Reconstruction of High Transverse Momentum Top Quarks at CMS

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Introduction

- Various New Physics particles decay into tt pairs with large branching fractions:
  - Randall-Sundrum KK gluon: $g_{KK} \rightarrow tt$

    L.Randall, R.Sundrum, Phys.Rev.Lett 88:3370-3374 (1999)
  - excited neutral gauge boson: $Z' \rightarrow tt$

- If Z'/g_{KK} is heavy enough (~TeV), tt daughters are highly boosted
  → top quark daughters, b and W (→q+q' or lepton+ν) are collimated into single high momentum "top" jet

- Top identification techniques based on b-tagging difficult in highly boosted jets
  - dense tracking environment — CMS note BTV-09-001
    → affects displaced track or vertex b-tagging
  - lepton ID not trivial for leptons inside boosted jets
    → affects "soft lepton" tagging
- Expect lower efficiency and higher mis-tag rates of most b-tagging methods

- Easier to associate jets with top-quark since jet daughters follow top direction

- New idea: Identify $t \rightarrow W(\rightarrow qq')\,b$ decays directly by studying the sub-structure of the collimated "top" jet

Boosted Top Tagging arXiv:0806.0848v2, Phys.Rev.Lett.101:142001,2008, D.Kaplan *et all*

- If boosted top decays to quarks only (hadronic mode): $t \rightarrow W(\rightarrow qq') b$

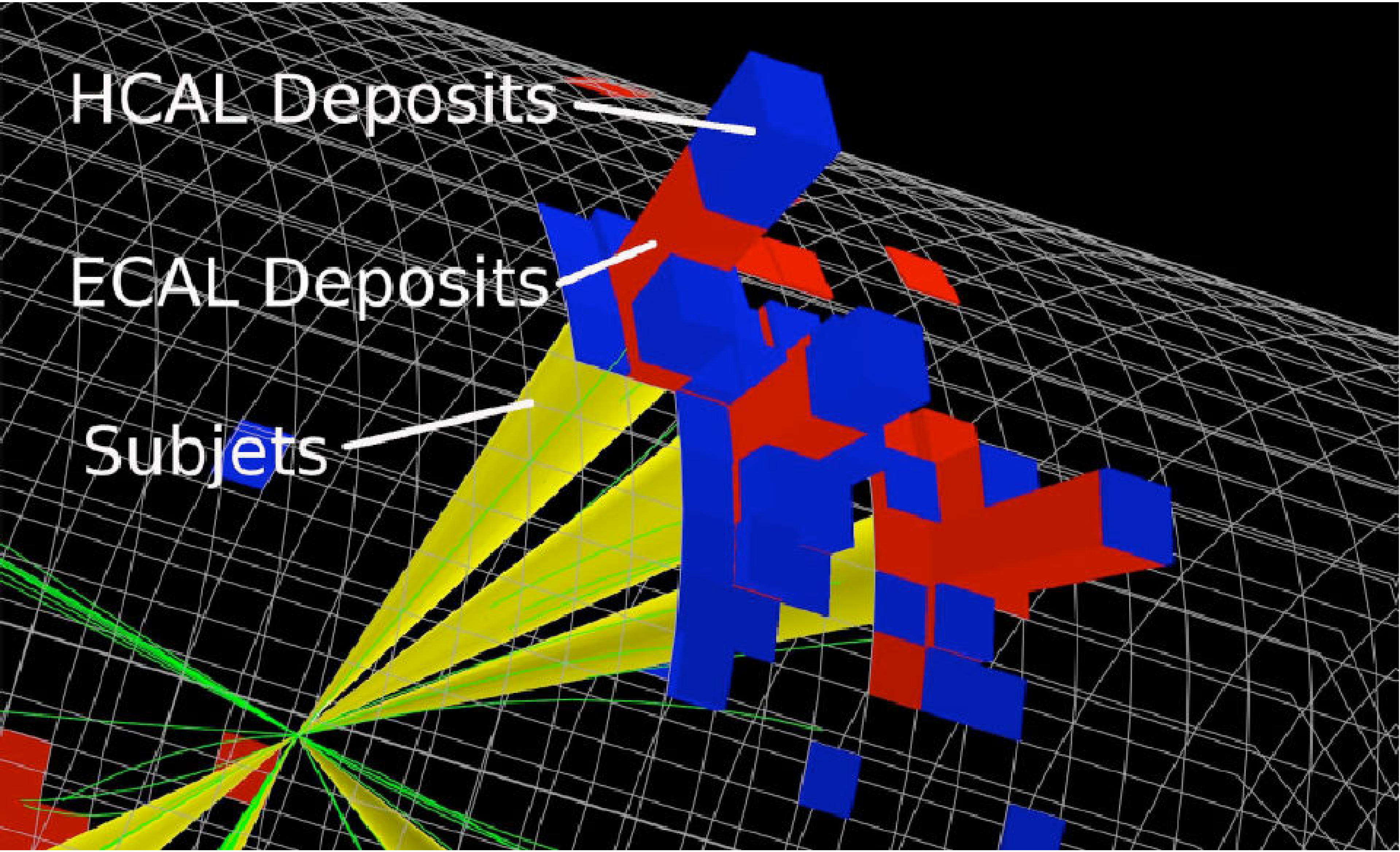
→ take advantage of large BR in all hadronic mode (46%)
→ decompose top jet into sub-jets corresponding to top daughters (bqq')
→ attempt to discriminate top jets from QCD jets using jet sub-structure information
→ challenge: large QCD jet background
→ expect 40% efficiency and 99% non-top background rejection

- Implement boosted top tagging algorithm at CMS
  - attempt to reconstruct top and W mass using sub-jets

- Is it possible to decompose boosted top jet into sub-jets ?

CMS Boosted Top MC Event

Yes, using CMS simulation find possible to resolve sub-jets inside boosted top jet:



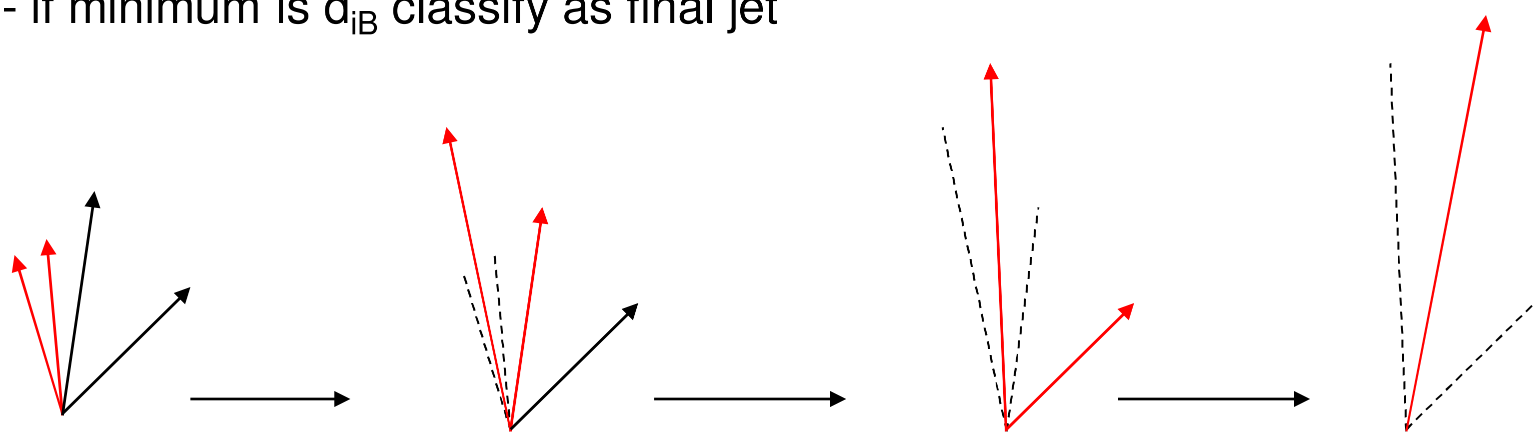
Cambridge Aachen Jet Clustering

- Cambridge Aachen (arXiv:hep-ph/9707323v2) is a sequential recombination (K_T type) clustering algorithm
- For each calorimeter cell and pair of cells determine:
  - K_T : n = 2
  - anti-K_T : n = -2
  - CA : n = 0

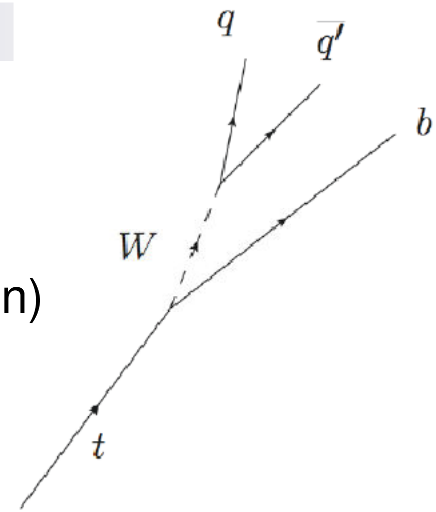
$$d_{ij} = \min(k_{T,i}^{n}, k_{T,j}^{n}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = k_{T,i}^{n}$$

- Algorithm steps:
  - find minimum of d_{ij} and diB
  - if minimum is d_{ij}, merge cells i and j and reiterate
  - if minimum is d_{iB} classify as final jet



Boosted Top Tagging at CMS

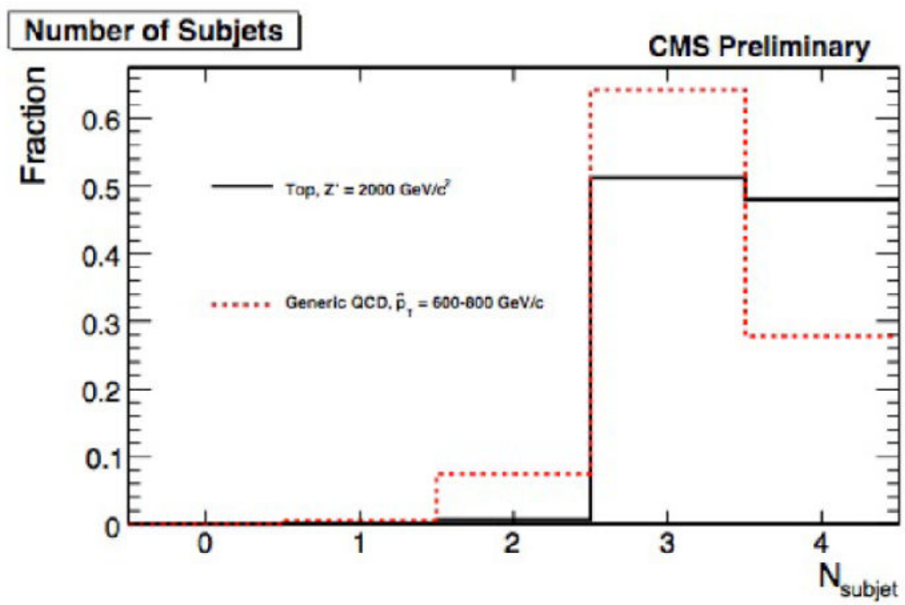


- Define "hard" jet as final jet reconstructed by CA algorithm
  - R = 0.8 → $d_{ij} < d_{iB}$ is same as $\Delta R < 0.8$ (merging condition)
  - Jet $P_T > 250$ GeV
  - $| y | < 2.5$

- Find sub-jets with P_T(sub-jet) > 0.05 × P_T(hard jet)
  - cluster sequence from previous slide is run backwards and soft clusters are removed

- If at least 3 sub-jets are found can apply top tagging algorithm

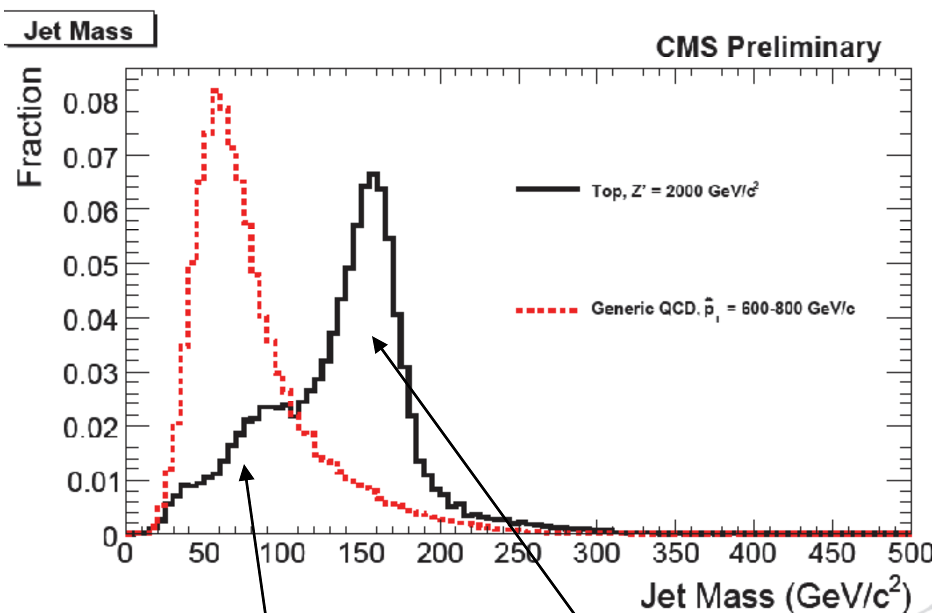
- Discriminating variables:
  - number of sub-jets: select hard jets with at least 3 sub-jets
  - jet mass as proxy to top mass
  - among three leading sub-jets minimum di-jet mass pair as proxy to W mass



Discriminating Quantities: Jet Mass

- Study discriminating variables on:
  - signal boosted top jets from Z' → tt decays with different Z' mass
  - background QCD jets with P_T similar to boosted top jet from Z'

- Very good discrimination provided by jet mass and sub-jet pair mass:



Partially merged jets   fully merged jets

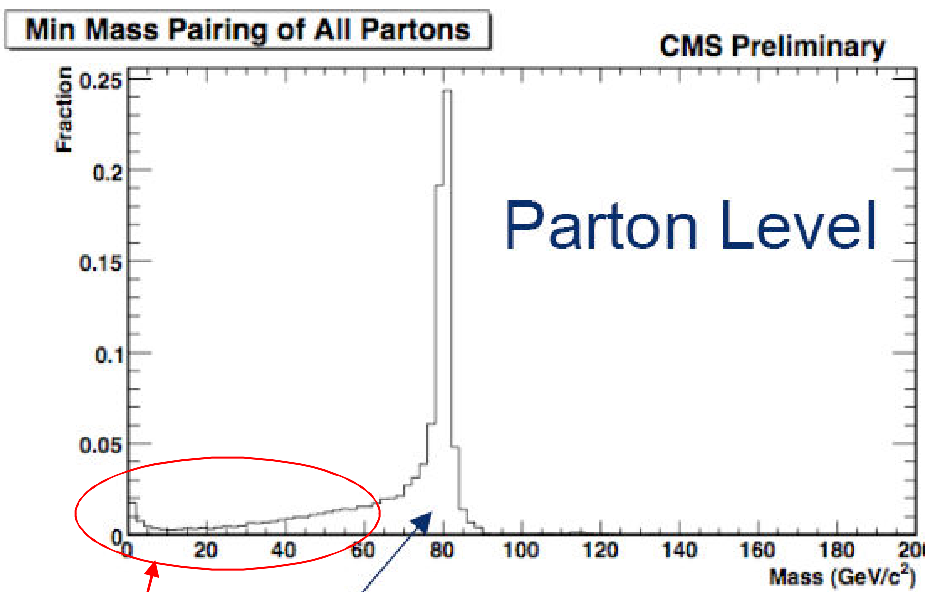
$$m_{ij}^2=(E_i+E_j)^2-(p_i+p_j)^2$$

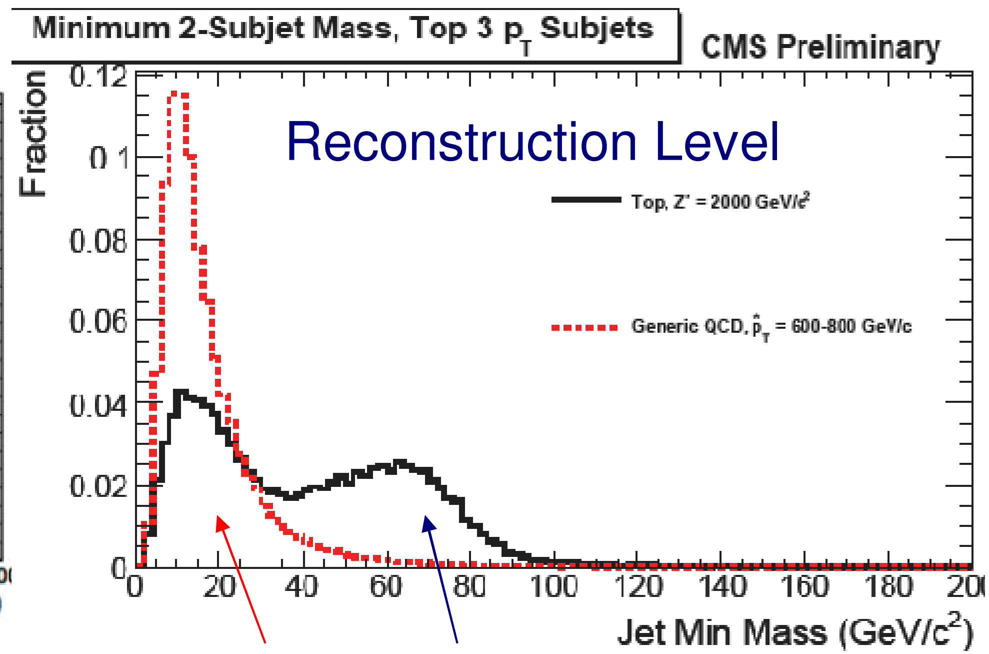
$$\text{MinMass}= \min\{m_{12}, m_{13}, m_{23}\}$$

- Select "hard" jets with 100 < jet mass < 250 GeV

Discriminating Quantities: Minimum Di-Jet Mass

- Minimum di-jet invariant mass is good proxy to W mass
    - provides excellent separation between signal and background
    - select minimum sub-jet pair mass > 50 GeV



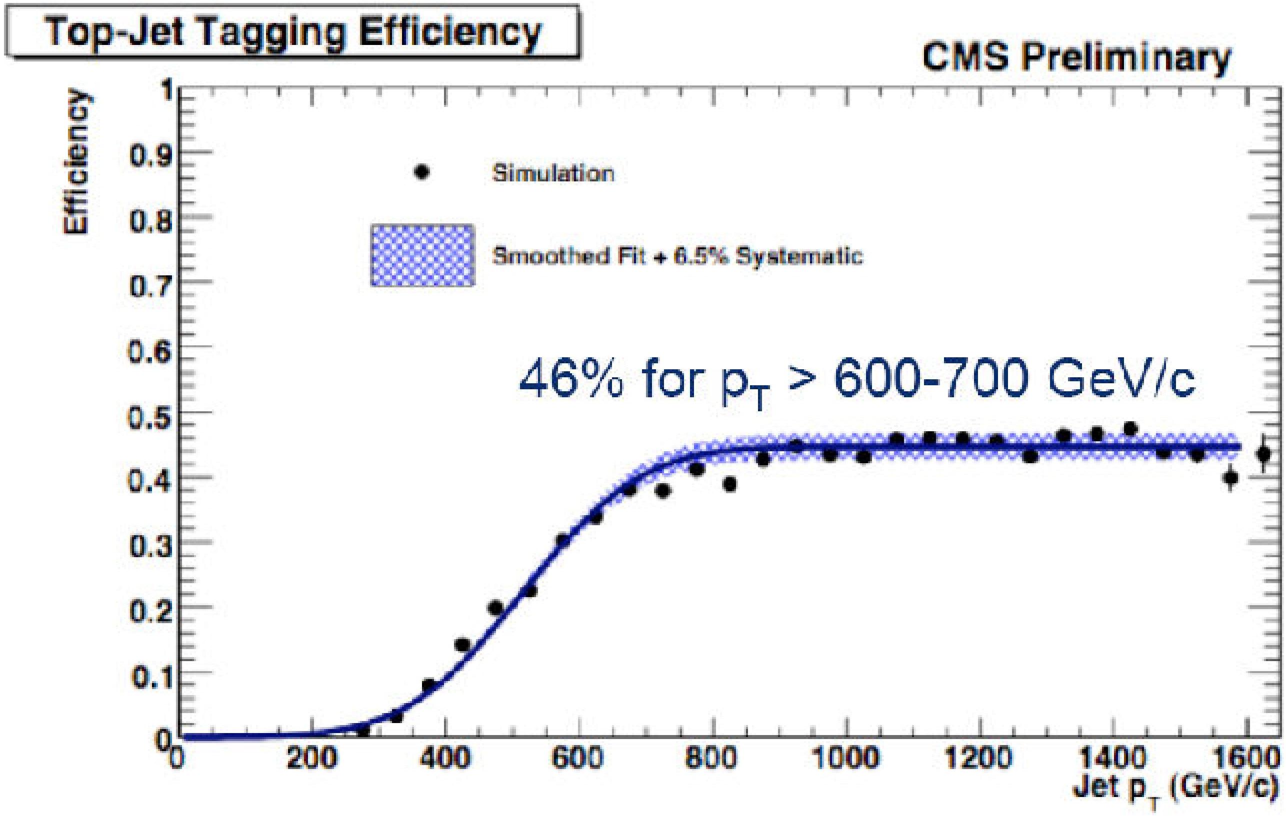


wrong pair bq, bq' | correct pair qq'

wrong pair bq, bq' | correct pair qq'

Efficiency

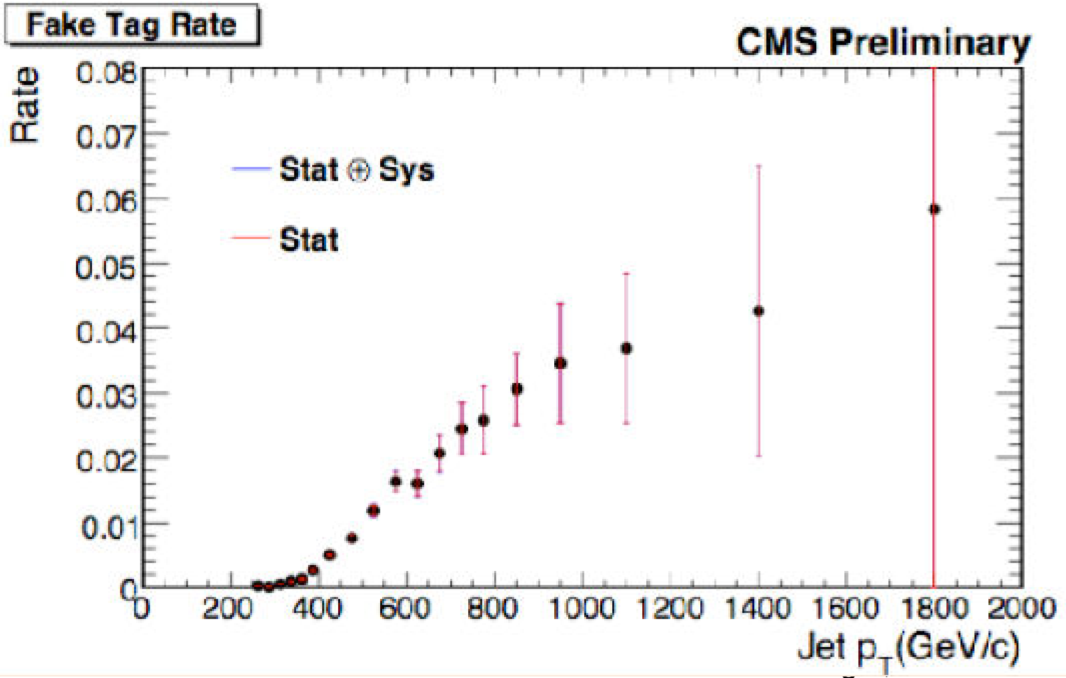
- Determined from simulation by counting selected top jets among all true top jets
- Systematic uncertainties:
  - Theoretical: re-normalization scale (Λ_{QCD}), fragmentation model, ISR/FSR
  - Experimental: due to P_T (10%), y(50%) and Φ (50%) resolution



Mistag Rates

- Determined from di-jet samples
- Select events with one jet that fails at least one of top tagging requirement (anti-tag):
    - at least 3 sub-jets
    -100 < jet mass < 250 GeV
    - min di-jet mass > 50 GeV

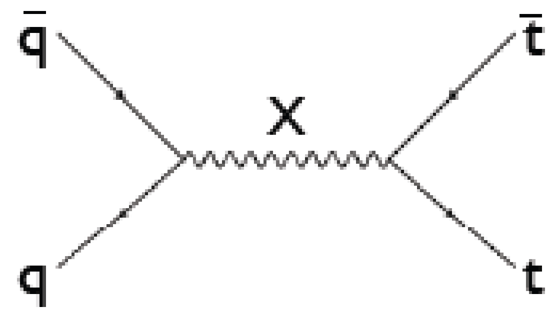
- Other jet in event used as "probe"
    - apply top tagging algorithm on these signal depleted jets

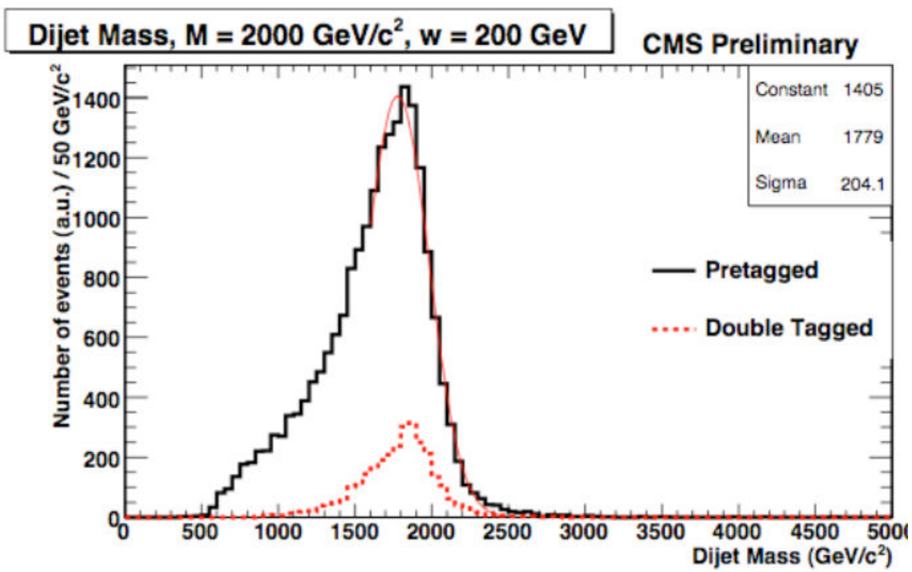


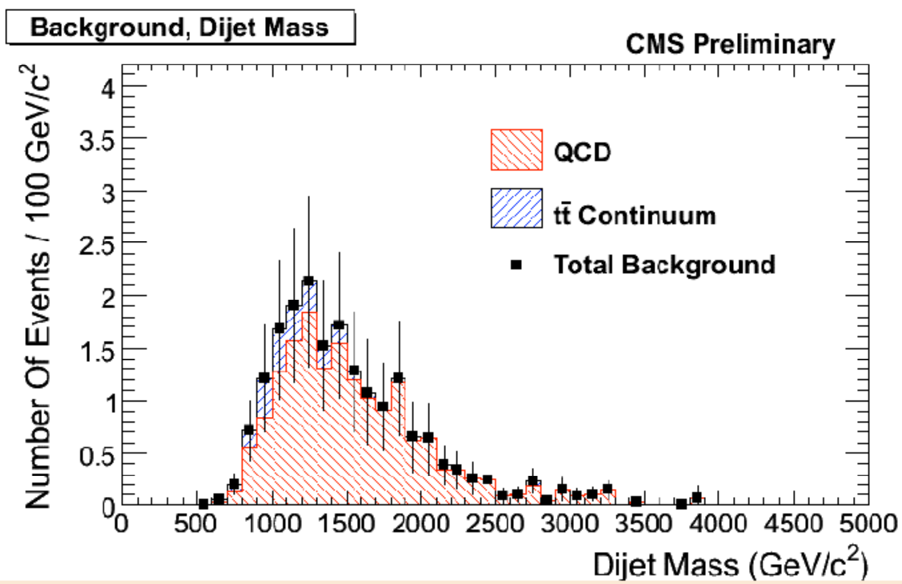
- Achieve 98% background rejection for 600 GeV jeys

Application: Heavy Resonance → $t\bar{t}$

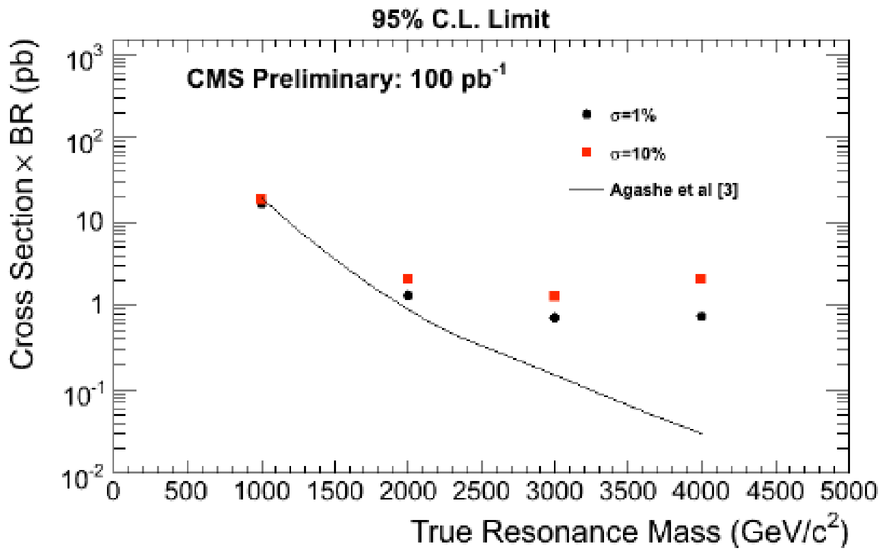
- Search for heavy resonances (Z', g_{KK}) decaying to $t\bar{t}$ pairs where top quarks decay hadronically (CMS note EXO-09-002)
- Select top jets using boosted top tagging algorithm
- Backgrounds
  - QCD jets (dominant)
  - continuum $t\bar{t}$, W/Z+jets, single top

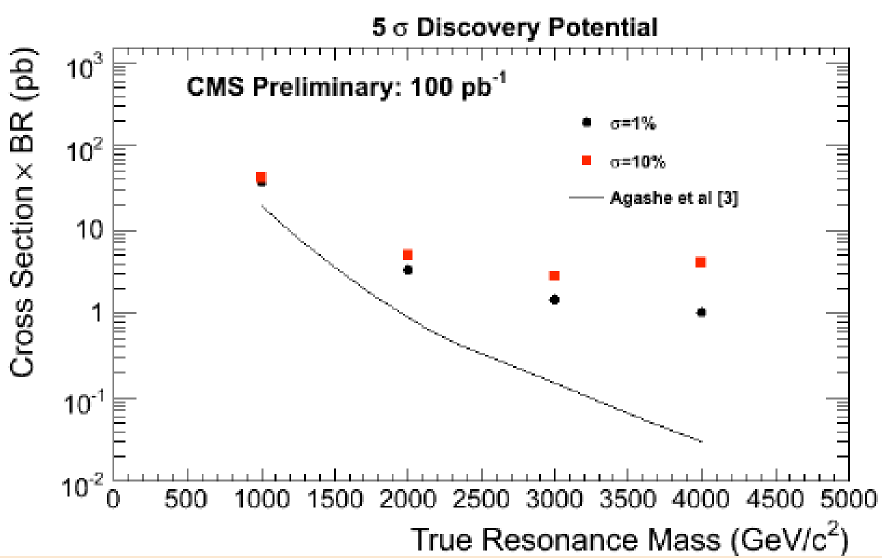






Heavy Resonance → tt Significance Study





CMS note PAS EXO-09-002

- Expected 95% C.L. :
  - 1 TeV: 17.2 pb
  - 2 TeV: 1.5 pb
  - 3 TeV: 0.7 pb

- Similar studies performed at CMS in muon+jet channel

CMS notes: EXO-09-008 TOP-09-009

- Combination of analyses will give the best limit

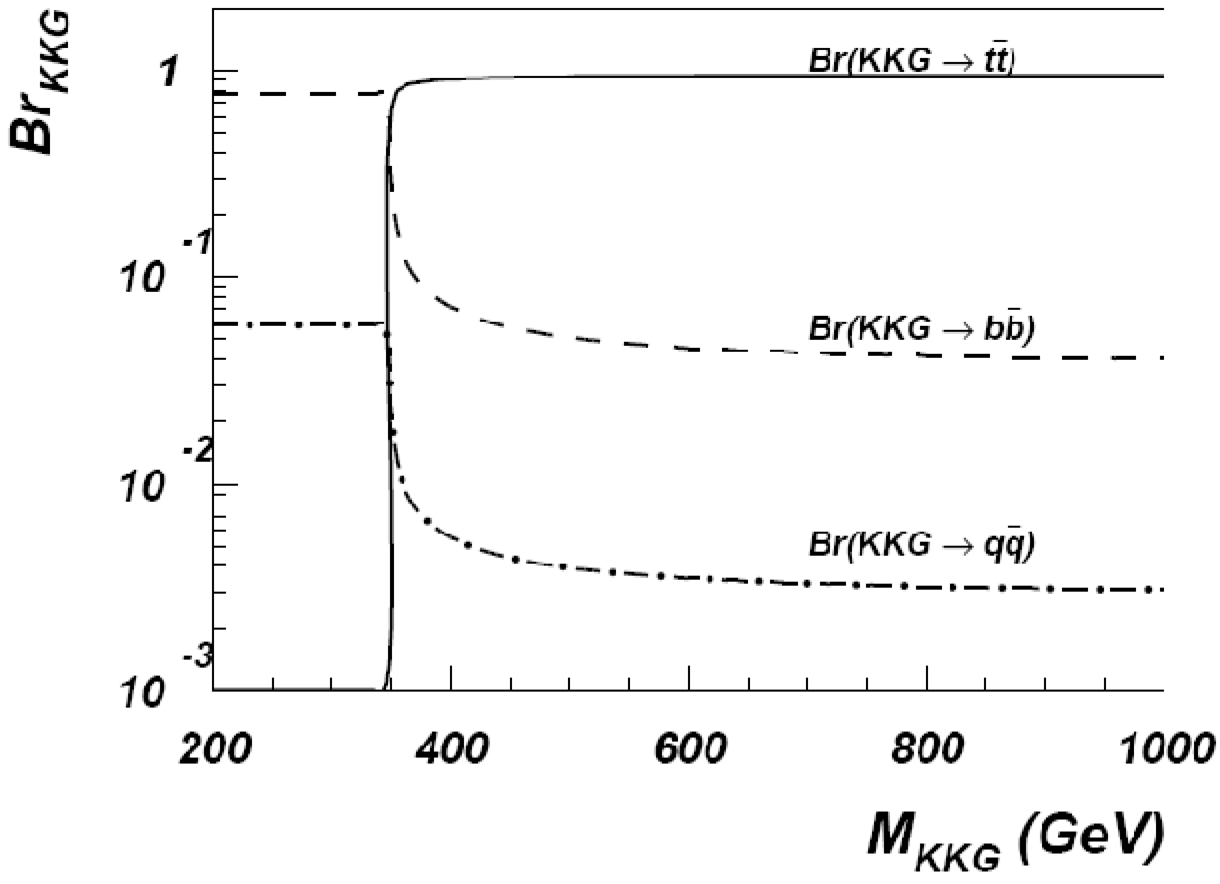
Conclusions

- Boosted top tagging algorithm implemented at CMS
    - identifies high P_T hadronic top decays
    - based on sub-jet identification

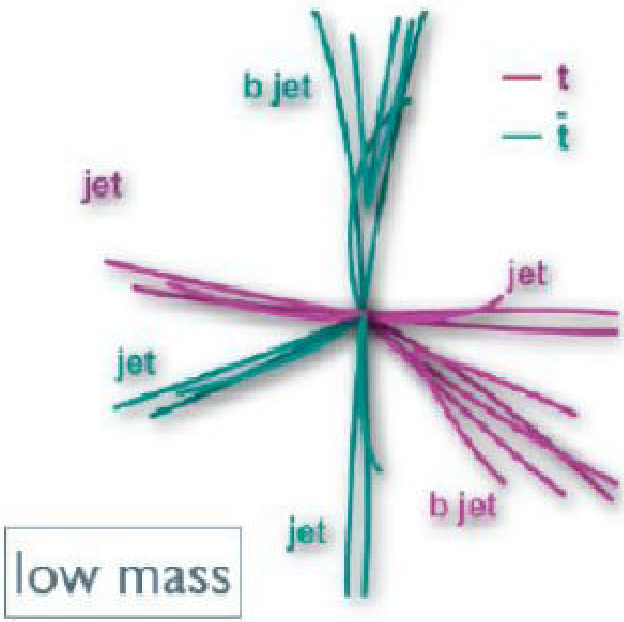
- Achieves ~46% efficiency and ~98% background rejection for ~600 GeV jets

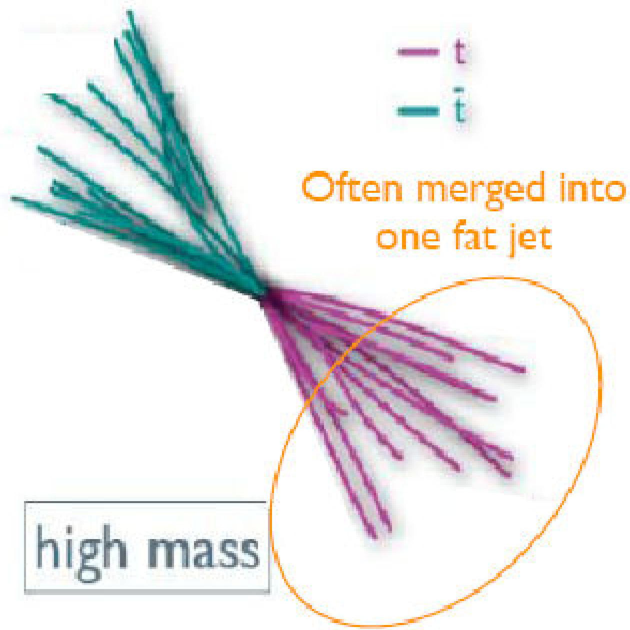
- Will be used in searches for high mass New Physics resonances

Phys.Rev.D77:015003,2008



Highly boosted tops ⇒ Easy to associate jets





Top pair ~ at rest
~6 jets

Boosted top pairs
~2-3 jets

Top Tagging Uncertainty

Effect	Systematic Uncertainty (%)
Initial State Radiation	1
Final State Radiation	2
Renormalization Scale	3
Light Quark Fragmentation	< 1
Heavy Quark Fragmentation	< 1
Theoretical Uncertainty	3.8
Momentum Smearing + 10%	3.3
Azimuthal Smearing + 50%	2.9
Rapidity Smearing + 50%	2.9
Detector-Based Uncertainty	5.3
Total Systematic Uncertainty	6.5

Signal and Background Systematic Uncertainty

Quantity	Relative Uncertainty	Uncertainty on S and B at $m_0 = 2$ TeV/c^2
Signal Uncertainties		
Top Tagging Efficiency	6.5%	13%
JES Uncertainty on Acceptance	5%	5%
Total Signal Uncertainty		14%
Background Uncertainties		
Statistical uncertainty	10%	10%
JES Uncertainty on QCD Background	35%	33%
$t\bar{t}$ Continuum Contribution	100%	5%
Luminosity	10%	10%
Total Background Uncertainty		36%