Measuring the polarization of boosted hadronic W bosons with jet substructure observables

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Based on arXiv:2008.04318v1 by
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Objective

To measure the longitudinal and transverse polarization fractions of hadronic decays of boosted W bosons

Motivation

1. In order to test unitarity in vector boson scattering (VBS), it will be ideal to measure the polarization fraction of both the outgoing weak bosons in a scattering process
2. The branching fraction of W boson decaying to hadrons is approximately 68%. It would greatly increase our statistical grasp of the polarization fractions, if we were able to measure the polarization of hadronic W bosons

Parton level angular distributions

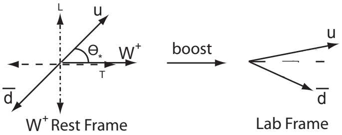

Figure: LEFT: The polar angle θ of the decay products of the W^+ as defined in W^+ rest-frame. RIGHT: Upon boosting to the lab-frame, the up and anti-down quarks can display an asymmetry in energy.

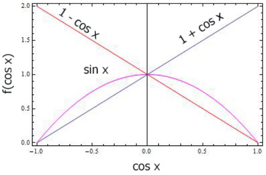

Figure: Distribution of amplitude in terms of $\cos\theta_*$

For transverse polarization of W-boson,

$$\mathcal{M}_\pm \propto \frac{1 \mp \cos\theta_*}{\sqrt{2}} \quad (1)$$

For longitudinal polarization of W-boson,

$$\mathcal{M}_0 \propto \frac{-\sin\theta_*}{\sqrt{2}} \quad (2)$$

Energy Difference

Potential observable in the lab frame at parton-level that can distinguish between longitudinal and transverse W^+ bosons,

$$\cos\theta_* = \frac{\Delta E}{p_w} \tag{3}$$

The distribution of the W^+ decay rate as a function of its decay polar angle,

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}|\cos\theta_*|} = \mathrm{f_T}\frac{3}{4}(1+|\cos\theta_*|^2) + \mathrm{f_L}\frac{3}{2}(1-|\cos\theta_*|^2) \tag{4}$$

where, the transverse polarization fraction $\mathrm{f_T}$ and the longitudinal polarization fraction $\mathrm{f_L}$ are related by, $f_T + f_L = 1$

Construction of proxy variable

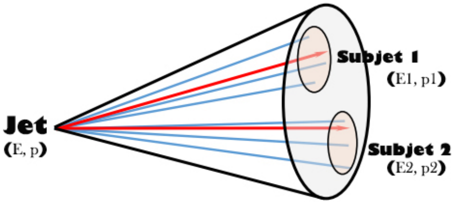

Figure: 2 subjets inside a jet (*Courtesy: Nick Amin's presentation on Jet Substructure*)

$$p_\theta = \frac{|\Delta E^{\text{reco}}|}{p_W^{\text{reco}}} \tag{5}$$

$|\cos\theta_*|$ distribution

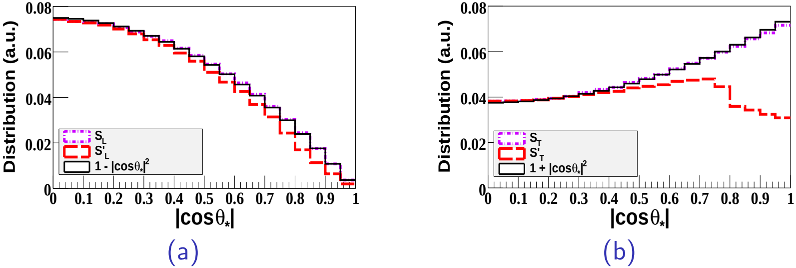

Figure: (a) Parton level truth information for the distributions of $|\cos\theta_*|$ for longitudinal W bosons in the untagged longitudinal W^+ sample, S_L and the tagged sample S'_L. Also shown is the theoretically expected $(1 - |\cos\theta_*|^2)$ distribution which agrees very well with the S_L distribution. (b) Same as the left panel, but with transverse W bosons. Here, the theoretically expected distribution is $(1 + |\cos\theta_*|^2)$.

Distribution of the proxy variable

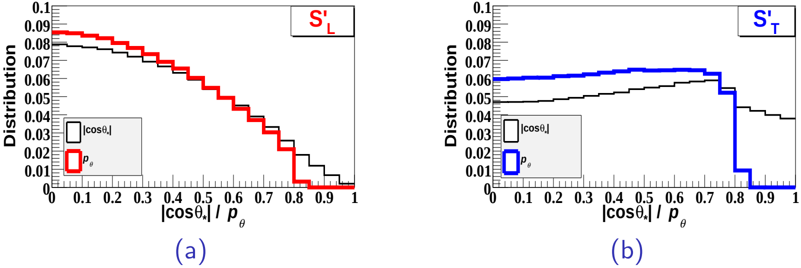

Figure: (a) Comparison of the distribution of p_θ with that of $|\cos\theta_*|$ for the $\mathcal{S}'_L$ event sample. (b) Same comparison for the $\mathcal{S}'_T$ sample.

Polarization Reconstruction in semi-leptonic VBS

The semi-leptonic VBS channel, $pp \to W^- W^+ jj \to \ell^- \nu_\ell jjjj$, where the W^+ boson decays hadronically and the W decays leptonically

1. **Basic selection cuts**
   1. p_T of the lepton: $p_T^\ell > 25$ GeV
   2. η of the lepton: $|\eta^\ell| < 2.5$
   3. p_T of the jets: $p_T^j > 30$ GeV
2. **Associated jet cuts**
   1. Pseudo-rapidity gap between the associated forward jets: $|\Delta\eta_{jj}| > 4.0$
   2. Invariant mass of the associated jets: $M_{jj} > 200$ GeV
   3. η of the forward jets: $2 < |\eta_\mathrm{j}| < 4.7$
3. **Hadronic W^+ tagging and selection cuts**
   1. Fat jet mass cut: 60 GeV $< M_j <$ 100 GeV
   2. Mass-drop cut: $\mu^{\mathrm{cut}} < 0.25$, $y^{\mathrm{cut}} < 0.09$
   3. N-Subjettines Ratio: $\tau_2/\tau_1 < 0.3$
   4. p_T of the tagged jet: $p_T^j > 400$ GeV

Polarization Reconstruction in semi-leptonic VBS

If the longitudinal polarization fraction in a sample is denoted as f_L *before* the tagging cuts are applied, then the polarization fraction *after* tagging cuts are applied (which we denote as f_L') will be given by,

$$f_L' = \frac{\epsilon_L f_L}{\epsilon_L f_L + \epsilon_T (1 - f_L)}. \quad (6)$$

Here, ϵ_L and ϵ_T are the tagging efficiencies for longitudinal and transverse W bosons respectively.

Using this procedure, we find the expected longitudinal polarization fraction after tagging cuts are applied as $f_L' = 0.15$

Monte-Carlo Truth Information

Polarization Reconstruction in semi-leptonic VBS

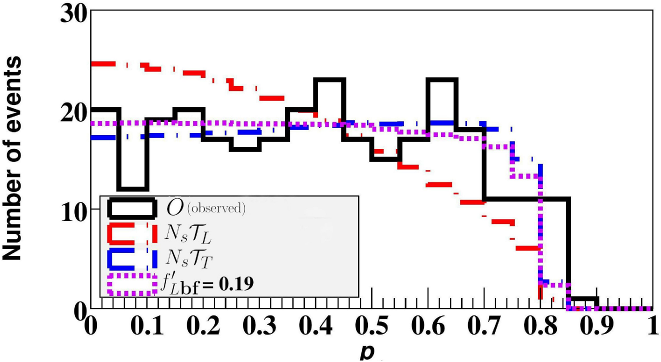

Figure: p_θ distribution for a benchmark sample of $N_s = 288$ VBS events, corresponding to ~ 3 ab^{-1} of luminosity, and after all selection and tagging cuts are applied (black curve). The best-fit linear combination of templates with longitudinal W fraction $f'_{L\mathrm{bf}} = 0.19$ is shown with the magenta dotted curve. Also shown are the longitudinal and transverse templates ($\mathcal{T}_L$ and $\mathcal{T}_T$) rescaled to N_s events.

Polarization Reconstruction in semi-leptonic VBS

The χ^2 test-statistic with one parameter f_L' is given by,

$$\chi^2(f_L') = \sum_{i=1}^{B} \frac{(O_i - N_s(f_L'\mathcal{T}_{L\,i} + (1 - f_L')\mathcal{T}_{T\,i}))^2}{\sigma_i^2} \tag{7}$$

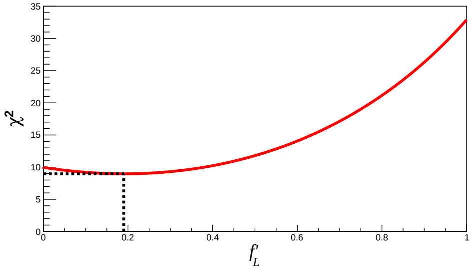

Figure: χ^2 distribution as a function of the longitudinal polarization fraction f_L' for fits to the pseudo-experiment data. We obtain a best-fit value of $f'_{L\mathbf{bf}} = 0.19$ with a 1-σ range between $[0.00, 0.38]$. The fit is quite good at the minimum with a χ^2 per degree of freedom of 0.6. Values of $f_L' > 0.88$ can be ruled out at the 95% confidence level.

Conclusion

1. At the parton level, the distribution of the decay polar angle $|\cos\theta_*|$ allows us to extract the longitudinal vs transverse polarization fraction
2. We found our hadron level proxy variable p_θ to track the $|\cos\theta_*|$ extremely well
3. For semi-leptonic WW scattering, we showed that with 3 ab^{-1} of integrated luminosity at the HL-LHC, we potentially reconstruct the observed longitudinal polarization fraction to within a ± 0.15 uncertainty at the 1-σ level


THANK YOU!

Backup slides

N-Subjettiness Definition

The N -subjettiness technique can be used to identify the number of hard centres of energy within a fat-jet. For each N candidate subjets, we construct the following variable,

$$\tau_N = \min_{\hat{n}_1, \hat{n}_2, ..., \hat{n}_N} \tilde{\tau}_N, \text{ where},$$

$$\tilde{\tau}_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{(\Delta R_{1,k}), (\Delta R_{2,k}), ..., (\Delta R_{N,k})\} \tag{8}$$

1. $\tau_N \approx 0 \Rightarrow$ there are N or fewer subjets & $\tau_N \gg 0 \Rightarrow$ there are at least N+1 subjets
2. The ratio τ_2/τ_1 is preffered as a dicriminating variable to discrimnate between W boson and the QCD background

Construction of templates

Generated 1 million events:
$pp \to \phi \to W^+W \to jjjj$ at $\sqrt{s} = 13$ TeV in MadGraph.
At the generator level, 800 GeV $< p_T^W <$ 1000 GeV

↓

Showered & hadronized in Pythia

↓

Clustered using the CA algorithm in FastJet with a jet radius $R_0 = 1.0$. Also, implemented pruning to remove soft tracks

↓

1. Mass cut: 60 GeV $< M_J <$ 100 GeV,
2. Mass-drop cut: $\mu^{\text{cut}} < 0.25$ and $y^{\text{cut}} < 0.09$,
3. N-subjettiness cut: $\tau_2/\tau_1 < 0.3$

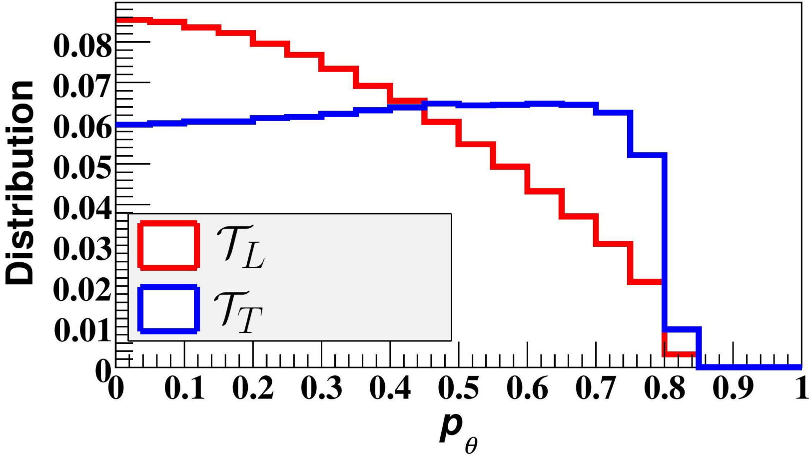

Figure: We now define universal templates $\mathcal{T}_L$ and $\mathcal{T}_T$ for the proxy variable distributions, as shown in the figure. These templates can be used to extract W boson polarization in a mixed sample.