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

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on behalf of the CMS Collaboration

Institute of Experimental Particle Physics

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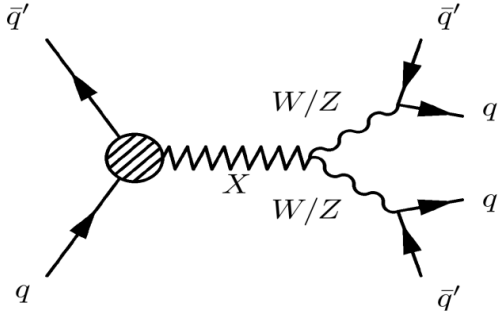
Motivation

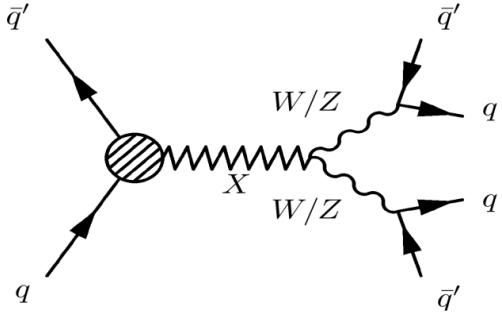


- SM issues addressed by many BSM models which suggest **new particles** at the electroweak scale
- 2 classes of models which predict resonant **decay to W, Z, and H bosons** widely probed by experiments:

Heavy Vector Triplet (HVT)

- simplified model
- one neutral (Z') and two charged (W'$^{\pm}$)
- 3 coupling parameters g_V, c_H, c_F
- model A $\equiv$ couples mostly to fermions, $g_V = 1, c_H = -0.55, c_F \approx 1$
- model B $\equiv$ couples mostly to SM bosons, $g_V = 3, c_H \approx -1, c_F \approx 1$

Motivation



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Randall-Sundrum Warped Extra Dimensions

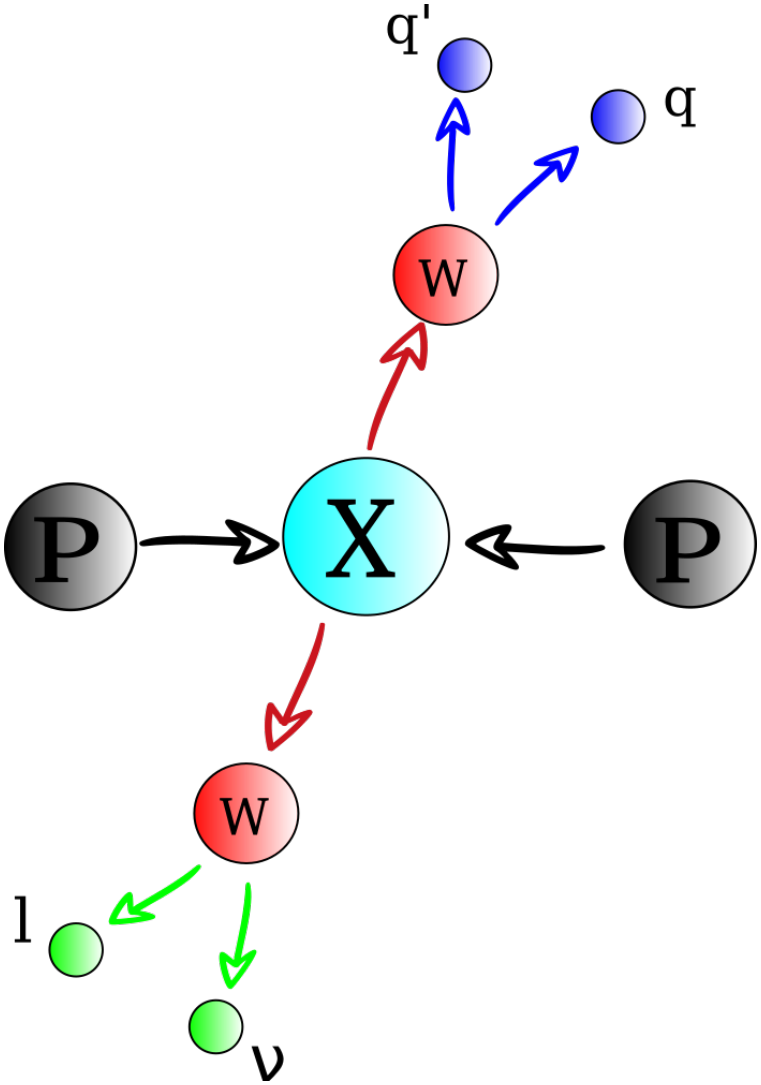
- tower of heavy particles (Kaluza-Klein excitations)
- spin-0 radions and spin-2 gravitons
- large focus on the bulk graviton model
- 2 free parameters: $m(G_{bulk})$, $\widetilde{k} = \frac{k}{M_{Planck}/\sqrt{8\pi}}$ usually set to 0.5

CMS searches

Overview over CMS searches for resonances decaying to W/Z/H bosons			
	W/Z→qq	H→bb	Z→ $\ell\ell$
W/Z→qq	PRD 97 (2018) 072006	EPJC 77 (2017) 636	Submitted to JHEP
H→bb	EPJC 77 (2017) 636	CMS-PAS-B2G-17-019, PLB 781 (2018) 244	Submitted to JHEP
H→ $\tau\tau$	CMS-PAS-B2G-17-006	CMS-PAS-B2G-17-006	
W→ $\nu\ell$	JHEP 05 (2018) 088	Submitted to JHEP	
Z→ $\ell\ell$	Submitted to JHEP, JHEP 06 (2018) 127	Submitted to JHEP	JHEP 06 (2018) 127
Z→ $\nu\nu$	JHEP 07 (2018) 075		JHEP 06 (2018) 127 , JHEP 03 (2018) 003

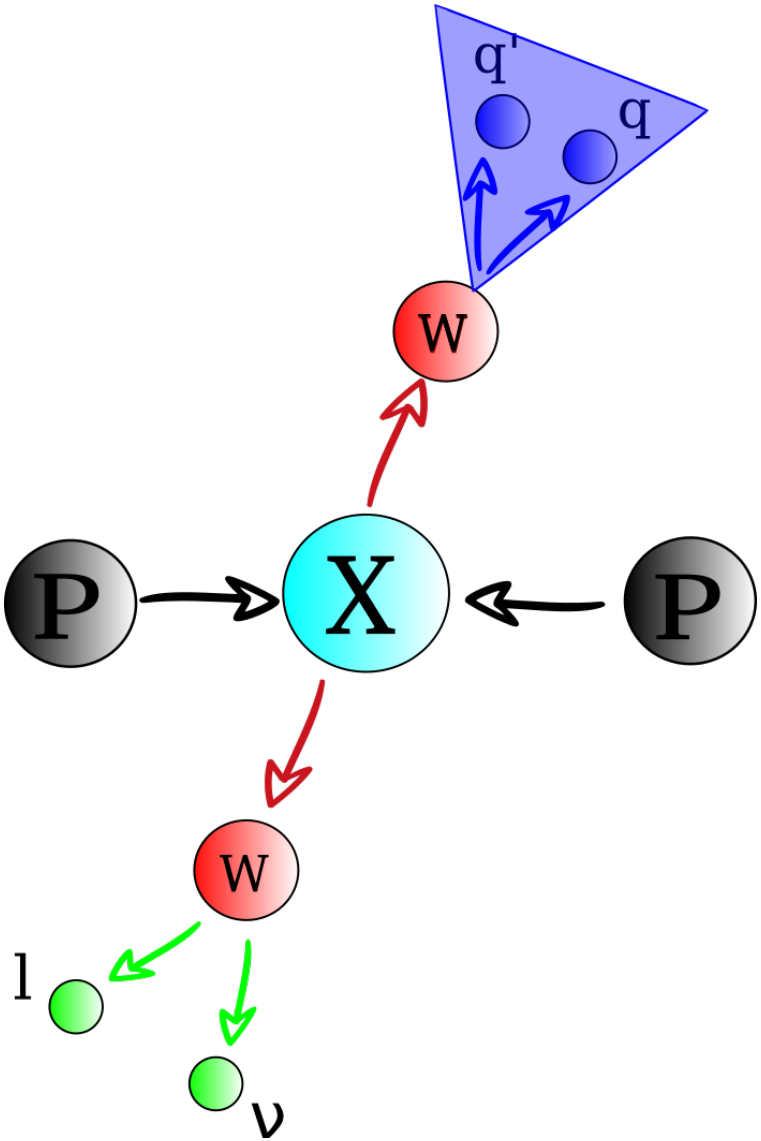
this talk: focus on boosted diboson topology, results based on 35.9 fb^{-1} of pp collisions

Reconstructing boosted bosons



decay products of energetic W/Z/H bosons are highly collimated ⇒ use of dedicated reconstruction techniques

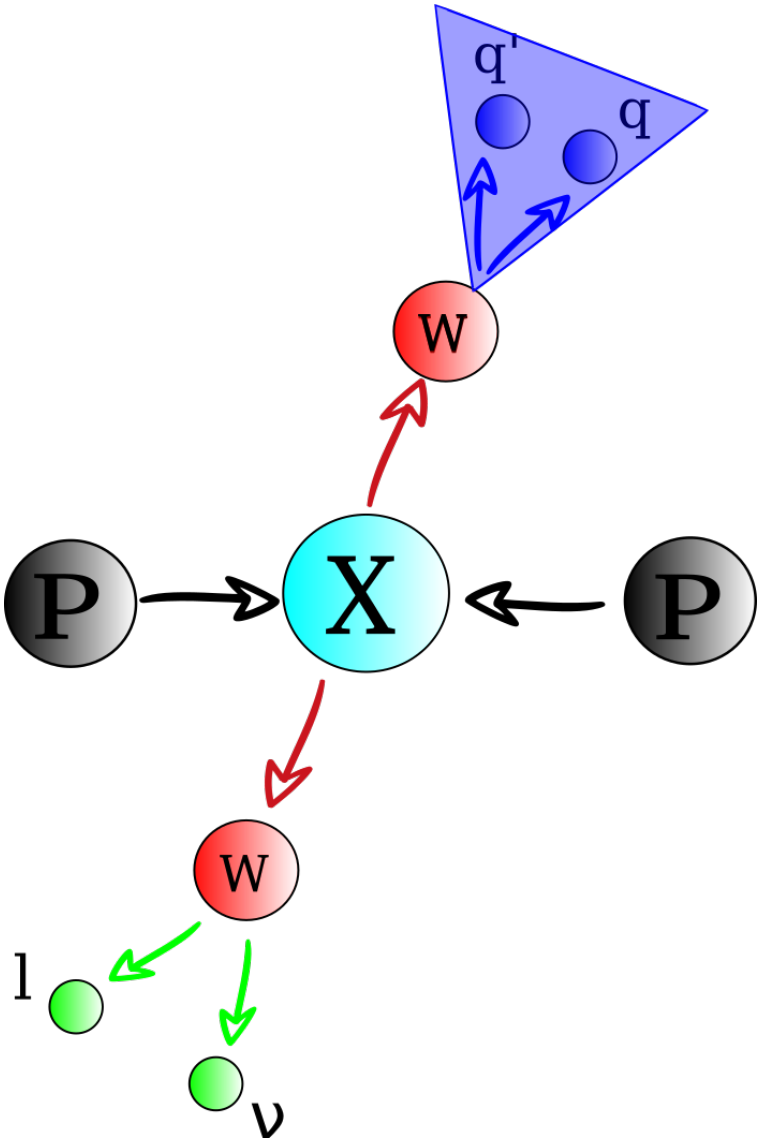
Reconstructing boosted bosons



decay products of energetic W/Z/H bosons are highly collimated ⇒ use of dedicated reconstruction techniques

- hadronic decays:
  - decay products reconstructed as one large-radius jet (R=0.8)
  - **boson tagging** techniques to discriminate against QCD jets
  - dedicated b-tagging for H→bb

Reconstructing boosted bosons



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- hadronic decays:
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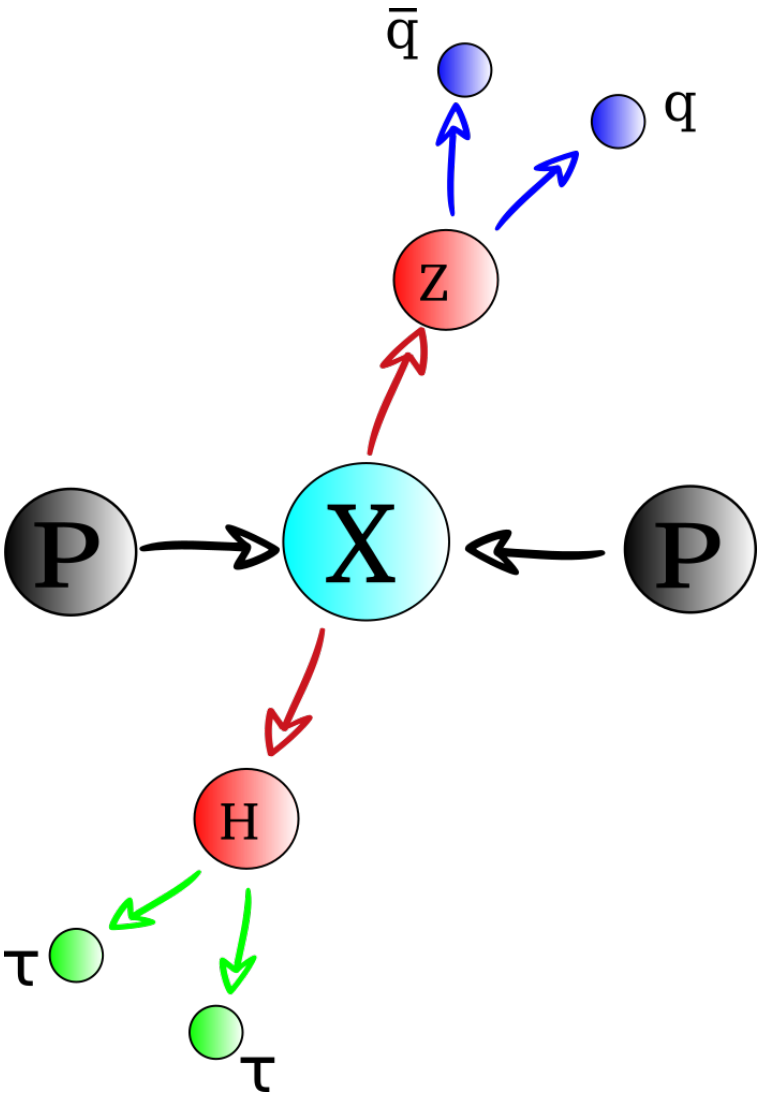
- leptonic decays:
  - **neutrinos** ⇒ large missing transverse momentum p_T^{miss}
  - special reconstruction/isolation for high-p_T electrons and muons

Reconstructing boosted bosons



decay products of energetic W/Z/H bosons are highly collimated ⇒ use of dedicated reconstruction techniques

- hadronic decays:
  - decay products reconstructed as one large-radius jet (R=0.8)
  - **boson tagging** techniques to discriminate against QCD jets
  - dedicated b-tagging for H→bb
  - hadronic τ decays: special reconstruction for hadronic τ decays
- leptonic decays:
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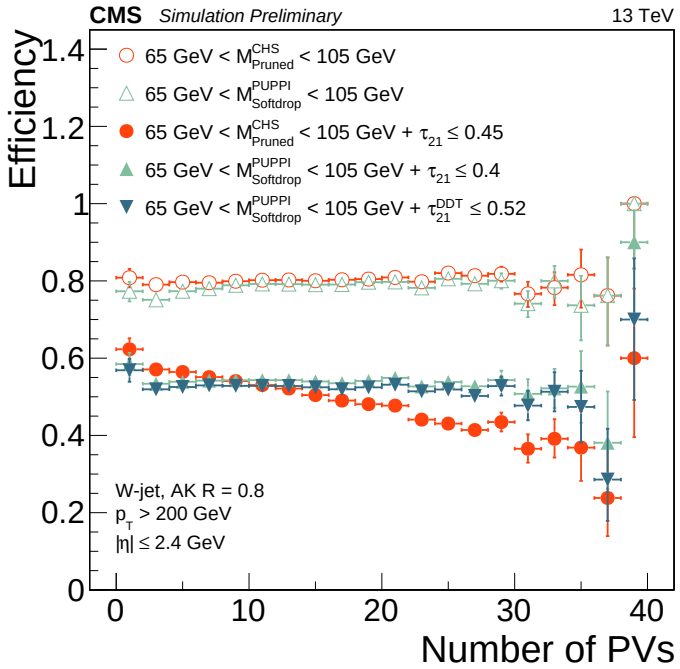
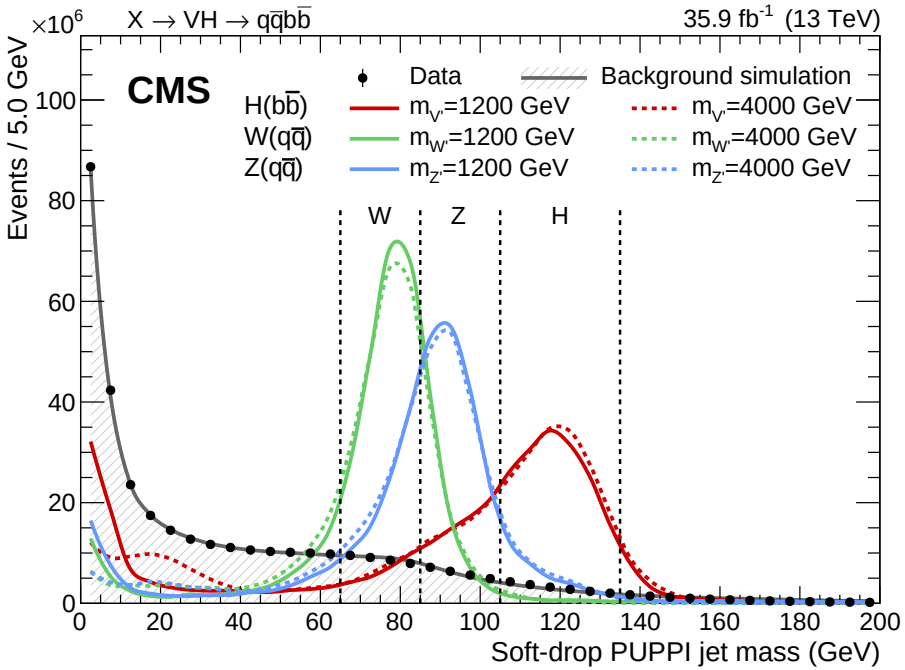
  - special reconstruction/isolation for high-p_T electrons and muons

Jet substructure: boson tagging

- pileup subtraction based on **P**ile**U**p **P**er **P**article **I**dentification
  - re-scale particle four-momenta based on compatibility of originating from primary vertex
  - cluster jets with modified particles
- **soft-drop algorithm (modified mass-drop algorithm):**
  - subtract soft and large-angle radiation to construct sudakov safe variables
  - soft-drop jet mass used in V/H jet tagging and in sideband definitions or as additional variable in multidimensional fits





CMS-PAS-JME-16-003

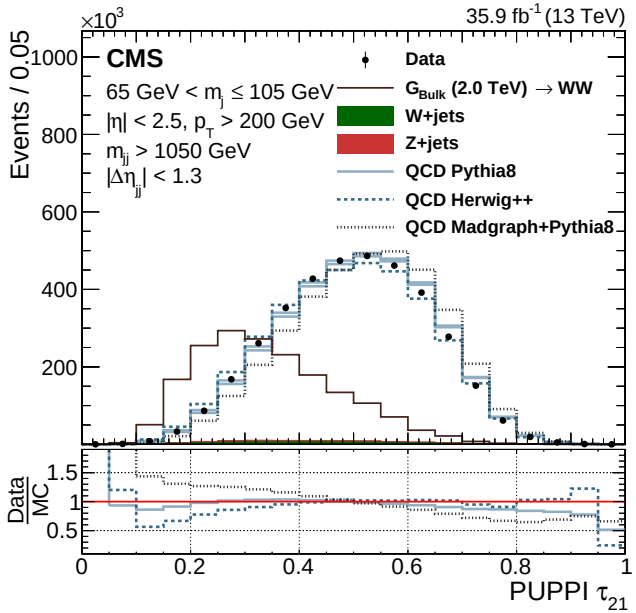
EPJC 77 (2017) 636

Jet substructure: boson tagging

N-subjettiness $\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\right)$

- different energy pattern in jets from boosted boson decays ⇒ "count" number of hard energy bundles
- low values of τ_N means compatibility with N jet-axes
- most prominent discriminant: ratio of 2- over 1-subjettiness (τ_{21}):
  - τ_{21} threshold depending on analysis
  - split into high purity (HP) and low purity (LP) categories
  - LP categories for recovering signal efficiency at very high masses

PRD 97 (2018) 072006



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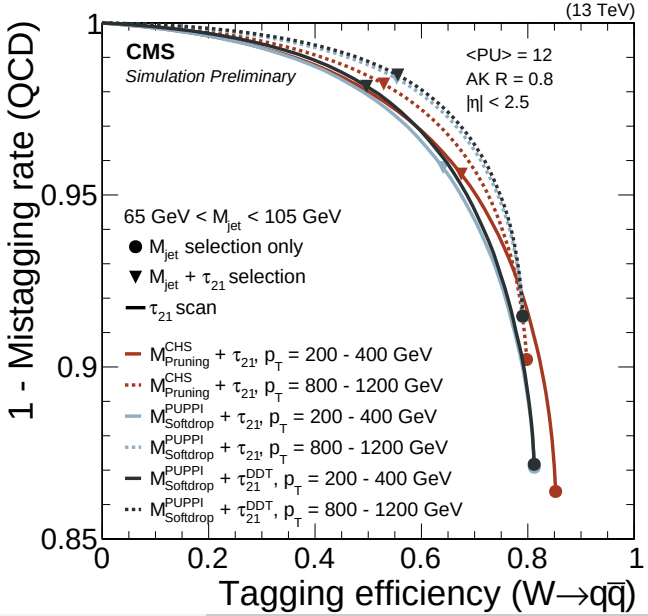

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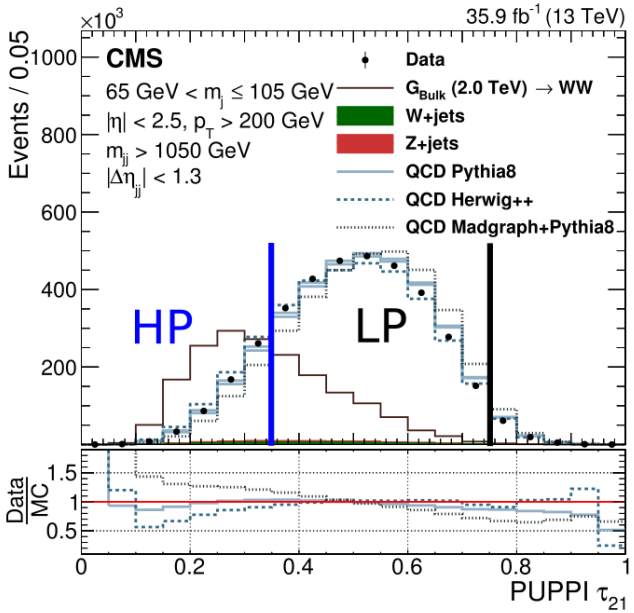

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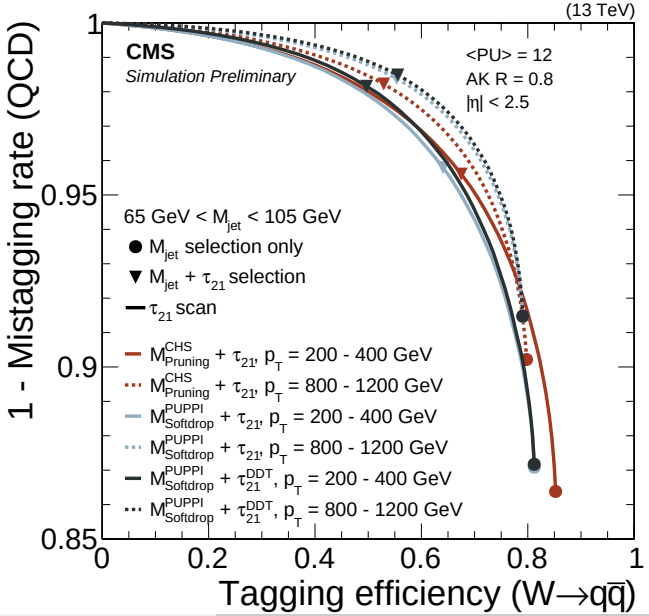
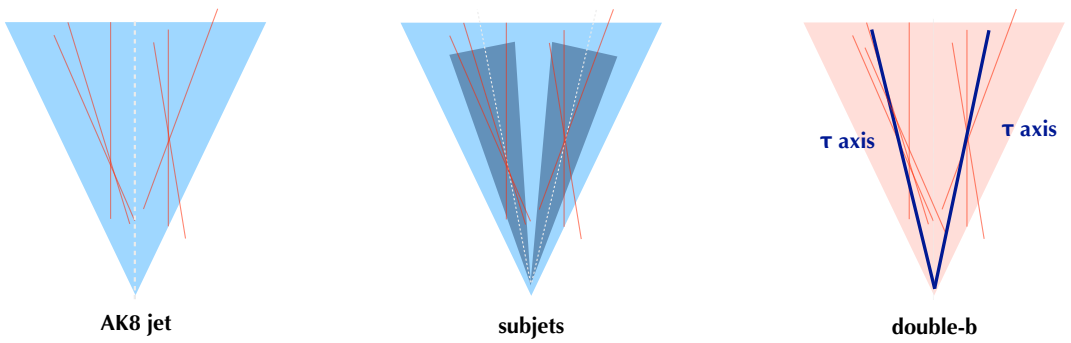
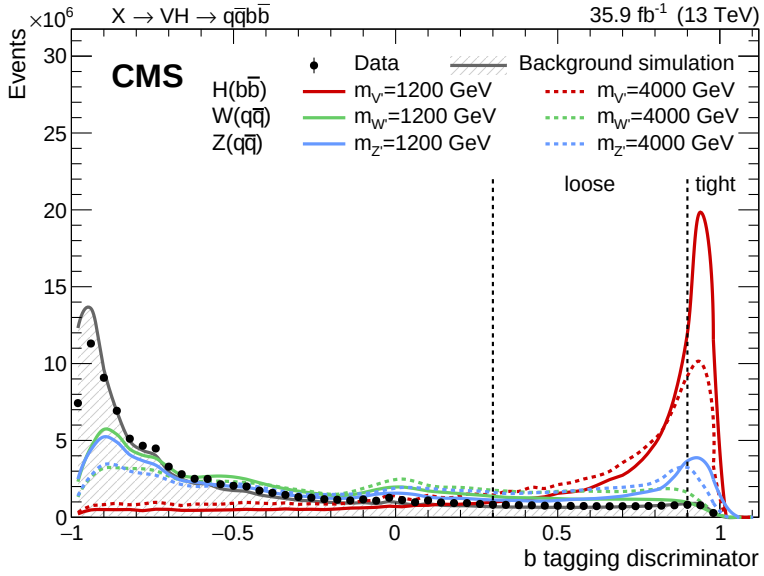


Jet substructure: H→bb tagging





EPJC 77 (2017) 636

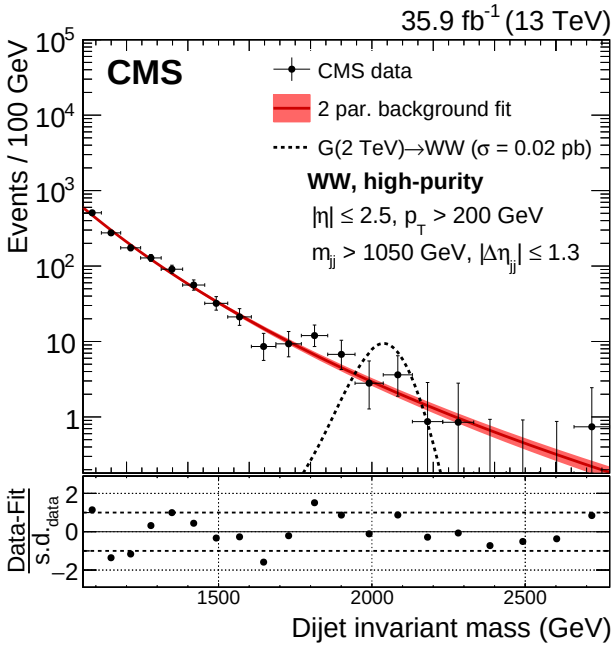
two methods to tag H→bb decays (JINST 13 (2018) P05011):

- both use multivariate techniques to combine track and vertex information into a single discriminant property
- **default CSV tagger applied to sub-jets:**
  - used in VH→ $(2\ell/\ell\nu/2\nu)$bb and HH→ $\tau\tau$ bb
- **double-b tagger:**
  - associate secondary vertices with the jet axes from N-subjettiness
  - used in HH→4b and VH→qqbb

VV/VH→qqqq

VV→4q

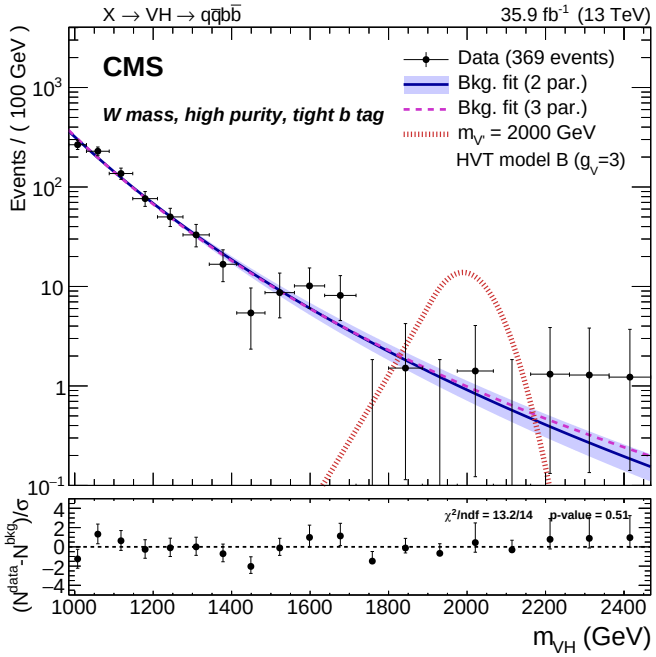
- 2 large-radius jets with high p_T, $65 < m_{jet}^{softdrop} < 105$ GeV
- $\tau_{21} < 0.35$ for both jets: HP category, $0.35 < \tau_{21} < 0.75$ for one jet other passing HP requirement: LP category
- data-driven background: fit with analytic function



PRD 97 (2018) 072006

VH→4q

- 2 large-radius jets with high p_T
- V jet: soft-drop mass window, 2 τ_{21} categories
- H jet: double-b tagger discriminant > 0.9 HP, $0.3 - 0.9$ LP category
- data-driven background: fit with analytic function

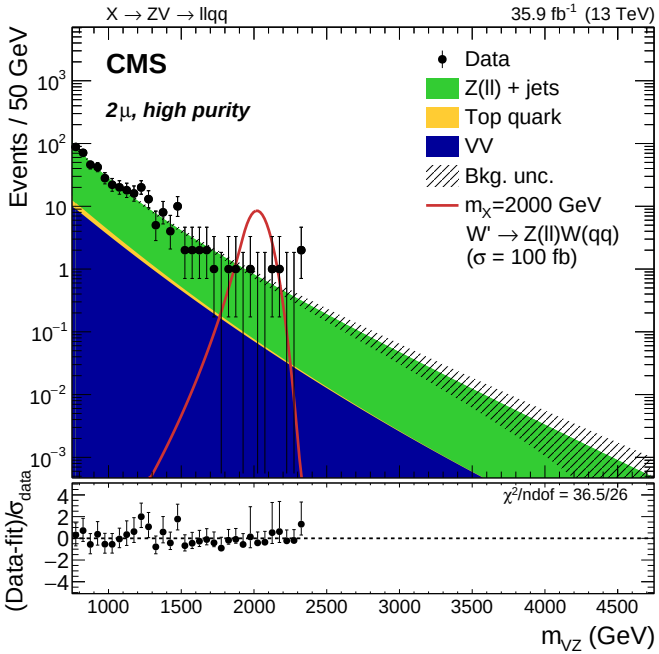


EPJC 77 (2017) 636

ZV$\rightarrow \nu\nu(\ell\ell)$qq

ZV$\rightarrow \ell\ell$qq

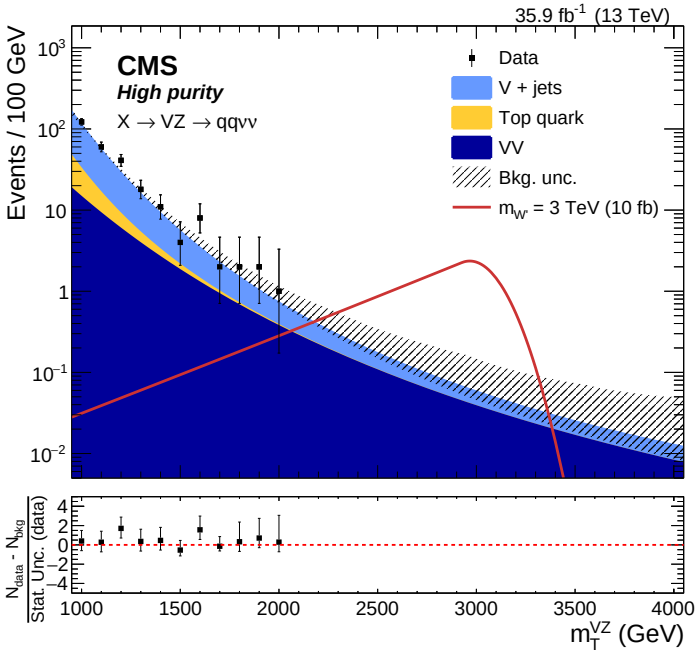
- two opposite sign isolated electrons/muons, $70 < m_{ll} < 110$ GeV
- V jet: $65 < m_{jet1}^{softdrop} < 105$ GeV, $\tau_{21} < 0.35$ HP category, $0.35 < \tau_{21} < 0.75$ LP category
- Z+jets background yield and shape through simulation-assisted method using sideband ratios (α method)



Submitted to JHEP

ZV$\rightarrow \nu\nu$qq

- $p_T^{miss} > 200$ GeV, 1 large-radius jet
- V jet: τ_{21} HP and LP categories, soft-drop mass window
- bump hunt in transverse mass $m_T^{ZV} = \sqrt{2E_T^j p_T^{miss}(1-\cos\Delta\phi)}$
- α method to estimate Z+jets

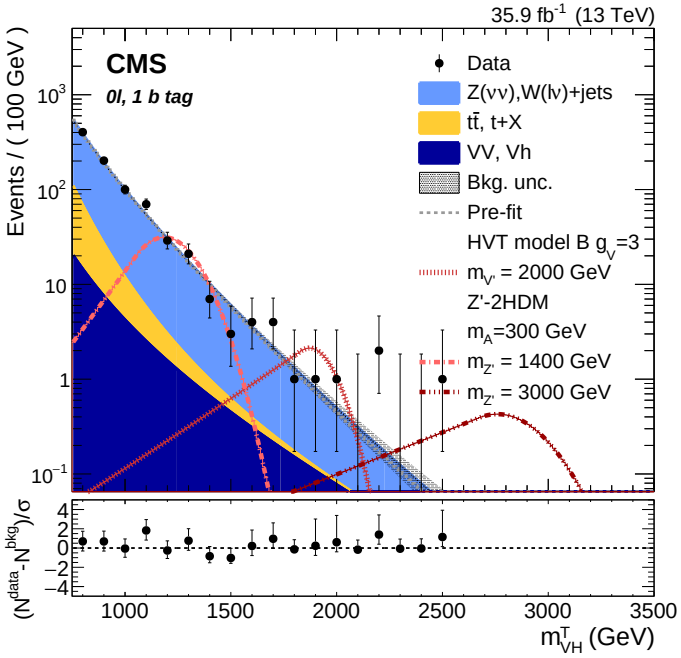


JHEP 07 (2018) 075

VH/HH→ $\nu\ell(\ell\ell)$(qq)qq

VH semileptonic

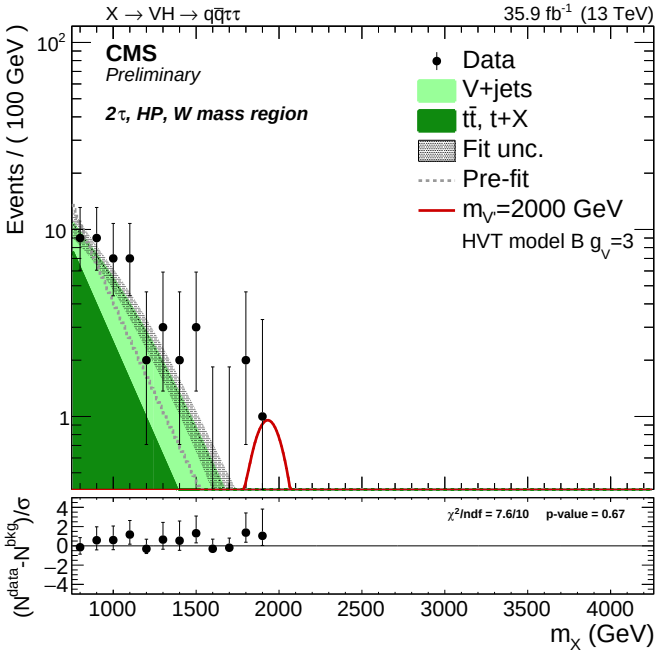
- 0/1/2 leptons, $p_T^{miss} > 250, 80$ GeV, no additional b-tagged jets
- subjet b-tagger: ≥ 1 b-tagged subjets
- softrdop mass requirement for H jet
- V+jets estimated using α method and jet mass SB



Submitted to JHEP

HH/HV→ $\tau\tau$bb

- 0/1/2 leptons, $p_T^{miss} > 200$ GeV, 1 large-radius jet
- soft-drop mass window for H/V, V jet $0(0.4) \leq \tau_{21} < 0.4(0.75)$
- H jet: 1 or 2 b-tagged sub-jets, b-tag veto on additional jets in the event
- V+jets/multijet estimated with α method

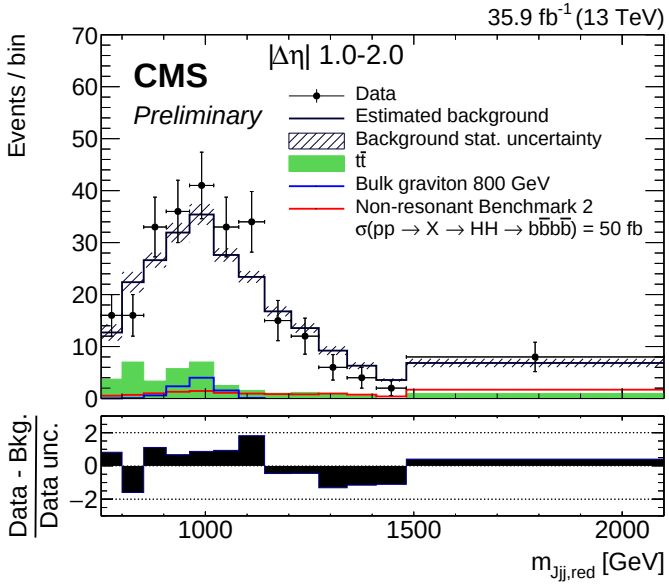


CMS-PAS-B2G-17-006

HH $\rightarrow$4b + WV $\rightarrow \ell\nu$qq

HH$\rightarrow$4b

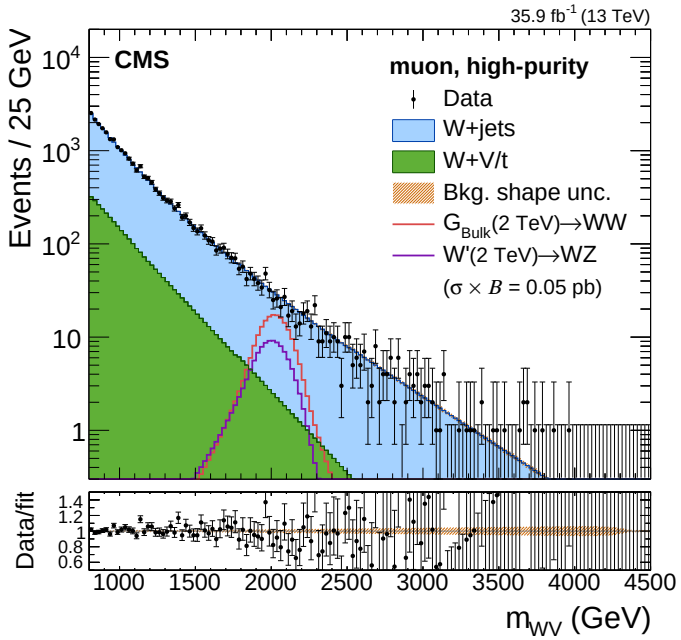
- fully merged and (semi)-resolved final states
- soft-drop mass requirement, double-b tagger discriminant > 0.8
- search for excess in HH invariant(-reduced) mass spectrum
- data-driven background estimation using sideband (alphabet method) to estimate yield and shape of multijet background



(CMS-PAS-B2G-17-019)

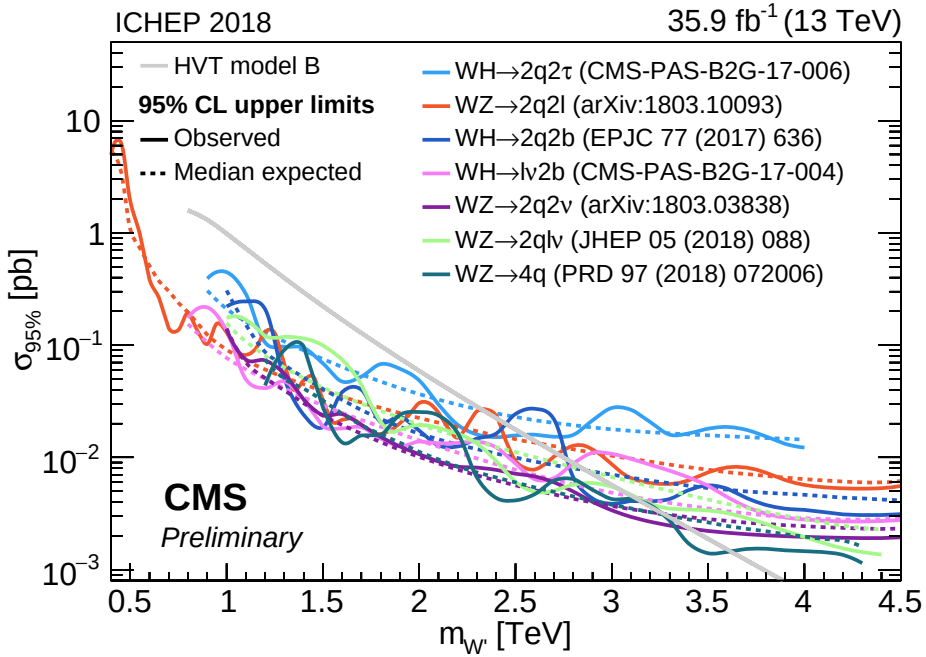
WV$\rightarrow \ell\nu$qq

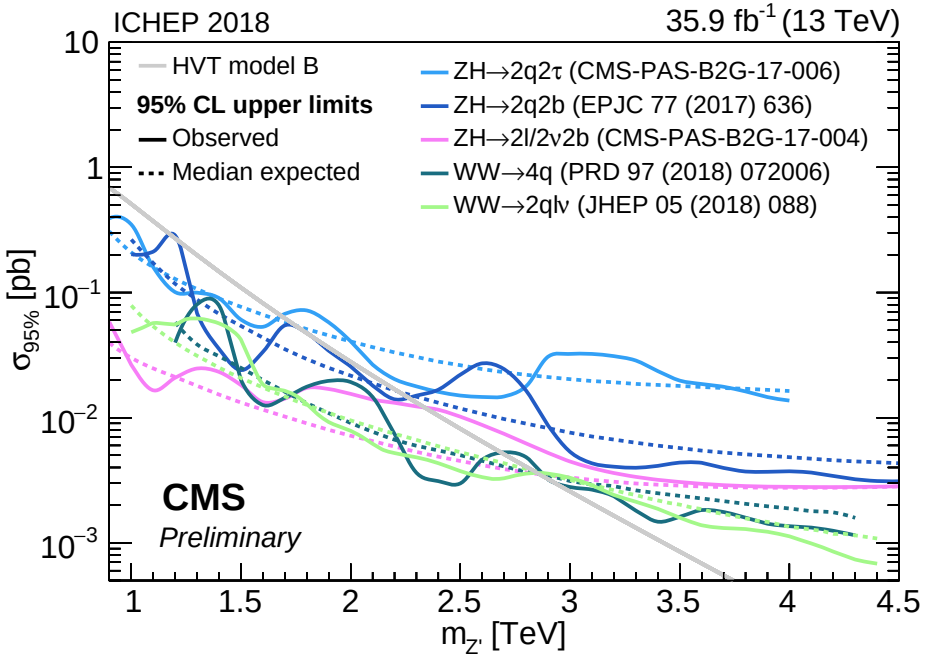
- 1 isolated lepton + p_T^{miss} +1 large-radius jet
- mass window of $30 < m_{jet1}^{softdrop} < 210$ GeV
- events rejected with ≥ 1 b-tagged jets (medium WP CSV)
- HP $\tau_{21} \leq 0.55$, LP $0.55 < \tau_{21} \leq 0.75$
- 2 dimensional fit in m_{jet} and m_{WV}



JHEP 05 (2018) 088

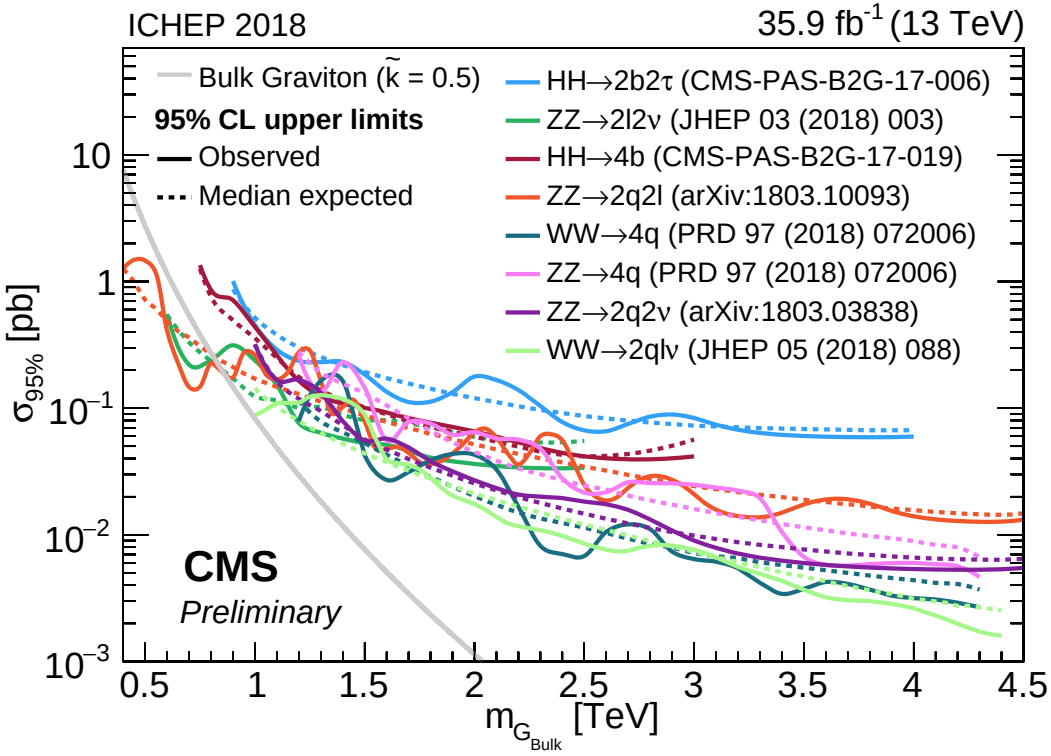
Results HVT model





- All searches for W'/Z' from HVT model B with WZ/WH, ZH/WW intermediate states interpreted as 95% CL upper limits on signal cross sections.
- Data is consistent with background expectations
- mass limits from CMS now at 3.1 TeV for W' and 2.7 TeV for Z' (WZ→2q2ν, WW→ 2q$\ell\nu$)

Results bulk graviton model



- All searches for spin-2 bulk gravitons ($\tilde{k}$= 0.5) with WW, ZZ or HH intermediate states interpreted as 95% CL upper limits on signal cross sections.
- Data is consistent with background expectations
- for low masses best limits from ZZ→ $2\ell\ 2\nu$ search, for high masses coming from WW→2q$\ell\nu$ and WW→4q

Conclusion and Outlook

- heavy resonances decaying to two SM bosons were sought in many final states using the full 2016 data
- data are consistent with the background expectations from SM backgrounds $\Rightarrow$ upper limits are set on the production cross section for spin-1 and spin-2 resonances and interpreted within the bulk graviton or HVT model
- with the full Run-II data $\approx$ 4 times the luminosity can be expected
- a lot of progress is being made in terms of analysis strategy
  - development of jet related algorithms
  - multidimensional background fits to optimally constrain and understand backgrounds

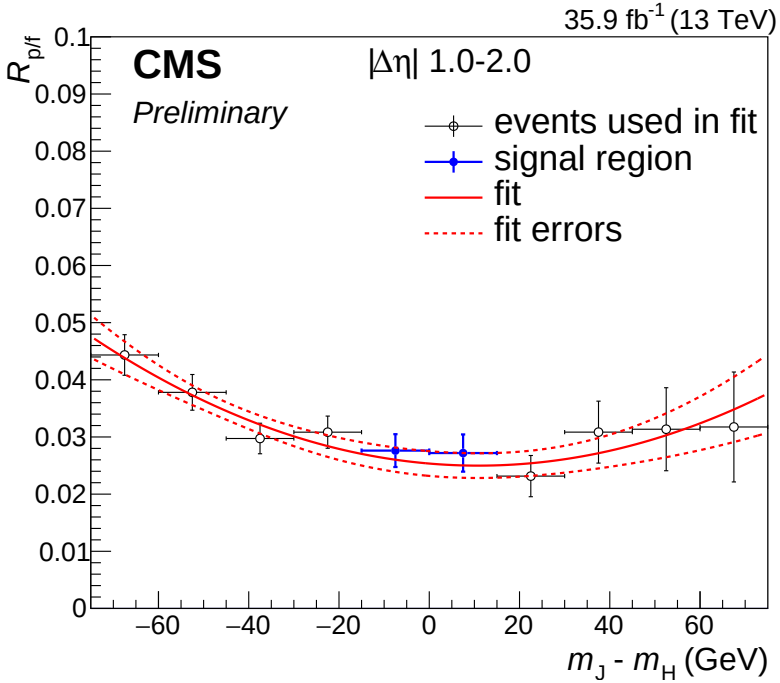
EXCITING TIMES AHEAD!

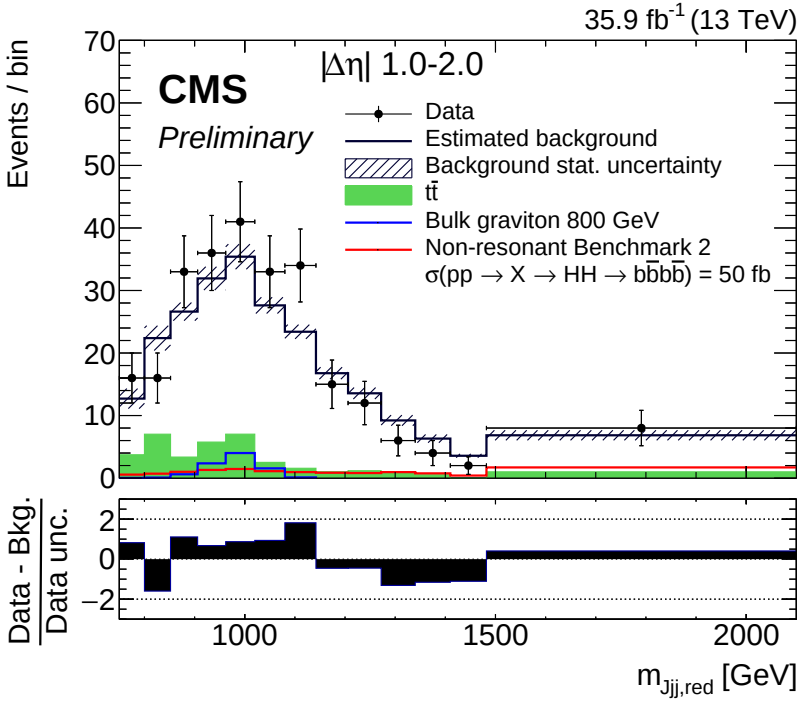
BACKUP

HH→bbbb search (CMS-PAS-B2G-17-019)

Search for radion/graviton excitation in WED models using HH→ bbbb:

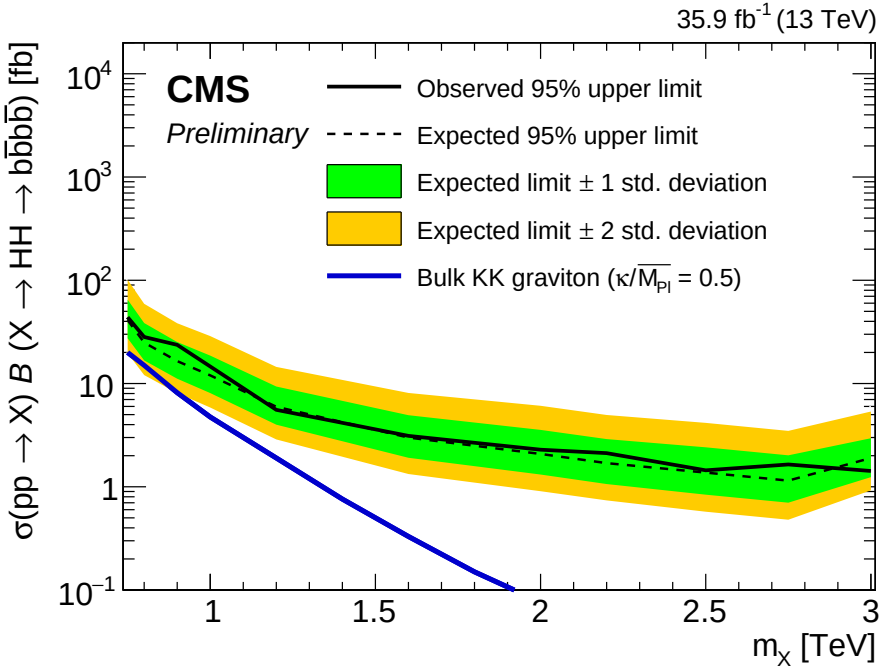
- $105 < m_{jet}^{softdrop} < 135$ GeV, trigger semi-resolved and boosted events
- $\tau_{21} < 0.55$, double-b tagger discriminant > 0.8 (for semi-resolved case DeepCSV used)
- search for excess in HH invariant(-reduced) mass spectrum
- sidebands defined using the mass cut and the double-b tagger cuts
- calculate pass/fail ratio (for b-tagging) in sidebands → calculate pass/fail for signal region
- scale the failed "signal region" to get the estimation of background in the signal region (in bins of m_{jj})

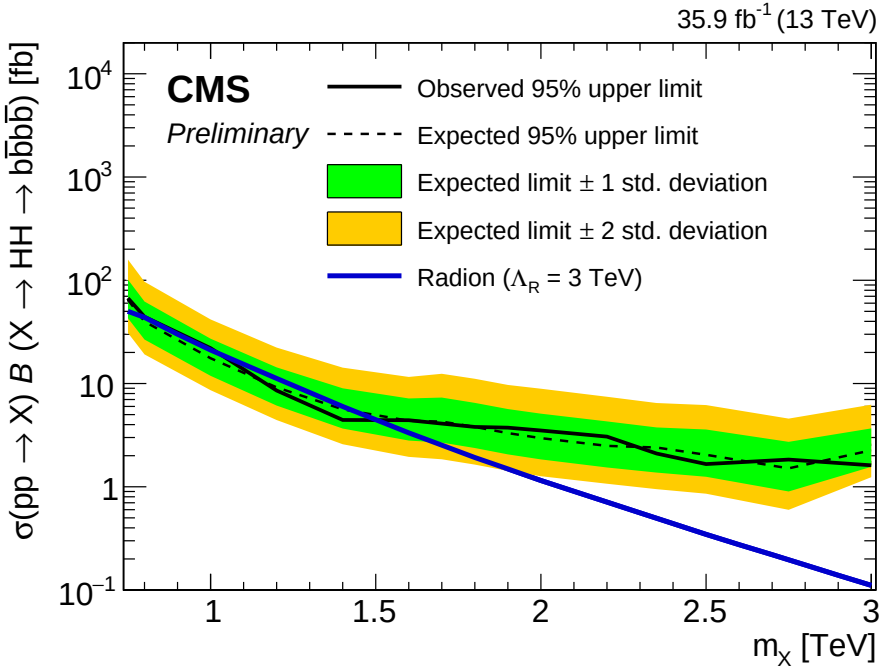




HH→bbbb search (CMS-PAS-B2G-17-019)

Search for radion/graviton excitation in WED models using H→ bbbb limits:

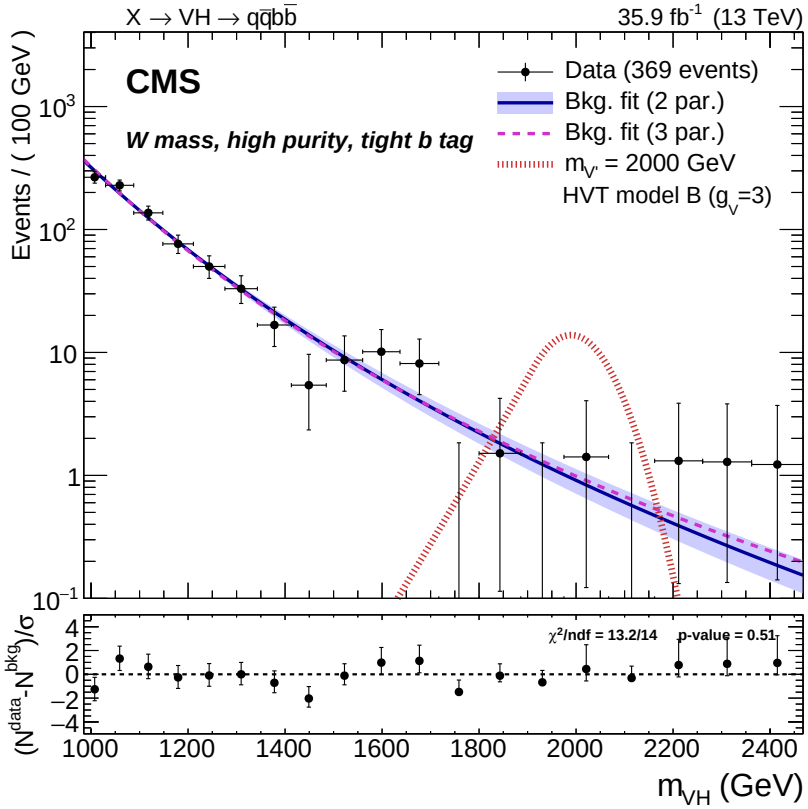


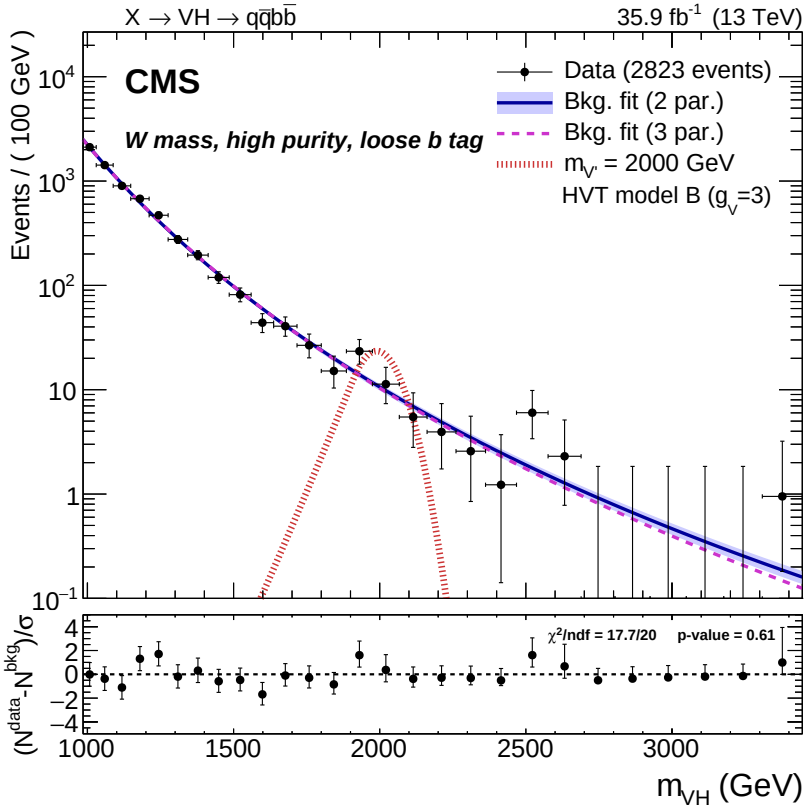


VH→qqbb search EPJC 77 (2017) 636

Search for exotic resonances decaying to VH→qqbb:

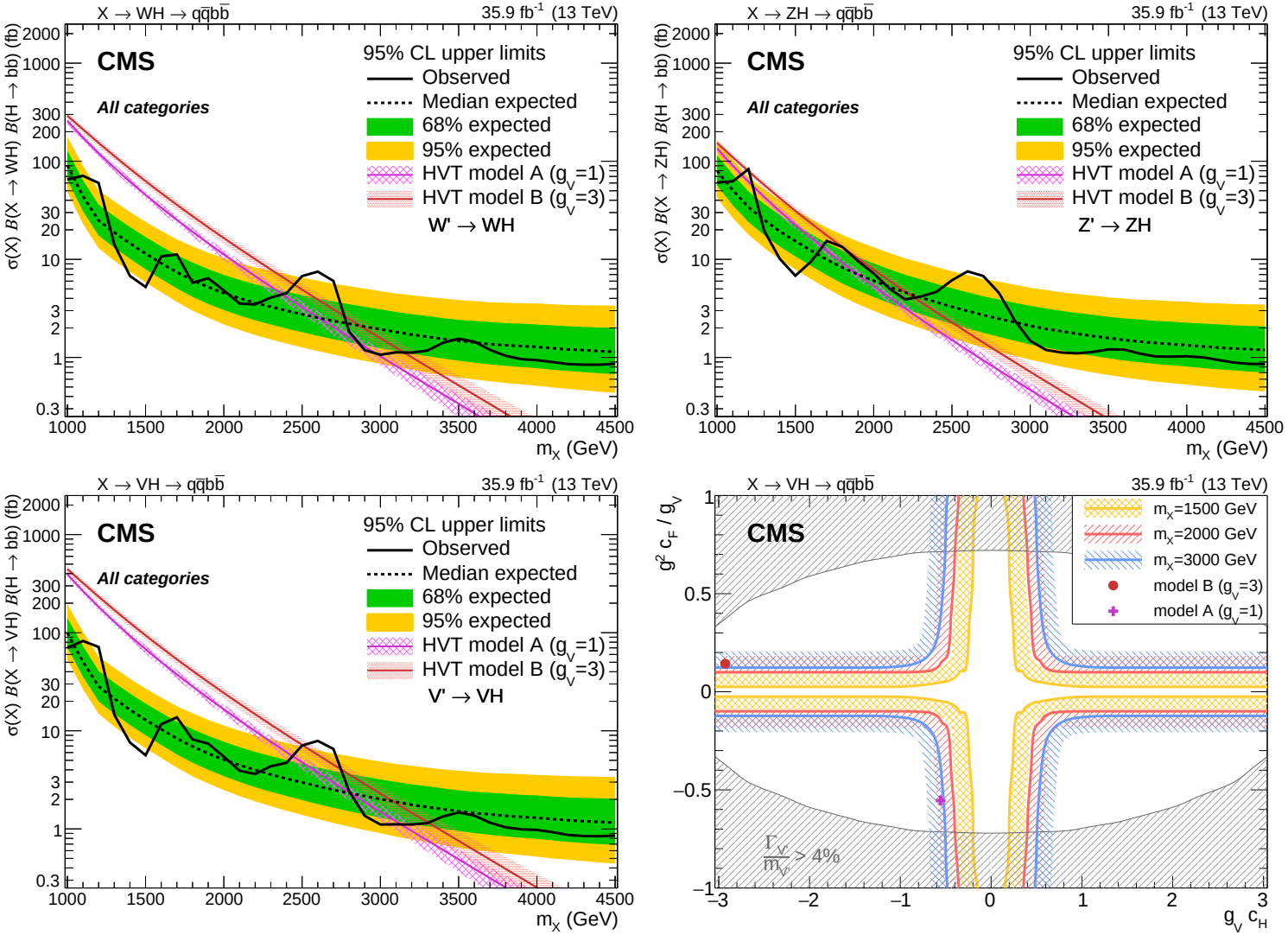
- 2 CHS-AK8 jets (PUPPI used for mass and substructure variables)
- $105 < m_{jet1}^{softdrop} < 135$ GeV, $65 < m_{jet2}^{softdrop} < 105$ GeV
- for V jet: $\tau_{21} < 0.35$ HP category, $\tau_{21} < 0.75$ LP category
- for Higgs jet: double-b tagger discriminant > 0.9 of HP, between $0.3 - 0.9$ for LP category
- data-driven background estimation by fitting analytic function to data





VH→qqbb search EPJC 77 (2017) 636

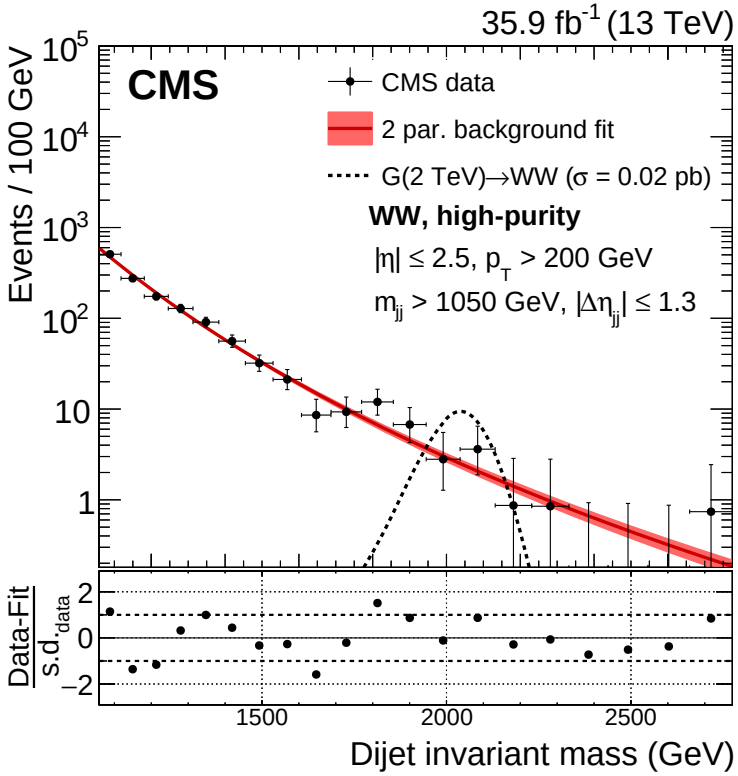
Search for exotic resonances decaying to VH→qqbb limits:

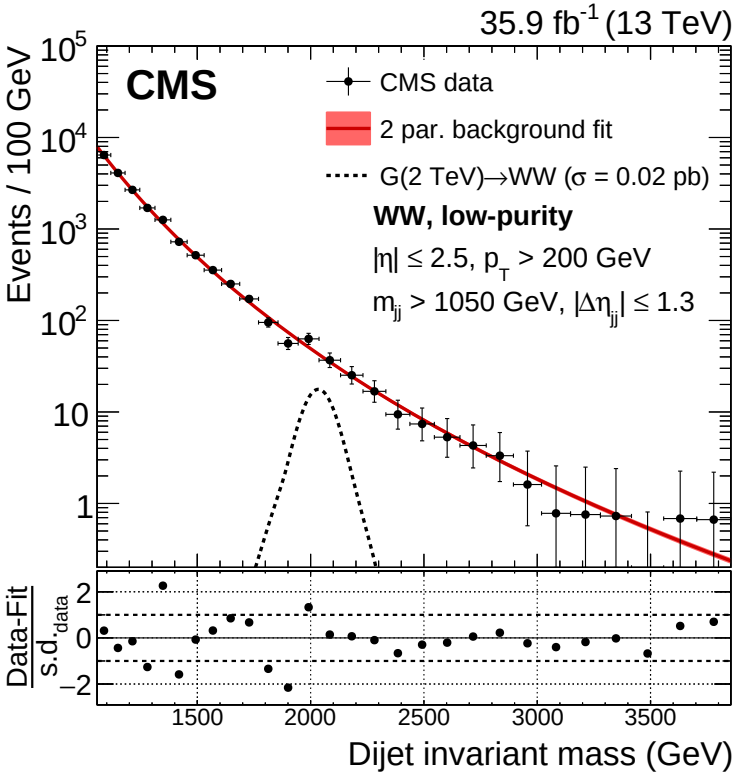


VV→qqqq search PRD 97 (2018) 072006

Search for exotic resonances decaying to VV→qqqq:

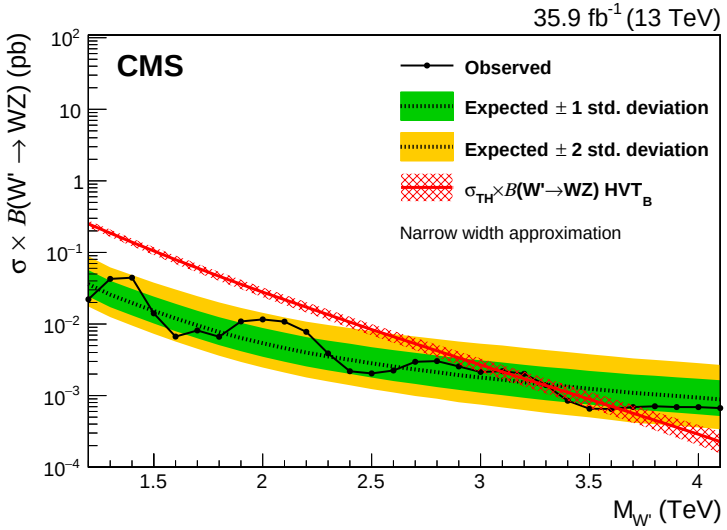
- search strategy very similar to VH analysis except for not utilizing b-tagging

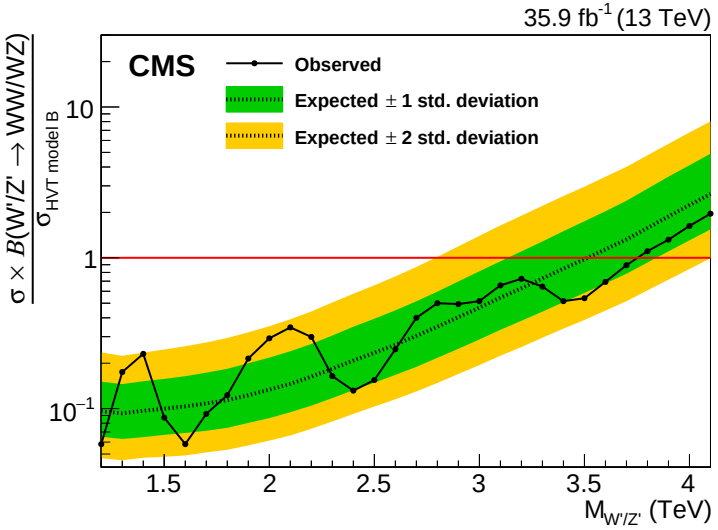


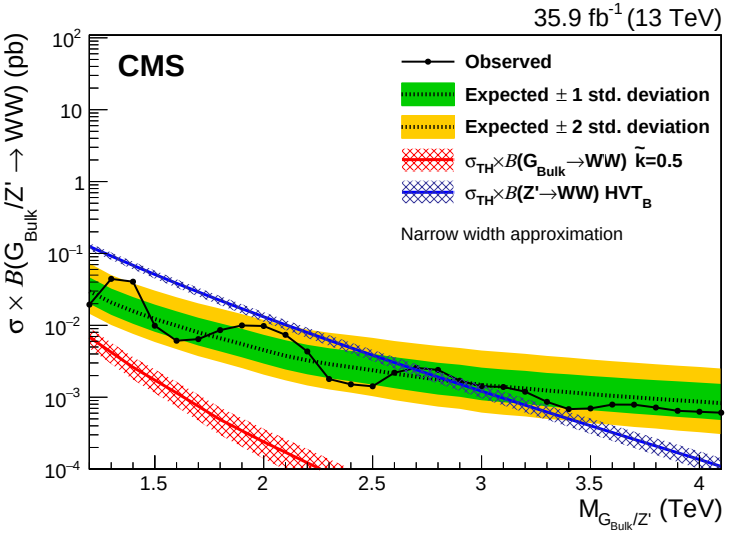


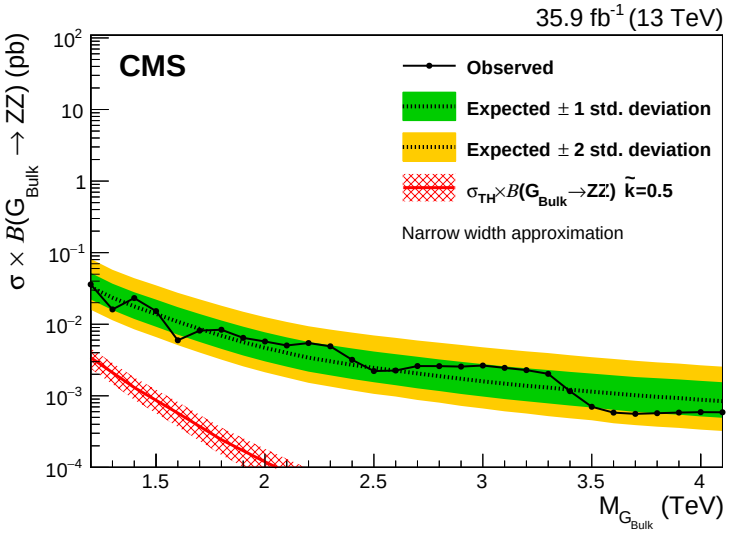
VV→qqqq search PRD 97 (2018) 072006

Search for exotic resonances decaying to VV→qqqq results:



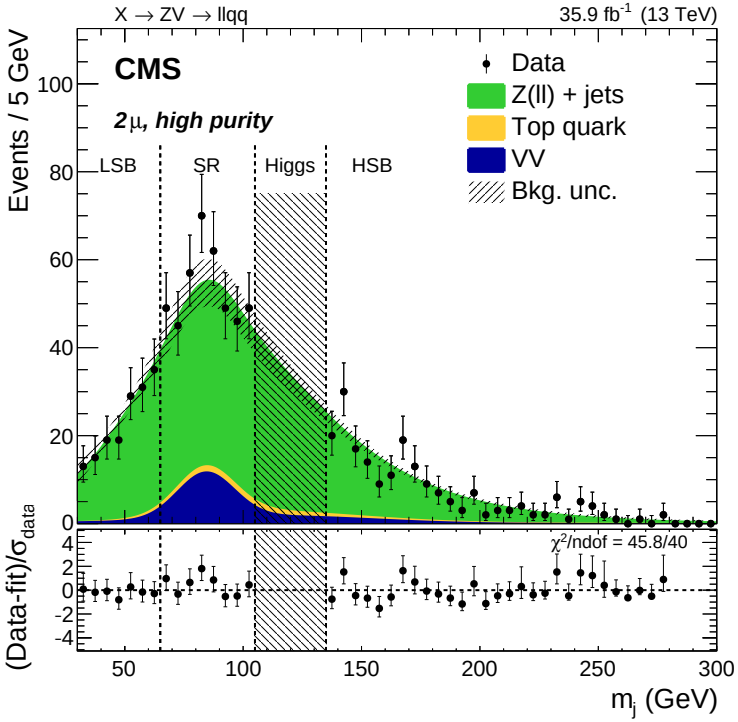


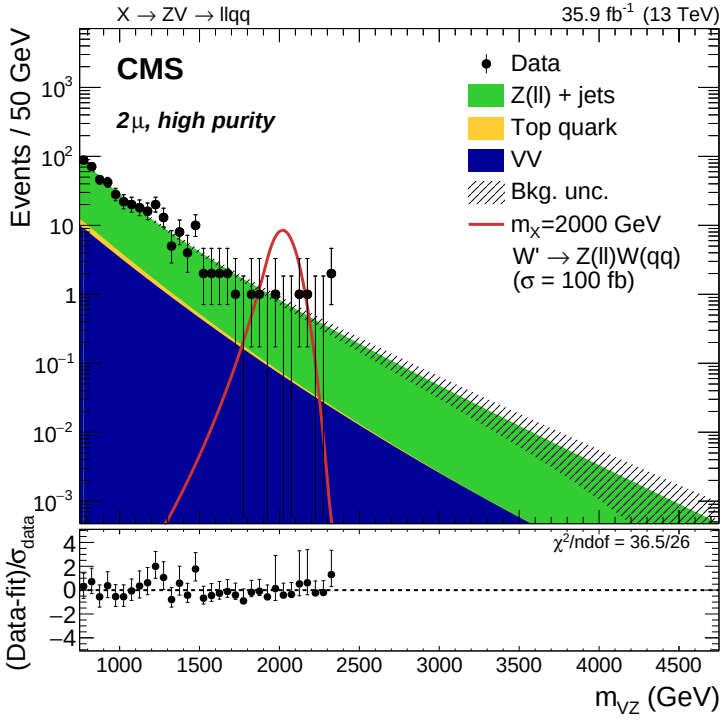




ZV→ $\ell\ell$qq Submitted to JHEP

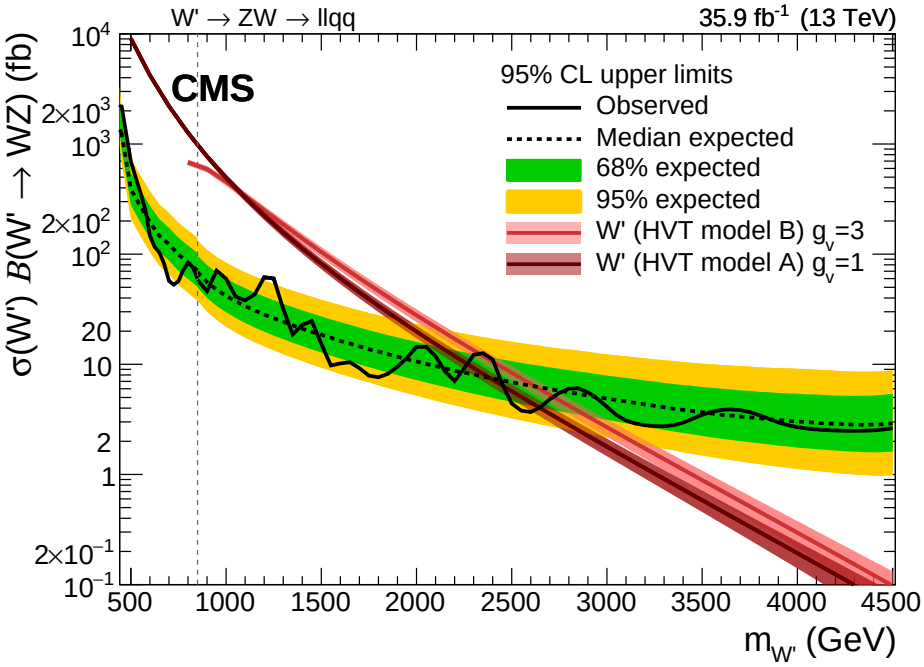
- high mass and low mass search: here focus on high mass
- two opposite sign isolated electrons or muons
- $70 < m_{ll} < 110$ GeV, $65 < m_{jet1}^{softdrop} < 105$ GeV
- for V jet: $\tau_{21} < 0.35$ HP category, $\tau_{21} < 0.75$ LP category
- main background (Z+jets) estimated using jet mass sideband region
- extract yield in SR from fit of analytic functions to m_j using both sideband regions
- extract shape of invariant mass distribution m_{ZV} using α method → transfer function defined from MC from SB to SR; fit function to data-SB and MC SB+SR → correct with α function

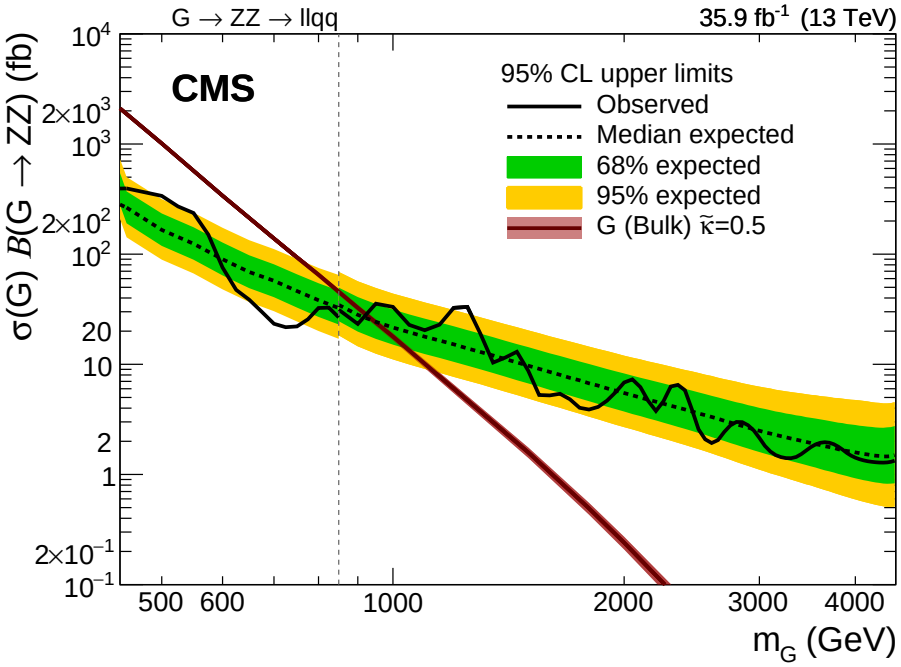




ZV→ $\ell\ell$qq Submitted to JHEP

Search for heavy resonance decaying to ZV→llqq results:

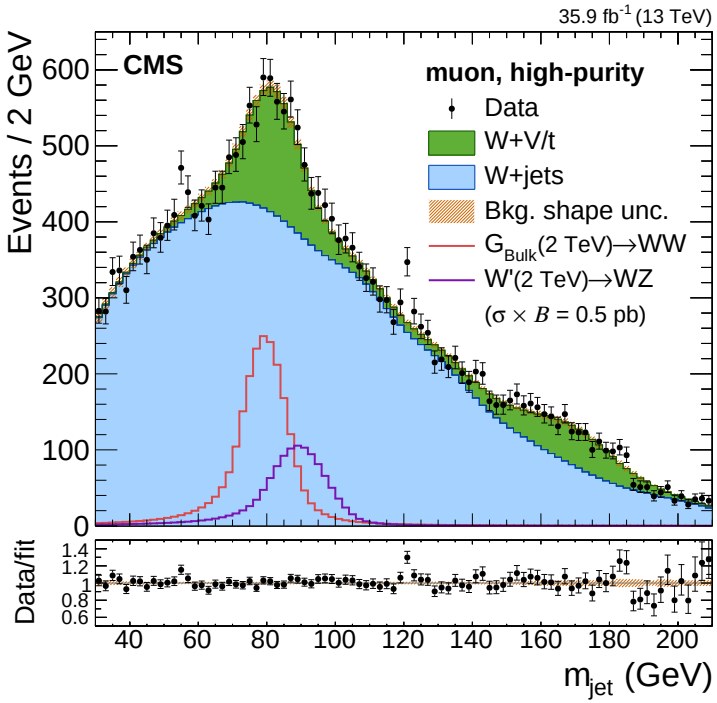


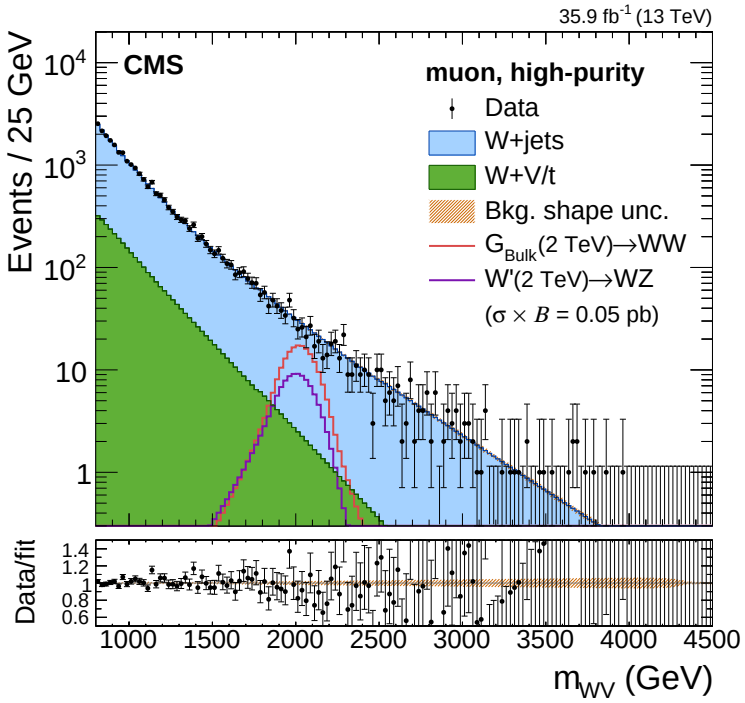


WV→ $\nu\ell$qq JHEP 05 (2018) 088

Search for exotic resonances decaying to WV→ νlqq:

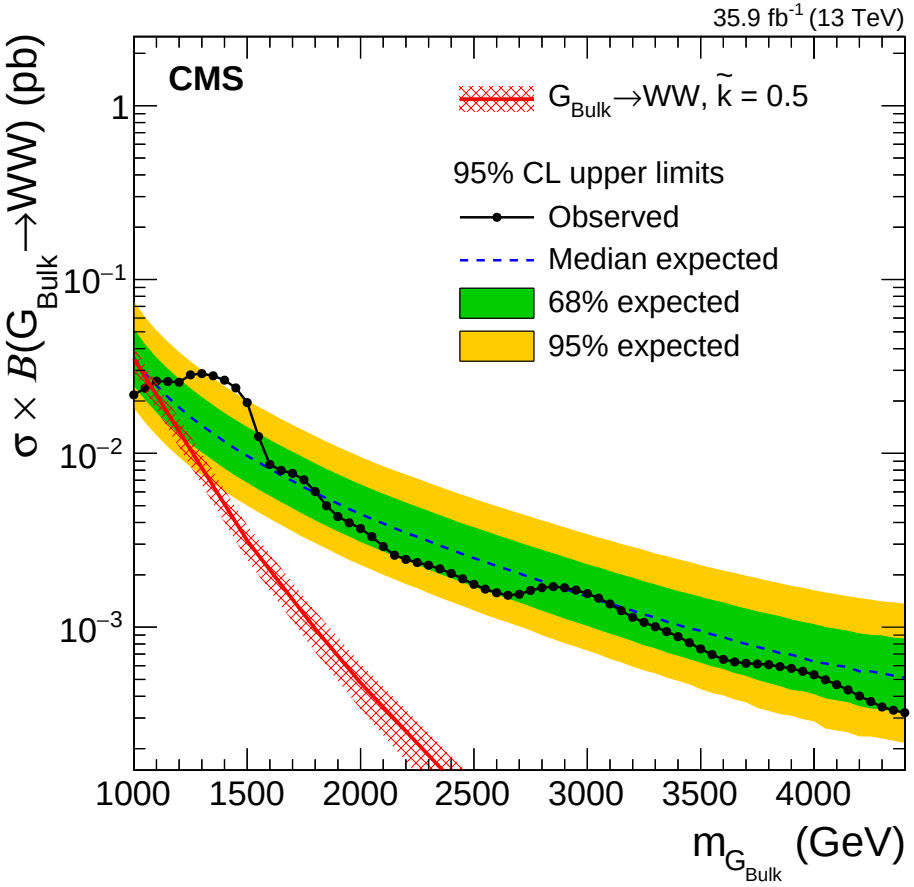
- 1 isolated lepton + p_T^{miss} +1 PUPPI-AK8 jet
- 2 dimensional fit method for background estimation using $30 < m_{jet1}^{softdrop} < 210$ GeV
- reject events with CSV discriminant passing the medium WP
- HP $\tau_{21} \leq 0.55$, LP $0.55 < \tau_{21} \leq 0.75$
- 2dim background fit in m_{jet} and m_{WV} with conditional templates built from simulation using forward folding kernel approach

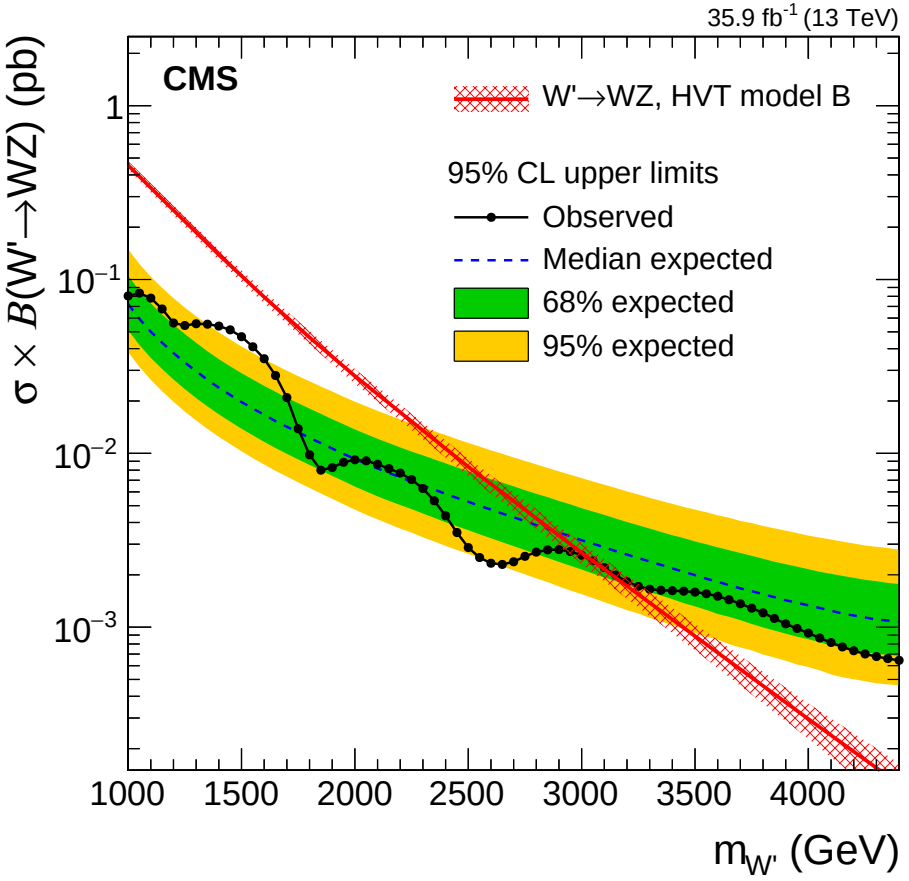




WV→ $\nu\ell$qq JHEP 05 (2018) 088

Search for exotic resonances decaying to WV→ νlqq results:

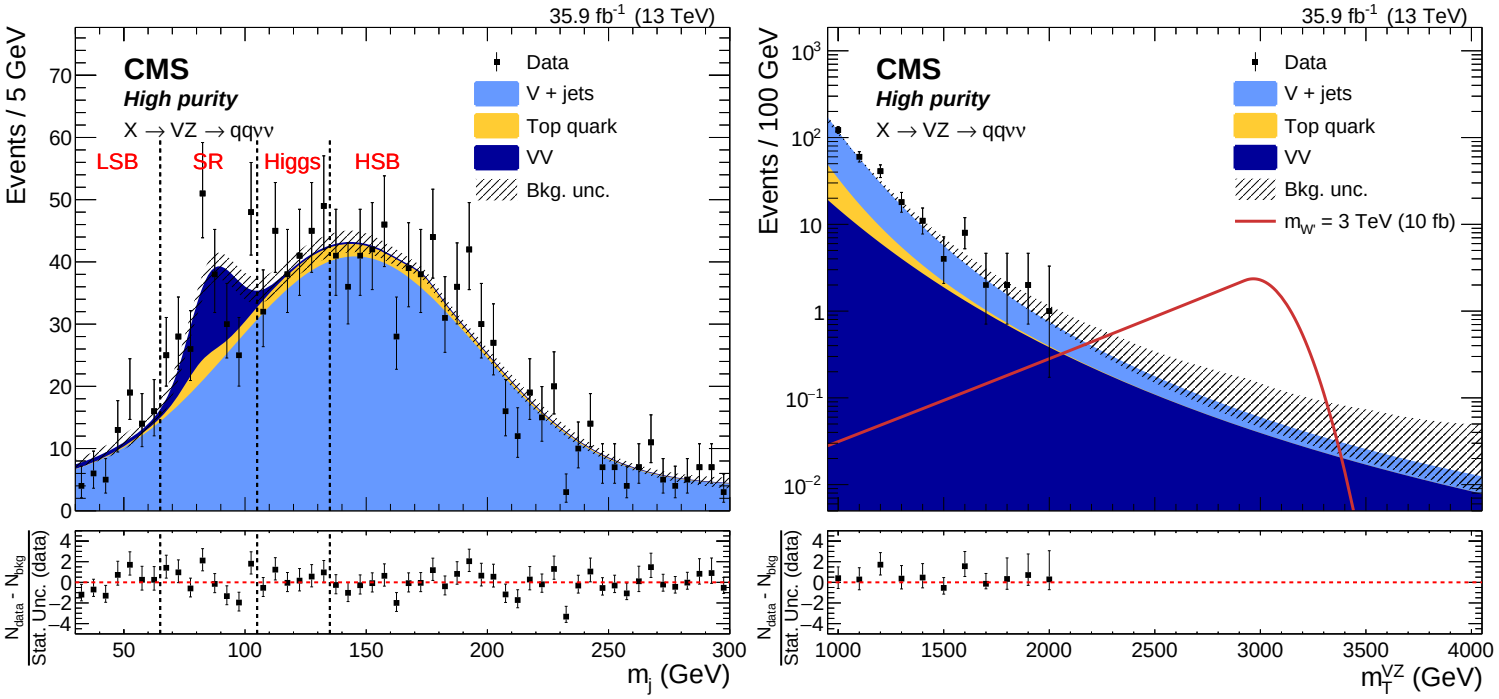




ZV$\rightarrow \nu\nu$qq JHEP 07 (2018) 075

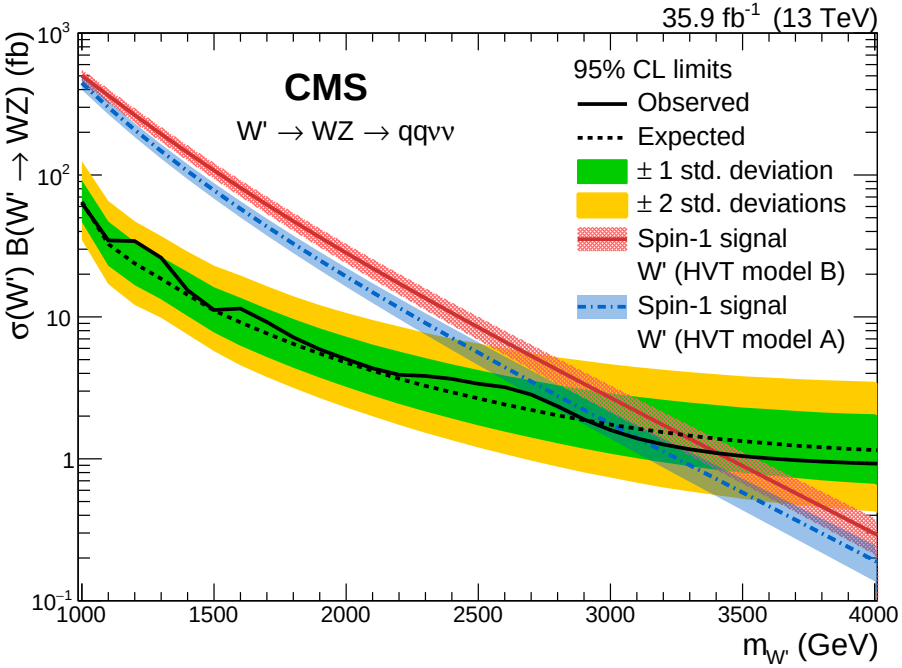
Search for exotic resonances decaying to ZV$\rightarrow \nu\nu$qq results:

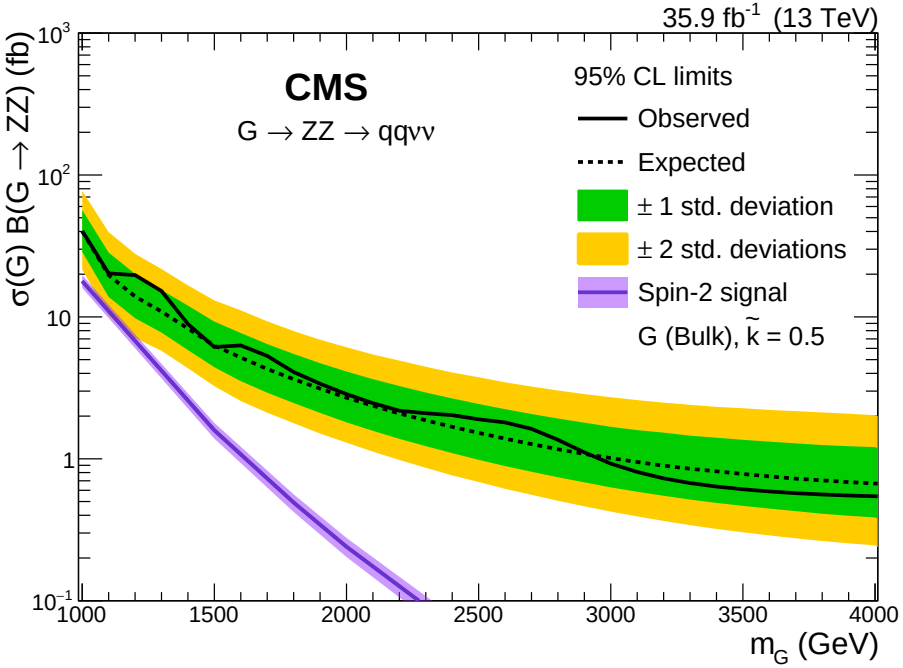
- $p_T^{miss} > 200$ GeV, 1 merged AK8 jet
- for V jet: $\tau_{21} < 0.35$ HP category, $\tau_{21} < 0.75$ LP category, $65 < m_{jet1}^{softdrop} < 105$ GeV
- $m_T^{ZV} = \sqrt{2E_T^j p_T^{miss}(1 - \cos\Delta\phi)}$ transverse mass with ϕ azimuthal angle between p_T^{miss} and the transverse momentum vector of the hardest jet
- α method to estimate main background (Z+jets)



ZV→ $\nu\nu$qq JHEP 07 (2018) 075

Search for exotic resonances decaying to ZV→ $\nu\nu$qq results:

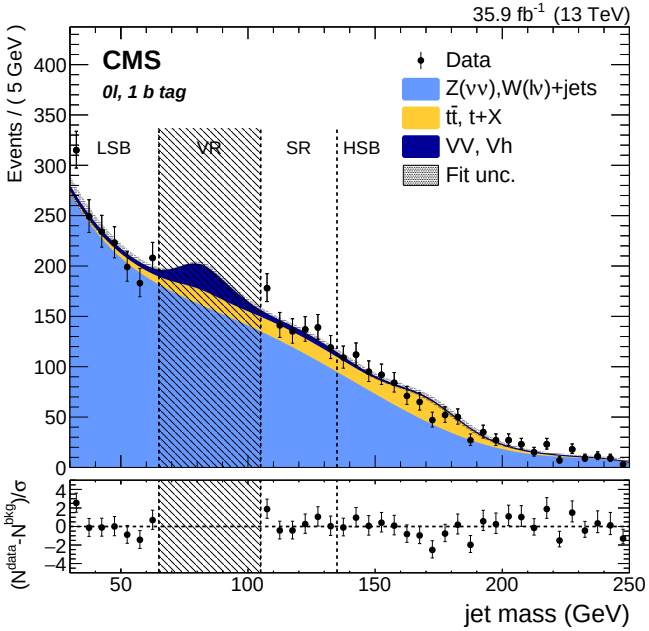


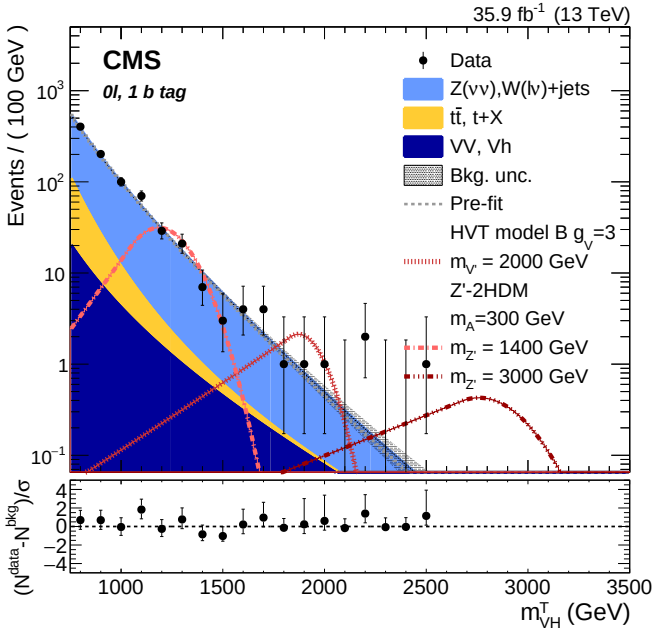


HV$\rightarrow \nu\ell(\ell\ell)$bb Submitted to JHEP

Search for exotic resonances decaying to HV$\rightarrow \nu\ell(\ell\ell)$bb:

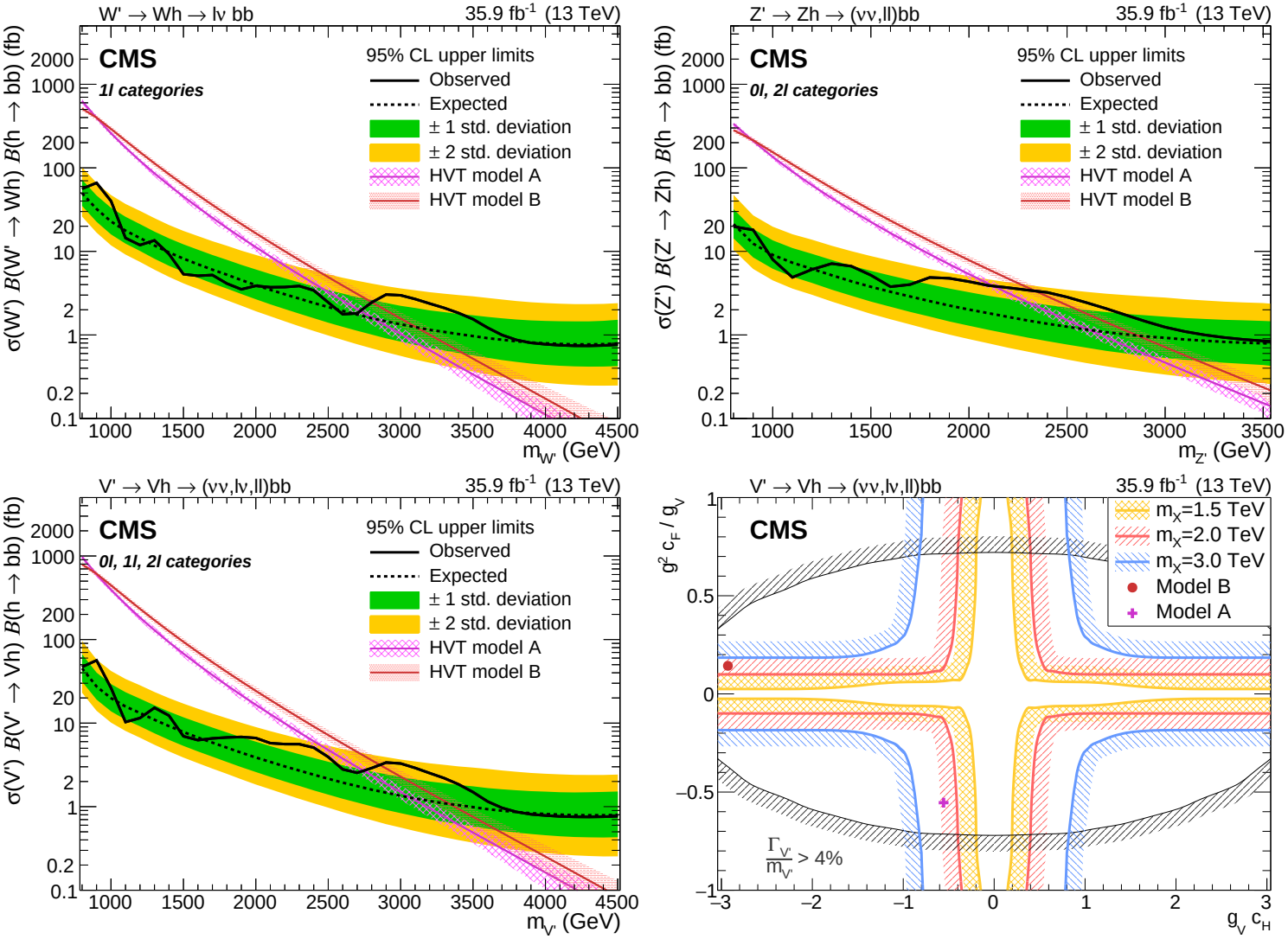
- 0/1/2 leptons, $p_T^{miss} > 250, 80$ GeV, no additional b-tagged jets
- H-jet required to have 1 or 2 b-tagged sub-jets, mass requirements for V and H jets
- background estimation:
  - $t\bar{t}$ yield from SB inverting the b-jet veto, distribution from simulation
  - V+jets estimated using α method and jet mass SB
- search also interpreted in 2HDM scenarios





HV→ $\nu\ell(\ell\ell)$bb Submitted to JHEP

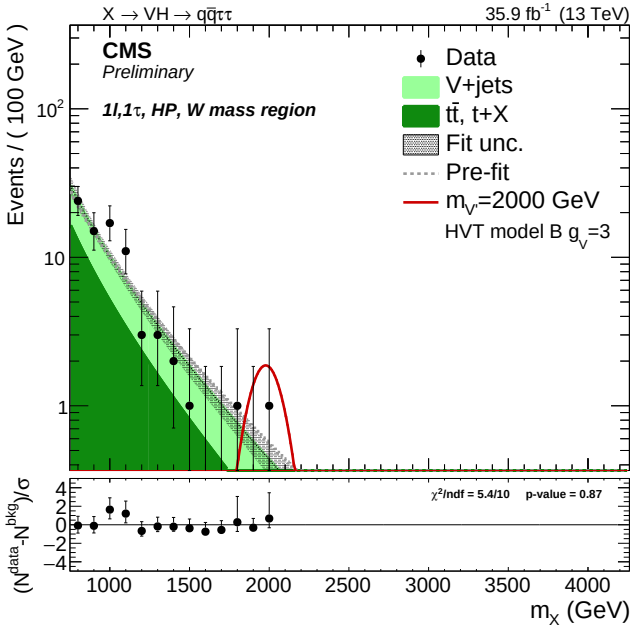
Search for exotic resonances decaying to HV→ $\nu\ell(\ell\ell)$bb:

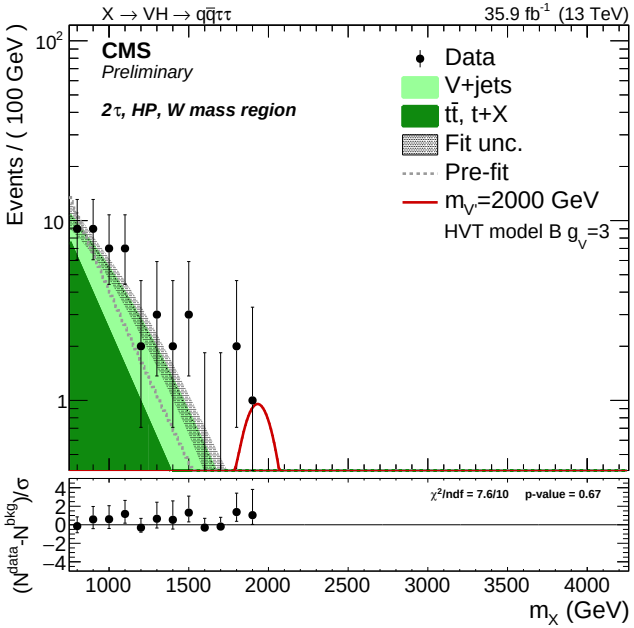


HH/HV→ $\tau\tau$bb CMS-PAS-B2G-17-006

Search for exotic resonances decaying to HH/HV→ $\tau\tau$bb:

- $\tau \to e/\mu\nu$(qq) final states considered; H→ $(\tau_q\tau_q)\tau_q$l
- $65 < m_{jet}^{softdrop} < 135$ GeV categorized using usual mass windows for W/Z/H, V jet $0(0.4) \leq \tau_{21} < 0.4(0.75)$, H jet 1 or 2 b-tagged sub-jets
- $p_T^{miss} > 200$ GeV, b-tag veto on additional jets in the event
- background estimation ($t\bar{t}$ also includes single top, V+jets accounts also for SM diboson and multijet)
  - $t\bar{t}$ yield from SB inverting the b-jet veto, distribution from simulation
  - V+jets estimated using α method and jet mass SB





HH/HV→ $\tau\tau$bb CMS-PAS-B2G-17-006

Search for exotic resonances decaying to HH/HV→ $\tau\tau$bb results: