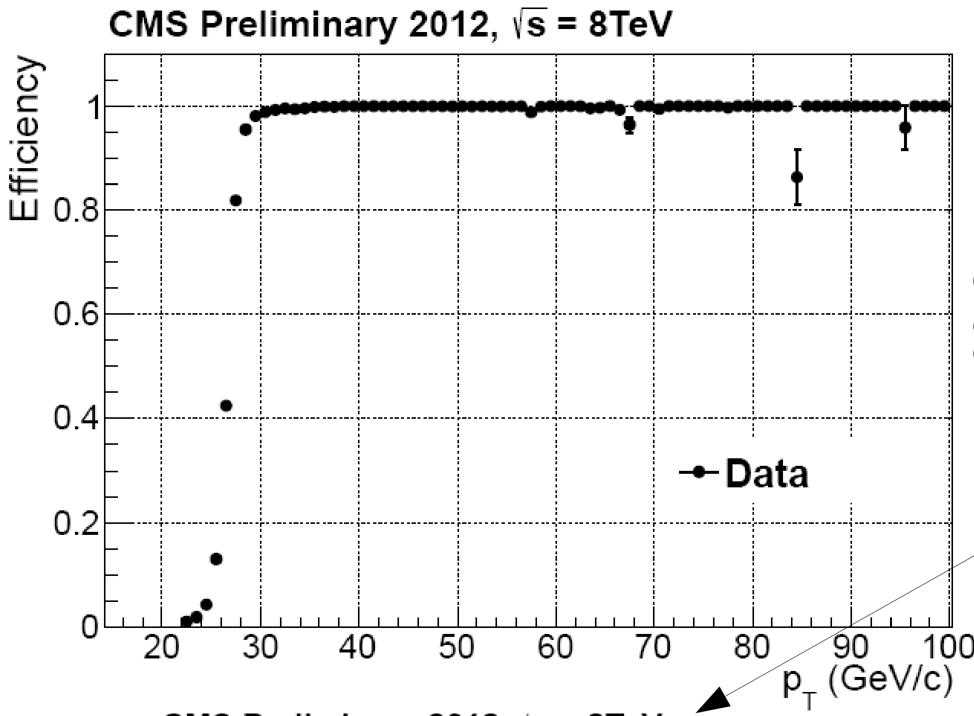
HLT tracking





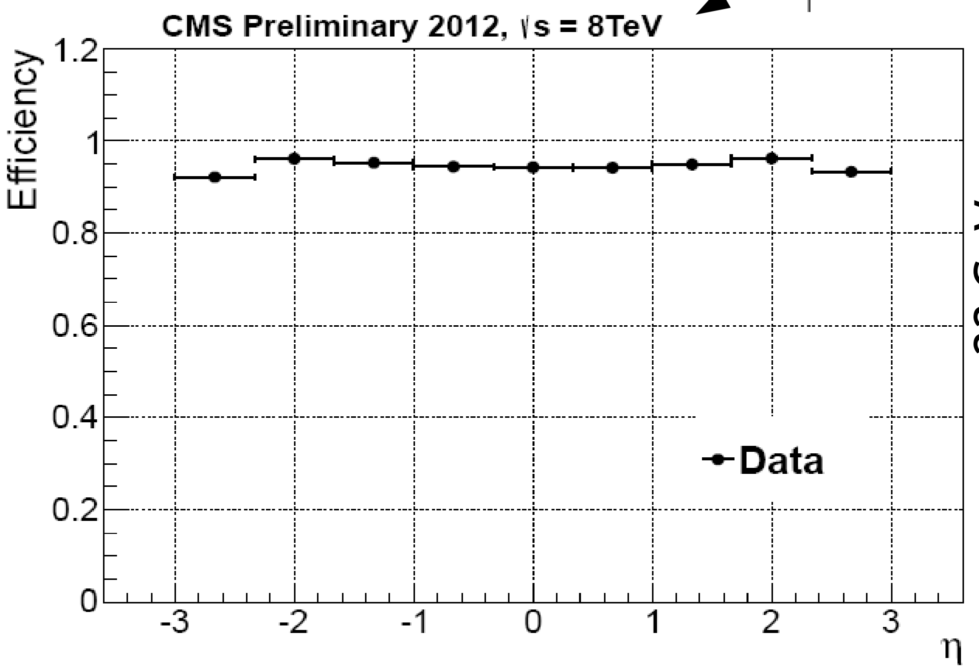
linearity of the HLT tracking performance vs. pileup, measured by the number of reconstructed (pixel) tracks and vertices vs. the number of interactions

HLT photons and electrons



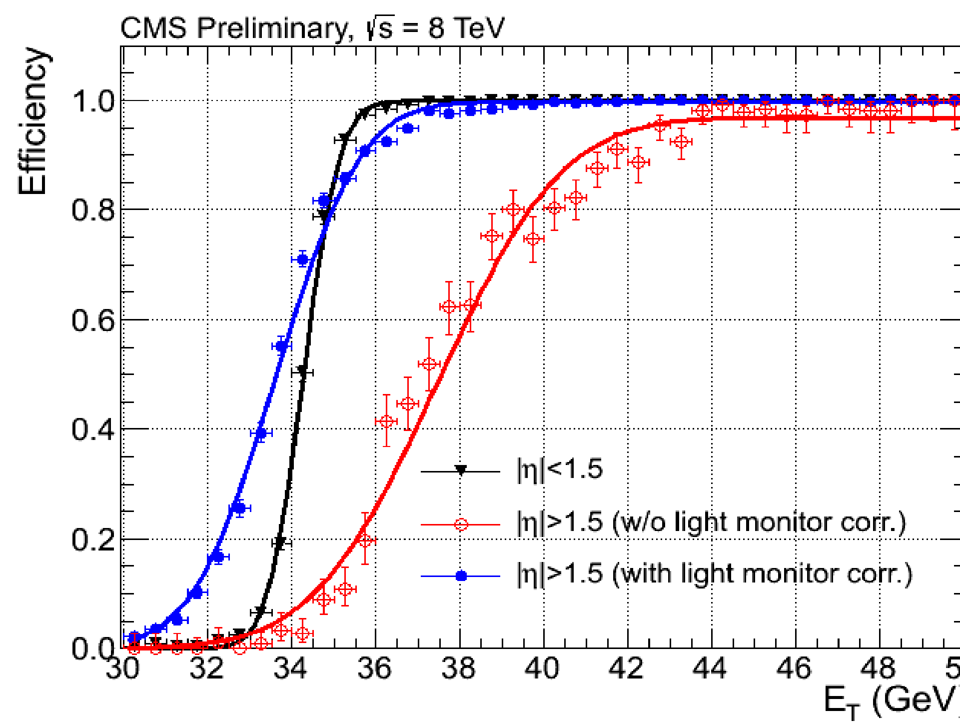
p_T > 22 GeV

HLT photon reconstruction efficiency vs. offline p_T and η



p_T > 22 GeV

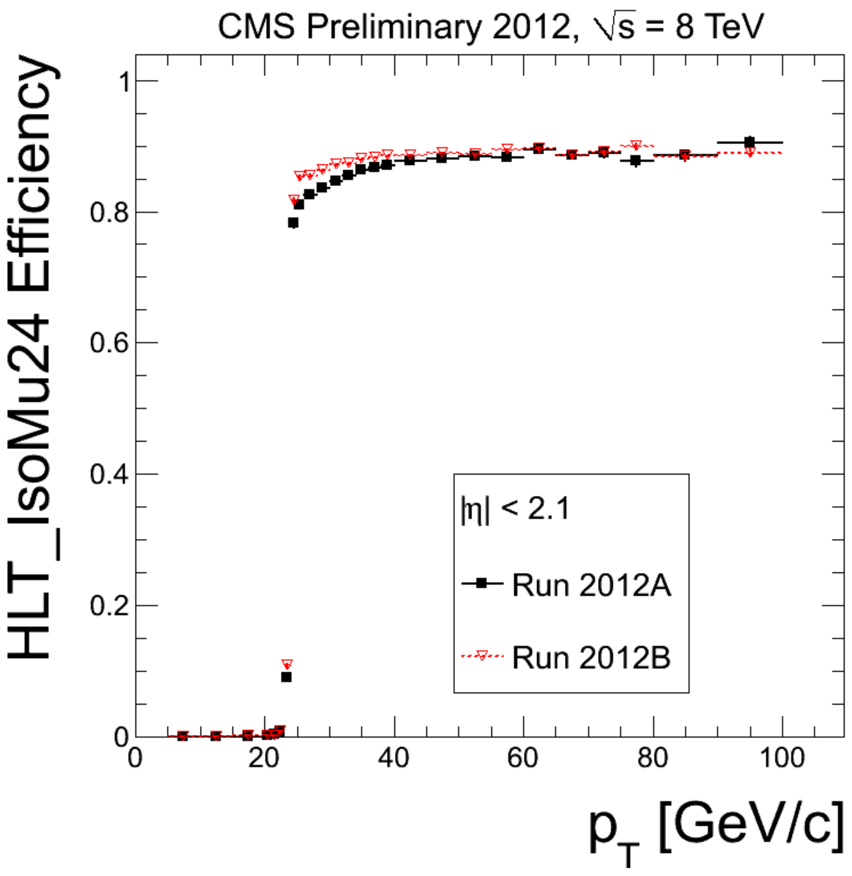
HLT electron efficiency vs. offline p_T in the **barrel** and **endcap**

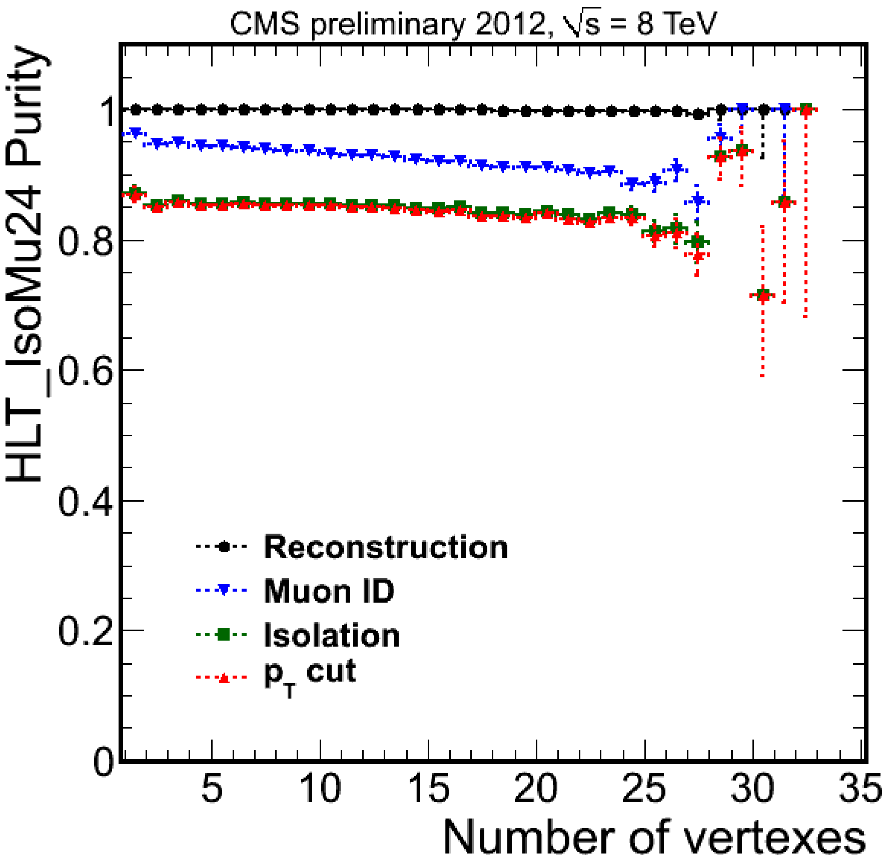


p_T > 33 GeV

HLT muons

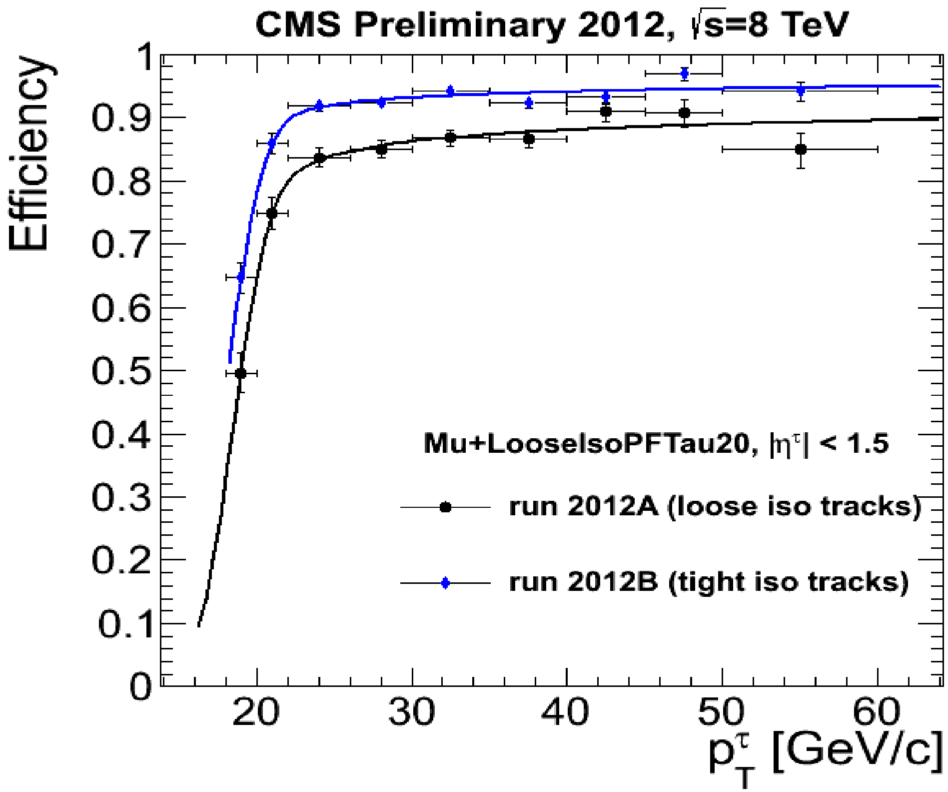
HLT isolated muon efficiency vs.offline p_T

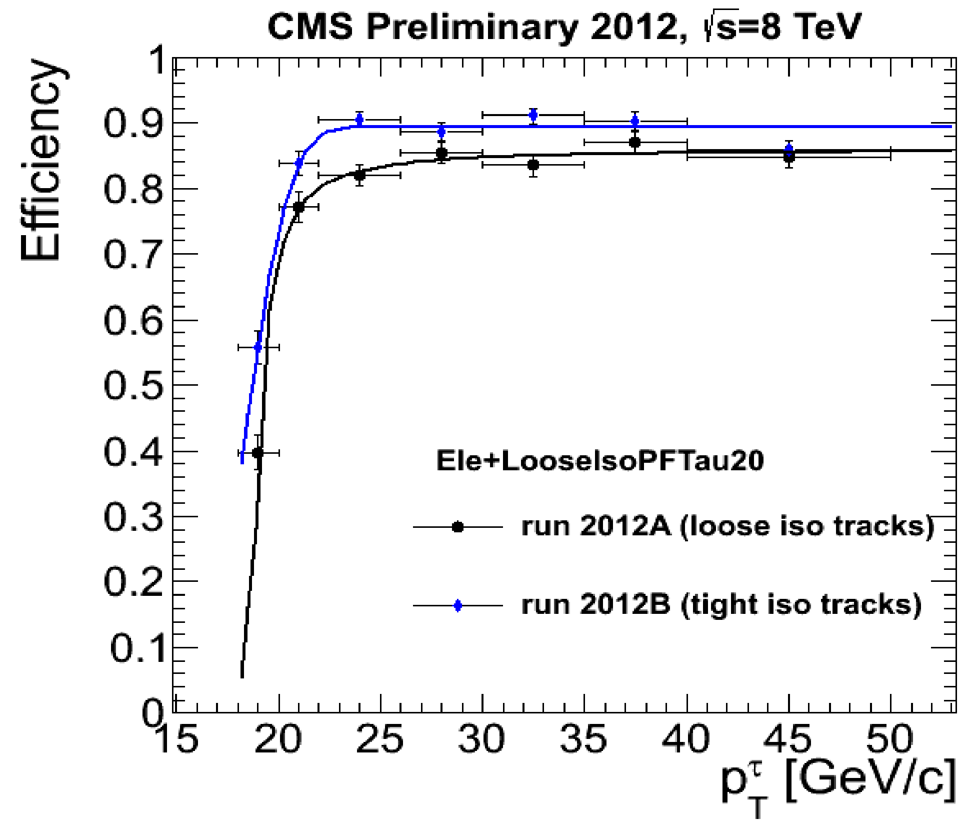




HLT isolated muon purity vs.pile-up
(number of reconstructed vertices)

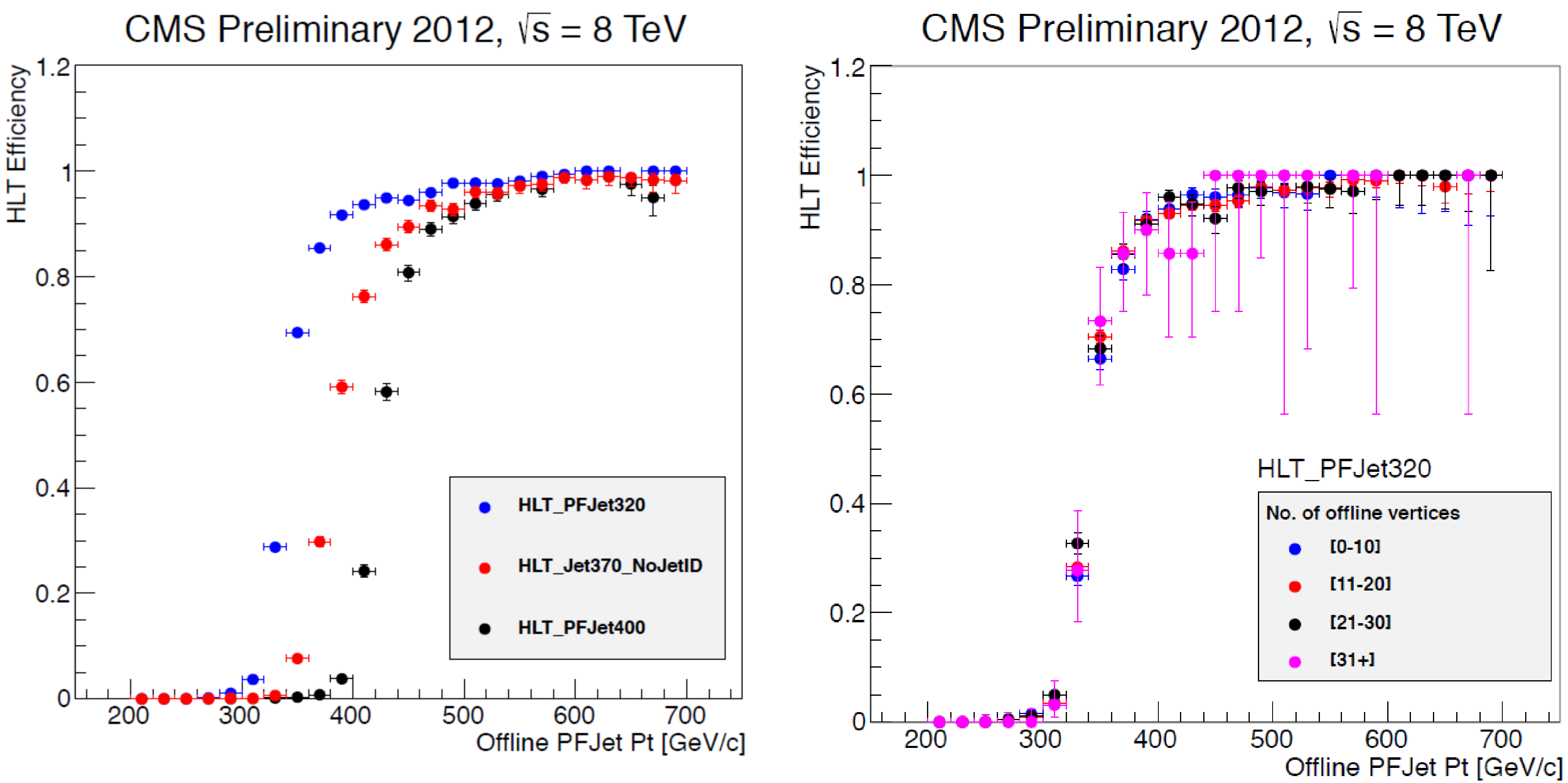
HLT taus





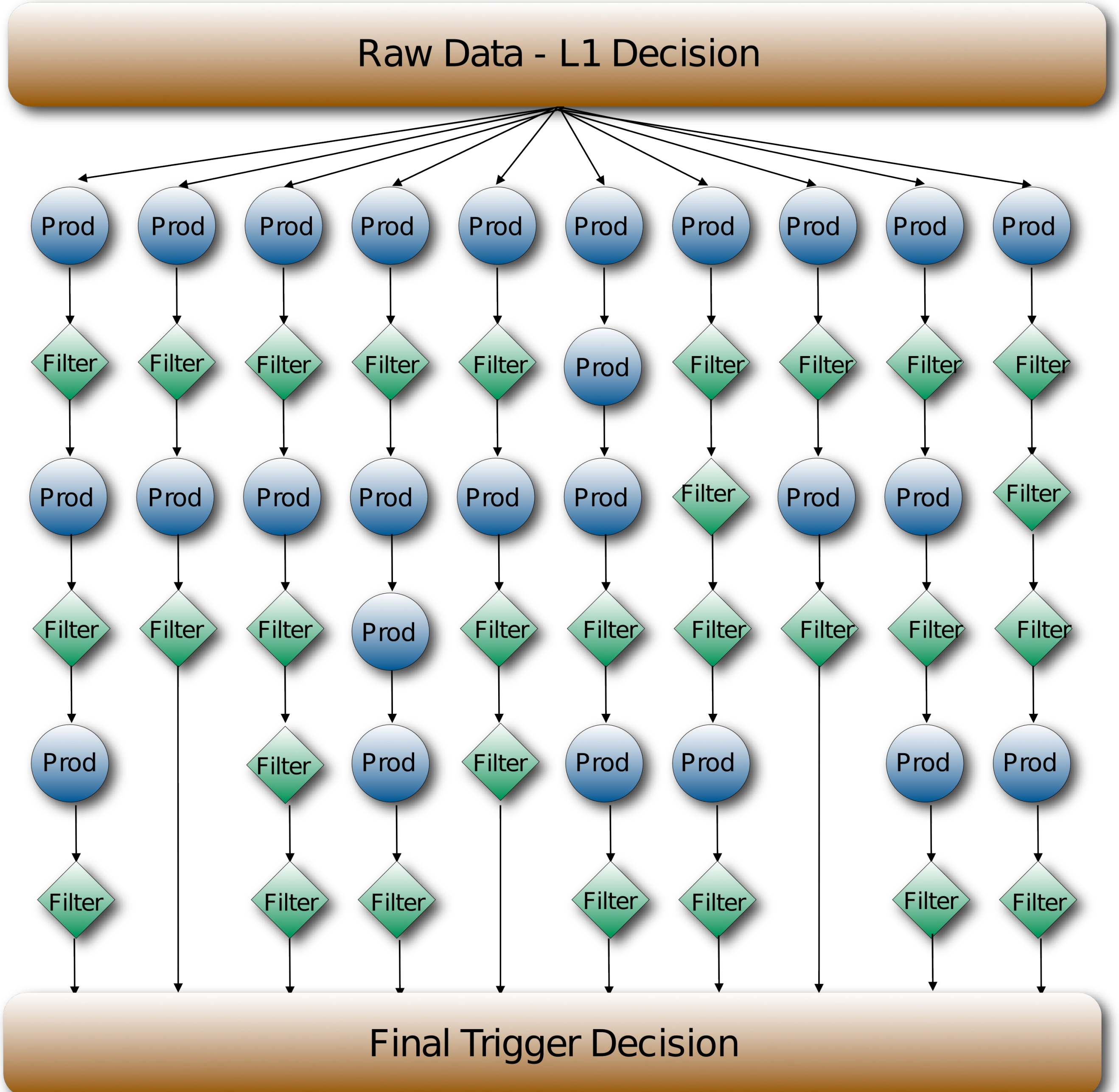
HLT tau reconstruction efficiency vs.offline p_T
measured in $Z \rightarrow \tau\tau, \tau \rightarrow \mu$ and $Z \rightarrow \tau\tau, \tau \rightarrow e$ events

HLT jets



HLT jet efficiency vs. offline p_T , for different jet algorithms and different pile-up conditions

HLT menu



- many algorithms running in parallel
  - logically independent
- determine
  - the trigger decision
  - how to split the events, online and offline

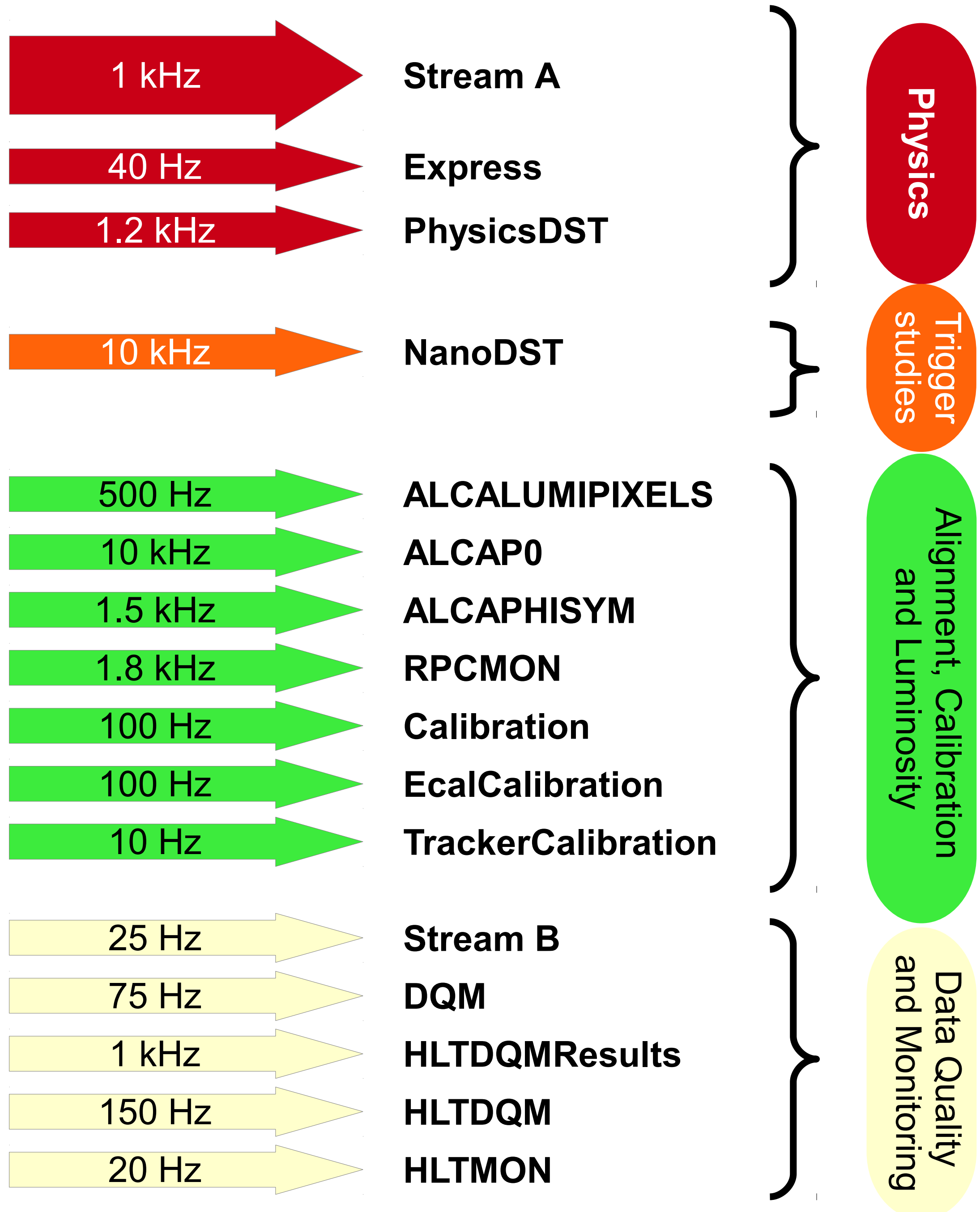
(some) HLT thresholds used in 2012

(Unprescaled) Object	Trigger Threshold (GeV)	Physics
Single Muon	40	Searches
Single Isolated muon	24	Standard Model
Double muon	(17, 8) [13, 8 for parked data]	Standard Model / Higgs
Single Electron	80	Searches
Single Isolated Electron	27	Standard Model
Double Electron	(17, 8)	Standard Model / Higgs
Single Photon	150	Searches
Double Photon	(36, 22)	Higgs
Muon + Ele x-trigger	(17, 8), (5, 5, 8), (8, 8, 8)	Standard Model / Higgs
Single PFJet	320	Standard Model
QuadJet	80 [45 for parked data]	Standard Model / Searches
Six Jet	(6 x 45), (4 x 60, 2 x 20)	Searches
MET	120 [80 for parked data]	Searches
HT	750	Searches

Streams …

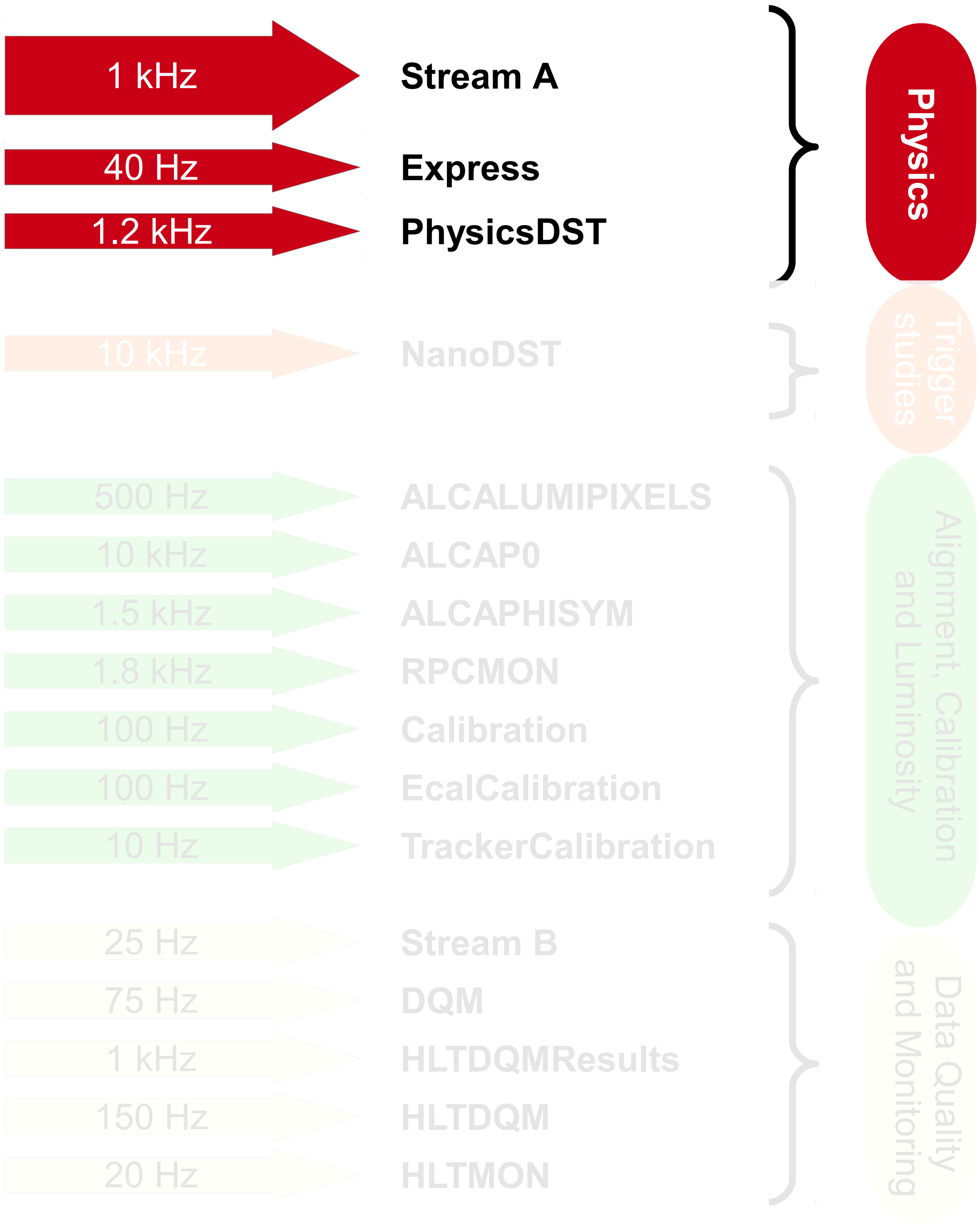
- the High Level Trigger is responsible also for splitting the data in different streams
    - different purposes
    - different event content
    - different rates

- physics, calibrations, monitoring, etc.



Streams …

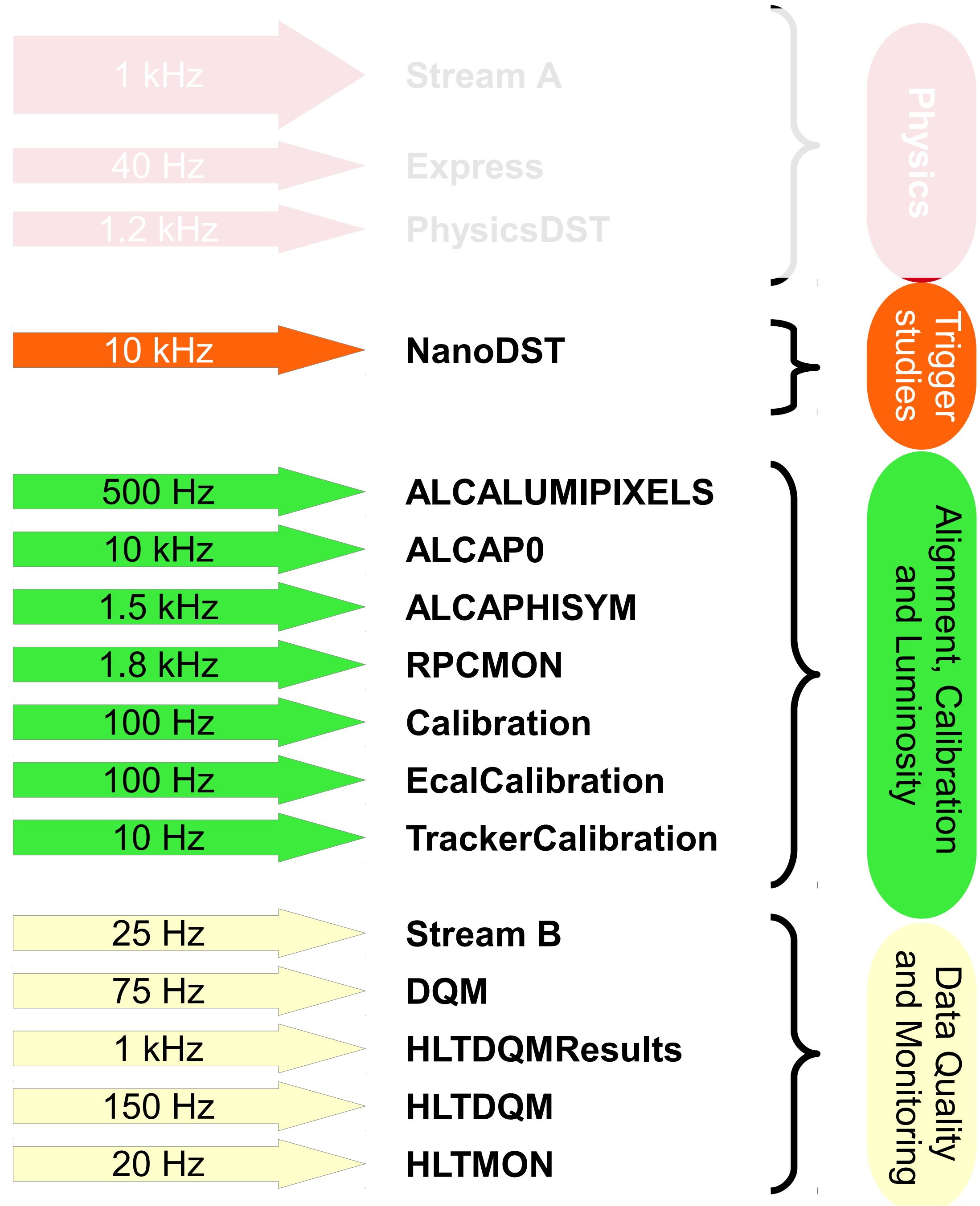
- **Stream A** collects all the events for physics analysis
  - average: ~ 400 Hz
- including ***parked data***
  - collected in 2012, but reconstructed and analysed only during 2013-14
  - average: ~ 600 Hz



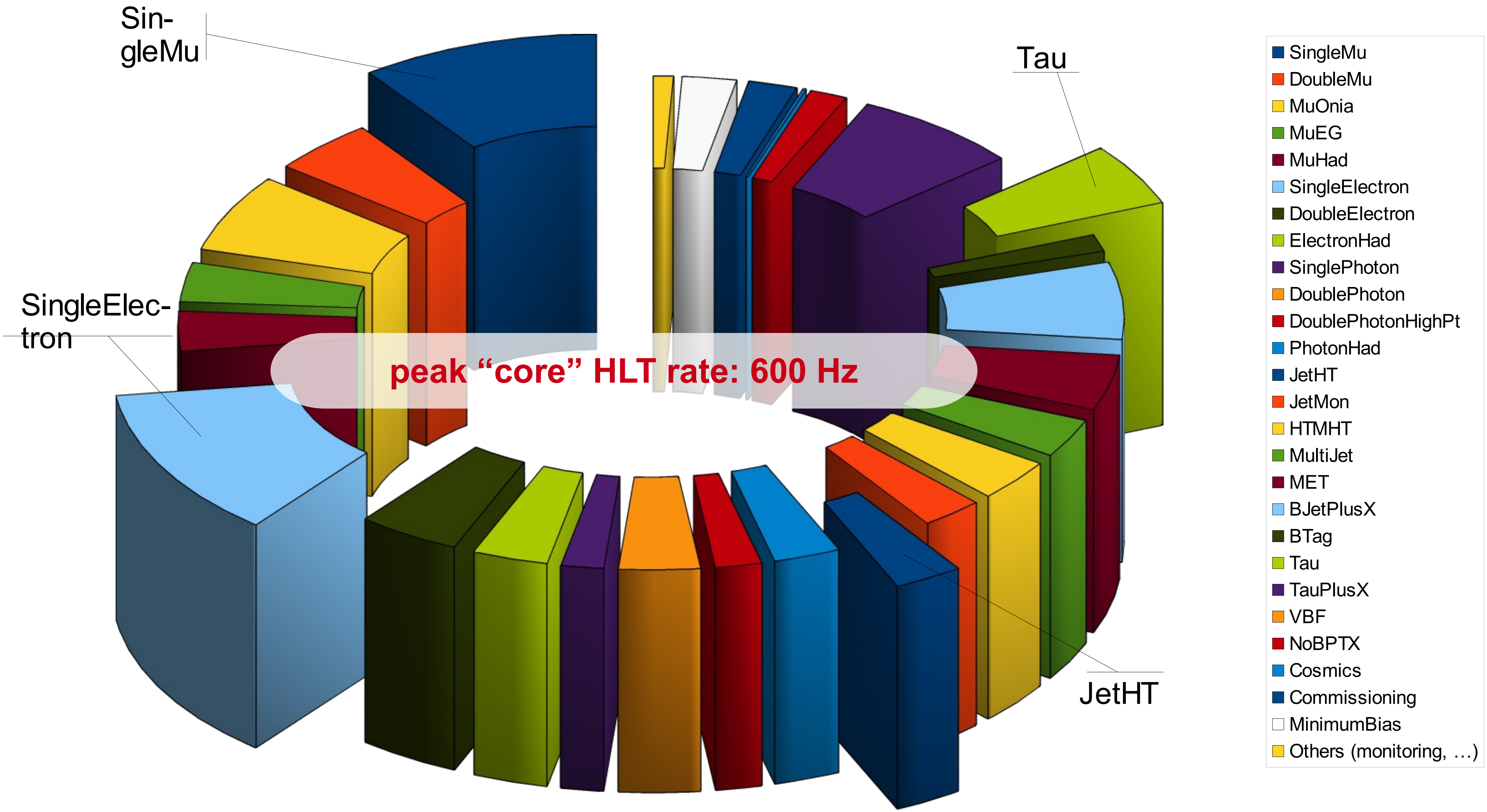
- **PhysicsDST "scouting" stream**
  - analysis performed directly on HLT objects
  - no offline reconstruction

Streams ...

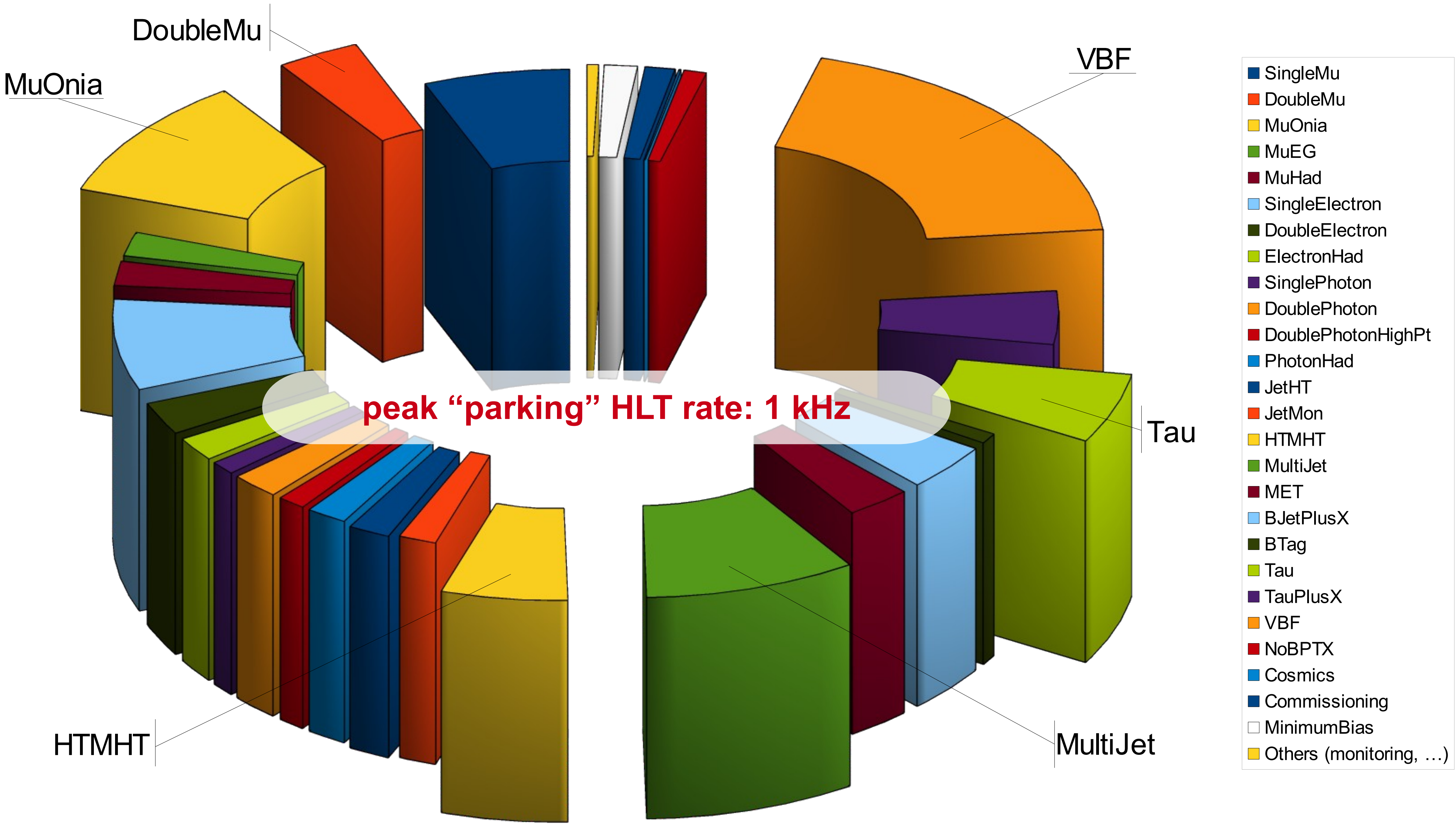
- **NanoDST stream**
  - Saves trigger information for 10% of all L1-accepted events
  - Useful for trigger studies
- **AlCa streams** collect events for dedicated calibration workflows
  - Only a fraction of the detector is read: small event size, high rate
- **Stream B** and **multiple DQM streams**
  - Monitor different aspects of data taking (online, offline, parking)



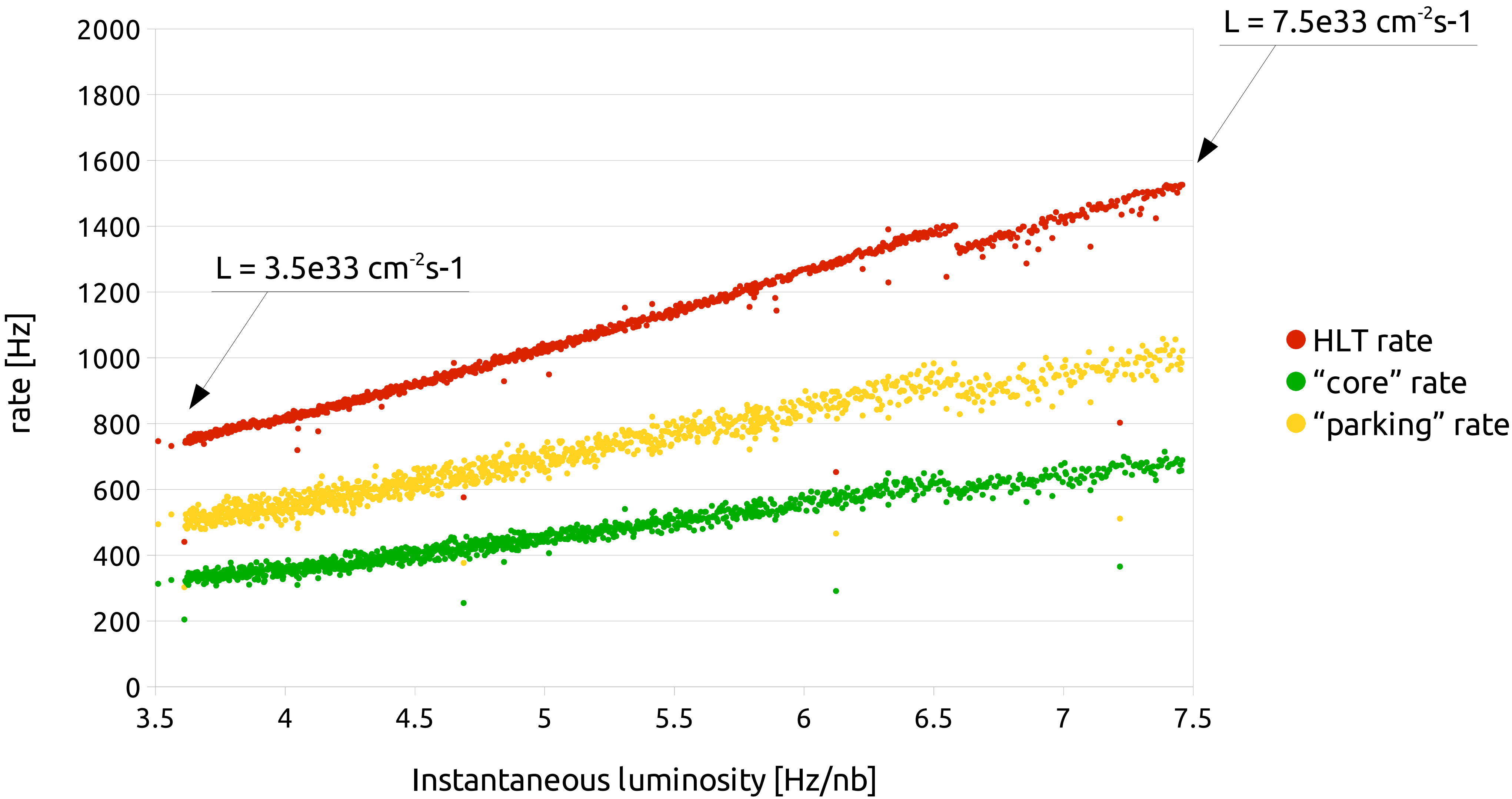
… and datasets



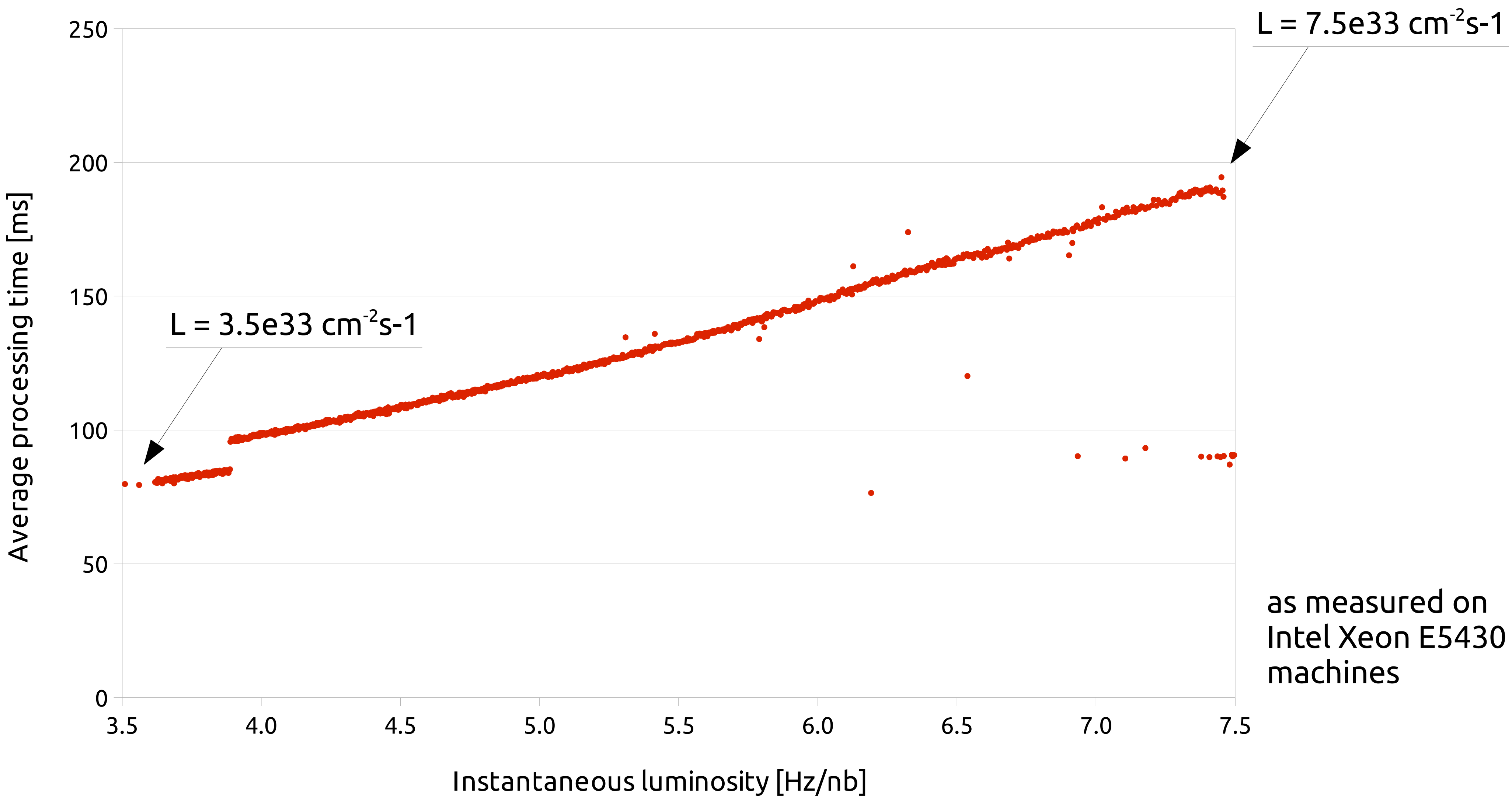
… and datasets (parking)



HLT rates vs. Luminosity



HLT timing vs. Luminosity



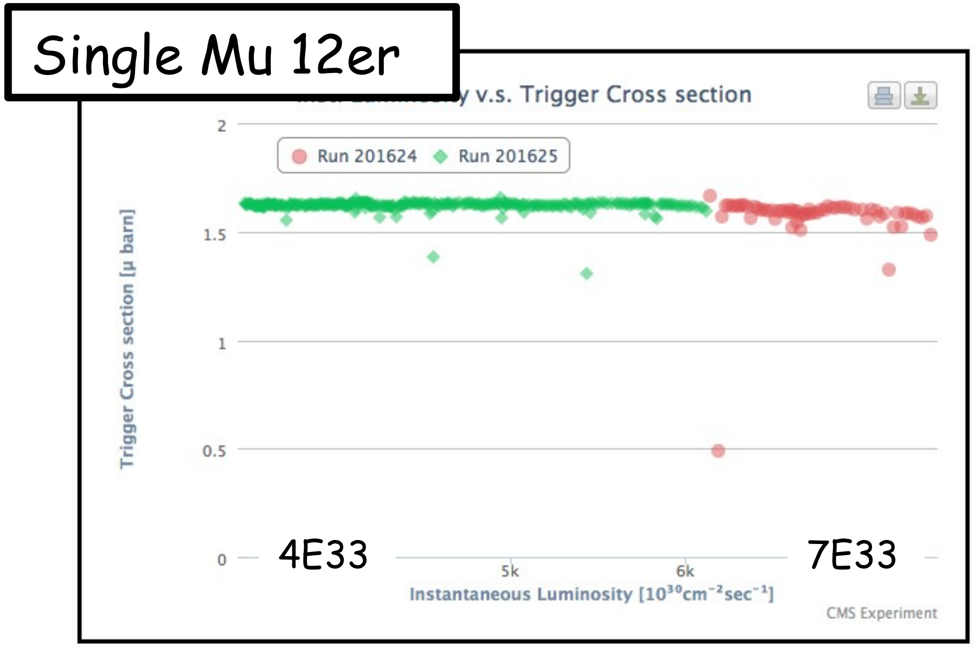
as measured on Intel Xeon E5430 machines

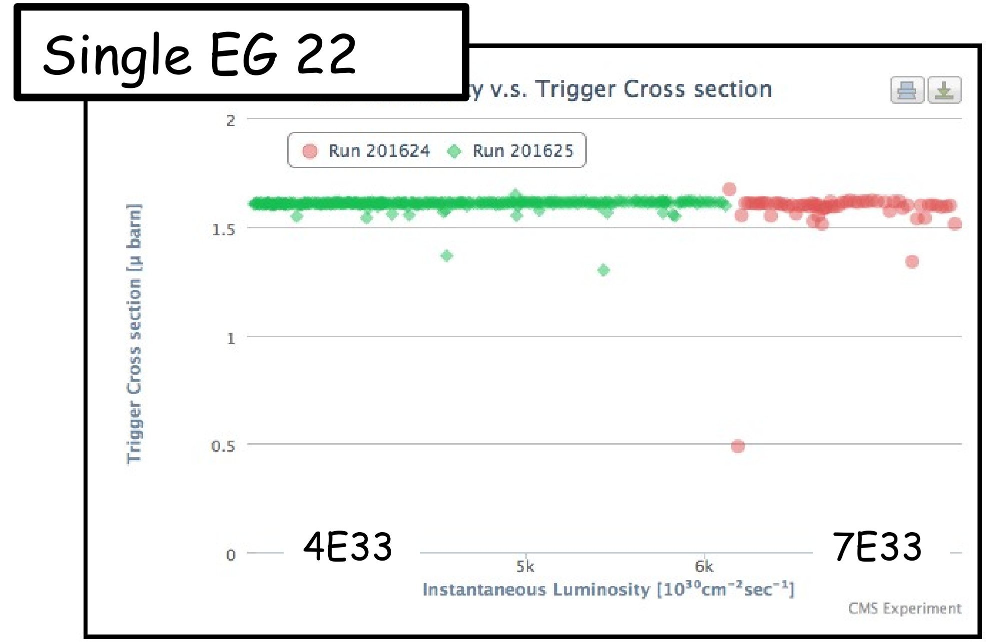
Trigger cross sections

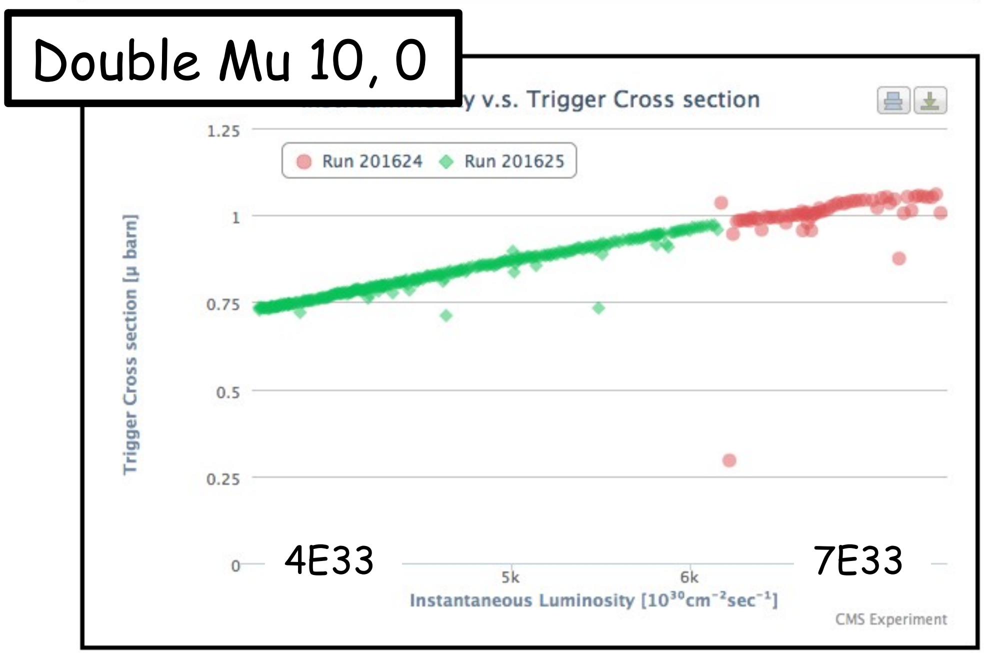
Trigger *cross sections*

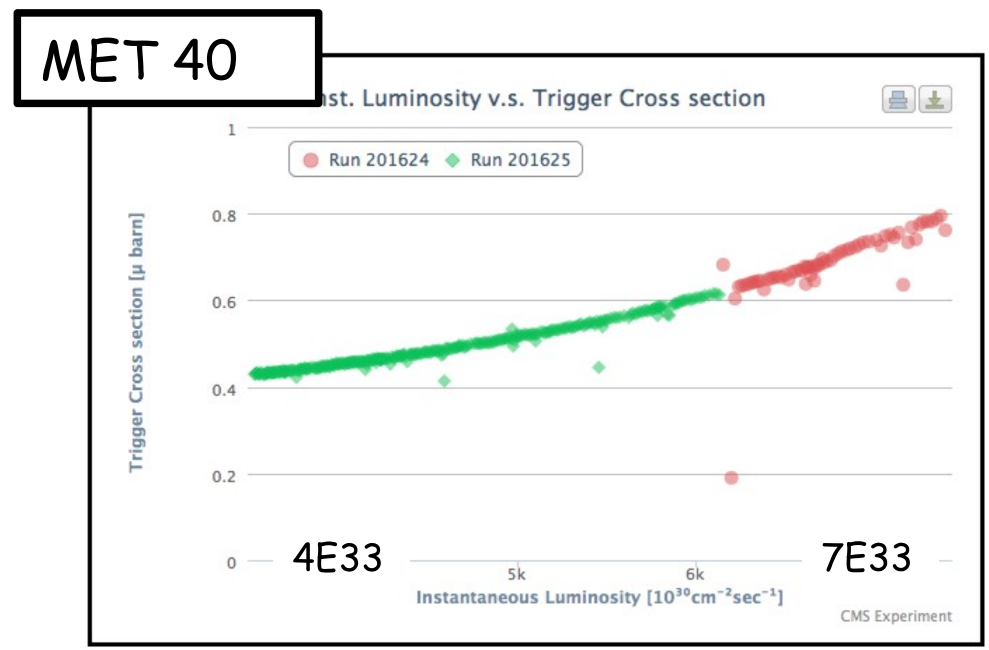
- triggers can exhibit different behaviours with varying luminosity
  - ideal behaviour
    - linear dependency of the rates vs. luminosity
    - i.e. flat cross section
  - often this is not the case
    - multi-object triggers can be faster than linear due to combinatorial effects
    - a higher luminosity means a higher pile-up: additional energy deposits (or soft tracks) can raise the rates of jet and MET-like triggers
    - for isolated lepton triggers, the same effect may lead to artificially tighter isolation requirements at higher pile-up
  - the effects of pile-up can be mitigated with *ad hoc* solutions or more general approaches
    - higher thresholds on leading constituents (e.g. jet seeding)
    - vertex constraint for track-based objects
    - average pile-up subtraction for calorimetric-objects

L1 leptons and MET



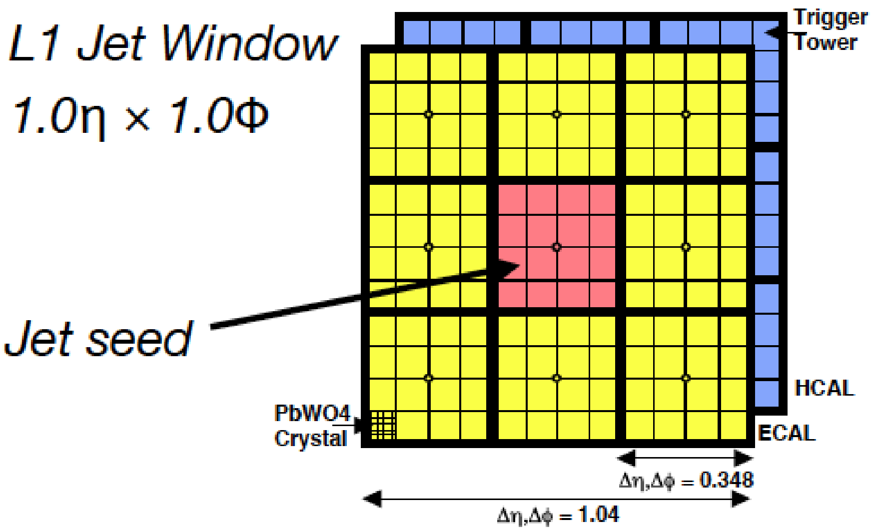


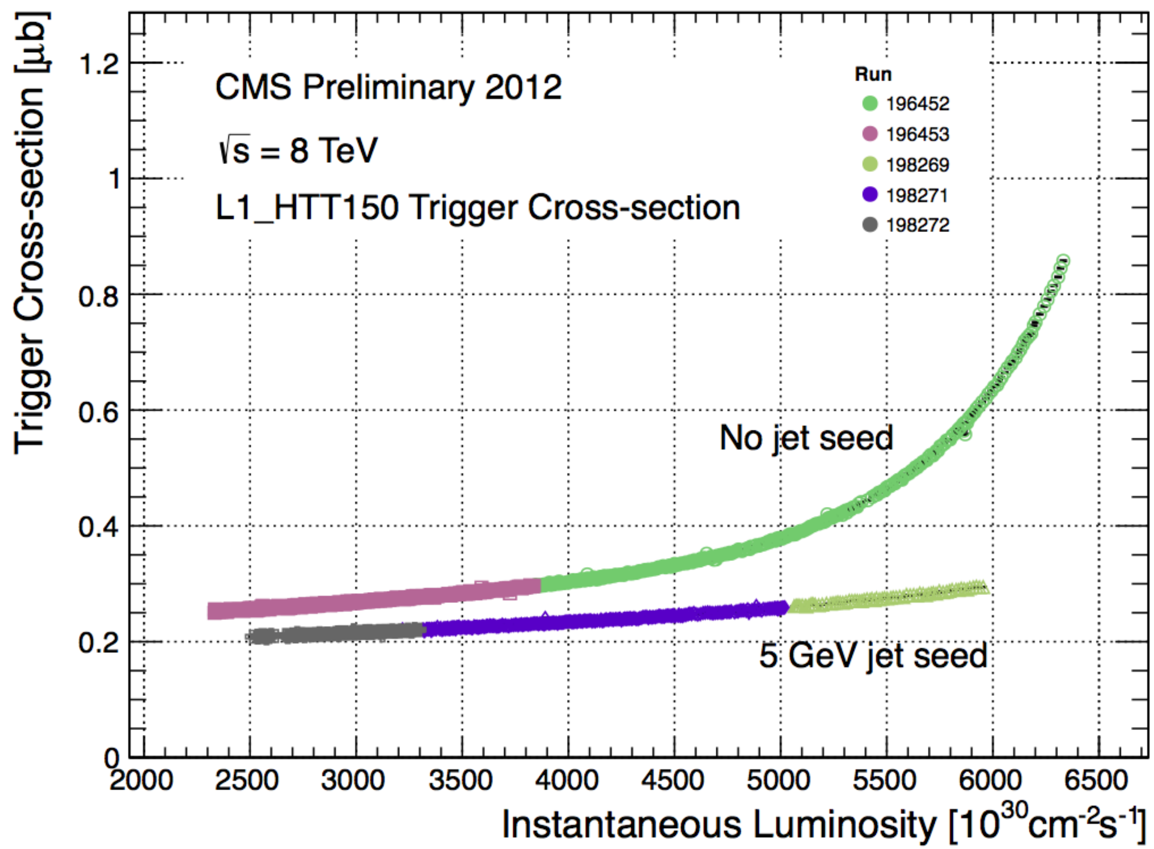




L1 jets and HTT: jet “seeding”

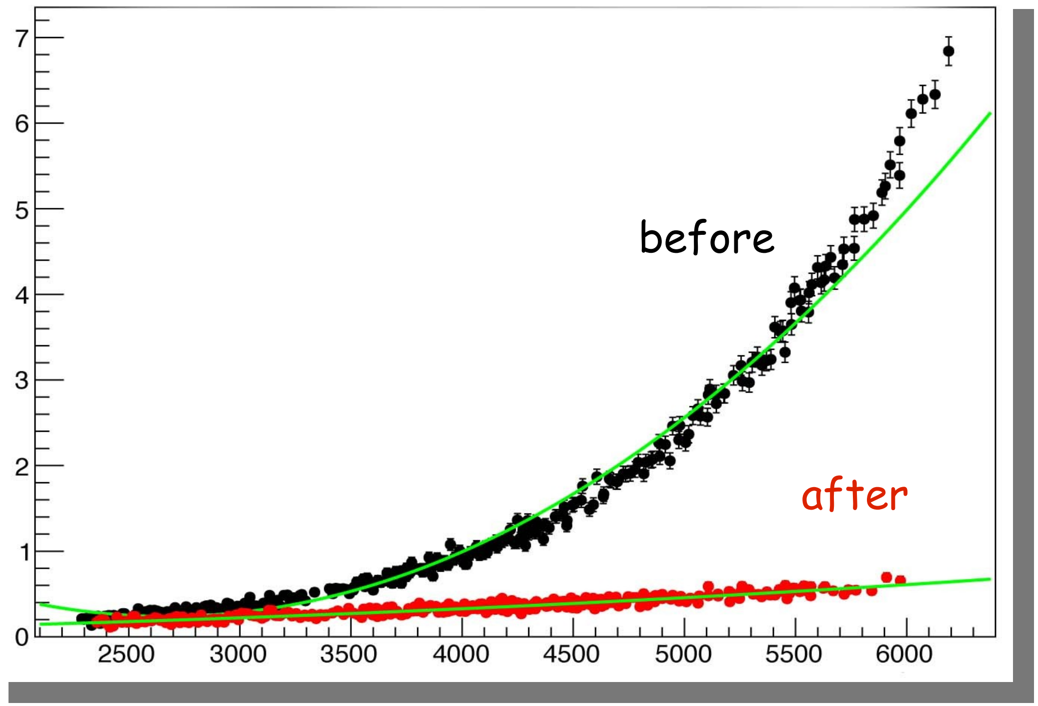
- L1 HTT
  - sum of the energy of all jets above a certain threshold
  - very sensitive to pile-up
- temporary solution
  - require each jet to have a single tower above a fixed threshold





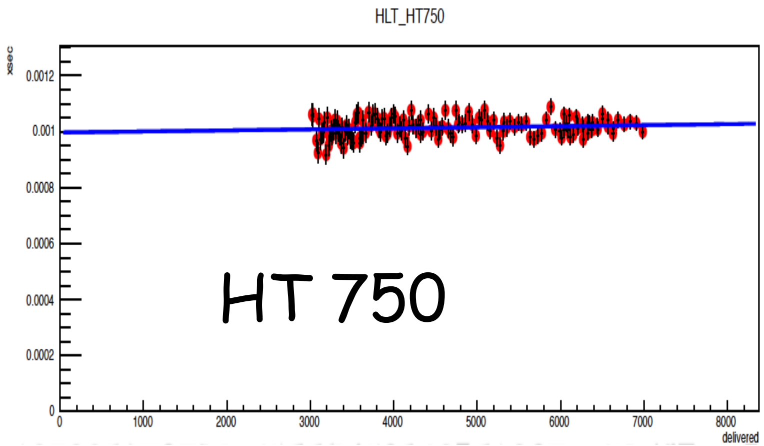
Effect of pile up on Jets

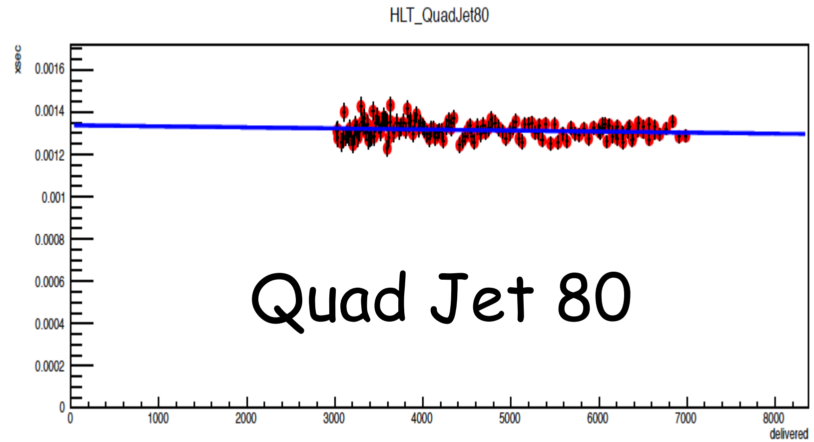
- low threshold calorimetric and particle flow jets show a strong dependency on pileup
  - can be cured with dedicated corrections
  - subtract from the jet energy a value proportional to the jet area, and the average energy from the pile-up



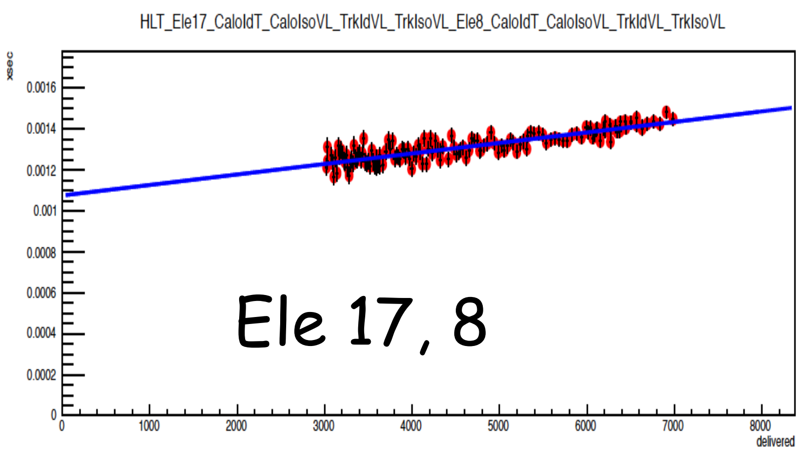
Effect of pile up on composite triggers

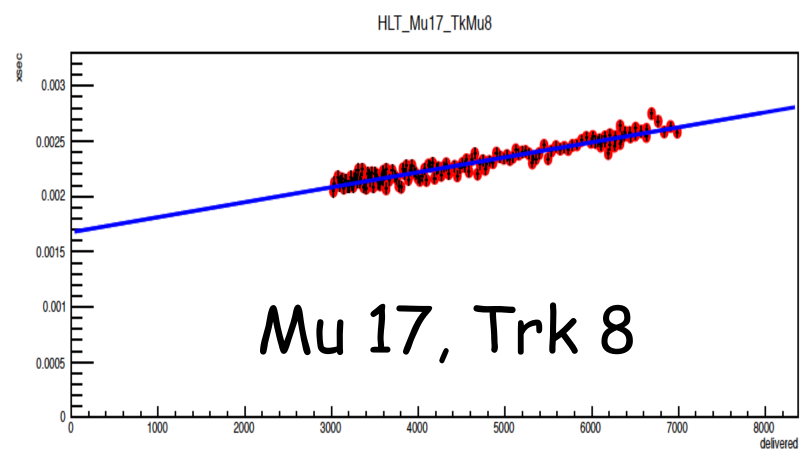
multi object triggers with pile up corrections





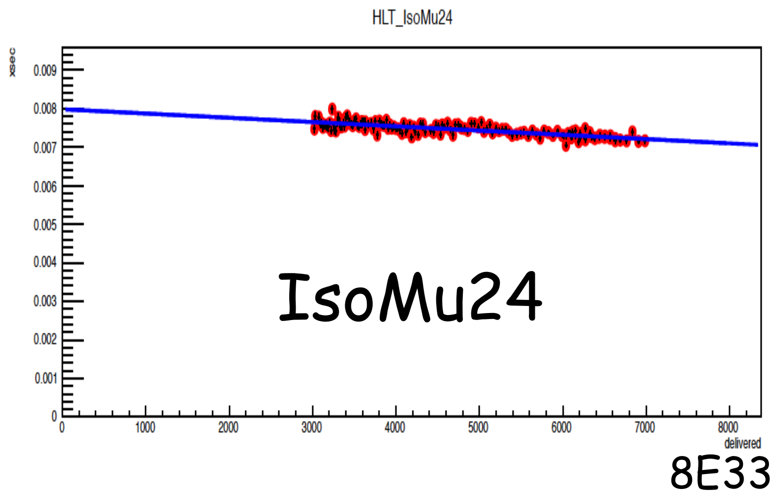
multi object triggers affected by pile up

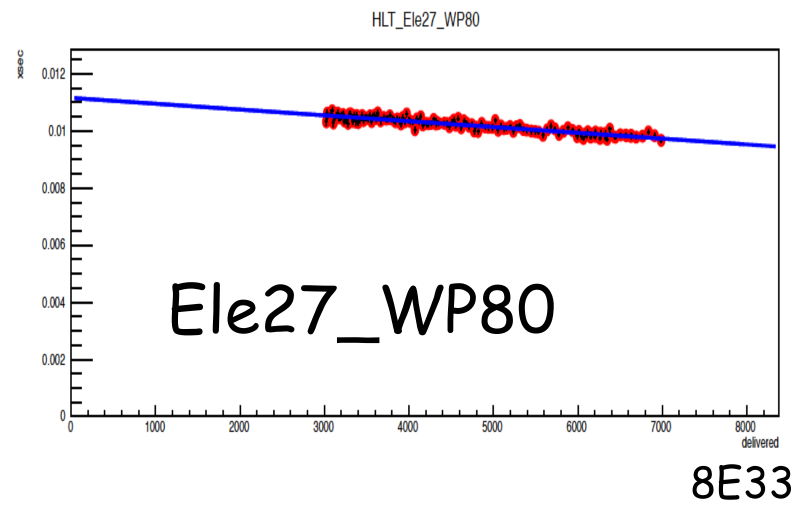


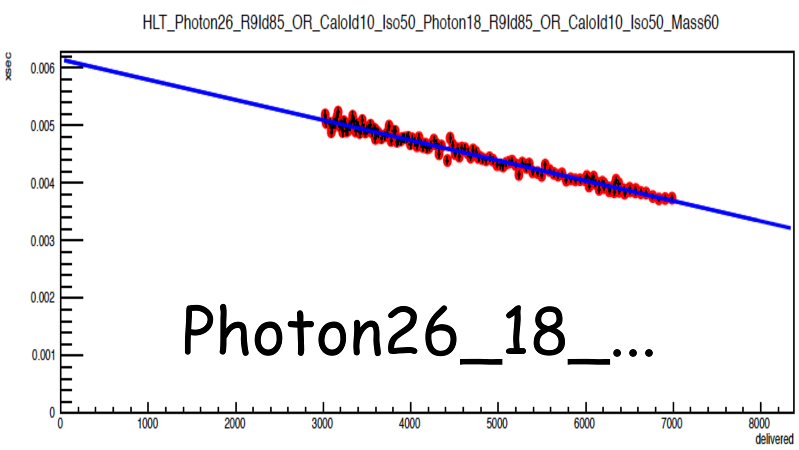


40

Effect of pile-up on isolation cuts







Conclusions

Conclusions

- CMS has been designed with a 2-level trigger system

- the Level 1 Trigger, with a coarse reconstruction of jets, muons, electrons and photons, allows a first rejection of background events
  - though implemented in hardware, it maintains enough flexibility to cope with the increase in instantaneous luminosity observed during 2010-2012
  - to cope with even higher luminosities, a dedicated upgrade plan is in place, both for the next data taking run, and for the Phase 2 upgrade

- the High Level Trigger, implemented in software using the same software used for offline reconstruction and analysis, has full access to the whole detector data, and allows the introduction of advanced selection criteria directly online
  - this flexibility has allowed CMS to successfully address all kind of data taking scenarios
  - this system is easily expandable in view of the upcoming upgrades