# Far-Backward Pair Spectrometer

Dhevan Gangadharan, Nick Zachariou

Pair Spectrometer Wiki Page:

ePIC collaboration meeting
Warsaw, July 29th 2023

# Measuring Luminosity at the EIC

**Experimental Goal:**

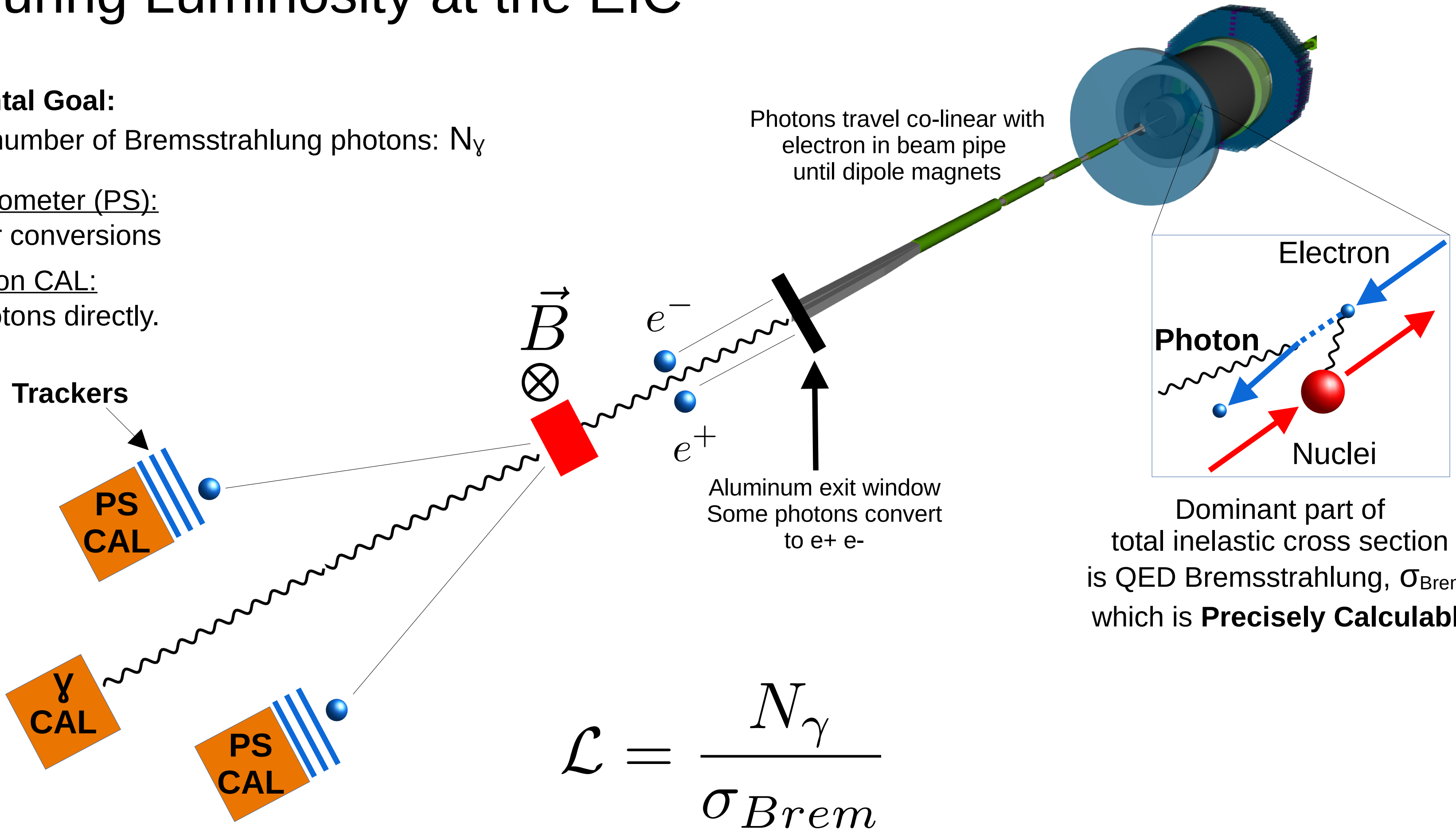
Count the number of Bremsstrahlung photons: $N_\gamma$

Pair Spectrometer (PS):

Counts pair conversions

Direct photon CAL:

Counts photons directly.



Photons travel co-linear with
electron in beam pipe
until dipole magnets

Aluminum exit window
Some photons convert
to e+ e-

Dominant part of
total inelastic cross section
is QED Bremsstrahlung, $\sigma_{\mathrm{Brem}}$,
which is **Precisely Calculable**

$$\mathcal{L} = \frac{N_\gamma}{\sigma_{Brem}}$$

# Lessons Learned from ZEUS Lumi Systematics

EIC Yellow Report Requirements:

- ~1% uncertainty for absolute luminosity.
- Less than $10^{-4}$ for relative lumi.

NIM A 744 (2014) 80-90

| Component | Sub-Component systematics |
|---|---|
| **Acceptance** (**1.6%: Total**) | **1.0%:** Aperture and detector alignment |
| | **1.2%:** X-position of photon beam |
| Photon conversion in exit window (**0.7%: Total**) | 0.1%: Thickness |
| | 0.3%: chemical composition |
| | 0.6%: photon conversion cross section |
| RMS-cut correction (**0.5%: Total**) | Rejection of proton gas interactions |
| **Total** | **1.8%** |

Reduction routs for ePIC:

1) 5*σ obstruction-free aperture
2) low-lumi runs with coincidences of low-Q2 tagger and pair spec. **Tagger critical for pair spec calibration/verification**

With a well understood acceptance, 1% absolute lumi precision within reach.

For relative lumi, all systematics should cancel, and required statistical precision reached in less than 1 hour.

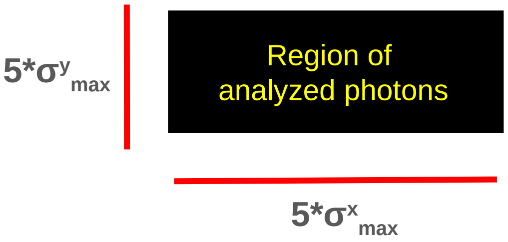
# Photon Acceptance

Need to provide an unobstructed path for Bremsstrahlung photons to propagate from the IP to the lumi exit window, and then from the exit window to the Pair Spectrometer.

Photon beam width $\sigma(Z) = \Delta\Theta$ (electron beam divergence) * Z.

$3*\sigma_{Gaus}$ covers 99.7% of population, but beam may not be Gaussian and it's preferable not to extrapolate.

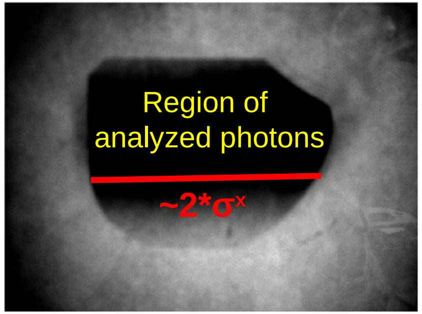
**$5*\sigma_{max}(Z)$ conical region should provide adequate acceptance.**



This!

Not this!

ZEUS photon aperture



This was the dominant source of uncertainties for the HERA luminosity

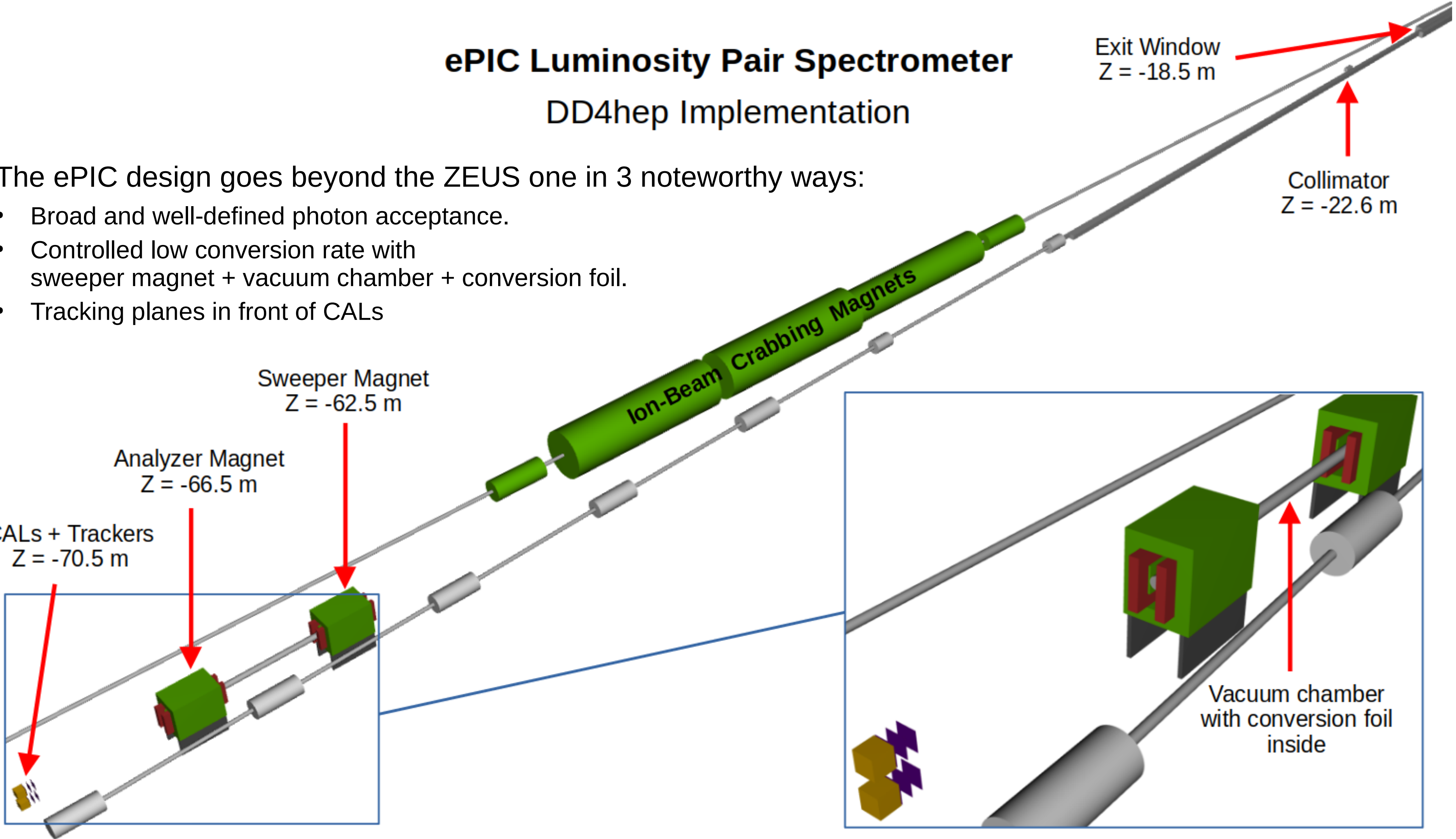
We need a simple and broad acceptance!

# ePIC Luminosity Pair Spectrometer

## DD4hep Implementation

The ePIC design goes beyond the ZEUS one in 3 noteworthy ways:

- Broad and well-defined photon acceptance.
- Controlled low conversion rate with
  sweeper magnet + vacuum chamber + conversion foil.
- Tracking planes in front of CALs



Exit Window
Z = -18.5 m

Collimator
Z = -22.6 m

Sweeper Magnet
Z = -62.5 m

Analyzer Magnet
Z = -66.5 m

CALs + Trackers
Z = -70.5 m

Vacuum chamber
with conversion foil
inside

# Design Considerations – **System Placement**

- The Pair Spectrometer system starts 62 m from the IP, and 43.5 m from the vacuum exit window.
- That's lots of air for the photons to travel through. The EM radiation length in air is 304 m.

$$P_{conv} = 1 - e^{-\frac{\Delta Z}{(X_0\, 9/7)}} \approx 10\%$$

$$\begin{aligned} X_0^{\text{air}} &= 304\ \text{m} \\ \Delta Z &= 43.5\ \text{m} \end{aligned}$$

- 10% of the Bremsstrahlung photons will convert in air before arriving at the sweeper magnet.
- That's OK.
- The pair-conversion and Bremsstrahlung cross sections are cross channels of the **same** reaction.

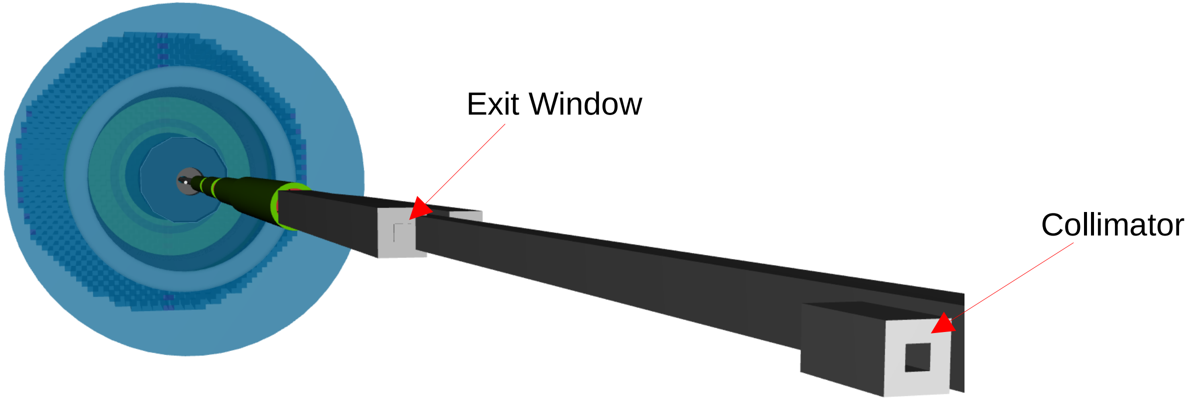
$$e^- + p^+ \to e^- + \gamma + p^+$$

$$\gamma + p^+ \to e^- + e^+ + p^+$$

- Bremsstrahlung cross section known to at least 0.2%. Conversion uncertainty ~ 10% * 0.2% = **0.02%.**

**Negligible contribution to lumi systematics.**

# Design Considerations – **Exit Window and Collimator**



Exit Window (Z = -18.5 m)

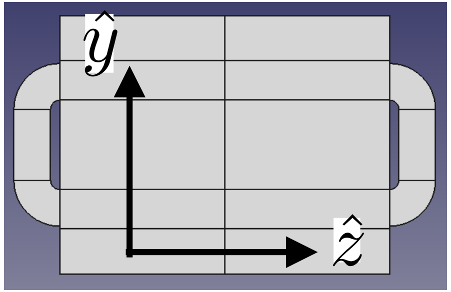
- It should have a simple geometry: constant effective thickness vs X and Y.
- Thickness and chemical composition ( a% Al + b% Si + …)
  **needs to be precisely known before installation!**
- Conversion rate in exit window can also be determined in special low-lumi runs by turning off the sweeper magnet

Collimator (shortly after the exit window)

- Just a block of steel to shield our downstream detectors from unnecessary radiation damage.
- It defines the outer limits of our acceptance (aperture size).
- Should have an opening half-width of $5 * \Delta\theta_{max} * Z = 5 * 211e\text{-}6 \text{ rad} * 22.6 \text{ m} = 2.4 \text{ cm}$

# Design Considerations – **Dipole Magnets**

Peng’s CAD model



Sweeper & Analyzer Dipole Magnets Requirements

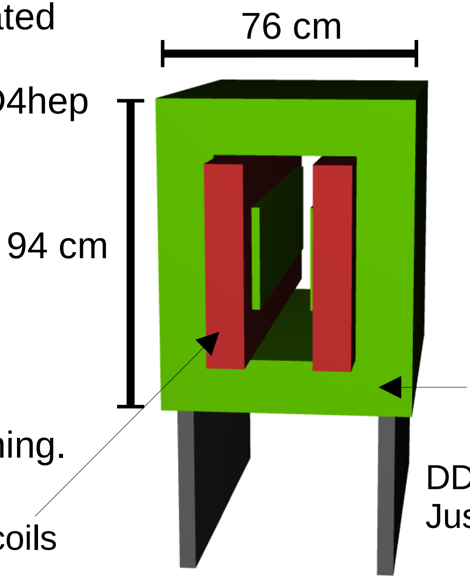
- Large $\int B_x * dz \sim 1$ Tm to keep our system compact
- 15 cm bore diameter: 5*σ unobstructed photon acceptance
- Fringe fields at electron beam pipe < 10 Gauss

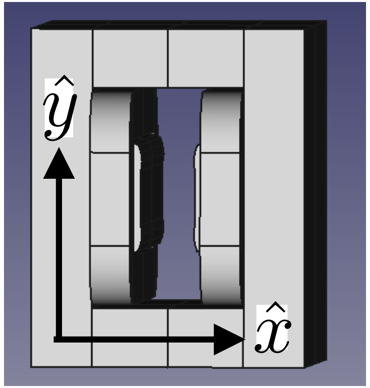
New magnets are to be built.
Magnet designer Peng Xu (BNL) has designed and simulated the magnets for us.
Field maps have been provided and will soon be put in DD4hep

Design properties:

- 1.2 m long with field reaching about 0.8 T
- 15 cm bore diameter
- Fringe field at electron beam pipe < 4 Gauss.
- 6 metric tons each, excluding leg supports.
- Pre-covid cost: ~$3 per kg of soft iron, including machining.
  > $20k per magnet.

DD4hep model





Iron yolk

Cu coils

DD4hep model by
Justin Chan (UH)

# Design Considerations – **Vacuum Chamber**

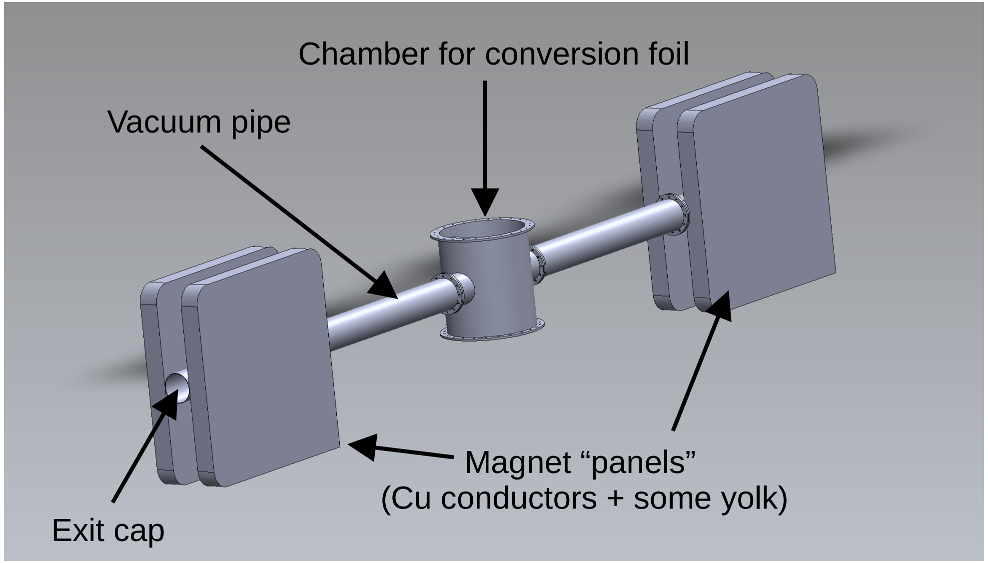
Vacuum chamber (-67 m < Z < -62 m)

- Allows us to precisely control the Bx*dz for the conversion electrons. Conversions in air in magnet smear the Bx*dz.
  → Easier to get a well defined electron acceptance.
- Foil inside allows us to precisely control the rate of conversions by varying its thickness
  → Avoids pileup.

Studies underway by Igor:

- Exit cap optimization (thickness and material)
  → minimize $e^+$ $e^-$ multiple scattering.
- Conversion foil thickness and cooling method. Must withstand synchrotron rad heating.
- Vacuum pressure:
  - First, compare conversion rates:
    1 mm Al conversion foil: $P_{conv} = 0.9\%$.
    5 m of STP air ($10^3$ mbar) inside $P_{conv} = 1.3\%$
  - To reduce conversions in air to well below 1% that of foil, we need a **vacuum with < 1 mbar**. Note that vacuum near the IP = $10^{-9}$ mbar

Igor Korover (MIT & Tel Aviv University)



July 11th 2023 PS meeting

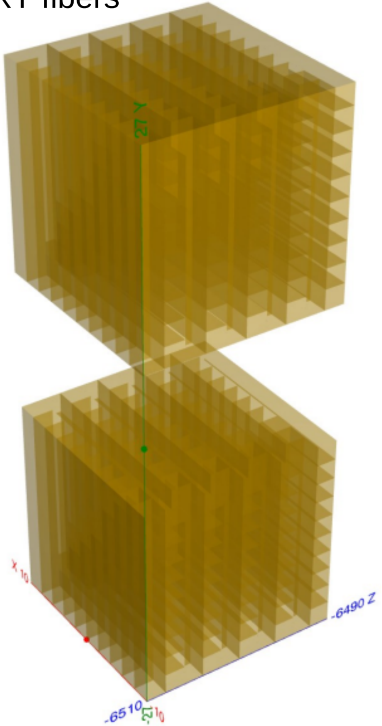
# Design Considerations - **CALs**

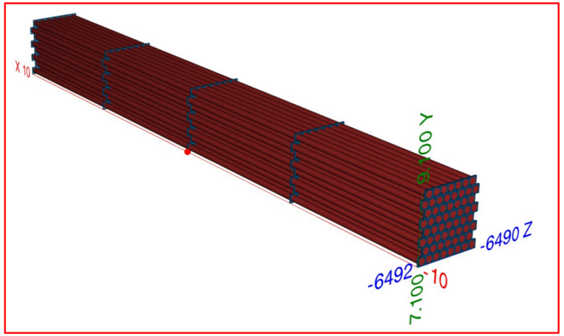
Construction of each module can follow the method of Oleg Tsai,
W-powder + epoxy infused into a bundle of scintillating fibers (like fECAL).

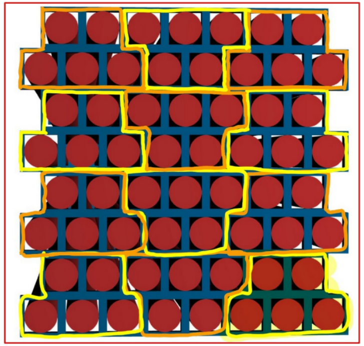
We are exploring a 2D XY fiber design: more detailed shower profiling.

Design by Aranya Giri

2D
XY fibers



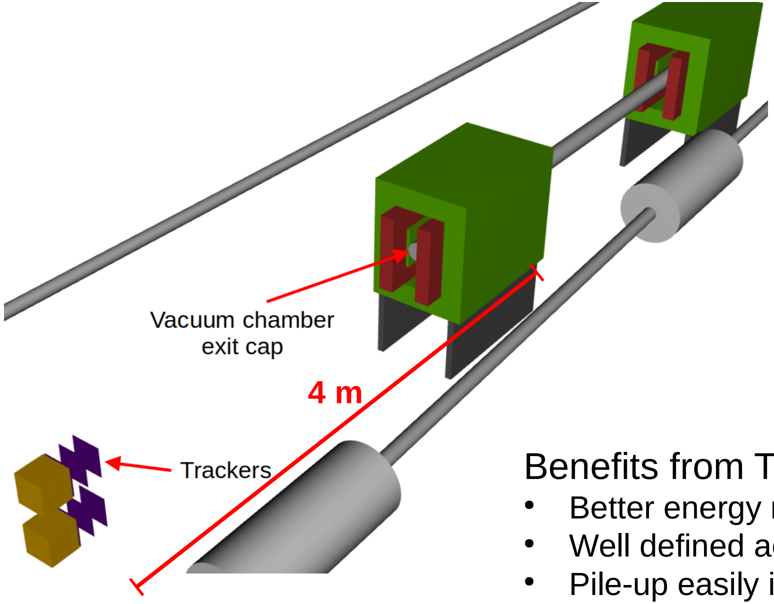




- Calorimeter size - 20 x 20 x 20 $cm^3$
- Alternating Layer of Y-rot and X-rot module
- Each Layer has 10 modules
- Module size - 2 x 2 x 20 $cm^3$
- Fiber Size - radius – 0.1 cm , height - 20 cm
- Fiber # in a module - 60
- W-Scifi Ratio - 1 : 1
- Fiber Holder
  - Material - Brass
  - thickness – 0.05 cm
  - 5 x Fiber Holders 5 cm apart
- 5 closest fibers are bundled to make a single readout channel.

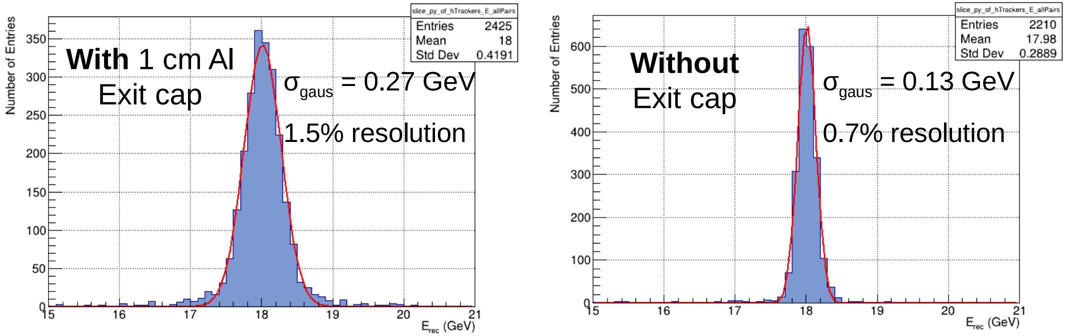
University of York In kind contribution (awaiting decision on proposal)

# Design Considerations - **Trackers**



## Energy Resolutions

for 18 GeV electrons



Benefits from Tracking Planes in front of CALs:

- Better energy resolutions attainable than from CALs.
- Well defined acceptance, no “fuzzy” edges as with CALs.
- Pile-up easily identified and treated.
- Tracks allow rejection of background particles (beam-gas) and assessments of the electron beam divergence.

**3 Timepix4 tracking planes assumed so far, but given the rough $2M price tag,**
**we will explore the performance with 2 or even just 1 plane (acceptance and pile-up treatment only).**

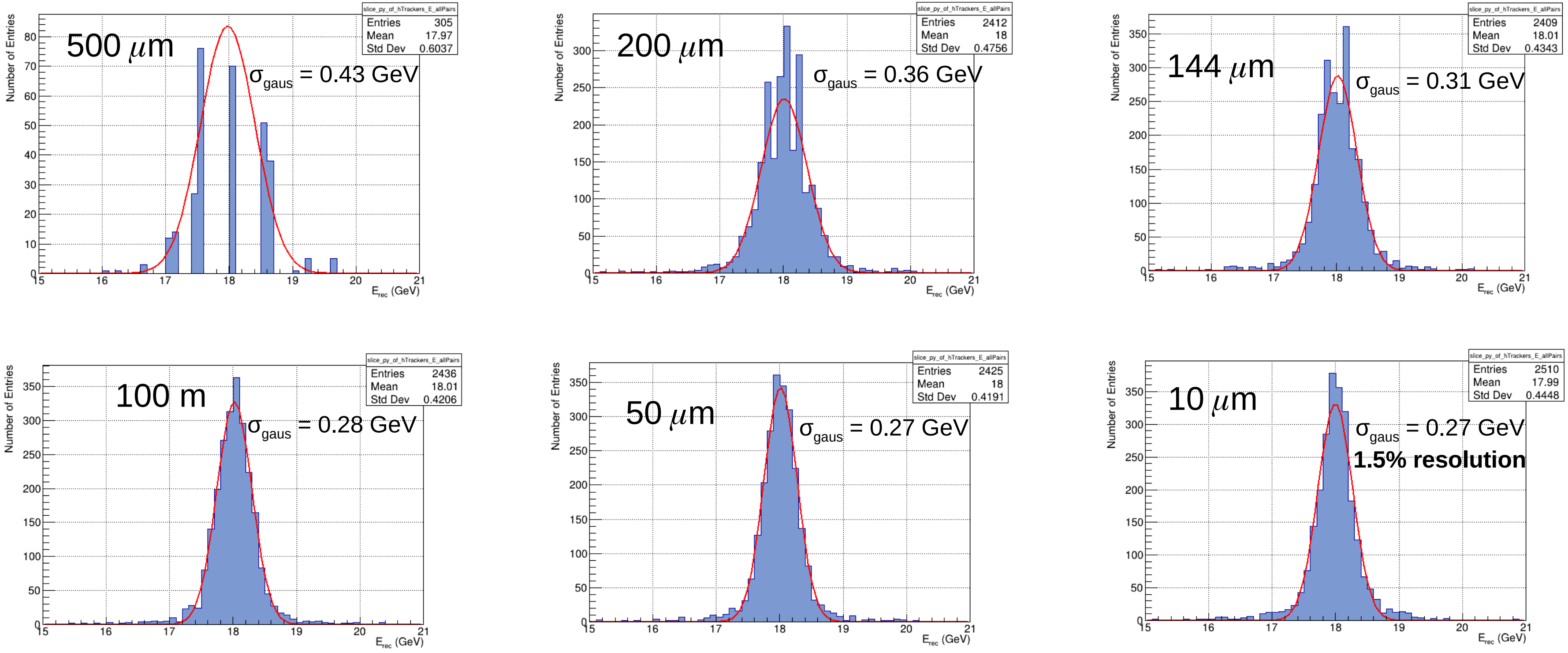
In principle, either trackers or CALs alone can do the job, but having both is advantageous

# Concluding Remarks

- EIC bremsstrahlung rates will be much higher than those at HERA.
  - More sophisticated pair spectrometer design wrt ZEUS needed for precise lumi at the EIC.
- Having a simple and broad photon acceptance is very important for the Lumi program.
  - No obstructions to our 5*σ(Z) conical photon beam, please.
- New dipole magnets (sweeper + analyzer) have been designed that satisfy our requirements.
  - Allows our system to be quite compact.
- CAL design will follow the W-powder + SciFi design used in the forward ECAL.
  - 2D XY fiber design being considered.
- Tracking planes provide many benefits to the system and should to be included.
  - Number of planes needed to be determined.
- Side note: electron bunches with no colliding ion bunch (pilot bunches) are required for measurements of beam-gas backgrounds to the lumi measurements.

# Backup

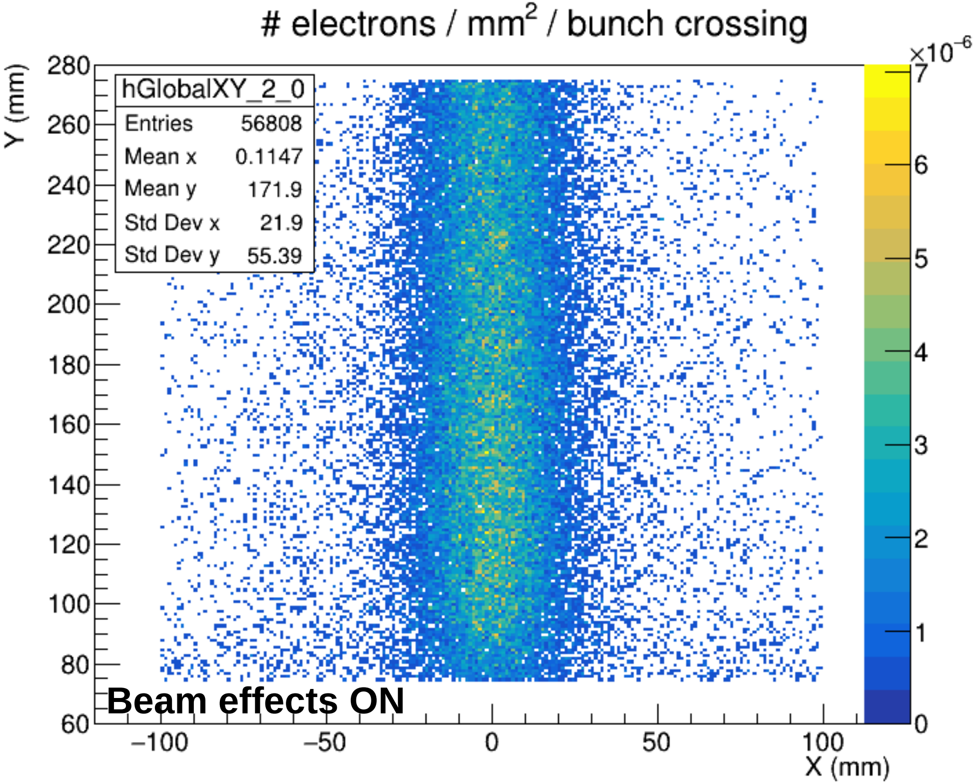
# Trackers - Pixel Size and Energy Resolutions



- Clear discretization effects visible for “large” pixels, due to small angular range of tracks: ~0.7° to ~4°.
  Note, charge-sharing effects would improve E resolutions somewhat.

# Trackers - Occupancies

## ep 18x275 (44 ns bunch spacing)



~ $10^{-5}$ electrons per mm$^2$ per bunch crossing.

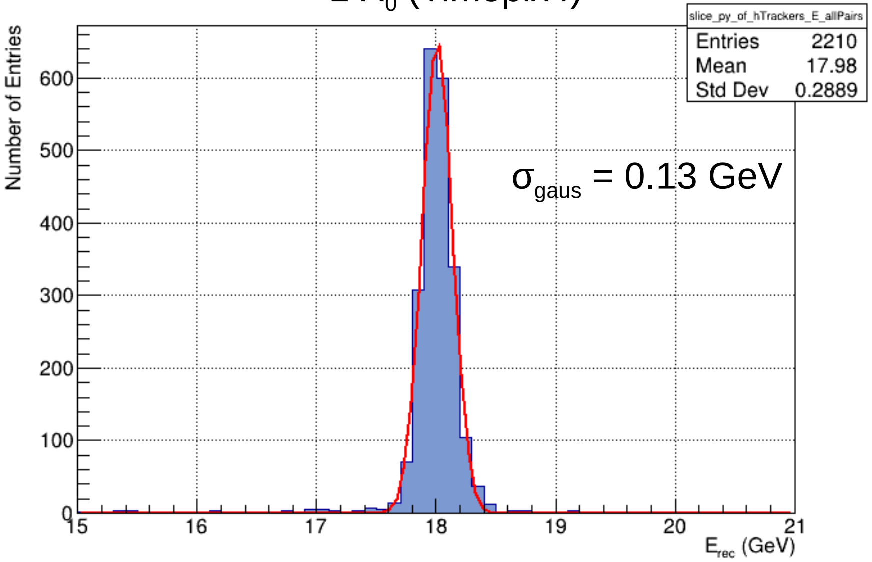
~ $10^{-5}$ electrons per 55 um pixel per bunch crossing in the “brightest” eA setting.

**Large sensor integration times are not a problem (even $\mu$sec level).**

# Trackers - Material Budget

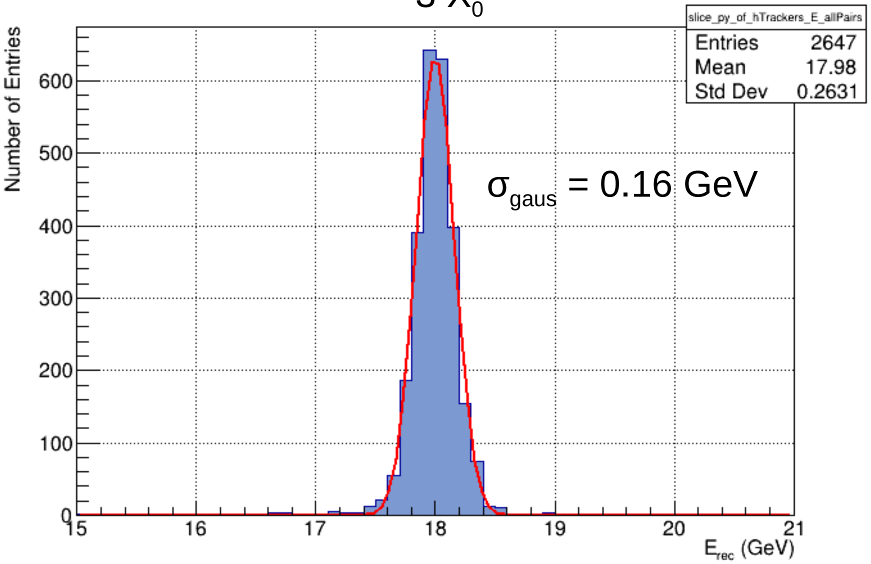
## 50 $\mu$m without exit cap

1 $X_0$ (Timepix4)



$\sigma_{gaus}$ = 0.13 GeV

3 $X_0$



$\sigma_{gaus}$ = 0.16 GeV

No stringent requirement on the sensor material budget.

# Summary of Tracker Requirements

| | |
|---|---|
| Total sensor Area | 2 sets * 3 layers * 20 cm * 20 cm = 2,400 cm2 |
| Pixel size | ~ 50 um |
| Material budget | no stringent requirements |
| Integration times | no stringent requirements |
| Time resolution | ~nsec, to distinguish bunch crossings |

Considered technologies for the Trackers:

- **Timepix4 (preferred option so far)**
- Microstrips (quote from a company on next slide)
- AC-LGAD
- AstroPix
- MAPS

# Microstrip sensors

For what its worth...here is a price quote I obtained for microstrips that might suite our needs

Product Catalogue

**Micron Semiconductor Limited**

Units 1-5 Royal Buildings
85 Marlborough Rd
Lancing
West Sussex
United Kingdom
BN15 8SJ
Tel: +44 1903 755252

Company Registration No: 1694255 England
VAT No: GB 376 8710-14
EORI No: GB 376 8710 14000

E-Mail: sales@micronsemiconductor.co.uk
www.micronsemiconductor.co.uk

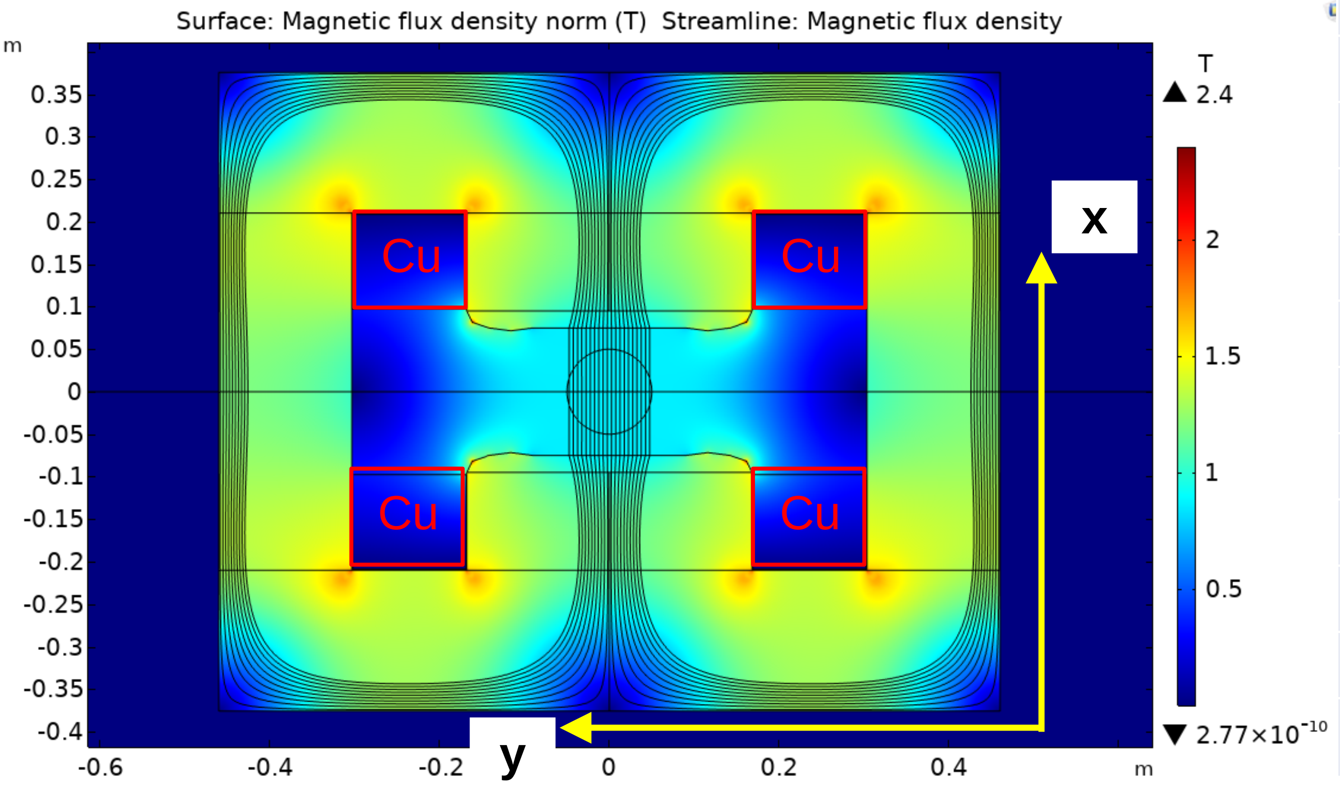
| Description | Quantity | Unit Price | VAT | Amount USD |
|---|---|---|---|---|
| DDD5 (DS) 300 2M/2M AC coupled chip only detectors | 120.00 | 5000.00 | Zero Rated | 600000.00 |
| NRE custom dedicated test and shipping trays for sample testing, shipping and storage | 120.00 | 175.00 | Zero Rated | 21000.00 |
| NRE masks | 2.00 | 1850.00 | Zero Rated | 3700.00 |
| NRE probe cards; 128 channels | 2.00 | 1250.00 | Zero Rated | 2500.00 |
| NRE copy masks | 12.00 | 650.00 | Zero Rated | 7800.00 |
| NRE Silicon 5K - 10K N Type <1-0-0> 6 inch | 100.00 | 150.00 | Zero Rated | 15000.00 |
| Prices US dollars FOB destination | | | | |
| | | | Subtotal | 650000.00 |
| | | | Total Zero Rated | 0.00 |
| | | | **TOTAL USD** | **650000.00** |

DDD5 dual sided Si microstrips

- 50 um pitch
- orthogonal dual sided strips
  not sure if readouts from both sides could be read out from one end
- 2 cm x 12 cm chips (need 120 of them)

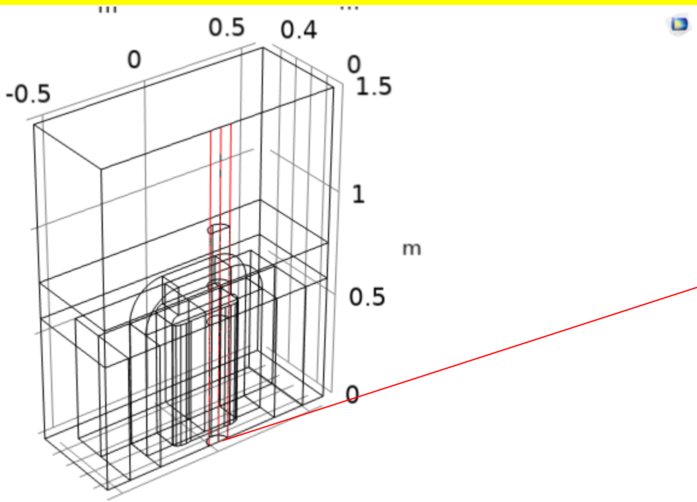
This price doesn't include ASICs, assembly, etc.
Appropriate total could be well over $1M.

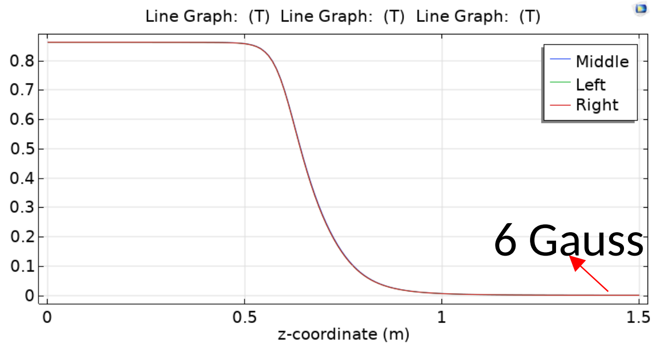
# Analyzer Dipole Magnet



| Parameters | Value |
|---|---|
| Magnet half gap (h) [m] | 0.075 |
| Optimized x=a/h with 1e-4 quality | 1.040 |
| Optimized pole overhang a [m] | 0.078 |
| Yoke 1 heigh [m] | 0.115 |
| Yoke 1 width [m] | 0.168 |
| Cu coil width [m] 7*19.05mm | 0.133 |
| Cu coil height [m] 7*15.88mm | 0.111 |
| Return yoke width [m] | 0.460 |
| Return yoke height [m] | 0.166 |
| Current density [A/mm^2] | 3.5 |
| Field at the center [T] | 0.865 |
| Calculated Field Quality | ±1.6e-4 |

# Field along length and width the magnet

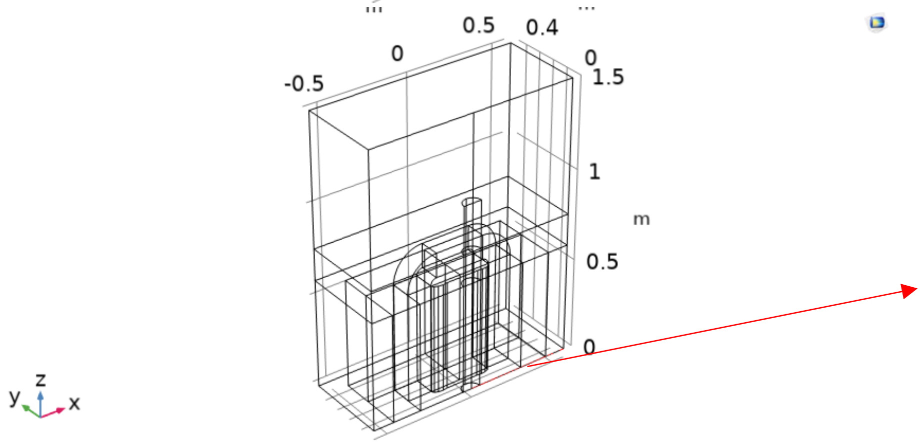


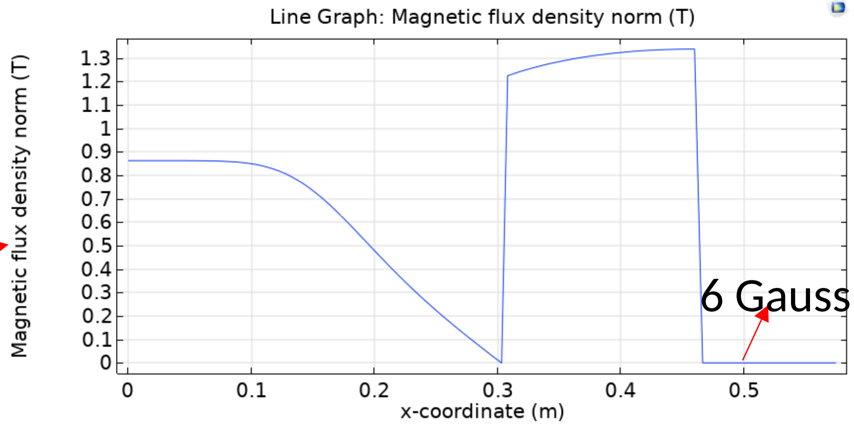


6 Gauss

Integrated field along 0.6 m: 0.51258 T*m

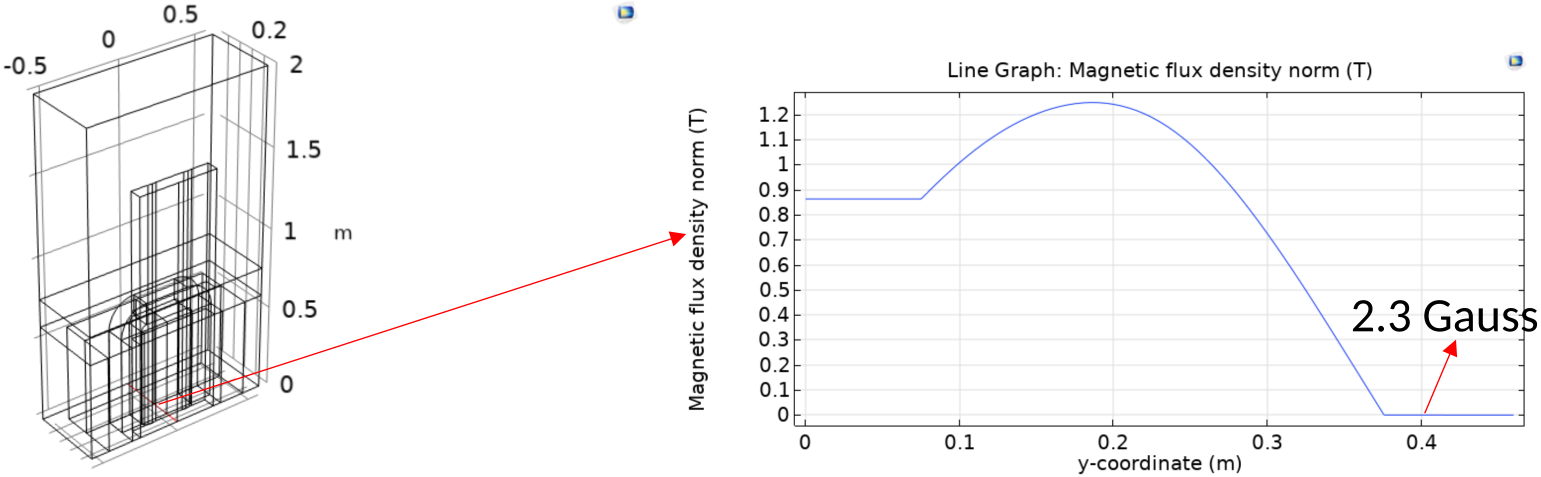
For a 1.2 m long magnet, the





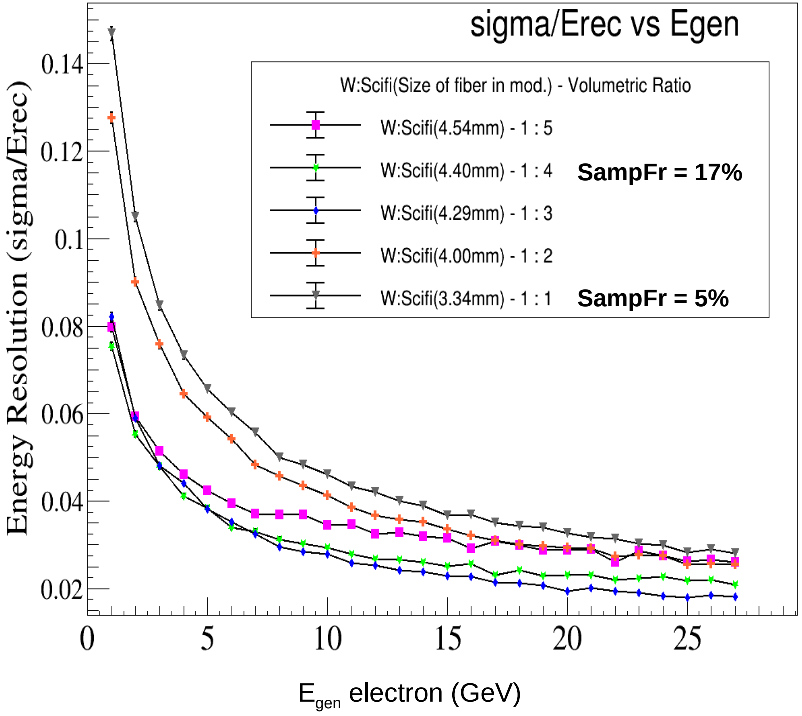
6 Gauss

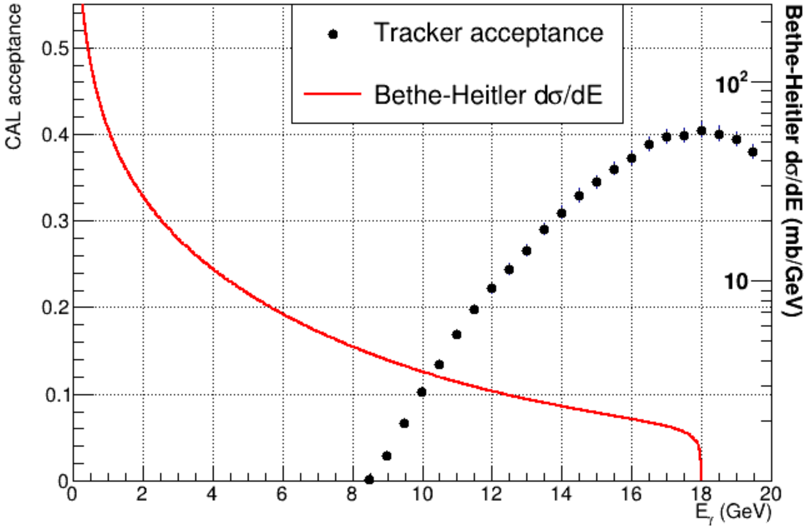
# Field along the depth of the magnet



2.3 Gauss

# Current CAL design results (fibers running along X & Y)





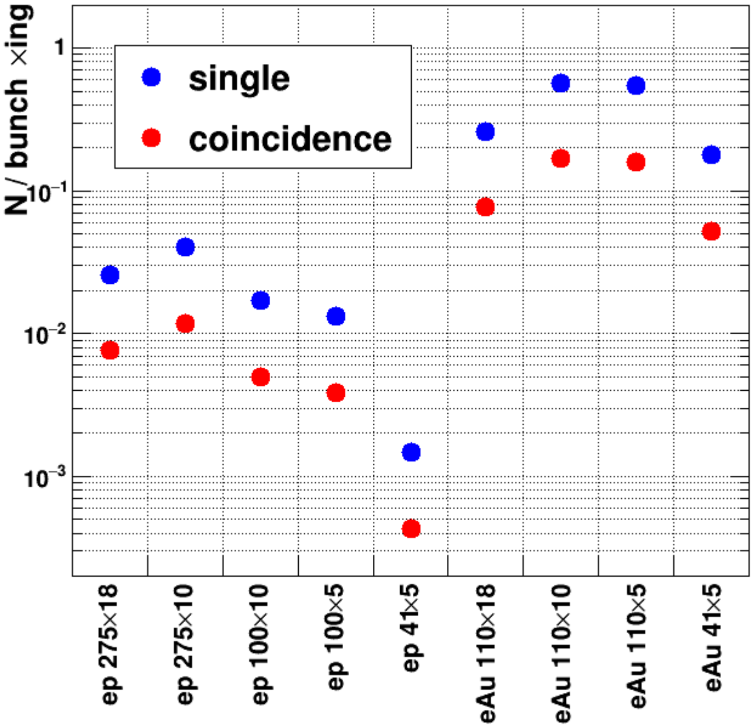
- For the most “bright” eA runs, we want such an acceptance to keep the rates low.
- For dimmer ep runs, we can shift the acceptance curves to the left by lowering our B fields.

- Need to study the how the Moliere radius changes with W:SciFi ratios (need to keep it small).

# Expected Rates of electrons at spectrometer CALs

Bethe-Heitler formula for unpolarized ep Bremstrahlung

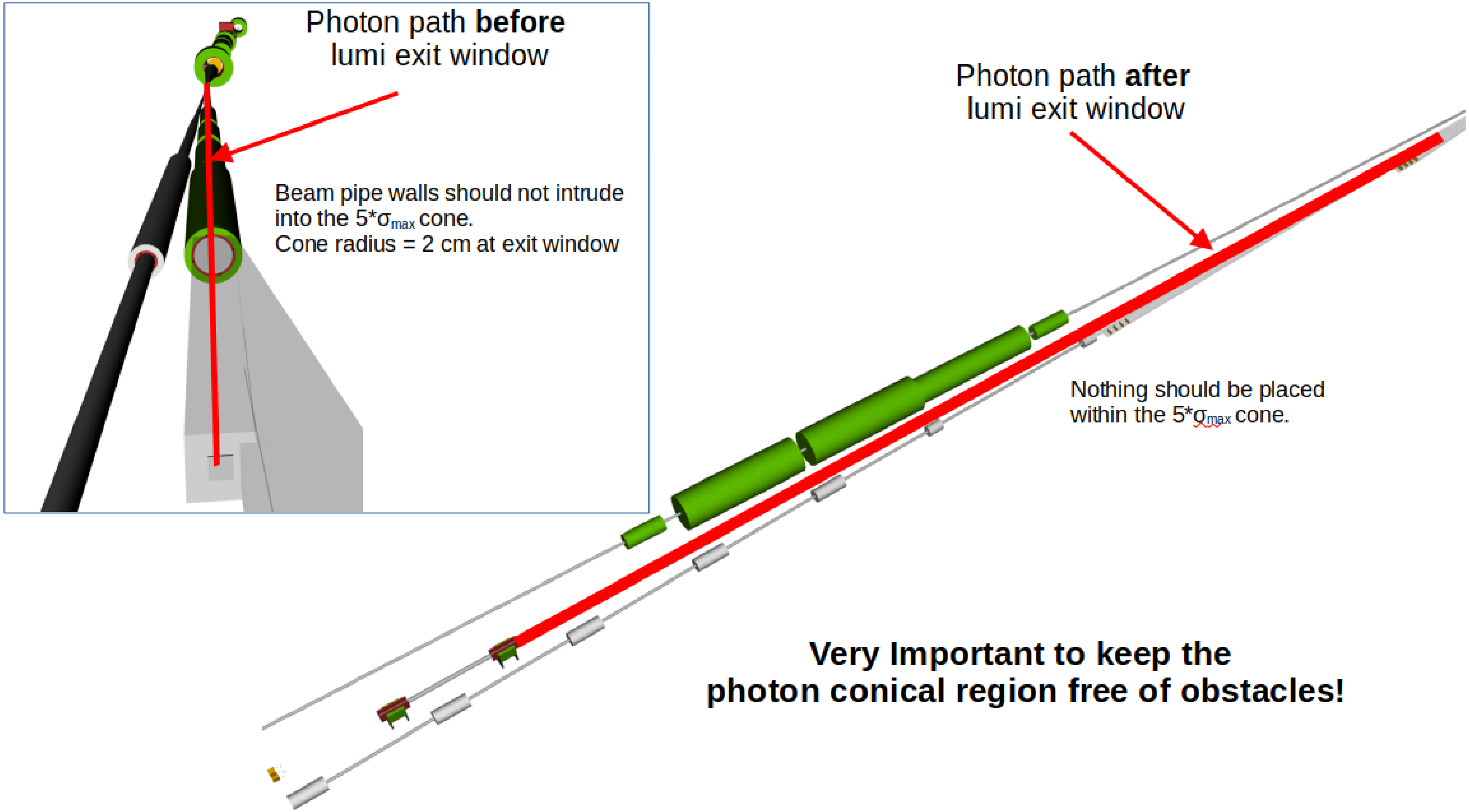
$$\frac{d\sigma}{dE_\gamma} = 4\alpha Z^2 r_e^2 \frac{E'_e}{E_\gamma E_e}\left(\frac{E_e}{E'_e}+\frac{E'_e}{E_e}-\frac{2}{3}\right)\left(\ln\frac{4E_pE_eE'_e}{m_pm_eE_\gamma}-\frac{1}{2}\right)$$



- Bremstrahlung σ is much larger for eAu than ep, but the bunch luminosity will be lower for eAu.
- These rates depend also on the design (acceptance) of the spectrometer CALs as well as the converter thickness (1 mm Al).
- **Pileup greatly suppressed with low conversion rate!**

See Bill Schmidke's talk
for studies assuming 10 mm converter

# General Pair Spectrometer Requirements



Photon path **before** lumi exit window

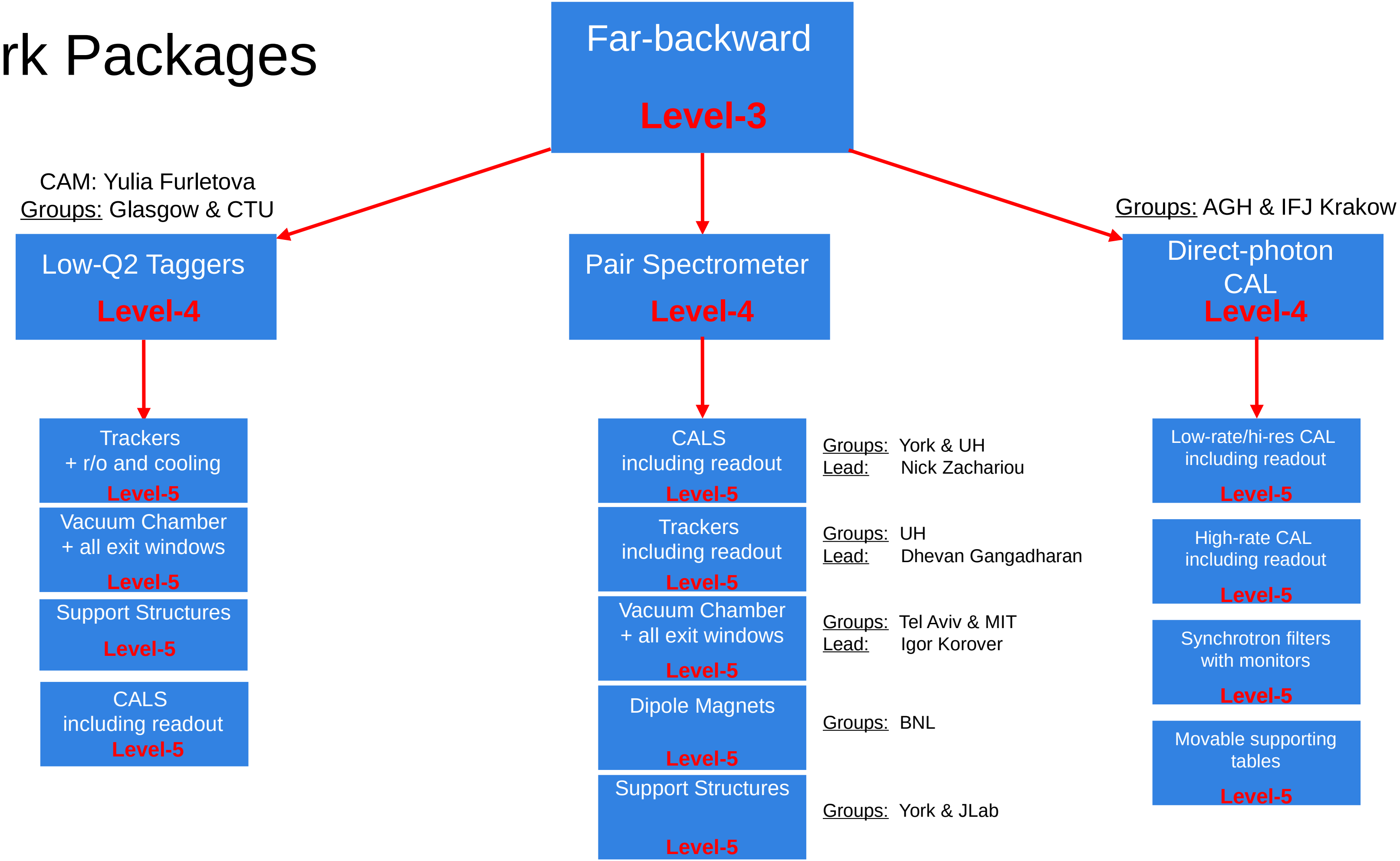
Beam pipe walls should not intrude into the $5{*}\sigma_{max}$ cone.
Cone radius = 2 cm at exit window

Photon path **after** lumi exit window

Nothing should be placed within the $5{*}\sigma_{max}$ cone.

**Very Important to keep the photon conical region free of obstacles!**

# Work Packages



Far-backward

Level-3

CAM: Yulia Furletova
Groups: Glasgow & CTU

Low-Q2 Taggers

Level-4

Trackers
+ r/o and cooling
Level-5

Vacuum Chamber
+ all exit windows
Level-5

Support Structures
Level-5

CALS
including readout
Level-5

Pair Spectrometer

Level-4

CALS
including readout
Level-5

Groups: York & UH
Lead: Nick Zachariou

Trackers
including readout
Level-5

Groups: UH
Lead: Dhevan Gangadharan

Vacuum Chamber
+ all exit windows
Level-5

Groups: Tel Aviv & MIT
Lead: Igor Korover

Dipole Magnets

Level-5

Groups: BNL

Support Structures

Level-5

Groups: York & JLab

Groups: AGH & IFJ Krakow

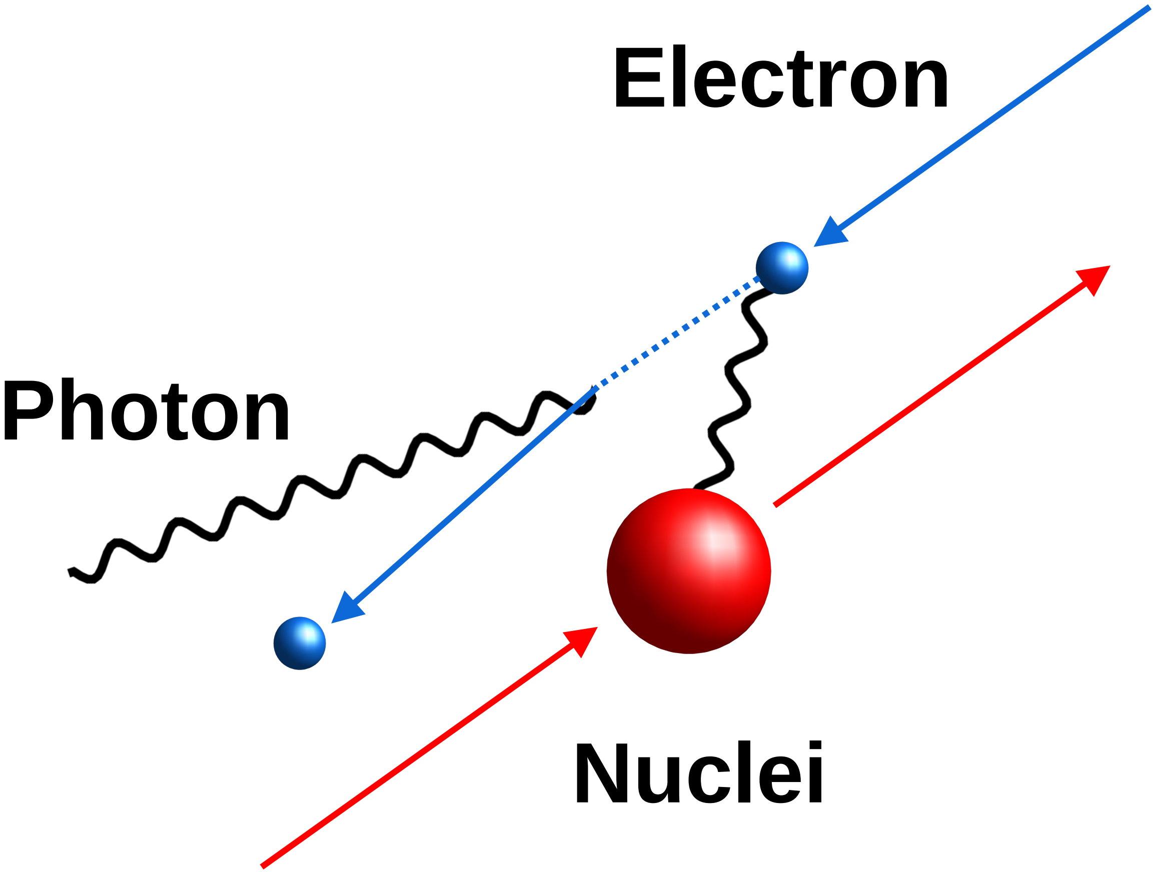
Direct-photon CAL
Level-4

Low-rate/hi-res CAL
including readout
Level-5

High-rate CAL
including readout
Level-5

Synchrotron filters
with monitors
Level-5

Movable supporting
tables
Level-5


Electron
Photon
Nuclei