High p_T Top Quark Production at the LHC

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all results are preliminary

1. Motivation
2. Detecting Very Energetic Top Quarks
3. Background Calculations
4. Conclusions

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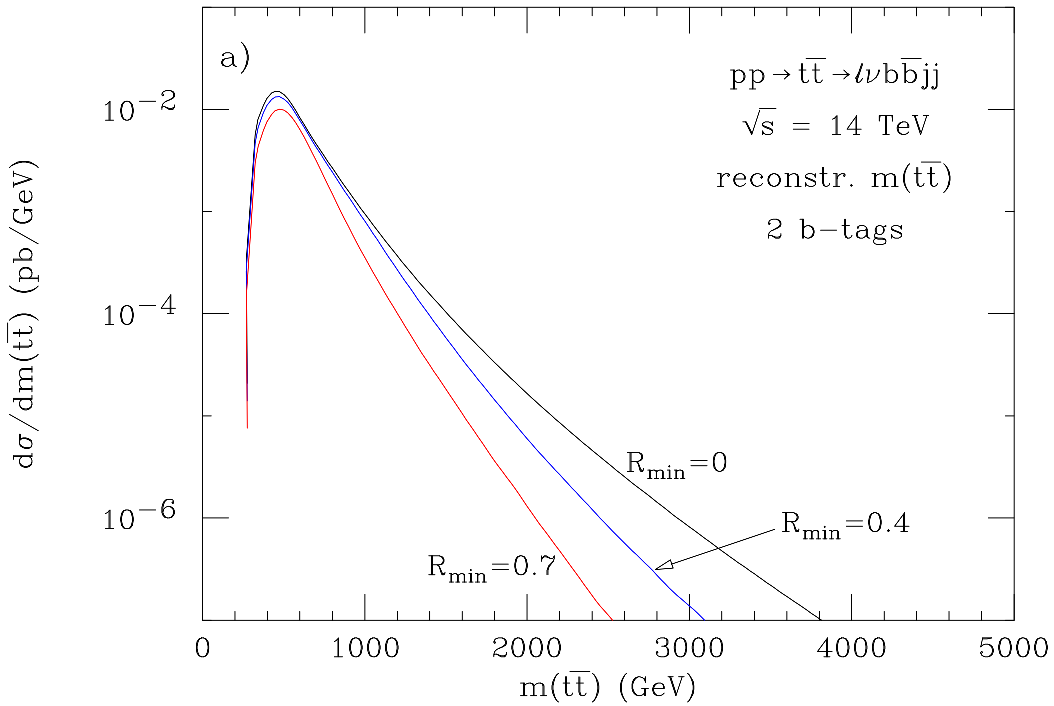
1 – Motivation

- Many (most?) models of New Physics predict new particles which decay into $t\bar{t}$ and have masses in the TeV range:
  - ☞ topcolor (Z')
  - ☞ Little Higgs (Z')
  - ☞ extra dimensions (KK gluons, KK gravitons) [see talk by B. Lillie]
  - ☞ torsion gravity (axial vector boson)
  - ☞ technicolor, chiral color models, etc....
- to search for $t\bar{t}$ resonances in the TeV region, one must be able to efficiently detect very energetic top quarks

- consider $t\bar{t} \to \ell\nu b\bar{b}q\bar{q}'$ (leptons+jets channel)
- Standard ATLAS/CMS requirements for identifying top pairs in the lepton+jets channel:
  - ☞ one isolated charged lepton ($\Delta R(\ell, j) > 0.4$)
  - ☞ missing transverse energy/momentum
  - ☞ four isolated jets ($\Delta R(j_i, j_k) > 0.4$)
  - ☞ two jets are b-tagged
- these requirements are not optimized for detecting very energetic top quarks:
  - ☞ due to the Lorentz boost, top quark decay products tend to be more and more collimated with increasing energy
  - ☞ requiring isolated leptons and jets greatly reduces the cross section at large $t\bar{t}$ invariant masses

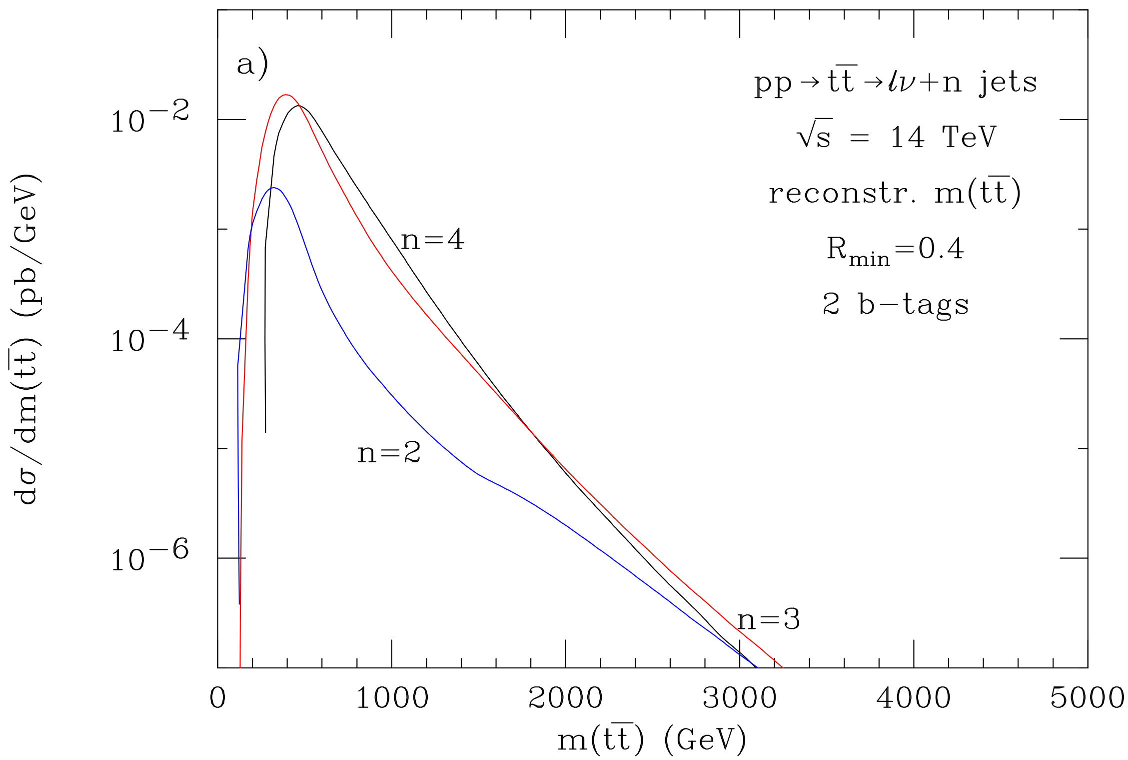


- LO calculation
- reconstruct $p_L(\nu)$ by requiring $m(\ell\nu) = M_W$
- b-tagging efficiency: $\epsilon_b = 60\%$
- benchmark differential cross section for reach:
  10^{-7} pb/GeV: 1 event/100 GeV bin/100 fb^{-1}

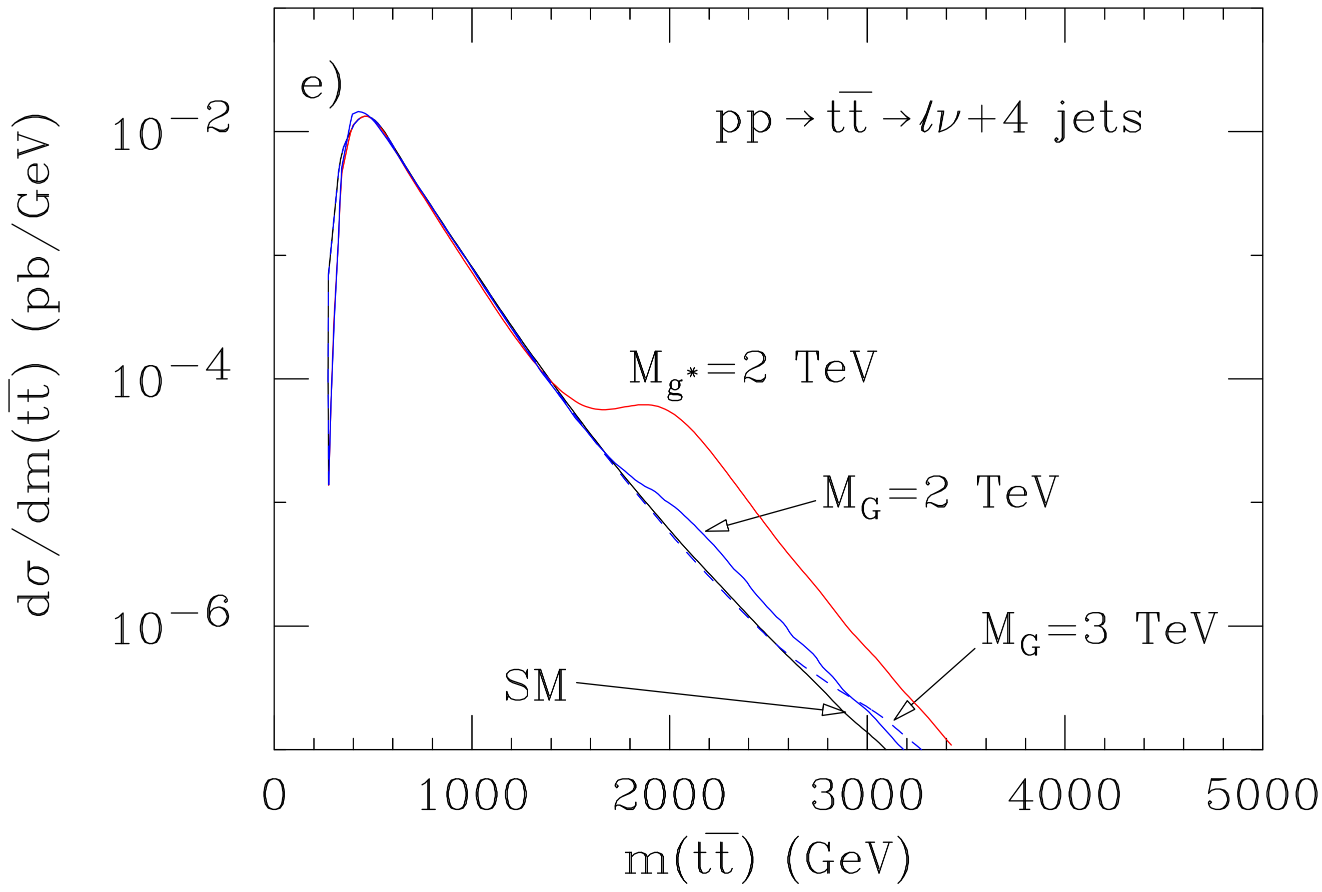
2 – Detecting Very Energetic Top Quarks

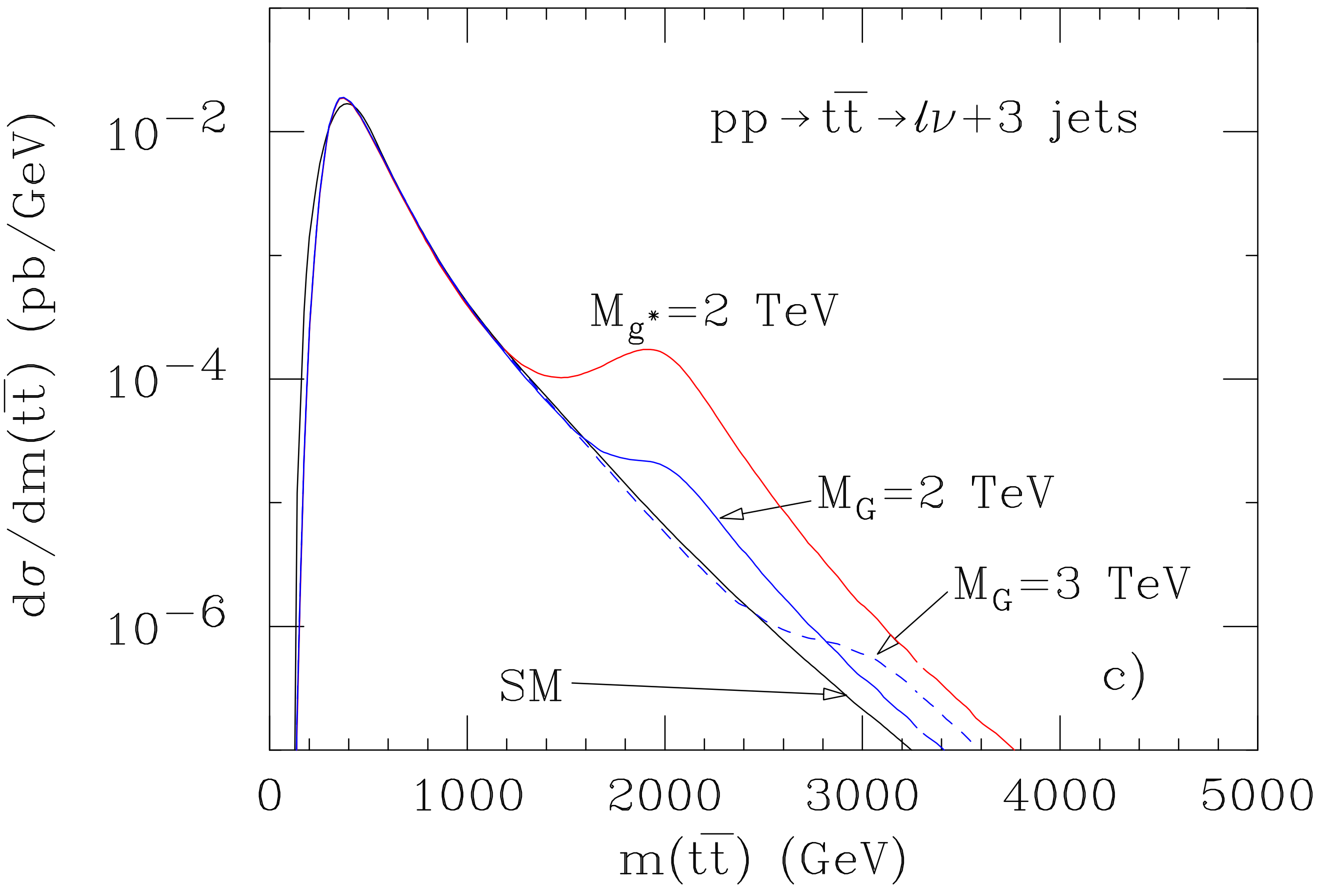
- How can we improve the efficiency of detecting very energetic top quarks?
- Consider the lepton+jets final state again
- Give up isolated leptons?
  - ☞ needed for triggering
  - ☞ non-isolated lepton can be confused with lepton from b-decay
  - ☞ enhanced background from QCD $b\bar{b}+$ jets background if lepton is not isolated

- Most of the suppression comes from the isolation cut on $t \to bjj$ decay jets: no isolation cut is imposed on the neutrino in $t \to b\ell\nu$
- jets with $\Delta R < 0.4$ merge:
  → consider $t\bar{t} \to \ell\nu + n$ jets with $n = 2,\ 3,\ 4$

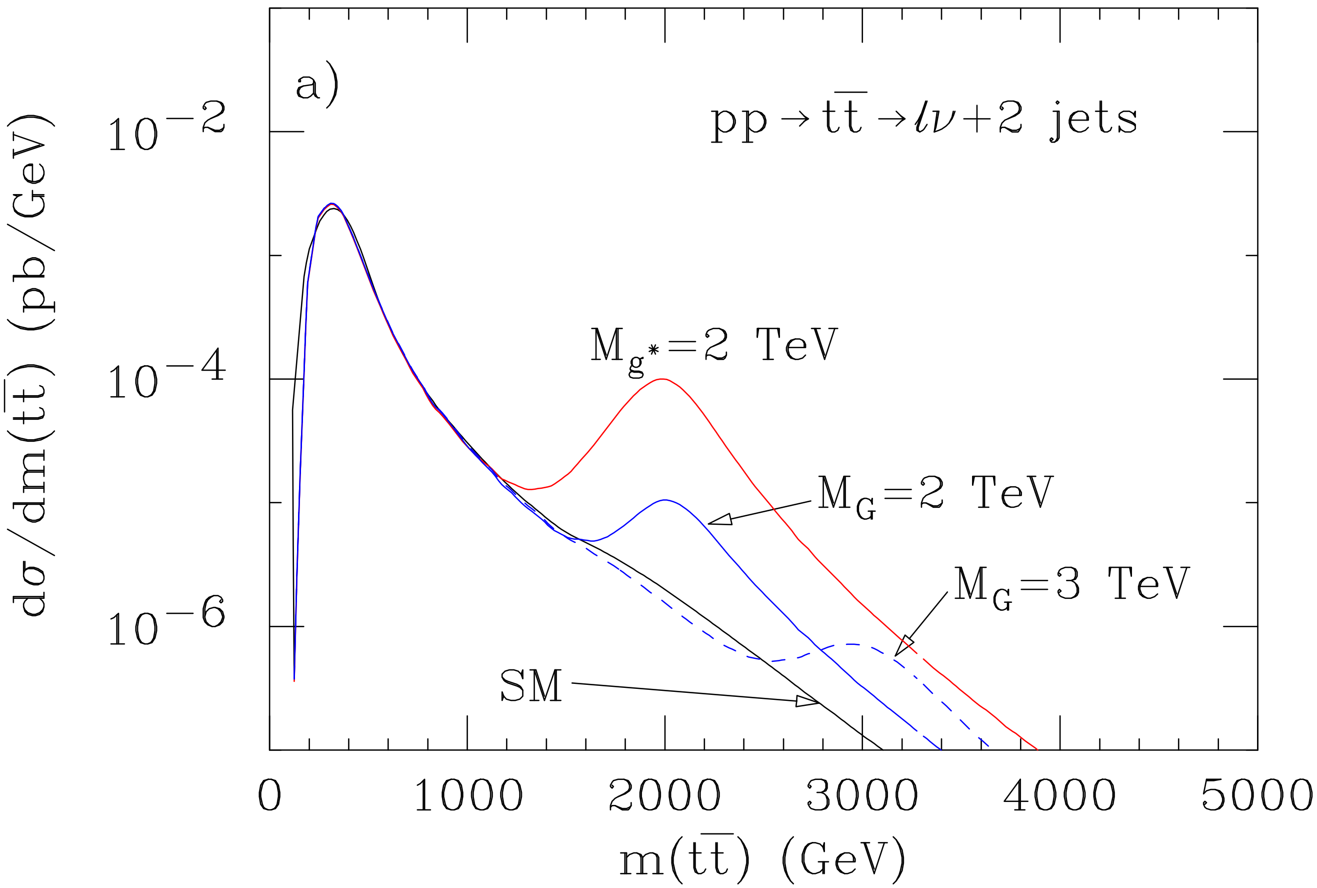


- For small $m(t\bar{t})$, events where one or two jets do not satisfy the p_T and rapidity cuts (here: $p_T(b,j) > 30$ GeV, $|y(b,j)| < 2.5$) are the largest source of 2 jet and 3 jet events
- At large $m(t\bar{t})$, jet merging is the dominant source
- In the 2 jet final state, the hadronically decaying top becomes one b-tagged jet
- Making use of the 2 jet and 3 jet final state quadruples the observable $t\bar{t}$ cross section at large $m(t\bar{t})$
- Use $t \to b\ell\nu$ to trigger event, then try to find $t \to bjj$ in hadronic recoil
- The benefit is larger for s-channel resonances in the $t\bar{t}$ channel: Examples: KK gluons, g^*, and bulk RS KK gluons, G


e)
pp → $t\bar{t}$ → ℓν+4 jets
M_{g^*}=2 TeV
M_G=2 TeV
M_G=3 TeV
SM
10^{-2}
10^{-4}
10^{-6}
0
1000
2000
3000
4000
5000
m($t\bar{t}$) (GeV)
dσ/dm($t\bar{t}$) (pb/GeV)



$pp \to t\bar{t} \to \ell\nu + 3$ jets
$M_{g^*}=2$ TeV
$M_G=2$ TeV
$M_G=3$ TeV
SM
c)
10^{-2}
10^{-4}
10^{-6}
0
1000
2000
3000
4000
5000
$m(t\bar{t})$ (GeV)
$d\sigma/dm(t\bar{t})$ (pb/GeV)


a)
pp → tt̄ → ℓν+2 jets
10^{-2}
10^{-4}
10^{-6}
M_{g^*}=2 TeV
M_G=2 TeV
M_G=3 TeV
SM
0
1000
2000
3000
4000
5000
m(tt̄) (GeV)
dσ/dm(tt̄) (pb/GeV)

- issues:
  - b-tagging:
    - → ATLAS: ϵ_b at large $m(t\bar{t})$ may be a factor 3 smaller than at small values
    - → and the light jet mistagging probability, $P_{j\to b}$ may be a factor 3 higher
    - → observable cross section reduced by an order of magnitude
    - → the background is potentially large
    - → potential solution: use events with one b-tag; the efficiency ($2(1-\epsilon_b)\epsilon_b$) is far less sensitive to ϵ_b
    - → have to worry about background for events with one tag
  - QCD radiation: cut on invariant mass of jets may help to discriminate QCD jets and $t \to bjj$ jets

- what about other $t\bar{t}$ final states?
  - ☞ di-lepton channel ($t\bar{t} \to \ell\nu_\ell\ell'\nu_{\ell'}b\bar{b}$)
    - → small branching ratio: $\approx 4.7\%$
    - → small background
    - → cannot reconstruct $m(t\bar{t})$ – use $\ell\ell' b\bar{b}$ cluster transverse mass instead
    - → $\ell\ell' b\bar{b}$ cluster transverse mass falls much faster than $m(t\bar{t})$
    - → but: smaller loss of rate due to isolation cut (two neutrinos...)
    - → we find that the di-lepton mode adds insignificantly to the search reach for $t\bar{t}$ resonances

☞ all-hadronic mode ($t\bar{t} \to b\bar{b} + n$ jets)

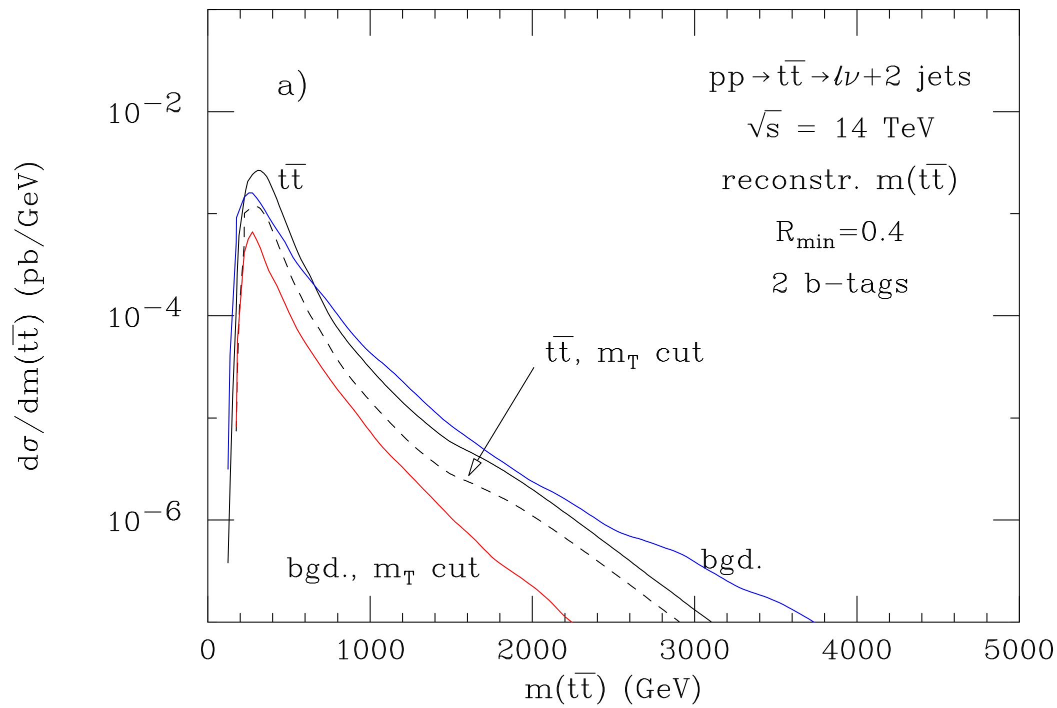
- ➞ somewhat larger branching ratio than lepton+jets final state
- ➞ jet merging: $n = 0, ..., 4$
- ➞ QCD multi-jet background is very large; probably have to require two b-tags
- ➞ need to impose invariant mass cuts on jet systems ($1 - 3$ jets)
- ➞ large combinatorial background
- ➞ potentially less gain than from lepton+jets mode with one b-tag

3 – Background Calculations

- Concentrate on $t\bar{t} \to \ell\nu + n$ jets ($n = 2,\ 3,\ 4$) with one or two b-tags from now on
- For $n = 4$ and two b-tags, the background is known to be small at the LHC
- For 2 jet and 3 jet final states, the background is potentially more worrisome, because it arises at lower order in perturbation theory
- backgrounds considered:
  $W+$ jets, $Wb\bar{b}+$ jets, $(t\bar{b}+\bar{t}b)+$ jets ($t \to b\ell\nu$), $Wb+$ jets, $(t+\bar{t})+$ jets ($t \to b\ell\nu$), Wt, Wtj and Wbt ($t \to bjj$)
- use $\epsilon_b = 0.6$ and $P_{j\to b} = 1/100$ in the plots shown below

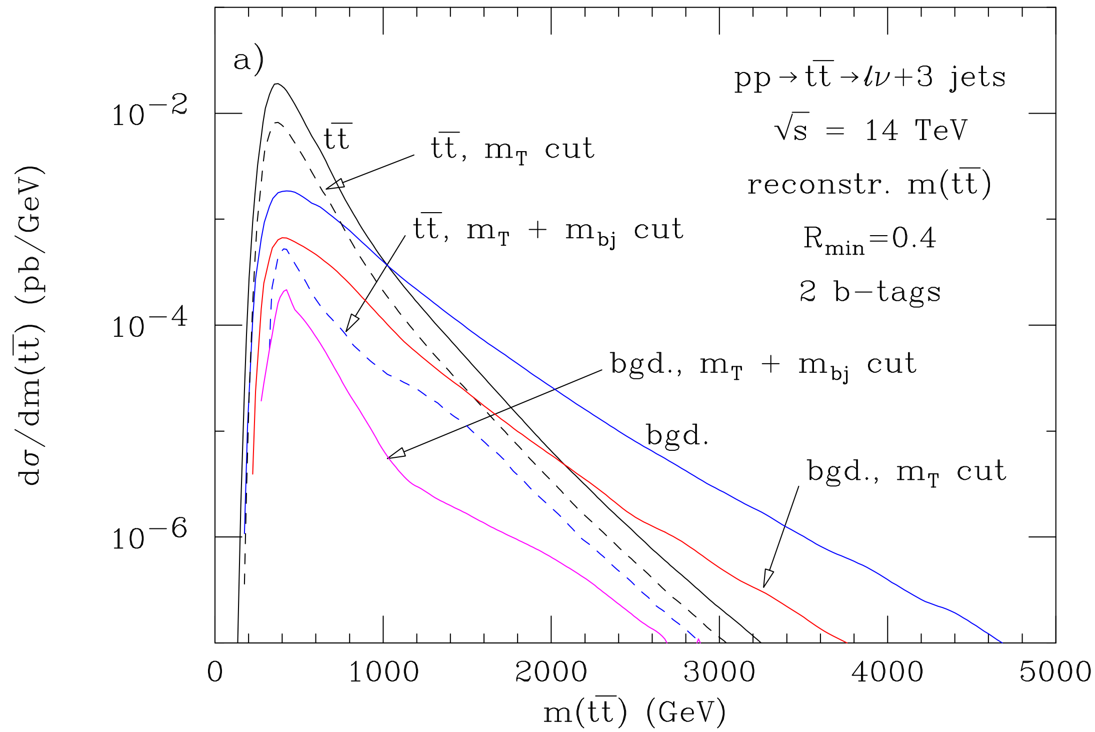
Final states with two b-tags

2 jet final state



- After imposing a cut on the $b\ell\nu$ cluster transverse mass, $|m_T - m_t| < 20$ GeV, the background is small
- for $\epsilon_b = 0.2$ and $P_{j\to b} = 1/30$, $S/B = 1/2$ even with m_T cut
  → a jet invariant mass cut should improve this

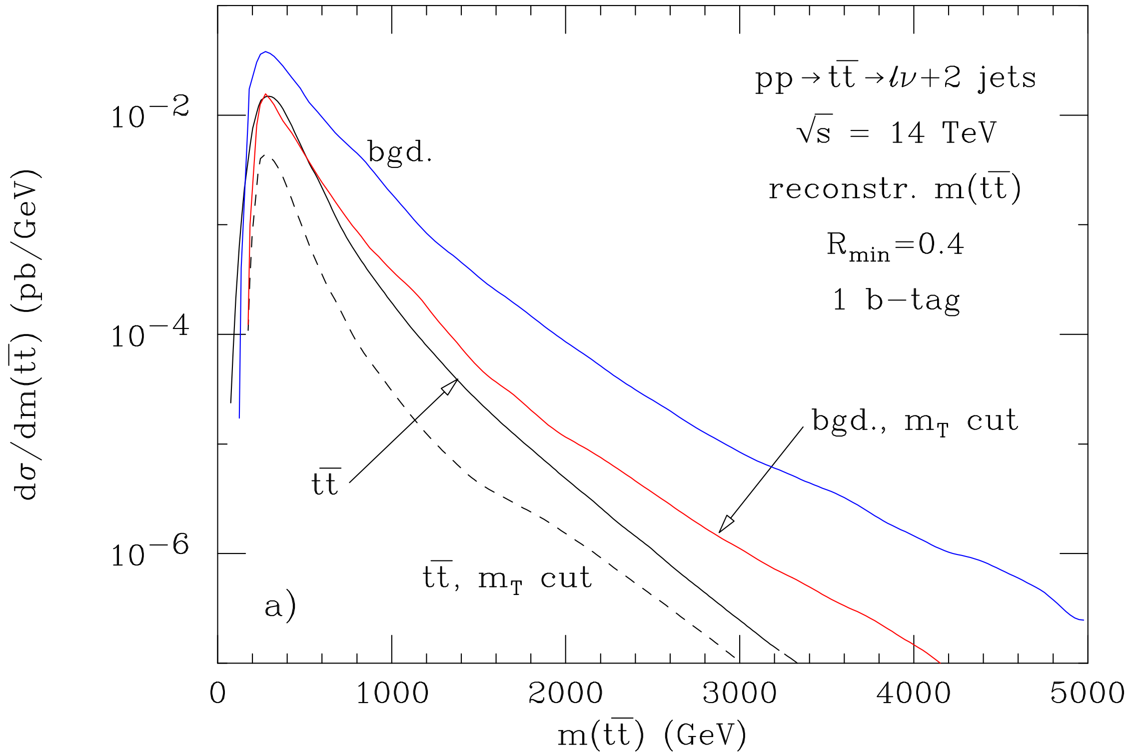
3 jet final state



- After imposing a m_T and a $|m(jj) - m_t| < 20$ GeV cut, the background is small
- Even for $\epsilon_b = 0.2$ and $P_{j\to b} = 1/30$, $S/B > 1$

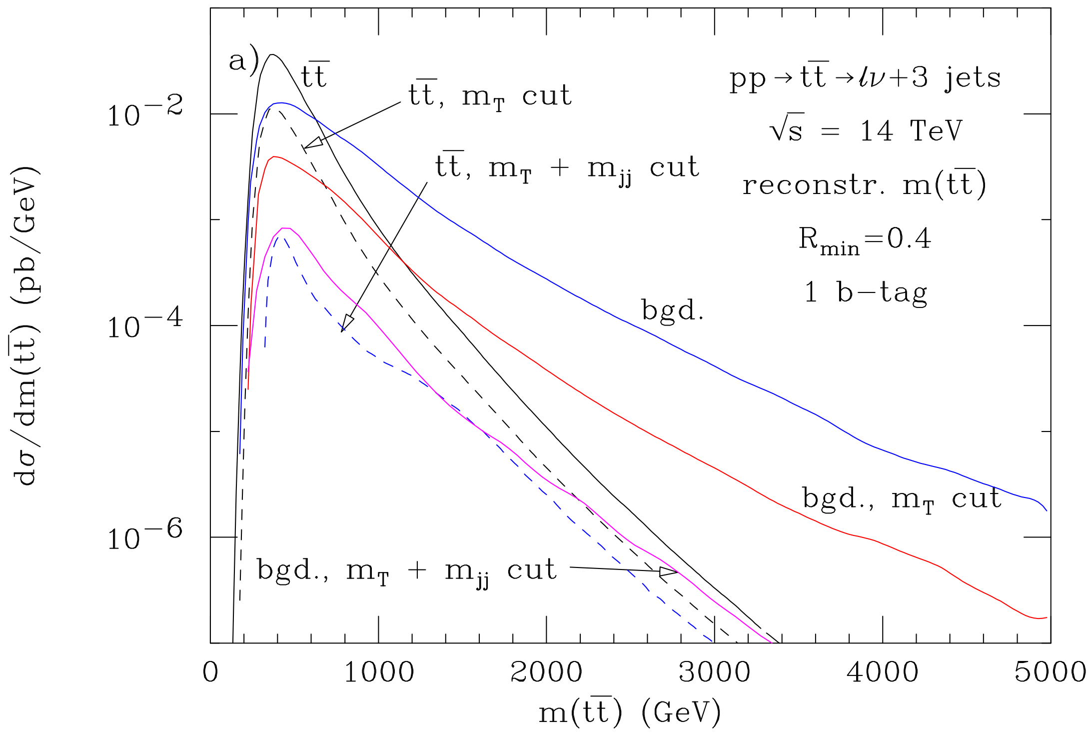
Final states with one b-tag

2 jet final state



- Even after imposing a m_T cut, the background is still large
  → have to consider a cut on jet invariant mass

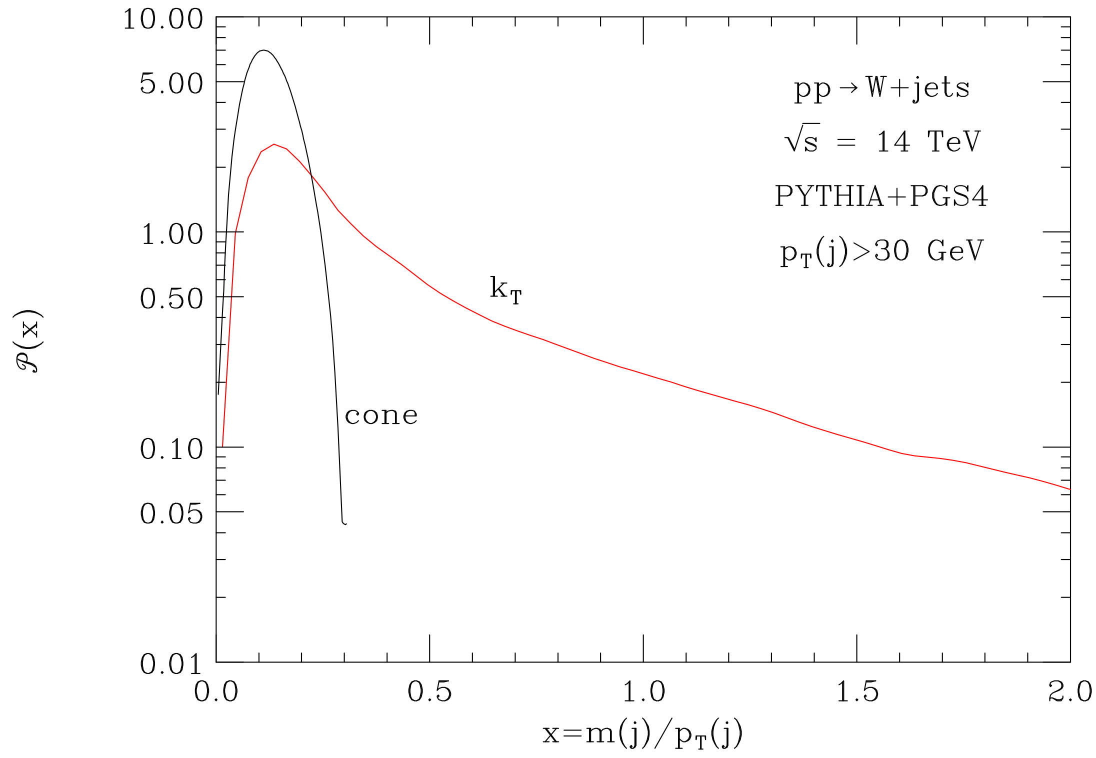
3 jet final state



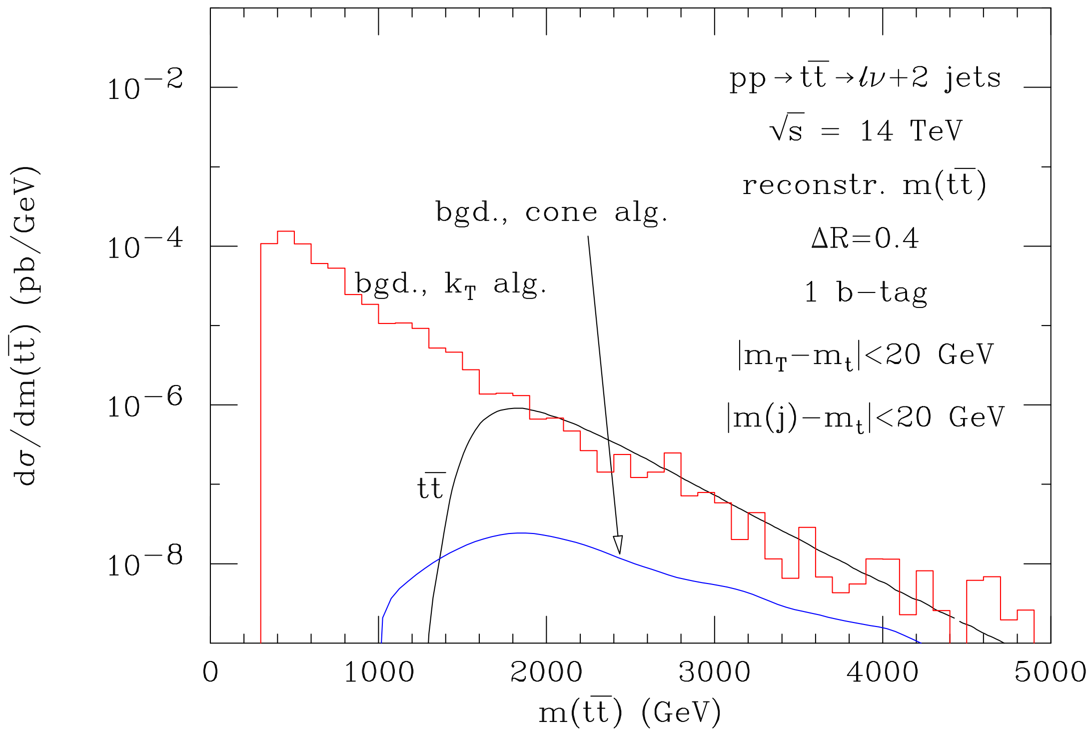
- After imposing a m_T and a $|m(jj) - m_t| < 20$ GeV cut, the background is still a bit larger than the signal
- For $\epsilon_b = 0.2$ and $P_{j \to b} = 1/30$, S/B worsens by a factor 3 (2.3) for the 2 jet (3 jet) final state

Jet invariant mass cut

- Consider $t\bar{t} \to \ell\nu + 2$ jets with one b-tag
- main background: $W + 2$ jets, where one jet is mistagged as a b-jet, and $(t + \bar{t})j$, $t \to b\ell\nu$
- One of the jets in the signal has $m(j) \approx m_t$
- background: LO: $m(j) \approx 0$, NLO: $m(j) > 0$
- but: have to take into account multi-gluon radiation and non-perturbative effects (underlying event)
  → results may depend on jet algorithm used
- to simulate a jet invariant mass cut:
  - ☞ determine the probability density matrix $\mathcal{P}(p_T(j), m(j))$ from $W+$ jets production in PYTHIA+PGS4
  - ☞ then convolute ME W+2 jet and tj calculation with $\mathcal{P}(p_T(j), m(j))$ and require $|m(j) - m_t| < 20$ GeV



- The invariant mass of a jet with a given p_T strongly depends on the jet algorithm used
- Long tail with k_T algorithm
- very difficult to have a jet with the cone algorithm which has $m(j) > 0.3 \times p_T(j)$



- This results in large differences in the background between the cone and k_T algorithm once a $|m(j) - m_t| < 20$ GeV cut is imposed
- Both signal and background are strongly reduced (signal mostly at small $m(t\bar{t})$)
- $S/B \geq 1$ (for $\epsilon_b = 0.2$ and $P_{j \to b} = 1/30$, $S/B > 1/3$)

4 – Conclusions

- $t\bar{t}$ resonances with masses in the TeV range are a signature of many New Physics models
- to maximize the reach of the LHC in searching for such resonances, the standard $t\bar{t}$ identification criteria have to be modified
- We found that the $t\bar{t} \to \ell\nu + 2$ jets and $t\bar{t} \to \ell\nu + 3$ jets final states with one or two b-tags offer improved chances over the traditional $t\bar{t} \to \ell\nu + 4$ jets channel in a search for $t\bar{t}$ resonances
- However, the background may become an issue at very large $m(t\bar{t})$, especially for final states with one b-tag