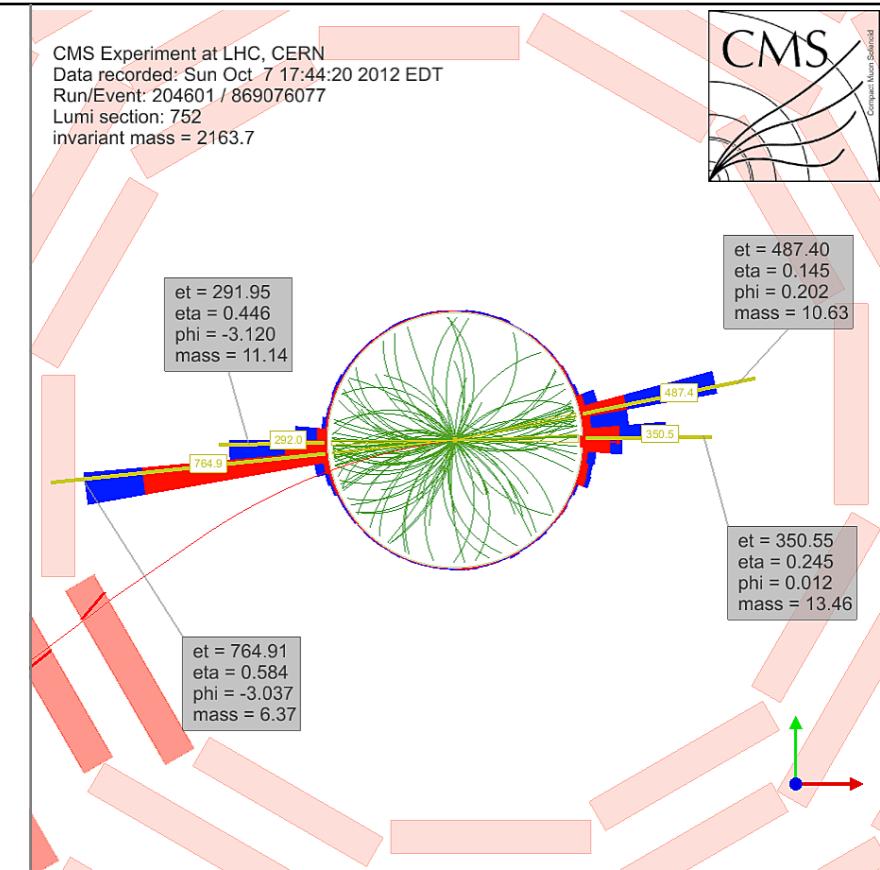


Search for heavy resonances decaying to dibosons at CMS

Devdatta Majumder
University of Kansas
On behalf of the CMS Collaboration

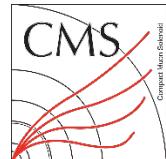
SUSY 2016, Melbourne, Australia



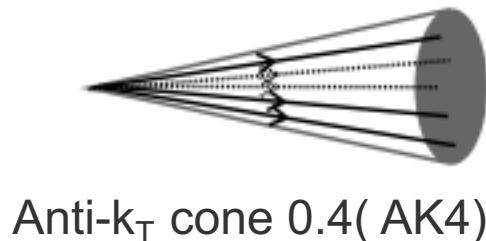
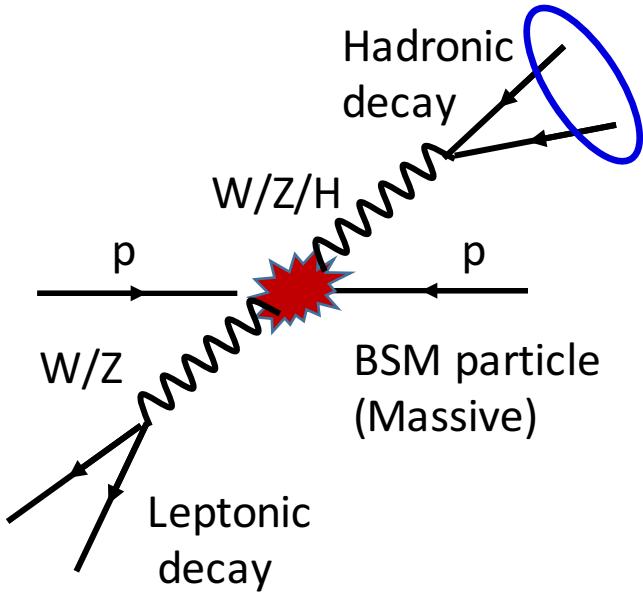
Overview of analyses

Search	Final states	VS (TeV)	Int. lumi. (fb ⁻¹)	Reference
VV (WW/ WZ/ ZZ)	lvjj, JJ	13	2.6	EXO-15-002
WH/ ZH	lljj, lvjj	13	2.17-2.52	B2G-16-003
WW	lvqq	13	2.3	B2G-16-004
VV (WW/ WZ/ ZZ)	lvjj, JJ	8+13	19.7 + 2.6	B2G-16-007

- All analyses done using 13 TeV data from 2015.
- Combination of 8+13 TeV data uses full Run 1 data and 2015 data.
- Common search strategy is to look for a narrow peaking signal over a smoothly falling background distribution (bump hunt).
- Searches being pushed to above ~TeV range for the resonance masses.
 - Need boosted techniques to tag boson jets (J).



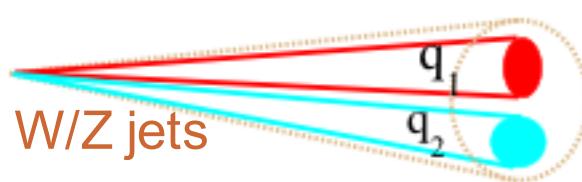
Analysis techniques



Anti- k_T cone 0.4(AK4)

New physics

- ⇒ Massive resonances (W/Z/H)
- ⇒ Decay to standard model bosons with high Lorentz boost
- ⇒ At least one boson decaying hadronically. Can be reconstructed using large sized jets and substructure

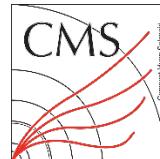


Anti- k_T cone 0.8 (AK8)

$$\Delta R \approx \frac{2M}{p_T}$$



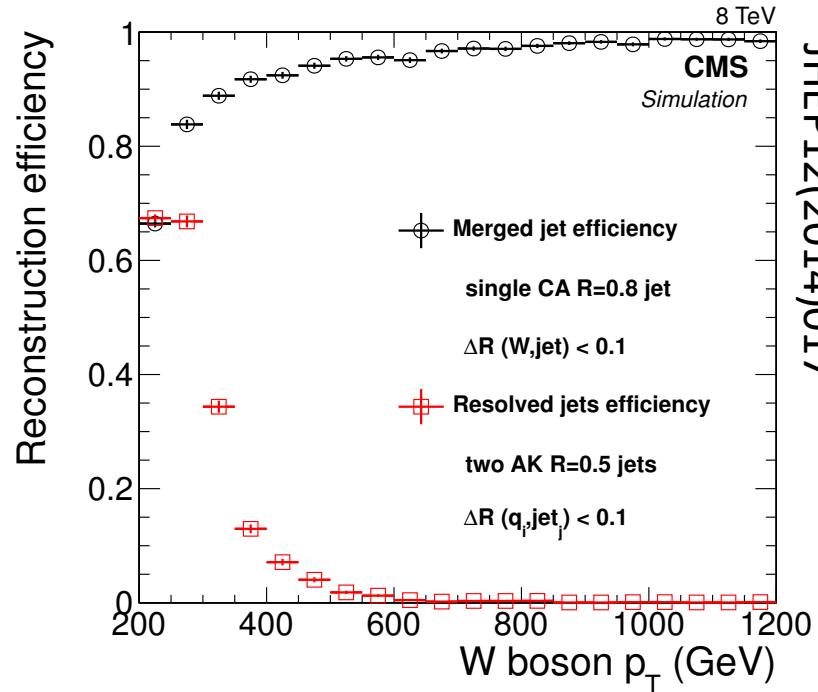
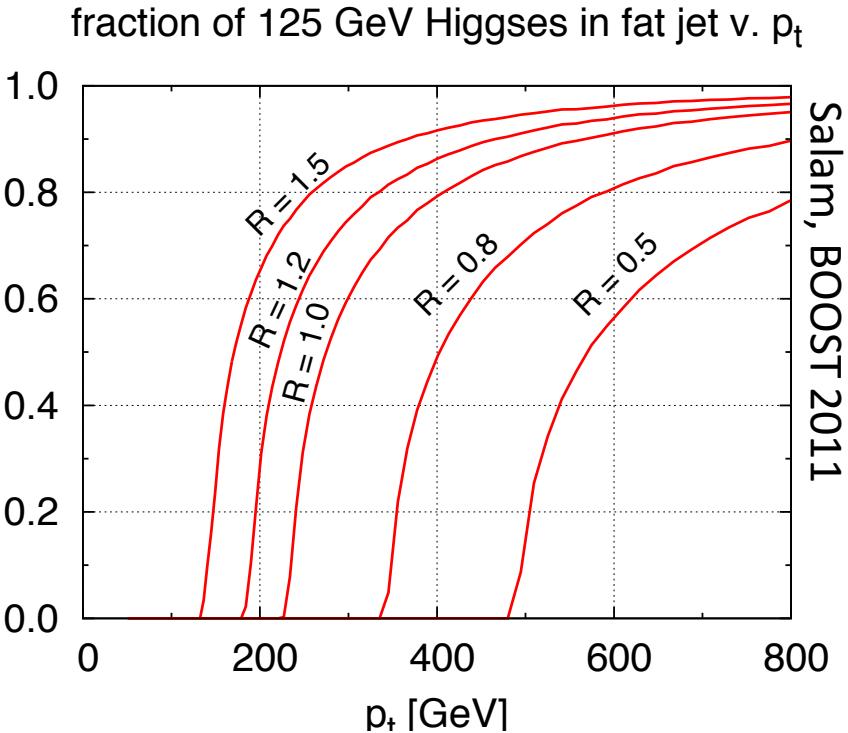
Anti- k_T cone 0.8
(AK8)
B tagging subjets



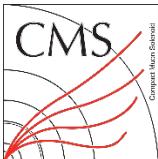
Compact Muon Solenoid

Rock Chalk, JAYHAWK!

Why boosted jets

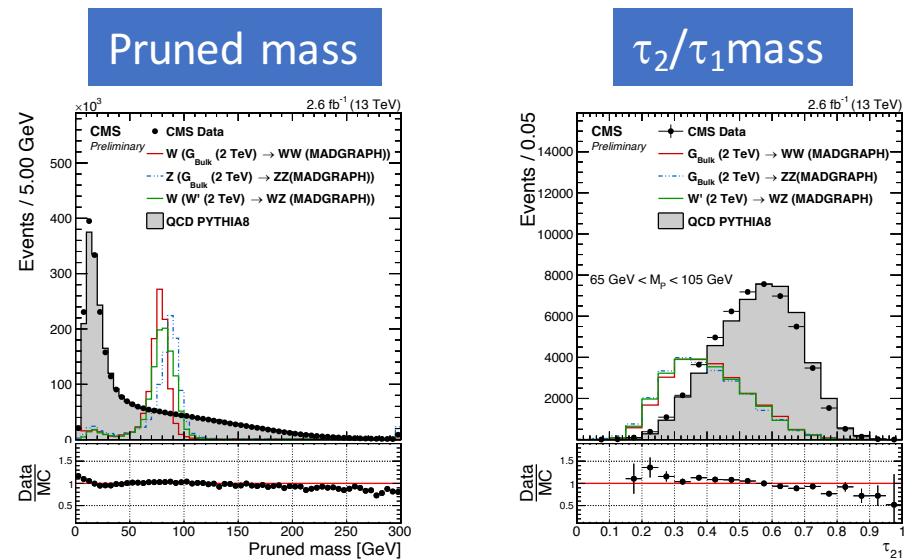


- Higher efficiency of reconstructing boosted W/Z/H using fat jets than using slimmer resolved jets.



VV resonances at 13 TeV

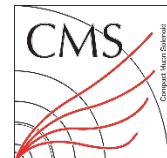
- Search for WW/ WZ/ ZZ
 - ❖ lvqq and qqqq final states
- $p_T(\mu/ e) > 53 / 120$ GeV
- $E_T^{\text{miss}} > 40 (80)$ GeV for muon (electron) channel.
- Boosted hadronic $W \rightarrow q\bar{q}'$ and $Z \rightarrow q\bar{q}$ tagged using large area jets and substructure techniques.
- $65 < \text{pruned mass} < 105$ GeV
 - ❖ W cand.: 65-85 GeV
 - ❖ Z cand.: 85-105 GeV
- N-subjettiness $\tau_2/\tau_1 < 0.75$



Events categories:

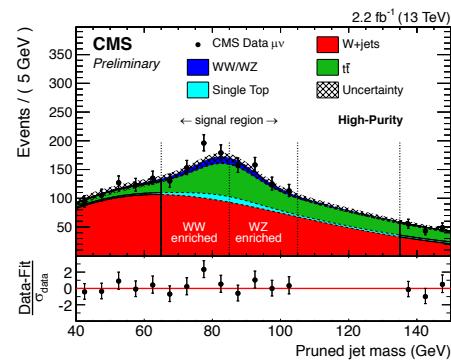
- ❖ $\tau_2/\tau_1 < 0.6$ (high purity)
- ❖ $0.6 < \tau_2/\tau_1 < 0.75$ (low purity)
- ❖ $\tau_2/\tau_1 < 0.45$ (high purity)
- ❖ $0.45 < \tau_2/\tau_1 < 0.75$ (low purity)

Semi-leptonic
Hadronic

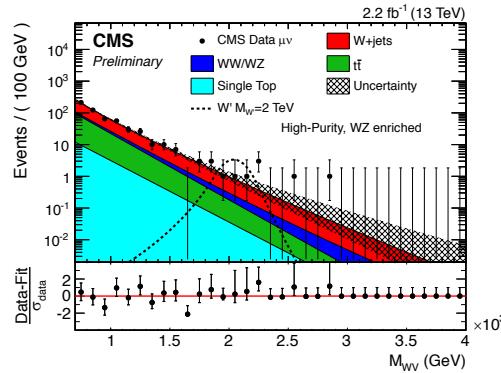
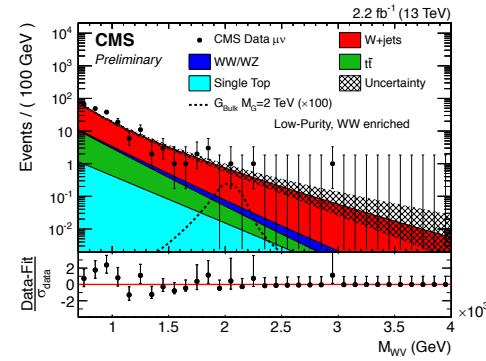


Background estimation

- Backgrounds from sidebands in the pruned jet mass for the leptonic analysis

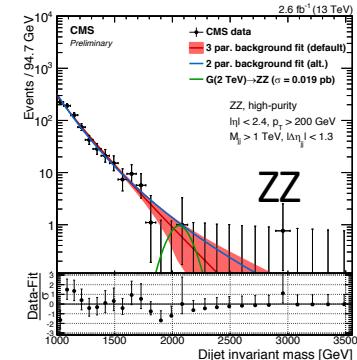
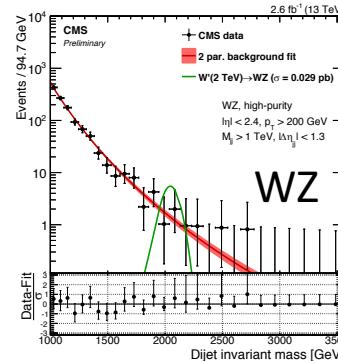


- $105 < M < 135$ GeV kept blinded (signal region for other analysis)

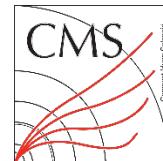


- For all-hadronic analysis, background and signal modelled using functional forms.

- Fit to the data



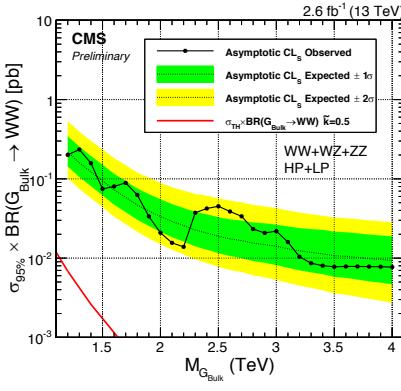
- Two parameter fit are used for WW/ WZ high purity category.
- Three parameter fit needed for ZZ category. Two parameter fit also tried.



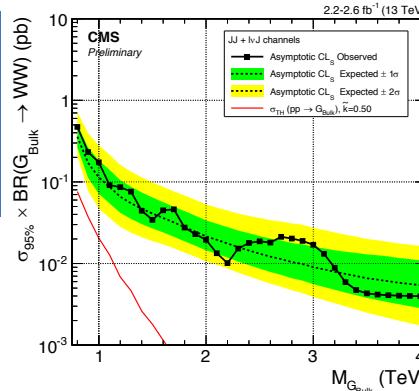
Results for WW/ WZ/ ZZ

- Limit on bulk gravitons in Warped extra dimensions

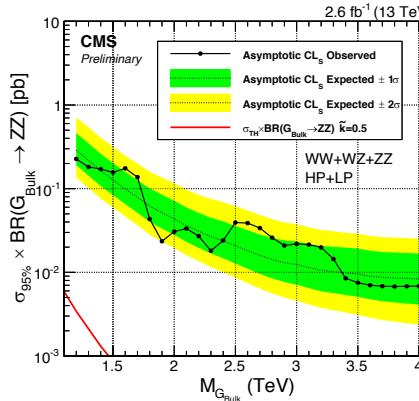
All-hadronic



Had-lep.

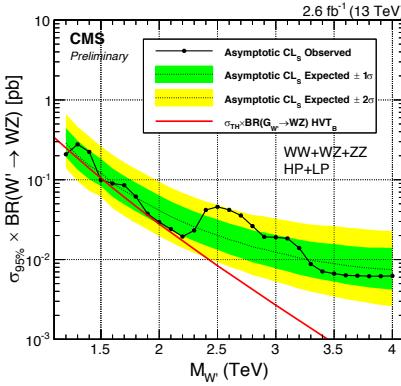


All-hadronic

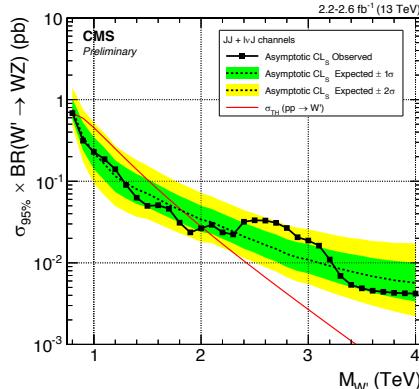


- Limit on W' in HVT model B

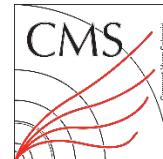
All-hadronic



Had-lep.

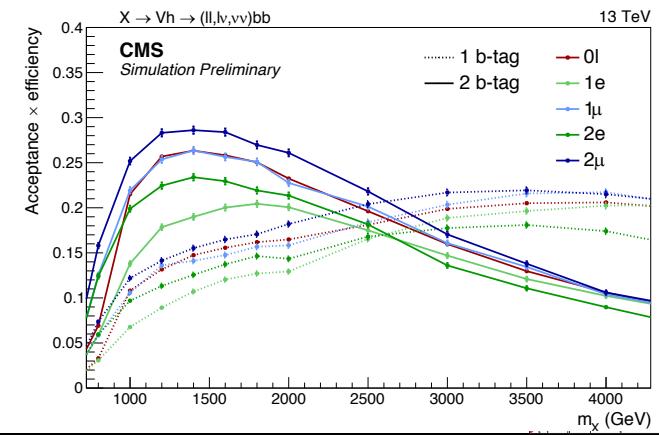
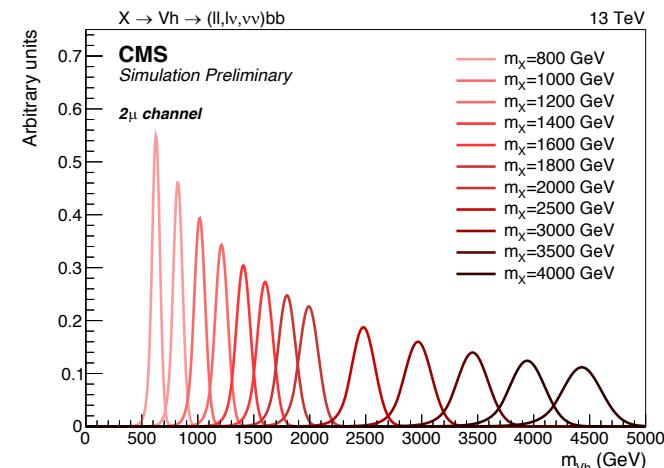


- Limit set on resonance branches between 800-4000 GeV.
- W' in HVT model B eliminated up to 2 TeV.



WH/ ZH \rightarrow llvv/ llvv/ vvbb

- ❑ 0, 1l, or 2l channels, depending on the V boson decay ($Z \rightarrow vv$, $W \rightarrow ll$, and $Z \rightarrow ll$, $l = e$ or μ).
- ❑ Mass reconstruction of resonance X
 - ❖ Reconstruction of m_{VH} for 1l and 2l final state.
 - ❖ Reconstruction of transverse mass m^T_{VH} for 0l final state.
- ❑ Higgs jet: $p_T(\text{AK8}) > 200 \text{ GeV}$ ❖ $105 < \text{pruned } M < 135 \text{ GeV}$ ❖ 1 or 2 subjets b tagged.
- ❑ vv channel: $E_T^{\text{miss}} > 200 \text{ GeV}$ ❖ No leptons with $p_T > 10 \text{ GeV}$ ❖ $\Delta\phi(E_T^{\text{miss}}, \text{all jet}) > 0.5$ ❖ $\Delta\phi(E_T^{\text{miss}}, \text{Higgs jet}) > 2$ ❖ No b tagged jets
- ❑ lv channel: $p_T(\mu/ e) > 55/ 135 \text{ GeV}$ ❖ $E_T^{\text{miss}} > 80 \text{ GeV}$ ❖ $\Delta\phi(E_T^{\text{miss}}, \text{jet}) > 2$ ❖ $\Delta\phi(l, E_T^{\text{miss}}) < 2$ ❖ $p_T(W \rightarrow lv) > 200 \text{ GeV}$
- ❑ ll channel: Same trigger and lepton selection as lv channel ❖ $70 < M(ll) < 110 \text{ GeV}$ ❖ $p_T(ll) > 200 \text{ GeV}$ ❖ $\Delta\eta(ll, \text{jet}) < 5$ ❖ $\Delta\phi(ll, \text{Higgs jet}) > 2.5$



Background estimation

□ SM backgrounds:

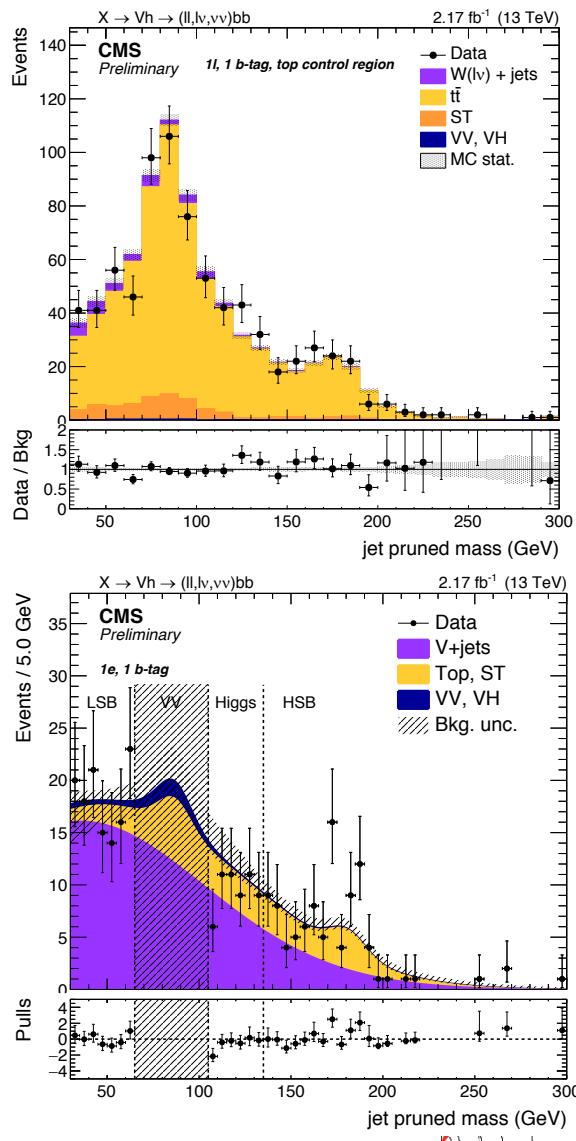
- ❖ DY+jets (using pruned mass sidebands)
- ❖ tt+jets and single top (events with b tagging)

□ Top background:

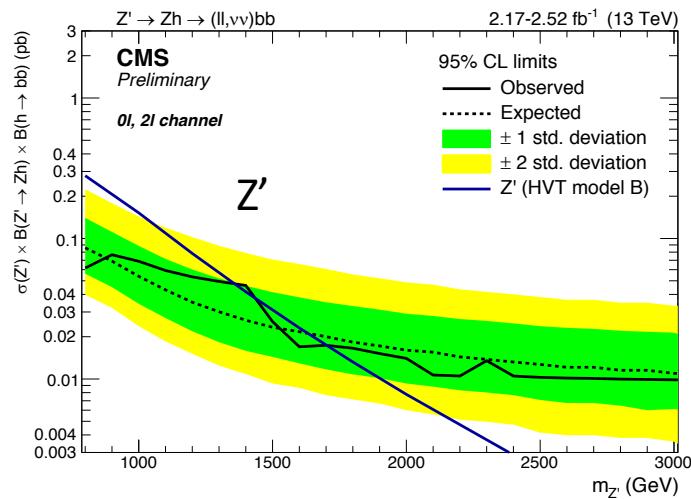
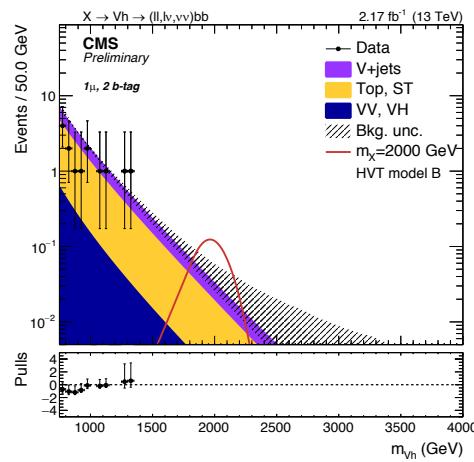
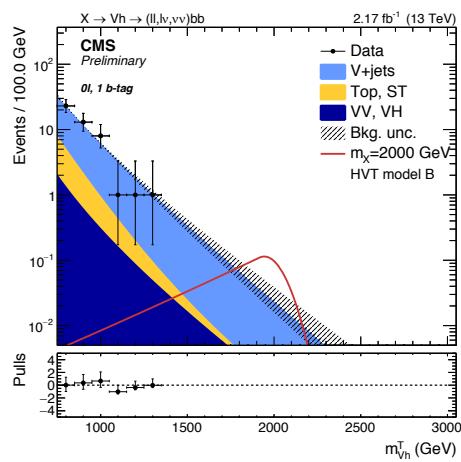
- ❖ Control samples with 0/ 1 lepton and 0/1 b-tagged subjects
- ❖ Require additional b-tagged AK4 jet to enrich in top quarks.
- ❖ Obtain da/MC normalization scale factor.
- ❖ Applied to top MC contribution in the signal region.

□ DY background:

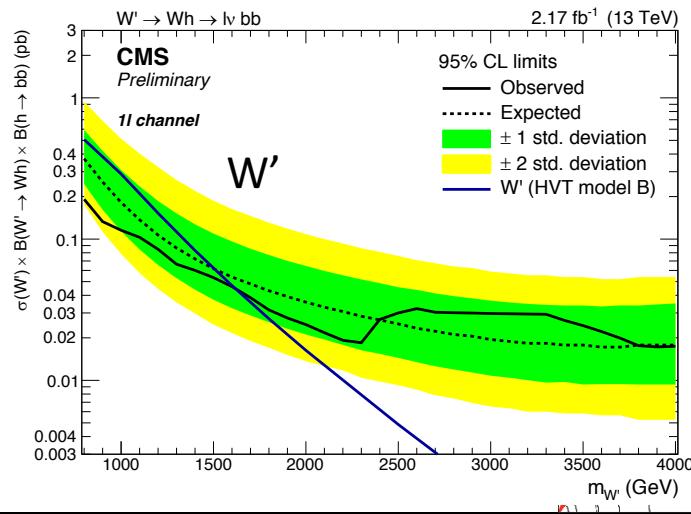
- ❖ Jet pruned mass m_j sidebands in data and MC are used:
 $30 < m_j < 65 \text{ GeV}$ and $m_j > 135 \text{ GeV}$.
- ❖ Data/MC scale factor is obtained for the m_j sideband by fitting the invariant mass



Results for WH/ ZH resonance



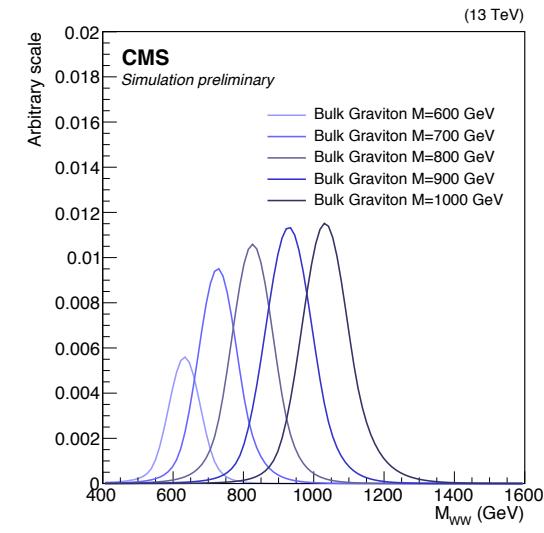
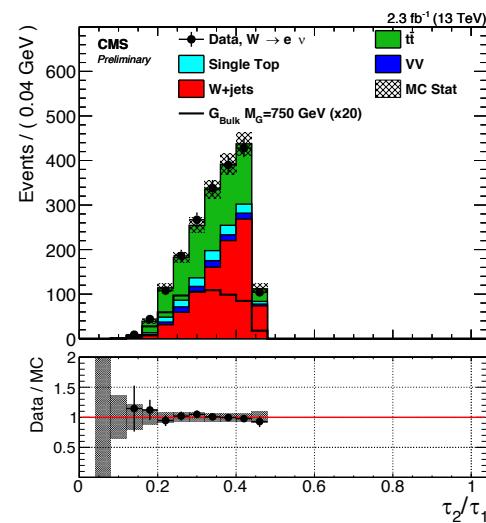
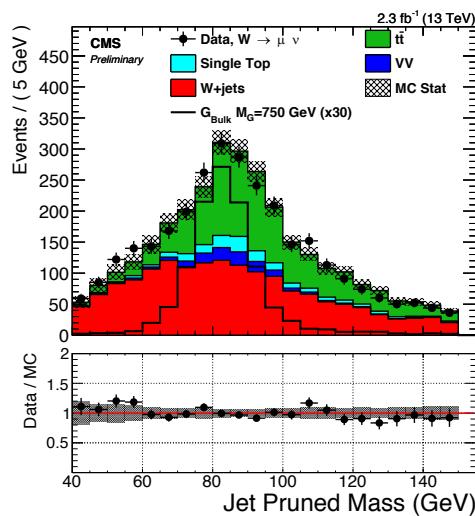
- ❑ Background/ signal shapes fit to the data distribution
- ❑ No excess found.
- ❑ Limits set on spin 1 W' and spin Z' cross section.
- ❑ Interpreted in terms of HVT model B



WW resonance

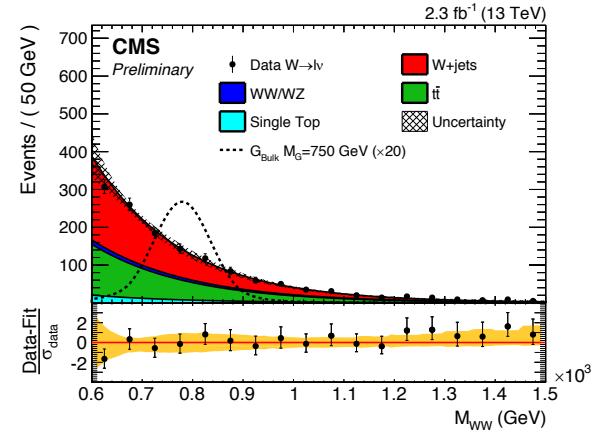
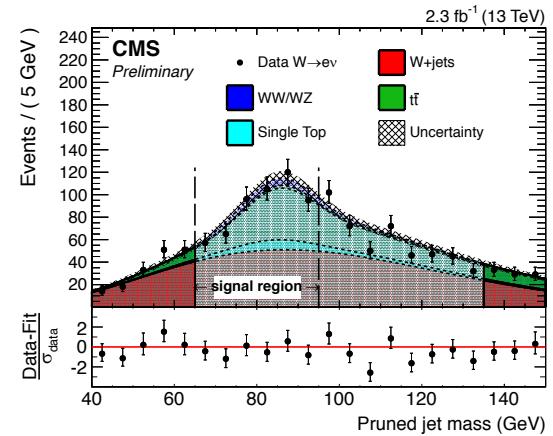
Semileptonic final state at low mass extension

- ❑ Low mass resonance search: 600-1000 GeV
 - ❖ One isolated muon(electron) with $p_T > 40$ (45) GeV
 - ❖ $E_T^{\text{miss}} > 40$ (80) GeV for muon (electron) channel
 - ❖ W tagging with AK8 jets: $65 < \text{pruned mass} < 95$ GeV
 - ❖ $\tau_2/\tau_1 < 0.45$
- ❑ Leptonic W reconstructed from lv and paired with hadronic W jet
 - ❖ $pT(W) > 200$ GeV
 - ❖ $\Delta\phi(WW) > 2$
 - ❖ b jet veto to reduce tt+jets



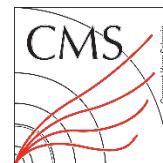
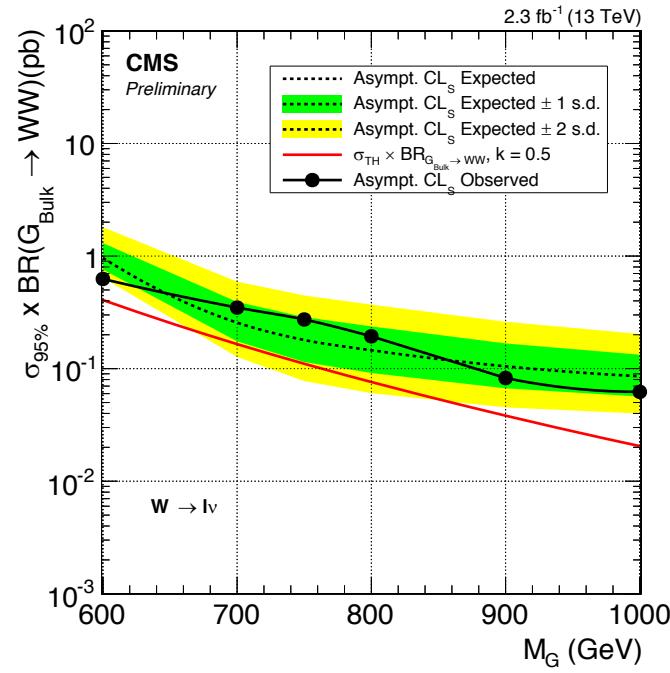
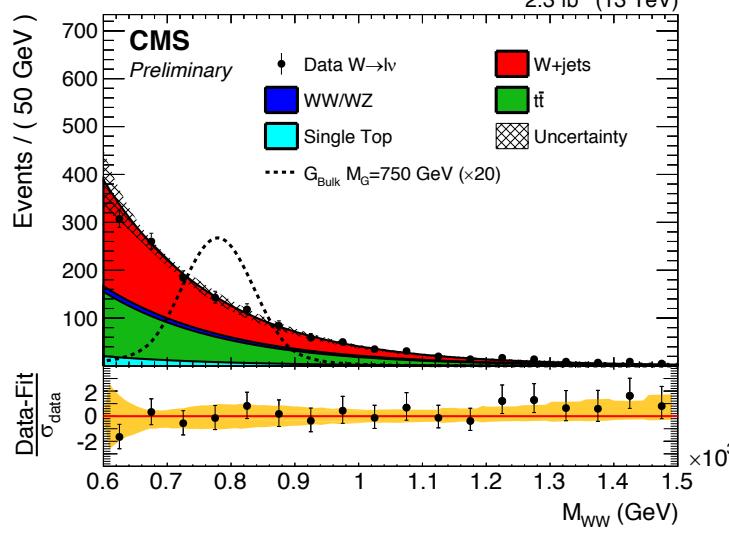
Background estimation

- Main backgrounds from SM: W+jets and tt+jets
- W+jets background:
 - ❖ WW invariant mass m_{WW} modelled in pruned mass sidebands:
 - ❖ $40 < \text{pruned pass} < 65 \text{ GeV}$ and $135 < \text{pruned mass} < 150 \text{ GeV}$
 - ❖ MC ratio $\alpha_{\text{MC}}(m_{WW})$ in signal region to sideband region obtained.
 - ❖ Background in signal region in data by rescaling m_{WW} in data sideband by $\alpha_{\text{MC}}(m_{WW})$.
- tt+jets background:
 - ❖ Control region selection:
Lepton + AK8 jet tagged as a W jet + b-tagged AK4 jet
 - ❖ Enriched in semileptonic top tt+jets
 - ❖ Data/ MC scale factors are derived:
muon-channel: 0.847 ± 0.049 and
electron channel: 0.865 ± 0.084 .



Results

- Data consistent with predicted background in the m_{WW} mass spectrum.
- Limit set on WW resonance combining muon and electron channel.
- Limit set on bulk graviton cross sections for different masses in warped extra dimension models ($\kappa/\sqrt{M_{Pl}} = 0.5$).

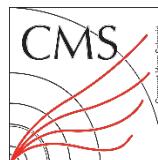


WW, WZ, ZZ, WH, and ZH 8+13 TeV combination

- Combining 8 and 13 TeV diboson resonance searches.
 - ❖ 19.6 fb⁻¹ at $\sqrt{s} = 8$ TeV and 2.2 - 2.6 fb⁻¹ data at $\sqrt{s} = 13$ TeV.
 - ❖ Combination performed for mass above 0.8 TeV
- Interpretation:
 - ❖ W'/Z' in heavy vector triplet models decaying to WZ/ WH/ ZZ/ ZH
 - ❖ Bulk gravitons decaying to WW or ZZ

particle	spin	charge	decay	production	W/Z polarization
W'	1	charged	mainly WZ, WH	mainly $q\bar{q}^{(\prime)}$	mostly longitudinal
Z'	1	neutral	mainly WW, ZH	mainly $q\bar{q}$	mostly longitudinal
G_{bulk}	2	neutral	mainly WW, ZZ	mainly gg	mostly longitudinal

- ❖ All resonances assumed to be narrow compared to the experimental mass resolution.

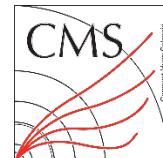


WW, WZ, ZZ, WH, and ZH 8+13 TeV combination procedure

- ❑ Combination using likelihood function for each analysis.
 - ❖ Histogram binned as a function of the diboson invariant mass for 3lv, $q\bar{q}q\bar{q}$, $q\bar{q}b\bar{b}$, $q\bar{q}q\bar{q}q\bar{q}$, $q\bar{q}\tau\tau$
 - ❖ Analytical function of diboson invariant mass for $l\nu q\bar{q}$, $l\nu b\bar{b}$.
- ❑ Systematic uncertainties treated as nuisance parameters modelled using log-normal priors and profiled.
 - ❖ Uncertainties are either fully correlated or fully uncorrelated.

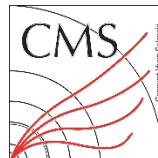
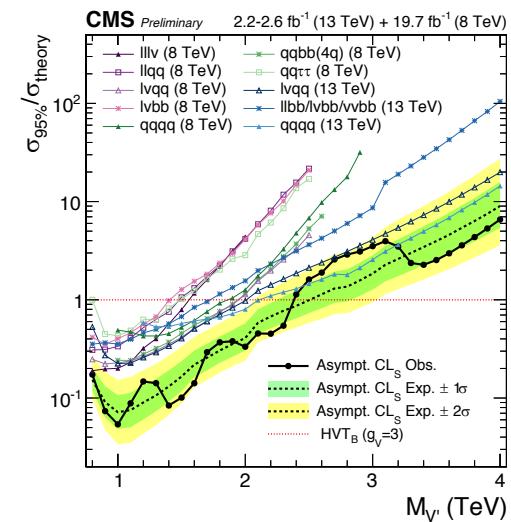
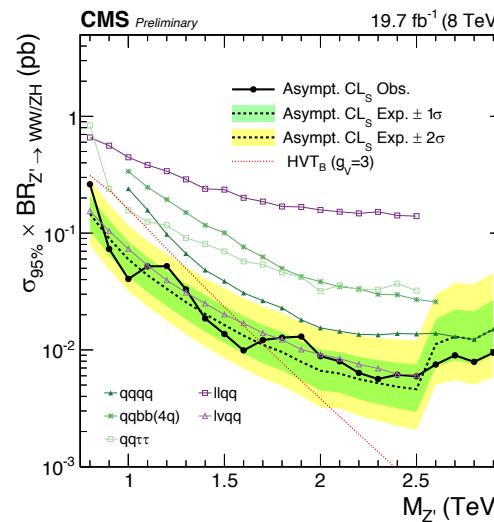
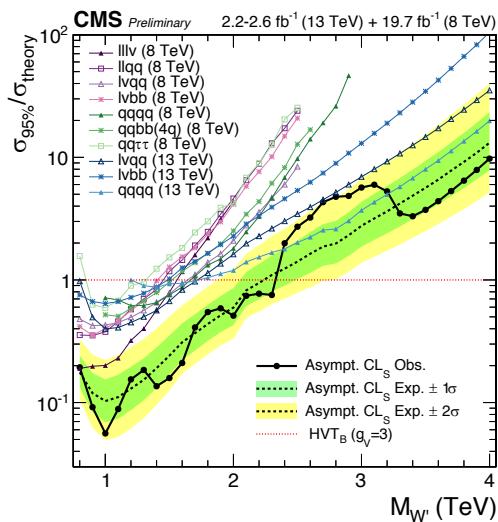
Correlation
of systematic
uncertainties

Systematic uncertainty	Type	8+13 TeV	$e+\mu$	HP+LP	W+Z
Lepton trigger	yield	no	no	yes	yes
Lepton identification	yield	no	no	yes	yes
Lepton momentum scale	yield, shape	no	no	yes	yes
Jet energy scale	yield, shape	no	yes	yes	yes
Jet energy resolution	yield, shape	no	yes	yes	yes
Jet mass scale	yield	no	yes	yes	yes
Jet mass resolution	yield	no	yes	yes	yes
b tagging	yield	no	yes	yes	yes
W tagging (HP/LP)	yield	no	yes	yes	yes
Integrated luminosity	yield	no	yes	yes	yes
Pileup	yield	no	yes	yes	yes
PDF	yield	yes	yes	yes	yes
μ_f, μ_r scales	yield	yes	yes	yes	yes



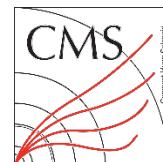
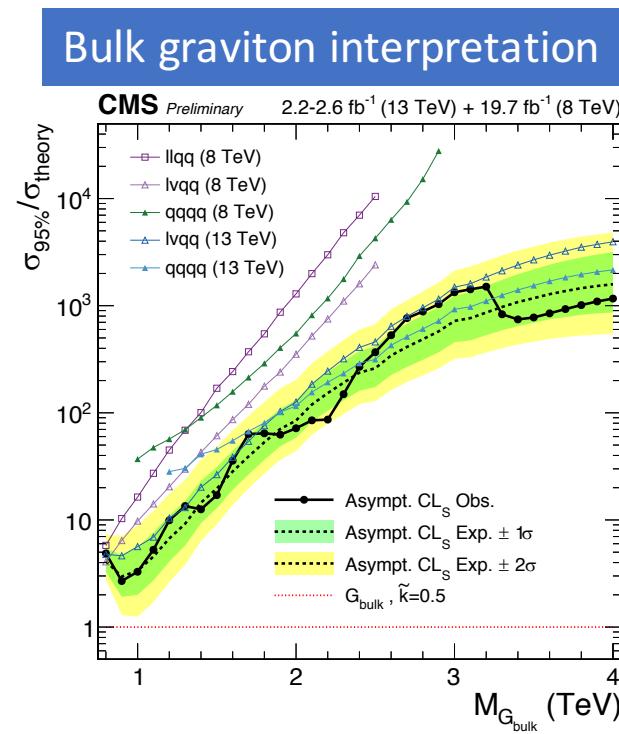
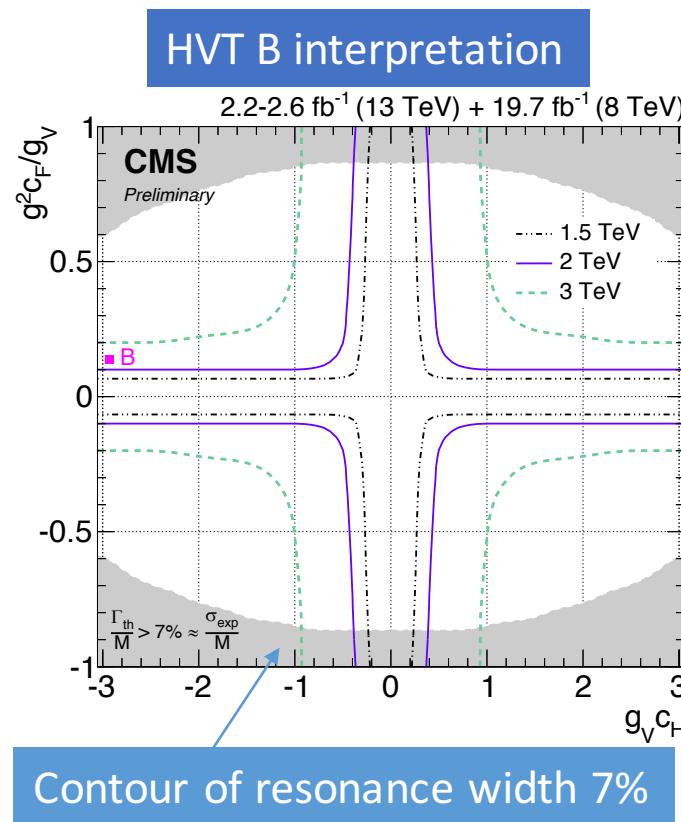
W' and Z' combination results

- ❑ Exclusion limit in range $0.8 < \text{resonance mass} < 4 \text{ TeV}$
- ❑ 13 TeV results dominate for high masses.
- ❑ For HVT interpretation the W' and Z' production cross section times branching fractions to different decay channels are combined.

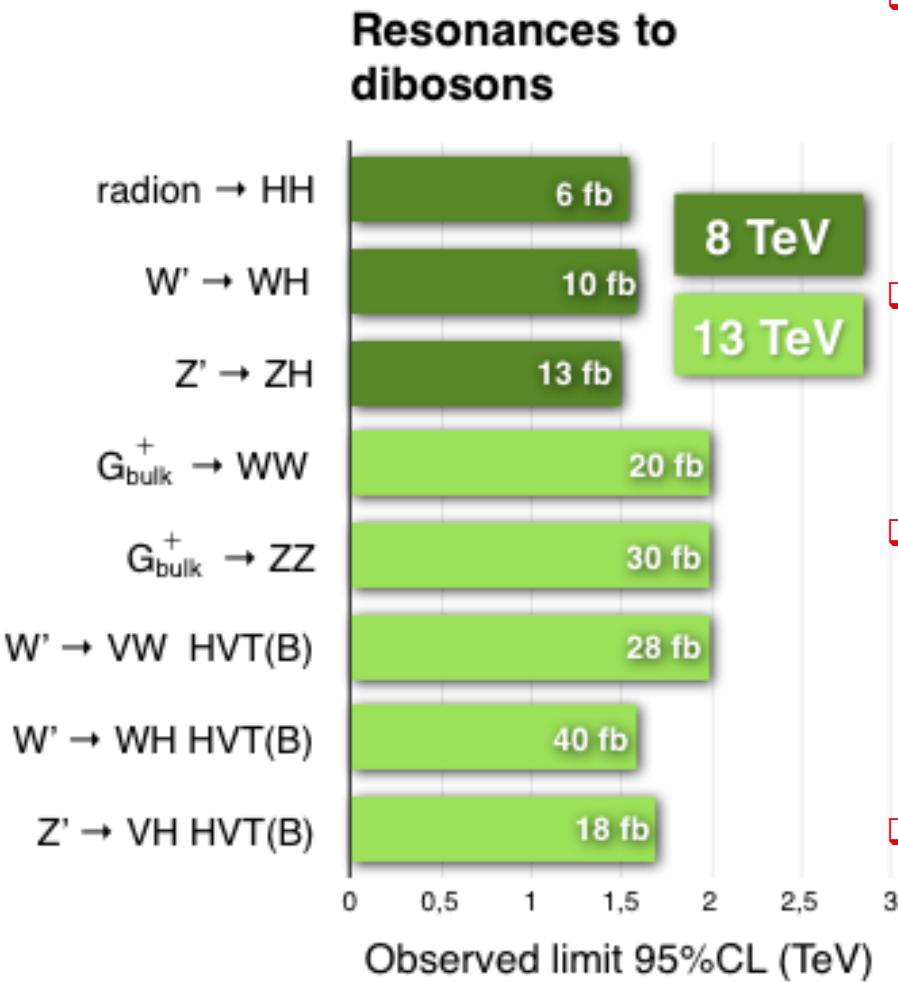


WW, WZ, ZZ, WH, and ZH 8+13 TeV combination

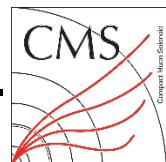
- Combination of 8 TeV (19.7 fb^{-1}) and 13 TeV (2.3 fb^{-1})



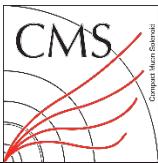
Summary



- ❑ CMS search for diboson resonances with first 13 TeV data performed.
- ❑ Significant coverage of new mass range. No excesses found.
- ❑ Combined results of 8+13 TeV set most stringent bounds on W'/Z' and spin 2 resonances.
- ❑ New 13 TeV data pours in. Challenging but exciting new grounds to cover. Stay tuned.

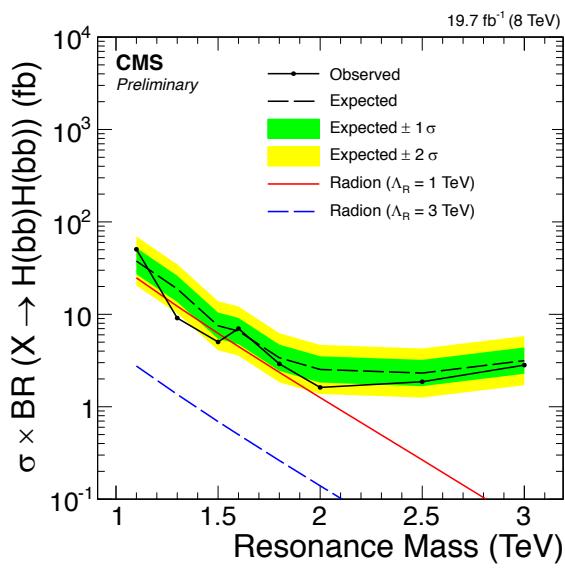
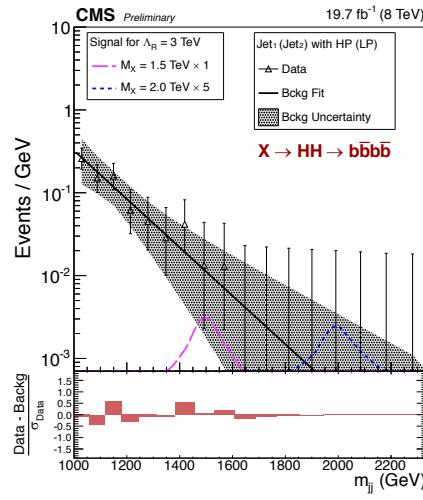


BACKUP

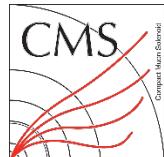
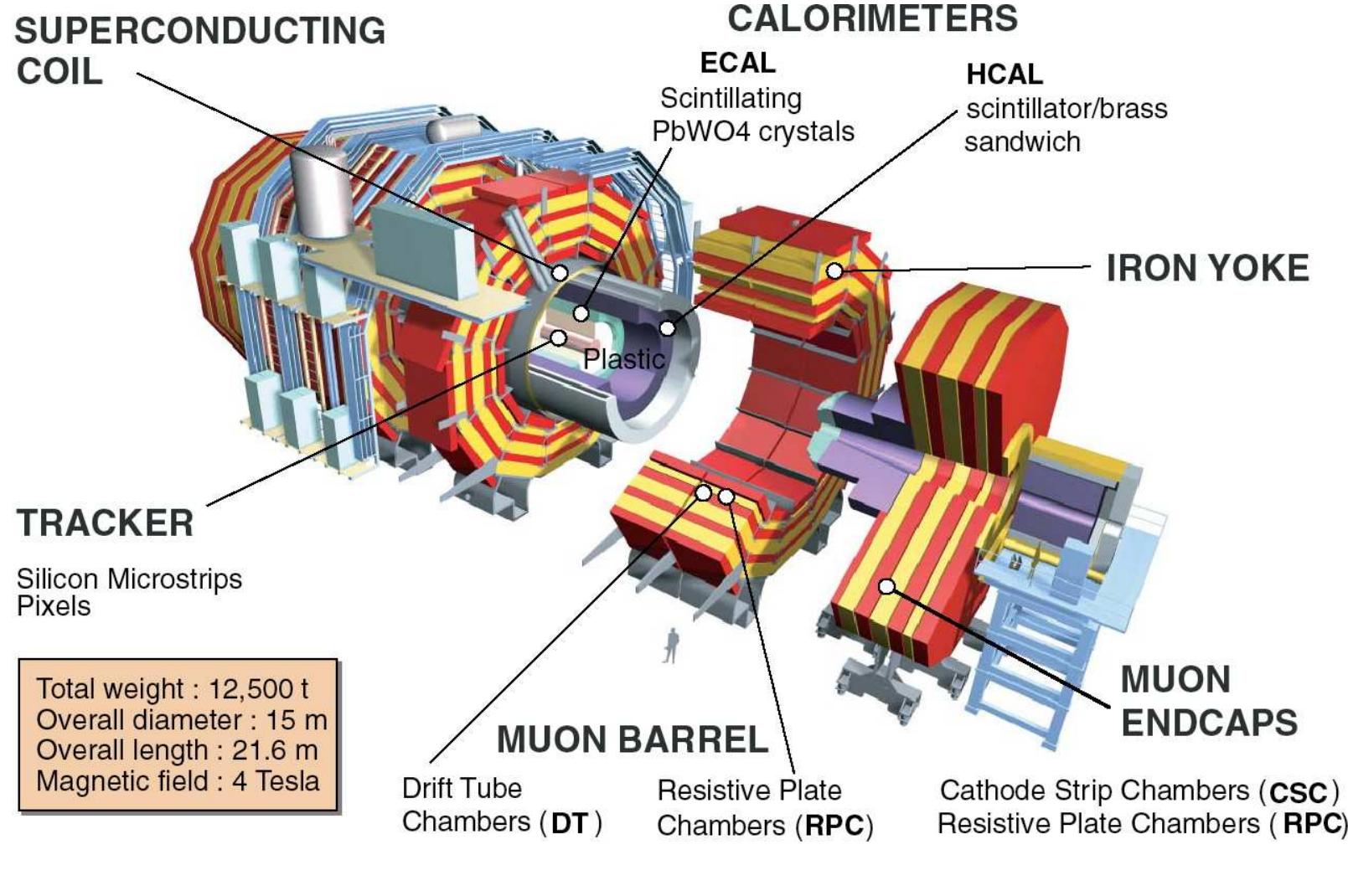


HH->bbbb: 8 TeV analysis

- ❑ Resonance X decaying to HH
 - ❖ Both Higgs decaying through H->bb
- ❑ Higgs jet reconstruction using pruned jet mass, substructure (τ_2/τ_1 and b-tagged subjets).
- ❑ Events categorized as leading (subleading)jet having
 - ❖ $\tau_2/\tau_1 < 0.5$ (high purity)
 - ❖ $0.5 < \tau_2/\tau_1 < 0.75$ (low purity).
- ❑ Exclusion limit set on radions in warped extra dimension models
- ❑ Main background is SM multijets production.
- ❑ Background modelled as a falling exponential.
- ❑ Radion ($\Lambda_R = 1$ TeV) below 1.4 TeV excluded



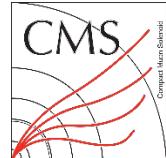
The CMS detector



WW, WZ, ZZ, WH, and ZH 8+13 TeV combination

- Signal efficiencies in percentage in various channels:

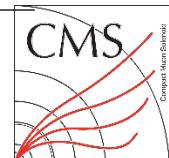
Channel	HVT				RS bulk	
	W'		Z'		WW HP/LP	ZZ HP/LP
	WZ HP/LP	WH HP/LP	WW HP/LP	ZH HP/LP		
q \bar{q} q \bar{q} (8 TeV)	5.9/5.5	0.8/0.7	5.7/5.3	0.8/0.7	3.8/3.1	5.7/4.2
$\ell\nu$ q \bar{q} (8 TeV)	4.8/-	-	9.4/-	-	10.6/7.1	-
$\ell\ell$ q \bar{q} (8 TeV)	1.1/-	-	-	0.2/-	-	3.0/1.0
3 $\ell\nu$ (8 TeV)	0.6	-	-	-	-	-
q \bar{q} q \bar{q} (13 TeV)	5.0/10.1	1.8/2.5	4.2/8.7	1.9/2.6	4.5/10.2	5.7/11.2
$\ell\nu$ q \bar{q} (13 TeV)	9.4/0.5	1.7/0.2	19.0/1.1	-	16.7/1.0	-
q \bar{q} b \bar{b} /q \bar{q} q \bar{q} q \bar{q} (8 TeV)	-	3.0/1.8	-	1.7/1.1	-	-
$\ell\nu$ b \bar{b} (8 TeV)	-	0.9	-	-	-	-
q \bar{q} $\tau\tau$ (8 TeV)	-	1.2	-	1.3	-	-
$\ell\ell$ b \bar{b} (13 TeV)	-	-	-	1.5	-	-
$\ell\nu$ b \bar{b} (13 TeV)	-	4.0	-	-	-	-
$\nu\nu$ b \bar{b} (13 TeV)	-	-	-	4.2	-	-



WW, WZ, ZZ, WH, and ZH 8+13 TeV combination

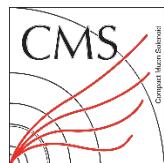
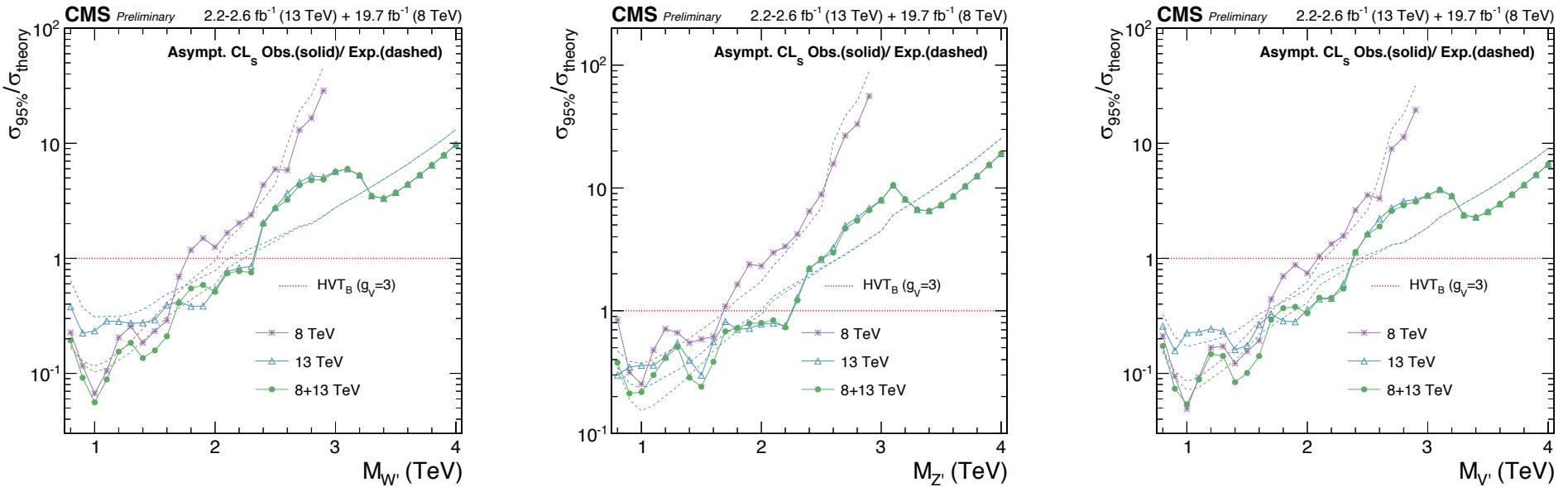
- Background estimation methods in various channels:

Channel	Main background	Estimation method
$q\bar{q}q\bar{q}$ (8 TeV)	QCD multijets	parametrized by smooth function
$\ell\nu q\bar{q}$ (8 TeV)	W+jets	normalization and shape from data in sidebands: m_{jet} in [40, 65] and [105, 130] GeV
$\ell\ell q\bar{q}$ (8 TeV)	Z+jets	normalization and shape from data in sidebands: m_{jet} in [50, 70] and [110, 130] GeV
$q\bar{q}q\bar{q}$ (13 TeV)	QCD multijets	parametrized by smooth function
$\ell\nu q\bar{q}$ (13 TeV)	W+jets	normalization and shape from data in sidebands: m_{jet} in [40, 65] and [135, 150] GeV
$q\bar{q}b\bar{b}/q\bar{q}q\bar{q}q\bar{q}$ (8 TeV)	QCD multijets	data driven
$\ell\nu b\bar{b}$ (8 TeV)	W+jets	normalization and shape from sidebands: m_{jet} in [40, 110] and [135, 150] GeV
$q\bar{q}\tau\tau$ (8 TeV)	Z/γ +jets $t\bar{t}$, QCD multijets	data driven estimate from control regions
$\ell\ell b\bar{b}/\ell\nu b\bar{b}/\nu\nu b\bar{b}$ (13 TeV)	V+jets	normalization and shape from data in sidebands: m_{jet} in [30, 65] and > 135 GeV



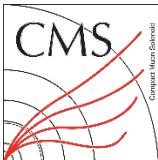
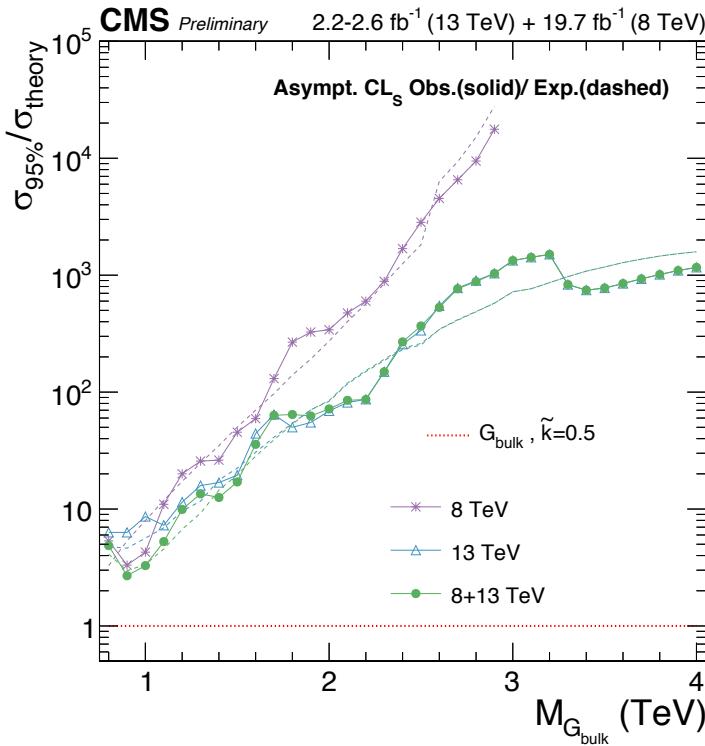
W' and Z' combination

Comparing 8, 13 and 8+13 TeV limits



Bulk graviton combination

Comparing 8, 13 and 8+13 TeV limits



VV 8+13 TeV combination

Statistical significance of excesses

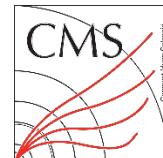
Combination	W'	Z'	HVT ($W' + Z'$)	G_{bulk}
VV 13 TeV	0.00	0.10	0.00	0.00
VV+VH 13 TeV	0.00	0.00	0.00	-
VV 8 TeV	1.22	0.56	1.03	1.61
VV 8+13 TeV	0.20	0.46	0.33	0.35
VH 8 TeV	2.05	0.56	1.79	-
VV+VH 8 TeV	2.22	0.77	1.95	-
VV+VH 8+13 TeV	0.86	0.00	0.83	-

Significance at $M_X = 1.8 \text{ TeV}$

Combination	W'	Z'	HVT ($W' + Z'$)	G_{bulk}
VV 13 TeV	0.00	0.07	0.00	0.00
VV+VH 13 TeV	0.00	0.00	0.00	-
VV 8 TeV	0.77	0.75	0.76	0.44
VV 8+13 TeV	0.23	0.45	0.29	0.06
VH 8 TeV	0.00	0.00	0.00	-
VV+VH 8 TeV	0.58	0.60	0.48	-
VV+VH 8+13 TeV	0.00	0.00	0.00	-

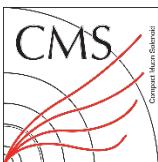
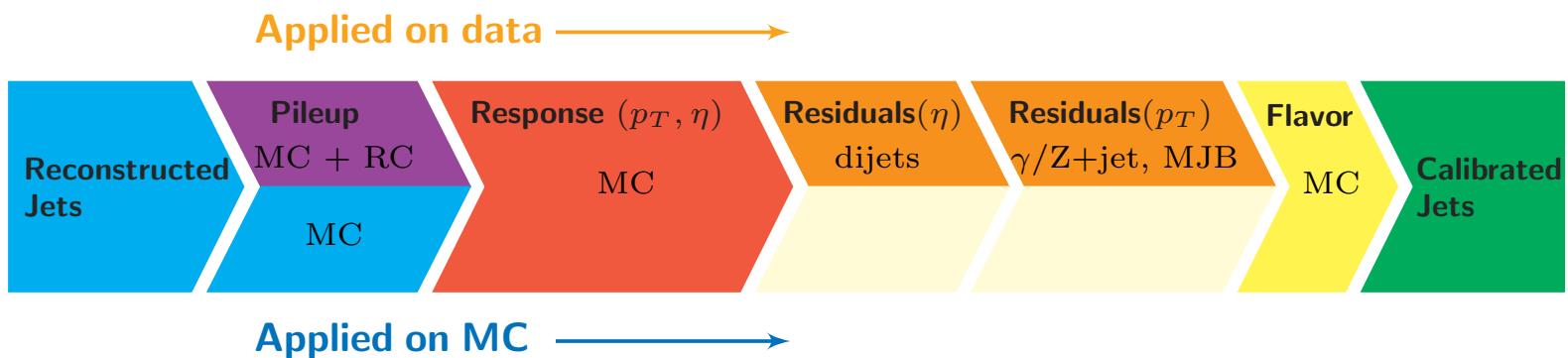
Significance at $M_X = 2 \text{ TeV}$

Combination	W'	Z'	HVT ($W' + Z'$)	G_{bulk}
VV 13 TeV	0.00	0.05	0.00	0.00
VV+VH 13 TeV	0.00	0.00	0.00	-
VV 8 TeV	1.20	0.46	0.91	1.05
VV 8+13 TeV	0.00	0.30	0.00	0.00
VH 8 TeV	2.17	1.41	1.78	-
VV+VH 8 TeV	2.32	1.02	1.89	-
VV+VH 8+13 TeV	0.33	0.00	0.20	-



CMS jet energy corrections

CMS-JME-13-004



LHC+CMS performance

CMS Integrated Luminosity, pp, 2015, $\sqrt{s} = 13 \text{ TeV}$

