Snowmass2021 - Letter of Interest

Energy Peak and Its Implications on Collider Phenomenology: Top Quark Mass Determination and Beyond

Kaustubh S. Agashe[a], Roberto Franceschini[b], and Doojin Kim[c]

[a]Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742, USA
[b]Universitá degli Studi and INFN Roma Tre, Via della Vasca Navale 84, I-00146, Rome, Italy
[c]Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77845, USA

EF Topical Groups: (check all that apply ☐/■)
☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
■ (EF03) EW Physics: Heavy flavor and top quark physics
☐ (EF04) EW Physics: EW Precision Physics and constraining new physics
☐ (EF05) QCD and strong interactions:Precision QCD
☐ (EF06) QCD and strong interactions:Hadronic structure and forward QCD
☐ (EF07) QCD and strong interactions: Heavy Ions
☐ (EF08) BSM: Model specific explorations
■ (EF09) BSM: More general explorations
■ (EF10) BSM: Dark Matter at colliders

TF Topical Groups: (check all that apply ☐/■)
☐ (TF01) String theory, quantum gravity, black holes
☐ (TF02) Effective field theory techniques
☐ (TF03) CFT and formal QFT
☐ (TF04) Scattering amplitudes
☐ (TF05) Lattice gauge theory
☐ (TF06) Theory techniques for precision physics
■ (TF07) Collider phenomenology
☐ (TF08) BSM model building
☐ (TF09) Astro-particle physics & cosmology
☐ (TF10) Quantum Information Science
☐ (TF11) Theory of neutrino physics

Contact Information:
Doojin Kim (Texas A&M University) [doojin.kim@tamu.edu]

Introduction: It is very well-known that in the rest frame of a parent particle undergoing a two-body decay, the energy of each of the child particles is fixed in terms of parent and the child particle masses. This implies that we can determine the mass of the parent particle if we can measure these rest-frame energies of the child particles.

However, the parent particle is often created in the laboratory with a boost whose magnitude and direction are a priori unknown. Moreover, boosts of parent particles produced at hadron colliders vary event-to-event. Such a boost distribution depends on the production mechanism of the particle and on the structure functions of the hadrons, and is thus a complicated function. This implies that the energy of the two-body decay product observed in the laboratory frame develops a distribution. Thus it seems like the information that was encoded in the rest-frame energy is lost, and we are prevented from extracting (at least at an easily tractable level) the mass of the parent particle along the lines described above.

Remarkably, it was shown that if one of the child particles from the two-body decay is massless and the parent is unpolarized (i.e., not just restricted to the scalar parent) but no further model assumptions are imposed, then such is not the case: specifically, the distribution of the child particle's energy in the laboratory frame has a *peak* precisely at its corresponding rest-frame energy [1]. In other words, the peak position is boost-*invariant* irrespective of the production details of the parent particle. In this Letter of Interest, we discuss the idea of energy peak (also called energy-peak method), its collider implications, especially in terms of mass determinations of the Standard Model (SM) top quark and property measurements of new physics particles, and future directions with the energy peak in the energy-frontier physics program.

"Invariance" of the energy peak: We consider the decay of a heavy particle B of mass m_B, i.e., $B \to Aa$ with A having mass m_A and a being a massless visible particle, in which the energy of a in the rest frame of B, E^* is given by $E^* = \frac{m_B^2 - m_A^2}{2m_B}$. If parent particle B is boosted by a Lorentz factor γ in going to the laboratory frame, then the a energy seen in the laboratory frame E is

$$E = E^* \gamma (1 + \beta \cos\theta^*) \,, \tag{1}$$

where θ^* defines the direction of emission of particle a in the B rest frame with respect to the boost direction $\vec{\beta}$ of B in the laboratory frame. Due to our assumption of the parent being not polarized, the probability distribution of $\cos\theta^*$ is flat. This implies that, for a fixed γ, the distribution of E is flat as well. More precisely, since $\cos\theta^* \in [-1, 1]$, for any fixed γ the shape of the E distribution is a simple "rectangle" spanning the range

$$E \in \left[E^* \left(\gamma - \sqrt{\gamma^2 - 1} \right), E^* \left(\gamma + \sqrt{\gamma^2 - 1} \right) \right] . \tag{2}$$

A few crucial observations are in order. First, the lower (upper) bound of Eq. (2) is smaller (larger) than 1 for an arbitrary γ, which implies that every rectangle contains E^*. Remarkably, E^* is the only energy value to enjoy such a property as long as the distribution of parent particle boost is non-vanishing in a small region around $\gamma = 1$. Furthermore, the energy distribution being flat for every γ, there is no other value of the energy which gets a larger contribution than E^*. Thus, up on "stacking up" the rectangles of different widths, corresponding to a range of γ's, we see that the peak of the a energy distribution is unambiguously located at $E = E^*$ [1]. We emphasize that no model details other than a *two-body* decay of *unpolarized* parent B into a *massless* child a are assumed, i.e., this "*invariance*" property against the boost is *model-independently* valid.

More formally, the a energy spectrum $f(E)$ is given by superimposing the above-mentioned rectangles weighted by the boost distribution $g(\gamma)$:

$$f(E) = \int_{\frac{1}{2}\left(\frac{E}{E^*} + \frac{E^*}{E}\right)}^{\infty} d\gamma \frac{g(\gamma)}{2E^* \sqrt{\gamma^2 - 1}} \,. \tag{3}$$

Since $g(\gamma)$ is in general unknown, a closed form of the above expression is generally not available. One may instead employ an ansatz to capture the functional properties encoded in (3): i) $f(E/E^*) = f(E^*/E)$, ii) $f_{\max} = f(E = E^*)$, iii) $f(E \to 0, \infty) \to 0$, and iv) $f(E) \to\sim \delta(E - E^*)$ in some limit of its parameters. These properties are not sufficient to single out a functional form for $f(E)$, so we proposed a successful ansatz of the following form [1]

$$f(E) \propto \exp\left[-\frac{p}{2} \left(\frac{E}{E^*} + \frac{E^*}{E} \right) \right] , \tag{4}$$

where p is a parameter which encodes the width of the peak.

Application to the top quark mass measurement: The idea of energy peak was first applied to the top quark mass measurement, as a top quark (identified as B) is produced in an *unpolarized* way due to QCD interactions and decays to *two* child particles, a W gauge boson (identified as A) and a bottom quark (identified as a) [1]. Note that the method is not only insensitive to the production details of top quark such as QCD effects, PDF uncertainties etc but valid even in the case where production is "contaminated" by non-SM contributions as far as unpolarized production of top quarks holds, whereas many of other traditional methods rely on the assumption of SM top quark. Here the bottom quark is not massless, but it is so boosted in the top quark decay that the phase space invalidating the above argument is negligible. We studied a detector-level sample of fully leptonic top decays from the process, $pp \to t\bar{t} \to b\bar{b}\mu^- e^+ \nu_e \bar{\nu}_\mu$, at the LHC7 with an ansatz of the b-jet energy spectrum, and demonstrated that the extracted mass is almost the same as the input value with an error of $\sim 1.5\%$.

The CMS Collaboration adopted this idea to perform a (complementary) measurement of the top quark mass using the b-jet energy distribution and reported $m_t = 172.29 \pm 1.17(\mathrm{stat.}) \pm 2.66(\mathrm{syst.})$ [2]. One of the dominant sources of systematics is the one from jet energy scaling which would be mitigated with higher statistics, so the upcoming (high-luminosity) LHC would provide a better opportunity for a more precise measurement along the line.

Indeed, understanding higher-order effects, especially final state radiation of b quark, is crucial to reduce the systematics in the top quark mass measurement. In a follow-up work [3], we investigated our b-jet energy method with QCD NLO taken into account at the LHC14, and showed that for a 1% jet energy scale uncertainty the systematic error estimate would be improved to $\pm(1.2(\mathrm{exp}) + 0.6(\mathrm{th}))$ GeV. As an alternative route to get around the jet energy scaling issue, we studied the idea of using the B-hadron energy which can be measured at the tracker and ECAL [3]. In a similar spirit, we further investigated various B-hadron observables again at the LHC14 and pointed out that constraining the relevant Monte Carlo parameters in event generators such as PYHIA 8 and HERWIG 6 by $\mathcal{O}(1-10\%)$ would allow us to determine the top quark mass within an uncertainty of $\lesssim 0.5$ GeV [4]. We believe that these ideas can be tested in the upcoming LHC runs and make a contribution to the task of precision top quark mass measurements.

Application to new physics: Applications of the energy-peak method are not limited to the SM top quark mass measurement, but readily extended to property measurements of new physics particles. In particular, since the method is valid irrespective of visibility of the other decay product, it can be useful for a wide range of new physics models including the ones containing dark matter candidate(s). To show its broad applicability in realistic examples, we performed a few benchmark studies in the scenario where pair-produced parent particles undergo a two-step cascade decay terminating in an invisible particle which arises in many of the new physics models [5], in the scenario where a parent particle goes through a three-body decay [6], and in the scenario where the decay products are (non-negligibly) massive [7]. Beyond the mass measurements of new particles, the energy-peak method can be used for distinguishing dark matter stabilization symmetries, e.g., Z_2 vs. Z_3, in combination with the M_{T2} variable [8].

These studies essentially cover most of the scenarios that arise in typical new physics models such as supersymmetry, extra dimensions, and dark matter models. Therefore, upon discovery of new physics at the upcoming LHC or future colliders, we expect that the energy-peak method can play an important role in unmasking the underlying model details.

Future plan: We are now planning to propose a new top quark mass measurement technique, developing the method of the energy-peak improved B-hadron decay length. The B-hadron decay length can be considered as a "proxy" for its energy. Similarly to the aforementioned technique of utilizing B-hadron observables, we expect that the method will be unaffected by the jet energy scale uncertainty as the main observable is the decay length of (long-lived) B hadrons measured in the tracker of LHC detectors. Indeed, a similar technique was used to measure the top quark mass by the CMS Collaboration with the assumption of the SM top quark [9]. By contrast, we expect that the involvement of the energy peak will ensure model-independency in the extraction of the top quark mass due to the properties of the energy peak as discussed before. In addition, this method would allow us to access different systematics, providing complementarity in the task of determining the top quark mass.

Summary: In conclusion, the idea of energy peak is not only theoretically interesting *per se* but providing a kinematic handle to measure the mass of the SM top quark irrespective of its production details and to extract properties of new physics particles. Given the scientific applications of the energy peak method, it will be an important aspect of both the energy-frontier physics program and the theory-frontier physics program in the next decade and beyond.

References

[1] K. Agashe, R. Franceschini and D. Kim, *Simple "invariance" of two-body decay kinematics*, *Phys. Rev. D* **88** (2013) 057701, [1209.0772].

[2] CMS collaboration, *Measurement of the top-quark mass from the b jet energy spectrum, CMS-PAS-TOP-15-002*, .

[3] K. Agashe, R. Franceschini, D. Kim and M. Schulze, *Top quark mass determination from the energy peaks of b-jets and B-hadrons at NLO QCD*, *Eur. Phys. J. C* **76** (2016) 636, [1603.03445].

[4] G. Corcella, R. Franceschini and D. Kim, *Fragmentation Uncertainties in Hadronic Observables for Top-quark Mass Measurements*, *Nucl. Phys. B* **929** (2018) 485–526, [1712.05801].

[5] K. Agashe, R. Franceschini and D. Kim, *Using Energy Peaks to Measure New Particle Masses*, *JHEP* **11** (2014) 059, [1309.4776].

[6] K. Agashe, R. Franceschini, D. Kim and K. Wardlow, *Mass Measurement Using Energy Spectra in Three-body Decays*, *JHEP* **05** (2016) 138, [1503.03836].

[7] K. Agashe, R. Franceschini, S. Hong and D. Kim, *Energy spectra of massive two-body decay products and mass measurement*, *JHEP* **04** (2016) 151, [1512.02265].

[8] K. Agashe, R. Franceschini, D. Kim and K. Wardlow, *Using Energy Peaks to Count Dark Matter Particles in Decays*, *Phys. Dark Univ.* **2** (2013) 72–82, [1212.5230].

[9] CMS collaboration, *Measurement of the top quark mass using the B-hadron lifetime technique, CMS-PAS-TOP-12-030*, .