Chromatic Calorimetry

A Novel Proof of Concept of Innovative Calorimetry for Particle Discrimination and Energy Deposition through Crystal Stack Analysis

- **Devanshi Arora, CERN & Shizuoka Univeristy, Japan**

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CALOR 2024, the 20th International Conference on Calorimetry in Particle Physics

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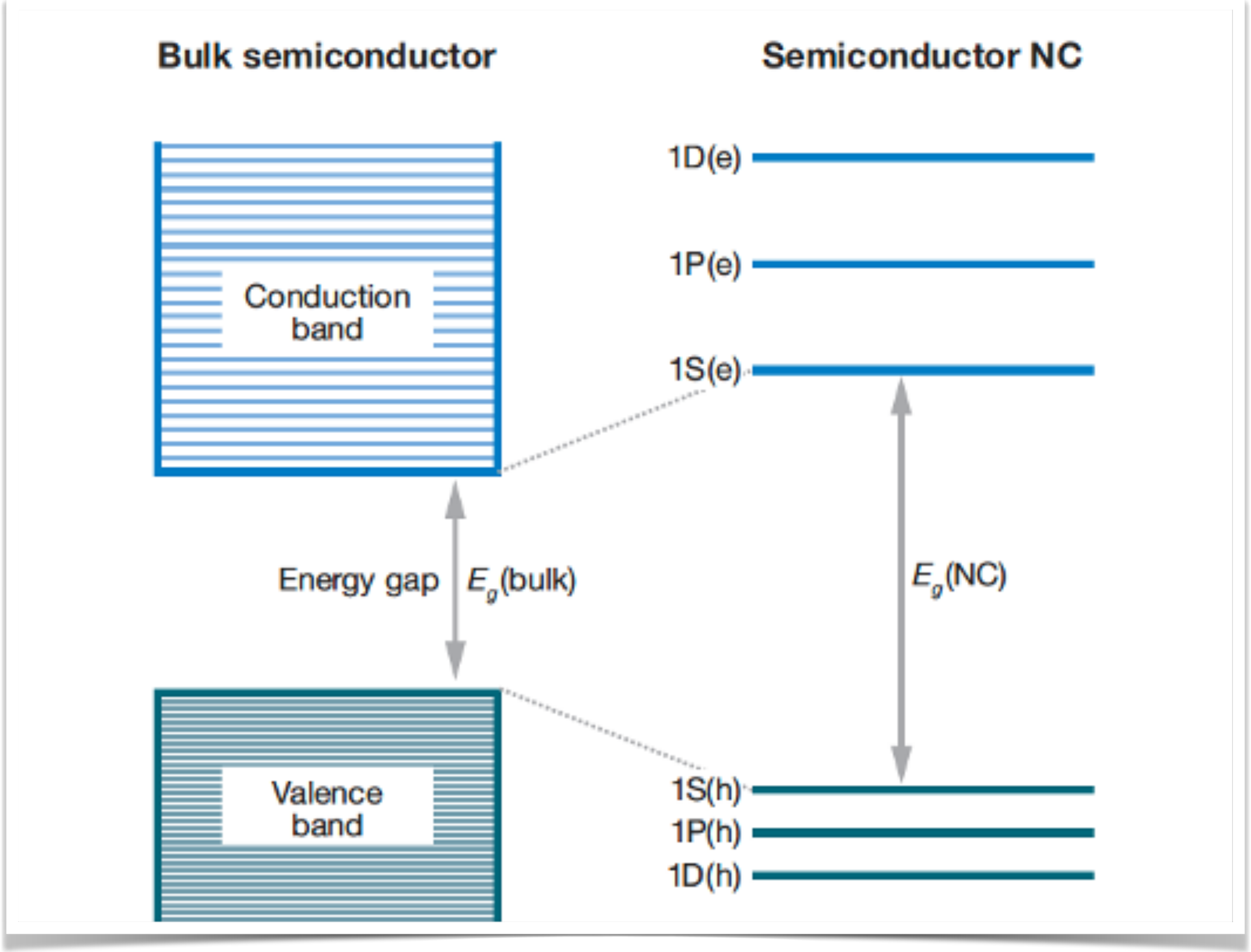
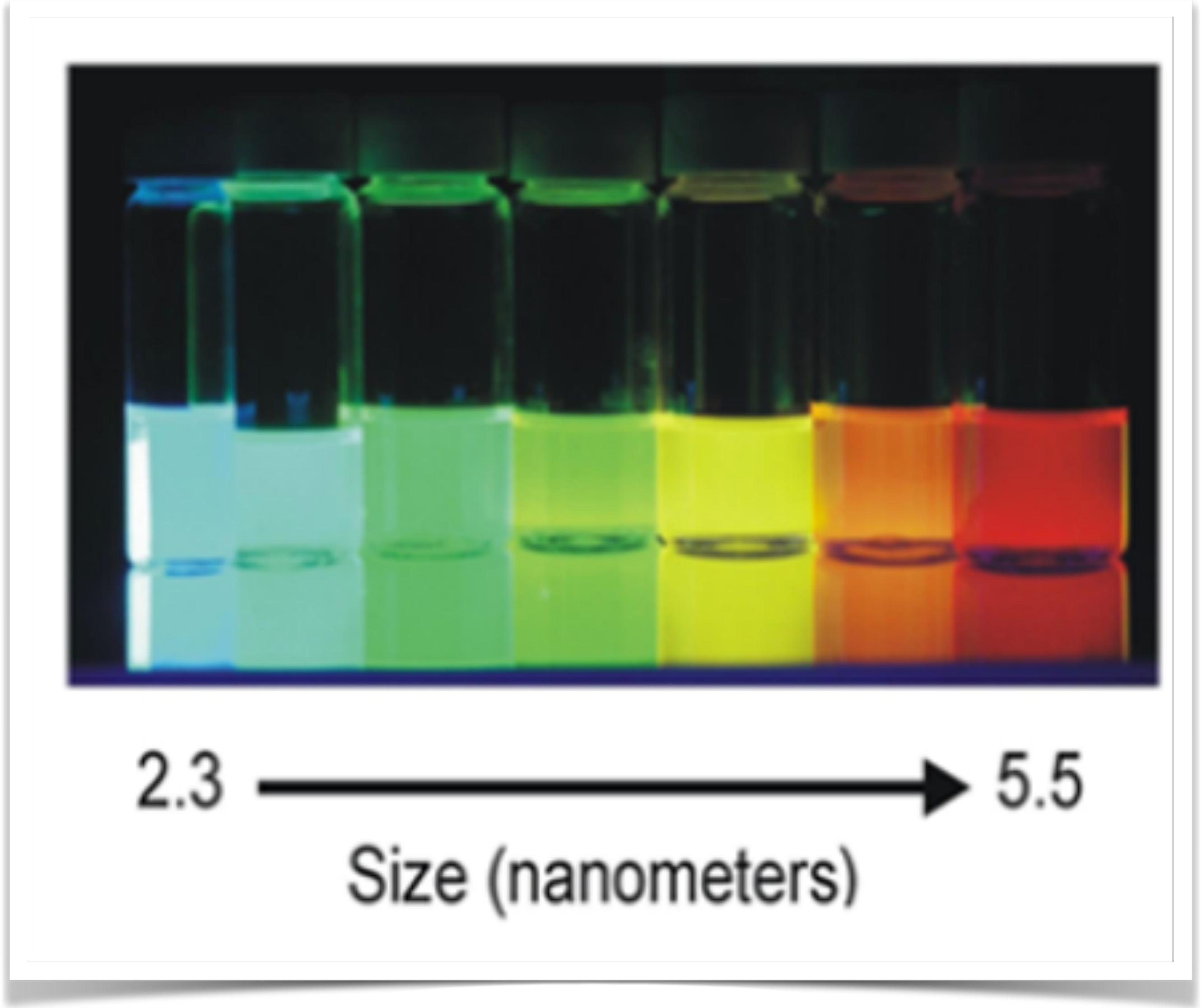
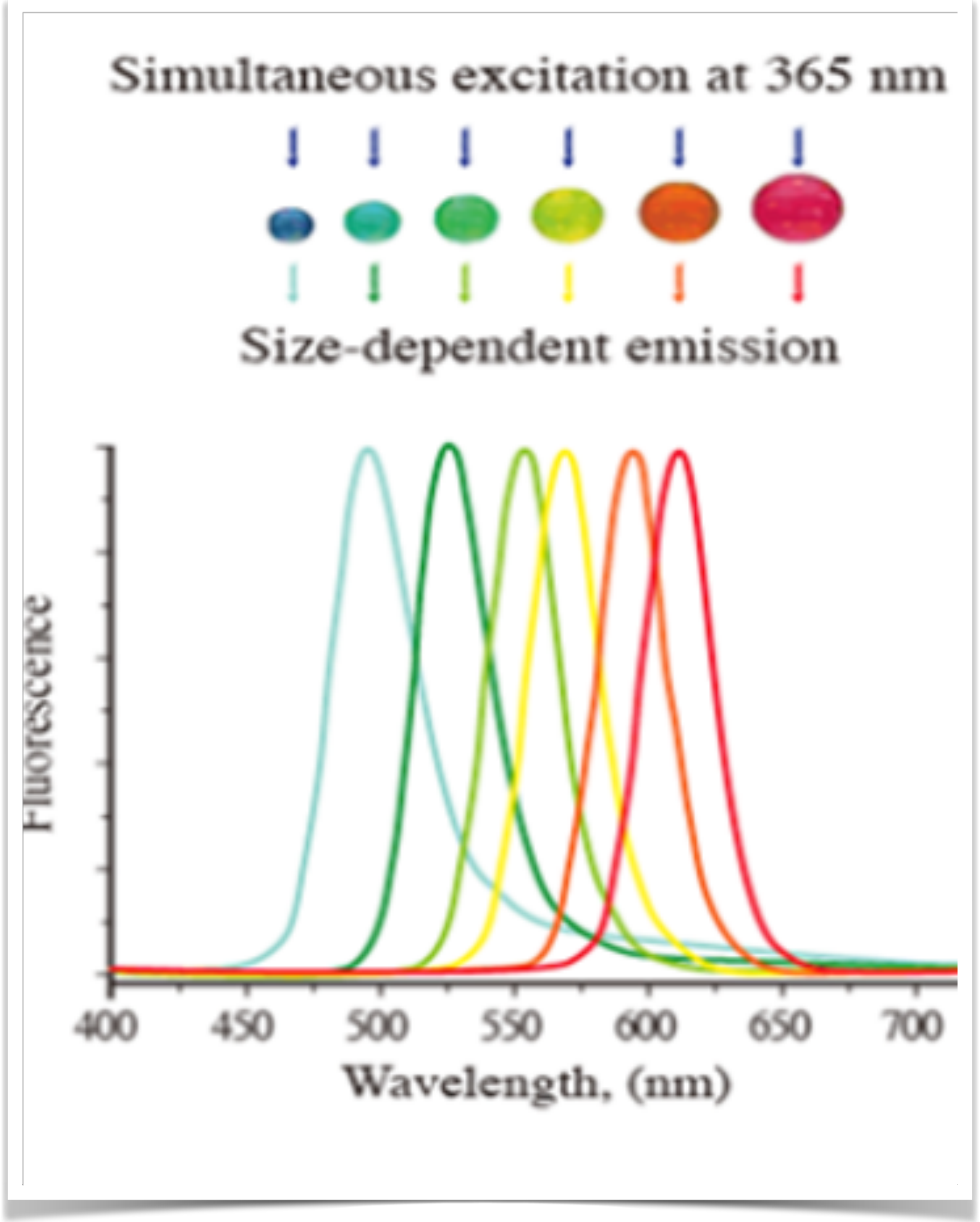
Introduction

QUANTUM DOTS : FROM BULK MATERIAL TO NANOCOMPOSITE



V. Klimov Annu Rev. Phys. Chem. 58 (2007) 535-573





from Benoit Dubertret and Hideki Ooba

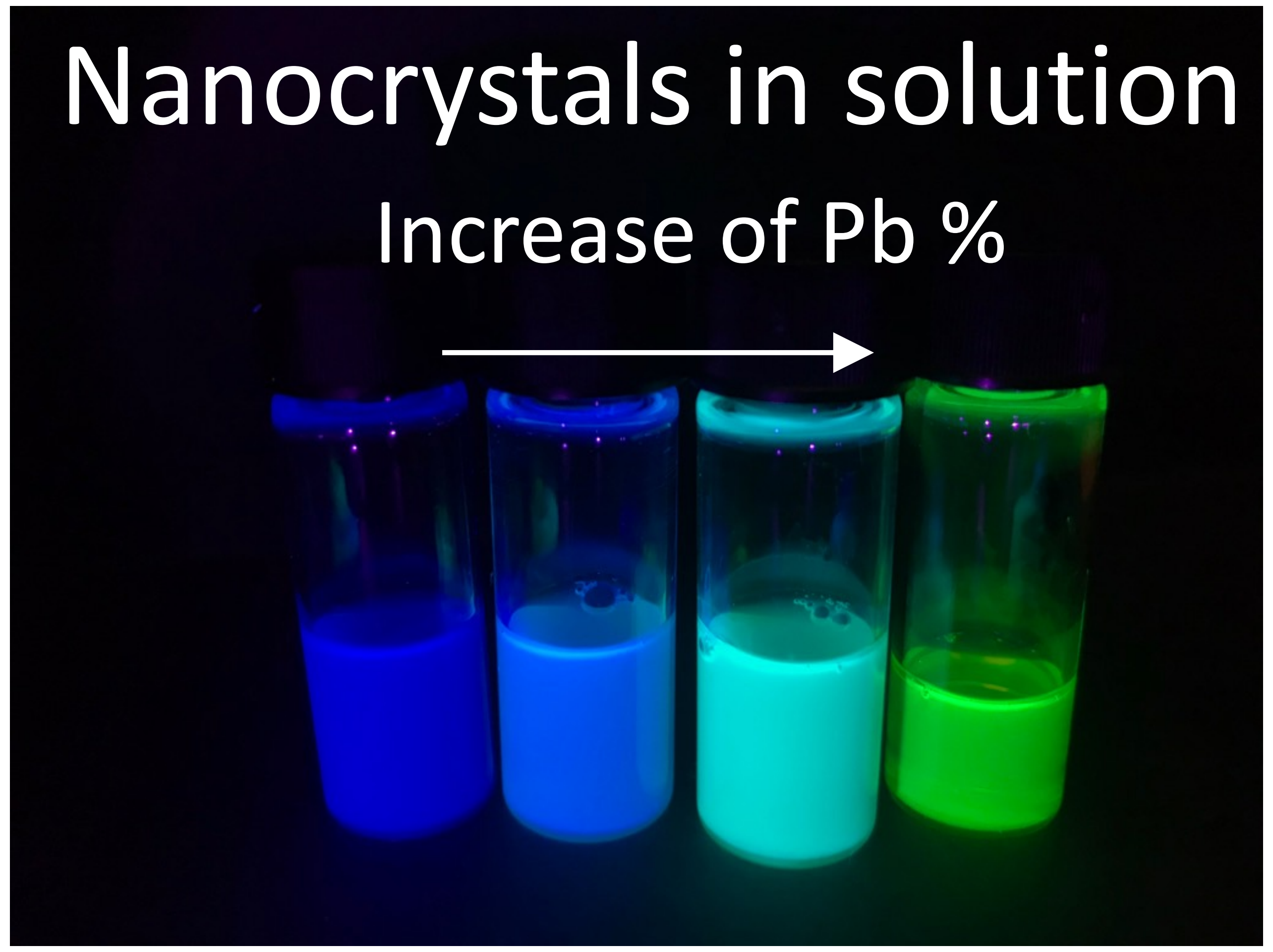
With decreasing crystal size
From "continuous band" to quantized energy levels

chromatic tunability/ tunable emission and absorption characteristics

motive? to achieve fast and tunable calorimeters which is why we explore the characteristics of fast timing and **tunable emission** of QDs

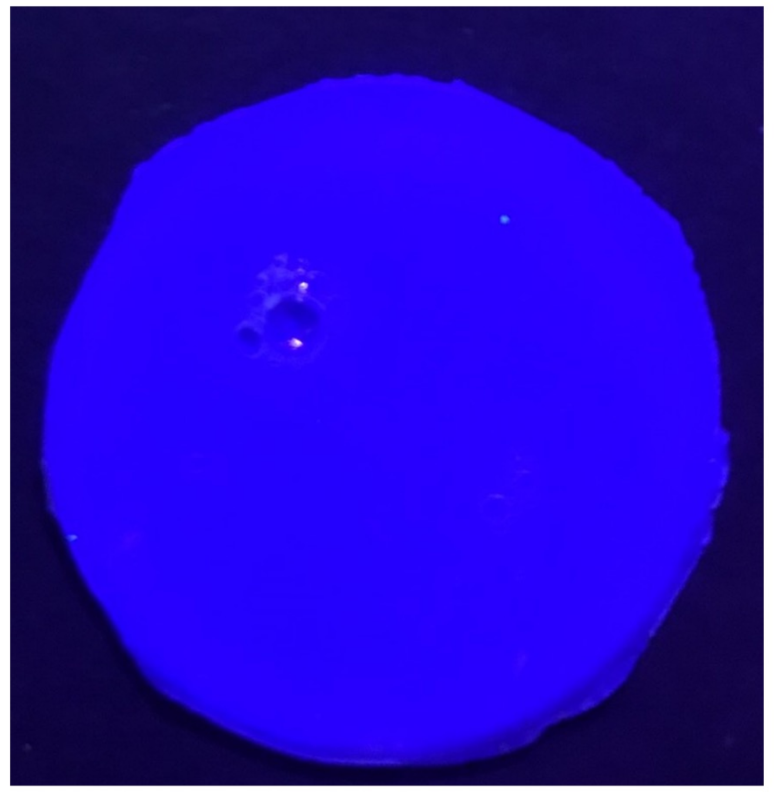
PEROVSKITES SCINTILLATING NANOCOMPOSITE

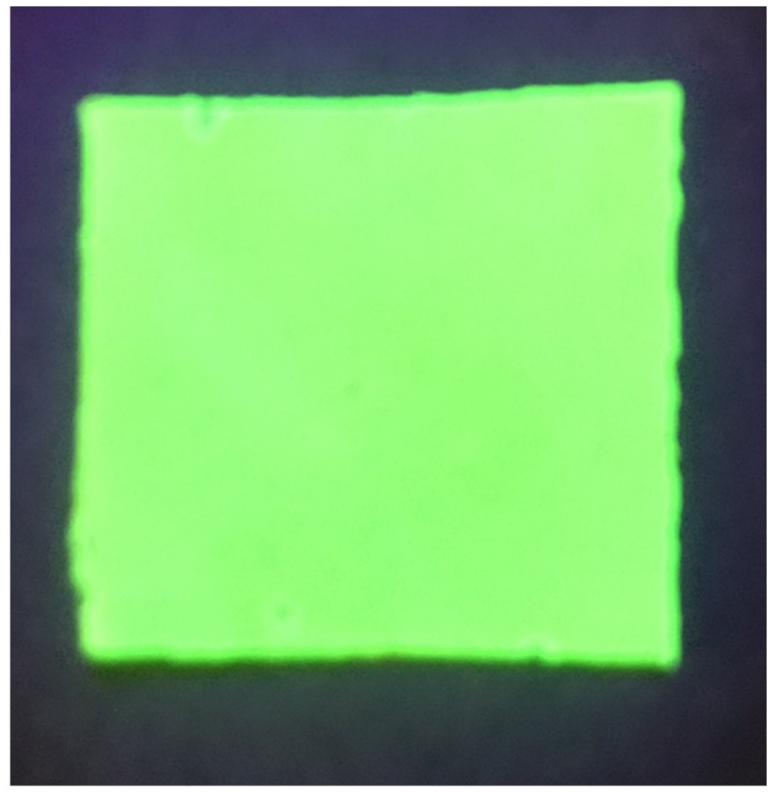
Tunable emission

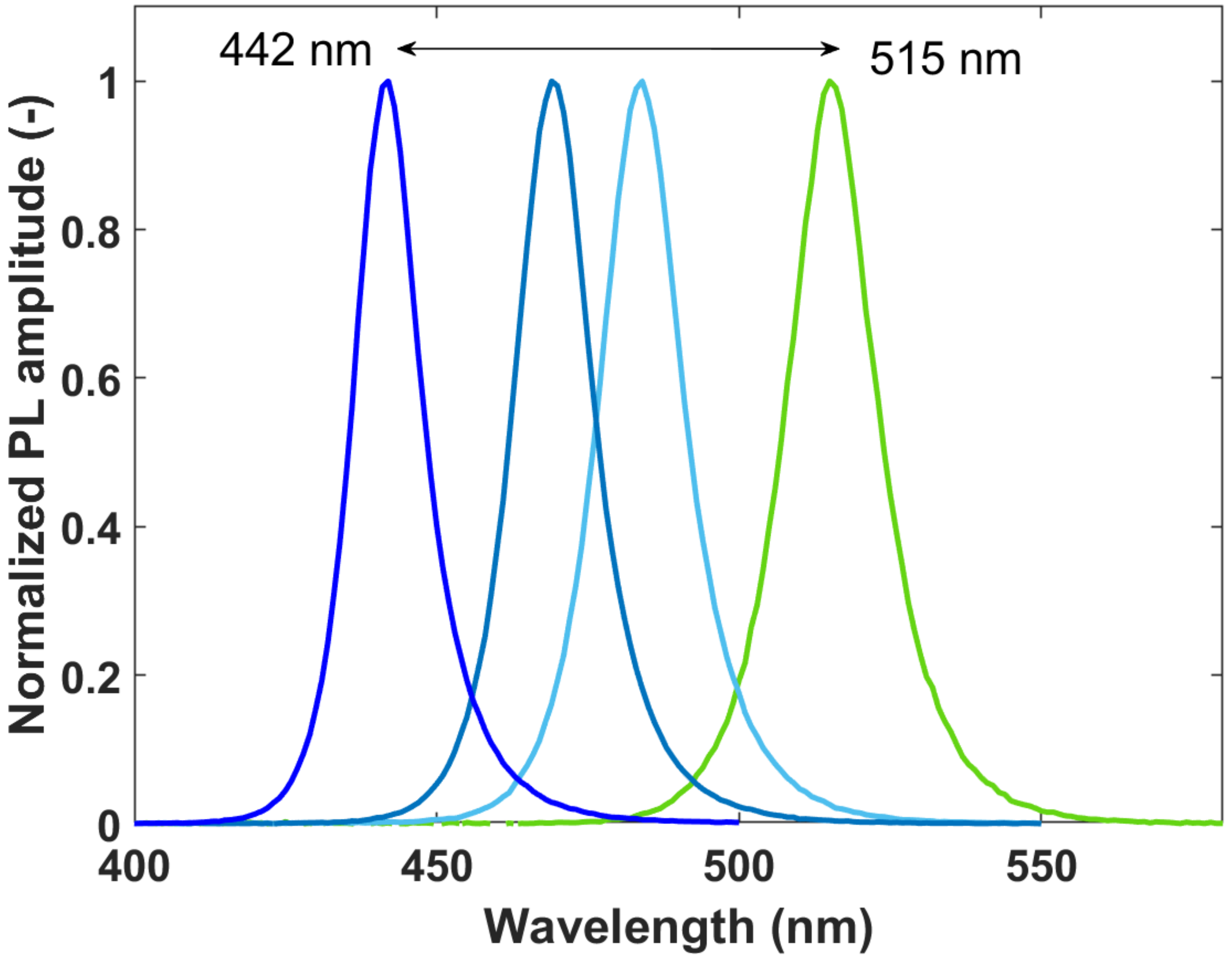


Polymerisation

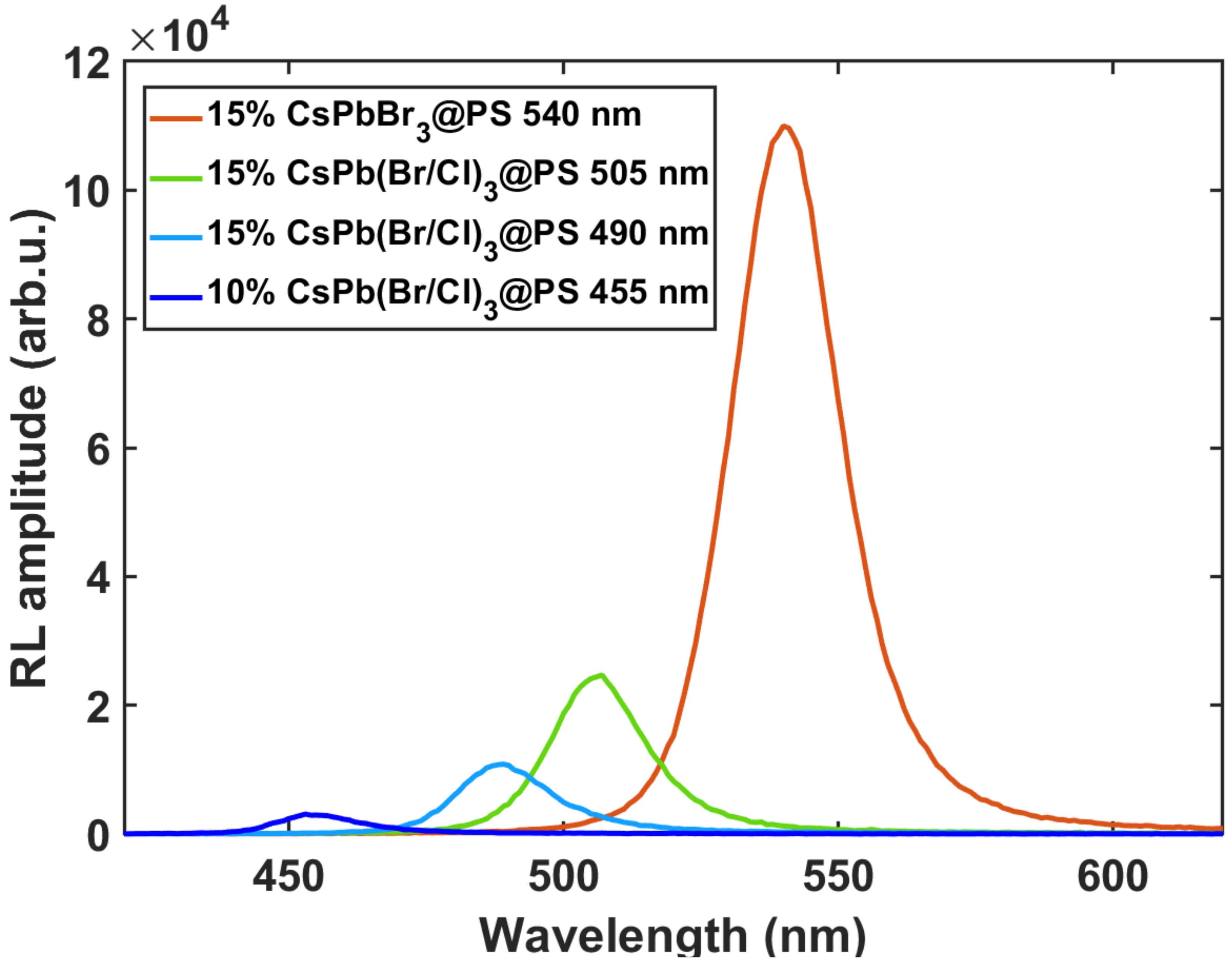
Nanocrystals embedded in polymer





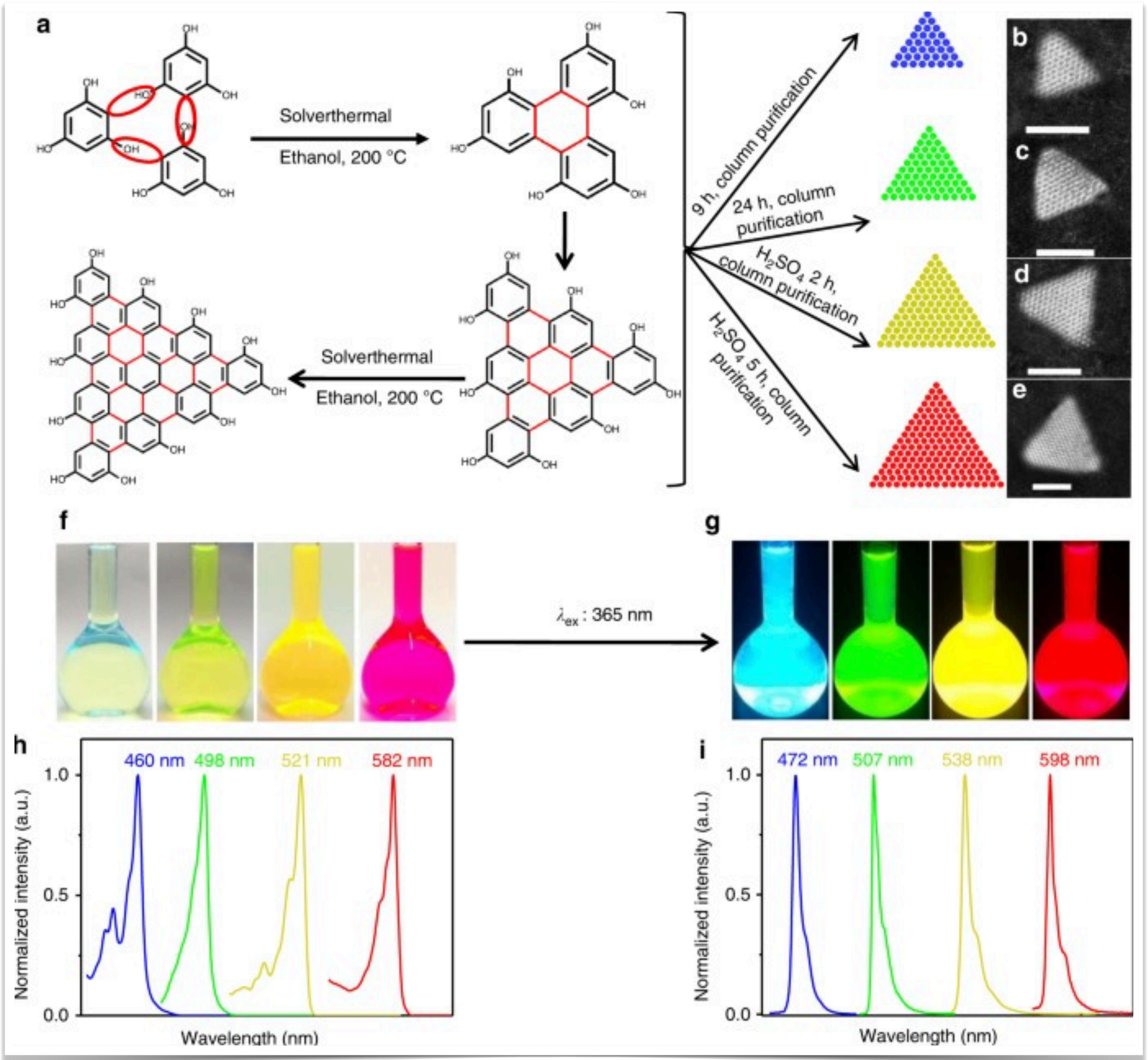


Courtesy J. Kral, CTU, Prague



QUANTUM DOTS: CHROMATIC CALORIMETRY

- idea: seed different parts of a "crystal" with nano composite scintillators emitting at different wavelengths, such that the wavelength of a stimulated fluorescence photon is uniquely assignable to a specific position



F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

QUANTUM DOTS: CHROMATIC CALORIMETRY

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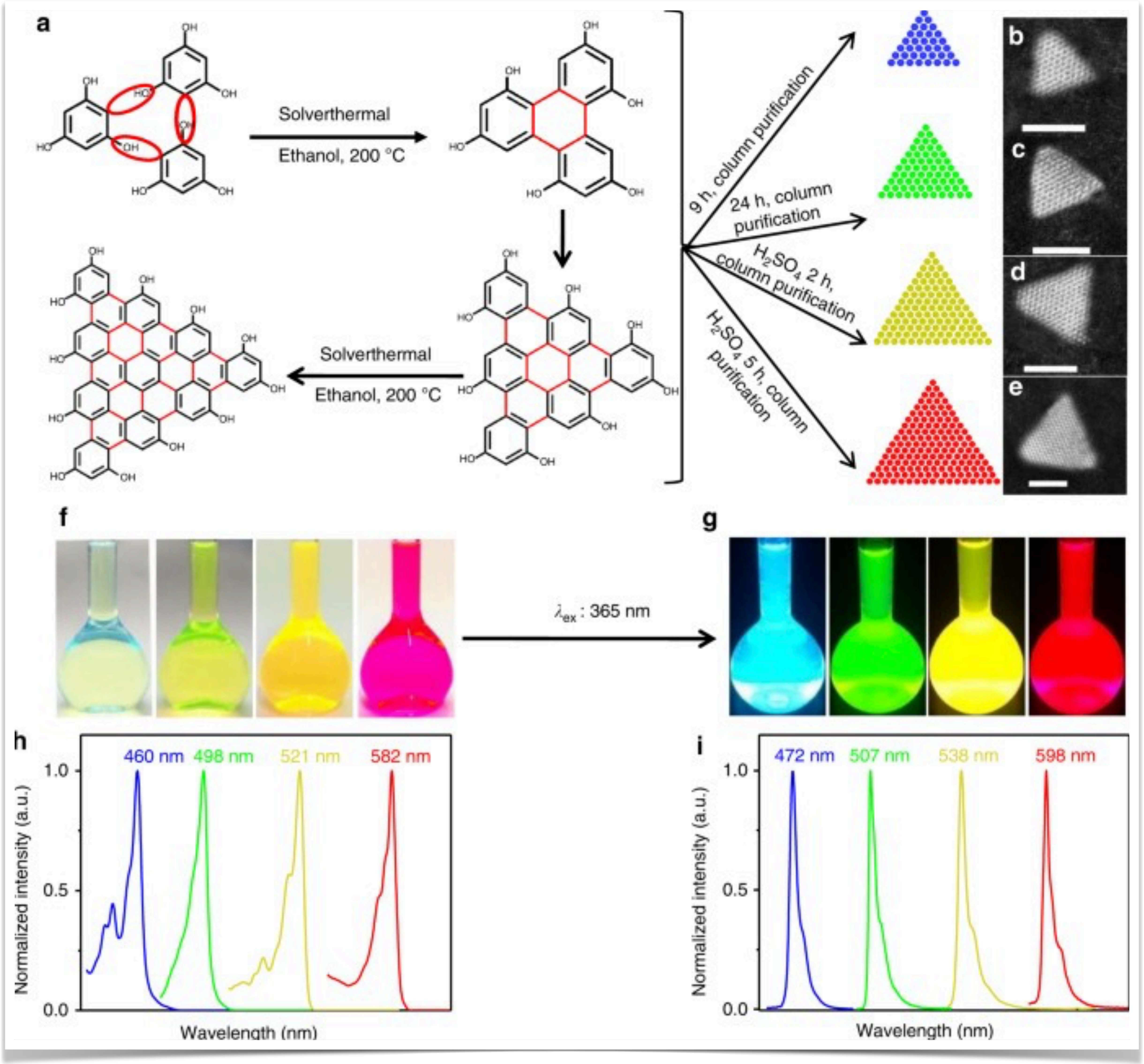
  requires:
  - narrowband emission (~20nm)
  - only absorption at shorter wavelengths
  - short rise/decay times

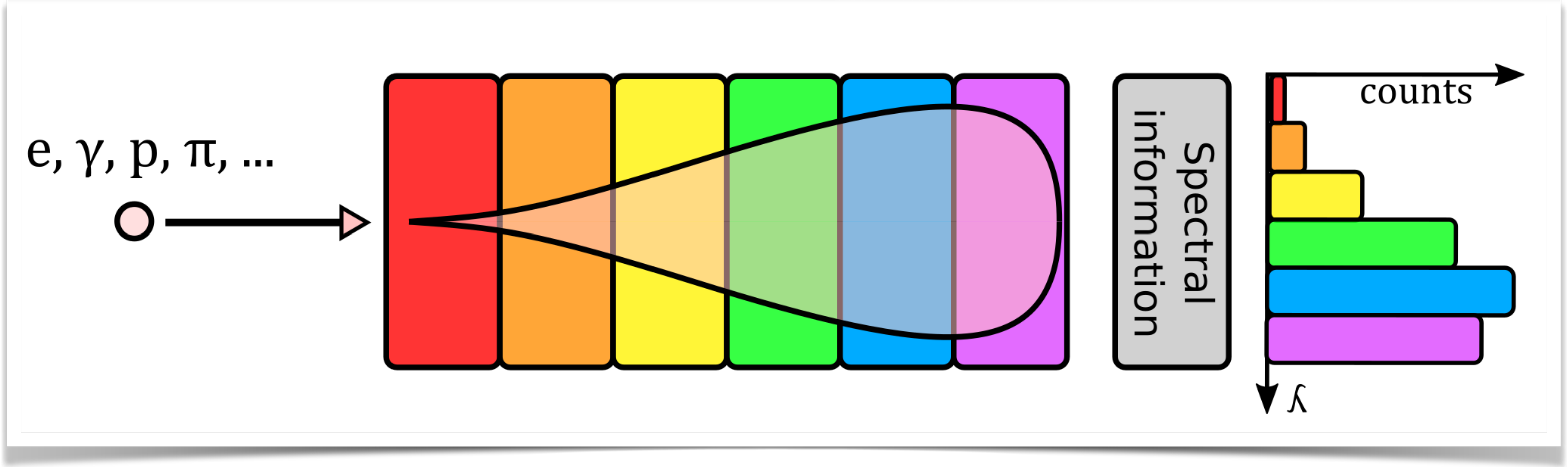
chromatic tunability optimizes for quantum efficiency of PD (fast, optimizable WLS)



F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

CHROMATIC CALORIMETRY: BASIC PRINCIPLE

concept: using different scintillating materials along the scintillator module to follow the shower propagation and a detector capable of discriminating different emission λ.



Absorption and emission of the "crystal" stack have to be <u>one directional transparent</u>.

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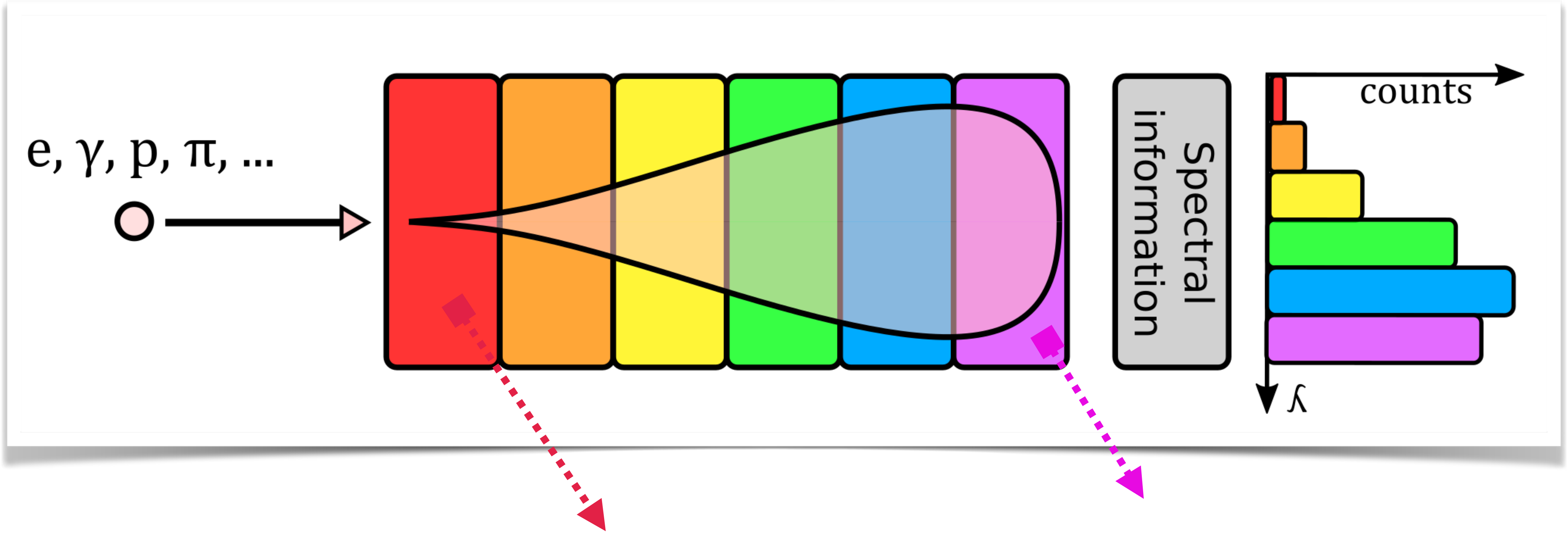
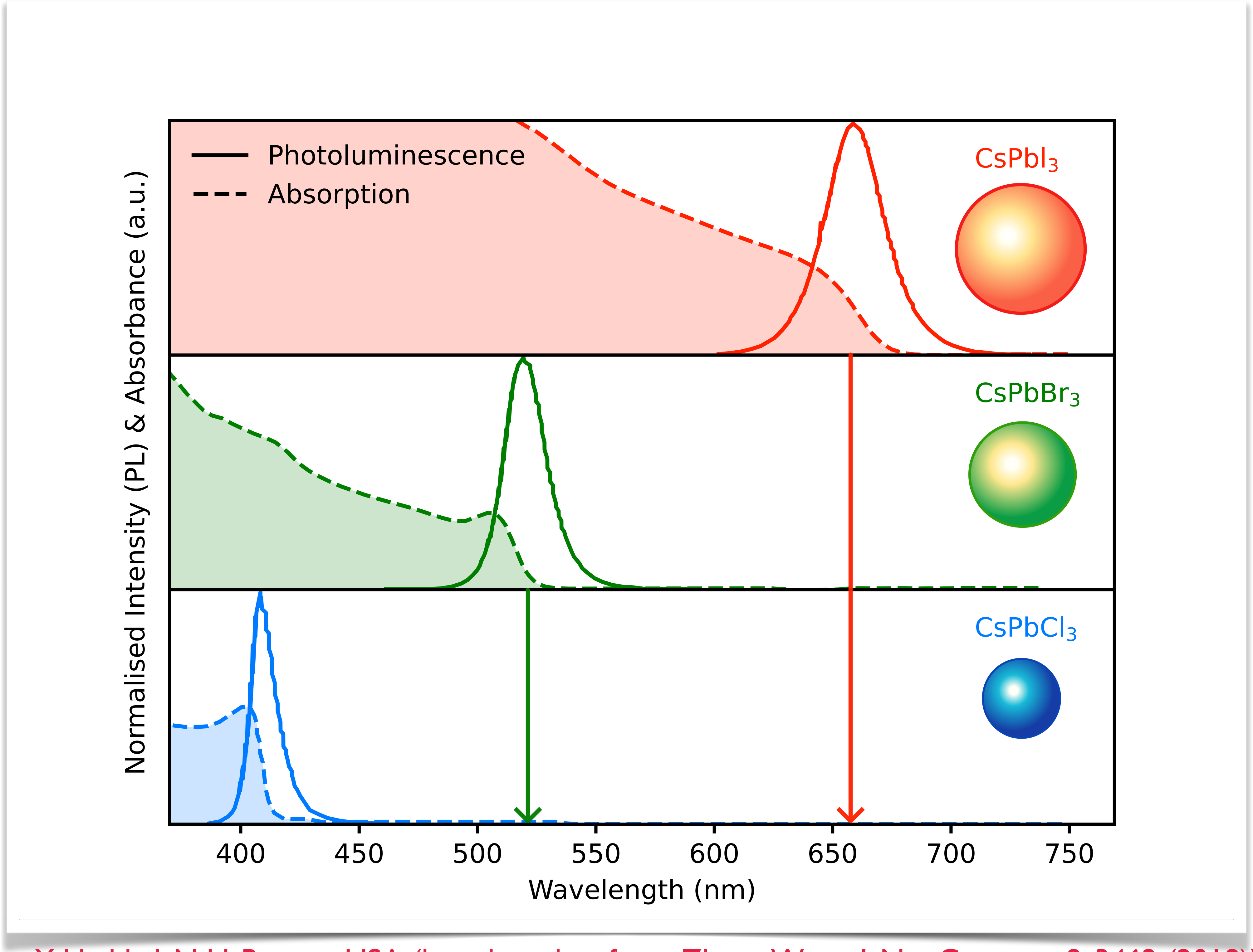


Absorption and emission of the "crystal" stack have to be one directional transparent.



courtesy Y. Haddad, N U, Boston, USA (based on data from: Zheng, W. et al, Nat Commun 9, 3462 (2018))

leftmost scint. material : absorb wavelengths < 650 nm emit at > 680 nm

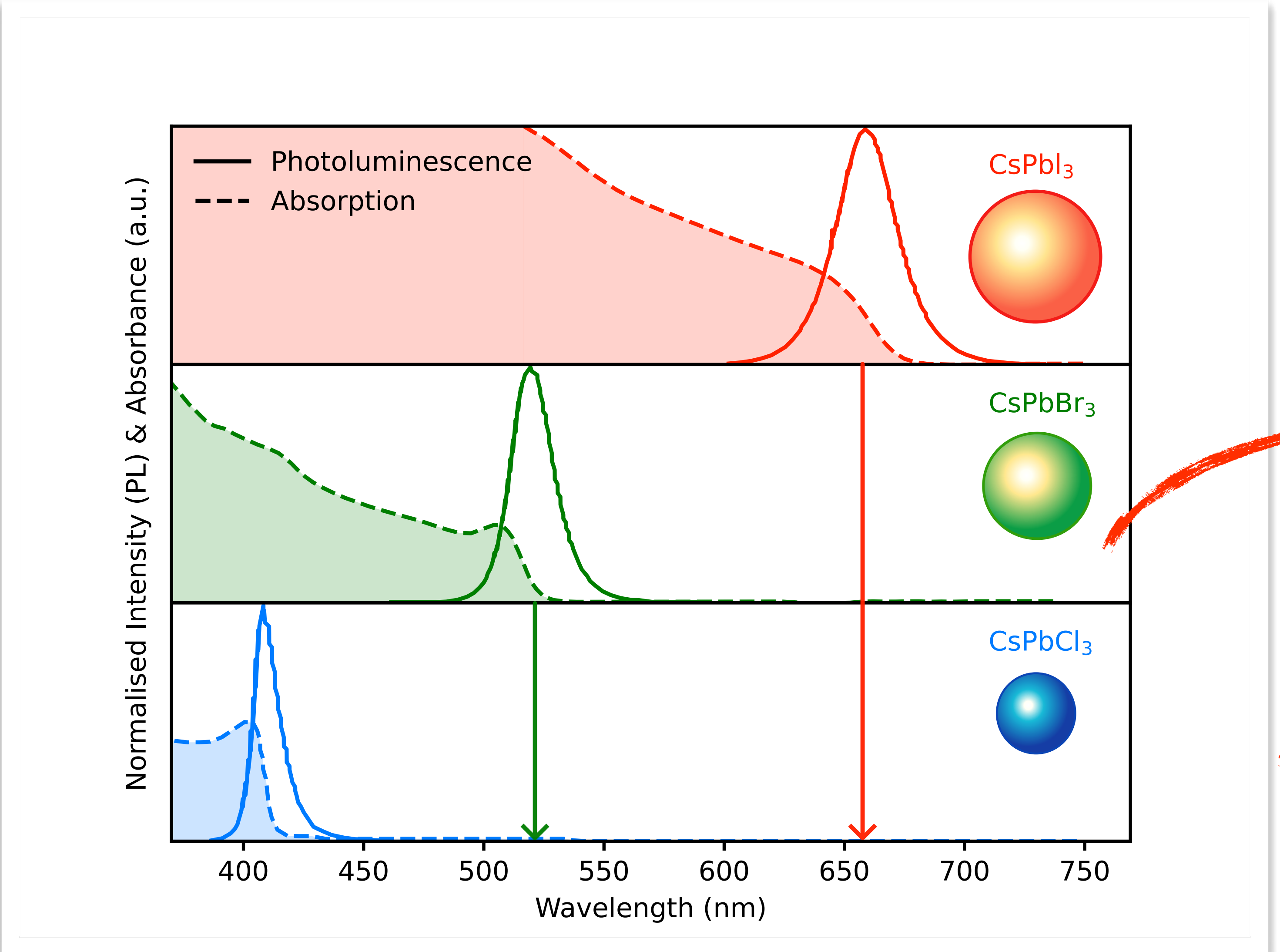
next band : absorb wavelengths < 590 nm emit at > 590 nm

rightmost scint. material : absorb wavelengths < 410 nm emit at > 420 nm

Geant4 Simulation

To understand QDs embedded in the chromocalo module, we performed simulations as a supportive idea of this theory

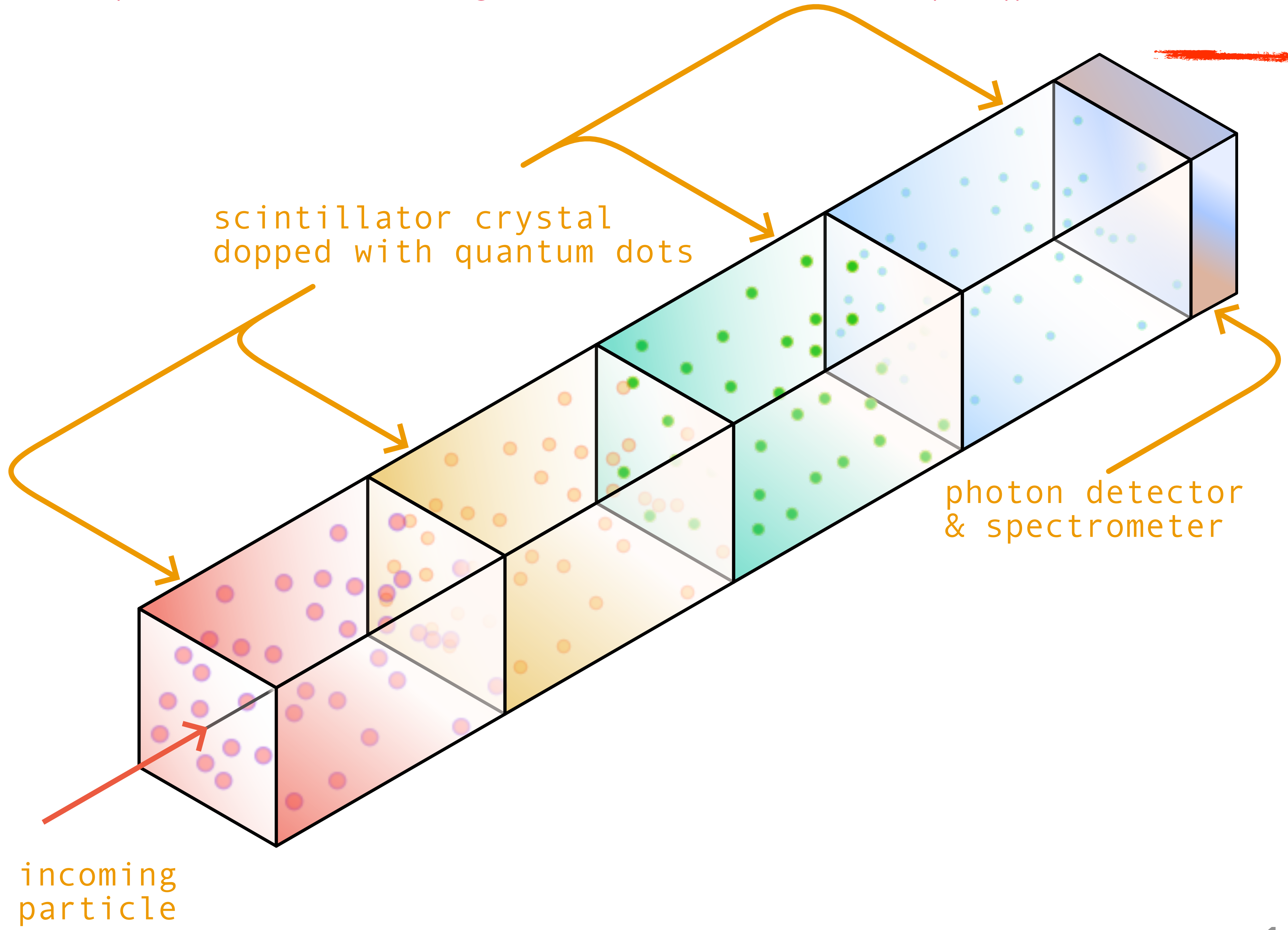
ADVENT OF CHROMATIC CALORIMETRY

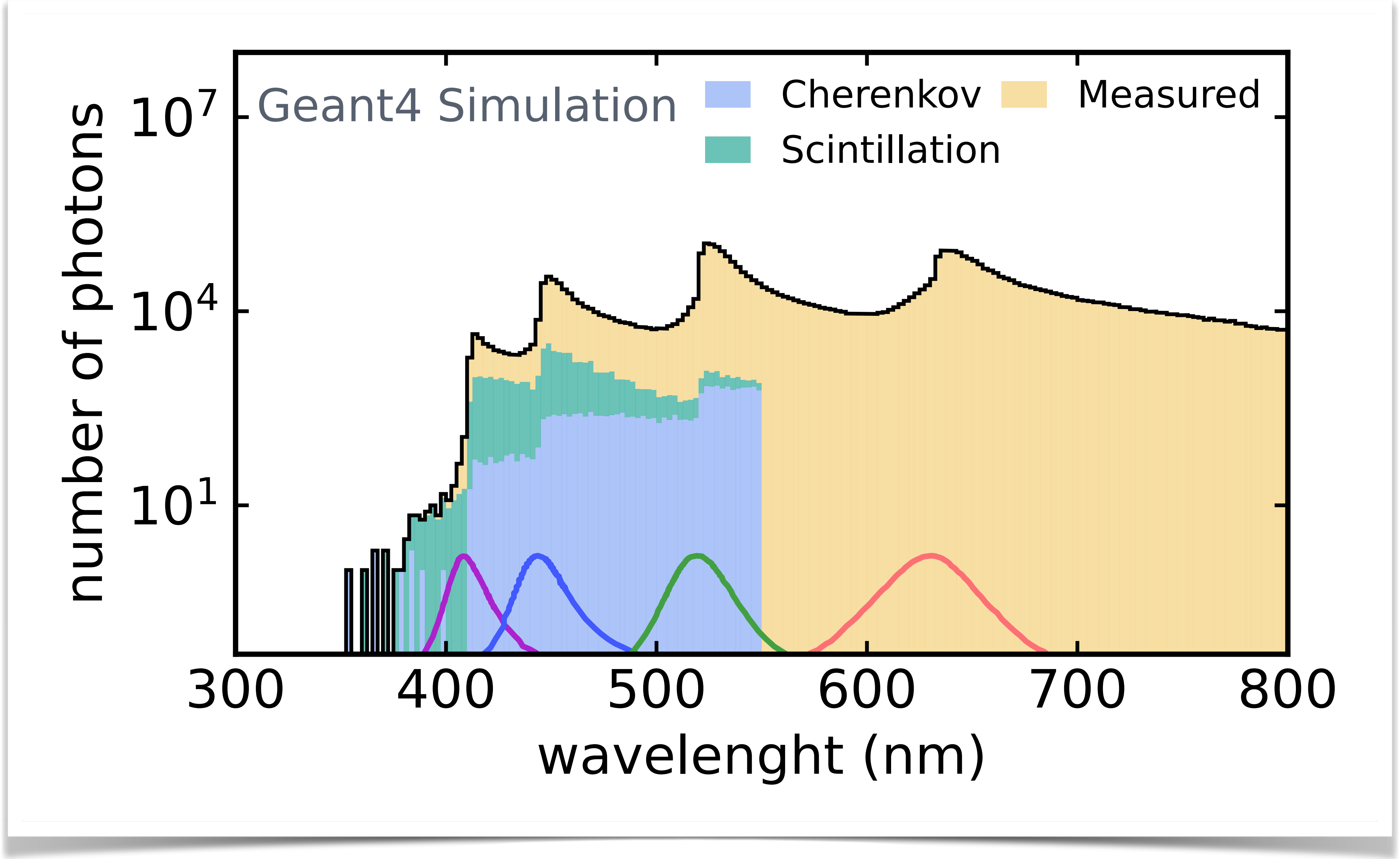


courtesy Y. Haddad, N U, Boston, USA (based on data from: Zheng, W. et al, Nat Commun 9, 3462 (2018))

- First layer: QDs absorb wavelengths <650nm emit at 670nm
- next layer: QDs absorb wavelengths <520nm emit at 530 nm
- .....
- Last layer: QDs absorb wavelengths <410nm emit at 420 nm

Readout

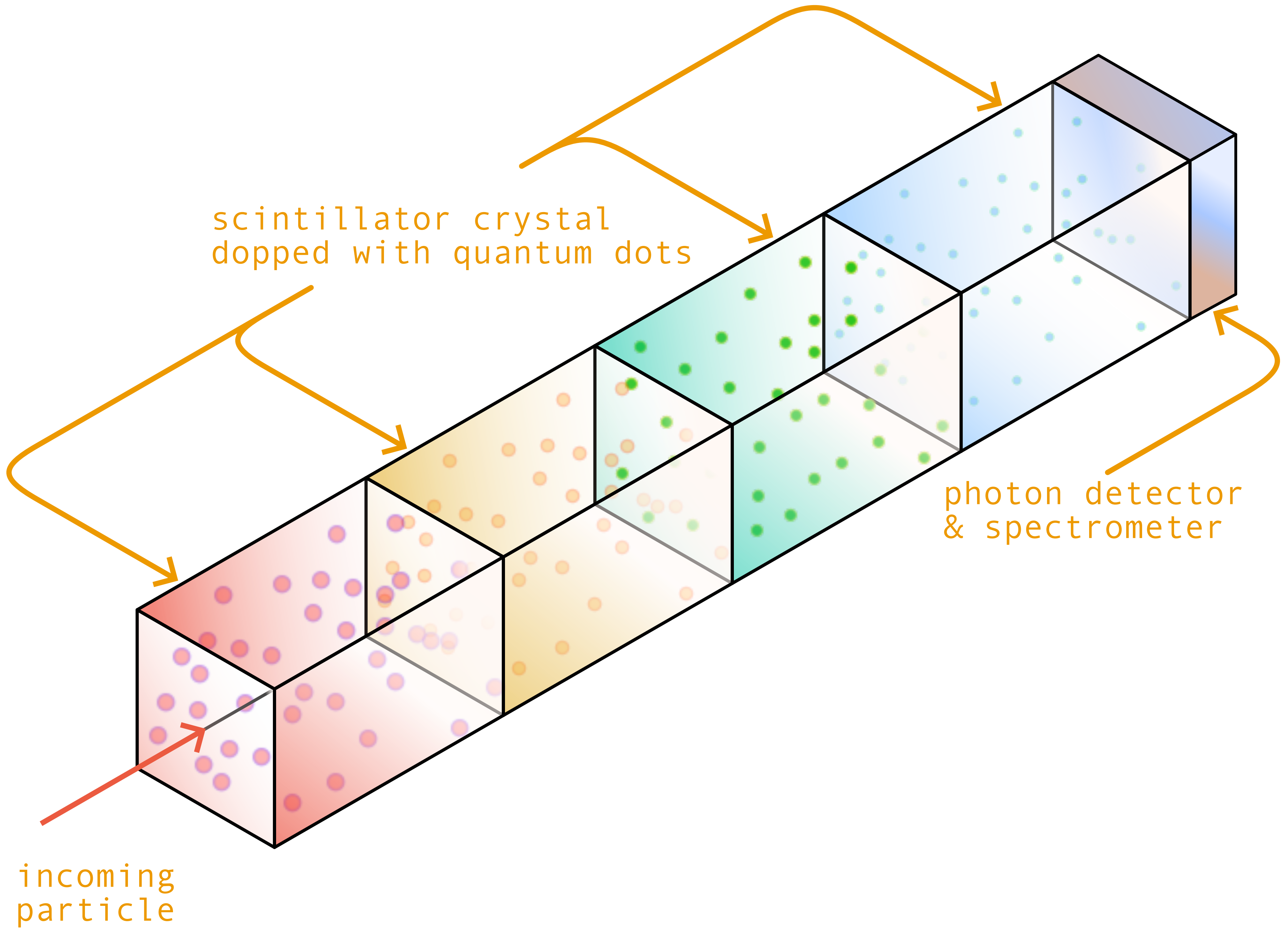


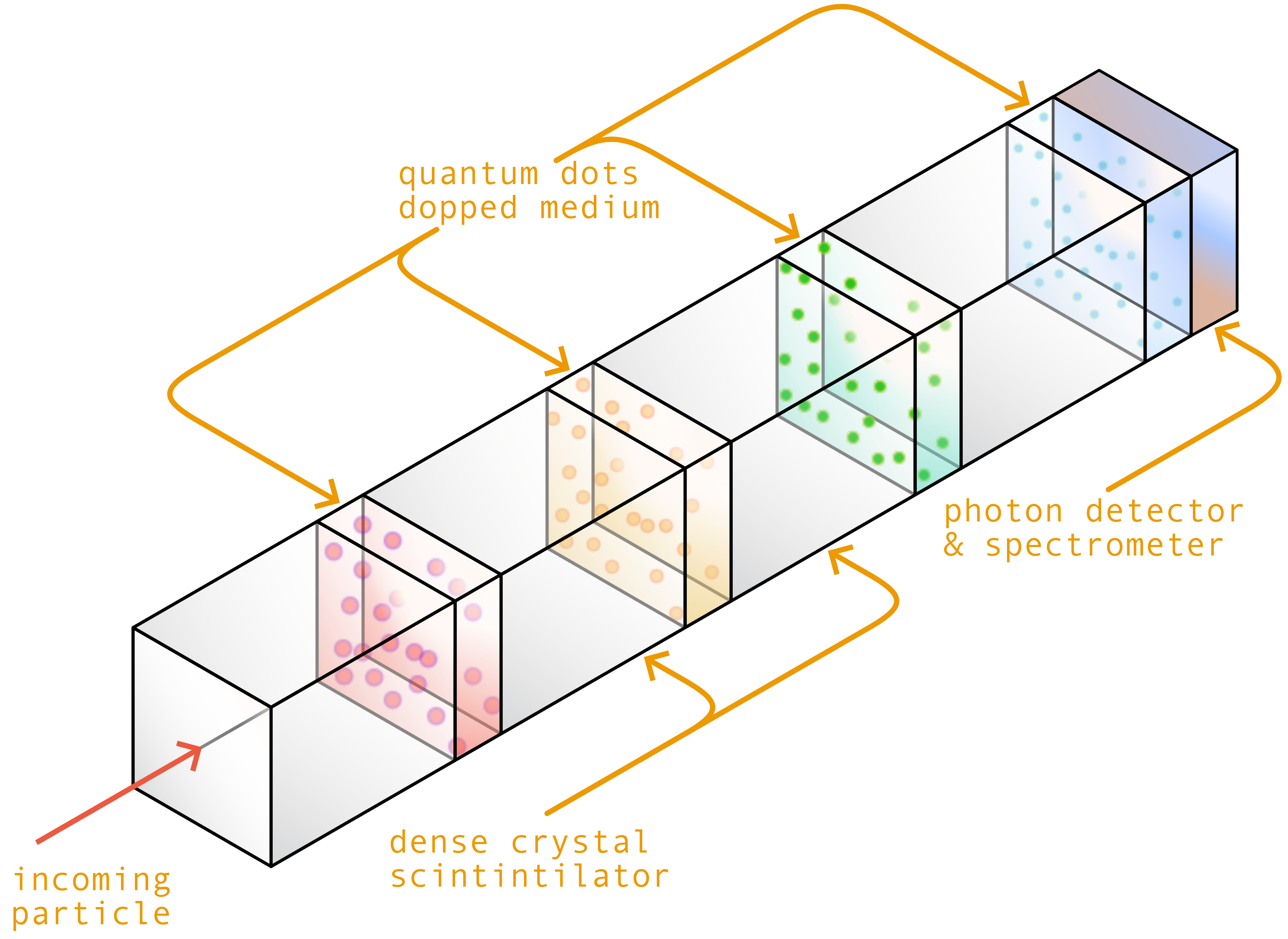


*** If high-Z substrate transparent in 400-700nm → no re-absorption of emitted light*

courtesy Y. Haddad, N U, Boston, USA

CHROMATIC CALORIMETRY: TWO OPTIONS





- Two Design Approaches: Exploring direct embedding of quantum dots in high-Z materials and a hybrid design combining inorganic and organic scintillators.
  - Working with specialized labs to develop suitable inorganic crystals for direct embedding.
- Hybrid Design Feasibility: Utilising organic scintillators like nanocomposite scintillators (nano scintillators embedded in a host polymer matrix) or like PbF2 as absorber -no emission, transparent than PWO, no scintillation-ideal case)
- Key Parameter Determination: Assessing quantum dot concentration, transparency, radiation hardness, time response, and light yield in various combinations.

courtsey Y. Haddad, N U, Boston, USA

CHROMATIC CALORIMETRY: SIMULATION

preliminary

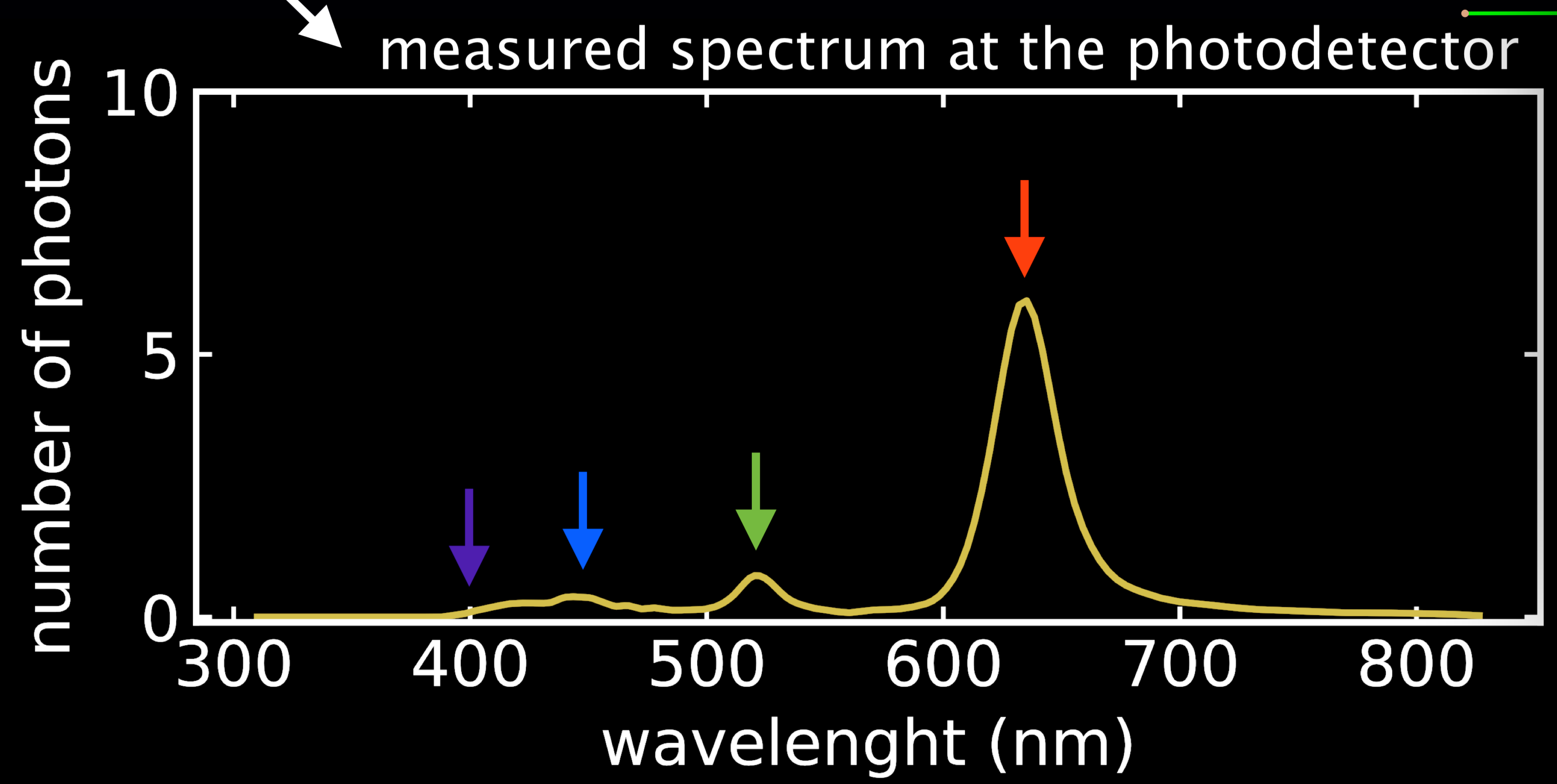
courtsey Y. Haddad, N U, Boston, USA

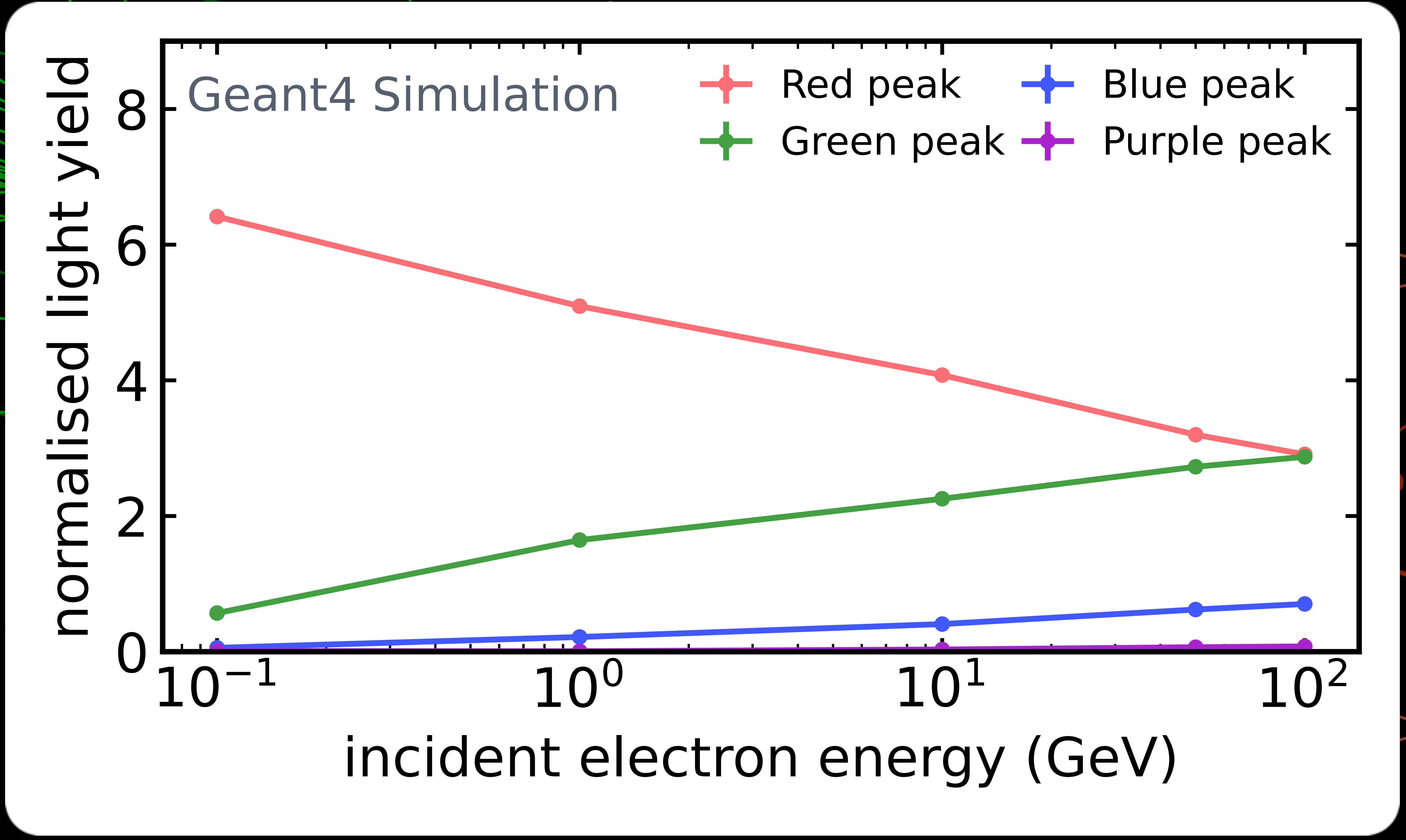
CHROMATIC CALORIMETRY: SIMULATION

CHROMATIC CALORIMETRY: SIMULATION

Simulated 50 GeV electron event

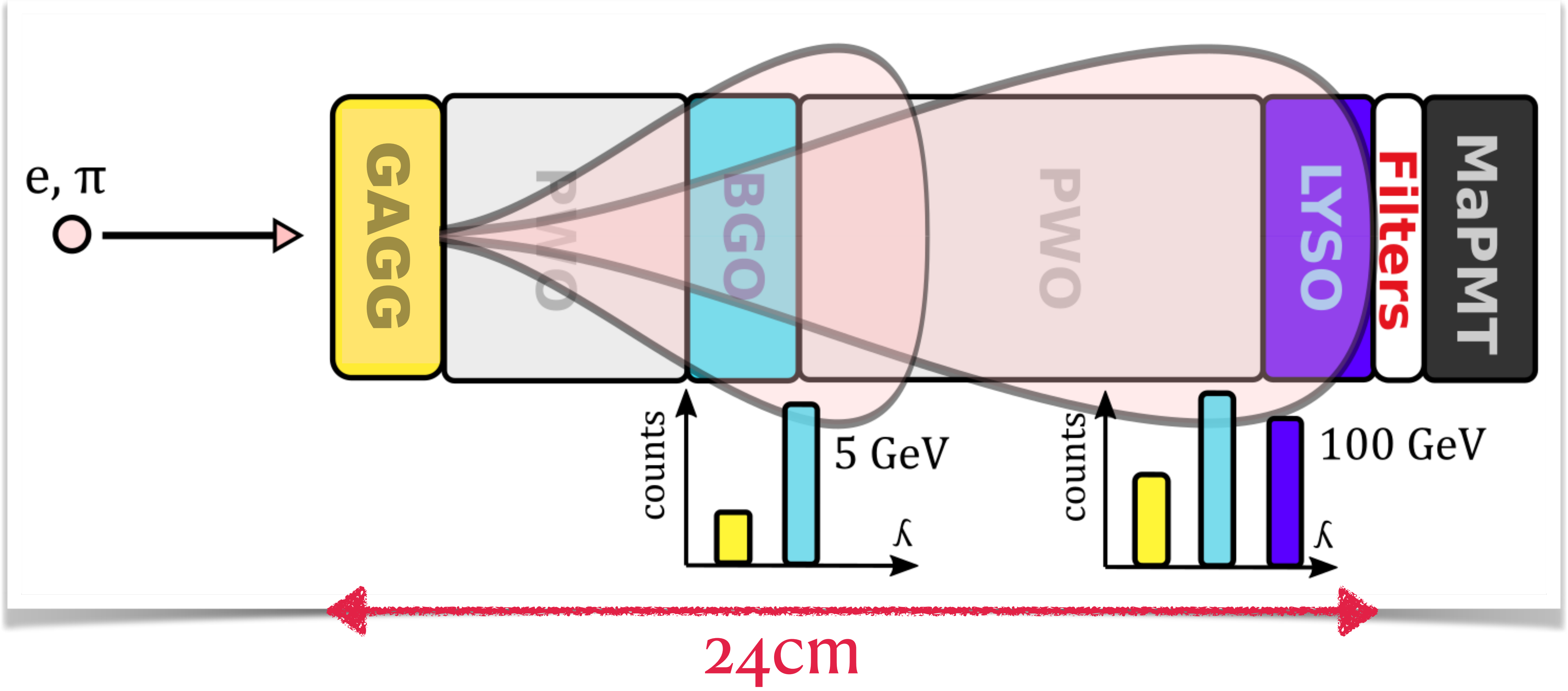
reconstruction of energy is possible, as energy increases-shower moves inside the calo module,reconstruction of energy using chromatic info is proven





CHROMATIC CALORIMETRY: PROOF OF CONCEPT, TEST-BEAM 2023

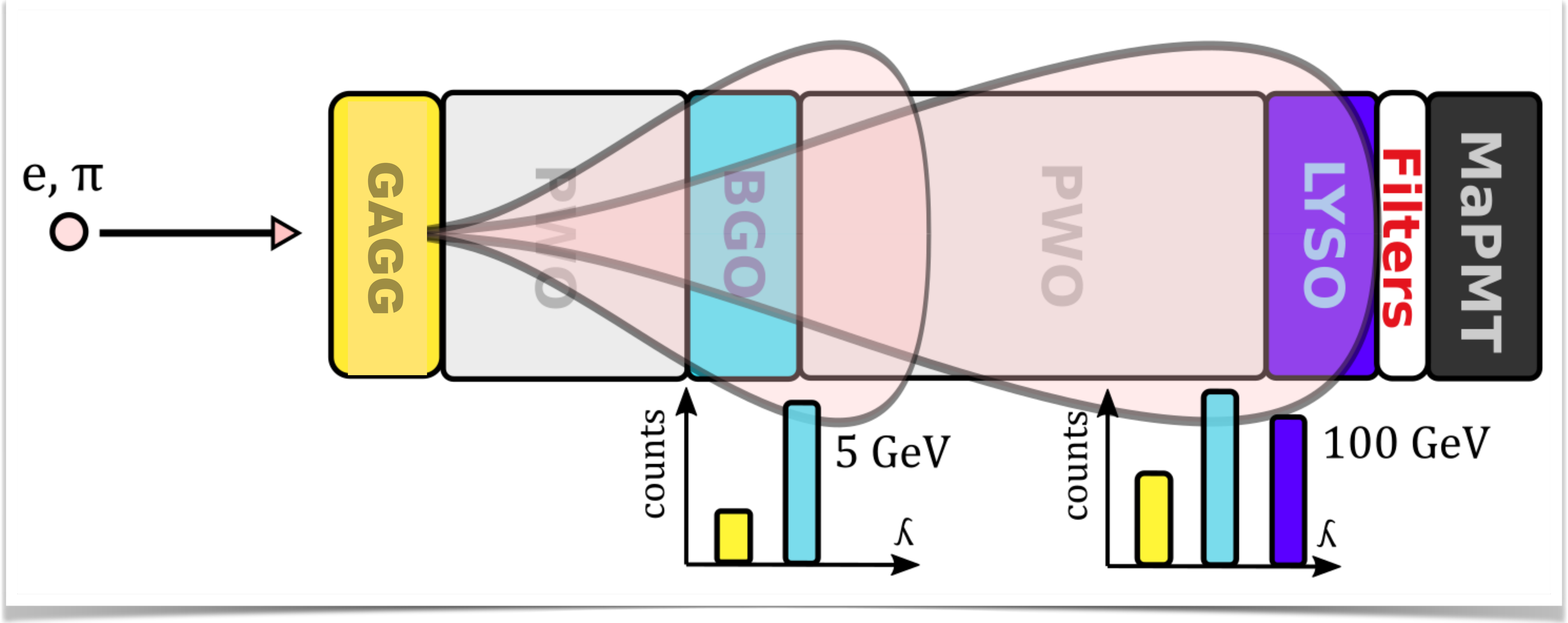
- seeding/embedding of QDs in the calo module is not feasible at the moment
- the first iteration of chromo calo, validating the relevance of this method
- utilizing standard inorganic bulk scintillating materials having different emission spectra, and PWO was chosen as an absorber although it is not ideally transparent



The order of the crystals along the shower propagation was chosen to mitigate re-absorption effects, ensuring efficient photon transmission throughout the stack.

CHROMATIC CALORIMETRY: TEST BEAM 2023

The crystal stack was constructed using the following inorganic scintillators (the last dimension is along the longitudinal shower propagation):
2x2x2 cm^3 gadolinium aluminum gallium garnet (**GAGG, 540 nm peak emission**),
2x2x5 cm^3 and 2x2x12 cm^3 lead tungstate (**PWO, 420 nm peak emission**),
2x2x3 cm^3 bismuth germanate (**BGO, 480 nm peak emission**), and
2x2x2 cm^3 lutetium yttrium oxy orthosilicate (**LYSO, 420 nm peak emission**)



objective: Study of the pulse shapes obtained with the scintillator module composed of crystal stacks with different energy exposition

to determine electron-pions discrimination, longitudinal shower profile, and energy deposited in the crystal stack.

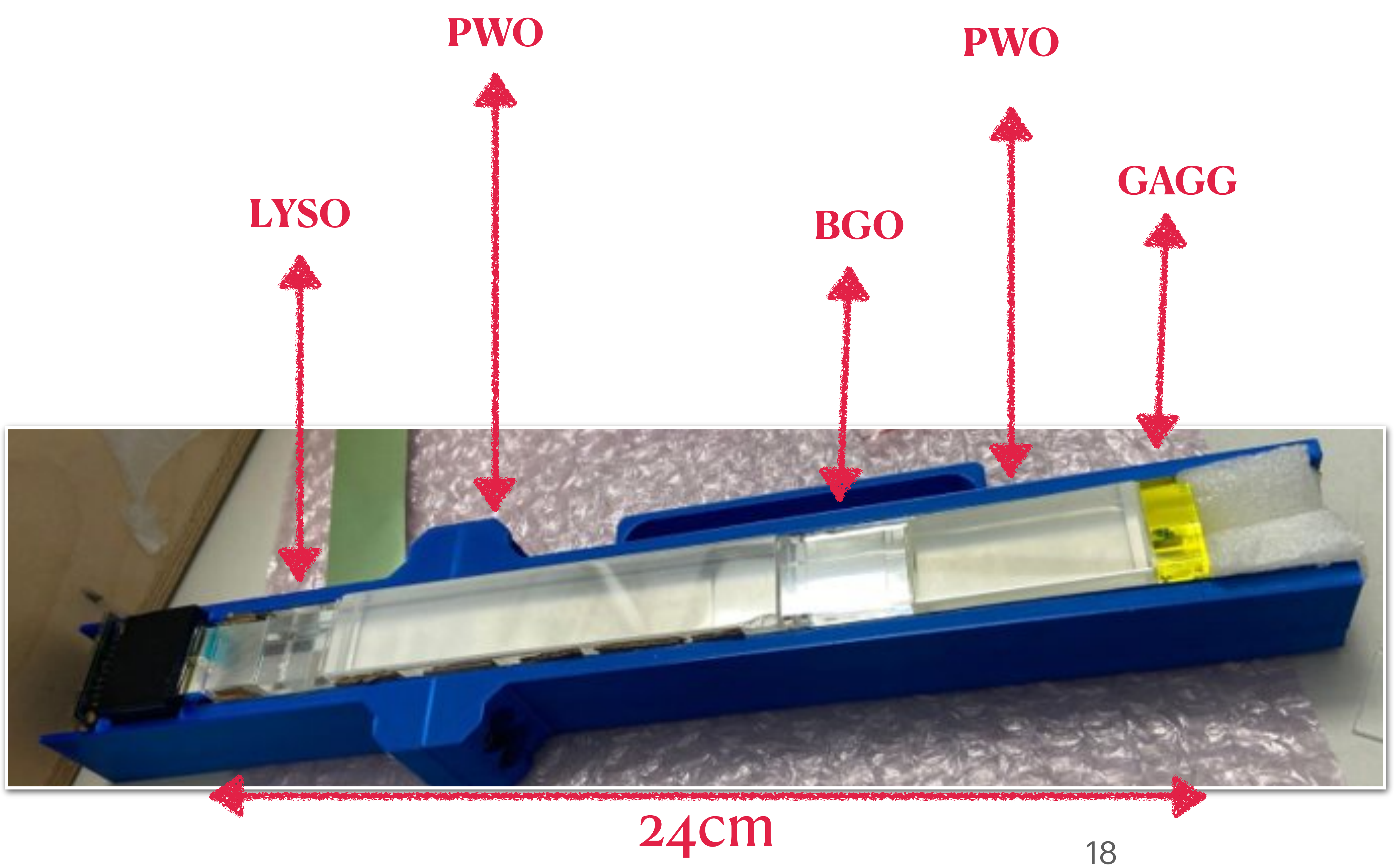
MATERIALS: CHROMATIC CALORIMETRY: TB 2023

GAGG [radiation length = 1.51 cm (for 1 cm length, 1.32 X0)]

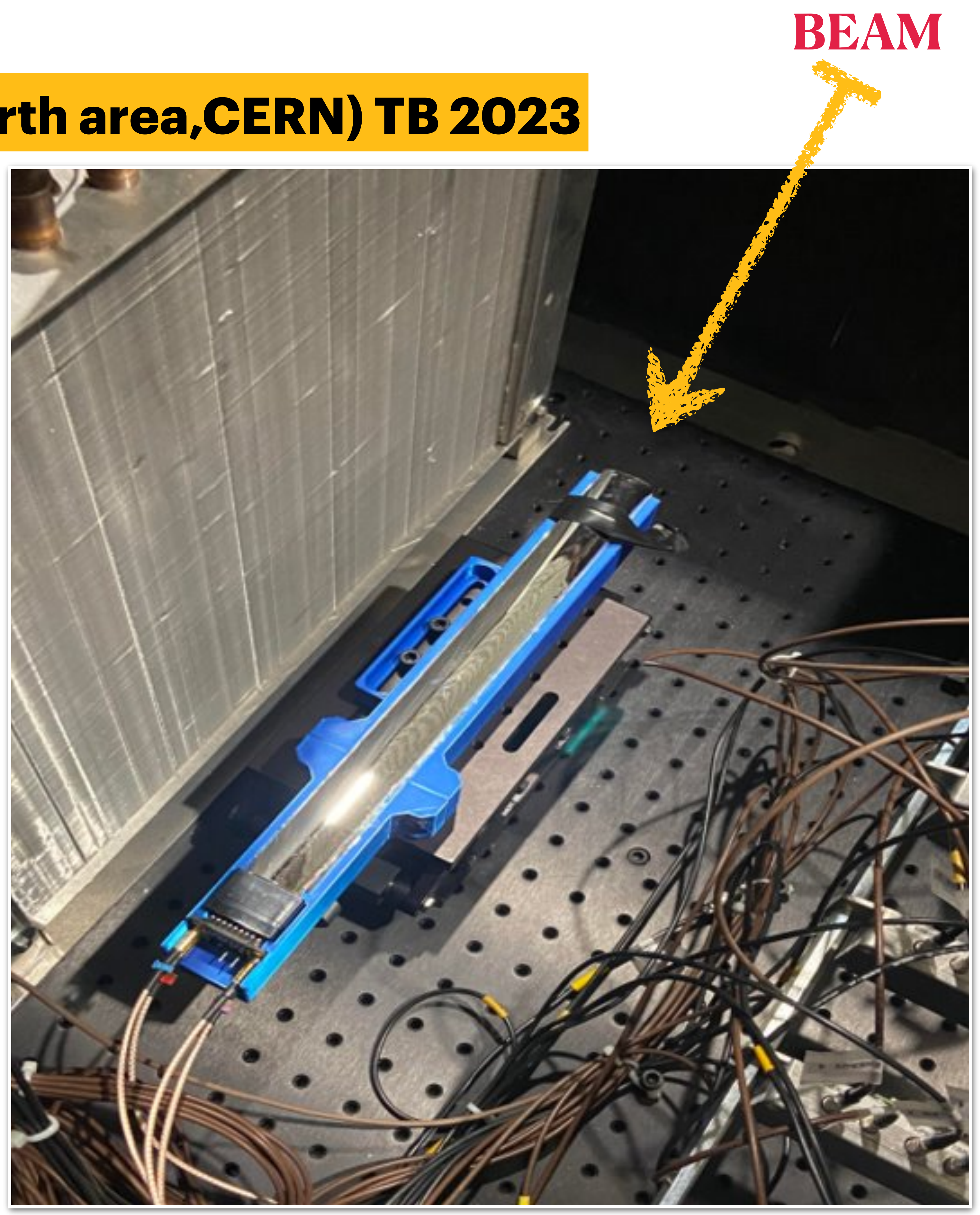
BGO [radiation length = 1.2 cm (for 3 cm length, 2.7 X0)]
-> in the shower max

LYSO [radiation length = 1.1 cm (for 2 cm length, 1.8 X0)]

PWO is used for adding X0 without compromising the transparency of the crystals' emission



SPS(north area,CERN) TB 2023



Measurements
25-100 GeV electrons
100 GeV pions
150 GeV muons

photodetector

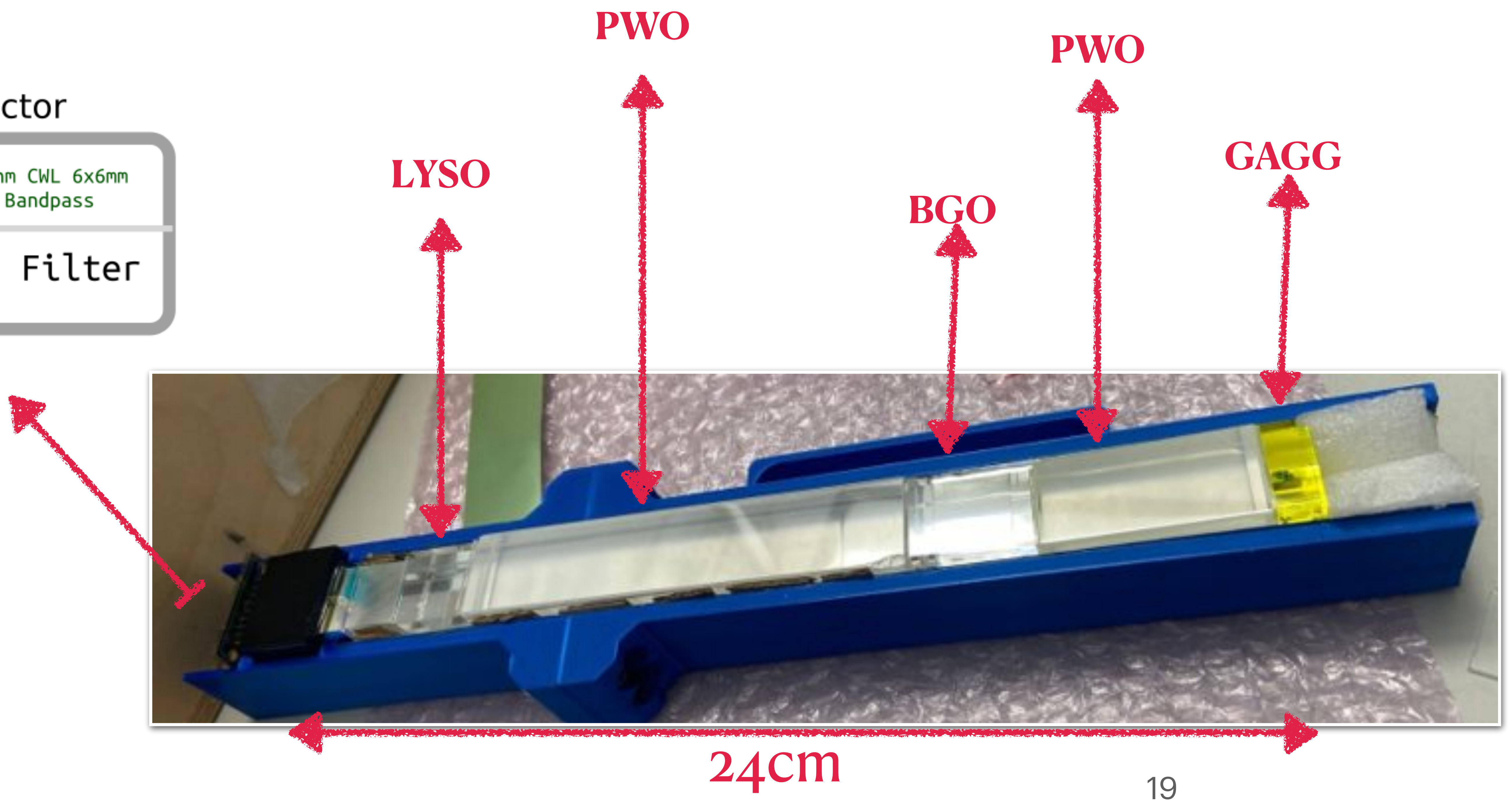
Multianode PMT (MAPMT, Hamamatsu R7600-M4) from Hamamatsu
Active area 18x18 milli-meter.
A light mixer was used to spread the light between LYSO and the filters

filters

long pass for the GAGG light: FELH0550 from Thorlab.
short pass for the LYSO light: FESH0450 from Thorlab.
bandpass for the BGO: FB490-10 from Thorlab.

Photo-detector

FELH0550	475nm CWL 6x6mm OD8 Bandpass
High Performanc OD 4.0 Shortpass Filters	No Filter



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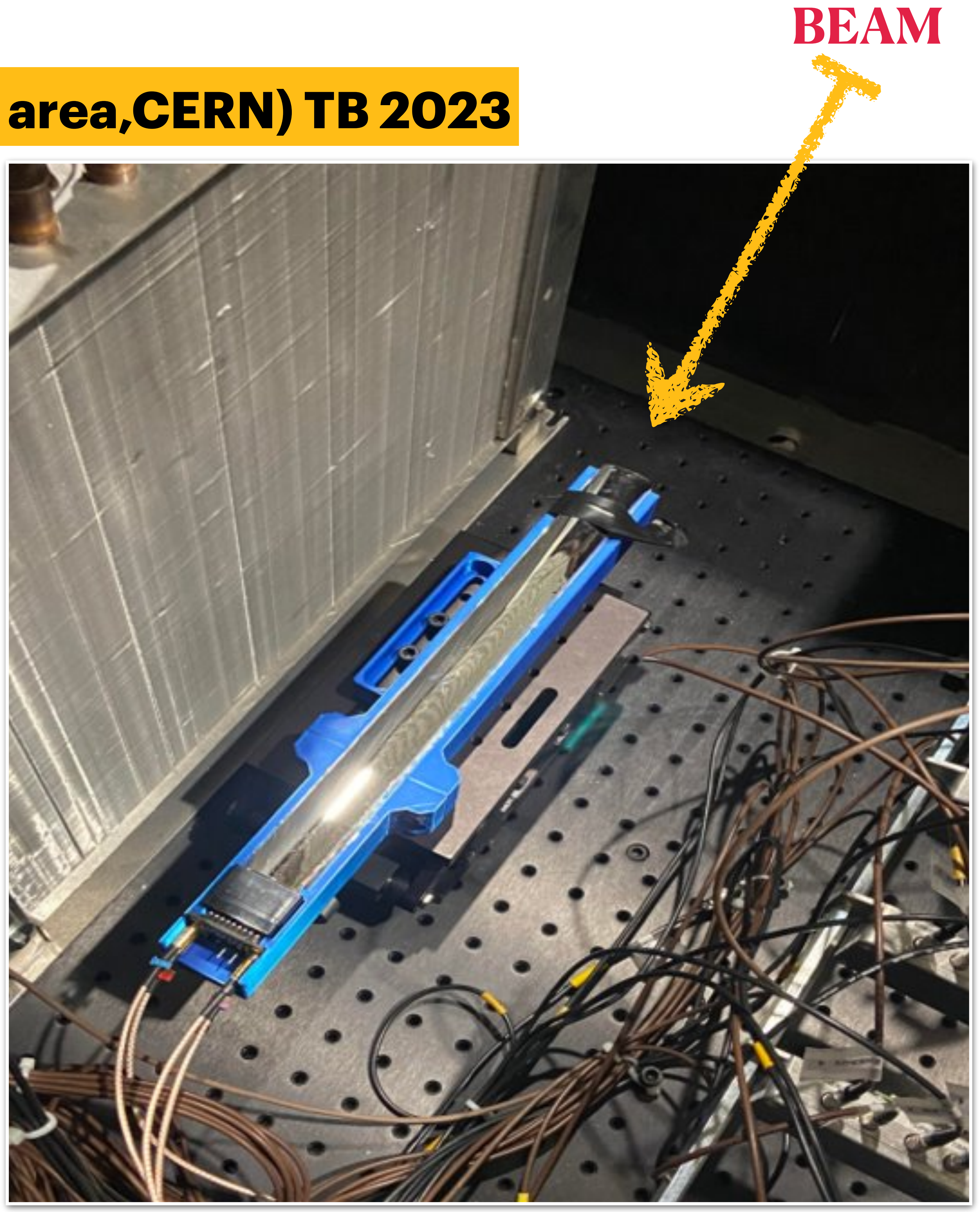
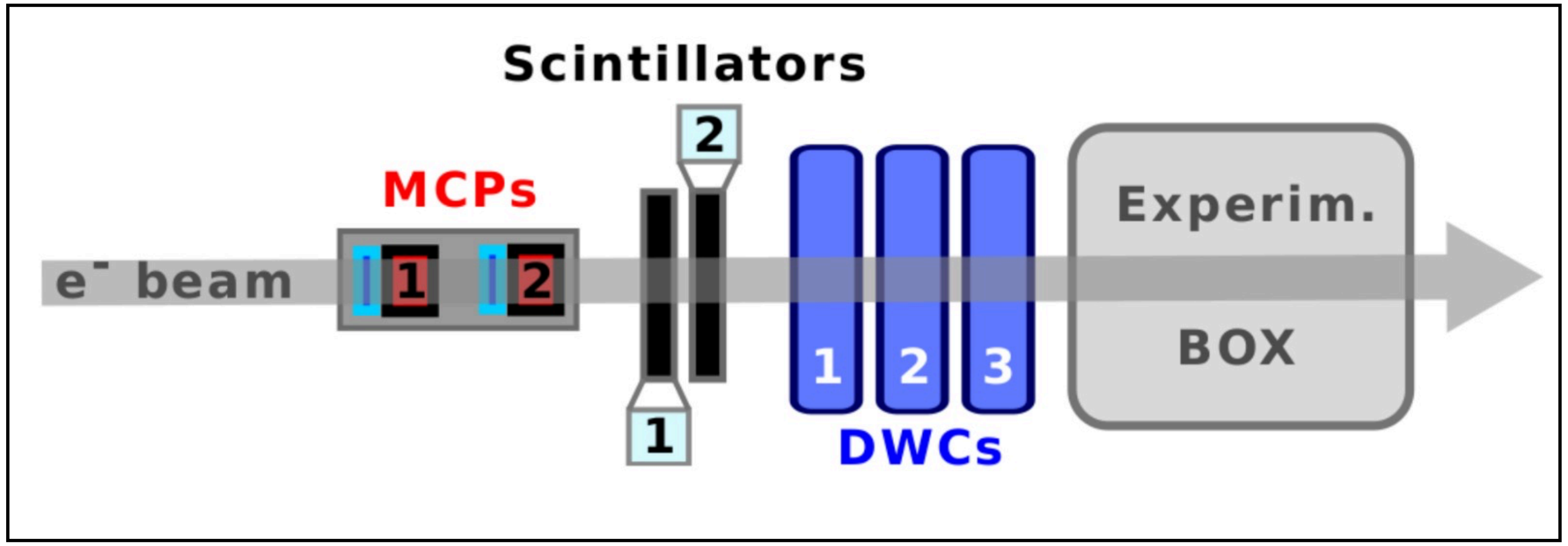


TEST-BEAM SETUP



An, L. & Auffray, E. et. al (2022) Performance of a spaghetti calorimeter prototype 1045. 167629

two MCPs provide the time reference, two scintillating pads the trigger signal, and three DWCs the tracking information.

Measurements
25-100 GeV electrons
100 GeV pions
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SPS(north area,CERN) TB 2023

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FELH0550	475nm CWL 6x6mm OD8 Bandpass
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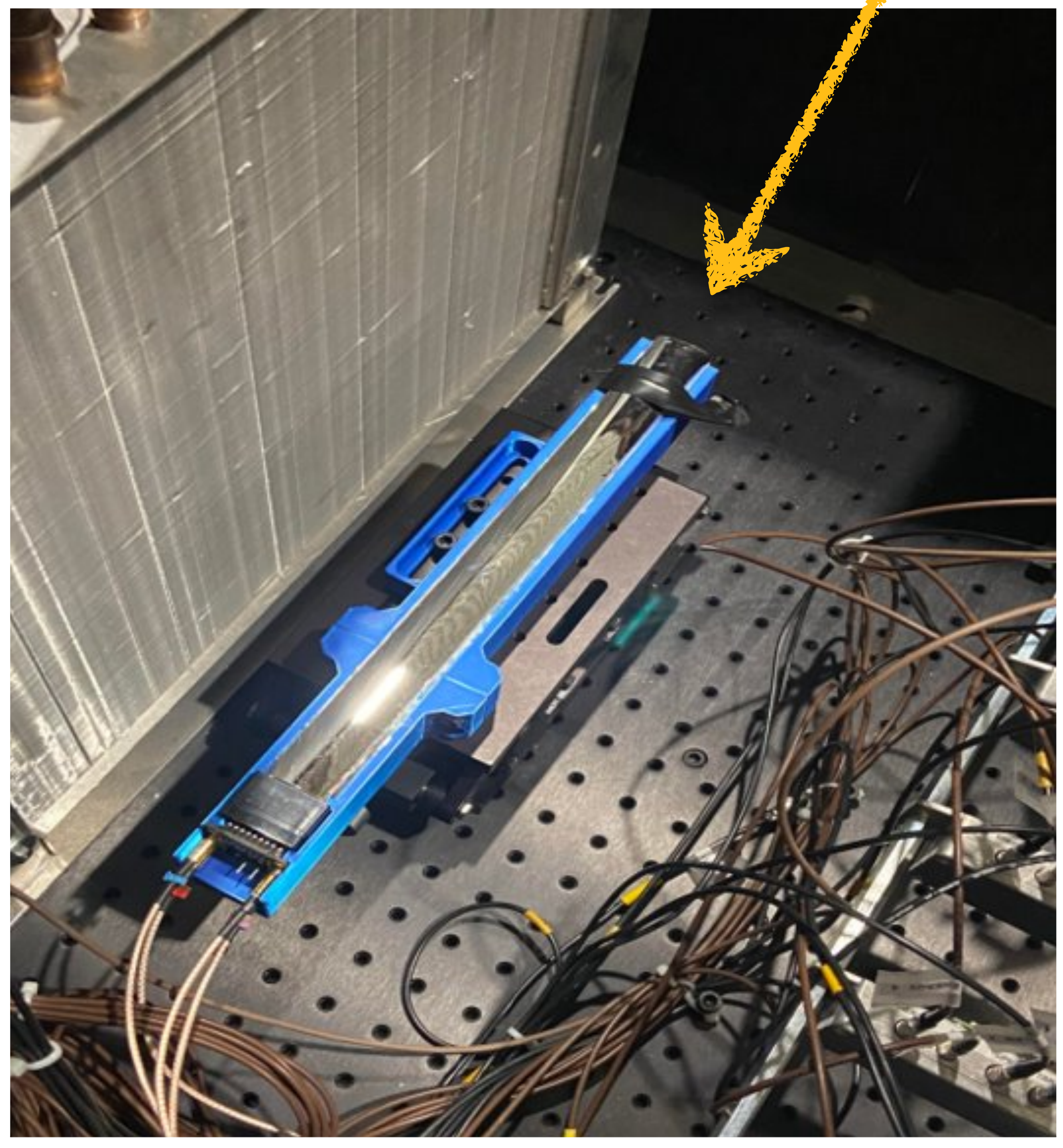
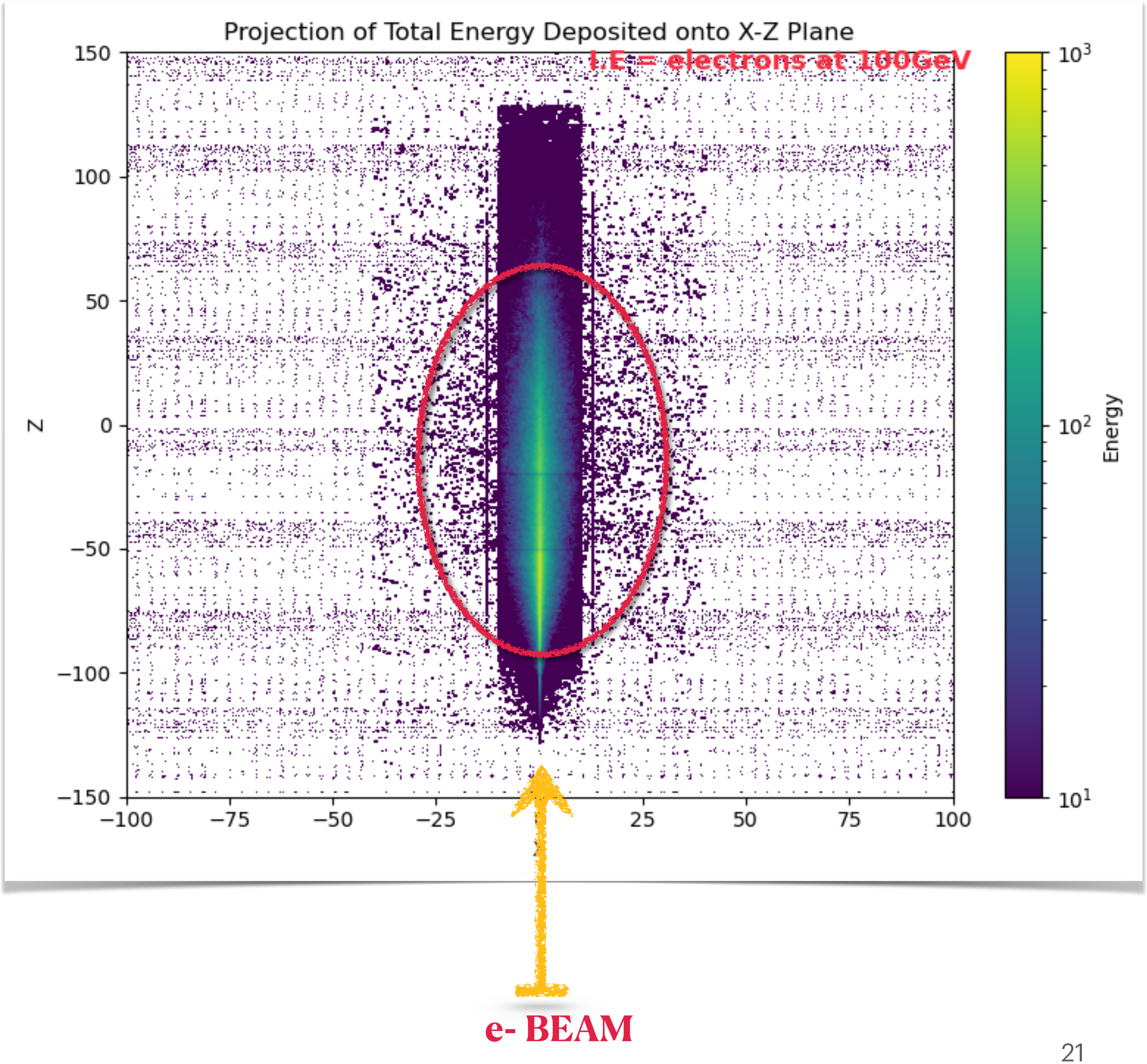


TESTED MODULE SIMULATION-LONGIDUTIONAL SHOWER PROFILE



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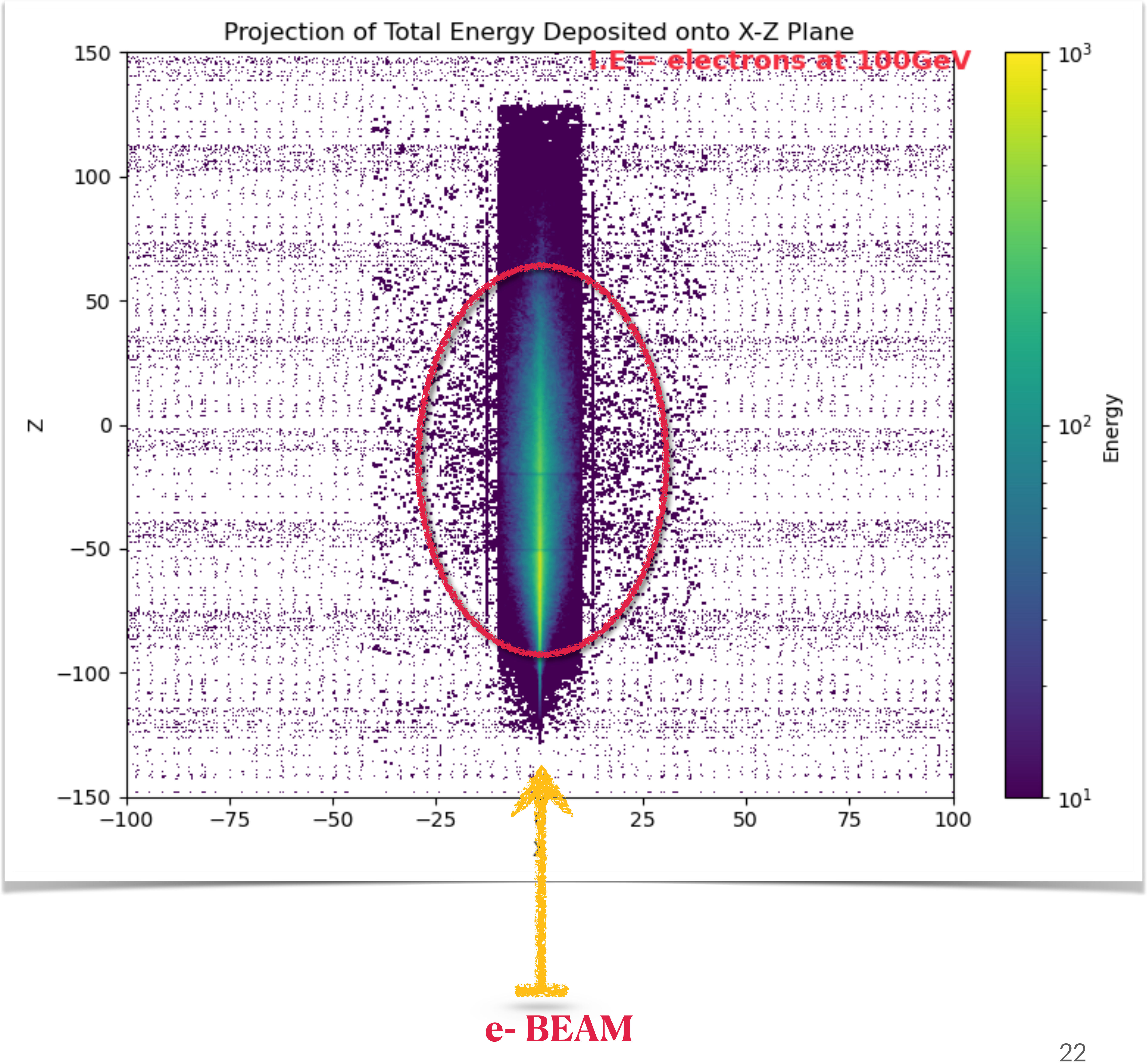
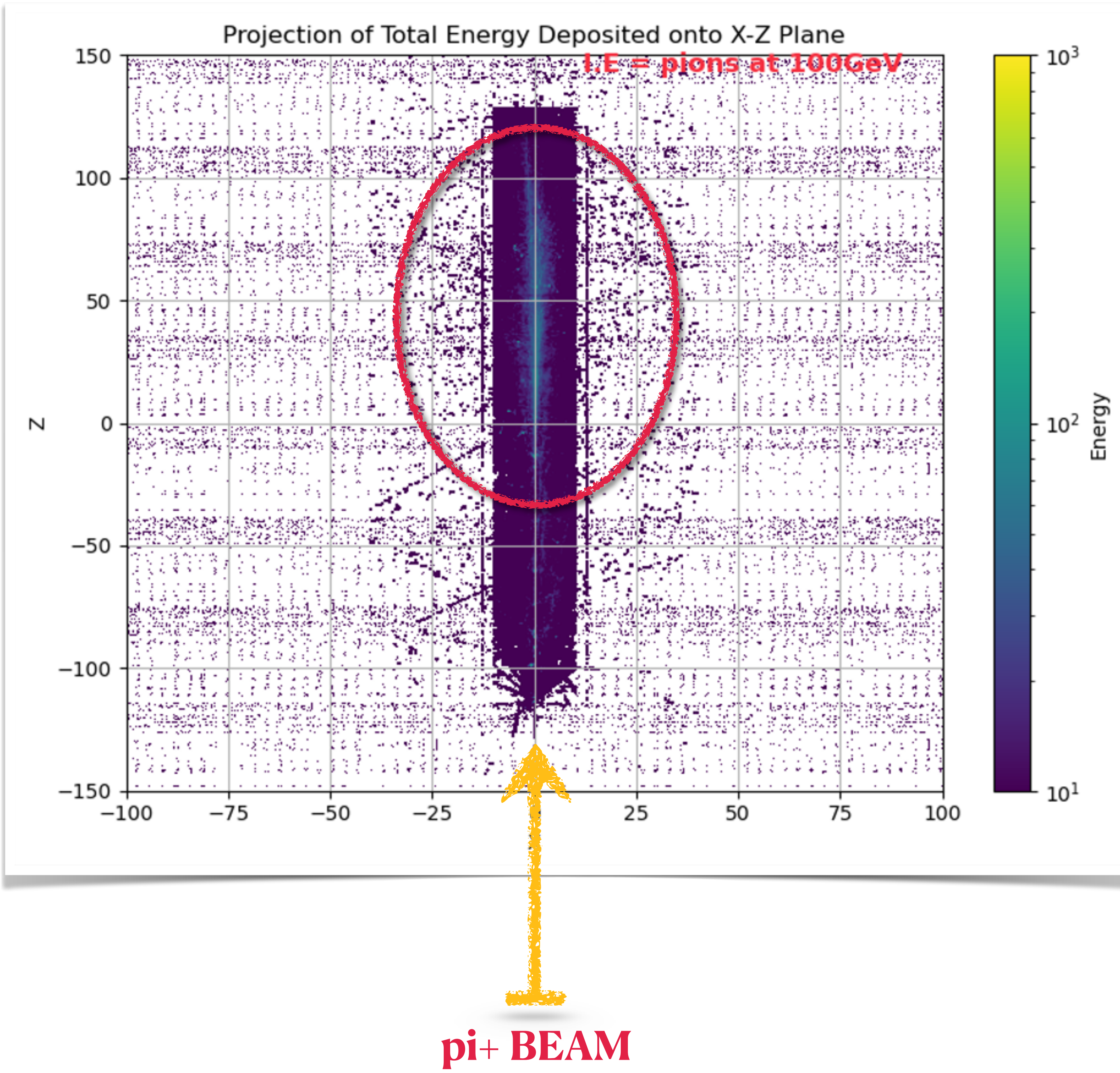
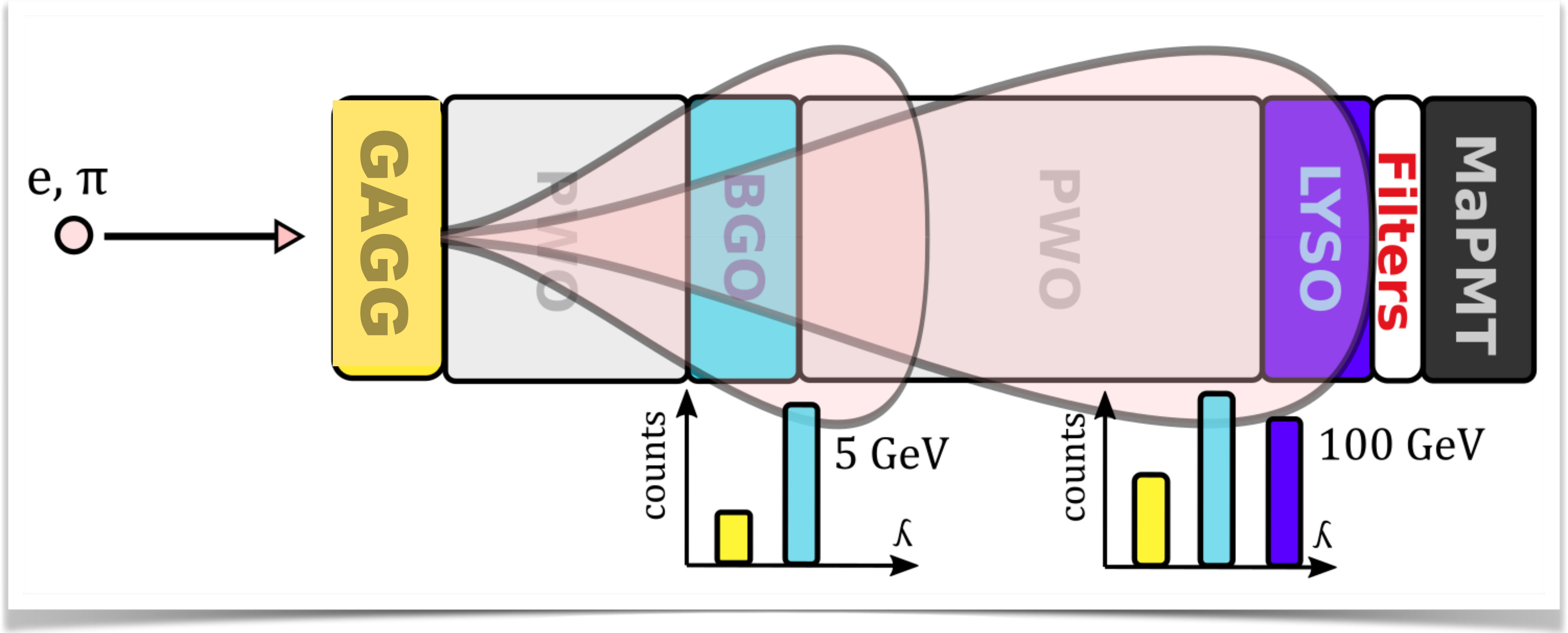
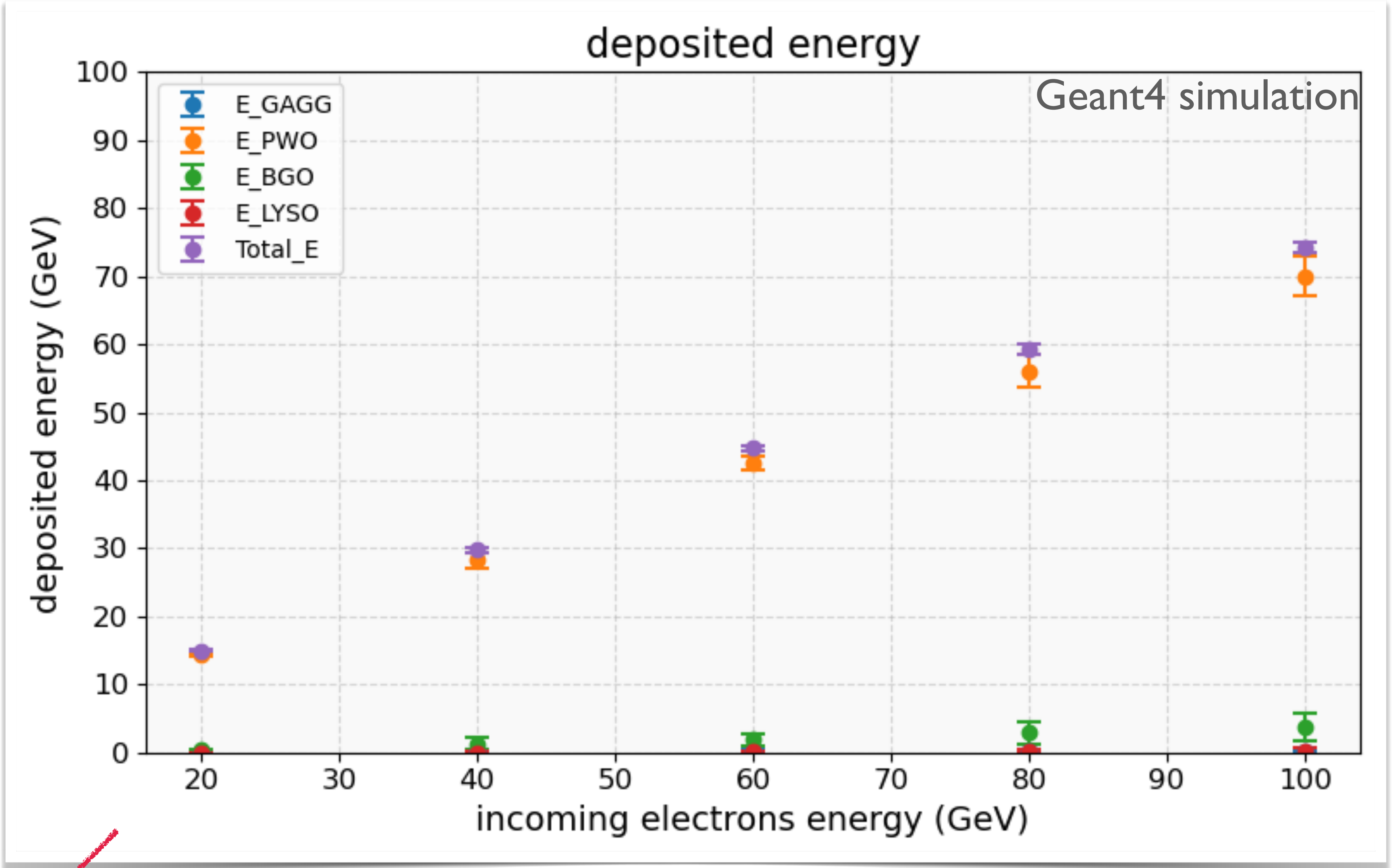
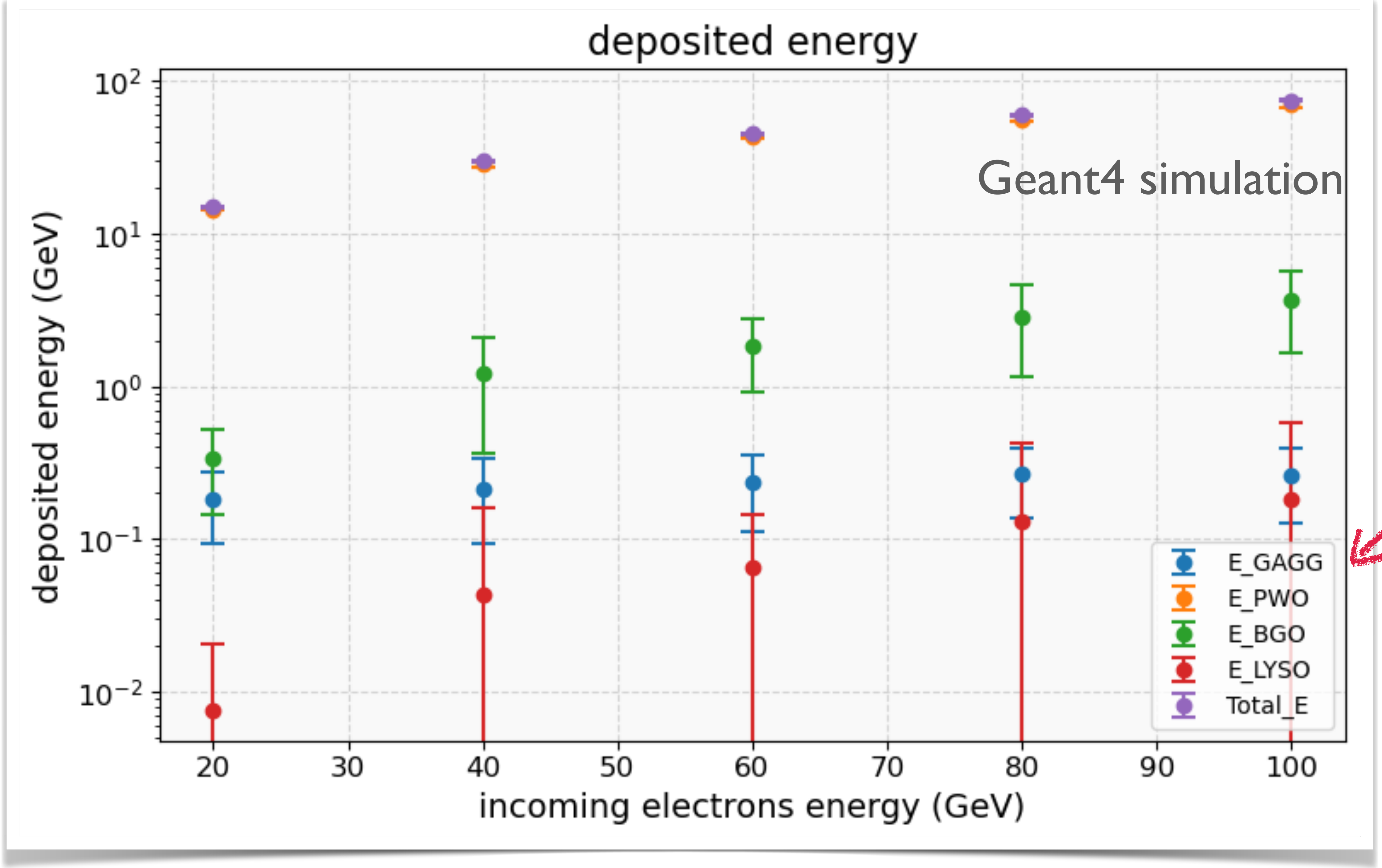




TESTED MODULE SIMULATION-ENERGY DEPOSITED PLOTS







in log scale

linear energy progression-reconstruction of energy is possible

the current stack is imperfect

preliminary

leak in energy dep. , and mix btw crystals, next chromocalo iteration?

TESTED MODULE SIMULATION:OPTICAL PHOTON ENERGY

max light is exiting from **PWO**

no filters embedded btw crystals

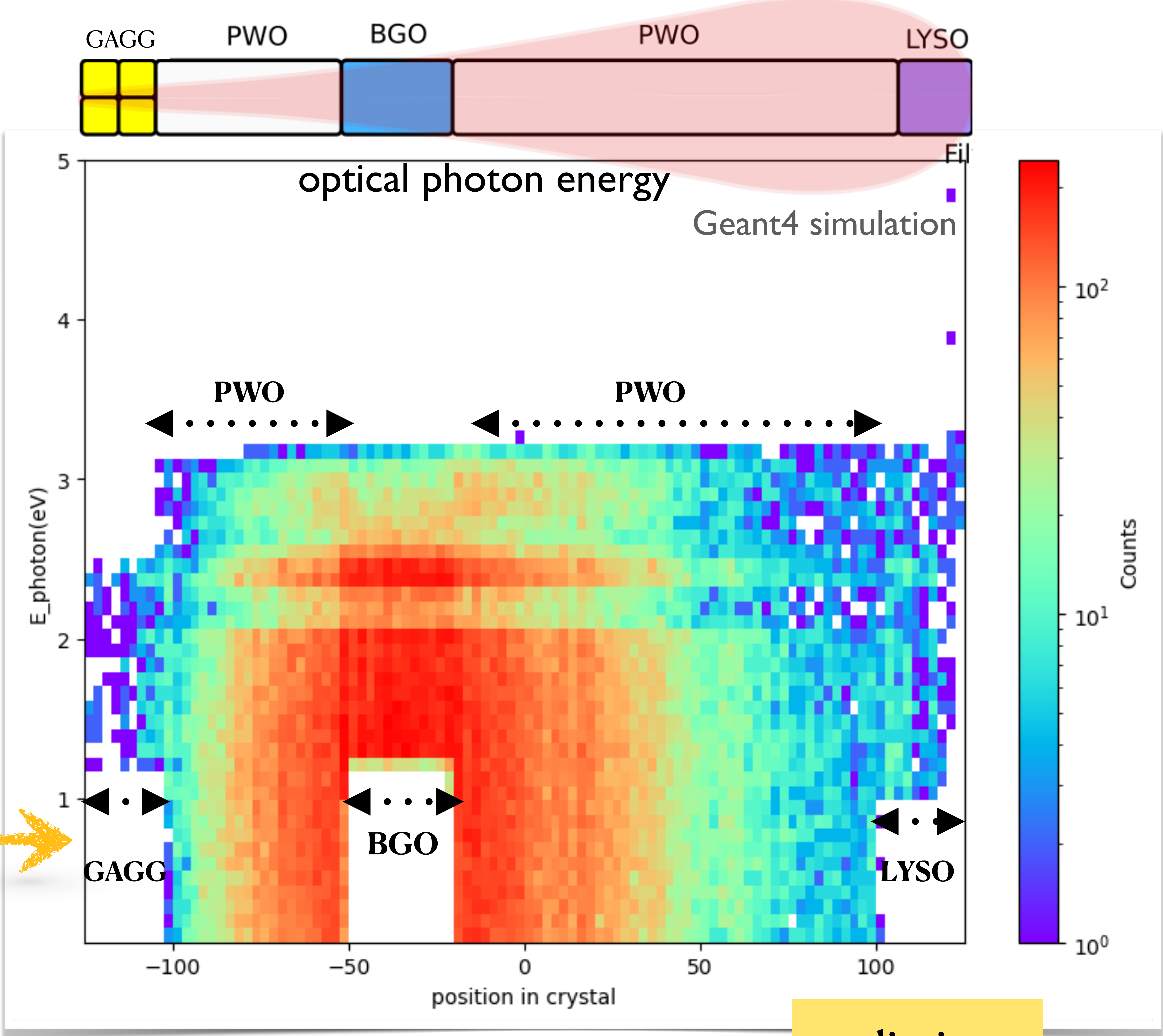
the current crsytal stack is imperfect

mix of light btw crystals, next chromocalo iteration?

better chromatic separation needed?

filters in btw the crystals?

e- beam, 100 GeV



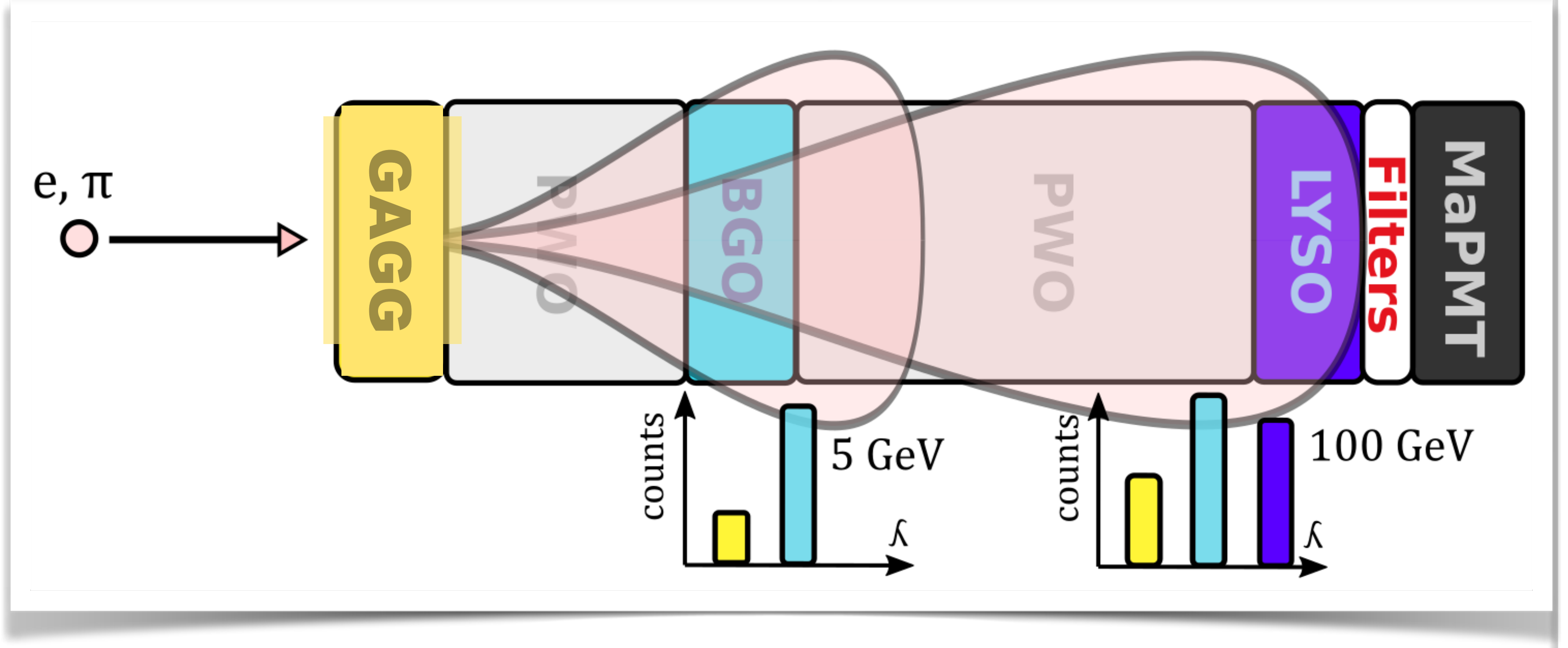
preliminary

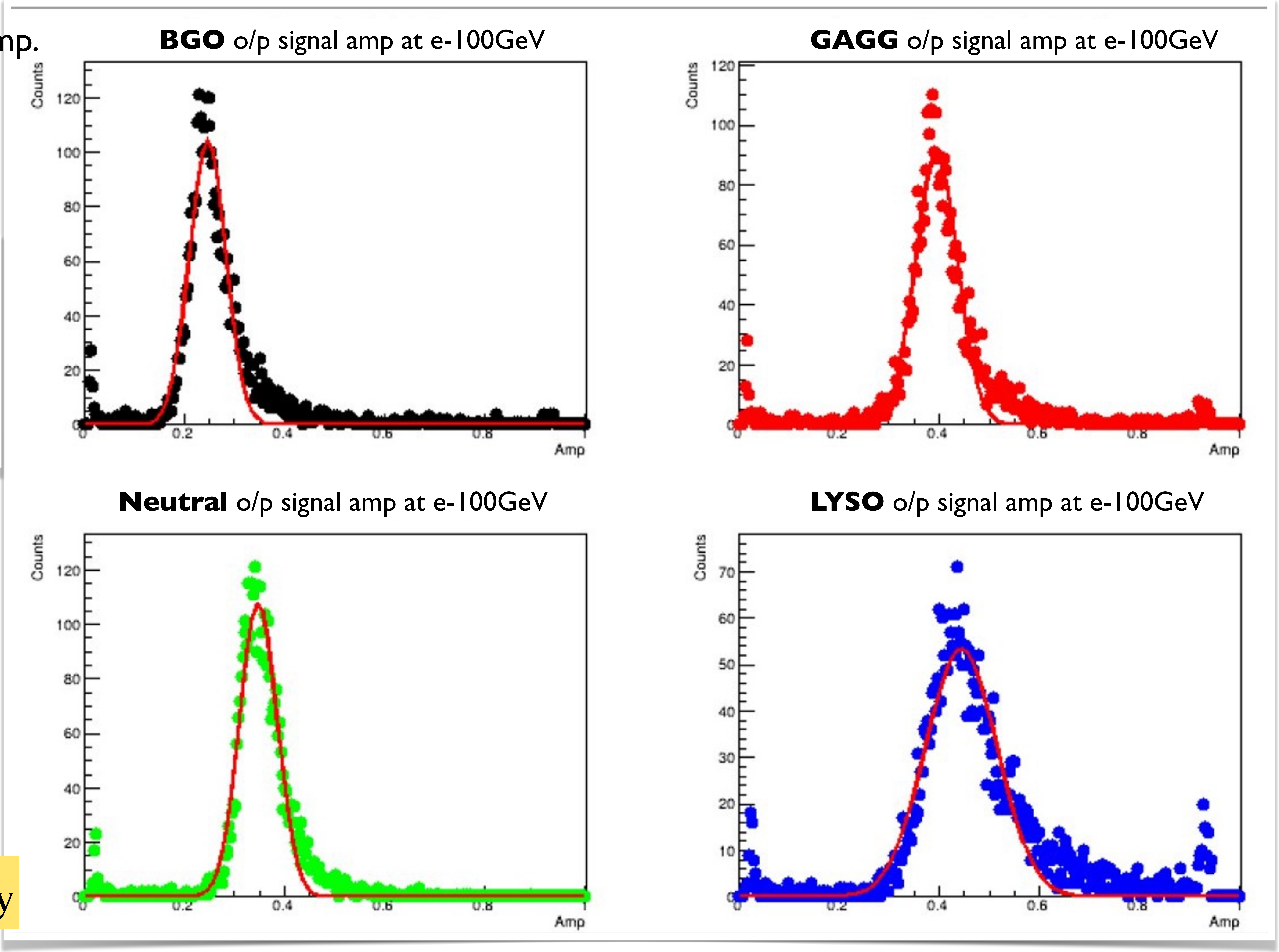
Simulation-based correlation & discrimination btw electron and pions events were also achieved.

Analysis- experimental results

TESTED MODULE ANALYSIS: OUTPUT AMPLITUDE PLOTS

MaPMT four op channel, signal amp.

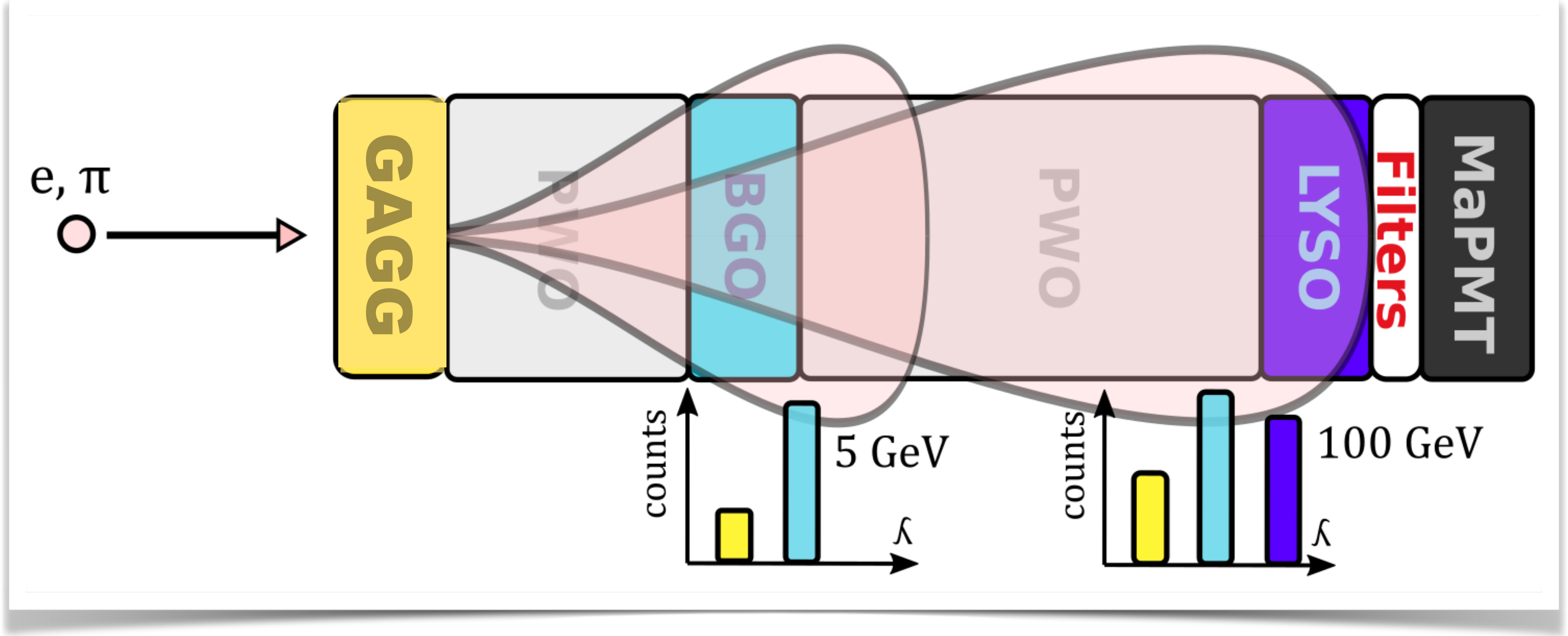


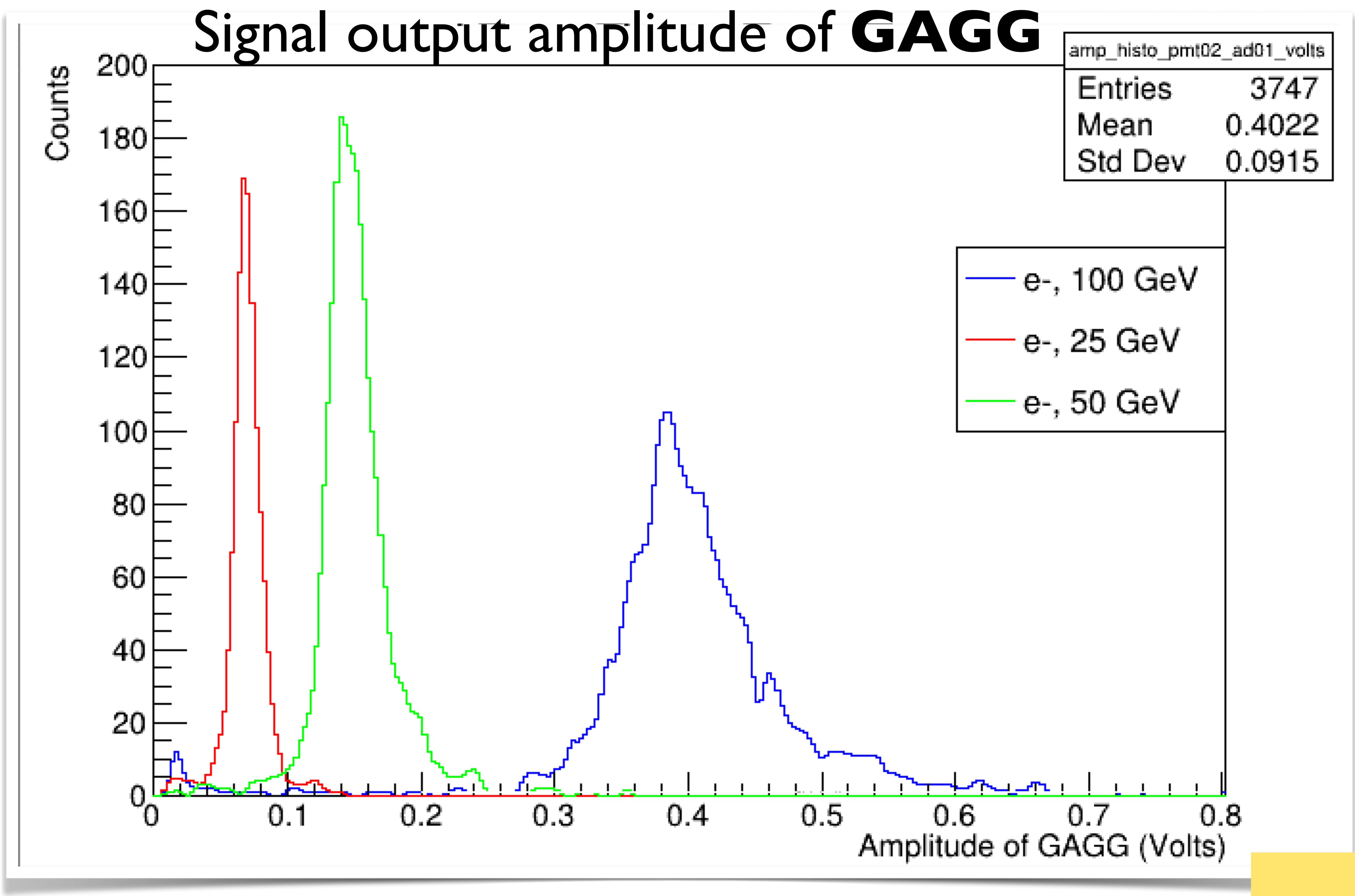


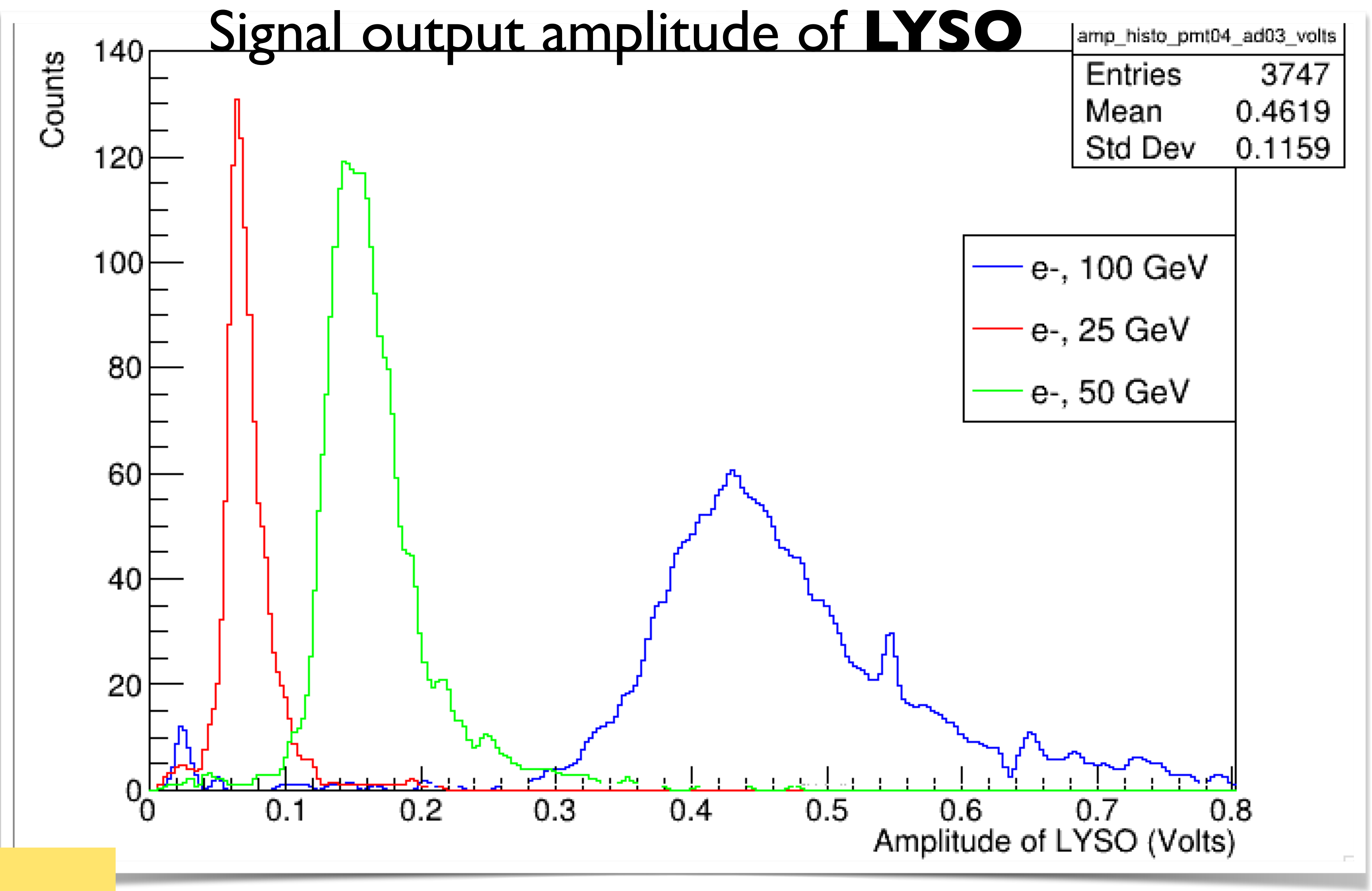
The two histograms show the number of counts associated to each scintillator as a function of the particle penetration

preliminary

OUTPUT AMPLITUDE PLOTS AT DIFFERENT ELECTRON ENERGY

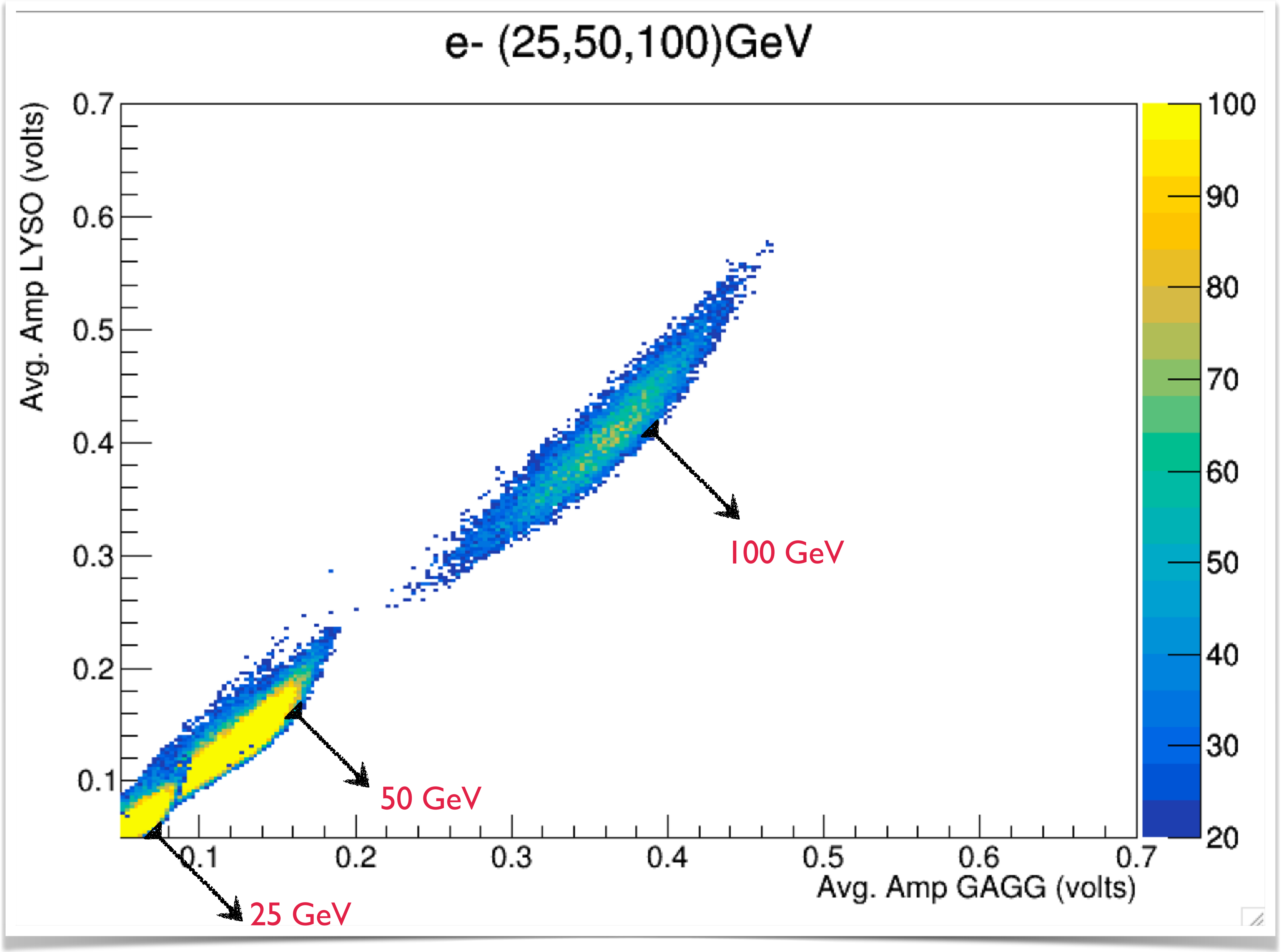


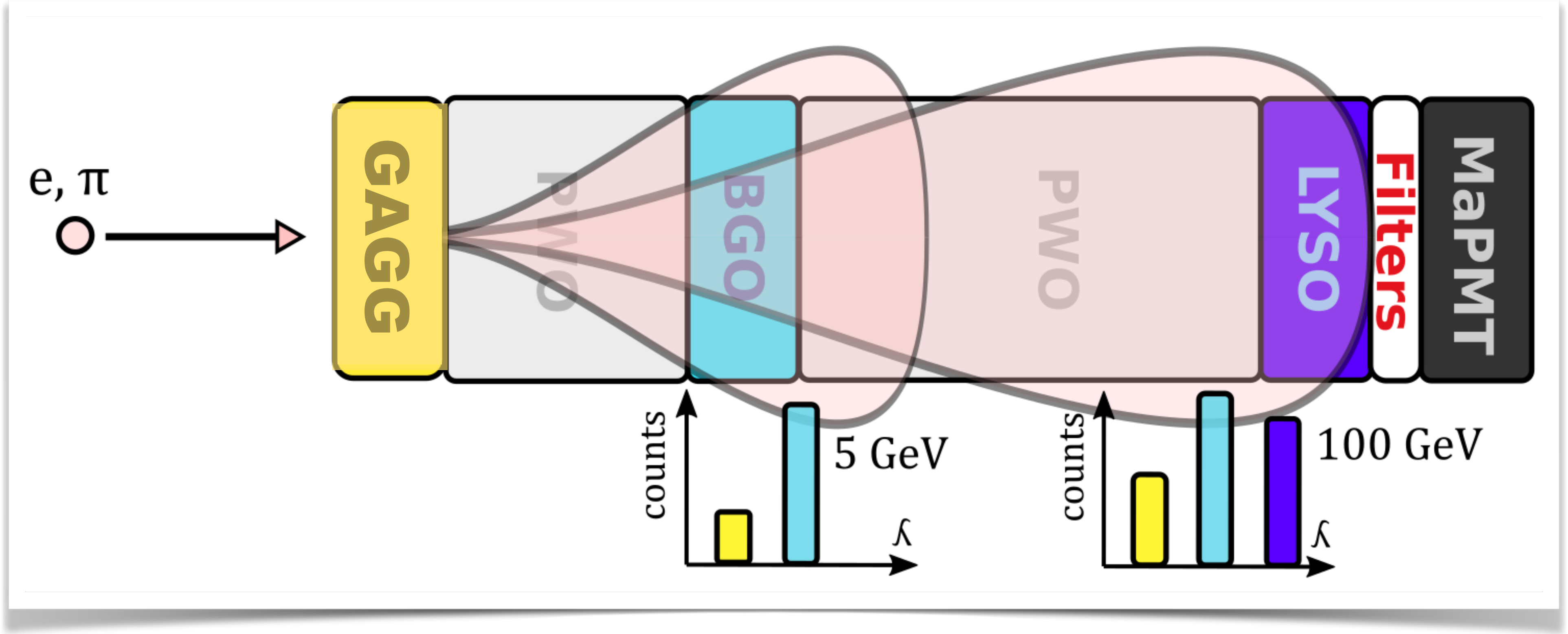




preliminary

ELECTRON ENERGY DISCRIMINATION PLOTS





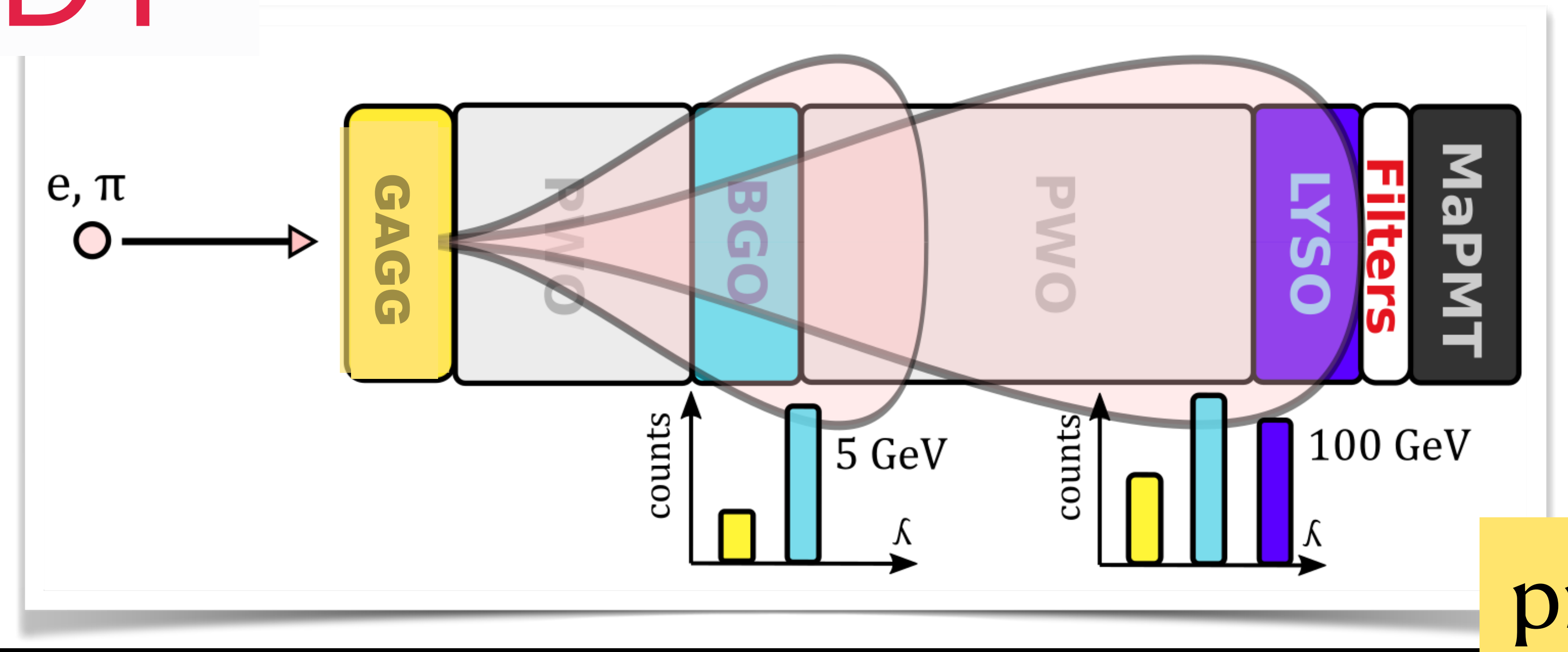
electron energy discrimination
fro GAGG and LYSO ,
at 25, 50 and 100GeV e- beam

preliminary

ANALYTICAL DISCRIMINATION STUDY

Scatter plots illustrating the relationship between the signal amplitudes measured in GAGG and LYSO for electrons (e−) and positively charged pions (π+) at 100 GeV.

Each point represents an event, with the x-axis indicating the signal amplitude measured in GAGG and the y-axis in LYSO.



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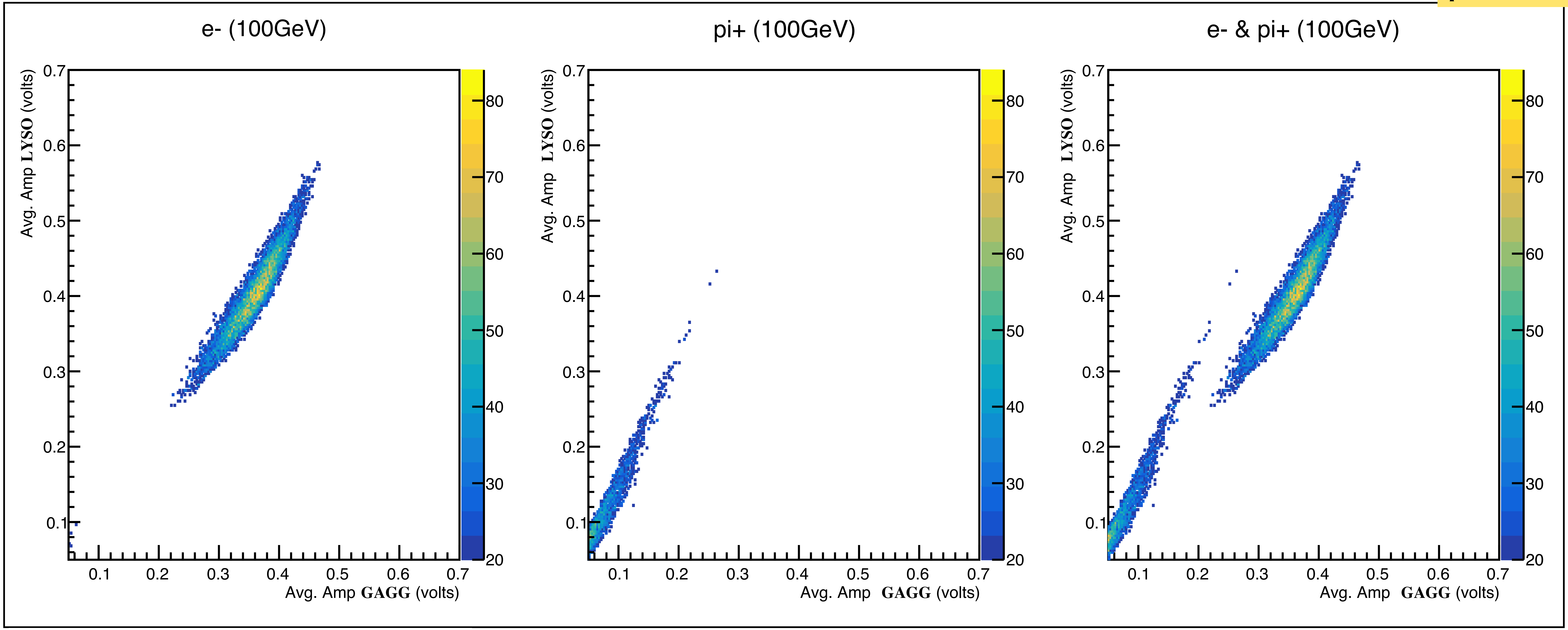

*Only events with bin counts above 20 are displayed

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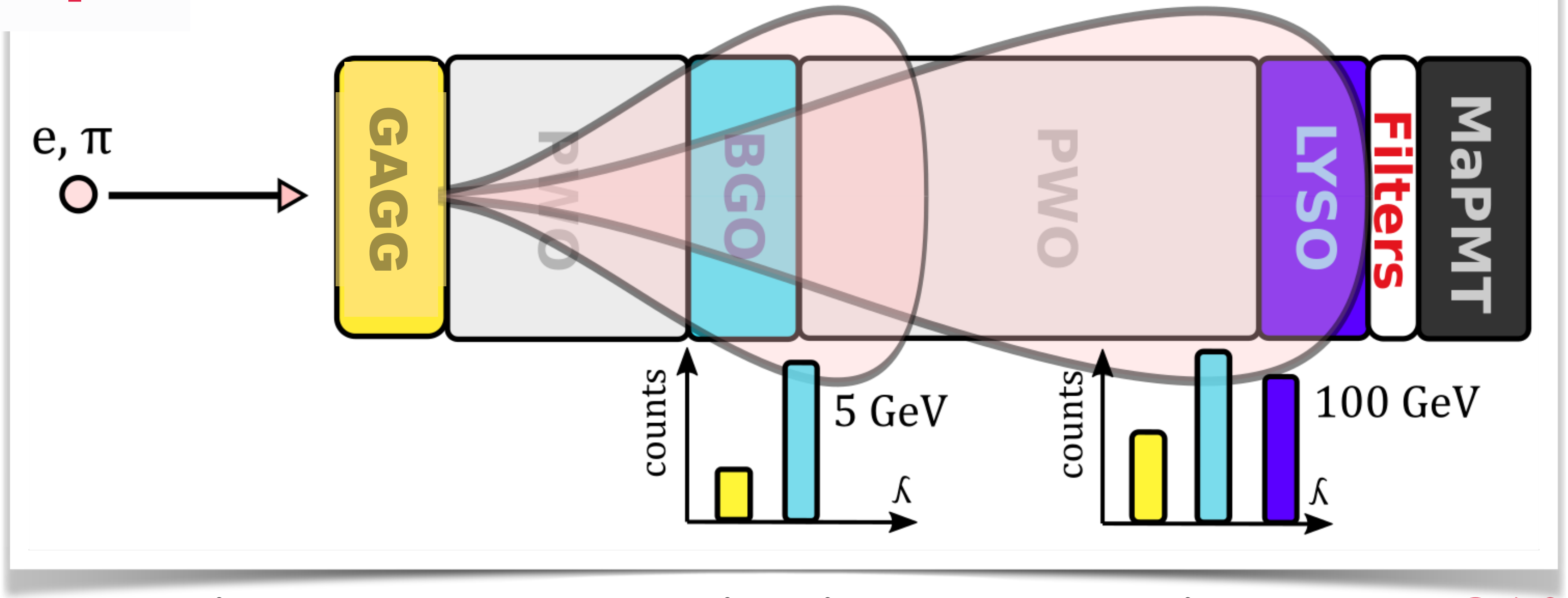
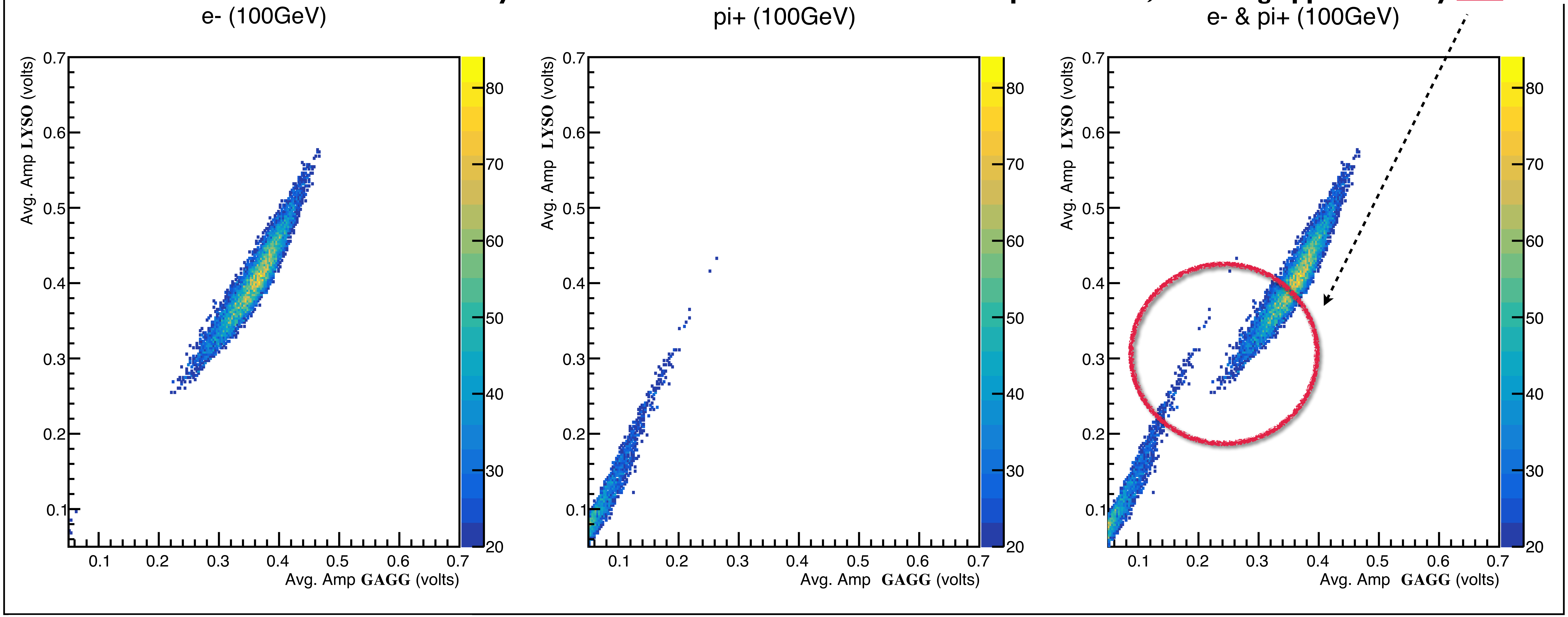


the analytical discrimination between electron and pion events, achieving approximately 86% accuracy.



*Only events with bin counts above 20 are displayed

CONCLUSION

It was observed that exposing the stack with high-energy electrons and pions, up to 100 GeV, leads to a shift in the output amplitude of GAGG, PWO, BGO, and LYSO. This shift allowed to discriminate electrons from pions with approximately **86%** accuracy

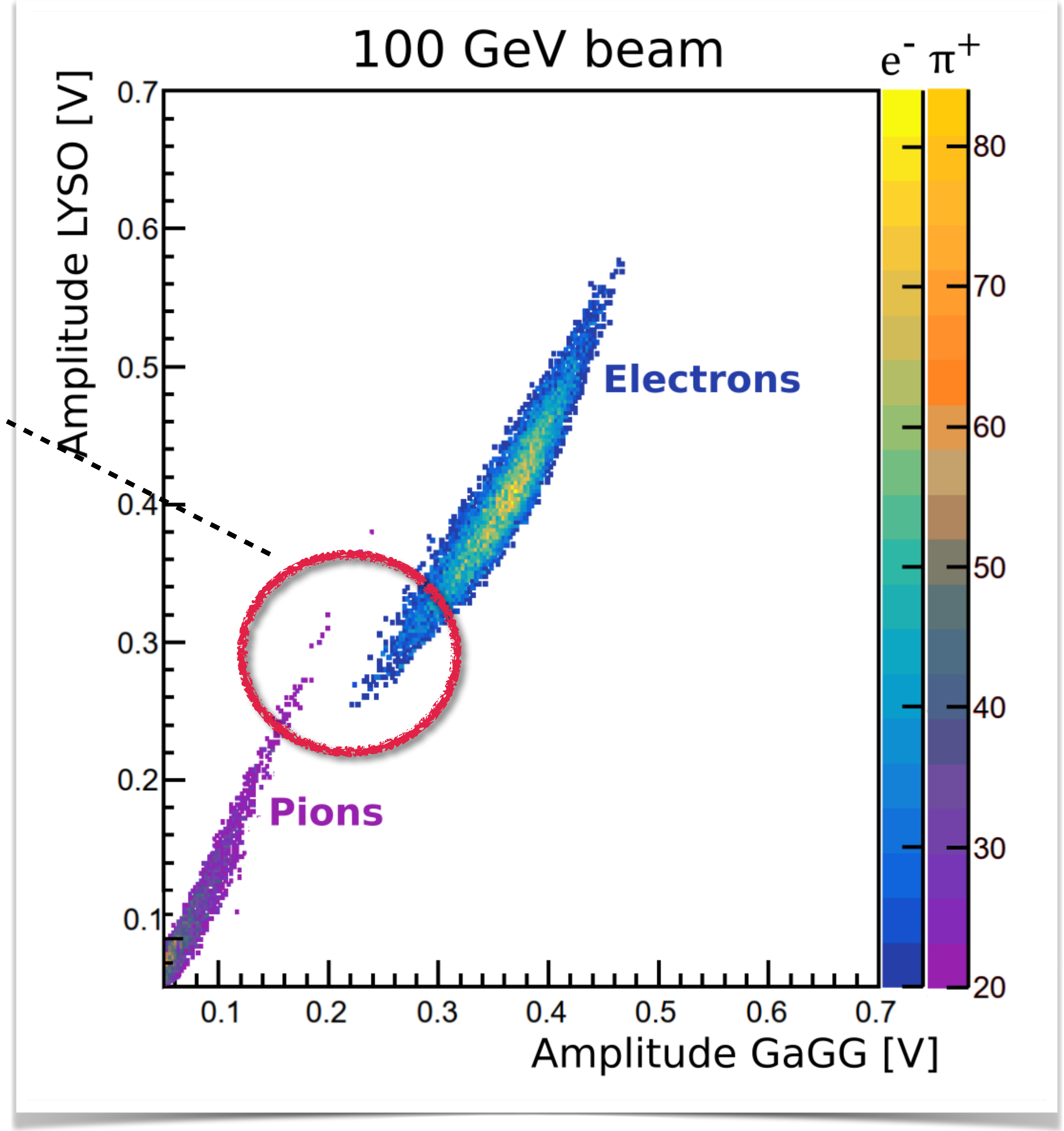
CONCLUSION

It was observed that exposing the stack with high-energy electrons and pions, up to 100 GeV, leads to a shift in the output amplitude of GAGG, PWO, BGO, and LYSO. This shift allowed to discriminate electrons from pions with approximately **86%** accuracy

G4 simulation and test beam results are complementary in terms of correlation-discrimination btw electrons and pions events

This novel proof-of-concept - validates the relevance and hence potential of chromatic calorimetry

The obtained results demonstrate how a simple stack of different inorganic scintillators can discriminate between electrons and pions of the same energy, owing to the distinct energy deposition profiles of these two particles.



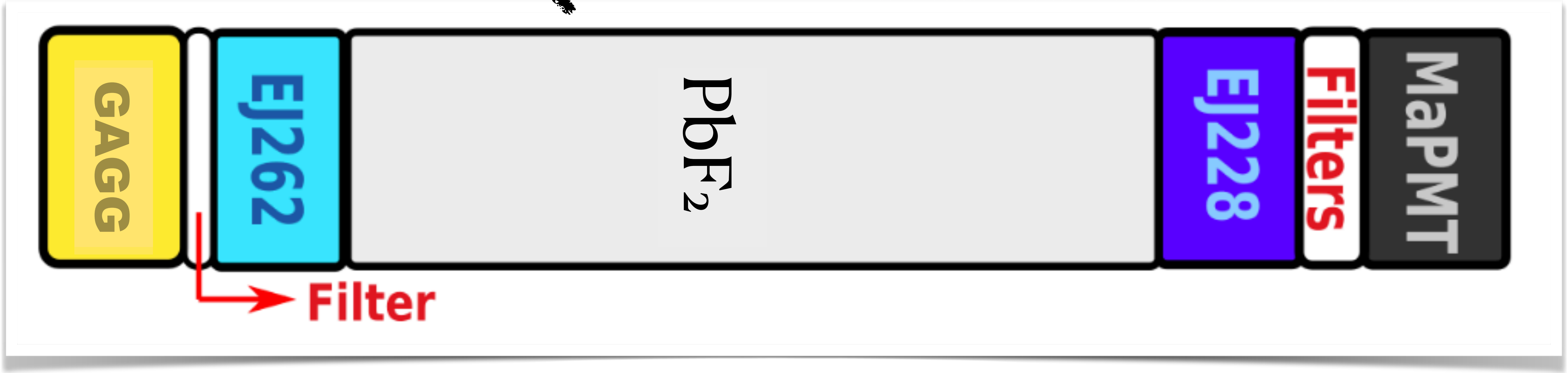
FUTURE PLANS

However, **downstream absorption** and **upstream emission** not well defined, resulting in the loss of chromatic information

2024 Test-Beam: aim to get better chromatic separation between layers

use of PbF_2 instead of PWO as it is ideally transparent,hence to understand better shower propagation

Two plastic scintillators EJ262 and 228 will be used because of their narrower emission compared to BGO and LYSO



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next iteration of chromo calo - we aim to study shower shape reconstruction, relationship betweek I.E and R.E

nanomaterial development - seeding stack with nanocomposite scinitillators (potential goal)

great progress-Nanoscintillator developments in **Crystal Clear Colab.-ECFA DRD5** future collaboration

Thank you!

Q & A?

Backup

TESTED MODULE SIMULATION:OPTICAL PHOTON ENERGY

max light is exiting from **PWO**

no filters embedded btw crystals

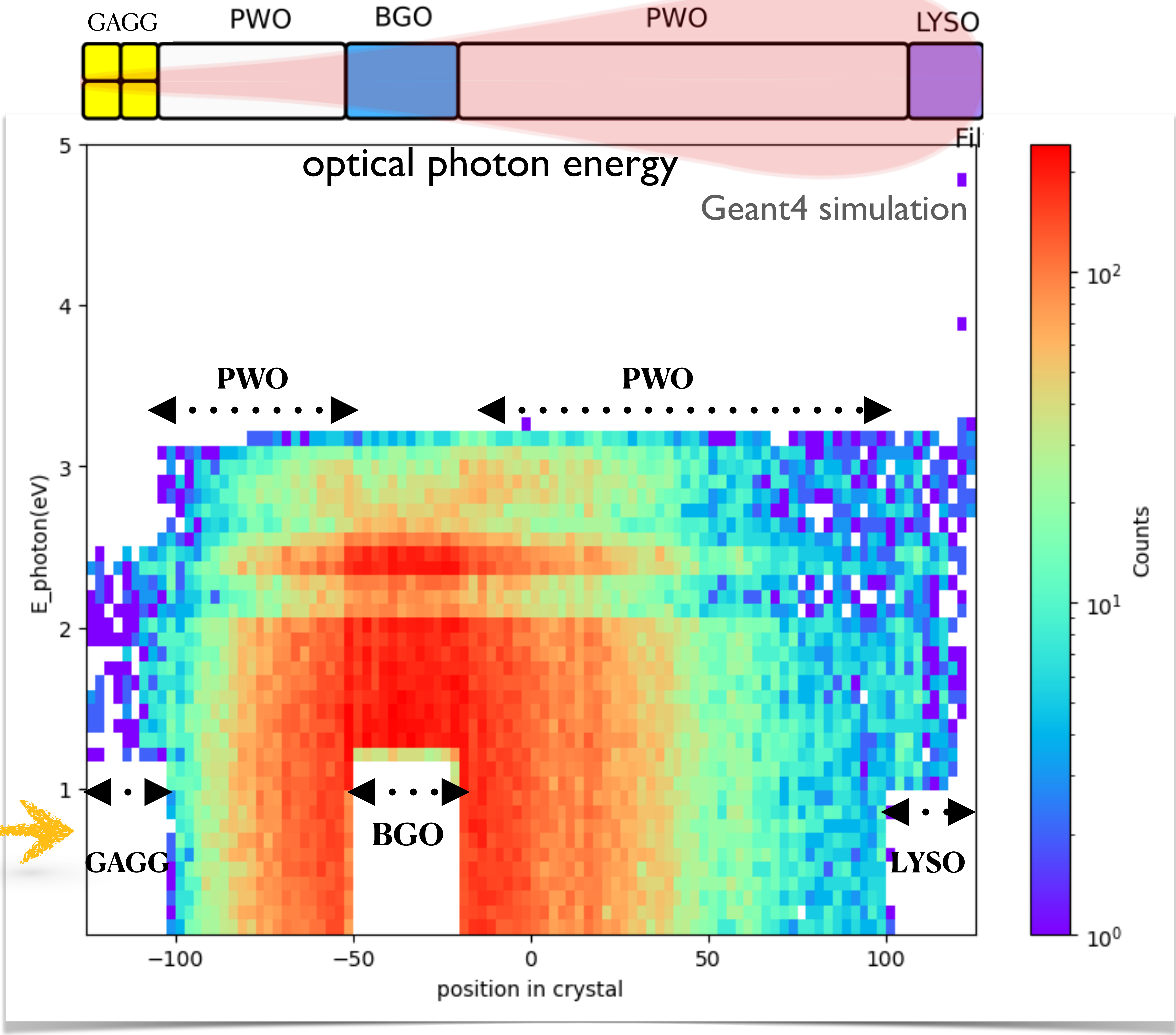
the current crsytal stack is imperfect

mix of light btw crystals, next chromocalo iteration?

better chromatic separation needed?

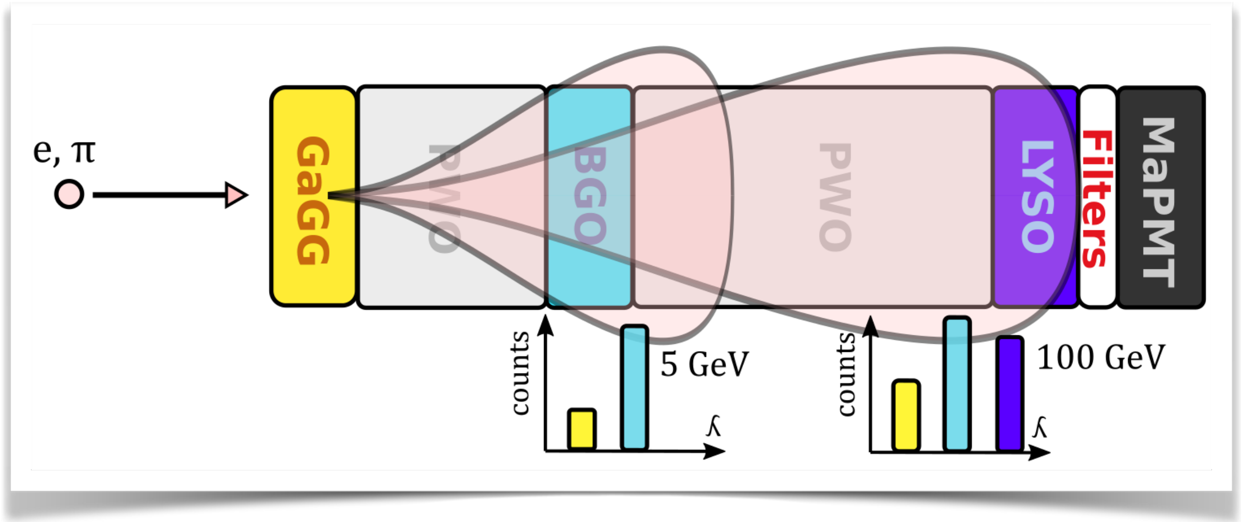
filters in btw the crystals?

e- beam, 100 GeV

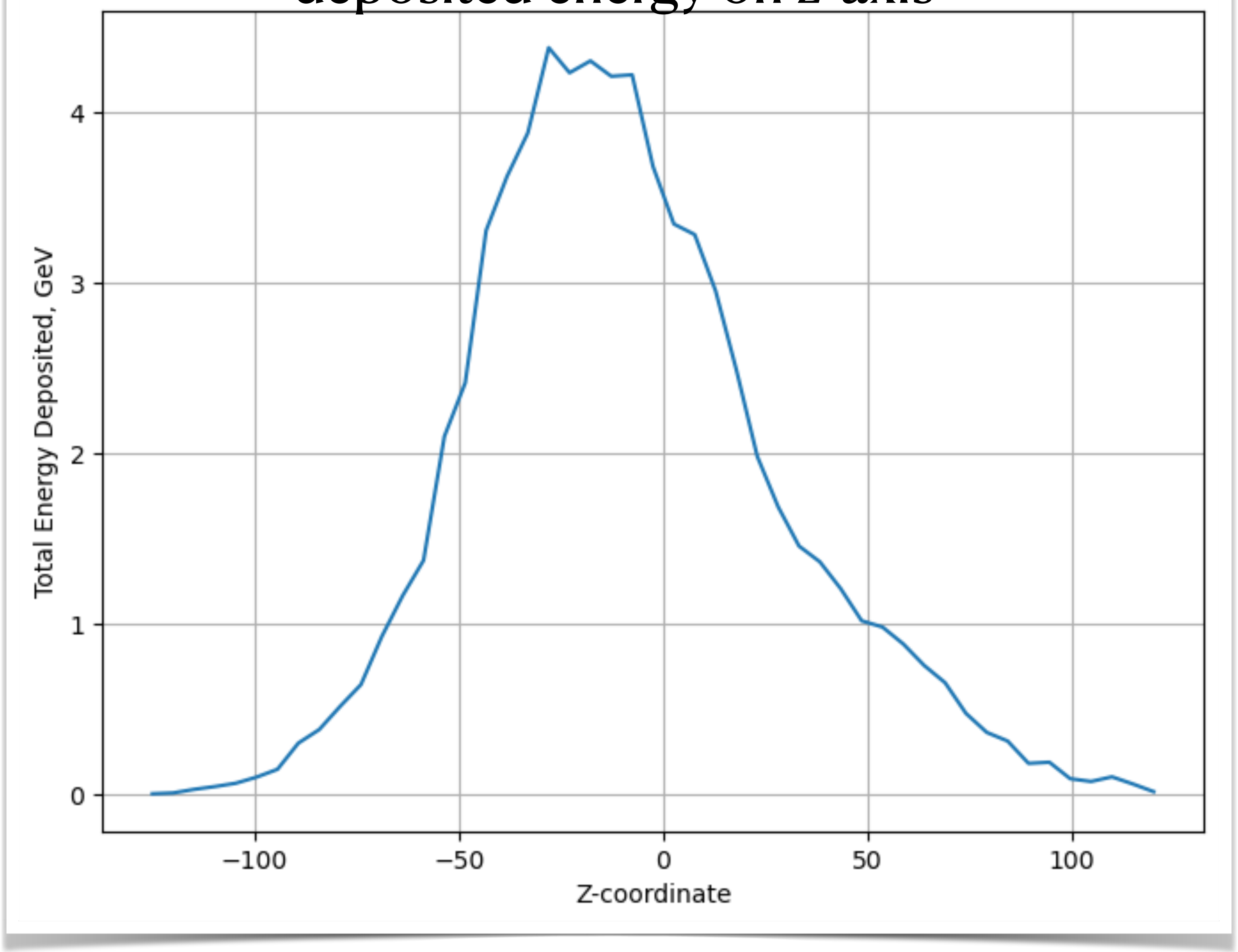


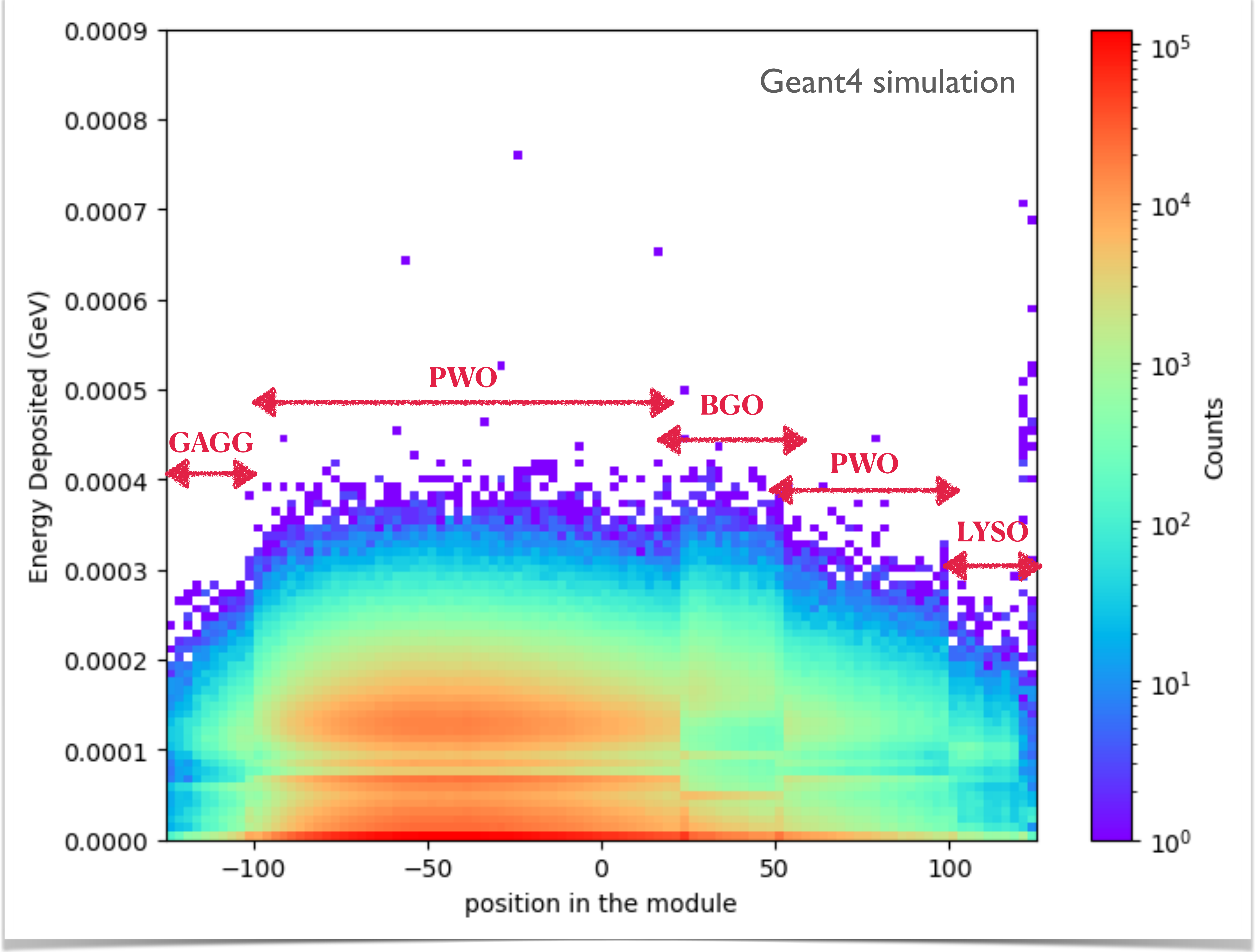
Simulation-based correlation & discrimination btw electron and pions events were also achieved.

TESTED MODULE SIMULATION: ENERGY DEPOSITED

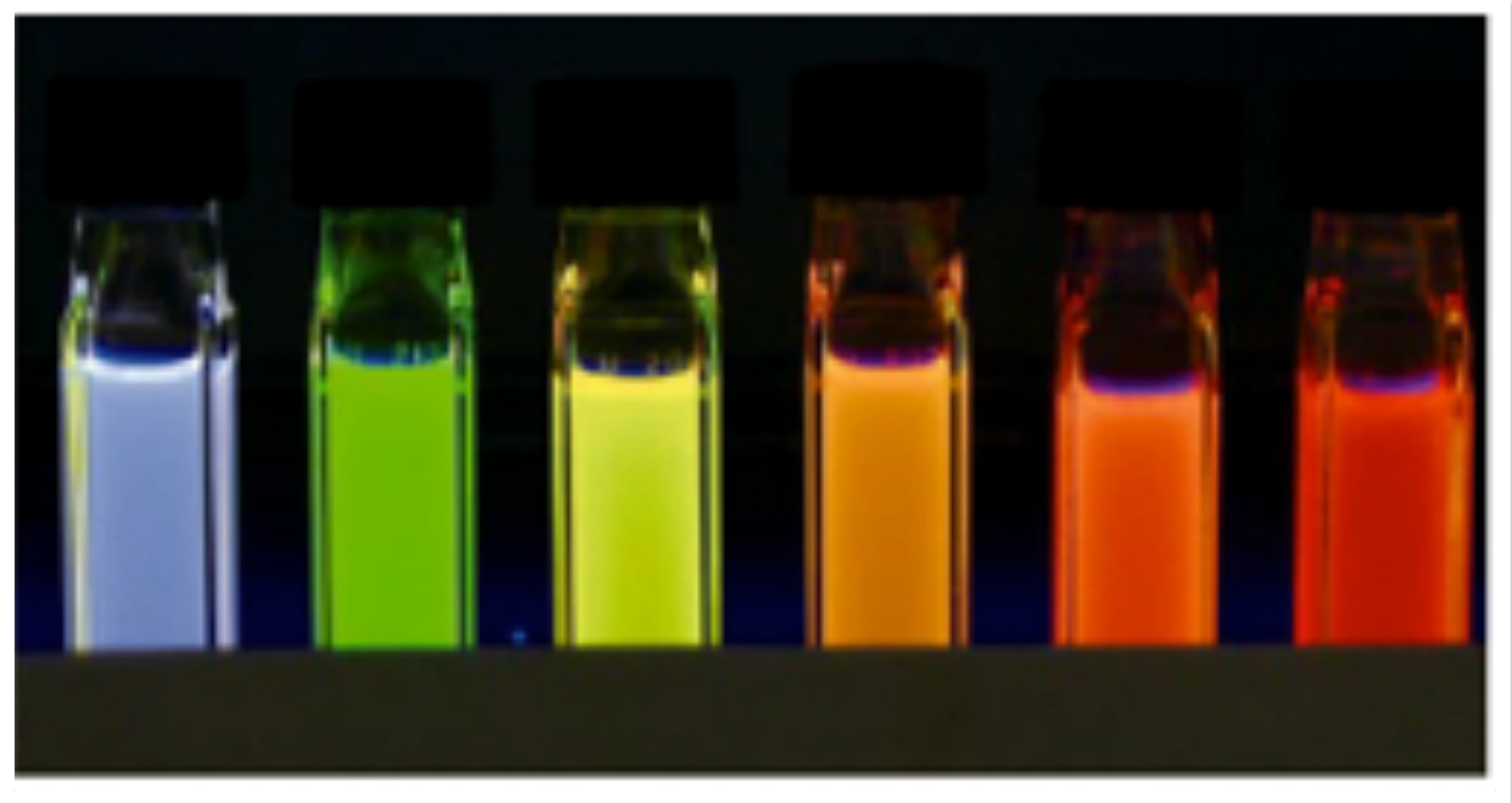


deposited energy on z-axis

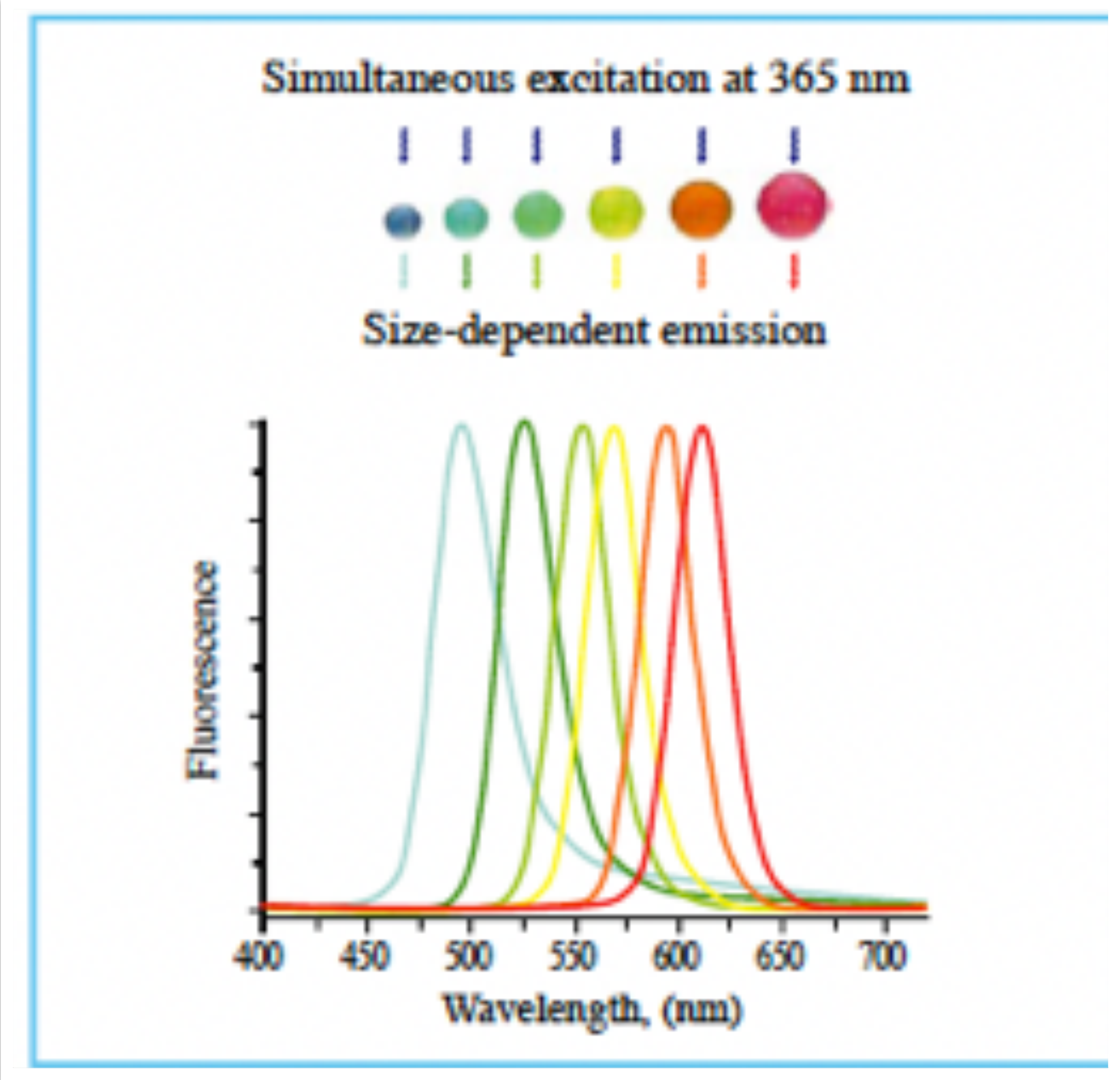




QUANTUM DOTS: CHROMATIC TUNABILITY



Hideki Ooba, “Synthesis of Unique High Quality Fluorescence Quantum Dots for the Biochemical Measurements,” AIST TODAY Vol.6 , No.6 (2006) p.26- 27



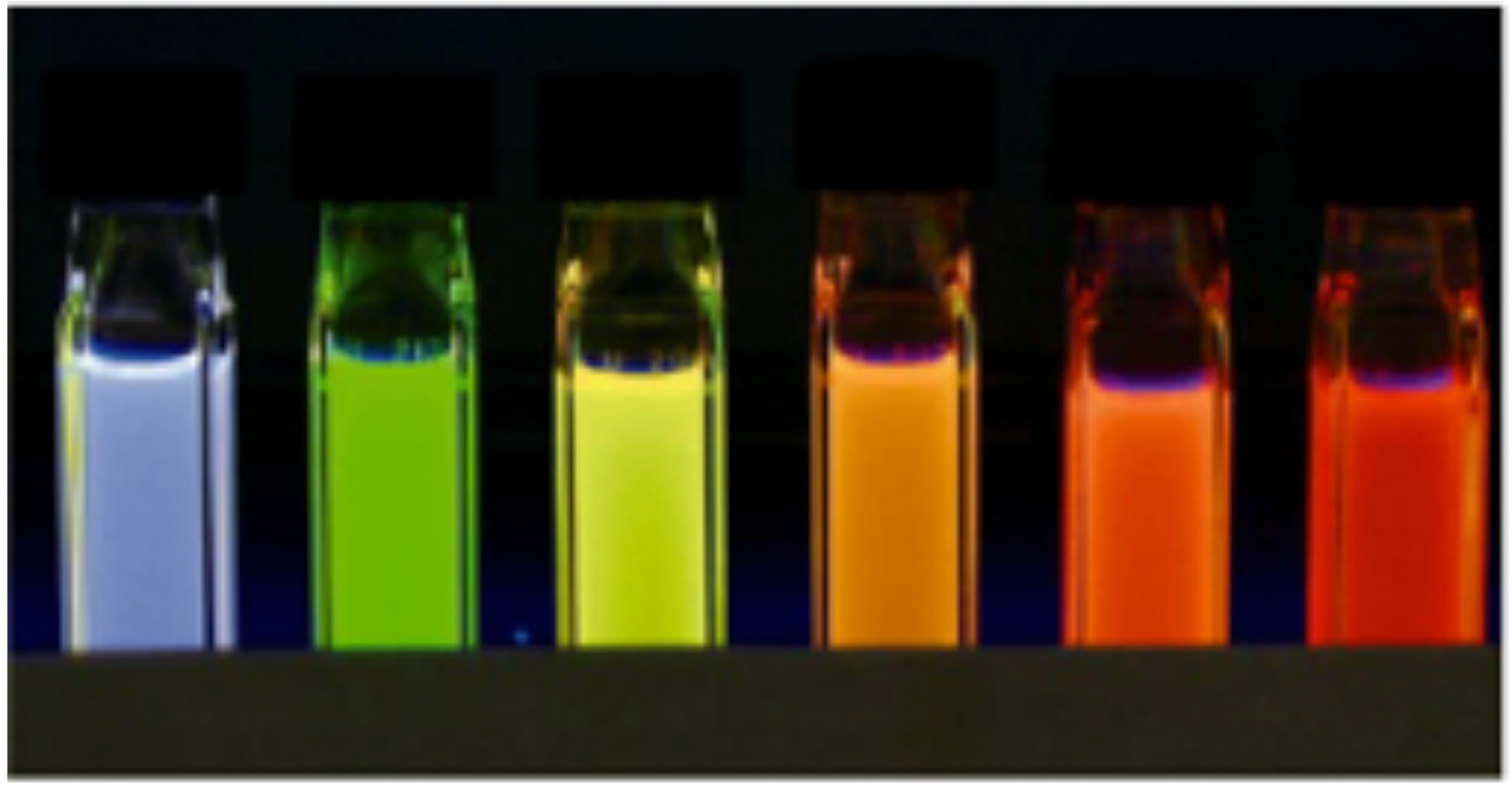
from Benoit Dubertret and Hideki Ooba

chromatic tunability optimizes for quantum efficiency of PD (fast, optimizable WLS)

deposit on surface of high-Z material thin layers of UV VIS WLS

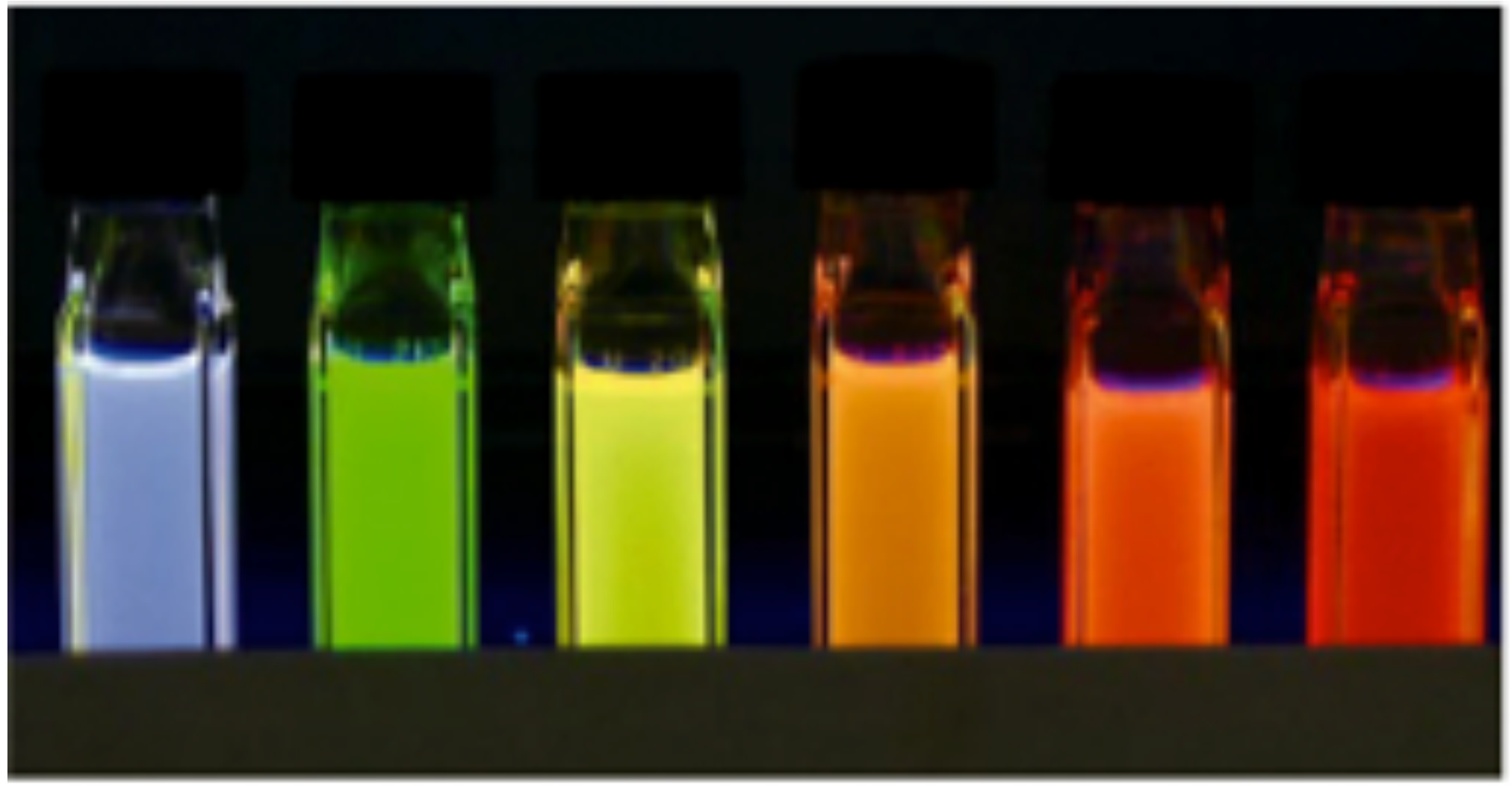
embed in high-Z material ? two-species (nanodots + microcrystals) embedded in polymer matrix? quasi continuous VIS-light emitter (but what about re-absorbtion?)

Quantum dots: timing



Hideki Ooba, "Synthesis of Unique High Quality Fluorescence Quantum Dots for the Biochemical Measurements," AIST TODAY Vol.6 , No.6 (2006) p.26- 27

Quantum dots: timing



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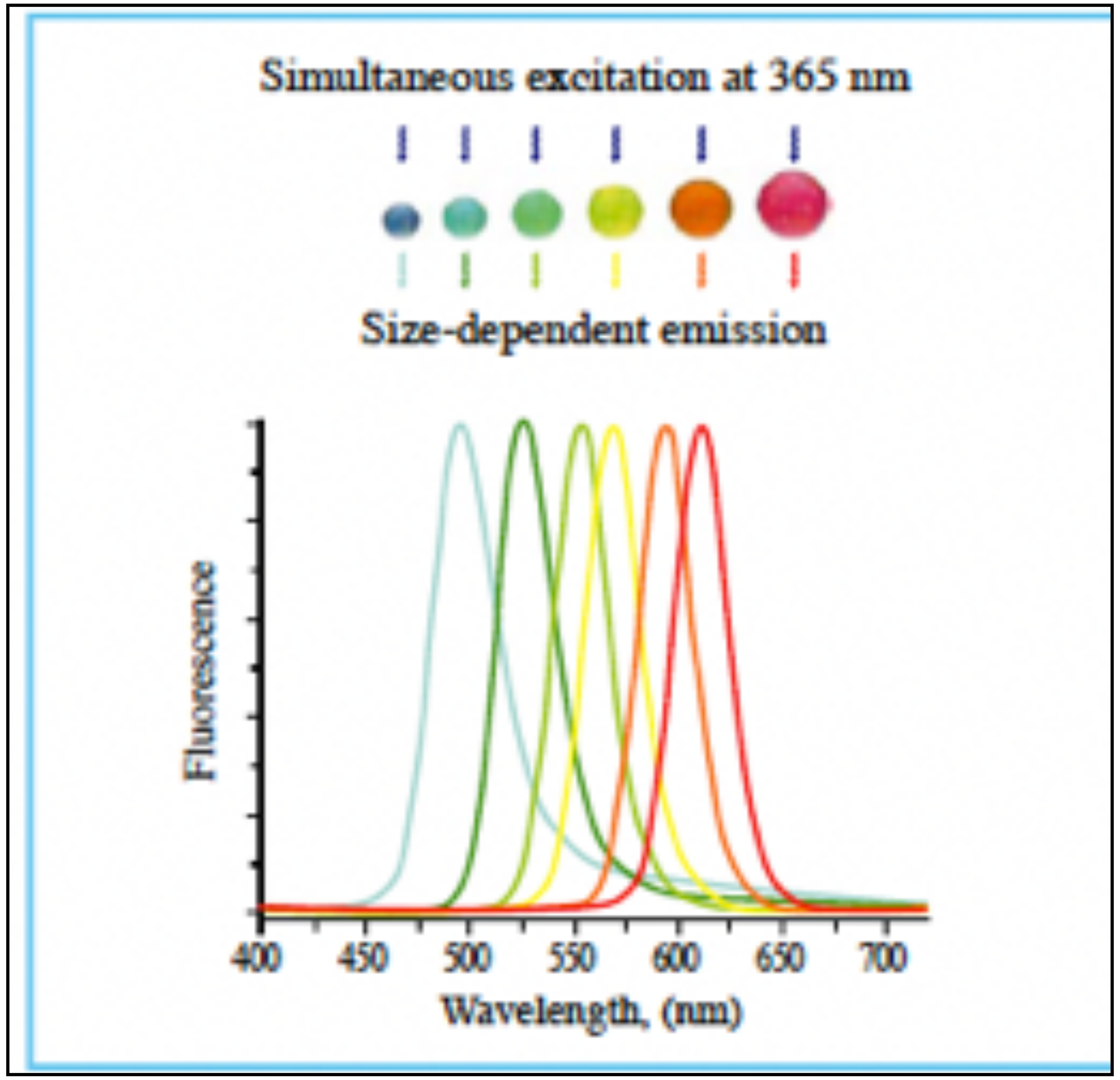
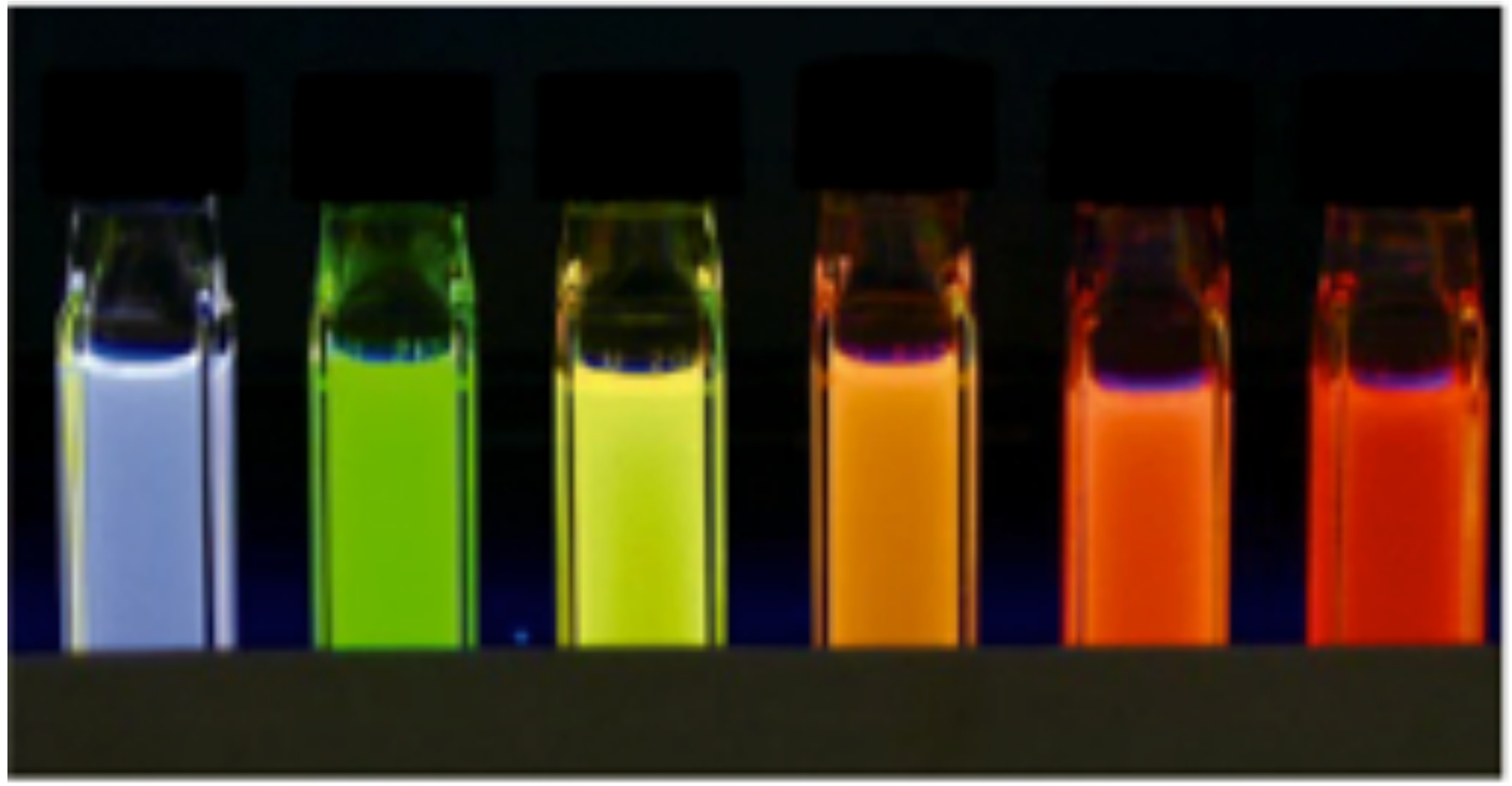
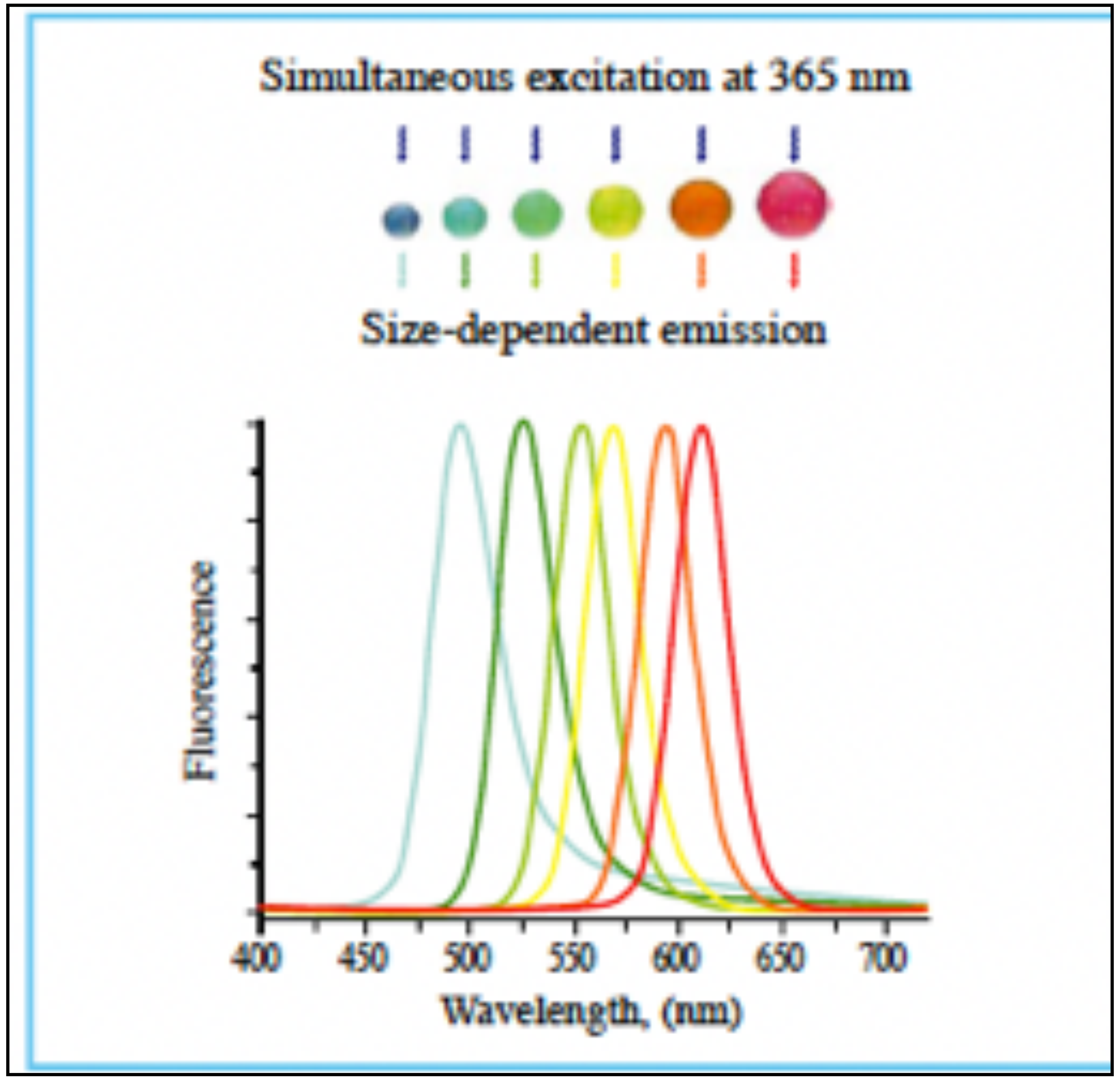


Doser M, Auffray E, et. al (2022) Front. Phys. 10:887738

Quantum dots: timing and tunability



Hideki Ooba, “Synthesis of Unique High Quality Fluorescence Quantum Dots for the Biochemical Measurements,” AIST TODAY Vol.6 , No.6 (2006) p.26- 27



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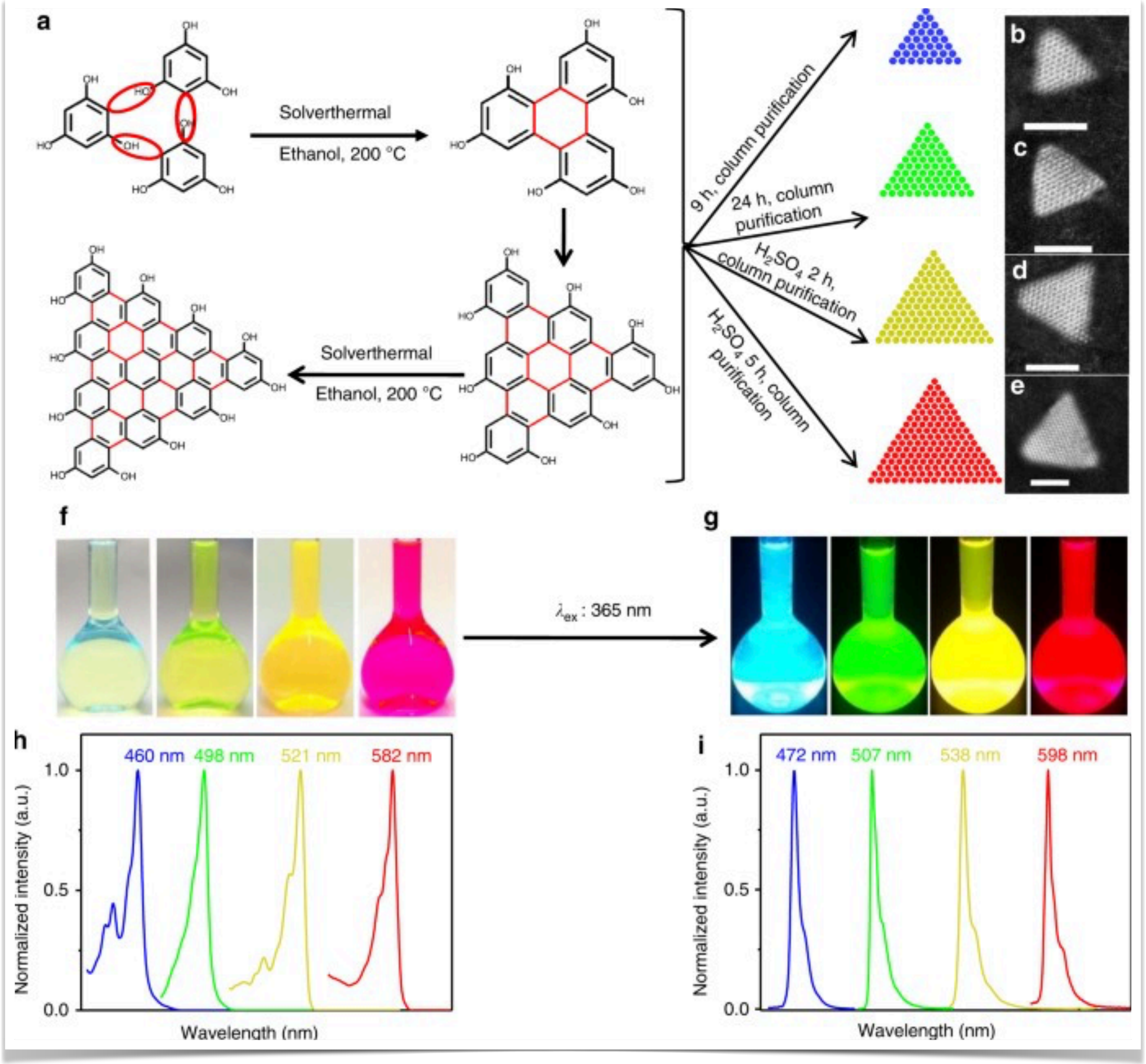
Quantum dots: chromatic calorimetry

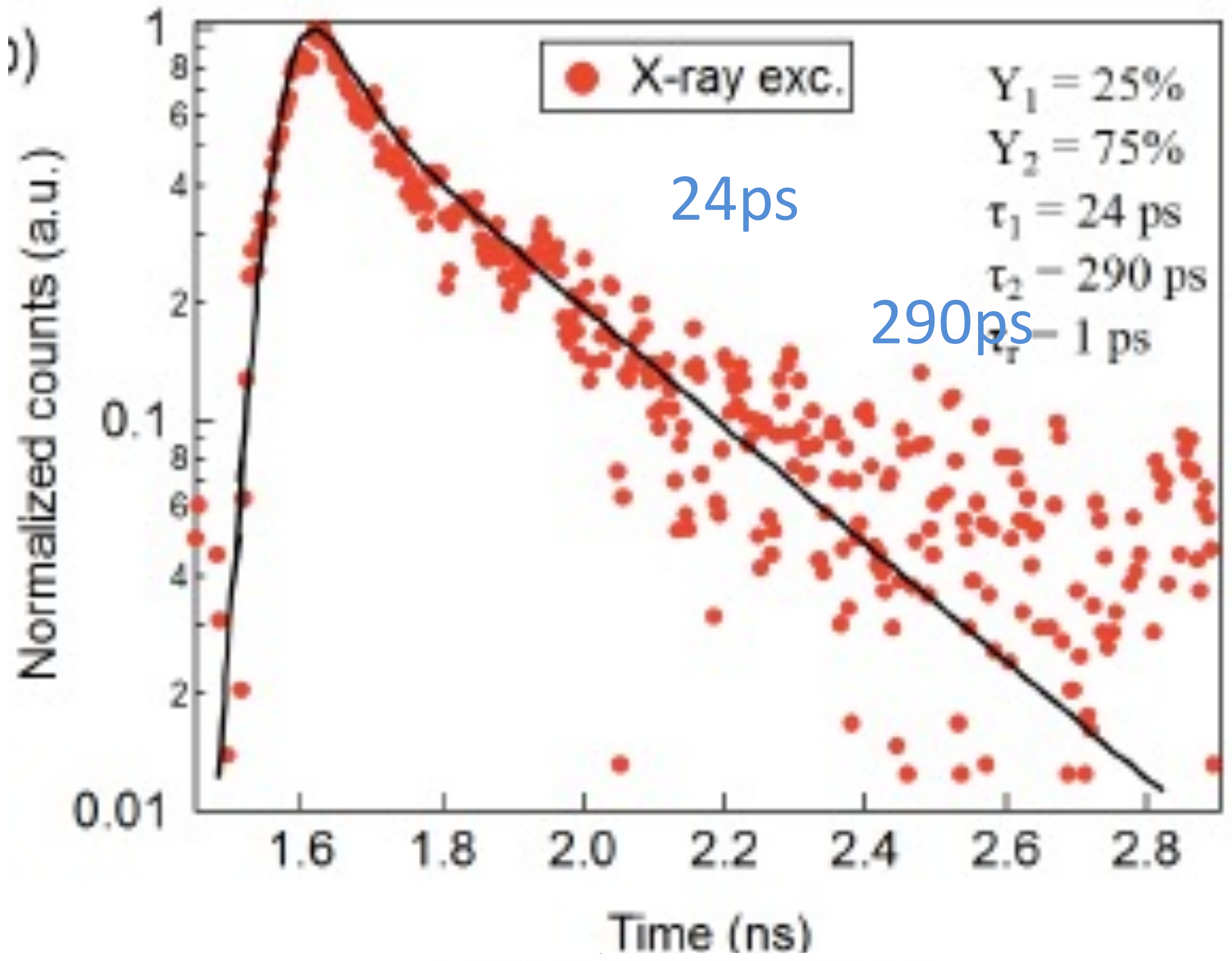
- idea: seed different parts of a "crystal" with nanodots emitting at different wavelengths, such that the wavelength of a stimulated fluorescence photon is uniquely assignable to a specific nanodot position

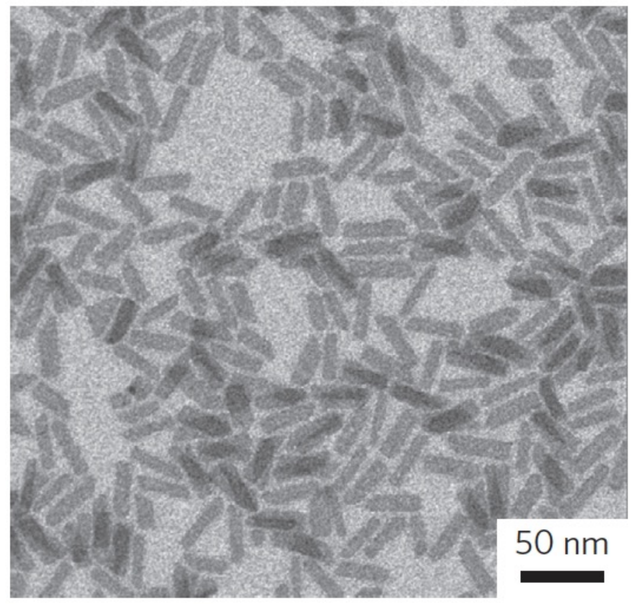


F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

SCINTILLATION DECAY TIME SPECTRA

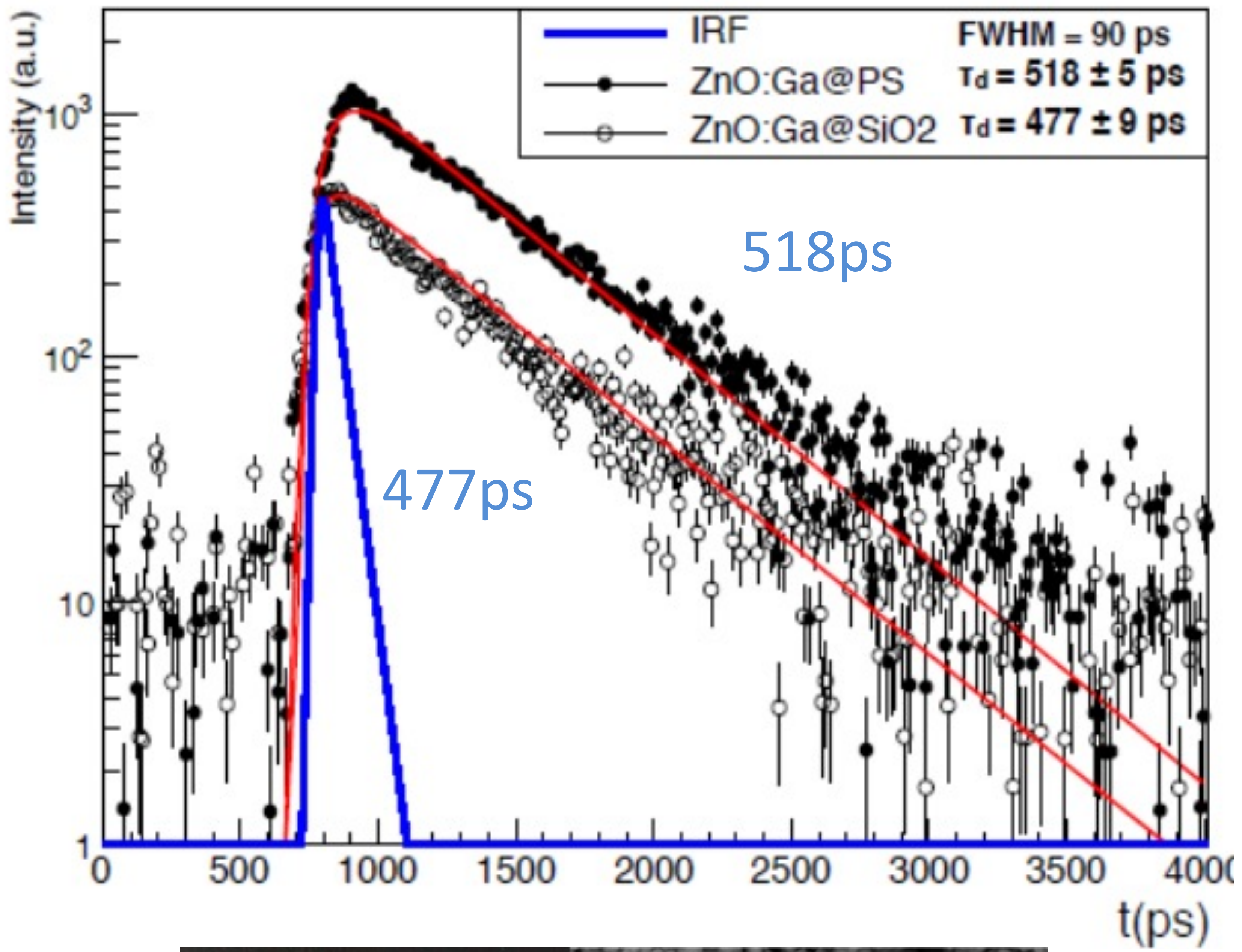
CdSe nanoplatelet,

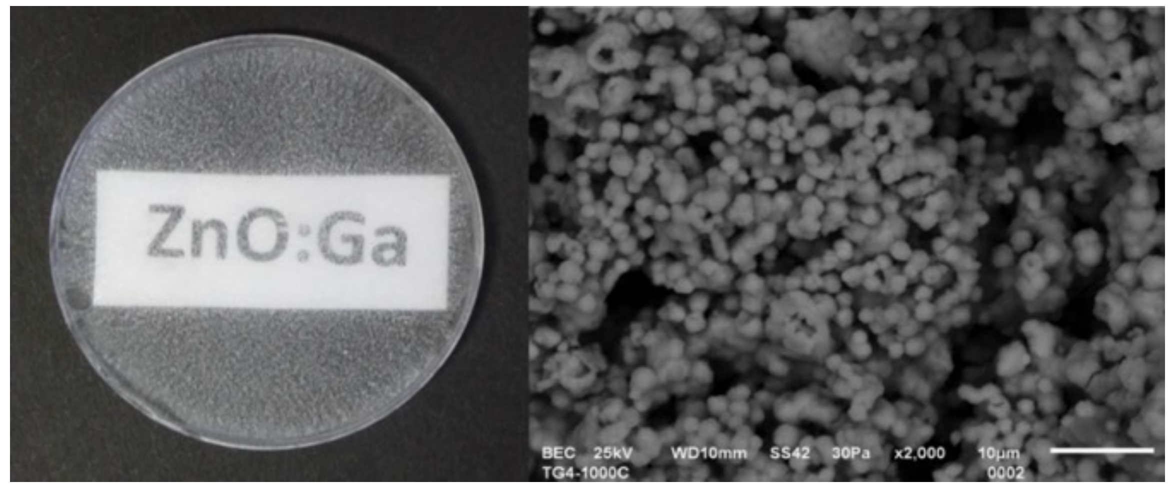




J. Grim et al., *Nature Nanotechnology*, **9**,2014, 891–895
R. Martinez Turtos et al., 2016 JINST_11 (10) P10015

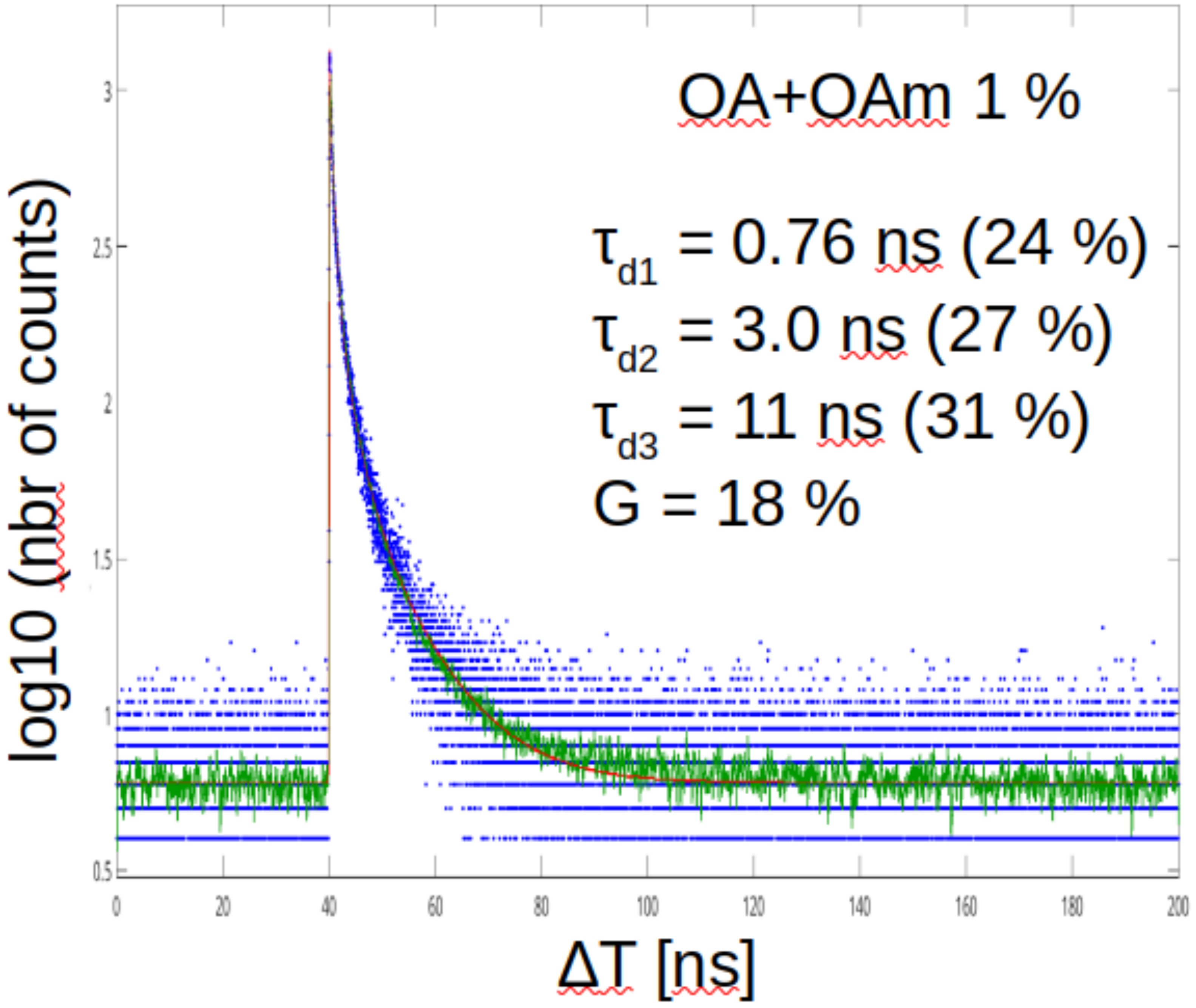
ZnO:Ga embedded in SiO_2 or polystyrene

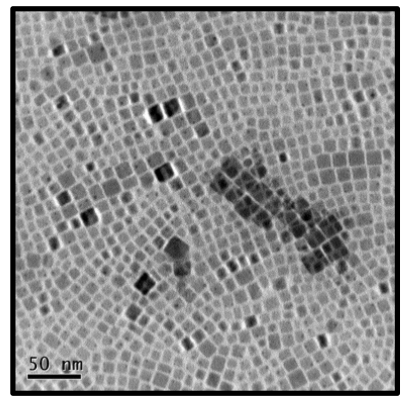




Procházková et al., Radiat Meas 90, 2016, 59-63
R. Turtos Phys. Status Solidi RRL 10, No. 11, 843–847 (2016)

$CsPbBr_3$ embedded in polystyrene





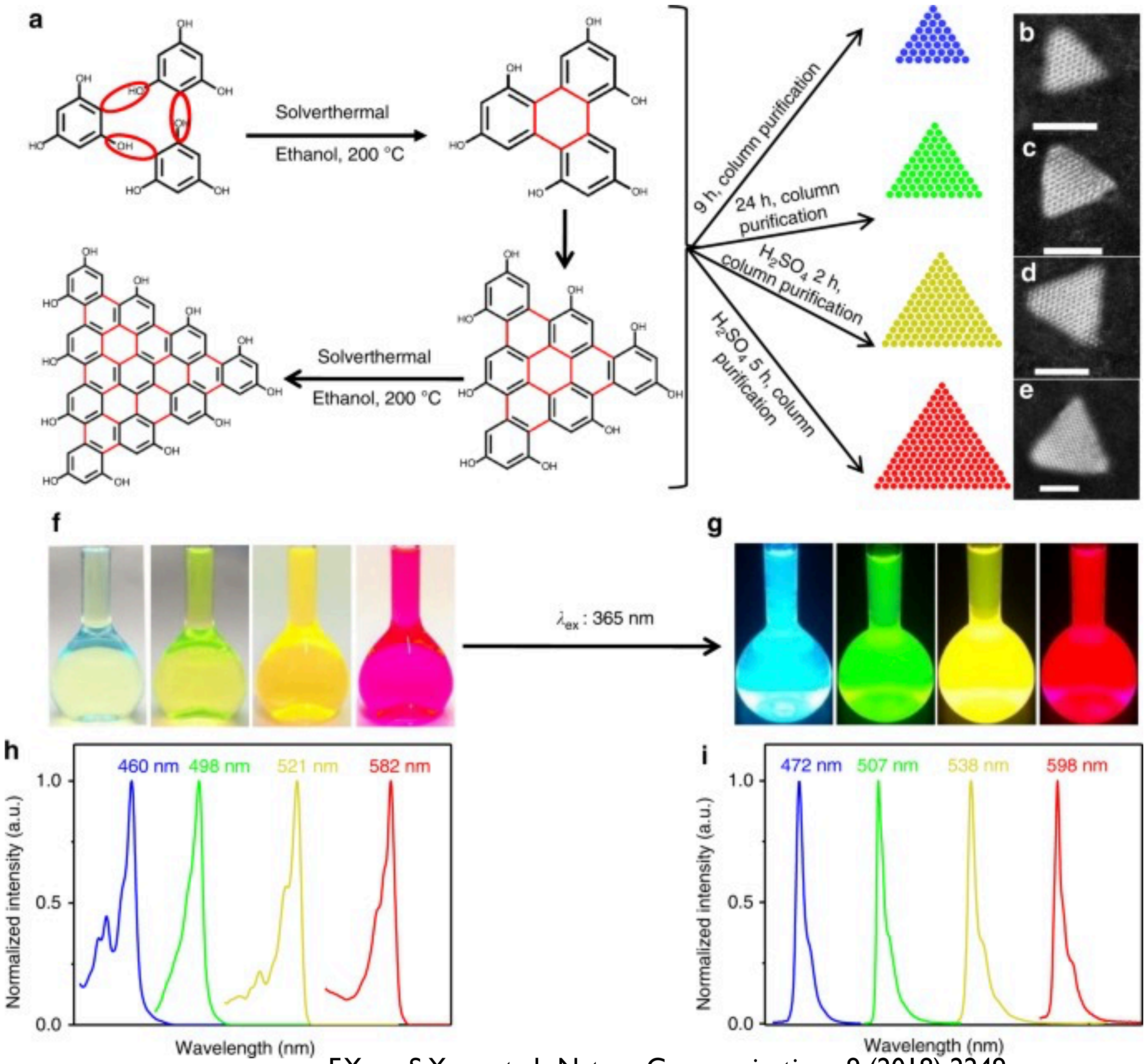
K. Děcká et al. Journal of Material Chemistry C 10(35):12,836–12,843.

Quantum dots: chromatic calorimetry

- idea: seed different parts of a "crystal" with nanodots emitting at different wavelengths, such that the wavelength of a stimulated fluorescence photon is uniquely assignable to a specific nanodot position

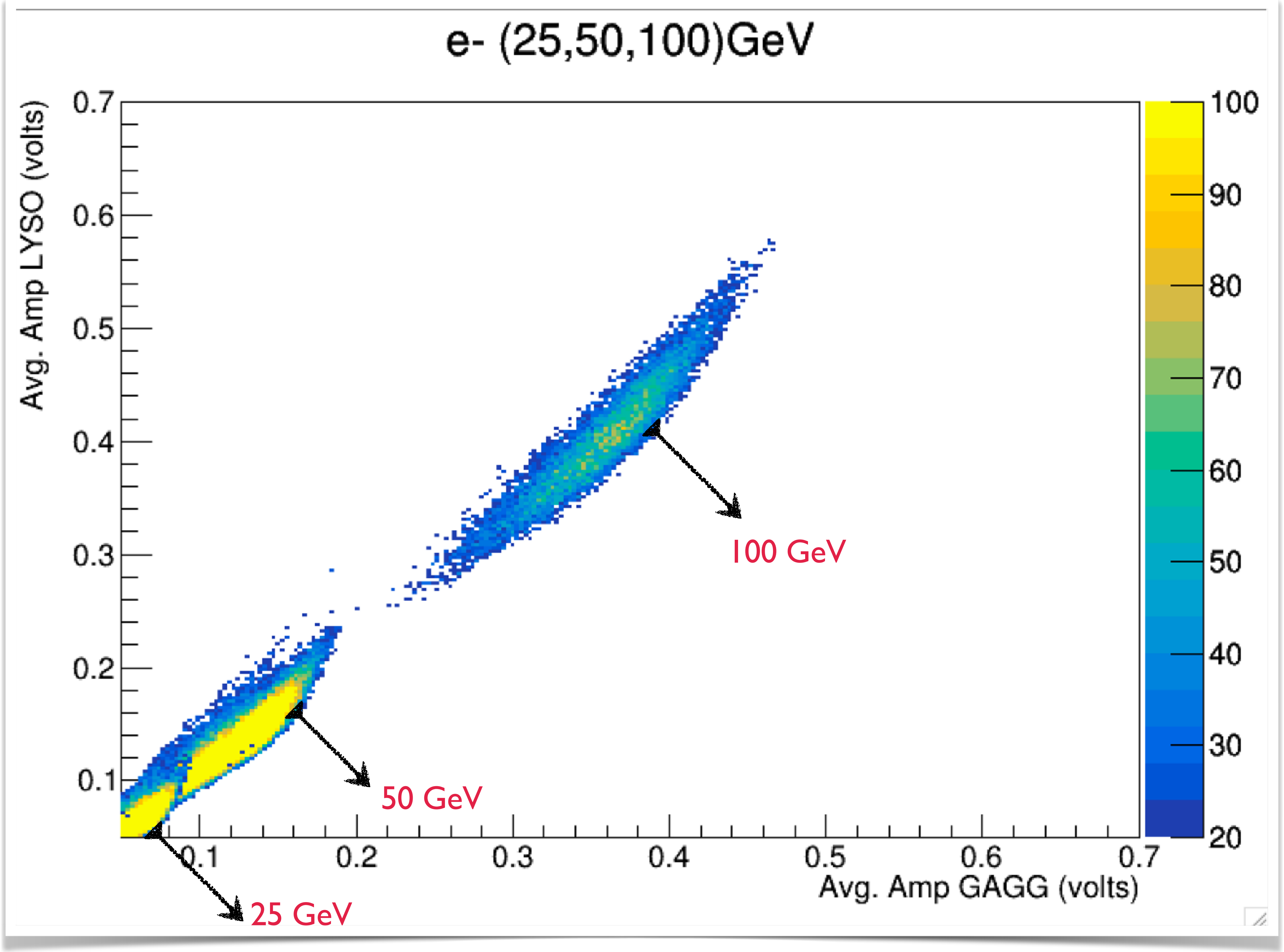
requires:

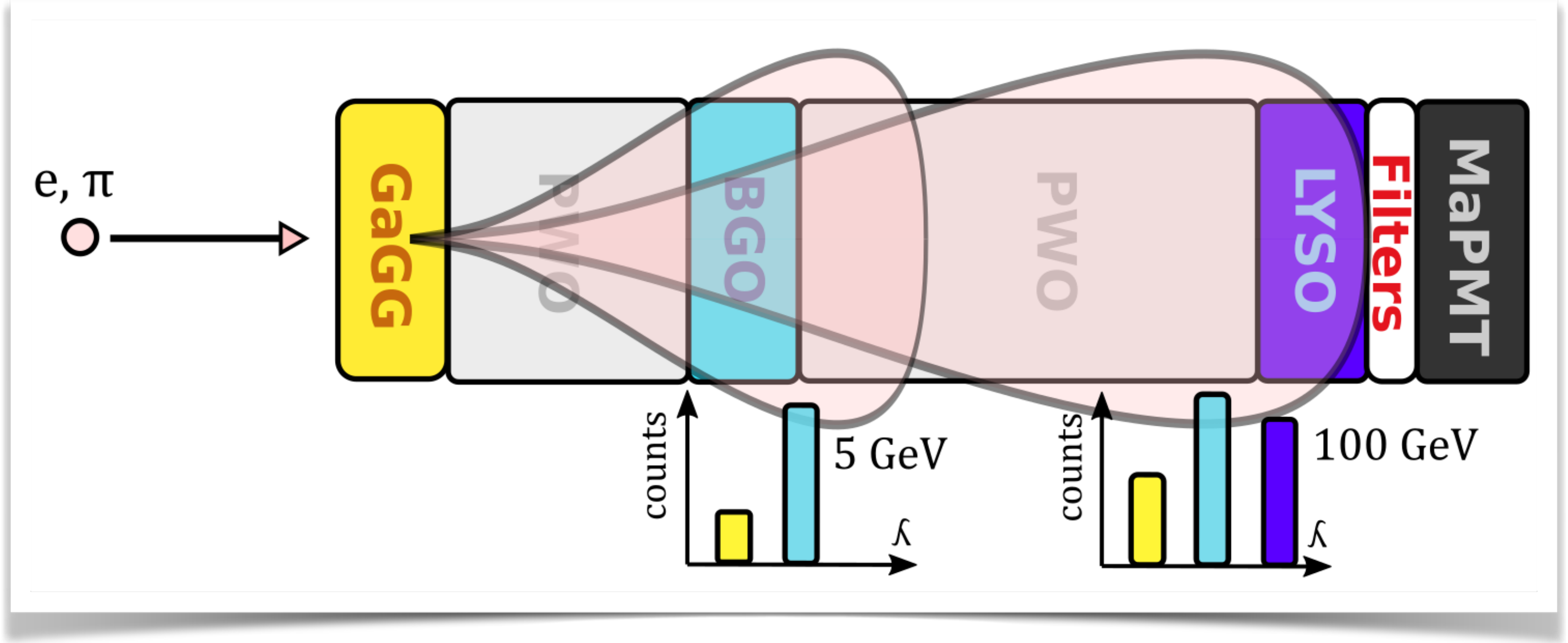
- narrowband emission (~20nm)
- only absorption at longer wavelengths
- short rise/decay times

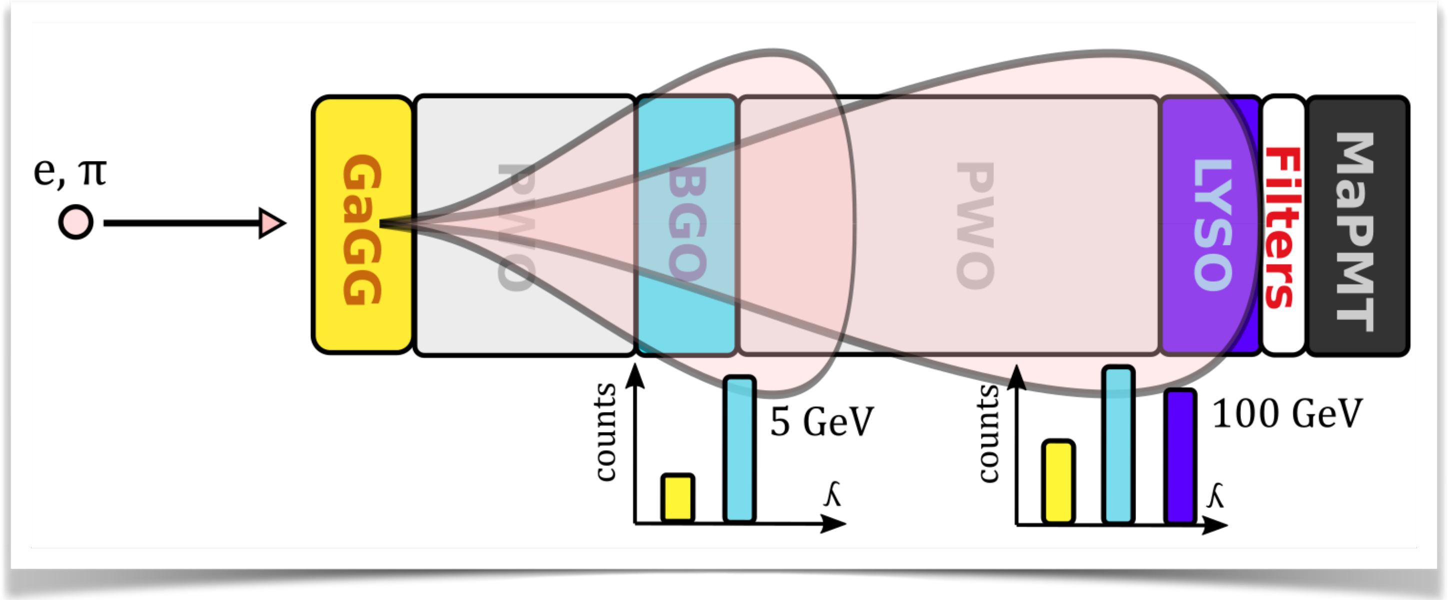


F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

electron energy discrimination

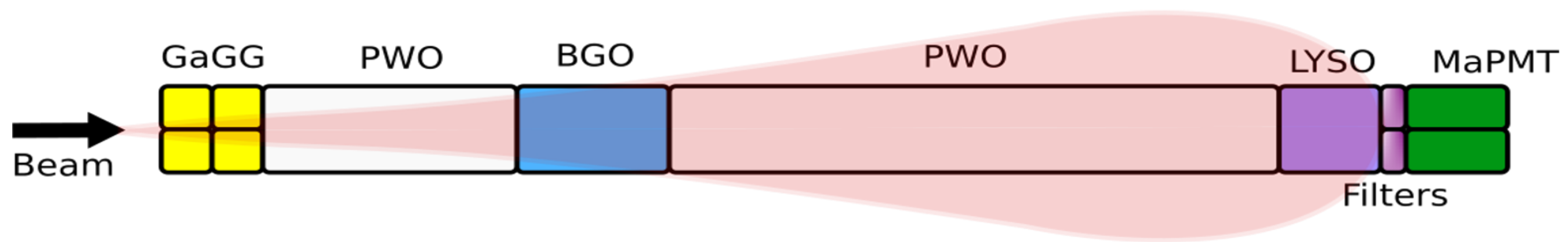


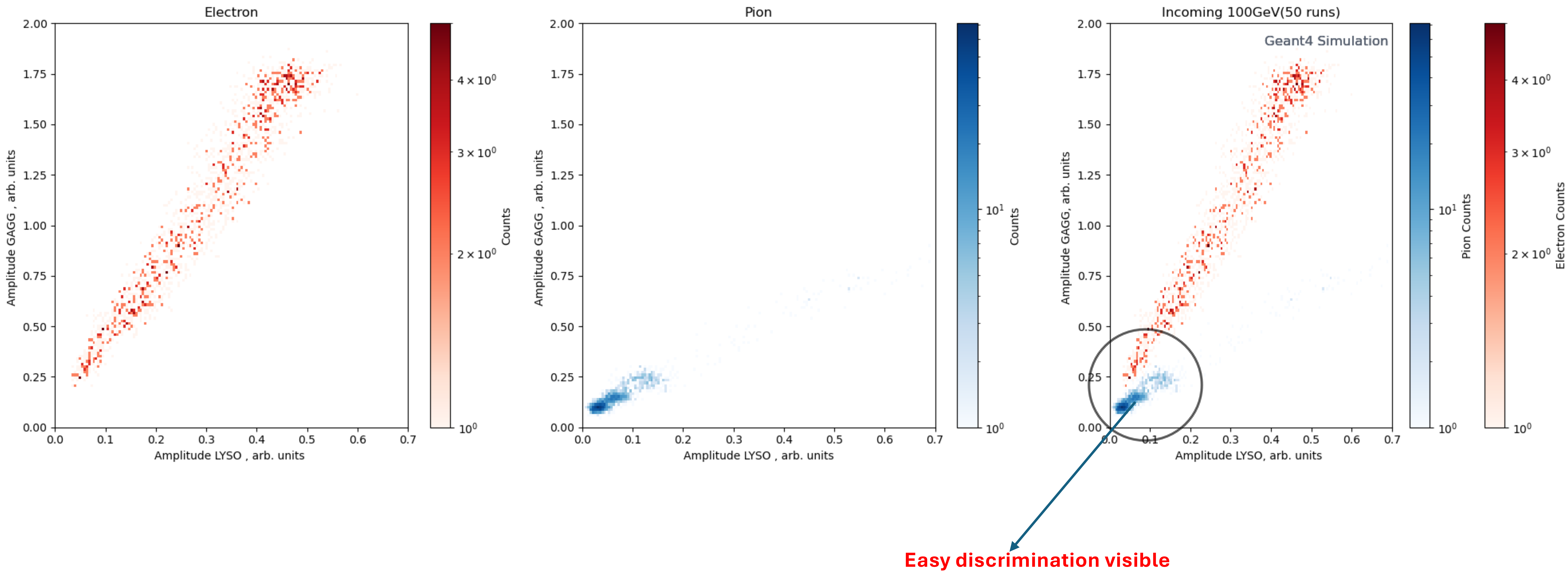




the analytical discrimination between electron and pion events, achieving approximately 58% accuracy.

Simulation-based discrimination between electrons and pions

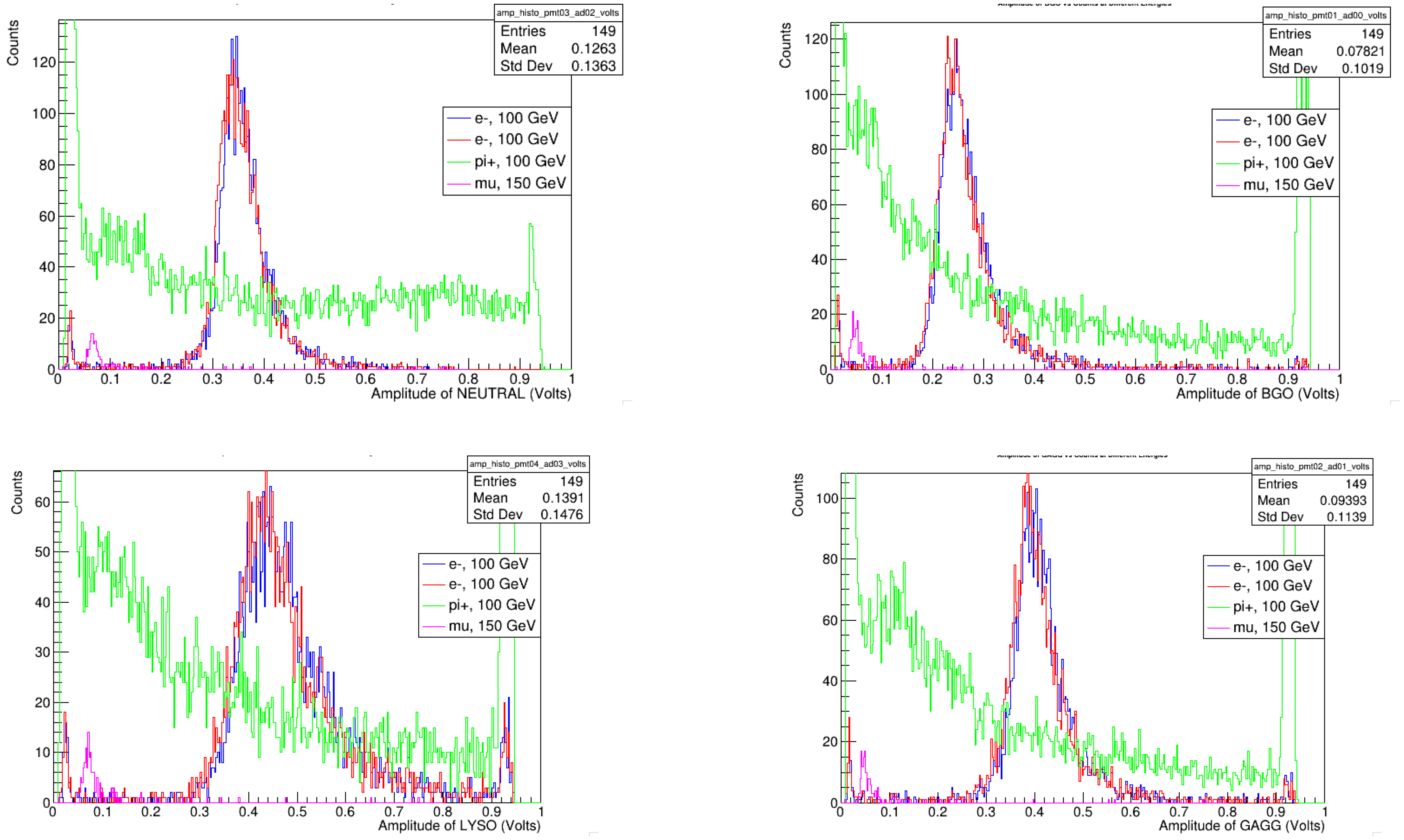




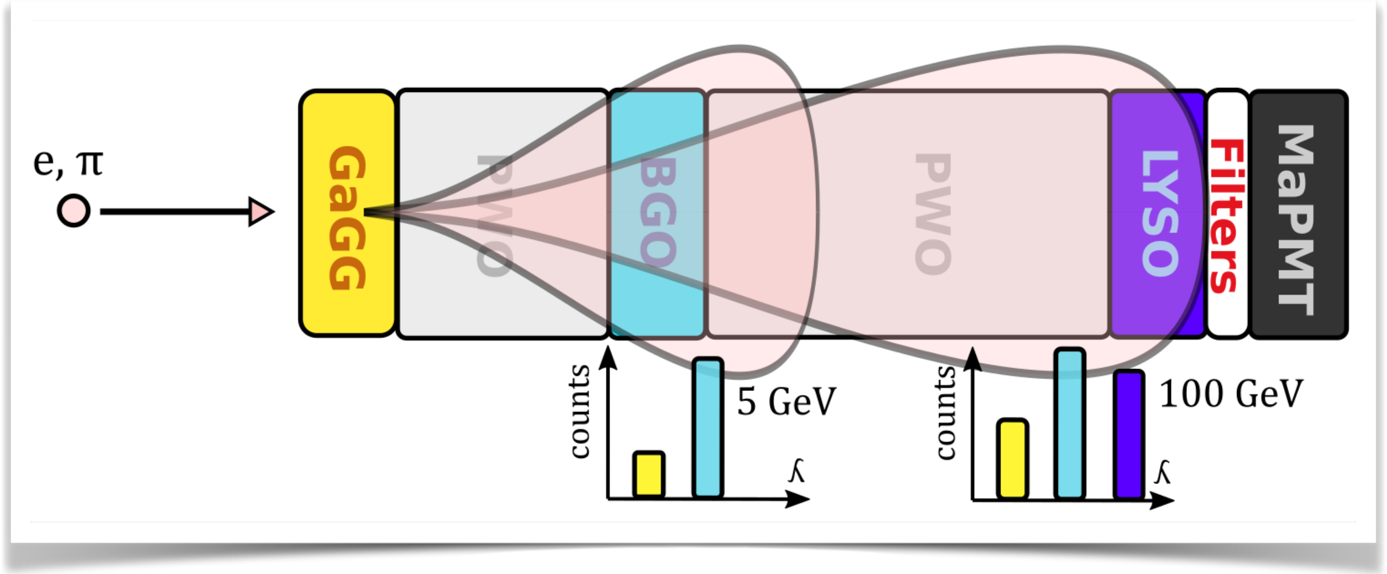
Discrimination precision % = 90% 16

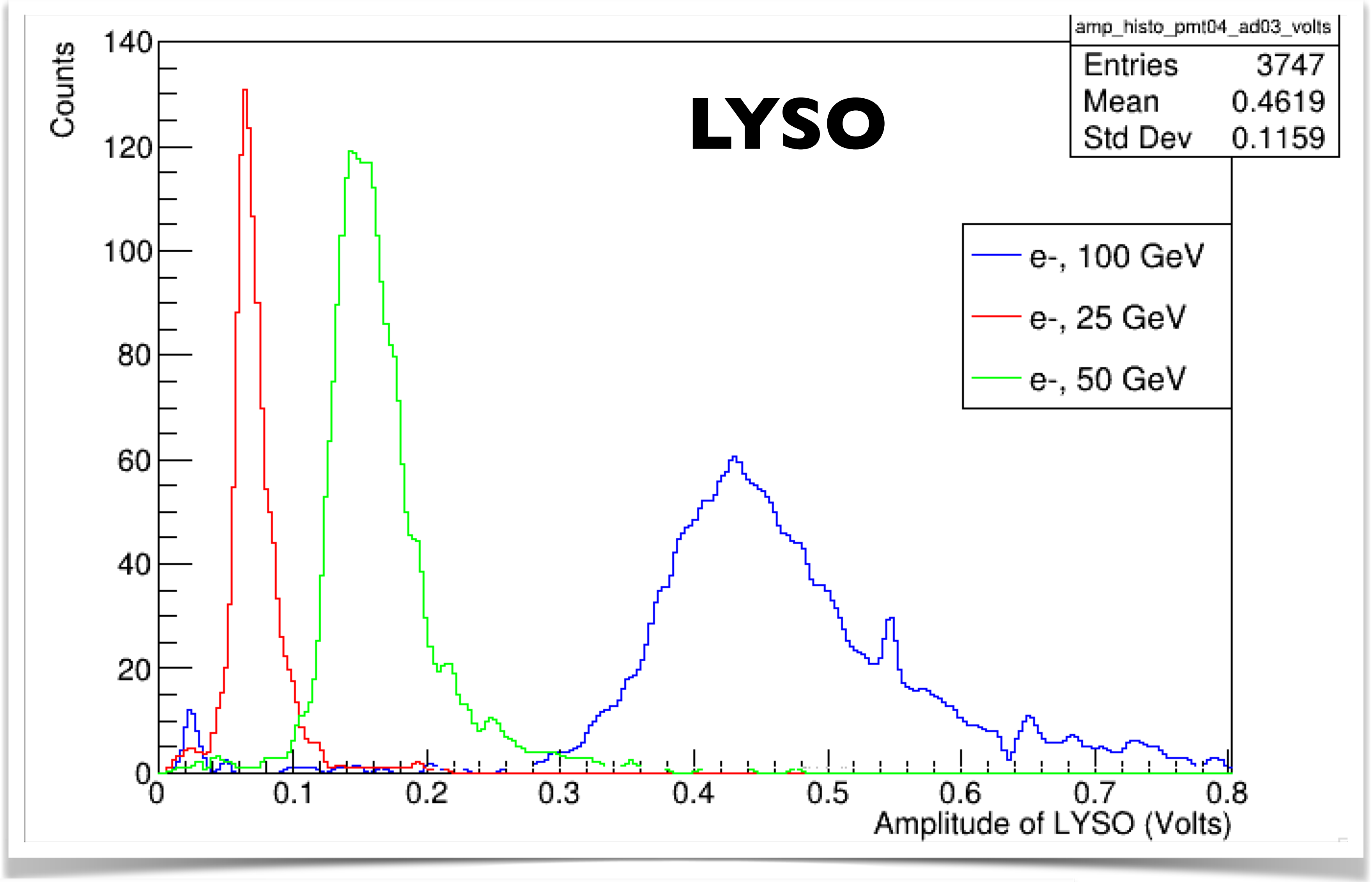
*** I.E 100 GeV, 50 runs**

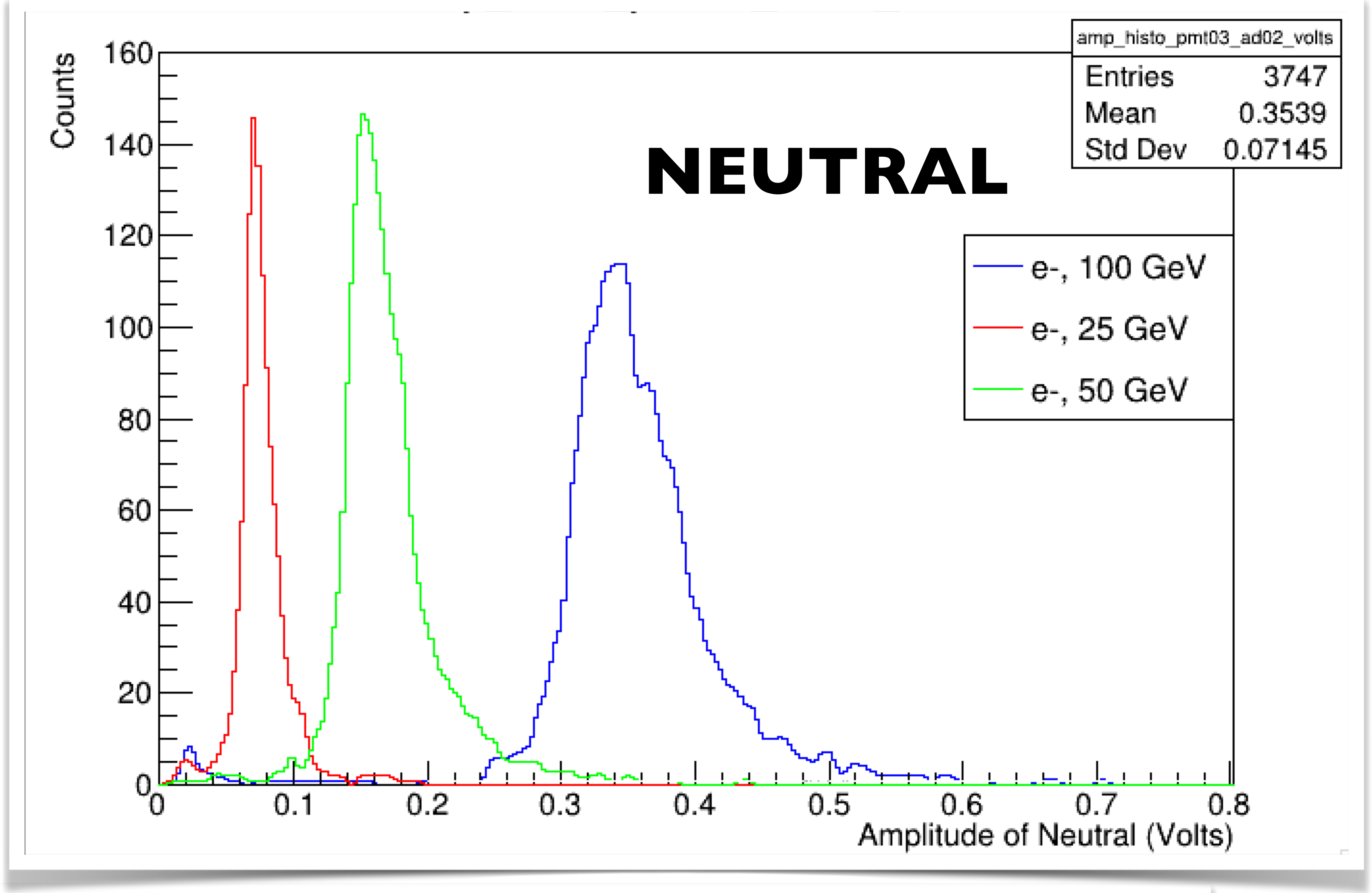
Output channels amp_o/p at different energies

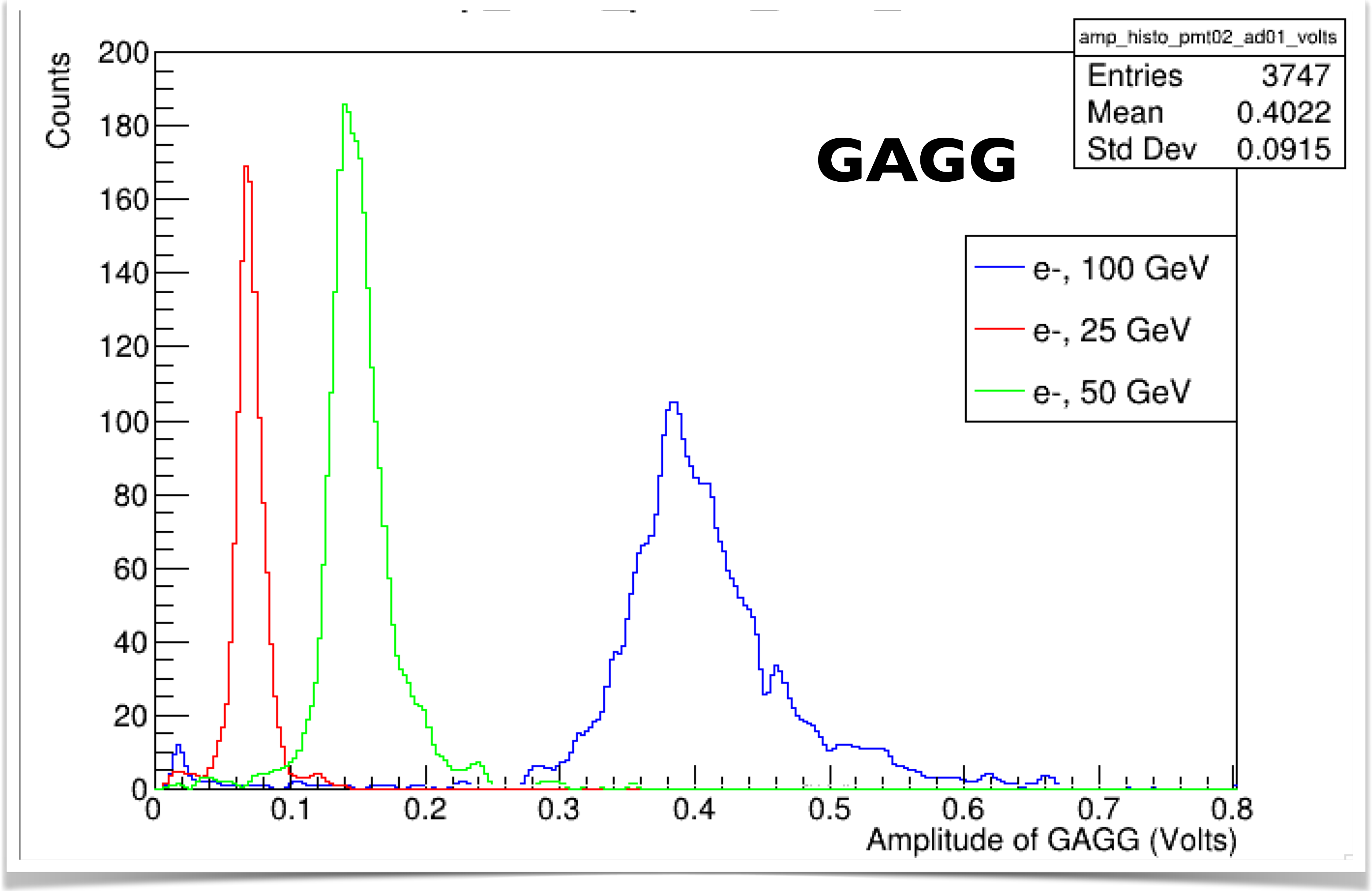


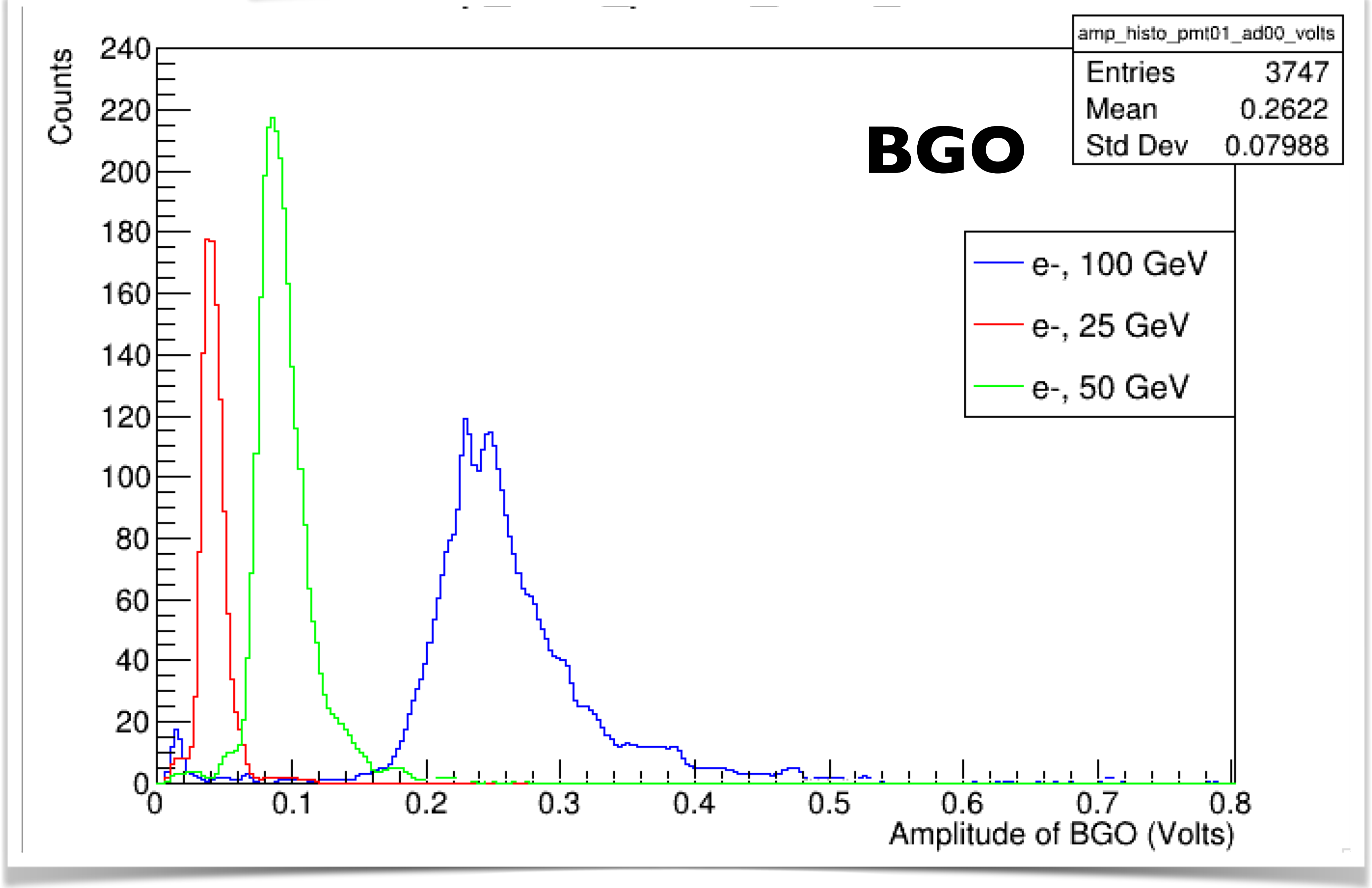
OUTPUT AMPLITUDE PLOTS AT DIFFERENT ELECTRON ENERGY

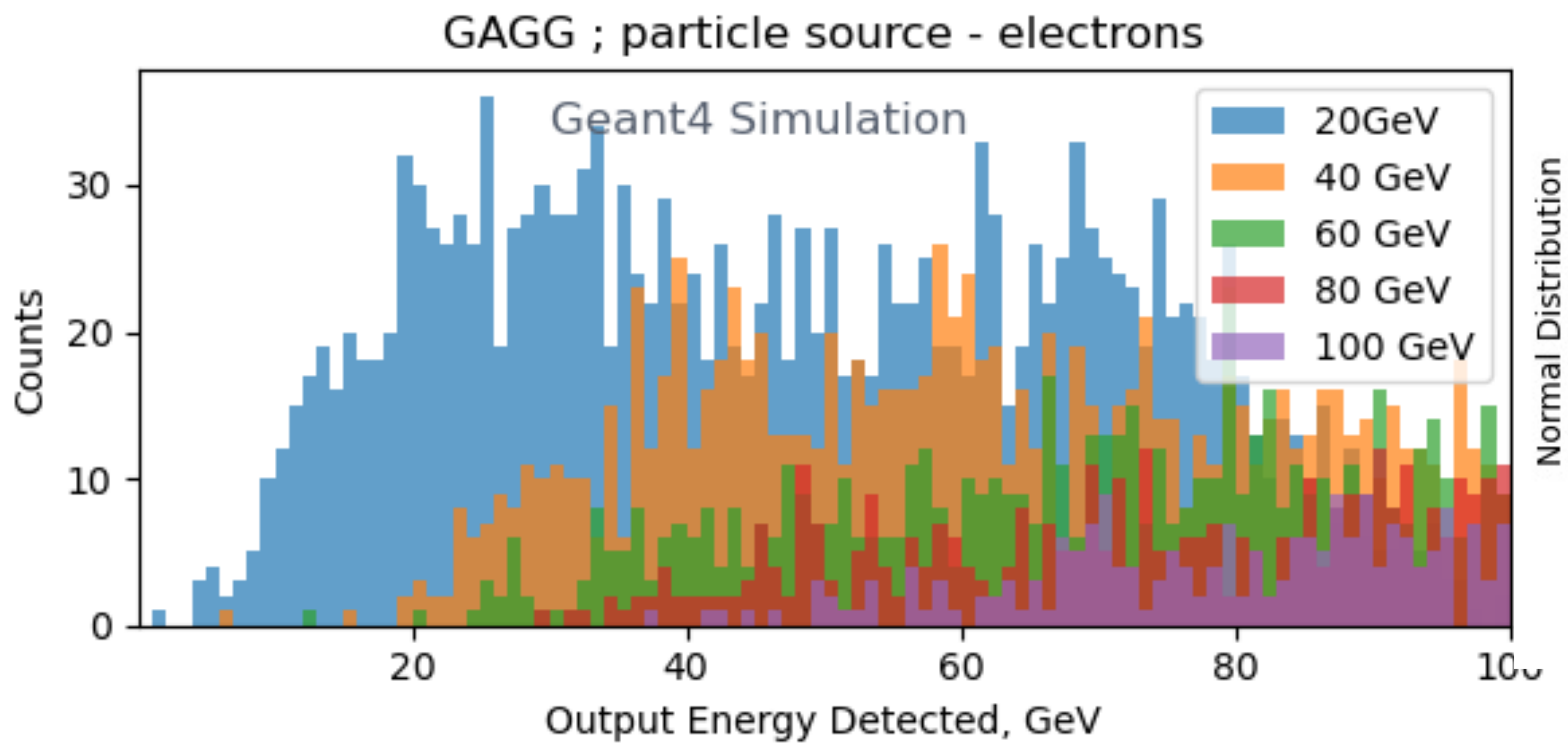


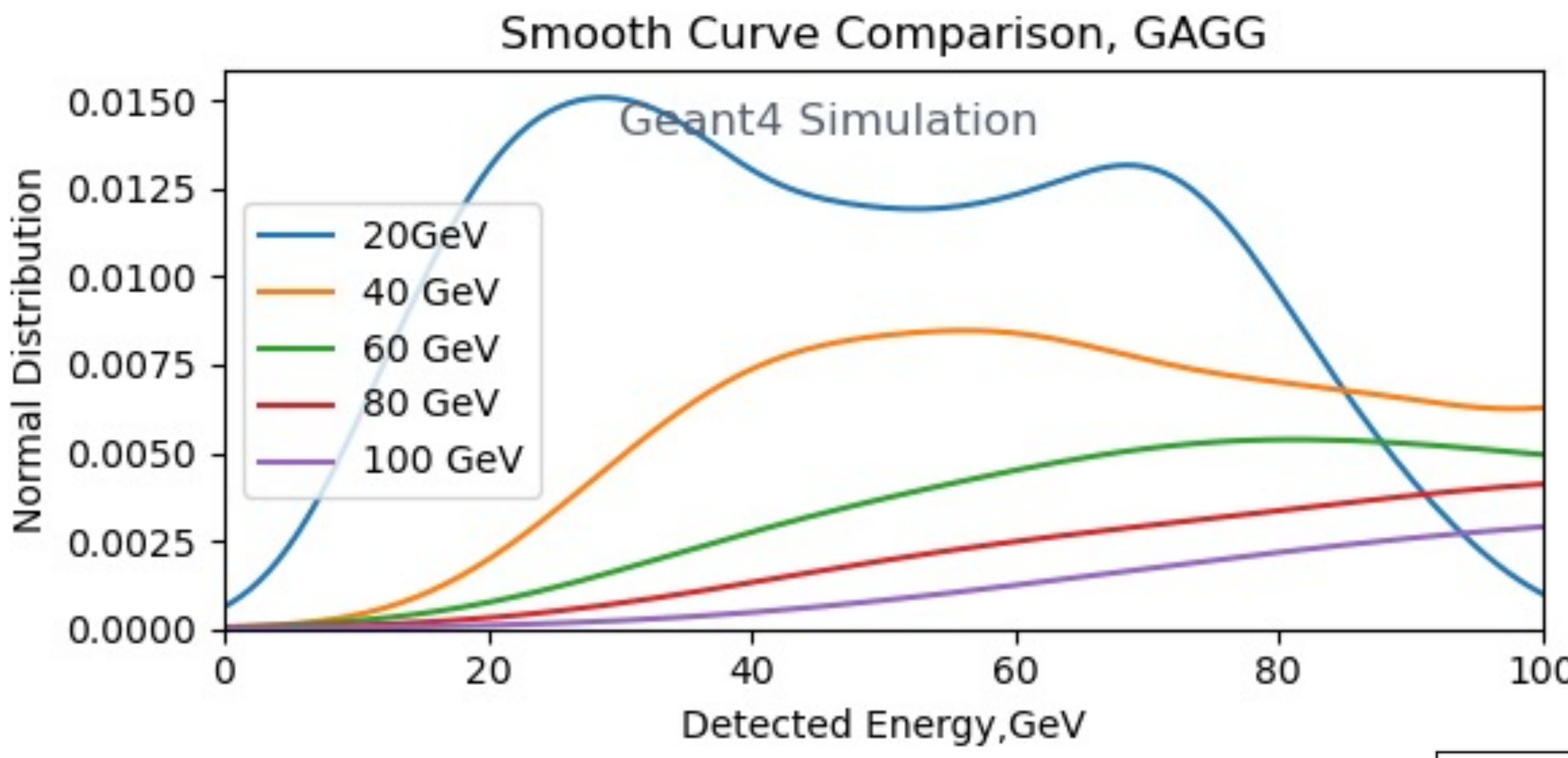


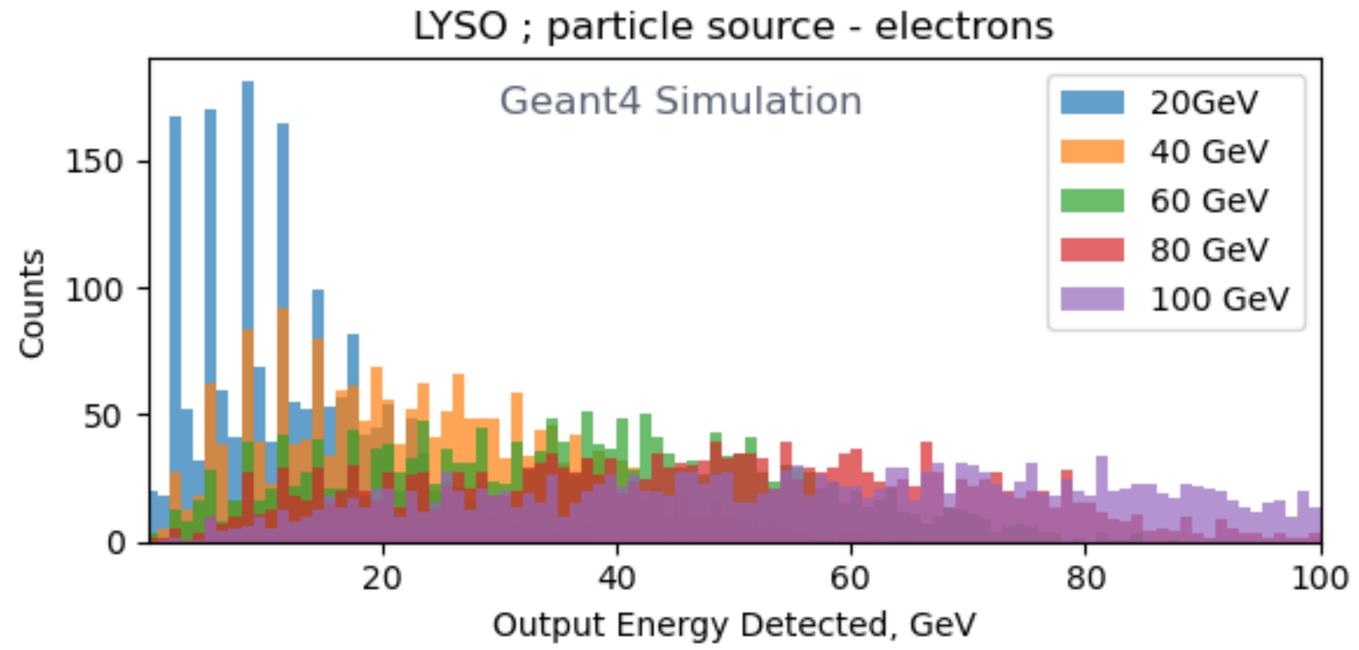


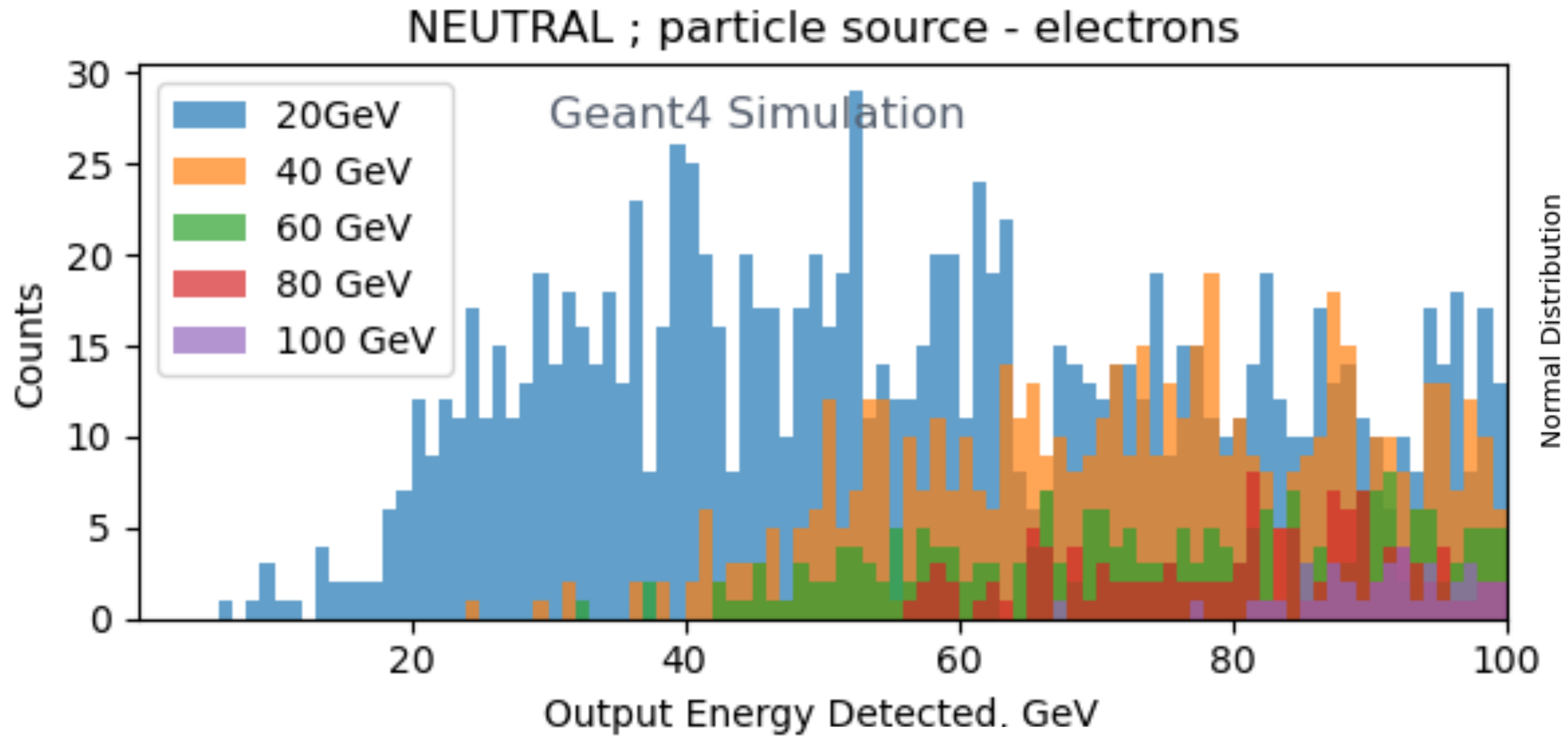


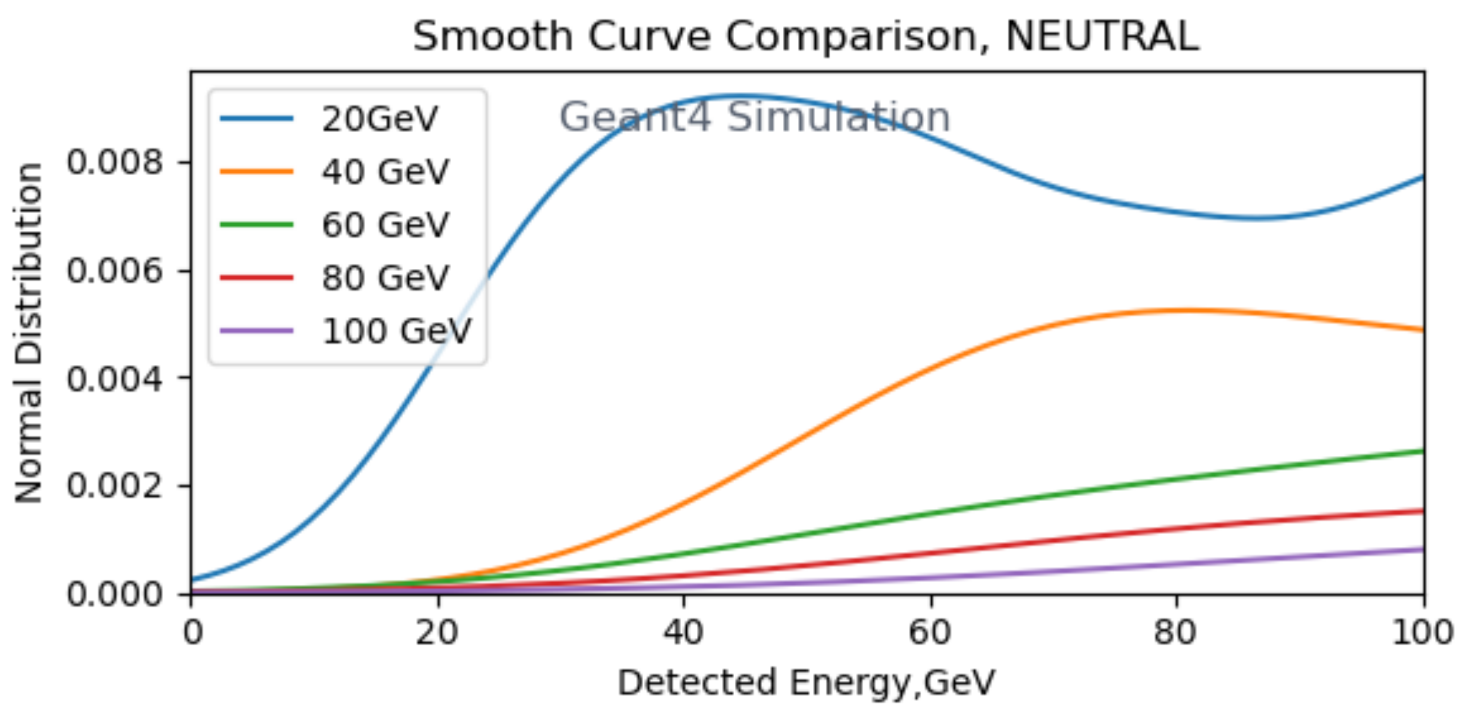


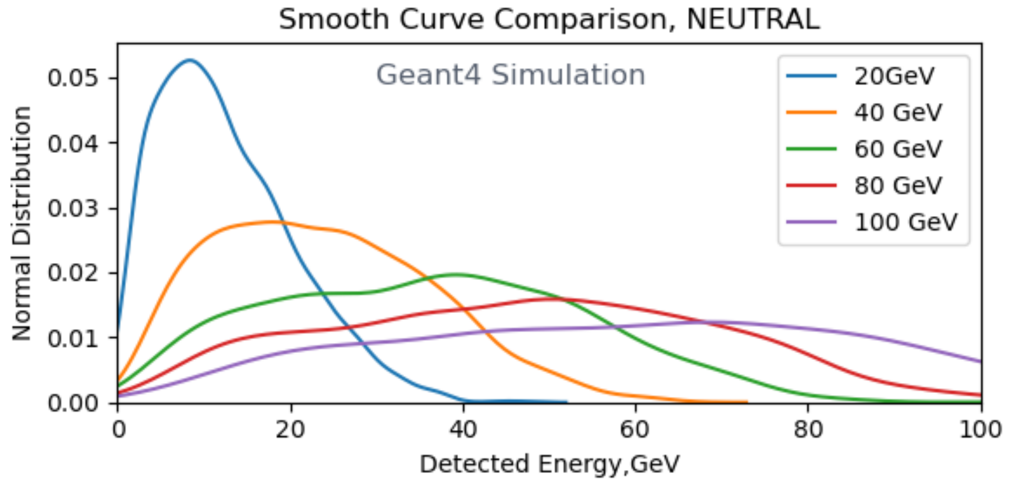


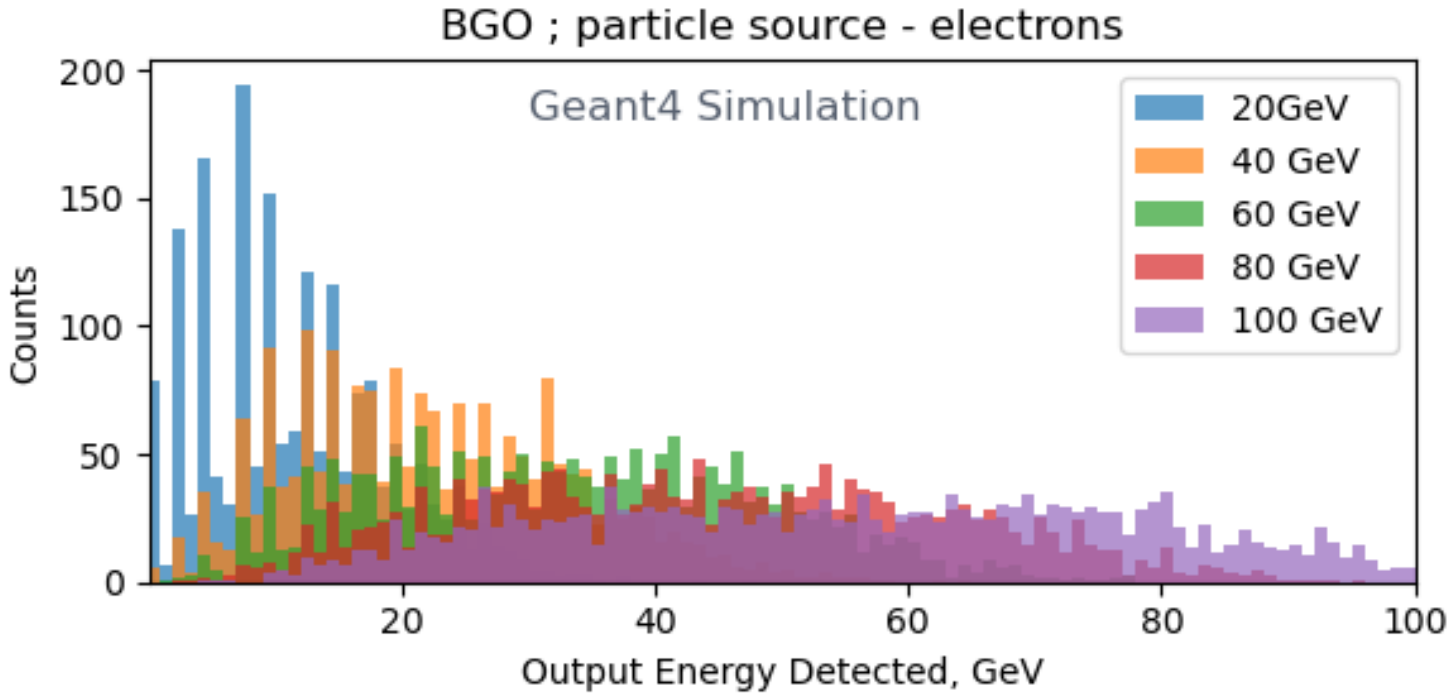


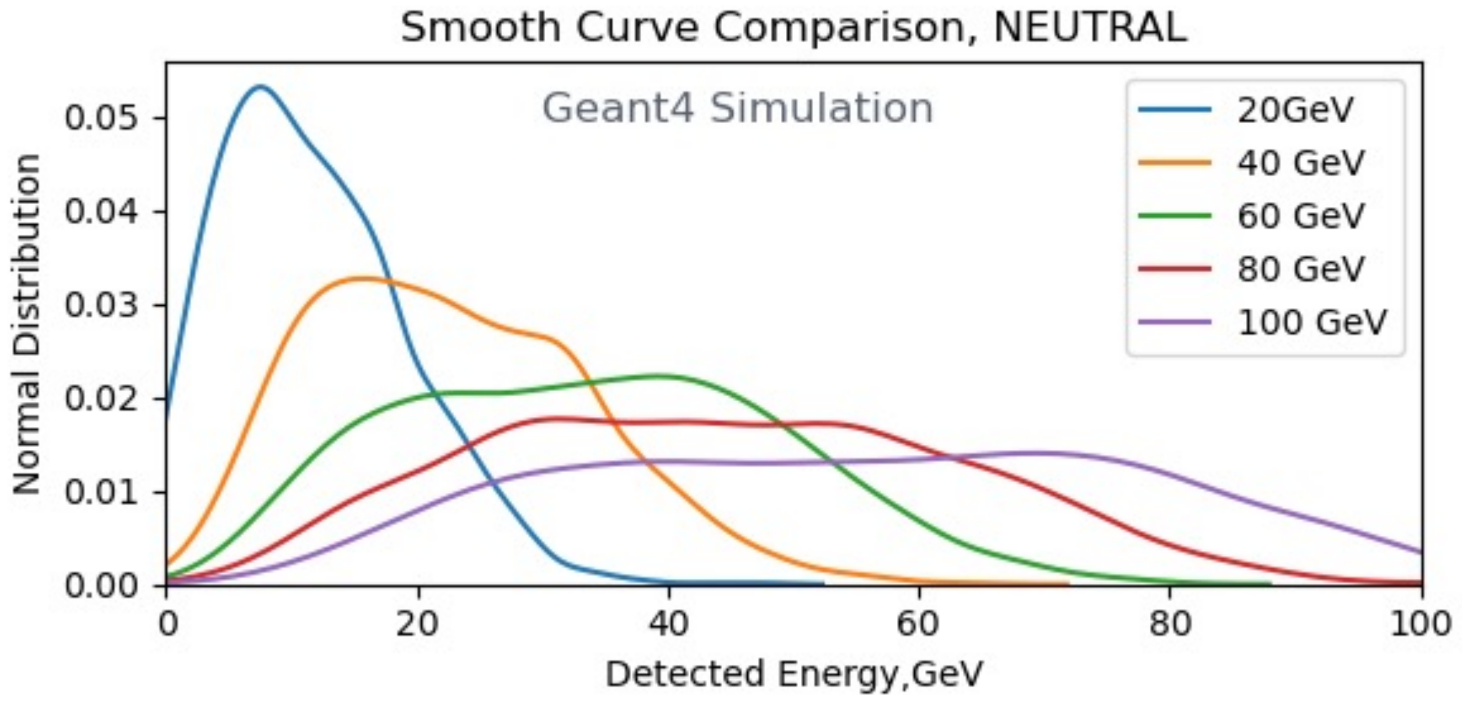








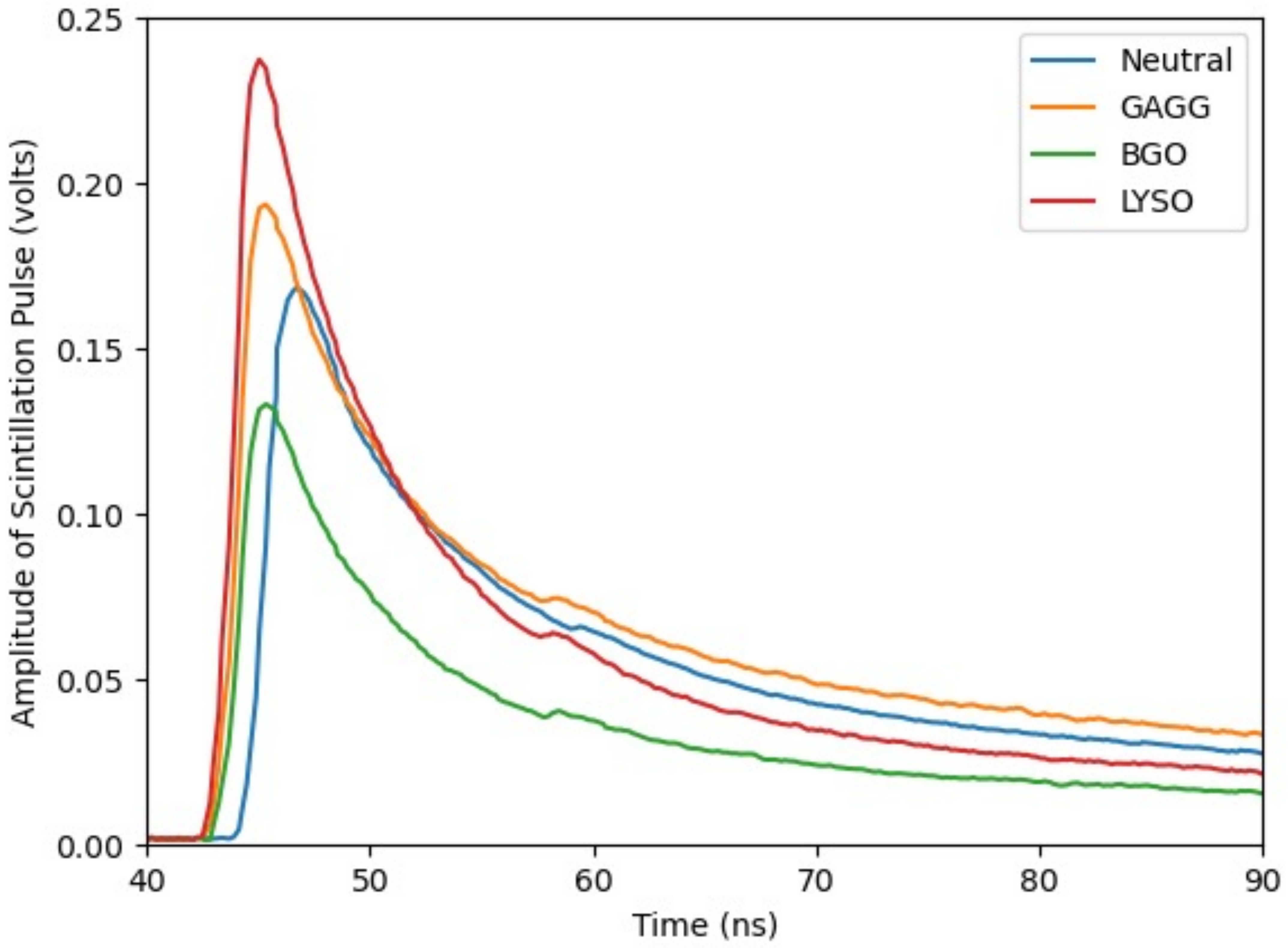




*** I.E electrons 0-100 GeV, 10 runs**

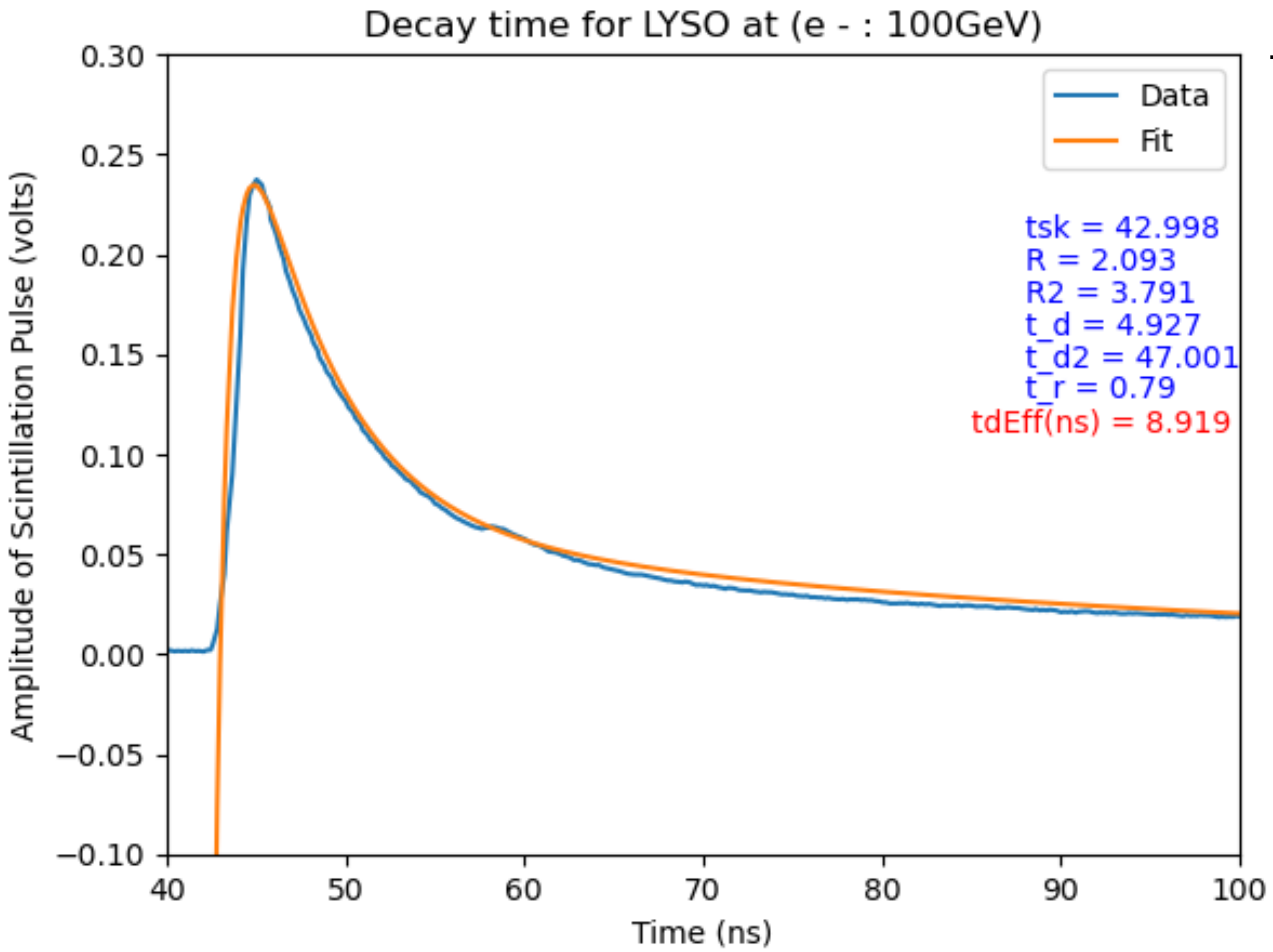
Decay time kinetics at (e- ,100GeV)

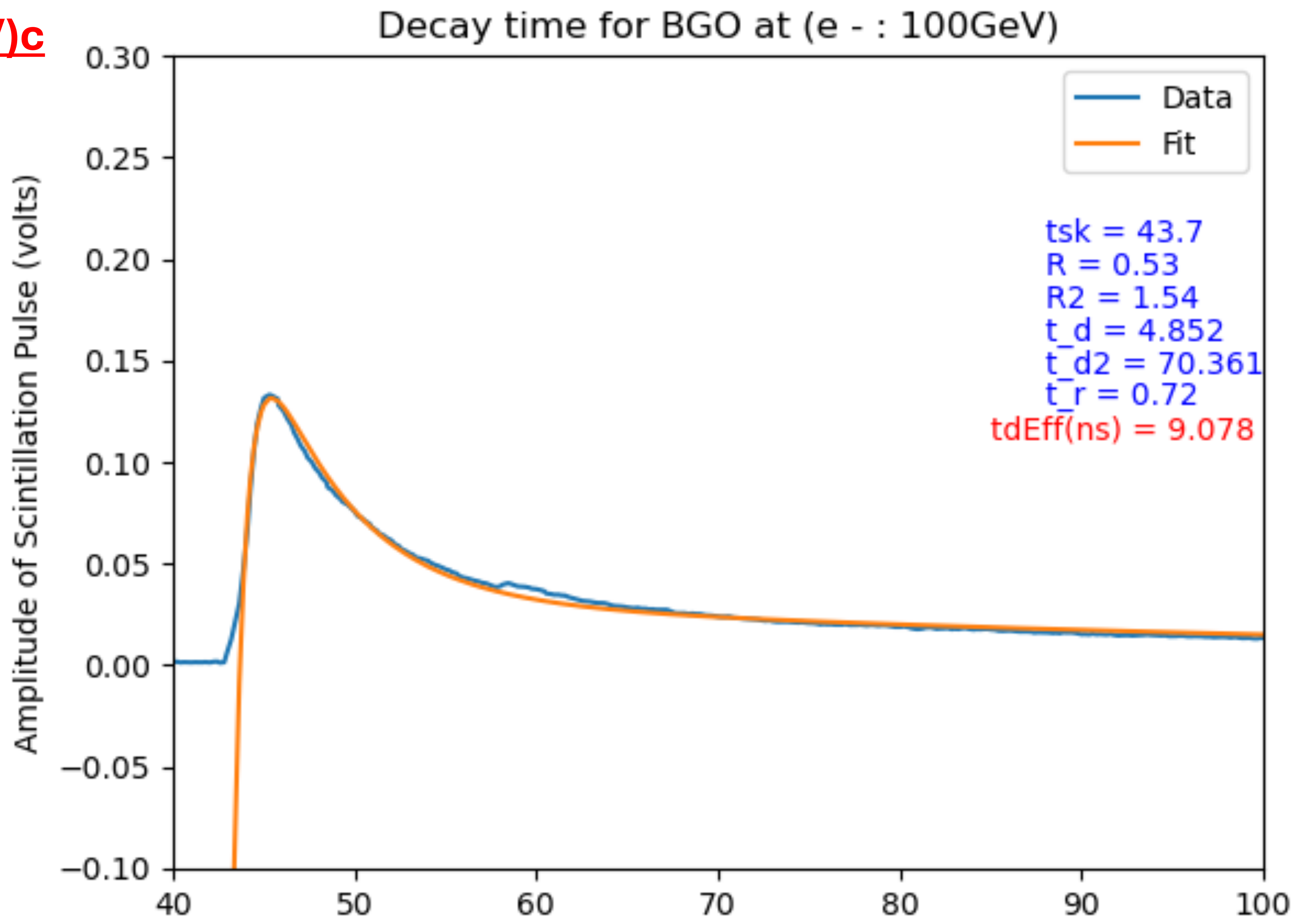
Crystals	Decay time [ns] *from previous paper (expected)	Decay time [ns] *ChromoCalo experiment
LYSO	38-44	
BGO	125-130	
GAGG	50-150	

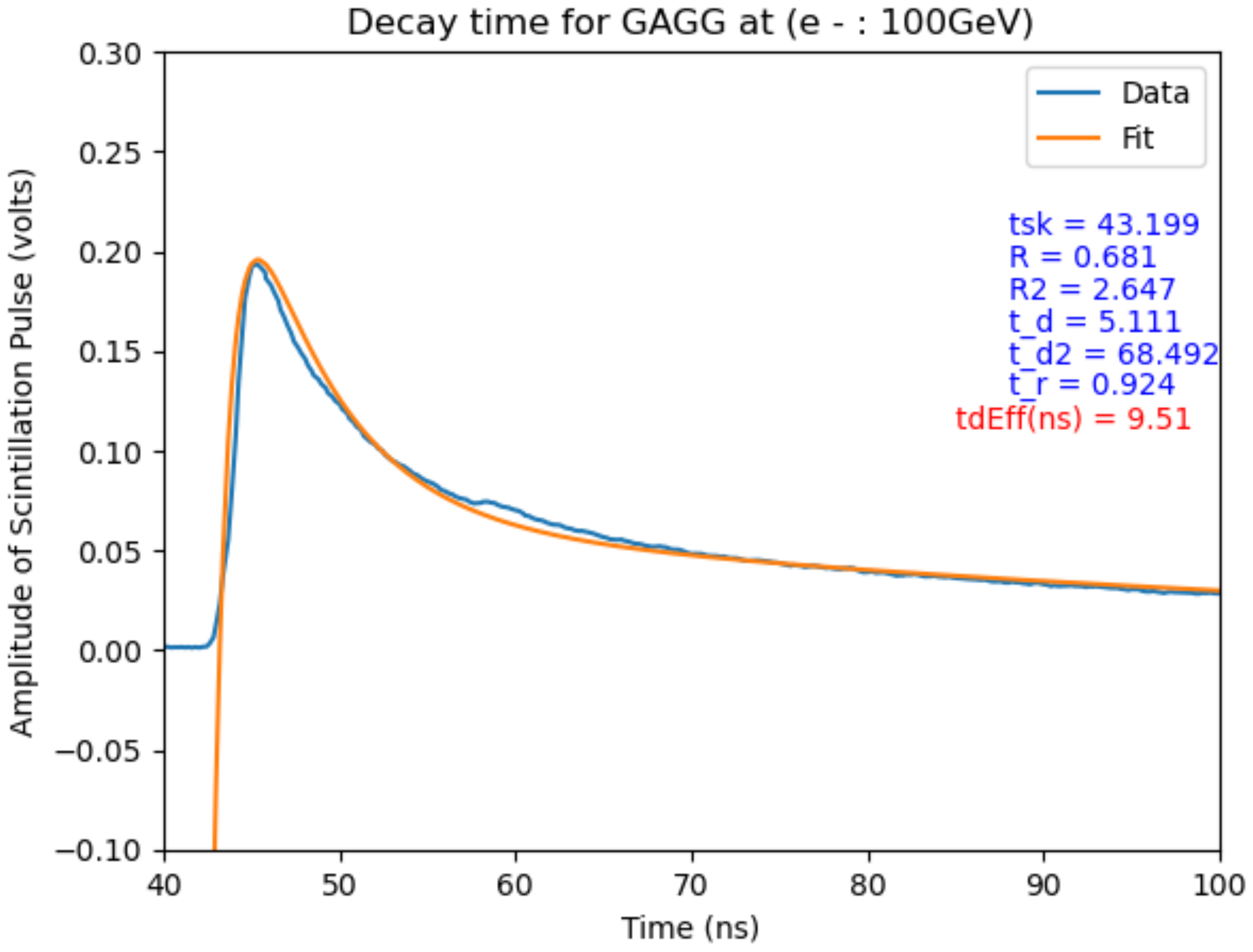


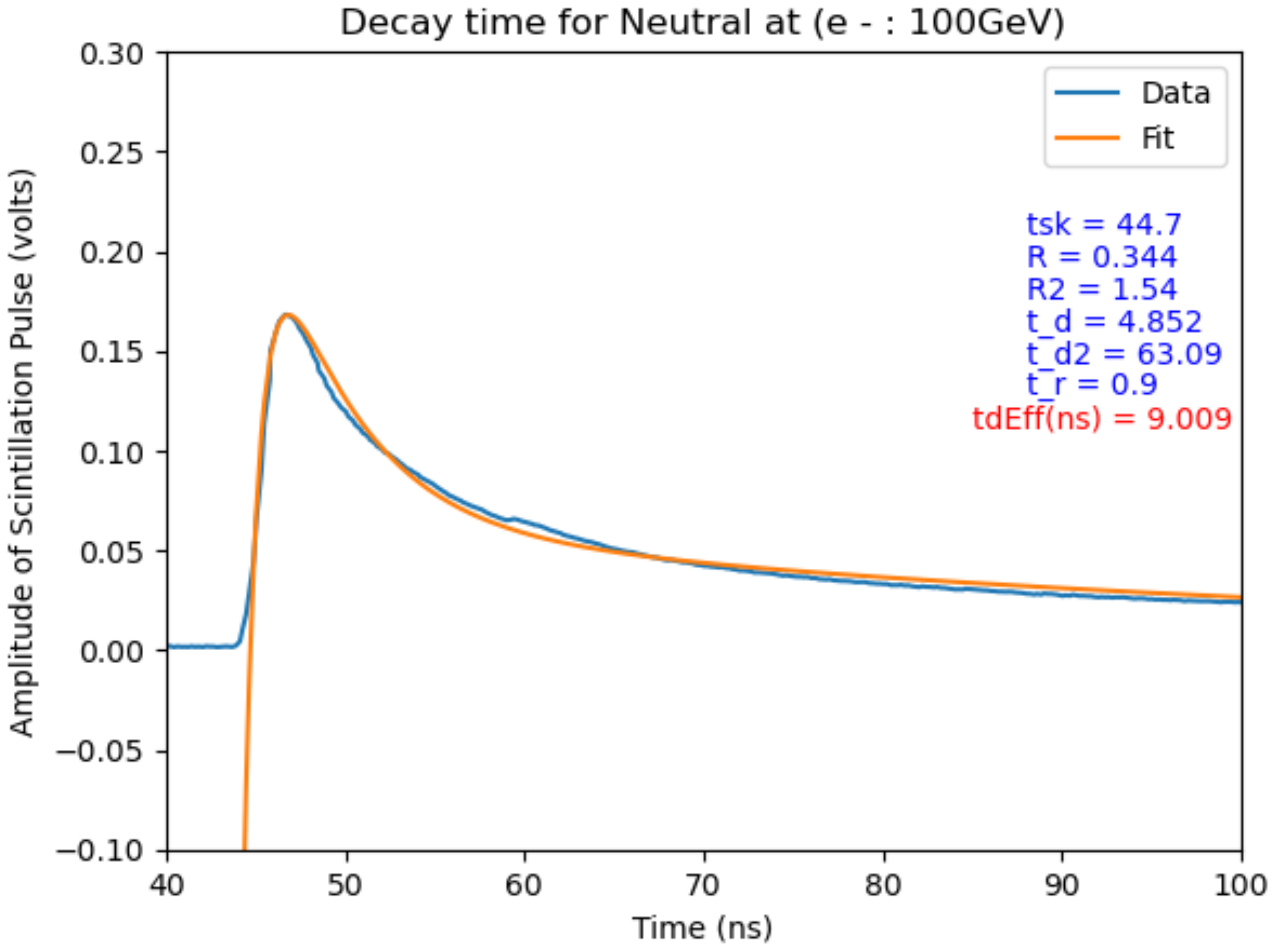
Decay time graphs at (e- ,100GeV)c

*Taking average of the all the pulses









* tsk, t_d, t_d2, t_r are bi-exponential components

* R, R2 are weight constraints in %

* tdEff (in ns) is the effective decay time