Measurement of $t\bar{t}$ spin correlation using Run 2 and Run 3 data with the ATLAS detector

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Among the known elementary particles of the Standard Model[1] (SM), the top quark occupies a particularly important role. As the heaviest known quark, it couples strongly to the Higgs sector and is therefore highly sensitive to possible new physics effects.

Unlike lighter quarks, the top quark decays before hadronization can occur, preserving quantum information that would otherwise be lost by strong-interaction effects. This unique property makes top-antitop ($t\bar{t}$) pairs an ideal probe for studying not only spin correlations, but also fundamental quantum effects such as entanglement in a relativistic quantum system at the highest possible energies, and possible deviations from Standard Model predictions.

The central tool of this project is the Spin Density Matrix (SDM), the complete quantum-mechanical description of the spin state of a $t\bar{t}$ pair. By extracting its coefficients from the angular distributions of the top-quark decay products recorded by ATLAS, using the full Run 2 (2015-2018) and Run 3 (2022-2026) datasets at the highest collision energies ever achieved, it becomes possible to probe the quantum structure of the interaction with unprecedented precision. This goes beyond simply testing whether spin correlations agree with Standard Model predictions.

The Spin Density Matrix framework

This project is focused on the measurement of spin correlations in top quarks, achieved by measuring the differential cross section as functions of one dimensional angular distributions at Parton level (i.e. the level of the fundamental quarks, before detector effects smear the picture) to extract the coefficients of the Spin Density Matrix (SDM).

I am focusing on the dilepton decay channel (ee, $\mu\mu$ and $e\mu$ pairs in the final state), which has a small branching ratio[2] but also a very good signal to background ratio, meaning that this decay has a clean signal with products that can be detected well in ATLAS.

In the SM the $t\bar{t}$ pair is unpolarized and has a rich structure of spin correlation. This means that because the tops do not have a preferred spin direction and because we also know that the spin of the top (t) and anti-top ($\bar{t}$) quarks are correlated, they can be

[1]SM: the theoretical framework describing the fundamental particles and their interactions through the electromagnetic, weak, and strong forces, confirmed experimentally with remarkable precision

[2]branching ratio: the probability that a particle decays via a specific pathway.

correlated in many different directions and combinations, as we can also observe in the equation of the Spin Density Matrix,

$$\rho = \frac{1}{4}\left[I_4 + B_i^+ \cos\theta_i^+ + B_j^- \cos\theta_j^- - C_{ij}\cos\theta_i^+ \cos\theta_j^-\right] \tag{1}$$

where ρ is the SDM, B represents the top quark spin polarization, C the 3×3 Correlation Matrix and θ_i (θ_j) is the angle between the lepton ℓ and the i (j) axis of basis used. In practice, this basis is defined by three perpendicular axes anchored to the top quark's direction of motion, defined by the unit vectors $\{\hat{r}, \hat{k}, \hat{n}\}$, with the k-axis being the direction of the top. This basis, called Helicity Basis (Figure 1), is a right handed coordinate system and the other two directions are described as,

$$\hat{r} = \frac{\hat{p} - \cos\phi \hat{k}}{\sin\phi} \; and \; \hat{n} = \hat{r} \times \hat{k}$$

where ϕ is the top quark production angle with respect to the direction of the proton beam $\hat{p}$ in the beam line, with $\cos\phi = \hat{k} \cdot \hat{p}$.

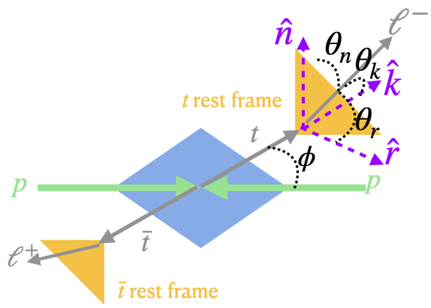

Abbildung 1: Schematic top quark decay in the Helicity Basis

This means that one can parametrize the SDM with 15 parameters, including 6 terms ($\boldsymbol{\cos\theta_i^+}$ and $\boldsymbol{\cos\theta_i^-}$) characterizing the individual spin polarization of each particle, 3 diagonal entries which are basically the probability of finding the $t\bar{t}$ pair in specific spin states ($\boldsymbol{\cos\theta_i^+ \cos\theta_i^-}$) and 6 off-diagonal entries which describe interferences between different spin states ($\boldsymbol{\cos\theta_i^+ \cos\theta_j^- \pm \cos\theta_j^+ \cos\theta_i^-}$).

$t\bar{t}$ Reconstruction in ATLAS

Short-lived particles such as the top quark decay before reaching the detector, therefor they cannot be observed directly. Instead, their properties must be inferred from the measurable decay products recorded in the different detector subsystems of ATLAS.

Since the detector unavoidably smears the measured quantities relative to their true values, the extracted angular distributions must be corrected through a profile likelihood unfolding procedure before the SDM coefficients can be compared to theoretical predictions.