國立清華大學

物理系

碩士學位論文

# 基於 SPA-Net 的雙頂夸克全強子衰變事件重建

# Event reconstruction of full hadronic Top-quark-pair decays using SPA-Net

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# Event reconstruction of full hadronic Top-quark-pair decays using SPA-Net

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## Abstract

The top quarks produces by *pp* collision in Large Hadron Collider(LHC), have a very complicated process still can't be well-classified today. In this project, we present a novel approach to the ‘all hadronic decay‘ process of Top quarks base on the neural networks with attention mechanism, we call it ‘Symmetry Preserving Attention Networks‘(SPA-Net). This networks identify the decay products of each quarks unambiguously and without combinatorial explosion. This approach perform a outstanding result compare to the existing state-of-the-are method. Our network can correctly assigning all hadronic decay in 93.0% of 6 jets, 87.8% of 7 jets, and 82.6% of $\geq 8$ jets event respectively.

# 摘要

在大型強子對撞機 (LHC) 實驗中，經由質子對撞所產生的頂夸克對具有非常複雜的過程以及產物，至今仍無法被非常正確的判別以及重建。在本研究中，我們提出了一個利用新穎的機器學習方法來對雙頂夸克全強子衰變過程進行重建。此方法基於 Attention mechanism，我們稱之為 Symmetry Preserving Attention Networks(SPA-Net)。這個模型架構可以在避免組合性爆炸的前提下對所有的衰變產物進行辨識以及重建。此方法對比於傳統的 $\chi^2$ 重建方式，表現出了非常巨大的差異。本方法可以在一、存在 6 jets 條件下正確的重建 93% 的事件；二、存在 7 jets 條件下正確的重建 87% 的事件；三、存在大於 8 jets 條件下正確的重建 82.6% 的事件。

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# Chapter 1

# Introduction

At Large Hadron Collider(LHC), two protons collide with very high energy and produce many kinds of products. A process that $pp$ collision produces a pair of Top quark and result in the 6 jets final state is called **Full Hadronic Top-quark-pair decay**. This process has a very complicated signature due to a large number of combinations. These jets produced by the top quark pair is hard to tag as a specific parton correctly. A traditional method is to reconstruct the event using $\chi^2$ reconstruction, but it takes such a long time to compute and cannot provide enough accuracy to reconstruct an event. The importance of studying Top quark and its full hadronic decay channel is 1. Top quark is the most heaviest fundamental particle in standard model and will decay before hadronization, 2. The brach ratio of full hardonic decay is the biggest part in Top quark decay(46%).

For a problem that contains a large amount of data and highly requires computing resources, machine learning can widely provide powerful support on solving the problem and helps to reduce the time-wasting. The machine learning method helps to discover physics phenomena with very outstanding effort. A remarkable discovery that helps by machine learning is the discovery of Higgs Boson. Both CMS and ATLAS groups apply the machine learning method to promote the searching of Higgs Boson. [1][2]

In this thesis, we perform a novel architechture for parton-jet assignment problem. This method is base on the state-of-the-art machine learning technology, Attention mechanism. We call this novel ML model **Symmetry Preserving Attention NETworks (SPA-NET)**. By applying attention networks, the SPA-NET perform a outstanding

performance compare to traditional method while avoiding combinatorial explosion. And thanks to the natural properties of attention network, the network reflect the permutation symmetry naturally and provide a chance to explore in set-based output.
We will discuss the Top physics and the concept of machine learning in chapter 2; and explain our event generation and simulation configuration in chapter 3; then introduce how we analyze the dataset and reconstruct the event using traditional method and ML approach in chapter 4. We will discuss our work in chapter 5 and summerize in chapter 6.

# Chapter 2

# The Top Physics and Machine Learning

## 2.1 The Top Physics

Top quark, the most massive fundamental particle in Standard Model(SM), is the only one quark that decay semi-weakly. Its large mass leads to short lifetime and decay before hadronization occur. Top quark contains so many propeties that interest us, such like its mass, couplings, and cross section, e.t.c. By measure these properties accurately can bring us a worth understanding of fundamental interactions and the key to Beyond Standard Model.[3]

In recent model, Top quark pair produced by $pp$ collision has three decay modes, **all-hadronic channel**, **semi-leptonic channel**, and **dileptonic channel**. The branch ratio of each channel, has shown in the Table 2.1. The decay width of Top quark predict in SM is[4]:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \times \left[1 - \frac{2\alpha)s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right] \tag{2.1}$$

Table 2.1: Top quark pair decay process[3]

| Decay Channel | Process | Branch Ratio(%) |
|---|---|---|
| All-hadronic | $t\bar{t} \to W^+bW^-\bar{b} \to q\bar{q}'bq''\bar{q}'''\bar{b}$ | 45.7 |
| Semi-leptonic | $t\bar{t} \to W^+bW^-\bar{b} \to q\bar{q}'b\ell^-\bar{\nu}_\ell\bar{b} + \ell^+\nu_\ell bq''\bar{q}'''\bar{b}$ | 43.8 |
| Dileptonic | $t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu_\ell b\ell'\bar{\nu}_{\ell'}\bar{b}$ | 10.5 |

In recent study, the most precise result of Top quark mass is measured in the lepton+jets channel due to its good signal-to-background ratio and the presence of one neutrino final state. Although all-hadronic channel has the most probability to appears in the Top quark pair decay process, but it couldn't provide a precise mass measurement due to its poor signal-to-background ratio. The poor signal-to-background ratio of all-hadronic channel is due to the difficult QCD background. The CMS and ATLAS group approach a precision of Top mass measurement using all-hadronic channel with 0.65% and 1.1%.[5][6]

The channel we are interested in this project is the **jet-parton assignment problem in all hadronic decay channel**. The reason that we are interested in this channel is the resolved 6 jets signature and the potential of machine learning method apply on the ambiguous event reconstruction problem. There exist 6 jets in the final state, 2 b-jets and 4 quark jets, they can be seprated into two groups $(b, q, q')$ and $(\bar{b}, q'', q''')$. A schematic of the decay products is shown in 2.1.

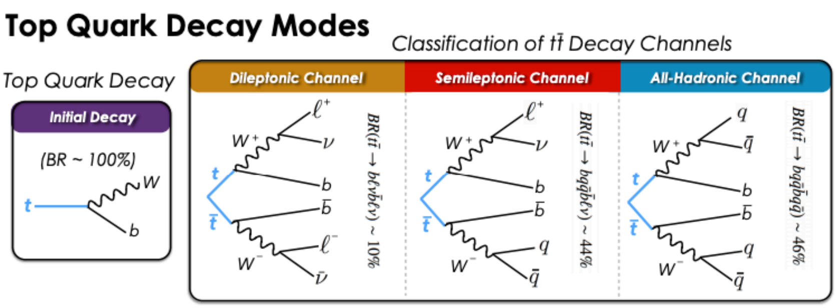


Figure 2.1: The schematic of Top quark decay channels.[7]

## 2.2 Machine Learning and its application on Particle Physics

Machine Learning has been applied to most of the region in recent age, so dose particle physics. From the search of higgs boson(neural network and BDT) to the b-tagging technology(BDT[8]), physicist already applied several kinds of machine learning method to recent researchs.

In a nut shell, machine learning can break into several cases, it can help to do classification, regression, and the clustering problem. It can not only helps to accelate the computation of well-defined problem, and also find a new path to unsloved area. We wil use a state-of-the-art machine learning technology, anttention mechanism. Attention mechanism is a technology base on the evolution of RNN.[9] The attention mechanism will not only consider local relationship and the sequence neighbor, but also calculate the global relation base on the self-attention calculation shown in Figure 2.2. Using this novel architecture, we will train on the relationship between each jet and try to figure out the correct pair information.

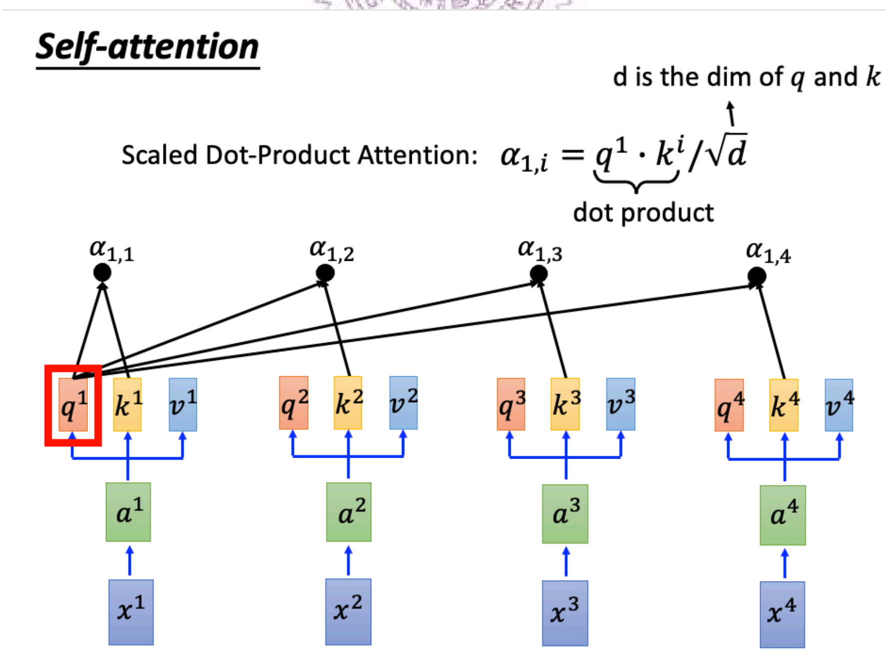


Figure 2.2: How self-attention works.[10]

# Chapter 3

# Event Generation

## 3.1 MC samples

For data preparation, we generate out dataset using a custom docker image with MadGraph_aMC@NLO(v2.7.2), Pythia8(v.8.2), and Delphes(v3.4.2) for showering, hadronization, and detector simulation. We apply the ATLAS parametrization during detector simulation. The data are generated at Leading order, including quantum chromodynamics(QCD). The top mass is configured as $m_{top} = 173\ GeV$. We force the W quark decay hadronically into a $(q, q')$ pair. Following is our configuration:

```
generate p p > t t~ QED=0, (t > W+ b, W+ > j j), (t~ > w- b~, w- > j j )
output <file_path>
launch <file_path>
shower=Pythia8
detector=Delphes
analysis=OFF
done
set nevents = 10000
set iseed = 1
Delphes/cards/delphes_card_ATLAS.tcl
done
exit
```

Listing 3.1: Configuration for generating samples

To get a more general performance, we scan the iseed value from 1 to 30000, each value has aroud 100 file with 10 thousand events before event selection. The reason for scanning iseed value is that the iseed value is the key to the random generation. Originally, the program will choose the iseed value randomly and generate different samples. By scanning the issed value, we can check whether the network can works well on differnet iseed number or not.

# Chapter 4

# Data analysis and Event reconstruction

## 4.1 Data analysis

### 4.1.1 Event selection

The top all hadronic decay channel has 2 b-jets and 4 quark jets, all of them in our configuration is not in boosted region. Follow the event selection used in the reference[7], we apply a event selection that an event should at least exists **2 b-jets** and **4 quark jets** satisfied $p_T$ larger than **25 GeV** and $|\eta|$ less than **2.5**. A cutflow table and figure can help us to understand how much events are killed by the selections. We may apply 5 cuts and see the evolution of survived event numbers. The rule of cuts is shown in Table 4.1, and the cutglow is shown in Figure 4.1. As the result, we found around 1820% events will survived after the event selection.

Table 4.1: Rule of cuts. All the cuts require a kinematic limitation that $p_T > 25$ GeV and $|\eta| < 2.5$.

| #Cut | Number of b-jets | Number of quark jets |
|---|---|---|
| C1 | 0 | 4 |
| C2 | 0 | 5 |
| C3 | 0 | 6 |
| C4 | 1 | 6 |
| C5 | 2 | 6 |

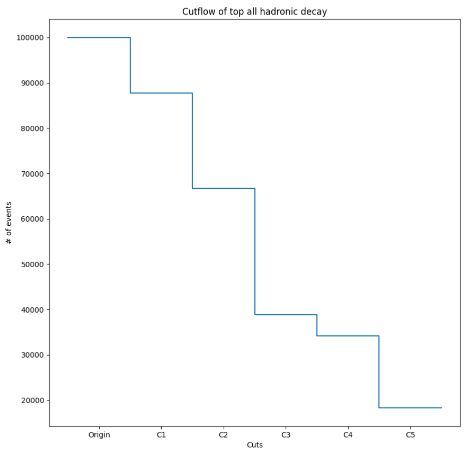


Figure 4.1: Cutflow of all hadronic top decay.

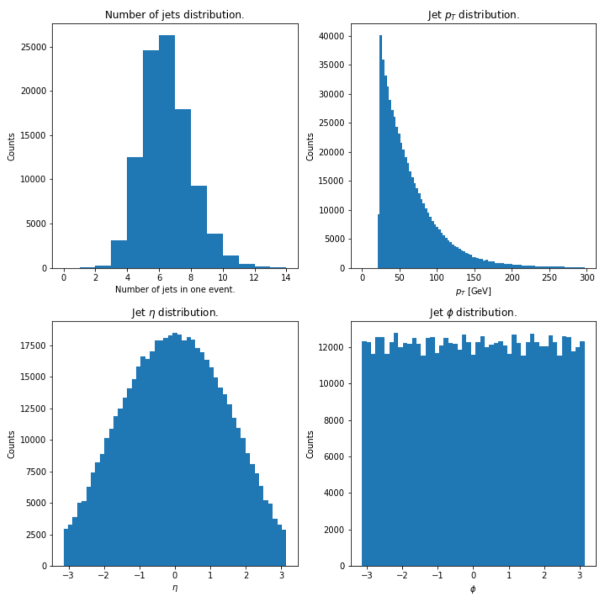


Figure 4.2: Demonstration of distributions.

### 4.1.2 Truth matching

The **truth matching**, which is also called **ΔR matching**, is to match the detector simulation(i.e. jet information generate by Delphes) data to truth record(i.e. parton level information). To calculate the $\Delta R$ value, we will find the daughters of top quarks, W boson and b quark. After the daughters of top quarks is found, we will find the daughters of W bosons. Finally, we will get six partons which are comes from the decay of top quark pairs. This six partons can match to the jets identically by considering their distances. The formula of calculating $\Delta R$ is:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \tag{4.1}$$

By using the kinematic properties provide in parton level and detector simulation information, we can calculate the the $\Delta R$ value between each parton and jets. Using the result of calculation, we may assign each parton to a specific jet.

### 4.1.3 Custom barcode system

To specify the relation between each parton, and the relation between mothers and daughters, we design a barcode system which helps us to declare the relationship.

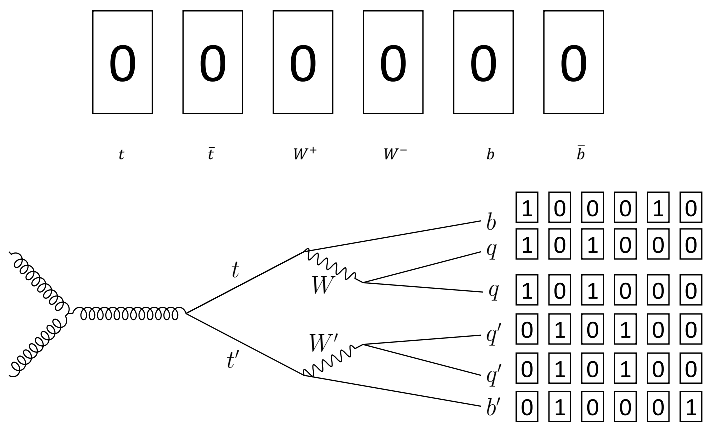


Figure 4.3: Design of barcode.

In Figure 4.3, we define a six-digits barcode, the first two digits is to show which top quark is the mother of this parton, the last four digits of sequece is to declare which daughter of top quark is the mother of parton. In case, we can use this barcode system to break six parton(jet) candidates into two subset which contains 3 elements.

## 4.2 Event reconstruction

### 4.2.1 $\chi^2$ reconstruction

### 4.2.2 Machine Learning Approach

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# Chapter 5

# Discussion

In this chapter, ...

## 5.1 Invariant mass

## 5.2 Reconstruct efficiency

# Chapter 6

# Conclusion

# Bibliography


[1] G. Aad *et al.* [ATLAS], "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," Phys. Lett. B **716**, 1-29 (2012) doi:10.1016/j.physletb.2012.08.020 [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS], "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," Phys. Lett. B **716**, 30-61 (2012) doi:10.1016/j.physletb.2012.08.021 [arXiv:1207.7235 [hep-ex]].

[3] P. A. Zyla *et al.* [Particle Data Group], PTEP **2020**, no.8, 083C01 (2020) doi:10.1093/ptep/ptaa104

[4] A. Quade, "Top quark physics at hadron colliders," Eur. Phys. J., 48, (2008)

[5] A. M. Sirunyan *et al.* [CMS], "Measurement of the top quark mass in the all-jets final state at $\sqrt{s} = 13$ TeV and combination with the lepton+jets channel," Eur. Phys. J. C **79**, no.4, 313 (2019) doi:10.1140/epjc/s10052-019-6788-2 [arXiv:1812.10534 [hep-ex]].

[6] M. Aaboud *et al.* [ATLAS], "Top-quark mass measurement in the all-hadronic $t\bar{t}$ decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector," JHEP **09**, 118 (2017) doi:10.1007/JHEP09(2017)118 [arXiv:1702.07546 [hep-ex]].

[7] T. Mccarthy, "Measurement of the Top Quark Mass in the All-Hadronic Top-Antitop Decay Channel Using Proton-Proton Collision Data from the ATLAS Experiment at a Centre-of-Mass Energy of 8 TeV," CERN-THESIS-2015-275.

[8] M. Paganini [ATLAS], J. Phys. Conf. Ser. **1085**, no.4, 042031 (2018) doi:10.1088/1742-6596/1085/4/042031 [arXiv:1711.08811 [hep-ex]].

[9] A. Vaswani *et al.*, “Attention is all you need,” Advances in Neural Information Processing Systems, NIPS (2017)

[10] Hung-Yi, Lee, “NTU course lecture note-Transformer”