Search for dark matter mediators using spin correlations in single top quark production processes

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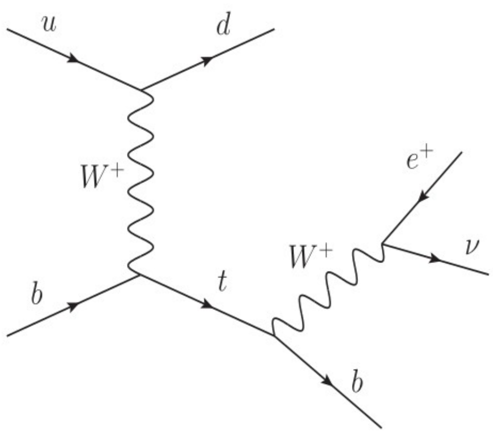
The potential of Single Top quark production processes for searching for Dark Matter

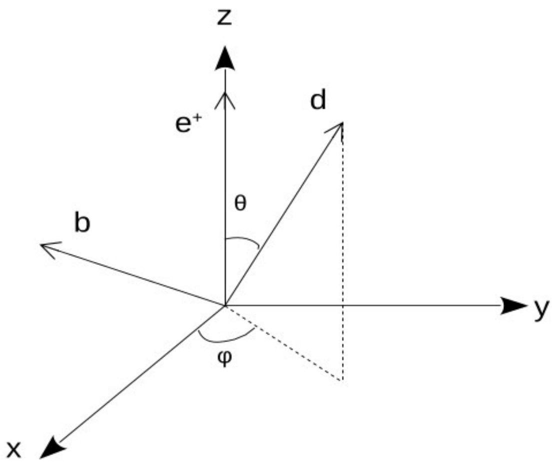
- In popular models of dark matter, the interaction of Standard Model (SM) particles with dark matter particles occurs through the exchange of mediator particles. The parameters of the interaction of scalar mediator particles with SM fermions are proportional to the mass of these fermions. Therefore, the study of processes involving massive third-generation fermions, such as the top quark, is of particular interest.

- In addition, in electroweak processes the top quark can be produced strongly polarized, which is due to the (V-A) structure of the vertices of such interactions. When the top quark decays, its initial polarization is transmitted to its decay products and manifests itself in the energy spectra of the particles from the decay, as well as in the spin correlations between the initial and final states. The participation of the mediator in processes with the top quark can manifest itself in a change in the correlations.

Processes of single top quark production in the SM framework

- In the t-channel process of single top quark production, in its rest frame, the spin direction of the top quark is strongly correlated with the momentum of the d quark.





θ — the angle between the momentum of a charged lepton and the direction of the top quark spin quantization axis (i.e. the momentum of the d quark), a φ — the angle in the plane perpendicular to the lepton momentum, measured from the line of intersection with the plane formed by the decay products of the top quark.

In the rest frame of the top quark, we have the following parameterization of the direction of the quantization axis of the top quark (i.e. the momentum of the d quark) and the 3-momenta of the positron and b quark:

$$\mathbf{s} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta), \qquad \mathbf{p}_{e^+} = |\mathbf{p}_{e^+}| \cdot (0,0,1), \qquad \mathbf{p}_b = |\mathbf{p}_b| \cdot (\sin\theta_{be}, 0, \cos\theta_{be})$$

For the angle φ we obtain an expression that is convenient to use to reconstruct the angle φ in numerical Monte Carlo simulation.

$$\phi = \arccos\left(\frac{\cos\theta_{bd} - \cos\theta_{be}\cdot\cos\theta}{\sin\theta_{be}\cdot\sin\theta}\right)$$

Processes of single top quark production in the SM framework

- In the work [**E. Boos, V. Bunichev, Phys. Rev. D 101, 5, 055012 (2020)**], exact analytical expressions for the triple and double differential cross sections of the complete process of top quark production with subsequent decay ($2 \to 4$) were obtained for the first time.

- Expressions are obtained for the top quark rest frame in the form of functions of the positron energy from the top quark decay and the top quark spin orientation angles.

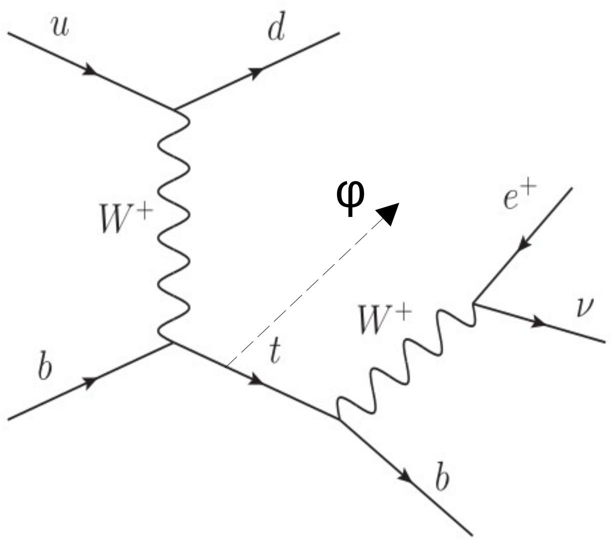
$$\frac{d\sigma_{SM}(\hat{s})_{ub\to db\nu e^+}}{d\epsilon \cdot d\cos\theta \cdot d\phi} = \tag{3}$$

$$\frac{\alpha^2 \cdot V_{ud}^2 \cdot V_{tb}^2}{8 \cdot 3 \cdot \sin^4\Theta_W \cdot m_W^2 \cdot (1-r^2)^2(1+2r^2)} \cdot \frac{(\hat{s}-m_t^2)^2}{\hat{s}(\hat{s}-m_t^2+m_W^2)} \cdot (1-\epsilon)\cdot\epsilon\cdot(1+\cos\theta)$$

где: $\epsilon = 2E_{e^+}/m_t, \quad \epsilon_{max} = 1, \quad \epsilon_{min} = r^2, \quad r = m_W/m_t.$

- Deviations from the corresponding SM distribution profiles in experimental data should indicate the presence of a contribution from new physics.

Associated production of top quark with DM mediators



- In this paper, we considered several most general scenarios involving dark matter particles and their mediators. We assessed the possibility of identifying and determining the properties of mediator particles in processes of single top quark production for the cases of scalar, pseudoscalar, and vector mediators.

- For the mediator mass, we took the current value of the lower boundary of the experimental limit for this particle, equal to **400 GeV**.

- The parameters of the mediator interaction do not play a role in our study, since we are investigating the profiles of normalized distributions

Effective Lagrangians of the interaction of mediators with fermions

The Lagrangian of the interaction of a scalar mediator with SM fermions and DM fermions:

$$\mathcal{L}_{\text{int}}^{\phi} = -\xi \sum_i \frac{m_i}{v} \phi \bar{\psi}_i \psi_i - g_{\text{D}} \phi \bar{\chi} \chi,$$

where ξ is the interaction parameter of the scalar mediator φ with the SM fermions, v=246, GeV is the vacuum expectation value of the SM Higgs field, g_D is the interaction parameter of the scalar mediator φ with the dark matter fermions χ.

The Lagrangian of the interaction of a pseudoscalar mediator with SM fermions and DM fermions:

$$\mathcal{L}_{\text{int}}^{\phi} = -i\xi \sum_i \frac{m_i}{v} \phi \bar{\psi}_i \gamma_5 \psi_i - i g_{\text{D}} \phi \bar{\chi} \gamma_5 \chi,$$

Lagrangian of the interaction of the vector mediator A' with SM fermions and DM fermions:

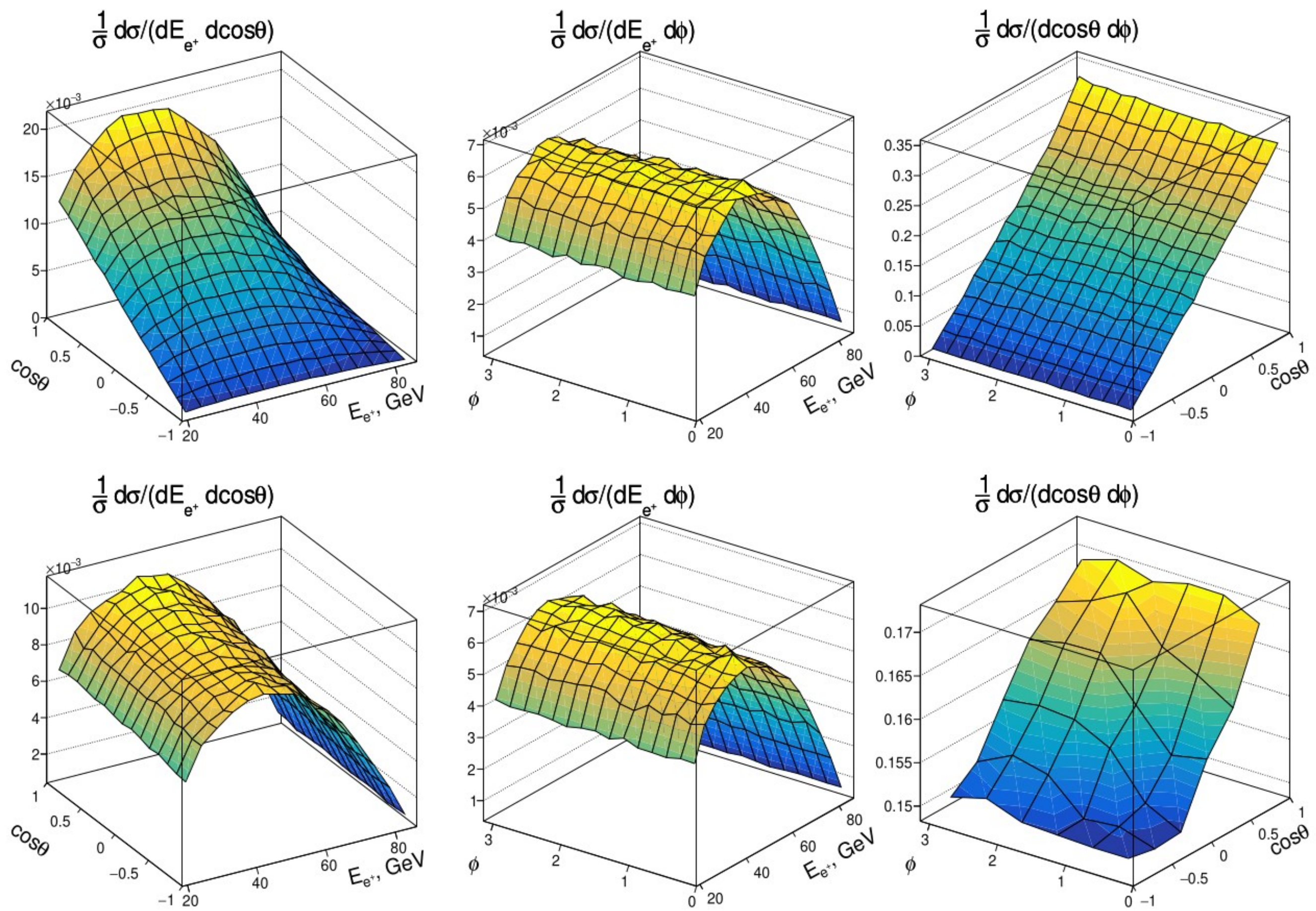
$$\mathcal{L}_{\text{int}}^{A'} = -\varepsilon e A'_{\mu} j^{\mu}_{\text{EM}} - e_{\text{D}} A'_{\mu} j^{\mu}_{\text{DM}}.$$

where εe is the interaction parameter of the vector mediator A' with the electromagnetic current of the SM j_{EM}, e_D is the interaction parameter of the vector mediator A' with the fermions of dark matter χ.

Two-dimensional differential cross sections for a model with a scalar mediator in a cluster system corresponding to the decay products of the top quark.

SM

SM + mediator



As can be seen from the lower left figure, for a given value of the scalar mediator mass, the correlation between d and e+ in the top quark system has disappeared. A contribution proportional to the factor (1 − cosθ) has appeared in the differential cross section, which compensates for the main contribution proportional to the factor (1 + cosθ). Moreover, the relative contribution of these terms depends on the mutual relationship of the mediator mass and the collision energy. Such a violation of the correlation occurred because we deflected the direction of the d quark relative to the cluster into which we perform the boost, separating the mediator component from this cluster.

Selecting a different reference system for constructing multivariate distributions.

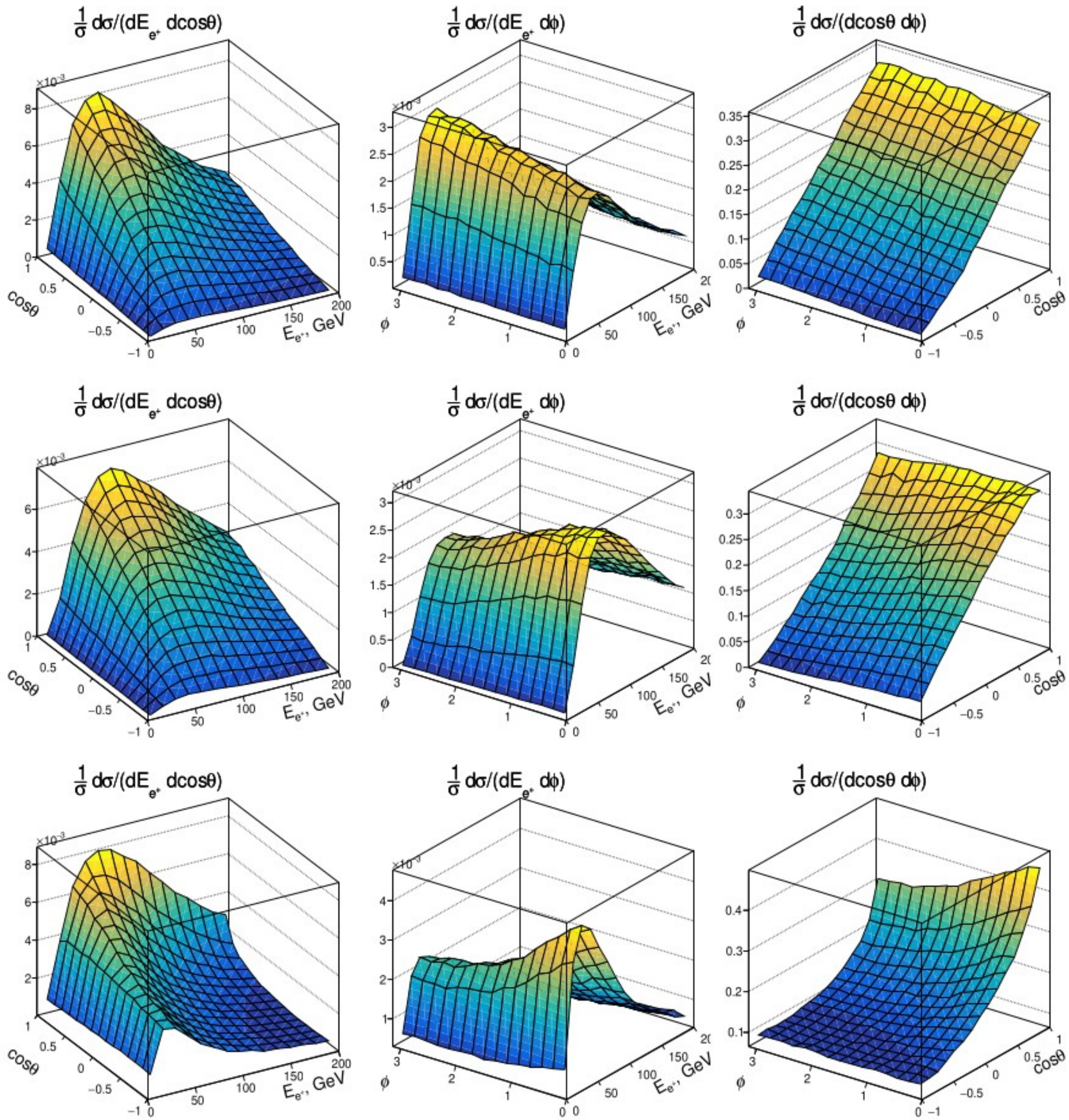
- We have analyzed the two-dimensional distributions in the system of the cluster corresponding to the decay products of the top quark. For this purpose, we have separated the neutrino momentum from the momentum of the cluster of decay products of the mediator.
- However, in practice this task is difficult to implement, since these particles are not registered by the detector and are defined as the total missing four-momentum.
- Taking this circumstance into account, we will further construct distributions in the system of the general cluster corresponding to the decay products of the top quark and the mediator.

Two-dimensional differential cross sections for a model with a scalar mediator in a cluster system corresponding to the decay products of the top quark and the mediator.

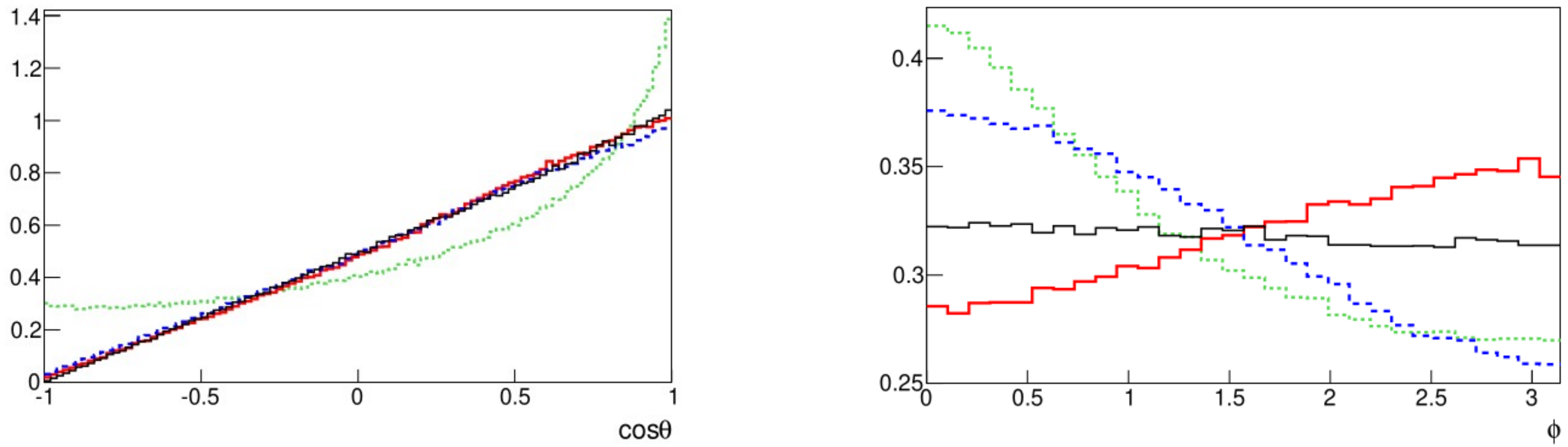
SM + scalar mediator

SM + pseudoscalar mediator

SM + vector mediator



One-dimensional differential cross sections for a model with a scalar mediator in a cluster system corresponding to the decay products of the top quark and the mediator.

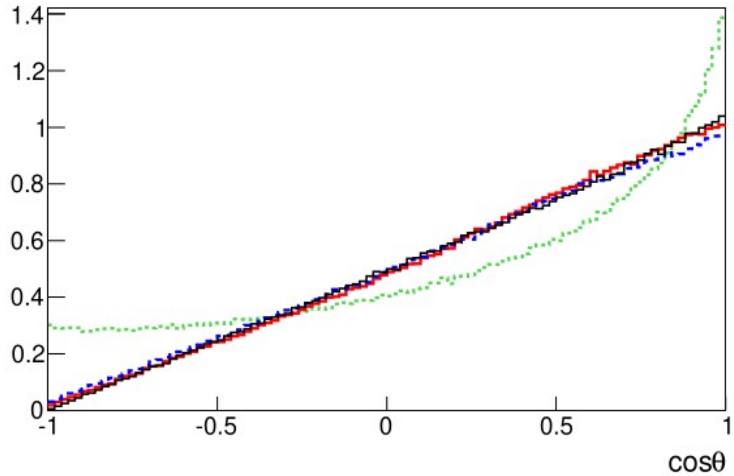


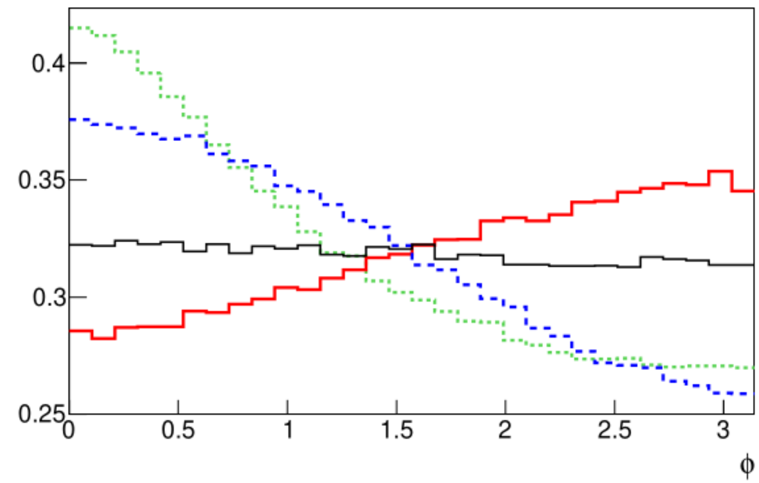
Distributions of cosθ and φ in the cluster system corresponding to the decay products of the top quark and mediator: scalar (red solid line), pseudoscalar (blue dashed line), vector (green dotted line). The SM case is shown by the black solid line.

- In the rest frame of the cluster corresponding to the decay products of the top quark and mediator, for the cases of scalar and pseudoscalar mediators, a direct correlation between the directions of the momenta of the d-quark and positron is preserved. This is explained by the fact that in the chosen frame the momentum of the d-quark preserves its position relative to the cluster containing the decay products of the top quark.

- In this system, the dependence on the angle φ changes, as shown in the right figure. This is due to the fact that the angle φ is measured from the plane containing the momenta of the positron and the b-quark. In the top quark system, the energy of the b-quark has a fixed value, and the energy of the positron is limited by the values $E_{min} = m_W^2 /(2m_t)$ и $E_{max} = m_t/2$. In the new system of the top quark and mediator decay product cluster, the b-quark energy has different values from 0 to $\sqrt{s}/2$. Due to the change in the kinematics of b and e+, the behavior of the angle φ changes, and a dependence on this angle appears in the differential cross section.

One-dimensional differential cross sections for a model with a scalar mediator in a cluster system corresponding to the decay products of the top quark and the mediator.





In the rest frame of the cluster corresponding to the decay products of the top quark and mediator, for the cases of scalar and pseudoscalar mediators, the total matrix element of the production and subsequent decay of the polarized top quark can be factorized and represented as the product of the matrix element of the production of the unpolarized top quark and the matrix element of the decay of the polarized top quark.

SM:

$$|M|^2_{ub\to db\nu e^+} = \Big(\sum_s |M|^2_{ub\to dt}\Big) \cdot D_t \cdot F_0 \cdot (1+\cos\theta_{e^+d})$$

SM + scalar mediator:

$$|M|^2_{ub\to db\nu e^+} = \Big(\sum_s |M|^2_{ub\to dt}\Big) \cdot D_t \cdot \Big(\ F_1 \cdot (1+\cos\theta_{e^+d}) + F_2 \cdot (F_3 + \sin\theta_{e^+d}\cos\phi)\ \Big)$$

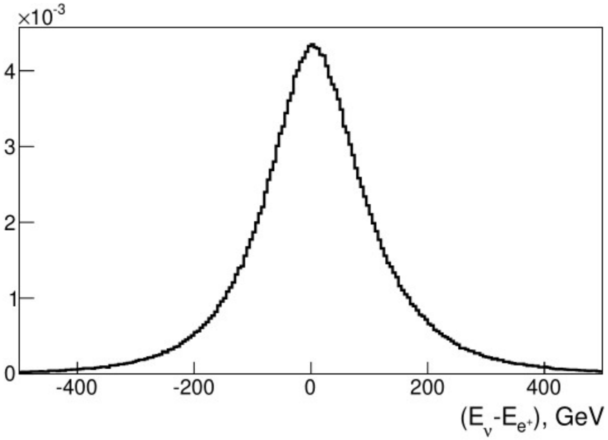
SM + pseudoscalar mediator:

$$|M|^2_{ub\to db\nu e^+} = \Big(\sum_s |M|^2_{ub\to dt}\Big) \cdot D_t \cdot \Big(\ F_1 \cdot (1+\cos\theta_{e^+d}) + F_2 \cdot (F_3 - \sin\theta_{e^+d}\cos\phi)\ \Big)$$

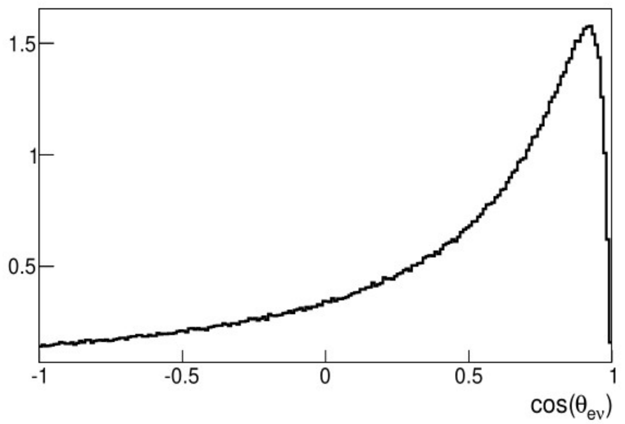
$$D_t = \frac{1}{\left((p_b+p_\nu+p_{e^+}+p_\phi)^2 - m_t^2\right)^2 + \Gamma_t^2 m_t^2}$$

Measuring the mass of the mediator.

- In the rest frame of the cluster corresponding to the decay products of the top quark and the mediator, the top quark and the mediator run in opposite directions. The absolute values of their three-dimensional momenta are equal to each other.
- In this system, in the case of a sufficiently large mass of the mediator, the top quark has a large momentum, part of which it transfers during decay to the W boson, and it transfers it to the positron and neutrino. Thus, in this system, the positron and neutrino run co-directionally in a narrow sector, and their energy values are close to each other, as shown in the distributions:



Distribution of the difference in energy of a neutrino and a positron in the rest frame of a cluster corresponding to the decay products of the top quark and a scalar mediator.



Distribution of the cosine of the angle between the direction of motion of a neutrino and a positron in the rest frame of a cluster corresponding to the decay products of the top quark and a scalar mediator.

Measuring the mass of the mediator.

Thus, in most cases the momenta of the neutrino and positron are similar, and we can replace the momentum of the neutrino with the momentum of the positron in this system. According to the relativistic relation, the mass of the mediator is:

$$M_\phi = \sqrt{E_\phi^2 - \mathbf{p}_\phi^2} = \sqrt{(E_{miss} - E_\nu)^2 - (\mathbf{p}_{miss} - \mathbf{p}_\nu)^2}$$

Replacing the four-momentum of the neutrino with the four-momentum of the positron, we obtain:

$$M_\phi = \sqrt{(E_{miss} - E_{e^+})^2 - (\mathbf{p}_{miss} - \mathbf{p}_{e^+})^2}$$

Since the three-dimensional momentum of the mediator is equal to the total momentum of the decay products of the top quark with the opposite sign, and the momentum of the neutrino is equal to the momentum of the positron, we can write:

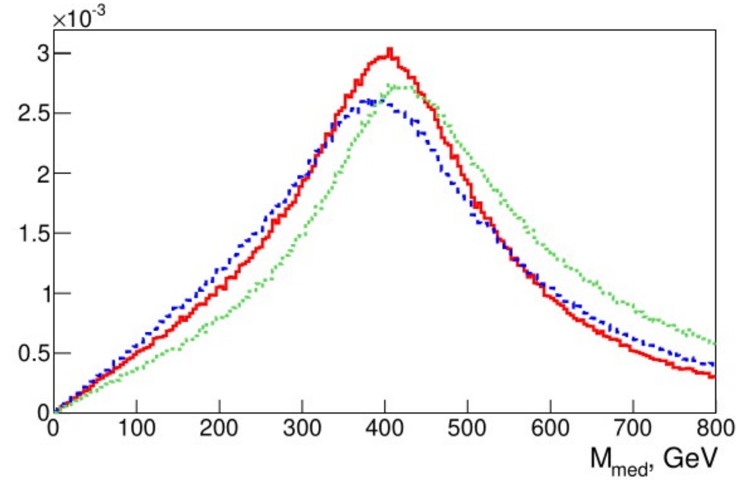
$$M_\phi = \sqrt{(E_{miss} - E_{e^+})^2 - (\mathbf{p}_b + 2\mathbf{p}_{e^+})^2}$$

where E_{miss} is the total missing energy in the rest frame of the cluster corresponding to the decay products of the top quark and mediator.

Measuring the mass of the mediator.

- Using the obtained expression, one can determine the reconstructed mass of the mediator for most of the Monte Carlo events studied. The position of the maximum of this distribution will be the exact value of the mediator mass. The scheme works for cases of a sufficiently heavy mediator, where in the cluster system (W-boson, b-quark, mediator) the W-boson is fast.

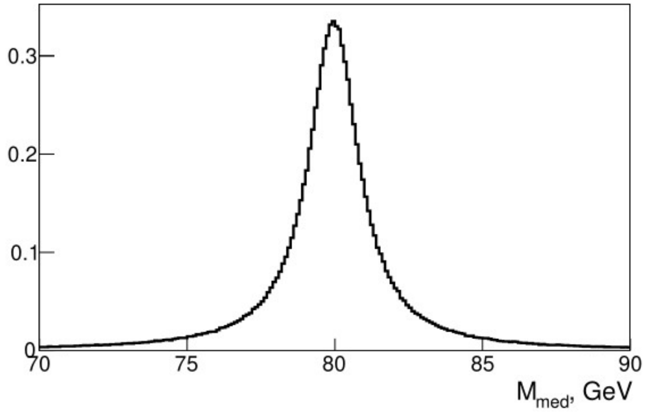
- The distribution profile, in the case of a vector mediator, has shifted slightly to the right. This is due to the fact that the process involving a vector mediator is contributed by diagrams with mediator radiation from the lines of the initial u and b quarks, as well as the final d quarks, violating the kinematics of the main subprocess:



The reconstructed mass of the mediator in the rest frame of the cluster corresponding to the decay products of the top quark and the mediator: scalar (red solid line), pseudoscalar (blue dashed line), vector (green dotted line).

Measuring the mass of the mediator.

If we apply the method to SM samples, we obtain a distribution with a maximum at the W-boson mass value. Such an application does not make sense, since it goes beyond the applicability of the method.



In addition to measuring the mediator mass, the described method can be used to select events involving the mediator and dark matter. If we impose a kinematic cutoff on a new variable corresponding to the reconstructed mediator mass at a value equal to the top quark mass and cut off all events corresponding to smaller values, then we can effectively separate events with new physics from SM events.

Results obtained

- Multidimensional differential production cross sections characterizing spin correlations in the processes of associative production of dark matter and a single top quark at the Large Hadron Collider have been obtained.

- Processes involving scalar, pseudoscalar and vector mediator particles are considered in detail.

- Based on the analysis of multidimensional differential cross-sections, methods for identifying mediator particles, as well as determining their spin and parity, have been developed. It has been shown that the corresponding two-dimensional distributions for different scenarios differ significantly from each other, which allows identifying the type of mediator involved in the process.

- A new method for precise measurement of the mass of the mediator particle in processes of single top quark production is proposed.

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