College of Natural Sciences and Mathematics
UNIVERSITY OF HOUSTON

Simulation Study of W-ScFi Calorimeter for Pair Spectrometer Luminosity Detector at ePIC

Early Career Day – EICUG 2024 – Lehigh University

Aranya Giri

Relativistic Heavy Ion Lab

Department of Physics, University of Houston

Advisor – Prof. Rene Bellwied

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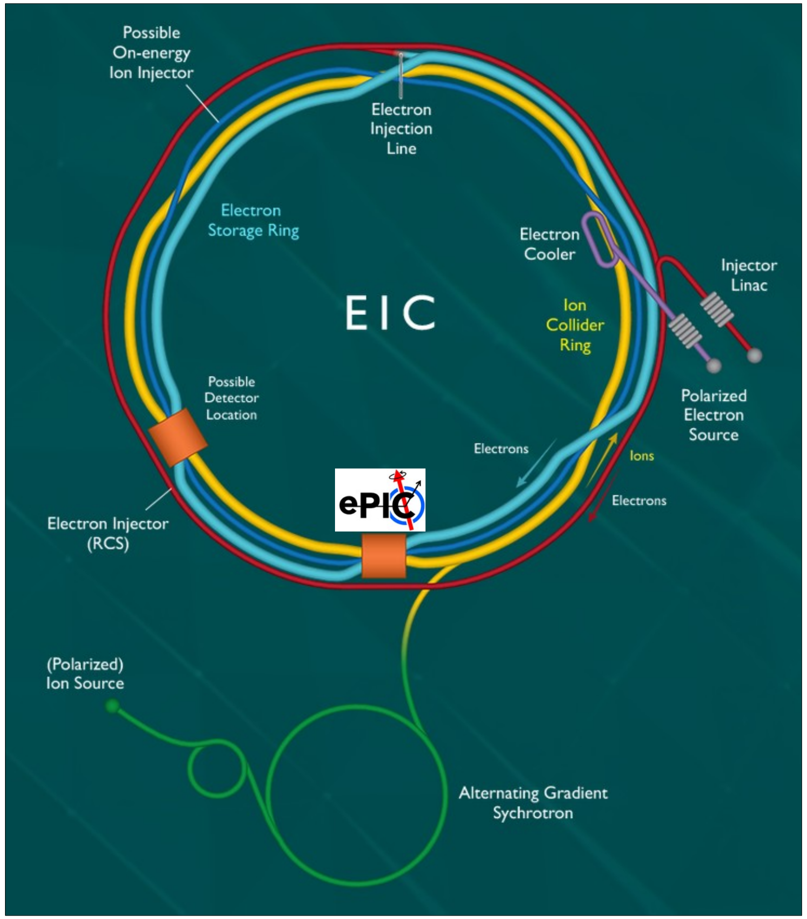
The Electron Ion Collider

- Brookhaven National Laboratory (BNL), New York is the host site for the future Electron-Ion Collider (EIC).



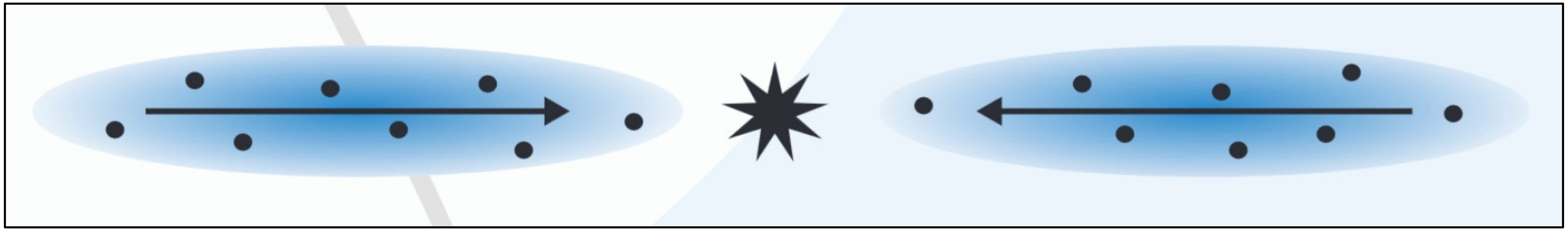
- First detector (experiment) is @ IP6, the electron Proton-Ion Collider (ePIC) experiment.
- The collider and experiment is expected to commission at 2032.

- Variable e-p **COM energy** range from ∼ 20 to 100 GeV, upgradable to ∼140 GeV.
- High electron-nucleon **luminosity**.

arXiv.2103.05419

Luminosity

Luminosity is the maximum no. of collisions that can be produced in the collider



$$L = f\,N^2 / 4\,\pi r^2$$

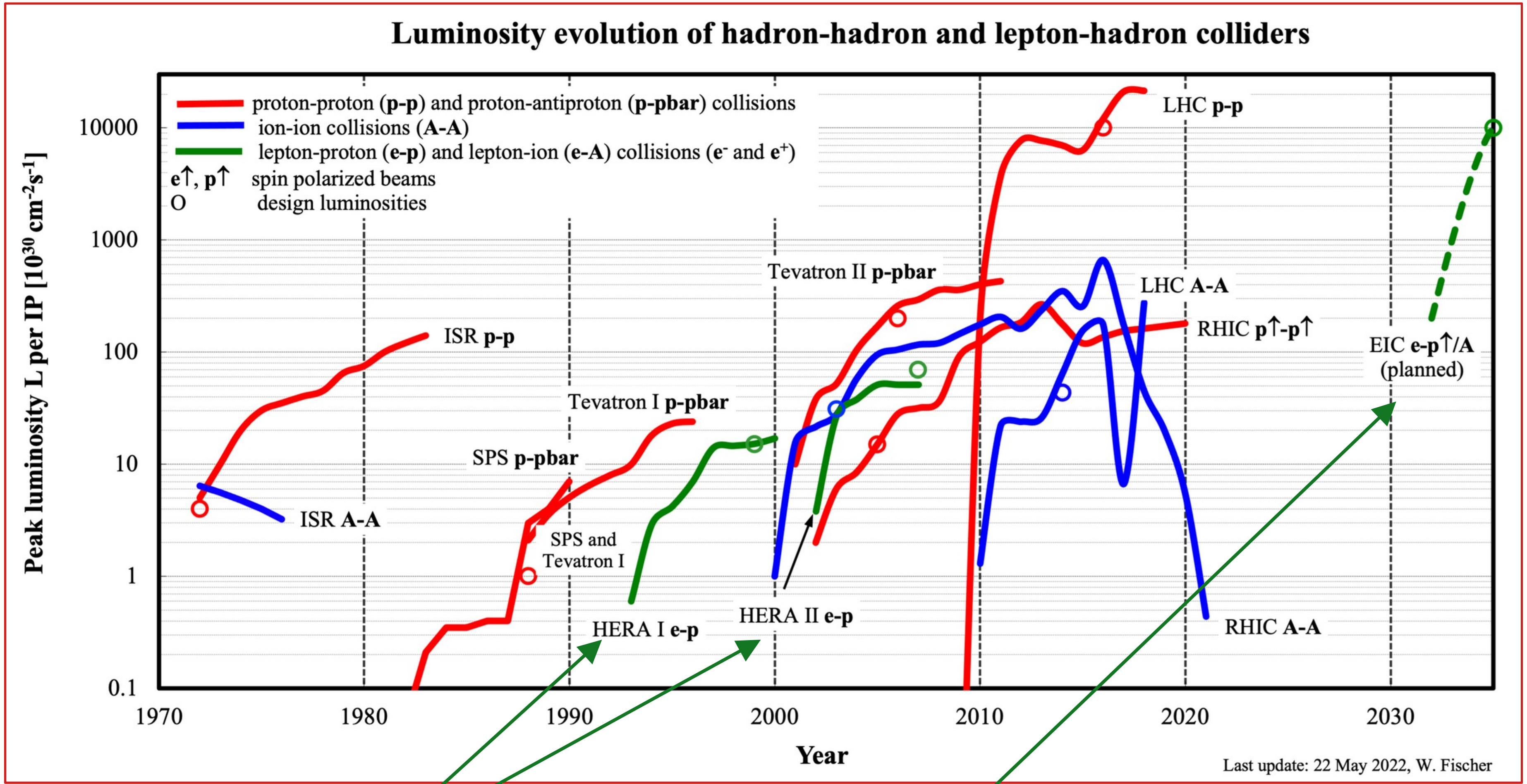
Rate of any event during collision (R) $= L \cdot$ cross-section (σ) of the associated process

Precise measurement of L = Precise measurement of σ
Higher Luminosity = Higher rate to observe any physics processes

At EIC, precision ~ 1% & High Luminosity ~ $10^{33\text{-}34}$ cm^{-2} s^{-1}

https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.luminosity

Luminosity Detector – Past to Future



The Forerunner (precision of ~ 2%)

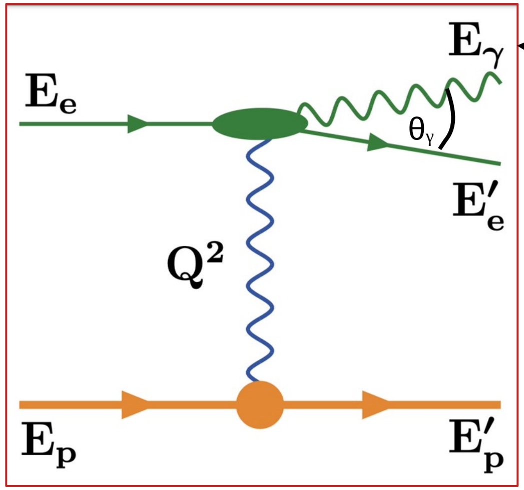
The Future !

[1] https://www.rhichome.bnl.gov/RHIC/Runs/

Luminosity Detector – Bremsstrahlung Process

- HERA (Forerunner of EIC) measured luminosity via Bremsstrahlung (BH) radiation produced during collisions.
- Radiation due to elastic scattering of electron near strong electric field (p / Nu).

E_e : Incoming e^- energy
E_p : Incoming p energy



E_e' : Outgoing e^- energy
E_p' : Outgoing p energy

1. High Rate ~ 4.7 MHz [2]

2. Precisely calculable cross-section from QED, Bethe-Heilter equation

3. Almost all produced BH γs are along e- beam direction, $\theta_\gamma \sim m_e / E_e$

[1] https://arxiv.org/pdf/2106.08993.pdf [2] http://www-library.desy.de/preparch/desy/1992/desy92-066.kek.pdf

Interaction Region of ePIC at EIC

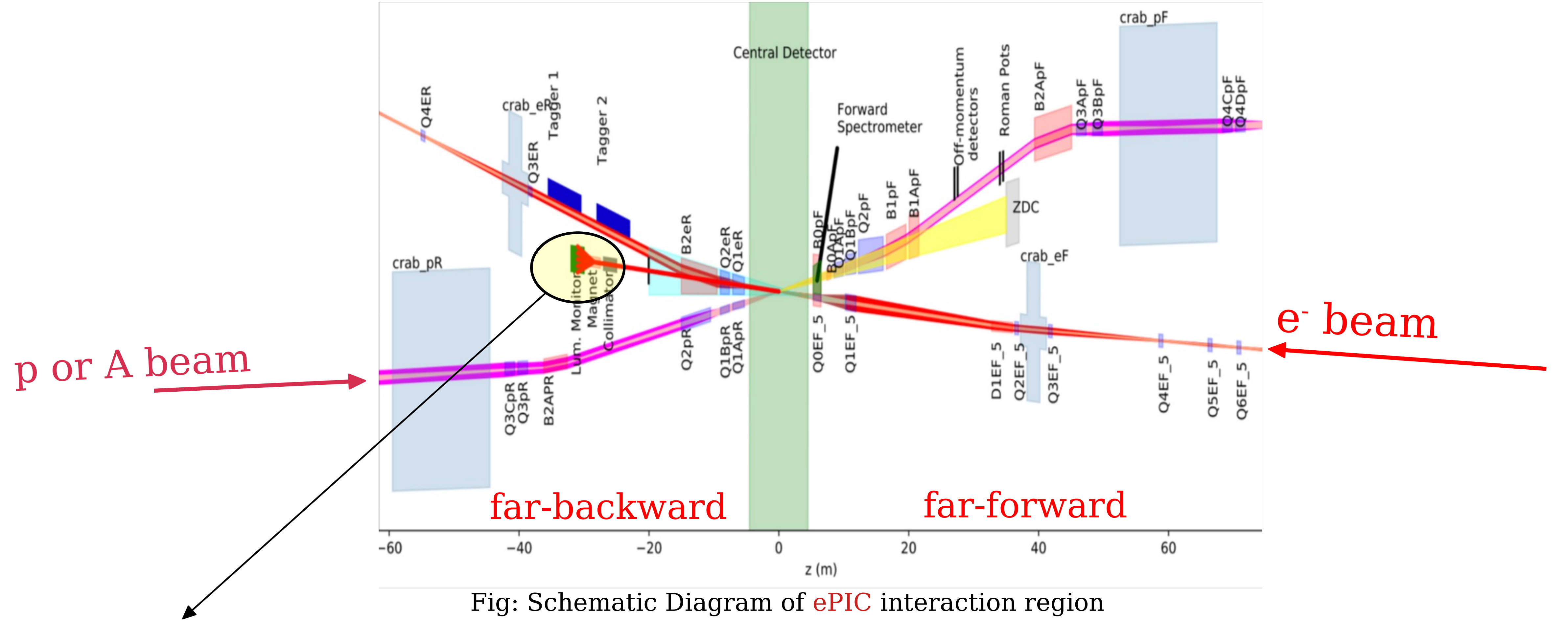


Fig: Schematic Diagram of ePIC interaction region

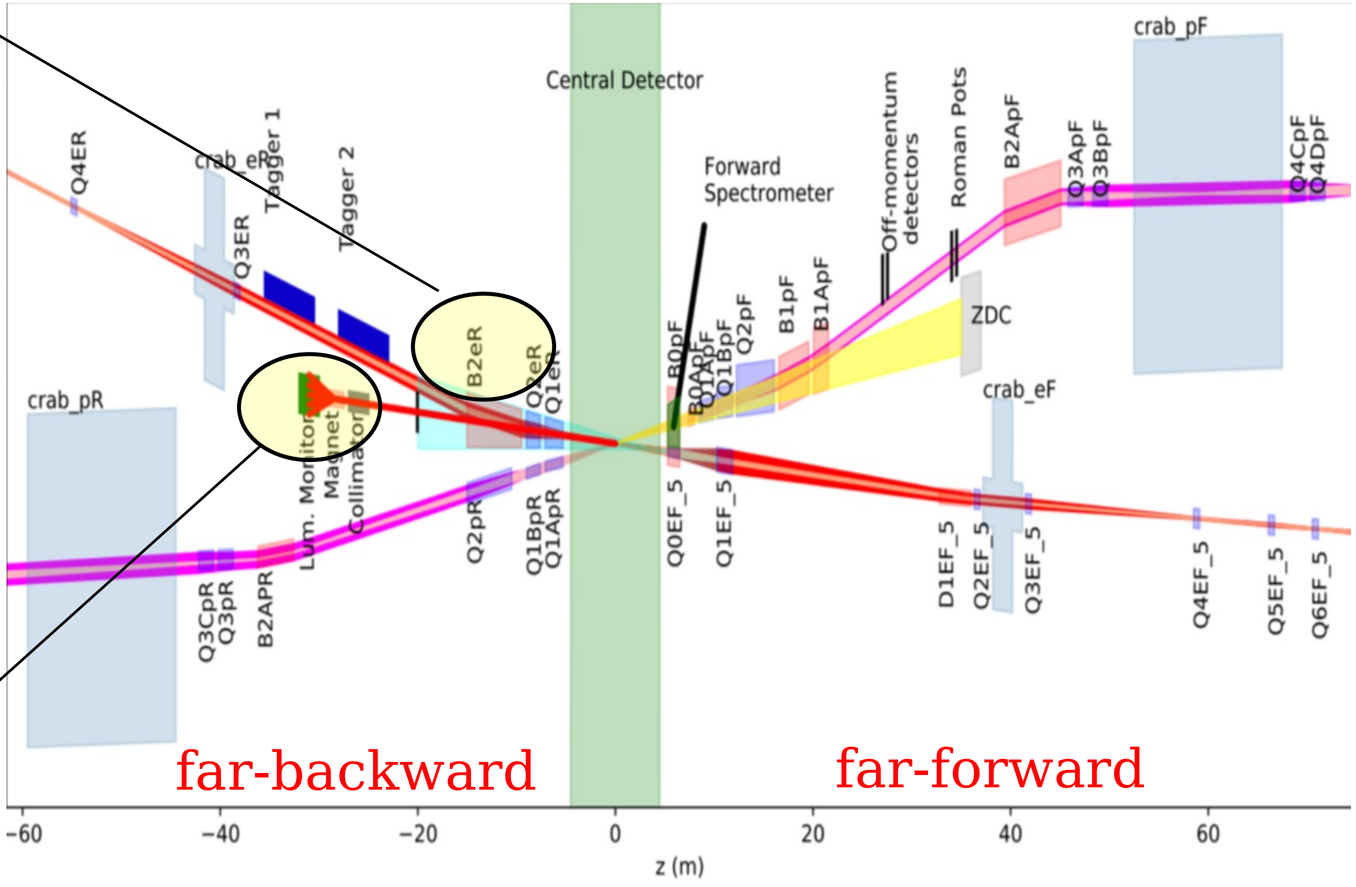
Measurement of bremsstrahlung photons

https://arxiv.org/abs/2103.05419

Interaction Region of ePIC at EIC

Low energy synchrotron radiation as major background

p or A beam



e^- beam

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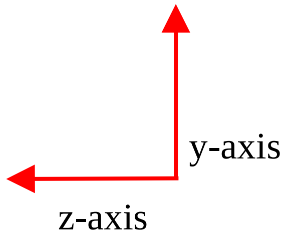
Pair Spectrometer Luminosity Detector



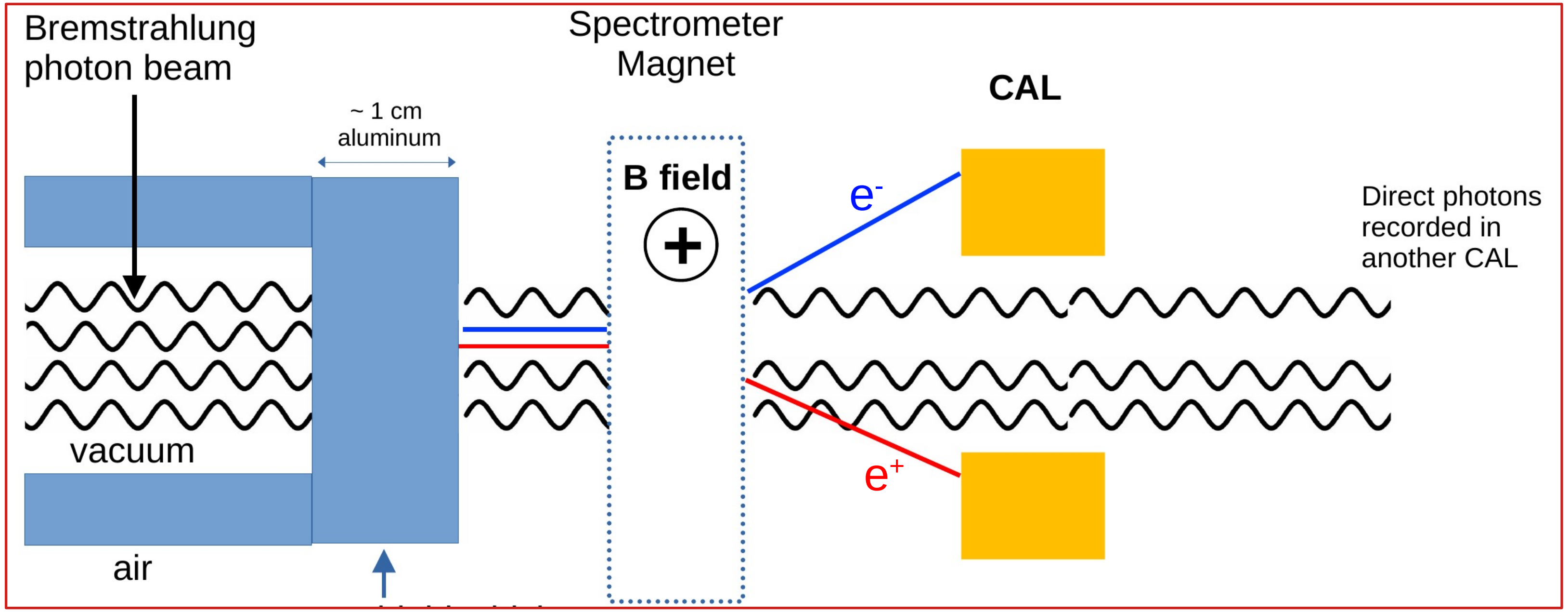


Fig. The base model of ePIC Pair Spectrometer Luminosity Detector

To measure LUMINOSITY !

$$L = R / \sigma_{BH}$$

Pair Spectrometer Luminosity Detector

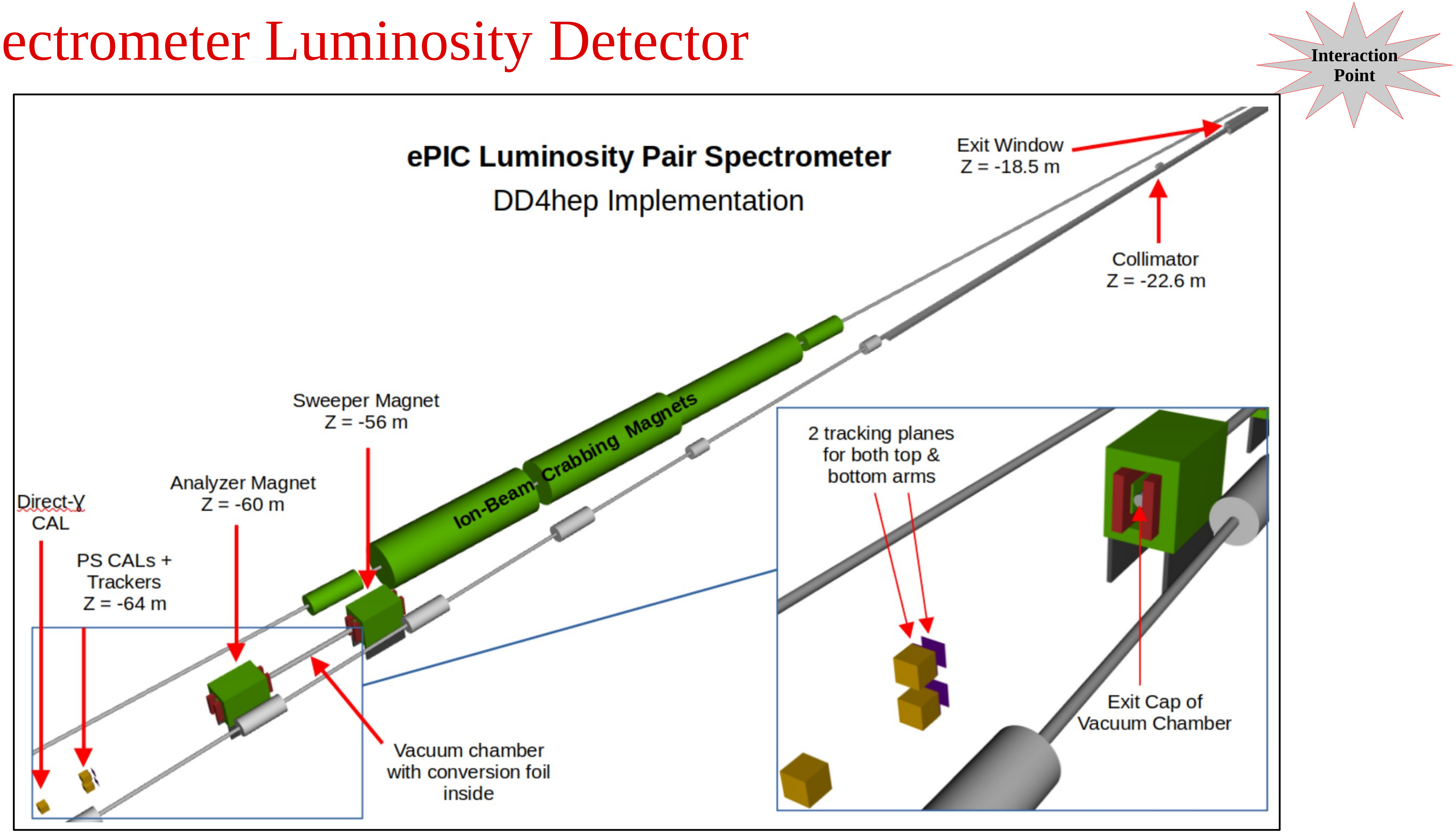


Fig. Current ePIC Luminosity Detector design with e^- and p beam pipes and magnets built by Dhevan G., Aranya G. & Justin C. in DD4hep. The placement of different component not fixed, changes according to experimental needs.

https://arxiv.org/pdf/2106.08993.pdf

Calorimeter

- Calorimeters completely absorbs the incident particle and measure its energy and position.

- The incident particle initiates a particle shower. Each secondary particle deposits energy and produces further particles until the full energy is absorbed.

- The composition and the dimensions of these showers depend on the type and energy of the primary particle (e±, photons or hadrons) .

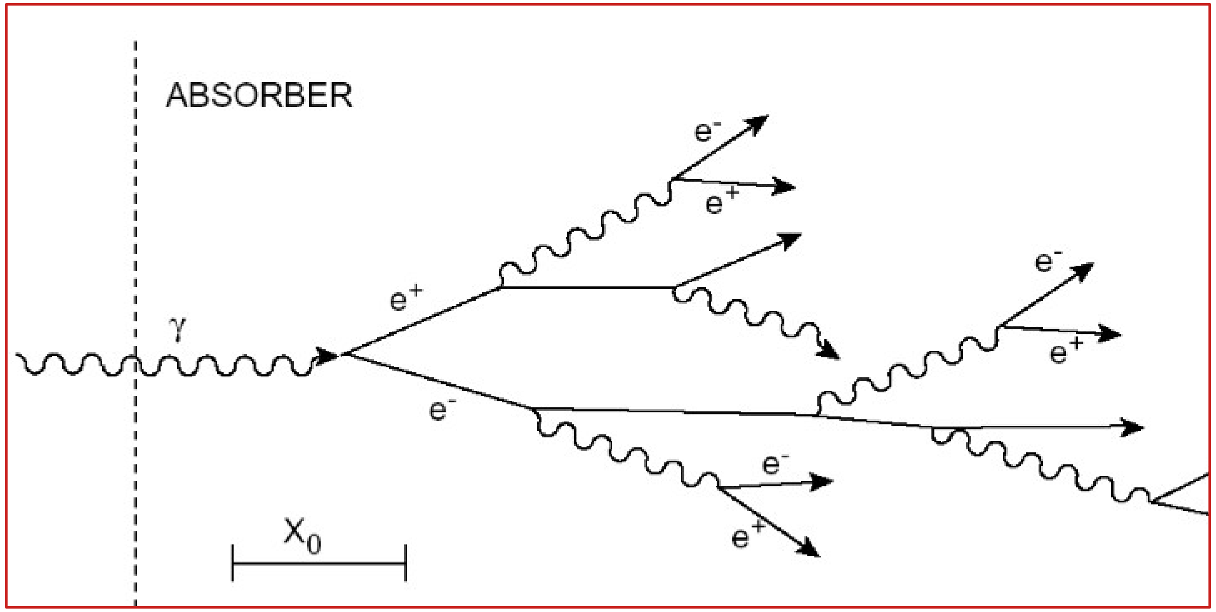


Fig. Shower generation by photon in EM CAL

W-ScFi Calorimeter

1) Requirements
   I. Fairly good energy and position resolution.
   II. Radiation Hard for compact size.
   III. Low integration time (≤ 10 ns bunch spacing).
   IV. Track shower profile for improved pile-up (multiple e^- hits) treatment.

2) A Electromagnetic Sampling Calorimeter
   I. Passive “hard” material – Tungsten (W)
   II. Active Absorber – Plastic Scintillating Fibers

3) The Volumetric Ratio of W : ScFi is 4:1

4) Layered Structure – Alternate layers have fiber running parallel along X or Y direction.

5) Brass holders are used to keep the fibers uniform.

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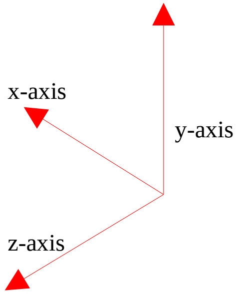


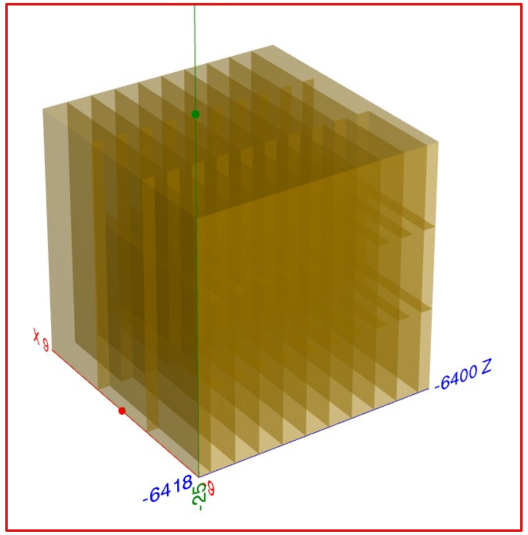


Fig. W-SciFi calorimeter built in DD4hep

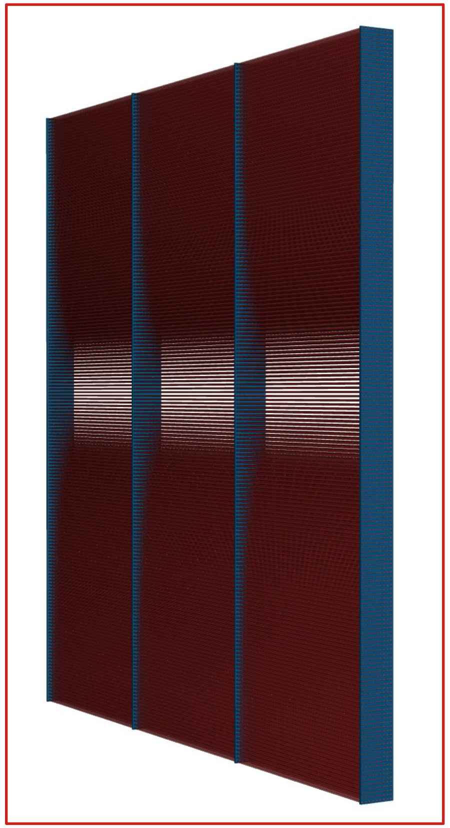


Fig. X|| layer in CAL

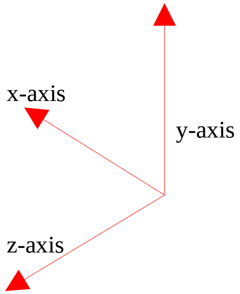
W-ScFi Calorimeter

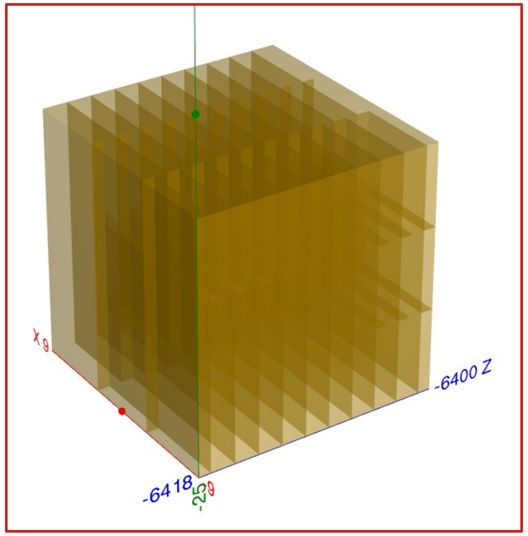
Y-Z shower profile from X|| layer

e^-

X-Z shower profile from Y|| layer

e^-





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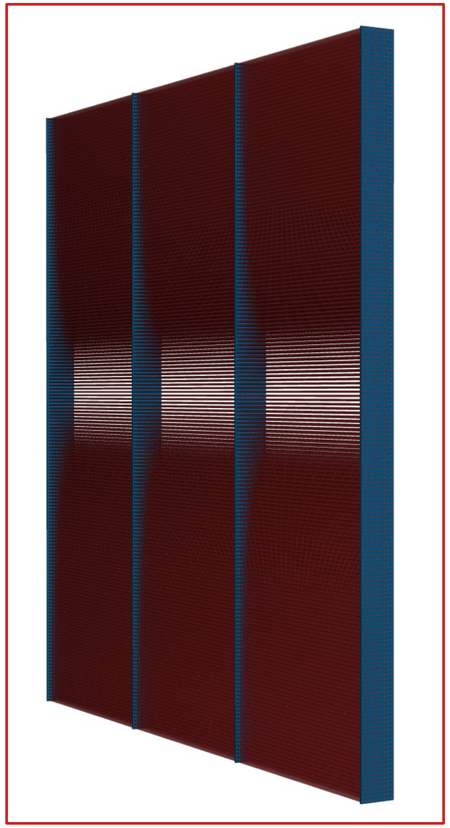
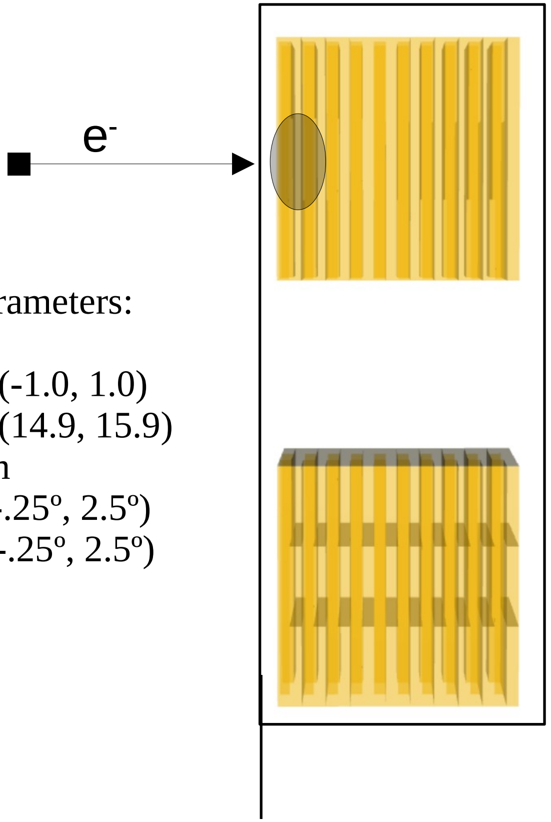


Fig. X|| layer in CAL

Simulation Results – Sampling Fraction

Sampling Fraction is ~ 3% and independent of incident particle energy

Simulation Results – Energy Resolution



Electron Gun Parameters:

- V_x = Uniform(-1.0, 1.0)
- V_y = Uniform(14.9, 15.9)
- V_z = -6388 cm
- θ = Uniform(-.25°, 2.5°)
- φ = Uniform(-.25°, 2.5°)

Z = -6400 cm

Egen = 3.5 GeV

Egen = 11.5 GeV

1) For each generated energy (0.5, 18.0) GeV, the reconstructed energy distribution is fitted with Gaussian distribution.

2) The fit parameters, mean (Erec) and sigma is used to calculate energy resolution.

Simulation Results – Energy Resolution

$\sigma^2/E^2 = a^2/E + b^2/E^2 + c^2$

Simulation Results – Energy Resolution

$\sigma^2/E^2 = a^2/E + b^2/E^2 + c^2$

Energy resolution of a calorimeter is determined by fluctuations in the processes by which energy is deposited and measured.

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Respective terms in the equation :

Stochastic (a): Includes the event-by-event fluctuations of shower development in calorimeter. ($8.8\%/\sqrt{E(\mathrm{GeV})}$)

Noise (b): From the electronic noise of the readout chain and depends on the detector technique and on the features of the readout circuit. (20 MeV)

Constant (c): From non-uniformity, like from imperfections in the detector mechanical structure and readout system, from temperature gradients, from the detector aging, from radiation damage, etc. (~ 0)

Simulation Results – Position resolution

Egen = 3.5 GeV

Egen = 3.5 GeV

Egen = 11.5 GeV

Egen = 11.5 GeV

1) For each generated energy (1.0, 18.0) GeV, the (reconstructed – generated) vertex distribution is fitted with Gaussian distribution.

2) The fit parameters,
   1. sigma is used to calculate position resolution.
   2. Mean ideally should be equal to zero but deviations was observed.

*Position measurements are in centimeters

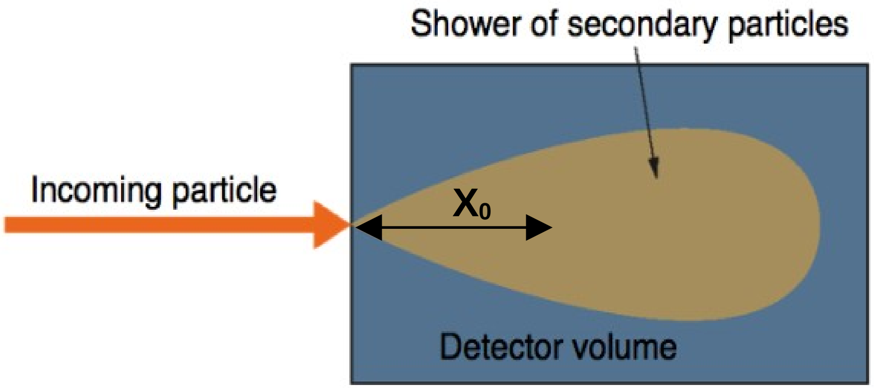
Simulation Results – Position Resolution

- Both x or y resolution is inversely proportional to energy of incident particle.
- Position resolution increases as the energy increases.

- The mean should ideally be 0 but for both x & y shows max deviation of about 0.06 cm.

*Position measurements are in centimeters

Simulation Results – Radiation Length



Radiation length (X_0) of a calorimeter is the longitudinal distance where energy of shower becomes 1/e times the incident energy.

- Depends on material of calorimeter.

Egen = 3.5 GeV

Egen = 11.5 GeV

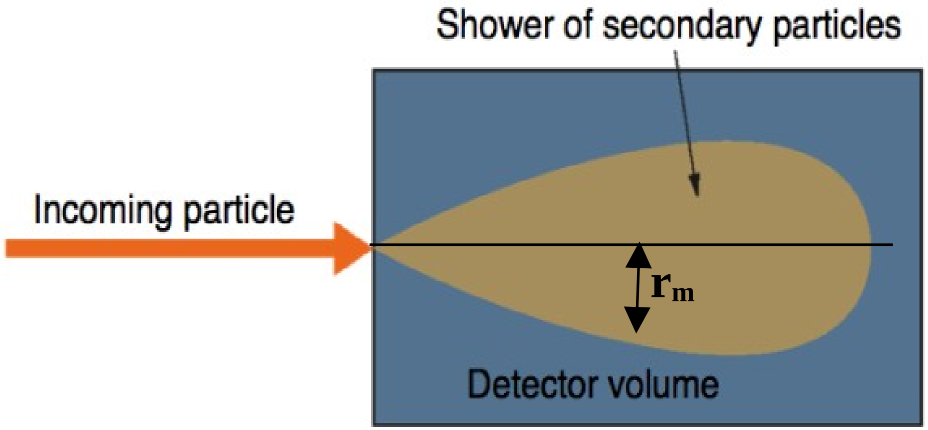
1) For each generated energy (1.0, 18.0) GeV, the deposited energy distribution along longitudinal direction (z) is fitted with Gamma distribution.

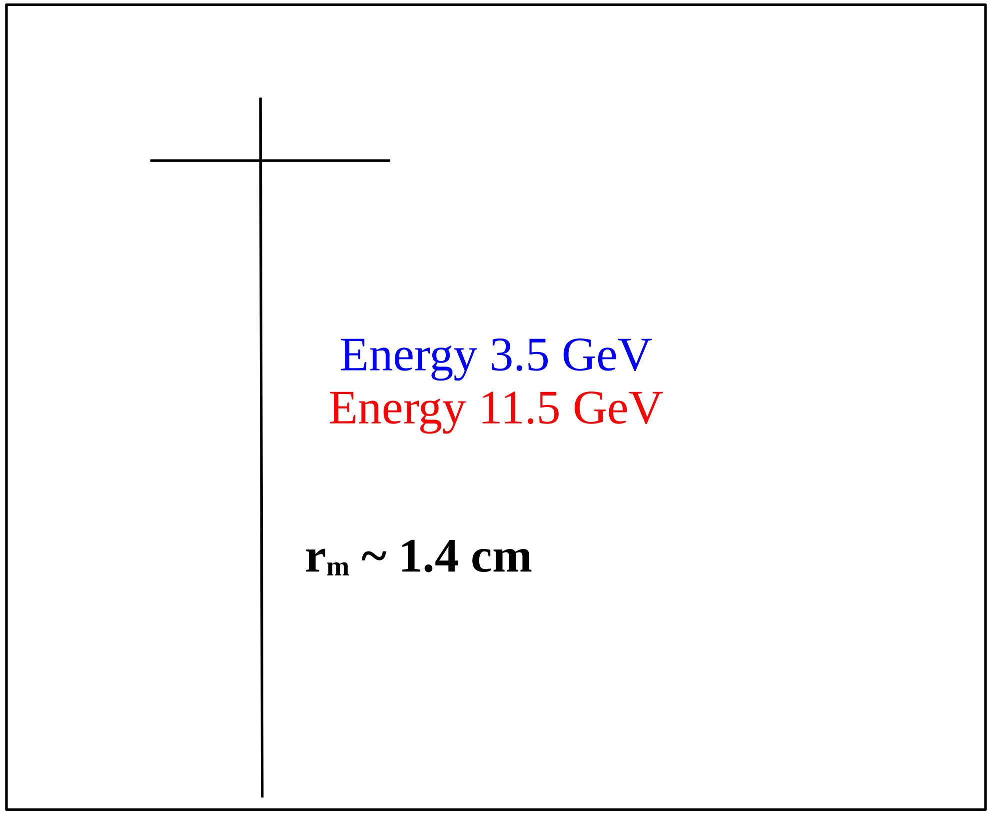
$$f(x;\alpha,\beta) = \frac{x^{\alpha-1} e^{-\beta x} \beta^{\alpha}}{\Gamma(\alpha)} \quad \text{for } x > 0 \quad \alpha, \beta > 0$$

Simulation Results – Radiation Length & Shower Depth

- The fit parameters, alpha and beta is used to calculate $z_{max} = (\alpha - 1)/\beta$, the location where maximum energy is deposited.
- $z_{max} = X_0 (\mathit{log}(\text{Egen}) + c)$, $X_0 = 0.8248$ cm
- Shower Depth – Longitudinal depth of calorimeter in terms of X_0 : (18 cm / 0.8248 cm) = $22X_0$

Simulation Results – Moliere Radius





Moliere radius (r_m) is the radius of a cylinder containing on average 90% of the shower's energy deposition.

- Depends on the material of calorimeter.

Conclusion

Design of W-ScFi calorimeter of Pair Spectrometer Luminosity Detector at EIC for ePIC experiment.

- It has been successfully implemented DD4hep for simulation.
- Characteristics of calorimeter like energy resolution, position resolution, radiation length & Moliere radius is studied.

Future Work

- To study effect of radiation damage in the calorimeter.
- Study optical parameters of scintillating fiber.
- Beam test with first prototype build with collaborators at York University, UK

Thank You

Simulation Results – Position Resolution

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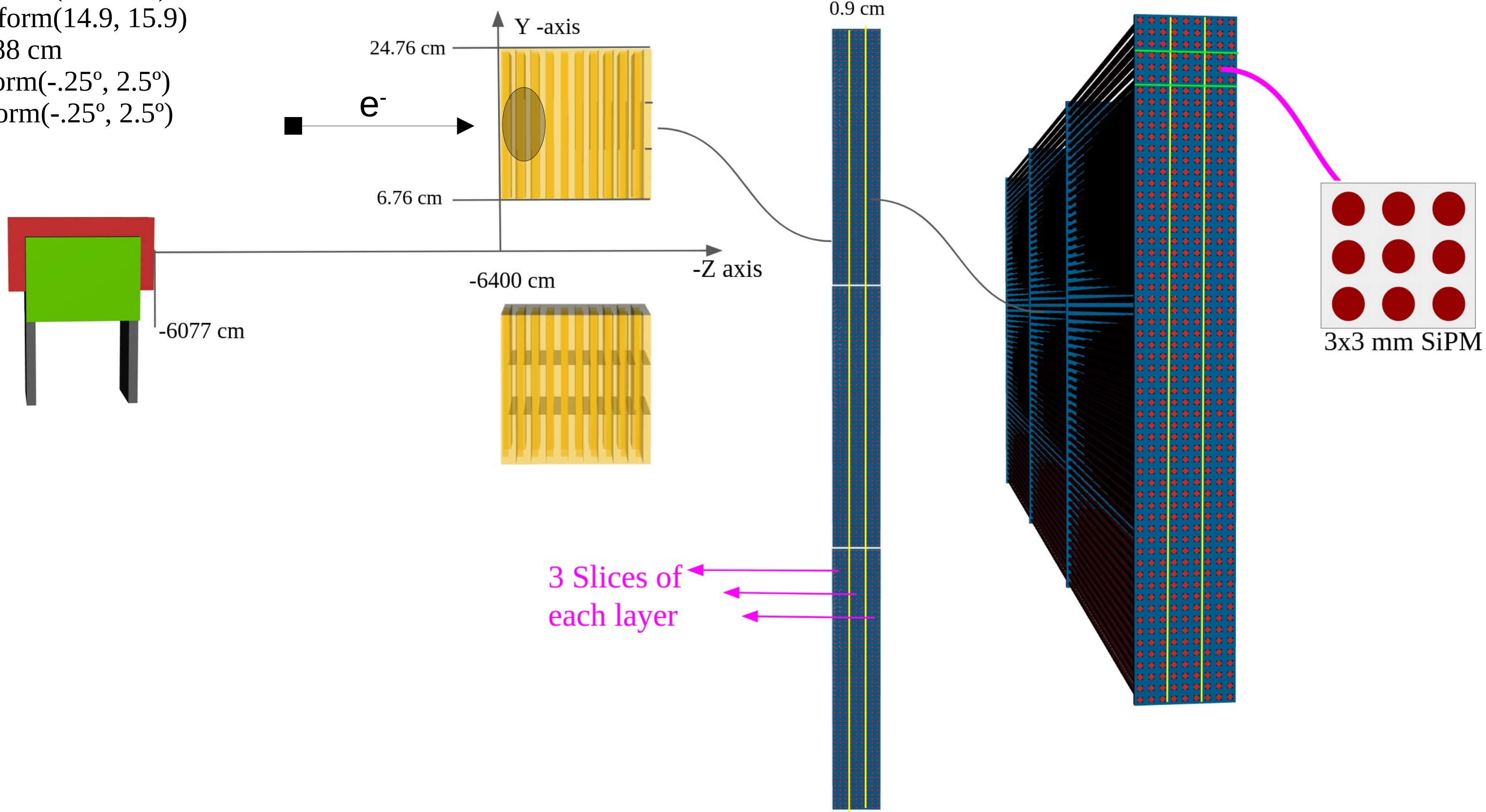
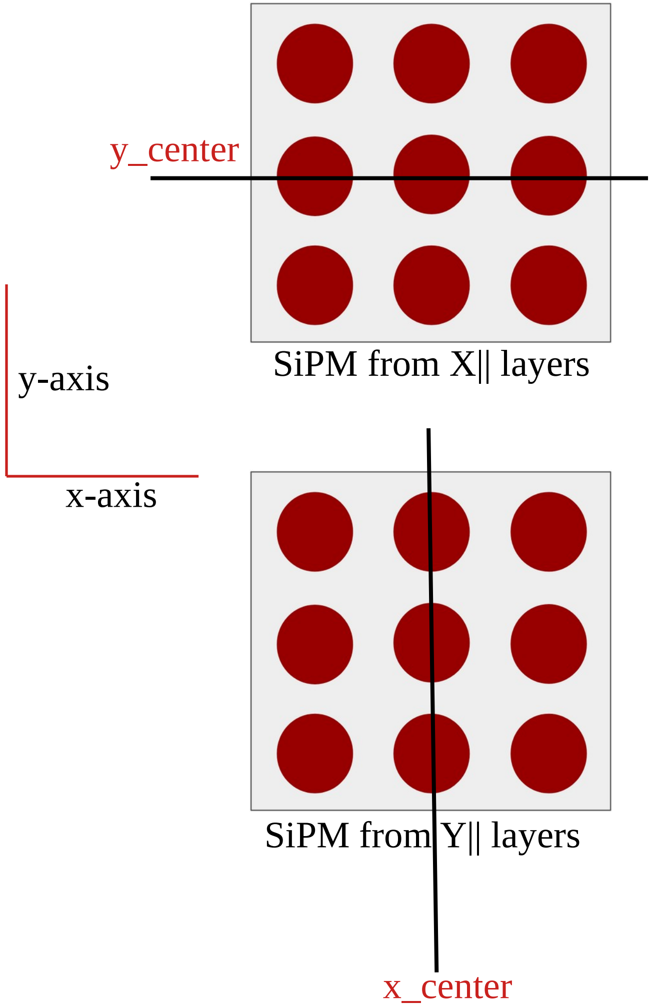
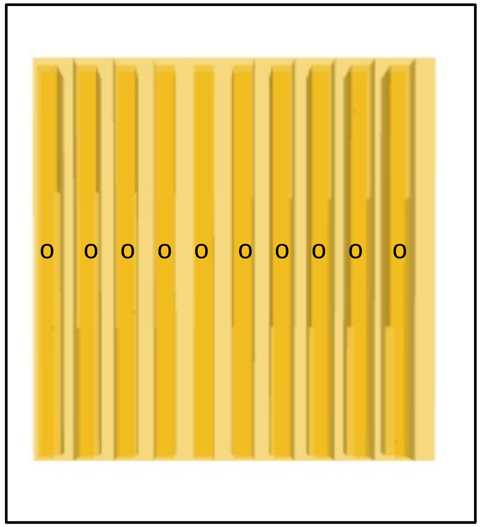


Simulation Results – Position Resolution

- Energy deposition (Edep_i) in 9 fibers of each SiPM is associated with a position, pos_i where i = {SiPMs}
- The center of SiPM is the associated position , Pos_i = { x_center or y_center } depending on layer.
- For a slice say j, in Suppose X|| layers, the mean y_j is $y_j = \frac{\sum_i^{i\in j} y_i E_{dep}^i}{\sum_i^{i\in j} E_{dep}^i}$
- Find the mean position in each slice



$$\bar{t} = \frac{\sum_j^{j\in slices} t_j E_{dep}^j}{\sum_j^{j\in slices} E_{dep}^j} \qquad t \in y, z$$



$$m = \frac{\overline{yz} - \bar{y}\bar{z}}{\overline{z^2} - \bar{z}^2}$$