CPT analysis with top physics

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CONTENTS

DISCRETE SYMMETRIES

1.- Charge Conjugation (C)

Turns particle into anti-particle preserving helicity

$$t^-_L \rightarrow \bar{t}^+_L$$

2.- Parity (P)

Inverts spatial coordinates and reverses helicity

$$r \rightarrow -r$$

$$t^-_L \rightarrow t^-_R$$

3.- Time reversal (T)

Reverses the direction or sing of time (τ) preserving helicity

$$\tau \rightarrow -\tau$$

$$t^-_L \rightarrow t^-_L$$

PRODUCT SYMMETRIES

4.- CP

Product of the charge conjugation (C) and Parity (P)

5.- CPT

Product of CP and the Time reversal symmetry (T)

Magnitude	P	T	C	CP	CPT
Space: $\vec{x}$	$-\vec{x}$	$\vec{x}$	$\vec{x}$	$-\vec{x}$	$-\vec{x}$
Time: t	t	$-t$	$-t$	$-t$	t
Momentum: $\vec{p}$	$-\vec{p}$	$-\vec{p}$	$\vec{p}$	$-\vec{p}$	$\vec{p}$
Energy: E	E	E	E	E	E
Angular Momentum: $\vec{L}$	$\vec{L}$	$-\vec{L}$	$\vec{L}$	$\vec{L}$	$-\vec{L}$
Spin: $\vec{s}$	$\vec{s}$	$-\vec{s}$	$\vec{s}$	$\vec{s}$	$-\vec{s}$
Charge: Q	Q	Q	$-Q$	$-Q$	$-Q$

THE NON-SYMMETRIC REALITY

C and P are maximally violated in weak interactions. CP non conservation and T violation have been observed in the neutral kaon system.

Interactions	Gravitational	Electromagnetic	Strong	Electroweak
Relative Magnitude	10^0	10^{38}	10^{40}	10^{15}
Range	∞	∞	10^{-15} m	10^{-18} m
P-conservation	$\surd$	$\surd$	$\surd$	$\times$
T-conservation	$\surd$	$\surd$	$\surd$	$\times$
C-conservation	$\surd$	$\surd$	$\surd$	$\times$
CP-conservation	$\surd$	$\surd$	$\surd$	$\times$
CPT-conservation	$\surd$	$\surd$	$\surd$	$\surd$

No experimental signature of CPT violation has been observed so far.

CPT THEOREM

CPT is the combined transformation of C, P and T, which can be applied in any order as they commute.

The CPT conservation is guaranteed by the CPT theorem, which is based on three assumptions:

1.- Locality
2.- Lorentz invariance
3.- Hermiticity of Hamiltonian

CPT Conservation

A.- Equal mass for particle and antiparticle
B.- Equal lifetime for particle and antiparticle

CPT CONSERVATION

There are not present evidence of non conservation of CPT. On the contrary , there are important tests that constraint the CPT violation.

We will focus on the CPT violation ratio associated to a a general particle “a”.

$$R_{CPT}(a) \equiv \frac{2(m_a - m_{\overline{a}})}{m_a + m_{\overline{a}}}$$

We can observe the current constraints on this ratio in the table.

Particle (a)	$R_{CPT}(a) \equiv \frac{2(m_a - m_{\overline{a}})}{m_a + m_{\overline{a}}}$
W^+	$(-2 \pm 7) \times 10^{-3}$
e^+	$< 10^{-9}$ (90% c.l.)
π^+	$(2 \pm 5) \times 10^{-4}$
K^+	$(-0.6 \pm 1.8) \times 10^{-4}$
K^0	$< 10^{-18}$ (90% c.l.) *
p	$< 10^{-8}$ (90% c.l.) *
n	$(9 \pm 5) \times 10^{-5}$

MOTIVATIONS FOR CPT STUDIES

CPT violation is a clear signal of new physics.

A.- CPT violation in the neutrino sector has been proposed to explain the LSND, atmospheric and solar oscillation data without resorting to sterile neutrinos.

H. Murayama and T. Yanagida, PLB 520, 263 (2001)	G. Barenboim *et al.*, JHEP 0210, 001 (2002)

B.- There are several CPT violating models and extensions of the Standard Model (SM), whose origin can be provided by string theory.

V.A. Kostelecky and S. Samuel, PRL 66, 1811 (1991)

However, $R_{CPT}(a)$ inconsistent with zero for any particle is a model independent signature of non conservation of CPT.

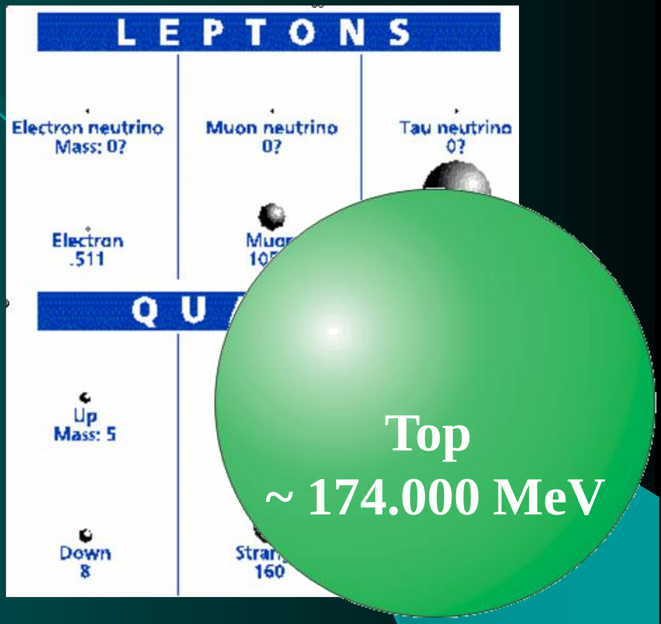
Interesting topic: testing CPT in the frontiers of the SM

TOP QUARK: border of the SM

The unique status of the top quark leads to speculate with the presence of new physics:

1.- It is the most massive elementary particle (40 times heavier than the heaviest quark).

2.- It is the only fermion with an unsuppressed coupling to the electroweak symmetry breaking sector.

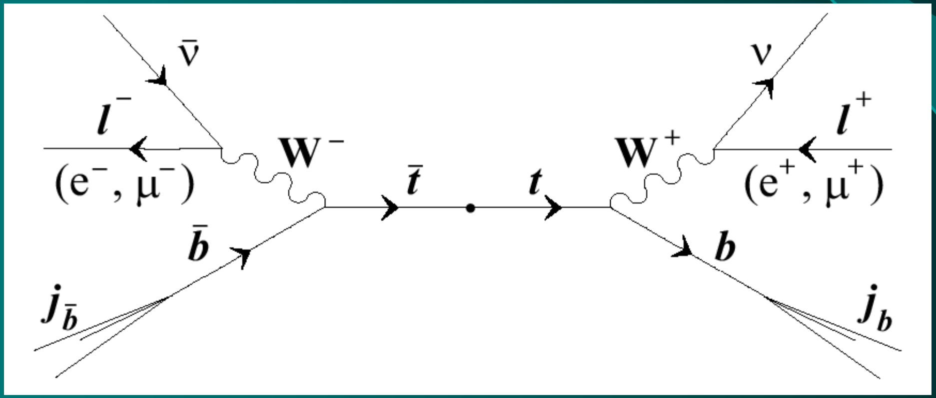


In this work we will focus on the analysis of a possible difference between the top (t) and anti-top (t) mass through the ratio:

$$R_{CPT}(t) \equiv 2(m_t - m_{\bar{t}})/(m_t + m_{\bar{t}})$$

HADRONIC COLLIDERS: di-lepton channel

The signature of a di-lepton event consists of two isolated leptons with high transverse momentum, high missing transverse energy and two jets.



Main backgrounds

a. $b\bar{b}$

b. W^+W^-+jets

c. $Z/\gamma(\to l^+l^-)$+jets

INVARIANT MASS ANALYSIS

We can reconstruct the top or anti-top mass using the invariant mass of the lepton and b quark (m_{lb}) coming from the single decay of the top or anti-top:

$$m_t{}^2 = m_W^2 + 2\langle m_{\ell b}^2\rangle/[1 - \langle\cos\theta_{\ell b}\rangle]$$

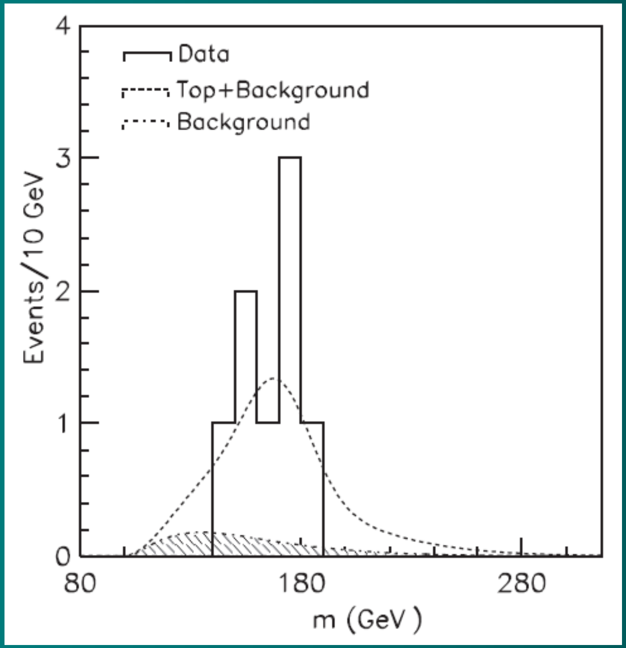
The mean value $\langle\cos\theta_{\ell b}\rangle$ can be evaluated from the SM tree-level calculation: $m_W^2/(m_t{}^2 + 2m_W^2)$.

This method is sensitive to a difference between the top and anti-top masses. Indeed, the reconstructed mass distribution should present two different peaks if we add the top and anti-top decays.

CONSTRAINTS AND PROSPECTS

We can perform a first estimation of the present constraint with the CDF data (Fermilab Tevatron). Its analysis using this technique is consistent with only one distribution peak at: $m_t = m_{\bar{t}} = 163 \pm 2(stat.) \pm 9(syst.)\ \mathrm{GeV}$

F. Abe *et al.*, PRL 80, 2779 (1998)



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Supposing the two masses centered on the central value we can compute the bound on the CPT violating ratio:

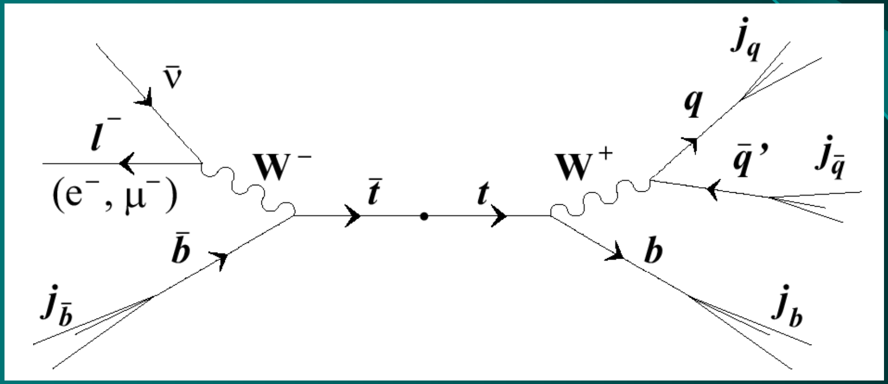
$$|R_{CPT}(t)| \ < \ 0.13$$

For the LHC, the expected statistical uncertainty has been estimated as $\pm 0.9\ \mathrm{GeV}$ **. Systematic errors due to effects of the Initial and Final State Radiation (ISR and FSR) are about** $1\ \mathrm{GeV}$**, whereas those due to varying the jet energy scale 1% are** $0.6\ \mathrm{GeV}$ **.** → $|R_{CPT}(t)| \simeq 0.026$

M. Beneke *et al.*, hep-ph/0003033

HADRONIC COLLIDERS: lepton + jets

A more promising signal is provided when one of the W decays leptonically whereas the other one has associated a hadronic decay.



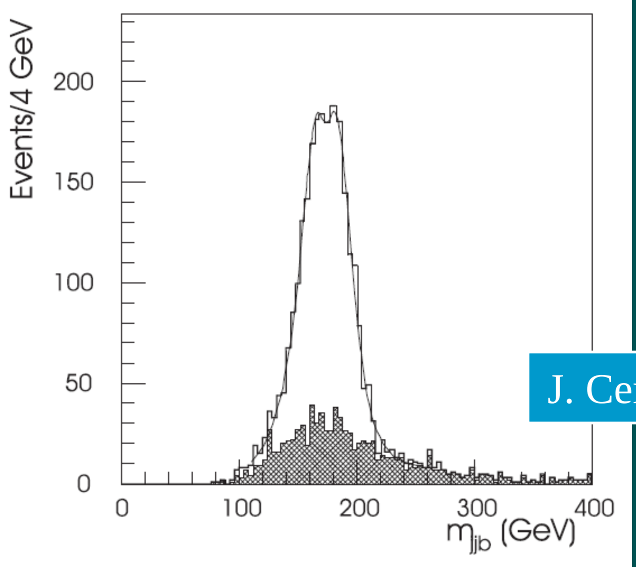
Main backgrounds

$$b\bar{b},\ Z(\to l^+l^-)Z(\to q\bar{q}),\ W(\to l\nu)Z(\to q\bar{q}),\ W(\to l\nu)W(\to q\bar{q}),\ Z(\to l^+l^-)+jets,\ W(\to l\nu)+jets \text{ and } W(\to l\nu)q\bar{q}$$

INVARIANT MASS ANALISIS

We can reconstruct the top or anti-top mass using the invariant mass associated to the hadronic decay (m_{jjb}).

If the masses of the top and anti-top are different we should find two peaks when we plot the events in function of the invariant mass m_{jjb} .



J. Cembranos *et al.*, EPL 82, 21001 (2008)

CONSTRAINTS AND PROSPECTS

An analogous estimation using the data of CDF and D0 provides a more constraining bound:

Experiment		$\lvert R_{CPT}(t)\rvert$ (95% c.l.)
D0	B. Abbott *et al.*, PRL 79, 1197 (1997)	$< 10.9 \times 10^{-2}$
CDF	F. Abe *et al.*, PRL 80, 2767 (1998)	$< 10.1 \times 10^{-2}$
combined		$< 9.2 \times 10^{-2}$

These constraints are dominated by systematic errors coming from the jet energy scale and gluons with high transverse momentum.

For the LHC, the expected statistical error has been estimated as $\pm 0.25\ \text{GeV}$, which remains well below the systematic uncertainties, that can be reduced up to $1\ \text{GeV}$ by using samples with high transverse momentum (the main sources are associated to the Jet energy scale, b-quark fragmentation, the background and the ISR and FSR)

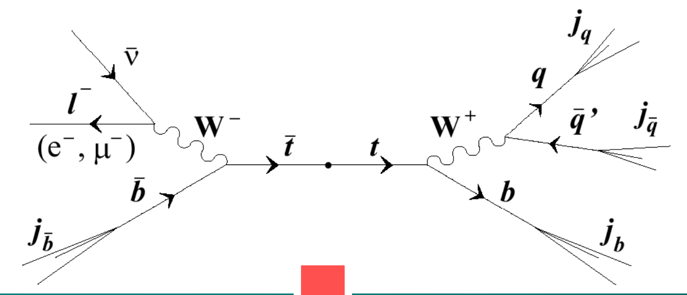
M. Beneke *et al.*, hep-ph/0003033

$\Rightarrow$ $\lvert R_{CPT}(t)\rvert \simeq 0.014$

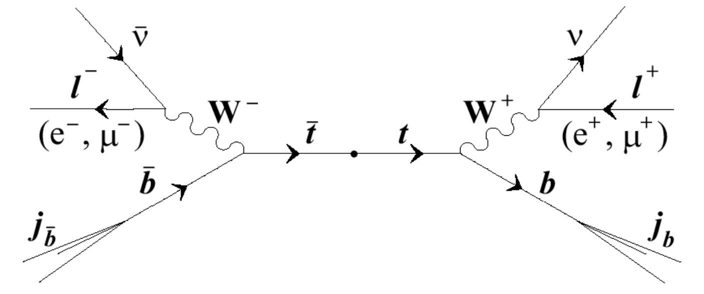
ILC: top anti-top quark production

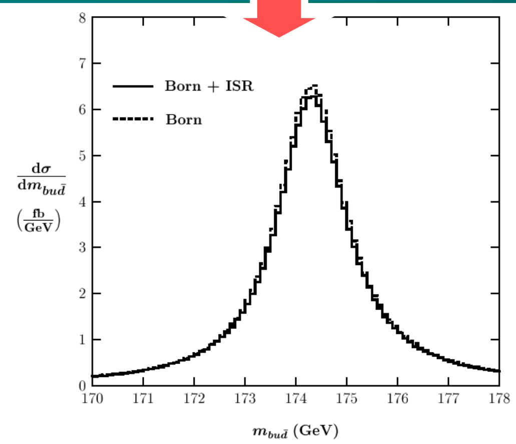
We can study the top anti-top quark production in the same way that for Hadronic colliders:

Lepton+Jets channel



Di-lepton channel





The ILC presents fewer statistics than the LHC, but the systematic uncertainties are reduced. This fact improves the total sensitivity.

ISR analysis | $e^+e^- \to bu\bar{d}\bar{b}\mu^-\nu_\mu$ | $\sqrt{s} = 500$ GeV

A. Biernacik, K. Kolodziej, A. Lorca and T. Riemann, hep-ph/0311097

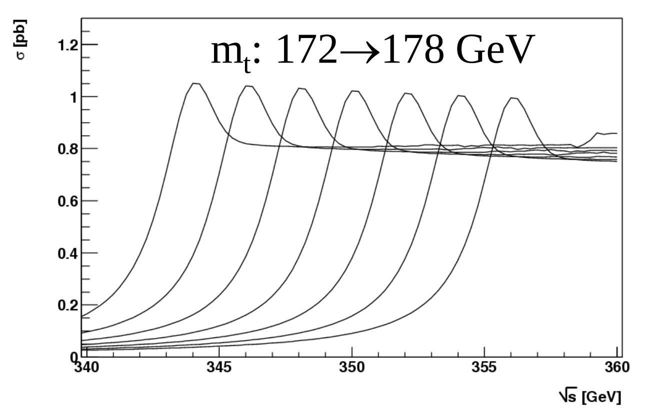
OTHER POSIBLE ANALISES

There are many other interesting possibilities to study CPT non conservation in the top quark phenomenology

1. Threshold scan at a LC

   High precision: $\Delta m \sim 100$ MeV

   Model dependent

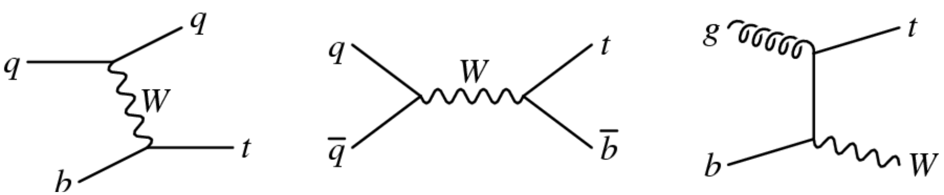


S. Boogert and D. Miller, ALCPG, Victoria (2004)

2. Analysis of the J/ψ from the b decay in the LHC

   Improvement of the systematic uncertainties

3. Single top production



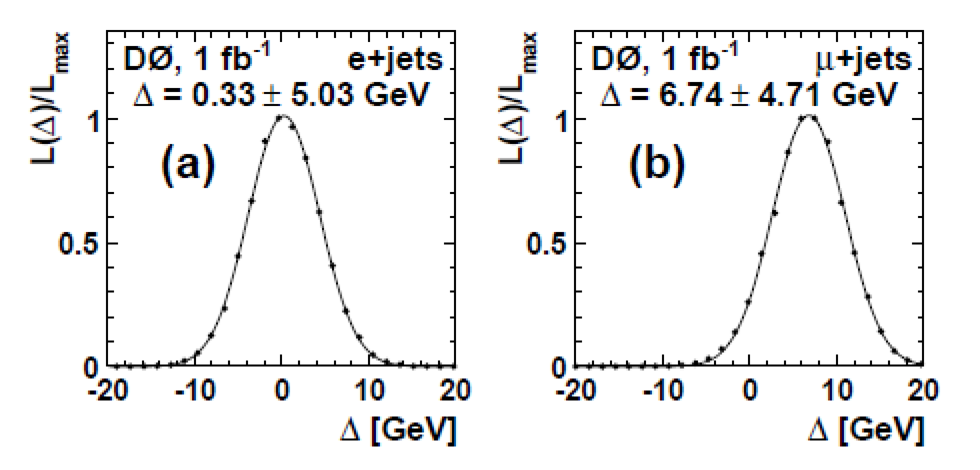
Feyman diagrams for single-top production in hadronic colliders

…

n. Combination of different measurements.

IMPROVEMENTS

Tevatron precision has improved in a very important way for top measurements.



V. Abazov *et al.*, (D0) PRL 103, 132001 (2009)

Fundamentally, improvement on the control of systematic uncertainties.

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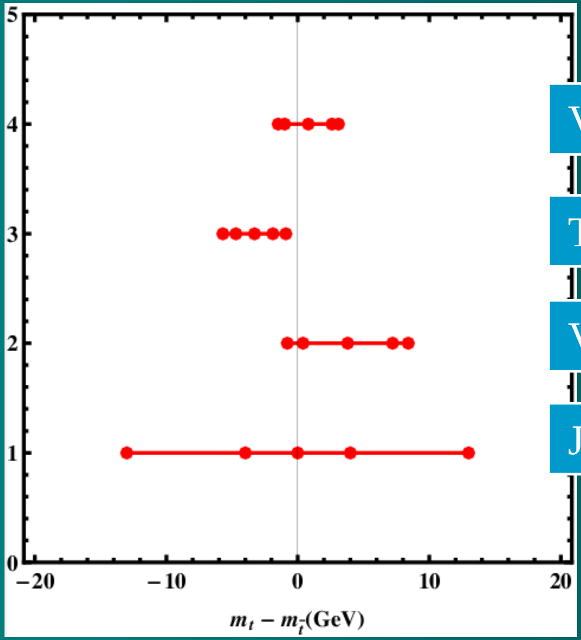

$$\Delta m = 0.84 \pm 1.81\ (\text{stat.}) \pm 0.48\ (\text{syst.})\ \text{GeV}.$$

V. Abazov *et al.*, (D0) PRD 84, 052005 (2011)

T. Aaltonen *et al.*, (CDF) PRL 106, 152001 (2011)

V. Abazov *et al.*, (D0) PRL 103, 132001 (2009)

J. Cembranos *et al.*, EPL 82, 21001 (2008)

Fundamentally, improvement on the control of systematic uncertainties.

CONCLUSIONS

1.- The precision measurements inside the top sector have began with the second run at the Tevatron.

2.- We have introduced the possibility to observe evidences of CPT violation associated with the top quark.

3.- We have performed a model independent analysis parameterized by the mass difference between top and antitop quarks:

$$R_{CPT}(t) \equiv 2(m_t - m_{\bar{t}})/(m_t + m_{\bar{t}})$$

4.- Present bound by D0 collaboration is: $R_{CPT} < 0.029$.

3.- The sensitivity of the LHC and the ILC can reach the below 1% level:

$$\Delta m_{\mathrm{t}} = -0.44 \pm 0.46 \;(\mathrm{stat.}) \pm 0.27 \;(\mathrm{syst.})\,\mathrm{GeV}$$

$R_{CPT} < 0.0094$.

S. Chatrchyan *et al.*, (CMS) arXiv: 1204.2807 (2009)

D0 SYSTEMATICS

Important improvements in the systematic uncertainties:

Dominated by several theoretical issues

and b-tagging efficiency.

Source	Change in Δm (GeV)
Modeling of physical processes:	
Higher-order corrections	0.26
ISR/FSR	0.21
Hadronization and underlying event	0.23
Color reconnection	0.27
b-fragmentation	0.03
PDF uncertainty	0.10
Multiple hadron interactions	0.06
Modeling of background	0.07
Heavy-flavor scale factor	0.02
Modeling of detector:	
Trigger selection	0.07
b-tagging efficiency	0.25
Momentum scale for e	0.05
Momentum scale for μ	0.06

V. Abazov *et al.*, (D0) PRD 84, 052005 (2011)