Search for CP violation in single top quark production processes

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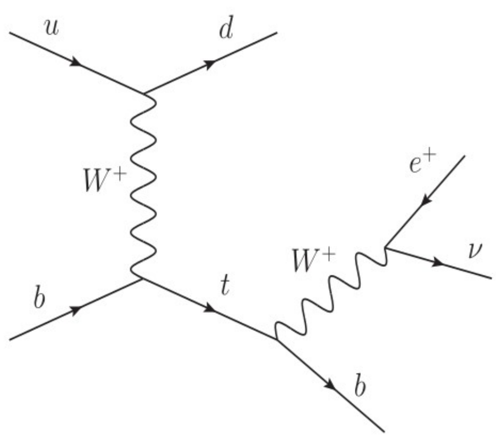
Prospects for Single Top Quark Production Processes for Searching for CP Violation Effects

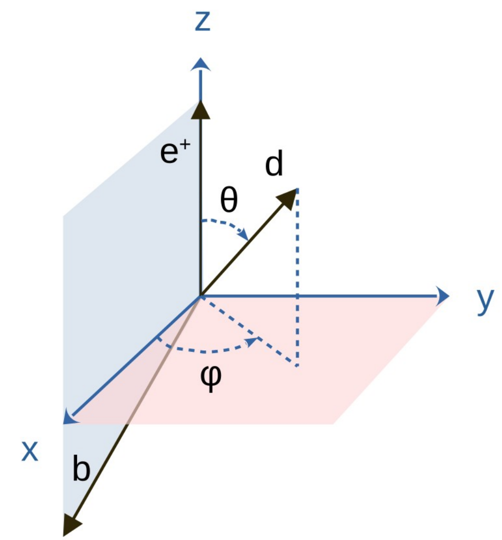
- CP violation is of great interest in particle physics, but its origin is still unclear. A better understanding of this rare phenomenon could lead to modifications to the theoretical model that could explain both the origin of mass and the prevalence of matter over antimatter in the modern Universe. The SM predicts that CP violation effects in top physics are very small. This is primarily because the large mass of the top quark makes the Glashow-Iliopoulos-Maiani (GIM) cancellation particularly effective. Therefore, studying CP violation effects in the top sector is important, since any observation of such effects would be clear evidence for physics beyond the SM.

- In addition, in electroweak processes the top quark can be produced strongly polarized, 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 decay particles, as well as in the spin correlations between the initial and final states. CP violation effects can manifest themselves in changes in the correlations.

Single top quark production processes at the LHC within the SM framework

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





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

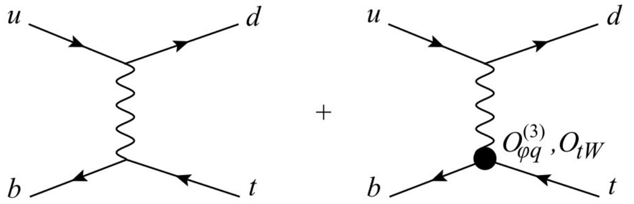
Угол **φ** можно выразить через углы между векторами **b**, **d** и **e⁺** :

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

The effective field theory (SMEFT) approach for parameterizing "new physics"

- To parameterize the "new physics" in the processes under study, the Standard Model Lagrangian can be extended by higher-dimensional operators. These operators are obtained by functional integration over massive modes of hypothetical states that can be produced on energy scales that are currently inaccessible:

$$L_{eff} = L_0 + \frac{1}{\Lambda}L_1 + \frac{1}{\Lambda^2}L_2 + \cdots$$



- **The CP-violating effects at the Wtb vertex can be parameterized using the anomalous right tensor interaction operator $O_{uW}^{(33)}$ with an imaginary Wilson coefficient $\mathrm{Im}C_{uW}^{(33)}$, which gives a linear contribution to the polarized top decay matrix element proportional to the CP-violating triple product $(\mathbf{p}_e \times \mathbf{p}_b)\,\mathbf{p}_d$.**

$$O^{(33)}_{uW} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I t_R)\tilde{\phi}\,W^I_{\mu\nu}$$

let's denote: $\mathbf{f_{RT}} = \sqrt{2}v^2 \cdot \frac{C^{(33)}_{uW}}{\Lambda^2}$

- Additionally, we introduce the operator of anomalous left vector interaction:

$$O^{(3,33)}_{\phi q} = \frac{i}{2}\left[\phi^\dagger\tau^I(D_\mu\phi) - (D_\mu\phi^\dagger)\tau^I\phi\right](\bar{q}_{L3}\gamma^\mu\tau^I q_{L3})$$

let's denote: $\mathbf{f_{LV}} = V_{tb} + v^2 \cdot \frac{C^{(3,33)}_{\phi q}}{\Lambda^2}$

- Modified Lagrangian of the electroweak interaction of the top quark:

$$\mathcal{L} = -\frac{g}{2\sqrt{2}}\bar{b}\gamma^\mu \mathbf{f_{LV}}(1-\gamma_5)tW^-_\mu - \frac{g}{2\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}}{2M_W}\mathbf{f_{RT}}(1+\gamma_5)tW^-_{\mu\nu} + H.c.$$

Estimation of the allowed region of the parameter of the operator $O_{uW}^{(33)}$ taking into account experimental limitations.

- **Optical theorem:** from the unitarity of the S-matrix it follows that the imaginary part of the forward scattering amplitude is proportional to the total cross section of the process:

$$\sigma = \frac{1}{s}\mathrm{Im}\left(A(\theta=0)\right) = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2 \qquad a_0 = \frac{1}{16\pi\lambda}\left|\int_{t_-}^{t_+} dt \cdot A\right| \qquad |\mathrm{Re}(a_0)| < \frac{1}{2}$$

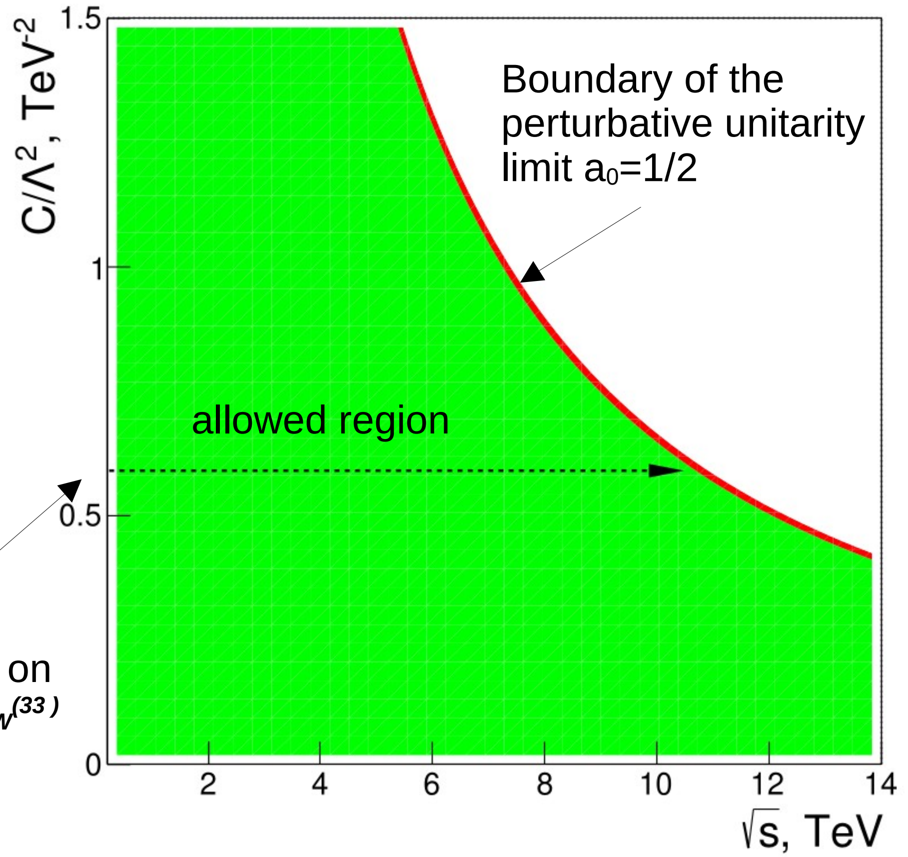
- Leading amplitude of the t-channel process:

$$A = \left(\frac{C_{uW}^{(33)}\, v^2\sqrt{2}}{\Lambda^2}\right)\frac{g^2 V_{ud}}{2M_W}\,\frac{\beta_t\sqrt{stu}}{(t-M_W^2)}$$

- Partial amplitude:

$$a_0 \approx \left(\frac{C_{uW}^{(33)}\, v^2\sqrt{2}}{\Lambda^2}\right)\frac{g^2 V_{ud}}{64\, M_W}\,\beta_t^3\sqrt{s}$$

$$\beta_t = \sqrt{1-\frac{M_t^2}{s}}$$



Experimental constraints on the Wilson coefficient $C_{uW}^{(33)}$

Differential cross section of the complete process of production with subsequent decay of the top quark, with the participation of the operators $O_{\varphi q}^{(3,33)}$ and $O_{uW}^{(33)}$

$$\frac{d\sigma(\hat{s})_{ub\to db\nu e^+}}{d\epsilon \cdot d\cos\theta \cdot d\phi} = -\frac{|\mathbf{f_{RT}}|^2 \cdot \left((1+2r_s^2)\cdot ln(a) - (1+c_1)\cdot c_2\beta^2\right)}{|\mathbf{f_{LV}}|^2 \cdot (1+2r^2) + \mathbf{Ref_{LV}} \cdot \mathbf{Ref_{RT}} \cdot 6r + |\mathbf{f_{RT}}|^2 \cdot (r^2+2)} \times \frac{\alpha^2 \cdot (1-\epsilon)}{12 \cdot \sin^4\Theta_W \cdot m_W^2 \cdot (1-r^2)^2} \times$$

$$\Big[+ |\mathbf{f_{LV}}|^2 \cdot \epsilon \cdot \cos\theta + |\mathbf{f_{RT}}|^2 \cdot \left(\frac{2r\cdot c(\epsilon)}{\epsilon}\cdot \sin\theta\cos\phi + \left(\frac{2r^2}{\epsilon} + \epsilon - r^2 - 1\right)\cdot\cos\theta\right) + \mathbf{Ref_{LV}} \cdot \mathbf{Ref_{RT}} \cdot 2 \cdot (c(\epsilon)\cdot\sin\theta\cos\phi + r\cdot\cos\theta) \Big]$$

$$+ \frac{|\mathbf{f_{LV}}|^2 \cdot c_2\beta^4 + \mathbf{Ref_{LV}} \cdot \mathbf{Ref_{RT}} \cdot 2r_s\sqrt{1-\beta^2}\,(ln(a) - c_2\beta^2) + |\mathbf{f_{RT}}|^2 \cdot \left((1+2r_s^2)\cdot ln(a) - (1+c_1)c_2\beta^2\right)}{|\mathbf{f_{LV}}|^2 \cdot (1+2r^2) + \mathbf{Ref_{LV}} \cdot \mathbf{Ref_{RT}} \cdot 6r + |\mathbf{f_{RT}}|^2 \cdot (r^2+2)} \times$$

$$\times \frac{\alpha^2 \cdot (1-\epsilon)}{24 \cdot \sin^4\Theta_W \cdot m_W^2 \cdot (1-r^2)^2} \times$$

$$\Big[+ |\mathbf{f_{LV}}|^2 \cdot \epsilon \cdot (1+\cos\theta) + |\mathbf{f_{RT}}|^2 \cdot \left(1 + r^2 - \epsilon + \frac{2r\cdot c(\epsilon)}{\epsilon}\cdot\sin\theta\cos\phi + \left(\frac{2r^2}{\epsilon} + \epsilon - r^2 - 1\right)\cdot\cos\theta\right) + \mathbf{Ref_{LV}} \cdot \mathbf{Ref_{RT}} \cdot 2 \cdot (c(\epsilon)\cdot\sin\theta\cos\phi + r\cdot(1+\cos\theta)) - \mathbf{Ref_{LV}} \cdot \mathbf{Imf_{RT}} \cdot 2 \cdot c(\epsilon)\cdot\sin\theta\sin\phi \Big]$$

$c(\epsilon) = \sqrt{(1-\epsilon)(\epsilon - r^2)}$ $\quad \epsilon = 2E_{e^+}/m_t$ $\quad r = m_W/m_t$ $\quad c_1 = \beta^2 + 2r_s^2$ $\quad c_2 = \frac{1}{\beta^2 + r_s^2}$ $\quad a = 1 + \frac{\beta^2}{r_s^2}$ $\quad r_s = \frac{m_W}{\sqrt{\hat{s}}}$ $\quad \beta^2 = 1 - \frac{m_t^2}{\hat{s}}$

Expansion of the differential cross section into a series in terms of the inverse scale of “new physics”.

$$\frac{d\sigma_{ub\to db\nu e^+}}{d\epsilon\cdot d\cos\theta\cdot d\phi} = K_0 + K_1\cdot\frac{\mathbf{ImC_{uW}^{(3,3)}}}{\mathbf{\Lambda^2}} + ...$$

let's denote: $F_1 = \frac{\alpha^2\cdot V_{ud}^2}{8\cdot 3\cdot\sin^4\Theta_W\cdot m_W^2\cdot(1-r^2)^2(1+2r^2)}\cdot\frac{(\hat{s}-m_t^2)^2}{\hat{s}(\hat{s}-m_t^2+m_W^2)}$

$$K_0 = \frac{d\sigma_{SM}(\hat{s})_{ub\to db\nu e^+}}{d\epsilon\cdot d\cos\theta\cdot d\phi} = V_{tb}^2\cdot F_1\cdot(1-\epsilon)\cdot\epsilon\cdot(1+\cos\theta)$$

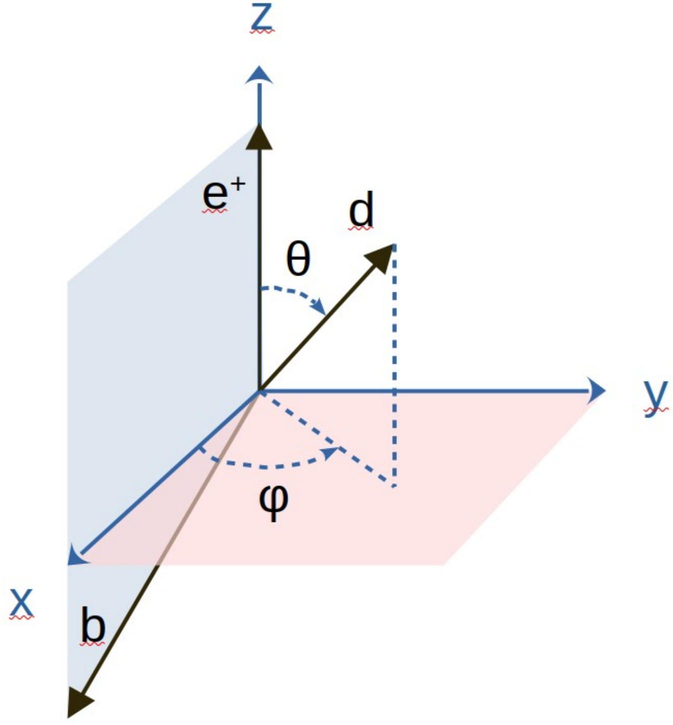
$$K_1 = \frac{d(\sigma-\sigma_{SM})_{ub\to db\nu e^+}}{d\epsilon\cdot d\cos\theta\cdot d\phi} = -2\cdot v^2\cdot V_{tb}\cdot F_1\cdot\sqrt{(1-\epsilon)^3(\epsilon-r^2)}\cdot\sin\theta\sin\phi$$

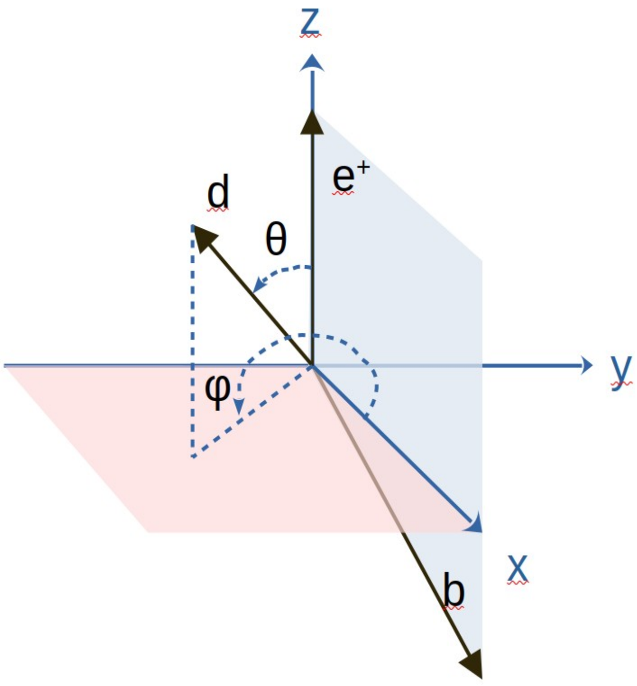
Direction of polarization of the top quark in processes including the operator $\mathrm{ImC}_{uW}^{(33)}$

$$T = (\mathbf{p}_{e^+} \times \mathbf{p}_b) \cdot \mathbf{d}$$

If $T > 0$: $\phi \in (0,\, \pi)$

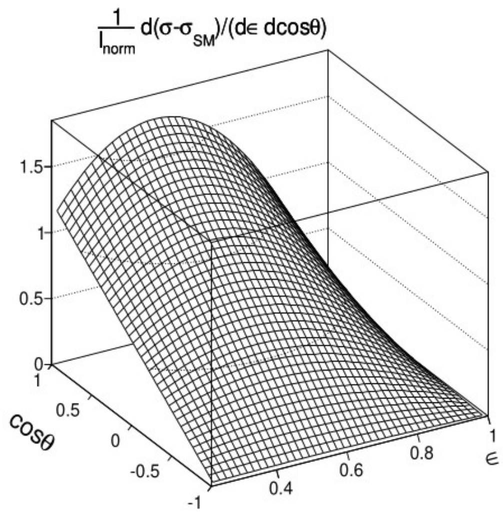
If $T < 0$: $\phi \in (\pi,\, 2\pi)$

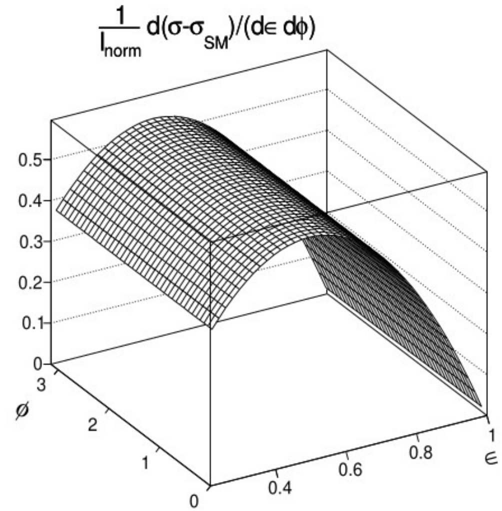


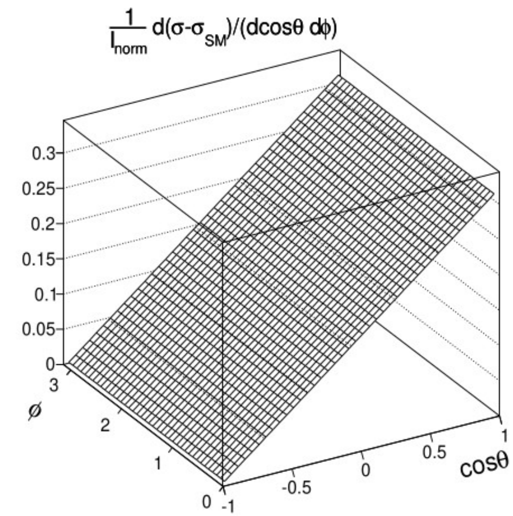


$$\frac{d(\sigma - \sigma_{SM})_{ub \to db\nu e^+}}{d\epsilon \cdot d\cos\theta \cdot d\phi} = -\frac{\mathbf{ImC_{uW}^{(33)}}}{\mathbf{\Lambda^2}} \cdot 2 \cdot v^2 \cdot V_{tb} \cdot F_1 \cdot \sqrt{(1-\epsilon)^3(\epsilon - r^2)} \cdot \sin\theta \sin\phi$$

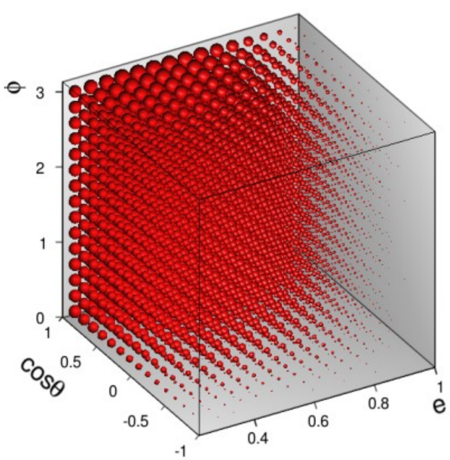
Multidimensional differential cross sections for the complete process of top quark production with subsequent decay (Standard Model)







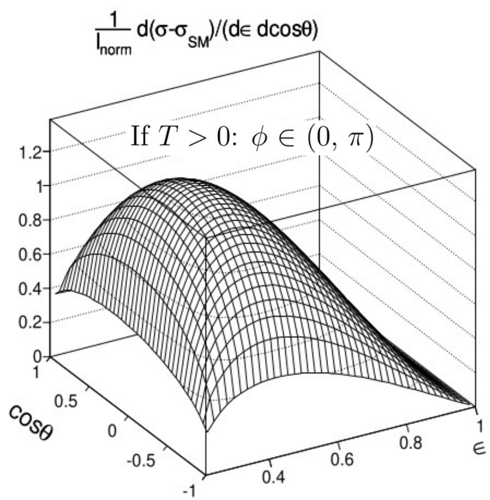
Probability density in 3D space (ε, cosθ, φ)

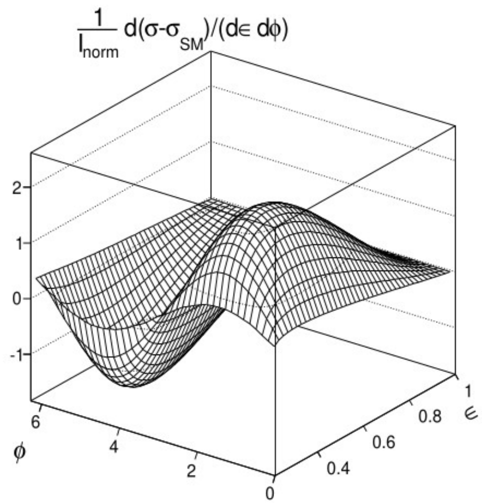


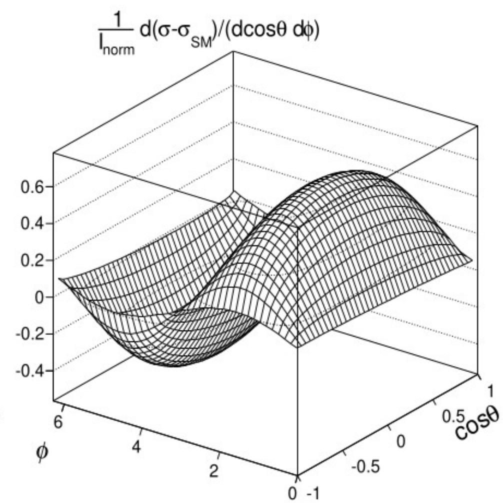
Any deviation from the SM shapes should indicate the contribution of new physics.

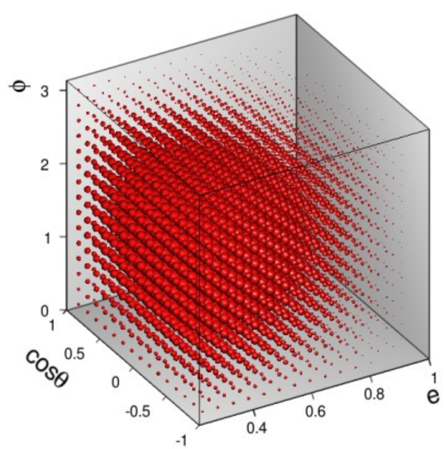
Multidimensional differential cross sections for the complete process of top quark production with subsequent decay (scenario $ImC_{uW}^{(33)}/\Lambda^2 = -0.57$)

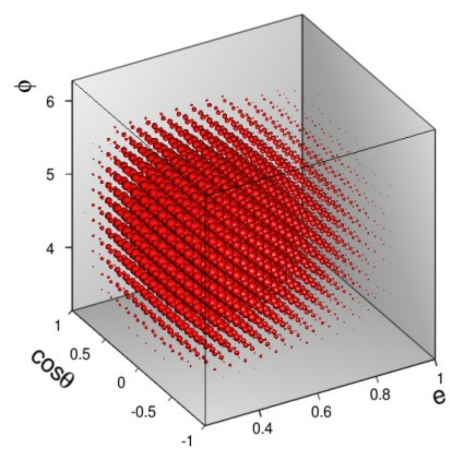
The main difference from the case of real Wilson coefficients is the
— asymmetry of the distributions for intervals of the angle φ: (0,π) and (π,2π)



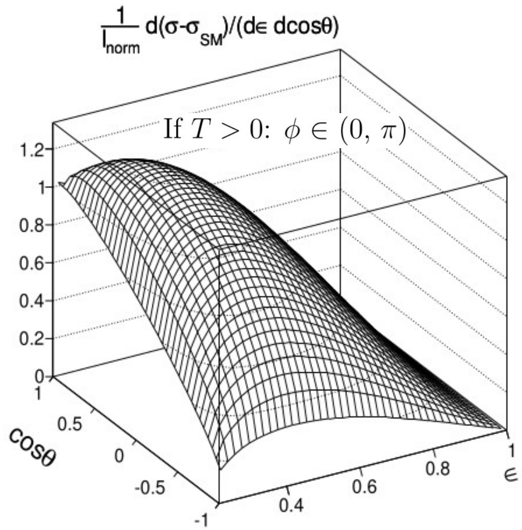


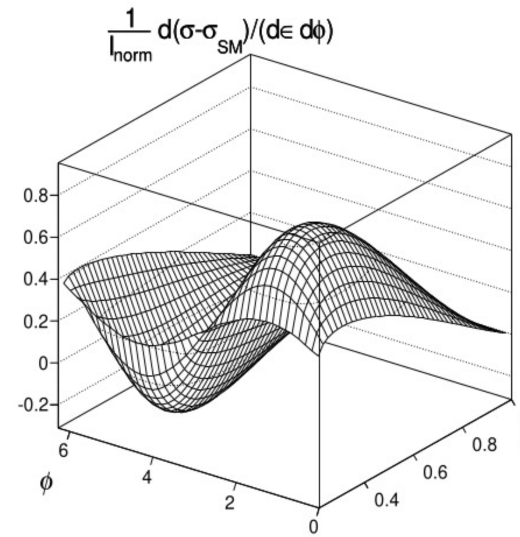


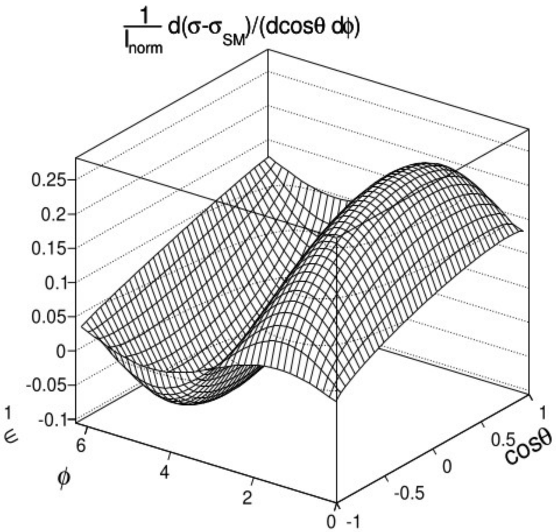


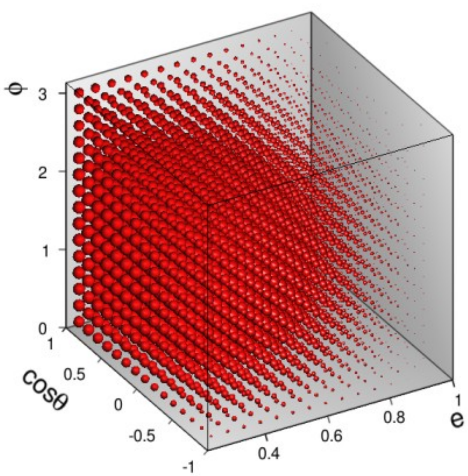


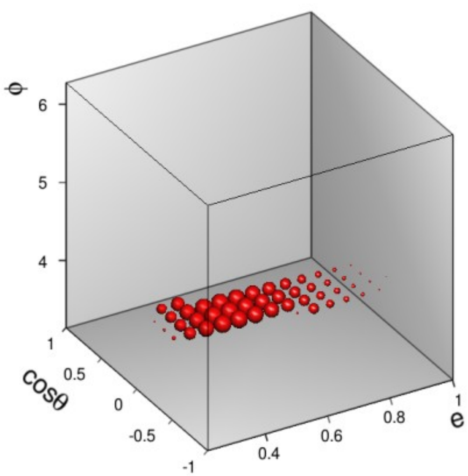
Multidimensional differential cross sections for the complete process of top quark production with subsequent decay (scenario $ReC_{uW}^{(33)}/\Lambda^2 = 0.12$, $ImC_{uW}^{(33)}/\Lambda^2 = -0.57$)











Accuracy of measurement of imaginary interaction parameters

Using the obtained analytical expressions of the triple differential cross-section, the fitting method was used to estimate the accuracy of measuring the imaginary Wilson coefficient of the operator $\mathbf{O_{uW}^{(33)}}$

$L,\ fb^{-1}$	$\delta\ ReC_{\phi q}^{(33)}/\Lambda^2$	$\delta\ ImC_{uW}^{(33)}/\Lambda^2$
30	0.02	0.07
300	0.003	0.01
3000	0.001	0.005

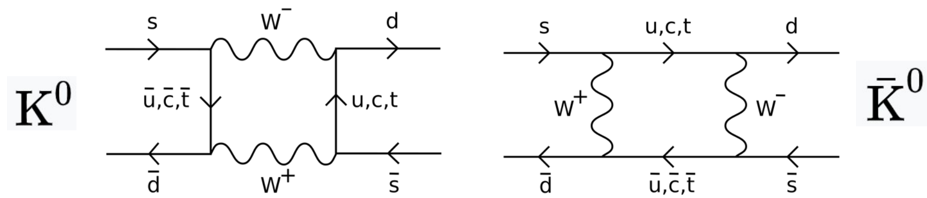
Results obtained:

- Unitary limits for the use of the $\mathbf{O_{uW}^{(33)}}$ operator in processes of single top quark production are determined.
- A triple differential cross section of the complete process of single production with subsequent decay of the top quark is obtained, taking into account the operator $\mathbf{O_{uW}^{(33)}}$ with an imaginary coefficient.
- The obtained differential cross-section was expanded into a series of the inverse scale of “new physics”.
- Several physical scenarios were investigated taking into account the $\mathbf{O_{uW}^{(33)}}$ operator in the processes of single top quark production.
- Using the obtained analytical expressions of the triple differential cross-section, the fitting method was used to estimate the accuracy of measuring the imaginary Wilson coefficient of the operator $\mathbf{O_{uW}^{(33}}$ in processes of single top quark production at modern hadron colliders.

This study was carried out as part of the scientific program of the National Center for Physics and Mathematics, the project “Particle Physics and Cosmology”.

Backup slide 1
CP violation and Glashow-Iliopoulos-Maiani cancellation (GIM):

Transition amplitudes between neutral Kaons:



States with definite CP-parity: **K_1** and **K_2**

$$K_1^0 = \frac{K^0 + \tilde{K}^0}{\sqrt{2}} \qquad K_2^0 = \frac{K^0 - \tilde{K}^0}{\sqrt{2}}$$

Observed states **K_L** and **K_S**:

$$K_{L,S} = K_{2,1} \pm \varepsilon K_{1,2}$$

Difference in masses of states K_L and K_S:

$$\Delta m_{LS} = \frac{G^2 m_c^2 f_K^2 m_K B_K}{6\pi^2}\left[1 + \zeta s_2^2 (s_2^2 + s_3^2 \cos 2\delta + 2 s_2 s_3 \cos\delta) + 2 s_2 (s_2 + s_3 \cos\delta) \ln\zeta\right]$$

$$f_K \approx 165 \text{ МэВ} \qquad \zeta = m_t^2/m_c^2$$

Parameter of mixing K_L and K_S, responsible for CP violation

$$\varepsilon = \frac{\Gamma i \mu_{21}}{\Delta m_{LS} + \frac{i}{2}(\Gamma_S - \Gamma_L)} \approx \frac{e^{i\varphi}}{\sqrt{2}} s_2 s_3 \sin\delta \, \frac{1 + \zeta s_2 (s_3 \cos\delta - s_2) - \ln\zeta}{1 + \zeta s_2^2 (s_2^2 + 2 s_2 s_3 \cos\delta + s_3^2 \cos 2\delta) + 2 s_2 (s_3 + s_2 \cos\delta) \ln\zeta}$$

Parameterization of the CKM matrix:

$$(\bar{u}, \bar{c}, \bar{t}) \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 - e^{i\delta} s_2 s_3 & c_1 c_2 s_3 + e^{i\delta} s_2 c_3 \\ s_1 s_2 & -c_1 s_2 c_3 - e^{i\delta} c_2 s_3 & -c_1 s_2 s_3 + e^{i\delta} c_2 c_3 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Backup slide 2
CP-violating terms of the top decay matrix element:

$$|M_{t\to b\nu e^+}|^2 = \frac{g^4}{(2(p_\nu p_{e^+}) - m_W^2)^2 + \Gamma_W^2 m_W^2} \cdot [$$

$$+ |f_{LV}|^2 \cdot (p_b p_\nu) \cdot (\ (p_{e^+} p_t) - (p_{e^+} s) \cdot m_t\ )$$

$$+ |f_{LT}|^2 \cdot \frac{2}{m_W^2} \cdot (p_b p_{e^+})(p_\nu p_{e^+}) \cdot (\ (p_{e^+} p_t) - (p_{e^+} s) \cdot m_t\ )$$

$$+ |f_{RT}|^2 \cdot \frac{2}{m_W^2} \cdot (p_b p_\nu)(p_\nu p_{e^+}) \cdot (\ (p_\nu p_t) + (p_\nu s) \cdot m_t\ )$$

$$+ |f_{RV}|^2 \cdot (p_b p_{e^+}) \cdot (\ (p_\nu p_t) + (p_\nu s) \cdot m_t\ )$$

$$+ (Ref_{LV} \cdot Ref_{RT} + Imf_{LV} \cdot Imf_{RT}) \cdot \frac{2}{m_W} \cdot (p_b p_\nu) \cdot (\ (p_\nu p_{e^+}) \cdot m_t + (p_\nu s)(p_{e^+} p_t) - (p_\nu p_t)(p_{e^+} s)\ )$$

$$+ (Ref_{LT} \cdot Ref_{RV} + Imf_{LT} \cdot Imf_{RV}) \cdot \frac{2}{m_W} \cdot (p_b p_{e^+}) \cdot (\ (p_\nu p_{e^+}) \cdot m_t + (p_\nu s)(p_{e^+} p_t) - (p_\nu p_t)(p_{e^+} s)\ )$$

$$+ (Ref_{LV} \cdot Imf_{RT} - Imf_{LV} \cdot Ref_{RT}) \cdot \frac{-2}{m_W} \cdot \epsilon_{\alpha\beta\rho\sigma} p_t^\alpha p_b^\beta p_{e^+}^\rho s^\sigma \cdot \left(\frac{m_t^2}{2} - (p_{e^+} p_t) \right)$$

$$+ (Ref_{LT} \cdot Imf_{RV} - Imf_{LT} \cdot Ref_{RV}) \cdot \frac{-2}{m_W} \cdot \epsilon_{\alpha\beta\rho\sigma} p_t^\alpha p_b^\beta p_{e^+}^\rho s^\sigma \cdot \left((p_b p_t) + (p_{e^+} p_t) - \frac{m_t^2}{2} \right) \quad]$$

If we introduce CP-odd φ_f and CP-even δ_f phases, then we can express the right and left interaction parameters at the Wtb vertex as follows:

$$f_1^L = \bar{f}_1^L = 1,$$
$$f_2^R = f e^{i(\phi_f + \delta_f)}, \qquad \bar{f}_2^L = f e^{i(-\phi_f + \delta_f)}$$

In this case, the differential decay widths of the polarized top and anti-top quarks will have the form:

$$d\Gamma(t \to bW^+) \sim f \sin(\delta_f + \phi_f) \epsilon(p_t, p_b, p_{\ell^+}, s_t) + \cdots$$
$$d\Gamma(\bar{t} \to \bar{b}W^-) \sim f \sin(\delta_f - \phi_f) \epsilon(p_{\bar{t}}, p_{\bar{b}}, p_{\ell^-}, s_{\bar{t}}) + \cdots$$