The CMS High Level Trigger

Daniele Trocino (*Northeastern University*)

on behalf of the CMS Collaboration

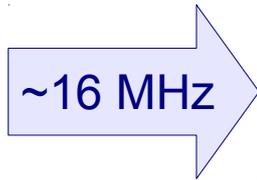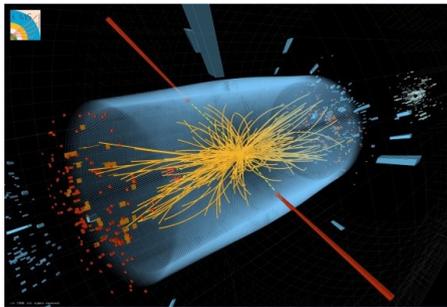20th International Conference on Computing in High Energy and Nuclear Physics (CHEP 2013)
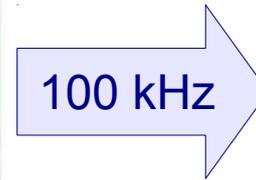
14-18 October 2013 – Amsterdam (NL)

The CMS Trigger

LHC

Level 1

High Level Trigger

~16 MHz

100 kHz

1 kHz
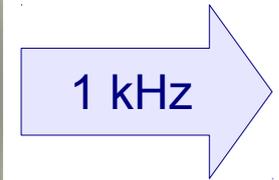
CMS was designed with a two-level trigger system

The CMS Trigger

LHC   ~16 MHz   **Level 1**   100 kHz   **High Level Trigger**   1 kHz
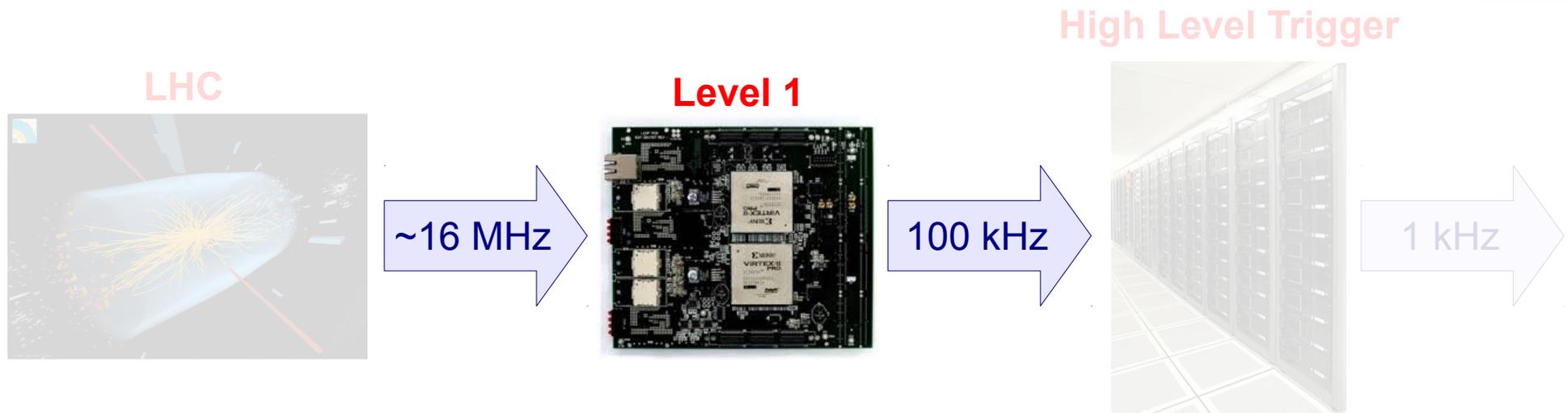
CMS was designed with a two-level trigger system

1. Level 1 (L1)

   ~16 MHz input rate (2012), maximum latency < 4 µs → must be fast

   - hardware-implemented on custom programmable processors

   - partial detector information: only muon spectrometer and calorimeters, limited granularity

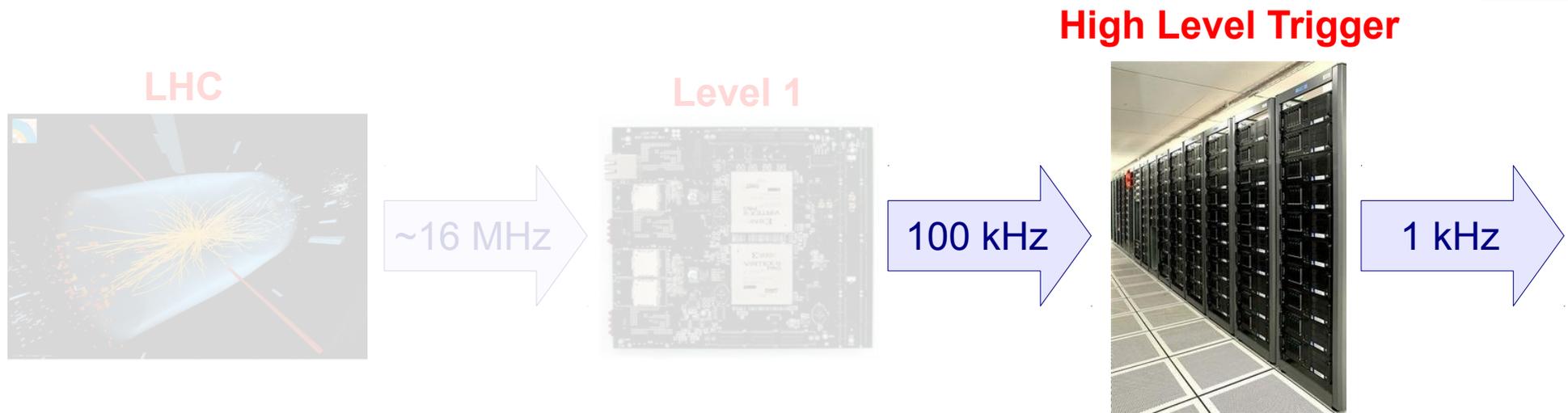   - maximum output rate allowed by CMS readout: 100 kHz

The CMS Trigger

LHC → ~16 MHz → Level 1 → 100 kHz → **High Level Trigger** → 1 kHz

CMS was designed with a two-level trigger system

2. High Level Trigger (HLT)

    100 kHz input from L1, average processing time 200 ms (2012)

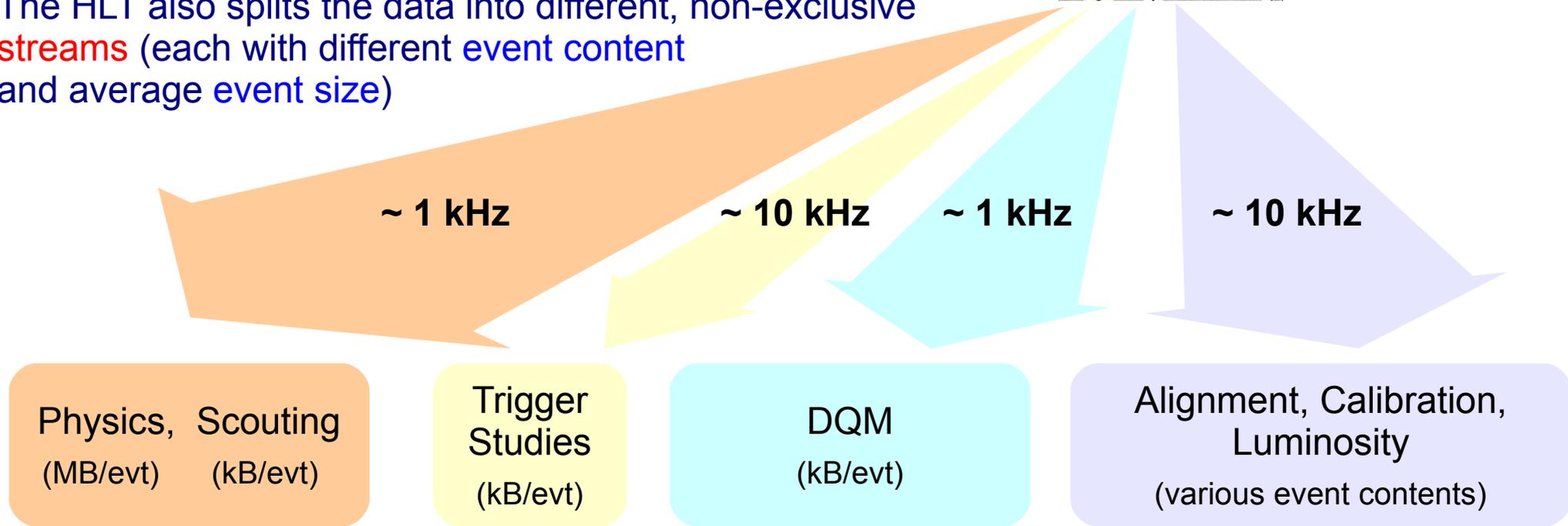- CMS opted for a fully-software implementation, running on commercial PCs (~13k CPU cores)

- same software used for offline reconstruction and analysis, optimized to cope with the tight time constraints of online selection → ~ 100 times faster

- information from all sub-detectors, including the tracker, with full granularity

- average output rate in 2012: 1 kHz (400 Hz core + 600 Hz parked)

The CMS Trigger

High Level Trigger

LHC

Level 1

~16 MHz

100 kHz

1 kHz

The HLT also splits the data into different, non-exclusive streams (each with different event content and average event size)

~ 1 kHz

~ 10 kHz

~ 1 kHz

~ 10 kHz

Physics,   Scouting
(MB/evt)   (kB/evt)

Trigger Studies
(kB/evt)

DQM
(kB/evt)

Alignment, Calibration, Luminosity
(various event contents)

Main Challenges for the HLT

The HLT needs a trade-off between physics acceptance, output rate, and CPU time

- High efficiency is ensured by using the same sophisticated reconstruction algorithms used in the offline analyses

- The HLT rate is kept under control by optimizing energy/momentum thresholds and identification criteria on the reconstructed objects, possibly modeled after offline analysis selections → reduce the rate while keeping high efficiency

- Several strategies are adopted to reduce the processing time

  - modular approach

    - an HLT menu is comprised of O(400) independent paths

    - each path is a sequence of reconstruction and filtering modules of increasing complexity → fastest objects are reconstructed first

    - if a filter fails, skip the rest of the path

  - regional reconstruction

    - read the detector only around L1 or higher-level candidates

   - essential especially for tracking: reconstruct tracks only inside jets or around leptons

L1 DECISION RAW DATA
↓
PROD
↓
FILT
↓
PROD
↓
FILT
↓
PROD
↓
FILT
↓
HLT DECISION
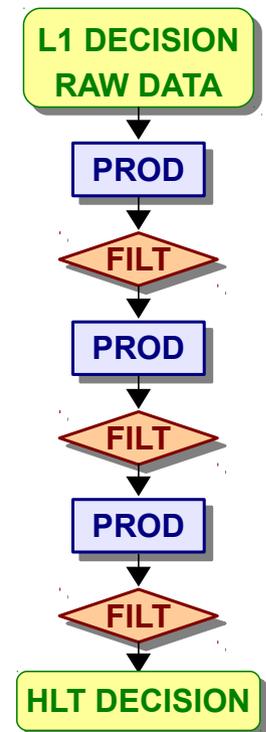
New Challenges...

- During 2011-12, the LHC instantaneous luminosity increased up to ~$7.5 \cdot 10^{33}$ cm^{-2}s^{-1}, pile-up reached ~ 35 interactions per bunch crossing

- Consequences on the processing time

  - CPU time/event increases linearly with pile-up → upgrades of the HLT farm needed over the years

  - current farm (13k cores w/ hyper-threading) allows up to ~200 ms/process → safe up to ~$8 \cdot 10^{33}$ cm^{-2}s^{-1}

HLT limit with 100 kHz L1 input

CMS Preliminary 2012

(Average processing time [ms] vs Average pile-up)

- Degradation in the performance of many triggers

  - jet and MET triggers have higher rate due to the additional tracks and deposits from pile-up

  - likewise, lepton isolation efficiency decreases with higher pile-up

  - multi-object triggers show higher rate due to combinatorial effects

  - higher luminosity increases the transparency losses in the electromagnetic calorimeter (ECAL), degrading electron and photon reconstruction
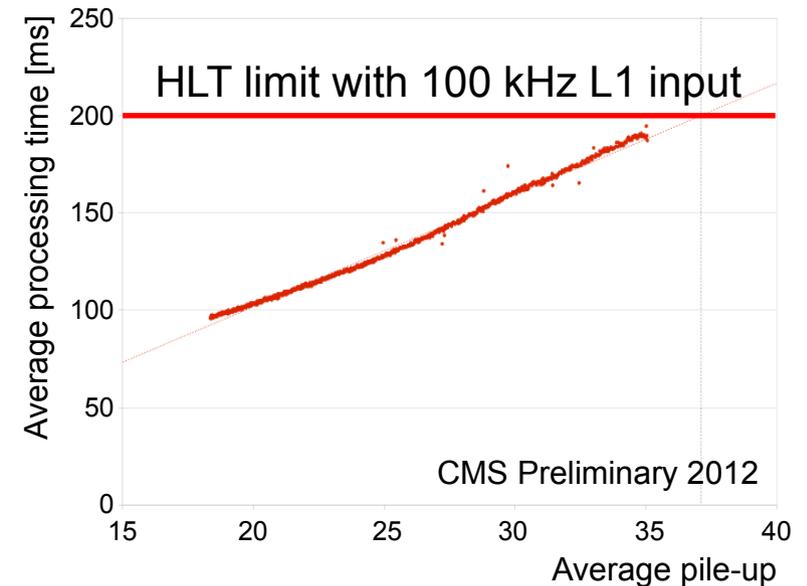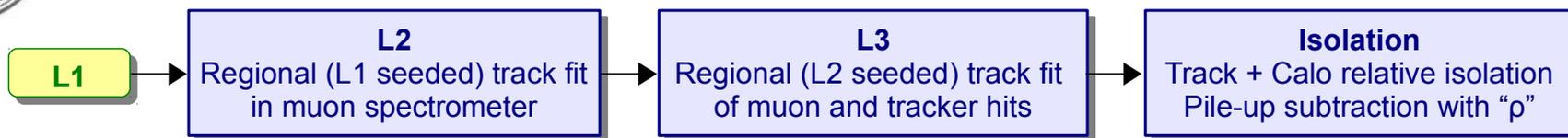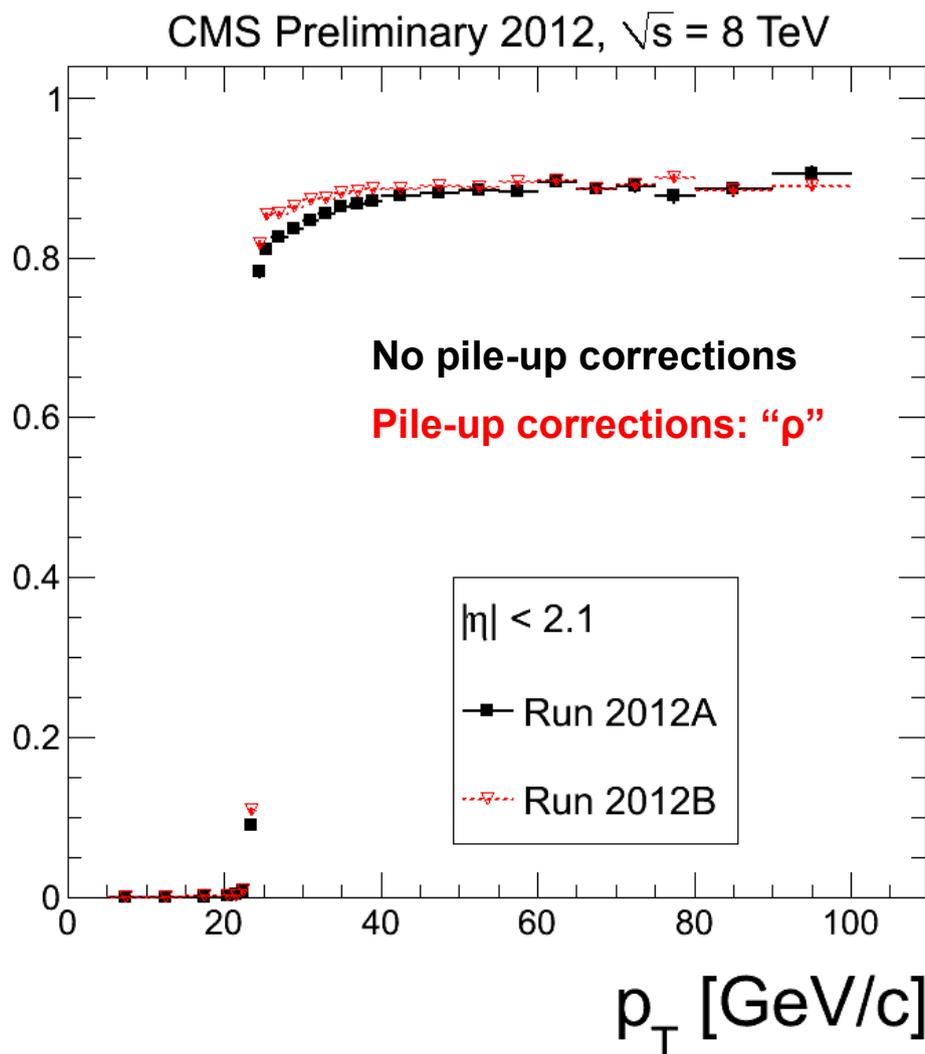
… and New Strategies

- Several solutions were adopted to mitigate the effects of luminosity and pile-up

    - Tuning of thresholds on object constituents → seeding of jet reconstruction

    - Vertex constraint on track-based objects → jet reconstruction, lepton isolation, less combinatorics in multi-object triggers

    - Subtraction of the average energy density "ρ" × area of the jet or isolation cone → jet reconstruction, lepton isolation

    - Corrections for ECAL crystals transparency loss, obtained from a dedicated laser monitoring system with ~ weekly frequency → electron, photon reconstruction

- Extended use of "particle-flow" (PF) reconstruction, as in offline

    - Reconstruction of the global collision event, identifying each particle individually with full detector information

    - Used in HLT for τ, jets and MET reconstruction

    - Advantages of PF reconstruction

        – better resolution

   – refined techniques for pile-up subtraction

Muon Triggers: Efficiency

L1	→	**L2** Regional (L1 seeded) track fit in muon spectrometer	→	**L3** Regional (L2 seeded) track fit of muon and tracker hits	→	**Isolation** Track + Calo relative isolation Pile-up subtraction with "ρ"

CMS Preliminary 2012, $\sqrt{s}$ = 8 TeV

No pile-up corrections
Pile-up corrections: "ρ"

$|\eta| < 2.1$

- Run 2012A
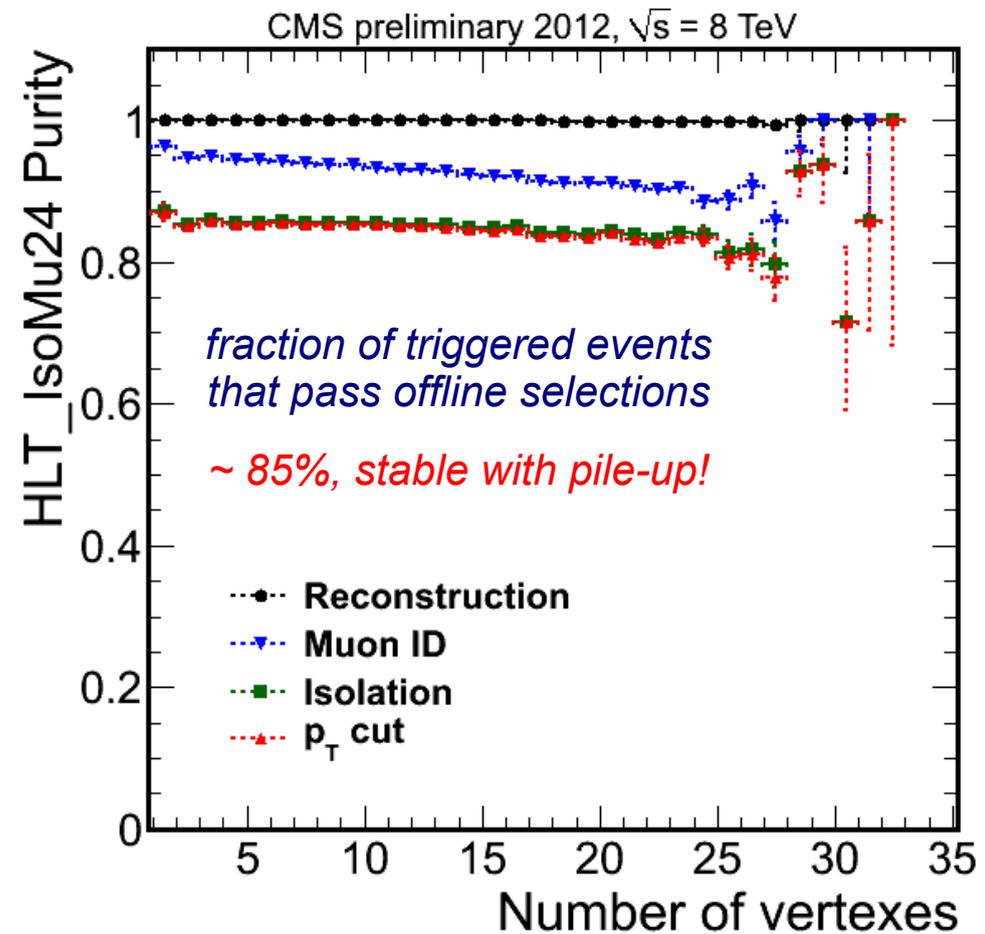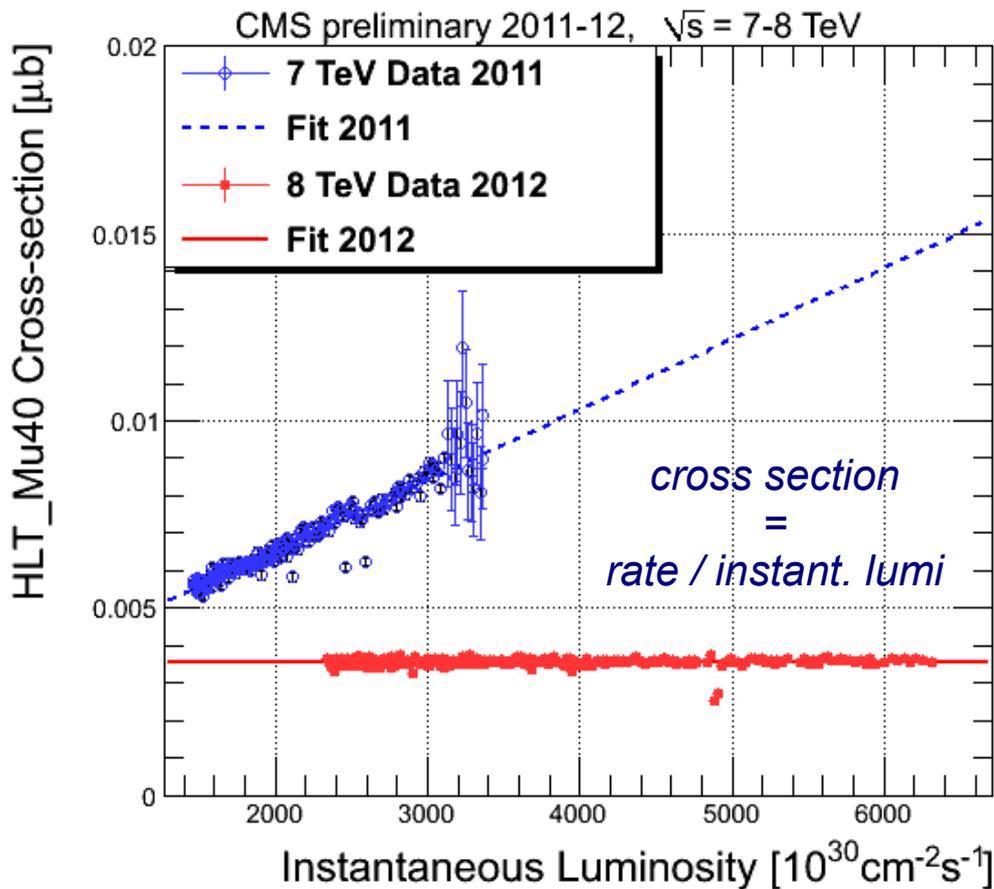- Run 2012B

- Isolated single-muon trigger, p_T > 24 GeV/c

  - plateau ~ 90%

- No pile-up corrections vs pile-up corrections

  - with corrections, sharper turn-on curve

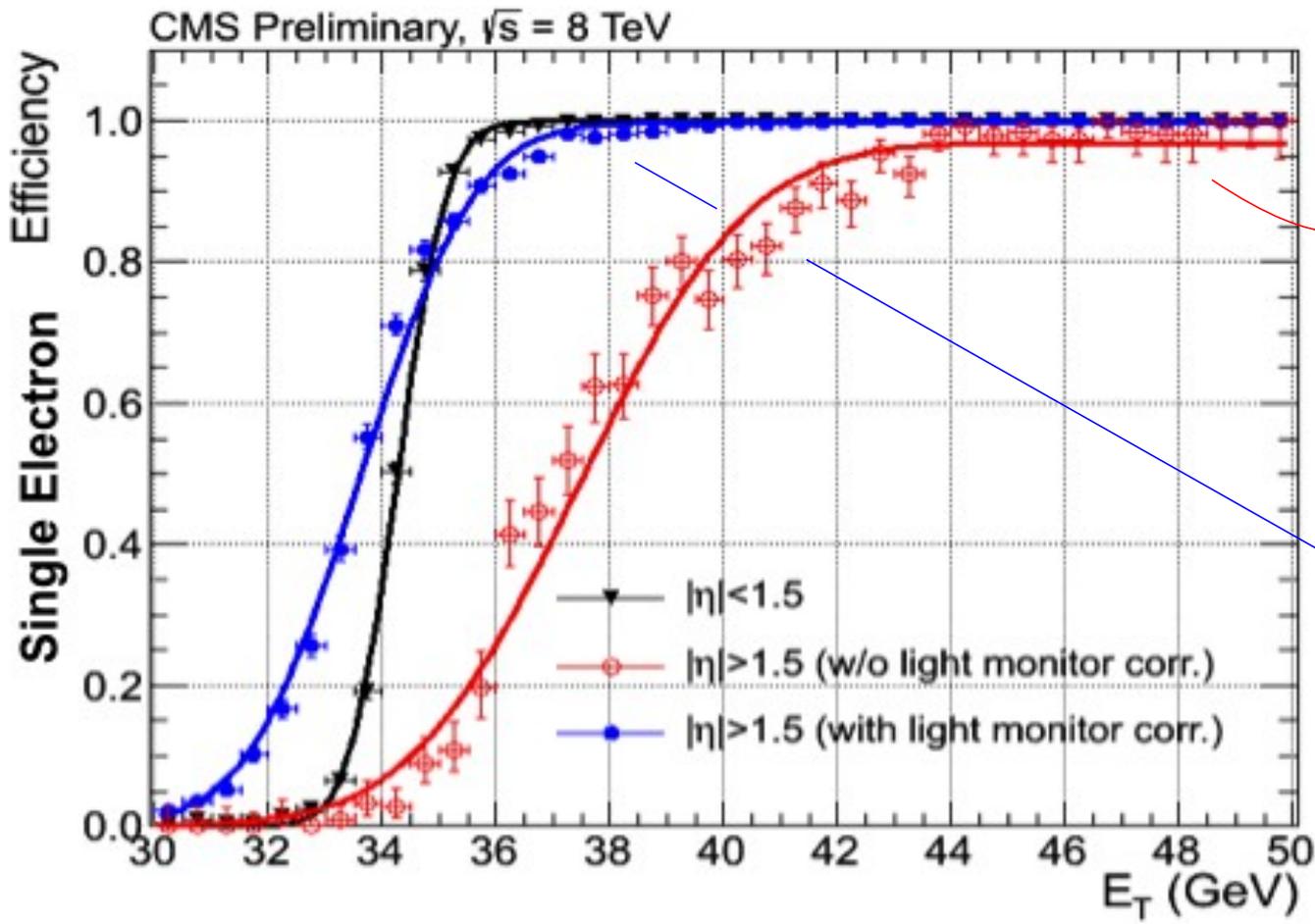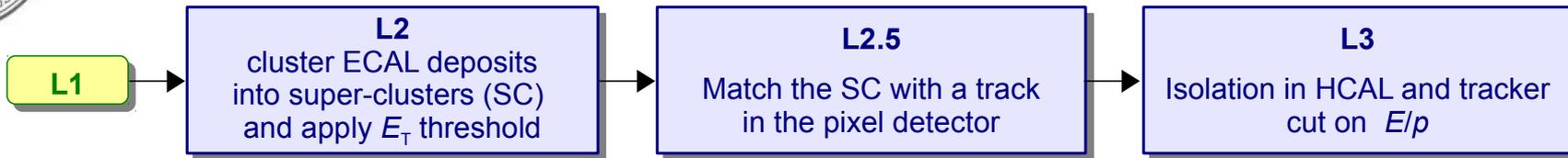# Muon Triggers: Cross Section, Purity
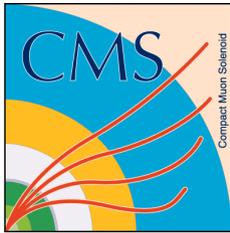
2011. muon trigger rates exhibited a non-linear increase with luminosity (⇒ increasing cross sections), due to fake muons at high pile-up

2012. tighter HLT muon identification, with cuts on impact parameters and track quality
→ constant cross section restored, high purity (~ 85%)

Electron Triggers

L1 →

L2
cluster ECAL deposits into super-clusters (SC) and apply E_T threshold

→

L2.5
Match the SC with a track in the pixel detector

→

L3
Isolation in HCAL and tracker cut on E/p

CMS Preliminary, $\sqrt{s}$ = 8 TeV

- $|\eta|<1.5$
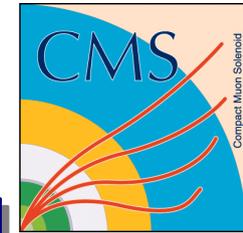- $|\eta|>1.5$ (w/o light monitor corr.)
- $|\eta|>1.5$ (with light monitor corr.)

- Irradiation reduces the transparency of ECAL crystals

  → electron reconstruction degrades especially in the endcaps

- A sophisticated laser system monitors the transparency of each crystal and allows for the measurement of energy corrections

  - in 2012, corrections for HLT reco (endcaps only) were updated weekly

  → sharper turn-on and higher plateau efficiency
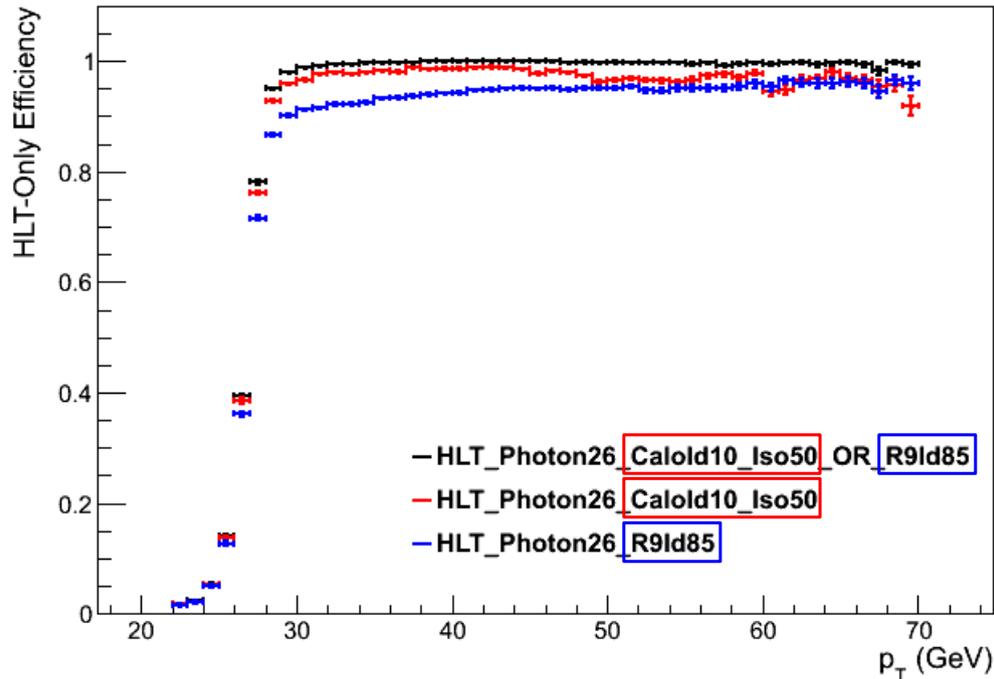
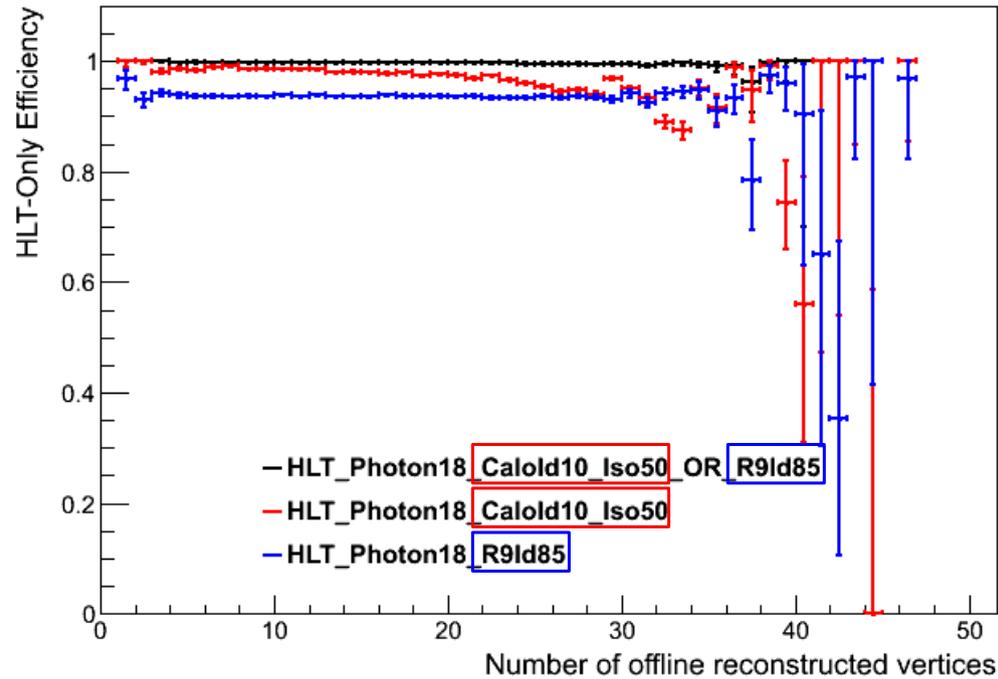 → keep low energy thresholds

Photon Triggers

L1 → **L2**
cluster ECAL deposits into super-clusters (SC) and apply E_T threshold → **L3**
Isolation in HCAL and tracker

- High-E_T photon and diphoton trigger paths can use different identification criteria, based on isolation, cluster shape, HCAL/ECAL energies, etc.

- Many physics searches (e.g. $H \to \gamma\gamma$) use the OR of all these paths, to ensure maximum efficiency and stability against pile-up
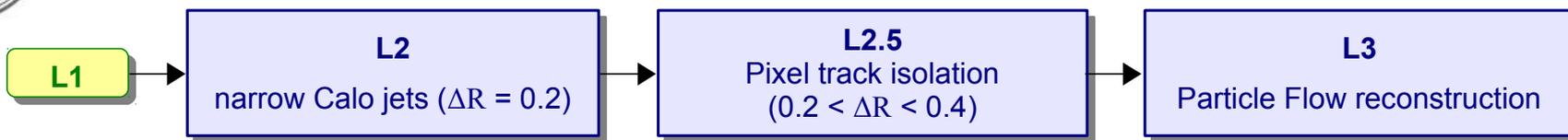

CMS Preliminary 2012, $\sqrt{s}$ = 8 TeV

- HLT_Photon26_CaloId10_Iso50_OR_R9Id85
- HLT_Photon26_CaloId10_Iso50
- HLT_Photon26_R9Id85

CMS Preliminary 2012, $\sqrt{s}$ = 8 TeV

- HLT_Photon18_CaloId10_Iso50_OR_R9Id85
- HLT_Photon18_CaloId10_Iso50
- HLT_Photon18_R9Id85

Tau Triggers

L1 → **L2** narrow Calo jets (ΔR = 0.2) → **L2.5** Pixel track isolation (0.2 < ΔR < 0.4) → **L3** Particle Flow reconstruction
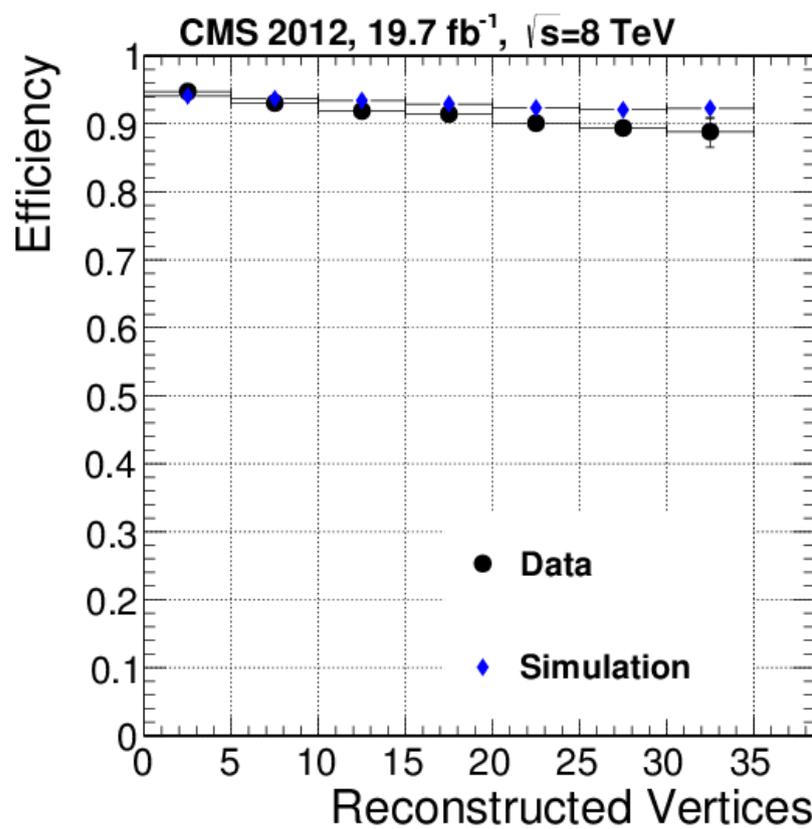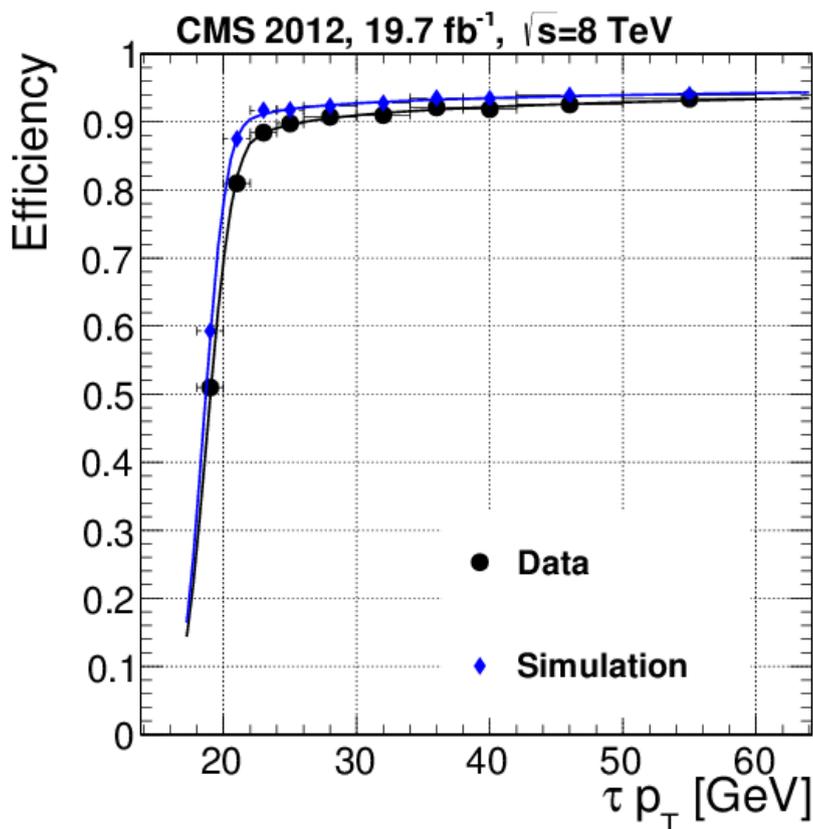
- Rather sharp turn-on, plateau > 90%, mild pile-up dependence

- In analyses such as $H \rightarrow \tau\tau$, triggers combine a hadronic τ with a μ or e + MET → efficiencies as high as 90% can be reached

Jet, MET Triggers

> **Calo Jets**
> Iterative cone algorithm in calorimeters
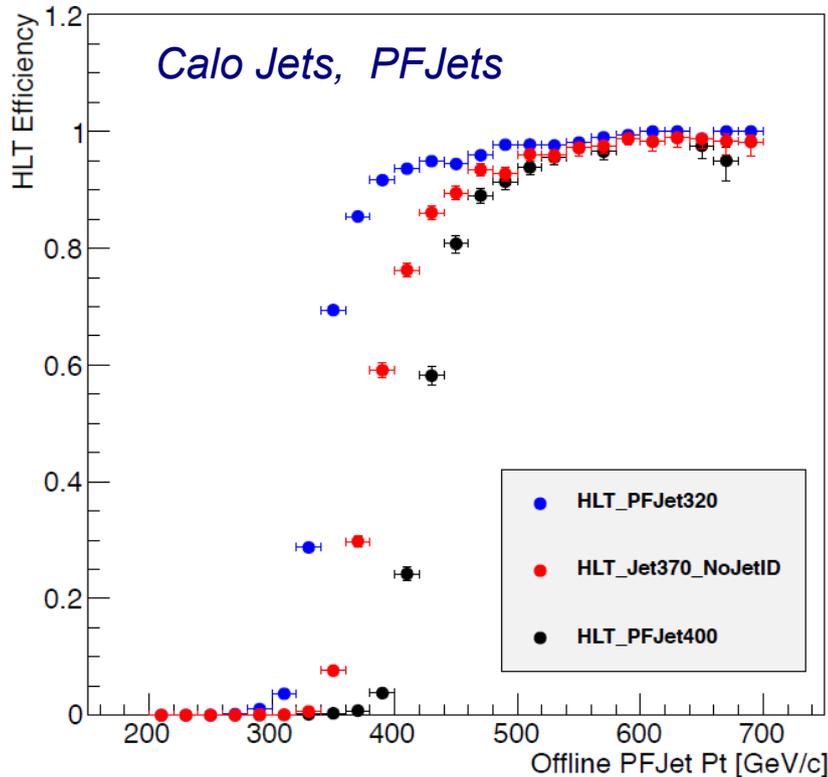> energy corrections, pile-up subtraction

> **MET**
> Vector sum of transverse energy
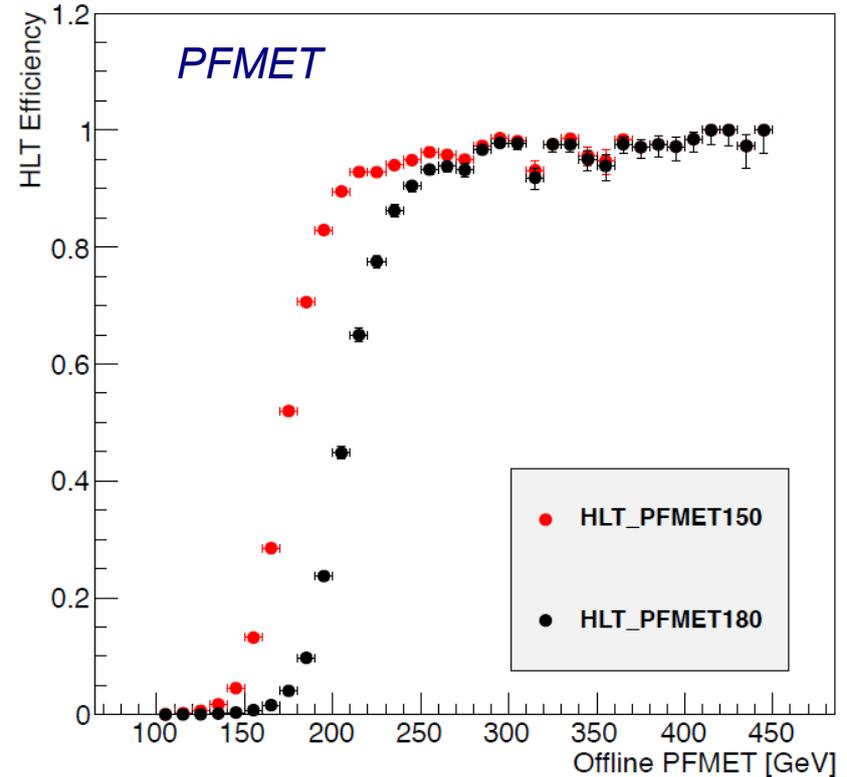> deposits in calorimeters, incl. muons

OR

> **PFJets, PFMET**
> From global event description
> (Particle Flow)

- PFJets, PFMET have better resolutions than CaloJets, MET, especially at low energy, where the tracker has better resolution than the calorimeters

Data Parking

- During 2012, besides ~400 Hz of data from "core" physics triggers,
  CMS collected ~600 Hz of extra data for future extension of the physics program

  - core data are promptly reconstructed at T0

  - additional raw data are temporarily "parked" at T0 and T1,
    to be processed when computing resources become available

    – processed during the current LHC shutdown

    – 5% was promptly reconstructed for monitoring

- Parked triggers can be

  - looser versions of core triggers
    → more statistics for precision SM measurements

  - new triggers with small overlap with core
    → for new physics searches

- Examples

  - Vector Boson Fusion: $M(jj) > 650$ GeV/c^2, $\Delta\eta(jj) > 3.5$

 - HT: for SUSY searches

  - MuOnia: low $M(\mu\mu)$
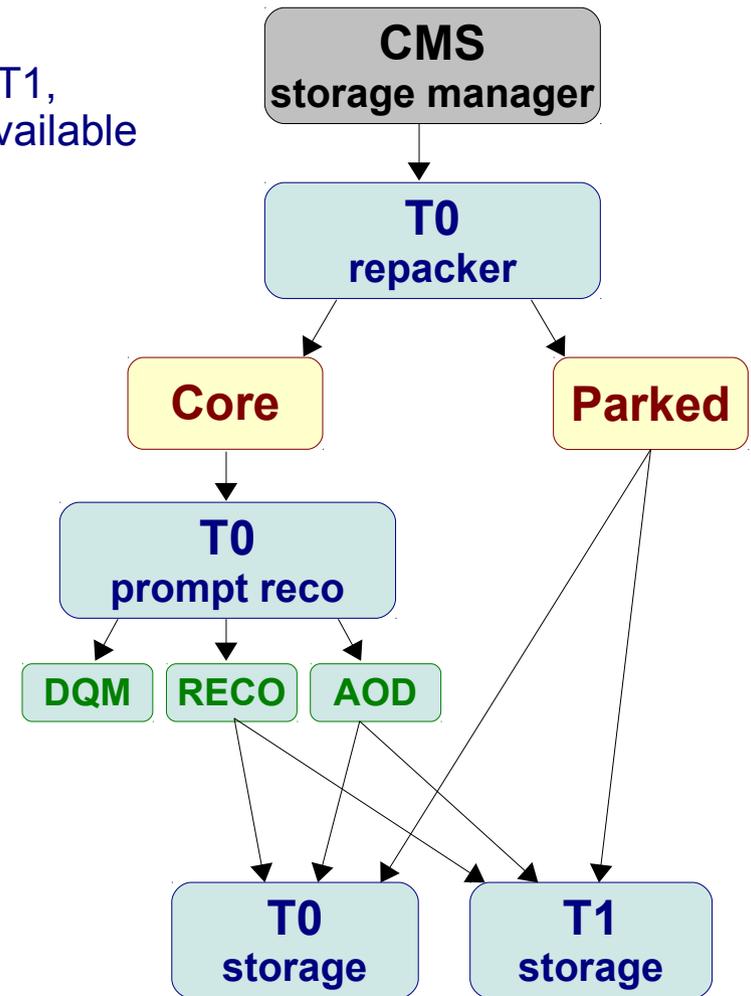
Data Scouting

- Special strategy to explore kinematic regions normally excluded from data taking due to bandwidth limitation

  - low trigger thresholds ⇒ high rate, $O(\text{kHz})$

    - e.g. $H_T > 250$ GeV for new physics searches in hadronic final states at low p_T / H_T

  - reduced event content from HLT reco, $O(\text{kB})$; no raw data, no offline reconstruction

    - e.g. store only HLT calo-jets

  ➔ bandwidth under control

  - Analysis of HLT objects in DQM-like framework

  - If something interesting shows up in "scouting", it's possible to change the core physics triggers or parked triggers, so to include the region in question


data scouting extended the dijets searches below 1 TeV
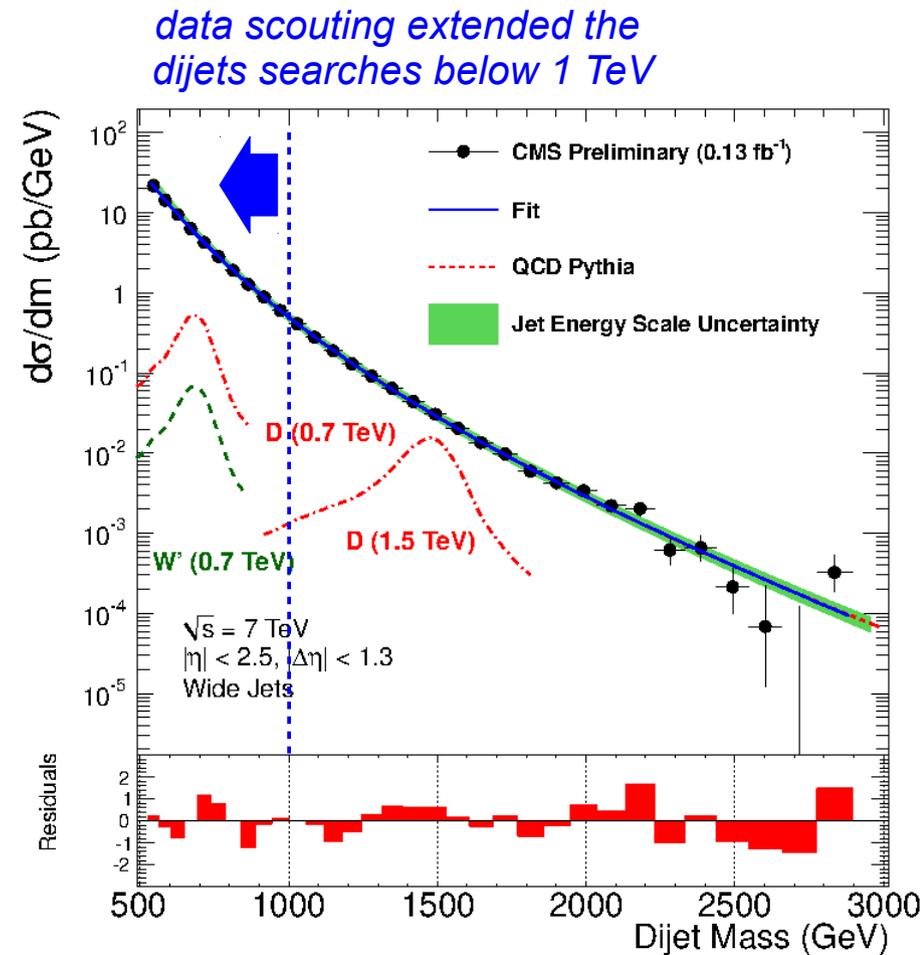
Summary: Example of HLT Menu

| Object	Threshold [GeV]	Physics
Single muon	40	Searches
Single isolated muon	24	SM
Double muon	(17,8) [13,8 parked]	SM / Higgs
Single electron	80	Searches
Single isolated electron	27	SM
Double electron	(17,8)	SM / Higgs
Single photon	150	Searches
Double photon	(36,22)	Higgs
Muon + electron	(17,8), (5,5,8)	SM / Higgs
Single PFJet	320	SM
QuadJet	80 [45 parked]	SM
Six Jet	45, (4×60, 2×20)	Searches
MET	120 [80 parked]	Searches
HT	750	Searches

Some of the unprescaled HLT paths used in 2012

2012 HLT rates vs instant. luminosity for core, parked, and full menu
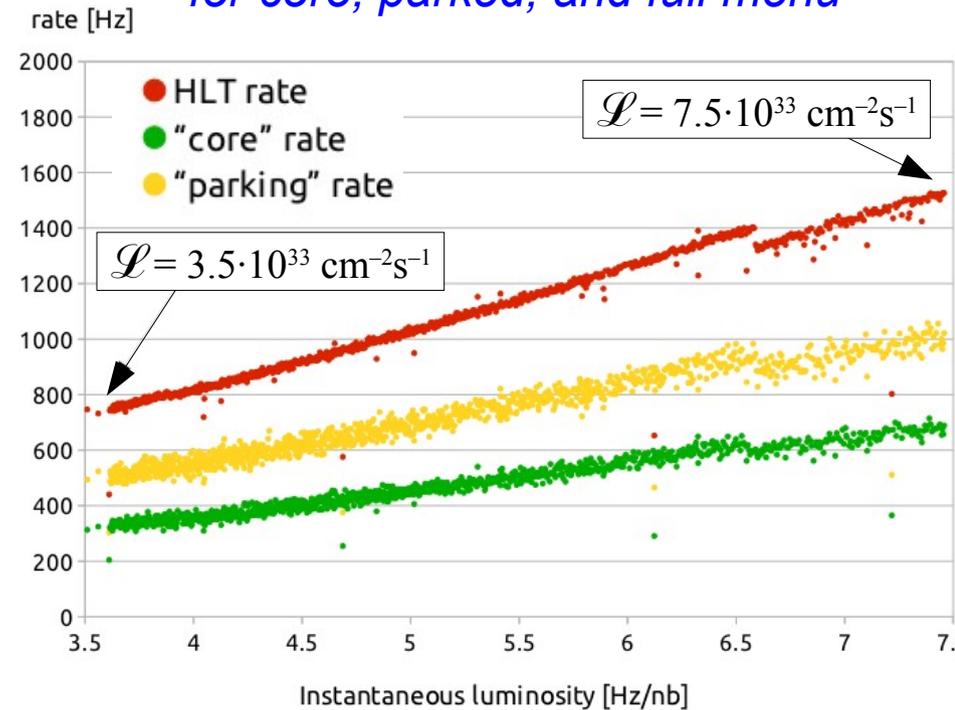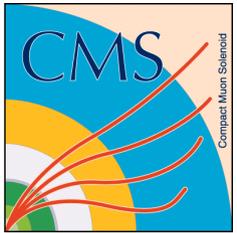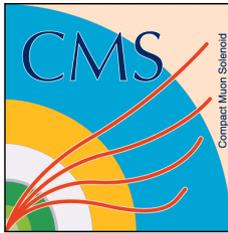
Conclusions
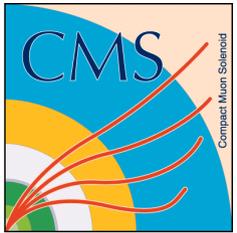
- The CMS High Level Trigger has shown excellent performance

  - capability to select a great variety of physics signals

  - strategies to explore and record collision events even beyond its standard rate constraints
    → "scouting" and "parking"

  - flexibility to adapt to the continuously evolving LHC luminosity and pile-up conditions

- The CMS HLT flexibility is ensured by its design

  - fully software-implemented

  - possibility to exploit the same sophisticated algorithms used in offline analyses

  - these include specific treatments for high pile-up and luminosity
    → remarkable stability with pile-up

  - all HLT objects show high efficiencies, sharp turn-on curves, stable rates and cross sections

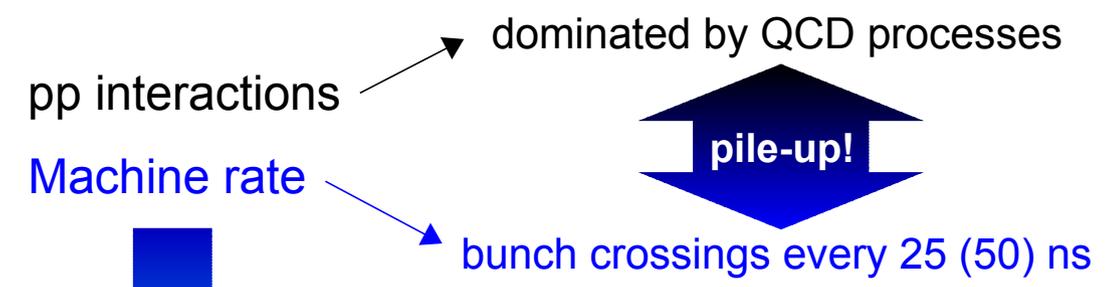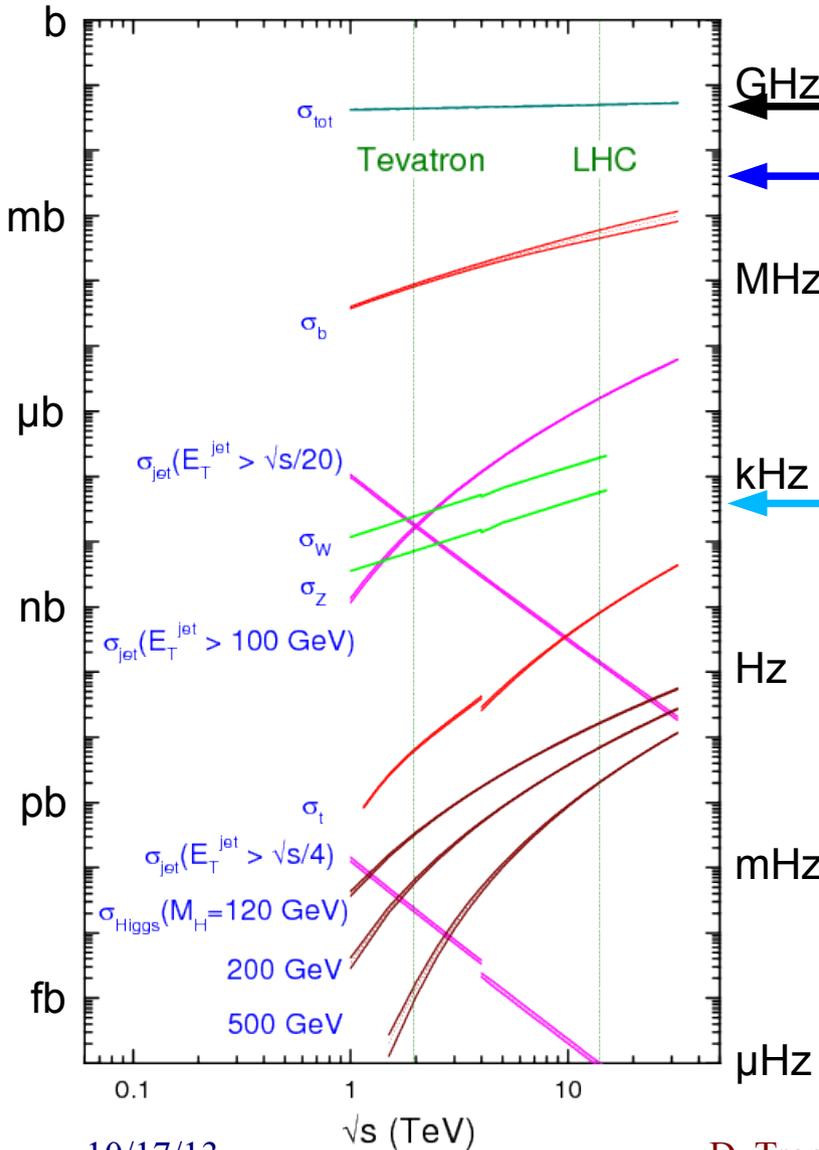 - the system is easily expandable in view of the upcoming upgrades

Backup

D. Trocino – CHEP 2013, Amsterdam (NL)

Why a Trigger?

σ [pp̄]

Rate @
$\mathcal{L} = 10^{34}$ **cm^{-2}s^{-1}**

Reduce the LHC collision rate to a manageable level

dominated by QCD processes

pp interactions ← GHz

pile-up!

Machine rate ← (blue arrow)

bunch crossings every 25 (50) ns

Trigger selection

Acceptable rate ← kHz

- Bandwidth limited by storage and analysis sustainability

- Physics processes of interest typically have rates of $\mathcal{O}(10\ Hz)$ or below

Physics-driven selection!