Rare & exclusive W decays in a $t\bar{t}$ environment

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Valencia

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in collaboration with Michelangelo Mangano
W decay table

PDG table, [http://pdg.lbl.gov](http://pdg.lbl.gov)

<table>
<thead>
<tr>
<th>W⁺ DECAY MODES</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
<th>Confidence level</th>
<th>$p$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell^+ \nu$</td>
<td>[b] (10.80 ± 0.09)%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+ \nu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^+ \nu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau^+ \nu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hadrons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \gamma$</td>
<td>&lt; 8 $\times 10^{-5}$</td>
<td>95%</td>
<td>40192</td>
</tr>
<tr>
<td>$D^+_s \gamma$</td>
<td>&lt; 1.3 $\times 10^{-3}$</td>
<td>95%</td>
<td>40168</td>
</tr>
<tr>
<td>$cX$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c\bar{s}$</td>
<td>(33.4 ± 2.6)%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>invisible</td>
<td>[c] (1.4 ± 2.9)%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CDF limit: $< ~7 \times 10^{-6}$
# Z decay table

PDG table, [http://pdg.lbl.gov](http://pdg.lbl.gov)

<table>
<thead>
<tr>
<th>Z DECAY MODES</th>
<th>Fraction ( (\Gamma_i/\Gamma) )</th>
<th>Scale factor/Confidence level</th>
<th>( p ) (MeV/c)</th>
<th>( X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^+ e^- )</td>
<td>(3.363 ± 0.004) %</td>
<td>( \chi_{c2}(1P)X )</td>
<td>45594</td>
<td>( \tau(1S)X + \tau(2S)X + \tau(3S)X )</td>
</tr>
<tr>
<td>( \mu^+ \mu^- )</td>
<td>(3.366 ± 0.007) %</td>
<td>( \tau(1S)X )</td>
<td>45594</td>
<td>( \tau(2S)X )</td>
</tr>
<tr>
<td>( \tau^+ \tau^- )</td>
<td>(3.370 ± 0.008) %</td>
<td>( \tau(1S)X )</td>
<td>45599</td>
<td>( \tau(3S)X )</td>
</tr>
<tr>
<td>( \ell^+ \ell^- )</td>
<td>[b] (3.3658 ± 0.0023) %</td>
<td>( (D^0/D^0)X )</td>
<td>-</td>
<td>( D^\pm X )</td>
</tr>
<tr>
<td>invisible hadrons</td>
<td>(4.2 ± 0.9) × 10^{-6}</td>
<td>( D^*(2010)^\pm X )</td>
<td>45594</td>
<td>( D_s(2536)^\pm X )</td>
</tr>
<tr>
<td>( (u\bar{u}+c\bar{c})/2 )</td>
<td>(20.00 ± 0.06) %</td>
<td>( D_s(2573)^\pm X )</td>
<td>-</td>
<td>( D^*(2629)^\pm X )</td>
</tr>
<tr>
<td>( (d\bar{d}+s\bar{s}+b\bar{b})/3 )</td>
<td>(69.91 ± 0.06) %</td>
<td>searched for</td>
<td>-</td>
<td>( B^+X )</td>
</tr>
<tr>
<td>( c\bar{c} )</td>
<td>(11.6 ± 0.6) %</td>
<td>searched for</td>
<td>-</td>
<td>( B^0X )</td>
</tr>
<tr>
<td>( b\bar{b} )</td>
<td>(15.6 ± 0.4) %</td>
<td>searched for</td>
<td>-</td>
<td>( B^+X )</td>
</tr>
<tr>
<td>( b\bar{b}b\bar{b} )</td>
<td>(12.03 ± 0.21) %</td>
<td>searched for</td>
<td>-</td>
<td>( \Lambda^cX )</td>
</tr>
<tr>
<td>( g g g )</td>
<td>(15.12 ± 0.05) %</td>
<td>searched for</td>
<td>-</td>
<td>( \Xi^c_0X )</td>
</tr>
<tr>
<td>( \pi^0 \gamma )</td>
<td>(3.6 ± 1.3) × 10^{-4}</td>
<td>searched for</td>
<td>-</td>
<td>( \Xi^bX )</td>
</tr>
<tr>
<td>( \eta \gamma )</td>
<td>&lt; 1.1 %</td>
<td>( \eta \gamma )</td>
<td>-</td>
<td>( \gamma \gamma )</td>
</tr>
<tr>
<td>( \omega \gamma )</td>
<td>&lt; 5.2 × 10^{-5}</td>
<td>( \omega \gamma )</td>
<td>-</td>
<td>( \gamma \gamma )</td>
</tr>
<tr>
<td>( \eta(958) \gamma )</td>
<td>&lt; 5.1 × 10^{-5}</td>
<td>( \eta(958) \gamma )</td>
<td>-</td>
<td>( \gamma \gamma )</td>
</tr>
<tr>
<td>( \gamma \gamma )</td>
<td>&lt; 6.5 × 10^{-4}</td>
<td>( \gamma \gamma )</td>
<td>-</td>
<td>( \gamma \gamma )</td>
</tr>
<tr>
<td>( \gamma \gamma \gamma )</td>
<td>&lt; 4.2 × 10^{-5}</td>
<td>( \gamma \gamma \gamma )</td>
<td>-</td>
<td>( \gamma \gamma \gamma )</td>
</tr>
<tr>
<td>( \rho^\pm \rho^\mp )</td>
<td>&lt; 6.5 × 10^{-4}</td>
<td>( \rho^\pm \rho^\mp )</td>
<td>-</td>
<td>( \rho^\pm \rho^\mp )</td>
</tr>
<tr>
<td>( J/\psi(1S)X )</td>
<td>(3.51 ± 0.23) × 10^{-3}</td>
<td>( J/\psi(1S)X )</td>
<td>-</td>
<td>( J/\psi(1S)X )</td>
</tr>
<tr>
<td>( \psi(2S)X )</td>
<td>(1.60 ± 0.29) × 10^{-3}</td>
<td>( \psi(2S)X )</td>
<td>-</td>
<td>( \psi(2S)X )</td>
</tr>
<tr>
<td>( \chi_{c1}(1P)X )</td>
<td>(2.9 ± 0.7) × 10^{-3}</td>
<td>( \chi_{c1}(1P)X )</td>
<td>-</td>
<td>( \chi_{c1}(1P)X )</td>
</tr>
</tbody>
</table>

Note: \( S \) stands for the survival probability.
No limits set on interesting rare decays e.g. lepton number / flavour violating.

Order of magnitude less precision on known branching ratios of W to leptons than the Z boson.
No exclusive hadronic decay mode of any fundamental standard model boson has ever been observed

Higgs exclusive decays - recent theoretical interest. Need (future) hadron collider statistics

In this study: $W \rightarrow \pi \gamma \quad W^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}$ and related decays

1st excl. had. measurement possible at LHC
Experimental knowhow, open up further techniques.
“LHC is a top factory”

There are $\sim 3 \times 10^9 \bar{t}t$ events by the end of the HL-LHC run

Tag on $b$-jets & lepton and missing $E_t$

Small QCD background

$\sim 10^9 W$ bosons on other side of event to study
Exclusive hadronic $W$ decays

• $W$
Exclusive hadronic $W$ decays
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10^10 Ws

Some 3 particle decays produced by PYTHIA:

W^± → π^± π^± π^±
W^± → π^± K^+ K^−
W^± → π^± p p̅
W^± → π^± n^0 n̅^0
W^± → π^± γ π^0
Exclusive hadronic W decays

Branching ratio for \( W^\pm \rightarrow \pi^\pm \pi^+ \pi^- \)

Pythia gives \(10^{-6}\) to \(10^{-7}\) but large experimental (LEP) error

Possible resonance through \( W \rightarrow \pi \rho \rightarrow \pi \pi \pi \)

Certainly \(10^{-5}\) not excluded

Branching ratio for \( W \rightarrow \pi \gamma \)

Arnellos, Marciano, Parsa, ’81 \(~3.10^{-9}\)

Keum & Pham, ’94 \(\sim10^{-8}\) to \(10^{-6}\)
Exclusive hadronic W decays

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- W
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Possible resonance through

$W \rightarrow \pi \rho \rightarrow \pi \pi \pi$

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Branching ratio for $W \rightarrow \pi \gamma$

$\sim 10^{-9}$

$\int d^4x < \pi | T[J^\mu_W(x) J^\lambda_\gamma(0)] | 0 >$

use Operator Product Expansion

$J^\mu_W(x) J^\lambda_\gamma(0) = \sum_i C_i(x) O_i(0)$
Monte Carlo Study

Signal sample: $p \ p \rightarrow t \ \bar{t} \rightarrow W^{+} \ l^{-} \ \nu l \ b \ b$, with $W^{+} \rightarrow (\pi \ \pi \ \pi)$ or $(\pi \ \gamma)$

Background samples: $p \ p \rightarrow t \ \bar{t} \rightarrow W^{+} \ l^{-} \ \nu l \ b \ b$, with $W^{+} \rightarrow$ more than $3/2$ particles

Send to PYTHIA 8

1. **Require t tbar selection cuts**
   
   2 b-tagged jets: fastjet, anti-kT, $p_{T}>20$ GeV, $|\eta|<2.5$, $R=0.4$
   
   1 electron or muon $p_{T}>20$ GeV and $|\eta|<2.5$
   
   Missing $p_{T}>30$ GeV

2. **Remove hadrons in the b-jets from the event**

3. **Single particle jet isolation**

   A single particle jet means a jet with constituents of one charged hadron
   Define a “single” photon-jet’ which consists of purely photons

   Require single particle jets for the signal (3 π-jets, or 1 π-jet & 1 γ-jet), allowing the jet parameter $R=R_{iso}$ to vary
Monte Carlo Study

$W \rightarrow \pi \gamma$

$\sim 3$ sigma discovery

with a BR $\sim 3 \times 10^{-7}$

Probing upper limit, best exclusion can be set

$W^\pm \rightarrow \pi^\pm \pi^+ \pi^-$

Sensitivity to a BR of few $\times 10^{-7}$

Well within expected SM region
Related decays

Replace $\pi$ with $K$ or $p$

Analysis remains unchanged (particle ID on statistical basis)

Possible decay $W \rightarrow u/c, d/s$

E.g. $W \rightarrow K\pi\pi$ vs $W \rightarrow \pi\pi\pi$
gives info on $V_{us}$ vs $V_{ud}$

Decays to whole spectrum of higher spin mesons and baryons which decay with distinctive signatures before detector e.g. $W \rightarrow D, D_s, B$ mesons — to be studied in more detail
Conclusions

- $t\bar{t}$ events provide promising environment under which to study rare $W$ decays. $\sim 10^9$ such $W$s at the LHC.
- Improve PDG $W$ decay table - add new decays (e.g. lepton number/flavour violating searches) and reduce errors on known branching ratios.
- LHC could access a spectrum of rare exclusive hadronic decays, here we highlight three-hadron decays as particularly promising.
- Would be first excl. had. measurement of a fundamental boson. Test & develop new experimental techniques, application to Higgs, further understanding of strong dynamics.