Searches for heavy resonances decaying into Z, W and Higgs bosons at CMS

SUSY17 conference – Mumbai, 10-15 december 2017

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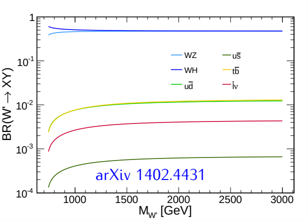
Theoretical motivations

- Beyond Standard Model theories: enlarging SM symmetry group → new heavy particles

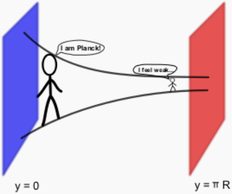
Heavy Vector Triplet

- General framework (including Composite Higgs, Sequential Standard Model)
  - Introduction of spin-1 (X^0, X^+, X^-)
  - Few additional parameters in the lagrangian
- HVT-A model: $BR(X \to f\bar{f})$ dominates
- HVT-B model: $BR(X \to VV) \approx BR(X \to VH)$ dominates



Warped extra dimensions

- Tentative solution of the hierarchy problem of the Higgs mass
- 5-dimensional bulk: Planck brane and TeV brane
- Spin-0 radions and spin-2 bulk gravitons and SM particles propagate among branes through warped extra dimension
  - Gravitons produced at TeV scale via gluon fusion, significant branching ratio into bosons

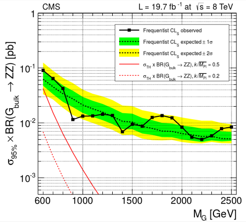


Data-driven motivations

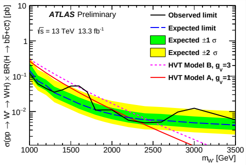
Highlights from previous searches

Diboson excesses

CMS EXO-13-009, 2012 data: local excess @ 1.8 TeV (2. σ)

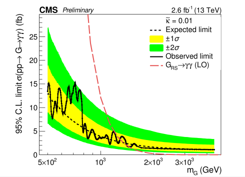


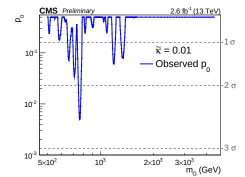
ATLAS-CONF-2016-083, 2016 reduced dataset: local excess @ 1.6 TeV (2.5 σ), @ 3 TeV (3.5 σ)



The infamous $\gamma\gamma$ bump... was a diboson too!

CMS EXO-15-004, 2015 data: local excess @ 760 GeV (2.6 σ)

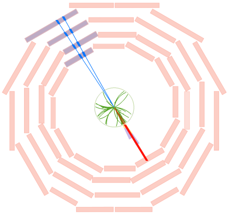




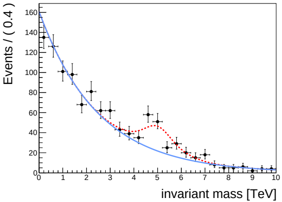
- Rising interest in diboson resonances
- Probing (almost) all the final states..

Search for heavy diboson resonances with 2016 data

	$V \to q\bar{q}$	$W \to \ell\nu$	$Z \to \ell\ell$	$Z \to \nu\nu$	$H \to b\bar{b}$	$H \to \tau\tau$
$V \to q\bar{q}$	B2G-17-001	B2G-16-029	B2G-17-013	B2G-17-005	B2G-17-002	B2G-17-006
$W \to \ell\nu$	B2G-16-029					
$Z \to \ell\ell$	B2G-17-013			B2G-16-023		
$Z \to \nu\nu$	B2G-17-005		B2G-16-023			
$H \to b\bar{b}$	B2G-17-002				B2G-16-026	B2G-17-006
$H \to \tau\tau$	B2G-17-006				B2G-17-006	



$\Rightarrow$



General approach:

- narrow resonances $\to$ width $<$ resolution
- build the di-boson candidate
- look for a local excess in the invariant mass spectrum

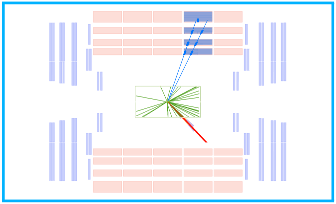
This talk: focus on

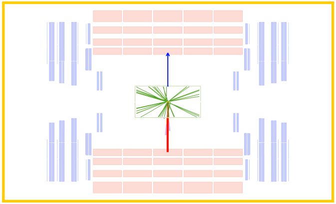
- Hadronic decays: $V = (W, Z) \to q\bar{q}$: larger branching fraction
- $H \to (b\bar{b}, \tau^+\tau^-)$: larger branching fraction
- Leptonic decays: $Z \to (\ell^+\ell^-, \nu\bar{\nu})$; $W \to \ell\nu$: clear signature

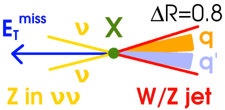
Search for heavy diboson resonances: boosted topologies

Signal features

- Heavy (~1 TeV) $X \to B_1 B_2$ ($B = W, Z, H$): Lorentz boost
- Decay products are collimated $\to$ dedicated reconstruction techniques
- Hadronic final states:
  - $V_{\rm had} \to q\bar{q}'$: 1 large-cone boosted jet (2 merged subjets)
  - $H \to b\bar{b}$: 1 large-cone boosted jet (2 merged subjets, b-tagged)
  - $H \to \tau^+\tau^- \to$ hadrons: 1 large-cone boosted jet (2 subjets, τ-tagged)
- Leptonic final states:
  - $Z_{\rm lep} \to \ell^-\ell^-$: couple of close-by leptons (e,μ)
  - $Z_{\rm lep} \to \nu\bar{\nu}$: neutrino reconstructed as missing transverse energy E_T^{miss}
  - $W_{\rm lep} \to \ell\nu$: one isolated lepton (e,μ) + E_T^{miss}



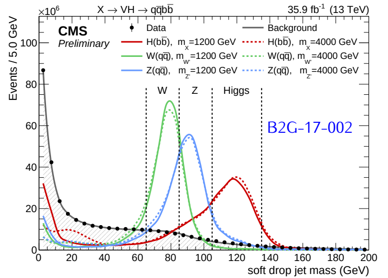




Grooming of the jet mass

new! softdrop algorithm removes soft radiation components

new! PUPPI algorithm removes pile-up contributions (spectators of X production vertex)

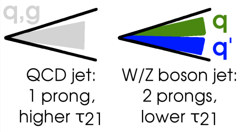


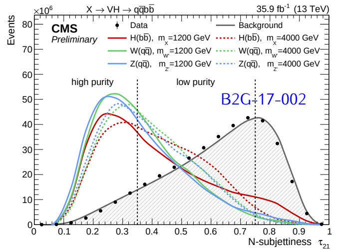
- if $V_{\text{had}} = W \rightarrow \text{SR} = [65,85]$ GeV
- if $V_{\text{had}} = Z \rightarrow \text{SR} = [85,105]$ GeV
- if $V_{\text{had}} = Higgs \rightarrow \text{SR} = [105,135]$ GeV

Jet substructure: *n*-subjettiness

new! τ_{21} subjettiness: "probability" of being a 2-prong jet vs 1-prong jet

- 1 prong → QCD jets → background!
- 2 prongs → W/Z jets → signal!

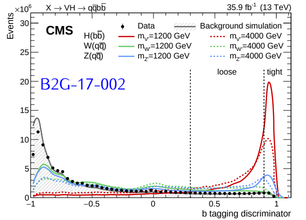




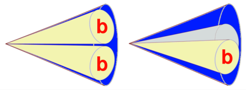
$H \to b\bar{b}$ tagging

new! double b-tagger algorithm

- MVA approach combining tracking, vertexing (b quark) and jet informations (n-subjettiness)
- Loose and Tight working points

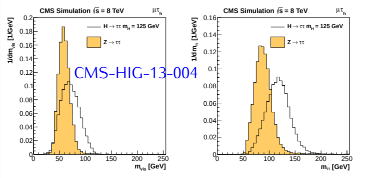


- b-tagging algorithm applied to subjets: exclusive categories (0,1,2 b-tagged subjets)



$H \to \tau^+\tau^-$ tagging

- Reconstruction for $\tau_h \to$ hadrons in boosted regime
  - starting from a large-cone jet
  - then standard τ reconstruction applied
  - identification through intermediate decays
- Dedicated algorithm (SVfit) identifies a di-tau system
  - suitable for both $\tau \to$ leptons and $\tau \to$ hadrons
  - combines informations from leptons, τ_h and E_T^{miss}

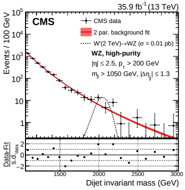


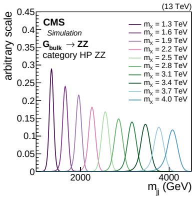
$VV \to q\bar{q}q\bar{q}$

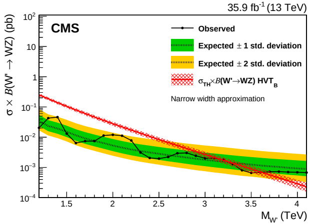
CMS-B2G-17-001;arXiv 1708.05379

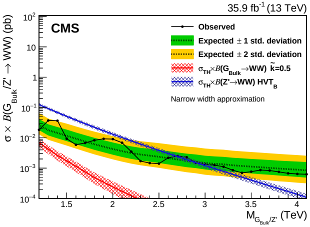
Analysis summary

- 2 large-cone V-tagged jets: 6 categories ($WW \times WZ \times ZZ$) $\times$ ($LP \times HP$)
- Two τ_{21} purity categories
- Background estimation:
- "Bump hunt": fit to data with power law or exponential falling functions
- 10% CL Fisher test to determine the optimal number of parameters (2–5)
- signals modelled as Crystal Ball (narrow-width)





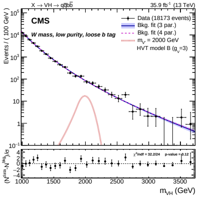


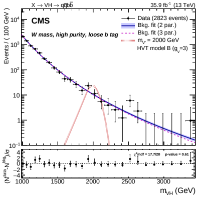


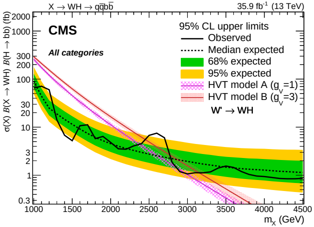
- Limits on HVT model B:
  - W' excluded up to 3.6 TeV
  - Z' up to 2.7 TeV

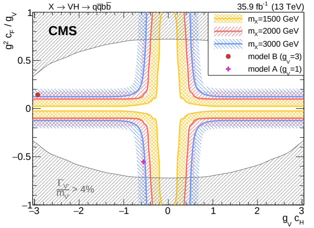
Analysis summary

- 2 large-cone V-tagged/H-tagged jets: 8 categories $(W \times Z) \times (LP \times HP) \times (Loose \times Tight)$
- Two τ_{21} purity categories
- Background estimation:
- "Bump hunt": fit to data with power law or exponential falling functions
- 10% CL Fisher test to determine the optimal number of parameters (2–5)
- signals modelled as Crystal Ball (narrow-width)





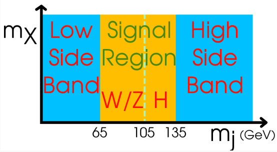


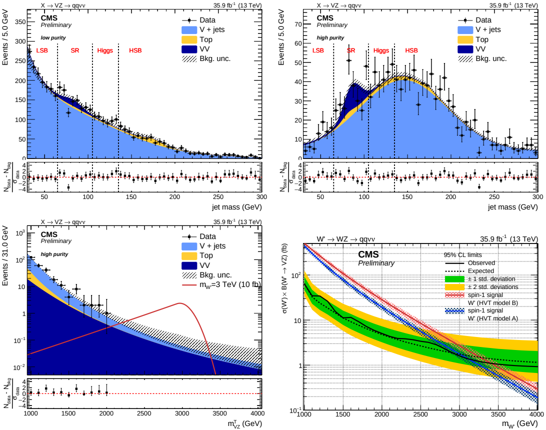


- Limits on W' model A/B up to 3.0/3.2 TeV
- Limits on Z' model A/B up to 1.7/2.3 TeV
- Exclusion in the HVT parameter space

Analysis summary

- $W, Z \to q\bar{q}$: one large-cone jet
- $Z \to \nu\nu$: $E_T^{miss} > 200$ GeV
- Two τ_{21} purity categories
- Background estimation:
- Main: V+jets, estimated with α-ratio method
  - SideBands (signal depleted) based on $m_J^{softdrop}$ $\to$ SB = [30,65] ; [>135] GeV
  - W/Z Signal Region $\to$ SR = [65,105] GeV
  - Data in SideBands used to predict the background in the Signal Region through the α-ratio SB $\to$ SR transfer function
- Secondary: top and dibosons taken from simulations





- Limits on HVT model A/B:
  - W' excluded up to 3.1/3.4 TeV

$VZ \to q\bar{q}\ell^+\ell^-$

CMS-B2G-17-013

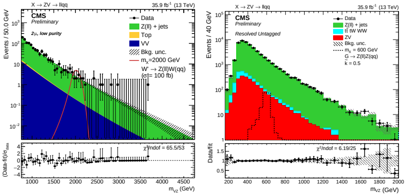
NEW!

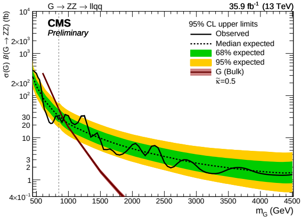
High-mass analysis: $850 < m_X < 4500$ GeV

- dedicated boosted muon identification
- $70 < m_{Z\to\ell\ell} < 110$ GeV
- $W, Z \to q\bar{q}$ one large-cone jet
  - $65 < m_J^{softdrop} < 105$ GeV $\to W, Z$
  - Two τ_{21} purity categories
- Background estimation: α-ratio method

Low-mass analysis: $400 < m_X < 850$ GeV

- merged category: $V \to q\bar{q}$ 1 large-cone jet
  - $65 < m_J^{softdrop} < 105$ GeV $\to W, Z$
  - One $\tau_{21} < 0.4$ purity category
- resolved category: $V \to q\bar{q}$ 2 standard jets
  - $m_{jj} > 30$ GeV; $p_T^{jj} > 100$ GeV
- futher b-tagging categorization (at least 1 subjet/jet b-tagged vs untagged)
- Background estimation:
- Main: Z+jets MC constrained in data sidebands
- Secondary ($t\bar{t}$, t, WW): $e\mu$ data control regions





- Limits on HVT model A/B: W' excluded up to 2.3 TeV
- Limits on bulk graviton ($\tilde{k} = 0.5$) excluded up to 925 GeV

$HH \to b\bar{b}\tau^+\tau^-$; $VH \to q\bar{q}\tau^+\tau^-$

CMS-B2G-17-006

NEW!

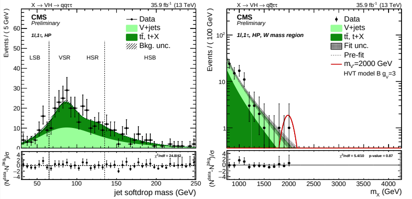
Analysis summary

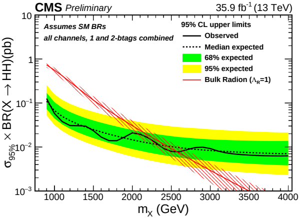
- $H \to \tau\tau$ tagging: $50 < m_{\tau\tau}^{\mathrm{SVfit}} < 150$ GeV
- $W, Z \to q\bar{q}$ large-cone jet
  - $65 < m_J^{softdrop} < 85$ GeV $\to W$
  - $85 < m_J^{softdrop} < 105$ GeV $\to Z$
  - Two τ_{21} purity categories
- $H \to b\bar{b}$ large-cone jet
  - $105 < m_J^{softdrop} < 135$ GeV $\to H$
  - 1 or 2 subjet b-tagged

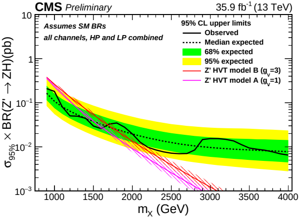
Background estimation: α-ratio method

Main: V+jets

t, $t\bar{t}$: checked in data control regions







- Limits on HVT model B: W' excluded up to 2.3 TeV, Z' up to 1.7 TeV
- Limits on radion ($\Lambda_R = 1$) excluded up to 2.5 TeV

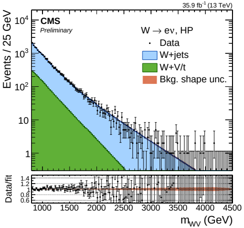
$VW \to q\bar{q}\ell\nu$

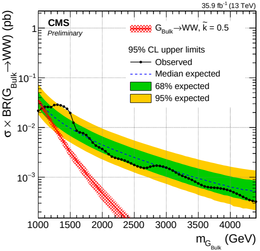
CMS-B2G-16-029

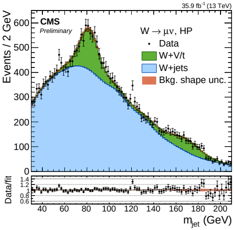
NEW!

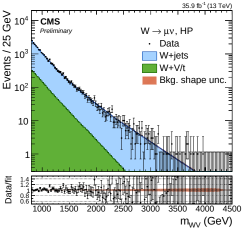
Analysis summary

- $W, Z \to q\bar{q}$ 1 large-cone jet: $30 < m_J^{softdrop} < 310$ GeV
- $W \to \ell\nu$: 1 muon or 1 electron + E_T^{miss}
- kinematical reconstruction of p_z^ν imposing m_W to (ℓ, ν)
- Background estimation: 2D ML fit on (m_J, m_X)
  - Signal, main background (non-resonant V+jets), secondary background (resonant top, diboson): 2D templates populated from simulation
  - each generated event → gaussian kernel (function of generated p_T^J) added to the templates
  - α method gives compatible results





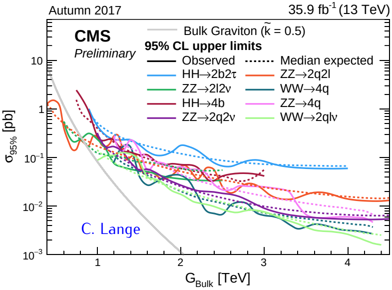


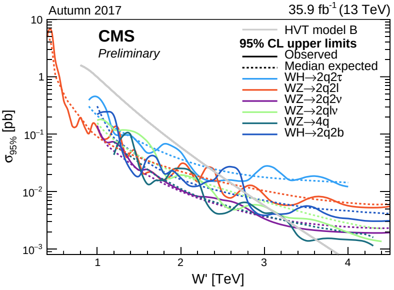


- W' HVT model B: excluded up to 3 TeV
- Bulk graviton ($\tilde{k} = 0.5$) excluded up to 1 TeV

Summary of diboson searches

	$V \to q\bar{q}$	$W \to \ell\nu$	$Z \to \ell\ell$	$Z \to \nu\nu$	$H \to b\bar{b}$	$H \to \tau\tau$
$V \to q\bar{q}$	B2G-17-001	B2G-16-029	B2G-17-013	B2G-17-005	B2G-17-002	B2G-17-006
$W \to \ell\nu$	B2G-16-029				soon!	
$Z \to \ell\ell$	B2G-17-013			B2G-16-023	soon!	
$Z \to \nu\nu$	B2G-17-005		B2G-16-023		soon!	
$H \to b\bar{b}$	B2G-17-002	soon!	soon!	soon!	B2G-16-026[1]	B2G-17-006
$H \to \tau\tau$	B2G-17-006				B2G-17-006	



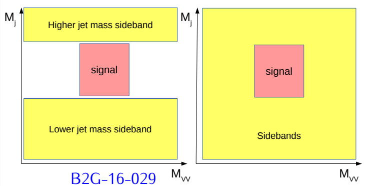


[1] In Devdatta's talk: link

Perspectives and conclusions

New tools

- Improving jet mass resolution: recursive softdrop
- Improving pile-up removal (Soft PUPPI)
- Machine learning:
  - to remove pile-up; b-tagging; jet substructure
- Improve sensitivity: 2D fit approach:
  - better modelling of correlations between m_J and m_X
  - categorization in W, Z, H bands not needed:
  - → more statistics available than splitting the dataset in SB
  - → simultaneous fit of all possible signals (i.e. VV, VH)
  - extended to 3D ($VV \to J_1 J_2$) $\to$ (m_{J_1}, m_{J_2}, m_{JJ})

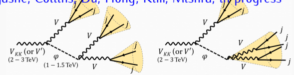


B2G-16-029

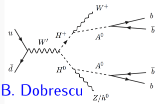
New signals

- Spin-1 V_{KK} in extended warped models: triboson decays, mediated by a scalar ϕ

Agashe, Collins, Du, Hong, Kim, Mishra, in progress



- Exotic cascade decays (SUSY-like)



B. Dobrescu

Conclusions

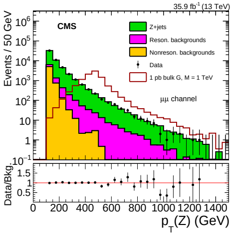
- Diboson searches: vivid sector in CMS
- ✧ 8 different publications with 2016 data (others are coming!)
- Next aim: combination 2016 + 2017 (+2018) data
- Plenty of new ideas and tools on the table

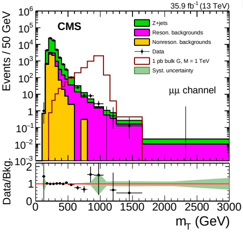

Thank you for your attention!

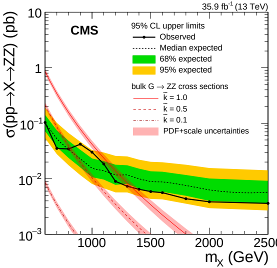
Backup slides

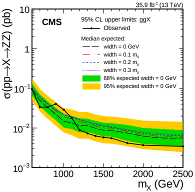
Analysis summary

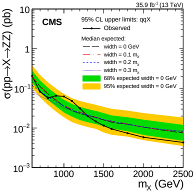
- $Z \to \ell\ell$: couple of opposite-charge muons or electrons SR: $90 < m_{Z\to\ell\ell} < 110$ GeV; $p_T^{Z\to\ell\ell} > 100$ GeV
- $Z \to \nu\nu$: $E_T^{\rm miss} > 50$ GeV
- Background estimation:
  - Main: Z+jets
    - described using γ+jets data, reweighted to Z+jets MC according to boson p_T, hadronic recoil fit to tune $E_T^{\rm miss}$
  - ZZ, WZ: NLO MC
  - $t\bar{t}$, single t and WW
    - modelled with $e\mu$ pair in data, using the side-band outside m_Z window











- Graviton ($\tilde{k} = 0.5$) excluded up to 800 GeV
- Limits at different widths and production mechanisms (gg fusion or $q\bar{q}$)

Softdrop algorithm

arXiv 1402.2657

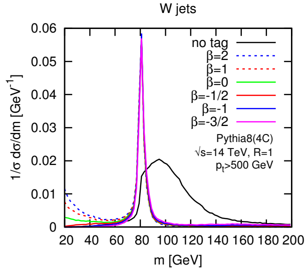
Softdrop procedure:

- jet declustered into two subjets, j_1 and j_2, by reverting the final step of Cambridge-Aachen algorithm;
- if j_1 and j_2 respect the softdrop condition (eq. 1), j is defined as the groomed jet;
- if they don't pass the condition, the leading subjet in p_T is redefined as the new j;
- if j can't be declustered anymore, it is defined as the groomed jet.

Soft drop condition:

$$\frac{\min(p_T^1, p_T^2)}{p_T^1 + p_T^2} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}, \qquad (1)$$

z_{cut} (soft threshold) and β parameters affect the degree of jet grooming: if $\beta \to \infty$ – jet ungroomed, if $\beta \to 0$ – more soft collinear radiation removed.



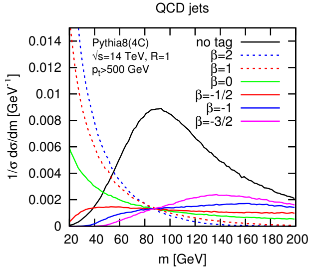


Fig: Distributions of the jet mass in W + jet signal simulations (top) and multi-jet QCD background (bottom), before (in black) and after applying softdrop algorithm. Each curve corresponds to a different value of the parameter β. arXiv 1402.2657

N-subjettiness

arXiv 1011.2268

Re-clustering of jet constituents with the k_T algorithm, forced to return n subjets. The n-subjettiness, τ_n, is:

$$\tau_n = \frac{1}{d_0} \sum_k p_{T,k} \min\left(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{n,k}\right), \qquad (2)$$

k labels the particles in the jet, $p_{T,k}$ is the transverse momentum of k, $\Delta R_{i,k}$ is the angle between k and i subjet candidate. The parameter d_0 is a normalization factor:

$$d_0 = \sum_k p_{T,k} R_0, \qquad (3)$$

R_0 is the clustering parameter of the jet. The τ_n variable describes to what degree a jet can be considered as composed by n substructures; smaller values of τ_n correspond to higher compatibility with the n-prong hypotesis. The most powerful discriminating variable is the ratio $\tau_{21} = \tau_2/\tau_1$:

$$\tau_{21} = \frac{\frac{1}{d_0}\sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k})}{\frac{1}{d_0}\sum_k p_{T,k} \Delta R_{1,k}}. \qquad (4)$$

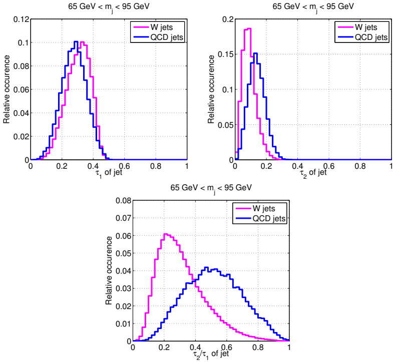
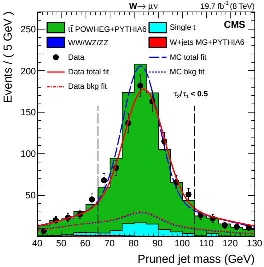


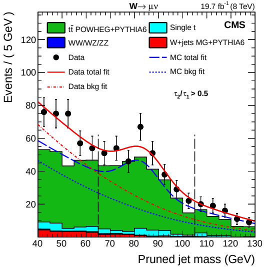
Figure: Distribution of τ_1 (top left), τ_2 (top center), and τ_{21} (bottom) variables, in simulations of a W plus jets process (in pink) and for a multi-jet QCD originated process (in blue). Selections applied: $65 < m_j < 95$ GeV; jets clustered with parameter $R_0 = 0.6$, $p_T > 300$ GeV, $|\eta| < 1.3$ (arXiv 1011.2268).

W tagging scale factors

arXiv 1410.4227

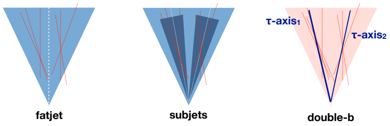
- a selection on the jet τ_{21} scuplts the jet mass spectrum is sculpted
- distributions of the groomed jet mass and τ_{21} compared in data and simulations, by selecting samples of di-jet, $t\bar{t}$ and W + jets events: discrepancy observed (10%)
- scale factors extracted by selecting a $t\bar{t}$ sample in data (high p_T W boson is produced by the top quark decay)
- jet mass distributions of events passing (top plot) and failing (bottom plot) the selection on the τ_{21} variable are fitted simultaneously, both in data and in simulations
- V-tagging scale factors are the ratio of the τ_{21} categorization efficiencies in data and MC

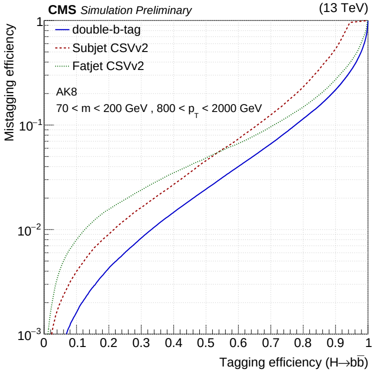


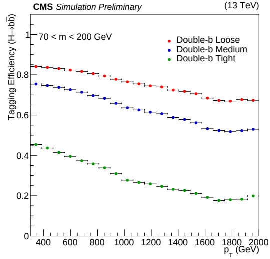


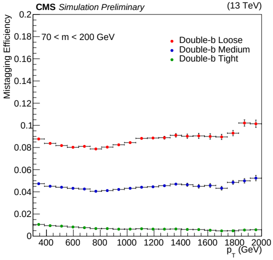
Double b-tagger

CMS-PAS-BTV-15-002









- Signal events in (m_{WV}, m_J) plane modelled as:

$$P_{sig}(m_{WV}, m_J \theta(M_X)) = P_{WV}(m_{WV}|\theta_1(M_X)) \times P_j(m_J|\theta_2(M_X))$$

  - P_{WV} and P_j are double crystal-ball functions; parameters described by polynomial interpolations, θ_1 and θ_2

- W+jets background is a conditional probability of m_{WV}, function of m_J:

$$P_{W+\text{jets}}(m_{WV}, m_J) = P_{WV}(m_{WV}|m_J, \theta_1) \times P_j(m_J|\theta_2)$$

  - conditional probability accounts for the correlations between m_J and m_{WV}; due to dependence of m_J with jet p_T during hadronization process
  - 2D templates populated with a kernel method starting from generated events
  - a resolution model is derived for m_J and m_{WV} as a function of true jet p_T $\to$ sums of 2D Gaussian distributions fill the 2D template (mean of the Gaussians is the true value of m_J and m_{WV}; the 2D covariance matrix given by the resolution model
  - Gaussians weighted by the cross section
  - final step: smooth the tails for high values of m_{WV} (no empty bins)
  - nuisances: accounts for differences between data and simulation

- $W + t$ and WV backgrounds modelled as:

$$P_{W+V}(m_{WV}, m_J|\theta) = P_{WV}(m_{WV}|\theta_1) \times P_j(m_J|\theta_2(m_{WV}))$$