ZDC simulation, acceptance and light-by-light analysis

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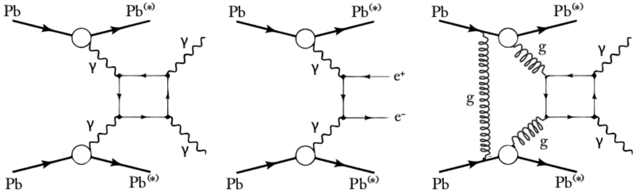
1. ZDC in light-by-light analysis

LbL in PbPb



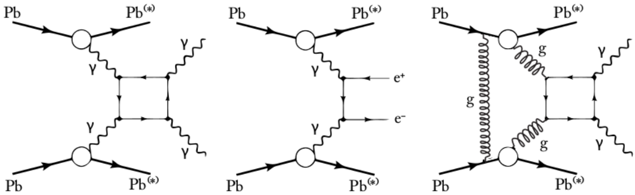
Signal:

- LbL: $\gamma\gamma \to \gamma\gamma$
- + Axion-like particle (ALP): $\gamma\gamma \to a \to \gamma\gamma$

Background contributions:

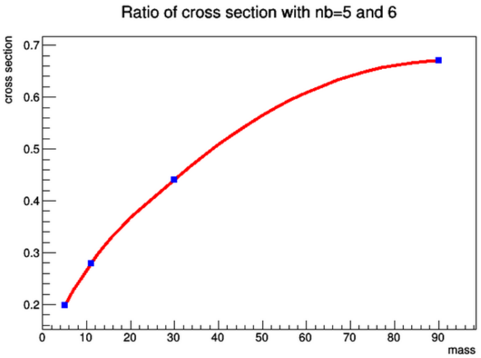
- QED: $\gamma\gamma \to e^+e^-$
- CEP: $gg \to \gamma\gamma$

LbL in PbPb



- Idea: photonuclear excitations (and related neutron emission) is higher (80%) for CEP background as impact parameter is generally smaller
- Using a ZDC veto would efficiently remove these events
- But what signal fraction do we remove?
- What is the energy distribution of neutrons, when not only a single neutron is produced? Are GDR parameters still apply?

Preliminary results



- Done by Matyas Horvath (summer student at our university)
- Using STARlight simulation
- Fraction of events with forward neutrons as a function of ALP mass
- Now producing the same plot for e^+e^- MC sample
- Need to check data as well, software is ready, waiting for HiForest files with ZDC included

2. ZDC geometrical acceptance

Geometrical acceptance calculations

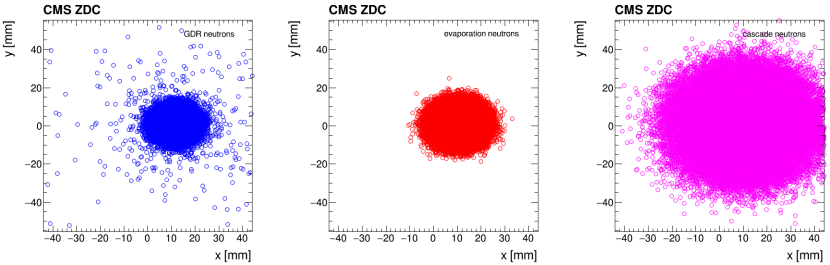
- Crossing angle (160 μrad for 2018)
- Beam divergence from $\beta^* = 50$ cm

$\Rightarrow$ Introducing magnification of beam:

$$M(z) = \frac{\sigma(z)}{\sigma(0)} = \sqrt{\frac{\varepsilon\beta(z)}{\varepsilon\beta^*}} = \sqrt{1 + \frac{z^2}{\beta^{*2}}} \approx 233$$

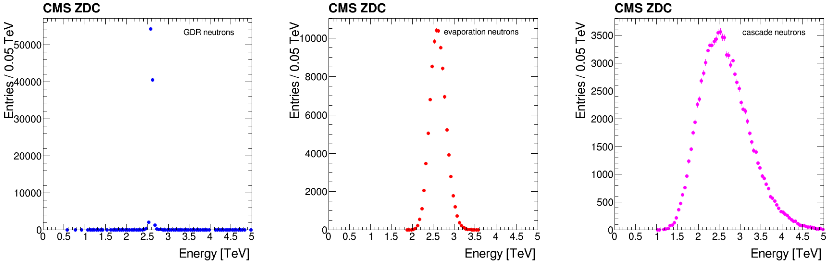
- Assuming the beamspot is magnified according to this
- Taking into account beamspot parameters
- Considering three physics scenarios:
  - GDR: Breit-Wigner with $E_0 = 13.5$ MeV and $\Gamma = 4$ MeV
  - Black: Maxwell-Boltzmann with $T = 5$ MeV (uncertain)
  - Grey: Maxwell-Boltzmann with $T = 50$ MeV (uncertain)

Geometrical acceptance – results



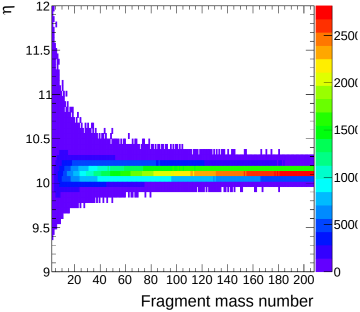
- All three process has $> 99\%$ geometrical acceptance
- GDR has a heavy tail due to BW energy distribution
- As Cherenkov calorimeters are sensitive to the core of a shower, efficiency for neutrons should be similarly high
- Running GDR neutrons through ZDC simulation would allow to calibrate EM section and even RPD

Energy distributions



- GDR is very sharp
- Single neutron peak (dominated by GDR) reflects the resolution of the detector pretty well.

Extra: nuclear fragments



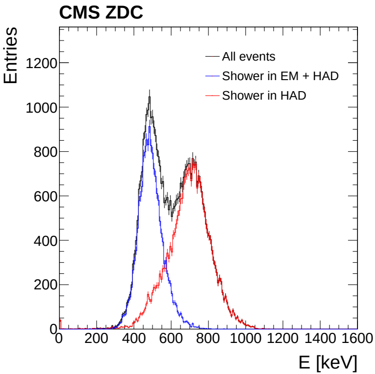
- Using Fermi gas model
- Taking into account crossing angle
- Fragments in incoherent $gg \to \gamma\gamma$ is not detected by HF, can be only tagged by ZDC neutrons
- (ZDCs do not see these fragments as they are charged)

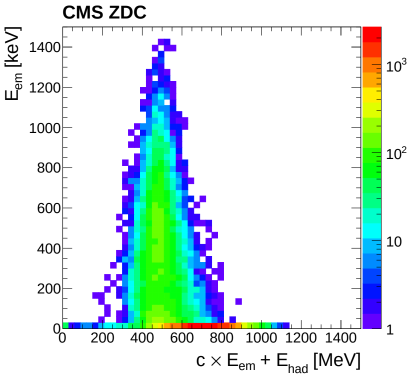
3. ZDC simulation

ZDC simulation status

- ZDC only simulation tested (no RPD yet!)
- Shower library gives very poor results
- Cherenkov-based simulation
- Tested with lightguiding included

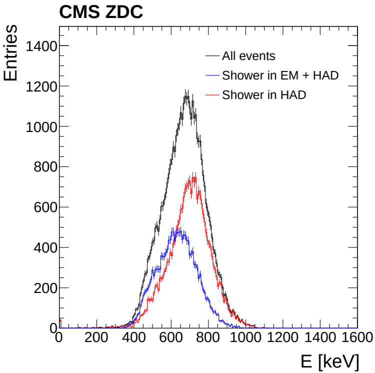
Results

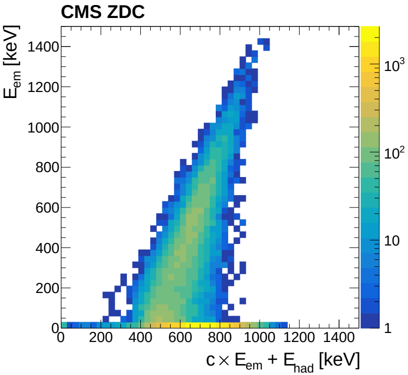




- Energy independence from EM deposit required
- $c = 0.3$
- Leakage in BRAN region is well visible
- Loss seems too large, compared to data

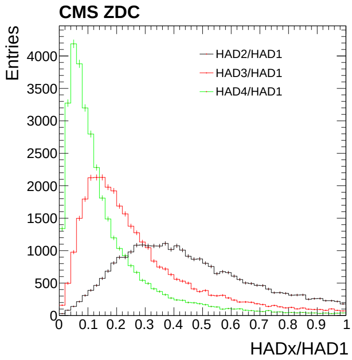
Results





- Best common neutron resolution is required
- Resolution: $\approx 18\%$
- $c = 0.65$

Results – shower shape



- Numbers from 2010 PbPb:
  - $\mathrm{HAD2}/\mathrm{HAD1} = 0.62$
  - $\mathrm{HAD3}/\mathrm{HAD1} = 0.32$
  - $\mathrm{HAD4}/\mathrm{HAD1} = 0.26$
- Factor of 2 difference
- Source of discrepancy should be investigated
- Calibration constants derived from this results should be tested, they may be even better

Open questions

- Too large leakage in BRAN region
- Discrepancy in shower shape variables
- Question about lightguiding:
  - Critical angle between cladding and core is $\approx 82^\circ \rightarrow$ not very efficient for light guiding...
  - What about cladding and air outside? CA $\approx 43^\circ$
  - Is really air surrounding the fiber?
  - Is the fiber painted or somehow covered from outside?
- Detector geometry should be cross-checked
  $\rightarrow$ **a precise schematic is needed**

Backup: previous results

Cherenkov simulation

- Cherenkov angle and Cherenkov criterion:

$$\cos\theta = \frac{1}{n\beta} \qquad \longrightarrow \qquad \beta > \frac{1}{n}$$

- Mean number of Cherenkov photons per path length x and photon energy E_γ:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}x\mathrm{d}E_\gamma} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(E_\gamma)}\right)$$

- We should give $n(E_\gamma)$ for SiO_2 in the range $[E_{\mathrm{min}}, E_{\mathrm{max}}]$
  Link: *Optical properties of* SiO_2

Cherenkov simulation

- Minimum and maximum energy of Cherenkov photons:

$$E_\mathrm{a} = \begin{cases} E_\mathrm{min} & \text{if} \quad \beta > \frac{1}{n_\mathrm{min}} \\ E(\beta) & \text{else} \end{cases}$$

$$E_\mathrm{b} = \begin{cases} E_\mathrm{max} & \text{if} \quad \beta > \frac{1}{n_\mathrm{max}} \\ \text{no photons are produced,} & \text{if} \quad \beta < \frac{1}{n_\mathrm{max}} \end{cases}$$

- Calculating average number of Cherenkov photons in a G4Step (δx is steplength):

$$\int\limits_{E_\mathrm{a}}^{E_\mathrm{b}} \int\limits_{x_i}^{x_f} \frac{\mathrm{d}^2 N}{\mathrm{d}x \mathrm{d}E_\gamma} \mathrm{d}x \mathrm{d}E_\gamma = \frac{\alpha z^2 \delta x}{\hbar c} \left((E_\mathrm{b} - E_\mathrm{a}) - \frac{1}{\beta^2} \int\limits_{E_\mathrm{a}}^{E_\mathrm{b}} \frac{\mathrm{d}E_\gamma}{n^2(E_\gamma)} \right)$$

- Integral of $1/n^2$ is tabulated

Cherenkov simulation

- Generate Poisson(N) photons for the step
- Sample momentum for each photon:

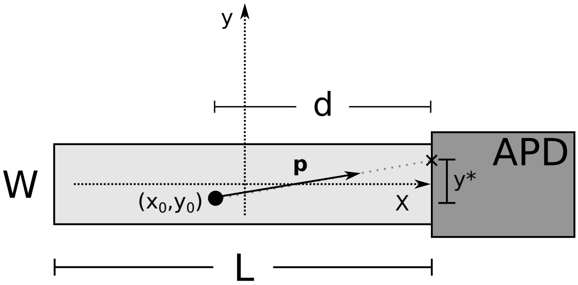
$$\tilde{p} = E_{\mathrm{min}} + \mathrm{Uniform}(0,1) \cdot (E_{\mathrm{max}} - E_{\mathrm{min}})$$
$$\tilde{\theta} = \arccos\left(\frac{1}{\beta n(\tilde{p})}\right)$$
$$\tilde{\phi} = 2\pi \cdot \mathrm{Uniform}(0,1)$$

  Reject if $\sin^2\tilde{\theta} < \mathrm{Uniform}(0,1) \cdot \sin^2\theta_{\mathrm{max}}$ and sample a new momentum for the same photon

  - Why using $E_{\mathrm{min,max}}$ and not $E_{\mathrm{a,b}}$?
  - Why do we need the rejection condition?
  - Why sampling uniform momentum/energy? Why not using the density function from slide 3?

- If accepted: $(\tilde{p}, \tilde{\theta}, \tilde{\phi}) \to (p_x, p_y, p_z)$ – w.r.t G4Step

Cherenkov simulation

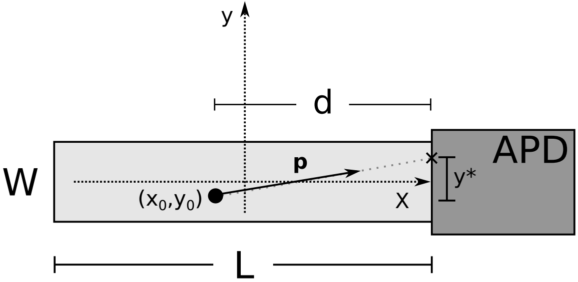


Last step in DREAM detector:

- Change to local frame with respect to crystal
- Calculate distance from APD:

$$d = \frac{L}{2} - x_0$$

Cherenkov simulation



- Calculate hit coordinate:

$$\frac{y^*}{d} = \frac{p_y}{p_x}$$

- Photon detected if $|y^*| < W/2$
  - Why not using $y^* + y_0$?
  - What about photons moving backwards?

Important question: how fibers behave? Do we need this?

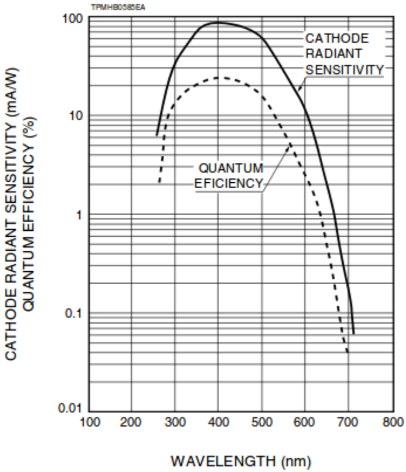
Cherenkov simulation

Finally:

- Take into account PMT efficiency:

$$E_{\text{det}} = \tilde{p} \cdot \varepsilon_{\text{PMT}}(\lambda)$$

- For ZDC PMT: *ZDC PMT datasheet*

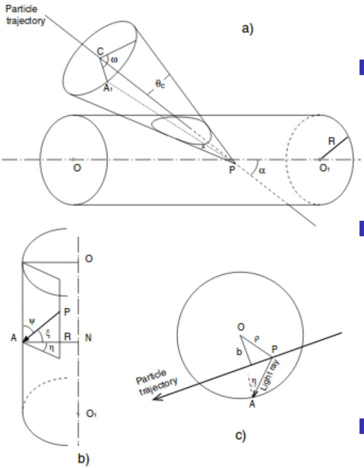


Cherenkov simulation in ZDC

- SiO_2 refractive index is constant within a few percentage in the PMT sensitivity range $\rightarrow$ easy integration
- Uniform energy distribution of Cherenkov photons
- Light can get out of the fiber with total internal reflection

$\Rightarrow$ Angle of incidence on fiber surface larger than critical angle

Cherenkov simulation in ZDC



- Lightguide condition:

$$\xi \geq \arcsin\left(\frac{n_{\text{clad}}}{n_{\text{core}}}\right) \approx 81\text{–}82^\circ$$

- Very complicated math:

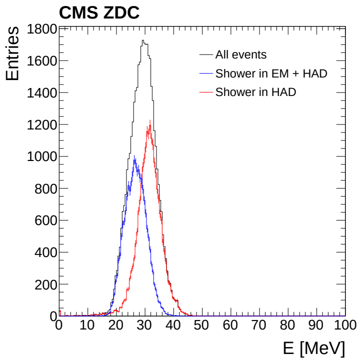
$$\cos\xi = \cos\eta \sin\psi$$

$$\sin\eta = \frac{\rho}{R}\sin\left(\arctan\frac{\sin\theta_c \sin\omega}{\cos\theta_c \sin\alpha + \cos\omega \sin\theta_c \cos\alpha} + \arcsin\frac{b}{\rho}\right)$$

$$\cos\psi = \cos\alpha\cos\theta_c - \sin\alpha\sin\theta_c\cos\omega$$

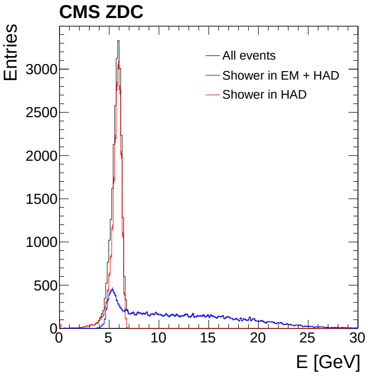
- Still working on the coding

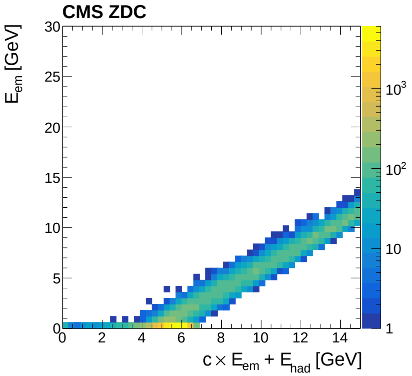
Cherenkov simulation in ZDC - results



- Cherenkov photons generated
- No lightguiding yet, every photons' energy is summed up
- Weighting with PMT quantum efficiency
- Main features are still present
- Resolution:
  - dE/dx: 13.5%
  - Cherenkov: 16.5%

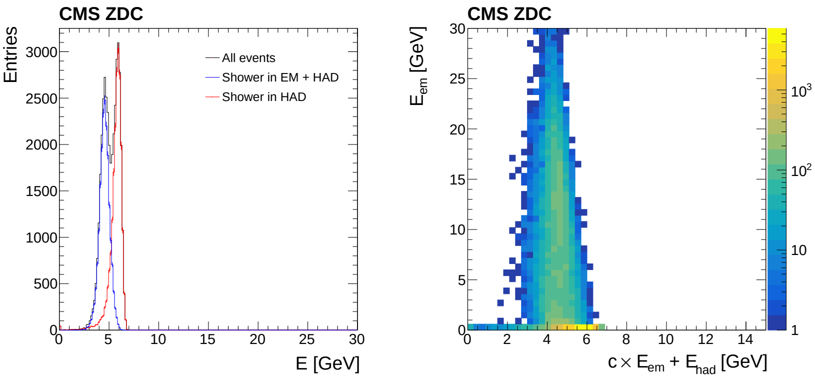
Raw neutron response





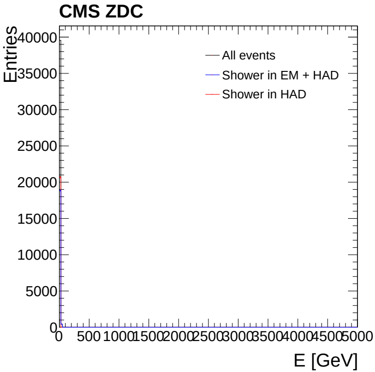
- Shower in EM+HAD if $E_{\mathrm{EM}} > 0.1$ GeV
- Relative volume of quartz is much higher ($\approx 30\%$) for EM section
- HAD section light yield is different due to tilted cells
- EM section should be matched

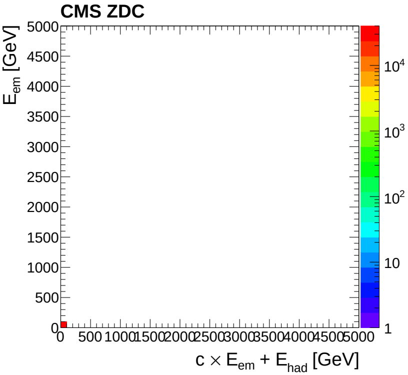
Matching of EM section



- 0.1 weight for EM hits minimizes resolution of EM+HAD showers
- But slightly different energy response
  - Absorbed by BRAN?
  - Non-linearity effect?

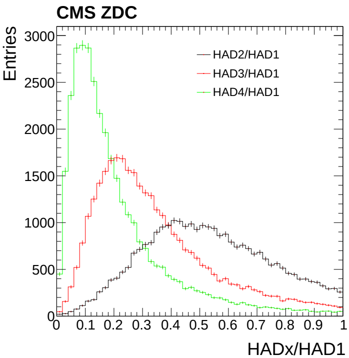
Matching of EM section





- 0.15 manage to merge peaks
- Resolution: 13.5%
- HAD only: 10%
- 2016 pPb data: 23% (together with physics)

Shower shapes for HAD section



- Can be used for HAD section intercalibration
- Numbers from 2010 PbPb:
  - $\mathrm{HAD2}/\mathrm{HAD1} = 0.62$
  - $\mathrm{HAD3}/\mathrm{HAD1} = 0.32$
  - $\mathrm{HAD4}/\mathrm{HAD1} = 0.26$

- Calibration of EM section (or even RPD)? Need to know:
  - Crossing angle $\rightarrow$ OK
  - Beam divergence?
  - p_T distribution of neutrons???
  - $\rightarrow$ Generating neutrons with appropriate angular distribution