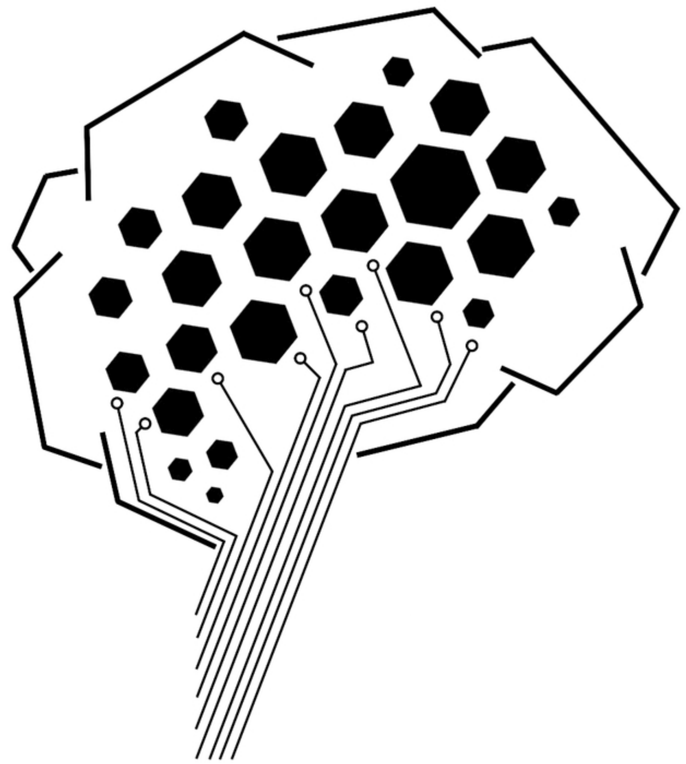


X-ray Polarimetry with Machine Learning:

A Hybrid Approach for Tracks Reconstruction in Gas Pixel Detectors

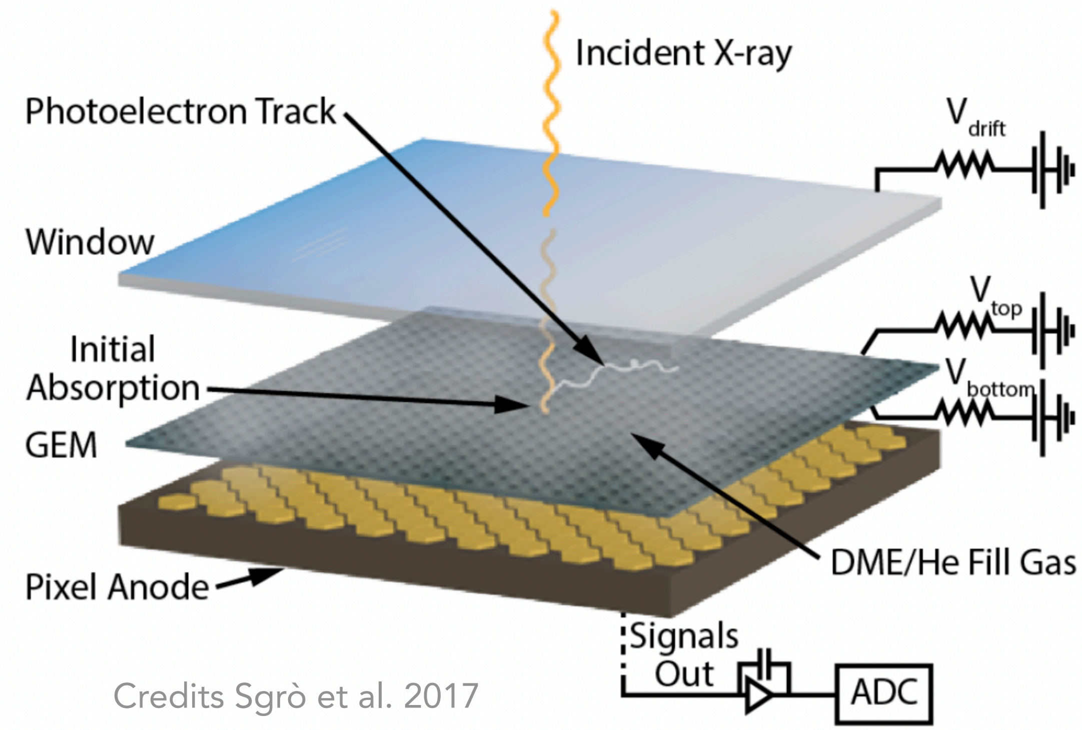
Nicolò Cibrario on behalf of the team
Università degli Studi di Torino
nicolo.cibrario@unito.it

Gas Pixel Detector

Detector onboard of the **Imaging X-ray Polarimetry Explorer (IXPE)**

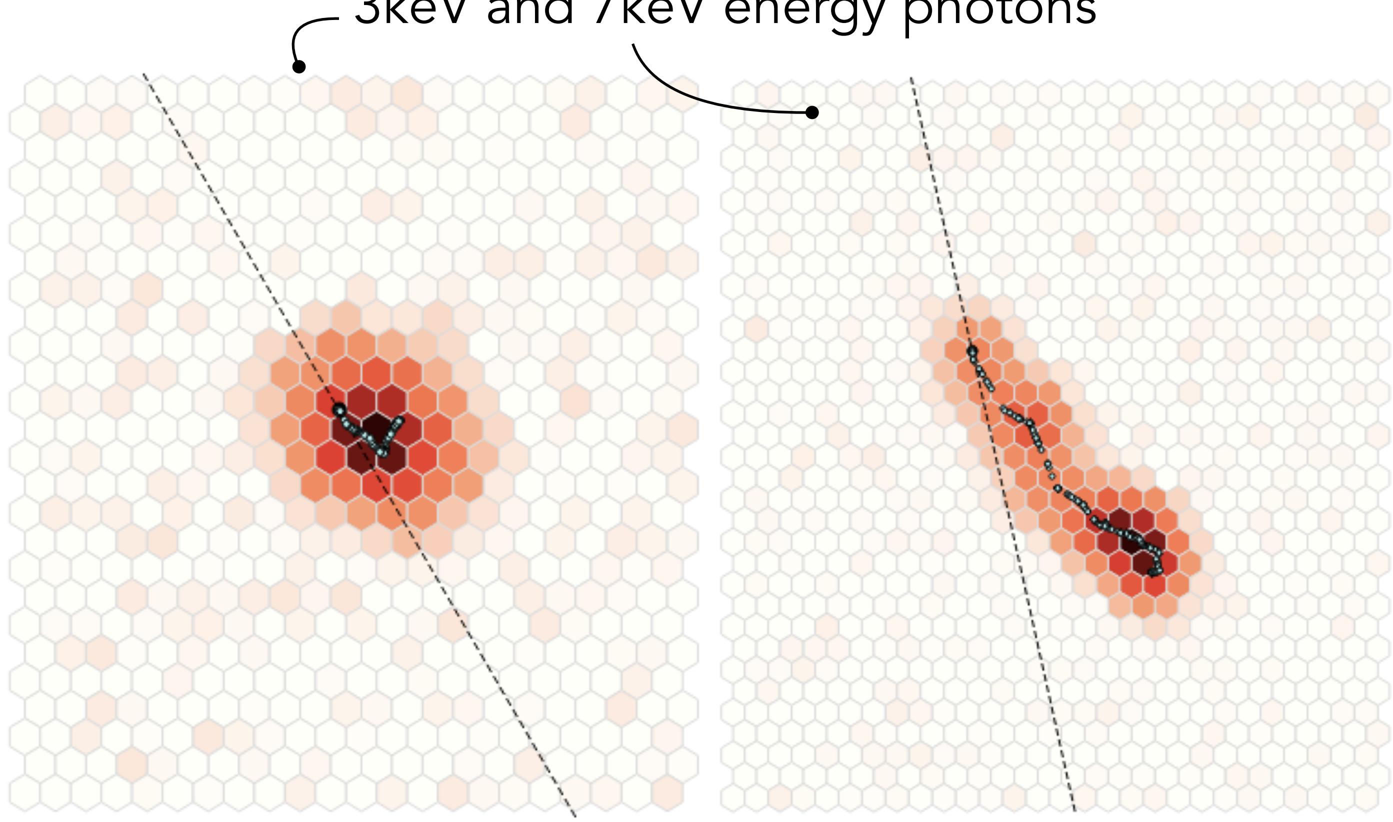
Tested on **CubeSat PolarLight** and will be on board of the **enhanced X-ray Timing and Polarimetry mission (eXTP)**

GPD energy range:
2-8 keV



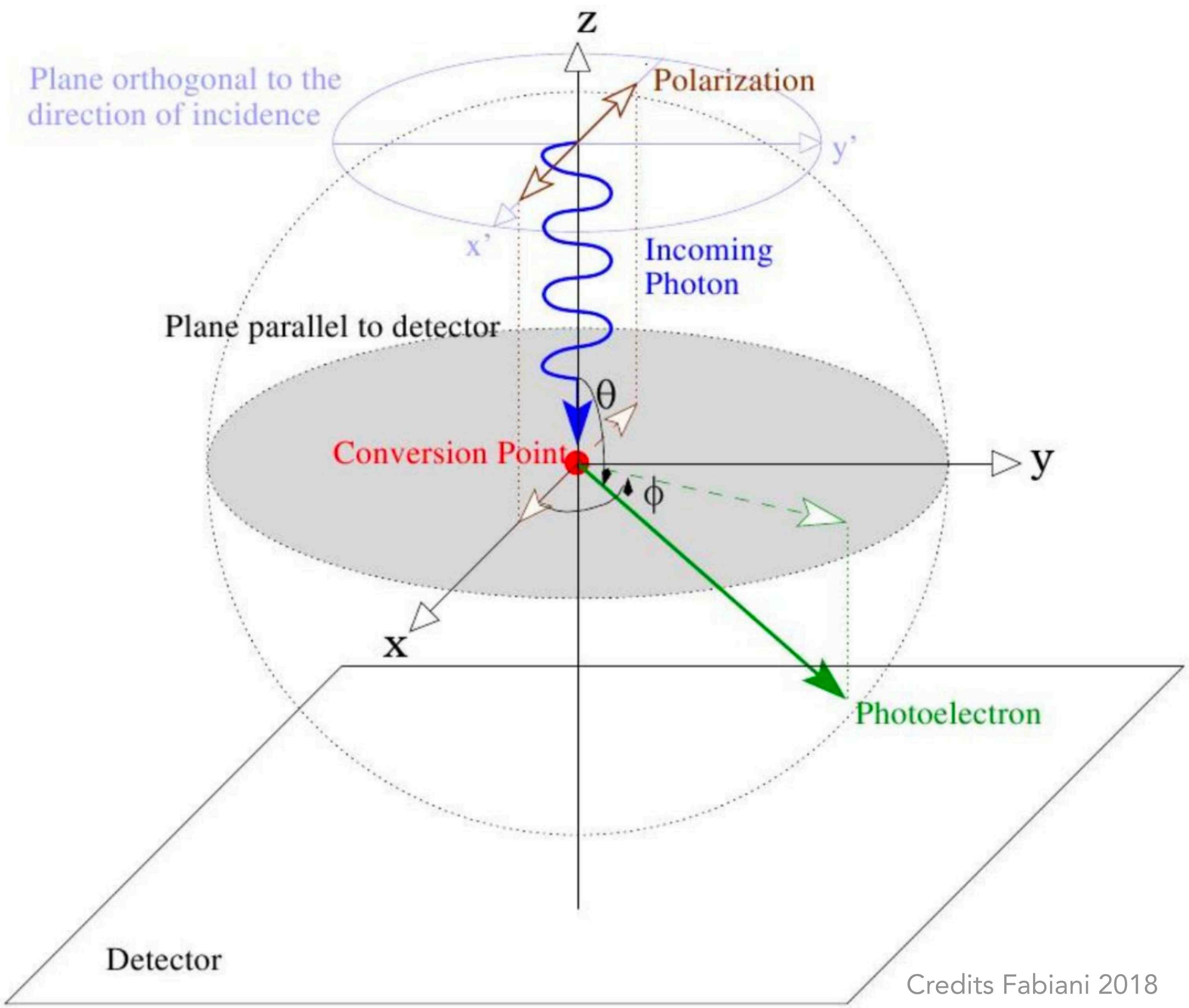
Credits Sgrò et al. 2017

Photo-electron tracks produced by 3keV and 7keV energy photons



From tracks to polarization

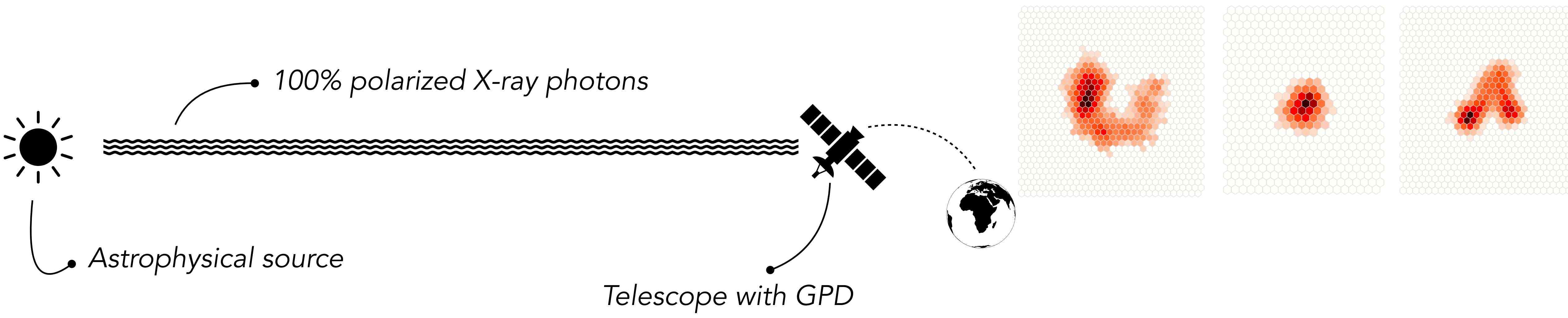
$$\frac{d\sigma_c^k}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta \cos^2\phi}{(1+\beta\cos\theta)^4}$$

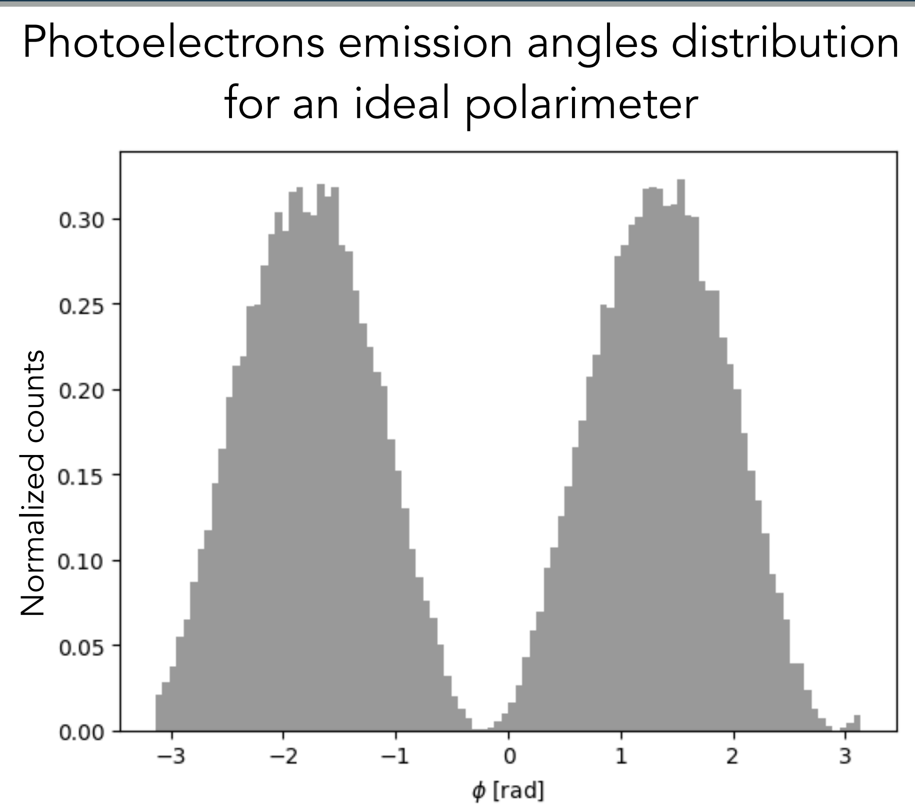


Credits Fabiani 2018

From tracks to polarization

$$\frac{d\sigma_c^k}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta \cos^2\phi}{(1+\beta\cos\theta)^4}$$

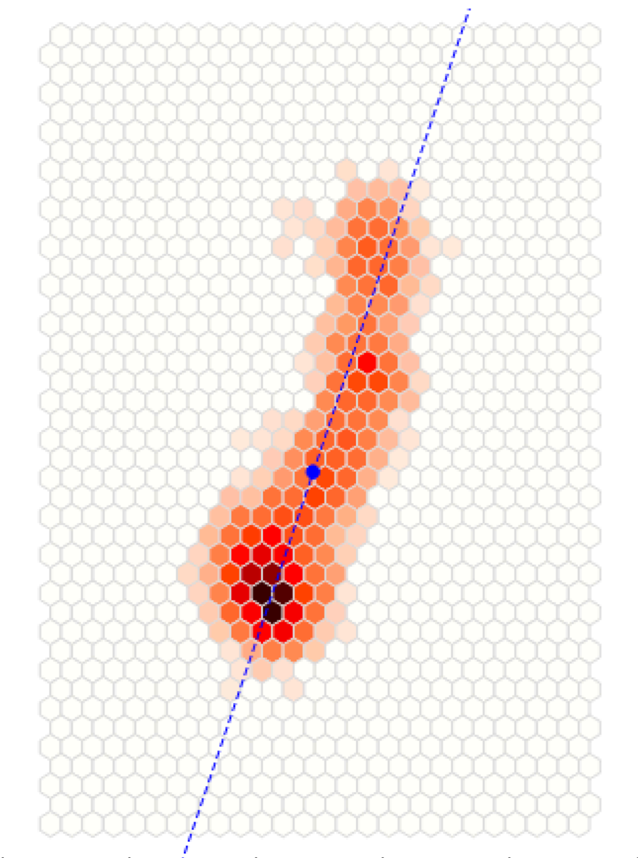




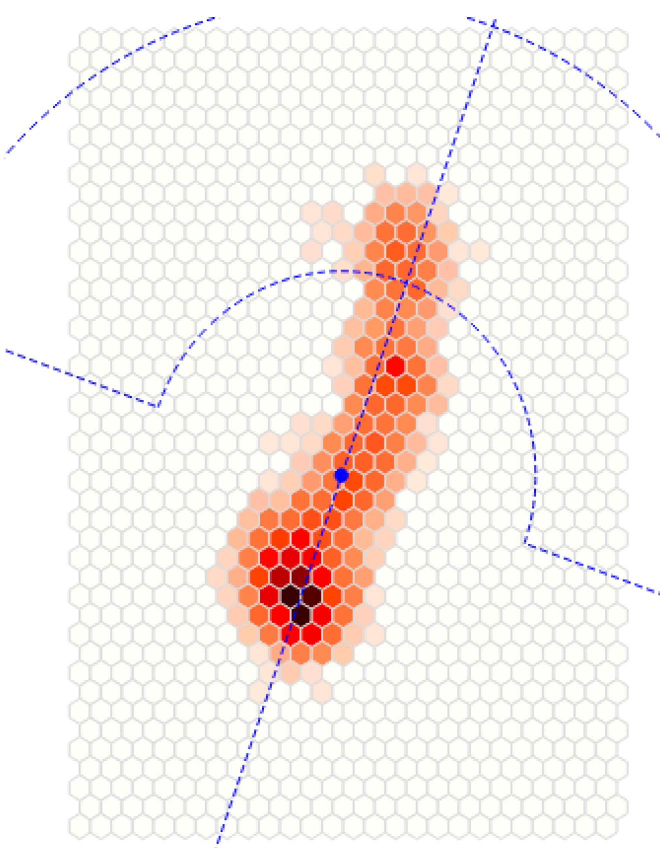
Track reconstruction

Algorithm developed by IXPE collaboration: **Moment Analysis**
Analytic reconstruction of the track parameters

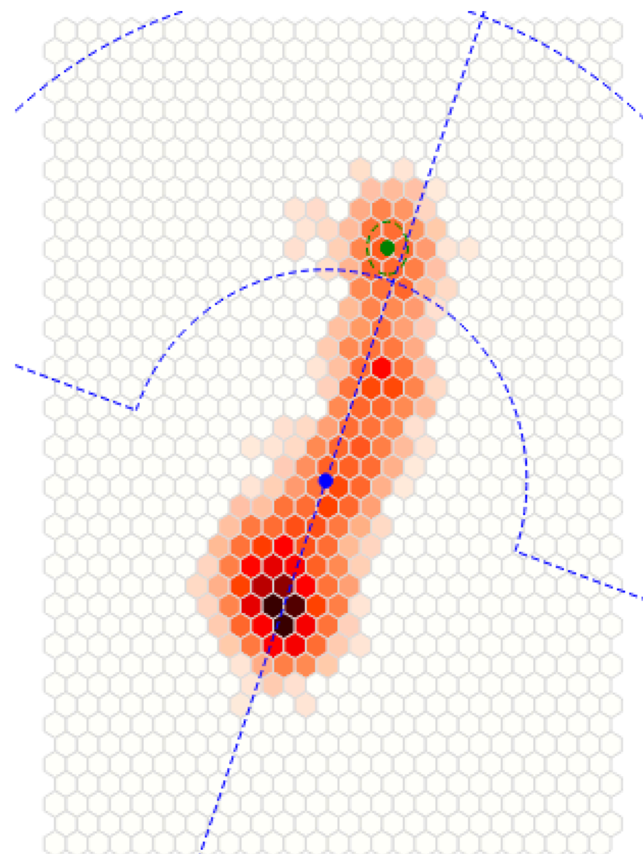
1. Barycenter and second moment of the charge distribution



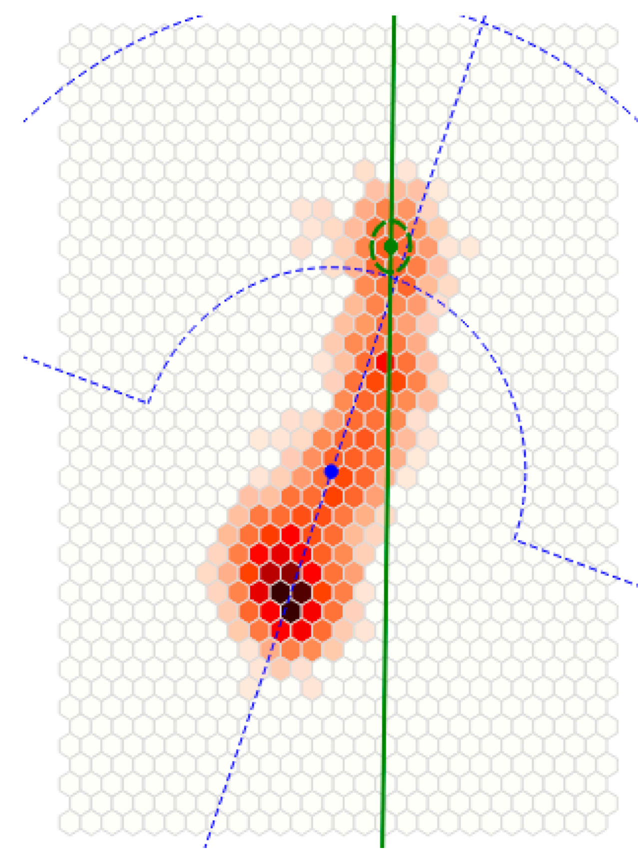
2. Identification of the initial part of the track



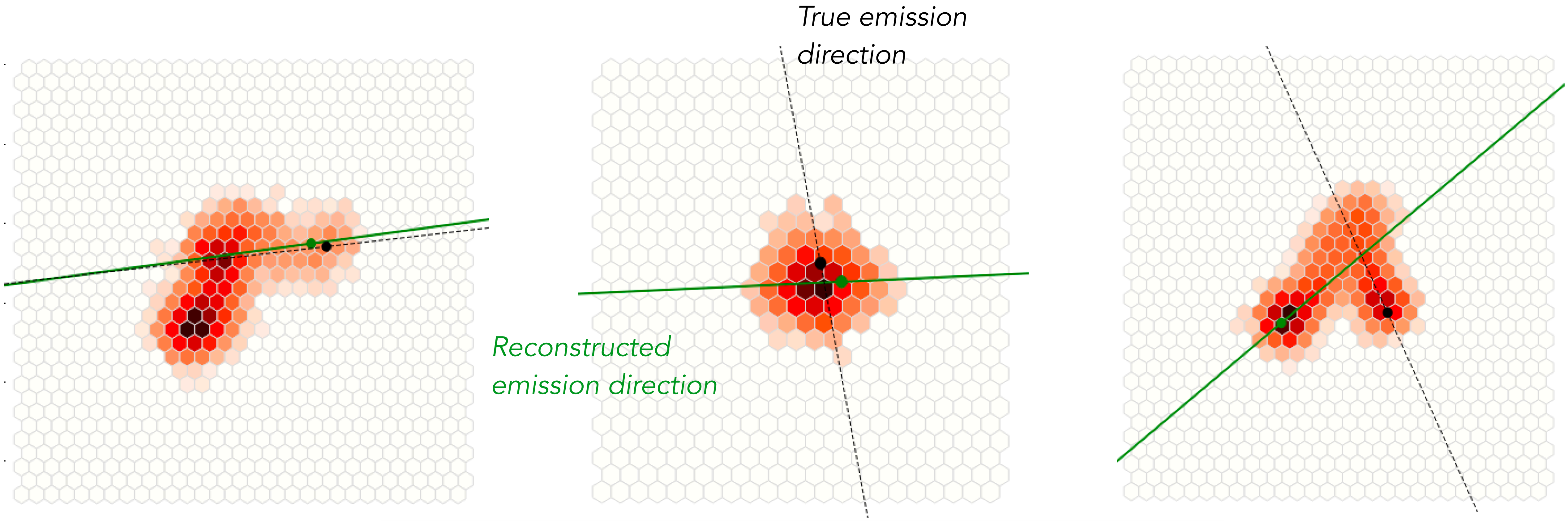
3. Reconstruction of the impact point



4. Reconstruction of the emission direction

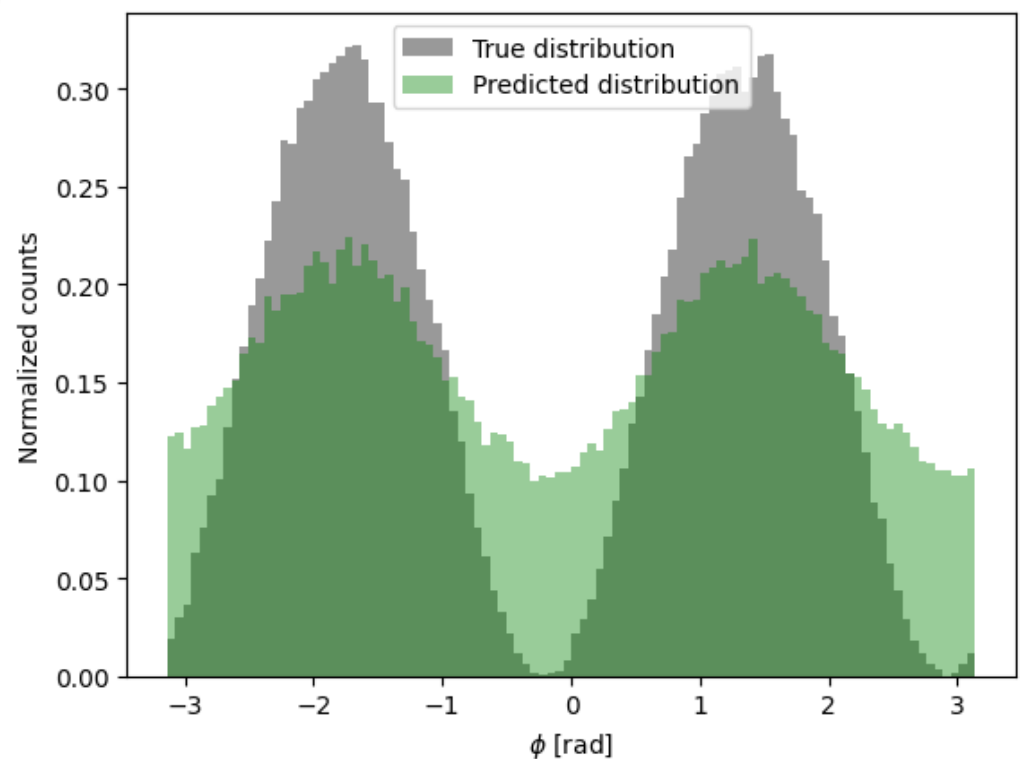


Examples

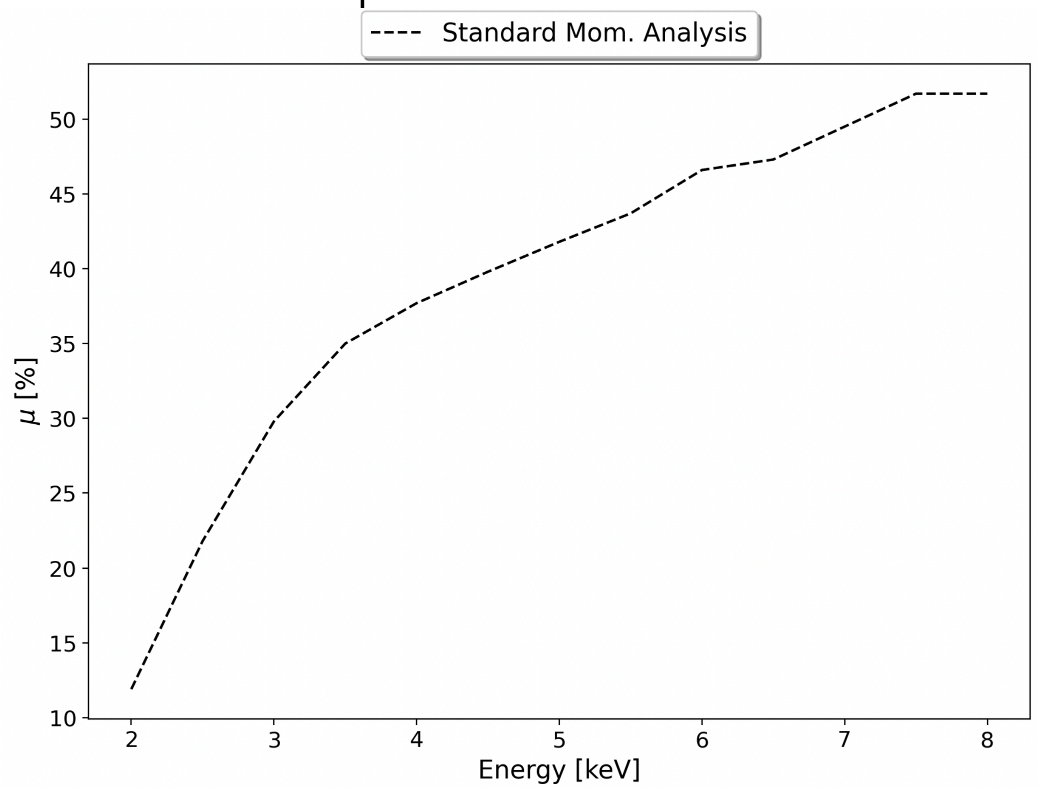


The reconstruction of the emission angle ϕ depends on the quality of the impact point reconstruction

Imperfect reconstruction: 1st implication

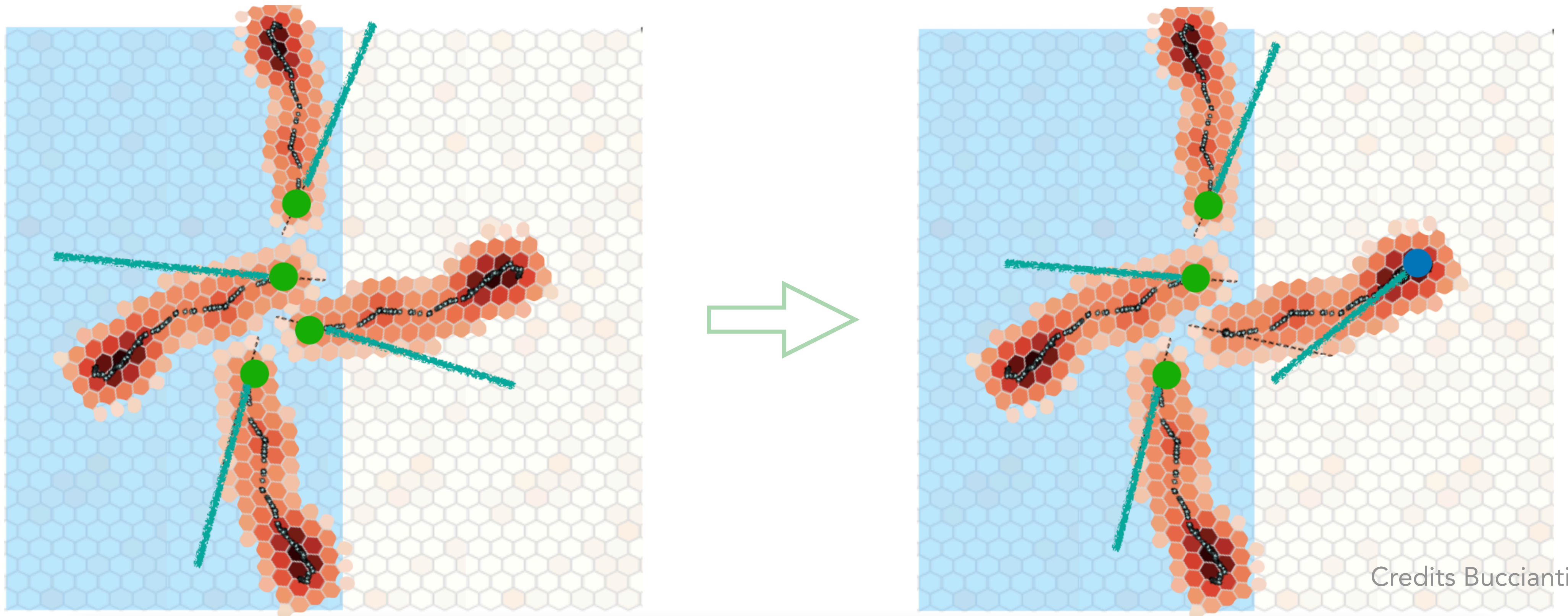


Modulation factor: reconstructed polarization fraction for a 100% polarized beam



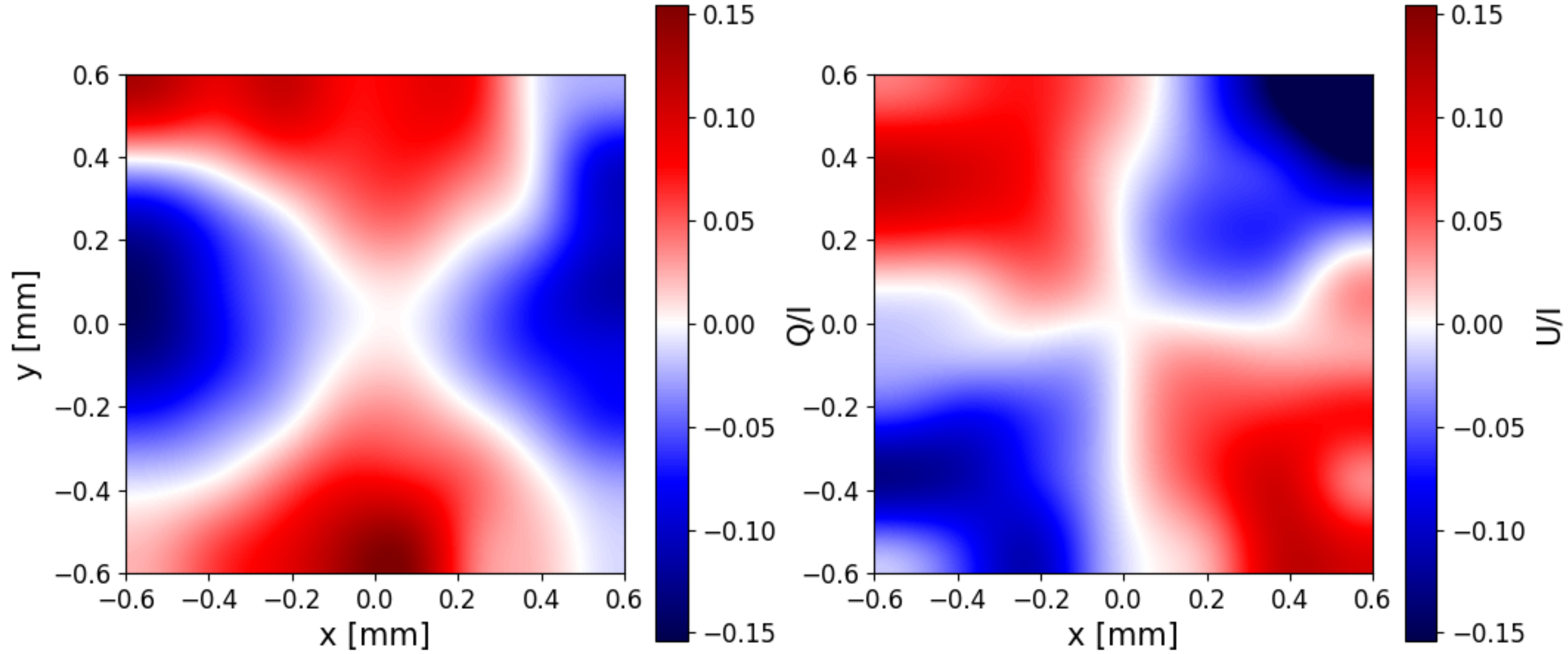
Imperfect reconstruction: 2nd implication

Polarization Leakage: systematic caused by the incorrect impact point reconstruction



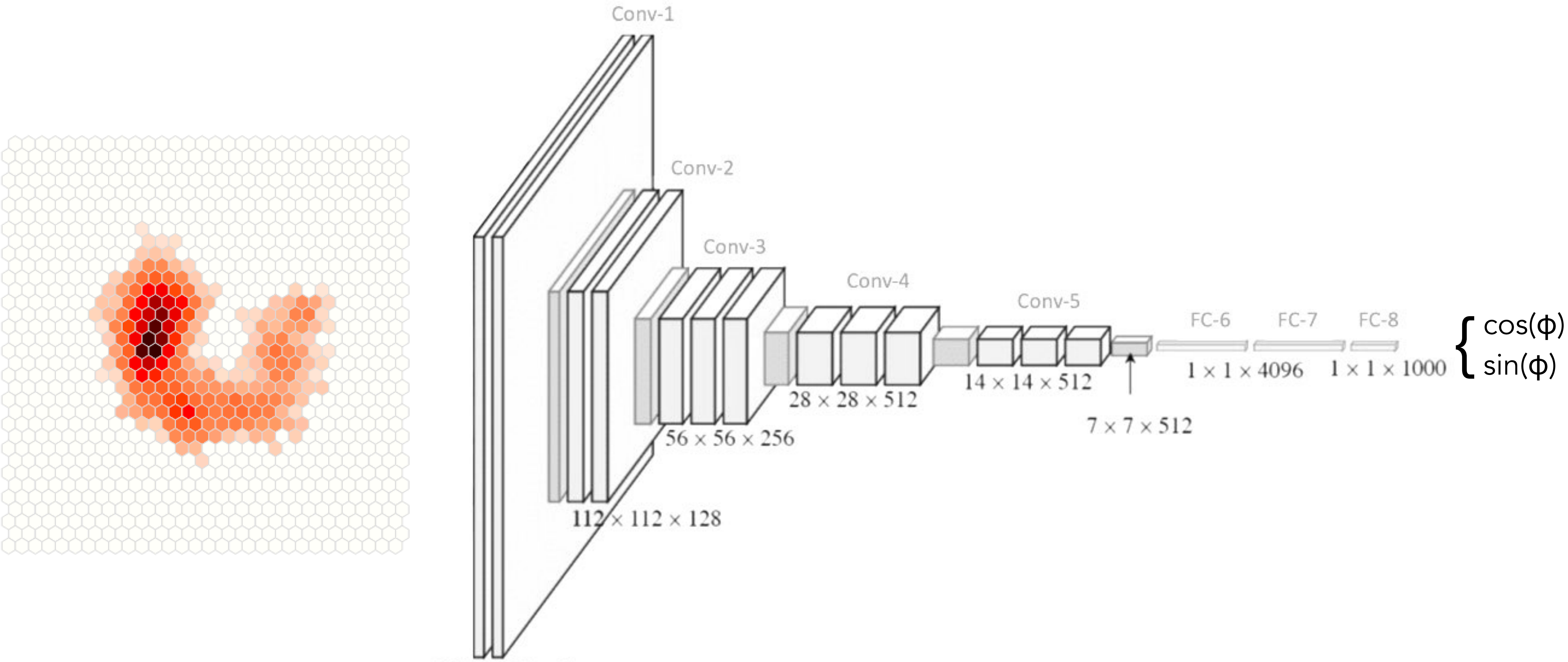
Credits Bucciantini et al. 2023

Unpolarized point sources: a radial polarization pattern is generated



Convolutional Neural Networks (CNN)

Developing of Machine Learning algorithm trained to reconstruct the emission angle starting from the track images



Kitaguchi et al. 2019
https://arxiv.org/abs/1907.06442

Moriakov et al. 2020
https://arxiv.org/abs/2005.08126

Peirson et al. 2021
https://arxiv.org/abs/2007.03828

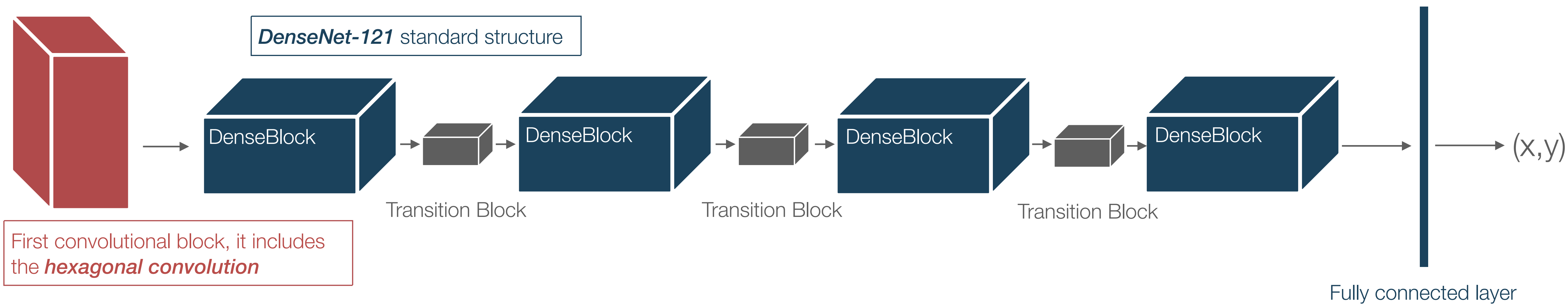
Main challenges

It's difficult to handle the hexagonal structure of the pixels

Potential introduction of additional systematics compared to the standard moment analysis

Hybrid algorithm: joining CNN and moment analysis

We developed a network specifically for the impact point reconstruction



The CNN-predicted impact point replaces the one predicted by the standard moment analysis

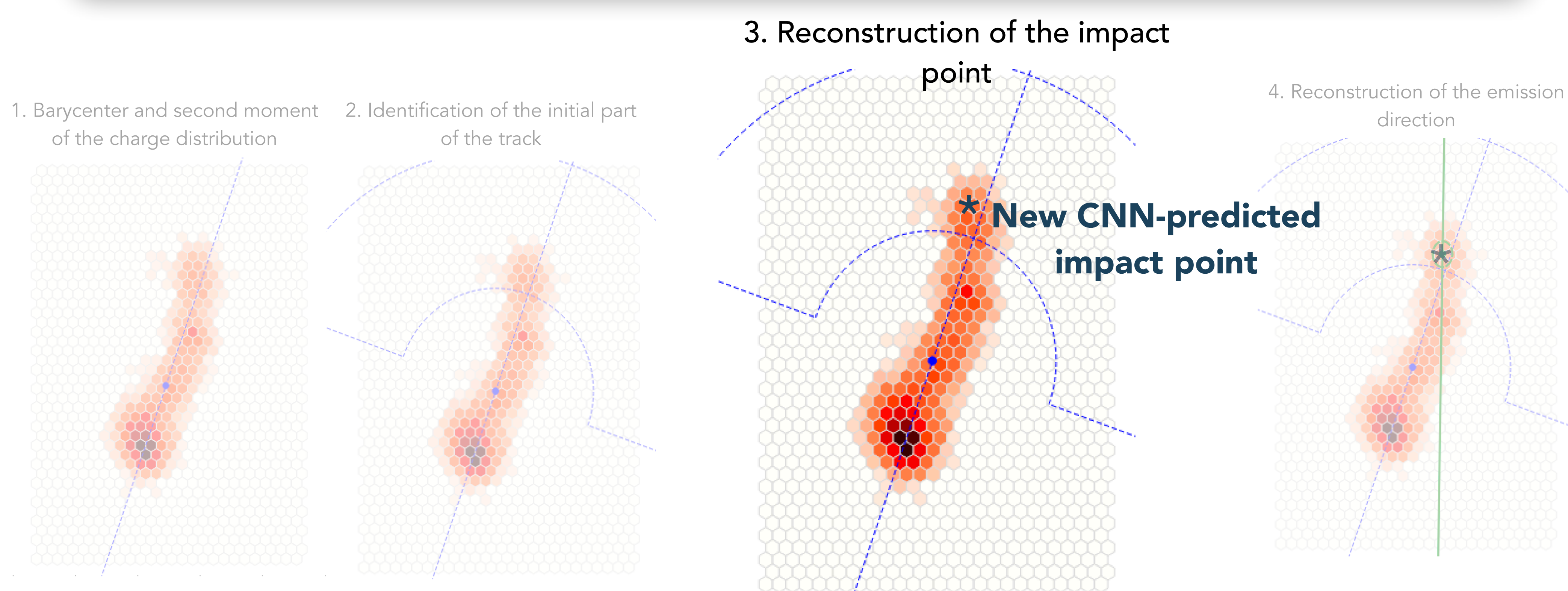
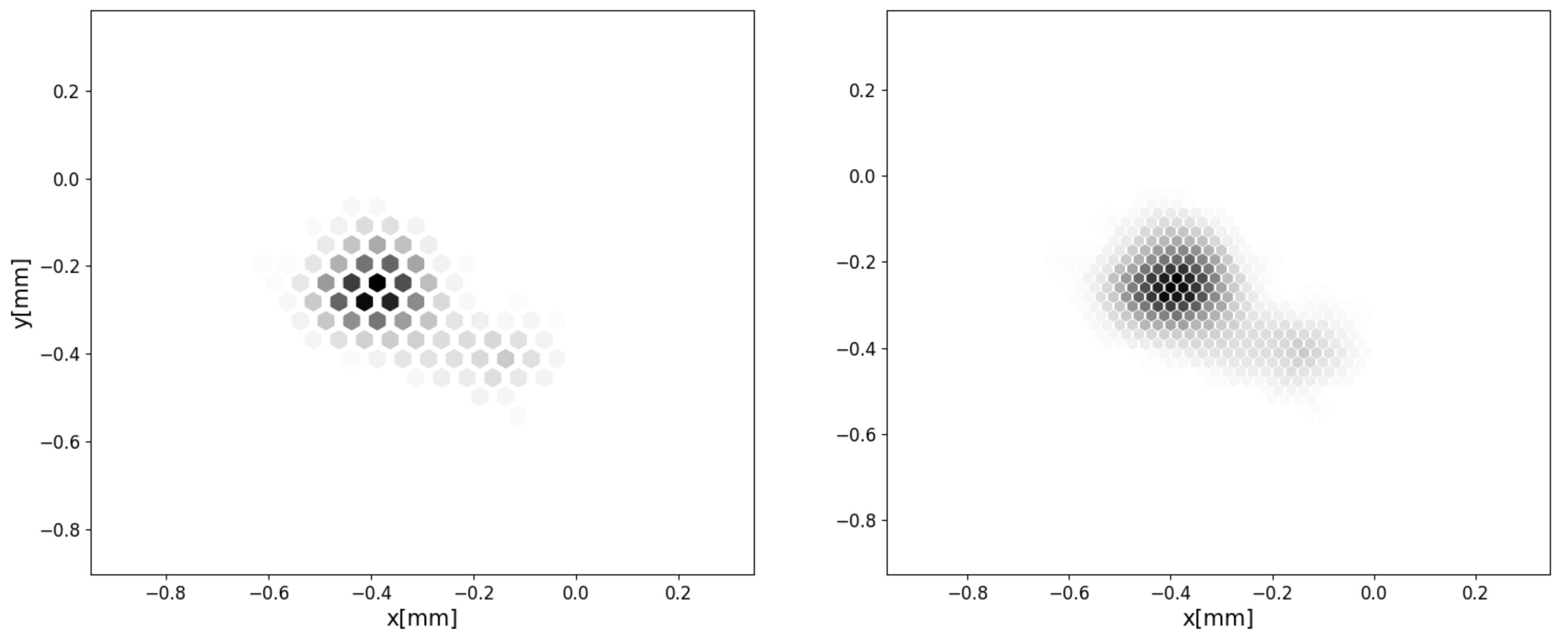
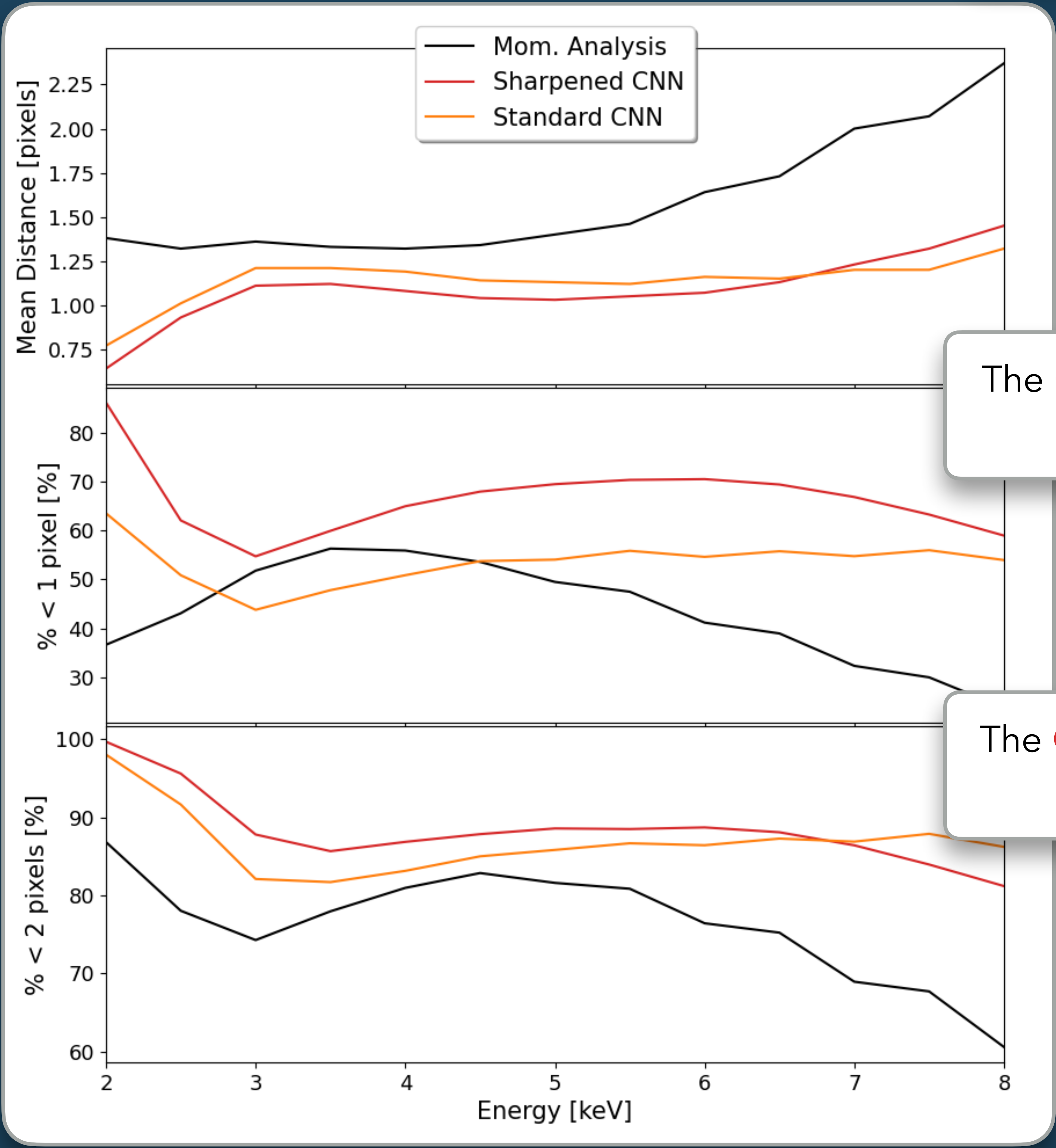


Image sharpening

Artificial sharpening of the images. The hexagonal symmetry is preserved.



Impact point: results

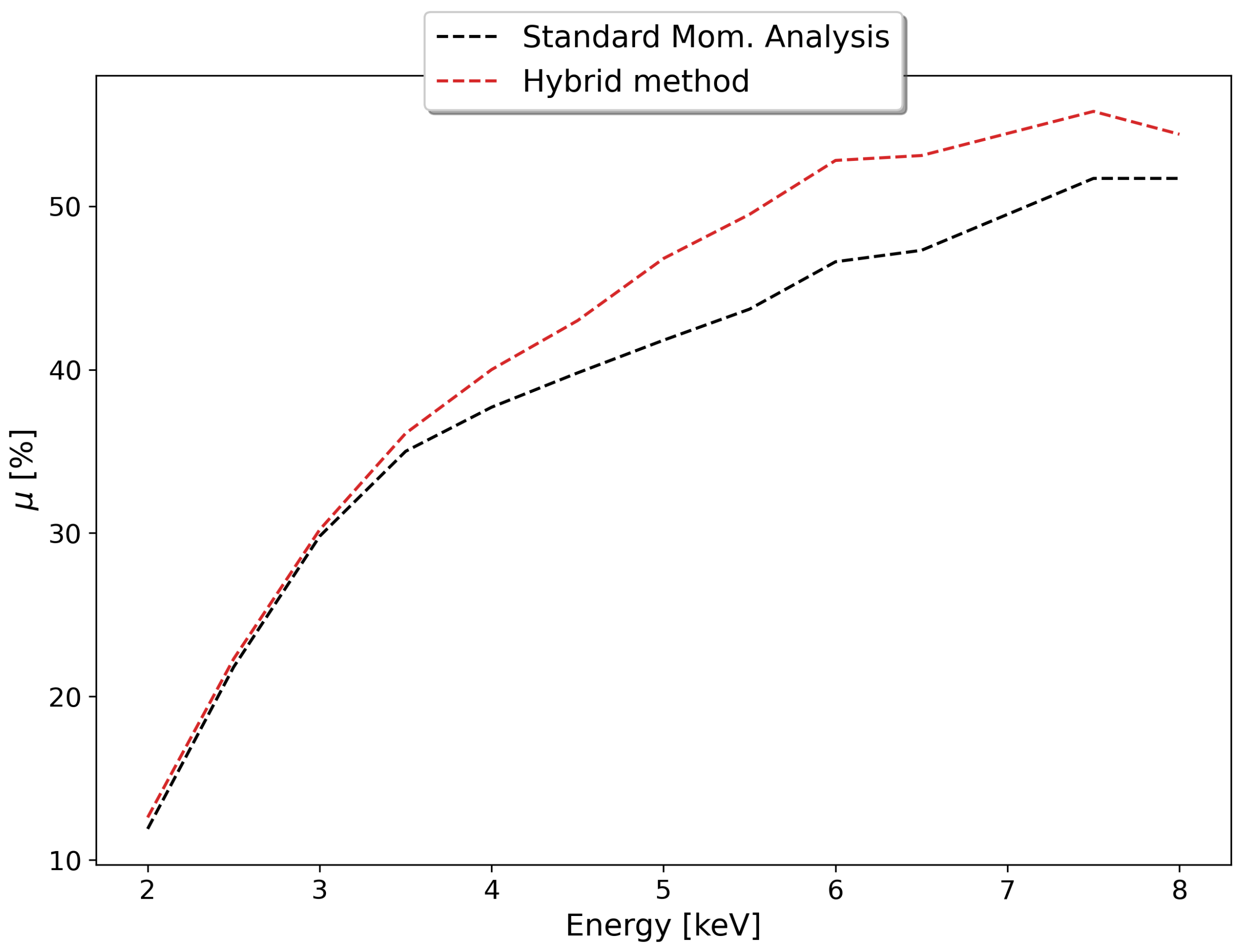


The CNN + Sharpening has improved performance compared to the Standard CNN

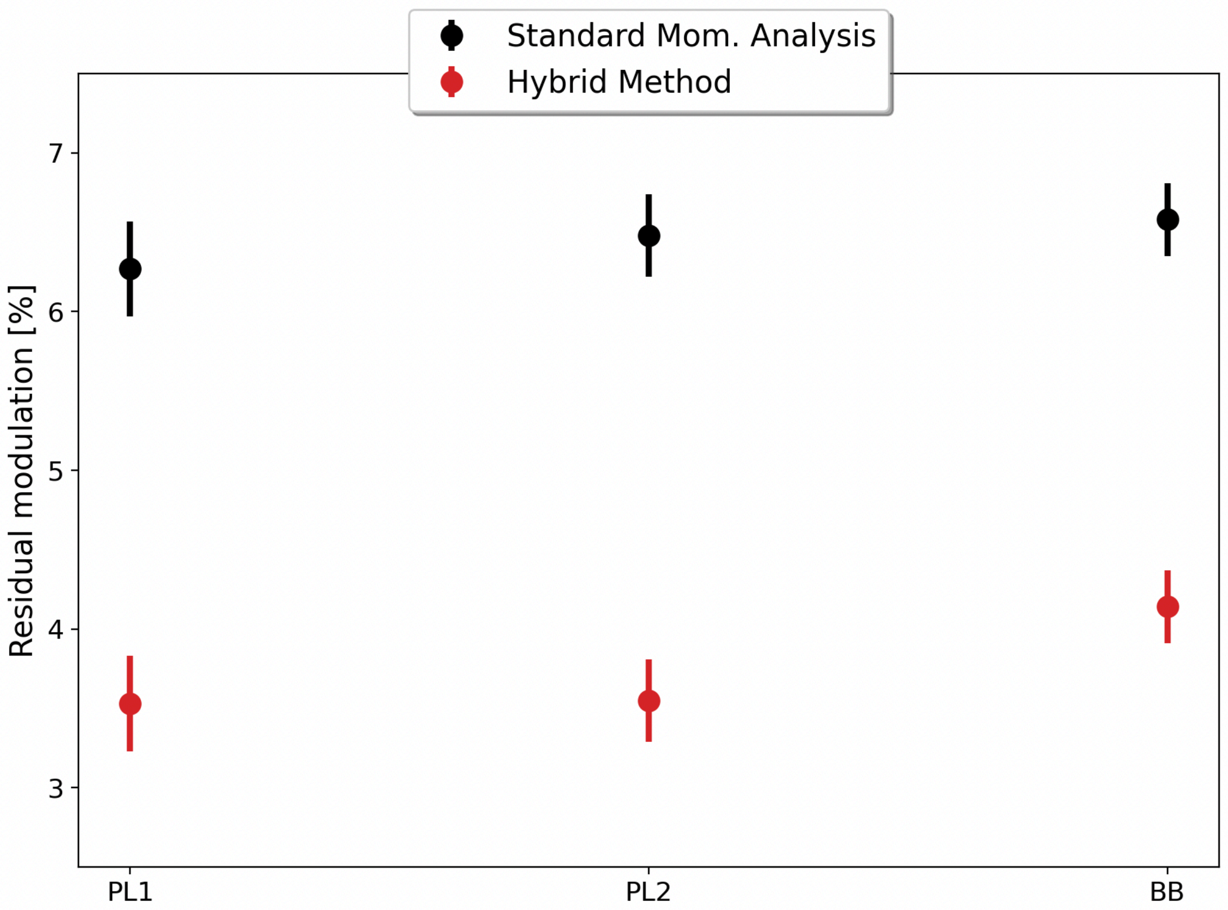
The CNN + Sharpening has improved performance compared to the **Moment analysis**

Polarization: results

Modulation Factor



Polarization Leakage



Marginal improvement of the **modulation factor** (1% at 3keV; 6% at 6 keV)

Significant reduction of the **polarization leakage** (~ factor 2)

Summary

We developed a **hybrid algorithm** for polarization measurements with GPDs

We introduced a fast algorithm for the **hexagonal convolution** and an **artificial sharpening** of the images

We improved the **reconstruction of the impact point position**

We marginally improved the **modulation factor** and significantly reduced the **polarization leakage effect**

A&A 674, A107 (2023)
https://doi.org/10.1051/0004-6361/202346302

Astronomy & Astrophysics

Joint machine learning and analytic track reconstruction for X-ray polarimetry with gas pixel detectors

N. Cibrario[1,2], M. Negro[3,4,5], N. Moriakov[6], R. Bonino[1,2], L. Baldini[7,8], N. Di Lalla[9], L. Latronico[1], S. Maldera[1], A. Manfreda[7,10], N. Omodei[9], C. Sgró[7] and S. Tugliani[1,2]

On going…

We are validating the algorithm with real lab data, and we are calibrating a dedicated facility in Torino.

Backup slides

Moment Analysis

1.Determination of the barycenter and of the second moment of the distribution of charge

$$x_b = \frac{\sum_i q_i x_i}{\sum_i q_i} \quad y_b = \frac{\sum_i q_i y_i}{\sum_i q_i}$$

$$M_2(\phi) = \frac{\sum_i q_i[(x_i - x_b)\cos(\phi) + (y_i - y_b)\sin(\phi)]^2}{\sum_i q_i}$$

2. Determination of the third moment of distribution of charge to select the initial part of the track

$$M_3(\phi) = \frac{\sum_i q_i[(x_i - x_b)\cos(\phi) + (y_i - y_b)\sin(\phi)]^3}{\sum_i q_i}$$

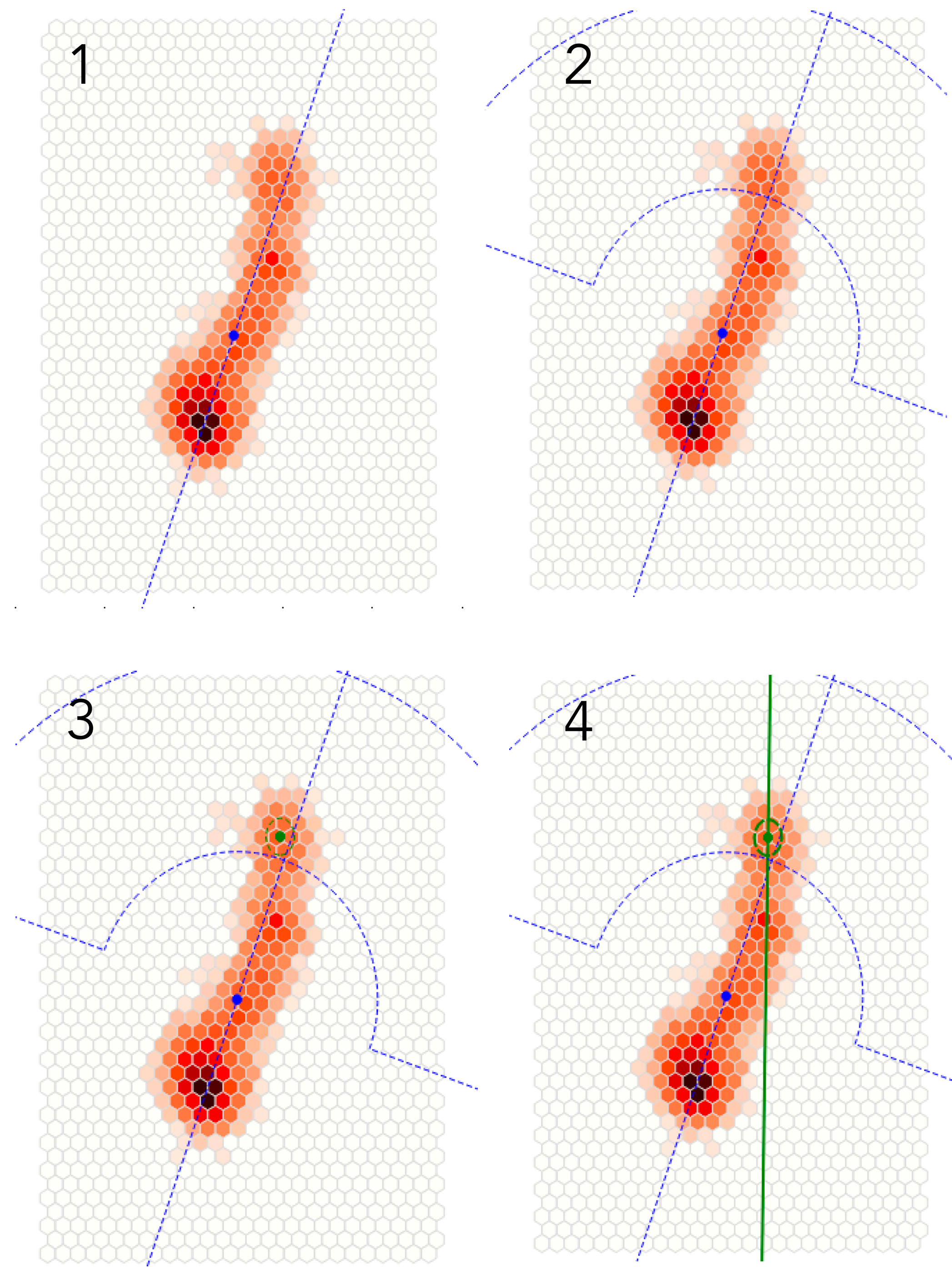
3. Calculation of the weights respect to the initial part of the track, and subsequent determination of the impact point

$$w_i = e^{-\frac{d_{b,i}}{d_s}}$$

$$x_{IP} = \frac{\sum_i w_i x_i}{\sum_i w_i} \quad y_{IP} = \frac{\sum_i w_i y_i}{\sum_i w_i}$$

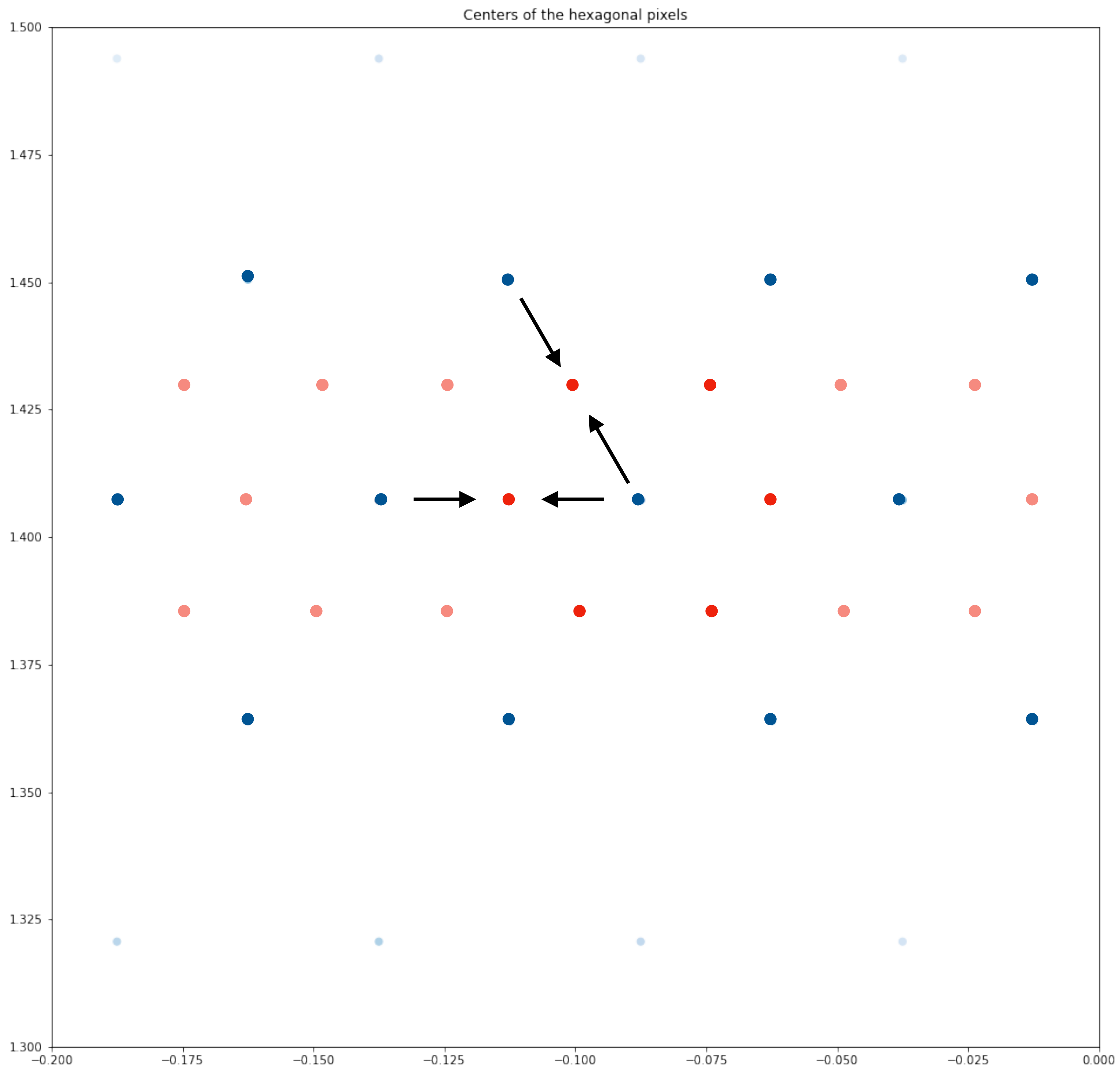
4. Re-determination of the second moment of charge distribution, this time respect to the predicted impact point*

$$M_2'(\phi) = \frac{\sum_i w_i[(x_i - x_{IP})\cos(\phi) + (y_i - y_{IP})\sin(\phi)]^2}{\sum_i w_i}$$

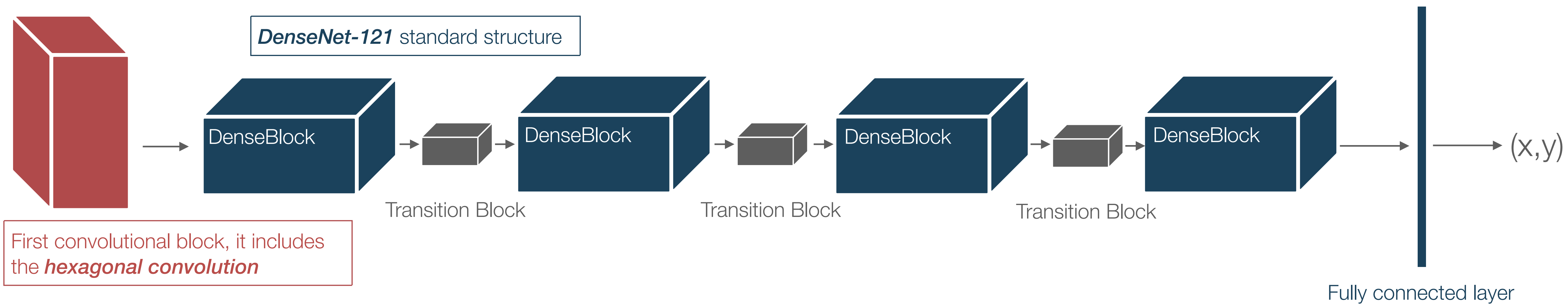


* In Hybrid algorithm, we use the CNN-predicted one!

Image sharpening



CNN hyper-parameters



Number of epochs: **60**

Introduction of **OHEM** process from 30th epoch

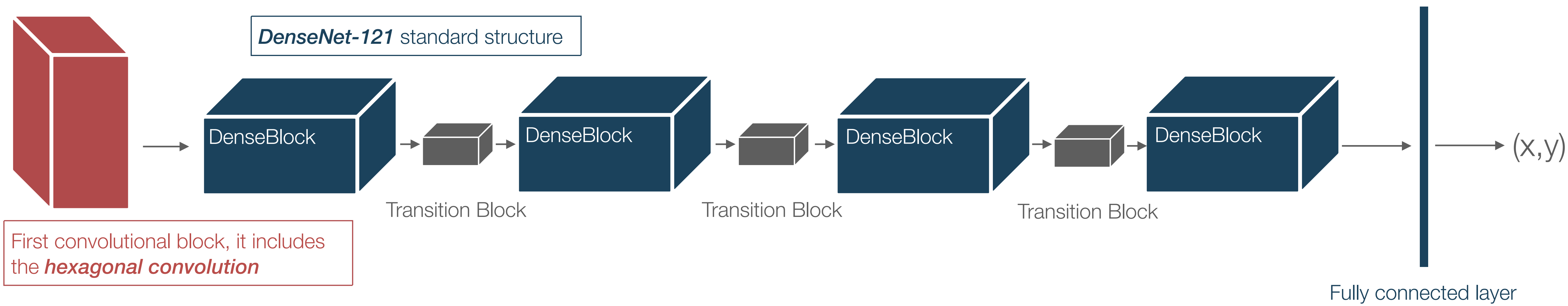
Images size: **72x72 Pixels**

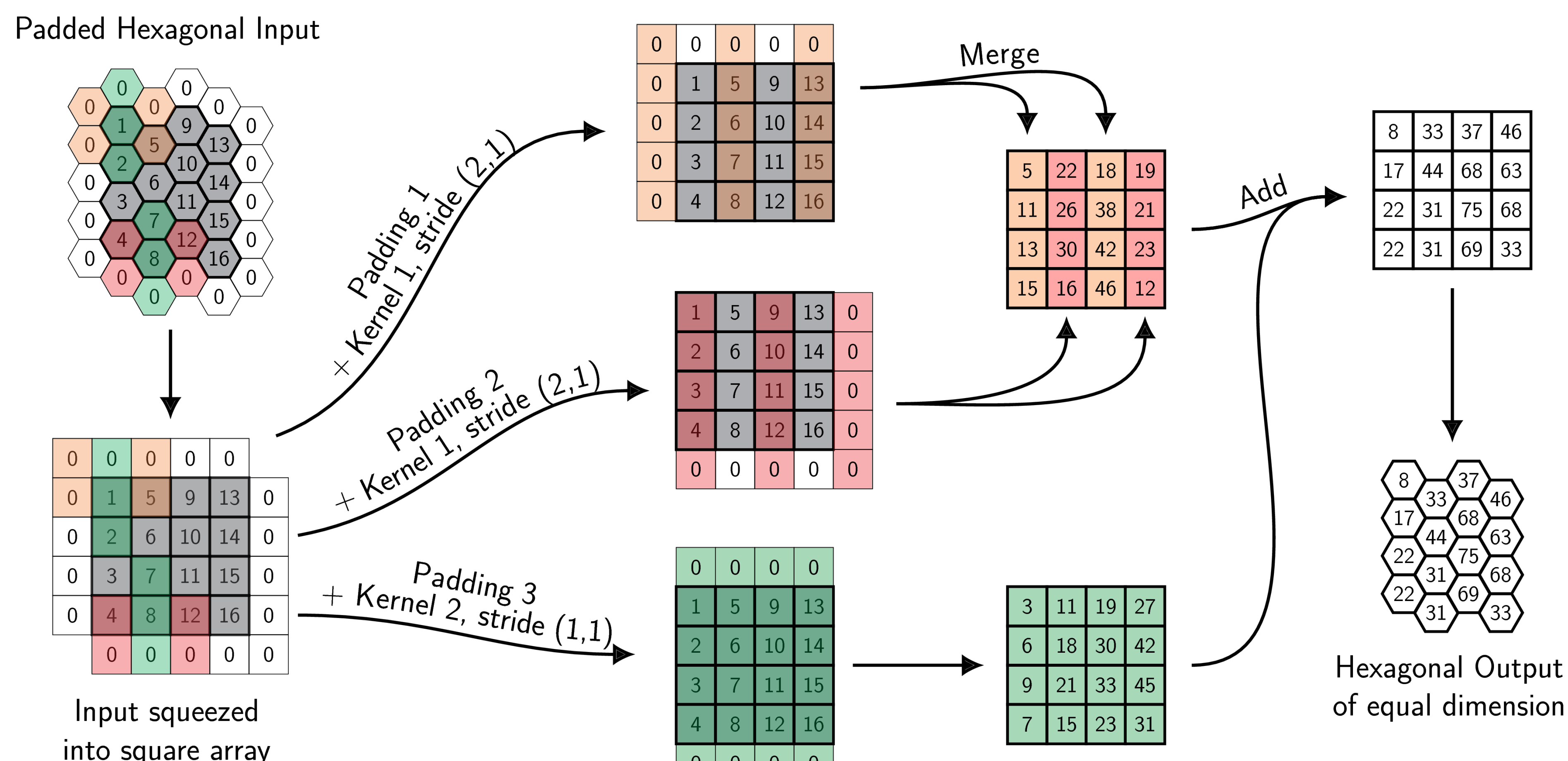
Adam optimizer, with decreasing *lr*

Loss function:

$$L(x_{true}, y_{true} | x_{pred}, y_{pred}) = |(x_{true}, y_{true}) - (x_{pred}, y_{pred})|$$

Hexagonal Convolution





Credits Steppa & Holch 2019

Radial Modulation

We align the reference axis to the radial direction: this allows to determine a potential radial polarization in the source