Next-to-Leading-Order Computations of Energy Flow Observables

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Introduction

At the LHC, many of the particles that we considered to be heavy at previous accelerators will be frequently produced with a (transverse) momentum greatly exceeding their rest mass. Good examples are the electro-weak gauge bosons W± and Z, the top quark, the Higgs boson or bosons and possibly other new particles in the same mass range. The abundant presence of heavy SM particles will yield promising signatures for searches for new physics (NP) .

When these boosted objects decay they form a highly collimated topology in the detector. Algorithms and techniques developed for the reconstruction and isolation of objects produced at rest are often inadequate for their boosted counterparts. Energy flow methods [1,2,3] have been developed to fully benefit from the potential of these states.

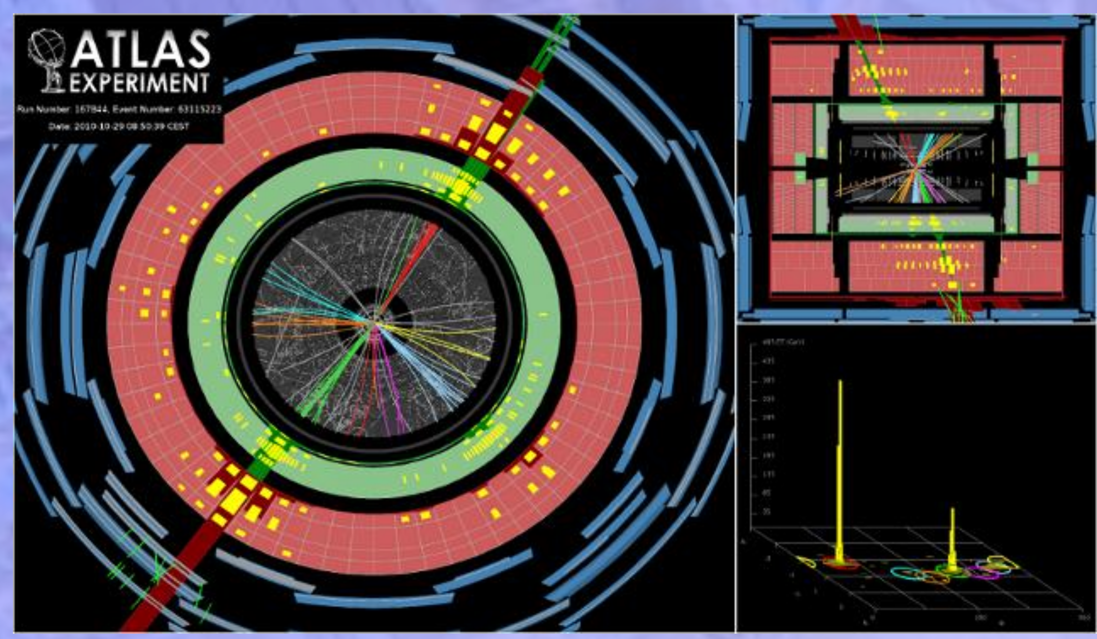


Fig. 3*: Event display of Run 167607, Event 63115223. This shows the highest-pT jet collected during 2010, which has pT of 1.5 TeV. The two leading jets are central high-pT jets with an invariant mass of 2.8 TeV. They have (pT, y) of (1.5 TeV, -0.58) and (1.0 TeV, 0.44), respectively. The missing ET in the event is 310 GeV.*
From ATLAS-CONF-2011-047.

Energy flow methods

Most methods to analyze high-p_T jets make use of the small, but noticeable differences in the substructure of light-parton QCD jets compared to those from particle decays.

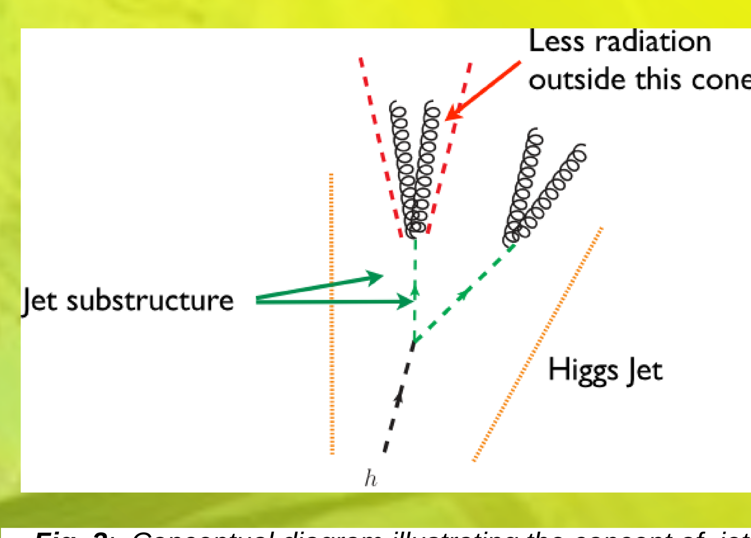


Fig. 2*: Conceptual diagram illustrating the concept of jet substructure in a highly-boosted Higgs jet.*

The energy flow methods [Ref 3] are based on direct quantitative comparison of the energy flow of observed jets at high-pT with the flow from specific partonic decay modes of boosted heavy particles. Especially when combined with event shape information, the analysis of energy flow provides a potentially powerful tool.

Overlap formalism

A method of making use of the energy flow involves the construction of energy-flow "templates" [3]. These take the energy flow, discretised in θ and ϕ (templates), for each possible orientation of the decay plane. Then for a given jet, *j*, in an event, the method finds the template, *f*, that provides the best match event to that jet's energy flow pattern, with a measure of the match quality that involves Gaussians of the difference between actual and template energy flows:

$$Ov^{(F)}(j,f) = \max_{\tau_n^{(R)}} \exp\left[-\frac{1}{2\sigma_E^2}\left(\int d\Omega\left[\frac{dE(j)}{d\Omega}-\frac{dE(f)}{d\Omega}\right]F(\Omega,f)\right)^2\right]$$

$$\tau_n^{(R)} \equiv \int \prod_{i=1}^{n} \frac{d^3\vec{p}_i}{(2\pi)^3 2\omega_i}\,\delta^4(P-\sum_{i=1}^{n} p_i)\,\Theta(\{p_i\},R)$$

The template overlaps can be systematically improved by including the effects of gluon emissions, which contain color flow information. This is particularly important to identify jets from particles which at LO typically have a two-subjet topology.

Planar flow

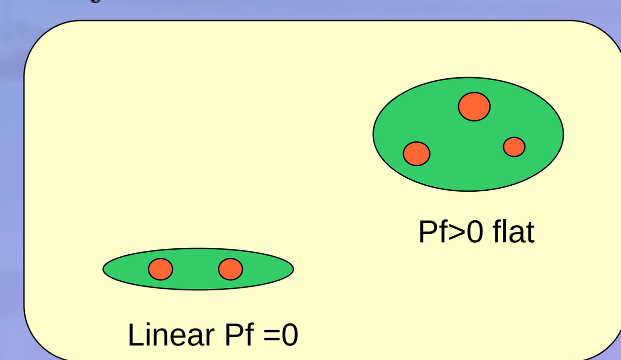
Some particle decays (e.g. top decays) often feature a triangular structure, transverse to the boost axis. Jet-shape type measures can be applied to the jet constituents to help establish whether such a triangular structure is present.

Ref. [1,2] both proposed planar flow type observables, for which one computes a matrix of the form

$$I_\omega^{kl} = \frac{1}{m_J}\sum_i \omega_i \frac{p_{i,k}}{\omega_i}\frac{p_{i,l}}{\omega_i}$$

$$\mathrm{Pf} = \frac{4\det I_\omega}{(\mathrm{tr} I_\omega)^2}$$

Planar flow, Pf, provides a measure of the jet planarity.

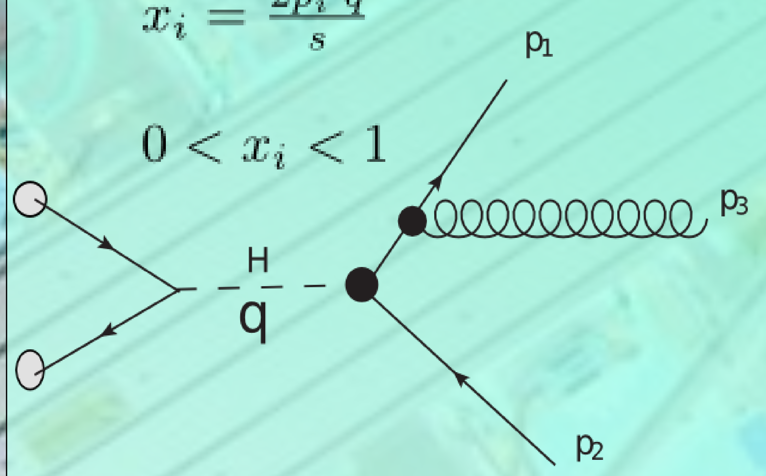


Higgs and three-body decay

A natural application of NLO template is SM Higgs identification, using the peak overlap method above in the analysis of the first-order radiative α_s corrected decay rate $H\to b\bar{b}g$.

$$x_i = \frac{2p_i\cdot q}{s}$$

$$0 < x_i < 1$$



The templates are determined by specifying two energy fractions x1, x2 and three angles ψ, ϑ and φ,

$$p_a^\mu(x_1,x_2,\psi,\theta,\phi) = L_z(\gamma)R_z(\psi)R_x(\theta)R_z(\phi)\,p_a^\mu|_{P_J^z=0}(x_1,x_2)$$

and distributed according to the differential NLO cross section

$$\frac{d\sigma(H\to q\bar{q}g)}{\sigma_0} = \frac{1}{8\pi^2}C_F\alpha_s\frac{(1-x_1-x_2)^2+1}{(1-x_1)(1-x_2)}\,dx_1dx_2\,d(\cos\theta)d\phi$$

An useful quantity is the probability of measuring various values of Pf. Up to NLO in QCD, this is given by

$$\frac{d\sigma^{\rm NLO}}{d\mathrm{Pf}} = \int d\mathrm{PS}\,\frac{d\sigma}{dx_1dx_2}\,\delta\left(\mathrm{Pf}-\frac{E_J^3}{E_1E_2E_3}\,S\cos^2\theta\right)$$

$$S \equiv (1-x_1)(1-x_2)(x_2+x_1-1)$$

$$E_J:\ \text{Jet energy}\ E_i \equiv E_i(x_1,x_2,\theta,\phi)$$

This expression can be integrated for Pf>0 (Fig 4). Resummation is needed for small values of Pf~0, but the tail region is already well described by NLO.

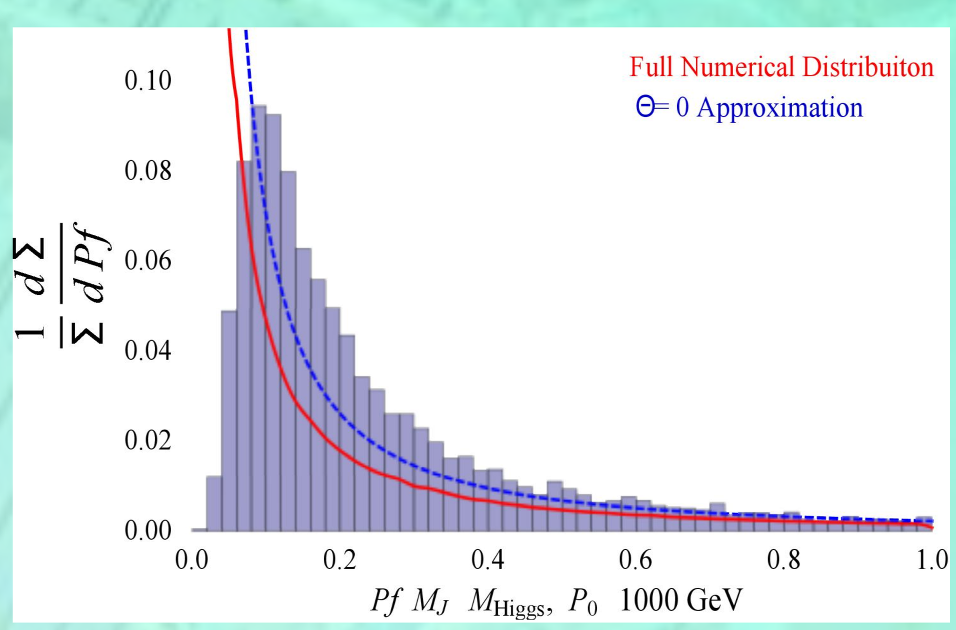


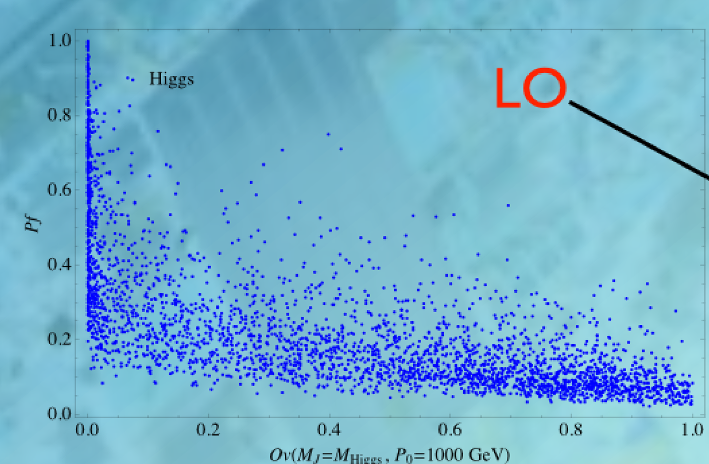
Fig.4*: A histogram of Pf for Higgs jets and the corresponding NLO distribution, before hadronization effects are taken into account .*

Template overlap at NLO

The Higgs template can be combined with planar flow jet shape to increase signal to background ratios in the selection of Higgs candidate events.

At LO, the events with large values of Ov tend to have smaller values of Pf. However, when NLO corrections are included, the NLO template also captures some of the events with large Pf.

LO



NLO (preliminary)

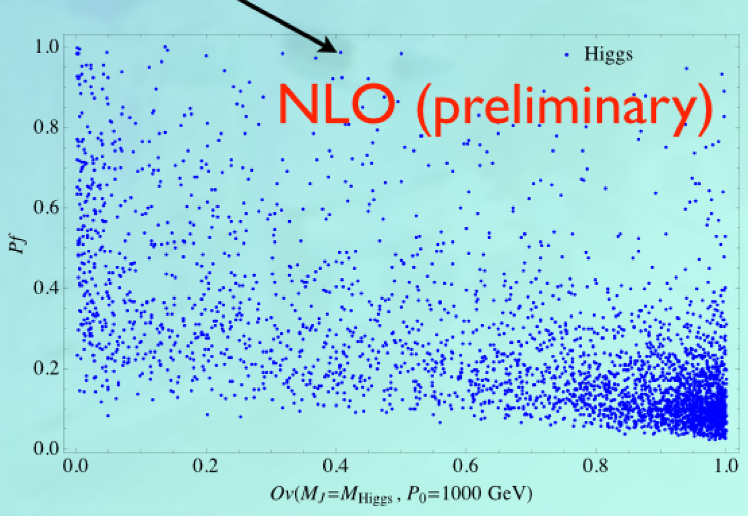


Fig.5*: Scatter plots of planar flow (Pf) vs template overlap (Ov) for Higgs jets, using LO templates (Upper-left) and NLO templates (Bottom- right)*

This method can be easily extended to other resonances than the Higgs boson, using our knowledge of the signal to perform a custom analysis.

References

[1] J. Thaler and L.-T. Wang, Strategies to Identify Boosted Tops, JHEP 07 (2008) 092, [arXiv:0806.0023].
[2L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, Phys. Rev. D 79, 074017 (2009) [arXiv:0807.0234 [hep-ph]],arXiv:1007.2221
[3]L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, and I. Sung, Template Overlap Method for Massive Jets,Phys. Rev. D82 (2010) 054034, [arXiv:1006.2035].

Conclusions

The selection criteria can be optimised to increase signal to background ratios in the selections using template methods. When combined with jet shapes, this can create a selection criteria with greater significance than traditional cut-based methods.
The template overlaps described above are capable of systematic improvement by weighting according to the lowest order matrix elements and/or including higher order corrections in the template phase space.
The application of NLO templates for Higgs and BSM resonance identification is under investigation to enhance previous analysis.