Exotic Group

Reconstructing dark matter in events with top quarks using neural networks

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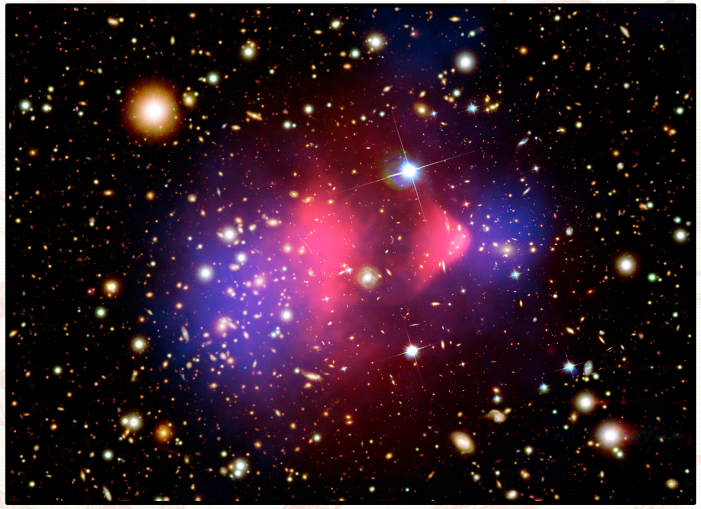
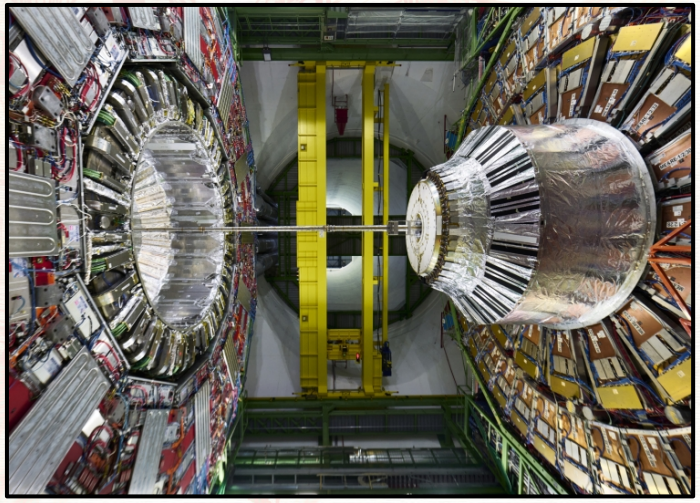
Dark Matter

Evidences for dark matter in the Universe:



- Rotation velocity of the stars in the galaxies;
- High-speed, gravitationally bound clusters of galaxies;
- Gravitational Lensing;
- Observations from **cluster collisions**;

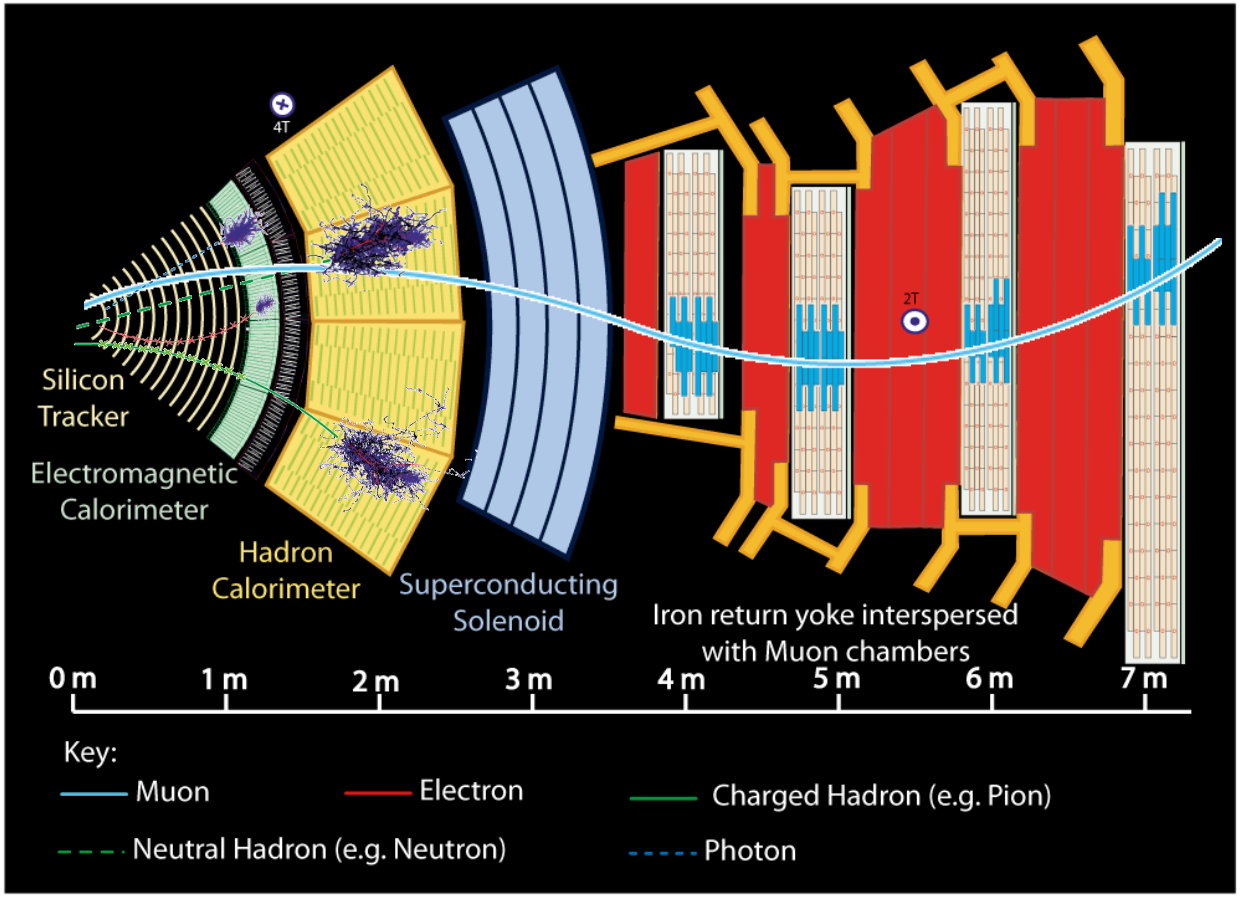
Its search at LHC:



- DM might be produced during collisions
- How can we measure it in CMS?

CMS

Particle identification:

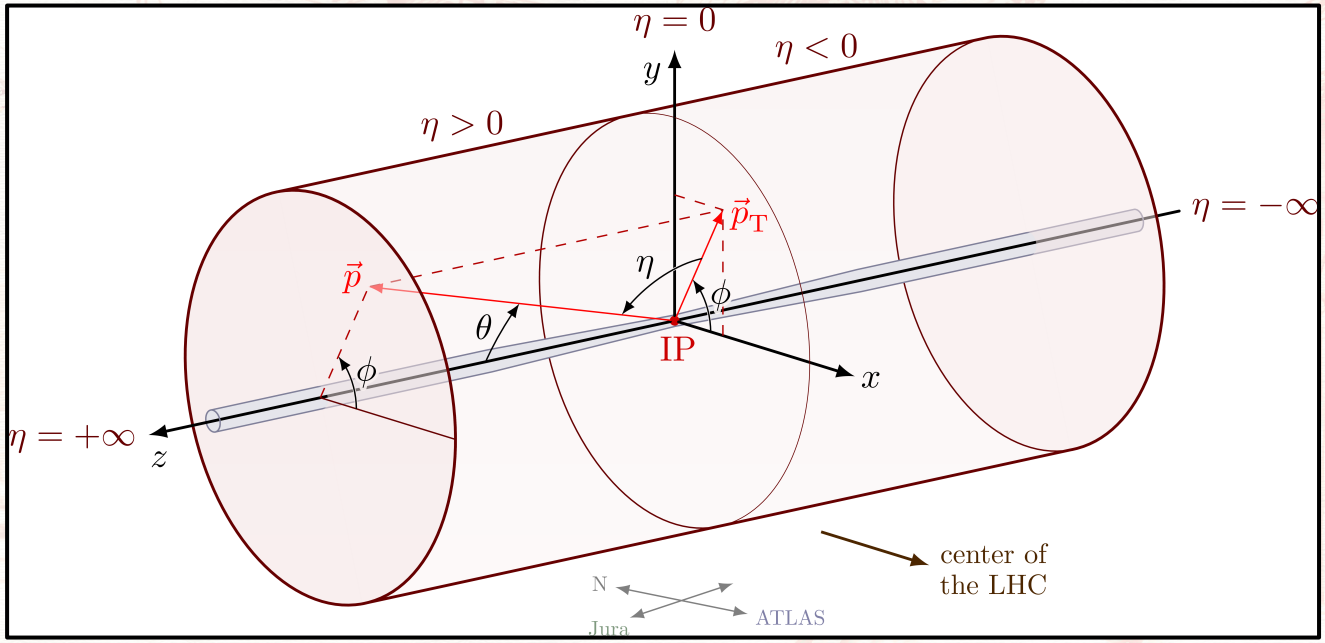


- Particles are identified by their interactions with different components of the detector
- Good measurement of leptons
- Quarks → Jets → more difficult to measure
- Undetectable particles:
  - Neutrinos
  - Dark Matter

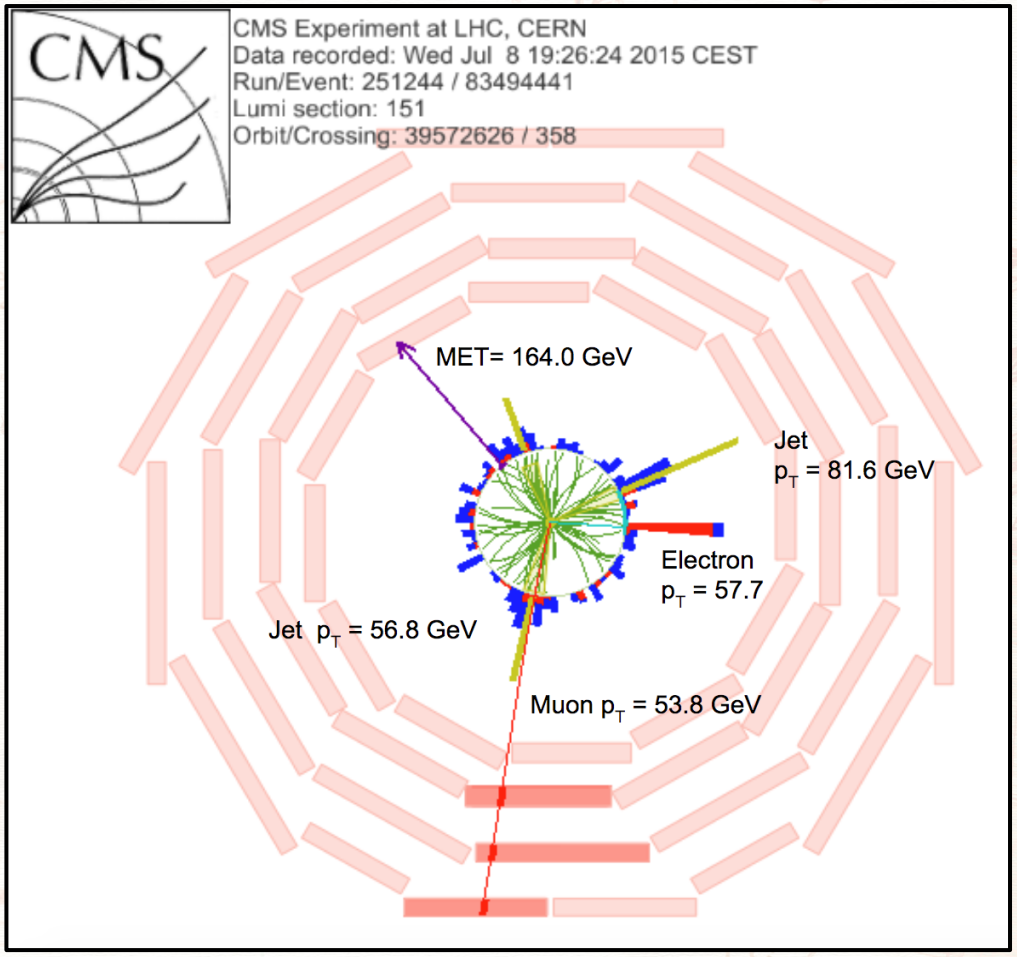
CMS

Coordinate systems:

- XYZ coordinate:
  - x points towards the center of LHC
  - z along the beam direction
- $p_T\eta\varphi$ coordinate:
  - p_T : projection of the momentum in the tranverse plane xy
  - η: pseudorapidity → Lorentz invariant



Undetectable particles:



- Undetectable particles:
  - Neutrinos
  - Dark Matter
- The sum of all the p_T of the particles arising from the collision is ideally 0
- If some undetactable particles are produce → we measure some p_T missing
- Definition: **MET**

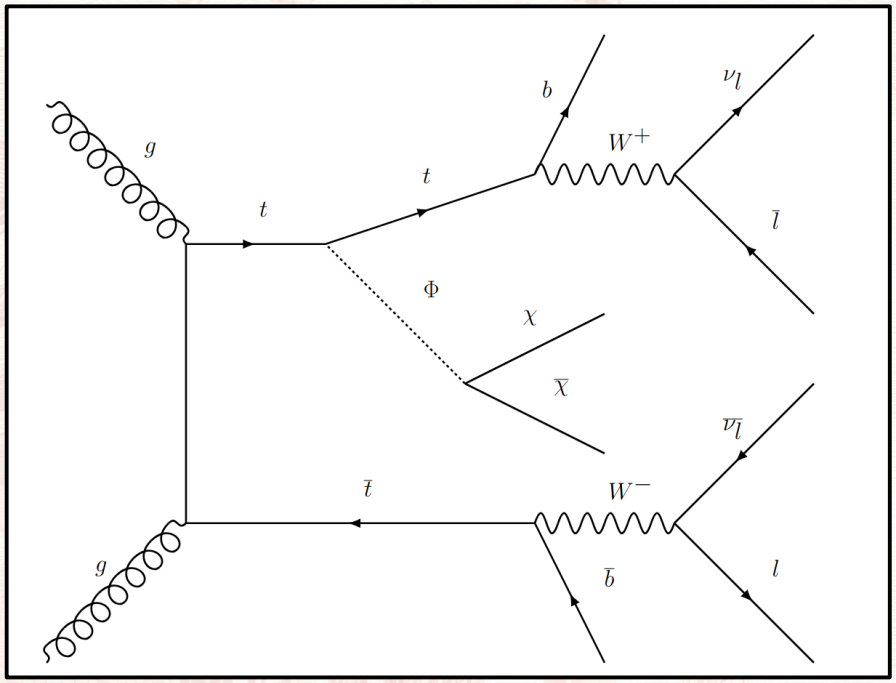
Dark Matter Model

Simplified Model with spin-0 extended Higgs sector

- **Scalar** mediator **Φ**:

$$L_{\Phi} \supset -g_{\chi}\Phi\,\bar{\chi}\chi - \frac{\Phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} g_q\, y_q\, \bar{q}q$$

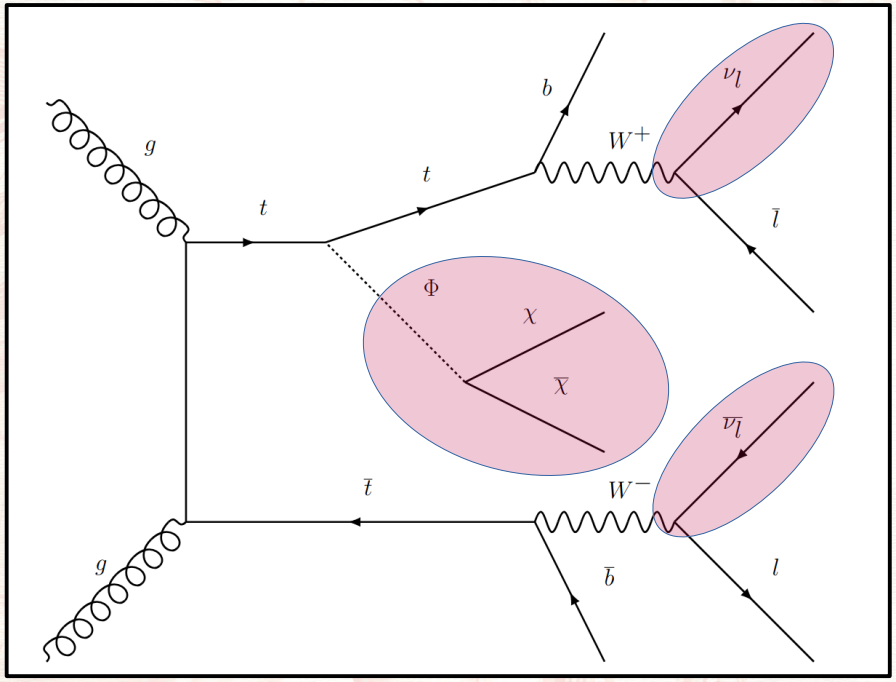
- Assumptions:
  - Yukawa coupling $y_q = \sqrt{2}\frac{m_q}{v}$
  - Dilepton decay channel for the top quarks
- **Signature**:
  - **2 leptons**
  - **2 jets** associated to the bottom quarks
  - **MET** coming from both the neutrinos and the production of the DM



Kinematic reconstruction

HOW CAN WE RECONSTRUCT THE KINEMATICS?

- **Challenges**:
  - **Jets multiplicity →** Correct identification of bottom Jets
  - Undetectable particles: two neutrinos and DM



- **Definition**:
  - Assuming it is possible to reconstruct all the standard model particles:

$$(P_\phi)_T = \mathrm{MET} - (P_\nu + P_{\bar{\nu}})_T$$

  - From now on also called **dark p_T**

Analytical Methods

Reconstruction of ttbar momenta in dilepton decay

Sonnenschein

- **Algebraic** approach:
  - The problem is expressed with two **quartic equations** the neutrinos transverse momenta
  - Assumption:
  - MET exclusively from neutrinos

Betchart

- **Geometrical** approach:
  - The kinematic and the MET limit neutrinos transverse momenta in two **ellipses**
  - 0, 1, 2 or 4 intersections are the possible solutions
  - Point of closest approach taken when ellipses do not overlap

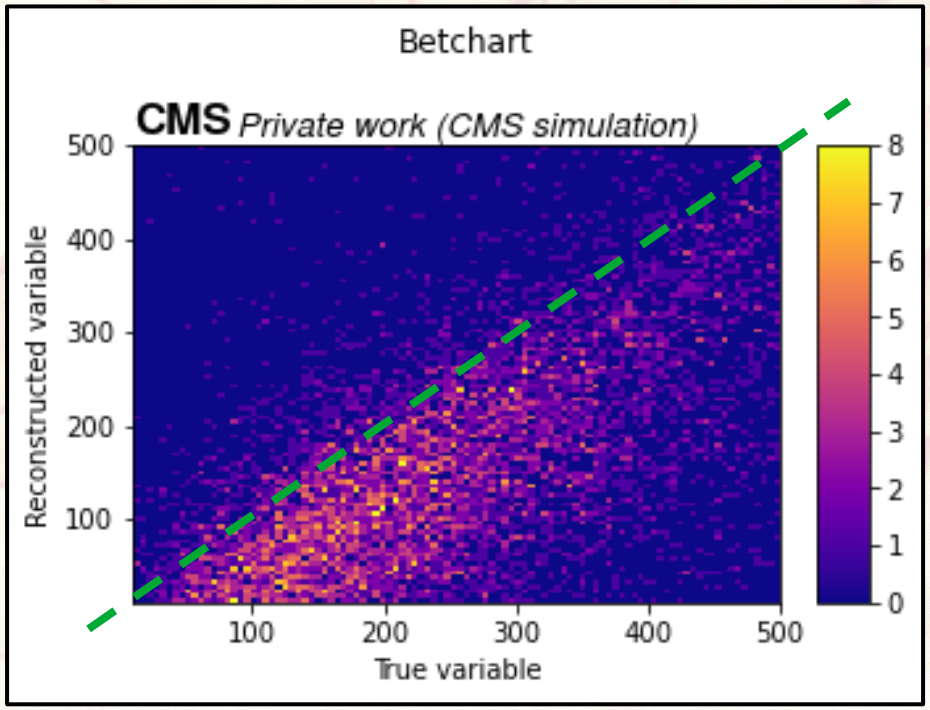
Metrics

Useful Definitions

f (x) is the **prediction**, **t** represents the **true value**

$$Relative\ Bias = mean\left(\frac{f(x)-t}{t}\right)$$

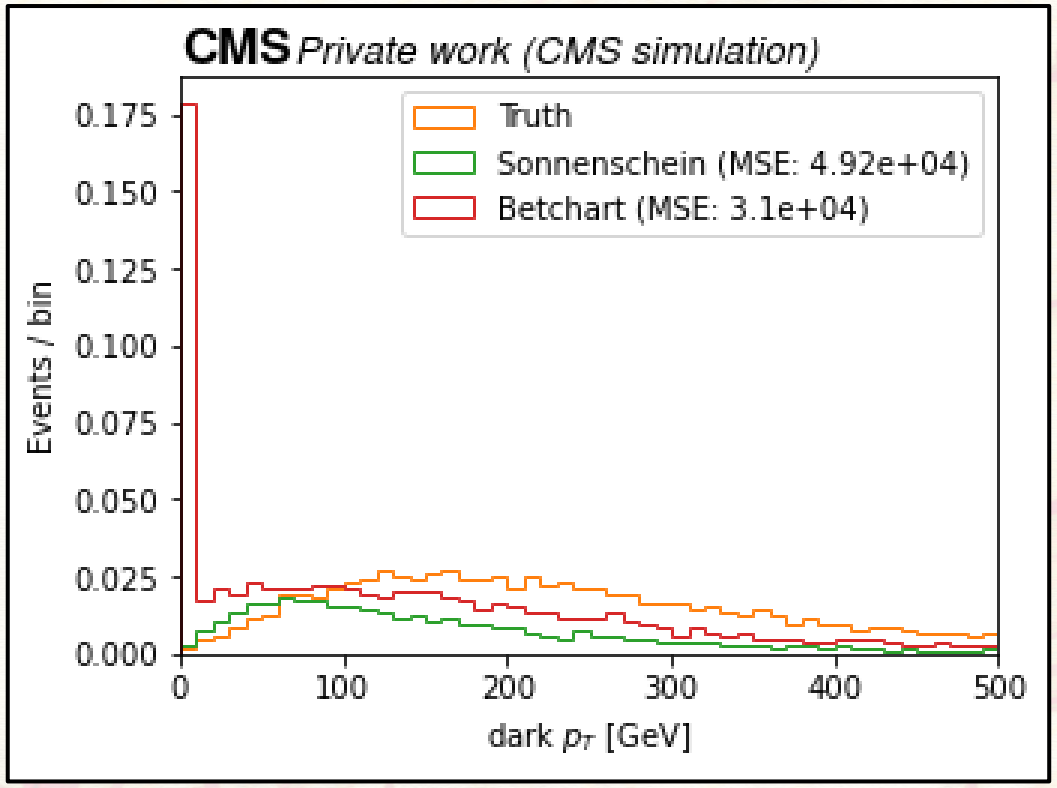
$$Resolution = \sqrt{mean\left[\left(\frac{f(x)-t}{t}\right)^2 - (relative\ bias)^2\right]}$$



Performance in DM

Generated vs Reconstructed dark p_T

- Mediator mass 250 GeV, χ mass of 1 GeV

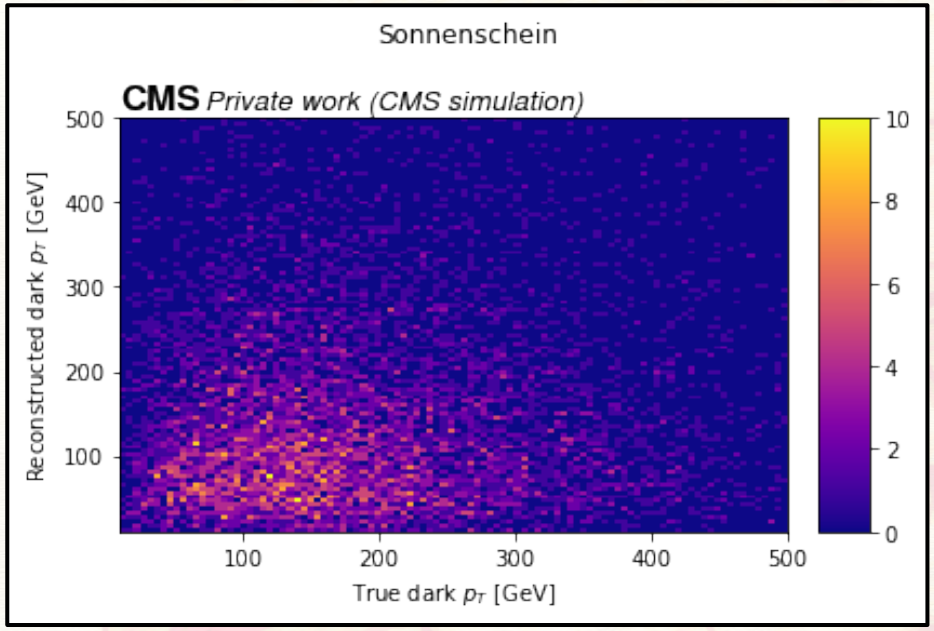


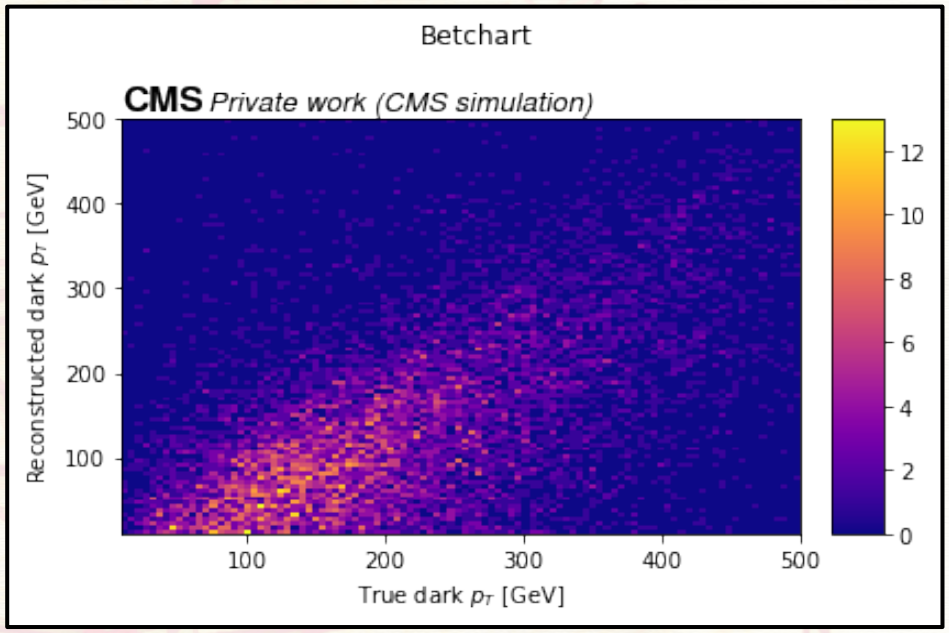
- Betchart algorithm reconstruct most events with 0 dark p_T
- Remove the first bin in following plots

Performance in DM

Generated vs Reconstructed dark p_T

- Mediator mass 250 GeV, χ mass of 1 GeV





What's happening

Problem

- The algorithms are working in the assumption of no DM;
- The problem contains many degrees of freedom → no good analytical solution;
- Furthermore they are also completely failing (NaN) in:
  - **Betchart**: **~5%** of the cases
  - **Sonnenschein**: **~40%** of the cases

Idea

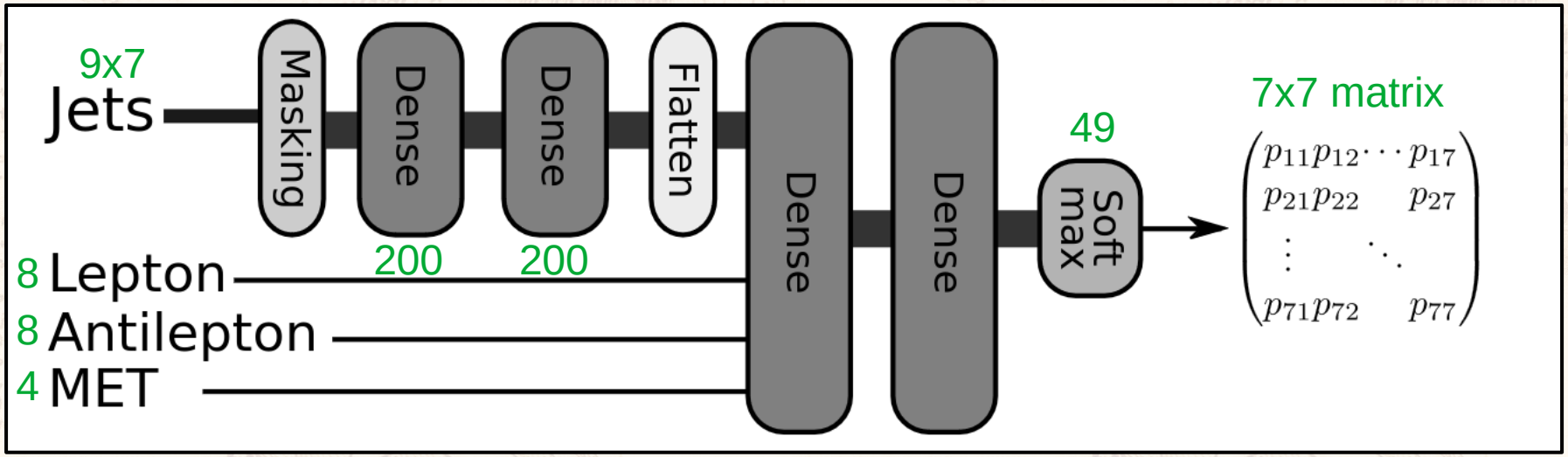
- Implement a neural network to reconstruct the kinematics

Dense NN Model

Neural Nework for bottom jet tagging

- Input:
  - Up to 7 jets 4-momenta + DeepJet b tag;
  - All 4-momenta are given in xyzE and p_Tφηm coordinates;
- Output:
  - A 7x7 matrix. Each entry O_{ij} is interpreted as the probability that the ij jets come from by bb-bar quarks;

Number of neurons in green

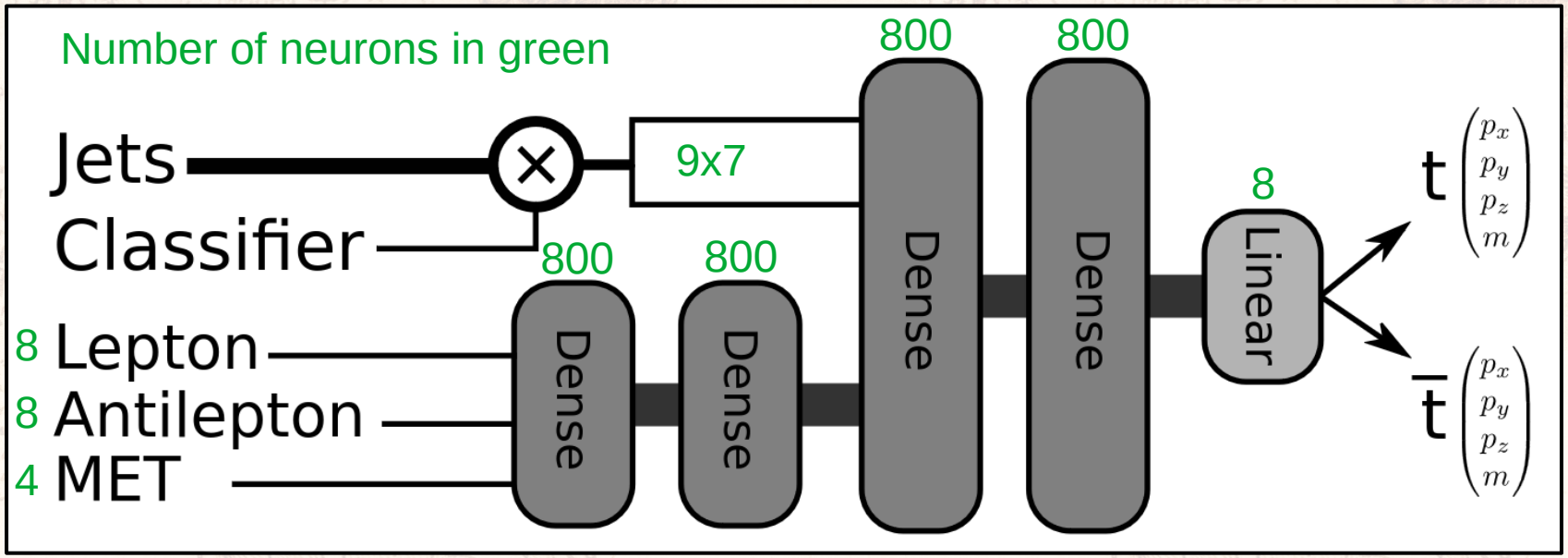


Dropout probability for each layer is 0.25

Dense NN Model

Neural Nework for top quarks 4-momenta reconstruction

- Input:
  - Up to 7 jets 4-momenta + DeepJet b tag
  - All 4-momenta are given in xyzE and p_Tφηm coordinates
- Output:
  - Reconstructed ttbar 4-momenta in xyzm coordinates



Dropout probability for each layer is 0.25

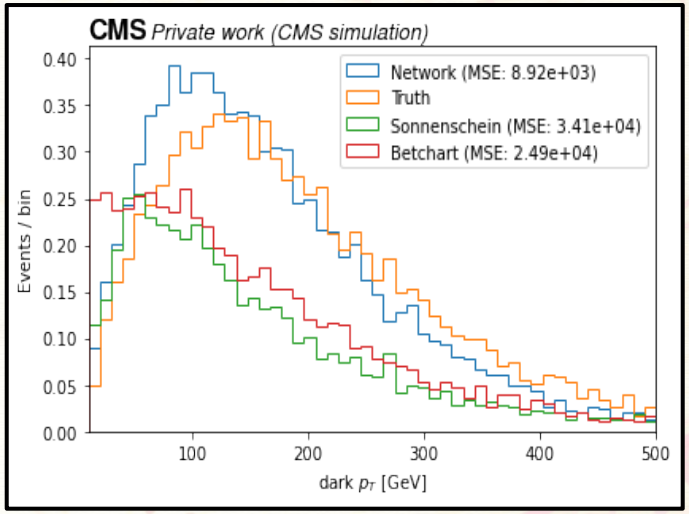
Training the model

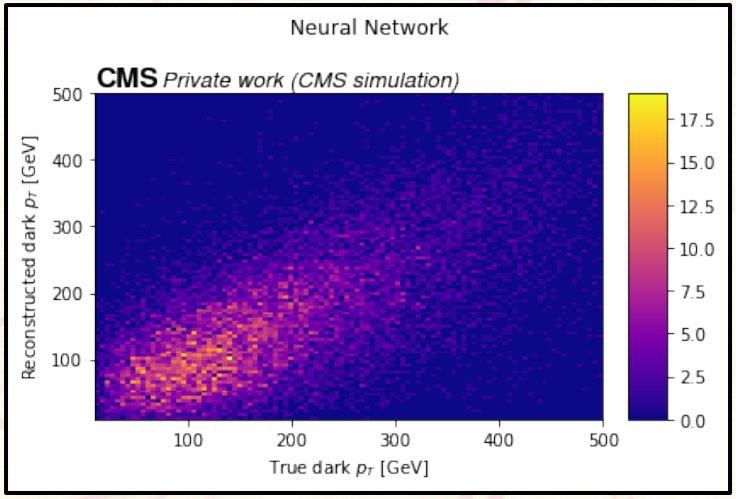
Datasets

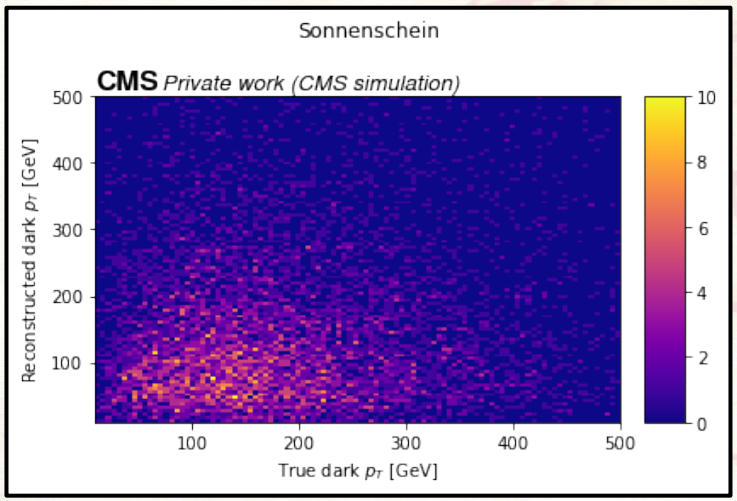
- One dataset with SM events
- 10 datasets with DM events
- χ mass of 1 GeV and Φ mass in [50, 500] GeV at steps of 50 GeV
- Model trained and validated separately once for each data set

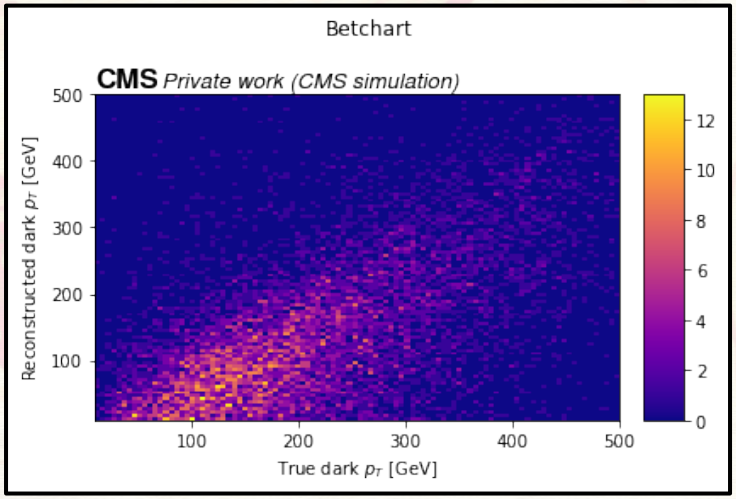
Results with DM training

Mediator mass 250 GeV:









Results with DM training

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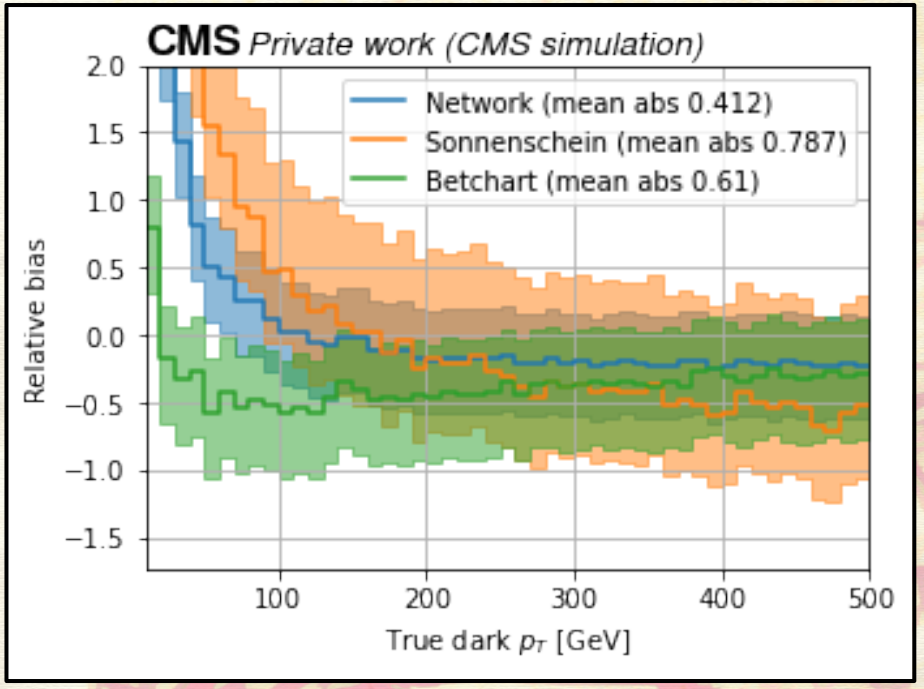
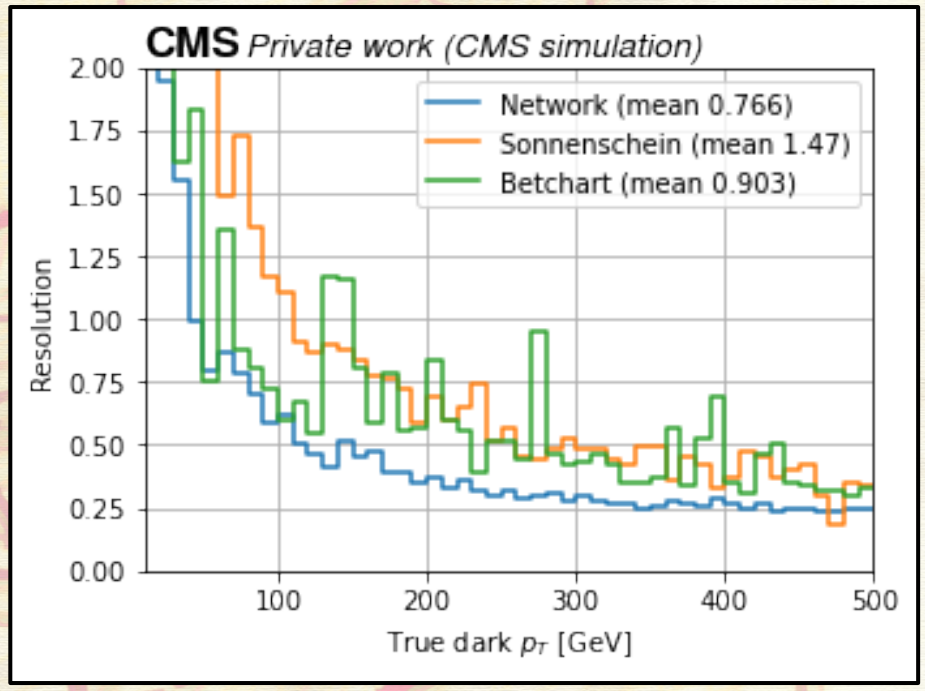




Results with DM training

Pros:

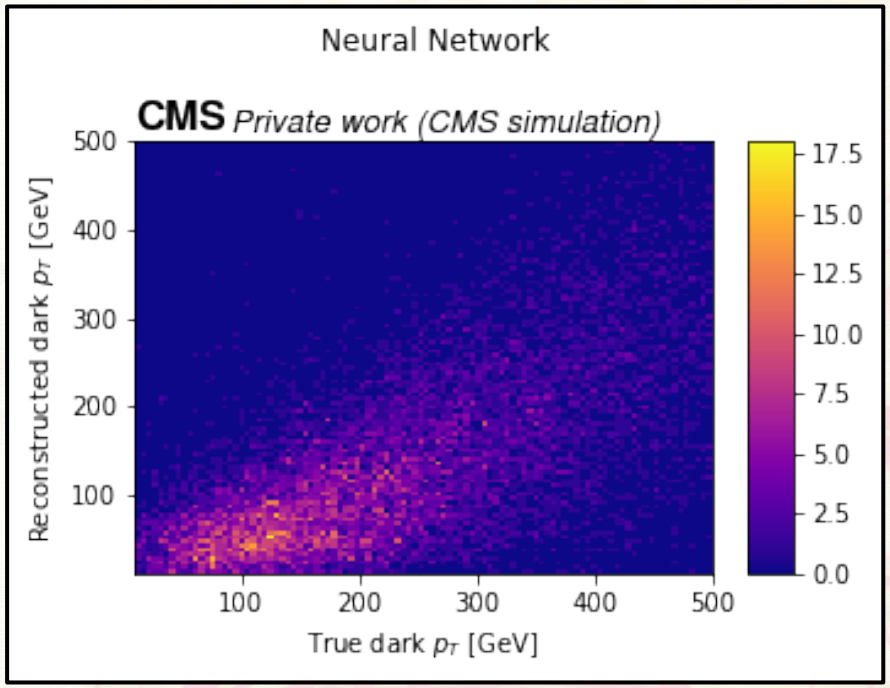
- The **Neural Network outperforms** the **analytical** methods:
  - It never fails;
  - Reproduces better the original distribution of the dark p_T;
  - Similar results for the others mass points;

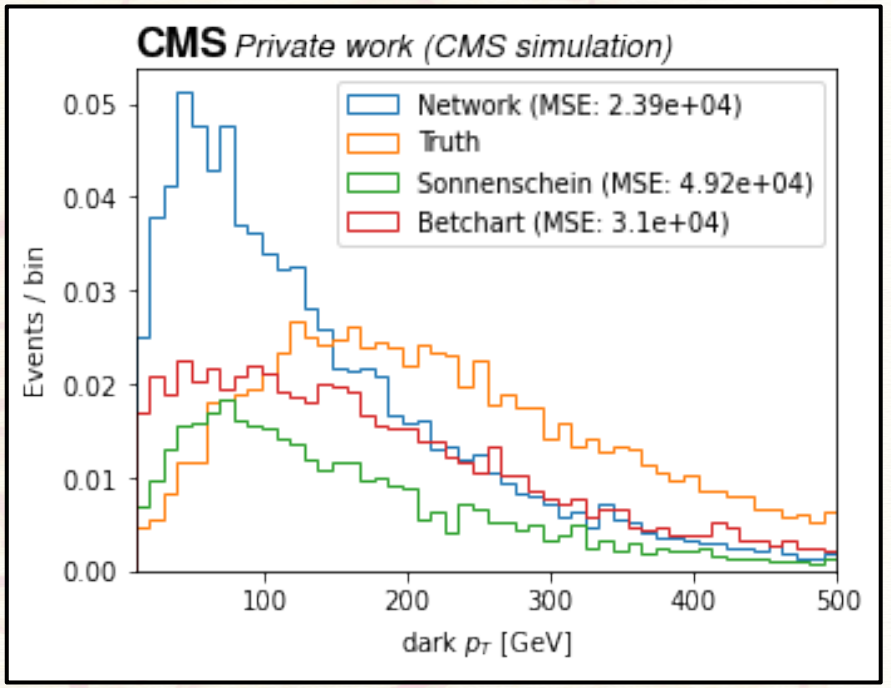
Questions:

- Is it somehow **specific** for the **mediator mass** of the train?
- Is it powerful enough to produce a **discrimination** between the **SM background** and the **signal**?
  - Can we try to set limits with this approach?

Specificity of the NN

Mediator mass: training 50 GeV, validation 500 GeV





Strategy

Observation:

- The **Neural Network** is quite specific to the mediator mass that has been used during the training.

Approach:

- Train with a mixture of **SM** and **DM** events;
- **Re-weighting events** to balance the importance of SM vs. DM.

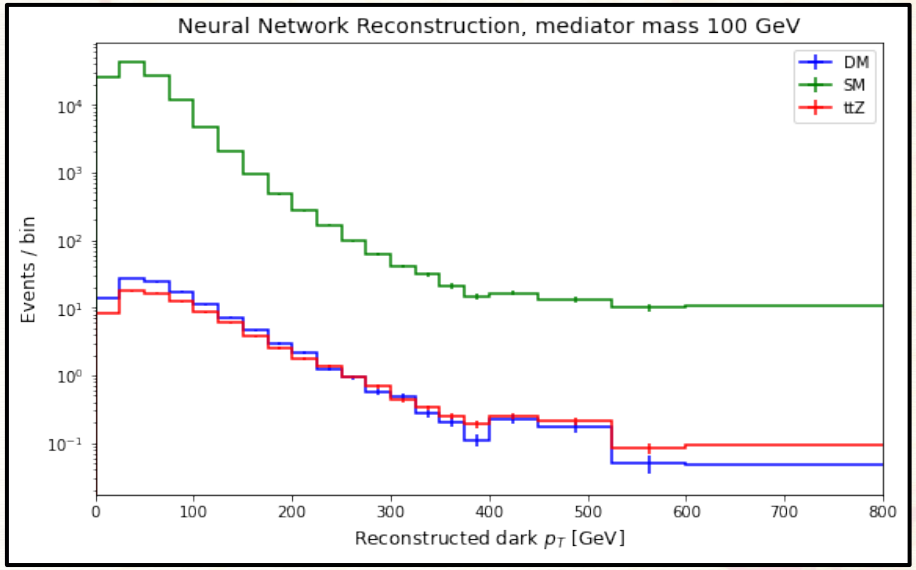
Sensitivity estimation

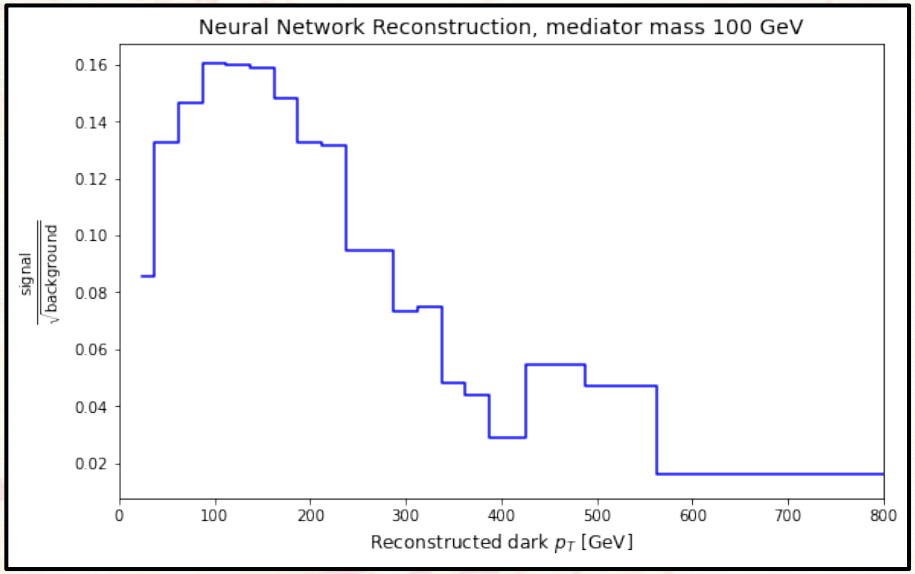
- NN method**:**
  - Generate a **histogram** of the **predicted dark p_T** separating the SM background and the signal for a given mediator mass.

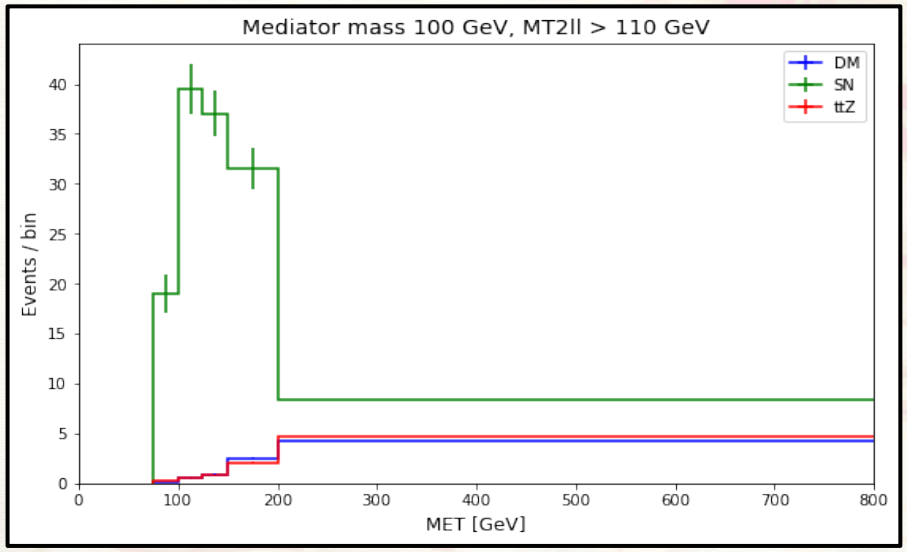
- Baseline method: apply a cut on **mt2ll > 110 GeV** and generate the histogram of the **MET distribution**

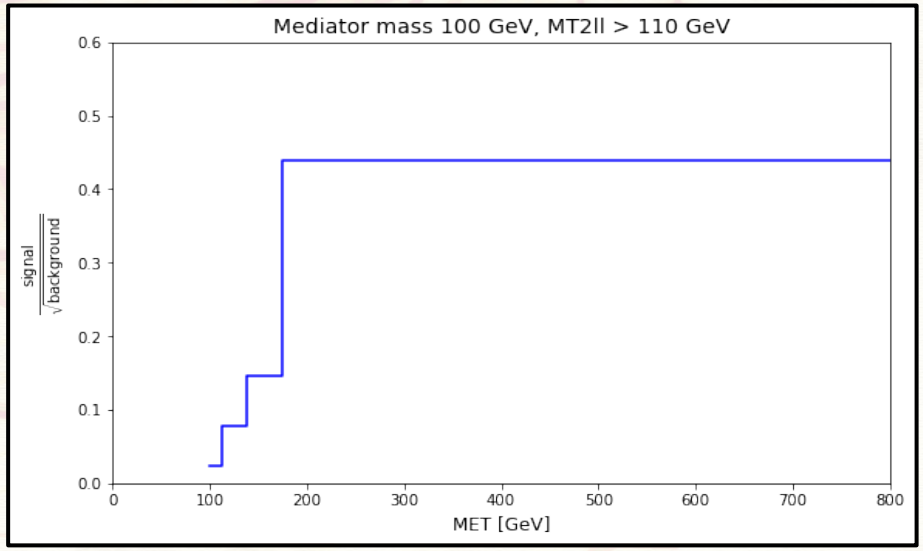
- Consider the **ratio** $\frac{signal}{\sqrt{background}}$: **indication about** the **limit** that we could obtain.
- Background:
  - SM tt dilepton decay;
  - ttZ with neutrinos in the final state.

Sensitivity estimation









Conclusions

Results

- The **NN** has the potential to reconstruct the kinematic of the problem, **outperforming** the **analytical** approaches
- Can be used in future analyses, giving better resolution for top variables

Outstanding challenge

- The **NN struggles** to **separate** the **SM** and the **DM** events

Future Ideas

- Try optimizing the NN model, for instance using different loss functions
- Try more advanced NN architectures

Exotic Group

Thanks for your attention

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