CASTOR performance during LHC Run 2

Calor2016
2016, Daegu, Korea (South)

Merijn van de Klundert[1] on behalf of the CMS collaboration
contact: hn-cms-castor@cern.ch

[1]Antwerpen University, Belgium

Motivation

Challenges involved with working with CASTOR

- CASTOR is installed in a very challenging environment:
    - Installed in very forward region
    - Very high radiation level
    - non-negligible stray magnetic field
- Consequenses:
    - Conventional calibration methods (so far) unsuccessful:
        - Searches for resonances unsuccessful
        - Jet p_t balance methods not yet working
        - CASTOR affected by stray magnetic field
    - Installation and alignment delicate task:
        - CASTOR needs dedicated (de)installation for data taking
        - 2 Tonnes at 1 cm from beampipe
        - Platform moves in magnetic field!
        - Small uncertainty on position gives large contribution to uncertainty on scale

→ Present our solutions and improvements to these difficulties at LHC Run 2!

- Emphasis: relationship between various (entangled) aspects of performance CASTOR

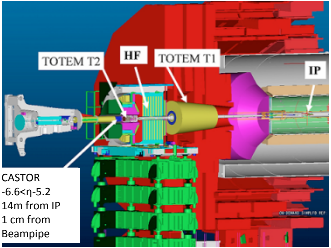


Figure: Location of CASTOR at CMS

Content CALOR2016 talk

Emphasise key points talk:

- **Magenta: improvements performance in Run 2 w.r.t. Run 1, new techniques developed, lessons learned**
- **Blue: key numbers** obtained with CASTOR design as reference
- **Orange: future improvements** to improve CASTOR performance

Introduction

CASTOR: an introduction

- CASTOR: forward em+hadronic sampling Cherenkov calorimeter
- Uses fine-mesh PMT's (Hamamatsu R5505 and R7494)
- Equiped with fibers with LED pulses for in-situ commissioning
- Design motivated by fast response ($\leq$ 50ns) Cherenkov process and radiation hardness
- Relative energy resolution pions: $18.3 \oplus \frac{187}{\sqrt{E}}$ (Eur. Phys. J. C 67 (2010) 601-615)

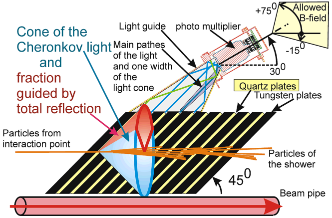


Figure: Schematic drawing of a CASTOR channel

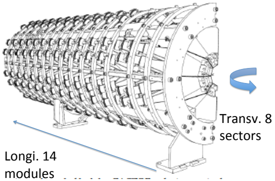


Figure: Schematic picture of one CASTOR half

Intercalibrating CASTOR using Beam Halo Muons

LHC beam causes beam halo muons traversing CASTOR towers

- MIP causes on average $\mathcal{O}(1)$ photoelectron per channel
- Collect muons at maximal allowed gain (1800 V, amplification factor $\approx 10^6$)
- Collect isolated beam halo muons with trigger during circulating beam periods
  - Online: demand exclusively in one tower minimally 1 module above threshold (baseline + 5 σ_{noise} $\approx$0.5 GeV)
  - Offline: exclusively in one tower minimally 3 channels above channel-specific threshold in 3 different longitudinal sections of tower
- **Maximal gain improves collection efficiency (relevant for CASTOR). No improvement uncertainty final result**
- **Relative uncertainty on IC constants: 16%**

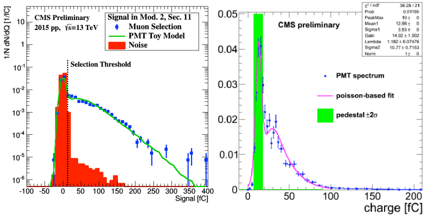


Figure: Left: Run 2 charge spectrum for an offline isolated muon event selection (blue), overlaid noise (red) and a tuned PMT toy model (green) after pedestal subtraction. The tuned model predicts $\langle 0.5 \rangle$ photoelectron per event. Plot from CMS DP-2016/006.
Right: Run 1 charge spectrum for an offline isolated muon event selection. The data are fitted with Poisson$\otimes$Gauss. The good description and lack of long tails indicates negligible muon showering.

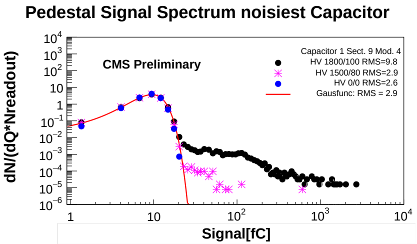


Figure: Pedestal charge spectrum for the noisiest capacitor of a typical CASTOR channel for various cathode/last dynode Voltage settings. Plot from CMS DP-2016/006

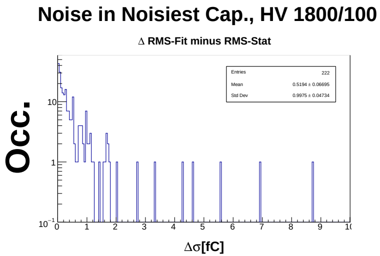


Figure: Difference per channel of fitted and statistical RMS

CASTOR channel baseline and threshold at maximal gain

- **3 Noise contributions to signal in pedestal energy spectrum at 1800 V**
    - Electronic noise: $\mathcal{O}(0.1)$ GeV, no dependence V
    - Thermal photoelectrons: $\mathcal{O}(1)$ GeV,
    - Rare discharges (likely afterpulsing): max $\mathcal{O}(100)$ GeV
- **Take fitted parameters to determine thresholds. Fitted RMS $\approx$ 10% lower!**
- **Use difference stat. and fitted RMS as indicator bad channels. $\Delta_{RMS} \geq 2$ is suspicious**
- **Future improvement: suppress non-electronic noise by applying tower quality criterium using CASTORs longitudinal segmentation**
- **Tower cutoff empty bunch analysis: 6 σ cutoff $\approx$ 1.5 GeV**

Correcting gain from muon to physics Voltage

- Correct from max. gain to custom gain recipe (optimised to maximal dynamic range)
- Survey: dedicated lab dark box measurements on PMT's performed
- Different method available at CASTOR as well (statistical method):
    - Deduce G_{corr} from corrected LED signal (in situ)
        - Corrected Signal $S_c = S_t - S_p = G \cdot N_{p.e.}$
        - $\sigma_{S_c} \approx G \cdot \sqrt{N_{p.e.}} \rightarrow G = \frac{\sigma_c^2}{S_c}$

$\rightarrow$ Test consistency and use both!

Gain vs HV for survey

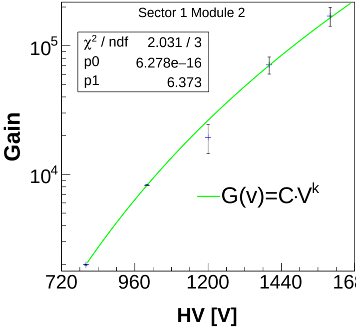
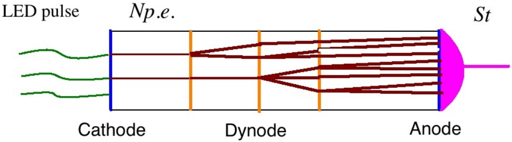


Figure: Dark Box measurements with fitted gain parameterization



Consistency Survey and statistical method

Statistical method vs Dark box survey

- **Survey and statistical method give reasonably consistent results on G_{corr}**
- Survey uncertainty (⟨1%⟩) smaller than uncertainty statistical method (⟨17%⟩)
- **Future improvement: reduce uncertainty statistical method by fitting HV dependence (as done for survey)!**

Relevance for other subsystems

- Survey laborious lab measurement only for B=0!
- Statistical method gives reasonably consistent estimate gain and works in situ at B$\neq$ 0T

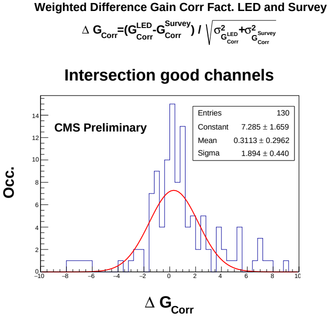
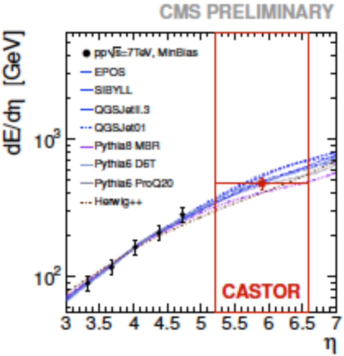
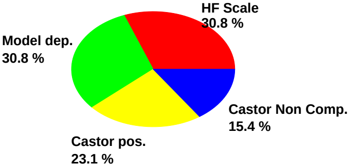


Figure: Pull distribution with Gauss fit of gain correction factors from survey and statistical method. Plot from CMS DP-2016/006



Contributions to Uncertainty Energy Scale Castor Run 2
Total Uncertainty 17 %



CASTOR state of the art Absolute Calibration

- **Full data/MC residual correction future goal (likely jet p_t balance)**
- Currently use state of the art (hybrid) calibration:
  - Obtain estimate of incident energy on HF on particle level. Extrapolate to CASTOR acceptance. Apply shape correction factors
  - Obtain absolute scale well consistent with test beam results
  - **Total uncertainty state of the art calibration: 15%**
  - Alignment adds substantial contribution to overall uncertainty on scale

Contribution CASTOR Alignment to systematic uncertainty

Procedures and methods for alignment

- Delicate measurement: 1 cm shift leads to shift η from -6.6 to -6.4. Large systematic for analyses!
- **Run 2: better calibration IR sensors w.r.t. curved object (beampipe). Uncertainty <1.6> mm per coordinate**
- Contribution alignment to systematic uncertainty for energy flow measurement:
  - **Run 1: 16%**
  - **Run 2: 7.5%** →≈ 50% improvement!

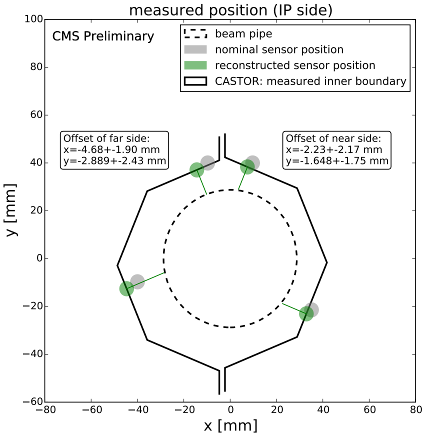


Figure: Illustration of the global fit result of the CASTOR position for data taking during LHC Run 2 pp collisions (B=0T). Plot from CMS DP-2016/006

Outlook Run 1 and 2 physics results:

- CASTOR can probe to $x \approx 10^{-6}$, region sensitve to various QCD phenomena. Observables:
  - Energy deposits
  - Jet Spectra
  - Rapidity gaps
- CASTOR extends acceptance other measurements:
  - Inelastic/diffractive cross section measurements
  - Veto for exclusive vector meson production in Heavy Ion analyses
  - Forward-central jet studies in various hadron collisions
- Recently Run 2 CASTOR results presented at DIS conference:
  - energy flow in CASTOR (FSQ-16-002)
  - Inelastic cross section measurement (FSQ-15-005)
  - limiting fragmentation (FSQ-15-006)
  - Inclusive jet spectrum in CASTOR at 13 TeV (FSQ-16-003)
- Uncertainty on energy scale needs improvement.
- **Future strategy bifold: take ratio of measurements to cancel the scale uncertainty. Try to improve energy scale by jet p_t balance**

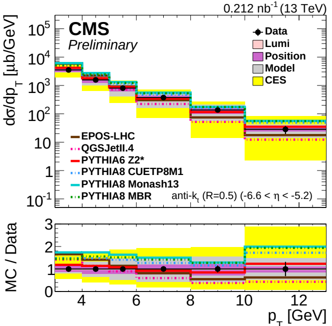


Figure: Unfolded CASTOR jet energy spectrum for 13 TeV pp collisions with various MC models. Plot from CMS PAS FSQ-16-003

Developing a method for ratios between different installation periods

- Conventional absolute calibration done per run at CMS
- For CASTOR state of the art calibration fixed for Run 1. Depends on Run 1 intercalibration constants and conditions
- Intercalibration software and HV setting for muon collection differs between Run 1 and Run 2
- **Developed a method to fix scales consistently between Run 1 and Run 2:**
  - Analyse Run 1 Minbias data with Run 1 and Run 2 intercalibration
  - Preliminary: difference in reconstructed total energy gives difference in scale → **Diffference Run 1 and Run 2: ≈ 10 %. In range of uncertainty. Important for ratios of measurements!**

Summary and Lessons Run 2 performance

CASTOR Intercalibration

- **Obtain noise threshold per channel from fit pedestal spectrum**
- **Difference fitted and statistical RMS indication noise in channel**
- **Future improvement: develop algorithm to distinguish afterpulsing from physics signals**
- Collect muons at maximal gain: improved collection efficiency, no improvement uncertainties. **Uncertainty intercalib constants: 16%**
- **Results on statistical gain correction factors reasonably consistent with Survey results. Large range of applicability!**

CASTOR alignment

- **Uncertainty on alignment: <1.6> mm per coordinate. Resulting uncertainty on energy scale: 7.5%** (**improved ≈ 50%!**)

Overall uncertainty Run 2

- Uncertainty absolute calibration and alignment together **yield 17% uncertainty energy scale**
- **Future steps: take ratios of measurements and try to improve uncertainty on scale**

Content Backup

Backup slides

- Installing CASTOR
- Physics potential of CASTOR, completed analyses
- Determining the uncertainty on intercalibration using bootstrapping
- Details of gain analysis:
  - Statistical method
  - Survey method
  - Results on G_{corr}
- Noise in PMT's:
  - Results on noisy PMT's
  - Initial and final bad channel selection
- Castor Jet trigger efficiency
- Fixing the scale for Run 2

Installing CASTOR

Figure: Installing CASTOR for 2015 data taking

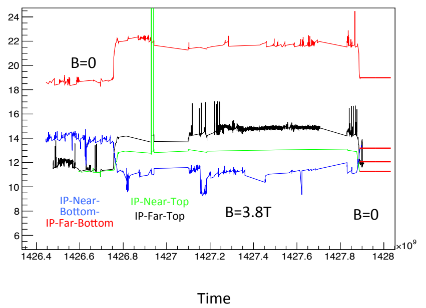


Figure: Distance of infrared position sensors at the interaction point side of CMS in mm w.r.t beam pipe during a full cycle of the magnet ramp. Near and Far indicate the halves of CASTOR.

Installing 2 tonnes at 1 cm from beampipe

- CASTOR can't be installed permanently. Neutron flux measurement nearby CASTOR: $13 \pm 3(1/\mu\mathrm{b}^{-1}/\mathrm{cm}^2\mathrm{sec})$
- Unconventional heavy object in close vicinity (1cm) to beampipe
- Anticipate movements of platform (± 3mm) due to magnet ramp during installation!
- Movements in magnet cycle (per installation) quite predictable

Procedures and methods for alignment

- Three methods for alignment:
  - Measure CASTOR w.r.t. fixed points in Cavern
  - Sensors: measure CASTOR w.r.t. beampipe
  - Alignment using TOTEM T2 (Run 1 only): make "x-ray"

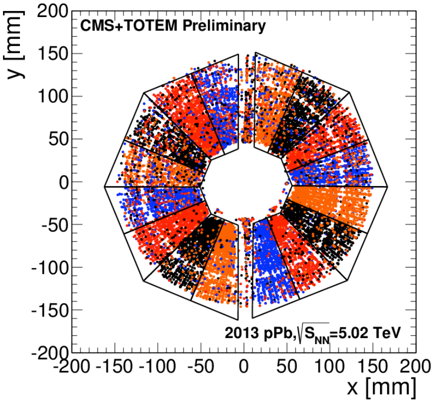


Figure: Alignment of CASTOR using tracks in Totem T2- telescope

Physics potential of CASTOR

- CASTOR well equipped for energy deposits, forward jets and forward rapidity gaps
- CASTOR physics program involves various QCD and small-*x* phenomena (probe down to $x \approx 10^{-6}$!)
- Extend CMS acceptance for event selection
- Potential for exotic study: strangelets and Centauro-like events

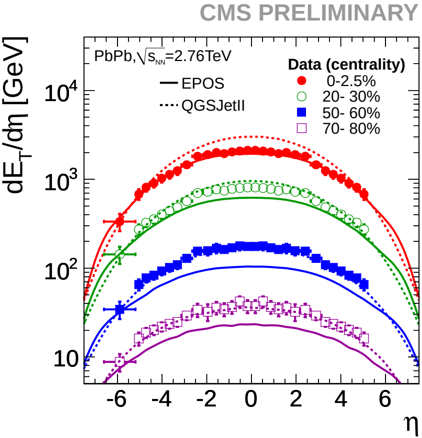


Figure: Corrected transverse energy density for different centralities in Pb+Pb collisions at $\sqrt{s} = 2.76$ GeV.
CMS-PAS-HIN-12-006

CASTOR contributed to following completed Run 1 physics analyses

- Measurement of the η and centrality dependence of the very forward energy density in PbPb collisions Results from **CMS-PAS-HIN-12-006**
- Study of the underlying event at forward rapidity **JHEP 04 (2013) 072**
- Measurement of diffractive dissociation cross section **Phys. Rev. D 92, 012003 (2015)**

CASTOR contributes to other physics fields of CMS by improving knowledge on proton structure and generator models with applications in pileup and luminosity estimates

Physics outlook CASTOR data:

- CASTOR can probe to $x \approx 10^{-6}$. Searches for signals of nonlinear evolution equations, saturation, MPI.. Various observables available:
  - Energy flow
  - Jets
  - Gaps
- Recently Energy flow, total cross section, limiting fragmentation and Jets in CASTOR presented at DIS!

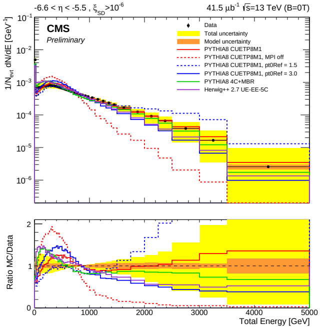


Figure: Unfolded energy spectrum at CASTOR for 13 TeV pp collisions with various MC models. Plot from FSQ-16-002

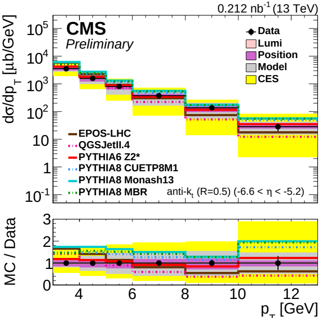


Figure: Unfolded CASTOR jet energy spectrum for 13 TeV pp collisions with various MC models. Plot from CMS PAS FSQ-16-003

Uncertainty on intercalibration

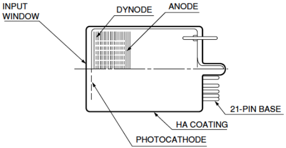
Bootstrapping procedure

- 1. Randomly choose a sector where the muon should go through
- 1.a. For all channels in this sector take a random energy with a PDF from their real data muon signal distribution
- 1.b. For all other channels take a random energy with a PDF from their real noise signal distribution
  → obtain a "muon like" event for castor created with our fake rechit energies.
- 2. This event goes now through the whole muon analysis chain
- 2.a. If the muon is found, for every channel in this sector we fill the fake muon signal in our new muonsignal channel hist.
- 3. Redo step 1,2 as often we have muons in real data (10k)
- 3.a. Now we have for every channel new fake muon signal histstograms. Calculate new IC constants (as we do in real data)
- 4. Redo step 1 to 3 to a whole bundle of IC constants for every channel
- 4.a. The variation of the IC constants in every channel should give us the stat. uncertainty of the IC value

The Electronic and Photonic gain of a PMT

G_e vs G_γ

- Electron gain G_e converts photoelectrons (at Cathode) to Anode electrons: $N_{p.e} \cdot G_e = N_{e,A}$
- Photon gain G_γ converts incident photons to Anode electrons: $N_\gamma \cdot G_\gamma = N_{e,A}$
- Note $G_\gamma = QE \cdot G_e$ (QE is Quantum Efficiency)



Two methods to measure gain of CASTORs PMT

- Performed dedicated Dark Box PMT survey measurements (in lab). Allows determination of G_γ
  - Precision measurement which requires dedicated tools and setup
- In situ LED and Pedestal Runs. Allow for determination G_e.

G_e from Statistical Analysis LED and Pedestal Runs

Obeservables

- Measure LED and Pedestal Energy Response distribution
- Fit to pedestal gives estimate S_p
- Fit to LED gives estimate S_t (sum pedestal and LED signal)
  $\rightarrow$ Obtain corrected signal $S_c = S_t - S_p$
  σ_{S_c} follows from statistical properties S_t and S_p

Try determine G_e from statistical properties S_c

- $N_{p.e} \cdot G_e = N_{e,A} = S_c$
- $\frac{\sigma_{S_c}}{S_c} = \frac{\sigma_{N_{p.e}}}{N_{p.e}} \oplus \frac{\sigma_{G_e}}{G_e}$
  - Assume $\sigma_{N_{p.e}} = \sqrt{N_{p.e}}$ (Poissonian distributed)
  - Assume $\frac{1}{\sqrt{N_{p.e}}} >> \frac{\sigma_{G_e}}{G_e}$
    $\rightarrow \sigma_{S_c} = G_e \cdot \sqrt{N_{p.e}}$
- Obtain $G_e = \frac{\sigma^2_{S_c}}{S_c}$ (δ_{G_e} from stat. uncertainties S_c, σ_{S_c})

Why one cannot obtain G_γ from statistical analysis

Try instead determine G_γ from statistical properties S_c

- Try to determine G_γ from statistical properties S_c:
- $N_\gamma \cdot G_\gamma = N_{e,A} = S_c$
- $\frac{\sigma_{S_c}}{S_c} = \frac{\sigma_{N_p}}{N_p} \oplus \frac{\sigma_{G_\gamma}}{G_\gamma}$
  - $\frac{\sigma_{G_\gamma}}{G_\gamma} = \frac{\sigma_{G_e}}{G_e} \oplus \frac{\sigma_{QE}}{QE}$
  - Cannot assume $\frac{1}{\sqrt{N_p}} >> \frac{\sigma_{QE}}{QE}$!!

→ From statistical analysis of LED Runs we can only determine the electron gain (no estimate G_γ)

Estimating G_γ from Analysis PMT survey

Setup and observables

- Direct photon beam on test PMT
- Need to compensate for lumen fluctuations. Split incident photon beam. Direct fraction beam on test PMT and fraction on reference PMT
- Test PMT: measure Cathode current I_C*, Anode Current I_A. Reference PMT: measure current I_R (at anode)
  - $G_e = I_A / I_C$
  - Quantum efficiency scales with I_C / I_R

  * Measuring Cathode current: delicate measurements on nano-Ampere scale
- In an intercalibration interested in relative channel-to-channel differences, so can use I_C / I_R as QE
- Obtain Relative $G_\gamma = QE \cdot G_e$

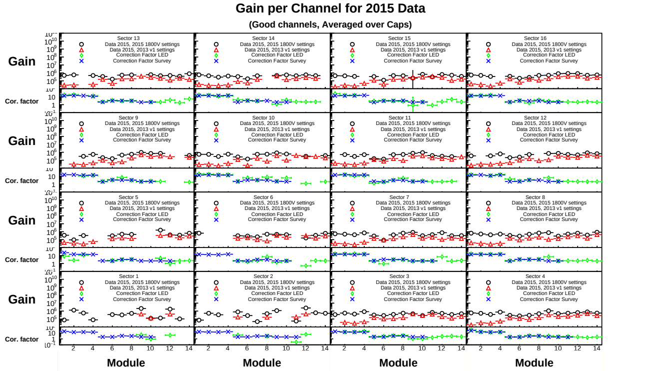
Summary

summary

- With statistical method can in situ determine G_e (no estimate Quantum Efficiency and Optical efficiency)
- With PMT survey determine photon gain (but no estimate optical efficiency)
- Muon intercalibration takes all effects into account
  → Note for gain correction factor Quantum and optical efficiency divide out

G_e and G_{corr} for LED and Survey results

- Observe some channels large uncertainty
- Overall agreement qualitatively quite reasonable



Ratio correction factors survey and statistical method

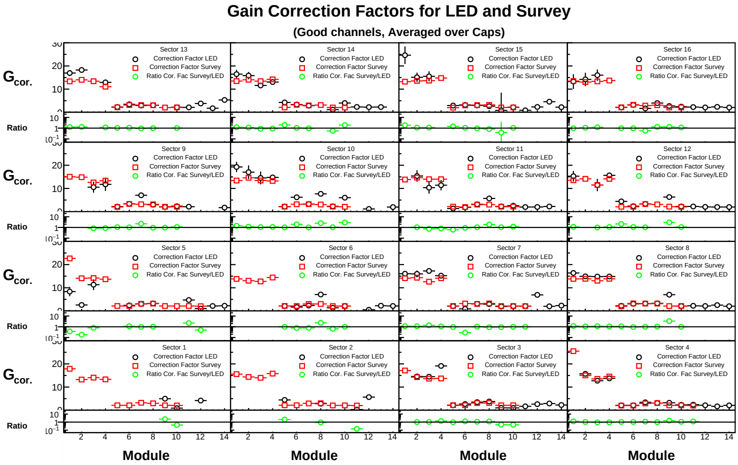


Figure: Gain correction factors and their ratio determinded by statistical method and analysis survey results

Parameter C

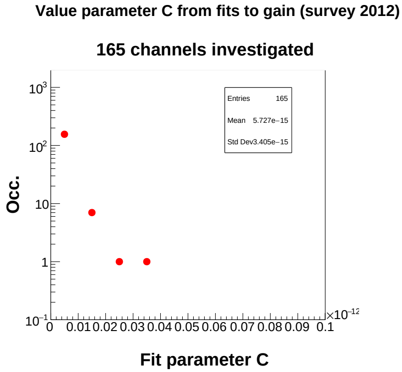


Figure: Parameter C from PMT survey

Parameter K

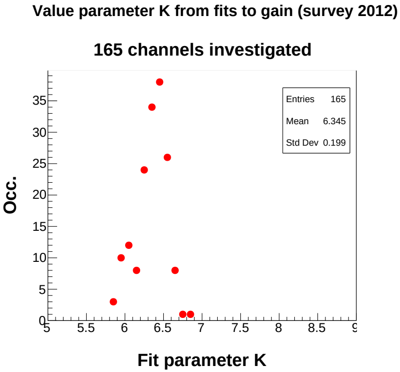


Figure: Parameter K from PMT survey

Fits to Gain vs V

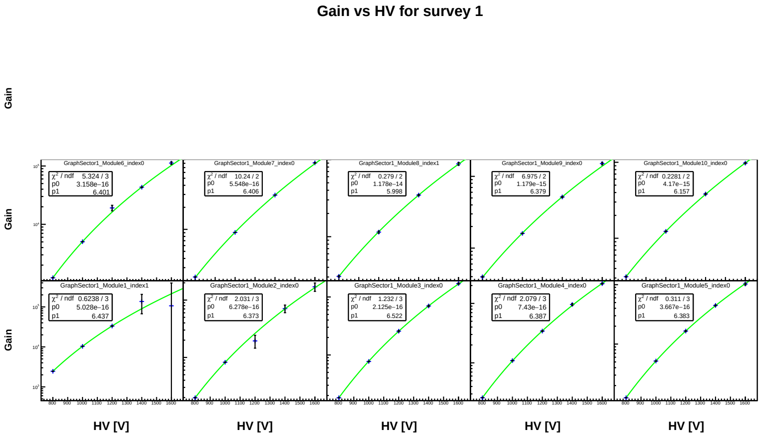
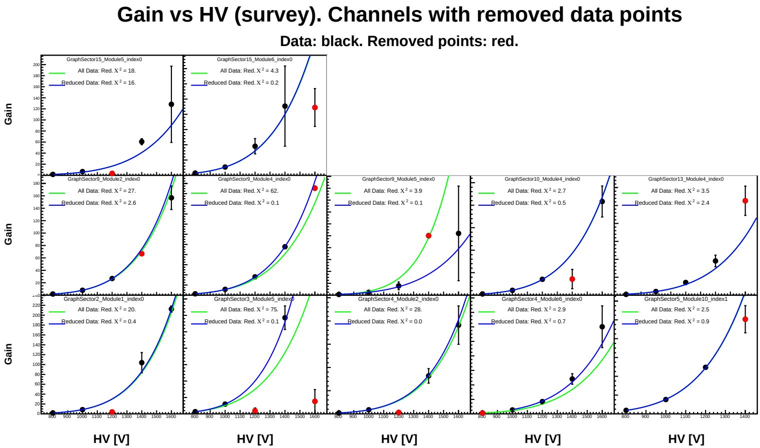


Figure: Gain measurements with corrections and fit

Fits to Gain vs V


Gain vs HV (survey). Channels with removed data points

Data: black. Removed points: red.

Figure: Gain measurements with corrections and fit

Possible causes noise in PMT’s

Various sources of noise in PMT’s

- Leakage current (Ohmic leakage; dominant at low voltage)
- Thermal photoelectrons (contribution scales exponentially with supply voltage acc. to producer)
- Scintillation glass envelope (can be minimized by coating)
- Field emission current (at excessive HV)
- Ion feedback (can be identified from timing)
- Cosmic rays, environmental gamma rays, ..
- Problems in HV supply (can be identified by correlations between channels)

Channel Quality

Selecting noisy channels at maximal gain

- Channel too noisy:
  - Can't intercalibrate
  - Compromises online muon trigger
- **Difference statistical and fitted width indicator of channel quality**
- Select noisy channels with cuts (spectra in backup slides)
- Final judgement by individual inspection

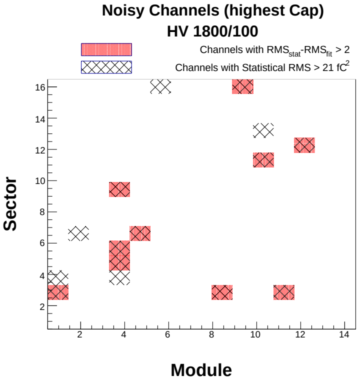


Figure: The initial and final noisy channel selection (final bad channels with blue dot)

Defining the Cut parameter for finding noisy channels

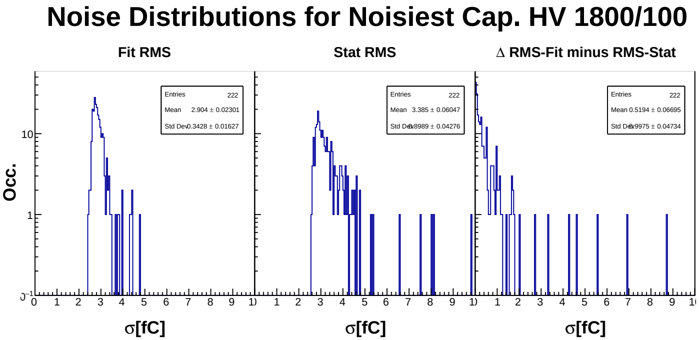


Figure: Noisy channels in CASTOR

CASTOR Jet trigger for Run 2

Evaluating trigger efficiencies at p+p $\sqrt{s} = 13$ TeV

- Medium Jet Trigger implemented. Triggers on sector with Energy ≥ 850 GeV
- Medium Jet trigger 100% efficient in Data and MC from 2 TeV onwards (≈ 3.5 TeV on particle level)
- **Efficiency medium energy CASTOR jet trigger well understood and 100% efficient in data/MC above Jet energy of 2TeV**

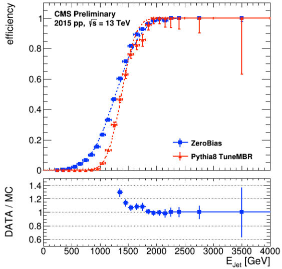


Figure: Trigger efficiency of CASTOR Medium Jet Trigger in LHC Run 2 Zero Bias pp $\sqrt{s}$ = 13 TeV data and a Pythia 8 Monte Carlo Minimum Bias event sample (B=0T) with fitted Error function. The efficiency is defined as the fraction of events with an offline reconstructed leading jet that cause a jet trigger.

A consistent Absolute Calibration of CASTOR

Boundary conditions

- Assume in 2013 a full inter and absolute calibration procedure was performed
- Idea presented here assumes no change in response PMT's or electronics since last abs. calibration (like alteration of PMT's, ...)
- Assume we can compensate for effect of B field between 2013 and 2015 intercalib, for example by LED corrections or that effect is negligible

A consistent Absolute Calibration of CASTOR

Goal

- Given above aim to perform abs calibration of CASTOR in 2015 to compensate for following effect:
    - Statistical fluctuations gain measurements of reference channel. Account for possibility reference channel in 2015 being 20% too high or low w.r.t. 2013
    - Statistical fluctuation between front and back channels (should statistically average out in principle)
    - Systematic differencesd due to different procedures Run 1 and Run 2

  Note even with assuming the Run 1 inter and absolute calibration apply for Run 2, a 2015 inter calibration was still relevant for module 7 and 8 since 13 TeV Run 2 data collected with no magnetic field!

Revise method of Absolute Calibration

Review

- Start deriving a compensation factor F_{det} using MC:
  - In simulation CASTOR is "perfect calibrated" for electrons (no intercalibration issues!)
  - Simulate total energy per event for collisions in CASTOR with CASTOR tuned to data-taking conditions. Energy incident: E_{inc}. Measured (first 5 modules): E_{det}.
  - Determine the fraction $F_{det} = E_{inc}/E_{det}$ due to noncompensation, bad channels, longi leakage etc.
    → this number compensates the measured energy for detector effects like noncompensation, leakage, bad channels.. Conditions dependent!

Fixing the GeV/fC scale C_{abs}

GeV/fC scale

- For a given dataset determine the incident energy A in GeV (on particle level) on CASTOR with extrapolation HF measurement (from real data)
- Measure the total raw energy in front modules CASTOR per event $E_{fC,raw}$ in real collisions in fC (energy in fC only after intercalibration with ch. 9.4=1!)
- Subsequently perform absolute calibration by $A[GeV] = F_{det} * E_{fC,raw} * C_{abs}$
  Obtain $A[GeV]$ from HF extrapolation. Get F_{det} from MC simulation. → C_{abs} is constrained!

Fixing and verifying Absolute scale for 2015 intercalib using 2013 data

- Concept: for 2013 dataset C_{abs}^{2013} fixed. → Can constrain C_{abs}^{2015} by reconstructing 2013 data!
- Reconstruct raw Energy $E_{fC,raw}^{2013}$ for 2013 data with 2013 intercalib and conditions*
- Reconstruct raw energy $E_{fC,raw}^{2015}$ for 2013 data with 2015 intercalib and 2013* conditions, corrected for magnetic field
- Impose the reconstructed energy in GeV to be independent from intercalib: $E_{fC,raw}^{2013} * C_{abs}^{2013} \equiv E_{fC,raw}^{2015} * C_{abs}^{2015}$
- We obtain $C_{abs}^{2015} = \frac{E_{fC,raw}^{2013}}{E_{fC,raw}^{2015}} * C_{abs}^{2013}$

  * Might reconstruct with 2013 bad channels merged with 2015 bad channels, if a bad behaving channel not in intersection bad channel lists

Pro's/Con's

Pro's

- Obtain an absolute calibration Consistent with 2013 calibration
- Uncertainty on scale fixed by uncertainty from 2013 procedure
- Obtain consistent intercalibration for 2015 as well for mod 7,8! Naturally can later verify scale with HF (do for example complete procedure including mod 7,8)

Pro's/Con's

Con's

- Need to assumes 2015 PMT response not deteriorated w.r.t. 2013 detector
  Do data-analysis with last 2013 runs, PMT's likely not changed in LS1
- One needs to compensate for the B-field (which was off for 13 TeV Run 2 data taking) Results on doing this using LED data are encouraging!