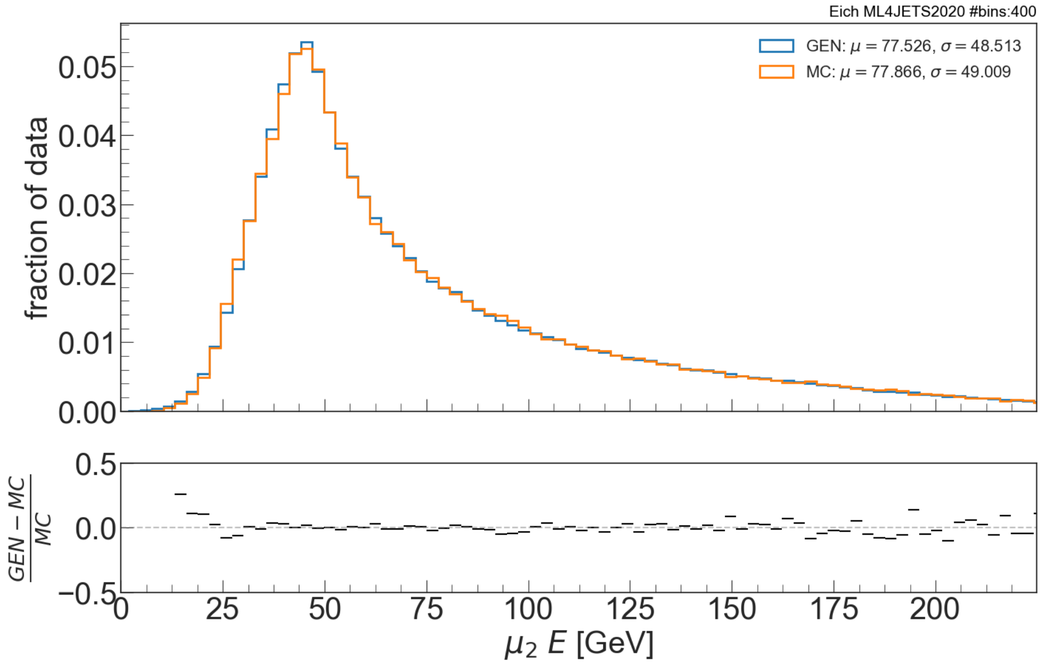

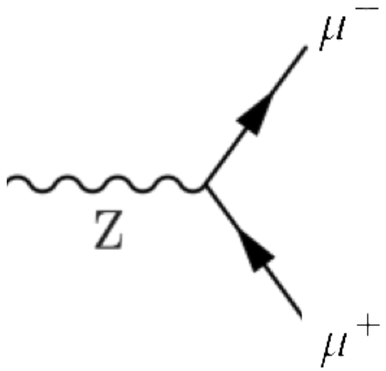

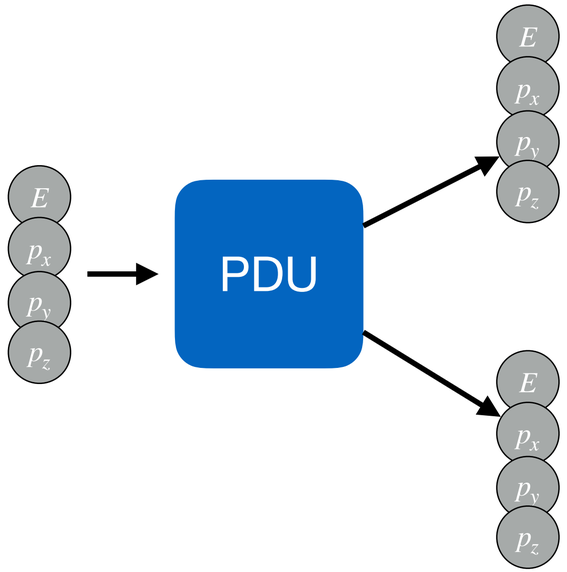

A generator cell for LHC event GANs: Particle Decay Unit

Niclas Eich, Martin Erdmann, Benjamin Fischer
RWTH Aachen University

ML4Jets2020

15th January 2020

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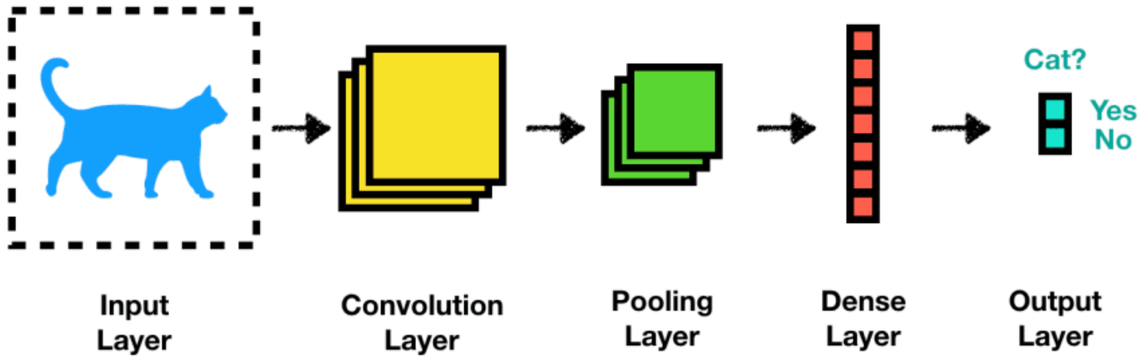
Our Goal

Computer Vision (CV)

Convolutions are the fundamental operations of image recognition

- Accelerated CV in deep learning
- Many successful applications in physics as well

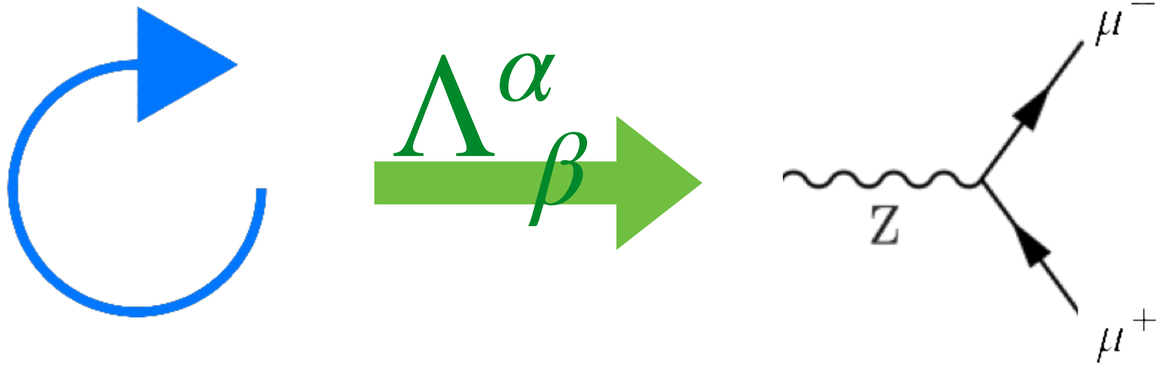


Physics

The **Lorentz group**, **boosts** and **rotations**, are the fundamental transformations of particle physics

➜ Can a generating network be built with these transformations?

➜ Study this at a simple process $Z \to \mu^+\mu^-$



Generation of a two-body decay

1. **Rest frame** of decaying particle

$$Z = \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix} \rightarrow \begin{pmatrix} M \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

2. **Energy**- and **momentum-conservation** (back to back)

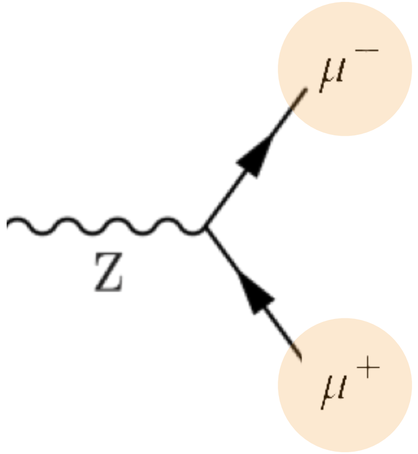
$$p_1 = \frac{\sqrt{\left(M^2 + m_1^2 - m_2^2\right)^2 - 4M^2 m_1^2}}{2M} \qquad l_i = \begin{pmatrix} \sqrt{m_i^2 + p_i^2} \\ \pm\vec{p_i} \end{pmatrix}$$

3. Pick **random orientation** isotropically

$$l_i = \begin{pmatrix} E_i \\ cos(\theta)sin(\phi)p_i \\ sin(\theta)sin(\phi)p_i \\ cos(\phi)p_i \end{pmatrix}$$

4. **Boost** into lab frame of mother particle

$$l_i^{\alpha'} = \Lambda_{\alpha}^{\alpha'} l_i^{\alpha}$$



Generation of a two-body decay

Niclas Eich - ML4Jets2020

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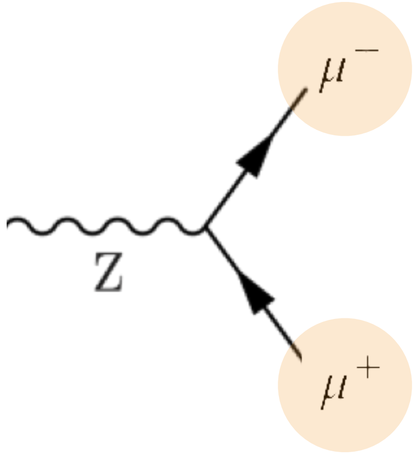
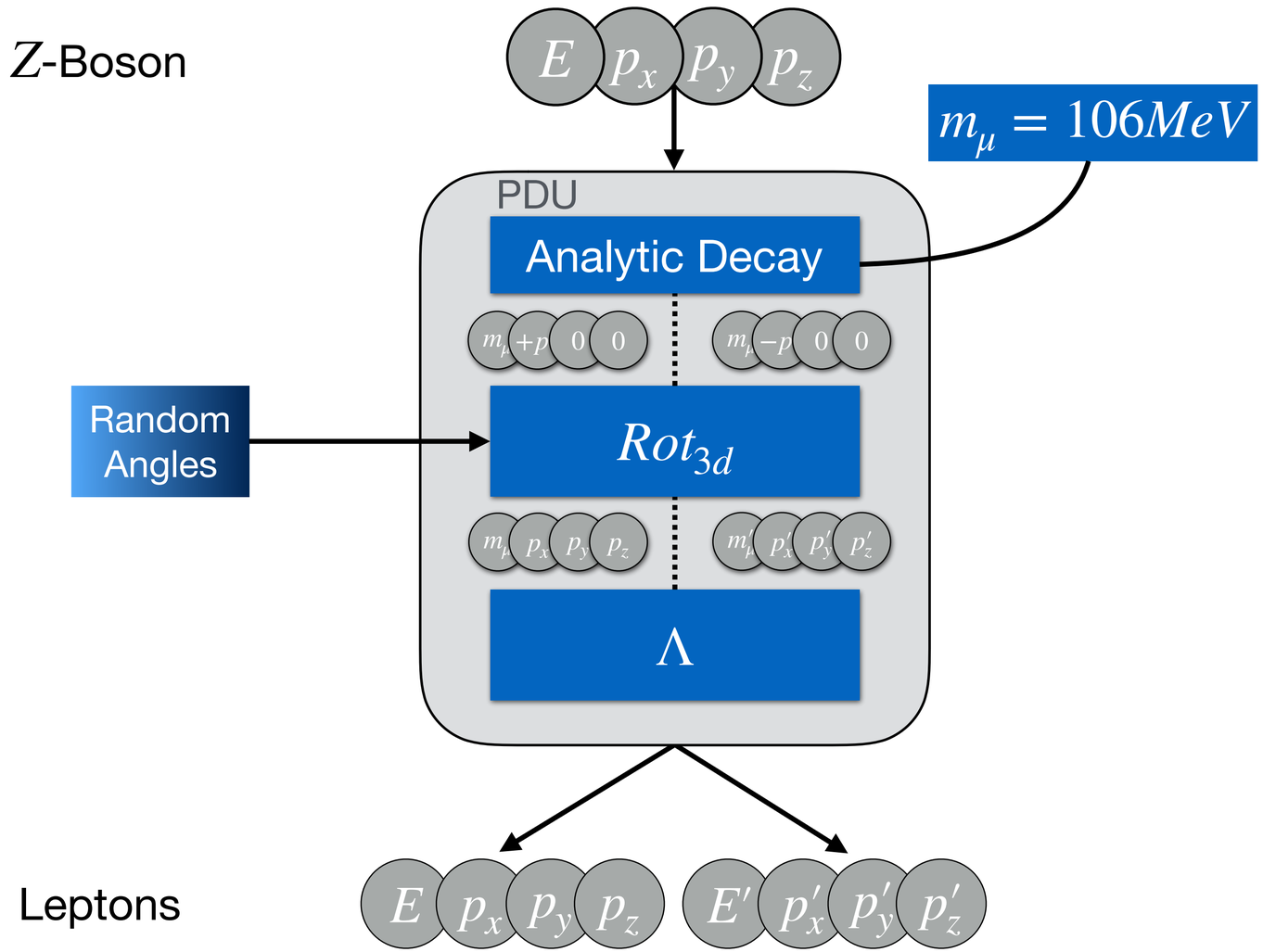


Embed this recipe inside a neural network

4 Particle Decay Unit (PDU)

Full Generator:

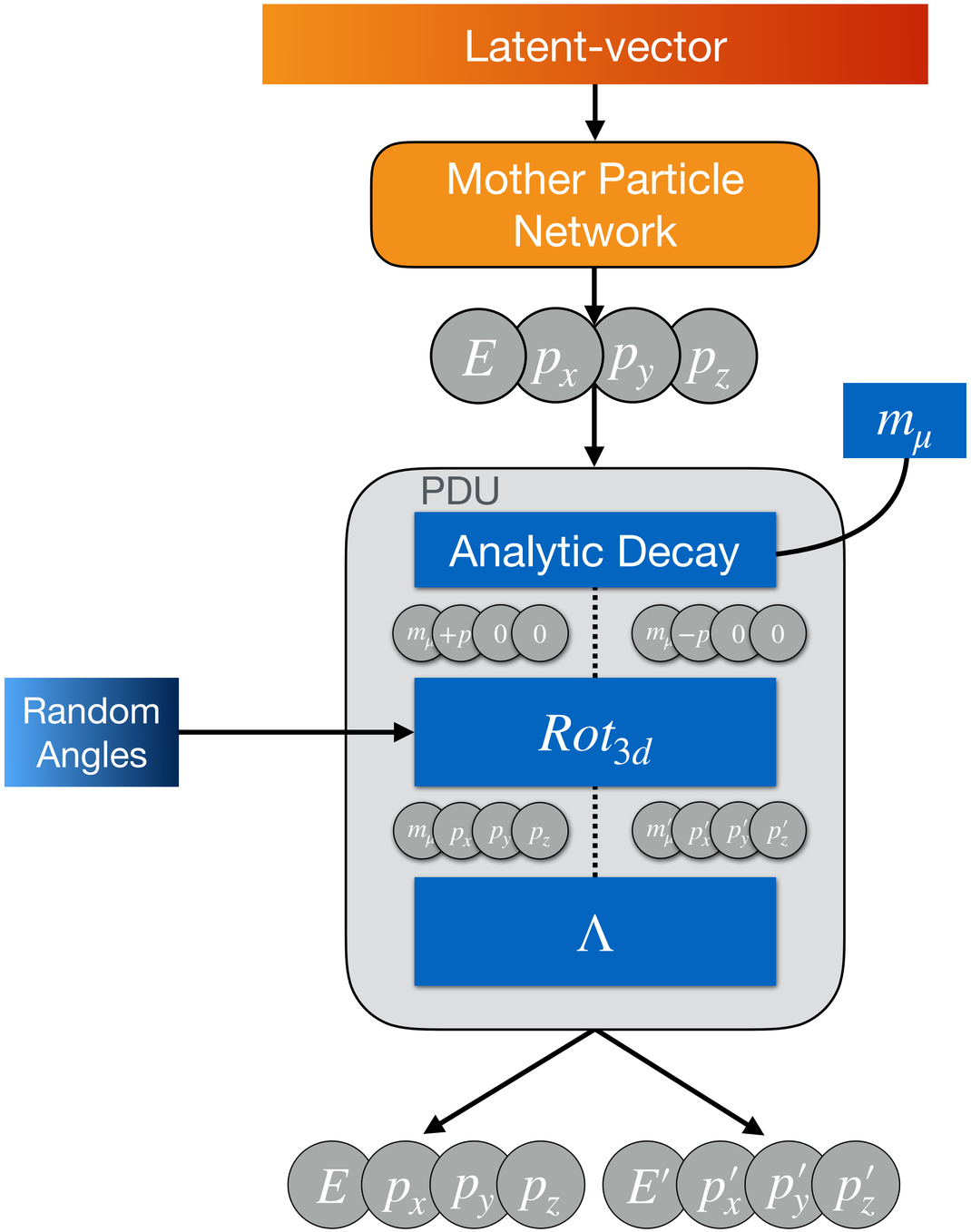
- ☐ Variance
- ☐ Detector acceptance
- ☐ Detector effects & higher orders



5 Mother particle modelling

Full Generator:

- ✓ Variance
- ☐ Detector acceptance
- ☐ Detector effects & higher orders



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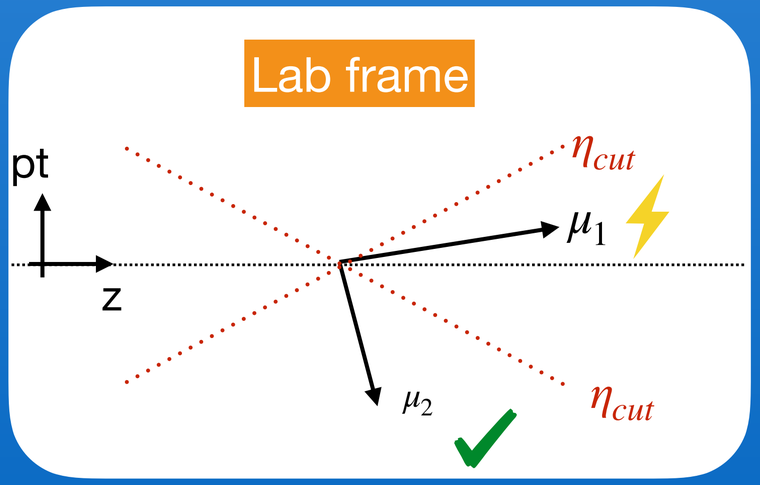
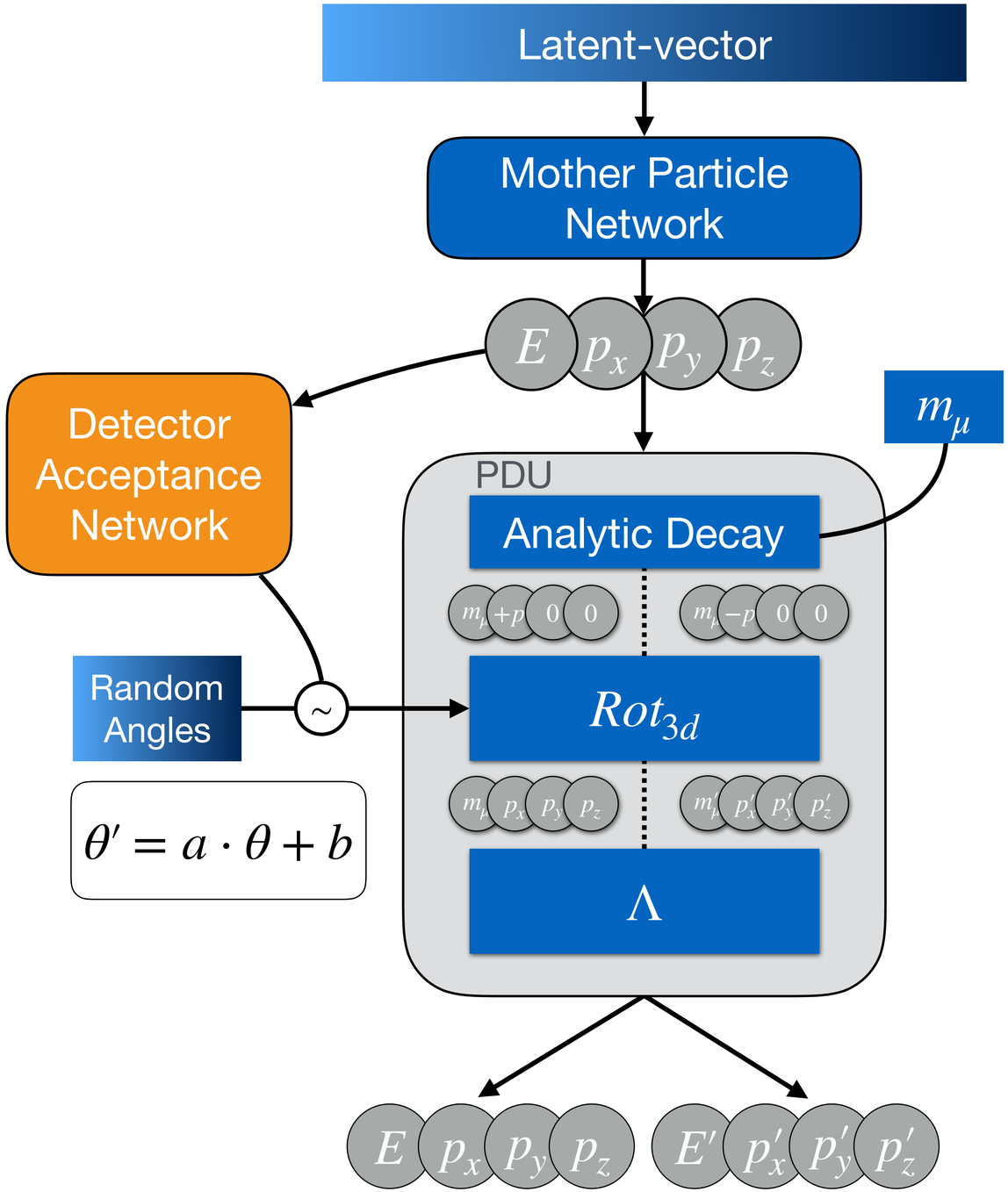
Parametrised Rotation

Full Generator:

- ✓ Variance
- ✓ Detector acceptance
- ☐ Detector effects & higher orders

Decay products need to be in detector acceptance





4-vector refinement

Full Generator:

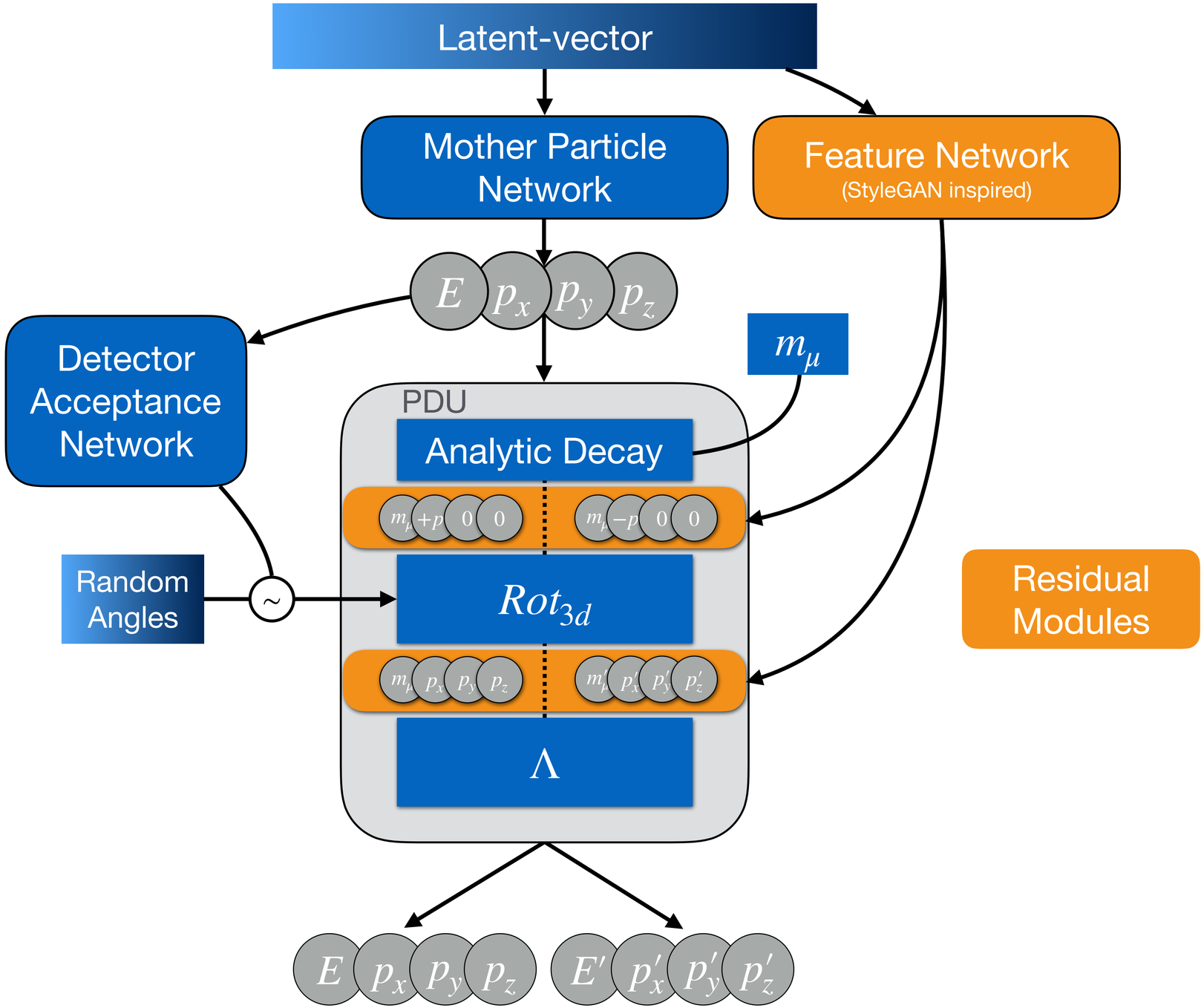
- ✓ Variance
- ✓ Detector acceptance
- ✓ Detector effects & higher orders

Feature Network preprocesses noise [arXiv:1812.04948]

Additional residual modules further model effects on the 4-vectors

$x' = x + f_{Res}(x)$

➜ only small changes



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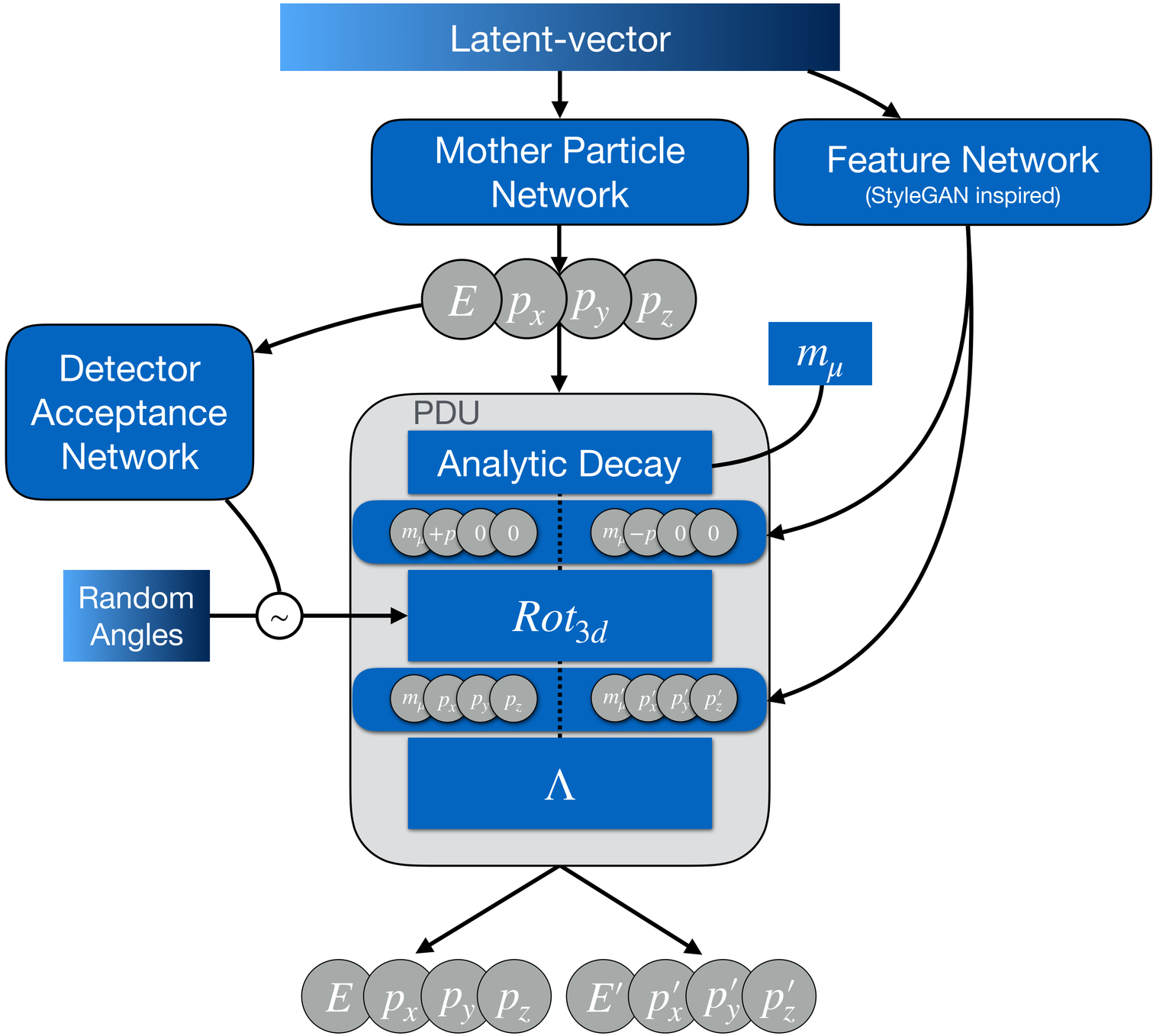
Generator Network

Full Generator:

- ✓ Variance
- ✓ Detector acceptance
- ✓ Detector effects & higher orders

Every component has a physical interpretation to it



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WGAN Training

WGAN Setup

Wasserstein Loss

$$\mathrm{EMD}\left(P_r, P_\theta\right) = \sup_{\|f\|_{L\leq 1}} \mathbb{E}_{x\sim P_r} f(x) - \mathbb{E}_{x\sim P_\theta} f(x)$$

Gradient penalty for Lipschitz-constraint [arXiv:1704.00028]

Schedule:

1/10 Generator/Critic updates

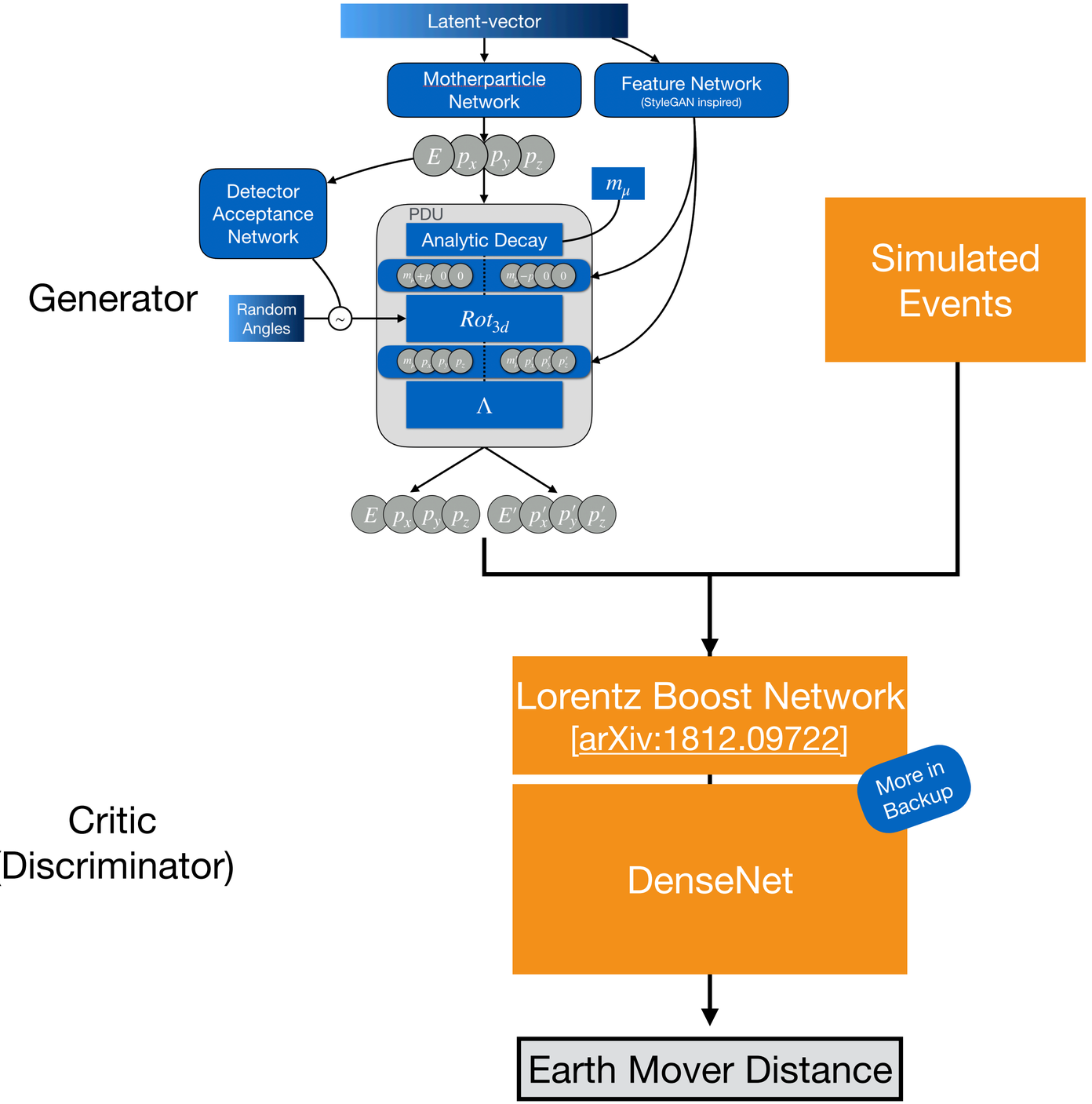
Simulation:

$Z \to \mu^+\mu^-$

450k events

MadGraph5_aMC@NLO

Delphes



10 Critic Network

Pre-Stage:

Lorentz Boost Network

[arXiv:1812.09722]

Can combine particles to mother particle candidate

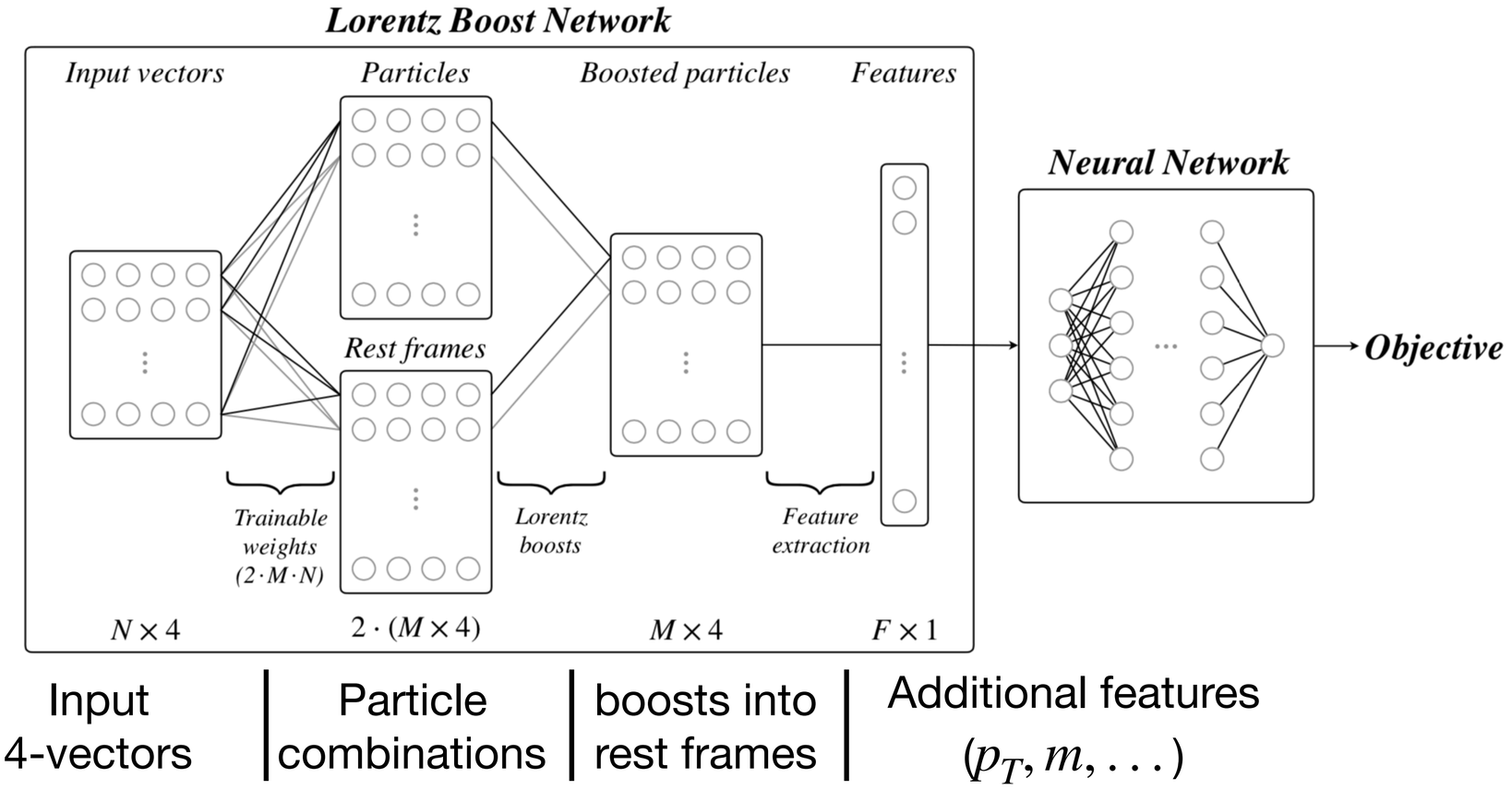
$$1.0 \cdot \vec{p_1} + 1.0 \cdot \vec{p_2} + 0.0 \cdot \vec{p_i} = \vec{p_\alpha} \rightarrow \vec{p'_\alpha}$$

DNN-Part:

DenseNet Architecture (shortcuts)

3×2 Layers, 280 Nodes,

leaky ReLU activation



Input 4-vectors	Particle combinations	boosts into rest frames	Additional features $(p_T, m, \ldots)$

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Basic Kinematics

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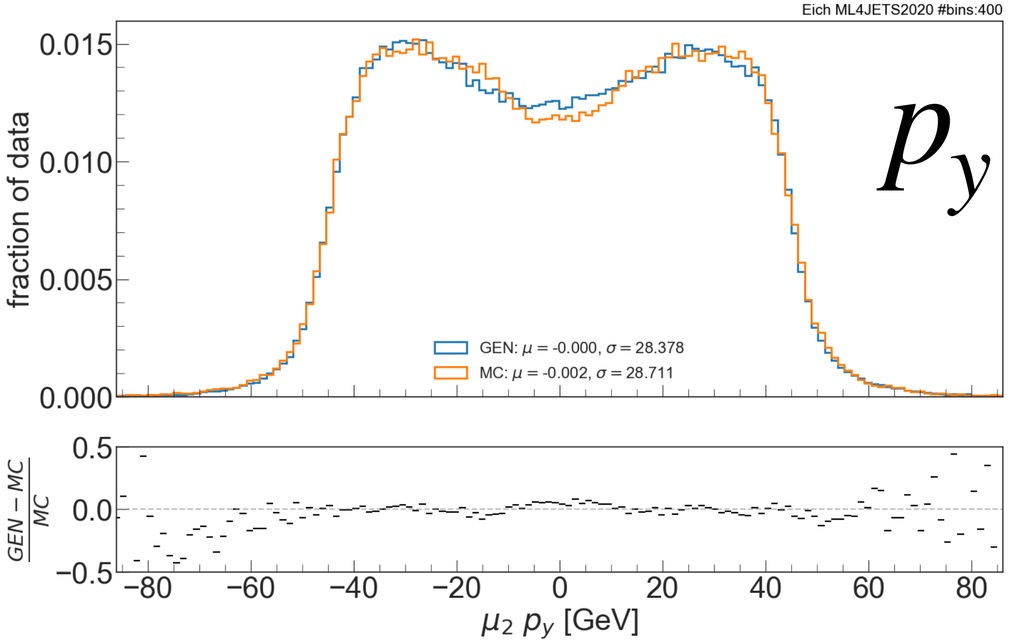
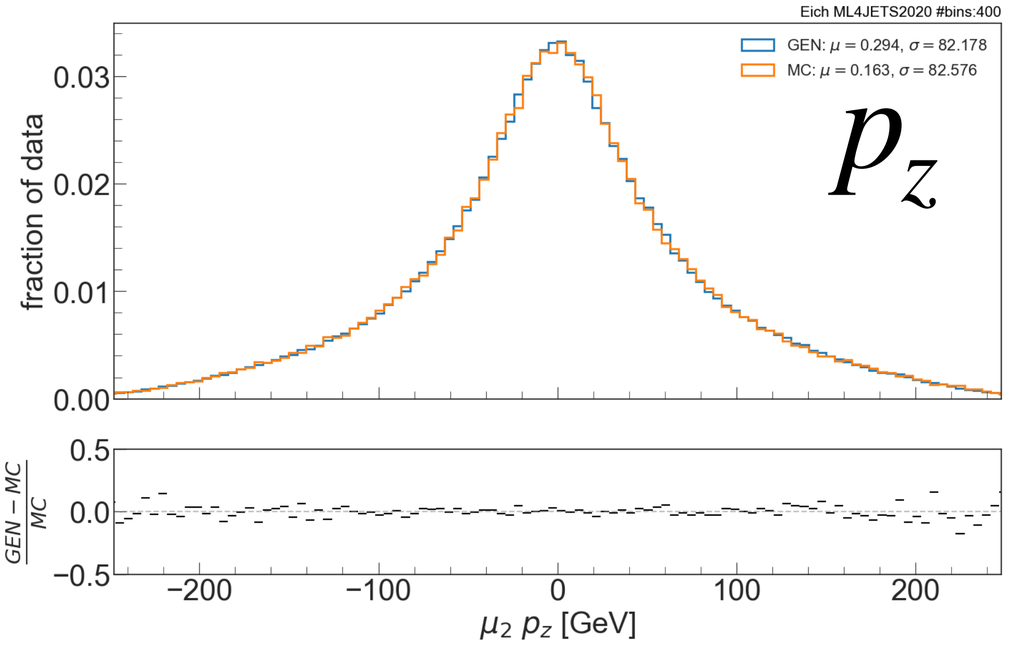
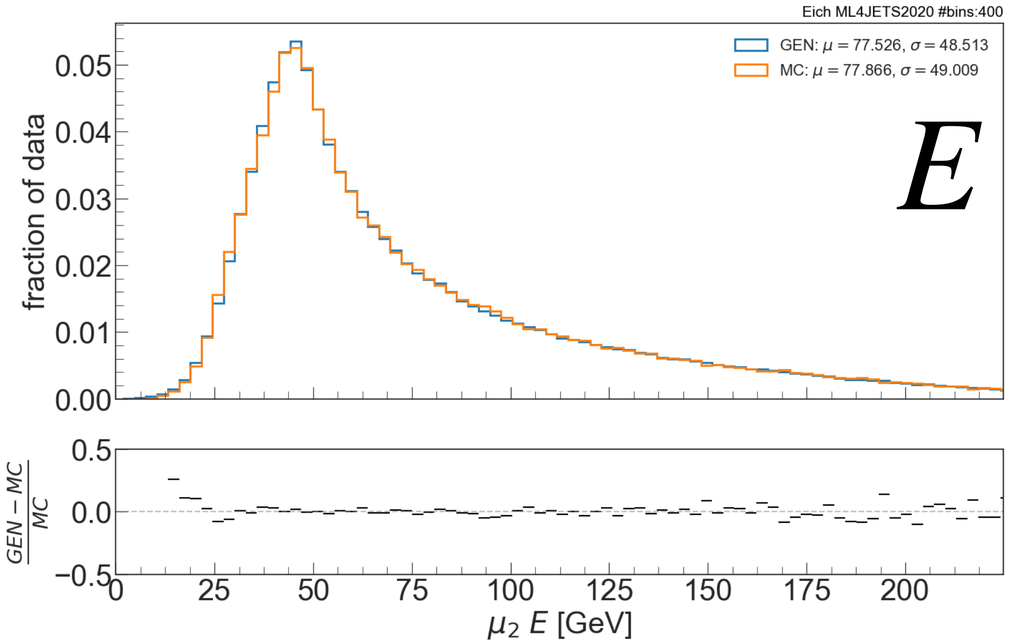
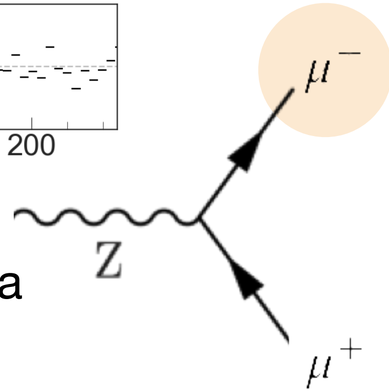


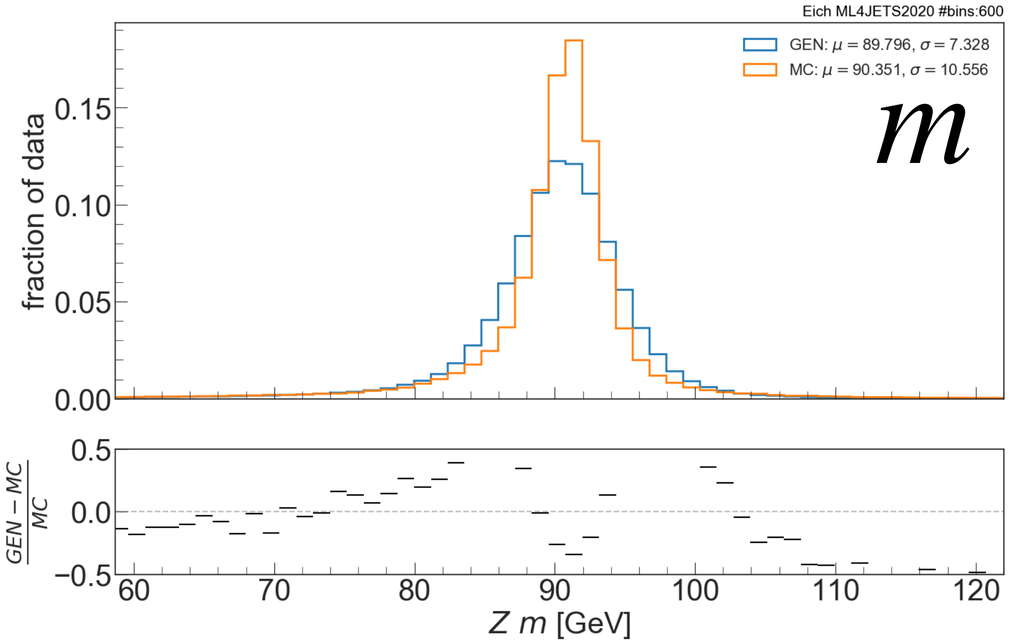


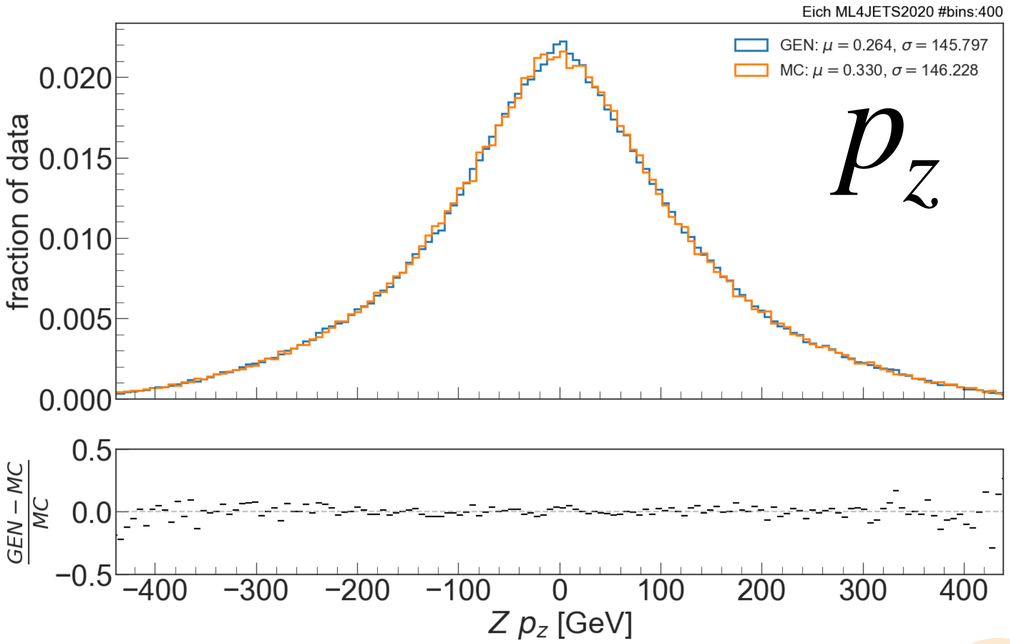


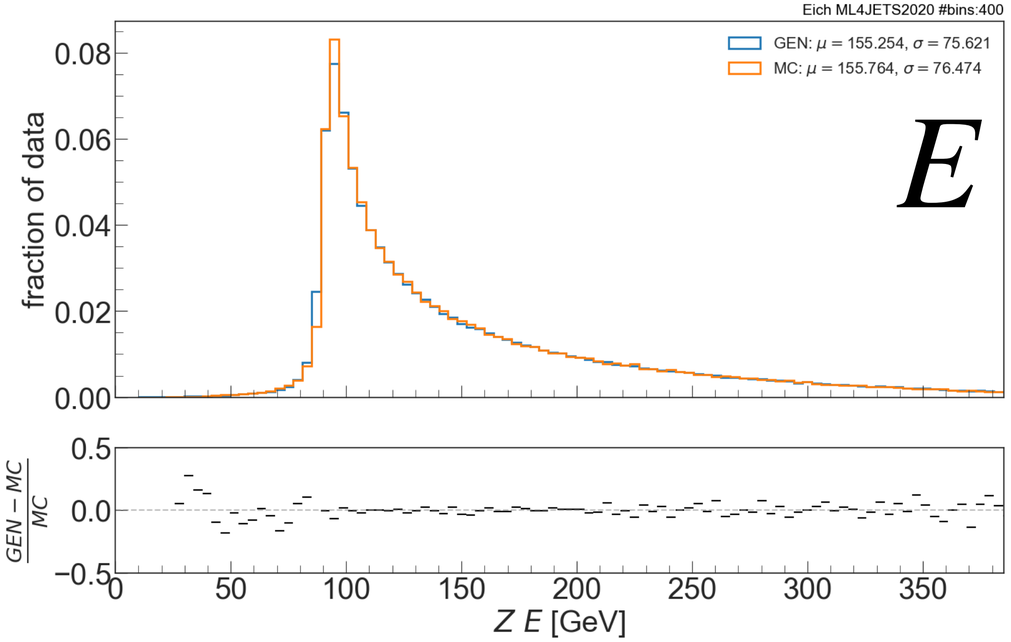


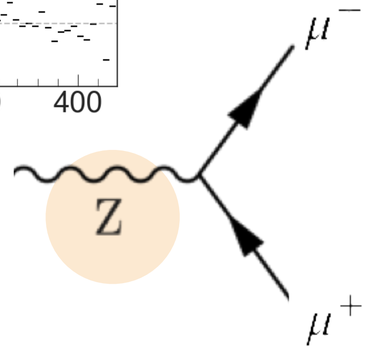
- Good agreement of generated data to simulation
- Almost independently of high/low occupancy regions

Mother Particle Candidate









- Add muons to reconstruct Z

  $\overrightarrow{\mu_1} + \overrightarrow{\mu_2} = \overrightarrow{Z}_{Candidate}$

- Mass too much spread
- E and p_z good agreement

Detector Acceptance & Isotropy

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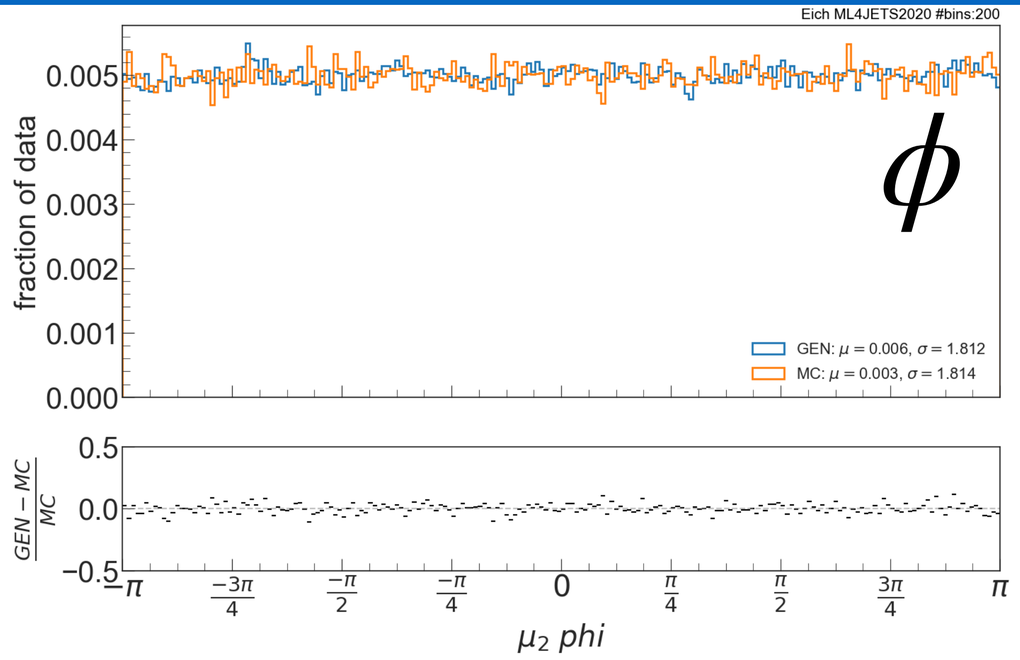
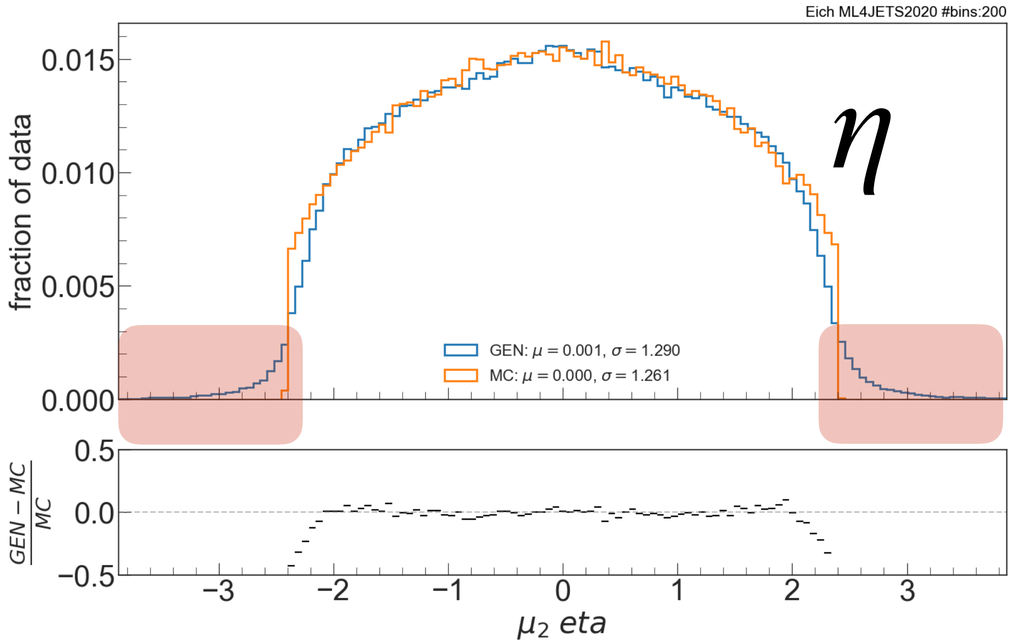
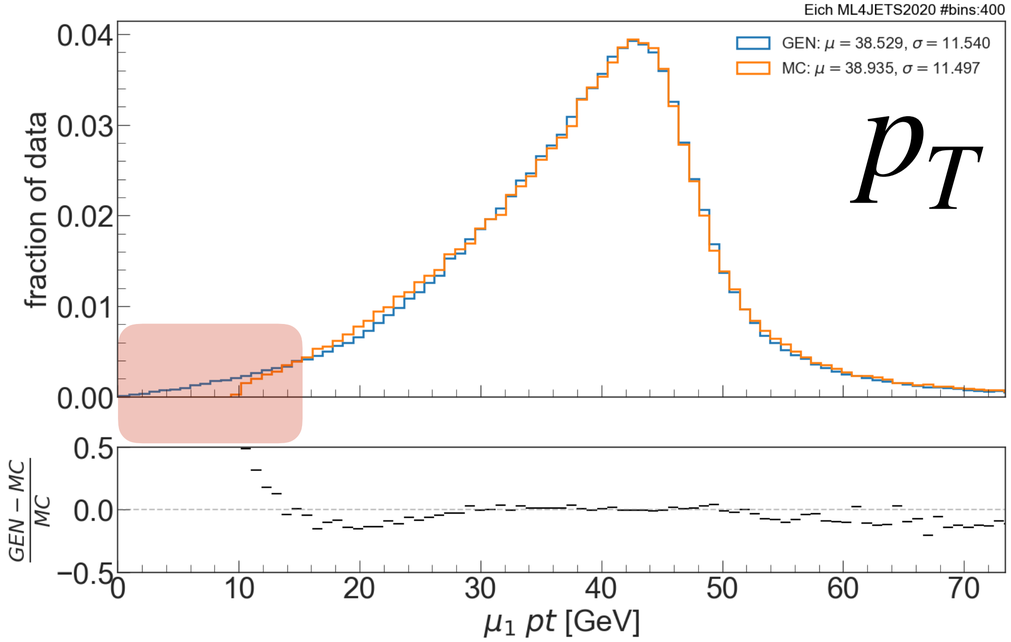
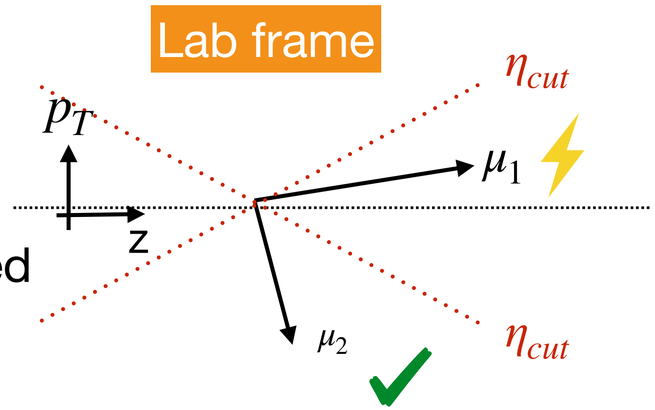






- Decay stays isotropic after residual modules (ϕ-Distribution)
- p_T and η are not modelled perfectly



Detector Acceptance Network: Effects

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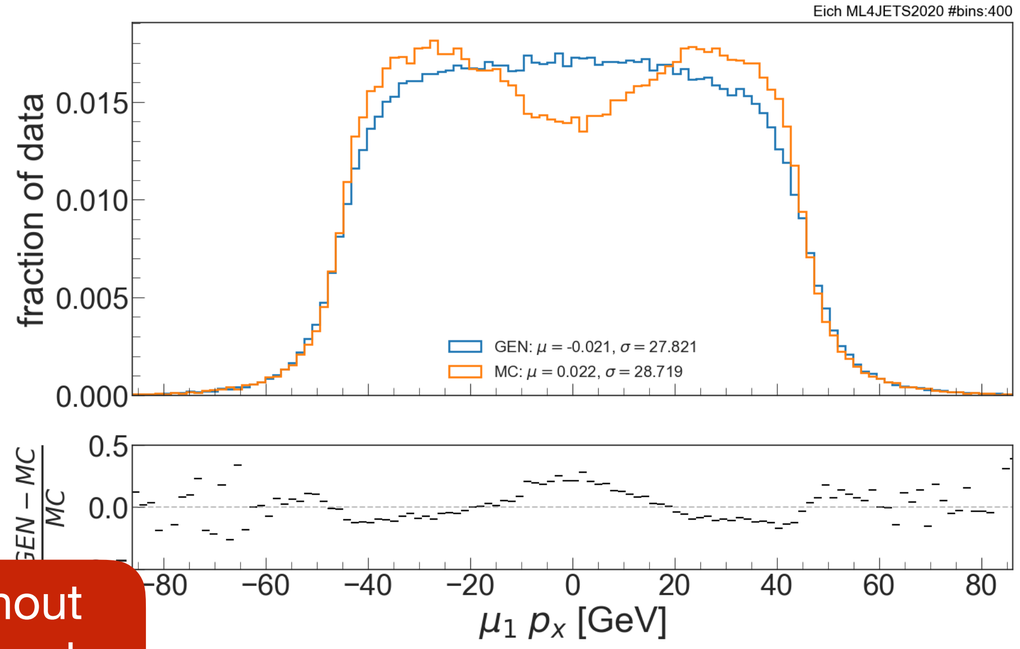
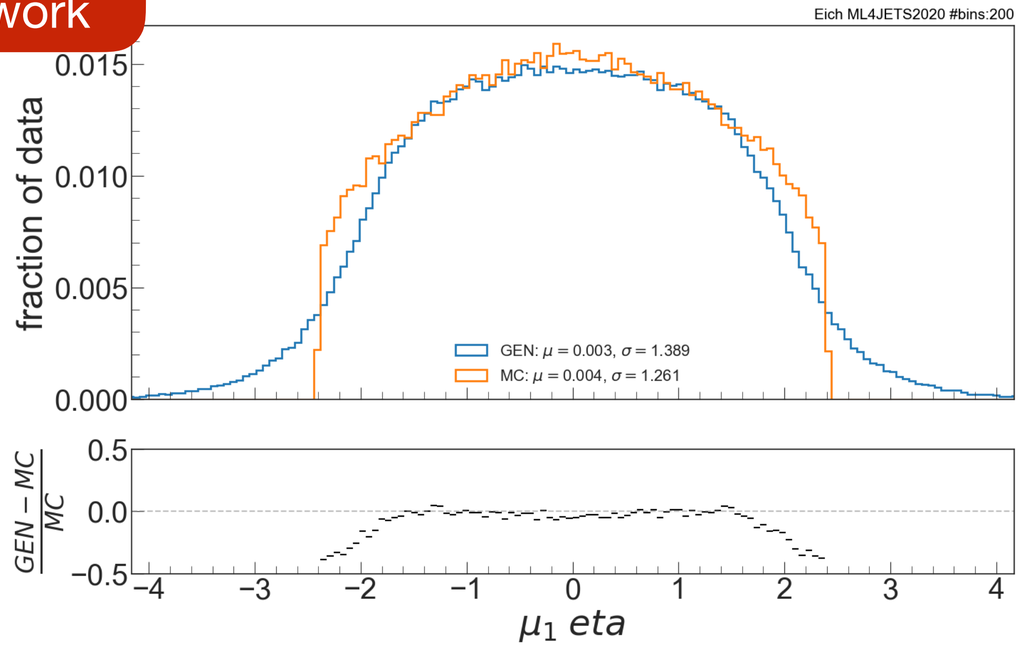
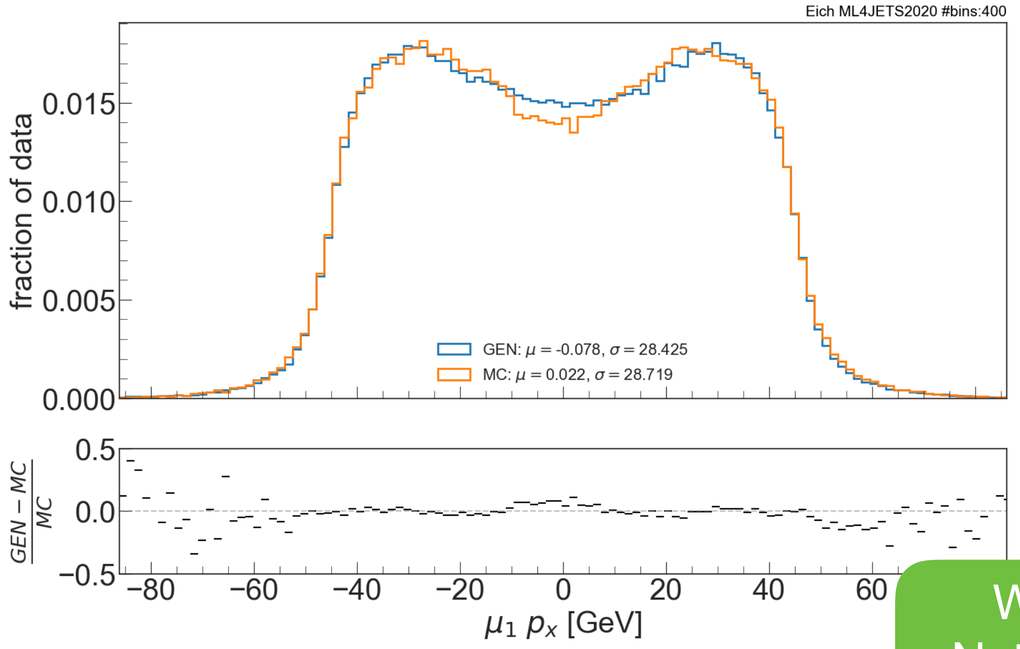
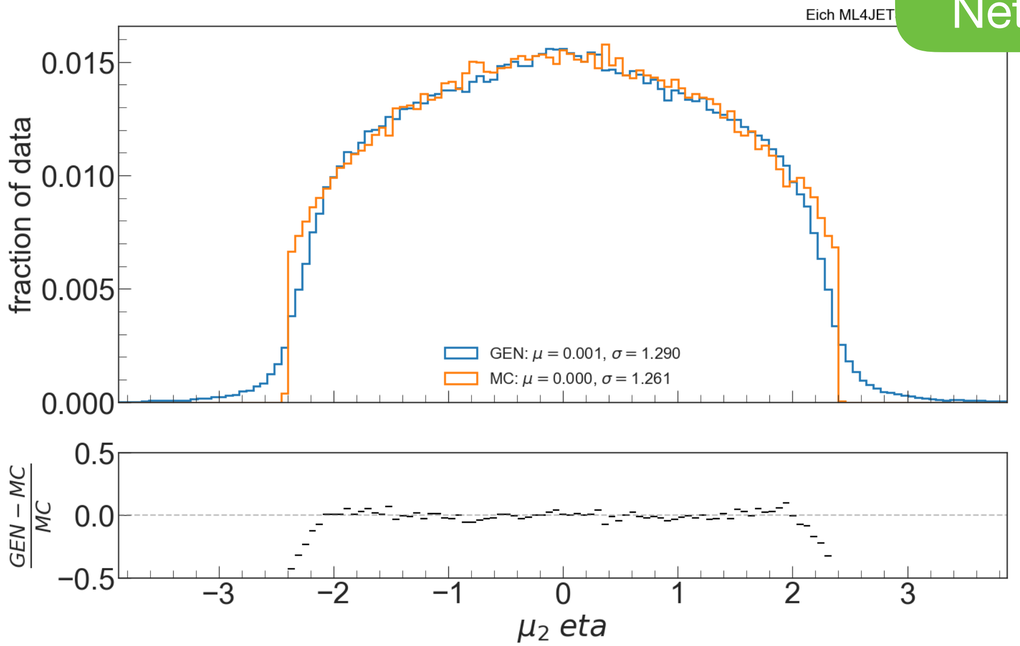
Without Network





With Network





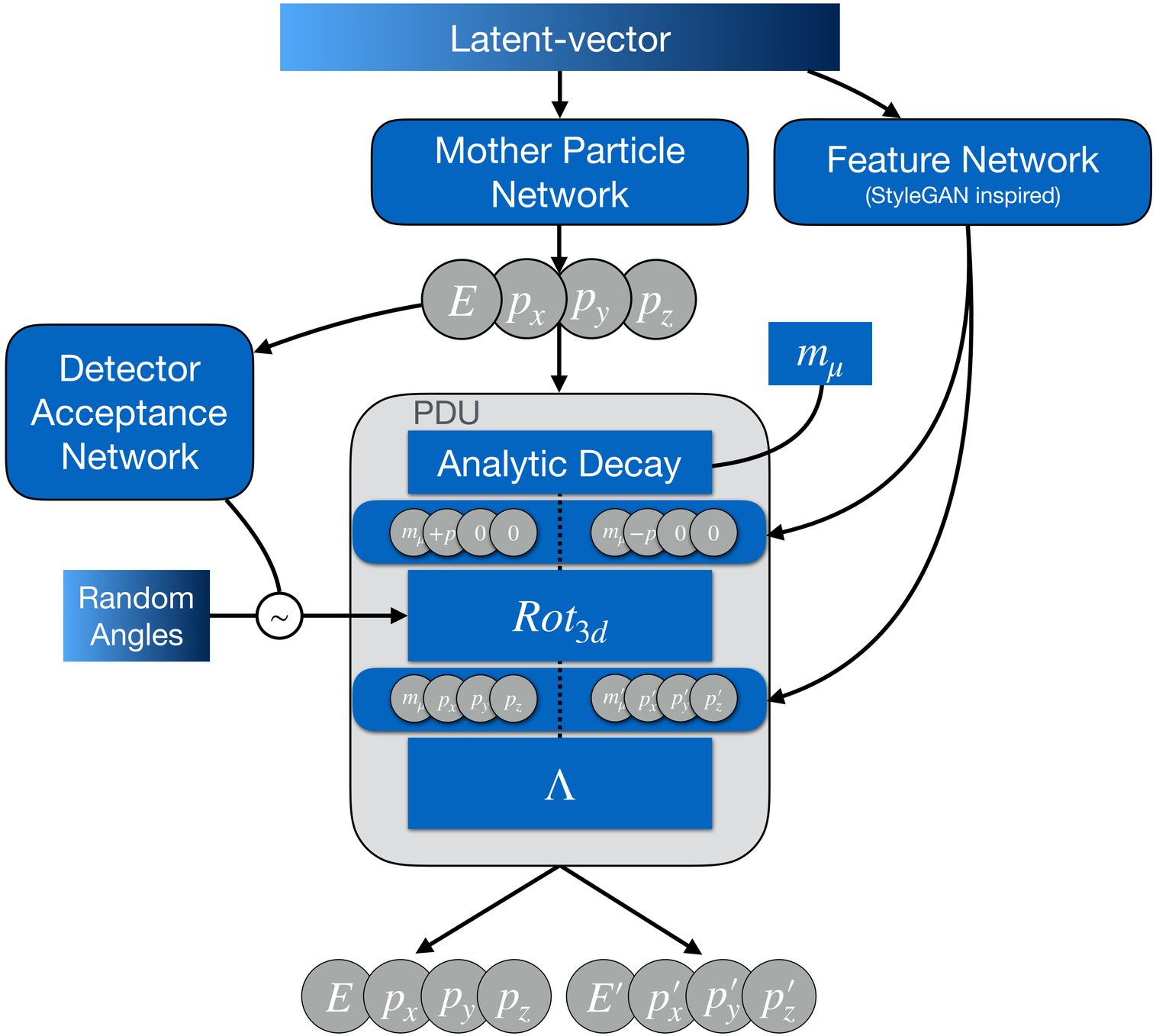
15 Network Structure

Network Size:

- Mother particle Network
  - 3 Layers
  - 600 Nodes
  - SeLU Activation
- Feature-Network
  - 3×3 Layers densely connected
  - 280 Nodes
  - ReLU Activation
- Detector Acceptance Network
  - 6 Layers
  - 280 Nodes
  - ReLU Activation
- Residual Modules
  - 2×3 Layers added on 4-vectors
  - 280 Nodes
  - ReLU Activation

Total:

- 0.5M - **3.3M** Params
- 6 hours Training
  (GTX 1080)



Challenges

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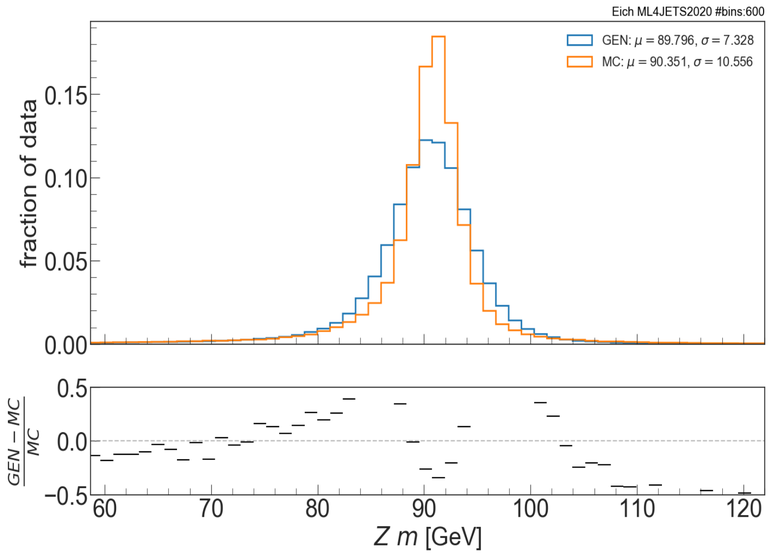
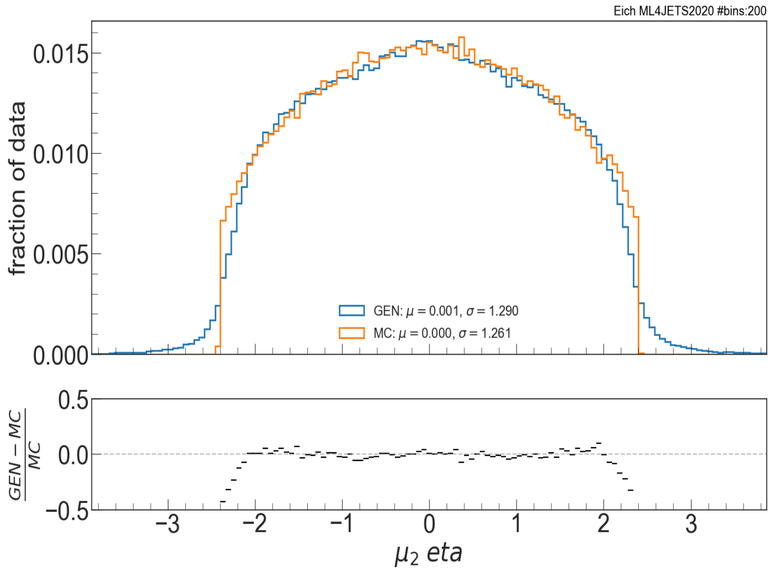
- Mass modelling

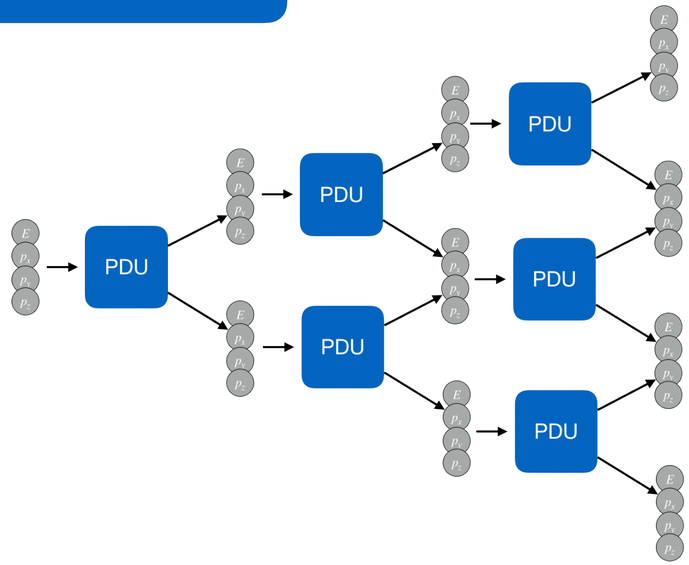




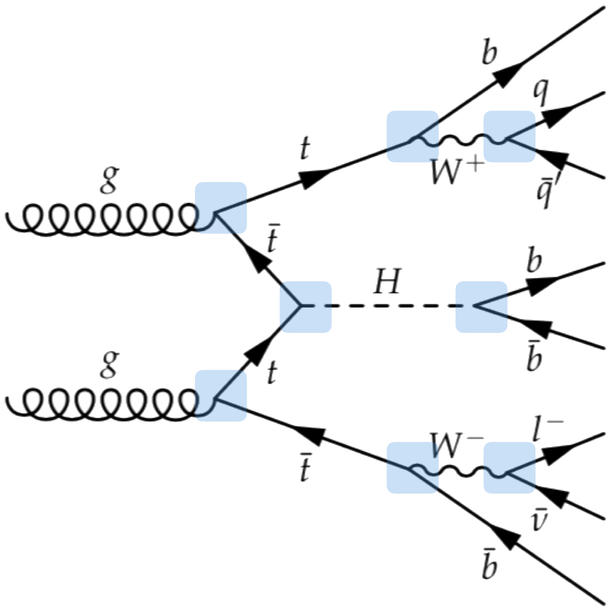
- Detector Acceptance, p_T/η cuts

- Free floating masses inside the PDU

$$m_\mu = f(\dots)$$



- Jets and more complex Feynman diagrams
  - $Z \to b\bar{b}$
  - QCD modelling



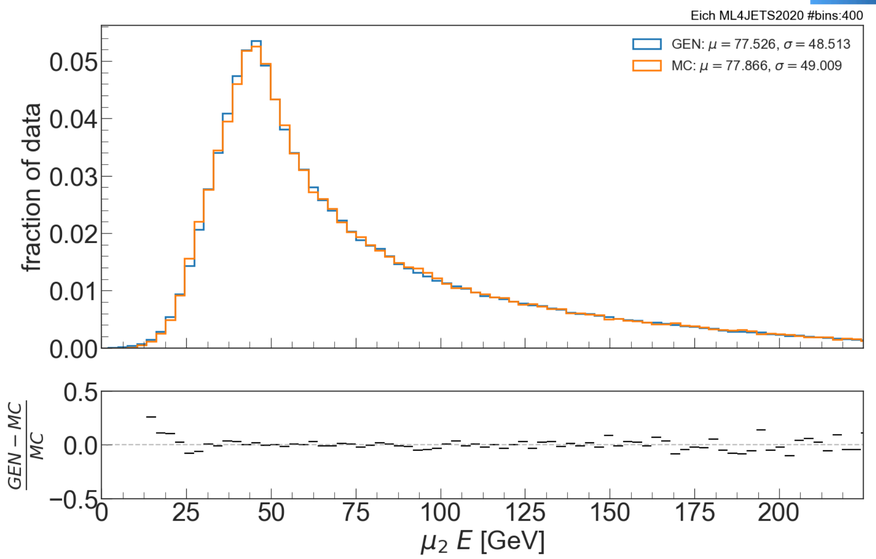
- Application on full simulation

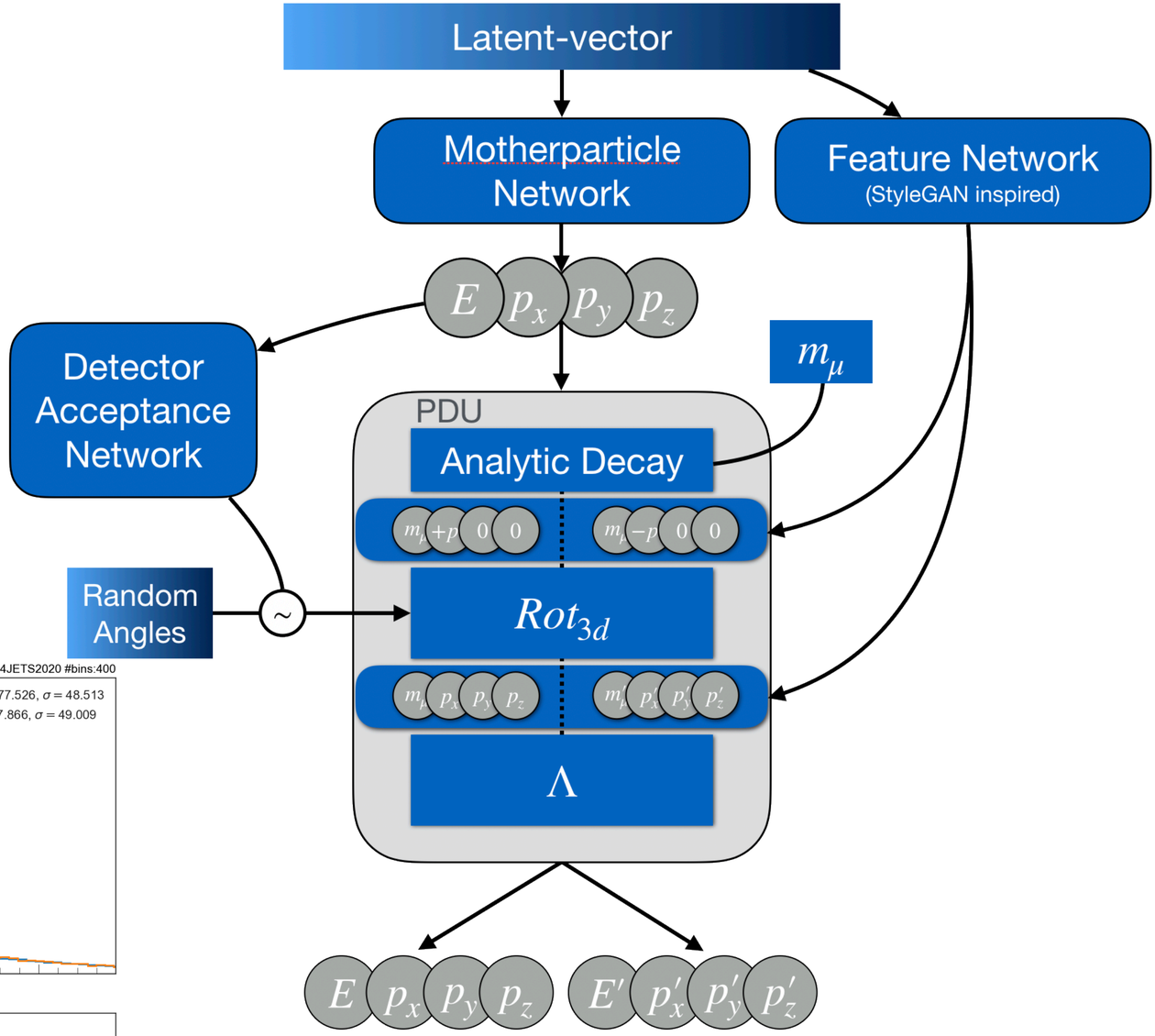
Summary

- Built Particle Decay Unit with:
  - Lorentz Boosts
  - Rotations

- Generator components have physical interpretation
  - No black-box

- Generated decay particles are in good agreement with simulation.
  Control plots of reconstructed mother particle and detector acceptance still to be improved
  (m, p_T, η)

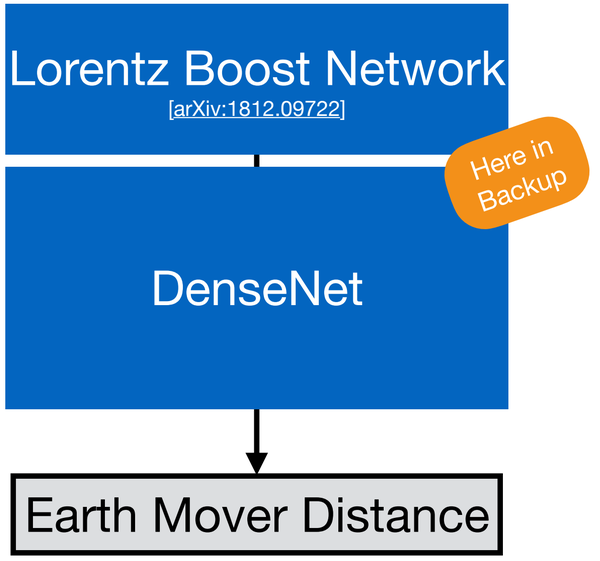




Backup

Critic Setup - Generation Time

- Additional computed features on 4-vecs: η, ϕ, m
- Pre-stage: Lorentz Boost Network [arXiv:1812.09722]
  - Autonomously combines particles and boosts them into learned rest frames
  - Especially useful for processes with more final state particles
- Main-Body
  - DenseNet architecture fully connected [arXiv:1608.06993]
    - 3×2 Layers, 280 Nodes, leaky ReLU activation
  - Minibatch-discrimination like layer [arXiv:1606.03498]
    - Computes mean and variance across batch as features



Generation Time

- **~100k Events/s** at batch-size ~1000
- GTX 1080

Training	Generator	Critic
Optimizer	Adam	Adam
Beta1/2	0.5/0.9	0.5/0.9
Learning Rate	$5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$
LR-Decay	10^{-2}/1500 epochs	
Trained epochs	2000	
Gradient Penalty	1.0	

Training Loss Plots - no improvement in longer Training

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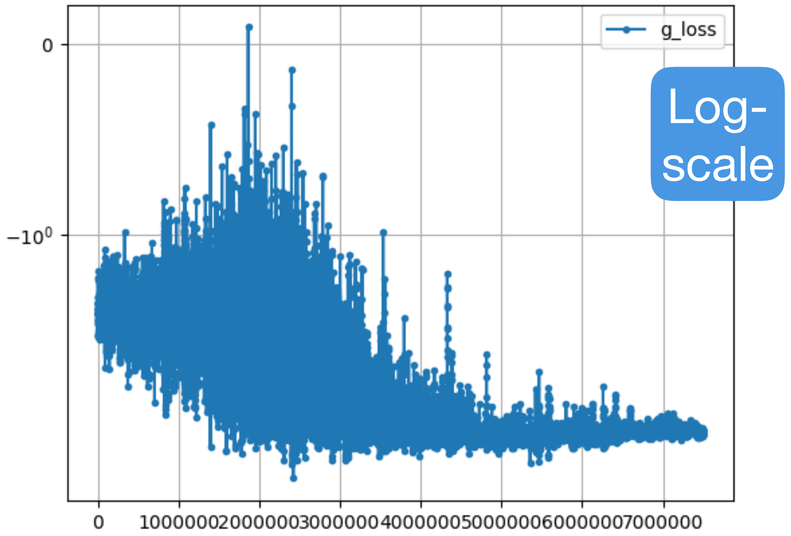
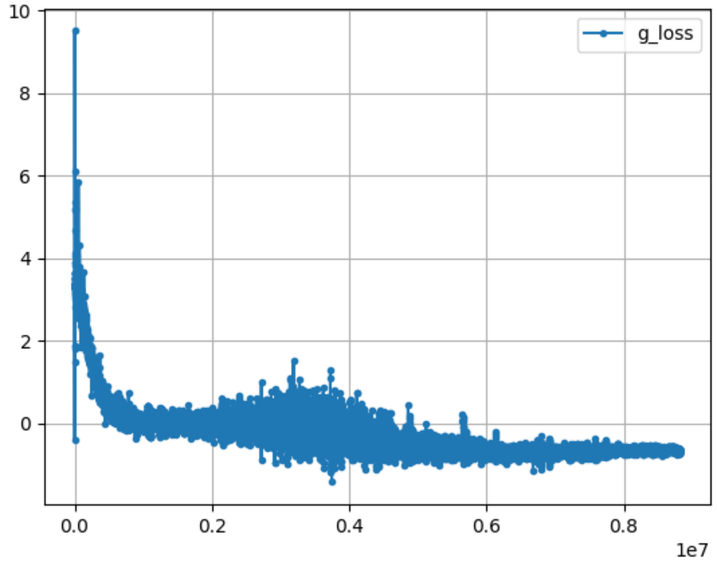
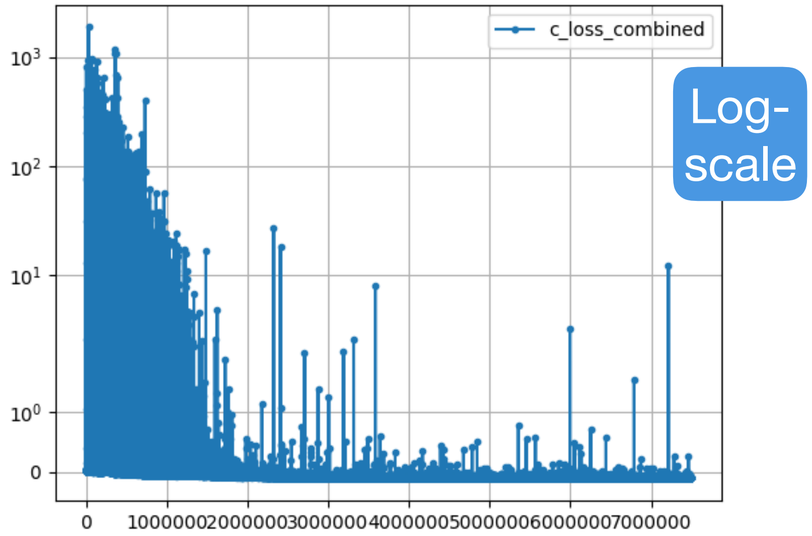
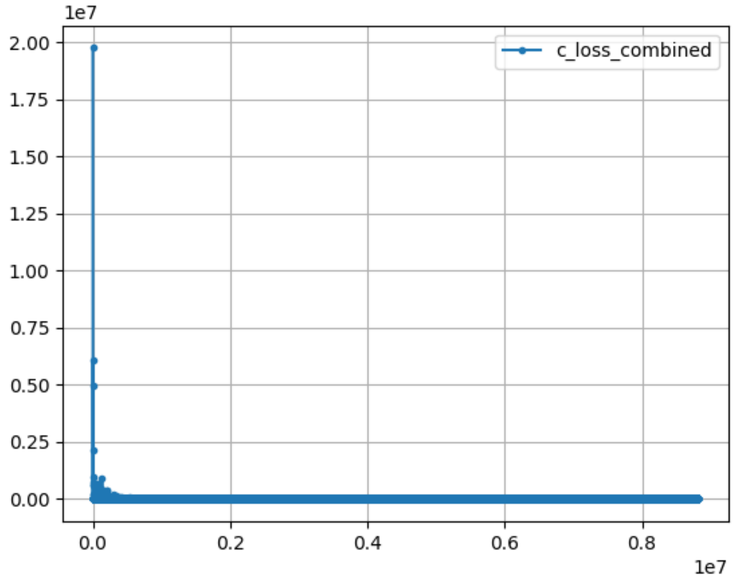
Generator



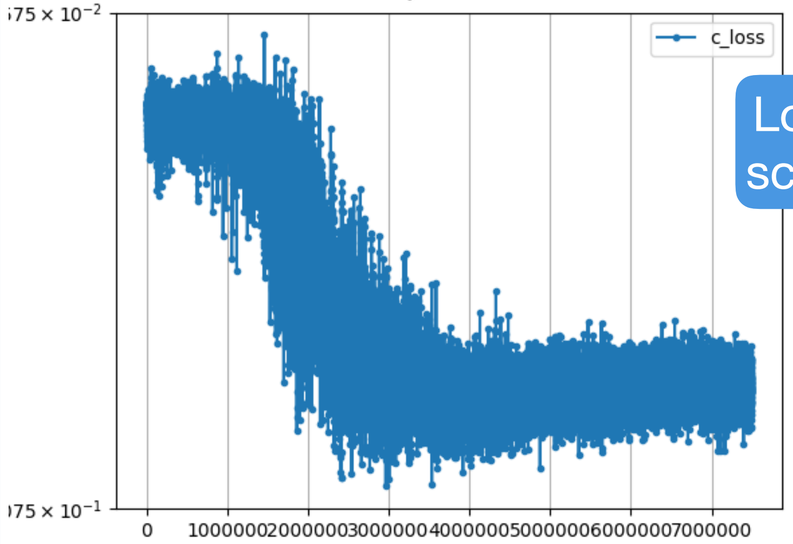


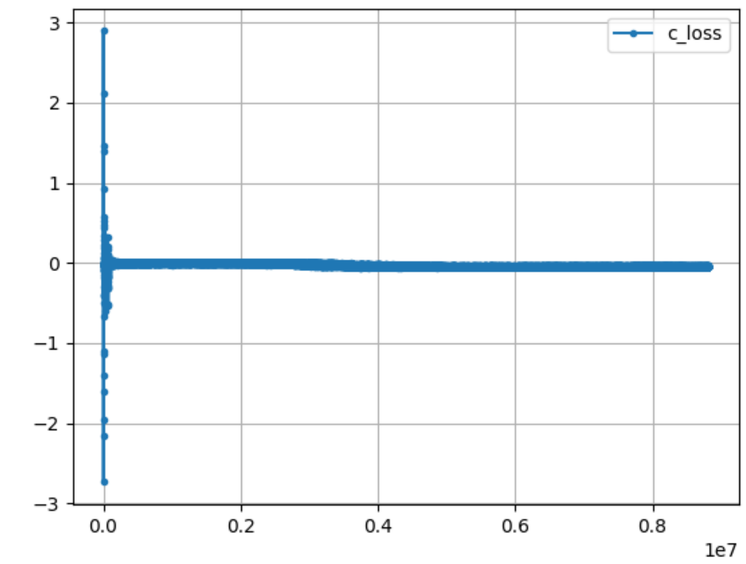
Full Critic



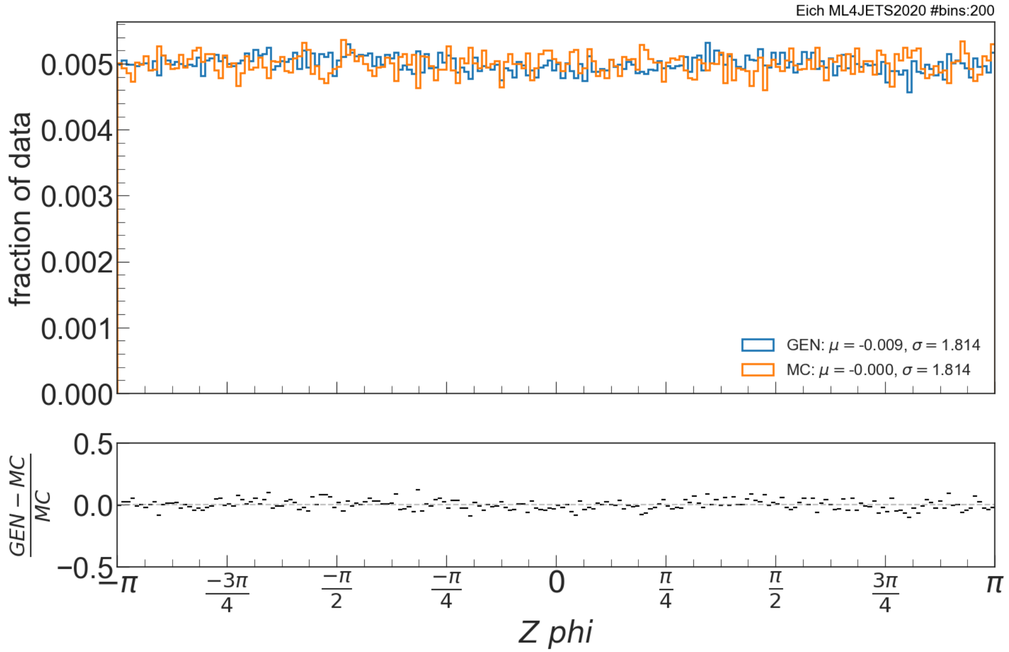


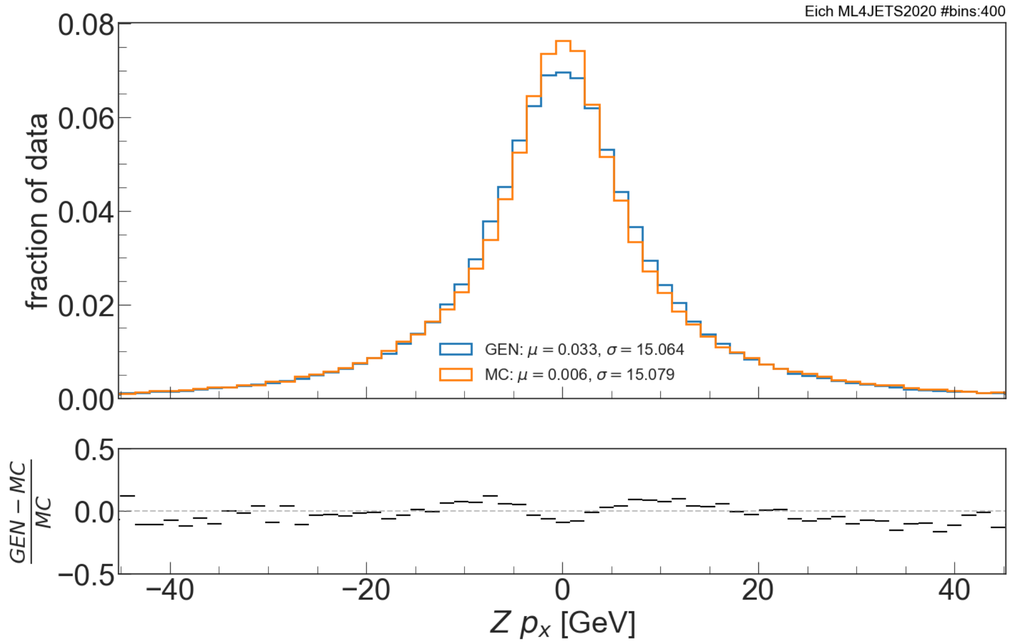
Critic Only EMD

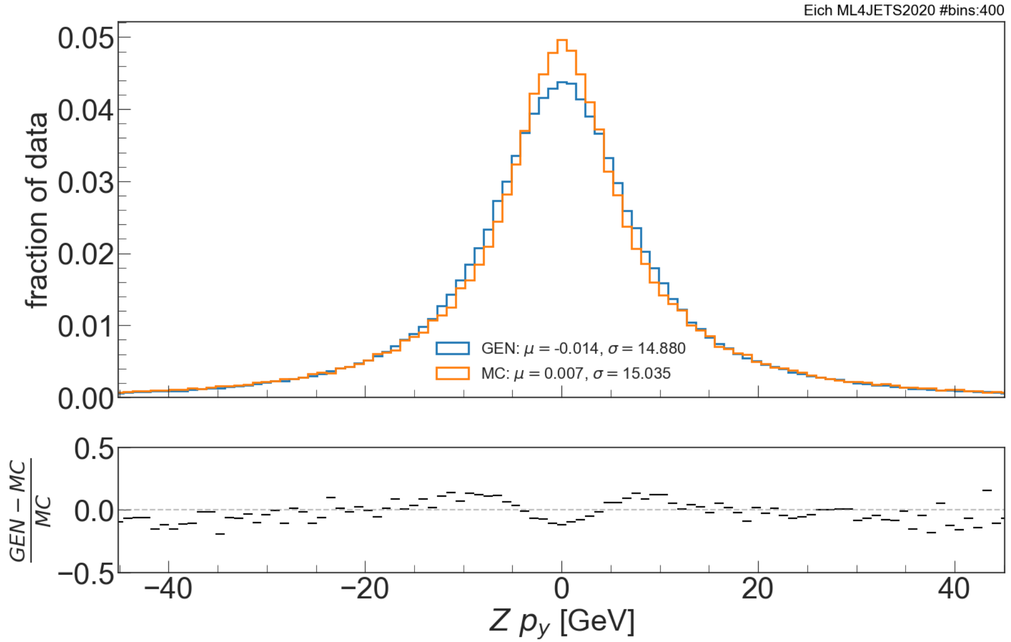


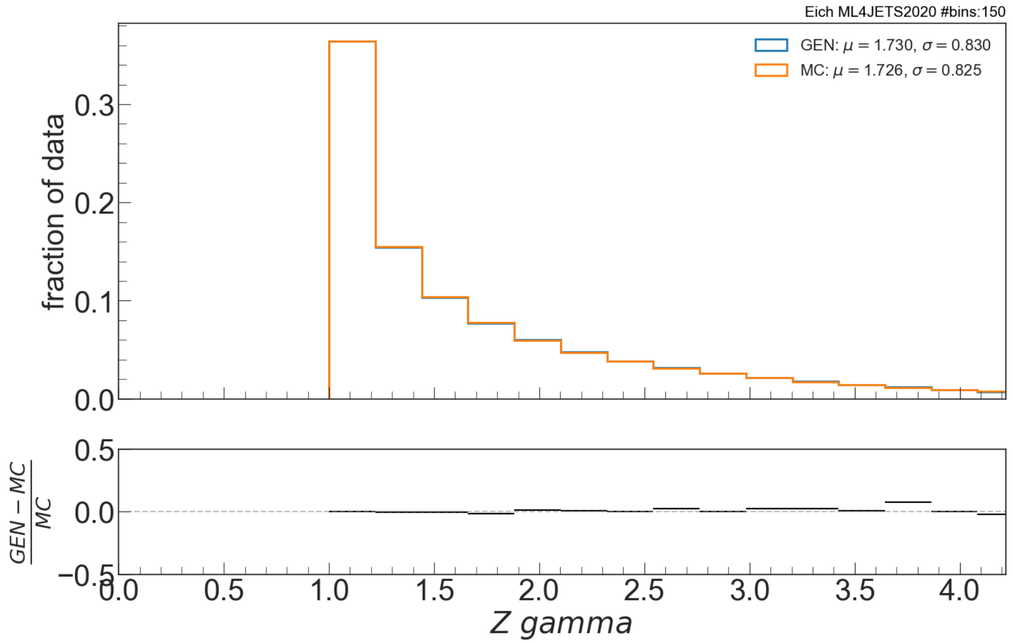


$Z \rightarrow \mu^+\mu^-$ - more distributions - ϕ, p_x, p_y, γ

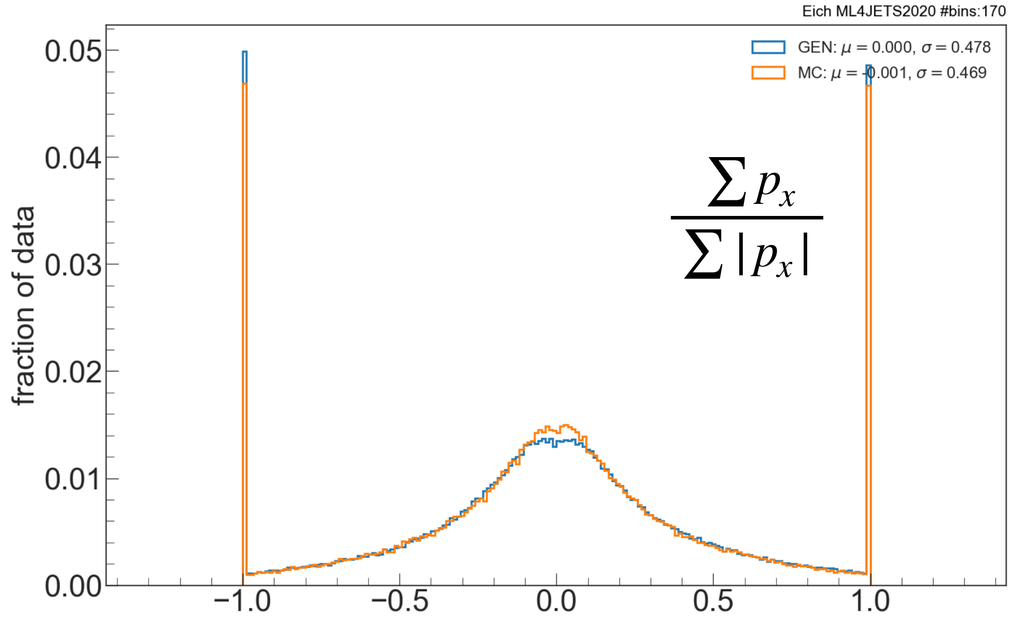


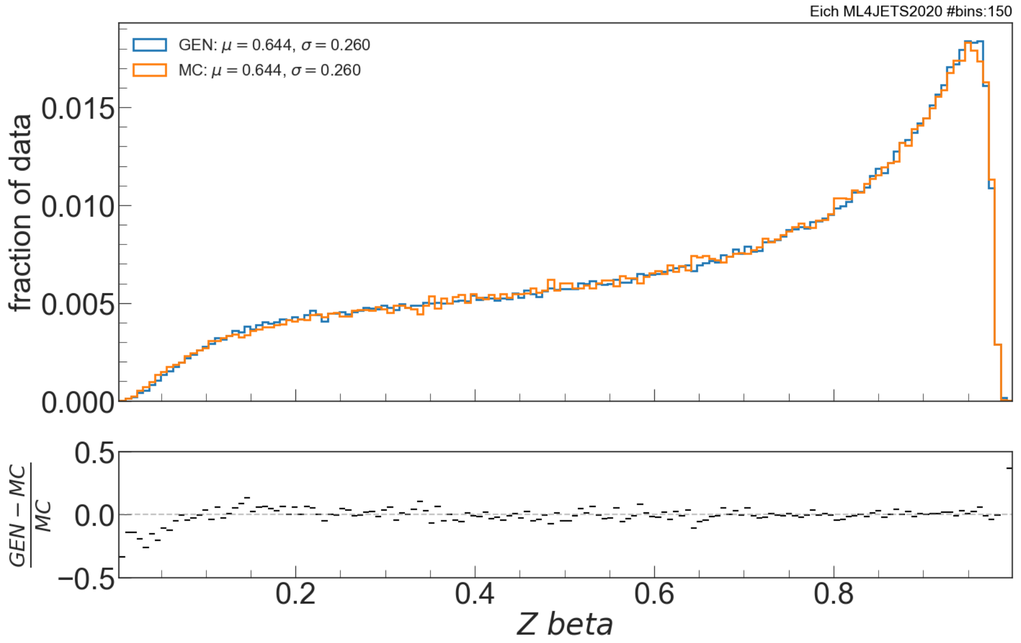


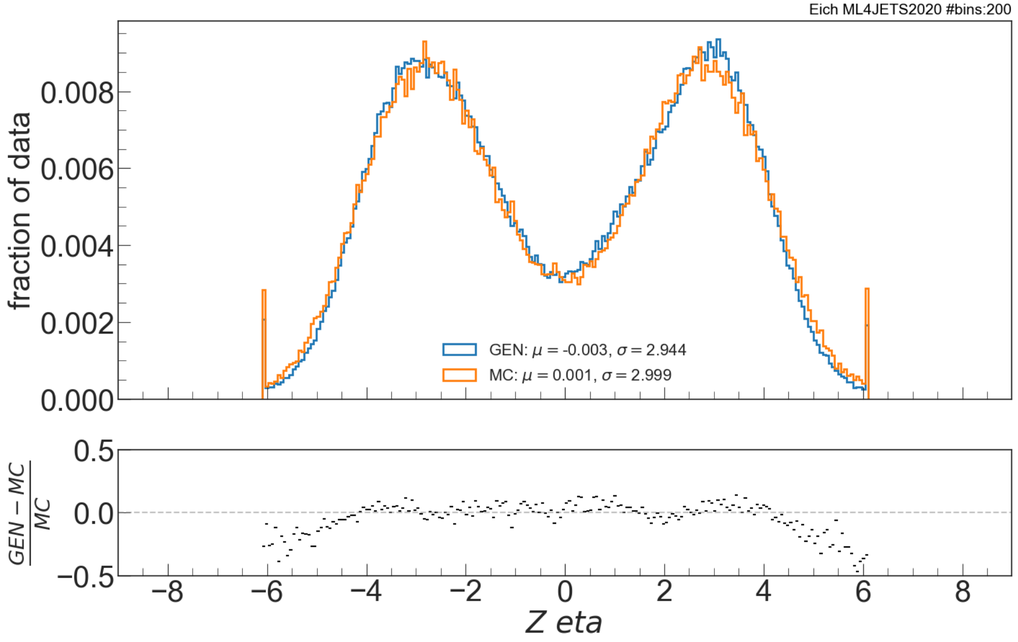


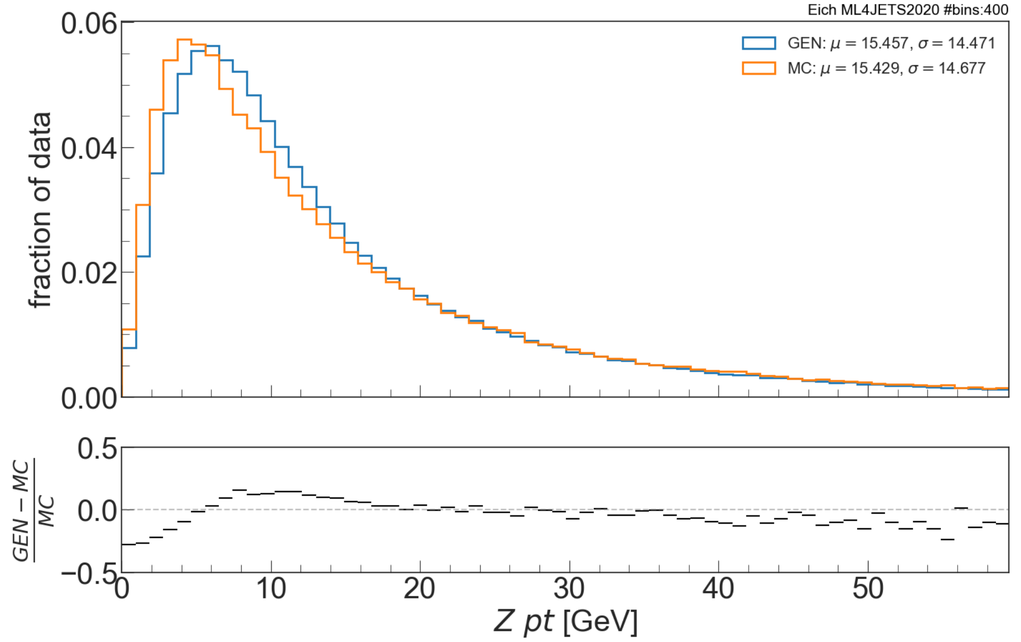


$Z \rightarrow \mu^+\mu^-$ - more distributions $\Delta p_x, \beta, \eta, p_T$





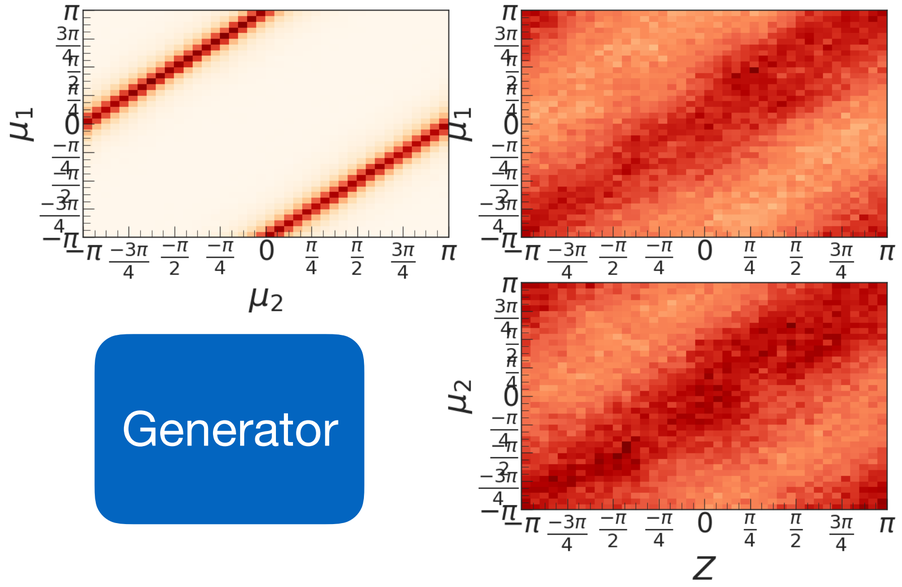




$Z \to \mu^+\mu^-$ - 2d histograms ϕ, η

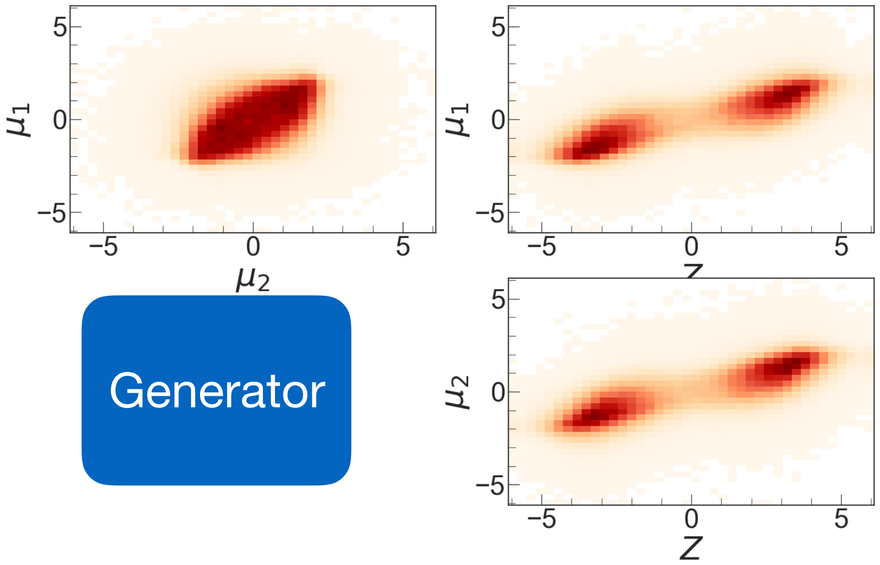
Niclas Eich - ML4Jets2020

phi - 2d histograms



Generator

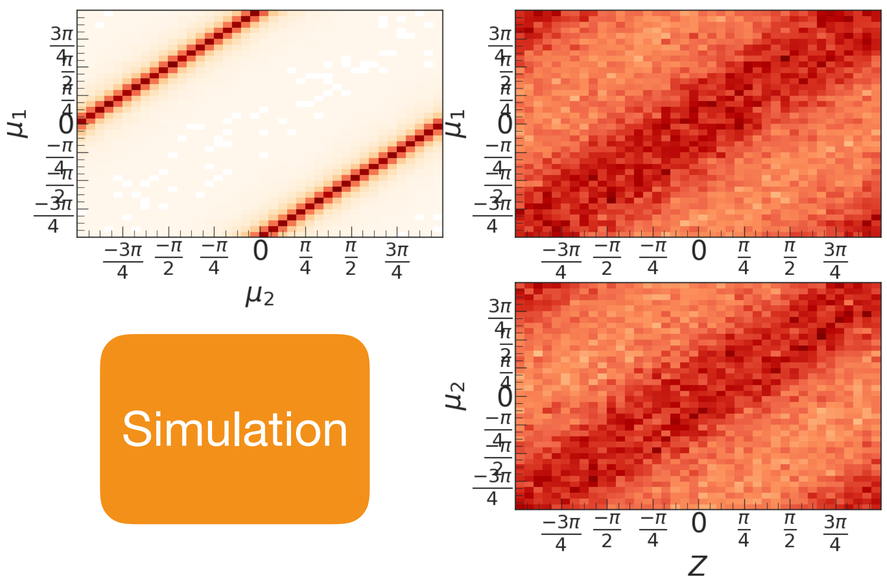
eta - 2d histograms



Generator

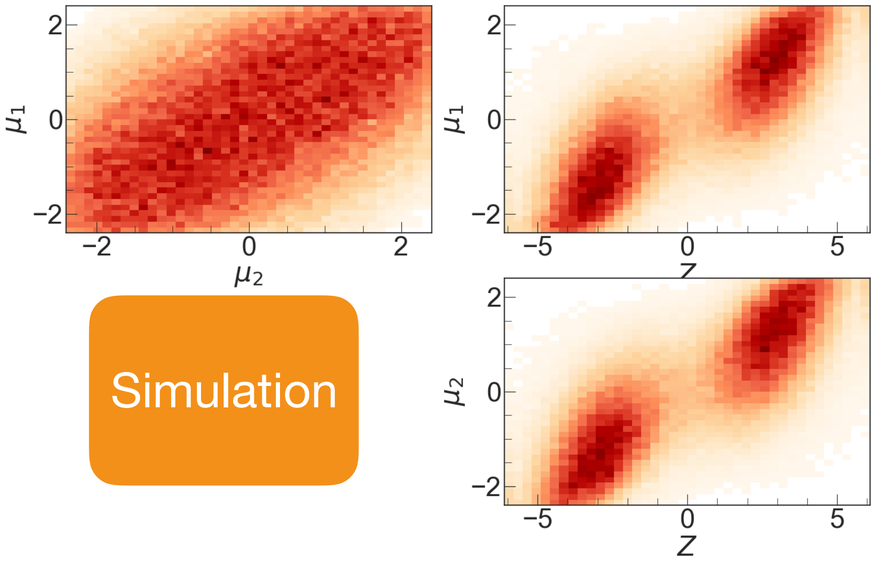
Plot axis scaled differently!

phi - 2d histograms



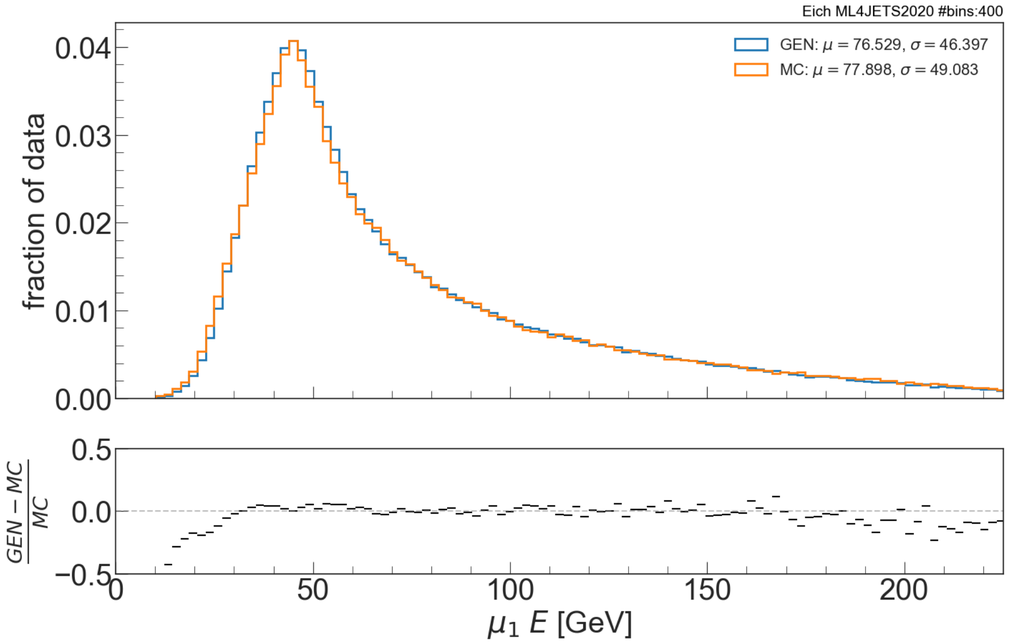
Simulation

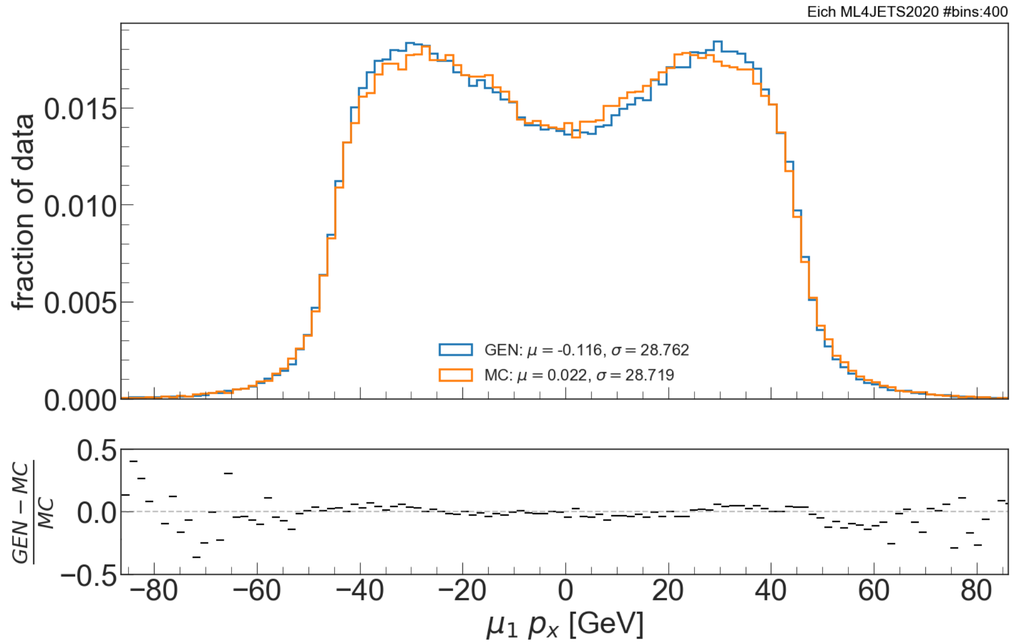
eta - 2d histograms

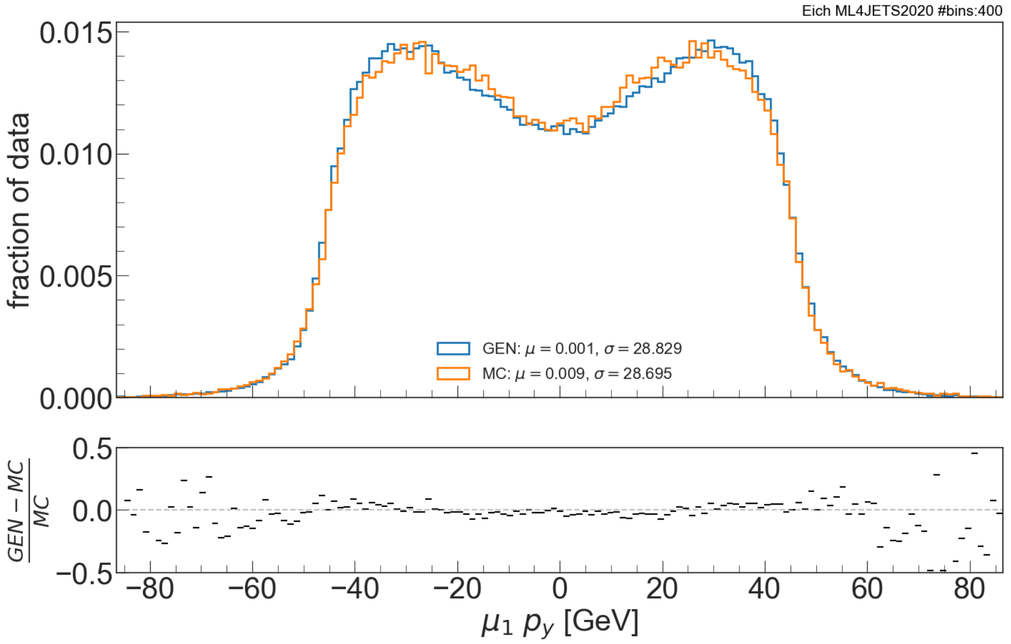


Simulation

$Z \rightarrow \mu^+\mu^-$ - applied η, p_T-cuts after generation

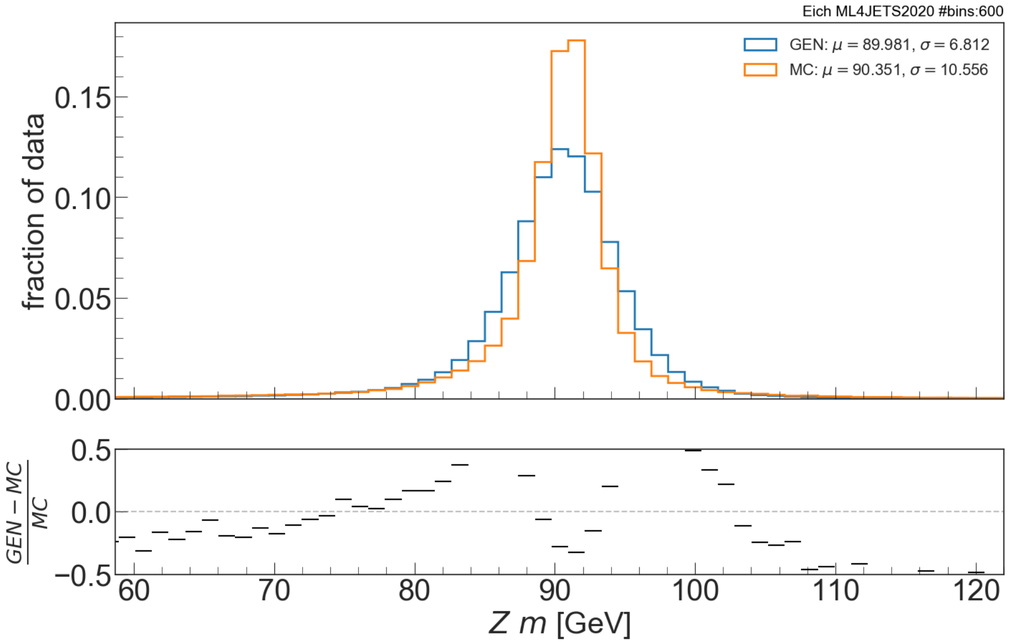


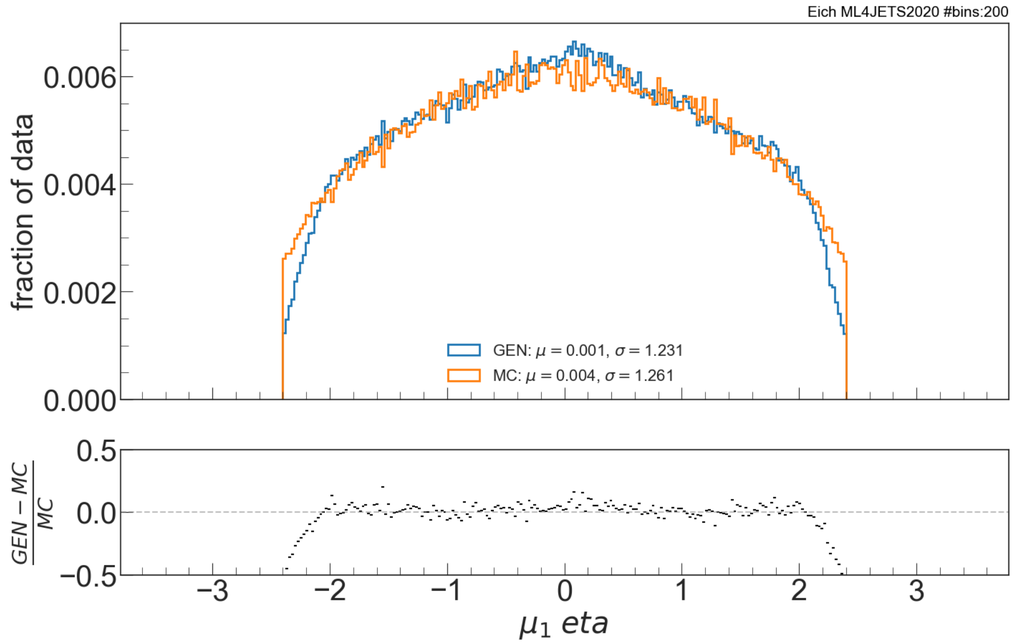


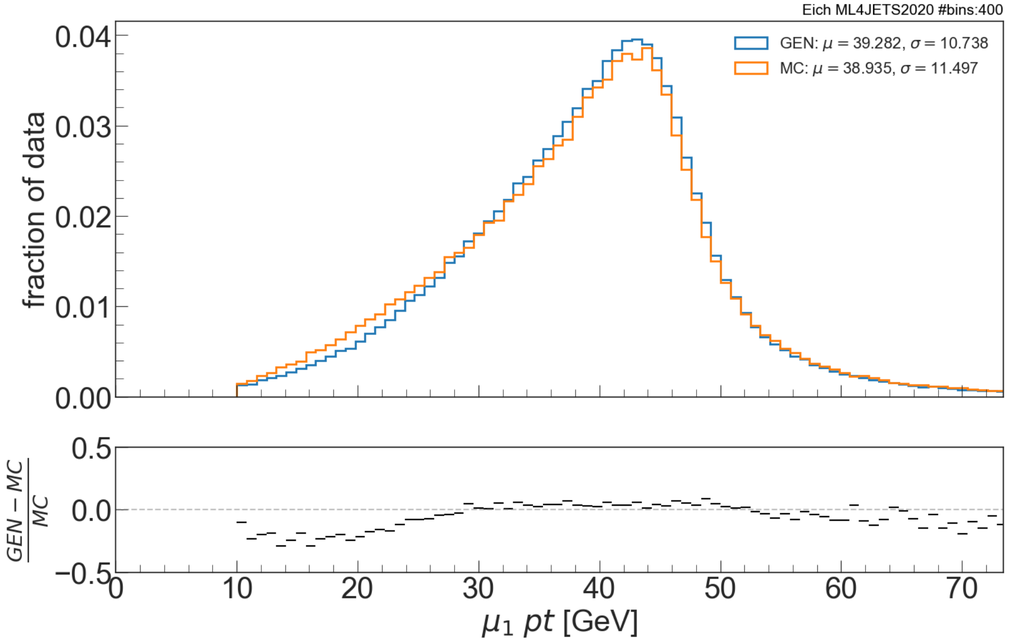


- Cuts improve transverse momenta p_x, p_y of the final state particles
- Rising slope of E-distribution gets worse
- Only losing < 1% events

$Z \rightarrow \mu^+\mu^-$ - applied η, p_T-cuts after generation

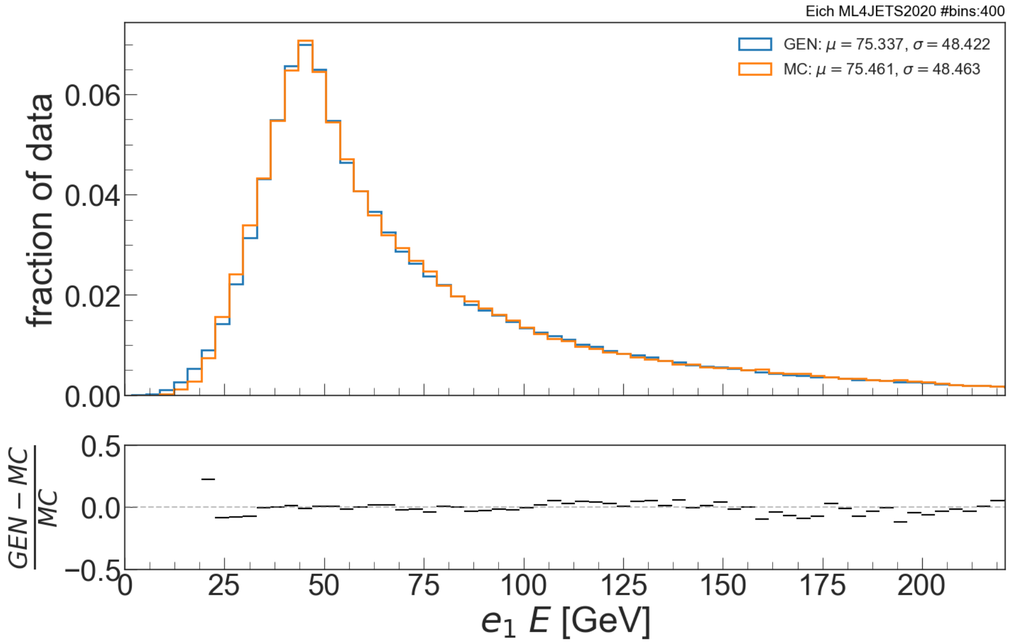


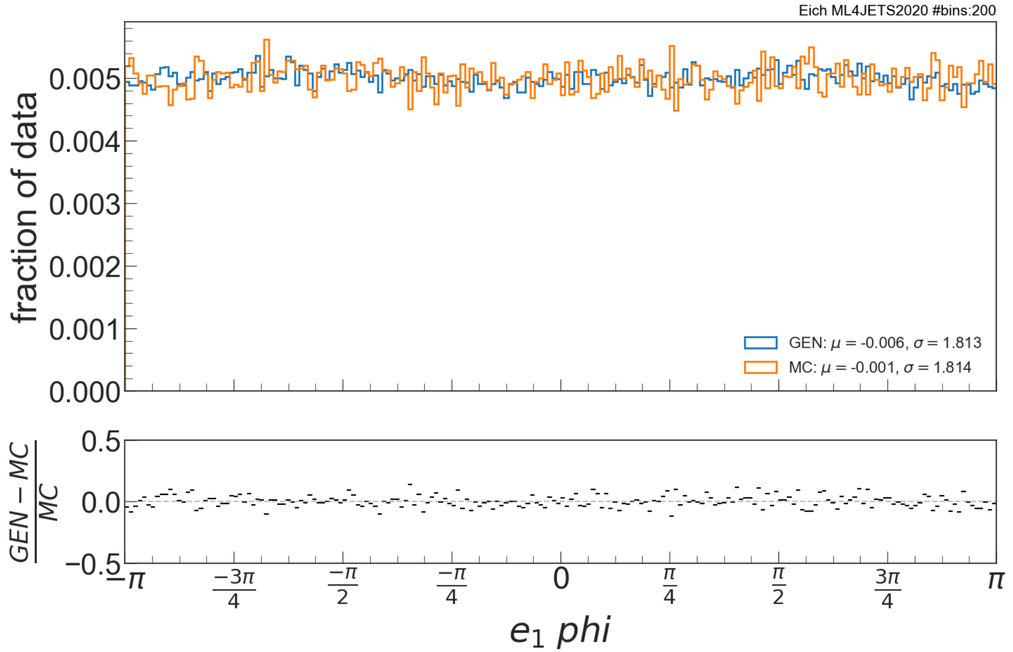


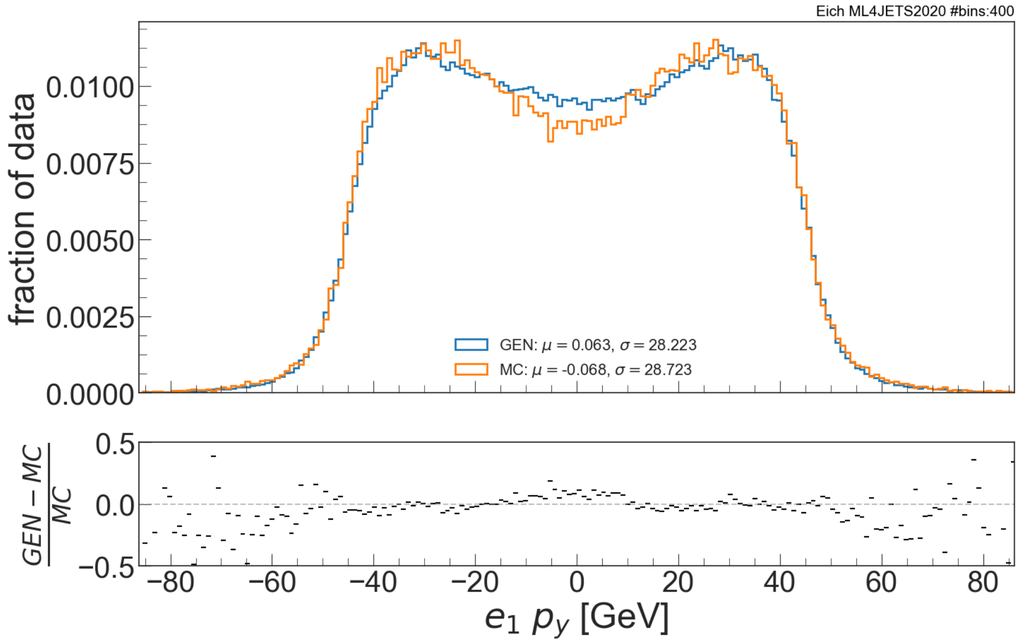


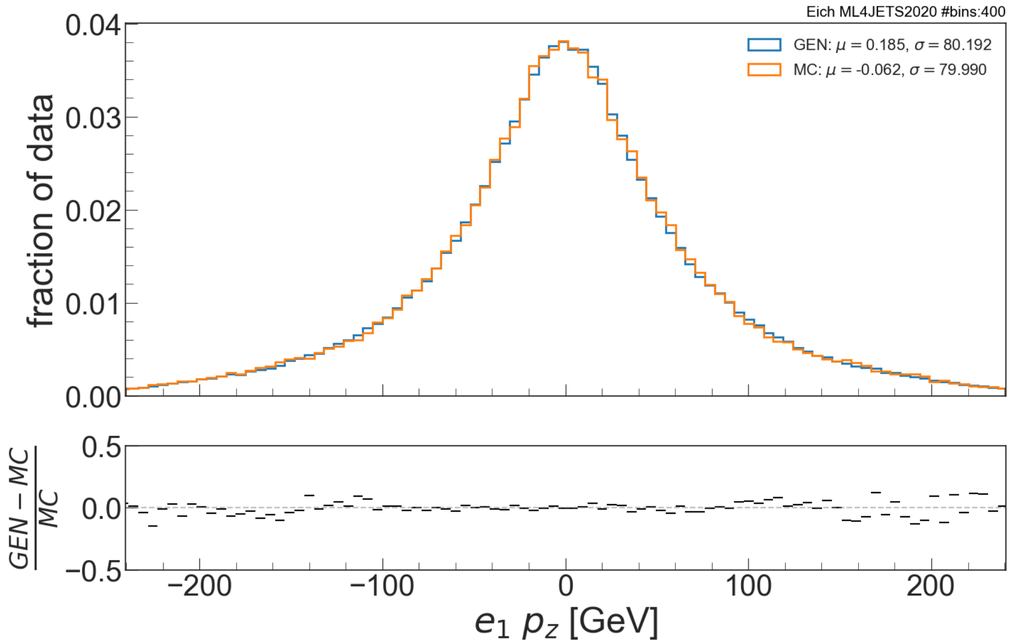
- Z mass does not improve
- Shape of p_T and η not in same agreement with simulation as other distributions

$Z \rightarrow e^+e^-$ - basic kinematics

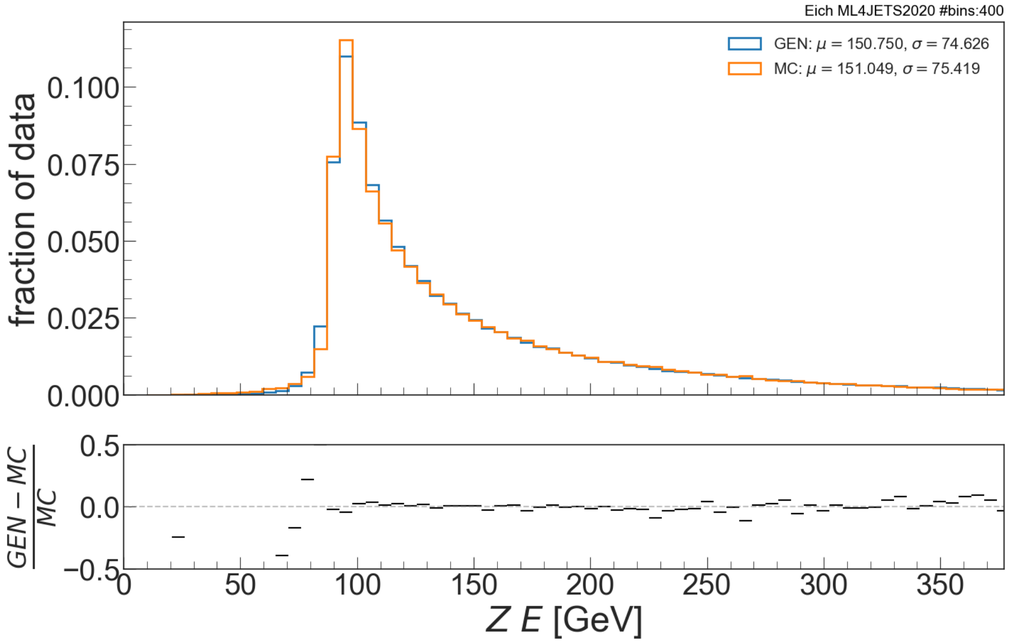
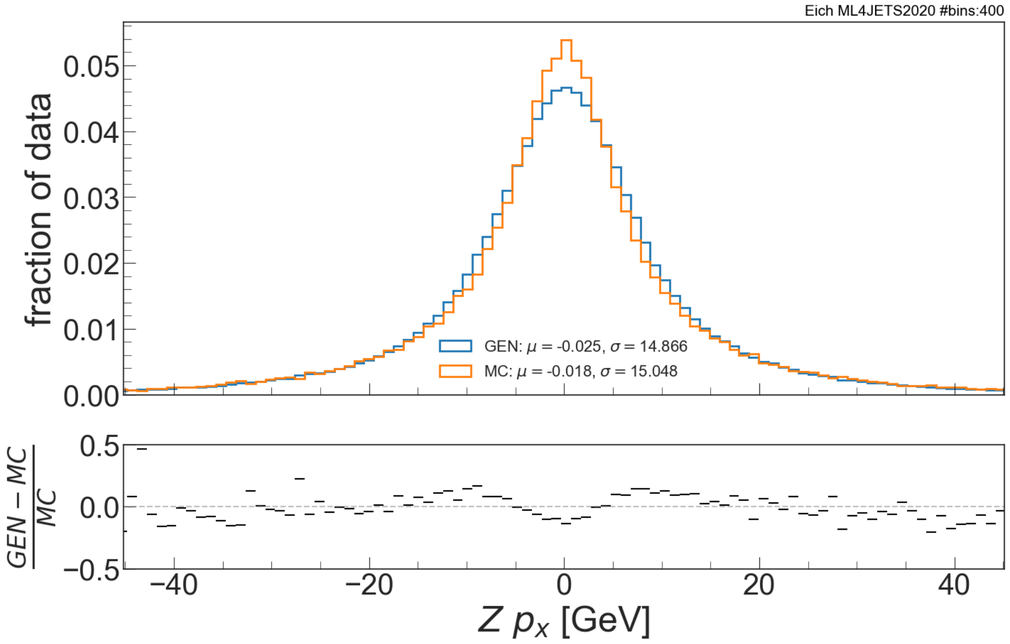
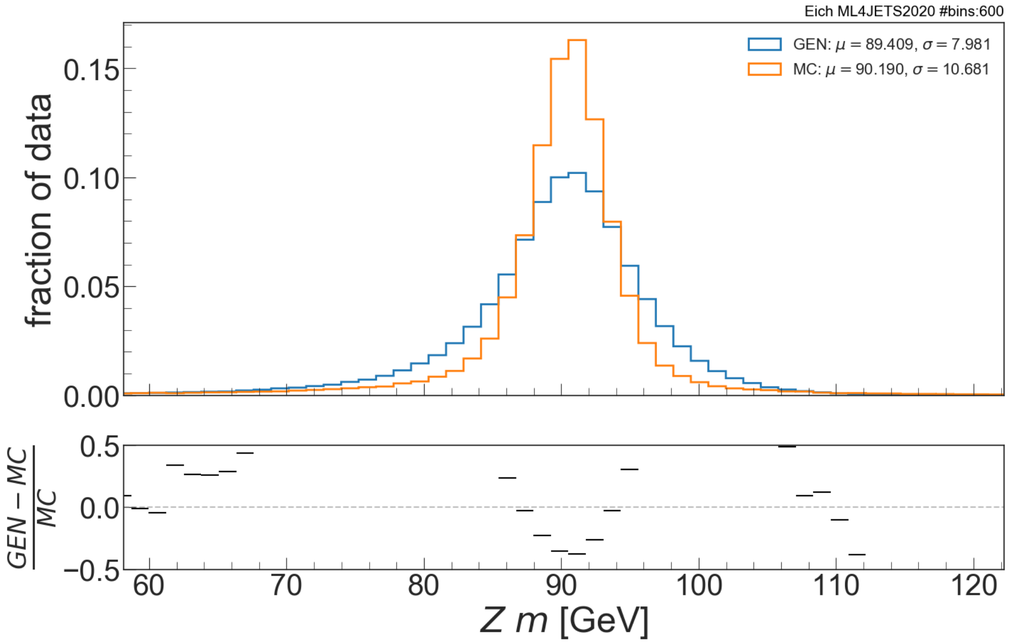
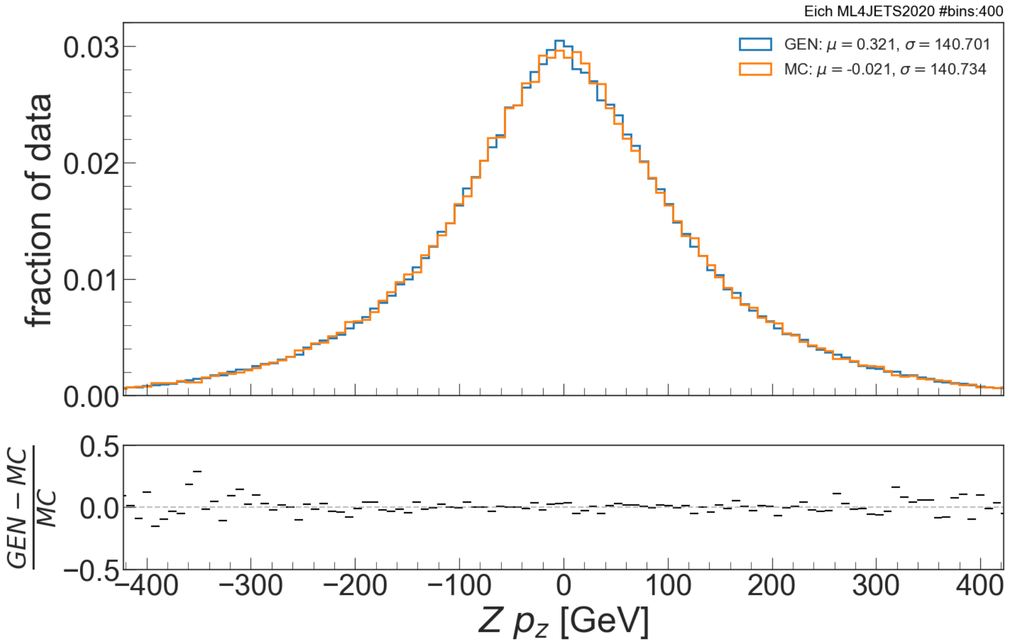








$Z \rightarrow e^+e^-$ - Z-candidate

$$\overrightarrow{e_1} + \overrightarrow{e_2} = \overrightarrow{Z}_{Candidate}$$

Dataset has very similar behaviour to $Z \rightarrow \mu^+\mu^-$