Super-resolution for calorimetry

F. A. Di Bello, E. Dreyer, S. Ganguly, E. Gross, M. Kado, M. Pitt, L. Santi, J. Shlomi, N. Kakati

Learning to discover
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paper

Istituto Nazionale di Fisica Nucleare

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

SAPIENZA
UNIVERSITÀ DI ROMA

東京大学
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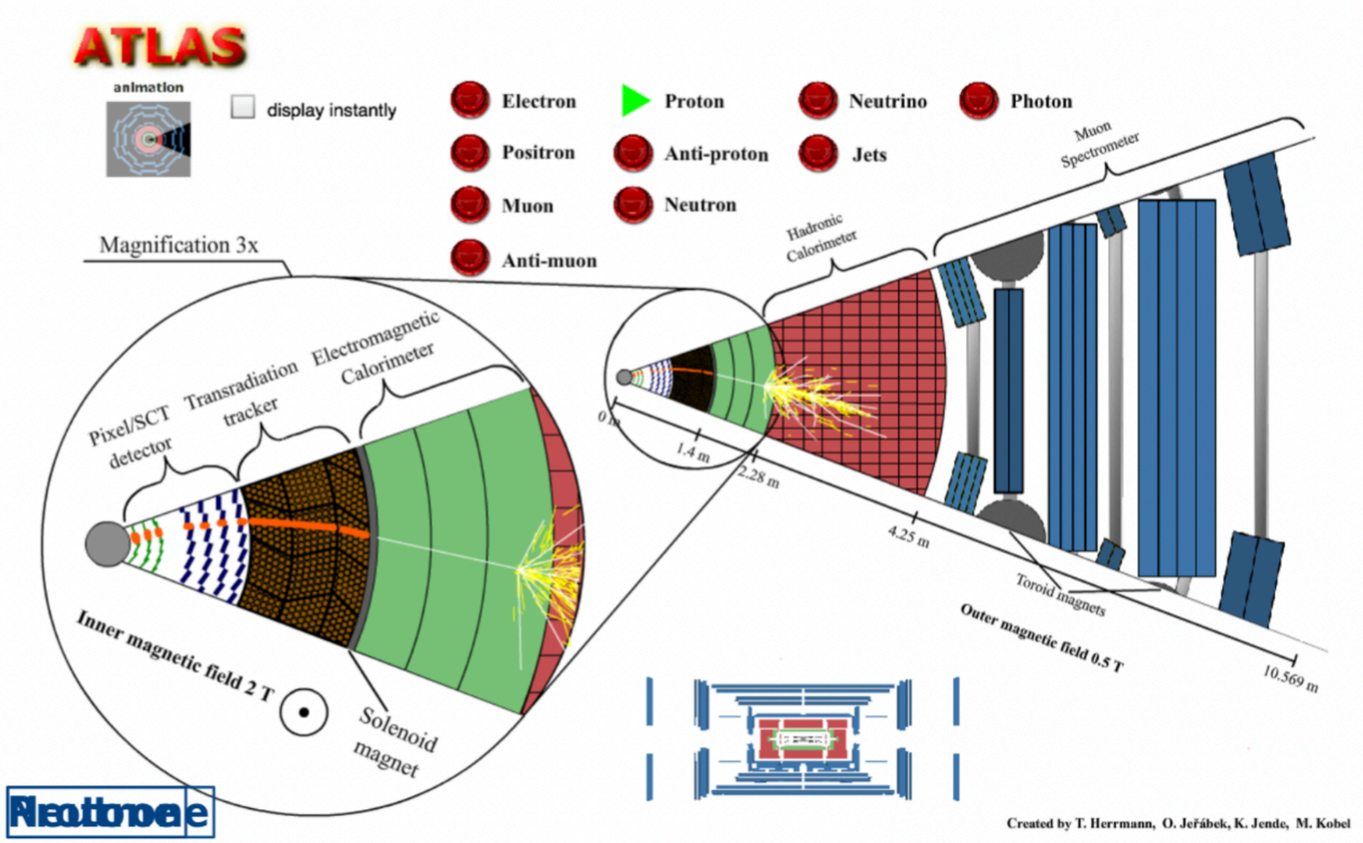
International Center for Elementary Particle Physics
The University of Tokyo

Intro

- Pflow algorithms exploit the different energy resolution measured in the tracker and calorimeter



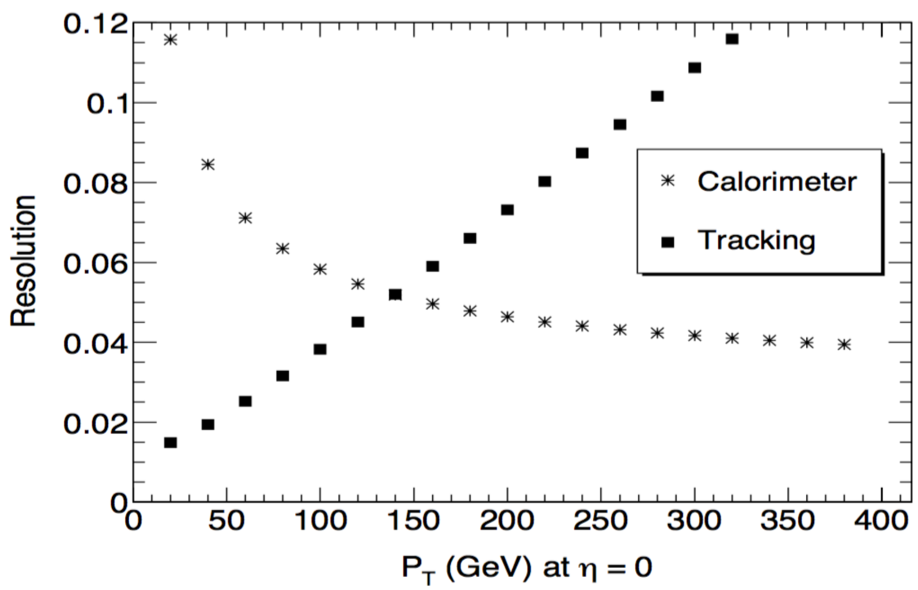
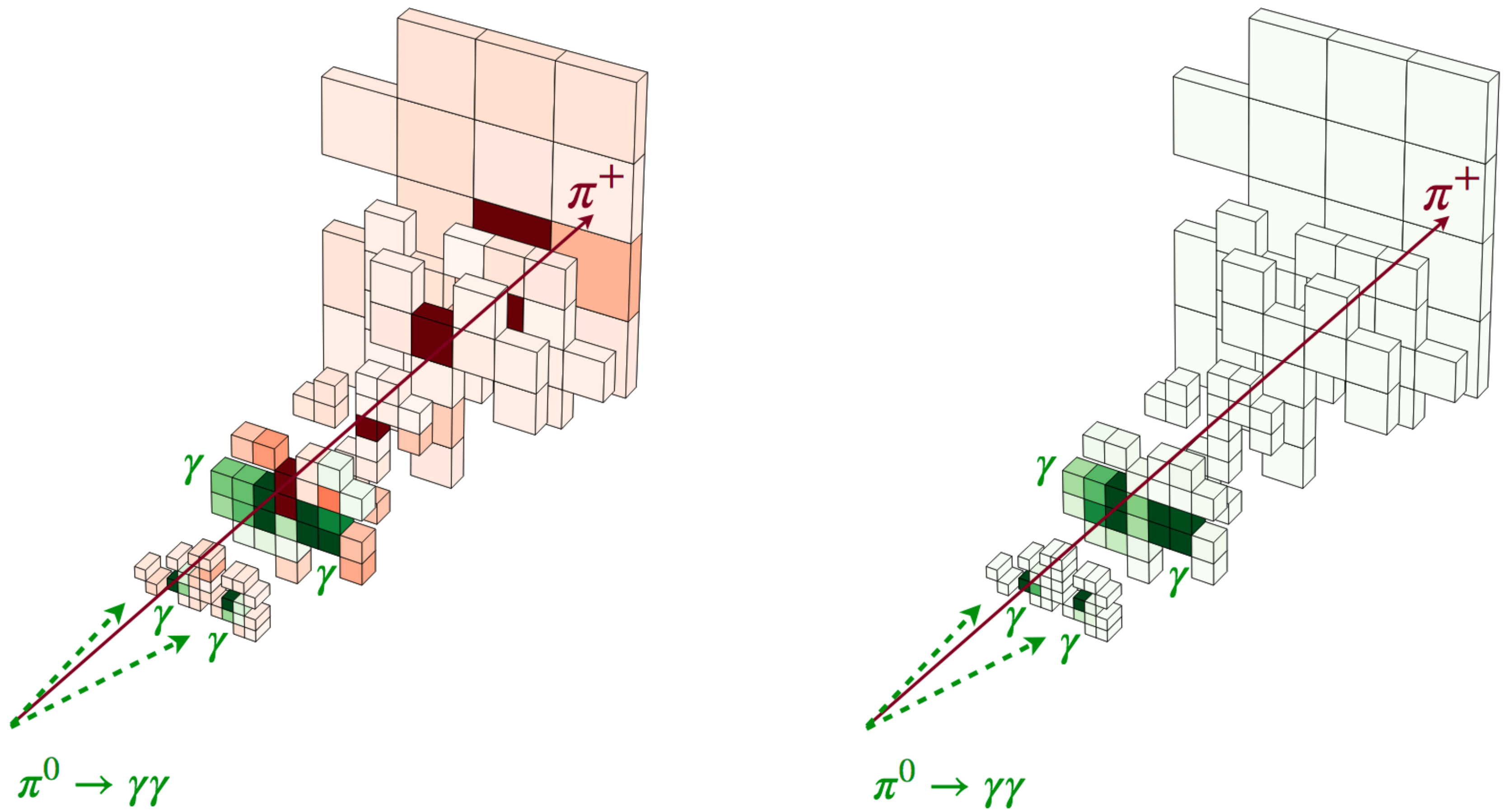


Figure 1: Resolution of Single Pions at $\eta = 0$ in Calorimeter and Charged Particle Tracking Detectors

The detector model



Pi+/p0 simulated with different energy ranges from 2 to 20 GeV

track pt obtained via smearing: $\frac{\sigma(p)}{p} = 5 \times 10^{-4} \times p\,[GeV],$

The ML task

Regress the neutral energy for each cell

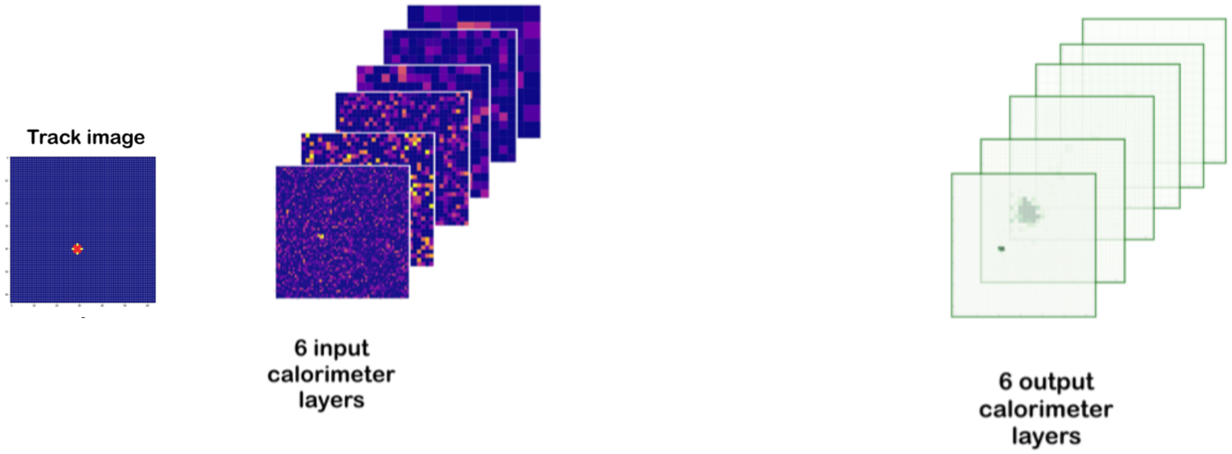
For CNNs the trick is to cope with images with different sizes, no such problems for graphs

$$L_{event} = \frac{1}{E_{tot}} \sum_c E_c (f_t^c - f_d^c)^2$$

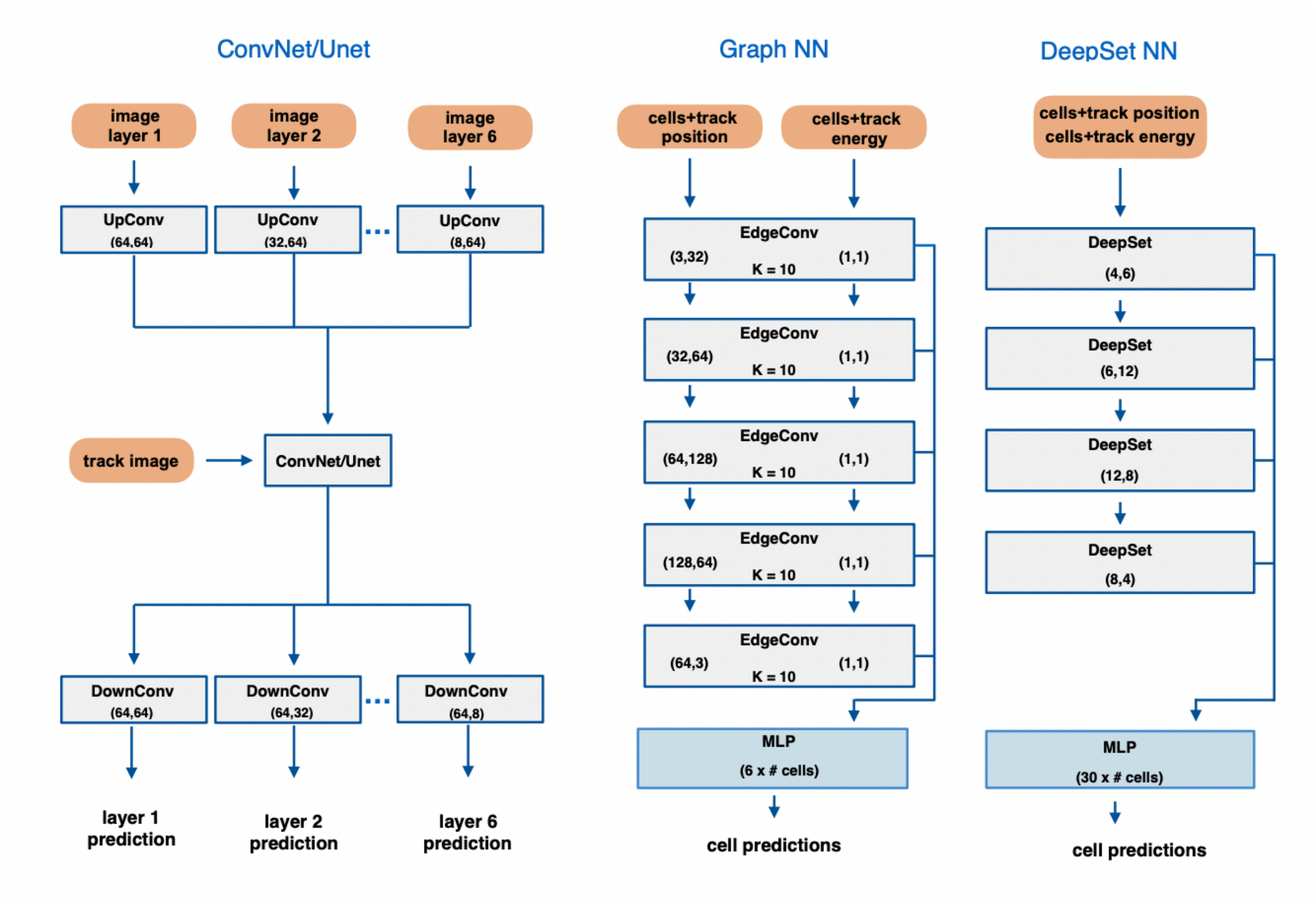
Common network structure for energy overlap removal task

Cell energies + positions + track → Neural Network → Cell neutral energy fractions

Convnet,
Convnet + UNet,
Graph network
Deepsets



Some of the models



An event display

Topoclusters in white

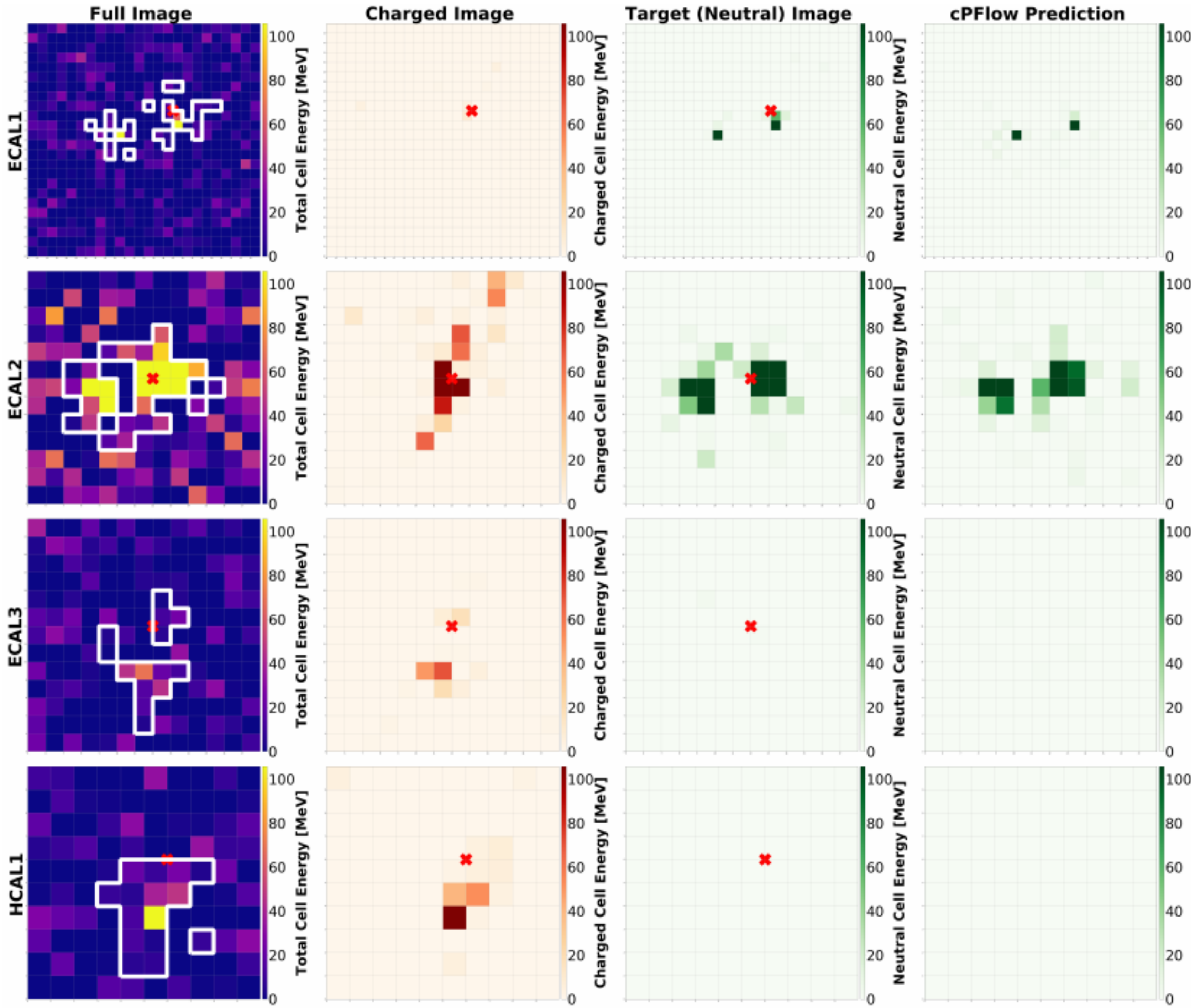
Compare with traditional Pflow

and ML approaches.

Several tried out: CNNs, graph

networks & deep sets (more

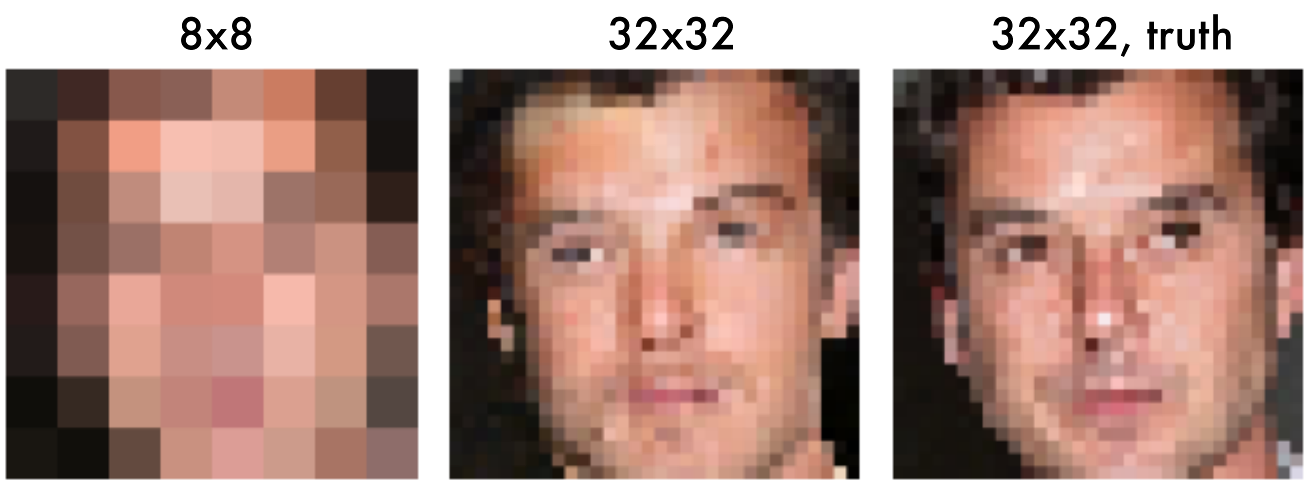
suited to cope with cells+track).



Super-resolution

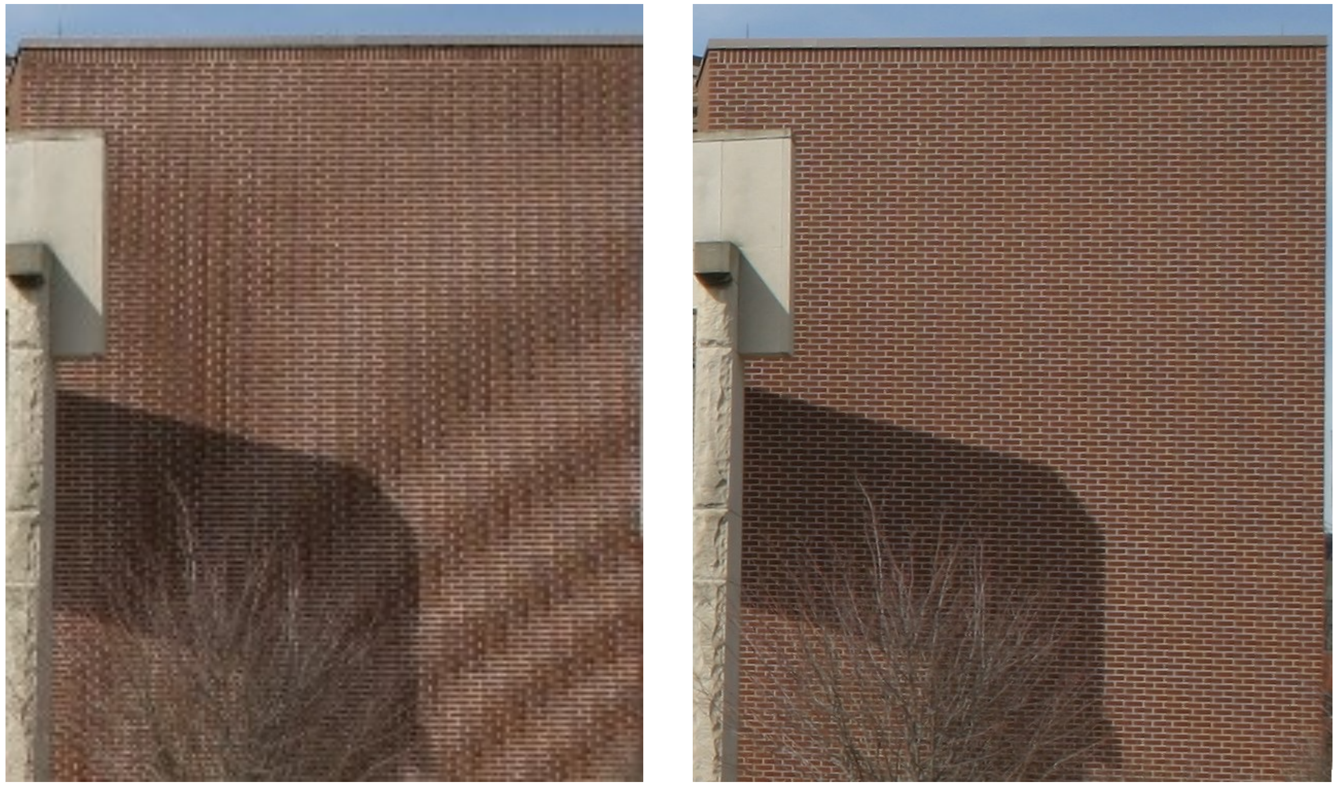
Introduction to super-resolution

- Imaging for camera etc [Ref., Ref.]



google CNN (2017) for large up-scaling factor

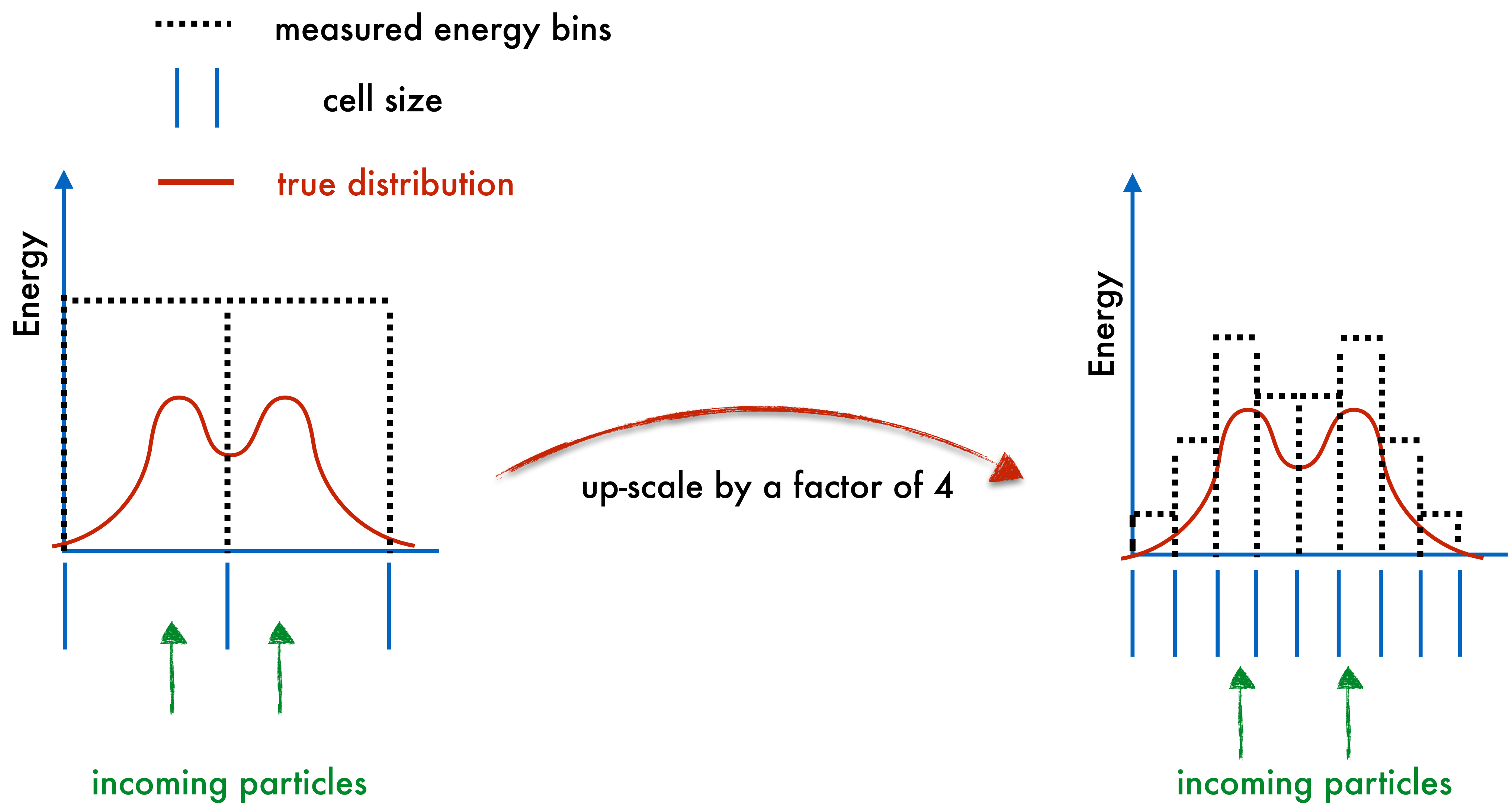
One of the main problem: how to get the HR target?



"Super-resolution usually involves applying prior knowledge about the object and the imaging process [...] in order to produce a single higher-resolution image"

Application to HEP

- The granularity of the measuring device is identified by the pixel/cells sizes (tracking/calorimetry)



Impossible to distinguish two particles or single particle hitting in between

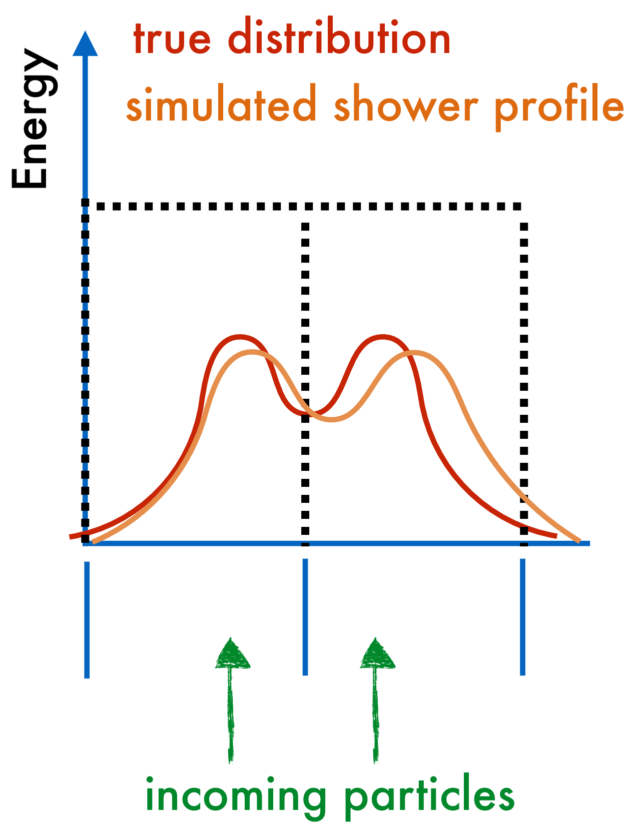
So far trivial statement:

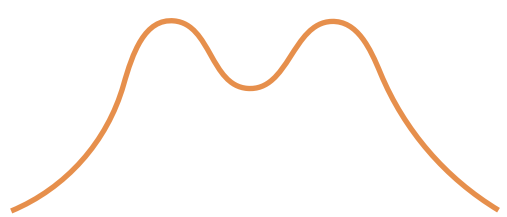
"higher spatial resolution allows to resolve additional features "

but how to construct the high-resolution image?

Application to HEP

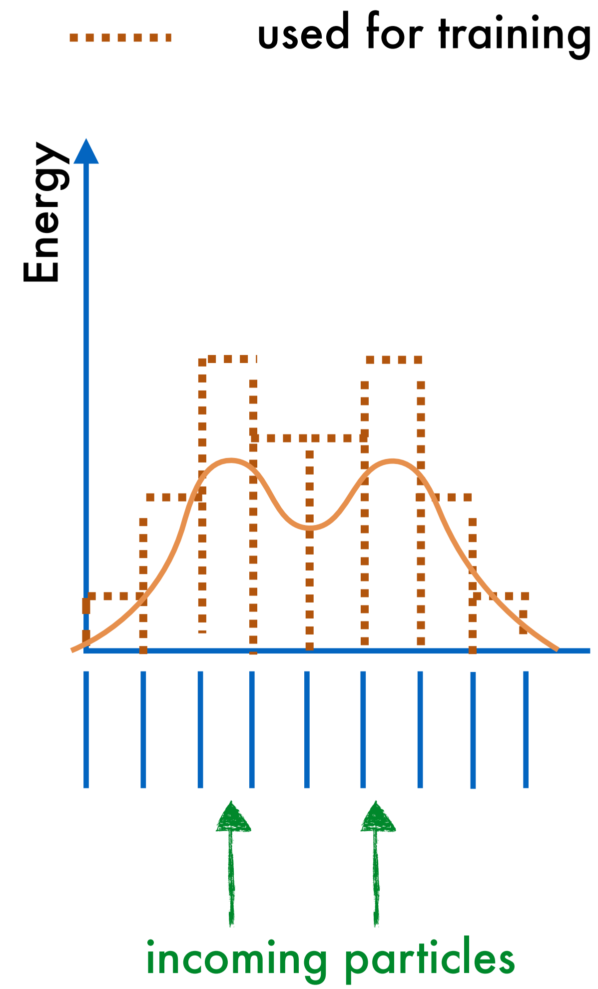
- Profit from MC simulations to build the “super” detector used as the target for training





GEANT4 based simulation

for our purposes this is a continuous line that can be used to build high-resolution detector



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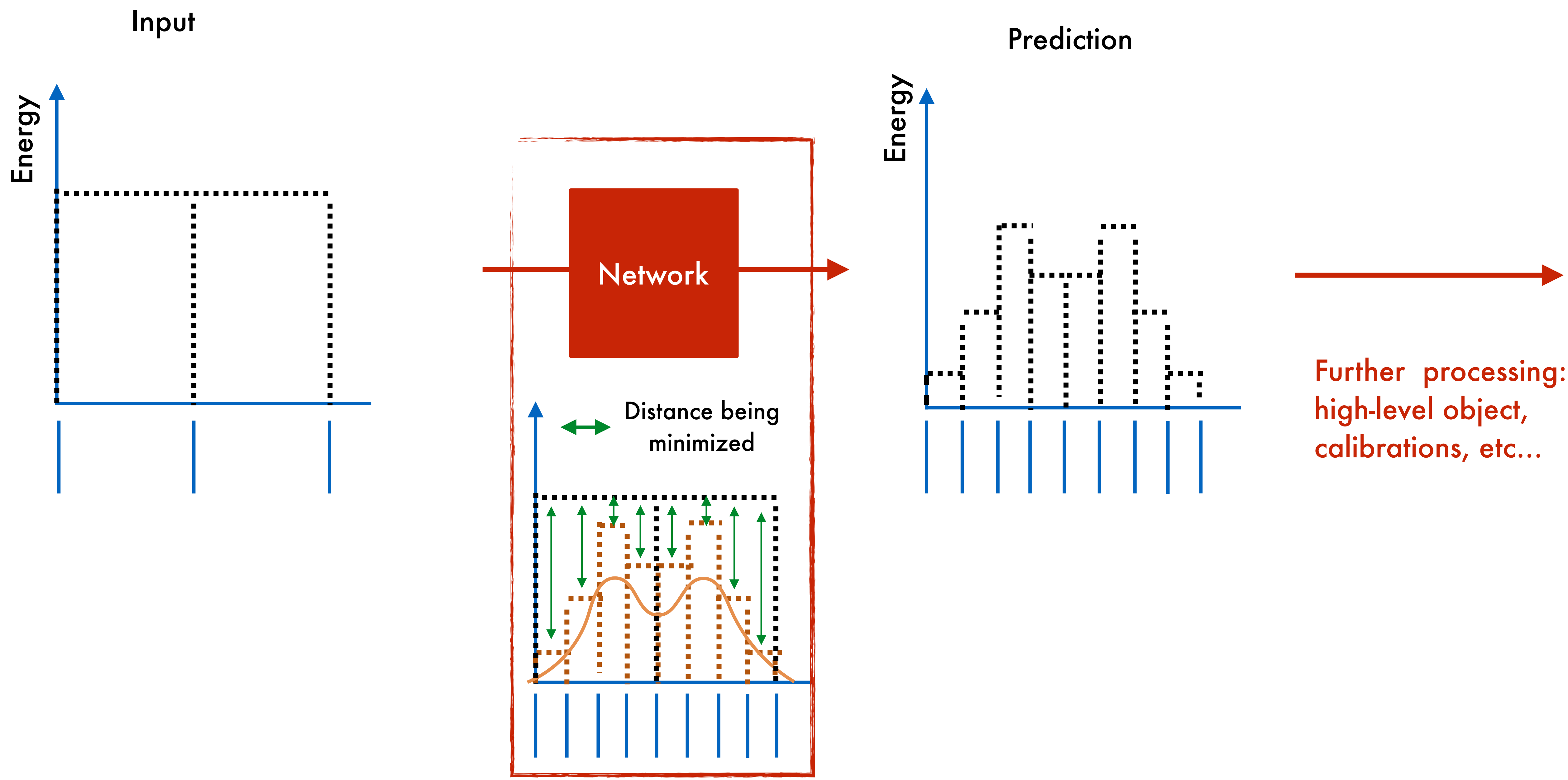
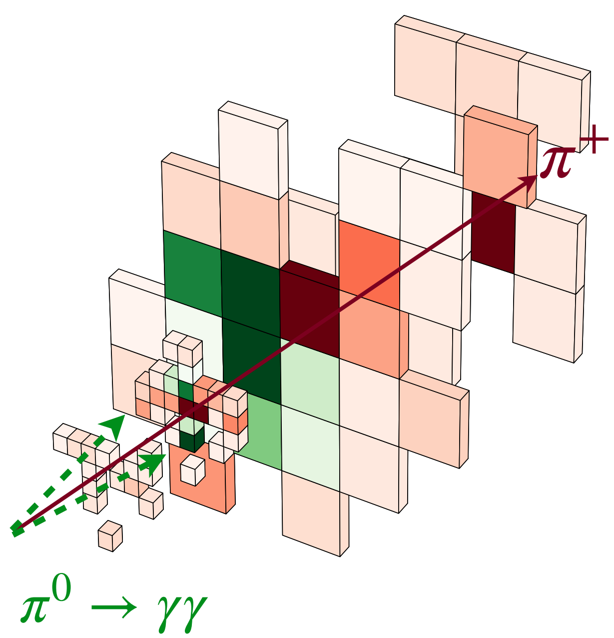
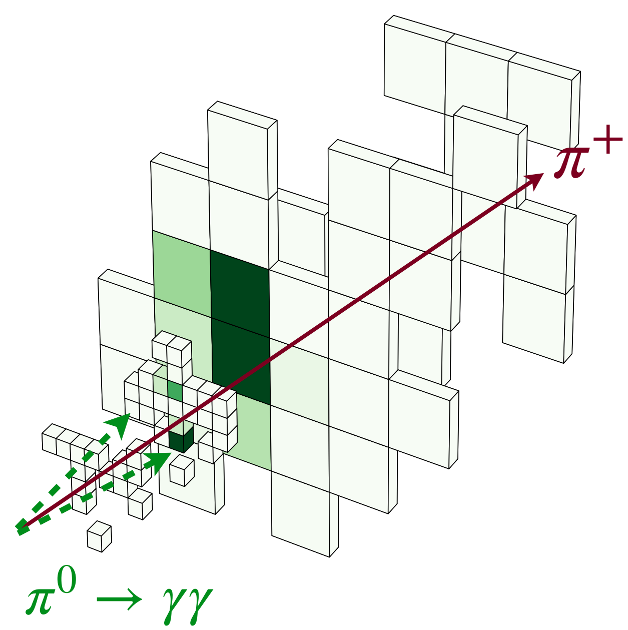
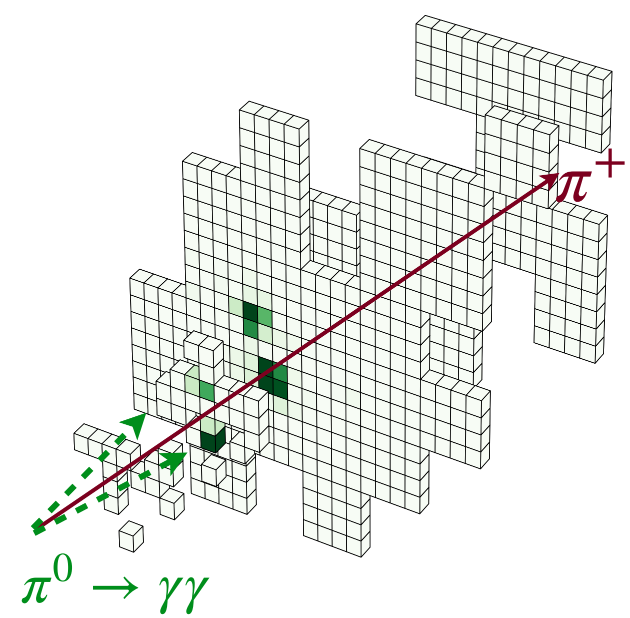


Experimental setup

- Going back to 3D in a pi+ and pi0 environment - similar geometry to what presented previously







Low-Resolution

charged + neutral+noise

Low-Resolution - neutral only

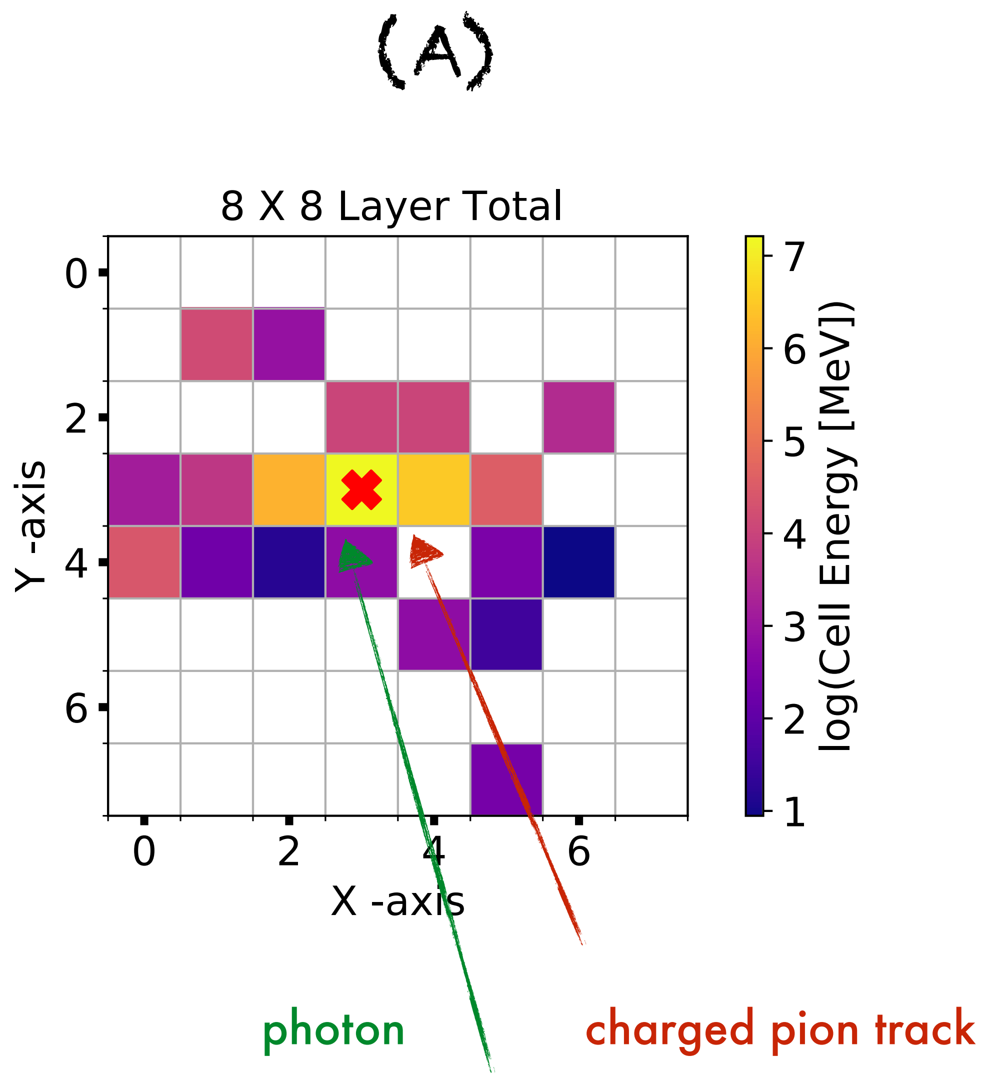
second layer: 8x8

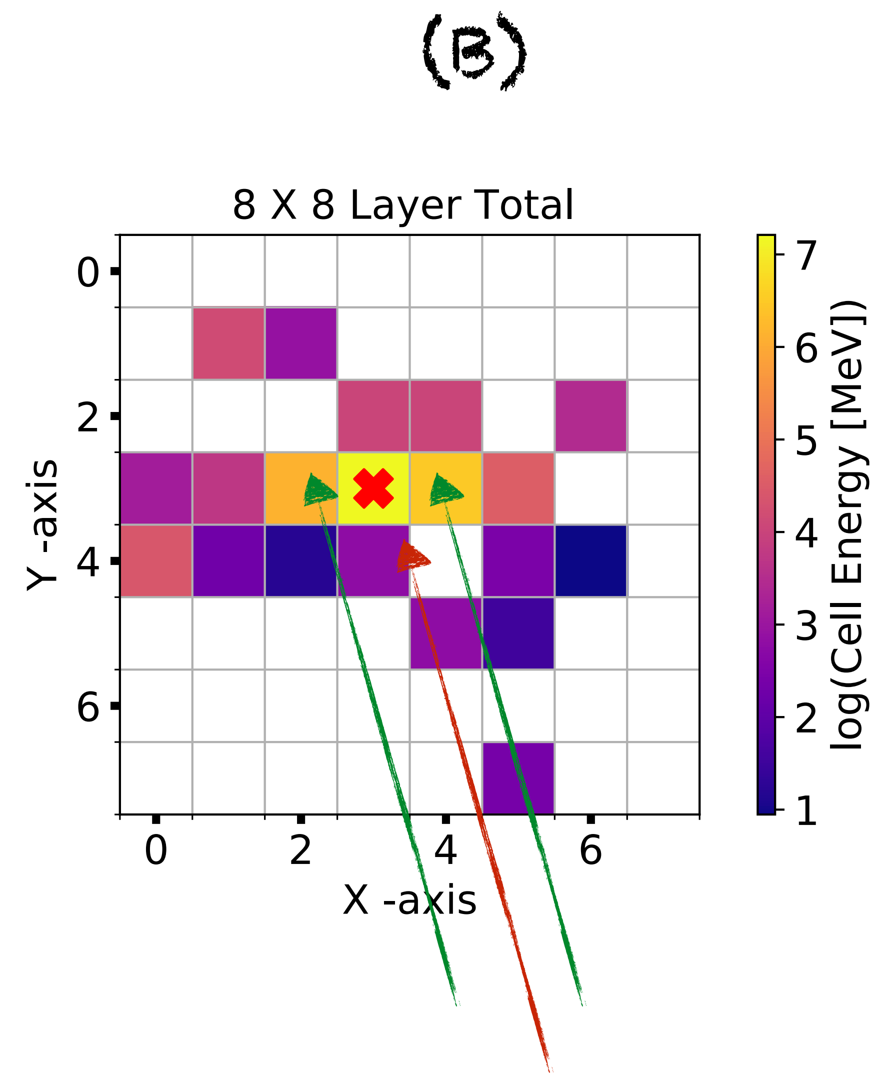
High-Resolution - neutral only

second layer: 32x32

A quiz

- Which one is correct?





The model

Common network structure for energy overlap removal task

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Convnet,
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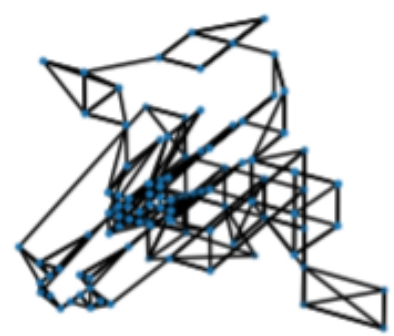
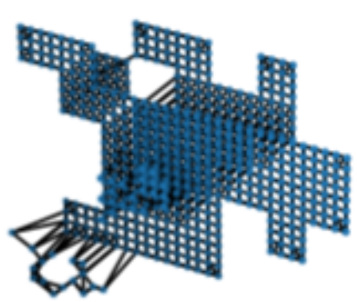
Graph network
Deepsets

$$L_{event}^{\text{super-res}} = \frac{1}{E_{tot}} \sum_{c} E_c \sum_{s=0}^{us^2} (f_t^{sc} - f_d^{sc})^2$$

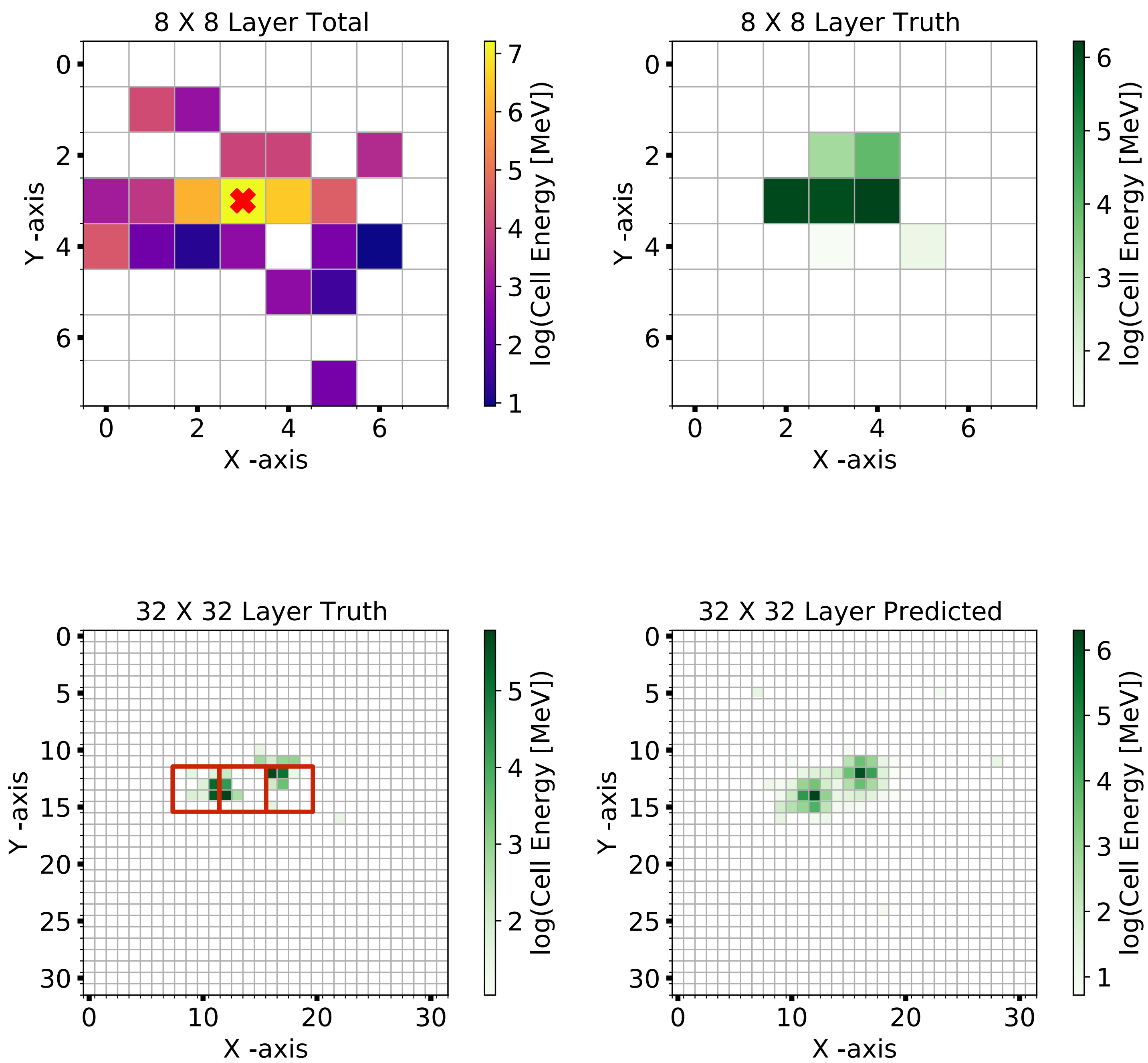




we minimize each HR cell (s) in a given standard cell (c)

Results - quiz answer

- Super-resolution at work



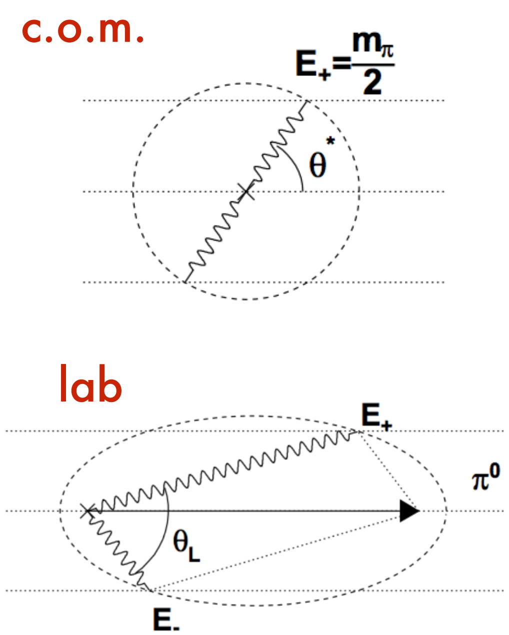
Results 2

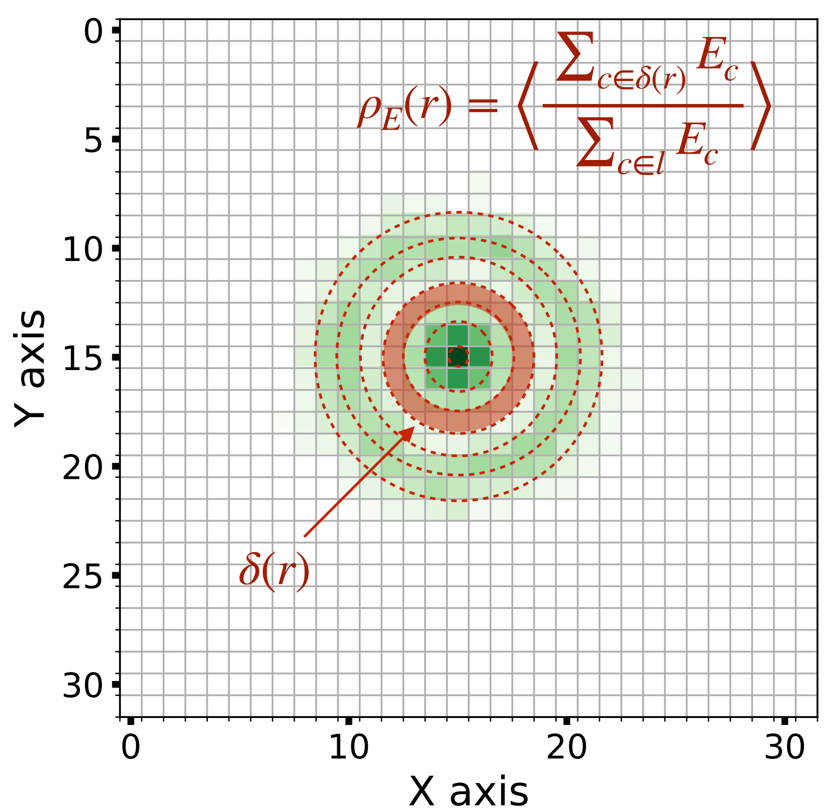
- Can we resolve the two photons from the decaying pi0?

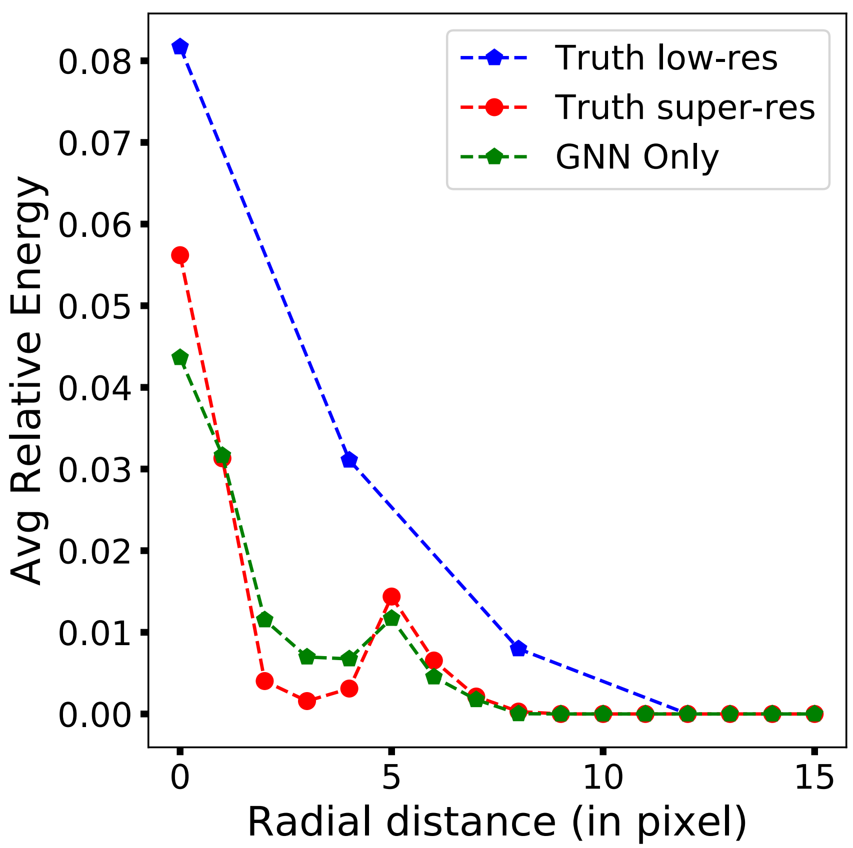
- Check by centering the image for each event around the most energetic cell and averaging for all the events

- For a fixed momentum of the p0 (and fiducial cuts to ask the two photons within detector acceptance), a circle representing the secondary photon is expected

truth average image

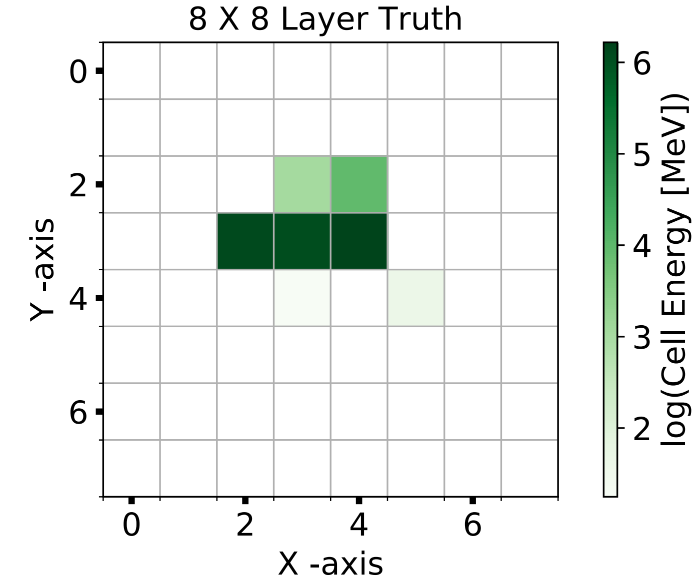


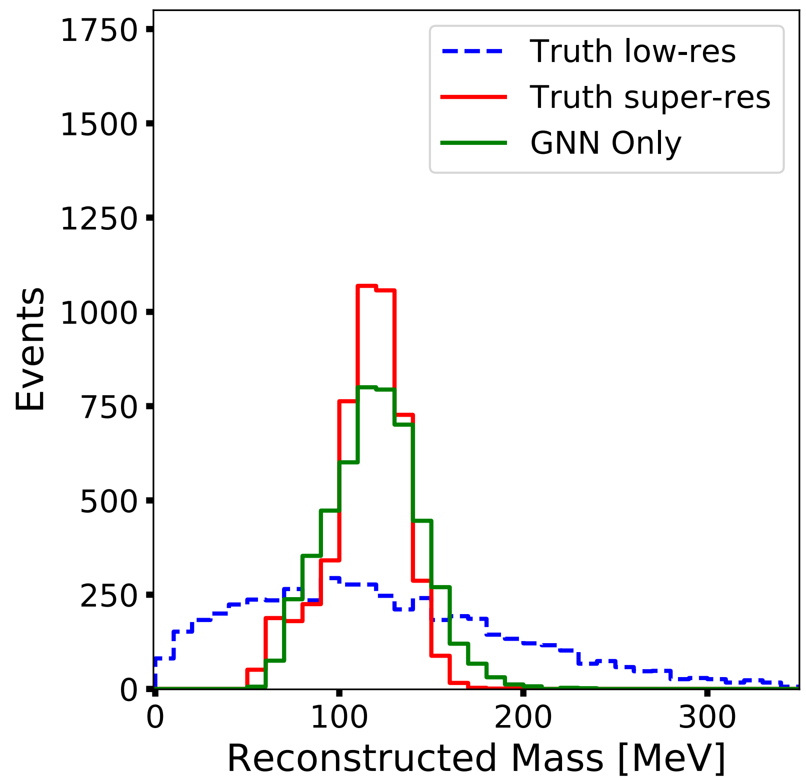




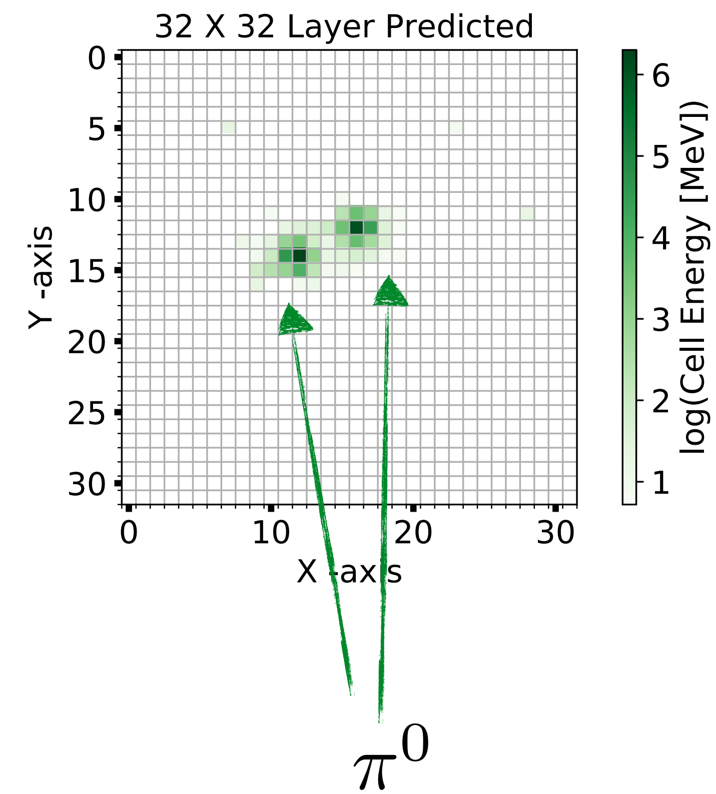
Results 3

- Can we reconstruct the mass of the pi0?
- K-mean clustering algorithm min n-cluster = 2 was used to cluster HR image
- Four-momenta of the photons computed from the production location of pi0
- SF applied to “calibrate” the truth as well as predicted to the pi0 mass



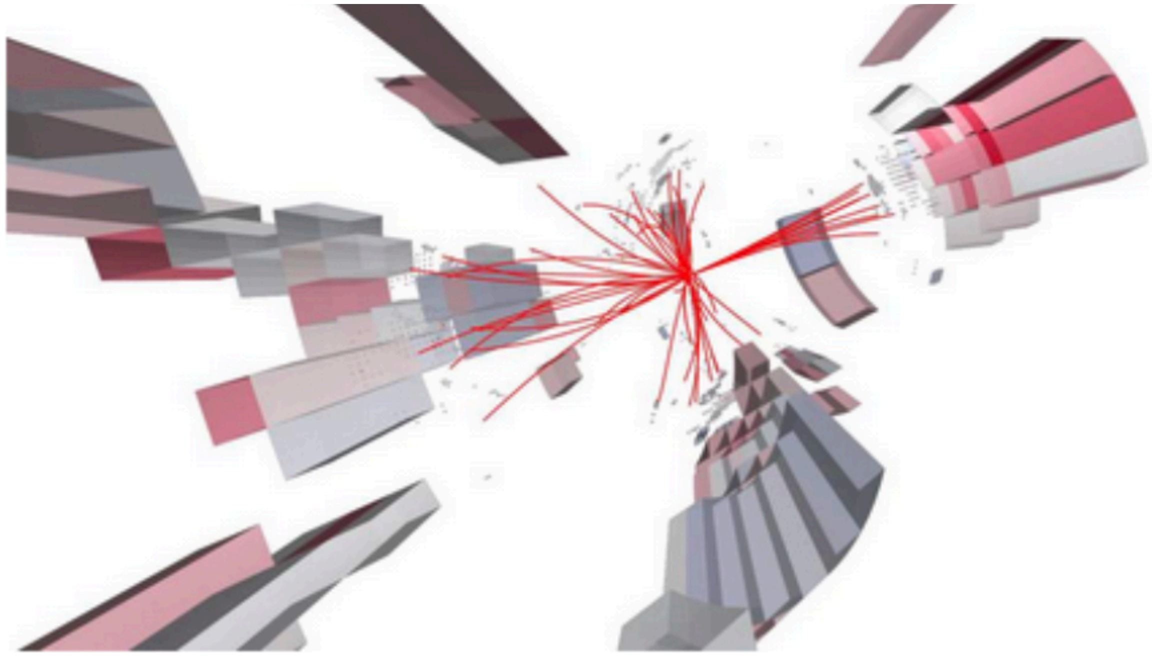


nice high-resolution peak



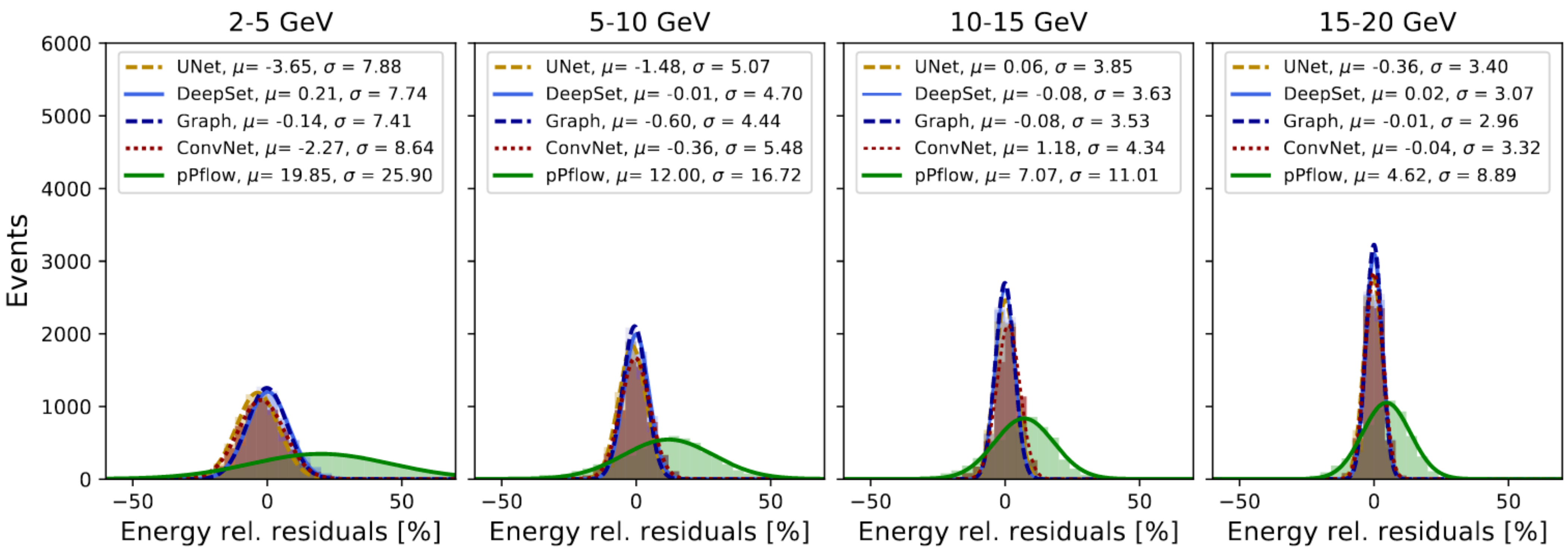
Conclusions

- Simple toy model developed
- Performance evaluated on a simplistic pi0/pi+ overlap
- Results show promising advantages: improving energy and spatial resolution (especially sup-res) of measuring systems
- Could be an Interesting "intermediate" steps toward construction of more complete Pflow algorithms



Results

(1) Energy in topo clusters (also per cell in backup)



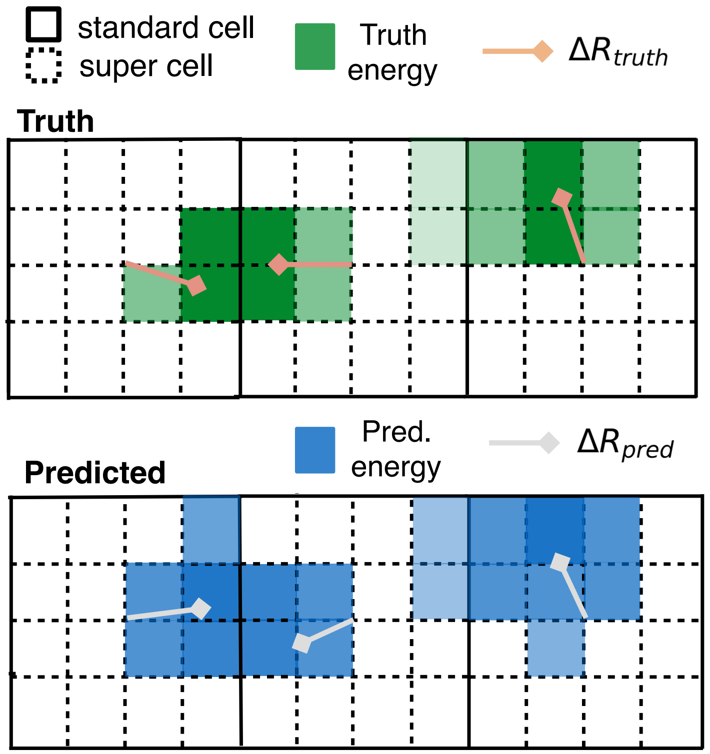
$$(E_{predicted} - E_{Neutral})/(E_{Neutral})$$

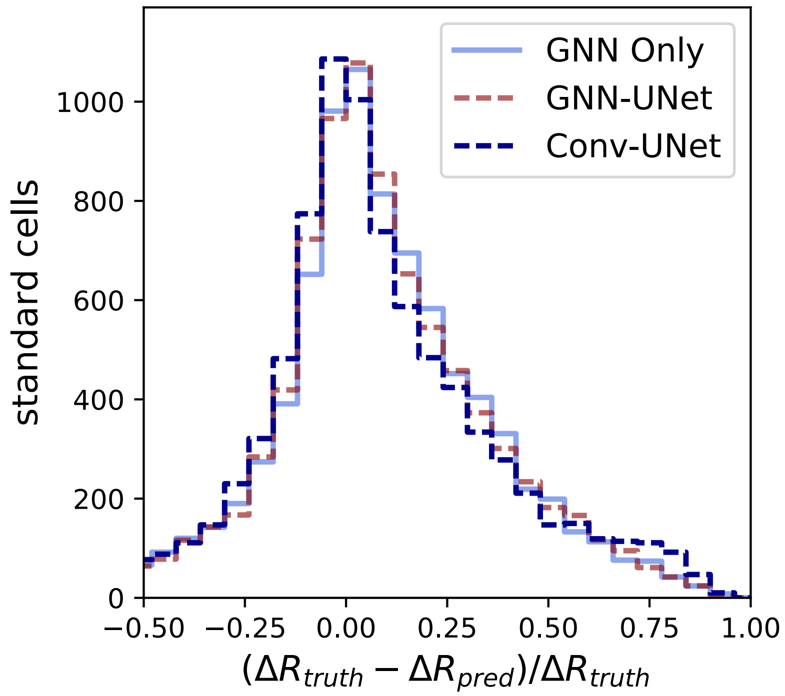
Less bias, much improved sigma for all models

Results 2

- Expect correlation between the radial distance of each standard cell

$$\Delta R = \sum_{sc}^{up^2} E_{sc}\sqrt{x_{sc}^2 + y_{sc}^2} / \sum_{sc}^{up^2} E_{sc}$$

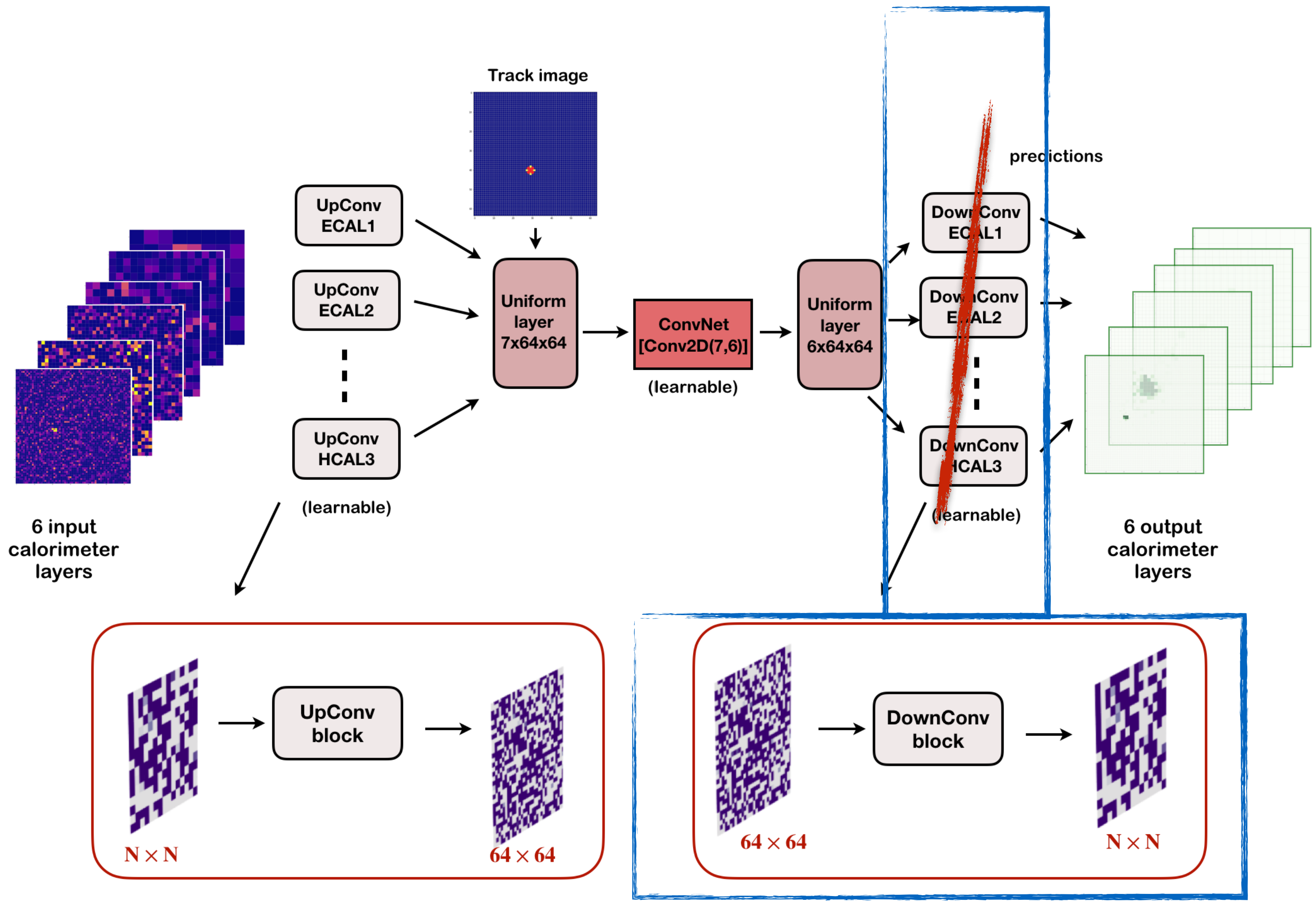




Learning high-resolution patterns

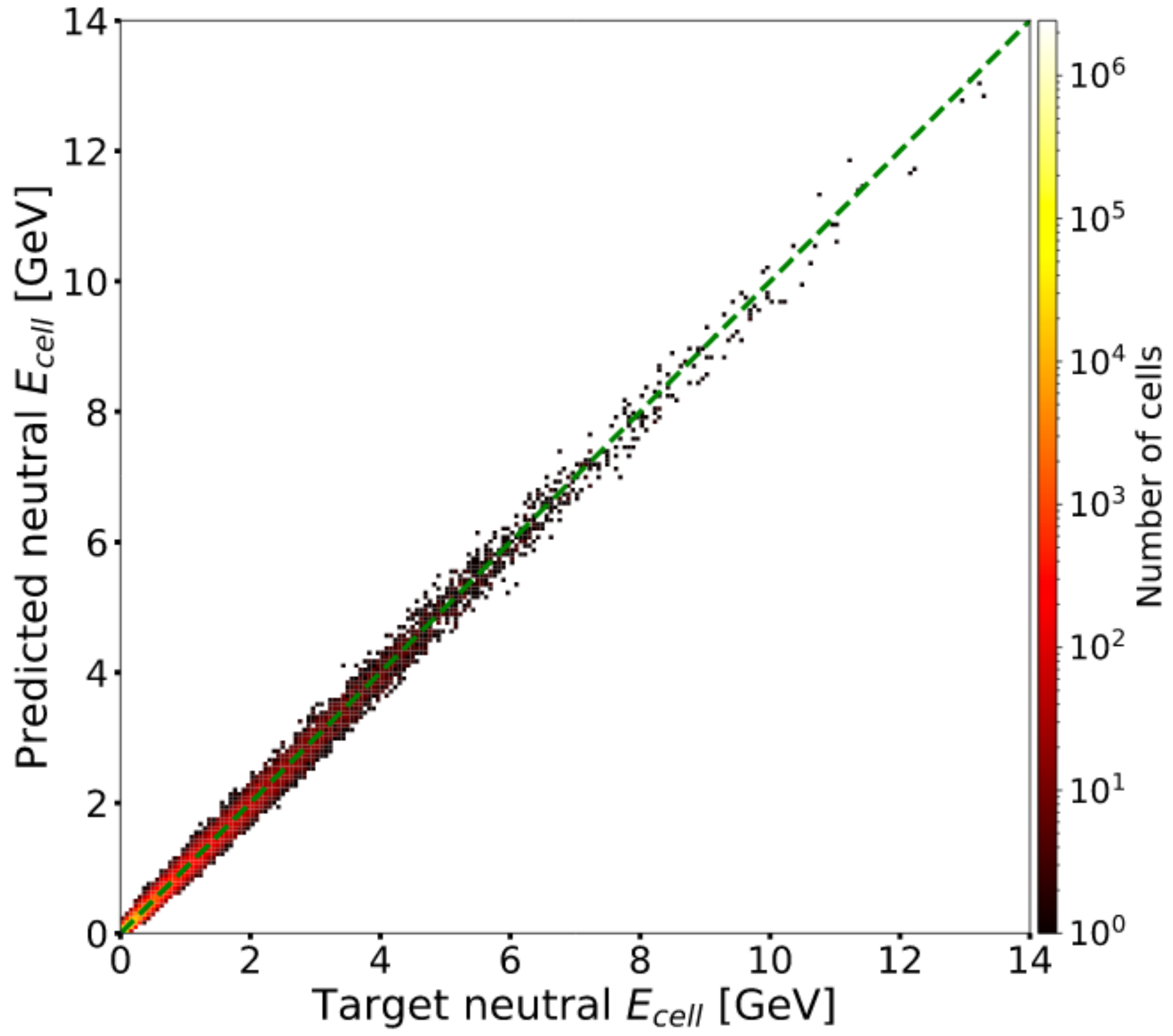
Asymmetryc tails, the NN tend to smooth a bit the output image

The model



Track image
UpConv ECAL1
UpConv ECAL2
UpConv HCAL3
(learnable)
Uniform layer 7x64x64
ConvNet [Conv2D(7,6)]
(learnable)
Uniform layer 6x64x64
predictions
DownConv ECAL1
DownConv ECAL2
DownConv HCAL3
(learnable)
6 input calorimeter layers
6 output calorimeter layers
N × N
UpConv block
64 × 64
64 × 64
DownConv block
N × N

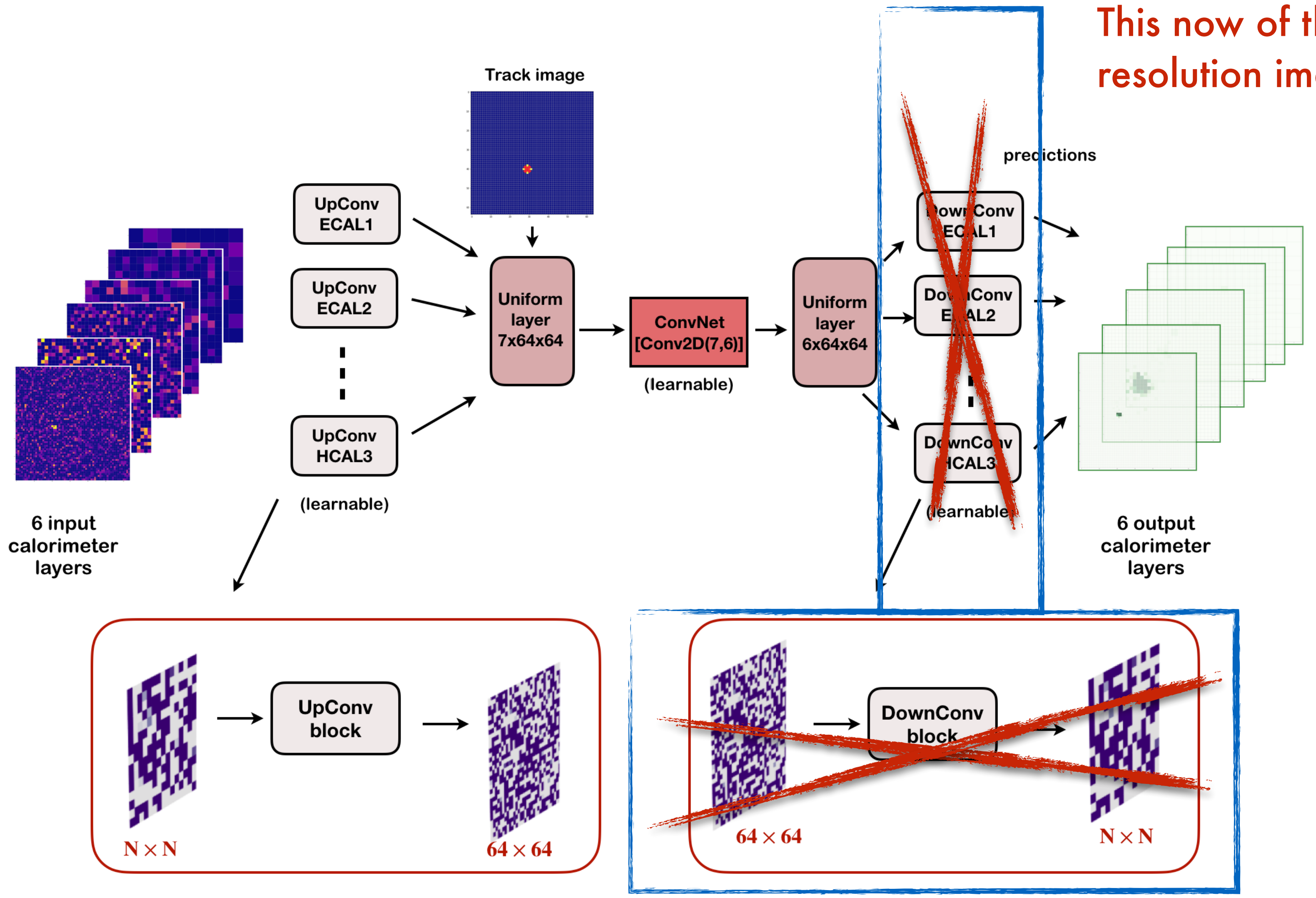
The model



Predicted neutral E_{cell} [GeV]
Target neutral E_{cell} [GeV]
Number of cells
0
2
4
6
8
10
12
14
10^0
10^1
10^2
10^3
10^4
10^5
10^6

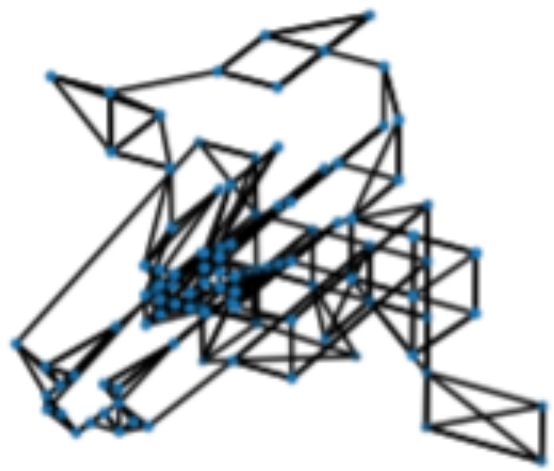
The model

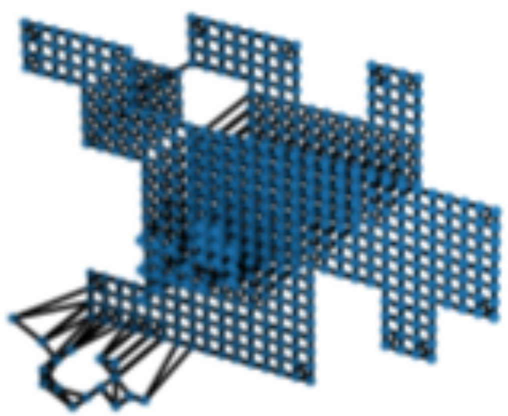
- For CNN, the same model with minor modifications can be used
- SImilarly for the graphs, even if not shown in an image



This now of this images as High-resolution images

Graph model



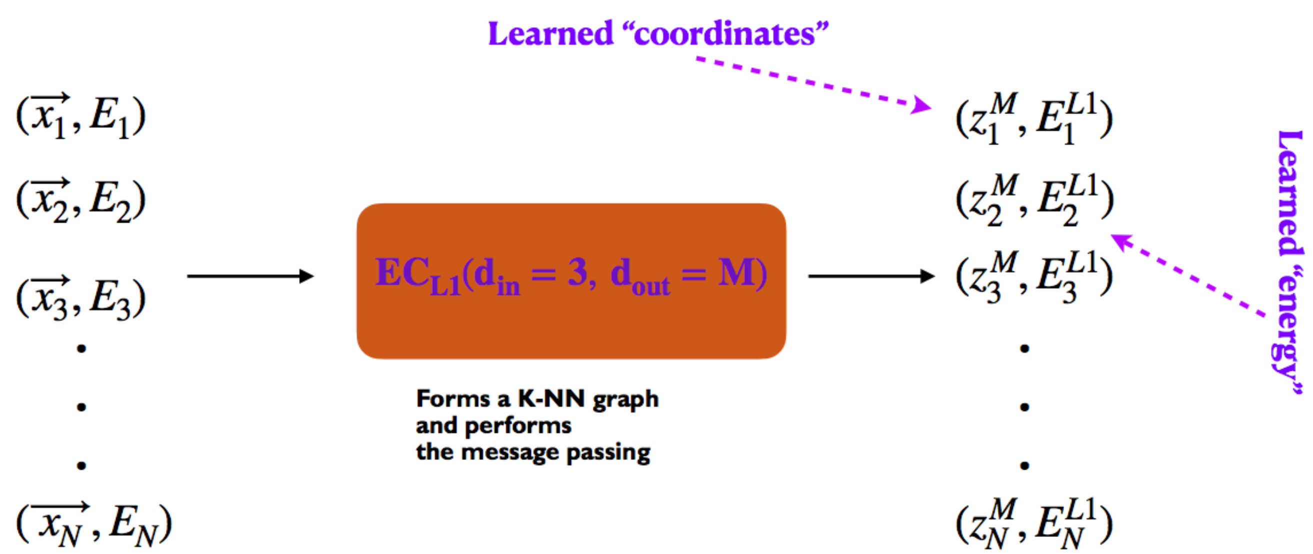


Graph model

https://arxiv.org/pdf/1801.07829.pdf

$$(x')_i^{l+1} = max_{j \in \mathcal{N}(i)}\ \Theta_x(x_j^l - x_i^l) + \Phi_x(x_i^l)$$

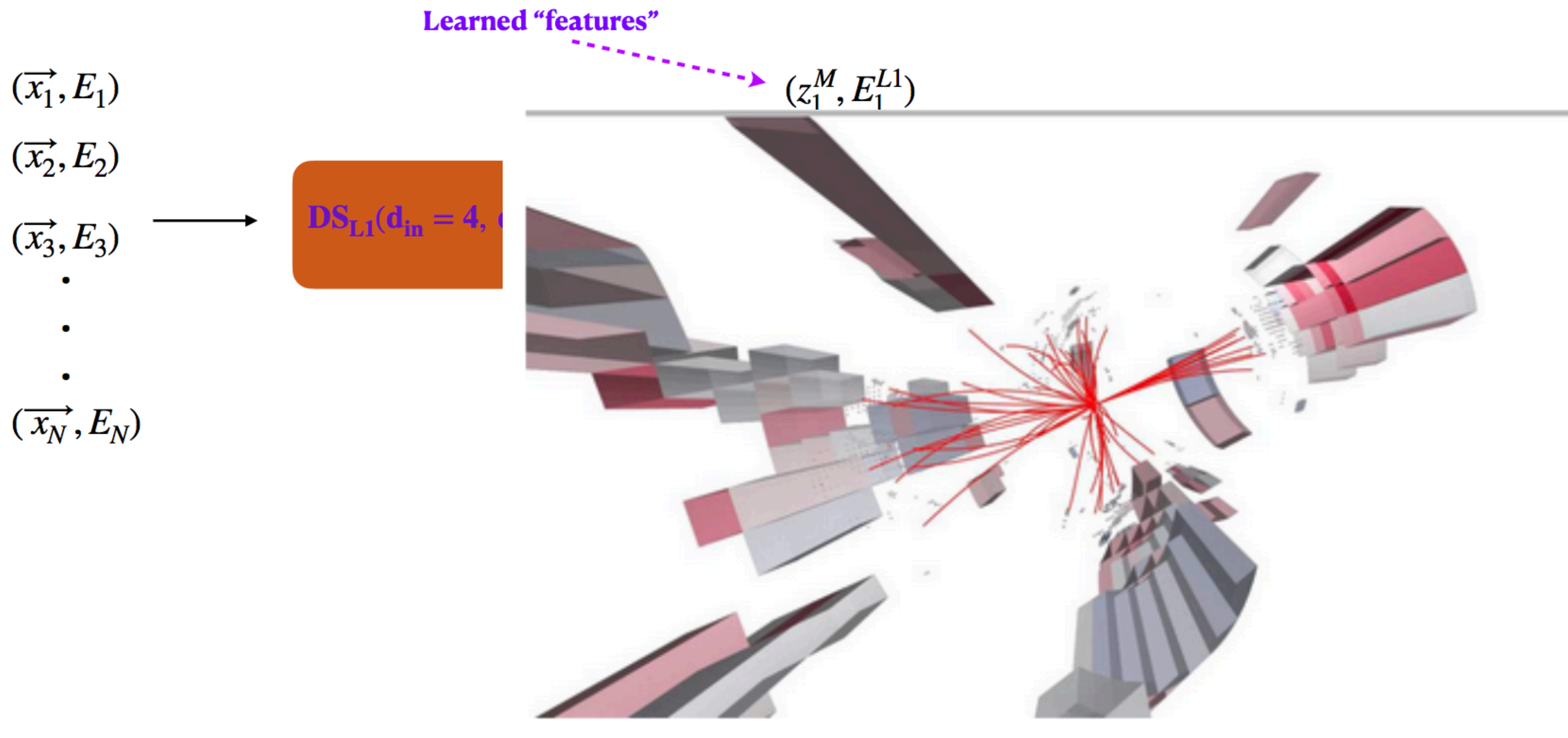
$$(e')_i^{l+1} = mean_{j \in \mathcal{N}(i)}\ \Theta_e(e_j^l - e_i^l) + \Phi_e(e_i^l)$$



Deep sets

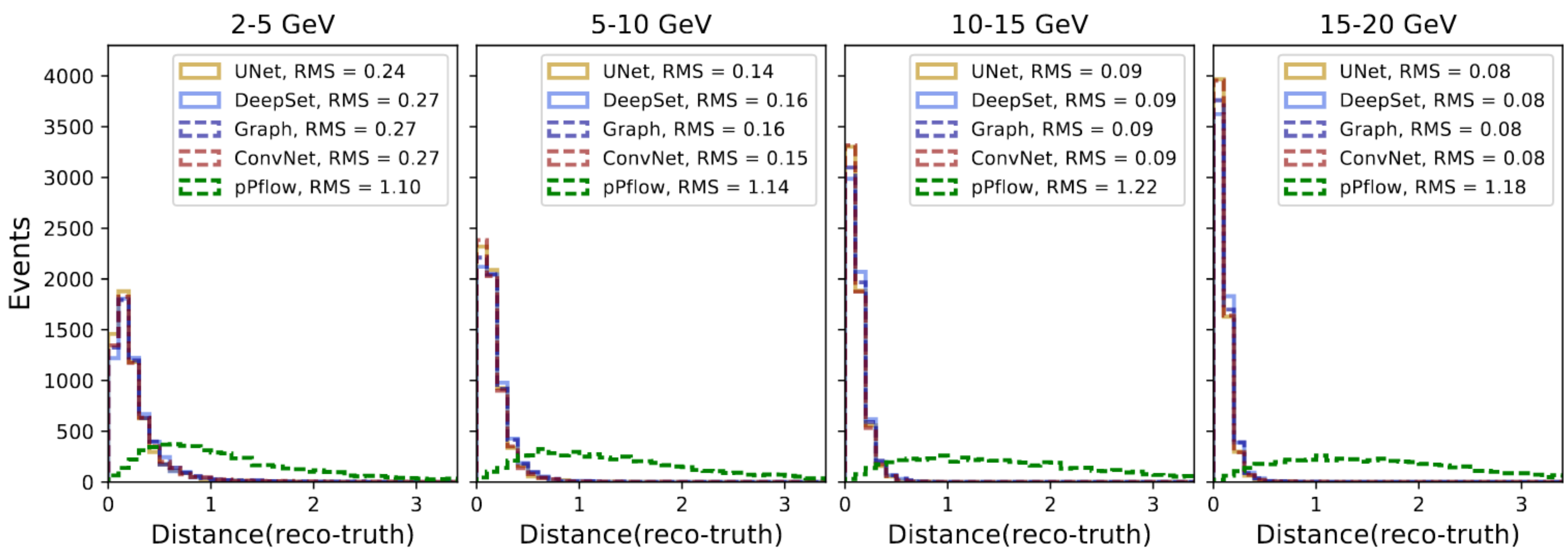
https://arxiv.org/pdf/1703.06114.pdf

$$\mathcal{O}\left(\{p_1, \ldots, p_n\}\right) = F\left(\sum_{i=1}^{n} \Phi\left(p_i\right)\right),$$



Results

(2) Position



distance in number of cells for ECAL layer 2

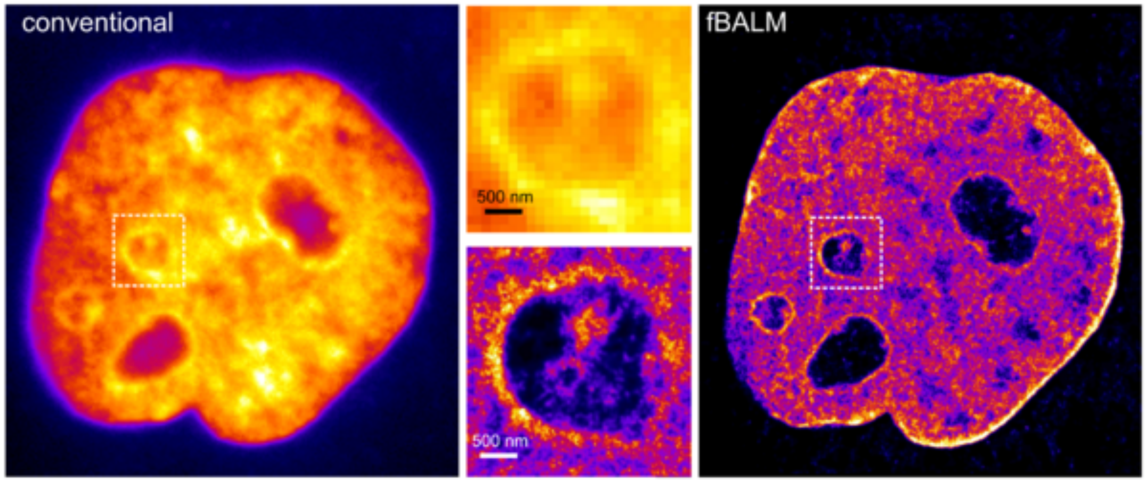
Introduction to Super-resolution

- Lorenzo's master thesis!

- Super-resolution is typically referred to as algorithms used to enhance the resolution of the measuring device

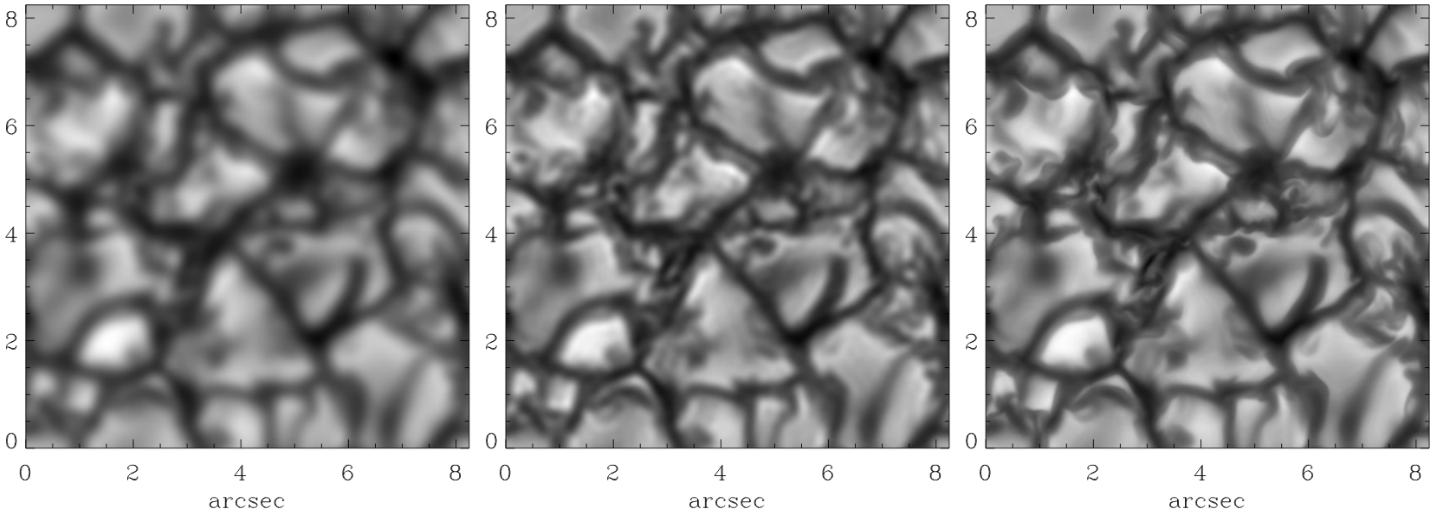
- Outside HEP, it has a large field of application (not a complete list):

- Super-Resolution microscopy [Ref.]
  - Molecule -



2014 chemestry nobel: "for the development of super-resolved fluorescence microscopy"

- Astronomy [Ref.]
  - solar granulation -



and industrial application....

The Geant model

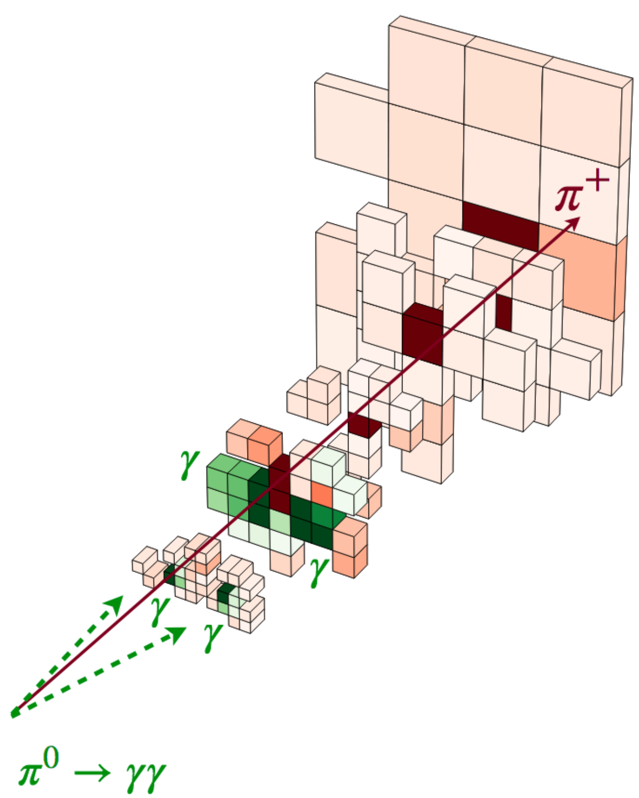
Detector	Absorber	Scintillator	Subdetector (Legth)
ECAL	Lead **1.2**	Liquid Argon **4.5**	ECAL1 (**3** $\mathbf{X_0}$) ECAL2 (**16** $\mathbf{X_0}$) ECAL3 (**6** $\mathbf{X_0}$)
HCAL	Iron **4.7**	Plastic organic **1.0**	HCAL1 (**1.5** λ_{int}) HCAL2 (**4.1** λ_{int}) HCAL3 (**1.8** λ_{int})

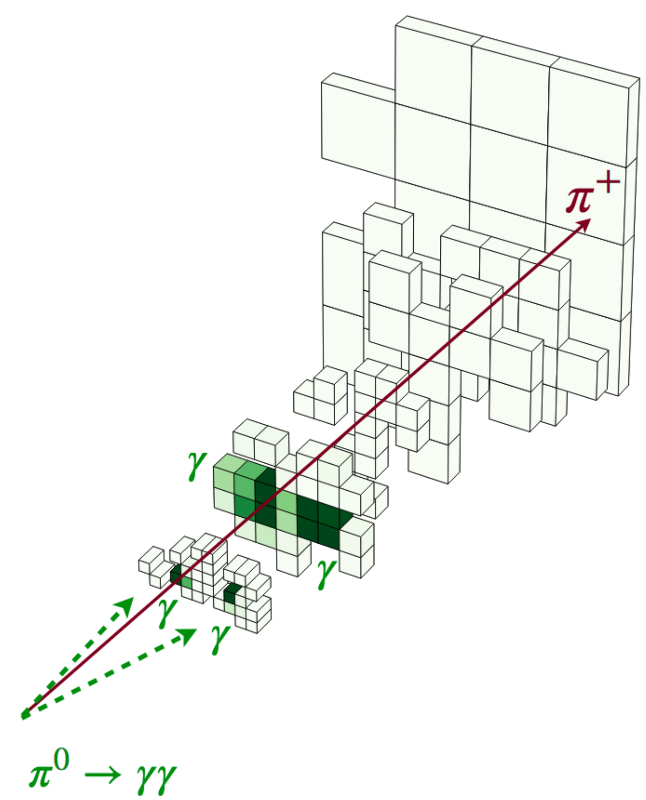
$\mathbf{X_0 = 3.9\ cm}$

$\lambda_{\text{int}} = \mathbf{17.4\ cm}$

Detector Layer	Res. (HG)	Res. (LG)	Noise [MeV] (cf)
ECAL1	64×64	32×32	13 (4)
ECAL2	32×32	8×8	34 (16)
ECAL3	32×32	8×8	17 (16)
HCAL1	16×16	8×8	14 (4)
HCAL2	16×16	8×8	8 (4)
HCAL3	8×8	8×8	14 (1)

random noise added per cell with gaussian shapes





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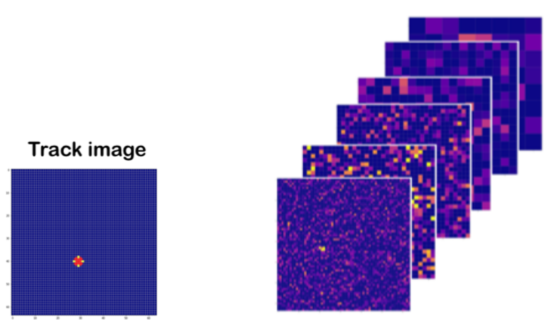
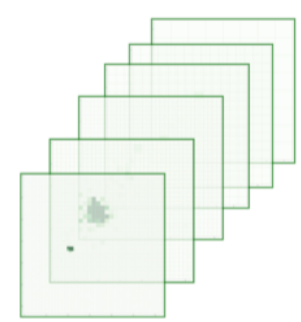


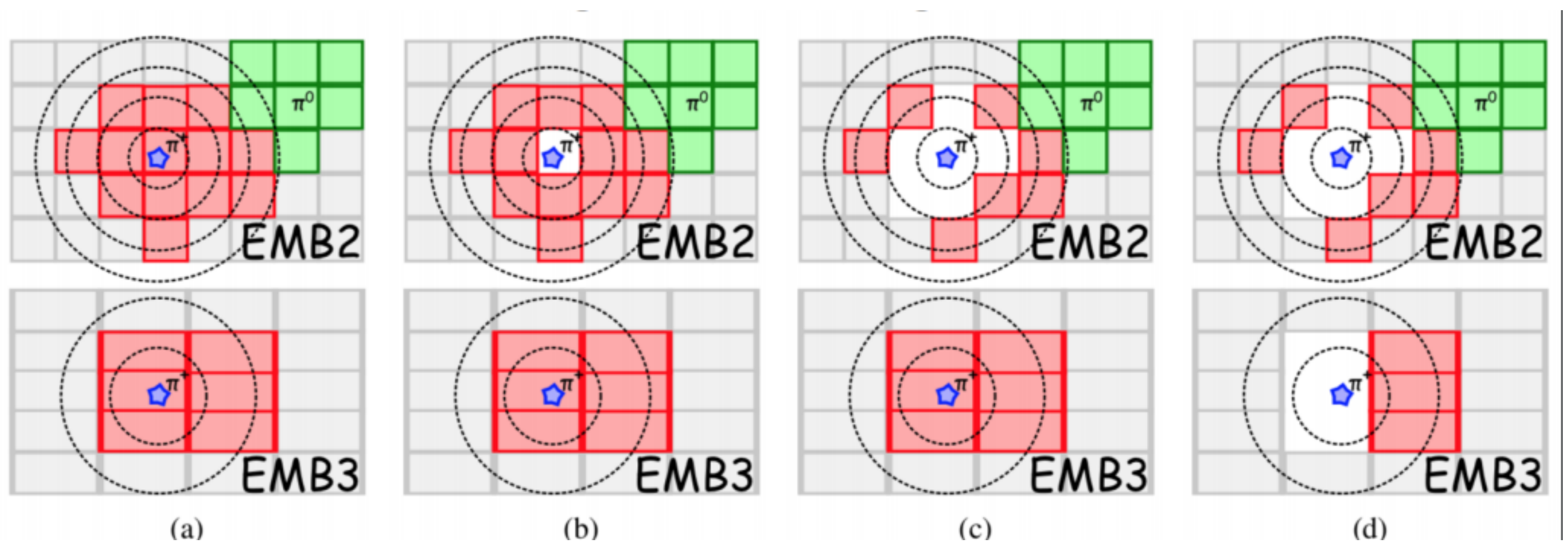
6 input calorimeter layers



6 output calorimeter layers

Atlas Pflow

- Particle flow algorithm (ATLAS like):



- … what if the two pion energies overlap? Parametric form not really suited to cope with overlapping scenarios