Mitigation of Direct APD signals in the CMS Barrel Electromagnetic Calorimeter

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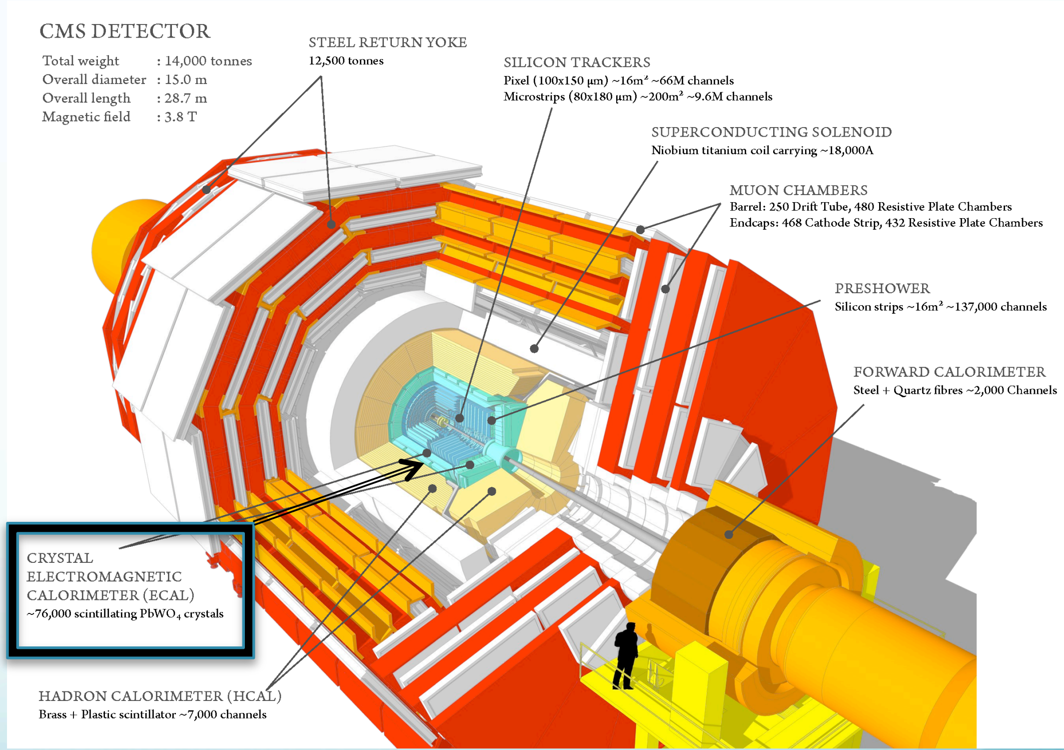
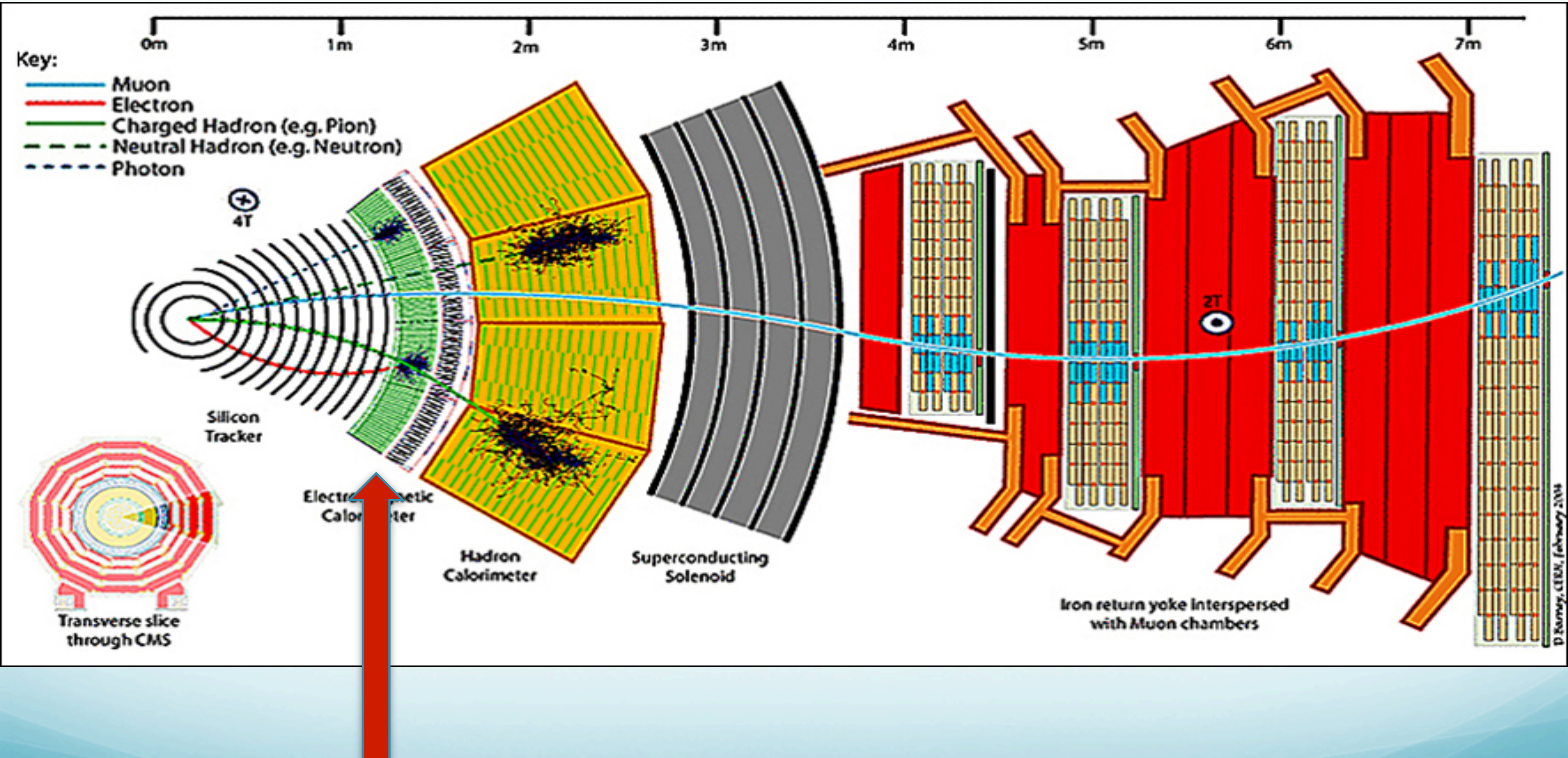
Outline

- Collider & Detector
- What are direct APD signals
- Mitigation of APD signals
  - Offline and online rejection algorithms
- Optimization
  - 2017 Optimization Study
  - Effect of pedestals
  - Phase II

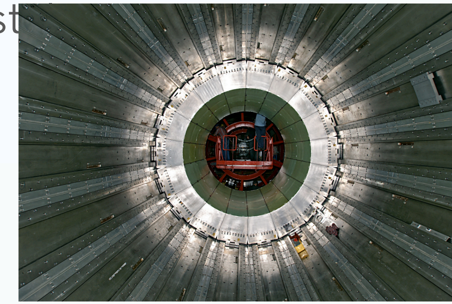




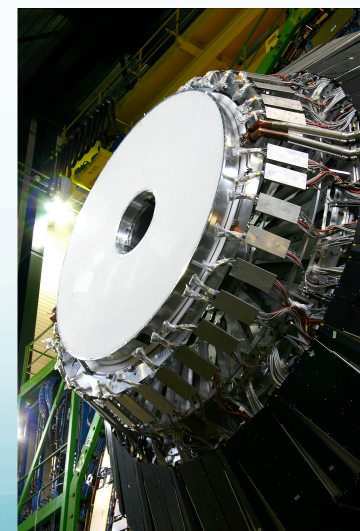
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electr etic
Calor ter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS

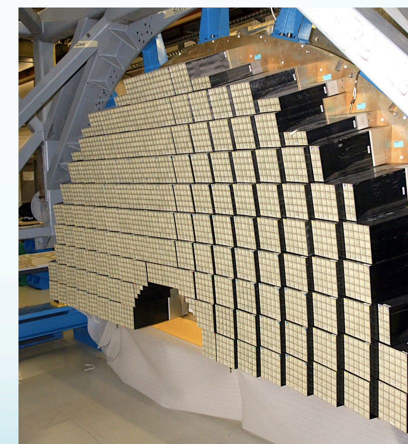
CMS ECAL Geometry

- Consists of 75,848 lead tungstate ($PbWO_4$) cryst



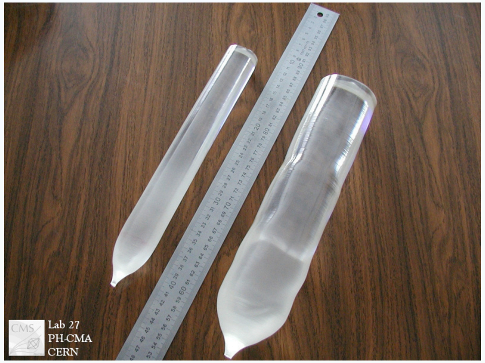
- Organized into 3 sections
  - Barrel (EB)
    - 36 supermodules of 1700 crystals each
    - Total of 61200 crystals
    - Covers $|\eta| < 1.48$
  - Endcap (EE)
    - 4 half-disk Dees of 3662 crystals
    - Total of 14648 crystals
    - Covers $1.48 < |\eta| < 3.0$
  - Preshower (ES)
    - Two Lead/Si planes
    - Total of 137,216 Si strips ($1.9*61\ mm^2$)
    - Covers $1.65 < |\eta| < 2.6$





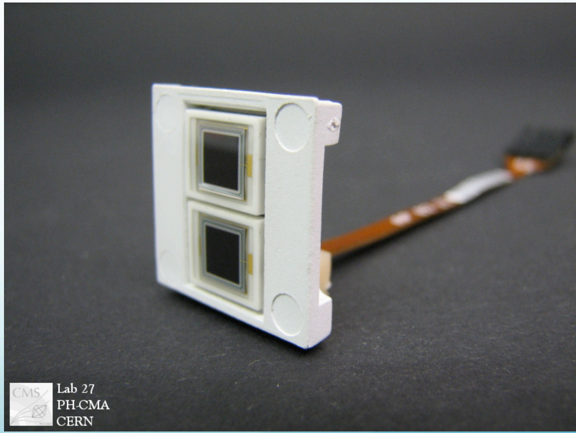
ECAL Crystals

- Compact:
  - Dense
  - Short radiation length (0.89 cm)
  - Small Moliere radius (2.2 cm)
- Scintillation time ~ 25 ns
- Difficulties
  - Low light production
  - Temperature dependent light production
  - Suffer some radiation damage
- Photodiodes glued to the ends



The Photodetectors

- Vacuum Phototriodes (VPTs) in the ECAL Endcaps
- Avalanche Photodiodes (APDs) in the ECAL Barrel
  - Hamamatsu type S8148 reverse structure avalanche photodiodes
  - Each has an active area of $5 \times 5\ mm^2$
  - A pair is mounted in a capsule which is glued to the crystal
  - Operated at gain 50 and read out in parallel
  - Internal construction includes a 5μm thick ‘high gain’ silicon layer



ECAL & CMS Trigger

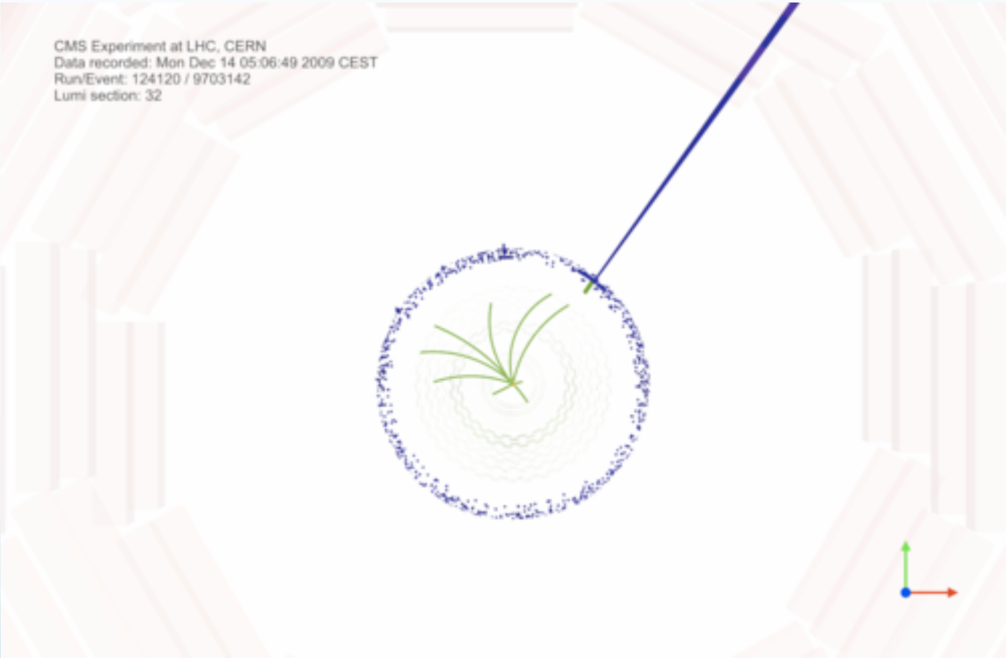
- Trigger Tower (TT)
  - 5×5 array of crystals
- Trigger Primitives (TPs)
  - TPs are transverse energy sums formed on-detector from TTs
  - TPs are formed on-detector.
  - Used to form electron/photon, jet, tau candidates, and energy sums
  - Sent to Level-1 (L1) trigger at 40 MHz
    - Total L1 trigger bandwidth is 100 kHz

ECAL Front End Card → ECAL Trigger Concentrator Card → Level-1 Calorimeter trigger cards

TP path summary

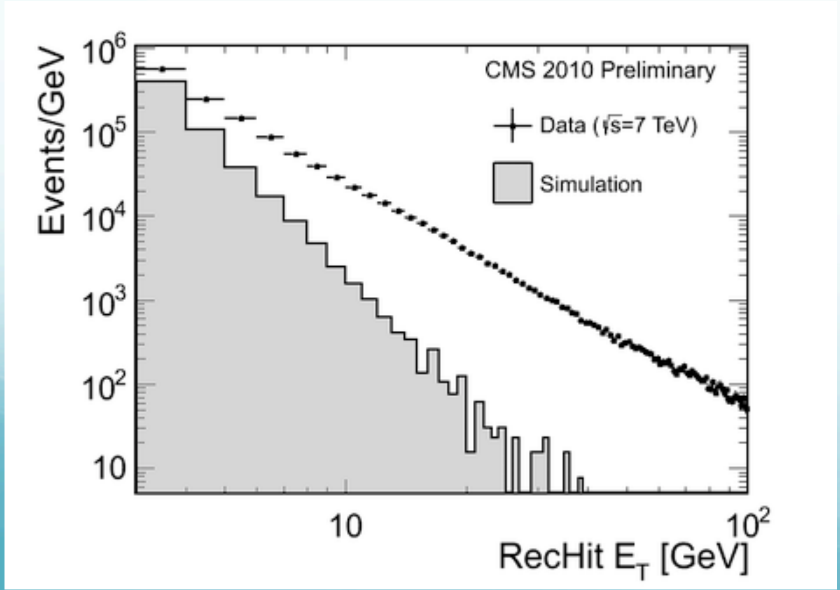
Direct APD Signals

- Caused by particles striking the APDs and occasionally interacting and causing large anomalous signals through direct ionization of the silicon
- Also called 'spikes'
- Spike rate proportional to collision rate.
- Can be detected online or offline
- Algorithms designed to detect them are also known as 'Spike Killer' (SK)
- Trigger rates depend on performance of online spike rejection algorithm



Spike Energy Spectrum

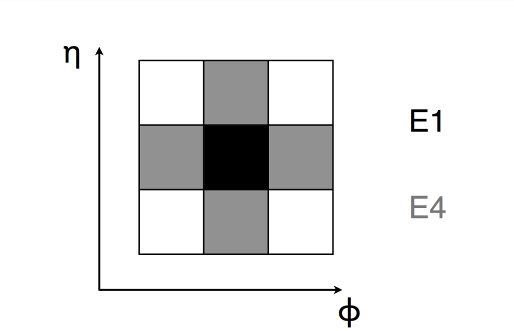
- ECAL spikes often satisfy the conditions for triggering electrons and photons in CMS
- Spike contamination grows with energy
- To maintain low unprescaled electron/photon triggers, spikes must be identified and removed

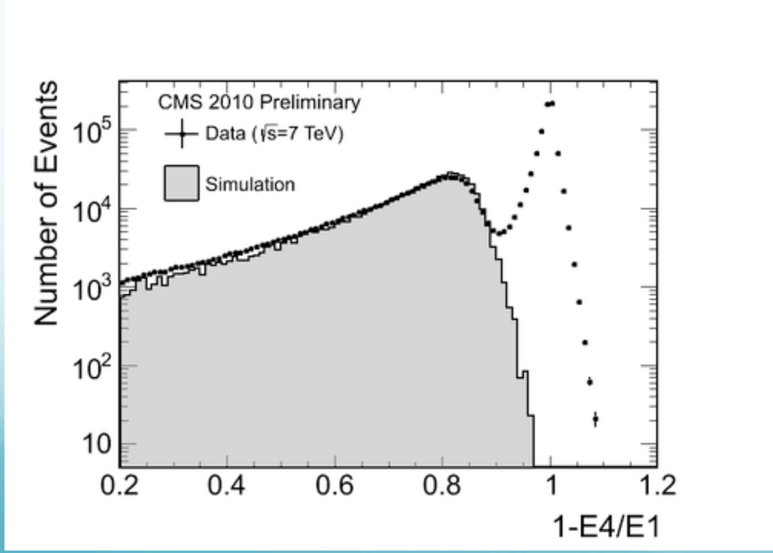


Distribution of the transverse energy of the highest energy signals for data and MC
Both distributions are normalized to the same number of events with E_T>3 GeV and 1-E4/E1<0.9

Offline Rejection: Swiss Cross

- Spikes deposit energy in a single channel
- Swiss Cross Variable (1-E4/E1)
  - EM showers have ~80% of their energy in the central crystal.
  - A selection of 0.95 is applied

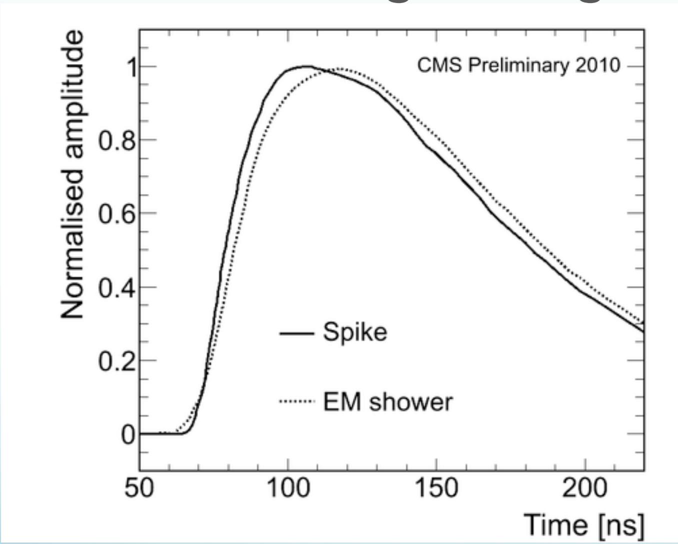




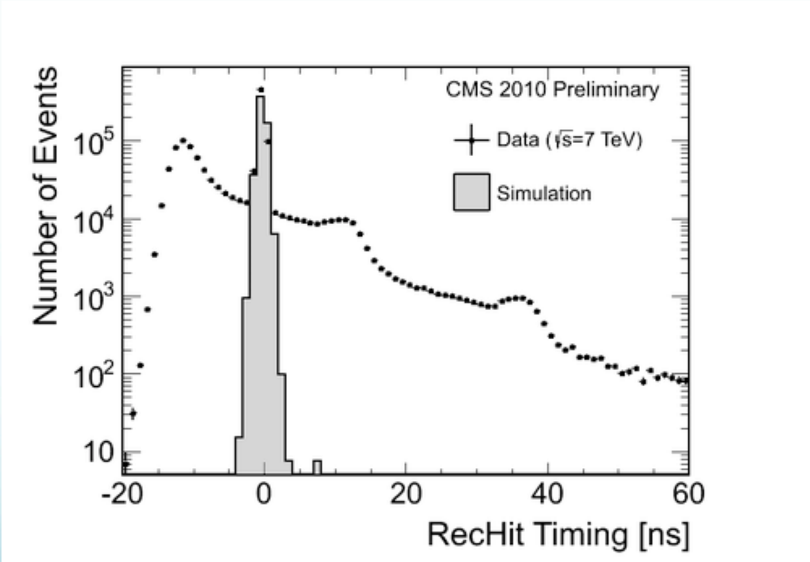
The distribution of the "Swiss-cross" variable (1 – E4/E1) for data and Monte Carlo minimum bias events

Offline Rejection: Timing

- Spikes lack the scintillation response time
- Appear early when the pulse is fitted to extract timing
- Selection of ±3ns on signal timing is applied (timing resolution <1ns for electromagnetic signals with energy > 1 GeV)



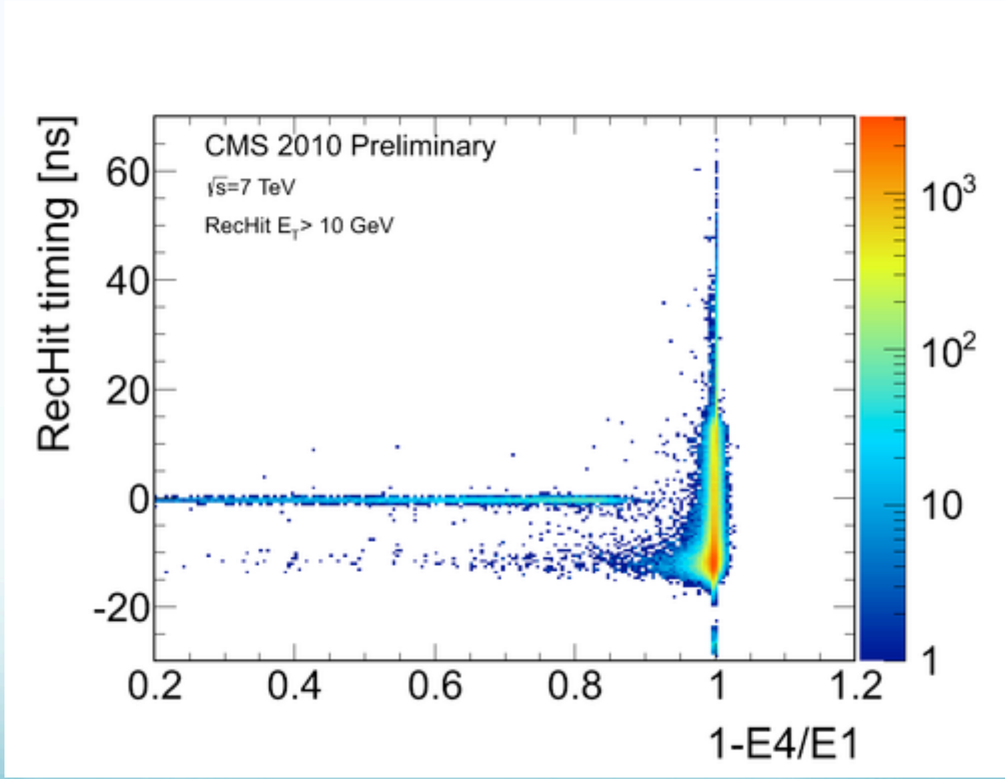
Average ECAL Pulse shapes for spike and EM signals, measured on data



Distribution of the reconstructed time of the highest energy signals for data and MC

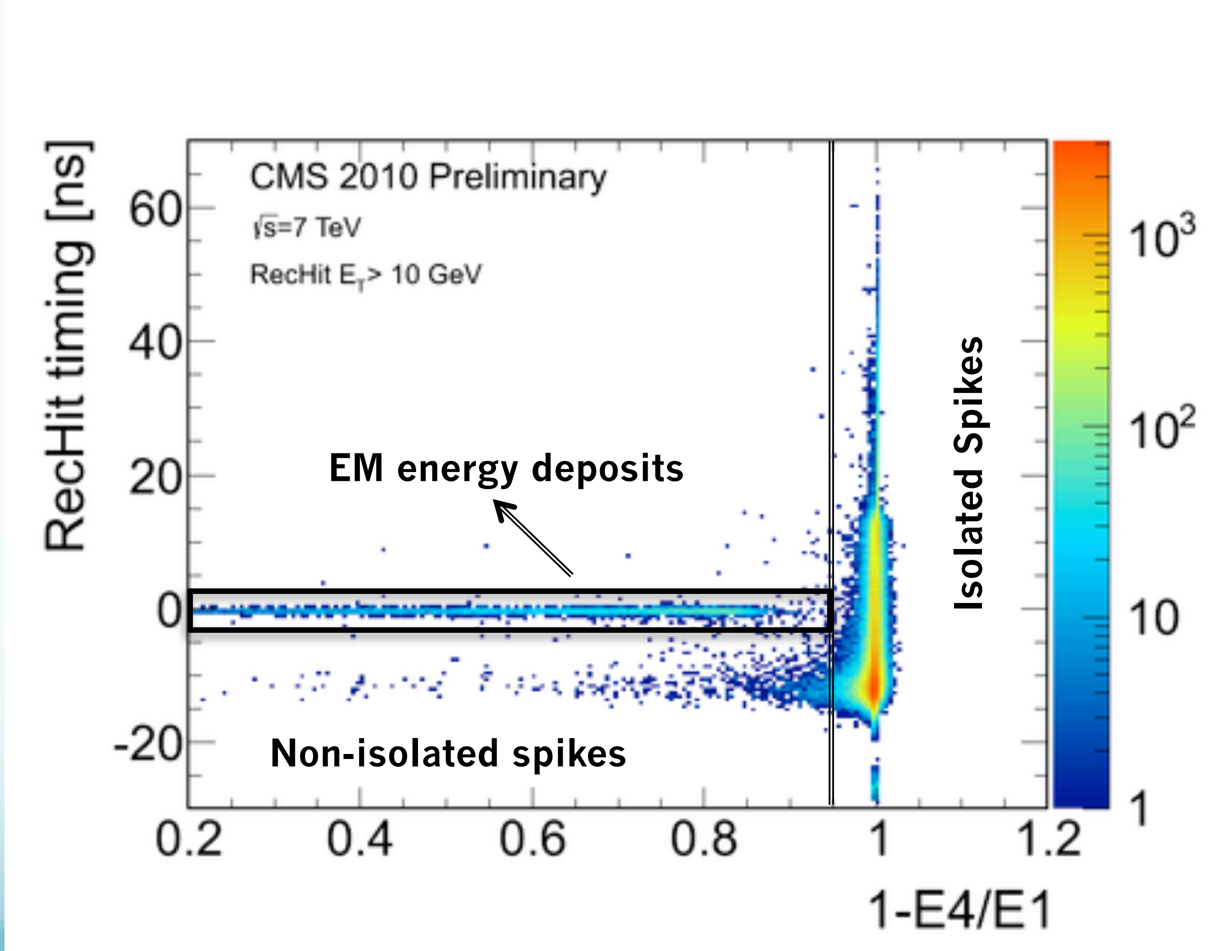
Efficiencies of Offline Rejection

- Signal Timing vs Swiss-cross
- Together were measured to reject >99.9% of spikes with E_T>10 GeV.



2D distribution of signal timing vs Swiss-cross variable for CMS Data

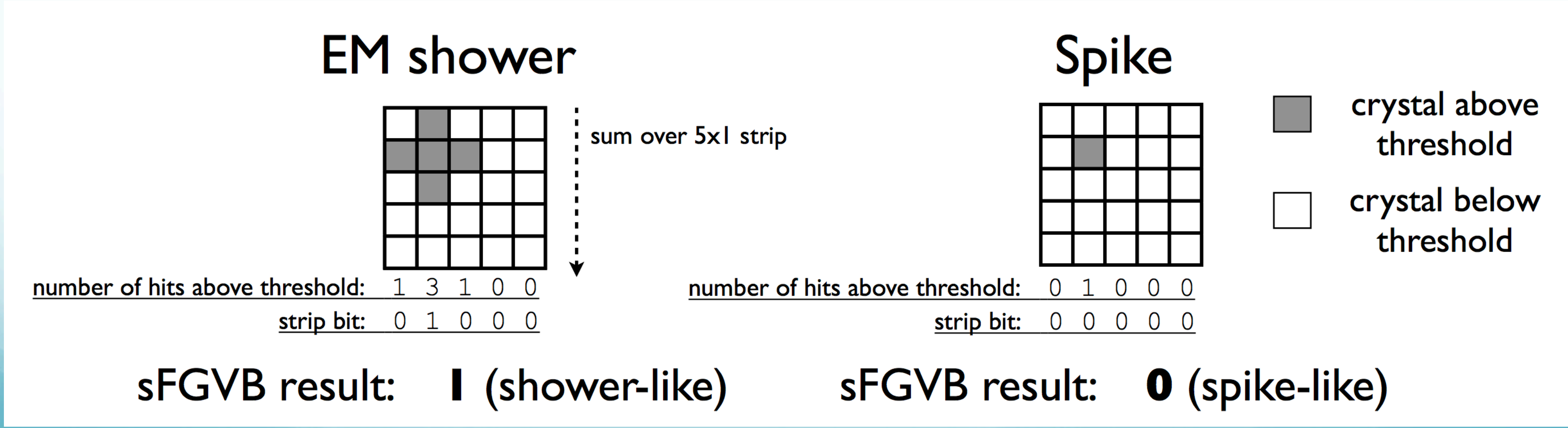
Efficiencies of Offline Rejection



2D distribution of signal timing vs Swiss-cross variable for CMS Data

Online Rejection

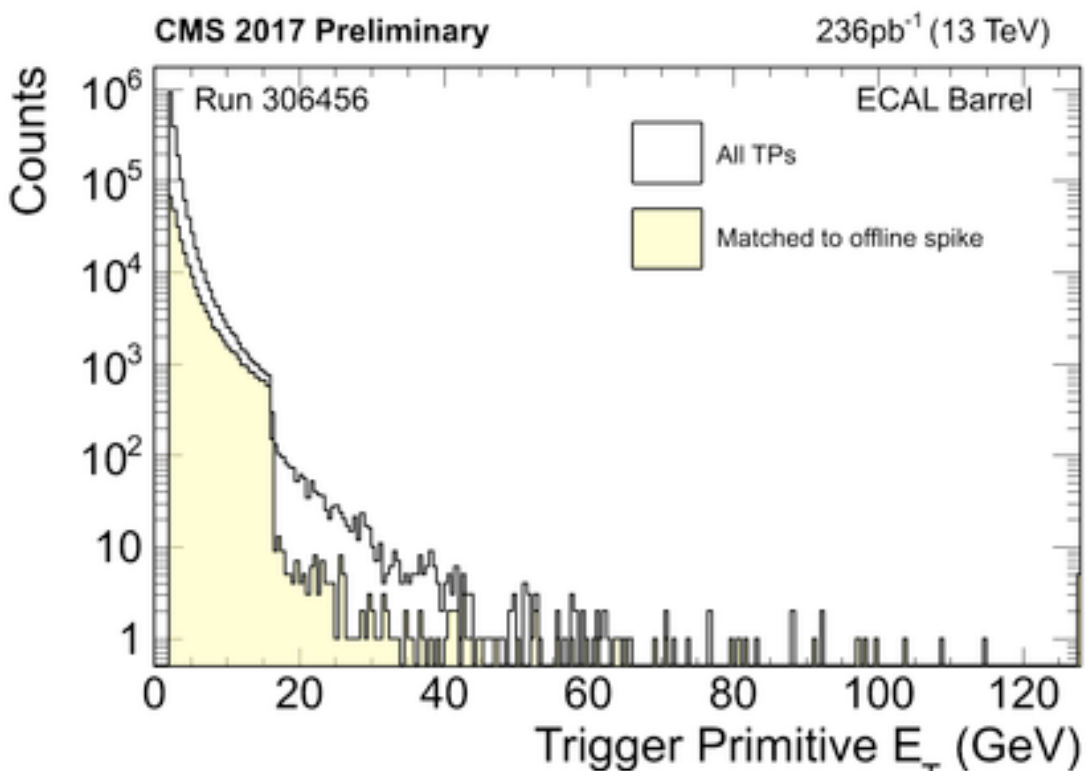
- Strip Fine-Grained Veto Bit (sFGVB)
- If the sFGVB is 0 and the trigger tower energy is greater than the threshold, the energy deposit is considered spike-like.
- Two thresholds, single crystal for the sFGVB and the tower E_T



2017 Performance Check

- Most recent retuning of the sFGVB done in 2016.
- In 2017, used pedestals from the end of 2016
- Plots shown from a high pileup (PU) run: 45<PU<55

Trigger Primitive (TP) E_T Spectrum



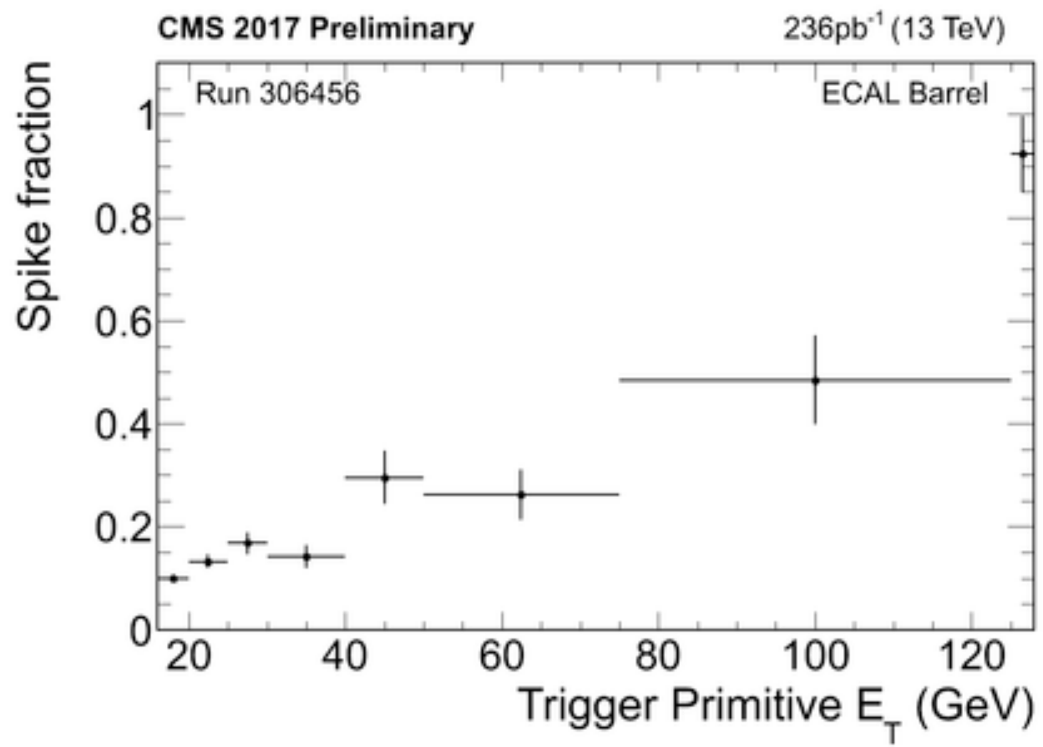
Transverse energy distribution
Black: TP spectrum
Yellow: Residual spikes, matched offline using Swiss-cross and timing
Discontinuity at 16 GeV due to online spike rejection

Residual Spike Contamination per E_T bin

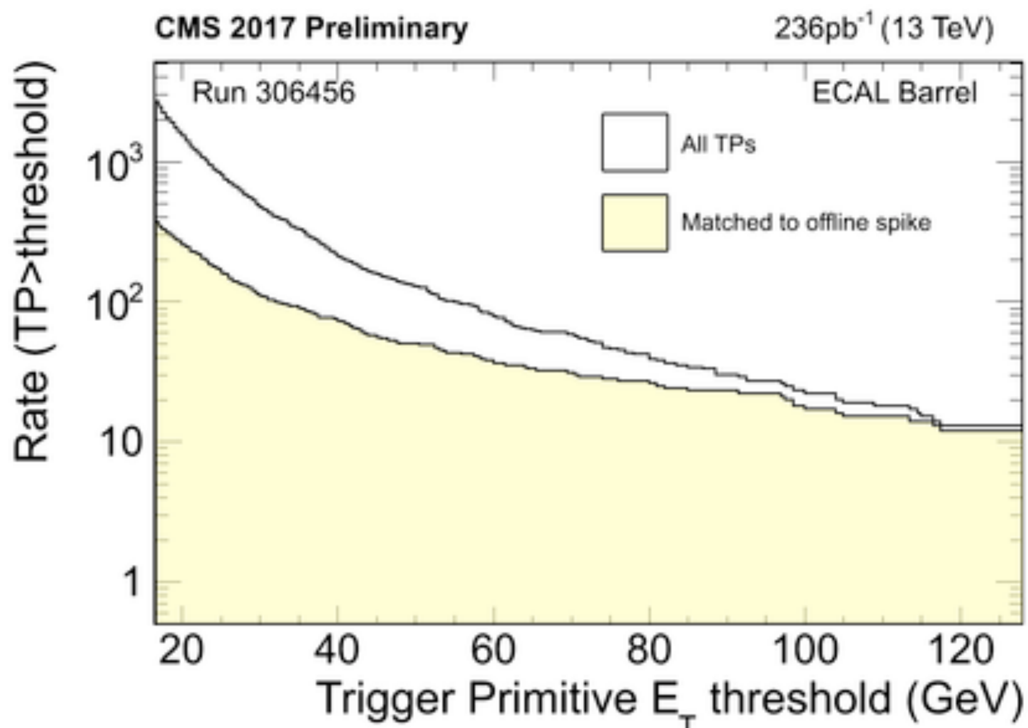
Residual spike contamination in the TPs as a function of transverse energy

Ratio of the two distributions (yellow and black) of the previous slide

Shows spike contamination grows with E_T, the last point is the saturated TPs



Integral TP Spectra



Integral of the TP transverse energy spectrum as a function of transverse energy

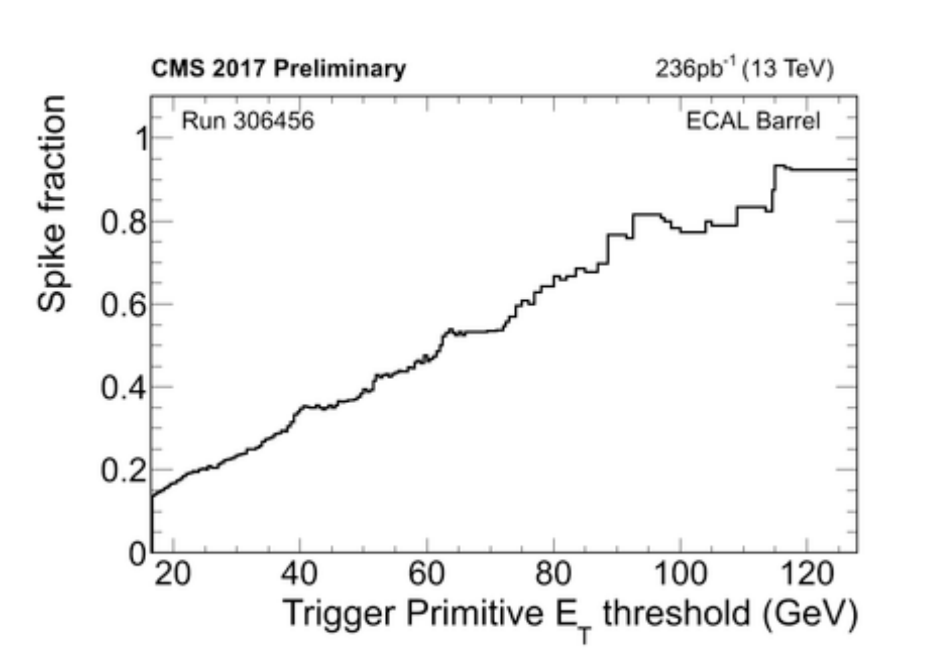
TPs in black, residual spikes in yellow

Another way of showing spike contamination grows with E_T

Misidentified Spike Fraction

Fraction of TPs, above a given E_T threshold, due to spikes
Ratio of the two distributions of the plot on the previous slide

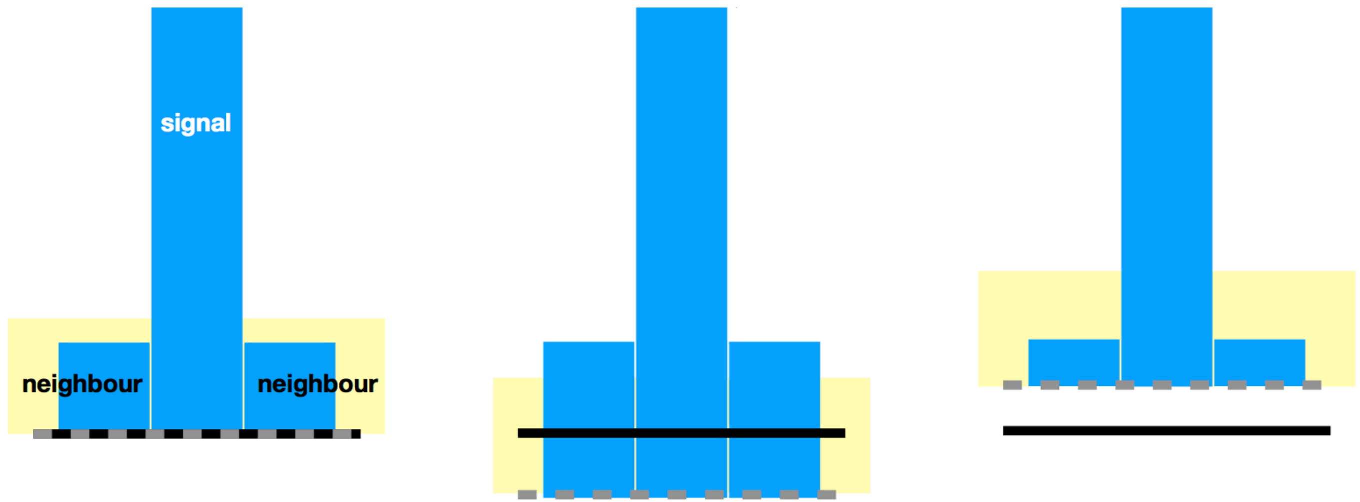
E_T Threshold	Spike Fraction
20 GeV	17%
30 GeV	24%
40 GeV	35%
50 GeV	39%



Effect of incorrect pedestals

true pedestal — applied pedestal — sFGVB threshold

Ideal | **Underestimated** | **Overestimated**



Applied pedestal = real pedestal

Nominal behaviour

Applied pedestal < real pedestal

Signal less isolated

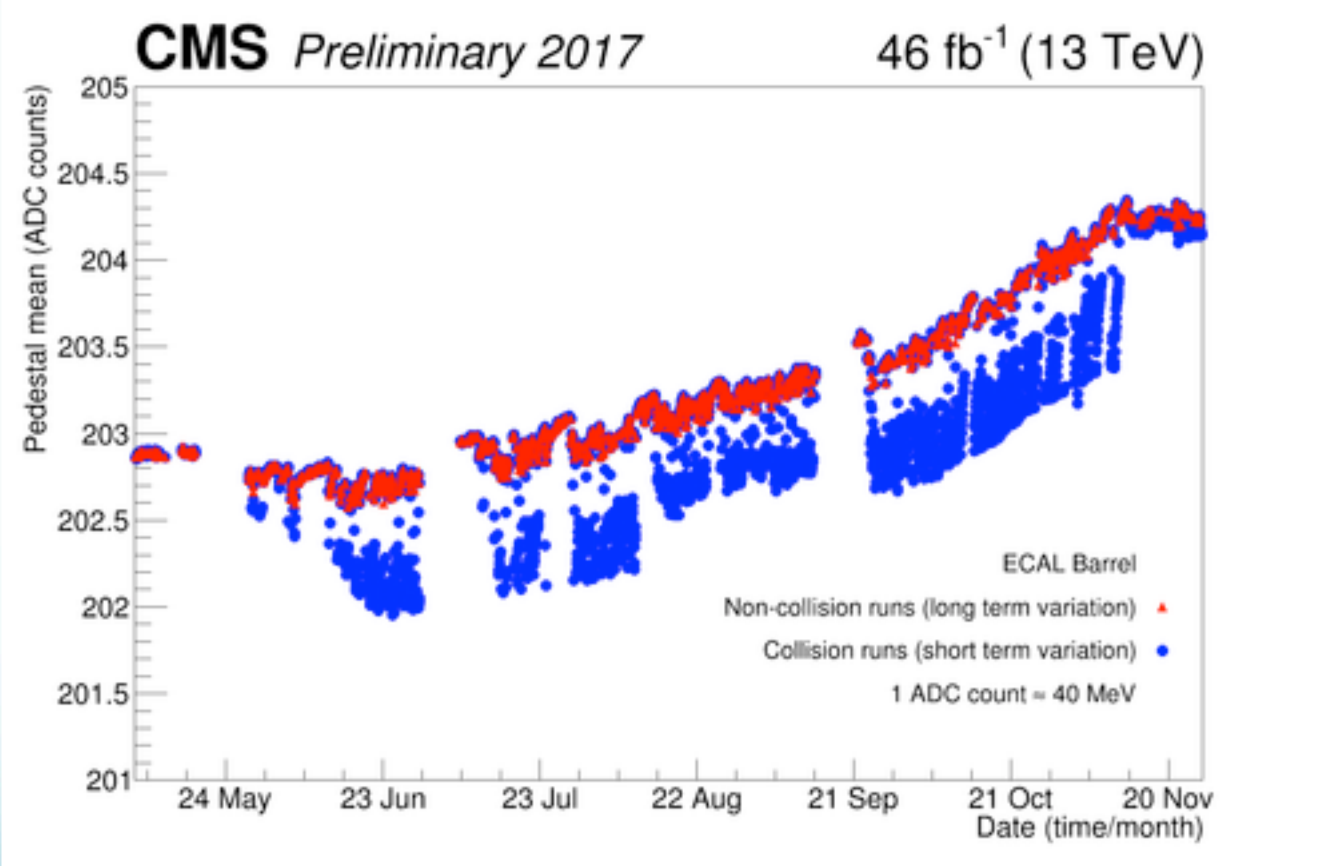
Spike rejection ↓
Electron efficiency ↑=

Applied pedestal > real pedestal

Signal more isolated

Spike rejection ↑=
Electron efficiency ↓

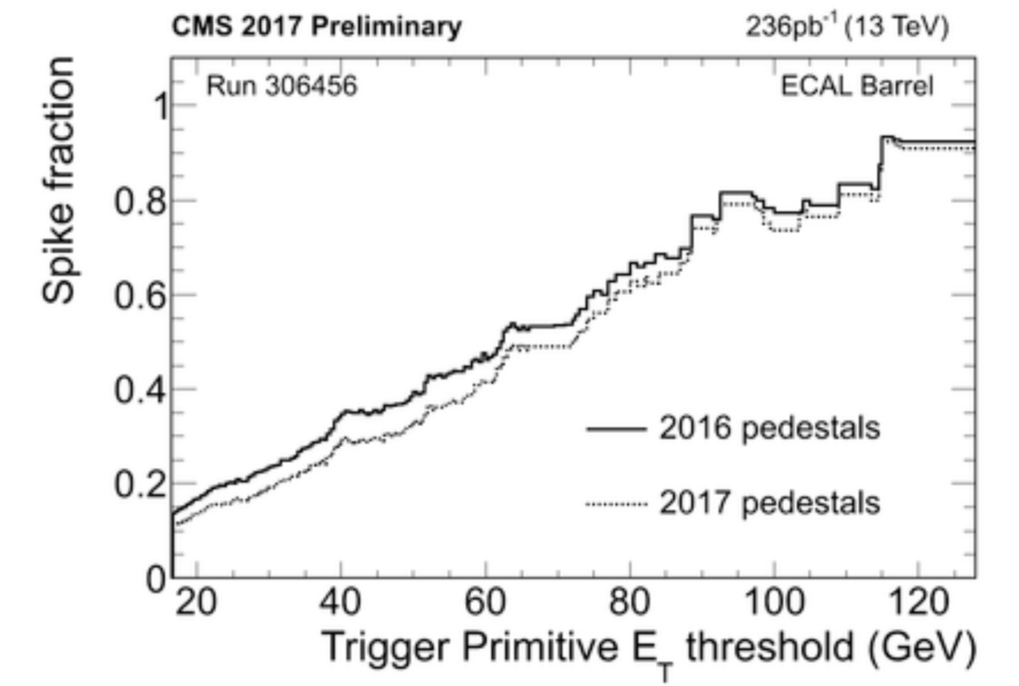
Pedestal Drifts



EB pedestal mean history in 2017

Monotonic drift upward + in-fill effects

Spike Contamination with Updated Pedestals



Fraction of TPs above a given E_T due to spikes
2016 pedestals from Run 296917,
2017 pedestals from Run 305848

E_T threshold	Old pedestals	New pedestals
20 GeV	17%	14%
30 GeV	24%	19%
40 GeV	35%	29%
50 GeV	39%	33%

L1 efficiency

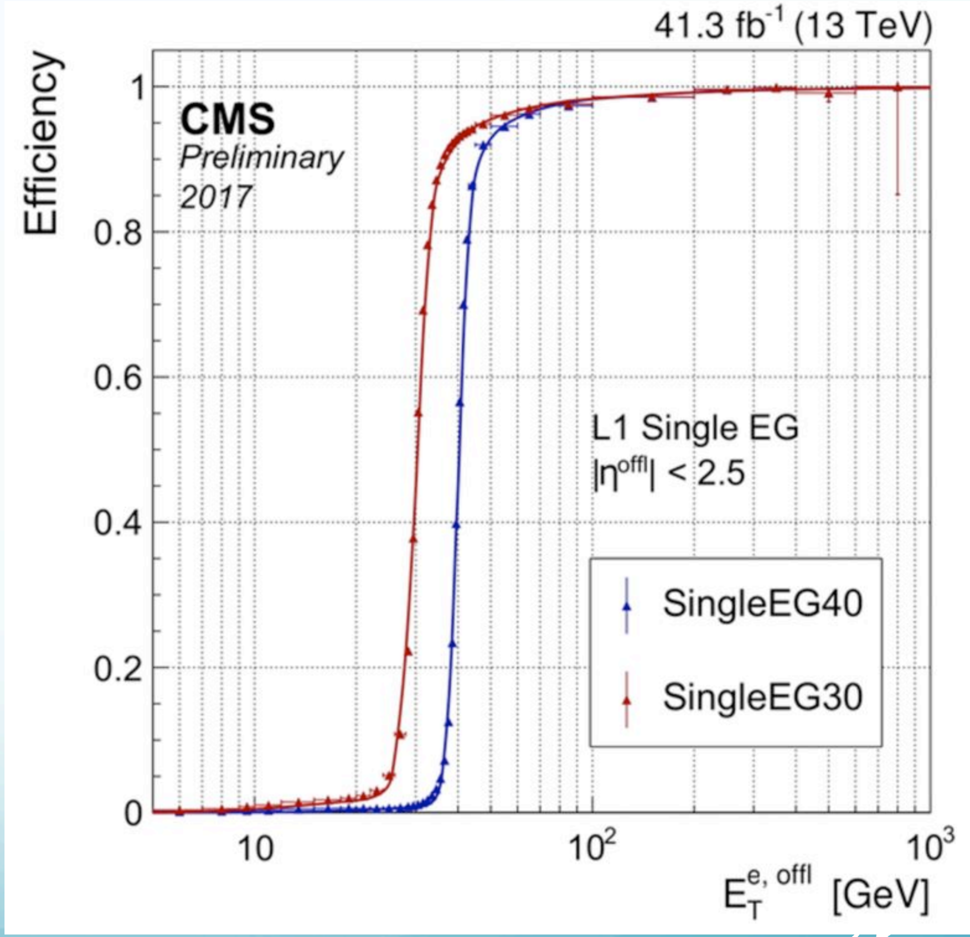
Efficiency of the Level-1 electron/photon (EG) trigger as a function of the offline electron supercluster transverse energy

Uses a tag-and-probe method with $|\eta|<2.5$ (EB+EE)

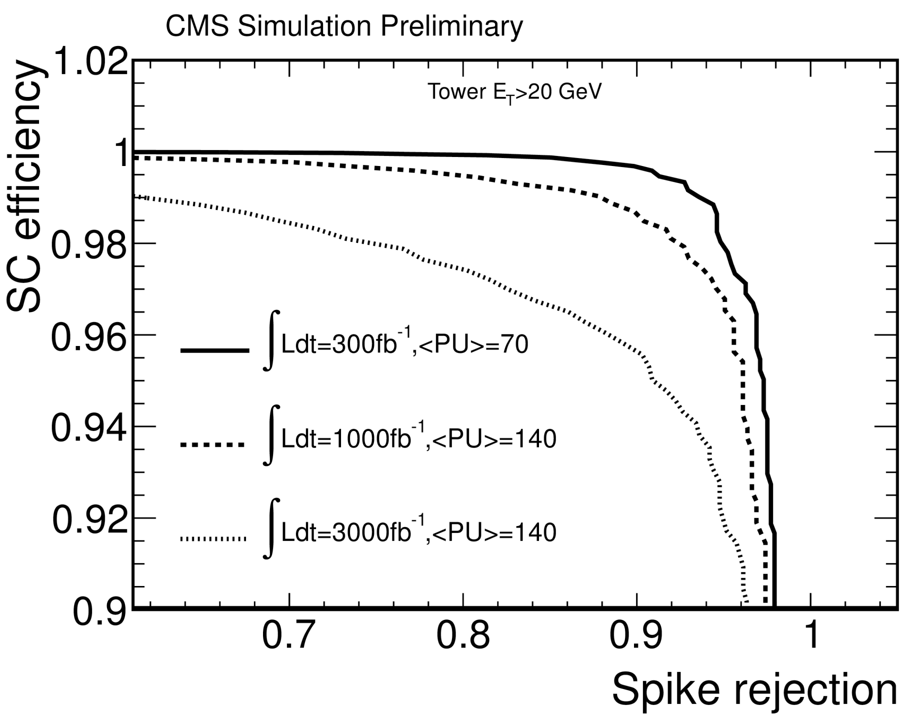
Plotted for L1 EG candidates with E_T>30 GeV and E_T>40 GeV

Shows excellent performance of L1 Spike Killer during 2017

Verified signal efficiency is unaffected by pedestal update



Phase II: Online SK Performance



Predicted efficiency of online SK algorithm vs. signal acceptance (EM showers Z to ee events) for a range of detector aging and event pileup conditions

Only towers with E_T>20GeV are considered

Up to end of Phase I (300fb^{-1}) current SK algorithms perform well

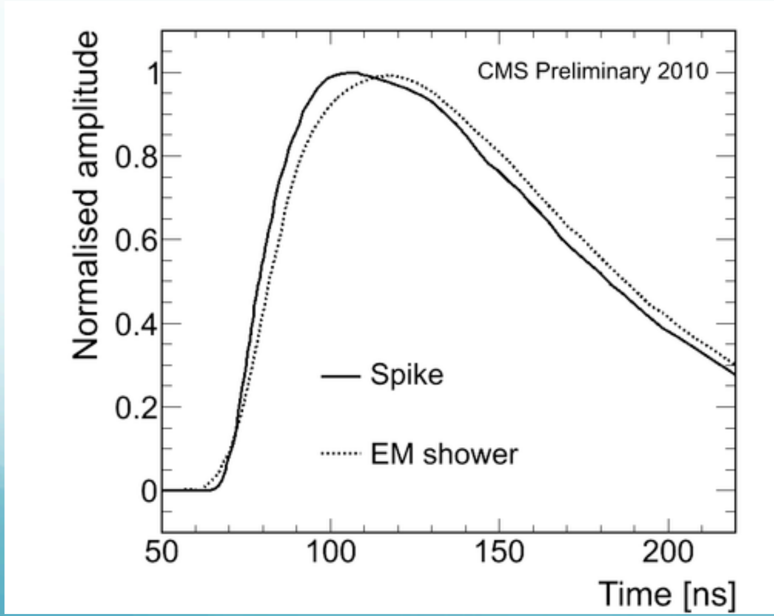
Performance degraded in Run II due to larger pileup and APD noise

Upgrade required for Phase II

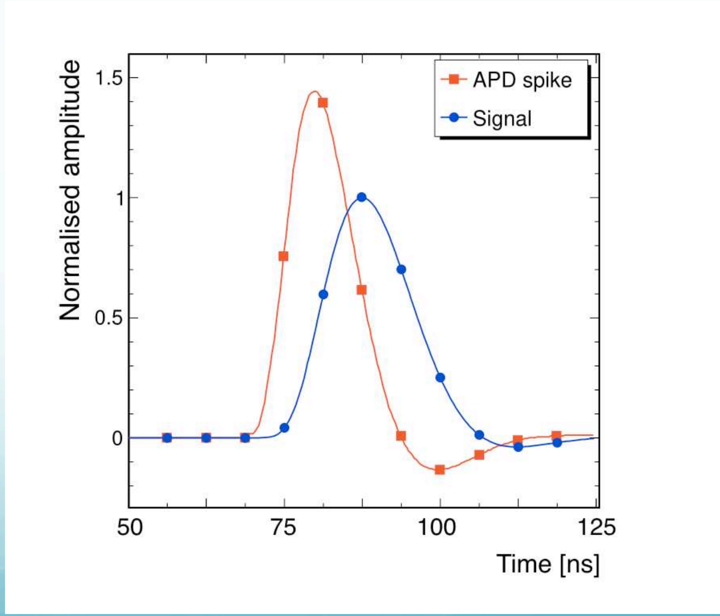
Phase II: Offline SK Performance

- ECAL Barrel Phase II upgrade will replace on-detector and off-detector electronics
- Will improve spike rejection in the L1 trigger due to shorter pulse shaping in the on-detector electronics

Current



Upgrade



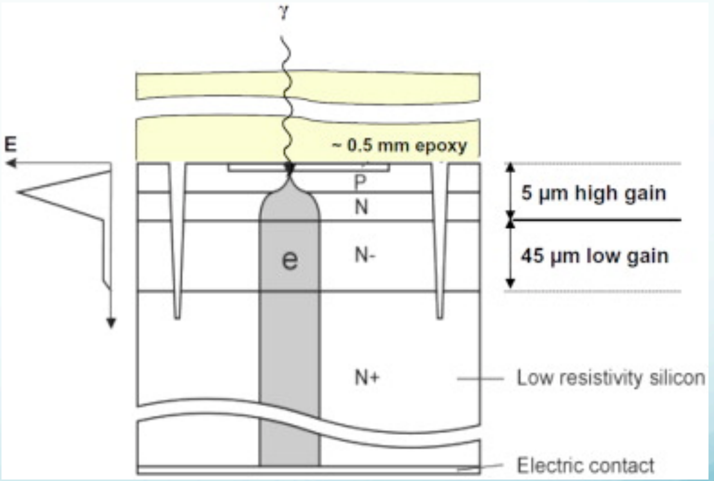
Summary

- Large isolated signals ('spikes') have been observed in the CMS ECAL Barrel in pp and HI collisions at the LHC
- The rate of spikes is proportional to the minimum bias collision rate
- The online and offline rejection algorithms developed for spikes continue to perform well
- The algorithms have been retuned for the higher LHC luminosities of Run II
- Further study and optimization will take place as beam conditions and detector noise levels evolve

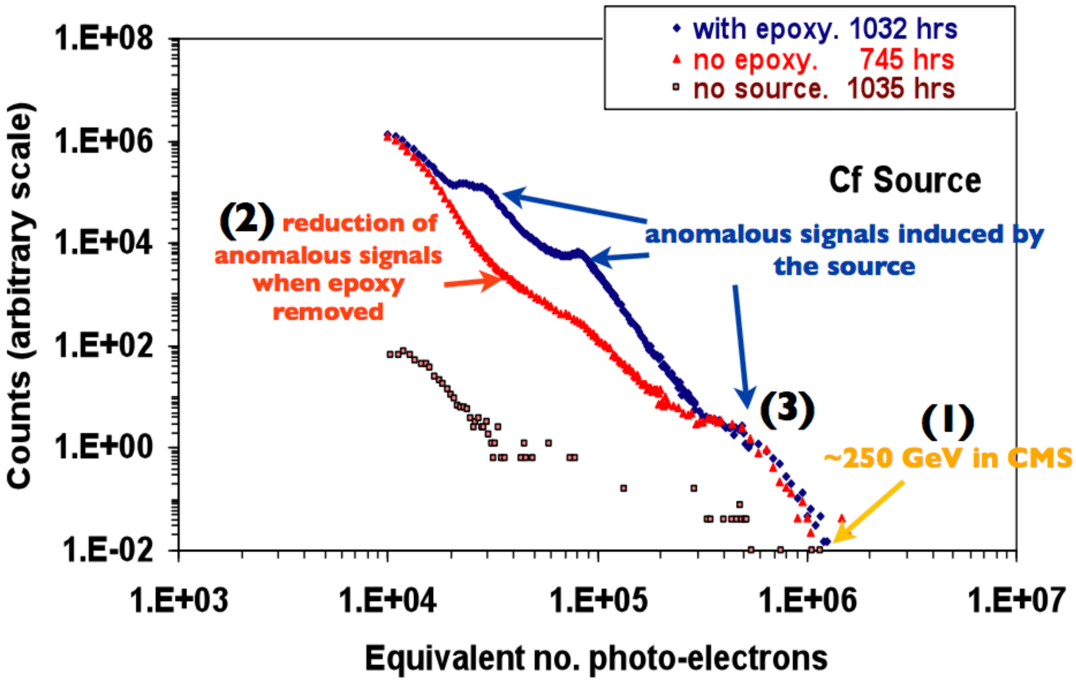
Backup

APD Properties Summary
At Gain 50 and 18 °C

Sensitive area	$5\times5 mm^2$
Operating voltage	340–430 V
Breakdown voltage – operating voltage	45 ± 5 V
Quantum efficiency (430 nm)	75 ± 2%
Capacitance	80 ± 2pF
Excess noise factor	2.1 ± 0.2
Effective thickness	6 ± 0.5 μm
Series resistance	< 10 Ω
Voltage sensitivity of the gain (1/M • dM/dV)	3.1 ± 0.1%/V
Temperature sensitivity of the gain (1/M • dM/dT)	−2.4 ± 0.2 %/°C
Rise time	< 2 ns
Dark current	< 50 nA
Typical dark current	3 nA
Dark current after 2×10^{13} n/cm^2	5 μA



Laboratory Tests



APD spectrum with/without ^{252}Cf source.

for the data indicated by the **red points**: the protective epoxy layer is removed

(1) Neutrons can induce high energy signals in the APDs with equivalent energies up to several hundreds of GeV in CMS

(2) np interactions in the protective epoxy later, specifically in the hydrogen component, are an important component of the anomalous APD signals

(3) At higher energies, signals due to direct ionization of the silicon are observed

Response of CMS avalanche photo-diodes to low energy neutrons, R.M. Brown, K.Delters Q. Ingram, D. Renker
http://dx.doi.org/10.1016/j.nima.2011.12.005

Monte Carlo Spike Studies

- A detailed model of the APD structure has been implemented (using Geant 4) in the CMS Monte Carlo simulation to further understand the origin of spikes and their rates in CMS