Charge asymmetry of heavy quarks at hadron colliders

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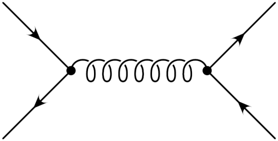
Introduction

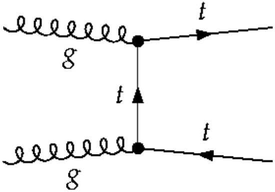
- Two possible processes for $t\bar{t}$ production:

$q\bar{q}$ annihilation



- Only at first order $t\bar{t}$ production is totally symmetric because the gluon doesn't 'remember' the direction of the initial state quarks.

Gluon fusion



- Gluon fusion is always totally symmetric, because we can't distinguish between the initial state gluons.

Introduction

- The asymmetry in $t\bar{t}$ production is predicted by the SM. Deviations from the theoretical values of the asymmetry would be a sign for physics beyond SM.
- SM predicts only a small asymmetry of around $\sim 5\%$.
- But previous measurements at TEVATRON showed that there is an asymmetry up to 15% for the differential distribution at certain angles.

The origin of the charge asymmetry

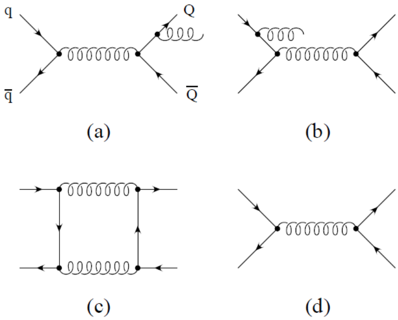


Figure: Interference of final-state (a) with initial-state (b) gluon bremsstrahlung and interference of the box (c) with the Born diagram (d).

The origin of the charge asymmetry

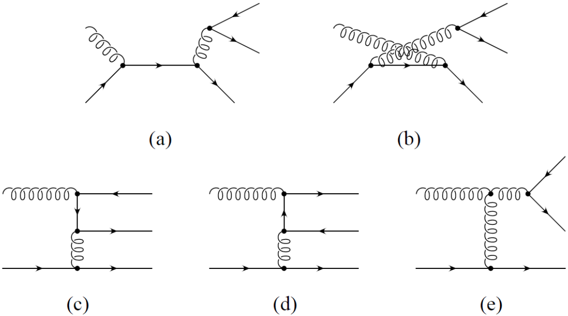


Figure: Origin of the charge asymmetry through flavor excitations. With contributions to the cross section of α_s^3.

The origin of the charge asymmetry

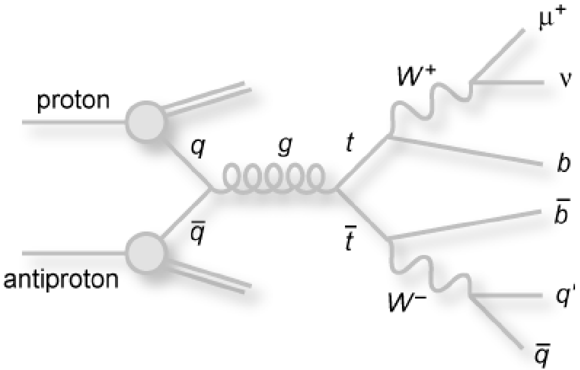
- Sum the amplitudes of the Feynman diagrams with indistinguishable final and initial states:

$$P = (A_1 + A_2) \cdot (A_1 + A_2)^* = |A_1|^2 + \mathrm{Re}(2A_1 A_2^*) + |A_2|^2 \qquad (1)$$

- This introduces an asymmetric interference term $2A_1 A_2^*$.

How to investigate the asymmetry?

We can tag top quarks through their decay $t \to b\,W^+$



Tagging

- There are three possible final states: A (all jets), B (lepton+jets), C (dilepton).

	A	B	C
b-jet	2	2	2
Hadronic jets	4	2	0
Leptons (high p_T)	0	1	2
Missing p_T	No	Yes	Yes

- Channel A has a large background due to W + jets and multijets production.
- Note: Consider efficiency and purity of b-tagging ($\epsilon \sim 60\%$).
- Finally reconstruct the invariant mass of the top quark through the analysis of the decay products (special software required).

Differential asymmetry

$$\hat{A}(\cos\hat{\theta}) = \frac{N_t(\cos\hat{\theta}) - N_{\bar{t}}(\cos\hat{\theta})}{N_t(\cos\hat{\theta}) + N_{\bar{t}}(\cos\hat{\theta})} \qquad (2)$$

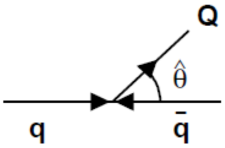


Figure: $\hat{\theta}$ is the top production angle in the restframe of $q\bar{q}$.

Because of charge conjugation symmetry (requires CP conservation):

$N_{\bar{t}}(\cos\hat{\theta}) = N_t(-\cos\hat{\theta}) \Rightarrow \hat{A}(\cos\hat{\theta})$ is a F-B asymmetry.

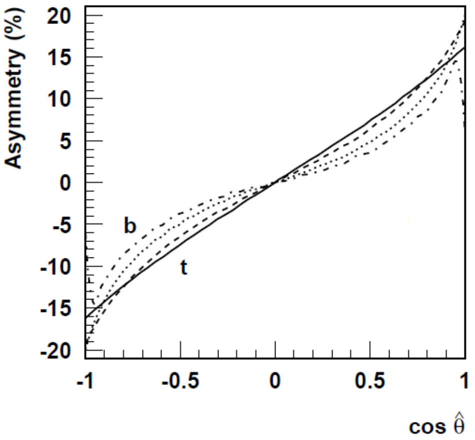


Figure: Differential charge asymmetry in top quark pair production for fixed partonic COM energy $\sqrt{\hat{s}} = 400$ GeV (solid), 600 GeV (dashed) and 1 TeV (dotted); b-quark with 400 GeV (dashed-dotted).

Integrated charge asymmetry

$$\langle \hat{A} \rangle = \frac{N_t(\cos\hat{\theta} \geq 0) - N_{\bar{t}}(\cos\hat{\theta} \geq 0)}{N_t(\cos\hat{\theta} \geq 0) + N_{\bar{t}}(\cos\hat{\theta} \geq 0)} \tag{3}$$

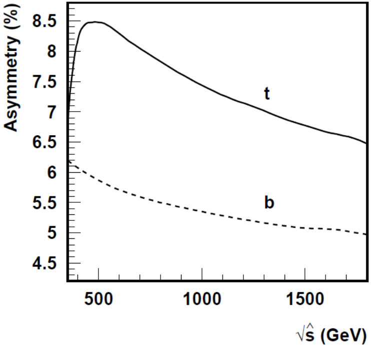


Figure: Integrated charge asymmetry for top and bottom quark pair.

Lepton asymmetry

- In addition to the $t\bar{t}$-based asymmetries, the TEVATRON experiments measure asymmetries based on the rapidities of the charged leptons from the t decay.

$$A^{l}_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)} \tag{4}$$

$$A^{ll}_{FB} = \frac{N(\Delta y_l > 0) - N(\Delta y_l < 0)}{N(\Delta y_l > 0) + N(\Delta y_l < 0)} \tag{5}$$

- With q_l the lepton charge and $\Delta y_l = y_{l^+} - y_{l^-}$.
- The A^{l}_{FB} can be measured in the $l + jets$ or dilepton channel, whereas the A^{ll}_{FB} requires the two charged leptons and is measured only in the dilepton channel.

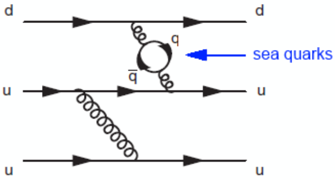
LHC vs. TEVATRON

- **TEVATRON**: $p\bar{p}$ accelerator, colliding valence quarks, well defined momenta.

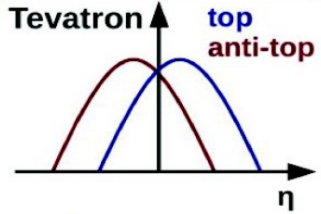
$$f_u^{(p)}(x) = f_{\bar{u}}^{(\bar{p})}(x) \tag{6}$$

- **LHC**: pp accelerator, valence quarks colliding with sea-quark, so momenta following PDF distribution.

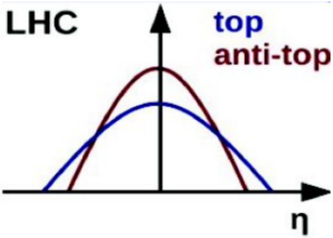
$$f_u^{(p)}(x) \neq f_{\bar{u}}^{(p)}(x) \tag{7}$$



LHC vs. TEVATRON



$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$



$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

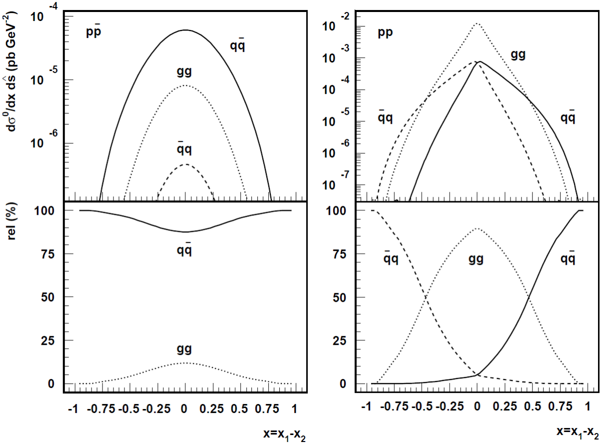
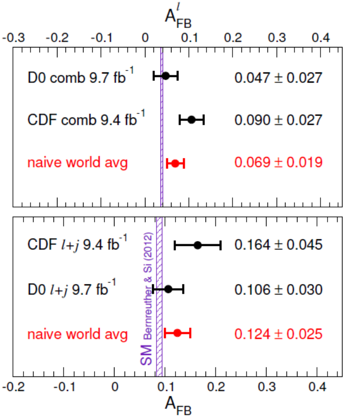
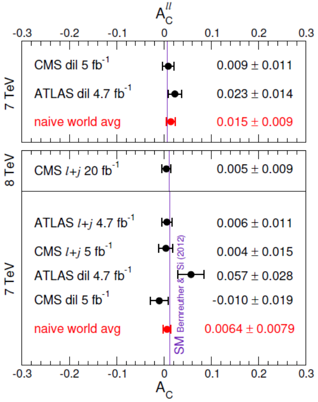


Figure: Differential cross sections and relative amount of $q\bar{q}$, $\bar{q}q$, gg initiated processes as functions of $x_1 - x_2$, for $\sqrt{s} = 1.8$ TeV in $p\bar{p}$ (left) and $\sqrt{s} = 14$ TeV in pp (right) collisions with $\sqrt{\hat{s}} = 400$ GeV.

Summary

- Experimental results from LHC and TEVATRON are so far compatible with SM expectations.





Summary

- Today's uncertainties are way too large to say the window for physics beyond SM is already closed.

- The next run of the LHC with higher energy and greater luminosity should provide better accuracy...

References

- Charge asymmetry in hadroproduction of heavy quarks, J.H. Kühn, G. Rodrigo, 1998, arXiv:hep-ph/9802268v2
- Charge asymmetry of heavy quarks at hadron colliders, J.H. Kühn, G. Rodrigo, 1998, arXiv:hep-ph/9807420v1
- Asymmetries in top quark pair production, J.A. Aguilar-Saavedra et al., 2014, arXiv:1406.1798 [hep-ph]

Backup Slide

TABLE I. Expected and observed numbers of signal and background events assuming a $t\bar{t}$ production cross section $\sigma_{t\bar{t}} = 7.45$ pb and $M_{\rm top} = 172.5$ GeV$/c^2$.

	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
W + jets	703 ± 199	170 ± 60	102 ± 37	11.6 ± 4.9	8.4 ± 3.5
Z + jets	52.3 ± 4.4	8.9 ± 1.1	5.9 ± 0.7	0.8 ± 0.1	0.5 ± 0.1
Single top	4.8 ± 0.5	10.5 ± 0.9	6.8 ± 0.6	2.2 ± 0.3	1.7 ± 0.2
Diboson	60.3 ± 5.6	11.1 ± 1.4	8.5 ± 1.1	1.0 ± 0.2	0.8 ± 0.1
Multijets	143 ± 114	34.5 ± 12.6	20.7 ± 16.6	4.4 ± 2.5	2.5 ± 2.4
Background	963 ± 229	235 ± 61	144 ± 41	19.9 ± 5.5	13.8 ± 4.2
$t\bar{t}$ signal	645 ± 86	695 ± 87	867 ± 108	192 ± 30	304 ± 47
Expected	1608 ± 245	930 ± 106	1011 ± 115	212 ± 30	318 ± 47
Observed	1627	882	997	208	275