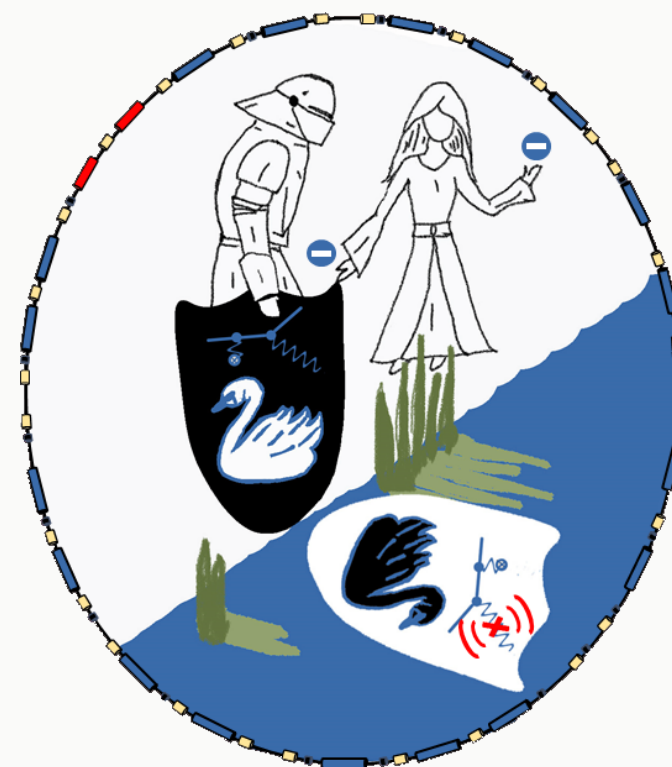


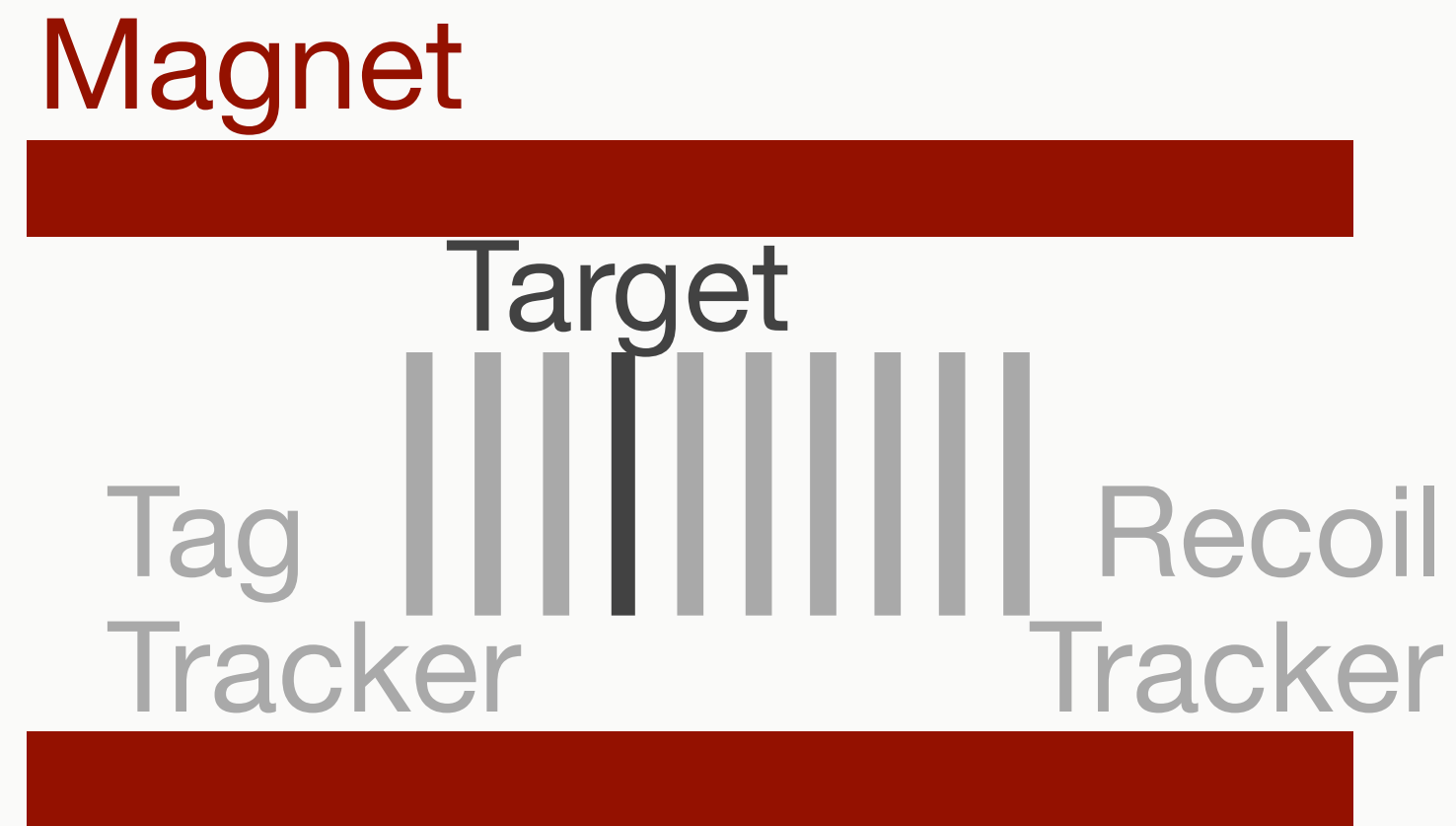
Investigation of Electro-Nuclear Backgrounds for Lohengrin

Laney Klipphahn for the Lohengrin Study Group

01.10.2026 - Accelerating the Search for Disappearing Light Dark Matter - a Community Workshop



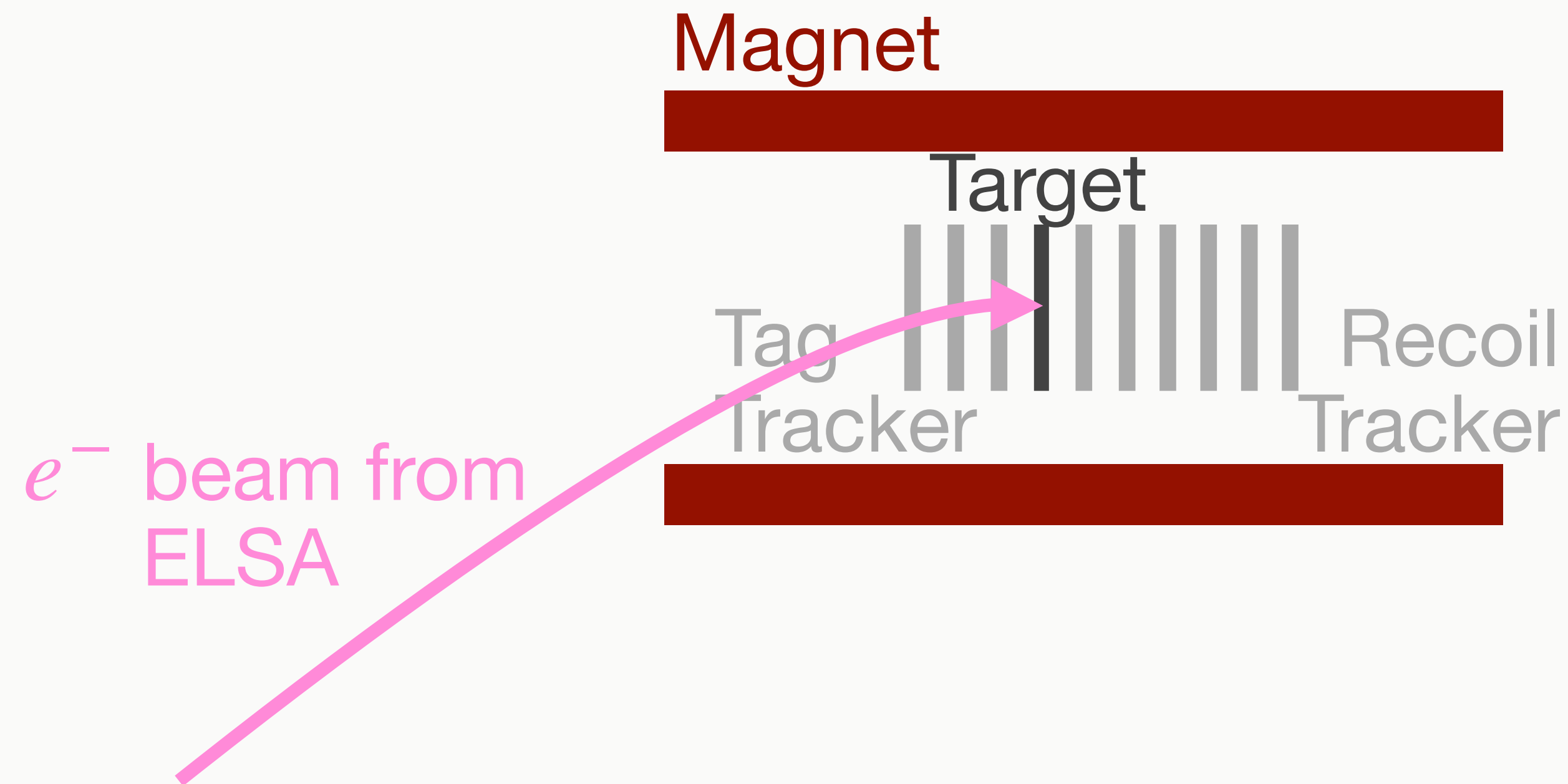
Short Reminder: The Lohengrin Experiment



HCAL

ECAL

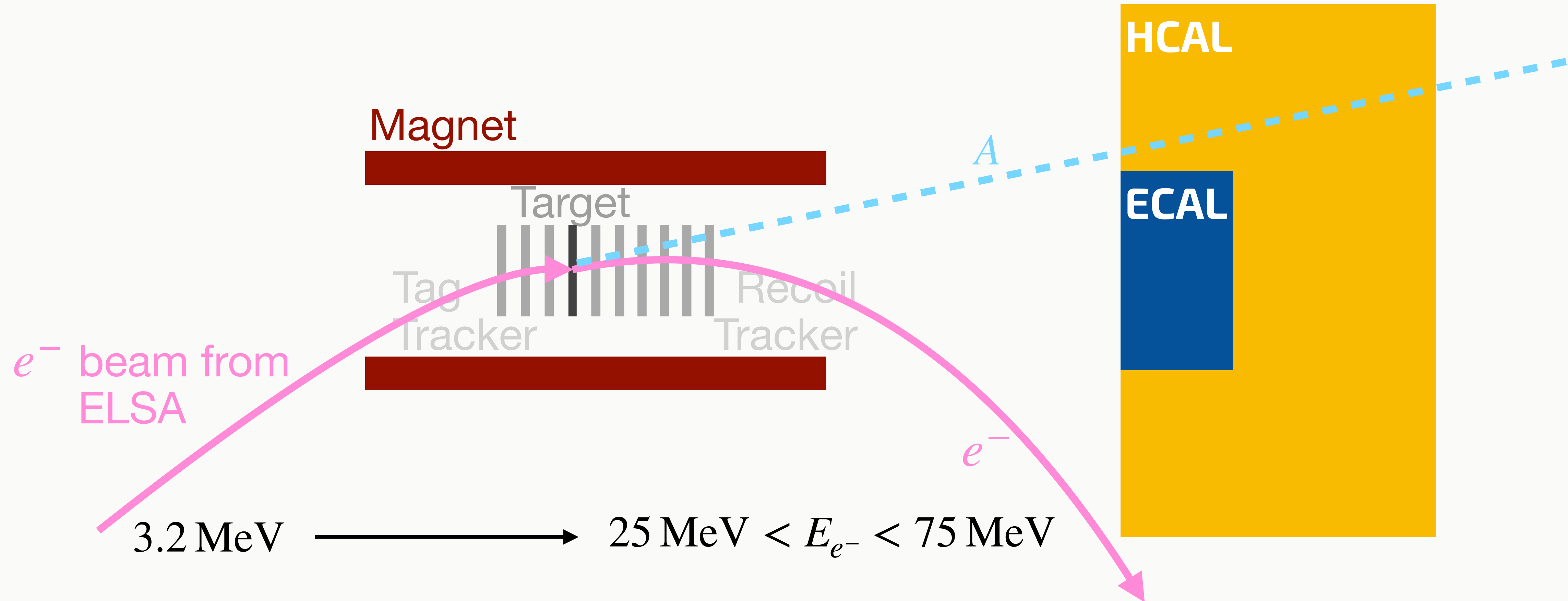
Short Reminder: The Lohengrin Experiment



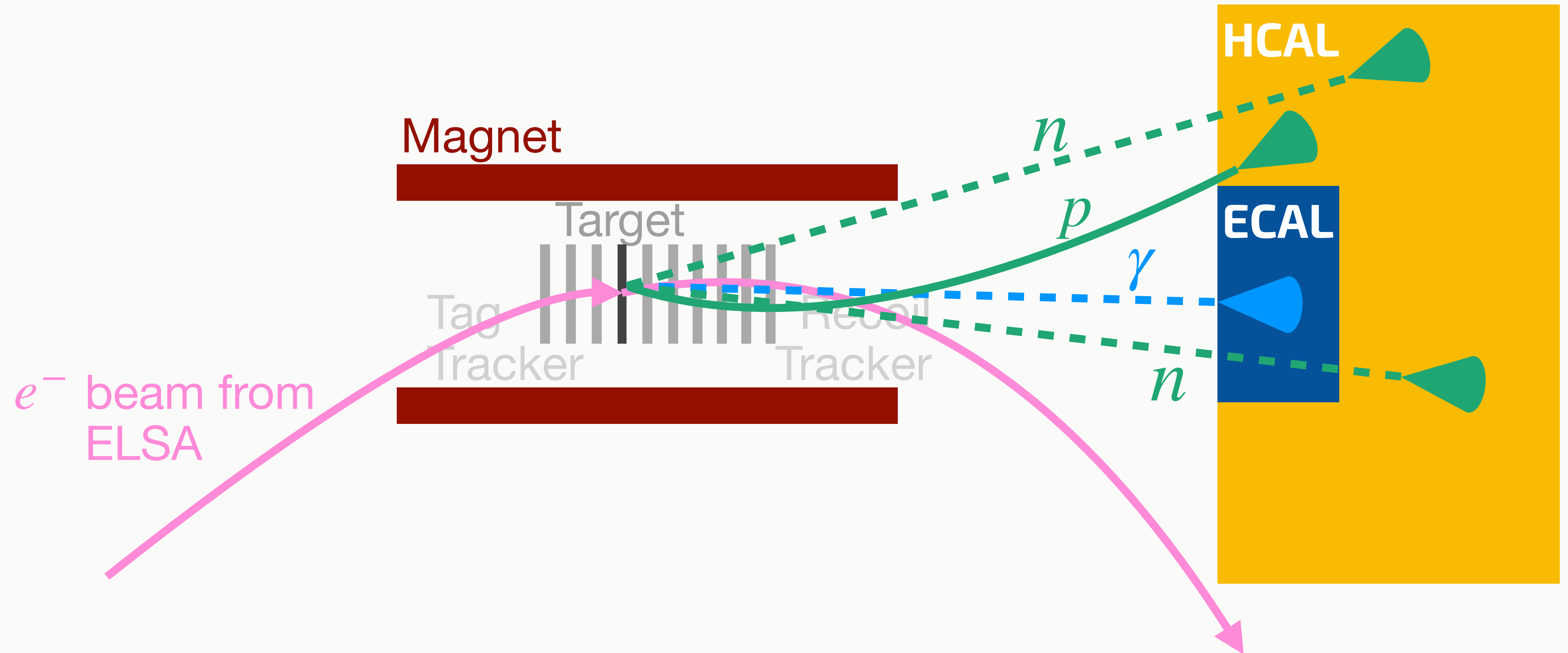
HCAL

ECAL

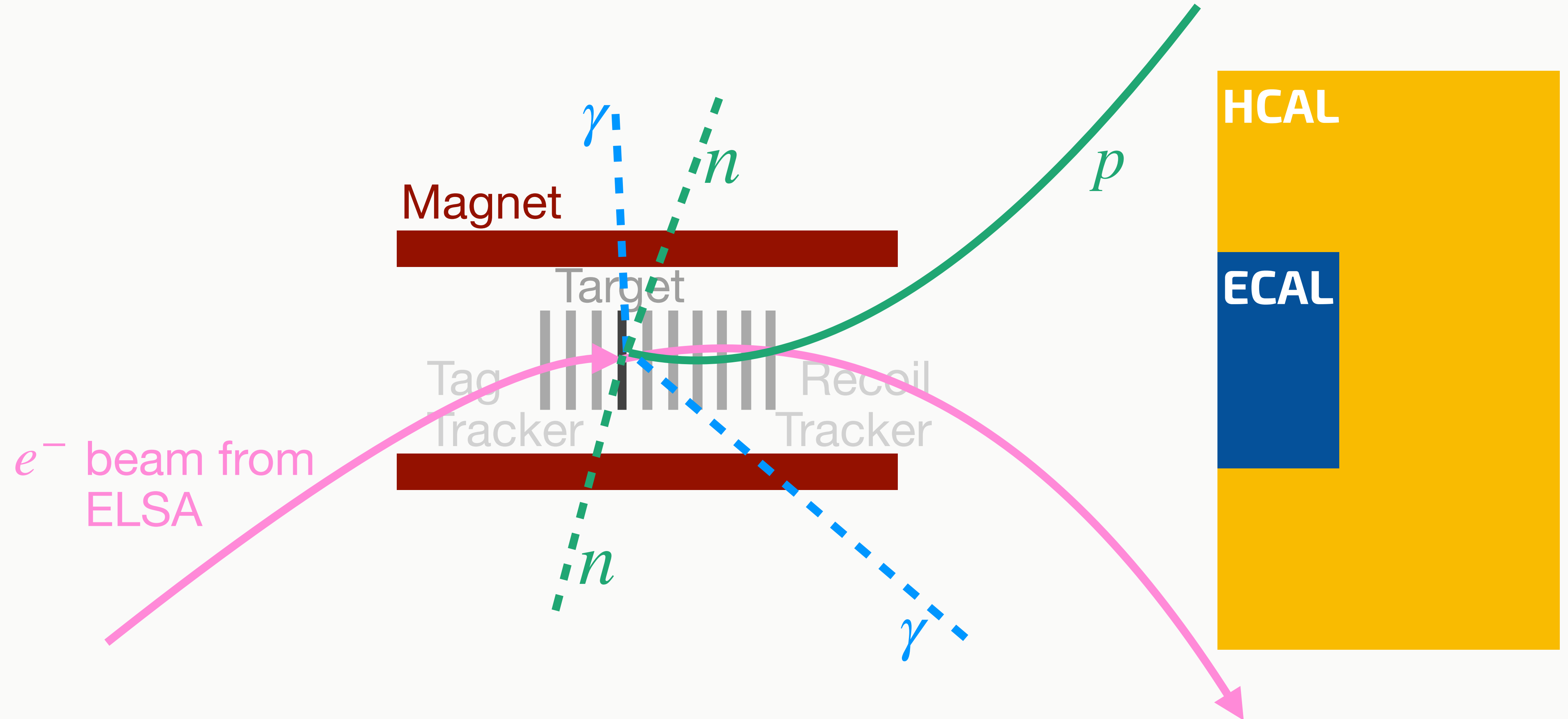
Short Reminder: The Signal



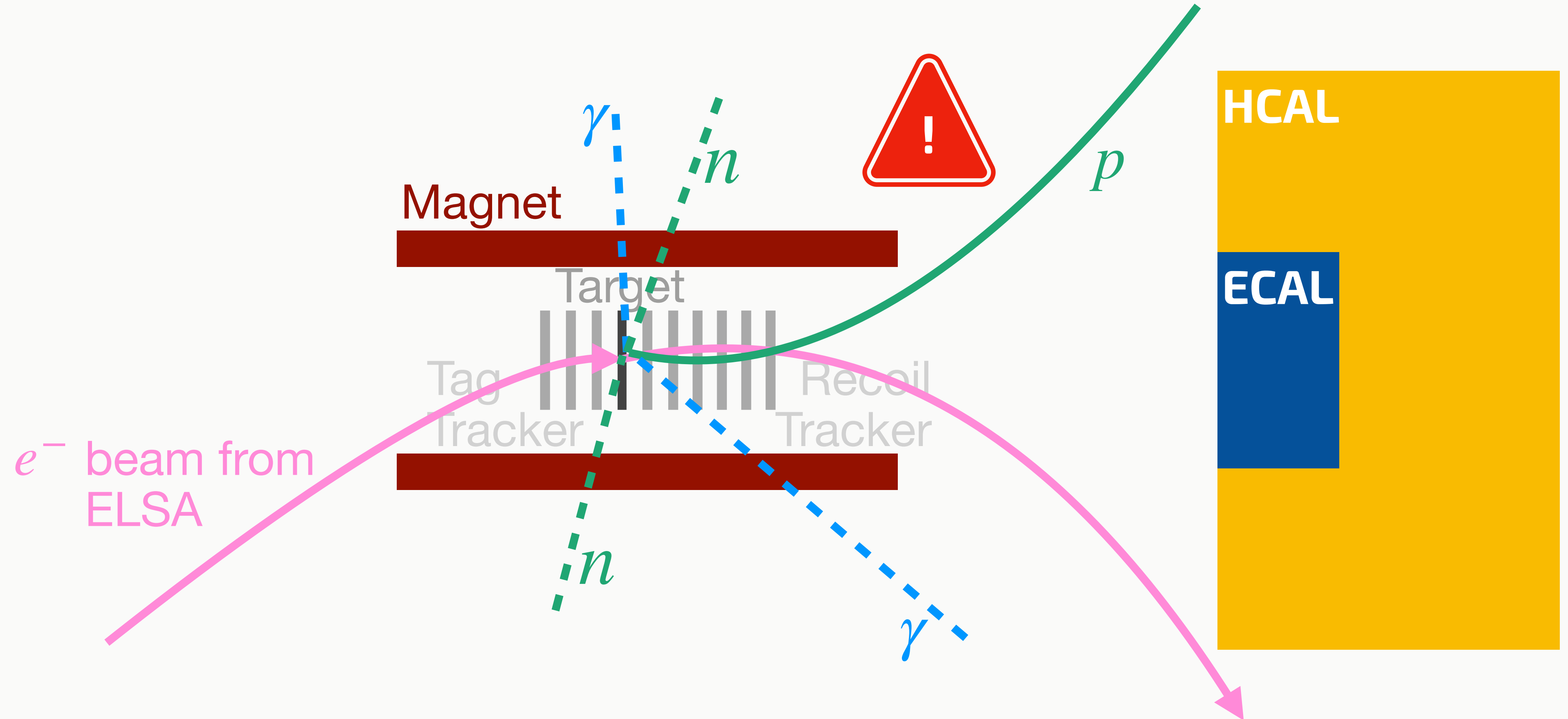
Short Reminder: Hadronic Backgrounds



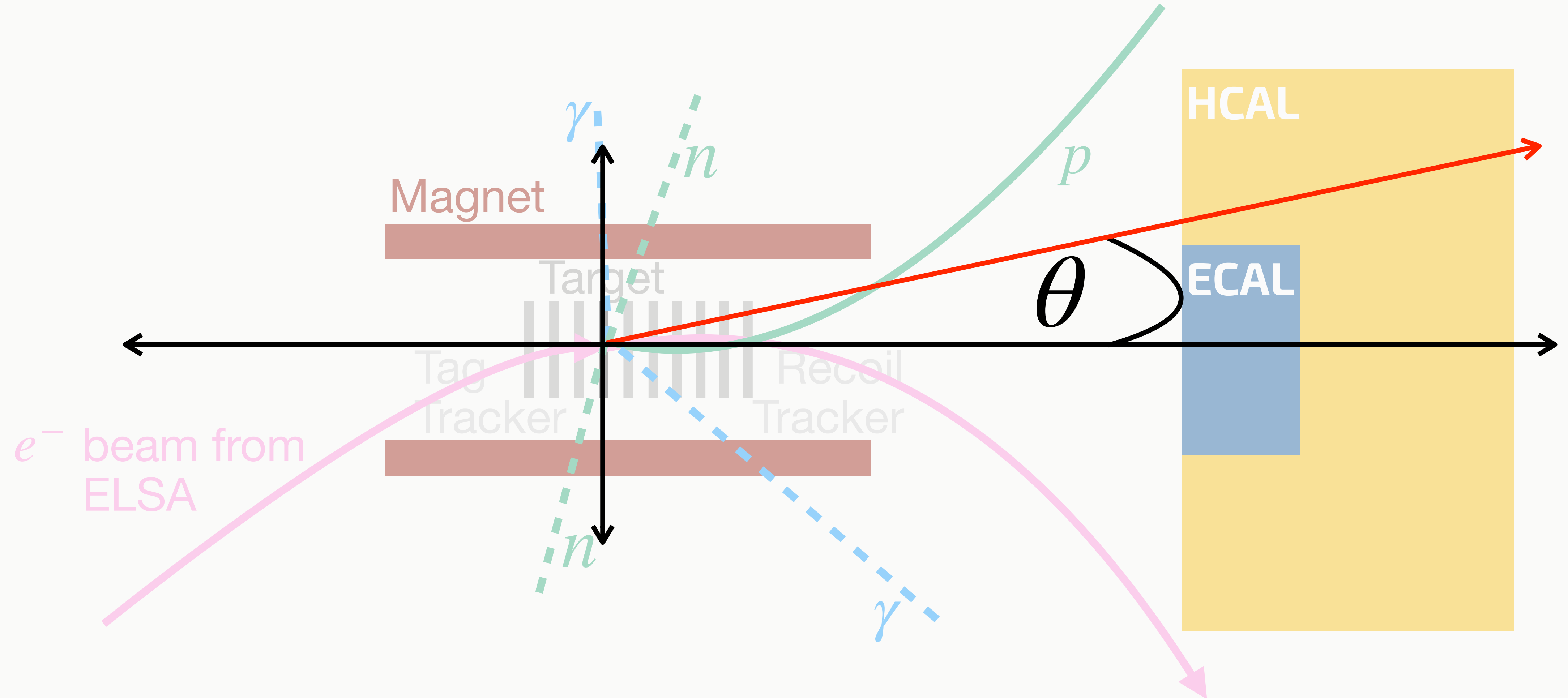
Short Reminder: Hadronic Backgrounds II



Short Reminder: Hadronic Backgrounds II

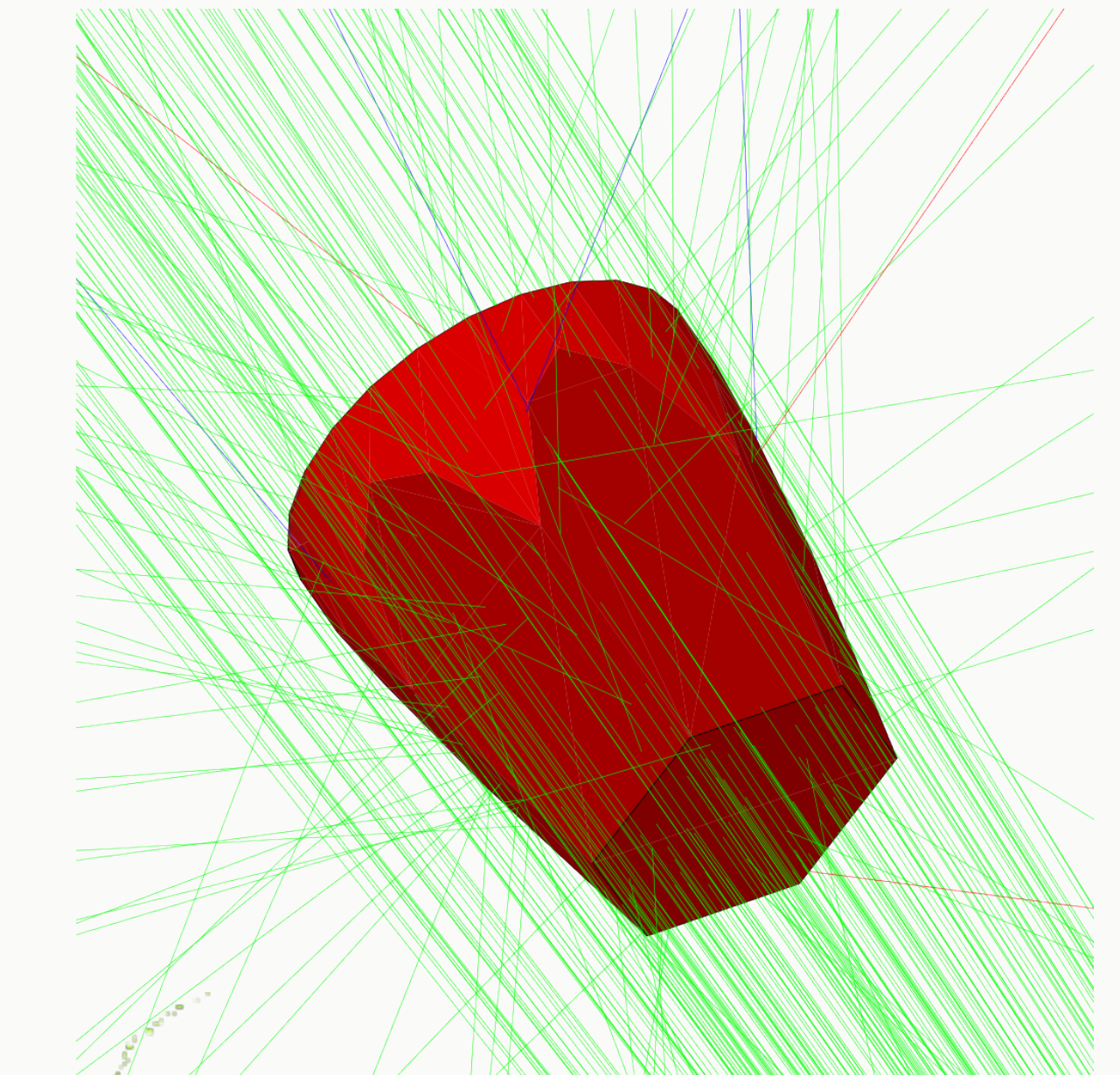
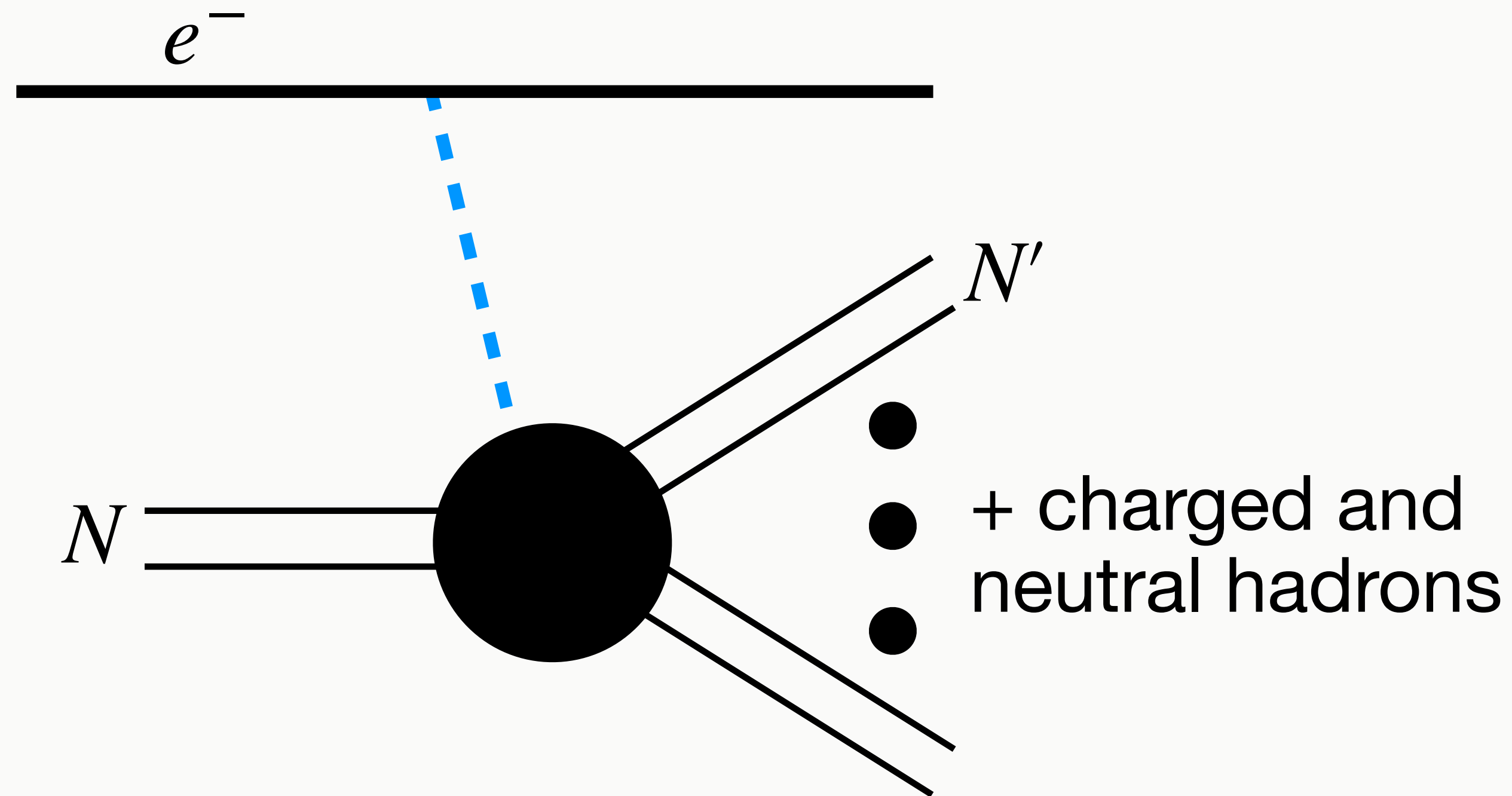


Short Reminder: Hadronic Backgrounds II



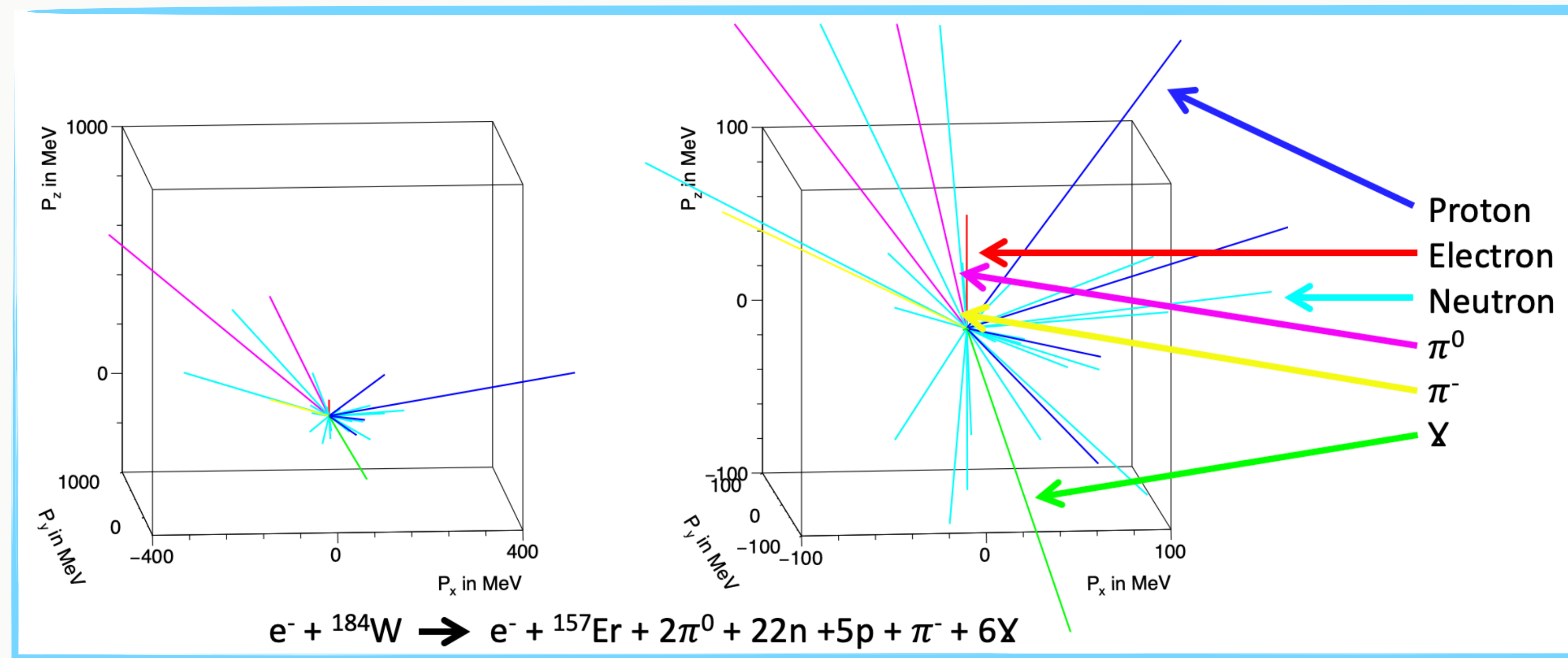
Electro-nuclear Event Generation

- Simplification: ^{184}W as target material
- Investigate hard electro-nuclear interactions

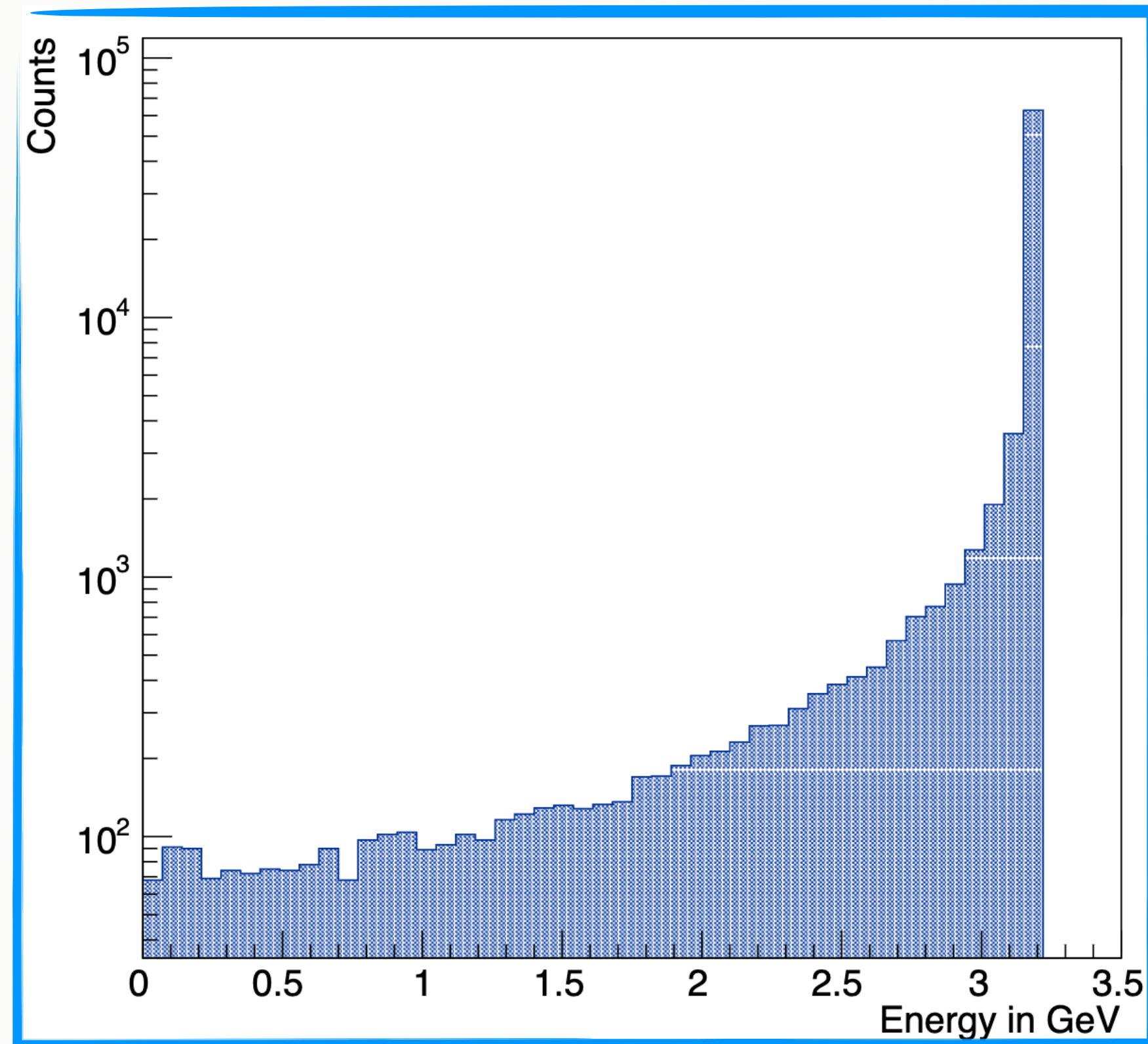


Electro-nuclear Events with

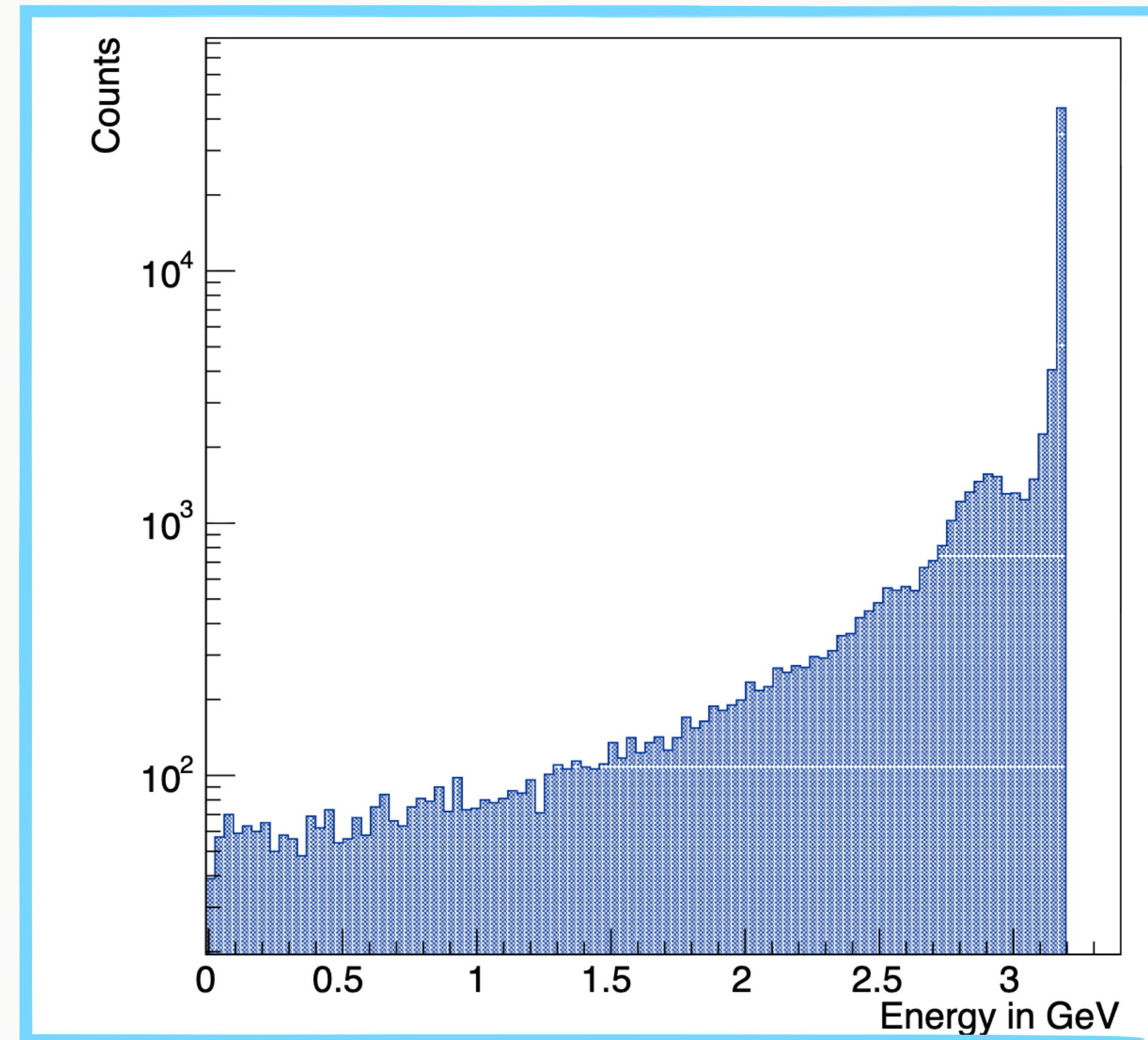
- Problems in G4 with large momentum transfers (& momentum conservation)
Bug will be fixed in December release of G4!!
- FLUKA can simulate this (supposedly) well!
- Simulate electro-nuclear interaction for $2.5 \cdot 10^9$ e.o.t.



The electron

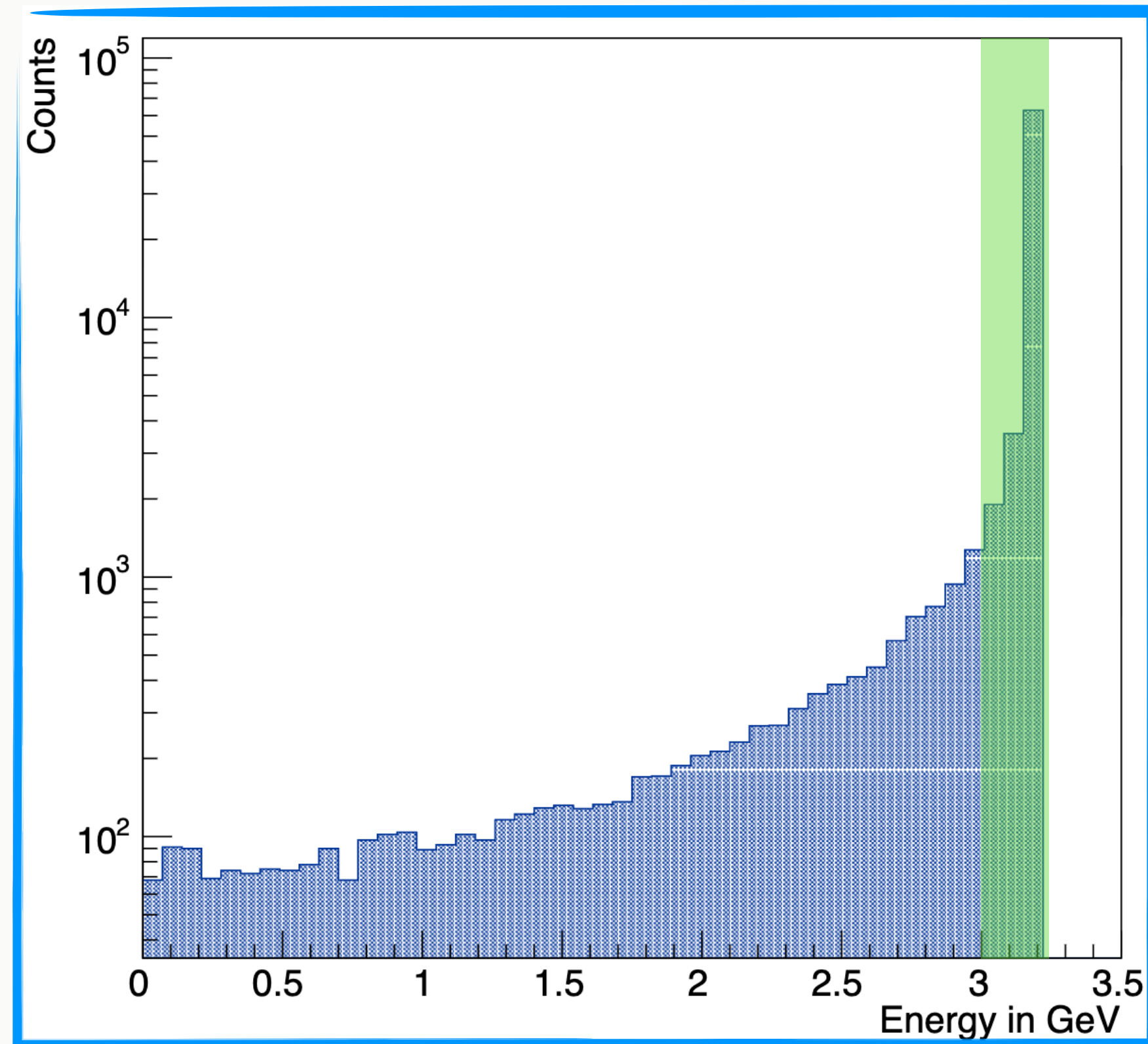


Incoming

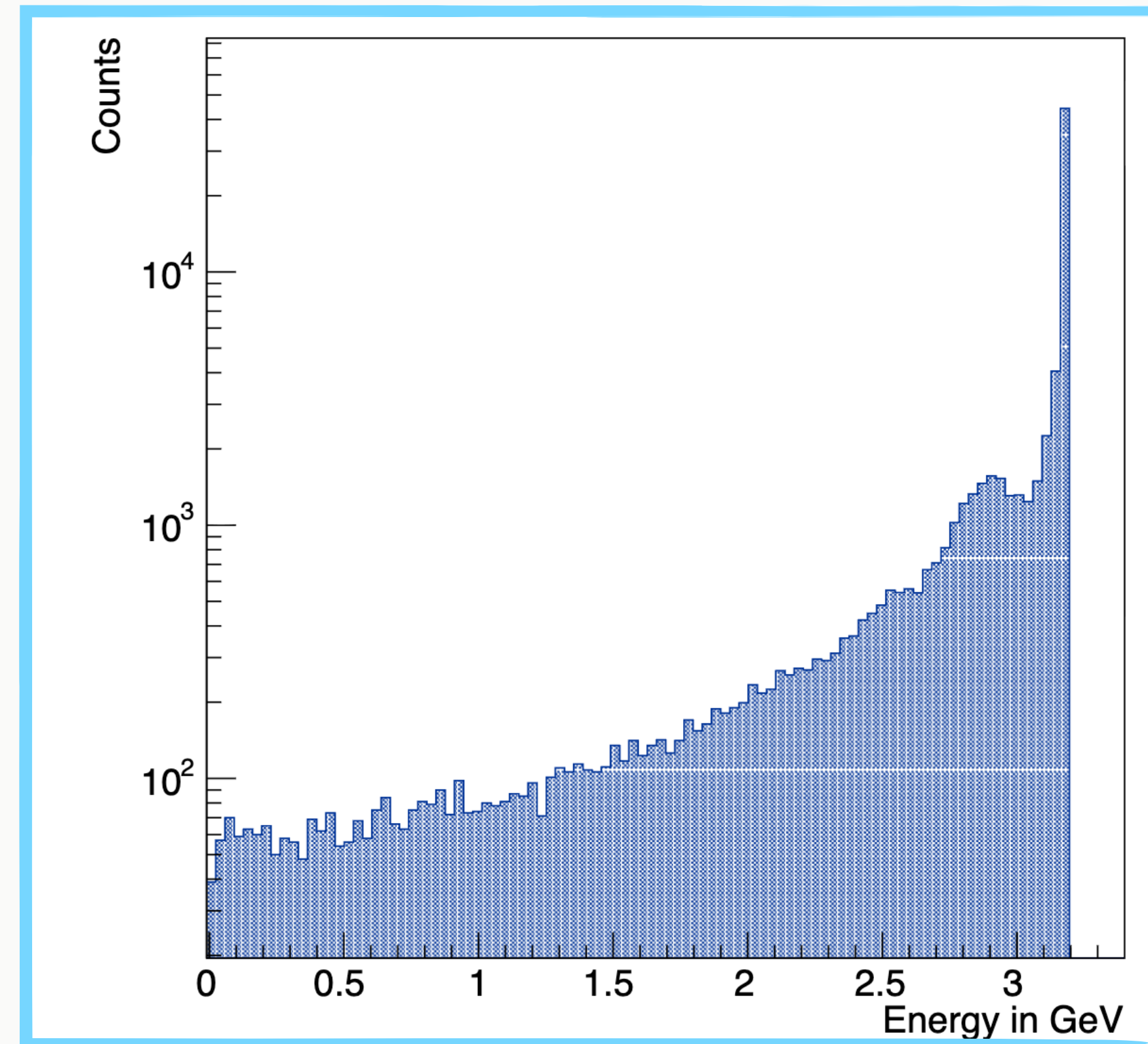


Recoiling

The electron

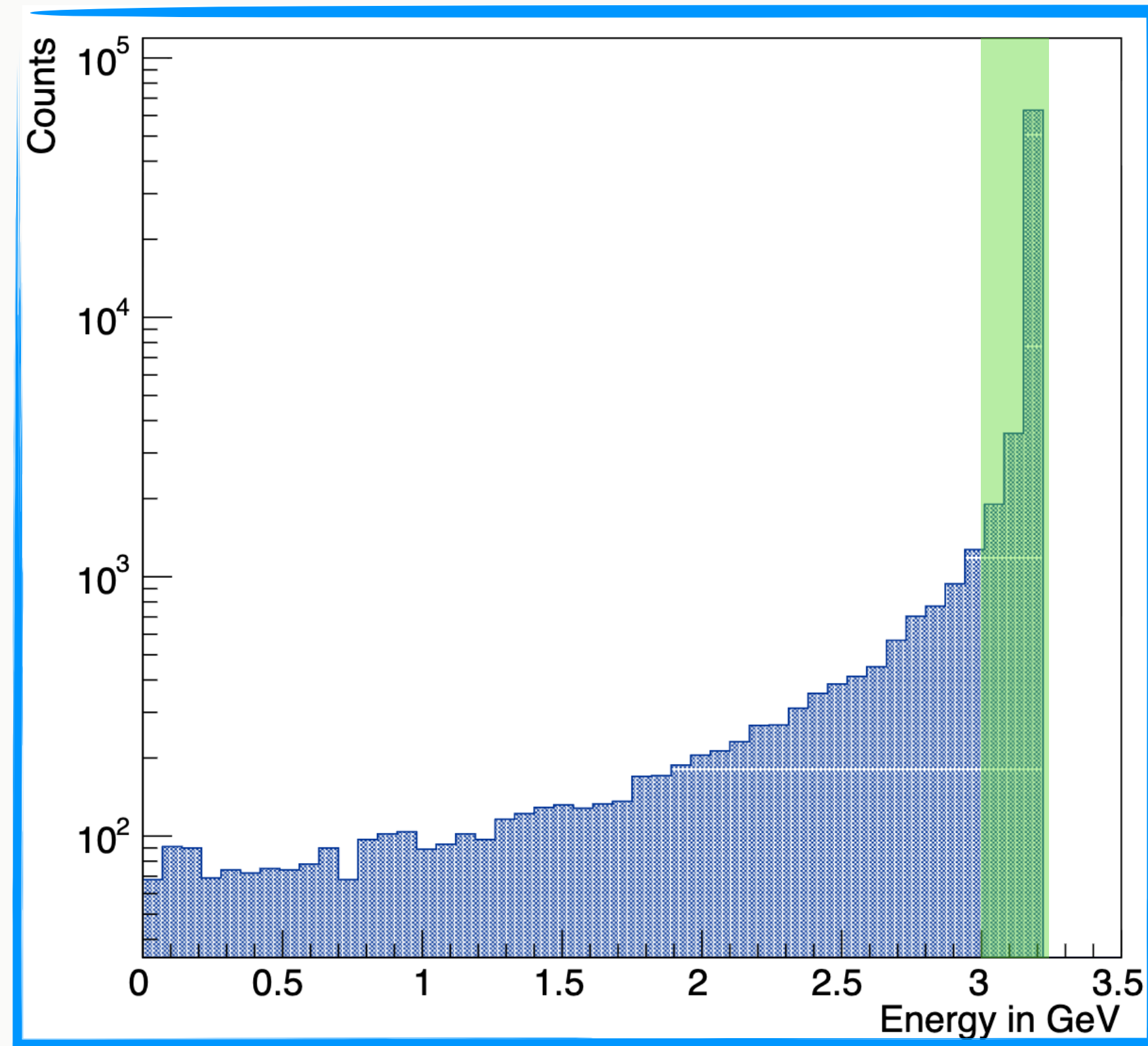


Incoming

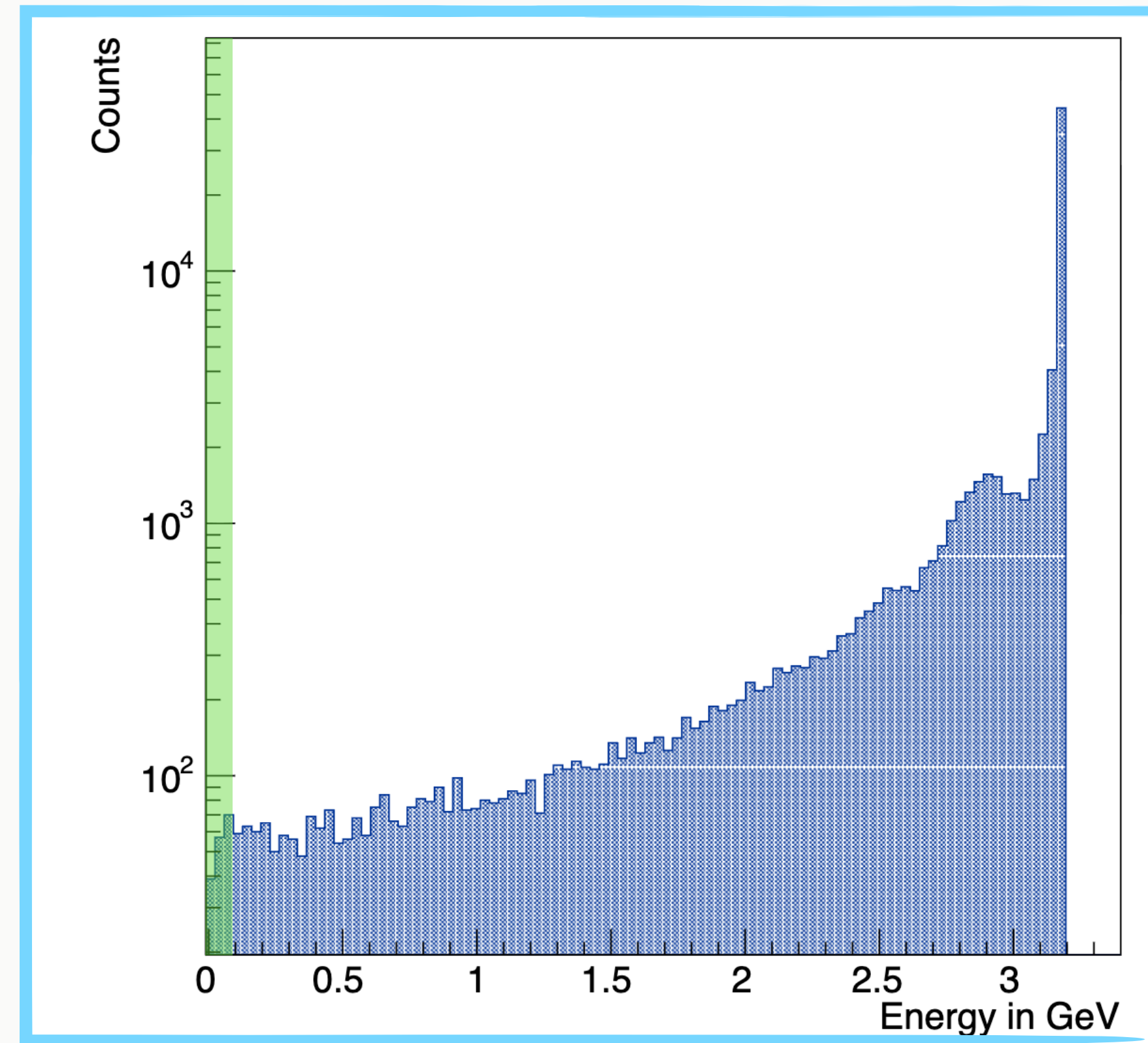


Recoiling

The electron

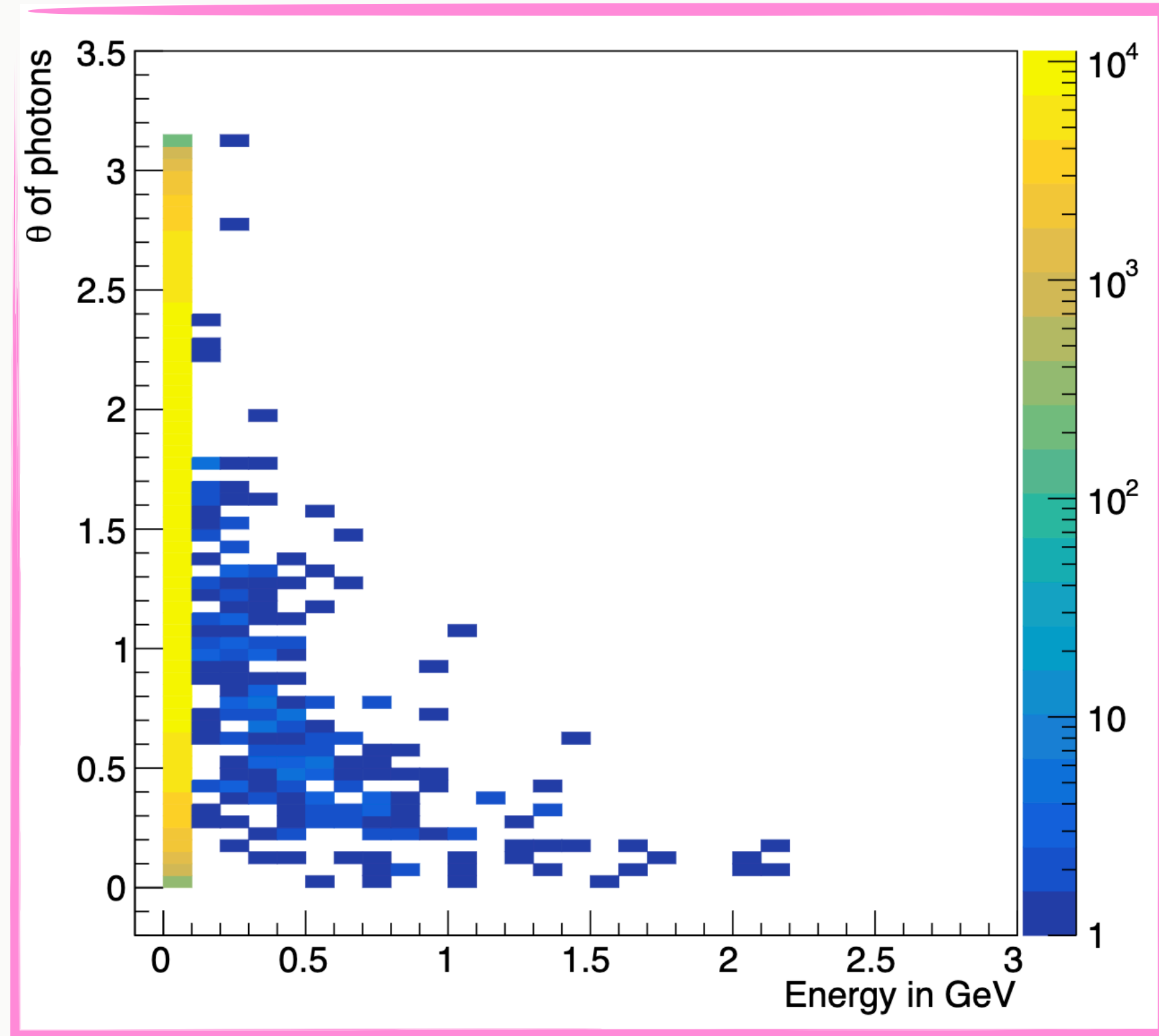


Incoming

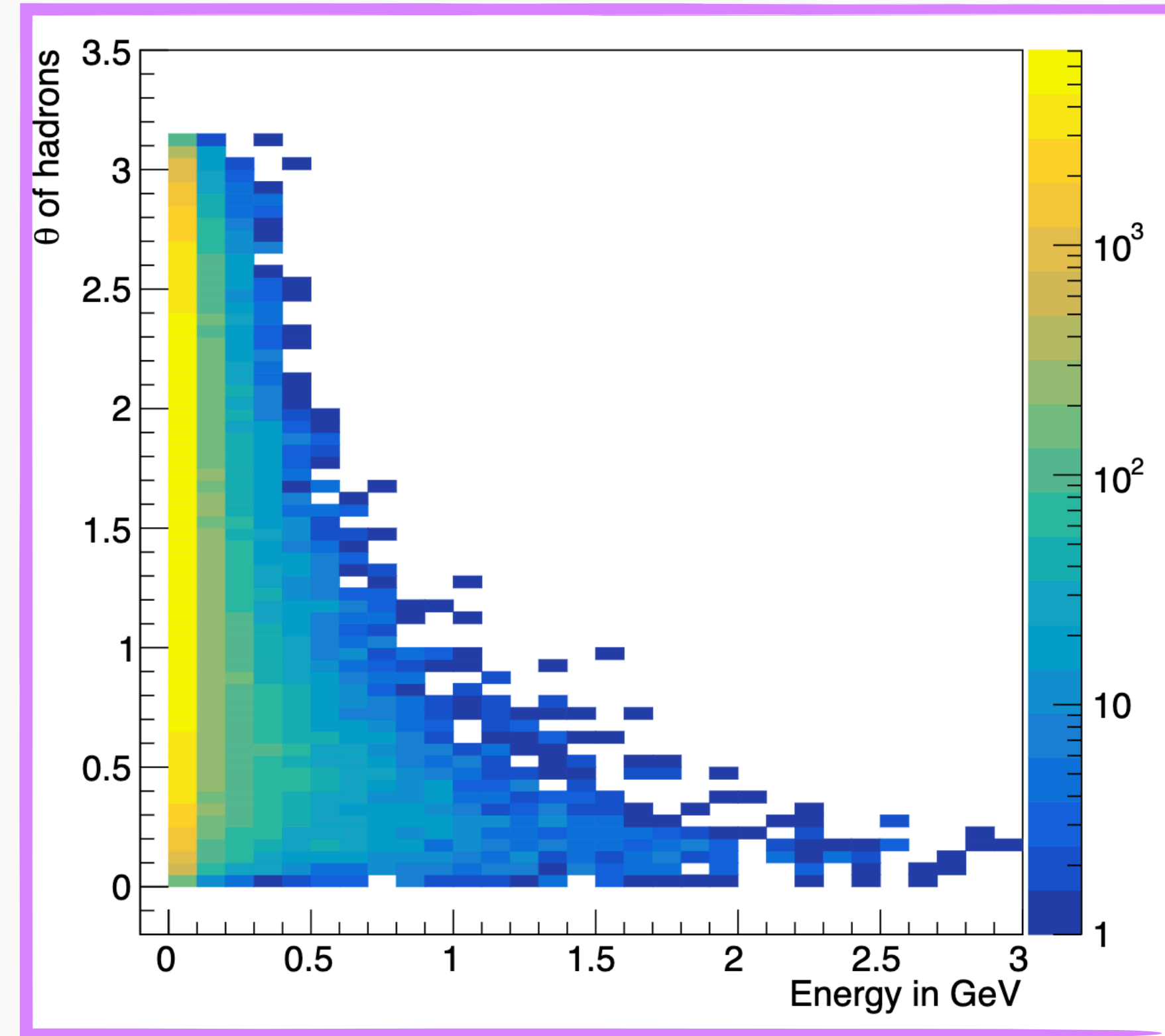


Recoiling

The Secondaries

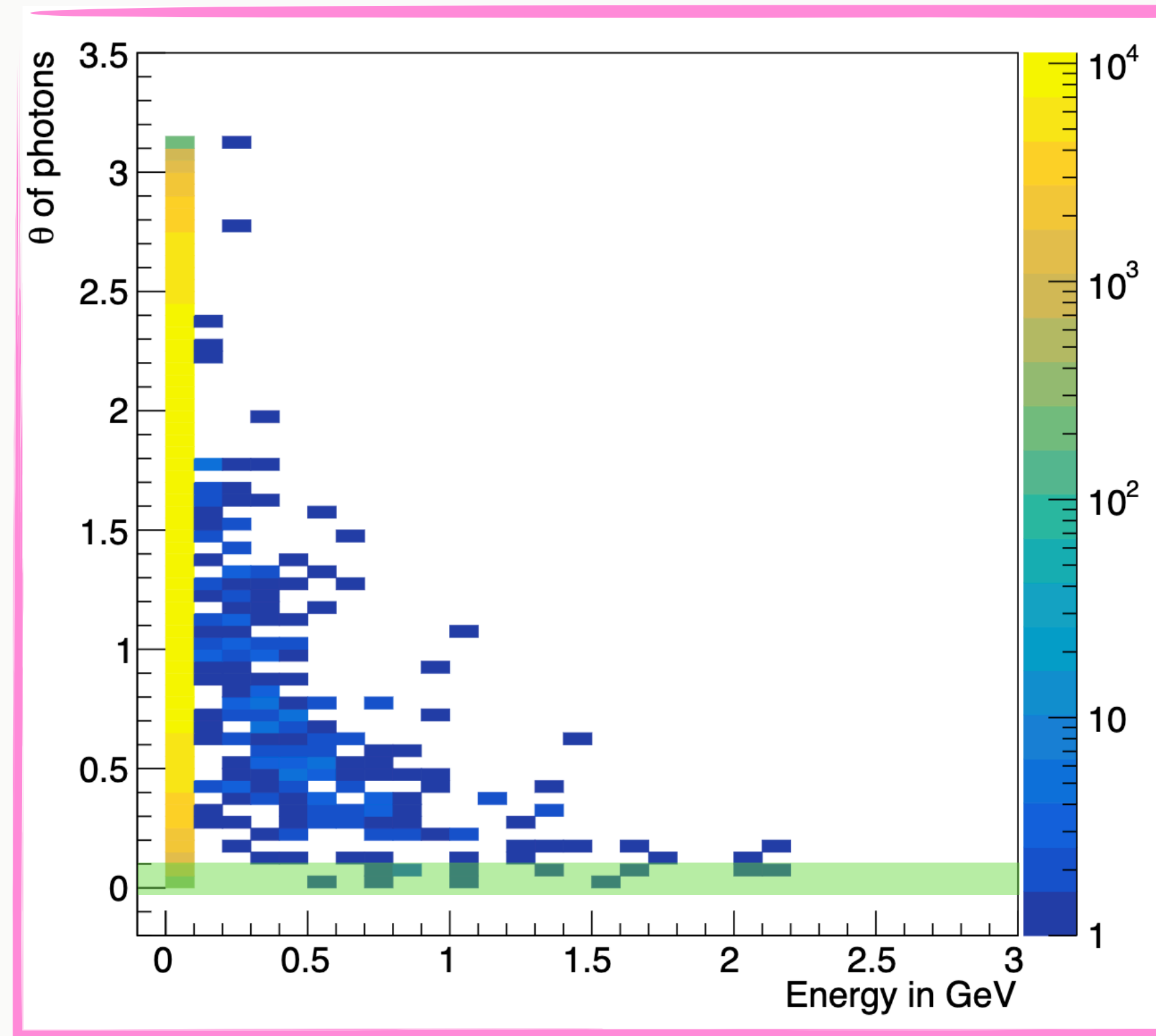


Photons

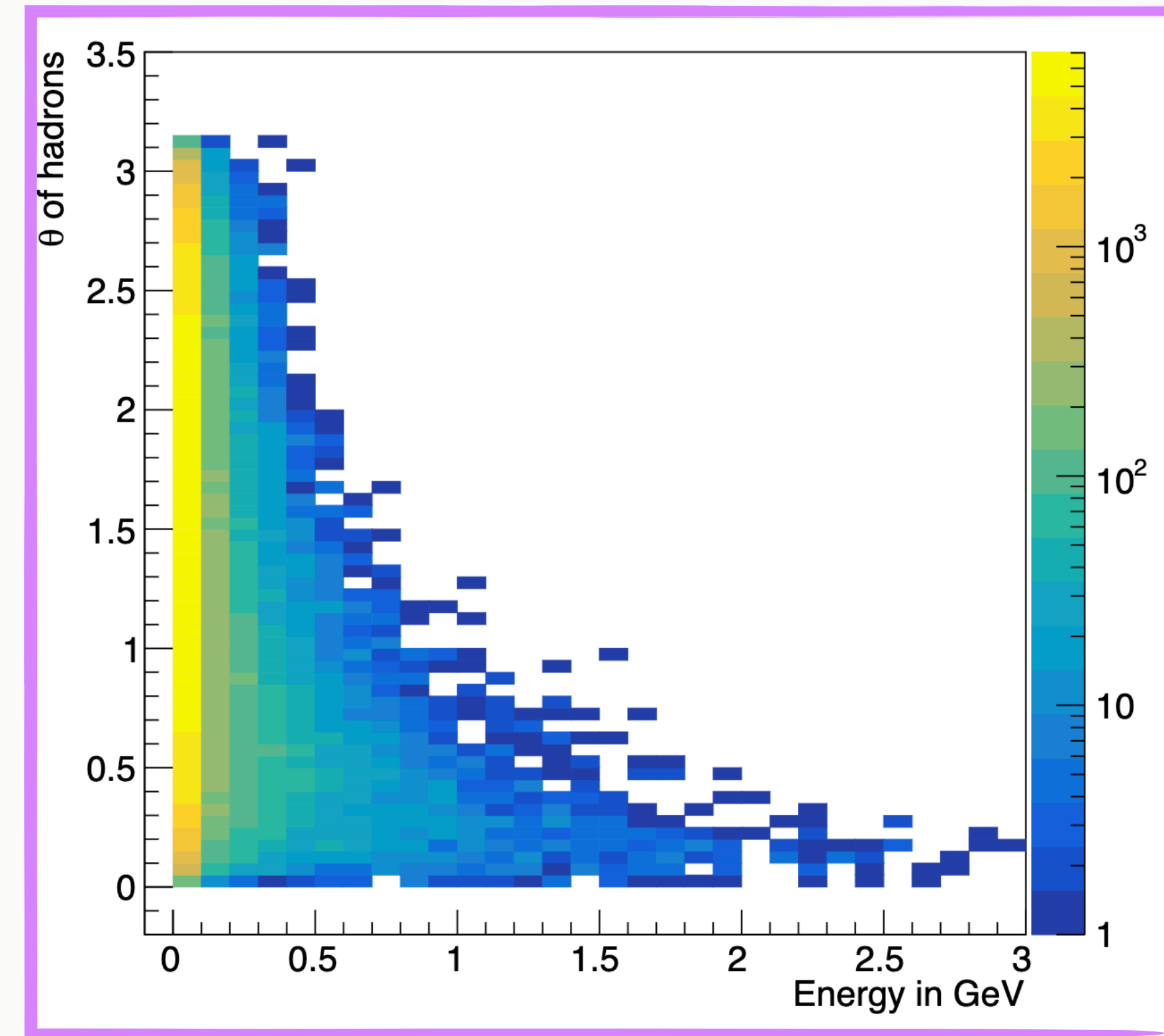


Hadrons

The Secondaries

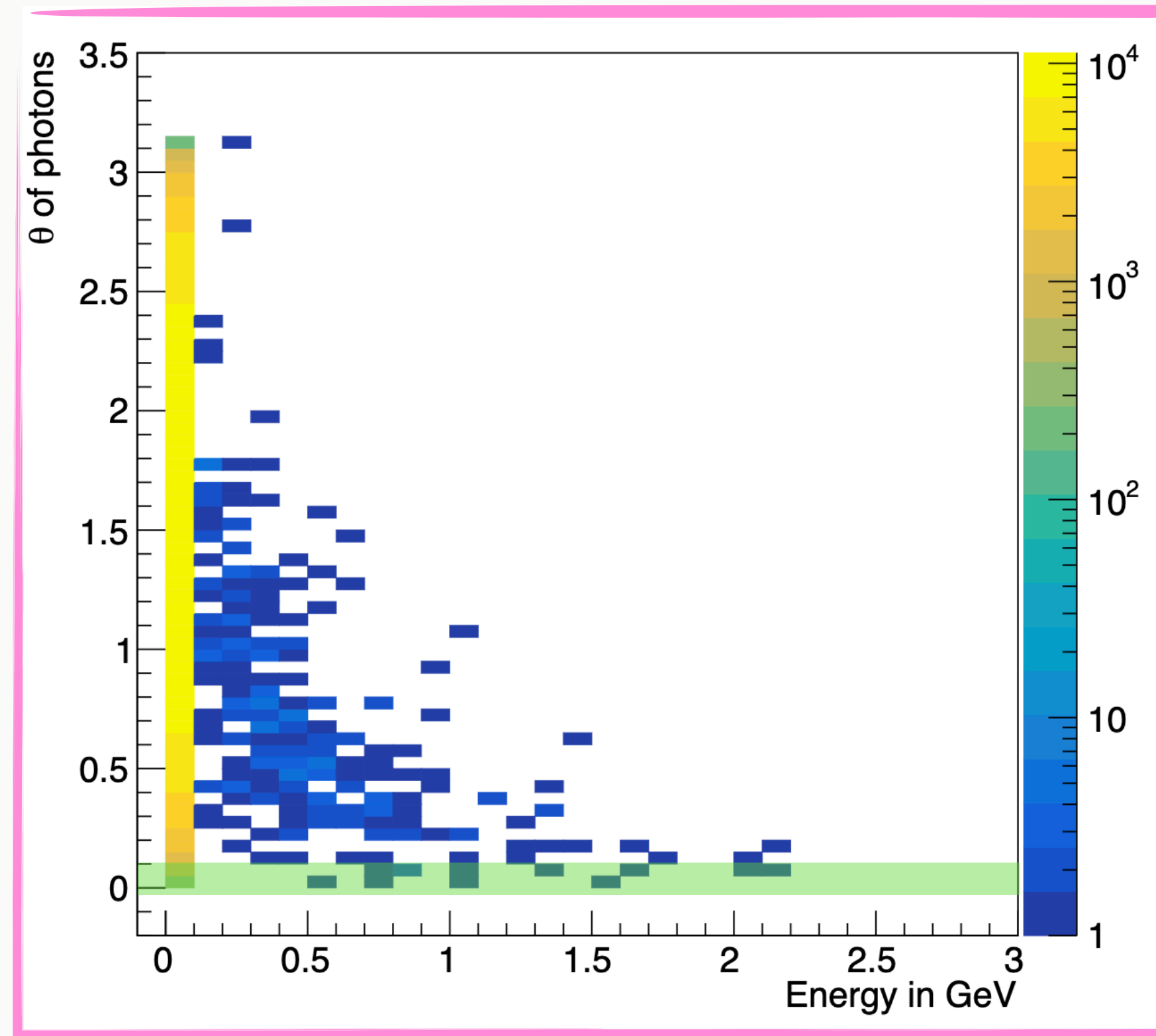


Photons

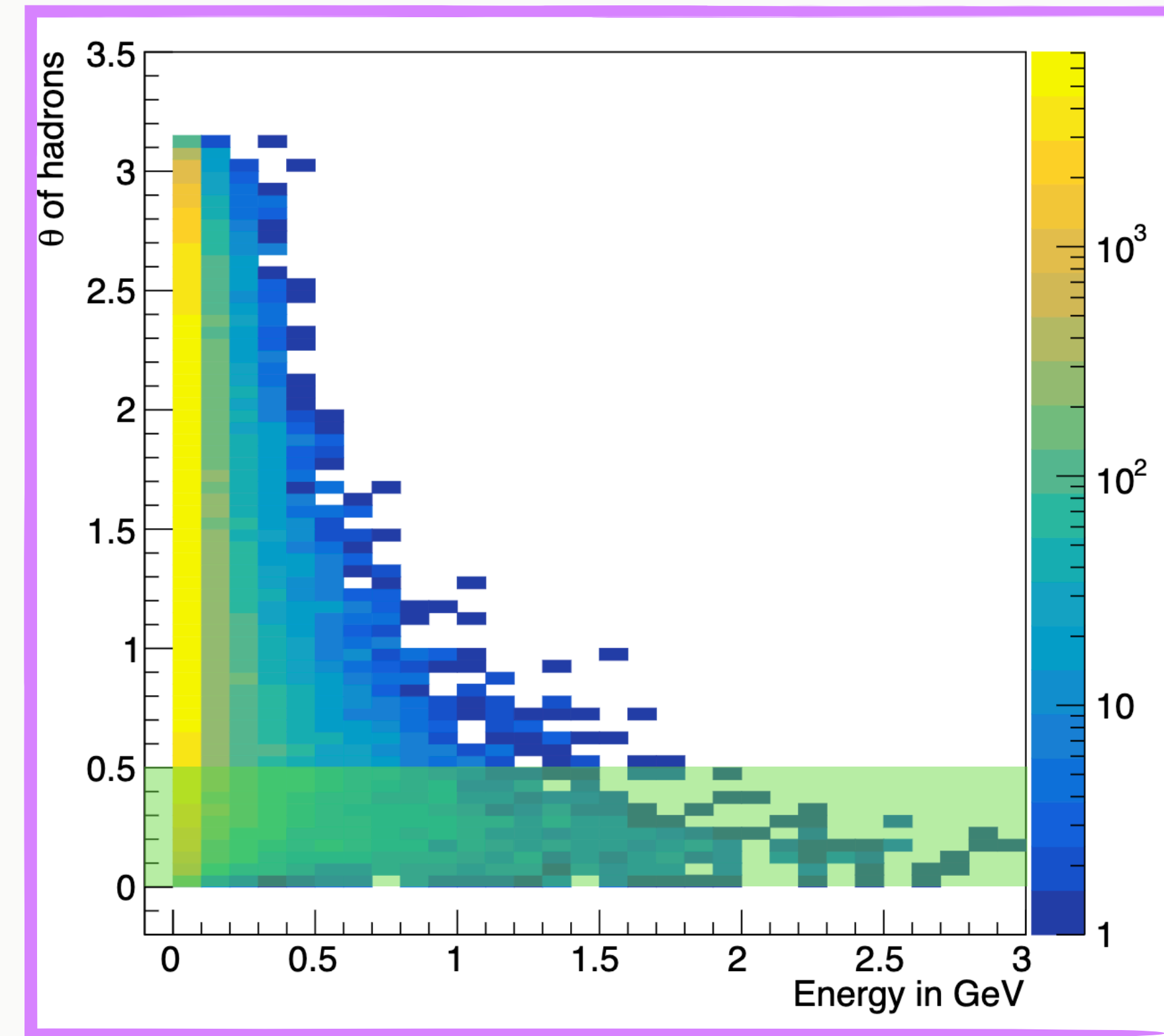


Hadrons

The Secondaries

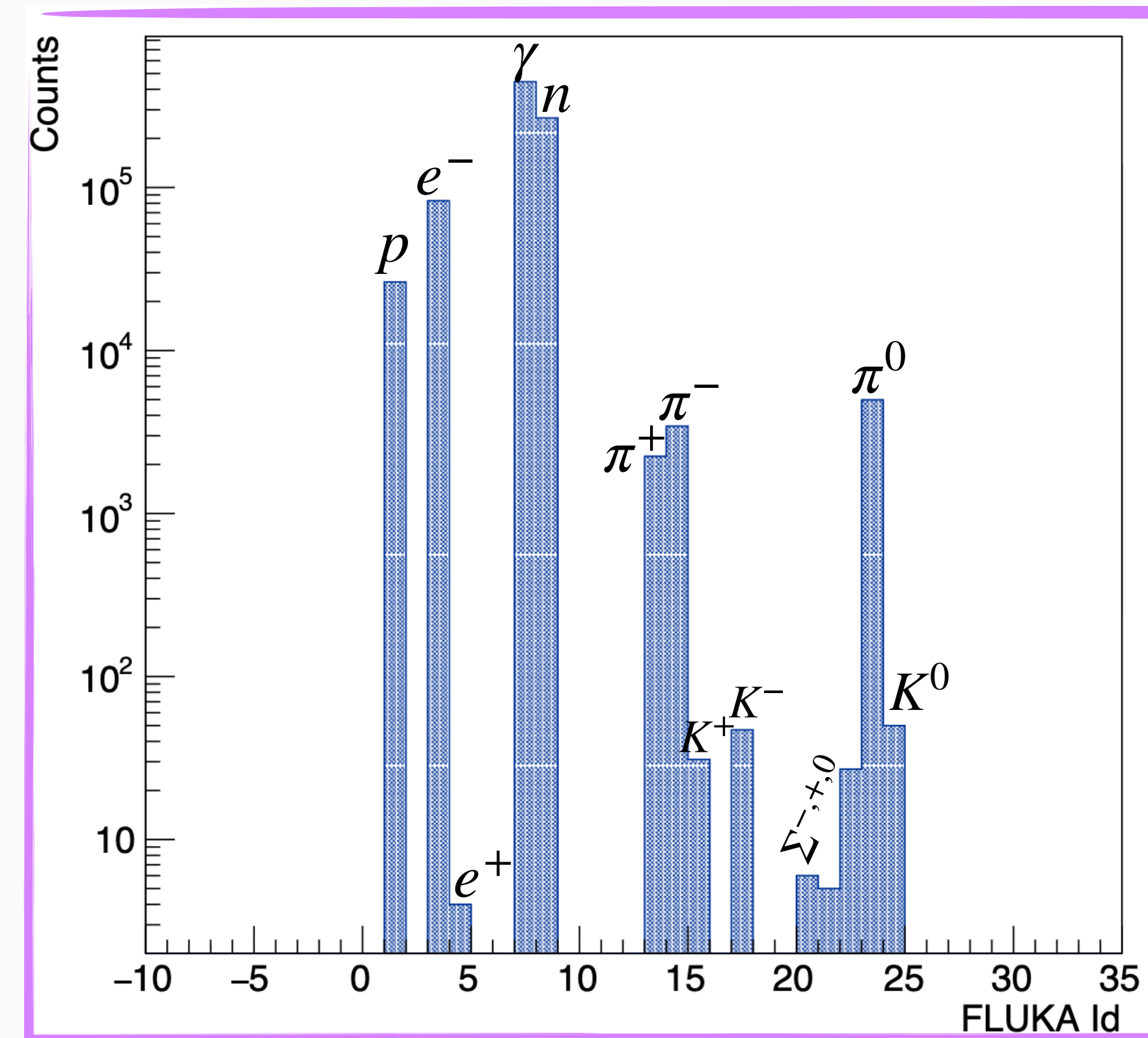
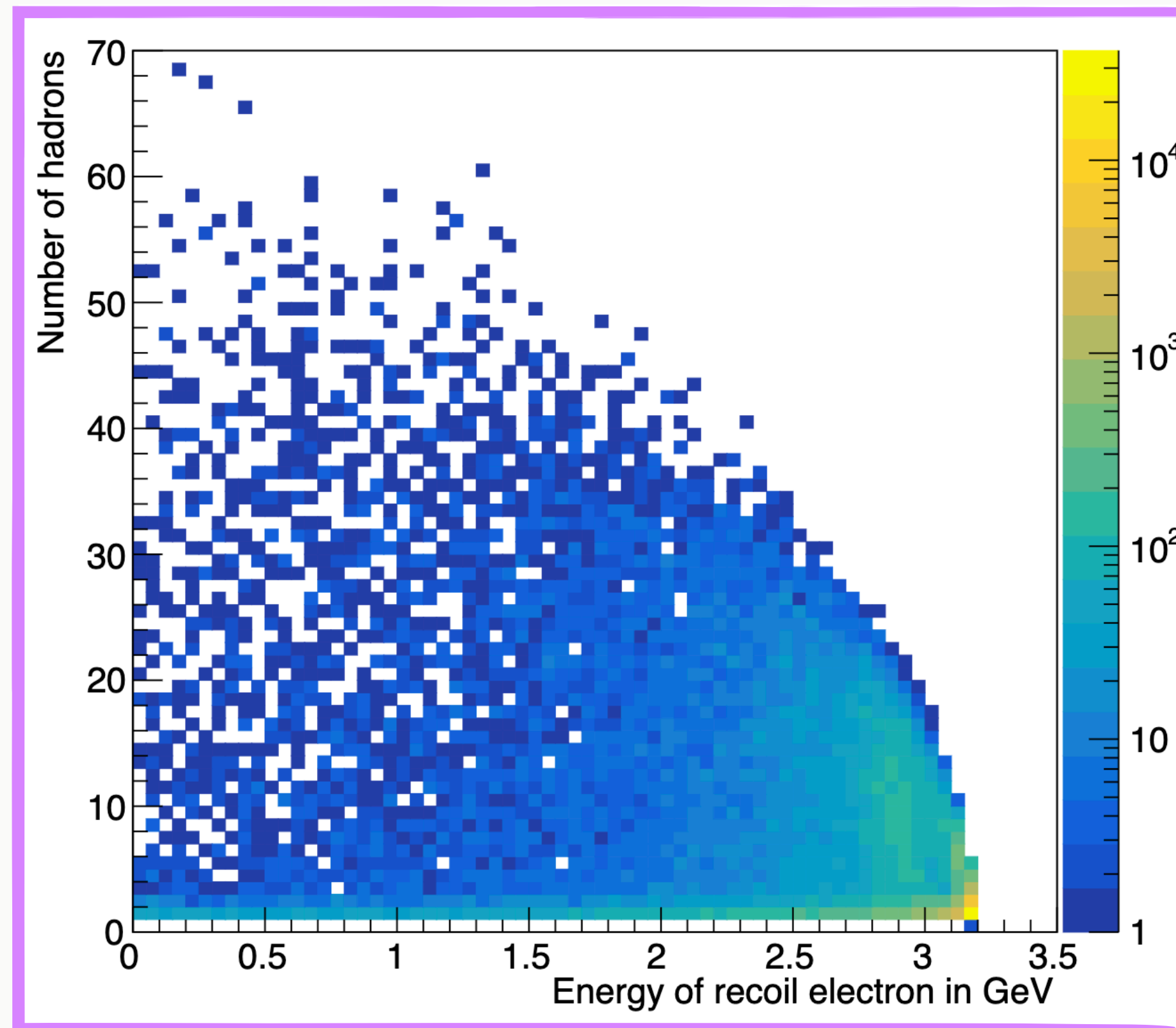


Photons

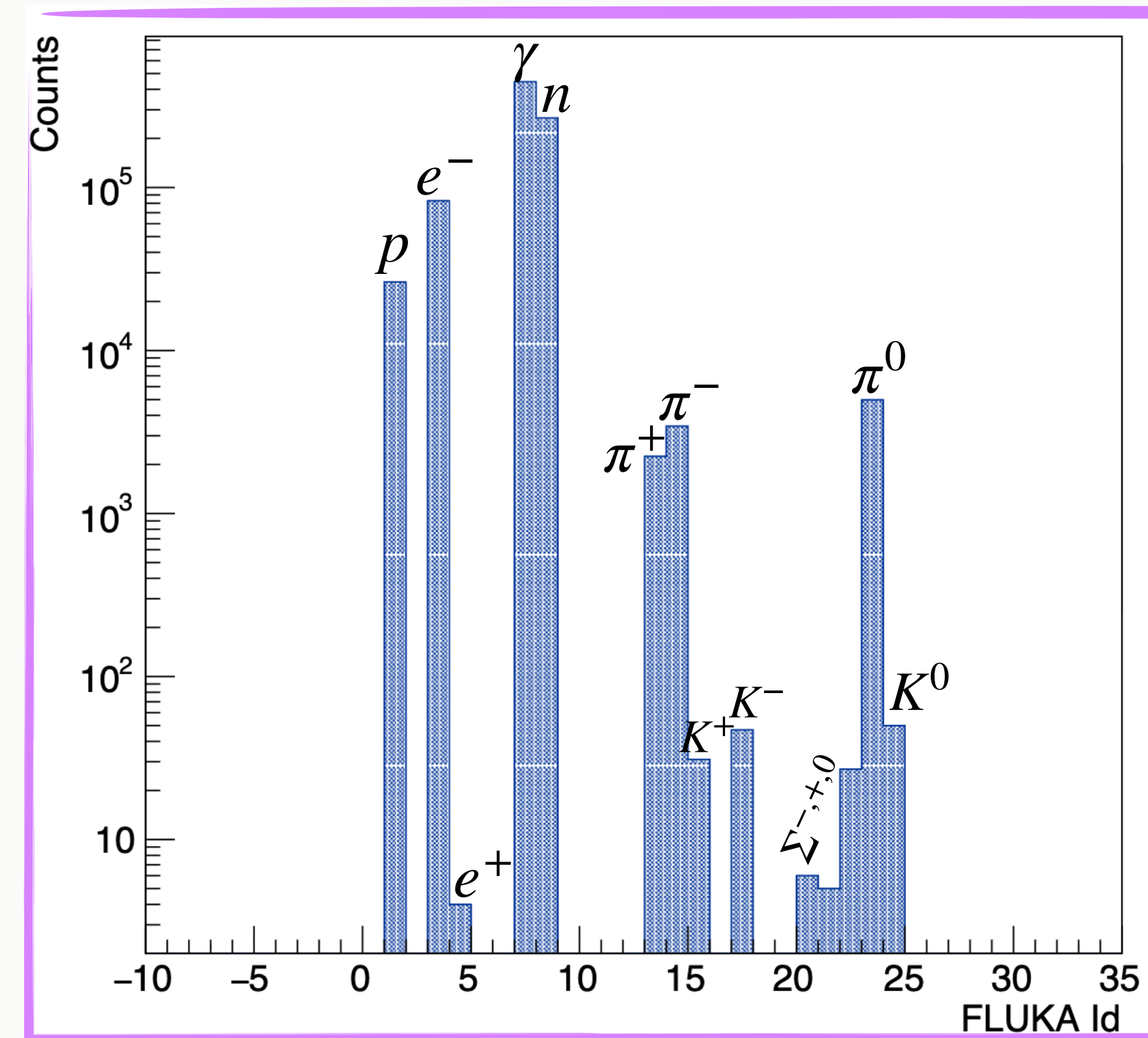
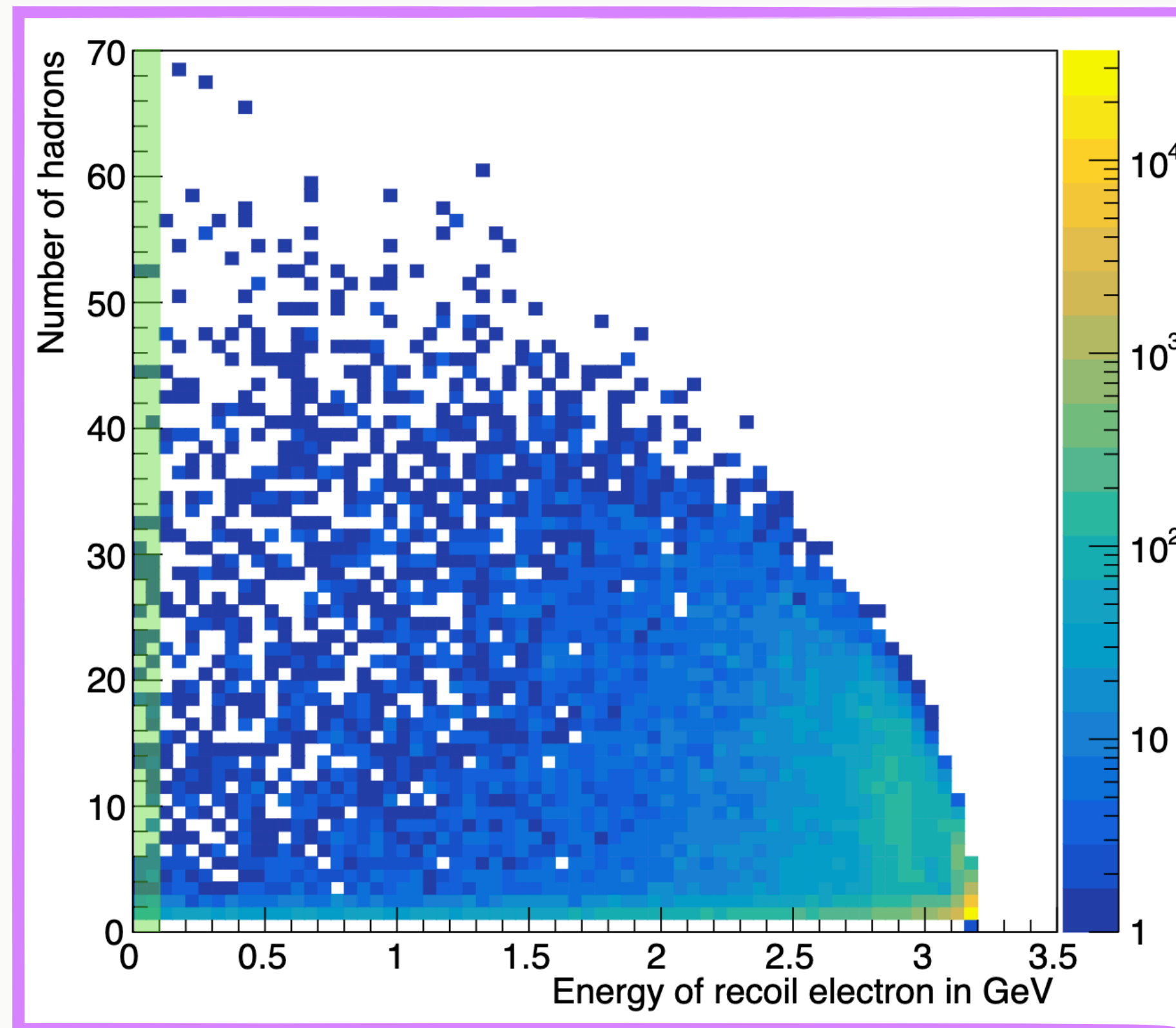


Hadrons

The Secondaries - hadrons



The Secondaries - hadrons



Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

Criteria
$E_{\text{recoil}} < 75 \text{ MeV}$
$\theta_{\text{recoil}} < 0.2 \text{ rad}$
$E_{\text{recoil}} > 25 \text{ MeV}$
$\theta_{\text{had}} < 0.5 \text{ rad}$
$\theta_{\text{photon}} < 0.1 \text{ rad}$
$\theta_{\text{charged had}} < 0.588 \text{ rad}$

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

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$\theta_{\text{charged had}} < 0.588 \text{ rad}$



Recoiling electron in signal region

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

Criteria
$E_{\text{recoil}} < 75 \text{ MeV}$
$\theta_{\text{recoil}} < 0.2 \text{ rad}$
$E_{\text{recoil}} > 25 \text{ MeV}$
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$\theta_{\text{charged had}} < 0.588 \text{ rad}$

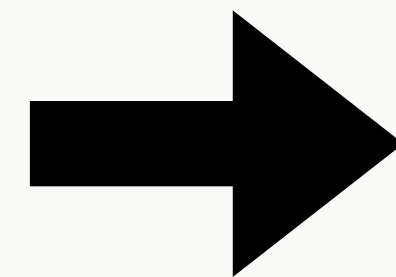
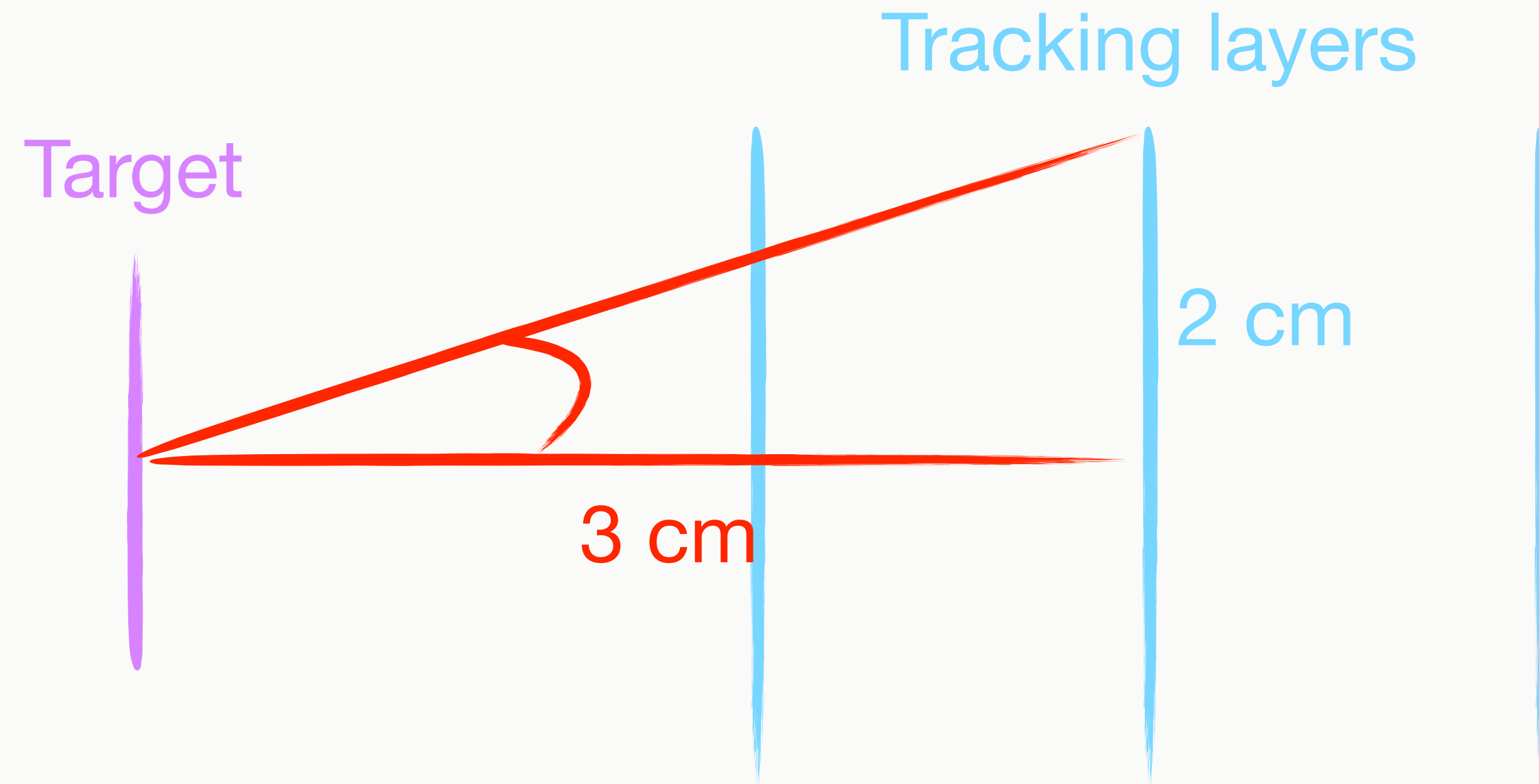


Hadrons in HCal and Photons in ECal

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

Criteria
$E_{\text{recoil}} < 75 \text{ MeV}$
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$E_{\text{recoil}} > 25 \text{ MeV}$
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$\theta_{\text{photon}} < 0.1 \text{ rad}$
$\theta_{\text{charged had}} < 0.588 \text{ rad}$



= 0.588 rad and $E > 25 \text{ MeV}$

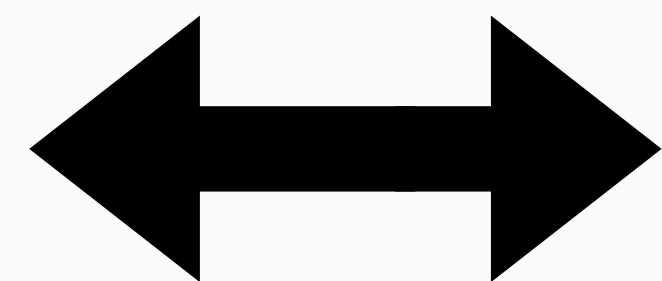


Charged hadrons in at least 2 tracking planes

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

Selection 1
$E_{\text{recoil}} < 75 \text{ MeV}$
$\theta_{\text{recoil}} < 0.2 \text{ rad}$
$E_{\text{recoil}} > 25 \text{ MeV}$
$\theta_{\text{had}} < 0.5 \text{ rad}$
$\theta_{\text{photon}} < 0.1 \text{ rad}$
$\theta_{\text{charged had}} < 0.588 \text{ rad}$



Selection 2
$E_{\text{recoil}} < 75 \text{ MeV}$
$\theta_{\text{recoil}} < 0.2 \text{ rad}$
$E_{\text{recoil}} > 25 \text{ MeV}$
$\theta_{\text{had}} < 0.1 \text{ rad}$
$\theta_{\text{photon}} < 0.1 \text{ rad}$
$\theta_{\text{charged had}} < 0.588 \text{ rad}$



Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

Scenario	# signal-like events	# hadrons	# photons
1	165	3620	825
2 	3062	66385	13660

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

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1	165	3620	825
2 	3062	66385	13660

$O(10^2 - 10^3)$ for $2.5 \cdot 10^{12}$ e.o.t.

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

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Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

Scenario		# photons
1		825
2 		13660

$O(10^4 - 10^5)$ for $4 \cdot 10^{14}$ e.o.t.

$O(10^2 - 10^3)$ for $2.5 \cdot 10^{12}$ e.o.t.



Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

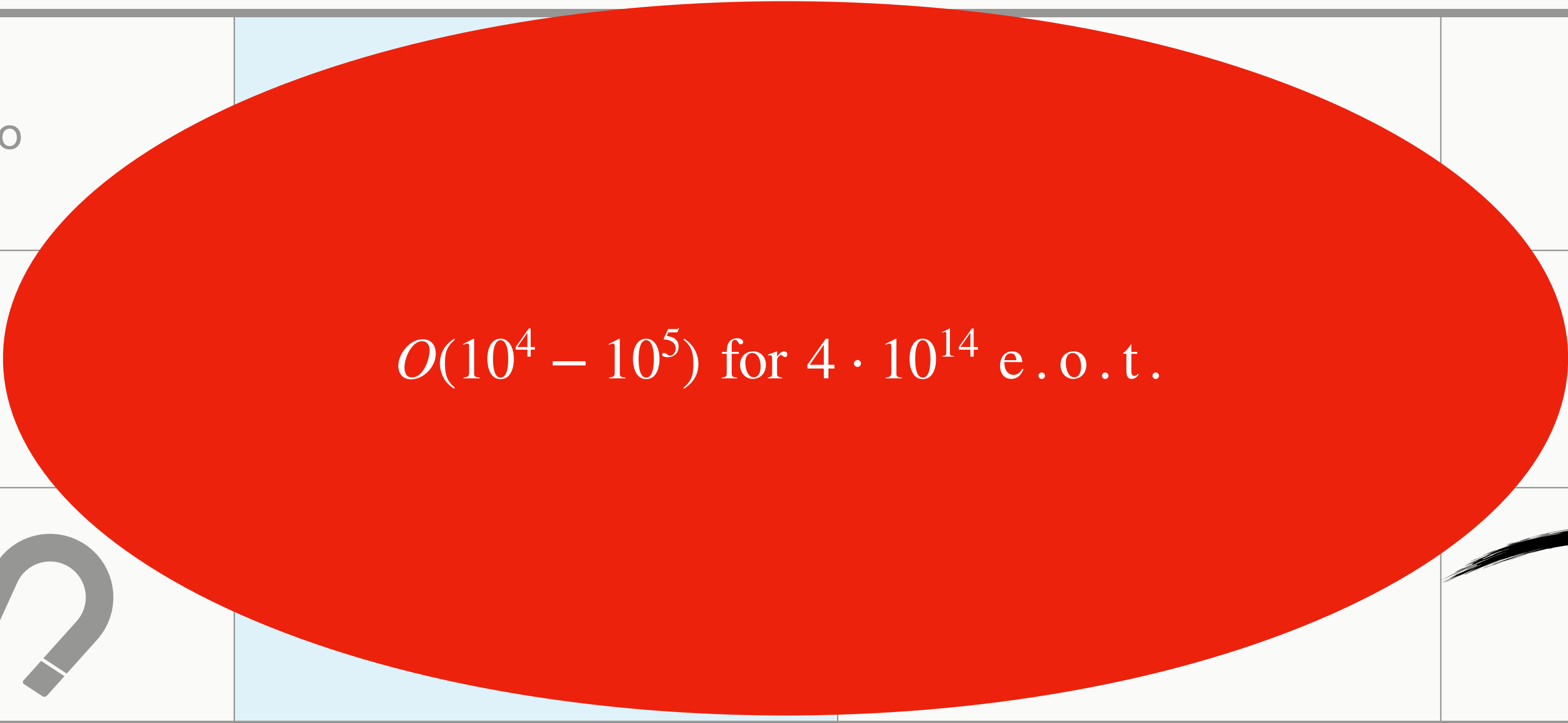
Scenario		# photons
1		825
2 		13660

$O(10^4 - 10^5)$ for $4 \cdot 10^{14}$ e.o.t.

$O(10^2 - 10^3)$ for $2.5 \cdot 10^{12}$ e.o.t.

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

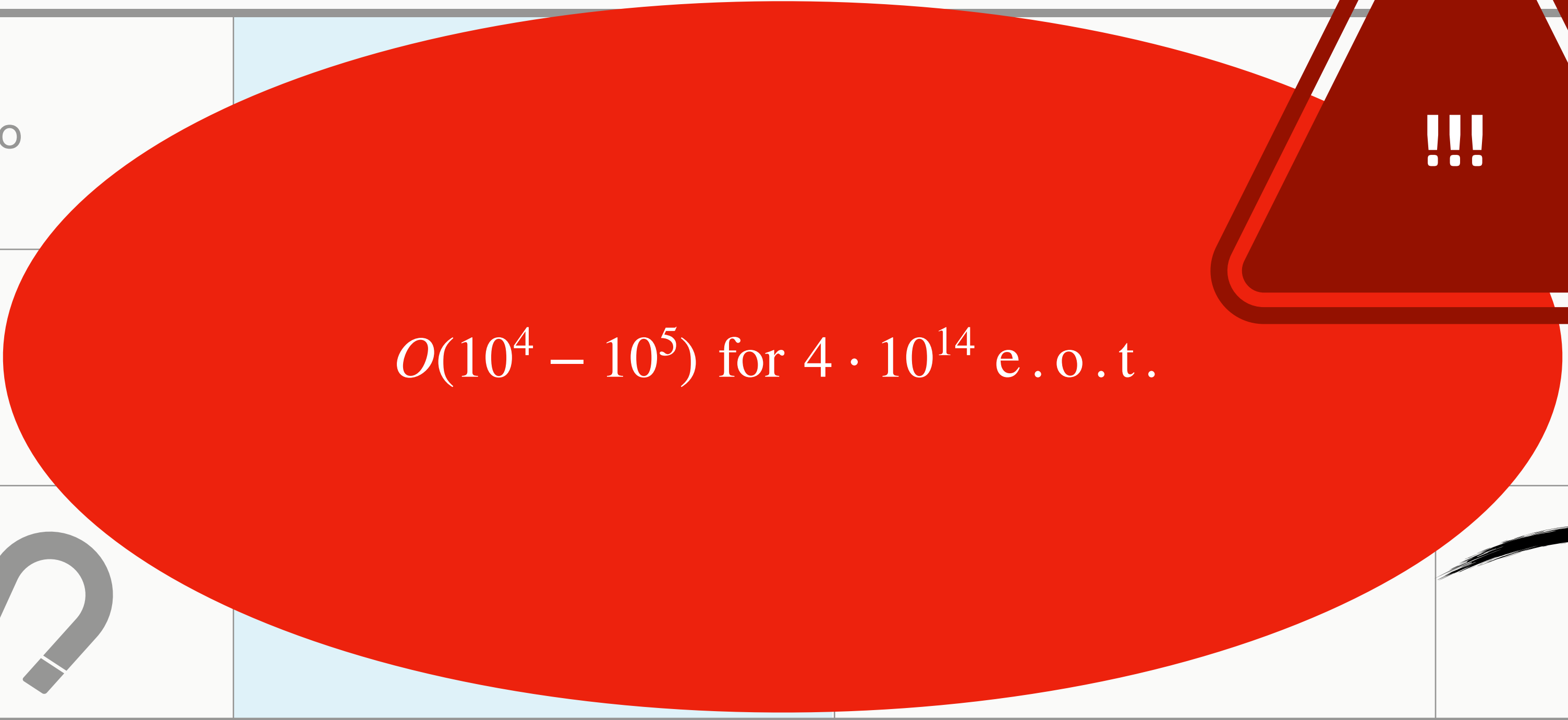
Scenario		# photons
1		825
2 		13660

$O(10^2 - 10^3)$ for $2.5 \cdot 10^{12}$ e.o.t.

1 – 100 signal events

Event Selection

- Take data set with $2.5 \cdot 10^{12}$ e.o.t.

Scenario		# photons
1		825
2 		13660

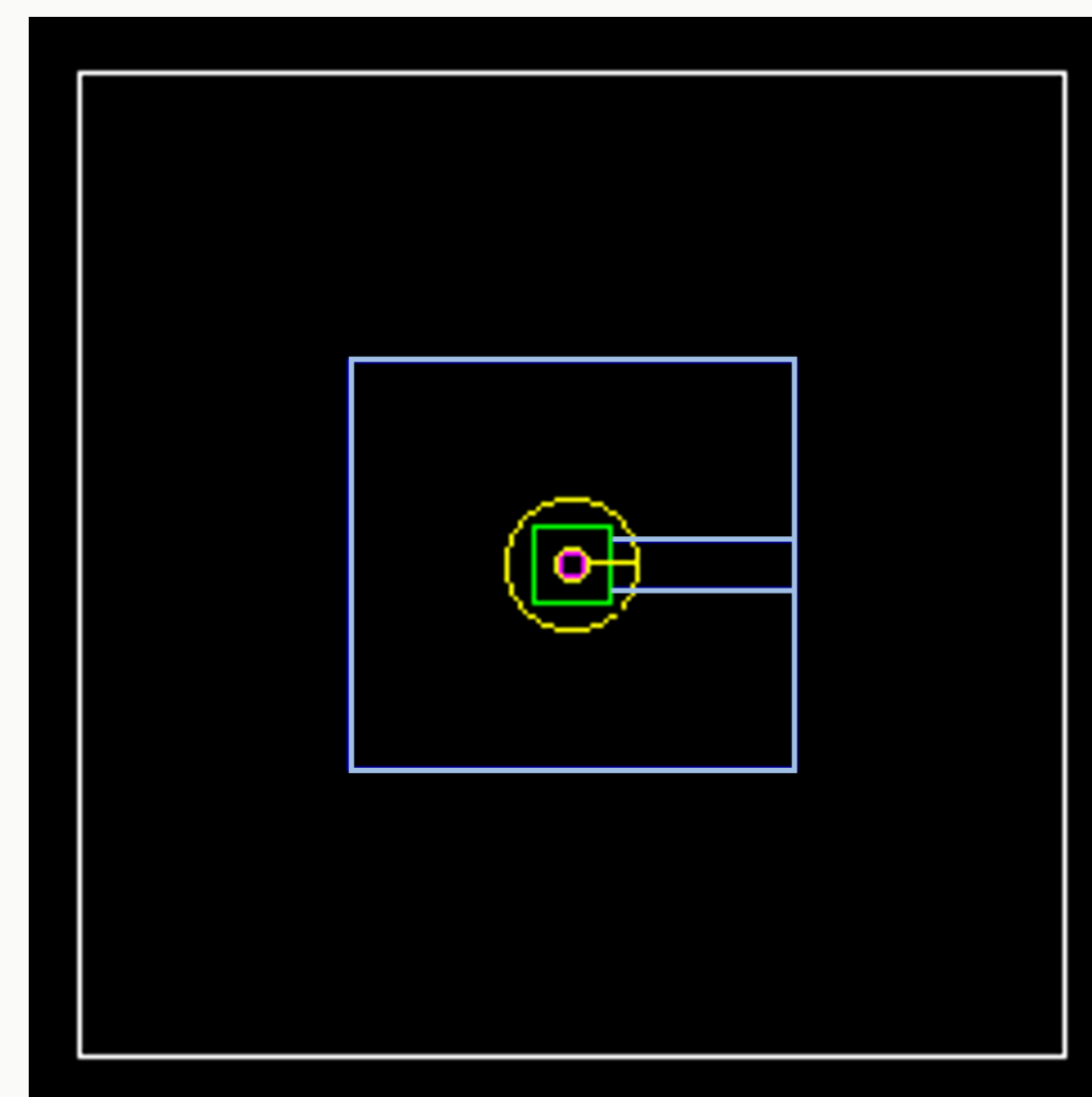


$O(10^2 - 10^3)$ for $2.5 \cdot 10^{12}$ e.o.t.

1 – 100 signal events

FLUKA Events in GEANT4

- Previously: only hard electro-nuclear interaction
- No particle transport, no magnetic field, no detector response, etc.
- Ideally: use PERCEVAL (coming soon!)
- For now: read FLUKA data into G4 geometry



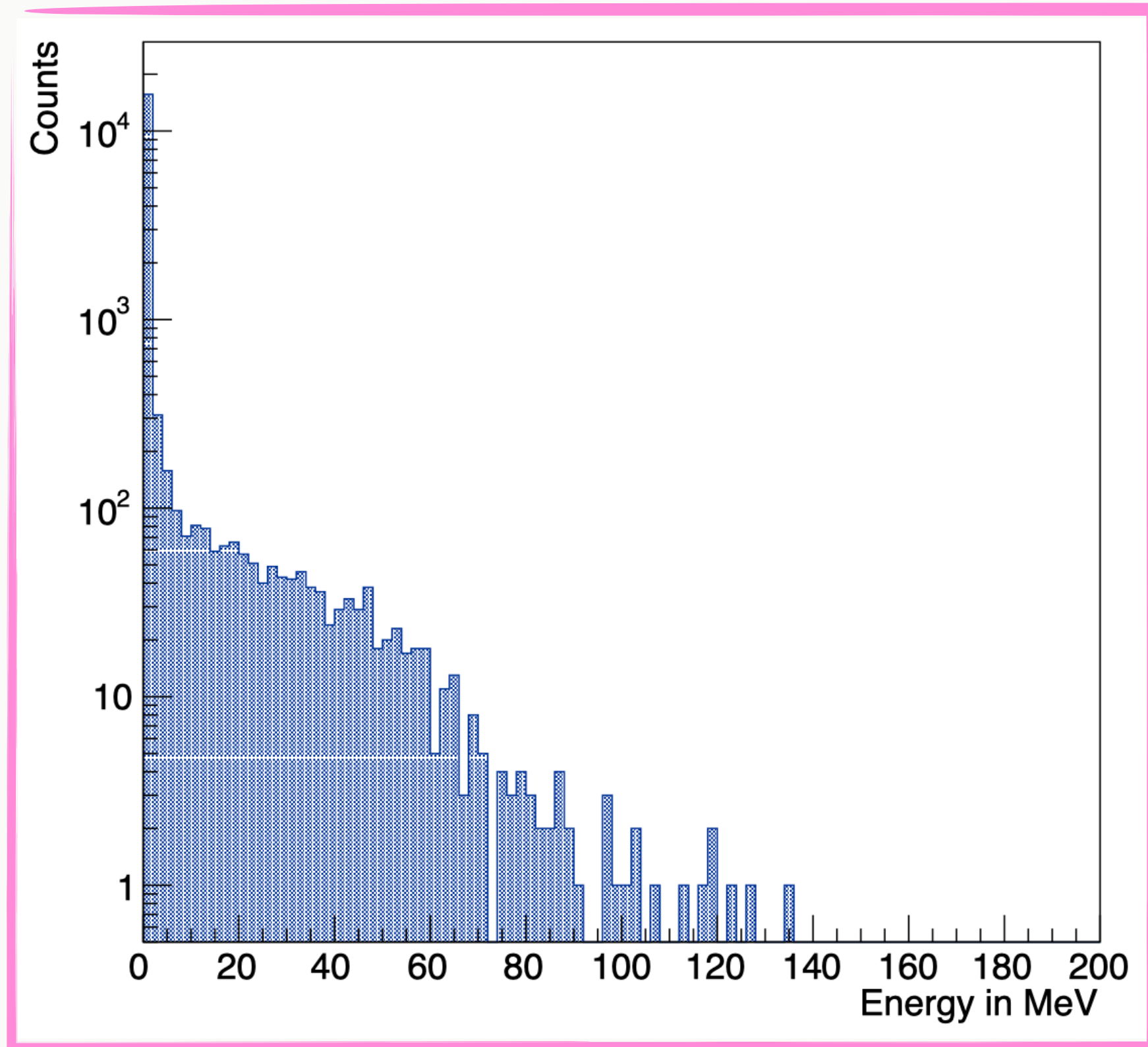
Energy deposited



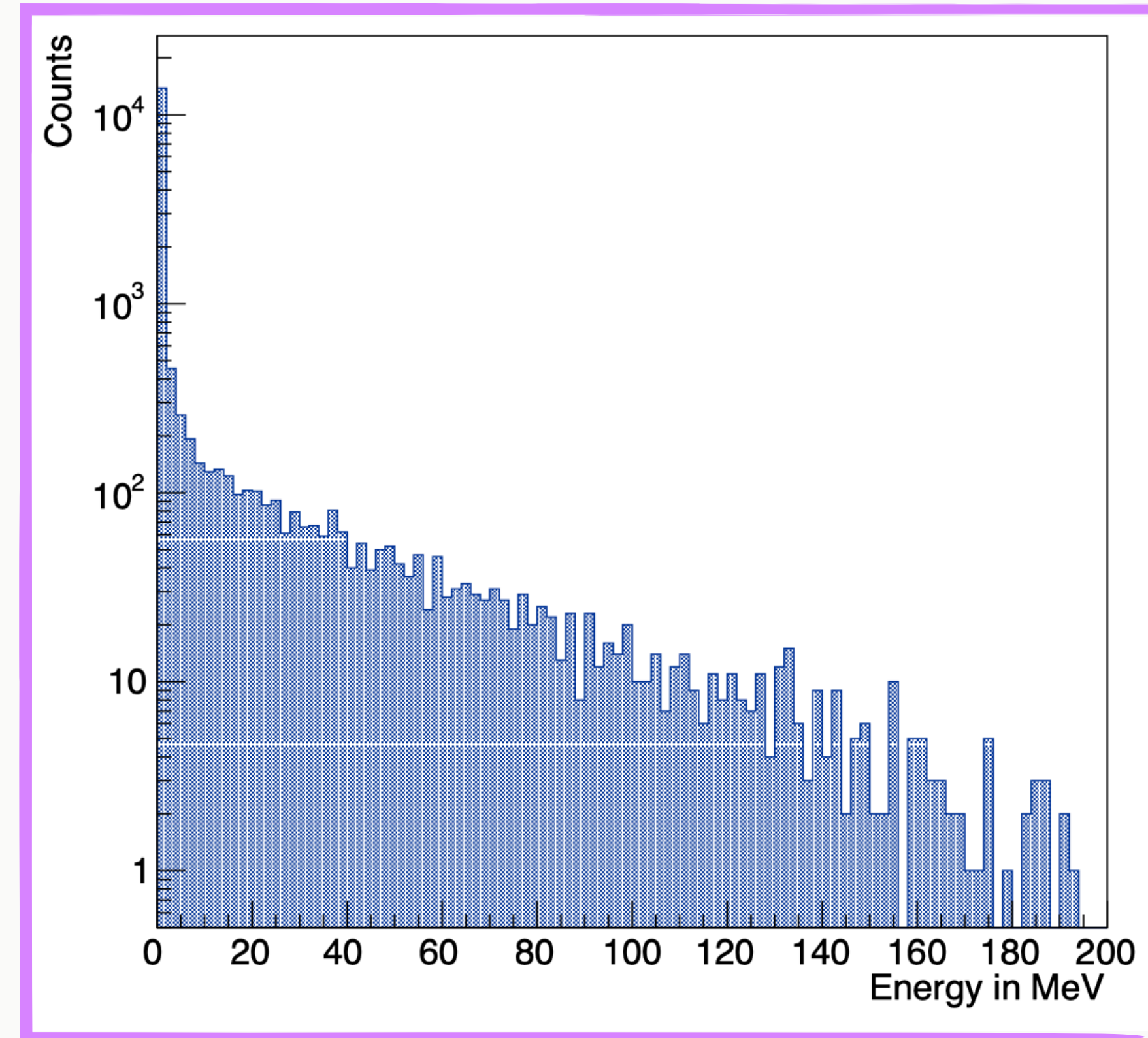
GEANT4
A SIMULATION TOOLKIT



FLUKA



ECal



HCal

Energy deposited



Energy deposited in ECal	Energy deposited in HCal	Vetoed events
30 MeV	20 MeV	2312
20 MeV	15 MeV	2708
20 MeV	10 MeV	2986
20 MeV	1 MeV	4113
1 MeV	1 MeV	4569
> 0 MeV	> 0 MeV	5526

Total of 17394 events

Energy deposited



Energy deposited in ECal	Energy deposited in HCal	Vetoed events
30 MeV	20 MeV	2312
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20 MeV	10 MeV	2986
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11868 for $2.5 \cdot 10^{12}$ e.o.t.

Total of 17394 events

Energy deposited



GEANT4
A SIMULATION TOOLKIT



FLUKA

Energy deposited in ECal	Energy deposited in HCal	Vetoed events
30 MeV	20 MeV	2312
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11868 for $2.5 \cdot 10^{12}$ e.o.t.

Total of 17394 events

Energy deposited



Energy deposited in ECal	Energy deposited in HCal	Vetoed events
30 MeV		2312
20 MeV		2708
20 MeV		2986
20 MeV		4113
1 MeV		4569
> 0 MeV	> 0 MeV	5526

$1.9 \cdot 10^6$ for $4 \cdot 10^{14}$ e.o.t.

11868 for $2.5 \cdot 10^{12}$ e.o.t.

Total of 17394 events

Energy deposited



Energy deposited in ECal	Energy deposited in HCal	Vetoed events
30 MeV		2312
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$1.9 \cdot 10^6$ for $4 \cdot 10^{14}$ e.o.t.

11868 for $2.5 \cdot 10^{12}$ e.o.t.

Total of 17394 events

Energy deposited



Energy deposited in ECal	Energy deposited in HCal	Vetoed events
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20 MeV		2708
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$1.9 \cdot 10^6$ for $4 \cdot 10^{14}$ e.o.t.

11868 for $2.5 \cdot 10^{12}$ e.o.t.

Total of 17394 events

1 – 100 signal events

Energy deposited



Energy deposited in ECal	Energy deposited in HCal	Number of events
30 MeV		2312
20 MeV		2086
20 MeV		2986
20 MeV		4113
1 MeV		4569
> 0 MeV	> 0 MeV	5526

$1.9 \cdot 10^6$ for $4 \cdot 10^{14}$ e.o.t.

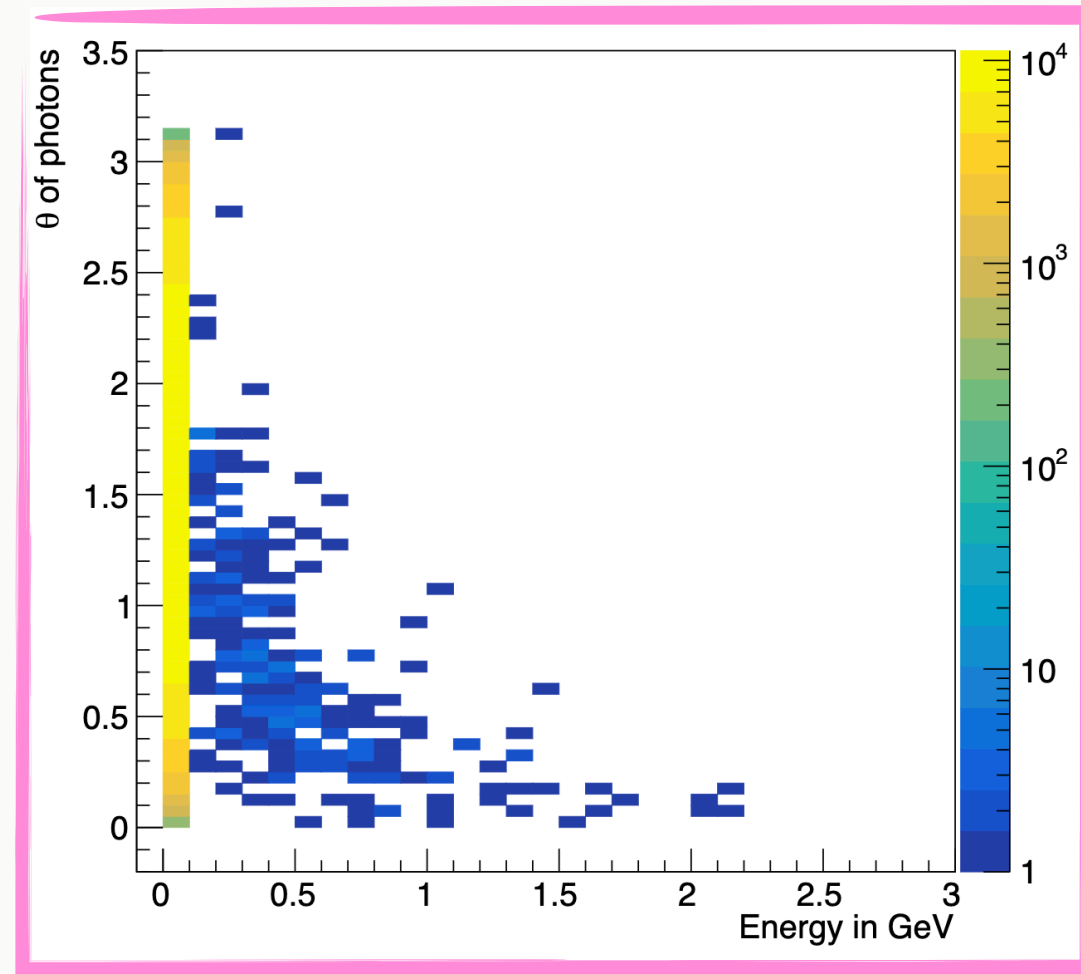


11868 for $2.5 \cdot 10^{12}$ e.o.t.

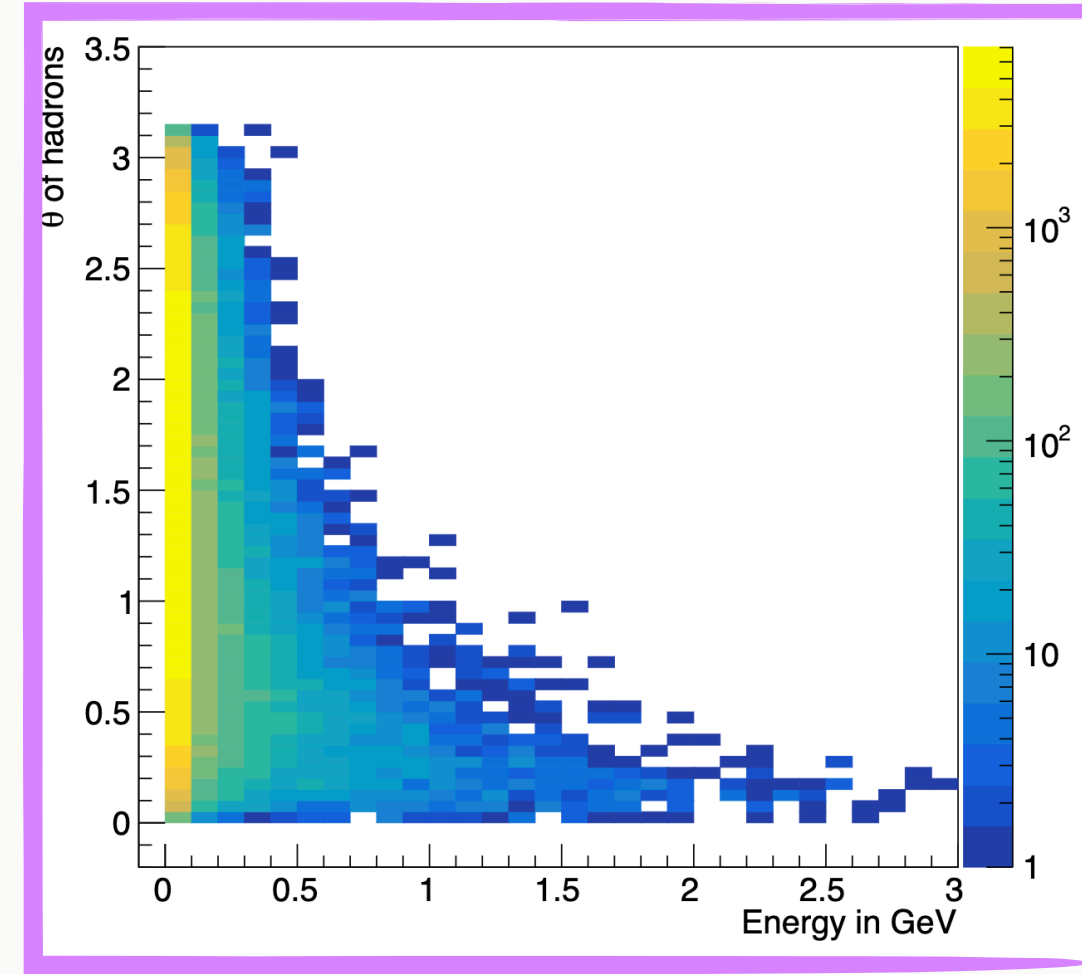
Total of 17394 events

1 – 100 signal events

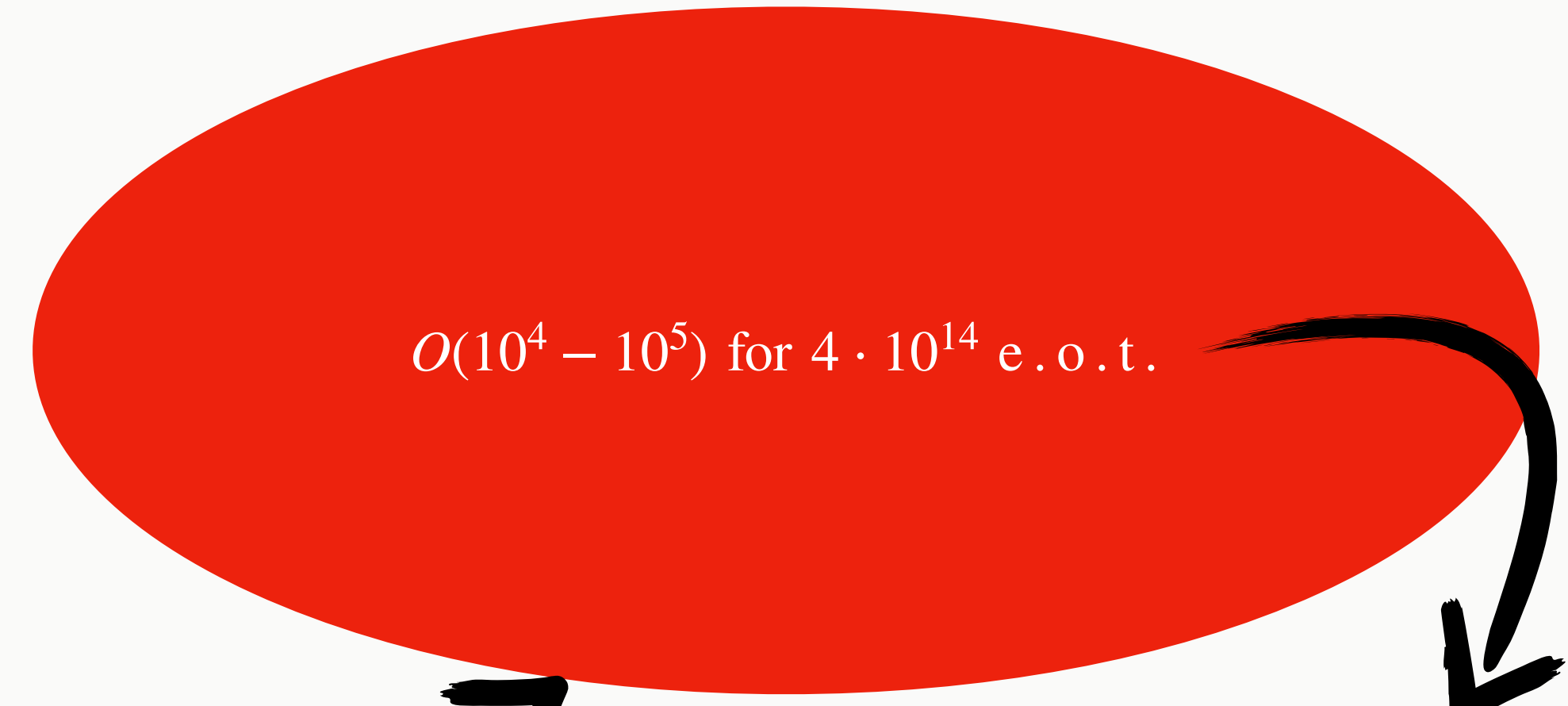
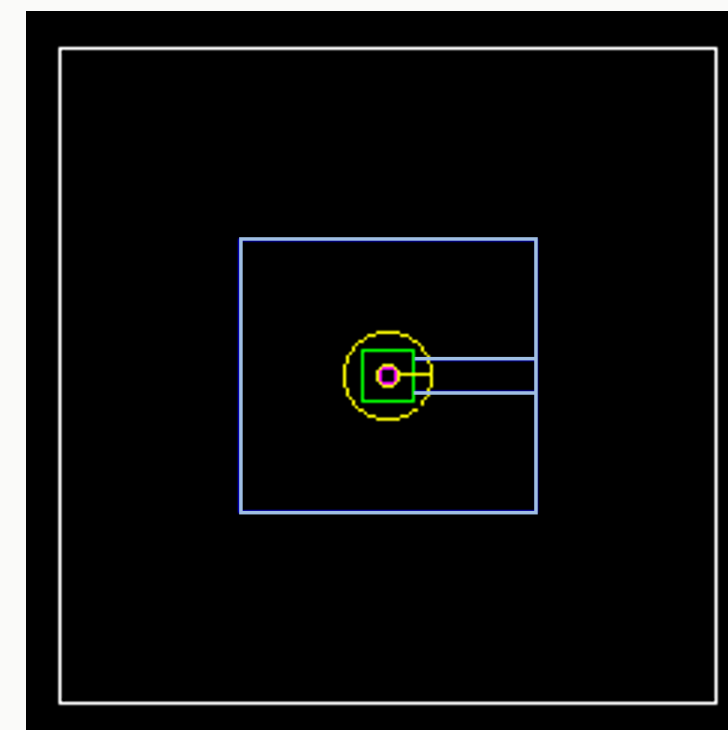
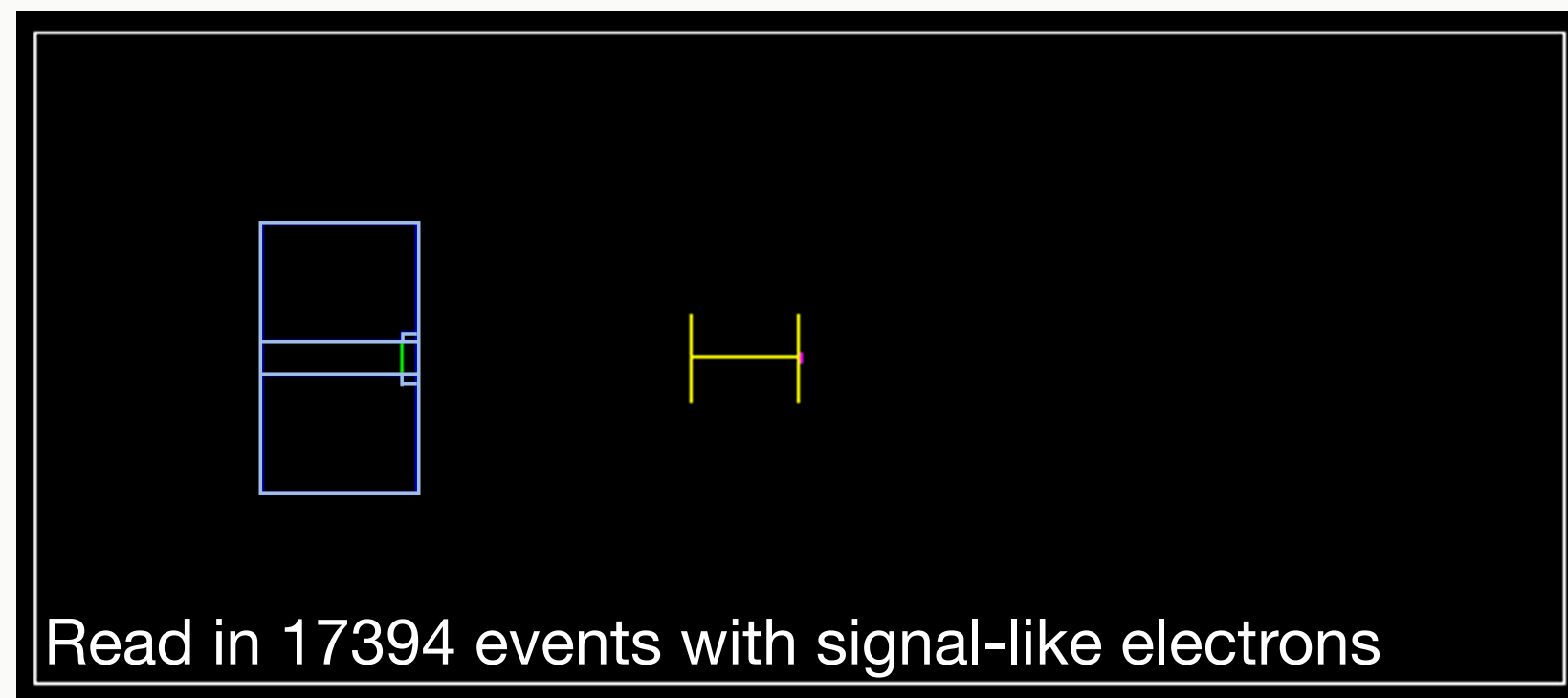
Summary



Photons

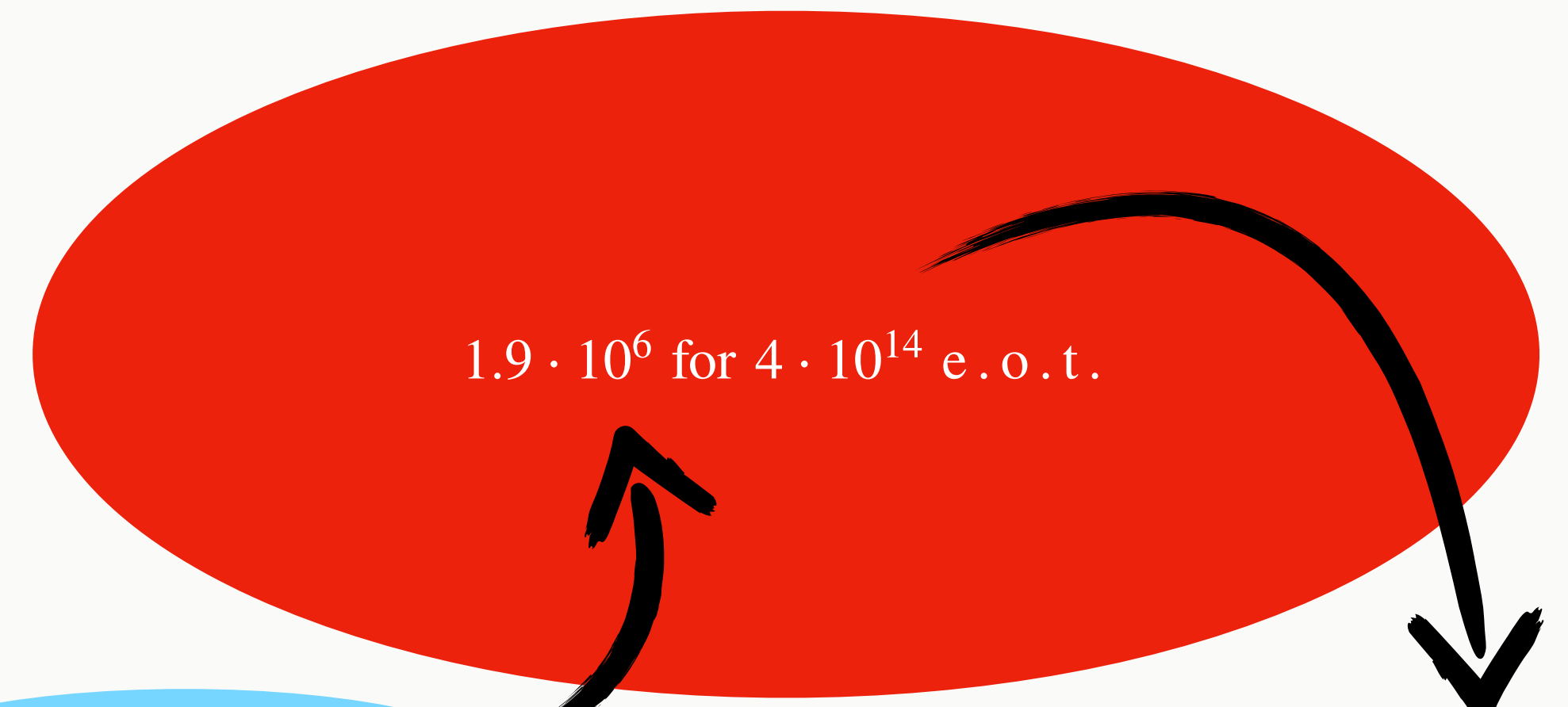


Hadrons



$O(10^2 - 10^3)$ for $2.5 \cdot 10^{12}$ e.o.t.

1 – 100 signal events

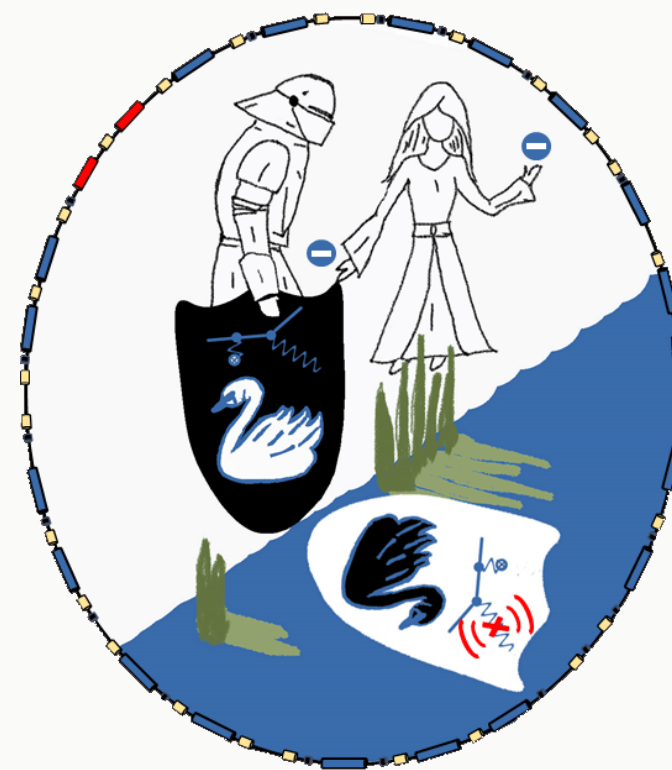


11868 for $2.5 \cdot 10^{12}$ e.o.t.

1 – 100 signal events

Next Steps

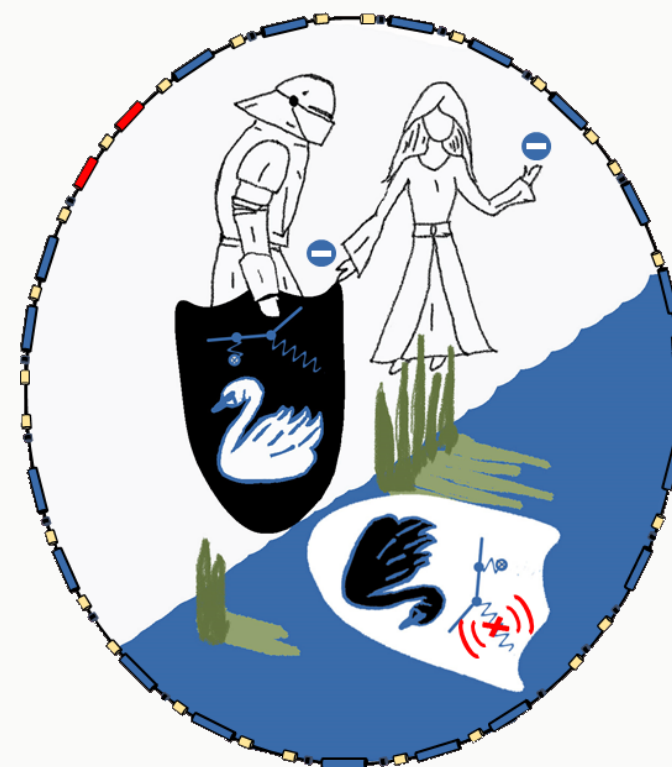
- Full simulation in PERCEVAL with tracking!
- Analyze full event topology: “Stichprobenartig” verified (more verification in the works)
- Investigate different positions of the target in the magnet volume (BA Carla Vermöhlen)
- Investigate possibility of Calorimeter inside the magnet volume



Questions?

More details: <https://www.pi.uni-bonn.de/desch/de/ergebnisse> MA Laney Klipphahn 2025
<https://arxiv.org/pdf/2410.10956> Lohengrin White Paper 2025

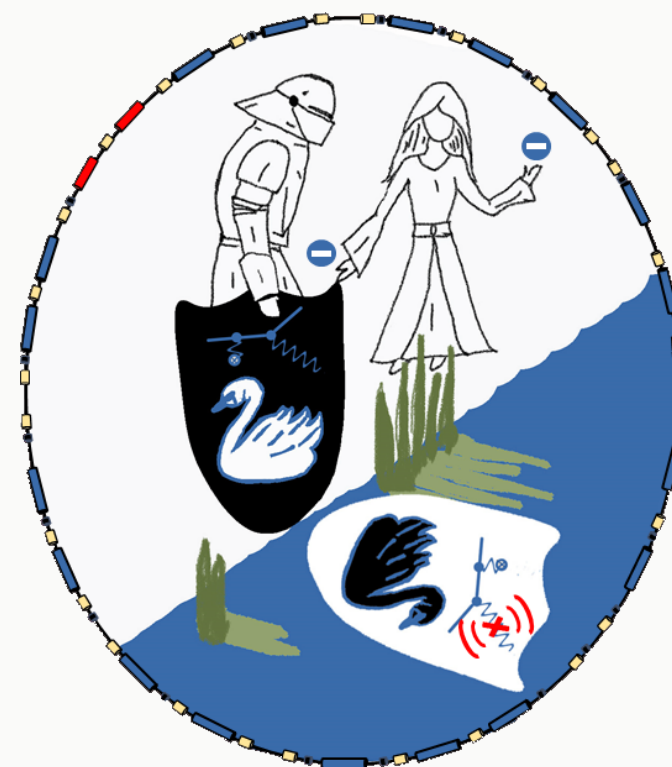
01.10.2026 - Accelerating the Search for Disappearing Light Dark Matter - a Community Workshop



Backup

Laney Klipphahn for the Lohengrin Study Group

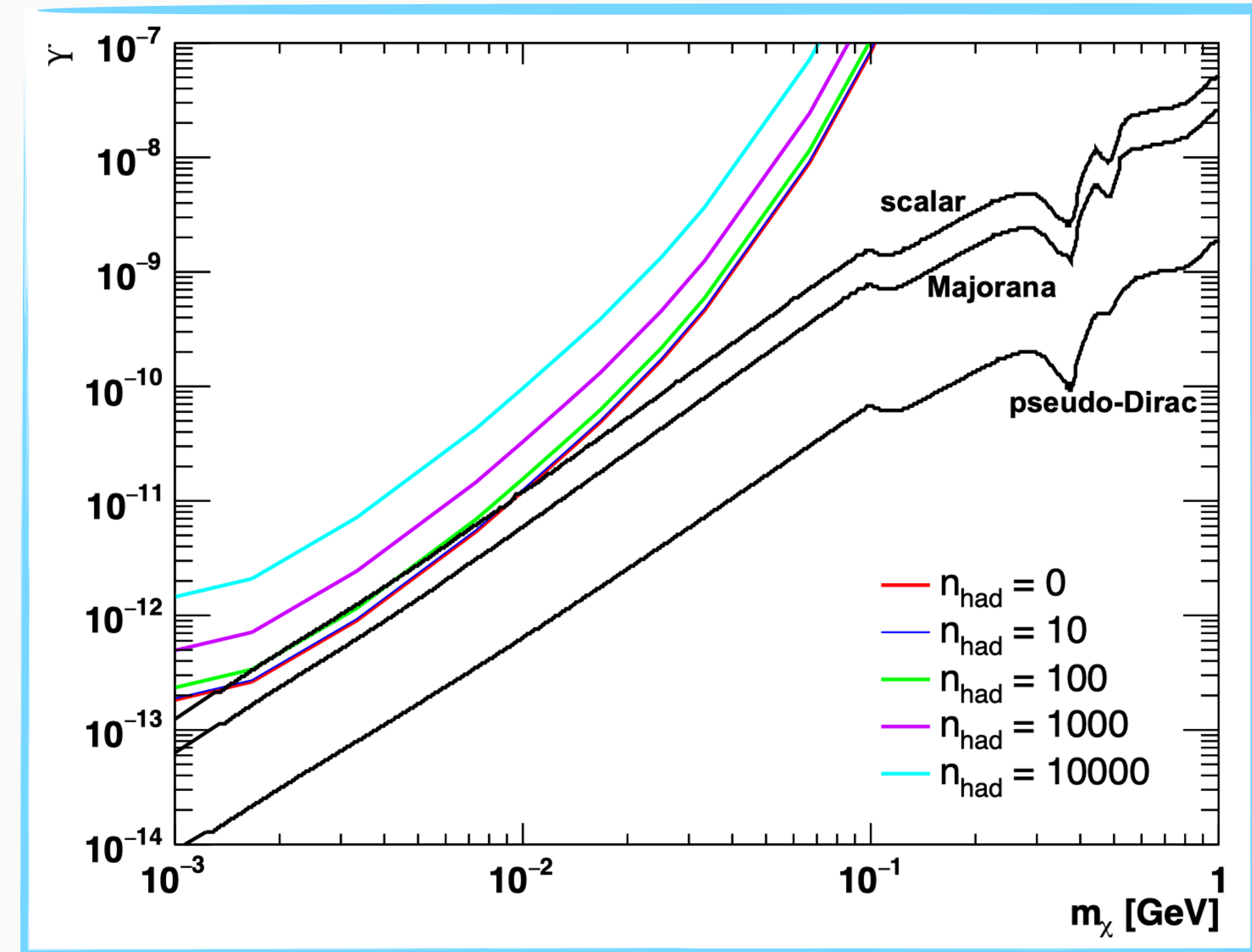
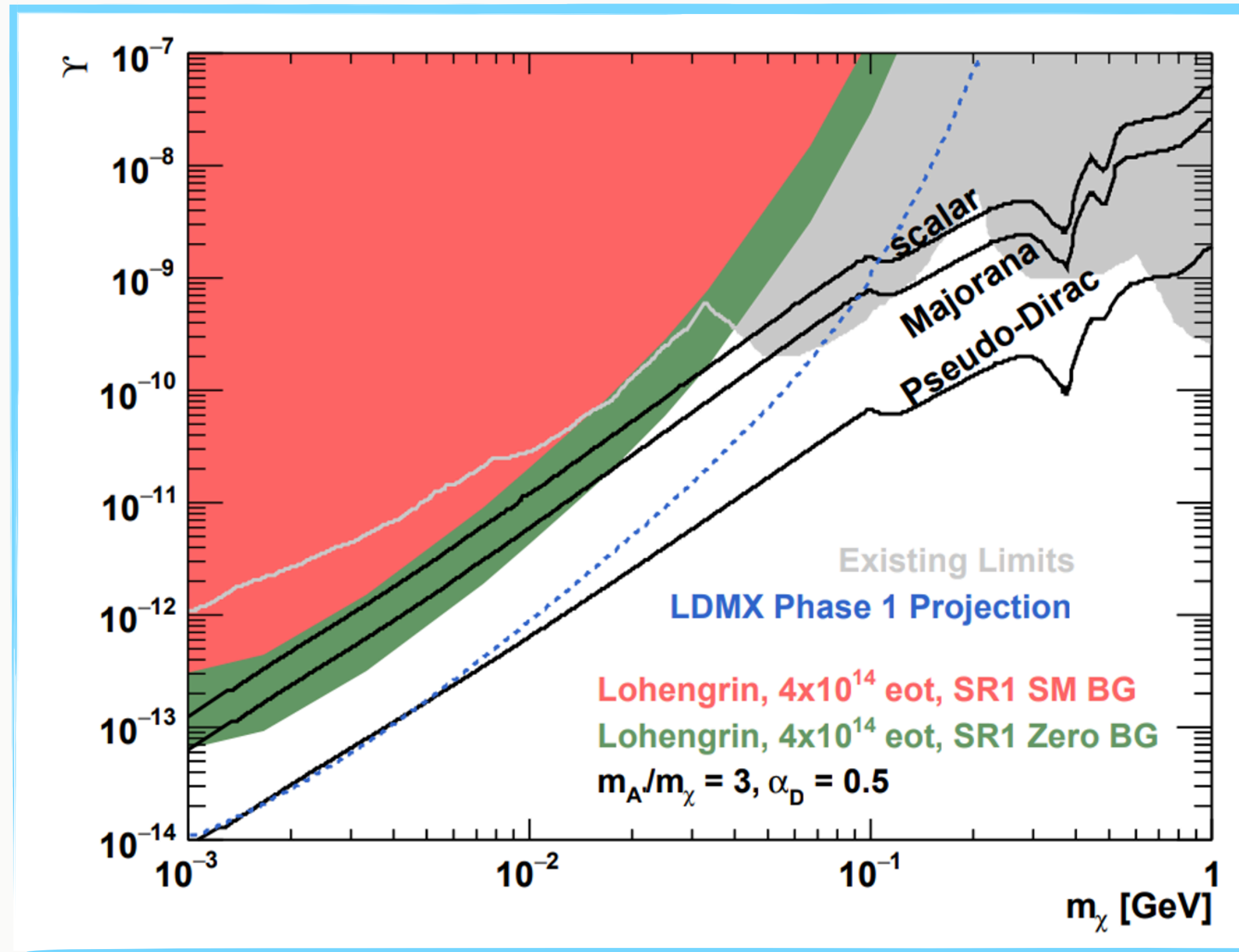
01.10.2026 - Accelerating the Search for Disappearing Light Dark Matter - a Community Workshop



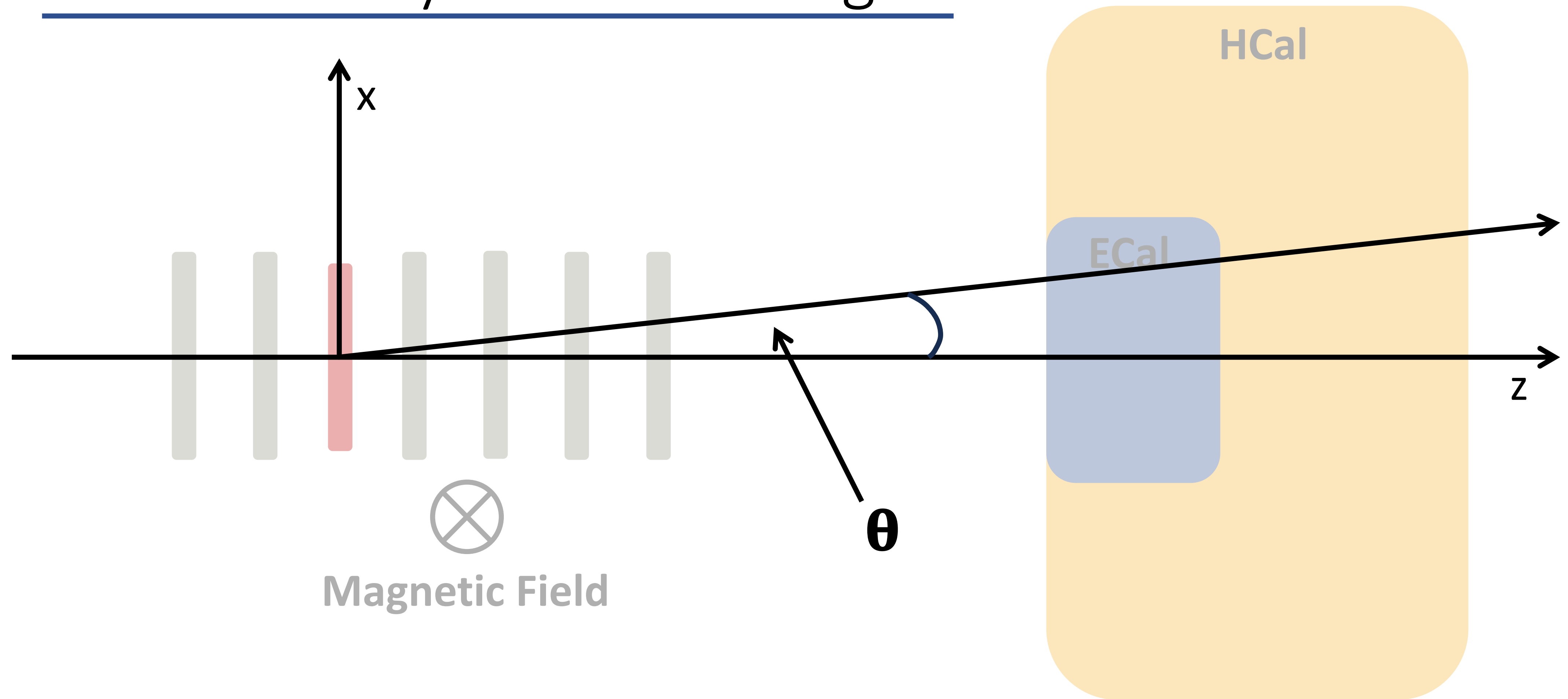
Additional side quests

- Investigated different target materials
- Verified small impact of ^{183}W
- Impurities in target have little impact on the overall results
- Photo-nuclear interactions yield similar results
- Looked at different target materials

Why hadronic backgrounds are so tricky:

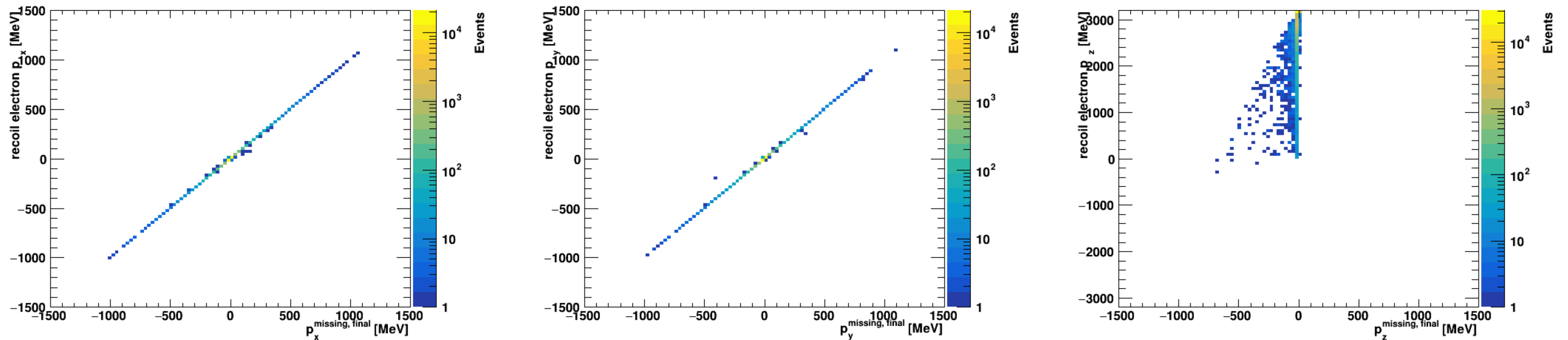


Coordinate Sytem at Lohengrin



GEANT4 – first steps

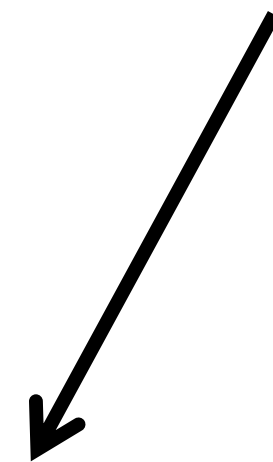
- Noticed something off with electro-nuclear kinematics in GEANT4
- Simple momentum conservation sanity check: failed!



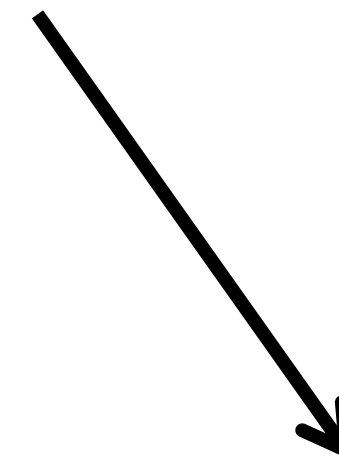
<https://geant4-forum.web.cern.ch/t/frame-of-reference-for-secondaries-in-hadronic-interactions/12413>

GEANT4 – Electro-nuclear kinematics

- Two bugs in the source code of GEANT4 electro-nuclear interactions

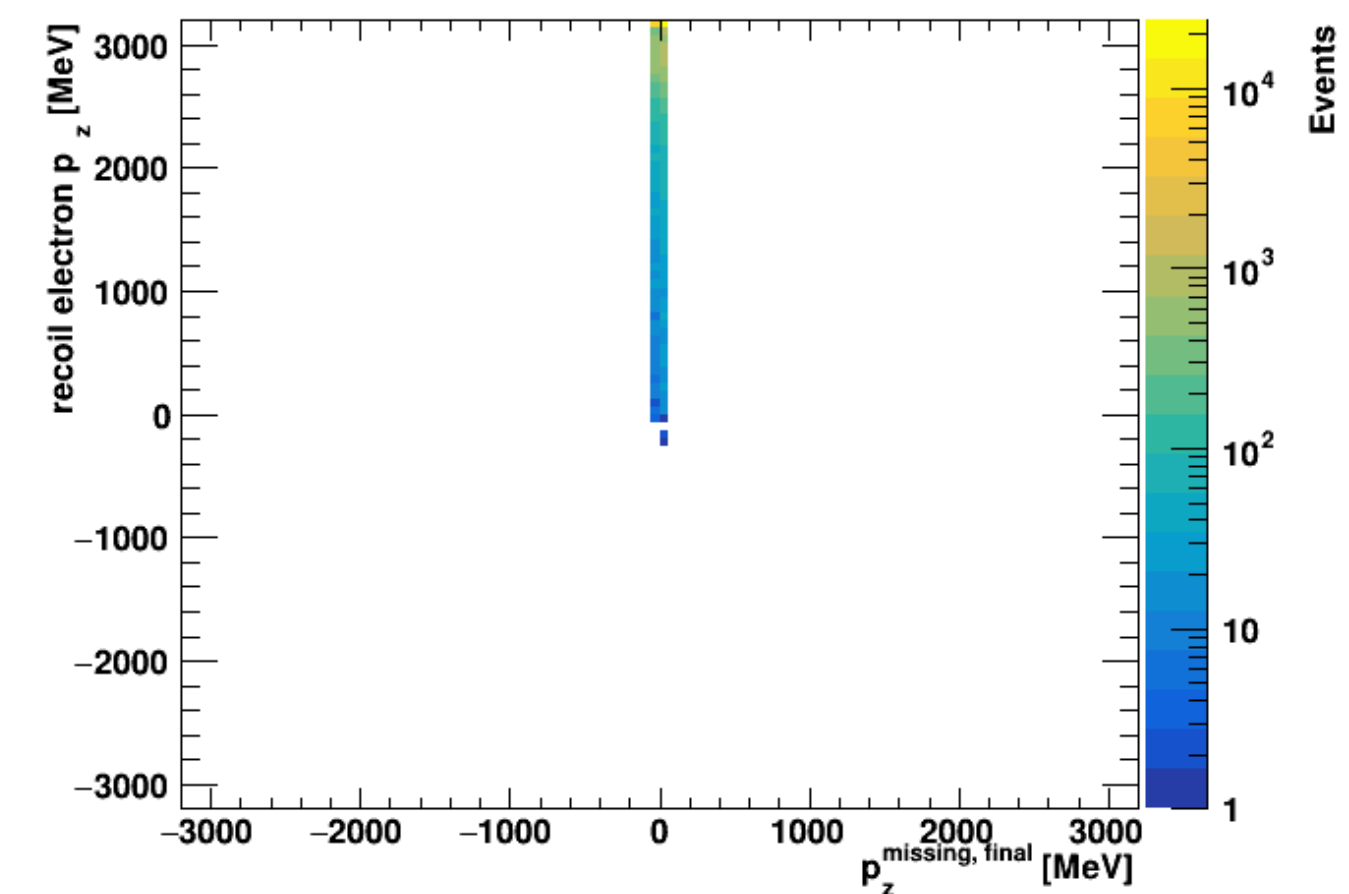
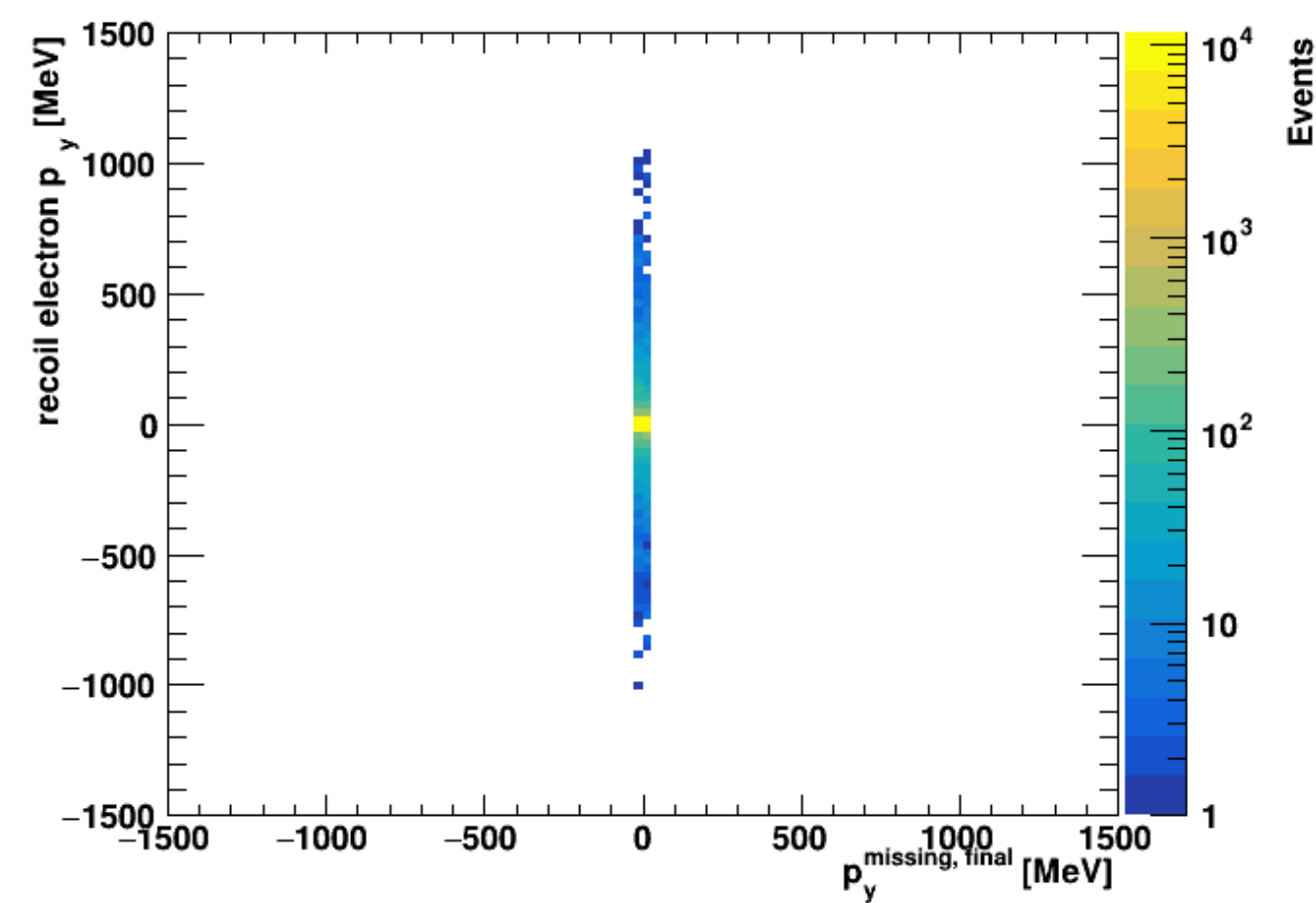
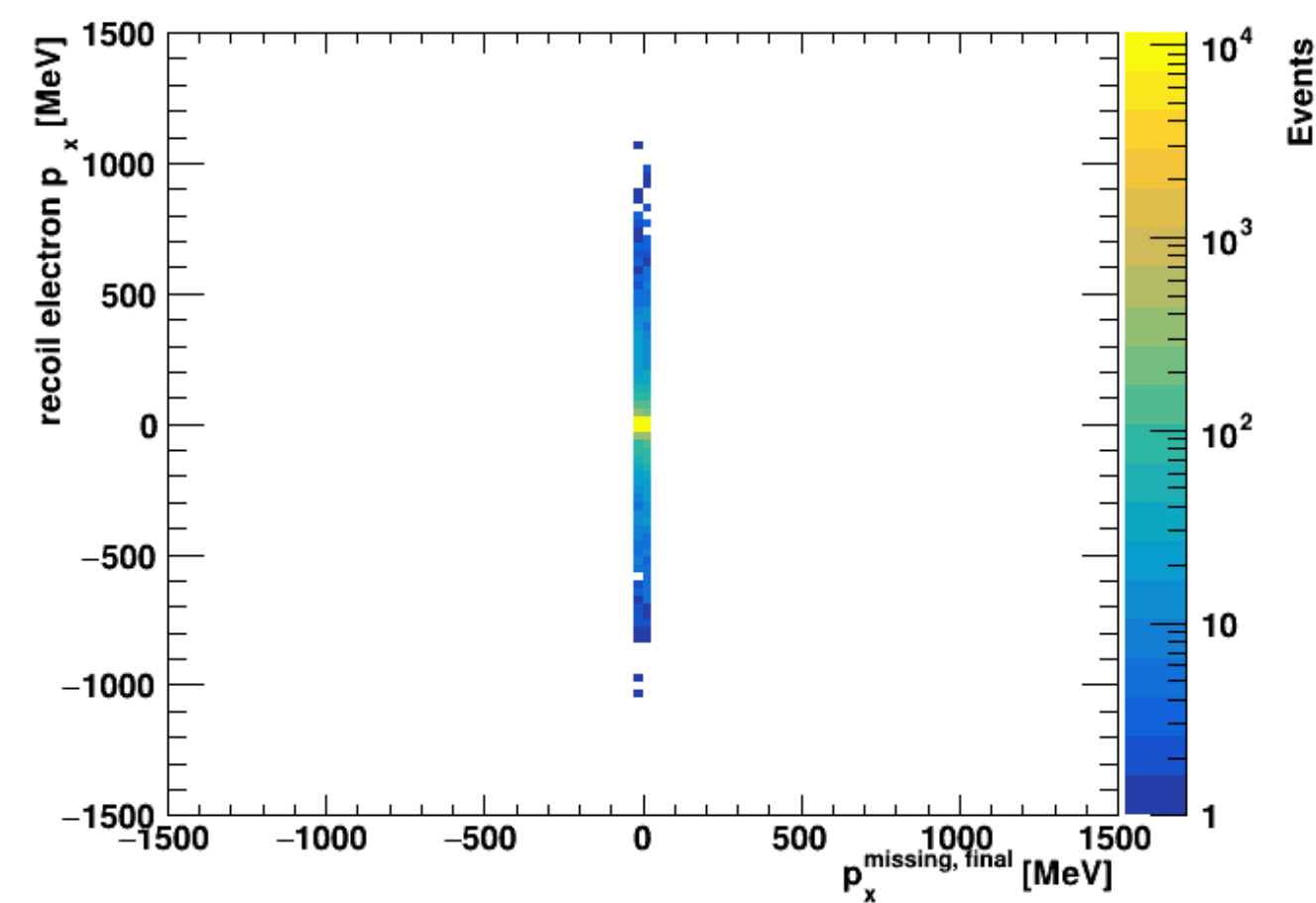


Transferred Photon
momenta cut-off to
maintain $q^2=0$



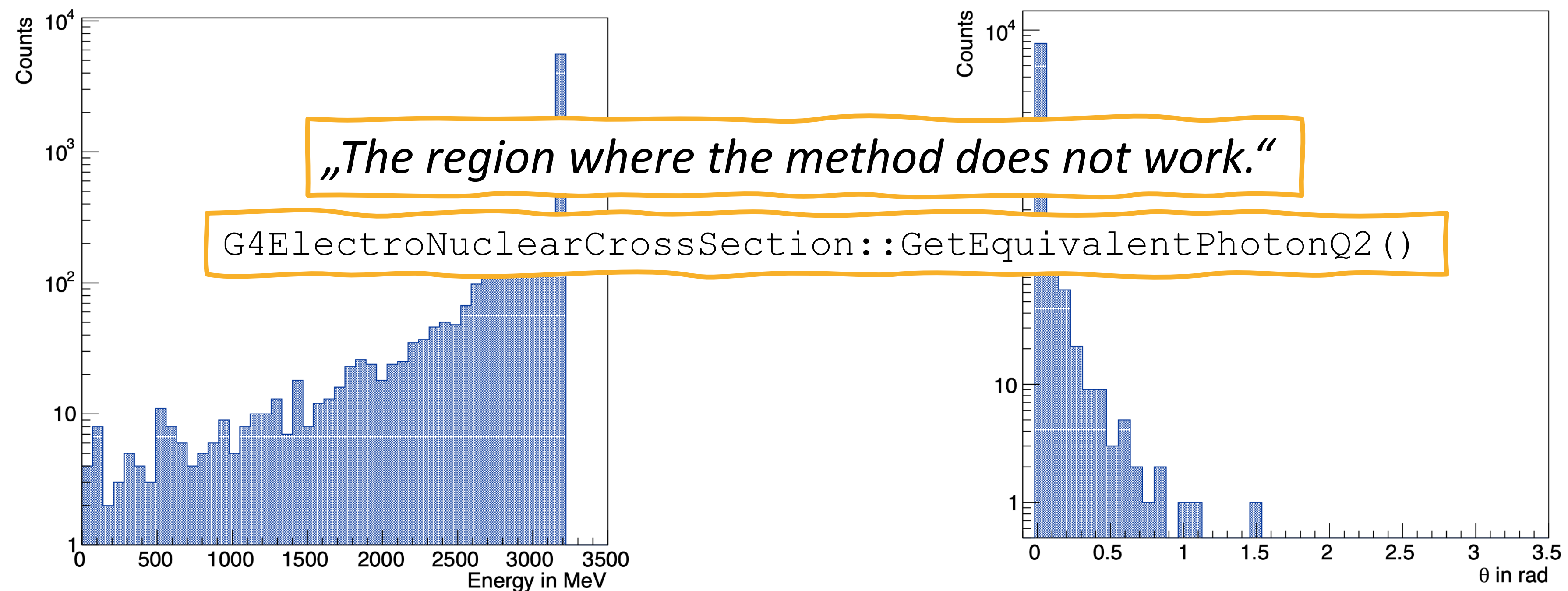
Secondary particles
not rotated back into
lab frame

GEANT4 – Fixed Momentum Bugs

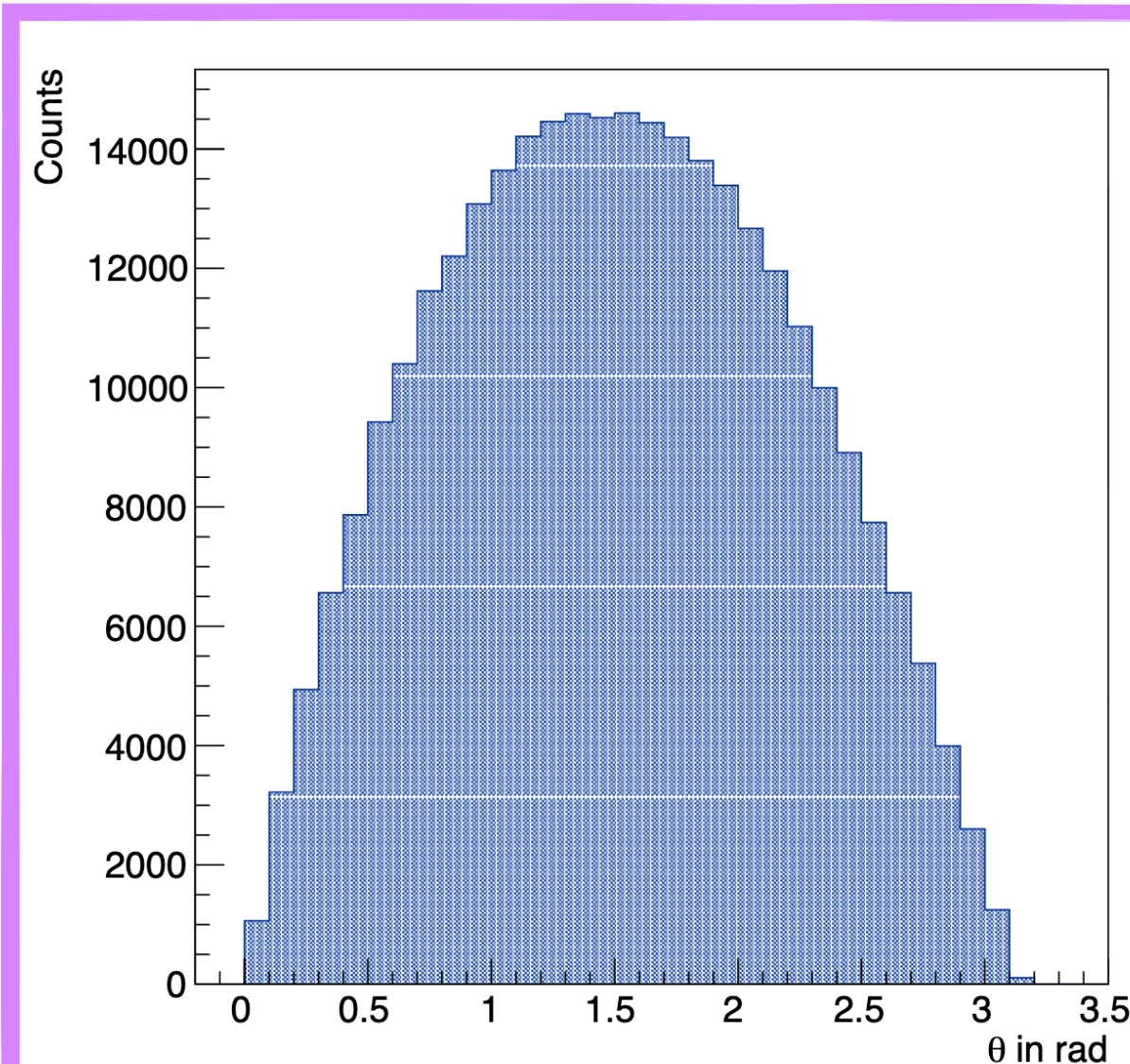


GEANT4 – New Issue

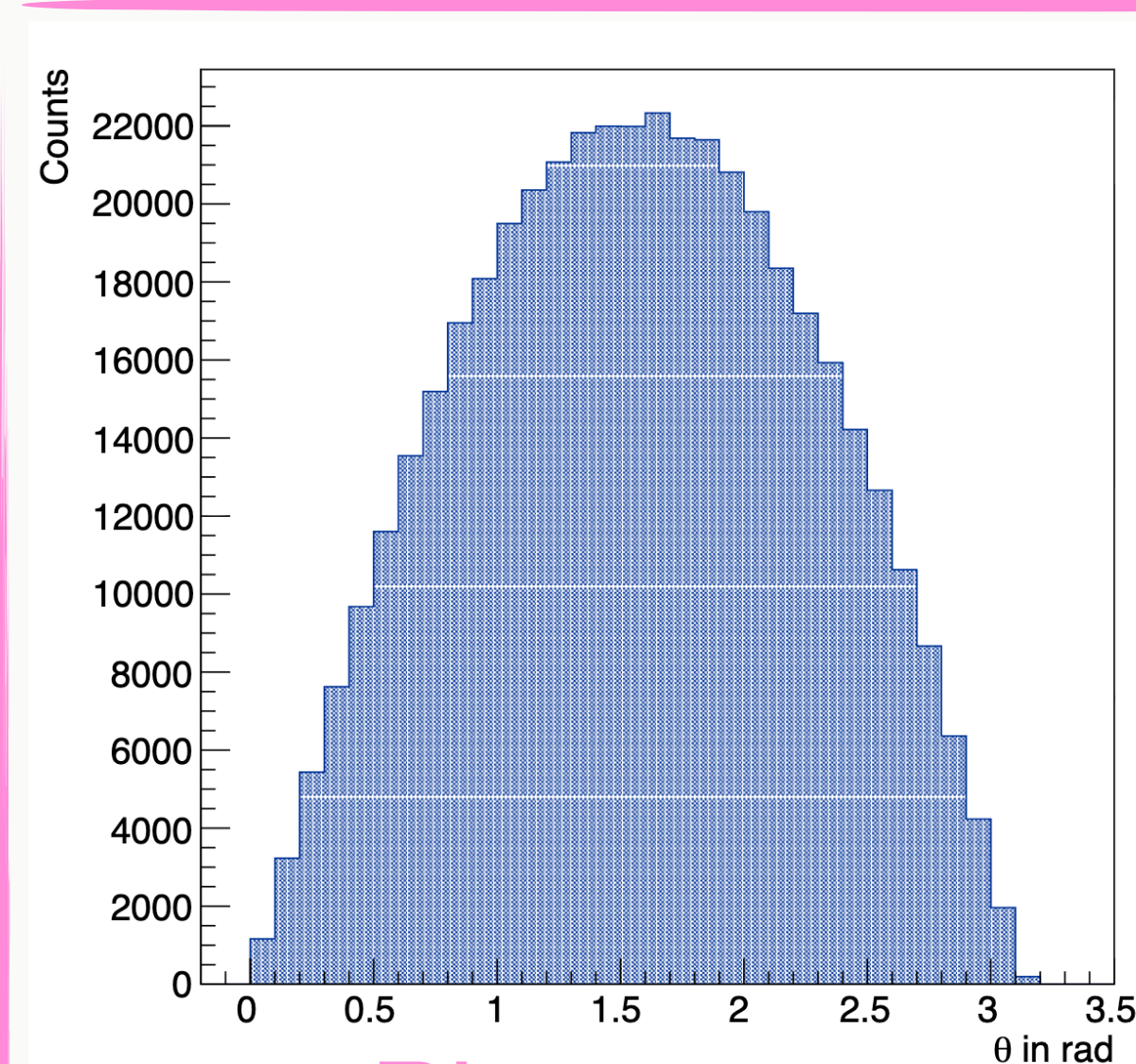
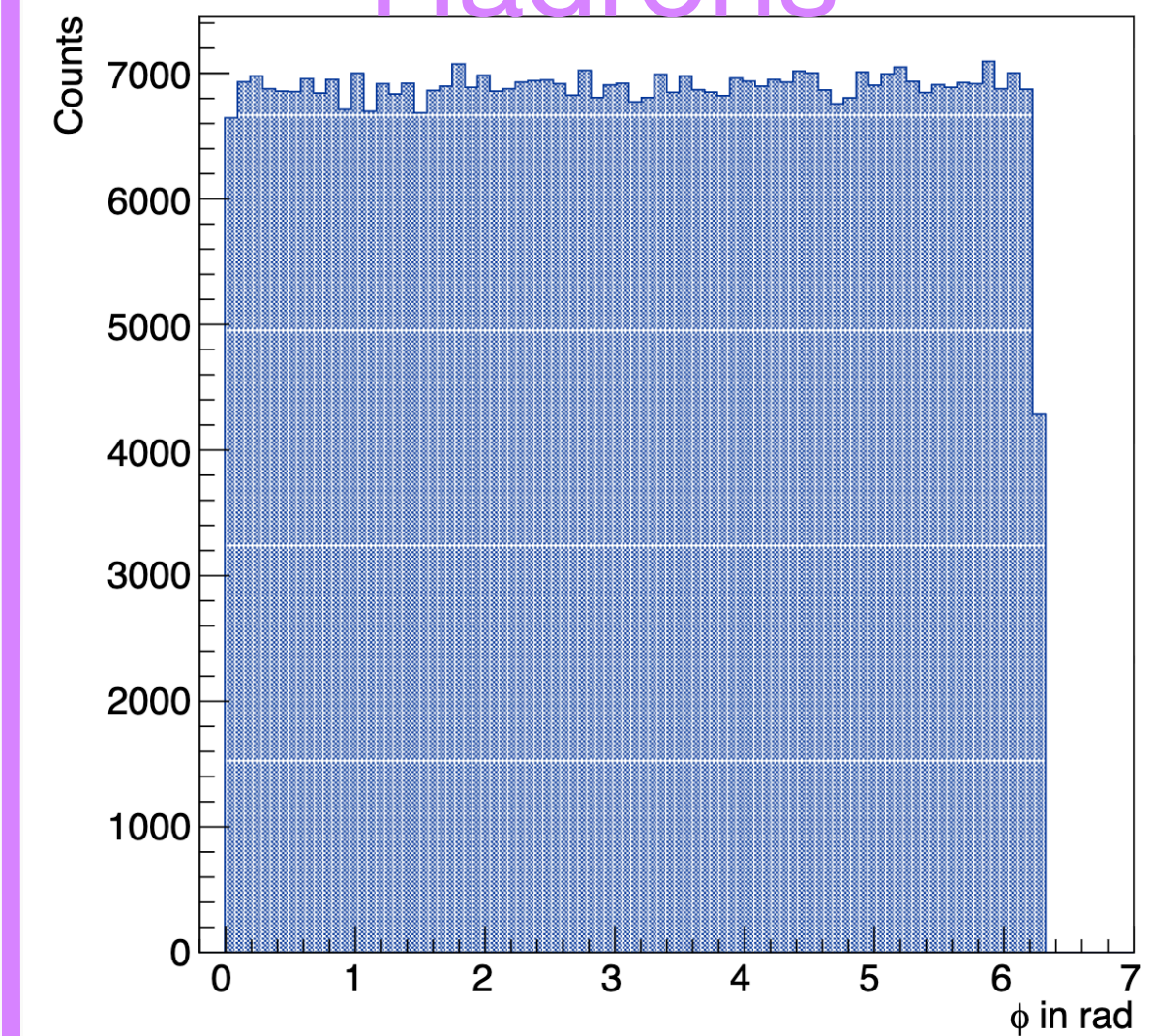
- Recoiling electron kinematics: all electrons in the Lohengrin signal region have forward recoiling electron with $\theta = 0$
- At recoil energies below 183MeV : $\text{acos}(\theta) = 1 \rightarrow \theta \stackrel{!}{=} 0$



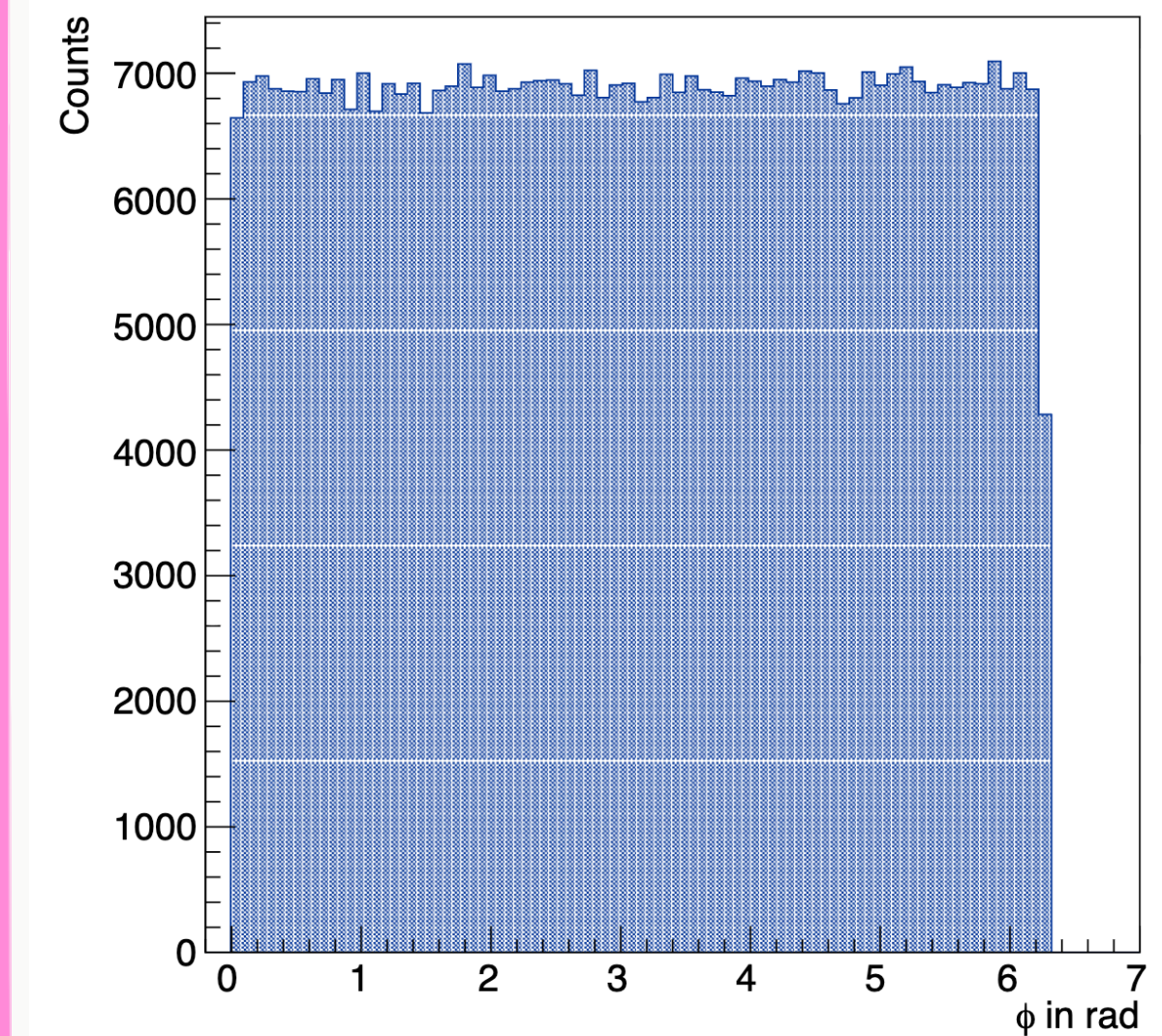
Secondaries angles



Hadrons



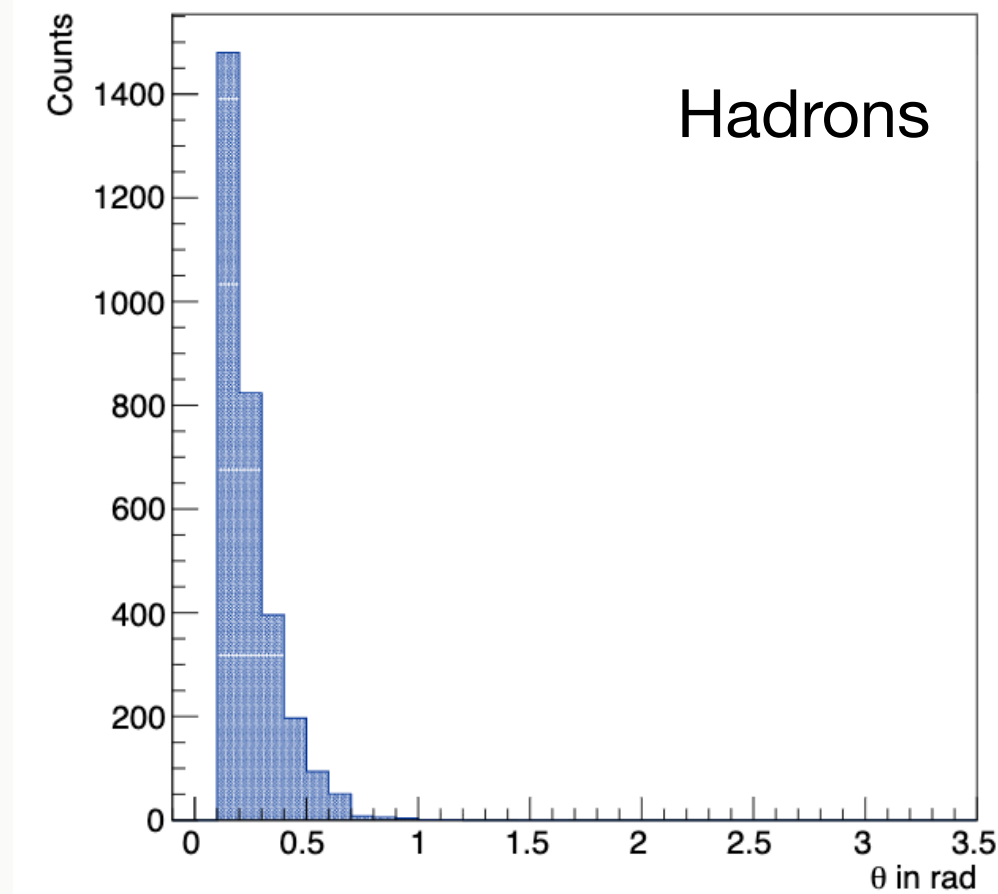
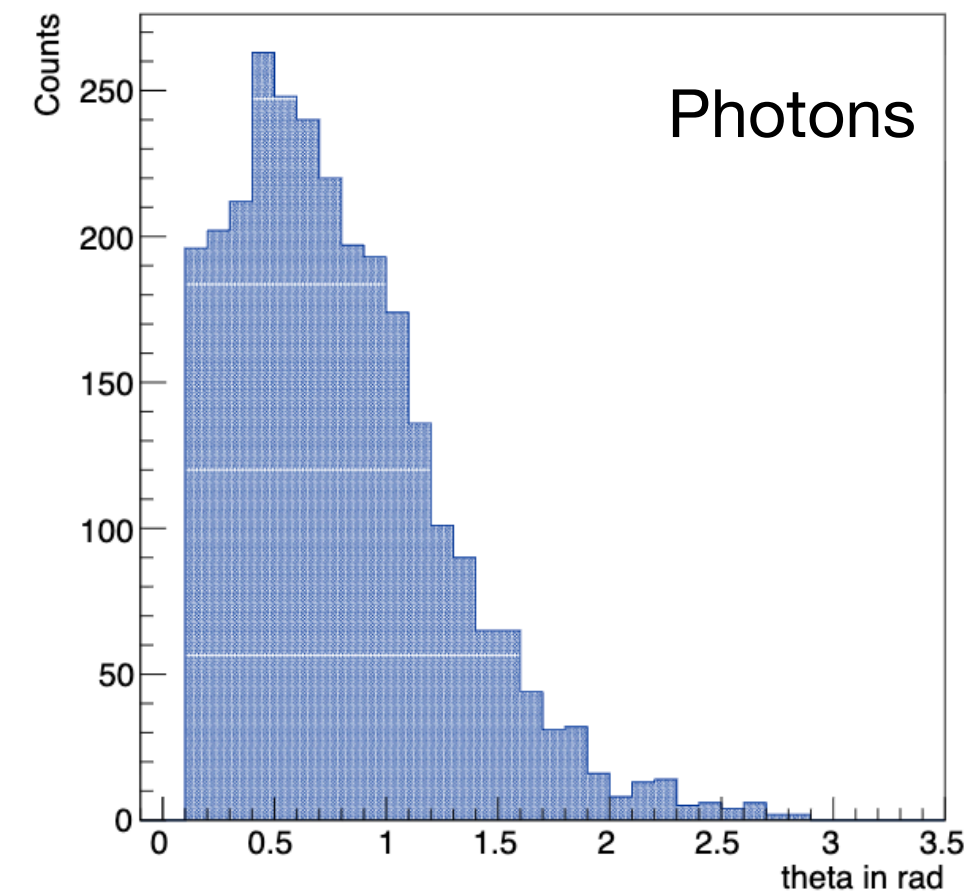
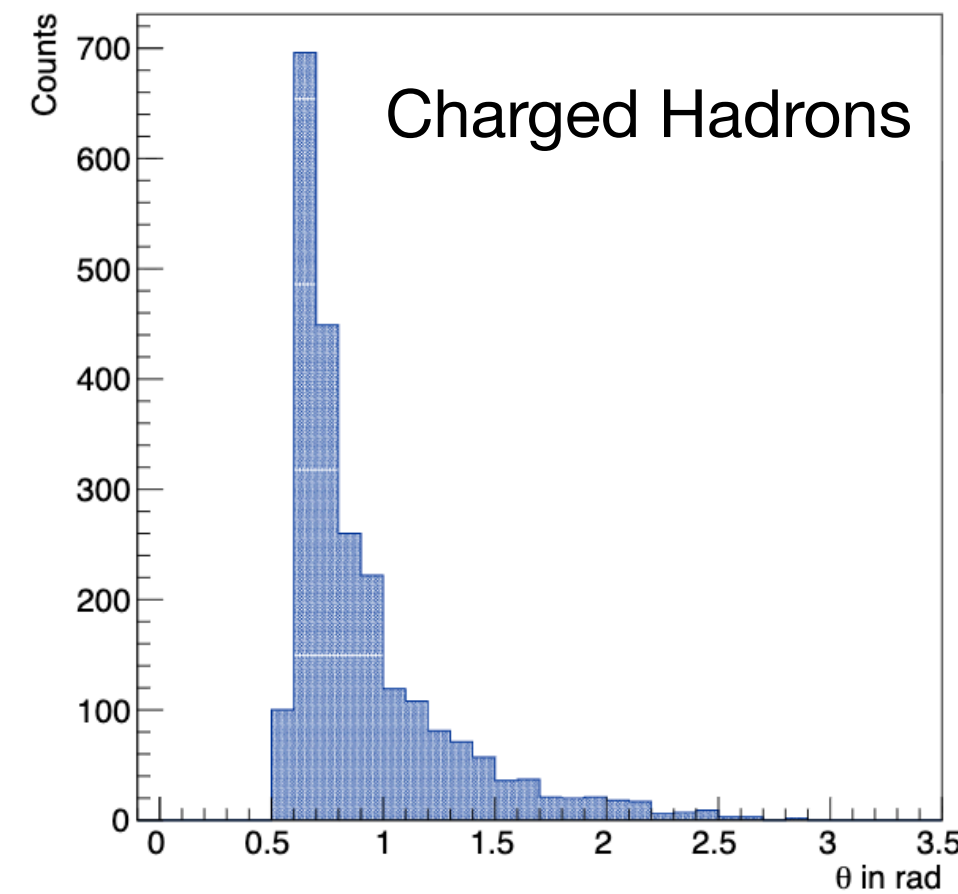
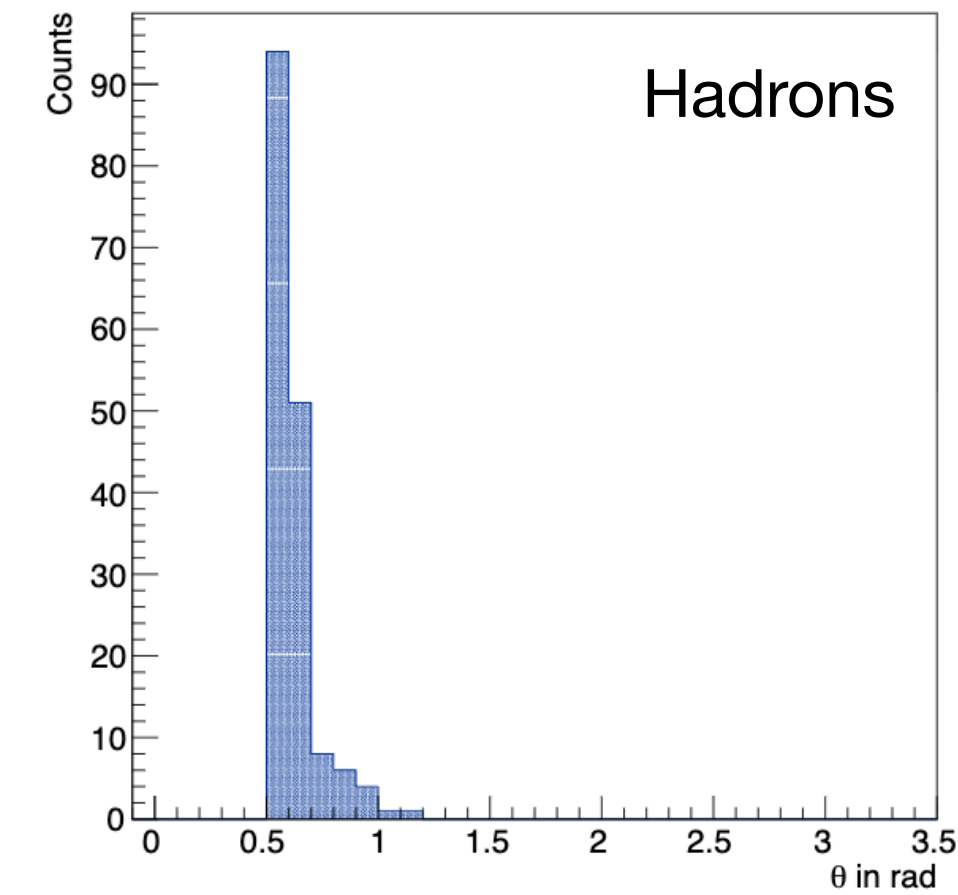
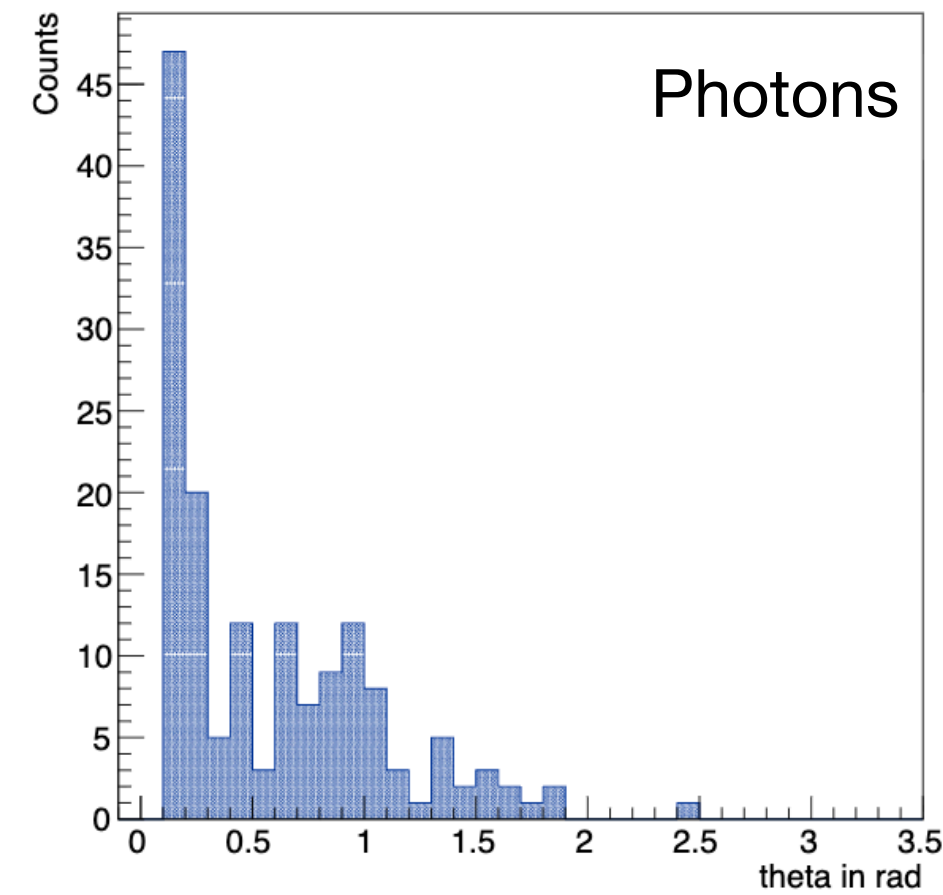
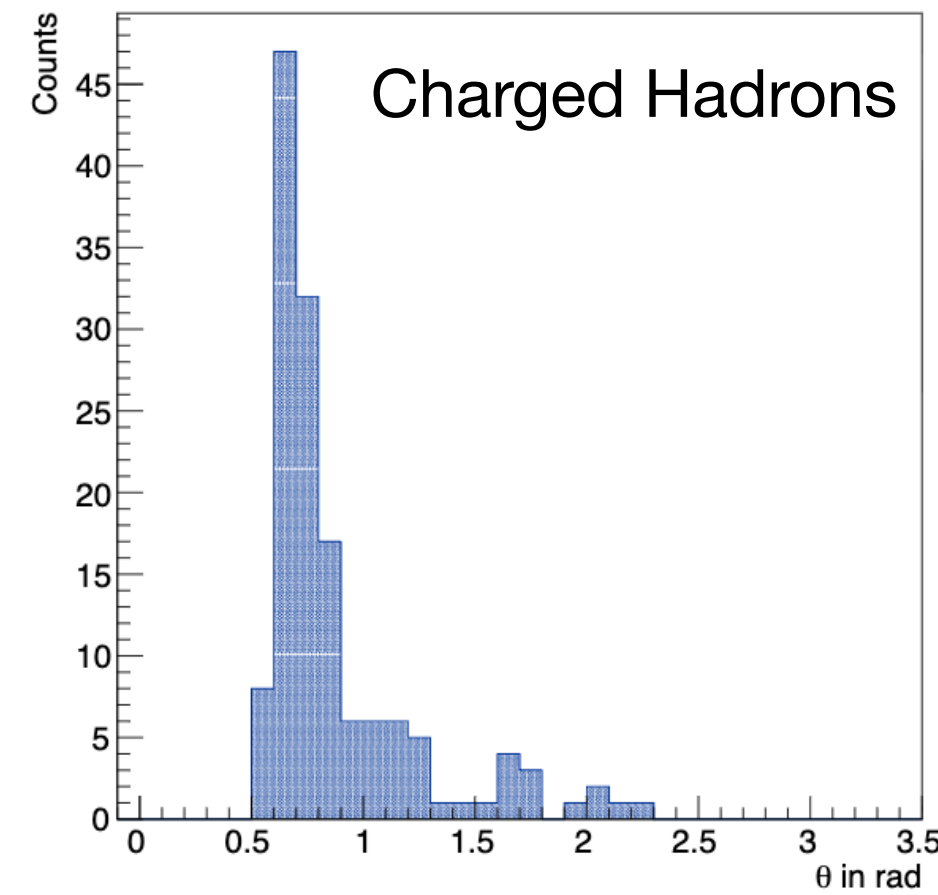
Photons



Secondaries minimal angles



Scenario 1

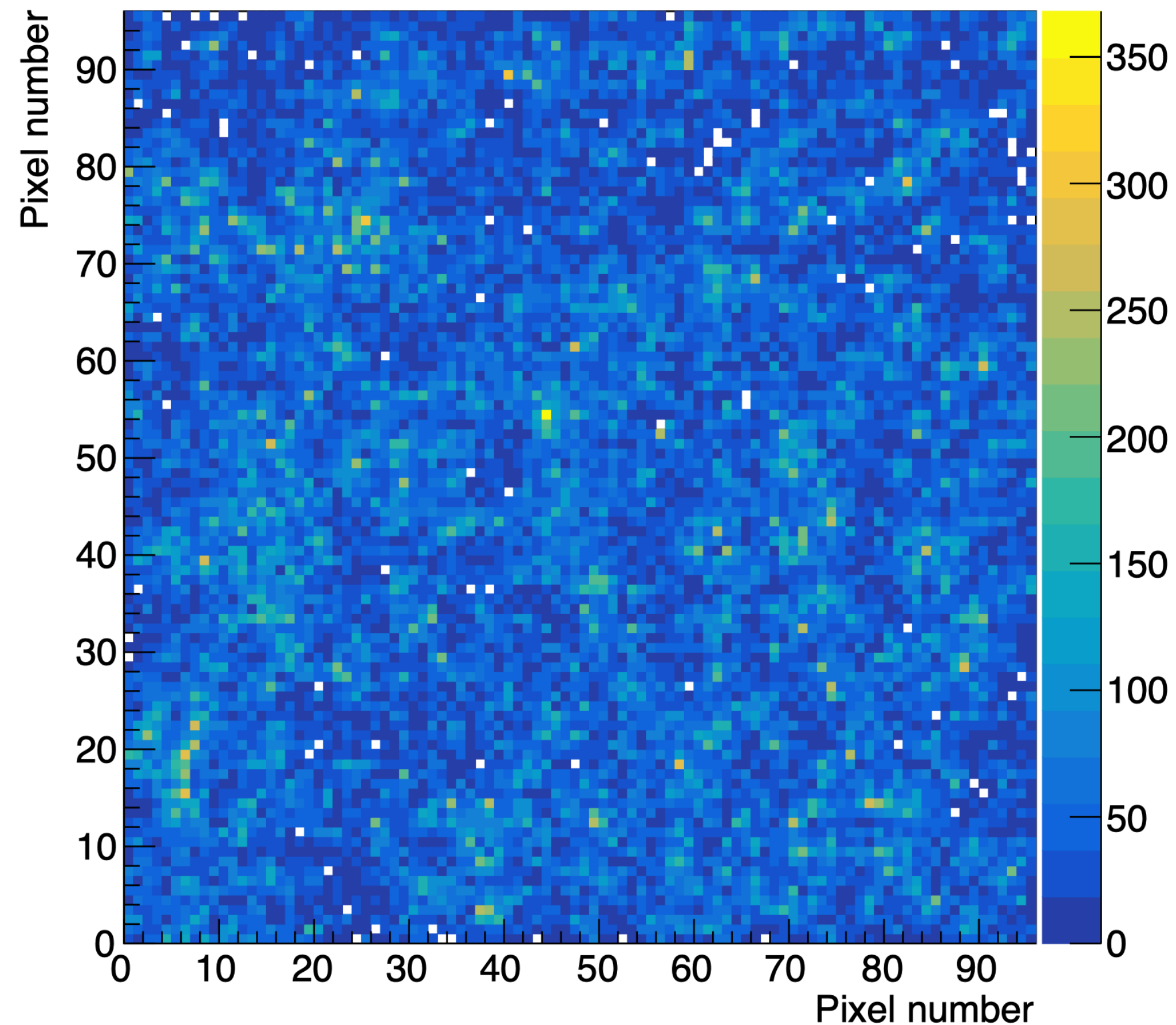


Scenario 2

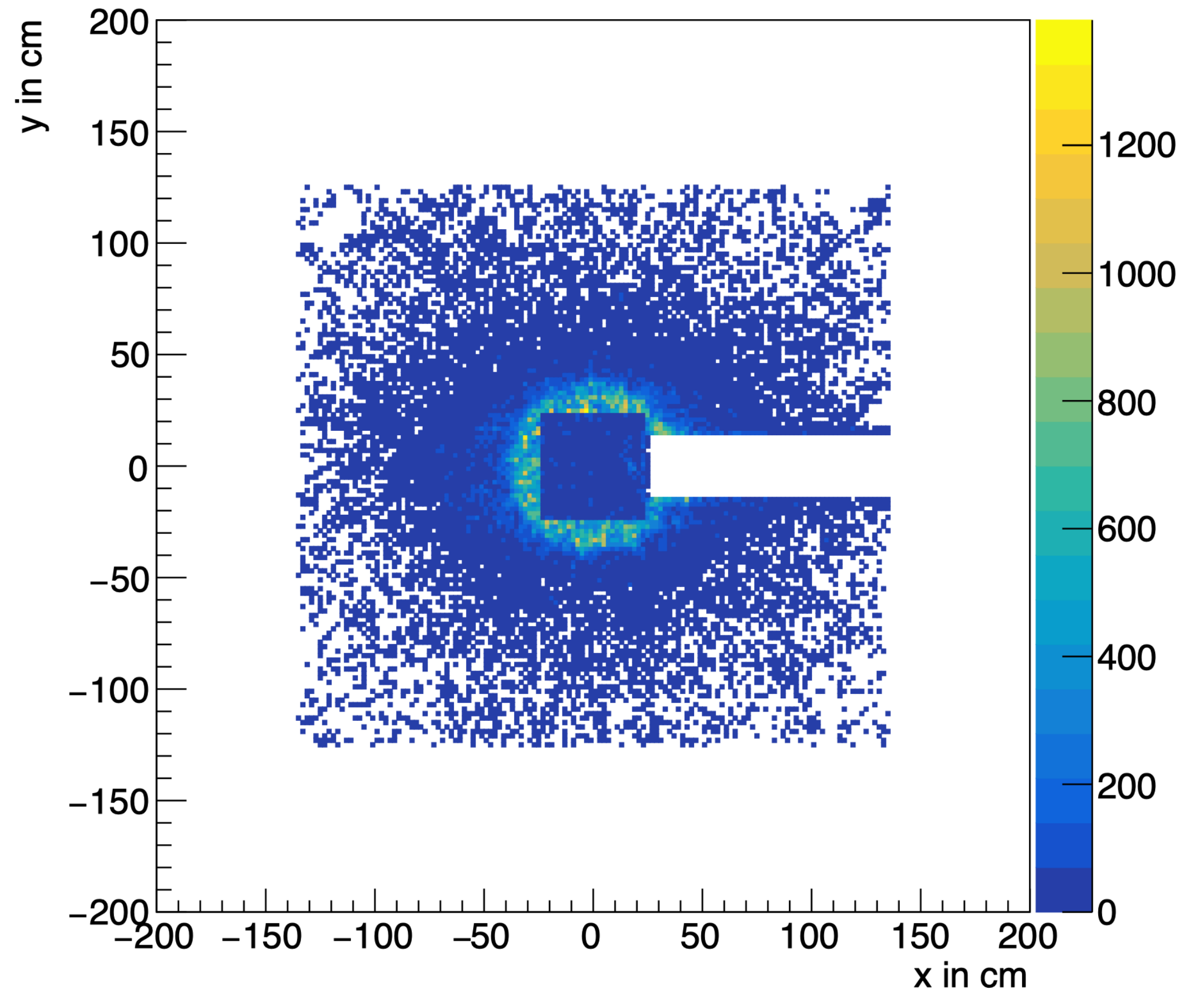
Secondaries angles

ECal and HCal Hit Maps

ECal



HCal



Secondaries angles

ECal and HCal Hit Maps – FLUKA Secondaires

