B-tagging performance studies using the Wt single top production channel

Simona Rolli, Tufts University,
Marina Cobal and Mario Paolo Giordani
University of Udine and INFN-Trieste
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We present some studies on b-tagging algorithms perfomance obtained using simulated data of single top production via the Wt channel. We compare some of the leading algorithms, both in terms of absolute performance and rejection factors for light jets.

The LHC will start running *pp* collisions in the Spring of 2007. The ATLAS and CMS detectors will undergo a commissioning phase where data corresponding to physics process with relatively high cross sections will be used to calibrate the performance of the detector components and test various physics algorithms. Top production, especially pair production, given the high cross section for strong production, will be among the physics processes to be used for commissioning the ATLAS detector. Single top production could be used to the same extent, even if the production cross section is relatively lower. On the other hand top physics presents already interesting aspects concerning the calibration and testing of algorithms and tools. Top physics is a good testing ground for jet energy calibration for example, or b-tagging performance. In particular single top production via Wt associated production will give the opportunity to study b-tagging in a final state signature containing only one b-jet, and relatively low jet multiplicity.

In this note we describe the results of some preliminary tests of several b-tagging algorithms, currently implemented in the ATLAS reconstruction framework, performed on simulated single top data produced in 2005 ("Rome samples"). The aim of the study is mainly to test the current tools and data structure and set up the machinery necessary to study real data next year. The results are clearly preliminary and will change with future software releases and the arrival of real data. After a short introduction on single top production at LHC, we will describe the data sample used, and the current taggers available on the market. We will then show comparisons for two of the main taggers as for b-jet selection efficiency and light jet rejection. We will then present our conclusions.

Single Top production at LHC

The strong production of $t\bar{t}$ pairs yelds large top quark samples, allowing detailed studies of many properties of top quark production and decay. However, the precise determination of the properties of the $W-t-b$ vertex, and the associated coupling strenghts, will more likely be obtained from measurements of the electroweak production of single top quarks. Single top quarks can be produced via three different reactions. These reactions are shown in figure 1 from left to right in order of decreasing cross-sections.

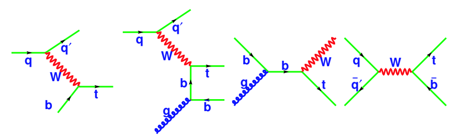

FIG. 1: Single Top generation processes at LHC

The first two graphs in figure 1, usually referred to as the $2 \rightarrow 2$ and $2 \rightarrow 3$ processes, respectively, both refer to the same physical W-gluon fusion process. In previous TDR[1] study the NLO correction as a separate process has been ignored. Rather, simulations based on the 2-2 process only have been used and normalised to the cross-section for a properly combined set of the two graphs. Since the W-gluon fusion process is the largest source of single top production at the LHC, with an expected cross-section of approximately 250 pb, it will be the source for much of the physics sensitivity, as well as a serious background for the other single top processes. The second production mechanism (the third graph from the left), referred to as the Wt process, is the direct production of a top quark and a W boson. This process is immeasurably small at the Tevatron, but is predicted to have a sizeable cross-section ($\sim$ 60-110 pb) at the LHC. The third reaction proceeds via production of an off-shell W and will be called the $W*$ process. The cross-section for the $W*$ process is predicted to be only about 10 pb, since there are no valence anti-quarks in the initial state at the LHC.

The primary physics interest in single top production is the ability to directly determine the coupling strength for the t-W-b vertex. The single top cross-section is unambiguously predicted by the SM (apart from the coupling), and it is important to cross check the W-gluon fusion, Wt, and $W*$ cross-sections separately. The various processes of single top production have different sensitivities to new physics. For example, the $W*$ channel is sensitive to an additional heavy W' boson, since new s-channel diagrams in which the W' is exchanged would occur. In contrast, additional contributions to the W-gluon fusion process from new t-channel diagrams with a W' would

TABLE I: Signal selection efficiency compared to the TDR studies. Efficiencies are expressed in %.

Cut (GeV/c^2)	TDR	Our study, cone 0.7	Our study cone 0.4
Pre-selection cuts	25.5	37.3	30.5
$n_{jets} = 3; P_T > 50$ GeV	3.41	17.7	14.8
$n_{bjet} = 1$	3.32	4.8	3.9
$m_{tot} < 300$ GeV	1.43	not applied	not applied
65 ¡ $m_{jj} < 95$	1.27	0.8	0.6

be suppressed by $1/m^2_{W'}$. Therefore, existence of a W' boson would be expected to produce an enhancement in both $\sigma(W*)$ and $\sigma(W*)/\sigma(Wg)$. On the other hand, the W-gluon fusion process channel is more sensitive to modifications of the top quark's couplings to the other SM particles. For example, an anomalous chromo-magnetic moment in the top-gluon vertex, or a V+A contribution at the t-W-b vertex, could lead to both an increase in single top production and a modification of the decay angular distributions. Also, anomalous FCNC couplings could give rise to new contributions to single top production, such as $gu \rightarrow t$. These processes could modify the W-gluon process of single top production, while not affecting the rate of Wt and $W*$ channels. Therefore, in this case one would expect a decrease in the ratio of $\sigma(W*)/\sigma(Wg)$.

Because it is an inherently weak production process, the W and top quark are produced in the appropriate mixture of helicities, as unambiguously predicted by the SM. A helicity analysis of top quark decay can check for new physics, such as right handed couplings, or an unexpected admixture of the left handed and longitudinal components for the W.

In order to reduce the enormous QCD multi-jet backgrounds, as well as provide a high P_T lepton for trigger purposes, single top production with $t \rightarrow Wb$ followed by a leptonic decay $W \rightarrow l$, where the charged lepton is a muon or an electron has been considered. The initial pre-selection cuts required the presence of at least one isolated lepton with $P_T > 20$ GeV, at least two jets with $P_T > 30$ GeV, and at least one b-tagged jet with $P_T > 50$ GeV. After these cuts, the dominant backgrounds are from processes with a real W in the final state, namely tt and Wjj (and in particular Wbb) production. The strategy for measuring the Wt cross-section relies on the nature of Wt events makes them relatively easy to separate from Wjj and difficult to separate from tt events. Assuming the tt cross-section will be well measured at the LHC, this does not preclude performing a precise measurement of the Wt cross-section. In addition to the pre-selection cuts, the number of jets in the central region is required to be exactly three. Requiring at least three jets significantly reduces non-top backgrounds, while not allowing four or more jets reduces tt background. Exactly one of these jets is required to be tagged as a b-jet. By not allowing more than one b-tag the tt background is reduced, while at least one b-tag is necessary to suppress Wjj. In previous TDR studies, the total invariant mass of all reconstructed leptons and jets was required to be less than 300 GeV/c^2 in a further attempt to reduce the tt background. We didn't place the cut now. Finally, the presence of a second W in Wt and tt events is exploited by requiring the reconstructed mass of the two untagged jets to be consistent with m_W by satisfying $65\ GeV < m_{jj} < 95\ GeV$. The efficiencies of these cuts have been calculated with the AOD sample and found to be in good agreement with the numbers reported in earlier TDR studies (Table I).

Data samples and data selection

The data used were produced and simulated in 2005 (Rome samples) and correspond to 65020 events from samples 4531 and 4530[3]. The production of single top via Wt channel was simulated using TopReX, 4.09 and Athena 9.0.4. Release 9.0.4 was used for simulation and release 10.0.1 was used to reconstruct the events. TopReX is an external process generator for PYTHIA. Implemented processes include LO ttbar (with and without spin correlations), EW singletop processes, FCNC top decays and SUSY-mediated top production. The following parameters were used to setup the process: one of the W was set to decay leptonically (e,μ), the other hadronically. This gives rise to a signature corresponding to one high P_T lepton, large transverse missing energy, and three jets, one of which is coming from a b=quark. Data were reprocessed to obtain b-tagging information for jets reconstructed with cone 0.4 following the instructions given at [4] with with release 10.0.1. Data were read from AOD and put into a private ntuple[5].

We used the physics object collections present in the AOD[6] and did back-navigation to ESD to retrieve some information relative to the b-parton. In particular we accessed the ElectronCollection, METFinal, ConeTowerParticleJets and ConeTower04ParticleJet and the BJetCollection. We started by studying events with high P_T electrons, as the ID variables are better understood. We plan to include high P_T muons in a forthcoming study. Electrons are selected with P_T ¿ 25 GeV, η ¡ 2.5 and XRatio ¿ 0.6. XRatio is a likelihood variable derived by using the information on the energy in different calorimeter samplings, the shower shapes in both eta and phi and E/P. No TRT information is used to select the electrons. Two variables are used, called emweight and pionweight from which a likelihood ratio is constructed (XRatio). The ratio is defined by: emweight/(emweight+pionweight). Emweight is the product of pdf's for electrons and pionweight is the product of pdf's for pions. Requiring XRatio ¿ 0.6 will give more than 90% eff for electrons[7]. Further we selected events with $\not{E}_T$ ¿ 20 GeV and three jets, of which one is required to be coming from a b-quark, with E_T ¿ 30 GeV (50 GeV for the b-tagged jet) , η ¡ 2.5. Jets are reconstructed using a cone of fixed radius $R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)} = 0.7$ or 0.4. Finally we placed a cut on the invariant mass of the two untagged jets, which is required to lay in the range 65 ¡ m_{jj} ¡ 95 GeV/c^2. The result of our selection is reported in Table I (for both jets reconstructed in cone of 0.4 and 0.7) and compared with a similar selection performed in the TDR.

B-tagging algorithms

We did choose to benchmark the performance of two main b-tagging algorithms: the first one makes use of a likelihood variable constructed using the information coming from different taggers (lifetime based and secondary vertex based) to select b-jets as opposed to light jets, and it is called LHSig[4]. The second one makes use of a "jet weight" variable which is analogously built combining the information coming from a lifetime tagger and secondary vertex tagger. Depending on the type of data accessed (AOD vs CBNT) it is called with different names, SV1 in CNBT and SV (or FabSV) for AOD. In what follows we will call it FabSV[8].

The Combined Likelihood tagger is derived by combining the information coming from lifetime btaggers (LifeTimeTag1D, LifeTimeTag2D, LifeTimeTag3D) and secondary vertex tagger (SecVtxTagBU and SecVtxTagTD). In particular, the lifetime tag uses the larger impact significances of tracks coming from decaying b-flavoured particles. Due to the on average longer lifetime of b-mesons and b-baryons the decay will take place away from the primary vertex resulting in larger impact significances. The impact significance is defined as

$$s = \frac{d}{\sigma_d}$$

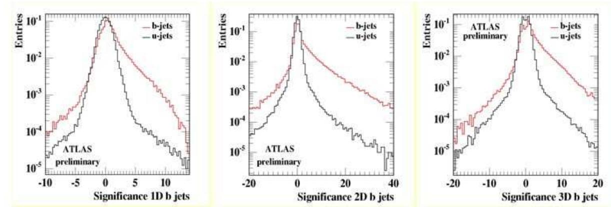

FIG. 2: The distributions of the signed impact parameter determined from a) the z-distance (1D), b) the $r-\phi$-plane distance (2D), and c) from the distance $z - r\phi$(3D) of the point of closest approach of the track to the reconstructed primary vertex. From reference [4]

where d can be the distance in z(1D), in the $r\phi$-plane (2D) or the three-dimensional distance in $z - r\phi$ (3D) of the point of closest approach of the track to the reconstructed primary vertex. The sign of s is determined by the crossing point of the track with respect to the jet-axis. If the track crosses ahead (behind) of the primary vertex s gets a positive (negative) sign (see figure 2).

In addition to the higher values of the impact significance it is possible to reconstruct secondary vertices in the b-flavoured jets. There are several ways of seeding the secondary verices and assigning tracks to the vertices. One way is to fit vertices with all pairs of tracks, retaining the fit with the highest probability and fitting the remaining tracks of the jet to this vertex. All tracks below a certain fit probability will be rejected. This approach is implemented in the build-up (BU) algorithm. An other approach is to start with all tracks in the jet, fit a vertex, and reject tracks below a certain fixed fit probability. This has been implemented in the tear-down (TD) algorithm. After the secondary vertex finding properties of the vertex, such as mass, fit probability, multiplicity and distance from the reconstructed primary vertex can be studied. In figure 3 the properties of the vertex found by the build-up method is shown.

The variables are combined into a secondary vertex likelihood. The combined b-tagging likelihood is built using the signed 2D-impact parameters and the build-up secondary vertex likelihood. Its distribution is reported in figure 3 where LHSig is plotted for b-jets and light jets, using Wt events.

Similar lifetime taggers and secondary vertex taggers have also been developed[8] (they are known as: IP2D, IP3D, SV1 and SV2). For each discriminating variable x in a tagger, calibration functions for the two hypothesis (the jet coming from a b-quark and the jet coming from a light quark or gluon) are built: $P_b(x)$ and $P_u(x)$. The final discriminating variable (at the jet level) is called weight and it is built as follows:

$$W = \Sigma_x \ln(\frac{P_b(x)}{P_u(x)})$$

A large weight implies a high probability that the jet

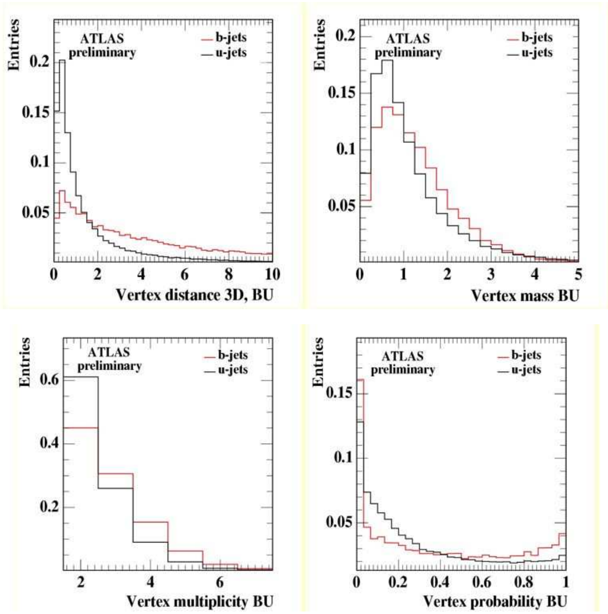

FIG. 3: Discriminating variables from the build-up secondary vertex tag: a) The distance of the reconstructed vertex to the primary vertex, b) the mass of the vertex. c) the number of tracks reconstructed in the vertex, and d) the fit probability of the vertex. From reference [4]

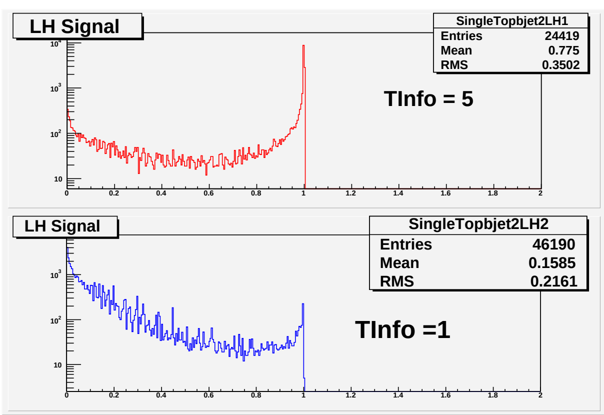

FIG. 4: Combined likelihood distribution for b-jets and light jets in Wt events. The selection has been made by matching the TruthInfo to the reconstructed bjet.Cone 0.4 jets were used.

originates from the b-quark. Weights for b-jets and light jets (cone 0.4) are reported in figure 5.

B-tagging performance studies

We calculated the b-jet selection efficiencies as a function of the cut on the discriminating variable (likelihood signal or weight)in the following way: we form the ratio between the number of b-jets matched to a b-parton (via TruthInfo) with $P_T > 50$ GeV and $\eta < 2.5$ (denomina-

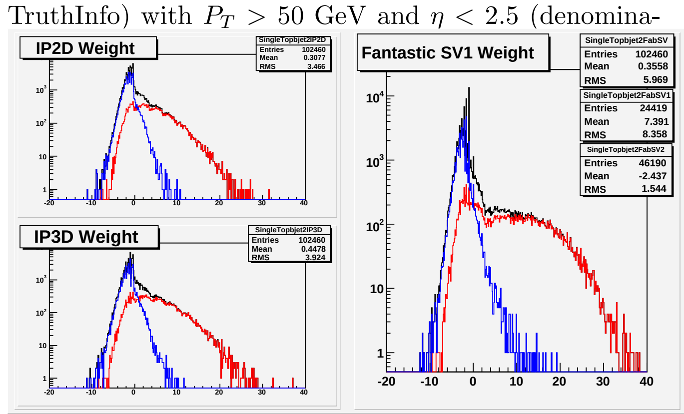

FIG. 5: Weight distributions for b-jets (red) and light jets (blue) and all jets (black) for the IP2D, IP3D and SV1+IP3D (FabSV) taggers in Wt events. The selection has been made by matching the TruthInfo to the reconstructed bjet.Cone 0.4 jets were used.

tor) and the same quantity but with a cut on the variable of choice (FabSV and LHSig). The results are reported in Table II.

By selecting a fixed value of the cut, we also calculated the efficiency for selecting a b-jet as a function of the P_T of the jet and η. In figure 6 and 7 we report such efficiencies, for 4 taggers: IP2D, IP3D, FabSV (all cut at $W > 3$) and the combined likelihood (LHSig > 0.9).

Calculating the efficiency for b-jet detection is important, but it is also important to understand how well the tagger performs in rejecting light jets. To this aim a rejection factor variable has been studied, which is defined as follows:

$$\frac{1}{R_u}$$

where R_u is the inverse of the ratio obtained by counting the number of light jets matched to a light parton

TABLE II: FabSV and LHSig taggers efficiency to select a b-jet with P_T¿ 50 GeV and η ¡ 2.5 for different values of the weight/likelihood cut. A statistical error of about 10% is assumed on the reported efficiencies. No systematic error is calculated.

FabSV cut	ϵ (0.7)	ϵ (0.4)	LHSig cut	ϵ (0.7)	ϵ (0.4)
1	0.63	0.63	0.1	0.80	0.75
2	0.59	0.59	0.2	0.76	0.72
3	0.55	0.57	0.3	0.72	0.69
4	0.53	0.54	0.4	0.70	0.67
5	0.51	0.51	0.5	0.68	0.66
6	0.48	0.48	0.6	0.67	0.65
7	0.46	0.46	0.7	0.65	0.63
8	0.43	0.43	0.8	0.63	0.61
9	0.41	0.40	0.9	0.60	0.57

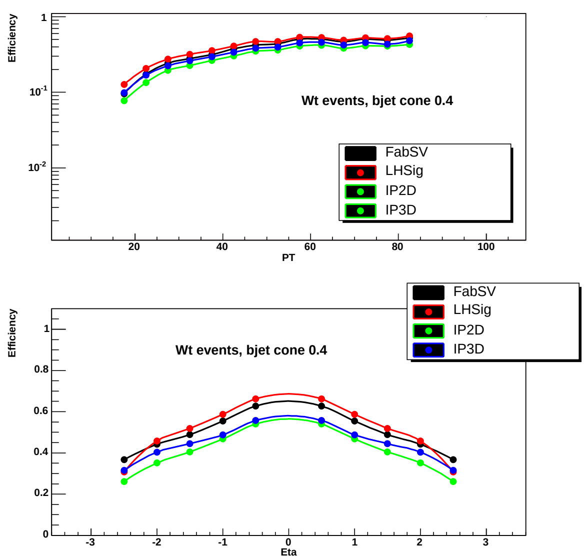

FIG. 6: B-tagging efficiencies in Wt event as a function of P_T and η of the jet, for cone 0.4 jets.

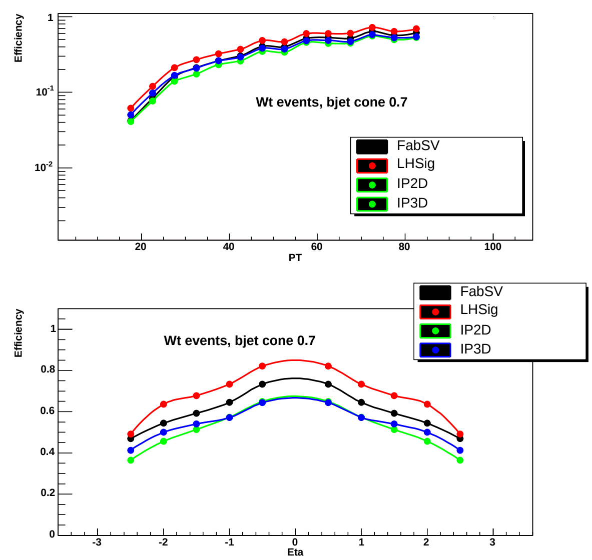

FIG. 7: B-tagging efficiencies in Wt events as a function of P_T and η of the jet, for cone 0.7 jets.

(via TruthInfo) with $P_T > 50$ GeV and $\eta < 2.5$ (denominator) and the same but with a cut on the variable of choice (FabSV and LHSig). In figure 8 and 9 we report the rejection factors as a function of the b-tagging efficiency (ie the likelihood/weight cut).

Conclusions

We have performed some preliminary studies of b-tagging algorithms performance, with particular reference to two algorithms, FabSV and LHSig. We used a sample of events of single top produced in association with a vector boson, where the signature is particularly clean to select a b-jet (there is only one in the event). We presented b-jet selection efficiency and light jet rejection factors. These numbers can be compared with similar studies performed using different samples ($t\bar{t}$ or WH[9] for example): the results are in general quite dif-

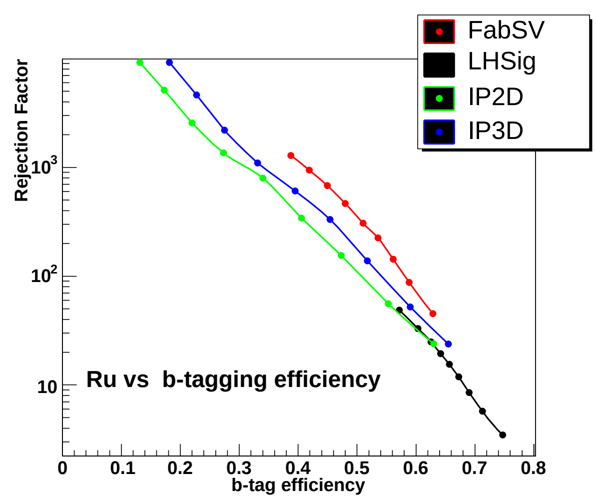

FIG. 8: Light jet rejection factors as a function of b-tagging efficiencies in Wt events, calculated with cone 0.4 jets.

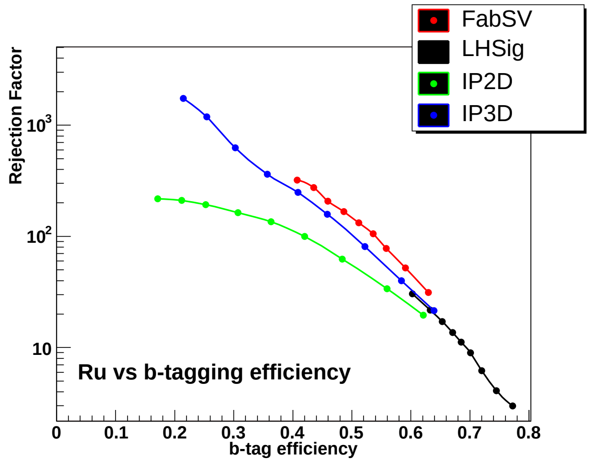

FIG. 9: Light jet rejection factors as a function of b-tagging efficiencies in Wt events, calculated with cone 0.7 jets.

ferent, which is what we would expect given the different event topology. Our preliminary conclusion is that while in terms of signal selection the two taggers show similar efficiencies, LHSig has a much poorer rejection factor for light jets. We will follow the development of the reconstruction software and update our results accordingly.

Acknowledgements

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[1] http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html
[2] A. Lucotte, Single Top Studies,Rome ATLAS Physics Workshop, Rome June 2005 http://agenda.cern.ch/askArchive.php?base=agenda&categ=a044738&id=a044738s11t6/transparencies.
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