Zero-degree neutron measurements with CMS

Olivér Surányi

Eötvös Loránd University
Wigner RCP
Budapest, Hungary

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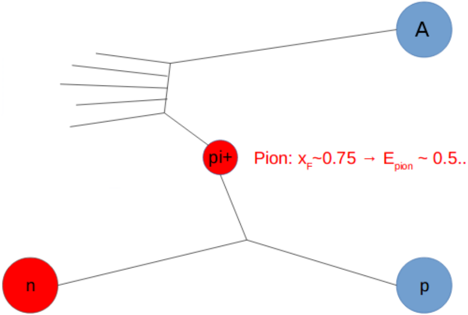
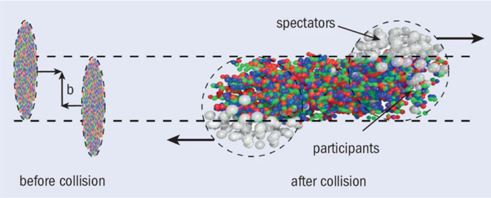
Cosmic ray physics motivation: Charge exchange in pA/pp collisions



- π^+A (or $\pi^+ p$) collision $\rightarrow$ different structure functions than pA/pp
- Pion not available at these energies
- **Extremely relevant for ultra-high energy cosmic ray physics**
- Process can be tagged by detecting neutron

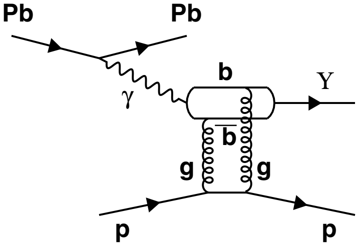
Particle physics motivation 1: Centrality in pA/AA coll.



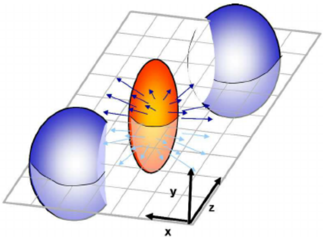
- Heavy ion (AA) collisions:
  - Impact parameter $\sim$ Number of binary collisions (N_{coll})
  - Important in the measurement of nuclear modification factor:
$$R_{AA} = \frac{\mathrm{d}N^{AA}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}} \rangle \mathrm{d}N^{pp}/\mathrm{d}p_{\mathrm{T}}}$$
  - Typical centrality estimator: charged particle multiplicity
- Hadron-nucleus (hA) collisions:
  - Relevant quantity is N_{coll}, but only loosely correlated with impact parameter and multiplicity
  - Unbiased centrality estimator: zero degree energy

Particle physics 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. Υ photoproduction $\rightarrow$ probing gluon pdf of proton



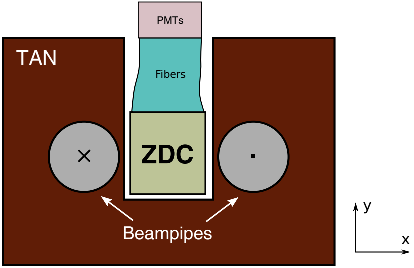
Particle physics motivation 3: Flow and reaction plane

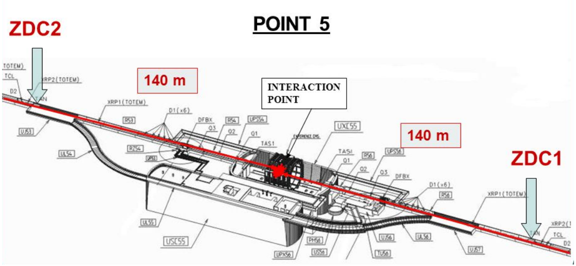


- Hot, dense matter produced in heavy ion collisions
- ϕ-distribution of particles w.r.t. reaction plane expanded to Fourier modes (v_n).
- v_n: flow coefficients, signature of anisotropy and behaviour of hot, dense matter
- Important: reaction plane, but very hard to measure $\rightarrow$ can be estimated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

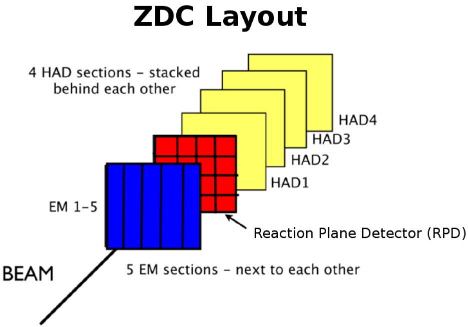
Zero Degree Calorimeter

- Located in neutral particle absorber (TAN), $\sim$ 140 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



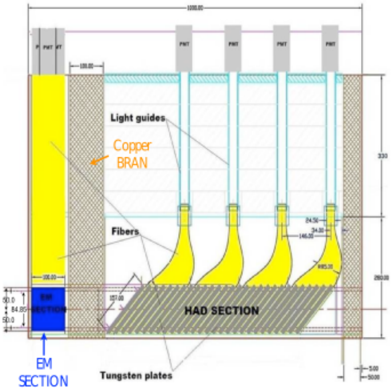
Segmentation:

- 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):

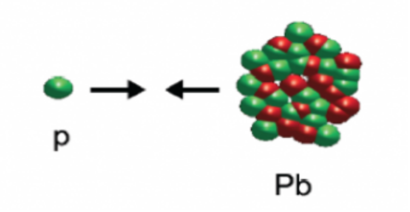
- 33 vertical tungsten plates
- 19 radiation lengths or one nuclear interaction length.
- 5 divisions in the x direction

(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° $\rightarrow$ maximizes the light that a fiber can pick up.
- Divided into 4 segments in z direction

ZDC in pA collisions



ZDC on Pb-going side:

- Nuclear/heavy-ion physics
- Disintegration of residual nucleus
- Giant dipole resonance
- Centrality, event plane
- UPC collisions

ZDC on p-going side:

- Cosmic ray physics
- Charge exchange

⇒ Tagging neutrons

⇒ Measurement of neutron energy loss

Forward neutrons in pA and AA collisions

Hadron-nucleus collision

Forward neutrons in pA and AA collisions

Hadron-nucleus collision

$\Downarrow$

NN collisions $\Rightarrow$ **cascade nucleons** ($\beta_A \in [0.3, 0.7]$)

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Excited nucleus

Forward neutrons in pA and AA collisions

Hadron-nucleus collision

$$\Downarrow$$

NN collisions $\Rightarrow$ **cascade nucleons** ($\beta_A \in [0.3, 0.7]$)

$$\Downarrow$$

Excited nucleus

$$\Downarrow$$

Break-up of nucleus

Forward neutrons in pA and AA collisions

Hadron-nucleus collision

$\Downarrow$

NN collisions $\Rightarrow$ **cascade nucleons** ($\beta_A \in [0.3, 0.7]$)

$\Downarrow$

Excited nucleus

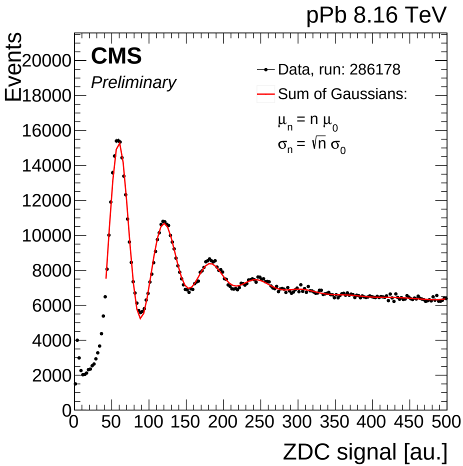
$\Downarrow$

Break-up of nucleus

$\Downarrow$

Nuclear evaporation $\Rightarrow$ **evaporation nucleons** ($\beta_A < 0.3$)

Calibration – neutron peaks

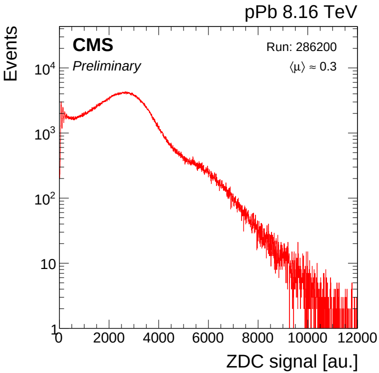


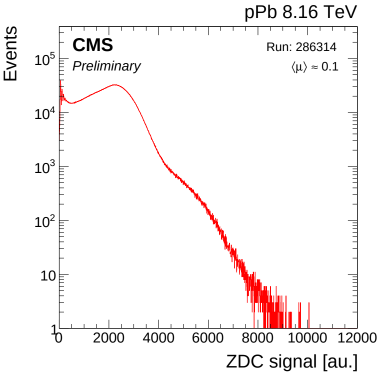
- Pb-going side
- Nearly monoenergetic neutrons due to large boost of Pb-ion
- 1, 2, 3 neutron peaks are clearly visible
- Fit with sum of Gaussians, with fixed mean and variance:

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

- 1 neutron peak at 2.56 TeV
  (nominal value for $\sqrt{s_{NN}} = 8.16$ TeV)
- Resolution: $\approx 24\%$

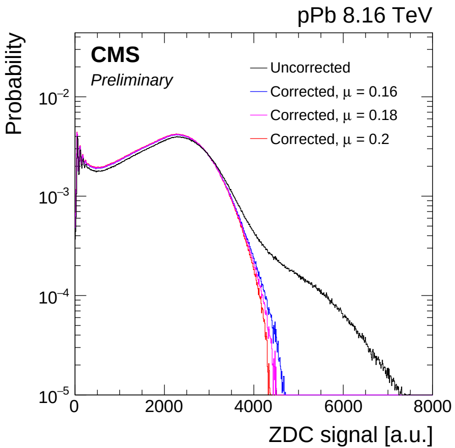
Pileup in ZDC runs





- 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.

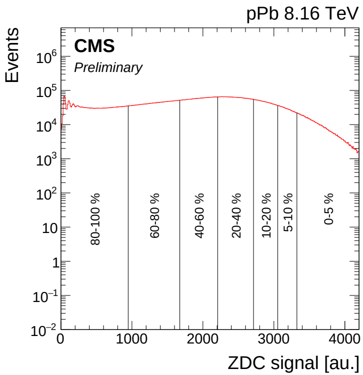
Application 1: Centrality with ZDC in pPb collisions

Number of spectator neutrons:

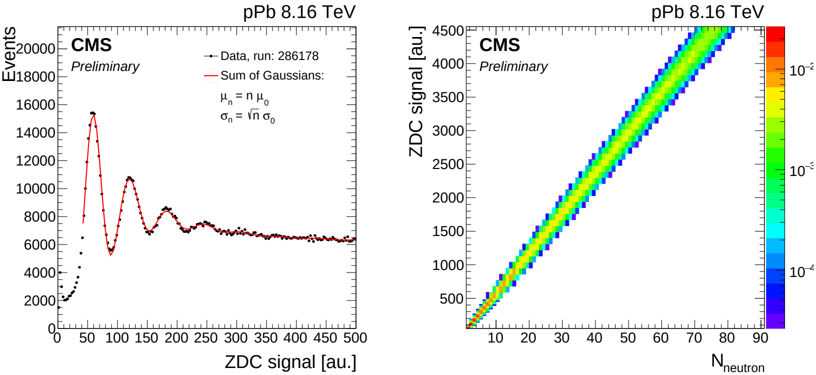
- Unbiased centrality estimator in pPb collisions
- Theoretical model needed to describe the relation

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

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

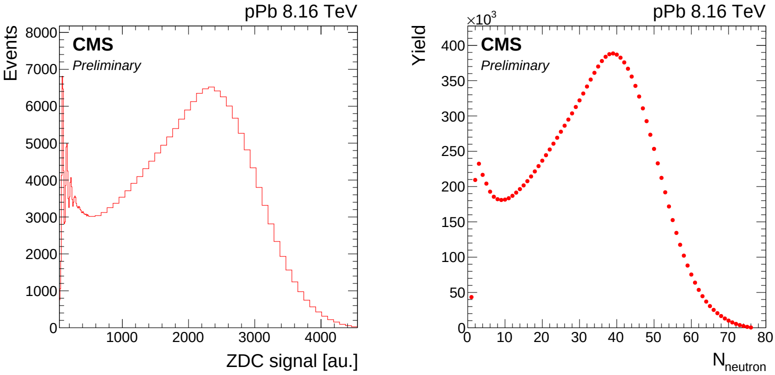


Application 2: Measuring neutron number distribution



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

Application 2: Measuring neutron number distribution



Using linear regulatization to unfold neutron number distribution

Summary

- Zero Degree Calorimeter – ZDC
- Zero degree neutrons are observed with CMS ZDC
- ZDC is calibrated using neutron peaks
- Wide variety of physics capabilities:
  - Charge exchange measurements
  - Study of nuclear disintegration
  - Tagging UPC events
  - Centrality estimator
  - Measure event plane (RPD)

Thank you for your attention!

1. Backup

Cherenkov angle

Cherenkov angle:

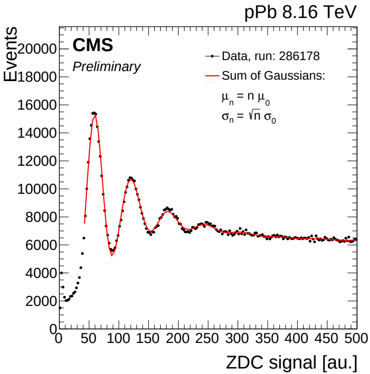
$$\cos\theta = \frac{1}{n\beta}$$

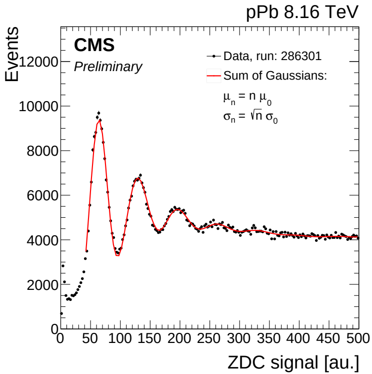
$$\beta \approx 1 \quad \text{for relativistic particles,}$$

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

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

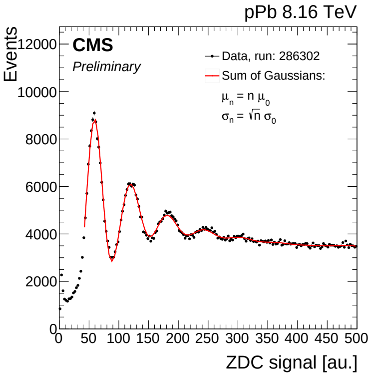
Example fits – 1

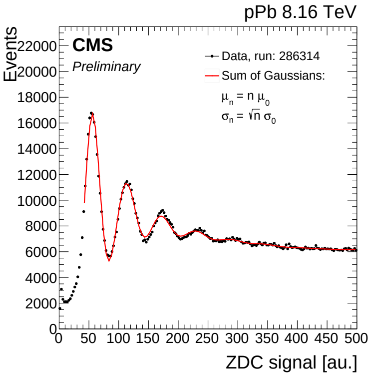




Run number	286178	286301	286302	286314
1 n peak location	59.2 ± 0.04	63.70 ± 0.05	59.02 ± 0.04	55.79 ± 0.03
1 n peak width	14.24 ± 0.02	15.25 ± 0.03	13.94 ± 0.03	13.14 ± 0.03

Example fits – 2





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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)

μ: 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:

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

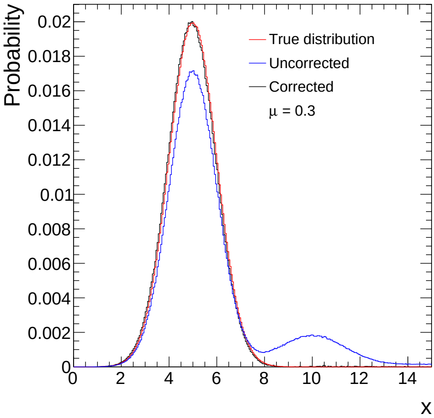
Taking the Fourier transform of both sides
($f(x) \to F(\omega)$, $g(x) \to G(\omega)$):

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

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

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

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

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

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

Need to solve matrix equation:

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