



Search for diboson and di-Higgs resonances

COMPOSE-IT
PERUGIA

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on behalf of the CMS Collaboration

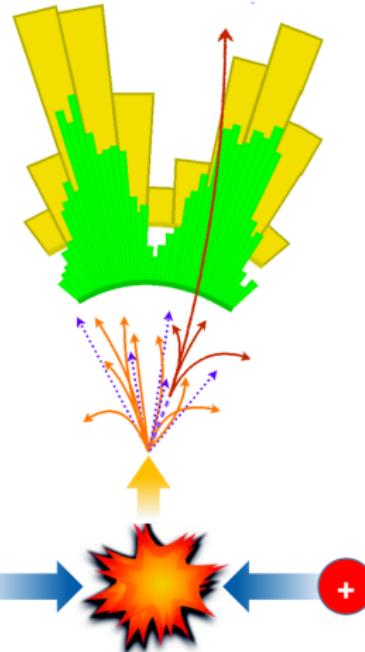
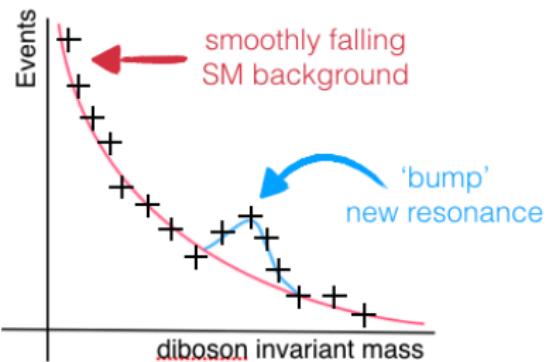
January 28, 2020



Introduction

- Hadronic colliders (LHC) intrinsically favored for heavy resonances discovery
- Reconstruction of final-state particles in the detector → look for bumps in the invariant mass spectrum

- ll
- $\gamma\gamma$
- $q\bar{q}$ (+ $t\bar{t}$)
- VV, VH, HH
- $\gamma V, \gamma H$

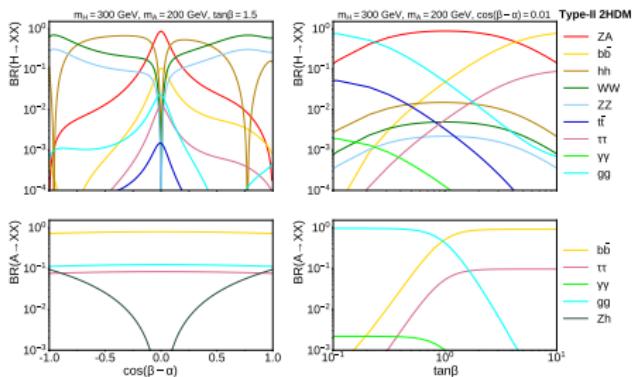
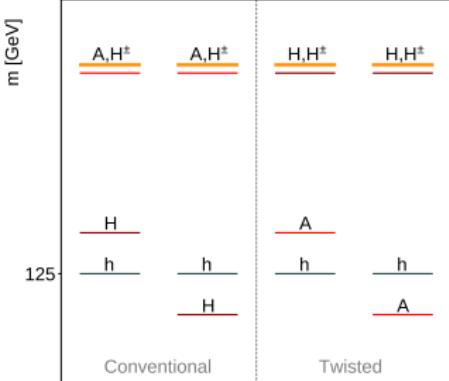


- Large resonance mass implies **large Lorentz boost** of the decay products
- **Boosted object reconstruction** (W, Z, H, t) is crucial for these searches

The Two Higgs Doublet model

2HDM introduction

- Two Higgs Doublet Models (2HDM) are minimal extensions of the SM Higgs sector obtained by adding a second scalar doublet
- 5 physical states arise, h , H , A , H^\pm mass hierarchy not defined a-priori
- Some declinations of the 2HDM assume a “twisted” hyerarchy, where e.g. H and A are swapped
- Rich phenomenology thanks to the multiple decay chains beyond the “classic” SM channels [HIG-18-012]



Model parameters

- Two types of 2HDM are considered:

Type I : all quarks and charged leptons couple to the same Higgs doublet

Type II : up-type and down-type quarks couple to different doublets

Lepton-specific : quarks couple to one Higgs doublets, charged leptons to the other

Flipped : up-type fermions and charged leptons couple to one Higgs doublets, down-type quarks to the other

- Large number of free parameters: m_h , m_H , m_A , m_{H^\pm} , m_{12} , β , α , $\lambda_{6,7}$

- Recommendations from the Higgs Working Group:

- $m_H = m_A = m_{H^\pm}$: A searches not really dependent on m_H , m_{H^\pm} anyway
- $m_{12}^2 = m_A \frac{\tan \beta}{1 + \tan^2 \beta}$ (soft breaking term): discrete Z_2 symmetry broken as in MSSM
- $\lambda_{6,7} = 0$ to avoid CP-violation at tree level

- Two parameters left other than m_A :

α : mixing angle of the two doublets

$\tan \beta$: the ratio of the vev of the two doublets

- For each mass point, perform a scan in $\tan \beta$ and $\cos(\beta - \alpha)$

■ $0.1 < \tan \beta < 100$,

■ $-1 \leq \cos(\beta - \alpha) \leq 1$

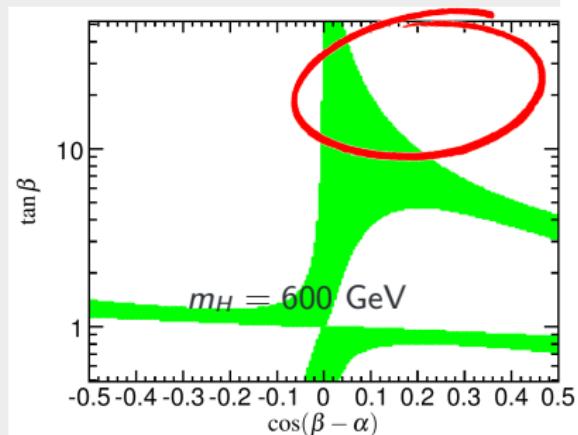
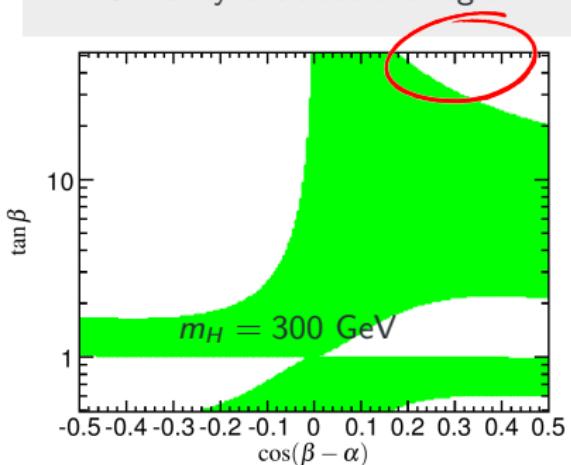
$0 \leq \beta - \alpha \leq \pi$

- Unitarity conditions in Higgs-Higgs scattering depend only on parameters λ_i of the Higgs potential

The Two Higgs Doublet model

Short discussion about unitarity

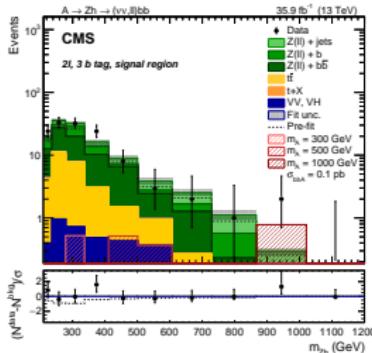
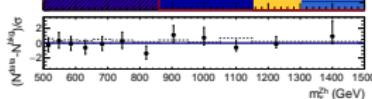
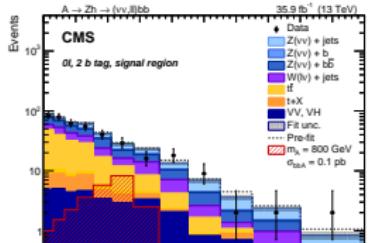
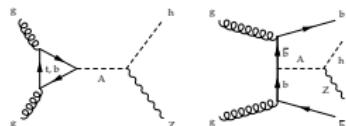
- Unitarity depends on the λ_i parameters of the 2HDM
- Paper from Haber, Stal [1] performs a scan with $Z_4 = Z_5 = -2$ and $Z_7 = 0$
- Green areas fulfill perturbative unitarity and stability constraints
- Unitarity excludes the region in the upper right corners



- Interesting region is $\cos(\beta - \alpha) \rightarrow 0$ (alignment limit: h is the SM Higgs)
- However, the benchmark parameters are different than the CMS scan (hybrid basis vs physical basis)

Search for $A \rightarrow Zh \rightarrow (\nu\nu, \ell\ell)bb$

[HIG-18-005, EPJC 79(2019)564]



The analysis in a nutshell

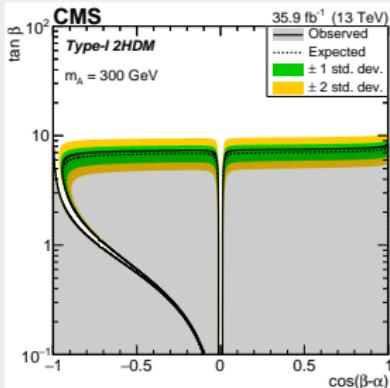
- Identify and select the decay products in the detector
 - two opposite sign, same flavour, isolated leptons or large MET
 - two jets tagged as originated from b-quarks
 - additional accompanying b-quarks from bbA process
- Build intermediate candidates $Z(\ell\ell)$ (or $\ell\ell_T$) and $h(bb)$, where h is the SM h with $m_h = 125$ GeV
- Reconstruct the A candidate as Zh (transverse) mass
- The signal would manifest as a **narrow peak** in the (transverse) mass distribution over the SM background
- Maximize signal sensitivity with **kinematic constraints, multivariate** discriminators
- Define appropriate **control regions (CR)** to check background shape and normalization with data by inverting selections
- Fit simultaneously signal and control region for the presence of a signal

Search for $A \rightarrow Zh \rightarrow (\nu\nu, \ell\ell) b\bar{b}$

[HIG-18-005, EPJC 79(2019)564]

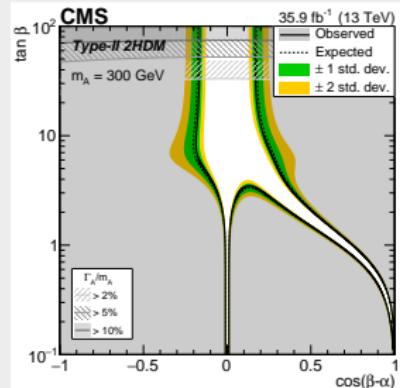


Type-1

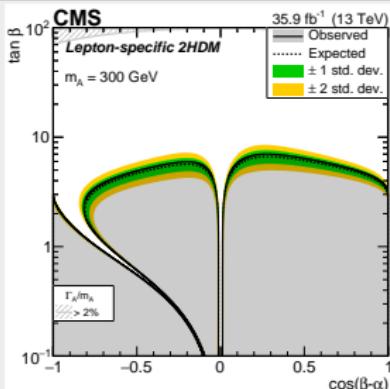


- Scan $[\cos(\beta - \alpha), \tan \beta]$ fixing $m_A = 300$ GeV
- Expected exclusion up to $\tan \beta \approx 6 \sim 7$ in Type I (was 4 ÷ 5 in Run I)
- Large parameter space excluded in Type II, also at high $\tan \beta$
- Show validity regions of the narrow-width approximation

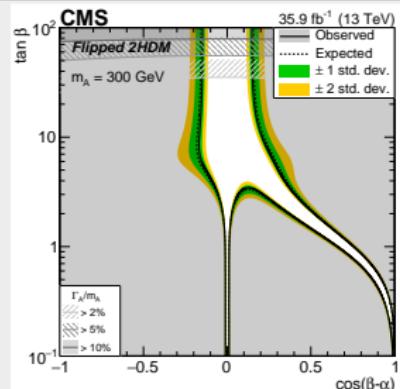
Type-2



Type-3 (lepton specific)



Type-4 (flipped)

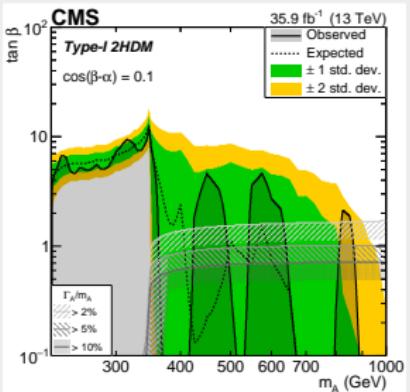


Search for $A \rightarrow Zh \rightarrow (\nu\nu, \ell\ell) b\bar{b}$

[HIG-18-005, EPJC 79(2019)564]

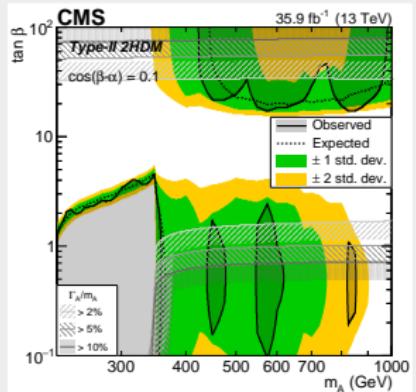


Type-1

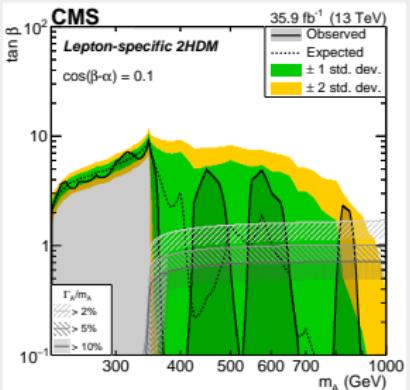


- Fixing $\cos(\beta - \alpha) = 0.1$ and scanning $[m_A, \tan \beta]$
- Expected exclusion up to $\tan \beta \approx 6 \sim 7$ in Type I (was 4 ÷ 5 in Run I)
- Large parameter space excluded in Type II, also at high $\tan \beta$
- Show validity regions of the narrow-width approximation

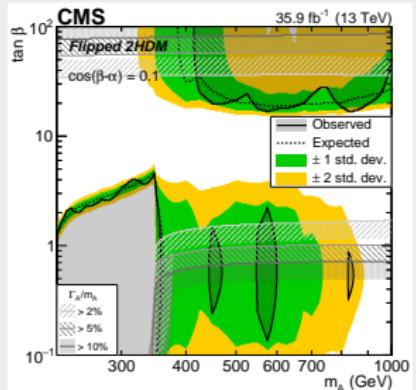
Type-2



Type-3 (lepton specific)

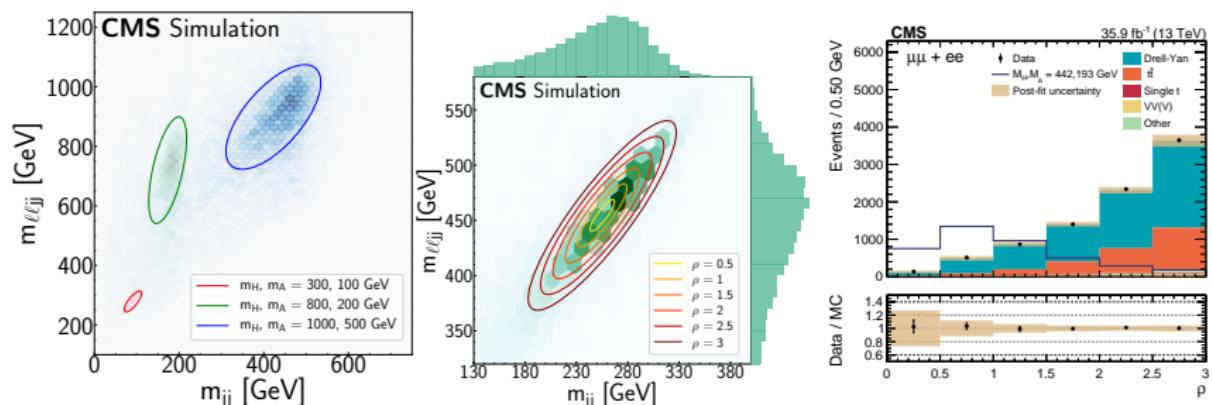


Type-4 (flipped)



Twisted hierarchy search

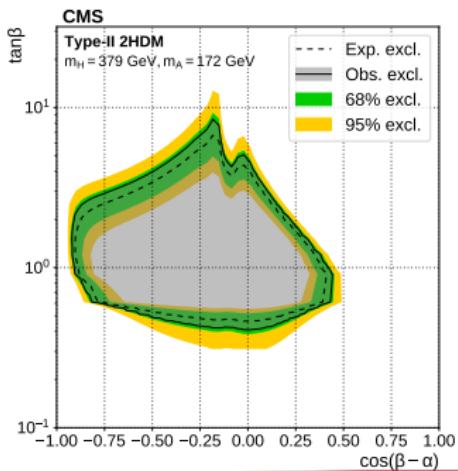
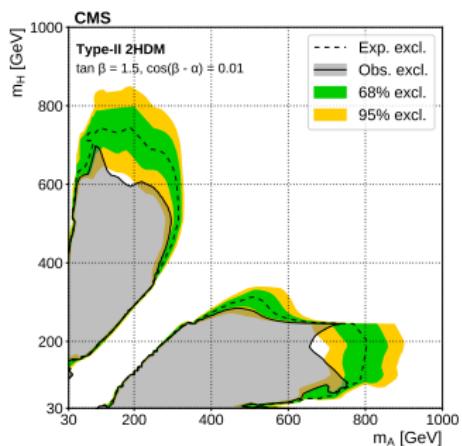
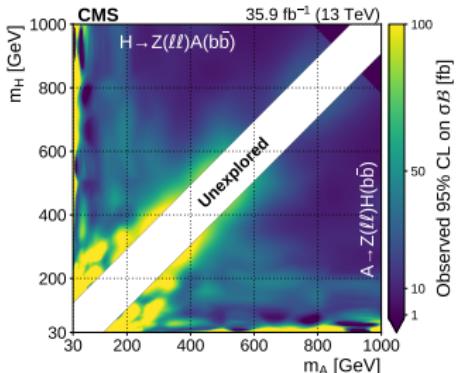
- Besides h decay chains, there is also the $A \rightarrow HZ$ or $H \rightarrow AZ$
- Experimentally, this implies that we have two unknown masses to scan ($m_{H/A} \sim m_{\ell\ell jj}$ and $m_{A/H} \sim m_{jj}$)
- On the other hand, the signal peaks in two dimensions, and the background does not
- Variable ρ is a distance in the $[m_{\ell\ell jj}, m_{jj}]$ plane from the signal 2D peak



Search for $H/A \rightarrow Z(A/H)$

[HIG-18-012]

- Limits places for both H and A , simultaneously
- No significant excess observed
- Limits on 2HDM parameters space as a function of $[m_H, m_A]$
- Less sensitive than $A \rightarrow Zh$, but more generic approach resulting from less strong assumptions on the lightest boson



Diboson overview

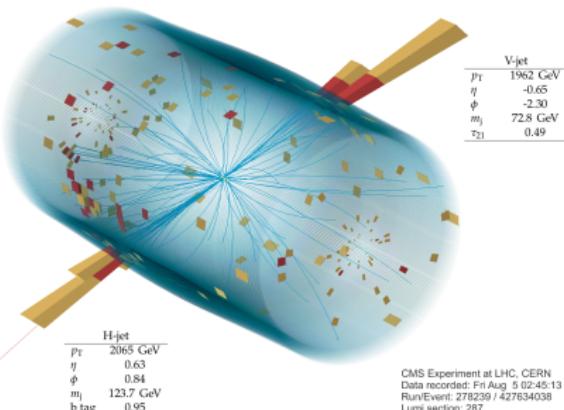
- Heavy BSM resonances ($\gtrsim 1$ TeV) may decay into SM bosons (W, Z, H)
- Plethora of final states, each one with its own peculiarities:

| | $V \rightarrow q\bar{q}$ | $W \rightarrow l\nu$ | $Z \rightarrow ll$ | $Z \rightarrow \nu\nu$ | $H \rightarrow b\bar{b}$ | $H \rightarrow \tau\tau$ |
|--------------------------|--------------------------|----------------------|--------------------|------------------------|--------------------------|--------------------------|
| $V \rightarrow q\bar{q}$ | ATLAS | ATLAS | ATLAS | ATLAS | ATLAS | ATLAS |
| $W \rightarrow l\nu$ | ATLAS | ATLAS | | | ATLAS | ATLAS |
| $Z \rightarrow ll$ | ATLAS | | ATLAS | ATLAS | ATLAS | ATLAS |
| $Z \rightarrow \nu\nu$ | ATLAS | | ATLAS | | ATLAS | ATLAS |
| $H \rightarrow b\bar{b}$ | ATLAS | ATLAS | ATLAS | ATLAS | ATLAS | ATLAS |
| $H \rightarrow \tau\tau$ | ATLAS | | | | ATLAS | ATLAS |



W mass, low purity, tight tag

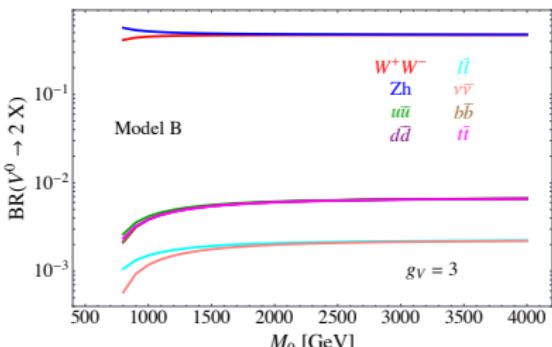
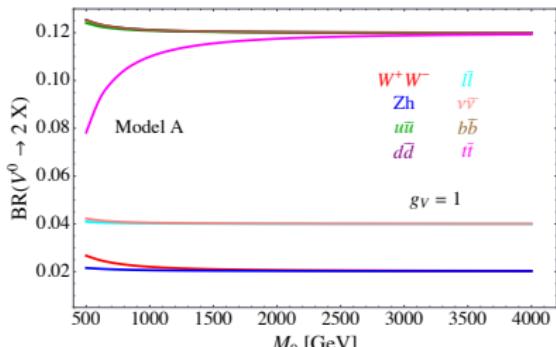
Dijet invariant mass
 $m_{VH} = 4919$ GeV



CMS Experiment at LHC, CERN
Data recorded: Fri Aug 5 02:45:13 2016 CEST
Run/Event: 278239 / 427634038
Lumi section: 287

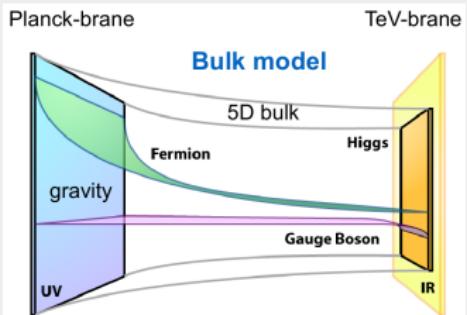
The Heavy Vector Triplet

- Heavy spin-1 Z' , W' predicted by several models: Little Higgs, **composite Higgs**, Minimal Walking Technicolor
- Described by a **simplified Lagrangian** in the **HVT framework** [1] [2]
- 3 new BSM vector fields V^+ , V^- , V^0 , new parameters:
 - g_V strength of the new interactions
 - c_H coupling to Higgs and longitudinally-polarized vector bosons
 - c_F couplings to SM fermions
- Two possible scenarios:
 - couplings to fermions dominating (**Model A**): $g_V c_H \simeq g^2 c_F / g_V \simeq g^2 / g_V$
 - as for a new **composite vector boson** in **Composite Higgs models**: almost unconstrained for $g_V \gtrsim 5$
 - coupling to fermions **suppressed** w.r.t. to SM bosons (**Model B**):
 $g_V c_H \simeq -g_V$, $g^2 c_F / g_V \simeq g^2 / g_V$



Warped Extra Dimension (WED)

- WED models as possible solution to the hierarchy problem
- Radion (spin-0) and Graviton (spin-2)
- Radion scale Λ_R depends on Planck scale, Warp factor $k/\bar{M}_{Pl} \sim \text{TeV}$
- May have similar coupling strength to SM fermions and gauge boson
- Production through DY and gluon-fusion, decay to WW (20%), ZZ (10%), HH (10%)

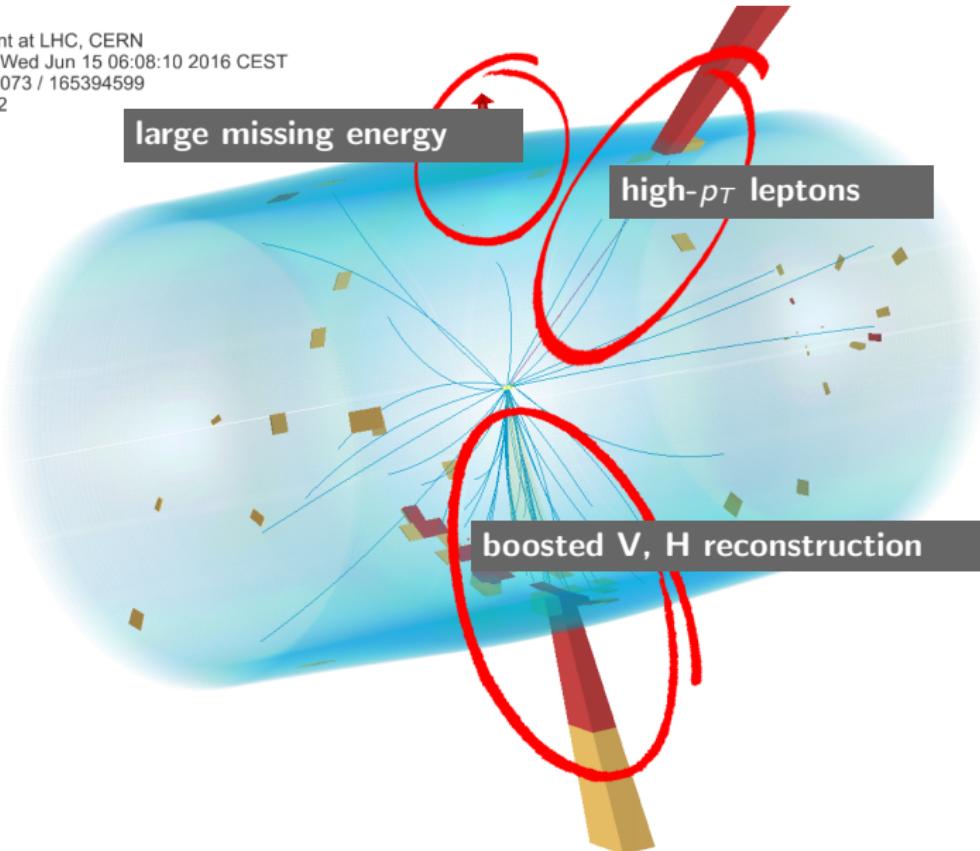


| model | particles | spin | charge | main production | main decay |
|-------------------------------------|---------------|------|------------|----------------------|--------------------|
| HVT model A, $gv = 1$ | W' singlet | 1 | ± 1 | $q\bar{q}'$ | $\ell\nu$ |
| HVT model A, $gv = 1$ | Z' singlet | 1 | 0 | $q\bar{q}$ | $\ell\ell$ |
| HVT model A, $gv = 1$ | W'+Z' triplet | 1 | $0, \pm 1$ | $q\bar{q}/q\bar{q}'$ | $\ell\nu/\ell\ell$ |
| HVT model B, $gv = 3$ | W' singlet | 1 | ± 1 | $q\bar{q}'$ | WZ, WH |
| HVT model B, $gv = 3$ | Z' singlet | 1 | 0 | $q\bar{q}$ | WW, ZH |
| HVT model B, $gv = 3$ | W'+Z' triplet | 1 | $0, \pm 1$ | $q\bar{q}/q\bar{q}'$ | WW, WZ, WH, ZH |
| RS bulk Graviton, $\tilde{k} = 0.5$ | G_{bulk} | 2 | 0 | gg | WW, ZZ, HH |

Diboson resonances and object reconstruction



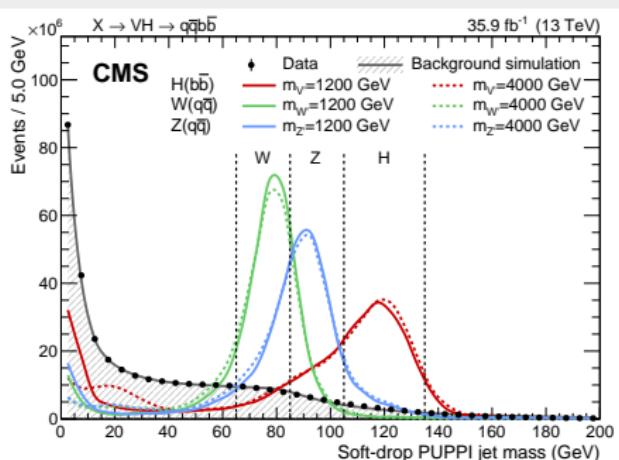
CMS Experiment at LHC, CERN
Data recorded: Wed Jun 15 06:08:10 2016 CEST
Run/Event: 275073 / 165394599
Lumi section: 92



W, Z, H reconstruction and identification

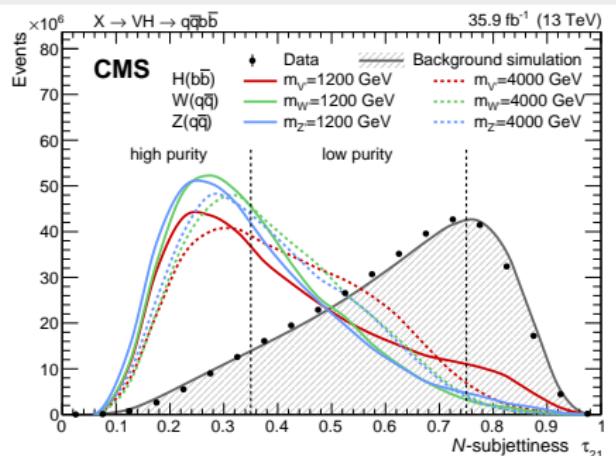
Grooming and jet mass

- Jet grooming removes soft and large angle radiation
 - Trimming [1] (ATLAS)
 - Pruning [2] (CMS 2015)
 - Soft drop [3] + PUPPI [4] (CMS 2016)
 - stability vs pileup
 - good m_j resolution ($\approx 10\%$)
- Orthogonal m_j categories



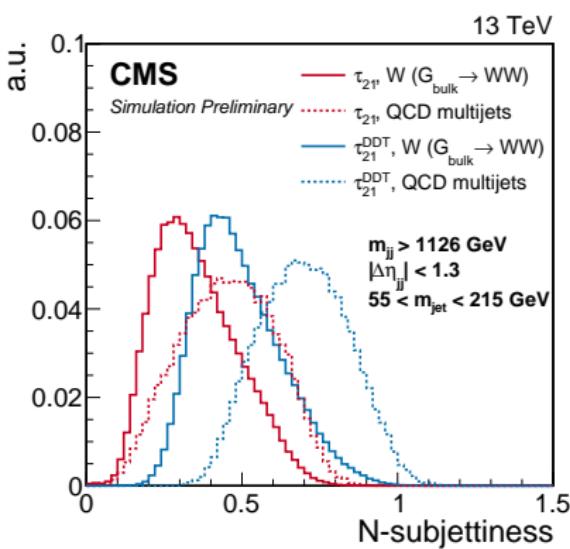
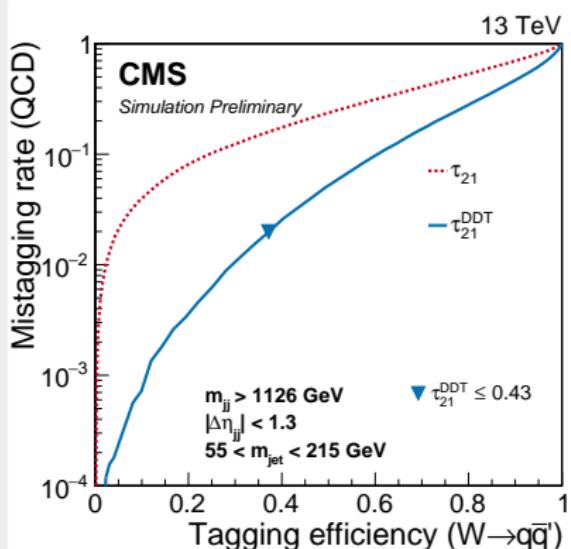
Vector boson tagging ($V \rightarrow q\bar{q}$)

- ATLAS: Energy Corr. Functions (N_2)
- CMS: N-subjettiness (τ_{21}) + PUPPI [4]
 - measures how consistent is the jet with the 2 sub-jets hypothesis
- Scale factor and uncertainties derived from $W \rightarrow q\bar{q}$ in $t\bar{t}$ -enriched sample
- Categorization according to purity



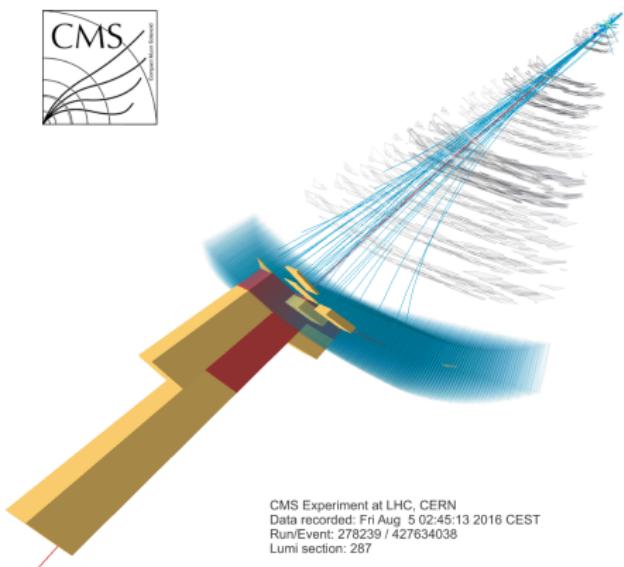
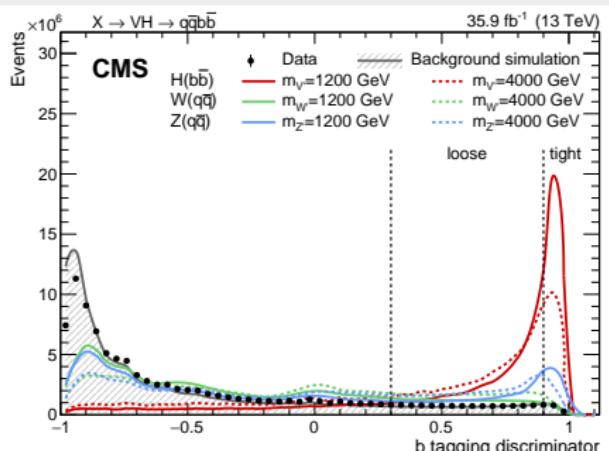
Mass-decorrelated N-subjettiness (τ_{21}^{DDT})

- τ_{21} is (strongly) correlated with the jet mass
 - \rightarrow a N-subjettiness selection also sculpts significantly the m_j shape
- Decorrelate the τ_{21} from m_j through a **linear transformation** $\rightarrow \tau_{21}^{DDT}$
 - more stability for m_j is crucial for some background estimation methods
 - benefit in the tagger performances, too



Higgs boson tagging ($H \rightarrow b\bar{b}$)

- Subjet b-tagging (ATLAS, CMS)
 - split jet to two subjets
 - apply b-tagging algorithms to both subjets independently
- Dedicated algorithms [5] (CMS)
 - exploit b-tagging to identify **two** b-quarks within the same jet
 - use soft lepton (e, μ), tracking and vertexing information

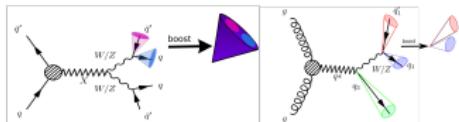
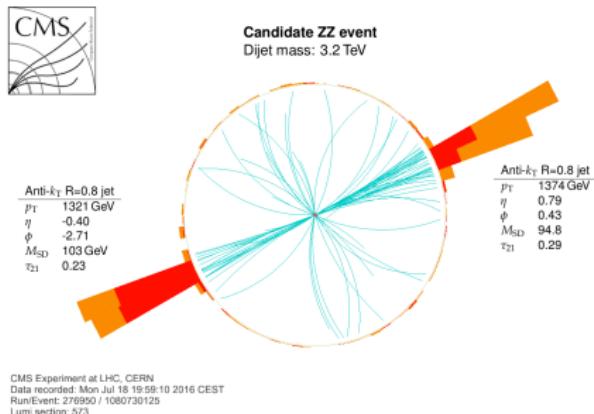


All-hadronic final states

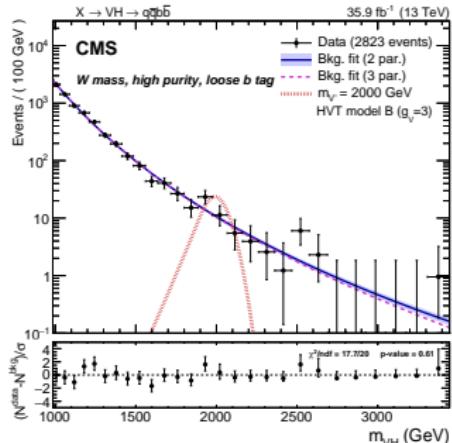
VV all-hadronic [B2G-17-001, PRD 97, 072006(2018)], VH all-hadronic [B2G-17-002, EPJC77(2017)67]



- ✓ Large ($W, Z \rightarrow q\bar{q}$, $H \rightarrow b\bar{b}$) branching fraction
- ✗ Overwhelming QCD background (difficult prediction)



- Background estimation:
“bump-hunt” fit with power law functions directly to data
- Number of parameters (2-5)
determined with F-test



- At least 2 large-cone jets,
back-to-back topology
- Requires trigger efficiency ~ 1
- Extensive bias studies

All-hadronic final states with b-quarks

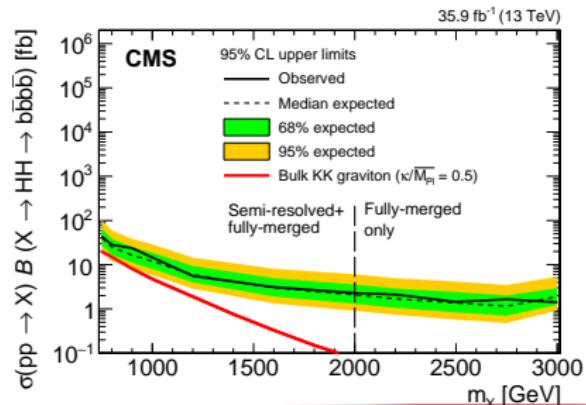
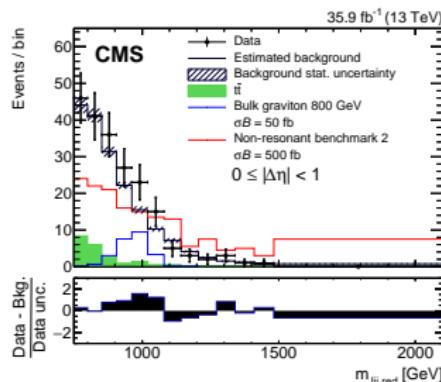
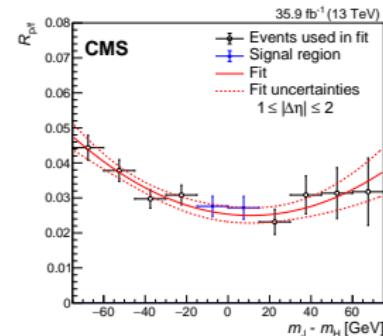


HH all-hadronic [B2G-16-026, PLB781(2018)244] [B2G-17-019, JHEP01(2019)040]

- Search for resonant di-Higgs in all-hadronic (4b) final states
- Consider fully boosted topology (1+1) but also resolved (2+1)

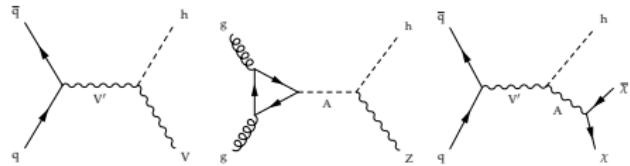
Alphabet method

- Extension of the ABCD method to multiple regions
- Normalization from mass sidebands
- Shape from simultaneous fit to "tag" and "anti-tagged" $H \rightarrow b\bar{b}$ events



Semileptonic final states

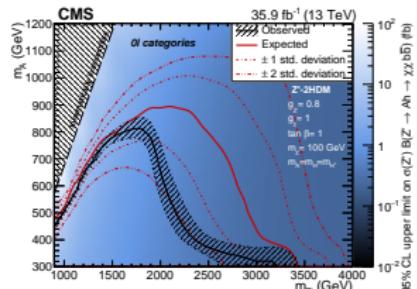
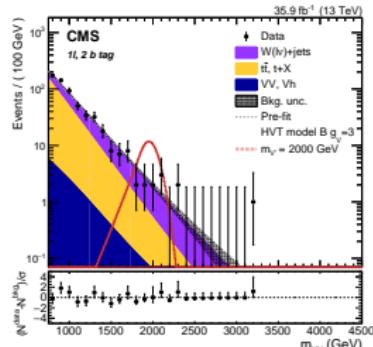
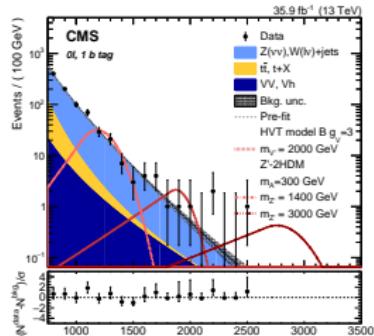
$VZ(\nu\nu qq)$ [B2G-17-005, JHEP07(2018)075] [B2G-17-013, JHEP09(2018)101]



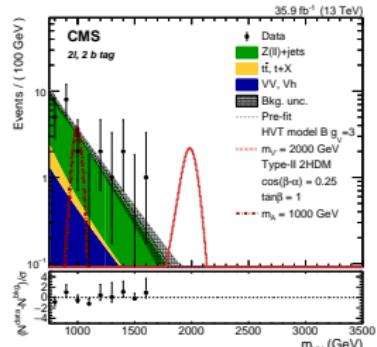
- ✓ Clean final state, more reliable background simulation
- ✗ Small branching fraction

■ Experimental challenges:

- $Z \rightarrow \nu\nu$: use transverse mass m_T
- $W \rightarrow l\nu$: very high p_T lepton reconstruction
- $Z \rightarrow ll$: high-efficiency dilepton identification, isolation



very stringent limits on
mono-Higgs DM search (see
Livia's talk)



Semileptonic final states

VZ, VH semileptonic (B2G-16-003, B2G-17-004, B2G-17-005, B2G-17-006, B2G-17-013)



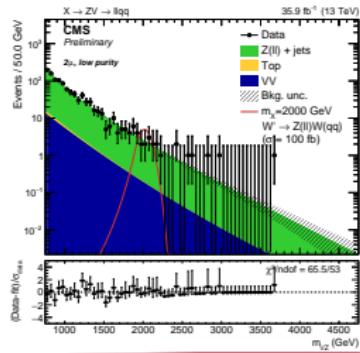
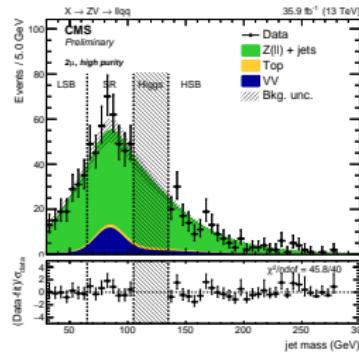
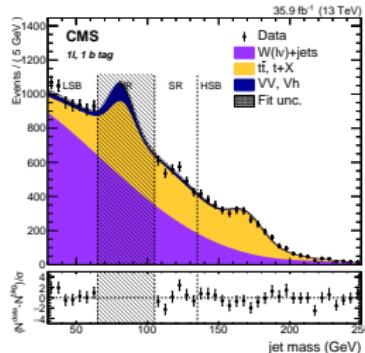
Analysis strategy (α -method)

Get background **normalization** in SR from m_j sidebands:

- Build background model:
 $F(m_j) = n^{V\text{jets}} \cdot F^{V\text{jets}}(m_j) + n^{\text{Top}} \cdot F^{\text{Top}}(m_j) + n^{\text{VV}} \cdot F^{\text{VV}}(m_j)$
- Fit normalization and shape of the main background to data **in jet mass SB**
- Secondary backgrounds normalization and shape fixed in the fit

Get background **shape** in m_{VH} :

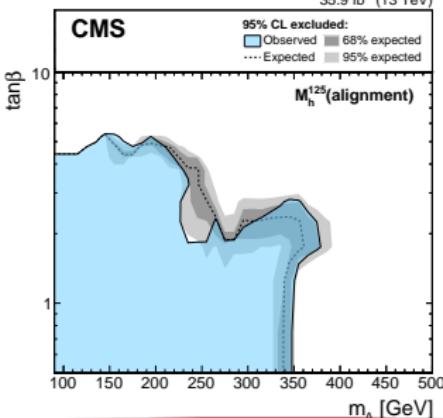
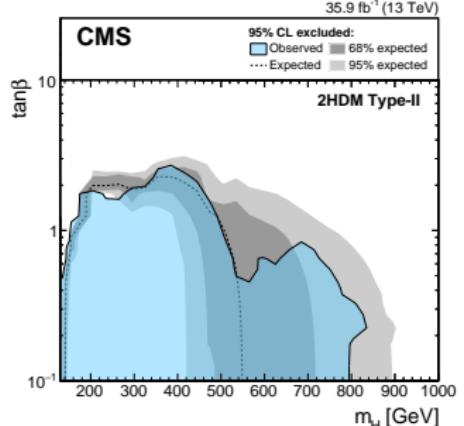
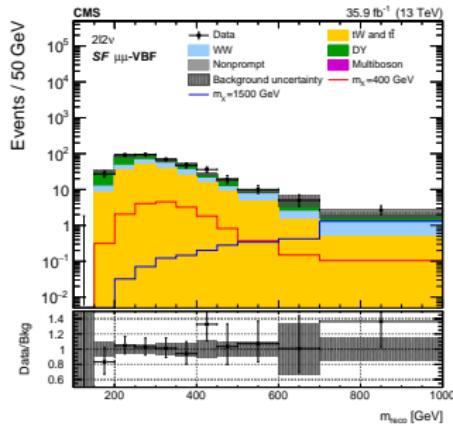
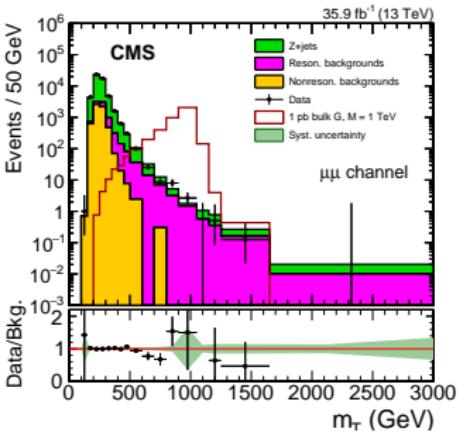
- Main bkg SB \rightarrow SR transfer factor from MC: $\alpha(m_{VH}) = \frac{N_{SR}^{MC, \text{bkg}}(m_{VH})}{N_{SB}^{MC, \text{bkg}}(m_{VH})}$
- Main bkg prediction in SR: $N_{SR}^{\text{pred}}(m_{VH}) = N_{SB}^{\text{data}}(m_{VH}) \times \alpha(m_{VH})$



Fully-leptonic final states

$ZZ(\nu\nu\ell)$ [B2G-16-023, JHEP03(2018)003], $WW \rightarrow (\ell\nu\ell\nu, \ell\nu qq)$ [HIG-17-033]

- ✓ Small background, mostly from SM diboson
- ✗ Even smaller branching fraction, lepton “fakes”
- Experimental challenges:
 - use transverse mass m_T
 - \cancel{E}_T recoil corrections from $\gamma + \text{jets}$ when necessary
- WW search also investigates the **VBF topology**
- WW interprets the results in 2HDM and MSSM
 - also imposing the light scalar $m_h = 125$ GeV

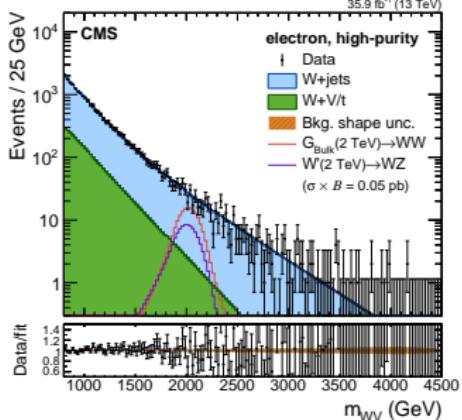
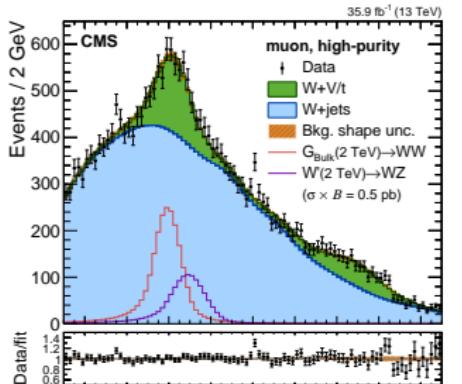
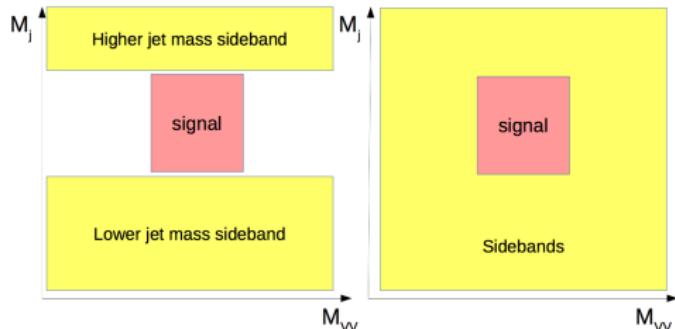


Going 2D

WV semileptonic [B2G-16-029, JHEP05(2018)088]

2D background estimation

- 1D fit (α): mass sidebands aided bump hunt
- 2D fit: full 2D bump hunt over $[m_j, m_{VV}]$
- exploit correlations between m_j and m_{VV}
- larger statistics and full line-shape information from jet mass
- optimal modeling of correlations directly from data

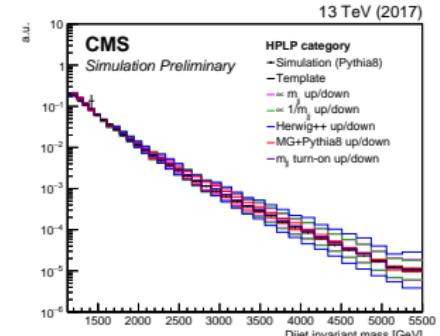
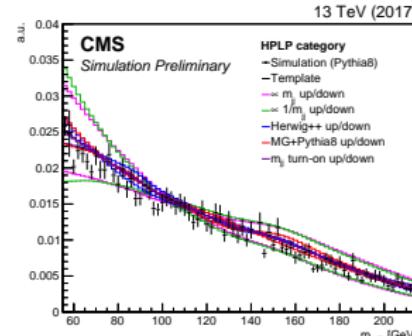
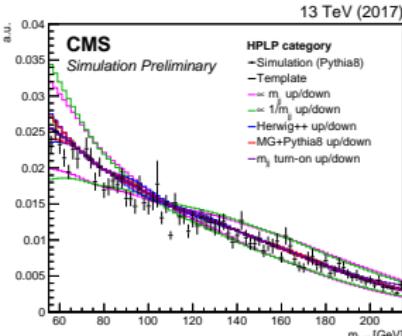
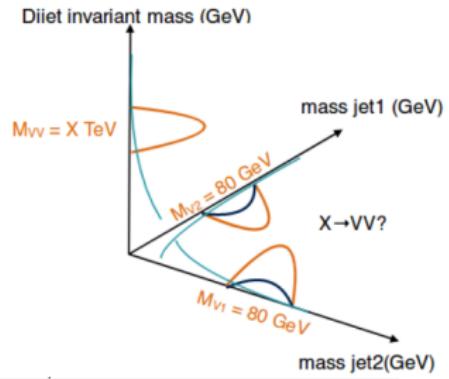


Going 2D → 3D

VV all-hadronic [B2G-18-002]

Extension to the third dimension

- 2D fit: 2D bump hunt in the $[m_j, m_{VV}]$ plane
- 3D fit: natural extension for all hadronic final states $\rightarrow [m_{j1}, m_{j2}, m_{VV}]$
- 3D templates built similarly to 2D fit from kernel density estimators using generator-level information
- Rather large shapes uncertainties get constrained by data

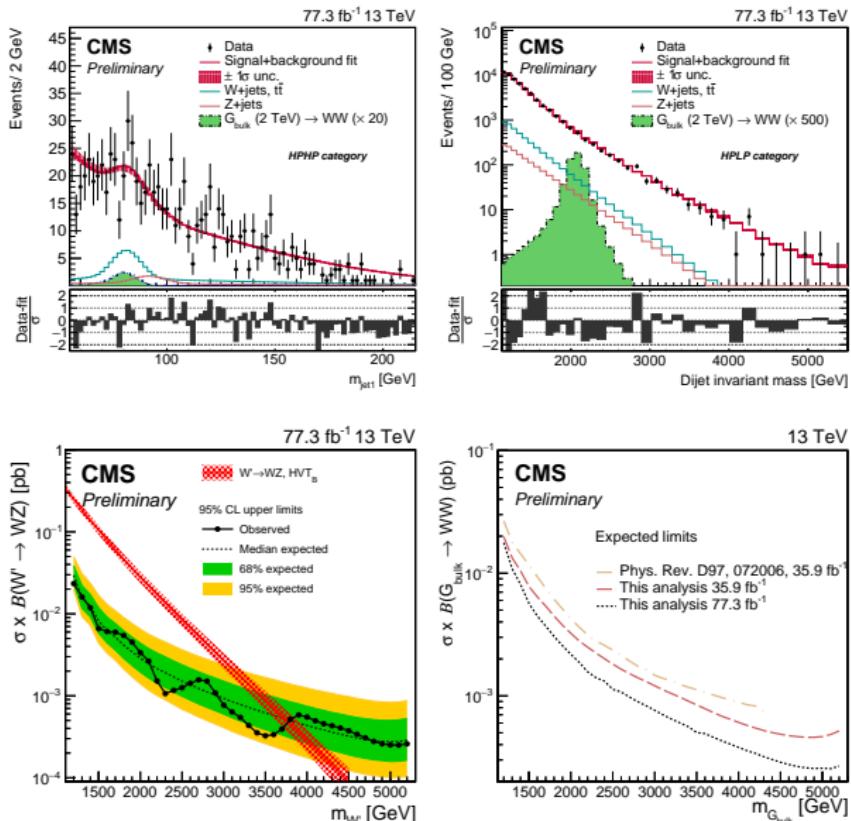


VV all-hadronic 3D fit

VV all-hadronic [B2G-18-002]

3D fit

- Data is able to naturally constrain the uncertainties
- Overall background uncertainty is reduced with respect the 1D bump-hunt
- Boosted SM diboson is clearly visible, and consistent with SM cross sections
- Exclusion limits show no significant excess
- Up to 30% improvements from 3D fit and tagger tuning

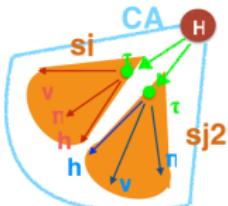
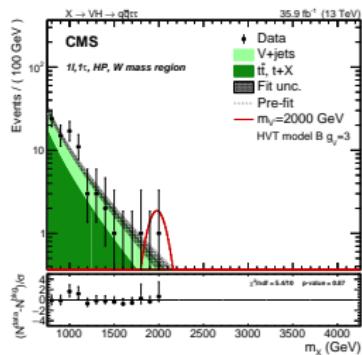
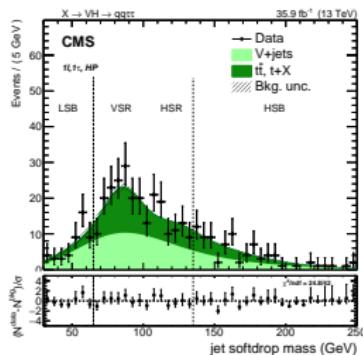


$$X \rightarrow VH \rightarrow (qq, \ell\nu, \ell\ell)\tau\tau$$

VH, HH ($\tau\tau$) [B2G-17-006, JHEP01(2019)051]

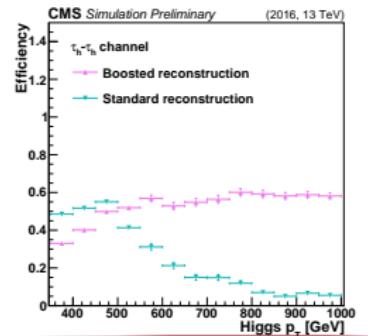
- Search with **boosted τ** for $V \rightarrow qq$, $H \rightarrow \tau\tau$ ($\tau_h\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_h$)
- Background estimated with the α -method

| Final state | Signal searched |
|--------------------|-----------------------|
| | $W' \rightarrow WH$ |
| $qq\tau\tau$ | $Z' \rightarrow ZH$ |
| | $R, G \rightarrow HH$ |
| $\ell\nu\tau\tau$ | $W' \rightarrow WH$ |
| $\ell\ell\tau\tau$ | $Z' \rightarrow ZH$ |



Boosted τ reconstruction (CMS-DP-2016-038)

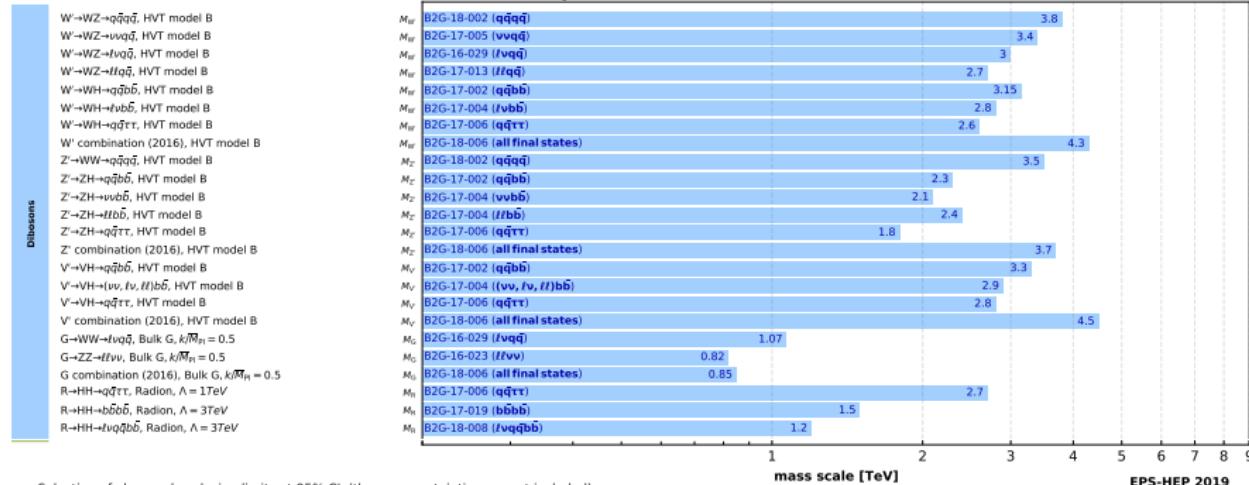
- CA8 jets split in two subjets
- subjets provided as seeds to the HPS τ_h reconstruction algorithm
- τ_h : MVA isolation, τ_μ : τ_h subtraction



Diboson combination

[B2G-18-006, PLB 798(2019)134952]

- Several channels have comparable sensitivity, **large gain** from combination



- Added **EXO di-leptonic resonances** ($W' \rightarrow l\nu$, $Z' \rightarrow ll$) when resonances couple predominantly with leptons
- Complementary to diboson channels to probe $c_H \rightarrow 0$

Diboson combination and orthogonality



[B2G-18-006, PLB 798(2019)134952]

- Statistical independence is achieved through many different selections:
 - lepton number (0, 1, 2)
 - jet mass (m_W, m_Z, m_H) if at least 1 boosted jet
 - other selections ($m_{\ell\ell}, \Delta\phi(\ell, \not{E}_T)$)

| Ref. | Channel | Final state | ℓ | τ_h | AK8 jets | AK8 jet mass | AK4 b jets |
|------|------------|---------------------|--------|----------|----------|--------------------------------|------------|
| [1] | WW, WZ, ZZ | $q\bar{q}q\bar{q}$ | veto | — | 2 | $2[m_W, m_Z]$ | — |
| [2] | WZ, ZZ | $\nu\nu q\bar{q}$ | veto | veto | 1 | m_V | veto |
| [3] | WW, WZ | $\ell\nu q\bar{q}$ | 1 | — | 1 | $m_j \text{ shape}/[m_W, m_Z]$ | veto |
| [4] | WZ, ZZ | $\ell\ell q\bar{q}$ | 2 | — | 1 | m_V | — |
| [5] | ZZ | $\ell\ell\nu\nu$ | 2 | — | — | — | — |
| [6] | WH, ZH | $q\bar{q}b\bar{b}$ | veto | veto | 2 | $[m_W, m_Z], m_H$ | — |
| [7] | ZH | $\nu\nu b\bar{b}$ | 0 | veto | 1 | m_H | veto |
| [7] | WH | $\ell\nu b\bar{b}$ | 1 | veto | 1 | m_H | veto |
| [7] | ZH | $\ell\ell b\bar{b}$ | 2 | veto | 1 | m_H | — |
| [8] | WH, ZH | $q\bar{q}\tau\tau$ | — | 2 | 1 | $[m_W, m_Z]$ | veto |
| [8] | HH | $\tau\tau b\bar{b}$ | — | 2 | 1 | m_H | veto |
| [9] | HH | $b\bar{b}b\bar{b}$ | — | — | 2 | $2m_H$ | — |
| [10] | HH | $b\bar{b}b\bar{b}$ | — | — | 1 | m_H | 2 |
| [19] | $\ell\nu$ | | 1 | — | — | — | — |
| [20] | $\ell\ell$ | | 2 | — | — | — | — |

Systematic uncertainties

[B2G-18-006, PLB 798(2019)134952]

| | Correlation | Type | Variation | $q\bar{q}q\bar{q}$ [?] | $t\bar{t}q\bar{q}$ [?] | $\ell\nu q\bar{q}$ (2D fit) [?] | $\ell\ell q\bar{q}$ [?] | $t\bar{t}\ell\ell$ [?] | $q\bar{q}t\bar{t}b\bar{b}$ [?] | $(\nu\nu, \ell\nu, \ell\ell)b\bar{b}$ [?] | $(q\bar{q})t\bar{t}\tau\tau$ [?] | $b\bar{b}b\bar{b}$ [? ?] | $\ell\nu$ [?] | $\ell\ell$ [?] |
|------------------------------------|-------------|--------------|-----------|------------------------|------------------------|---------------------------------|-------------------------|------------------------|--------------------------------|---|----------------------------------|--------------------------|---------------|----------------|
| Bkg. modeling | no | shape | — | f | b | f | b | b | f | b | b | b | b | b |
| Bkg. normalization | no | yield | 2–30% | f | b | f | b | b | f | b | b | b | b | b |
| Jet energy scale | yes | yield, shape | 1–2% | s | s | b | s | — | s | s | s | s | — | — |
| Jet energy resolution | yes | yield, shape | 3–7% | s | s | s | b | s | — | s | s | s | — | — |
| Jet mass scale | yes | yield, migr. | 1–36% | s | s | s | b | s | — | s | s | s | — | — |
| Jet mass resolution | yes | yield, migr. | 5–25% | s | s | s | b | s | — | s | s | s | — | — |
| Jet triggers | yes | yield | 1–15% | s | — | — | — | — | s | — | — | s | — | — |
| e, μ id., iso., trigger | yes | yield, shape | 1–3% | — | — | s | s | s, b | — | s | s | — | s, b | s, b |
| e, μ scale and res. | yes | yield, shape | 1–6% | — | s | — | s | s, b | — | s | — | — | s, b | s, b |
| τ_h reco., id., iso. | yes | yield | 6–13% | — | s | — | — | — | — | s | s | — | — | — |
| τ_h energy scale | yes | yield, shape | 1–5% | — | — | — | — | — | — | — | s | — | — | — |
| τ_h high- p_T extr. | yes | yield, shape | 18–30% | — | — | — | — | — | — | — | s | — | — | — |
| p_T^{miss} scale and res. | yes | yield | 1–2% | — | s | — | s, b | — | s | s | — | s, b | — | — |
| p_T^{miss} triggers | yes | yield | 1–2% | — | s | — | — | — | — | s | s | — | — | — |
| b quark identification | yes | yield, migr. | 1–9% | — | s | s, b | — | — | s | s | s | s | — | — |
| τ_{21} identification | yes | yield, migr. | 11–33% | s | s | s, b | s | — | s | — | s | s | — | — |
| τ_{21} high- p_T extr. | yes | yield, migr. | 2–40% | s | s | s, b | s | — | s | — | s | s | — | — |
| m_H selection | yes | yield | 6% | — | — | — | — | — | s | s | s | s | — | — |
| Pileup | yes | yield | 1–2% | s | s | — | s | — | s | s | s | s | s, b | — |
| Luminosity | yes | yield | 2.5% | s | s | s | s | s, b | s | s | s | s | s, b | s, b |
| PDF and QCD accept. | yes | yield | 1–2% | s | — | s | s | s, b | s | s | s | s | — | s, b |
| PDF and QCD norm. | yes | yield | 2–78% | t | t | t | t | t, b | t | t | t | t | t, b | t, b |

- Low mass point ($m_X = 1000$ GeV):

- Most important uncertainties: V-tagging efficiency, jet mass resolution, jet energy scale (shape), PDF scale (signal normalization)

- High mass point ($m_X = 3000$ GeV):

- Most important uncertainties: PDF and QCD scale (signal normalization), V-tagging extrapolation, jet energy scale (shape)

Model-independent limits on the cross section

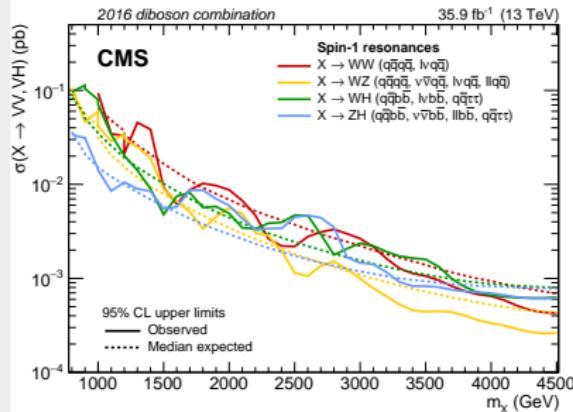
[B2G-18-006, PLB 798(2019)134952]

- Derive (almost) “model-independent” limits separated by spin

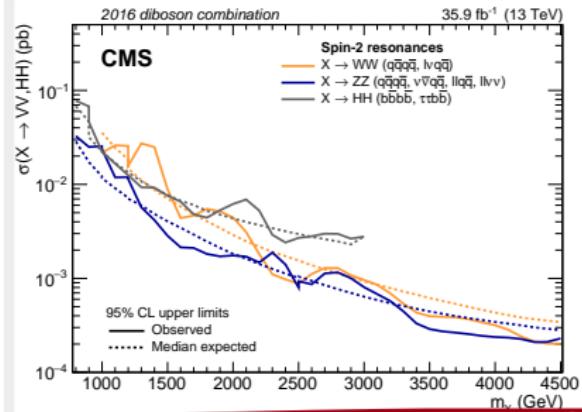
| | | | | |
|-----------|------------|------------|------------|------------|
| WW | B2G-17-001 | B2G-16-029 | | |
| WZ | B2G-17-001 | B2G-16-029 | B2G-17-005 | B2G-17-013 |
| ZZ | B2G-17-001 | B2G-17-005 | B2G-17-013 | B2G-16-023 |
| WH | B2G-17-002 | B2G-17-004 | B2G-17-006 | |
| ZH | B2G-17-002 | B2G-17-004 | B2G-17-006 | |
| HH | B2G-16-026 | B2G-17-006 | | |

- The spin of the resonance affects the acceptance and the polarization on the bosons, which in turn change the angular distributions of the quarks
→ different V-tagging efficiencies

Spin-1 resonances



Spin-2 resonances

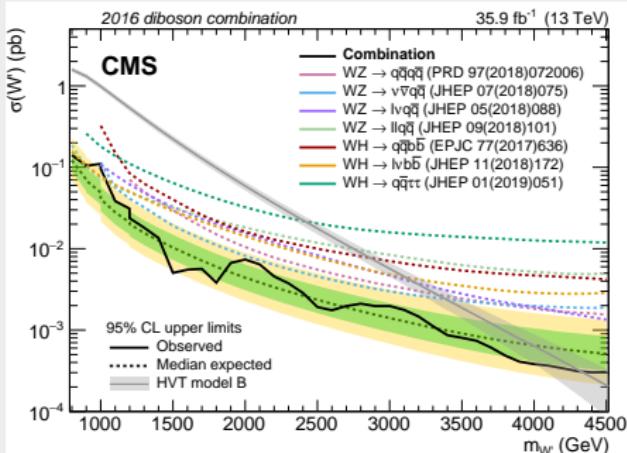


Exclusion limits on the W' and Z' singlet

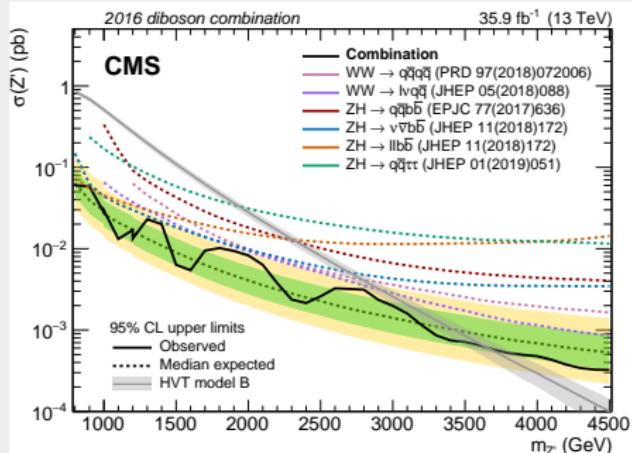
[B2G-18-006, PLB 798(2019)134952]

- Exclusion limit on the $W' \rightarrow WZ, WH$ singlet (7 channels)
 - HVT model B excluded up to **4.3 TeV**
 - Largest significance ($m_X = 1.0$ TeV) 2.8σ (local) / 1.3σ (global)
- Exclusion limit on the $Z' \rightarrow WW, ZH$ singlet (6 channels)
 - HVT model B excluded up to **3.7 TeV**
 - Largest significance ($m_X = 1.9$ TeV) 2.6σ (local) / 0.7σ (global)

Exclusion on $\sigma(W')$



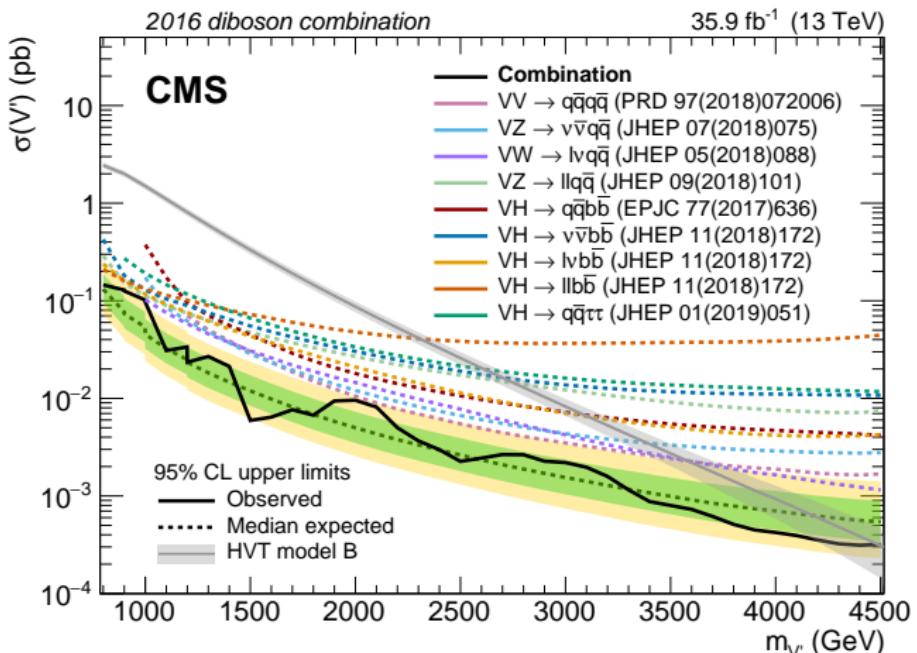
Exclusion on $\sigma(Z')$



Exclusion limits V' triplet

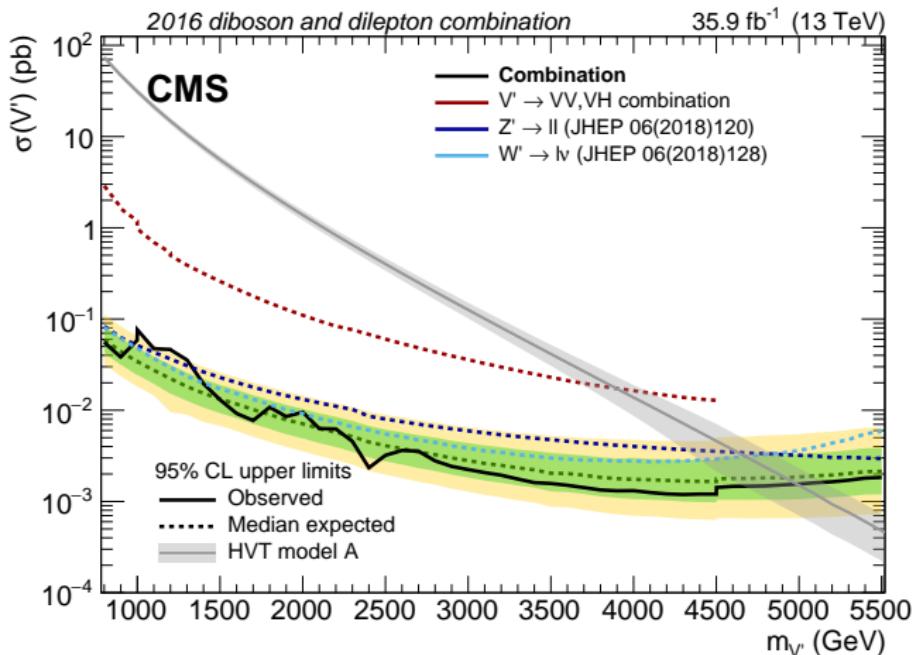
[B2G-18-006, PLB 798(2019)134952]

- Exclusion limit on the $V' \rightarrow WW, WZ, WH, ZH$ singlet (9 channels)
 - HVT model B excluded up to 4.5 TeV
 - Largest significance ($m_X = 2.0$ TeV) 2.5σ (local) / 0.5σ (global)



HVT model A

[B2G-18-006, PLB 798(2019)134952]

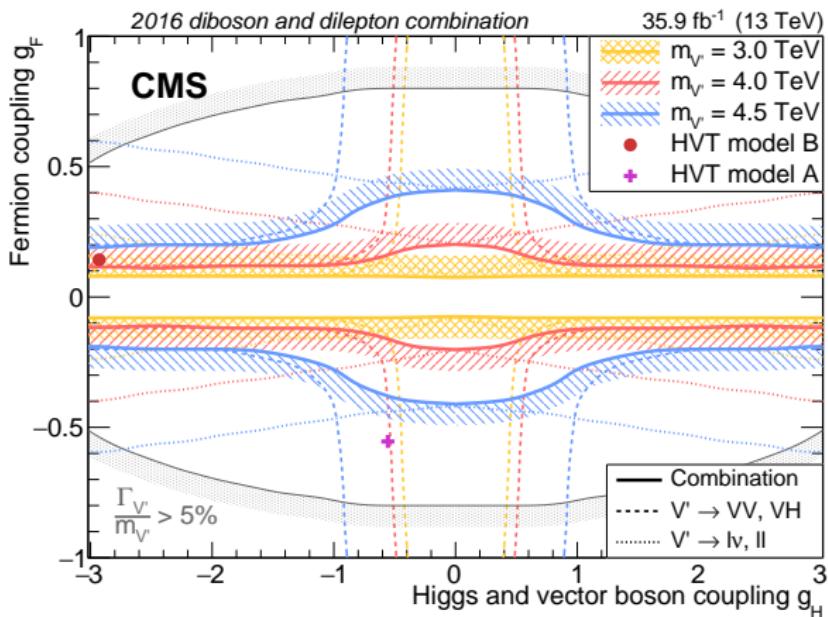


- As expected, dilepton channels dominate the sensitivity in model A
- Largest significance ($m_V = 1.2 \text{ TeV}$) 2.7σ (local) / 1.6σ (global)
- HVT model A V' excluded up to 5.0 TeV (4.9 TeV expected)

HVT model interpretation

[B2G-18-006, PLB 798(2019)134952]

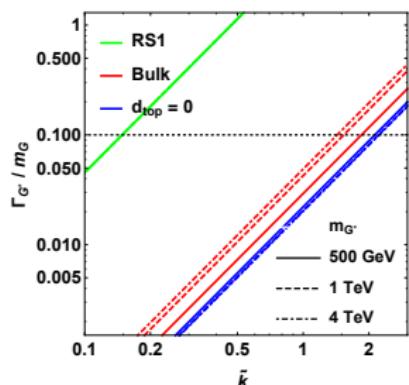
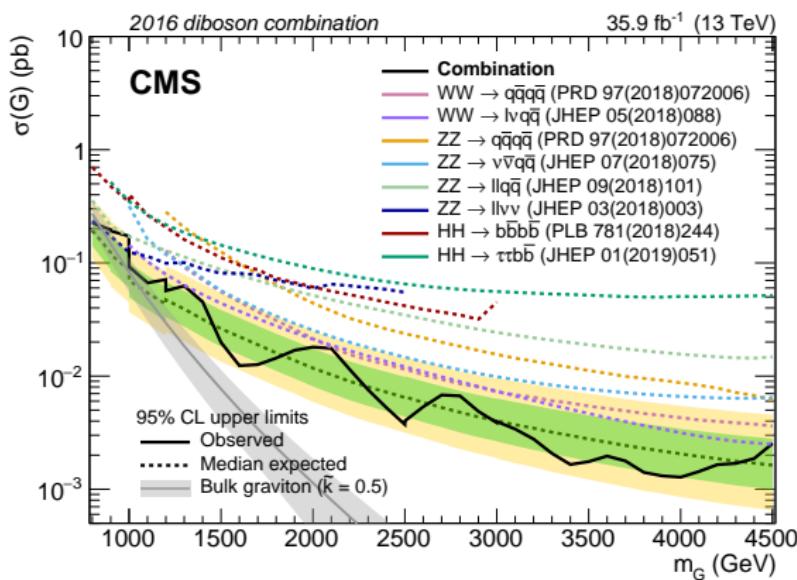
- Scan of the HVT parameter space:
- $g^2 c_F / g_V$ is proportional to the couplings to **fermions**
- $g_V c_H$ is proportional to the couplings to **bosons**
- Including dileptonic analyses to exclude the phase space where $g_V c_H \rightarrow 0$



Exclusion limits Bulk Graviton

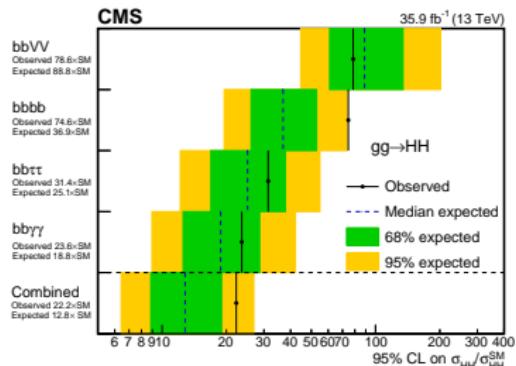
[B2G-18-006, PLB 798(2019)134952]

- Exclusion limit on the $G \rightarrow WW, ZZ, HH$ singlet (8 channels)
 - Bulk scenario with $\tilde{k} = 0.5$ excluded up to **850 GeV**
 - \tilde{k} choice has immediate consequences on the Graviton width
 - Largest significance ($m_X = 1.3$ TeV) 2.2σ (local) / 0.7σ (global)



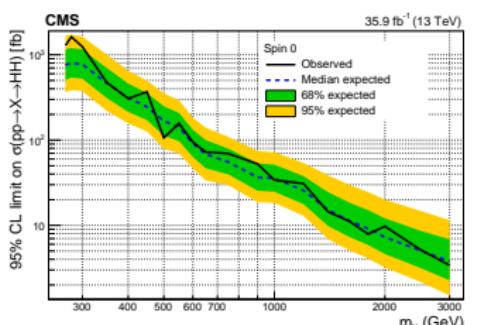
Low-mass HH combination

[HIG-17-030, PRL 122, 121803 (2019)]

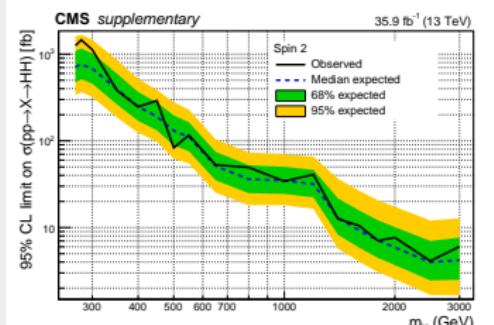


- Combination of the best 5 channels for di-Higgs production in the **resolved** topology
- Both resonant and non-resonant production has been considered
- Non-resonant excludes 20 times the SM cross-section
- Resonant limits placed on Spin-0 and Spin-2 BSM resonances

Spin-0



Spin-2



Concluding remarks

- Impressive and continuous flow of analyses on 2016 data
 - CMS has collected 4 times more luminosity, and many will be updated very soon with full luminosity
- No convincing excess, so far
- No more jumps in energy or luminosity foreseen in the next years: is the party over?

No: many new ideas on the table, can further improve by $30 \sim 50\%$ the reach of our searches

- machine learning, n-dimensional fits, ...
- improved detectors

Food for thoughts

- What if the resonance has moderate mass (~ 1 TeV), but large width?
 - a broad Z' would contribute to explain the lepton flavor anomalies
- Need adequate background prediction methods
- Heavy resonance searches \leftrightarrow precision SM differential measurements

Thank you!



W mass, low purity, tight b tag

Dijet invariant mass
 m_{VH} 4919 GeV

H-jet
 p_T 2065 GeV
 η 0.63
 ϕ 0.84
 m_j 123.7 GeV
b tag 0.95

V-jet
 p_T 1962 GeV
 η -0.65
 ϕ -2.30
 m_j 72.8 GeV
 τ_{21} 0.49

CMS Experiment at LHC, CERN
Data recorded: Fri Aug 5 02:45:13 2016 CEST
Run/Event: 278239 / 427634038
Lumi section: 287