

Recent B2G Search Highlights from CMS

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on behalf of the CMS Collaboration

B2G Spring Workshop — Hamburg, Germany
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Introduction

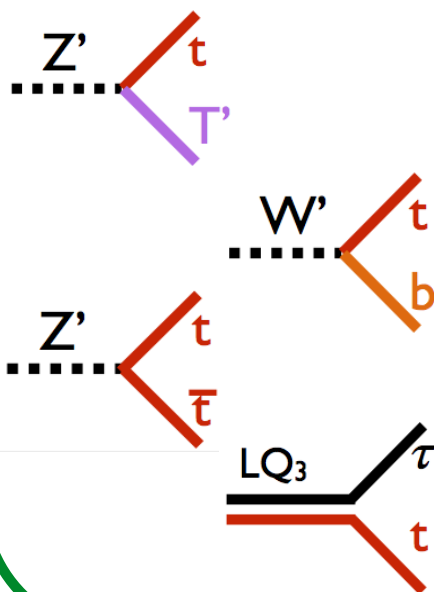
▶ What is the B2G group?

- ▶ "Beyond 2 Generations"
- ▶ Crossroads with CMS Exotica, SUSY groups

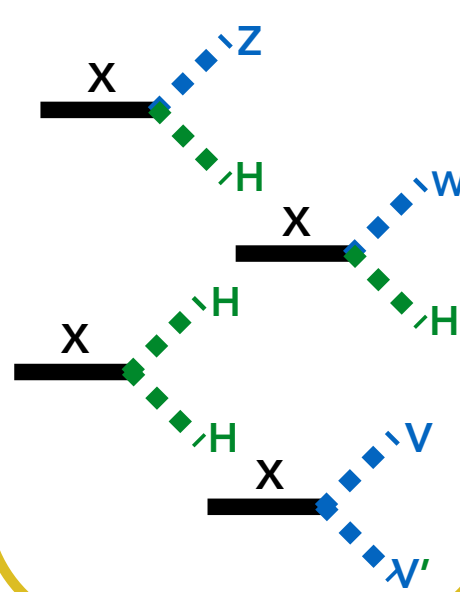
- ▶ Searches for new physics in unique topologies
 - ▶ 4th generation or new resonance production; decays to 3rd generation SM quarks / gauge bosons

Beyond 2 Generations Searches

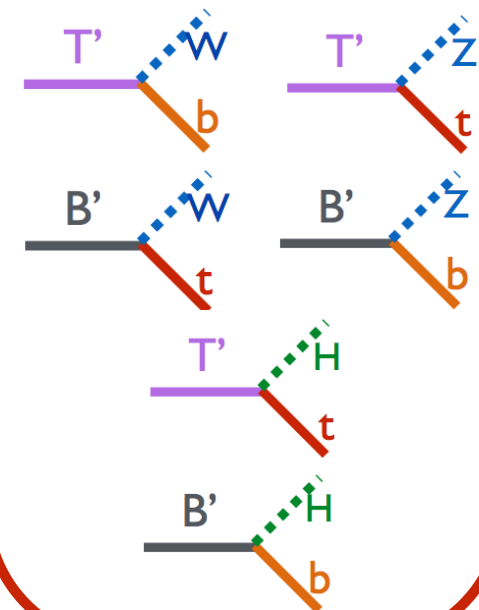
Resonances



Dibosons

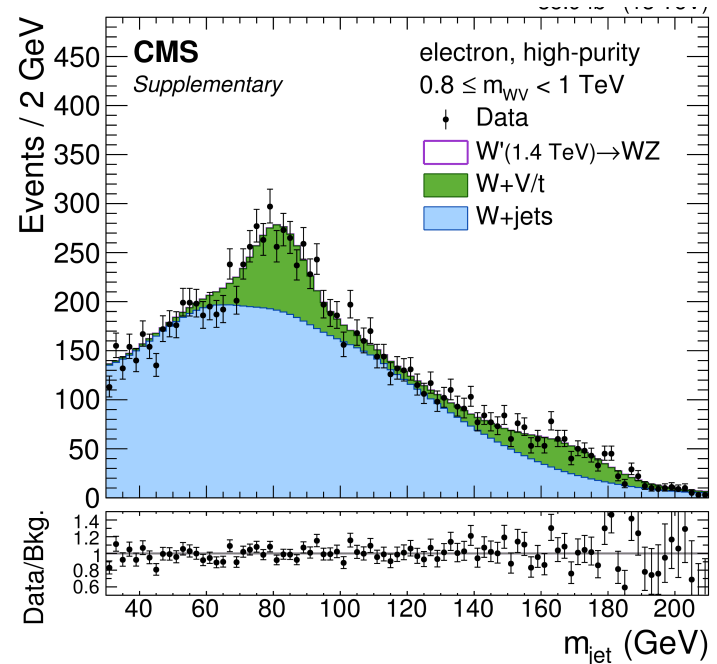
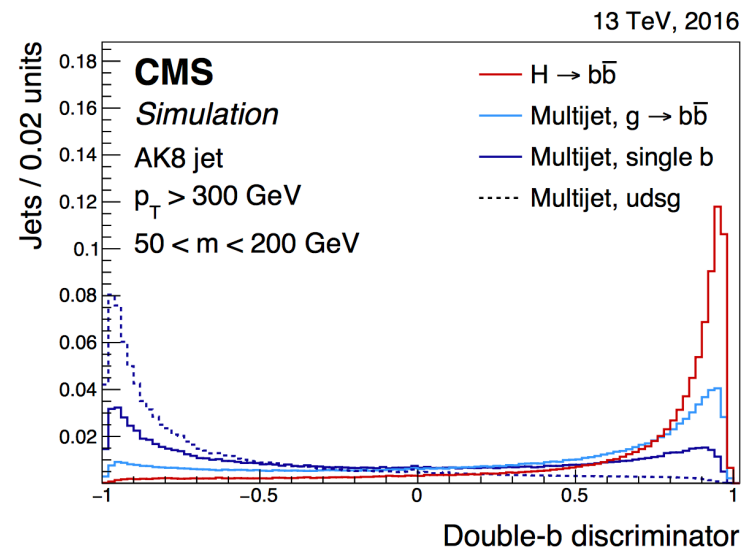
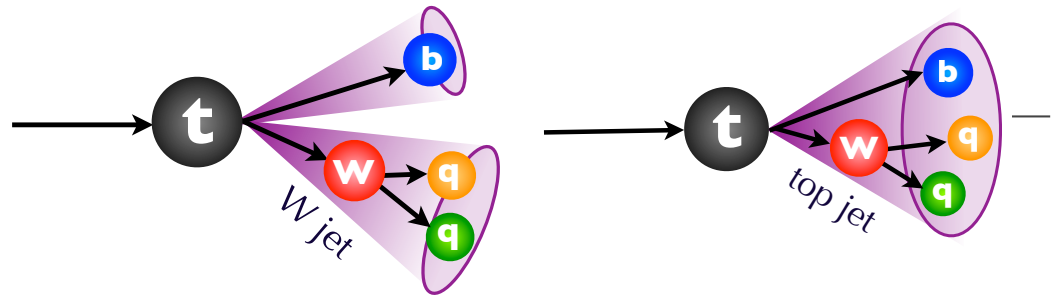


Heavy Quarks



Key Points

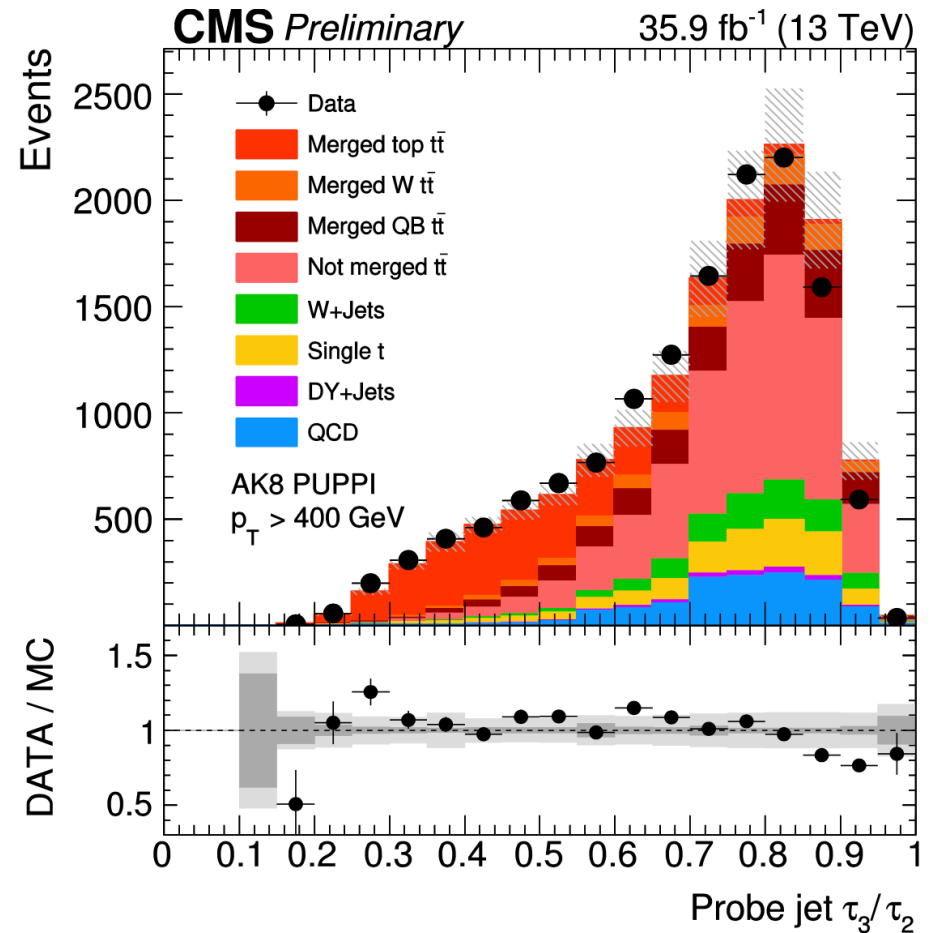
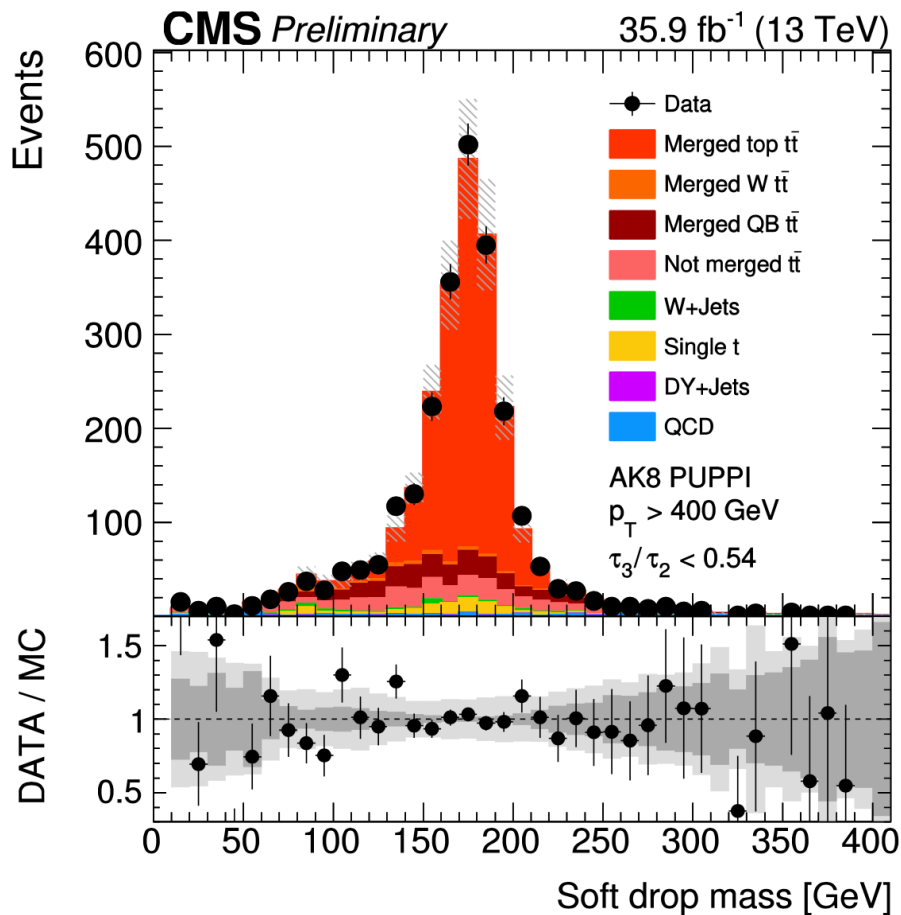
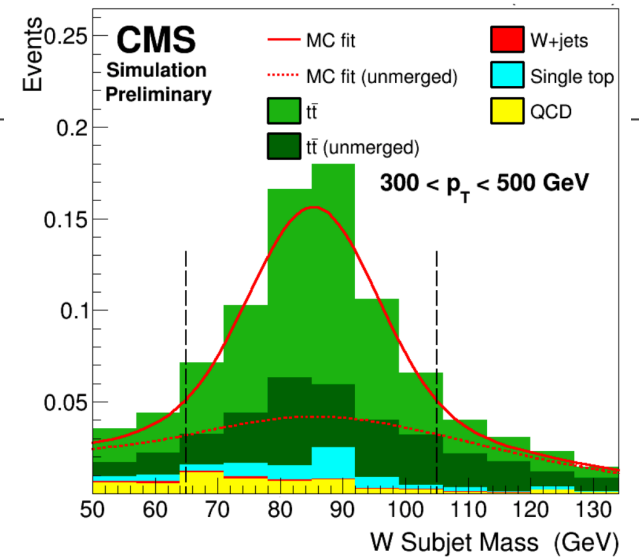
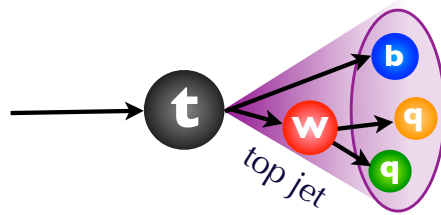
- ▶ Decays of massive particles produce highly Lorentz-boosted SM objects
 - ▶ **Jet substructure techniques critical to B2G searches**
 - ▶ Active in commissioning + validating new tools
- ▶ **Take advantage of ever-increasing knowledge of Higgs boson**
 - ▶ Double-b-tagging
 - ▶ Higgs jet tagging with substructure quantities
- ▶ Huge amount of data to analyze
 - ▶ **Develop and rely on data-driven methods** to estimate challenging backgrounds



Jet Substructure

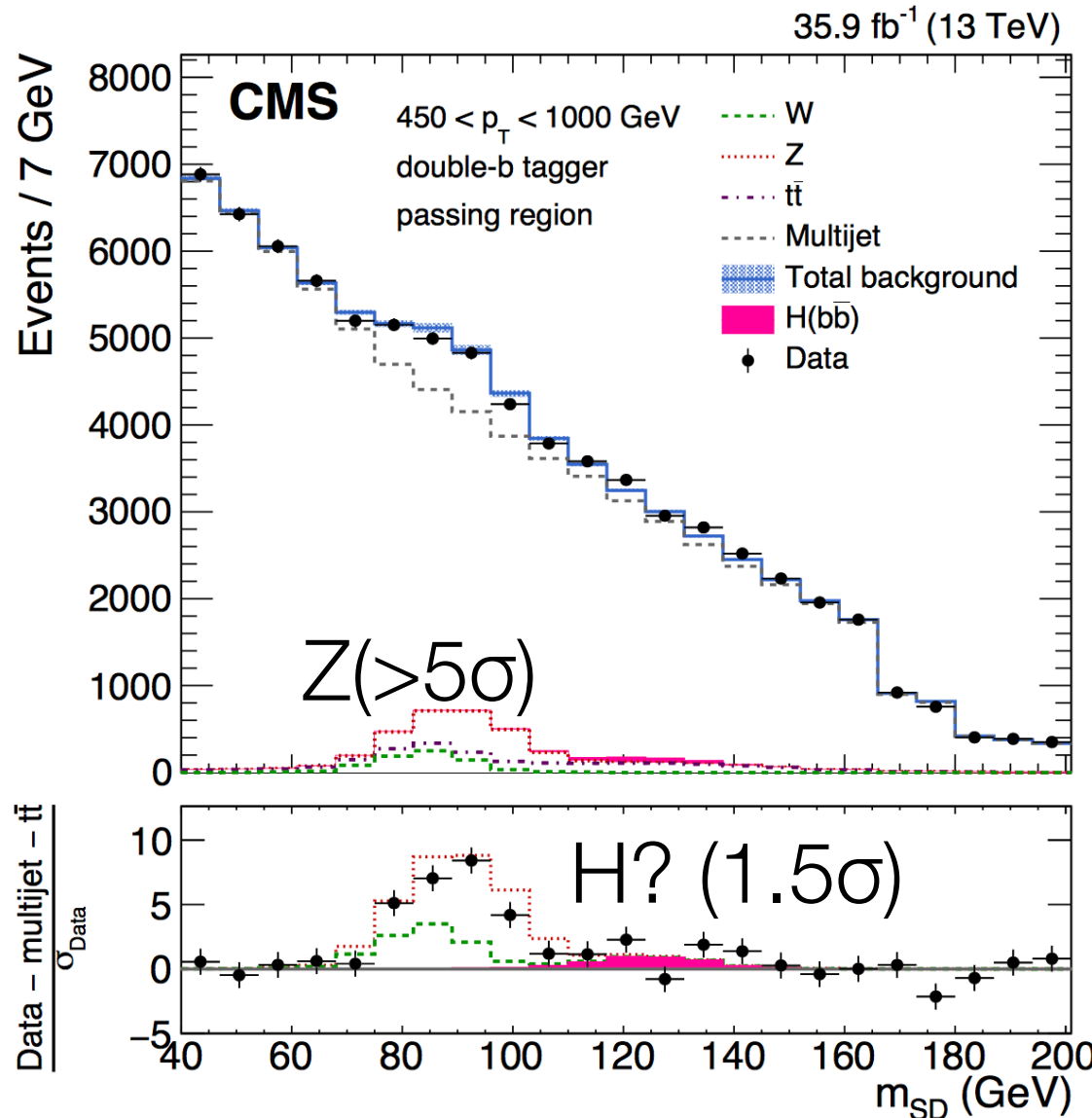
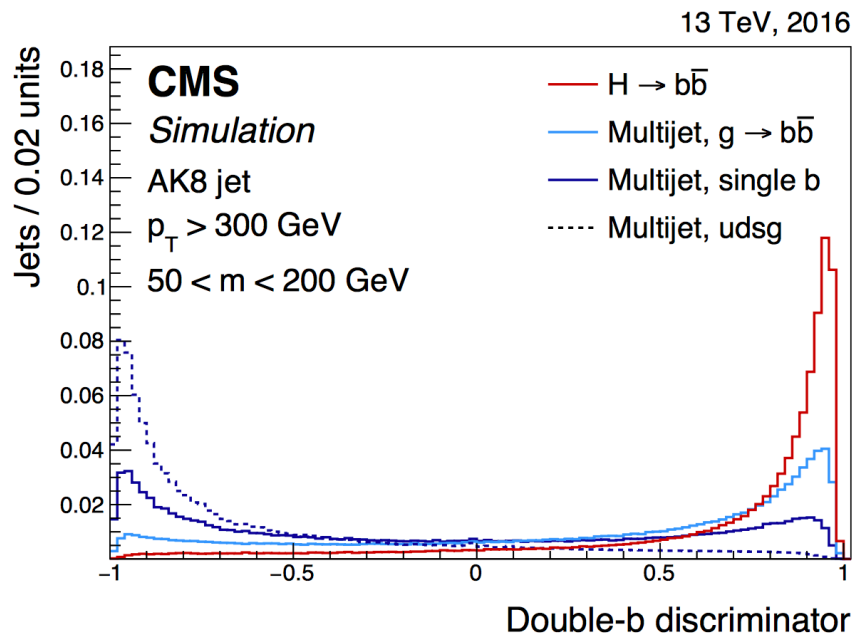
CMS DP-17-026

- ▶ Top/W tagging in large-radius (AK8) jets now widespread in CMS
 - ▶ Based on soft-drop mass, N-subjettiness cuts



Higgs Tagging

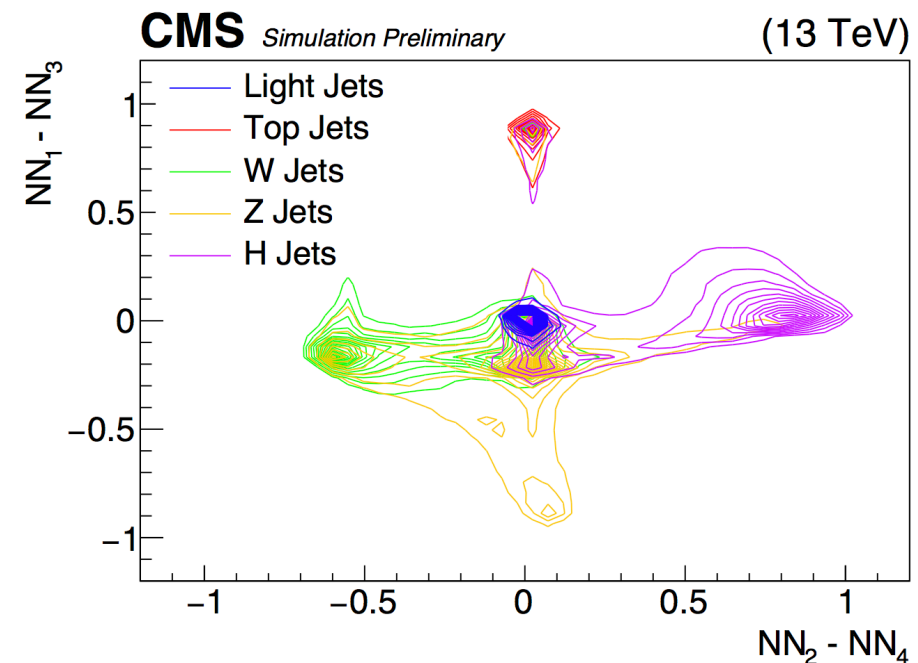
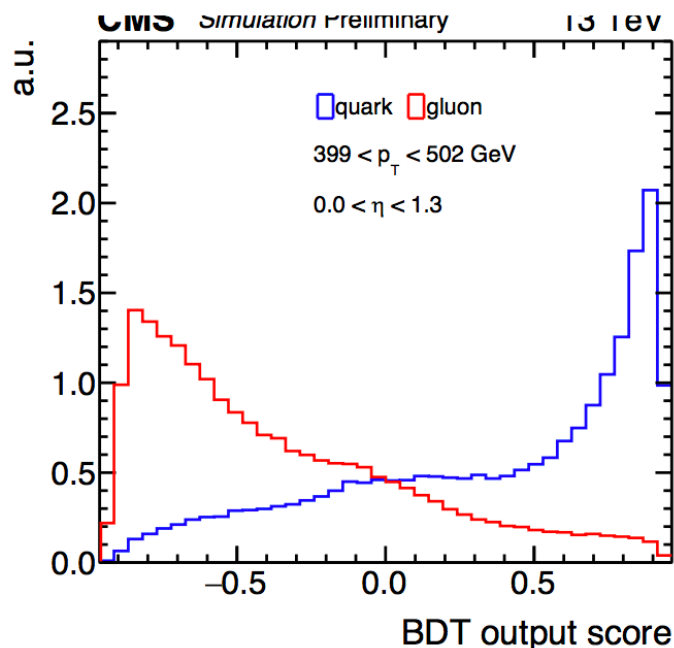
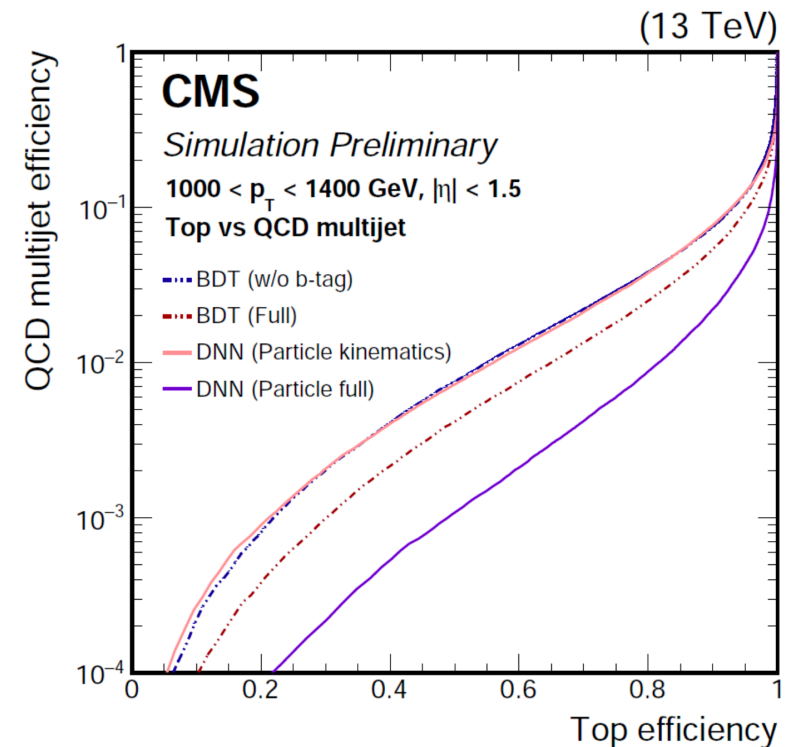
- ▶ Techniques for top/W/Z-tagging well established and commissioned
 - ▶ Move to Higgs tagging optimization
- ▶ Double-b tagger provides increased efficiency
 - ▶ BDT used with track, secondary vertex, substructure inputs
 - ▶ Validated in $Z \rightarrow b\bar{b}$, $g \rightarrow b\bar{b}$
 - ▶ Moving to deep NN structure



Jet Substructure Development

CMS DP-17-027

- ▶ New tools currently being developed and commissioned for future analyses
- ▶ Deep NNs using particle-level inputs instead of kinematic quantities
- ▶ Multiclassification algorithms
 - ▶ Simultaneously target t/W/Z/H/b/QCD jets
- ▶ Quark vs gluon discrimination

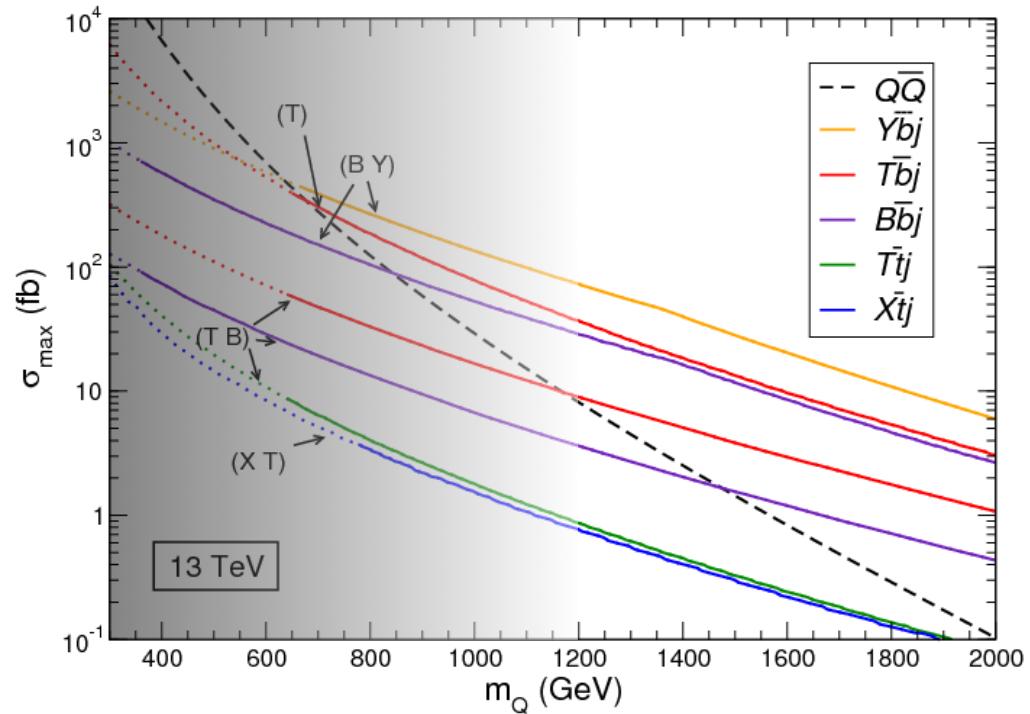


Vector-Like Quarks

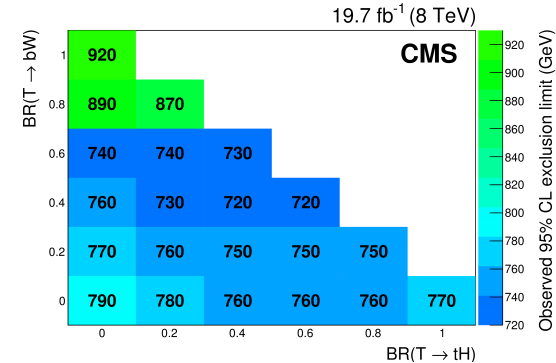
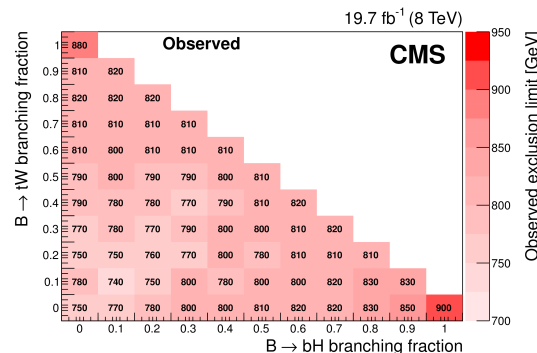
- ▶ A special type of 4th generation particle predicted by many models
 - ▶ Non-typical Higgs coupling
 - ▶ Solves hierarchy problem while escaping Higgs cross section constraints

- ▶ Different decay modes possible
 - ▶ $B \rightarrow tW, bZ, bH$
 - ▶ $T \rightarrow bW, tZ, tH$
- ▶ **With high p_T T/B — heavy reliance on jet substructure techniques for reconstruction!**

- ▶ Diverse final states possible when considering pair production
 - ▶ Single production also important at 13 TeV



- ▶ “Examine triangles, not points”

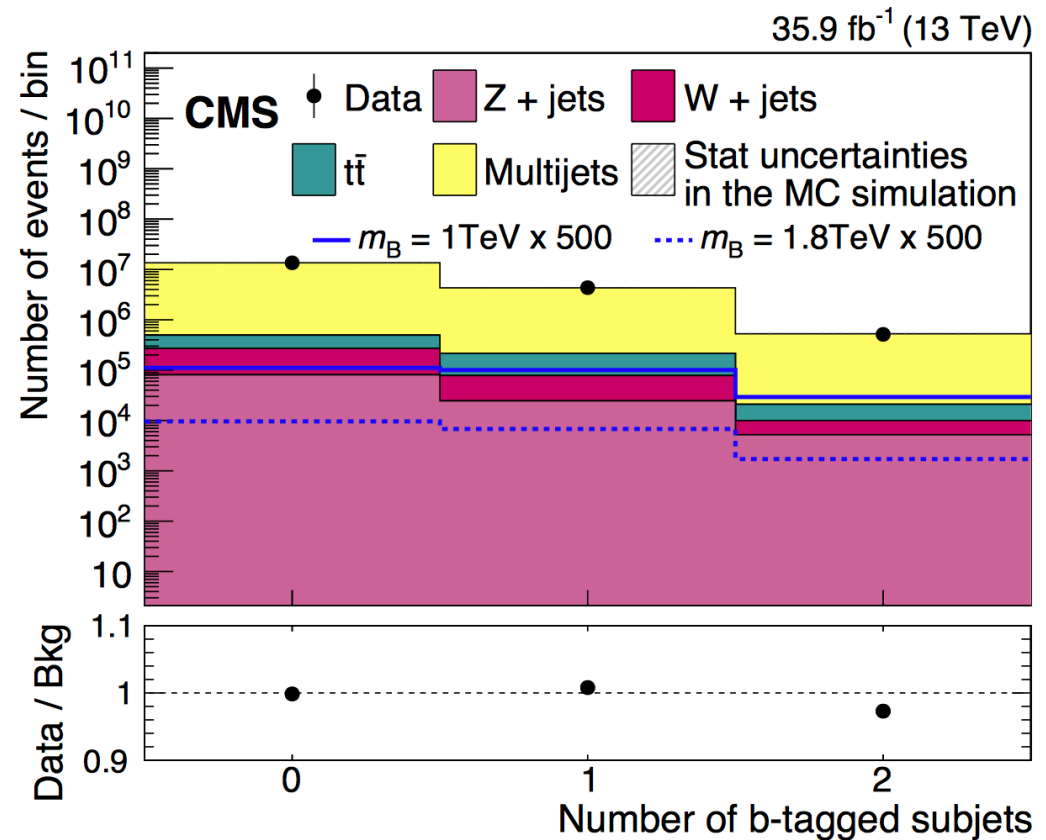
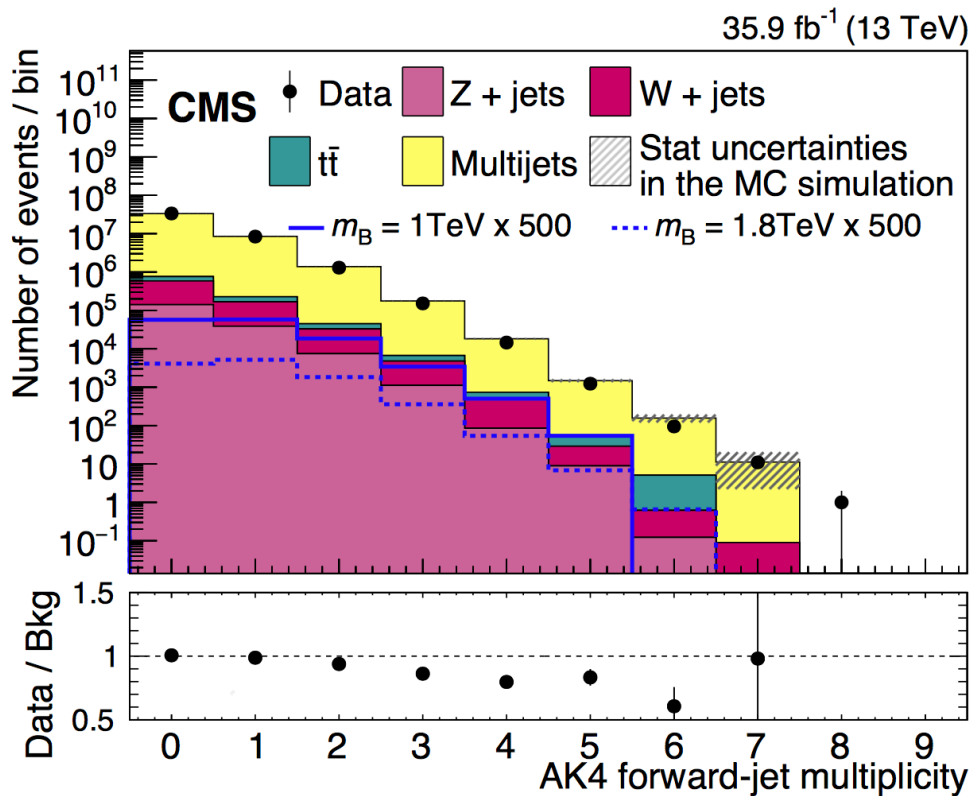
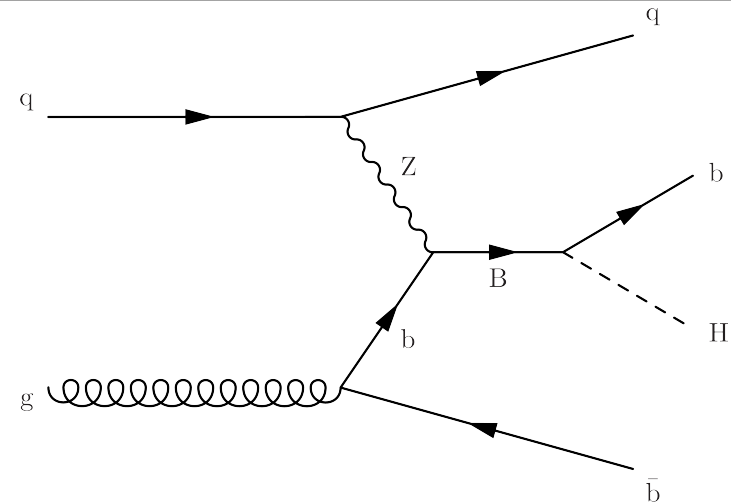


B2G-13-005
B2G-13-006

Single VLQ Production

CMS B2G-17-009

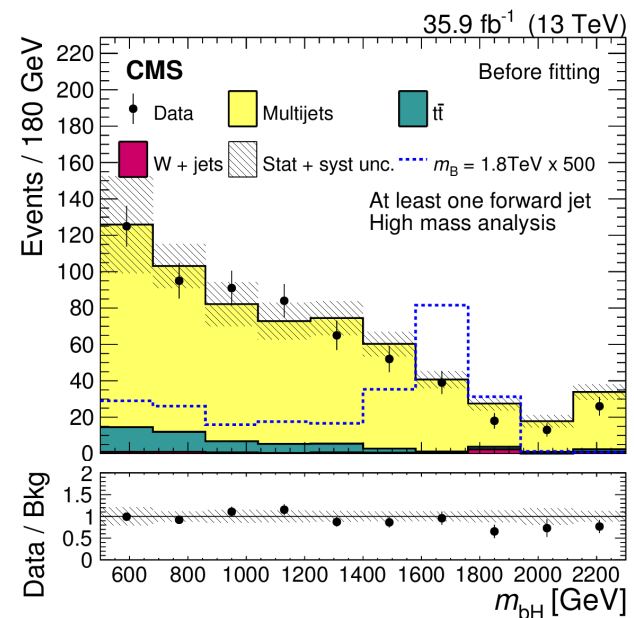
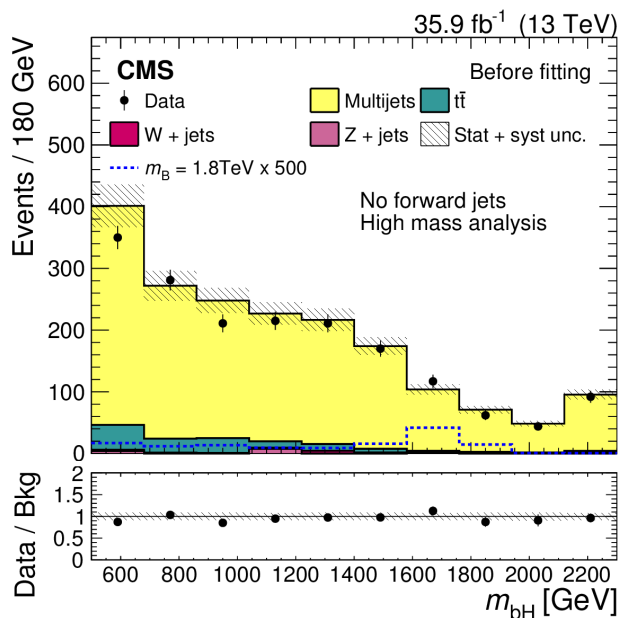
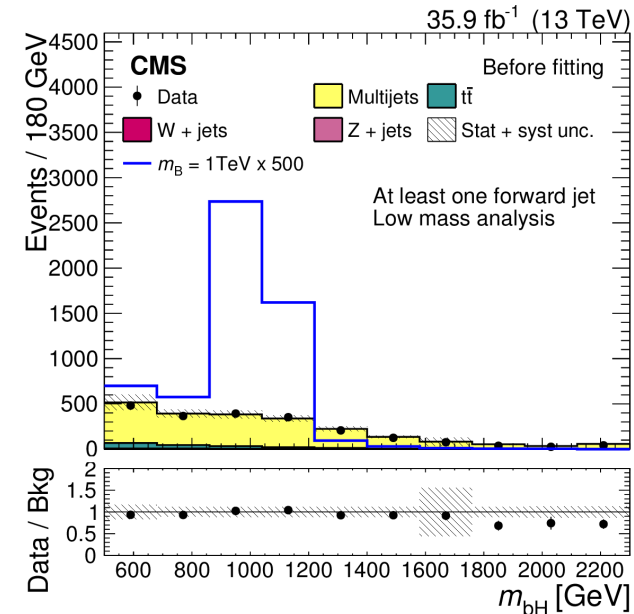
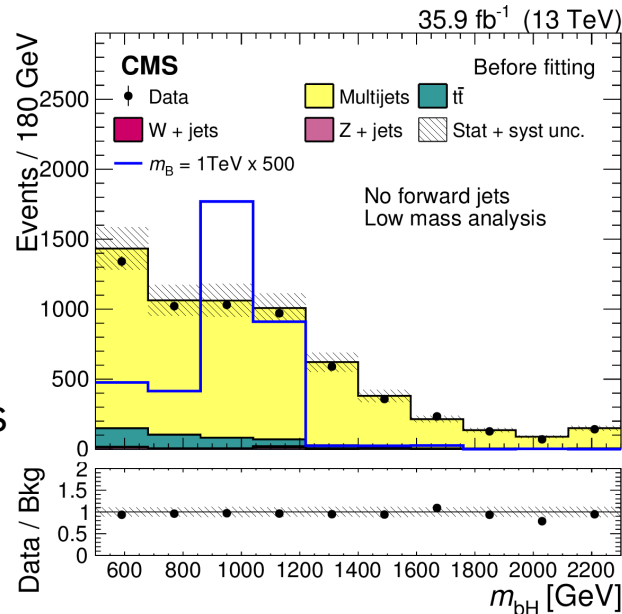
- ▶ Target $B \rightarrow bH$ production with merged $H \rightarrow bb$ decay
 - ▶ Tag Higgs-jet with mass, b-tagged subjects
 - ▶ Require forward light jets to enhance signal purity



Single VLQ Production

CMS B2G-17-009

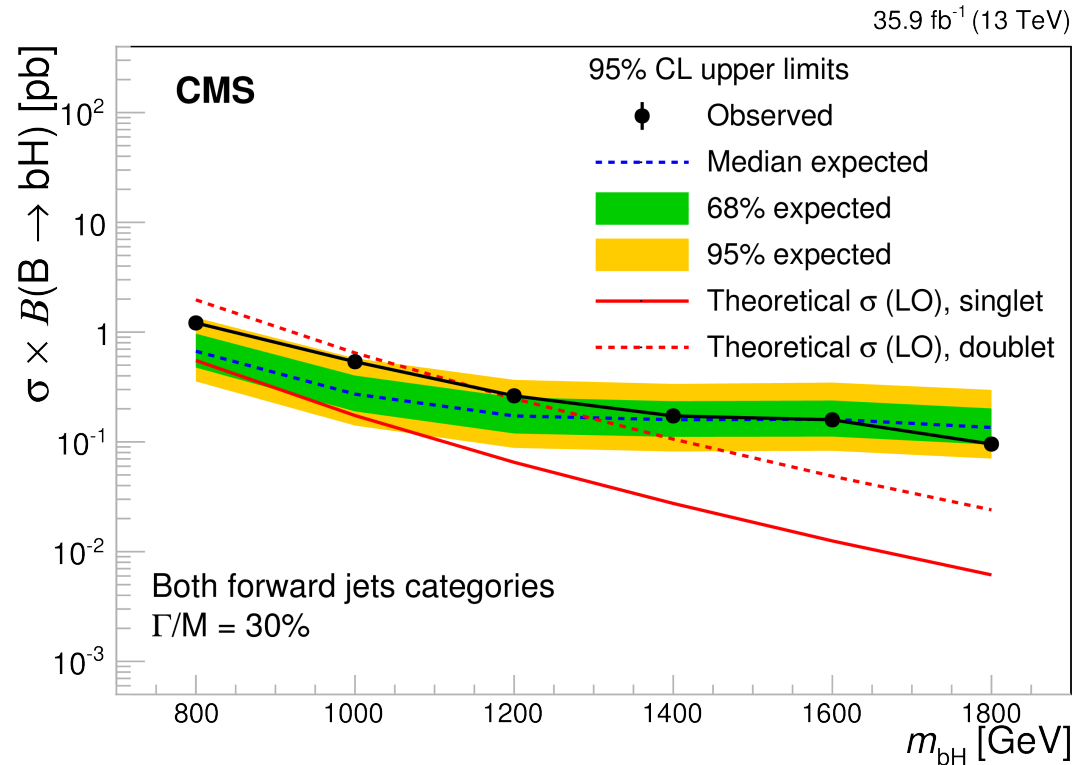
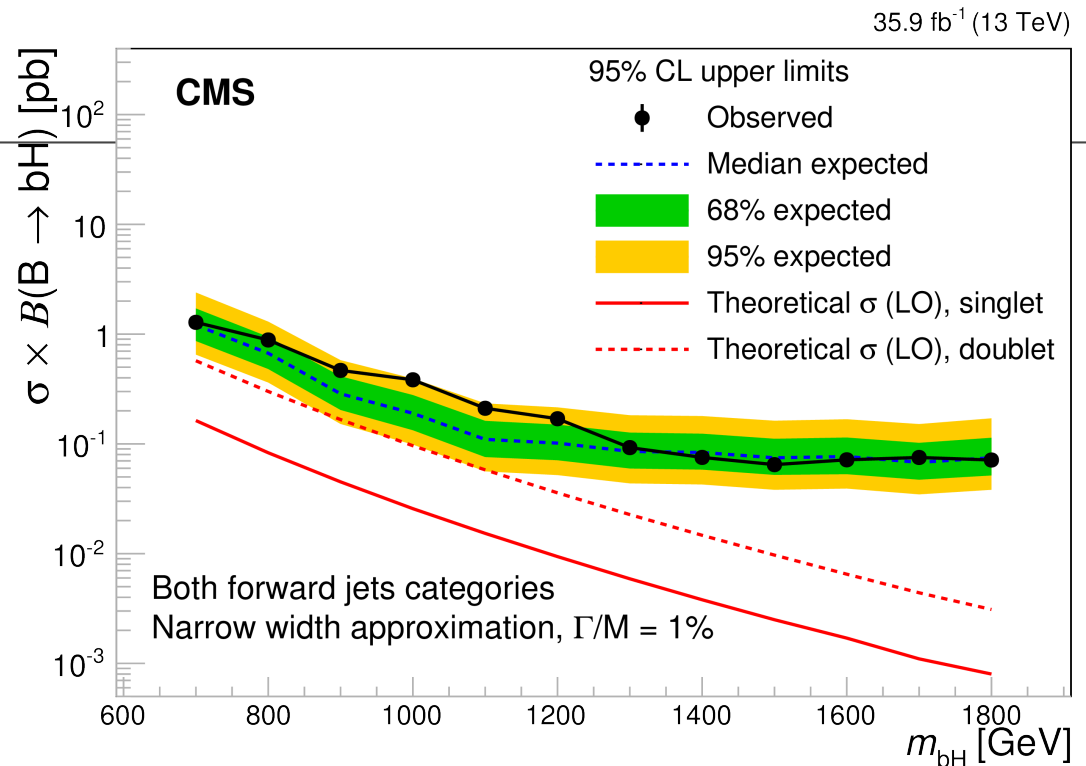
- ▶ Dominant background is from QCD multijet events
 - ▶ Estimate from data using sidebands in H-jet mass, number of b-tags
- ▶ Split events into signal regions based on p_T / forward jets



Single VLQ Results

- ▶ Dominant background is from QCD multijet events
 - ▶ Estimate from data using sidebands in H-jet mass, number of b-tags
- ▶ Split events into signal regions based on p_T / forward jets

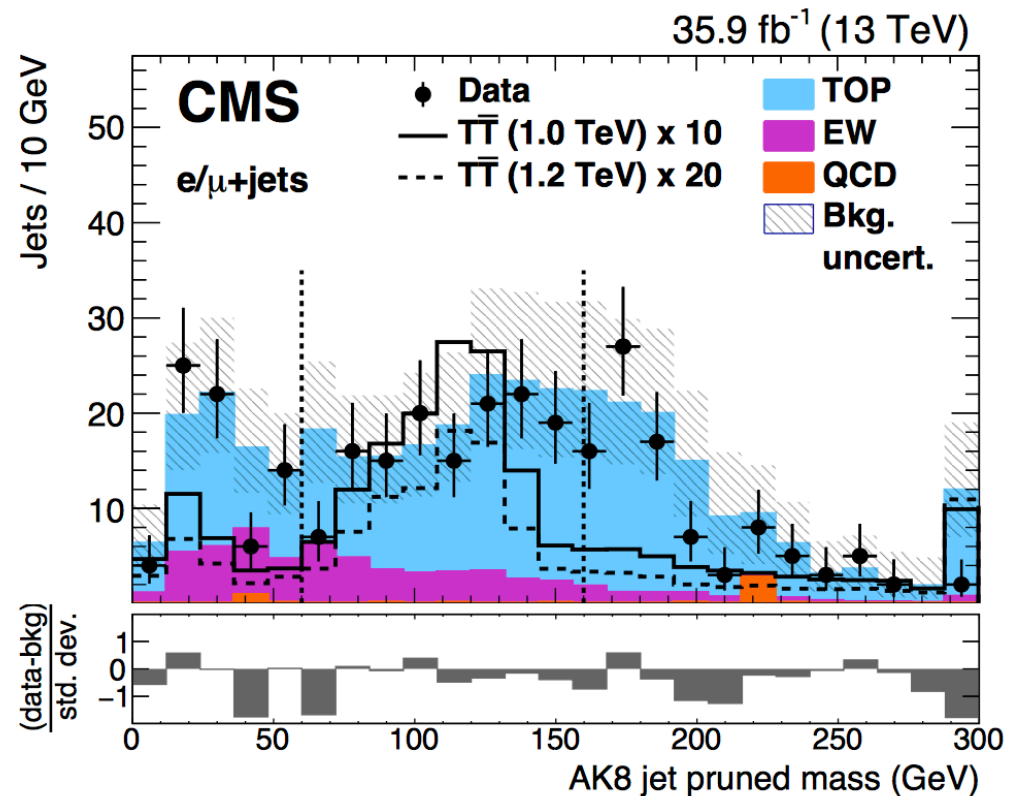
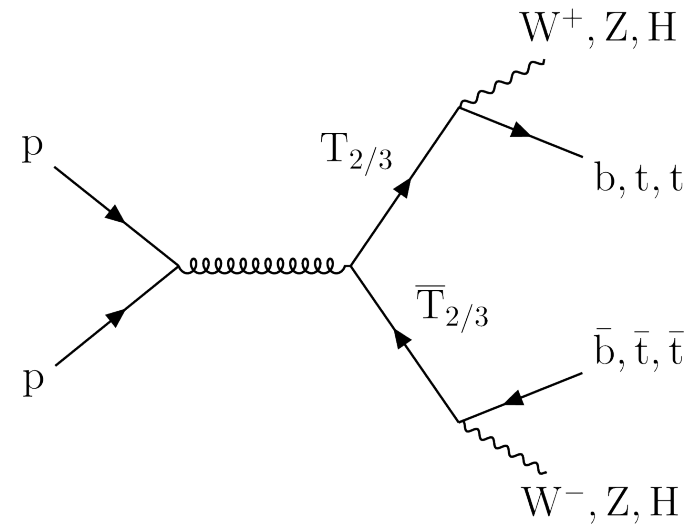
- ▶ Set limits on cross sections for narrow and wide VLQ models
 - ▶ Exclude B up to ~ 1150 GeV for 30% relative width
 - ▶ **First search to study finite-width effects!**



Pair VLQ Production

CMS B2G-17-011

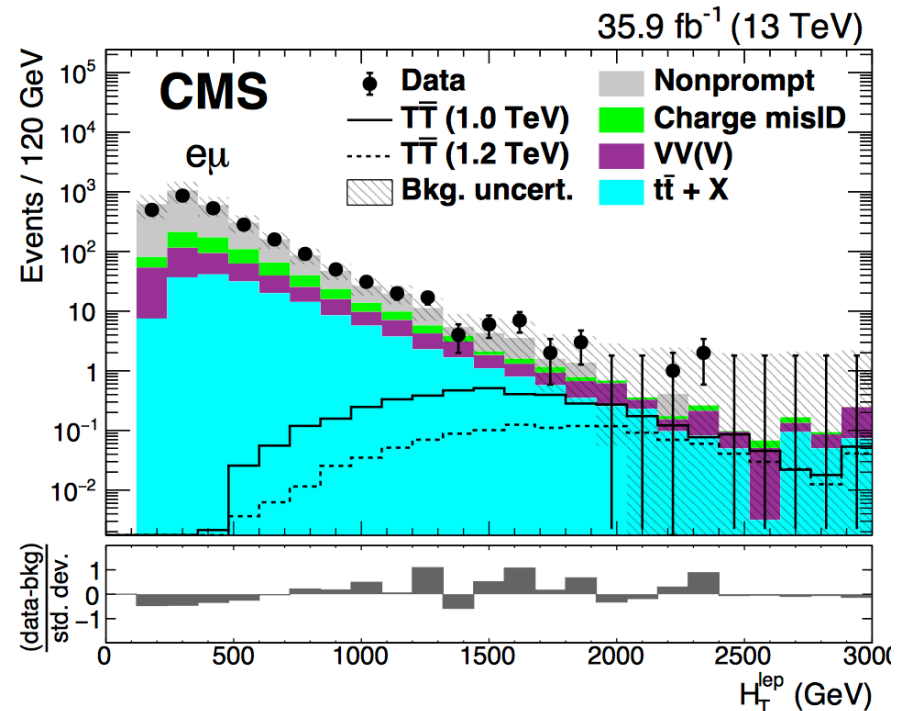
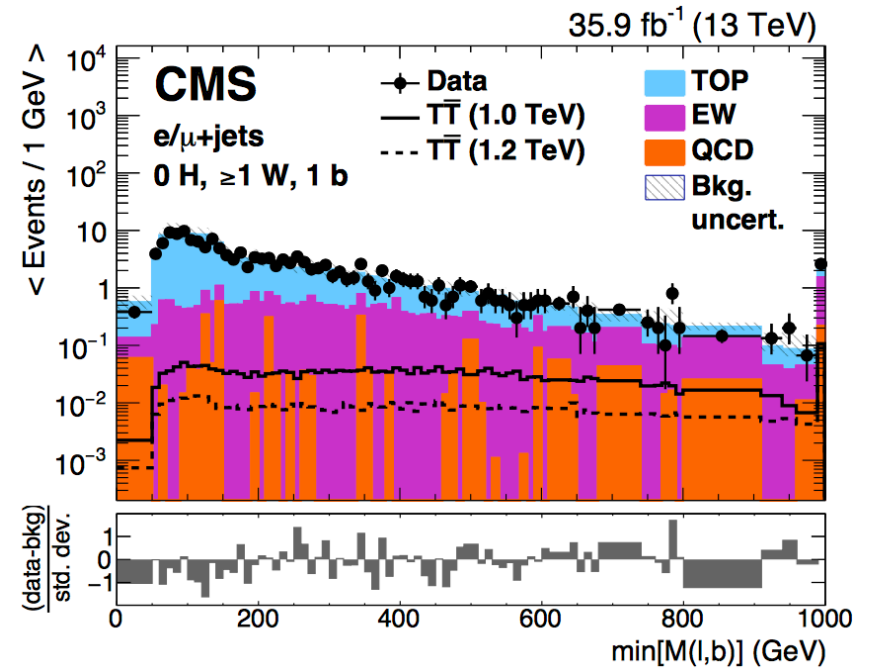
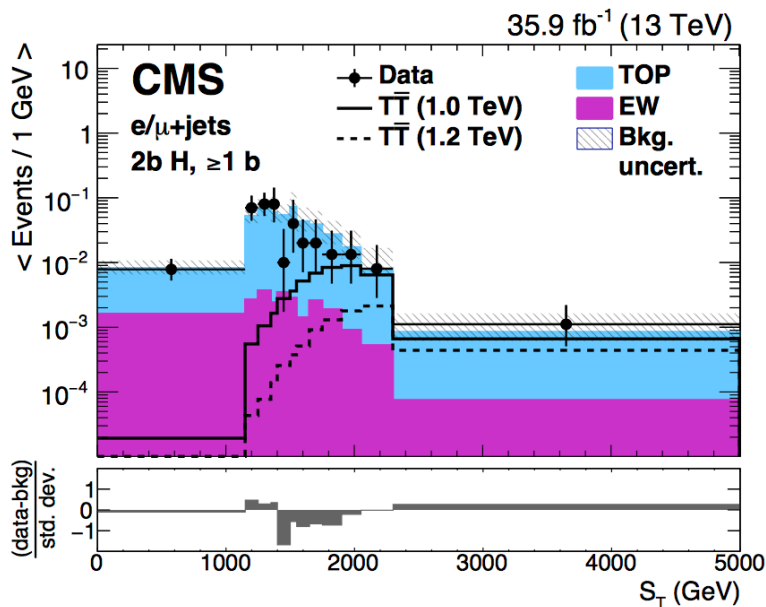
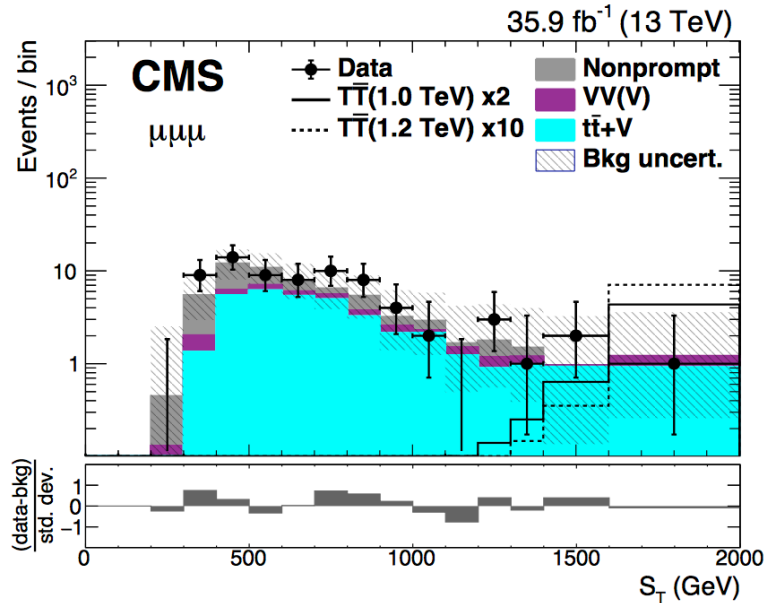
- ▶ Can also search for VLQs in pair-production mode
 - ▶ Including leptons gives a nice way to trigger, cuts down multi jet backgrounds
- ▶ Divide events into many categories to search in inclusive way across BRs
 - ▶ Single lepton
 - ▶ Identify H-tagged, W-tagged, b-tagged jets
 - ▶ Same-sign dilepton
 - ▶ Trilepton
- ▶ Rely heavily on detector-based background measurements



Pair VLQ Production

CMS B2G-17-011

- Discriminating variable depends on event category — S_T or $\min(M_{l,b})$,

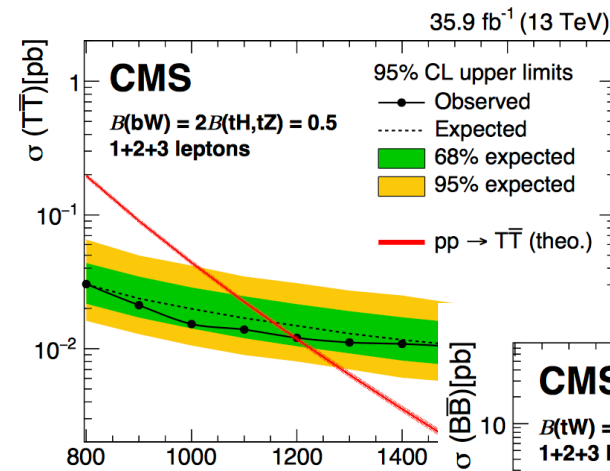


Pair VLQ Production

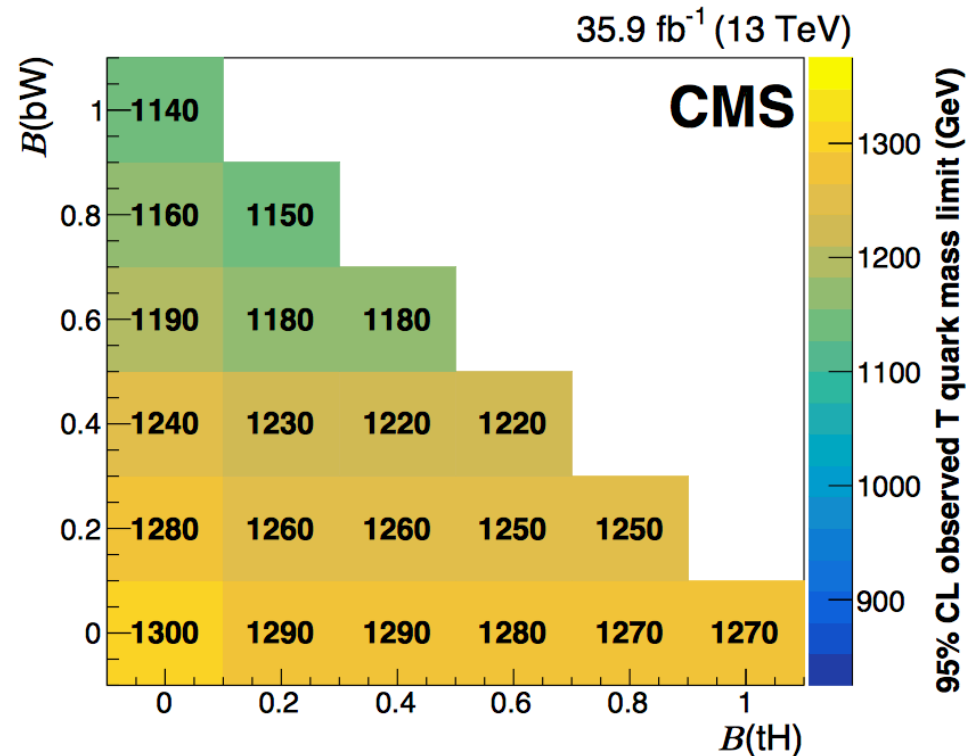
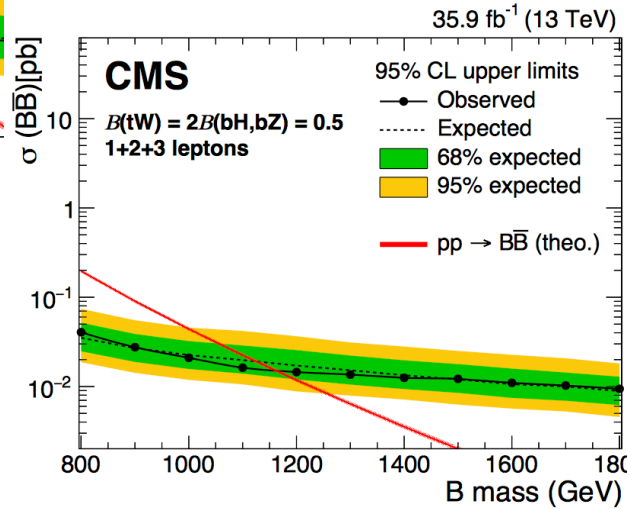
- ▶ Statistically combine all search categories
 - ▶ Nicely cover the different BB/TT decay modes

Decay mode	TT̄ (1.4 TeV)			Decay mode	BḄ (1.4 TeV)		
	1ℓ	SS2ℓ	≥3ℓ		1ℓ	SS2ℓ	≥3ℓ
tHtH	11.7	1.5	0.81	bHbH	3.2	0.19	0.07
tHtZ	10.8	0.95	1.47	bHbZ	2.0	0.07	0.18
tHbW	13.3	0.49	0.30	bHtW	13.4	0.75	0.29
tZtZ	9.3	0.29	1.87	bZbZ	1.0	0.02	0.20
tZbW	10.9	0.75	0.85	bZtW	11.0	0.29	0.81
bWbW	11.8	0.03	—	tWtW	15.4	3.05	1.36

- ▶ Scan over T/B branching ratios
 - ▶ Exclude masses ranging from:
 - ▶ 1140 - 1300 GeV (T)
 - ▶ 910 - 1240 GeV (B)



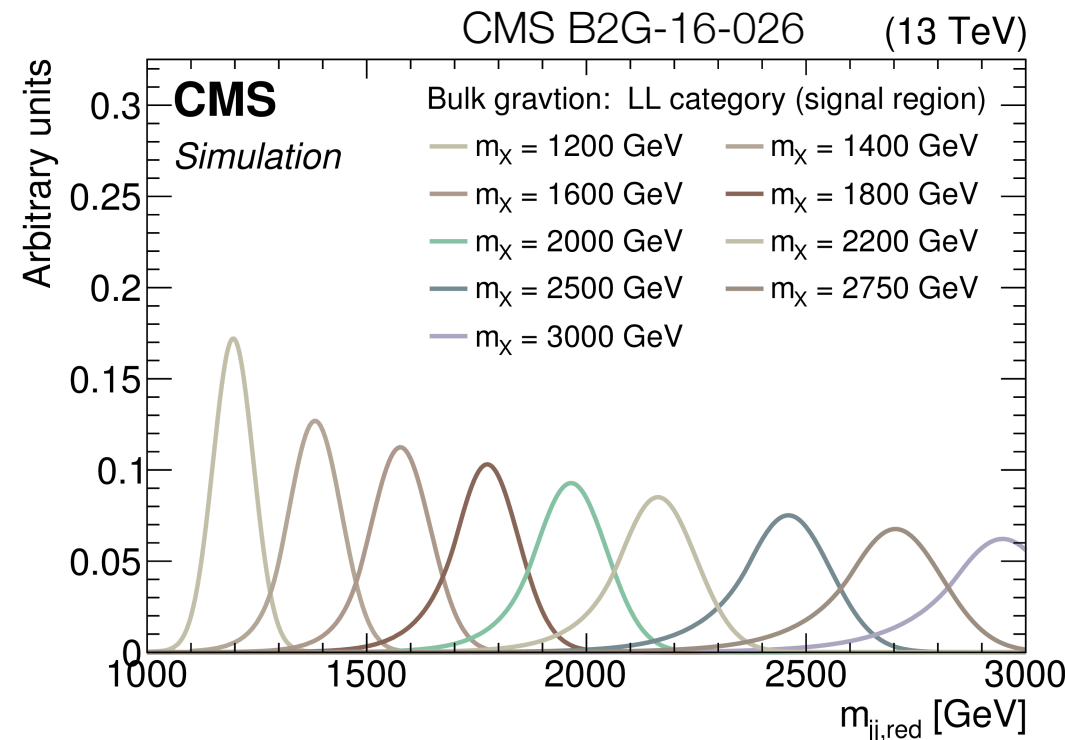
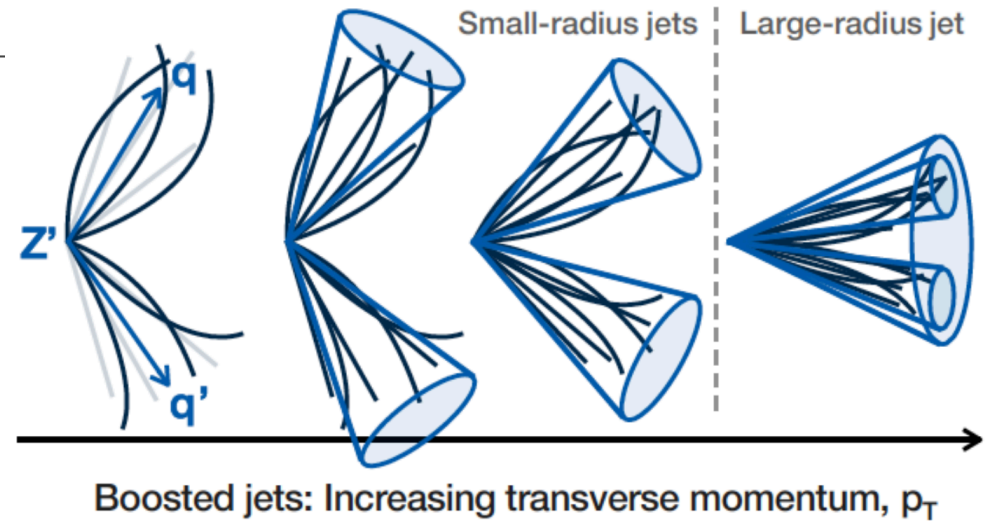
CMS B2G-17-011



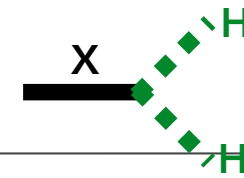
Diboson Resonances

- ▶ Many BSM physics theories predict additional symmetries → new gauge bosons to be produced
 - ▶ Heavy Vector Triplet, RS Graviton, little Higgs
 - ▶ High-mass particles → boosted objects in final state

- ▶ Ability to reconstruct resonance results in a 'bump-hunt' search
 - ▶ Reliant on a stable and well-understood background model
 - ▶ Usually data-driven methods employed due to difficulty modeling unique topologies

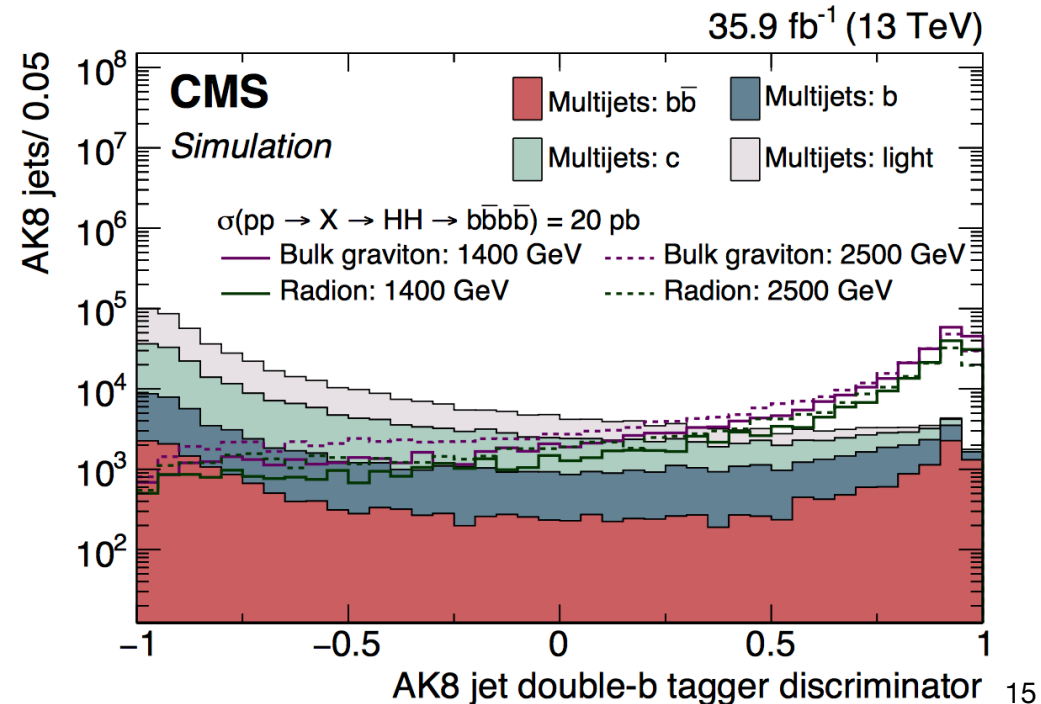
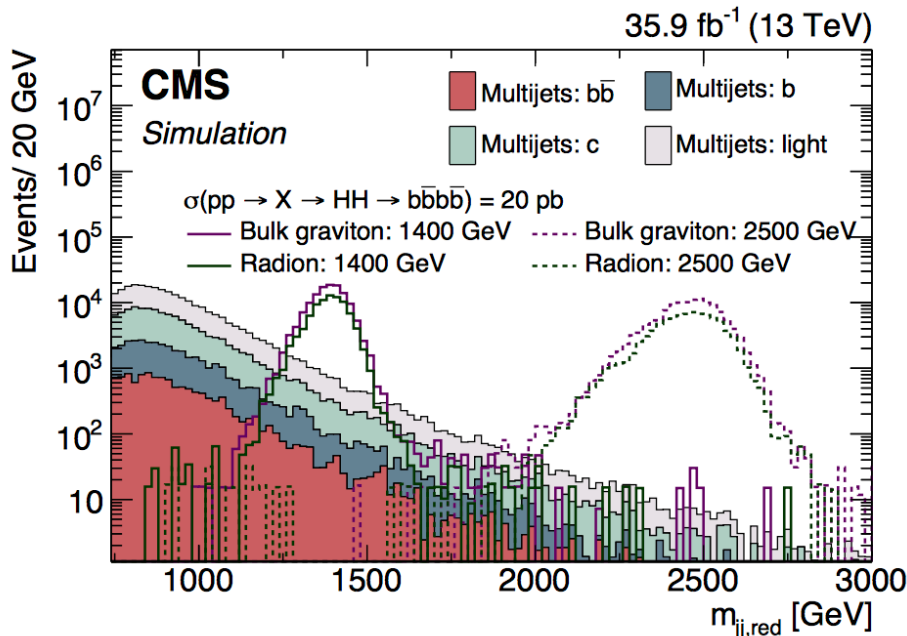
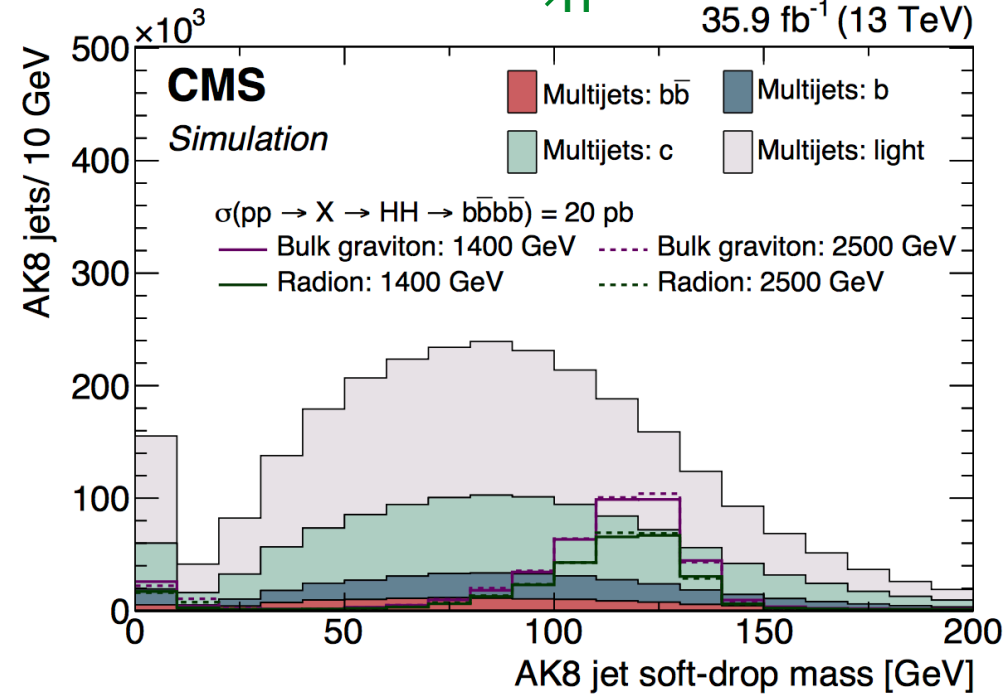


Diboson Search with Higgs



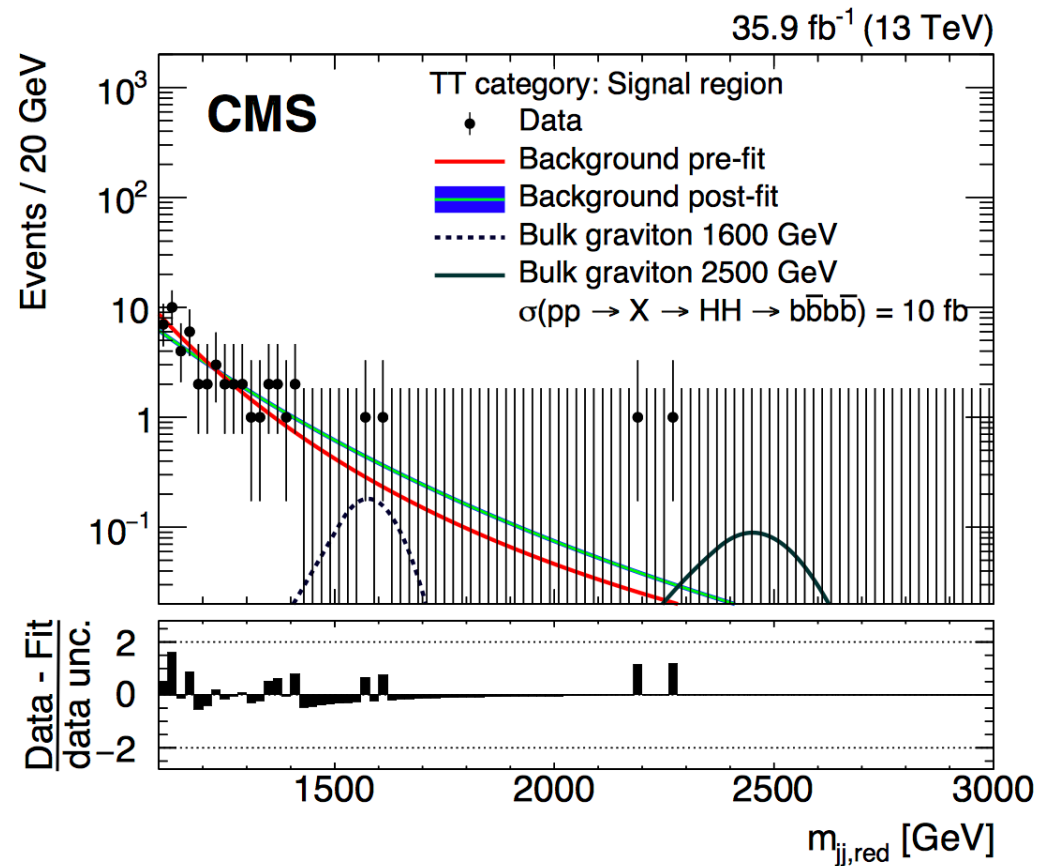
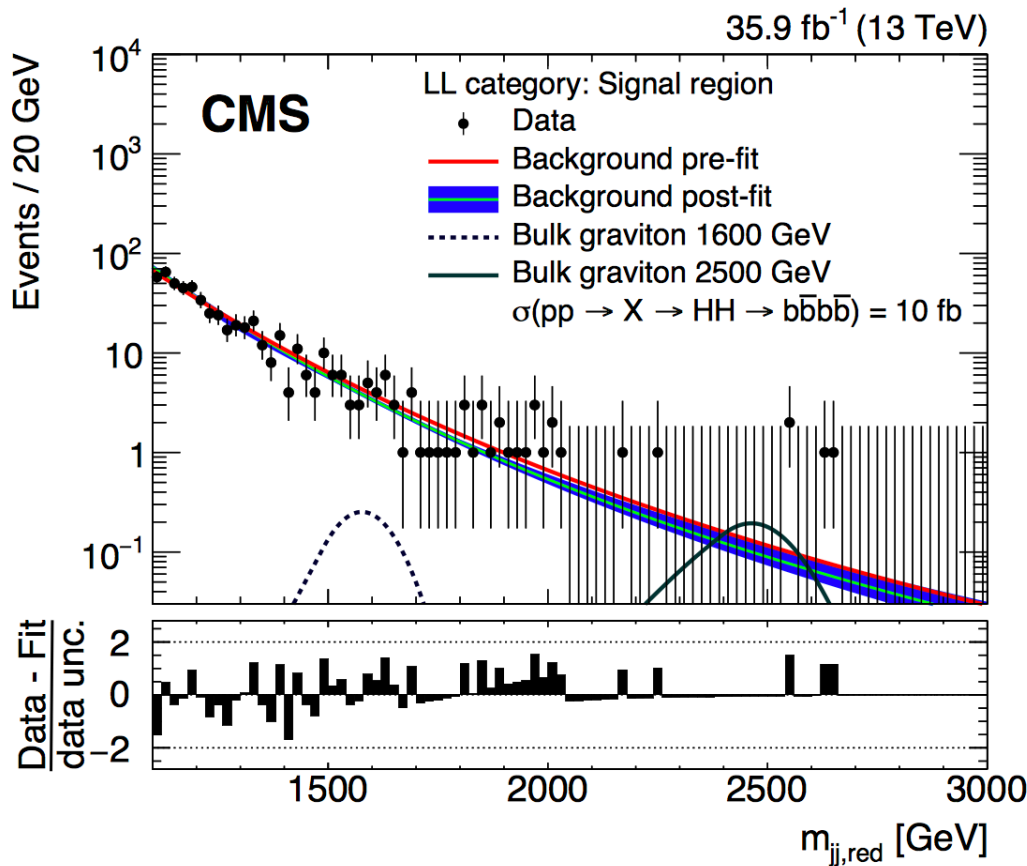
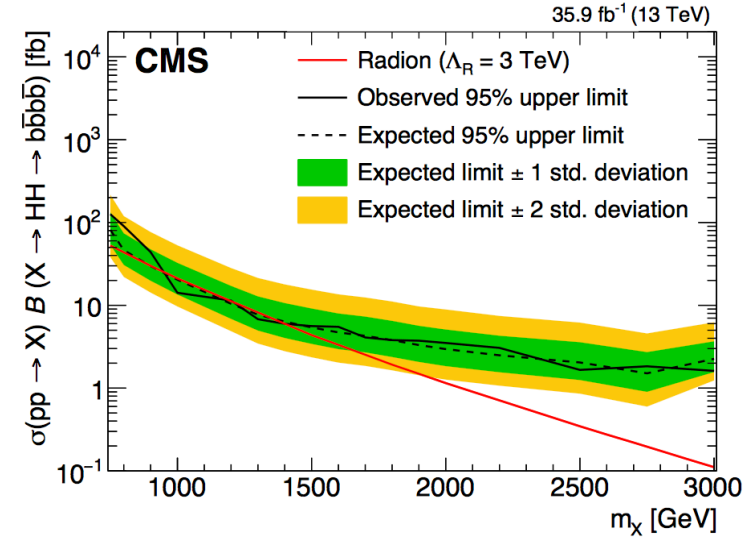
CMS B2G-16-026

- ▶ Search for $HH \rightarrow 4b$ in a dijet final state
 - ▶ 2 large-radius jets with substructure-based H-tagging applied
 - ▶ Soft-drop mass, τ_{21} , Double-b tagger
- ▶ Compute 'reduced' dijet mass
 - ▶ $m_{red,jj} = m_{jj} - (m_1 - m_H) - (m_2 - m_H)$
 - ▶ Account for loss in soft-drop mass reconstruction



Diboson Search with Higgs

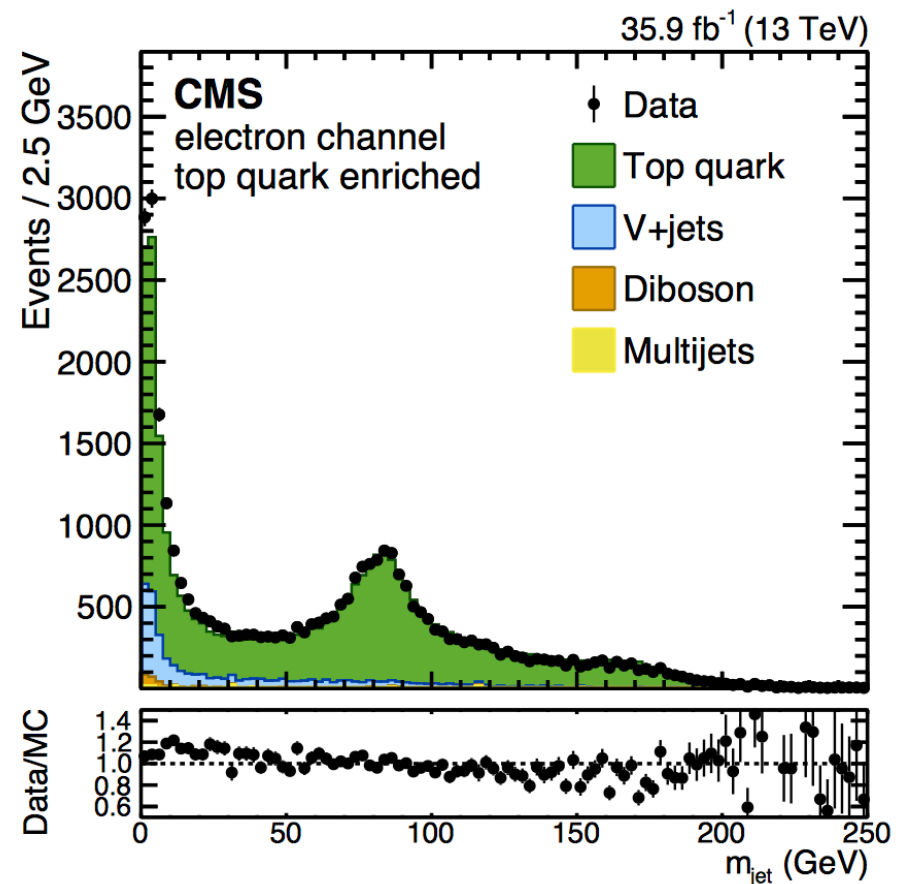
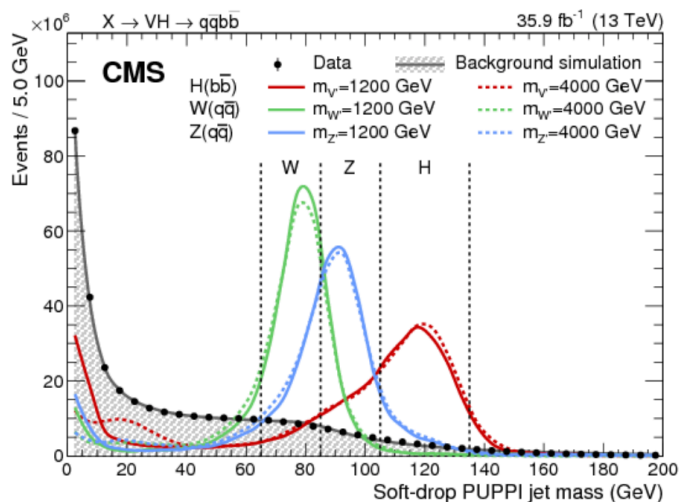
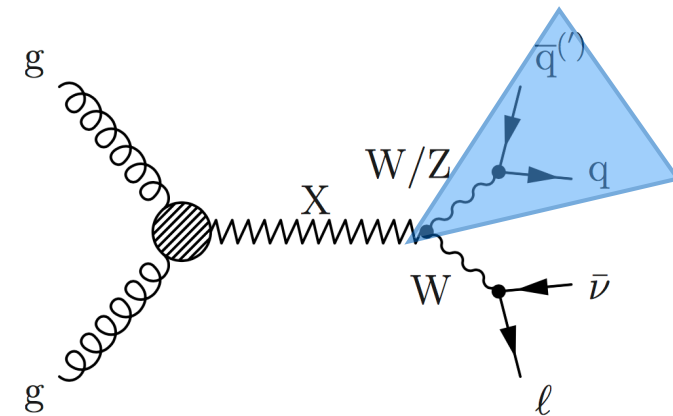
- ▶ Use modified exponential function to fit data
 - ▶ Test for the presence of a bump
- ▶ No significant excess, limits exclude radions up to 1.4 TeV



WV Search with 2D Fit

CMS B2G-16-029

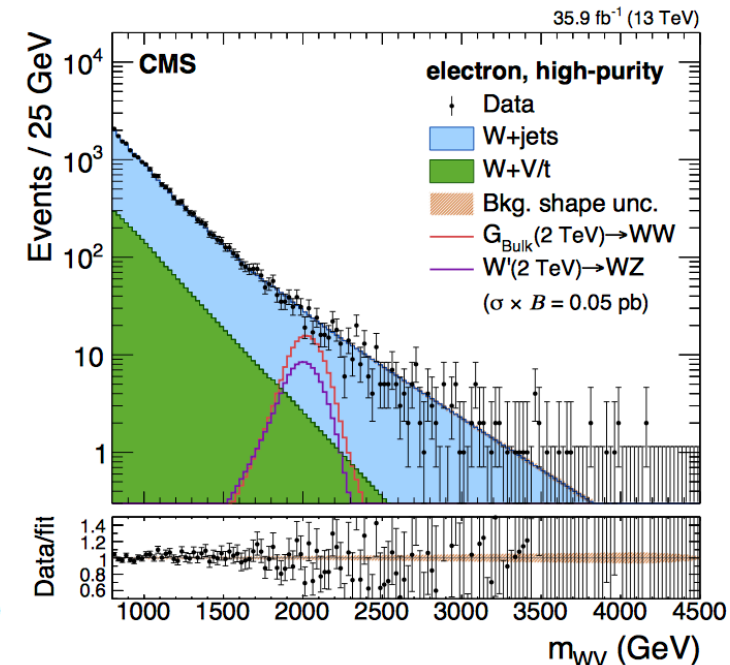
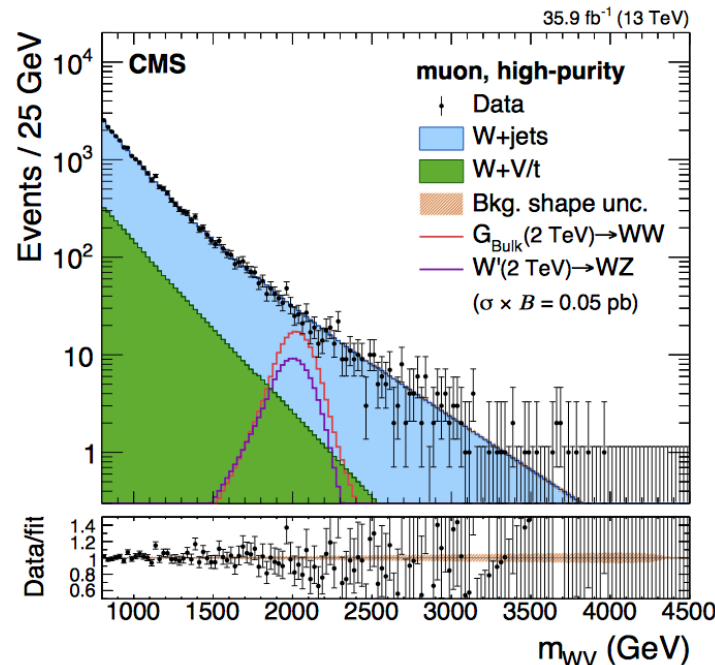
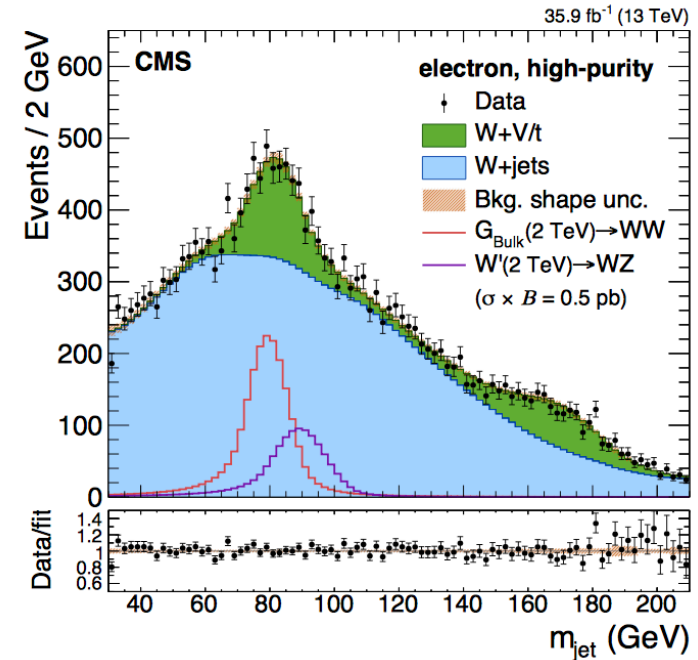
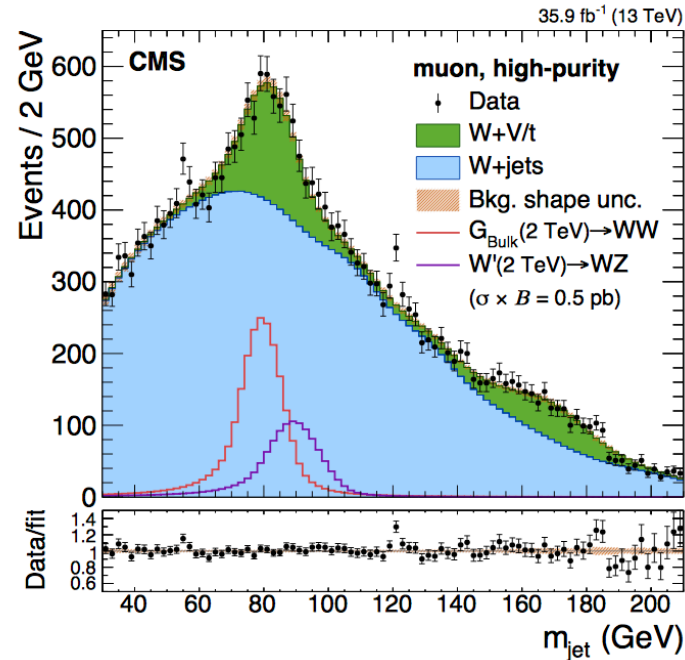
- ▶ For a lepton+large-radius jet diboson search, a new method has been employed
- ▶ Simultaneous 2D fit in plane of the large-radius jet mass and reconstructed resonance mass m_X
 - ▶ Allows acceptance and calibration of boosted top, W, Z in situ with signal extraction
 - ▶ No worry from overlap of tagging working points



WV Search with 2D Fit

CMS B2G-16-029

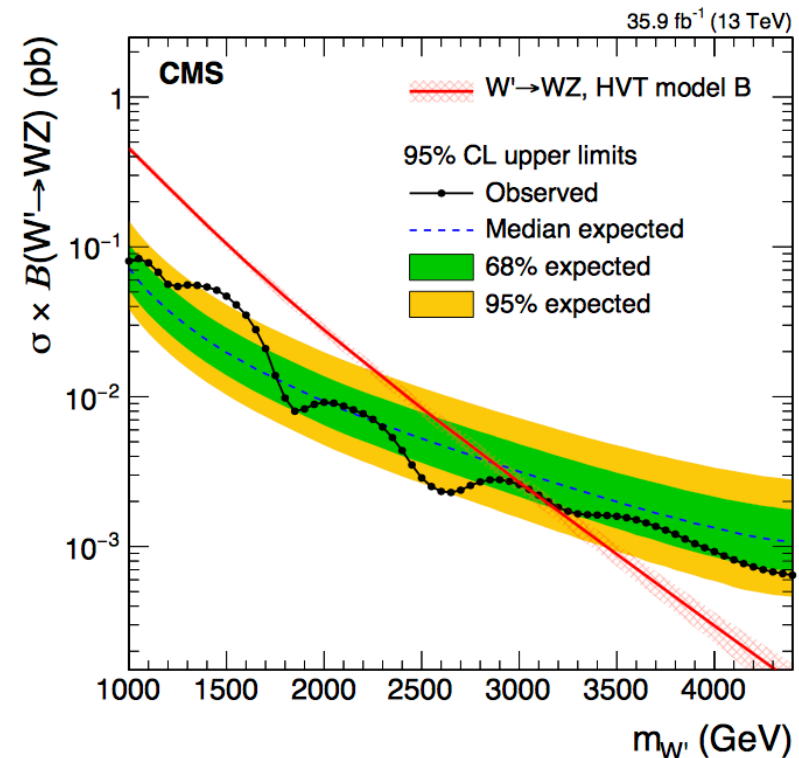
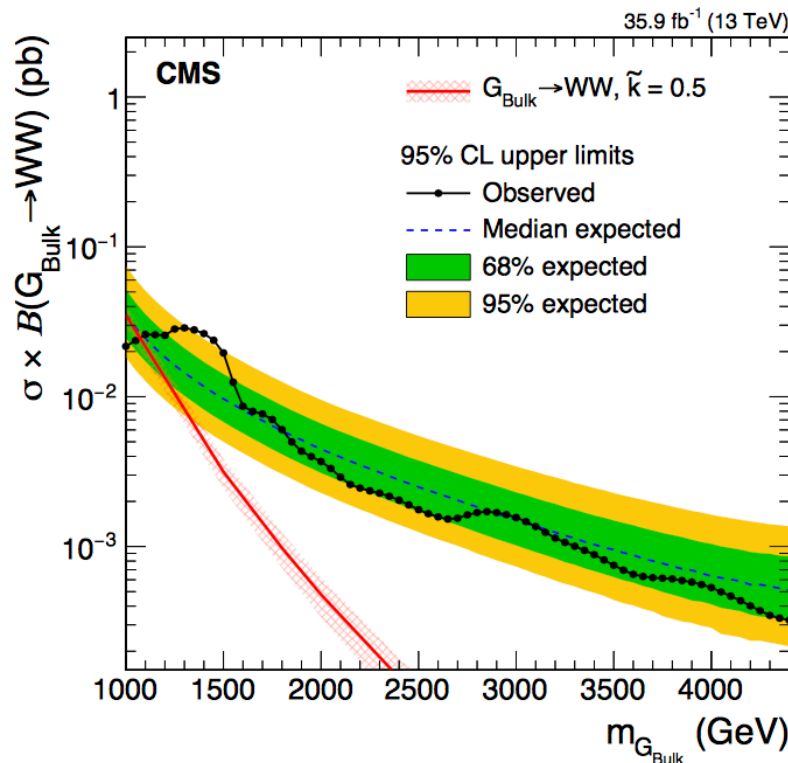
- ▶ Use data to obtain templates for main backgrounds (W+jets)
- ▶ Simultaneous fit of four categories:
 - ▶ Electron / muon events
 - ▶ Low purity / high purity
- ▶ Robust method that can be extended to other search channels in the future



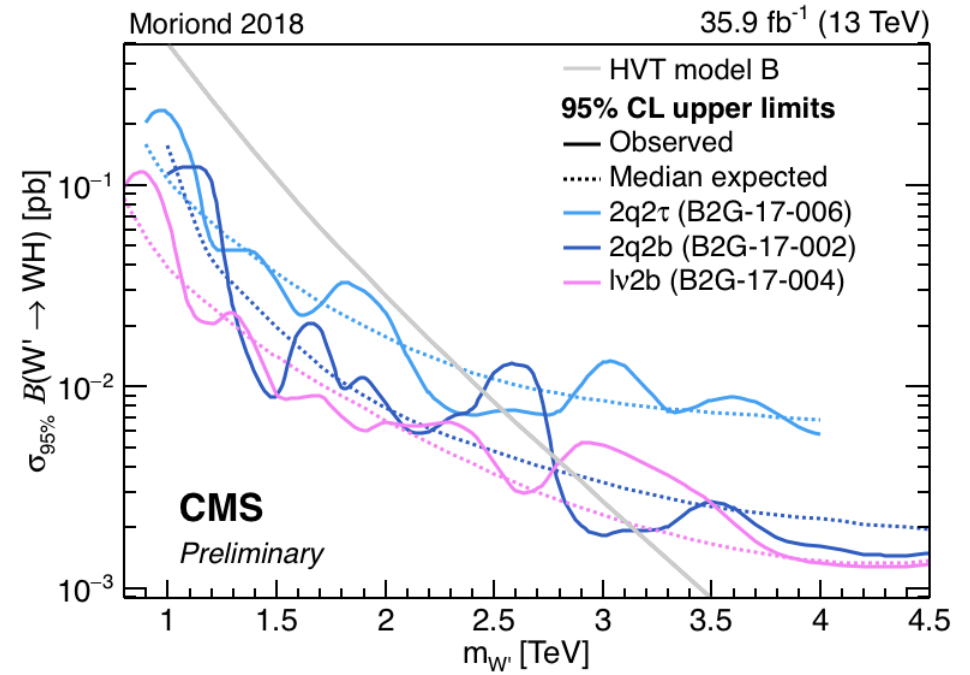
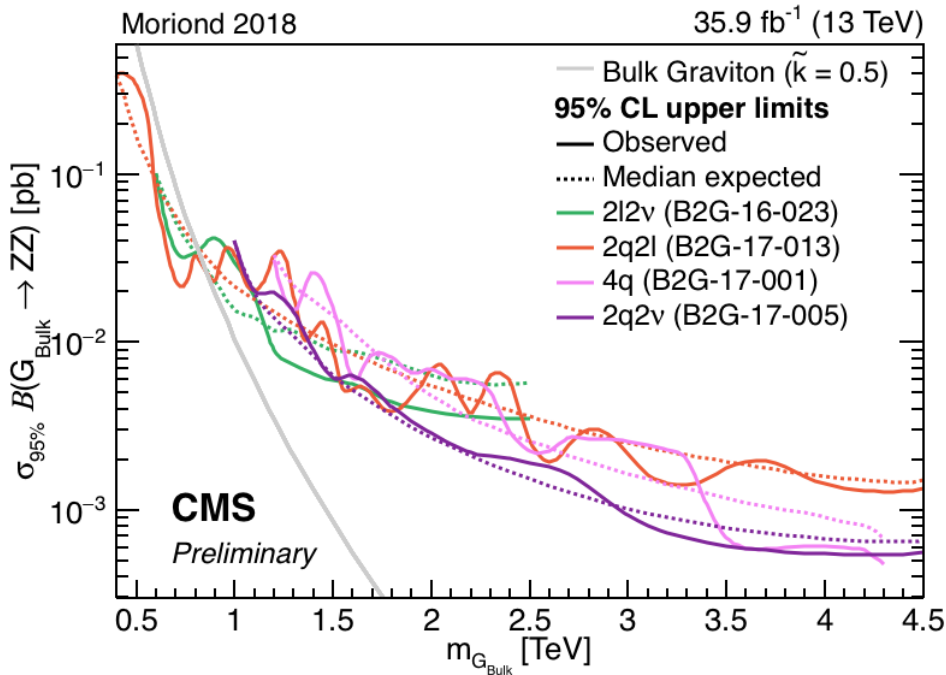
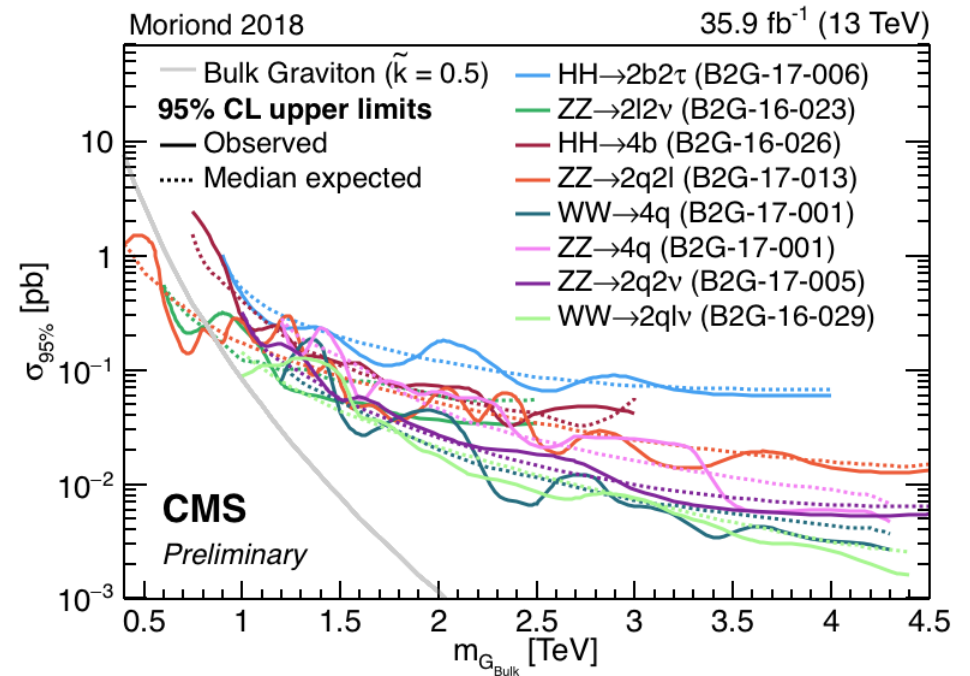
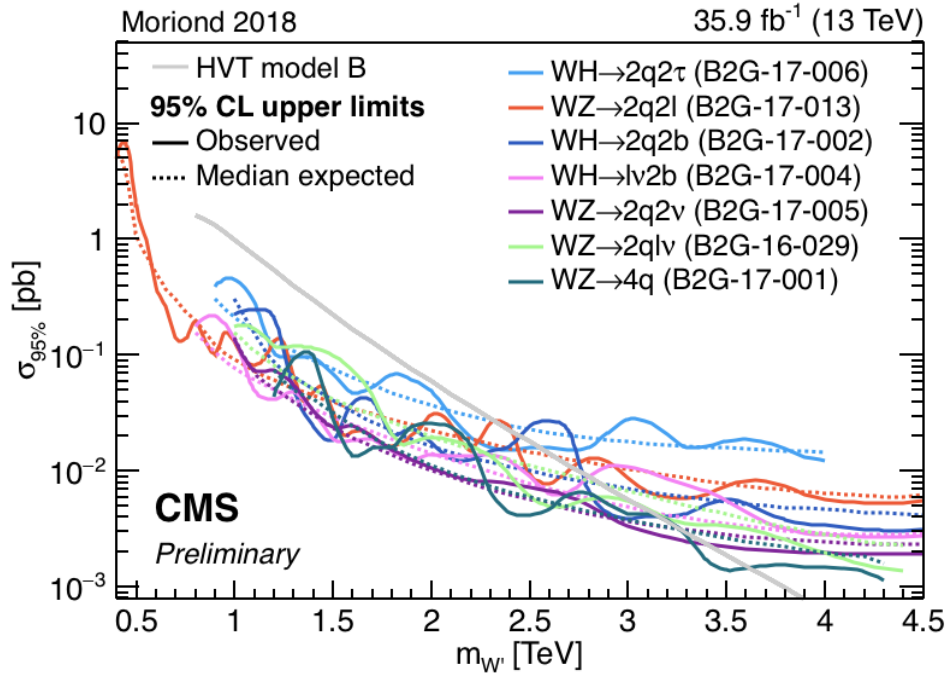
WV Search with 2D Fit

CMS B2G-16-029

- ▶ Use data to obtain templates for main backgrounds (W+jets)
- ▶ Robust method that can be extended to other search channels in the future
- ▶ Exclude bulk gravitons (WW) up to 1.07 TeV
- ▶ Exclude W' (WZ) up to 3.05 TeV



Diboson Summary



Leptoquark Search (top + tau)

CMS B2G-16-028

- ▶ Leptoquark pair production
 - ▶ Decays to third generation are favored theoretically

- ▶ Events divided into categories

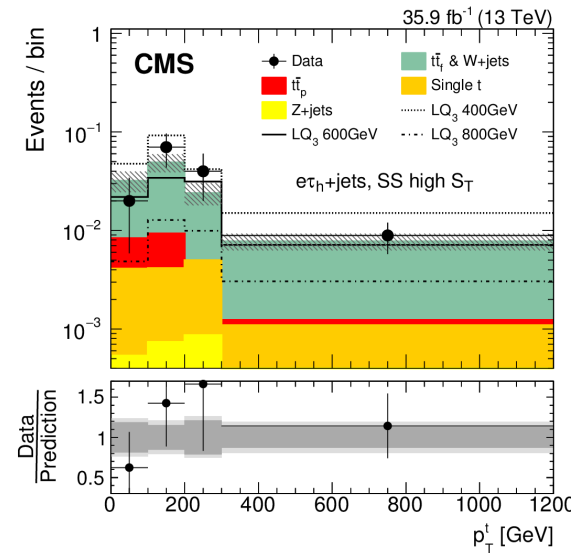
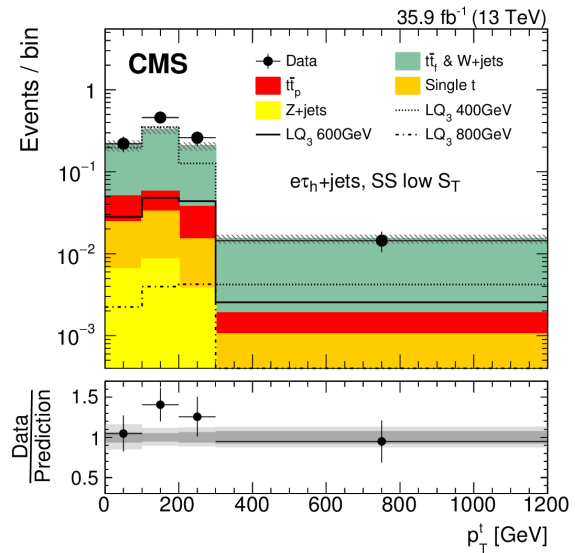
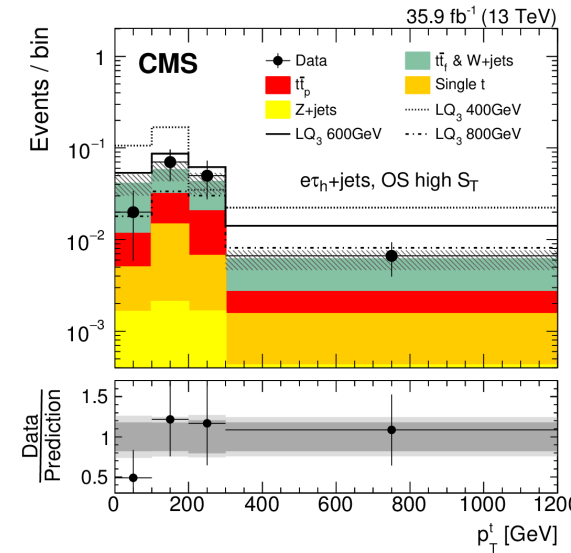
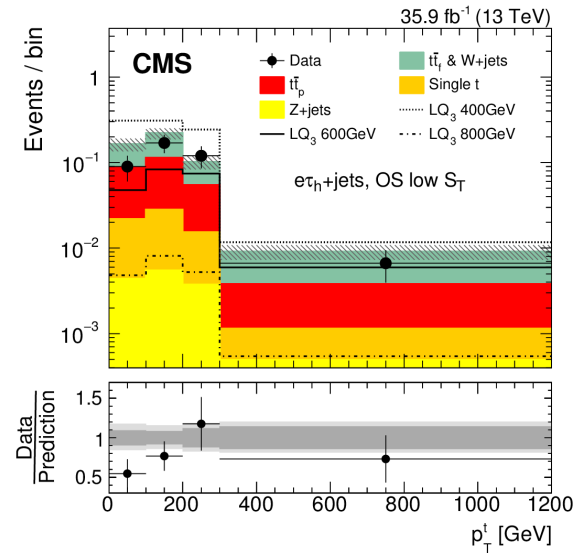
- ▶ Same-sign e/mu + tau
- ▶ Opposite-sign e/mu + tau
- ▶ e/mu + 2 tau

- ▶ Split also by S_T

- ▶ Backgrounds extrapolated from control region

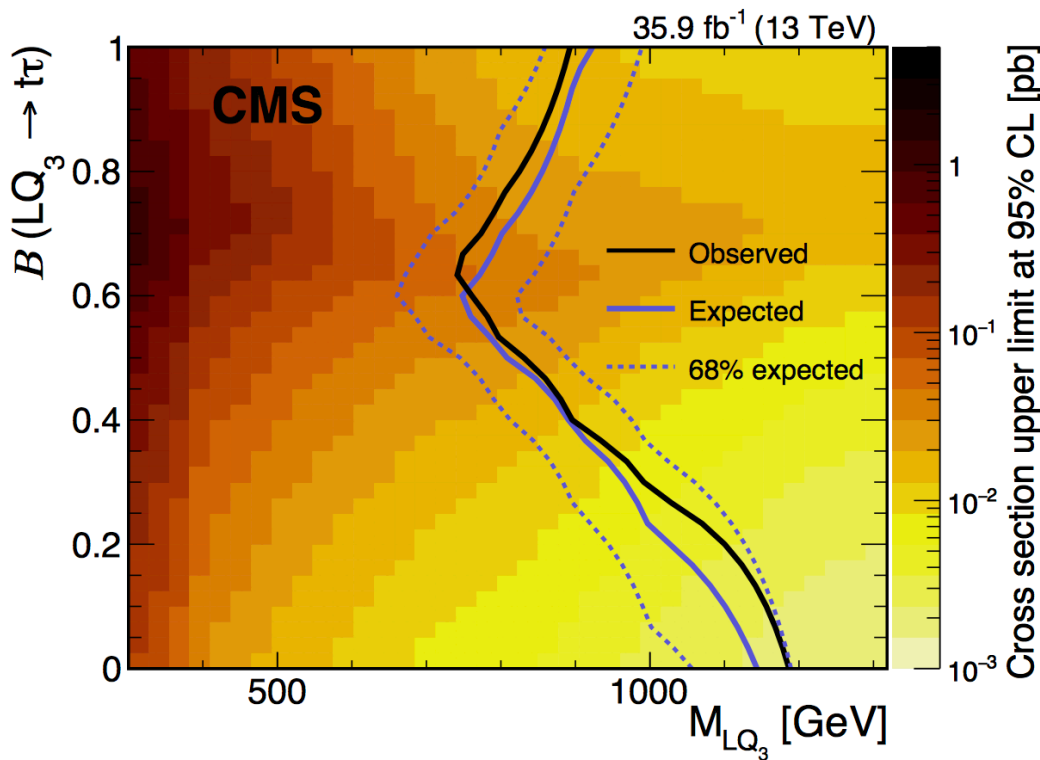
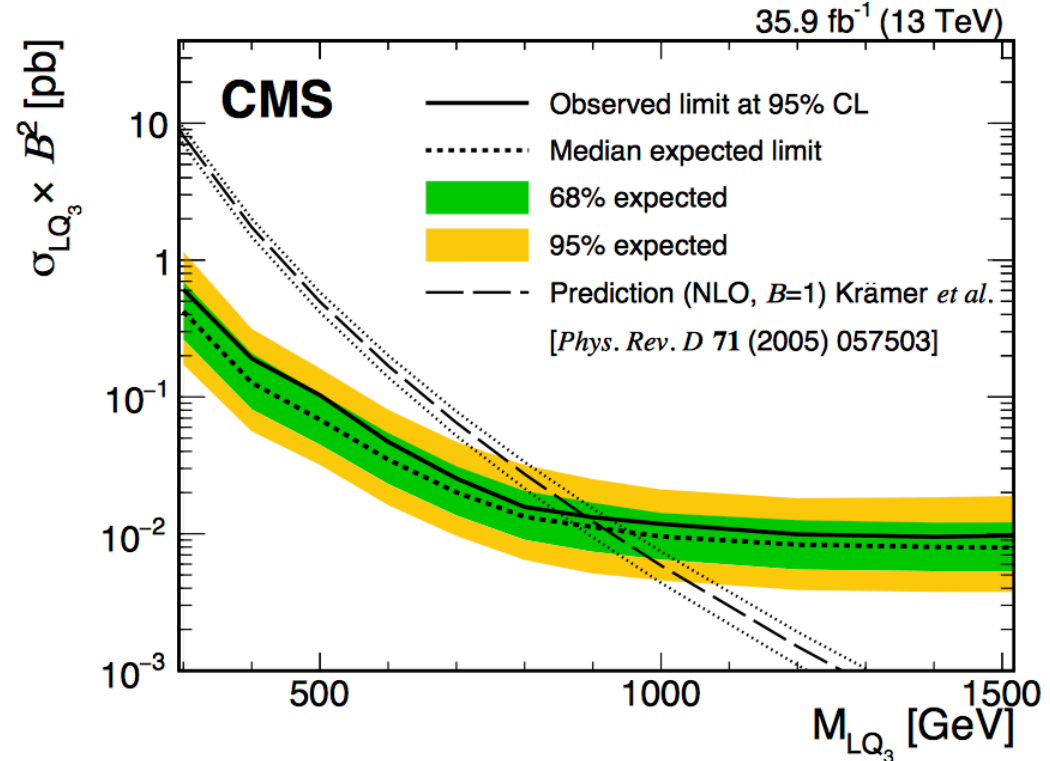
- ▶ Mis-ID'd hadronic taus important contribution

- ▶ $p_T(\text{top})$ used to discriminate signal



Leptoquark Results

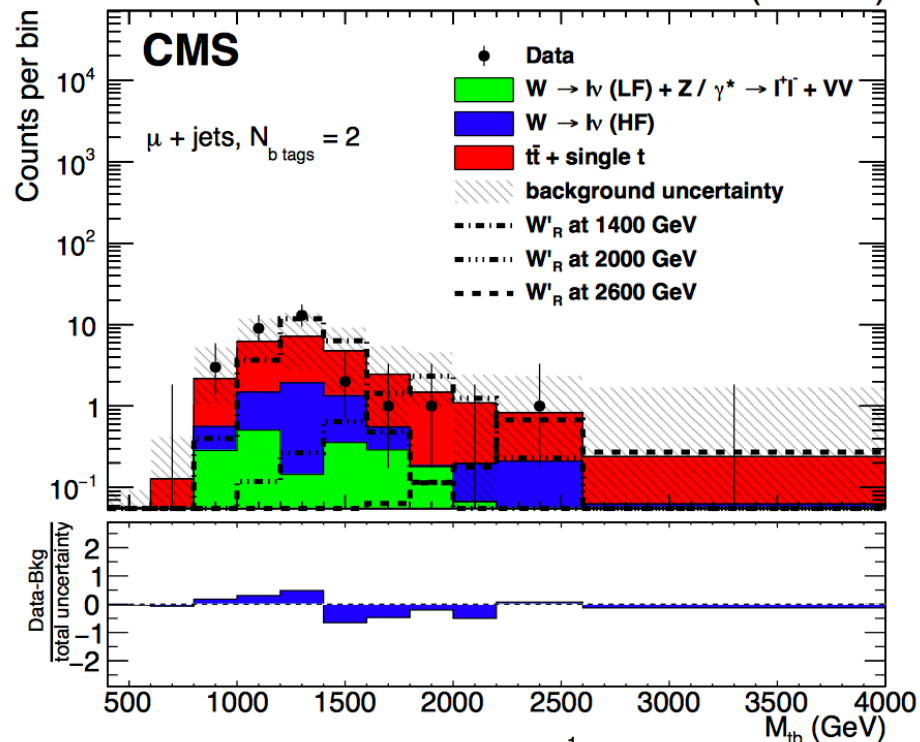
- ▶ Search excludes $LQ \rightarrow \text{top} + \text{tau}$ up to ~ 900 GeV
- ▶ Can also scan over branching ratios by including the $b\nu$ mode (combined here with a sbottom SUSY search)



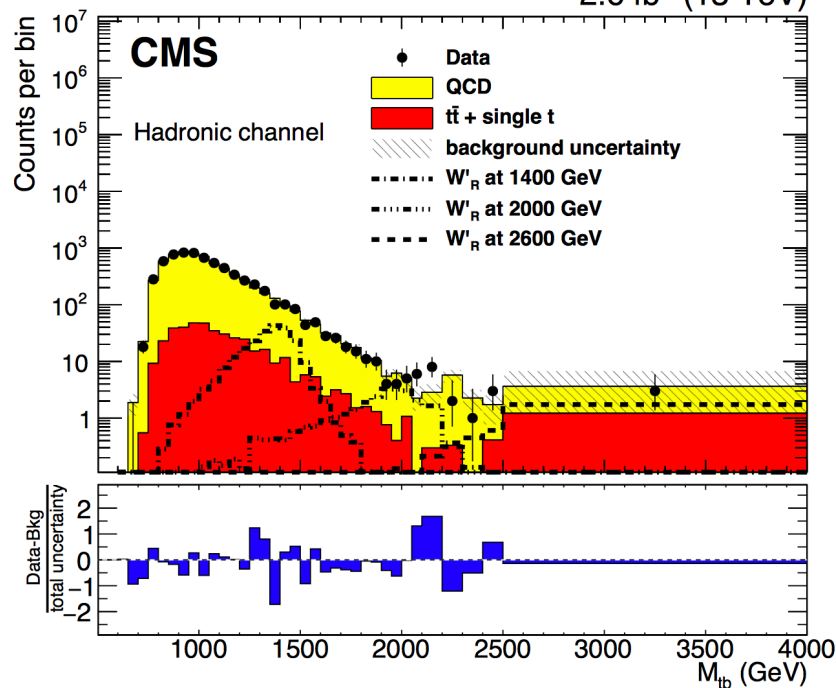
W' Resonances

- ▶ Search for $W' \rightarrow tb$ including both lepton+jets and hadronic final states
- ▶ Lepton+jets channel — reconstruct M_{tb} from lepton, MET, two jets
 - ▶ Solve for neutrino momentum with W mass constraint
 - ▶ Combine “best” jet with W to reconstruct top
 - ▶ Then combine with highest- p_T remaining jet to form W' candidate
- ▶ Hadronic channel — use large-radius jets for top-tagging
 - ▶ W' candidate formed from leading dijet combination

2.2 fb⁻¹ (13 TeV)



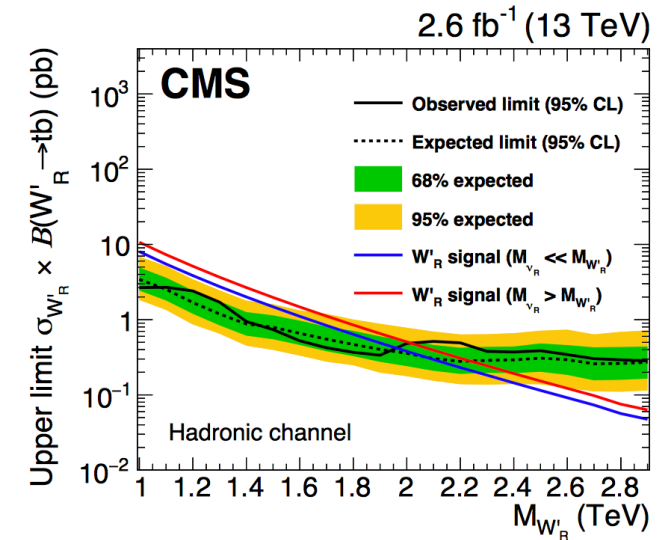
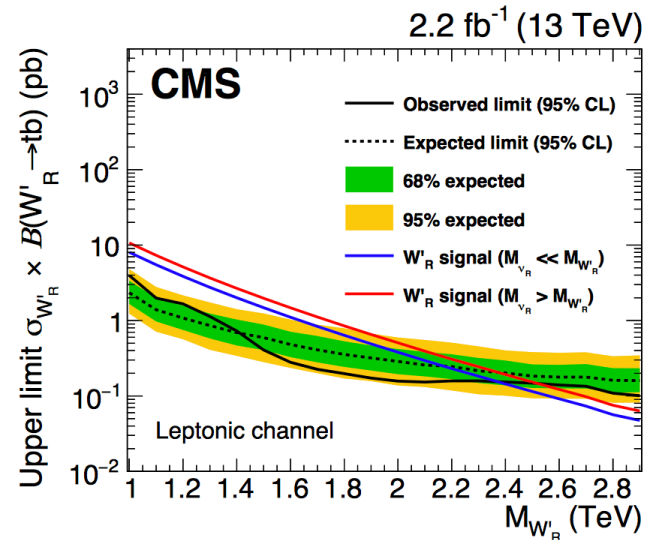
2.6 fb⁻¹ (13 TeV)



W' Resonances

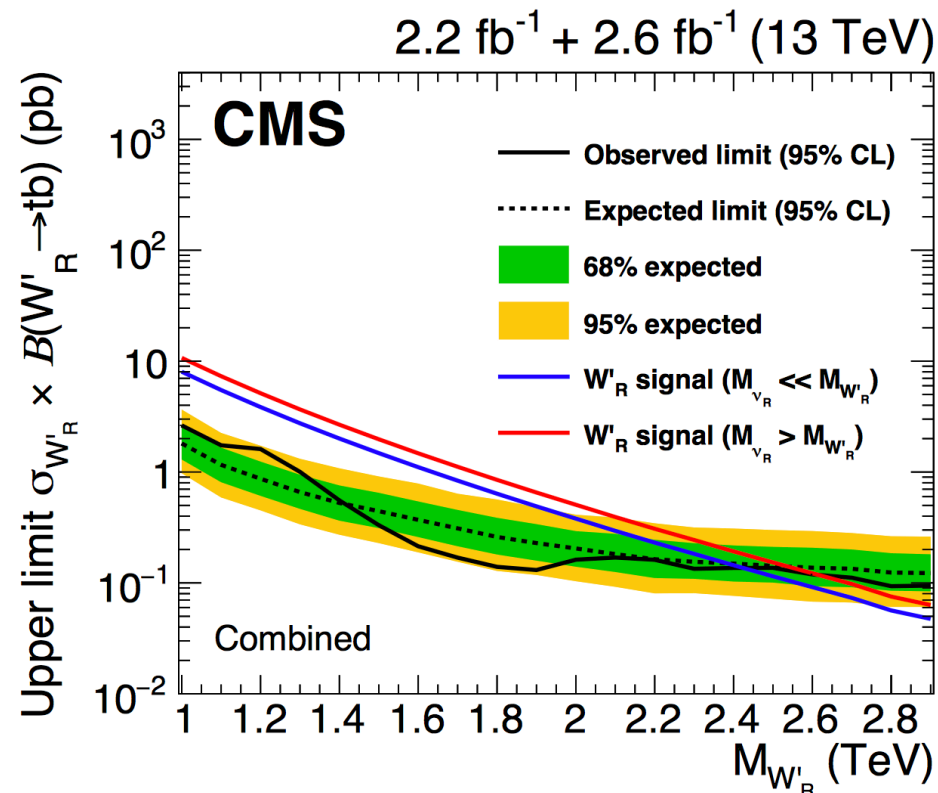
CMS B2G-16-016

- ▶ Limits set on right-handed W' model



- ▶ Statistical combination of lepton+jets and hadronic channels

- ▶ Exclude W' up to 2.4 TeV for heavy W' ($m_{W'} \gg m_{\nu_R}$)
 - ▶ 2.6 TeV exclusion for $m_{W'} < m_{\nu_R}$

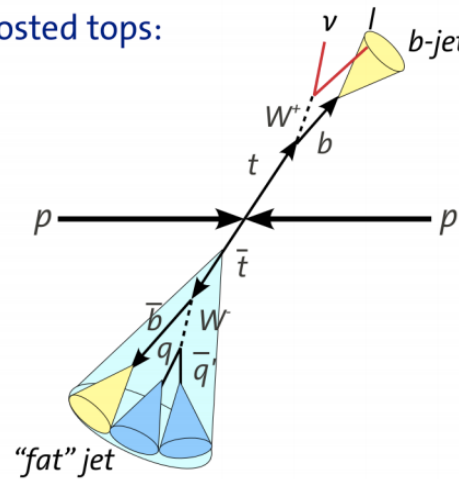


Top Pair Resonances

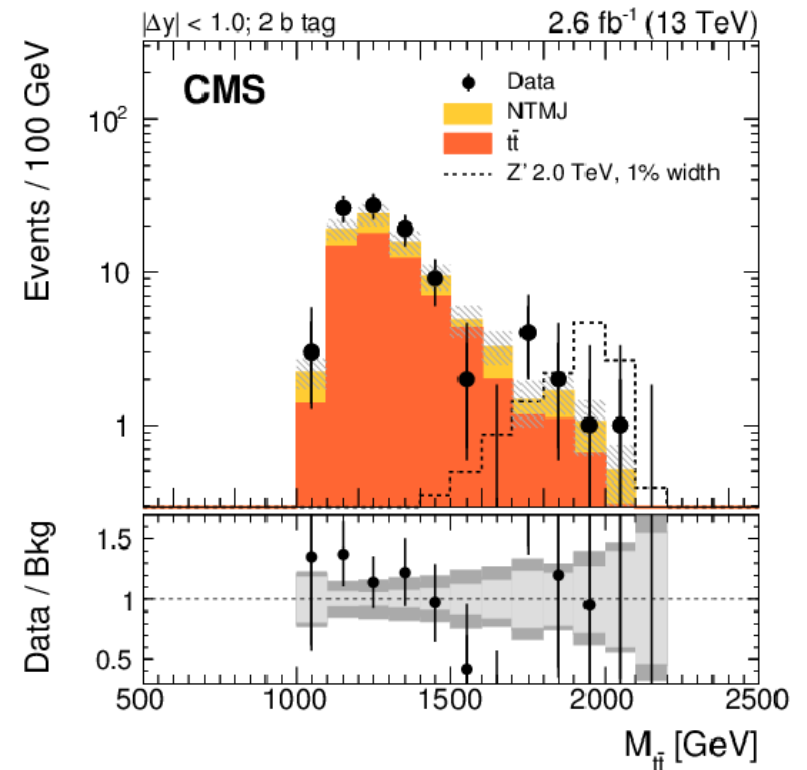
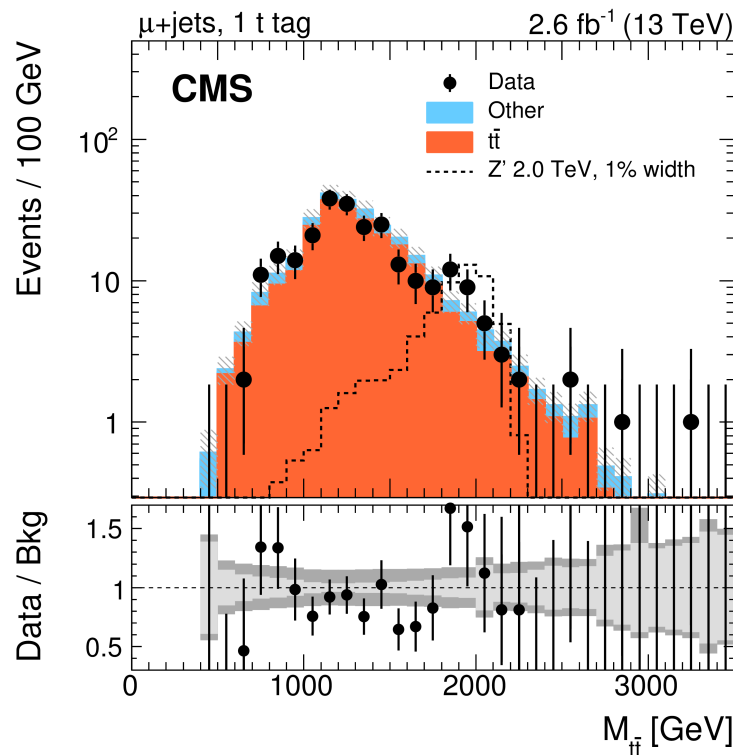
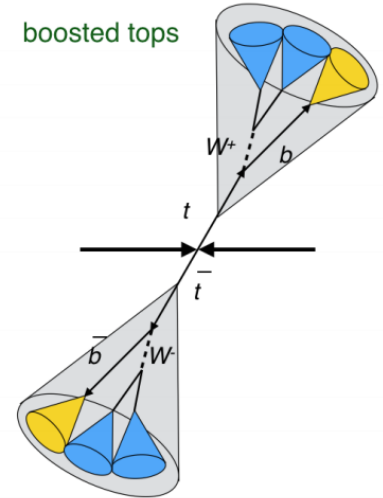
CMS B2G-16-015

- ▶ Search for heavy resonance decaying to two top quarks
 - ▶ Use lepton+jets, and fully hadronic decay modes of $t\bar{t}$ system
- ▶ Reconstruct top pair invariant mass for signal discrimination
 - ▶ Good control of backgrounds (QCD estimated from data sideband region)

Boosted tops:

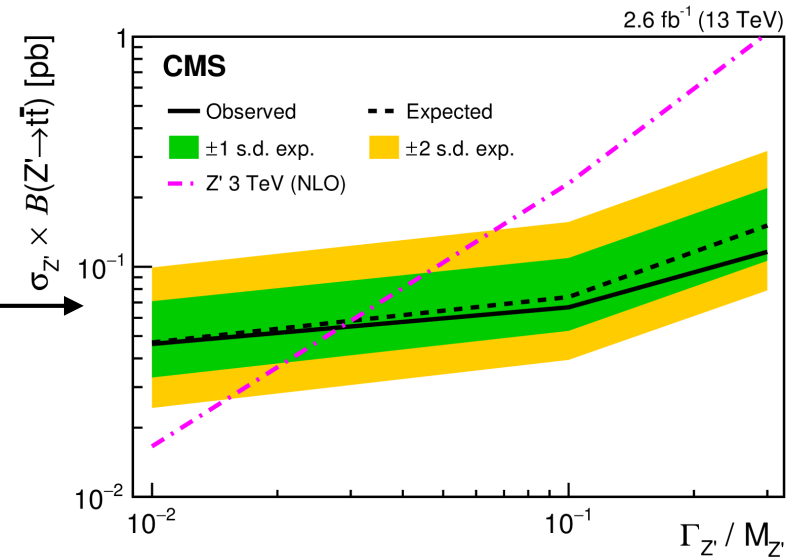
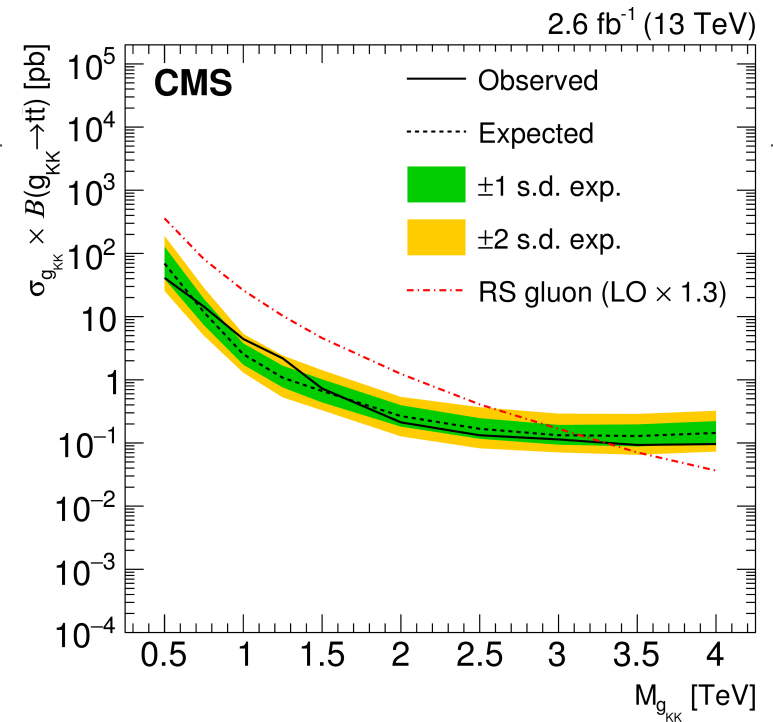


boosted tops



Top Pair Resonances

- ▶ Test for resonances with various widths (1%, 10%, 30%) and a model-specific Randall-Sundrum Kaluza-Klein gluon
- ▶ Combination of lepton+jets and all-hadronic channels
- ▶ Exclude RS KK gluons up to 3.3 TeV
 - ▶ Generic narrow Z' resonance excluded to 2.5 TeV
- ▶ Limits presented as a function of resonance width also (1%, 10%, 30%)



Result	Excluded mass ranges [TeV]							
	Z' ($\Gamma/M = 1\%$)		Z' ($\Gamma/M = 10\%$)		Z' ($\Gamma/M = 30\%$)		RS KK Gluon	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
Lepton+jets	0.6 – 2.1	0.6 – 2.3	0.5 – 3.5	0.5 – 3.4	0.5 – 4.0	0.5 – 4.0	0.5 – 2.9	0.5 – 2.9
Fully hadronic	1.2 – 1.8	1.4 – 1.8	1.0 – 3.2	1.0 – 3.5	1.0 – 3.7	1.0 – 4.0	1.0 – 2.6	1.0 – 2.4
Combined	0.6 – 2.4	0.6 – 2.5	0.5 – 3.7	0.5 – 3.9	0.5 – 4.0	0.5 – 4.0	0.5 – 3.1	0.5 – 3.3

Summary

- ▶ Very unique high- p_T topologies considered in B2G searches
 - ▶ Jet substructure, b-tagging tools are critical to reconstruct them
- ▶ Great number of new B2G results to discuss over the first half of this year!
 - ▶ Not able to mention them all here
 - ▶ See <https://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html> for all!
- ▶ More results in the pipeline as we speak!

Beyond 2 Generations Publications				
43	B2G-17-011	Search for vector-like T and B quark pairs in final states with leptons at $\sqrt{s} = 13$ TeV	Submitted to JHEP	13 May 2018
42	B2G-17-013	Search for a new heavy resonance decaying into a Z boson and a Z or W boson in $2\ell 2q$ final states at $\sqrt{s} = 13$ TeV	Submitted to JHEP	27 March 2018
41	B2G-17-005	Search for a heavy resonance decaying into a Z boson and a vector boson in the $\nu\bar{\nu}q\bar{q}$ final state	Submitted to JHEP	10 March 2018
40	B2G-16-028	Search for third-generation scalar leptoquarks decaying to a top quark and a τ lepton at $\sqrt{s} = 13$ TeV	Submitted to EPJC	8 March 2018
39	B2G-16-029	Search for a heavy resonance decaying to a pair of vector bosons in the lepton plus merged jet final state at $\sqrt{s} = 13$ TeV	Accepted by JHEP	26 February 2018
38	B2G-17-009	Search for single production of vector-like quarks decaying to a b quark and a Higgs boson	Accepted by JHEP	5 February 2018
37	B2G-16-025	Search for pair production of excited top quarks in the lepton+jets final state	PLB 778 (2018) 349	29 November 2017
36	B2G-16-023	Search for ZZ resonances in the $2\ell 2\nu$ final state in proton-proton collisions at 13 TeV	JHEP 03 (2018) 003	13 November 2017
35	B2G-16-026	Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	PLB 781 (2018) 244	16 October 2017
34	B2G-17-003	Search for pair production of vector-like quarks in the $bW\bar{b}W$ channel from proton-proton collisions at $\sqrt{s} = 13$ TeV	PLB 779 (2018) 82	2 October 2017
33	B2G-17-010	Search for heavy resonances decaying to a top quark and a bottom quark in the lepton+jets final state in proton-proton collisions at 13 TeV	PLB 777 (2017) 39	28 August 2017
32	B2G-17-001	Search for massive resonances decaying into MM, MW, WZ, WW with dilepton final states at $\sqrt{s} = 13$ TeV	PLB 67 (2018) 072008	17 August 2017

Outlook

- ▶ As we collect more data, gains in sensitivity become harder to realize
- ▶ We continue to develop and improve analysis strategies, background estimation methods, and more to increase search power
 - ▶ Collaboration with other groups in CMS to develop new tools (jet substructure, b-tagging, e.g.)
 - ▶ More data allows for high-statistics control samples of various backgrounds
- ▶ Discussions with theorists have also been very fruitful
 - ▶ We continue to target specific models as well as remain model independent for other interpretations
 - ▶ Width effects in VLQ and resonance searches implemented
 - ▶ Mixing effects between SM and BSM important to consider
- ▶ **In conclusion, the B2G group is an exciting place to work and we are ready for an upcoming discovery!**