The Forward Detectors of CMS experiment

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Performance of the CMS Zero Degree Calorimeters in the 2016 pPb run
1. Physics motivation
1. Centrality in hA and AA collisions

Heavy ion (AA) collisions:
- Impact parameter $\sim$ Number of binary collisions ($N_{\text{coll}}$)
- Important in the measurement of nuclear modification factor:

$$R_{AA} = \frac{dN^{AA}/d\rho_T}{\langle N_{\text{coll}} \rangle dN^{pp}/d\rho_T}$$

- Typical centrality estimator: charged particle multiplicity

Hadron-nucleus (hA) collisions:
- Relevant quantity is $N_{\text{coll}}$, but only loosely correlated with impact parameter and multiplicity
- Unbiased centrality estimator: zero degree energy
2. Slow nucleons in hadron-nucleus collisions

Hadron-nucleus collision
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Hadron-nucleus collision

\[ \Downarrow \]

\[ \text{NN collisions} \Rightarrow \text{grey nucleons } (\beta \in [0.3, 0.7]) \]
2. Slow nucleons in hadron-nucleus collisions

Hadron-nucleus collision

\[ \Rightarrow \]

\( NN \) collisions \( \Rightarrow \) grey nucleons \( (\beta \in [0.3, 0.7]) \)

\[ \Rightarrow \]

Excited nucleus
2. Slow nucleons in hadron-nucleus collisions

Hadron-nucleus collision

$\downarrow$

$NN$ collisions $\Rightarrow$ **grey nucleons** ($\beta \in [0.3, 0.7]$)

$\downarrow$

Excited nucleus

$\downarrow$

Break-up of nucleus
2. Slow nucleons in hadron-nucleus collisions

Hadron-nucleus collision

\[\downarrow\]

\[NN\] collisions \(\Rightarrow\) **grey nucleons** \((\beta \in [0.3, 0.7])\)

\[\downarrow\]

Excited nucleus

\[\downarrow\]

Break-up of nucleus

\[\downarrow\]

Nuclear evaporation \(\Rightarrow\) **black nucleons** \((\beta < 0.3)\)
3. Utraperipheral collisions

- Interacting only via EM field (\( \sim p\gamma \) and \( \gamma\gamma \) collisions)
- Using ZDC as a veto:
  - Ensures intact nucleus/nuclei.
- E.g. \( \Upsilon \) photoproduction → probing gluon pdf of proton
4. Flow and reaction plane

- Hot, dense matter produced in heavy ion collisions
- $\phi$-distribution of particles w.r.t. reaction plane expanded to Fourier modes ($v_n$).
- $v_n$: flow coefficients, signature of anisotropy and behaviour of hot, dense matter
- Important: reaction plane, but very hard to measure → can be estimated by considering spectator neutron spatial distribution
2. The CMS Zero Degree Calorimeter
Zero Degree Calorimeter

- Located in neutral particle absorber (TAN), \( \sim 140 \, \text{m} \) from IP5 – between the two beampipes.
- Measures forward neutral particles at \(|\eta| > 8.5\).
- Charged products are wiped out by magnets.
Segmentation of 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)
ZDC detector

Electromagnetic section (EM):
- 33 vertical tungsten plates
- 19 radiation lengths or one nuclear interaction length.
- 5 divisions in the x direction
  (Not enough room for read-out of y-segmentation)

Hadron section (HAD):
- 24 tungsten plates
- 5.6 hadronic interaction length
- Plates are tilted by $45^\circ$ → maximizes the light that a fiber can pick up.
- Divided into 4 segments in z direction
3. Calibration
Continuous readout with 25 ns timeslices.
- 100 ns bunch spacing → out-of-time pileup in TS7 and TS-1.
- Maximum in time slice 3 (TS3).
- The definition of ZDC signal for a given \( i \) channel:

\[
Q_i = Q_{i,TS3} - \frac{1}{2}(Q_{i,TS2} + Q_{i,TS6})
\]
Low gain ZDC signal

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

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

- $R$ is calculated from not saturated events:

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

Relative gain matching:

- Intercalibration
- Cross-calibration to 2010 data, using variables:
  - HAD2/HAD1
  - HAD3/HAD1
  - HAD4/HAD1
- Choosing $w_i$ weights to match the maximum of distributions

Total ZDC signal:

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

where $i \in \{\text{EM1-5, HAD1-4}\}$

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Pb-going side

Nearly monoenergetic neutrons due to large boost of Pb-ion

1, 2, 3 neutron peaks are clearly visible

Fit with sum of Gaussians, with fixed mean and variance:

\[ \mu_n = n \mu_0 \]
\[ \sigma_n^2 = n \sigma_0^2 \]

1 neutron peak at 2.56 TeV (nominal value for \( \sqrt{s_{NN}} = 8.16 \) TeV)
4. Pileup correction
Pileup in ZDC runs

- Larger shoulder for larger pileup values
- Looking for $\langle \mu \rangle = 0$ case, expectation: shoulder disappears
- Using Fourier deconvolution method
Assume that $n$ number of pPb collisions in a bunch crossing is Poisson distributed:

$$p_n = \frac{\mu^n}{n!} \frac{e^{-\mu}}{1 - e^{-\mu}}$$

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

$\mu$: ZDC-effective number of collisions.

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

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

where $Y_i$ is the random variable describing ZDC energy deposit for an event with single collision.
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:

\[
f(x) = g(x) \, p_1 + (g \ast g)(x) \, p_2 + (g \ast g \ast g)(x) \, p_3 + \ldots
\]

Taking the Fourier transform of both sides

\( f(x) \rightarrow F(\omega), \ g(x) \rightarrow G(\omega) \):

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

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

\[
g(x) = \mathcal{F}^{-1} \left[ \frac{1}{\mu} \log \left[ 1 + (e^\mu - 1)F(\omega) \right] \right]
\]
Simple model: ZDC signal distributed as Gaussian + Poisson pileup.

Method is validated by the toy model.
Pileup correction

Results are consistent with the expectation. The $\mu = 0.18$ result is used in the following step.
5. Application 1: Centrality with ZDC in pPb collisions
Centrality with ZDC in pPb collisions

Number of spectator neutrons:

- Unbiased centrality estimator in pPb collisions
- Theoretical model needed to describe the relation

\[ \langle N_{\text{coll}} \rangle = f(N_{\text{neutron}}) \]

- Models working only for lower energies
- Measuring spectator neutron multiplicity distribution: useful input for tuning MC event generators to describe LHC energies
6. Application 2: Unfolding neutron number distribution
Assuming Gauss shape ZDC response for single neutron
Assuming linear ZDC response
Using linear regularization to unfold neutron number distribution
Summary

- Zero Degree Calorimeter – ZDC
- Spectator neutrons are observed with CMS ZDC
- ZDC is calibrated using neutron peaks
- Pile-up corrected with Fourier transform method
- Neutron number distribution unfolded
- Physics capabilities:
  - Tagging UPC events
  - Centrality estimator
  - Measuring spectator neutron multiplicity distribution

Thank you for your attention!

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7. Backup
Cherenkov angle:

\[ \cos \theta = \frac{1}{n\beta} \]

\[ \beta \approx 1 \quad \text{for relativistic particles,} \]

\[ n \approx \sqrt{2} \quad \text{for quartz fiber} \]

\[ \Rightarrow \theta \approx 45^\circ \]
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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<th>286178</th>
<th>286301</th>
<th>286302</th>
<th>286314</th>
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Unfolding with linear regularization

Solve problem as a linear optimization problem:

\[ R \cdot u = c \]

- **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

\[(R \cdot u - c)^T V^{-1} (R \cdot u - c) + \lambda (D \cdot u)^2\]

- \(V\): covariance matrix, \(V_{ij} \approx \delta_{ij}c_i\)
- \(D\): first difference matrix
- \(\lambda\): regularization coefficient

Need to solve matrix equation:

\[(R^T V^{-1} R + \lambda D^T D)u = R^T V^{-1} c\]