# MET Identification in TTbar events

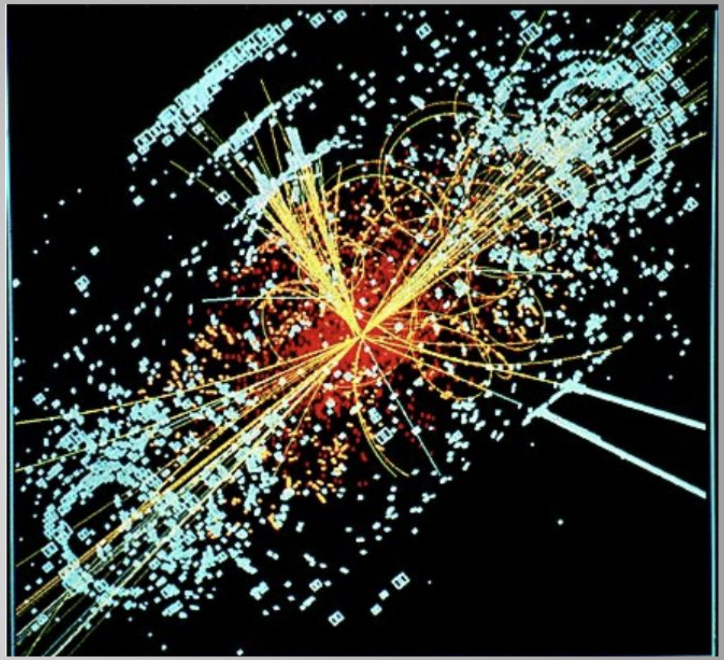
Mert DİL

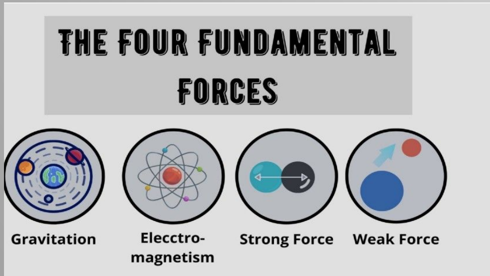
# Standard Model

Physics is a theory of the elementary particles, which are either fermions or bosons

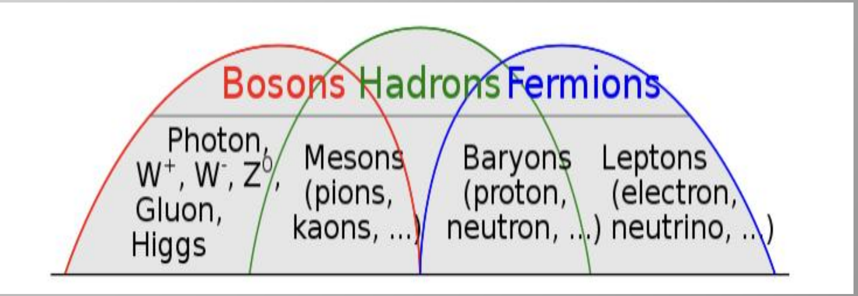
The standard model falls short of being a theory of everything:

- not include the full theory of gravitation as described by general relativity.
- not explain the accelerating expansion of the universe (as possibly described by dark energy).
- **not contain any dark matter particle that has all the properties observed in observational cosmology.**
- demonstrated huge and continued successes in experimental predictions, but it does leave some things unexplained.



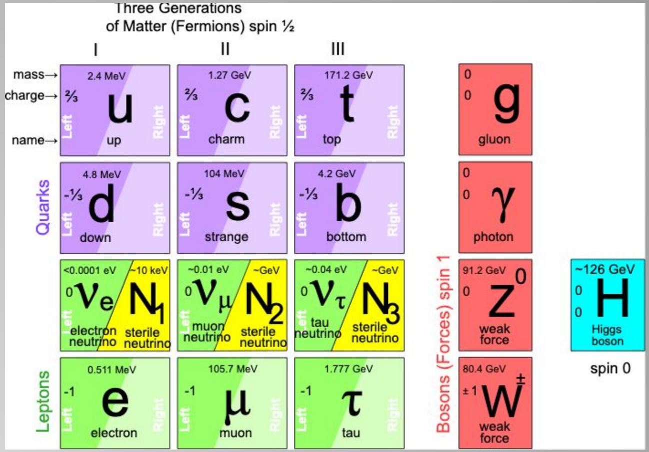


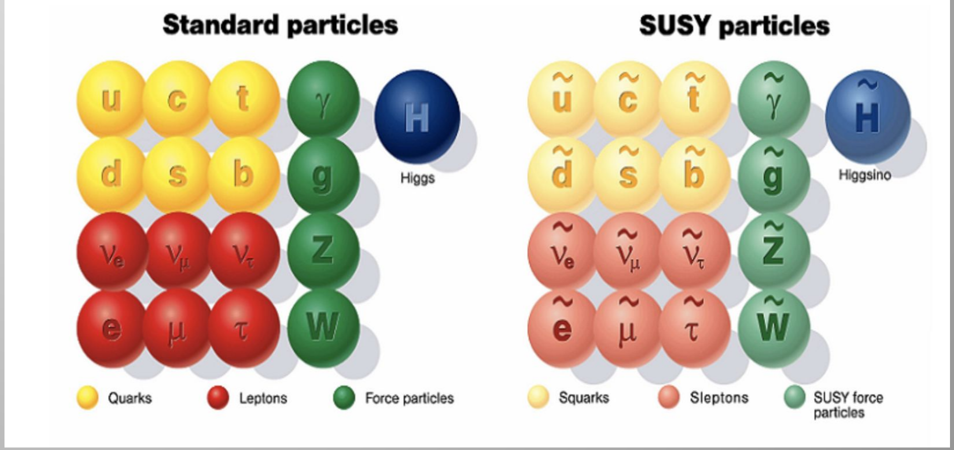

The Four Fundamental Forces and corresponding visuals. Source: Sci Myst



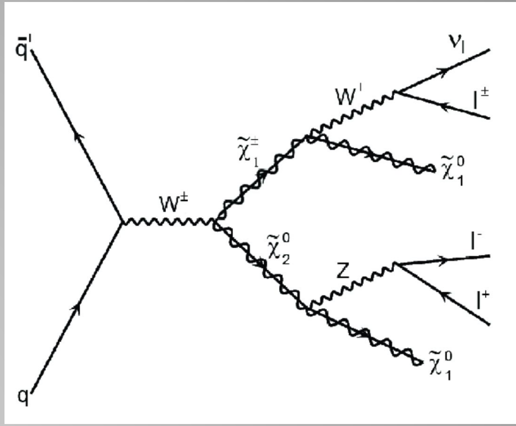
# Beyond Standard Model (BSM)

- Standard Model has many known limitations
- New particles proton-proton collisions at the Large Hadron Collider (LHC).
- **If new physics exists, it is therefore either heavy or hidden**
- Supersymmetric theory the equations for force and the equations for matter are identical.
- Supersymmetry, each particle from one class would have an associated particle in the other

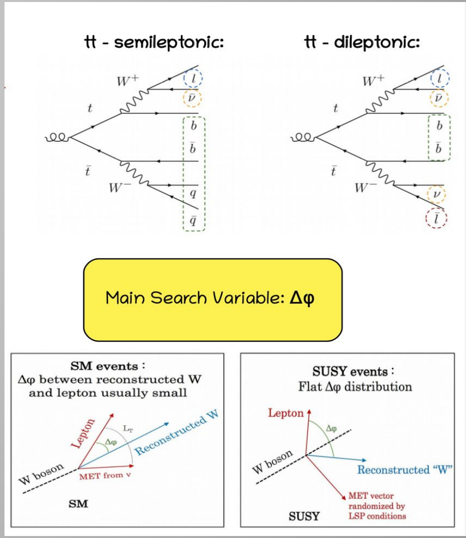


# Why New Physics Is Needed At The LHC




- Opportunity open for the search of direct evidence of physics
- Anomalies have been identified in the production of leptons at the ATLAS and CMS experiments of the LHC.
- Anomalies remain unexplained by MC tools.
- Concentrate on non-resonant searches in signatures
- Considered generative modelling to mimic relevant discrimination of observables
- Here, GANs are used to mimic the MC predictions.



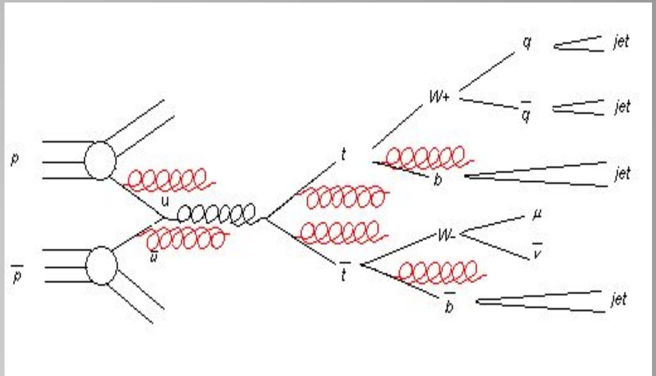

**These include a number of final states**:

- opposite-sign,
- same sign di-leptons,
- three leptons in the presence
- absence of b-quarks.

Ref:https://arxiv.org/abs/2105.14933

# Top Quark production (TTbar)

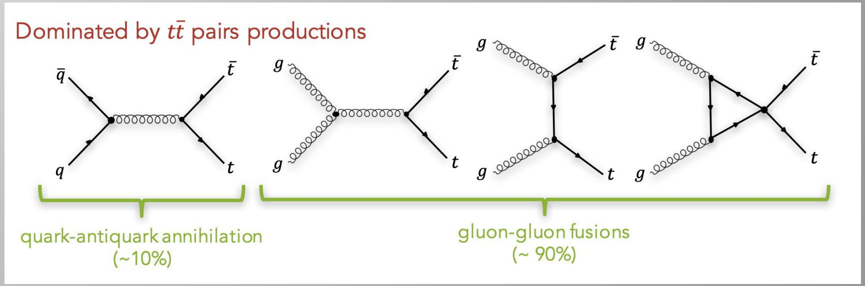
- TTbar events are among the most copious signatures
- One top quark decays leptonically and the other hadronically, the signature is characterized by one lepton, missing transverse energy and four jets,
- At the LHC, about 50% of events have extra hard jets coming from initial or final state radiation.
- Focusing on the mass of the hadronically-decaying topquark.
- Construction performed via Delphes using the detector configuration




The radiated gluons themselves are not directly observed

A Particle abundantly produced at the LHC: **Top Quark Pairs**

- The most common is (production of a top–antitop pair) via (strong interactions)).
- In a collision, a highly energetic (gluon) is created,
- Subsequently decays into a top and antitop. (Tevatron:Quark-Antiquark)



# Kinematics of Elementary Particle Physics

## 1-Pseudorapidity

Detector Acceptance

- Choice of analysis region

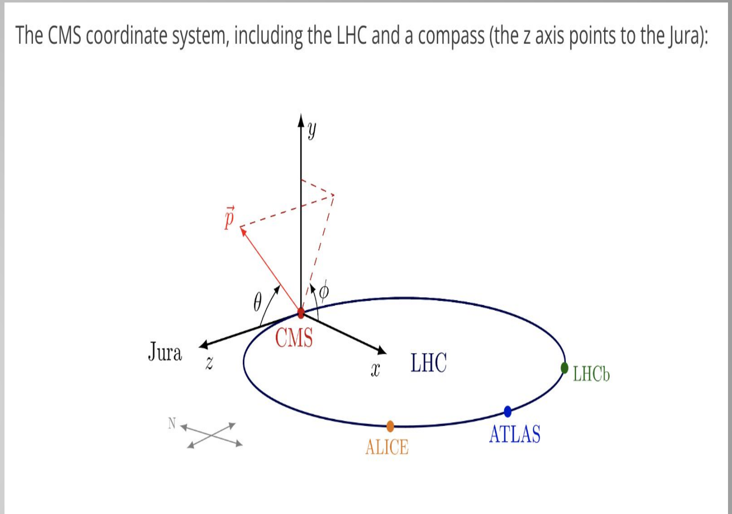
$$\eta = \frac{1}{2}\ln\left(\tan\frac{\theta}{2}\right)$$

## 2-Phi ($\phi$)

- Angular distributions
- Azimuthal asymmetry

## 3-Transverse Variables (Energy and Momentum)

- unknown fraction of the beam energy
- each event escapes down the beam pipe.
- Net momentum can only be constrained
- the plane transverse to the beam z-axis!




Experimental Coordinate System

$$\sum p_T(i) = 0$$

$$|p| = p_T \cosh\eta$$

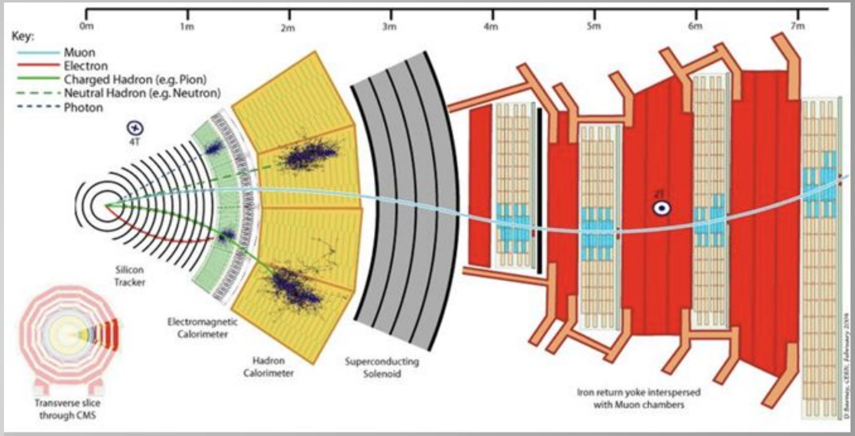
$$E_T = \frac{E}{\cosh\eta}$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$p_x = p_T\cos\phi$$
$$p_y = p_T\sin\phi$$
$$p_z = p_T\sinh\eta$$

# Detecting Kinematic distributions–Monte Carlo Simulation

1. **Tracking Devices (momentum)-**reveal the paths of electrically charged particles
2. **Calorimeter (energy)**-stop, absorb and measure a particle's energy; measure the energy particle losses purpose
3. **Particle Identification Detectors (velocity)**-use a range of techniques to pin down a particle's identity.Combination with the momentum




| | |
|---|---|
| ✓ Mass | [Unit: eV/c$^2$ or eV] |
| ✓ Charge | [Unit: e] |
| ✓ Energy | [Unit: eV] |
| ✓ Momentum | [Unit: eV/c or eV] |
| ✓ (+ spin, lifetime, …) | |

# Missing Transverse Energy in TTbar events

- Top quarks decay into a lepton and a neutrino.
- Jets and leptons can be identified and measured with high precision by the CMS detector
- While neutrinos escape undetected and reveal themselves as missing energy.
- MET is the negative of the vector sum of the transverse momenta
- Beyond-the-standard-model scenarios predict events with large MET.

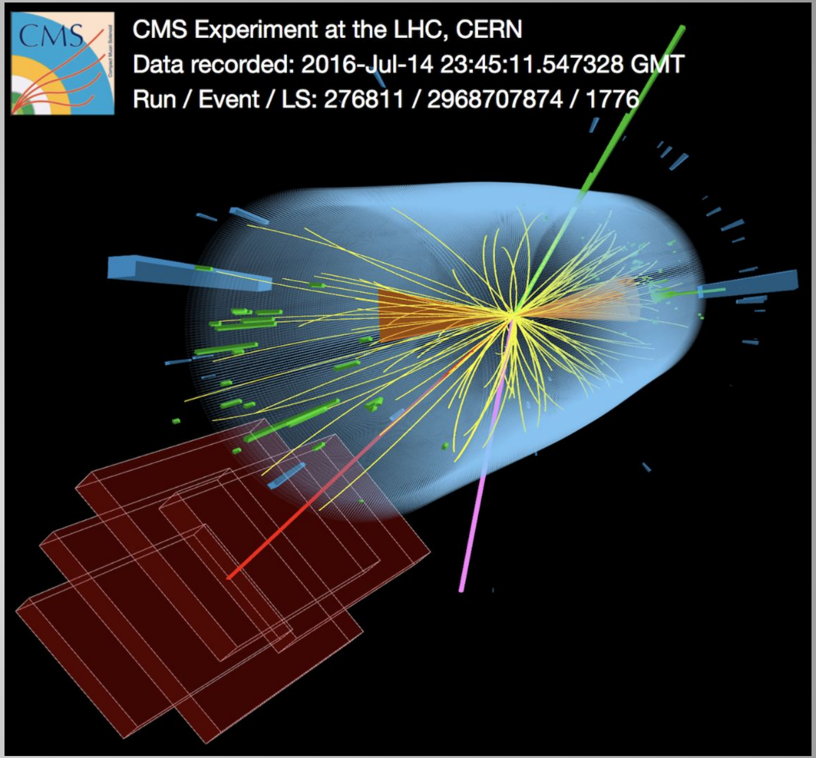



Figure : Display of an LHC collision detected by the CMS detector that contains a reconstructed top quark-antiquark pair. The display shows an electron (green) and a muon (red) of opposite charge, two highly energetic jets (orange) and a large amount of missing energy (purple).

# Experimental Challenges

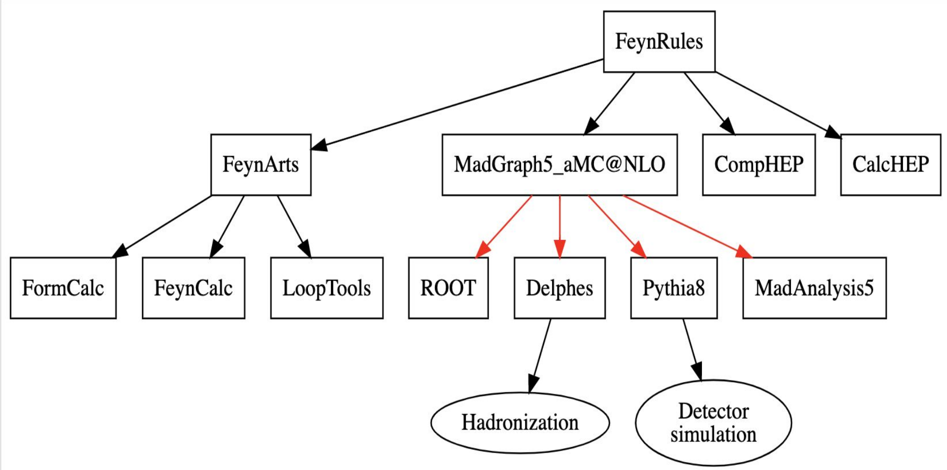
1. **Energy Resolution** :Need excellent energy resolution in all calos. (Usually limited by non-linearities of calorimeter response)
2. **Multi-jet events:** Resolution is limited due to the statistical fluctuations in showering
3. **Non-compensating HCAL (hadron calorimeter)**
4. **Electronic noise, Pile-ups and Underlying Events**
5. **MET tails: These are large and non-Gaussian.**
6. **High Magnetic field**
7. **Energy loss due to punch throughs**
8. **Faulty calorimeter cells**

Total visible transverse energy:

$$E_T = \sum_n \frac{E_n}{\cosh \eta_n}$$

# Monte Carlo simulations: Problems & Solutions

- MC simulations is conventionally used to setup the event selection
- Monte Carlo (MC) events used to estimate the corresponding trials factor through a frequentist inference.
- MC events that are based (on full detector simulations) are resource intensive.
- The probability of false signals  estimated on the basis of  Monte Carlo (MC) studies.
- MC samples is CPU expensive.
- Machine learning explore a deeper phase-space available at the LHC



A software network for particle physics

# Delphes and Root-Response Of Detector Simulations with Monte Carlo

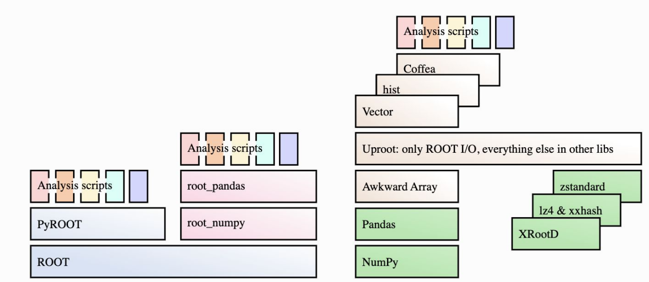
- Delphes.3.0 fast-simulation is presented.
- Reconstructed from the simulated detector response.
- Flexible enough to be adapted
- Typical work-flow chart of the Delphes fast simulation.
- Event files coming from external Monte-Carlo generators
- Provides leptons (electrons and muons),photons,missing transverse energy (calo-based or particle-flow

DELPHES
fast simulation

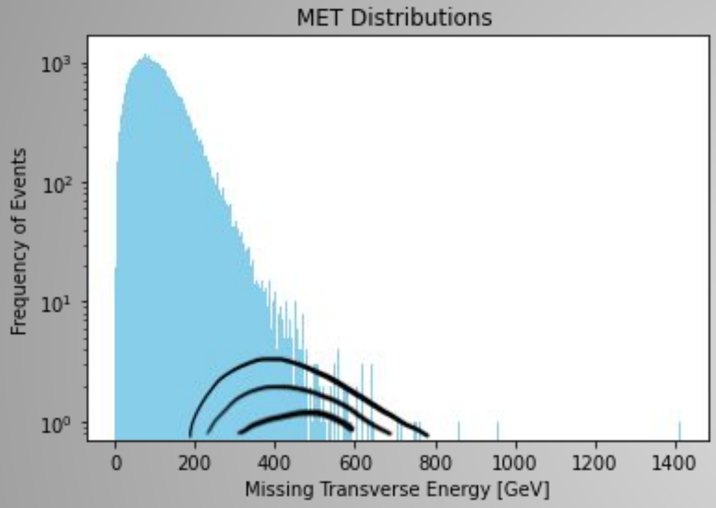
With ROOT you can:

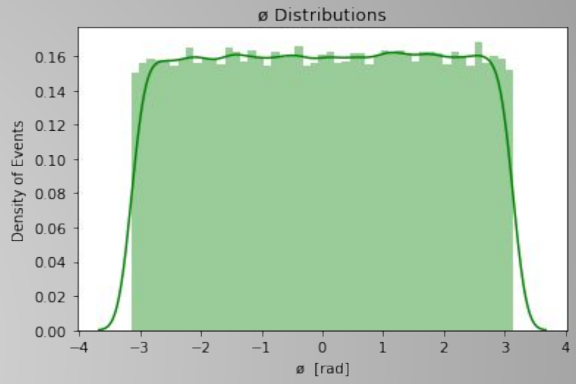
- Save data
- Access data
- Mine data
- Publish results
- Run
- Use with uproot and pyroot

ROOT
Data Analysis Framework



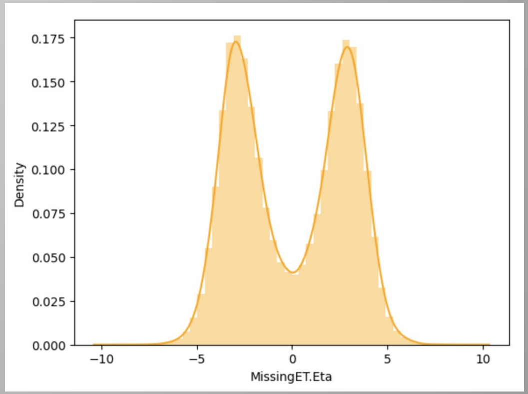
# Delphes samples with kinematic variables –Missing ET



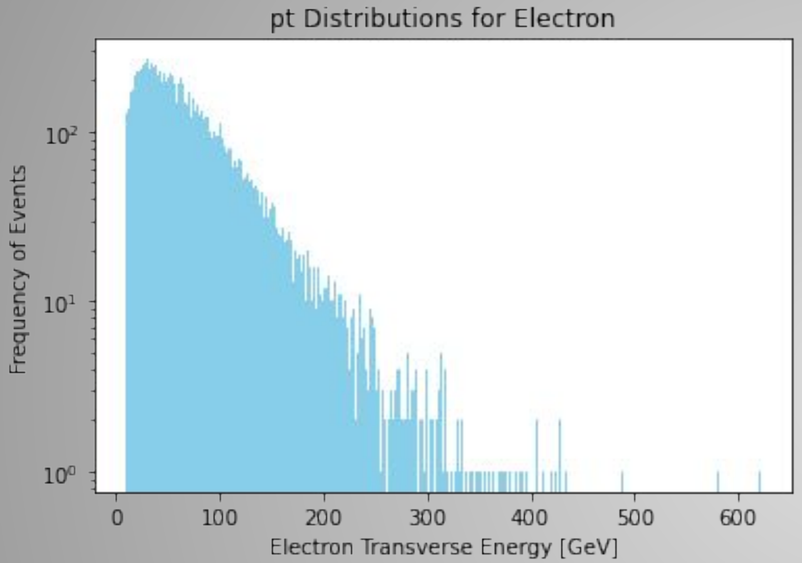



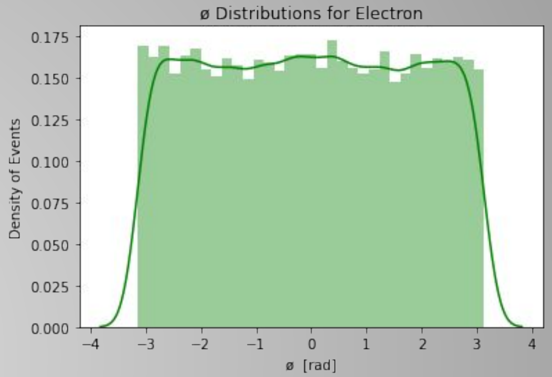

- Executed programs that mimics hard scattering,showing and hadronization process namely MadGraph and Pythia.
- The response of the detector simulated using Delphes
- process pp>LEPTONS,NEUTRINOS
- The jets are used in the kinematic selection
- The MET is selected with originated pp collisions
- mt=172.5 GeV
- nevents 100000
- tt,tt+jet,tt+2jet

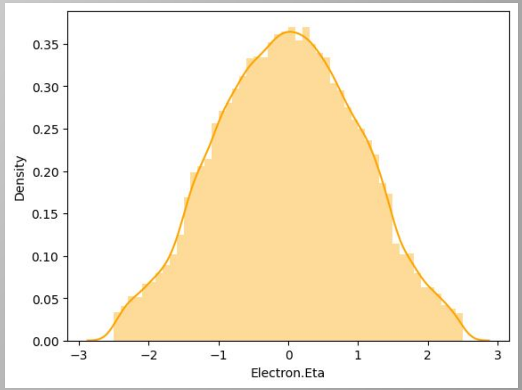
```
t > w+ b, w+ > l+ vl
t~ > w- b~, w- > l- vl~
w+ > l+ vl
w- > l- vl~
```



# Kinematic variables of Charged Leptons–Electron

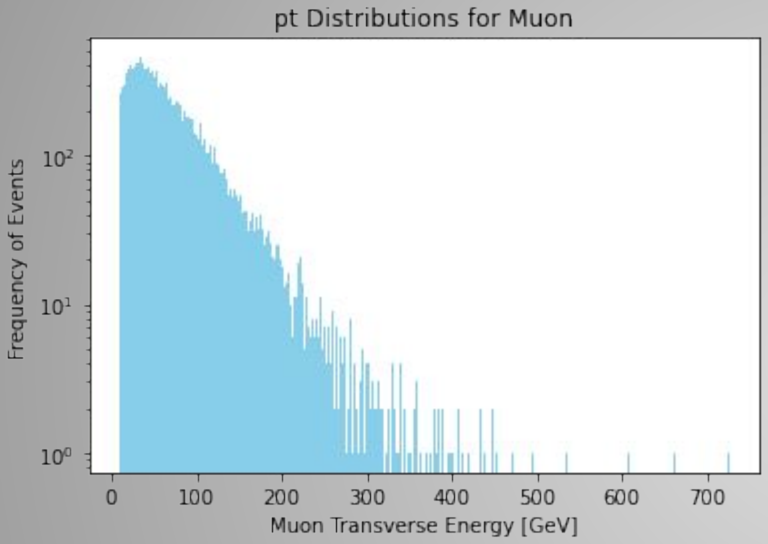


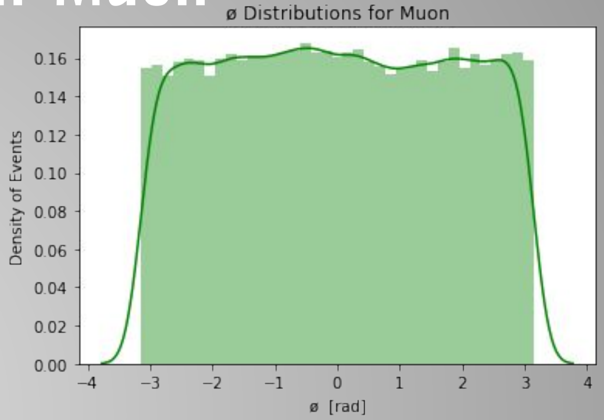



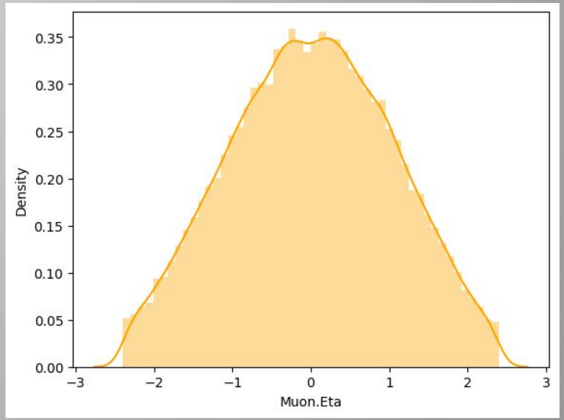




- The electron ( e− or β− ) is a subatomic particle with a negative one elementary electric charge.
- Electrons belong to the first generation of the lepton particle family
- They are generally thought to be elementary particles because they have no known components or substructure

# Kinematic variables of  Charged Lepton-Muon

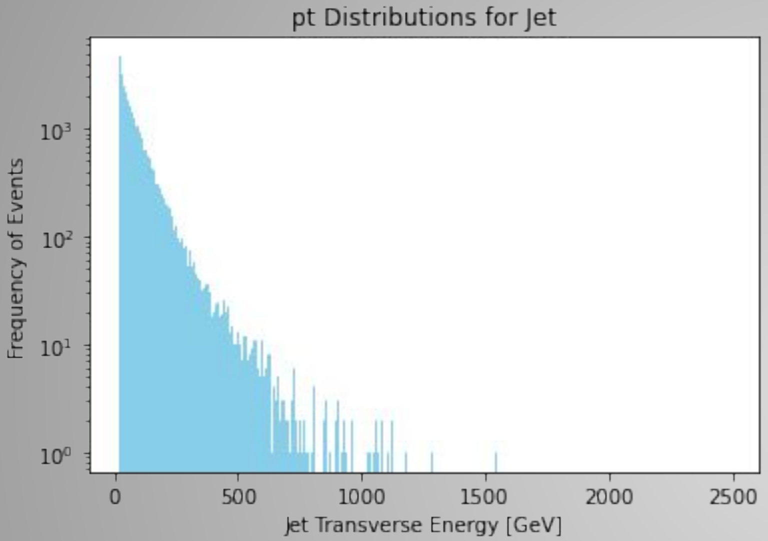


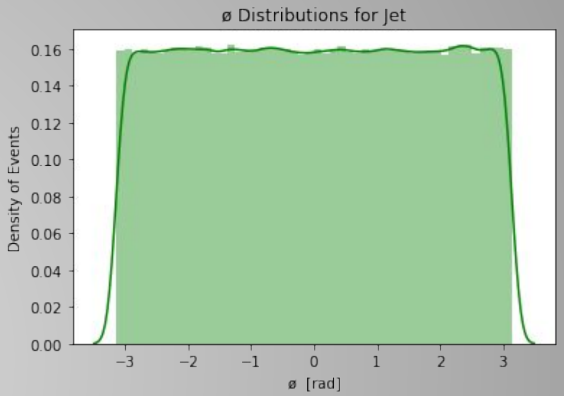



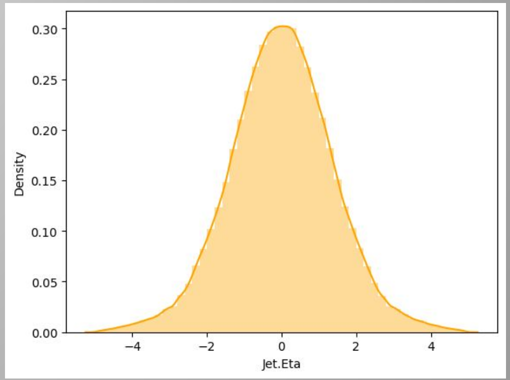




- A **muon** is an elementary particle similar to the electron, with an electric charge of −1 *e* and a spin of $^1\!/_2$, but  with a much greater mass. It is classified as a lepton.
- As with other leptons, the muon is not thought to be composed of any simpler particles; that is, i
- t is a fundamental particle.

# Kinematic variables of  Jet

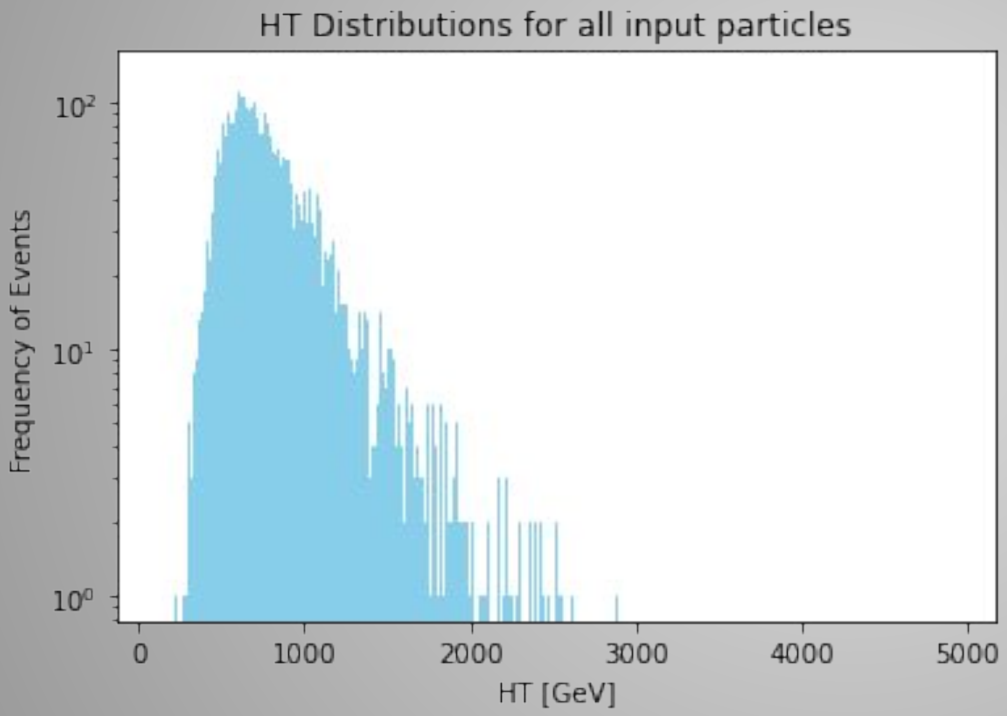



- A jet is a narrow cone of hadrons and other particles produced by the hadronization of a quark or gluon in a particle physics or heavy ion experiment.
- Particles carrying a color charge, such as quarks, cannot exist in free form because of quantum chromodynamics (QCD) confinement which only allows for colorless states.

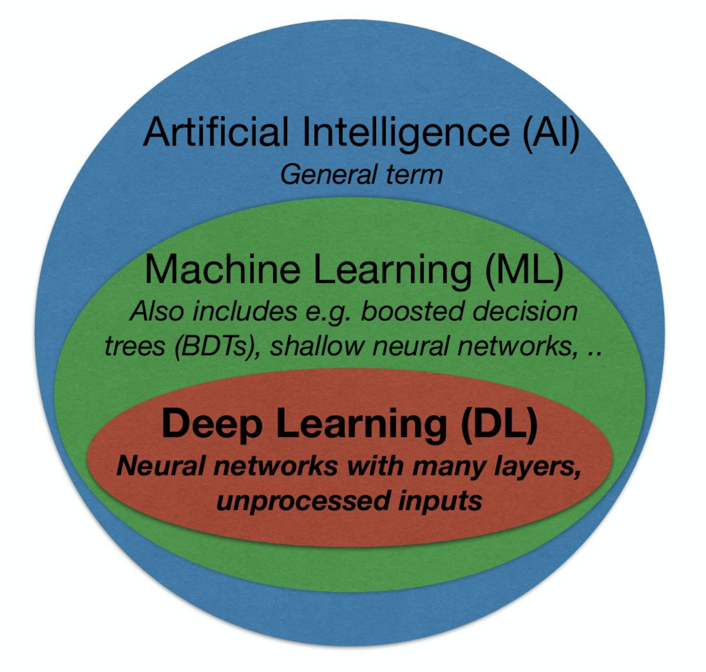
# HT (the scalar sum of all input particles' momenta)




- HT (the scalar sum of all input particles' momenta)are used as inputs to the final prediction.
- H⊥, the scalar sum of the transverse momenta of the charged lepton,and the jet.
- Variable in which one often does experimental cuts in searches for new phenomena
- Not expected to be very sensitive to the particulars in the merging schemes.

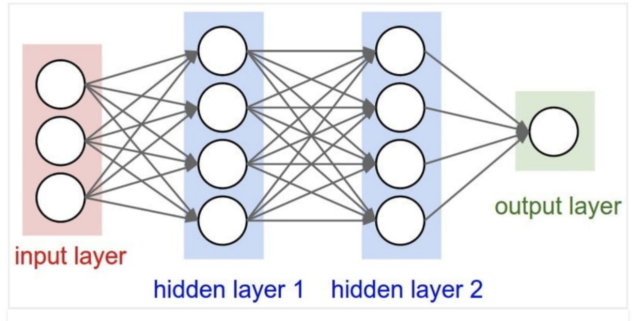
# Machine Learning at the High Energy Physics

- No prior knowledge of the yield nor the model dependence of the BSM signal are required.
- Classify between SM backgrounds and new BSM physics,
- Essential that a good understanding of background modelling
- Explore a deeper BSM at the LHC
- Side-bands, or signal-depleted and signal-enriched samples are defined.
- The side-band brings insights from the SM background

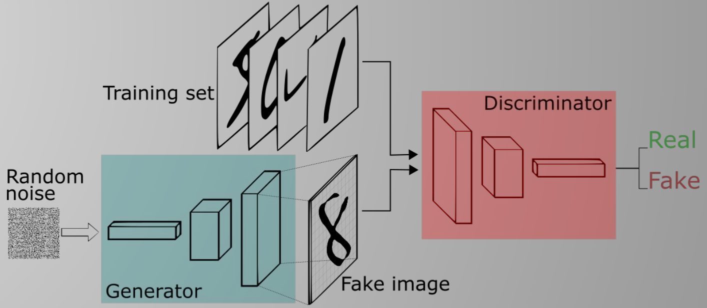


# MC Simulations and Deep Neural Networks

- Creating models spawned the development of artificial neural networks.
- Hidden layer stores information regarding the input's importance
- The importance of combinations of inputs.
- Unsupervised learning technique called Generative-Adversarial Networks (GANs)
- Synthesise fake looking samples
- Mostly used to generate photo-realistic images,medical imaging
- Reproduce the kinematic distributions.



Two or more hidden layers comprise a Deep Neural Network



# Generative Adversarial Networks (GAN) and Wasserstein GAN (WGAN)

- A class of unsupervised generative models
- Deployed in an adversarial settings of two network blocks
- After training, a GAN model provides sample from the learned distribution
- Competitive two- player minimax game with players being D and G with the optimal solution being a D(x) = D(G(z)) = 0.5
- The training objective of a vanilla GAN:

$$V_{\text{GAN}} = \min_{\theta} \max_{\phi} \mathbb{E}_{\mathbf{x} \sim \mathbb{P}_d(\mathbf{x})} \left[ \log D_\phi(\mathbf{x}) \right] + \mathbb{E}_{\mathbf{z} \sim \mathbb{P}_z} \left[ \log(1 - D_\phi(G_\theta(\mathbf{z}))) \right].$$

- A WGAN differs from the vanilla-GAN
- Minimizes the Earth-Mover distance (also known as the Wasserstein distance)
- Minimum amount of energy to transform one probability mass

$$W(\mathbb{P}_d, \mathbb{P}_g) = \inf_{\gamma \in \Pi(\mathbb{P}_d, \mathbb{P}_g)} \mathbb{E}_{(\mathbf{x}, \mathbf{y}) \sim \gamma} \left[ \|x - y\| \right],$$

$$V_{\text{WGAN}} = \min_{\theta} \max_{\phi \in \Omega} \left[ \mathbb{E}_{\mathbf{x} \sim \mathbb{P}_d(\mathbf{x})} \left[ D_\phi(\mathbf{x}) \right] - \mathbb{E}_{\mathbf{z} \sim \mathbb{P}_{\mathbf{z}}} \left[ D_\phi(G_\theta(\mathbf{z})) \right] \right],$$

# WGAN-Gradient Penalty (GP)

- D no longer plays a role of a classifier but rather a regressor, hence referred to as a critic.
- Tasked to learn a function that approximates $W(P_g,P_d)$.
- WGAN has a critic that does not suffer from vanishing gradients.
- Supports cases where the distributions do not overlap.
- Constraints by adding a gradient penalty (GP) term to the critic's objective
- Penalises the objective whenever the norm of the critic's gradients exceeds 1.
- This further improves the value function by adding a penalty term, making the function to be:

$$V_{\text{WGAN-GP}} = V_{\text{WGAN}} + \lambda \mathbb{E}_{\hat{\mathbf{x}} \sim \mathbb{P}_{\mathbf{d}}(\hat{\mathbf{x}})} \left[ (\|\nabla_{\hat{\mathbf{x}}} D_\phi(\hat{\mathbf{x}})\|_2 - 1)^2 \right],$$

# WGAN-GP processing in MC simulation

- Number of applications ranging from images to non-image data applications.
- One of the earliest non-image data GAN within HEP was around the years of 2018 by for an unfolding task.
- Active area of research is mainly focused on parton showers and event generation
- Attractive solution and of potential to searches studies Beyond the Standard Model
- Given that we can synthesize fake MC samples with high accuracy and speed.
- Allows us to address the multi-lepton problem by simulating the dedicated MC samples
- Events to test the look-elsewhere effect in the semi-supervision study in HEP.

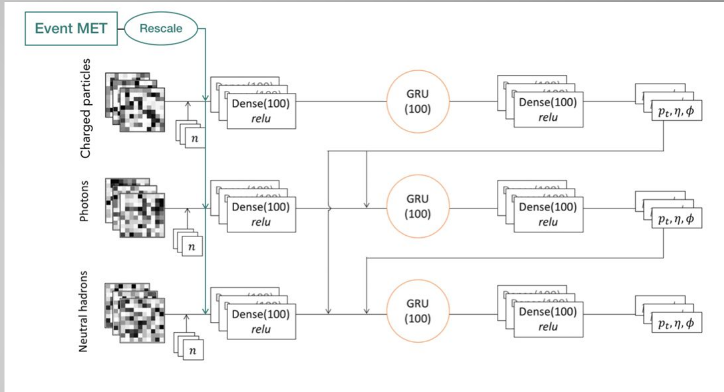
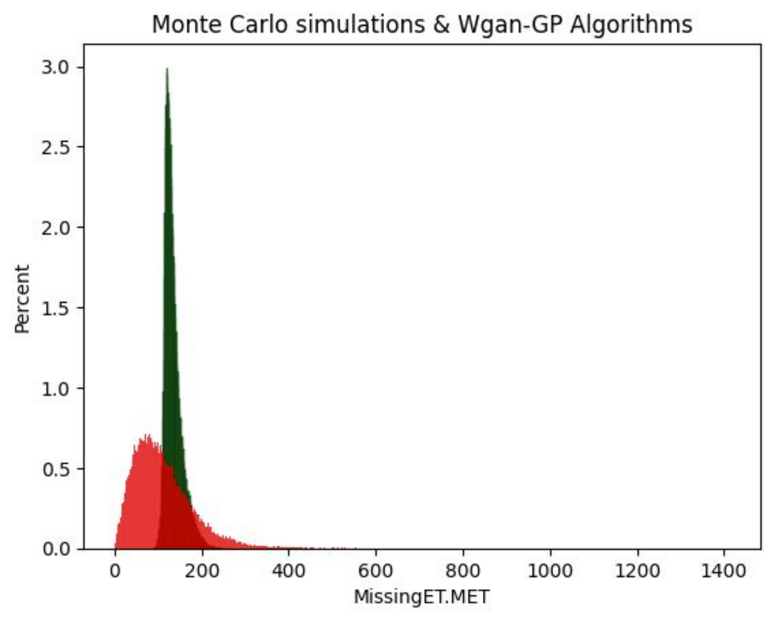


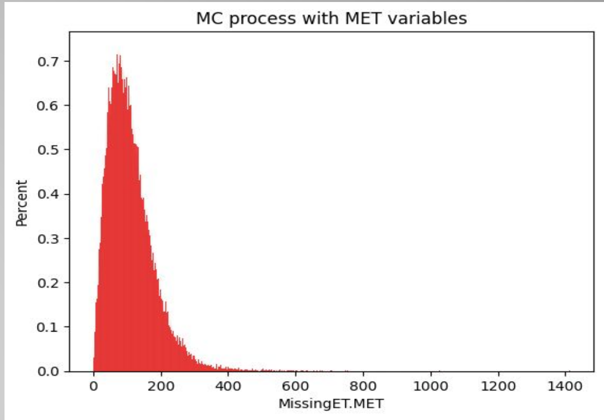

Figure 1: The architecture of conditional pGAN: generator Gcond (left) and discriminator Dcond (right). Arrows signify concatenation

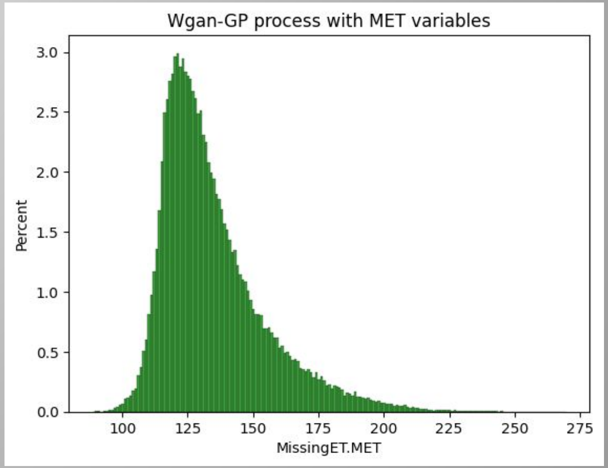
https://arxiv.org/abs/1912.02748

# Results: Missing Transverse Energy (Delphes&WGAN-GP)

Epoch: 30 | disc_loss: -0.0053850337862968445 | gen_loss: 0.040450792759656906

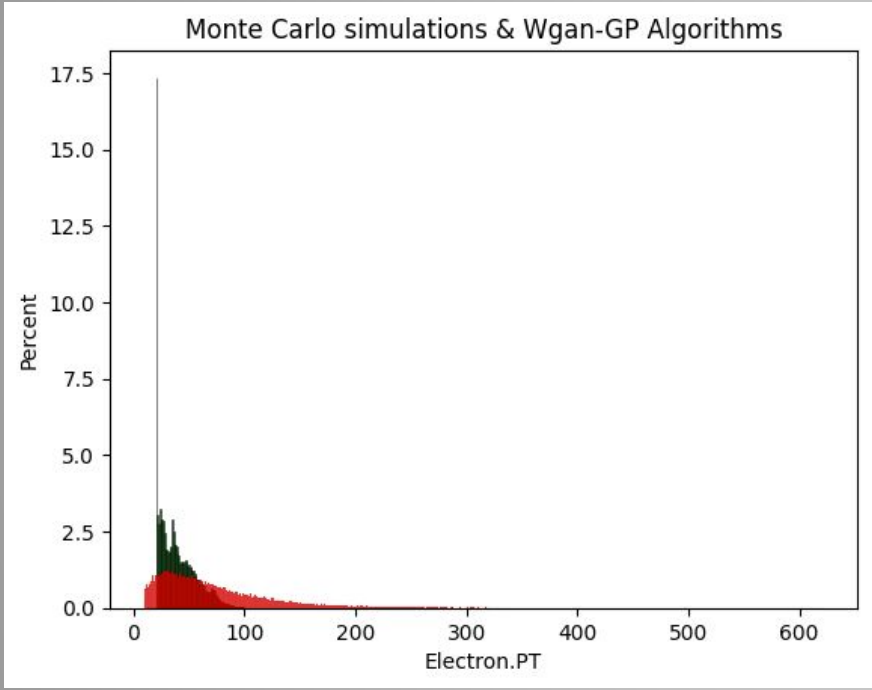


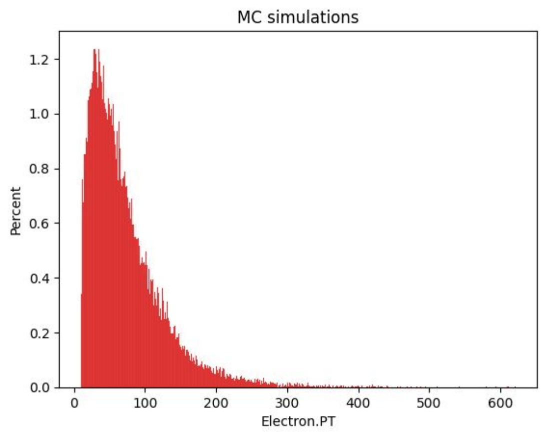



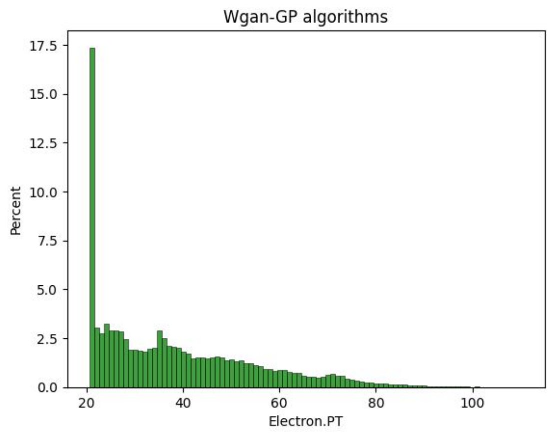




- Looking for is a similarity in the long tail parts
- Breaks are estimated similarly to the mean
- Better match should be future work

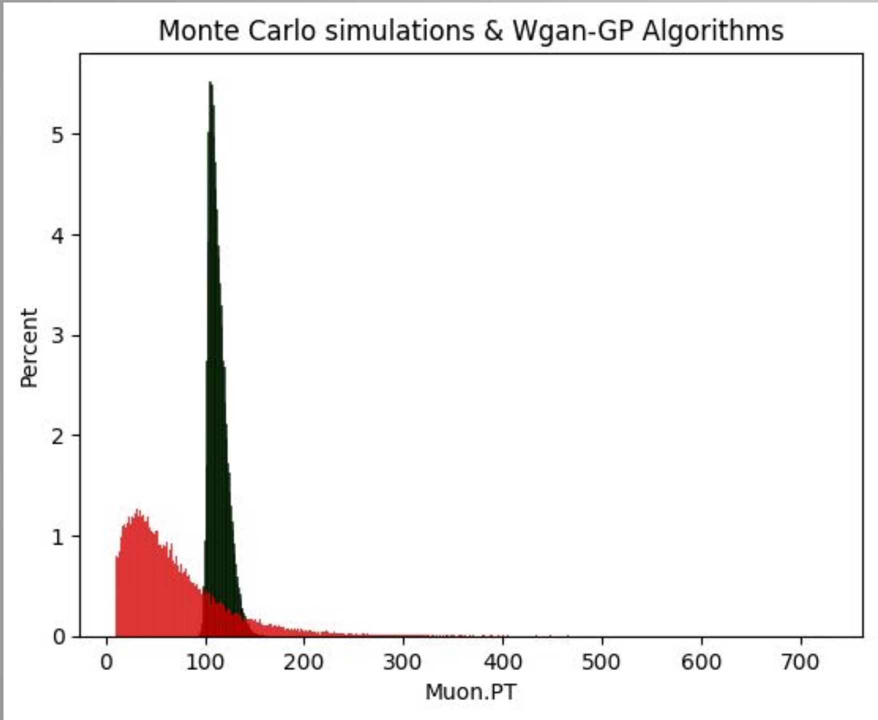
# Results:Charged Leptons -Electron (Delphes &WGan-GP)

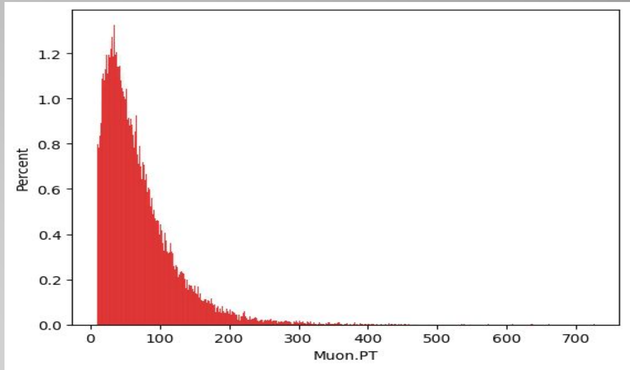


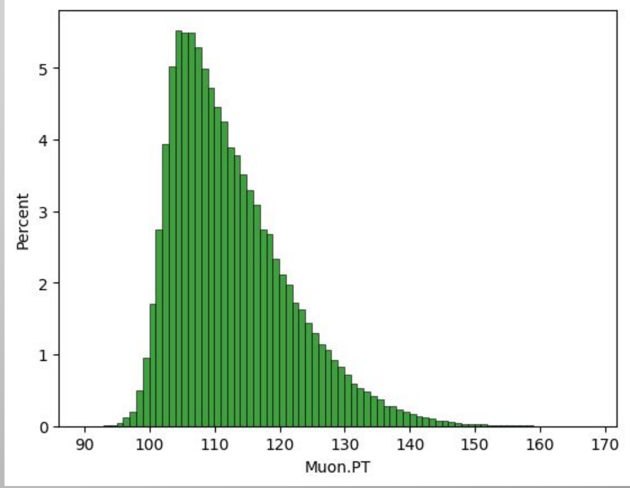



# Results: Charged Lepton- Muon (Delphes &WGAN-GP)



# Conclusion

- GAN is not easy to generalize each setup to other tasks
- Each architecture tends to solve only a specific problem.
- Studies have been done between events generated by MC and WGAN-GP,
- Showed a density difference on the two graphs due to the difficult integration
- Training time is a major constraint we face with the current setup of Keras with Tensorflow backend
- PyTorch increase our research productivity while scaling on GPUs
- Can reduce training iteration time in generative modeling from weeks to days.
- Further strengthen the convergence by studying conditional WGAN-GP.