Charge Asymmetries of Top Quarks: a Window to New Physics at Hadron Colliders

Paola Ferrario

Instituto de Física Corpuscular
UVEG-CSIC

Discrete '08, Valencia, December 12

IFIC
INSTITUT DE FÍSICA
CORPUSCULAR

LHC is starting soon! (hopefully...)

Runs

- $\sqrt{s} = 14$ TeV, $\mathcal{L} = 10$ fb^{-1}/year
- $\sqrt{s} = 14$ TeV, $\mathcal{L} = 100$ fb^{-1}/year in a second phase

LHC is starting soon! (hopefully...)

Huge production of top quarks

- More top-antitop quark pairs than in the whole Tevatron life
- Possibility of new physics discovery thanks to the high statistics
- $\sqrt{s} = 14$ TeV, $\sigma = 950 \ \mathrm{pb} \rightarrow$ for $\mathcal{L} = 10 \ \mathrm{fb}^{-1}/\mathrm{year}$ 10 millions of events per year!

Paola Ferrario

Charge Asymmetries of Top Quarks: a Window to New Physics at Hadron Colliders · 3/21
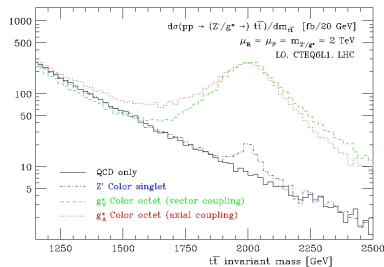
Charge asymmetry

Difference in top-antitop production

$$\frac{N_t - N_{\bar{t}}}{N_t + N_{\bar{t}}}$$

- In QCD it is different from zero at $\mathcal{O}(\alpha^3)$. appendix
- Tops are produced mostly in the direction of the quarks.
- It arises mostly from $q\bar{q}$ and small contribution of qg events, because gg is symmetric.

Resonances

- New physics color-octet resonances have been predicted to be detected at LHC by decaying to top-antitop. Masses under around 1 TeV already ruled out at Tevatron.

- Resonances appear as a **peak in the cross section** → we could observe these resonances in events with invariant masses close to the resonance mass.

Resonances

- High momenta top pairs are difficult to distinguish from light quark jets, because the decay products are more collimated. Standard reconstruction algorithms are not efficient anymore at $p_T > 400$ GeV. Studies for new algorithms see
  * Kaplan, Rehermann, Schwartz and Tweedie, arXiv:0806.0848 [hep-ph]
  * Thaler and Wang, JHEP 0807 (2008) 092
  * L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, arXiv:0807.0234 [hep-ph]

Resonances

- High momenta top pairs are difficult to distinguish from light quark jets, because the decay products are more collimated. Standard reconstruction algorithms are not efficient anymore at $p_T > 400$ GeV. Studies for new algorithms   see
  - * Kaplan, Rehermann, Schwartz and Tweedie, arXiv:0806.0848 [hep-ph]
  - * Thaler and Wang, JHEP 0807 (2008) 092
  - * L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, arXiv:0807.0234 [hep-ph]

- Resonances can produce asymmetries. Since these arise from interference terms, they are more sensitive to higher masses than the differential cross section, because they are less suppressed.

Resonances

- High momenta top pairs are difficult to distinguish from light quark jets, because the decay products are more collimated. Standard reconstruction algorithms are not efficient anymore at $p_T > 400$ GeV. Studies for new algorithms see
  - * Kaplan, Rehermann, Schwartz and Tweedie, arXiv:0806.0848 [hep-ph]
  - * Thaler and Wang, JHEP 0807 (2008) 092
  - * L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, arXiv:0807.0234 [hep-ph]

- Resonances can produce asymmetries. Since these arise from interference terms, they are more sensitive to higher masses than the differential cross section, because they are less suppressed.

- This makes more effective studying asymmetries than cross sections.

Charge asymmetry @LHC

- At Tevatron charge asymmetry = forward–backward asymmetry $\simeq 5\%$
- pp is symmetric $\rightarrow$ no FB asymmetry BUT it's possible to look for a charge asymmetry in an appropriate kinematic region appendix
- Main problem: 85% of the events is $gg \rightarrow t\bar{t}$ (symmetric)

Charge asymmetry @LHC

- At Tevatron charge asymmetry = forward–backward asymmetry $\simeq 5\%$
- pp is symmetric $\rightarrow$ no FB asymmetry BUT it's possible to look for a charge asymmetry in an appropriate kinematic region appendix
- Main problem: 85% of the events is $gg \rightarrow t\bar{t}$ (symmetric)
- At low x the gluon contribution dominates $\rightarrow$ cuts on the top-antitop invariant mass eliminate low x momenta where gluon density is bigger than the quark one.

Charge asymmetry @LHC

- At Tevatron charge asymmetry = forward–backward asymmetry $\simeq 5\%$
- *pp* is symmetric $\rightarrow$ no FB asymmetry BUT it's possible to look for a charge asymmetry in an appropriate kinematic region appendix
- Main problem: 85% of the events is $gg \rightarrow t\bar{t}$ (symmetric)
- At low x the gluon contribution dominates $\rightarrow$ cuts on the top-antitop invariant mass eliminate low x momenta where gluon density is bigger than the quark one.
- Asymmetry is enhanced, even with less statistic.

Charge asymmetry @LHC

- At Tevatron charge asymmetry = forward–backward asymmetry $\simeq 5\%$
- *pp* is symmetric $\rightarrow$ no FB asymmetry BUT it's possible to look for a charge asymmetry in an appropriate kinematic region appendix
- Main problem: 85% of the events is $gg \rightarrow t\bar{t}$ (symmetric)
- At low x the gluon contribution dominates $\rightarrow$ cuts on the top-antitop invariant mass eliminate low x momenta where gluon density is bigger than the quark one.
- Asymmetry is enhanced, even with less statistic.

Not a problem at LHC

Pure QCD

- Central asymmetry, built choosing a limited rapidity region

$$A_C(y_C) = \frac{N_t(|y| \leq y_C) - N_{\bar{t}}(|y| \leq y_C)}{N_t(|y| \leq y_C) + N_{\bar{t}}(|y| \leq y_C)}$$

- Cut on the top-antitop invariant mass $m_{t\bar{t}}$ to have more $q\bar{q}$, gq events.
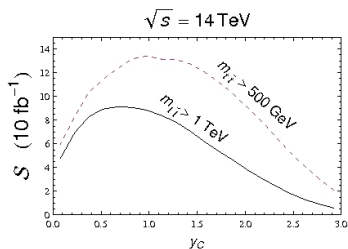
Pure QCD

QCD predicts that tops (antitops) are produced mostly in the direction of the incoming quarks (antiquarks)
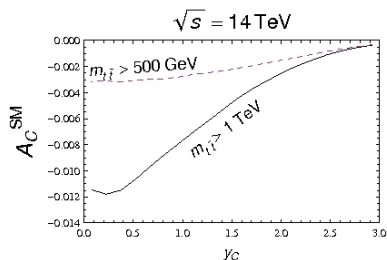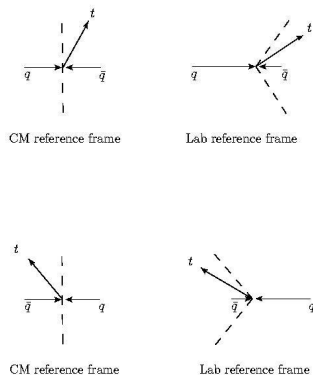
For low y_C only the region with more abundant antitops is selected $\longrightarrow$ the asymmetry is negative and decreases in magnitude with y_C

Pure QCD: significance

$$\mathcal{S}^{\mathrm{SM}} = \frac{\text{signal}}{\sqrt{\text{background}}} = \frac{N_t - N_{\bar{t}}}{\sqrt{N_t + N_{\bar{t}}}}$$


$\sqrt{s} = 14\,\mathrm{TeV}$

- Significance is greater for lower cuts $\rightarrow$ identifying soft tops is easier than the highly boosted ones
- The higher statistic compensates the smaller asymmetry
- The maximum is around $y_C \simeq 0.7 - 1$

Pure QCD: significance

$$\sqrt{s} = 14\,\text{TeV}$$

Plot: vertical axis $\mathcal{S}$ $(10\,\text{fb}^{-1})$, horizontal axis $m_{t\bar{t}}^{\text{min}}(\text{GeV})$
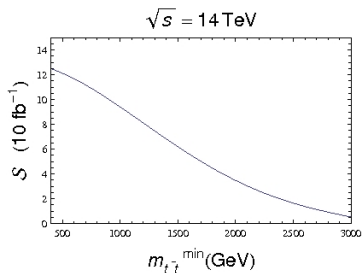
- Even if the asymmetry is smaller, the significance is greater at low cuts in $m_{t\bar{t}}$
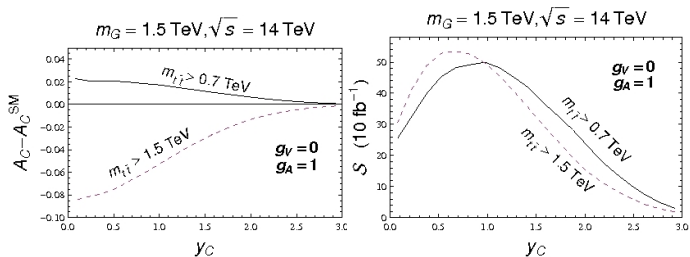- $10\,\text{fb}^{-1}$ luminosity allows to measure the charge asymmetry

Color-octet boson resonance exchange
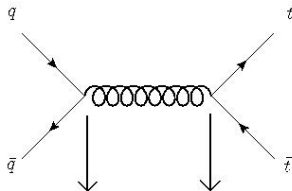

$$\left(g_V + g_A\gamma_5\right)\gamma_\mu$$

- Arbitrary couplings g_V, $g_A \in [0,2]$
- Couplings independent on flavour $g_{V(A)}^q = g_{V(A)}^t$
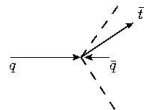- Examples: axigluon ($g_V = 0$, $g_A = 1$), KK gluon

Color-octet boson resonances

$m_G = 1.5\,\text{TeV}, \sqrt{s} = 14\,\text{TeV}$

$m_G = 1.5\,\text{TeV}, \sqrt{s} = 14\,\text{TeV}$

In the partonic cross section $\boxed{\text{cross section}}$ we have $\hat{s} - m_G^2$, so for low $\hat{s}$ it is negative $\longrightarrow$

- Positive charge asymmetry for low cuts
- If the cut grows, the asymmetry changes sign and becomes negative
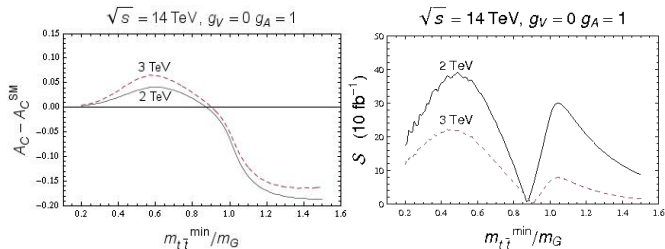- Maximum for the significance at $y_C \simeq 0.7$
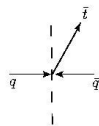
CM reference frame   Lab reference frame

for $\hat{s} < m_G^2$

Varying $m_{t\bar{t}}$

- A_C goes from positive to negative $\rightarrow \mathcal{S}$ reaches a maximum there and goes to zero.
- A_C grows negative $\rightarrow \mathcal{S}$ increases again and has another maximum before the number of events becomes small.
- The maxima are at $m_{t\bar{t}}^{\min}/m_G = 0.5$ and $m_{t\bar{t}}^{\min}/m_G = 0.8 - 1$ for almost all couplings $\rightarrow$ a low cut is enough for a good statistical significance
- The maxima position does not depend on the mass

Conclusions

- Charge asymmetry in top-antitop production in QCD and through a color-octet massive resonance exchange
- @LHC
  - Pure QCD analysis: the statistical significance is greater with no cuts in the invariant mass
  - Resonances: a cut of $1/2$ the resonance mass is enough to see the asymmetry and detect or exclude these particles
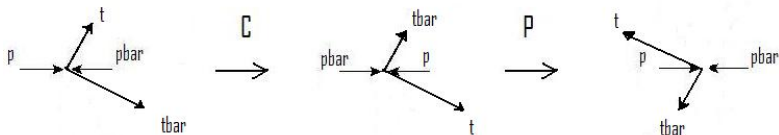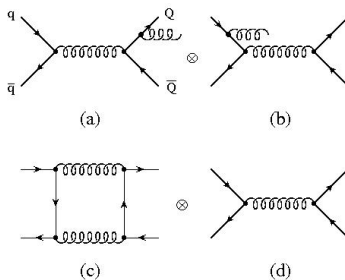
¡Gracias!

Appendix

- Pair asymmetry
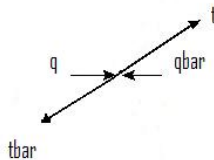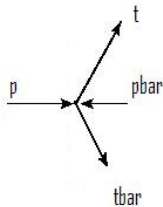
Appendix

- Tevatron

Appendix

- Interference contributions to QCD charge asymmetry

Appendix

- Cross section and FB asymmetry

$$\sigma = \int_{1}^{-1} d\cos\hat{\theta} \frac{d\sigma}{d\cos\hat{\theta}} + \int_{-1}^{1} d\cos\hat{\theta} \frac{d\sigma}{d\cos\hat{\theta}}$$
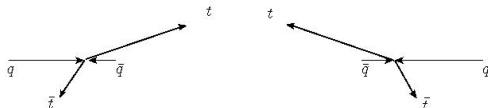
$\rightarrow$ only even terms in $\cos\hat{\theta}$ contribute.

$$A_{\mathrm{FB}} \propto \frac{d\sigma(\cos\hat{\theta})}{d\cos\hat{\theta}} - \frac{d\sigma(-\cos\hat{\theta})}{d\cos\hat{\theta}}$$

$\rightarrow$ only odd terms in $\cos\hat{\theta}$ contribute. ◂ Back

Appendix

- Charge asymmetry at LHC

Color-octet boson resonance: differential cross section

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_s^2\,\frac{T_F C_F}{N_C}\,\frac{\pi\beta}{2\hat{s}}\left(1+c^2+4m^2+\frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2+m_G^2\Gamma_G^2}\left[g_V^q g_V^t\times\right.\right.$$

$$\times\;(1+c^2+4m^2)+2g_A^q g_A^t c\Big]+\frac{\hat{s}^2}{(\hat{s}-m_G^2)^2+m_G^2\Gamma_G^2}\times$$

$$\times\;\left[\left((g_V^q)^2+(g_A^q)^2\right)\left((g_V^t)^2(1+c^2+4m^2)+\right.\right.$$

$$+\;(g_A^t)^2(1+c^2-4m^2)\Big)+8g_V^q g_A^q g_V^t g_A^t c\bigg]\Bigg)$$

$$c \equiv \sqrt{1-4\frac{m_t^2}{\hat{s}}}\cos\hat{\theta}\;\;\text{appendix}$$

◂ Back