Phenomenology of *b*-associated TeV scale scalar production with baryon-number violation in $t\psi$ final states at the LHC

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Necessary conditions for a matter-dominated universe

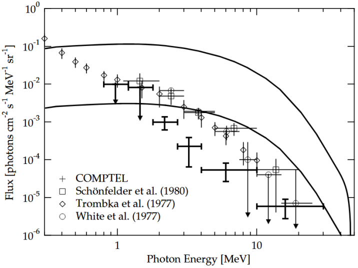
- If matter and antimatter symmetric, gamma rays from annihilation expected at contact borders (right)
- Not observed, need to explain baryon asymmetry from early universe on

$\rightarrow$ Need to satisfy Sakharov conditions

1. Violation of baryon number $\mathcal{B}$ $\rightarrow$ convert anti-matter to matter or vice versa
2. $\mathcal{B}$-violating interaction out of thermal equilibrium $\rightarrow$ must stop before recombination
3. C and CP violation $\rightarrow$ favour matter

- Let's introduce a model with $\Delta\mathcal{B} = 2$

Astrophys.J.495:539-549,1998



TeV scale scalar with baryon-number violation model

- Combine dark matter (DM) with baryon asymmetry mechanism
- There are several versions of this (ours: arXiv:2404.14844v2) with a massive scalar mediator X, a fermionic DM candidate ψ, production couplings to down-type quarks, and decay couplings to up-type quarks

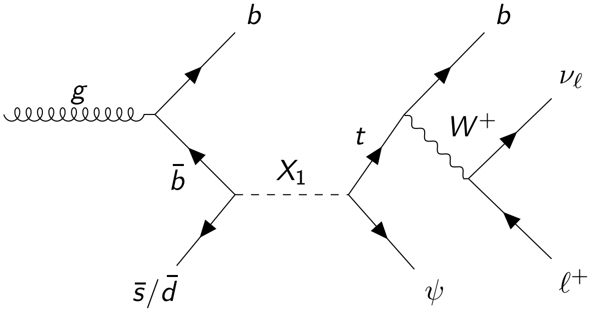
$$\mathcal{L} \supset \lambda_{\alpha i} X_\alpha \psi u_i^c + \lambda'_{\alpha ij} X_\alpha^* d_i^c d_j^c + \frac{m_\psi}{2} \bar{\psi}^c \psi + \text{h.c.} \quad (1)$$

- Assuming all quark couplings are equal, production at LHC dominated by d-s fusion (limits $m_X > 3.4$ TeV)
- No principal reason for that assumption to be true $\rightarrow$ look at third generation case

$$\mathcal{L}_{\text{single top}} \supset \lambda_{\psi t} X_1 \psi t^c + \lambda'_{db} X_1^* d^c b^c + \lambda'_{sb} X_1^* s^c b^c + \text{h.c.} \quad (2)$$

- Simplification $m_{X_1} \ll m_{X_2}$, suppresses loop-level interference terms
- Production (decay) coupling $\lambda_1 = \lambda'_{db} = \lambda'_{sb}$ ($\lambda_2 = \lambda_{\psi t}$)

How could one look for this?



- In principle, can have any up-type quark and phi decay of $X \to$ monojets
- Chose to focus on top scenario $\to$ monotops
- m_{X_1} expected TeV scale $\to$ boost
- ψ $\mathcal{O}$(GeV) DM candidate

cross section σ [fb]				
λ_1	λ_2			
	0.1	0.2	0.5	1.0
0.1	2.22	5.42	9.12	10.3
0.2	2.40	8.13	25.5	36.3
0.5	2.47	9.62	51.1	132
1.0	2.57	10.3	61.1	210

Table: Cross sections for $m_{X_1} = 1$ TeV. The cross section is inversely proportional to $2|\lambda_1|^2 + |\lambda_2|^2$.

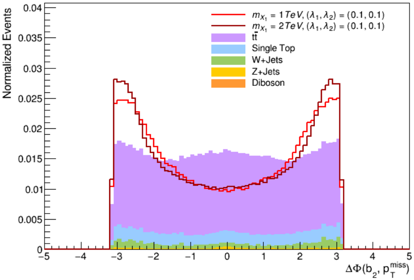
Analysis strategy and BDT optimization

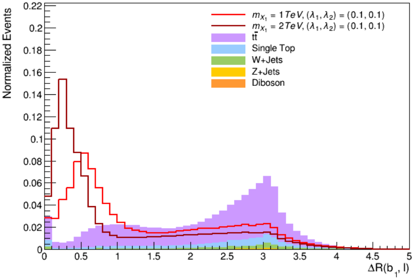
- Delphes-level description with modified (b-tag eff. & jet radius) CMS card setup
- Select leptonic top decays to avoid dependence on boosted hadronic top modeling
- One ℓ (e or μ) with p_{T} >30 GeV, non-isolated
- We remove the leading lepton from any jet it might be merged with (important, later)
- At least two b-tagged jets with p_{T} >50 (30) GeV for (sub-)leading jets
- $p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV

- Train Boosted Decision Tree (BDT) after baseline selection (above) for several coupling points $\lambda_i = 0.1, 0.3, 1.0$ vs $t\bar{t}$, single top, W+jets, DY+jets, and diboson backgrounds
- Optimized hyperparameters (NTree and MaxDepth) depending on m_X
- Set limits for cut on BDT output chosen by largst significance

Features distinguishing Monotop from SM backgrounds

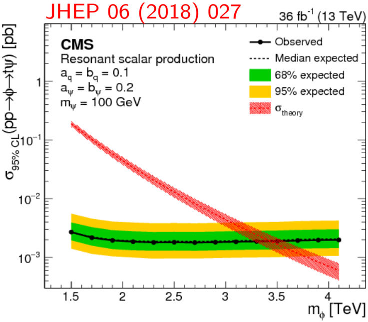
- Lepton and b-tagging requirements preselect mostly $t\bar{t}$ and single top as SM backgrounds
- Probed a list of variables: p_{T} and η of the b_1, b_2, l, and $b_1 + \ell$, $\Delta R(b_1, b_2)$, $\Delta R(b_1, \ell)$, $\Delta\phi(b_2, p_{\mathrm{T}}^{\mathrm{miss}})$, $\Delta\phi(\ell, p_{\mathrm{T}}^{\mathrm{miss}})$, $m_{\mathrm{T}}(b_1, p_{\mathrm{T}}^{\mathrm{miss}})$, $m_{\mathrm{T}}(\ell, p_{\mathrm{T}}^{\mathrm{miss}})$
- Most significant azimuthal angular difference between b_2 and $p_{\mathrm{T}}^{\mathrm{miss}}$ and angular distance between ℓ and b_1

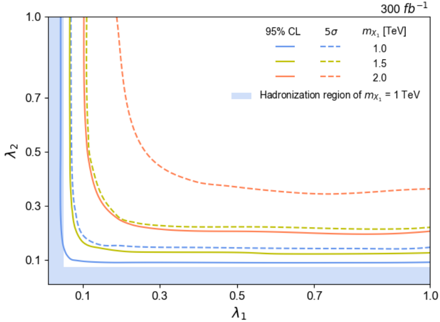




- Strong correlation with m_{X_1} due to top boost

Results compared to existing monotop searches



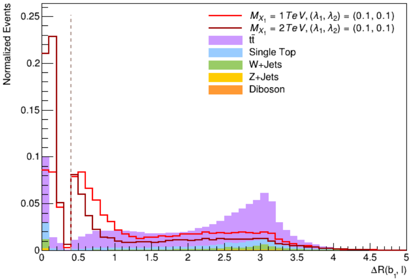


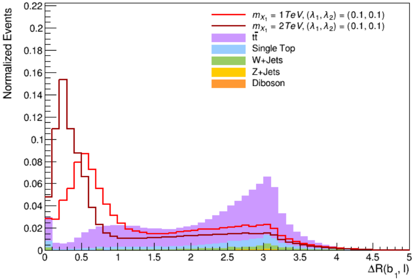
$$\mathcal{L} = \phi \bar{\mathrm{d}}_i^C [(a_q)^{ij} + (b_q)^{ij}\gamma^5]\mathrm{d}_j + \phi\bar{\mathrm{t}}[a_\psi + b_\psi\gamma^5]\psi + \mathrm{h.c.}$$

- Hadronic monotop analysis by CMS (left, see model Lagrangian) vs our phenomenological results at 300/fb (right)
- Traditional monotop analyses veto b-tagged jets beyond the first
- Accounting for differences in int. Lum. and t-decay branching ratio, similar performance on exclusion (bar realistic systematics for pheno)
- Actually enter region for $m_{X_1} = 1$ TeV where X_1 would hadronize

Why removing the leading lepton from its jet is important

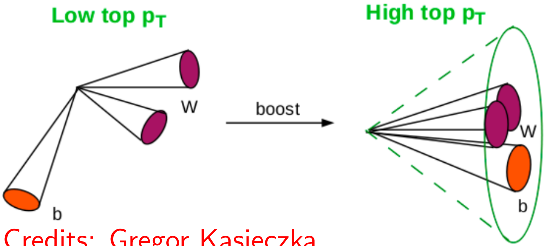
- Leptons are to a jet just clusters to be gobbled up





- Jet radius is 0.4 with anti-kT jet algorithm as in realistic CMS
- If we don't treat the lepton, it often becomes part of b_1 (left)
- This is not as good in separation power as removing it manually (right)
- Cause: Lepton clustering changes jet direction drastically (1/3 of the energy in $b + \ell$ on average in ℓ)
- Also issue of doublecounting energy of lepton separately and again in jet

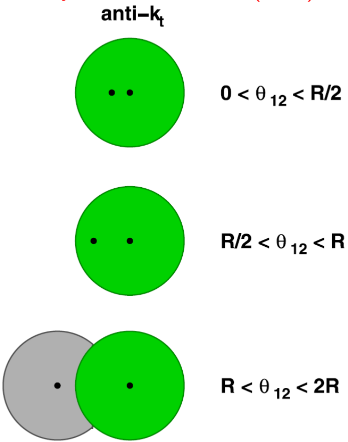
The fallibility of jet clustering algorithms under strong boosts even in semi-leptonic decays



Credits: Gregor Kasieczka

- Top momentum boost collimates angles of decay products (top)
- Anti-kT jet clustering algorithm produces circular jets, as long as jet centers farther apart than jet radius
- Between 0.4 and 0.8, more energetic jet will impact less energetic jet shape
- $p_{\mathrm{T}}(\ell) < p_{\mathrm{T}}(b_1) \rightarrow$ no issue?

Eur. Phys. J. C 67, 637-686 (2010)



- Behaviour valid, but undesirable

A brief description of a Scale-Invariant Filtered Tree (SIFT)

- An alternative algorithm for jet clustering designed to be fully scale-invariant is e.g. SIFT

$$\delta_{AB}^{\mathrm{SIFT}} \equiv \frac{\Delta M_{AB}^2}{E_{\mathrm{T}A}^2 + E_{\mathrm{T}B}^2}$$

- Can relate to collider angular coordinates with $\xi = p_{\mathrm{T}}/E_{\mathrm{T}}$:

$$\Delta m_{AB}^2 = 2E_{\mathrm{T}}^A E_{\mathrm{T}}^B (\cosh \Delta y_{AB} - \xi^A \xi^B \cos \Delta \phi_{AB})$$

- Take angular component of measure as modified angular distance:

$$\Delta \tilde{R}^2 = \cosh \Delta y_{AB} - \xi^A \xi^B \cos \Delta \phi_{AB}$$

- Mitigates azimuthal differences in non-relativistic limit

→ Avoids clustering massive/low momentum objects

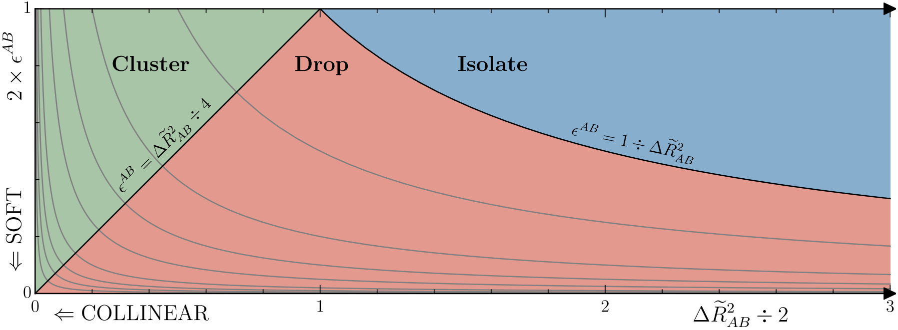
- Denominator can also be reformed with $u := \ln(E_{\mathrm{T}}/[\mathrm{GeV}])$:

$$\epsilon_{AB} = (2 \cosh \Delta u_{AB})^{-1}$$

- Prefers disparate scale pairings

Would SIFT cluster that lepton?

- In boosted regime, fake mass is generated by large angle soft radiation randomly clustered into jets
- Softdrop is the usual counterpoison, SIFT has a similar inbuilt measure during clustering



- Can assume $E_{\mathrm{T}}(\ell) = E_{\mathrm{T}}(b_1)/2 \to \epsilon_{AB} = 0.4$
- Will cluster for $\Delta\tilde{R}^2/2 < 0.8 \to$ even more often than anti-kT
- Even using boost-specialized algorithm, boosted lepton needs special treatment

Aside on astrophysical constraints

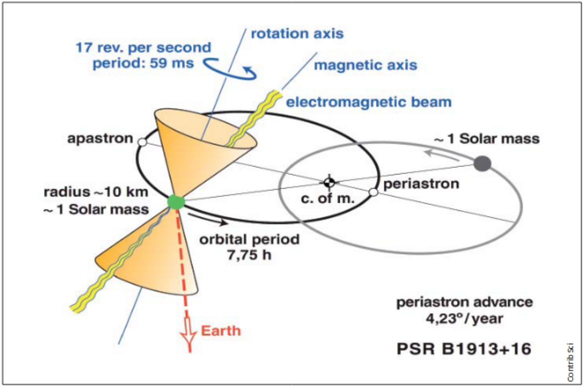


Fig. 2. Illustration of binary pulsar PSR B1913+16.

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- Astrophysics showed us there's an abundance of matter
- Used high energy particle physics to look for mechanism
- Full circle: Binary pulsars can also be used to constrain possible coupling space
- See Adrian Thompson's talk on saturday

Conclusions

- Among the principal unsolved issues of physics, the way to a grand unified theory is unclear, dark energy is hard to pin down, dark matter has lots of possible solutions
- Baryon asymmetry stands out as a large effect with an unknown mechanism, but well-known conditions for solutions
- Presented a baryon-number-violating phenomenological study looking for third generation quark couplings in b-jet-associated monotop events arXiv:2404.14844v2
- Fully complementary to regular monotop studies by selections, similar expected reach despite lower branching ratio (looked at leptonic decays)
- Treatment of boosted lepton very important
- Boosted physics in general becomes more important at higher energies for reconstruction $\rightarrow$ need to develop better scale-invariant tools
- Can be creative with source of constraints, collider or astronomy