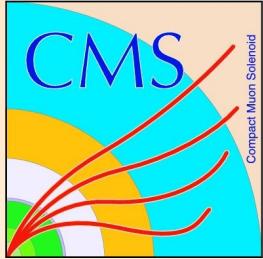


# CMS prospects for boosted objects

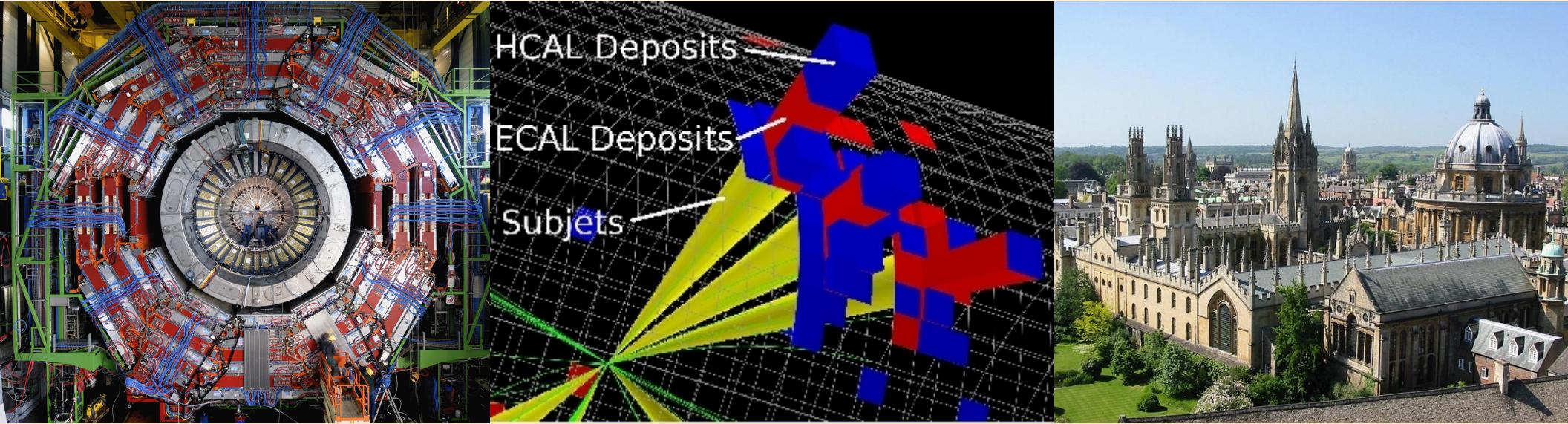


Jeannine Wagner-Kuhr  
Institut für Experimentelle Kernphysik, KIT  
*on behalf of the CMS Collaboration*



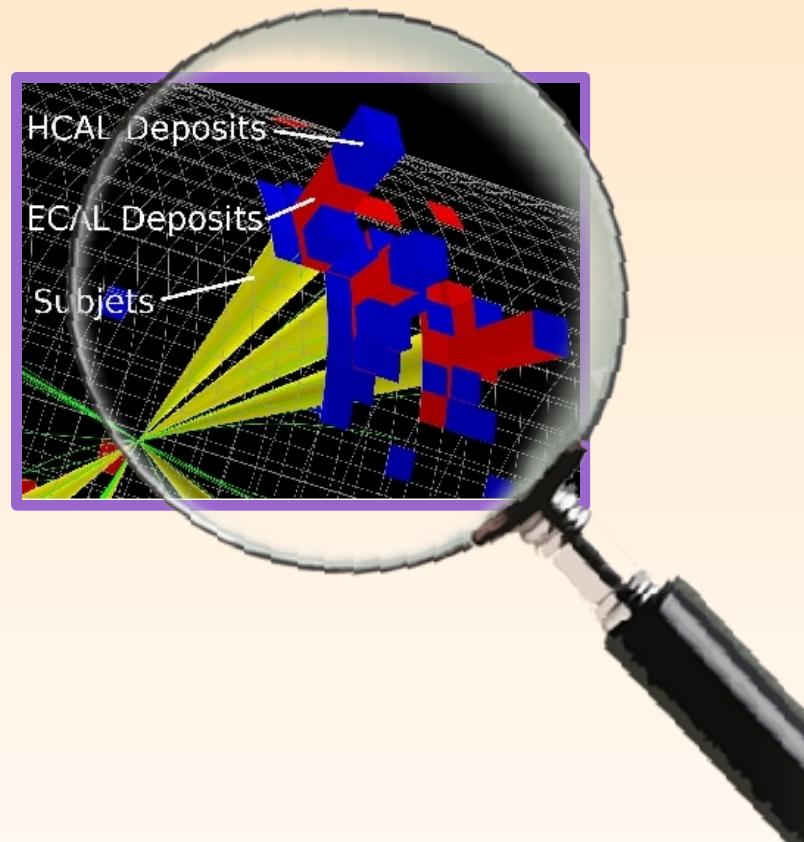
BOOST2010

*Oxford, 23.6.2010*



# Overview

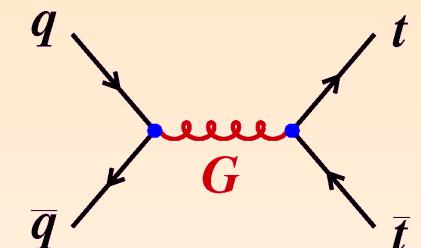
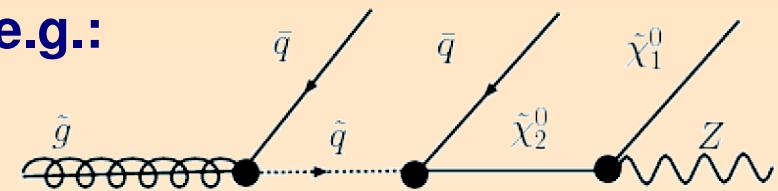
- Introduction
- CMS boosted object activities
- Boosted top quarks
  - Lepton+jets analyses  
*(CMS PAS TOP-09-009, EXO-09-008)*
  - All-hadronic analysis  
*(CMS PAS EXO-09-002, JME-09-001)*
- Summary



# Motivation for boosted objects

Many BSM models predict new heavy particles, e.g.:

- SUSY particles: decay cascades  $\rightarrow Z, W, H, t$
  - Heavy dark matter (DM) particles decaying to light DM particles
  - composite fermions:  $q^* \rightarrow Z q$
  - $KK \rightarrow WZ$ ;  $W' \rightarrow tb$ ;  $X \rightarrow t\bar{t}$  (e.g. X: KK, G, Z')
- decay products are highly boosted (high  $\beta, \gamma$ ) and their decay products (leptons, jets) are collimated

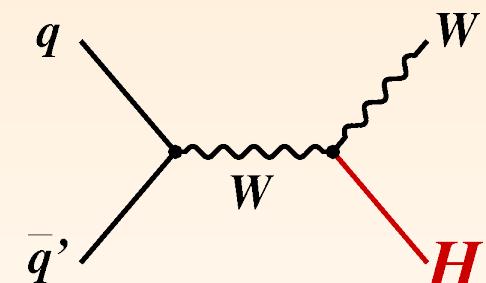


Boosted regime can help to suppress backgrounds:

- $VH, H \rightarrow b\bar{b}$

Distinguish between hadronic and leptonic final state:

- Leptonic: collimated multi leptons  
(eg.  $Z \rightarrow ee$ ,  $WZ \rightarrow eee\nu$ , DM-decay)
- Hadronic: subjets in fat jets  
(eg.  $H \rightarrow b\bar{b}$ ,  $t \rightarrow bW \rightarrow bqq'$ )



# Boosted object activities at CMS

## Leptonic final state

- Excited quark,  $q^* \rightarrow Zq \rightarrow ee\bar{q}$

- Ongoing analysis

*See talk by James Jackson*

- Dark matter photon ( $\gamma^*$ ) decay

- Ongoing analysis

*See talk by Eva Halkiadakis (at LHC)*

## Hadronic final state

- Boosted Higgs  $VH, H \rightarrow b\bar{b}$

- Ongoing analysis

- Hadronic top decay:  $t \rightarrow bqq'$

- PAS JME-09-001, EXO-09-002

## Semileptonic final state

- Semileptonic top decay:  $t \rightarrow bl\nu$

- PAS TOP-09-009, EXO-09-008

# Boosted object activities at CMS

## Leptonic final state

- Excited quark,  $q^* \rightarrow Zq \rightarrow ee\bar{q}$ 
  - Ongoing analysis
- Dark matter photon ( $\gamma^*$ ) decay
  - Ongoing analysis

*See talk by Eva Halkiadakis (at LHC)*

I.

## Hadronic final state

- Boosted Higgs VH,  $H \rightarrow b\bar{b}$ 
  - Ongoing analysis
- Hadronic top decay:  $t \rightarrow bqq'$ 
  - PAS JME-09-001, EXO-09-002

## Semileptonic final state

- Semileptonic top decay:  $t \rightarrow bl\nu$ 
  - PAS TOP-09-009, EXO-09-008

# Boosted object activities at CMS

## Leptonic final state

- Excited quark,  $q^* \rightarrow Zq \rightarrow ee\bar{q}$ 
  - Ongoing analysis
- Dark matter photon ( $\gamma^*$ ) decay
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*See talk by Eva Halkiadakis (at LHC)*

I.

## Hadronic final state

- Boosted Higgs VH,  $H \rightarrow b\bar{b}$ 
  - Ongoing analysis
- Hadronic top decay:  $t \rightarrow bqq'$ 
  - PAS JME-09-001, EXO-09-002

II.

## Semileptonic final state

- Semileptonic top decay:  $t \rightarrow bl\nu$ 
  - PAS TOP-09-009, EXO-09-008

# Boosted object activities at CMS

## Leptonic final state

I.

- Excited quark,  $q^* \rightarrow Zq \rightarrow ee\bar{q}$

- Ongoing analysis

*See talk by James Jackson*

- Dark matter photon ( $\gamma^*$ ) decay

- Ongoing analysis

*See talk by Eva Halkiadakis (at LHC)*

## Hadronic final state

II.

- Boosted Higgs VH,  $H \rightarrow b\bar{b}$

- Ongoing analysis

III.

- Hadronic top decay:  $t \rightarrow bqq'$

- PAS JME-09-001, EXO-09-002

## Semileptonic final state

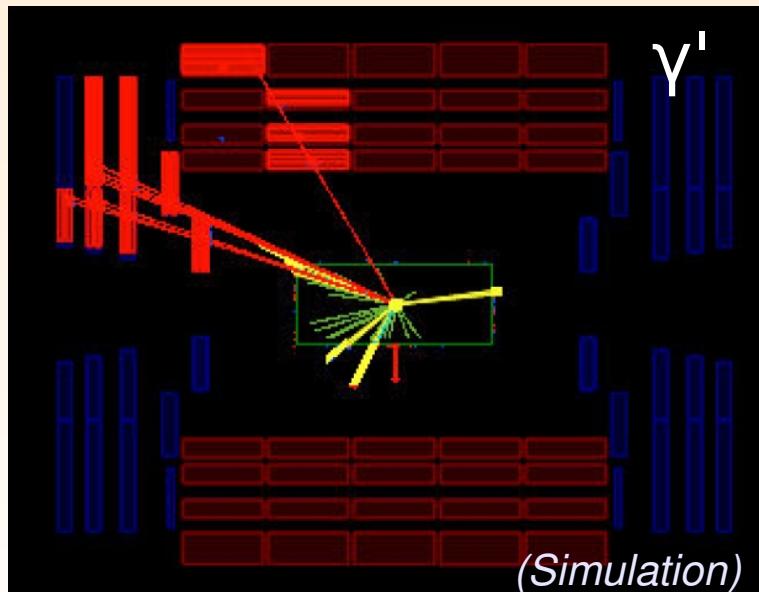
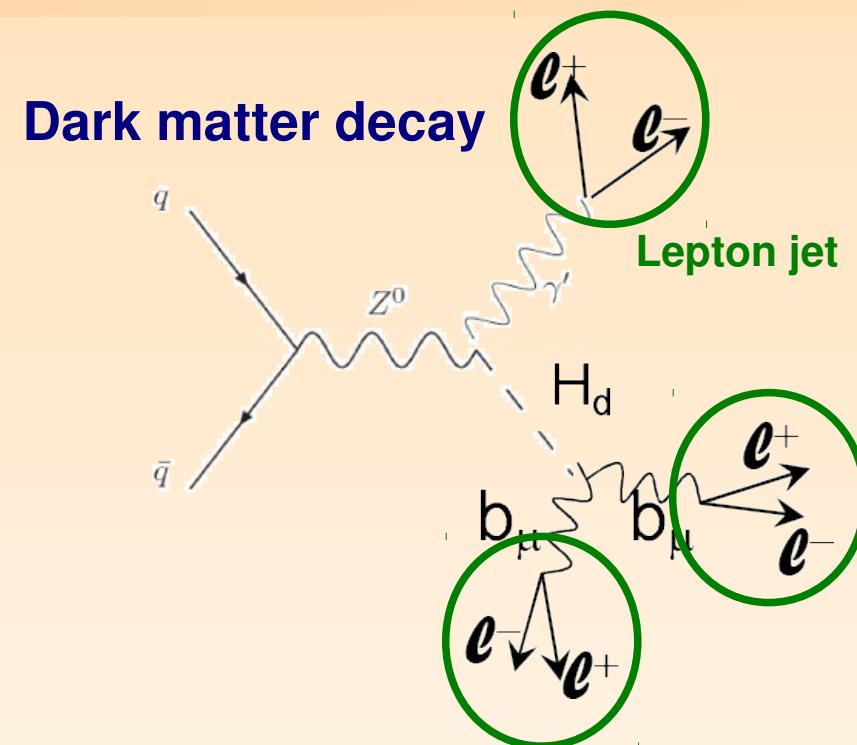
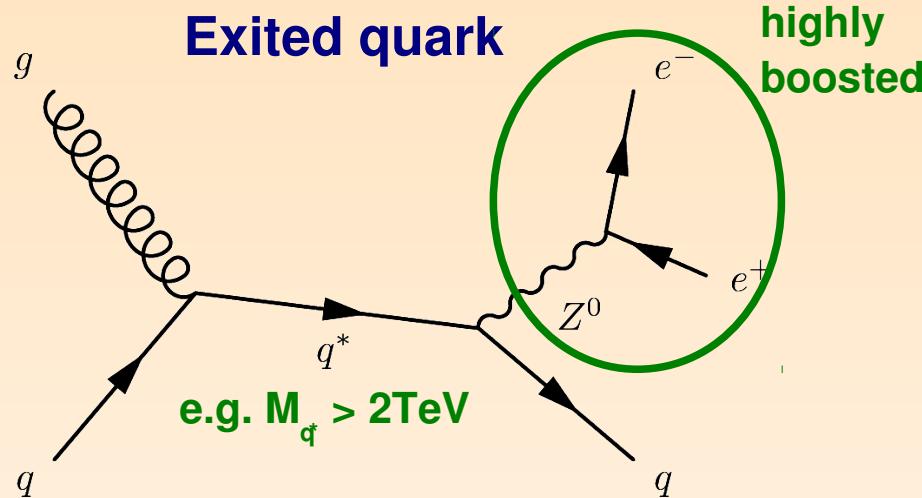
III.

- Semileptonic top decay:  $t \rightarrow bl\nu$

- PAS TOP-09-009, EXO-09-008

Main topic  
of this talk

# Leptonic final state



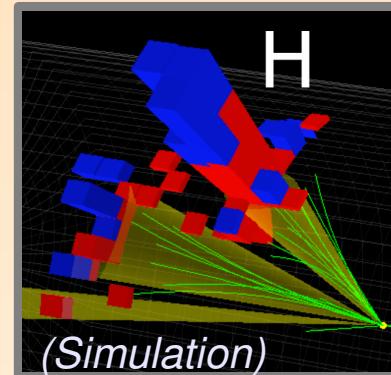
## General issues:

- Reconstruction of close leptons ( $\Delta R, \lesssim 0.1$ )  
e.g. less efficient standard e reconstruction
- Leptons might be low energetic ( $\sim 5\text{ GeV}$ )  
e.g. leptons from dark matter decay cascades

# Boosted Higgs, $H \rightarrow b\bar{b}$

**Issue:** For  $\Delta R_{bb} \lesssim 1$  conventional jet reconstruction will lump together b-quark jets  $\rightarrow$  poor efficiency and mass resolution

$$R_{bb} \simeq \frac{1}{\sqrt{z(1-z)}} \frac{m_H}{p_T} , \quad (p_T \gg m_H)$$



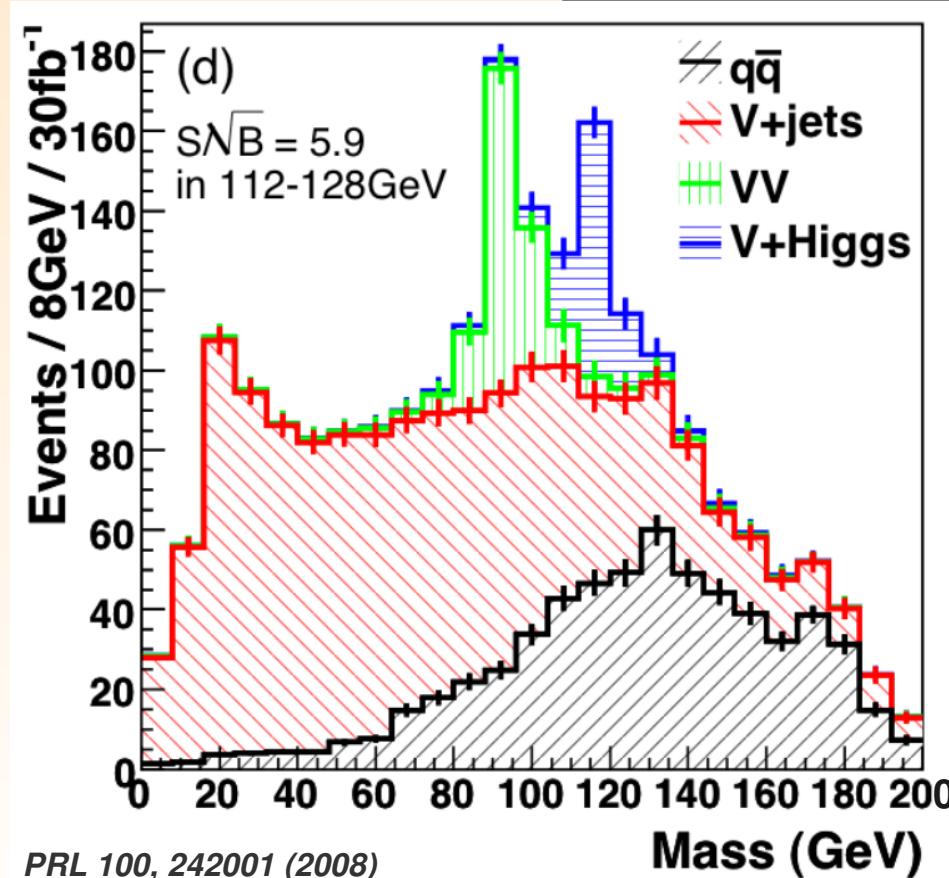
## Proposed solution - subjet/filter algorithm

(J. Butterworth et al., PRL 100, 242001 (2008))

- Adapts to  $p_T(H)$ -dependence of  $R_{bb}$
- Minimizes underlying event and pile up effects for optimal mass resolution

**Atlas:** Confirmation that this idea works with a full detector simulation

**CMS:** ??? (*Work in progress*)



# Boosted top pairs - Motivation

**Standard Model:**

Top pair production with  $p_T > 500 \text{ GeV} \approx 0.5\%$

**New physics:**

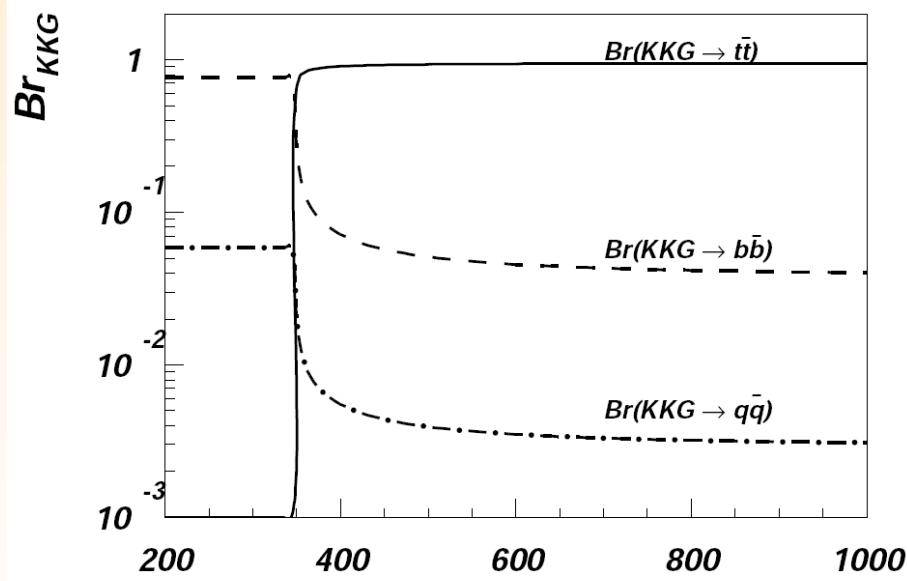
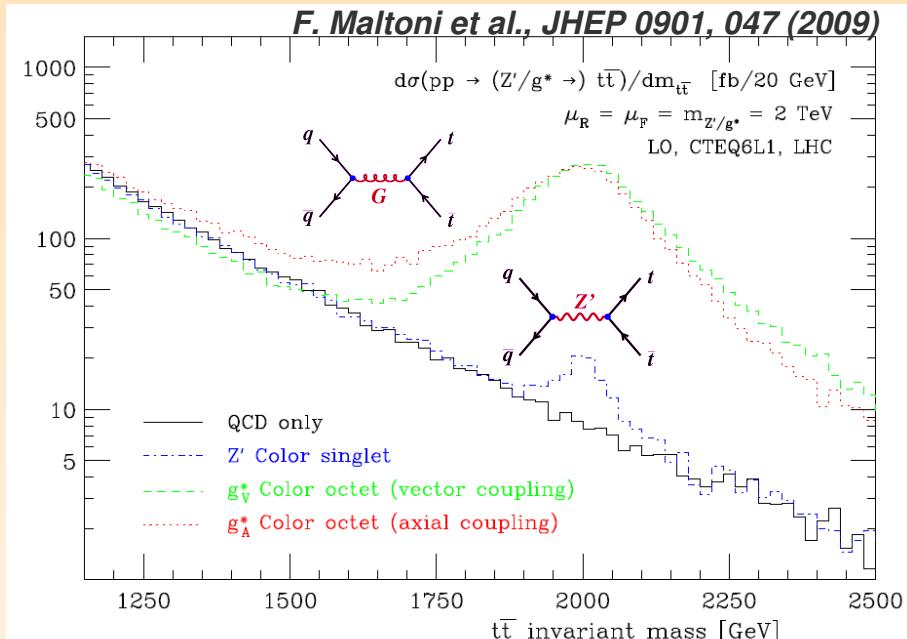
Many heavy particles decaying to top quark pairs are predicted

(spin 0, 1, 2; color singlet and octet; different couplings to SM particles)

**Examples:**

- Heavy Higgs *(spin 0, color singlet)*
- Model independent Z' *(spin 1, color singlet)*
- KK-gluon, coloron, axigluon *(spin 1, color octet)*
- KK-gravitons (RS/ADD) *(spin 2, color singlet)*

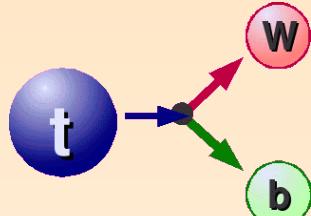
The heavier these new particles the more boosted are the top quarks



*K. Agashe et al., PRD 77, 015003 (2008)*  $M_{KKG}$  (GeV)

# Decay of top quark pairs

## Top quark decay



$$t \rightarrow b \ W \approx 100 \%$$

## W boson decay

- 'Leptonic':

$$W \rightarrow l \nu \approx 2/9 \quad \text{with } l=e,\mu$$

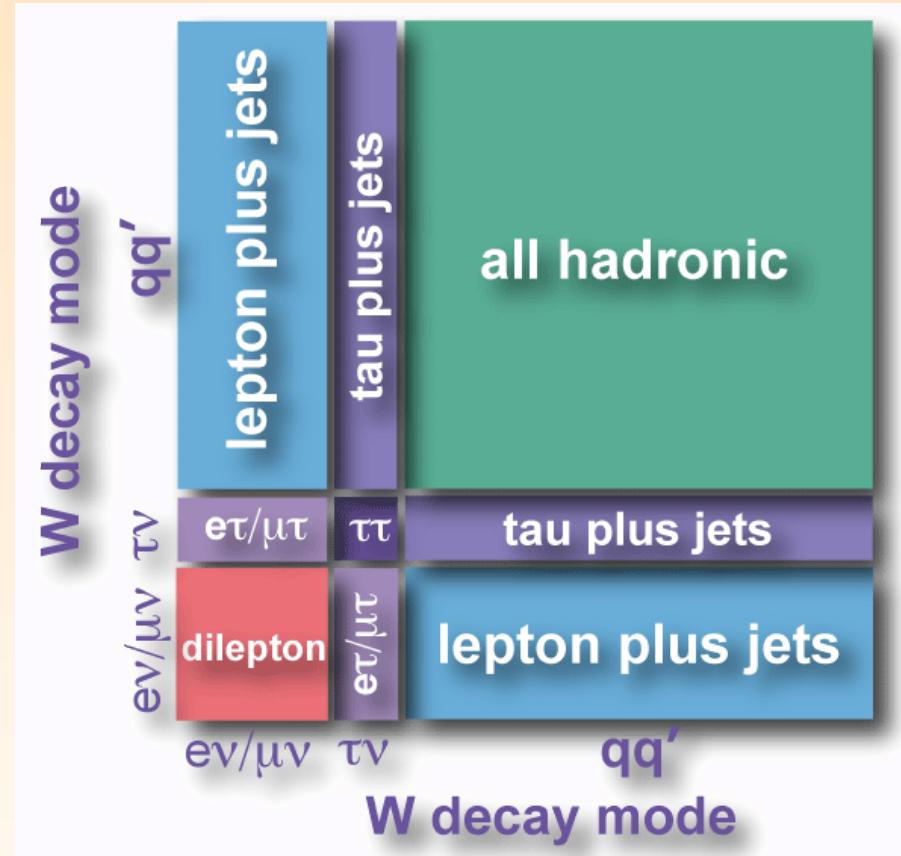
- Tauonic:

$$W \rightarrow \tau \nu \approx 1/9 \quad \text{Difficult to identify}$$

- Hadronic:

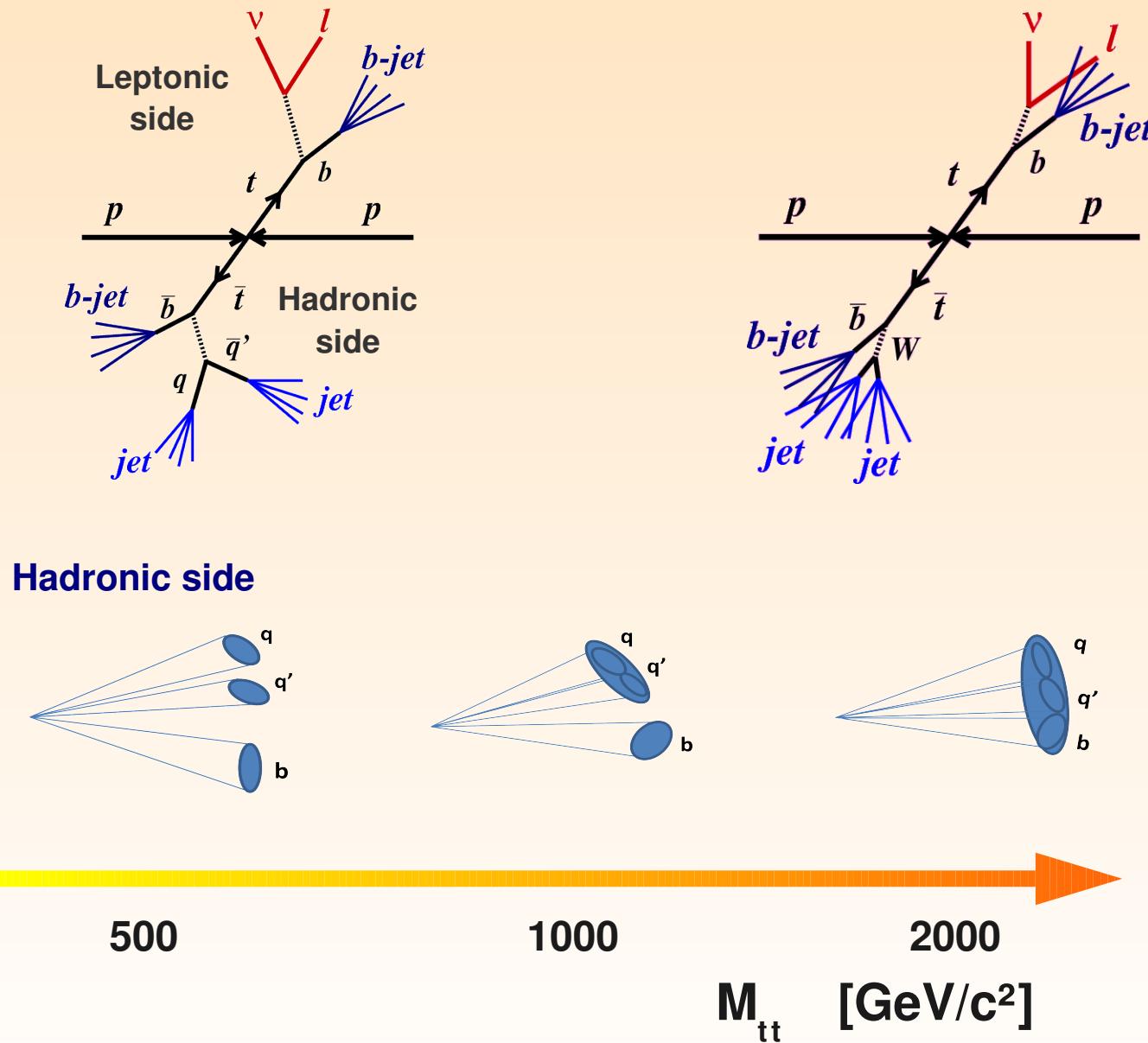
$$W \rightarrow q\bar{q}' \approx 6/9 \quad q, \bar{q}' \text{ hadronize to jets}$$

## Decay channels of top quark pairs



Dilepton	$\approx 5\%$
Lepton+jets	$\approx 30\%$
All hadronic	$\approx 44\%$

# Boosted top pairs - challenge



The larger the invariant top pair mass  $M_{tt}$ , the more boosted the top quarks and the smaller the angles between the decay products

## Leptonic side:

Lepton close to b-jet  
or in b-jet  
(lepton not isolated)

## Hadronic side:

Jets overlap → reconstruction of 1 or 2 jets instead of 3  
(jet with substructure)

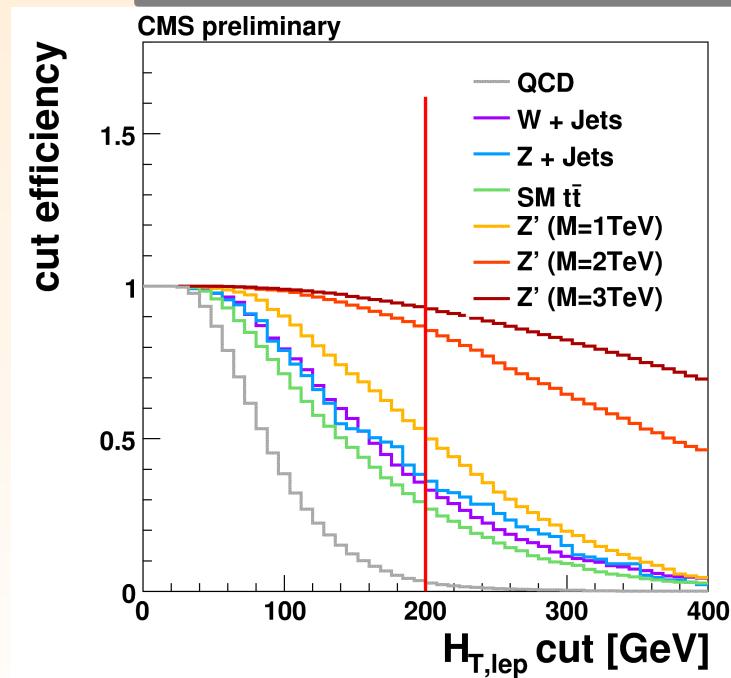
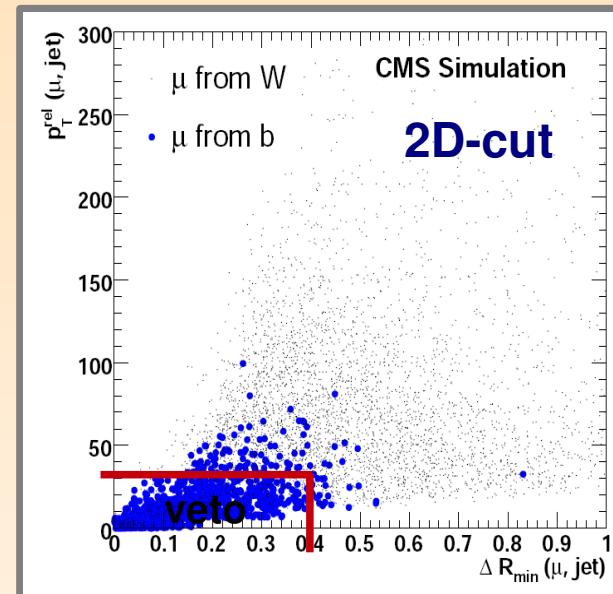
# Muon+jets analyses - selection

## Standard selection:

- $N_{\text{jets}} \geq 4$  ( $p_T > 35 \text{ GeV}/c$ ,  $|\eta| < 2.4$ )
- Isolated muon ( $p_T > 25 \text{ GeV}/c$ ,  $|\eta| < 2.1$ )

## Changes:

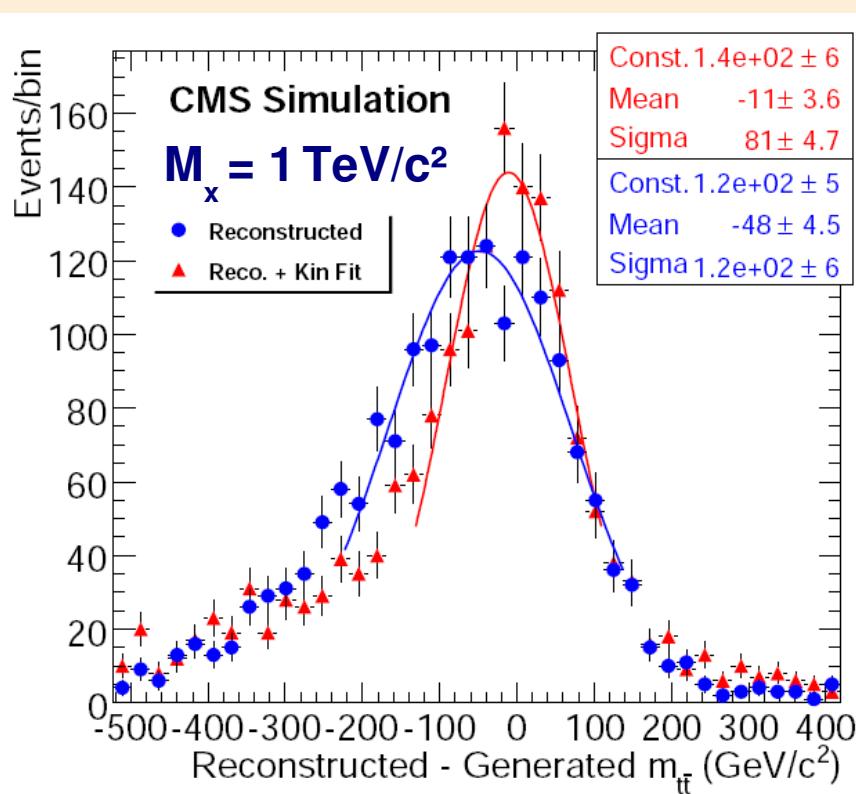
- Low and high  $M_{\text{tt}}$  (*account not well isolated lepton*):
  - 2D-cut instead of relative isolation cut  
 (Rel. isolation relates scalar sum of pT (ET) of tracks (calorimeter deposits) in a cone of  $R=0.3$  around the muon to the muon momentum)
- High  $M_{\text{tt}}$  (*account for jet merging*):
  - $N_{\text{jets}} \geq 2$  ( $p_T > 50 \text{ GeV}/c$ ,  $p_{T,\text{jet}} > 260 \text{ GeV}/c$ ,  $|\eta| < 2.4$ )
  - $H_{T,\text{lep}} = p_T(\mu) + E_T^{\text{miss}} > 200 \text{ GeV}$



# Muon+jets analyses - reconstruction

## Low $M_{t\bar{t}}$ :

- Select 4 jets which minimize  $\chi^2$   
(had. masses ( $W, top$ ),  $\Delta R(l,b)$ ,  $m_T(l,b,MET)$  and  $\Sigma p_T(jets)$ )
- Perform kinematic fit using selected 4 jets ( $(E,\eta,\Phi)$  of jets,  $p_{x,y,z}$  ( $\nu$ ),  $E(\mu)$ )



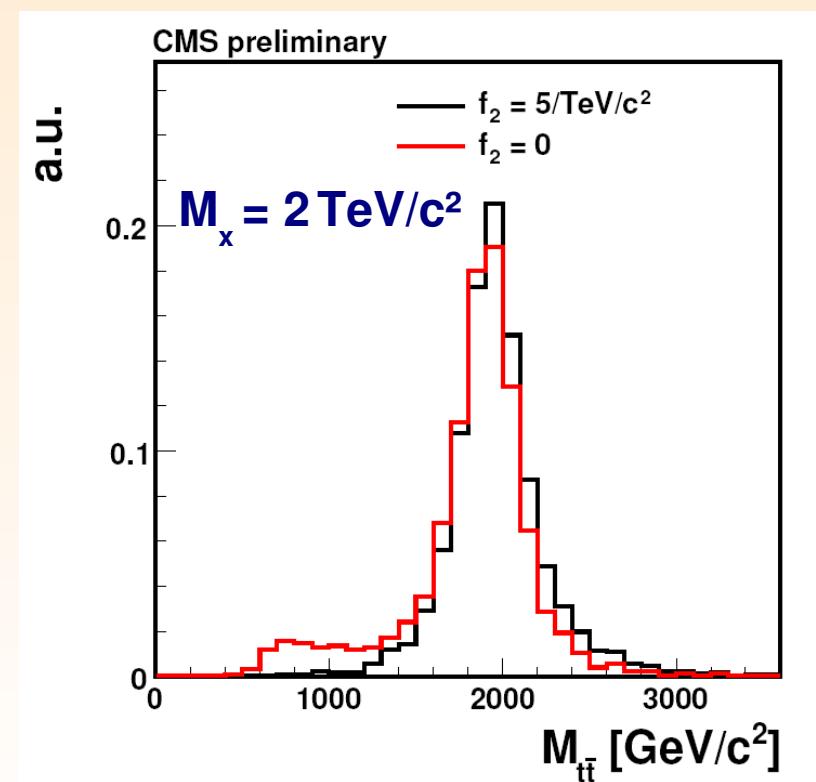
## High $M_{t\bar{t}}$ :

$\Delta R_{sum} = \underbrace{\Delta R(t_\ell, \mu) + \Delta R(t_\ell, \nu) + \Delta R(t_\ell, b_\ell)}_{\text{small separation of decay products}}$

$f_1 \Delta R(t_\ell, t_h) - f_2 M_{t_\ell t_h}$  reduces tails at low mass edge

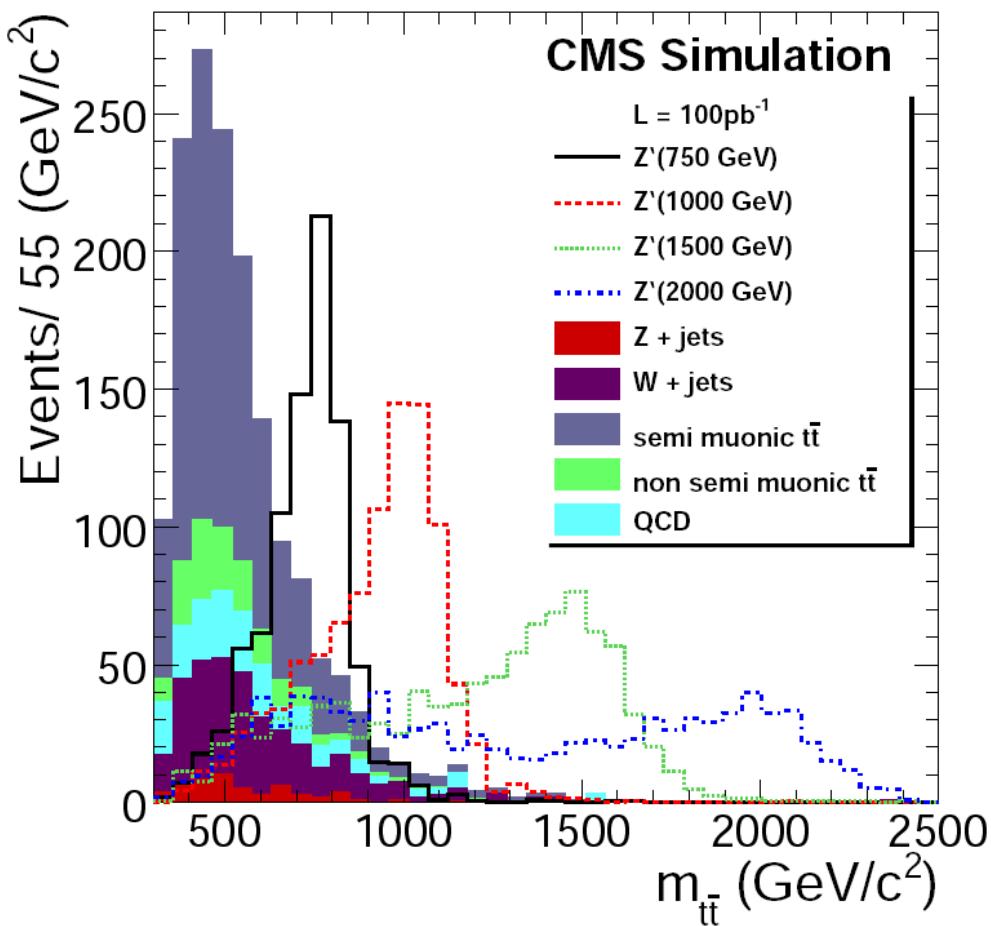
large separation of top quarks

with  $f_1=0.5$ ,  $f_2=(0,1,5)/\text{TeV}/c^2$  for (2,3,4) jets

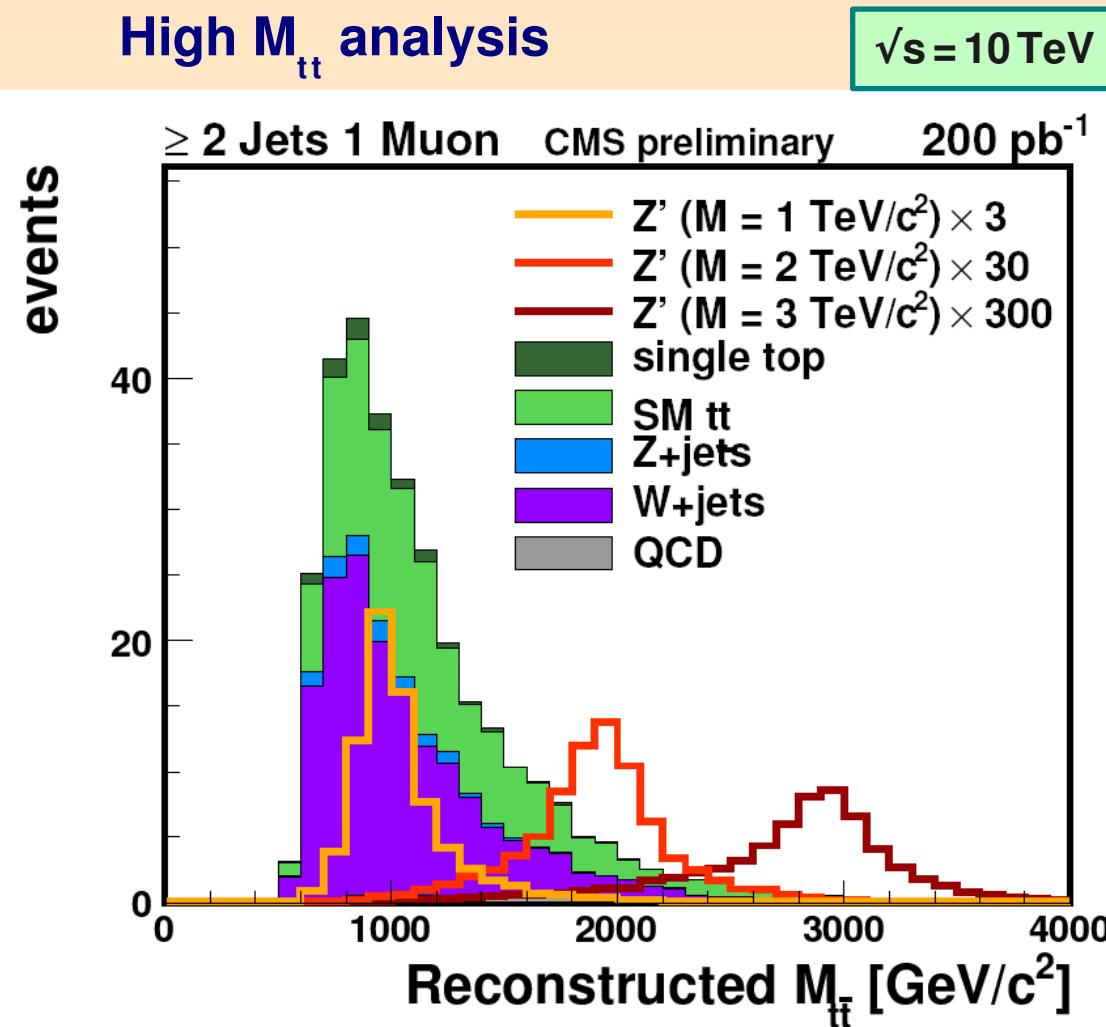


# Muon+jets analyses – top pair mass

## Low $M_{t\bar{t}}$ analysis



## High $M_{t\bar{t}}$ analysis



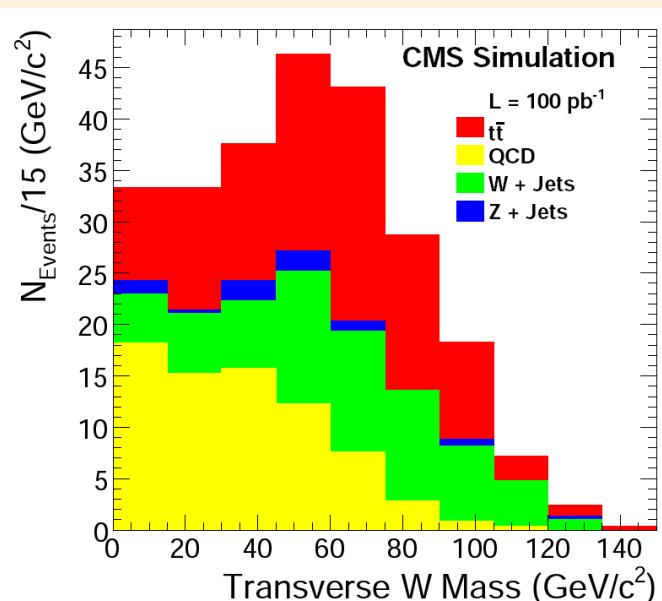
- Low background even at small  $M_{t\bar{t}}$
- $M_{t\bar{t}}$  resolution optimal for low  $M_{t\bar{t}}$

- Background relative large at small  $M_{t\bar{t}}$
- $M_{t\bar{t}}$  resolution optimal for high  $M_{t\bar{t}}$

# Muon+jets analyses – QCD background

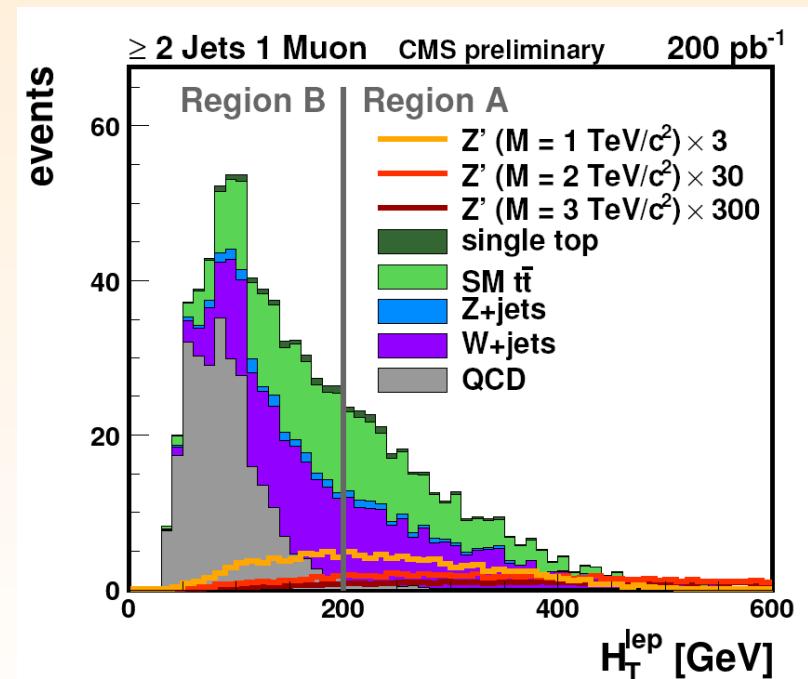
## Low $M_{t\bar{t}}$ :

- Determination of  $N_{QCD}$  for  $H_T < 350 \text{ GeV}$  by fitting transverse mass of W boson
- QCD sample selected by inverting 2D-cut  $(p_T^{\text{rel}}(\mu, \text{jet}) < 35 \text{ GeV}/c,$   $0.1 < \Delta R_{min}(\mu, \text{jet}) < 0.4)$
- Extrapolate to  $H_T > 350 \text{ GeV}$  by using the ratio of  $N_{QCD}$  of high to low  $H_T$  events



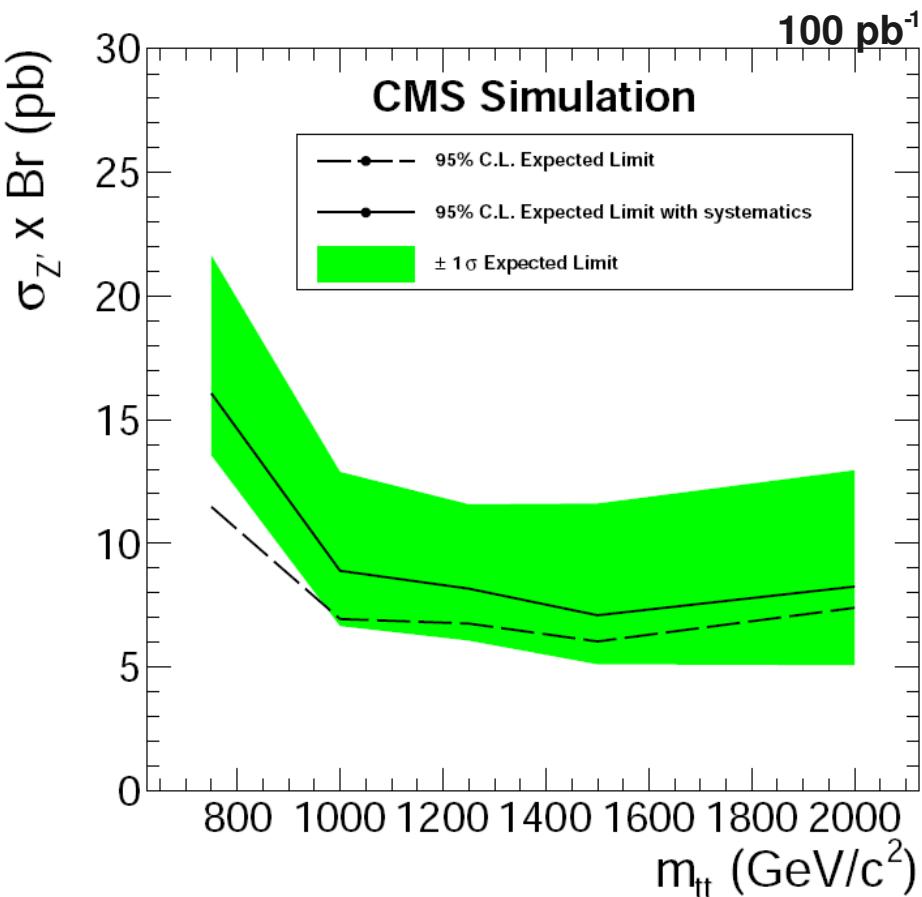
## High $M_{t\bar{t}}$ :

- QCD sample selected by inverting 2D-cut
- Contribution of heavy resonances not negligible below  $H_T^{\text{lep}} < 200 \text{ GeV}$
- Simultaneous fit to signal region (A,  $M_{t\bar{t}}$ ) and background region (B,  $H_T^{\text{lep}}$ )



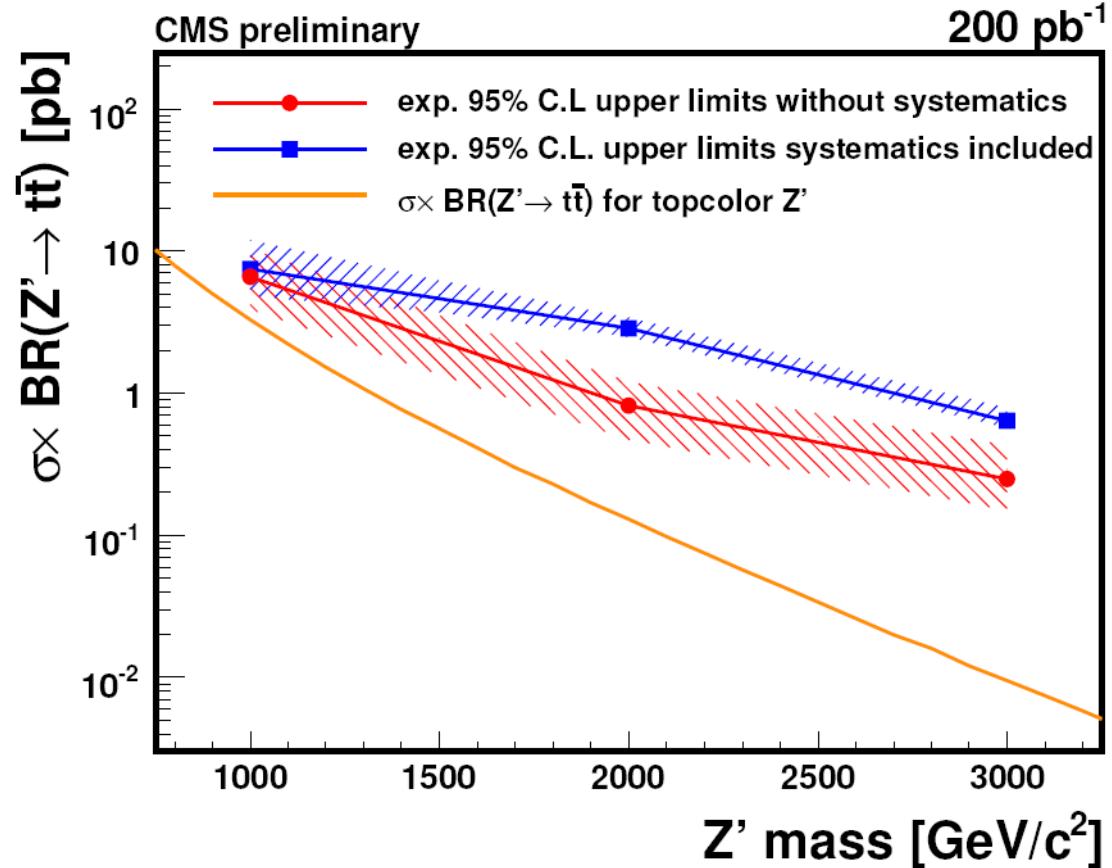
# Muon+jets analyses – exp. sensitivity

## Low $M_{tt}$ analysis



## High $M_{tt}$ analysis

$\sqrt{s}=10 \text{ TeV}$



Good exp. sensitivity at low  $M_{tt}$

Improved exp. sensitivity at high  $M_{tt}$

# Hadronic decay of tops – Top Tagging

## Top Tagging algorithm, modified CMS version:

D. Kaplan et al.,  
PRL 101, 142001 (2008)

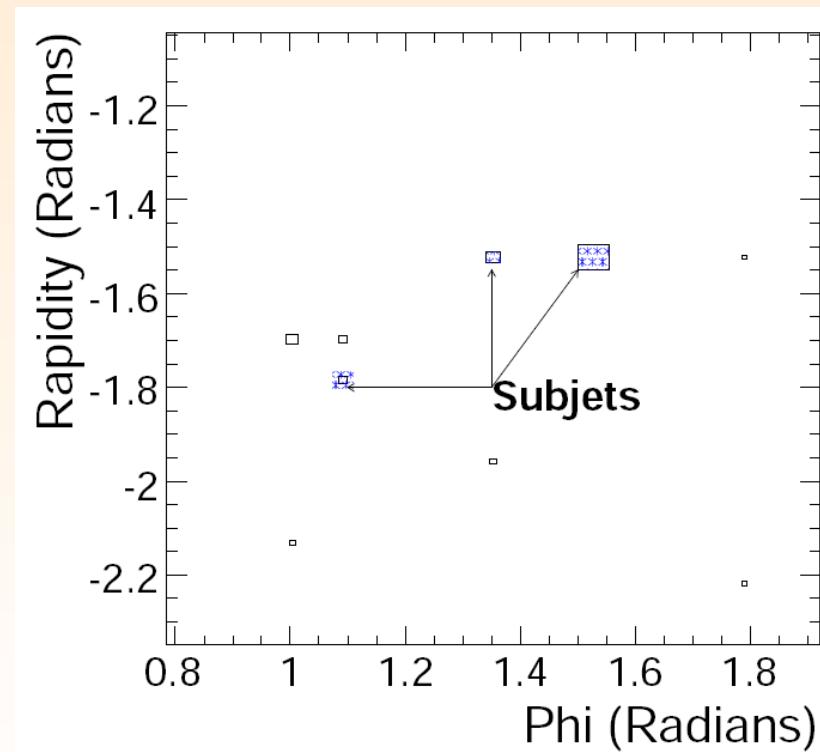
- Cluster input particles (*calorimeter clusters*) with  $k_T$ -like algorithms with large distance parameter ( $R=0.8$ ) to contain all top decay products into hard jet

$$d_{ij} = \min(k_{T,i}^n, k_{T,j}^n) \frac{\Delta R_{ij}^2}{R^2} \quad \text{beam distance: } d_{iB} = k_{T,i}^n$$

Algorithms:  $k_T \rightarrow n=2$  ;  
 $\text{anti-}k_T \rightarrow n=-2$  ;  
Cambridge-Aachen (C-A)  $\rightarrow n=0$

C-A: Capable of discerning components closest to the hard jet  $\rightarrow$  well suited to discriminate softer subjets within harder jets

- Decompose hard jets ( $p_T > 250\text{GeV}/c$ ,  $|y| < 2.5$ ) by undoing clustering steps of cluster sequence
  - Consider only clusters with  $p_T > 0.05 p_T^{\text{hadjet}}$   
 $\rightarrow$  throw out soft clusters
  - If two hard parent clusters are found, a further decomposition is performed  
 $\rightarrow$  get 3-4 subjets

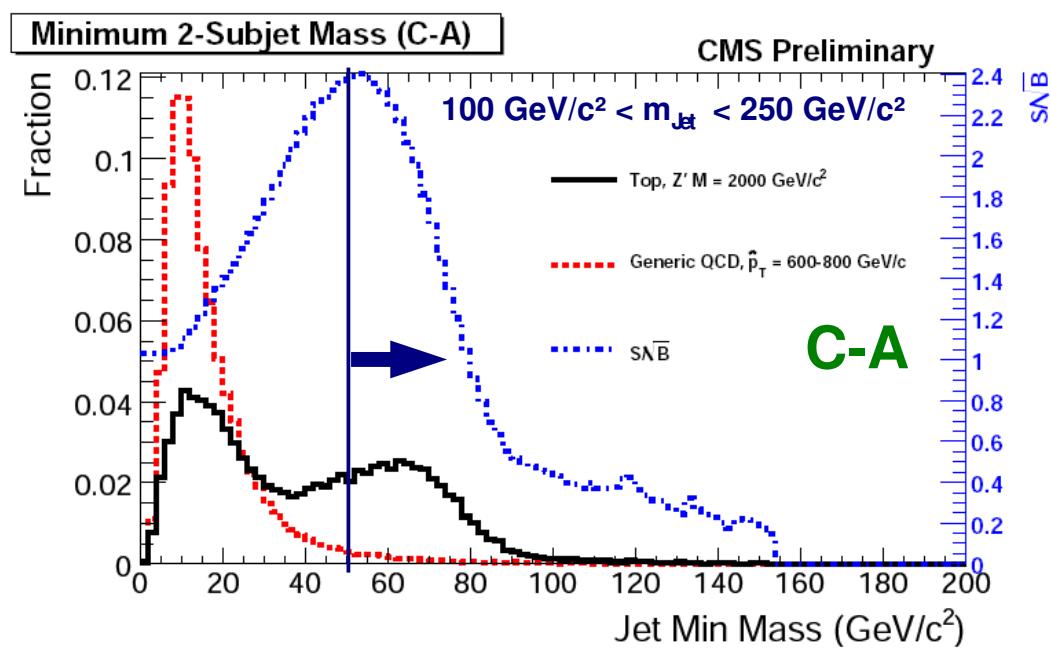
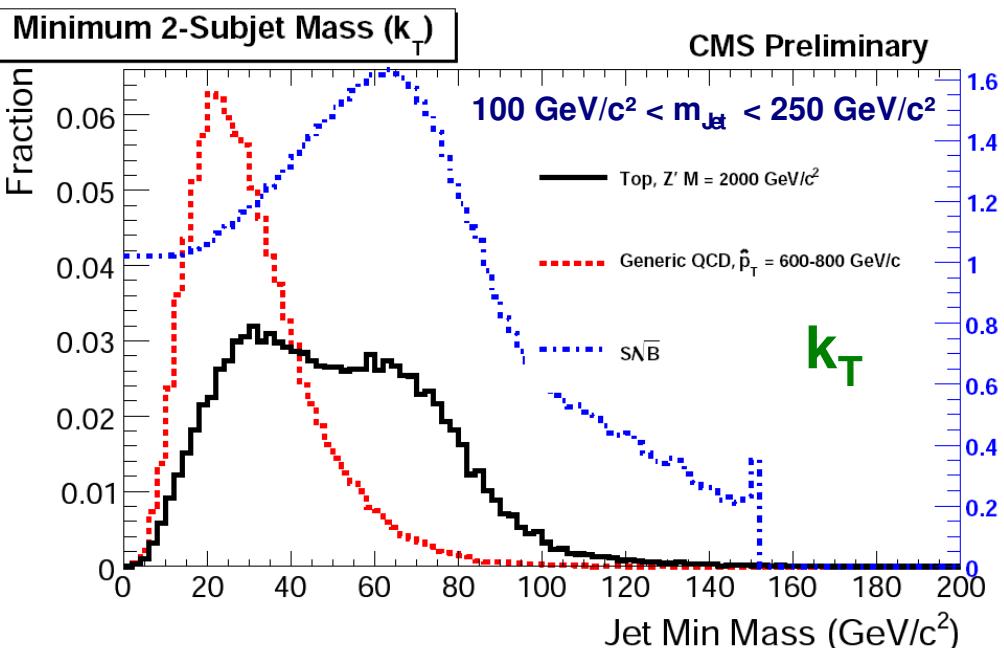
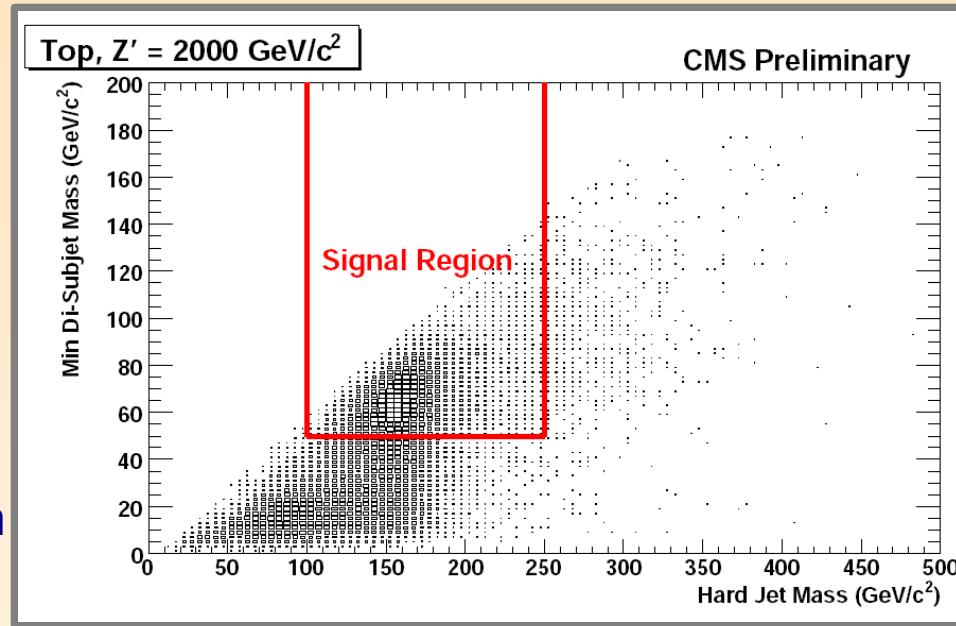


# Top Tagger – kinematic cuts

- Mass of original hard jet:  
 $100 \text{ GeV}/c^2 < m_{\text{jet}} < 250 \text{ GeV}/c^2$   
*(loose, not optimized)*
- Min. mass of subjet pairs:  
 $m_{\min} > 50 \text{ GeV}/c^2$   
*(chosen to optimize  $S/\sqrt{B}$ )*

Best discrimination obtained with C-A algorithm

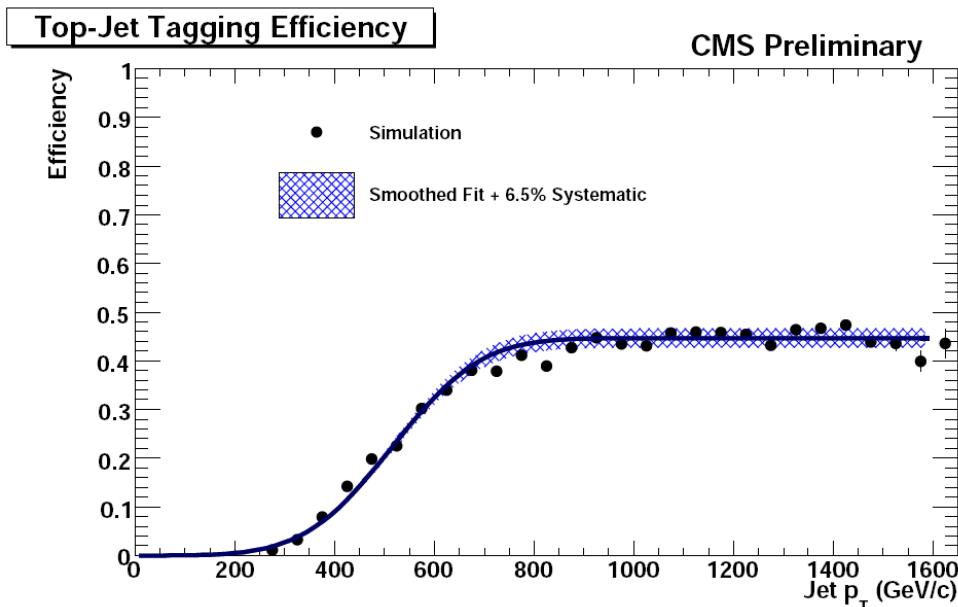
$$S/\sqrt{B} = 2.4 \text{ (C-A)} , 1.6 \text{ (} k_T \text{)} , 1.3 \text{ (anti-} k_T \text{)}$$



# Performance of C-A Top Tagger

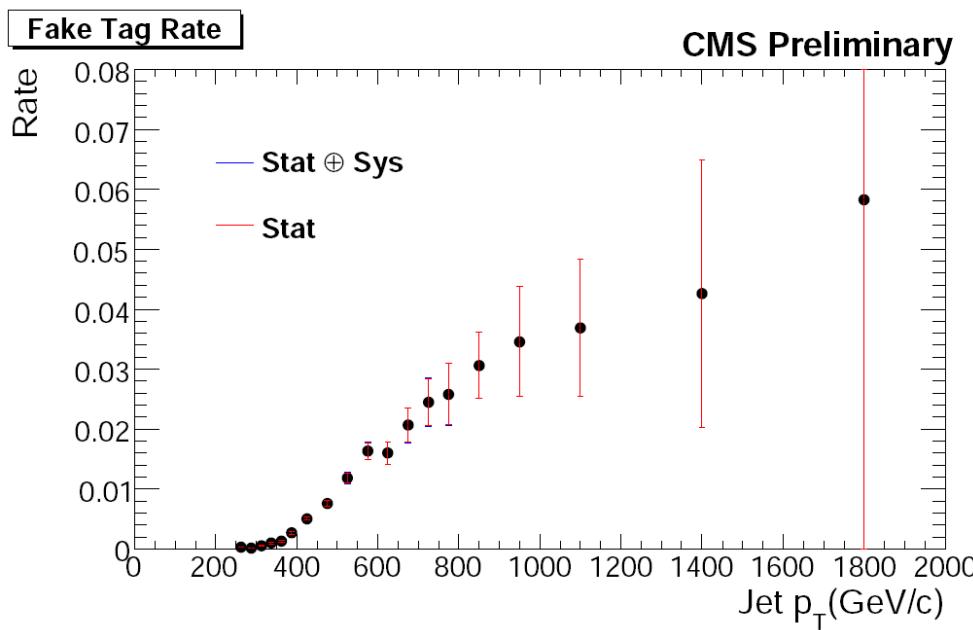
## Efficiency for hadronic top-jets (from MC)

- Top jets with  $p_T > 600 \text{ GeV}/c$ :  $\epsilon \approx 46\%$
- Determined from MC, since stat. of top pair events in lepton+jets too low for these  $p_T$ 
  - Largest theory uncertainty (ren. Scale): 3%
  - Jet resolution ( $p_T, y, \text{angular}$ ):  $\approx 3\%$  each



## Fake rate (data driven method)

- Non top jets with  $p_T = 600 \text{ GeV}/c$ :  $\epsilon \approx 1.5\%$
- Use of “anti-tag and probe” method:
  - Select events, where one jet is anti-tagged ( $\leq 2$  subjets,  $> 2$  subjets but failed kin. cuts)
  - Contamination from continuum top pair production is subtracted (simulation)
  - The other jet (probe-jet) is used to determine the tag-rates

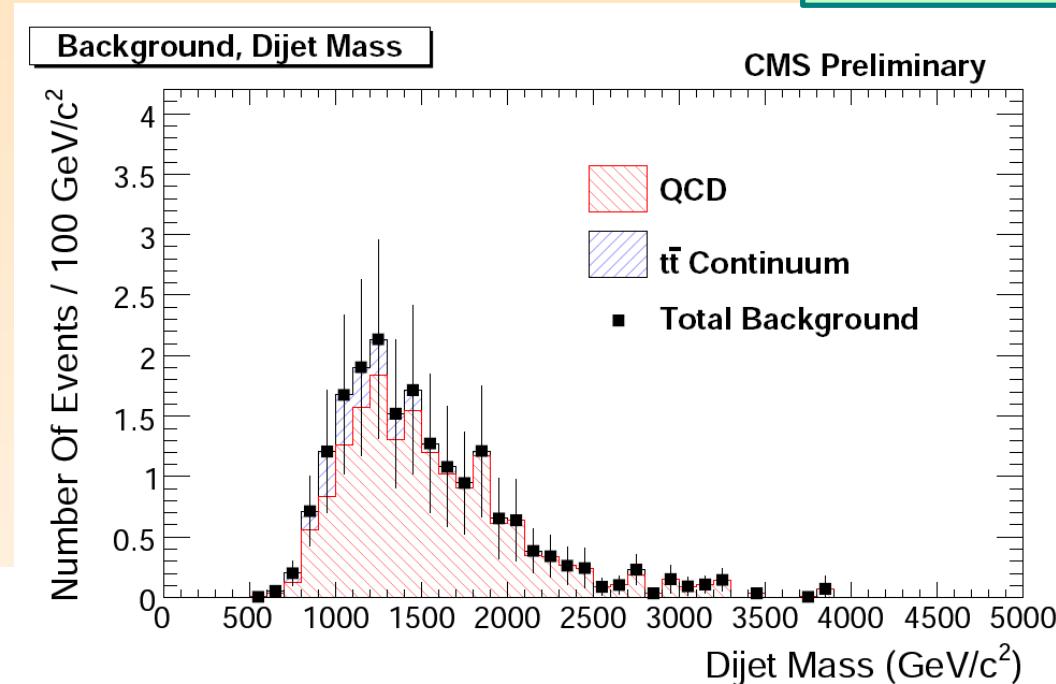
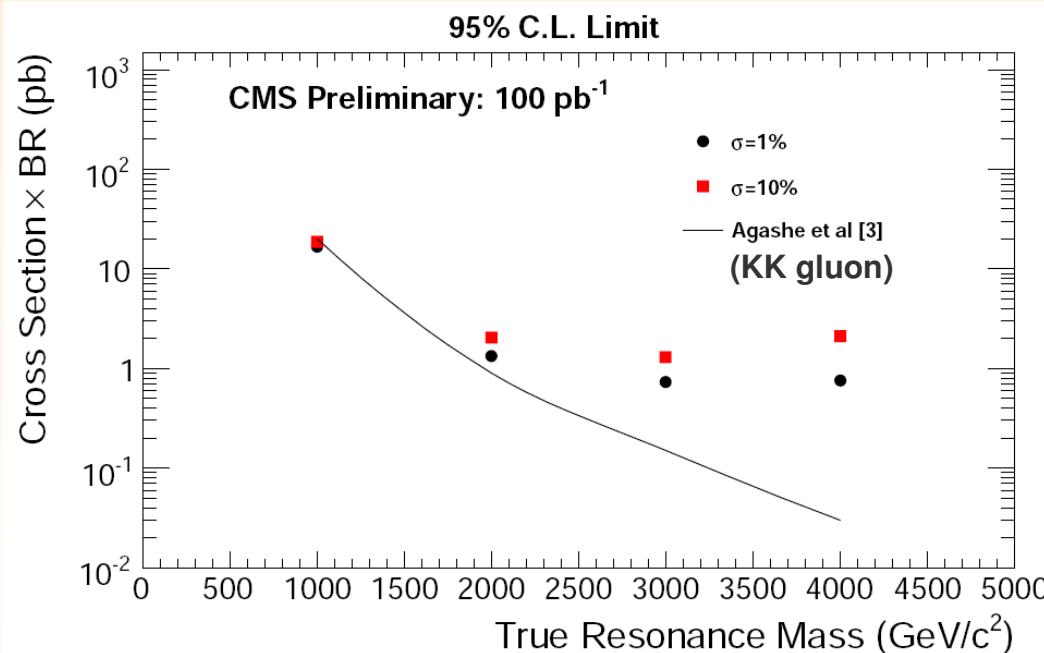


# All-hadronic analysis

$\sqrt{s} = 10 \text{ TeV}$

## Selection and backgrounds:

- 2 C-A jets with  $p_T > 250 \text{ GeV}/c$  -  $|\eta| < 2.5$
- Each jet is tagged by C-A top tagger:  
*3 or 4 subjets,  $m_{min} > 50 \text{ GeV}/c^2$ ,  
 $100 \text{ GeV}/c^2 < m_{jet} < 250 \text{ GeV}/c^2$*
- QCD dijet events dominate  
*Small contribution from top pair continuum,  
W/Z+jets and single top negligible*



## Analysis method:

- Count events in a selected mass window

Sensitivity excellent at high  $M_{t\bar{t}}$

# Summary

## Overview of CMS activities on boosted objects:

- Boosted top pairs:
  - Modified selection and rec. for lepton+jets due to altered topology
  - Application of C-A top tagger to all-hadronic channel looks promising

*No public results on boosted Higgs and lepton jets yet*

## Outlook:

- Apply top tagger to lepton+jets analysis
- Handle transition region between non boosted and boosted top

**Commissioning of top tagger started  
(first public results hopefully soon)**

