Phenomenology 2021 Symposium (**Pheno 2021**), University of Pittsburgh

24th May, 2021

Prompt vs Displaced Jets in the Hadron Calorimeter using CNN

based on

Study of energy deposition patterns in hadron calorimeter for prompt and displaced jets using convolutional neural network

Biplob Bhattacherjee, Swagata Mukherjee, RS

JHEP 11 (2019) 156, arXiv:1904.04811 [hep-ph]

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Discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 completed the Standard Model of particle physics (SM), which successfully explains as well as predicts many fundamental phenomena of particles.

Dark Matter

Neutrino masses

Baryon-asymmetry

many more…

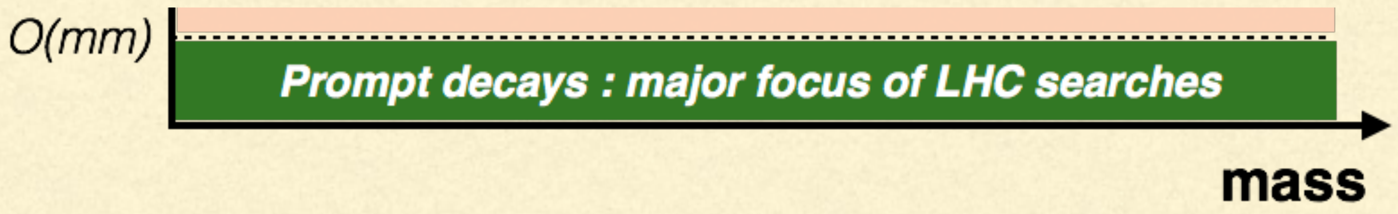
We need to look beyond the SM (BSM)

Experiments like the Large Hadron Collider (LHC) are putting stronger constraints on the nature of new physics.

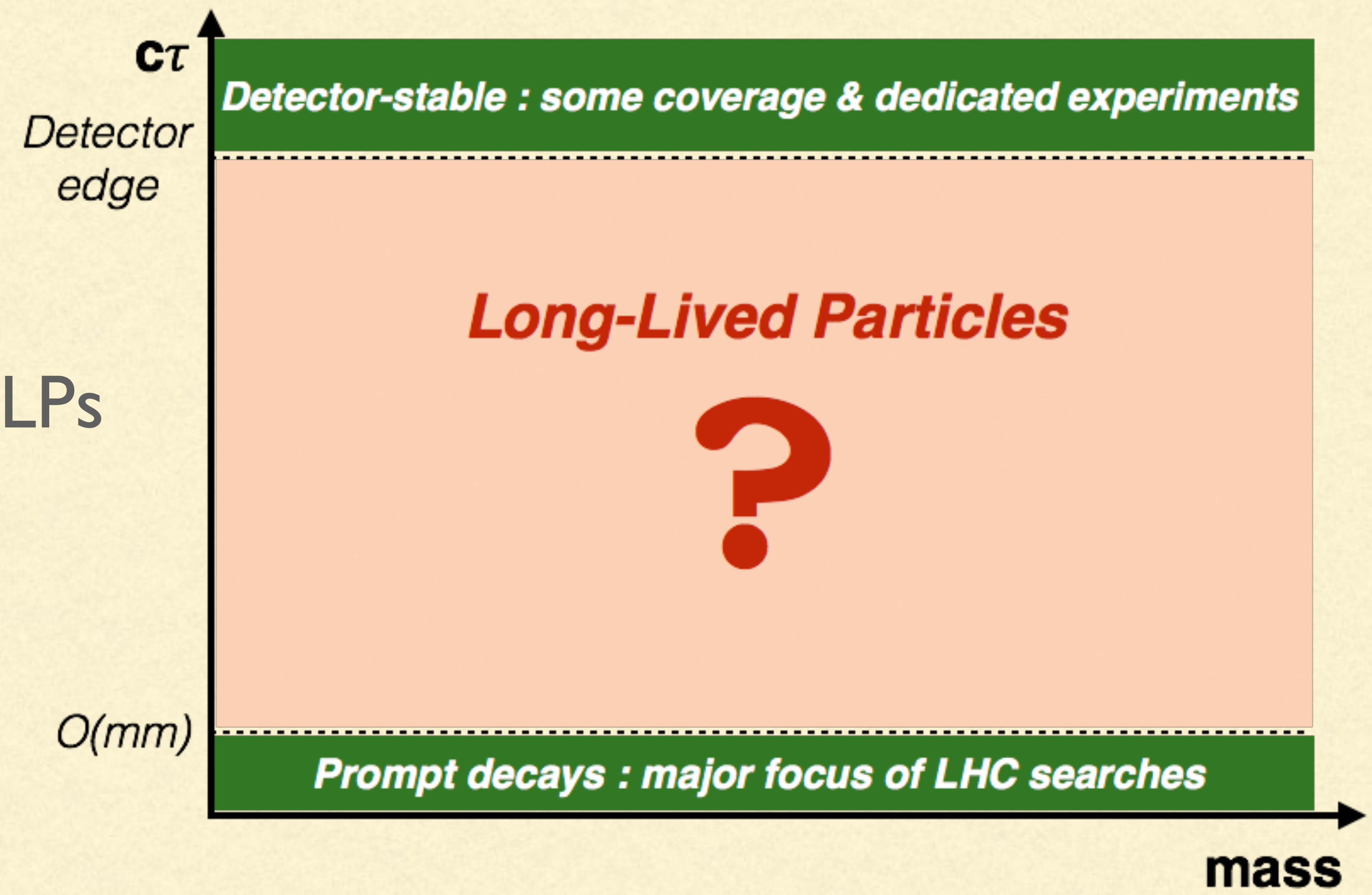
At this stage, it is natural to ask

Are we covering the full phase-space of new physics? Or are we missing something?

Most of the conventional LHC searches assume prompt decay of particles.



Recent focus on LLPs

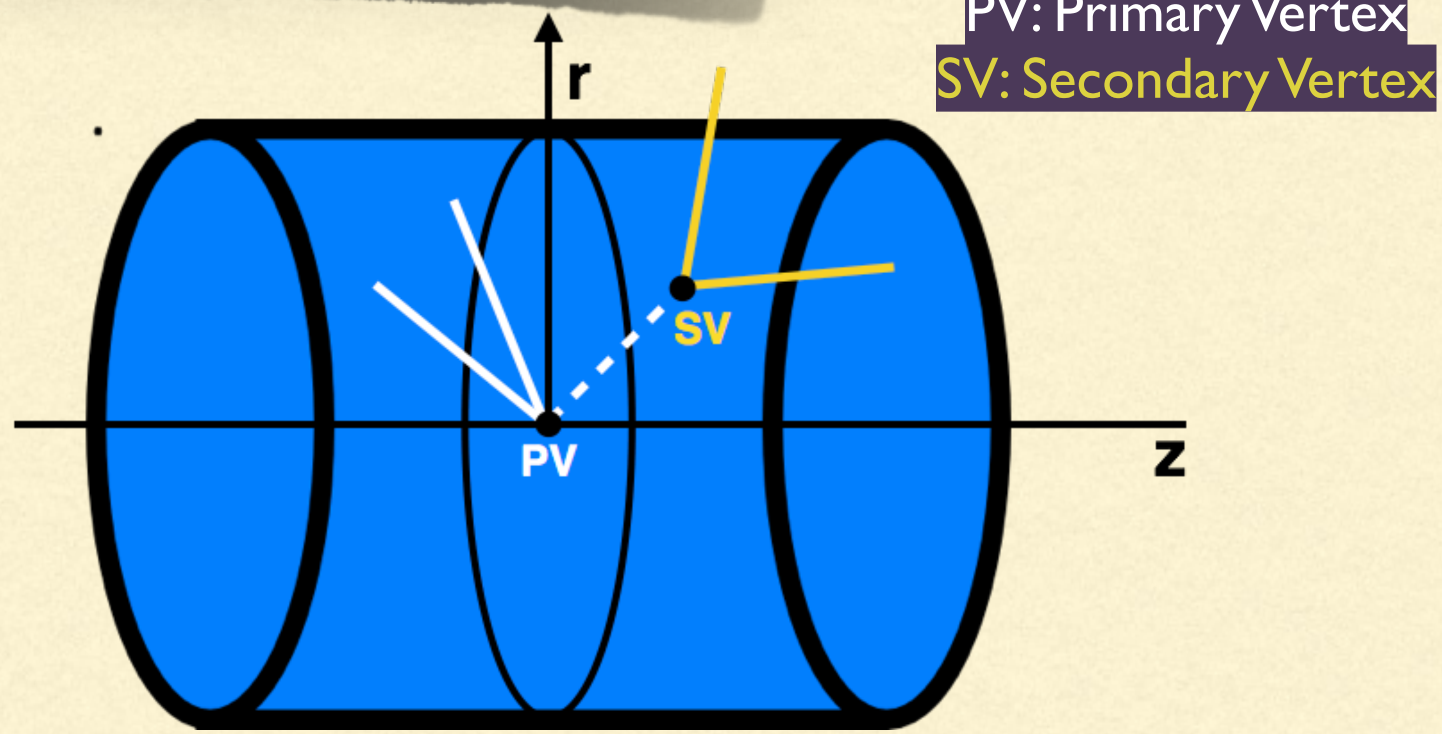


EXPLORING THE LIFETIME FRONTIER

- *Presence of long-lived particles - **well motivated in many BSM scenarios***
- ***Largely unexplored** - needs dedicated searches to ensure that no possible new physics avenue is left out*

For a comprehensive overview of LLPs: arXiv:1903.04497

LONG-LIVED PARTICLES



Particles having lifetimes such that they have **macroscopic decay lengths** $> \mathcal{O}(\text{mm})$ inside the detector.

$$\Gamma\left(\text{or } \frac{1}{\tau}\right) \propto |\text{Amplitude}|^2 \times (\text{Phase space factor})$$

<u>Heavy scales</u>, $\Gamma \sim \left(\frac{m}{M}\right)^{\#}$

e.g., muon (SM), gluino in Split-SUSY (BSM)

<u>Small couplings</u>

e.g., c and b quarks (SM), RPV SUSY (BSM)

<u>Kinematic squeezing</u>

e.g., neutron (SM), compressed SUSY scenarios (BSM)

LLPs IN COLLIDER DETECTORS

Decay length in the detector (lab frame)

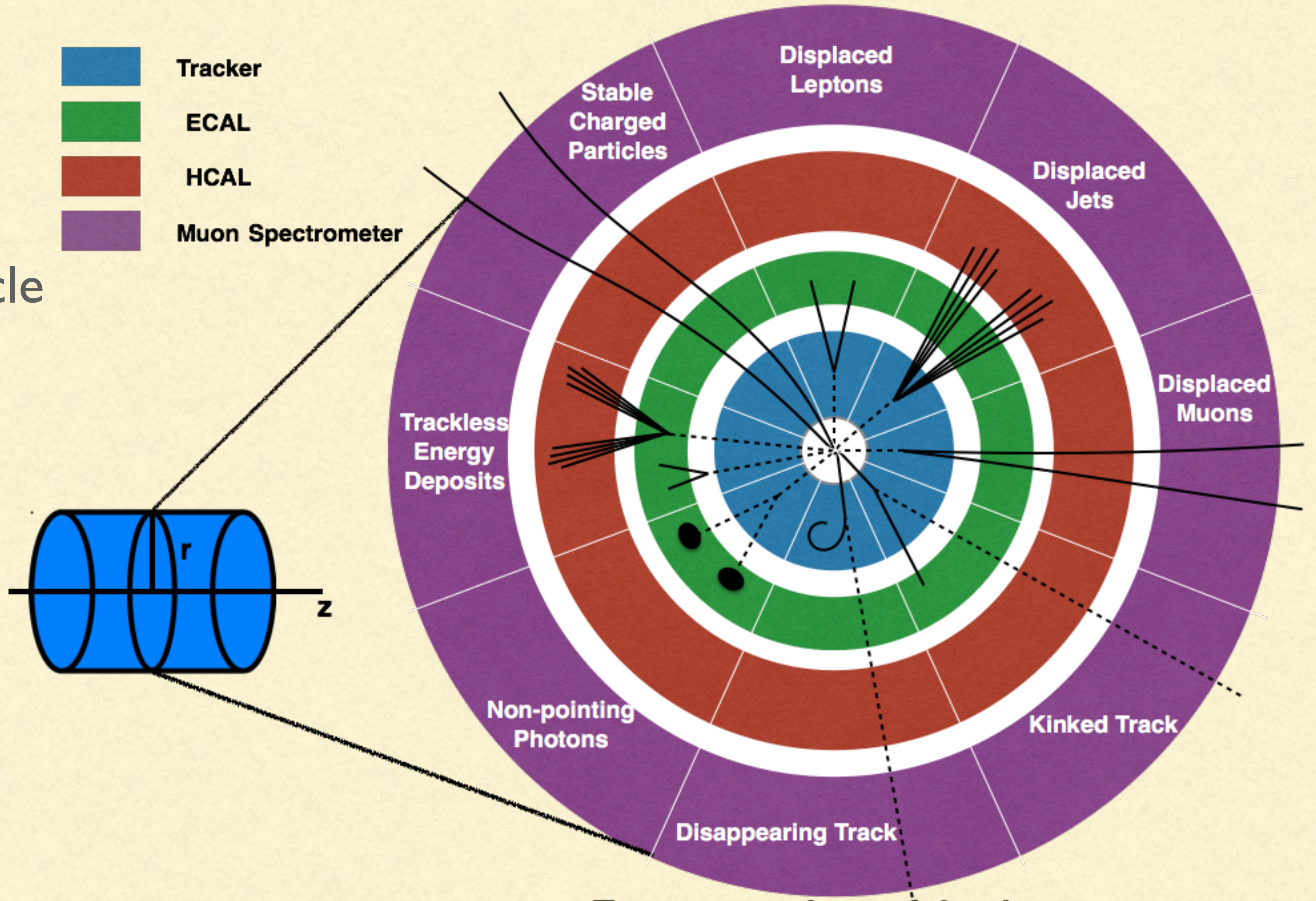
$$d = \beta\gamma c\tau$$

$\beta\gamma = \dfrac{p}{m}$: boost factor

c : speed of light

τ : lifetime of the particle

Signatures of LLP depend on **where the particle decays** inside the detector



Transverse plane of the detector

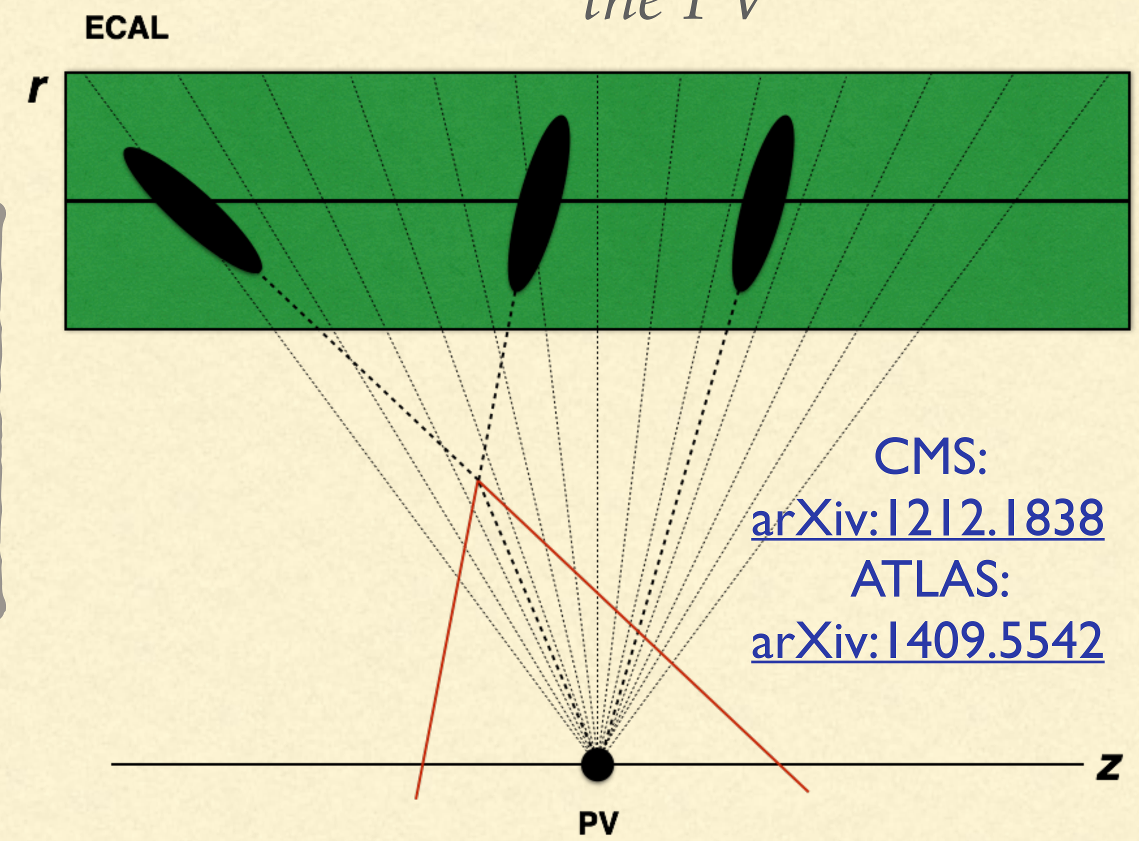
MOTIVATION

Detectors have:

1. η-ϕ segmentation
2. Layered structure

Non-pointing photons

Photons that don't point back to the PV



CMS: arXiv:1212.1838
ATLAS: arXiv:1409.5542

Mismatch of *displaced particle's η-ϕ direction* with *η-ϕ segmentation of the calorimeter*

Previous work in this direction:

Novel signature for long-lived particles at the LHC
Shankha Banerjee, Geneviève Bélanger, Biplob Bhattacherjee, Fawzi Boudjema, Rohini M. Godbole, and Swagata Mukherjee: Phys. Rev. D 98, 115026

- Many well motivated models where LLPs can decay to quarks or gluons (direct decay or indirect decay through SM particles) ⇒ ***Displaced Jets***
  - *How is this mismatch affected for displaced jets - which contain many displaced particles?*
  - *Does this effect get washed out due to the coarser resolution of the HCAL, compared to ECAL?*

MOTIVATION

How is the energy deposition pattern of displaced jets different from prompt jets in the HCAL?

Can a convolutional neural network (CNN) learn these features and discriminate prompt jets from displaced jets?

STANDARD ANALYSES ?

- **Standard displaced jets analysis** of ATLAS and CMS loses sensitivity with increasing distance of the secondary vertex. For example, in arXiv:2012.01581 displaced jets are required to have $d_T < 550$ mm.
- Triggers like **trackless jets**, and those based on $\mathbf{E}_{\mathrm{ECAL}}/\mathbf{E}_{\mathrm{HCAL}}$ **ratio** are sensitive to higher displacements - however, they do not study the difference in shape and size of the energy deposit of displaced jets from prompt jets. arXiv:1305.2284

FAST DETECTOR SIMULATIONS ?

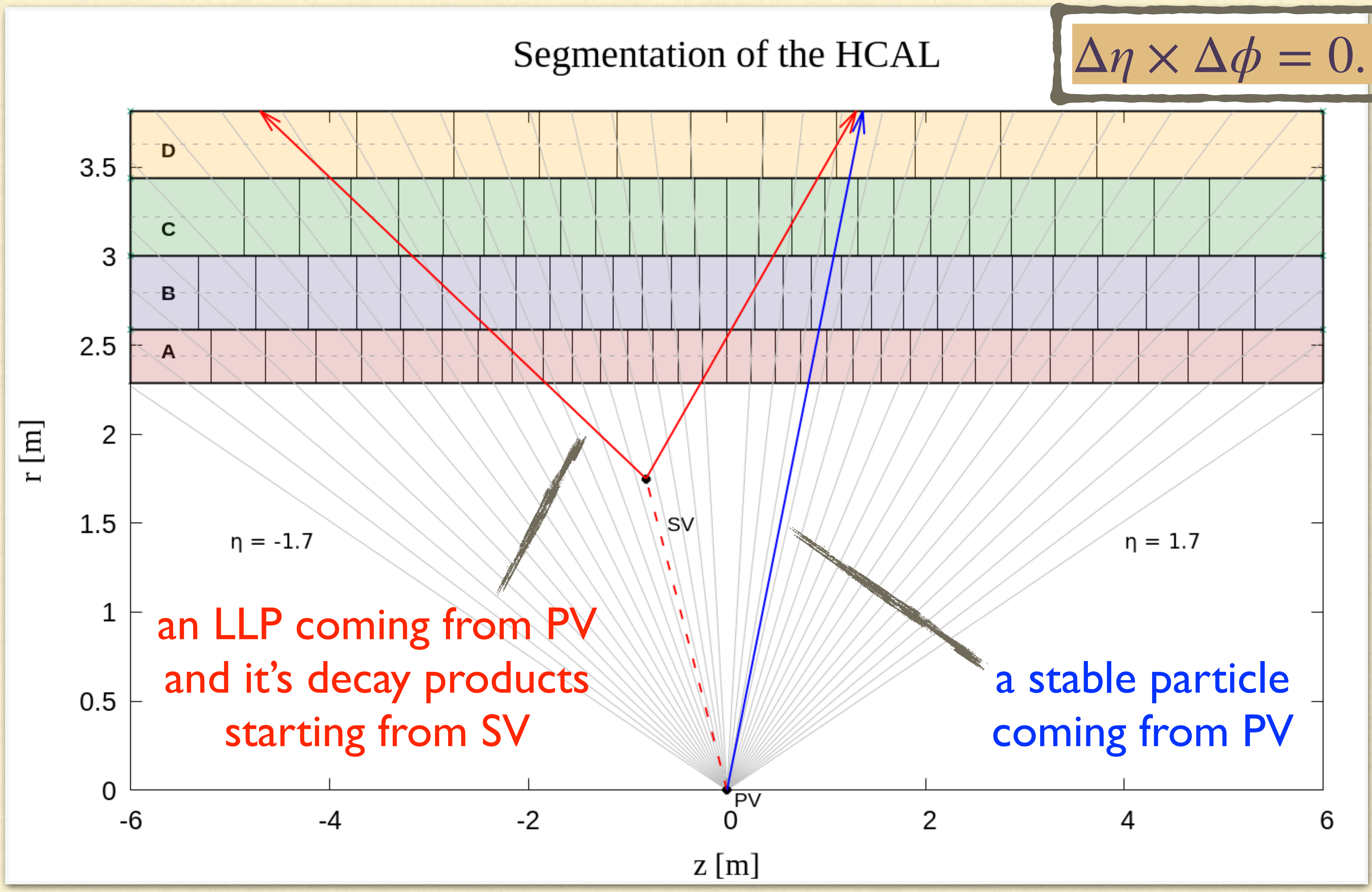
Fast detector simulations (eg. `Delphes`) **will not work** because:

- **no layered calorimeter structure**
- **no segmentation in the physical Z direction**

SIMPLIFIED SEGMENTATION OF HCAL

We simulated a simplified calorimeter closely resembling barrel hadron calorimeter (HCAL) of ATLAS.

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$



PHYSICS SCENARIOS

Scenario I: Jets coming from displaced Z

$$X(\text{LLP}) \to Z(\text{SM}) + Y(\text{Invisible}), \quad Z \to jj, \quad [m_X = 800 \text{ GeV}]$$

Scenario II: Jets coming directly from decay of LLP

$$X(\text{LLP}) \to jjj, \quad [m_X = 100 \text{ GeV}]$$

Along with the **non-displaced case** *of each of the two scenarios, the following four displaced cases have been considered:*

LLP decays in the Tracker

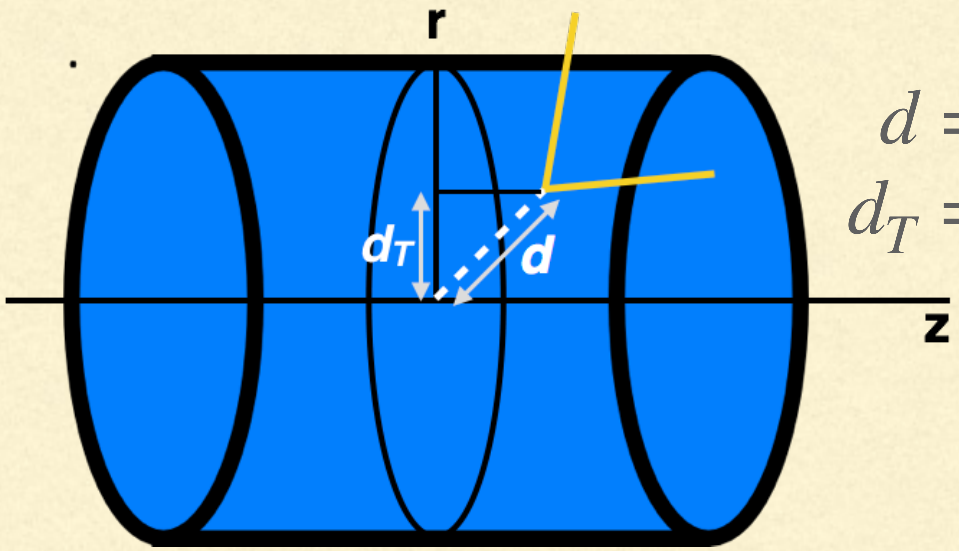
$30 \text{ cm} < d_T < 50 \text{ cm}$

$50 \text{ cm} < d_T < 70 \text{ cm}$

$70 \text{ cm} < d_T < 90 \text{ cm}$

LLP decays before entering HCAL

$200 \text{ cm} < d_T < 220 \text{ cm}$



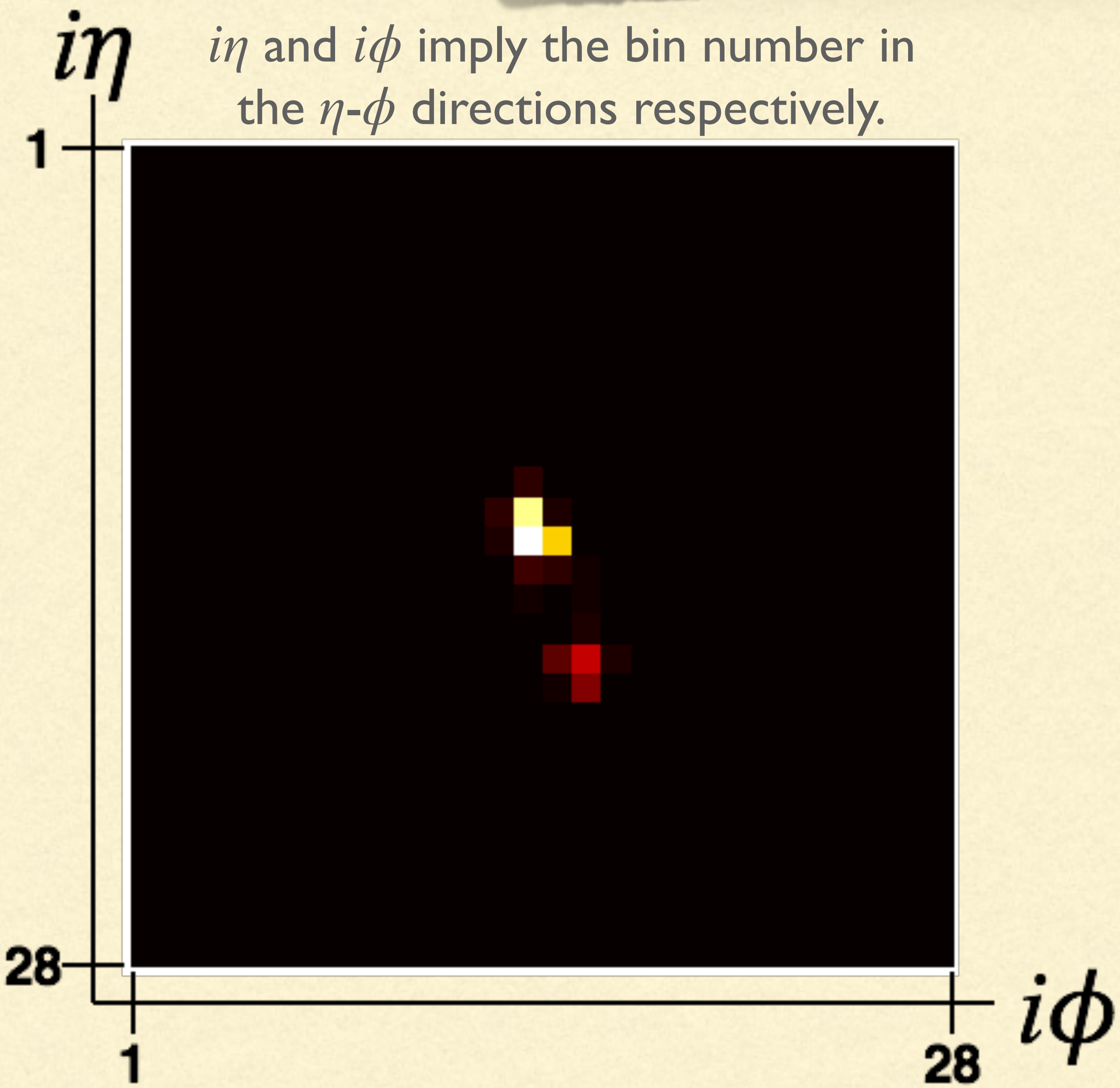
$d = \beta\gamma c\tau$

$d_T = \beta_T\gamma c\tau$

Lifetime and boost of the LLP controls the decay probability in each class of displacement.

ENERGY DEPOSITION IMAGE

$i\eta$ and $i\phi$ imply the bin number in the η-ϕ directions respectively.



- Any tower of the HCAL having energy deposit < 1 GeV is ignored
- Normalise the energy in each tower of an event using the maximum energy deposited in a HCAL tower
- ***Intensity of each pixel = Energy in each tower***
- The energy deposition of an event stored as a 28×28 image with the highest energy tower at the centre of the $i\eta$-$i\phi$ plane

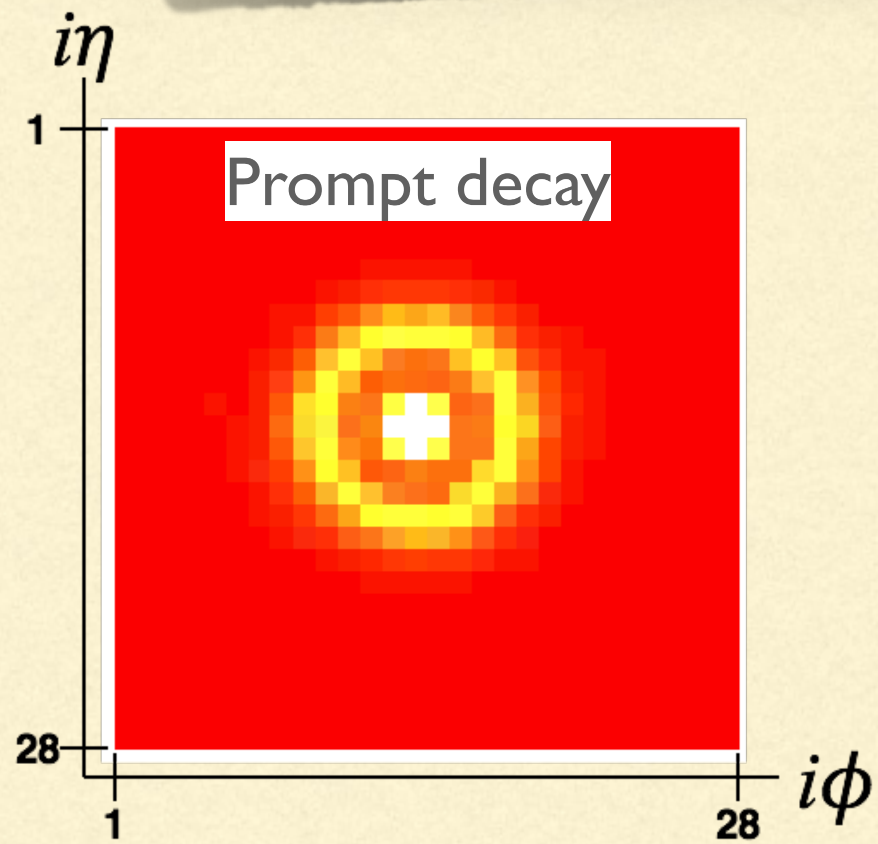
An energy window cut of $(400{,}500)$ GeV is applied on the total energy deposition in the HCAL.

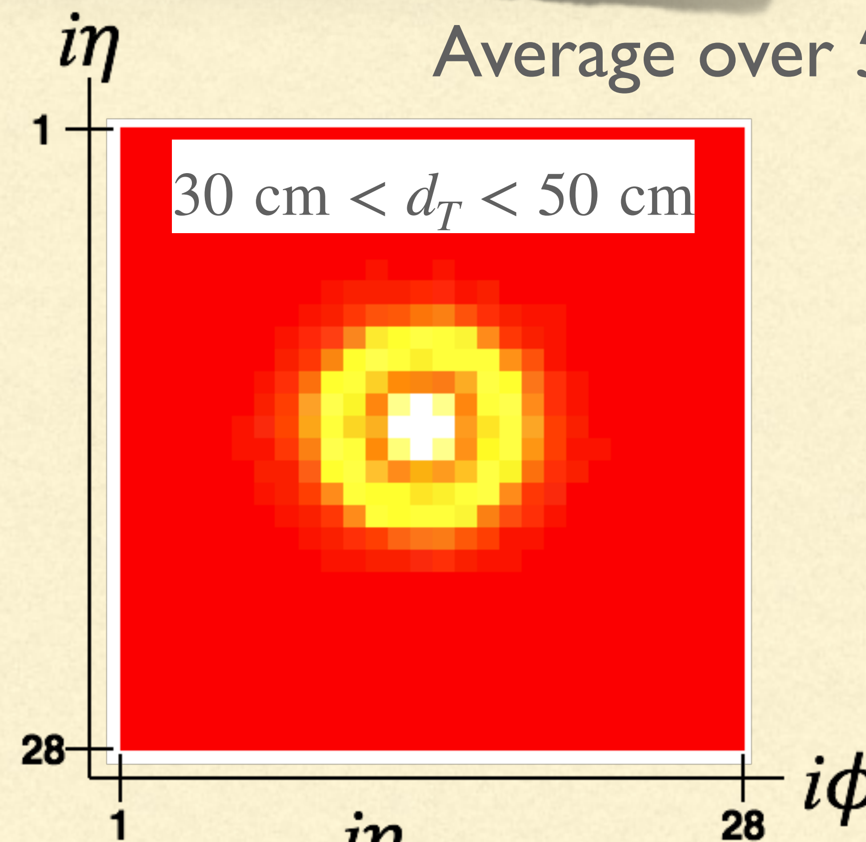
Both scenarios boosted enough to bring the displaced jets closer in the η-ϕ plane.

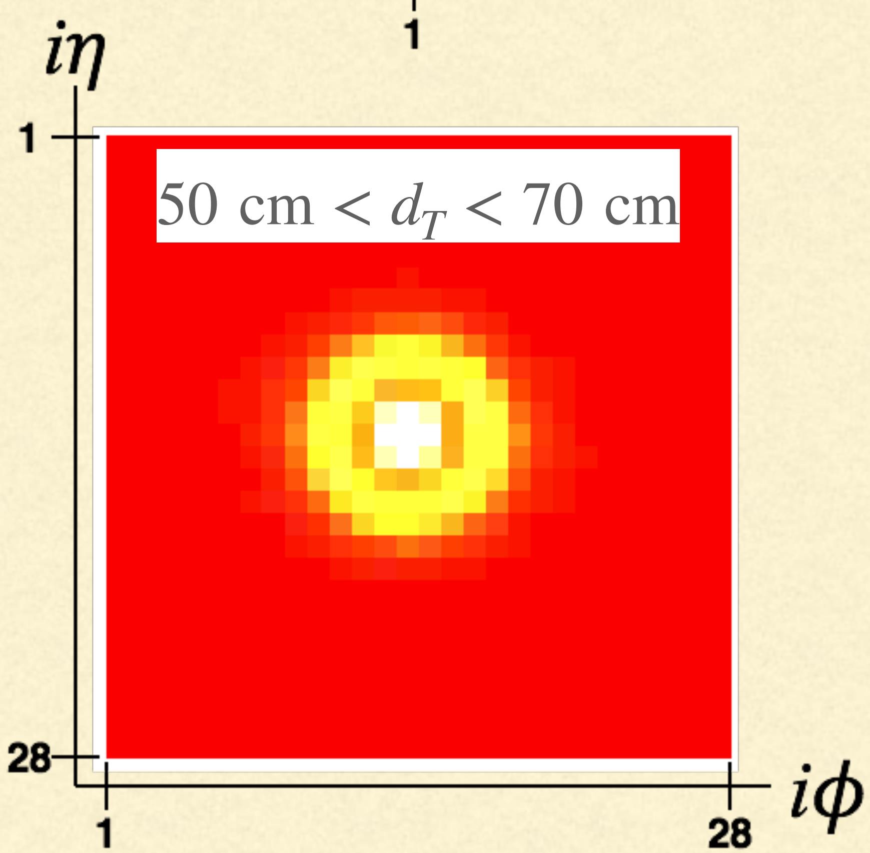
SCENARIO I : AVERAGE IMAGE

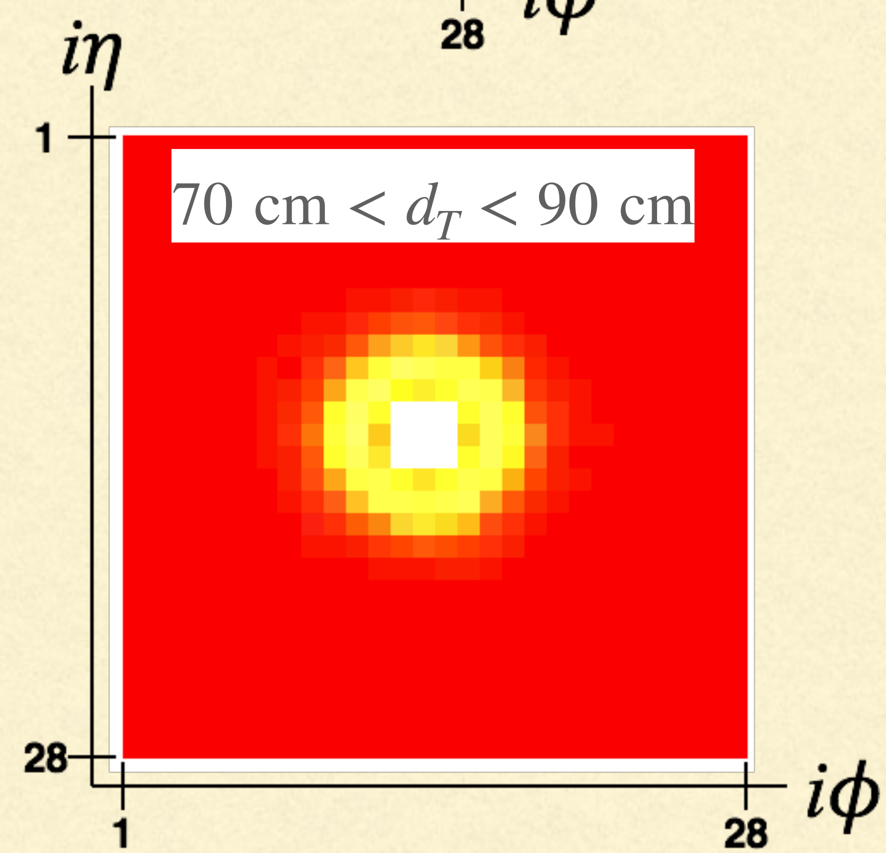
Average over 50 000 images

$$\Delta R \sim \frac{2m_Z}{p_T^Z}$$

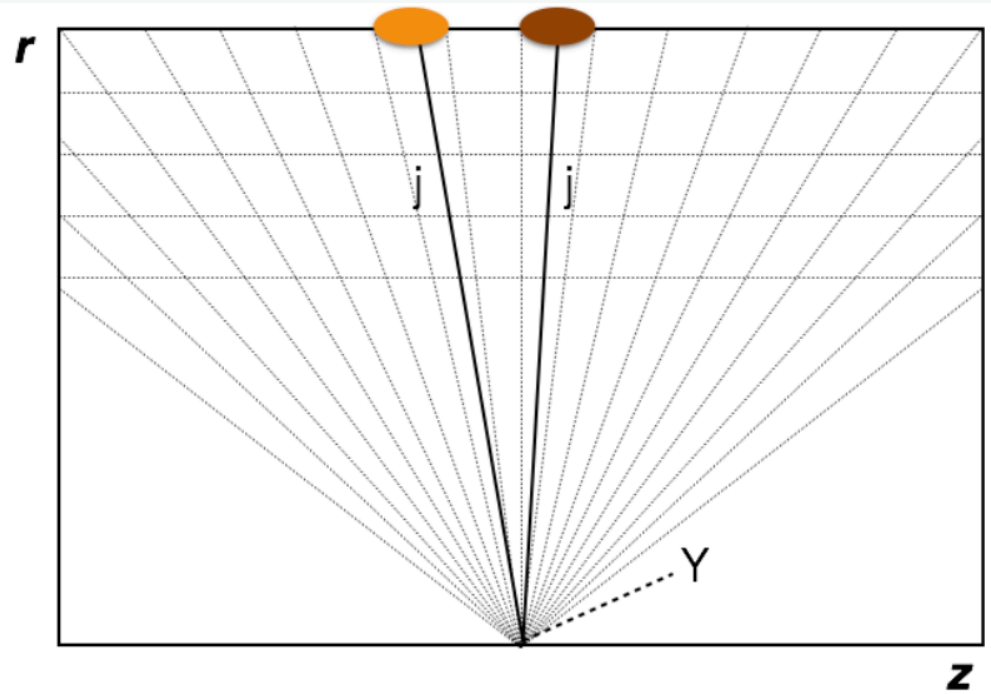




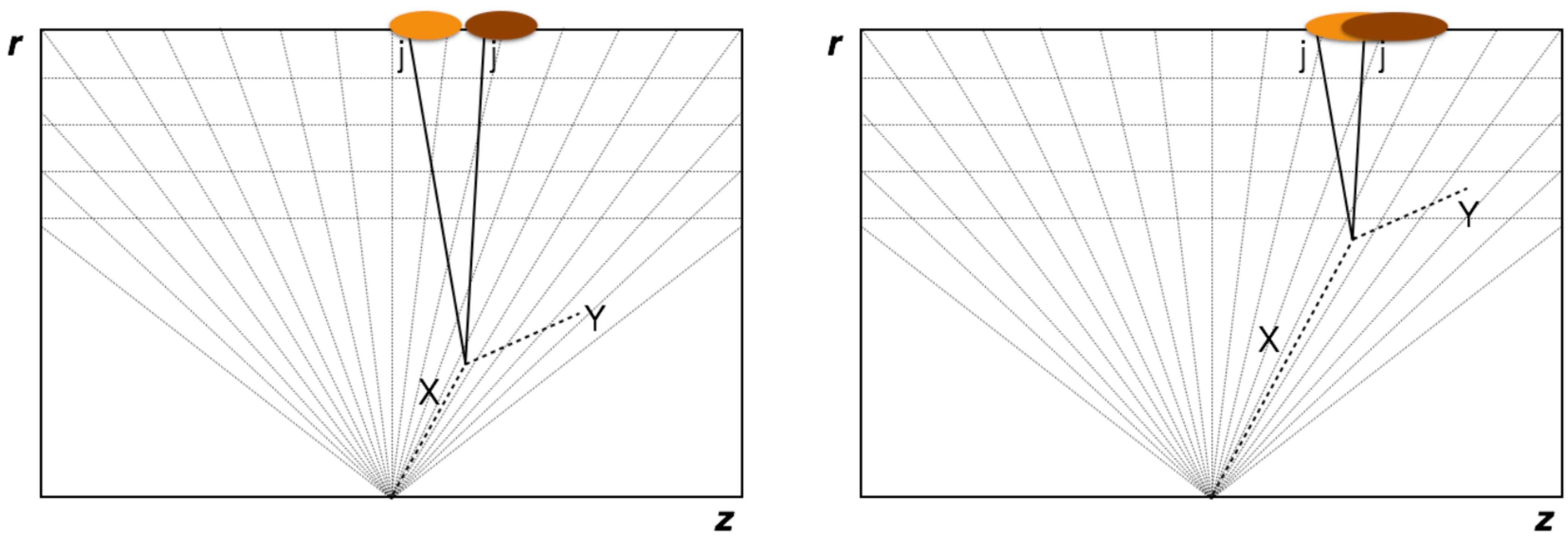




SCENARIO I : ILLUSTRATION



Prompt jets



Displaced jets

LESSONS LEARNT

Scenario II in backup

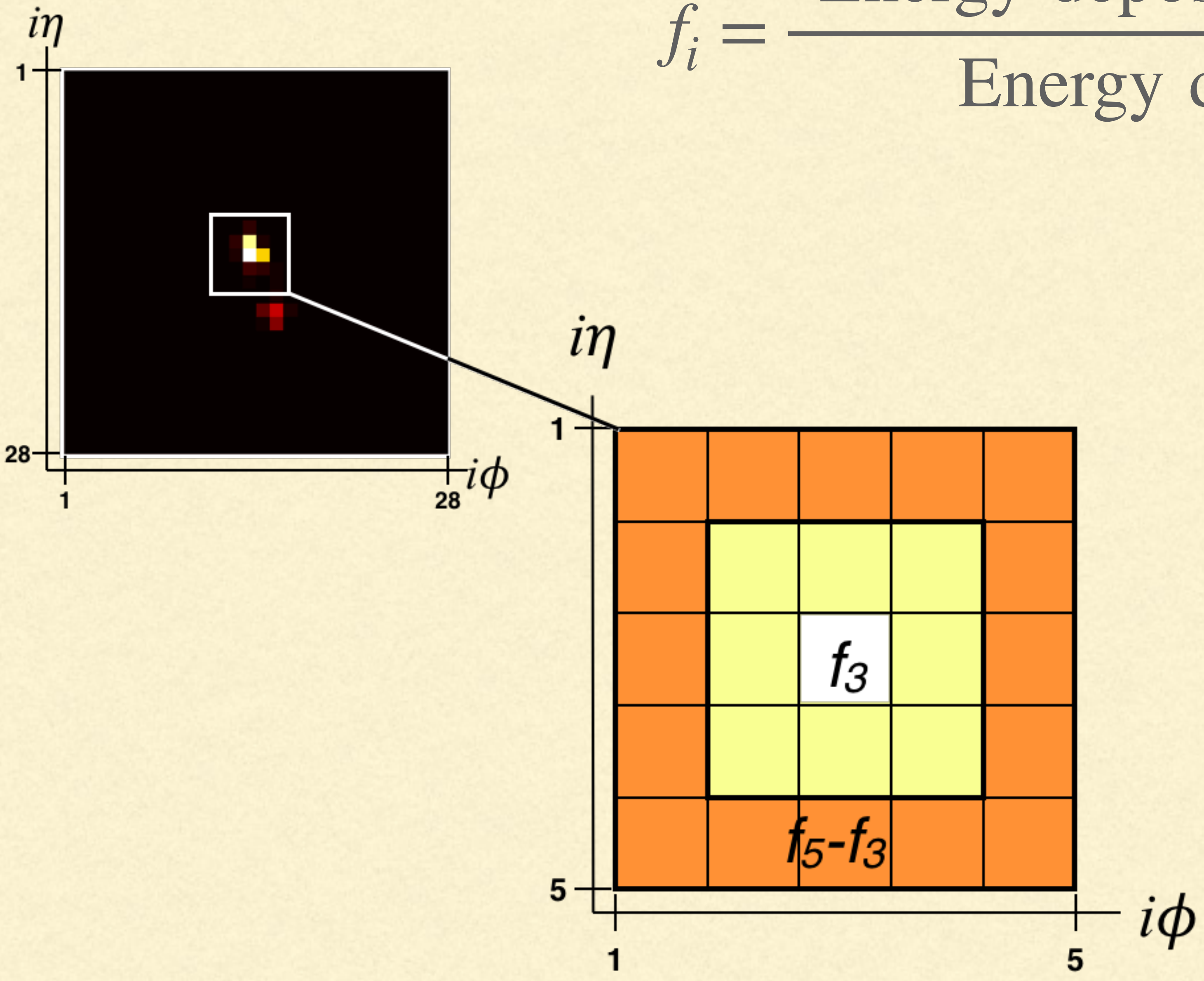
1. **Elongated energy deposition in the HCAL**

   Mismatch of displaced particles' η-ϕ direction with standard calorimeter η-ϕ towers − ***energy deposition of displaced jets have more <u>elongated patterns</u> different from standard patterns of prompt jets***

2. **Total energy deposit more contained in the $i\eta$-$i\phi$ region**

   Later the decay of X, <u>smaller the physical region</u> in which the deposited energy is contained in HCAL

ENERGY DEPOSITION PATTERN: ENERGY FRACTION



$$f_i = \frac{\text{Energy deposited in } i \times i \text{ block of the image}}{\text{Energy deposited in } 28 \times 28 \text{ image}},$$

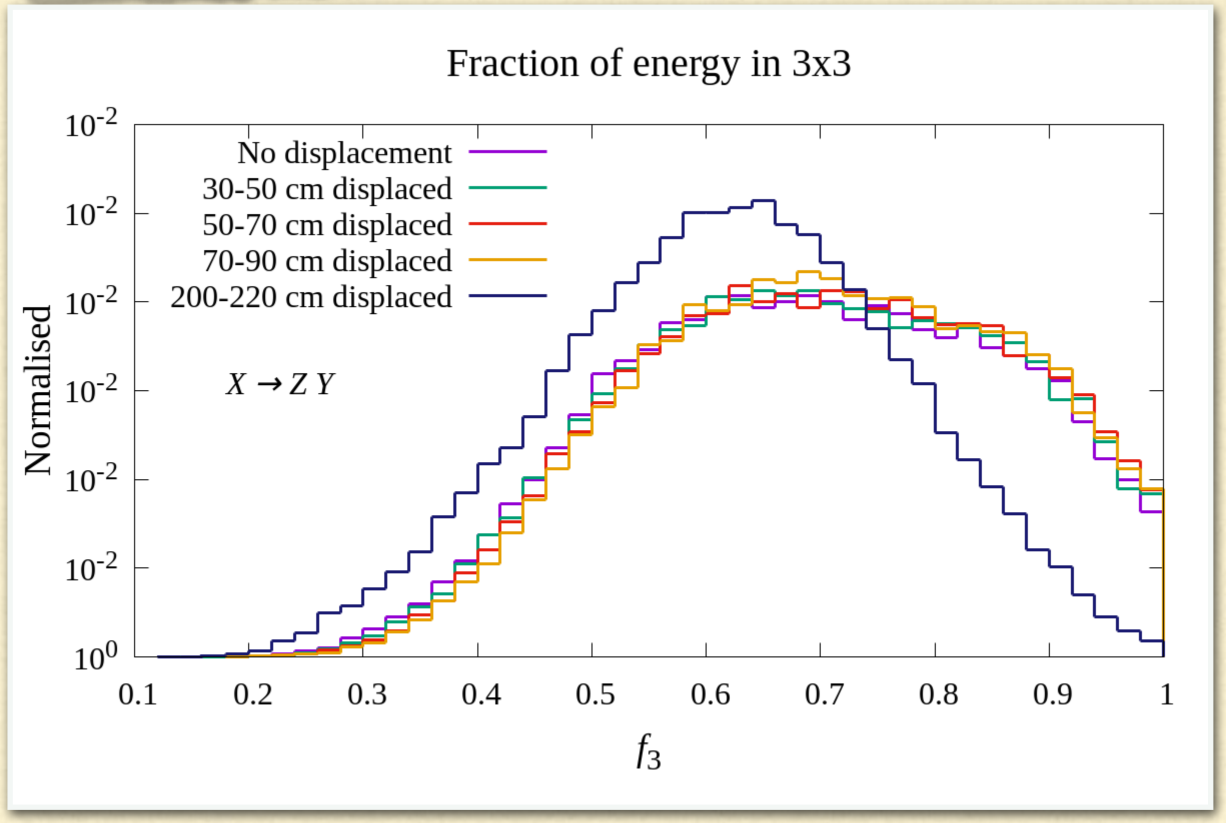
$$i = 3,5,9,11$$

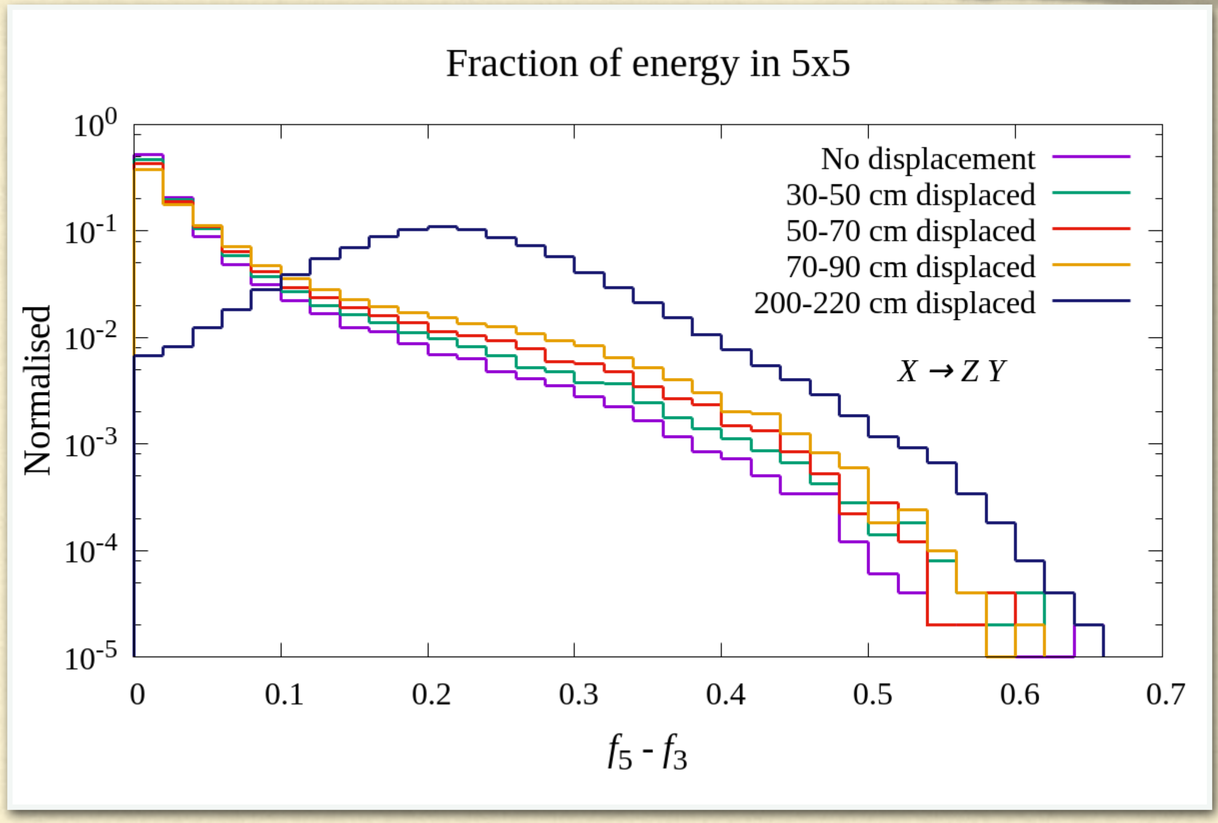
Consider distributions of:

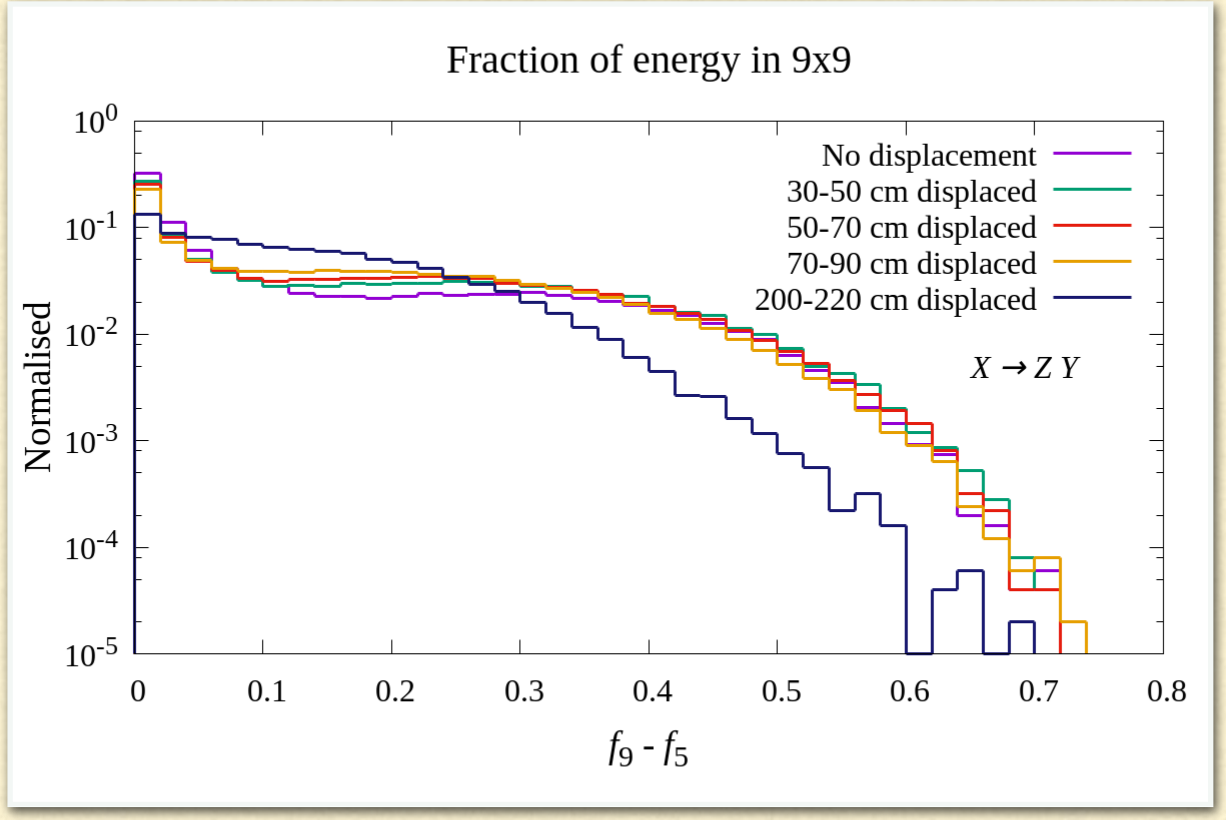
- energy fraction f_3 – *includes the central highest energy tower*
- exclusive energy fractions :

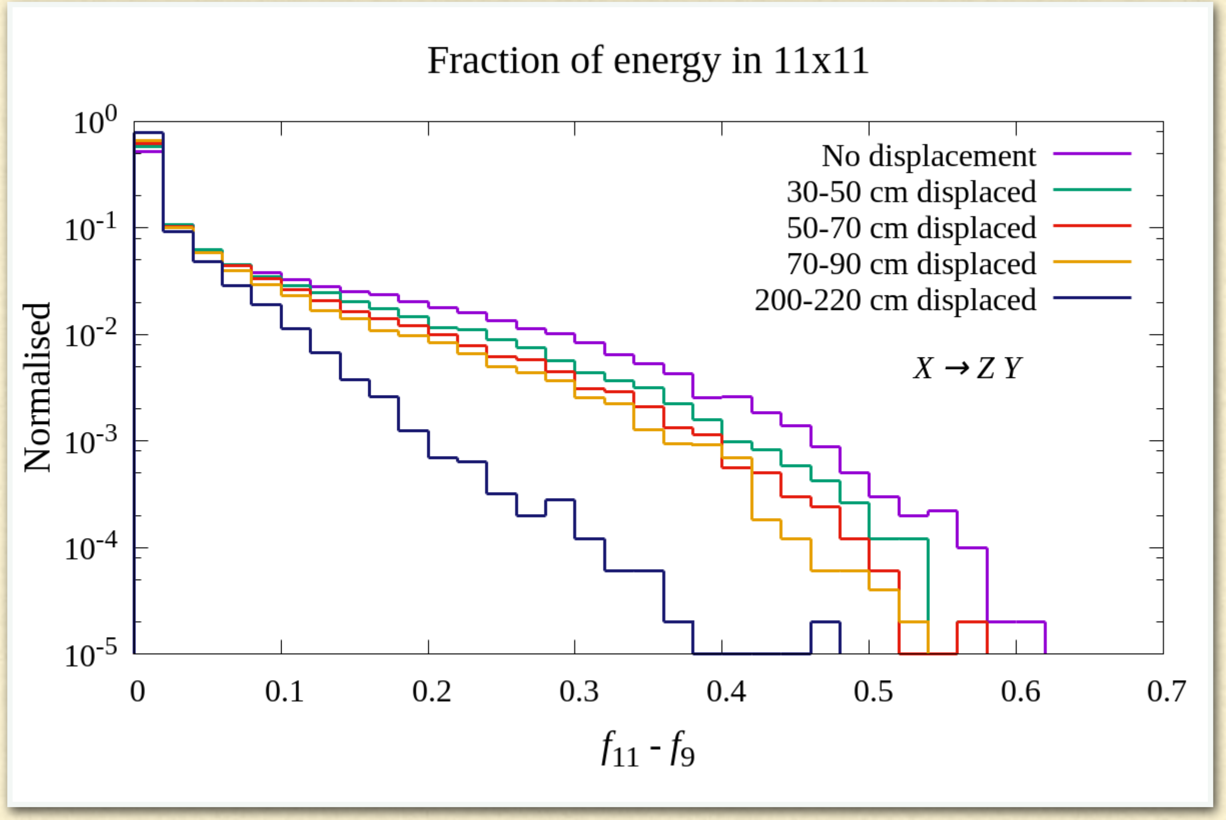
$f_5 - f_3$, $f_9 - f_5$, and $f_{11} - f_9$

SCENARIO I : ENERGY FRACTION HISTOGRAMS



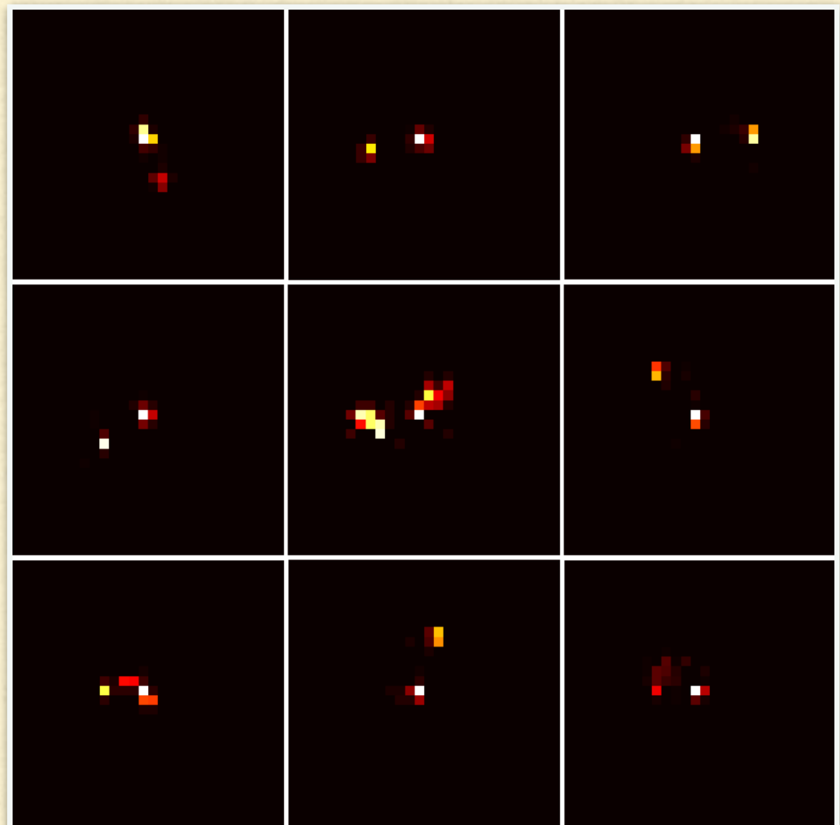




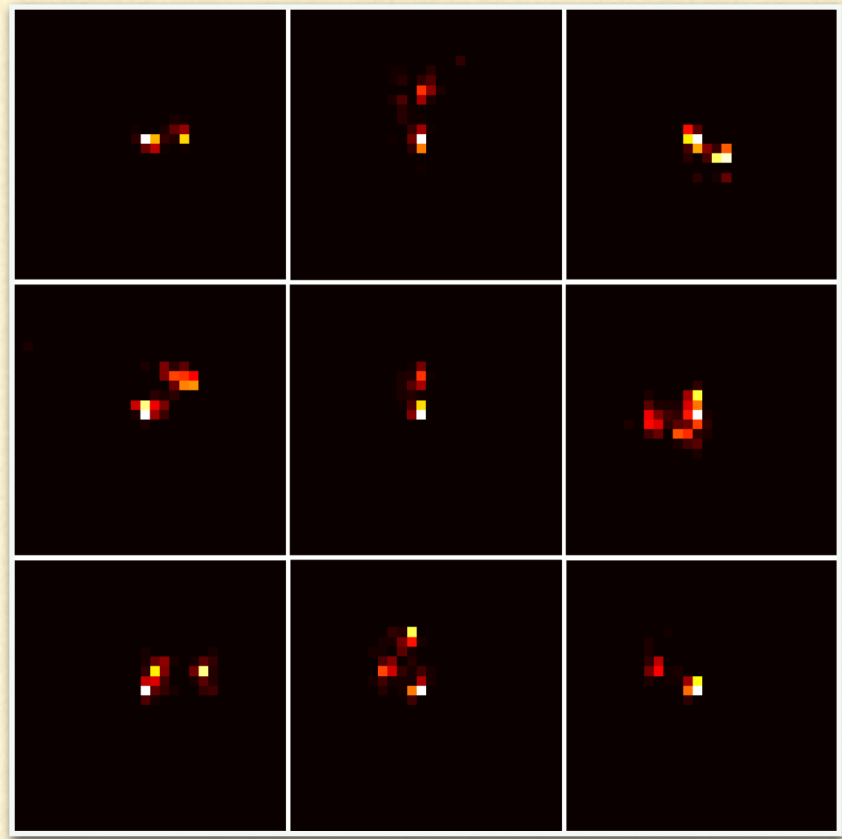


SCENARIO I : INDIVIDUAL IMAGES

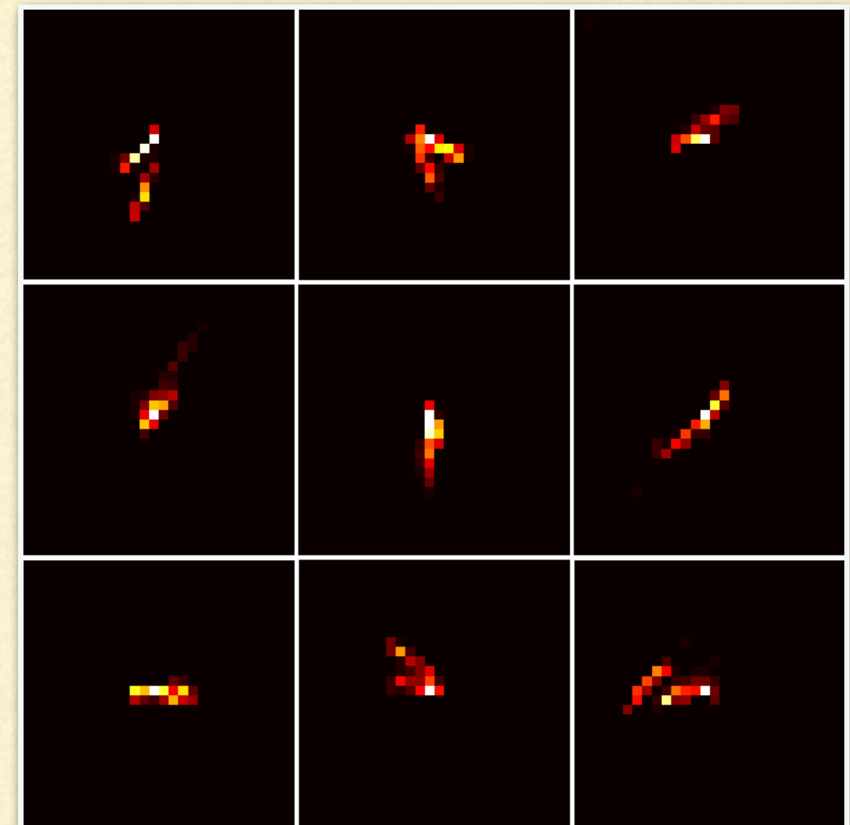
Prompt decay



50 cm < d_T < 70 cm



200 cm < d_T < 220 cm

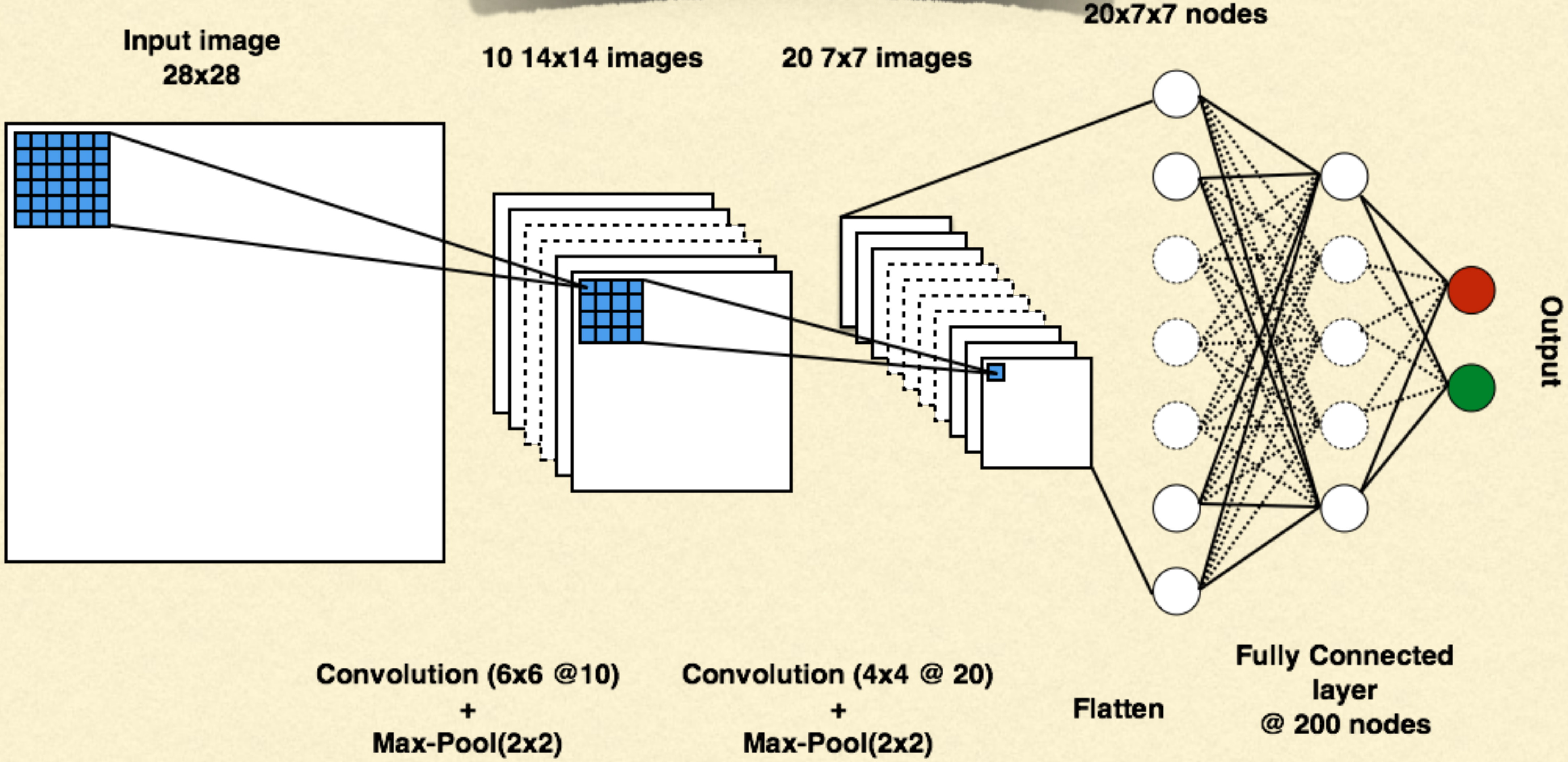


Although statistically different, discriminating individual images

not an easy task **–**

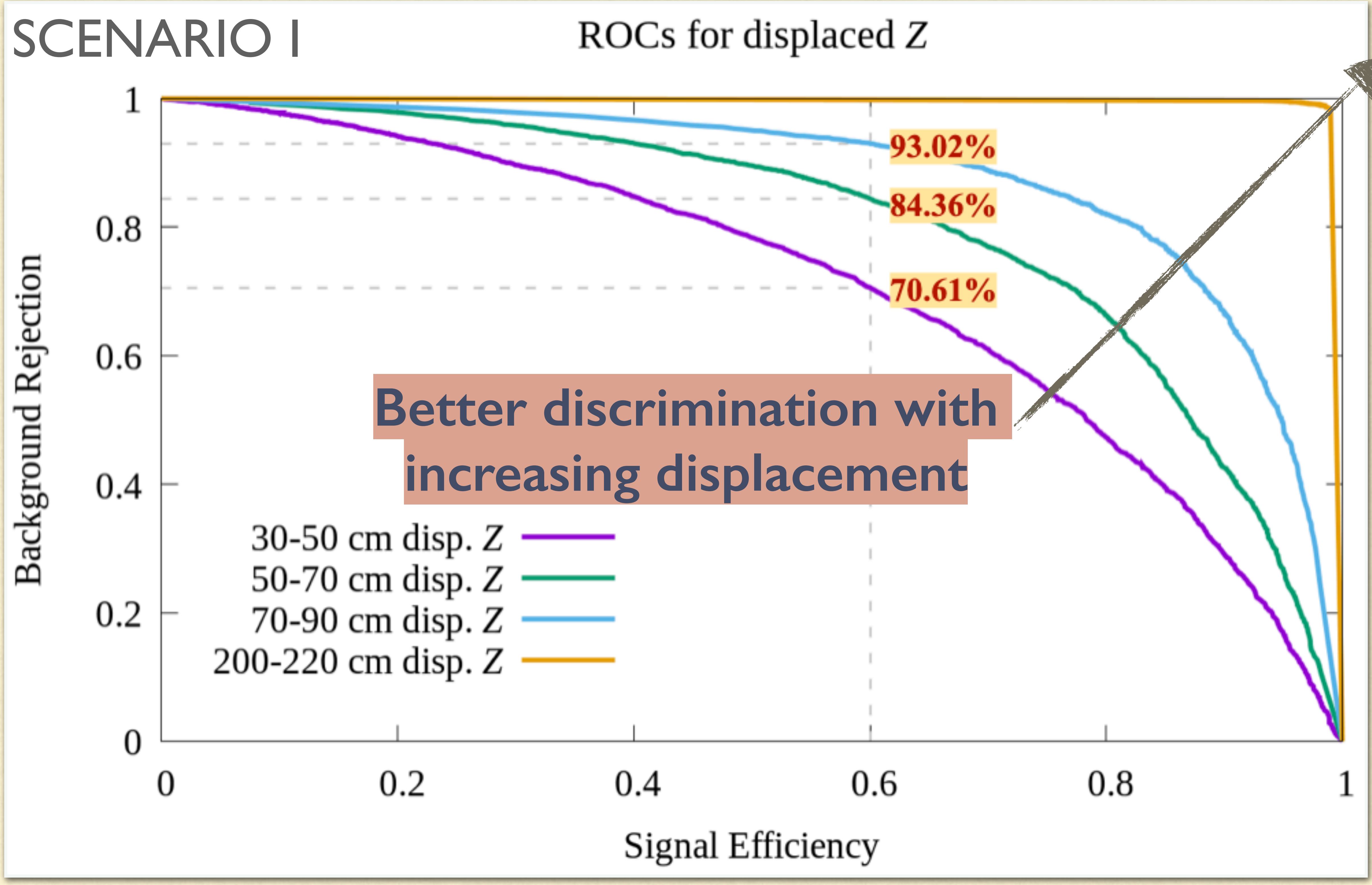
employing image-recognition technique

CNN ARCHITECT

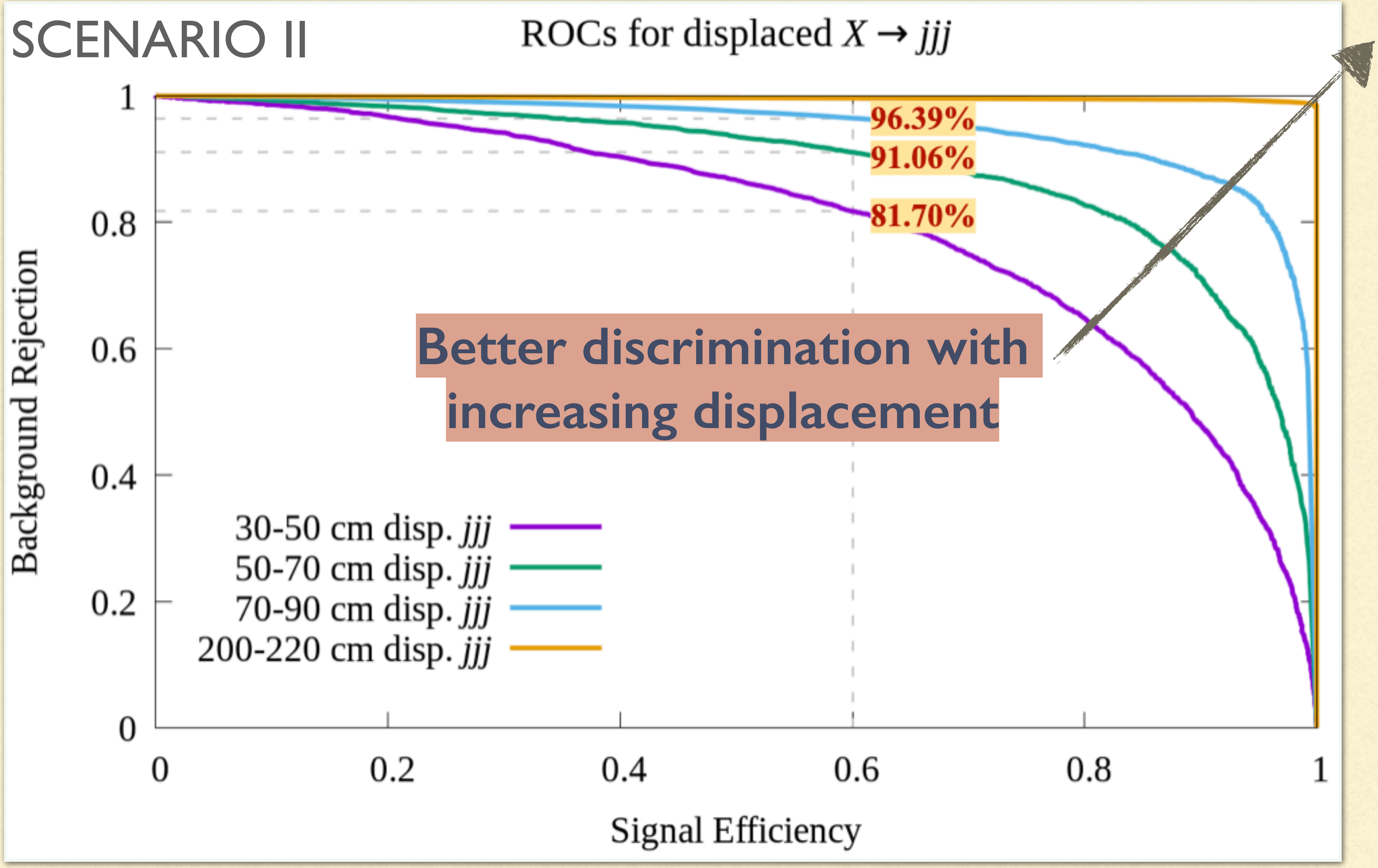


- Minimal preprocessing of images.
- Adam Optimizer; Activation by RELU.
- Learning rate: 0.001; Dropout: 50%.
- 60,000 images for training, 20,000 for validation and another 20,000 for testing the network.
- Batch size: 200.
- Training was stopped at the epoch with minimum validation loss.

RESULTS

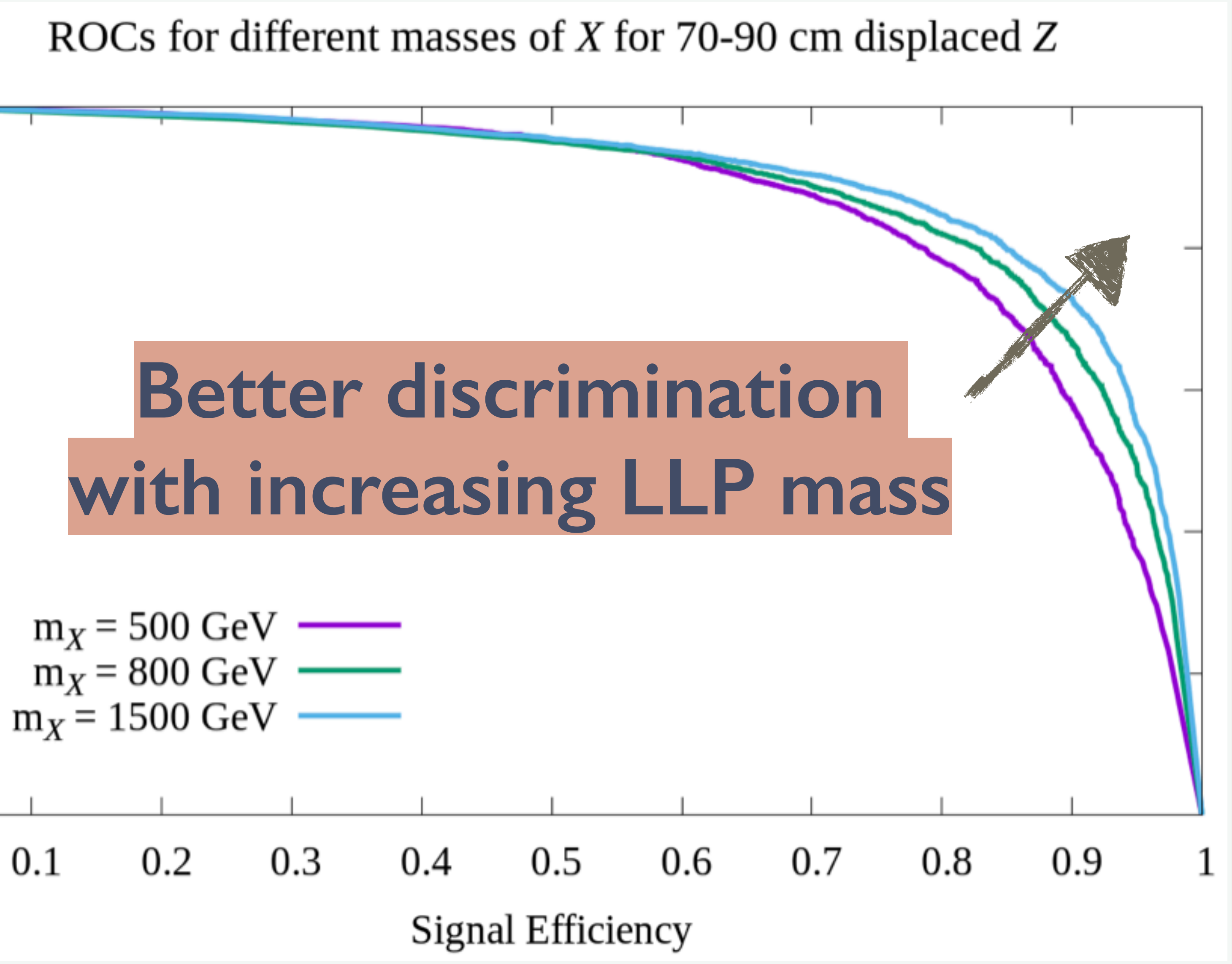

SCENARIO I
ROCs for displaced Z
Background Rejection
Signal Efficiency
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
93.02%
84.36%
70.61%
Better discrimination with increasing displacement
30-50 cm disp. Z
50-70 cm disp. Z
70-90 cm disp. Z
200-220 cm disp. Z

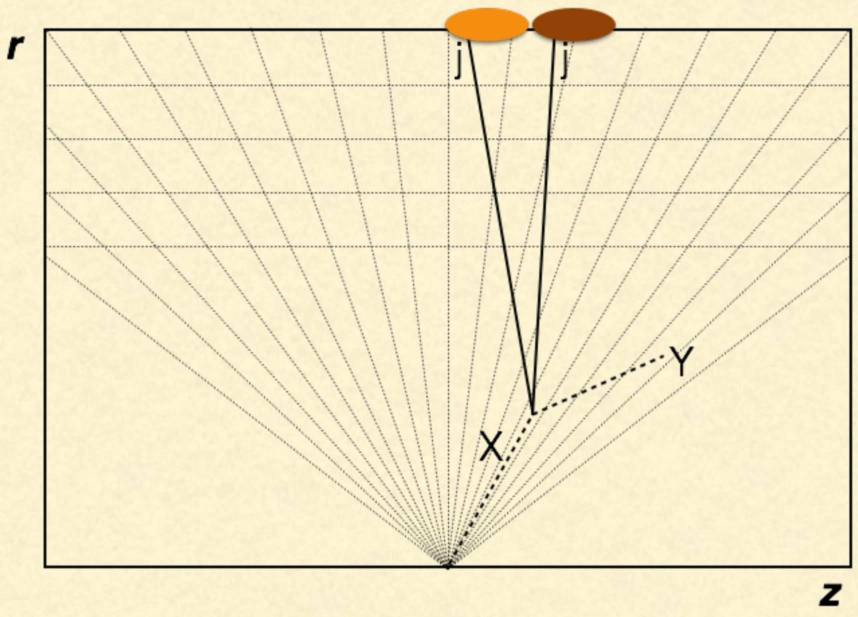
RESULTS


SCENARIO II
ROCs for displaced $X \to jjj$
Background Rejection
Signal Efficiency
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
96.39%
91.06%
81.70%
Better discrimination with increasing displacement
30-50 cm disp. *jjj*
50-70 cm disp. *jjj*
70-90 cm disp. *jjj*
200-220 cm disp. *jjj*

RESULTS

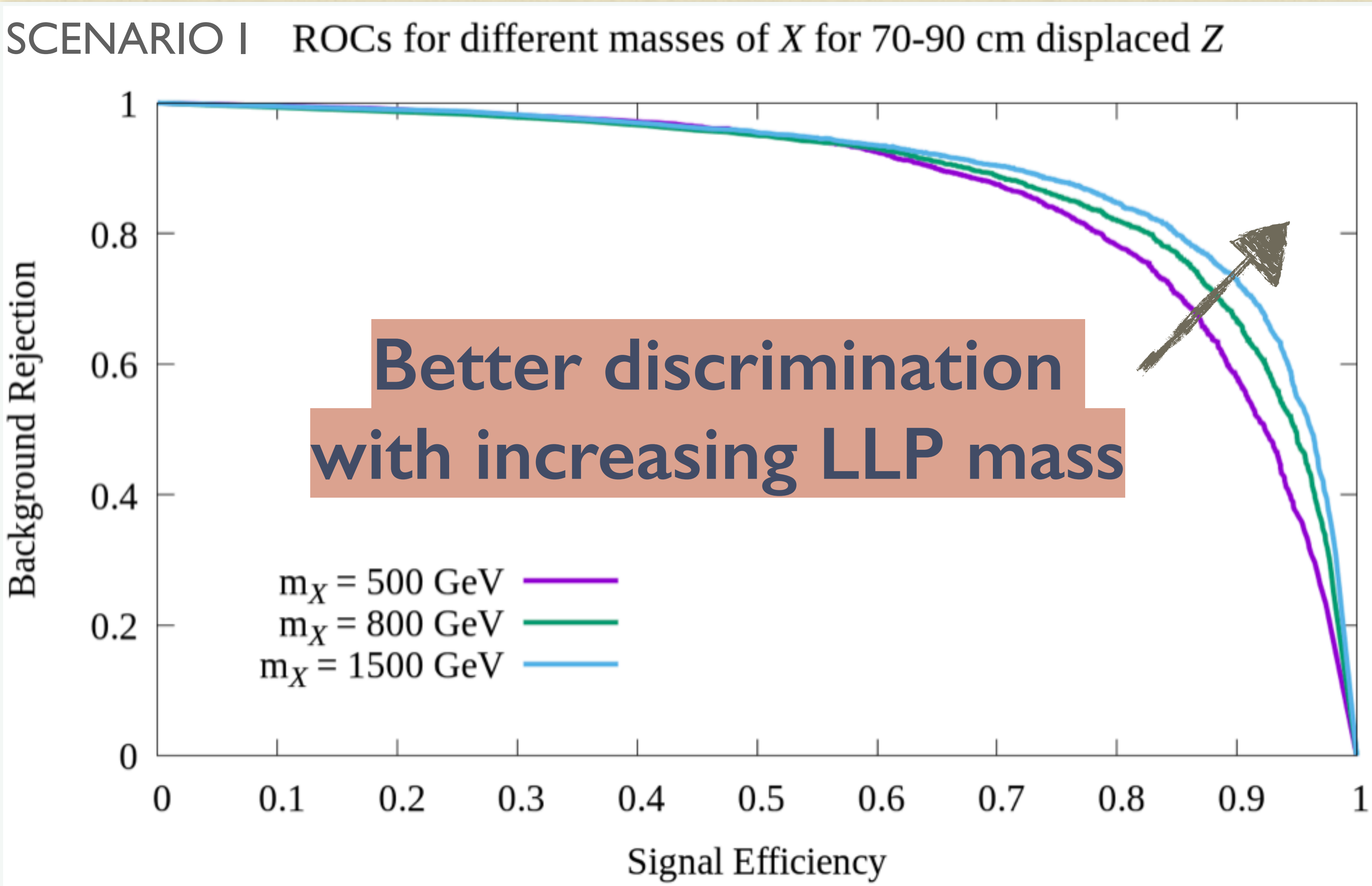
SCENARIO I



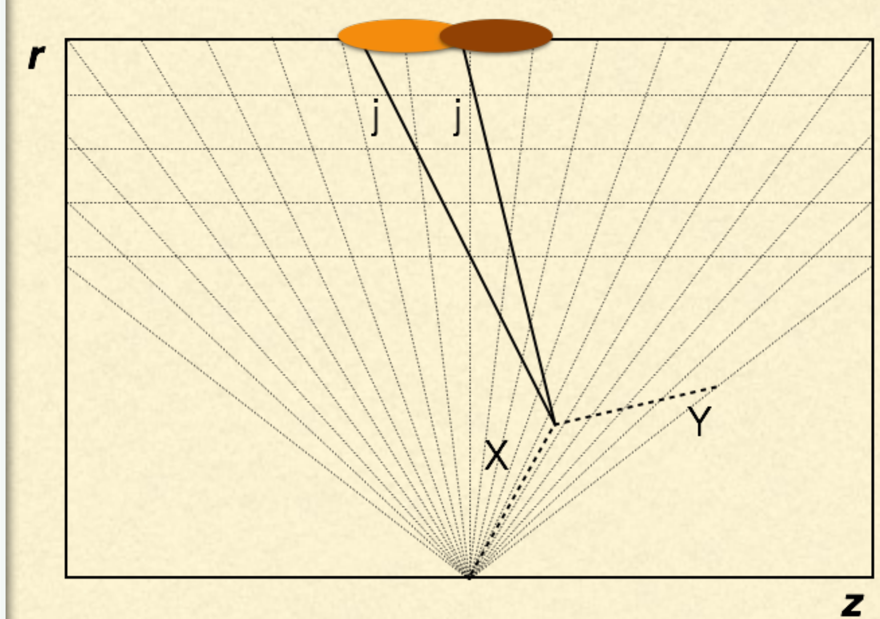


Larger the mass of LLP — slower it moves — ΔR between decay products increase — ***more mismatch with detectors' segmentation***

RESULTS

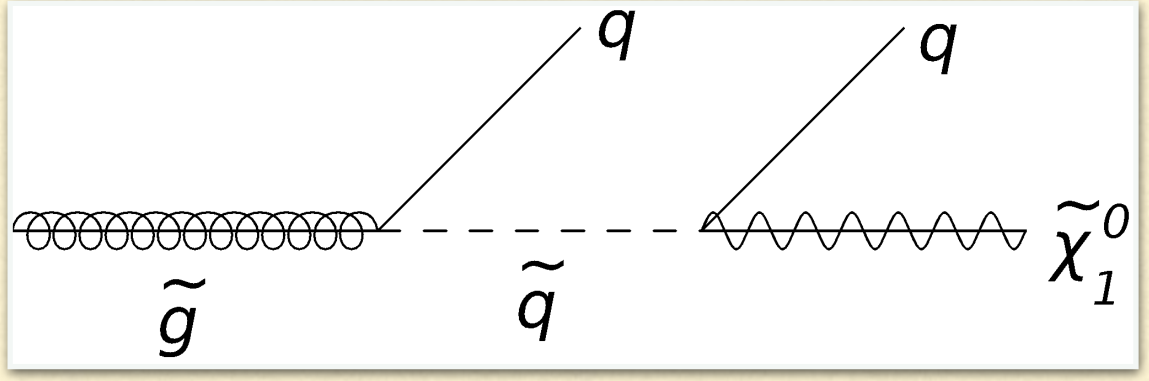


increasing LLP mass



Larger the mass of LLP – slower it moves – ΔR between decay products increase – ***more mismatch with detectors' segmentation***

STOPPED PARTICLE SCENARIO



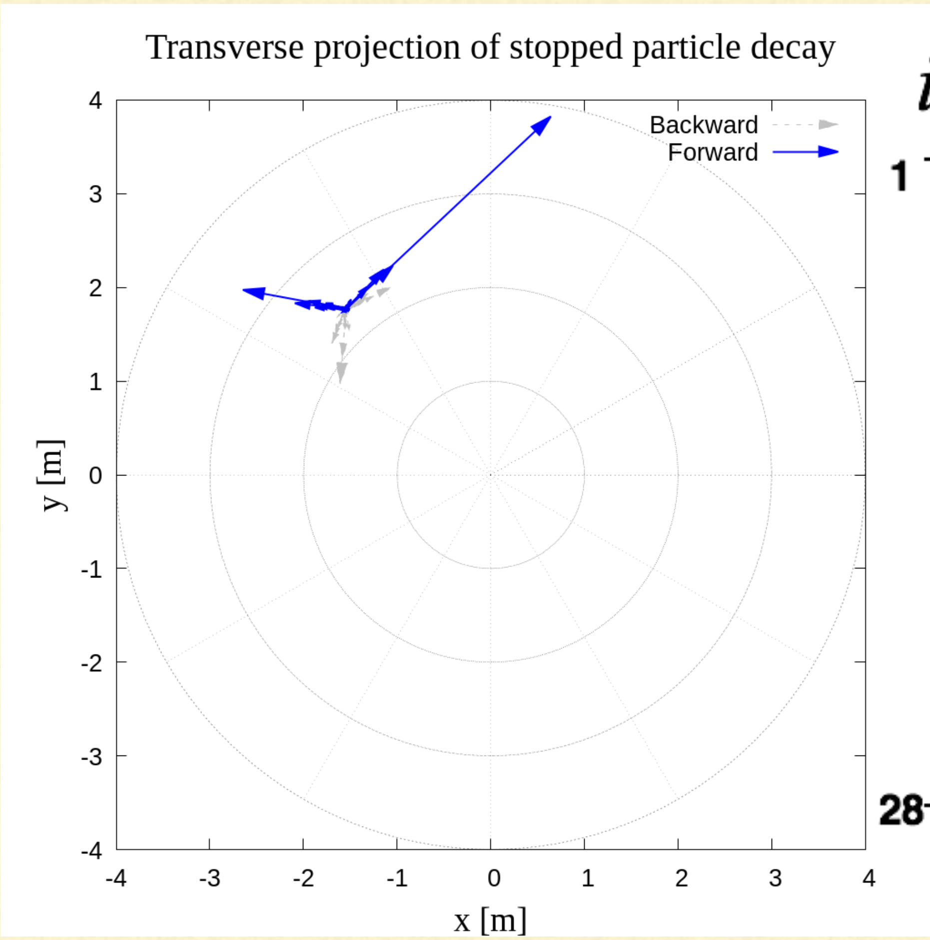
$$\Gamma_{\tilde{g}} \sim \frac{m_{\tilde{g}}^5}{m_{\tilde{q}}^4}$$

- Large gluino-squark mass splitting can make the gluino long-lived.
- If $\Gamma_{\tilde{g}} < \Lambda_{\rm QCD}$, the gluino would hadronize before decaying and make **“R-hadrons”**.
- These hadrons lose energy via ionization while traversing the detector and can eventually **stop before decaying**.
- “Stopped” R-hadrons may decay seconds, days, or even weeks later, resulting in out-of-time energy deposits in the calorimeter.
- Proposed to search in **empty bunch-crossings**.

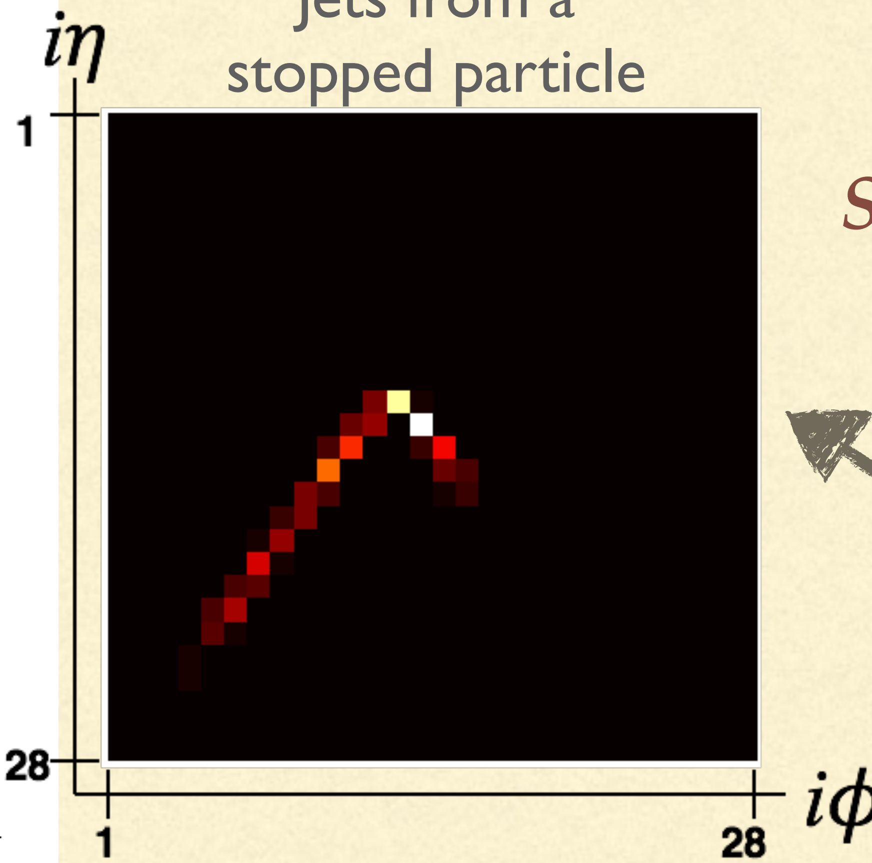
How does their HCAL energy deposition look like?

STOPPED PARTICLE SCENARIO

$X \to jjj, X$ decays at rest, $m_X = 1$ TeV

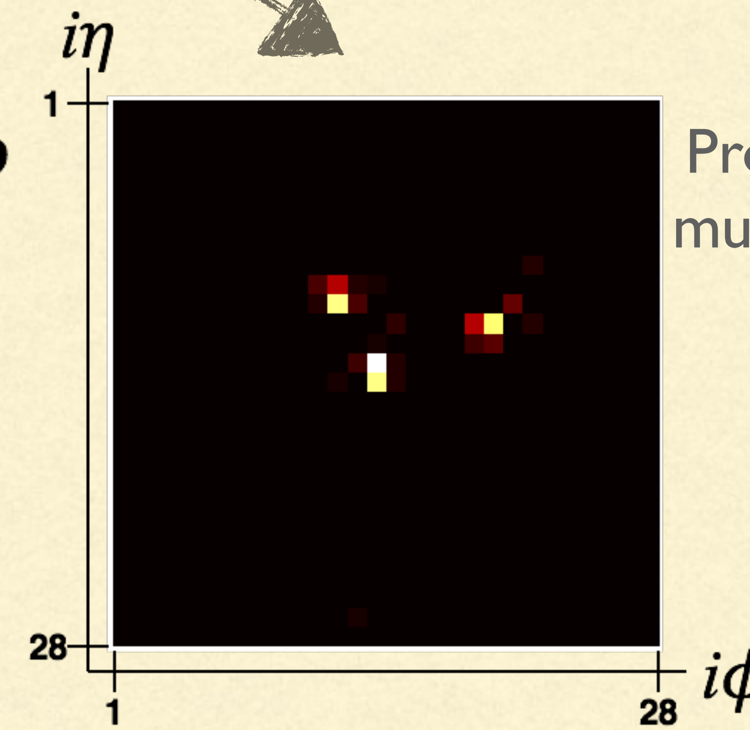


Jets from a stopped particle



Energy deposition range: (400,500) GeV

Significantly different energy deposition pattern compared to prompt multijets.



Prompt multijets

One can use ***such HCAL energy deposition images*** than waiting for empty bunch-crossings for stopped R-hadron searches.

CONCLUSION

- First attempt in studying LLPs using energy deposition images and image recognition techniques.
- Two key features:
  - Elongation in energy deposition due to mismatch of η and ϕ of decay products starting from SV and the standard detector η-ϕ segmentation.
  - Later the decay of the LLP, smaller the physical region in which the energy deposition is contained in HCAL.
- Better performance for LLPs which decay at larger distances from the PV, where usual displaced jets analysis might lose sensitivity due to failure of standard reconstructions − complementary to standard LLP analyses.
- Stopped particles − very different energy deposition patterns in the calorimeter − no need to wait for empty bunch crossings in stopped R-hadron searches.
- Minimal preprocessing done on the images; No advanced optimisations done. Advanced pre-processing and optimisations can be done for dedicated LLP searches.
- We believe that the features identified here will be similar for any scenario where an LLP decays into multiple jets in any collider detector.

For further details please have a look at

B. Bhattacherjee, S. Mukherjee, and RS, JHEP 11 (2019) 156, arXiv:1904.04811 [hep-ph]

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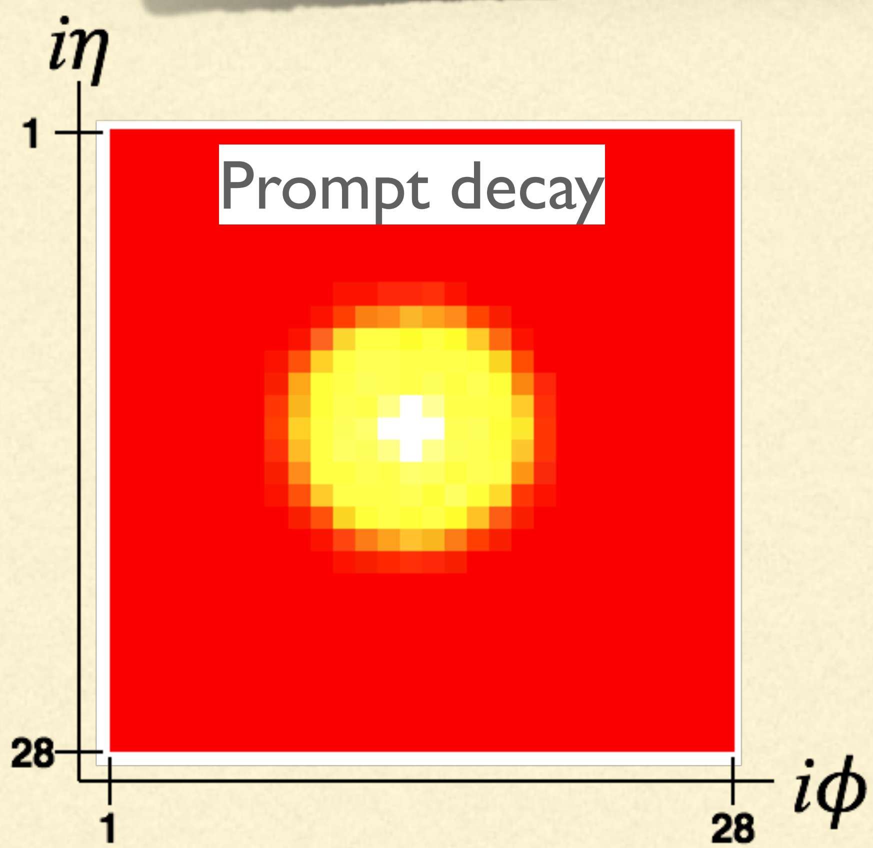
Thank you

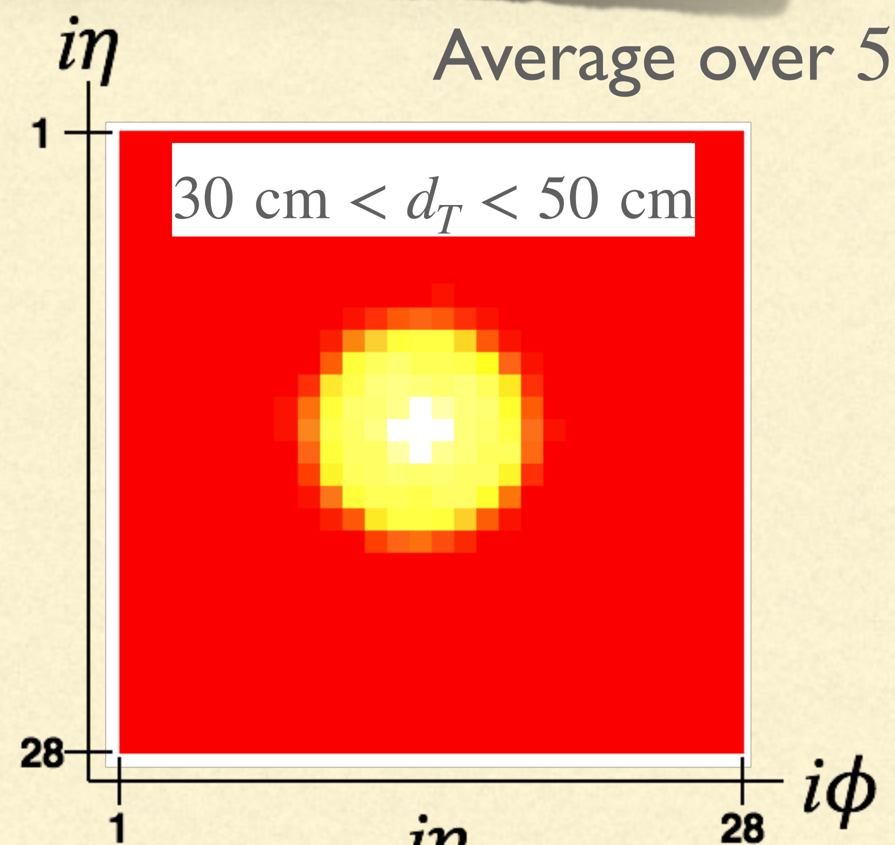
BACKUP

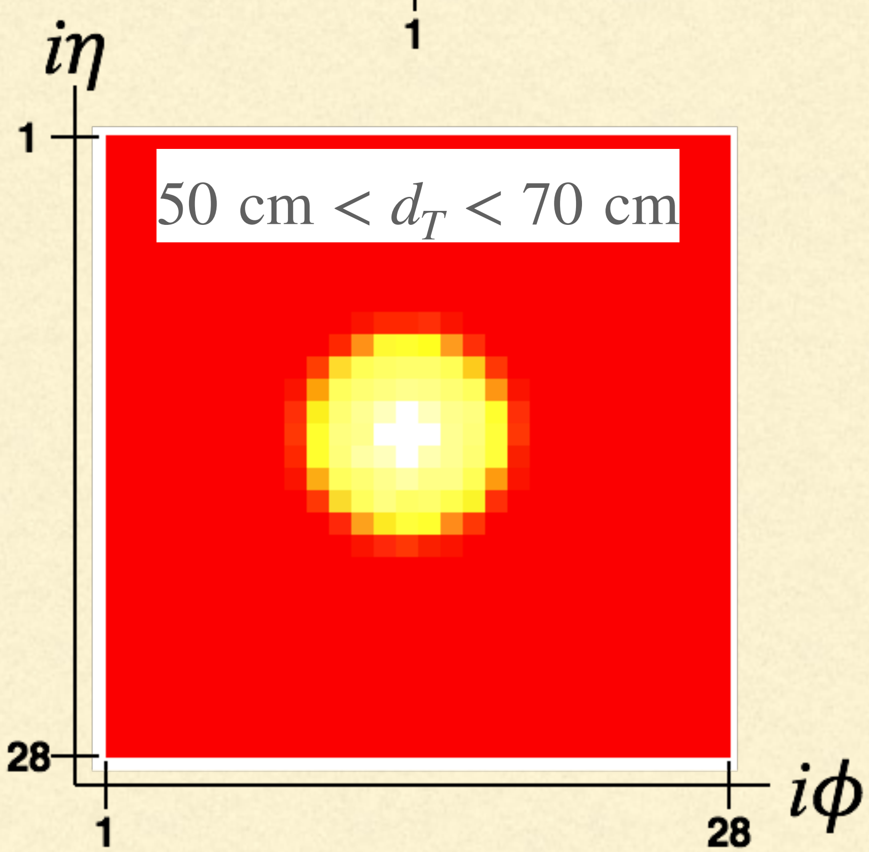
Back

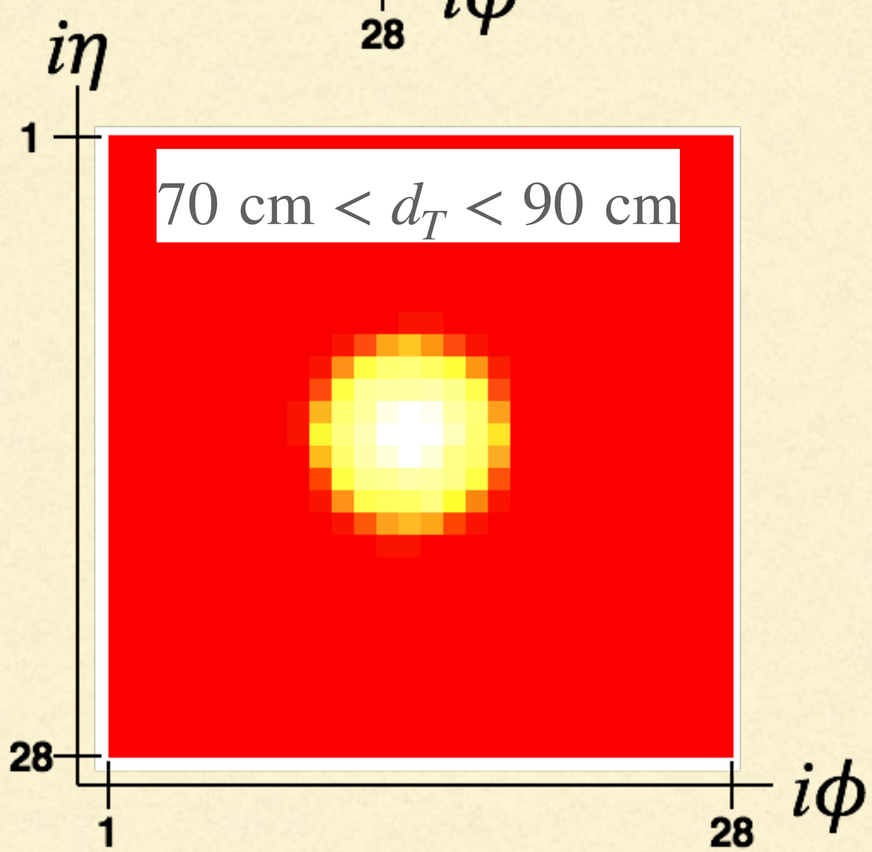
SCENARIO II : AVERAGE IMAGE

Average over 50 000 images

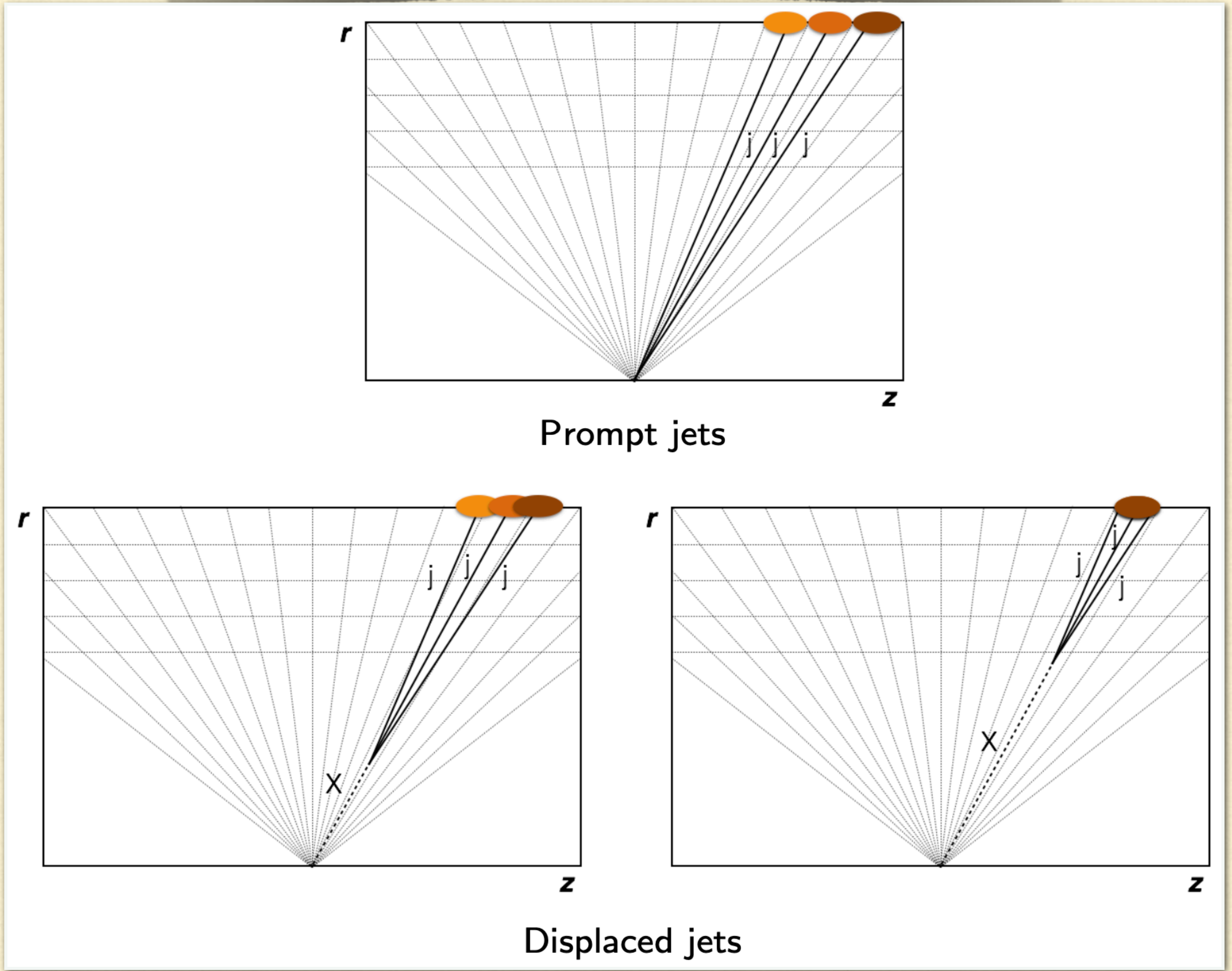








SCENARIO II : ILLUSTRATION



Back

SCENARIO II : ENERGY FRACTION HISTOGRAMS