Detector backscattering systematics

Andrea Nava

Tristan Workshop 2022

Outline

- **Backscattering shape in monochromatic and Tritium spectra**
- Backreflection in the KATRIN environment
- Test of the model with KATRIN data
- Preliminary impact on Tritium spectrum
- Conclusions

How to model backscattering

- Backscattering depends only on the electron scattering in Silicon → **simulated in Geant4**

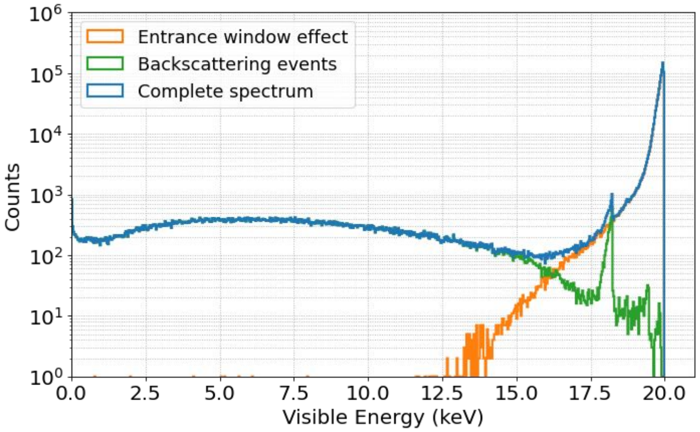
- electrons will arrive at the detector with different energies and incidence angles → need to do simulations at different energies and angles

- Shoot electrons on the detector: both the **energy deposited in the active volume** and the **energy-angle of the backscattered electrons** are saved

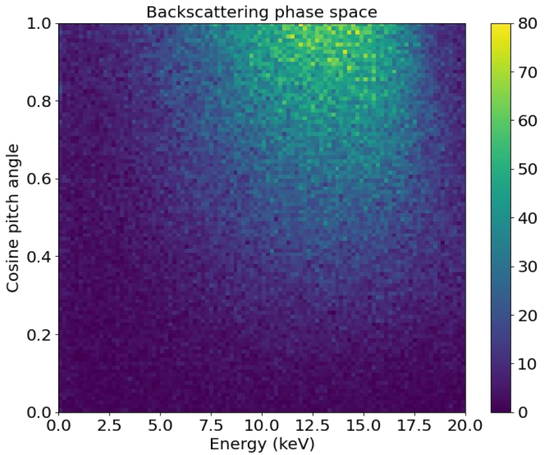
- Example: Geant4 simulation of 10^6 electrons with 20 keV and 0° incident angle (normal incidence) → an empirical model for the DL is applied

How to model backscattering

- Backscattering depends only on the electron scattering in Silicon → **simulated in Geant4**
- electrons will arrive at the detector with different energies and incidence angles → need to do simulations at different energies and angles
- Shoot electrons on the detector: both the **energy deposited in the active volume** and the **energy-angle of the backscattered electrons** are saved



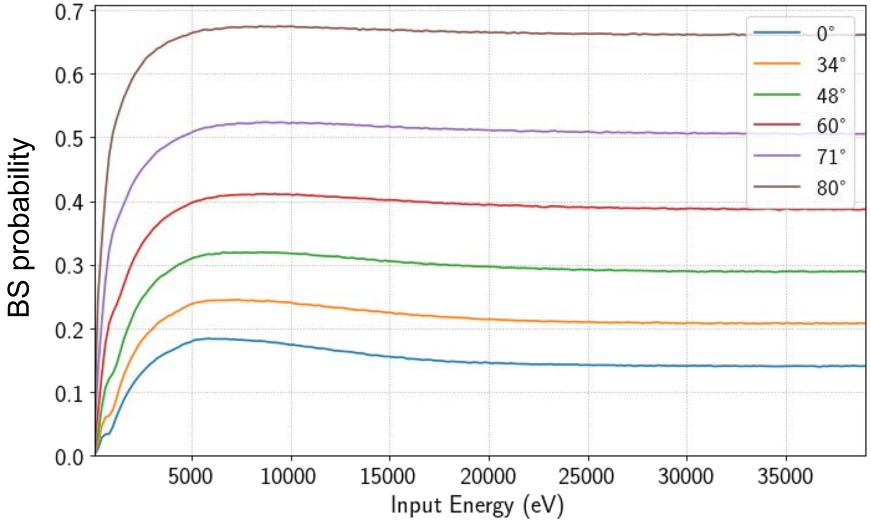
Detector response

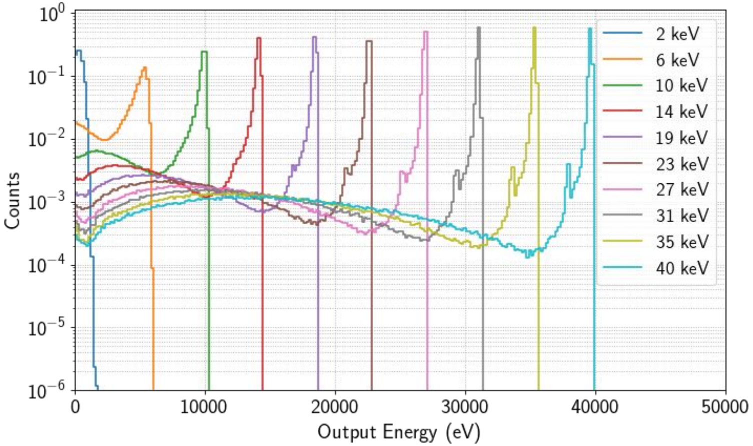


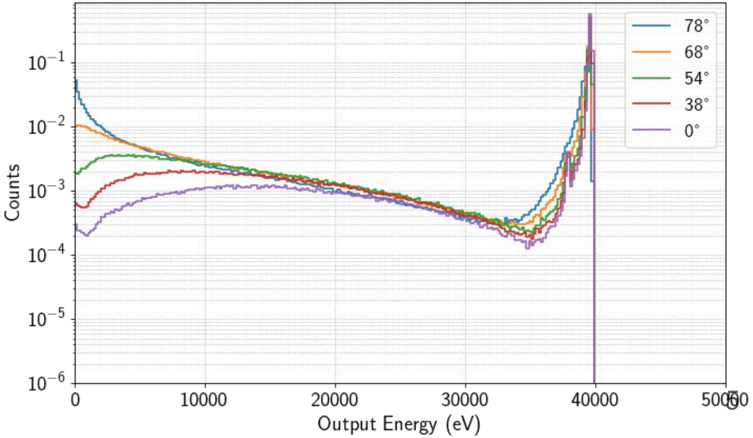
Backscattering response

The effect of different energies and angles

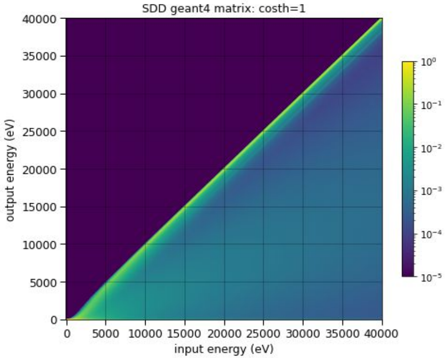
Backscattering probability increases a lot with the angle and slightly decreases with the energy

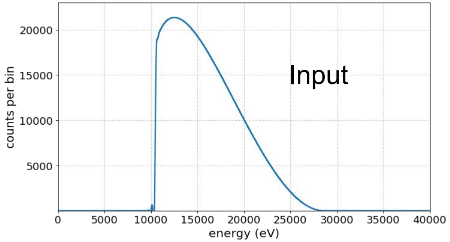


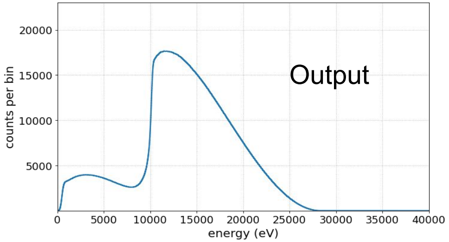


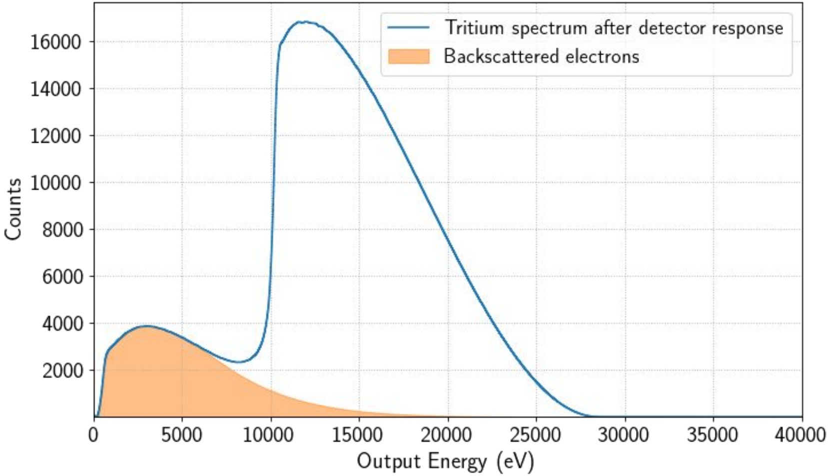


Impact on Tritium spectrum



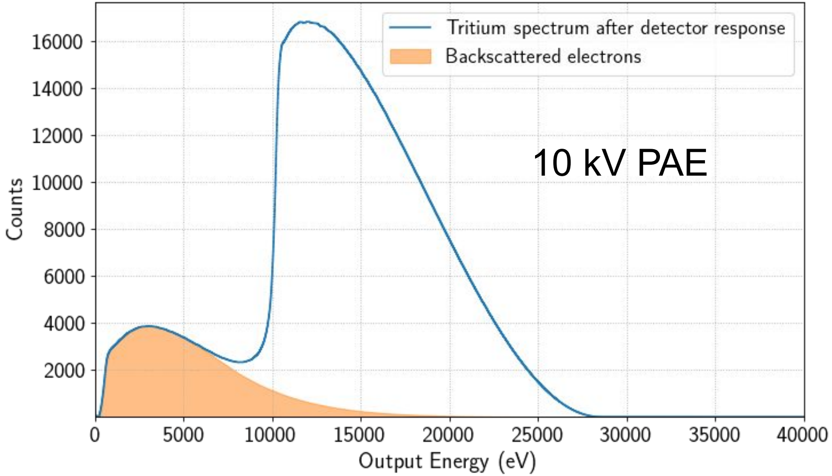




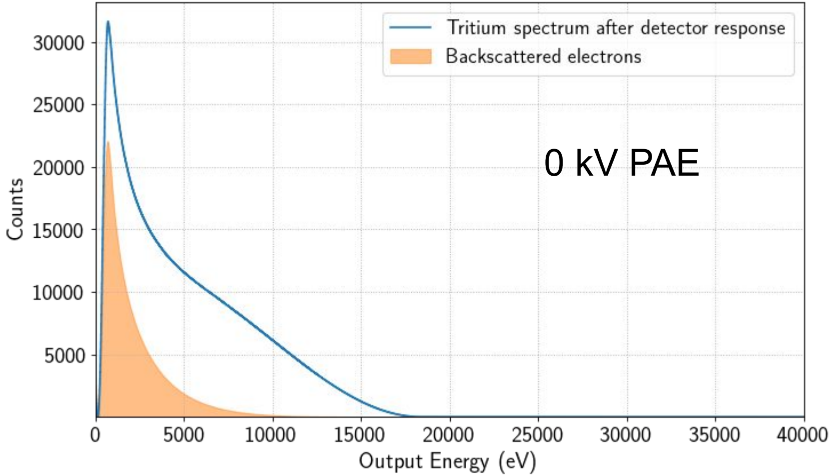


17% backscattering probability

Impact of PAE



17% backscattering probability, mainly outside the ROI



28% backscattering probability, completely inside the ROI

PAE: ⟶

- **higher energies** → slightly less BS
- **collimated electrons** → less BS towards 0°
- move **BS spectrum outside of the ROI**

Outline

- Backscattering shape in monochromatic and Tritium spectra
- **Backreflection in the KATRIN environment**
- Test of the model with KATRIN data
- Preliminary impact on Tritium spectrum
- Conclusions

Backreflection in KATRIN

- The actual model is not complete: **backscattered electrons can return back to the detector** due to electric or magnetic reflections

Backreflection in KATRIN

- The actual model is not complete: **backscattered electrons can return back to the detector** due to electric or magnetic reflections

- the reflection can happen due to:
  - detector magnet
  - post-acceleration potential
  - pinch magnet
  - ~~retarding potential~~

Backreflection in KATRIN

- The actual model is not complete: **backscattered electrons can return back to the detector** due to electric or magnetic reflections

- the reflection can happen due to:
  - detector magnet
  - post-acceleration potential
  - pinch magnet
  - ~~retarding potential~~

↓

a **Kassiopeia simulation** for the precise electron tracking in EM fields is needed

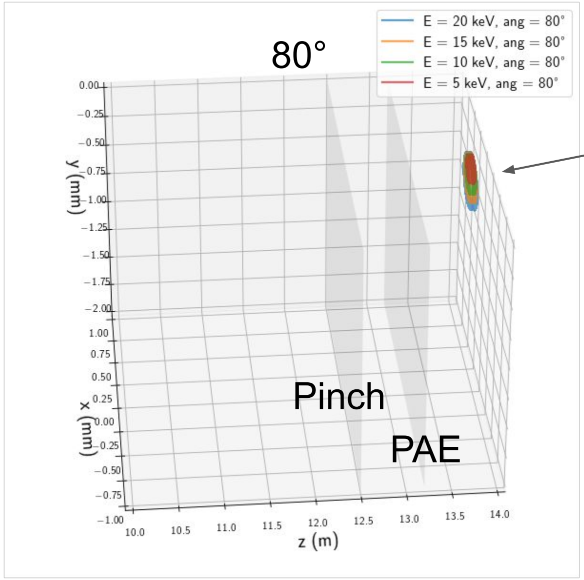
Backreflection in KATRIN

- The actual model is not complete: **backscattered electrons can return back to the detector** due to electric or magnetic reflections

- the reflection can happen due to:
  - detector magnet
  - post-acceleration potential
  - pinch magnet
  - ~~retarding potential~~

a **Kassiopeia simulation** for the precise electron tracking in EM fields is needed

PAE = 10kV, nominal B-fields



electrons generated at the detector position

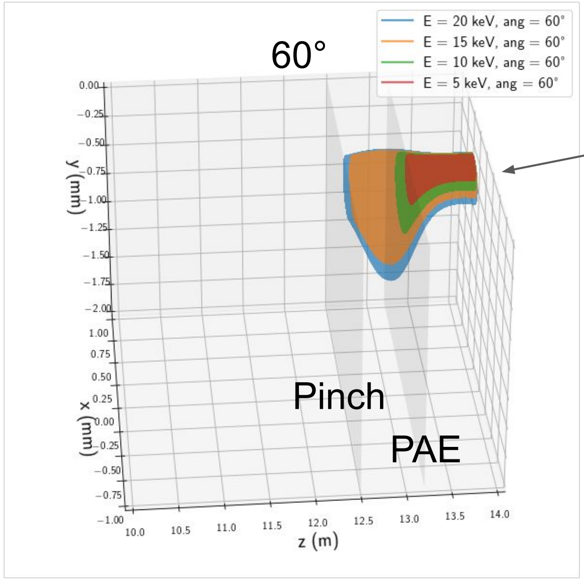
electrons with ang>75° are reflected by the detector magnet

Backreflection in KATRIN

- The actual model is not complete: **backscattered electrons can return back to the detector** due to electric or magnetic reflections
- the reflection can happen due to:
  - detector magnet
  - post-acceleration potential
  - pinch magnet
  - ~~retarding potential~~

a **Kassiopeia simulation** for the precise electron tracking in EM fields is needed

PAE = 10kV, nominal B-fields



electrons generated at the detector position

electrons with E<10keV are reflected by the PAE

electrons with large angles can also be reflected by the pinch

Backreflection in KATRIN

- The actual model is not complete: **backscattered electrons can return back to the detector** due to electric or magnetic reflections

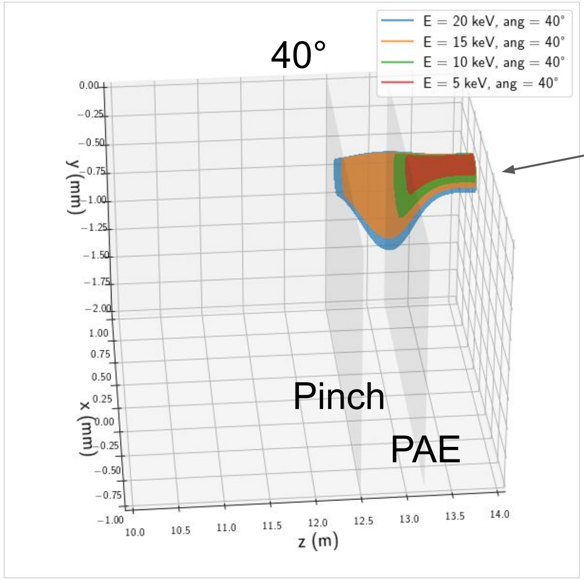
- the reflection can happen due to:
  - detector magnet
  - post-acceleration potential
  - pinch magnet
  - ~~retarding potential~~

↓

a **Kassiopeia simulation** for the precise electron tracking in EM fields is needed

↓

PAE = 10kV, nominal B-fields



electrons generated at the detector position

↓

electrons with E<10keV are reflected by the PAE

↓

electrons with large angles can also be reflected by the pinch

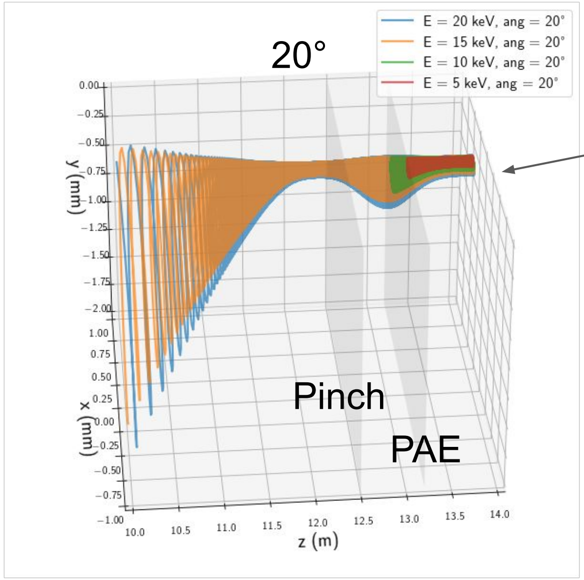
Backreflection in KATRIN

- The actual model is not complete: **backscattered electrons can return back to the detector** due to electric or magnetic reflections

- the reflection can happen due to:
  - detector magnet
  - post-acceleration potential
  - pinch magnet
  - ~~retarding potential~~

a **Kassiopeia simulation** for the precise electron tracking in EM fields is needed

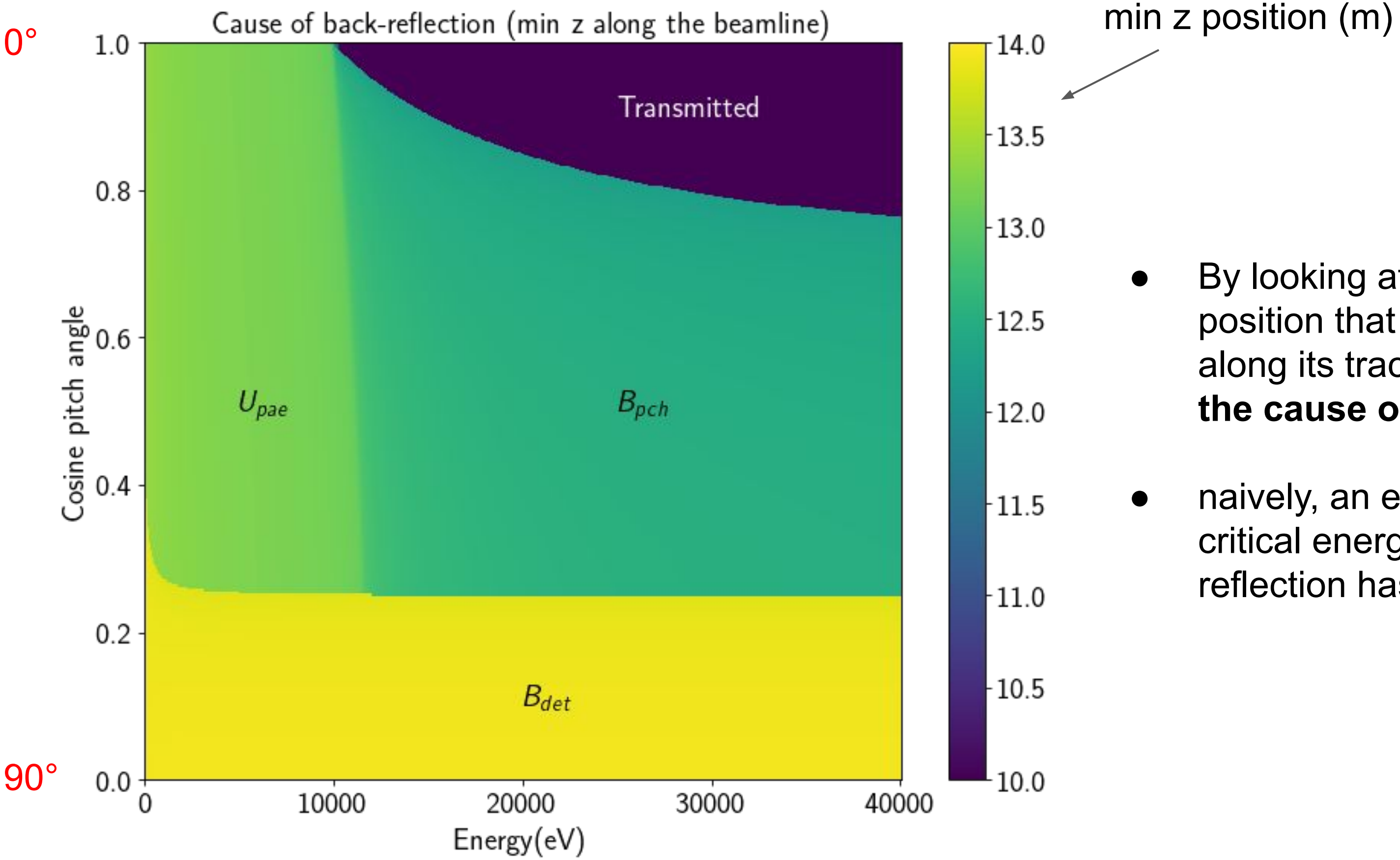
PAE = 10kV, nominal B-fields



electrons generated at the detector position

electrons with E>10keV and small angles are transmitted

Cause of the backreflection



- By looking at the minimum z position that the electron reaches along its tracking, **we can identify the cause of the backreflection**

- naively, an electric reflection has a critical energy, while a magnetic reflection has a critical angle

Two types of backreflection

- **some electrons will return back in a time long enough** that the detector can distinguish the new event with respect to the primary one → I will call this **slow reflection**

  → this will lead to **two different events**, and therefore this kind of reflection can be handled in the TRModel

Two types of backreflection

- **some electrons will return back in a time long enough** that the detector can distinguish the new event with respect to the primary one → I will call this **slow reflection**

  → this will lead to **two different events**, and therefore this kind of reflection can be handled in the TRModel

- **some electrons will return back in a very short time**: the detector cannot distinguish the two events, we will see a unique energy deposition → I will call this **fast reflection**

  →this will lead to a **single event**, these reflections have to be incorporated in Geant4

Two types of backreflection

- **some electrons will return back in a time long enough** that the detector can distinguish the new event with respect to the primary one → I will call this **slow reflection**

  → this will lead to **two different events**, and therefore this kind of reflection can be handled in the TRModel

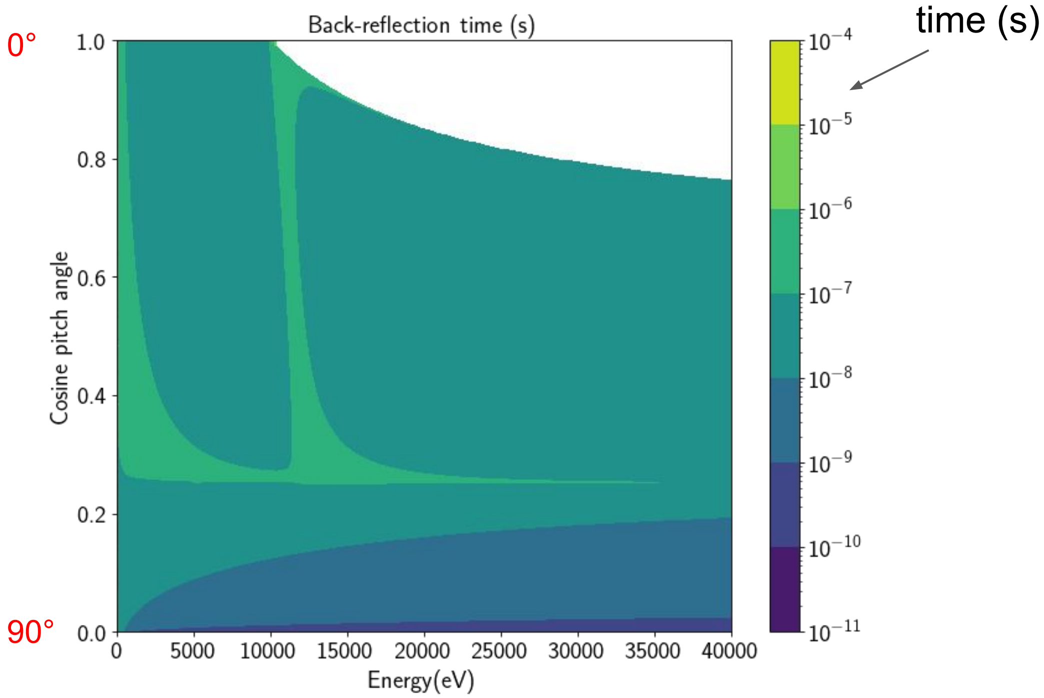
- **some electrons will return back in a very short time**: the detector cannot distinguish the two events, we will see a unique energy deposition → I will call this **fast reflection**

  →this will lead to a **single event**, these reflections have to be incorporated in Geant4

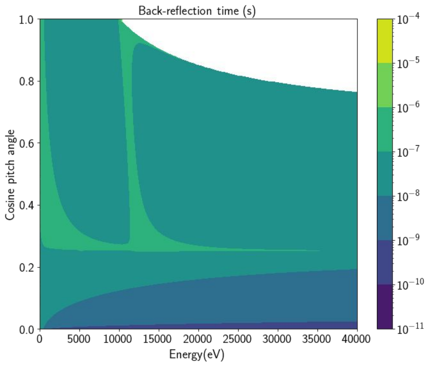
The time required to return back to the detector **depends on the energy and angle of the backscattered particle and on EM fields**

Time required to return back at the detector

By fixing the EM fields (e.g. Scenario 1 fields) we can have this information by **shooting electrons in Kassiopeia with different energies and angles**:



A model for the fast backreflection



Idea:

1. the time plot is loaded in Geant4 main and passed to the class that handles the tracking

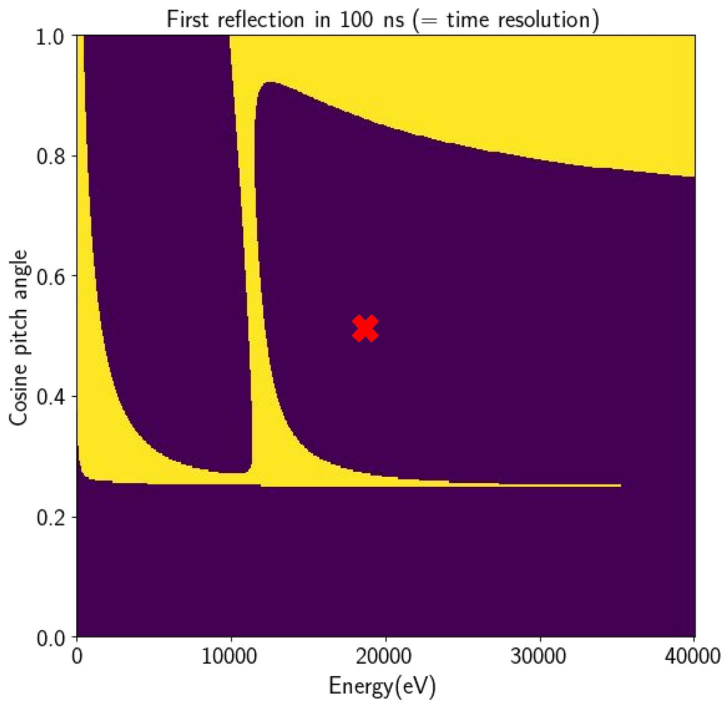
2. for every backscattered electron the time required to return back is evaluated

3. **if there is enough time available this electron is manually inverted in Geant4** and it is re-propagated in the detector

4. this procedure is iterative (multiple backscattering and backreflections inside the given time window)

Example

Let's suppose we have a **100 ns time window** → fast backreflection can only happen in **dark areas**



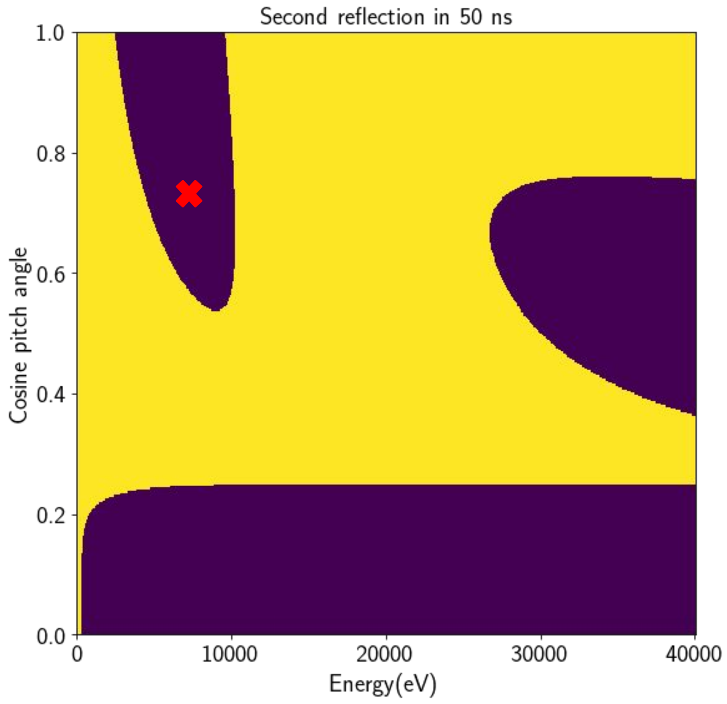
Consider a backscattered electron with an energy/angle for which the **time required to return back is 50 ns**

↓

It is **flipped in Geant4** and its tracking continues!

Example

Let's suppose that electron is **backscattered again** → since the time resolution is 100 ns, but it spended 50 ns for the first reflection, it now has **50 ns available** → fast backreflection can only happen in **dark areas**



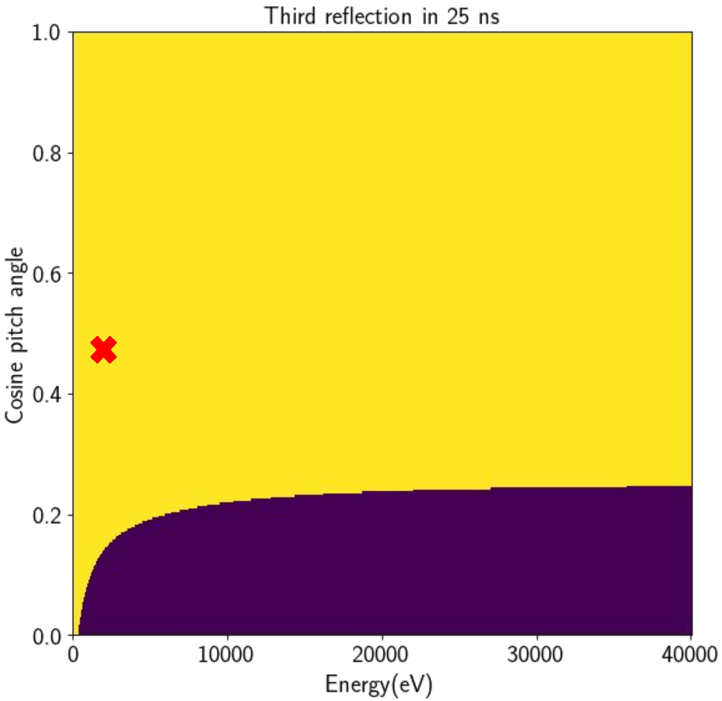
Consider an electron with an energy/angle for which the **time required to return back is 25 ns**

↓

It is **flipped in Geant4** and its tracking continues!

Example

Another backscattering → since the time resolution is 100 ns, but it spended 75 ns for the first two reflections, it now has **25 ns available** → fast backreflection can only happen in **dark areas**



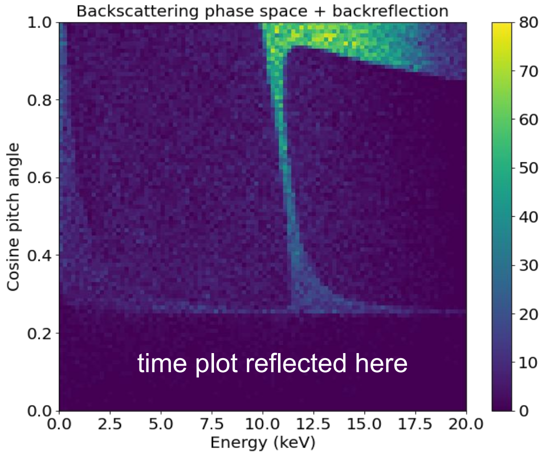
Consider an electron with an energy/angle for which the **time required to return back is bigger than 25 ns**

↓

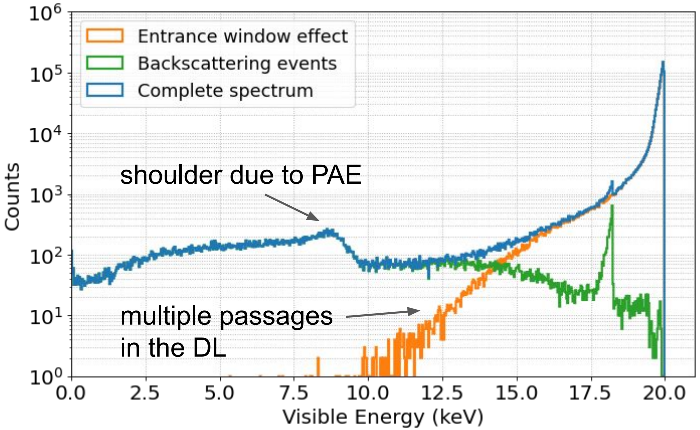
Its **tracking in Geant4 is finished** and its energy-angle are saved, together with the total energy deposited in the detector!

Output of the simulation: 20 keV and 0°

with the energy-angle saved we fill the **backscattering response** (electrons that will be re-propagated in the TRModel)

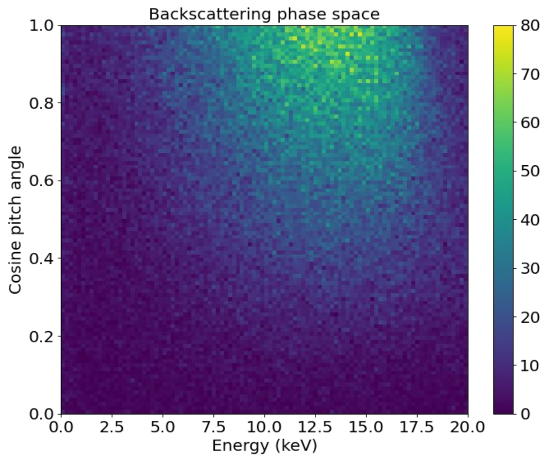


with the energy deposited in the detector we apply the DL model and fill the **detector response**

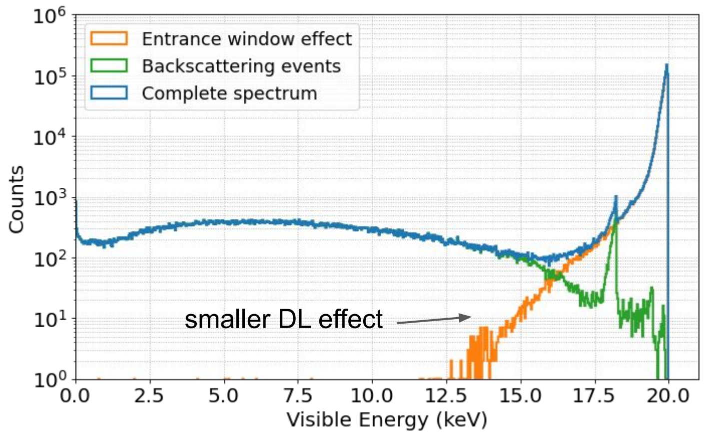


To be compared with

with the energy-angle saved we fill the **backscattering response** (electrons that will be re-propagated in the TRModel)



with the energy deposited in the detector we apply the DL model and fill the **detector response**



Outline

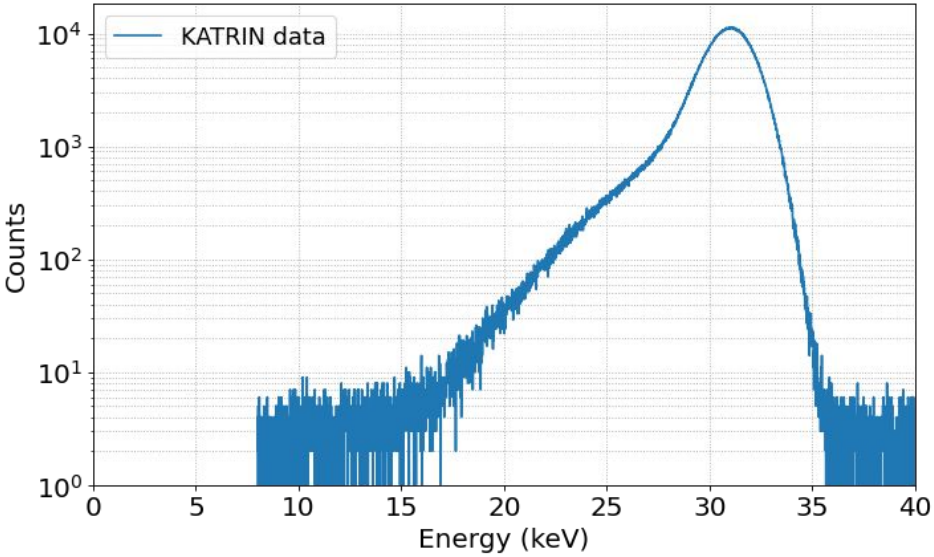
- Backscattering shape in monochromatic and Tritium spectra
- Backreflection in the KATRIN environment
- **Test of the model with KATRIN data**
- Preliminary impact on Tritium spectrum
- Conclusions

Fit to monochromatic spectra in KATRIN environment

- **Monochromatic 21.15 keV electrons** from an e-gun, 40° incidence angle
- **Nominal EM fields** (like Scenario 1), but retarding potential at -20.15 kV

- **excellent test for the fast reflection model**, since the FPD is slower than SDDs (1 order of magnitude) and the spectrum is totally dominated by this effect

- DL thickness and an horizontal gain are left free during the fit:



Fit to monochromatic spectra in KATRIN environment

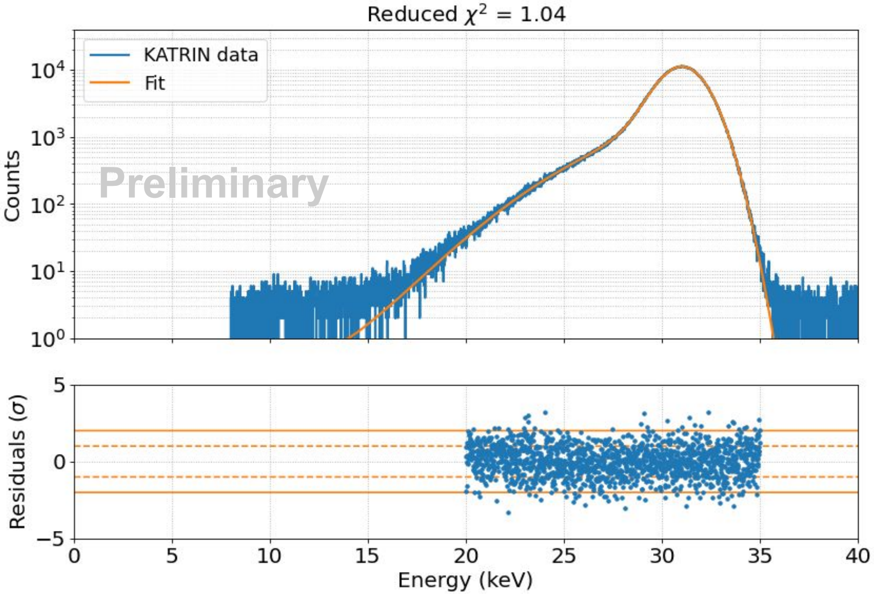
- **Monochromatic 21.15 keV electrons** from an e-gun, 40° incidence angle
- **Nominal EM fields** (like Scenario 1), but retarding potential at -20.15 kV

- **excellent test for the fast reflection model**, since the FPD is slower than SDDs (1 order of magnitude) and the spectrum is totally dominated by this effect

- DL thickness and an horizontal gain are left free during the fit:

  DL~110nm and gain~1

- A very good agreement can be seen between data and simulation!

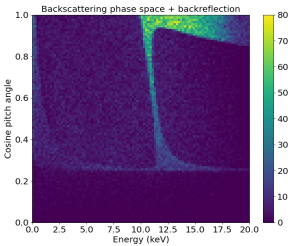


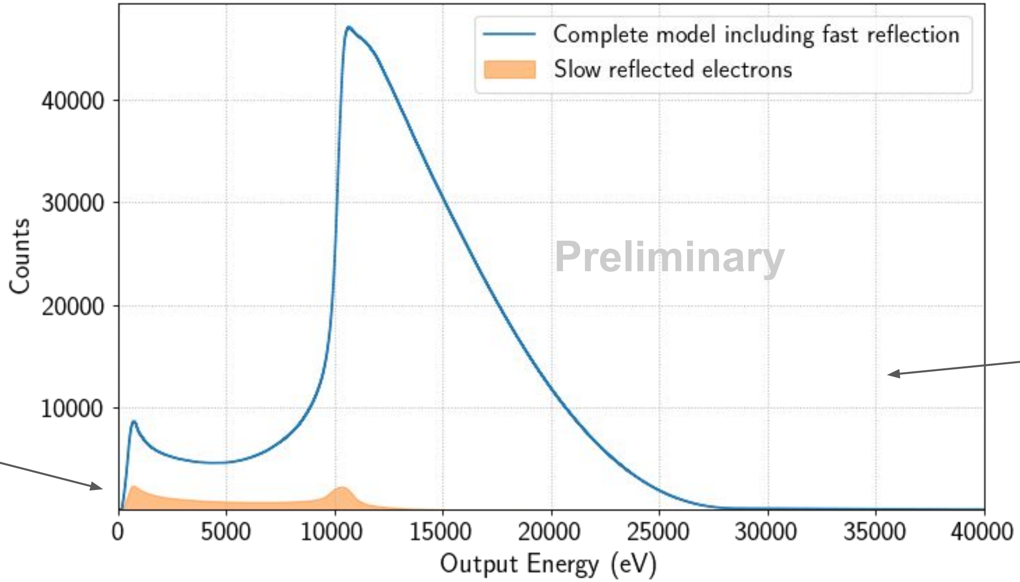
Outline

- Backscattering shape in monochromatic and Tritium spectra
- Backreflection in the KATRIN environment
- Test of the model with KATRIN data
- **Preliminary impact on Tritium spectrum**
- Conclusions

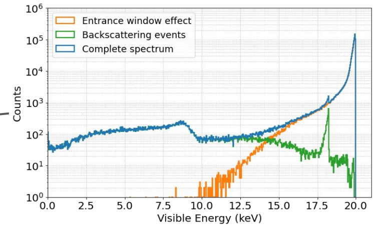
Backreflection impact on Tritium spectrum

these are the electrons that can be slow reflected



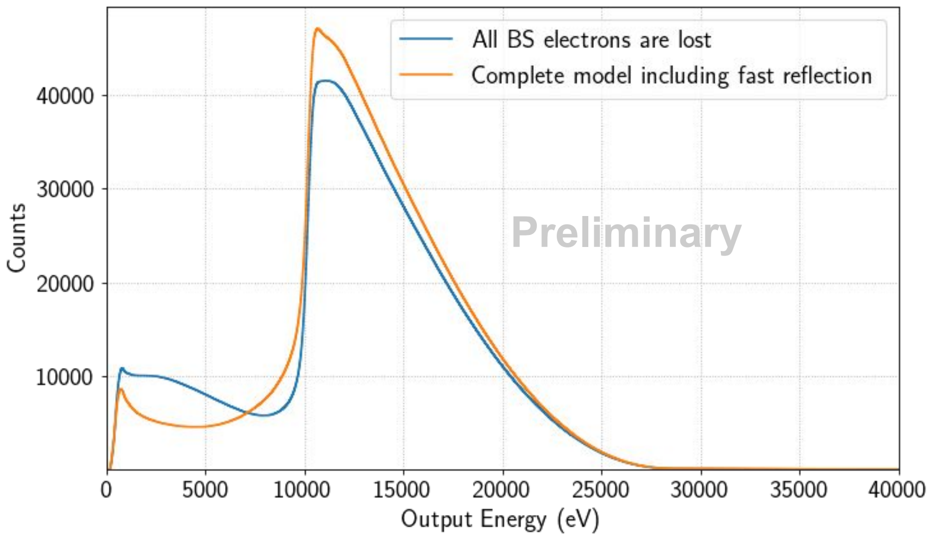


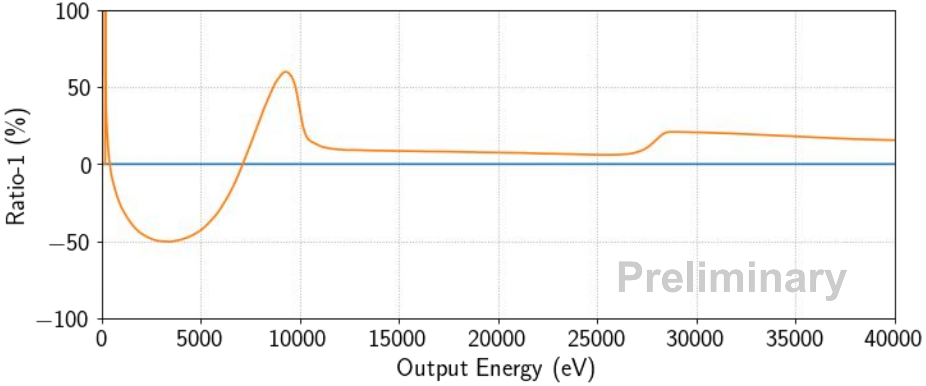
this is how detector responses look like



- very low backscattering tail with completely different shape
- only **few electrons are slowly reflected** → cause of the peak-like structure

Backreflection impact on Tritium spectrum





- very low backscattering tail with completely different shape
- **smooth ~10% difference in the ROI**

Outline

- Backscattering shape in monochromatic and Tritium spectra
- Backreflection in the KATRIN environment
- Test of the model with KATRIN data
- Preliminary impact on Tritium spectrum
- **Conclusions**

Conclusions

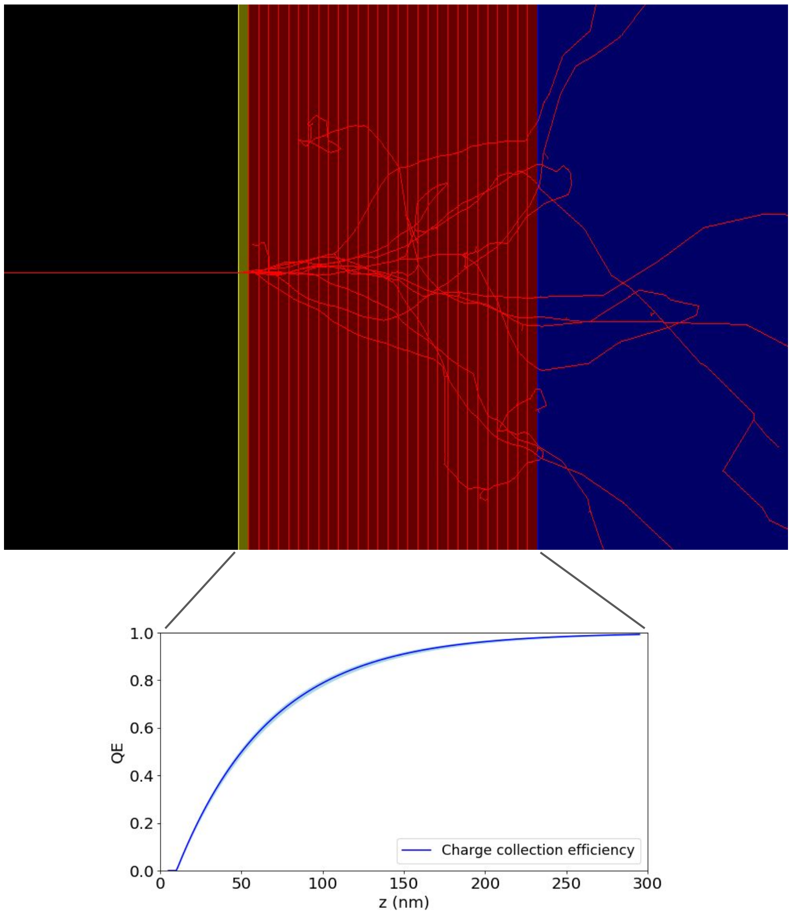
- a Geant4 simulation was developed to **produce detector and backscattering responses**
- these responses were **successfully implemented in the TRMod**
- an **integration between Geant4 and Kassiopeia** was done in order **to describe the fast reflection** due to EM fields
- this model well describes differential monochromatic spectra acquired from the FPD
- The impact on Tritium spectrum is shown thanks to the integration in the TRModel, the **next step is to evaluate the impact on sensitivity**

THANK YOU FOR YOUR ATTENTION!

Backup slides

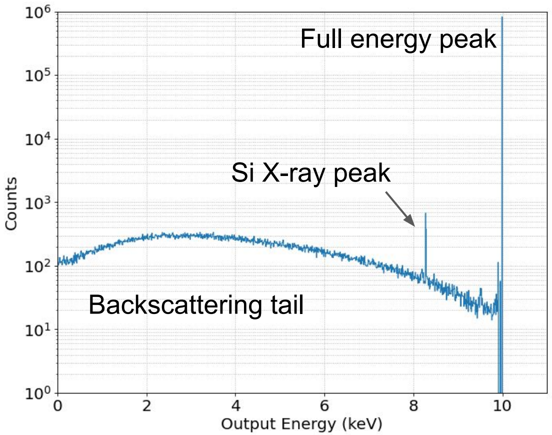
Backscattering and dead layer

- Starting point: **Geant4 simulation**
- **Backscattering already included** in the physics list
- **Dead layer effects added through an empirical model**:
  - first 10nm: SiO_2
  - other 29 Si layers, 10nm each one
  - bulk
  - the energy deposited in every region is saved
  - the visible energy is the weighted sum, where weights follow an exponential with **parameter λ**



Response to monochromatic electrons

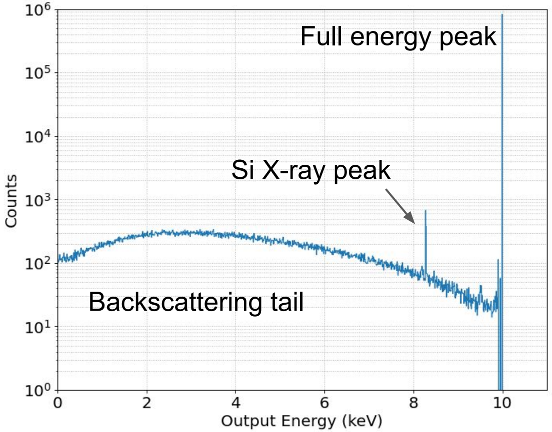
10^6 electrons with E=10keV and normal incidence



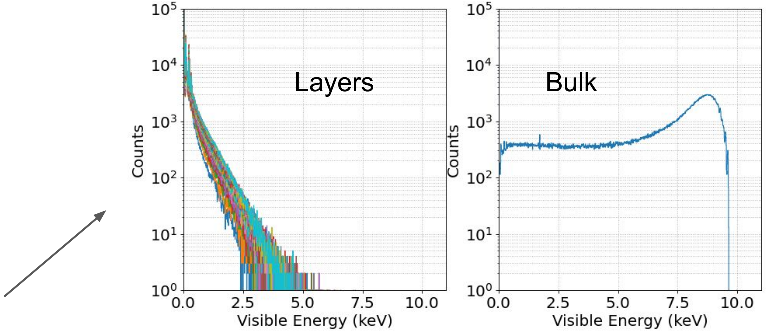
Raw spectrum: **total energy deposited** by the electrons in the SDD

Response to monochromatic electrons

10^6 electrons with E=10keV and normal incidence



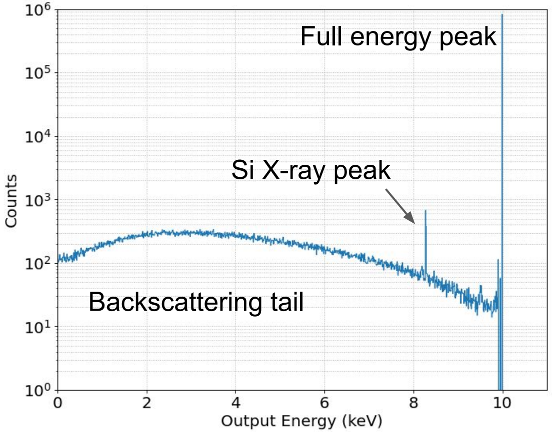
Raw spectrum: **total energy deposited** by the electrons in the SDD



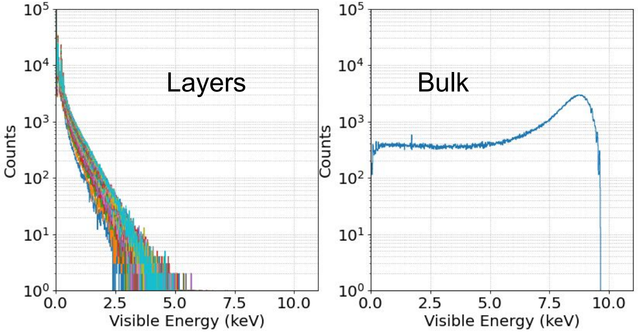
contributions from bulk and layers

Response to monochromatic electrons

10^6 electrons with E=10keV and normal incidence

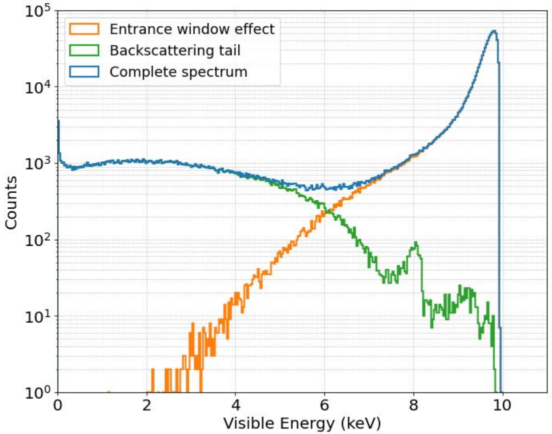


Raw spectrum: **total energy deposited** by the electrons in the SDD

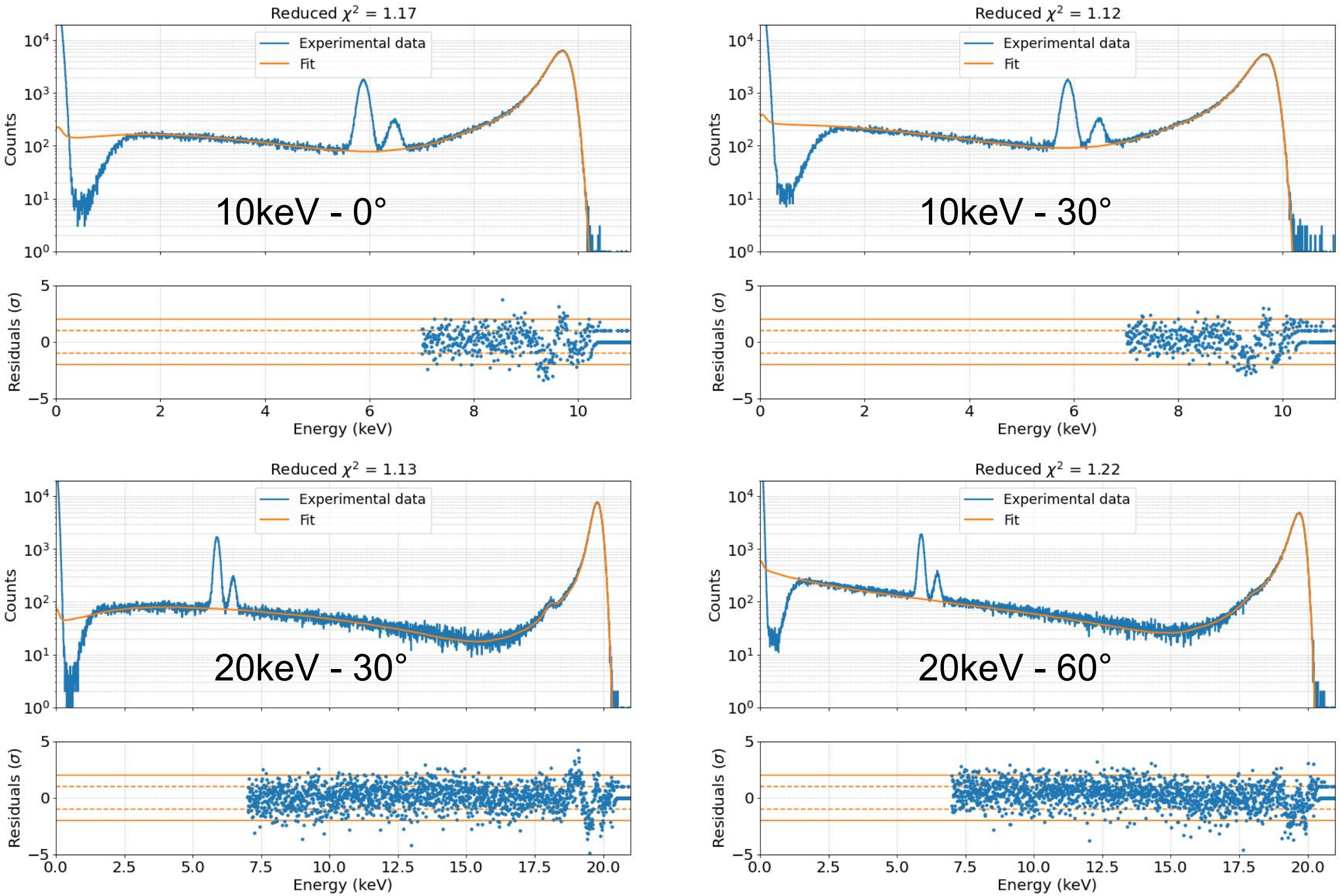


contributions from bulk and layers

Spectrum with QE applied



Comparison with data



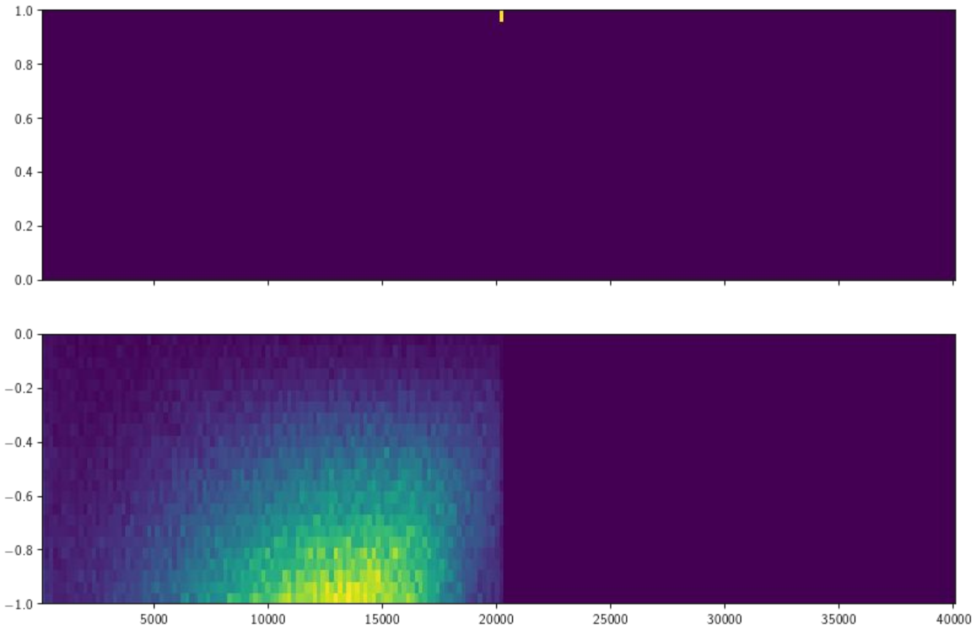
- monochromatic and collimated electrons from a SEM
- different energies and angles
- **good agreement** so far

Some checks

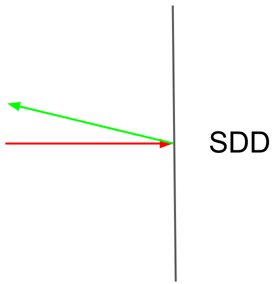
input energy near 20 keV, input angle near 0° (cos=1)

input cos (from 0 to 1)
= input ang (from 90° to 0°)

output cos (from -1 to 0)
= output ang (from 180° to 90°)

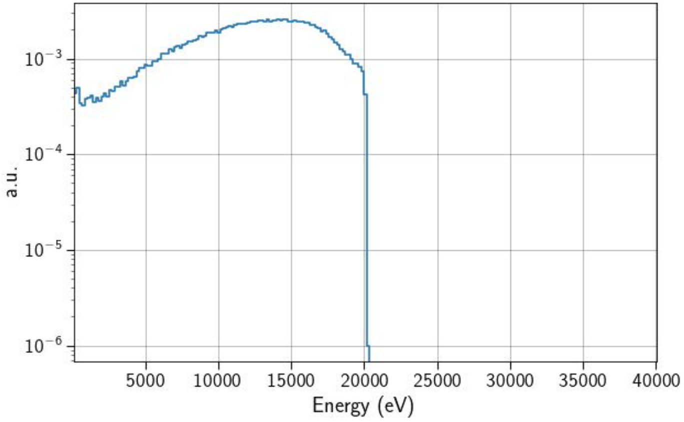


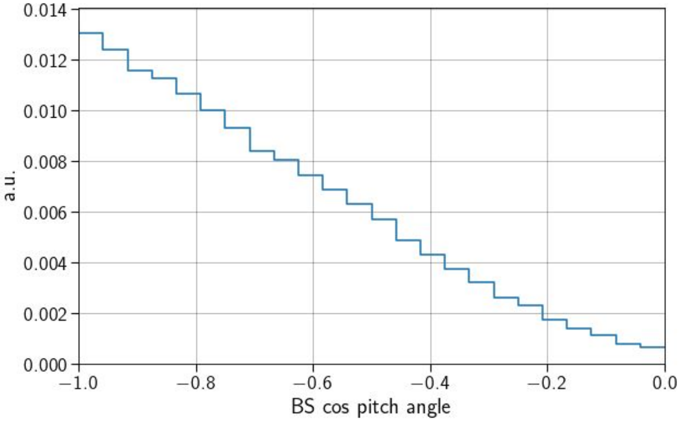
energy (eV)

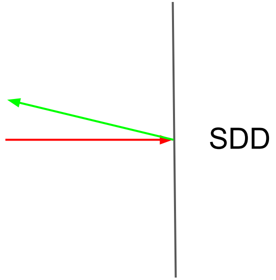


Some checks

input energy near 20 keV, input angle near 0° (cos=1)





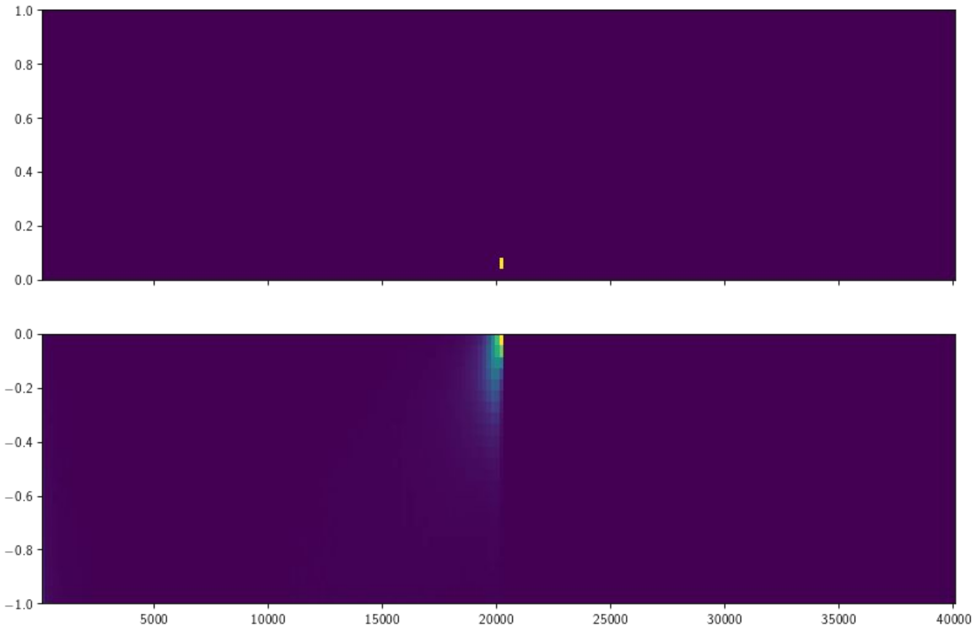


Some checks

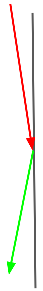
input energy near 20 keV, input angle near 90° (cos=0)

input cos (from 0 to 1)
= input ang (from 90° to 0°)

output cos (from -1 to 0)
= output ang (from 180° to 90°)



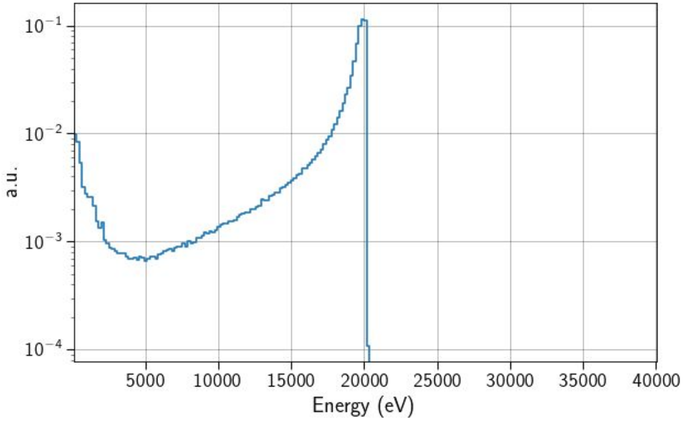
energy (eV)

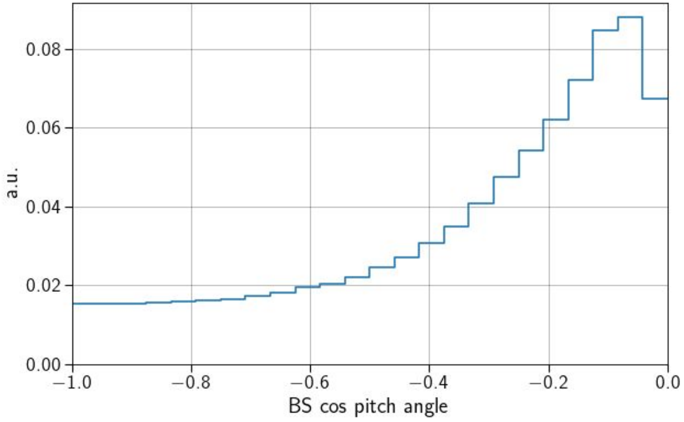


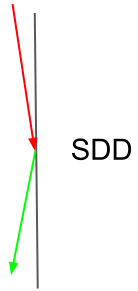
SDD

Some checks

input energy near 20 keV, input angle near 0° (cos=1)

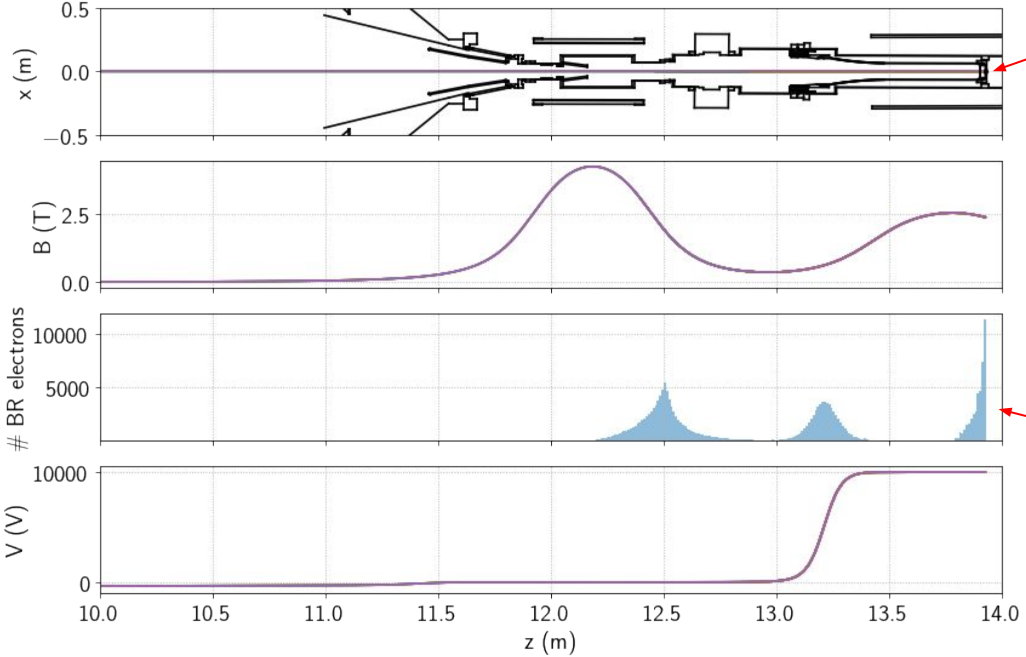






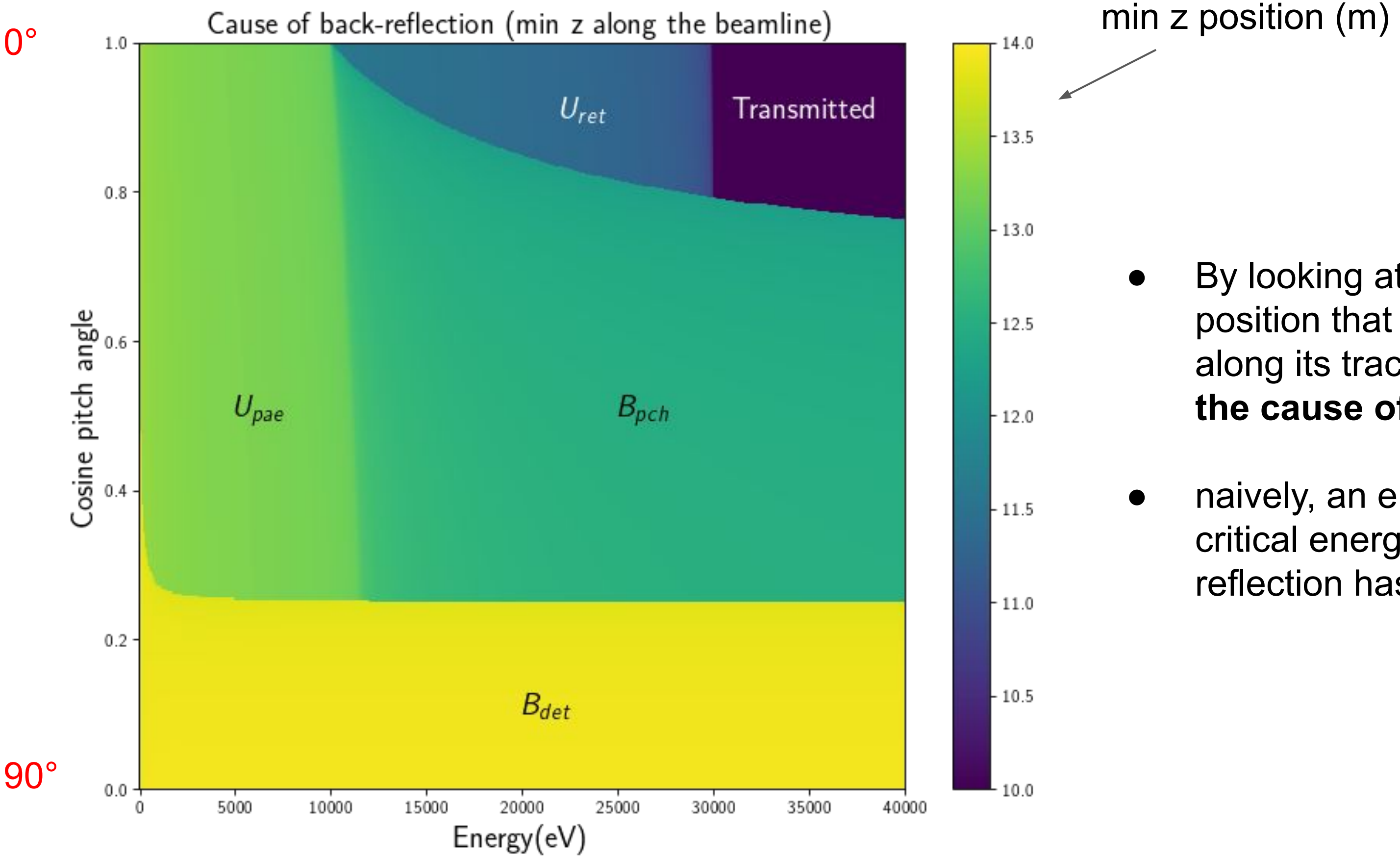
Backreflection simulation

- In order to know if the backreflection is fast or slow we need to know the time required to return back to the detector
- this can be **simulated with Kassiopeia**



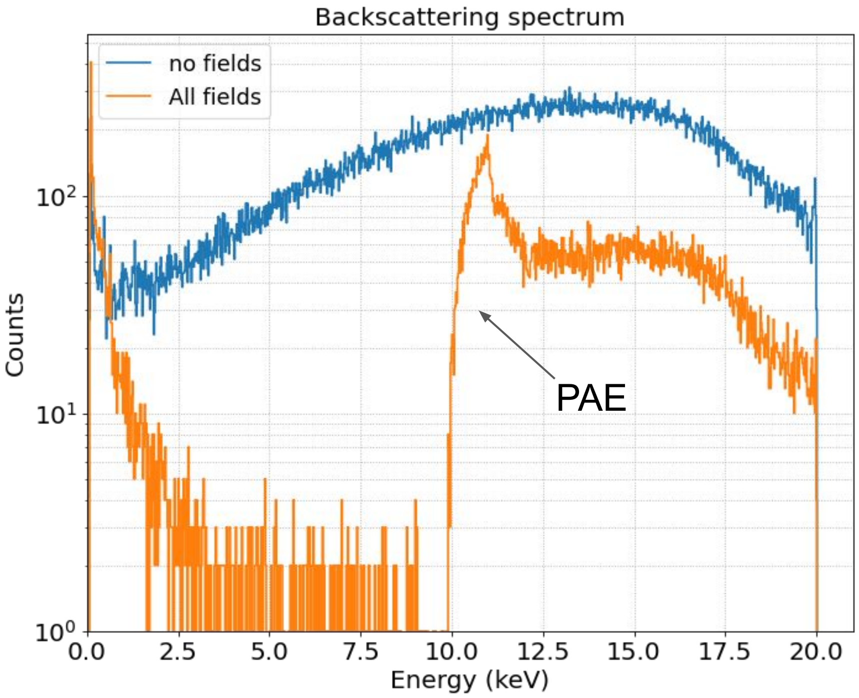
- **Electrons generated at the detector** → directed towards the source
- grid scan in energy and angle
- configuration:
  - B_{det} = 2.52 T
  - U_{pae} = 10 kV
  - B_{pch} = 4.2 T
- the blue histogram represents the point where the backreflection happens (B_{det}, U_{pae}, B_{pch})

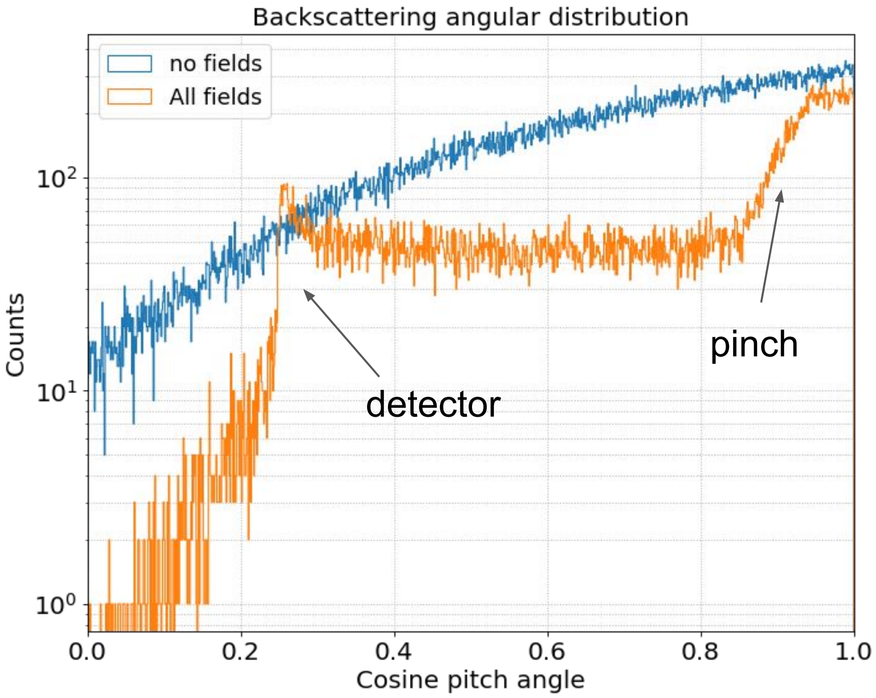
Cause of the backreflection



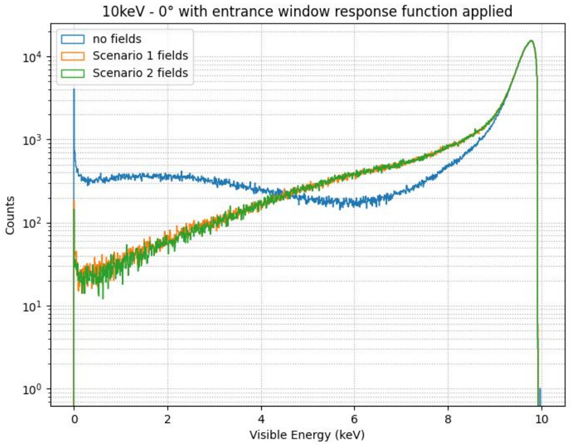
- By looking at the minimum z position that the electron reaches along its tracking, **we can identify the cause of the backreflection**
- naively, an electric reflection has a critical energy, while a magnetic reflection has a critical angle

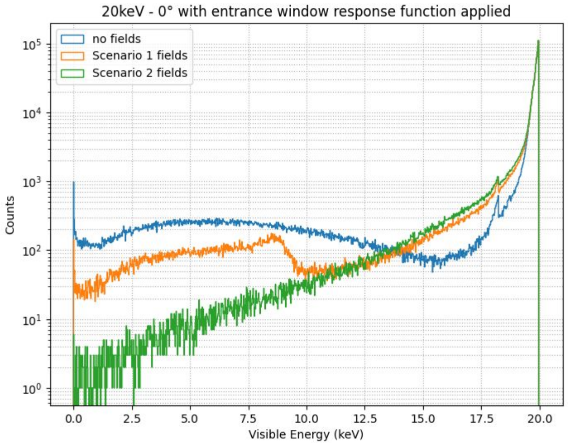
A look at the backscattering response

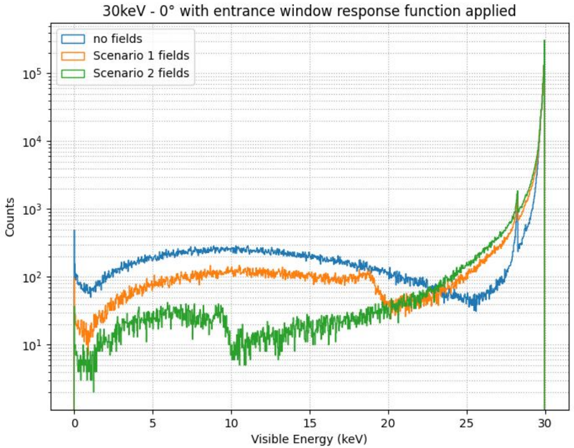




BR for different energies



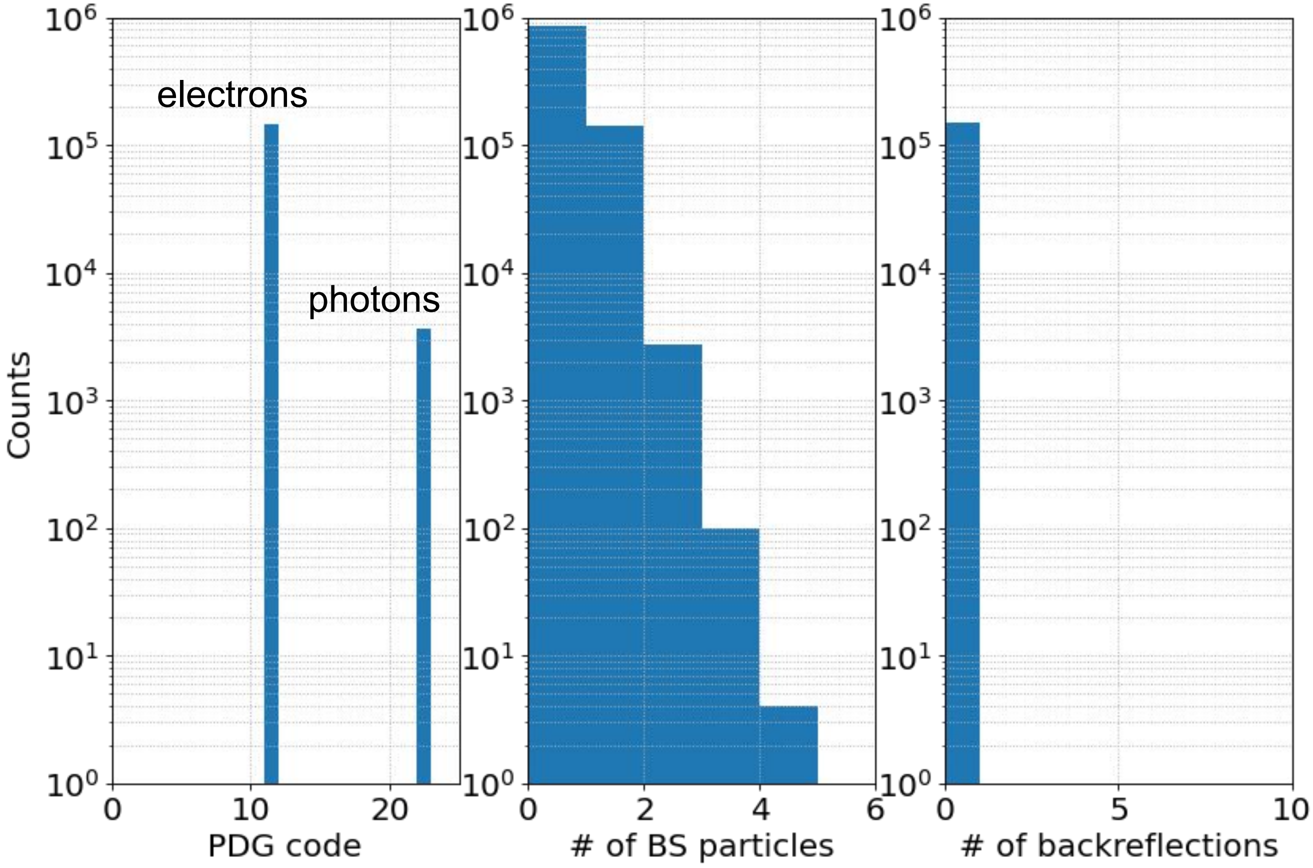




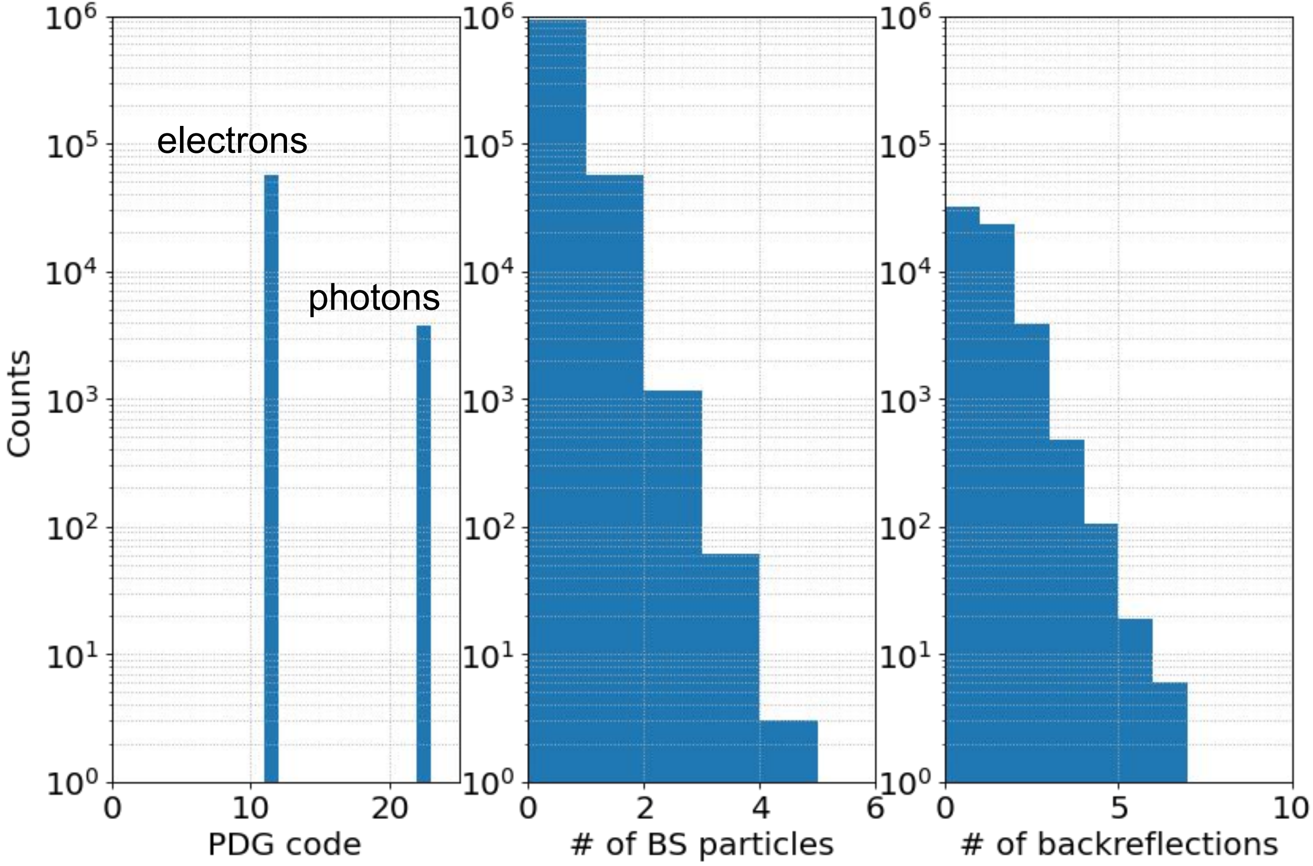
Shoulder in the response only present if a backscattered electron can overpass the PAE

- for Scenario1 more than 10 keV are needed
- for Scenario2 more than 20keV are needed

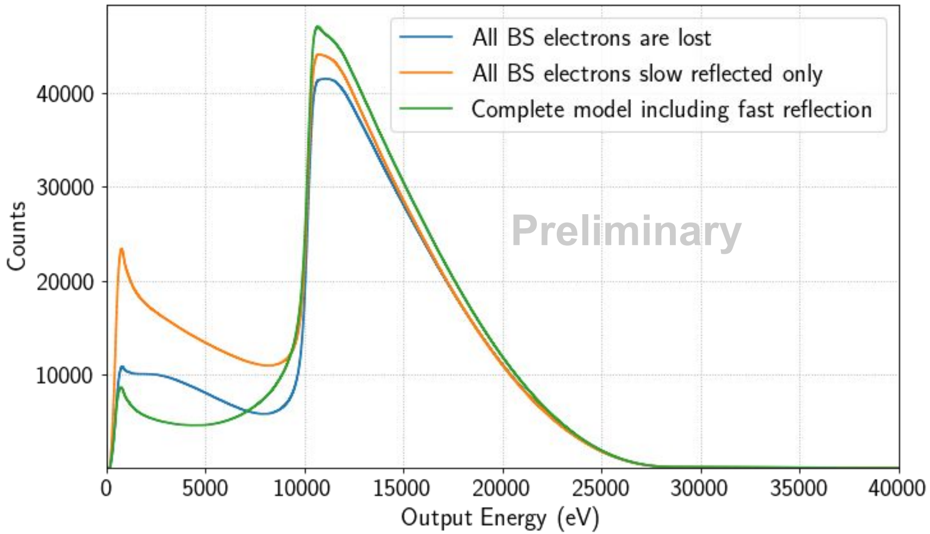
Some backscattering informations (w/o BR)

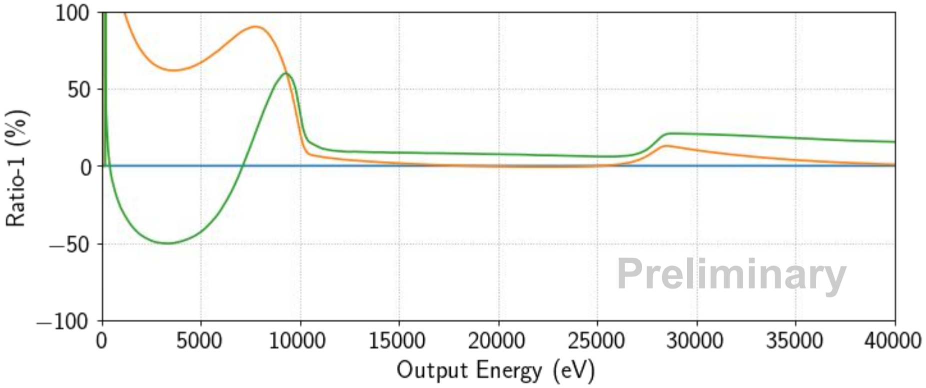


Some backscattering informations (with BR)



Backreflection impact on Tritium spectrum

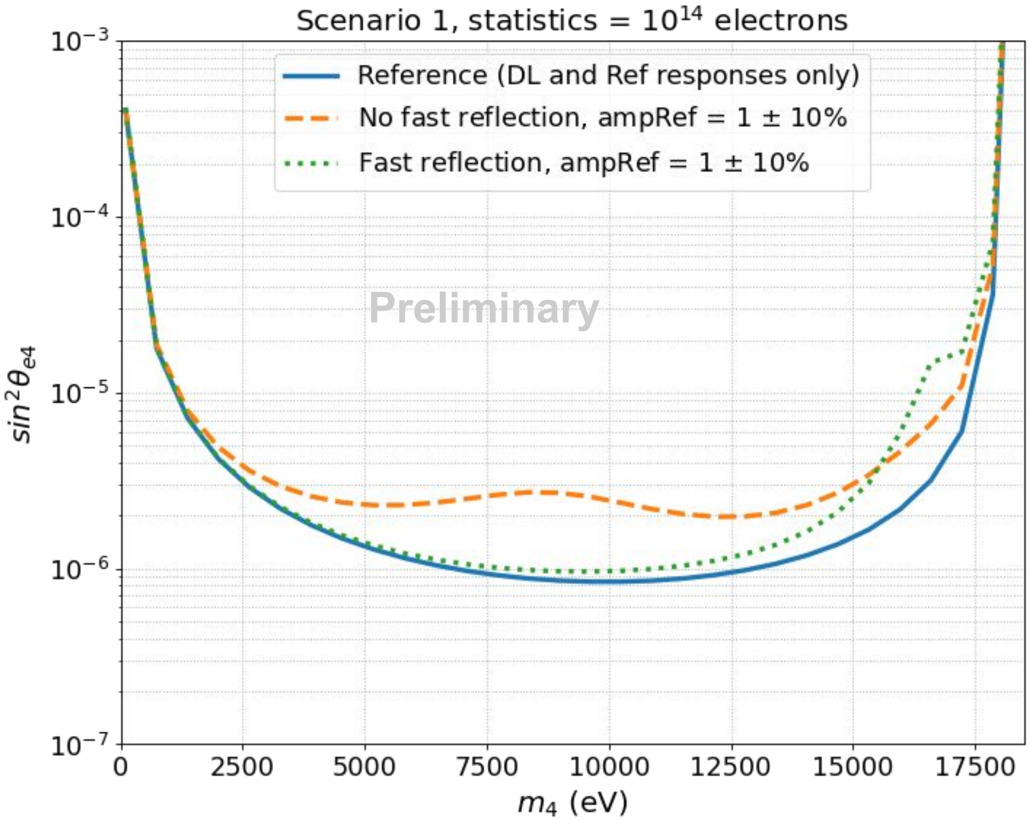




Super preliminary sensitivity

ampBR parameter:

- same implementation as ampRW
- 10% uncertainty considered
- reference spectrum with only DL and BS reflection responses



Super preliminary sensitivity

DL parameter:

- same implementation as always
- 5% uncertainty considered
- reference spectrum with only DL and BS reflection responses