Flavor tagging TeV jets for BSM

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In collaboration with **Zack Sullivan**
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Outline

1. **Introduction**
   - Searching for BSM
   - Rise of the light jets
2. **The μ_x boosted b tag**
   - Basics of b tagging
   - A new b tag from first principles
   - μ_x reconstruction
   - Tagging efficiencies
3. **Finding a leptophobic Z'**
   - A bump hunt
   - Discovery potential
4. **Conclusions**

Prime candidates for BSM physics

Many extensions of the Standard Model predict heavy, narrow particles which couple via a **vector current** ... the W' and Z'

- Sequential Standard Model
- broken $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$
- GUT models
- Kaluza-Klein excitations from extra dimensions
- non-commuting extended technicolor
- and many more ...

The "golden channel" is the obvious place to look...

- There are no $Z' \to l^+ l^-$ with SM-like coupling below 2.9 TeV (ATLAS/CMS, $\sqrt{s} = 8$ TeV)

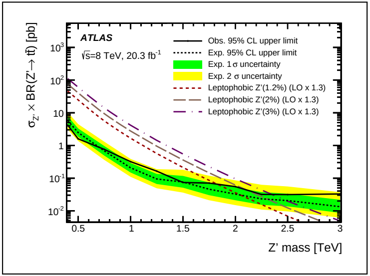
But what if the new physics is afraid of leptons?

- Leptophobic = more challenging = more *fun*

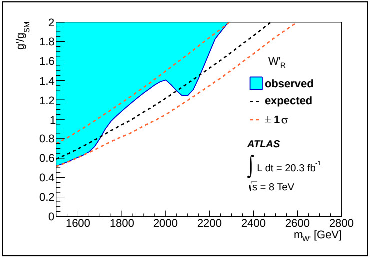
Leptophobic bosons

- To invent a model that doesn't couple to leptons can be complicated ...
  - Topcolor-assisted technicolor Z'
- or more straightforward ...
  - Right-handed W'
- Regardless, leptophobic means *jets*, and the dreaded QCD background.
  - We must flavor tag the jets!

JHEP**1508**(15)148[1505.07818] Fig. 11a



EPJC**75**(15)165[1408.0886] Fig. 8b



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- or more straightforward …
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- Regardless, leptophobic means *jets*, and the dreaded QCD background.
  - We must flavor tag the jets!
- $Z' \to t\bar{t}$ can look for bW^{+}_{leptonic} recoiling against $\bar{b}W^{-}_{\text{hadronic}}$ … must tag $2 \times b$ jets
  - No top-color Z' below 1.8 TeV
- $W' \to\ tb$ … must tag $2 \times b$ jets
  - No W'_{R} below 1.9 TeV
- *Why are these leptophobic limits ∼40% lower than the dilepton limit (∼3 TeV)?*

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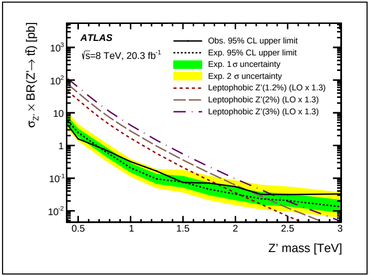

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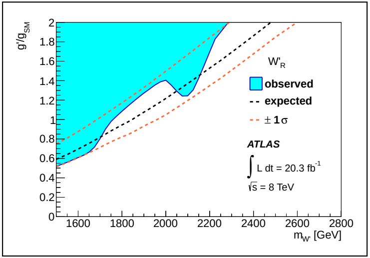
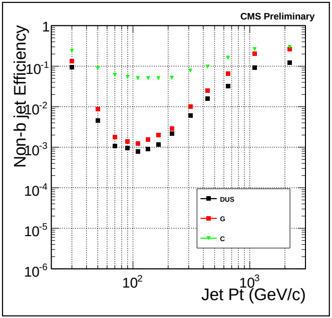


Rise of the light jets

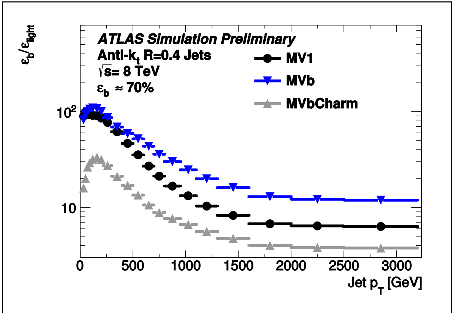
- Probability to tag light flavors *rises dramatically* for boosted jets!
  - Light jet = no b or c **hadrons**; experiments can't differentiate b-initiated jets and $g \to b\bar{b}$ jets.
- No complementary tags to cross-check performance as $p_T \to \mathcal{O}(\mathrm{TeV})$
  - Huge (40%) systematic uncertainties in tagging efficiency can dominate experimental results/exclusions.

[CMS PAS BTV-09-001] Fig. 12



Maintaining 50% b jet efficiency

[ATL-PHYS-PUB-2014-014] Fig. 14b



(b) QCD dijet

Call to action

We need a better, boosted b tag!

It must ...

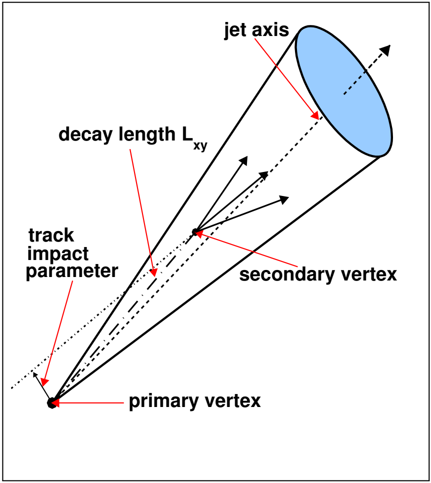
1. Rejects light jets ($\frac{\epsilon_b}{\epsilon_\text{light}} \gtrsim \mathcal{O}(10^2)$)
2. Robust performance for jet $p_T > 300$ GeV
   - Permits a cross-check with existing b tags, driving down the uncertainty for **both** tags (one hand washes the other)

We can validate the new tag on a challenging signal,
like a leptophobic $Z' \to b\bar{b}$ above 2 TeV.

Outline

Boosted b tag complications

- b tags at ATLAS and CMS use a jet's tracks to find a SV.
  - Good for $p_T \lesssim 300$ GeV; doesn't tag many **charm**/**light** jets.



Boosted b tag complications

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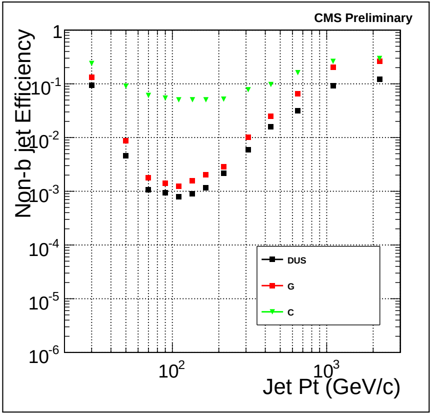
  - Good for $p_T \lesssim 300$ GeV; doesn't tag many **charm**/**light** jets.
- Fake rate $= \epsilon_{\mathrm{light}}$. Dramatic increase as jet $p_T \to \mathcal{O}(\mathrm{TeV})$.
- *Fundamental limitations.*
  - Collimated tracks
    ... dense environment.
  - Higher p_T tracks bend less
    ... harder to constrain.
- High-p_T gluons split more often ($g \to b\bar{b}$) ... *real b jets* initiated by **light partons**.

[CMS PAS BTV-09-001] Fig. 12

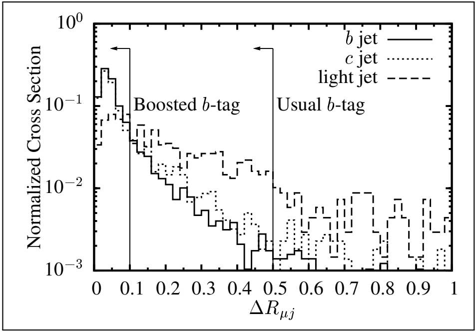


Maintaining 50% b jet efficiency

A muon-based boosted b tag

- A boosted b tag was proposed by Duffty and Sullivan in PRD**90**(2014)015031
    - Muon ($p_T \geq 20$ GeV) within a cone of $\Delta R = 0.1$ around jet's centroid.
- *Doesn't depend* on the muon's p_T (after initial cut), which is harder to measure as $p_T \to \text{TeV}$.

PRD**90**(14)015031[1307.1820] Fig. 2



Type	100 GeV	400 GeV	1000 GeV
b	4.8%	11.8%	15.0%
c	2.1%	5.5%	7.5%
light	0.1%	0.4%	0.6%

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- *Doesn't depend* on the muon's p_T (after initial cut), which is harder to measure as $p_T \to \mathrm{TeV}$.
- Heavy jet efficiencies plateau at 1 TeV, *but* $\epsilon_{\mathrm{light}}$ keeps rising.
- *And* a jet's centroid is **coarse** (QCD radiation, UE, pileup ...).
  - We can do better by studying boosted b tagging in the context of jet substructure.

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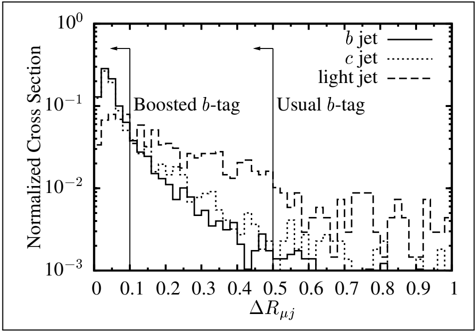

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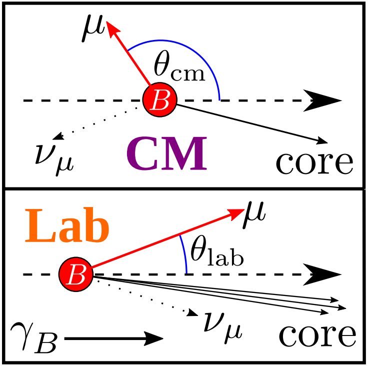
The subjet of semi-muonic B meson decay

- **CM**: The muon is emitted with speed $\beta_{\mu,\mathrm{cm}}$ at angle θ_{cm}.
- **Lab**: Muon is detected at angle θ_{lab} w.r.t. the centroid of the *decay subjet* (boosted by γ_B).

$$p_{\mathrm{subjet}} = p_\mu + p_{\nu_\mu} + p_{\mathrm{core}} \qquad (1)$$



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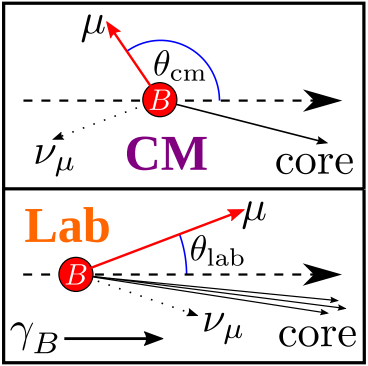


$$p_{\mathrm{subjet}} = p_\mu + p_{\nu_\mu} + p_{\mathrm{core}} \qquad (1)$$

- Defining $\kappa \equiv \beta_{\mathrm{B}}/\beta_{\mu,\mathrm{cm}}$,

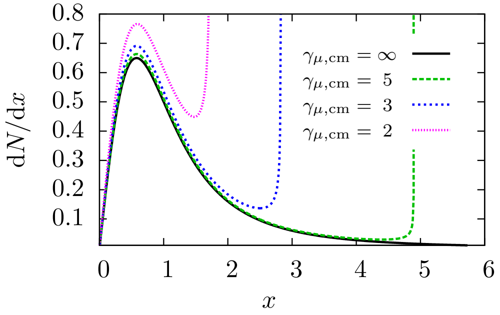
$$x \equiv \gamma_B \tan(\theta_{\mathrm{lab}}) = \frac{\sin(\theta_{\mathrm{cm}})}{\kappa + \cos(\theta_{\mathrm{cm}})} \qquad (2)$$

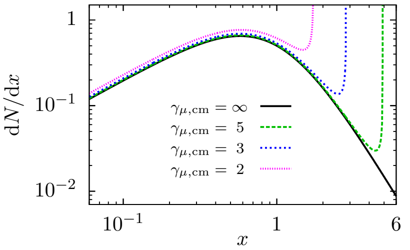
$$\boxed{x \approx \tan(\theta_{\mathrm{cm}}/2) \qquad (\text{when } \kappa \approx 1)}$$

$$\frac{dN}{dx} = \frac{2x}{(x^2+1)^2} K(x, \kappa) \qquad (\text{when } \kappa \geq 1) \qquad (3)$$

Theoretical lab frame muon distributions

- We are interested in a specific boosted subjets ...
  - boosted b jets ($p_T \geq 300$ GeV $\Longrightarrow \gamma_B \gtrsim 60$).
  - b hadron decays ($\gamma_{\mu,\mathrm{cm}} \leq \frac{m_B}{2\,m_\mu} \lesssim 25$)
- What does the **lab** dN/dx look like for these subjets?



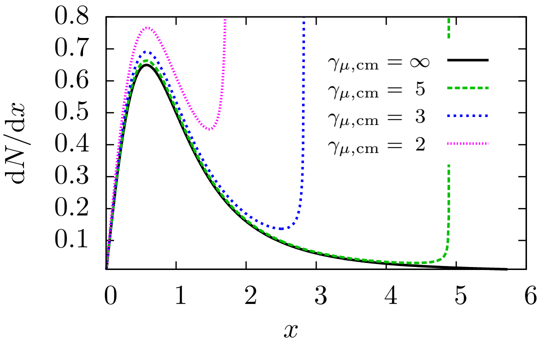


- $K(x,\kappa)$ restricts muons to boost cone boundary ($x \leq 1/\sqrt{\kappa^2 - 1}$).
- Once $\gamma_{\mu,\mathrm{cm}} \gtrsim 3$, **lab** muons approach a the universal boosted shape.

x marks the heavy-flavor tag

Using the universal boosted shape, the **lab frame** cone $0 \leq x \leq x_\rho$ captures **at least** a fraction ρ of muons from b hadron decay, where

$$x_\rho = \sqrt{\frac{\rho}{1-\rho}}. \quad (4)$$



- $K(x, \kappa)$ corrections shift muons to smaller x
    - x_ρ captures **at least** a fraction ρ.
    - $x_{90\%} = 3$.

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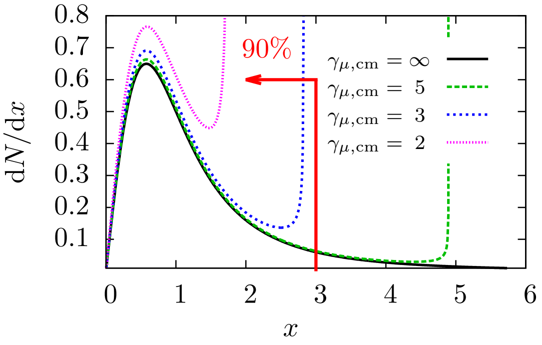

- $K(x, \kappa)$ corrections shift muons to smaller x
  - x_ρ captures **at least** a fraction ρ.
  - $x_{90\%} = 3$.
- $\boldsymbol{x_{\max}}$: a cut used to accept/reject muons consistent with boosted decay inside a jet
  - $x_{\max} = x_{90\%} = 3$

The μ_x boosted b tag

Measuring x requires reconstructing the muonic subjet

$$p_{\text{subjet}} = p_\mu + p_{\nu_\mu} + p_{\text{core}} \tag{1.1}$$

- $x \leq 3$ only indicates the muon is consistent with a *boosted* decay.
- It's heavy-flavor origin can be confirmed via a complementary measurement ... it should be carrying a *large fraction* of its jet's momentum.

$$x \equiv \gamma_B \tan(\theta_{\text{lab}}) \leq 3 \qquad\qquad f_{\text{subjet}} \equiv \frac{p_{T,\text{subjet}}}{p_{T,\text{jet}}} \geq 0.5$$

But, half the muons in b jets come from c hadrons! Is γ_B a valid observable?

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But, half the muons in b jets come from c hadrons! Is γ_B a valid observable?

No ... we can only observe γ_{subjet}.

Reconstructing the subjet

Anti-k_T jets are clustered with R $= 0.4$. Allowing muons to participate lets *hard muons* seed jet formation.

$$p_{\text{subjet}} = p_\mu + p_{\nu_\mu} + p_{\text{core}}$$

- *Taggable* **muons** must pass a quality cut ($p_T \geq 10\ \text{GeV}$).
- The **core** (the hadronic remnants of the semi-leptonic decay).
  - Re-cluster jet using $R = 0.04$ to localize core (3×3 grid)
  - γ_{subjet} needs mass of core — very poorly measured. Core mass is constrained to *best guess* (e.g. $m_D \approx 2$ GeV).
  - The "correct" core brings $\sqrt{p^2_{\text{subjet}}}$ closest to $m_B \approx 5.3$ GeV.
- Subjet's **neutrino**:
  - System is under-determined. Simplest estimate: *add muon a second time to simulate neutrino* ($p_{\nu_\mu} = p_\mu$).

Understanding what x is doing

Given $p_{\nu_\mu} = p_\mu$, we can imagine reconstructing an arbitrary subjet:

$$p_{\mathrm{subjet}} = 2p_\mu + p_{\mathrm{core}}$$

What x will we measure? Let's express it in terms of **direct** observables.

γ_{core}	$\lambda = \frac{2E_\mu}{E_{\mathrm{core}}}$	ξ (the angle between muon and **core**)

If $\beta \to 1$ for both the muon and the core,

$$x(\xi) \approx \underbrace{\gamma_{\mathrm{core}} \frac{1+\lambda}{\sqrt{1+2\lambda\,\gamma_{\mathrm{core}}^2(1-\cos(\xi))}}}_{\gamma_{\mathrm{subjet}}} \underbrace{\frac{\sin(\xi)}{\cos(\xi)+\lambda}}_{\tan(\theta_{\mathrm{lab}})} \tag{5}$$

Angle where ξ dominates m_{subjet}
$\xi_m = \sqrt{\frac{m_{\mathrm{core}}^2}{2E_{\mathrm{core}}\,E_\mu}}$

$\xi < \xi_m$	$\xi \gtrsim \xi_m$
$x(\xi) \approx \gamma_{\mathrm{core}} \cdot \xi$	$x \approx 1/\sqrt{\lambda}$

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$\xi < \xi_m$	$\xi \gtrsim \xi_m$
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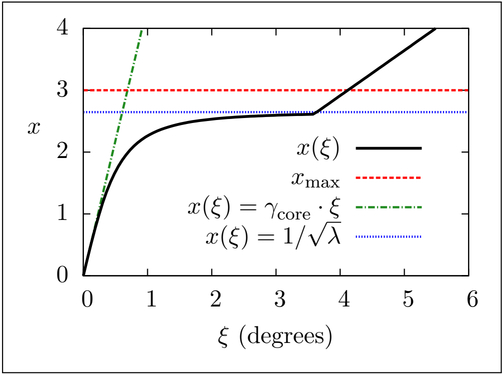
μ_x is a dynamic angular cut

A poorly reconstructed m_{subjet} is inevitable; a **large** m_{subjet} is *inconsistent* with heavy-hadron decay. So we implement a ceiling

$$m_{\text{subjet}} = \min(\sqrt{p^2_{\text{subjet}}}, 12\ \text{GeV}) \quad (6)$$



Subjet with a **hard muon** ($\gamma_{\text{core}} = 250$, $\lambda = 1/7$)

Solve for $\xi_{\max}$, the largest ξ which keeps $x \leq 3$.

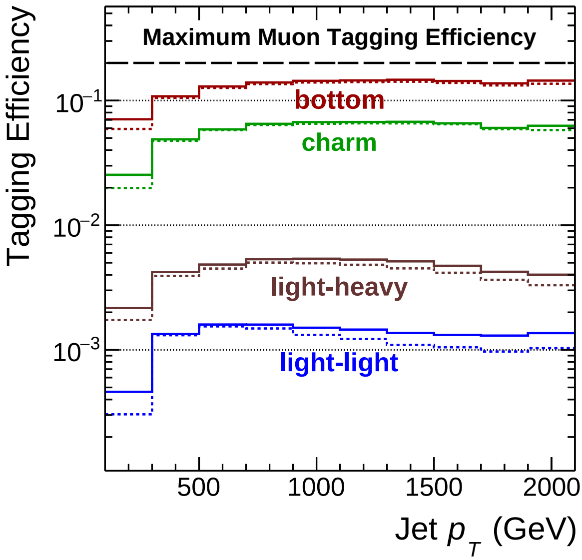
Hard muons ($\lambda \geq 1/9$)

$$\xi^{\textbf{hard}}_{\max} \approx \frac{18}{\gamma_{\text{core}}} \quad (7)$$

Soft muons ($\lambda < 1/9$)

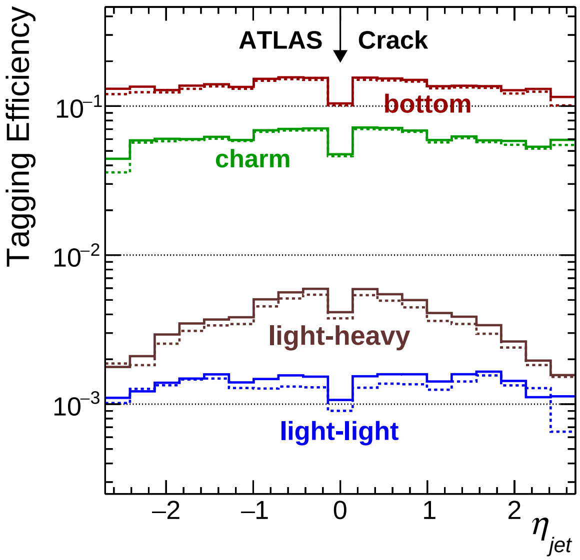
$$\xi^{\textbf{soft}}_{\max} \approx \frac{3}{\gamma_{\text{core}}} \left(\frac{1}{\sqrt{1 - 9\lambda}} \right) \quad (8)$$

Tagging Efficiency (Jet p_T)



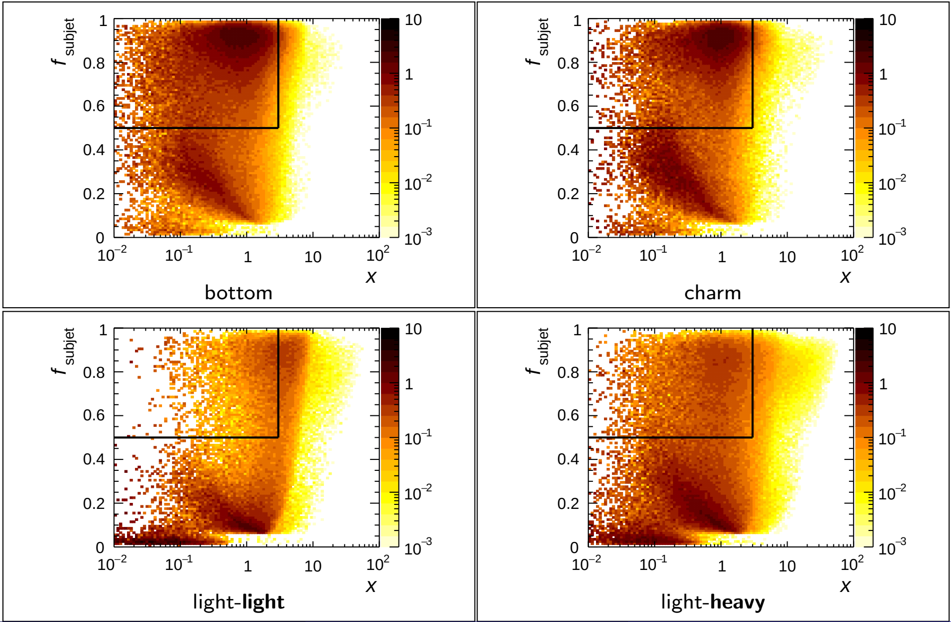
- Efficiency to tag jets at $\sqrt{s} = 13\ \mathrm{TeV}$.
- Boosted kinematics turn on at 300 GeV.
- **Light jets** classified by hadronic origin of taggable muon (normally, light-heavy is included in bottom/charm).
- Pileup helps (a bit)
  - *Solid*: no pileup
  - *Dotted*: $\mu = 40$

Tagging Efficiency (η_{jet})



- Sum over all jets with $p_T > 300$ GeV.
- Signal efficiencies
  - $\sim$ 14% of b-jets
  - $\sim$ 6.5% of c-jets
- Light jet fake rate
  - Light-light $\mathcal{O}(0.1\%)$
  - All light $\mathcal{O}(0.5\%)$
- η dependence of heavy jets driven by muon system
  - Endcap ($|\eta| > 1$).
  - ATLAS detector services crack ($\eta = 0$)

The proof is in the pudding



Outline

A leptophobic Z'

- One of the simplest BSM models is an additional $U(1)'$ symmetry, mediated by a neutral heavy boson (Z').
- *Dobrescu and Yu* [1306.2629, 1506.04435] outlined a simple, renormalizable, leptophobic Z'_B
  - Only SM quarks are charged (suggesting *baryon* number B association).
  - Coupling to quarks is flavor independent,

$$\mathscr{L} = \frac{g_B}{6} Z'_{B\mu} \bar{q} \gamma^\mu q + \dots \tag{9}$$

  - Narrow width:

$$\Gamma_{Z'}/M_{Z'} \approx \frac{1}{6} \alpha_B \left(1 + \frac{\alpha_S}{\pi}\right) \approx 1\text{–}5\% \tag{10}$$

  - Model needs vector-like fermions (anomalons); assume they're "kinematically inaccessible".

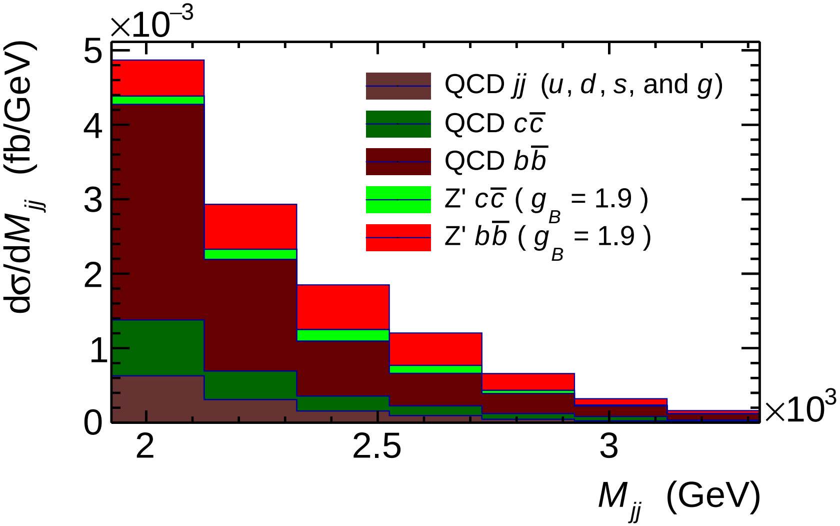
Simulating the leptophobic $Z' \to b\bar{b}$

MadGraph5 (w/ CT14llo) $\to$ Pythia 8 $\to$ Delphes 3 (w/ `FastJet` 3)

- Generate MLM matched Z'_B samples for a variety of $M_{Z'_B}$,
  $pp \to Z'_B \to b\bar{b}/c\bar{c}(+j)$.
- QCD dominates background: $pp \to b\bar{b}/c\bar{c}/j\bar{j}(+j)$, $jq_h \to jq_h(+j)$
- Look for signal excess in $d\sigma/dM_{jj}$ of width $[0.85, 1.25] \times M_{Z'}$ in 2-tag and 1-tag inclusive classes.
- We developed a custom Delphes module (`HighPtBTagger`) to implement μ_x tagging, available on GitHub:

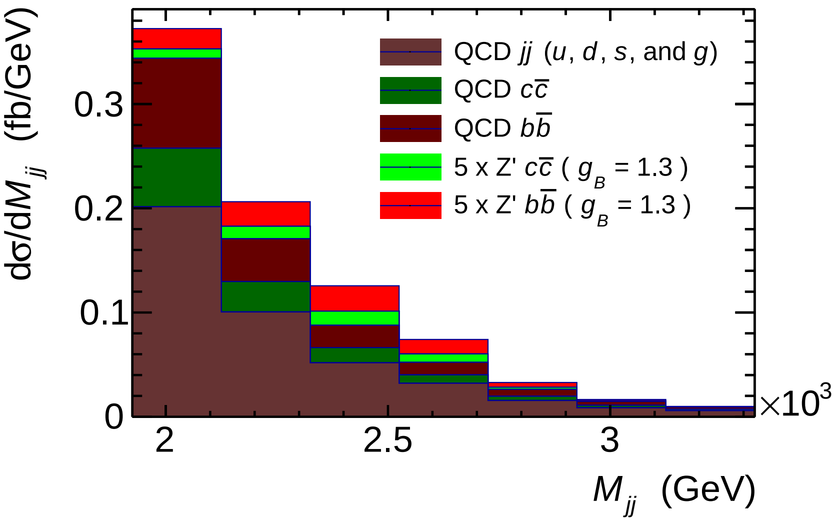
  https://github.com/keith-pedersen/delphes/tree/HighPtBTagger_devel

2-tag discovery ($M_{Z'} = 2.5$ TeV, $g_B = 1.9$)



- **Mass window**: 2.125–3.125 TeV
- $\left|\eta_{\text{jet}}\right| \leq 2.7, \quad \left|\Delta\eta_{jj}\right| \leq 1.5$

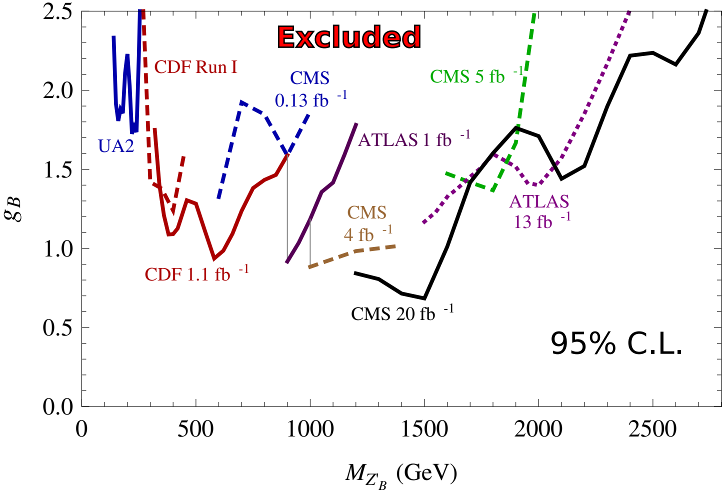
1-tag discovery ($M_{Z'} = 2.5$ TeV, $g_B = 1.3$)



- **Mass window**: 2.125–3.125 TeV
- $|\eta_{\rm jet}| \leq 2.7, \quad |\Delta\eta_{jj}| \leq 1.5$

Uncharted Waters

PRD**88**(13)035021[1306.2629] Fig. 1



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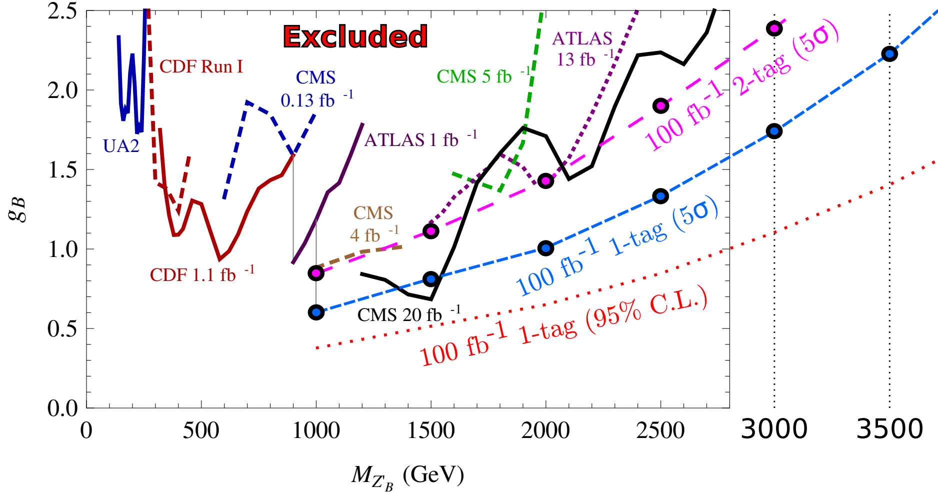
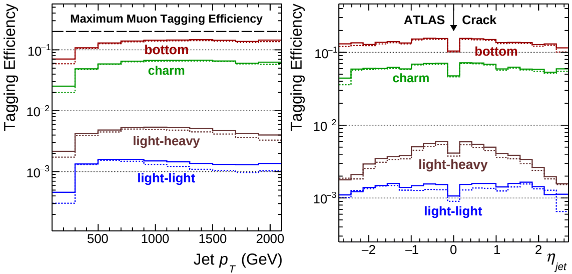
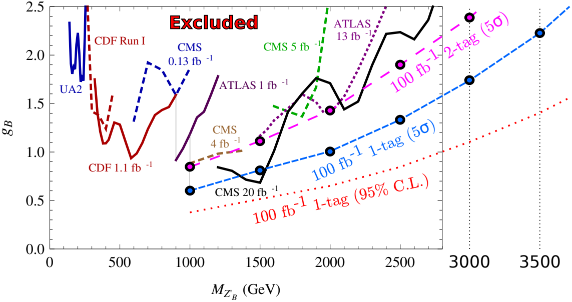


Conclusions

- μ_x tags heavy jets at the TeV scale.
  - ***b* jet**: $\sim$14%
  - **light-light**: $\sim$0.14%
- Flat p_T/η_{jet} response & minimal pileup sensitivity.
- μ_x tagging offers a significant improvement for leptophobic Z' searches.

THANK YOU!



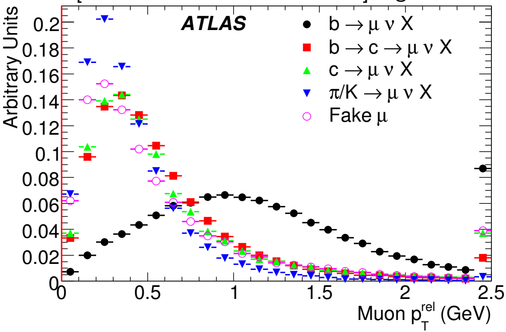


Backup Slides

p_T^{rel} muon tagging

- 20% of b jets have $N_{muon} \geq 1$
- Electrons in jets are hard to identify; luckily someone ordered the *muon chamber!*
- Previous studies have investigated $\boldsymbol{p_T^{\text{rel}}}$: muon momentum transverse to the *centroid* of its jet.

[ATLAS-PHYS-PUB-2009-021] Fig. 4



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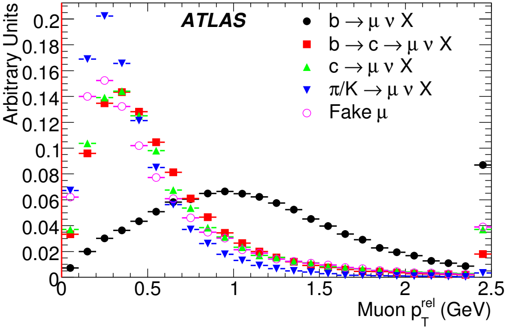

- *b* hadrons → large mass, hard muons → higher $p_T^{\rm rel}$.
  - $\epsilon_b = \mathcal{O}(10\%)$, light jet fake rate $= \mathcal{O}(0.3\%)$.
- $p_T^{\rm rel}$ stops working when jet p_T exceeds 140 GeV.
  - *Is this a problem of definition?*

Flavor tagging

heavy jets (b or c initiated) $\overset{\textbf{distinguish}?}{\Longleftrightarrow}$ **light** jets (d, u, s, or g initiated).

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b hadrons $\to$ c hadrons, so generally ...

heavy-flavor tags $\to$ b tags

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- Tracks provide the best angular information, *but* ...
  - Accurately tracking boosted jet constituents in a *fast detector* simulator is not possible; we only track "standalone" muons.
  - Jets are clustered from **Cal towers** and **muons**.

- **Trimming:** Before reclustering, discard Cal towers with low jet p_T fraction (we choose $f_{\mathrm{tower}}^{\mathrm{min}} = 0.05$). This reduces the core's sensitivity to *pileup*, *UE*, soft *QCD* , etc.

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- **ECal pointing:** Use the segmentation of the ECal to orient the combined (ECal+HCal) tower. This creates a *minimal angular resolution* independent of track reconstruction efficiencies.
  - We use the dimensions of ATLAS ECal L2: ($\Delta\, r\phi \times \Delta\eta = \mathbf{0.025} \times \mathbf{0.025}$)
  - Also ran coarser ($\mathbf{0.05} \times \mathbf{0.05}$); no degradation of heavy jet efficiency, the light jet fake rate is 20% larger at jet $p_T = 600$ GeV, but *no enhancement* in fake rate at $p_T = 2$ TeV.

Moving Forward

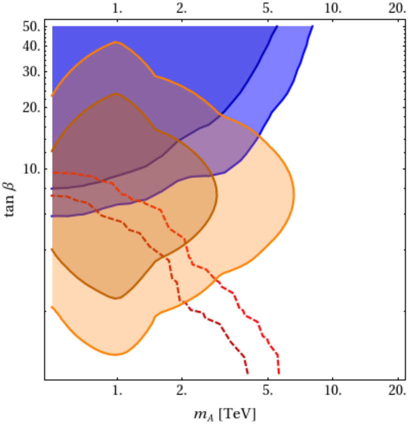
- A heavy Higgs (from quark fusion) produces a final state rich in bottom quarks (2$\times$ bottom, 2$\times$ top):

$$pp \to \bar{t}\bar{b}H^{+} \to \bar{t}\bar{b}tb$$

$$pp \to b\bar{b}H/A \to b\bar{b}t\bar{t} \text{ (or } b\bar{b}\tau^{+}\tau^{-})$$

- The discovery potential of these channels (with emphasis the "wedge" region") was recently investigated by Hajer et al.
- Based on personal communication, we believe their b tagging efficiencies and fake rates were **over-optimistic**.
  - How well can μ_x tagging do?

[1504.07617] Fig. 10a



H discovery potential at 100 TeV for $t\bar{t}$ (salmon) and $\tau^{+}\tau^{-}$ (blue) channels

$K(x, \kappa)$

$$\frac{dN}{dx} = \frac{2x}{(x^2+1)^2} K(x,\kappa), \text{ where} \tag{11}$$

$$K(x,\kappa) = \begin{cases} \frac{(1+\kappa^2)+x^2(1-\kappa^2)}{2\sqrt{1+x^2(1-\kappa^2)}} & 0 \le x \le 1/\sqrt{\kappa^2-1} \\ 0 & \text{everywhere else} \end{cases} \tag{12}$$