Flavor Tagging TeV Jets for BSM and QCD

Keith Pedersen
(kpeders1@hawk.iit.edu)

ILLINOIS INSTITUTE OF TECHNOLOGY

In collaboration with **Zack Sullivan**

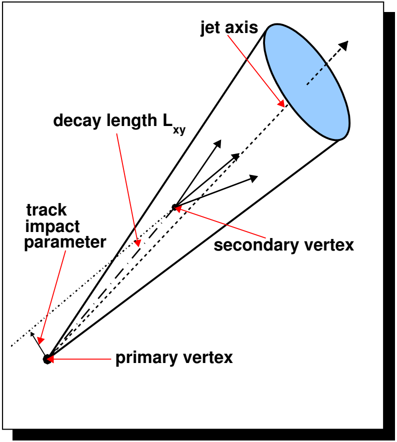
To appear in arXiv:1505.xxxx

Z' Models

- One of the simplest BSM models is an additional $U(1)$ symmetry, mediated by a *very heavy* boson (Z').
  - Di-lepton channels consistently show no heavy resonances – what if the Z' is "leptophobic"?
- We looked at a Z' from *Dobrescu* and *Yu* [arXiv:1306.2629]
  - Designed to be leptophobic
    - All leptons and SM bosons are neutral (no tree-level couplings).
    - Flavor independent coupling to SM quarks.
- Dijets are discovery channel; but only heavy flavored dijets are visible over QCD background.
  - *Need to tag heavy flavor jets!*

Track-based *b*-tag

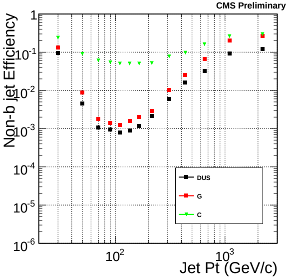
- *b*-hadrons have long lifetimes and decay at a secondary vertex (**SV**). Use tracks to find an **SV** inside a jet.
  - High efficiency for *b*-jets (.5-.8).
  - Also tag **charm** and **light** jets.



Track-based b-tag

- b-hadrons have long lifetimes and decay at a secondary vertex (**SV**). Use tracks to find an **SV** inside a jet.
  - High efficiency for b-jets (.5-.8).
  - Also tag **charm** and **light** jets.
- Probability to tag light jets increases severely as jet p_T approaches TeV.
  - 10^{-3} at 100 GeV $\rightarrow 10^{-1}$ at 1 TeV

CMS PAS BTV-09-001 (fig. 12)

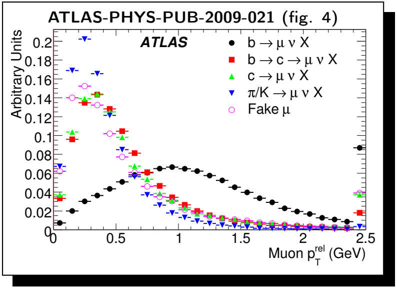


Maintaining 50% b-jet efficiency

- Resolving **SV** inside high p_T jets is *limited by tracking performance*.
  - Tracks have higher p_T and bend less – harder to constrain.
  - Tracks are more collimated – increased sensitivity to tracker resolution.
  - Dense tracking environment – fake tracks and false duplicates.
- Gluons split $(g \rightarrow b\bar{b})$ more often at high p_T – light flavor BG!

Muon-based b-tag

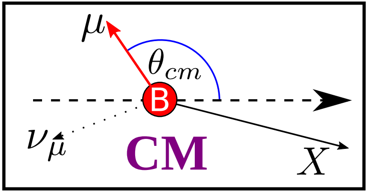
- b/c-hadrons frequently decay semi-leptonically (where $l \in \{e, \mu\}$):
  - $BR\left(b \to l\nu_l X\right) \approx 11\%$
  - $BR\left(c \to l\nu_l X\right) \approx 10\%$
  - 20% of b-jets have $N_{muon} \geq 1$
- Hard to see electrons inside *busy*, *boosted* jets – *muon chamber*!



- The angle muons make with boost axis of mother should be larger if its mother had a heavy flavor (and thus high mass).
  - Look at p_T^{rel} (muon momentum transverse to the centroid of its jet)
    - loses efficiency for boosted decays because *the centroid of the entire jet is too coarse a measure – need subjet of decay*.

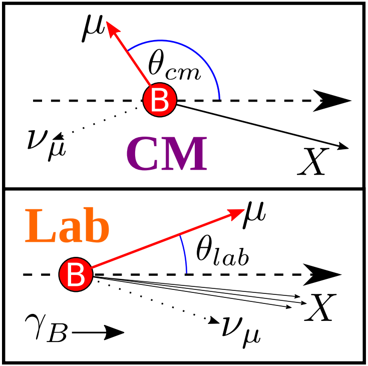
Muon Emission vs. Semi-leptonic Subjet

- **CM**: Muon is emitted with $\gamma_{\mu,cm}$ at angle θ_{cm} w.r.t. the boost axis.



Muon Emission vs. Semi-leptonic Subjet

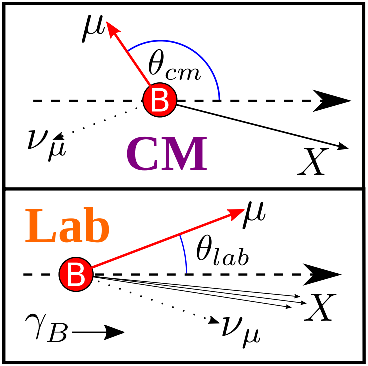
- **CM**: Muon is emitted with $\gamma_{\mu,cm}$ at angle θ_{cm} w.r.t. the boost axis.
- **Lab**: Muon is detected at angle θ_{lab} w.r.t. the centroid of the subjet (which has boost γ_B).
  - Define $\kappa \equiv \beta_B / \beta_{\mu,cm}$



Muon Emission vs. Semi-leptonic Subjet

- **CM**: Muon is emitted with $\gamma_{\mu,cm}$ at angle θ_{cm} w.r.t. the boost axis.
- **Lab**: Muon is detected at angle θ_{lab} w.r.t. the centroid of the subjet (which has boost γ_B).
  - Define $\kappa \equiv \beta_B / \beta_{\mu,cm}$

$$x \equiv \gamma_B \tan(\theta_{lab}) = \frac{\sin(\theta_{cm})}{\kappa + \cos(\theta_{cm})} \quad (1)$$

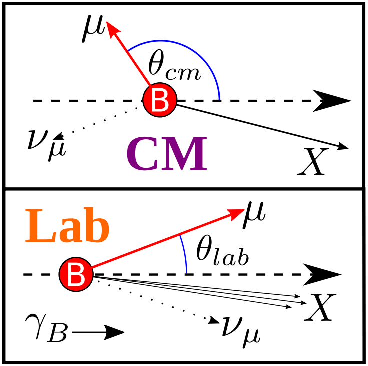


Muon Emission vs. Semi-leptonic Subjet

- **CM**: Muon is emitted with $\gamma_{\mu,cm}$ at angle θ_{cm} w.r.t. the boost axis.
- **Lab**: Muon is detected at angle θ_{lab} w.r.t. the centroid of the subjet (which has boost γ_B).
  - Define $\kappa \equiv \beta_B / \beta_{\mu,cm}$

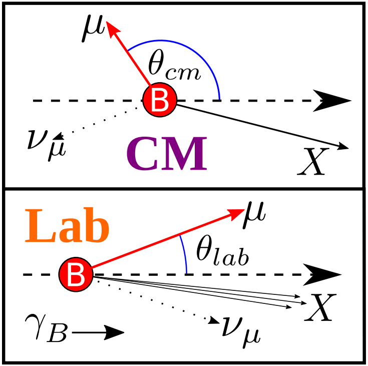
$$x \equiv \gamma_B \tan(\theta_{lab}) = \frac{\sin(\theta_{cm})}{\kappa + \cos(\theta_{cm})} \quad (1)$$

$$x \approx \tan(\theta_{cm}/2) \qquad (\text{when } \kappa \approx 1) \quad (2)$$



Muon Emission vs. Semi-leptonic Subjet

- **CM**: Muon is emitted with $\gamma_{\mu,cm}$ at angle θ_{cm} w.r.t. the boost axis.
- **Lab**: Muon is detected at angle θ_{lab} w.r.t. the centroid of the subjet (which has boost γ_B).
  - Define $\kappa \equiv \beta_B / \beta_{\mu,cm}$

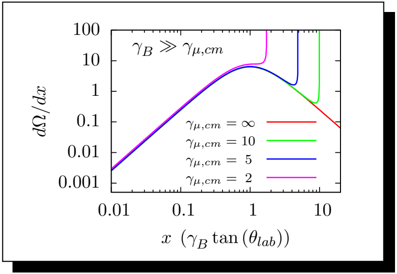


$$x \equiv \gamma_B \tan(\theta_{lab}) = \frac{\sin(\theta_{cm})}{\kappa + \cos(\theta_{cm})} \quad (1)$$

$$x \approx \tan(\theta_{cm}/2) \qquad (\text{when } \kappa \approx 1) \quad (2)$$

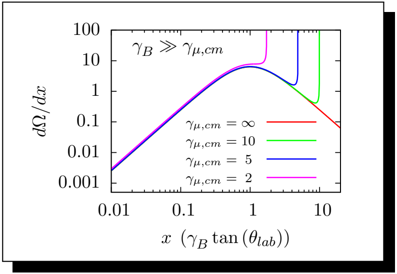
$$\frac{d\Omega}{dx} = 4\pi \frac{2x}{(x^2+1)^2} K(x,\kappa) \qquad (\text{when } \gamma_B \gg \gamma_{\mu,cm} \to \kappa > 1) \quad (3)$$

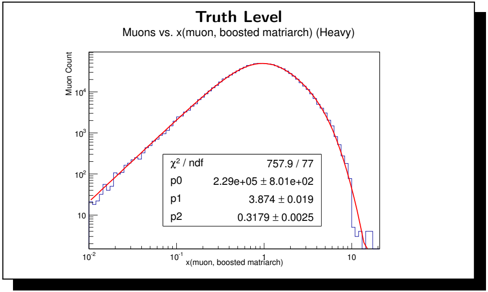
$d\Omega/dx$: Theory and Simulation



- Muons restricted to x_{max} defined by $\gamma_{\mu,cm}$.
- $K(x, \kappa)$ corrects for muon speed; small corrections for ultra-relativistic muons.

$d\Omega/dx$: Theory and Simulation



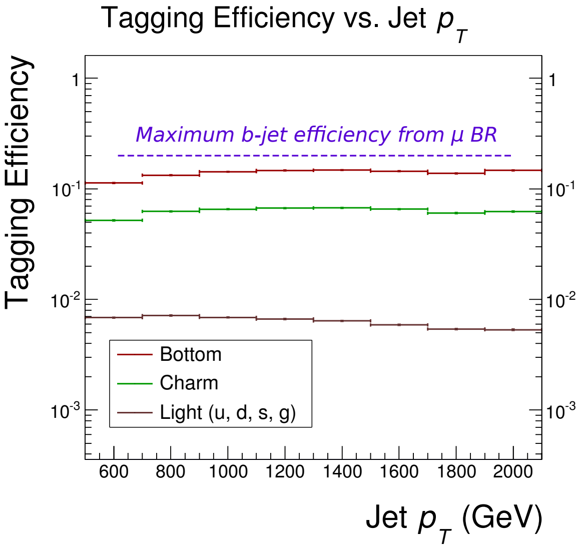


- Muons restricted to x_{max} defined by $\gamma_{\mu,cm}$.
- $K(x,\kappa)$ corrects for muon speed; small corrections for ultra-relativistic muons.
- Integrate over $\gamma_{\mu,cm}$ and distribute asymptote.
- Parameterize integrated shape with cutoff function (extra factor of x from binning in log-space):
  - $\frac{d\Omega}{dx} = \frac{2x}{(x^2+1)^2} \frac{p0\ x}{(1+\exp(2p2(x-p1)))}$

Defining the Semi-leptonic Subjet

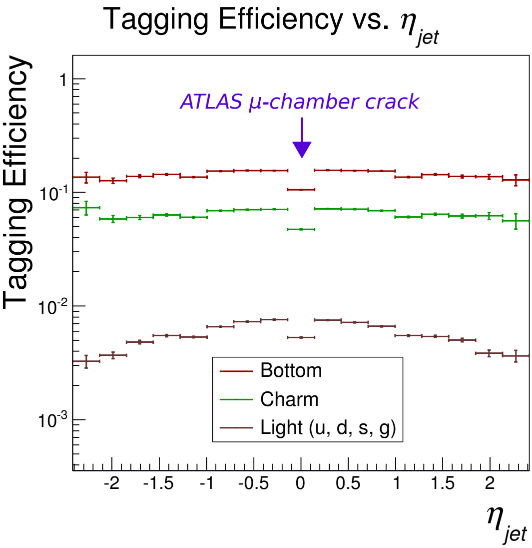
- Allow **muons** to participate in initial jet clustering (*hard muon seeds*):
  - A candidate jet has a muon passing a $p_{T\mu}$ cut (we used 10 GeV).
- Subjet's **hadronic** energy (the **core**)
  - Re-cluster candidate jets to find *extremely thin* core:
    - $R \approx 1/\gamma = \mathcal{O}(.01)$
  - γ_B needs ***mass*** of core – very poorly measured.
    - Constrain mass to *best guess* (e.g. $m_{D^\pm/D^0} \approx 2$ GeV).
  - Choose core which gets subjet mass closest to $m_{B^\pm/B^0} \approx 5.3$ GeV.
- Subjet's **neutrino**:
  - System is under-determined; must estimate neutrino. Simplest solution: *add muon again to simulate neutrino*.

- All studies simulated at ATLAS at $\sqrt{s} = 13$ TeV.
- Tag jets with $x \leq 3$
  - $\sim 14\%$ of b-jets
  - $\sim 7\%$ of c-jets
  - Mis-tag $\sim 0.7\%$ of light jets
- Gluon splitting BG is largely reducible.



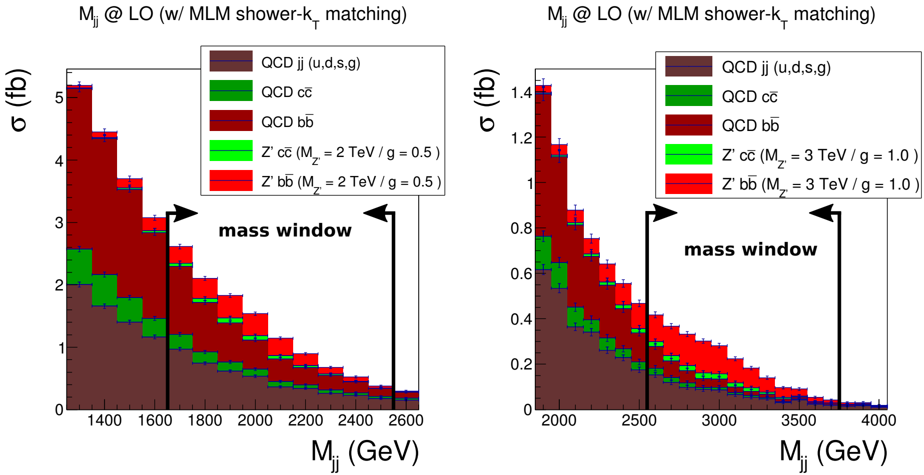
Tagging Efficiency (Jet η)

- η dependence *effectively flat* for bottom and charm.
  - Slight dip in endcap ($\eta > 1$).
  - Large dip at central crack in ATLAS Muon Spectrometer.
- Light jets lose extra forward efficiency because softer muons fail $p_{T\mu}$ cut.



Leptophobic Z' Bump Hunt

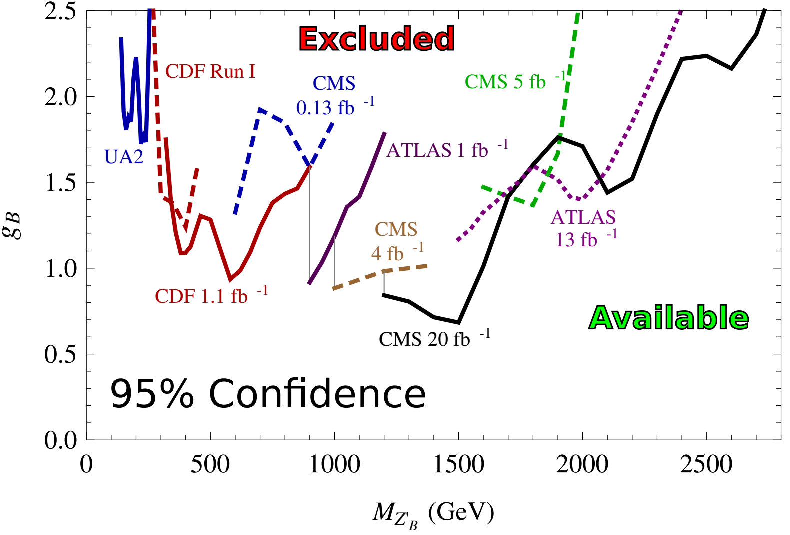
- MadGraph 5 → Pythia 8 → Delphes 3 (with FastJet 3)



- Require both jets to be tagged.
- Window: $M_{Z'}[-15\%, +25\%]$

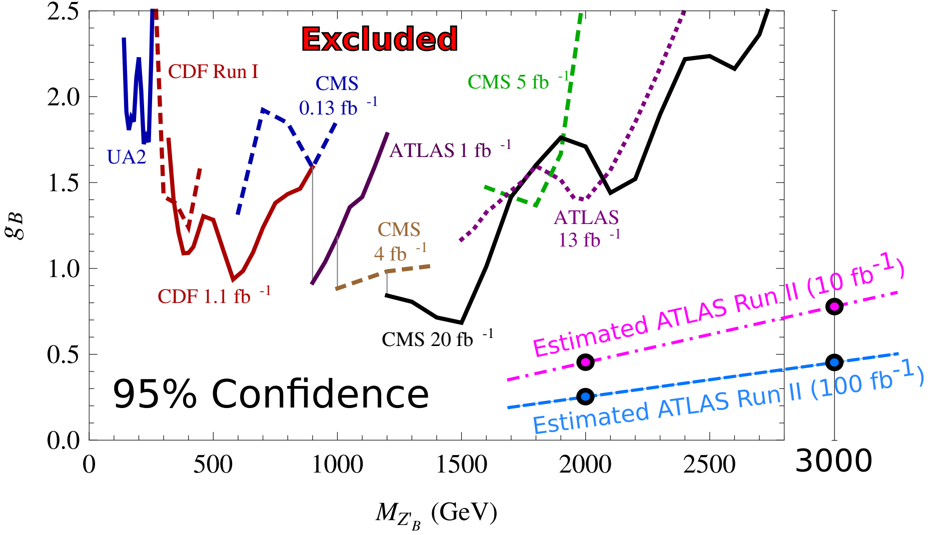
Uncharted Waters

Dobrescu & Yu [arXiv:1306.2629, fig. 1]



Uncharted Waters

Dobrescu & Yu [arXiv:1306.2629, fig. 1]



Conclusion

- New heavy flavor tagging technique for TeV scale jets.
- Flat response for signal in p_T and η.
- Tag 14% of b-jets and $< .7\%$ of light jets above 500 GeV.
- Should offer significant improvements in detecting Z' and other high energy states.