Azimuthal Correlations in Top Pair Decays and the Effects of New Heavy Scalars

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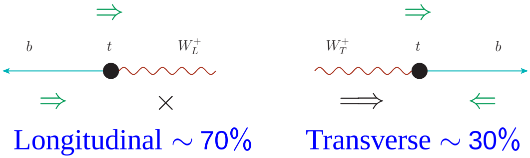
Outline

- Spin correlations in top quark decays
- QCD production of top pairs (Background)
- Scalar decays to top pairs (Signal)
- LHC cross sections and correlations

- The direction of the top decay products are correlated with its spin vector in its rest frame

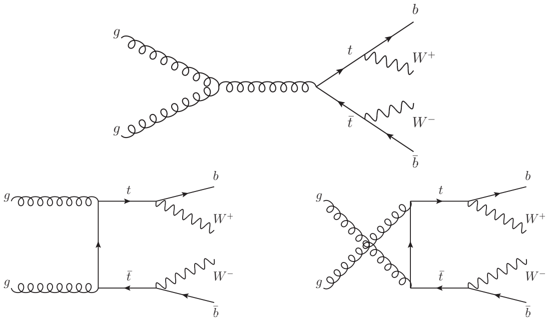


- The net effect is that

* $t \rightarrow$ b tends to be emitted in direction opposing t spin
* $\bar{t} \rightarrow$ $\bar{b}$ tends to be emitted in direction along $\bar{t}$ spin

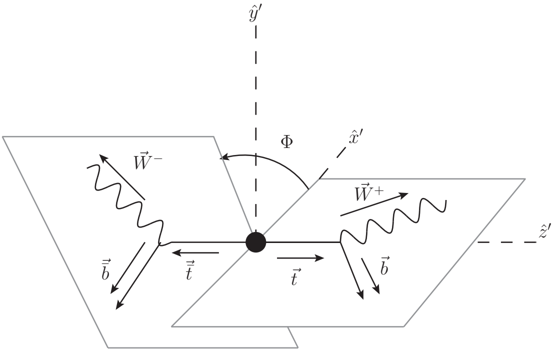
Effect can be seen in the correlations of $t\bar{t}$ decay products

- At the LHC, dominant production of $t\bar{t}$ in SM : $gg \to t\bar{t}$



- Correlated top quarks spins $\Rightarrow$ angular correlations of their decay products.
- We will focus on *azimuthal correlations*.

- Define the following coordinate system in c.o.m. of $t\bar{t}$ system:



Φ is the (azimuthal) angle between the t / $\bar{t}$ decay planes about the t momentum axis in $t\bar{t}$ rest frame

- For a given c.o.m. energy $\sqrt{\hat{s}}$:

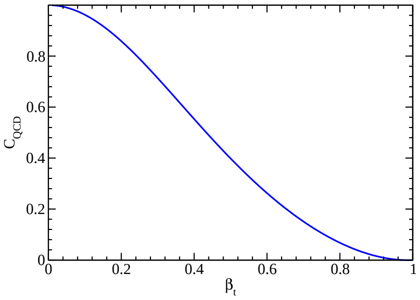
$$\frac{1}{\hat{\sigma}_{\mathrm{QCD}}}\frac{d\hat{\sigma}_{\mathrm{QCD}}}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 + C_{\mathrm{QCD}}(\beta_t)\left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\cos(\Phi)\right],$$

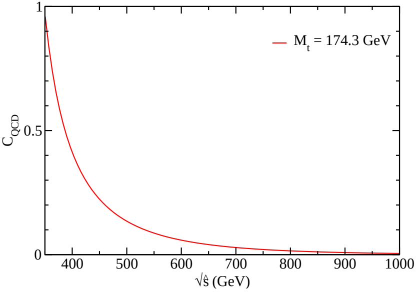
where

$$\rho_W = (m_t^2/M_W^2)$$

$$\beta_t = \sqrt{1 - 4m_t^2/\hat{s}}$$

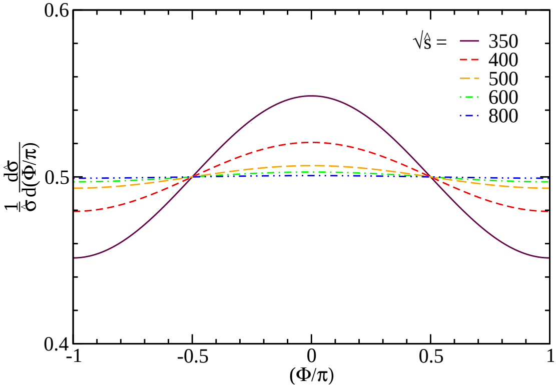
$$C_{\mathrm{QCD}}(\beta_t) = \left(\frac{(1-\beta_t^2)}{\beta_t^2}\right)\left(\frac{\beta_t(33-31\beta_t^2)-(1-\beta_t^2)(33-2\beta_t^2)\tanh^{-1}(\beta_t)}{\beta_t(59-31\beta_t^2)-2(33-18\beta_t^2+\beta_t^4)\tanh^{-1}(\beta_t)}\right)$$





- The function C_{QCD} takes the limits

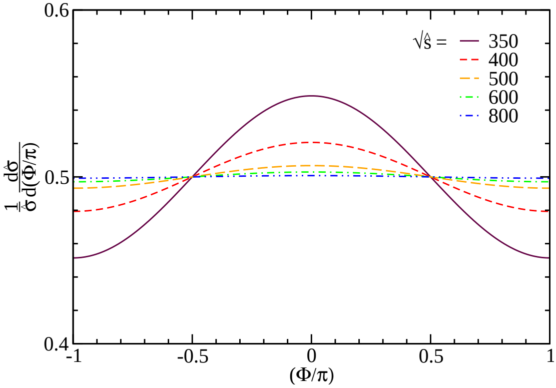
$$C_{\mathrm{QCD}} \to \begin{cases} 1 & \text{as} \quad \beta_t \to 0 \\ 0 & \text{as} \quad \beta_t \to 1 \end{cases}$$



low energies → *(Potentiallly) Visible correlation*

high energies → *flat*

This is the SM prediction at LO.



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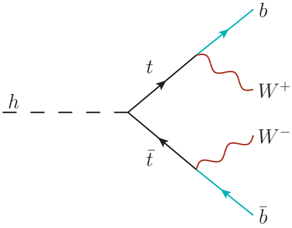
What about New Physics?

$t\bar{t}$ Resonances (?)

- Appear in many NP models
  - e.g. Top-color assisted TC, KK-excitations, colorons, ...
- Invoked to explain top forward-backward asymmetry at Tevatron
  - e.g. W', Z', *axigluon*, extended Higgs sectors, ...
- Worth seeing the consequences of different spins, SU(3) quantum numbers, and *CP* states
  - ***Spin-0***, Spin-1, Spin-2
  - ***Color singlet***, octet
  - ***CP-even***, ***CP-odd***, (***CP-violating?***)

- Let us first consider some scalar h which couples to the top



$$\begin{aligned}\mathscr{L} &\supset -h\left[A\left(\frac{m_t}{v}\right)\bar{t_R}t_L\right]+h.c.\\ &\supset -h\left[\left(\frac{m_t}{v}\right)\bar{t}(AP_L+A^*P_R)t\right]\\ &\supset -h\left[\left(\frac{m_t}{v}\right)\bar{t}(A_R-iA_I\gamma^5)t\right]\end{aligned}$$

where

$$A=(A_R+iA_I)\equiv|A|e^{i\alpha}$$

- The value of α determines the *CP* properties of h

$$\alpha=\begin{cases}0 & \textit{CP-Even} \rightarrow \textit{like SM Higgs}\\ \pm\frac{\pi}{2} & \textit{CP-Odd}\\ \text{otherwise} & \textit{CP-violating}\end{cases}$$

- Defining Φ as before

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 - \left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2} \frac{(A_R^2\beta_t^2 - A_I^2)\cos\Phi + (2A_I A_R \beta_t)\sin\Phi}{(A_R^2\beta_t^2 + A_I^2)}\right]$$

- Now define the phase χ such that

$$A_\chi = (A_R\beta_t + iA_I) = |A_\chi| e^{i\chi}$$

such that

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 - \left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\cos(\Phi - 2\chi)\right]$$

- The phase χ is related to the original phase α by

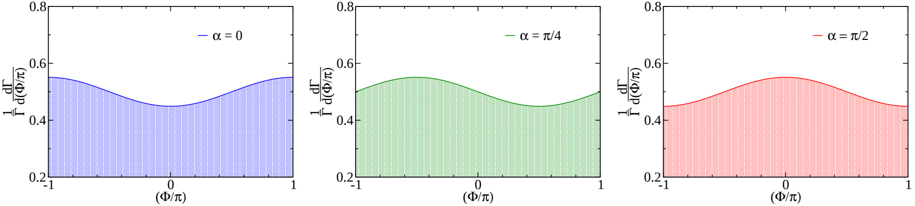
$$\tan\chi = \frac{A_I}{\beta_t A_R} = \left(\frac{1}{\beta_t}\right)\tan\alpha \approx \tan\alpha$$

- For the *CP* conserving cases this is just

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 - \left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\cos(\Phi)\right] \qquad CP-even$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 + \left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\cos(\Phi)\right] \qquad CP-odd$$

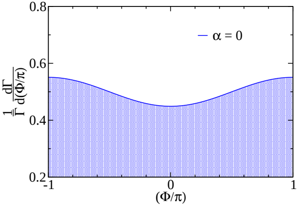
- The *CP*-violating case simply introduces a *phase shift* of $-2\chi \approx -2\alpha$

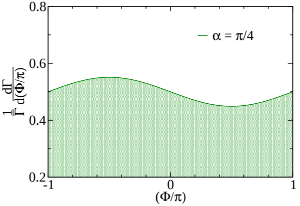


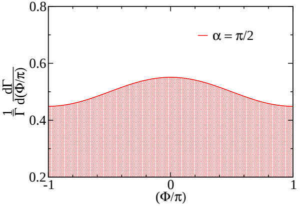
$\alpha =$ 0 $\pi/4$ $\pi/2$

Discriminates CP states

(Allows for determination of α)







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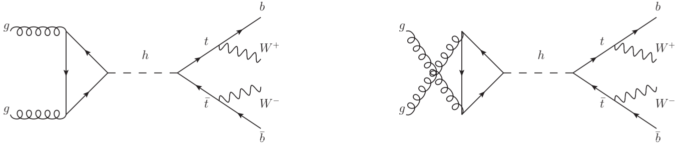
Discriminates CP states

(Allows for determination of α)

Is this observable above QCD at the LHC?

Scalar production

- LHC signal will depend on scalar production mechanism
- If *h* only couples (strongly) to heavy fermions then the only production mode is



- We will consider two scenarios:

* top-only case $\Rightarrow$ Only tops in the loop

* fourth-generation case $\Rightarrow$ Additional heavy quarks contribute

$$(m_{u4} \sim m_{d4} \equiv m_{Q4} = 500 \text{ GeV})$$

- For the total decay width, assume that

  * $m_h > 2m_t$
  * $h \to t\bar{t}$ is only relevant decay mode

- Then the decay width is given by

$$\Gamma_h = \left(\frac{3m_h}{8\pi}\right)\left(\frac{m_t}{v}\right)^2\left(A_R^2\beta_t^2 + A_I^2\right)\beta_t$$

Minimum possible width

- We assume $|A| = 1$ for the following.

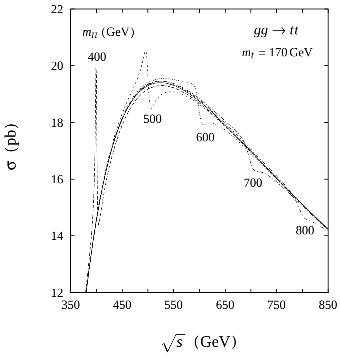


Figure 2

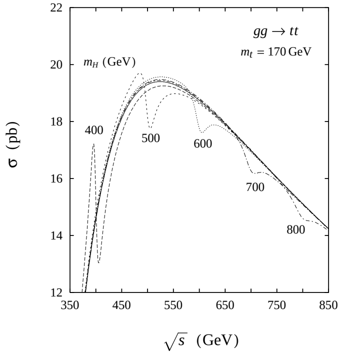


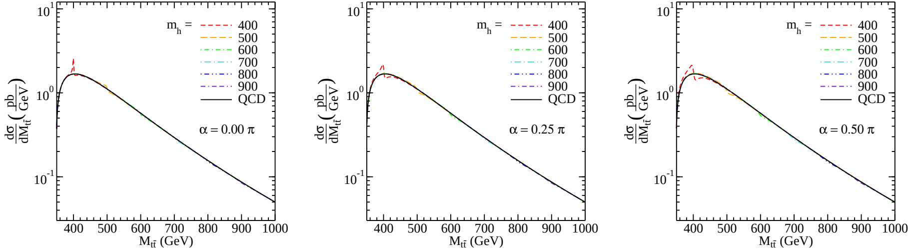
Figure 3

Ex: Dicus, Stange, & Willenbrock (1994)

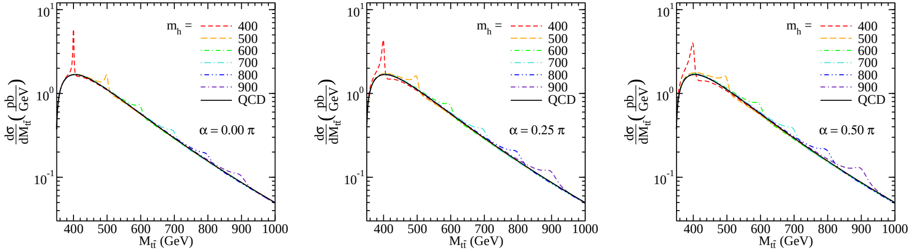
"Peak-dip" structure

Interference is important!

Top-only



Fourth-generation



(At $\sqrt{s} = 14$ TeV)

Azimuthal Correlations

- For the pure signal:

$$\frac{1}{\hat{\sigma}_{\rm H}}\frac{d\hat{\sigma}_{\rm H}}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 - \left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\cos(\Phi - 2\chi)\right]$$

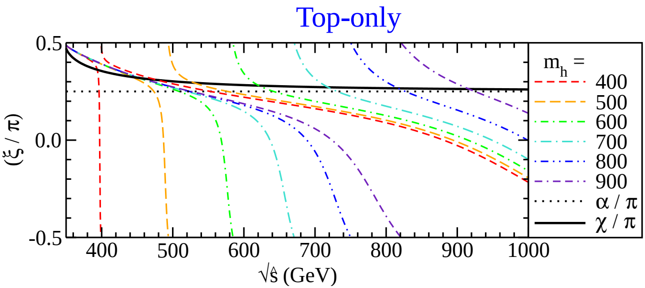
For the interference of the signal with QCD:

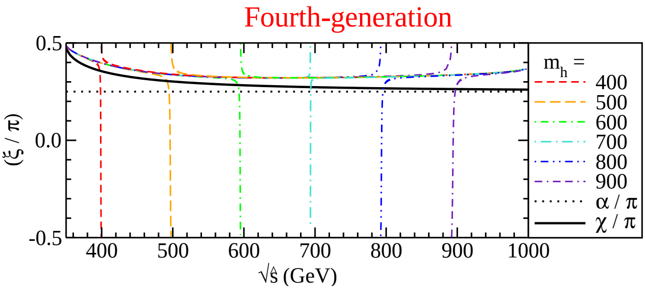
$$\frac{1}{\hat{\sigma}_{\rm INT}}\frac{d\hat{\sigma}_{\rm INT}}{d\Phi} = \left(\frac{1}{2\pi}\right)\left[1 - \left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\frac{\cos(\Phi-(\chi+\xi))}{\cos(\chi-\xi)}\right]$$

where

$$\tan\chi = \left(\frac{1}{\beta_t}\right)\tan\alpha$$
$$\tan\xi = \left(\frac{3\,\mathrm{Re}(F_A \mathscr{P}'_h)}{2\,\mathrm{Re}(F_H \mathscr{P}'_h)}\right)\left(\frac{1}{\beta_t}\right)\tan\alpha$$

- For $\alpha = 0$ or $\pm\frac{\pi}{2}$ $\Longrightarrow$ $\xi = \chi = \alpha$





e.g. CPV: $\alpha = \frac{\pi}{4}$

- Total distribution given by

$$\frac{1}{\sigma_{tot}}\frac{d\sigma_{tot}}{d\Phi} = \frac{1}{\sigma_{tot}}\left(\frac{d\sigma_{\mathrm{QCD}}}{d\Phi} + \frac{d\sigma_{\mathrm{H}}}{d\Phi} + \frac{d\sigma_{\mathrm{INT}}}{d\Phi}\right)$$

where each σ_i has been integrated over PDFs and some $M_{t\bar{t}}$ region

- Define

$$f_i(\Phi) \equiv \frac{1}{\sigma_i}\frac{d\sigma_i}{d\Phi} \quad , \quad w_i \equiv \left(\frac{\sigma_i}{\sigma_{tot}}\right)$$

then

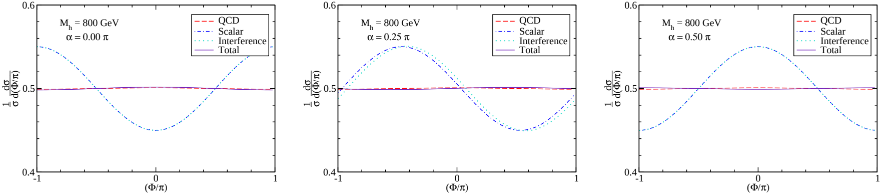
$$f_{tot}(\Phi) = (w_{\mathrm{QCD}} f_{\mathrm{QCD}}(\Phi) + w_{\mathrm{H}} f_{\mathrm{H}}(\Phi) + w_{\mathrm{INT}} f_{\mathrm{INT}}(\Phi))$$

and can be represented as

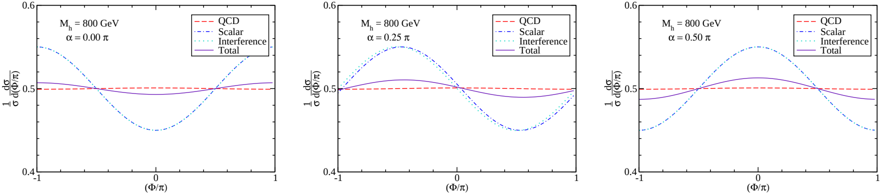
$$f_{tot}(\Phi) = \left(\frac{1}{2\pi}\right)\left(1 + C_{tot}\left(\frac{\pi}{4}\right)^2 \frac{(1-2\rho_w)^2}{(1+2\rho_w)^2}\cos(\Phi + \delta_{tot})\right)$$

- The question is then:
  - $C_{tot} \sim C_{QCD}$? $\qquad \delta_{tot} \sim 0$?

Top-only



Fourth-generation

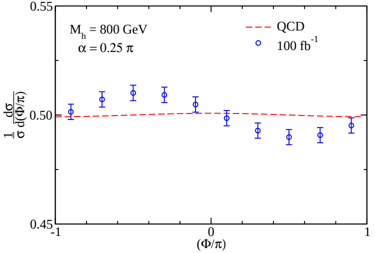


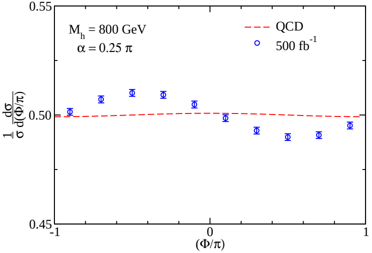
α = 0 $\qquad \pi/4 \qquad \pi/2$

$m_h = 800$ GeV

(integrated over $\sqrt{\hat{s}} = 790, 800\ GeV$)

Fourth-generation



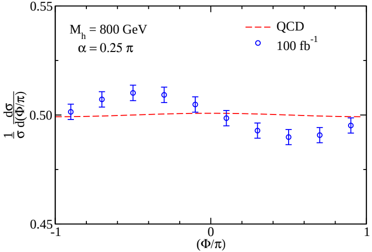


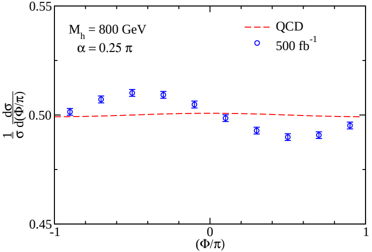
100 fb^{-1} 500 fb^{-1}

$$m_h = 800 \text{ GeV}$$

(integrated over $\sqrt{\hat{s}} = 790, 800\ GeV$*)*

Fourth-generation





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$$m_h = 800\ \mathrm{GeV}$$

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Measureable?

Conclusions

- Spin correlations in top pairs can be probed with azimuthal correlations of their decay products.
- In the case of a **scalar, color-singlet resonance** in $t\bar{t}$ production, these correlations can distinguish between *CP*-even, *CP*-odd, and *CP*-violating.
- There is non-trivial interference of such a mode with the QCD process $gg \to t\bar{t}$ which affects the cross sections and correlations.
- In some (simplified) scenarios, these correlations could in principle be measured at the LHC with $\mathcal{O}(100\ fb^{-1})$

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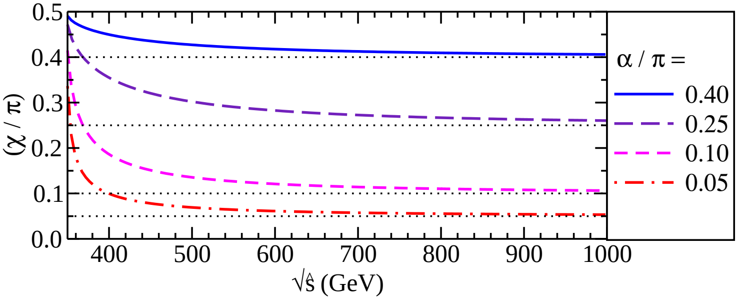
THANK YOU!

EXTRA SLIDES



All CPV states appear CP-odd near threshold.

- Define the loop integral sums

$$F_H \equiv \sum_Q A_H(\tau_Q), \qquad F_A \equiv \sum_Q A_A(\tau_Q).$$

where $\tau_Q = (4m_Q^2/\hat{s})$,

$$A_H(\tau) = \left(\tfrac{3}{2}\right)\tau(1+(1-\tau)f(\tau))$$
$$A_A(\tau) = \tau f(\tau)$$

and

$$f(\tau) = \begin{cases} \arcsin^2\left(\frac{1}{\sqrt{\tau}}\right) & \text{if} \quad \tau \geq 1 \\ -\frac{1}{4}\left[\ln\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \text{if} \quad \tau < 1 \end{cases}$$