

Neutron detection with CMS ZDC

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Wigner RCP

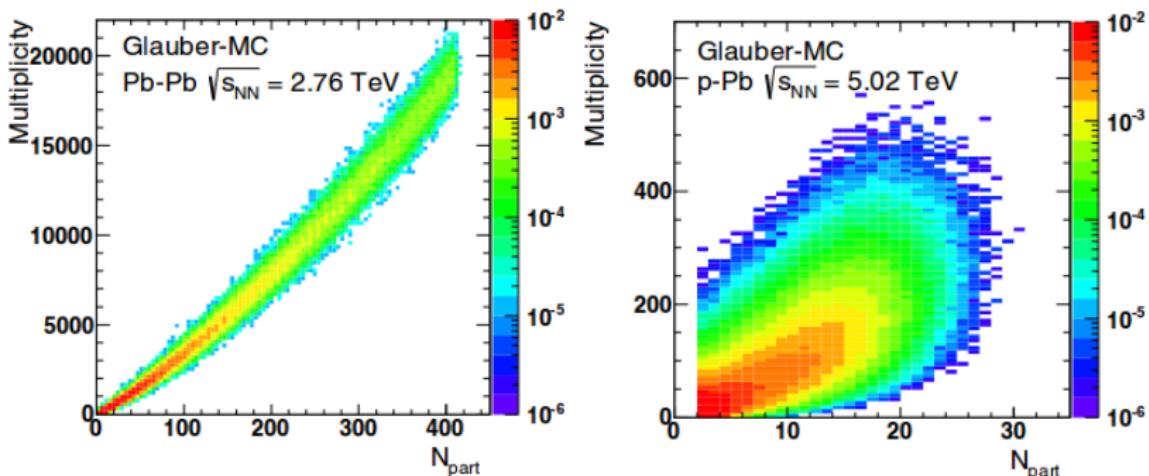
Eötvös Loránd University

Budapest, Hungary

Zimányi School, 5th December 2017

1. Motivation

Centrality



ALICE Collaboration, Phys. Rev. C 91 (2015) no.6, 064905, arXiv:1412.6828 [nucl-ex].

- Centrality in pPb collisions:

- Multiplicity fluctuations: PbPb centrality estimators cannot be used in pPb
- Number of spectator neutrons: unbiased centrality estimator in pPb → **Zero Degree Calorimeter – ZDC**

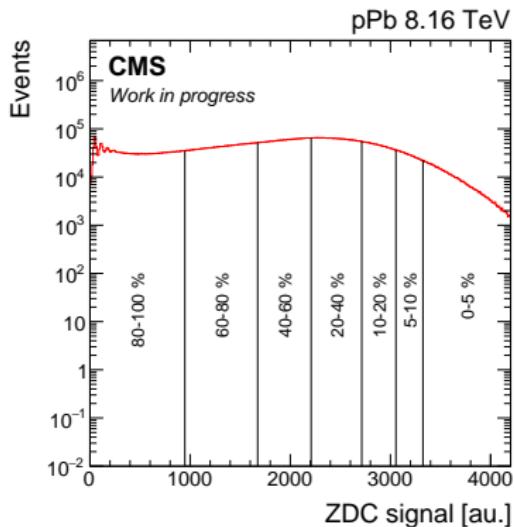
Centrality

Number of spectator neutrons:

- Unbiased centrality estimator
- 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



2. Slow nucleons in hadron-nucleus collisions

Slow nucleons

Hadron-nucleus collision

Slow nucleons

Hadron-nucleus collision



NN collisions \Rightarrow **grey nucleons** ($\beta \in [0.25, 0.7]$)

Slow nucleons

Hadron-nucleus collision



NN collisions \Rightarrow **grey nucleons** ($\beta \in [0.25, 0.7]$)



Excited nucleus

Slow nucleons

Hadron-nucleus collision



NN collisions \Rightarrow **grey nucleons** ($\beta \in [0.25, 0.7]$)



Excited nucleus



Break-up of nucleus

Slow nucleons

Hadron-nucleus collision



NN collisions \Rightarrow **grey nucleons** ($\beta \in [0.25, 0.7]$)



Excited nucleus



Break-up of nucleus

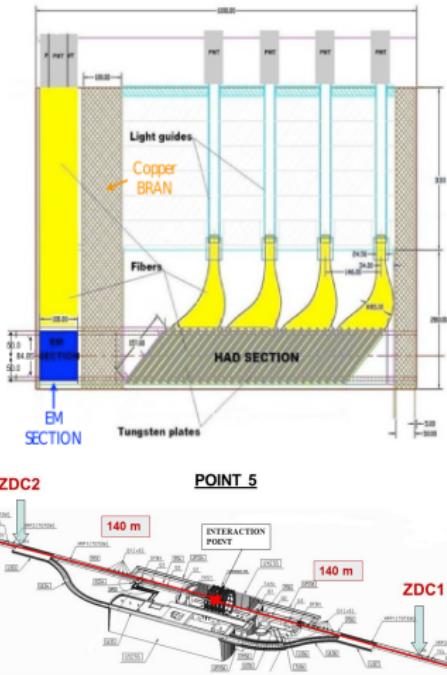


Nuclear evaporation \Rightarrow **black nucleons** ($\beta < 0.25$)

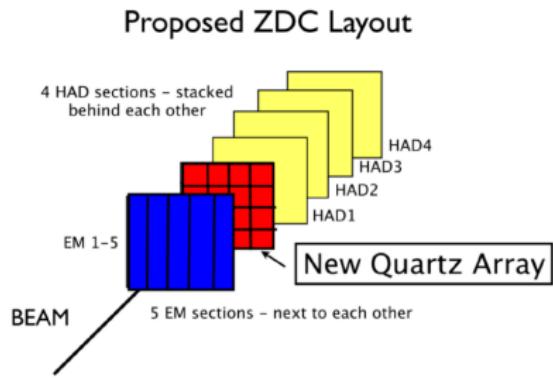
3. The CMS ZDC detector

ZDC detector

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



ZDC detector



Segmentation:

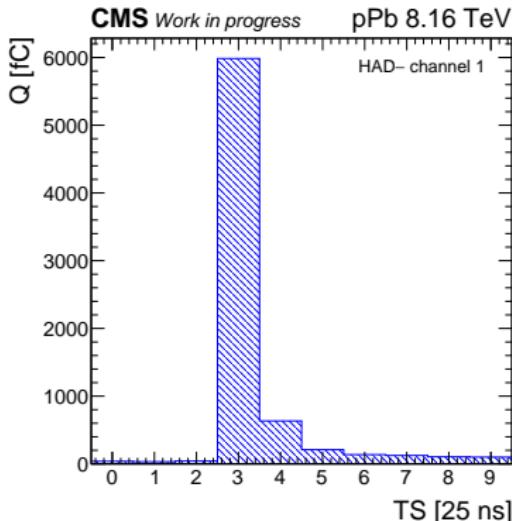
- EM: y-axis – 5 channels
- HAD: longitudinally – 4 channels
- RPD: 4 x 4 quartz array – 16 channels

Physics capabilities:

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

4. Calibration

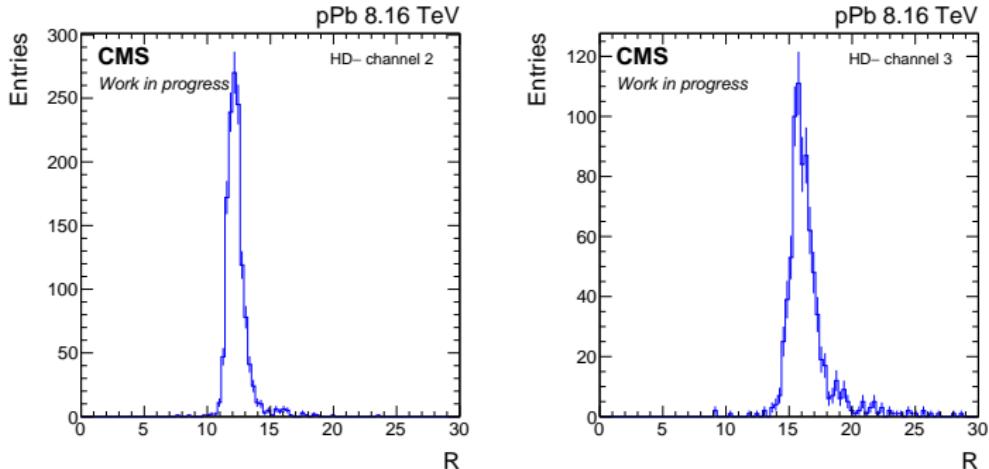
ZDC signal definition



- 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



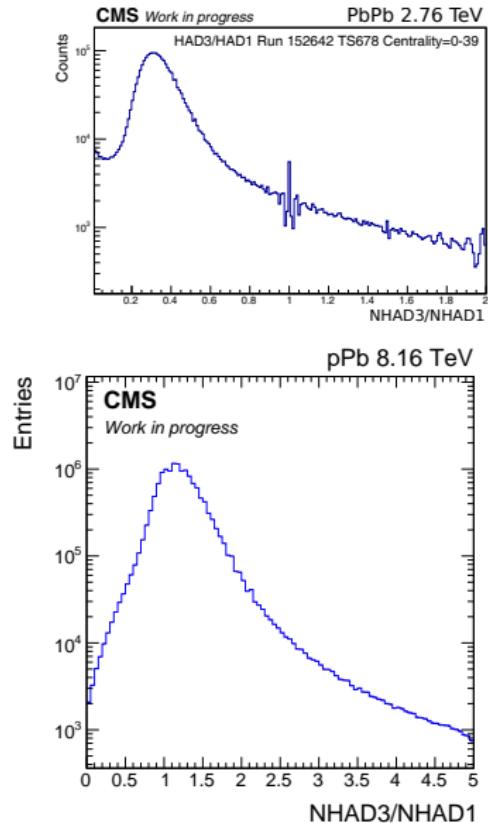
- When TS3 saturated, using $R \cdot TS4$
- Saturated signal:

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

- 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



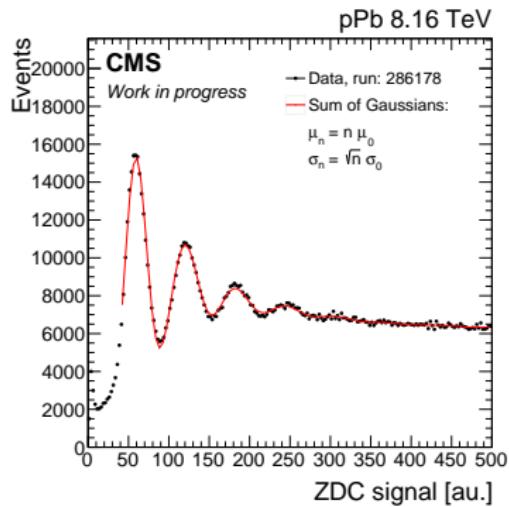
Relative gain matching:

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

Total ZDC signal:

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

Calibration – neutron peaks



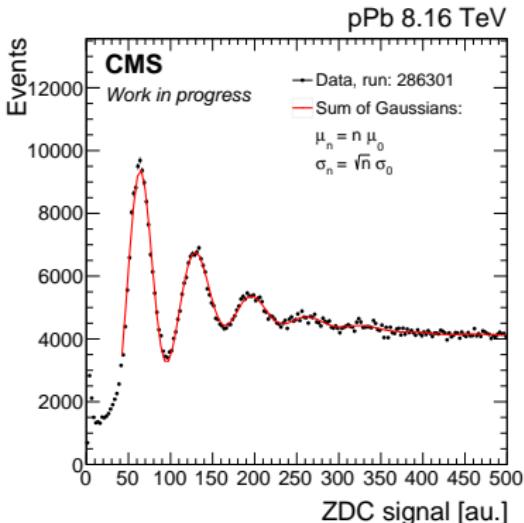
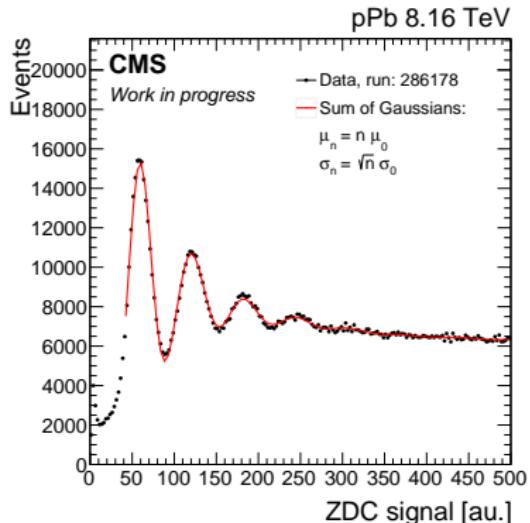
- Pb-going side
- 1, 2, 3 neutron peaks clearly visible
- Fit with sum of Gaussians, with:

$$\mu_n = n\mu_0$$

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

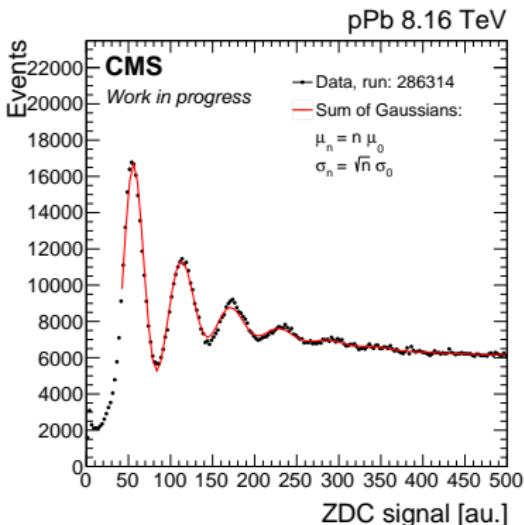
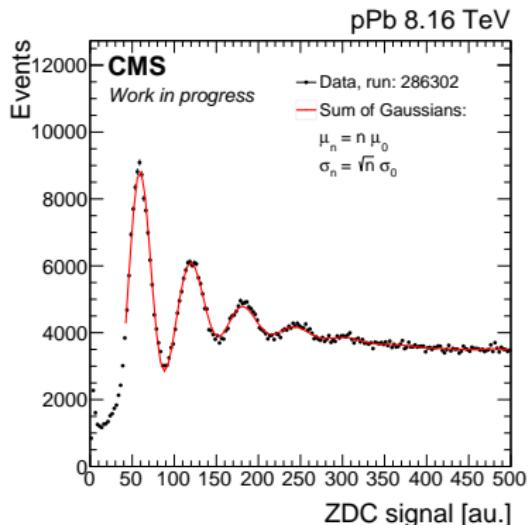
- 1 neutron peak at 2.56 TeV
(nominal value for $\sqrt{s_{NN}} = 8.16$ TeV)

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

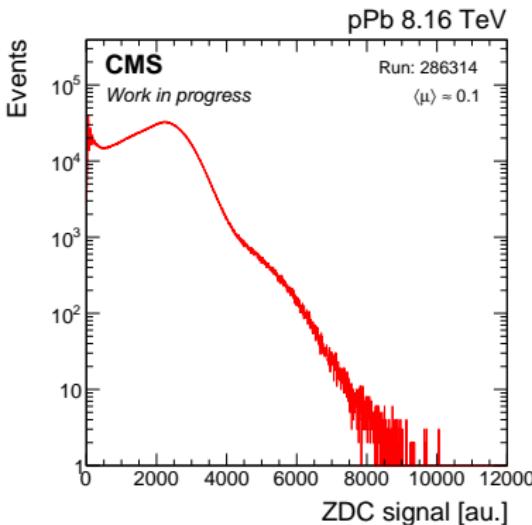
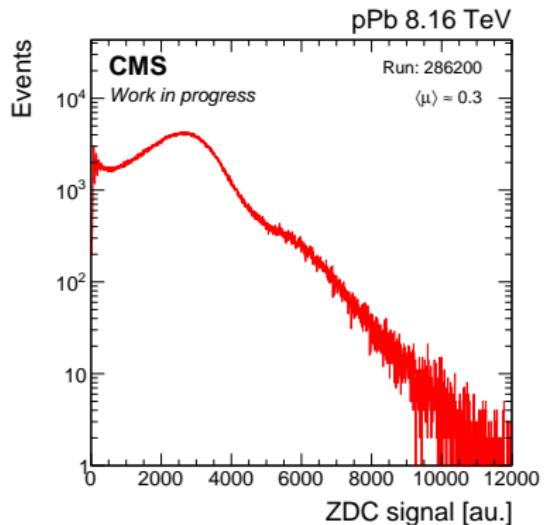
Example fits – 2



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

5. Pileup correction

Pileup in ZDC runs



- Effect of pileup is obvious.
- Possibilities for pileup subtraction:
 - Selecting single vertex events + corrections
 - Deconvolution via Fourier transform**

Deconvolution via Fourier transform

Assume that n number of collisions 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)

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:

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

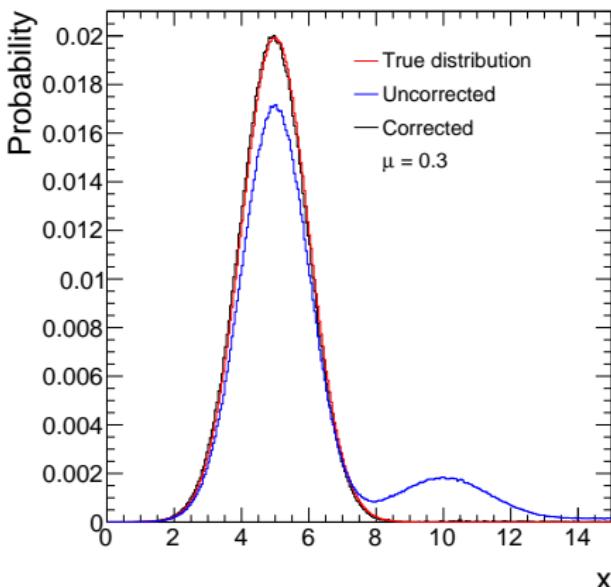
Taking the Fourier transform of both sides:

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

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

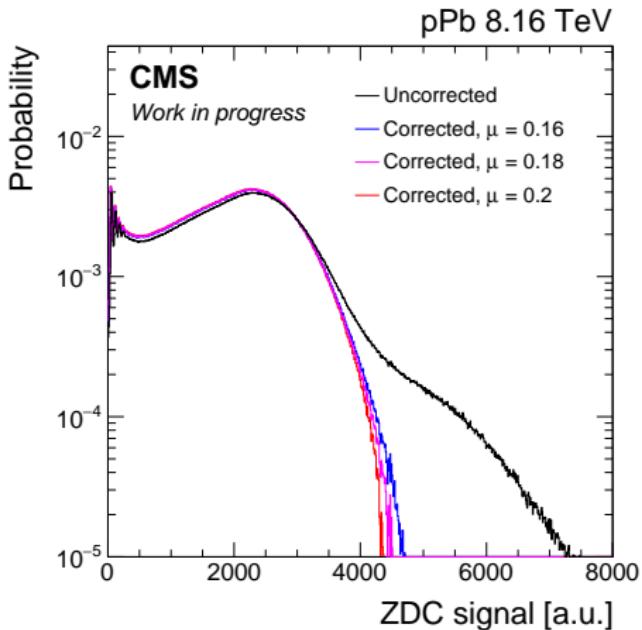
$$g(x) = \mathfrak{F}^{-1} \left[\frac{1}{\mu} \log [1 + (e^{\mu} - 1) F(\omega)] \right]$$

Result on toy model



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

Result on data



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

6. Unfolding neutron number distribution

Unfolding with linear regularization

Solve problem as a linear optimization problem:

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

- \mathbf{R} : response matrix
- \mathbf{u} : unknown neutron distribution
- \mathbf{c} : measured ZDC spectrum

Task: search for an \mathbf{u} vector, which fulfils the equation above and 'smooth enough'.

Unfolding with linear regularization

Minimize

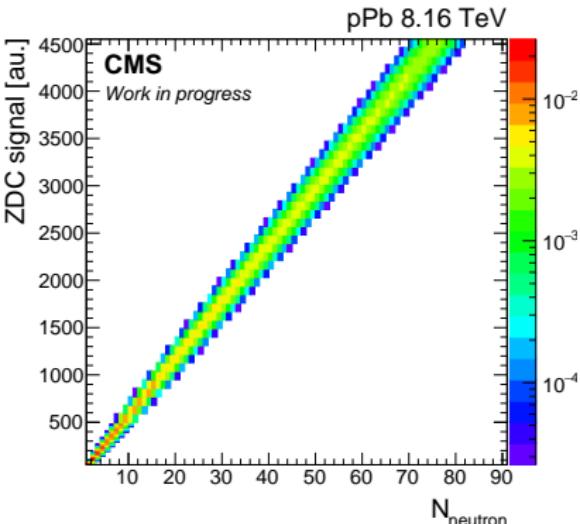
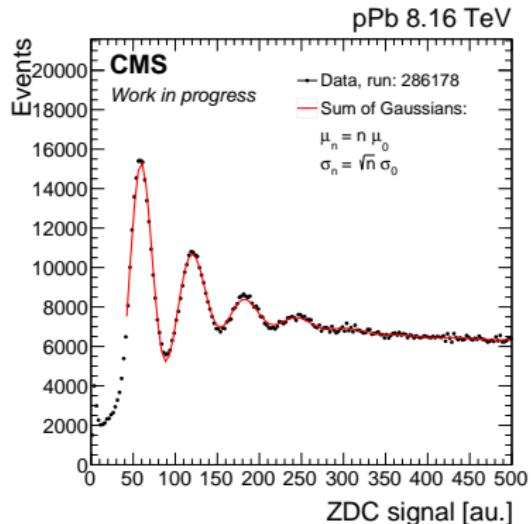
$$(\mathbf{R} \cdot \mathbf{u} - \mathbf{c})^T \mathbf{V}^{-1} (\mathbf{R} \cdot \mathbf{u} - \mathbf{c}) + \lambda (\mathbf{D} \cdot \mathbf{u})^2$$

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

Need to solve matrix equation:

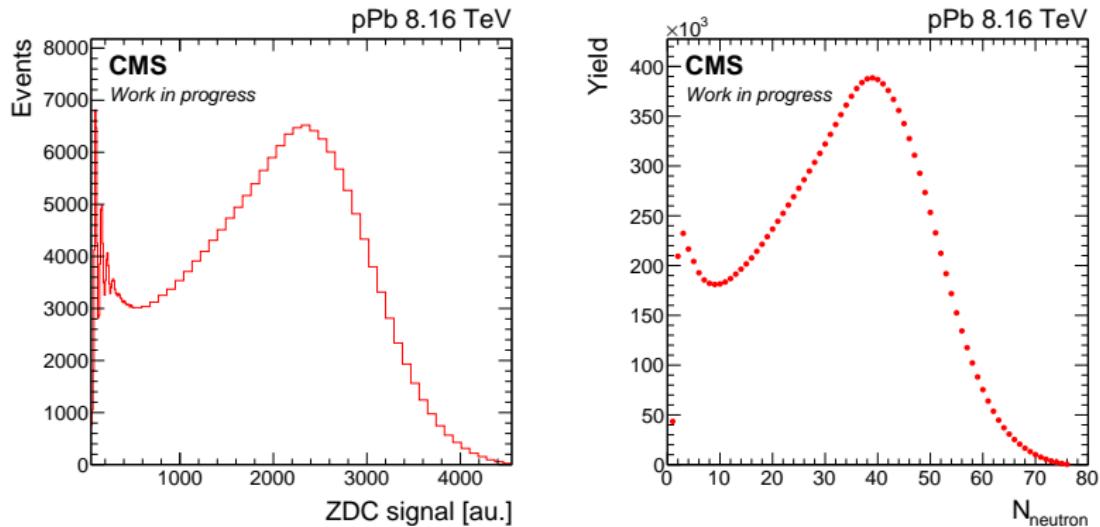
$$(\mathbf{R}^T \mathbf{V}^{-1} \mathbf{R} + \lambda \mathbf{D}^T \mathbf{D}) \mathbf{u} = \mathbf{R}^T \mathbf{V}^{-1} \mathbf{c}$$

Response matrix



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

Results



Neutron number distribution successfully unfolded.

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!