Searching for $t\bar{t}$ Resonances at the LHC

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1 – Introduction

- Many models of new physics predict new particles with mass in the TeV range which decay into a $t\bar{t}$ pair:
  - ☞ topcolor and Little Higgs models predict weakly coupled new vector bosons
  - ☞ ED models can have Kaluza-Klein (KK) excitations of the graviton, the weak and strong gauge bosons
  - ☞ axial vector bosons appear in torsion gravity models
  - ☞ resonances in the $t\bar{t}$ channel also appear in technicolor, chiral color, and models with a strong $SU(3) \times SU(3)$ gauge symmetry

- In some models, the couplings of the new particles to light quarks and gluons are suppressed, and the $t\bar{t}$ final state becomes their main discovery channel
  Example: bulk Randall-Sundrum models

- Searching for resonances in the $t\bar{t}$ channel at the LHC appears to be easy:
  - ☞ Select lepton+jets final state $t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu q\bar{q}'b\bar{b}$ $(\ell = e,\ \mu)$
  - ☞ Impose standard selection criteria:
    - → electron or muon
    - → missing E_T
    - → two b-tagged jets
    - → two or more jets which are not tagged
    - → standard p_T, rapidity and separation cuts

- ☞ Solve for longitudinal momentum of the ν assuming lepton and neutrino originate from $W \to \ell\nu$
- ☞ reconstruct $t\bar{t}$ invariant mass, $m(t\bar{t})$
- This works well for low invariant masses, but not in the TeV region

2 – Why Standard Cuts won't cut it

- Problems at high p_T and/or $t\bar{t}$ invariant masses:
  - ☞ top quark decay products are highly boosted → almost collinear
  - ☞ lepton frequently not isolated
  - ☞ jets from $t \to bjj$ often overlap or merge
  - ☞ frequently there are less than 4 observable jets in the final state
  - ☞ the b-tagging efficiency may be significantly smaller, and the light jet misidentification probabilities considerably larger than at low energies:

    ATLAS study: for $m(t\bar{t}) = 3$ TeV: $\epsilon_b = 0.2$, $P_{j\to b} \approx 1/30$
- consider final states with 2, 3 or 4 jets and one or two b-tags

3 – Background Analysis

- Main backgrounds contributing to $\ell\nu + n$ jet final state with $n = 2, 3, 4$:
  - ☞ $Wb\bar{b} + m$ jet production ($m = 0, 1, 2$)
  - ☞ $(Wb + W\bar{b})j + m$ jets
  - ☞ $Wjj + m$ jets
  - ☞ $(t\bar{b} + \bar{t}b) + m$ jets and $(t + \bar{t})j + m$ jets with $t \to b\ell\nu$
  - ☞ Wbt, Wt and Wjt production with $t \to bjj$
- The $Wb\bar{b} + m$ jets and $Wjj + m$ jets background are calculated with `ALPGEN`; all others with `MADEVENT`

- Reduce background by imposing a cluster transverse mass cut

$$|m_T(b_{min}\ell) - m_t| < 20 \text{ GeV}$$

where

$$m_T^2(b_{min}\ell) = \left(\sqrt{p_T^2(b_{min}\ell) + m^2(b_{min}\ell)} + \not{p}_T\right)^2 - \left(\vec{p}_T(b_{min}\ell) + \vec{\not{p}}_T\right)^2$$

$p_T(b_{min}\ell)$ ($m(b_{min}\ell)$): tr. momentum (invariant mass) of $b_{min}\ell$ system

b_{min}: b- or $\bar{b}$-quark with the smaller separation from the charged lepton

- Further reduce background by imposing

$$|m(t \to jet(s)) - m_t| < 20 \text{ GeV}$$

on jets from hadronic top decay

4 – KK gluons: Discovery Limits

- Models considered here:
  - ☞ basic RS model with the SM in the bulk (Lillie et al.)
  - ☞ models with a large brane kinetic term κr_{IR} (Davoudiasl et al., Carena et al.)
  - ☞ a model with $SO(5) \times U(1)_X$ bulk gauge symmetry and $N = 0$ or $N = 1$ additional KK custodial partner quarks which are light enough that G can decay into them
- the KK gluons of these models couple uniformly to left-handed and right-handed light quarks $q = u,\, d,\, s,\, c$
- they do not couple vector-like to the quarks of the third generation

- include full spin correlations and interference with SM $t\bar{t}$ amplitude in calculation of KK gluon cross section
- couplings:

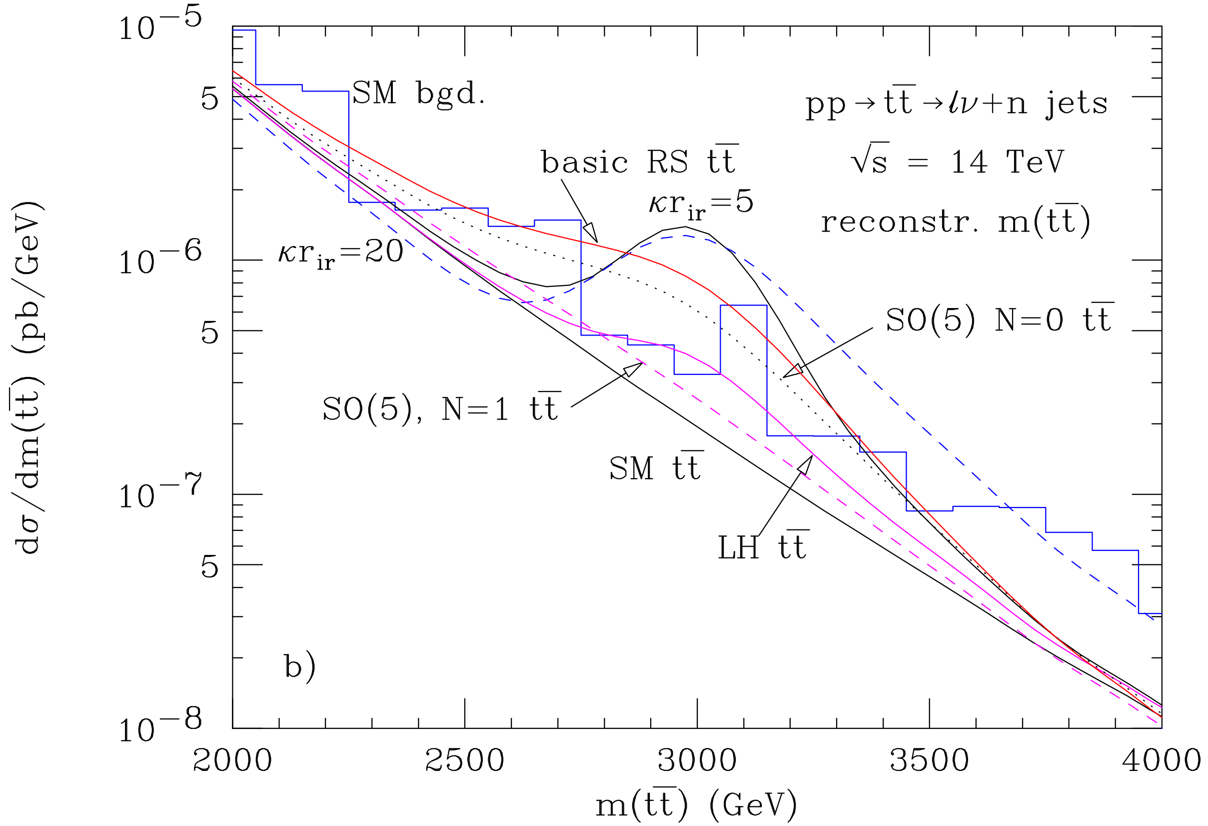
Model	g^q	$g^b_L = g^t_L$	g^b_R	g^t_R
Basic RS	$-0.2g_s$	g_s	$-0.2g_s$	$4g_s$
$\kappa r_{IR} = 5$	$-0.4g_s$	$-0.2g_s$	$-0.4g_s$	$0.6g_s$
$\kappa r_{IR} = 20$	$-0.8g_s$	$-0.6g_s$	$-0.8g_s$	$-0.2g_s$
$SO(5)$	$-0.2g_s$	$2.76g_s$	$-0.2g_s$	$0.07g_s$

g_s: QCD coupling constant

In the basic RS and $SO(5)$ model the coupling to light quarks are suppressed

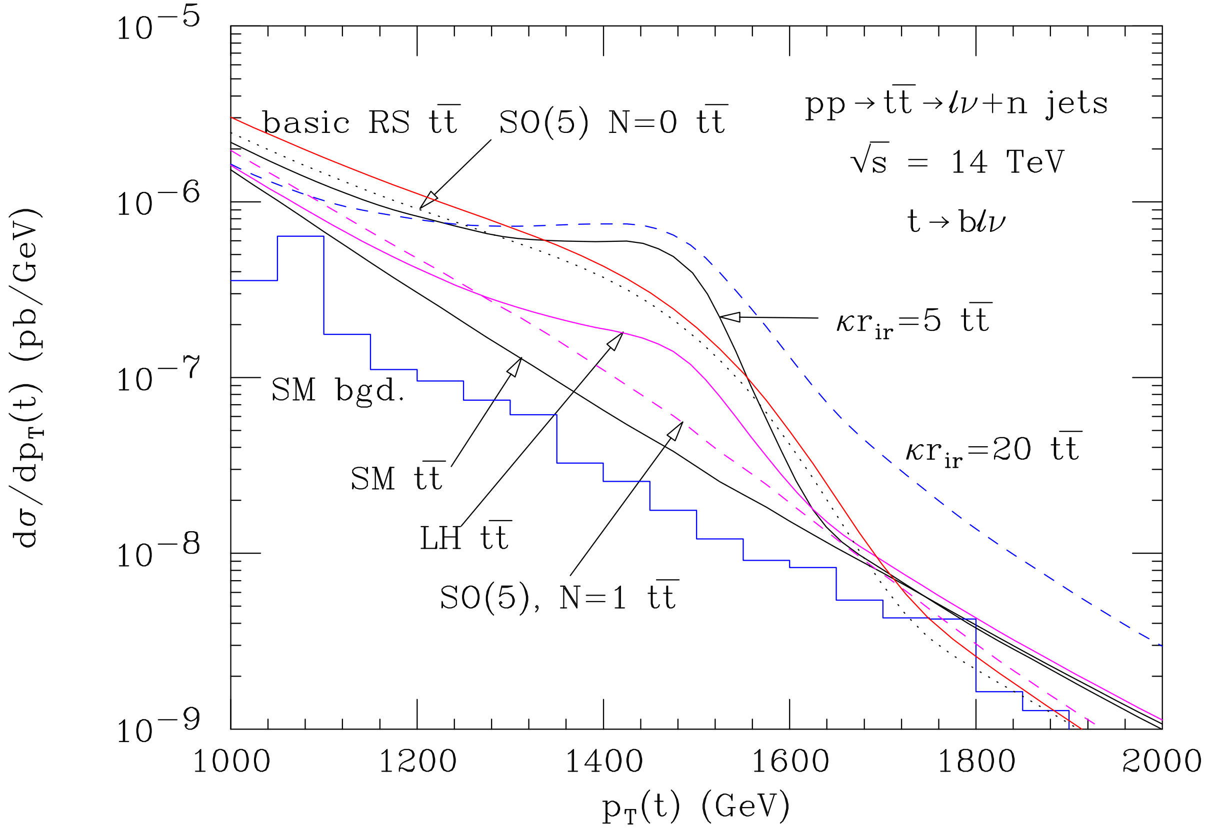
- for comparison, include Z_H of Littlest Higgs model with $\cot\theta = 1$

$m(t\bar{t})$ distribution:



- The background will substantially impact the search for KK gluons

$p_T(t \to b\ell\nu)$ distribution:



- Background is significantly smaller than for $m(t\bar{t})$ distribution
- drawback of p_T distribution: information from longitudinal component is lost

Deriving Discovery Limits

- Use log-likelihood test to derive 5σ discovery limits
- Combine $m(t\bar{t})$ and $p_T(t)$ distributions to derive discovery limits
- for comparison, we also list limits for Z_H boson (with $\cot\theta = 1$) and KK graviton in basic bulk RS model (Fitzpatrick et al.)

Model	limit 100 fb^{-1}	limit 300 fb^{-1}
Basic RS	3.8 TeV	4.3 TeV
$\kappa r_{IR} = 5$	3.4 TeV	3.9 TeV
$\kappa r_{IR} = 20$	3.5 TeV	4.1 TeV
$SO(5)$, $N = 0$	3.4 TeV	4.0 TeV
$SO(5)$, $N = 1$	2.4 TeV	3.0 TeV
Z_H	2.6 TeV	2.8 TeV
KK graviton	1.3 TeV	1.4 TeV

Discriminating KK Gluon Models

- One can also ask how well the LHC will be able to discriminate between various KK gluon models
- Example: $M_G = 3$ TeV, assume 100 fb^{-1}
- construct "discrimination matrix" (symmetric in limit of large statistics)

Model	basic RS	$\kappa r_{IR} = 5$	$\kappa r_{IR} = 20$	SO(5), N=0	SO(5), N=1
basic RS	0.0σ	6.1σ	10.5σ	3.1σ	7.5σ
$\kappa r_{IR} = 5$		0.0σ	5.2σ	4.3σ	7.3σ
$\kappa r_{IR} = 20$			0.0σ	7.8σ	9.9σ
$SO(5), N = 0$				0.0σ	4.8σ
$SO(5), N = 1$					0.0σ

5 – Conclusions

- Searching for new physics in the $t\bar{t}$ final state in the TeV region poses a number of problems
- because of low b-tagging efficiency need to include final states with one b-tag → background increases
- because of merging/overlapping jets need to include final states with two and three jets
- with cluster transverse mass and invariant mass cuts backgrounds can be suppressed to a manageable level
- background for the p_T distribution is smaller than for $m(t\bar{t})$ distribution
- can discover KK gluons in $t\bar{t}$ final state with mass up to $3.5 - 4.3$ TeV