A Summary of ALP Production and Acceptance using MadGraph

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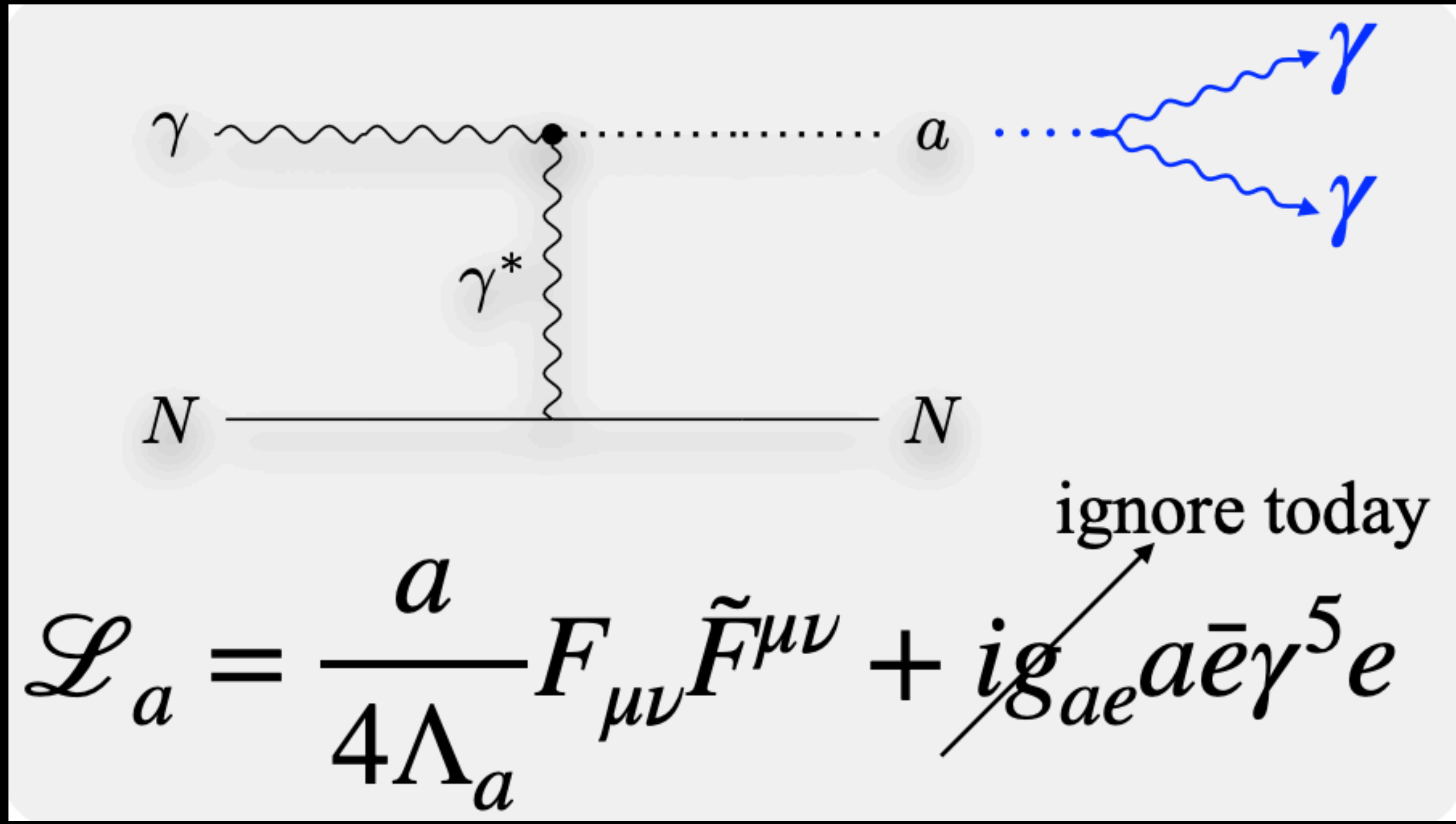
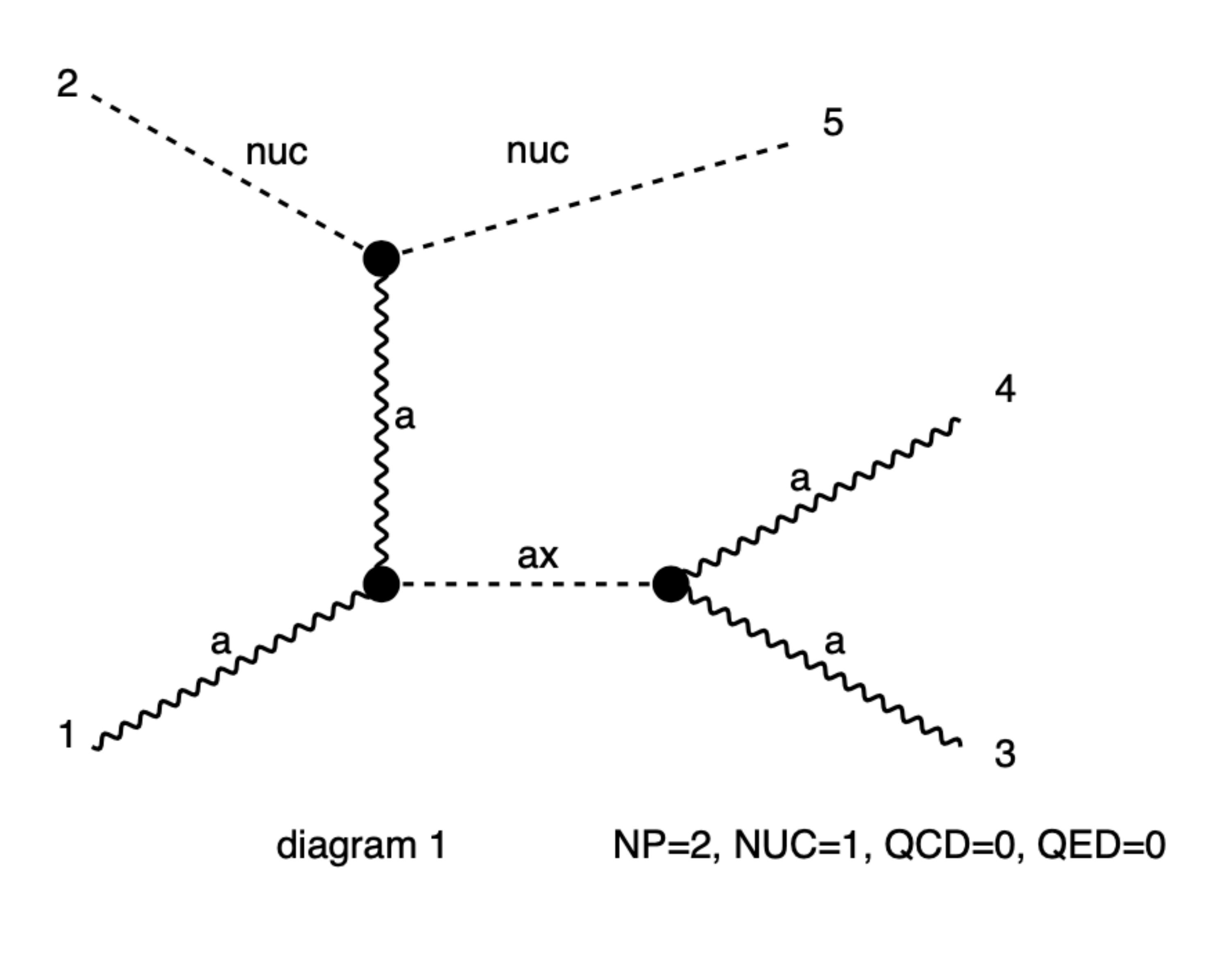
July 21, 2022
LUXE NPOD Detector Meeting
Weizmann Institute of Science, Israel

MadGraph model

- Generate this process:
  - a nuc -> ax nuc where a is photon, nuc is the nucleus of the tungsten dump and ax is the ALP (a BSM pseudoscalar particle).
  - Used the Primakoff production mechanism.
  - The dump is stationary.
- The ALP production UFO model is based on ALPsEFT (linear).
- The nuclear form factor was obtained from Iftah Galon (from a muonic force model)
  - This was implemented in the above UFO model of ALPsEFT.



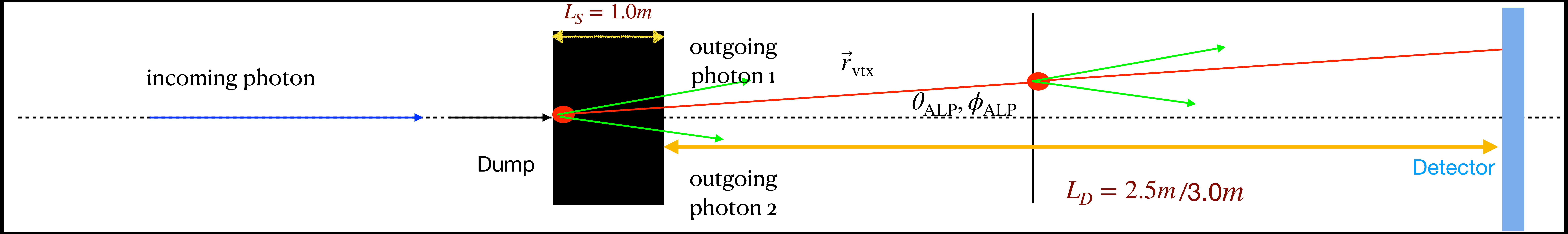
Primakoff production



MadGraph production

- The MadGraph generated output in the standard LHE file format.
  - Converted to root using ExRootConverter
- The root file contained these branches:
  - Particle four momentum, PDG, Status (incoming/outgoing), Event id, number of particles in the event etc.
- MadGraph does not smear the vertex position, so all “collisions” happen at z=0, t=0.
  - MadGraph decays ALP instantaneously - so we have two photons in the final state at z=0,t=0.
  - The 2 photons are produced at z=0 and t=0
    - We need to displace them according to the ALP’s lifetime for realistic acceptance calculation.

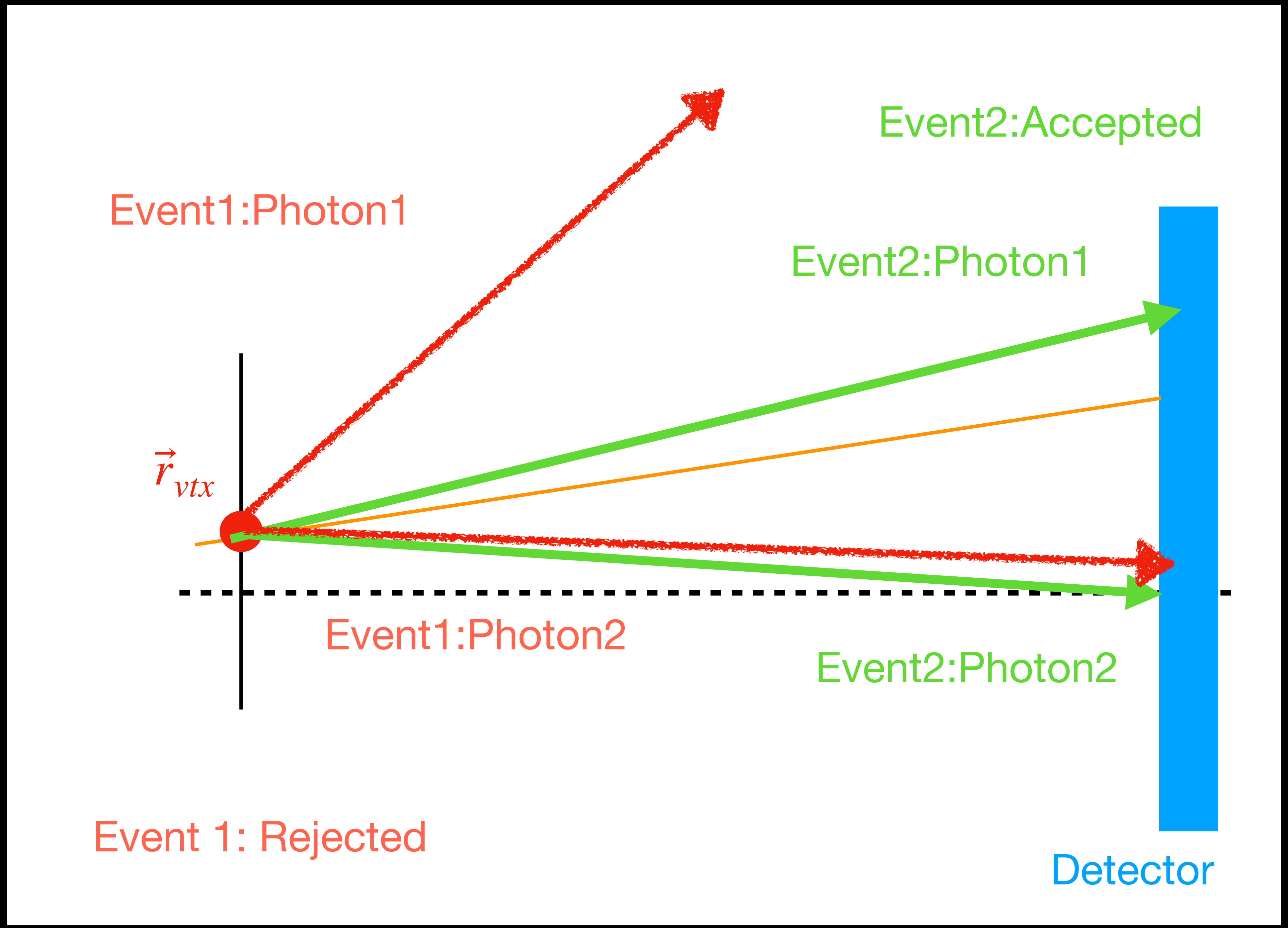
Acceptance Calculation: ALP decay volume



- The distance of decay (r_{vtx}) for each ALP is obtained by randomly drawing a length from the decay length distribution of the ALP.
- Decay length is obtained using $L_A = c\tau_A p_A/m_A$.
  - τ_A is the decay time of ALP, p_A/m_A is the Lorentz factor.
- r_{vtx} : randomly drawing a number from exp(-L/L_A).
  - The direction is determined by the momentum of ALP.
    - ALP momentum is reconstructed by vector addition of two outgoing photons' four momenta.
  - Now we have $\vec{r}_{vtx}$.
- Once the $\vec{r}_{vtx}$ is determined, photons are shifted to that position.
  - If $|\vec{r}_{vtx}|\cos(\theta_{ALP})$ is more than the dump length ($L_S = 1.0m$) and less than ($L_S + L_D$), then we proceed to the next stage, other wise the event is rejected.

Acceptance Calculation: Detector area

- Once the $\vec{r}_{vtx}$ is determined, and photons decay inside the decay volume
    - Given the opening angle of the photons at $\vec{r}_{vtx}$ and the distance still needed to travel to detector, we check if the photons are caught by the detector or not.
- If both the photons are caught by the detector (and $E_\gamma >$ 0.5 GeV), then that event is accepted.
    - If at least one photon has energy less than 0.5 GeV or/ and at least one photon is outside geometric acceptance, the event is rejected.
- Acceptance $\mathscr{A}$ $=$ events with both photons passing the energy cut and geometric constraints divided by the total number of events generated.



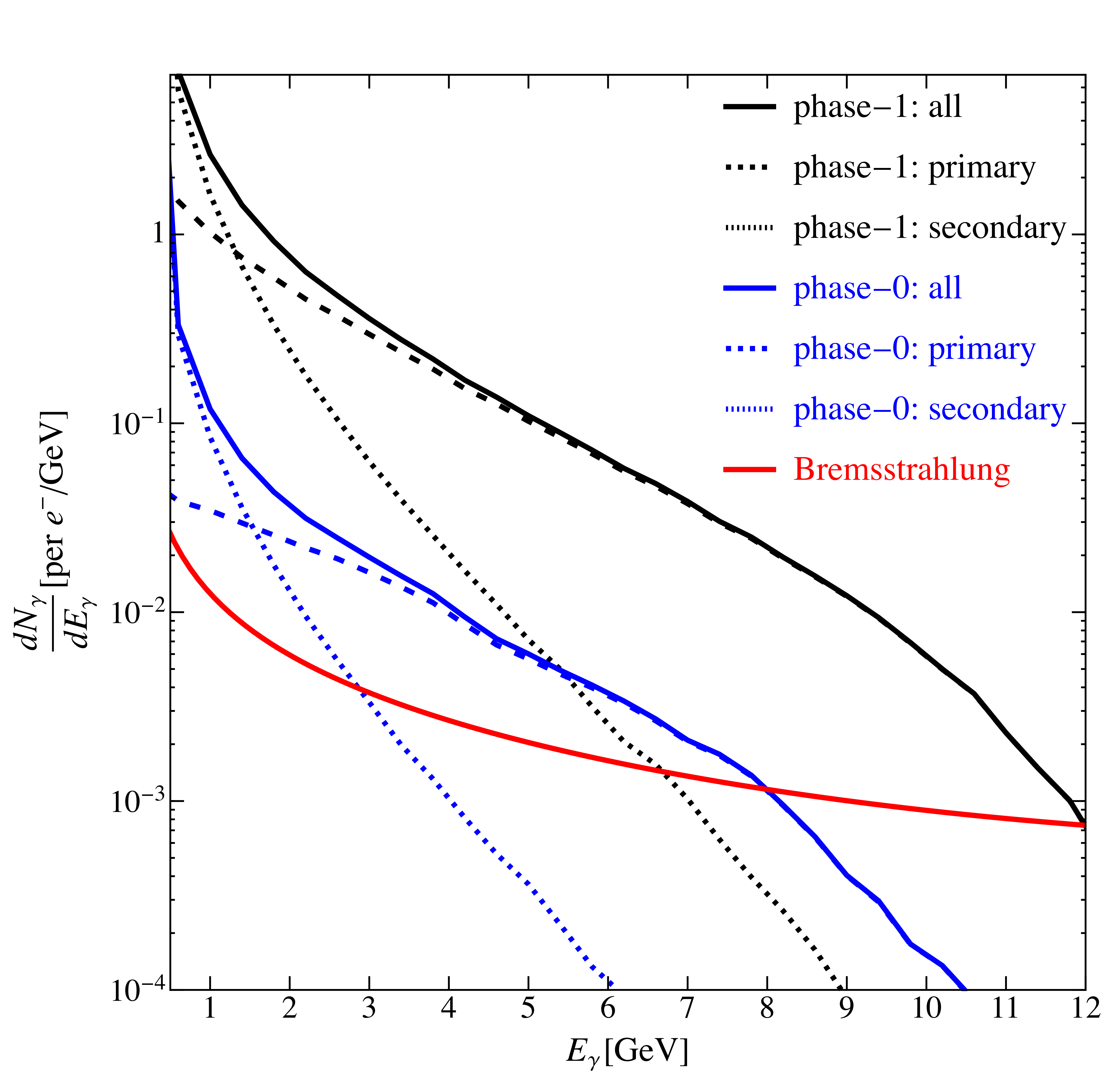
Expected number of ALPs:

- Once the geometric acceptance is obtained ($\mathscr{A}$), the factor is multiplied by the effective luminosity ($\mathscr{L}_{eff}$) and the cross-section of production (σ) to get the number of ALP events:
  - $N_{ALPs} \approx \mathscr{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a(E_\gamma, Z) \left(e^{-\frac{L_D}{L_a}} - e^{-\frac{L_V + L_D}{L_a}} \right) \mathscr{A},$ $\longrightarrow$ $\sigma_a(E_\gamma, Z)$ is the production xsec as a function of E_γ, $\mathscr{A}$ is the angular acceptance times efficiency of the detector.
  - $\mathscr{L}_{eff} = N_e N_p \frac{9\rho_N X_0}{7A_N m_0}$
    - $N_e = 1.5 \times 10^9$ electrons/bunch
    - $N_p = 10^7$ laser pulses a year
    - ρ_N density of dump, for tungsten 19.3 g/cm^3
    - X_0 is the radiation length of tungsten (0.35 cm)
    - A_N is the mass number of tungsten (184)
    - m_0 is the atomic mass unit in gram: 1.661×10^{-24} g.
  - The exponential factor in the above equation comes from the requirement that ALPs must decay after the dump and before the detector volume.
    - In simulation, we don't need that because we randomly draw the length propagated by ALP from its decay length distribution.
    - Therefore the exponential factor is absorbed in $\mathscr{A}$.
  - Replacing the integral with summation: $N_{\text{ALPs}} = \sum_i \mathscr{L}_{eff} \times \mathscr{A}_i \times \sigma_i \times N_{\gamma,i}$
    - Sum over incoming photon beam energy distribution, $N_{\gamma,i}$ in bins of 0.1 GeV (distribution in next side).

Incoming photon beam energy distribution:

- Showing spectra per primary electron
  - “Primary” from the IP
  - “Secondary” produced inside the dump
- Photons per electron (phase-1)
  - ~3.5 photons with $E_\gamma > 0.0$ GeV
  - ~1.7 photons with $E_\gamma > 0.5$ GeV

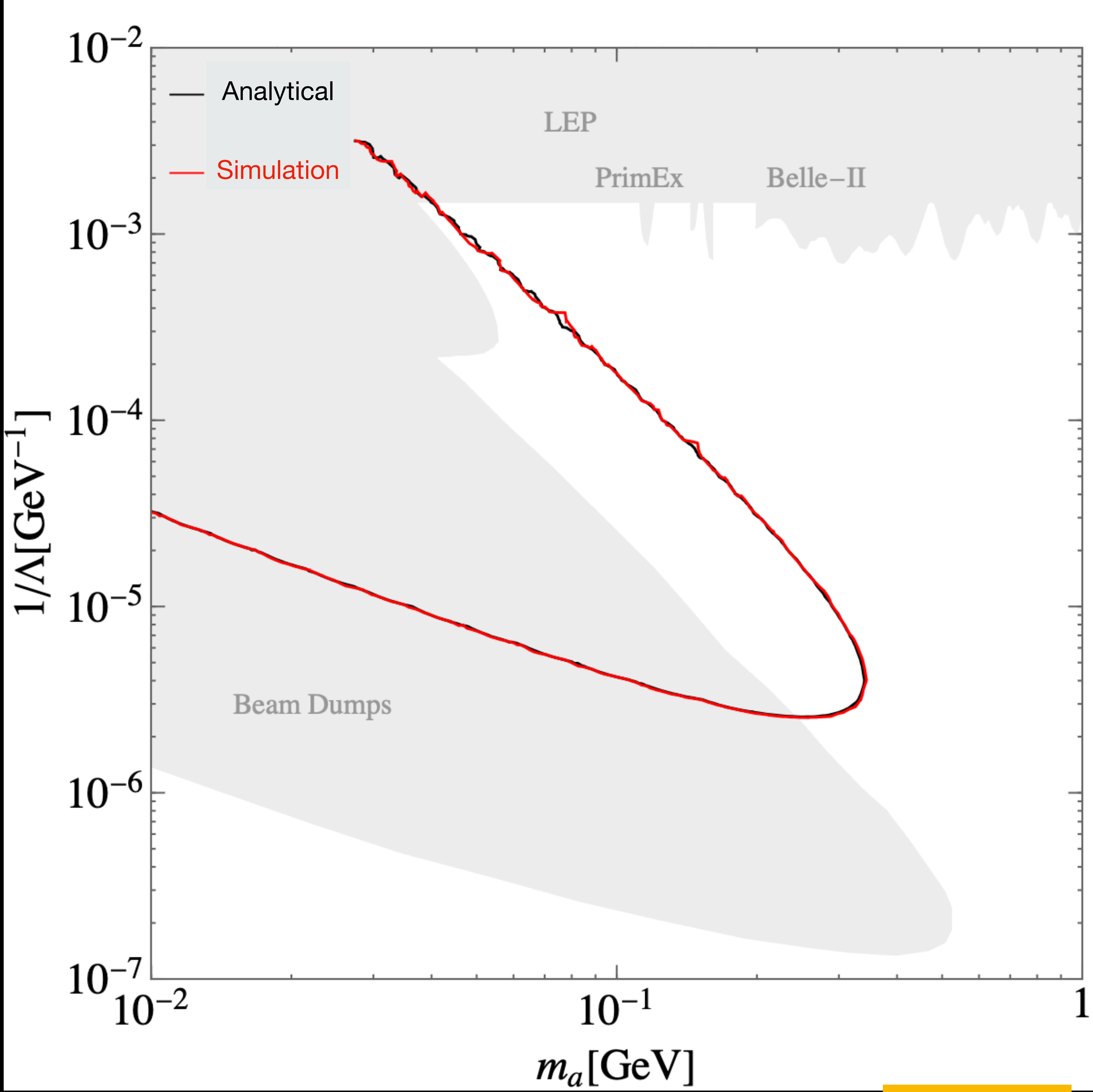
phase0:	**phase1:**
- $\tau_{pulse} = 25$ fs	- $\tau_{pulse} = 120$ fs
- $w_0 = 6.5\ \mu$m	- $w_0 = 10\ \mu$m
- $\xi = 2.4$	- $\xi = 3.4$
- $N_{\gamma/e} < 1$	- $N_{\gamma/e} = 3.5$ or 1.7 if $E_\gamma > 1$ GeV



Slide from Noam

LUXE ALP reach in parameter space:

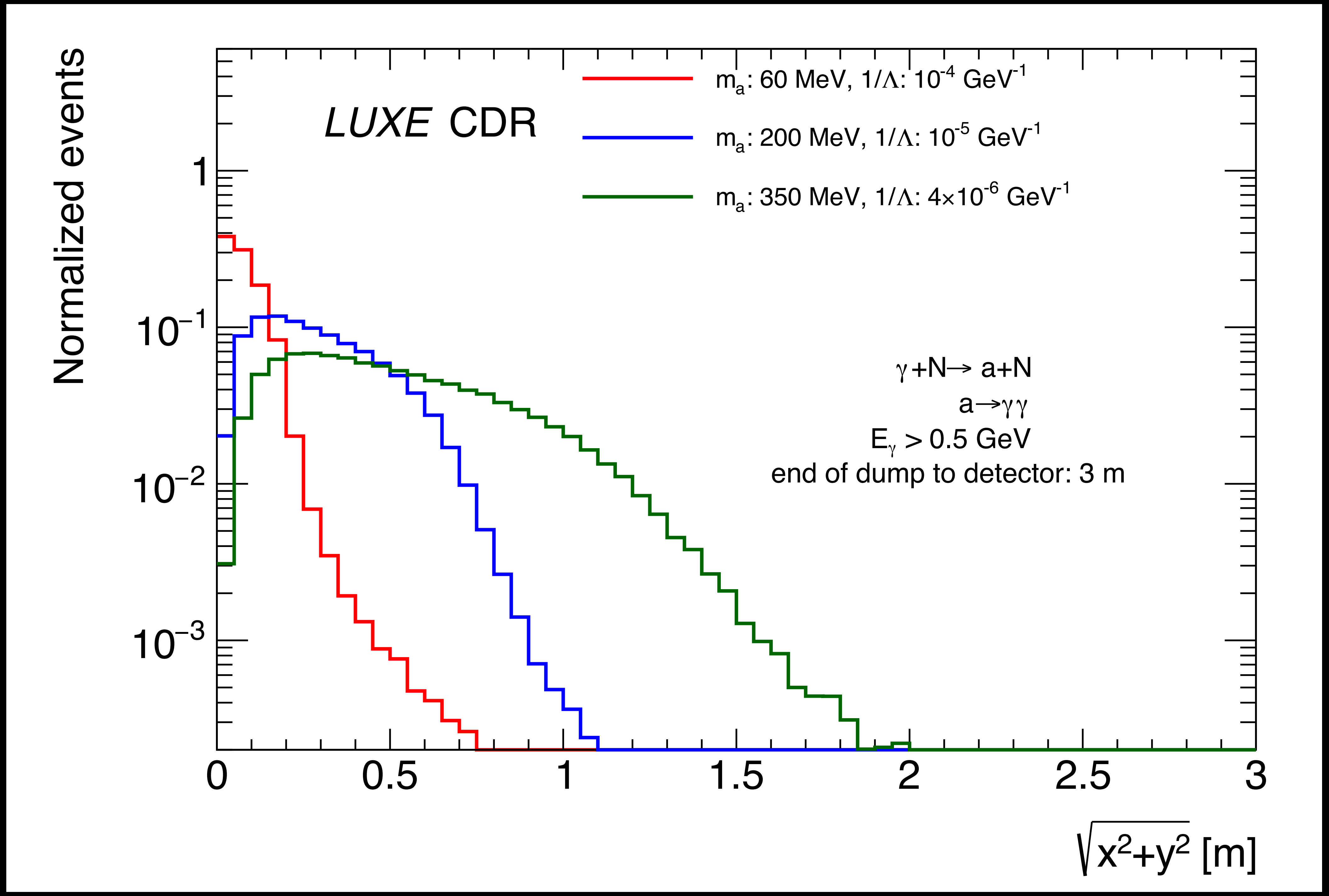
- The exclusion contour is drawn where LUXE expects at least 3 ALP events.
- Result coming from phase 1 incoming photon distribution.
- Yotam Soreq obtained the result analytically, I got the same result using MadGraph simulation independently.

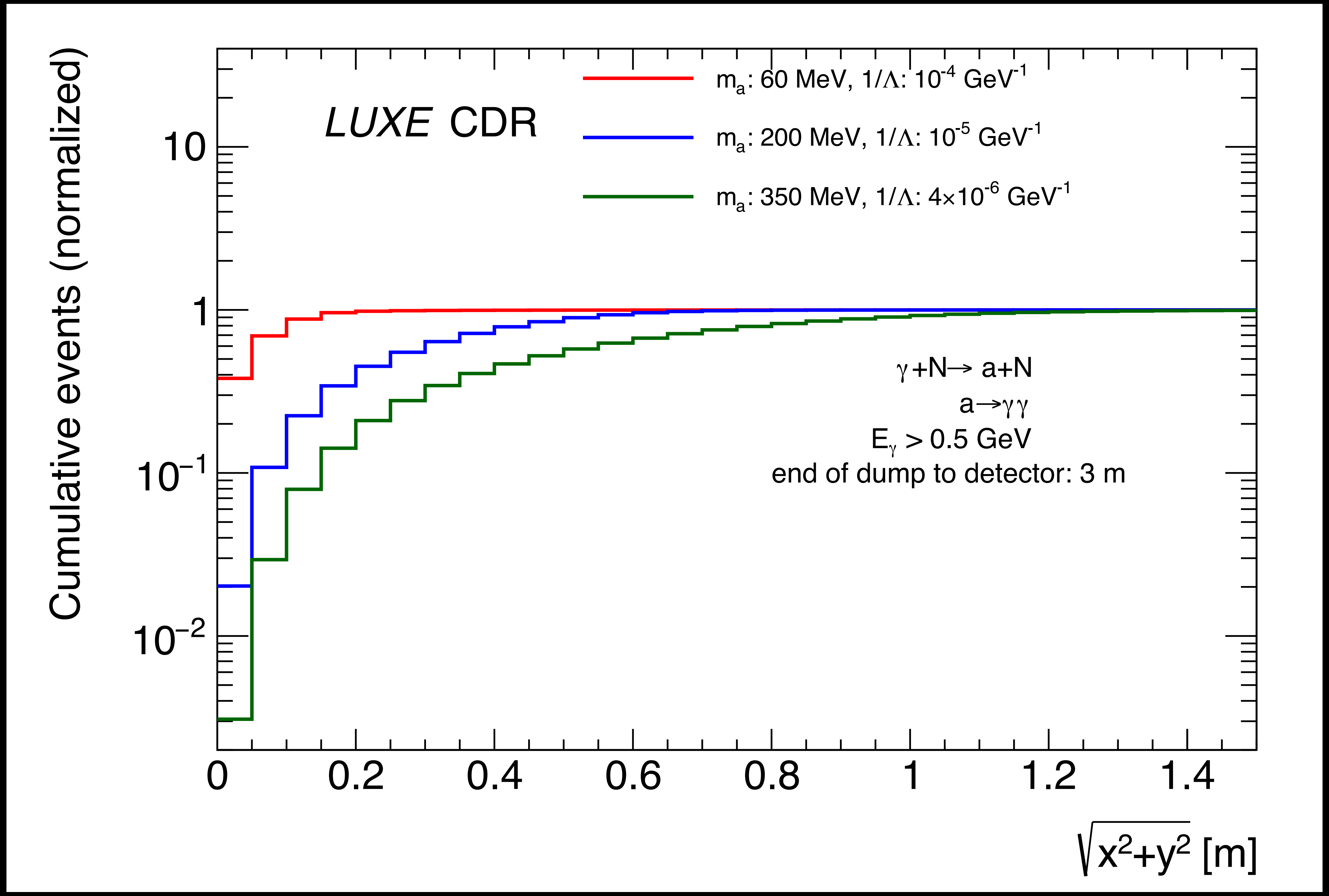


$L_D = 2.5m$

Some distributions from signal samples

Distance of photons from the z-axis:

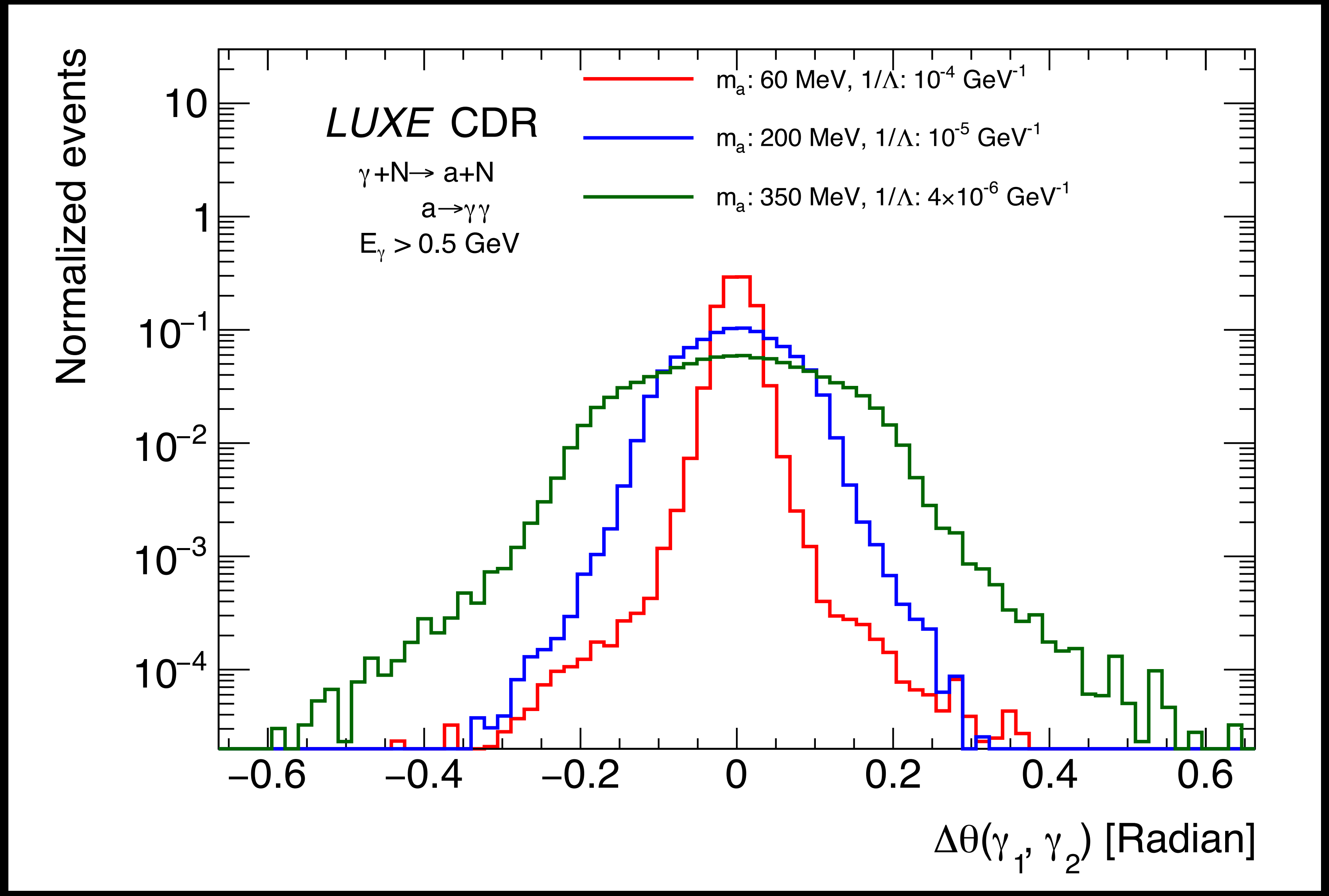


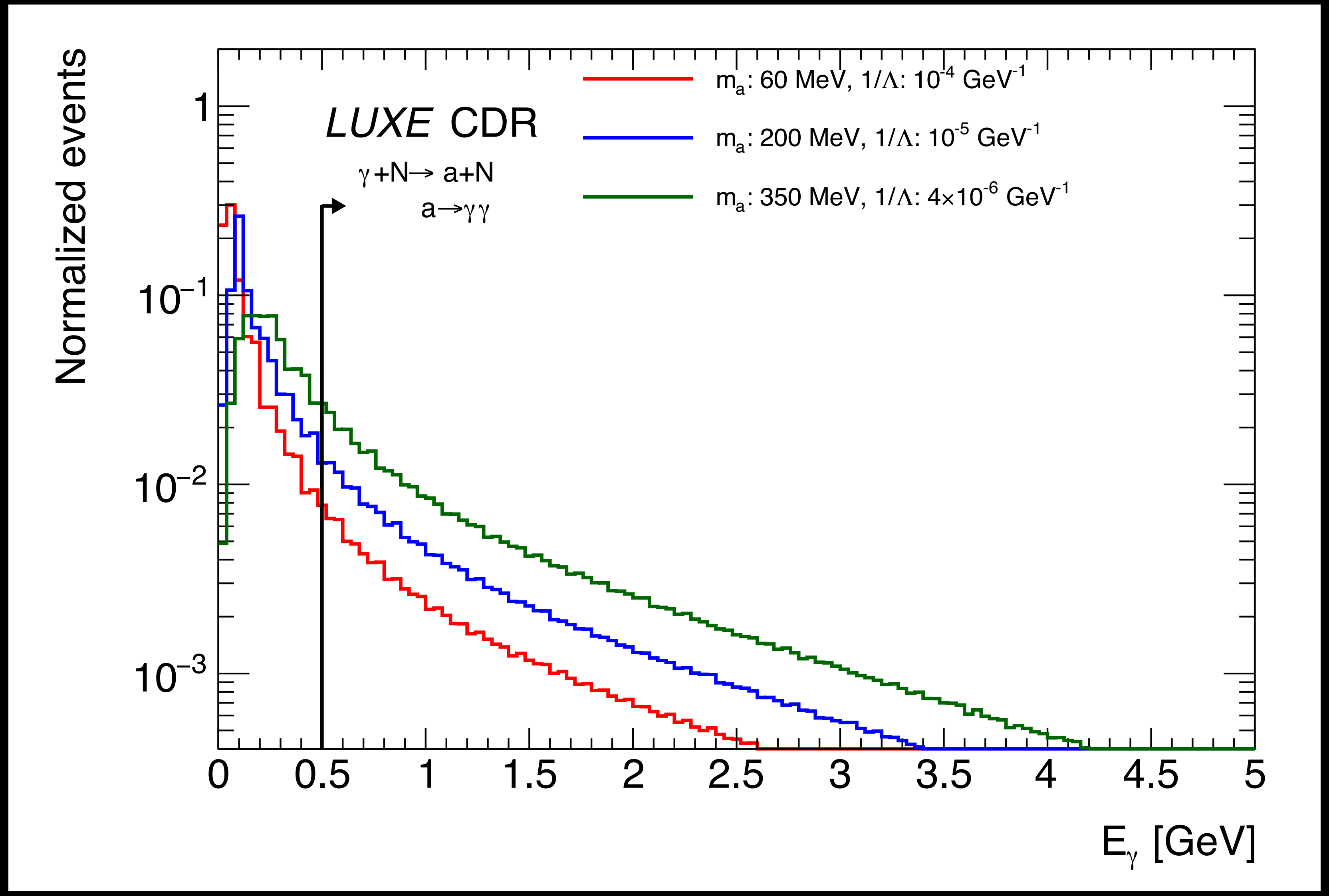


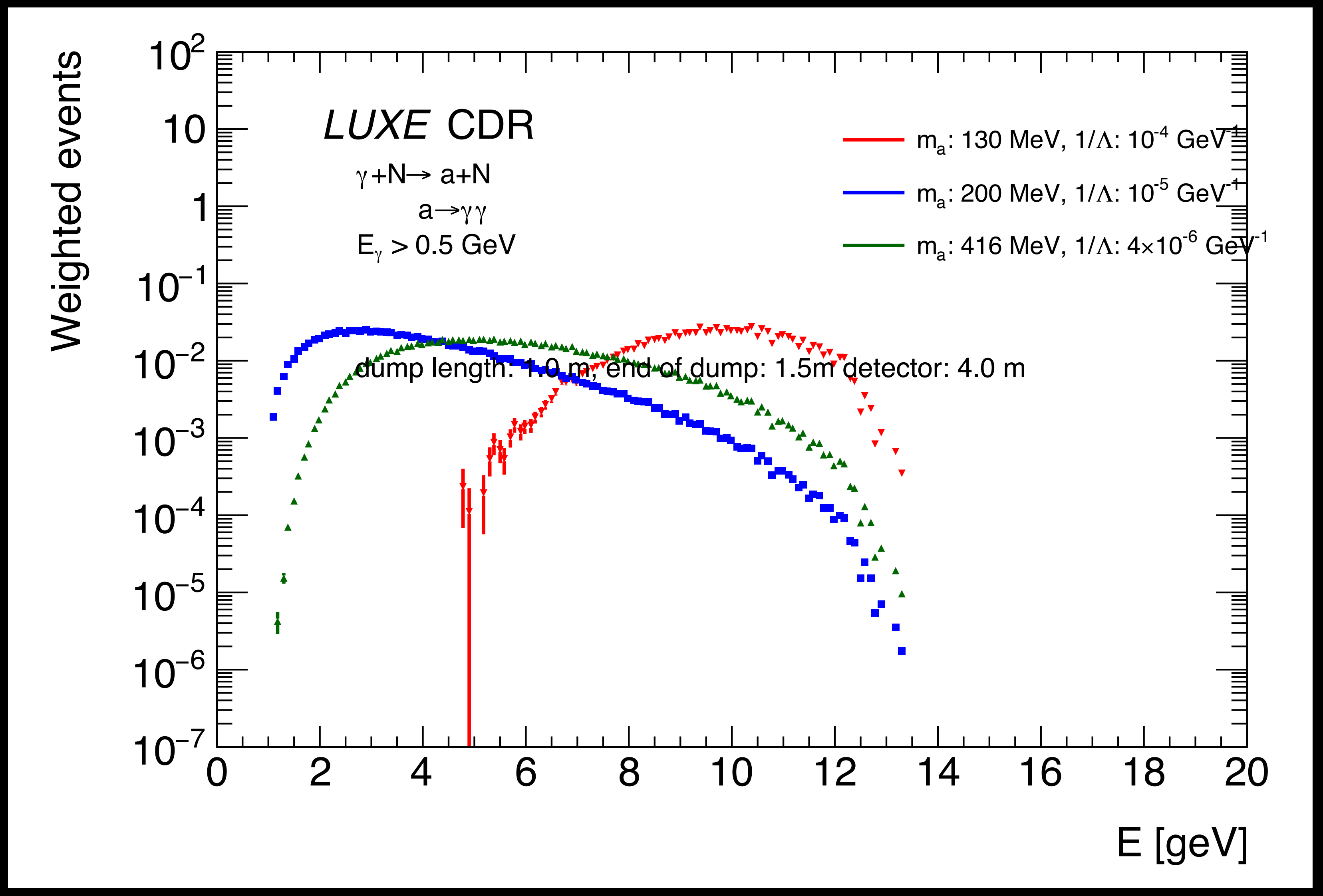
- ★Cumulative distribution: more than 90% photons are captured by a detector with radius 1m
  - ★This helps to determine the optimum detector radius.

$L_D = 3.0m$

More distributions:







★Photons opening theta

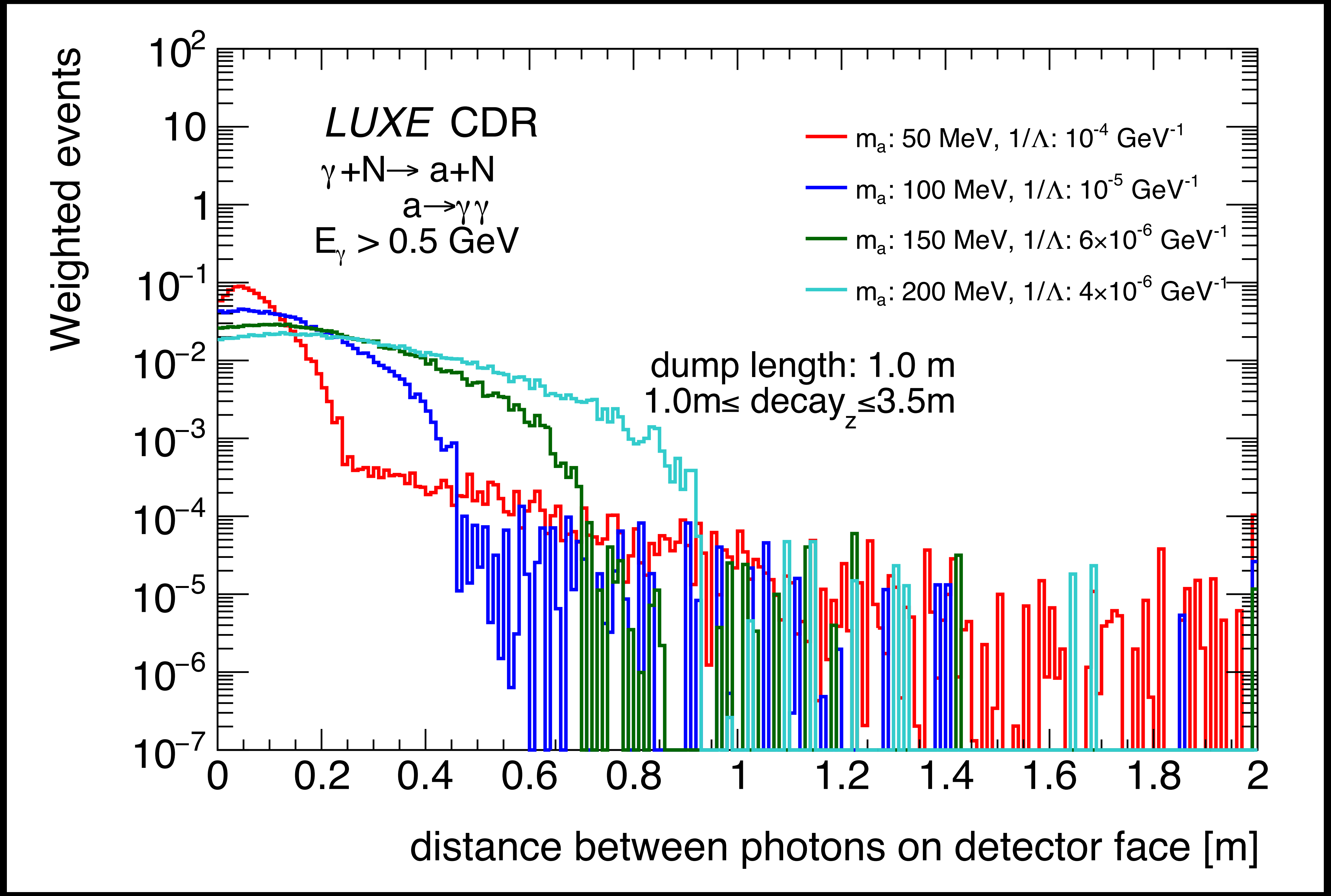
★Energy distributions of photons

★They are only accepted if energy is more than 0.5 GeV.

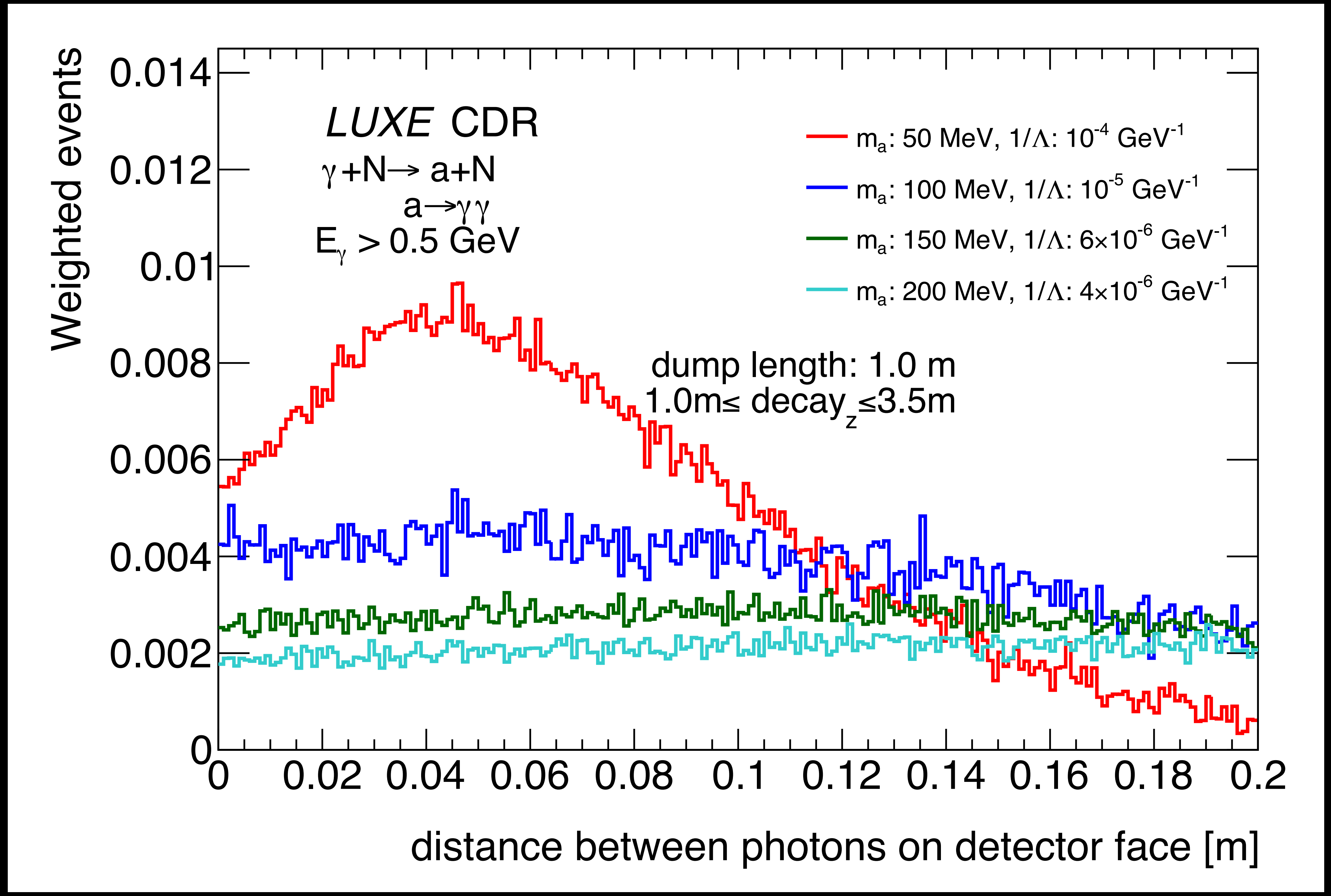
★ Energy of ALPs when photons are within acceptance of the detector (radius 1m)

$L_D = 2.5m$

More distributions: distance of two photons at the detector face



First 20 cm



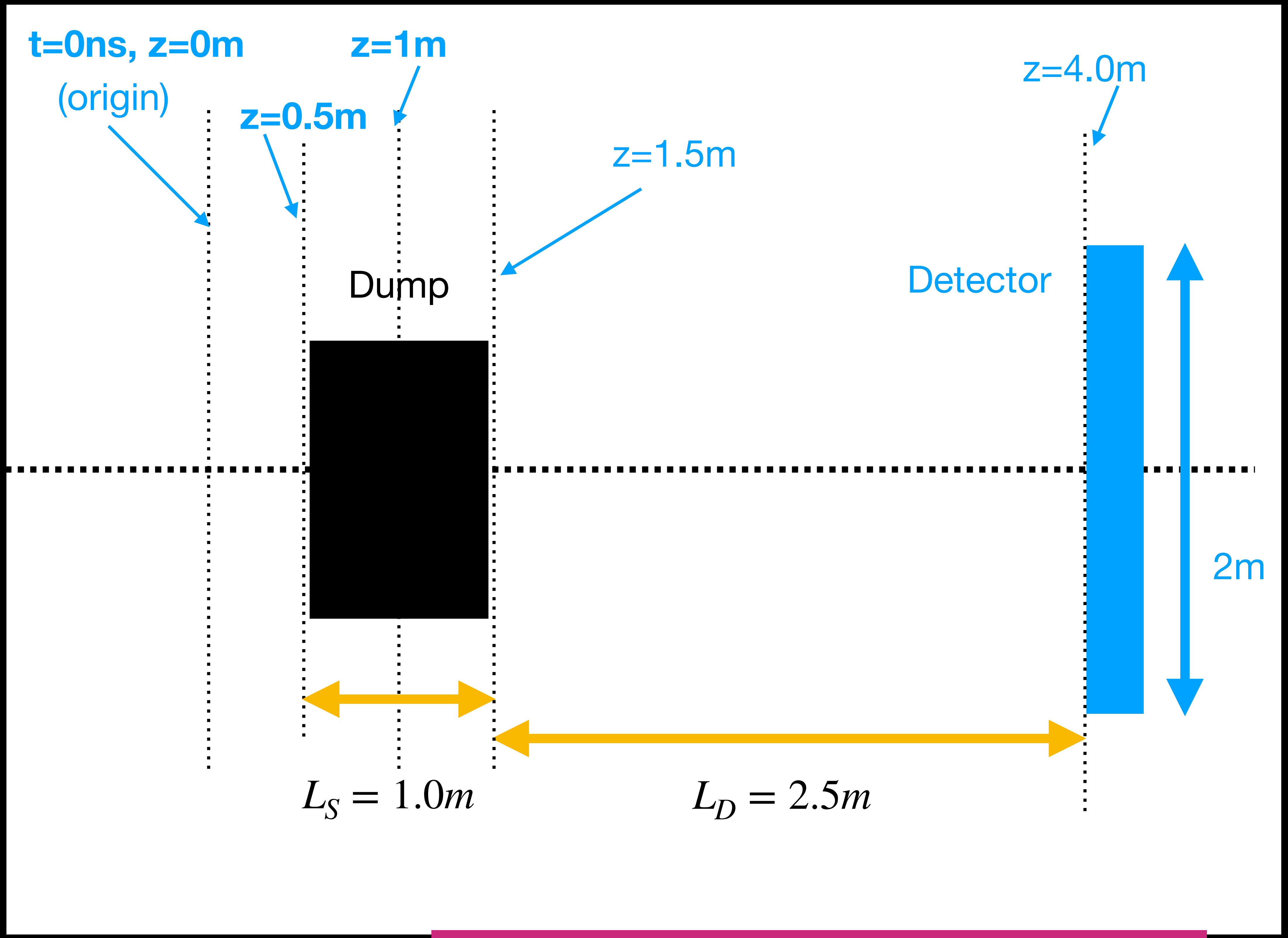
★Up to 2.0 m

★Up to 0.2 m

$L_D = 2.5m$

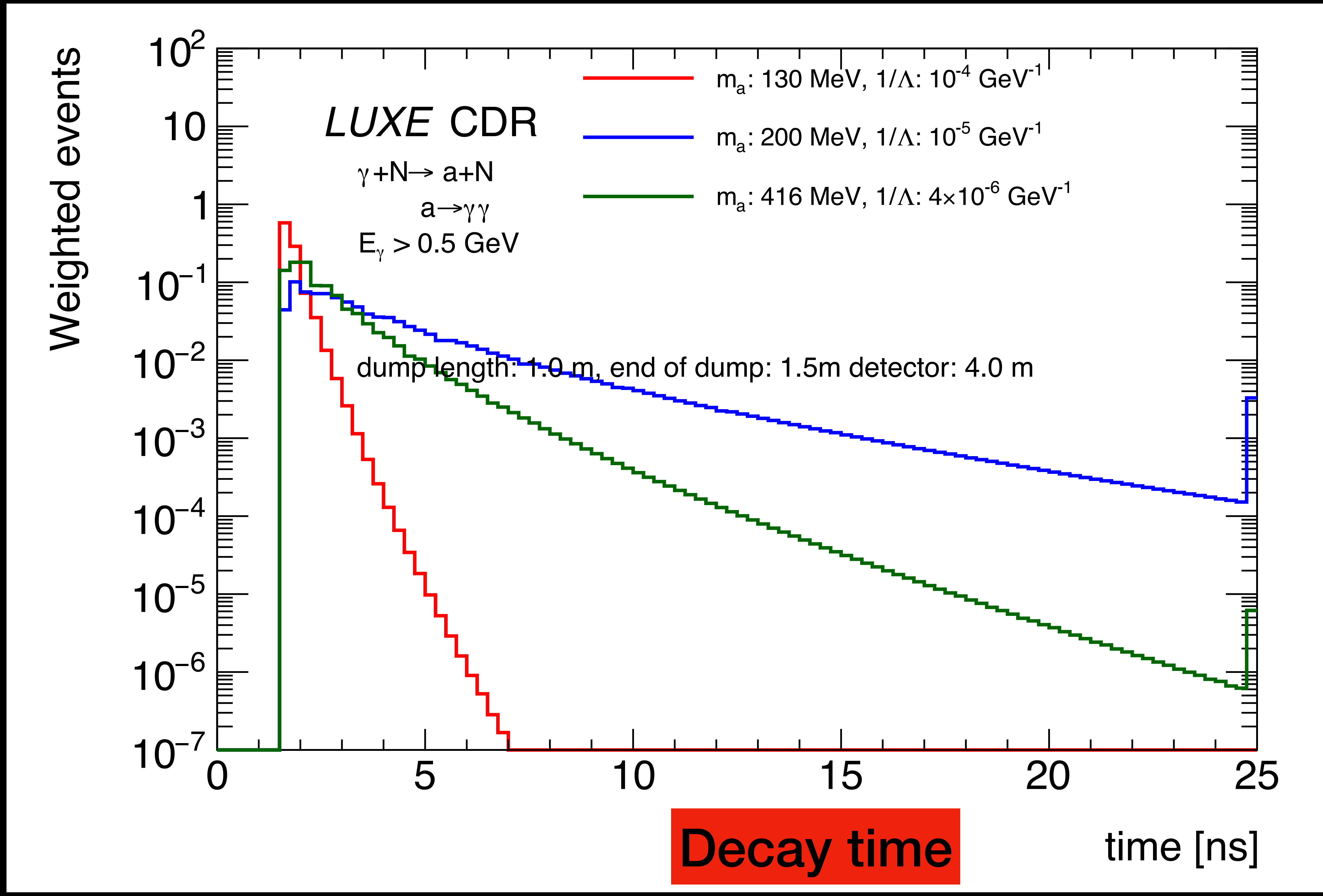
Distribution of Decay Time of ALP and Photons Arrival Time at the Detector

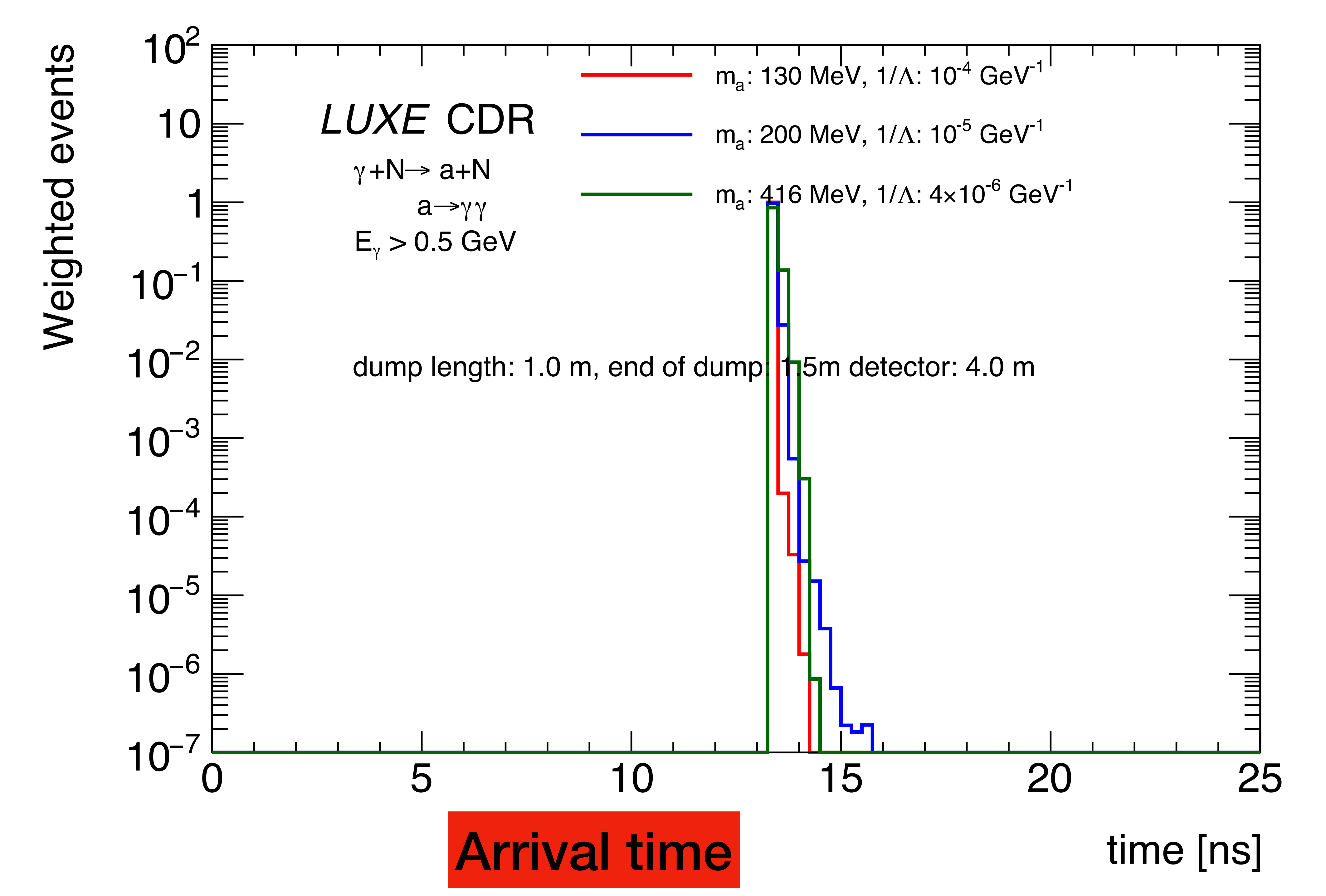
- The length of the dump = 1.0 m
  - Position of the center of the dump = 1.0 m
  - Beginning of the dump = 0.5 m
  - End of the dump = 1.5 m
  - distance to the detector from the end of the dump: 2.5 m
- The t=0 ns is the time when incoming photon beam crosses the z=0 point.
  - Hence the collision of photon and dump happens at t = 0.5*3.33 ns = 1.66 ns
- Velocity of ALPs are calculated using $\beta = |\vec{p}_{ALP}|/E_{ALP}$



Note the shift of 0.5m to the right

Decay Time and Arrival Time at the Detector





Decay according to the ALP width

- ★For the arrival time, only those events are considered where both the photons are within the detector geometric acceptance.
- ★Detector has the radius of 1 m, present at z=4.0 m.
- ★Time taken by the light to travel 4m ~ 13.3 ns.
- ★We trigger at t_0 (Eu.XFEL clock) and open a short time window Δt
  - ★most signal (and bkg) photons will arrive within $\Delta t \simeq 0.5$ ns
  - ★almost all bkg hadrons will arrive after that - need ~0.1 ns resolution (see Noam's talk)

Mass	1/lambda	Fraction upto 13.8 ns	Fraction upto 14.3 ns
130 MeV	10^{-4}	0.99998	1.0
200 MeV	10^{-5}	0.99971	1.0
416 MeV	4×10^{-6}	0.99431	1.0

$L_D = 2.5m$

Summary:

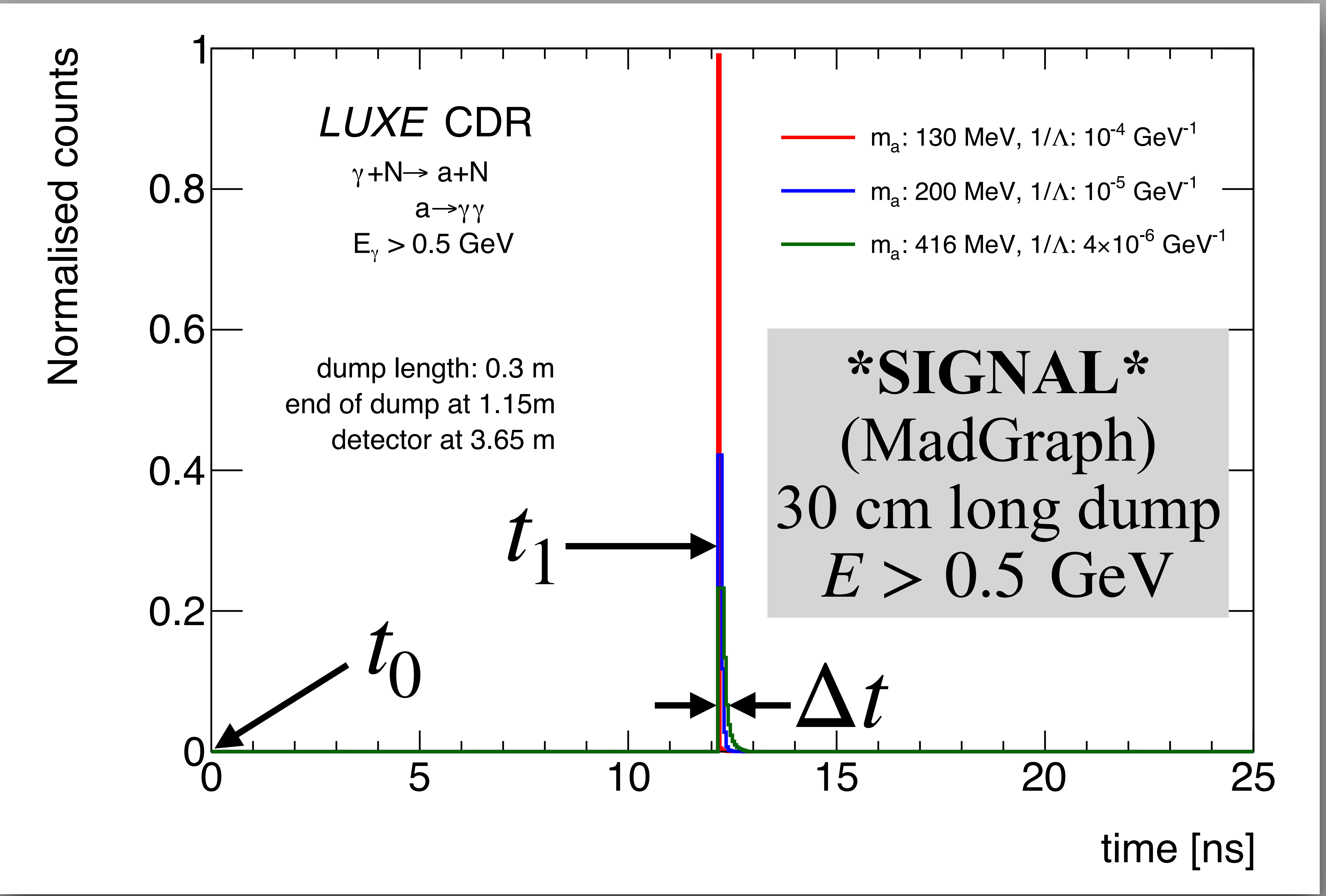
- MadGraph was used to generate the ALP signal samples.
  - Subsequent simulation was done on the basis of the output file of MadGraph.
  - The result matches very well with the analytical calculation.
- The signal samples were used to check some properties of the signals
  - Opening angle, time to arrive at the detector, distance of photons from the z-axis
  - These are important in order to finalize the detector radius, position and also background rejection.
- The scalar particles were also generated with MadGraph and they were found to have identical cross-sections/acceptance as the pseudoscalar ALPs.
- Things to do:
  - Finalize the NPOD setup (decay volume, radius of the detector)
  - Study the dump
    - Optimum dump design and material.
    - Realistic production vertex of ALP inside the dump (now it is at z=0).
    - Secondary photon generation inside the dump.
    - Background particles depending on dump material.

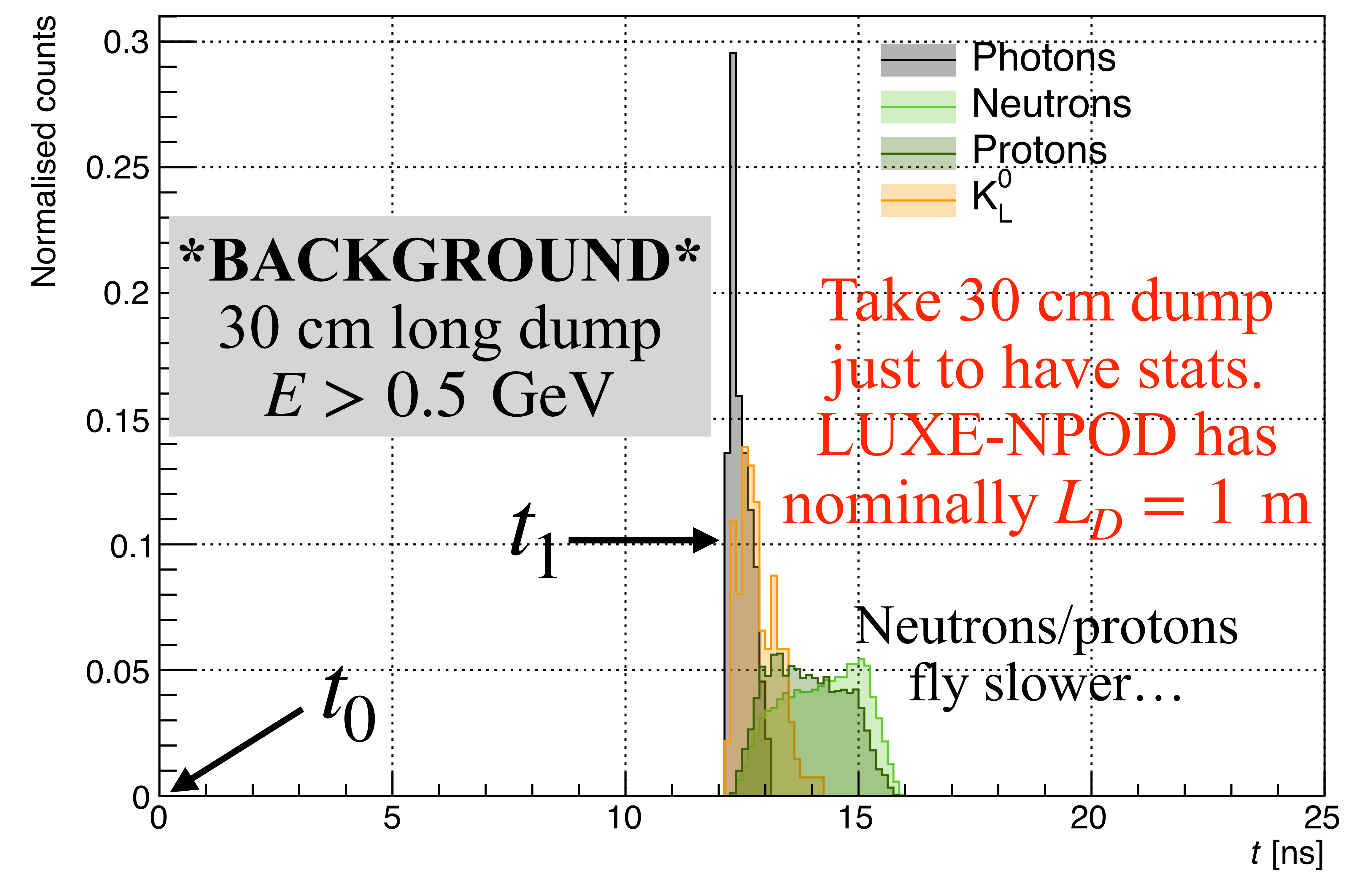
Back up

MadGraph config files

```
import model ALP_linear_UFO_FF
generate a nuc > ax nuc
set automatic_html_opening False
output NUCALP_beam1.0GeV_v2
launch NUCALP_beam1.0GeV_v2
set run_card ebeam1 1.0
set ebeam2 0
set lpp1 0
set lpp2 0
#### lepton cuts
set ptl -1.0
set etal -1.0
set drll -1.0
#### photon cuts
set pta -1.0
set etaa -1.0
set draa -1.0
set nevents 10000
set param_card mass 9000005 0.05
### for tungsten
set frblock 1 74
set frblock 2 183.8
set decay 9000005 Auto
set alppars 1 4.000000e+04
```

Timing cut





- The time it takes a bkg photon to fly from $z_0 = 0$ to the calorimeter face at $z_1 = z_D + L_D/2 + L_V = 3.65$ m, is $t_1 = t_0 + (12 + \Delta t)$ ns
  - with $z_D = 1$ m, $L_D = 0.3$ m and $L_V = 2.5$ m and $t_0 = 0$
- We trigger at t_0 (Eu.XFEL clock) and open a short time window Δt
  - most signal (and bkg) photons will arrive within $\Delta t \simeq 0.5$ ns
  - almost all bkg hadrons will arrive after that - need ~0.1 ns resolution

	Background rejection [%]				**Signal efficiency [%] for m_a:1/Λ_a**		
Δt [ns]	**γ**	**n**	**p**	**K_L**	**130:1e-4**	**200:e-5**	**416:e-5**
0.5	~16	~96	~94	~52	~99.9	~99.8	~95
1.0	~0	~80	~70	~13	100	~99.9	100