Tagging with the Lund Jet Plane

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Outline

- **W tagging**

- **Higgs tagging**
  - Lund jet plane and jet color ring
  - Lund jet plane and color sensitive observables
- **B-tagging**

- **Top tagging**
  F.A.Dreyer, and H.Qu, *JHEP* 03 (2021), 052

- **Quark-Gluon tagging**
  F.A.Dreyer, G. Soyez and A.Takacs, *JHEP* 08 (2022), 177
Boosted Jets

Figure taken from F. Dreyer’s slide, original figure credit: G. Soyez

Adapted from: https://www.physi.uni-heidelberg.de

Top Quark Decay

At rest

Large Radius Jet
Lund Jet Plane

Δ is the opening angle of the emission.

$k_T$ is the transverse momentum w.r.t the jet axis.

F.A.Dreyer, G.P.Salam and G.Soyez, JHEP 12 (2018), 064
(Primary) Lund Jet Plane

- Re-cluster the constituents using C/A algorithm.
- Start with declustering C/A jet (undo last clustering step) we get two subjects (ordered by momentum).
- Save the kinematic of each declustering step as a tuple $\mathcal{T} = \{k_t, \Delta, z, m, \psi\}$
  \[
  \Delta^2 \equiv (y_1 - y_2)^2 + (\phi_1 - \phi_2)^2 \quad k_t \equiv p_{t2}\Delta
  \]
  \[
  z \equiv \frac{p_{t2}}{p_{t1} + p_{t2}} \quad m^2 \equiv (p_1 + p_2)^2 \quad \psi \equiv \tan^{-1} \frac{y_2 - y_1}{\phi_2 - \phi_1}
  \]
- Following a history of the hardest branch, we get double logarithmic plane $\left(\ln \frac{1}{\Delta}, \ln \frac{k_t}{\text{GeV}}\right)$.
- Pixels corresponding to the splitting are turned on.

LundPlane library is publicly available as a part of FastJet contrib package.

F.A.Dreyer, G.P.Salam and G.Soyez, JHEP 12 (2018), 064
W and QCD Jets

F.A. Dreyer, G.P. Salam and G. Soyez, JHEP 12 (2018), 064
Example: Jet Images as an input to CNN

Energy of charged particles
Energy of neutral particles
Number of charged particles

- Center
- Crop
- Normalize

convolutional layer
pre-process
dense layer
max-pooling

P. T. Komiske, E. M. Metodiev and M. D. Schwartz, JHEP 01(2017), 110
W Tagging using Lund Jet Plane

F.A.Dreyer, G.P.Salam and G.Soyez, JHEP 12 (2018), 064

F.A.Dreyer, G.P.Salam and G.Soyez, JHEP 12 (2018), 064
Higgs Tagging using the Lund Jet Plane


Primary Lund plane regions

- ISR (large $\Delta$)
- soft-collinear
- hard-collinear (large $z$)
- MPI/UE non-pert. (small $k_t$)

$\ln \left( \frac{k_t}{\text{GeV}} \right)$

\[ p_T > 250 \text{ GeV} \]
\[ 110 < m_J < 140 \text{ GeV} \]

Lund Image $ZH(b\bar{b})$

Jet color ring
\[ \mathcal{O} = \frac{\theta_{ka}^2 + \theta_{kb}^2}{\theta_{ab}^2} \]

F.A.Dreyer, G.P.Salam and G.Soyez, JHEP 12 (2018), 064
Simulation Set-up

Tools: Madgraph 2.7.2, Pythia 8 and Fastjet 3.0.

High and moderate $p_T$ benchmarks: $p_T > 250$ GeV and $p_T > 550$ GeV.

Generation level cuts: $p_T > 200$ GeV and $p_T > 500$ GeV, $|\eta_j| < 5.0, |\eta_l| < 2.5$.

Jet mass cut: $110 < m_J < 140$ GeV.

$H \rightarrow b\bar{b}$
$pp \rightarrow ZH (Z \rightarrow \mu^+\mu^-, H \rightarrow b\bar{b})$
$pp \rightarrow Zb\bar{b} (Z \rightarrow \mu^+\mu^-)$

$H \rightarrow gg$
$pp \rightarrow ZH (Z \rightarrow \mu^+\mu^-, H \rightarrow gg)$
$pp \rightarrow Zjj (Z \rightarrow \mu^+\mu^-)$

Mapping Events to the (primary) Lund Jet Plane

- Consider a list of particles (except the muons from hard scattering).
- Form anti-$k_t R = 1$ jets using Fastjet.
- Cluster the constituents of the leading jet using C/A algorithm with a maximum allowed jet radius.
- Save the Lund coordinates history of the hardest branch.
- Use a double logarithmic plane $\left( \ln \frac{1}{\Delta}, \ln \frac{k_t}{\text{GeV}} \right)$.
- Pixels $(25 \times 25)$ corresponding to the splitting are turned on.
Lund Jet Plane

Signal

Background
(Averaged) Lund Jet Images

anti-$k_T$ R=1 jets, reclustered the constituents using C/A algorithm

CKK and S.Marzani, Phys. Rev. D 104 (2021) no.5, 055043
Color Singlet Tagger: Jet Color Ring

\[
\mathcal{O} = \frac{\theta_{ak}^2 + \theta_{bk}^2}{\theta_{ab}^2}
\]

Constructing the Jet Color Ring

Identify sub-jets within the large $R$ jet

- Charged particles with $p_T > 500$ MeV, $|\eta| < 5$.

- Construct $R = 0.2$ track-jets using anti-$k_t$ algorithm.

- Consider track jets with $p_T > 5$ GeV and $\Delta_{jj} < 0.8$.

$$\Delta_{jb/jb} < 0.2$$

$b$-jets \hspace{2cm} light-jets

$$O = \frac{\theta_{ka}^2 + \theta_{kb}^2}{\theta_{ab}^2}$$

Color Ring $ZH(b\bar{b})$ vs $Zb\bar{b}$

$\rho_T > 250$ GeV

$110 < m_J < 140$ GeV
CNN for Binary Classification

100K Events (balanced data)

Training: Validation:Test data = 60:20:20%

Cross-Entropy Loss function

\[ \text{Signal efficiency} \]

\[ \text{False positive rate} \]

\[ ZH(b\bar{b}) \text{ vs } Zb\bar{b} \]

Lund Plane (AUC = 0.88)
Color Ring (AUC = 0.85)

\[ p_T > 250 \text{ GeV} \]
\[ 110 < m_J < 140 \text{ GeV} \]
$H \rightarrow gg$ Analysis

Jet Color Ring:

- Signal distribution is the same as $H \rightarrow b\bar{b}$ case.
- Several color configurations are contributing to the background.
High $p_T$ Scenario

Lund Image $ZH(bb)$

$pt > 550$ GeV
$110 < m_J < 140$ GeV

Lund Image $Z\bar{b}\bar{b}$

$pt > 550$ GeV
$110 < m_J < 140$ GeV

Color Ring $ZH(bb)$ vs $Z\bar{b}\bar{b}$

$pt > 550$ GeV
$110 < m_J < 140$ GeV

$O = (\theta_{ba}^2 + \theta_{bh}^2)/\theta_{ab}^2$

$\sigma^{-1} d\sigma/4\pi$

Signal
Background

$Z\bar{h}(bb)$ vs $Z\bar{b}\bar{b}$

Lund Plane (AUC = 0.94)
Color Ring (AUC = 0.87)

False positive rate

Signal efficiency
Color sensitive observable and the Lund Jet Plane


Jet pull and its projections, $D_2$, and color ring, Lund jet plane
(Including detector effects)

Possible color connections for signal ($pp \to H \to b\bar{b}$) and for the background ($pp \to g \to b\bar{b}$)

Jet Pull

\[ \vec{t} = \frac{1}{p_{Ta}} \sum_{i \in J_a} p_{Ti} |\vec{r}_i|^2 \hat{r}_i \]

\[ \vec{r}_i = (y_i - y_a, \phi_i - \phi_a) \]

\[ t_{\parallel} = \vec{t} \cdot \hat{n}_{\parallel}, \quad \hat{n}_{\parallel} = \frac{1}{\sqrt{\Delta y^2 + \Delta \phi^2}} (\Delta y, \Delta \phi) \]

\[ t_{\perp} = \vec{t} \cdot \hat{n}_{\perp}, \quad \hat{n}_{\perp} = \frac{1}{\sqrt{\Delta y^2 + \Delta \phi^2}} (-\Delta \phi, \Delta y) \]

\[ \theta_p = \arccos \frac{t_{\parallel}}{|\vec{t}|} \]

A. Larkoski, S. Marzani and C. Wu, JHEP 01 (2020), 104
Jet Pull and its projections

$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$

$e_n^{(\beta)}$ is the normalized n-point energy correlation functions
Discrimination Performance

Invariant Mass Dependence

Background distribution of different ranges of classifier output.
Identification of b-jets

O. Fedkevych, CKK, S. Marzani and F. Sforza, Phys. Rev. D 107(2023) no.3, 034032
Identification of b-jets

PYTHIA MC; $p_{T,jet} > 500$ GeV

O. Fedkevych, CKK, S. Marzani and F. Sforza, Phys. Rev. D 107(2023) no.3, 034032
Effect of b-mass in the Lund Jet Plane

Ongoing work by
Francesco Giuli, Alberto Rescia, Federico Sforza

- Generate b & light jet events w/ MG5@NLO-Delta (v3.5.0)
  - Z(l⁺l⁻) + j final state at NLO in 5FS for light events
  - Z(l⁺l⁻) + bb with NLO in 4FS for b events
  - No kinematic cuts at generator level
- Shower with Pythia8 v8.309
  Analyse at truth-level with a dedicated Rivet routine
  - **Lepton cuts:**
    - $p_T > 27$ GeV, $|\eta| < 2.5$ and dilepton mass between 76-106 GeV
    - Isolation criterion: discard if $\Delta R < 0.4$ from jets
  - **Jets:**
    - Cluster final state hadrons into $R = 0.4$ jets
      - with $p_T > 20$ GeV and $|\eta| < 2.5$
      - Tag jets as b or light via ghost-matching
      - Require 2 tagged jets in final state
Effect of b-mass in the Lund Jet Plane

Ongoing work by
Francesco Giuli, Alberto Rescia, Federico Sforza

Preliminary Results
LundNet for Top Tagging

F.A.Dreyer, and H.Qu, JHEP 03 (2021), 052
Summary and Outlook

• In this talk, we discussed how Lund Jet Plane and machine learning techniques can be used for jet tagging.

• We are using color-sensitive observables and a primary Lund jet plane for the Higgs tagging.

• Other studies also considered more complex architectures like graph neural networks for boosted jet tagging.

• A comparison of these techniques for the same benchmark will be useful for their implementation in the experimental analysis.
Tagger Without Jet Mass Cut

Mass unspecified tagger using color information rather than prong multiplicities