Generation of PXD background using generative models

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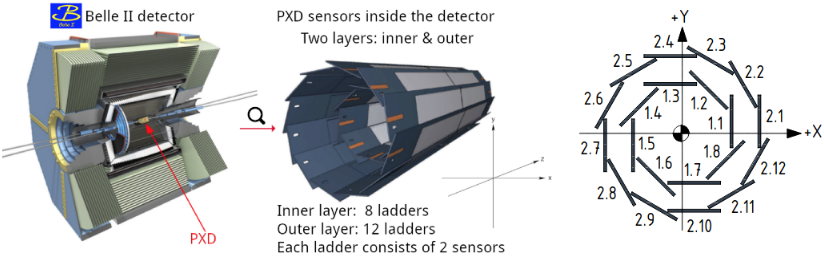
und Forschung

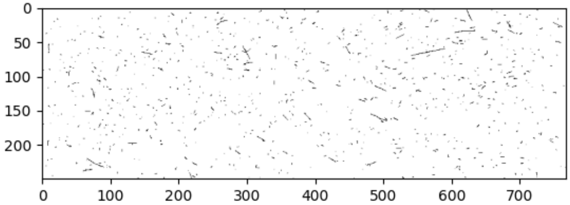
The Pixel Vertex Detector (PXD)

- The **Pixel Vertex Detector (PXD)** is the innermost semi-conductor sub-detector of Belle II, at 1.4 cm from the collision point.
- The sensitive area of the PXD is made up by 40 modules. Each module consists of a 250×758 pixel matrix.
- **Inner layer**: 16 modules implemented into 8 ladders.
- **Outer layer**: 24 modules implemented into 12 ladders.



Background

- PXD hits come mainly from background processes.



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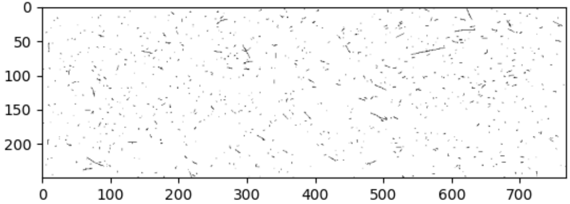
- Two ways to include background processes:
  - Monte Carlo generation $\longrightarrow$ shows sizeable discrepancies with measurements.
  - Taking random trigger events.



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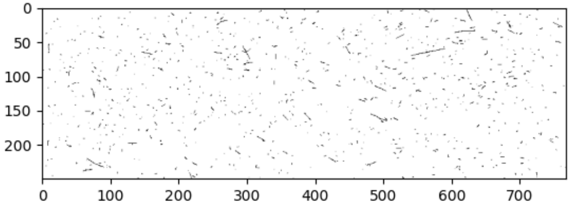
- **Problem: large amount of resources required for storage and distribution of the background data.**



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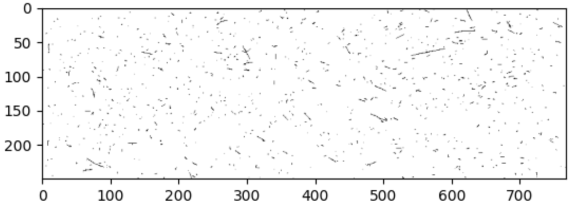
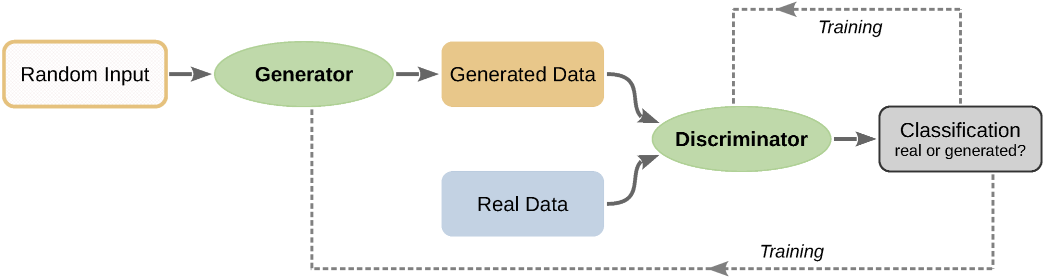
- **Problem: large amount of resources required for storage and distribution of the background data.**
- Solution: generate background hits on the fly for each sensor.



Generative Adversarial Network



Generating pixels with GAN

Previous approach:

- GAN conditioned on sensor number with a transformer-based relational reasoning module to reproduce the correlations between sensors(IEA-GAN).

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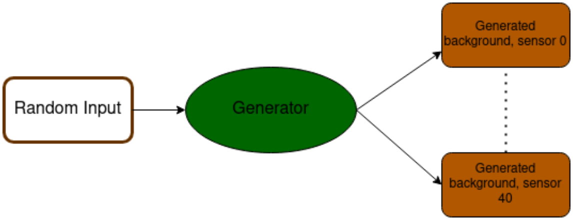
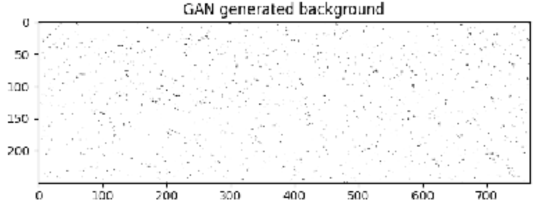
New approach: generate the background using a GAN without conditioning on the sensor number.

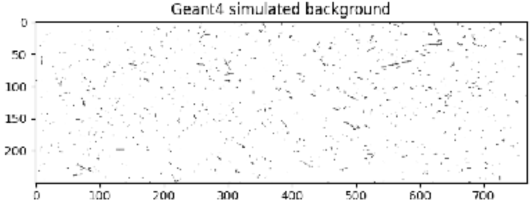
- Generate instances of background for all sensors at once.
- Wasserstein GAN with CNN layers used in the Generator and Discriminator.



Generated background

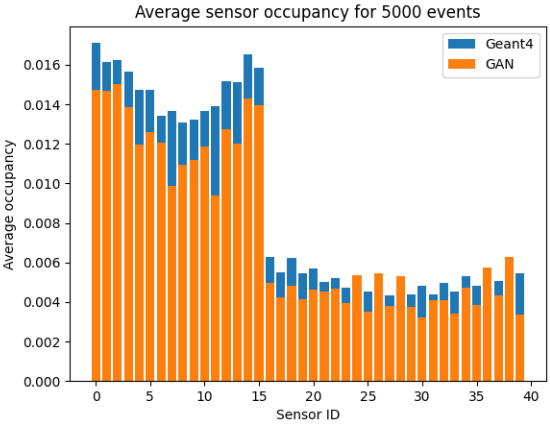
The generated images are visually very similar, but with some subtle differences.

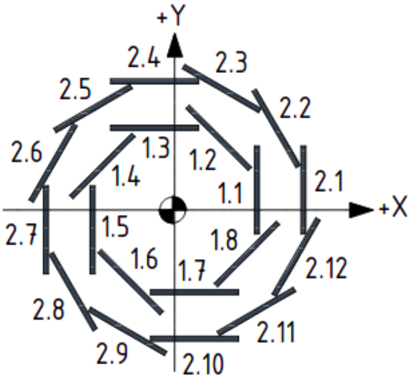




Evaluation - Occupancy per sensor

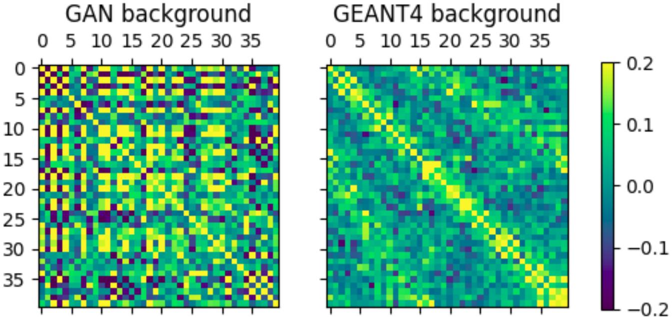
The model seems to reproduce quite well the sensor occupancy, aside from some minor details probably due to some fluctuations in the weights of the model.





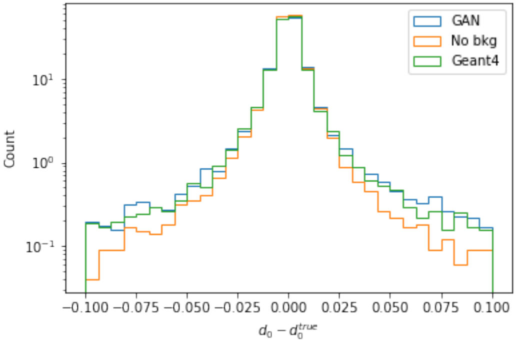
Evaluation - Correlation

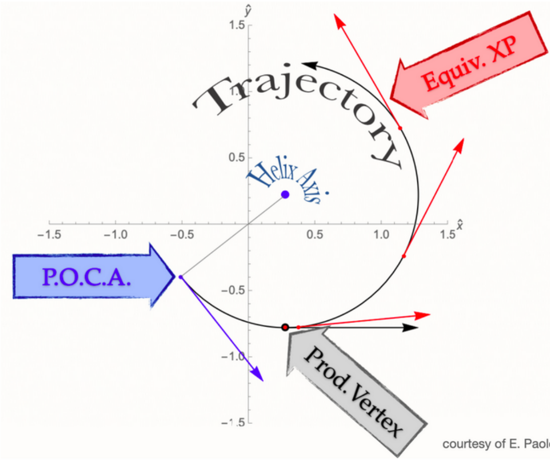
The model does not reproduce correctly the correlation between the sensor occupancy.



Evaluation - helix parameters resolution

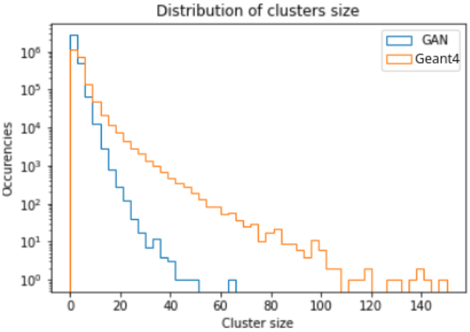
GAN background can be used to reproduce resolution of the helix parameters.

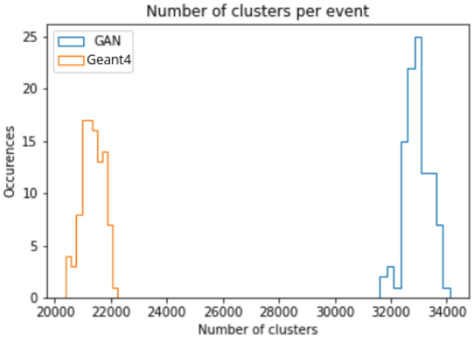




Evaluation: Clusters

The generated background images have different clusters distributions.





Cluster generation with GAN

- Train GAN to directly generate clusters instead of full sensor pixels.
- Trained using clusters of sizes from 1 to 30.
- Training dataset uniform in cluster size.

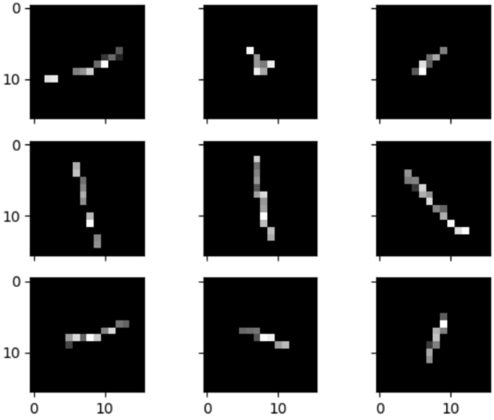
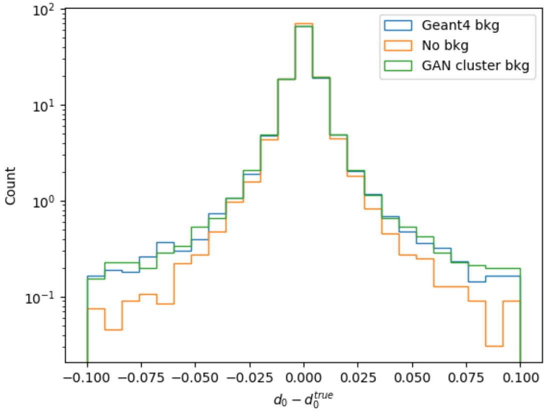
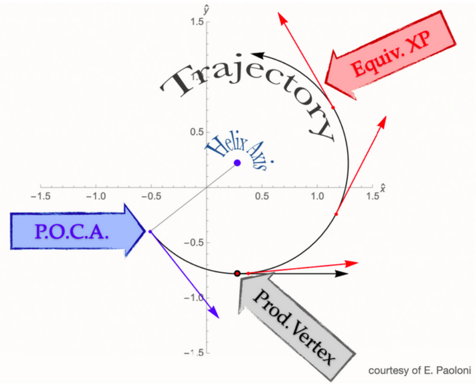


Figure: Example of generated clusters

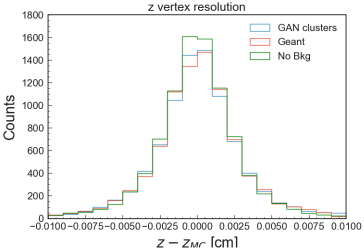
Evaluation - helix parameters resolution

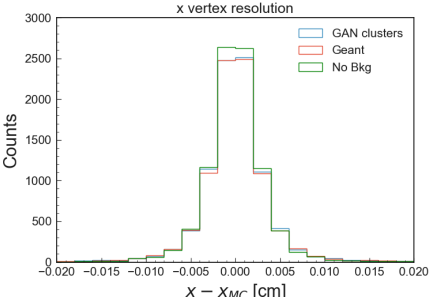


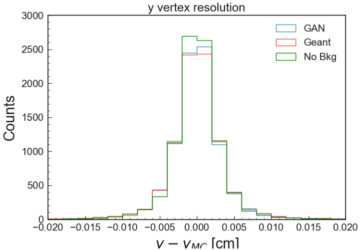


Evaluation - Vertex reconstruction

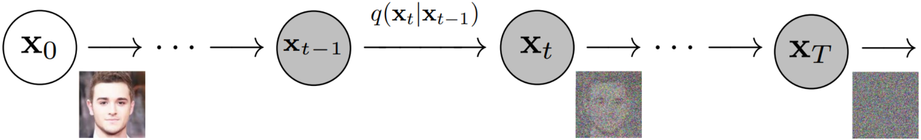
- Vertex resolution of D^0 in the decay $D^0 \to K^- \pi^+$
- Drop in efficiency when taking into account the background.







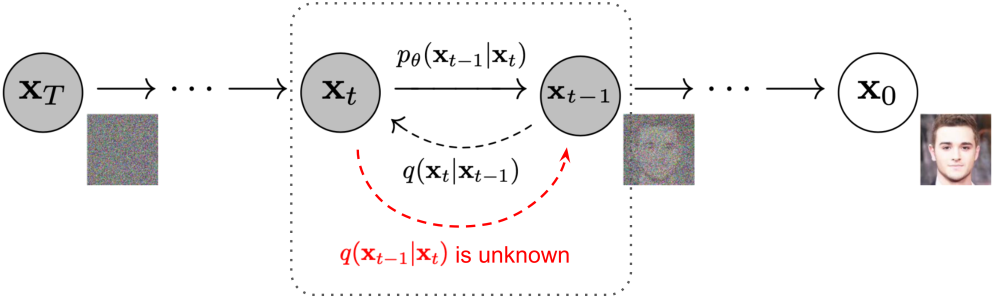
Diffusion model: forward process



$$q(\mathbf{x}_t|\mathbf{x}_{t-1}) = \mathcal{N}(\mathbf{x}_t; \sqrt{1-\beta_t}\mathbf{x}_{t-1}, \beta_t \mathbb{I}) \qquad \{\beta_t \in (0,1)\}_{t=1}^{T}$$

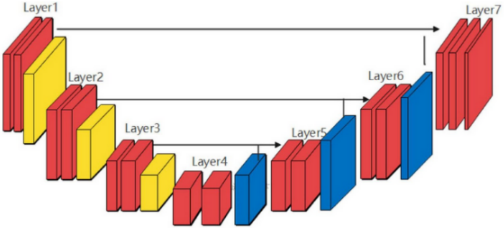
Diffusion model: inverse process

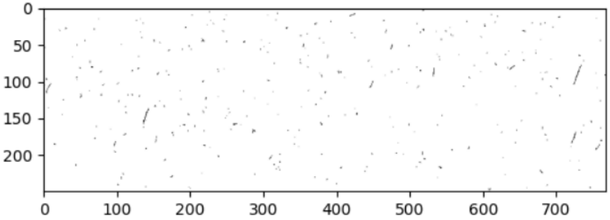
Use variational lower bound



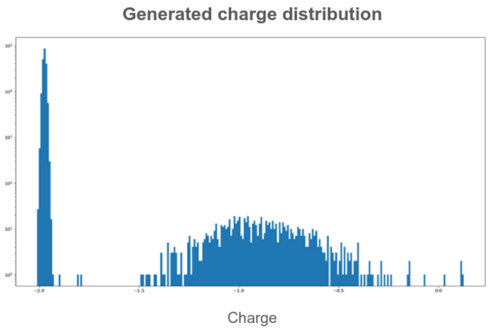
$$p_\theta(\mathbf{x}_{t-1}|\mathbf{x}_t) = \mathcal{N}(\mathbf{x}_{t-1}; \mu_\theta(\mathbf{x}_t, t), \Sigma_\theta(\mathbf{x}_t, t))$$

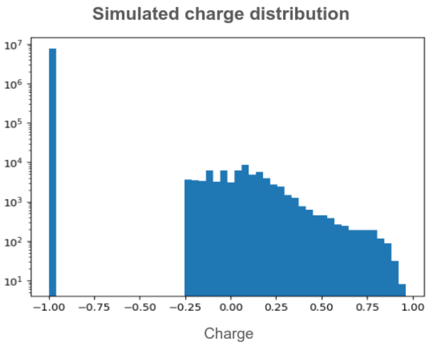
Example image of generated background





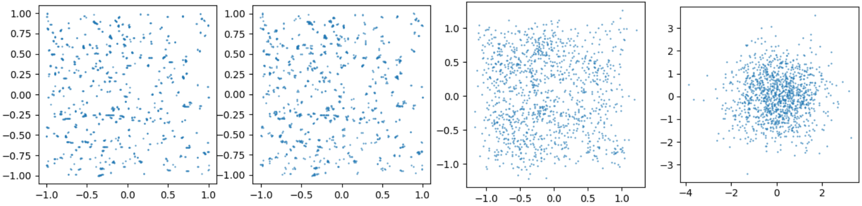
Preliminary results: charge distribution



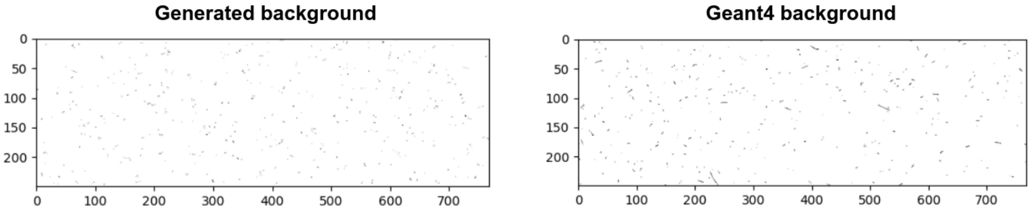


Graph Neural Network

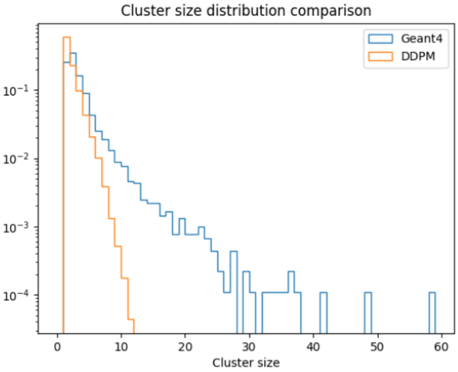
- IDEA: consider a point cloud representation of the BKG image and use a Graph Neural Network to predict the noise.
- In the GNN edge convolutional layers are employed.

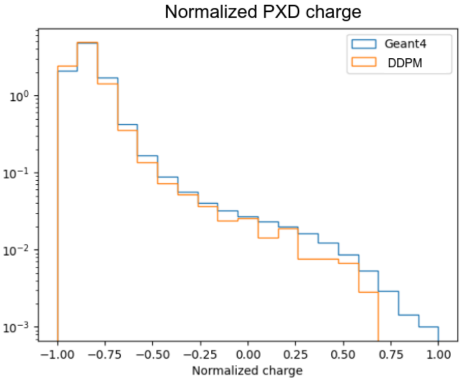


GNN: result


Generated background
0
50
100
150
200
0
100
200
300
400
500
600
700
Geant4 background
0
50
100
150
200
0
100
200
300
400
500
600
700

GNN: evaluation





Summary and conclusions

- Successfully trained a GAN to generate PXD hitmaps.
- Differences between simulated and generated images, especially regarding sensor occupancy correlation and clusters.
- Generated background reproduces helix parameters resolution well.
- Successfully trained a GAN to generate clusters.
- Generated clusters correctly reproduce the helix parameter resolution.
- Trained a diffusion model to generate background images.

Conclusions and outlook:

- Demonstrated that generative models can produce PXD background with the required accuracy.
- Possibility to use other methods which do not involve ML i.e. constructing BKG files by sampling techniques.

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Thanks for your attention!

Backup - Generator

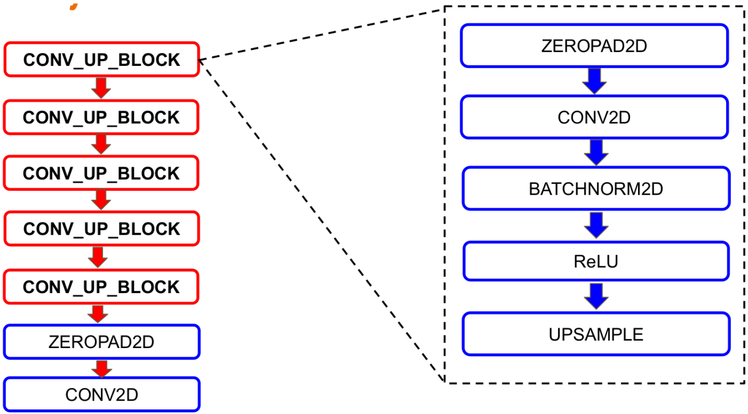

Figure: Generator architecture

Backup - Discriminator

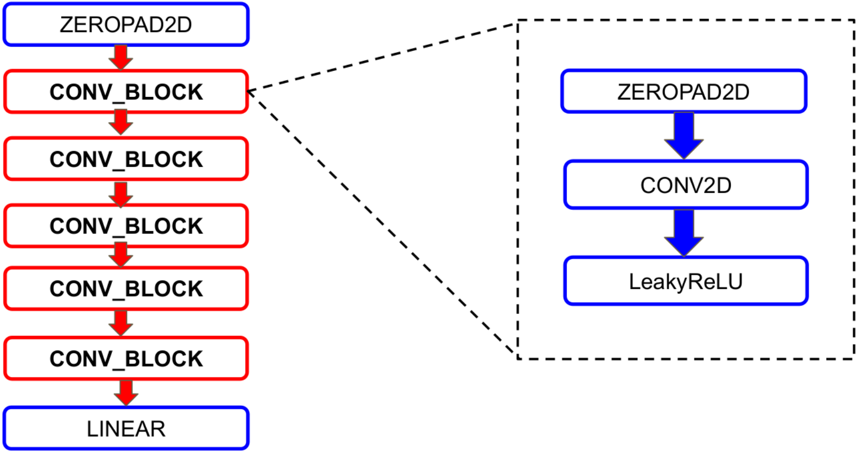

Figure: Discriminator architecture

Evaluation: cluster size