Jet Substructures of boosted hadronic tops

Hsiang-nan Li
Academia Sinica

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In collaboration with Yoshio Kitadono
Outlines

• Review of boosted leptonic tops
• Boosted hadronic tops
• Top jet energy profiles
• Conclusion
Review of boosted leptonic tops

Theoretically easy, but experimentally hard

Kitadono, Li, 1403.5512
Boosted heavy particles

• Heavy particles (Higgs, W, Z, top, new particles) may be produced with large boost at LHC

• Decaying heavy particle with sufficient boost gives rise to a single jet

• If just measuring invariant mass, how to differentiate heavy-particle jets from ordinary QCD jets? How to reveal properties of heavy particles?

• Use different jet substructures resulting from different weak and strong dynamics
Chirality vs helicity

- BSM heavy particles decay into boosted tops
- Chirality of BSM physics revealed by helicity of boosted tops
- How to determine helicity of boosted tops?
- Polarization of rest top determined by angular distribution of decay products
- Propose to measure jet substructures---energy profiles depend on helicity
- Require no b-tagging, W reconstruction

Scale hierarchy $E \gg \gg m_t \gg \gg m_J$

- The two lower scales $m_t$ and $m_J$ characterize different dynamics, which can be factorized

\[ O(m_J) \quad O(m_t) \]

light-quark jet

heavy-quark kernel
Spin decomposition and boost

• Spin projector
  \[ w_t = \frac{1}{2}(1 + \gamma^5 \gamma_t), \quad \bar{w}_t = \frac{1}{2}(1 - \gamma^5 \gamma_t), \]

  \[ (\kappa_t + m_t) = (\kappa_t + m_t)w_t + (\kappa_t + m_t)\bar{w}_t \]

• Easier to work in rest frame of top first, and then boost

• Helicity (+ or R, - or L) and Boost from Lorentz transformation

\[ s^\mu_t = (0, 0, 0, 1) \quad Z \text{ axis = top spin direction} \]

J. Shelton,
PRD 79, 014032 (2009)

Boost frame \( v_t \)

Right-handed

Left-handed
Jet energy profile

- Consider a test cone (angle \( r: 0 < r < R_t \)) in top-jet. Accumulate the sub-jet energy in the small cone.

\[
\text{Ratio}(E_{J_t}, R_t, r) = \frac{\text{Jet (transverse) energy in cone } r}{\text{Jet (transverse) energy in cone } R_t}
\]

- This ratio describes a "spread" of energy in the small cone \( r \) caused by the sub-jet distribution

Li, Li, Yuan, 1206.1344
Resummation approach

- Monte Carlo: leading log radiation, hadronization, underlying events
- Fixed order: finite number of collinear/soft radiations
- Resummation: all-order collinear/soft radiations

Calorimeter-level jets
Why resummation?

• Monte Carlo may have ambiguities from tuning scales for coupling constant
• NLO is not reliable at small jet mass
• Predictions from QCD resummation are necessary

Tevatron data vs MC predictions

N. Varelas 2009
Top-jet energy profile

Top-jet energy dependence

Top-jet radius dependence

Left > Right due to V-A feature (b jet anti-correlated to top spin)

|L-R| difference decrease as E_{jt} increase.

Top-jet radius dependence is not significant.

Kitadono, Li 2014
Boosted hadronic tops

Theoretically hard, but experimentally easy
Difficulty 1

• Three-body kinematics in $t \rightarrow b u d$
• In semileptonic decay neutrino kinematics is integrated out, basically two-body

$$k_l \sin \theta_l = k_b \sin \theta_b$$

complicated angular relation
Difficulty 2

- Treatment of soft gluons
- Consider a fat $b$ jet, which absorbs soft gluons in semileptonic case

still need soft function to absorb soft gluons
Difficulty 3

• Jet merging
• No jet merging issue in semileptonic case
• When subjets overlap, how to count their contribution to test cone?
• Ambiguity to define subjet radii

counted as single jet or two jets?
Sequential factorization

- Factorization of top jet into fat W-boson jet, fat bottom jet, and top decay kernel
- Fat bottom jet obeys universality for leptonic (Kitadono, Li, 2014) and hadronic tops
- Factorization of fat W-boson jet into fat light-quark jet, thin light-quark jet and W decay kernel (Isaacson, Li, Li, Yuan, 2015)
- At each step of factorization, handle only two-body kinematics
Heavy-boson jet profiles

E=500 GeV

Isaacson, Li, Li and Yuan, 1505.06368
No soft function

- Construct W-boson jet

contain soft gluons then construct top jet

soft gluon exchanges between b quark and color-singlet W boson are suppressed
No jet merging

• Up (fat) and down (thin) jets completely overlap, no jet merging issue

• W-boson (fat) jet and bottom (fat) jet completely overlap, no jet merging issue

• Fat jet has radius $R$ (top jet radius), and thin jet has radius $r$ (test cone radius, focusing on energy profile at small $r$)

• No ambiguity to define jet radii

• Double counting of soft gluons is negligible at small $r$
Top jet energy profiles
bottom jet contributes more to left-handed top
similar to energy profiles of leptonic top jet
W jet shows obvious dead-cone effect, and contributes more to right-handed top

sharp ascent---broader energy spread
Energy profiles of hadronic top jet
due to compensation of b and W jet contributions,
energy profile is not a useful discriminator
Differential energy profiles

Interplay between b and W jet contribution leads to different differential profiles

Maybe difficult to measure them at very small r
Conclusion

• Jet substructure helps identification of boosted particles
• can be studied by PQCD factorization and resummation technique
• Differential energy profile, instead of energy profile, is a useful discriminator for helicity of a boosted hadronic top
• Right-handed top jet shows quick descent with r
• Difference appears at very small r. Maybe difficult to measure?