Searching for New Physics in $t\bar{t} \to jj$ Production at the LHC

UB, Y. Cheung
in preparation

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Ulrich Baur
State University of New York at Buffalo

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
- Resonances in the $t\bar{t}$ channel have to have masses typically ≥ 2 TeV to satisfy constraints imposed by precision electroweak data
- Problems encountered in searching for TeV scale resonances in the $t\bar{t}$ channel: At high p_T and/or high $t\bar{t}$ invariant masses
  - ☞ top quark decay products are highly boosted ➞ almost collinear
  - ☞ lepton in $t\bar{t} \to$ lepton+jets channel is 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: for $m(t\bar{t}) = 3$ TeV: $\epsilon_b = 0.2$, $P_{j\to b} \approx 1/30$

- Conservative approach:
  - ☞ consider final states with 2, 3 or 4 jets and one or two b-tags
- can discover KK gluons in the $t\bar{t} \rightarrow$ lepton+jets channel with mass M_G up 4 TeV at the LHC ($\sqrt{s} = 14$ TeV) with 300 fb^{-1} using this approach (UB, L. Orr), and
- can distinguish various bulk RS models at the $4 - 10\sigma$ level, and
- can measure the couplings of KK gluons with a precision of $5 - 50\%$

- more sophisticated:
  - ☞ use top-tagging: discriminate jets from top decays from ordinary QCD jets using e.g. the jet invariant mass
- In all-hadronic top decays at high energies, each top-quark tends to produce one “fat” jet, $t\bar{t} \to jj$
- we examine the potential of the LHC to search for KK gluons in all-hadronic top decays, using top-tagging
- some KK-gluons also have a significant coupling to light quarks: search in the jj channel without top tagging

2 – Top-tagging

- Exploit invariant mass constraint and substructure of top jets
- similar ideas have been used to identify boosted $H \longrightarrow b\bar{b}$ (Butterworth *et al.*, Plehn *et al.*)
- Several approaches have been discussed in recent literature, which I will briefly summarize now
- Jet substructure observables such as the energy sharing variable (Thaler, Wang)
- Detailed analysis using jet invariant mass (Almeida *et al.*)
- Jet mass and “Ysplitter” (Brooijmans (ATLAS))
- Lifetime signature (Vos (ATLAS))

- Jet pruning (Ellis *et al.*)
- Jet trimming (Krohn *et al.*)
- VR algorithm (jets with variable $R \sim 1/p_T$) (Krohn *et al.*)
- we use the top-tagging efficiencies and light jet mistag probabilities of Kaplan *et al.*, as determined by CMS (CMS PAS JME-09-001)

Top-tagging algorithm

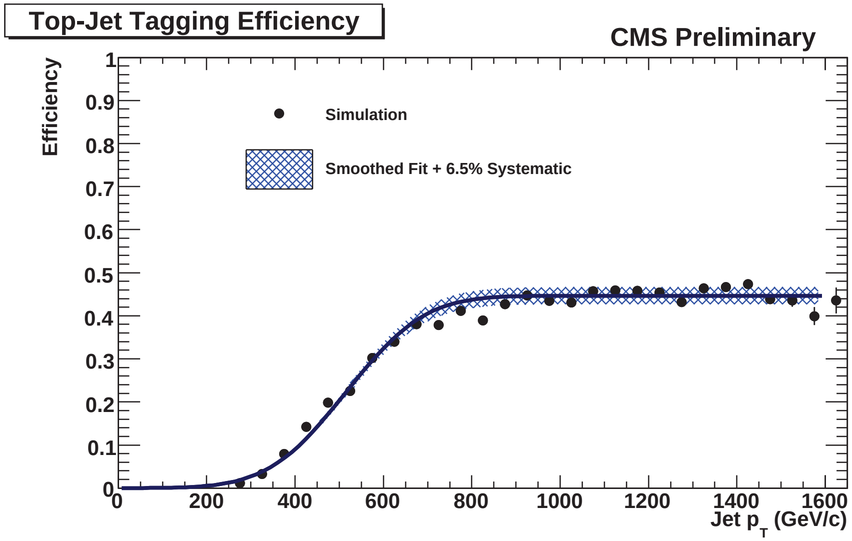
- taken from CMS PAS JME-09-001
- Use Cambridge-Aachen (k_T-like) algorithm to cluster particles
- require $p_T(j) > 250$ GeV, $|y(j)| < 2.5$
- find (up to 4) subjets
- require

  $$100 \text{ GeV} < m(j) < 250 \text{ GeV}$$

  to be roughly consistent with top mass
- construct pairs of the three highest p_T subjets, and require the minimum pairwise mass m_{min} to be

  $$m_{min} > 50 \text{ GeV}$$

Top-tagging Efficiency



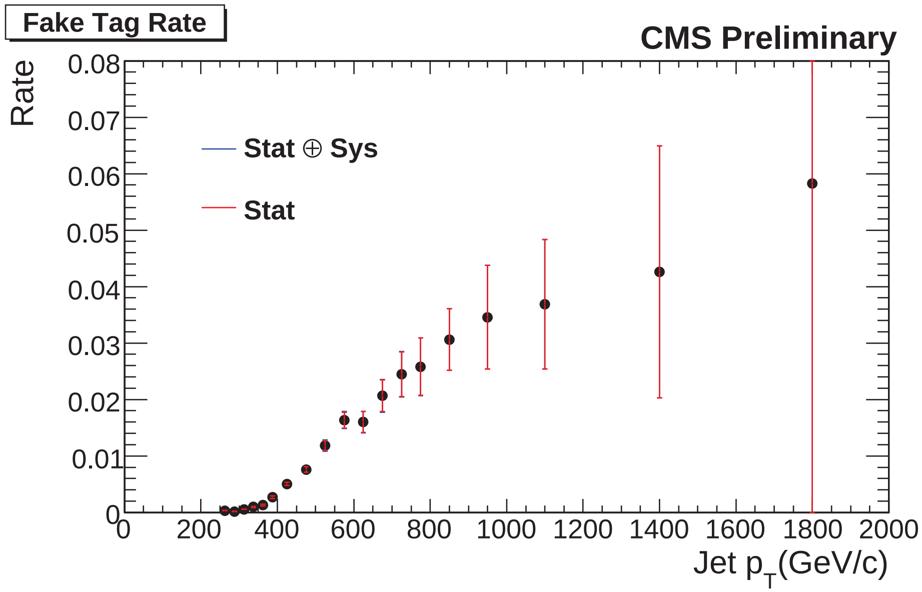
- CMS parametrizes the top-tagging efficiency via

$$\epsilon_t = 0.45 \frac{1}{2} \left(1 - erf \left(\frac{p_T - 516}{197} \right) \right)$$

with p_T being the top quark transverse momentum in GeV.

- at small p_T, ϵ_t is small: most top decays result in more than one (well separated) jet

Light jet mistagging probability P_j



- statistical errors are for simulated 100 pb^{-1} will hopefully improve
- in the following, we use the central values
- for $p_T > 1.8$ TeV, we explore 2 possibilities:

  ➡ a constant $P_j = P_j(1.8\ \mathrm{TeV})$ (P_{const} scenario)

  ➡ a linearly rising P_j with the slope determined from the last two points (P_{rise} scenario)

- questions to be answered:
  - ☞ is the mistagging probability small enough to make the all-hadronic channel competitive to the semileptonic final state?
  - ☞ how strongly do results depend on P_j?

3 – Searching for KK gluons in $t\bar{t} \to jj$ and jj Production

- 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

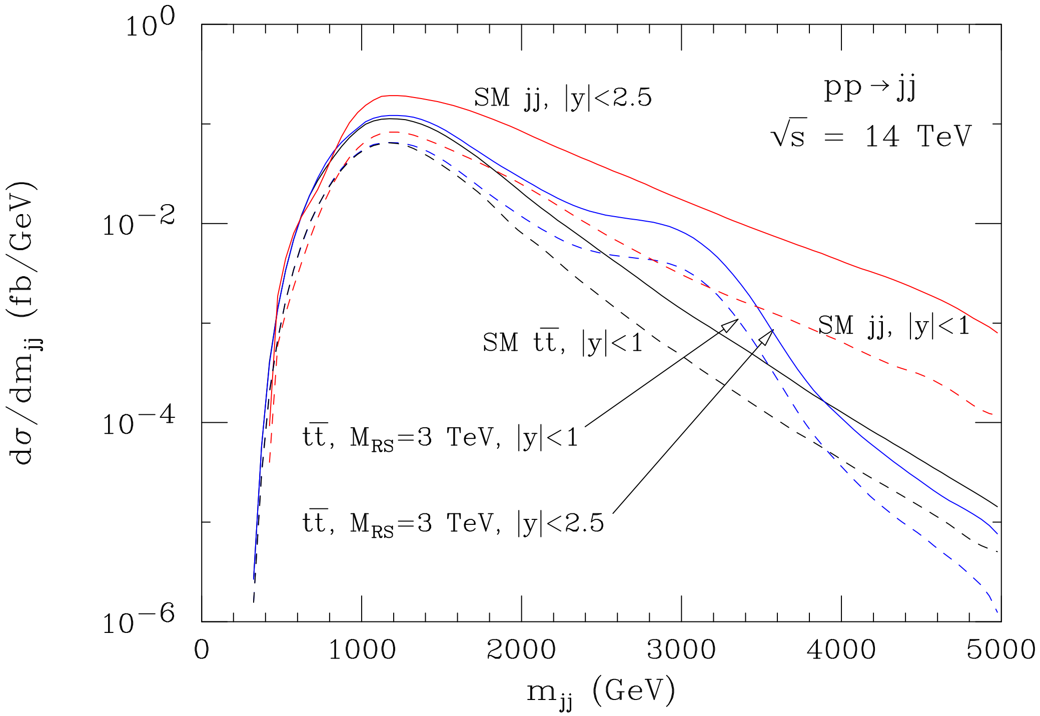
- include interference with SM $t\bar{t}$ amplitude in calculation of KK gluon cross section
- couplings:

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

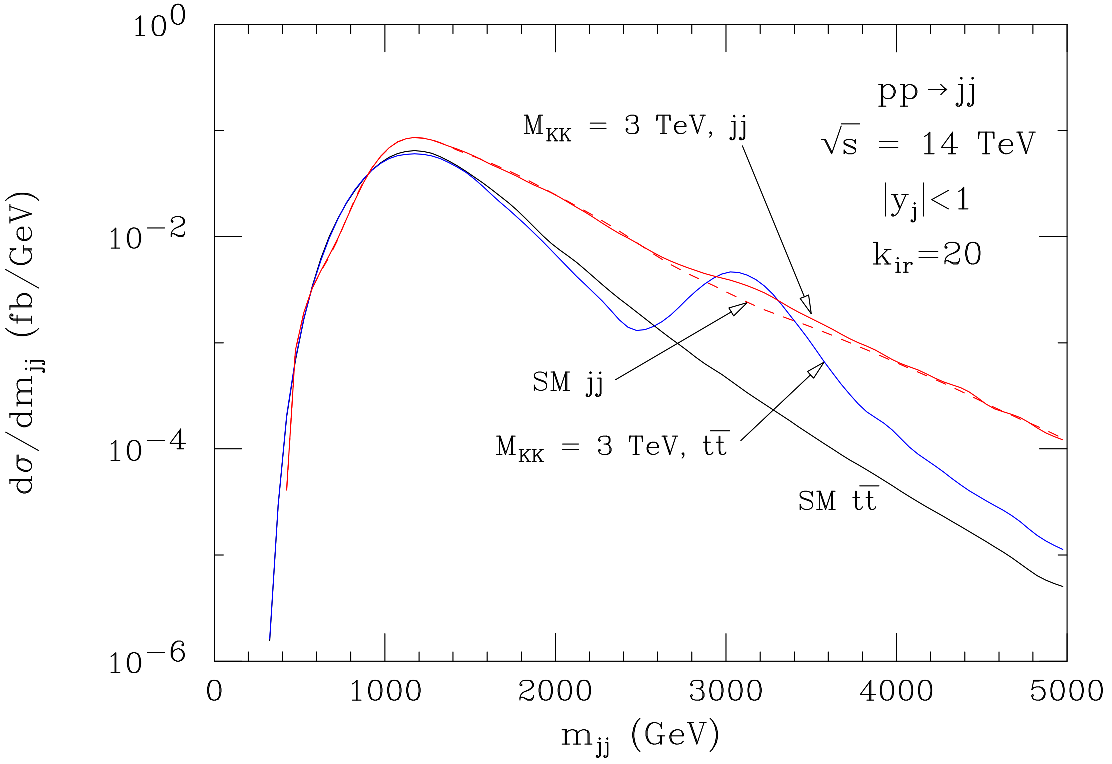
g_s: QCD coupling constant

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

- Calculation is straight-forward
- the following figures are for the optimistic P_{const} scenario; ϵ_t and P_j are taken into account
- a tight rapidity cut reduces the jj background (dominated by t-channel processes): use $|y| < 1$ in the following



- take KK gluon contribution to the mistagged light quark jets in $pp \to jj$ into account (substantial for κr_{ir} models)



- jj background is substantially larger than $t\bar{t}$ cross section
- but $S/B = \mathcal{O}(1)$ is possible in resonance region (depends on model)

Deriving Discovery Luminosities

- Use log-likelihood test to derive integrated luminosity required for a 5σ discovery from $m(jj)$ distribution
- Assume $M_G = 3$ TeV, $\sqrt{s} = 14$ TeV

Model	P_{const}	P_{rise}
Basic RS	20 fb^{-1}	90 fb^{-1}
$\kappa r_{IR} = 5$	15 fb^{-1}	44 fb^{-1}
$\kappa r_{IR} = 20$	11 fb^{-1}	16 fb^{-1}
$SO(5)$, $N = 0$	50 fb^{-1}	230 fb^{-1}
$SO(5)$, $N = 1$	130 fb^{-1}	500 fb^{-1}

- SO(5) $N = 0, 1$ with $N = 0$ or $N = 1$ additional KK custodial partner quarks
- the SO(5), $N = 1$ resonance is very broad with $\Gamma_G/M_G \approx 0.4$, and thus difficult to discover

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}, $\sqrt{s} = 14$ TeV
- construct "discrimination matrix" (symmetric in limit of large statistics) for P_{const} (P_{rise}) case

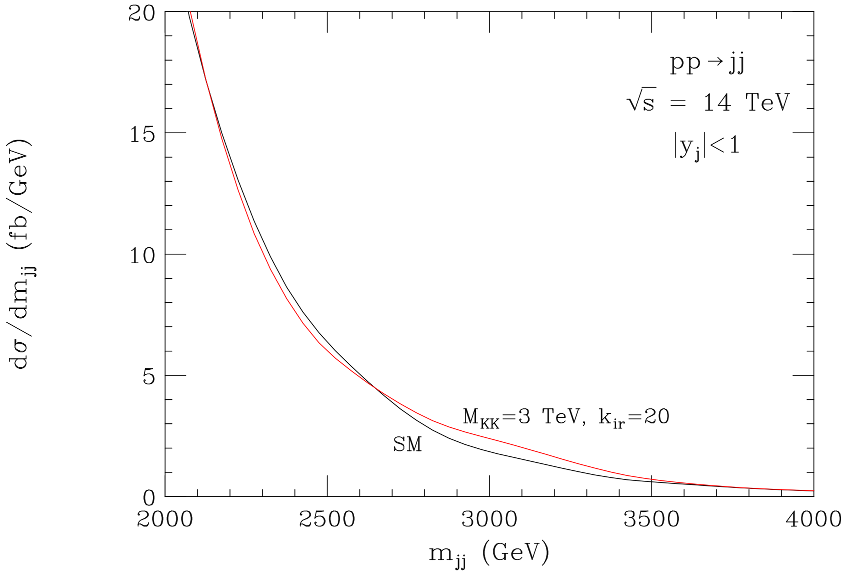
Model	RS	$\kappa r_{IR} = 5$	$\kappa r_{IR} = 20$	SO(5), N=0	SO(5), N=1
RS	0.0σ	7.4σ (6.2σ)	11.5σ (10.7σ)	6.6σ (3.0σ)	10.7σ (4.7σ)
$\kappa r_{IR} = 5$		0.0σ	6.8σ (7.3σ)	9.9σ (6.4σ)	13.4σ (7.7σ)
$\kappa r_{IR} = 20$			0.0σ	13.3σ (11.7σ)	16.1σ(12.8σ)
SO(5), N=0				0.0σ	6.7σ (2.6σ)
SO(5), N=1					0.0σ

- results are considerably better than those found for $t\bar{t} \rightarrow$ lepton+jets channel (UB, L.H. Orr)
- Analysis is based on tree level calculation
  ➞ NLO QCD corrections to SM $t\bar{t}$ and jj production are well known
  ➞ NLO QCD corrections for KK gluons should be similar to those for Z' production (Yuan *et al.*)

Searching for KK gluons in regular jj Production

- In models with a large brane kinetic term ($\kappa r_{ir} = 5,\ 20$), KK gluons couple rather strongly to ordinary quarks
  ➡ can search for them in (non-top-tagged) jj production (Lillie *et al.*)
- Very large cross section, but also very large background

- example: $\kappa r_{ir} = 20$, $M_{KK} = 3$ TeV



- can get a 5σ signal for about $200\ \text{pb}^{-1}$
- CAUTION! This result is based on a tree level calculation
- have to take into account higher order QCD (and EW) corrections
- guess: $\mathcal{O}(1\ \text{fb}^{-1})$ should be sufficient to produce a 5σ signal for the case considered here

4 – Conclusions

- The currently projected top-tagging efficiences and light jet mistagging probabilities appear to be sufficent to make all-hadronic top decays ($t\bar{t} \to jj$) a viable channel for a search for heavy resonances in $t\bar{t}$ production
- We find that the discovery limits are considerably better than those found for the lepton+jets final state
- For a KK gluon with $M_G = 3$ TeV $\mathcal{O}(10 - 100\ \mathrm{fb}^{-1})$ at $\sqrt{s} = 14$ TeV are needed for a 5σ signal
- For 100 fb^{-1}, it will be possible to discriminate between various bulk RS models with high confidence
- In some models ordinary jj production may yield a 5σ signal for $\mathcal{O}(1\ \mathrm{fb}^{-1})$, but a more sophisticated analysis is needed to get a more robust estimate