Study of EFT operators in the Top Quark Sector with ATLAS, based on their CP properties

By Maxime BARTHOUX
Supervised by Dr. Romain MADAR

Laboratoire de physique de Clermont
ATLAS team

30th of September, 2024

Overview

- **SM** is the most complete theory we currently have, but it not without **flaws,** that we want to understand
- We will use **EFTs** to investigate potential effects from physics unexplained by the SM
- It allows the incorporation of phenomena expected to arise at a **higher energy scale** than one we currently have access to
- We investigate the **top quark sector**, as its **large mass** serves several purposes for this study
- The distributions of interest are angular distributions, related to **spin correlations**
- The goal is to observe **deviations** from the Standard Model and understand them as much as possible

Standard model & Operators

- **Symmetries** are one of the most important fundamental concepts behind the Standard Model. The Lagrangian allows us to visualize the interactions constrained by those symmetries

$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}(i\gamma^{\mu}D_{\mu})e + (D_{\mu}\phi)^{\dagger}(D^{\mu}\phi) - y_e\bar{L}_L\phi e_R + \mathrm{h.c.}$$

- They dictate the content of the standard model in terms of operators, each being a combination of the field content of the model

- Symmetries can also be seen as transformations. Charge conjugation (C) transforms a particle into its antiparticle, and the Parity (P) flips the sign of spatial coordinates(x --> -x).

Standard model & Operators (2)

- These symmetries can **act** on the field content of the SM with respect to their properties, and therefore on operators
- The operators will be transformed under those symmetries, revealing some properties
- The symmetry of interest in our study is the CP symmetry, combination of the C and P symmetries
  - Some operator are left unchanged under a CP transformation, they are called CP-EVEN operators
  - Some operators present a flipped sign under this transformation, they are called CP-ODD operators
- These are the properties that we want to exploit during this study

Limits of the SM

- The SM is a theory that can't predict its own failure and limits

- But we know that the SM isn't a perfect theory : it works extremely well, but some observations are incompatible
- Some examples : observation of neutrino oscillations, meaning they must possess a mass, or the matter-antimatter asymmetry in the universe

- Therefore, we can treat the standard model as an effective theory, which will break down when the right conditions aren't met. However, it doesn't come with a range of validity in terms of energy scale.

EFTs, SMEFT

- An effective field theory is an **effective** theory, in the sense that it describes physics at a **certain energy**, or distance, and breaks down when not in such range.

- The operators of the standard model are constrained by the symmetries, but also by their dimension in terms of power of an energy, equal to 4.

    - EFTs provides a very good framework to **extend** the SM **systematically** : we consider operators that obey the symmetries, but not the constraint on their dimension

- By adding these **higher-dimensional** operators to the SM, we can observe what the impact of **higher-energies physics** would be on the physics at the energy we can **currently** experiment with.

- It also comes with a **given scale**, the scale of new physics, indicating at which energy level the newly introduced interaction becomes significant, and where the effective theory would start to break down.

Classes of operators with EFTs

- Same as with the SM, the different EFT operators can be of either CP-even or CP-odd class
- The currently observed CP violation in nature can't be explained solely by the SM
  - These observations could be the manifestation of phenomenon happening at a higher energy scale
- Studying EFTs operators might allow us to have access to and understand new sources of CP violation
- Comparing effects between CP-odd and CP-even operators can be a way to investigate these potential new sources

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{C_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

Process studied

- We consider the **top quark pair** production and decay
- There are 3 different channels; leptonic, semi-leptonic and hadronic
  - For the purpose of the study, related to spin correlations, we only consider the leptonic channel
- Moreover, decays containing τ leptons are excluded, as they are unstable

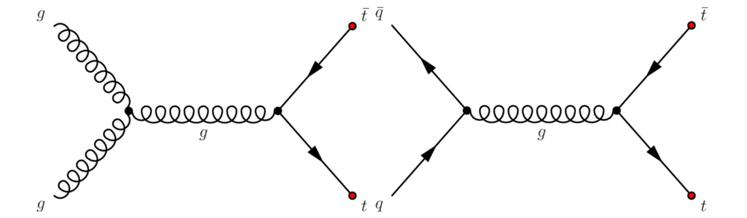
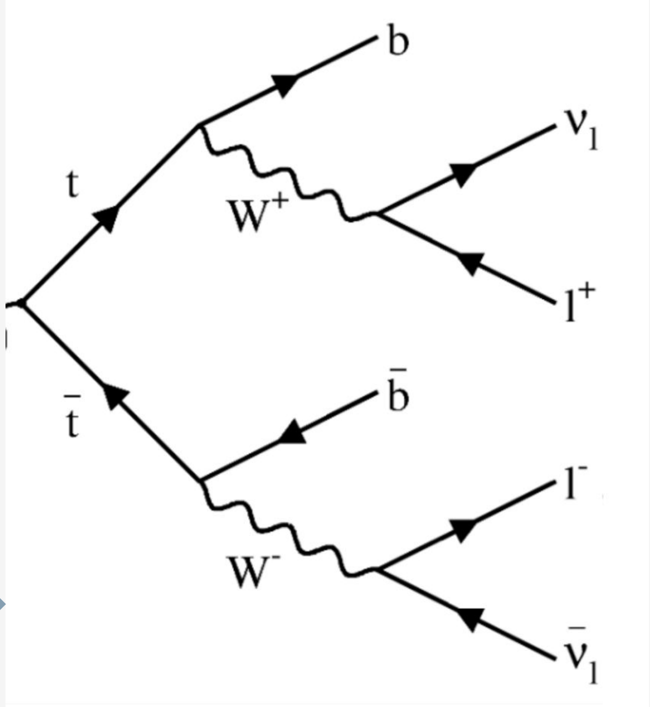


Figure 1: Feynman diagrams for top quark pair production: (left) Gluon-gluon fusion, (right) Quark-antiquark annihilation.

Production modes of the top quark pair



Decay Channel considered

Operators considered

- We will now consider the new operators to add to the standard model that are expected to modify the vertices of the diagram

- The two operators considered are called CTG and CTW, modifying the coupling of the top to the gluon (blue) and of the top to the W boson (green) respectively

- Each operator comes with a real and imaginary part, the two real parts form two CP-even operators, and the two imaginary parts form two CP-odd operators.

- In total, we will have 4 real parameters to investigate for the study

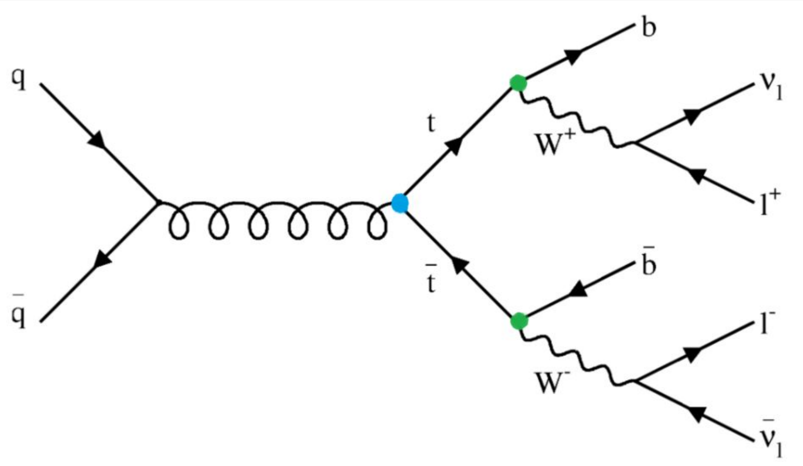


Figure 5: Feynman diagram illustrating where the coefficients C_{TG} (in blue) and C_{TW} (in green) can intervene in the top quark pair production and decay process.

Spin correlations

- The central concept of the analysis is **spin correlations**
- When produced in pairs, particles exhibit correlations of their spin
- The top quark, with its extremely **short lifetime**, decays before hadronization, therefore **conserving** the spin correlations in the decay products
- Spin correlations are also the reason for choosing the leptonic decay channel : it can be computed that the leptons are the **most correlated decay products** with respect to the top spin axis.

Theoretical challenge of spin correlations

- The spin correlations that can be recovered in the final state depend on a choice of basis

$$C_{\mathrm{t\bar{t}}} = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

- We must maximize or minimize the following ratio to maximize the correlation coefficient

$$R = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow)}{\sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

- Spin up or down are a projection of the total spin of the top on a given axis. The different cross section depends on the choice of basis, that will give us axis to project the spin

- The optimal basis will also depend on the kinematics and the production process of the top pairs

Choice of basis

- The basis chosen is composed of 3 vectors that we name **n**, **r** and **k**
- Once a basis is chosen, we can build the observables

$$\cos\theta_+^a = \ell_+ \cdot \hat{a}, \quad \cos\theta_-^b = \ell_- \cdot \hat{b}$$

- Leptons direction of flight in the top and antitop reference frame. a and b are the chosen axis for projection, independent for each lepton

.

	$\hat{\mathbf{a}}$	$\hat{\mathbf{b}}$
n	$\text{sign}(y_p)\,\hat{\mathbf{n}}_\mathbf{p}$	$-\text{sign}(y_p)\,\hat{\mathbf{n}}_\mathbf{p}$
r	$\text{sign}(y_p)\,\hat{\mathbf{r}}_\mathbf{p}$	$-\text{sign}(y_p)\,\hat{\mathbf{r}}_\mathbf{p}$
k	$\hat{\mathbf{k}}$	$-\hat{\mathbf{k}}$

Table 1: Definition of $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$ based on the choice of axis.

- These two cosines are the angular quantities that we use for building the final observables

Observables

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a\, d\cos\theta_-^b} = \frac{1}{4}\left(1 + B_1^a\cos\theta_+^a + B_2^b\cos\theta_-^b - C^{ab}\cos\theta_+^a\cos\theta_-^b\right)$$

The differential cross section for our process

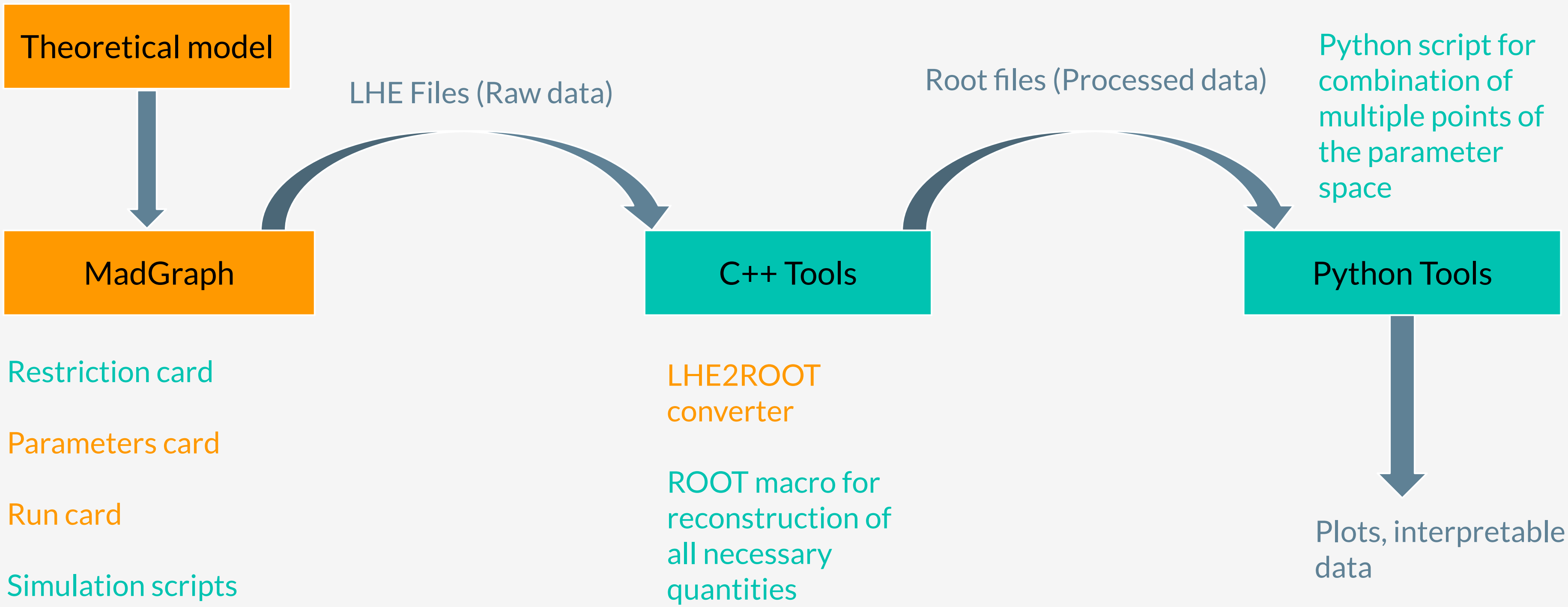
- B are the polarization coefficients and C are the correlation coefficients, the coefficients that we aim to study
  - There are 6 polarization coefficients, and 9 correlation coefficients
- The distributions of the coefficients of interest can be obtained directly through the distributions of the cosines

Classification of the observables

- We end up with **15** independent **observables**
- For each observable, we can compute its **sensitivity** to EFT operators, with respect to the **class** of operator.
    - In their bare form, most coefficients present sensitivities to both CP-even and CP-odd operators
    - By combining them in an appropriate way, we can build 15 independent coefficients, each one sensitive to only **CP-even** or **CP-odd** operators
- The diagonal coefficient C^{nn}, C^{rr}, C^{kk} are all CP-Even originally. They are the only coefficients that we keep in bare form
- For example, C^{rk} and C^{kr} becomes $C^{rk} + C^{kr}$ and $C^{rk} - C^{kr}$, with a CP-even and CP-odd sensitivity respectively
    - A similar procedure applied to all coefficients provides us with the final observables

What I use | What I create/modify

Workflow



Methodology

- We want to assess the effects of the newly introduced operators on our observables

- We use Madgraph simulations with a SMEFT model:

    - 1 000 000 events samples
    - 5 samples total : 1 SM sample, 1 sample for each operator
    - Each EFT sample has 1 coupling fixed to one and the rest to 0

- We can directly compare the SM predictions to the prediction of the SMEFT model with just one operator added, not considering any detector level effects.

Methodology (2)

- For every observable considered in the analysis, we produce 4 plots
  - 1 plot for each operator
  - Each plot consists of **two histograms**, 1 for the SM and one for SM+operator, allowing a visual comparison
  - A **ratio plot** is also shown, as it can improve the clarity of any visual effect
  - We use the χ^2 test and the **p-value** associated to measure as accurately as possible the significance of the deviation
- In order to compile all the information obtained, two **heatmaps** were produced
  - The main heatmap is based on the p-value of the χ^2 test, allowing to assess deviations for **all** considered observables and operators on the same plot
  - A Heatmap using the KS-test was also produced, but it simply considered a complementary plot as it doesn't provide information as clearly as the previous one

First observation : $\Delta\phi$

- This is the first distribution that was observed during the study
- It was expected to see a deviation as it depends on spin correlations
- From here, we expect to see effects especially in the top-gluon sector

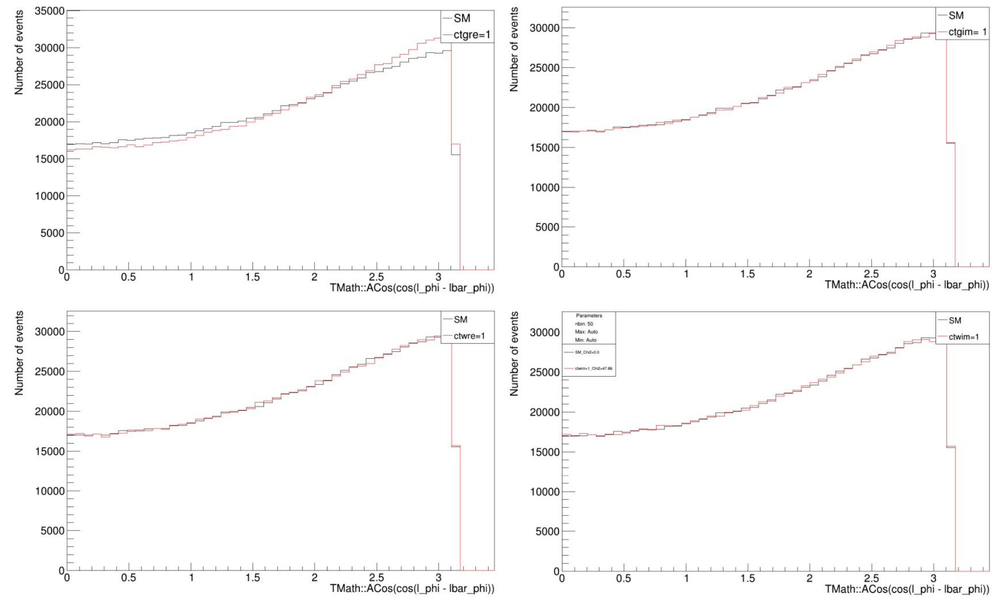
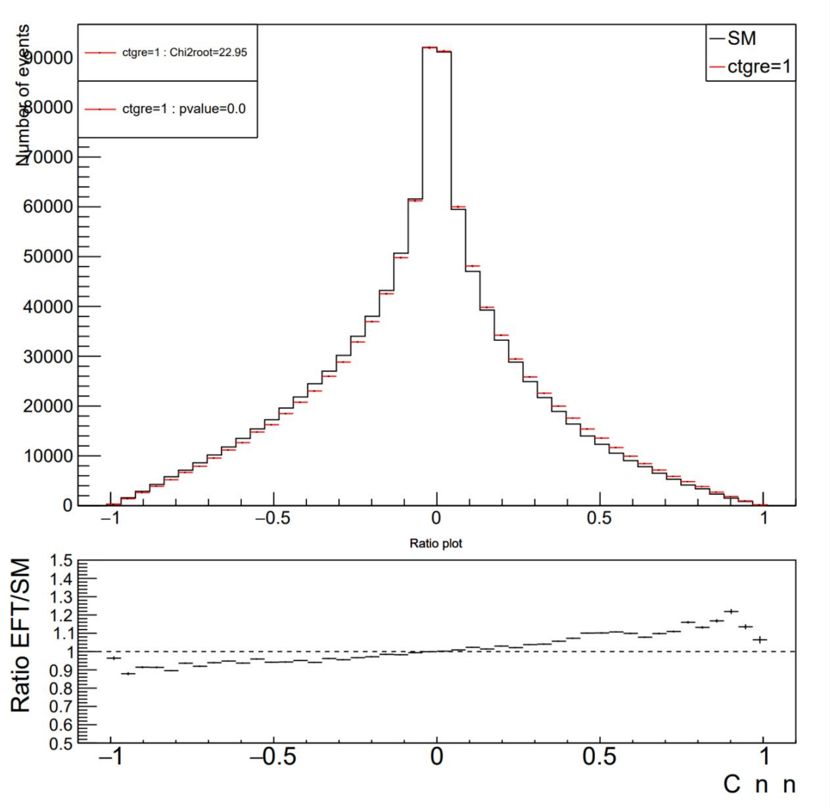


Figure 10: Distribution of $\Delta\phi$ for each operator. Top left: CTGRE, top right: CTGIM, bottom left: CTWRE, bottom right: CTWIM.

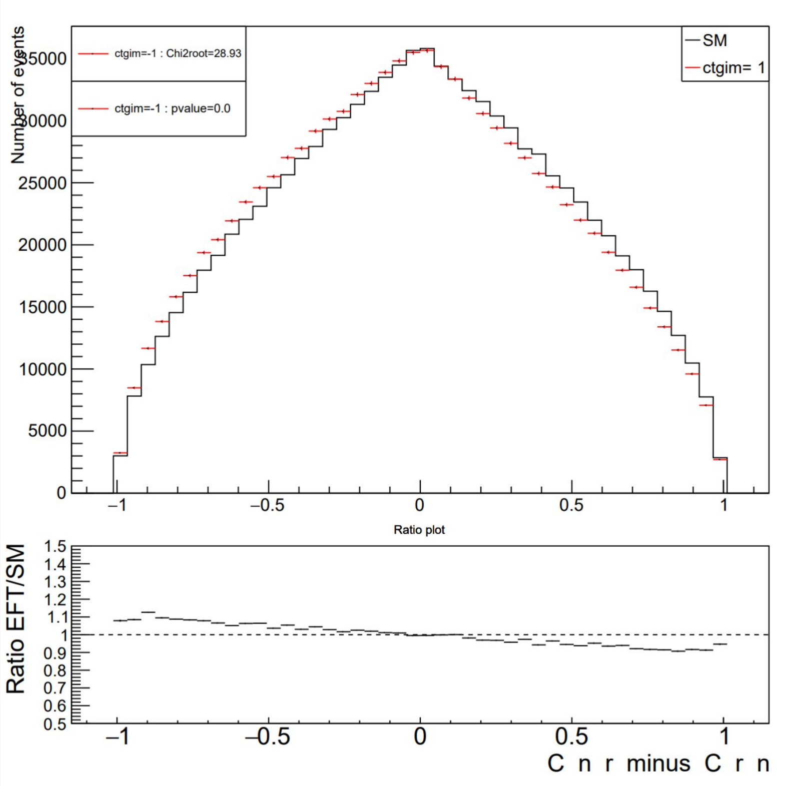
C^{nn}, CTGre

- We can see a clear deviation
- Even clearer in the ratio plot
- The p-value, rounded, is equal to 0
- Cnn is CP-even sensitive, CTGre is CP-even
- That plot meets our expectation



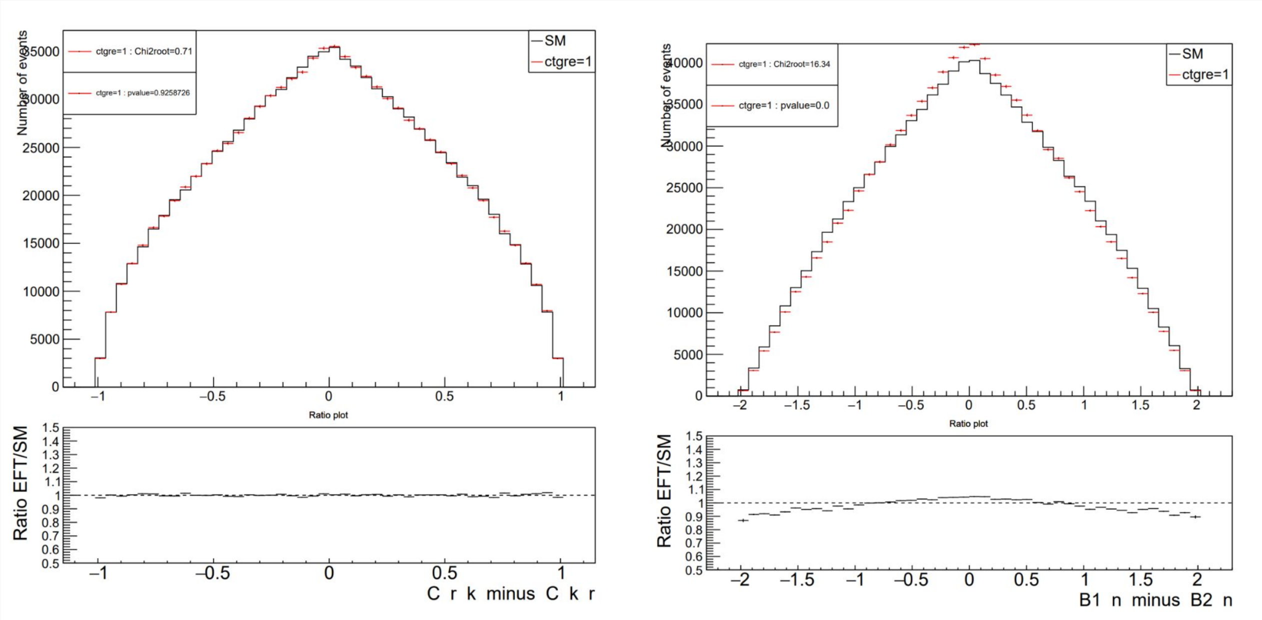
C^{nr} - C^{rn}, CTGim

- We can see a clear deviation
- Even clearer in the ratio plot
- The p-value, rounded, is equal to 0
- C^{nr} - C^{rn} is CP-odd sensitive, CTGre is CP-odd
- This is also a plot that meets our expectation, and confirms what was discussed



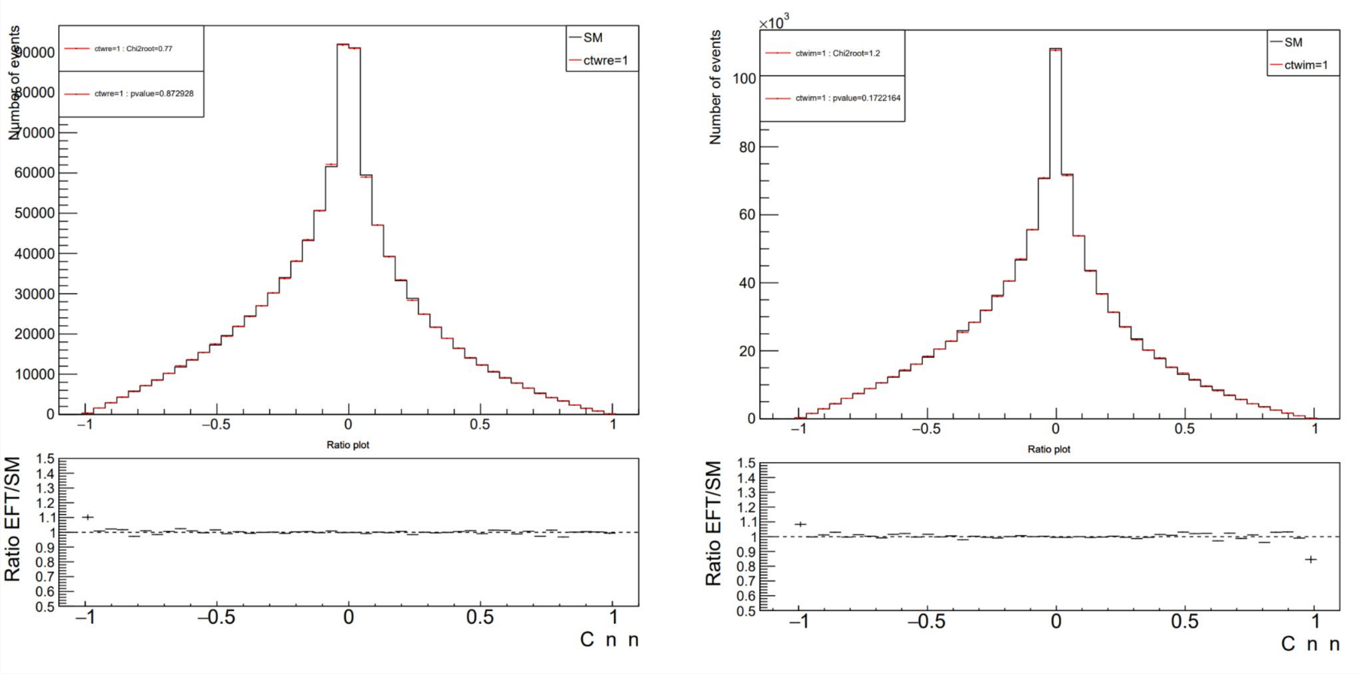
$C^{rk} - C^{kr}$, $B_1^n - B_2^n$, **CTGre**

- Left plot : CP-odd sensitivity, no deviation captured, visually or with the p-value
- Right plot : Also CP-odd sensitivity, however, a deviation is captured, which shouldn't be the case
    - This must be investigated

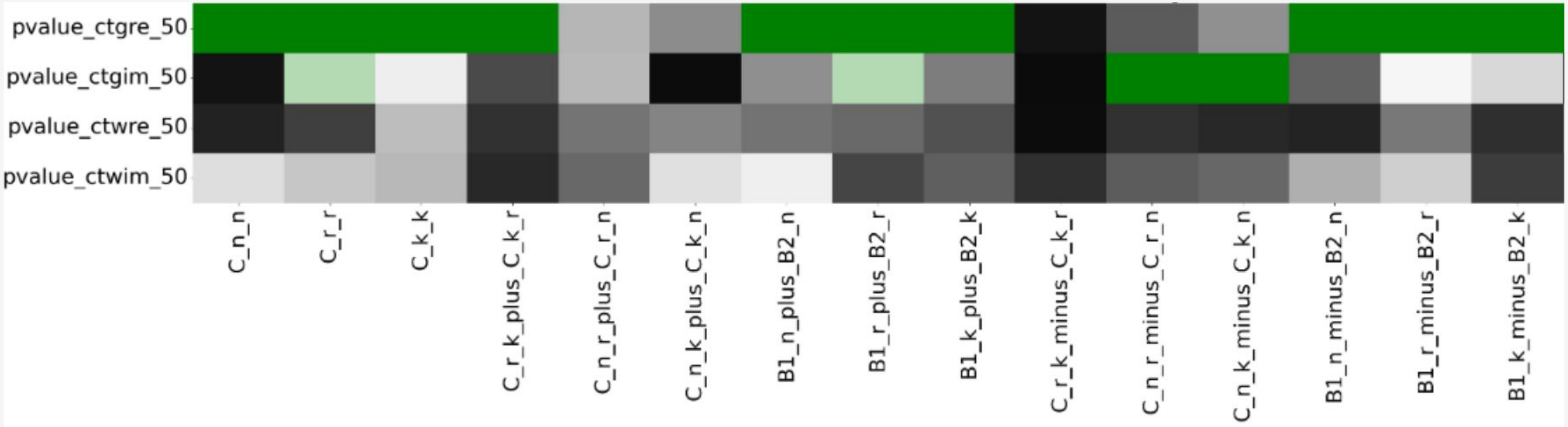


C^{nn}, CTWre & CTWim

- These two operators show a negligible impact on the distributions
- This is also an issue that should be investigated



Heatmap



- Each line corresponds to an operator, each column corresponds to an observable
- Each tile contain the information on the p-value obtained by comparing SM+operator with SM
- The colormap ranges from black to white for $1 < p < 0.05$, and from white to green for $0.05 < p < 0$, any green shade indicating $p < 0.05$, which is the threshold picked for a significant enough deviation, as standardly done.

Review of initial goals

- Originally, the internship was supposed to go far beyond this analysis
    - What was conducted was the first step, more of a “preliminary analysis”
    - The second step was to perform such analysis with samples **combining operators**
    - The end goal was to use machine learning to **build a model** that, given data, and assuming SMEFT, could **provide information** on the nature of the unknown EFT operators at play
- However, advancing one step requires the previous one to be done very **thoroughly**
    - The **understanding** of the effects of the **individual operators** achieved through this study are from sufficient, and many problems remain to be solved
    - Before considering combining, or adding new operators, we must **understand exactly** how they impact our **observables**

Conclusions

- The conducted analysis allowed us to **observe** the effects of **new operators** on **spin correlations**
  - It provided us with hints regarding how such effects would happen
  - A good part of the analysis was also spent on **studying the kinematics** of the process, and its **evolution** with new operators
  - This part provides a **foundation** for refining the analysis, however many **problems** also need **to be solved** in order to draw any conclusion
- However, the current achievements ask more questions than they answer:
  - Why are some observables not behaving as they should ?
  - Can we be sure the CTW operators really don't affect spin correlations ? If so, why is that the case ?
  - How would such effect evolve when combining operators ? When varying the coupling associated with the operators ?

Prospects

- Further work is necessary to reach better and more thorough conclusions
  - Use the kinematics to refine the analysis
  - Use different techniques to understand the incoherences that have appeared
  - Explain observed behavior of the distributions
- These new results and understanding would then become the foundation for proceeding to the next step

Thank you for your attention !

Special thanks to my supervisor Dr. Romain MADAR, as well as the ATLAS team of the laboratoire de Physique de Clermont for making this internship possible

I would also like to thank all the professors and the universities involved in this master's degree, that has been an amazing experience

Methodology (2)

- All the information from the simulations are extracted and placed in a ROOT file

- From there, a processing tool was developed, tailored to this study, such that it would construct all the necessary observables and provide a clean ROOT file for the analysis

- The final part of the work was to prepare python programs to process all the data, incorporate statistical methods, providing plots that can be read and interpreted