Azimuthal Angular Correlation as a Boosted Top Jet Substructure

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EF03 Heavy flavor and top
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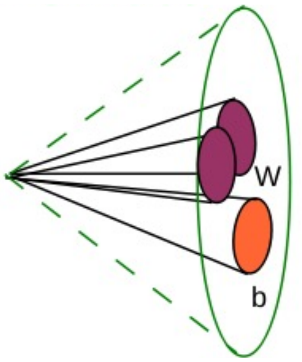
Zhite Yu and C.-P. Yuan, arXiv:2110.11539

Boosted top quark

☐ Important portal to New Physics [arXiv:1012.5412]

$pp \to X_{\text{heavy}} \to t \to bW(\to f\bar{f}')$ **boosted top quark ⟹ fat jet**



- **Easier to separate signal from the background.**
- **Important to measure the rate of boosted top production.**

☐ Tagging of boosted top quark jet

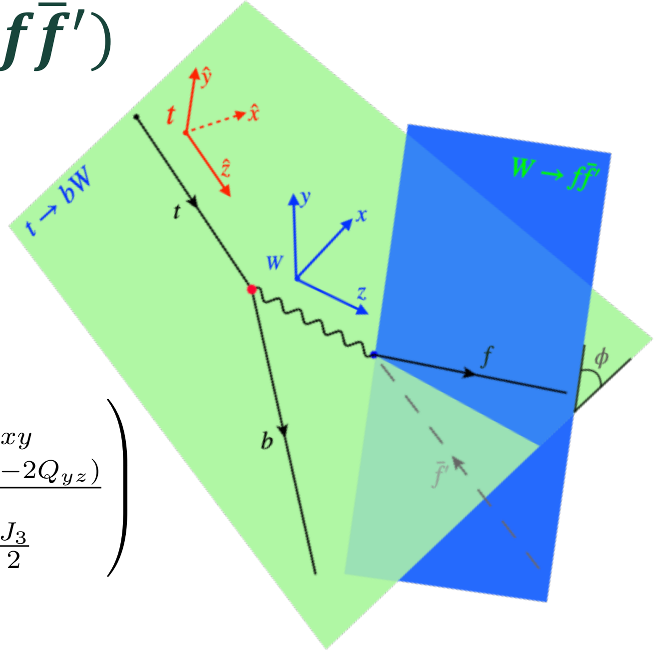
- ***W* and *t* mass constraints**
- **3-pronged jet substructure**
- **Azimuthal angular correlation**

CMS-PAS-JME-13-007, 1006.2833, 1808.07858

☐ Measurement of top polarization in *boosted* regime

- **Signature of the production mechanism** [arXiv:1103.3274]
- **Transverse polarization of top ⟸ azimuthal distribution of its decay**
- **Longitudinal polarization of top ⟸ azimuthal angular *correlation***

Azimuthal angular correlation in $t \to bW(\to f\bar{f}')$

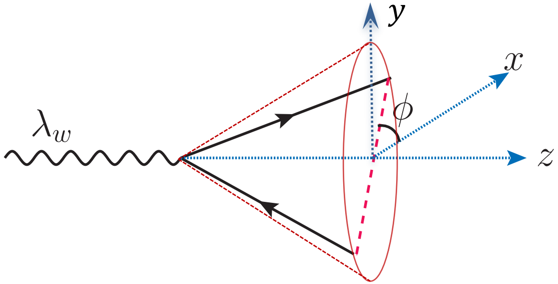


❑ Definition

Angle ϕ between $t \to bW$ and $W \to f\bar{f}'$ planes.
$\sigma^{-1}d\sigma/d\phi$ is the *angular correlation.*

❑ Depends on W polarization

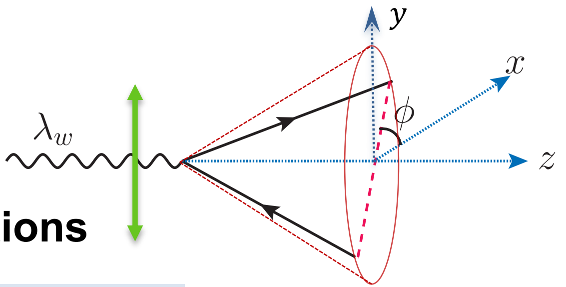
$$\left(\rho^{w}_{\lambda_w\lambda'_w}\right) = \begin{array}{c|ccc} & + & 0 & - \\ \hline + & \frac{1-\delta_L}{3}+\frac{J_3}{2} & \frac{J_1+2Q_{xz}-i(J_2+2Q_{yz})}{2\sqrt{2}} & \lambda_T - iQ_{xy} \\ 0 & \frac{J_1+2Q_{xz}+i(J_2+2Q_{yz})}{2\sqrt{2}} & \frac{1+2\delta_L}{3} & \frac{J_1-2Q_{xz}-i(J_2-2Q_{yz})}{2\sqrt{2}} \\ - & \lambda_T + iQ_{xy} & \frac{J_1-2Q_{xz}+i(J_2-2Q_{yz})}{2\sqrt{2}} & \frac{1-\delta_L}{3}-\frac{J_3}{2} \end{array}$$



$$\langle f\bar{f}'(\phi)|S|\lambda_w\rangle \propto e^{i\lambda_w\phi} \Longrightarrow |\langle f\bar{f}'(\phi)|S|\lambda_w\rangle|^2 \propto 1$$

- **Helicity eigenstate yields *no* ϕ distribution.**
- **Nontrivial ϕ distribution requires *interference*.**

Polarization of W from $t \to bW$



- ☐ **Interference between different helicity states of W**

$$|x\rangle = -\frac{1}{\sqrt{2}}\Big[|+\rangle - |-\rangle\Big], \quad |y\rangle = \frac{i}{\sqrt{2}}\Big[|+\rangle + |-\rangle\Big]$$

Linear polarizations

$$\langle f\bar{f}'(\phi)|S|x\rangle \propto -\frac{1}{\sqrt{2}}\left(e^{i\phi} - e^{-i\phi}\right) \qquad \Longrightarrow |\langle f\bar{f}'(\phi)|S|x\rangle|^2 \propto 1 - \cos 2\phi$$

$$\langle f\bar{f}'(\phi)|S|y\rangle \propto \frac{i}{\sqrt{2}}\left(e^{i\phi} + e^{-i\phi}\right) \qquad \Longrightarrow |\langle f\bar{f}'(\phi)|S|y\rangle|^2 \propto 1 + \cos 2\phi$$

Interference between W_R and W_L gives $\cos 2\phi$ (or $\sin 2\phi$) distributions.

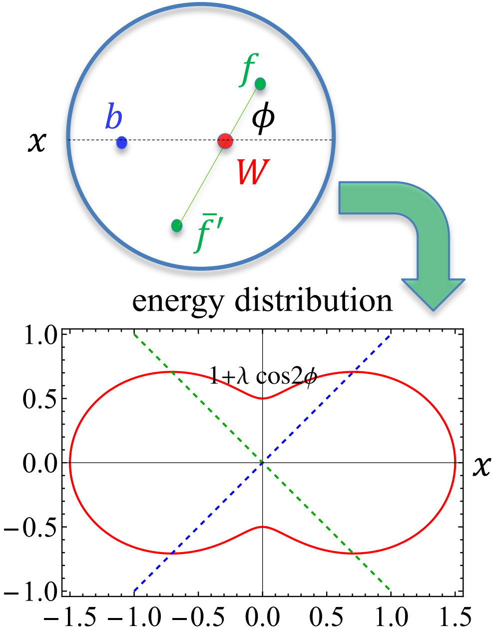
$$\left(\rho^{w}_{\lambda_w \lambda'_w}\right) = \begin{pmatrix} \frac{1-\delta_L}{3} + \frac{J_3}{2} & \frac{J_1+2Q_{xz}-i(J_2+2Q_{yz})}{2\sqrt{2}} & \lambda_T - iQ_{xy} \\ \frac{J_1+2Q_{xz}+i(J_2+2Q_{yz})}{2\sqrt{2}} & \frac{1+2\delta_L}{3} & \frac{J_1-2Q_{xz}-i(J_2-2Q_{yz})}{2\sqrt{2}} \\ \lambda_T + iQ_{xy} & \frac{J_1-2Q_{xz}+i(J_2-2Q_{yz})}{2\sqrt{2}} & \frac{1-\delta_L}{3} - \frac{J_3}{2} \end{pmatrix}$$

$\boldsymbol{\lambda_T \cos 2\phi + Q_{xy} \sin 2\phi}$

$\boldsymbol{J_1, Q_{xz}}$: $\cos\phi$
$\boldsymbol{J_2, Q_{yz}}$: $\sin\phi$

Similarly, interference between $W_{R,L}$ and W_0 gives $\cos\phi$ (or $\sin\phi$) distributions.

Azimuthal angular correlation in $t \to bW(\to f\bar{f}')$



❑ Azimuthal correlation

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} = \frac{1}{2\pi}\left[1 + \langle\lambda_T'\rangle\cos 2\phi - \frac{3\pi}{8}\langle J_1'\rangle\cos\phi\right] \qquad \phi \in [0,2\pi]$$

- $\langle\lambda_T'\rangle$ is the linear polarization (along x) − (along y).
    - $\langle\lambda_T'\rangle > 0$: $Wf\bar{f}'$ plane tends to be ∥ tbW plane.
    - $\langle\lambda_T'\rangle < 0$: $Wf\bar{f}'$ plane tends to be ⊥ tbW plane.

❑ cosϕ component

- Appears because $Wf\bar{f}'$ violates parity conservation.
- Visible only when we can distinguish f from $\bar{f}'$: semileptonic t decay.
- For hadronic t decay, we cannot tell ϕ from $\phi + \pi$: only $\cos 2\phi$ distribution.

$$\frac{1}{\sigma^{(h)}}\frac{\mathrm{d}\sigma^{(h)}}{\mathrm{d}\phi} = \frac{1}{\pi}\left[1 + \langle\lambda_T'\rangle\cos 2\phi\right] \qquad \phi \in [0,\pi]$$

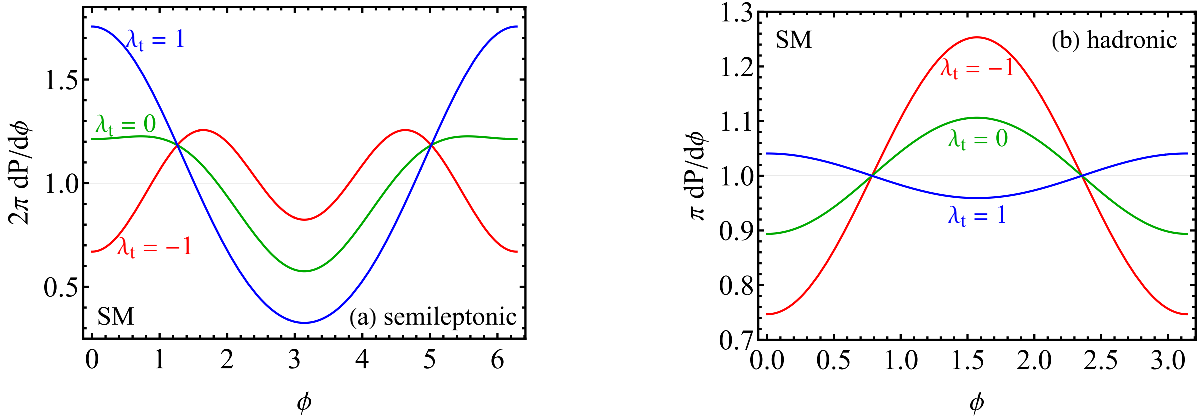
Dependence on top polarization

☐ Dependence on top kinematics

- $\langle \lambda_T' \rangle$ and $\langle J_1' \rangle$ depend on
  - top energy E_t ⟶ saturates fast as $E_t > 350\text{GeV}$
  - longitudinal polarization of t: λ_t

Approximate boosted top ($E_t > 500\text{GeV}$) as $E_t = \infty$

$$\langle \lambda_T' \rangle = -0.106 + 0.147\lambda_t, \quad \langle J_1' \rangle = -0.271 - 0.336\lambda_t$$



semileptonic **hadronic**

Angular correlation helps measure *top polarization λ_t*

Relation to new physics (NP)

☐ Impact by a more general tbW coupling

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\,\bar{b}\gamma^{\mu}\left(g_L P_L + g_R P_R\right) t W_{\mu} + \text{ h.c.}$$

SMEFT

$$Q_{\varphi q}^{(3)} = \left(\varphi^{\dagger} i \overset{\leftrightarrow}{D}{}_{\mu}^{I} \varphi\right)\left(\bar{q}_p \tau^I \gamma^{\mu} q_r\right)$$

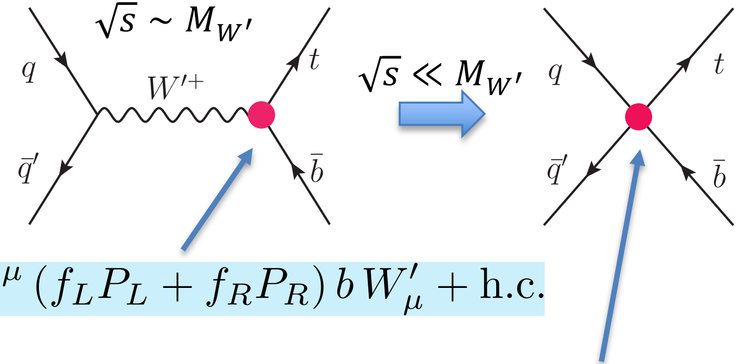
$$Q_{\varphi ud} = i\left(\tilde{\varphi}^{\dagger} D_{\mu} \varphi\right)\left(\bar{u}_p \gamma^{\mu} d_r\right)$$

$$\Rightarrow \quad g_L = 1 + \frac{v^2}{\Lambda^2} C_{\phi q}^{(3,33)}, \qquad g_R = \frac{v^2}{2\Lambda^2} C_{\phi ud}^{(3,33)}$$

$$\langle \lambda_T' \rangle = -0.106 + 0.147 \lambda_t f_t, \quad \langle J_1' \rangle = -0.271 f_t - 0.336 \lambda_t$$

$$f_t \equiv \left(g_L^2 - g_R^2\right) / \left(g_L^2 + g_R^2\right)$$

☐ Different NP models (W', Z', etc.) lead to different top polarizations λ_t

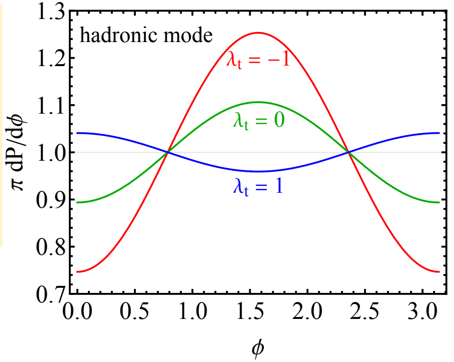


$$\bar{t}\gamma^{\mu}\left(f_L P_L + f_R P_R\right) b\, W'_{\mu} + \text{h.c.}$$

$$\left[\bar{t}\gamma^{\mu}\left(f_L P_L + f_R P_R\right) b\right] \cdot \left[\bar{q}'\gamma_{\mu}\left(f_L' P_L + f_R' P_R\right) q\right]$$

- $(f_L, f_R) = (1, 0)$: $\lambda_t \simeq -1$
- $(f_L, f_R) = (0, 1)$: $\lambda_t \simeq +1$
- $(f_L, f_R) = (1, 1)$: $\lambda_t \simeq 0$

$M_{W'} \gg m_t$



Summary

☐ The most general azimuthal distribution

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} = \frac{1}{2\pi}\left[1 + \langle \lambda_T' \rangle \cos 2\phi + \langle Q_{xy}' \rangle \sin 2\phi - \frac{3\pi}{8}\left(\langle J_1' \rangle \cos\phi + \langle J_2' \rangle \sin\phi\right)\right]$$

- **In the top rest frame, $\boldsymbol{\lambda_T = Q_{xy} = 0}$, no $\cos 2\boldsymbol{\phi}$ or $\sin 2\boldsymbol{\phi}$.**
  - **$\langle \boldsymbol{\lambda_T'} \rangle$ and $\langle \boldsymbol{Q_{xy}'} \rangle$ are generated due to boost effect.**
- **$\cos\boldsymbol{\phi}$ and $\sin\boldsymbol{\phi}$ appear because $\boldsymbol{W}$ decay breaks parity conservation.**
  - **only visible for semileptonic $\boldsymbol{t}$ decay.**
- **$\sin 2\boldsymbol{\phi}$ and $\sin\boldsymbol{\phi}$ exist only when $\boldsymbol{t \to bW}$ violates CP invariance.**

☐ Phenomenological significance

- **Help measure the top polarization.**
- **Help measure the general $\boldsymbol{tbW}$ interaction.**
- **Help suppress top background.**

Thank you!