Machine Learning for BSM search in tt+MET final state at the ATLAS Experiment

12th September 2024

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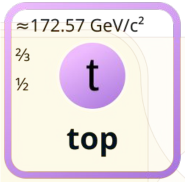
ATLAS EXPERIMENT

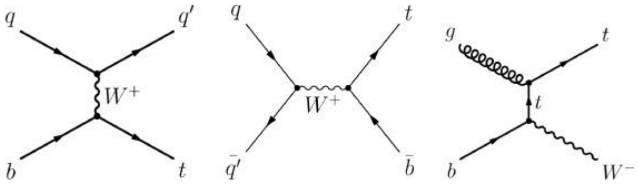
The top quark

- The Standard Model (SM) is a coherent but not complete theory: gravity, dark matter, dark energy, hierarchy problem, ...
- The top quark:
  - most massive elementary particle
    - large coupling to the Higgs boson
  - decays before hadronization
    - ideal candidate for spin correlation measurements
  - high impact on EW precision observables
  - production rate can be impacted by Beyond SM physics

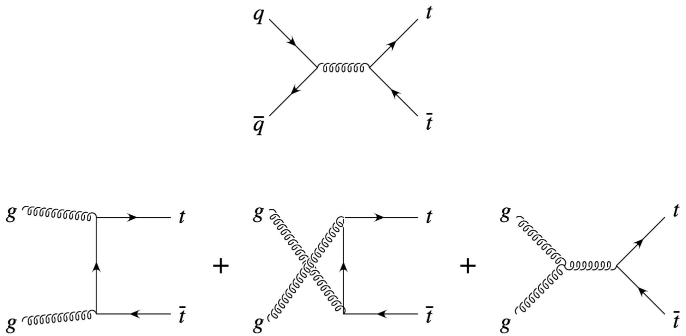


$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{\text{QCD}}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip} \\ 10^{-21}\ \text{s}}}$$

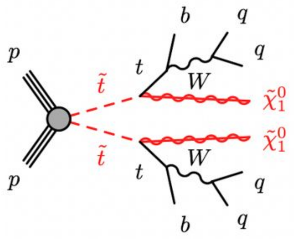
Single top production



Top pair production

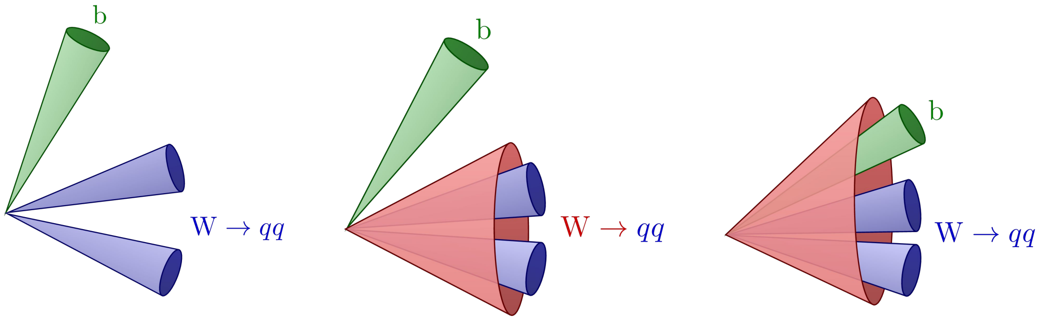


Stop pair production (tt+MET final state)

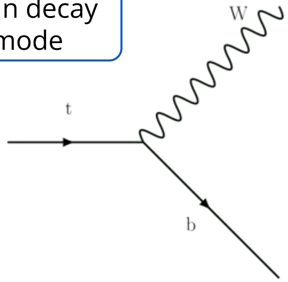


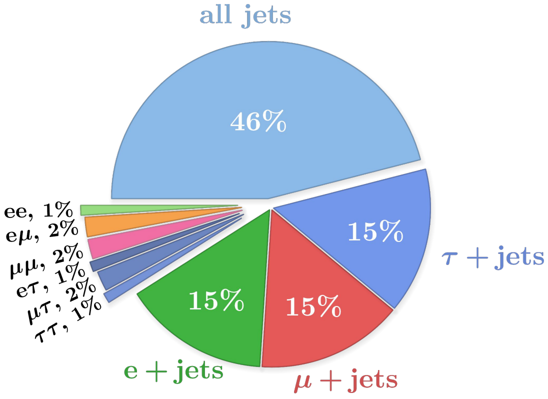
The top quark decay

- Top quark decays almost exclusively in Wb
  - final state depends on W boson decay: leptonic or hadronic
  - topology can be resolved or (partially) merged



Main decay mode



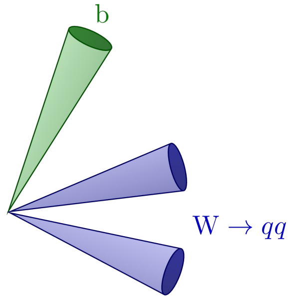


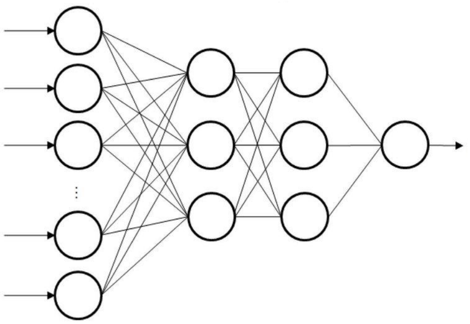
- Top pair preferentially decays to all hadronic final state
  - high combinatorial background for resolved topologies
- ML methods are being developed to match top and its decay products
  - boost the sensitivity in BSM searches

Multiplet classifier for resolved top decay

Train a **binary classifier** to identify the **multiplets** (1 b-jet + 1 or 2 light jets) that are **matched to a resolved hadronic top decay** in events with top pairs

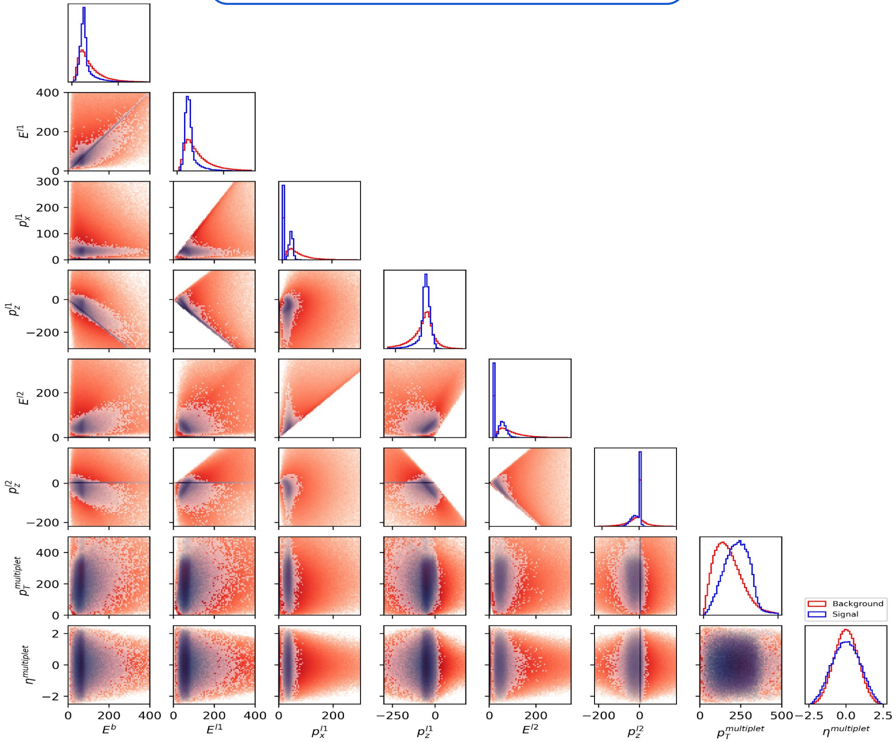
- Input:
  - non-trivial 4-momenta components of the multiplet in the centre-of-mass reference frame
  - boost parameters to the centre-of-mass reference frame
- Output:
  - probability of being matched to top



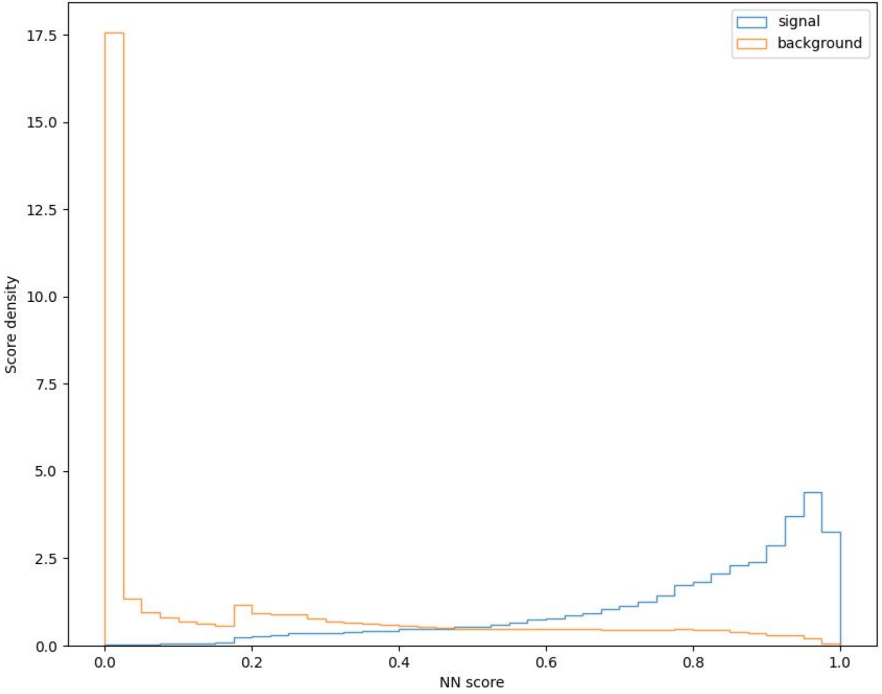


Multiplet classifier for resolved top decay

Input features
signal (blue) = matched multiplets
background (red) = unmatched multiplets



Multiplet score
signal (blue) = matched multiplets
background (red) = unmatched multiplets



Multiplet classifier for resolved top decay

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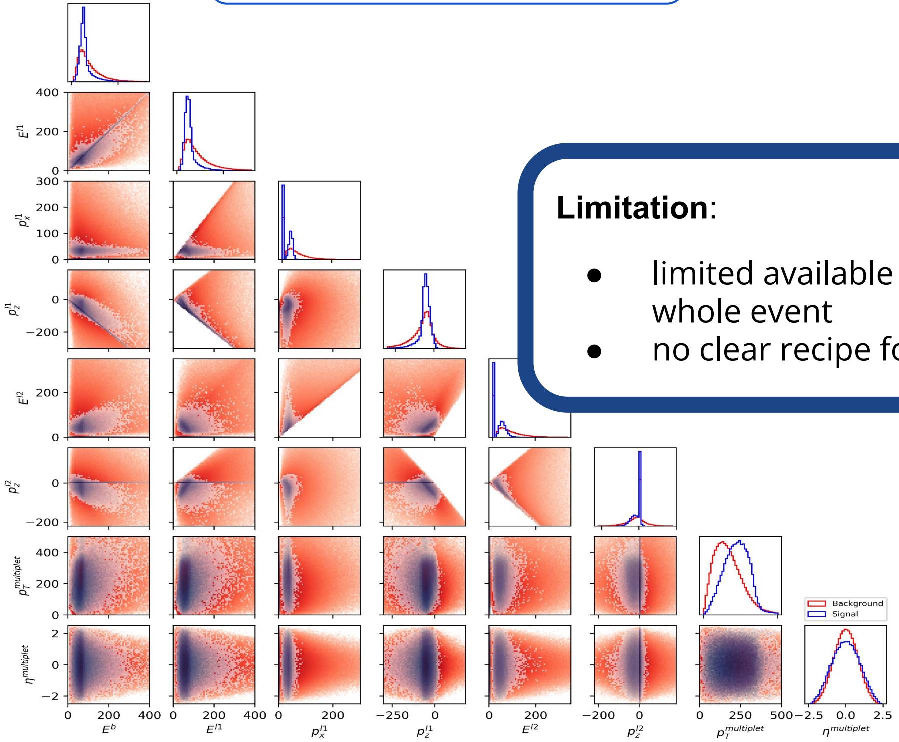

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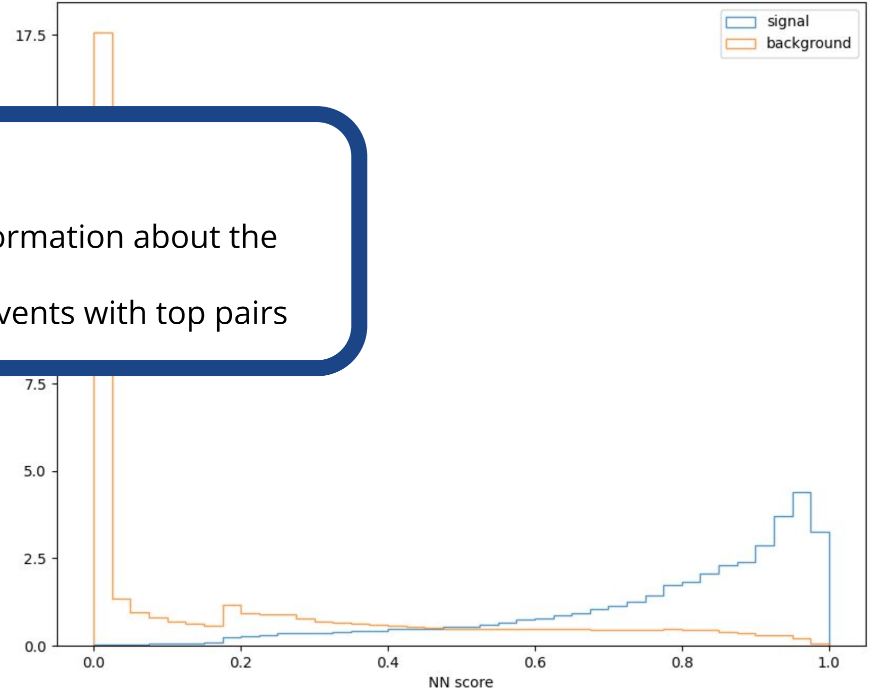


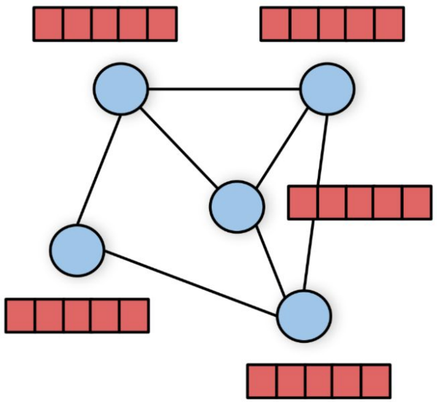
Limitation:

- limited available information about the whole event
- no clear recipe for events with top pairs

Introduction to Graph Neural Networks

Data is represented as:

- nodes with associated features
- edges connecting related nodes (can also have an associated feature)



Key node update method: message passing

$$\mathbf{x}_i' = \gamma_{\mathbf{\Theta}}\left(\mathbf{x}_i, \bigoplus_{j \in \mathcal{N}(i)} \phi_{\mathbf{\Theta}}\left(\mathbf{x}_i, \mathbf{x}_j, \mathbf{e}_{j,i}\right)\right)$$

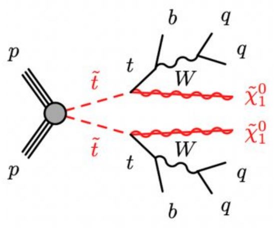
Classification and regression can be implemented at various levels on graphs:

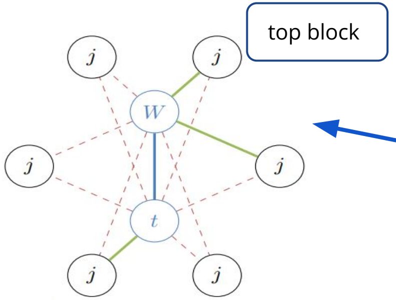
- nodes
- edges
- graph

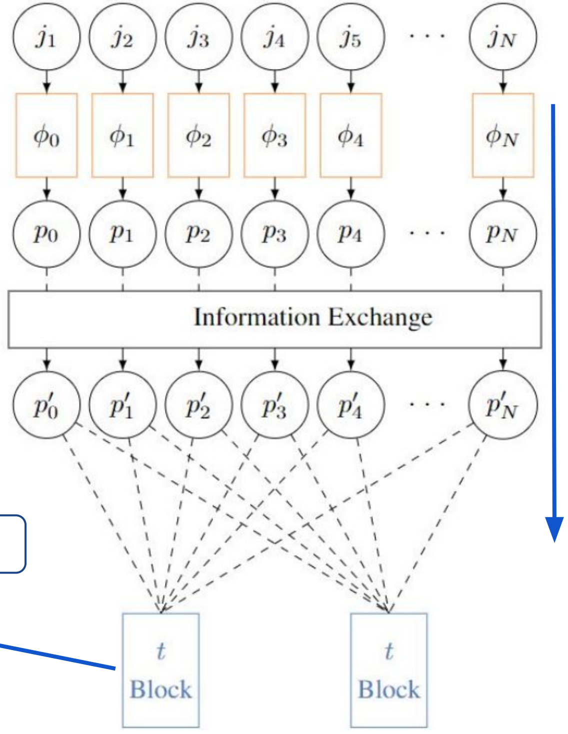
GNN (Topograph) for tt+MET

Train a GNN with multiple truth-level information

- Input:
  - all jets and leptons 4-momenta + MET
- Inductive bias:
  - add SM intermediate particles to the graph and connect final states to their potential parent particle
- Output (multi-task learning):
  - score for the intermediate-to-final state edges
  - regression of intermediate particle 4-momenta
  - signal/background classifier for BSM search - to be included



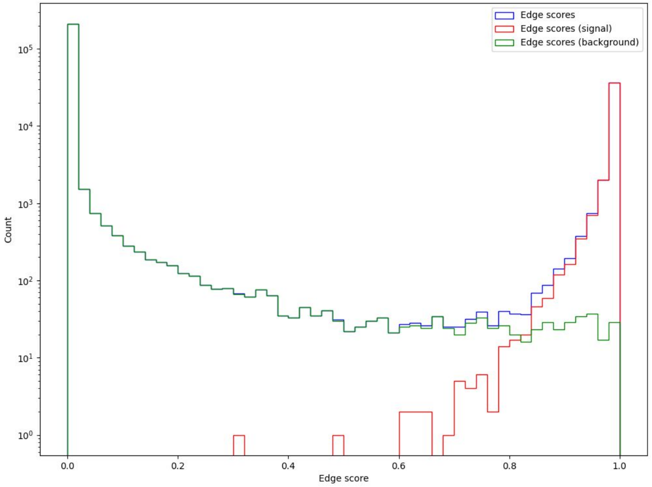




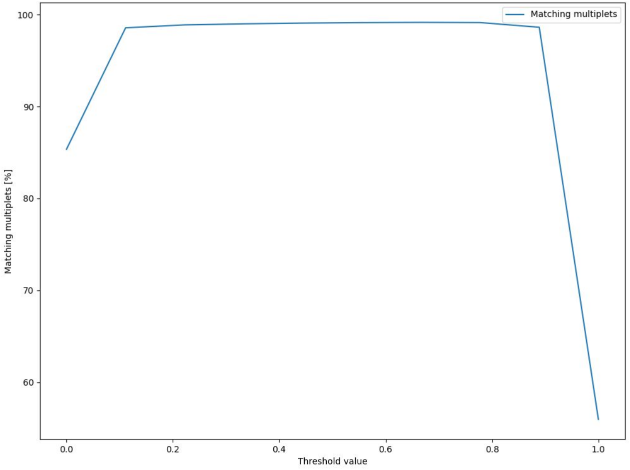
https://arxiv.org/pdf/2303.13937

GNN (Topograph) for tt+MET

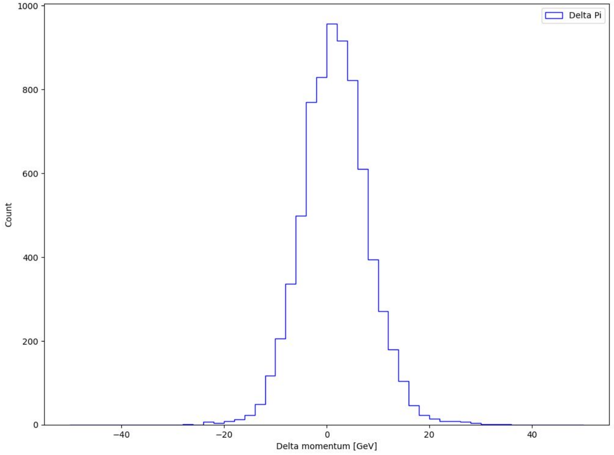
Edge score
signal (red) = true edge
background (green) = false edge



Matched multiplets (3 jets) reconstruction efficiency



Difference between reconstructed and true momentum



Important: the current training dataset is too small to ensure proper generalization, but most information bottlenecks have been identified and removed

Next steps

- Enlarge the training dataset to avoid overfitting
- Include signal/background classification
  - use ML output to identify regions of interest for the stop pair production search (check out Meinrad’s talk)
- Study the impact of these ML methods on the expected significance in the stop pair production search

Thank you!

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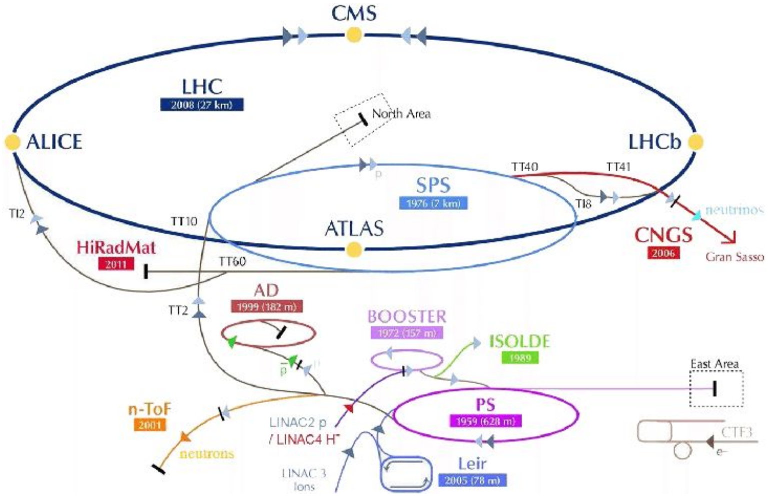
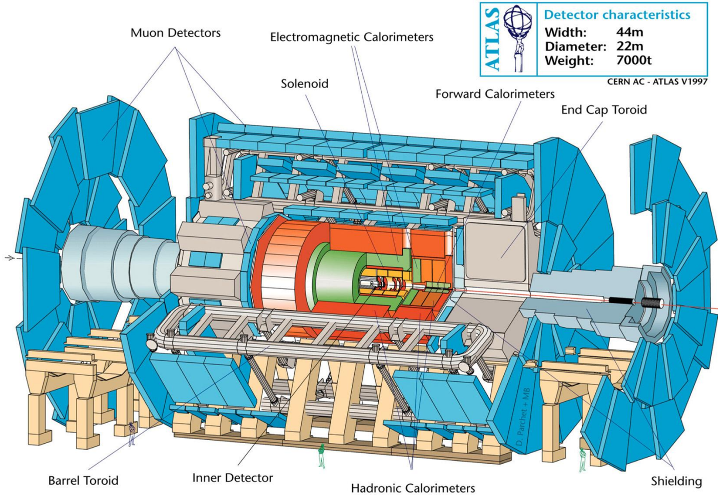
ATLAS EXPERIMENT

LHC and ATLAS in a nutshell

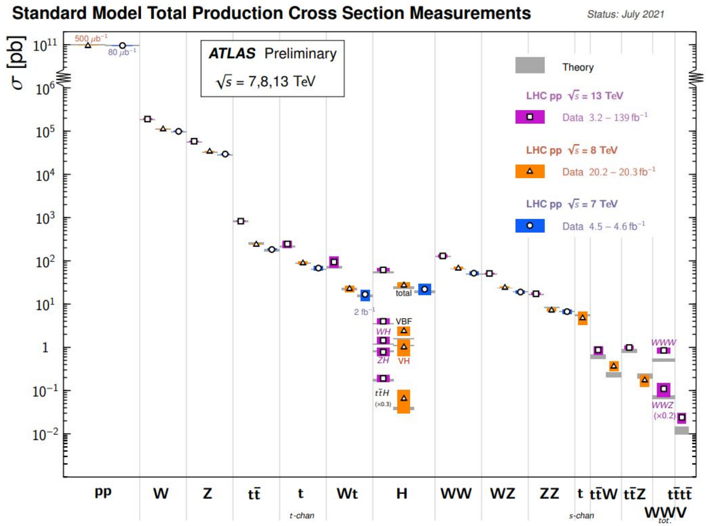
- The Standard Model (SM) is a coherent but not complete theory: gravity, dark matter, dark energy, hierarchy problem, …
- LHC and the ATLAS detector are the perfect tools to study the high-energy frontier
  - accelerate and collide protons at 13.6 TeV
  - produced particles propagate through the detector, leaving a signal
  - reconstruct the physics objects
  - perform a SM measurement or beyond SM search

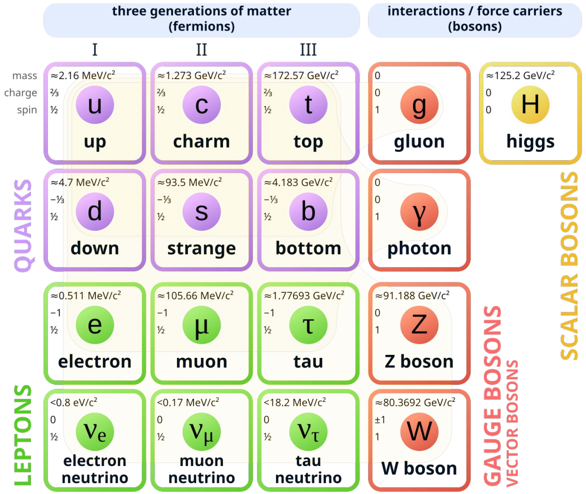




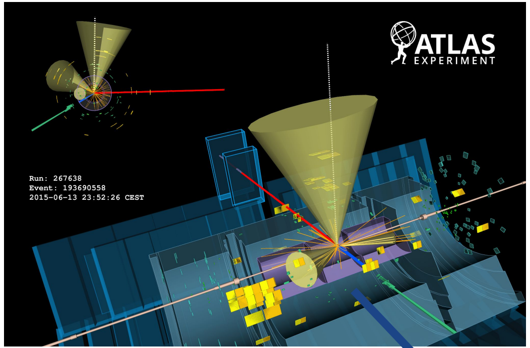
The Standard Model in a nutshell

- The Standard Model (SM) successfully predicts the interaction probability of particles over a large range orders of magnitude
- The last piece needed to guarantee the internal consistency of the SM was the Higgs boson, discovered in 2012
- The SM still leaves open questions: gravity, dark matter, dark energy, hierarchy, …



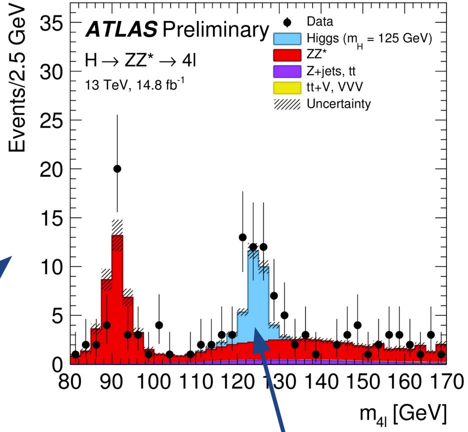


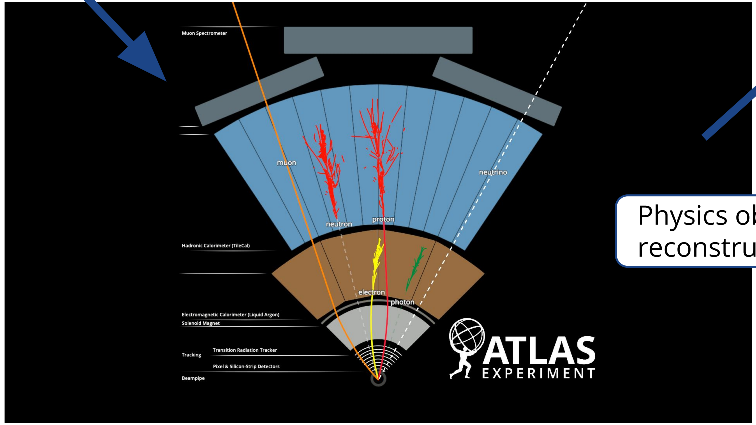
LHC and ATLAS in a nutshell



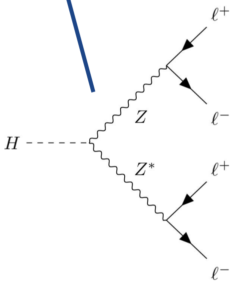
Particles produced in the collision leave a signal in the detector

- Measurement of SM process
  or
- New physics search



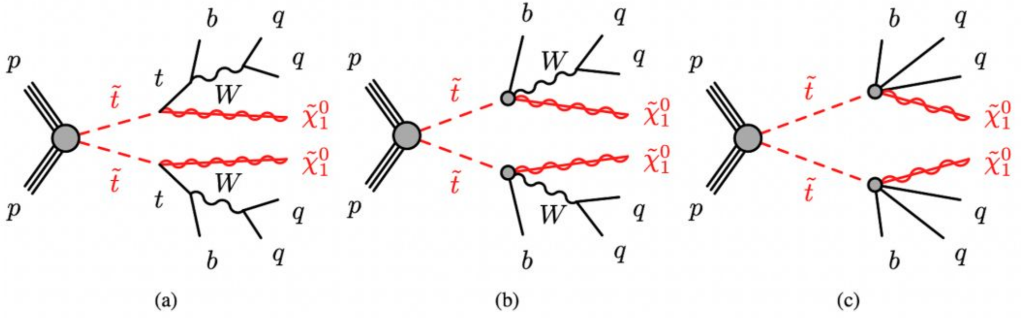


Physics objects are reconstructed



Signal processes

- Different scenarios depending on the mass splitting $\Delta\mathrm{m}(\tilde{t}, \tilde{\chi}_1^0)$
- (a) $\Delta\mathrm{m}(\tilde{t}, \tilde{\chi}_1^0) > \mathrm{m}(t)$
- (b) $\Delta\mathrm{m}(\tilde{t}, \tilde{\chi}_1^0) > \mathrm{m}(W + b)$
- (c) Compressed scenario

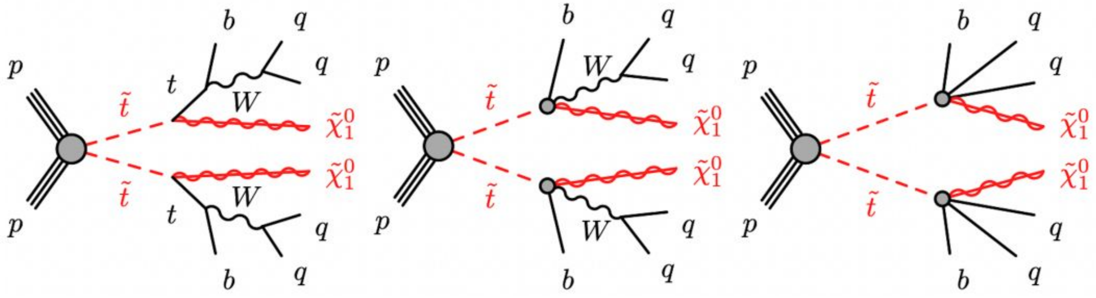


NN for resolved top reconstruction

Purpose: *identify the daughter particles of the top decays to boost the discovery potential*

How?

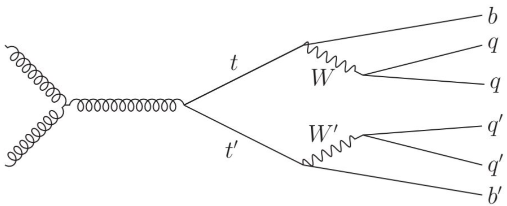
- Consider **all signal samples** (different stop and neutralino masses)
- For each event create **all possible multiplets** made of 1 b-jet + 2(1) l-jets
- Identify if any of the multiplet can be "**truth-matched**" to the top produced by the stop decay
- Train a neural network to **classify a multiplet** (baseline model, used in the previous analysis) as coming from a top or combinatorial background



Baseline methods

Common approach for resolved top pair reconstruction:

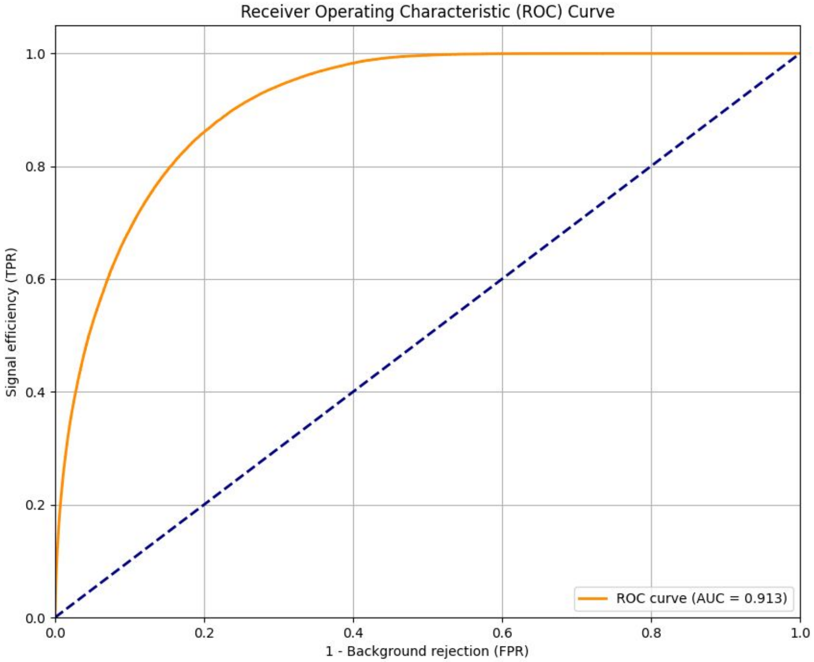
- test all the combinations and pick the combination that minimizes a χ^2-like variable



hadronic ttbar

$$\chi^2 = \frac{(m_{b_1 q_1 q_2} - m_t)^2}{\sigma_t^2} + \frac{(m_{b_2 q_3 q_4} - m_t)^2}{\sigma_t^2} + \frac{(m_{q_1 q_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{q_3 q_4} - m_W)^2}{\sigma_W^2},$$

Multiplet classifier for resolved top decay



Multiplet classifier for resolved top decay

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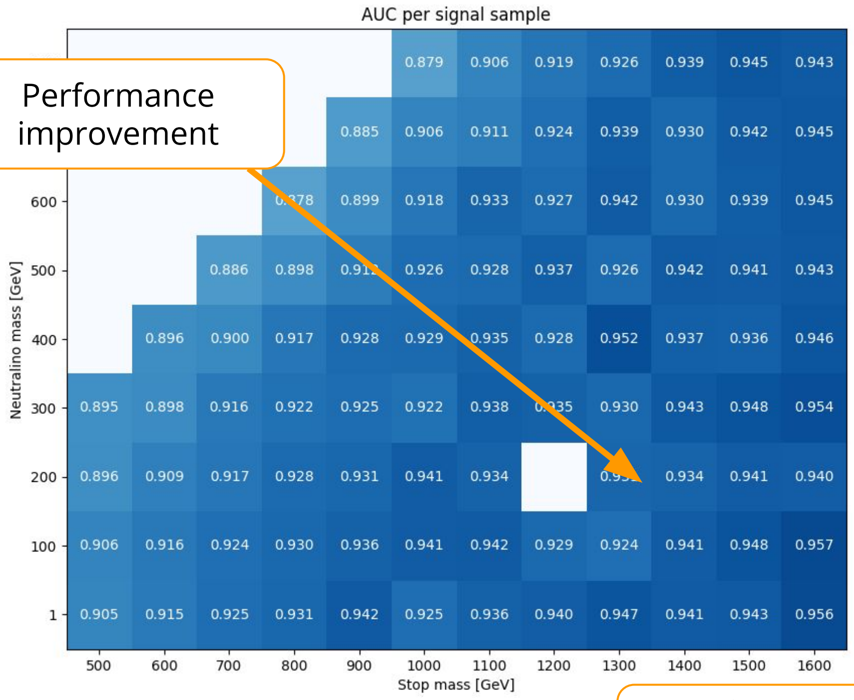
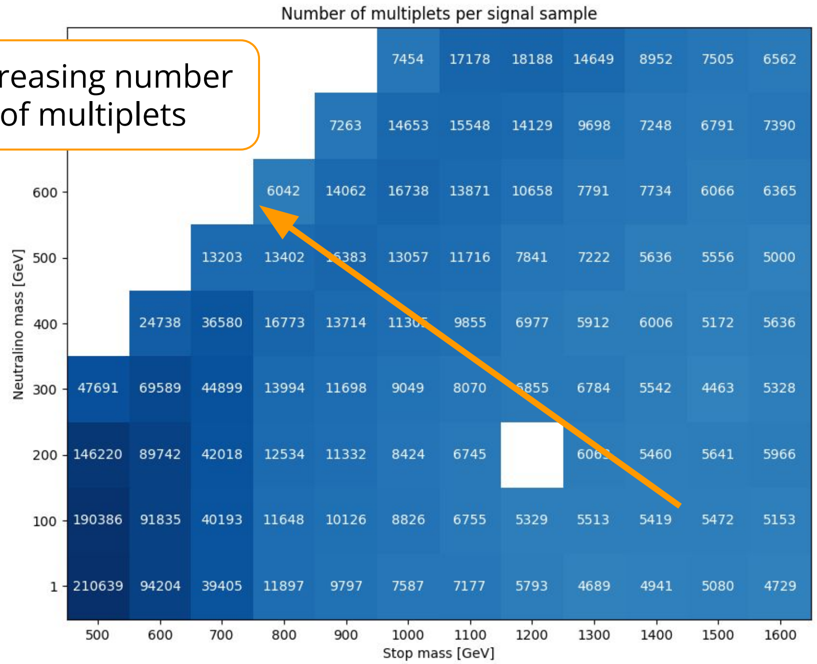
Performance improvement



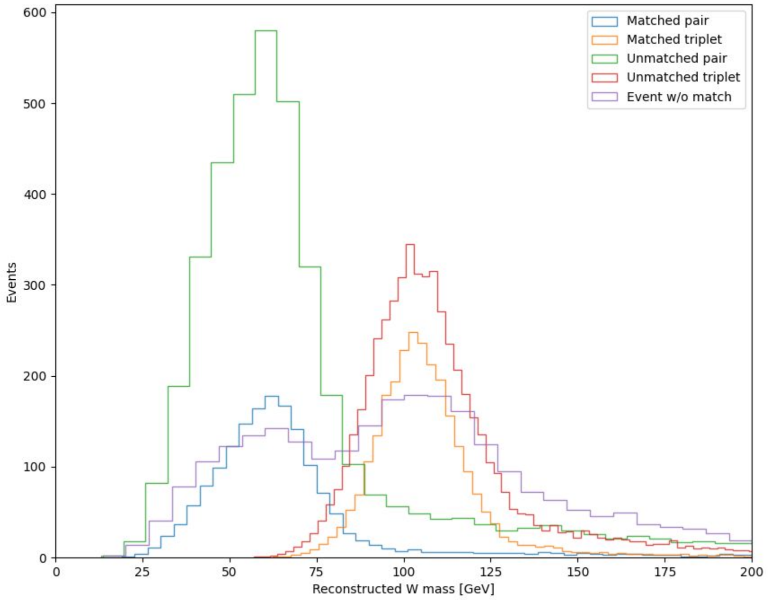
Increasing number of multiplets

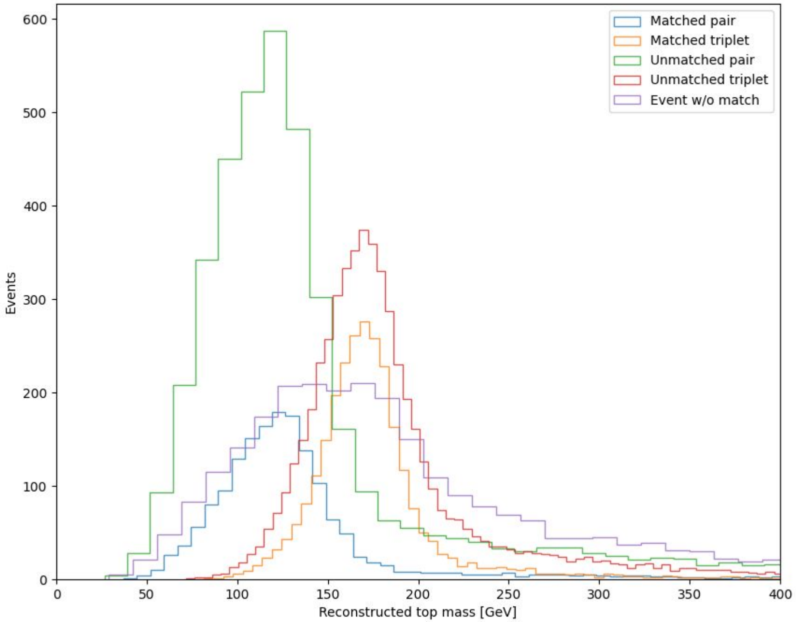


Performance gradient due to events being harder to reconstruct

Multiplet classifier for resolved top decay

Consider the two leading multiplets (in NN score) per event as identifying the top candidates

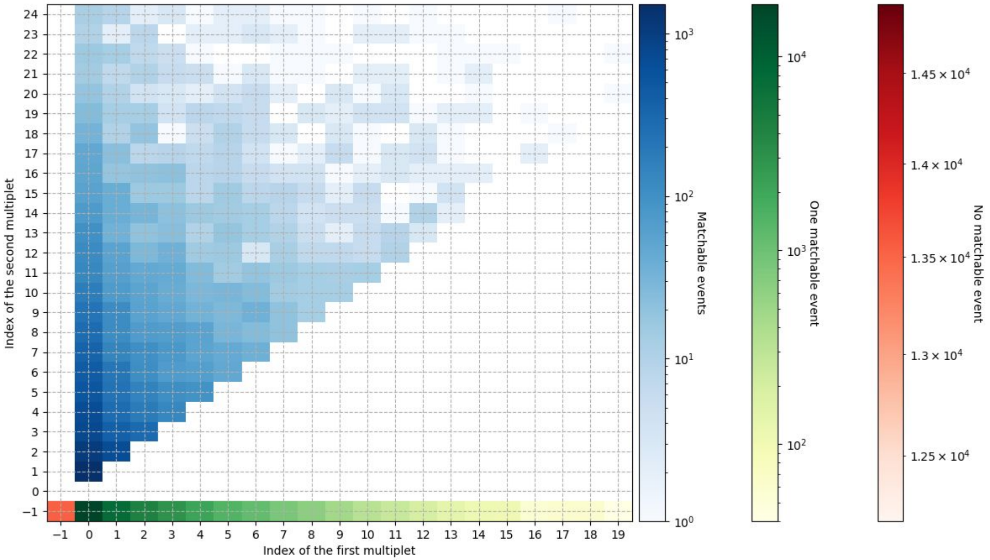




Multiplet classifier for resolved top decay

Limits of the approach:

- the 2 leading multiplets can overlap
- it’s not trivial to select the best 2 multiplets



References

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