The ATLAS Muon and Tau Triggers

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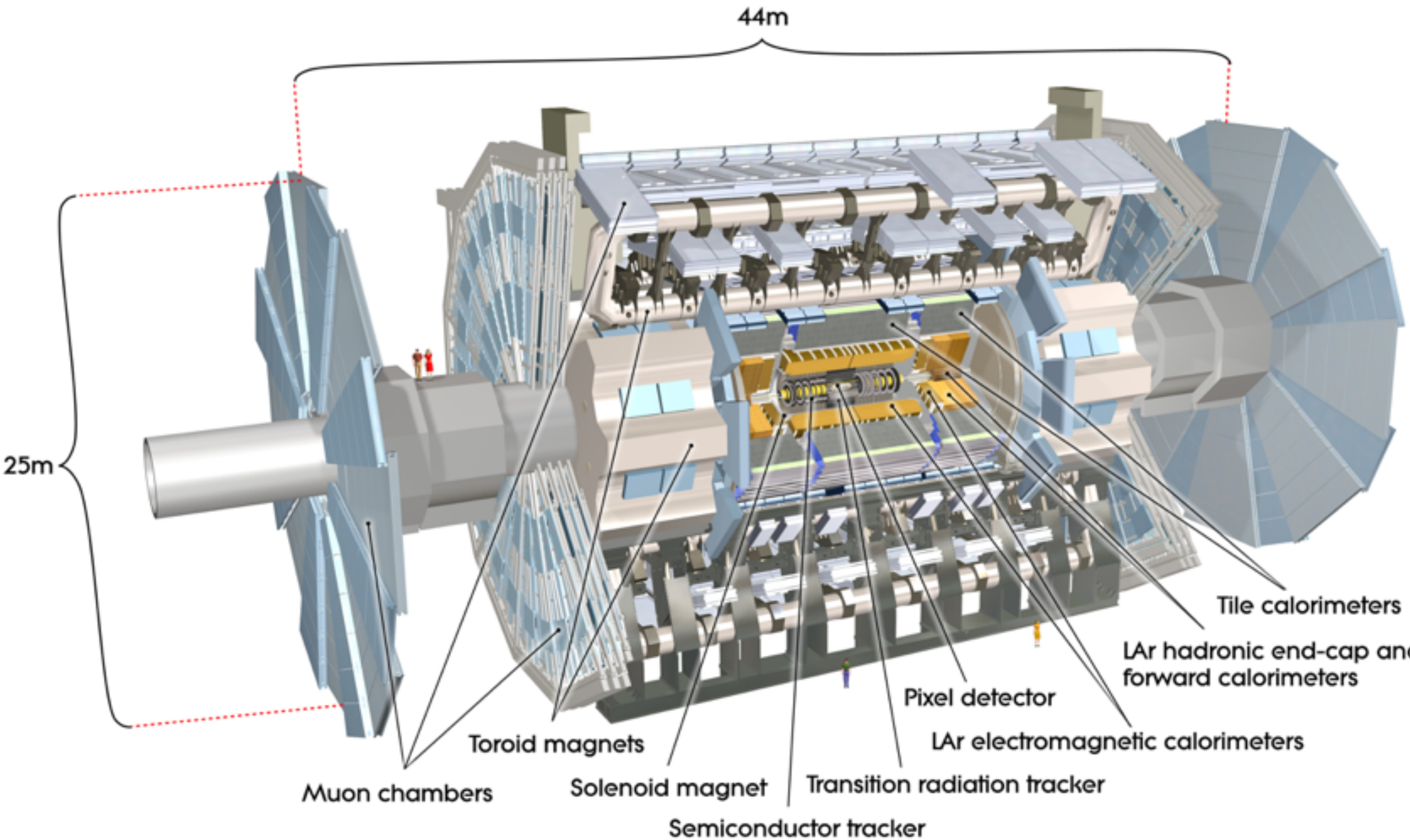
The ATLAS Experiment @ LHC

- The ATLAS Experiment is one of the two multipurpose experiments at the Large Hadron Collider (LHC).
  - Physics goals include the search for the Higgs boson and for new physics beyond the SM.



Why do we need a trigger system?

- In 2012, the LHC provided pp collisions at **20 MHz**, i.e. every 50 ns.
  - We only keep ~**400 Hz** for physics. Why?

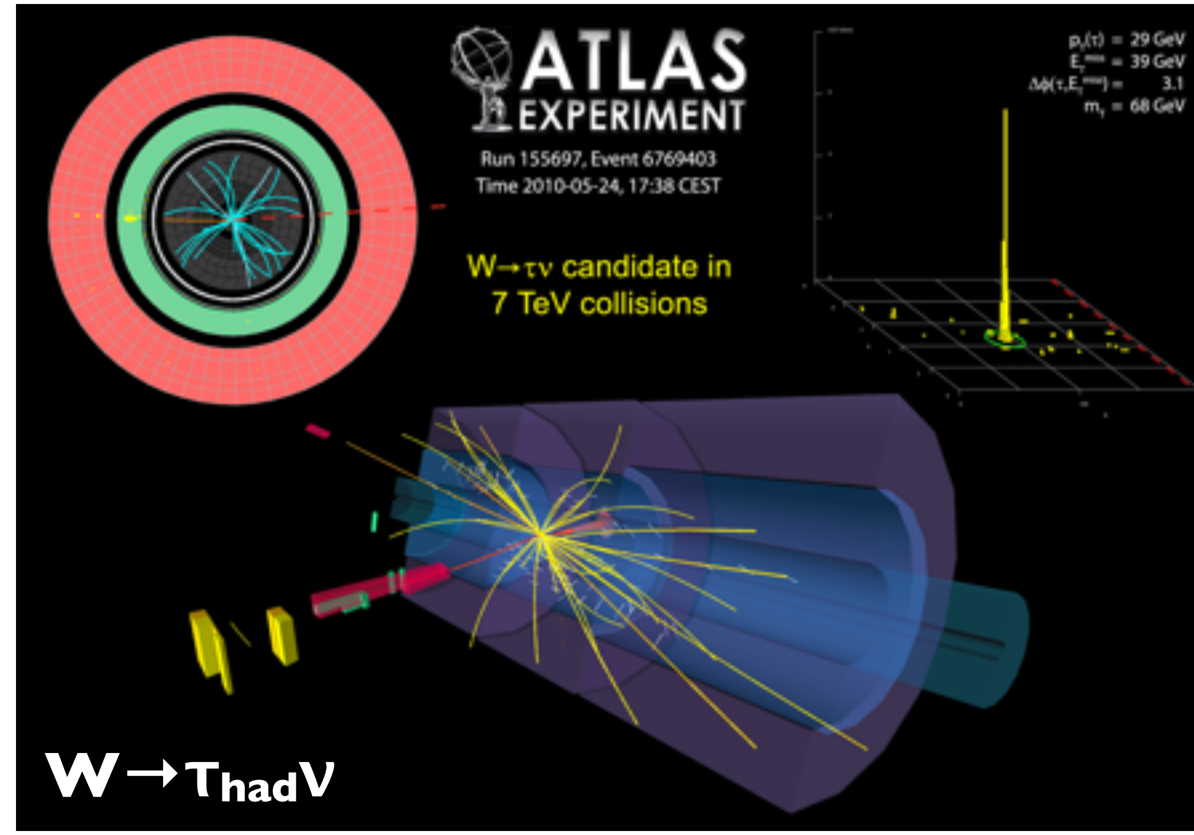
- "**Interesting physics**" occur mostly at rates of 10, 1 or < 0.1 Hz (e.g. Higgs boson production).
  - We are only interested in a tiny fraction of the events produced.
  - We do want to keep all of these, and reject most of the others.
    - Frequency of producing a process like $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$ is extremely rare: once in 10^{13} interactions (at 14 TeV).
- **Resources**: both computing time and data storage are challenging.
  - For ~10 s/event of offline processing time, we need 4000 CPUs to keep up.
  - ~1.5 MB/event for raw data and ~1.5 MB/event for reconstructed data. Up to 4300 TB a year per experiment (with a factor 2 for distributed analysis).
    - From ATLAS public website: "If all the data from ATLAS would be recorded, this would fill 100,000 CDs per second. This would create a stack of CDs 450 feet high every second, which would reach to the moon and back twice each year. [...] ATLAS actually only records a fraction of the data [...] and that rate is equivalent to 27 CDs per minute.".

⇨ We need an efficient trigger system!

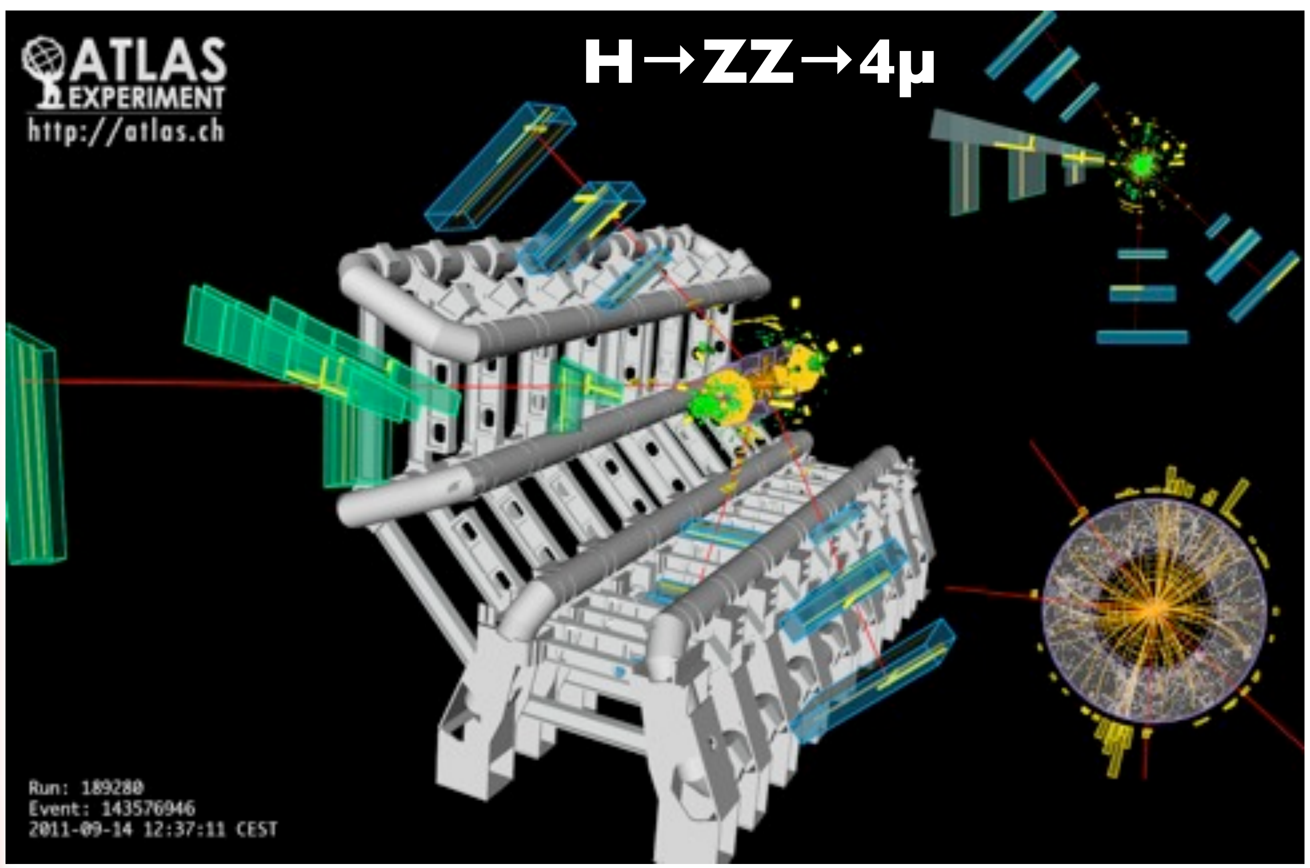
What do we want to select?
How can we select it?

What are we looking for?

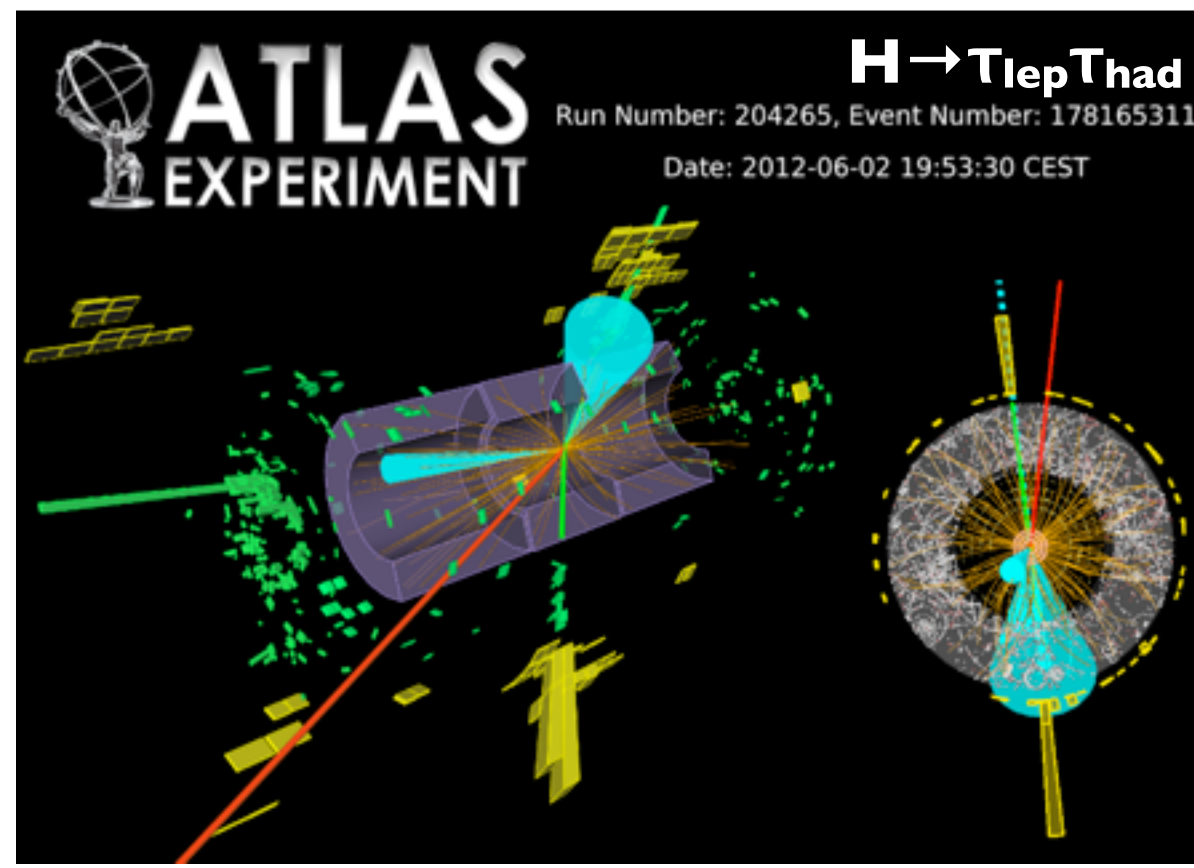
- Trigger signatures and trigger menus are driven by the **physics goals**.
  - Standard Model precision measurements.
  - Search for new particles.



$W \to \tau_{had}\nu$ candidate event



$H \to 4\mu$ candidate event, with m_{4l}=124.6 GeV



Event selected by the $H \to \tau_{lep}\tau_{had}$ analysis

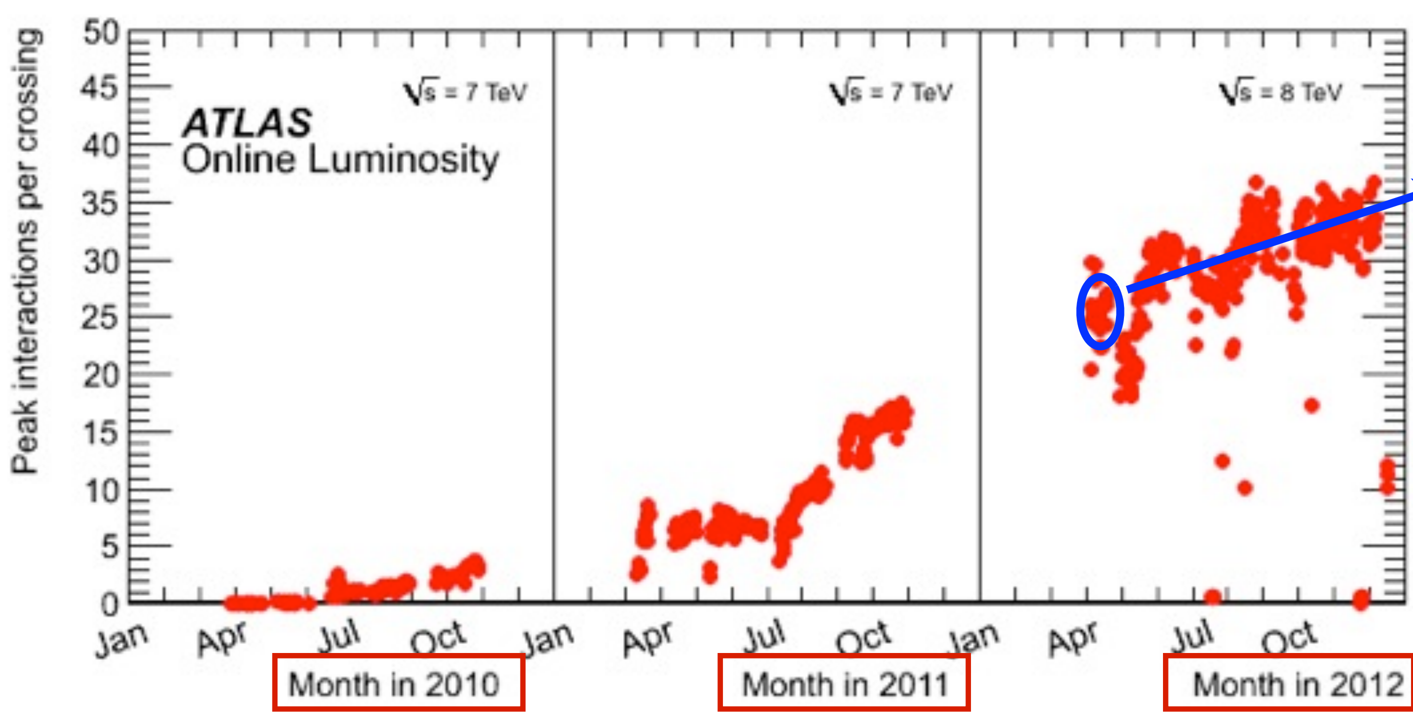
LHC Data Taking Conditions

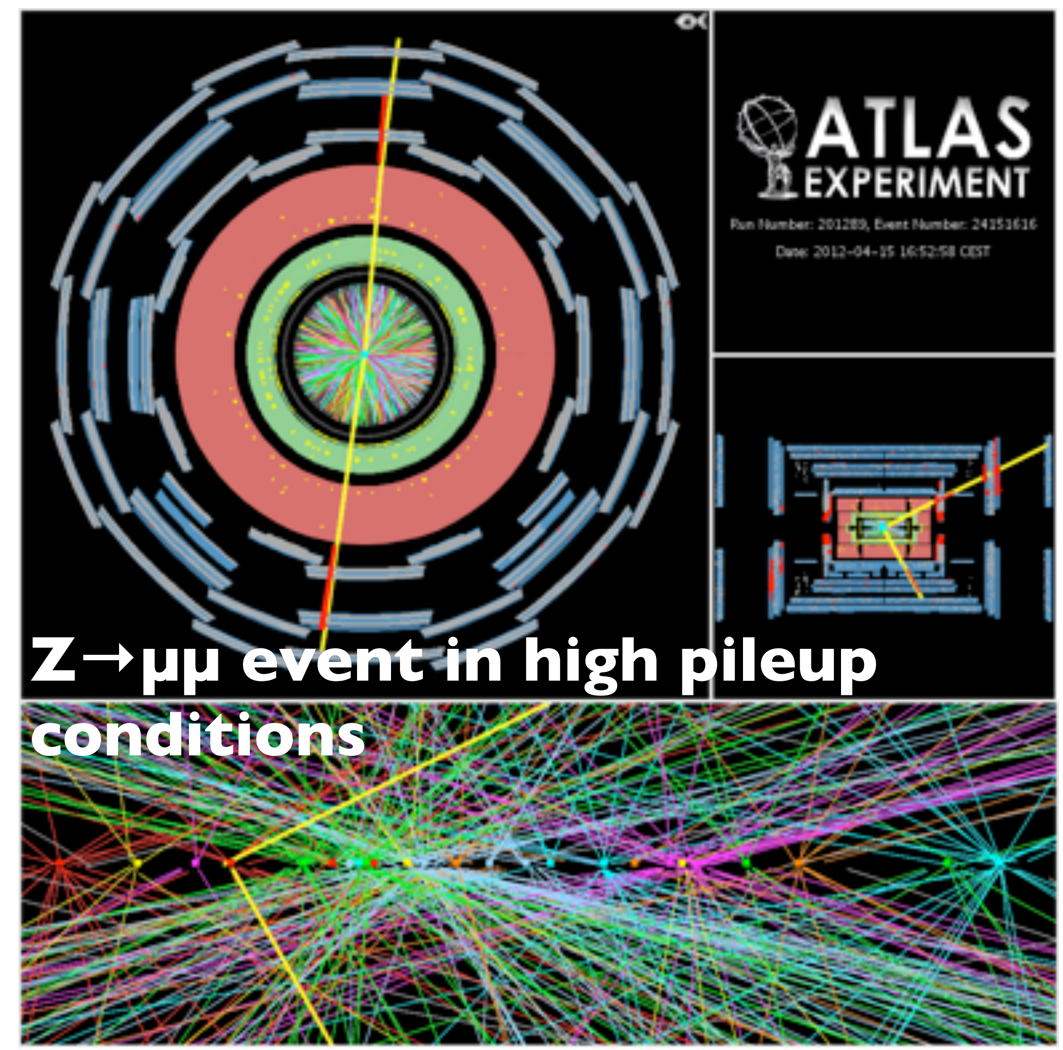
- Interesting events are hidden in the very **busy** LHC **environment**.
  - High **pile-up** (i.e. multiple interactions per crossing).
  - High charged multiplicity.
    - About 1000 tracks per event

      $\rightarrow 10^{12}$ tracks per second rate at

      $L = 10^{34}$ cm^{-2}s^{-1}.
  - We need several trigger levels to be able to use tracking for trigger decision.

Year	Center of mass energy	Peak Instantaneous Luminosity	Recorded Integrated Luminosity
2010	7 TeV	2.1×10^{32}cm^{-2}s^{-1}	45.0 pb^{-1}
2011	7 TeV	3.65×10^{33}cm^{-2}s^{-1}	5.25 fb^{-1}
2012	8 TeV	7.73×10^{33}cm^{-2}s^{-1}	21.7 fb^{-1}



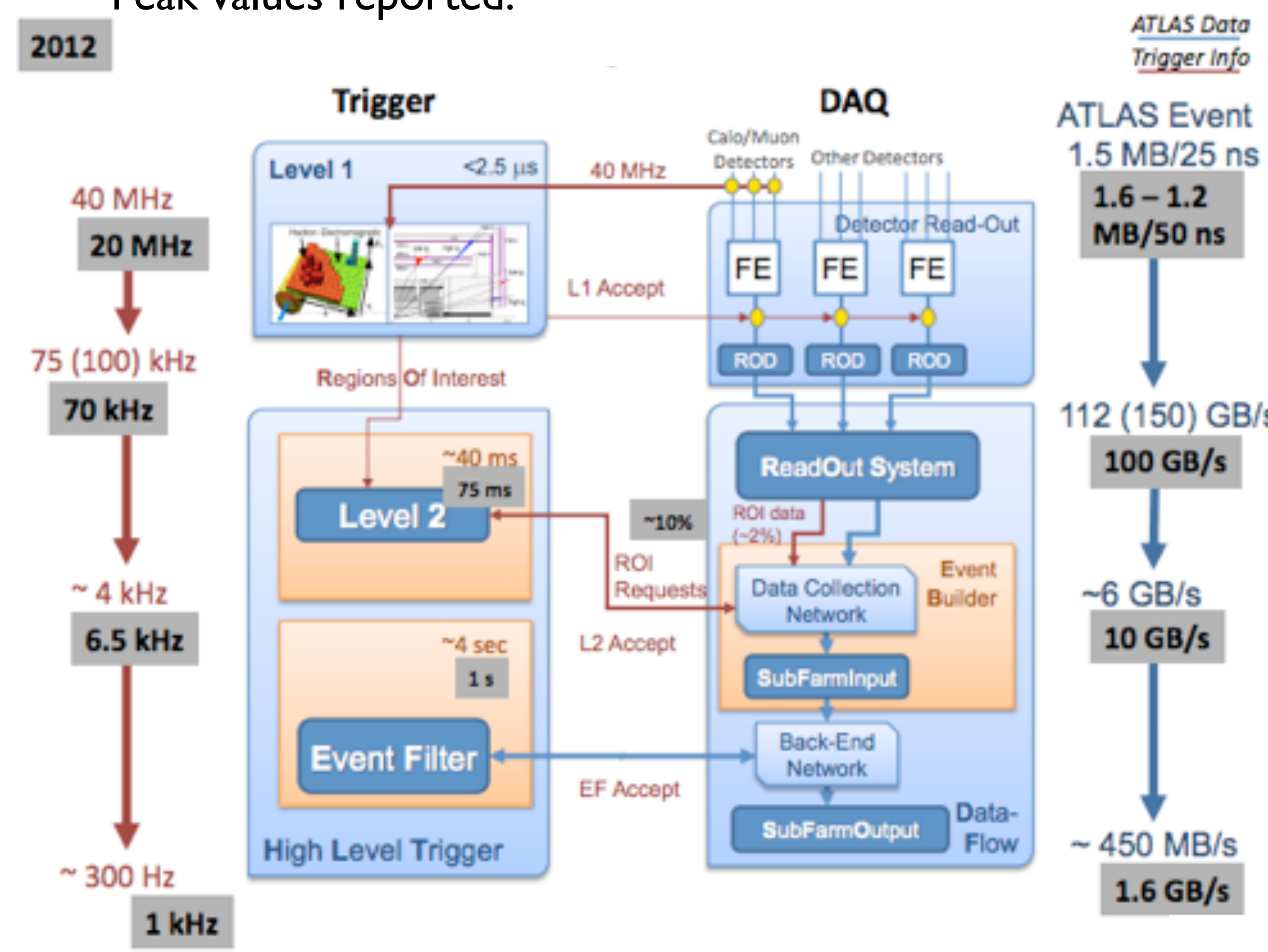


The ATLAS Trigger System

- To be able to exploit as much as possible the entire detector for trigger decision, the ATLAS Trigger System is divided into **three levels**.
- At each level, the rate is significantly reduced and more detailed information can be used.

- **Level 1** (L1)
  - hardware based
  - analyzes coarse granularity data from calorimeter and muon detectors separately
  - identifies Region-of-Interest (RoI)
- HighLevelTrigger - **Level 2** (HLT/L2)
  - software based
  - accesses full granularity data within RoI (~2% of total event size)
  - detector information are combined
  - adds tracking and topological cuts
- HighLevelTrigger - **Event Filter** (HLT/EF)
  - software based (uses offline algorithms)
  - exploits the seed from L2 using full event data

*Peak values reported.

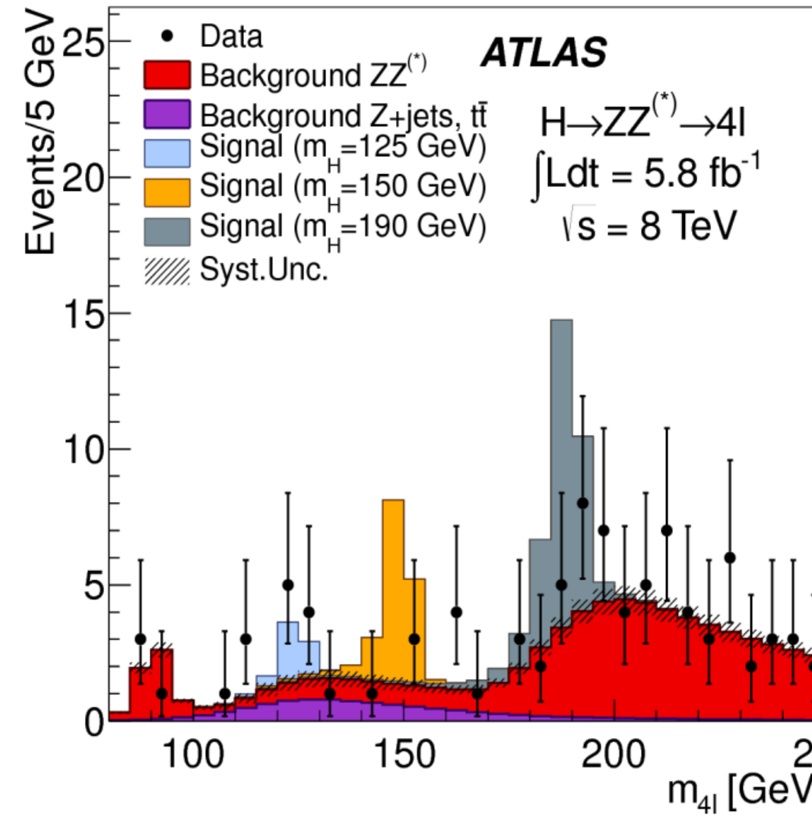


Rate Reduction factors in 2012	
L1	~300
L2	~10
EF	~10

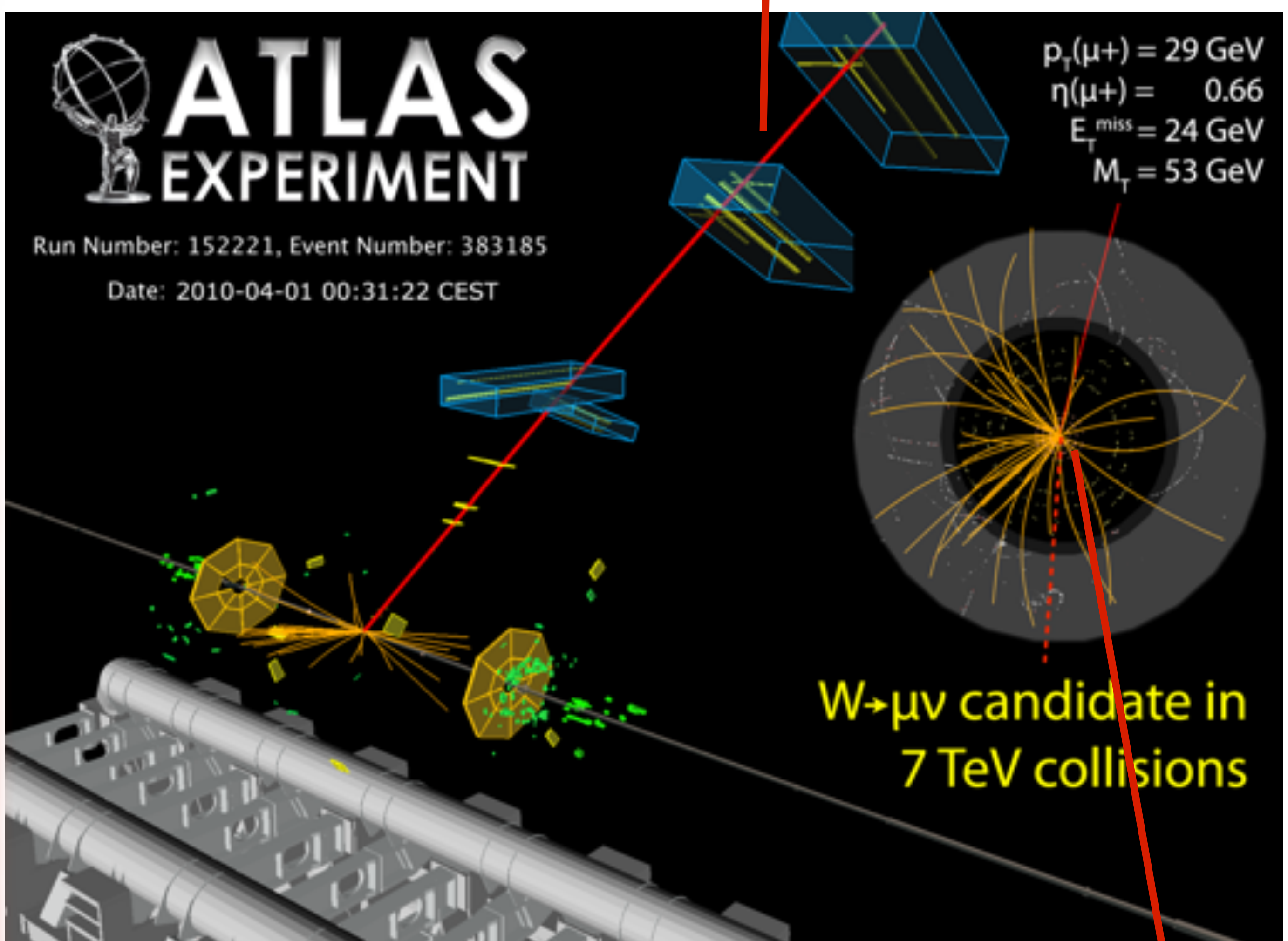
The Muon Trigger

Introduction

- **Muon** leptons played a fundamental role in the search for the Higgs boson.



Track in the Muon Spectrometer

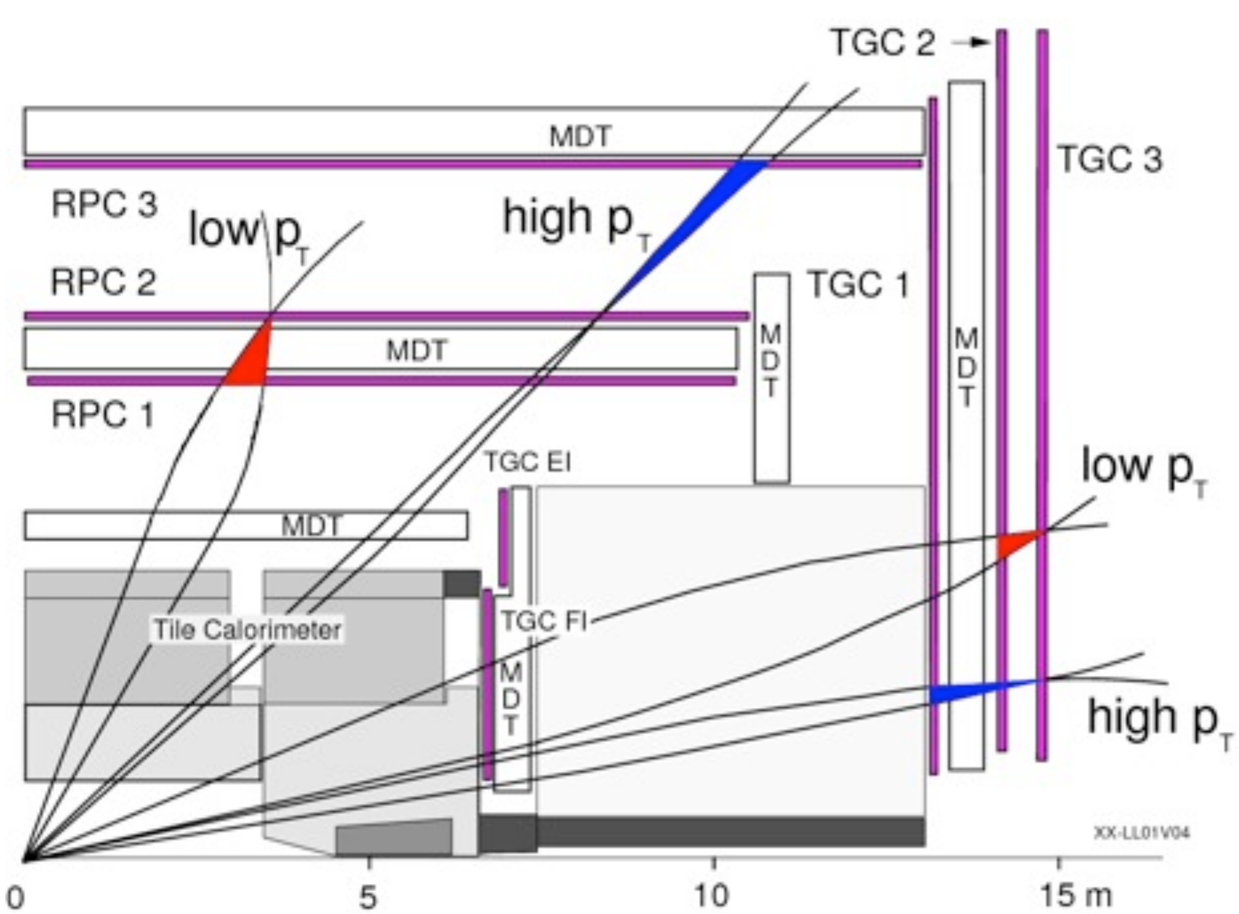


Track in the Inner Detector

- **Muons** are characterized by the presence of a track in the Muon Spectrometer (MS) and a track in the Inner Detector (ID).
- Muons are able to reach the outermost region of the ATLAS detector.
- ATLAS has specific detectors devoted to triggering these leptons.

Level 1

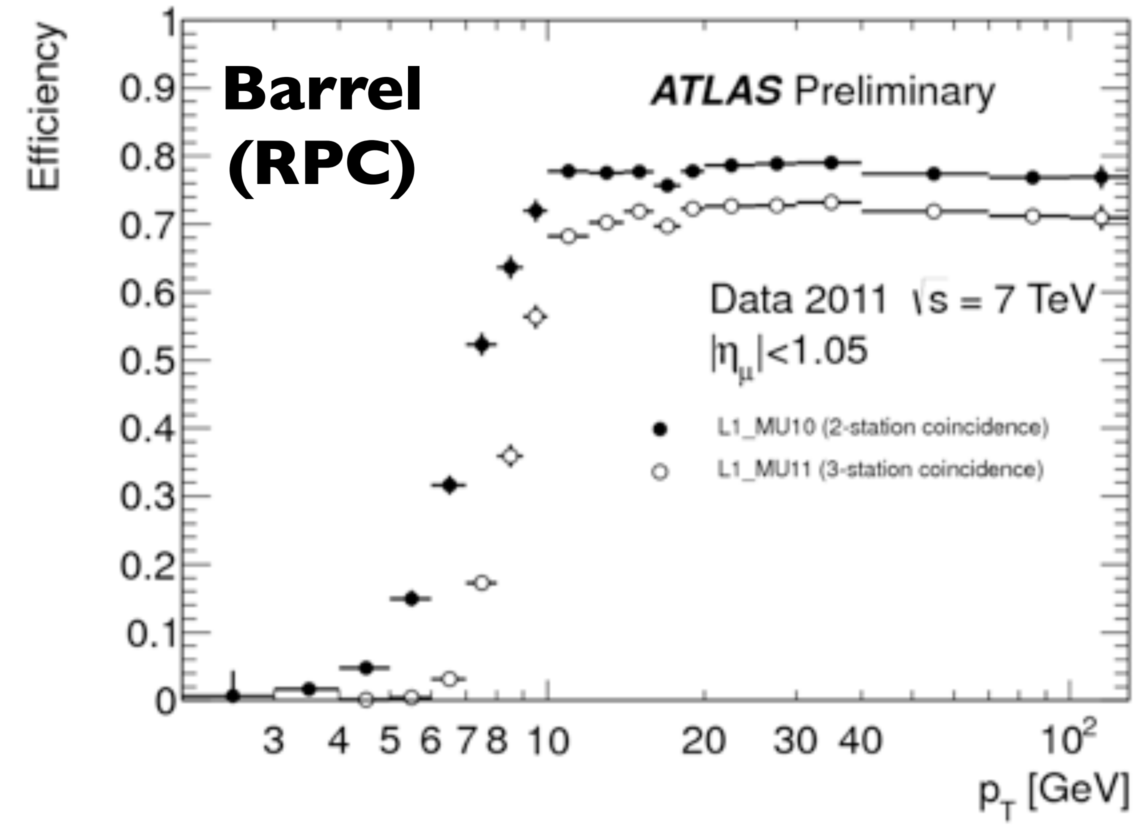
- The Level 1 Muon Trigger makes use of different detector technologies in different regions of the detector:
  - The **Barrel** region ($|\eta|<1.05$) is instrumented with Resistive Plate Chambers (RPC).
  - The **Endcap** regions ($1.05<|\eta|<2.4$) are instrumented with Thin Gap Chambers (TGC).
- The geometric **coverage** of the L1 trigger in the **endcap** regions is **~99%** and **~80%** in the **barrel** region.
  - The limited geometric coverage in the barrel region is due to a crack at around $\eta = 0$ to provide space for services of the ID and the calorimeters, the feet and rib support structures of the ATLAS detector and two small elevators in the bottom part of the spectrometer.

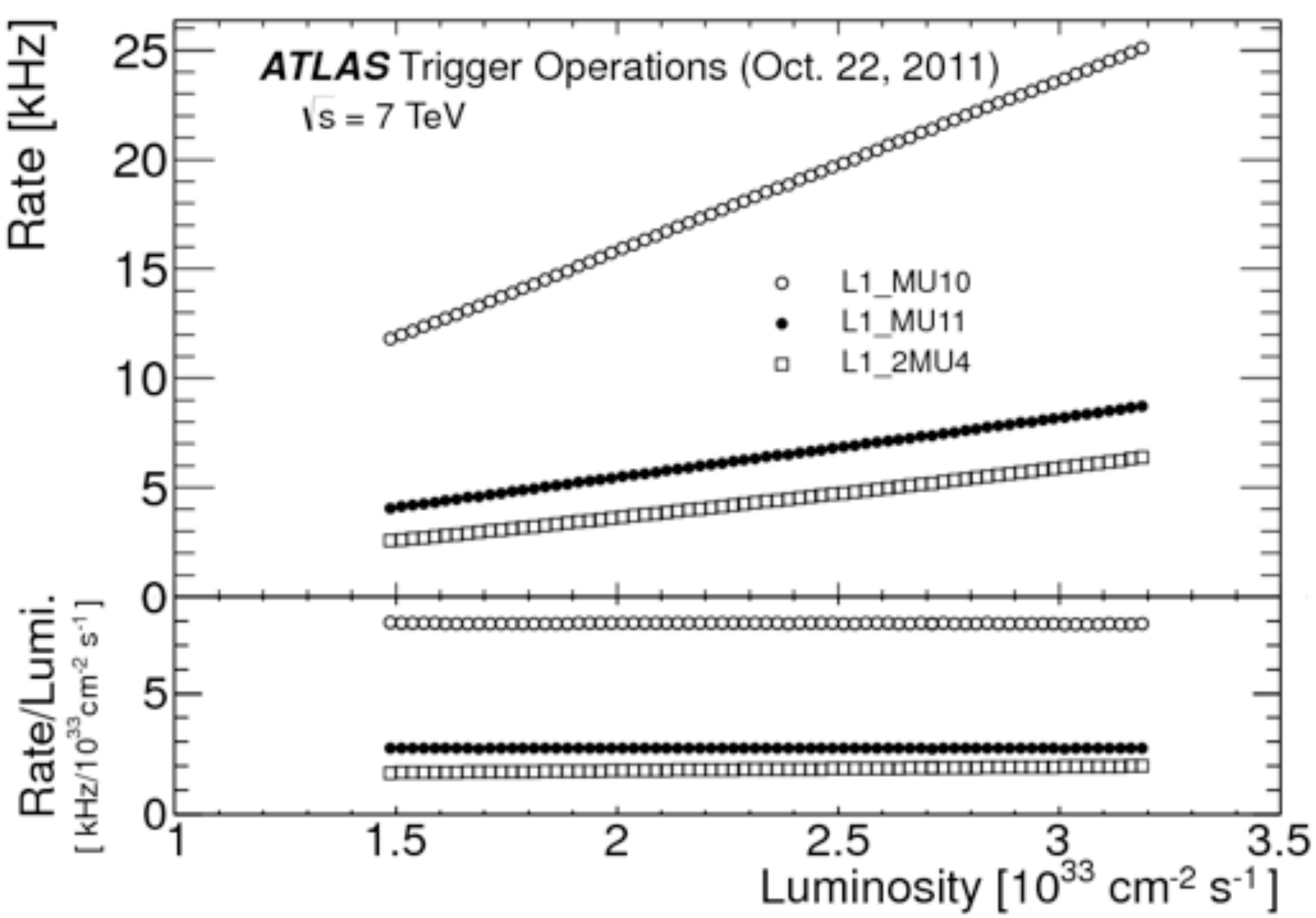


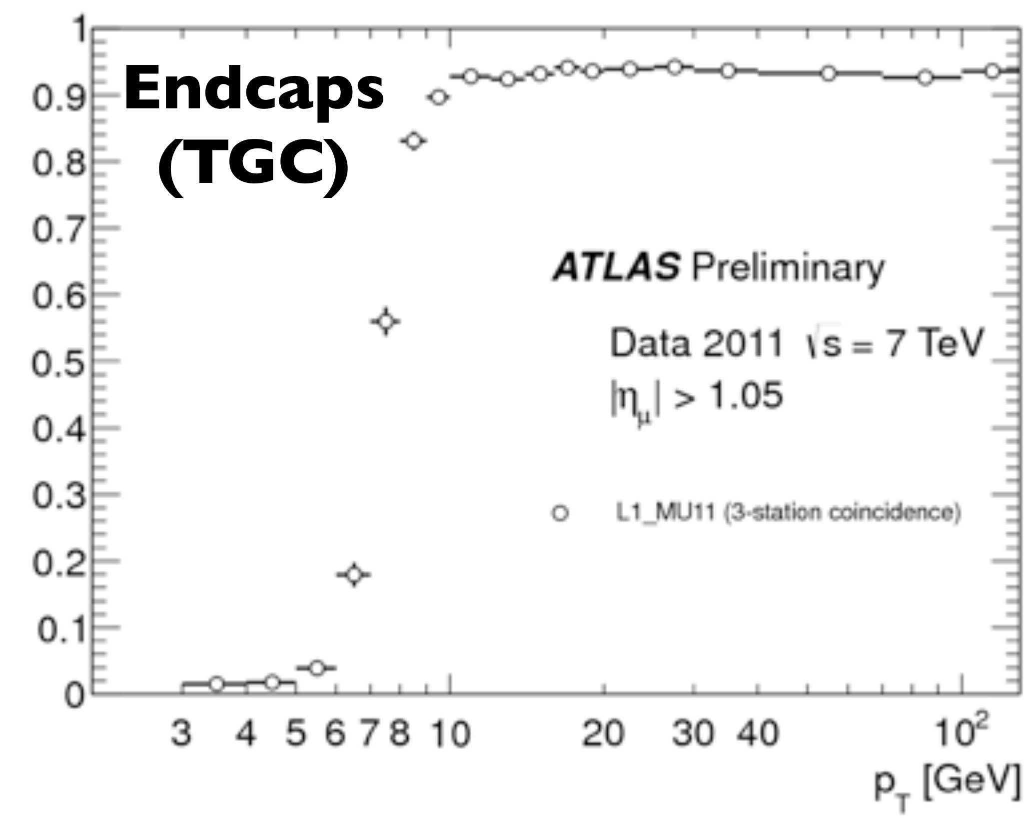
- Muon candidates are identified by custom built hardware that forms a **coincidence** of **hits** in layers of trigger chambers.
  - The hit **pattern** along the muon trajectory is used to **estimate** the $\mathbf{p_T}$ of the muon.
- Available **thresholds** in **2012**:
  - **high** p_T: 11, 15, 20 GeV
    - have 5-10% lower efficiency in barrel
  - **low** p_T: 4, 6, 10 GeV
- A L1 muon trigger signal carries the $\mathbf{p_T}$ information of the muon and the **position** information of the RoI, the detector region to be analyzed by the HLT.

Level 1 Performance

- Level 1 **rates** scale **linearly** with the instantaneous luminosity.
  - Pile-up robust.
- Typical **efficiencies** w.r.t. offline isolated muons of one of the main Muon Trigger items, L1_MU11, used by most analyses in 2011:
  - Barrel: 0.725
  - Endcaps: 0.935

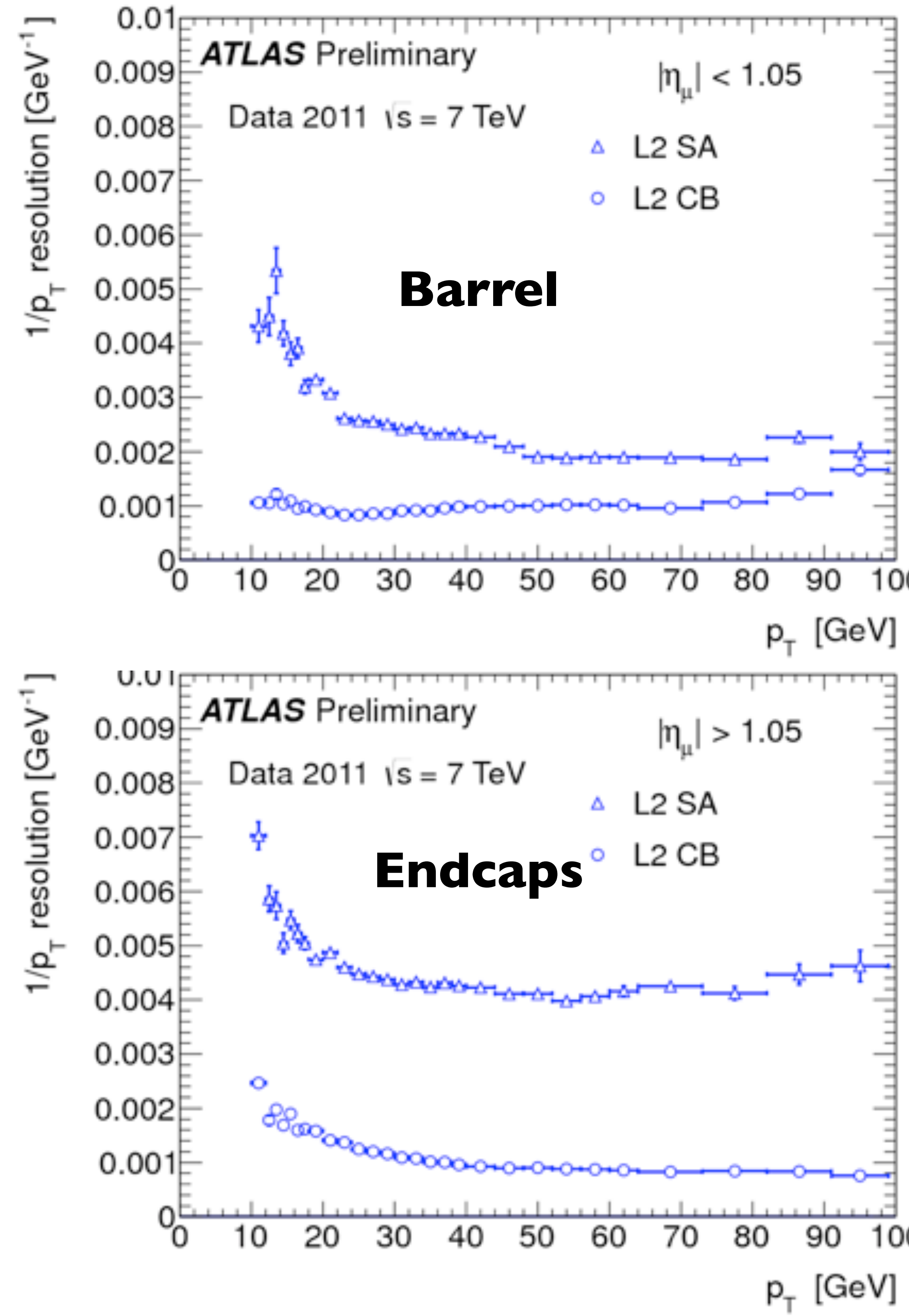






Level 2

- At Level 2, the candidate from L1 is **refined** by using the **precision data** from the Monitored Drift Tubes (MDT) chambers.
- The L2 muon **standalone** algorithm (SA) constructs a track using the MS data within the RoI defined by the L1 seed.
  - First, a **pattern recognition** algorithm selects hits from the MDT inside the RoI.
  - Second, a **track fit** is performed using the MDT hits, and a p_T measurement is assigned from Look Up Tables (LUTs).
- Reconstructed tracks in the ID are then **combined** (CB) with the tracks found by the L2 SA algorithm.
- Additionally, the **isolation** algorithm incorporates tracking and calorimetric information to find isolated muon candidates.

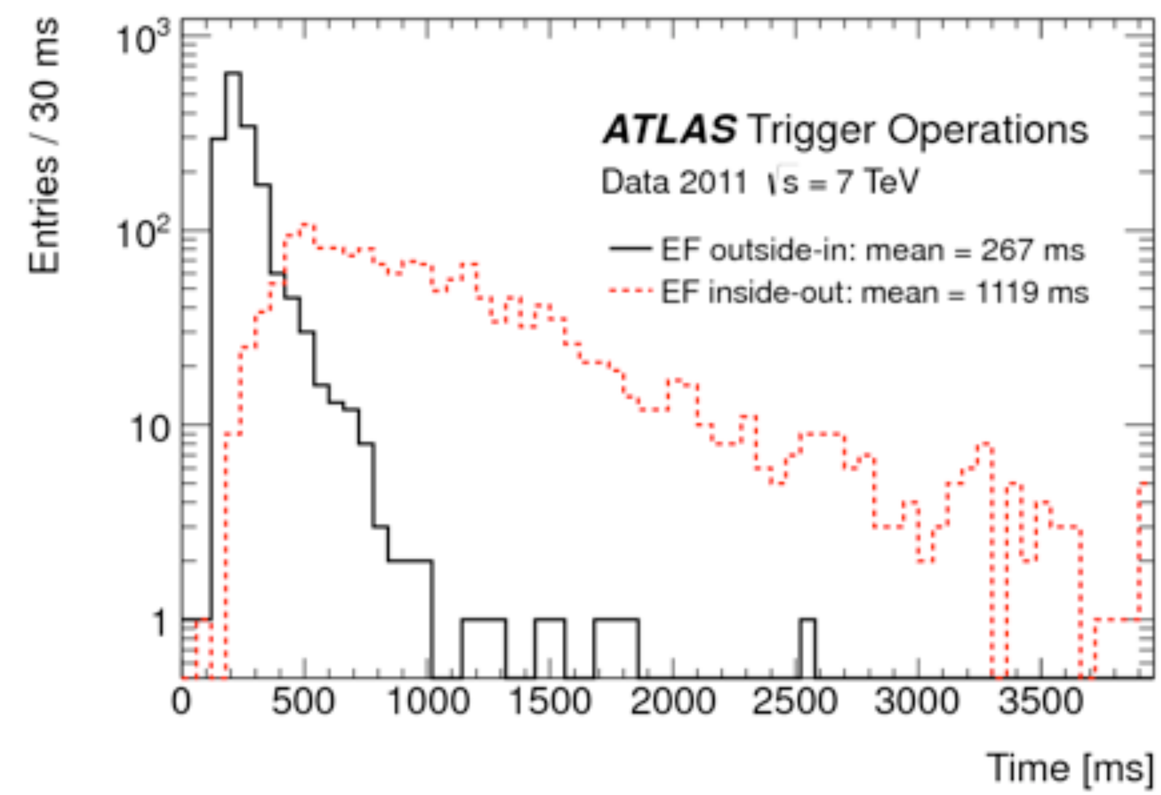


To evaluate the resolution, the residuals between the L2 and offline muon track parameters ($1/p_T$, η and Φ) are evaluated in bins of p_T. Then, the widths of the residual distributions are extracted in each bin with a Gaussian fit.

Muon Trigger

Event Filter - InsideOut & OutsideIn Algorithms

- At the Event Filter, the full event data are accessible.
- Two types of reconstruction algorithms are available.
    - Similar to the ones run offline for muon reconstruction.
- The **OutsideIn** algorithm:
    - starts from the RoI identified by L2, reconstructing segments and tracks using information from the MS.
    - The track is then extrapolated back to the beam line to determine the track parameters at the interaction point (muon EF SA trigger candidate).
    - Similarly to the L2 algorithms, the muon candidate is then combined with an ID track (muon EF CB trigger candidate).
- Instead, the **InsideOut** algorithm starts from the ID tracks and extrapolates them to the MS region.
    - Due to the extremely busy environment of the ID, the InsideOut algorithm is slower.



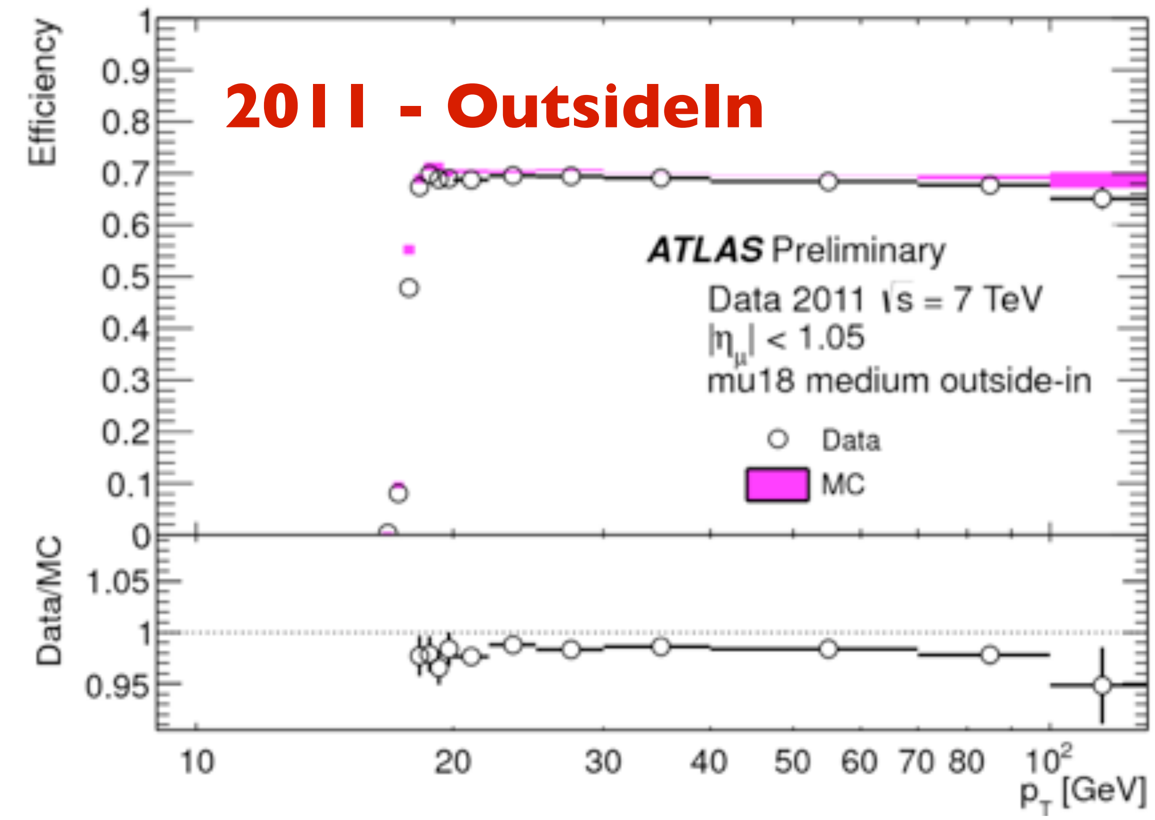
The complementary strategies employed by these two algorithms **minimize** the risk of **loosing events** at the online selection during the commissioning of the ATLAS muon trigger.

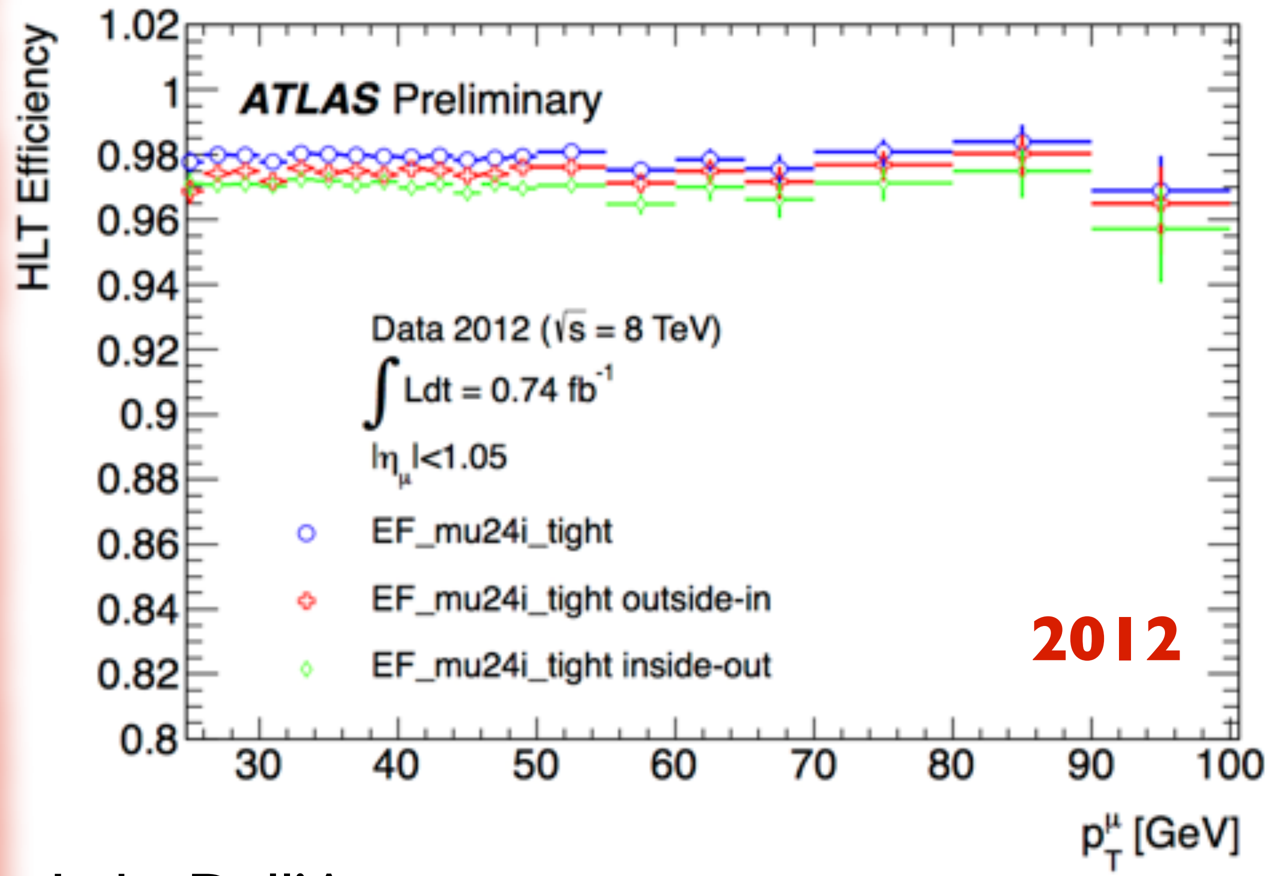
	Single muon trigger	Di-muon trigger
2011	EF_mu18[MG*,_medium]	EF_2mu10_loose
2012	EF_mu24i_tight	EF_2mu13

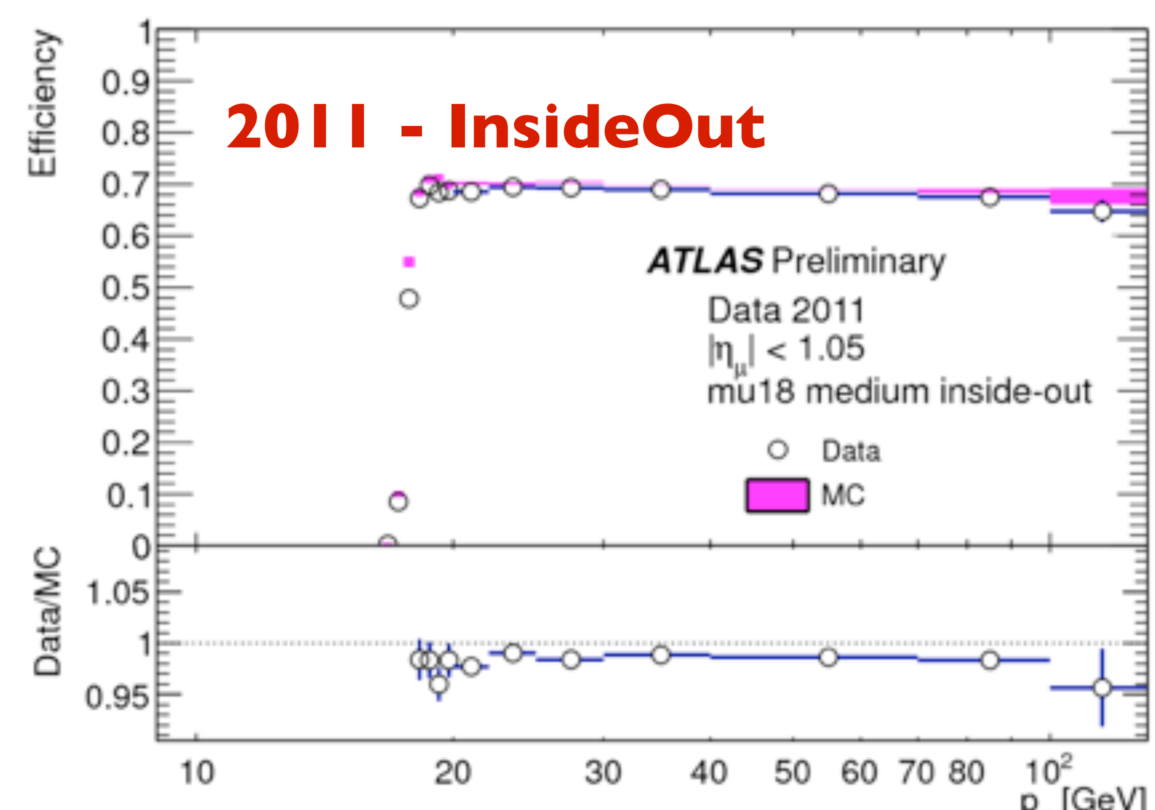
*"MG" denotes the InsideOut algorithm

Event Filter - InsideOut & OutsideIn Algorithms

- The Event filter **InsideOut** and **OutsideIn** algorithms were running separately during 2011 data taking.
- To save computing time, in 2012 the two algorithms were merged in a single chain, running the OutsideIn algorithm first and then, if that failed, the InsideOut one.
- Plots correspond to trigger efficiencies vs muon p_T in the **barrel** region only.

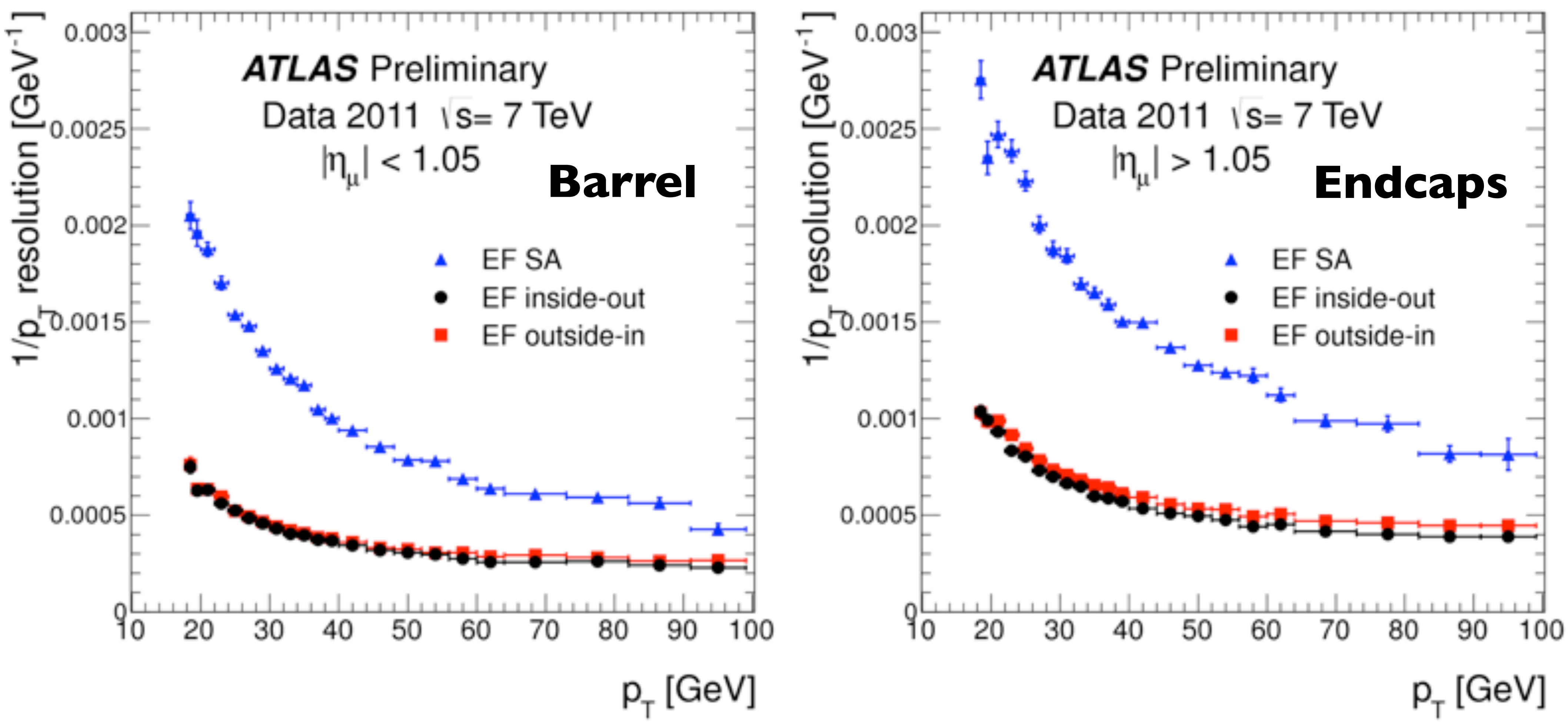






Event Filter - InsideOut & OutsideIn Algorithms

- It is also essential, for a good trigger performance, that the muon **track parameters** are reconstructed with enough **accuracy**.
  - To evaluate the accuracy, the **residuals** between the **EF** and **offline** muon track parameters ($1/p_T$, η and Φ) are evaluated in bins of p_T and the width of the residual distribution is extracted in each bin with a Gaussian fit.

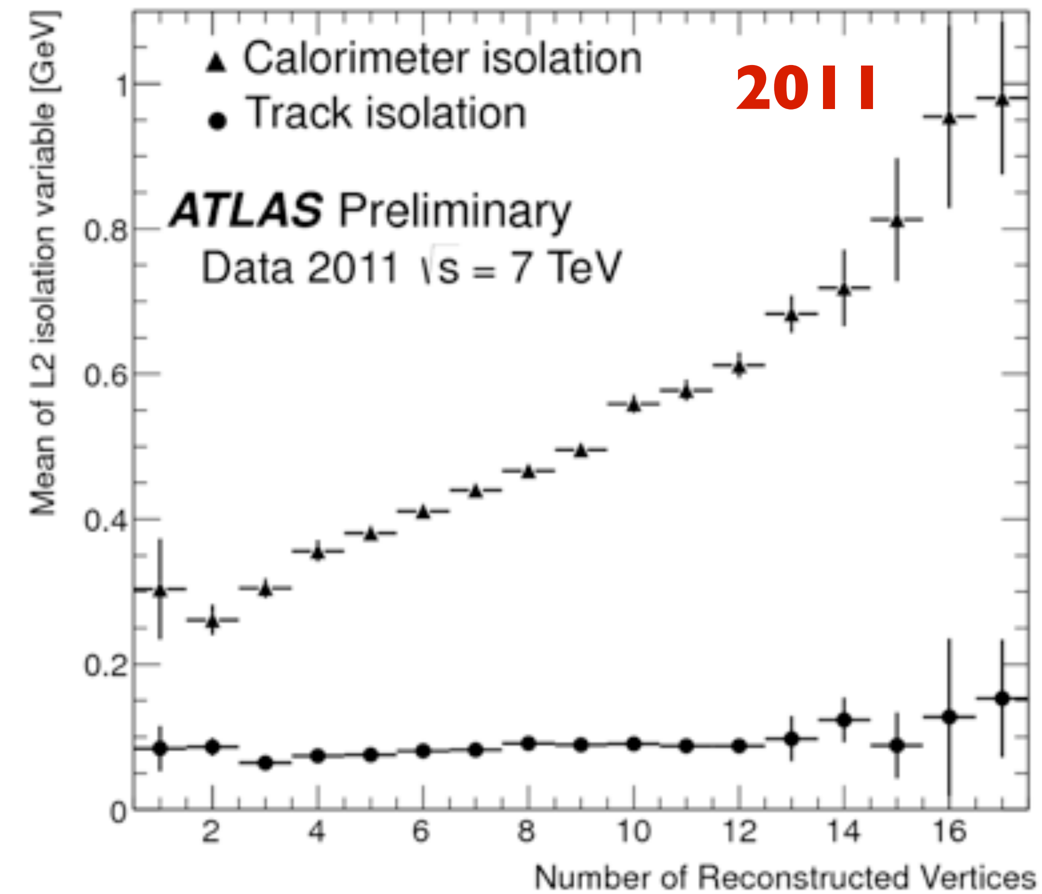


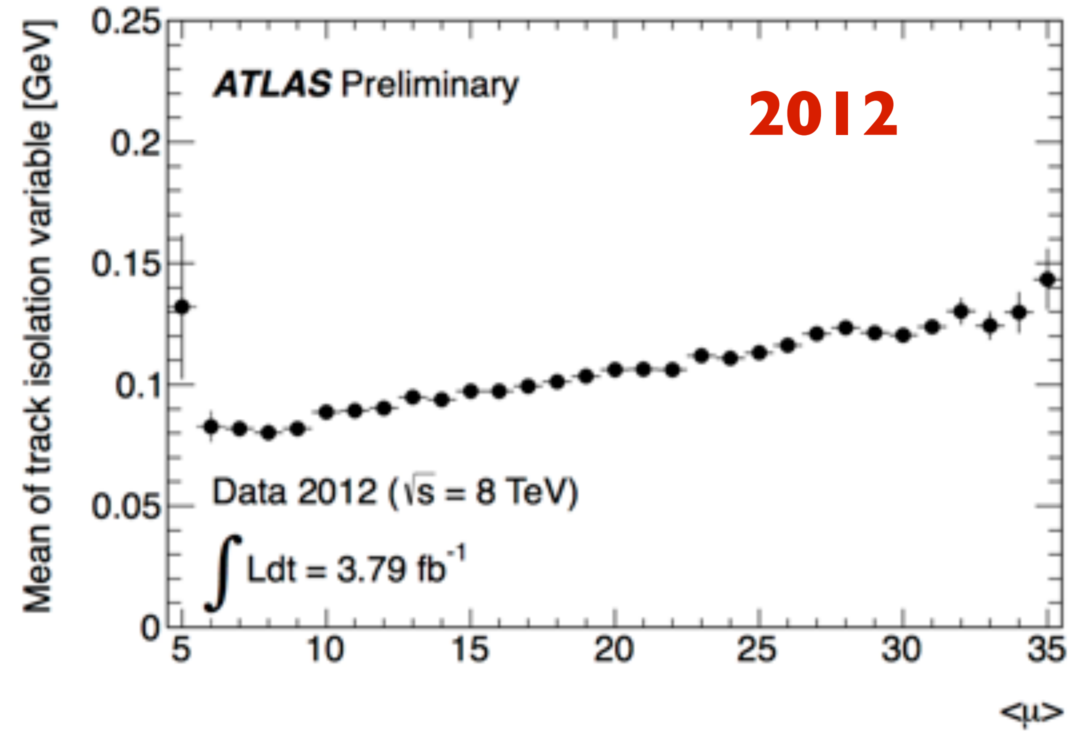
- Both OutsideIn and InsideOut algorithms allow to have **good resolution** on muon track parameters.

High Level Trigger - Isolation

- **Isolation algorithms** are run at the High Level Trigger.
  - They allow to **reduce the rate** of the muon trigger while **keeping p_T thresholds low**.
  - Critical aspect: pile-up robustness.

- Different types of **isolation** requirements:
  - **Calorimeter** isolation: based on energy deposits in the electromagnetic and hadronic calorimeters.
  - **Track** isolation: based on tracks around the muon candidate.
- In 2011 data taking the isolation algorithm was tested at L2.
- In 2012 the isolation algorithm was moved to the Event Filter and was made more **pile-up robust**.
  - Track based isolation was used in 2012 data taking.



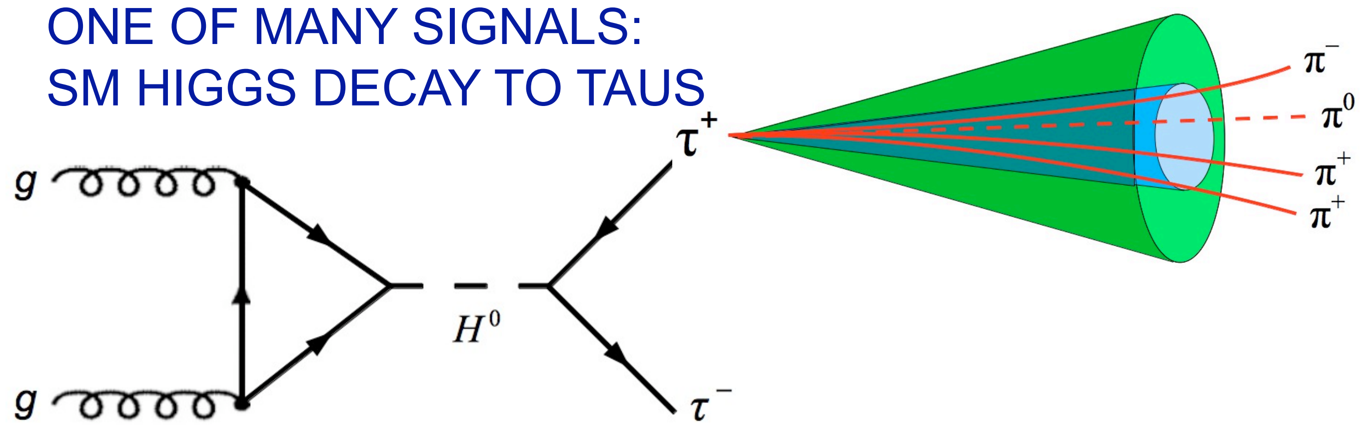


The Tau Trigger

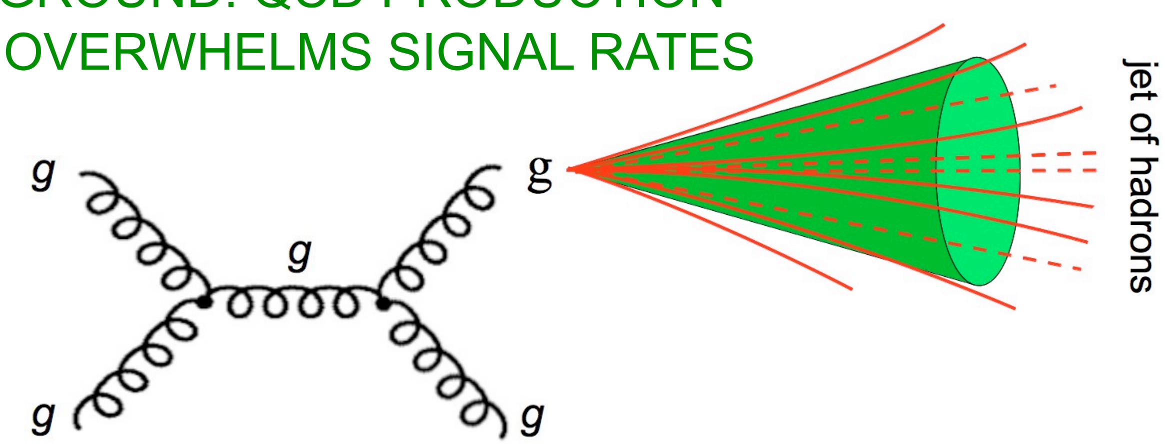
Introduction

- **Taus** play an important role in the search of the Higgs boson as well as supersymmetric and exotic particles.
- Taus decay hadronically 65% of the time.
- Jets from QCD processes are an overwhelming background to hadronic taus.

ONE OF MANY SIGNALS:
SM HIGGS DECAY TO TAUS



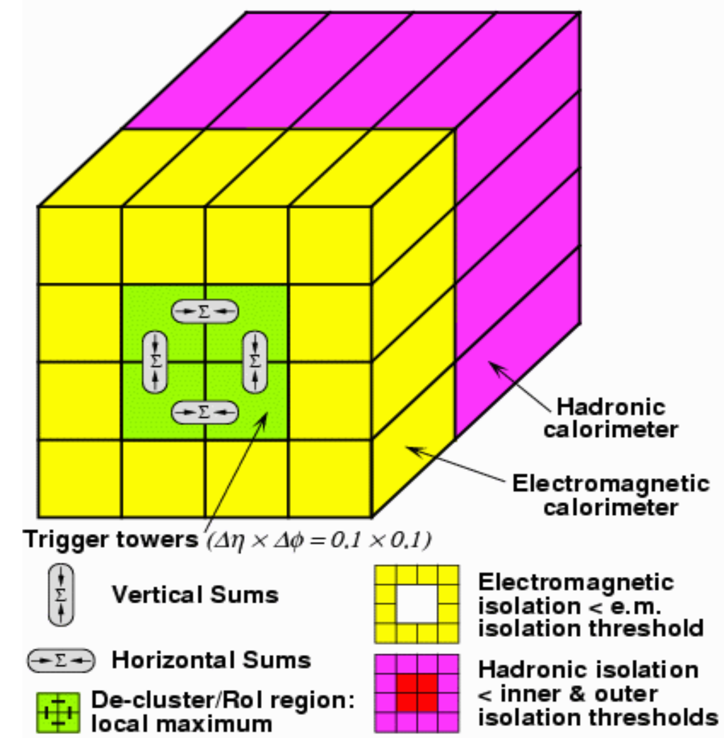
BACKGROUND: QCD PRODUCTION
RATE OVERWHELMS SIGNAL RATES

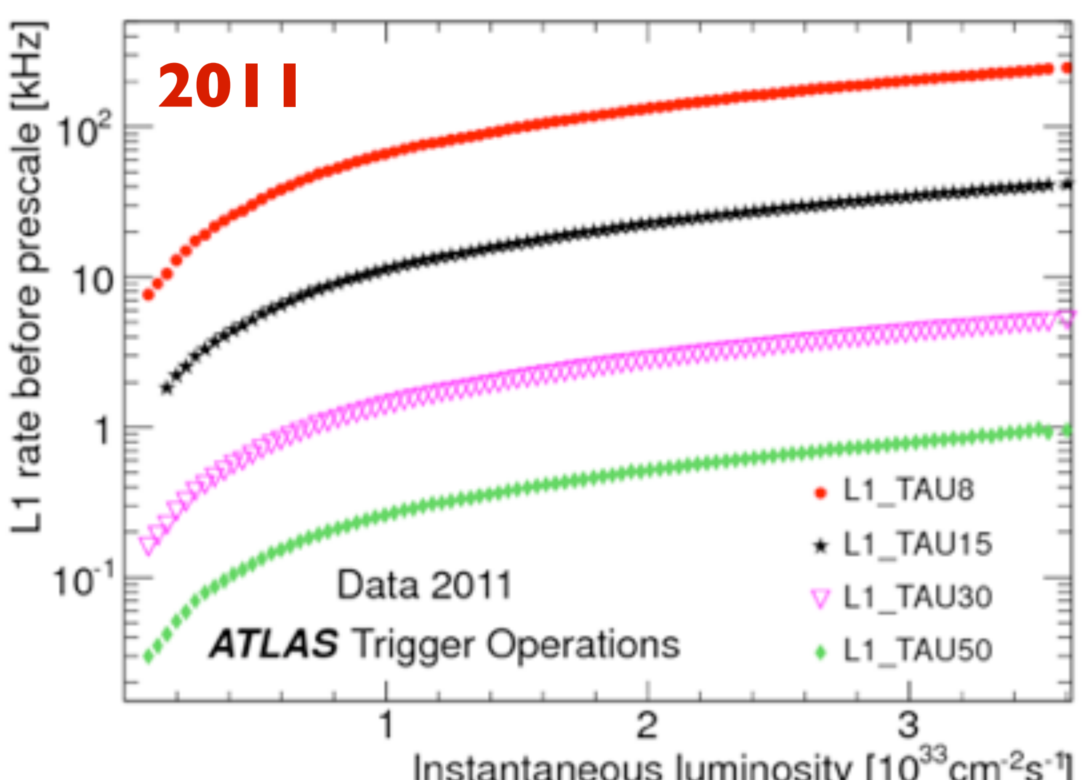


- Taus can be **distinguished** from **QCD** jets by means of some features:
  - low **track multiplicity**;
  - particles from the tau decay form a **narrow**, well **collimated jet**;
  - **isolation**: there is no activity around the narrow cone that contains the tau-candidate decay products.
- These features are exploited by the tau trigger.

Level 1

- The Level 1 Tau Trigger uses **electromagnetic** (EM) and **hadronic** (HAD) calorimeter trigger **towers** with granularity $\Delta\eta\times\Delta\varphi = 0.1\times0.1$.
- Hadronic tau decay modes are identified by the following features:
  - **sum of energy** in 2×1 pairs of EM towers,
  - **energy** in 2×2 HAD towers behind the EM cluster,
  - **energy** in a 4×4 isolation ring around the 2×2 core region.
- The **core** region is defined as the two-by-two trigger tower region of $\Delta\eta \times \Delta\varphi = 0.2 \times 0.2$.
- The **isolation** region is defined as a four-by-four trigger tower region minus a two-by-two core region in the center

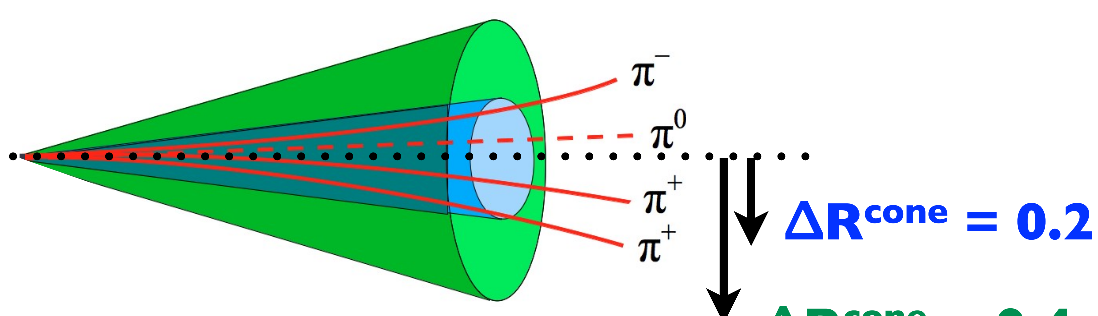




- In **2012**, used E_T **thresholds**: 8, 11, 15, 20, 40 GeV.
- To keep the rates within limited bandwidth and to keep thresholds low, **isolation** requirements are applied.
  - The absolute E_T in the EM isolation region is required to be smaller than 4 GeV.

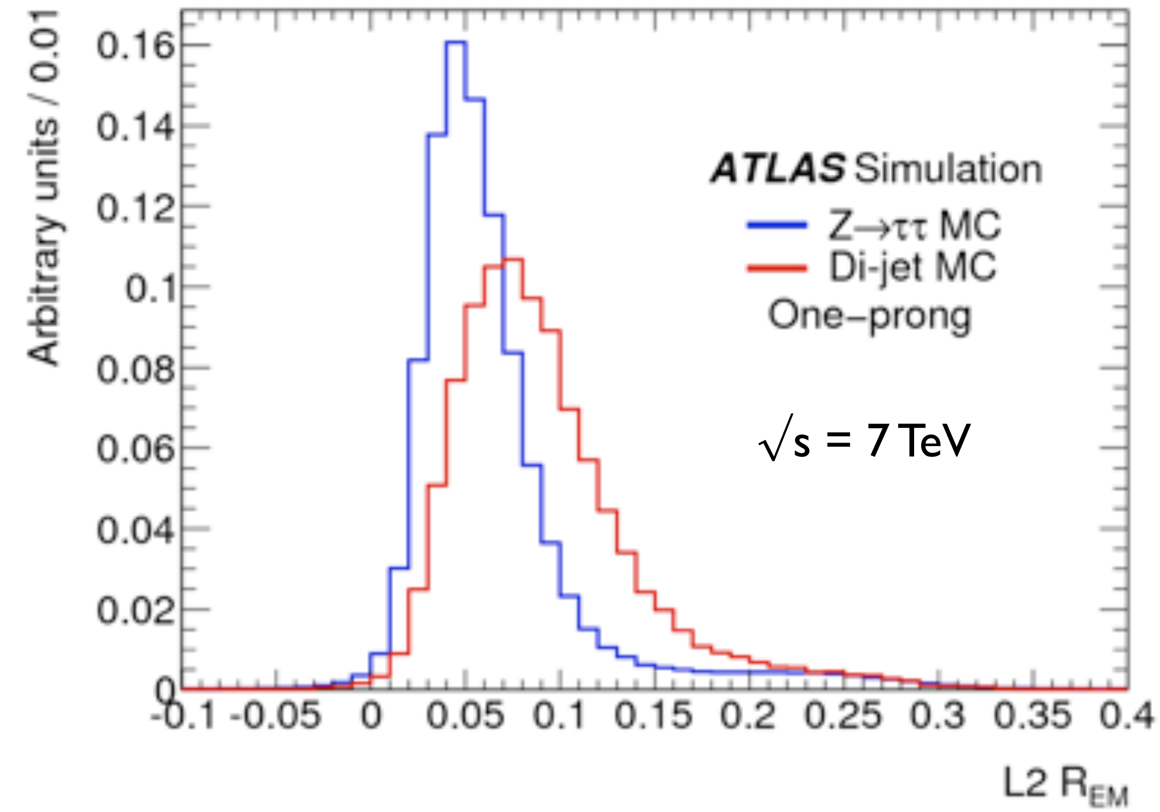
Level 2

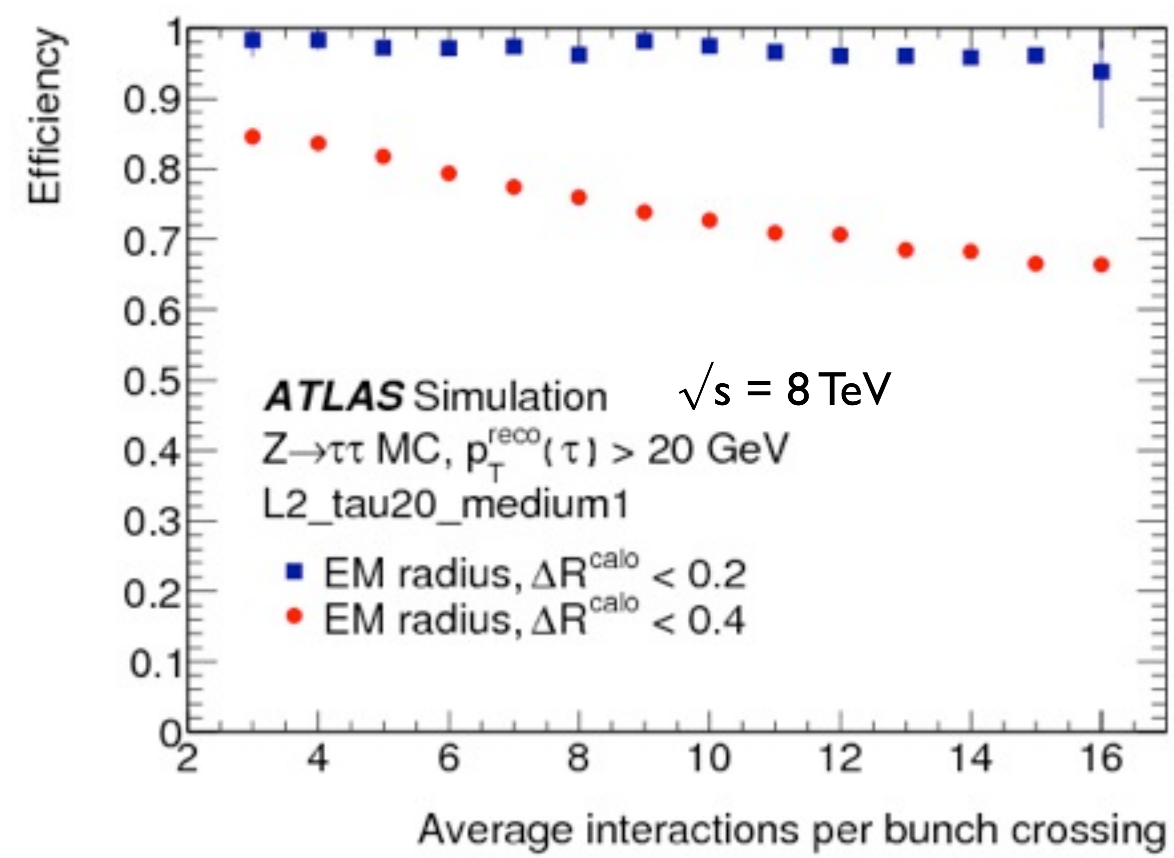
- The Level 2 **calorimeter** selection is applied to a restricted RoI, based on seeded information from L1.
- L2 uses the **full granularity** of information from all layers of the calorimeters within a region of $\Delta\eta \times \Delta\varphi = 0.8 \times 0.8$.
  - It refines the **position** of the RoI and obtains the total $\mathbf{E_T}$ and **shape variables**.
  - Shape variables are used to identify hadronically decaying taus.
- In **2012**, some improvements made the algorithm more pile-up robust.
  - The **cone** used to compute E_T and the shape variables changed from 0.4 to 0.2.



$$R_{EM} = \frac{\sum_{Cells} E_{cell} \cdot \Delta R_{cell}}{\sum_{Cells} E_{cell}}$$

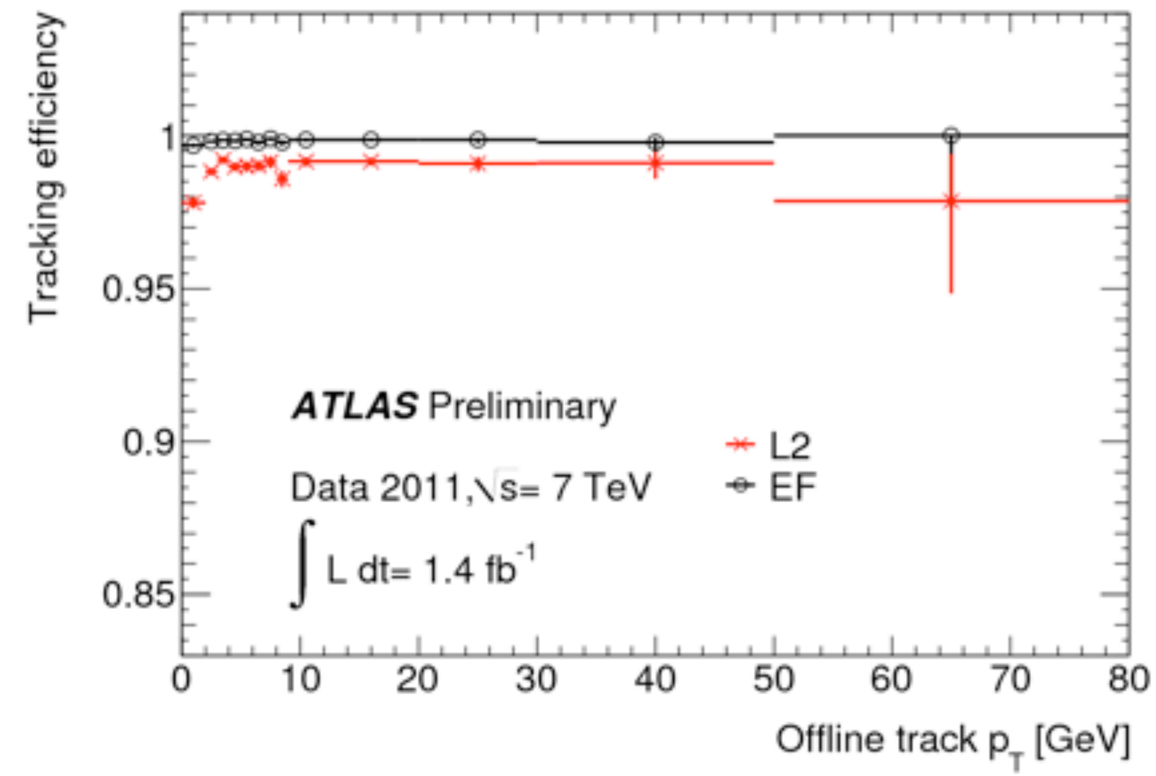
where the sum extends over all cells in the first three samplings of the EM calorimeter

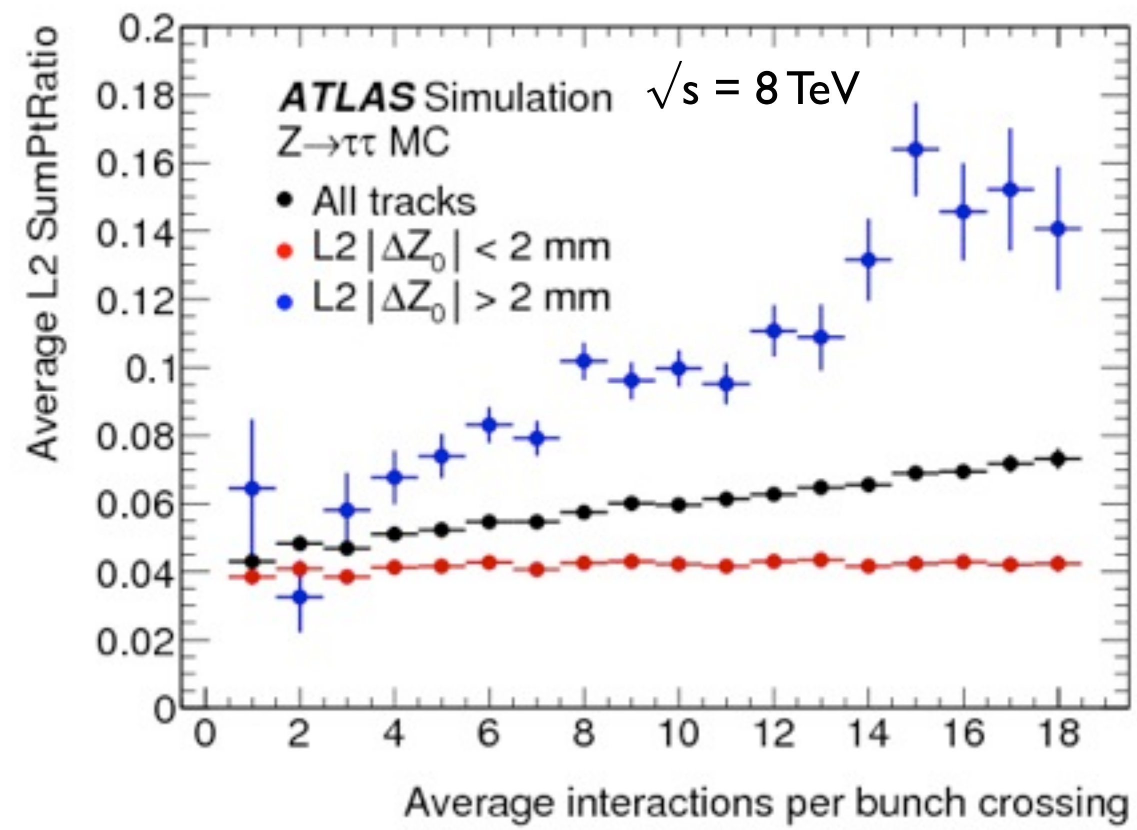




Level 2

- At L2, in addition to calorimeter information, **tracking** information from the ID is also used to refine the reconstruction.
  - Tracking in the tau RoIs uses fast custom algorithms based on combinatorial pattern recognition followed by a fast Kalman filter track fit.
    - The tracking efficiency is good and comparable to the one then used at the Event filter.
  - **Track counting** and track-based **isolation** use tracks found in core and isolation regions of radii 0.1 and 0.3 respectively.
    - These information are used to identify taus.
- In **2012**, some improvements made the tracking more pile-up robust.
  - Only tracks with an impact parameter compatible ($|\Delta z| < 2$ mm) with the leading track are used.

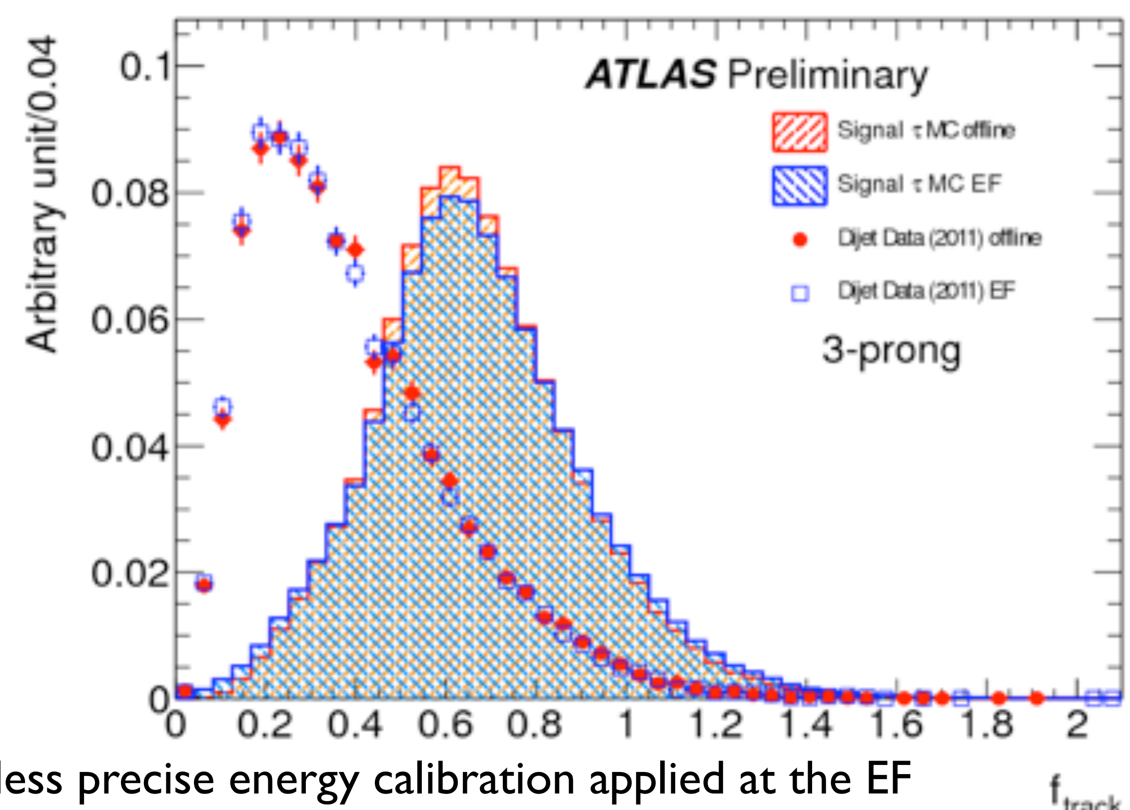




Event Filter - Tau Identification

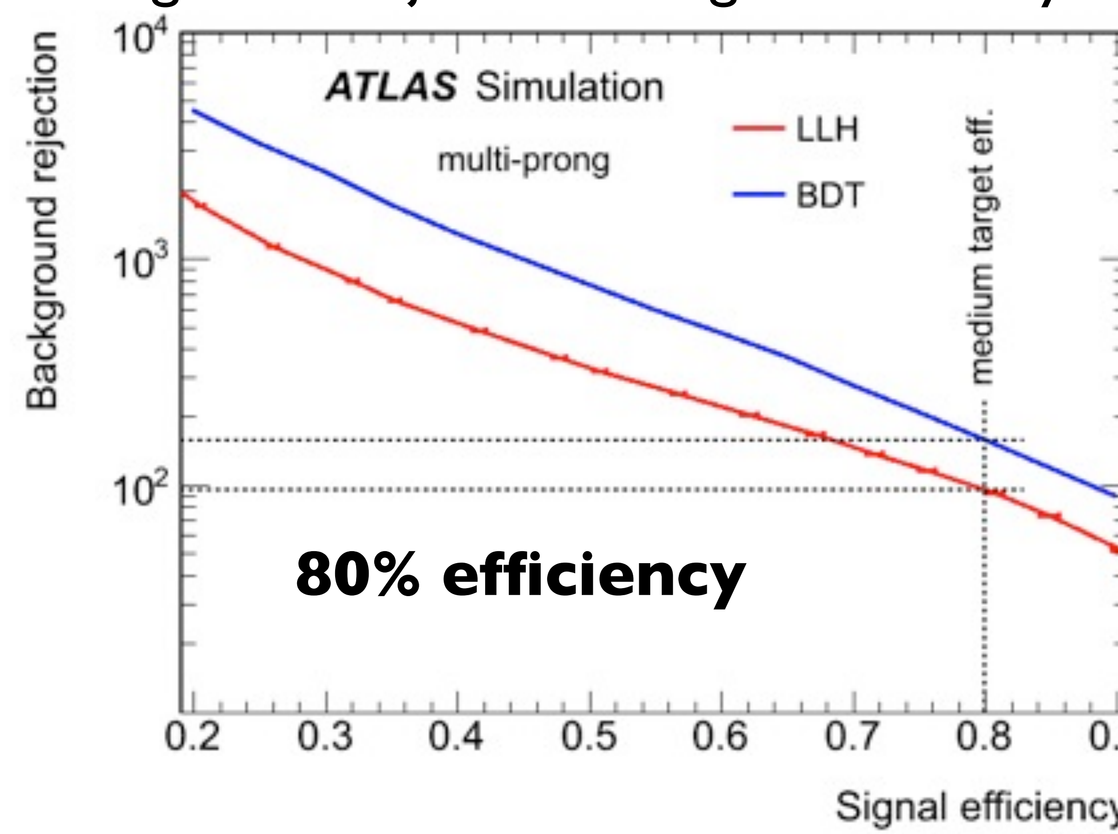
- In **2011** the hadronic tau identification was **cut based**.
  - Cuts parameterized as a function of E_T, number of tracks associated to the tau jet, and track and cluster shape variables.
  - The definition of these variables is the same as offline.
- In **2012**, to make the **online** tau identification as similar as possible to the **offline** one, an identification based on **multivariate** analyses was introduced, using the **TMVA Boosted Decision Tree** (BDT).
  - A "medium" identification criteria was chosen, which gives an efficiency of 85% for 1 prong and of 80% for multi prong taus.

One of the shape variables used for training.



A less precise energy calibration applied at the EF causes the small shift of the trigger distributions with respect to offline.

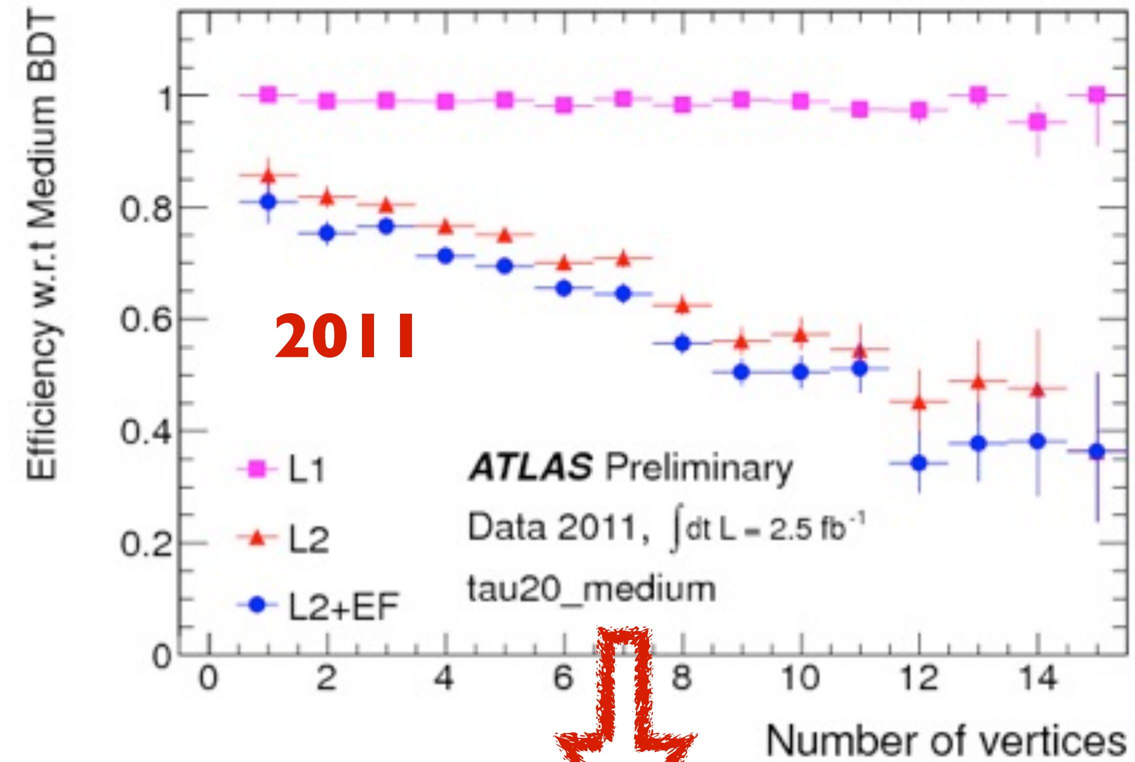
Background rejection vs signal efficiency

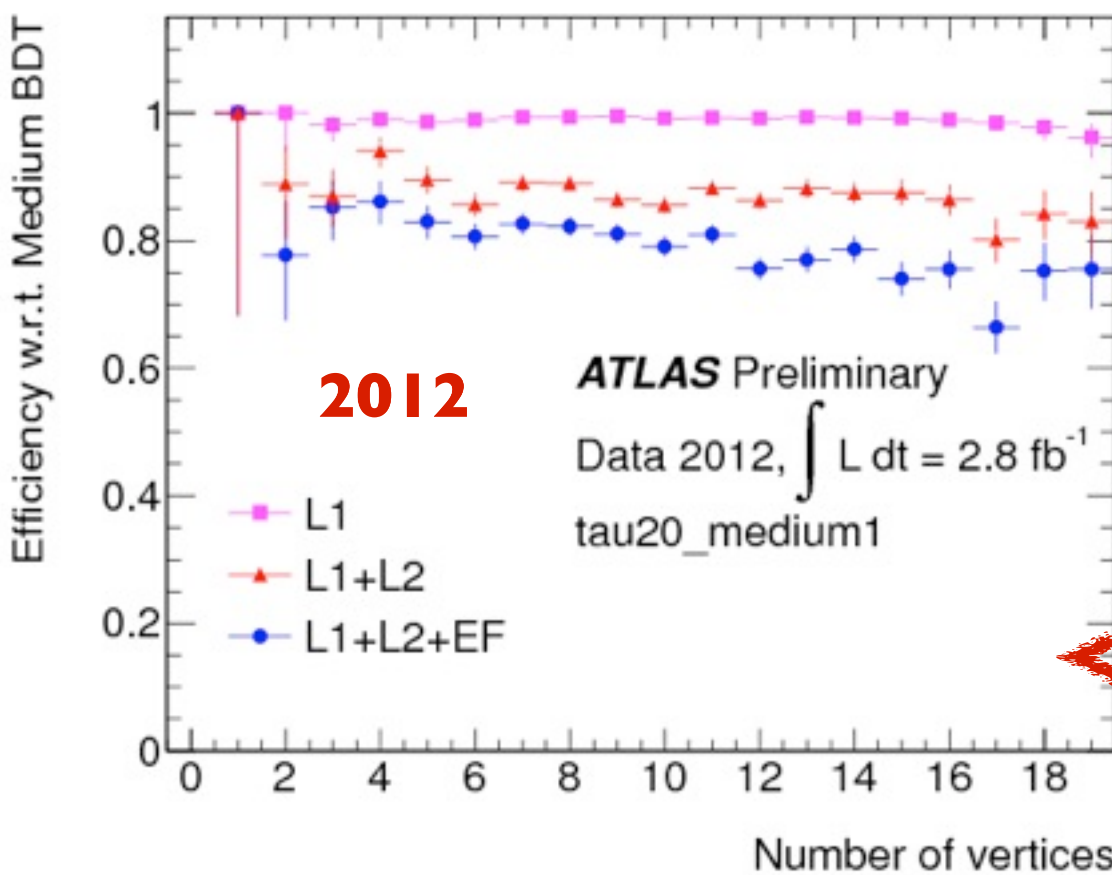


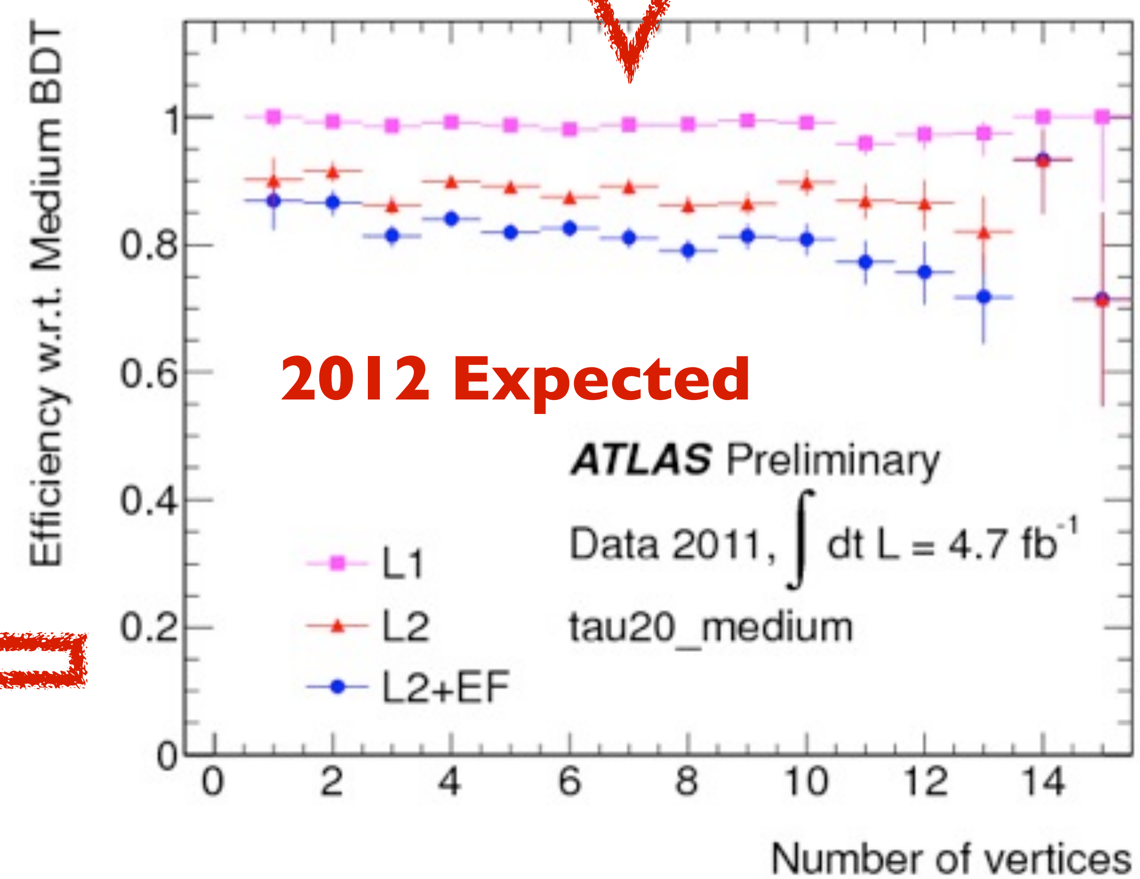
80% efficiency

High Level Trigger - Pile-up Robustness

- With the improvement of the algorithms at L2 and Event Filter, the dependence on pile-up was substantially reduced.
  - The pile-up robust algorithms were studied on 2011 data, to check the behavior expected in 2012 data taking.
  - 2012 data taking confirmed the **pile-up robustness**.

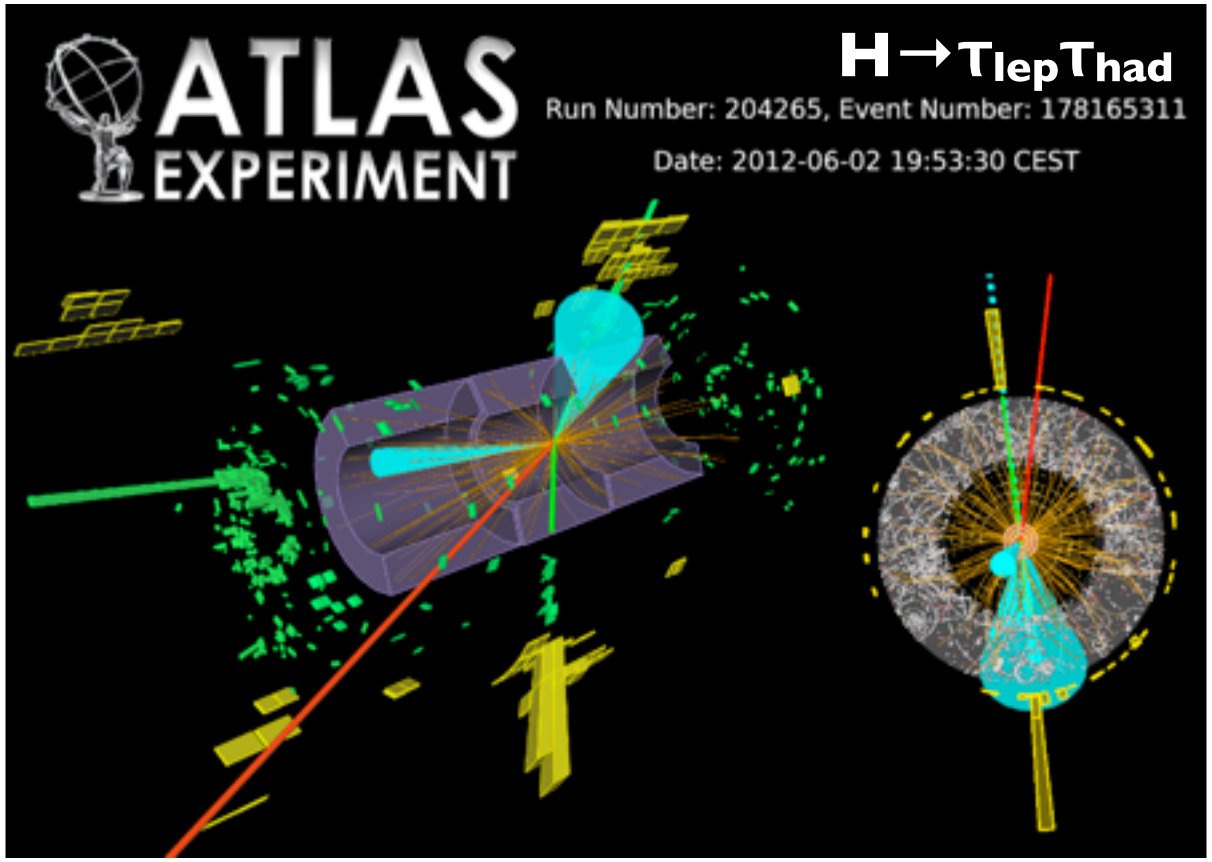






Conclusions

- The ATLAS Experiment has a **three level trigger system**, which allows to reduce the incoming rate of 20MHz LHC collisions to ~400 Hz selecting interesting events.
  - Trigger signatures and trigger menus are driven by the physics goals, e.g. SM precision measurements and Higgs boson search.
- The main challenges of the trigger system are to keep the **p_T threshold** of the selected objects **low** for having **high efficiency**, **good resolution** on object reconstruction and be **pile-up robust**.
- Dedicated **Muon** and **Tau Triggers** are available in ATLAS.
  - These triggers were used in the analyses that brought to the discovery of a particle compatible with the SM Higgs boson.
  - The description of both triggers and their performance have been shown.
  - The long shutdown of the LHC (see Attila's talk) will allow new studies in preparation of a new data taking period at higher luminosity, where pile-up robustness will be mandatory.

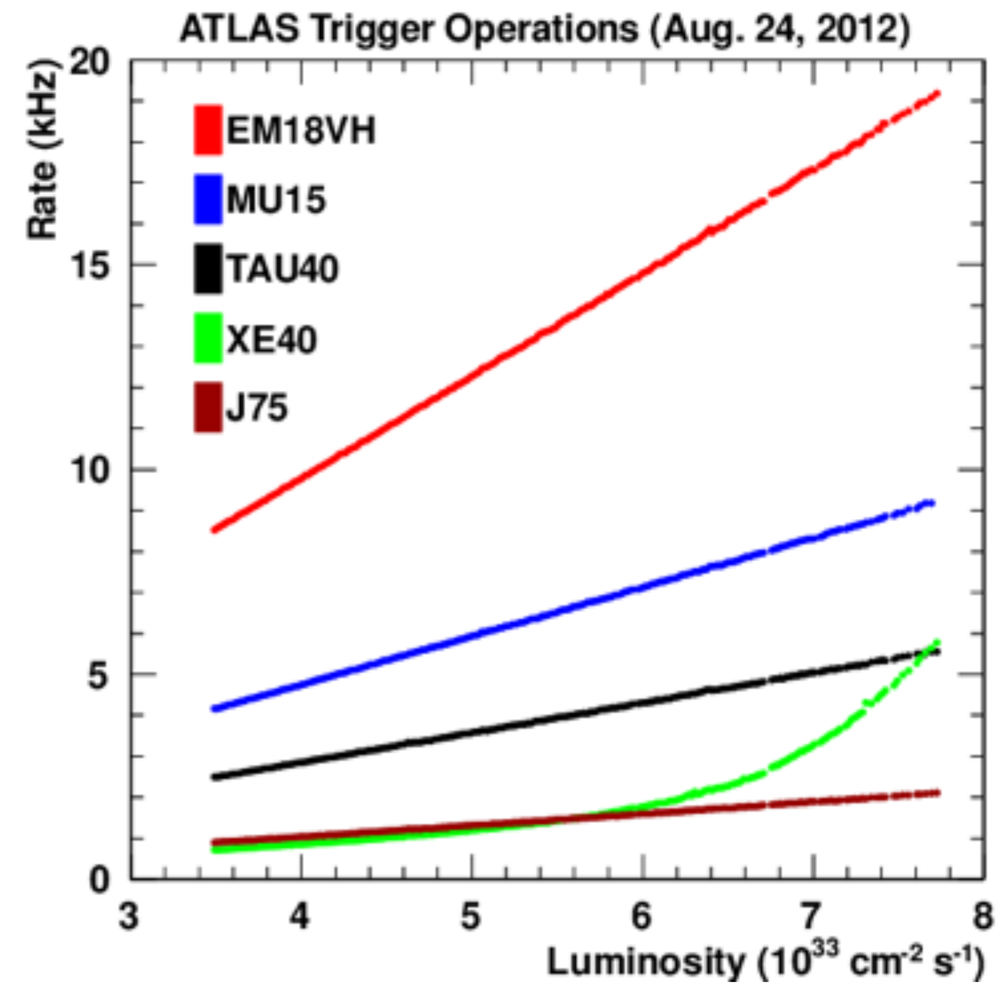


BackUp

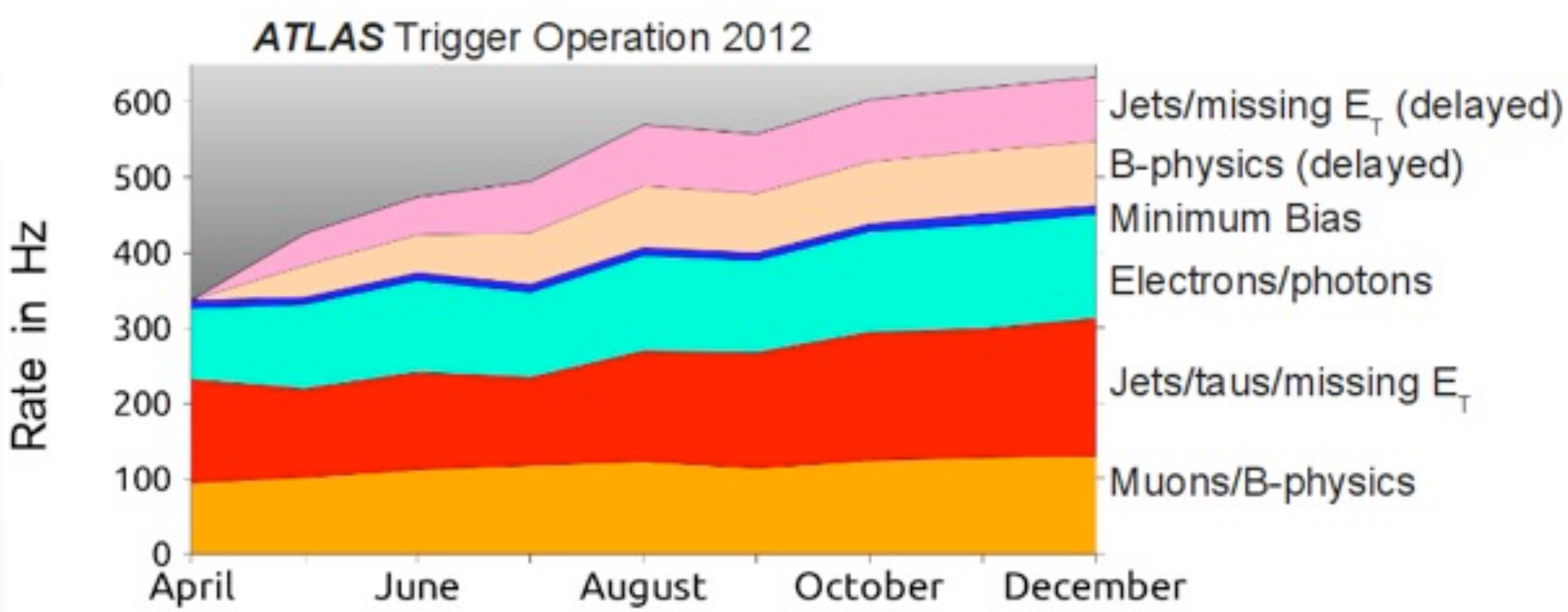
Trigger Menu & Rates

- According to physics goals, we have to fit best possible physics cocktail in the available bandwidth.
- Different type of triggers are available in the Trigger Menu, all starting at L1 mostly using muon spectrometer and calorimeter information.

Peak L1 rates during 2012



EF rates evolution during 2012



Introduction

Event Filter - InsideOut & OutsideIn Algorithms

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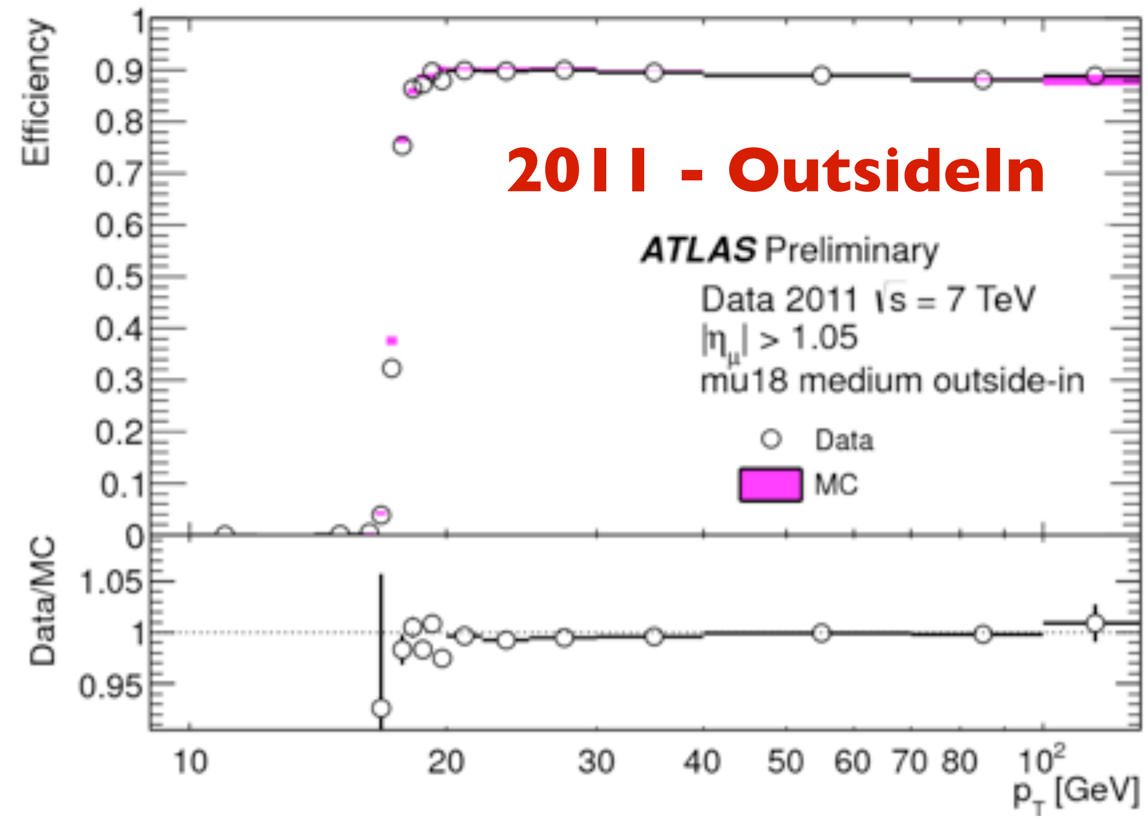
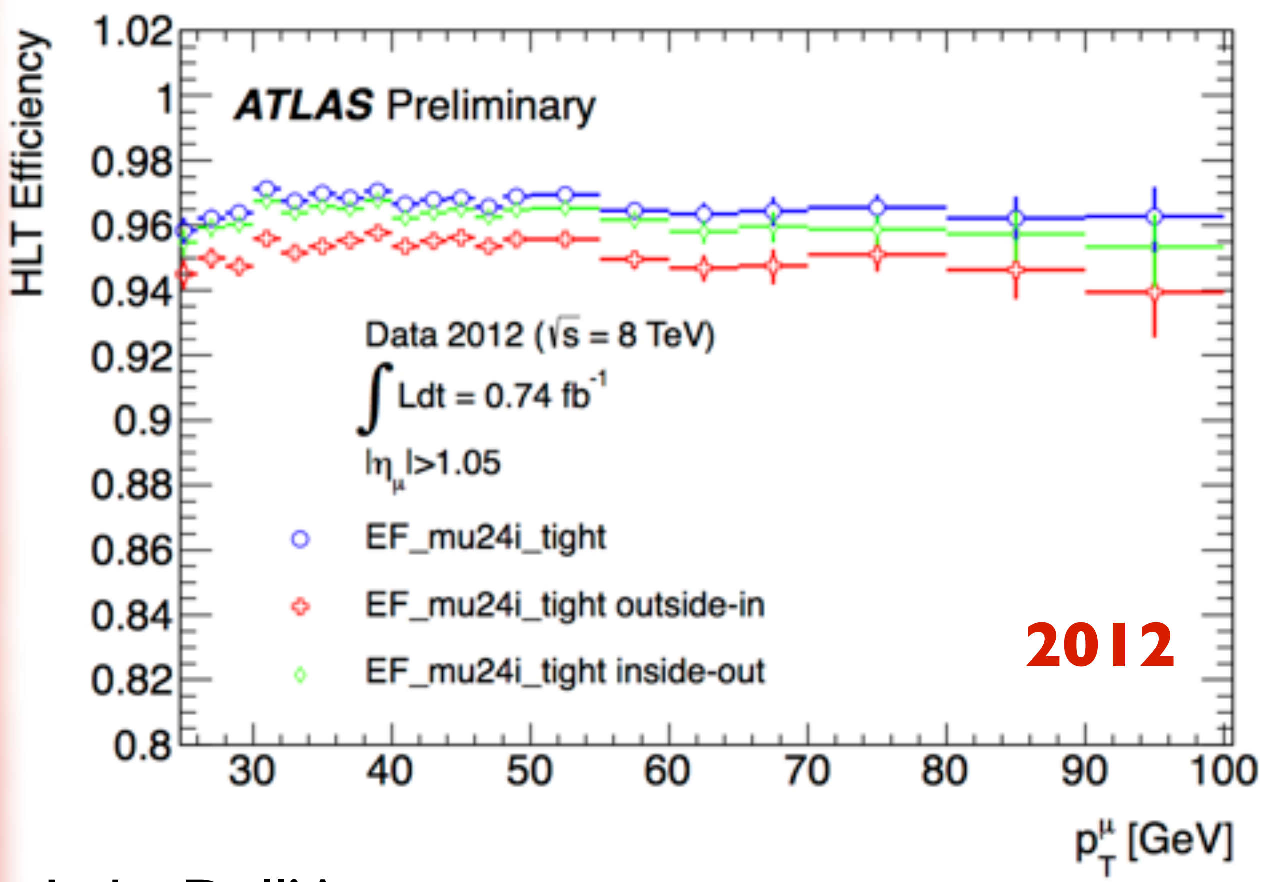
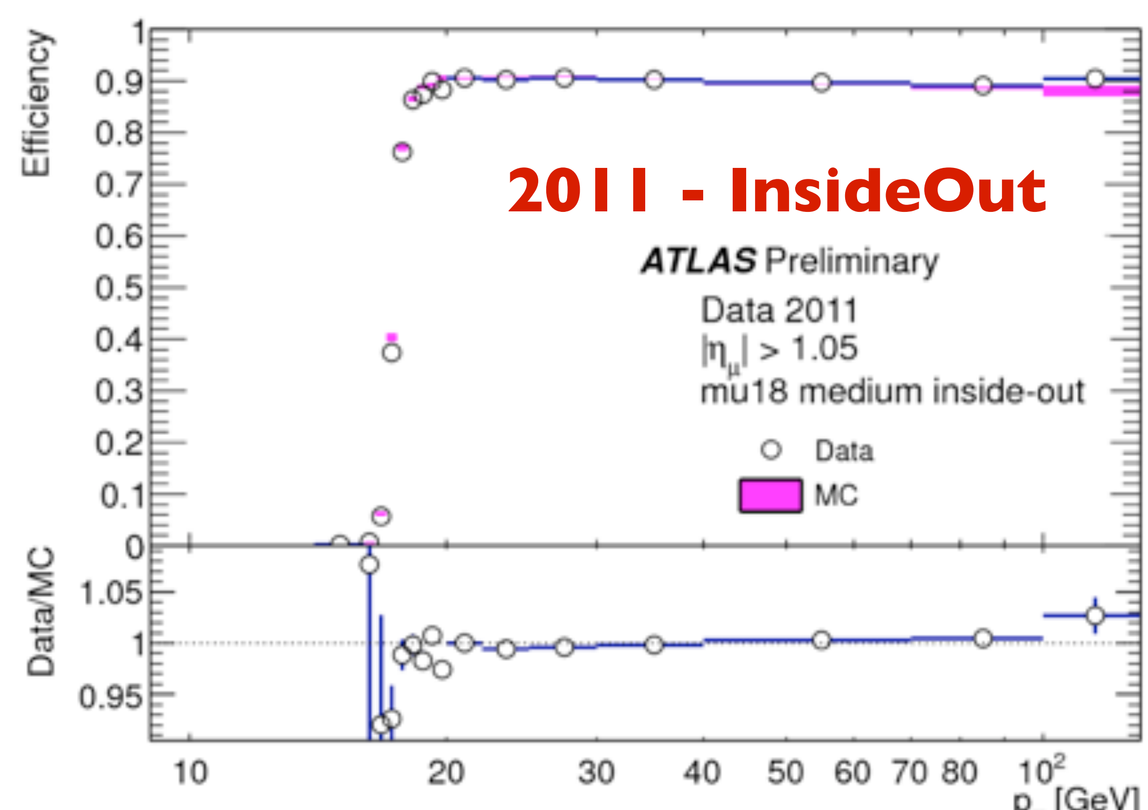
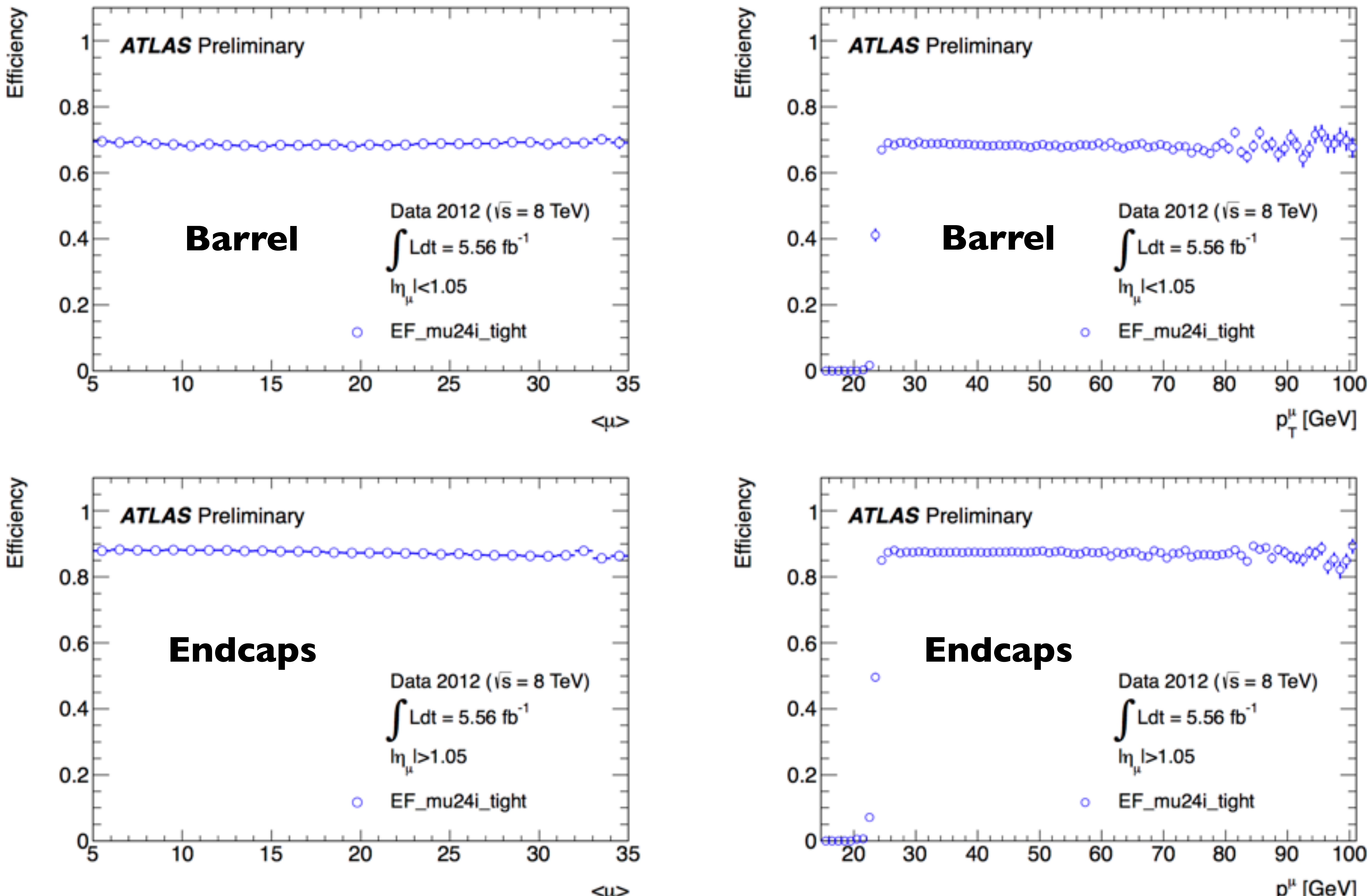
- To save computing time, in 2012 the two algorithms were merged in a single chain, running the OutsideIn algorithm first and then, if that failed, the InsideOut one.
- Plots correspond to trigger efficiencies vs muon p_T in the **endcap** regions only.





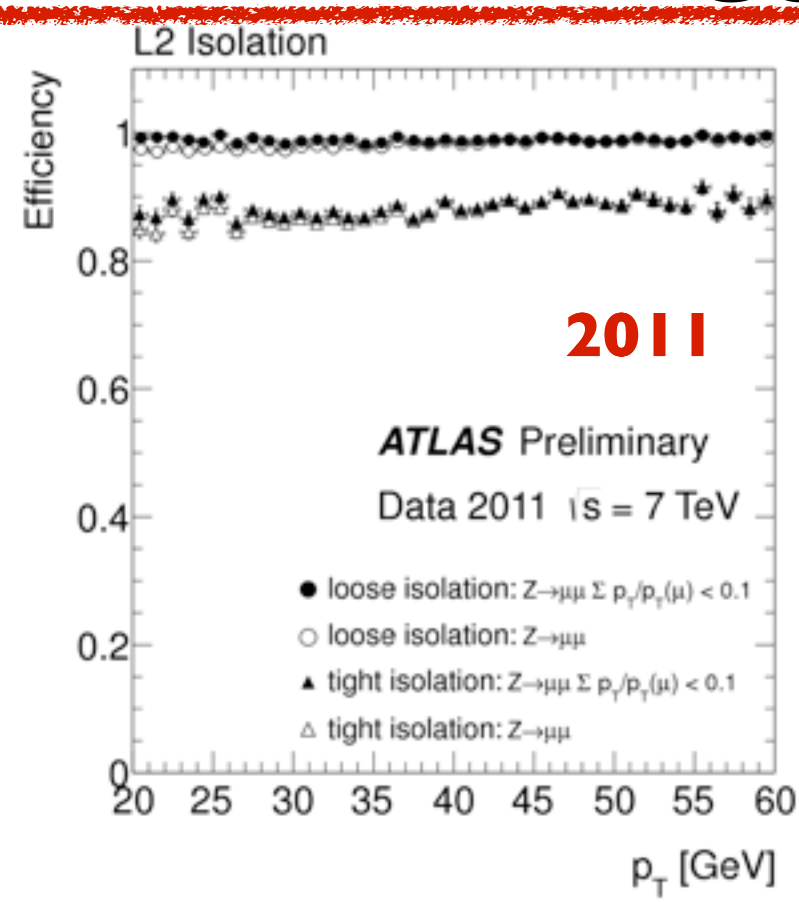


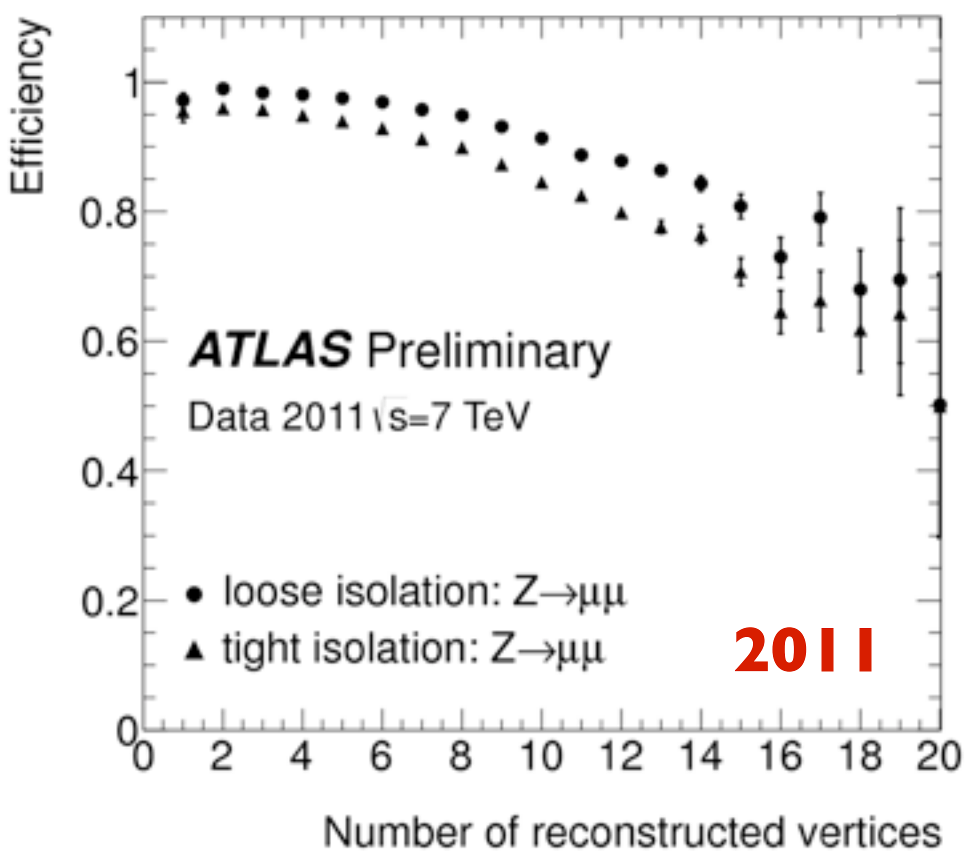
Event Filter in 2012



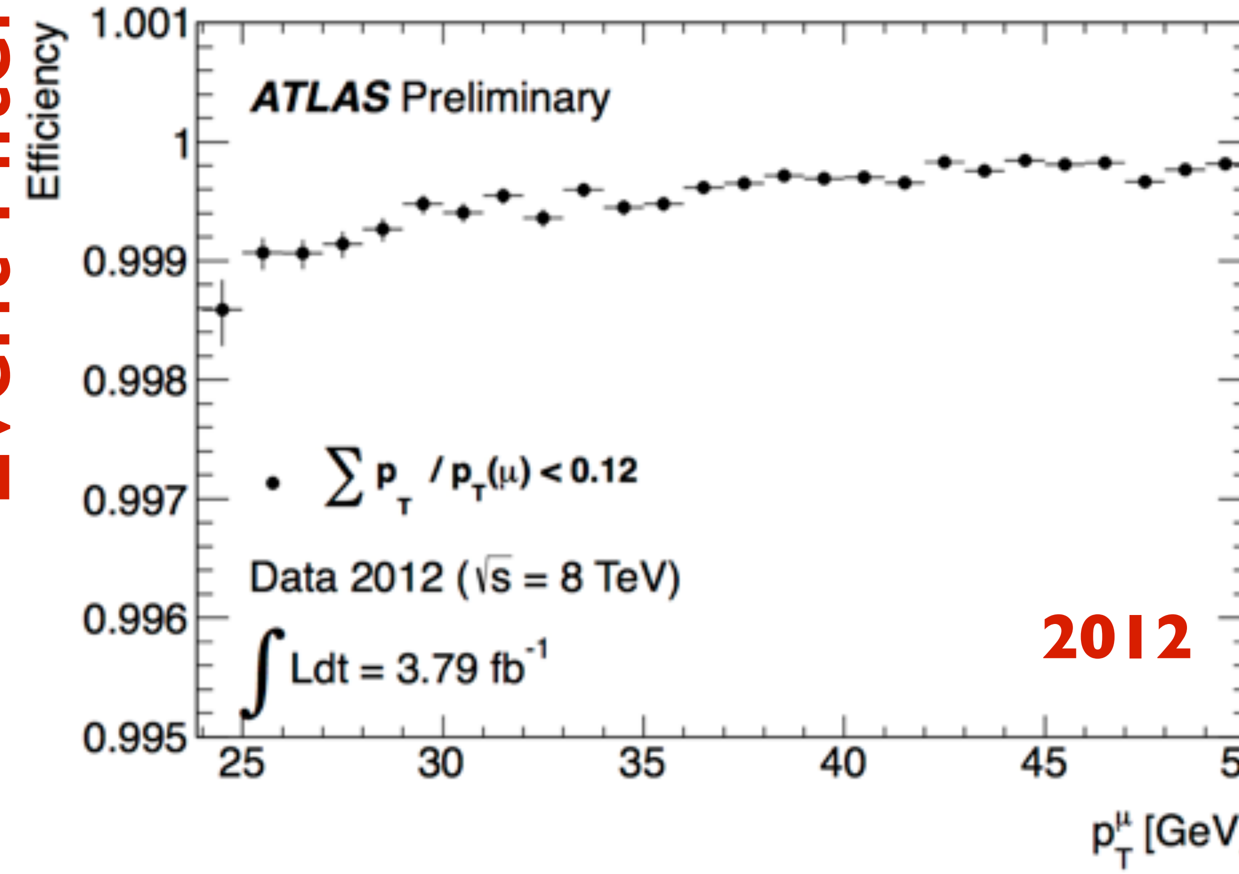
High Level Trigger - Isolation

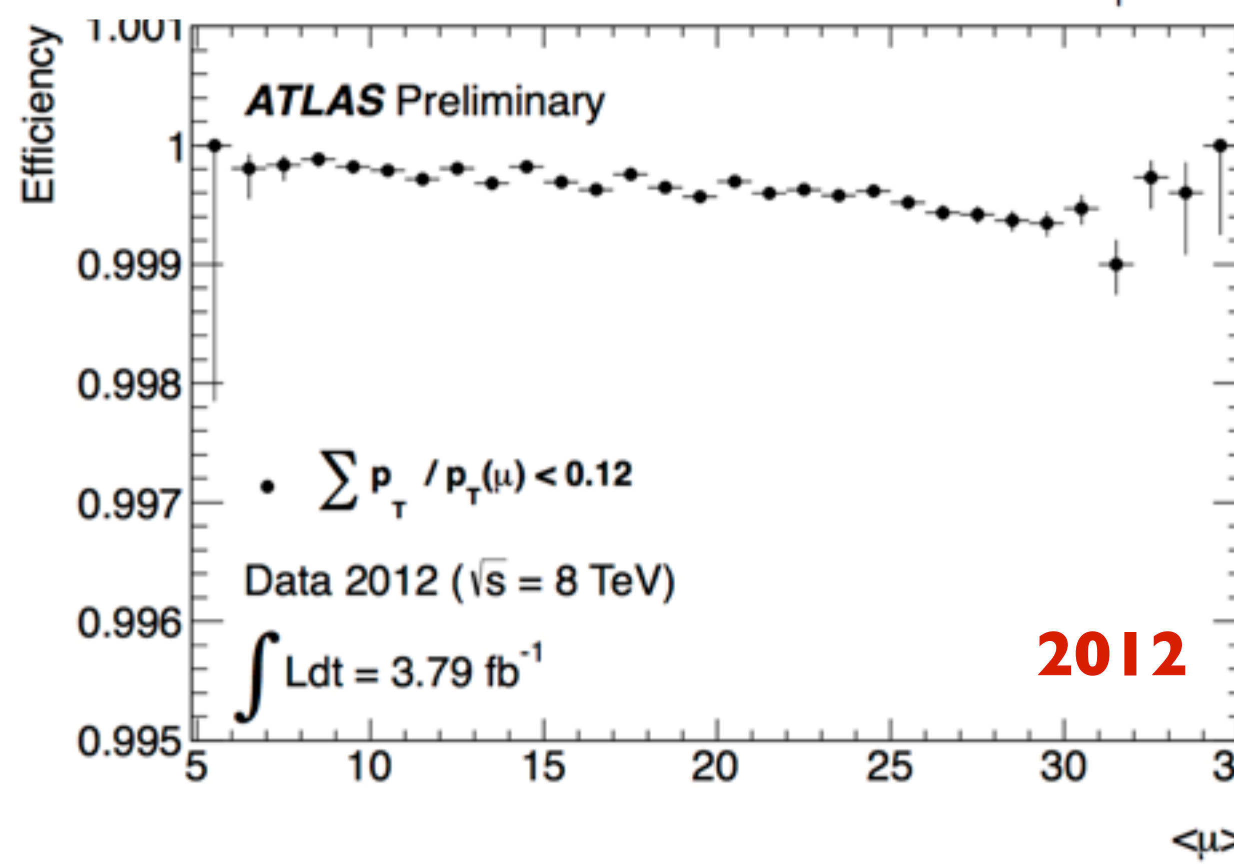
Level 2





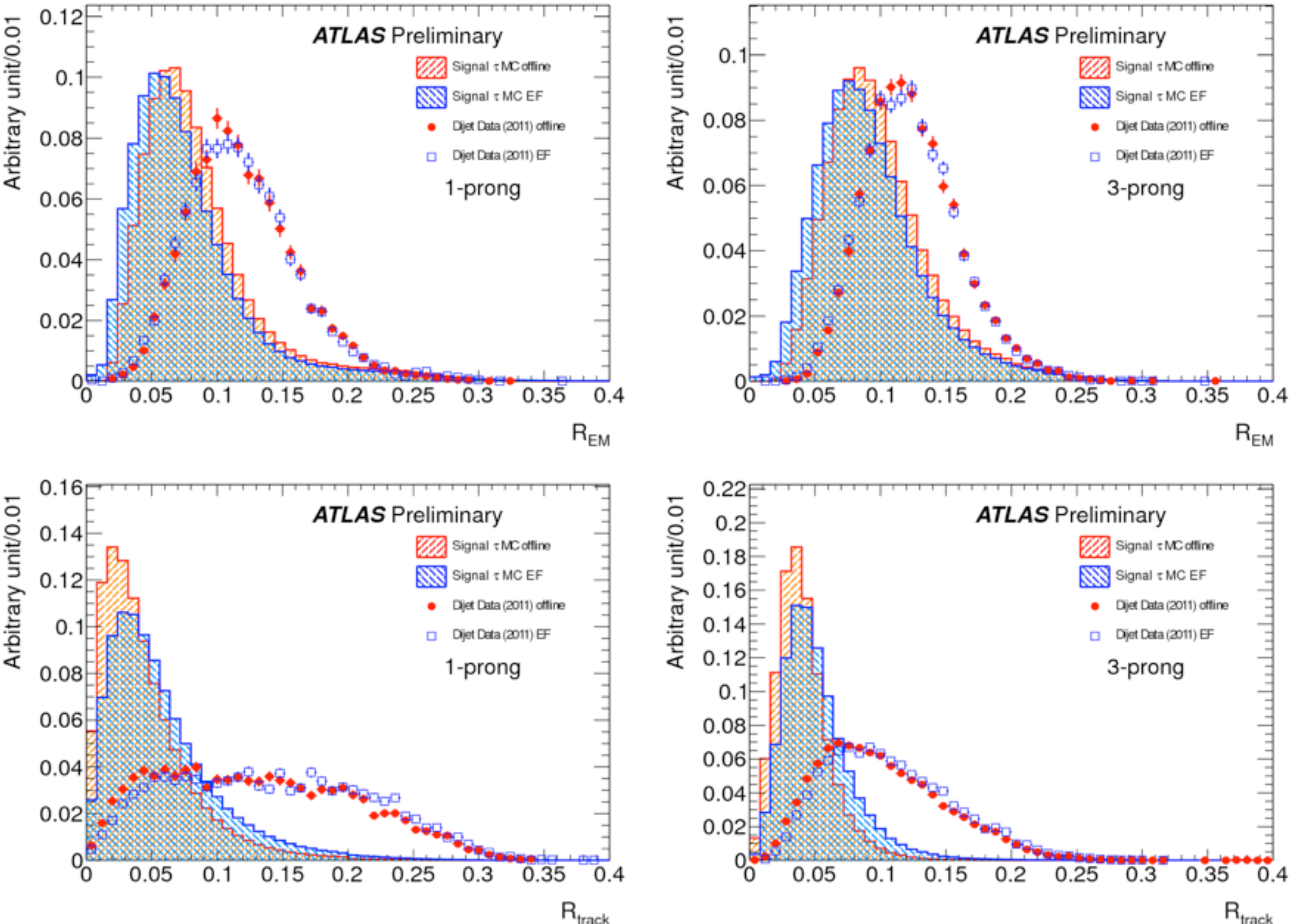
Event Filter





Muon Trigger

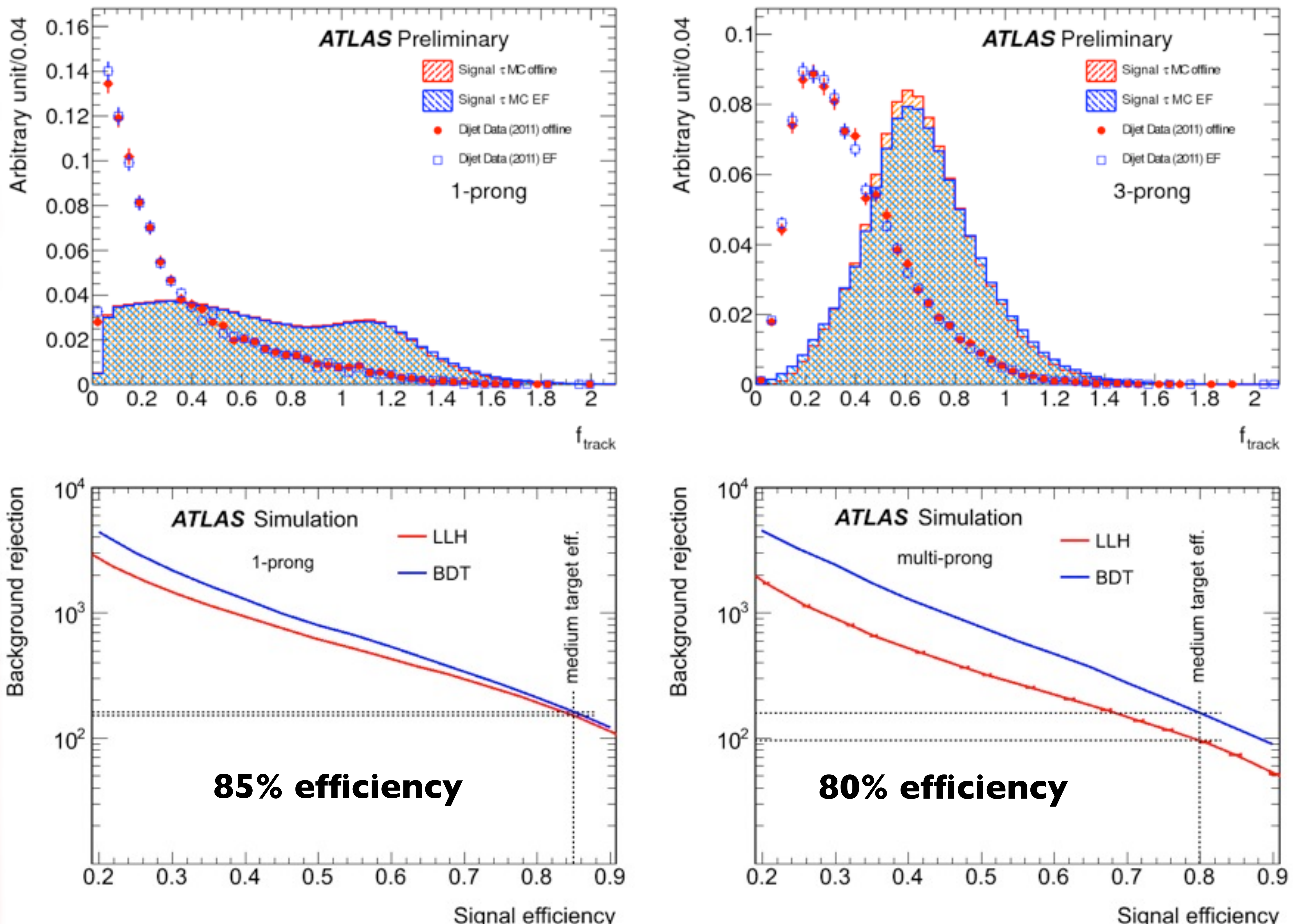
Event Filter - Tau Identification



A less precise energy calibration applied at the EF causes the small shift of the trigger distributions with respect to offline.

Tau Trigger

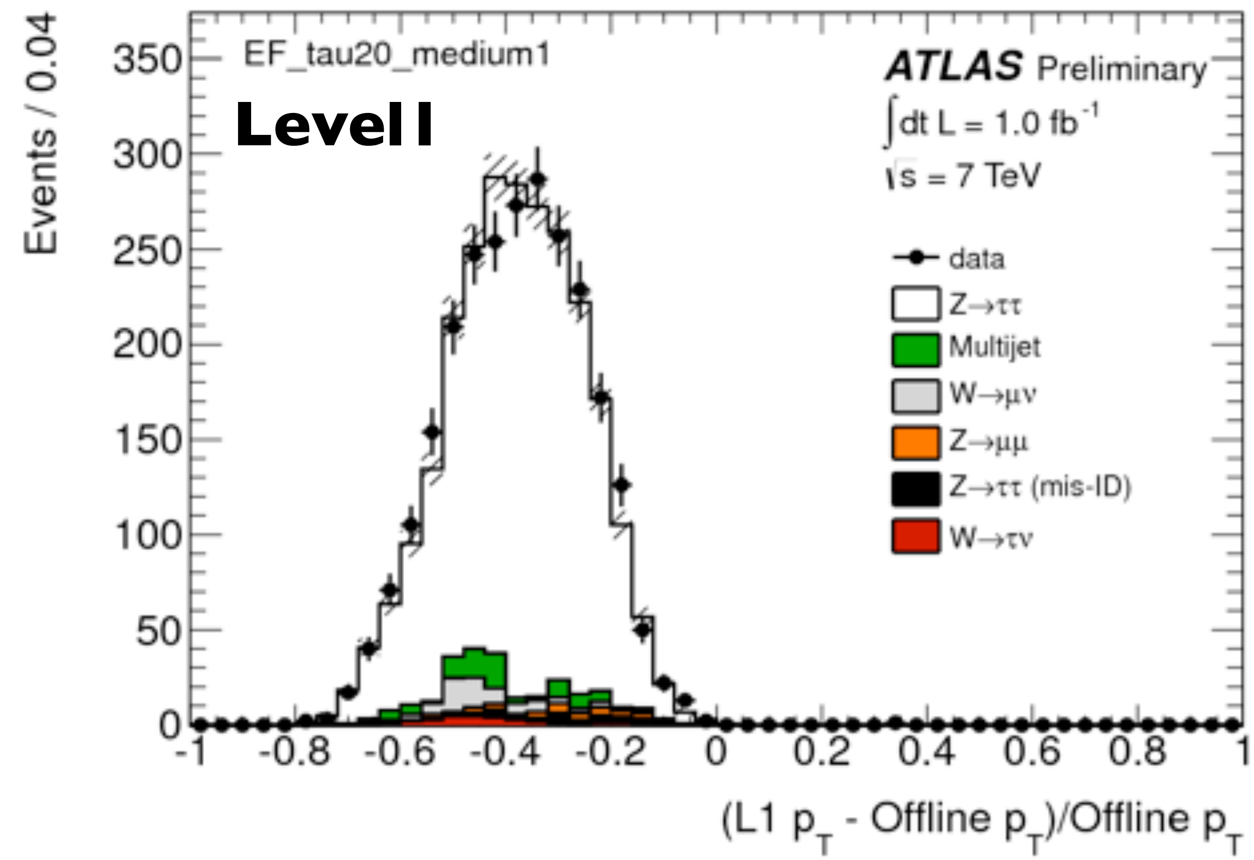
Event Filter - Tau Identification

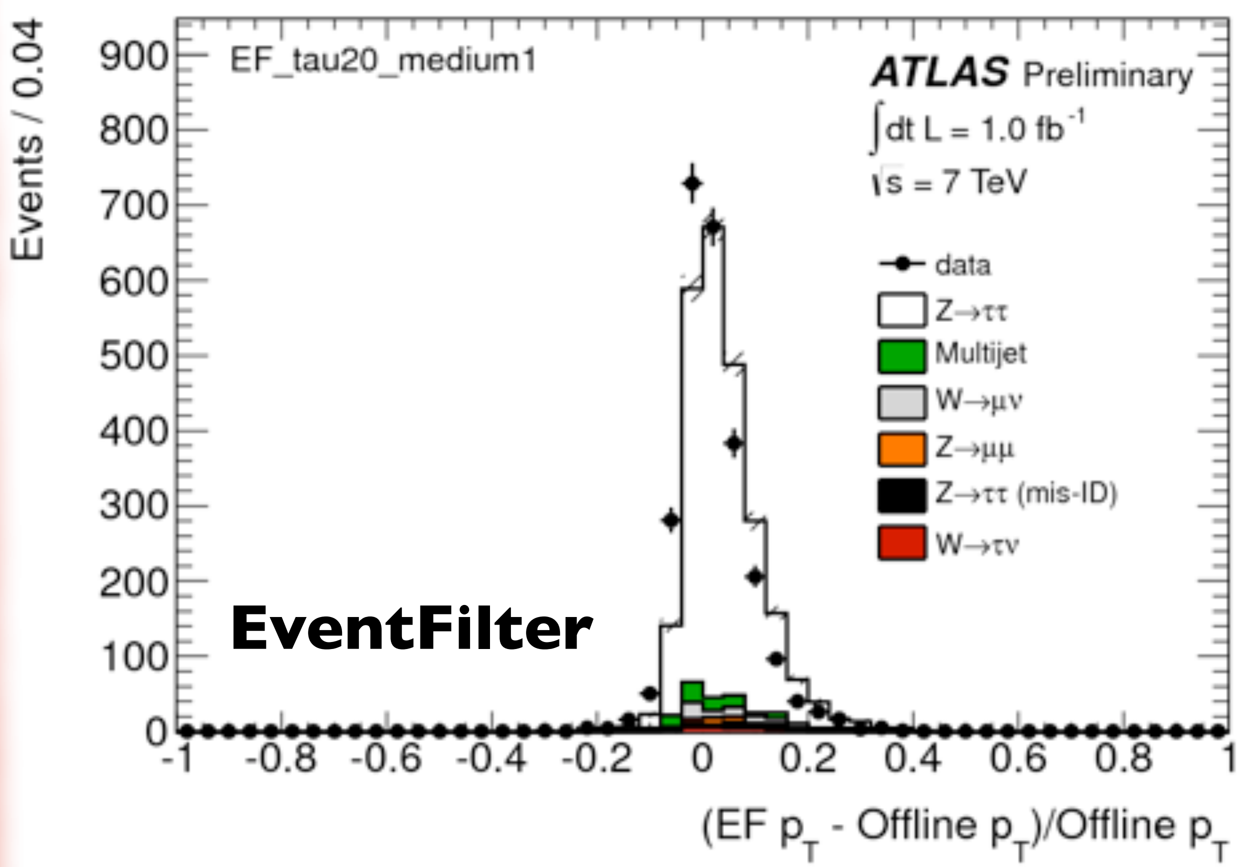


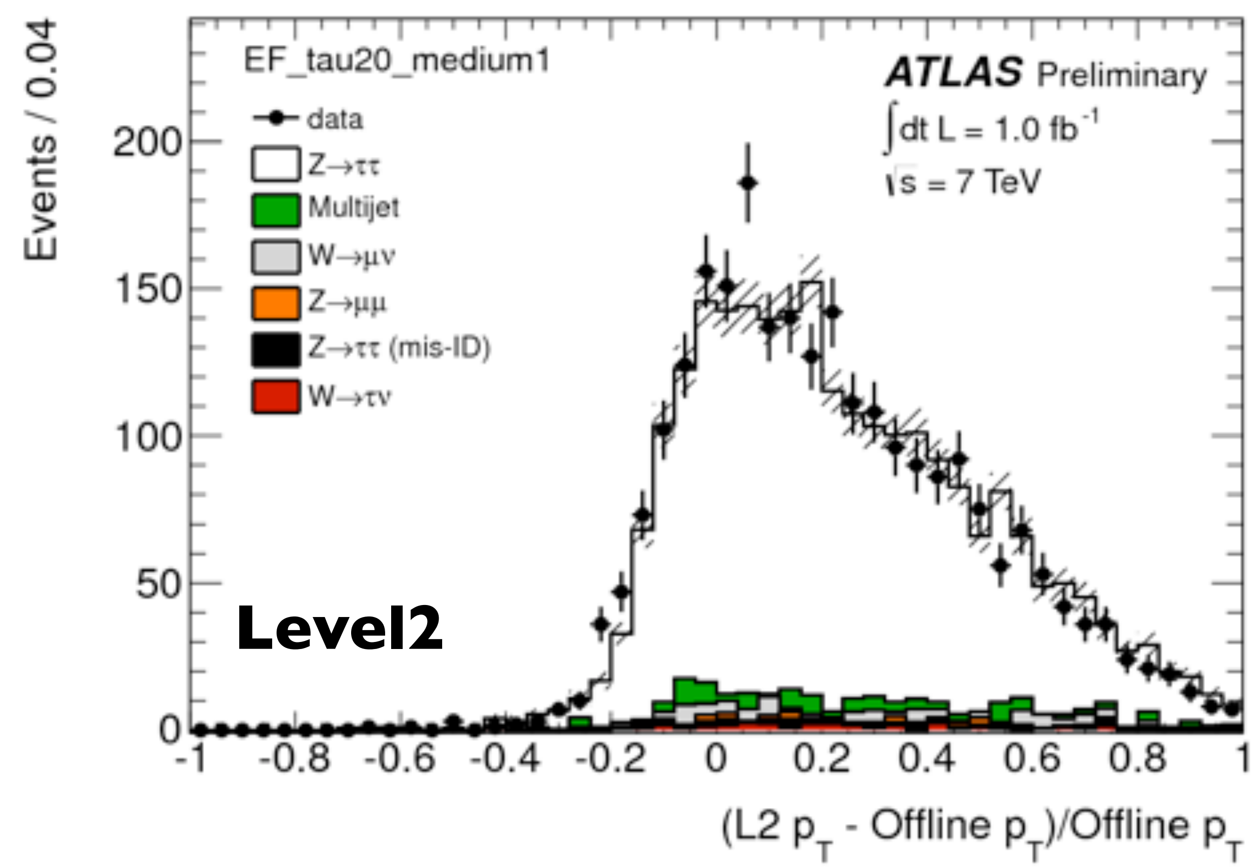
A less precise energy calibration applied at the EF causes the small shift of the trigger distributions with respect to offline.

Tau Trigger

p_T Resolution







Muon and Tau Triggers

- Evolution of muon, tau and muon-tau triggers in 2011 and 2012.

	Single muon trigger	Di-muon trigger
2011	EF_mu18[MG,_medium]	EF_2mu10_loose
2012	EF_mu24i_tight	EF_2mu13

	Single tau trigger	Di-tau trigger
2011	EF_tau100_medium EF_tau125_medium1	EF_tau29_medium1_tau20_medium1 EF_tau29T_medium1_tau20T_medium1
2012	EF_tau125_medium1	EF_tau29Ti_medium1_tau20Ti_medium1

	Muon-Tau trigger
2011	EF_tau16_loose_mu15 EF_tau20_medium_mu15
2012	EF_tau20_medium1_mu15