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XXVIth International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics“
https://indico.jinr.ru/event/5429/

RECOVERING COLLISION ENERGY CHARACTERISTICS FROM GEOMETRICALLY CONSTRAINED DATA BY MACHINE LEARNING

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Saint – Petersburg State University[1]

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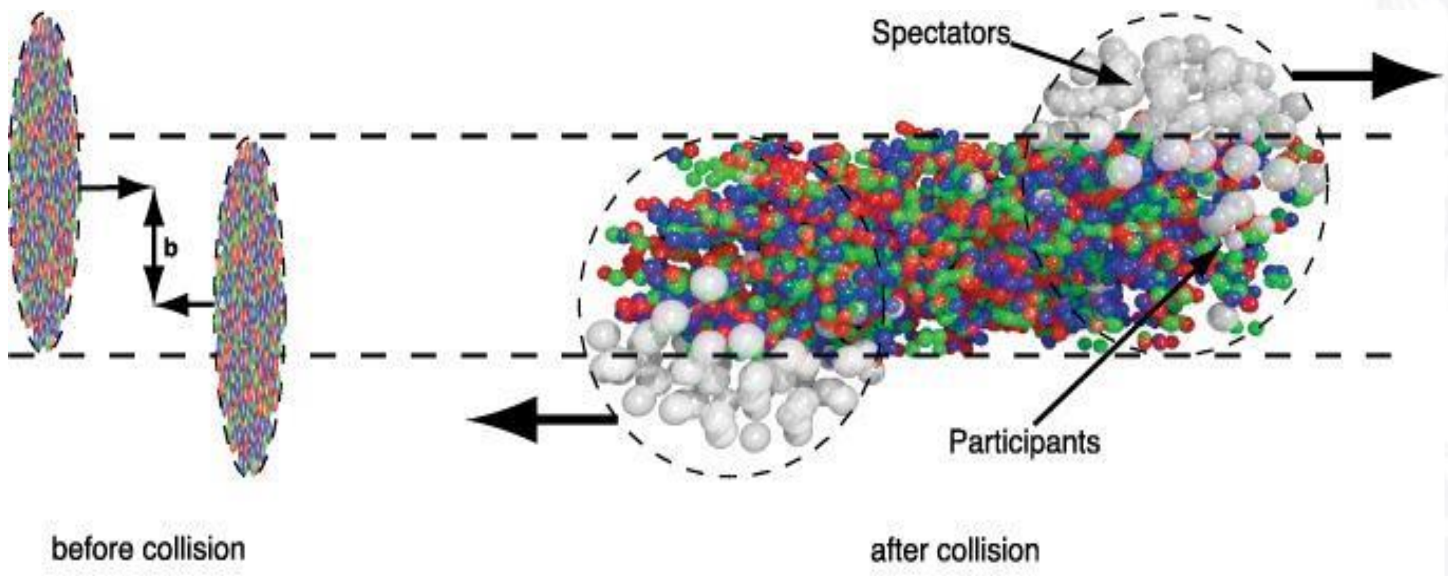
Moscow, Dubna
2025

Introduction



Impact parameter $\boldsymbol{b}$ – is the transverse distance between the centers of the two colliding nuclei, measured in the plane perpendicular to the beam direction.

Nucleon-spectators $\boldsymbol{N_{spec}}$ – nucleons, which didn't interact.

Nucleon-participants $\boldsymbol{N_{part}}$ – nucleons collided at least once.

$$\boldsymbol{N_{part} = A - N_{spectators}}$$

Goal of the research:

To estimate, at the event level, the energy of particles (both charged and neutral) produced in the collision of two relativistic gold nuclei using machine learning techniques, based on data obtained from detectors with limited-acceptance.

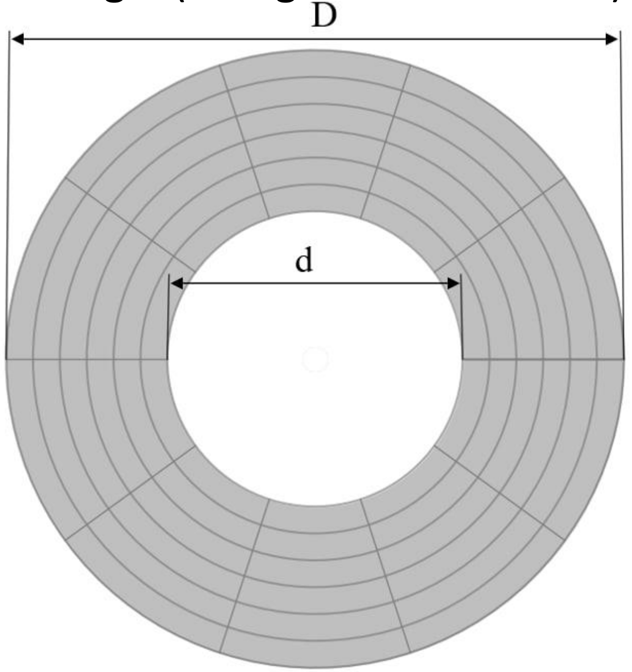
Objectives:

1. Based on the estimation of the energy conservation law, formulate the criteria for determining the energy released during the collision.
2. Investigate the dependence of the released interaction energy on the impact parameter of the collision based on QGSM generator data and explain the physical meaning of this dependence.
3. Develop a function capable of mapping the signal from limited-acceptance detectors to the energy released in the collision.

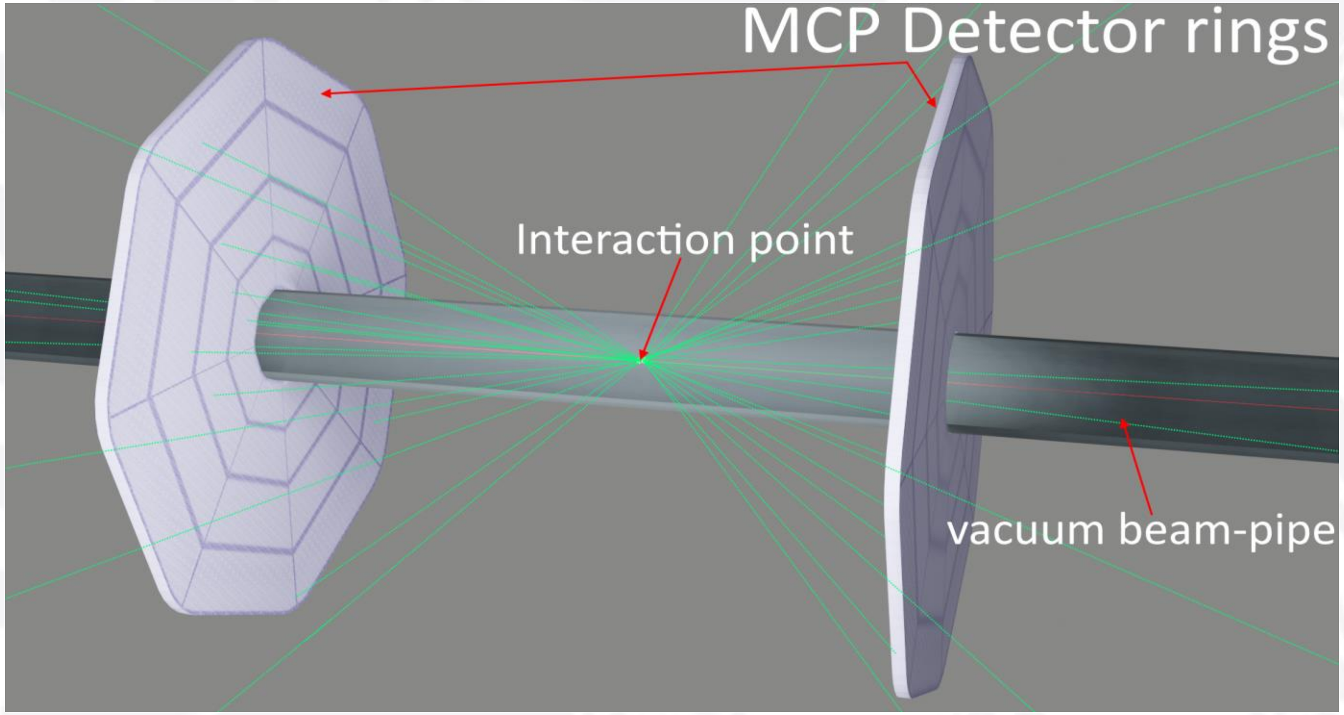
Experimental Model: Limited-Acceptance Detector

1. Single collision (Au+Au).
2. Events are considered in the center-of-mass system.
3. $A = 197$ – atomic mass of the gold nucleus, $Z = 79$ – charge.
4. A pad can register only one particle (the first one that reaches it).
5. The pseudorapidity of the detectable particles in the configuration is limited to the range $3.5 < \eta < 5.8$

Detector segmentation into sensitive pads by radius and angle (6 rings and 10 sectors).



Experimental scheme. Heavy-ion collision.



[1] Roudnev V. A., Galaktionov K. A., Valiev F. F. Detector Optimization Based on Artificial Neural Network Training //Bulletin of the Russian Academy of Sciences: Physics. – 2025. – T. 89. – №. 8. – C. 1335-1342.
[2] Abazov V. et al. Technical design report of the spin physics detector at NICA //arXiv preprint arXiv:2404.08317. – 2024.

Selection of Spectators

Key values used in the study:

1. $\sqrt{s_0} = 5.5034\ GeV$ - energy per nucleon
2. $\sqrt{s_{NN}} = 11.0067\ GeV$ - energy per nucleon–nucleon pair
3. $\sqrt{s_{total}} = 2A\sqrt{s_0} = 2168\ GeV$ - total energy of the two gold nuclei
4. $energy_{csm} = \sqrt{p_x^2 + p_y^2 + p_z^2 + m^2}$, energy of the particle in the center-of-mass frame
5. $\sqrt{\boldsymbol{s_{eff}}} = \sqrt{\boldsymbol{s_{total}}} - \boldsymbol{E_{sp}}, E_{sp} - \text{energy of spectators}$

The primary objective of this work is to separate spectator particles from other products of the collision. A spectator is defined as a particle that has not changed its trajectory and energy significantly after the interaction, and that **belonged to the nucleus before the collision**. Based on this definition, we implemented two selection filters: an energy-based filter and a momentum-based filter.

Momentum Filter:
The longitudinal momentum component is much larger than the transverse one.

Energy Filter:
The particle's energy before the collision is approximately equal to its energy afterward.

Momentum Filter:

$$(p_x^2 + p_y^2) \ll p_z^2$$

Energy Filter:

$$energy_{csm} \approx \sqrt{s_0}$$

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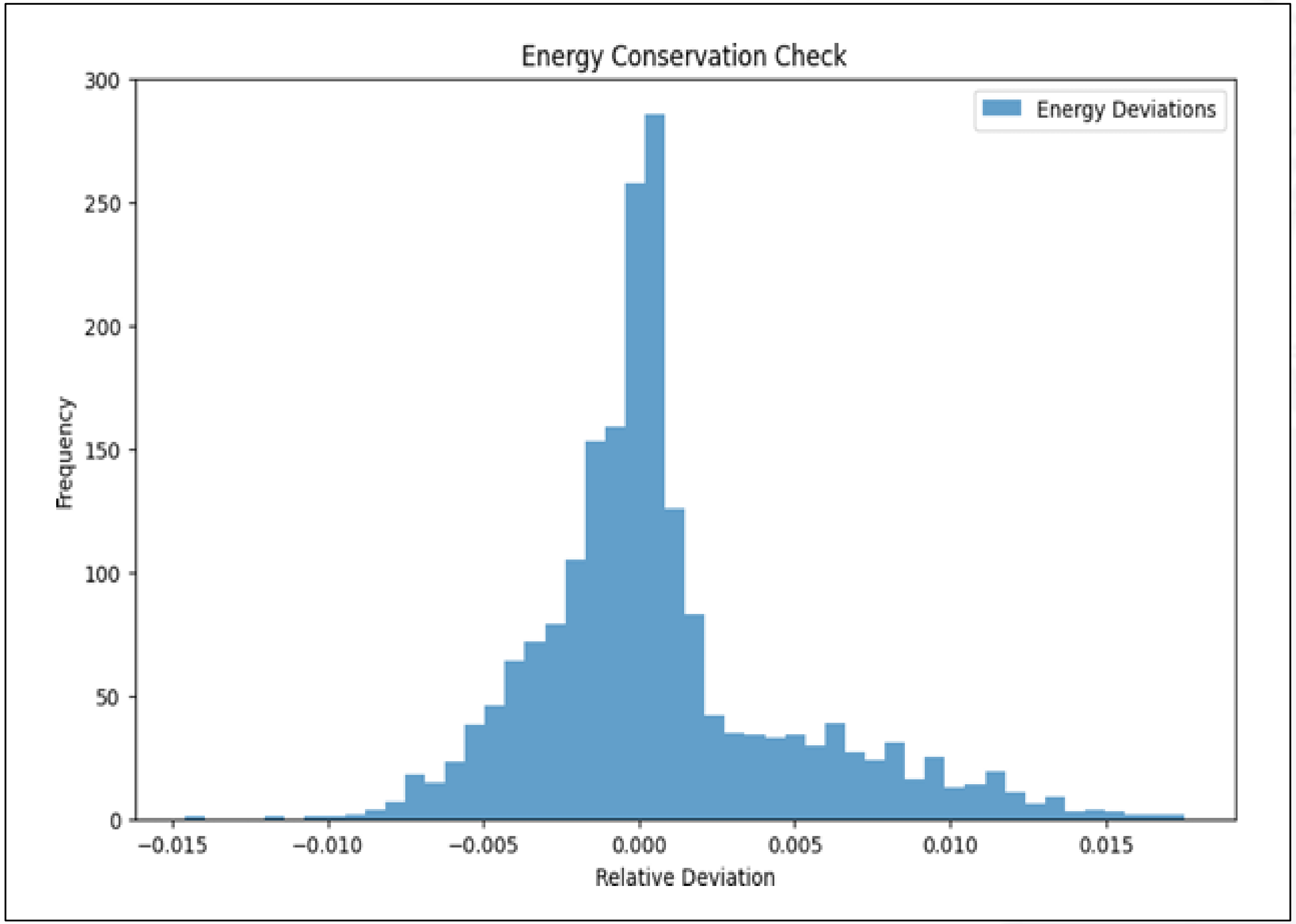
Verification of the energy conservation law for QGSM



Event distribution as a function of ζ

$$\zeta = \frac{E_1 - E_0}{E_0}$$

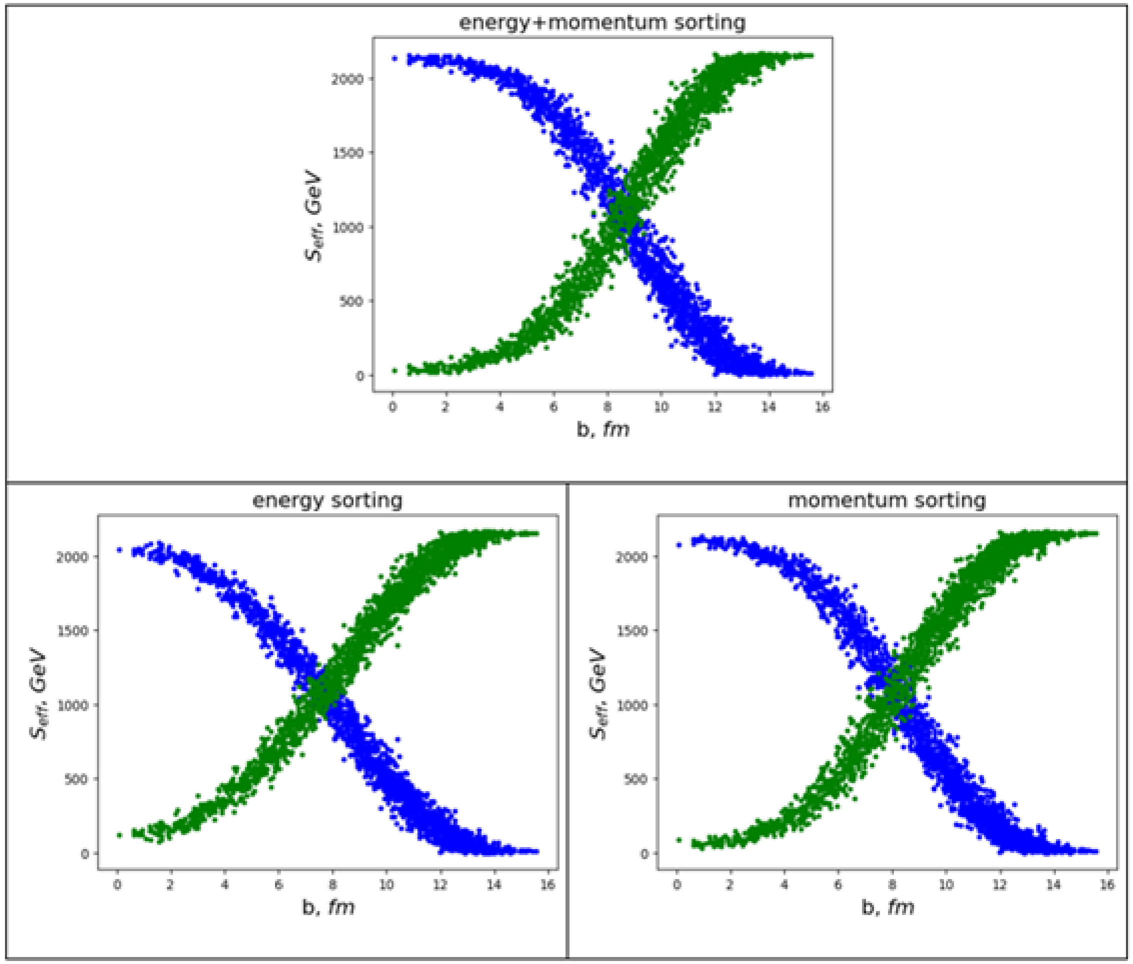
$\boldsymbol{energy_{csm}} = \sqrt{\boldsymbol{p_x^2 + p_y^2 + p_z^2 + m^2}}$, energy of the particle in the center-of-mass frame

$\boldsymbol{E_1 = \sum energy_{csm}}$, sum of particle energies per event

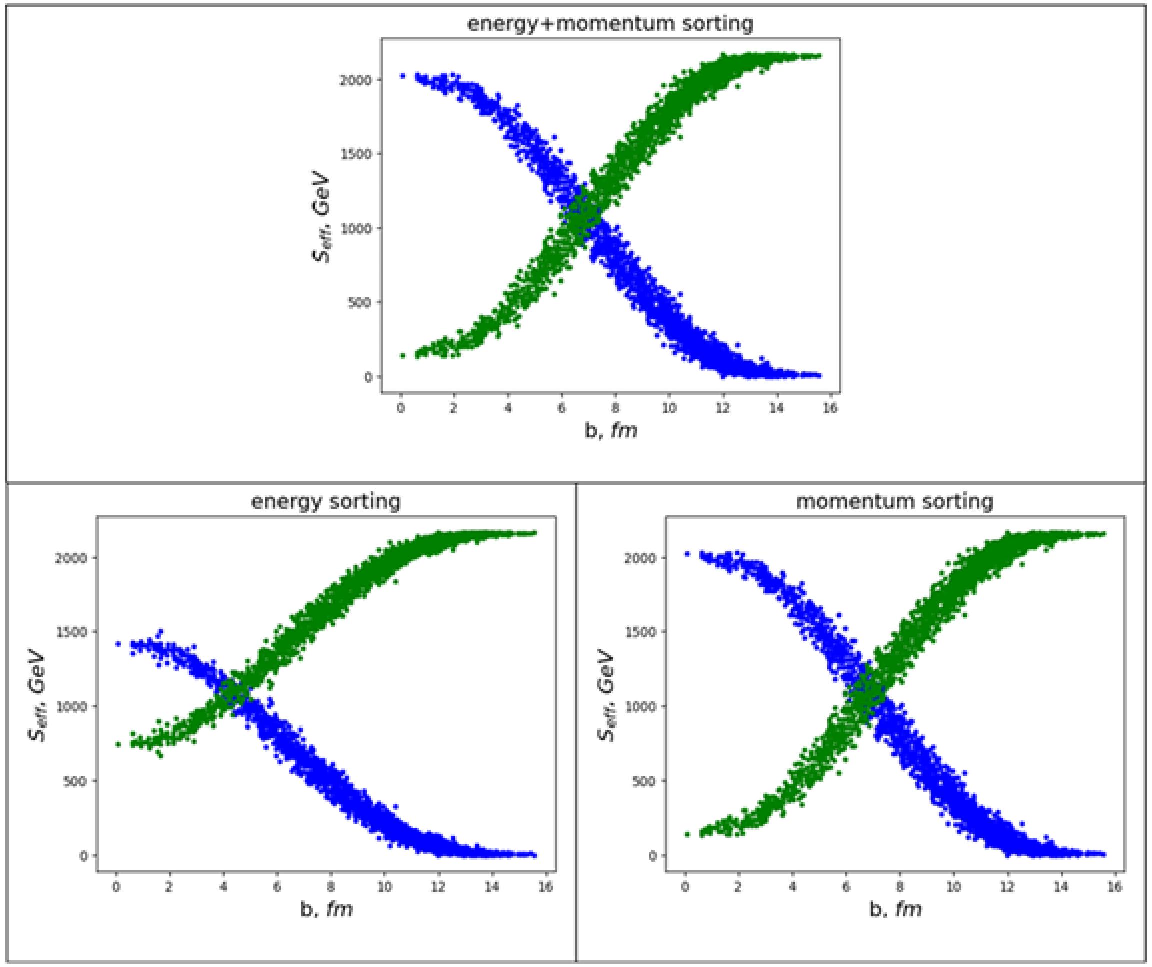
$\boldsymbol{E_0 = 2 * A * \sqrt{s_0} = \sqrt{s_{total}} = 2168\ GeV}$, where $A = 197$ – atomic mass of the gold nucleus, $\sqrt{s_0}$ – energy per nucleon, $\sqrt{s_{total}}$ – total energy of the two gold nuclei

Dependence of $\sqrt{s_{eff}}(b)$ in QGSM

$Dependence\ \sqrt{s_{eff}}\ (b) at\ SpCutoff\ = 5\%$



Dependence $\sqrt{s_{eff}}(b) at\ SpCutoff\ = 10\%$



Green: $E_{sp}(b)$, Blue: $\sqrt{s_{eff}}(b)$, $\sqrt{\boldsymbol{s_{eff}}} = \boldsymbol{E_0} - \boldsymbol{E_{sp}}, E_{sp} - energy\ of\ spectators.$

SpCutoff - The selection threshold used to classify a particle as a spectator or not.

[3] Miller M. L. et al. Glauber modeling in high-energy nuclear collisions //Annu. Rev. Nucl. Part. Sci. – 2007. – T. 57. – №. 1. – C. 205-243.

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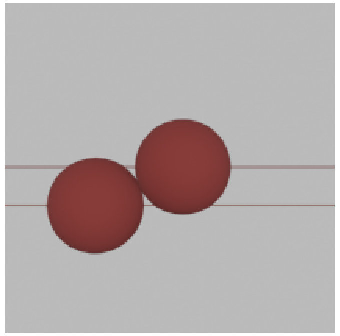
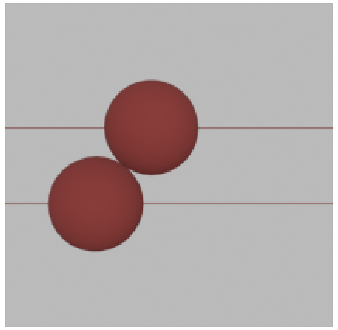
Dependence of $\sqrt{s_{eff}}(b)$ in QGSM

Collision model with different impact parameters:

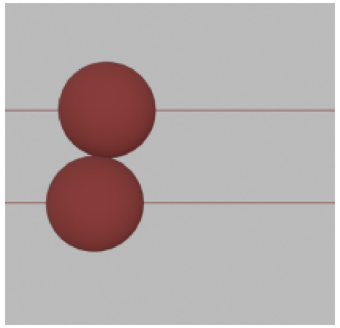
$b \in (0;7)Fm$



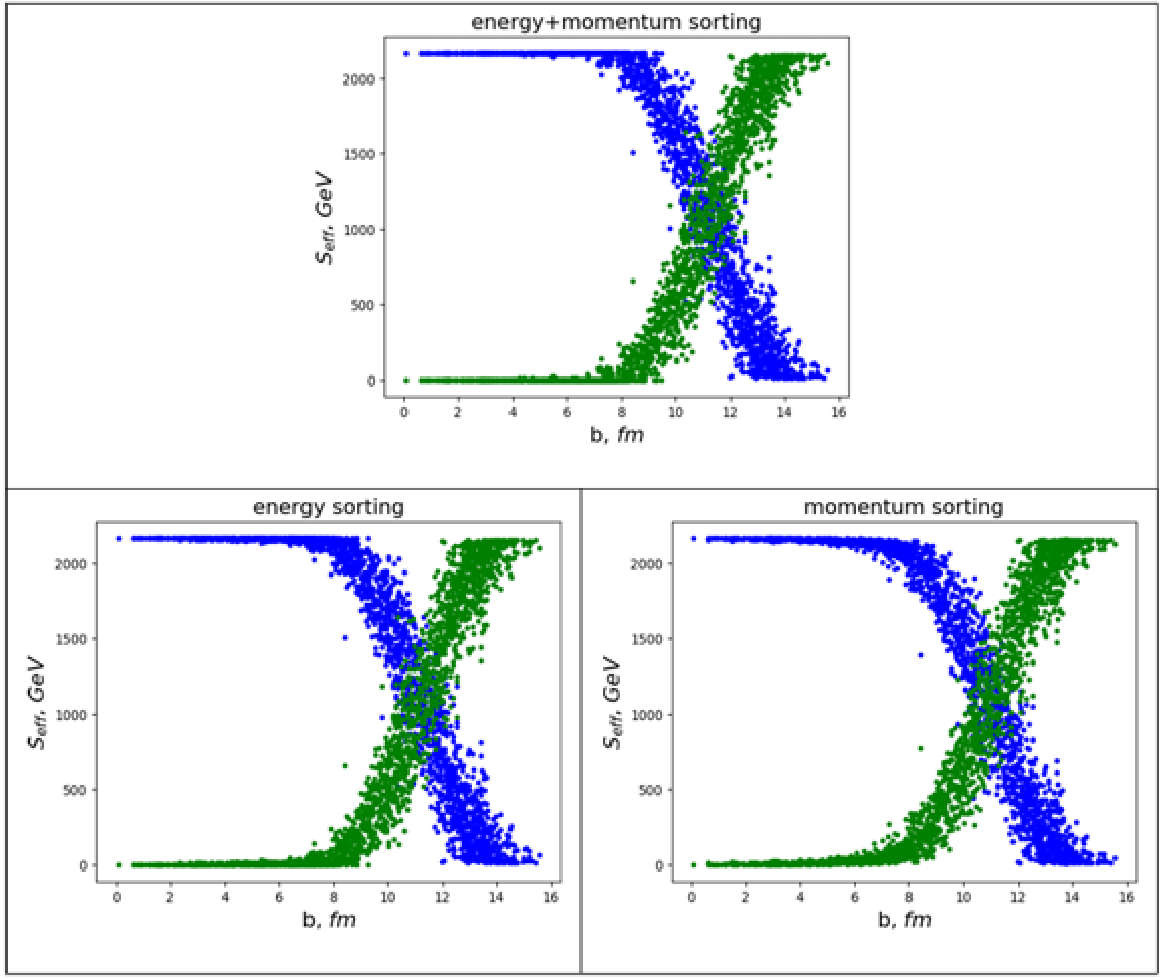
$b \in (9;12)Fm$



$b > 12\ Fm$



Error: 1.5% in energy and 2% in momentum



Dependence $\sqrt{s_{eff}}(b)$ $at\ SpCutoff_{en} = 1.5\%$ and $SpCutoff_m = 2\%$

Energy-based spectator selection cutoff: 1.5%

Momentum-based spectator selection cutoff: 2%

- For b $\approx 0\ fm$, spectator energy is negligible.
- As b increases, spectator energy grows.
- For $b > 12\ fm$, the energy of produced particles in Au-Au collisions tends to zero.

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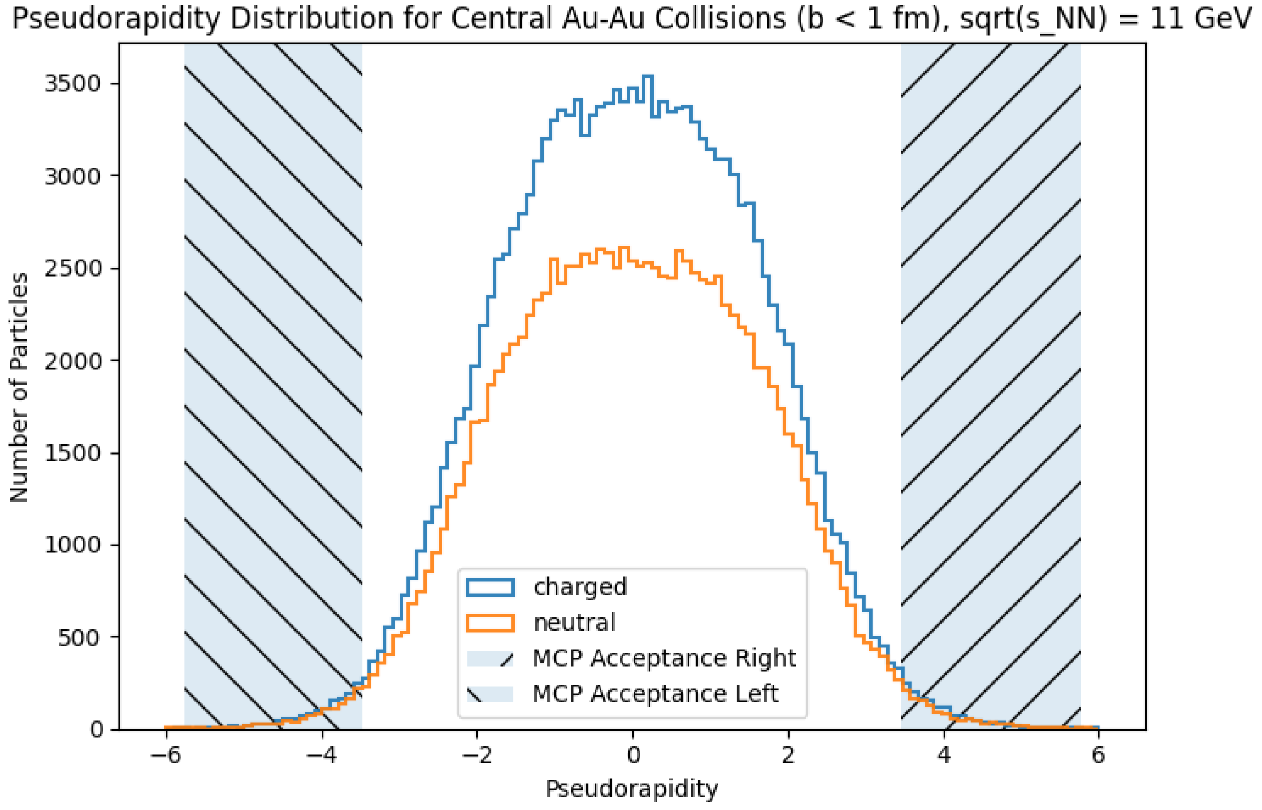
Problem Statement

- **Regression task**: event-wise reconstruction of the energy released in the collision with high accuracy.
- **Input** (Feature Vector (3; 120)) → **Output** ($\sqrt{s_{eff}}$).
- **Supervised training**: each feature vector is paired with the $\sqrt{s_{eff}}$ for that event (labeled data).
- **Limited-acceptance detector** registers only **charged particles** → the Feature Vector is built from charged particles only.
- The feature vector is formed based on the detector configuration: $(T, pad\ number, detector\ ID)$, where $T = \frac{z_0}{tof - t_0}$, $tof = \frac{z_0}{v}, v = \frac{p}{energy_{csm}} \cdot c$
  $detector\ ID$ – this is the ID of the detector that the particle hit. "Right" detector – 1, "Left" detector – 2.
  $pad\ number$ – this is the pad ID the particle hit. It's encoded as a two-digit code "ac", where "a" is the ring number and "c" is the sector number.

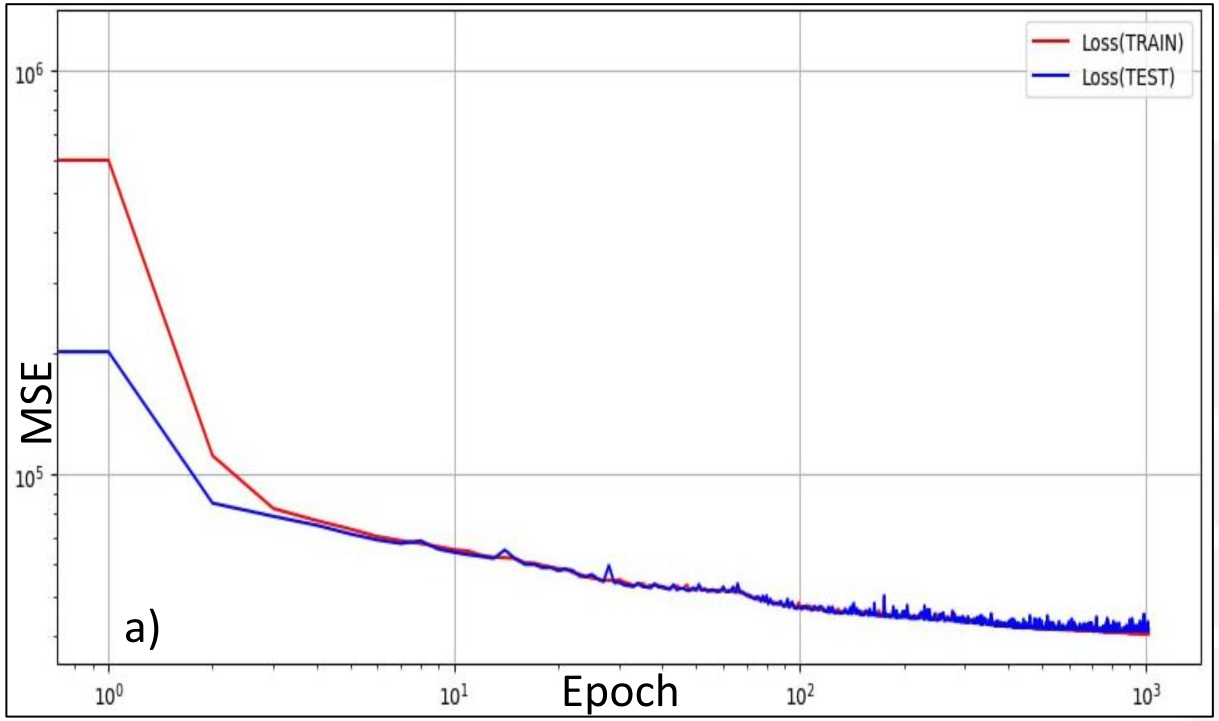
Histogram of Pseudorapidity (Number of Particles)



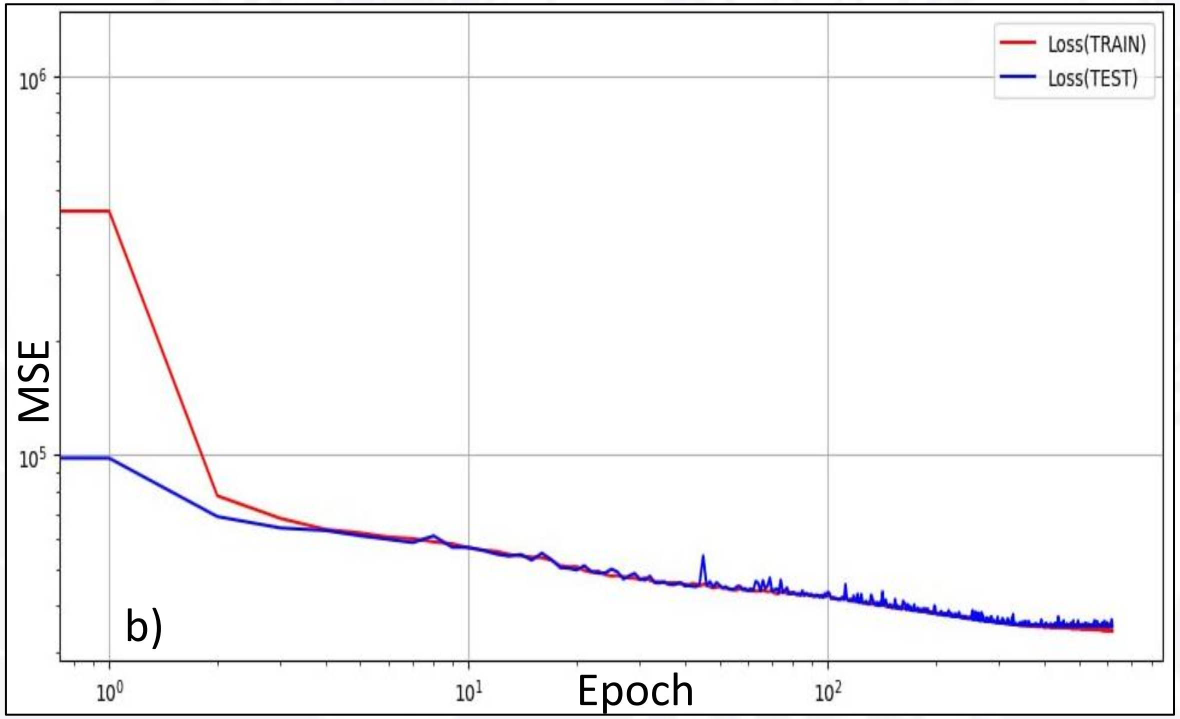
- **Train|Test Split**: 160,000 events/40,000 events.
- **Architectures**: (1) fully connected NN; (2) fully connected NN with a convolutional layer.
- **Targets considered**: predict the $\sqrt{s_{eff}}$ of **all** particles or $\sqrt{s_{eff}}$ of **charged** particles only produced in the collision.

MSE(epoch) Conv2D + Fully Connected NN

RMSE: 203.3 GeV



RMSE: 188.2 GeV



a) Model estimate of the $\sqrt{s_{eff}}$ of charged final-state particles. b) Model estimate of the $\sqrt{s_{eff}}$ of all final-state particles.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2}$$

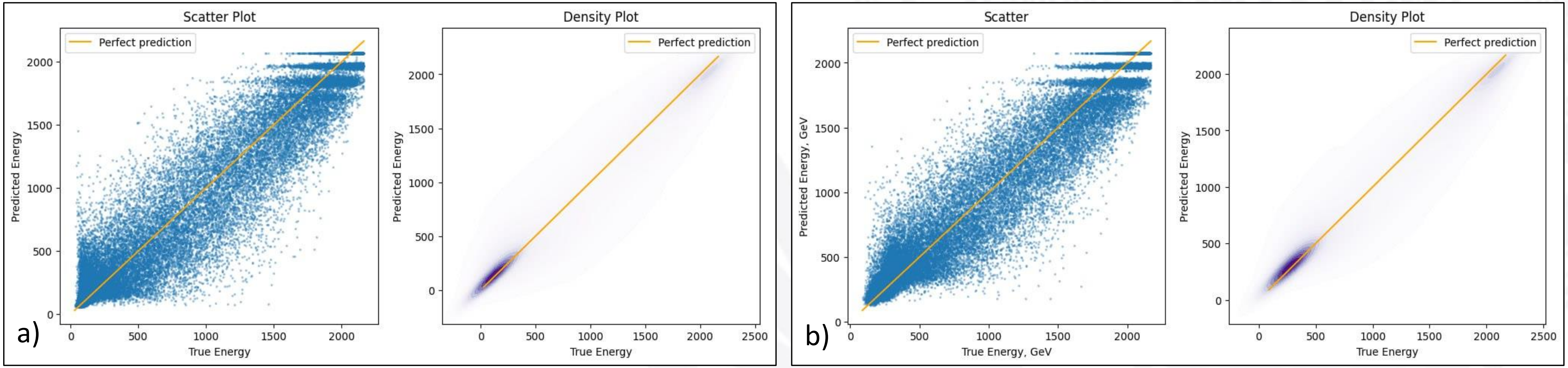
RMSE – root mean square error

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2$$

MSE – mean square error

Limited-acceptance detector; the feature vector is built only from charged particles.

$\hat{y}(y)$ Conv2D + Fully Connected NN



a) Model estimate of the $\sqrt{s_{eff}}$ of charged final-state particles. b) Model estimate of the $\sqrt{s_{eff}}$ of all final-state particles.

Relative Errors of the Models

$$\varepsilon = \frac{RMSE}{\sqrt{s_{total}}} \cdot 100\%$$

$\boldsymbol{\varepsilon}$ – relative error

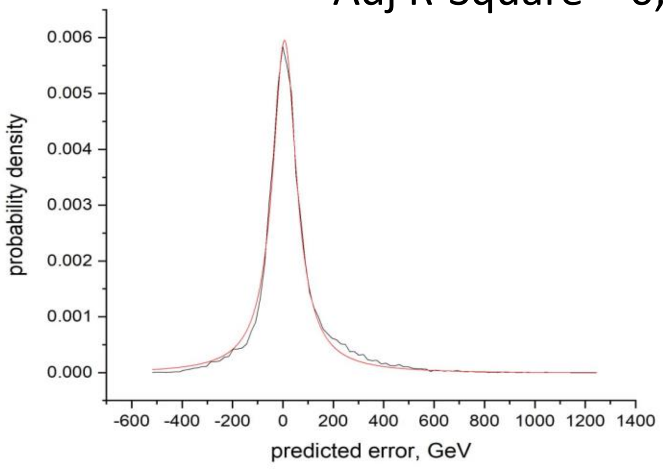
	Conv2D + Fully Connected NN	Fully Connected NN
Model estimate of the $\sqrt{s_{eff}}$ of all final-state particles	8.7%	8.8%
Model estimate of the $\sqrt{s_{eff}}$ of charged final-state particles	9.4%	9.8%

Prediction Error Density by Energy Range (All Final-State Particle Energy) Conv2D + Fully Connected NN

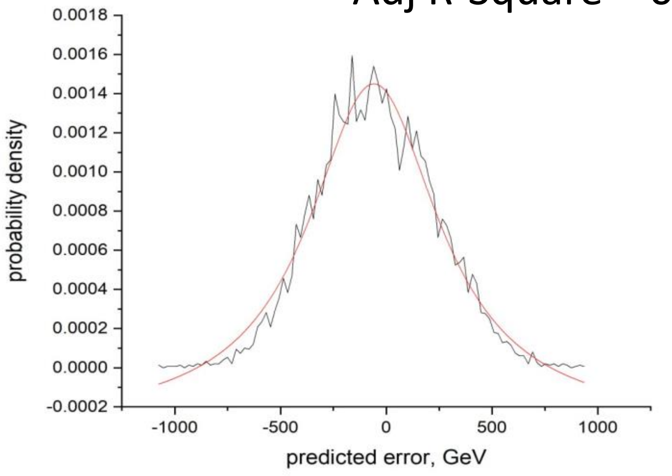
Low Energy Range | Medium Energy Range | High Energy Range

Lorentz

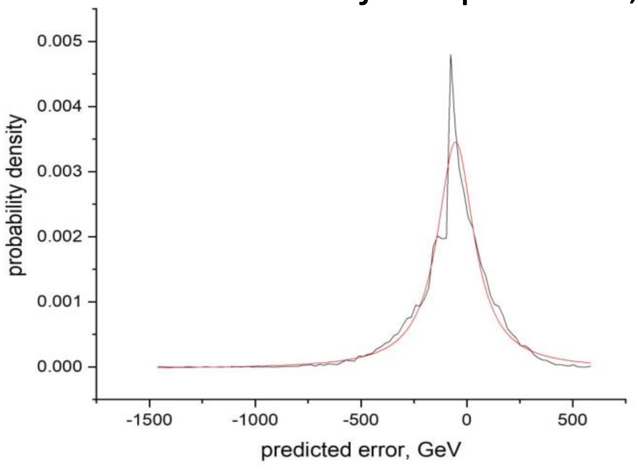
Adj R-Square = 0,994



Adj R-Square = 0,971

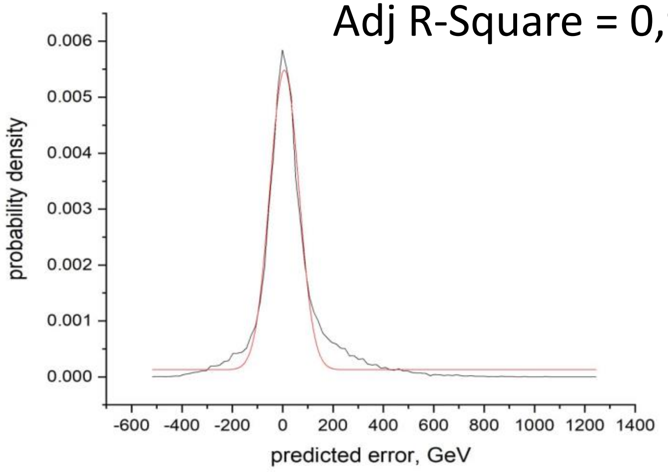


Adj R-Square = 0,939

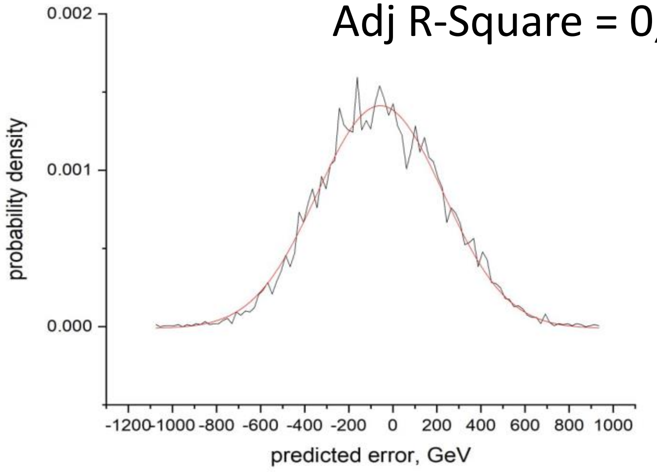


Gauss

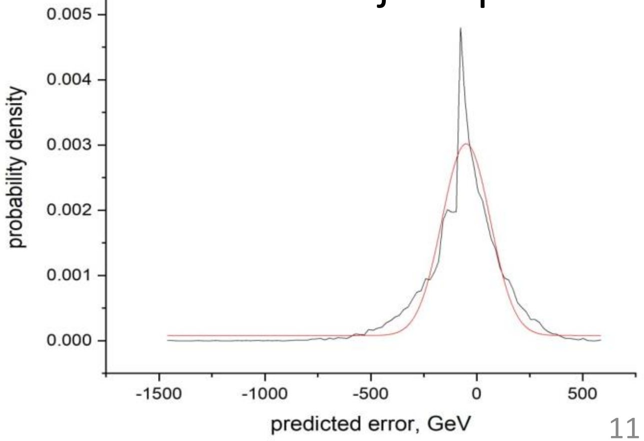
Adj R-Square = 0,975



Adj R-Square = 0,979



Adj R-Square = 0,904



Conclusions and Future Plans

Conclusions:

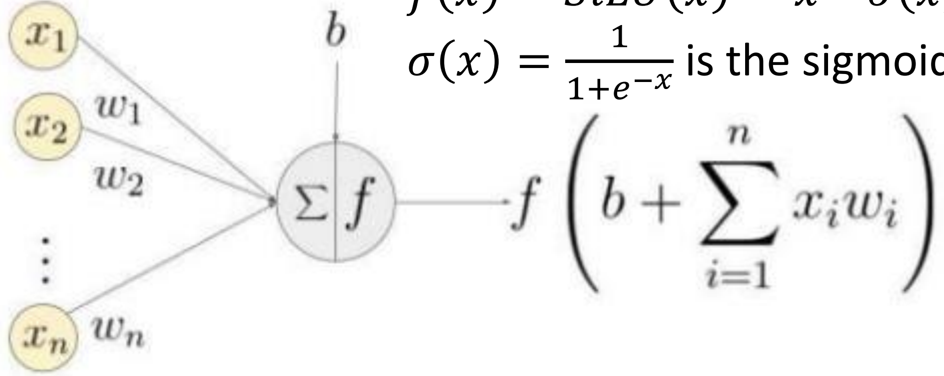
1. We constructed the dependence $\sqrt{s_{eff}}(b)$ using QGSM-generated events
2. The energy conservation laws were verified for the QGSM generator. Taking into account the conservation law estimation, a criterion was formulated (energy conservation is satisfied within **1.5%**) for determining $\sqrt{s_{eff}}$.
3. A function was constructed that maps the signal from a limited-acceptance detector to the energy of the final-state particles. Two targets were considered: (1) the energy of **all** final-state particles and (2) the energy of **charged** final-state particles only. The best performance is obtained with a model augmented by a convolutional layer when predicting the energy of all final-state particles: in this case the RMSE is below **190 GeV** and the relative error is under **9%**.
4. A detailed analysis was also performed for three energy ranges: low, medium, and high. It was found that the ranges of low and medium energies are poorly approximated by a Gaussian distribution, which is related to physical constraints not accounted for by the model in the collisions. To improve the $\sqrt{s_{eff}}$ estimation, the loss function should be chosen more carefully, explicitly incorporating relevant physical constraints.

The authors acknowledge Saint-Petersburg State University for a research project 103821868

Thank you for your attention!

Used ANN

$f(x) = SiLU(x) = x \cdot \sigma(x)$, where x is the input,
$\sigma(x) = \frac{1}{1+e^{-x}}$ is the sigmoid function



Loss function	Optimizator	Weight decay	Learning rate	Batch size	Epochs
MSE	Adam	10^{-5}	0.001	3000	1500

Conv2D + Fully Connected NN

NN with convolutional layer used for solving regression problem:

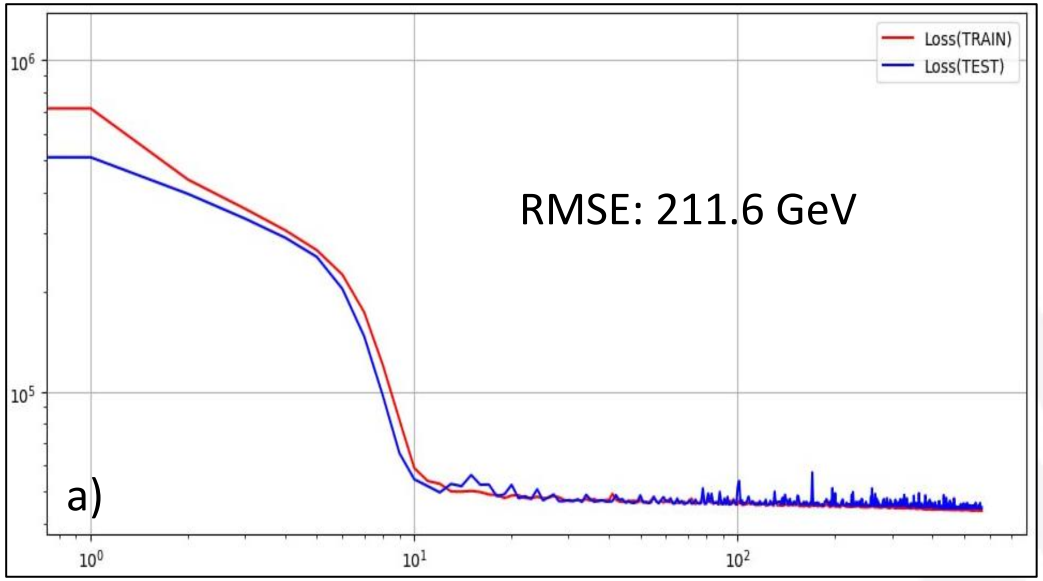
- Input: 3×120 features;
- Convolutional layer: 8 filters 3×6;
- 4 hidden layers (128, 64, 32, 16);
- Output – 1 neuron – $\sqrt{s_{eff}}$

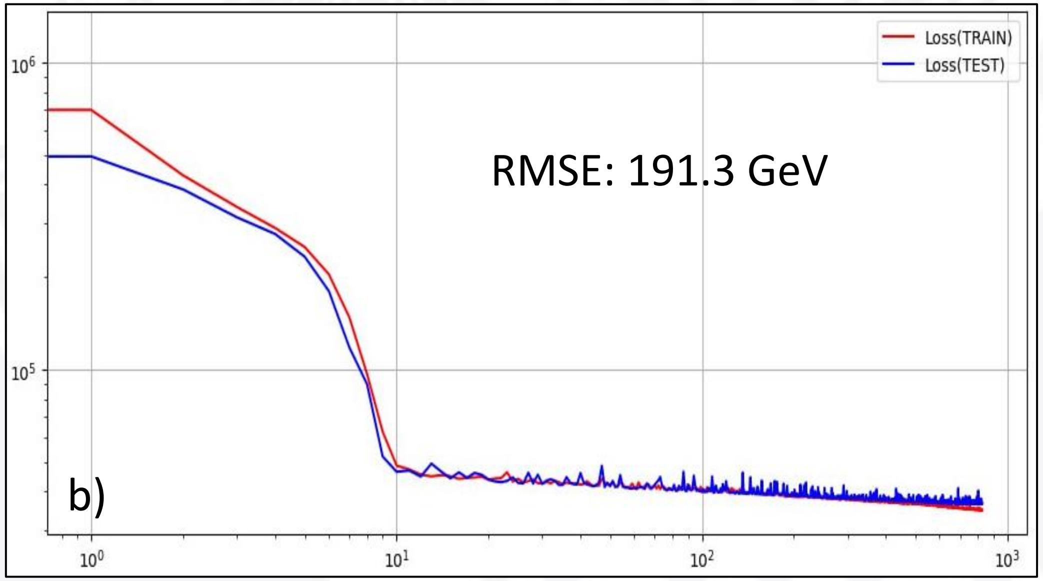
Fully Connected NN

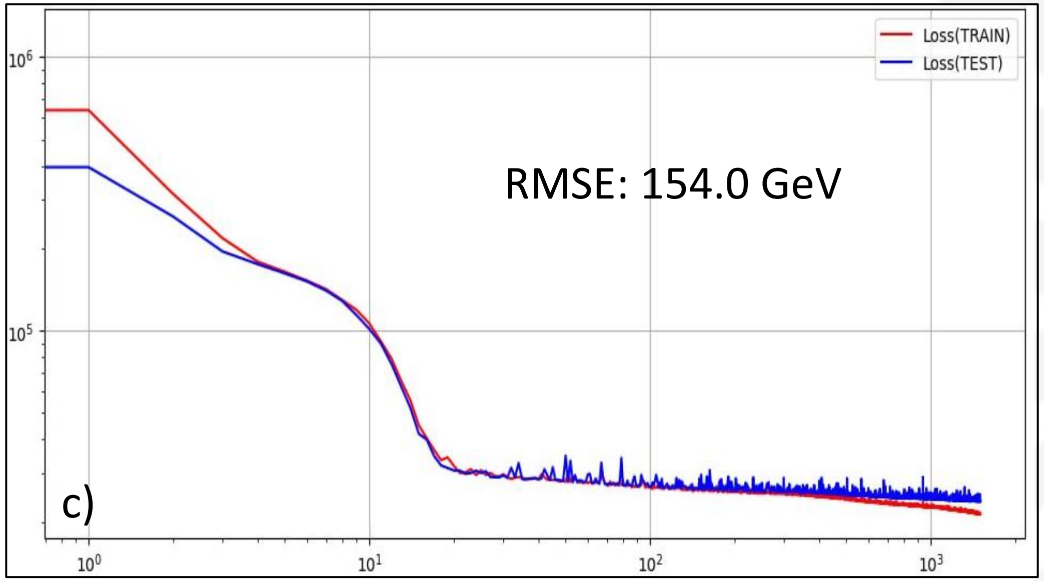
NN used for solving regression problem:

- Input 360 features (we take feature vector for 120 particles);
- 4 hidden layers (128, 64, 32, 16);
- Output – 1 neuron – $\sqrt{s_{eff}}$

Appendix: MSE(epoch) — Fully Connected NN

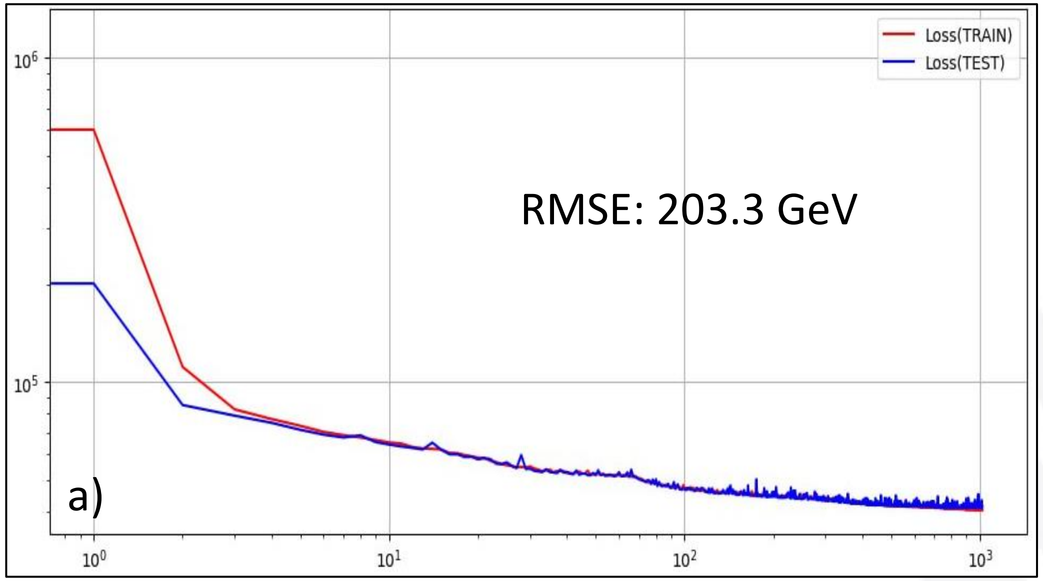


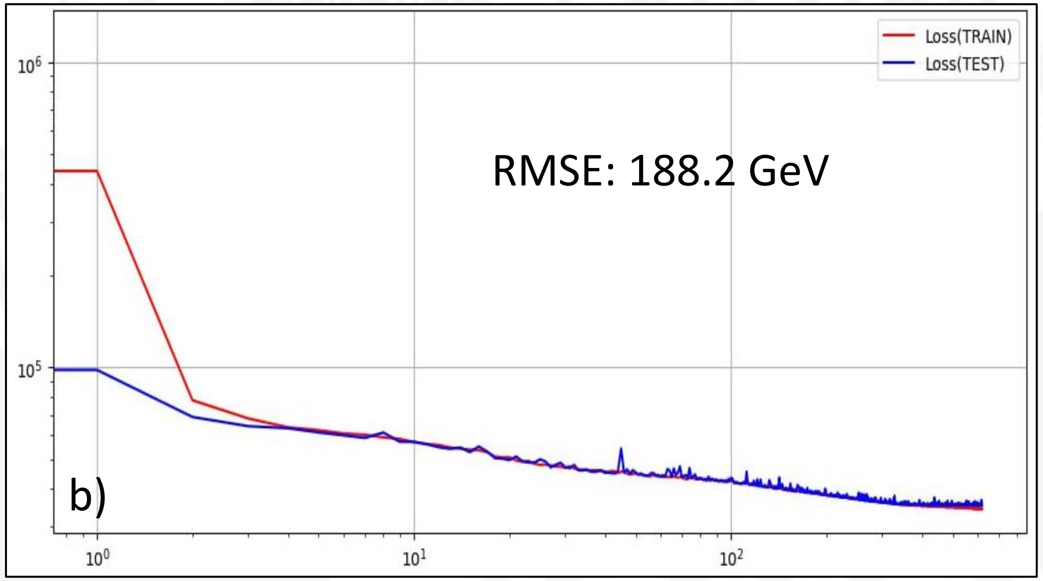


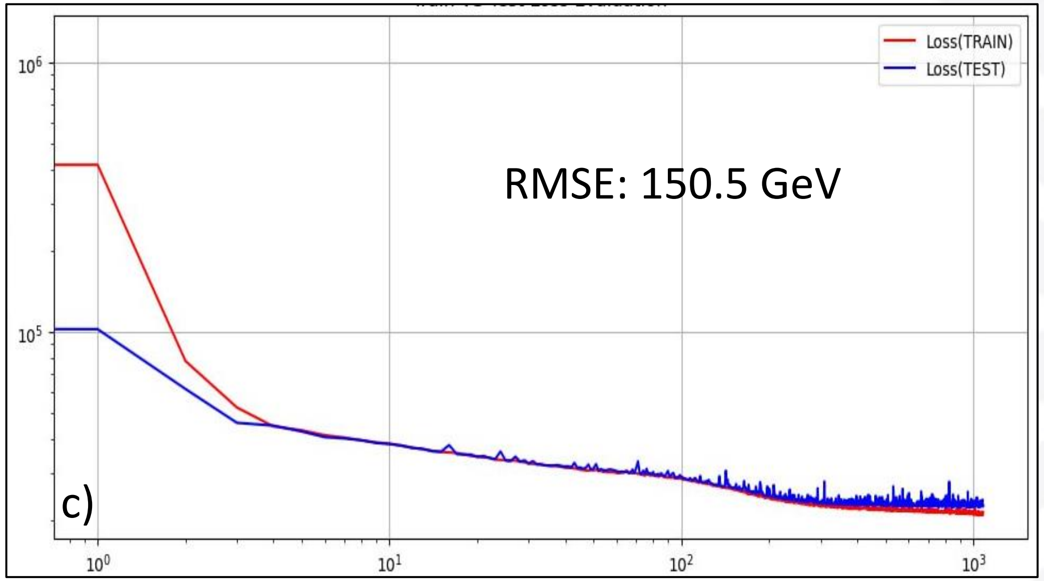


a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: MSE(epoch) Conv2D + Fully Connected NN







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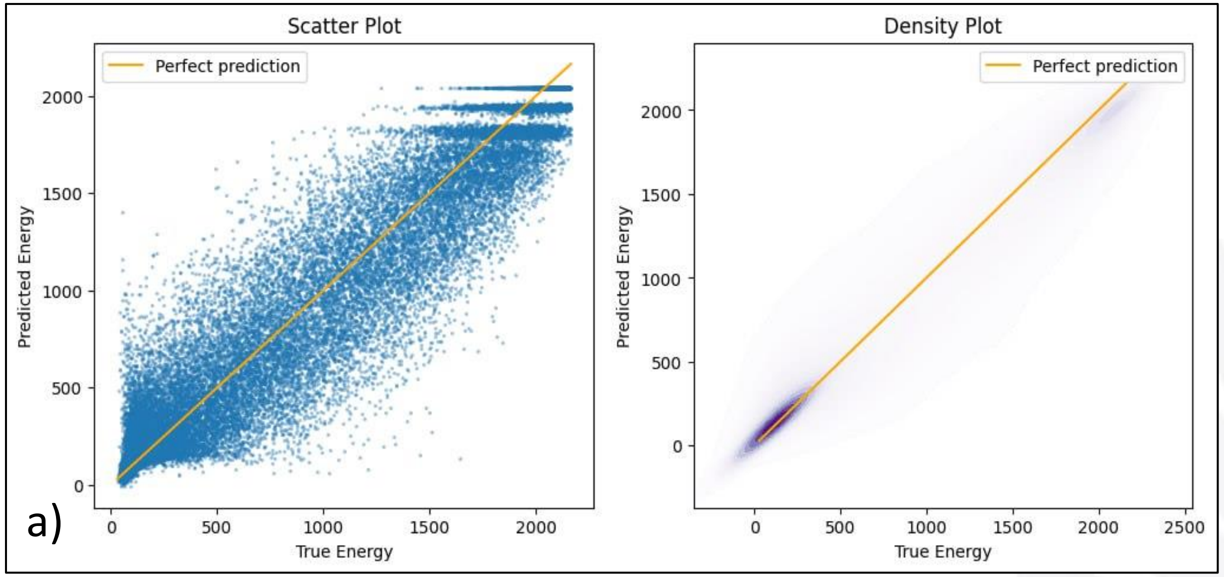
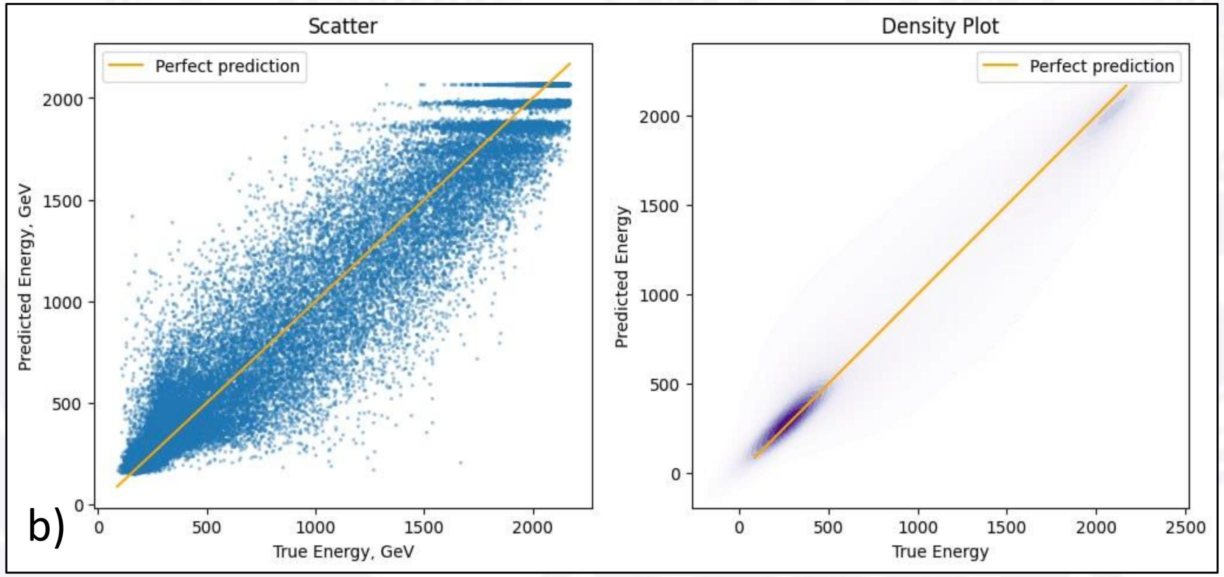
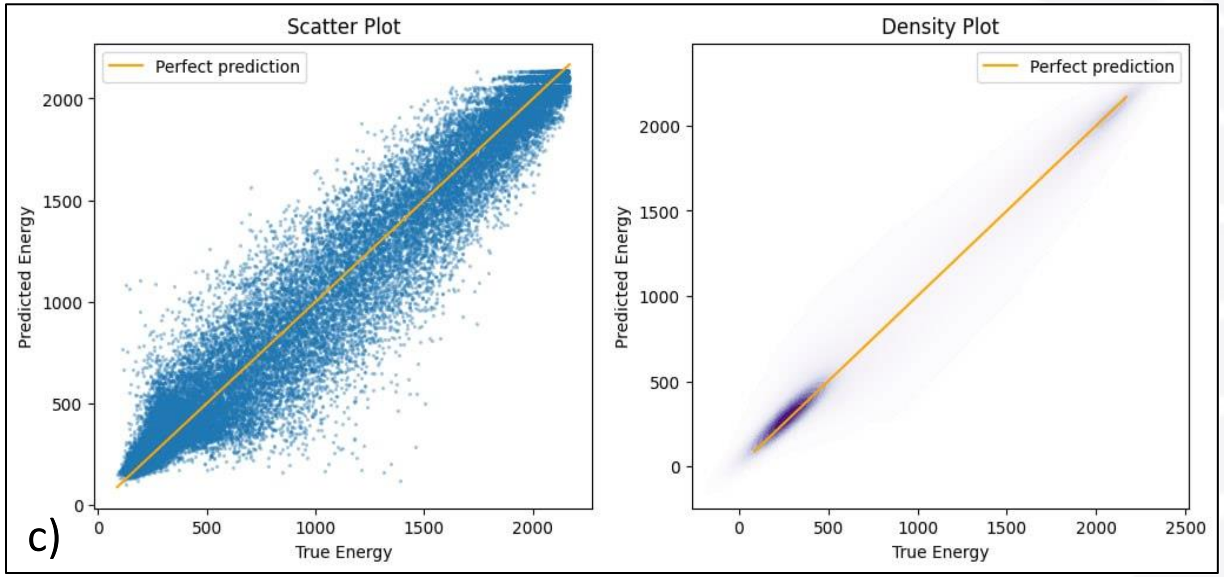
Appendix: $\hat{y}(y)$ Conv2D + Fully Connected NN







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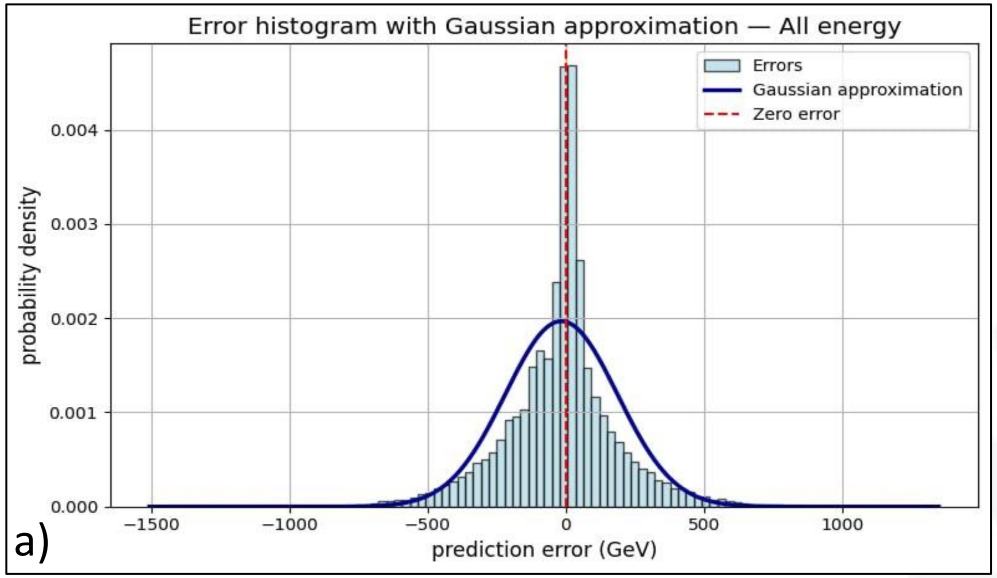
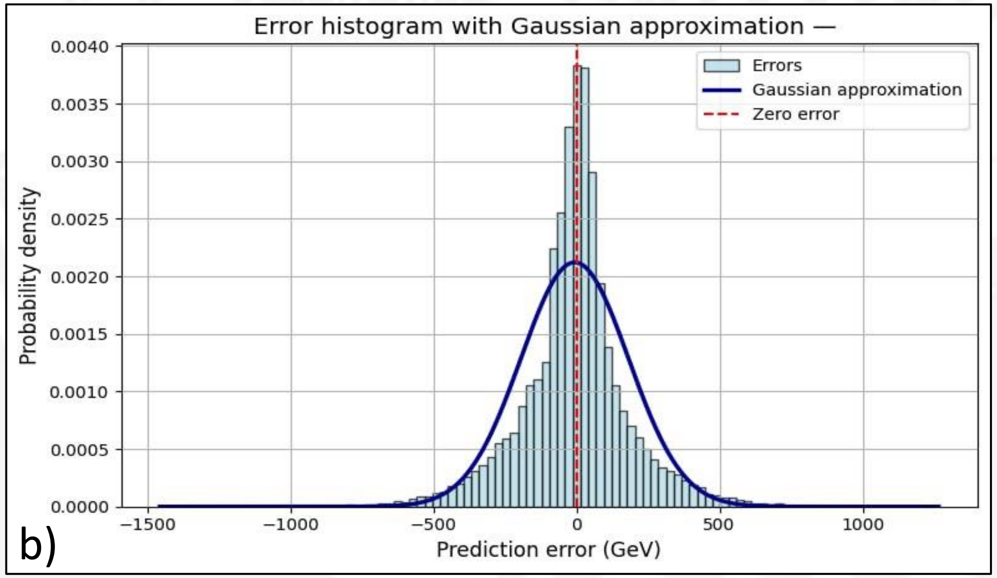
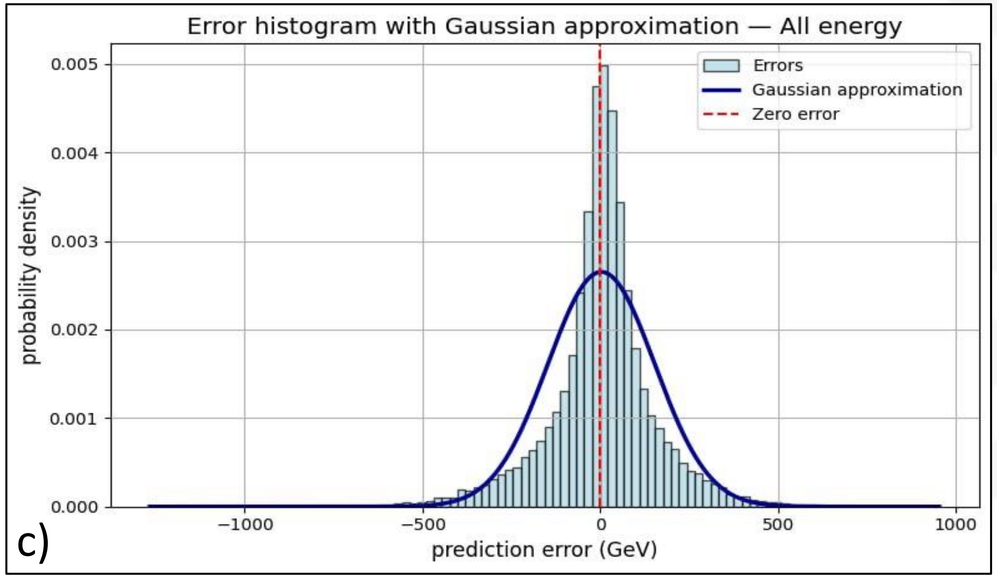
Appendix: Error Histogram — Conv2D + Fully Connected NN







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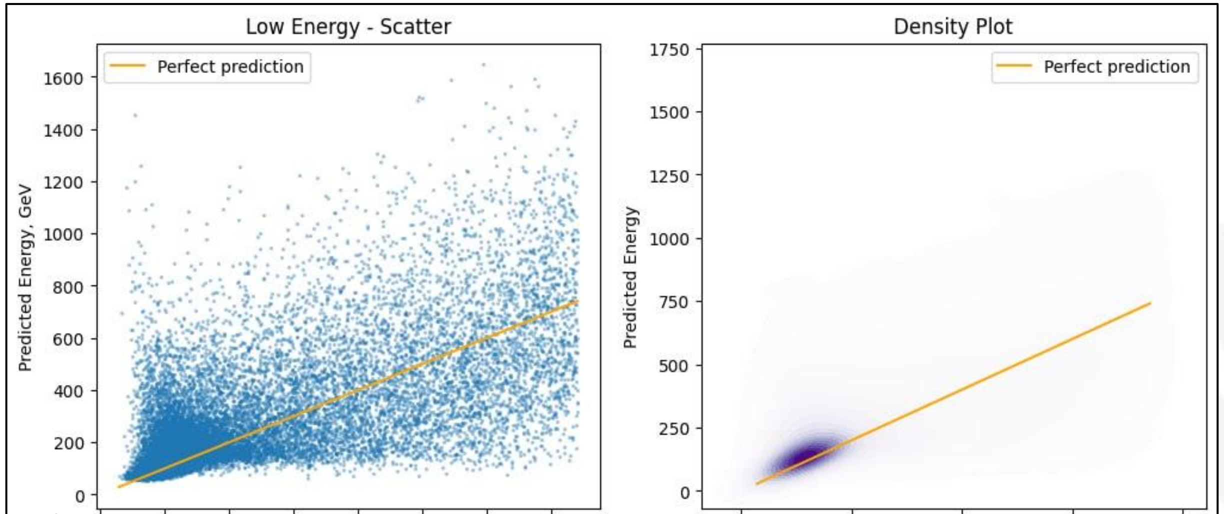
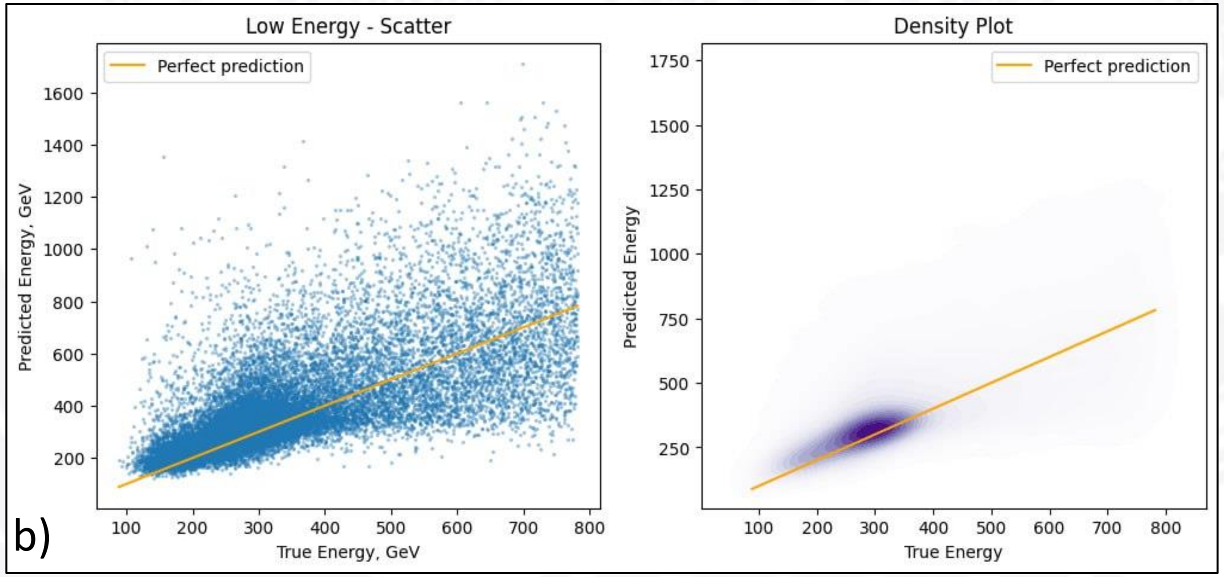
Appendix: $\hat{y}(y)$ – Low Energy

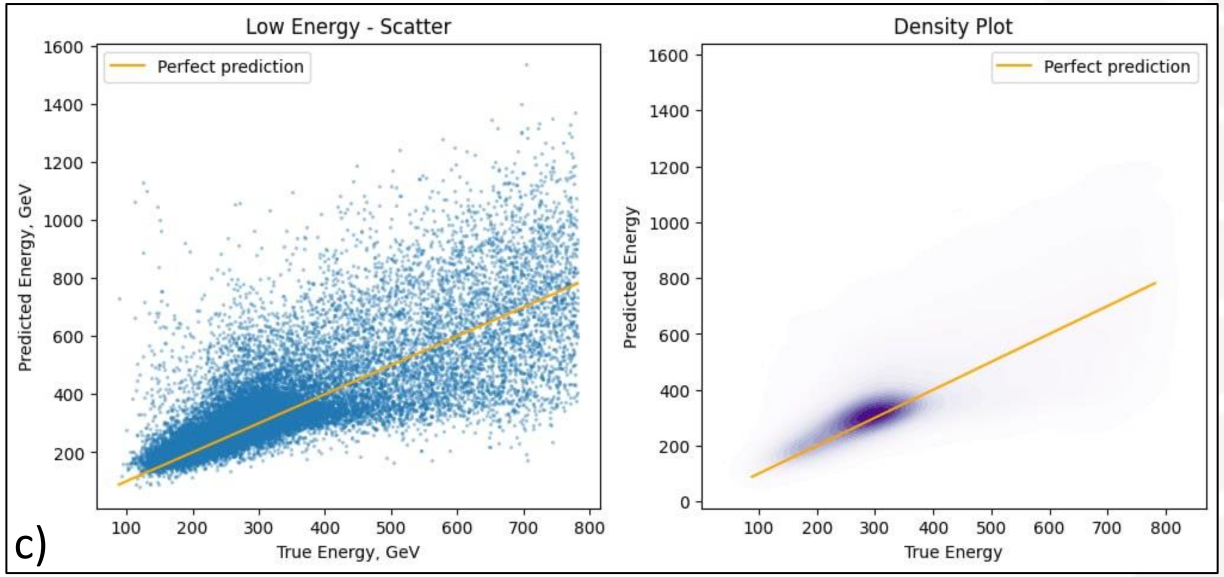
Fully Connected NN



a)



b)



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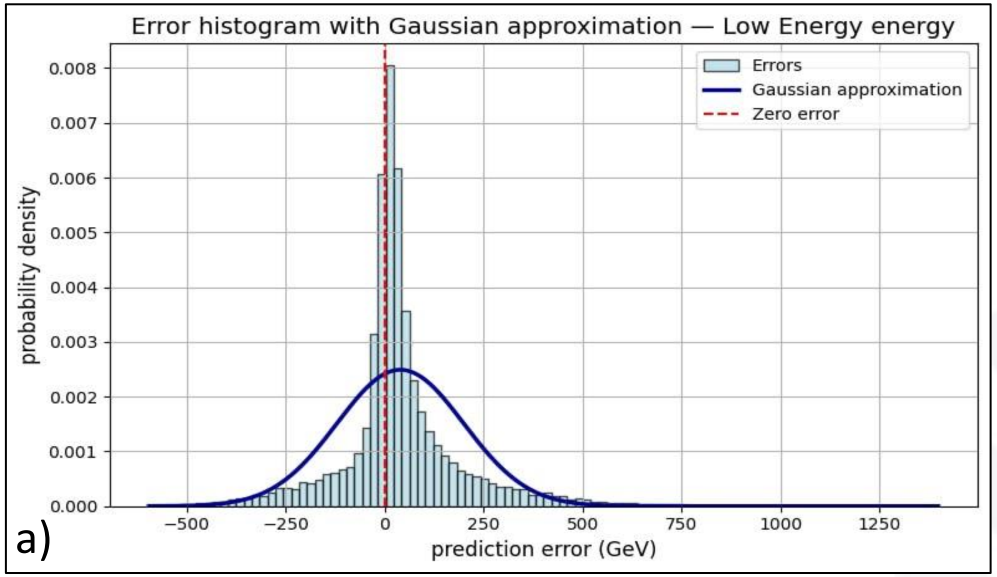
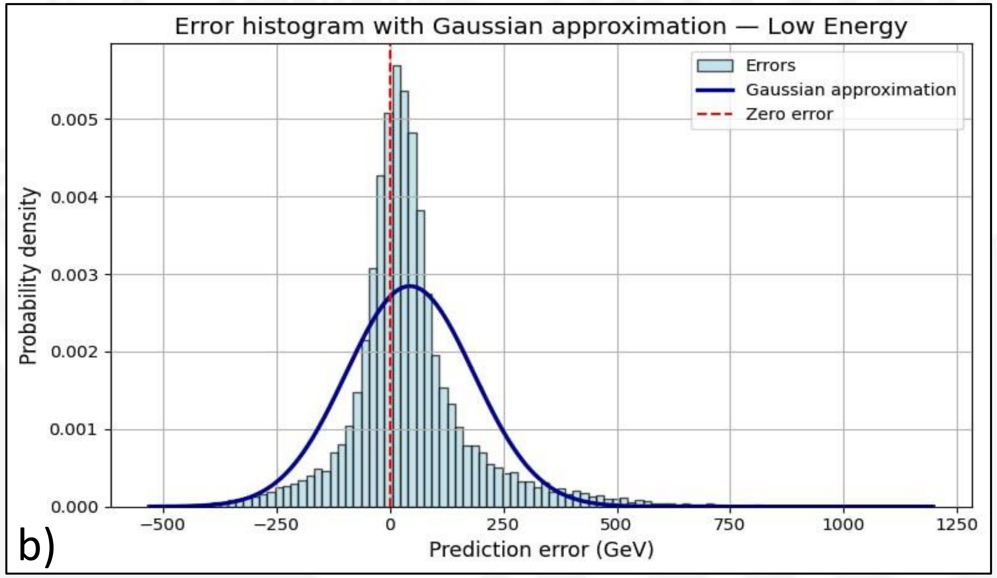
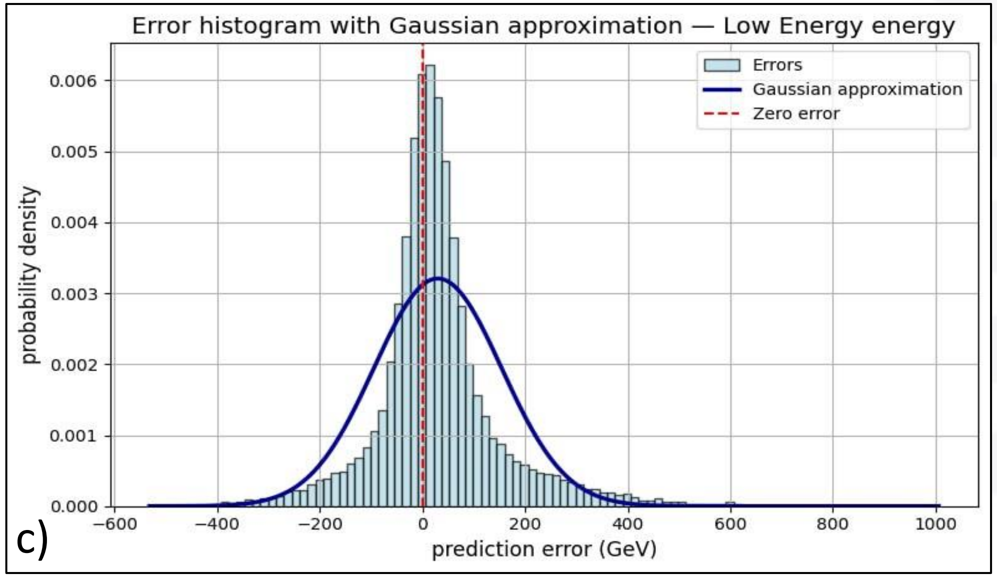
Appendix: Error His – Low Energy

Fully Connected NN







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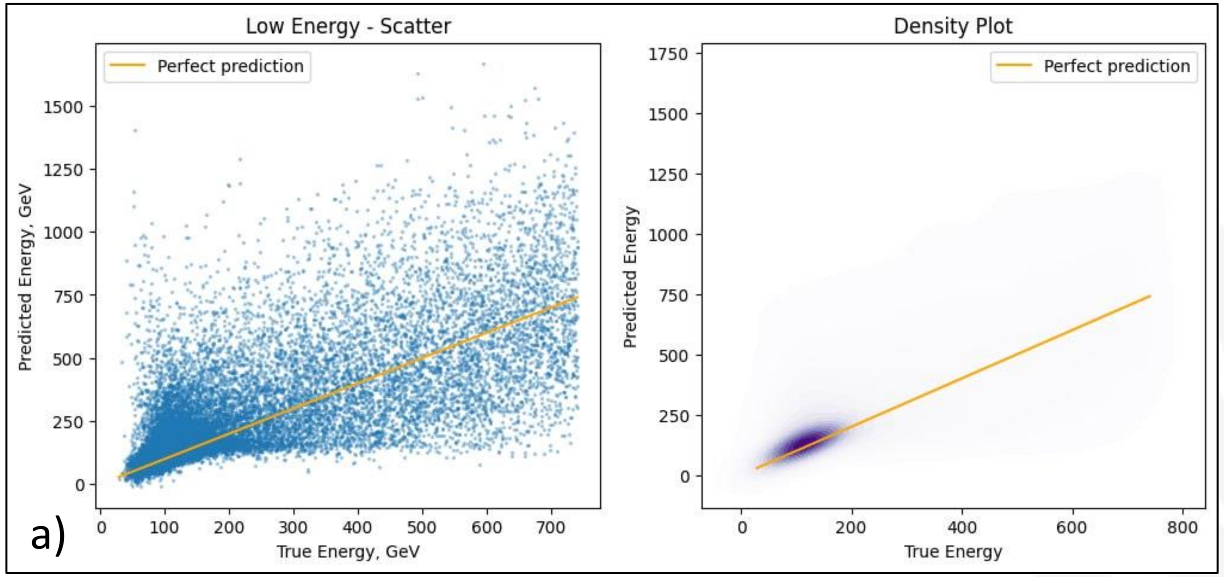
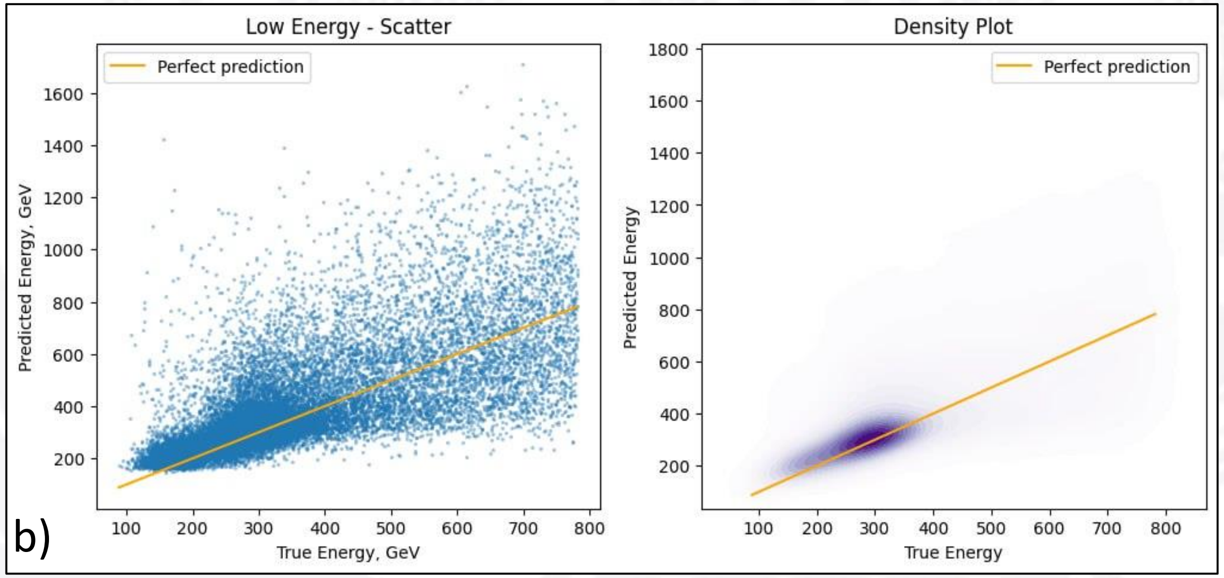
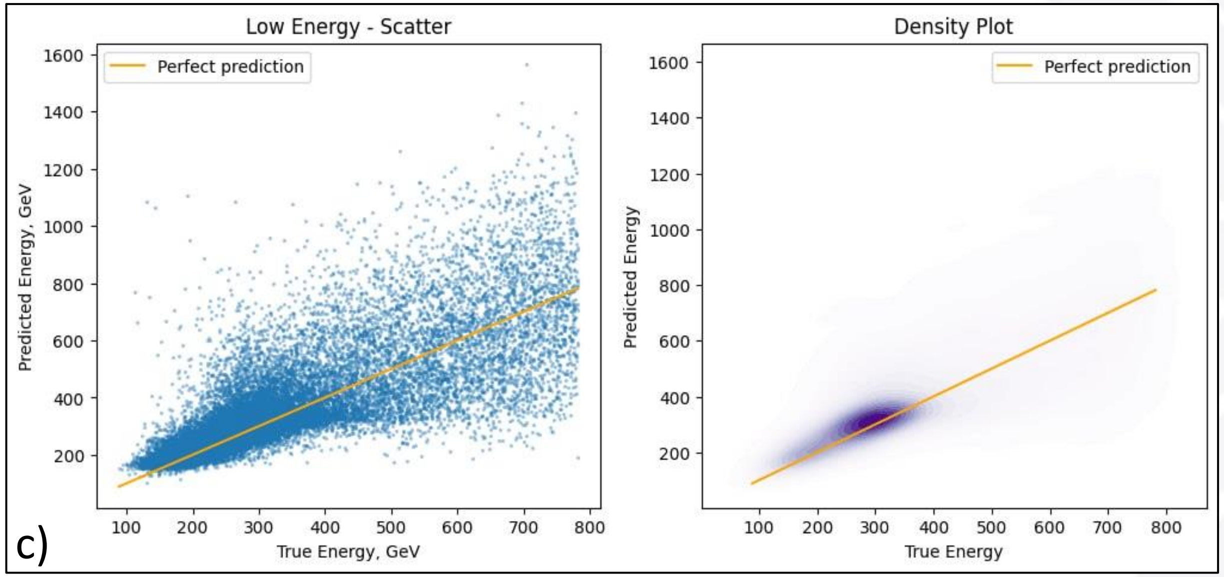
Appendix: $\hat{y}(y)$ – Low Energy Conv2D + Fully Connected NN







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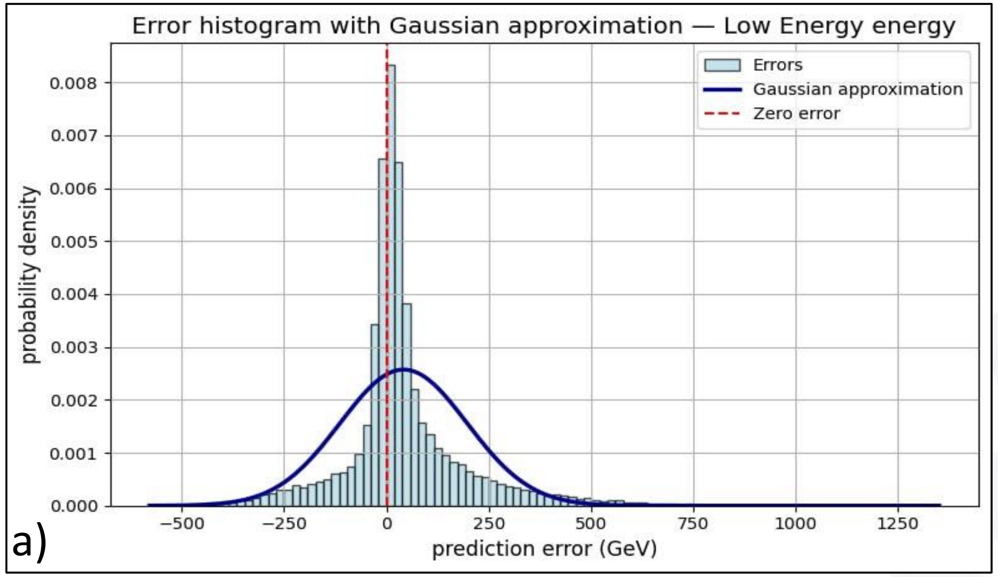
Appendix: Error His – Low Energy Conv2D + Fully Connected NN



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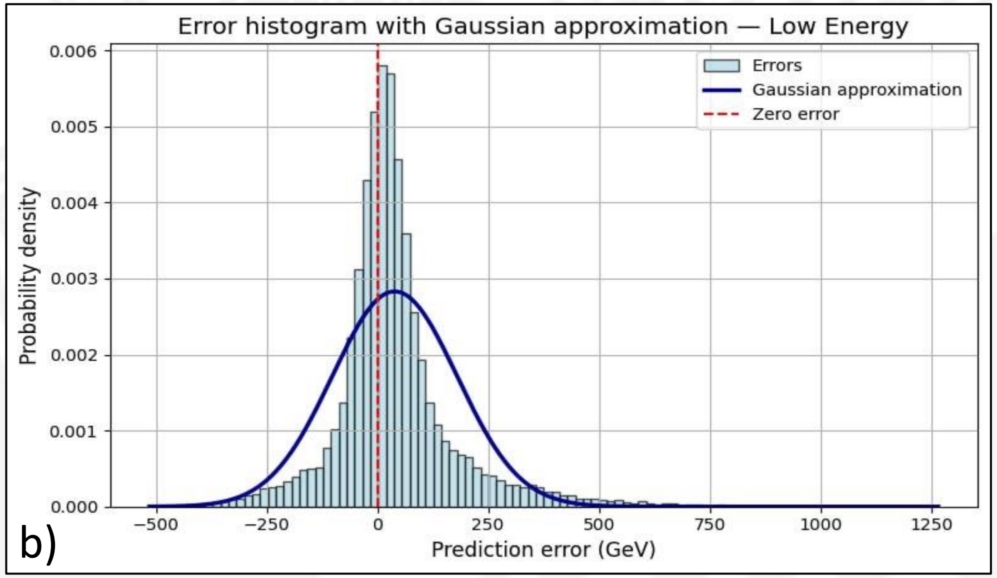
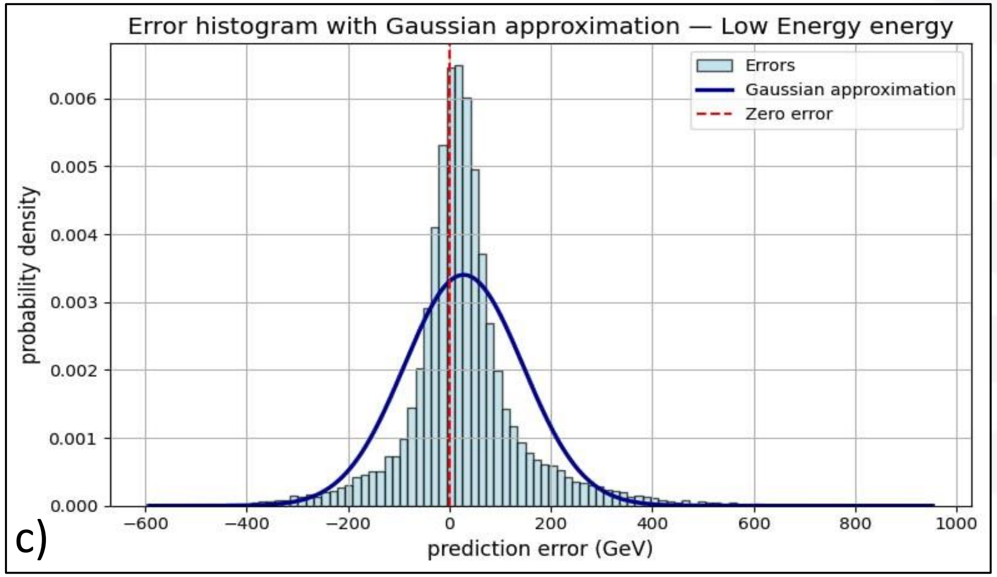


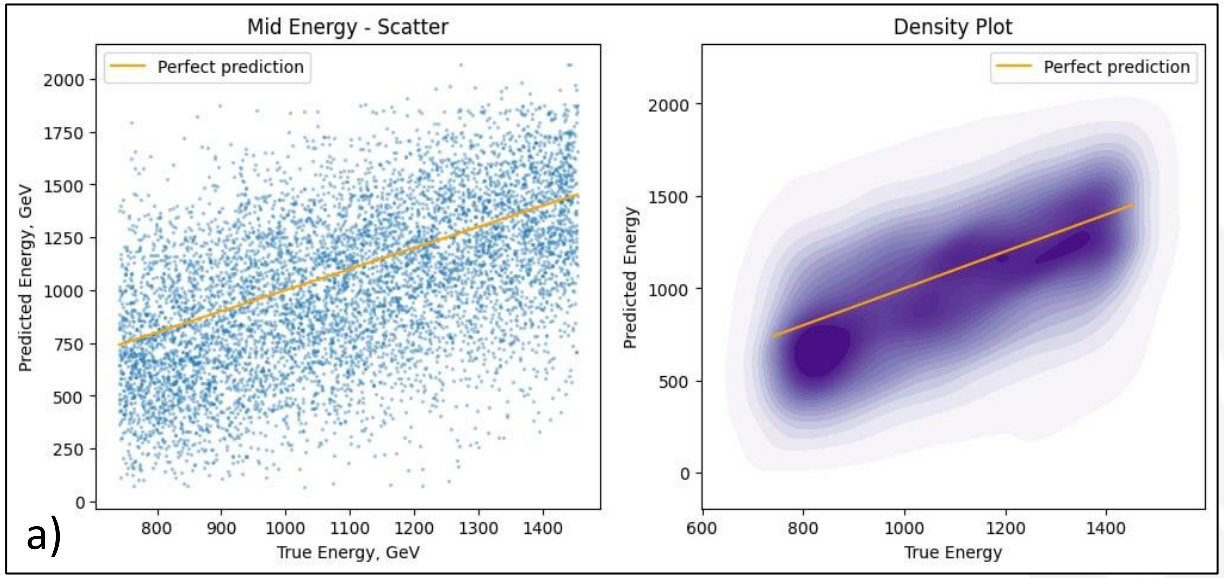
b)

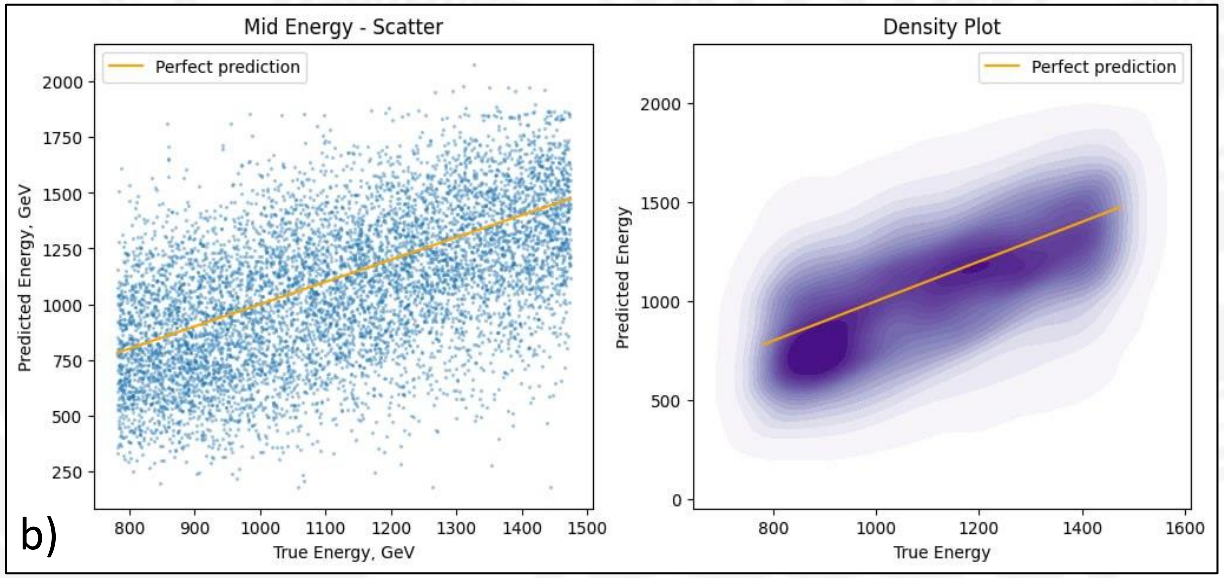


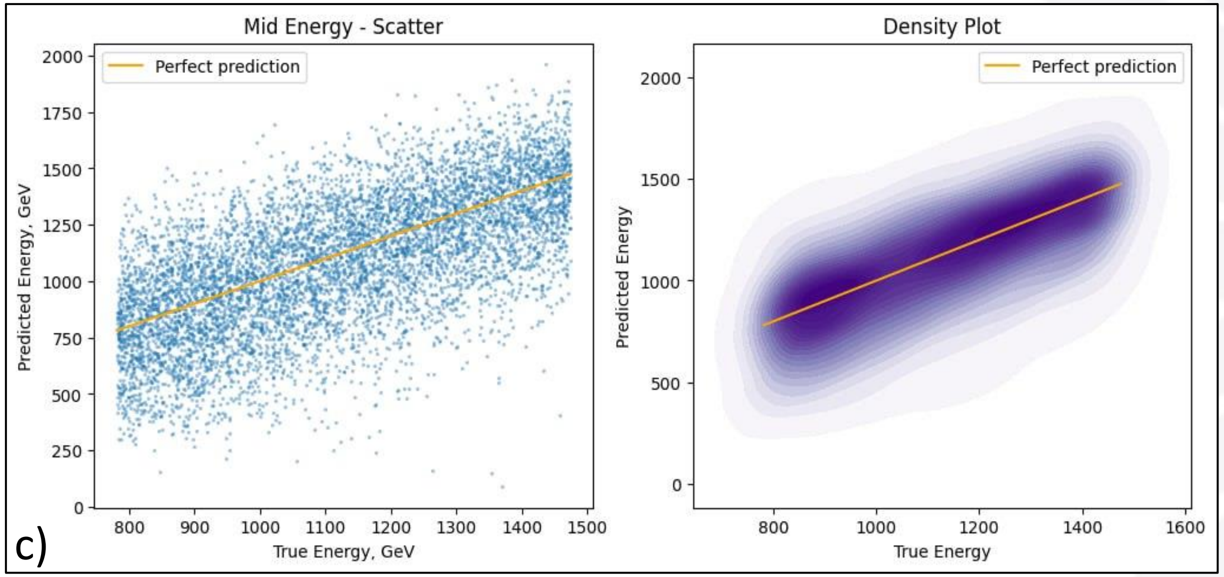
c)

a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: $\hat{y}(y)$ – Mid Energy Fully Connected NN

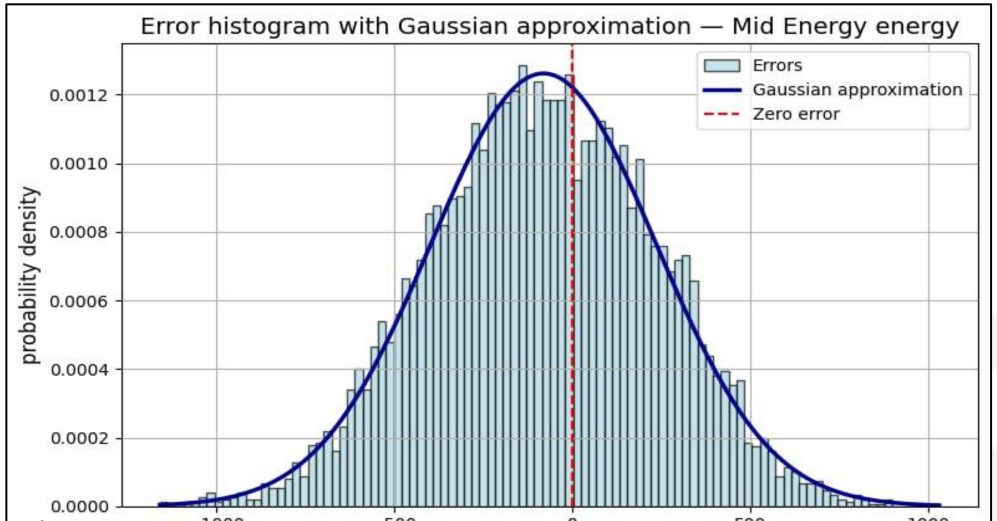




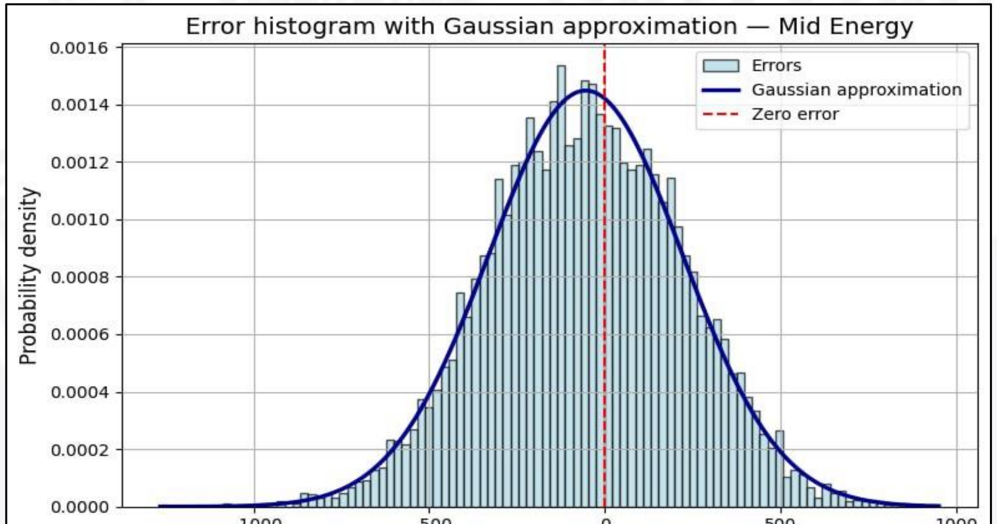


a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

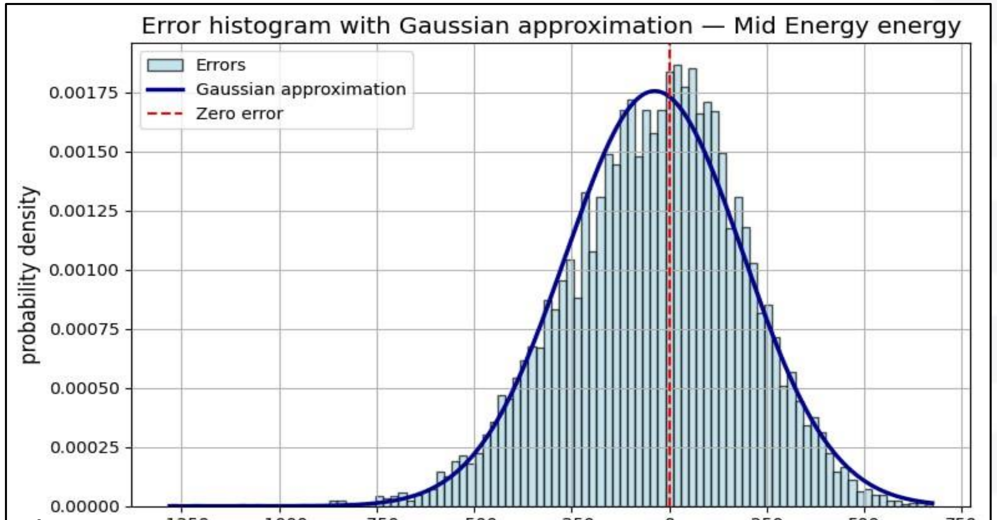
Appendix: Error Hist - Mid Energy   Fully Connected NN



a)



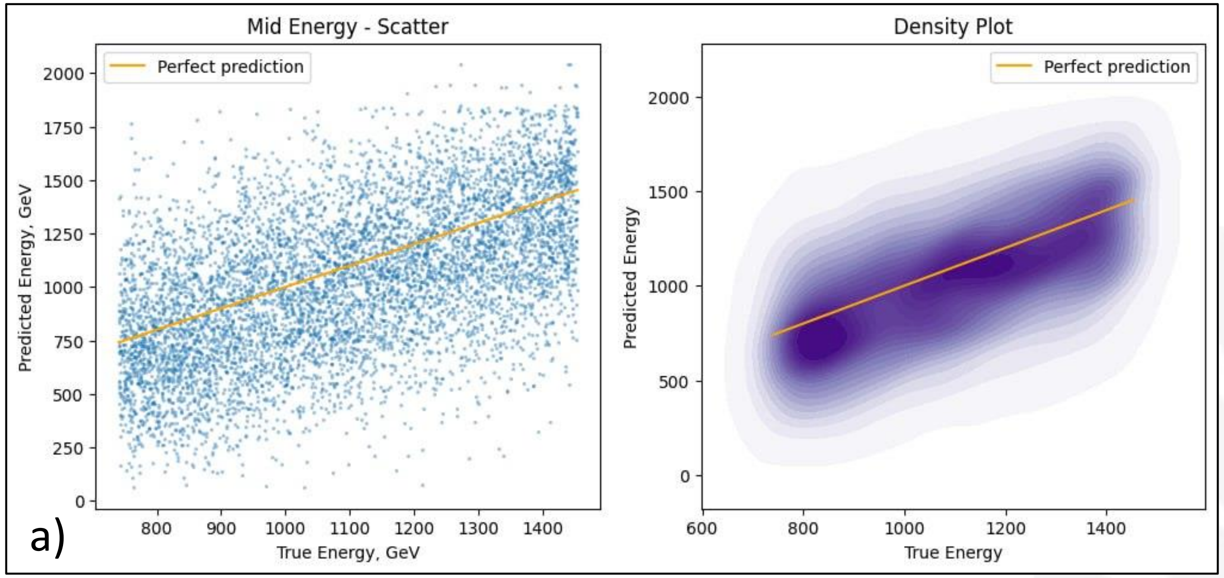
b)

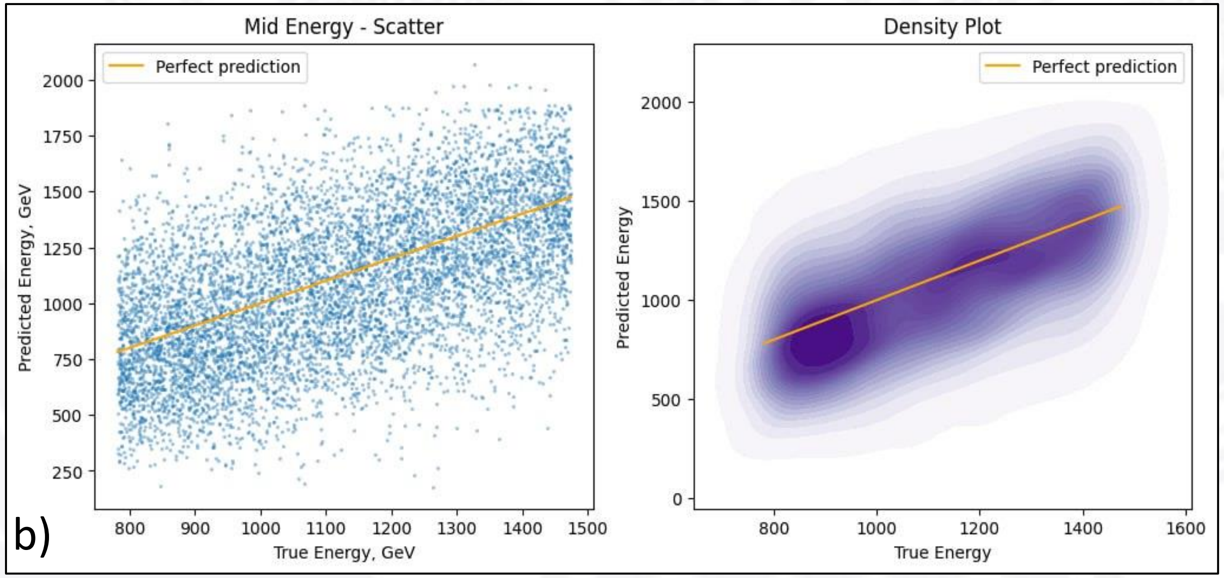


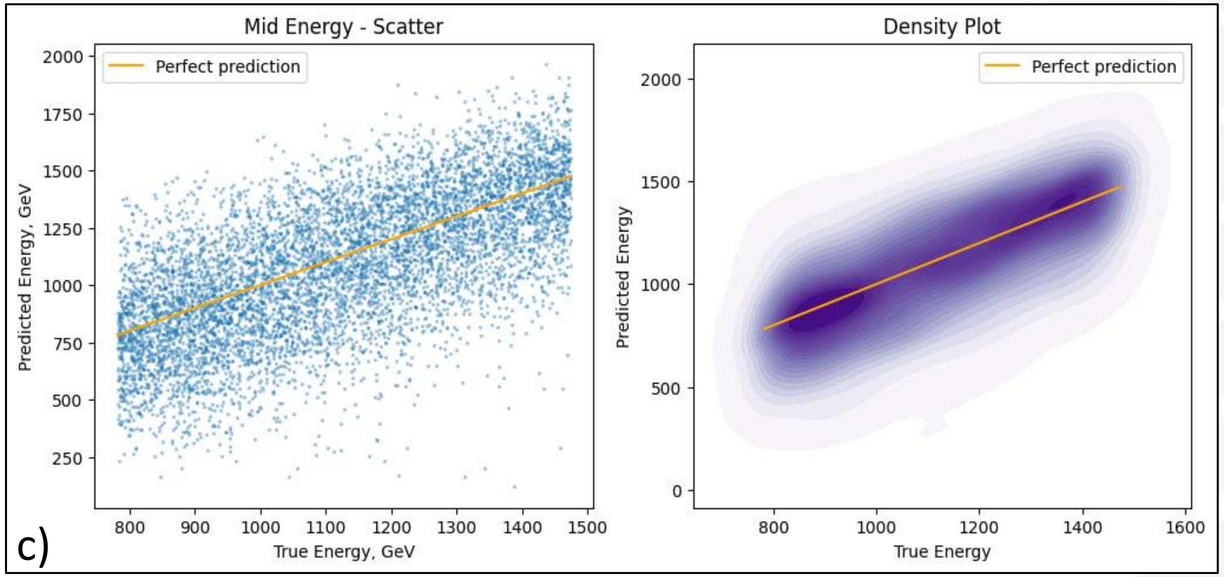
c)

a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: $\hat{y}(y)$ – Mid Energy Conv2D + Fully Connected NN

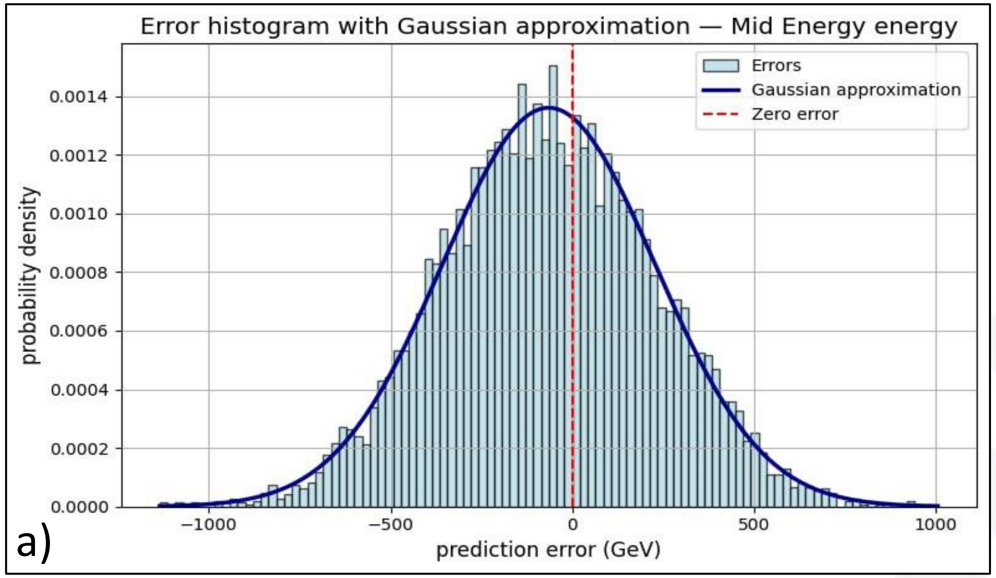


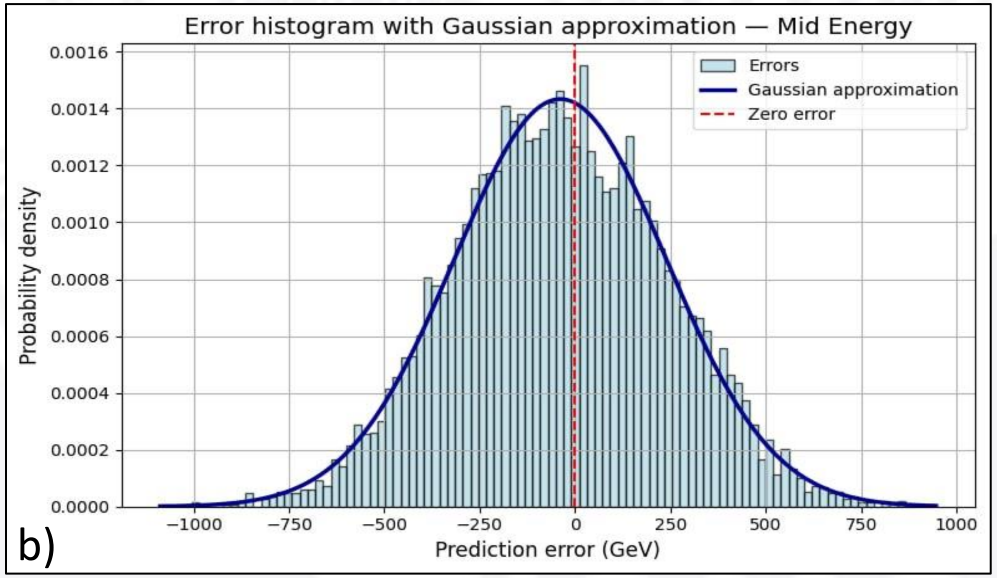


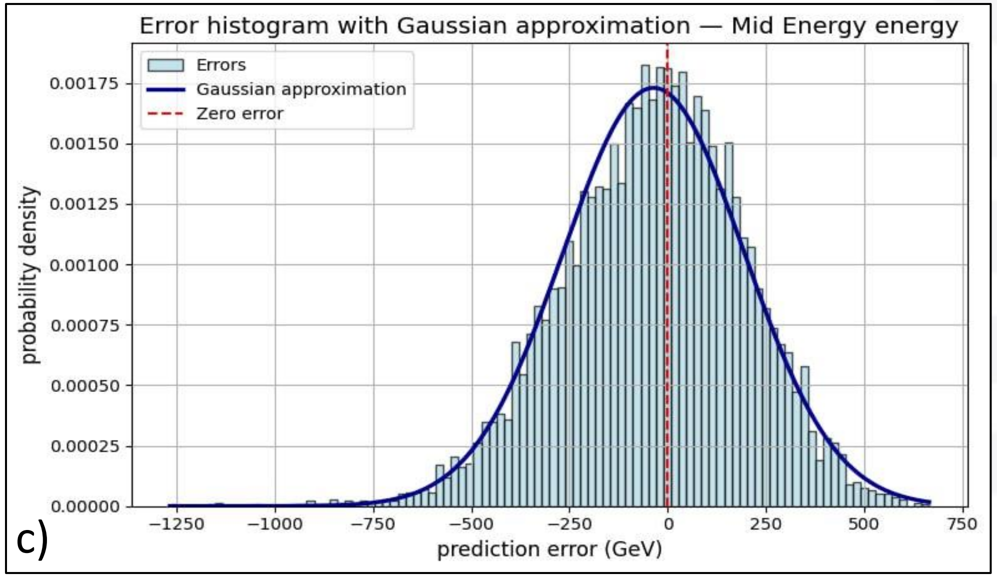


a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: Error Hist - Mid Energy Conv2D + Fully Connected NN

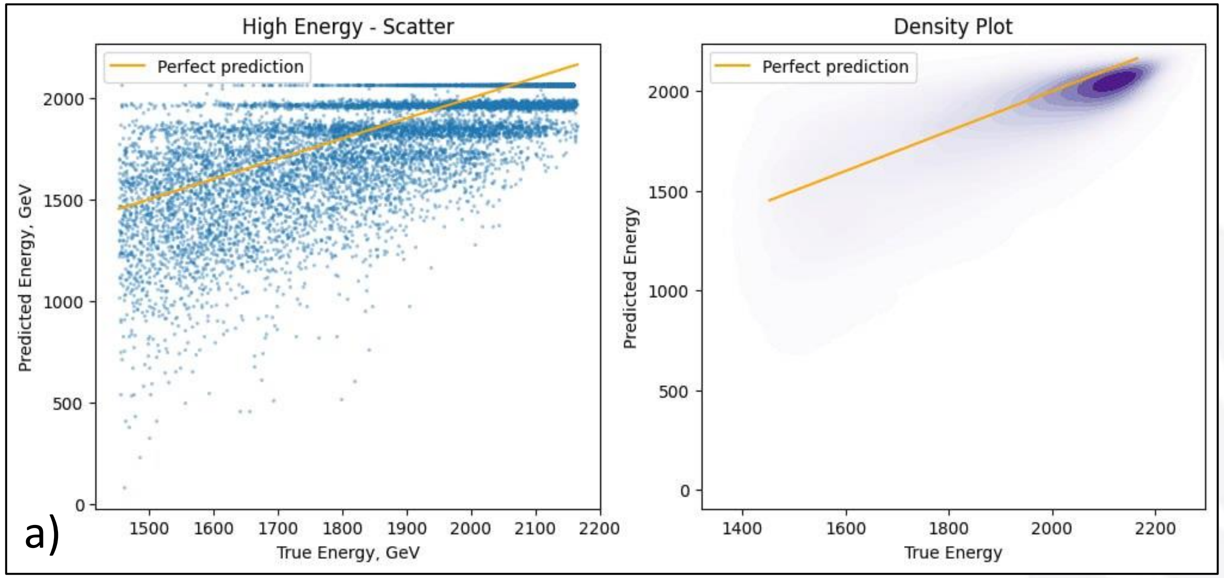


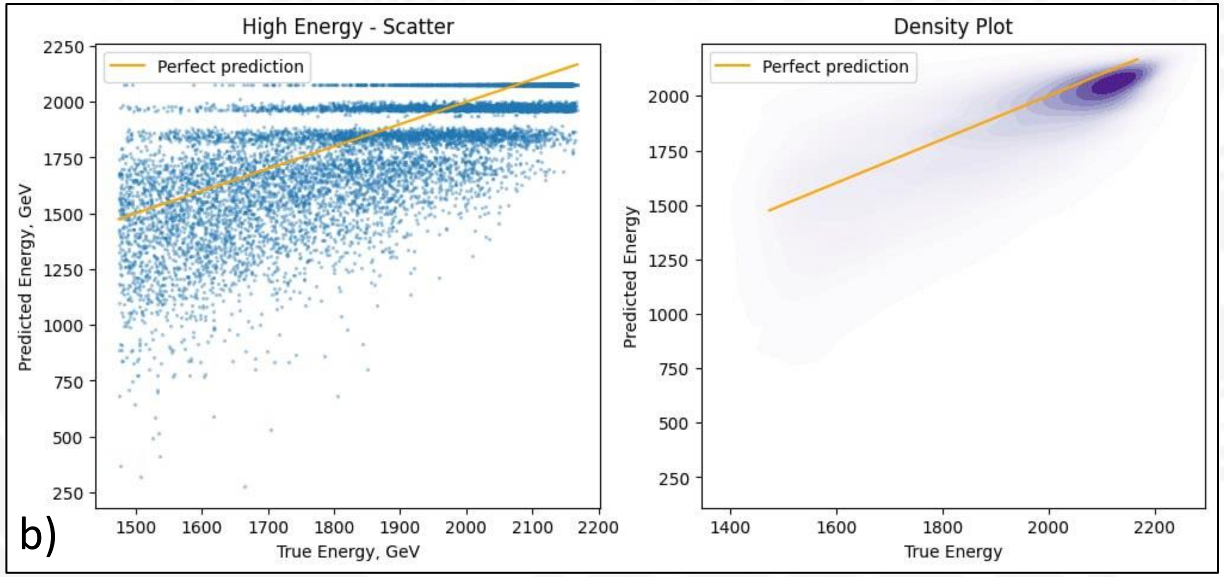


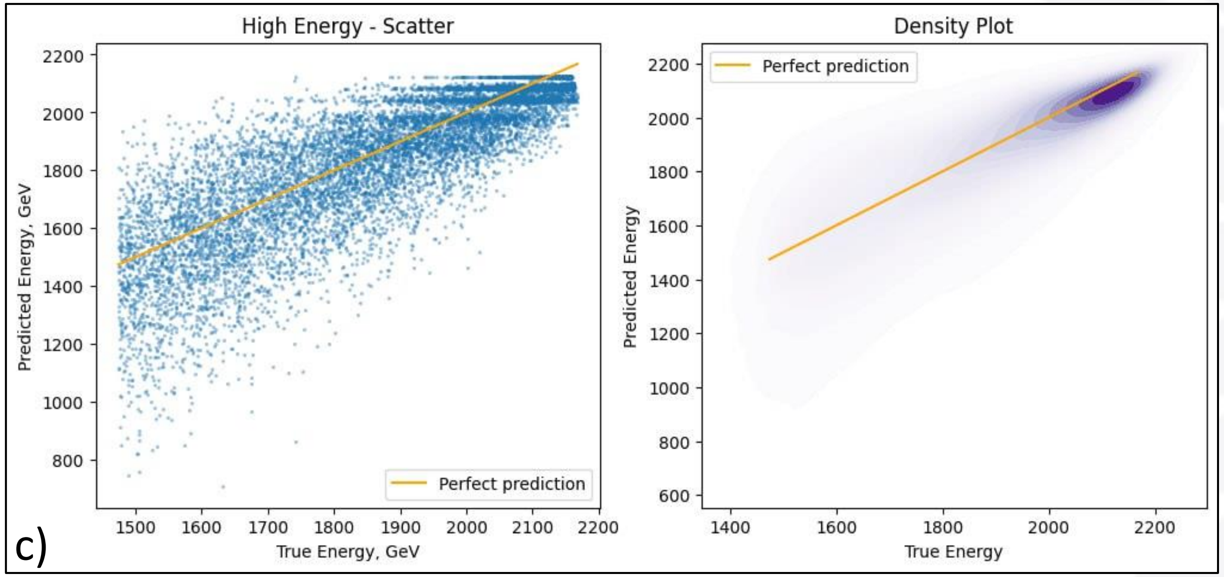


a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: $\hat{y}(y)$ – High Energy Fully Connected NN



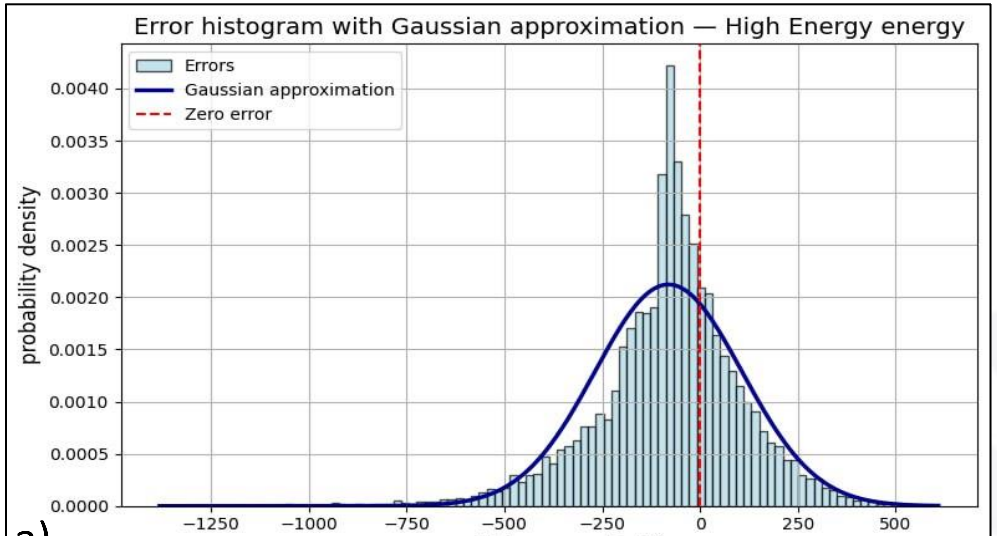




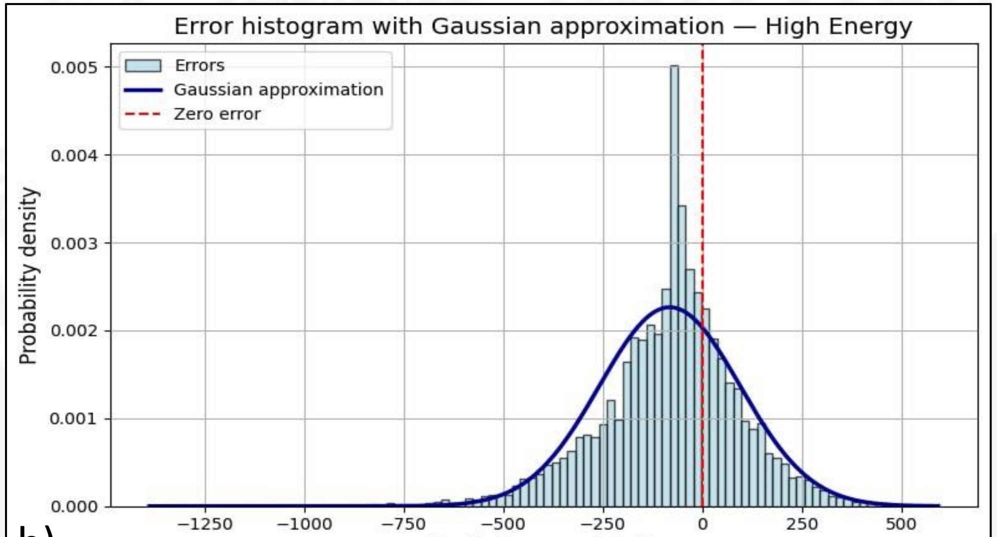
a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: Error Hist - High Energy

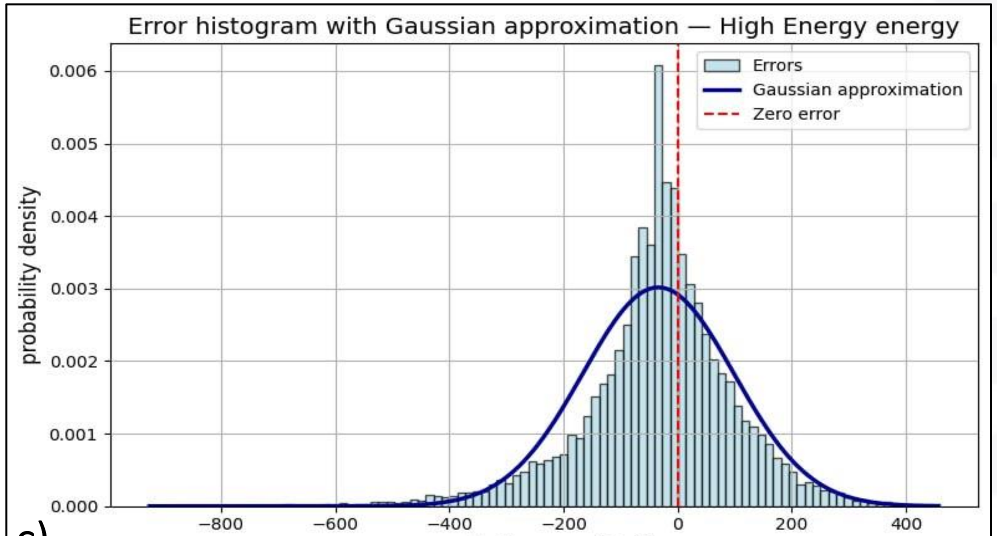
Fully Connected NN



a)



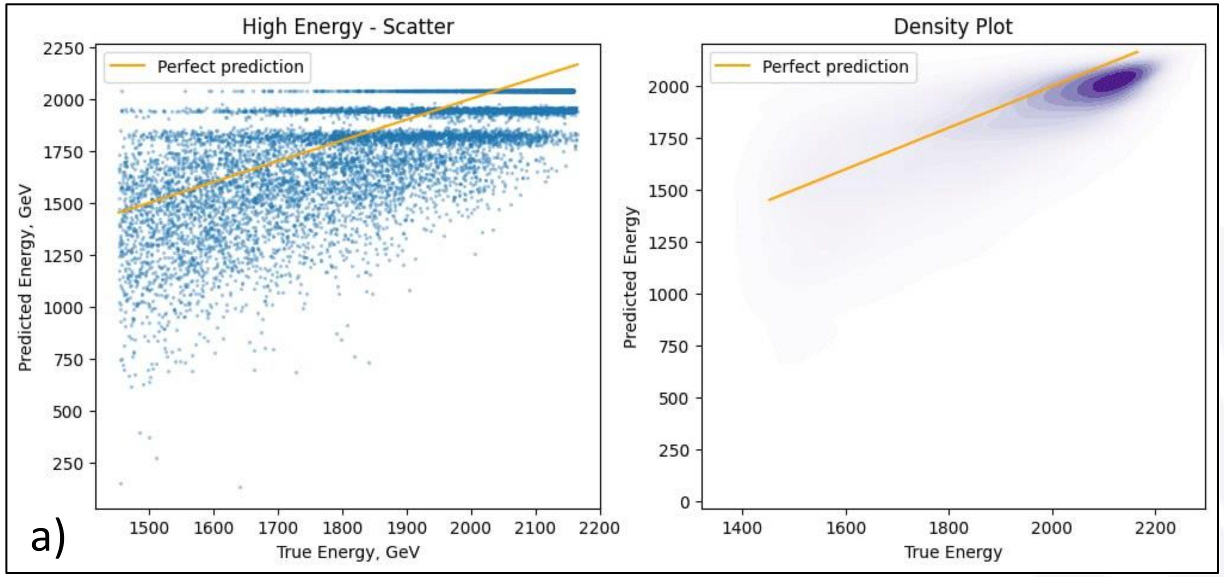
b)

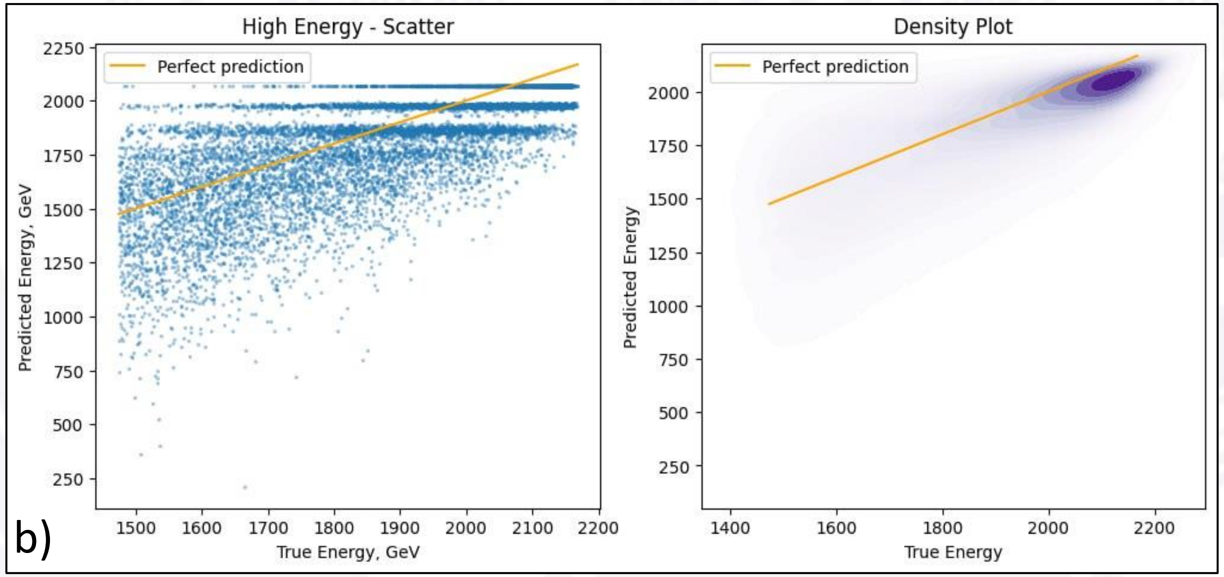


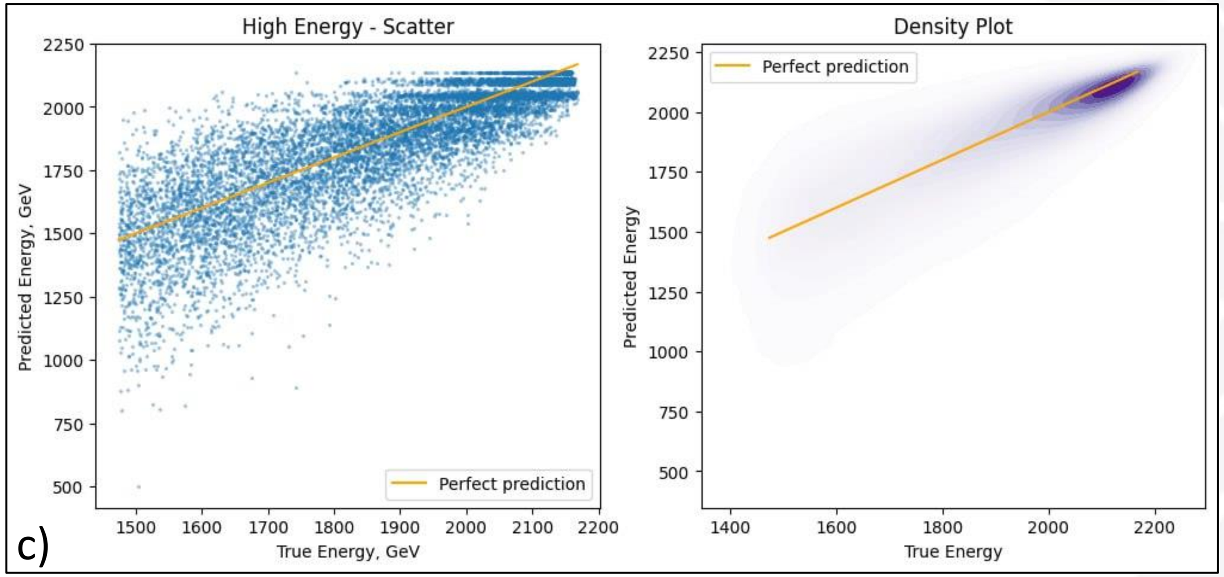
c)

a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: $\hat{y}(y)$ – High Energy Conv2D + Fully Connected NN

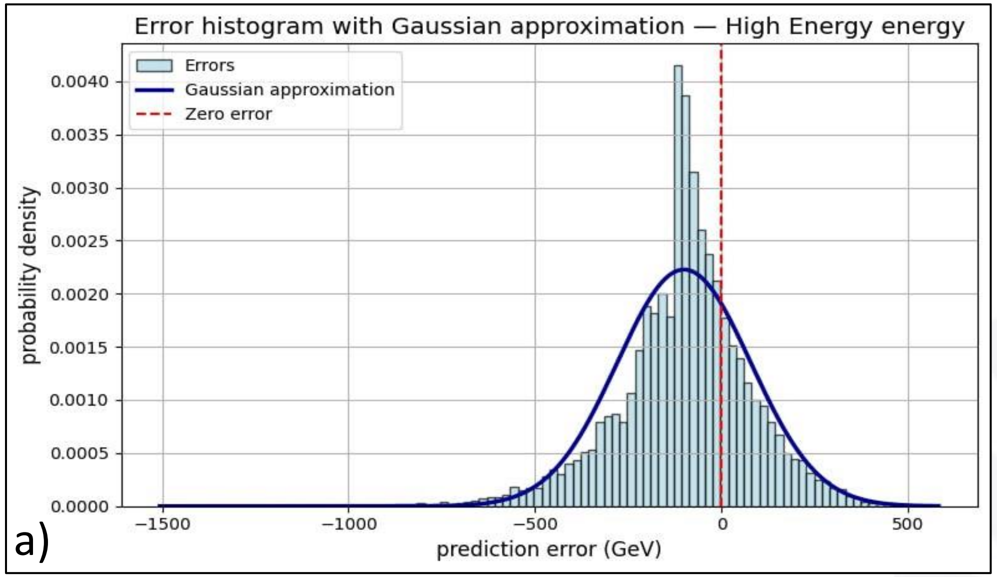




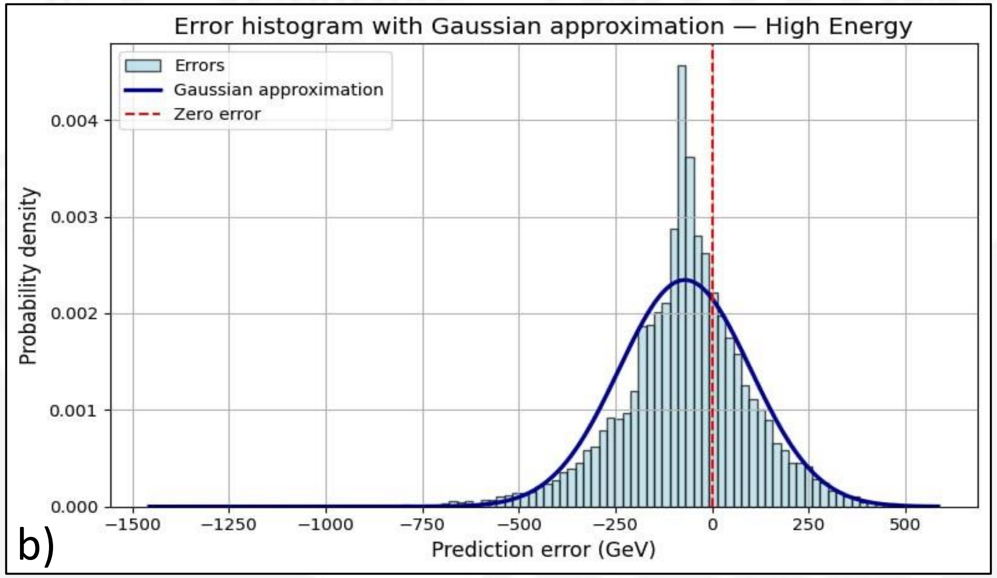


a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: Error Hist - High Energy Conv2D + Fully Connected NN



a)



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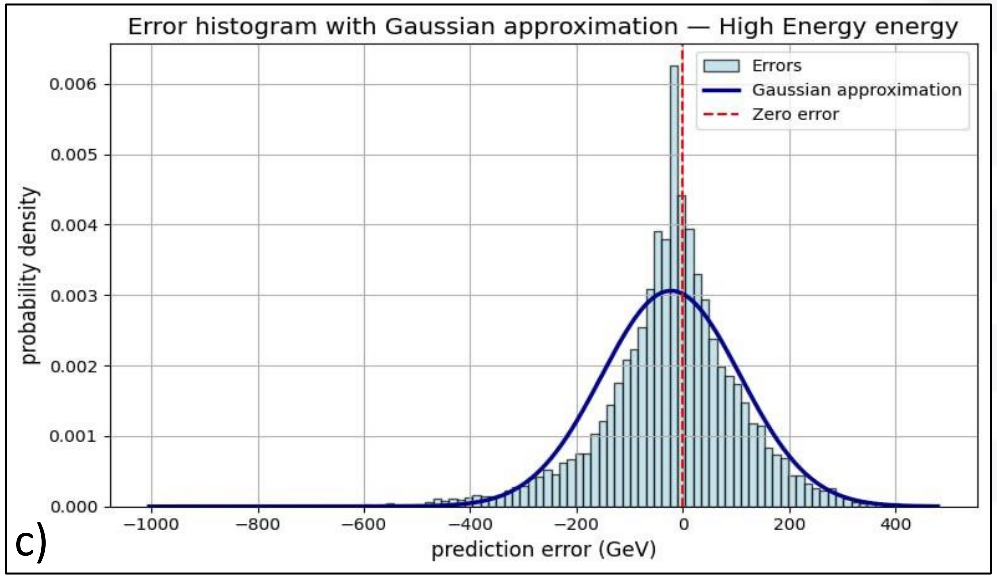
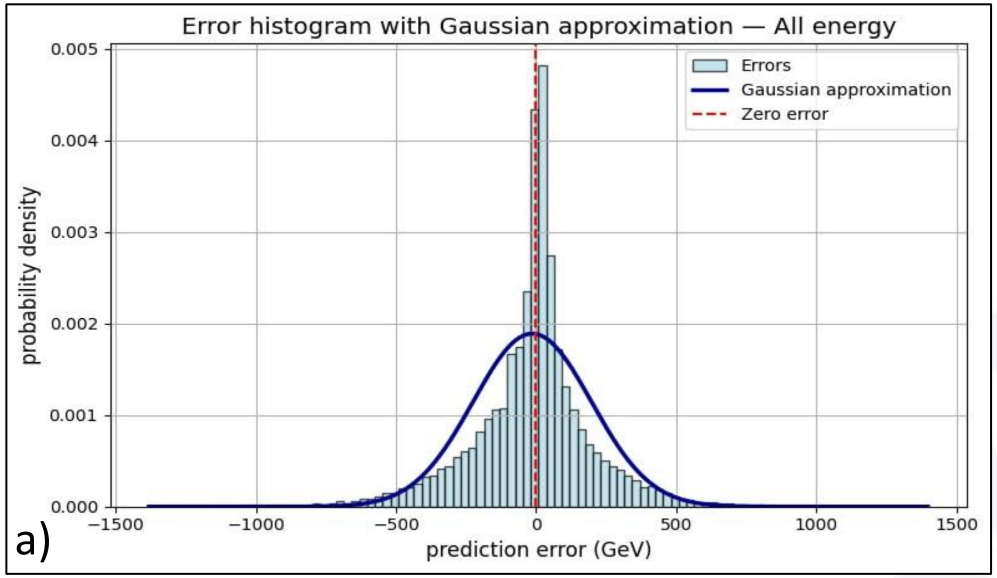


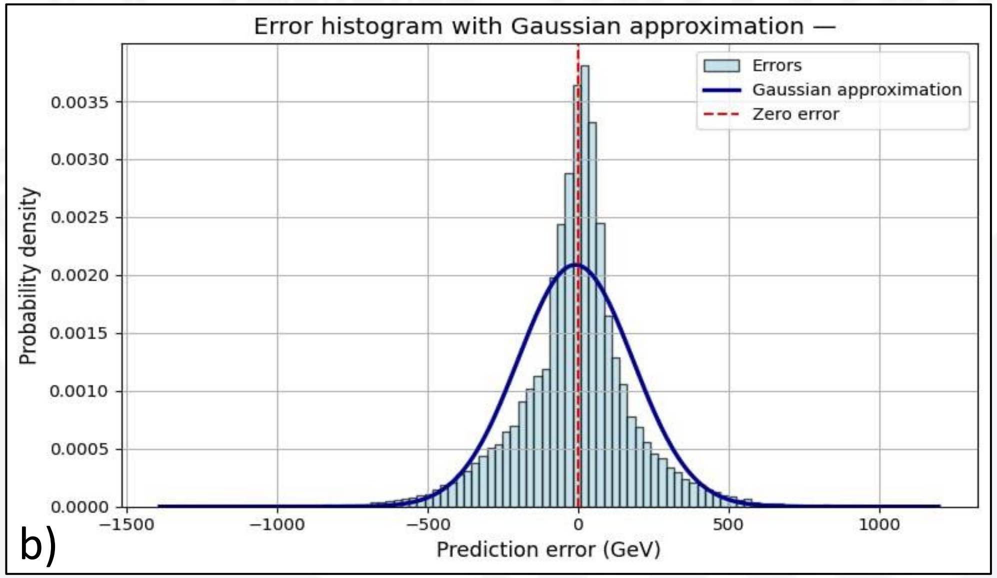
c)

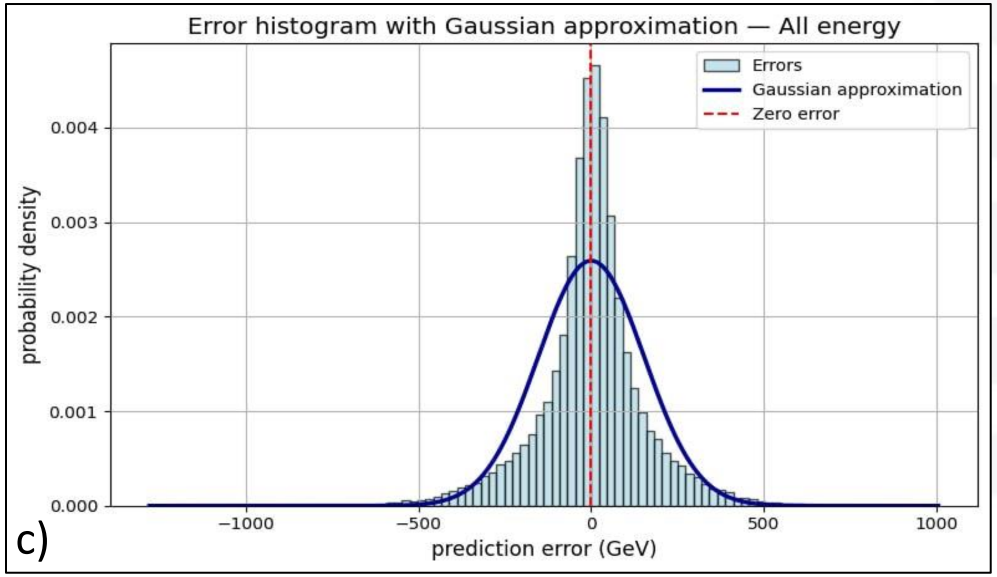
a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Appendix: Error Histogram

Fully Connected NN



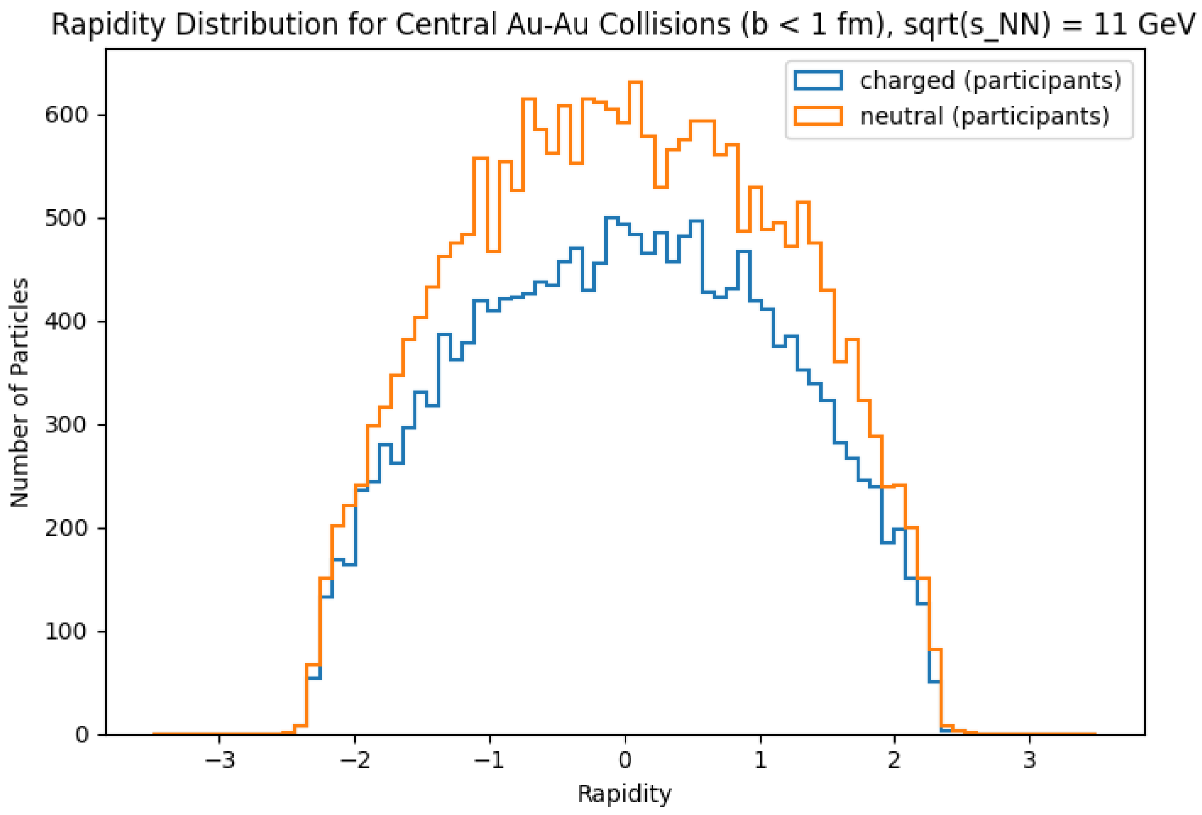




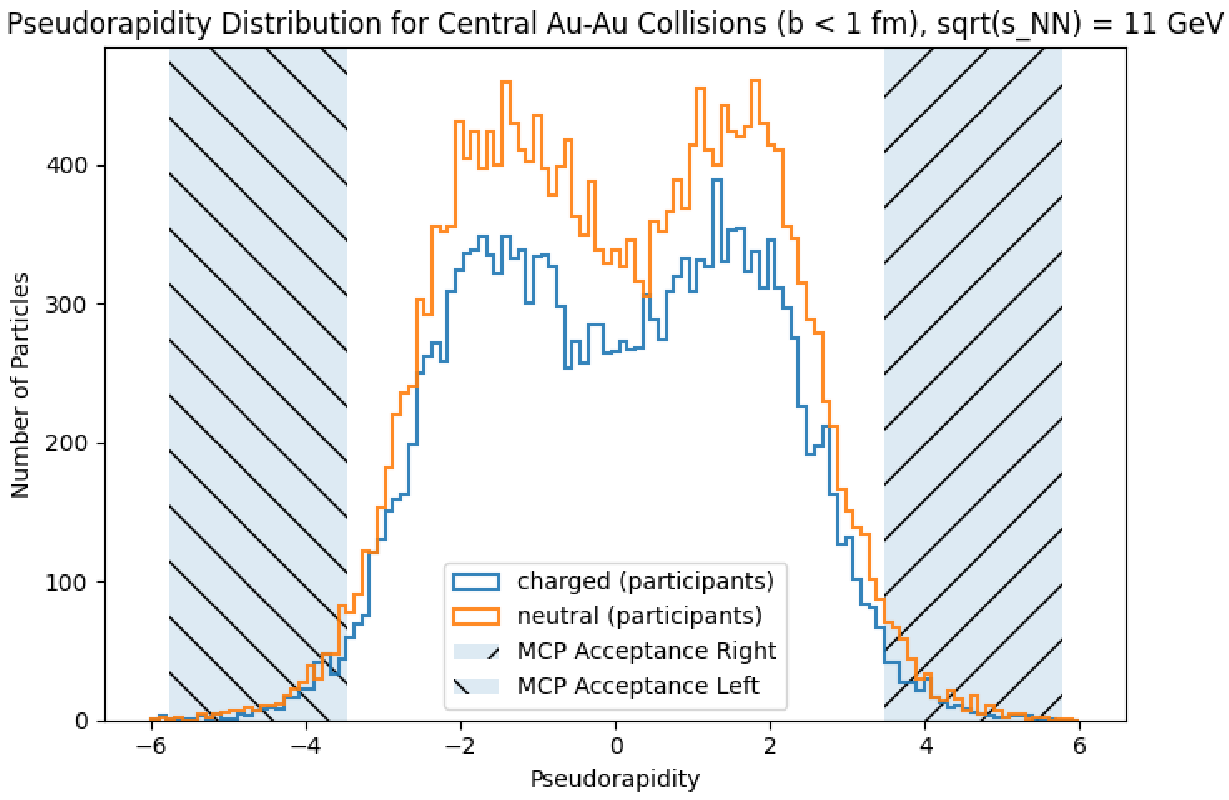
a) Contribution to the energy from charged particles, feature vector – from charged particles.
b) Contribution – all particles, feature vector constructed from charged particles.
c) Contribution – all particles, feature vector – all particles.

Results

Histogram of Rapidity(Number of Particles)

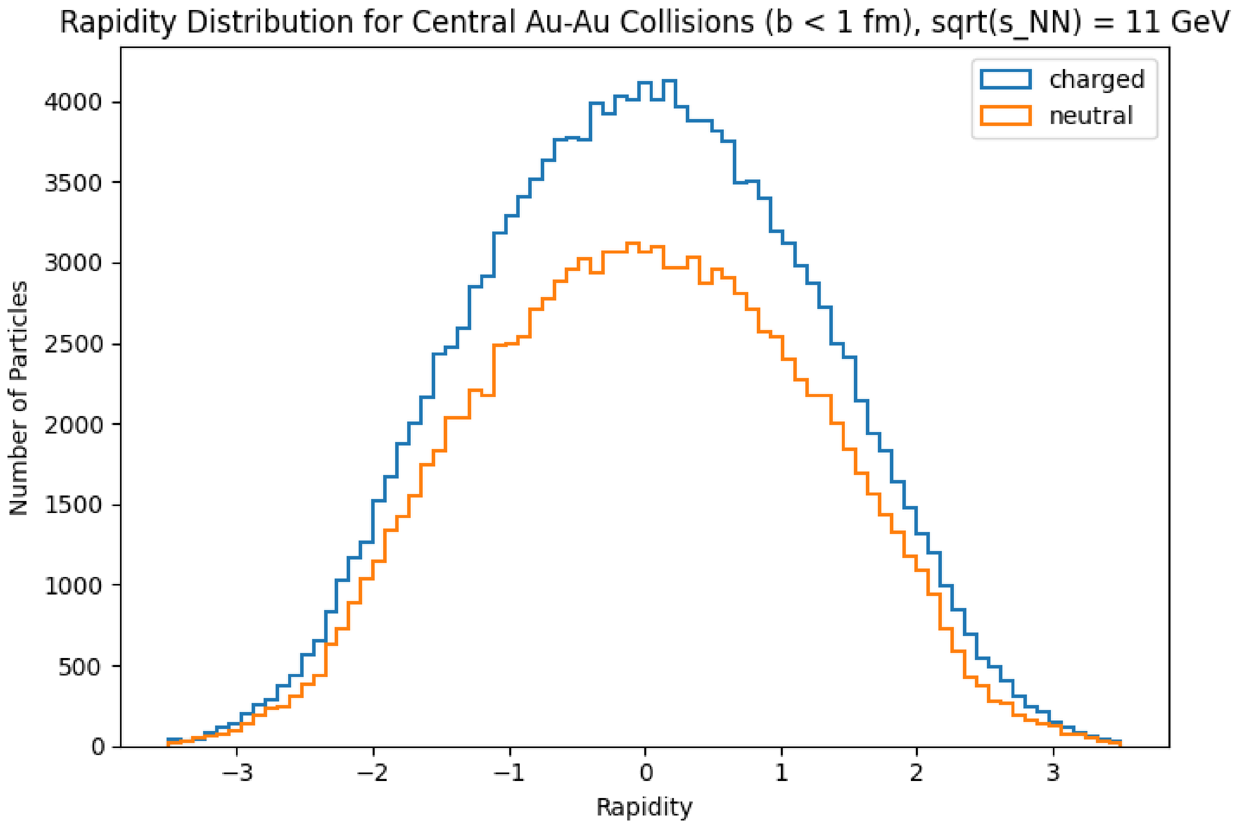


Histogram of Pseudorapidity(Number of Particles)



Results

Histogram of Rapidity(Number of Particles)



Histogram of Pseudorapidity(Number of Particles)