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CMS DP -2018/025

The Compact Muon Solenoid Experiment

CMS Performance Note

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28 November 2017 (v2, 05 June 2018)

The performance of CMS ZDC detector in 2016

CMS Collaboration

Abstract

The Zero Degree Calorimeter (ZDC) detects neutral particles in $\eta > 8.5$ region. In 2016, the ZDC is cross-calibrated to 2010 dataset. Peaks corresponding to 1, 2 and 3 are visible in the ZDC total signal distribution. The effect of pileup is corrected by a Fourier deconvolution method. Neutron number distribution is unfolded using linear regularization method. The ZDC can be used as an unbiased centrality estimator in pPb collisions - but theoretical models valid at LHC are needed for this. The CMS ZDC is able to measure the spectator neutron multiplicity distribution, which will be a useful information for developing such models.

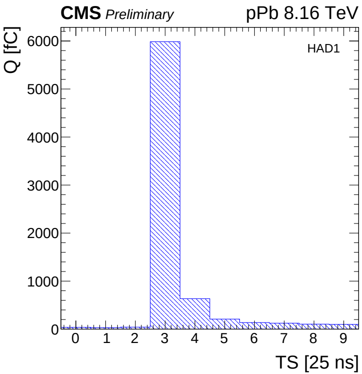
The performance of CMS ZDC detector in 2016

CMS Collaboration

January 9, 2018

1. Calibration

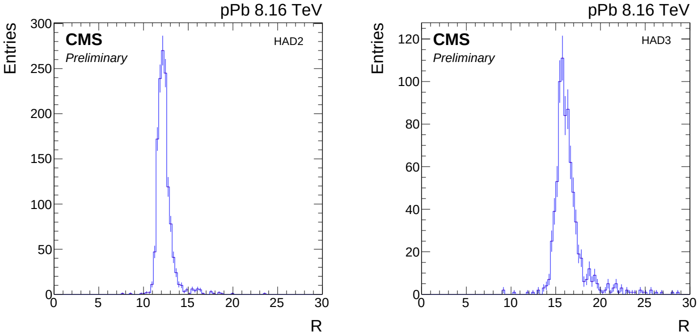
ZDC signal definition



- Maximum in time slice 3 (TS3)
- The definition of ZDC signal for a given *i* channel:

$$Q_i = Q_{i,\mathrm{TS3}} - \frac{1}{2}(Q_{i,\mathrm{TS2}} + Q_{i,\mathrm{TS6}})$$

Low gain ZDC signal



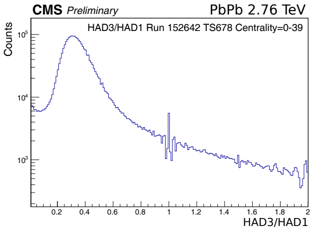
- When TS3 saturated, using $R \cdot \text{TS4}$
- Saturated signal:

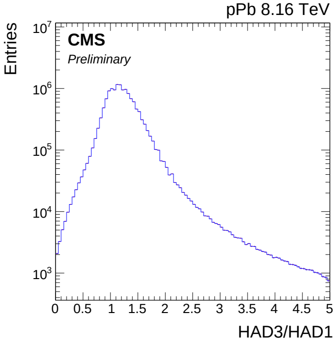
$$Q_i^* = R \cdot \left[Q_{i,\text{TS4}} - \frac{1}{2}(Q_{i,\text{TS2}} + Q_{i,\text{TS6}}) \right]$$

- R is calculated from not saturated events:

$$R = \left\langle \frac{Q_{i,\text{TS3}} - \frac{1}{2}(Q_{i,\text{TS2}} + Q_{i,\text{TS6}})}{Q_{i,\text{TS4}} - \frac{1}{2}(Q_{i,\text{TS2}} + Q_{i,\text{TS6}})} \right\rangle$$

Matching channel gains





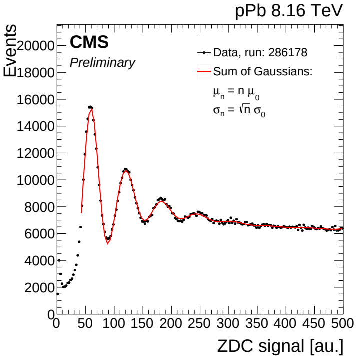
Relative gain matching:

- w_i weights for each channels.
- Cross-calibration to 2010 data, using variables:
  - HAD2/HAD1
  - HAD3/HAD1
  - HAD4/HAD1

Total ZDC signal:

$$Q_{\mathrm{ZDC}} = \sum_i w_i Q_i$$

Calibration – neutron peaks

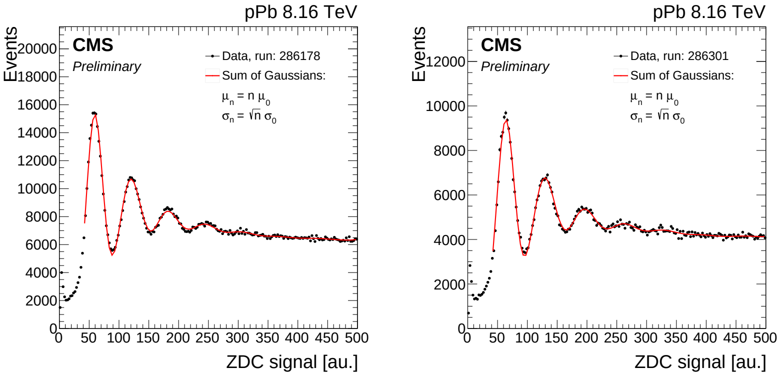


- Pb-going side
- Spectator neutrons are nearly monoenergetic due to large boost of the Pb ion.
- 1, 2, 3 neutron peaks clearly visible
- Fit with sum of Gaussians, with:

$$\mu_n = n\mu_0$$
$$\sigma_n^2 = n\sigma_0^2$$

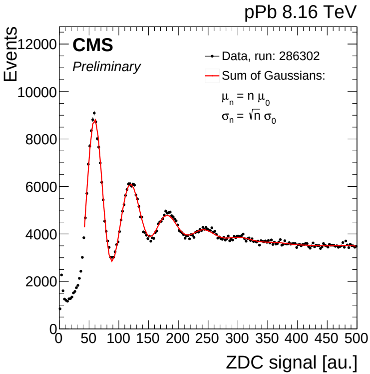
- 1 neutron peak at 2.56 TeV (nominal value for $\sqrt{s_{NN}} = 8.16$ TeV)

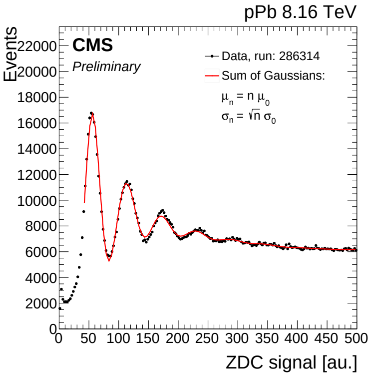
Example fits – 1



Run number	286178	286301	286302	286314
1 n peak location	59.2 ± 0.04	63.70 ± 0.05	59.02 ± 0.04	55.79 ± 0.03
1 n peak width	14.24 ± 0.02	15.25 ± 0.03	13.94 ± 0.03	13.14 ± 0.03

Example fits – 2





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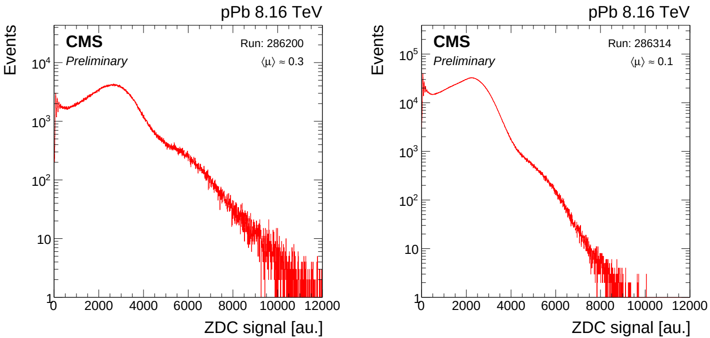
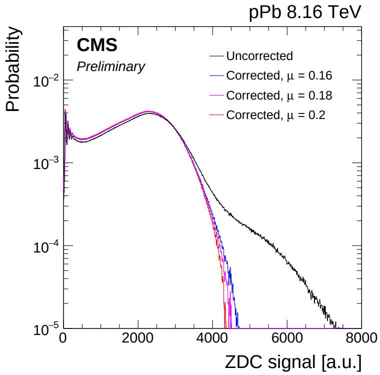
2. Pileup correction

Pileup in ZDC runs



- The shoulder at high signal values is the effect of pileup:
  - Larger tail at runs with higher pile-up.
- Possibilities for pileup subtraction:
  - Selecting single vertex events + corrections
  - **Deconvolution via Fourier transform**
- $\langle \mu \rangle$: mean number of collisions yielding neutrons in the ZDC acceptance. (Nuclear + electromagnetic + diffractive collisions.)

Pileup correction



- Pileup corrected with Fourier deconvolution method:

$$f(x) = g(x)\,p_1 + (g * g)(x)\,p_2 + (g * g * g)(x)\,p_3 + \dots$$

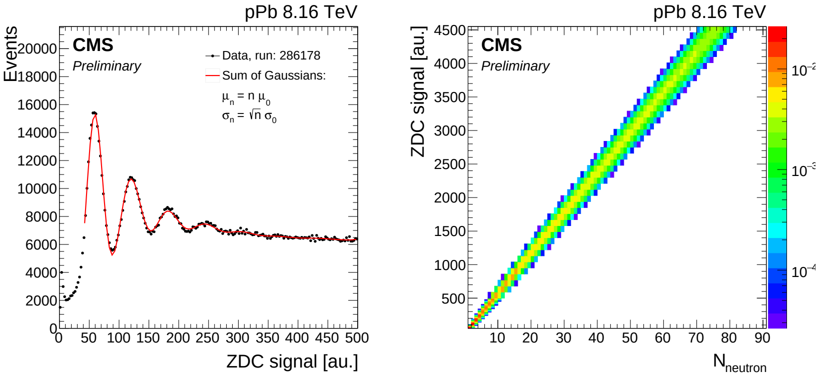
$$F(\omega) = \sum_{k=1}^{\infty} p_k\,G^k(\omega) = \frac{e^{-\mu}}{1 - e^{-\mu}} \sum_{k=1}^{\infty} \frac{(\mu\,G(\omega))^k}{k!} = \frac{e^{-\mu}}{1 - e^{-\mu}} \left(e^{\mu G(\omega)} - 1\right)$$

$$g(x) = \mathfrak{F}^{-1}\left[\frac{1}{\mu} \log\left[1 + (e^{\mu} - 1)F(\omega)\right]\right]$$

Similar method used in: A. Laszlo et al. JINST **11** (2016) no.10, P10017 [arXiv:1605.06939].

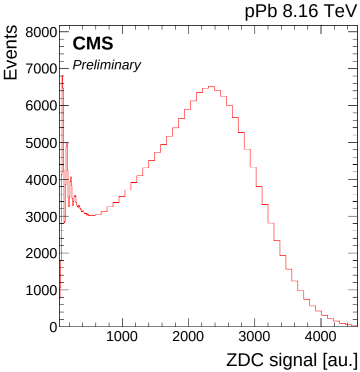
3. Unfolding

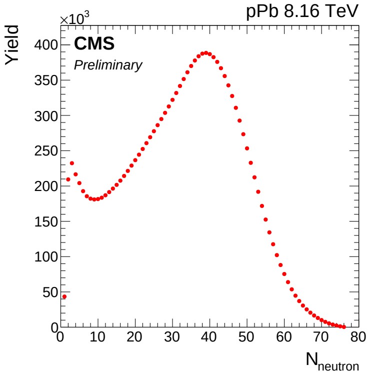
Unfolding



- Monoenergetic neutrons → neutron number distribution can be unfolded from ZDC signal distribution.
- Response matrix constructed from data with assumptions:
  - Assuming Gauss shape ZDC response for single neutron
  - Assuming linear ZDC response
- Using linear regularization for unfolding.

Unfolding





Neutron number distribution successfully unfolded.

4. Centrality

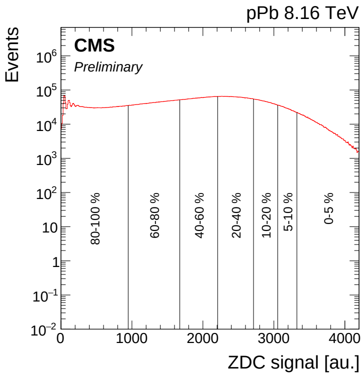
Centrality

Number of spectator neutrons:

- Unbiased centrality estimator
- Theoretical model needed to describe the relation

$$\langle N_{coll} \rangle = f(N_{neuton})$$

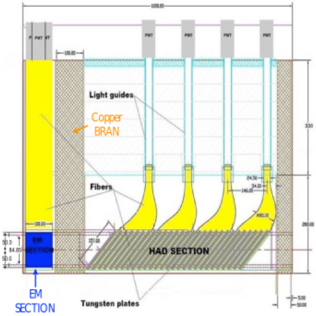
- Models working only for lower energies
- **Measuring spectator neutron multiplicity distribution**: useful input for tuning MC event generators to describe LHC energies

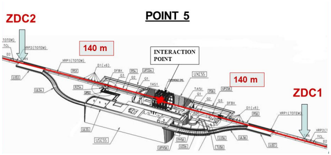


Backup

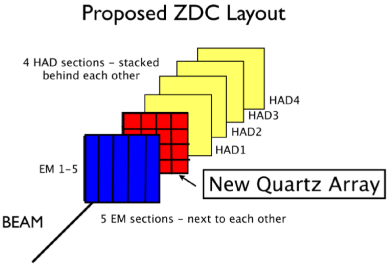
ZDC detector

- Tungsten + quartz-fibre sampling Cerenkov calorimeter
- Located in TAN, $\sim$ 140 m from IP5
- EM + hadronic sections
- Measures forward neutral particles (neutrons and photons) at $|\eta| > 8.5$





ZDC detector



Segmentation:

- EM: y-axis – 5 channels
- HAD: longitudinally – 4 channels
- RPD: 4 x 4 quartz array – 16 channels

Physics capabilities:

- Centrality in pA, AA
- Tagging UPC events
- Event plane (with RPD)

Deconvolution via Fourier transform

Assume that n number of collisions is Poisson distributed:

$$P(n) = \frac{\mu^n}{n!} \frac{\mathrm{e}^{-\mu}}{1 - \mathrm{e}^{-\mu}}$$

(only the $n > 0$ case is considered, $1 - \mathrm{e}^{-\mu}$ appears in the denominator to ensure proper normalization)

Then the ZDC energy deposit can be described by X probability variable:

$$X = \sum_{i=1}^{n} Y_i,$$

where Y_i is the probability variable describing ZDC energy deposit for a single event.

Deconvolution via Fourier transform

Aim: calculate the pdf of Y_i, $g(x)$ when the pdf of X is known: $f(x)$.
Using total probability theorem:

$$f(x) = g(x)\,p_1 + (g * g)(x)\,p_2 + (g * g * g)(x)\,p_3 + \dots$$

Taking the Fourier transform of both sides:

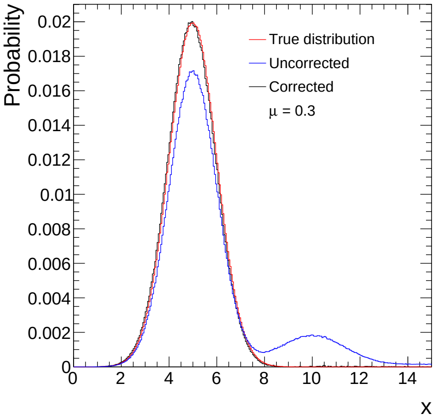
$$F(\omega) = \sum_{k=1}^{\infty} p_k\, G^k(\omega) = \frac{e^{-\mu}}{1 - e^{-\mu}} \sum_{k=1}^{\infty} \frac{(\mu\, G(\omega))^k}{k!} = \frac{e^{-\mu}}{1 - e^{-\mu}} \left(e^{\mu G(\omega)} - 1 \right)$$

After expressing $G(\omega)$ and doing inverse Fourier transform:

$$g(x) = \mathfrak{F}^{-1} \left[\frac{1}{\mu} \log \left[1 + (e^{\mu} - 1) F(\omega) \right] \right]$$

Similar method used in: A. Laszlo et al. JINST **11** (2016) no.10, P10017 [arXiv:1605.06939].

Result on toy model



- Simple model: ZDC signal distributed as Gaussian + Poisson pileup.
- Method is **verified** by the toy model.

Unfolding with linear regularization

Solve problem as a linear optimization problem:

$$\mathbf{R} \cdot \mathbf{u} = \mathbf{c}$$

- **R**: response matrix
- **u**: unknown neutron distribution
- **c**: measured ZDC spectrum

Task: search for an **u** vector, which fulfils the equation above and 'smooth enough'.

Unfolding with linear regularization

Minimize

$$(\mathbf{R} \cdot \mathbf{u} - \mathbf{c})^{\mathsf{T}} \mathbf{V}^{-1} (\mathbf{R} \cdot \mathbf{u} - \mathbf{c}) + \lambda (\mathbf{D} \cdot \mathbf{u})^2$$

- **V**: covariance matrix, $V_{ij} \approx \delta_{ij} c_i$
- **D**: first difference matrix
- λ: regularization coefficient

Need to solve matrix equation:

$$(\mathbf{R}^{\mathsf{T}} \mathbf{V}^{-1} \mathbf{R} + \lambda \mathbf{D}^{\mathsf{T}} \mathbf{D}) \mathbf{u} = \mathbf{R}^{\mathsf{T}} \mathbf{V}^{-1} \mathbf{c}$$