LMU LUDWIG-MAXIMILIANS-UNIVERSITY MUNICH

Generating PXD Background Heat Maps with Generative Adversarial Networks at Belle II

Matej Srebre, Thomas Kuhr, Martin Ritter, Hosein Hashemi

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- *Introduction to PXD*
- *Backgrounds and bkg Overlay problems*
- *GAN Solution*
- *Conditional GAN*
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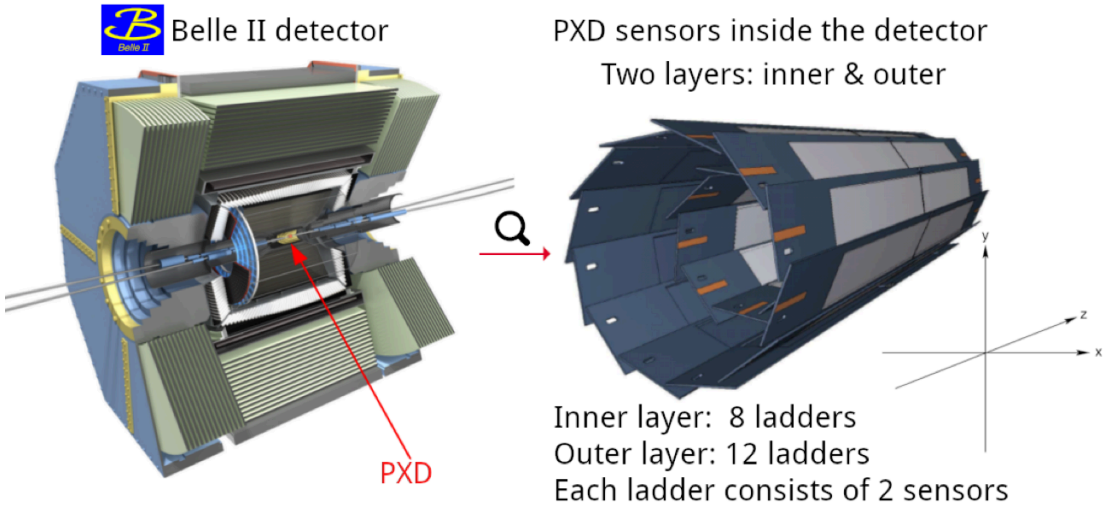
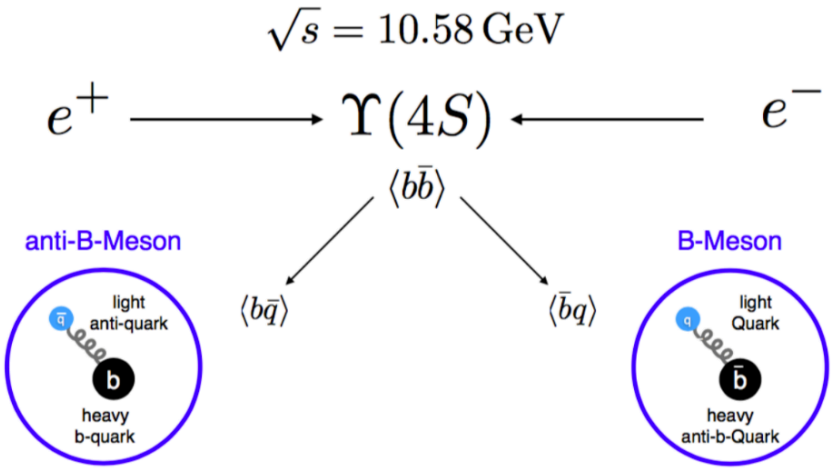
Introduction

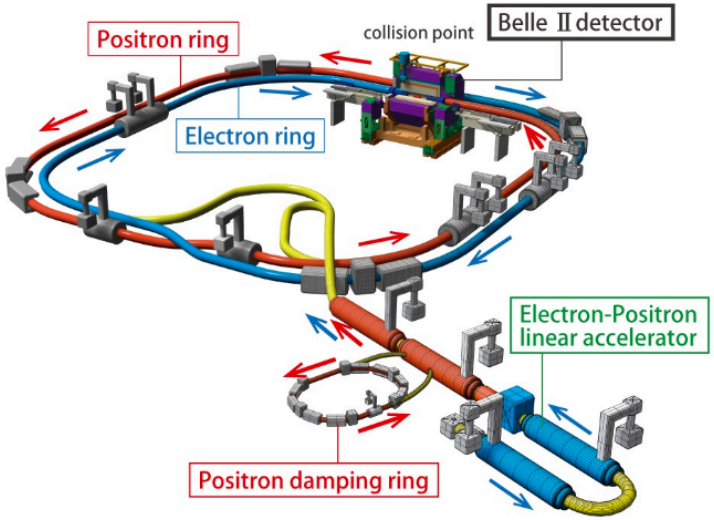
- ***The Pixel Vertex Detector (PXD)*** is the innermost semi-conductor sub-detector at Belle II.
- It measures the position of traversing particles originating from a particle collision → *The precise reconstruction of decay vertices.*
- The sensitive area of the PXD is assembled from ***40 modules***, where each module consists of a ***250*** × ***768*** pixel matrix of the pixel sensors.
- The size of PXD is defined by physics requirements, design and space limitations and readout speed.



Introduction

- ***The Pixel Vertex Detector (PXD)*** is the innermost semi-conductor sub-detector at Belle II.
- It measures [illegible]osition of traversing particles originating from a particle
  - e^+e^- SuperKEKB asymmetric collider at $10.58\,GeV$
  - **Goals:** *Search for new physics and precision measurement*





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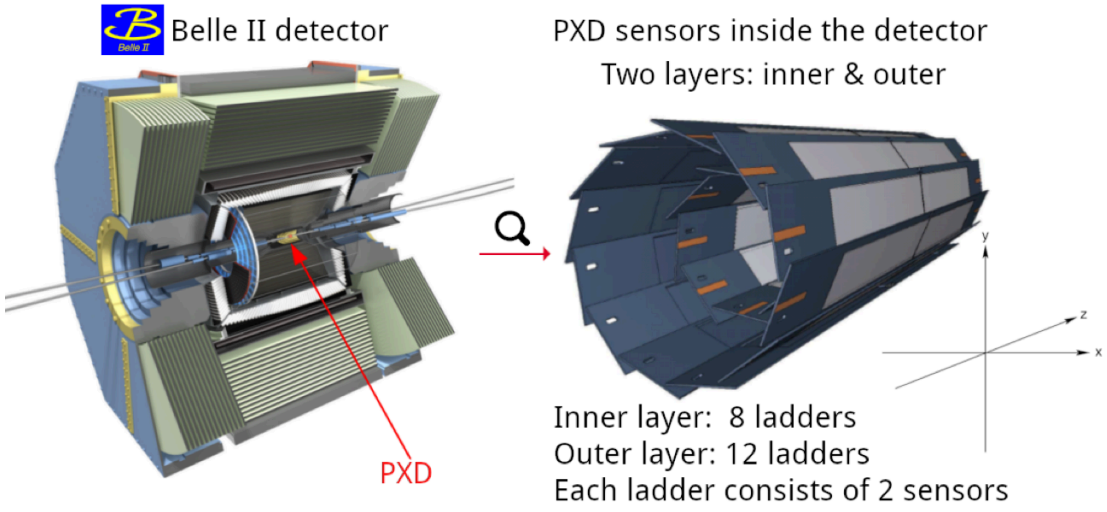
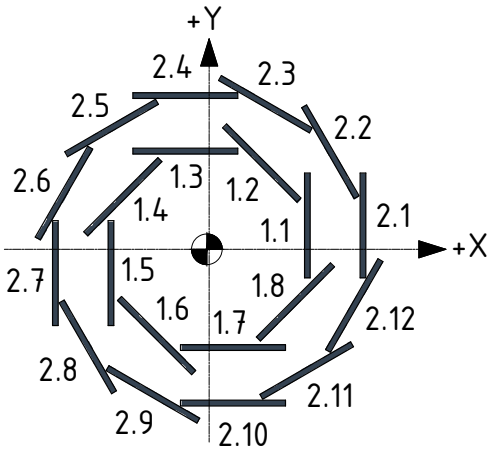
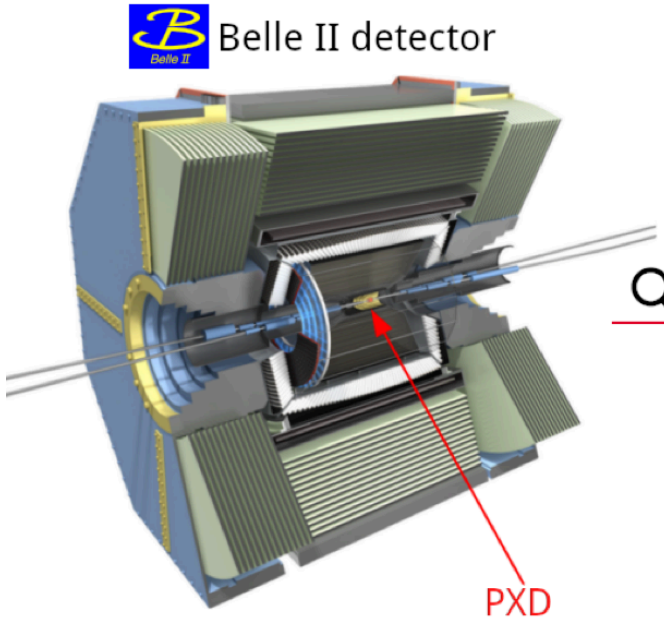


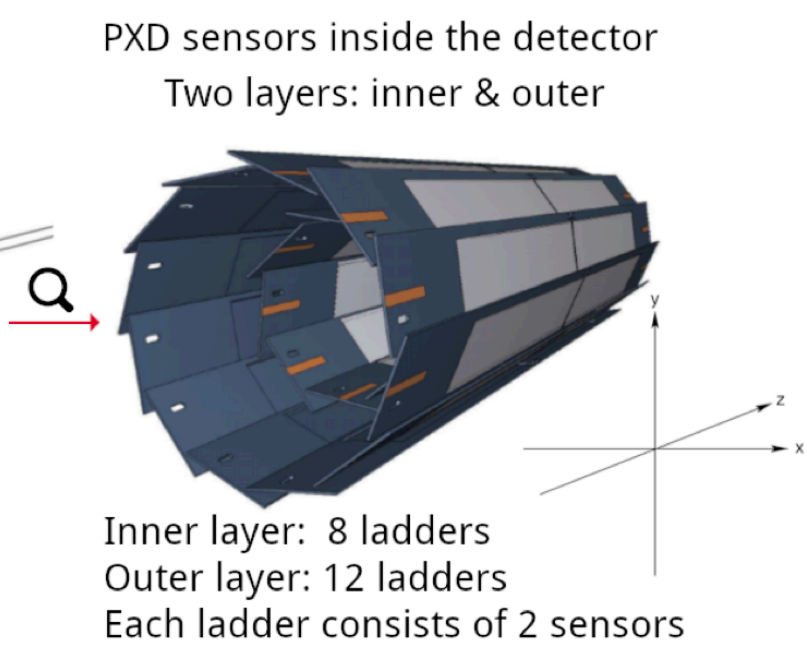
Introduction

The PXD consists of two layers of pixel modules:

1. ***The inner layer:*** *16 modules implemented into 8 ladders*
2. ***The outer layer:*** *24 modules implemented into 12 ladders*



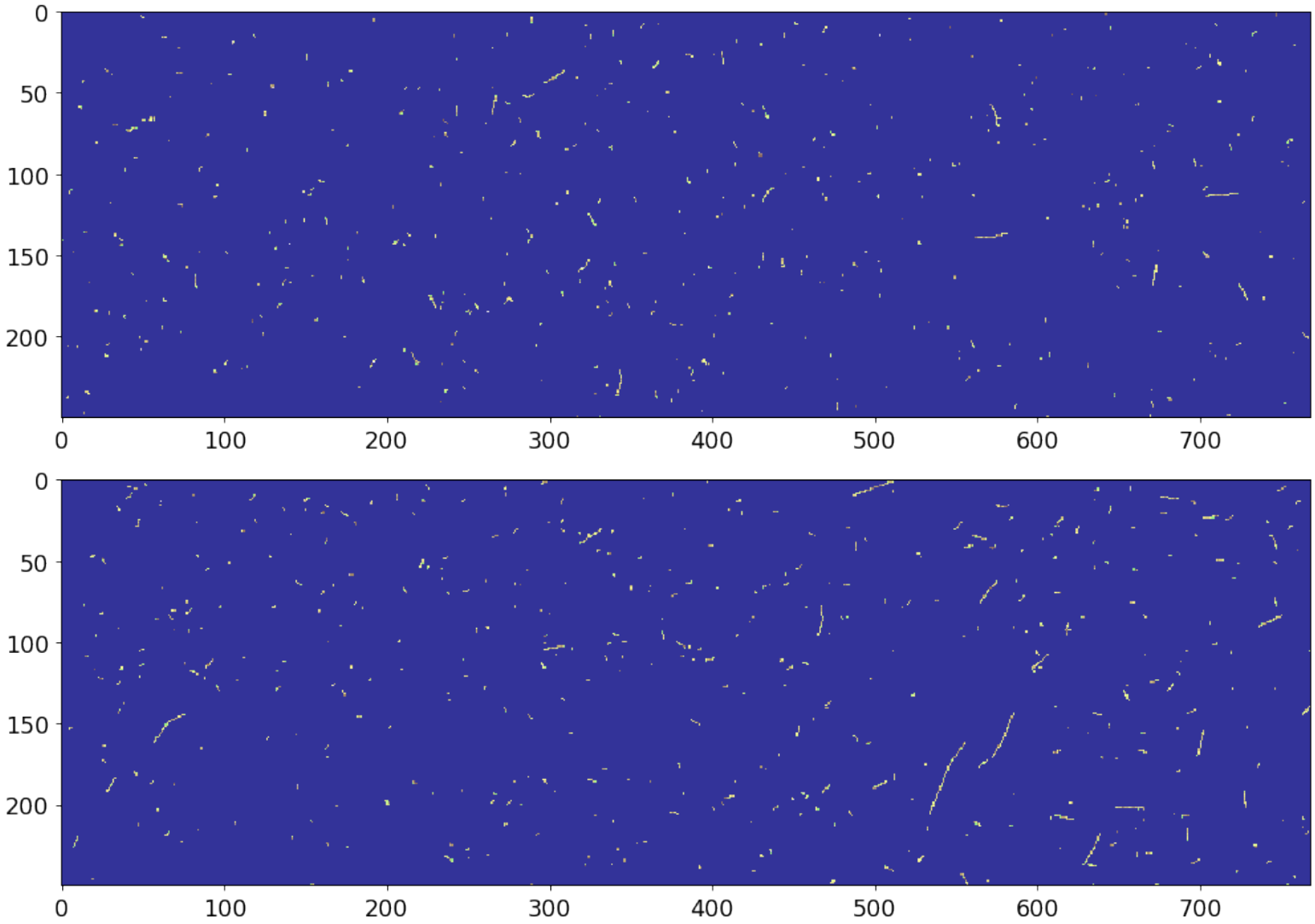




Backgrounds

- ***The PXD tracks are coming from two sources:***
  - Signal Decays
  - Backgrounds
    - ***A. Beam-induced:*** *intra-beam scattering, Beam-Gas scattering, synchrotron radiation*
    - ***B. Luminosity dependent:*** *Radiative Bhabha scattering, two-photon process*

Example of PXD bkg heat maps



Backgrounds

- **Realistic detector simulation has to take into account effects from background processes**
  - *Simulation requires many PXD heat maps with statistically independent background*
  - *PXD digits has the highest storage consumption, almost 100 KB per event cost*
  - *Requires distributing over all sites where MC is produced*

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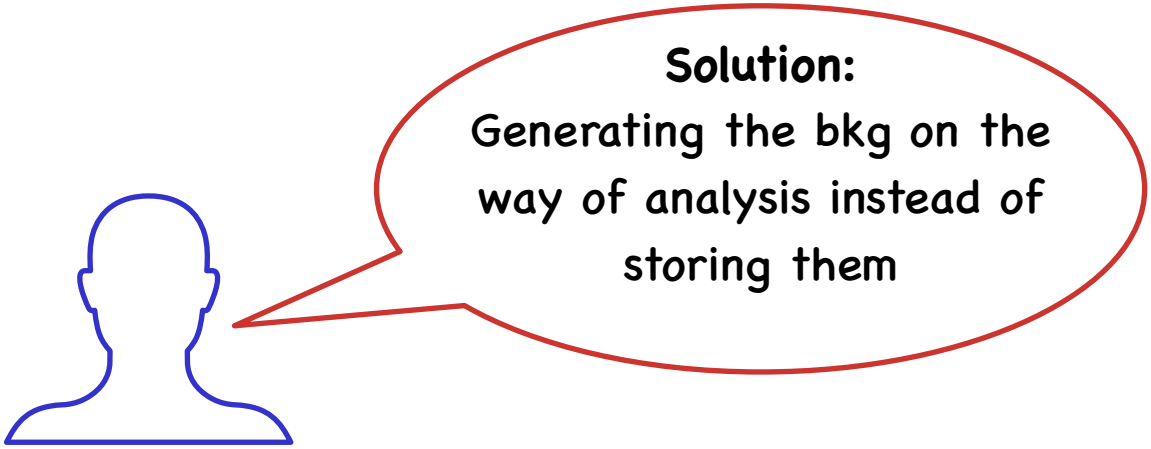
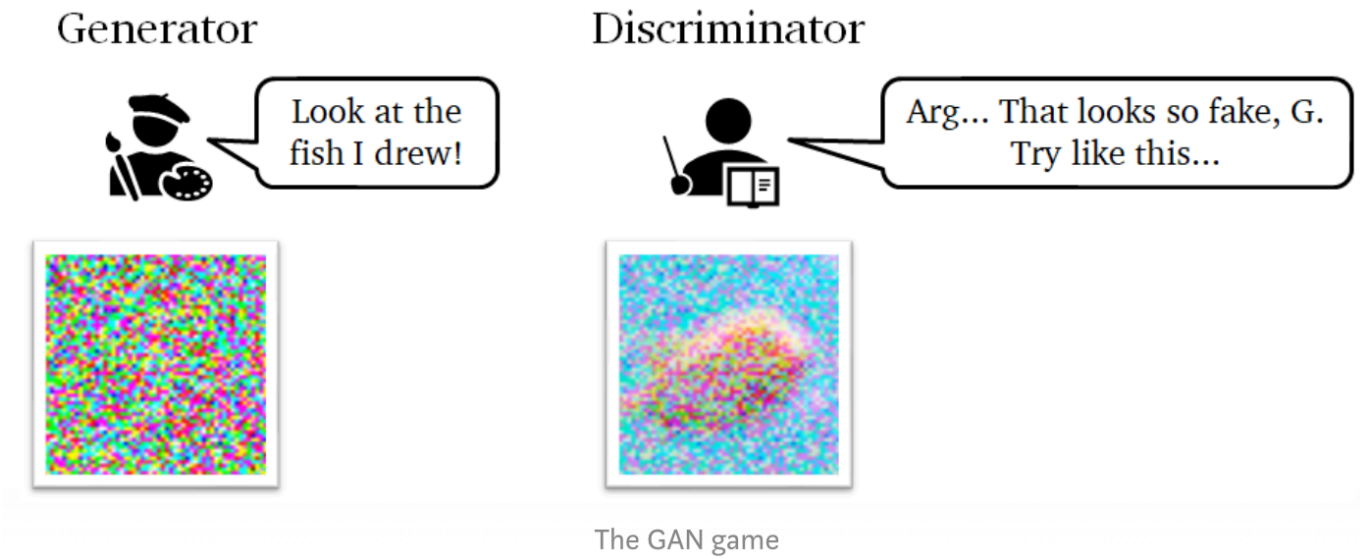


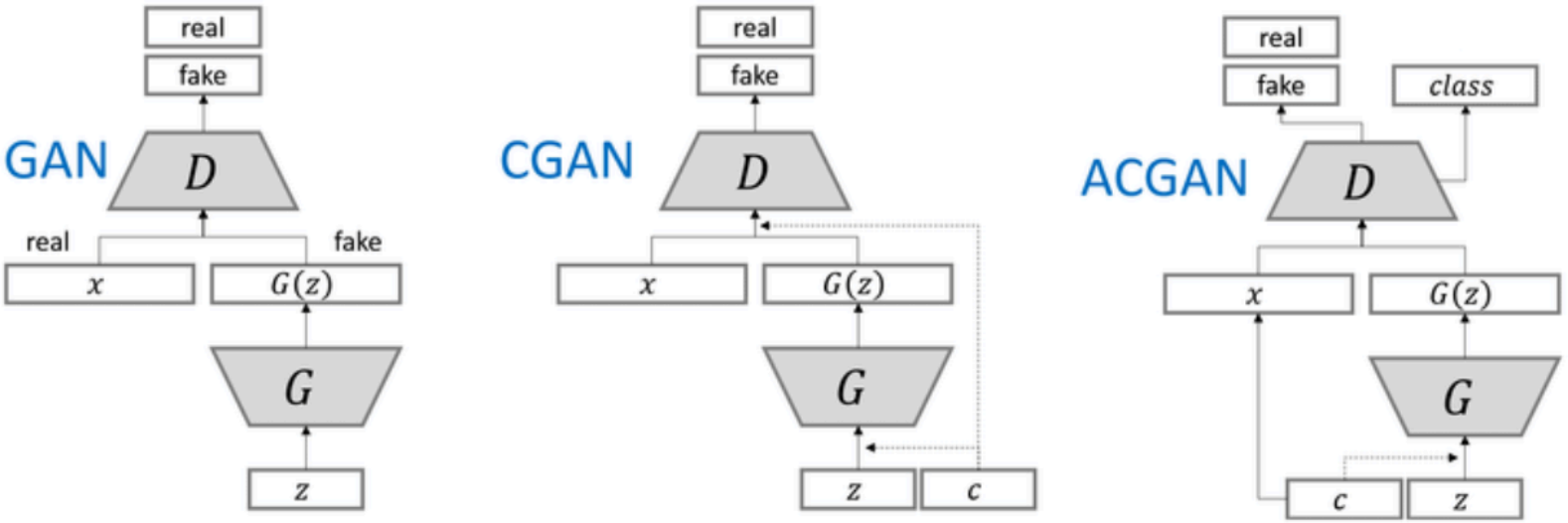
GAN is all you need!

- Generate PXD background events with Generative Adversarial Network **(GAN)**
- **Whats is GAN?**



GAN is all you need!

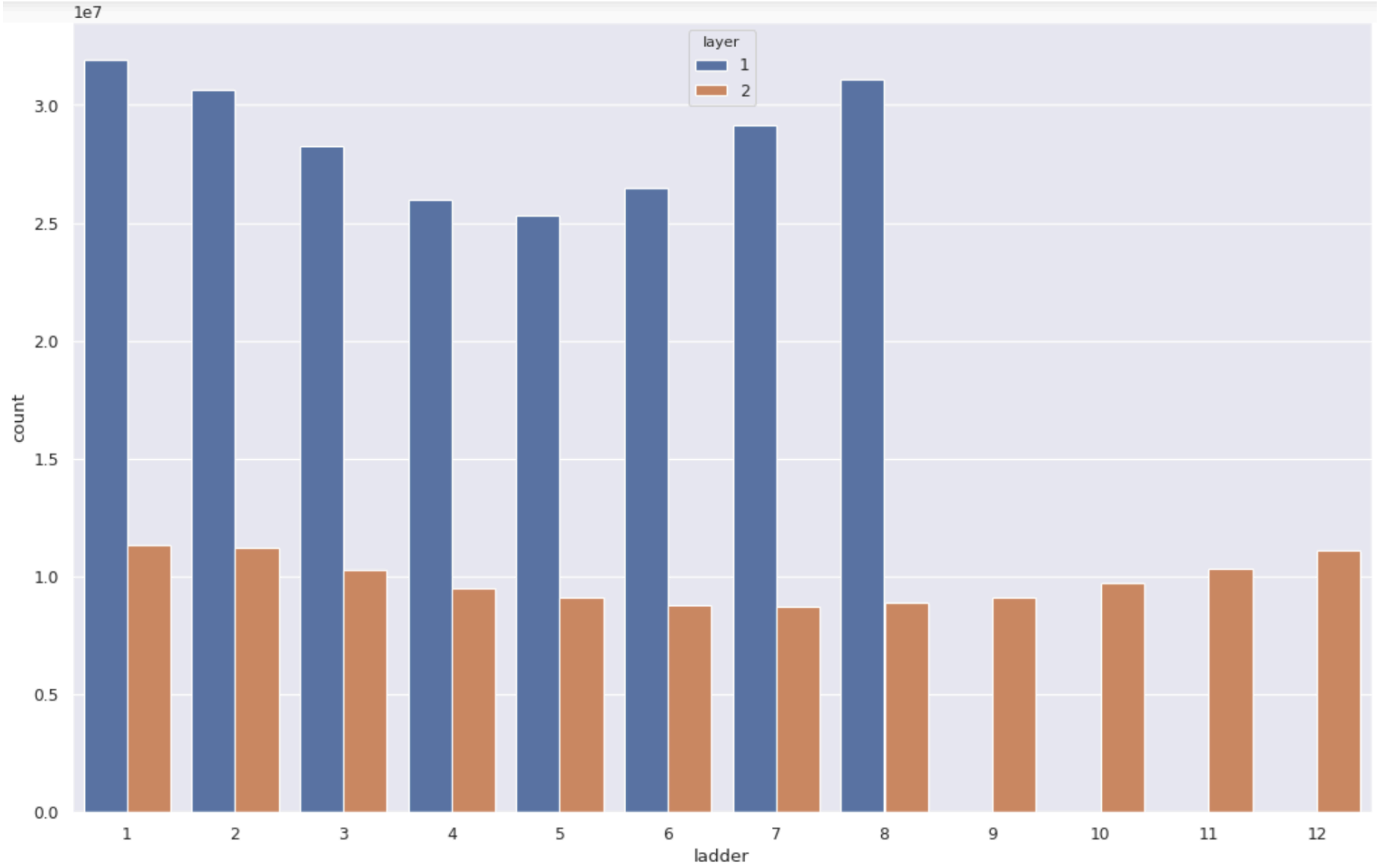
- Generate PXD background events with Generative Adversarial Network **(GAN)**
- **The Main structure:**



GAN is all you need!

- Generate PXD background events with Generative Adversarial Network **(GAN)**
- **Used Models:**

Number of hits per ladder



Conditional GAN

- Generate PXD background events with Generative Adversarial Network **(GAN)**
- **Used Models:**

LOGAN (LO-cWGAN) → BigGAN-AC → BigGAN-deep

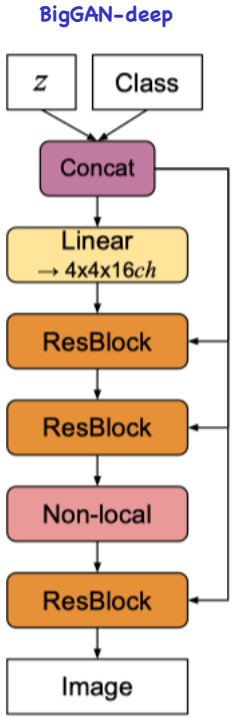
- Using Spatial class-conditions based on the layer number 1-40
- Increase the image fidelity
- Generate sensor-based images

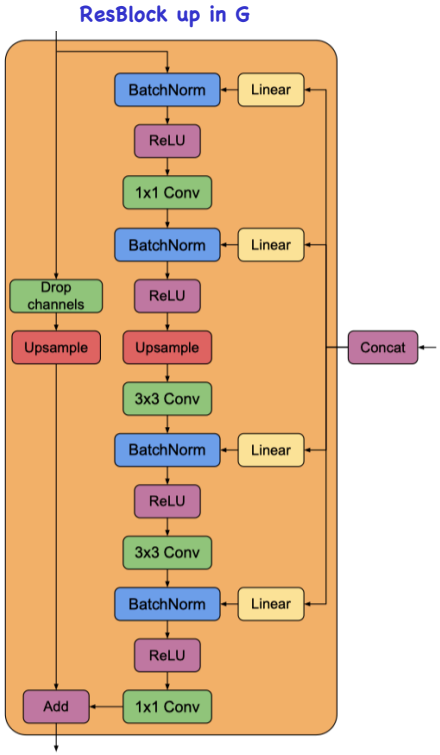
Conditional GAN

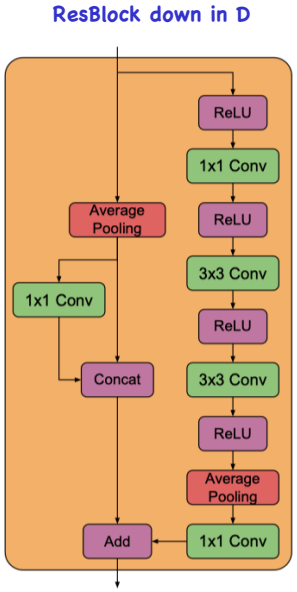
- Generate PXD background events with Generative Adversarial Network **(GAN)**
- **Used Models:**

DCGAN → **WGAN-gp** → **LOGAN (LO-cWGAN)** → **BigGAN-AC** → **BigGAN-deep**

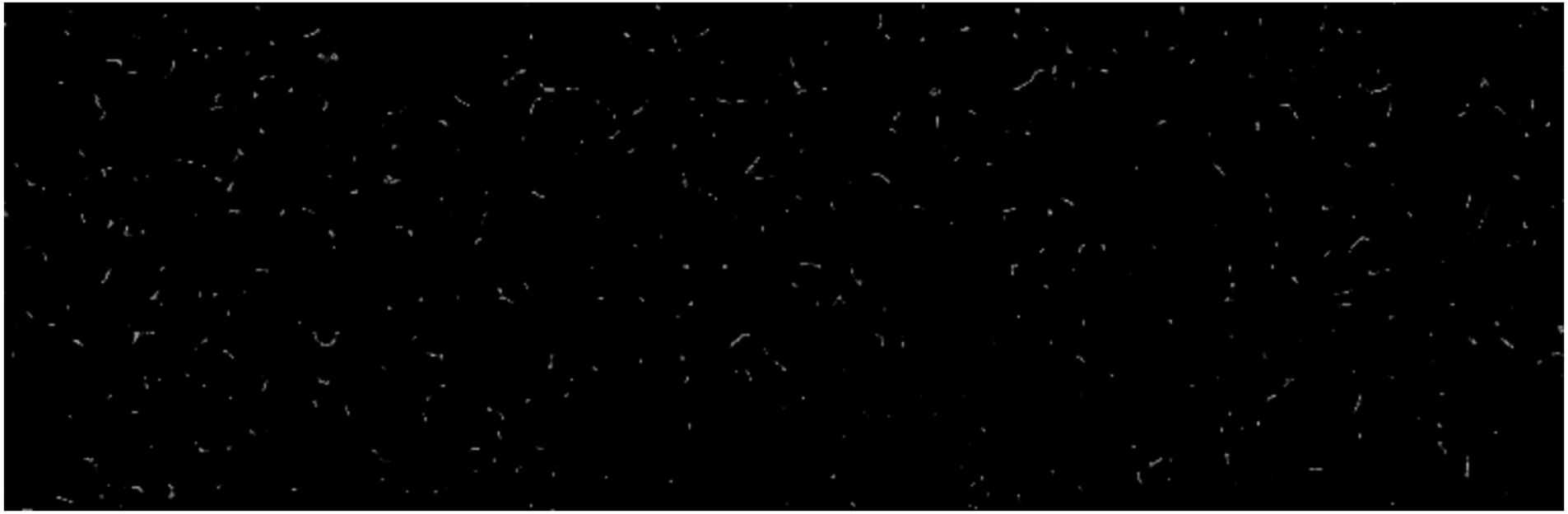
- **Technologies:**
  - *Self-Attention Module*
  - *Hinge Loss*
  - *Spectral Norm*
  - *Orthogonal regularisation*
  - *"Skip Connections" from noise*
  - *Orthogonal Weight init.*
  - *Latent Optimisation*
  - *Truncation trick (for BigGAN-AC)*



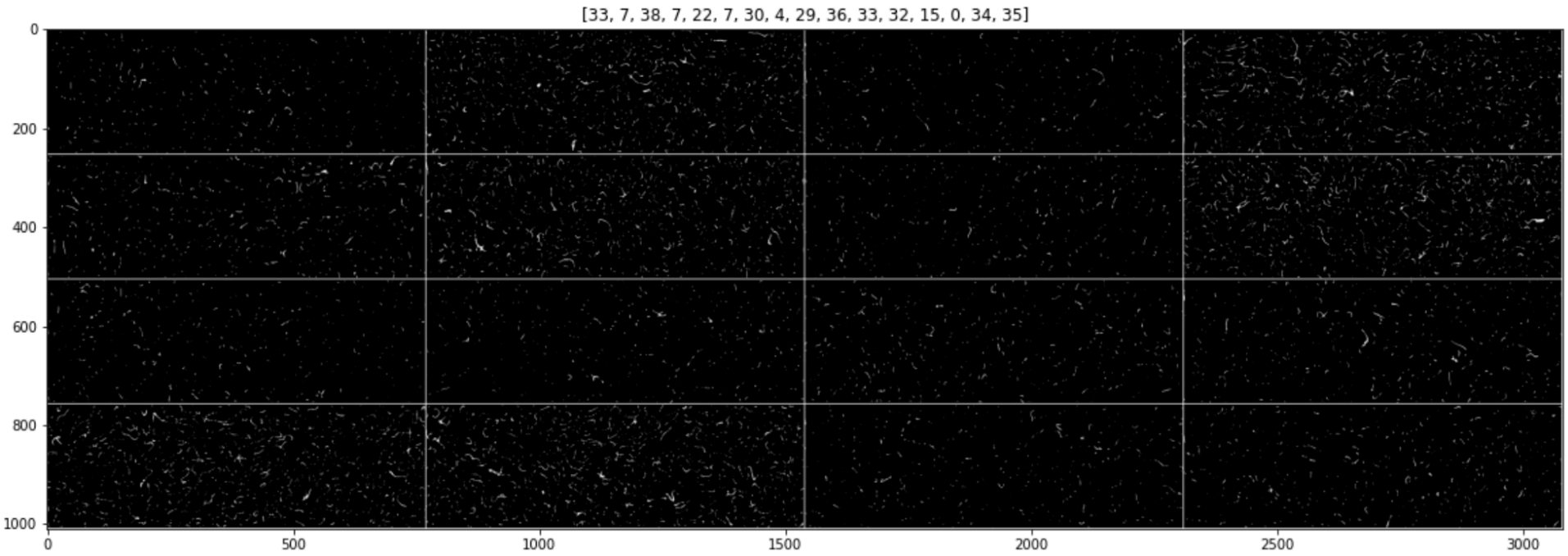




Example Generated PXD Images



Example Generated PXD Images



Validation of generated PXD images

Problem:

Missing a metric to say how good the generated images are.

Solutions:

- ☑ Evaluate tracking performance for
  - Signal + no bkg.
  - Signal + nominal bkg.
  - Signal + generated bkg.

  And compare:
    - Impact Parameter resolution: *Modified Frechet distance*
    - Track reconstruction efficiency
- ☑ Compare the number of hits per module

Validation of generated PXD images

Scoring: *Using Frechet Distance (2-Wasserstein distance):*

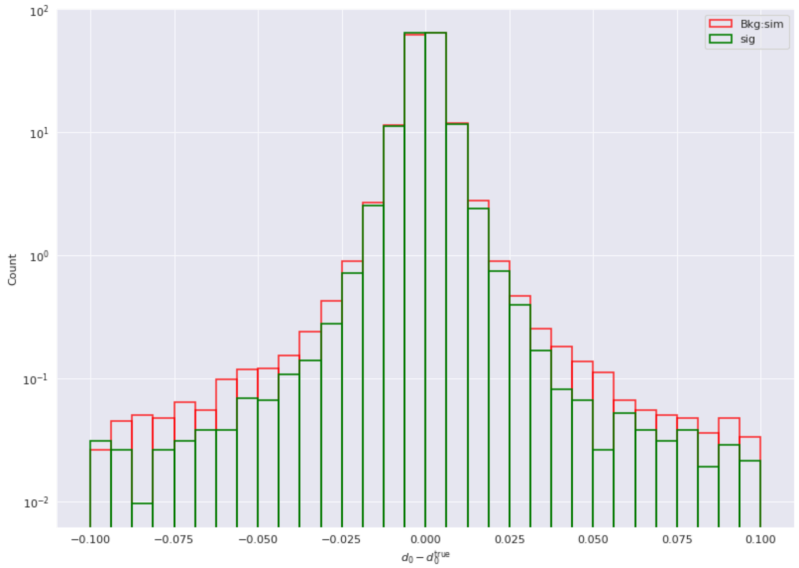
$$W_2(\mu_1, \mu_2)^2 = \|m_1 - m_2\|_2^2 + \text{trace}\left(C_1 + C_2 - 2\left(C_2^{1/2} C_1 C_2^{1/2}\right)^{1/2}\right).$$

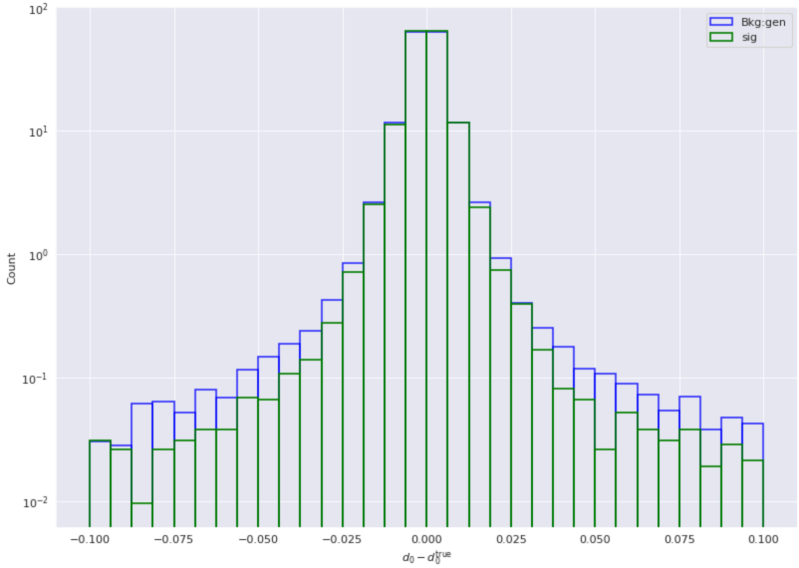
for $\mu_1 = N(m_1, C_1)$ and $\mu_2 = N(m_2, C_2)$.

Comparing the statistical features of Impact Parameters, then try to minimise the FD score for the best GAN model.

The Lower the FD score, the better the image quality and diversity from the physics point of view.

Validation of generated PXD images for d_0 impact parameter



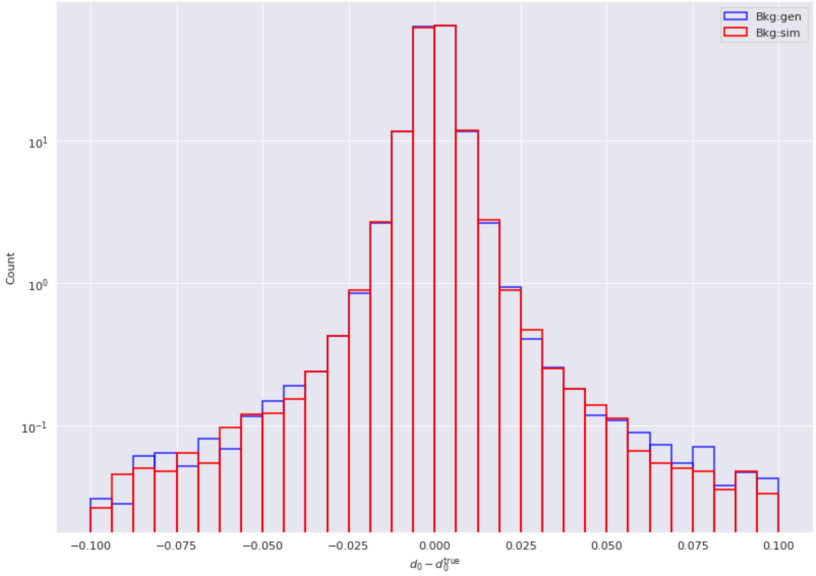


*FD scores of the new Model (**BigGAN-deep**) between:*

A. sim-sig : 5.42e-4

B. gen-sig : 7.41e-4

C. gen-sig : 1.64e-5



FD scores of the old Model (WGAN-gp) between:

A. sim-sig : 5.42e-4

B. gen-sig : 8.01e-4

C. gen-sig : 1.79e-5

Outlook

- Refine the GAN setup in order to capture ***correlation*** between two layers of PXD detector like a *motion picture generation* using *sequence based GAN models.*
- Train the model wrt to the class-condition of number of hits.
- Create a custom ***Inception Score (IS)***, based on simulated events in order to have a fully automated validation metric.
- Using bkg figures of merits such as cluster analysis to compare the spatial features of pixel clusters created by different background types.
- Comparing the performance of *Variational Auto Encoders* (the greatest enemy of GANs!)
- Simulation Software implementation.

Thank You


WOOF
WOOF
WOOF
WOOF
WOOF
WELL, THE DOGS COULDN'T TELL ANY DIFFERENCE, AND NIETHER COULD I. CONGRATULATIONS, YOU'VE CREATED A MACHINE THAT IS JUST AS INTELLIGENT AND CONSCIOUS AS DOGS.
THANK YOU, AND WITH YOUR GRANT MONEY, I'M SURE HUMANS AREN'T FAR BEHIND.
EXISTENTIAL COMICS

Average PXD occupancy values in %