The Case for an Exotic Physics Object Definition and Related Online Displaced Tracking Improvements

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In Application of the 2015 CMS Fundamental Physics Scholarship

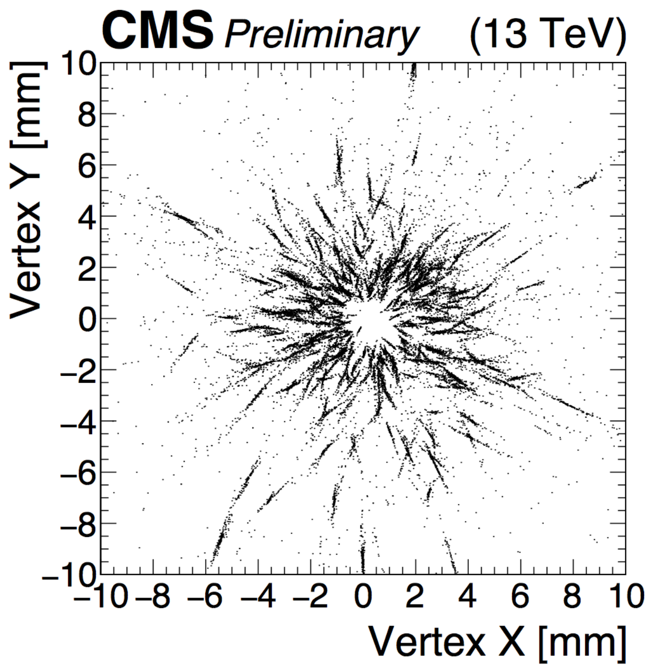

FIGURE 1. Displaced jet signal events where a neutral 300 GeV X^0 with a lifetime of $c\tau = 1$mm decays to a di-jet pair. For each jet, combinatorial vertices are fitted to pairs of tracks. Clustering combinatorial vertices gives visibly distinct displaced double and single jet secondary vertices. An overlay of multiple events is shown.

Introduction

The study of rare processes at the LHC yields exciting experimental signatures that will become increasingly important as purely kinematic gains from increasing $\sqrt{s}$ diminish with integrated luminosity. The time to start developing tools to search for exotic processes is now, so new tools are able to mature and trigger strategies improve for increasing pile up. New insights and developments would feed into ongoing detector and trigger system upgrades. Specific to this proposal, the decays of long-lived resonances to hadronic final states yield strikingly convincing signatures (Fig. 1), but for a variety of reasons require the development of new identification techniques that can be condensed into a single object definition: a displaced jet tag.

B-quark tagging (b-tagging) was originally developed and successfully utilized for the discovery of the top quark. Among other applications, b-tagging is now a tool for studying the Higgs and searching for beyond the standard model (BSM) physics. Since its inception, b-tagging has evolved including the implementation of particle flow, refined secondary vertex algorithms, and advanced multivariate techniques. The strength of b-tagging is not restricted to its signal to background differentiation, but includes the community sized impact of a well defined and supported physics object definition. The b-tagging algorithms are publicly documented with corresponding working points and data/mc factors derived by the physics object group (POG). The algorithms are integrated directly into the experiment software allowing fast adoption of subsequent improvements. The object can then be used interchangeably as part of a large toolkit of jets, leptons, taus, photons, and missing energy.

Analogous to b-tagging, CMS can benefit from a background motivated exotic physics object definition for displaced jets. The jet is considered displaced in the sense that the jet comes from a decay vertex measurably separated from the primary vertex of the event. As the prompt BSM parameter space becomes increasingly small, theorists continue to propose new models containing particles with detector scale lifetimes. These long lived particles generate striking signatures with high discrimination power enabling visibly convincing discoveries. Unfortunately, these events may not be selected at the trigger level or can erroneously be removed in a prompt analysis. A documented CMSSW implementation of a displaced jet tag would serve as the foundation of further sophistication and topological specificity.

It is the aim of this research proposal to use Princeton's experience studying displaced jets and displaced di-jets [1], to create and support a displaced jet tag to be used within multiple long lived Exotica subgroup analyses. The implementation would be performed with the intent of making the definition widely available within the experiment. With this object definition in mind, this proposal also investigates improvements to the online tracking algorithms to be used in future displaced jet trigger strategies.

Motivation

B-Tagging

Given the close analogy to b-tagging techinques, it is important to clarify where b-tagging algorithms are inefficient and where they could possibly be extended.

For shorter lifetime regimes ($c\tau < 1$ mm), b-tagging can still identify displaced jets, but leaves room for new extensions. Heavy long-lived resonsances undergoing a 2 body decay will have significantly more momentum transverse to the flight direction of the long lived particle (when compared to a b decay). This angle is a powerful discriminant to background nuclear interactions and is strongly correlated with the boost of the mother particle. Under the assumption that the angle is small, b-tagging uses only positively signed impact parameters for track identification (corresponding to to decays downstream of the flight path). Heavy particles produced nearly at rest will decay isotropically with impact parameters of negative sign (when decays occur backward relative to the mother's momentum direction).

For longer lifetimes, a transition occurs at distances larger than a few centimeters where new issues undaddressed by b-tagging arise. Although the b meson is displaced it is comparably straightforward to decern the primary vertex of the event. This allows b-tagging algorithms to more accurately calculate longitudinal quantities, such as 3D track impact parameters. For displaced jets, this is not the case and utilizing longitudinal quantities relative to a mis-identified primary vertex can yield sub-optimal performance. Pixel hit requirements are explcitly required for tracks used in b-tag secondary vertexing, but displaced jets decays can occur outside the pixel layers. In addition, b-tagging algorithms include upper bounds on longitudinal and transverse impact parameters to limit contributions from nuclear interactions.

Theoretical and Practical Experimental Motivations

A standalone displaced jet tag would reduce future duplication of effort related to long lived searches and enable a straightforward expansion of both prompt and long-lived searches. The theoretical motiviations for long lived particles decaying hadronically arise in variety of (but not limited to) scenarios:

- Split Supersymmetry [2] [3] [4] [5] [6]
- Twin Higgs [7]
- WIMP Baryogenesis [8]
- Hidden Valley Models and Higgs Portal Processes [9]
- R-Parity Violating SUSY [10]

Specifically, the displaced supersymmetry (SUSY) analysis [11] performed a search for pair-produced long-lived RPV stops decaying to a b quark and a lepton. The analysis focused on the two leptons and can benefit from the two long lived jets in the event. Currently an additional 4 all hadronic displaced jet analyses exist within the long lived group (emerging jets, single displaced jet + MET, displaced di-jet, and inclusive displaced jet with tags) all of which can benefit from the definition of an inclusive tag. New searches could arise from extensions of inclusive prompt searches like the mono-jet[12] analysis $\rightarrow$ mono-displaced jet analysis.

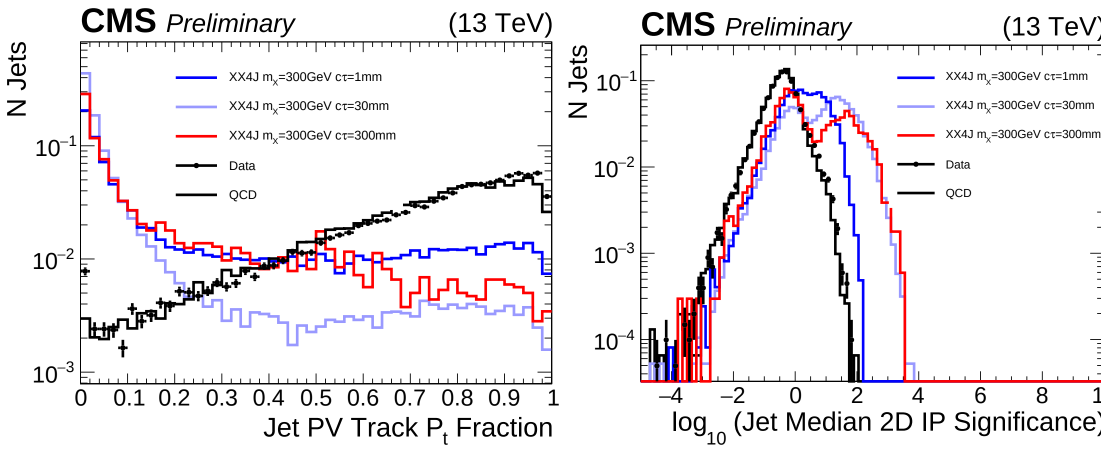

Figure 2. Candidate inclusive displaced jet identification criteria. The $XX4J$ events consist of 2 long lived neutral X decay to di-jet pairs with varied lifetime.

It has become increasingly common that changes in the reconstruction (PU subtraction and timing cuts) or new event filters (HCAL noise) need to consider exotic scenarios like those studied in the long-lived subgroup of Exotica. For instance, long-lived particles arrive late to the calorimetry mimicking out of time pile up and decays inside the HCAL can mimic noise (i.e. a high hadronic energy fraction deposit with no tracks pointing to it). A displaced object definition would provide a working point to more effectively communicate changes to analyzers and avoid preventable loss of sensitivity for the CMS Physics program.

Displaced Jet Identification

The CMS experiment has an advantage over ATLAS to collect data sensitive to displaced topologies at 13 TeV given the trigger coordination's flexible stance on allowing analyzers to develop specialized triggers. ATLAS's displaced vertex search [13] (with decays occurring within the detector) require the presence of another object motivated by the trigger used for the corresponding channel: jet, lepton, or MET. In 2014, CMS implemented a suite of displaced jet triggers developed by Princeton in coordination with the trigger studies group and iterative tracking experts. The goal of these triggers was to gain sensitivity to softer kinematics while remaining highly efficient to a variety of kinematic regimes and lifetimes. Two triggers are seeded at the L1 by an HT seed and two by a VBF seed specifically targeting Higgs decays. Two of the triggers utilize a specialized tracking iteration unique to displaced jet paths.

After the trigger development, a set of lifetime inclusive tagging variables were investigated in 25ns data. Building on the philosophy of the trigger strategy, the variables are background motivated and mostly utilize tracking quantities to reject "prompt" qualities. In example, summing the jet scalar track p_t contribution from tracks included in the primary vertex fit. For displaced jets this fraction should be small. This strategy proves to be very powerful. Utilizing 3 variables, the current tag definition achieves a QCD fake rate of 10^{-5} with 50% signal jet tag efficiency for particle lifetimes of $c\tau_0 = 3$cm. The variables are defined to have inclusive coverage of particles with long lifetimes (the tag also works for displaced electrons) with minimal model dependence. A corresponding displaced jet reconstruction note is in preparation based on early data.

To study clean samples of displaced jets, the particle gun interface utilized by object groups for performance studies (jet calibration, single pion, ect.) was modified to generate a long lived particle gun decaying to two jets. This modification gives finer control of event kinematics and the distribution of particle lifetimes. Additionally, there is certainty that all reconstructed tracks in an event are generated by the displaced vertex without performing track by track matching.

Timeline

The current state of displaced jet reconstruction studies is naturally aligned with the timeline of the CMS FPS Scholarship. Preliminary studies have been performed showing the strength of a displaced jet tag, a specialized suite of displaced jet triggers have been implemented online, and a note is in preparation on the variables that will enter the definition. What remains is finalizing the definition to provide a clean, well documented implementation for current and future analyzers.

The first 4-5 months of the scholarship tenure would be dedicated to finalizing a definition of the displaced jet tag and the continued study of the SM background due to nuclear interactions within the detector material and tracks from long lived Standard Model particles (Appendix I). During the summer I would like to work with a summer student generating the proper documentation and improving the code for wider distribution. The final months of the scholarship would be spent working on online iterative tracking improvements.

Project Impact

I have been fortunate to have received a National Science Foundation Graduate Research Fellowship. The fellowship finances the majority of the cost of being stationed at CERN, however the funding ends in 2016. When the funding ends, the CMS FPS scholarship's supplemental income would allow me maintain my presence at CERN for the next year without other external support. Working from CERN has been critical to the development of the triggers and the current state of of displaced jet identification. The current collaborators, as well as the possible beneficiaries are predominantly located at CERN. The project timeline also includes elements that necessitate being at CERN such as working with a summer student, the tracking DPG and B Tagging Variable POG. Additionally, the scholarship award would generate interest from within the experiment. More exposure would lead to wider use of the exotic object definition as well as a improved performance and implementation resulting from wider collaboration.

This is a critical period for potential discovery resulting from this work in the first 13 TeV data. It is consequently important to take advantage of the resources CERN provides in facilitating the project's success.

Conclusion

This proposal represents a *novel* approach to searching for beyond the Standard Model physics with displaced vertices by creating an exotic physics object. This strategy to-do list can be summarized as:

- Develop a fixed version of displaced jet tags
- Develop supporting documentation and CMSSW implementation with a summer student for current and future analyzers.
- Initially support the object within the Long-Lived Exotica sub-group, with the intent of expanding outside of the group.
- Improve tracking at the HLT to improving displaced jet trigger sensitivity.

Positive impacts for funding this project:

- The award enables me to maintain my presence at CERN which has been critical to the progress already made towards the project goal.
- A displaced tag can function as a foundation for future improvements and extensions, reducing duplication of effort for higher luminosity studies and expanding inclusive prompt searches.
- The tag could serve as a working point for communicating the effects of new reconstruction and filters on exotic physics signatures.
- The tag would be useful in motivating improvements in online tracking at the trigger level.
- Displaced jets are inclusive to a variety number of BSM scenarios that can be missed in prompt searches.

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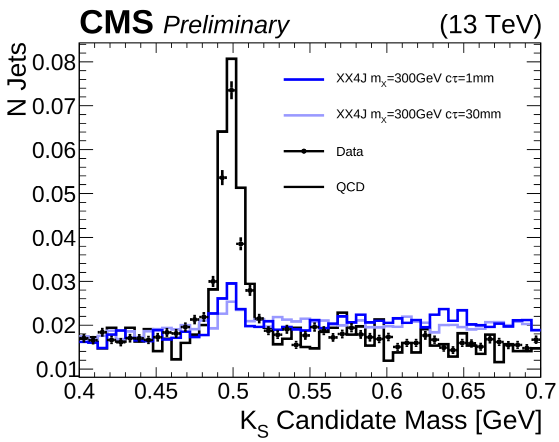
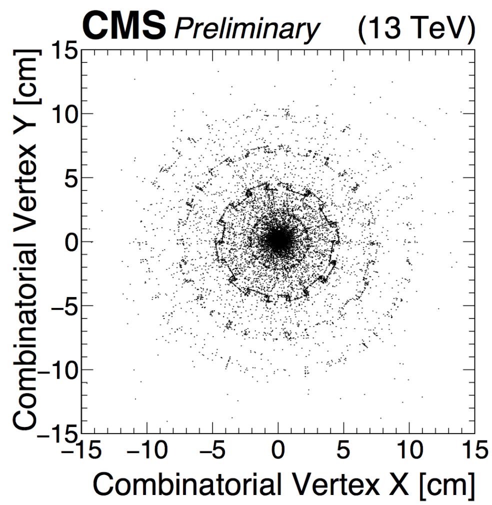
Appendix I. Jet Tagging Background Sources





There are a large number of particles in the standard Model with detector sized lifetimes. The most relevant to displaced jet identification are neutral particles that have no corresponding track pointing to the primary vertex such as the $\Lambda^0 \to p\pi^-$ and $K_s^0 \to \pi^+\pi^-$. These particles are an irreducible background containing truly displaced tracks with large impact parameters. By taking combinatorial pairs of tracks in jets, it is possible to tag these candidates by applying the corresponding mass hypothesis. Once identified, these tracks can be individually removed from the related impact parameter calculations.

Displaced vertices can result from nuclear interactions with the beampipe and detector material. By fitting all combinatorial vertices in a jet we can check the spatial distribution of the vertices. High multiplicities of vertices with large significance can be seen in the beam pipe and the first few pixel layers. As this can occur for both signal and background, the treatment of these interactions requires a more careful treatement than a strict veto.

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