LHCP 2017 The Fifth Annual Conference on Large Hadron Collider Physics

Searches for diboson resonances at CMS

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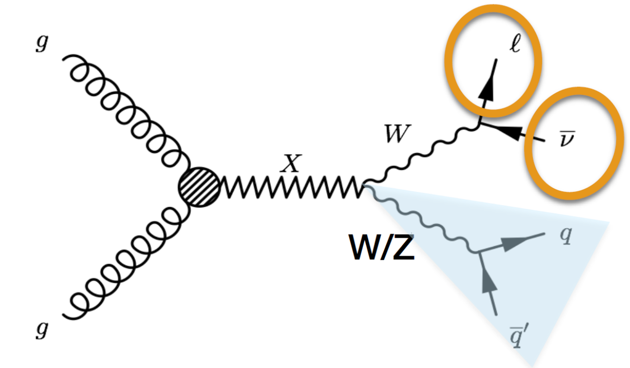
on behalf of the CMS collaboration

2017/5/19

Introduction



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

	$V \to q\bar{q}$	$W \to l\nu$	$Z \to ll$	$Z \to \nu\nu$	$H \to b\bar{b}$
$V \to q\bar{q}$	$VV \to q\bar{q}q\bar{q}$	--	--	--	--
$W \to l\nu$	$WV \to l\nu q\bar{q}$		--	--	--
$Z \to ll$	$ZV \to llq\bar{q}$			--	--
$Z \to \nu\nu$					--
$H \to b\bar{b}$	$VH \to q\bar{q}b\bar{b}$	$WH \to l\nu b\bar{b}$	$ZH \to llb\bar{b}$	$ZH \to \nu\nu b\bar{b}$	$HH \to b\bar{b}b\bar{b}$

Heavy vector triplet (HVT)

Heavy **Z'**, **W'** predicted by several models: Little Higgs, composite Higgs, Minimal Walking Technicolor

Two possible scenarios:

1. coupling to fermions dominating (**Model A**)
2. coupling to fermions suppressed w.r.t. SM bosons dominating (**Model B**)

Warped Extra Dimension (WED)

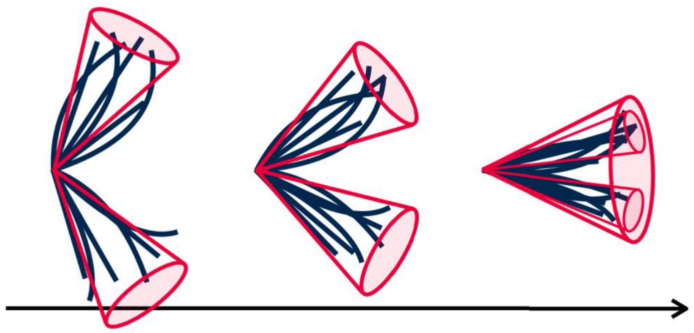
WED models as possible solution to the hierarchy problem

Radion (spin-0) and Graviton (spin-2)

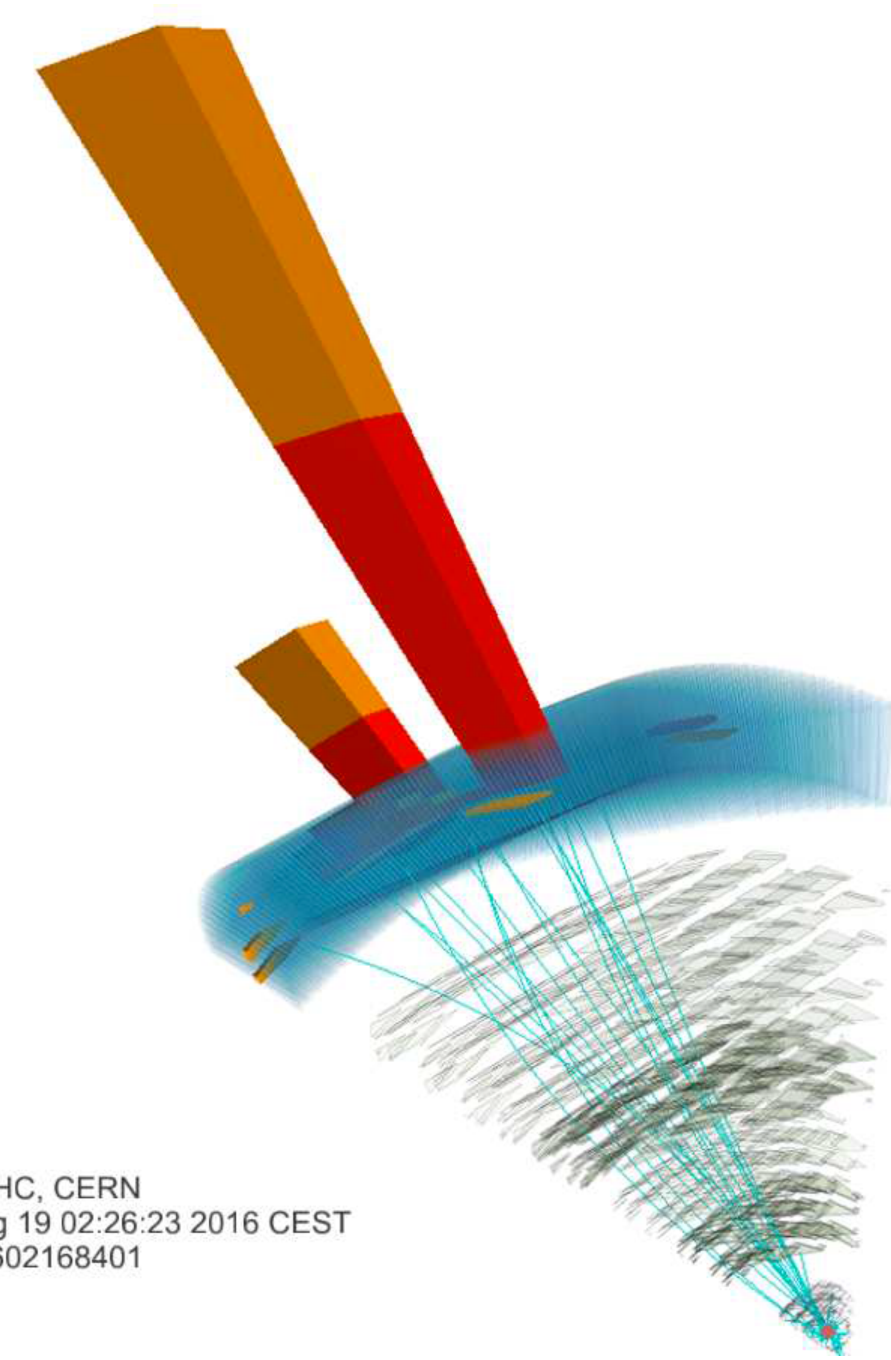
Production through DY and gluon-fusion, decay to WW, ZZ, HH

Reconstruction & Identification

- **Challenges**
- SM bosons decay mostly to quarks ($\boldsymbol{q\bar{q}}$, $\boldsymbol{b\bar{b}}$)
- Due to the large Lorentz boost W, Z, H decay products merge in to a single jet
- Clustered within a large-cone jet (R=0.8)
- Investigation of the ***jet substructure***
- ***Groomed jet mass*** to mitigate pileup contamination



Boosted jets: Increasing transverse momentum



CMS Experiment at LHC, CERN
Data recorded: Fri Aug 19 02:26:23 2016 CEST
Run/Event: 279024 / 602168401
Lumi section: 376

https://indico.cern.ch/event/517784/contributions/2496893/attachments/1461665/2258007/LHCP_Shanghai_2017_final.pdf

Reconstruction & Identification

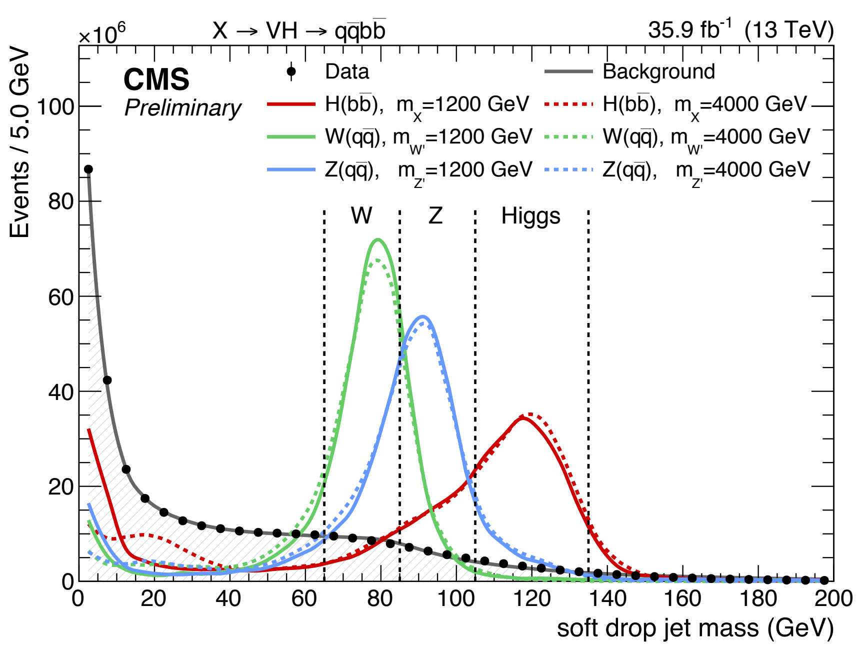
- **Grooming and jet mass**

  Boosted large-R jets (R=0.8) can be easily contaminated by pileup interactions.

  "Grooming" is to remove those pileup contaminations, to achieve stronger discrimination power for boosted jets.

- **PUPPI algorithm** (JHEP10(2014)059): pileup mitigation algorithm identifying and assigning small weights to the pileup particles served as input to jet clustering.

- **Softdrop algorithm** (JHEP05(2014)146): dropping soft jet constitution particles.



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

  The V-jets tagging variables and V/H-jet mass are calculated based on the ***groomed jets***

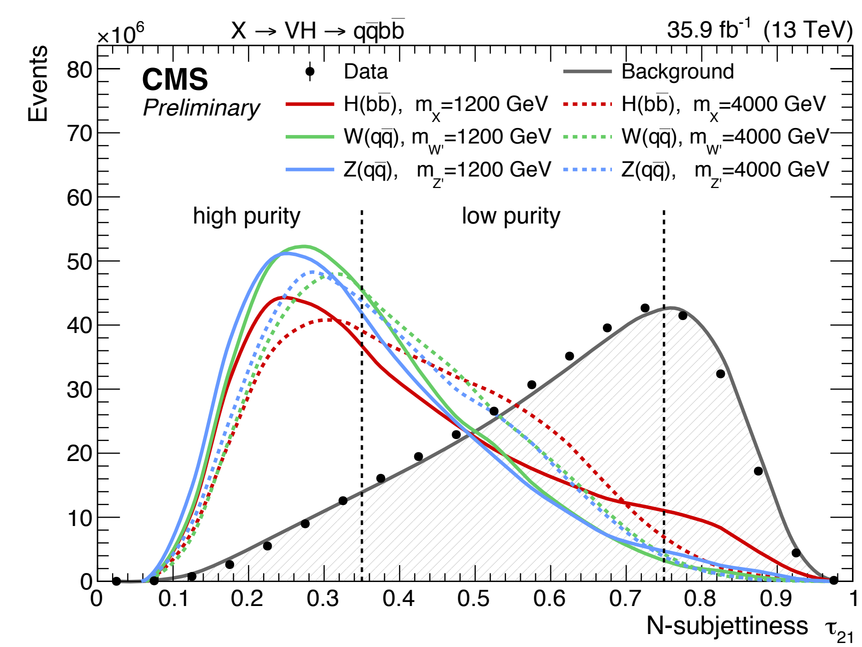
  Distinguish: Boosted W/Z jets (2-prong) vs. QCD q/g jets (1-prong)

- **N-subjettiness** (arXiv:1011.2268): how likely is a jet to have "N" subjets

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

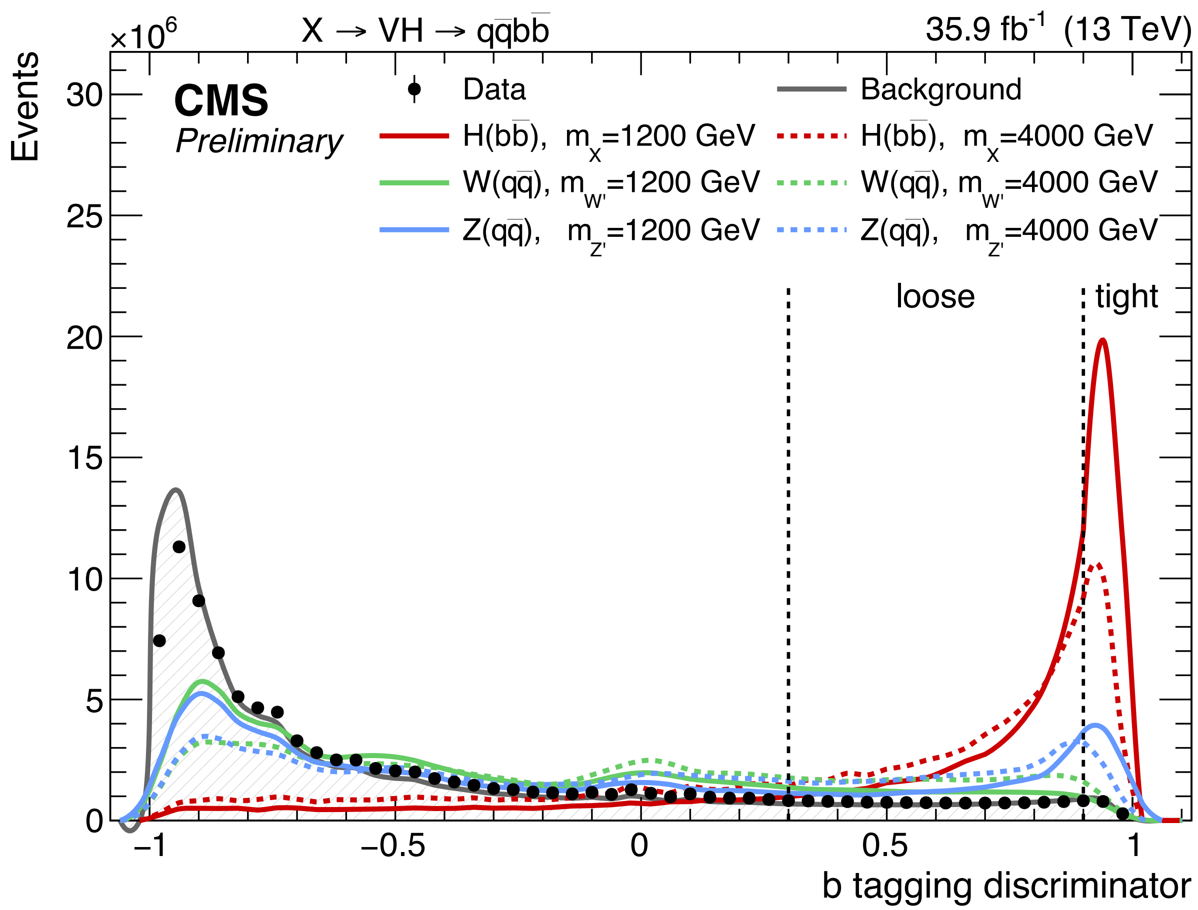
$$d_0 = \sum_k p_{\mathrm{T},k} \times R_0$$

Wjet tagger $\tau_2/\tau_1 = \tau_{21}$



Reconstruction & Identification

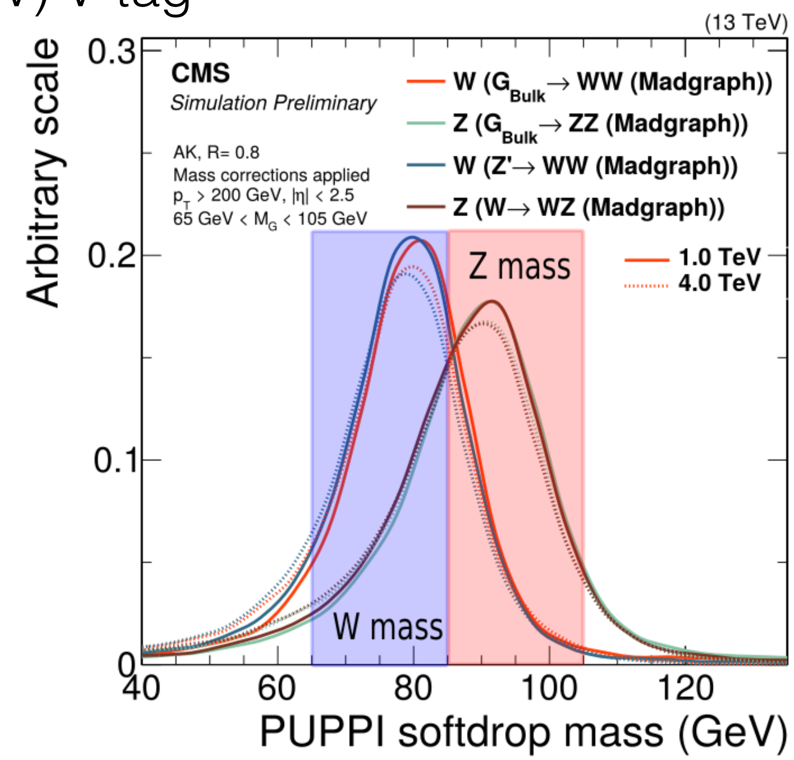
- **Higgs boson tagging ($H \rightarrow b\bar{b}$)** (CMS-PAS-BTV-15-002)
- Exploit b-tagging to identify **two** b-quarks within the same jet
- Also use soft lepton (e, μ) information
- Combines tracking and vertexing information in an MVA

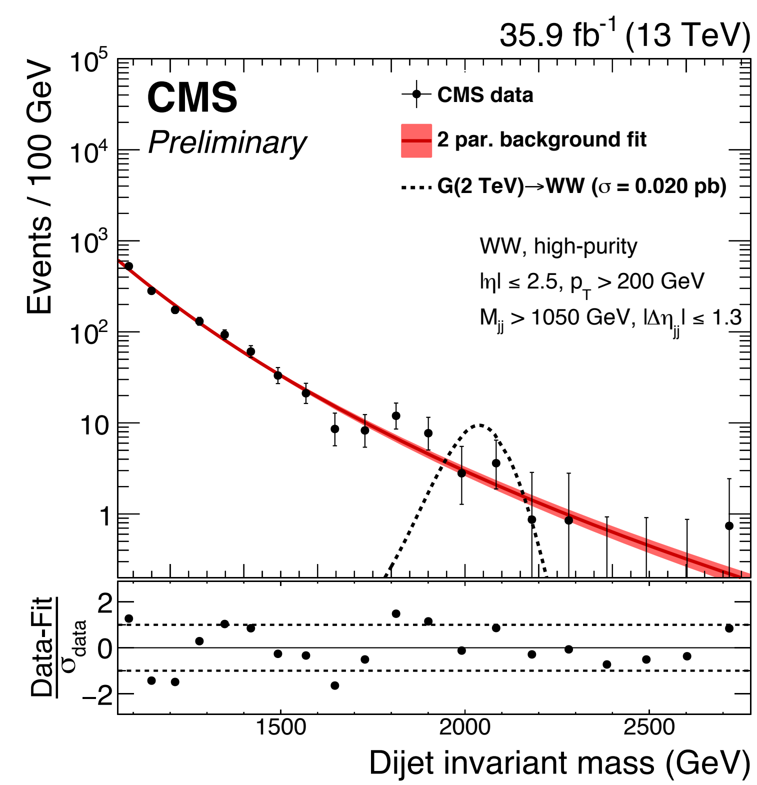


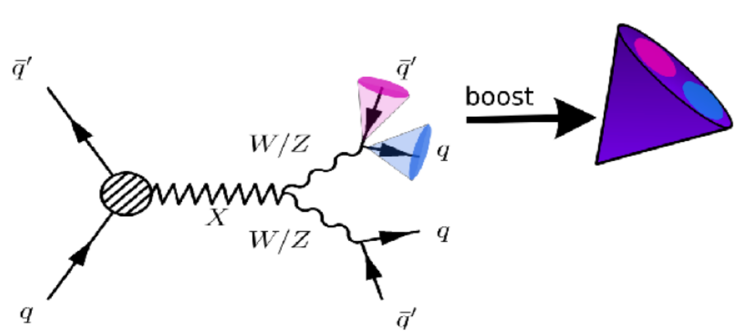
$X \to VV \to q\bar{q}q\bar{q}$

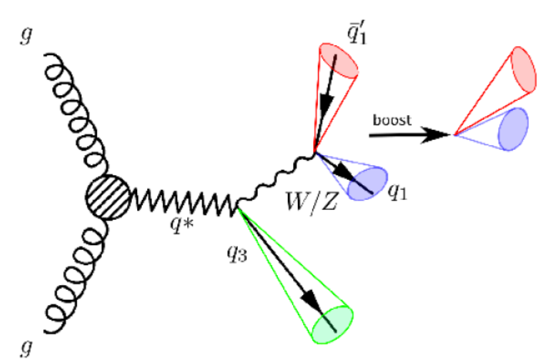
CMS-PAS-B2G-17-001

- All-hadronic resonance search with double (VV) or single (qV) V-tag
- Event categorization:
  - V-jet mass: W ($65 < m_j < 85 GeV$) or Z ($85 < m_j < 105 GeV$)
  - V-jet τ_{21}: high purity (τ_{21}<0.35), low purity ($0.35 < \tau_{21} < 0.75$)
  - 6 categories for VV: (WW/WZ/ZZ)×(HP/LP)
  - 4 categories for qV: (W/Z)×(HP/LP)
- Background modeling:
  - Multijets (dominant), $t\bar{t}$, V-jets
  - “bump-hunt” fit with power law functions directly to data
  - Number of parameters (2-5) determined with Fisher-test







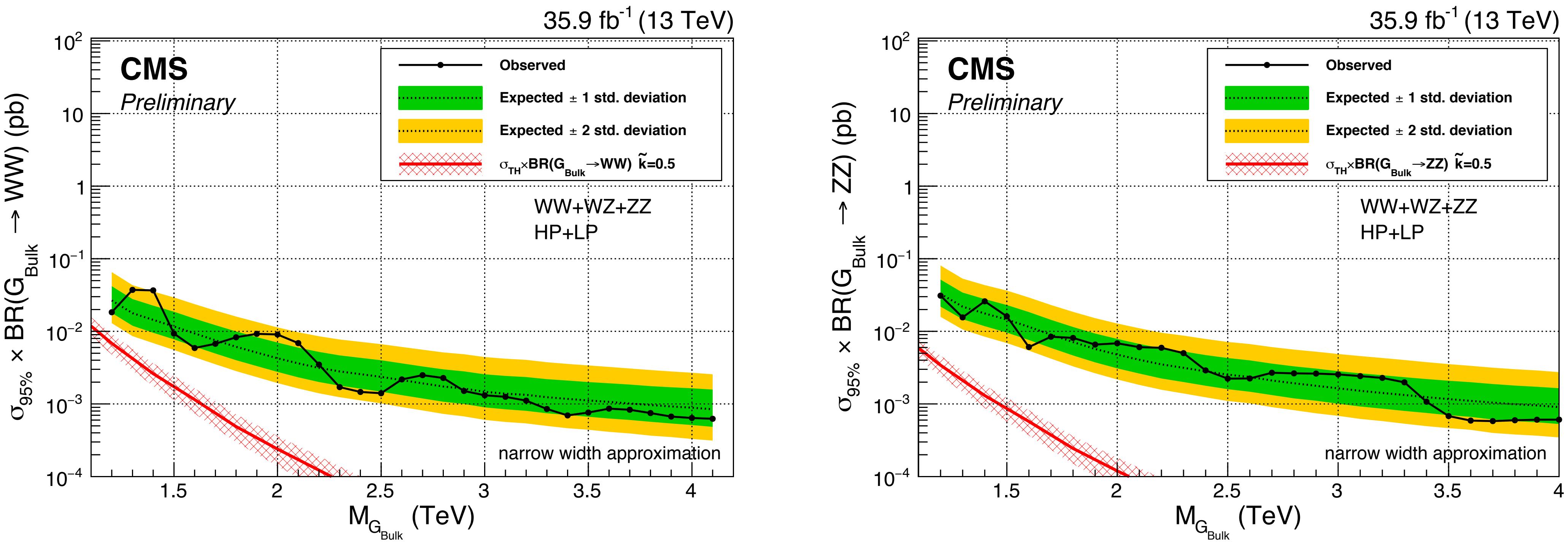


$X \to VV \to q\bar{q}q\bar{q}$

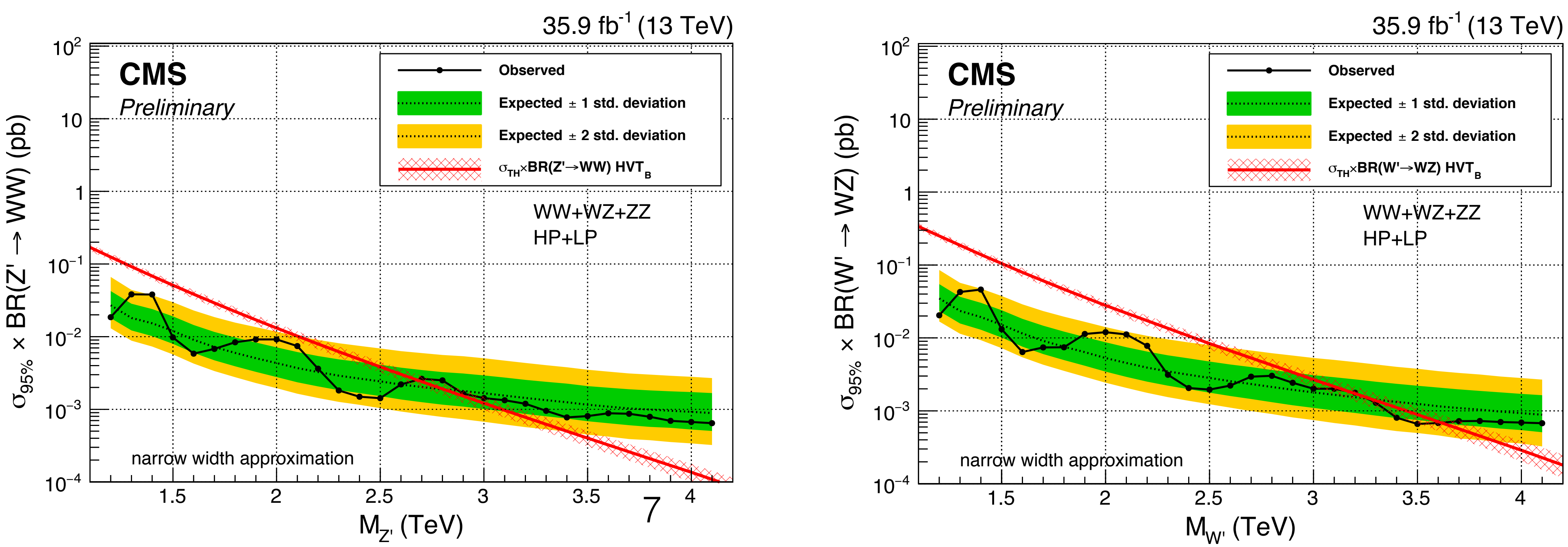
CMS-PAS-B2G-17-001

- No significant excess found in data
- Currently, the most stringent limits on $m_{Z'} < 2.7$ TeV and $m_{W'} < 3.6$ TeV

G_{Bulk}



Z'/W'



$X \to VH \to q\bar{q}b\bar{b}$

CMS-PAS-B2G-17-002

- All-hadronic resonance search for $V \to q\bar{q}$ and $H \to b\bar{b}$
- Similar topology and background estimation to VV resonances search, but dedicated identification for $H \to b\bar{b}$ (b-tagging)
- Same pre-selections as VV, $2\times2\times2 = 8$ categories depending on:

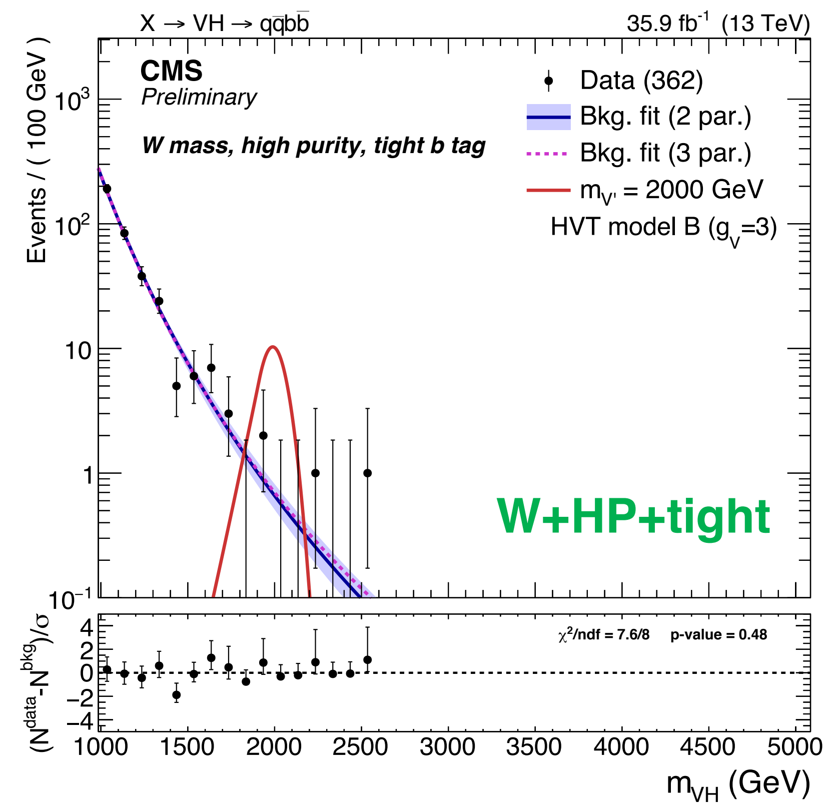
  1. V-jet mass: W ($65 < m_j < 85 GeV$) or Z ($85 < m_j < 105 GeV$)
  2. V-jet τ_{21}: high purity (τ_{21}<0.35), low purity ($0.35 < \tau_{21} < 0.75$)
  3. H-jet b-tagging: tight (Hbb>0.9) and loose (0.3<Hbb<0.9) b-tag

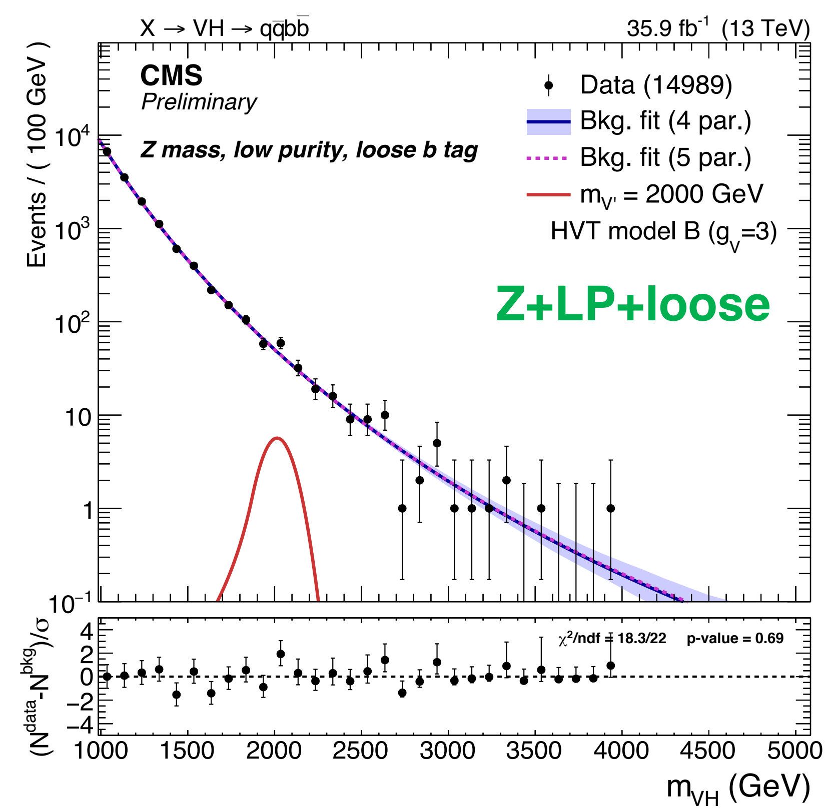
- Background modeling:

  Multijets (dominant), $t\bar{t}$, V-jets

  "bump-hunt" fit with power law functions directly to data

  Number of parameters (2-5) determined with Fisher-test



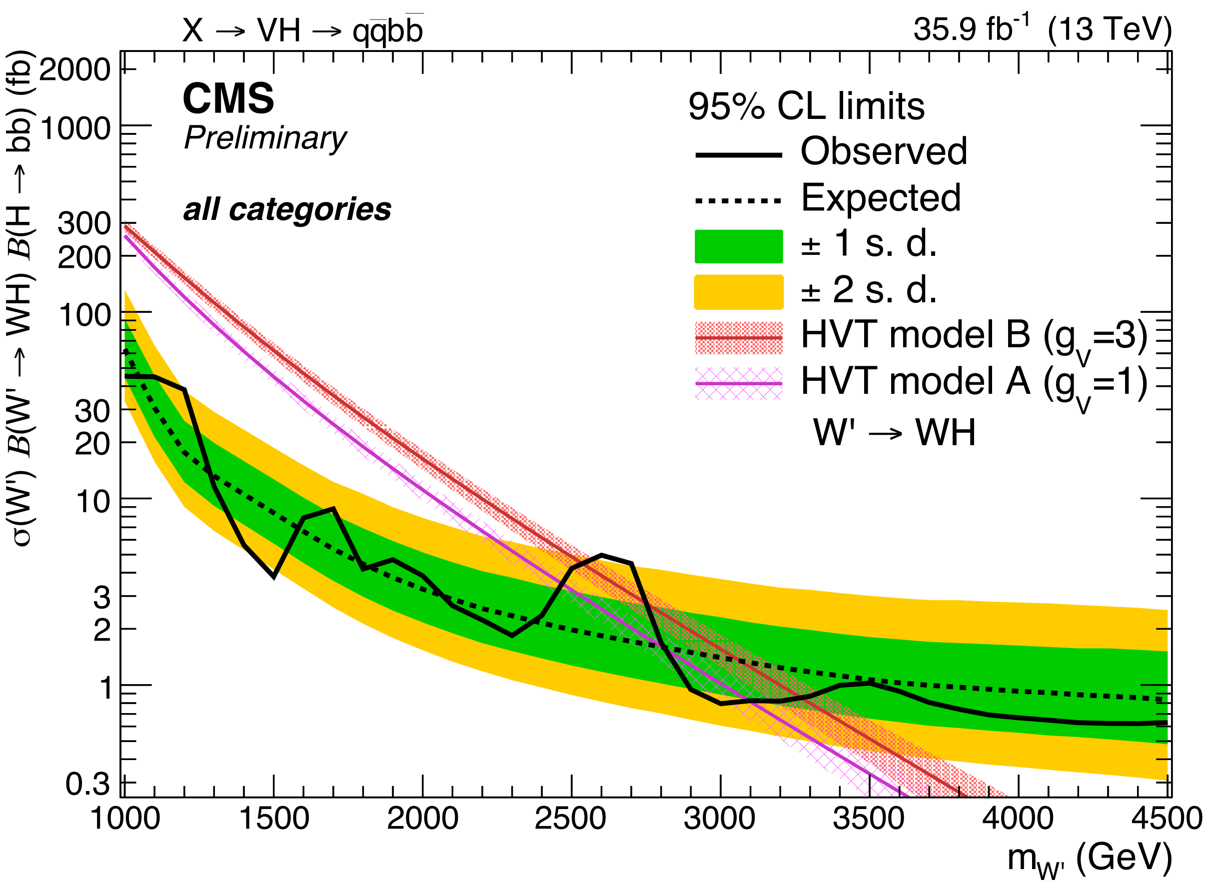


$X \rightarrow VH \rightarrow q\bar{q}b\bar{b}$

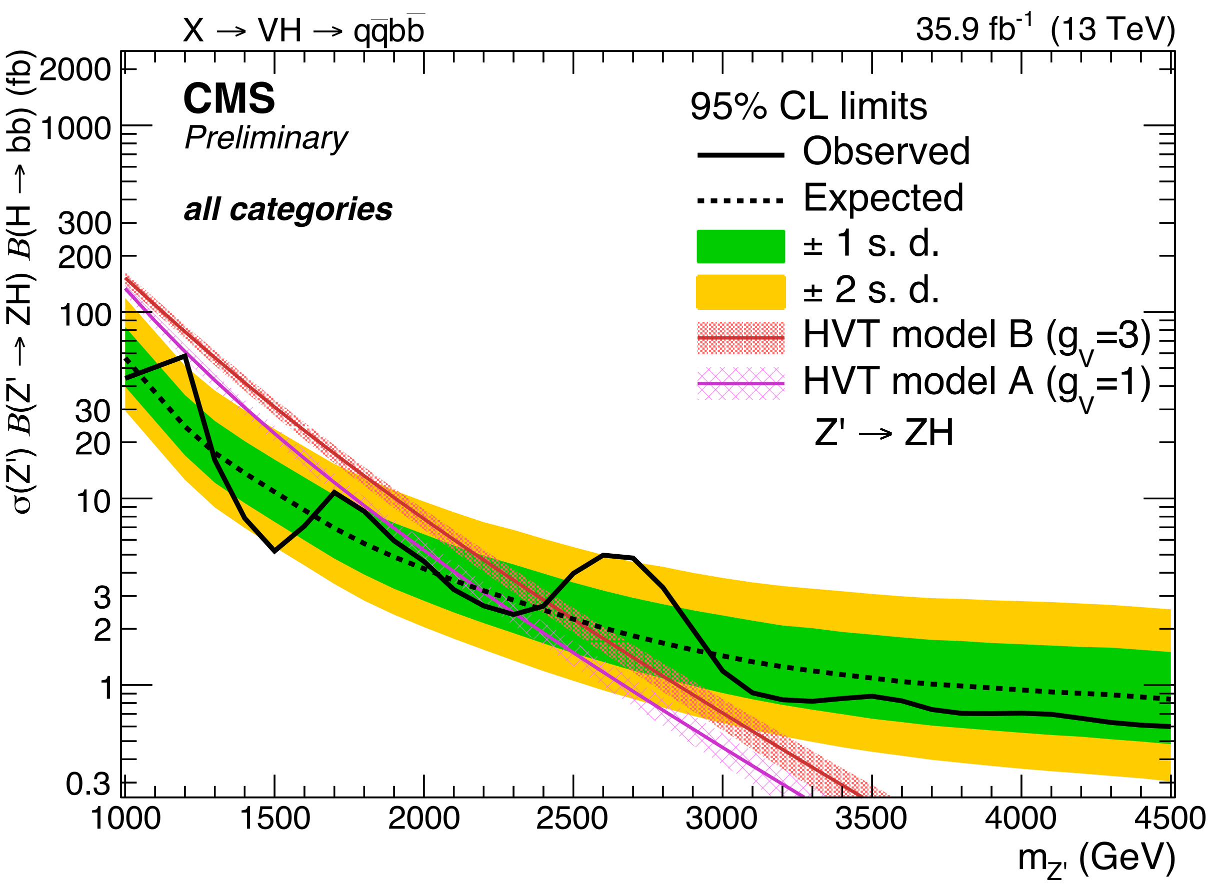
CMS-PAS-B2G-17-002

- No significant excess found in data
- Sensitivity close to VV search ($m_{Z'} < 2.4$ TeV and $m_{W'} < 3.3$ TeV)
- Combined exclusion in triplet hypothesis ($m_{V'} < 3.4$ TeV)

W'



Z'



New result

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

CMS-PAS-B2G-16-026

- All-hadronic resonance search for double $H \to b\bar{b}$
- Preselection:

  0. Tight jet ID with lepton veto, $|\Delta\eta(j_1, j_2)|$< 1.3

  1. V-jet mass: H $(105 < m_j < 135 GeV)$

  2. V-jet τ_{21}: high purity (τ_{21}<0.55)

  3. H-jet b-tagging: tight (Hbb>0.9) and loose (0.3<Hbb<0.9) b-tag ⟹ TT and LL category

- Background modeling:

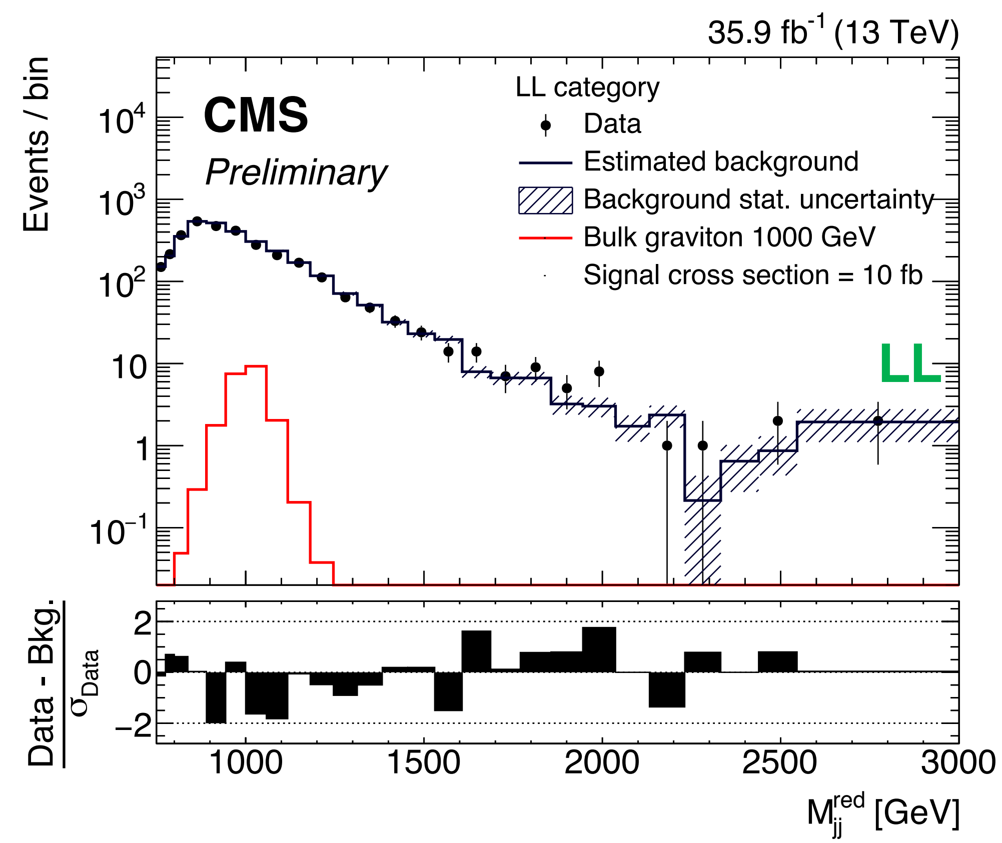
  Almost all background due to QCD multijet production. (Tiny fraction from other sources, but measured inclusively using the data.)

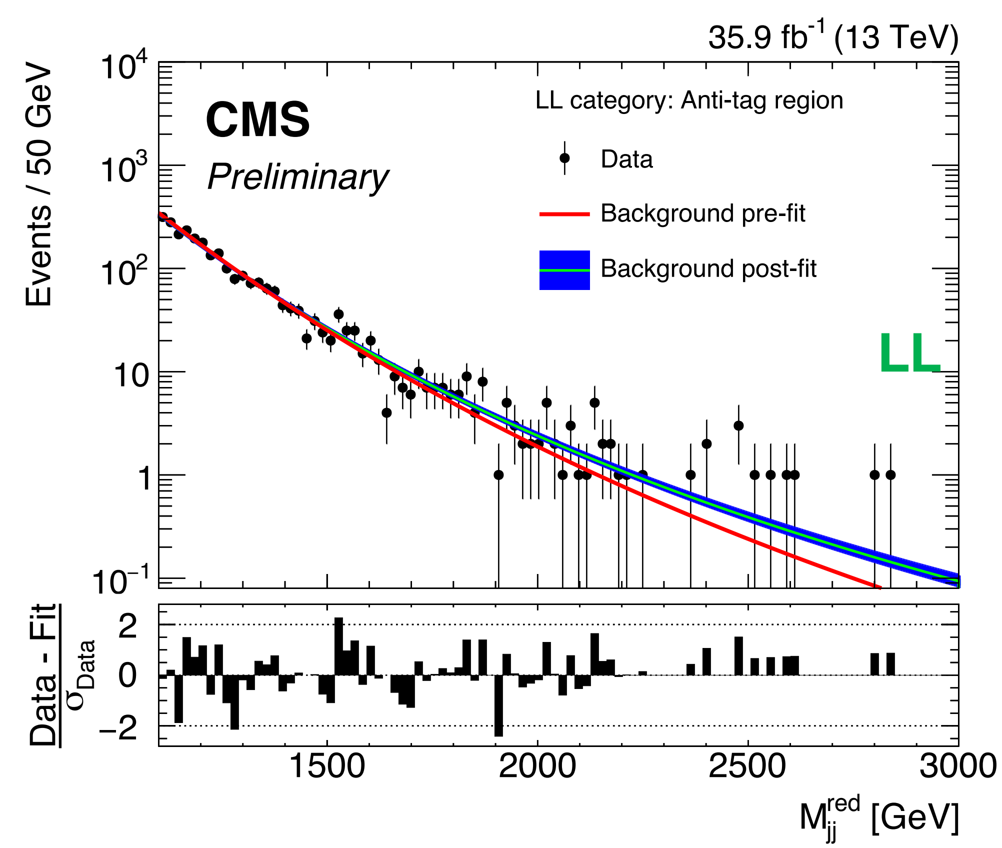
  Low mass: 750 < M(X) < 1200 Ge

  Alphabet method (extended ABCD method).

  High mass: M(X) >= 1200 GeV

  Alphabet-assisted bump hunt: AABH.-- Bump hunt with constraints on the normalization.





New result

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

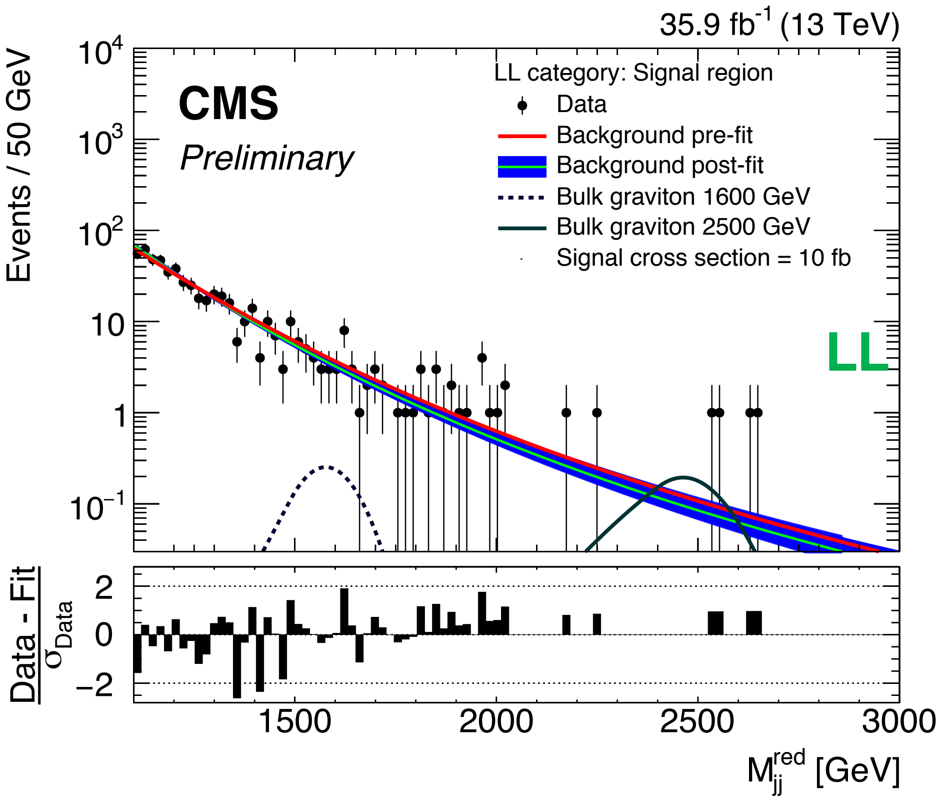
CMS-PAS-B2G-16-026

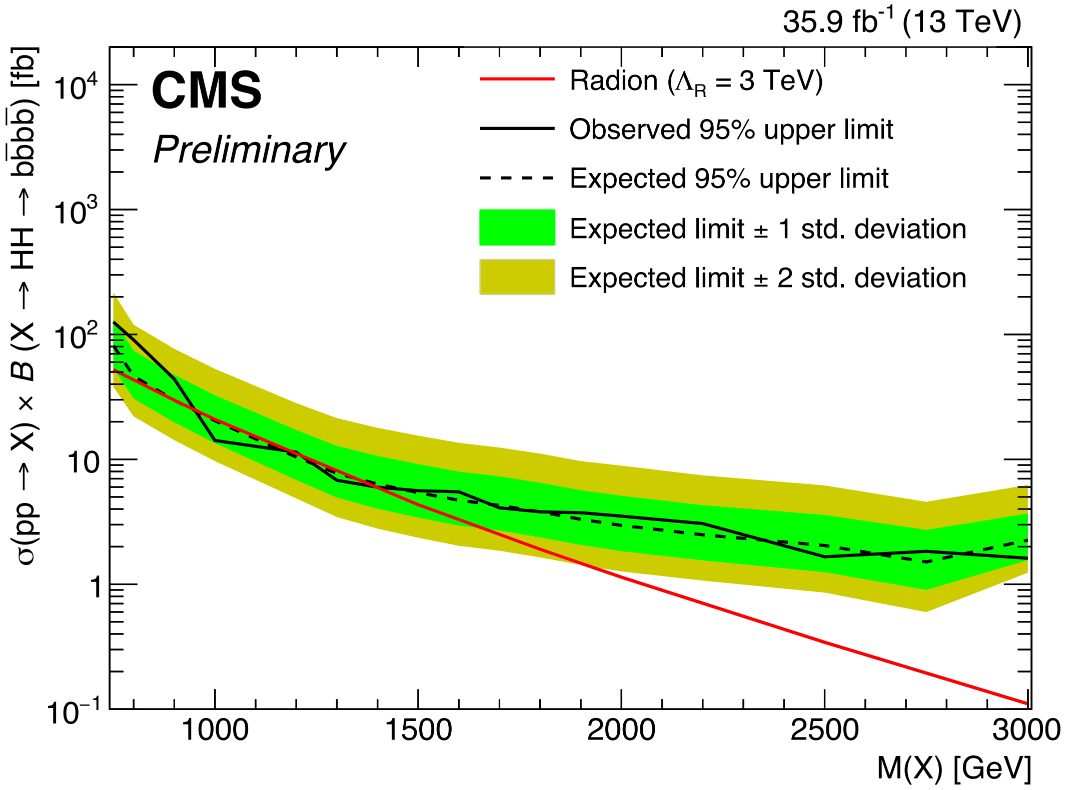
- **Alphabet method:**

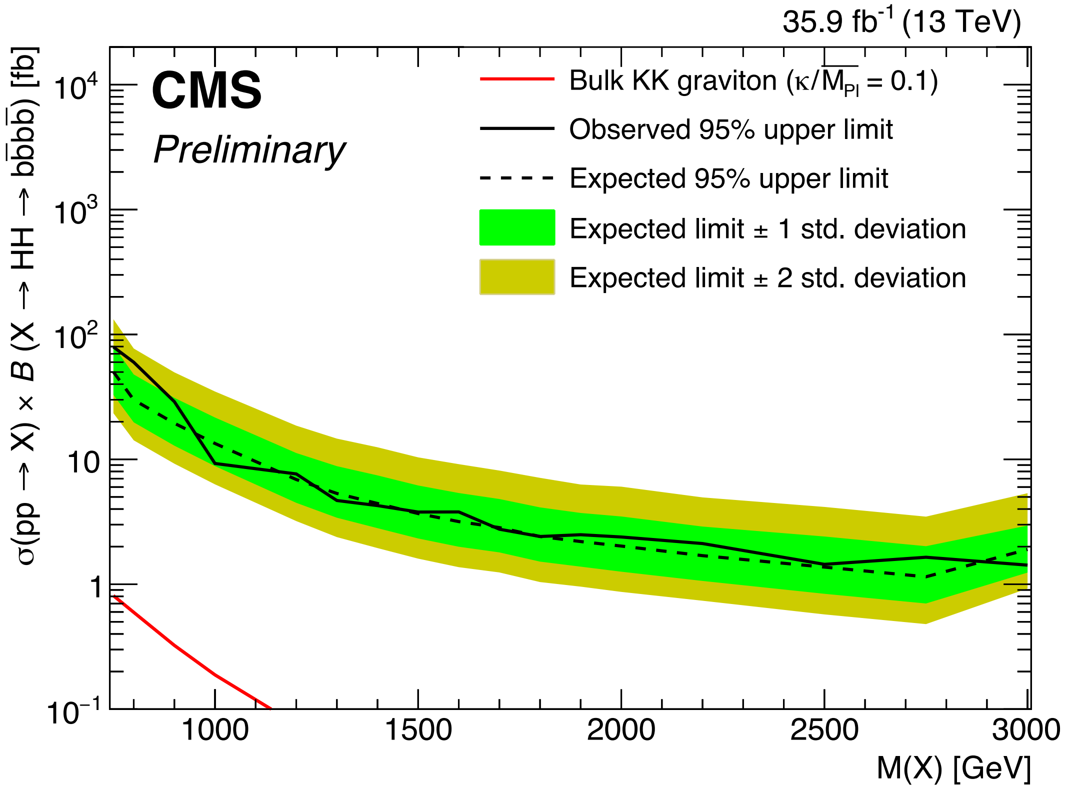
  Predicting background normalization and Mjj red shape based on several sidebands (generalized ABCD method)
- ***Two*** orthogonal variables:

  Jet soft drop mass

  Double b tagger discriminator
- Measure double b pass/ fail ratio ($R_{p/f}$) defined using leading p_T jet in the SD mass sidebands.
- Anti-tag region × $R_{p/f}$ = Background in the signal region







New result

$X \rightarrow ZZ \rightarrow l^- l^+ \nu\bar{\nu}$

CMS-PAS-B2G-16-023

- A highly boosted Z decay to a pair of leptons, High MET from the other Z decay into neutrinos
- Use transverse mass $\mathbf{m_T}$ as the observable to separate signal over background
- data:

  single e/μ data
- Background modeling:

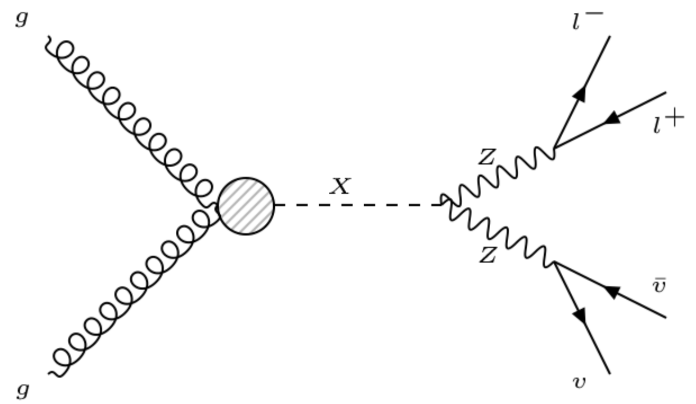
  main: Z+jets: data driven by $\gamma + jets$ data

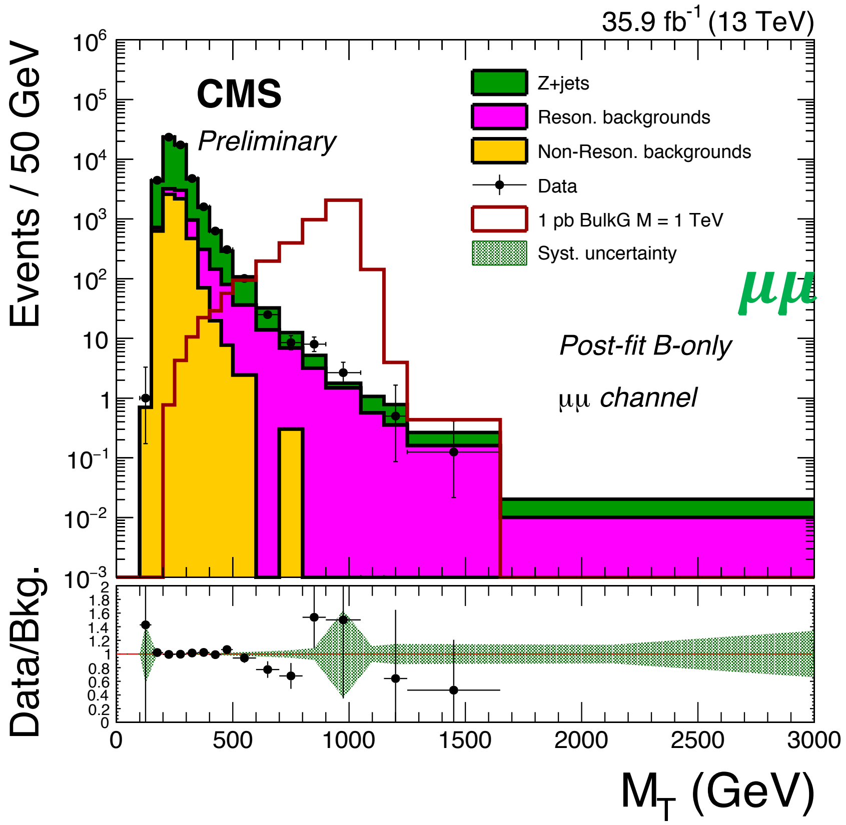
  (Z+jets MC only for validation)

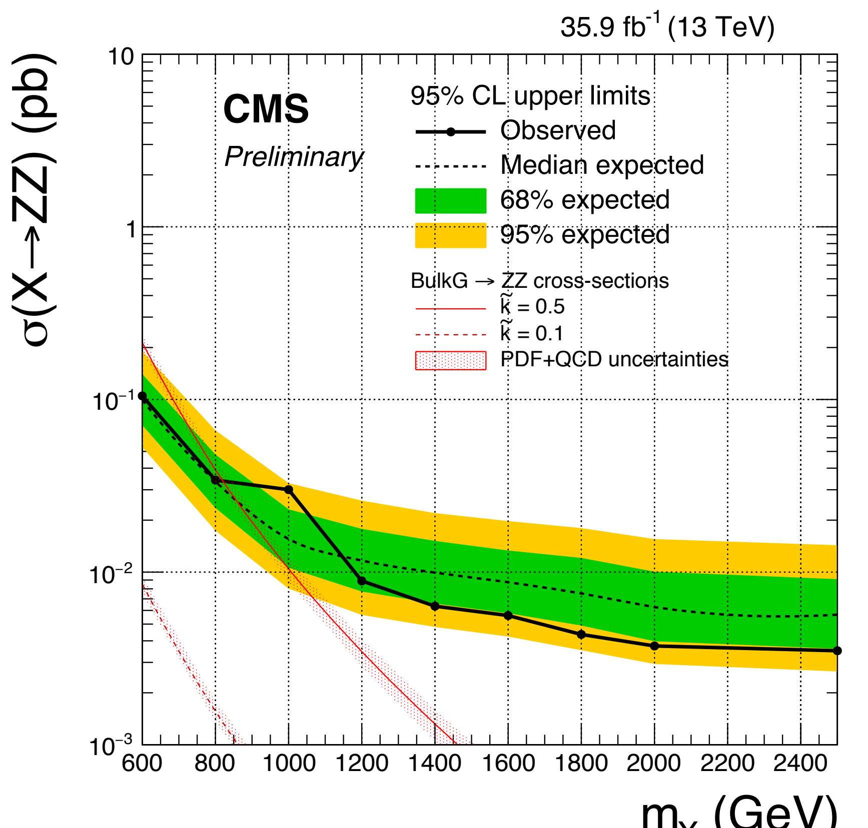
  resonance background: WZ, ttZ (MC)

  non-resonance background: WW, $t\bar{t}$

  data driven by di-lep (eμ) data



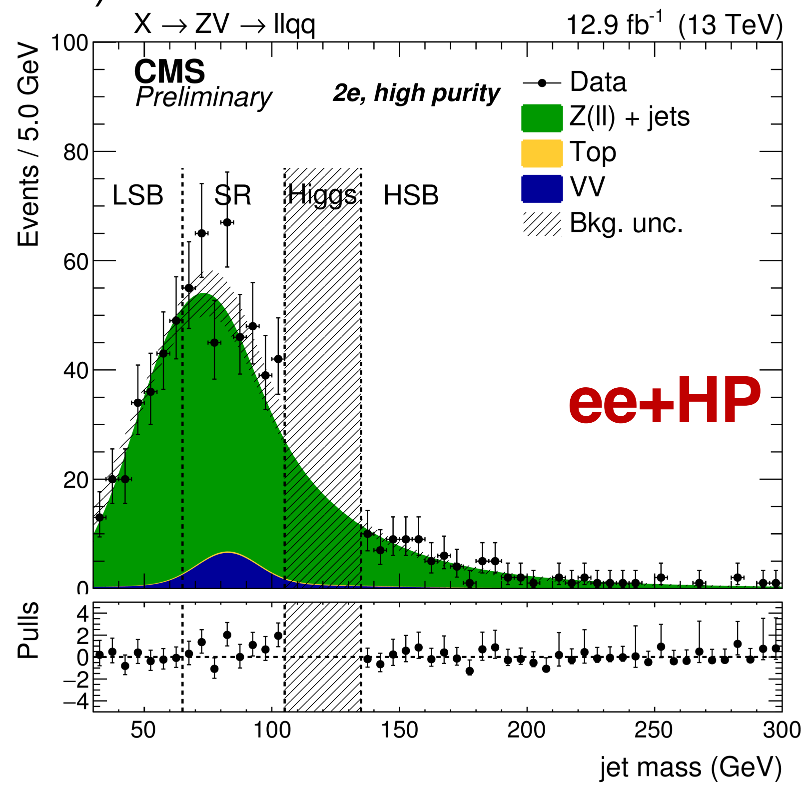




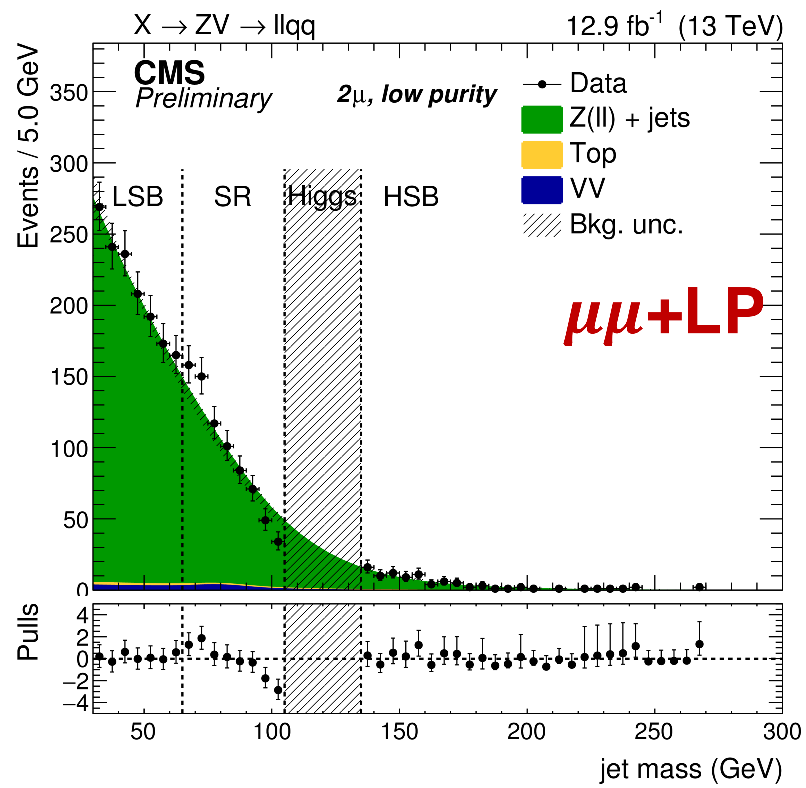
$X \to ZV \to llq\bar{q}$

CMS-PAS-B2G-16-022

- Search for resonances in the $Z \to ee$ or $\mu\mu$, $V \to q\bar{q}$ (either W or Z) channel:
  - ***C****lean final state (leptons)*
  - ***G****ood mass resolution*
  - ***L****arge signal efficiency (~65%)*
  - ***P****enalized by $Z \to ll$ branching fraction*
- Search with ICHEP dataset (12.9fb^{-1})
- Usual τ_{21} categorization (HP, LP)



- ***α-method background estimation***
- ***Normalization***
  1. Use suitable functions to parameterize main bkg (Z+jets)
  2. Fit them to data in the m_j sidebands (LSB & HSB)
  3. Take shape of second bkg (VV, $t\bar{t}$) from simulation



$X \to ZV \to ll q\bar{q}$

CMS-PAS-B2G-16-022

- ***α-method background estimation***
- ***Shape***

  1. transfer function: $\alpha^{MC} = \frac{F_{WW}(SR)^{MC}}{F_{WW}(SB)^{MC}}$

  2. Fit data $N_{SB}^{data}(m_X)$ in sideband

  3. background expectation in SR

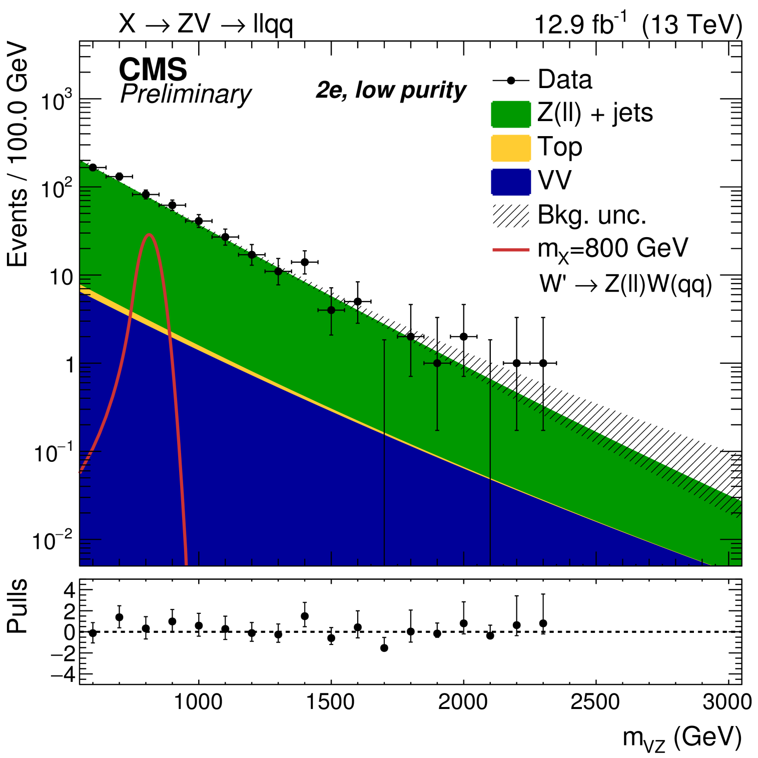
  $$F_{WW}(SR)^{Data} = F_{WW}(SB)^{Data} \times \alpha^{MC}$$

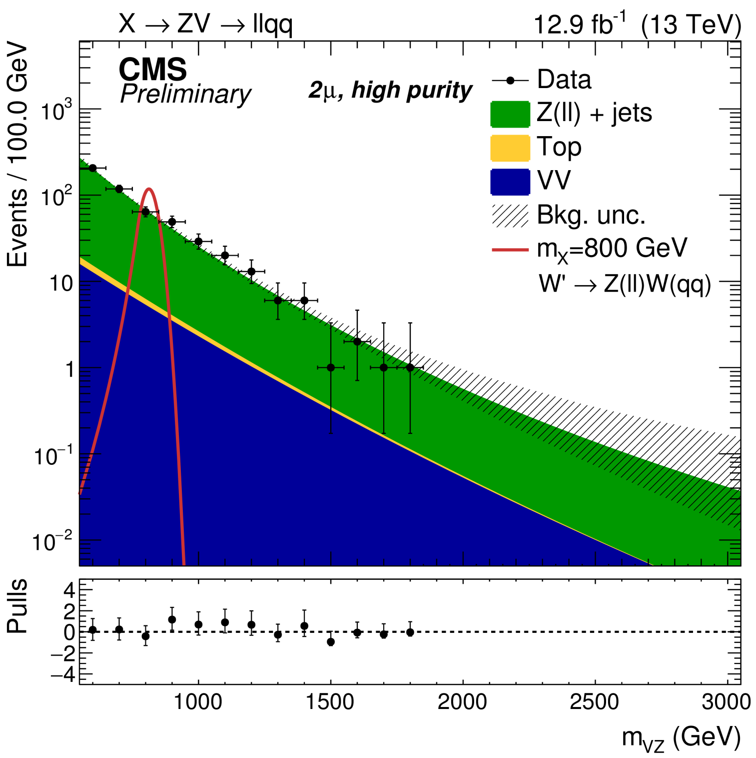
- Data compatible with the SM-only hypothesis
- Exclusion limits at 95% CL of the spin-1 W' singlet

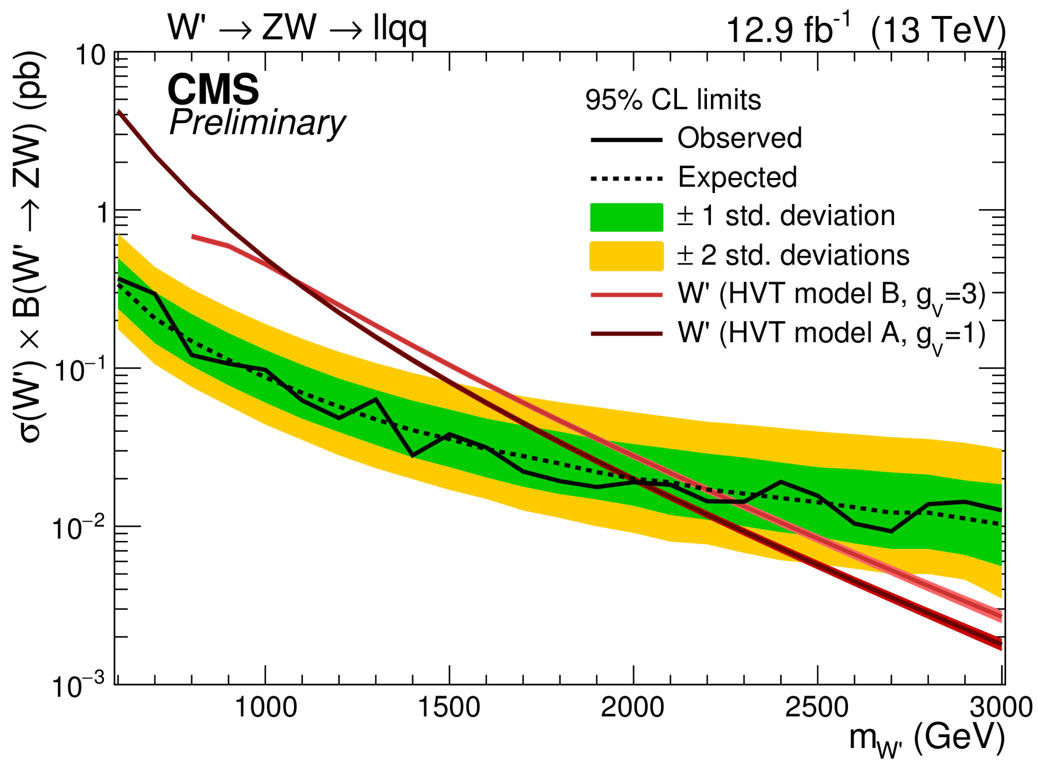
  HVT model A: $m_{W'} \lesssim 2.0$ TeV

  HVT model B: $m_{W'} \lesssim 2.3$ TeV

- Significant improvement w.r.t. 2015 search



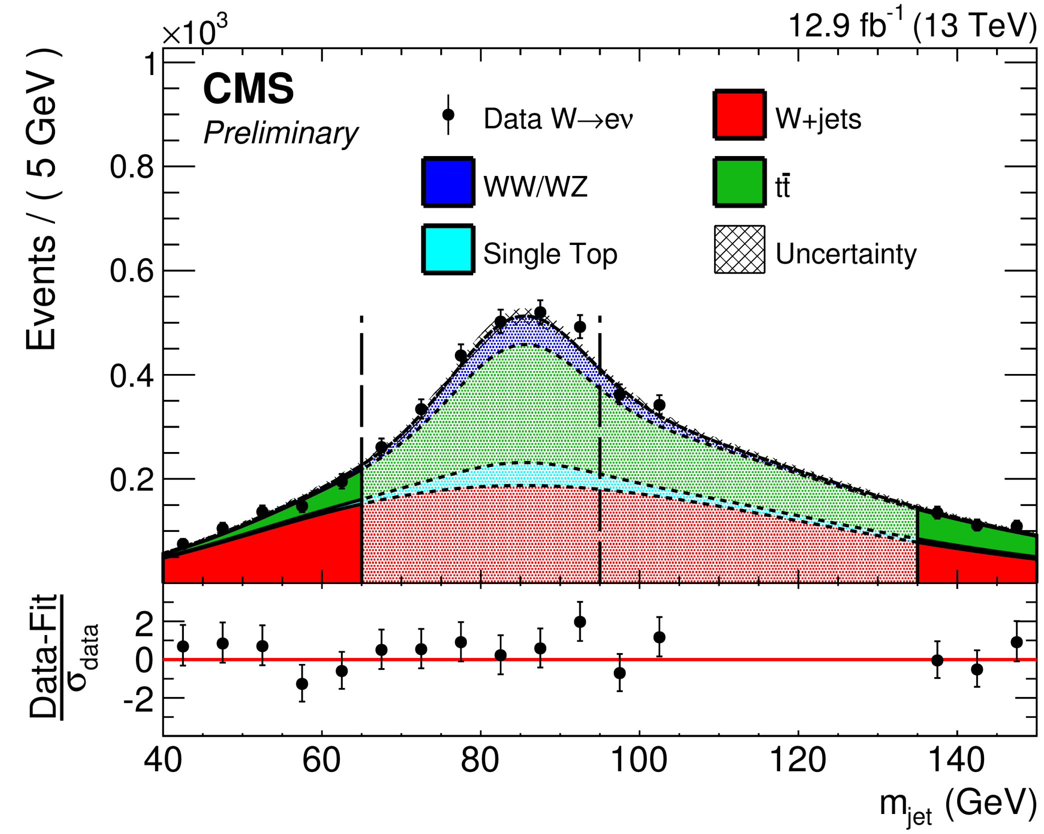


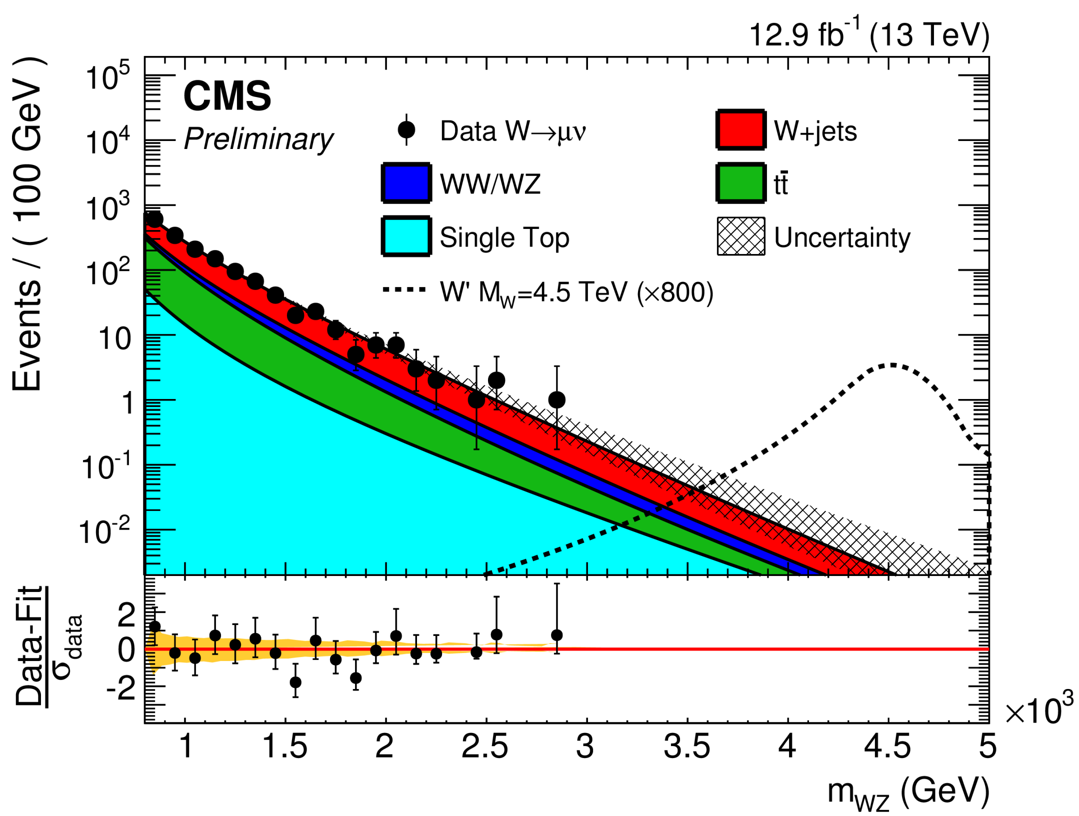


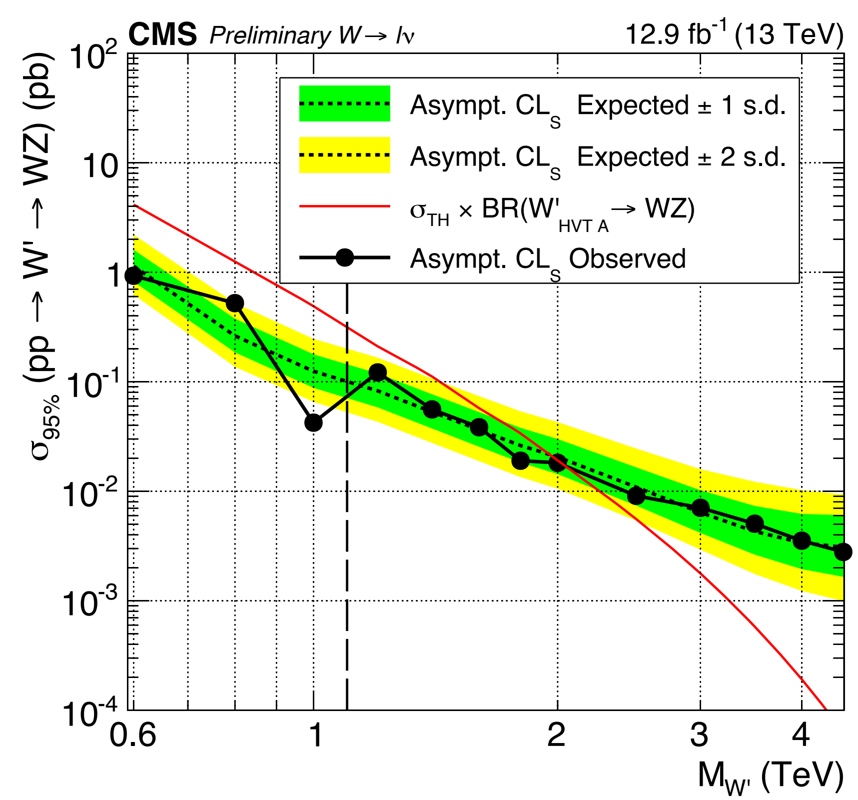
$X \to WV \to lvq\bar{q}$

CMS-PAS-B2G-16-020

- Search for a resonance decaying to WV in the leptonic channel ($W \to lv$, $V \to q\bar{q}$)
- ICHEP dataset (12.9 fb^{-1})
- Categorization in τ_{21} and W/Z mass
- Low mass extension down to 600 GeV
- Kinematic reconstruction of p_z^{ν} from m_W
- α-method for background prediction
- Sensitivity similar to $ZV \to llq\bar{q}$: HVT model A W' excluded up to 2.0 TeV



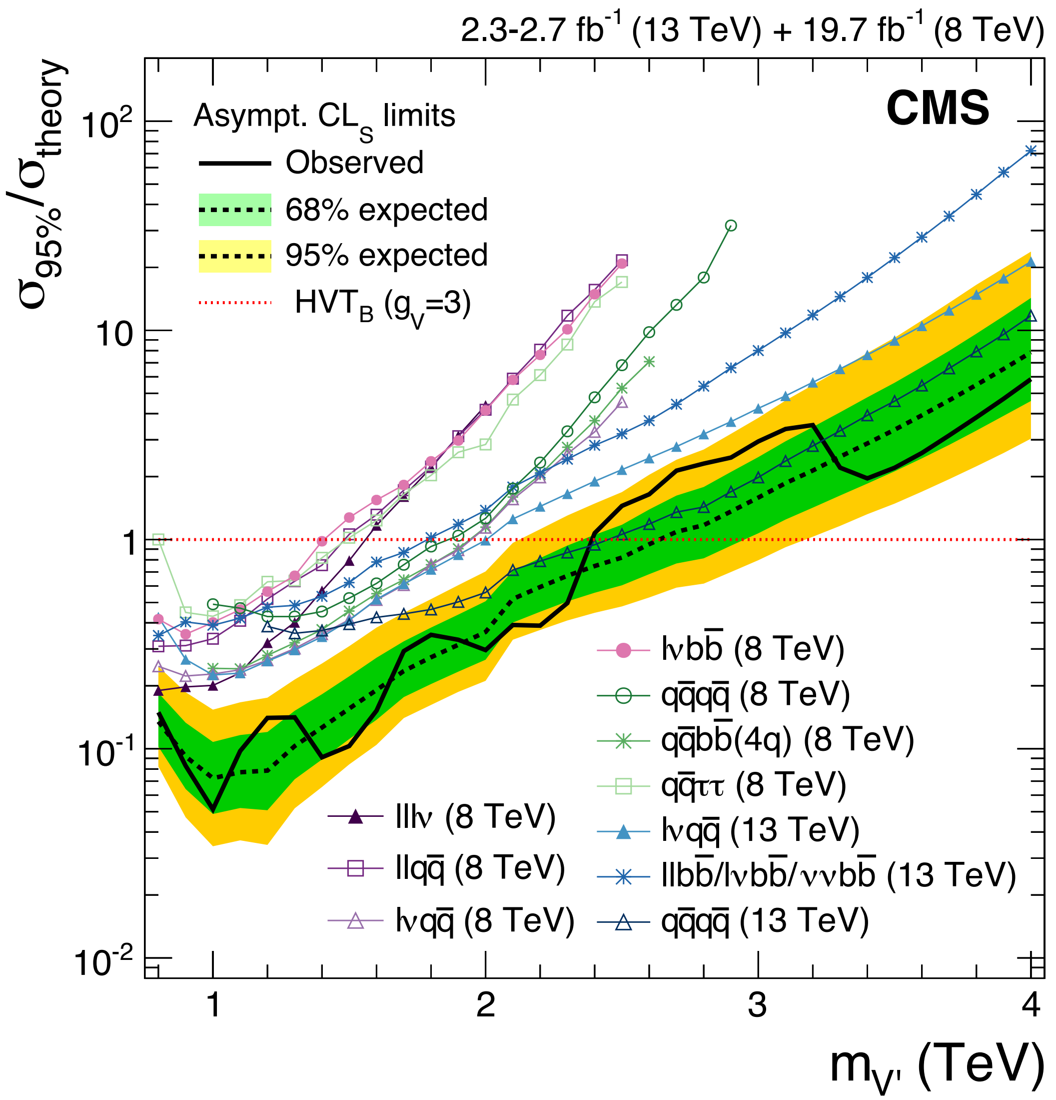


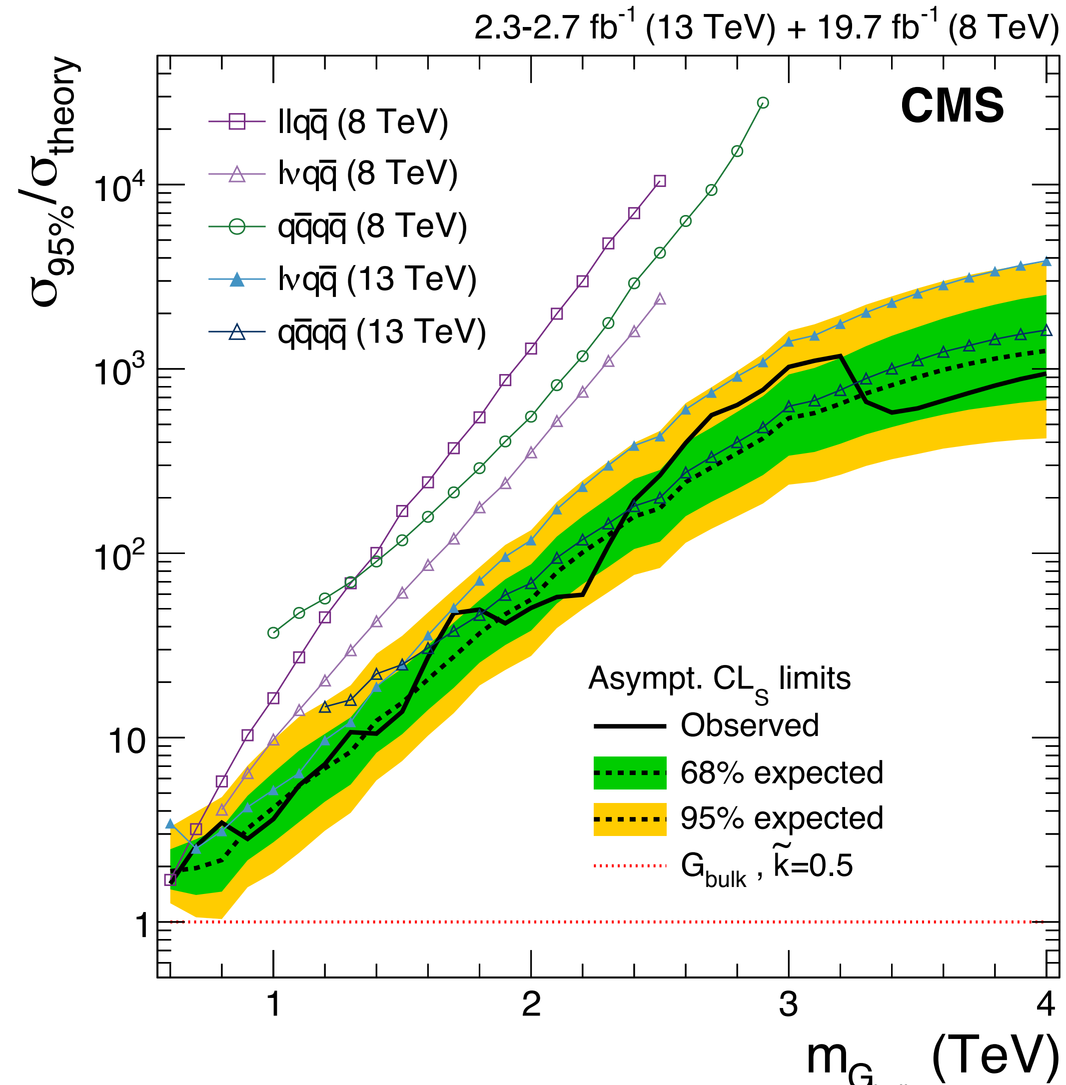


Combination

CMS-PAS-B2G-16-007

- Combination between 13 TeV (2015 data only) and 8 TeV searches **[WW, WZ, ZZ, WH, & ZH]**
- Favored by orthogonally between analyses and common techniques
- Excluding W' & Z' with masses up to about 2.4 TeV in HVT model B (g_V = 3).
- Not sensitive enough to exclude Bulk Graviton
- 2016 searches already more sensitive than combination



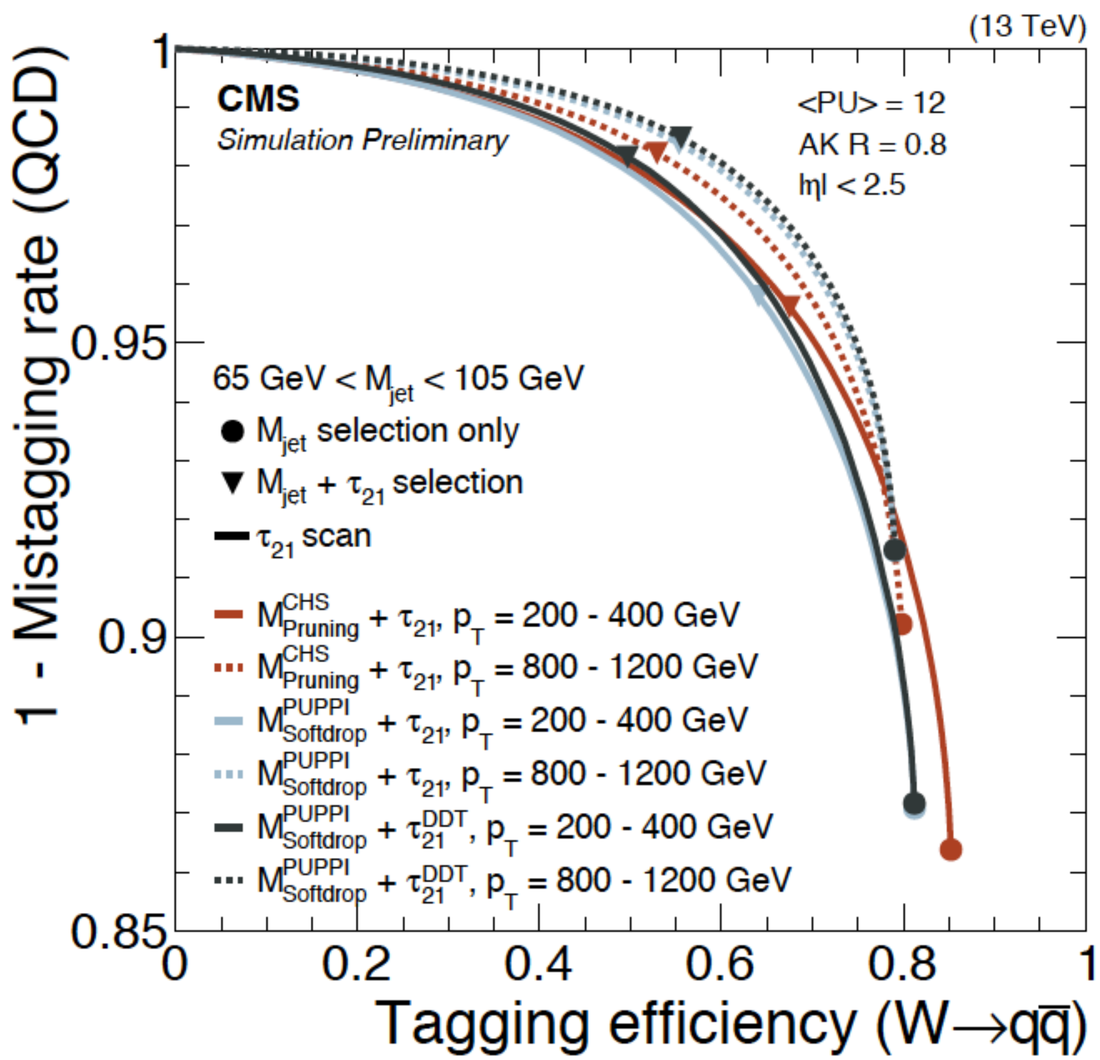


Conclusions

- Searching for heavy resonances is one of the most direct ways to find new physics at TeV scale
- Significant develepment in boosted object techniques
- Rich phenomenology & final states VV, VH, HH: clear experimental signatures and allows cross check among different channels
- No significant excess observed in data
- Only recent 13 TeV results are shown here today - many new results to arrive in the coming months.
- Exciting diboson results in preparation with the 2016-17 LHC data !!

- **Backup**

ROC curve



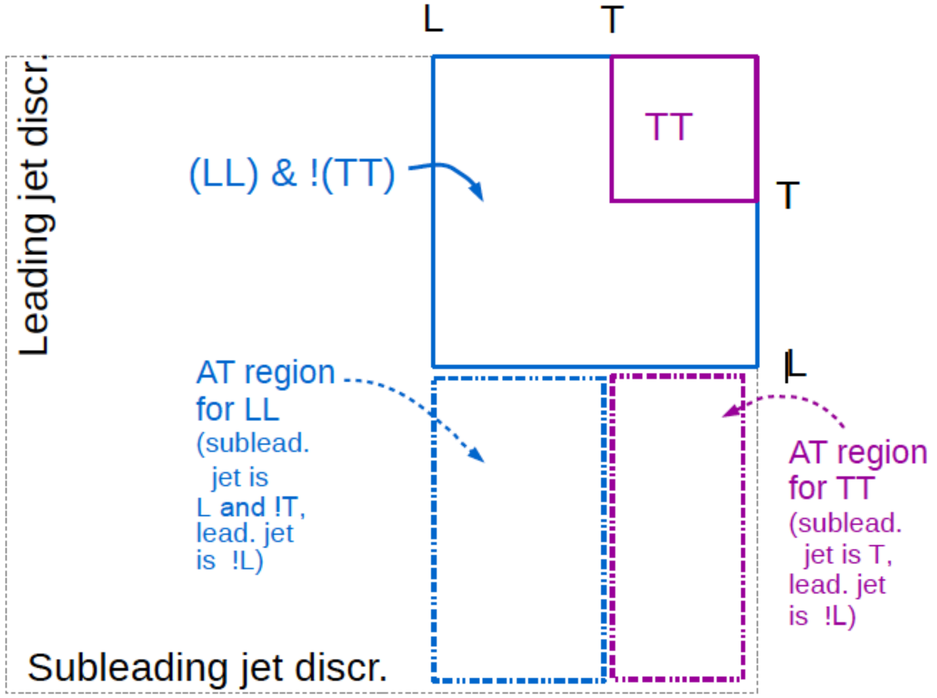
CMS-PAS-JME-16-003

Figure 16: Performance of several discriminants in the background-signal efficiency plane. The baseline selection for W tagging requiring a PF+CHS pruned or PF+PUPPI softdrop jet mass of $65 < m_{\text{jet}} < 105$ GeV, and N-subjettiness ratio (PF+CHS inputs) of $\tau_2/\tau_1 < 0.45$ or N-subjettiness ratio (PF+PUPPI inputs) of $\tau_2/\tau_1 < 0.4$ or $\tau_{21}^{\text{DDT}} < 0.52$ are indicated with symbols.

Alphabet

- Categories in double b values of leading and subleading jets:
  - Loose: > 0.3
  - Tight: > 0.8
- Both passing tight: TT
- Both passing loose but not in the TT category: LL
- Anti-tag regions defined by inverting double b requirement of the leading jet:

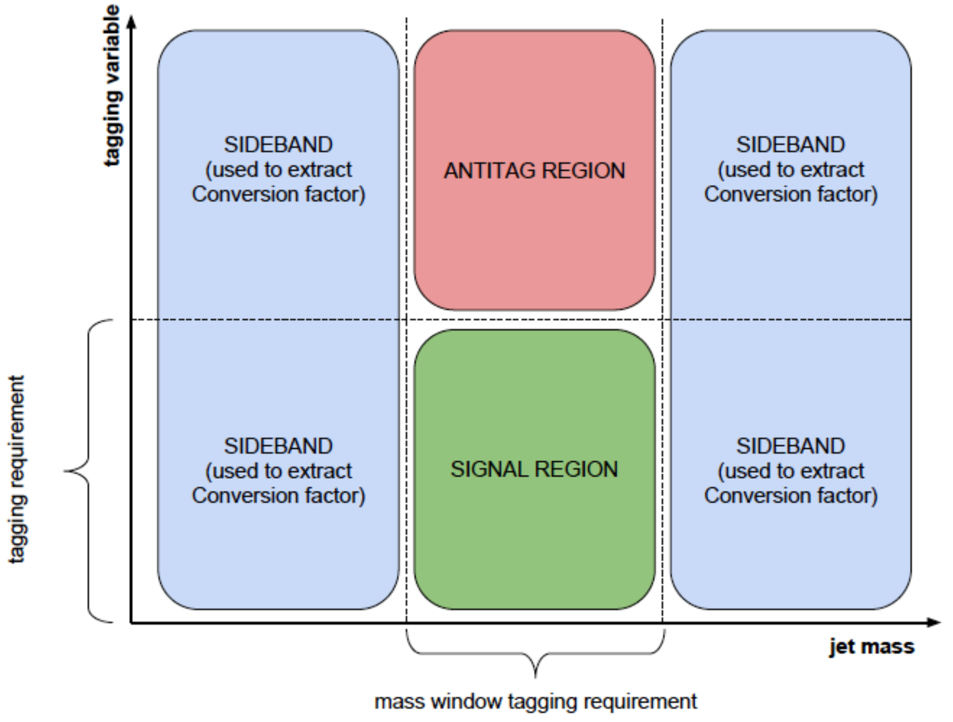
Cat.	Signal region	Control region
TT	Double b (j1) > 0.8 Double b (j2) > 0.8	Double b (j1) < 0.3 Double b (j2) > 0.8
LL	Double b (j1) > 0.3 Double b (j2) > 0.3 and not TT	Double b (j1) < 0.3 0.3 < Double b (j2) < 0.8



- All four regions fully statistically uncorrelated.

Alphabet

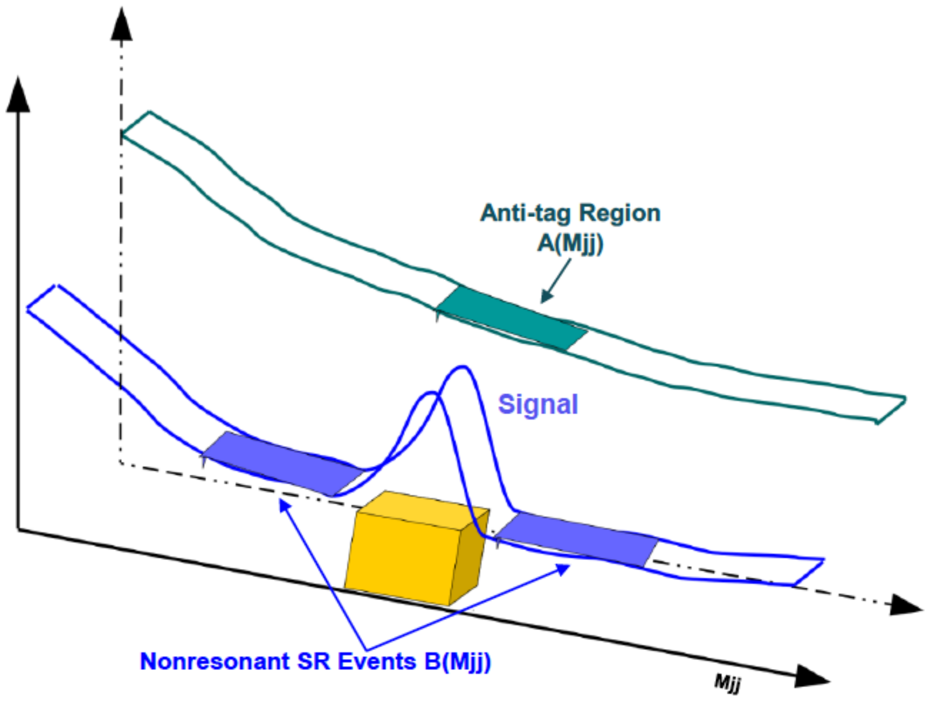
- Alphabet method:
  - Predicting background normalization and M_{jj}^{red} shape based on several **sidebands** (generalized *ABCD* method)
- Two orthogonal variables:
  - Jet soft drop mass
  - Double b tagger discriminator



- Measure double b pass/ fail ratio ($R_{p/f}$) defined using leading p_T jet in the SD mass sidebands.
- Anti-tag region × $R_{p/f}$ = Background in the signal region

AABH

- A step beyond the classic bump hunt.
- Constraint on background normalization in the signal region
  - From the Alphabet method we see that the background shape in the anti-tag and signal regions are similar.
  - Simultaneous fit of signal+background to the data using parametric functions
  - Normalization using anti-tag region and $R_{p/f}$
  - $R_{p/f}$ constrained with log-normal priors.
- Better constraint on background systematics.
- The fit can extend farther in M_{jj}^{red} since there are more events in the anti-tag region to predict the tails



- The AABH, like a bump hunt works only when the trigger is 100% efficient.
- Used for searches for M(X) > 1200 GeV