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

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On behalf of the CMS Collaboration

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Introduction

New CMS results related with searches for heavy resonances decaying into Z, W, and Higgs bosons using full Run-2 data:

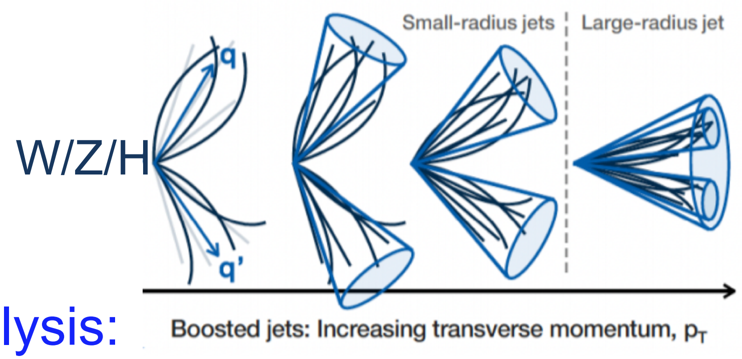
Search for weak vector boson and gluon-gluon fusion production of heavy resonances decaying to Z($\nu\bar{\nu}$)V(qq)	**CMS-PAS-B2G-20-008** **(Presented in Kamal's talk)**
Search for a heavy vector resonance decaying to a Z boson and a Higgs boson in proton-proton collisions	arXiv:2102.08198
Search for heavy resonances decaying to WW, WZ, or WH boson pairs in the lepton plus merged jet final state	**CMS-PAS-B2G-19-002**
Search for resonances decaying to decaying to three W bosons	**CMS-PAS-B2G-20-001**

Jet tagging

Boosted objects → small angular separation → merged jets

(W/Z → qq; H → bb/qqqq/qqlv)

- large-radius jets
- Jet grooming



Techniques for a successful boosted analysis:

➢ N-subjettiness $\tau_N = \frac{1}{d_0}\sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$

- ratios: $\tau_{21} = \tau_2/\tau_1$ to tag 2-prong objects
- Designing decorrelated taggers (DDT)

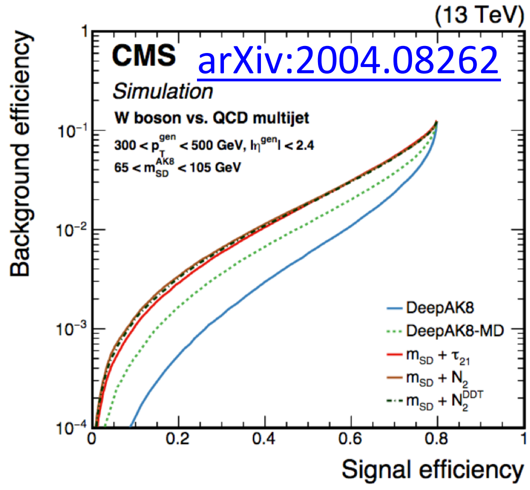
➢ DeepAK8 tagger

- multi-class tagger for t/W/Z/H tagging
- use PF candidates and secondary vertices

➢ Double-b tagger

- discriminate H → bb decays
- combine information from displaced tracks, secondary vertices as inputs to a BDT

Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)

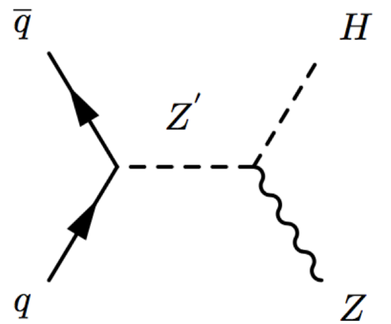


Resonances to ZH

arXiv:2102.08198

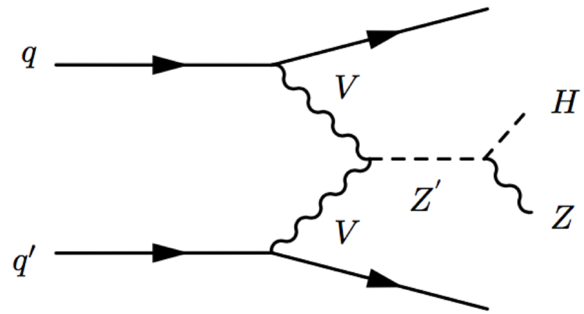
- Search for a heavy resonance X decaying to a pair of bosons:
  $X \to Z\ (ll/\nu\nu)\ H\ (inc)$

- Z' motivated by Heavy Vector Triplet (HVT) models:
  - Model A: Weakly coupled: Z' decays predominantly to leptons (through $q\bar{q}$ annihilation)
  - Model B: Strongly coupled: Z' decays predominantly to boson (through $q\bar{q}$ annihilation)
  - Model C: Z' couples only to boson (through Vector boson fusion, VBF)



- Vector boson Reconstruction
  - Z candidate
    - $Z \to ll$: Two leptons with same flavor, opposite sign
    - $Z \to \nu\nu$: Puppi MET
  - H candidate
    Leading AK8 jet with $p_T > 200$ GeV and mass $\in [105, 135]$ GeV
  - Heavy resonance mass (m_X or m_X^T)
    - $Z \to ll$: reconstructed from the Z and H jet four-momenta
    - $Z \to \nu\nu$: estimated by calculating the transverse invariant mass of the H jet and the MET:

$$m_X^T = \sqrt{2 p_T^{miss} p_T^H (1 - \cos\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^H))}$$



Topology and event cleaning

arXiv:2102.08198

0 lepton channel

- Back-to-back topology: $\Delta\Phi$(MET, H) > 2
- Top rejection: veto on other AK4 jets b-tagged with loose wp (DeepCSV)
- QCD rejection: min$\Delta\Phi$(MET, jets) > 0.5 between MET and all AK4 jets
- MET noise cleaning: H jet charged hadron fraction > 0.1 and MET/Hp_T > 0.6
- Kinematic selection VBF: $|H_\eta| < 1.1$

2 lepton channels

- Bkg rejection (only no VBF): Δ_η (Z, H) < 1.7
- Back-to-back topology: ΔR(H, Z) > 2

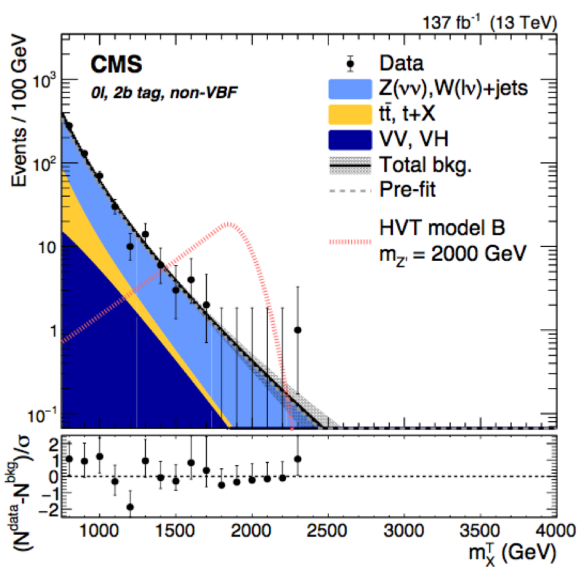
arXiv:2102.08198

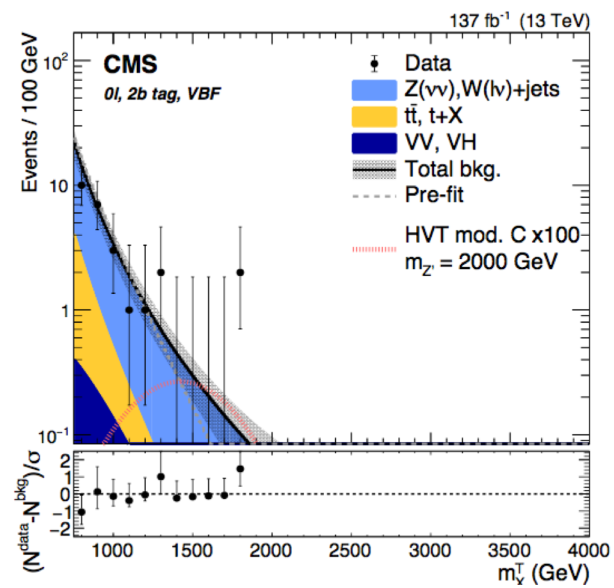
Dominant background: V+jets, ttbar, VV.

For the main background V+jets, m_X or m_X^T shape are estimated with a data-driven method, using the data in the jet mass sidebands, and a transfer function (**α method**).

- α ratio: $\alpha(m) = N_{SR}^{MC,bkg}(m) / N_{SB}^{MC,bkg}(m)$
- SB region: $m_j \in [30, 65], [135, 250]$ GeV

Secondary background (tt and single-top) is normalized from MC expectation

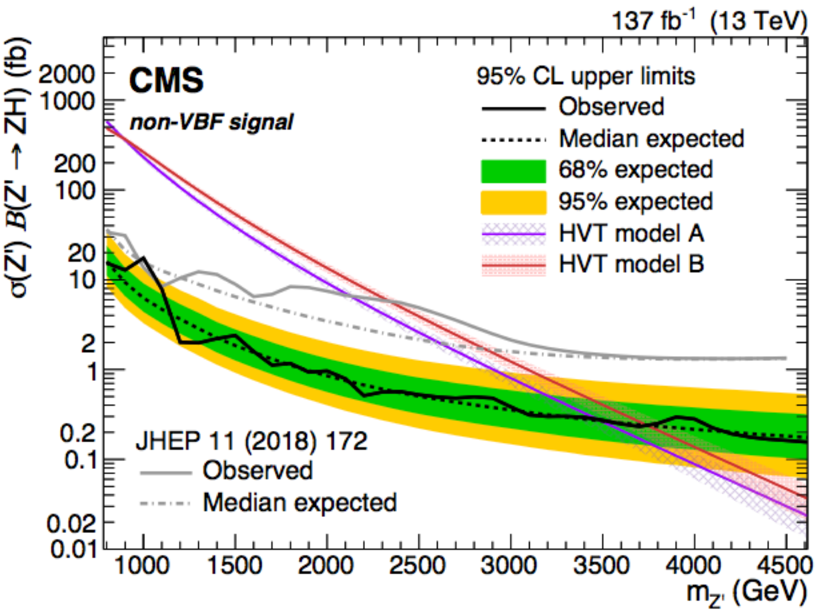


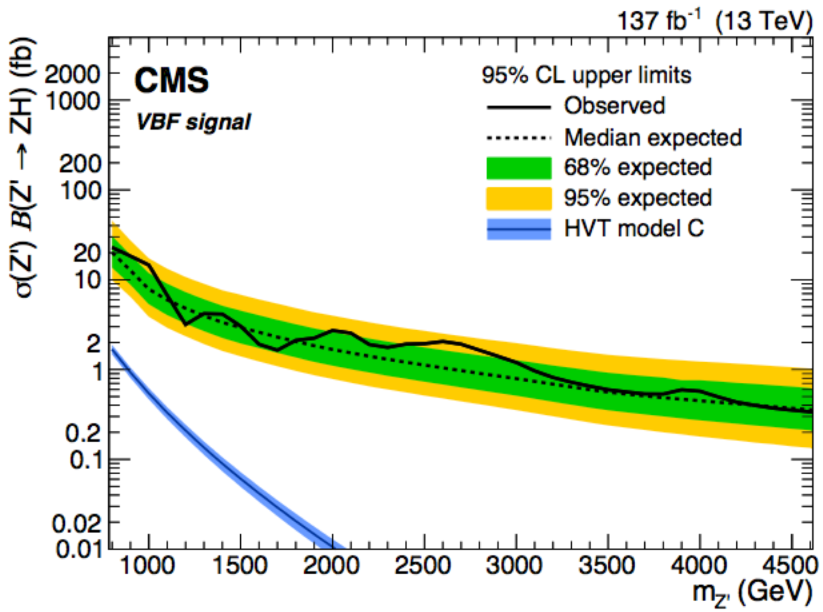


Limits

arXiv:2102.08198

- No significant excess observed. Upper limits are set on the cross-section x BR of the heavy resonance.





- ➢ Z’ with mass below 3.5 and 3.7 excluded at 95 % CL for model A and B, respectively
- ➢ For model C, cross section smaller than 0.3-23 fb is excluded

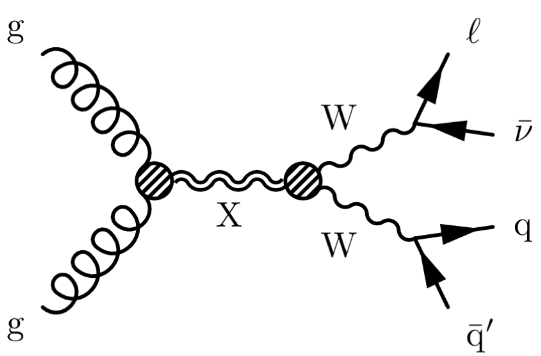
Resonances to WV/H

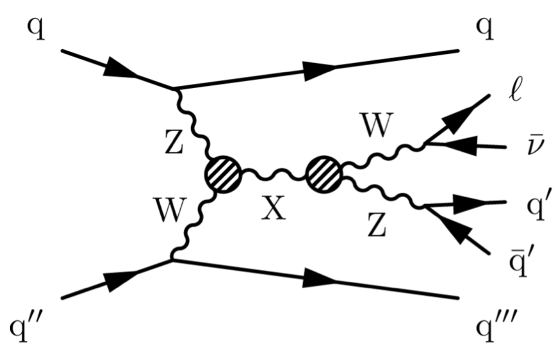
CMS-PAS-B2G-19-002

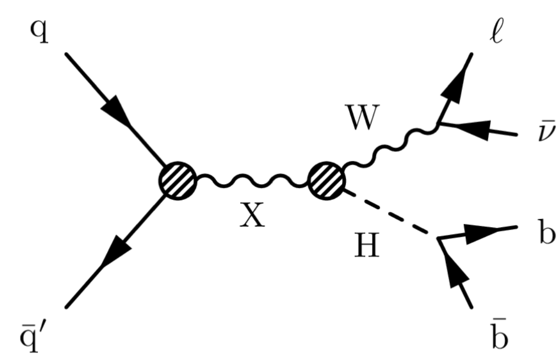
Search for a heavy resonance X decaying to a pair of bosons:

X → WV/H → lv qq/bb

- **production mechanisms**
  - gluon-gluon fusion (ggF)
  - Drell-Yan (DY)
  - VBF
- **benchmark models**:
  - Spin-0 radion (Randall-Sundrum)
  - Spin-1 vector (HVT)
  - Spin-2 graviton (Randall-Sundrum)







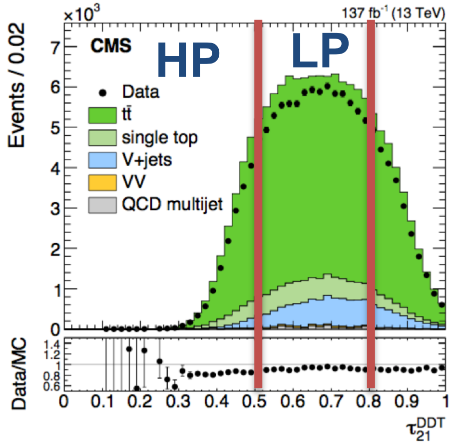
Event categorization

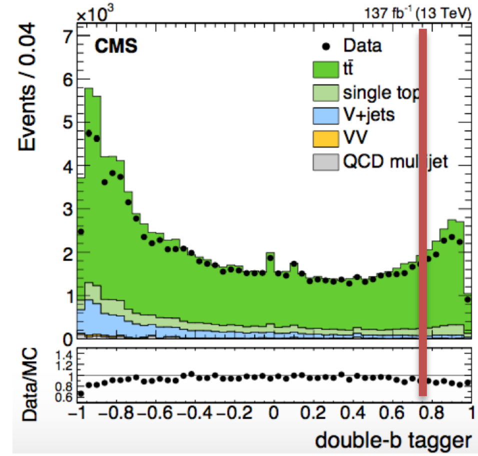
[CMS-PAS-B2G-19-002]

- signal region: $0.7 < m_{WV/WH} < 6$ TeV and $20 < m_{jet} < 210$ GeV
- split into **24 categories**, based on a combination of 4 criteria:

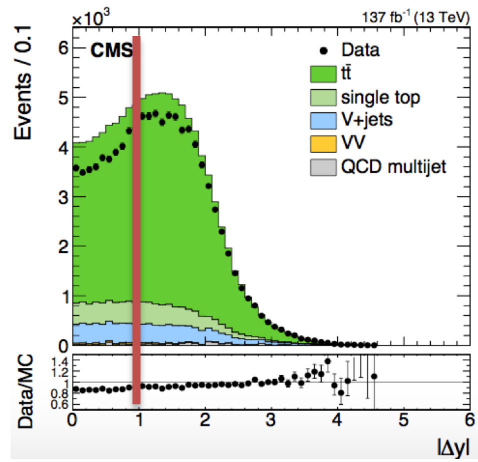
➢ lepton flavour (e or μ)

➢ V tagging information (HP or LP)
  HP: $\tau_{21}^{DDT} \leq 0.50$
  LP: $0.50 \leq \tau_{21}^{DDT} \leq 0.80$





➢ VBF-tagged and double-b-tagged (vbf, bb, nobb)
  vbf: VBF tag (≥ 2 VBF jets, $\Delta\eta_{jj} > 4$, $m_{jj} > 500$ GeV)
  bb: non VBF-tagged, Double-b ≥ 0.8
  nobb: non VBF-tagged, Double-b < 0.8

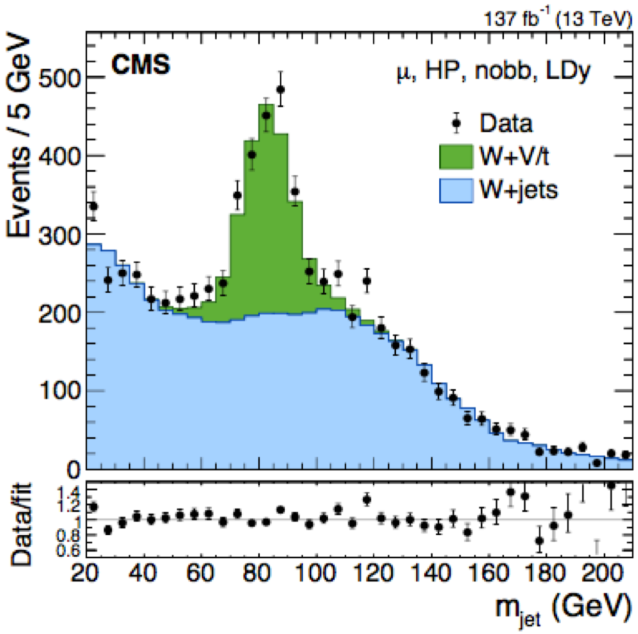


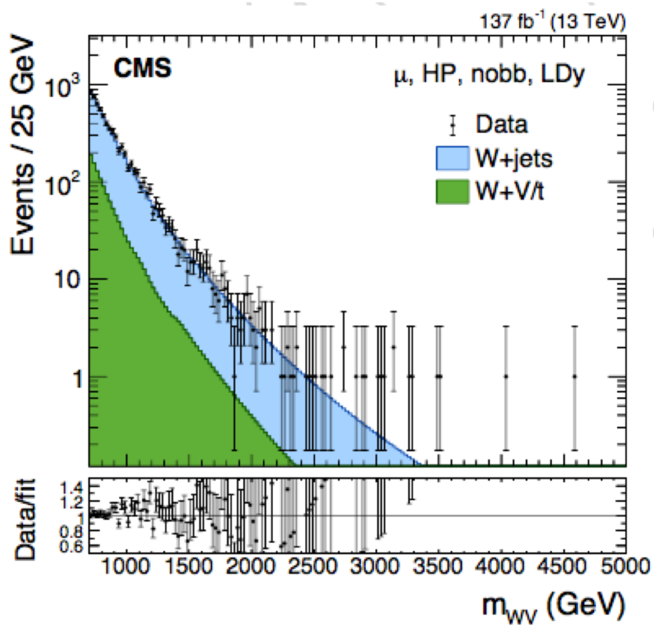
➢ rapidity between the reconstructed bosons (LDy or HDy)
  LDy: $|\Delta y| \leq 1$
  HDy: $|\Delta y| > 1$

2D fit strategy

CMS-PAS-B2G-19-002

- simultaneous maximum likelihood fit to the (m_{jet}, $m_{WV/WH}$) distributions in the 24 search categories
- Completely data-driven: backgrounds are constrained by the fit in the sideband regions of the 2D space.
- Post-fit spectra in one category:



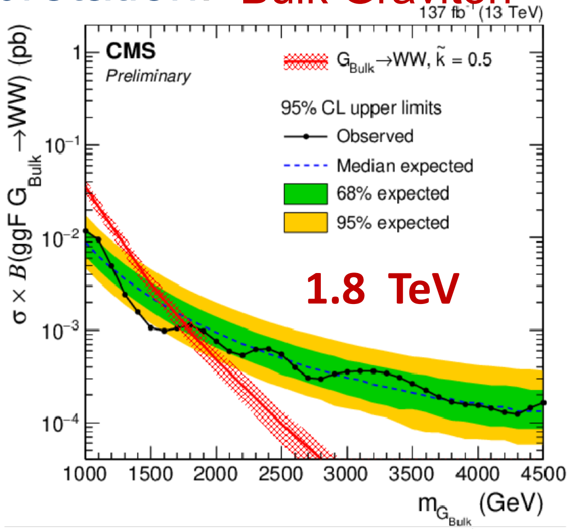


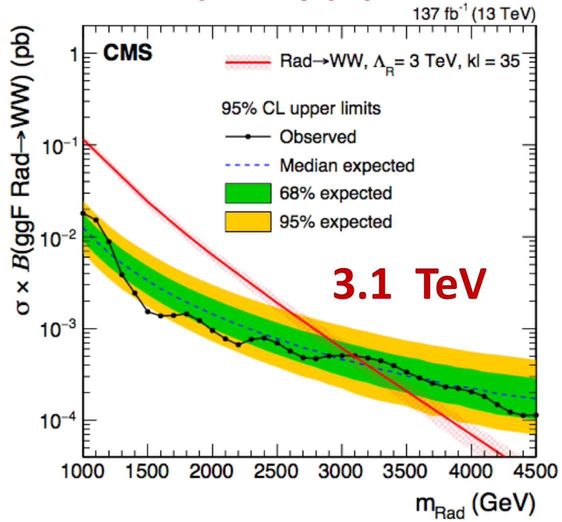
Limits

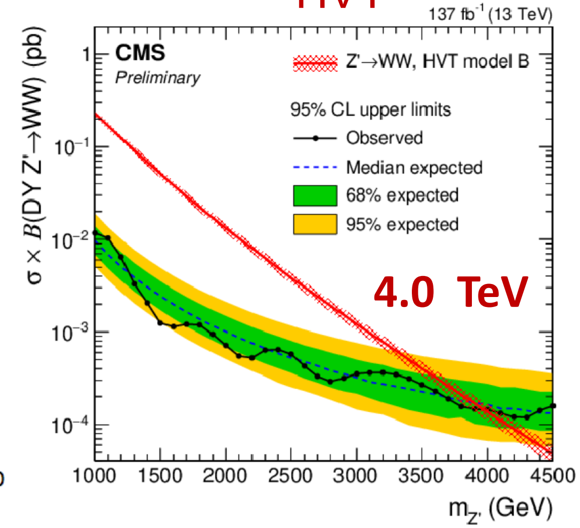
No significant excess is found

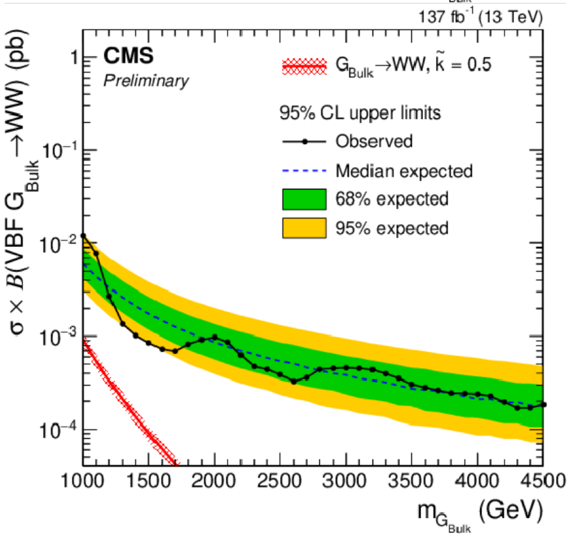
CMS-PAS-B2G-19-002

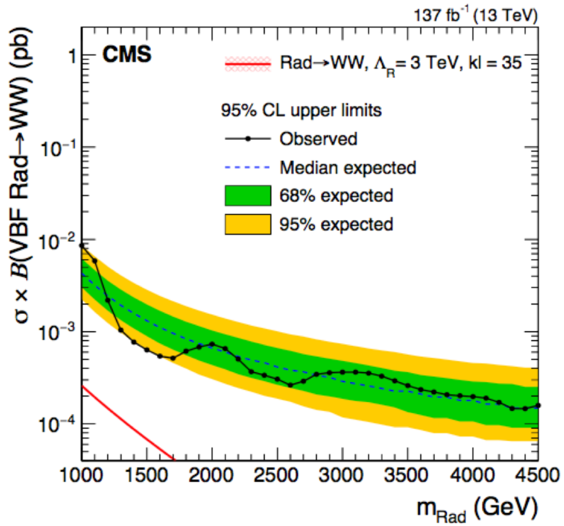
Interpretation: Bulk Graviton Bulk Radion HVT

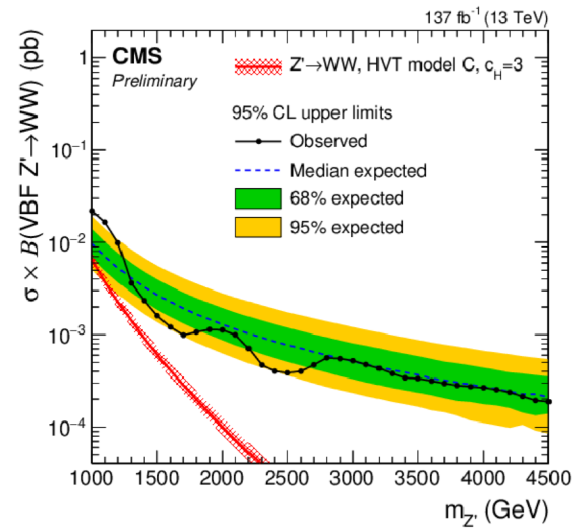










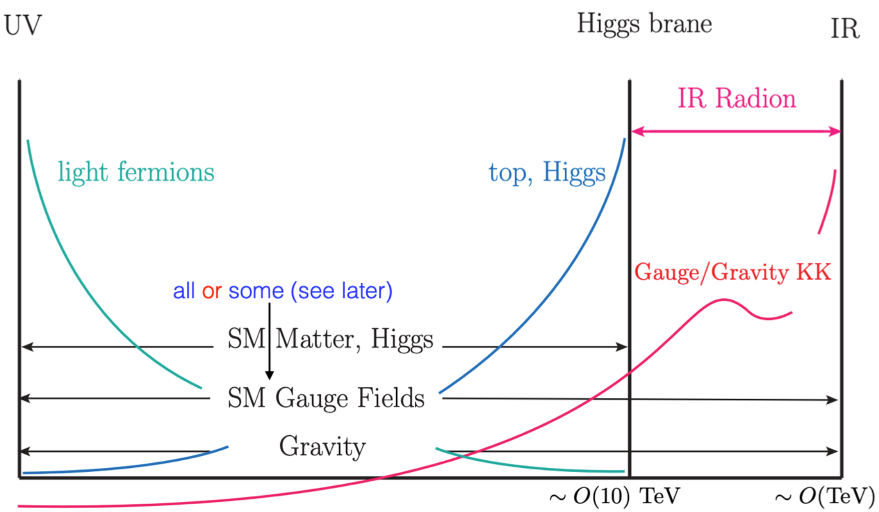


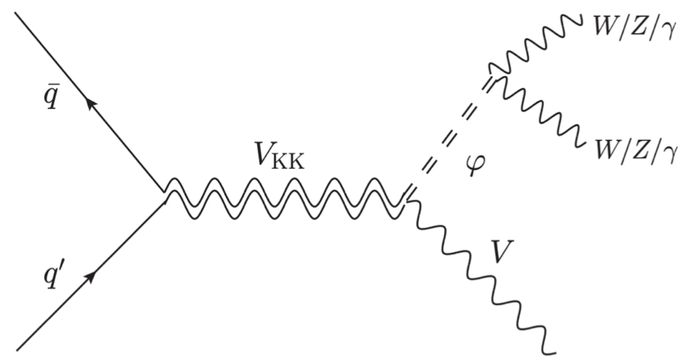
Tri-boson resonance

CMS-PAS-B2G-20-001

- First search for resonances decaying in cascade to final state with 3 W bosons

- Extended Warped ED model :
  - ➢ Extra brane by splitting the Bulk (arXiv:1711.09920 , arXiv:1612.00047);
  - ➢ Only EW bosons in the extended bulk → dominant: $V_{KK} \rightarrow R\,V \rightarrow VVV$
    - – WWW having the largest contribution





- Various fields propagate in different regions
- “di-SM” suppressed in favor of “tri-SM”

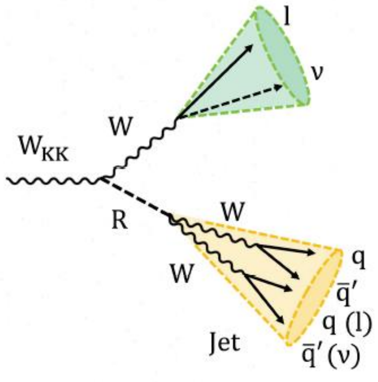
Signal region

CMS-PAS-B2G-20-001

- 1-lepton channel with BR of 42% is explored: $W_{KK} \rightarrow WWW \rightarrow l + \nu + jets$

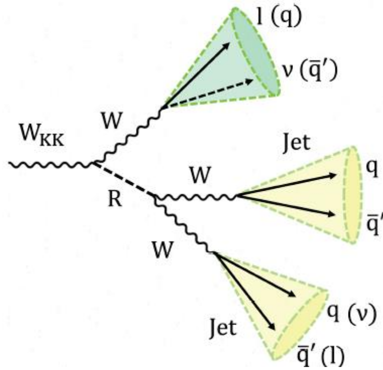
- Split to 6 signal regions based on:

➢ Merged: (SR1-3)
  - single massive large-radius jet
  - Bin over M_R: 60-100-200-... GeV
  - For 60 < M_j < 100 GeV, use deep-W
  - For Mj > 100 GeV, use deep-WH to tag radion



Merged R

➢ Resolved: (SR4-6)
  - 2 jets, ordered due to mass
    M_j^{max}: 60-100 GeV
    M_j^{min}:0-60-100 GeV binning
  - For 60 < M_j < 100 GeV, use deep-W



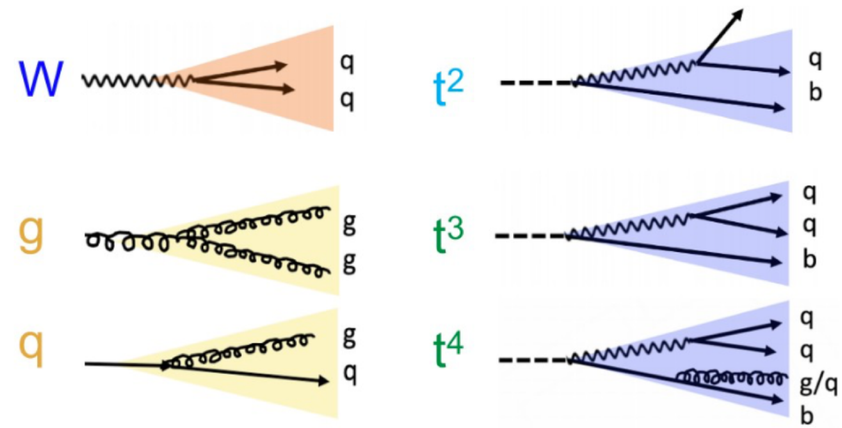
Resolved R

Region	m_j^{max} [GeV]	taggers	m_j^{min} [GeV]	tagger	N_j^{AK8}	N_j^{AK4}	N_b
SR1	60–100	deep-W > 0.7	—	—	1	≤ 2	0
SR2	100–200	deep-WH > 0.7	—	—	1	≤ 2	0
SR3	≥ 200	deep-WH > 0.7	—	—	1	≤ 2	0
SR4	60–100	deep-W > 0.5	60–100	deep-W > 0.5	2	≤ 2	0
SR5	60–100	deep-W >(<) 0.5	60–100	deep-W <(>) 0.5	2	≤ 2	0
SR6	60–100	deep-W > 0.7	0–60	—	2	≤ 2	0

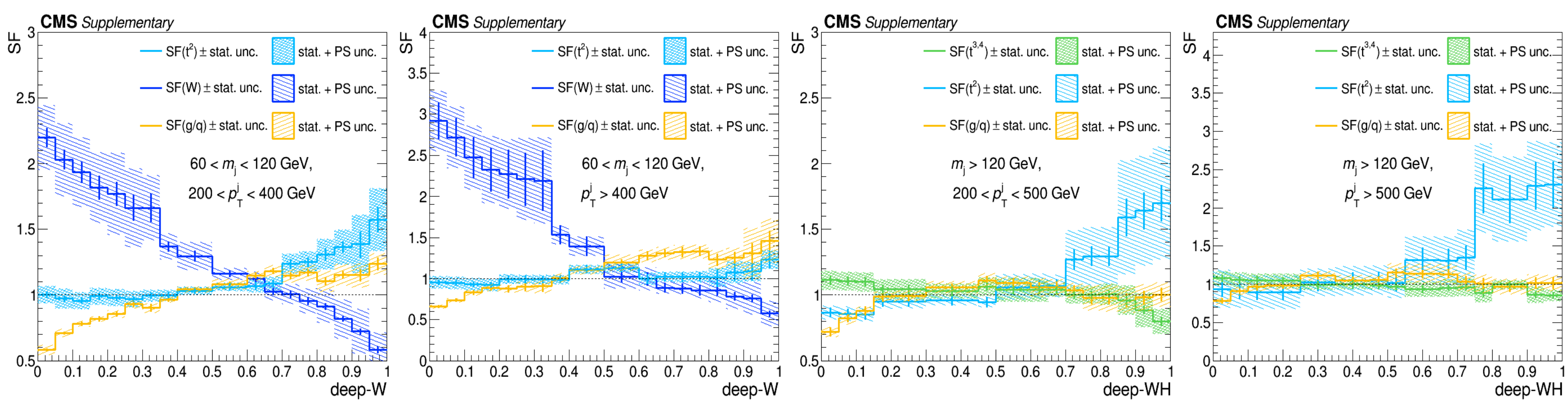
DeepAK8 tagger calibration

CMS-PAS-B2G-20-001

- Calibrate deep tagger discriminant shape using SM proxies:



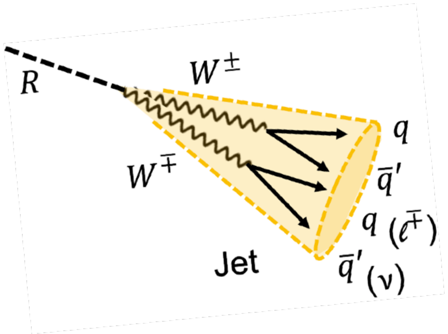
- Apply parton-level matching and correct MC shapes bin by bin



- Use these SFs to correct all jets for both BKG and signal (in the next slide)

Calibration for signal

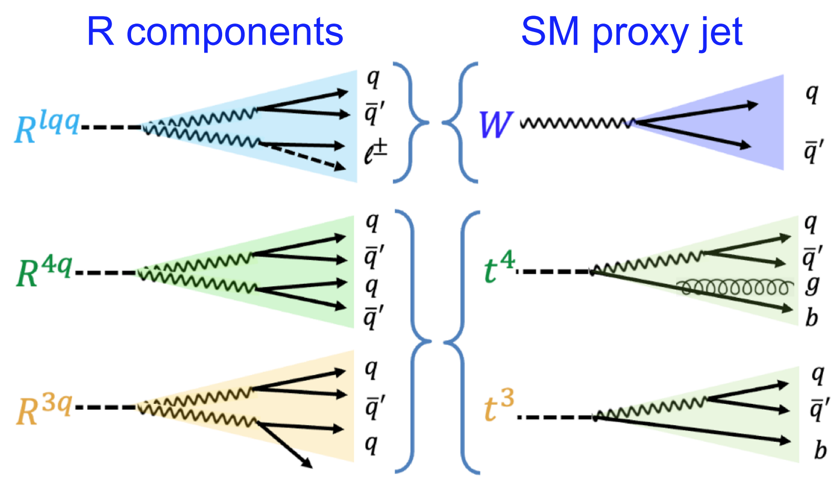
CMS-PAS-B2G-20-001



Merged Radion jet≈ R^{4q} + R^{3q} + R^{lqq}

Need special calibration
– no standard candle

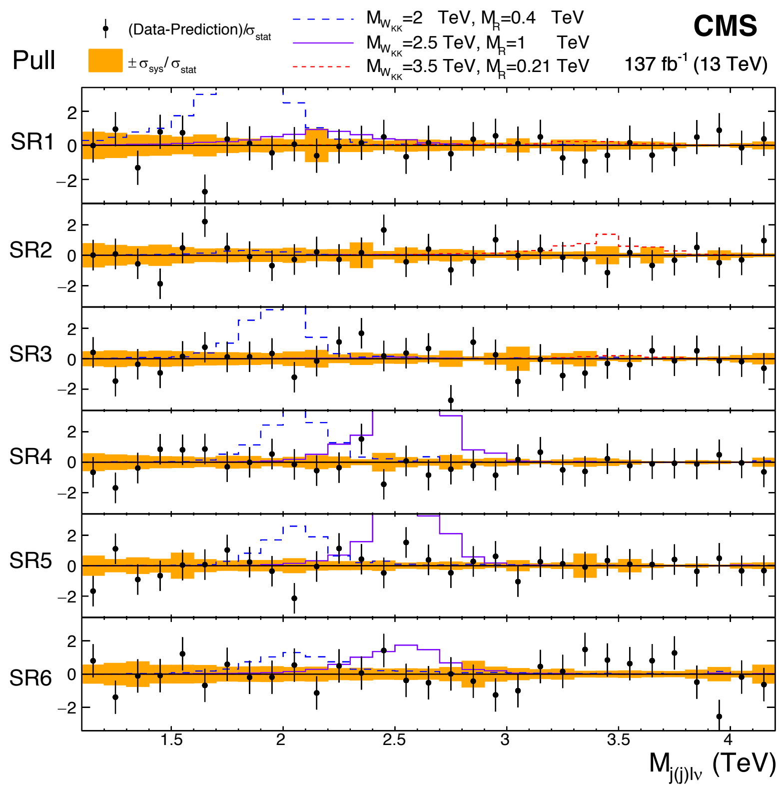
1. Observe similarity between W↔R^{lqq} jets
   → we apply scale factors for W, SF(W), on R^{lqq}
2. Observe similarity between R^{4q}↔R^{3q} jets with merged top: $t^{3,4}$
   → we apply SF($t^{3,4}$) on R^{4q}, R^{3q}
3. The difference between the performances of the SM candle and signal is taken into account as the systematic uncertainty.



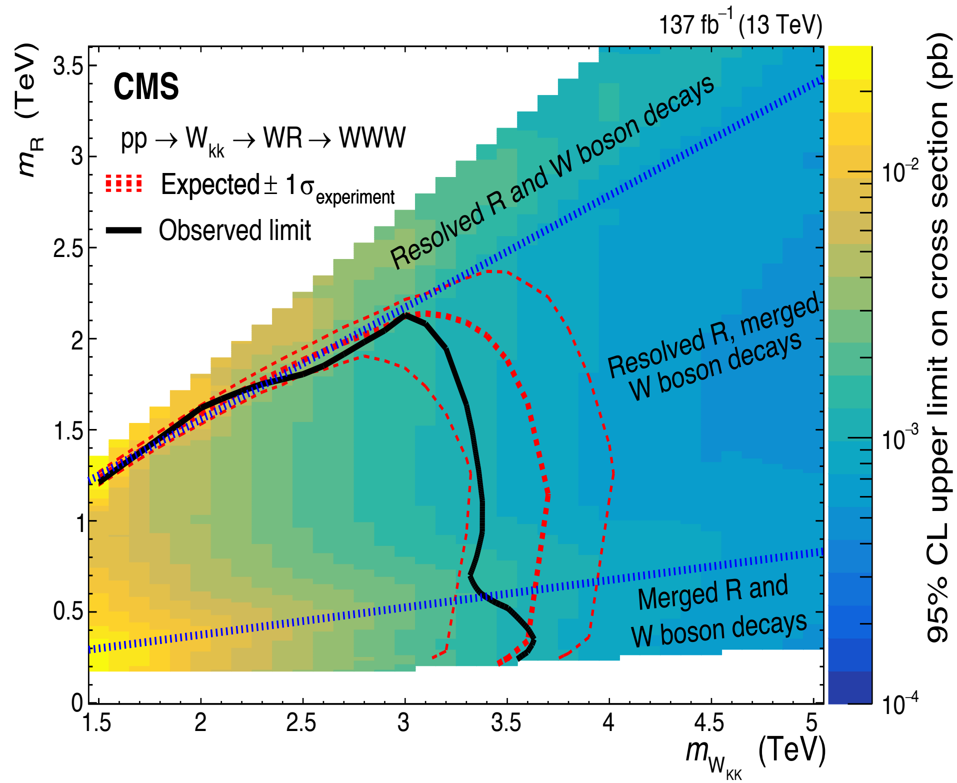
Results and limit

[CMS-PAS-B2G-20-001](CMS-PAS-B2G-20-001)

- Combined fit of six signal regions.
  (No excess over the background estimation is observed.)



- Limits in 2D W_{KK} vs. R mass plane. The first of their kind!



- The triboson resonances are excluded up to m_{WKK} = 3.4 (3.6) TeV for m_R = 1 (0.35) TeV.
- WKK masses below 3 TeV are excluded for $0.06 < m_R/m_{WKK} < 0.7$.

Summary

- Rich phenomenology & final states ZH, WV, WH, WWW, clear experimental signatures
- The use of jet substructure enables the search for heavy bosons resonances
- No evidence for new physics observed yet, 95% CL limits are set.
- More results to come out, and follow also here to keep track!
  - CMS publications

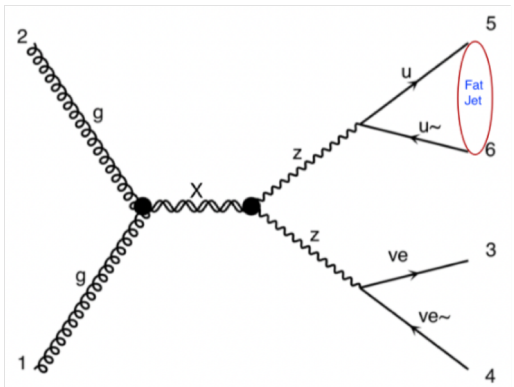
BACKUP

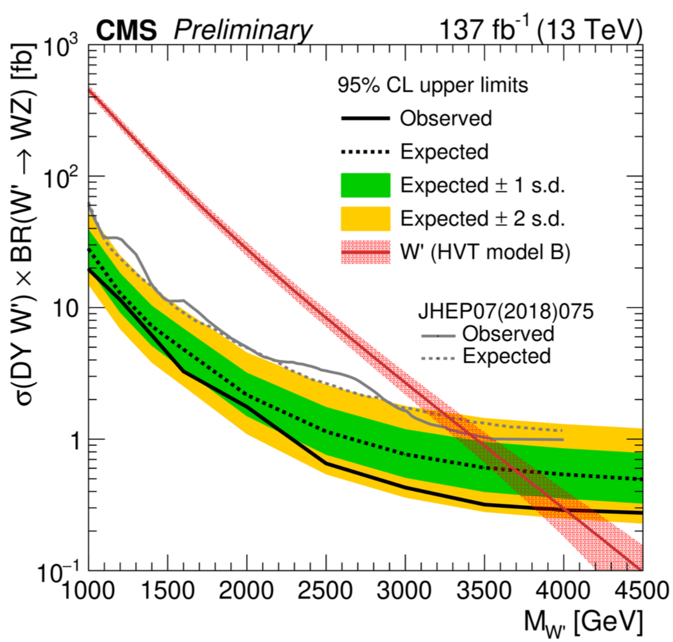
X→Z V→ νν qq

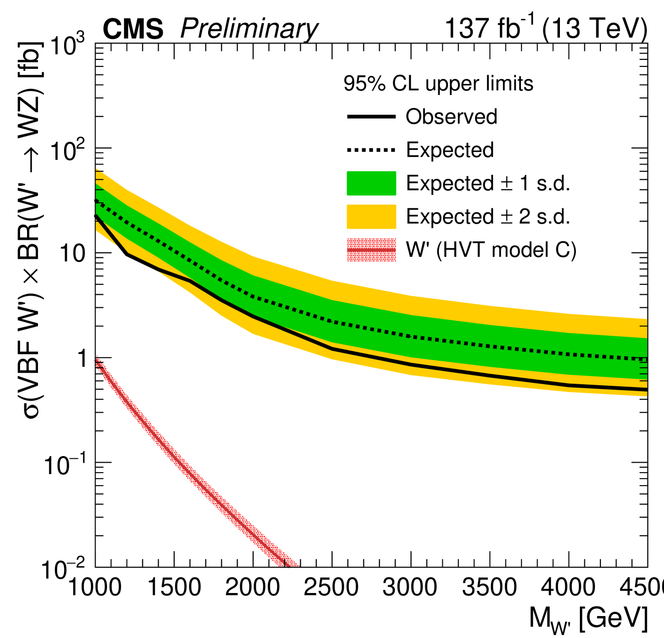
CMS-PAS-B2G-20-008

- Use transverse mass of hadronic V-jet+MET system
- Interpretation in radion, heavy vector triplet (HVT), and bulk graviton models—both Drell-Yan/gluon-gluon fusion (ggF) and vector-boson fusion (VBF) modes

Presented in Kamal's talk

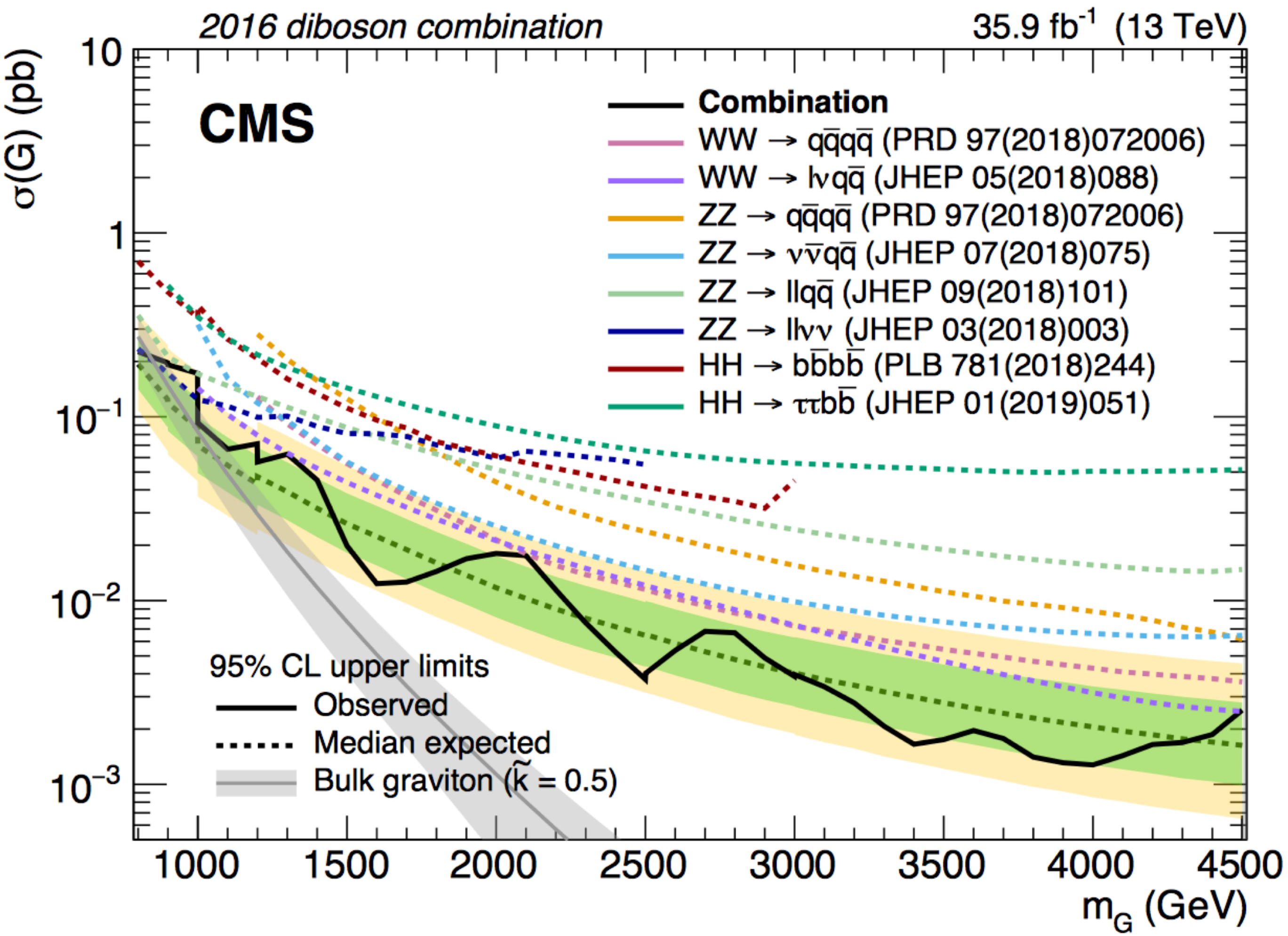






Diboson combination (2016)

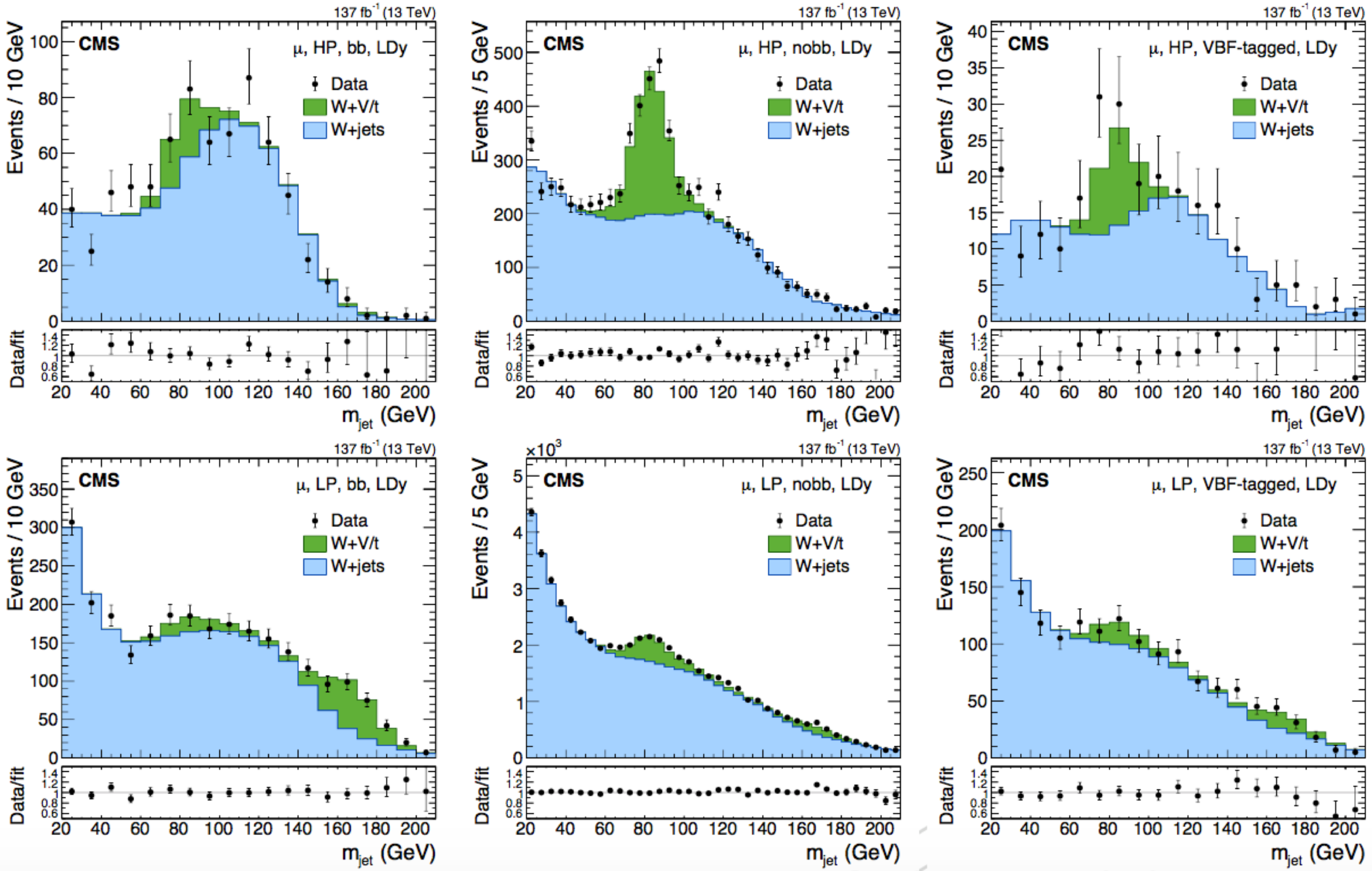
arXiv:1906.00057



X→ WZ/H → lν qq/bb

CMS-PAS-B2G-19-002

distributions of m_{jet} in the six muon-LDy categories



X→ WZ/H → lv qq/bb

CMS-PAS-B2G-19-002

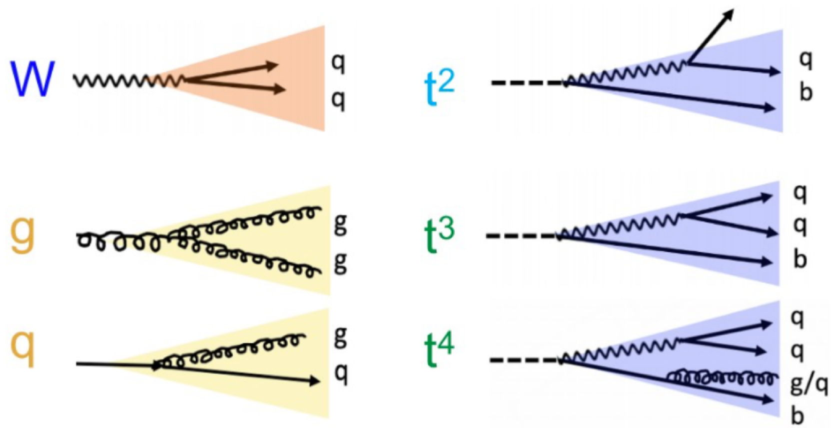
Table 1: Summary of the systematic uncertainties considered in the 2D fit, the quantities they affect, and their magnitude, when applicable. When ranges are given, the magnitude of the uncertainty depends on the signal model or mass.

Source	Relevant quantity	Magnitude
Jet p_T spectrum	W+jets and W+V/t m_{WV} shape	
Correlation between jet mass and p_T	W+jets m_{WV} and m_{jet} shape	
Jet mass scale	W+jets m_{jet} shape	
High-m_{WV} tail	W+V/t m_{WV} shape	
Jet mass scale	Signal and W+V/t m_{jet} mean	1%
Jet mass resolution	Signal and W+V/t m_{jet} width	8%
Ratio of W and top quark mass peaks	W+V/t m_{jet} shape	13%
W+jets normalization	W+jets yield	25%
W+V/t normalization	W+V/t yield	25%
Lepton selection efficiency	W+jets, W+V/t and signal yield	5%
Jet energy scale	Signal m_{WV} mean	2%
Jet energy resolution	Signal m_{WV} width	5%
p_T^{miss} scale	Signal m_{WV} mean	2%
p_T^{miss} resolution	Signal m_{WV} width	1%
Lepton energy scale	Signal m_{WV} mean	0.5% (e), 0.3% (μ)
V tagging	Signal yield	4% (HP), 4% (LP)
p_T-dependence of V tagging	Signal yield	1.7–19% (HP), 1.2–14% (LP)
double-b tagging	Signal yield	6–9% (bb), 0.4–2% (nobb)
$\lvert\Delta y\rvert$-based categorization	Signal yield	2–6% (LDy), 1.5–5.5% (HDy)
Integrated luminosity	Signal yield	1.8%
Pileup reweighting	Signal yield	1.5%
b tagging veto	Signal yield	2%
PDFs	Signal yield	0.1–2%

$W_{KK} \to WR \to WWW \to l\nu$+jets

[CMS-PAS-B2G-20-001](CMS-PAS-B2G-20-001)

- Calibrate deep tagger discriminant shape using SM proxies:

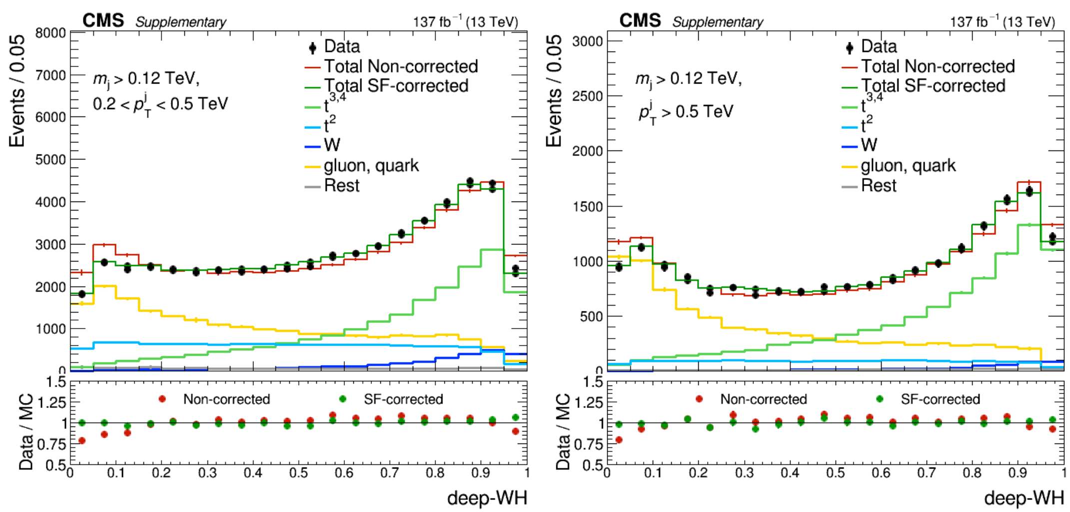


- Correct MC shapes, bin by bin

p_T: 200-500 GeV

p_T > 500 GeV

deep-WH @ M_j > 120 GeV



$W_{KK} \to WR \to WWW \to l\nu$+jets

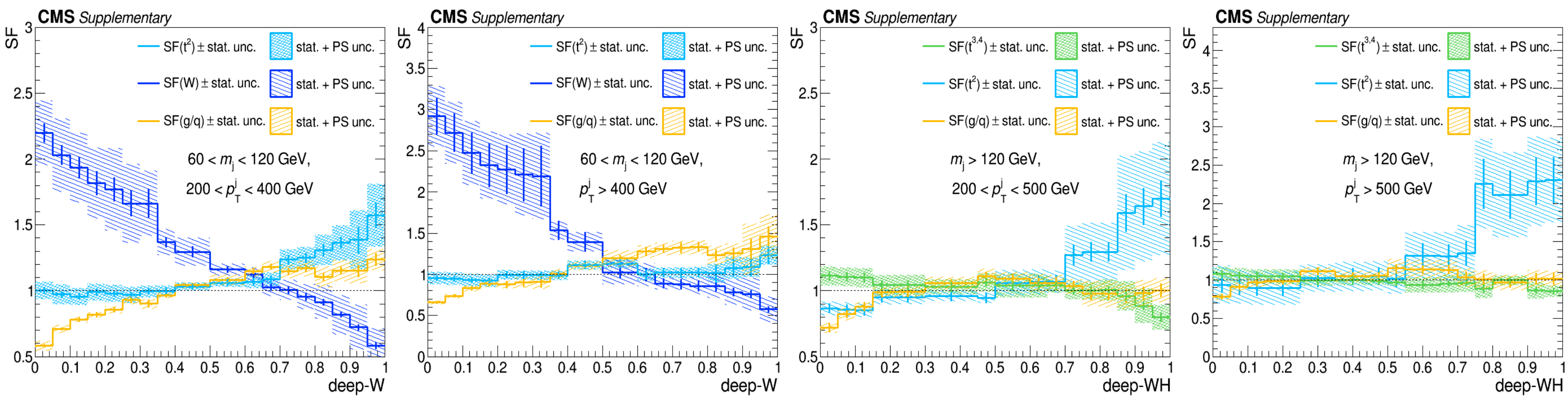
CMS-PAS-B2G-20-001

All **SFs** derived for all 4 bins (2 M_j , 2 p_T bins) and for all types of jets W, t^2, $t^{3,4}$, g/q

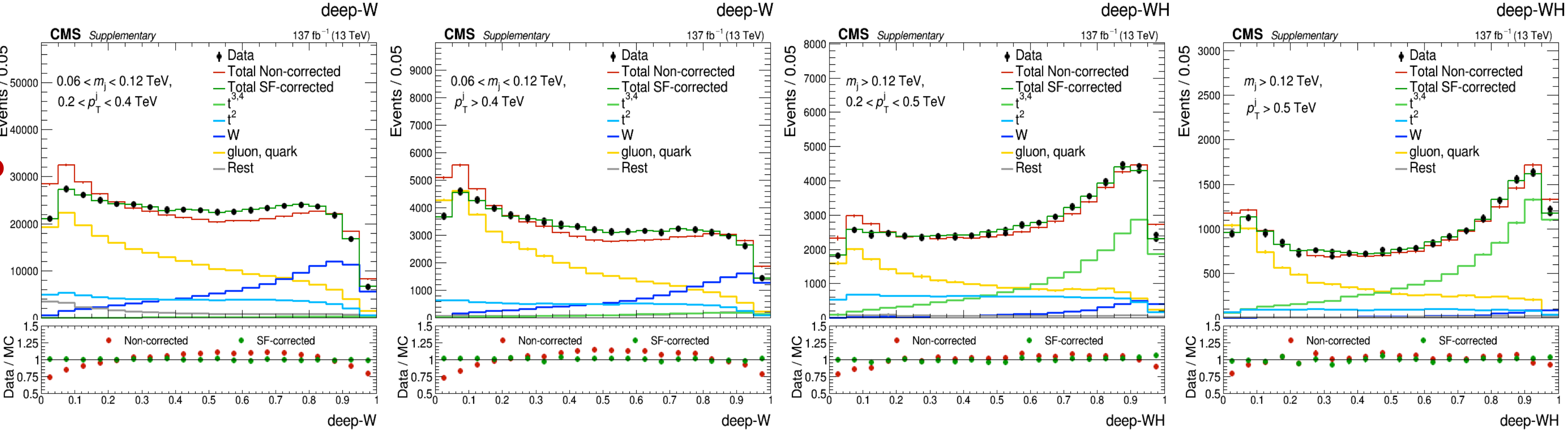
deep−W @ M_j: 60-120 GeV — P_T: 200-400 GeV | P_T > 400 GeV

deep−WH @ Mj > 120 GeV — P_T : 200-500 GeV | P_T > 500 GeV

SFs



w. and w/o correction



Good post SFs-correction performance; the method works!

$W_{KK}\rightarrow WR\rightarrow WWW\rightarrow lv$+jets

CMS-PAS-B2G-20-001

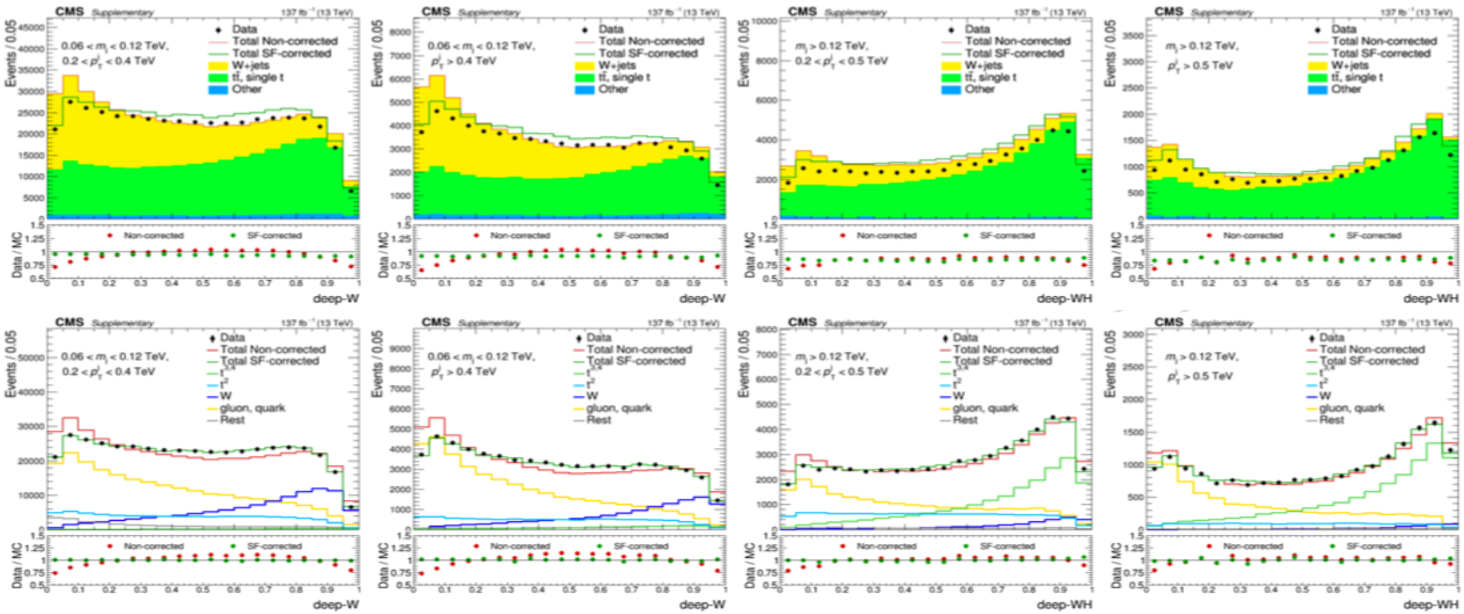


Figure 4: The deep-W (left two columns) and deep-WH (right two columns) discriminants of the jet with highest mass for different jet mass, m_{j}, and jet p_{T} ranges as indicated in the plots after preselection and vetoing the signal regions. The upper row shows the background processes (histograms) compared to the data (black markers). In the lower row, the background processes, which are normalized to the data, are split into categories that are defined by matching the reconstructed jet to processes at parton level: t^3 indicates a fully merged top-quark decay, t^4 contains an extra quark or gluon with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ inside the jet cone (both light green), and t^2 (light blue) contains only two quarks from the top-quark decay, but not both from the W boson decay. A merged W boson decay is indicated by W (dark blue), analoguously single quarks and gluons (yellow), and "Rest" indicates events not matching any of the categories. Before corrections (red), significant discrepancies between the prediction and the data can be observed, in particular at low and high discriminant values. The corrected distributions after scale factor (SF) application are shown using dark green. The lower panels show the Data/MC ratios before and after corrections.

$W_{KK} \rightarrow WR \rightarrow WWW \rightarrow l\nu$+jets

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$$D_1 = ag_1 + bW_1 + ct_1 + d_1$$
$$D_2 = ag_2 + bW_2 + ct_2 + d_2$$
$$D_3 = ag_3 + bW_3 + ct_3 + d_3$$

$$\begin{pmatrix} D_1 - d_1 \\ D_2 - d_2 \\ D_3 - d_3 \end{pmatrix} = \begin{pmatrix} g_1 & W_1 & t_1 \\ g_2 & W_2 & t_2 \\ g_3 & W_3 & t_3 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix}.$$

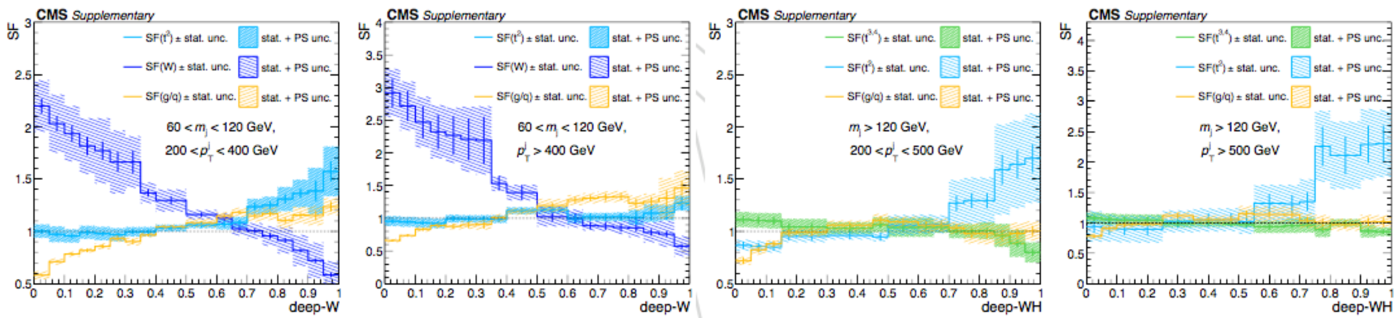

Figure 5: Scale factors (SFs) as a function of the deep-W (left two columns) and deep-WH (right two columns) discriminants of the jet with highest mass for different jet mass, m_{j}, and jet p_{T} ranges as indicated in the plots. For each of these ranges, the SFs are determined separately for the W (dark blue), $\mathrm{t}^{3,4}$ (green), t^{2} (light blue), and g/q categories, which are are defined by matching the reconstructed jet to processes at parton level. In order to determine the SFs, the matched jets are split into three samples (not shown), each one highly pure in a particular type of matched jets. As shown in the equation, for each of these samples, the sum of the categorized jet yields has to be equal to the observed data per deep-W(WH) bin. For this purpose, SFs a, b, c are introduced for each jet category. The t_i correspond to t^2, or $\mathrm{t}^{3,4}$ depending on the sample, W_i to the W category, g_i to quarks/gluons, and d_i to "Rest", and i runs over the three samples. The equations can be written as a 3×3 matrix system and solved for the SFs for each matched jet type and deep-W(WH) bin. The plots show the SFs derived in this way. Their parton shower (PS) and statistical uncertainties are shown as shaded bands. These SFs are used to correct the simulated deep-W(WH) spectra for each matched jet type in the corresponding m_{j} and $p_{\mathrm{T}}^{\mathrm{j}}$ ranges. Signal jets (categorized as W, R^{lqq}, R^{3q}, R^{4q}) receive the same corrections from the corresponding standard model proxy jet used here (where $\mathrm{R}^{lqq} \leftrightarrow \mathrm{W}$, $\mathrm{R}^{3q,4q} \leftrightarrow \mathrm{t}^{3,4}$).