Search for heavy resonances in diboson final states at CMS

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for the CMS collaboration

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Why…

Theoretical motivation

how can we explain the big difference between EW and gravitation?

$$m_H^2 = -2\mu^2 \sim \boxed{10^4\ \mathrm{GeV}^2} \ll M_{\mathrm{Pl}}^2 \sim \boxed{10^{38}\ \mathrm{GeV}^2}$$

natural explanation

SM is extended by another theory at the TeV scale

warped extra dimensions

- Tentative solution of the hierarchy problem
- Radion (spin 0) and graviton (spin 2) can decay to HH

heavy vector triplet

- General Framework
- Include Little Higgs, Composite Higgs
- Introduction of spin-1 resonance

What…

CMS performed an extensive multi-channel search

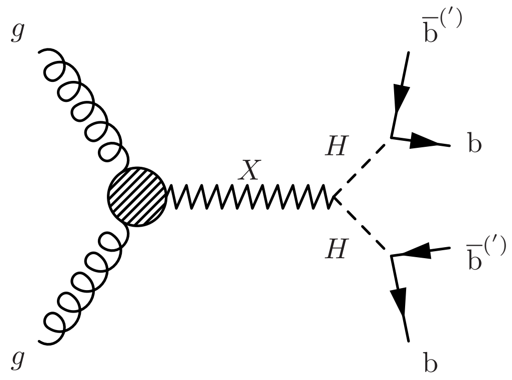
- Search for heavy resonances ($m_X \gtrsim 800$ GeV) decaying into 2 bosons
- Several combination and decaying mode considered

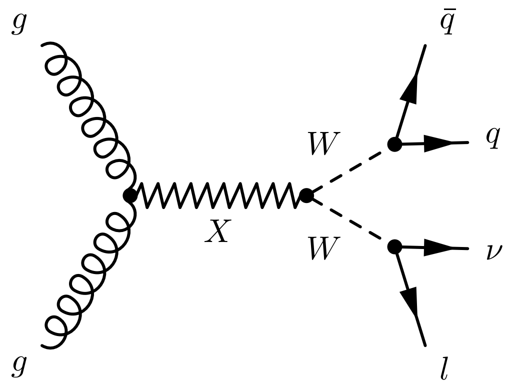
	$V \to q\bar{q}$	$W \to l\nu$	$Z \to ll$	$Z \to \nu\nu$	$H \to b\bar{b}$	$H \to \tau\tau$
$V \to q\bar{q}$	B2G-17-001	B2G-16-029	B2G-17-013	B2G-17-005	B2G-17-002	B2G-17-006
$W \to l\nu$	B2G-16-029				B2G-17-004	
$Z \to ll$	B2G-17-013			B2G-16-023	B2G-17-004	
$Z \to \nu\nu$	B2G-17-005		B2G-16-023		B2G-17-004	
$H \to b\bar{b}$	B2G-17-002	B2G-17-004	B2G-17-004	B2G-17-004	B2G-16-026	B2G-17-006
$H \to \tau\tau$	B2G-17-006				B2G-17-006	

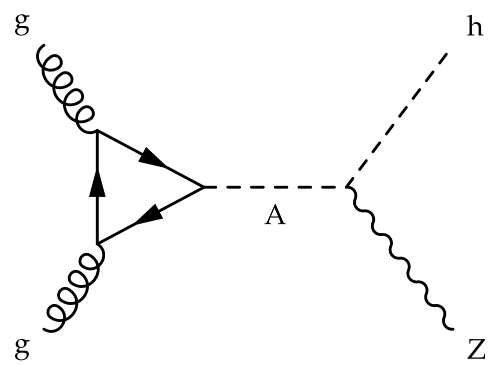
How…

How to detect these resonances at CMS

- Di-boson final states could help finding spin 0, 1 or 2 resonances
- Depending on model parameters, resonances may be narrow or wide
- Majority of analysis focus on **narrow resonance**





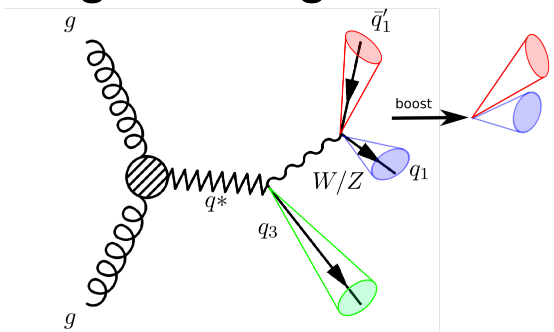


How…

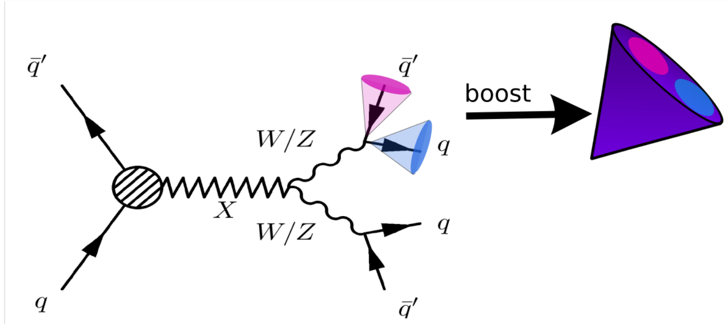
How to detect these resonances at CMS

- Bosons have been searched in all possible decay mode
  - W, Z in leptonic channels
  - W, Z in hadronic channels
  - Z invisible
  - H in $b\bar{b}$ e in $\tau^+\tau^-$
- For high mass resonances, bosons will be very energetic
  - Decay products are highly collimated
- Jets from partons are frequently merged
- Dedicated reconstruction algorithms needed for higt-p_T leptons
- Powerful τ-id needed

single W/Z tag:



double W/Z tag:



How…

How to trigger these resonances at CMS

All analysis use similar trigger strategies

- Single electron and single muon trigger if a lepton in the final state
  - Typically $p_T^{ele} > 50$ GeV with additional ID and isolation cuts and $p_T^{mu} > 50$ GeV
- Missing energy trigger or missing hadronic activity requests if neutrinos in the final state
  - H_T^{mis} or $E_T^{mis} > 90$, 110, 120 or 170 GeV depending on luminosity and pre-scaling of the trigger path
- Several combination of Jet and HT trigger when no E_T^{mis} and no leptons in the final state
  - Jets from anti-k_T algorithm with R = 0.8 and $p_T > 360$ GeV
  - Scalar sum of all jet p_T above 650, 700 or 800 GeV depending on luminosity or additional requests on jets

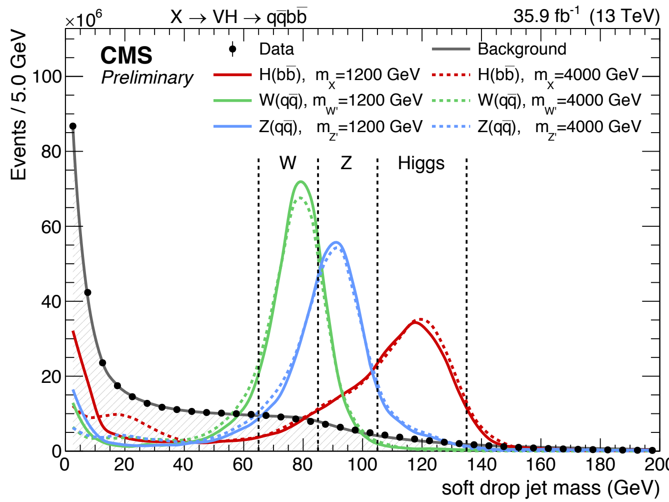
How…

Objects reconstruction

- A Particle Flow (PF) event algorithm is used to reconstruct and identify each individual particle
- All leptons are reconstructed with standard CMS cuts trying to maximize efficiency
  - Acceptance range is typically $|\eta| < 2.4$ for electrons, $|\eta| < 2.5$ for muons and $|\eta| < 2.3$ for hadronic taus
  - Requirements on minimum p_T for all leptons are applied
  - Isolation cuts as well as quality cuts are used to select only prompt leptons from bosons decays
  - A special reconstruction algorithm is used to identify hadronically decayed τ leptons
  - For leptonic decay of the Z boson, opposite charge is required
- Jets reconstruction uses anti-k_T algorithm with R=0.4 and 0.8 (fat-jet)
  - Jets p_T is corrected using the standard CMS energy scale (JES) prescription
- Missing transverse energy is calculated from all the PF particles
  - E_T^{mis} is corrected for JES and electrons and muons momentum scale
- Pile-up (PU) mitigation techniques are applied

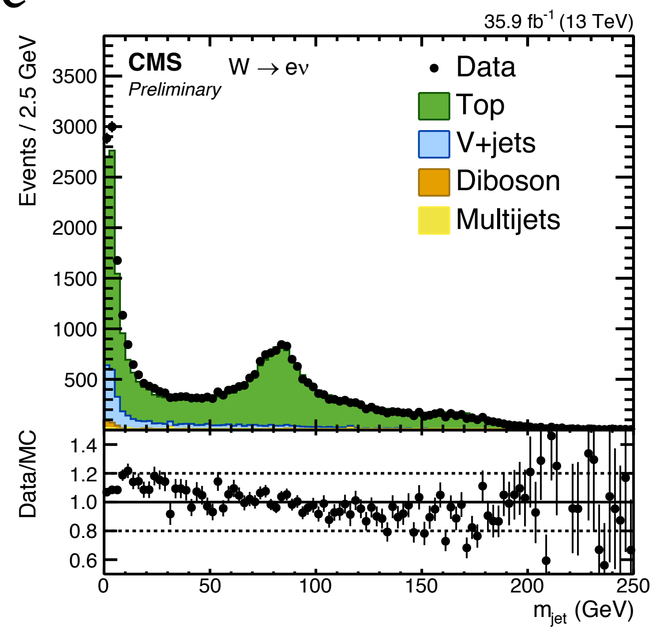
How…
Merged jets techniques

- For **resonances above 1 TeV**, a significant fraction of bosons is reconstructed as a single jet
  - Using R=0.8 jets helps collecting the full boson decay within a fat jet
- Mass of the jet (corrected for soft radiation contribution) can be used to select jets from bosons
- Jet grooming remove soft and large angle radiation
  - Before grooming, PU is removed
  - Re-cluster iteratively particles in 2 sub-jet and remove softer contribution
  - Jet mass resolution is approximately 10%
  - No W/Z/H ambiguity after mass selection



How…
Merged jets techniques

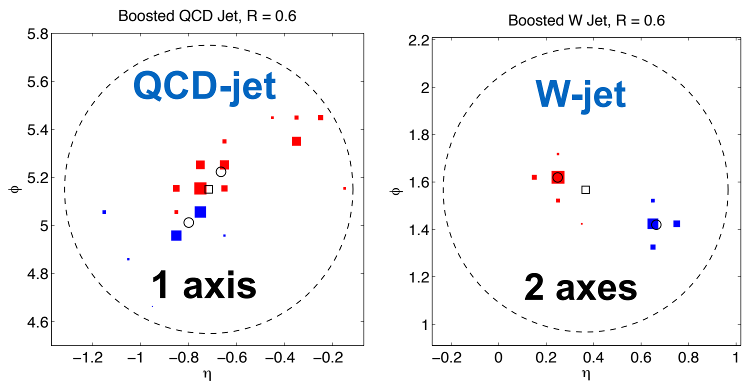
- For **resonances above 1 TeV**, a significant fraction of bosons is reconstructed as a single jet
  - Using R=0.8 jets helps collecting the full boson decay within a fat jet
- Jet pruning was used till 2015 but soft drop more stable against PU and it is both infrared and collinear safe
- All 2016 analysis use soft-drop
- Control sample (high momentum $t\bar{t}$) are used to check data-simulation agreement



How…

Merged jets techniques

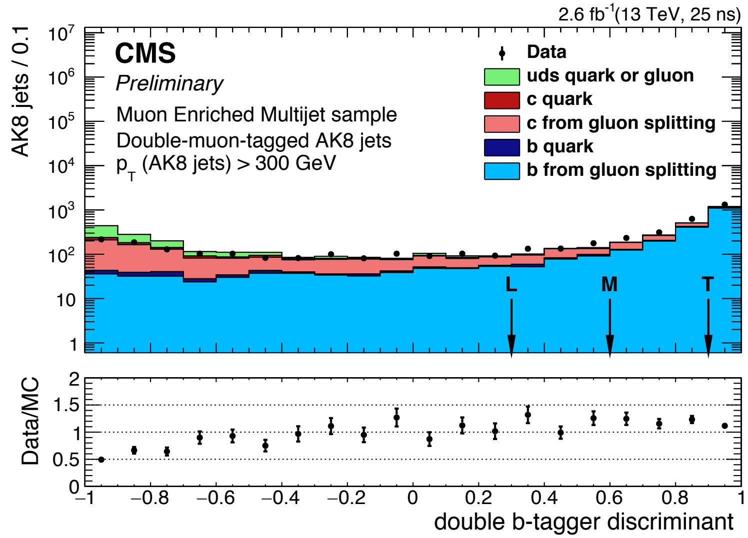
- For **resonances above 1 TeV**, a significant fraction of cases is reconstructed as a single jet
  - Using R=0.8 jets helps collecting the full decay within a fat jet
- N-subjettiness is another technique to identify a fat jet with more than one sub-jet
- If more than one parton contribute to the fat jet…
  - Energy-flow align along more than 1 momentum direction
- New variable (sub-jettiness ratio) used to discriminate 1-subjet to 2-subjets composition
  - Validation on data is needed
  - Uncertainties derived from $W \to q\bar{q}$ in $t\bar{t}$ enriched samples

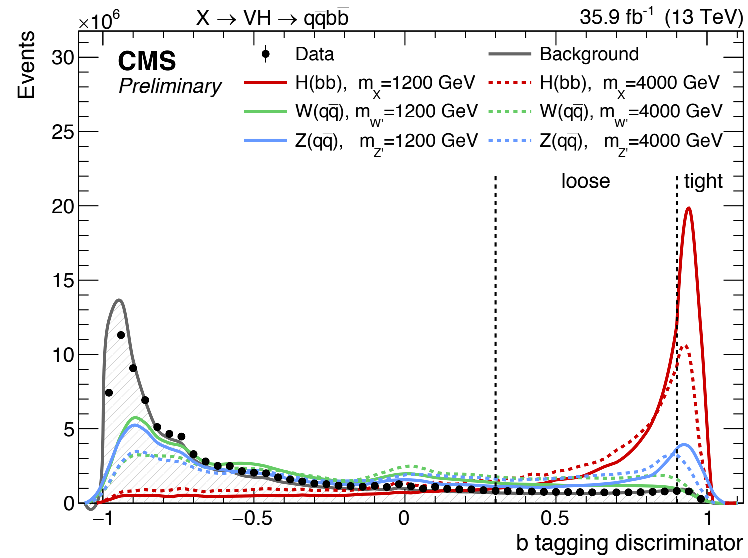


How…

b-jets tagging

- Dedicated Higgs-tagger using double-b tagger applied to fat jets
  - Inputs based on observables from secondary vertices and tracks associated to each sub-jet axis
  - MVA algorithm gives a 80% (30%) Higgs-Jet tag efficiency for tight (loose) working point
- At the same signal efficiency, the mis-tag rate is lower by a factor of 2 compared to the sub-jet b tagging approach
  - Identify 2 sub-jet
  - b-tag each sub-jet

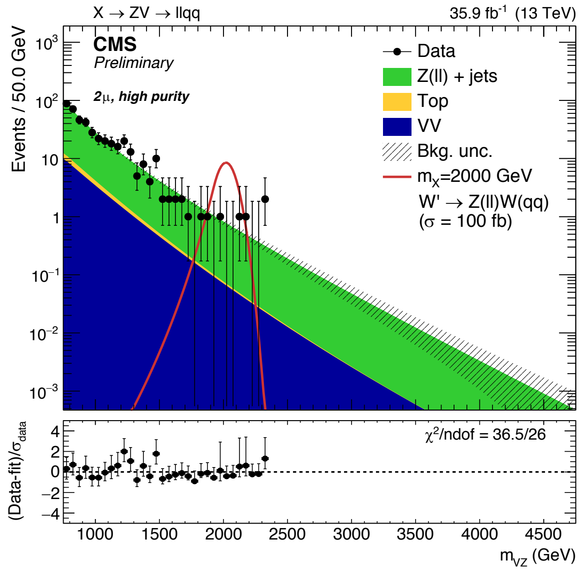


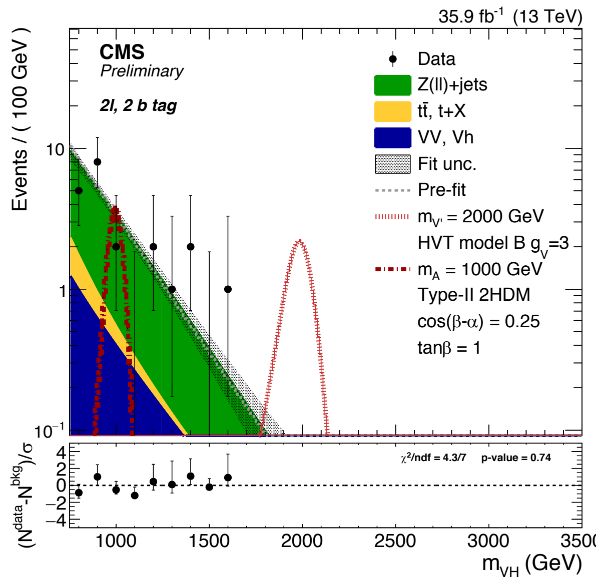


Resonances ZZ – ZW – ZH

Final state with $Z \rightarrow e^+e^-, \mu^+\mu^-$

- **Second boson decay**
  - 2q in 1 merged or 2 unmerged jets
  - 2 neutrinos
  - 1 fat jet from 2 merged b from the Higgs
- A bump search has been used in the 2q and 2b analysis
  - Low and high mass signal extracted separately for 2q
  - Mass limits on *W'* and spin-2 graviton signal extracted for 2q
  - Mass limits on Z', W' and the 2 Higgs doublet model for 2b
- A Jacobian edge has been searched for the 2 neutrinos analysis
  - Data driven bkgd estimation from γ+jets events
  - Good sensitivity for resonance below 1.5 TeV

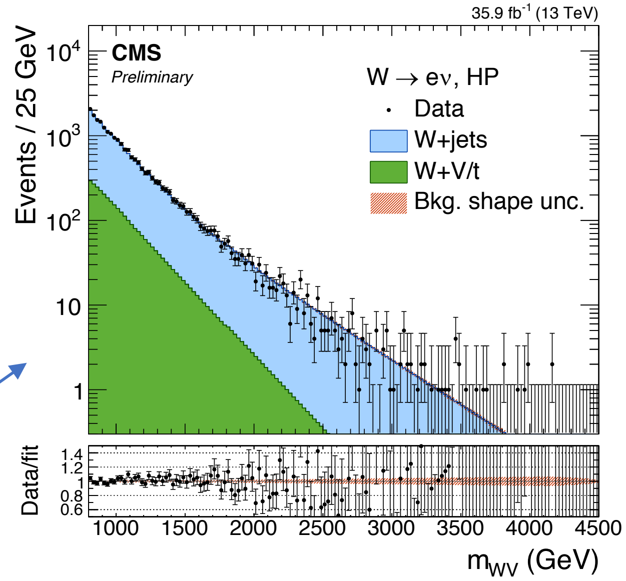


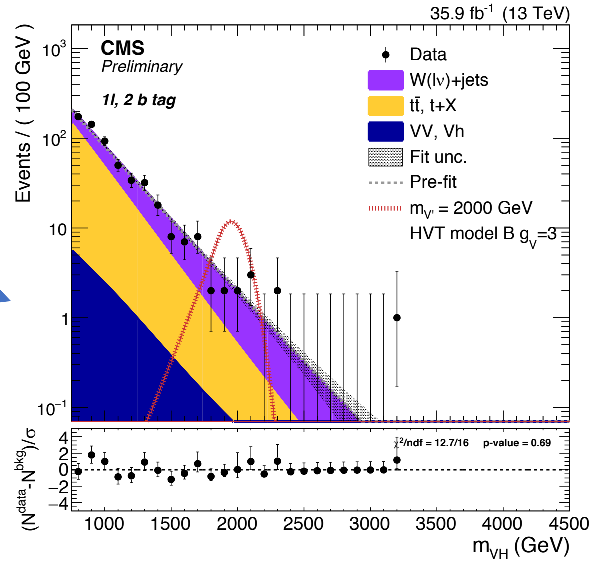


Resonances WZ – WW – WH

Final state with $W \rightarrow l\nu$

- **Second boson decay**
  - 2q in 1 merged jet from Z or W
  - 1 fat jet from 2 merged b from the Higgs
- The Higgs fat jet is required to have at least 1 b-tagged sub-jet
  - No significant deviation from the SM found
- Search in the 1.0 to 4.5 TeV range for Z and W as second boson
  - 4 categories depending on lepton flavor and sub-jettiness ratio
  - All distribution compatible with SM





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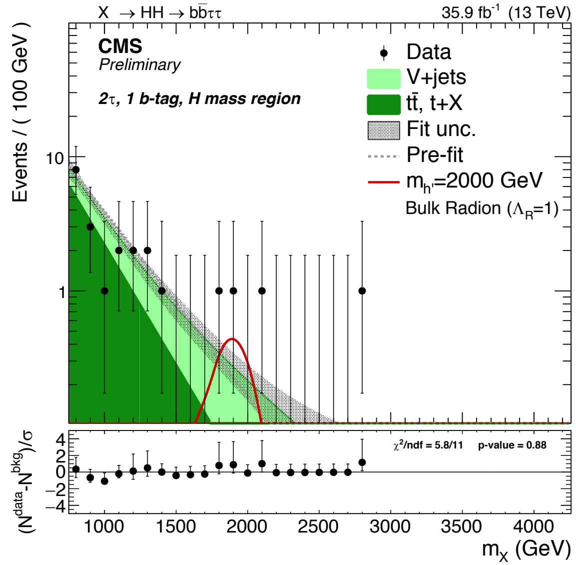
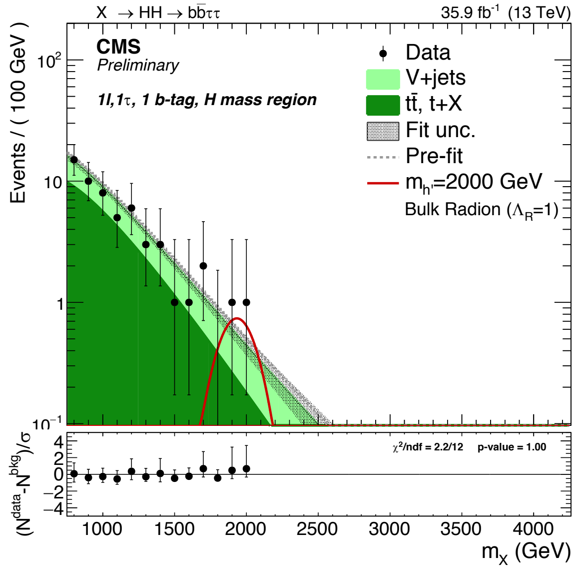
Resonances HZ – HW – HH

Final state with $H \to \tau^+\tau^-$

- Boosted taus in the final state
- Higgs searched as a single fat jet
- If 2-sub-jet in the fat jet → τ-id applied → 2 τ-tagged sub-jet → event selected
- Event selected also if a Higgs candidate found in $e\tau_h$ or $\mu\tau_h$
- **Second boson decay**
  - Soft-drop algorithm & N-subjettiness
  - b-Tag applied to identify the Higgs boson

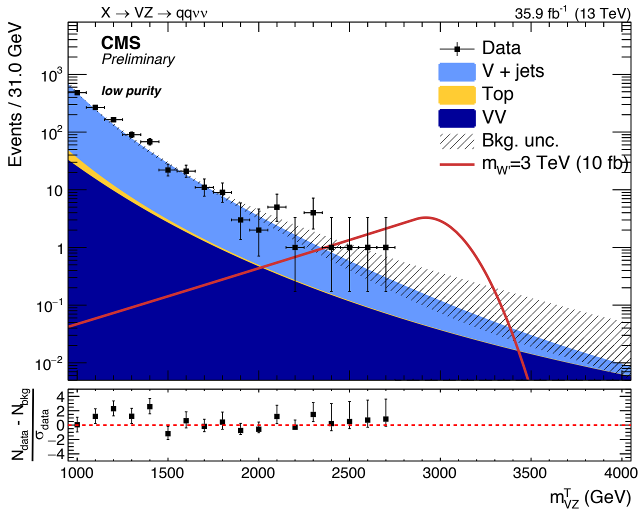


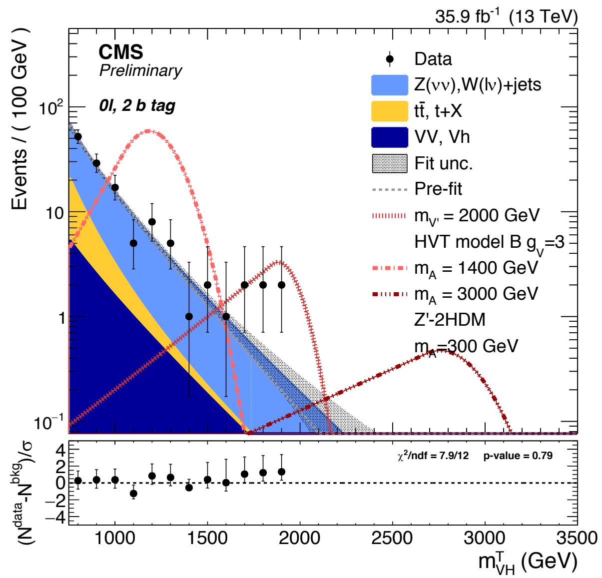


Resonances ZZ – ZW – ZH

Final state with $Z \rightarrow \nu\bar{\nu}$

- Large missing energy or missing hadronic activity
- **Second boson decay**
  - Largest fat jet and $p_T > 200$ GeV
  - Soft-drop algorithm & N-subjettiness
  - *b*-Tag applied to identify the Higgs boson
- Transverse mass is used for the reconstruction of the *ZV - ZH* candidate
  - Z boson $\vec{p}_T$ is set equal to $\vec{p}_T^{miss}$
- Unbinned profile likelihood fit on the transverse mass diboson candidate
- No excess found with respect to SM predictions





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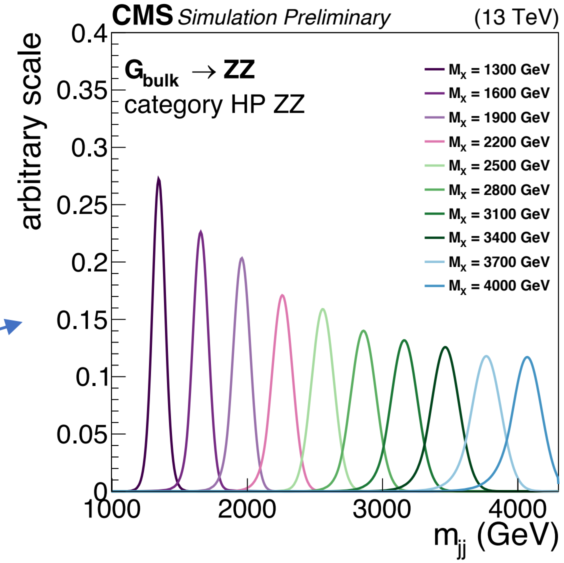
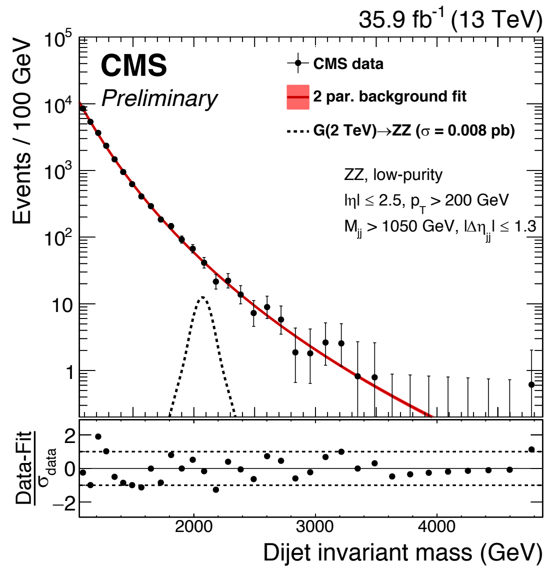
Resonances ZZ – ZW – WW

Final state with $(q\bar{q})(q\bar{q})$

- Events with 2 fat jets are selected
  - Both fat jet with $p_T > 200$ GeV
  - Soft-drop algorithm & N-subjettiness
  - No high p_T leptons
- Signal shape in di-jet invariant mass spectrum modelled with a Gaussian core and exponential tail
- Background modelled using smooth, parametrized, monotonically decreasing distribution
- Maximum likelihood fit performed on data, fixing the number of expected signal events to zero





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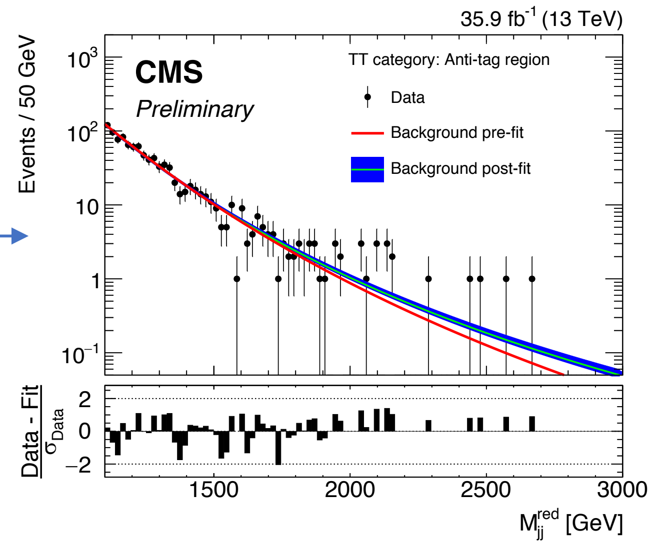
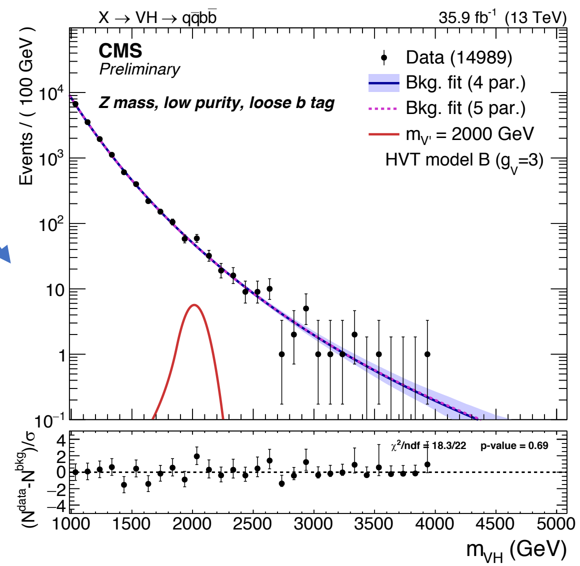
Resonances HZ – HW – HH

Final state with H → $b\bar{b}$

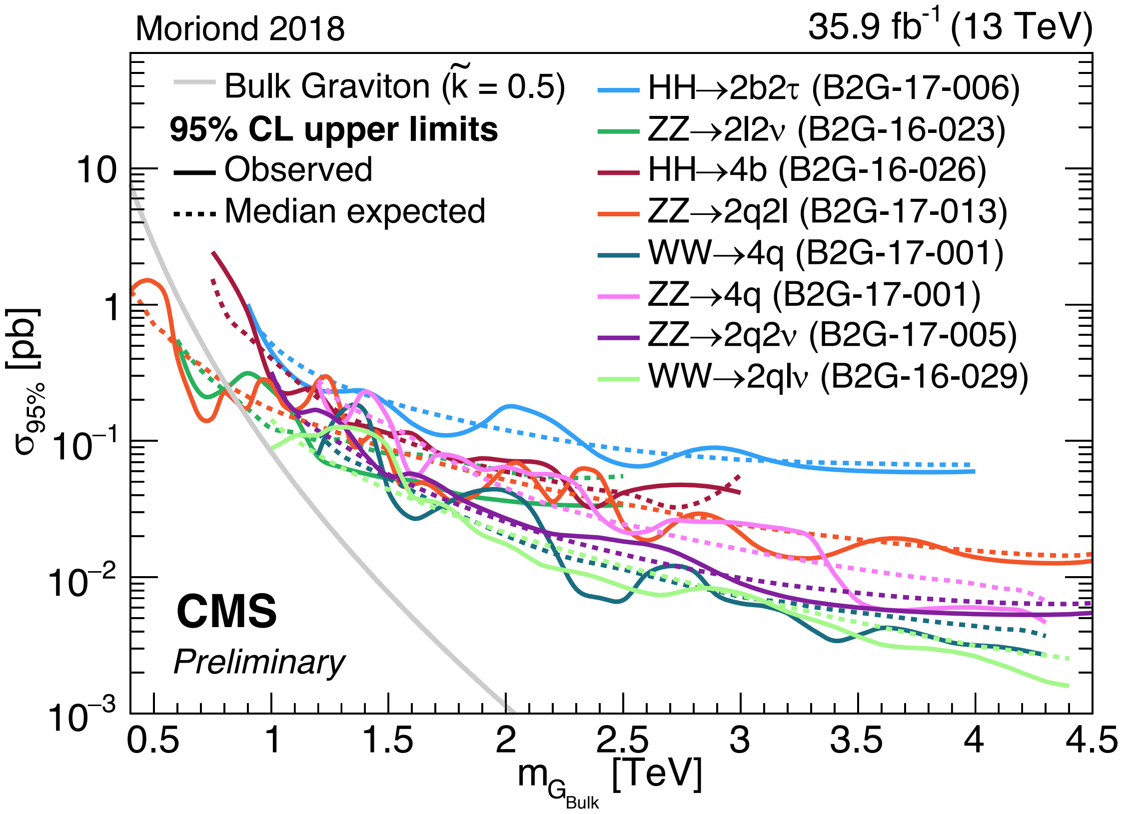
- **Second boson decay**
  - If H → $b\bar{b}$, 2 fat jets with with $p_T > 300$ GeV, soft-drop algo and double b-tagger for both jets
  - If $V \rightarrow q\bar{q}$, 2 fat jets with with $p_T > 200$ GeV, soft-drop algo and double b-tagger for the Higgs candidate
- Several categories defined in all 3 channels depending on the *b*-Tag working points and the soft-drop mass
- Separated unbinned profile likelihood fit on the background and signal shape





Limits

Spin-2 bulk graviton



$X \to ZZ \to ll\nu\bar{\nu}$

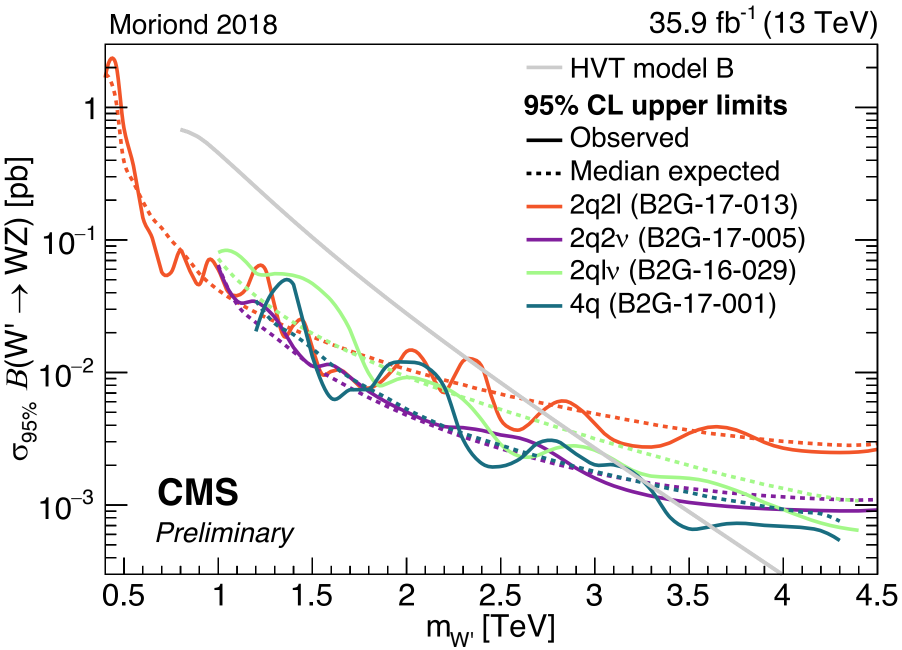
For the narrow width resonances with $\tilde{k} = 0.5$, the masses below 800 GeV are excluded at 95% CL

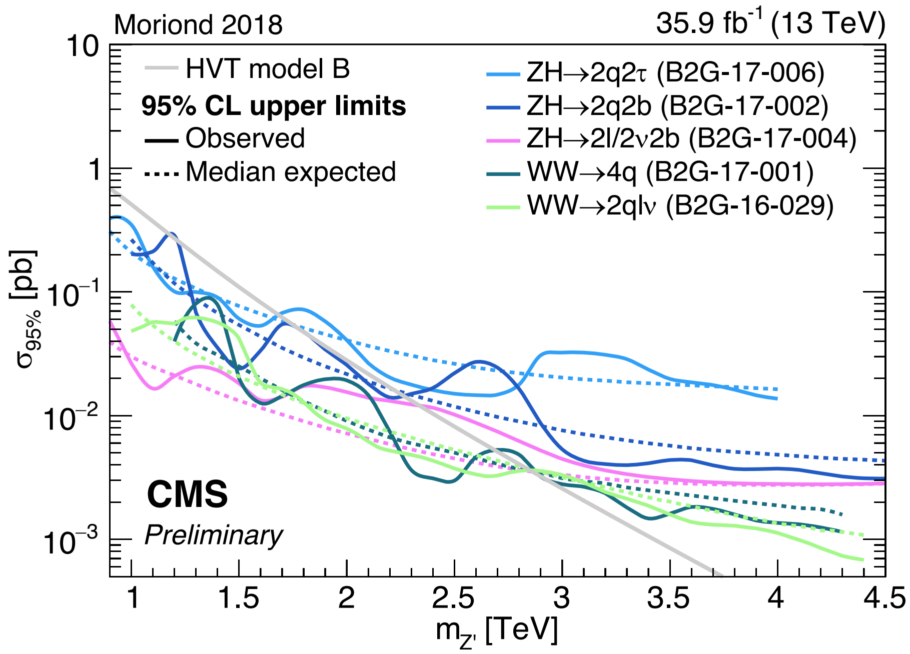
$X \to WW \to l\nu q\bar{q}$

WW resonances with $\tilde{k} = 0.5$, the masses below 1TeV are excluded at 95% CL

Limits

W′ and Z′ resonances in the HVT model A/B





$W' \rightarrow WZ \rightarrow q\bar{q}\nu\bar{\nu}$

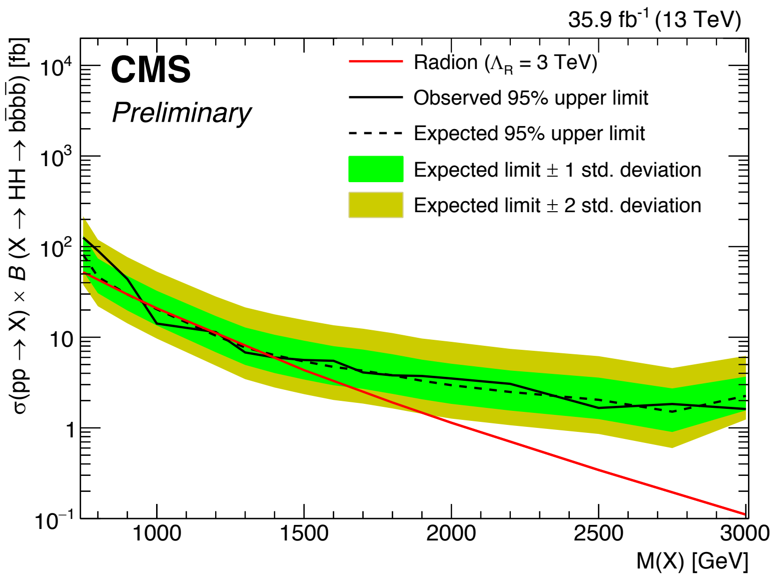
A *W'* resonance below 3.2 TeV in model A and 3.5 TeV in model B is excluded at 95% CL

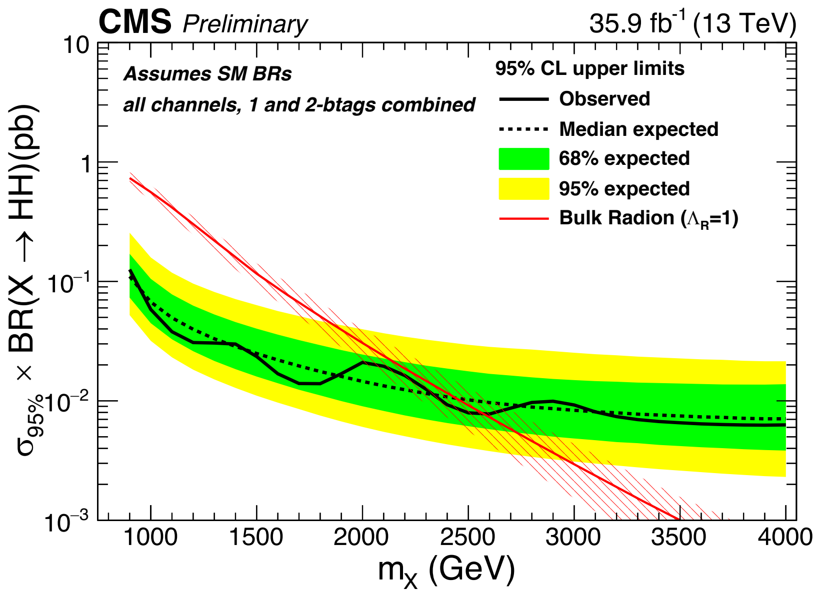
$Z' \rightarrow WW \rightarrow q\bar{q}q\bar{q}$

A *Z'* resonance below 2.7 TeV is excluded at 95% CL

Limits

Randall-Sundrum radion





$X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$

For the mass scale $\Lambda_R = 3$ TeV, a radion of mass between 970 and 1450 GeV is excluded at 95% CL

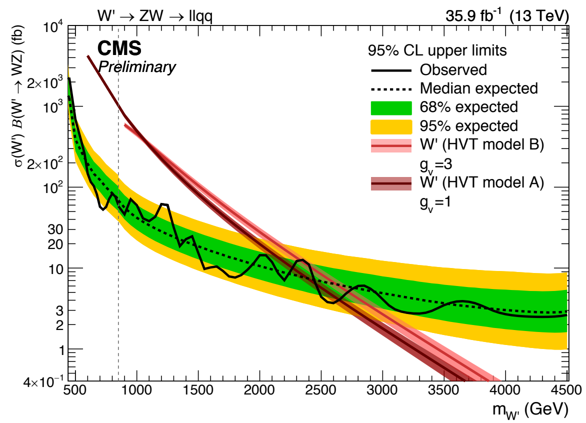
$X \rightarrow HH \rightarrow b\bar{b}\tau^+\tau^-$

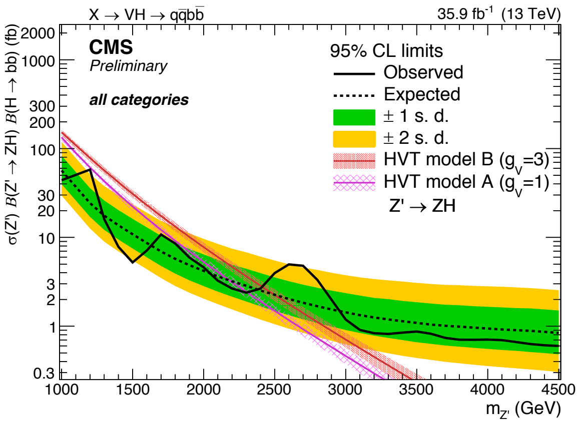
Assuming $\Lambda_R = 1$ TeV. a radion resonance with mass lower than 2.5 TeV is excluded at 95% CL

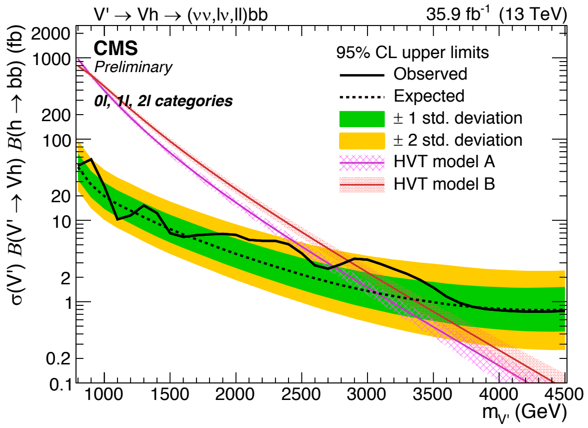
Limits

The other analysis…

- **No SM deviation found…**
- Process $W' \rightarrow WZ \rightarrow llqq$
- Process $V \rightarrow ZH \rightarrow llbb + l\nu bb + \nu\nu bb$
- Process Z'→ZH→$qqbb$







Conclusions
and the future…

- Wide program of di-bosons resonance search at CMS presented
  - We are probing many BSM theories
  - None till now has been found working…
  - But higher statistics is coming!
- CMS is ready to improve its searches
  - More work to better understand jets substructure
  - Non stop work to improve *b*-Tag and τ-Tag techniques
  - Multi-dimensional fits to make best use of statistics

Well set up to make best use of full Run-2 data set

Bibliography

- B2G-16-023 Search for diboson resonances in the 2l2ν final state
- B2G-16-026 Search for heavy resonances decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at s√=13 TeV
- B2G-16-029 Search for heavy resonances decaying to pairs of vector bosons in the l nu q qbar final state with the CMS detector in proton-proton collisions at sqrt s = 13 TeV
- B2G-17-001 Search for massive resonances decaying into WW, WZ, ZZ, qW and qZ in the dijet final state at √s=13 TeV
- B2G-17-002 Search for heavy resonances decaying into a vector boson and a Higgs boson in hadronic final states with 2016 data
- B2G-17-004 Search for a heavy resonance decaying into a vector boson and a Higgs boson in semileptonic final states at √s = 13 TeV
- B2G-17-005 Search for heavy resonances decaying into a Z boson and a vector boson in the νν qq¯ final state
- B2G-17-006 Search for heavy resonances decaying into two Higgs bosons or into a Higgs and a vector boson in proton-proton collisions at 13 TeV
- B2G-17-013 Search for new heavy resonances decaying into a Z boson and a massive vector boson in the 2ℓ2q final state at s√=13~TeV
- LHC Seminar Search for heavy resonances in diboson final states at CMS

Limits

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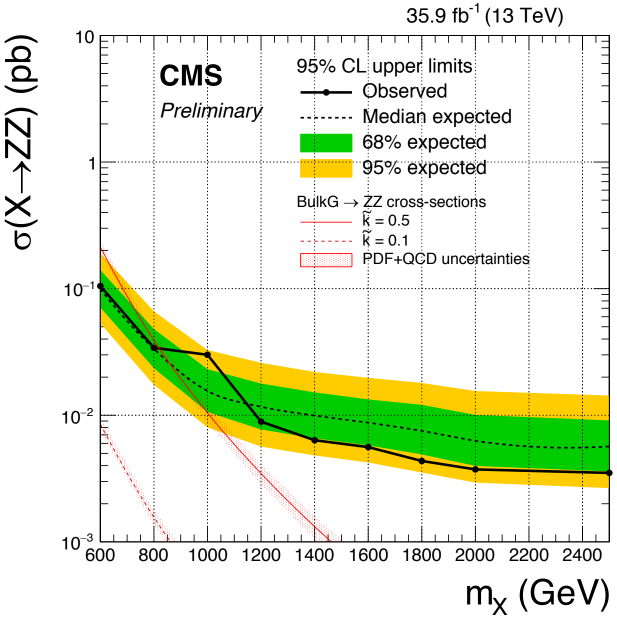

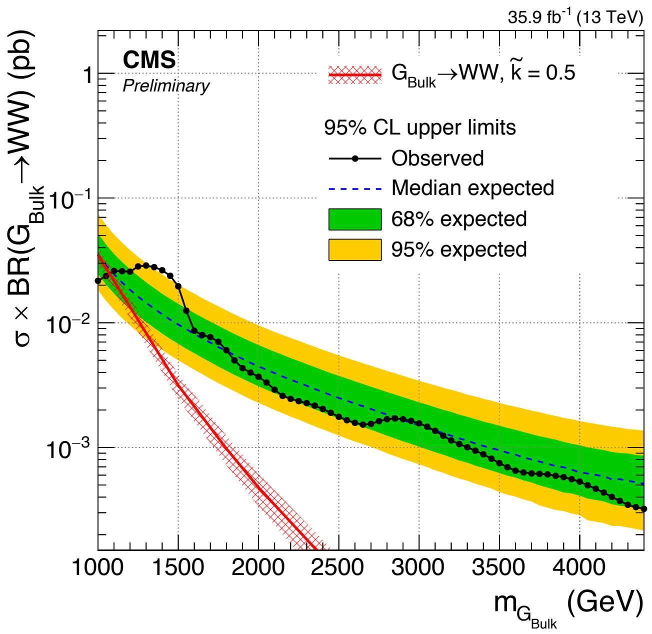

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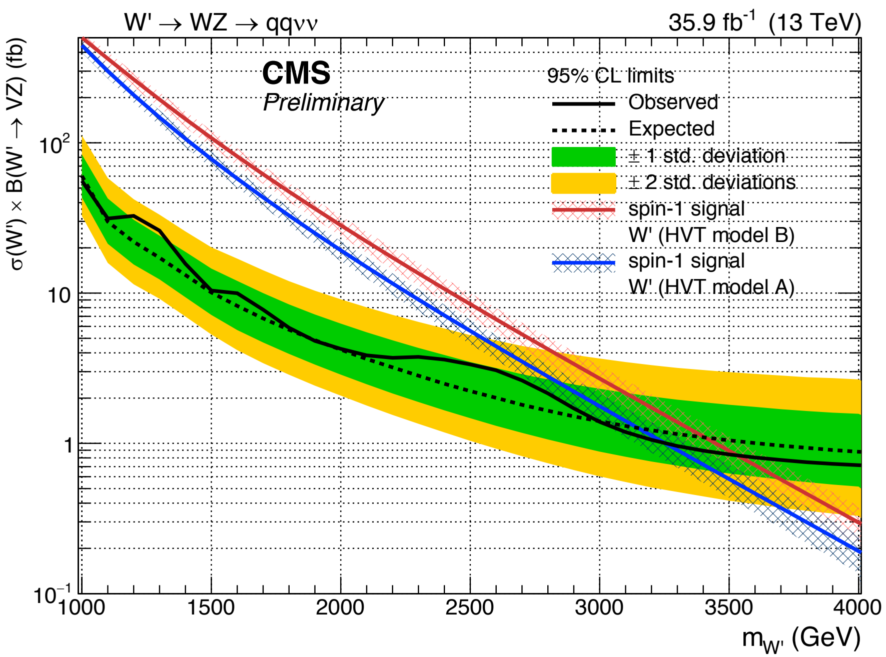

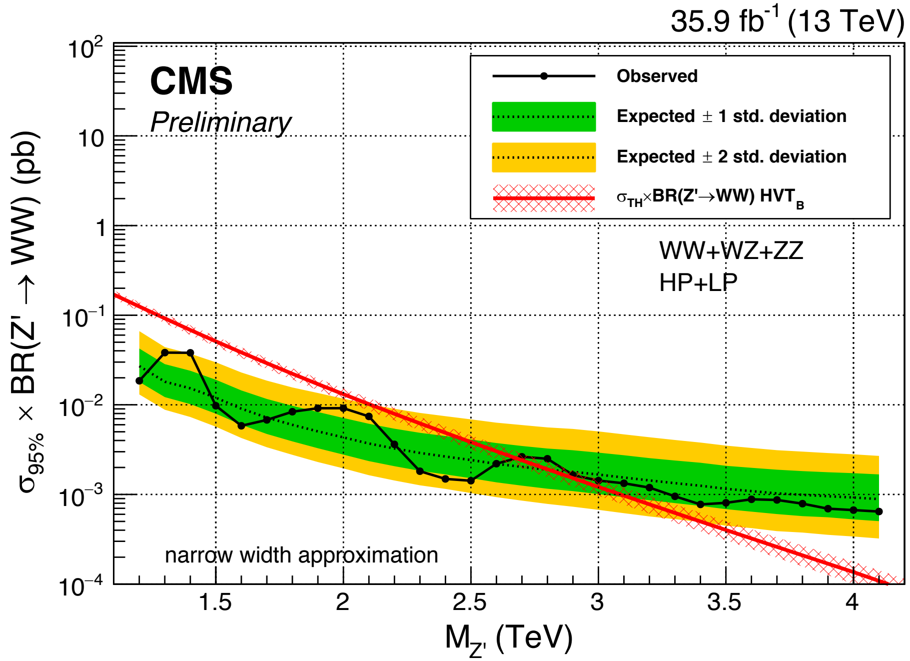

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Jet grooming: soft drop algo

- The goal of jet grooming is to re-cluster the jet constituents while applying additional requirements that eliminate soft, large-angle QCD radiation that increases the jet mass compared to the initial V-boson, quark or gluon mass.
- Soft drop is both infrared and collinear safe in contrast the *jet pruning* algorithm used in 2015 CMS analysis, while providing similar discrimination power
- The soft-drop algorithm use from a Cambridge-Aachen jet clustered from the constituents of the original AK8 jet

Backup

N-subjettiness ratio

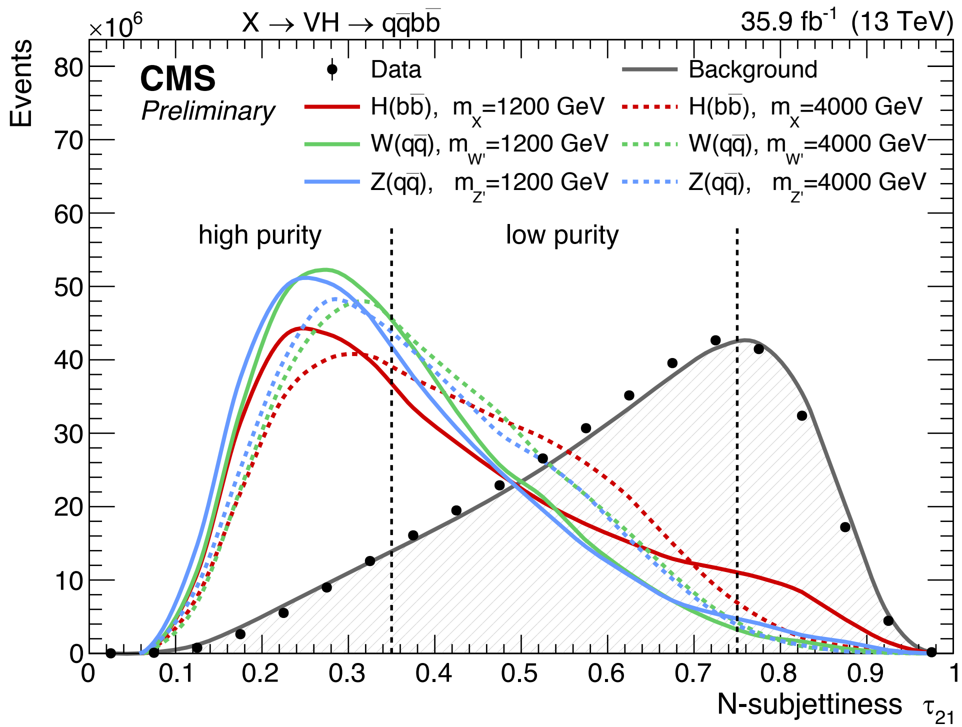
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k})$$

normalisation

sum over particles

minimise distance to candidate subjets

- Low value of τ_N → compatibility with the hypothesis of N axis
- Ratio τ_2/τ_1 has good discrimination power



Backup
B-Tagging

[CMS-PAS-BTV-15-002](CMS-PAS-BTV-15-002)
Identification of double-b quark jets in boosted event topologies