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Reconstruction of top associated final states using the Matrix Element Method

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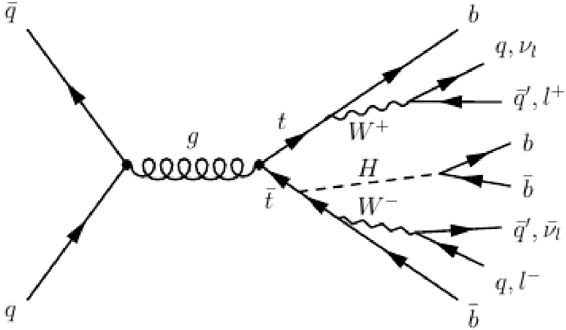
Introduction

- Present methods used to identify top associated final states
- Focus on the matrix element method and substructure techniques
- As an example, use $t\bar{t}H$, $H \rightarrow b\bar{b}$ process
- Observation of $t\bar{t}H$ earlier this year by ATLAS and CMS [1,2], with the Higgs decay to b quarks being a major contribution to the combination
- $t\bar{t}H$, $H \rightarrow b\bar{b}$ channel gives direct access to the Yukawa coupling to the top and b quarks

[1] ATLAS Collaboration, Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector, Phys. Lett. B 784, 173 (2018)

[2] CMS Collaboration, Observation of $t\bar{t}H$ production, Phys. Rev. Lett. 120, 231801 (2018)

Topology of $t\bar{t}H$, $H\rightarrow b\bar{b}$ events



- Consider Higgs decay to $b\bar{b}$
- Production of four b quarks, leptons and neutrinos or additional light quarks depending on the decay mode of the tops

Identification of $t\bar{t}H$, $H\rightarrow b\bar{b}$ events

- Complicated final state involving leptons, many jets and MET
- $t\bar{t}H$ production cross-section is only 0.5 pb (Gluon fusion: $\sim$ 44 pb)
- Main background ($t\bar{t}+bb$) cross-section is three orders of magnitude larger than the signal cross-section ($\sim$ 832 pb)
- $t\bar{t}+bb$ background is irreducible since the final state consists of the same particles than the signal
- Large theory uncertainties in the multiscale QCD background modelling

$\Rightarrow$ Reconstruction of $t\bar{t}H$, $H\rightarrow b\bar{b}$ events is challenging
Requires dedicated analysis techniques,
such as the Matrix Element Method

The Matrix Element Method (MEM)

Probability $P(\mathbf{x}|\boldsymbol{\alpha})$ for an event $\mathbf{x}$ to be the final state of process $\boldsymbol{\alpha}$:

$$P(\mathbf{y}|\boldsymbol{\alpha}) \propto \frac{1}{\sigma_\alpha} \int d\Phi(\mathbf{x})\, |M_\alpha|^2(\mathbf{x})\, W(\mathbf{x},\mathbf{y})$$

where

- σ_α is the total cross section of process $\boldsymbol{\alpha}$
- $d\Phi(\mathbf{x})$ is the phase-space measure
- $|M_\alpha|^2(\mathbf{x})$ is the LO scattering amplitude squared
- $W(\mathbf{x},\mathbf{y})$ is the transfer function (probability to obtain a detector response $\mathbf{y}$ for a particle level event $\mathbf{x}$)

Signal ($\mathbf{s}$) to background ($\mathbf{b}$) discriminant:

$$P_{s/b} = \frac{P(\mathbf{y}|\mathbf{s})}{P(\mathbf{y}|\mathbf{s}) + \kappa \cdot P(\mathbf{y}|\mathbf{b})}$$

with κ: scale factor optimized to 0.1

Transfer functions I

- MEM takes into account detector resolution by using transfer functions (TF) to relate observed quantities **y** to parton-level quantities **x**
- Need TFs for all observed objects: jets, leptons and MET
  - Leptons: Assume perfect momentum resolution
    → TF is a Dirac delta function
  - MET:

$$W_{\mathrm{MET}}(\mathbf{p}_T | \sum_k \mathbf{p}_k) = \frac{1}{2\pi|\Sigma|^{1/2}} \exp\left[-\frac{1}{2}(\mathbf{p}_T - \sum_k \mathbf{p}_k)^T \Sigma^{-1} (\mathbf{p}_T - \sum_k \mathbf{p}_k)\right]$$

with $\Sigma = \sigma_{\mathrm{MET}}\mathbf{I}$, $\sigma_{\mathrm{MET}} = 30$ GeV and $\mathbf{I}$ the identity matrix

Transfer functions II

- Jets: Evaluate TFs on MC simulation depending on momentum and flavour of the quark

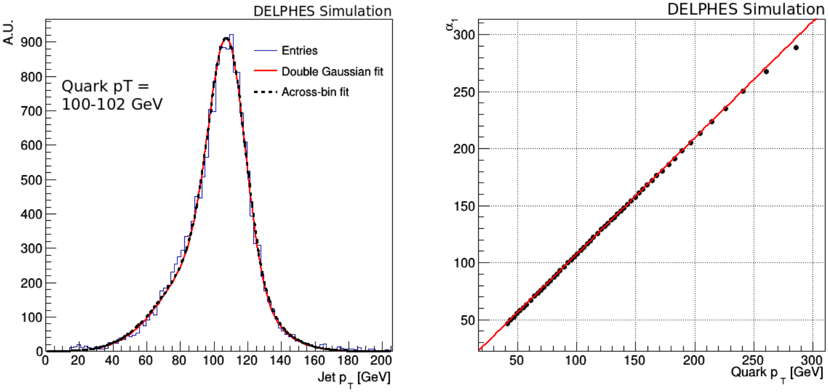
- Different transfer functions for b jets and light jets (including charm), and for $|\eta| < 1$ and $|\eta| > 1$
- TF evaluated separately for quarks of different p$_T$ to account for improving momentum resolution at higher p$_T$
- Double Gaussian fit performed in all bins in p$_T$:

$$TF(p_T|p_{T,\mathrm{gen}}) = N\left[0.7\exp\left(\frac{p_{T,gen} - p_T - \alpha_1}{\alpha_2}\right)^2 + 0.3\exp\left(\frac{p_{T,gen} - p_T - \alpha_3}{\alpha_2 + \alpha_4}\right)^2\right]$$

N: normalization factor

Transfer functions III

- Perform a polynomial fit (across-bin fit) in p_T for all four fit parameters of the individual Double Gaussian fits (α_i for $i \in 1, \cdots, 4$)
- Use parameters of polynomial fit to reconstruct transfer functions for each jet depending on its p_T , η and flavour



MEM specifications

- Requires exactly four b tagged jets to be computed
- Consider 12 permutations to evaluate all possibilities to match b quarks to b tagged jets:

b quarks	Remaining nb. of b jets	Permutations
2 from Higgs decay	4	$\binom{4}{2} = 6$ permutations
1 from top decay	2	$\binom{2}{1} = 2$ permutations
1 from antitop decay	1	$\binom{1}{1} = 1$ permutations
		$\Rightarrow$ 12 permutations

MEM for over and partially reconstructed events

Expect $\mathrm{N}_{\mathrm{quark}} = 4/6/8$ if two/one/zero top quarks decay leptonically

Extra radiation from QCD ($\mathrm{N}_{\mathrm{jets}} > \mathrm{N}_{\mathrm{quarks}}$):
Set $\mathrm{N}_{\mathrm{jets}} = \mathrm{N}_{\mathrm{quarks}}$, and ignore remaining jet(s) for all possible permutations of jets. Sum over all combinations in the integration of the MEM

Missing quarks in the reconstruction ($\mathrm{N}_{\mathrm{jets}} < \mathrm{N}_{\mathrm{quarks}}$):
Three possible reasons:

1. Jets out of acceptance
2. Jets below the energy threshold
3. Merged jets at high transverse momentum of top and / or Higgs

Solve 3 by combining MEM with substructure techniques (see later)
Solve 1,2 by integrating out the kinematics of the missed jets

MEM for partially reconstructed events

Extend space of observables:

$$\mathbf{y} \to \mathbf{y'} = (\mathbf{y}, (E_q, \mathbf{e}_q)_{\mathrm{q \in lost}})$$

and the MEM probability:

$$P(\mathbf{y}) \to P'(\mathbf{y'}) = \frac{1}{\sigma'} \frac{d\sigma_i}{d\mathbf{y} \prod_{\mathrm{q\in lost}} dE_q d\mathbf{e}_q}$$

Finally, integrate out unknown kinematics of lost quarks:

$$P(\mathbf{y}) = \int \left[\prod_{\mathrm{q\in lost}} dE_q d\mathbf{e}_q \right] P'(\mathbf{y'})$$

⇒ Add new integration variables, and extra combinations for identifying the quarks which failed reconstruction

- Longer computation time (more permutations to consider)
- Increases event selection for analysis

Why MEM?

Advantages:

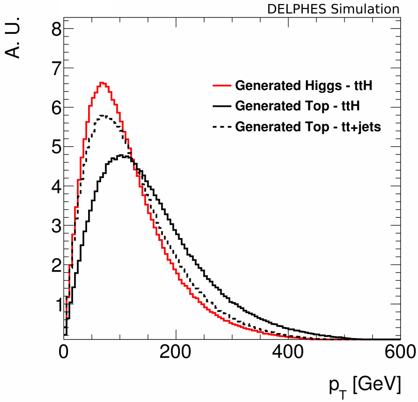
- Theoretically well motivated
- Performance compatible with most recent ML based techniques

Disadvantages:

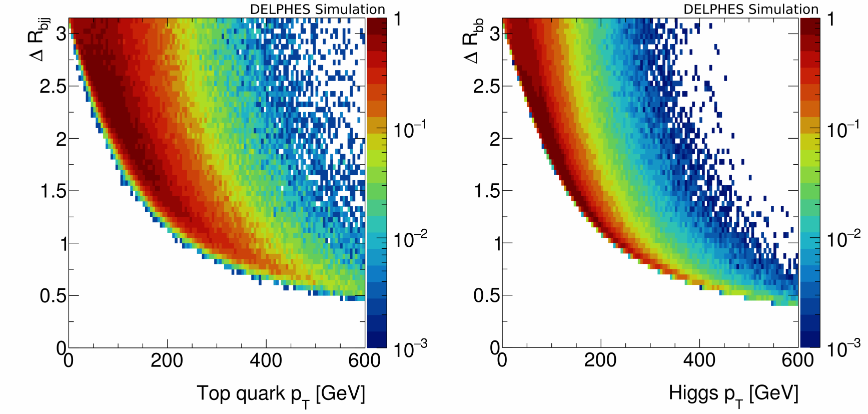
- Relies on precise evaluation of matrix element, which is a major source of uncertainty (ME only evaluated at LO)
- Computationally very expensive ($\sim$1 minute per event, not easily sustainable for HL-LHC)

Substructure methods in $t\bar{t}H$, $H \rightarrow b\bar{b}$ analysis

- Expect worse performance of the MEM at high p_T of the Top & Higgs, in particular because the hadronization of the quarks in which those particles decay is likely to be merged into a single jet
  $\Rightarrow$ MEM cannot easily associate jets to generator level quarks
- Possibility to combine MEM with substructure methods to recover such events
- Focus mostly on top tagging here



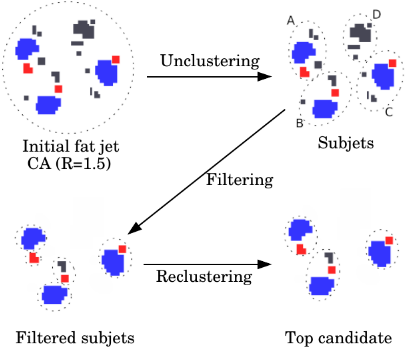
Kinematics of $t\bar{t}H$, H→$b\bar{b}$ events



- ΔR_{bjj}: Approximate CA jet size containing the top's decay products
- ΔR decreases with increasing p_T as $\Delta R \sim \frac{2 \cdot m}{p_T}$
- Sensitivity to top quarks with $p_T > 200$ GeV with a cone size of 1.5
- Possibility to also use jet substructure for Higgs reconstruction

Top candidate selection

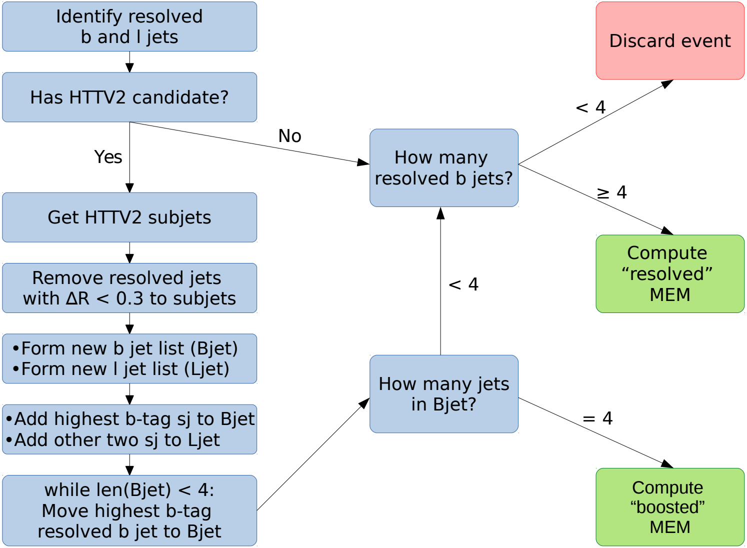
Use HEPTopTagger V2 (HTTV2) algorithm for top identification [3]



- Uses Cambridge-Aachen jets with a cone size of 1.5
- Filtering applied to remove contributions from pile-up and from underlying events
- HTTV2 performance optimal for moderate boosts (starting from p_T 200 GeV) of the top (which is the case in the $t\bar{t}H$, $H \rightarrow b\bar{b}$ analysis)
- Reconstructs exactly three subjets which are needed as an input to the MEM

[3] G. Kasieczka *et. al.*, Resonance Searches with an Updated Top Tagger, JHEP 1506, 203 (2015)

Combining substructure methods with the MEM



Removing permutations

Number of permutations can be reduced when knowing from which particle a jet arises:

- Standard boosted: 12 permutations
- Boosted with HTTV2 candidate: 3 permutations

b quarks	Remaining nb. of b jets	Permutations
1 from HTTV2 candidate	4	known origin
2 from Higgs decay	3	$\binom{3}{2} = 3$ permutations
1 from top/antitop decay	1	$\binom{1}{1} = 1$ permutations
		$\Rightarrow 3$ permutations

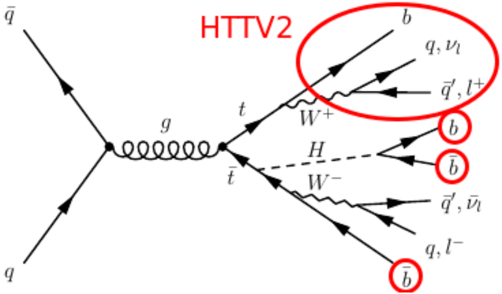
Computation time per event

Category	Time ttH hypothesis [s]	Total time [s]
Standard resolved	16.5 ± 9.4	52.5 ± 27.4
Boosted	4.1 ± 0.5	13.7 ± 1.4
Fixed permutation with HTTV2	1.1 ± 0.1	3.5 ± 0.3

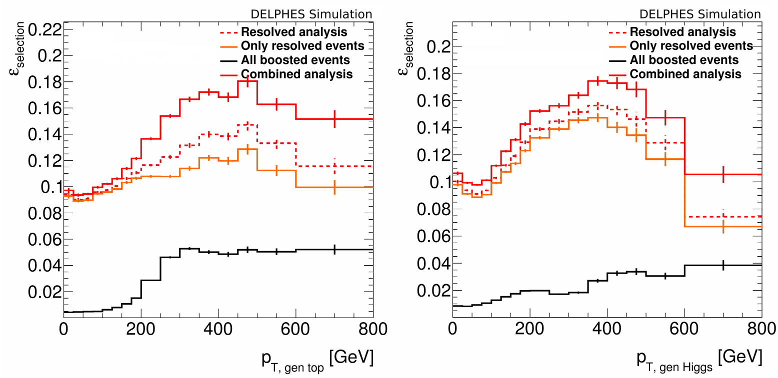
- Standard boosted analysis: Number of jets limited to 6 since QCD radiation jets can be identified and removed
  $\Rightarrow$ MEM computation time decrease by $\sim 75\%$ when using HTTV2 subjets
- Further decrease of $\sim 75\%$ when reducing number of permutations
- Large uncertainty on runtime due in particular to different quark kinematics, which have different transfer functions
- For Higgs tagging: 2 permutations left if only Higgs is tagged, 1 permutation if both Higgs and one hadronic top are tagged
  $\Rightarrow$ Expect reduction from $\sim 1\,\text{min}$ to $\sim 1\,\text{s}$ per event

New boosted events I

- MEM needs four b tagged jets as input
- For boosted tops, likely miss the jet originating from the b quark into which the top decays
- Possibility to recover events with only 3 resolved b tagged jets if they have a HTTV2 candidate:



New boosted events II



- Selection efficiency increases by $\sim 30\%$ at $p_{T,\text{Top}} > 200$ GeV
- Correlation between Higgs and top p_T
  $\Rightarrow$ analysis using boosted tops also targets high Higgs p_T events

Sensitivity to BSM physics models

- Various BSM models predict deviations from the SM in $t\bar{t}H$, $H\rightarrow b\bar{b}$ events which appear in the boosted regime
- Some examples:
  - Deviations from the SM prediction in the CP structure of the Top-Higgs coupling [4]
  - Additional contributions to $\mathcal{L}_{SM}$ such as the dimension-6 chromatic dipole and Higgs-gluon kinetic coupling which modify the SM Higgs momentum distribution [5]

[4] M. Buckley & D. Gonçalves, Boosting the Direct CP Measurement of the Higgs-Top Coupling, Phys. Rev. Lett. 116, 091801 (2016)

[5] J. Bramante *et. al.*, Cornering a Hyper Higgs: Angular Kinematics for Boosted Higgs Bosons with Top Pairs, Phys. Rev. D 89, 093006 (2014)

Conclusion

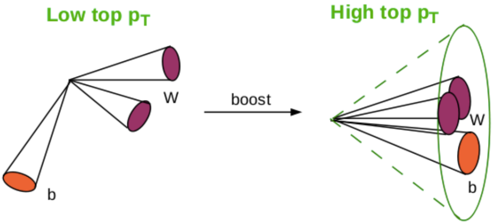
- Presented implementation of the Matrix Element Method for the analysis of the $t\bar{t}H$, $H\rightarrow b\bar{b}$ process
- Combining MEM with substructure techniques:
  - Reduce MEM computation time by 90%
  - Improve analysis performance by increasing event selection efficiency

Backup

Sample specifications

- NLO event generator POWHEG (v.2) used for simulation of signal and background
- Pythia 8.200 used for simulation of parton shower and hadronisation
- Higgs boson mass is assumed to be 125 GeV
- Top quark mass value is set to 172.5 GeV
- Assume pile-up of 30 (same conditions than in 2017 LHC run)

Substructure methods



- Decay products of boosted objects such as top quarks are more collimated at high p_T
- Contained in a large radius jet for hadronic decays

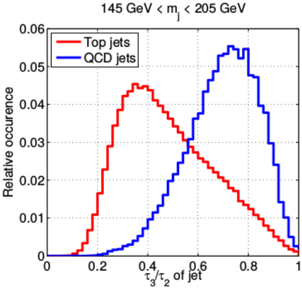
Selection criteria on HTTV2 candidates

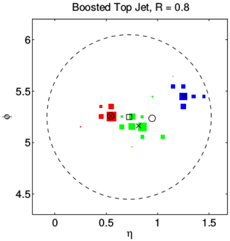
- $p_T > 200$ GeV
- $|\eta| < 2.4$
- ΔR (lepton, HTTV2 candidate) > 1.5
- Mass: 160 GeV $<$ m $<$ 380 GeV
- N-subjettiness: $\tau_{32\mathrm{SD}} < 0.8$ (evaluated from softdrop fatjet ($z_{\mathrm{cut}} = 0.1$, $\beta = 0$) associated to HTTV2 candidate)
- W mass compatibility: $f_{\mathrm{rec}} < 0.65$

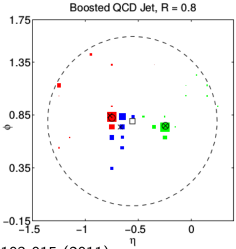
N-subjettiness [6]

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k}\}$$

- Small τ_i if jet compatible with i-prong substructure
- Top tagging: use ratio $\frac{\tau_3}{\tau_2}$





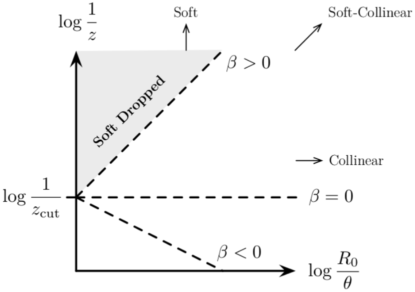


[6] J. Thaler & K. Tilburg, Identifying Boosted Objects with N-subjettiness, JHEP 1103 015 (2011)

Soft Drop [7]

- Remove low p_T wide-angle constituents
- Find hard substructure using step-wise unclustering
- Remove jet constituent if:

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} < z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$



[7] A. Larkoski *et. al.*, Soft Drop, JHEP 1405, 146 (2014)