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New physics in spin entanglement

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MD, Alessandro Strumia, Arsenii Titov, [2403.15860]

Measurement of entanglement in top pair

ATLAS and CMS confirmed
pp collisions at 13 TeV produce $\mathrm{t\bar{t}}$ pairs
with an entangled spin structure

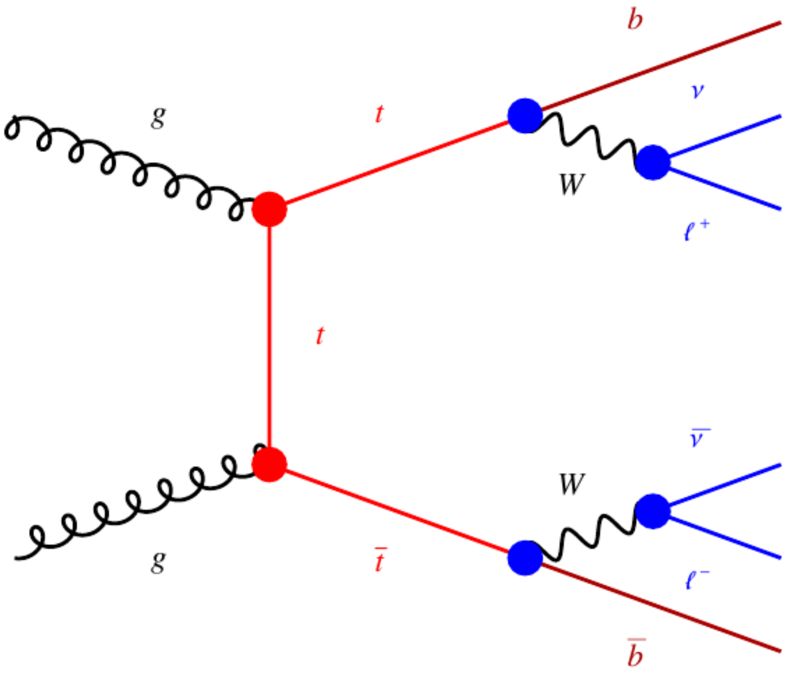
Standard Model prediction:

- dominant production process $\mathrm{gg} \to \mathrm{t\bar{t}}$
- maximally entangled top pair in the non-relativistic limit

$$|t_{\uparrow}\bar{t}_{\downarrow}\rangle - |t_{\downarrow}\bar{t}_{\uparrow}\rangle$$

- Top spin inferred from the angular distribution of leptons

$$t \;\to\; b\bar{\ell}\nu$$



Impact of new physics on entanglement

New physics modifying the processes $gg \to t\bar{t}$ and $t \to b\bar{\ell}\nu$ impacts entanglement observables.

It can be analyzed eg. using effective operators.

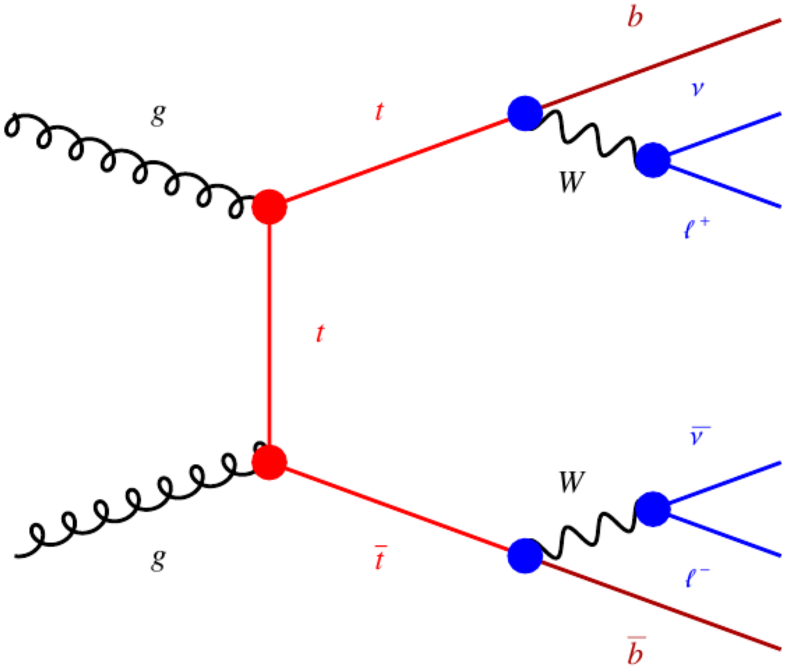
Aoude+, Fabbrichesi+, Severi+ 2022

Generally:

- affects total cross-section
- modifies differential angular and energy distributions

Is there a new physics sensitive first of all to entanglement observables?

- QCD and EW tree-level top production and decay rates left untouched
- modified spin structure
- loops affected often at higher orders



Modifying Dirac spinor field

Non-local transformation of the Dirac field

$$\tilde{\Psi}(x) = W(i\partial)\Psi(x) = \int \frac{d^3p}{(2\pi)^3}\frac{1}{\sqrt{2E_p}}\sum_s \left(\tilde{u}_s(p)a_{s\mathbf{p}}e^{-ip\cdot x} + \tilde{v}_s(p)b^\dagger_{s\mathbf{p}}\, e^{ip\cdot x}\right)$$

Modified spinors

$$\tilde{u}_s(p) \equiv W(p)u_s(p), \qquad \tilde{v}_s(p) \equiv W(-p)v_s(p)$$

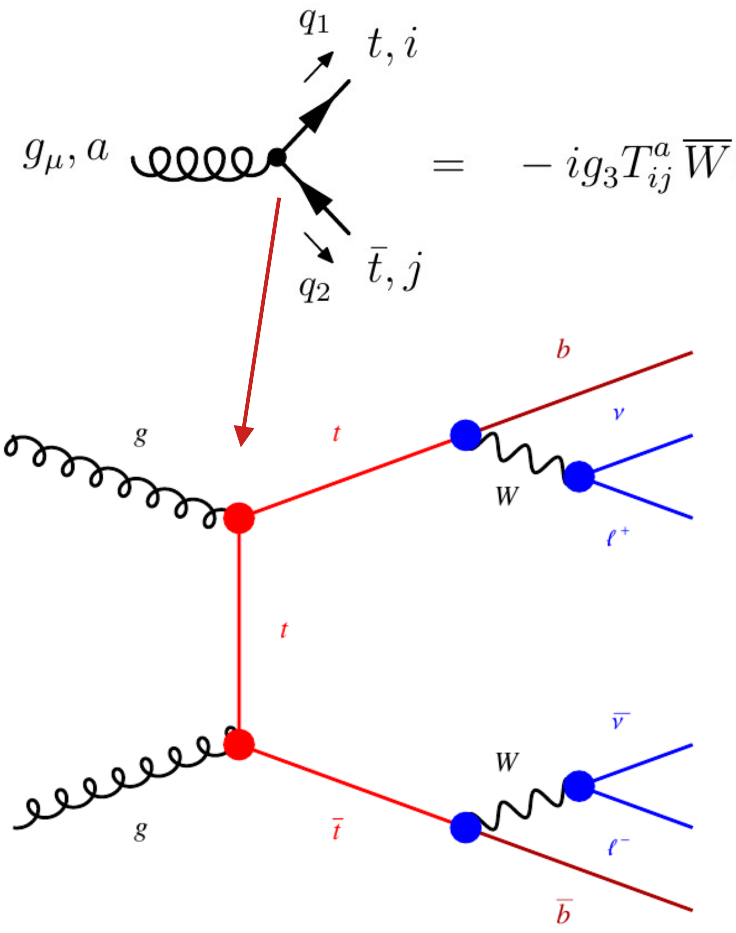
Kinetic terms

$$\bar{\Psi}\mathcal{K}\Psi \to \bar{\Psi}\overline{W}(\not{p} - M)W\Psi \equiv \bar{\Psi}\tilde{\mathcal{K}}\Psi \qquad \tilde{\mathcal{K}} \neq \mathcal{K} \equiv \not{p} - M$$

Modified fermion propagator

$$\Pi(p) = i/(\not{p} - M) \qquad \tilde{\Pi}(p) = W^{-1}(p)\cdot\Pi(p)\cdot\overline{W}^{-1}(p)$$

Modifying Dirac spinor field



$$= \; -ig_3 T^a_{ij}\,\overline{W}(q_1)\gamma^\mu W(-q_2)$$

Redefining a field everywhere leaves physics invariant

$$\Psi \to \tilde{\Psi} = W\Psi$$

Corrections to the propagators and vertices cancel

$$\tilde{\Pi}(p) = W^{-1}(p)\cdot\Pi(p)\cdot\overline{W}^{-1}(p)$$

Spin-summed cross-sections invariant if

$$\overline{W}W = \mathbb{1}, \qquad \overline{W}\not{p}W = \not{p}$$

$$\sum_s \tilde{u}_s(p)\bar{\tilde{u}}_s(p) = W(p)(\not{p}+M)\overline{W}(p) = \not{p}+M = \sum_s u_s(p)\bar{u}_s(p)$$

Lorentz symmetry breaking

$$W(p) \xrightarrow{\Lambda} W'(p') = \Lambda_{1/2}W(p=\Lambda^{-1}p')\Lambda^{-1}_{1/2} \qquad\qquad p' = \Lambda p$$

Lorentz breaking SO(3,1) → SO(2) or SO(2,1)

SO(2,1) distinguished direction

$$n^\mu = (0, \boldsymbol{n}) = (0,0,0,1)$$

$$J_z, K_x, K_y$$

rotation boosts

Dirac basis
W(0) - at rest

$$W(0) = \mathrm{diag}(U, V)$$

particle antiparticle

1. U=V $W(0) = \mathrm{diag}(e^{i\delta/4}, e^{-i\delta/4}, e^{i\delta/4}, e^{-i\delta/4})$

$$W(p) = \exp\left(i\delta[\not{n}, \not{p}]\gamma_5/8M_p\right)$$

2. U=V^-1 $W(0) = \mathrm{diag}(e^{i\delta/4}, e^{-i\delta/4}, e^{-i\delta/4}, e^{i\delta/4})$

$$W(p) = \exp(-i\delta\,\not{n}\gamma_5/4)$$

SO(2) choose SU(2) matrices U, V

$$W(p) = \Lambda_p W(0) \Lambda_p^{-1}$$

Lorentz transformation $u(p) = \Lambda_p u(0)$

In general reference frame

$$U \to U' = DUD^{-1} \qquad V \to V' = DVD^{-1}$$

D - Wigner rotation matrices

Boosted vector $n_p^\mu = (\Lambda_p)^\mu{}_\nu n^\nu$

$$W(p) = \exp(i\delta\,[\not{n}_p, \not{p}]\gamma_5/8M_p)$$

$$W(p) = \exp(-i\delta\,\not{n}_p\gamma_5/4)$$

broken Lorentz → special frame where vector n or matrices U,V are simple

Maximal Lorentz subgroup SIM 2

rotation boost

$$J_z, \qquad K_z, \qquad T_1 = K_x + J_y, \qquad T_2 = K_y - J_x$$

- a generic time-like four vector can be boosted to its rest frame
- speed of light c remains universal

$n^\mu = (1,0,0,1)$ is invariant under T_1, T_2, J_z, transforms multiplicatively under K_z.

$$W(p) = \exp\left(\frac{\delta}{4}\frac{[\not{n},\not{p}]}{n\cdot p}\right), \qquad \tilde{\mathcal{K}} \equiv \overline{W}(\not{p} - M)W = e^{\delta}\not{p} - M - \frac{p^2\,\not{n}}{p\cdot n}\sinh\delta$$

$$\tilde{\mathcal{K}} \neq \mathcal{K}$$

$$\tilde{\mathcal{K}}^2 = p^2 - M^2$$

Cohen, Glashow 2006

1.U=V

$$W(p) = \exp\left(i\frac{\delta}{4}\frac{[\not{n},\not{p}]\gamma_5}{n\cdot p}\right), \qquad W(0) = \mathrm{diag}(e^{i\delta/4}, e^{-i\delta/4}, e^{i\delta/4}, e^{-i\delta/4})$$

2.U=V^{-1}

$$W(p) = \exp\left[-i\frac{\delta}{4}\left(\frac{\not{n}\,M_p}{n\cdot p} - \frac{\not{p}}{M_p}\right)\gamma_5\right], \qquad W(0) = \mathrm{diag}(e^{i\delta/4}, e^{-i\delta/4}, e^{-i\delta/4}, e^{+i\delta/4})$$

SIM 2 invariant theory expected to affect entanglement observables

Spin correlation and entanglement

Density matrix $gg \to t\bar{t}$

spin correlation matrix

$$\tilde{\rho} = \frac{1}{4}\left(\mathbb{1}\otimes\mathbb{1} + (\boldsymbol{\sigma}\cdot\tilde{\boldsymbol{S}}_1)\otimes\mathbb{1} + \mathbb{1}\otimes(\boldsymbol{\sigma}\cdot\tilde{\boldsymbol{S}}_2) + \tilde{C}_{ij}\,\sigma_i\otimes\sigma_j\right)$$

$$\tilde{u}_{s_1}(q_1) = \Lambda_{q_1}(\Lambda_{q_1}^{-1}W(q_1)\Lambda_{q_1})u_{s_1}(0) \equiv \Lambda_{q_1}U_{s_1 s_1'}(q_1)u_{s_1'}(0) = U_{s_1 s_1'}(q_1)u_{s_1'}(q_1)$$

$$\tilde{\boldsymbol{S}}_1 = R_U^T\cdot\boldsymbol{S}_1, \qquad \tilde{\boldsymbol{S}}_2 = R_V^T\cdot\boldsymbol{S}_2, \qquad \tilde{C} = R_U^T\cdot C\cdot R_V$$

Spin singlet produced at threshold C=-1, for $W(0) = \mathrm{diag}(e^{i\delta/4}, e^{-i\delta/4}, e^{-i\delta/4}, e^{i\delta/4})$

$$|\delta\rangle = \frac{e^{-i\delta/2}|t_\uparrow\bar{t}_\downarrow\rangle - e^{i\delta/2}|t_\downarrow\bar{t}_\uparrow\rangle}{\sqrt{2}} \qquad \tilde{C} = -\begin{pmatrix}\cos\delta & -\sin\delta & 0\\ \sin\delta & \cos\delta & 0\\ 0 & 0 & 1\end{pmatrix}$$

Entanglement measure $D \equiv \frac{\mathrm{Tr}\,C}{3} = \frac{2}{3}\langle S^2\rangle - 1$ $\qquad D <$ -1/3 $\qquad \langle S^2\rangle < 1$

C-even theories U=V → approximately no effect, Tr C remains invariant

C-odd theories U=V^{-1} → $\tilde{D} = \frac{1}{3}\,\mathrm{Tr}\tilde{C} = -\frac{1}{3} - \frac{2}{3}\cos\delta$

Comparision with LHC data

$D \equiv \frac{\mathrm{Tr}\, C}{3} = \frac{2}{3}\langle S^2 \rangle - 1$ D < -1/3 → entanglement

ATLAS $D = -0.547 \pm 0.021_{\mathrm{syst}} \pm 0.002_{\mathrm{stat}}$ for $340\,\mathrm{GeV} < m_{t\bar{t}} < 380\,\mathrm{GeV}$

CMS $D = -0.480^{+0.020}_{-0.023}\,(\mathrm{syst})^{+0.016}_{-0.017}\,(\mathrm{stat})$ for $345\,\mathrm{GeV} < m_{t\bar{t}} < 400\,\mathrm{GeV}$

POWHEG + PYTHIA (including subdominant **$q\bar{q} \to t\bar{t}$**) $D_{\mathrm{SM}} = -0.470 \pm 0.018_{\mathrm{syst}} \pm 0.002_{\mathrm{stat}}$

Simple parton-level approximation in the non-relativistic region (ATLAS)

$$C_{\mathrm{SM}} \approx -\,\mathrm{diag}(0.54, 0.54, 0.18) \qquad \text{i.e.} \qquad D_{\mathrm{SM}} \approx -0.42$$

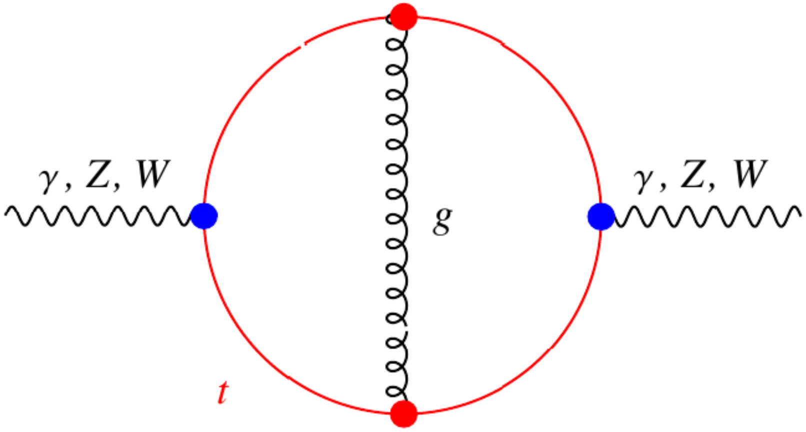
C-odd theories $U = V^{-1}$ → $\tilde{C} = R \cdot C_{\mathrm{SM}} \cdot R$

ATLAS (CMS) results imply the bound $\boxed{|\delta| \lesssim 0.6\ (0.7)\ \text{at}\ 3\sigma\ \text{with}\ \boldsymbol{n} = (0,0,1)}$

Bounds for perpendicular directions are only 20% weaker →
proper averaging over **LHC orientation is a minor effect**.

Example of loop effects

Electroweak precision physics

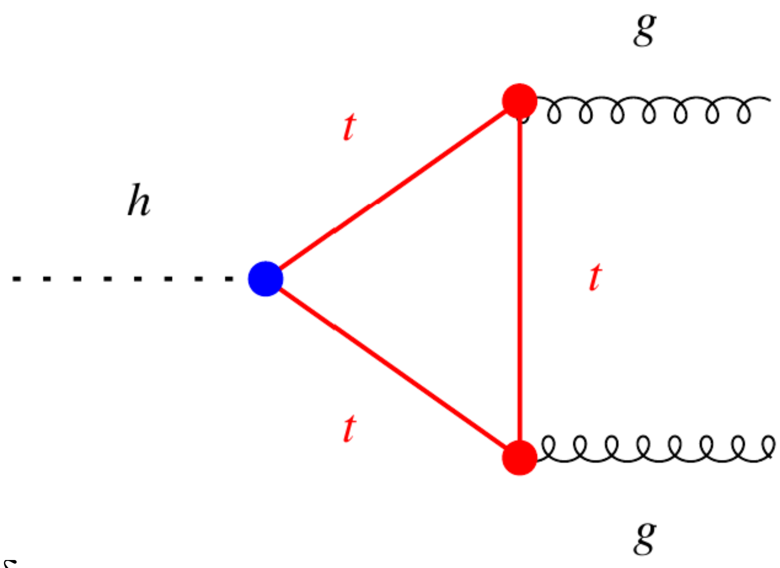


- $\rho \equiv M_W^2/M_Z^2 \cos^2\theta_W$
- parameter ϵ_b , $Zb_L\bar{b}_L$ coupling

one-loop diagrams involve
either QCD or EW interactions

modified at 2-loop level

Higgs physics



$\Gamma(h \to \gamma\gamma), \Gamma(h \to Z\gamma)$

modified at 2-loop level

$\Gamma(h \to gg)$ is affected at one-loop level

We calculated the leading corrections

$$\Delta\Gamma/\Gamma \approx \lambda\delta^2 M_h^2/M_t^2, \qquad \lambda \sim 1$$

ATLAS and CMS bounds on Higgs signal streng
give only slightly weaker bound on parameter δ
than entanglement observable D.

Summary

- ATLAS and CMS confirmed entanglement in the $t\bar{t}$ pair
- We were looking for new physics that could be tested by entanglement
- We found theories that leave tree-level differential production rate for top pair invariant, but
- modified spin correlation matrix is constrained by entanglement observable
- Loop effects give comparable (only slightly weaker) bounds

BACKUP

Photon mass

$$m_\gamma^2 (n_\mu F^{\mu\nu} / n^\alpha \partial_\alpha)^2$$

IR divergencies due to derivative at the denominator

Photon remains massless after regularisation

Dunn, Mehen 2006