# Electromagnetic calorimeters

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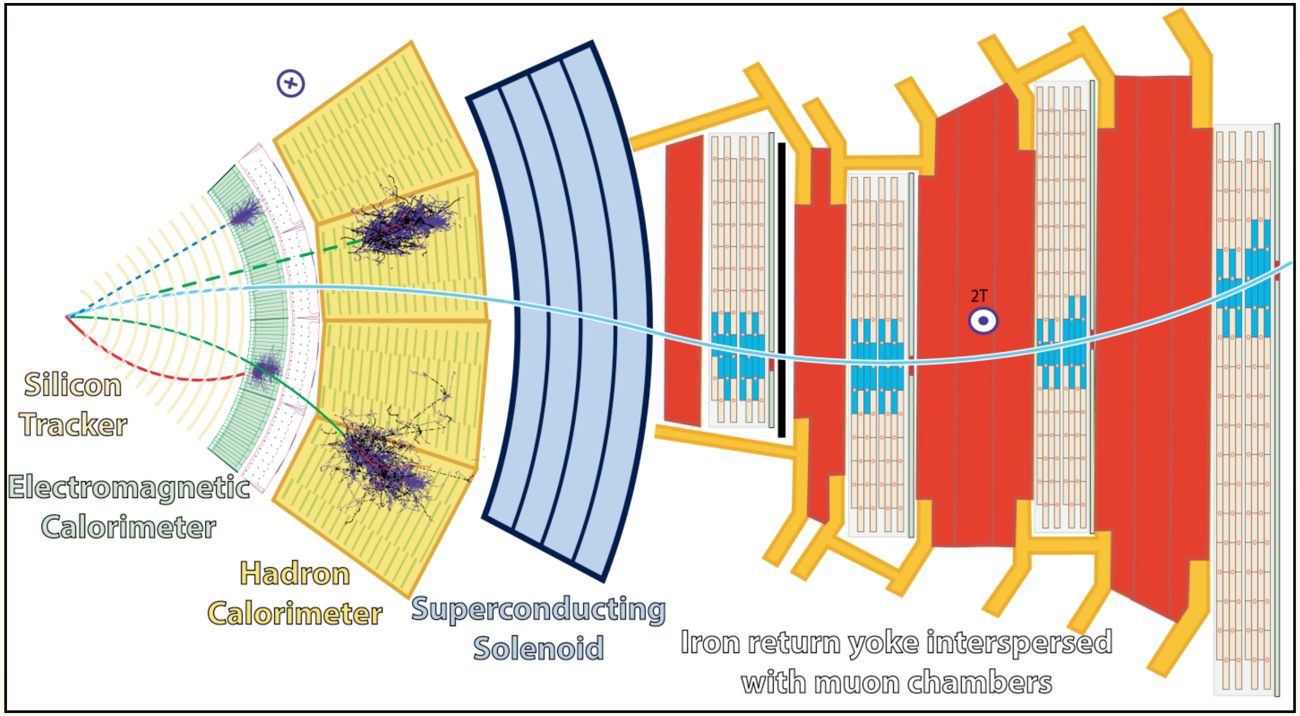
# What is a calorimeter?



- Detection of particles and their properties through full absorption
- All energy of the particle is finally converted to heat (and more)
- Essential to detect neutral particles

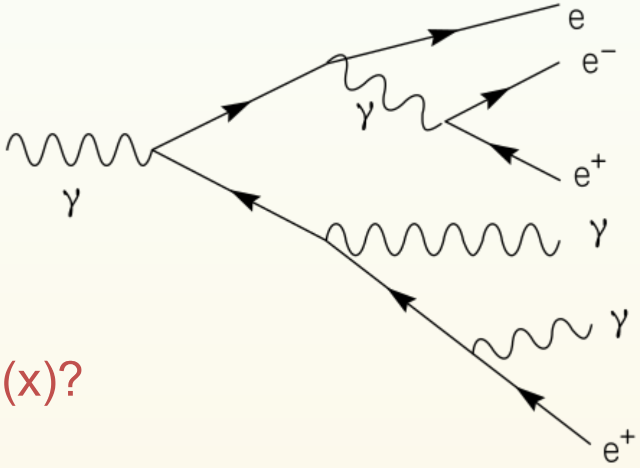
# Electromagnetic showers

- Governed by two main processes at energies > few hundred MeV
  - e+e- pair production

$$\sigma_{pair} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}}\right) = \frac{7}{9}\frac{A}{N_A X_0}$$

  - Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} = \frac{E}{X_0}$$



What is E(x)?

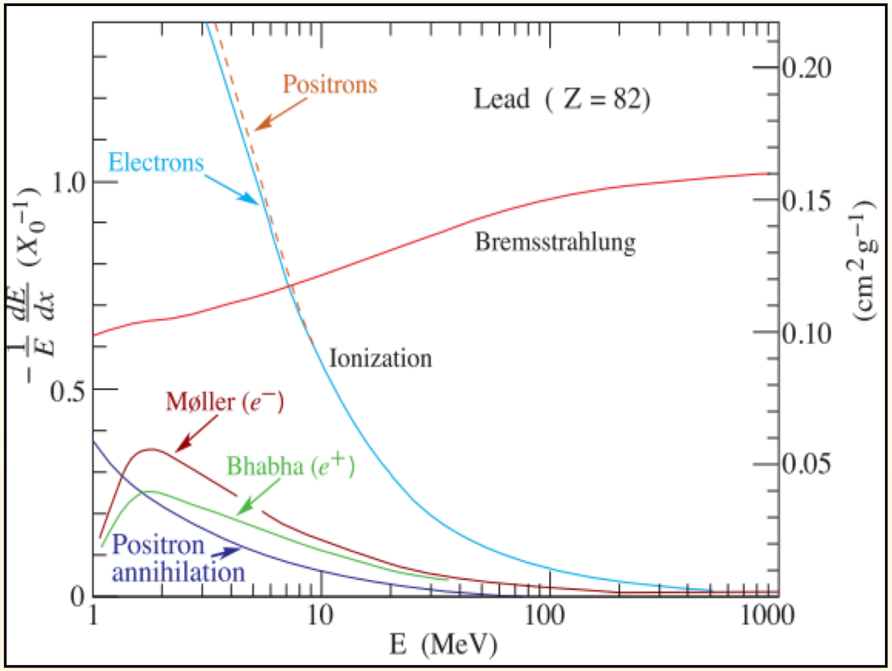
- $X_0$ is the radiation length:

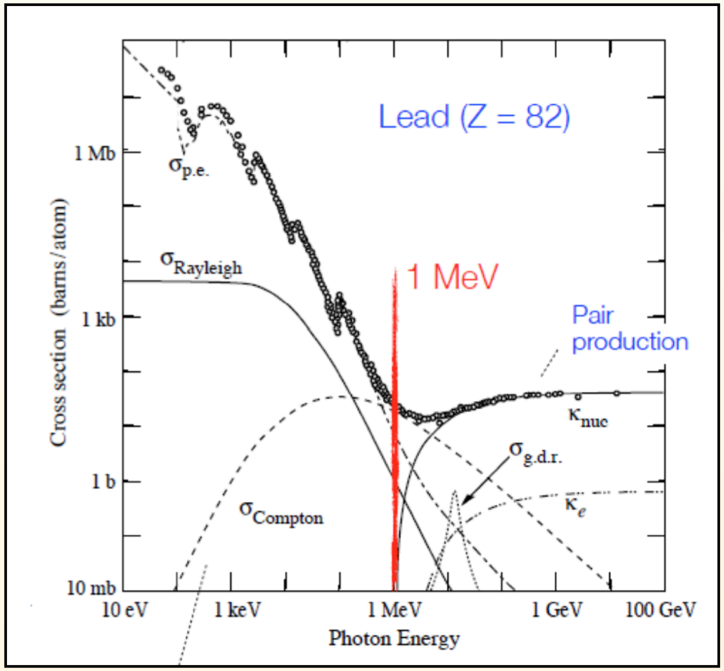
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Plot $X_0$ as a function of A and Z and
put points for the materials in our simulation

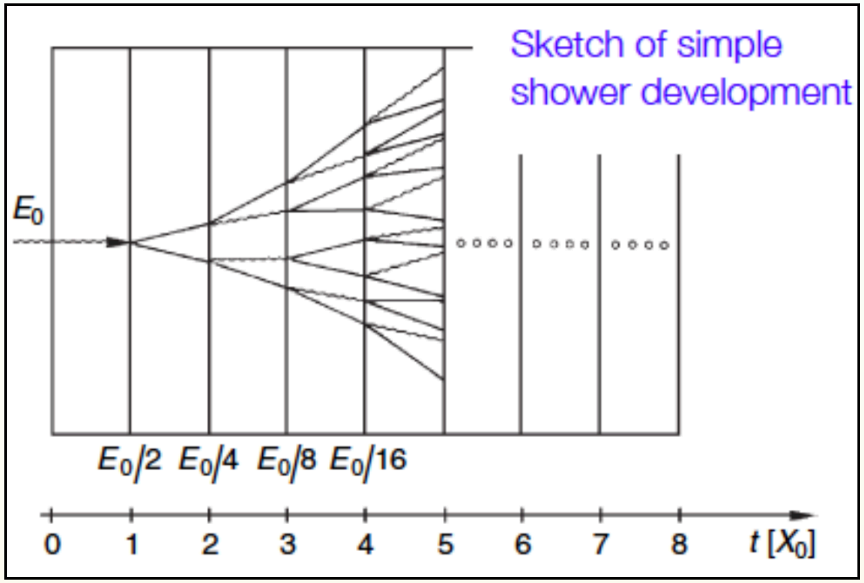
# An analytic shower model: longitudinal

- Simplified model [Heitler]:
  - Assumes bremsstrahlung and pair production only
  - Electron loses $1 - 1/e = 63\,\%$ of it's energy in one $X_0$
  - The mean free path of a photon is $9/7\ X_0$
- The radiation length $X_0$ is fundamental
- Model works only for sufficiently high energies - what is sufficient?





# What can we do with that model?



- Assume shower stops at $E_C$
- $N(t) = 2^t$
- Each with energy $E(t) = E_0/2^t$
- Stop if $E(t) < E_c = E_0 2^{t_{max}}$
- $t_{max} \propto \ln\left(E_0/E_c\right)$

Verify this for 3-4 choices of energies using simulation

How do we do this given our toolbox?

- $E_c \approx \dfrac{800\ \text{MeV}}{Z + 1.2}$
- Can be verified by creating a calorimeter with multiple layers and collecting energy each layer (e.g. one per $X_0$)
- For most materials used in calorimeters: $E_c \approx 10$ MeV

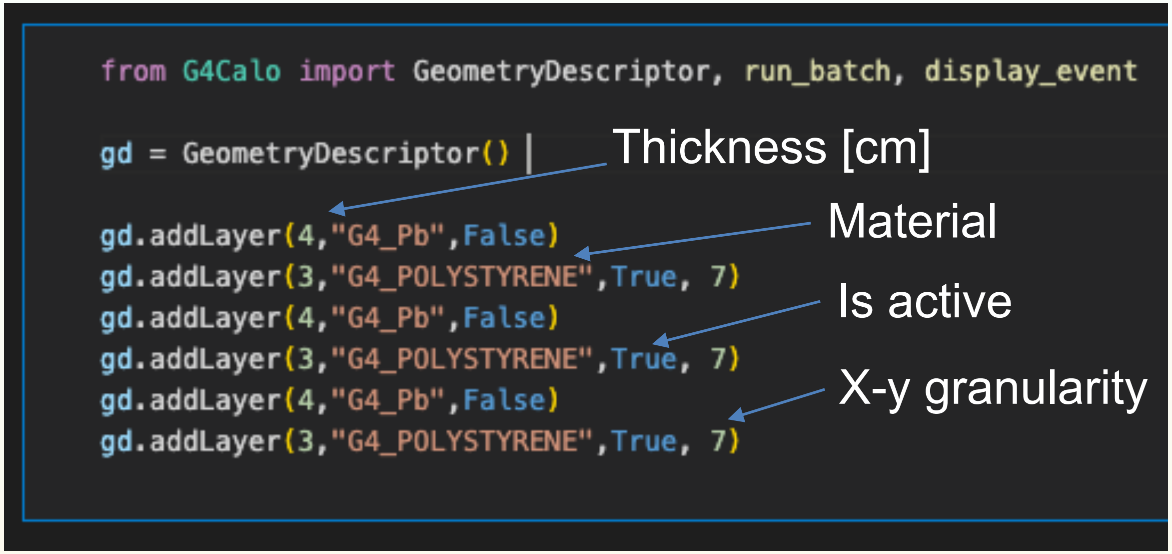
# What else can be infer from that model?

- $t_{max} \propto \ln\left(E_0/E_c\right)$ : thickness must increase with $E_0$
- After that, electrons will stop after about 1 $X_0$.
- Photons can travel much further
- Rule of thumb: $L(99\%) = (t_{max} + 0.08Z + 9.6)[X_0]$
  - For EM showers in reasonable range < 100 GeV

Verify this in simulation for a 50 GeV shower.

Also, how many $X_0$ are needed to capture 95% of the initial energy for 50 GeV shower? (this then also includes ionisation / excitation / Compton / Rayleigh …)

# The software



```python
from G4Calo import GeometryDescriptor, run_batch, display_event

gd = GeometryDescriptor()

gd.addLayer(4,"G4_Pb",False)
gd.addLayer(3,"G4_POLYSTYRENE",True, 7)
gd.addLayer(4,"G4_Pb",False)
gd.addLayer(3,"G4_POLYSTYRENE",True, 7)
gd.addLayer(4,"G4_Pb",False)
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```
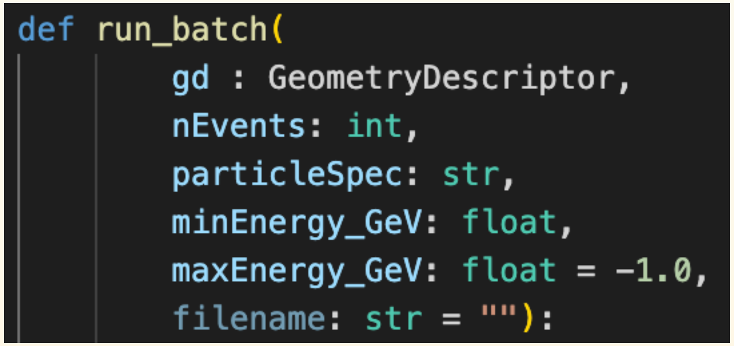

Thickness [cm]

Material

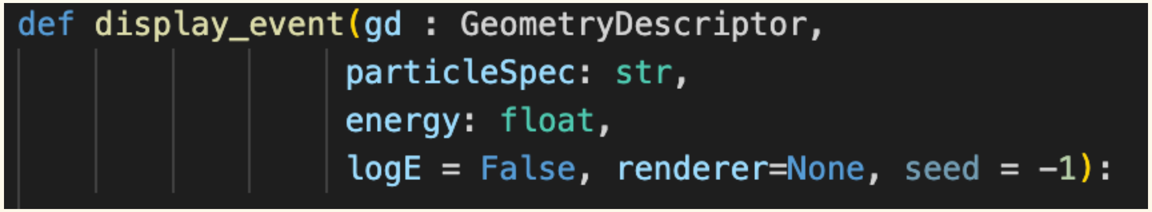
Is active

X-y granularity



```python
def run_batch(
        gd : GeometryDescriptor,
        nEvents: int,
        particleSpec: str,
        minEnergy_GeV: float,
        maxEnergy_GeV: float = -1.0,
        filename: str = ""):
```

Returns a pandas Dataframe

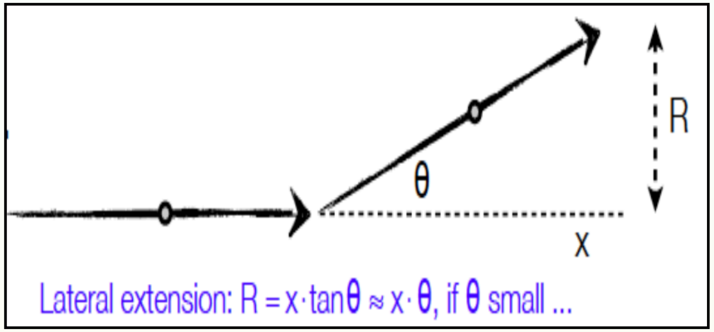


```python
def display_event(gd : GeometryDescriptor,
                  particleSpec: str,
                  energy: float,
                  logE = False, renderer=None, seed = -1):
```

Displays a 3D image of the event and the calorimeter

particleSpec: “gamma”, “pi-“, “pi+”, …

# Lateral shower development



- Opening angle defined by two processes:
  - Bremsstrahlung and pair production
    $< \theta^2 > \approx 1/\gamma^2 \rightarrow$ small angle!
  - Multiple coulomb scattering [Moliere]
    $< \theta > = E_s/E_e\sqrt{x/X_0} \rightarrow$ larger angle
    with
    $E_s = \sqrt{4\pi\alpha}\ (m_e c^2) = 21.2$ MeV
- Main contribution from low energy electrons close to Ec : Moliere radius

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21.2MeV}{E_c} X_0$$

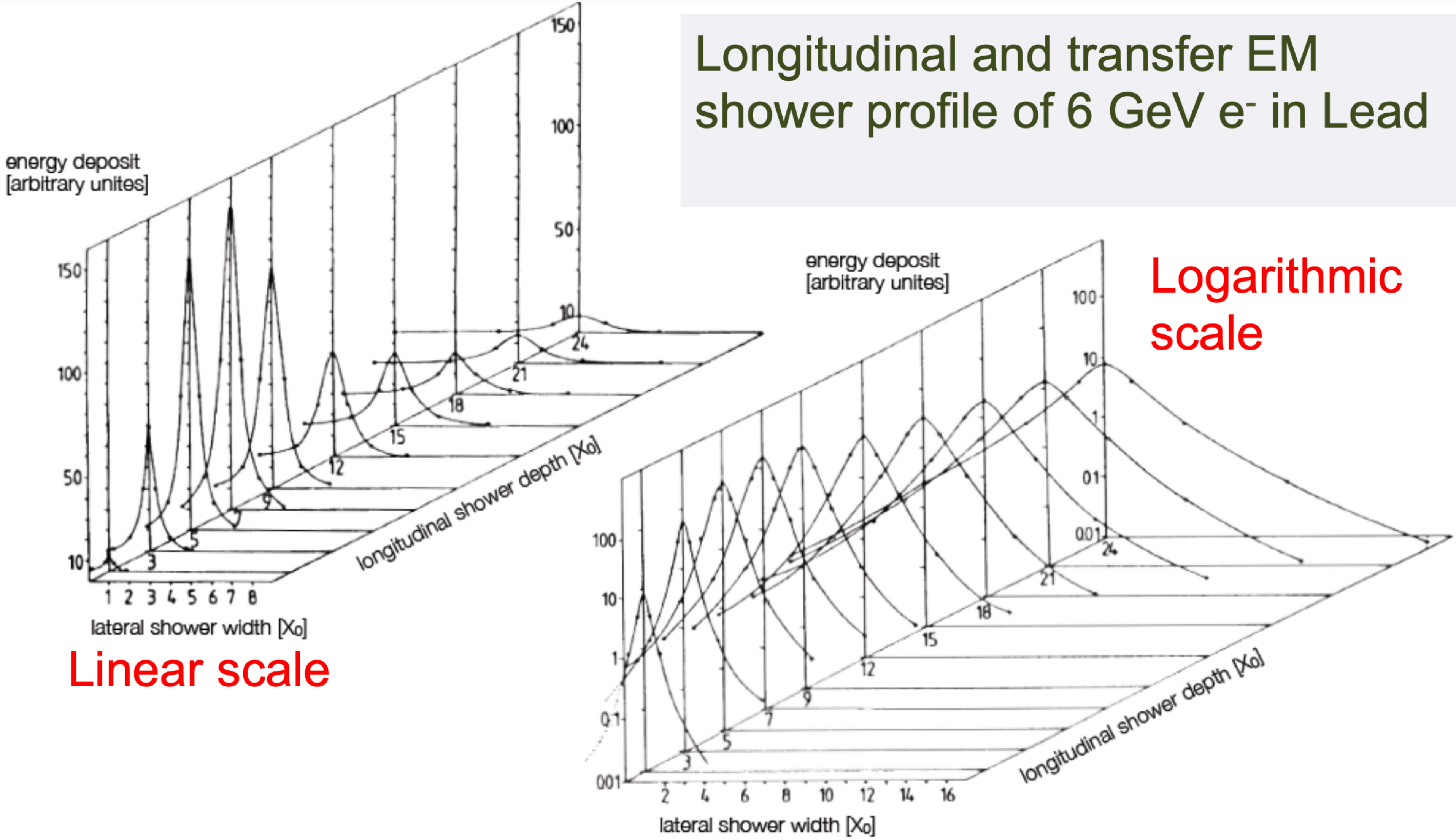
Use google: what is the Moliere radius of Pb or PbWO4 ?
What does that mean for our calorimeter?

- A cylinder around a shower with radius of $2R_M$ contains 95% of the shower energy

Optional: verify this qualitatively with a highly-granular detector in simulation

# Shower profiles

Longitudinal and transfer EM shower profile of 6 GeV $e^-$ in Lead



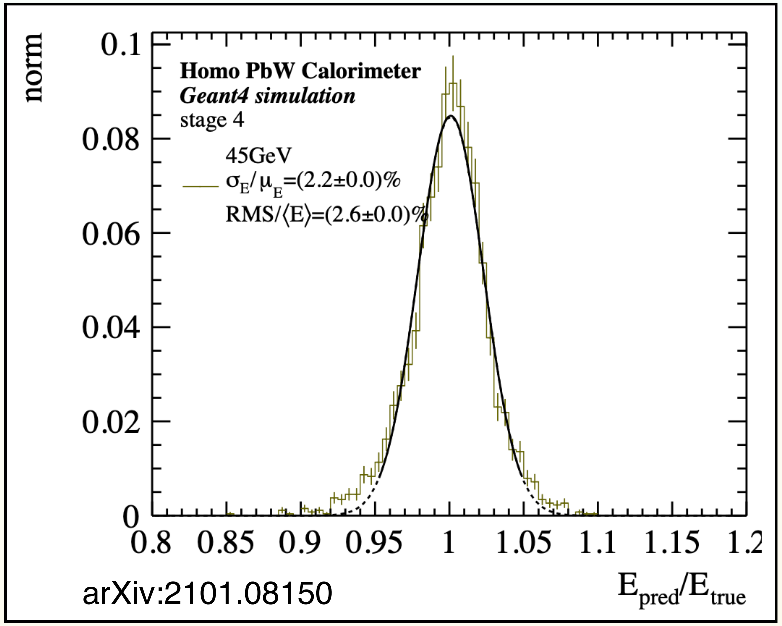
Linear scale

Logarithmic scale

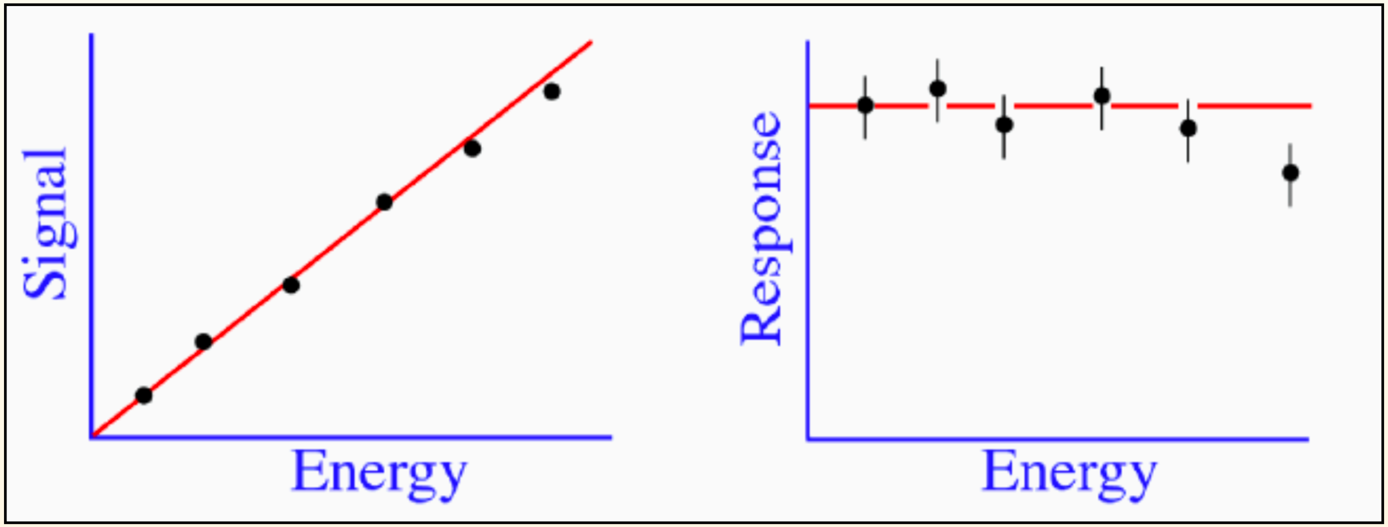
# How to detect energy?

- Scintillation
- Cherenkov light
- Ionisation
- Sometimes even heat

- Critical: response and resolution
  - The resolution is the width of the response distribution

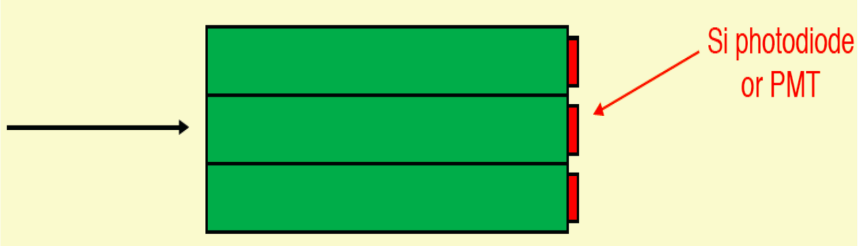


arXiv:2101.08150

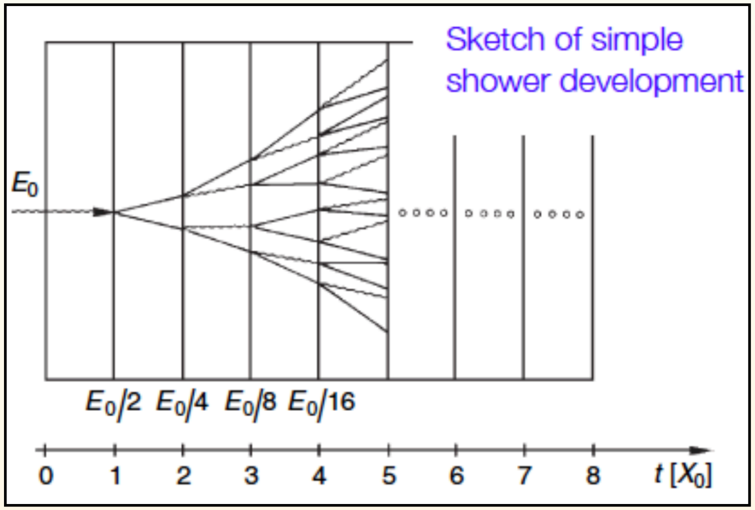


# Homogenous EM Calorimeters

- Use high density optically transparent material: light ~ deposited energy
- Stop particles entirely in the scintillator material
- Collect light at the end



- Advantages
  - Excellent energy collection → excellent resolution
  - Uniform, mostly linear response
- Disadvantages:
  - Limited segmentation
  - Cost



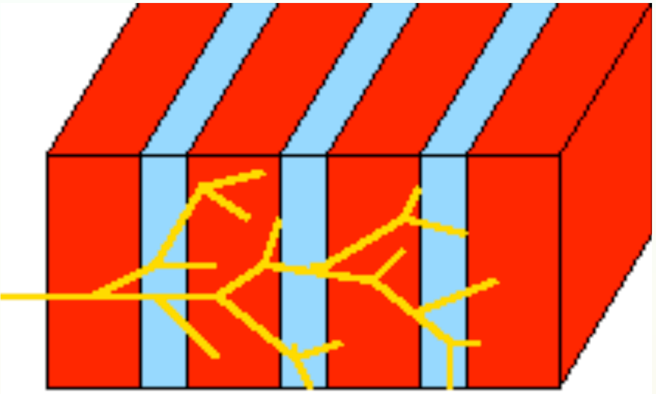
- Resolution: W: energy required to produce a signal

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{n}} = \frac{1}{\sqrt{E/W}}$$

why $1/\sqrt{n}$ ?

Used in Belle II and CMS

# Sampling calorimeters



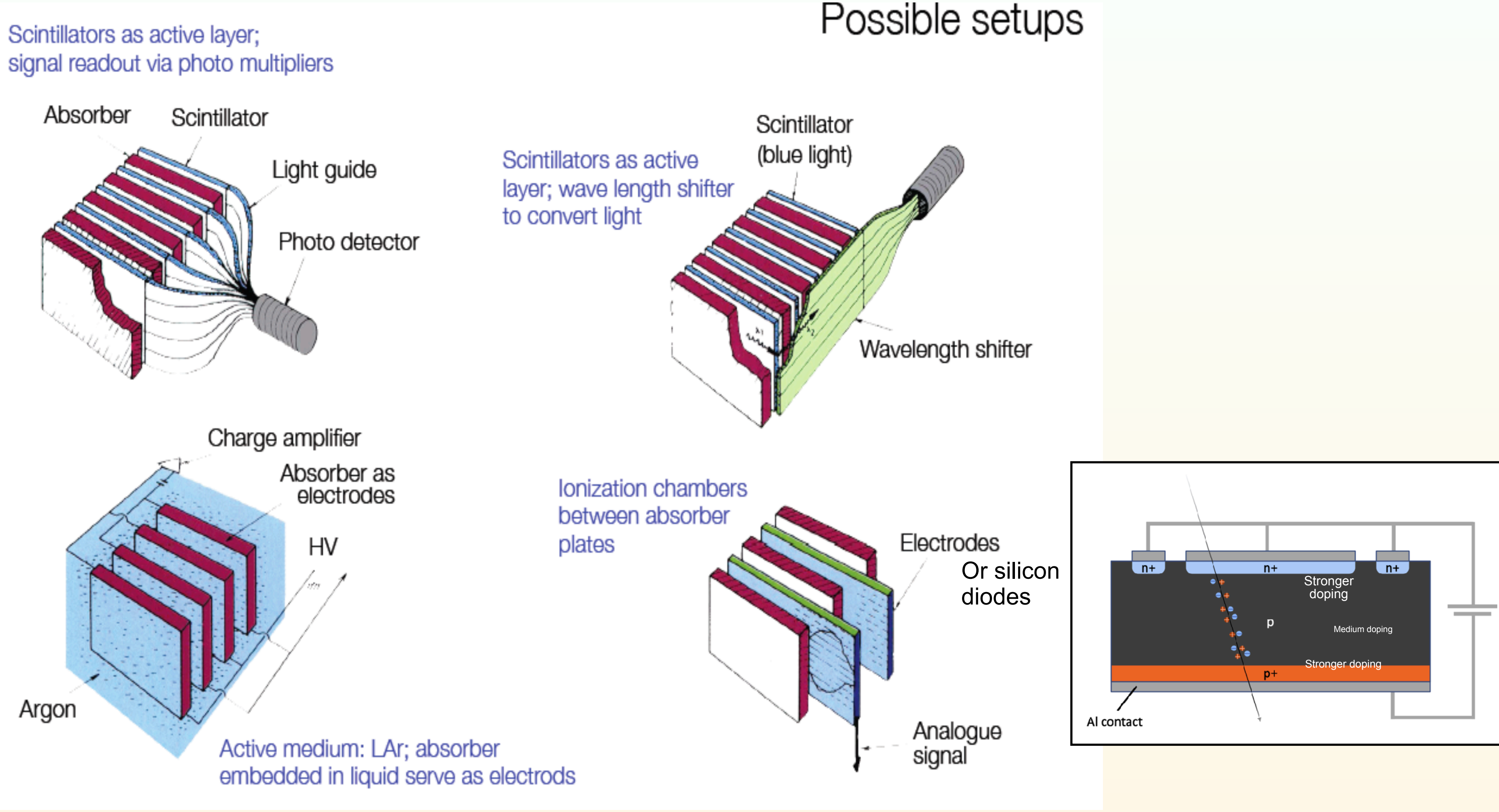
- Sandwich
  - Absorber (induces shower)
  - Detection material (e.g. scintillator)

- Advantages:
  - Can segment in depth
  - Spatial segmentation easier to achieve
  - Cost

- Disadvantages
  - Only part of showering occurs in detection material: loss of information and resolution: $f_{\text{sampling}} = E_{\text{vis}}/E_{\text{dep}}$

Used in ATLAS and most hadronic calorimeters

# Configurations



- For our simulation, we only consider scintillators and assume 100% efficient readout electronics

Compare the energy deposition in the same thickness for the different scintillator materials in the G4calo package

# Energy resolution

- This is what it is (mostly) about
- Ideally: $\sigma_E = \sqrt{E}$
- In practice, more terms appear

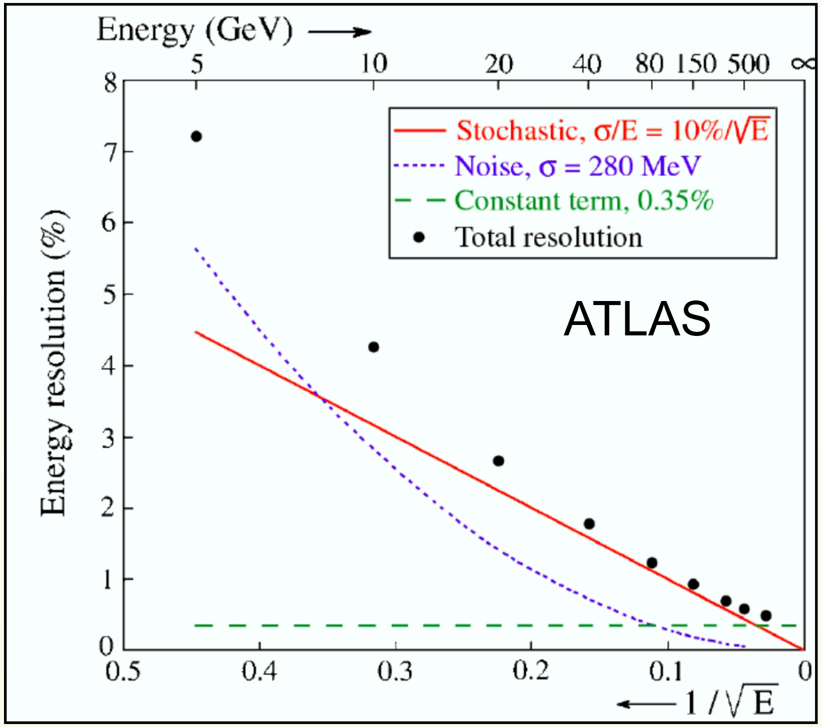
  $\sigma_E = a\sqrt{E} + bE + c$

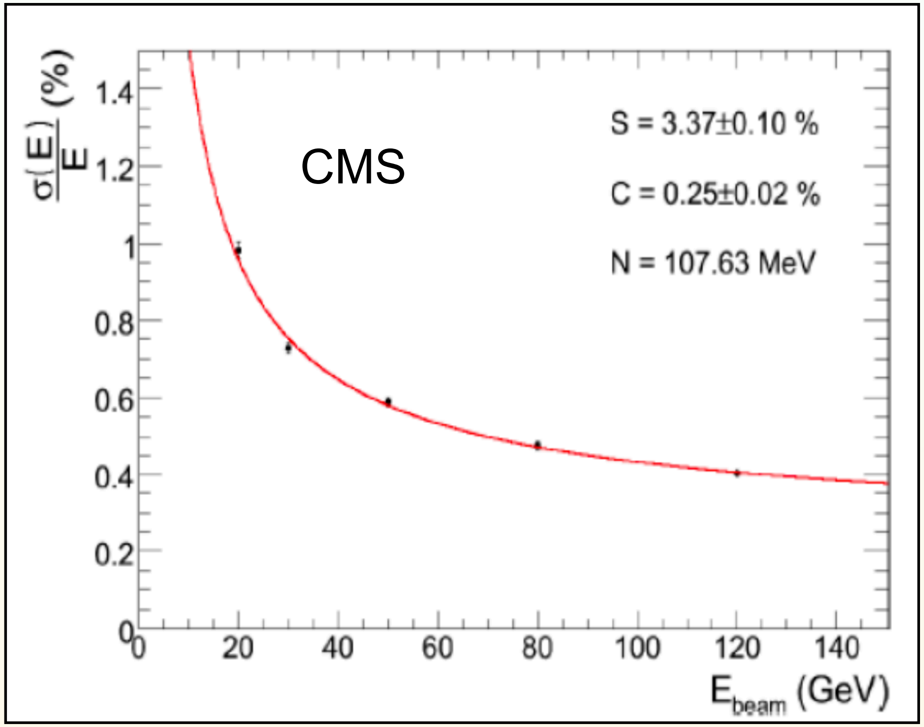
- **Stochastic term (a)**:
  - Intrinsic shower fluctuations
  - Sampling fluctuations
  - Signal quantum fluctuations

- **Constant term (b)**:
  - Inhomogeneities (hardware or calibration issues)
  - Non linearity of readout electronics
  - Leakage in the energy containment

- **Noise term (c)**, energy independent noise:
  - Constant electronics noise etc.

# Comparison ATLAS & CMS





Find the difference and explain it

Verify the difference qualitatively with the two calorimeter designs at 50 GeV (what does that correspond to in the ATLAS plot?)

# Summary

- Interactive :)

- EM matter interaction

- Response and resolution

- Homogenous vs. Sampling
- ATLAS vs CMS

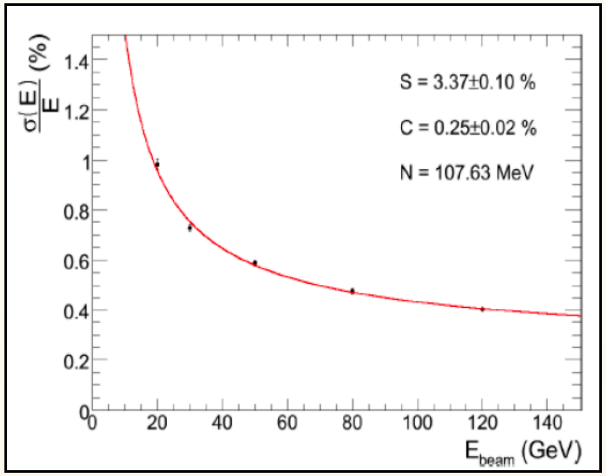
- Radiation length

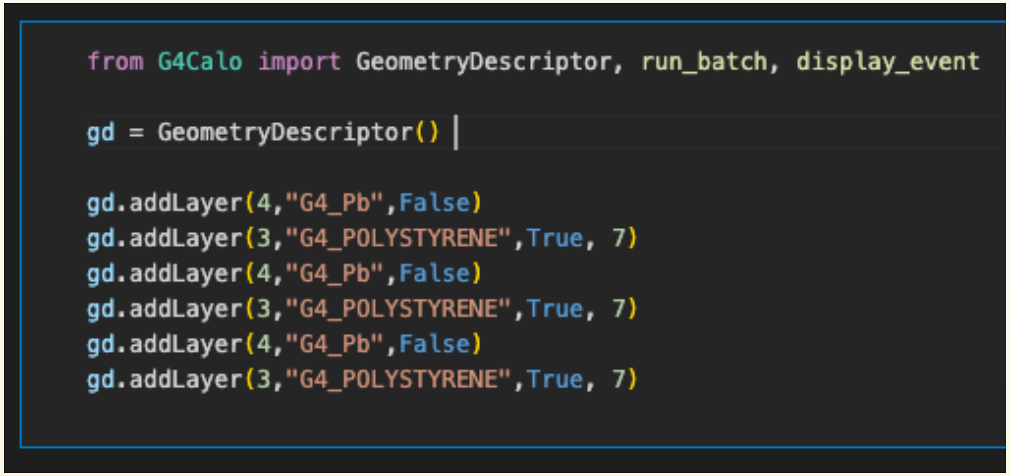
# More tasks

Create a class inheriting from GeometryDescriptor that also tracks the total material cost of the calorimeter (info is available in the repo)

Build an optimal EM calorimeter for showers with 50 GeV energy
(no transversal granularity).
Don’t spend more than 50k CHF

Try out the plotting script for different energies on that calorimeter (reproduce the plot below).
What do you observe?





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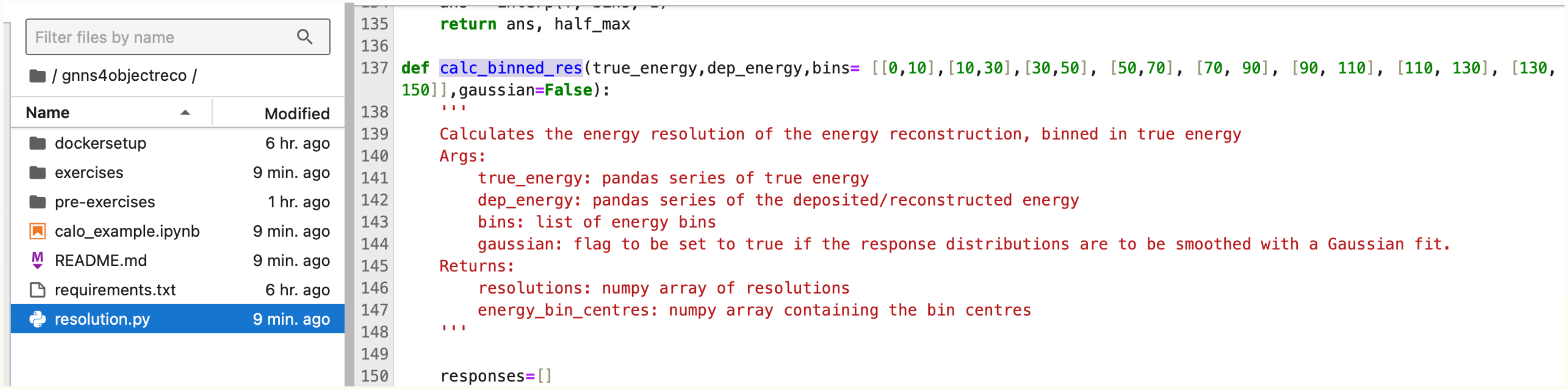
```

What was wrong with his calorimeter? (From previous presentation)

# For binned resolution…



/ gnns4objectreco /

| Name | Modified |
|---|---|
| dockersetup | 6 hr. ago |
| exercises | 9 min. ago |
| pre-exercises | 1 hr. ago |
| calo_example.ipynb | 9 min. ago |
| README.md | 9 min. ago |
| requirements.txt | 6 hr. ago |
| resolution.py | 9 min. ago |

```
    return ans, half_max

def calc_binned_res(true_energy,dep_energy,bins= [[0,10],[10,30],[30,50], [50,70], [70, 90], [90, 110], [110, 130], [130, 150]],gaussian=False):
    '''
    Calculates the energy resolution of the energy reconstruction, binned in true energy
    Args:
        true_energy: pandas series of true energy
        dep_energy: pandas series of the deposited/reconstructed energy
        bins: list of energy bins
        gaussian: flag to be set to true if the response distributions are to be smoothed with a Gaussian fit.
    Returns:
        resolutions: numpy array of resolutions
        energy_bin_centres: numpy array containing the bin centres
    '''

    responses=[]
```