Luminosity monitor for the EIC

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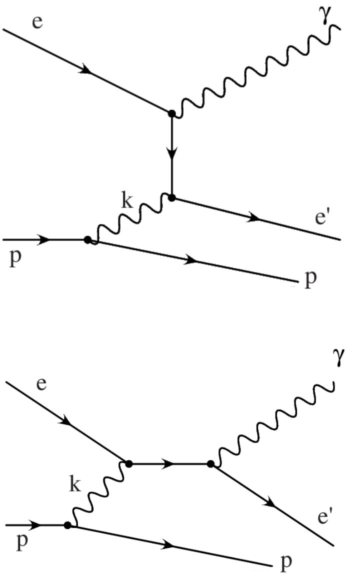
Introduction

- An overview of current status of simulations for luminosity monitor is given here
- Resources for luminosity studies (my github)
  - Drawings of interaction region with *irview*: https://github.com/adamjaro/irview
  - Event generator for luminosity studies *lgen*: https://github.com/adamjaro/eic-lgen
  - Geant4 framework for luminosity monitor *lmon*: https://github.com/adamjaro/lmon
- Outline for this talk:

1. Mechanism of luminosity measurement
2. Event generator for luminosity studies
3. Geant4 model of luminosity monitor
4. Photon exit window
5. Photon detector
6. Pair spectrometer
7. Light collection and energy resolution
8. Prediction for event rates

Mechanism of luminosity measurement at the EIC



- Luminosity is measured via elastic bremsstrahlung off electrons
- Independent of proton (nucleus) internal structure, large cross section $\sim$mb
- Luminosity monitor detects bremsstrahlung photons

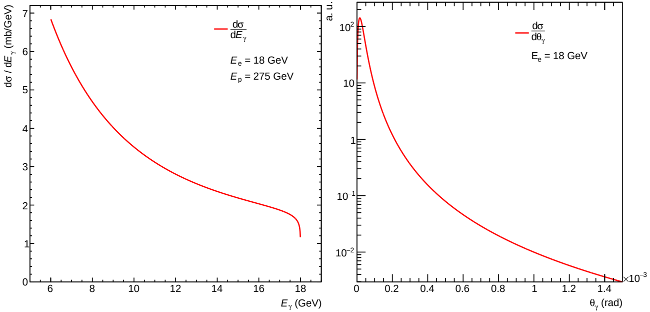


Figure: Bremsstrahlung cross section as a function of photon energy E_γ and polar angle θ_γ

Detector concept for luminosity measurement

- Following example of similar detector at ZEUS, HERA
- High luminosity demands two separate methods to count the bremsstrahlung photons:

1. Photon conversion to e^+e^- pairs for precise DIS cross sections
2. Direct, non converted photons for instantaneous collider performance

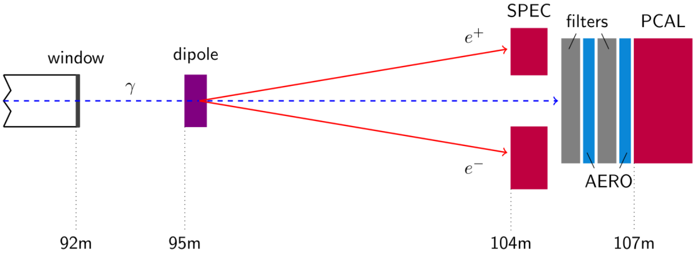
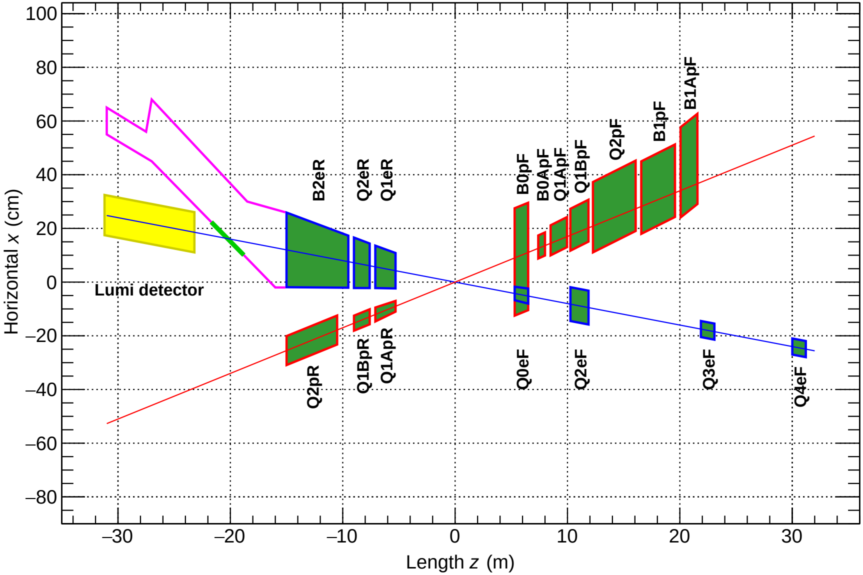


Figure: Layout of ZEUS luminosity detector

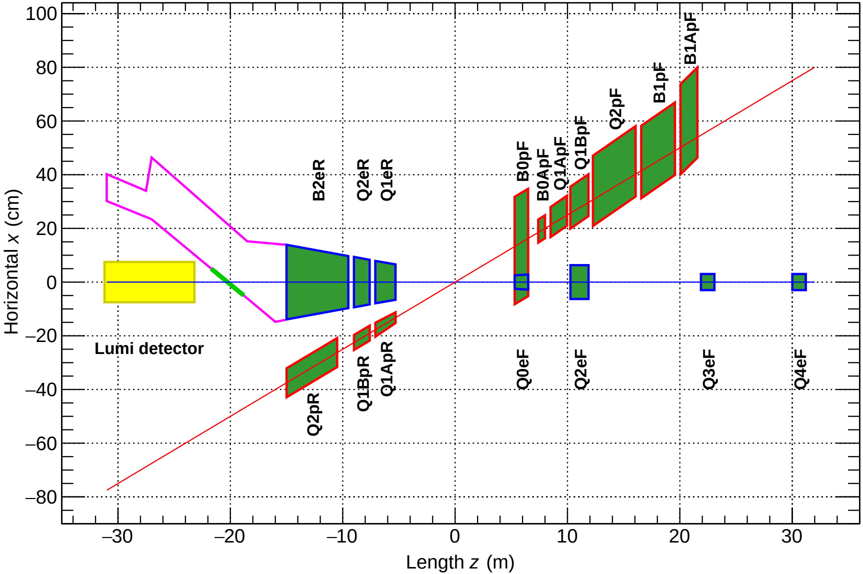
- Pairs are detected in spectrometer SPEC, direct photons in photon calorimeter PCAL

Nucl.Instrum.Meth. A744 (2014) 80-90, Nucl.Instrum.Meth. A565 (2006) 572-588

Luminosity detector in the layout of Interaction Region



IR layout along electron beamline



Event generator for bremsstrahlung photons

Generator *lgen* based on Bethe-Heitler formula

- Bremsstrahlung photons and scattered electrons are generated using cross section as a function of photon energy E_γ and polar angle θ_γ
- Parametrization used at ZEUS is given in terms of electron and proton beam energy E_e and E_p

$$\frac{d\sigma}{dE_\gamma} = 4\alpha r_e^2 \frac{E'_e}{E_\gamma E_e} \left(\frac{E_e}{E'_e} + \frac{E'_e}{E_e} - \frac{2}{3} \right) \left(\ln \frac{4 E_p E_e E'_e}{m_p m_e E_\gamma} - \frac{1}{2} \right) \tag{1}$$

- Scattered electron energy is constrained as $E'_e = E_e - E_\gamma$
- Equivalent parametrization from H1 is in terms of $y = E_\gamma / E_e$ and center-of-mass energy s

$$\frac{d\sigma}{dy} = \frac{4\alpha r_e^2}{y} \left[1 + (1-y)^2 - \frac{2}{3}(1-y) \right] \left[\ln \frac{s(1-y)}{m_p m_e y} - \frac{1}{2} \right] \tag{2}$$

- Angular distribution of the photons is given in terms of angle θ_γ relative to electron beam

$$\frac{d\sigma}{d\theta_\gamma} \sim \frac{\theta_\gamma}{\left((m_e/E_e)^2 + \theta_\gamma^2 \right)^2} \tag{3}$$

ZEUS: Eur.Phys.J. C71 (2011) 1574, H1: H1-04/93-287

Input and output of the generator

```
[lgen]

#main generator configuration

Ee = 18 ; energy of electron beam, GeV
Ep = 275 ; proton beam, GeV

emin = 1 ; minimal photon energy, GeV

#parametrization
#par = "h1"
par = "zeus"

#number of events to generate
nev = 12

#output file name
nam = "lgen"
#nam = "data/lgen_5x41_0p5min_12evt"

[beff]

#beam effects of angular divergence and emittance

use_beam_effects = true ; apply beam effects, true or false

sig_theta = 200e-6 ; angular divergence in theta, rad
sig_x = 0.236 ; vertex spread in x, mm
sig_y = 0.0162 ; vertex spread in y, mm
sig_z = 17.0 ; vertex spread in z, mm
```

Figure: Example *lgen* steering card

- Events are generated using cross section formulas in Eq. 1, 2 and 3
- It allows to select one of the parametrizations in Eq. 1 (ZEUS) or in Eq. 2 (H1), results are identical
- The generator is configured from a steering card in INI format
- Output is written to pythia6 text file, TX file, and ROOT TTree
- It is then input to Geant4 simulations
- Effects of beam angular divergence and emittance are implemented as Gaussian smearing of polar angles θ and 3-dimensional Gaussian vertex position

Validating the event generator by reproducing HERA cross section

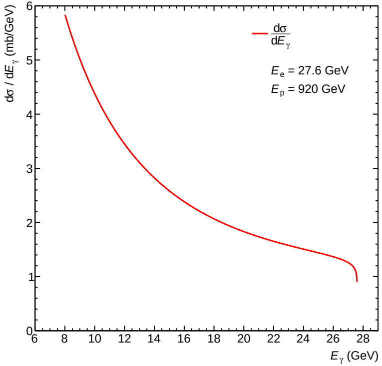


Figure: Cross section from *Igen*

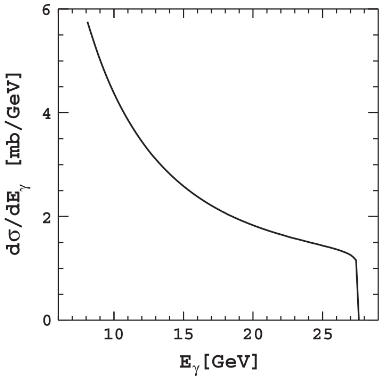
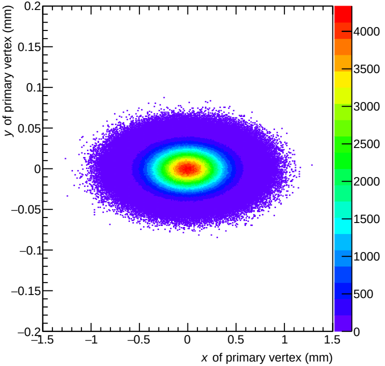
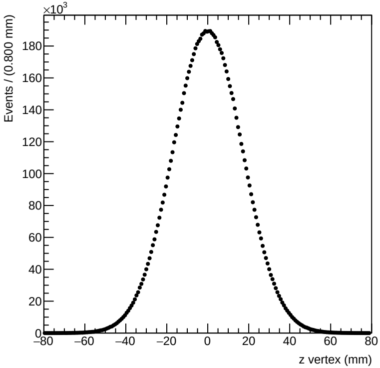


Figure: Cross section by ZEUS

- Generator *Igen* is set to HERA energy
- Resulting cross section has the same shape and values as reported by ZEUS in Nucl.Instrum.Meth. A744 (2014) 80-90

Generating primary vertices with Gaussian beam profile





- In each event the vertex position is a point where the bremsstrahlung photon is created
- Using pCDR high acceptance configuration without hadron cooling for 18 x 275 GeV ep beams
- IP RMS beam size σ_x = 236 µm, σ_y = 16.2 µm, $\Delta\theta$ = 200 µrad
- RMS bunch length σ_z = 1.7 cm

Effect of beam angular divergence

Figure: Divergence of 0.1 mrad

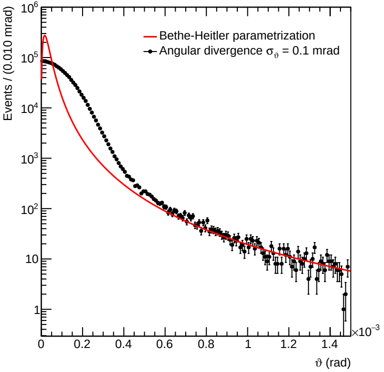
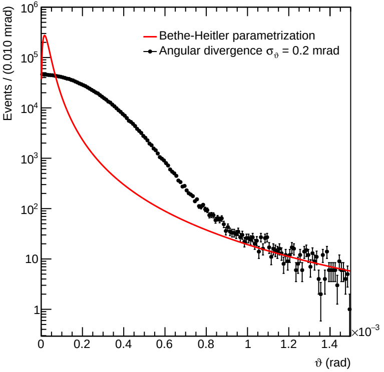


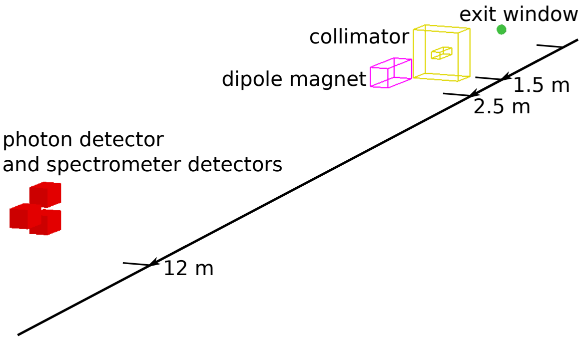
Figure: Divergence of 0.2 mrad



- Gaussian fluctuations with a given σ_ϑ are added to angles generated according to the Bethe-Heitler parametrization
- Value of 0.1 mrad was used in pCDR in lumi study
- Small angles are driven by beam divergence, large angles converge to the parametrization
- Similar behavior with two times bigger divergence

Geant4 model of luminosity monitor

Geant4 model of luminosity monitor



- Full Geant4 model of all essential part of luminosity monitor following the ZEUS design
- Photon exit window is located about 20 meters from interaction point
- Provides simulation chain from physics event generator to number of detected photoelectrons

Collimator

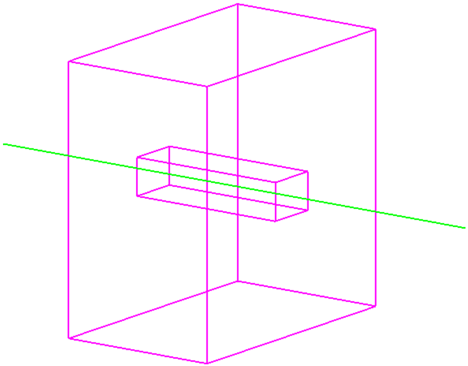


Figure: Bremsstrahlung photon passing through the collimator

- Stainless steel block to select photons or pairs coming along electron beam line
- Located 1.37 m behind photon exit window
- Inner aperture is 9.6×7 cm, length is 30 cm
- Used at ZEUS to filter the background
- Confirmed that it has no effect to bremsstrahlung signal

Spectrometer magnet

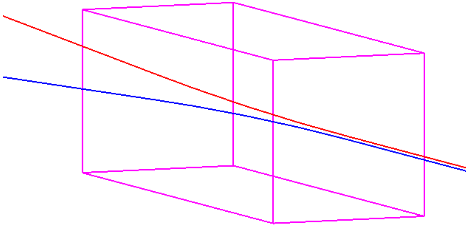
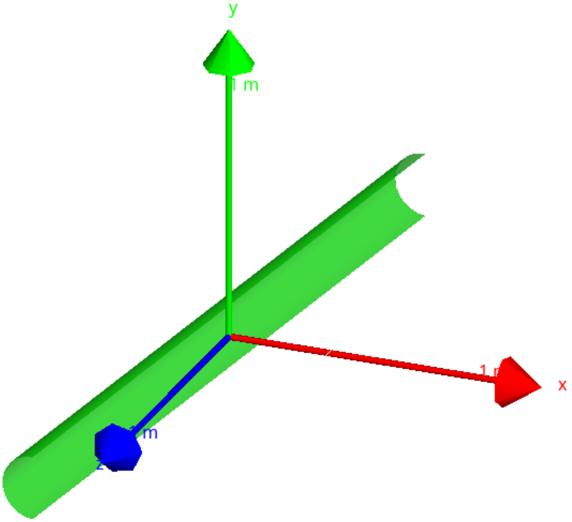


Figure: Electron and positron are deflected in the magnet

- Bends conversion electrons and positrons towards spectrometer detectors
- Placed 2.5 m behind photon exit window
- Magnetic field 0.25 T (half of the value used at ZEUS)
- Inner aperture is 10×10 cm
- Length is 30 cm
- Tracks are shown for e^+ (blue) and e^- (red) at 3 GeV

Photon exit window

Model of the exit window



- Layer of passive material to convert bremsstrahlung photons to e^+e^- pairs
- Also provides shielding against low energy synchrotron radiation
- Located 20 m downstream electron beam axis (exact location will depend on beam pipe geometry)
- Implemented as a half-cylinder of 1 mm thick aluminum, 10 cm radius and 100 mrad tilt along vertical y axis
- The tilt angle is motivated by synchrotron radiation studies

Photon impact points in *xy* and conversion points along *z*

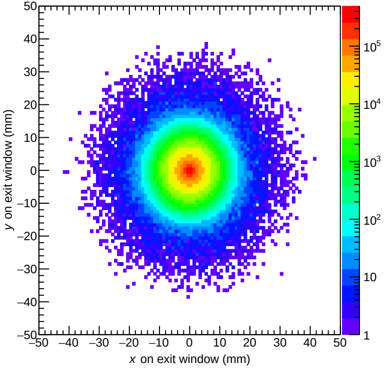


Figure: Impact points on exit window in *xy* plane, perpendicular to photon direction

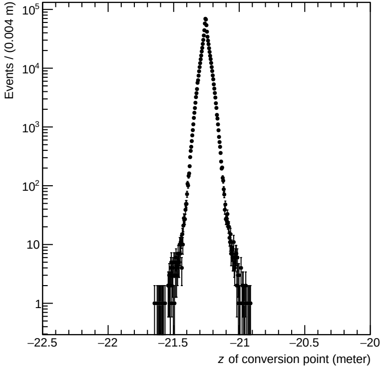


Figure: Points of photon conversion along *z*, longitudinal to photon direction

- Both plots are shown for tilted 100 mrad exit window
- Initial vertex *xy* asymmetry is completely smeared
- All events pass the 5 cm radius in *xy*
- Conversion points take place over ∼50 cm along *z*

Conversion probability as a function of photon polar angle ϑ and azimuthal angle ϕ

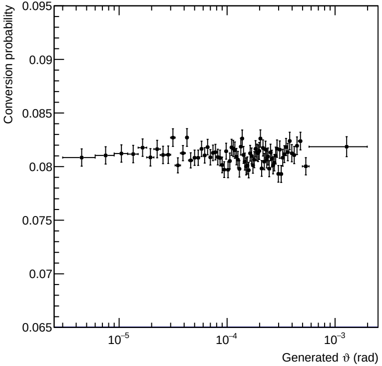


Figure: Polar angle ϑ

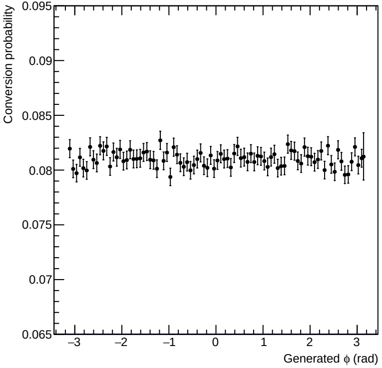


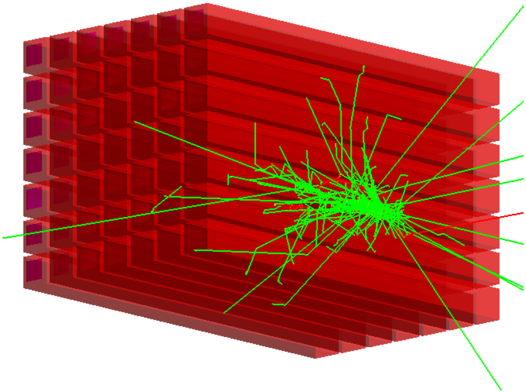
Figure: Azimuthal angle ϕ

- Conversion probability is a ratio of events where the primary photon converted to e^+e^- pair, to all generated events
- Simulations of 10 M events
- Bins are automatically set for binomial errors below 1%

- No significant dependence both on ϑ and ϕ
- We can continue integrating a 100 mrad, 1 mm thick aluminum exit window to the beam pipe without the risk of a significant geometry dependence

Photon detector

Model of photon detector



- Detects direct photons not converted on the exit window
- Placed along beam line (zero degree) 11.85 m behind the exit window
- Calorimeter is composed of 7×7 $PbWO_4$ cells
- Each cell consists of 3×3 cm casing made of carbon fiber, 2 mm thick, holding the $PbWO_4$ crystal inside
- Length of each cell is 35 cm, same for casing and crystal
- Only the crystals, shown in red, are sensitive volume
- Response to a 1 GeV photon is shown on the plot

Signal response in the photon detector

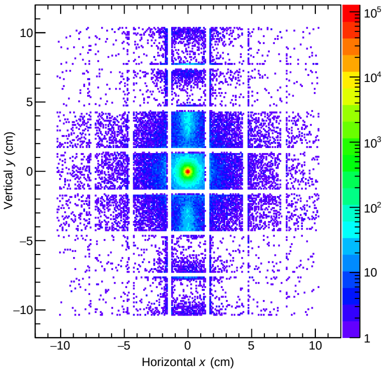


Figure: Position of first hit

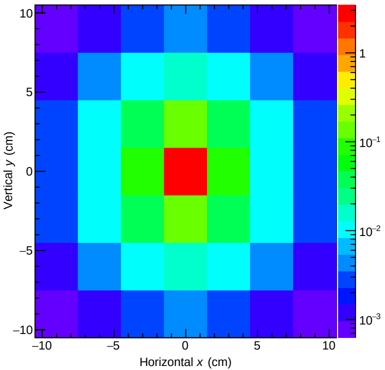
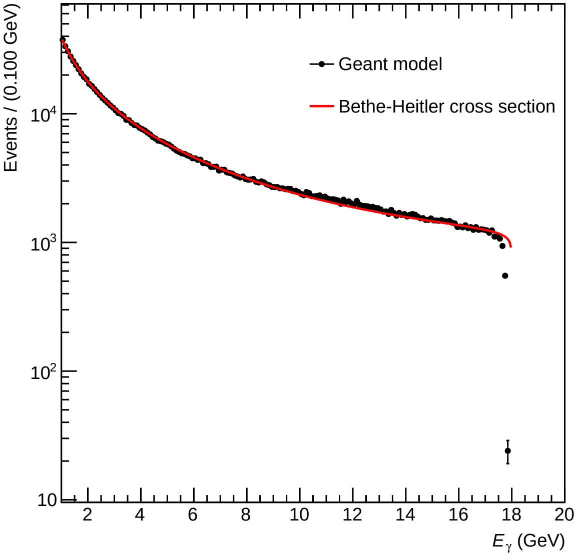


Figure: Energy (GeV) in cells

- Left: position of the first hit in photon detector in event
- Most photons enter the middle cell
- Electron and positron trails visible along y
- Shadow in $|y| \gtrsim 4$ cm is due to the pair spectrometer
- ZEUS detector had a filter in front of it

- Right: average energy (GeV) collected in individual cells per event (sum divided by number of events)
- The middle cell takes most of the shower, transversal spread is confined in the detector

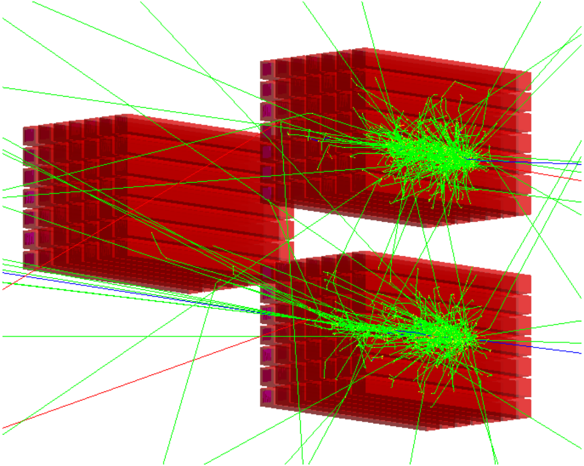
Energy spectrum from the photon detector



- Energy collected by the photon detector in a 1M events sample
- Taken as a sum of individual cells in each event
- Overlaid is theoretical Bethe-Heitler $d\sigma/dE_\gamma$ curve, scaled to the data
- High energy tail is missing because of no calibration of the photon detector
- Overall good agreement with the expectation

Pair spectrometer

Pair spectrometer detectors



- Pair of calorimeters to detect converted e^+ and e^-
- Same construction as the photon detector
- Placed 11.35 m from the exit window
- Aperture between the detectors is 8.4 cm
- Photon detector is located behind
- Shown is event with e^+ and e^- at 3 GeV, deflected by the magnet

Impact points in spectrometer detectors

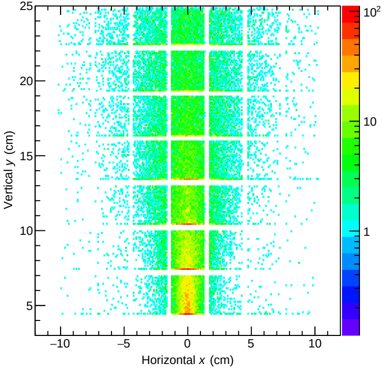


Figure: Up detector first hit

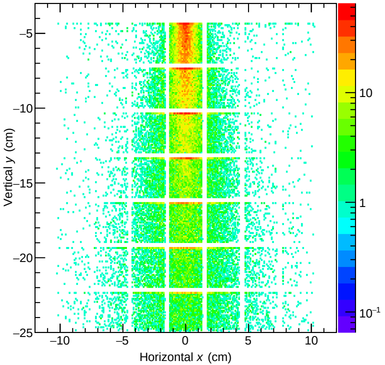


Figure: Down detector first hit

- First hits in event in spectrometer detectors
- Left: up detector (e^-), right: down detector (e^+)
- Both e^+ and e^- sweep across the middle of the detector
- Expected from conversion kinematics and deflection in the magnet

Signals from spectrometer detectors

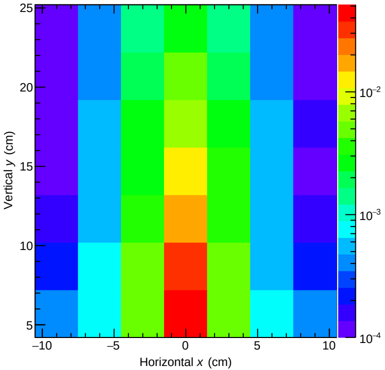


Figure: Up detector cells (GeV)

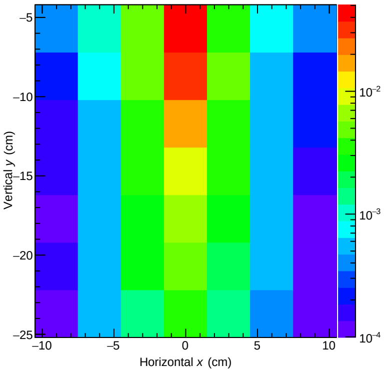
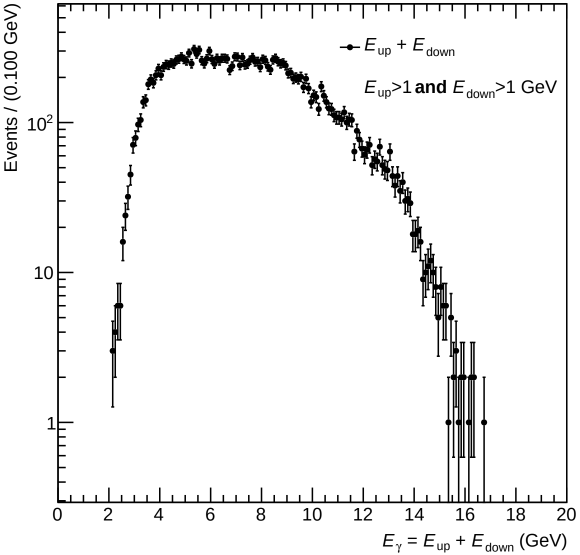


Figure: Down detector cells (GeV)

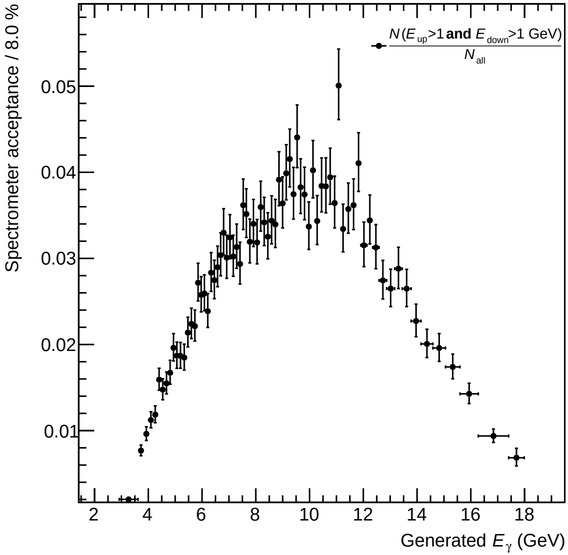
- Average energy (GeV) in individual cells in event
- Left: up detector (e^-), right: down detector (e^+)
- Shower is confined in horizontal direction
- Vertical shape is driven by the acceptance

Energy from spectrometer detectors



- Sum of energy from up and down spectrometer detectors
- Coincident deposition of at least 1 GeV in each detector
- Out of 1M generated events, about 20000 produced a coincident signal
- Similar shape was observed at ZEUS

Spectrometer acceptance as a function of photon energy



- The acceptance is ratio of number of events with coincident signal in both spectrometers to all generated events
- Bins of generated photon energy are set for binomial error below 8%
- Shape is given by magnetic field of the dipole magnet
- Higher field moves the peak towards higher energies
- The point is to keep the acceptance away from synchrotron radiation, but still get an accurate bremsstrahlung signal
- Similar dependence of the acceptance was observed at ZEUS (with different field for different energies)

Light collection and energy resolution

Optical properties and light detection in model of $PbWO_4$ crystal

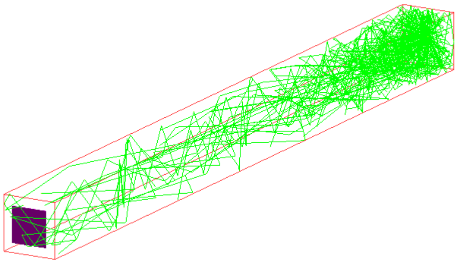
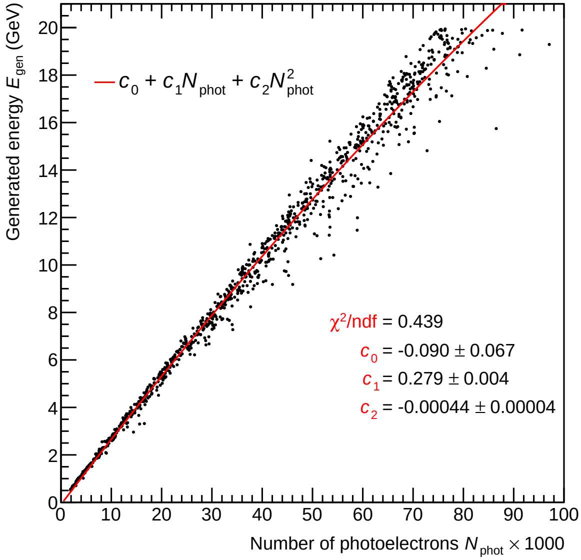


Figure: One calorimeter cell with 2 MeV deposition on the far side (facing the IP) and optical photon detector (magenta) on the opposite side. Optical photons are shown as green lines.

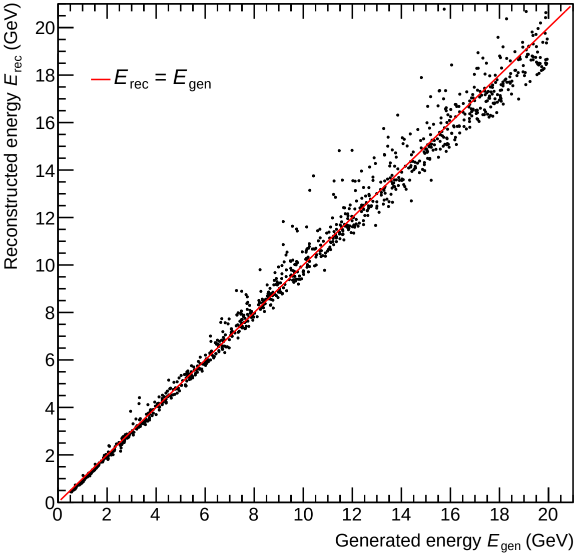
- Scintillation light yield is 200 per MeV with 6 ns decay constant (Knoll textbook)
- Wavelenght 420 nm (peak of emission as measured for ALICE)
- Optical properties approximately according to ALICE TDR
    - Uniform across 350 - 800 nm
    - Refractive index 2.4, absorption length 200 cm
    - Reflectivity 0.8, efficiency 0.9
- Detection by PIN diode, magenta square in the drawing
    - Silicon of 17×17 mm^2 area, 300 μm thickess (following ALICE device)
    - Reflectivity of optical boundary from the crystal is 0.1
    - Quantum efficiency is 0.8
    - Detected photon creates one photoelectron of signal (after applying quantum efficiency)
    - Number of photoelectrons is the output of the detector

Reconstructing the energy from number of photoelectrons



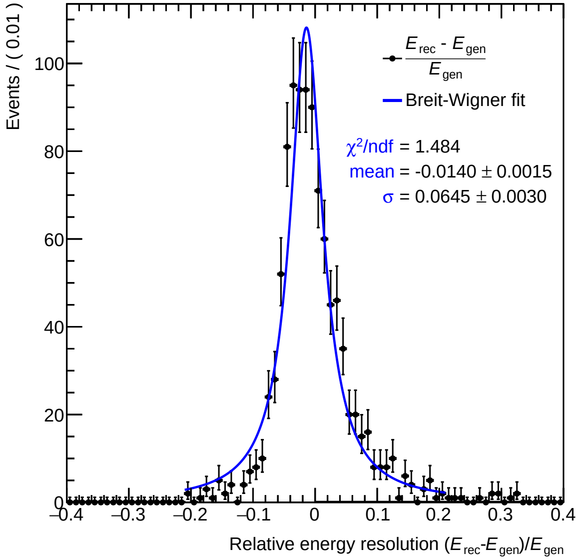
- Plot shows energy of generated photon entering the detector and number of photoelectrons from all cells
- One point is one event (1000 in total)
- Generated photons have uniform energy distribution in 0.5 - 20 GeV
- Fit is made by quadratic polynomial, not ideal but works
- Coefficients c0, c1, c2, known from the fit, allow to calculate reconstructed energy from number of photoelectrons

Reconstructed and generated energy



- Reconstructed energy is calculated from number of photoelectrons using c0, c1 and c2 determined from the fit on previous page
- Reconstructed energy is then compared to generated energy, same simulation of 1000 events
- Spread gets larger at energies beyond 10 GeV
- Caused by fluctuations in number of photoelectrons

Relative energy resolution



- Relative energy resolution is obtained as distribution of difference between reconstructed and generated energy, divided by generated energy
- Fit is made by Breit-Wigner distribution
- Width σ gives the relative resolution of 6.5% for energy in 0.5 - 20 GeV
- ALICE is quoting 3% over 0.2 - 10 GeV
- Difference is likely due to different energy range and conservative approach to light collection
- Light collection will need particular care because of limited light yield

Prediction for event rates

Predictions for event rates based on Bethe-Heitler cross section, pCDR luminosity and simulated efficiency

- Expected event rate f is given by Bethe-Heitler bremsstrahlung cross section σ_{BH}, luminosity L, and efficiency to observe a given process ϵ

$$f = \sigma_{\mathrm{BH}} \times L \times \epsilon \tag{4}$$

- The cross section σ_{BH} is determined from ZEUS parametrization used to generate events for simulation
- Simulated 10^5 events for E_e = 18 GeV and E_p = 275 GeV and minimal bremsstrahlung photon energy of 1 GeV
- The corresponding σ_{BH}= 129.6 mb
- Luminosity quoted in pCDR for this energy is L = 1.45×10^{33} cm^{-2}s^{-1} = 1.45×10^{6} mb^{-1}s^{-1}
- This is the highest value assumed in pCDR with strong hadron cooling and high divergence configuration
- Event rates f will be given for signal in direct photon detector, signals in spectrometer detectors and coincidence in the pair spectrometer

Results on event rates

- Individual efficiencies ϵ are obtained as a ratio of selected events having energy deposition over the threshold, to all simulated events
- Each event rate f is obtained by putting the particular ϵ into Eq. 4, $f = \sigma_{\mathrm{BH}} \times L \times \epsilon$
- Signal in direct photon detector, deposited energy over 1 GeV
  - $\epsilon_{\mathrm{phot}} = 0.8998 \pm 0.0009$
  - $f_{\mathrm{phot}} = 169.08$ MHz
- Signal in upper spectrometer detector, deposited energy over 1 GeV
  - $\epsilon_{\mathrm{up}} = 0.0293 \pm 0.0005$
  - $f_{\mathrm{up}} = 5.51$ MHz
- Signal in down spectrometer detector, deposited energy over 1 GeV
  - $\epsilon_{\mathrm{down}} = 0.0292 \pm 0.0005$
  - $f_{\mathrm{down}} = 5.48$ MHz
- Coincident signal in both spectrometer detectors, up and down detectors have at least 1 GeV of deposited energy
  - $\epsilon_{\mathrm{pair}} = 0.0116 \pm 0.0003$
  - $f_{\mathrm{pair}} = 2.19$ MHz
- We can expect large rates, luminosity monitor will have no problems with event statistics

Summary

- We now have a full simulation chain from event generator to possible event rates
- Details on every component to be addressed, for every collider energy:

1. Integration to the IR
   - Photon exit window on outgoing electron beam pipe
   - High load from synchrotron radiation
2. Event generator
   - Calculate with beam crossing angle and polarization
   - Extend to the case of *eA*
   - Implement the pileup
3. Geant4 simulations
   - Add low-Q^2 tagger
   - Reconstruction up to original photon kinematics
   - Response to synchrotron radiation
   - Pileup probability
   - Timing with respect to bunch frequency

Figure: "*I'm working on that.*", Stephen Hawking while visiting Star Trek set