

# Performance of the Zero Degree Calorimeters in CMS

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## Hadron-nucleus collision

# Forward neutrons in hA and AA collisions

Hadron-nucleus collision



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

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Excited nucleus

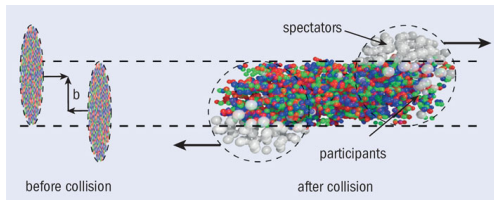


Break-up of nucleus



Nuclear evaporation  $\Rightarrow$  **black nucleons** ( $\beta < 0.3$ )

# Motivation 1: Centrality in hA and AA collisions



- Heavy ion (AA) collisions:

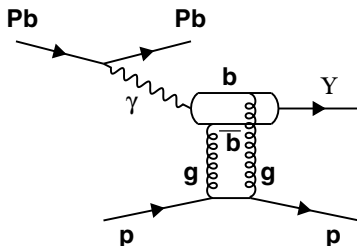
- Impact parameter  $\sim$  Number of binary collisions ( $N_{\text{coll}}$ )
- Important in the measurement of nuclear modification factor:

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

- 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

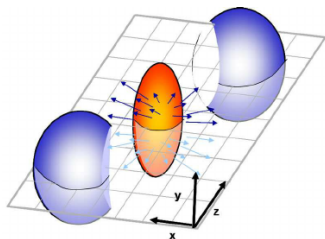
## Motivation 2: Utraperipheral collisions

- Interacting only via EM field ( $\sim p\gamma$  and  $\gamma\gamma$  collisions)
- Using ZDC as a veto:
  - Selects events where nucleus/nuclei remain intact.
- E.g.  $\Upsilon$  photoproduction  $\rightarrow$  probing gluon pdf of proton



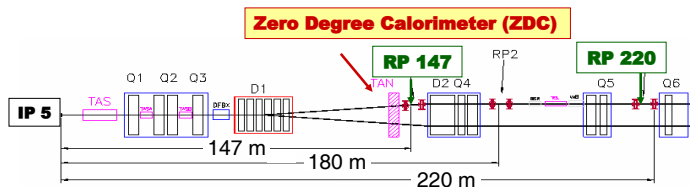
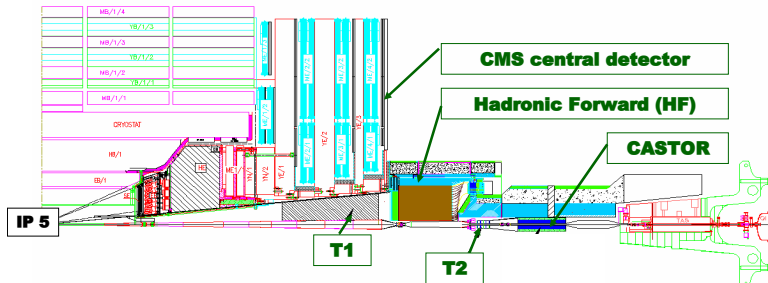


## Motivation 3: Flow and reaction plane



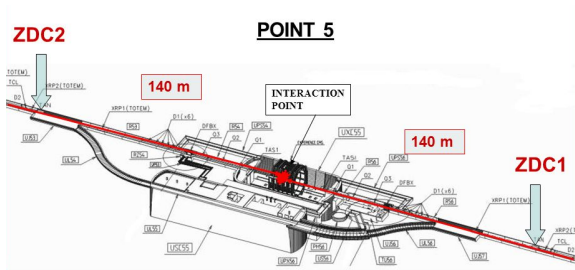
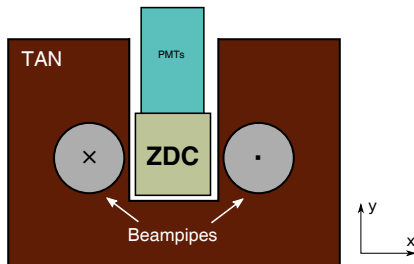
- Hot, dense matter produced in heavy ion collisions
- $\phi$ -distribution of particles w.r.t. reaction plane expanded to Fourier modes ( $v_n$ ).
- $v_n$ : flow coefficients, signature of anisotropy and behaviour of hot, dense matter
- Important: reaction plane, but very hard to measure  
→ can be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

# The Forward Detectors of CMS experiment

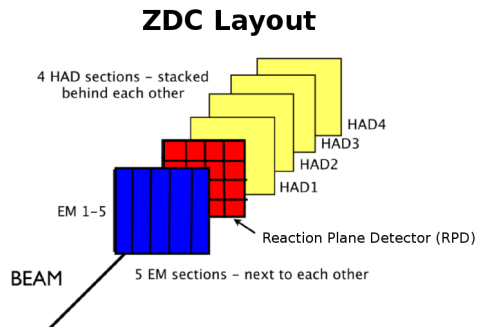


# Zero Degree Calorimeter

- Located in neutral particle absorber (TAN),  $\sim 140$  m from IP5 – between the two beamppipes.
- 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)

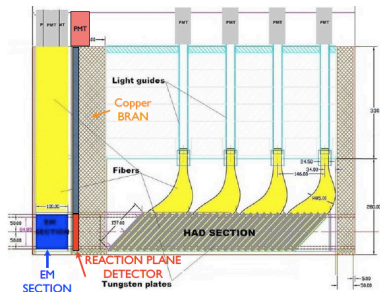
# ZDC detector

## Electromagnetic section (EM):

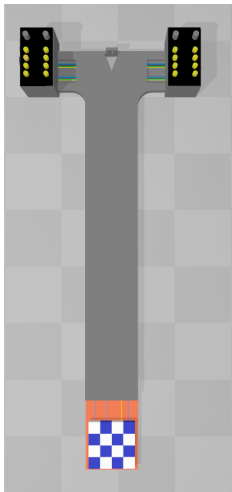
- 33 vertical tungsten plates
- 19 radiation lengths or one nuclear interaction length.
- 5 divisions in the x direction  
(Not enough room for read-out of y-segmentation)

## Hadron section (HAD):

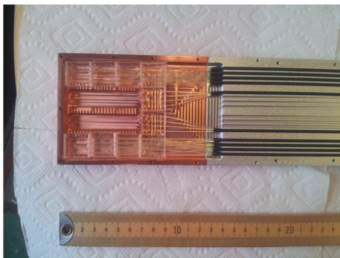
- 24 tungsten plates
- 5.6 hadronic interaction length
- Plates are tilted by  $45^\circ$  → maximizes the light that a fiber can pick up.
- Divided into 4 segments in z direction



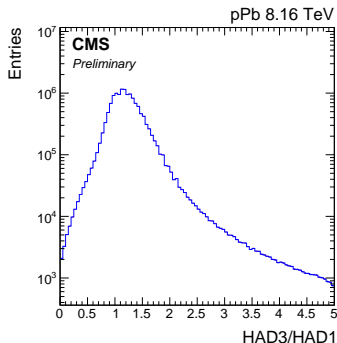
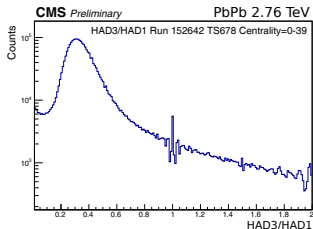
# Reaction Plane Detector



- 4x4 array of quartz fibers
- readout via wavelength shifting fibers.
- Improves energy resolution by catching leakage.
- Working on reaction plane(considering machine learning)



# Matching channel gains



Relative gain matching:

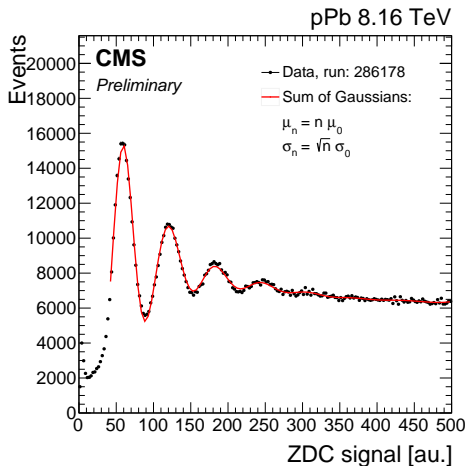
- Intercalibration
- Cross-calibration to 2010 data, using variables:
  - HAD2/HAD1
  - HAD3/HAD1
  - HAD4/HAD1
- Choosing  $w_i$  weights to match the maximum of distributions

Total ZDC signal:

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

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

# Calibration – neutron peaks



- 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:

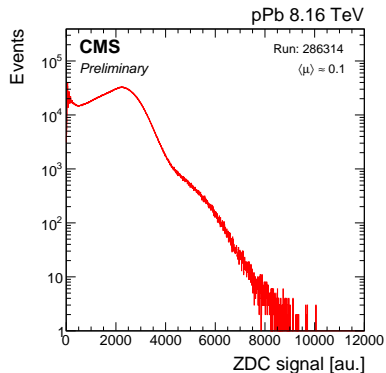
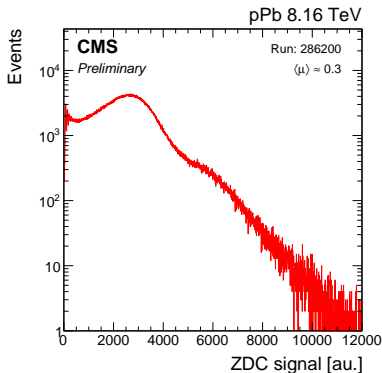
$$\mu_n = n \mu_0$$

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

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

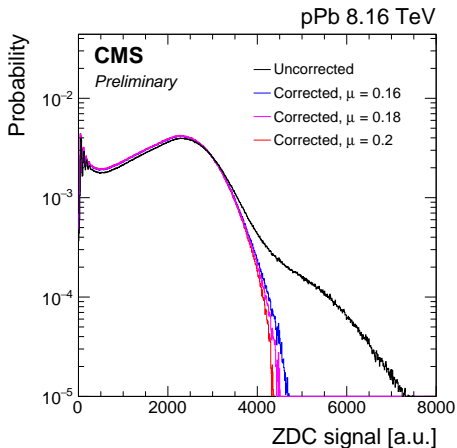


# Pileup in ZDC runs



- Larger shoulder for larger pileup values
- Looking for  $\langle\mu\rangle = 0$  case, expectation: shoulder disappears
- Using Fourier deconvolution method

# Pileup correction



Results are consistent with the expectation.  
The  $\mu = 0.18$  result is used in the following step.

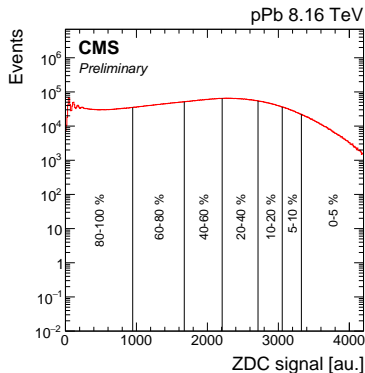
# Application 1: Centrality with ZDC in pPb collisions

Number of spectator neutrons:

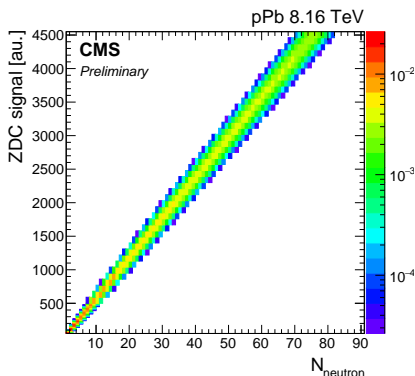
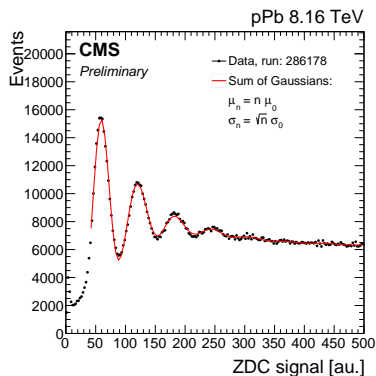
- Unbiased centrality estimator in pPb collisions
- Theoretical model needed to describe the relation

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

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

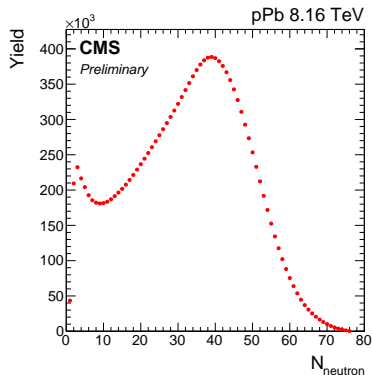
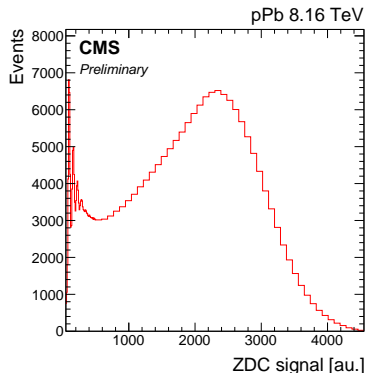


# Application 2: Measuring neutron number distribution



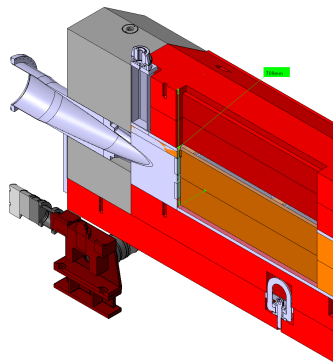
- Assuming Gauss shape ZDC response for single neutron
- Assuming linear ZDC response

## Application 2: Measuring neutron number distribution



Using linear regularization to unfold neutron number distribution

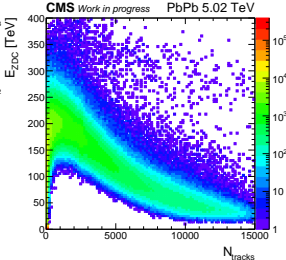
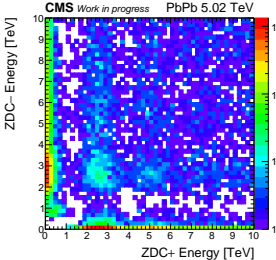
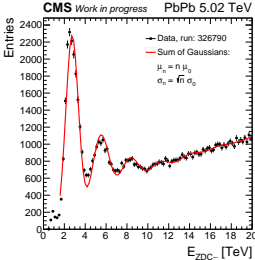
# ZDCs for High Luminosity LHC



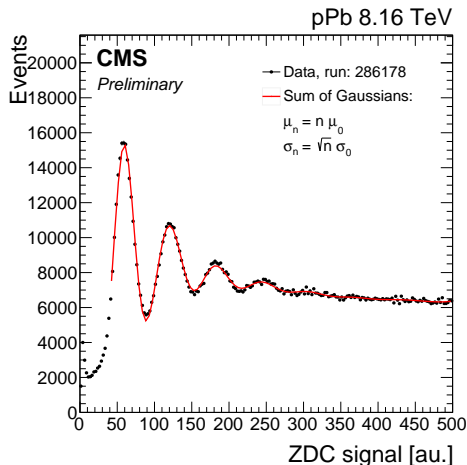
- ZDCs will move 15m closer to interaction point
- The TAN absorber will be replaced by the TAXN
- Slot will be reduced from 10cm to 5cm
- If the ZDCs are to be used for special runs they need to survive Grads
- Using ultra pure fused silica tested by BRAN group

# Recent results

## ZDCs working very well



# Summary



- ZDC calibrated using neutron peaks
- Pile-up corrected with Fourier transform
- Neutron number distribution unfolded
- Physics capabilities:
  - Tagging UPC events
  - Centrality estimator
  - Measuring spectator neutron multiplicity distribution
- Working with ATLAS on ZDCs for HL-LHC



# 1. Backup

# Cherenkov angle

Cherenkov angle:

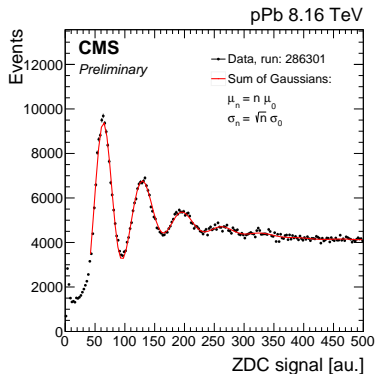
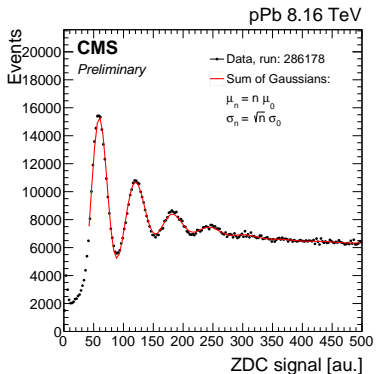
$$\cos \theta = \frac{1}{n\beta}$$

$\beta \approx 1$  for relativistic particles,

$n \approx \sqrt{2}$  for quartz fiber

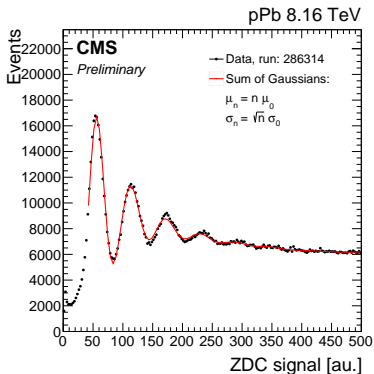
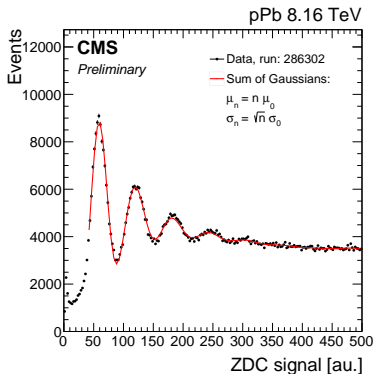
$$\Rightarrow \theta \approx 45^\circ$$

# Example fits – 1



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

## Example fits – 2



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

## Deconvolution via Fourier transform

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:

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

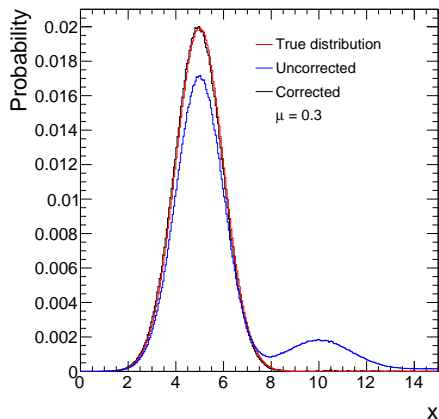
Taking the Fourier transform of both sides  
( $f(x) \rightarrow F(\omega)$ ,  $g(x) \rightarrow G(\omega)$ ):

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

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

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

# Pileup correction result on toy model



- Simple model: ZDC signal distributed as Gaussian + Poisson pileup.
- Method is **validated** 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

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

- $\mathbf{V}$ : covariance matrix,  $V_{ij} \approx \delta_{ij} C_i$
- $\mathbf{D}$ : first difference matrix
- $\lambda$ : regularization coefficient

Need to solve matrix equation:

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