Searches for heavy resonances decaying into W, Z, and Higgs bosons with the CMS detector

Simon Regnard
on behalf of the CMS Collaboration

University of California, Los Angeles

XXXIX International Conference on High Energy Physics

6 July 2018 — Seoul, Republic of Korea

Why search for diboson resonances?

- Outstanding enigma of particle physics: the **hierarchy problem**, i.e. the large difference between the scale of EWSB and the Planck scale.
- Addressed by many BSM models that suggest **new particles** at or just above the electroweak scale.
  - E.g. SUSY, composite Higgs bosons, warped extra spatial dimensions (WED).
- 2 classes of models that predict **new resonances decaying to W, Z, and H bosons** are widely probed by experimentalists:

Randall-Sundrum WED

- Heavy particles as Kaluza-Klein excitations of spin-0 radions and spin-2 gravitons.
- Focus on the bulk graviton model, 2 free parameters: $m(G_{Bulk})$ and $\tilde{k} = k/(M_{Pl}/\sqrt{8\pi})$, set to 0.5.

Heavy Vector Triplet (HVT)

- Triplet of heavy spin-1 bosons: one neutral (Z′), two electrically charged (W′±).
- 3 coupling parameters g_V, c_H, c_F.
- Model A = decay mostly to fermions, Model B = nearly 100% decay to SM bosons.

CMS search programme

Rich phenomenology of diboson decays to quarks and leptons,
with most accessible channels covered by dedicated CMS analyses:

	$W/Z \to q\bar{q}$	$W \to l\nu$	$Z \to ll$	$Z \to \nu\nu$	$H \to b\bar{b}$
$W/Z \to q\bar{q}$	Phys. Rev. D 97 (2018) 072006				
$W \to l\nu$	JHEP 05 (2018) 088				
$Z \to ll$	CMS-B2G-17-013 (submitted to JHEP) JHEP 06 (2018) 127		JHEP 06 (2018) 127		
$Z \to \nu\nu$	CMS-B2G-17-005 (submitted to JHEP)		JHEP 03 (2018) 003 JHEP 06 (2018) 127		
$H \to b\bar{b}$	Eur. Phys. J. C 77 (2017) 636	CMS-PAS-B2G-17-004	CMS-PAS-B2G-17-004	CMS-PAS-B2G-17-004	Phys. Lett. B 781 (2018) 244 CMS-PAS-B2G-17-019
$H \to \tau\tau$	CMS-PAS-B2G-17-006				CMS-PAS-B2G-17-006

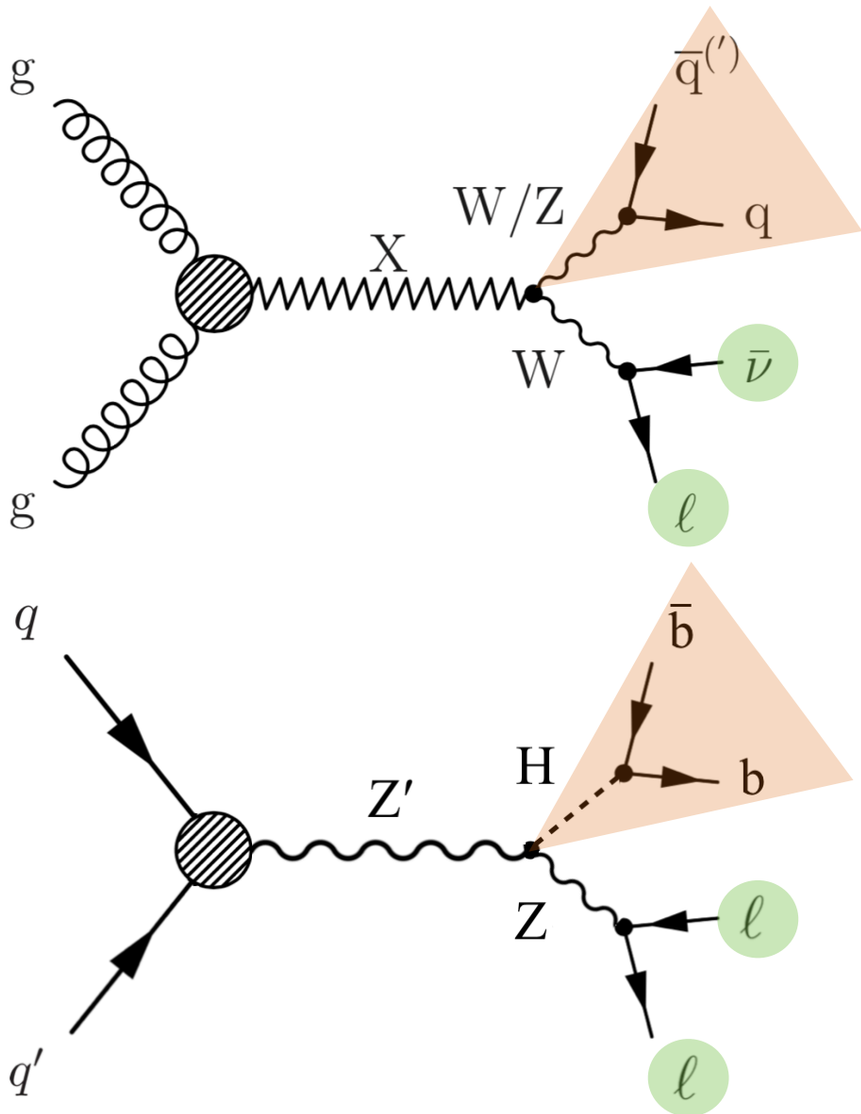
In this presentation:

- Focus on **boosted VV and VH topologies,** exploring resonance masses > 0.5 TeV, mostly > 1 TeV.
  (**HH searches** will be presented by Devdatta Majumder today at 15:00.)
- Results based on **35.9 fb^{-1}** of pp collision data ($\sqrt{s}$ = 13 TeV) collected in **2016** with the CMS detector.

Reconstructing boosted bosons

Very energetic W/Z/H bosons have **collimated decay products**

➔ Use dedicated reconstruction techniques.



Decays to quark pairs:

- Reconstruction of W/Z/H as one single **large-radius jet** (R=0.8),
- **Grooming** and **substructure** techniques,
- Dedicated **b tagging** for $H \to b\bar{b}$ decays.

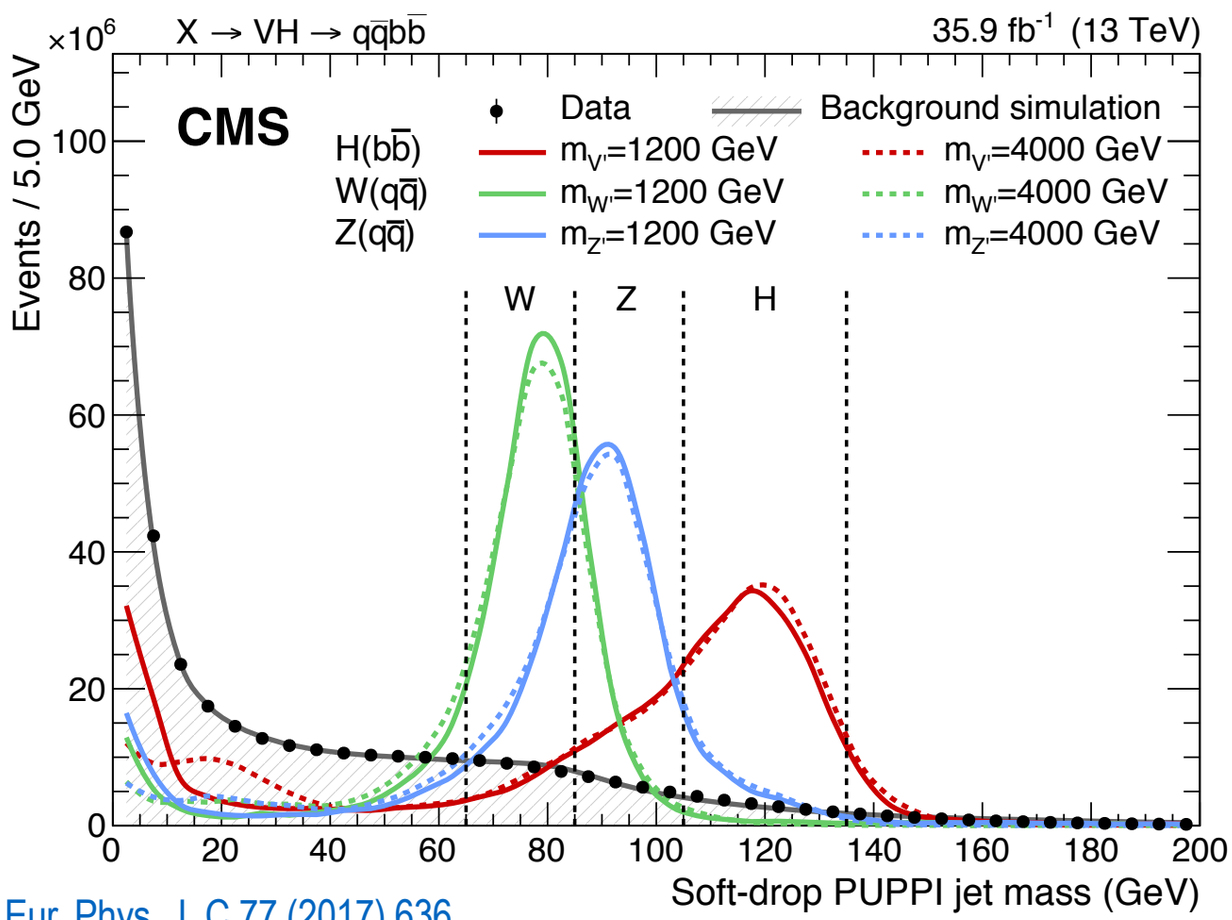
Decays to lepton pairs:

- Undetected **neutrinos**: large missing transverse momentum p_T^{miss},
- High-p_T **e/μ**: special reconstruction and isolation algorithms.

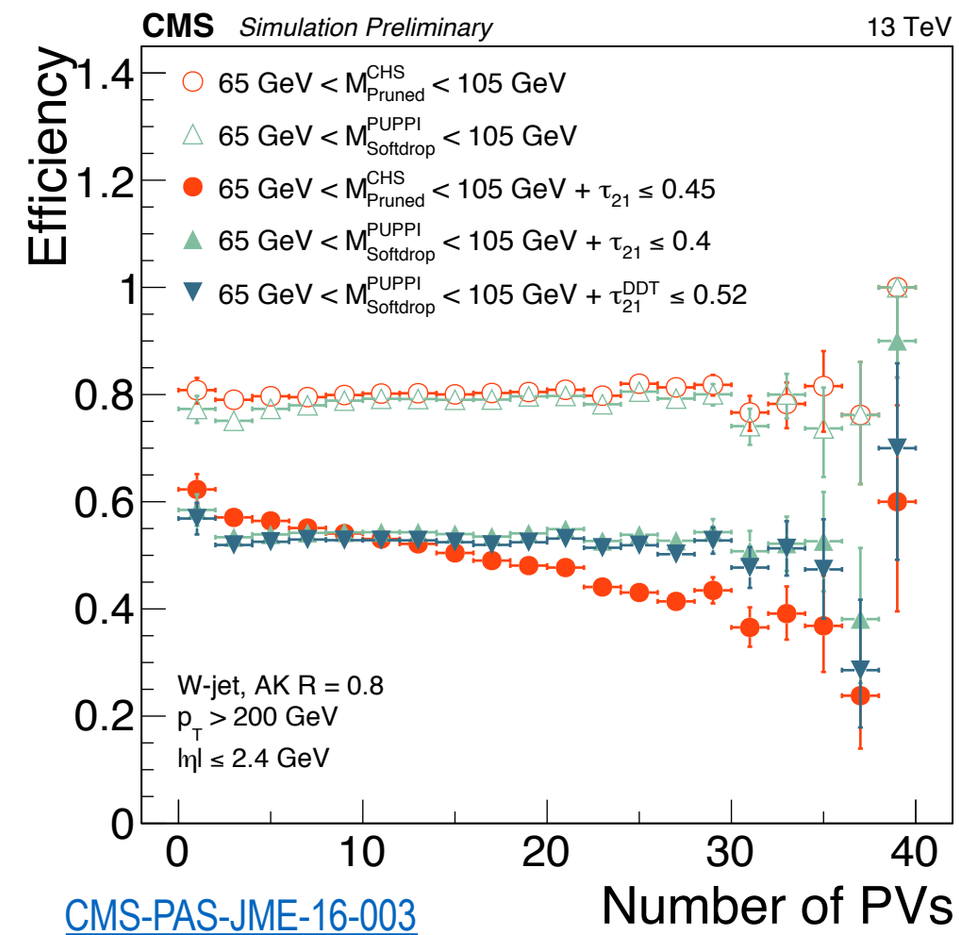
➔ Analysis strategies then rely on a **bump hunt** in the diboson invariant mass (or transverse mass) spectrum.

Jet substructure: grooming

- Pileup subtraction based on **PileUp Per Particle Identification (PUPPI)**:
  - Rescale particle momenta according to compatibility with primary vertex.
  - Re-cluster the jet with modified constituents.
- Removal of soft and large-angle radiation via the **soft-drop algorithm**:
  - Infrared and collinear safe.
  - Soft-drop jet mass (with dedicated corrections) used in V/H jet tagging, in definitions of sidebands, or as 2nd dimension in fits.



Eur. Phys. J. C 77 (2017) 636



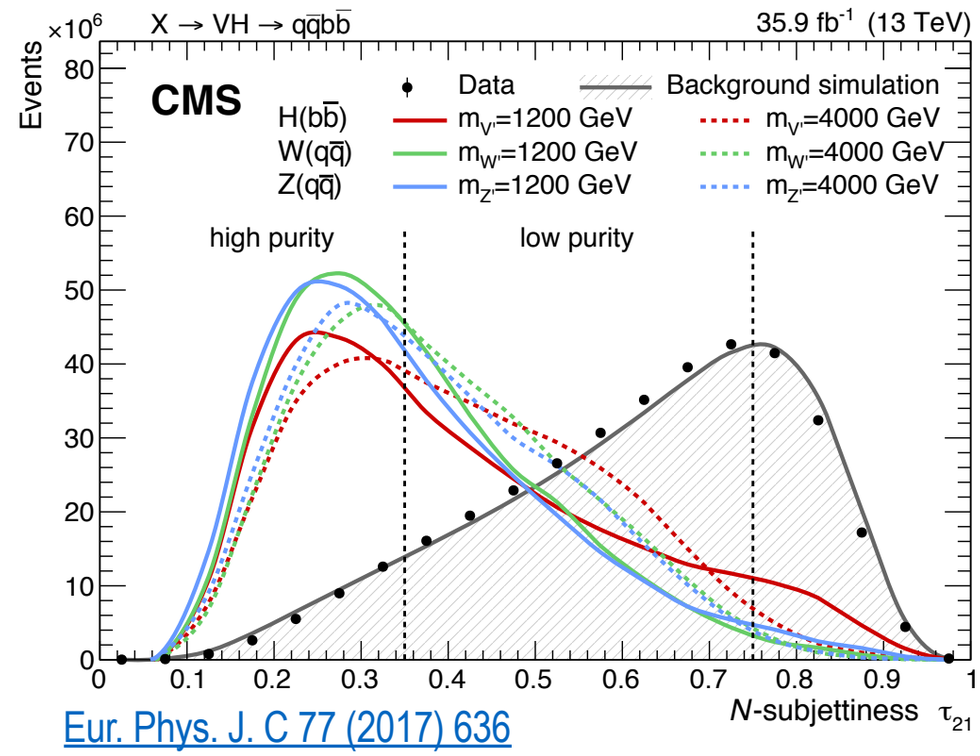
CMS-PAS-JME-16-003

Jet substructure: N-subjettiness

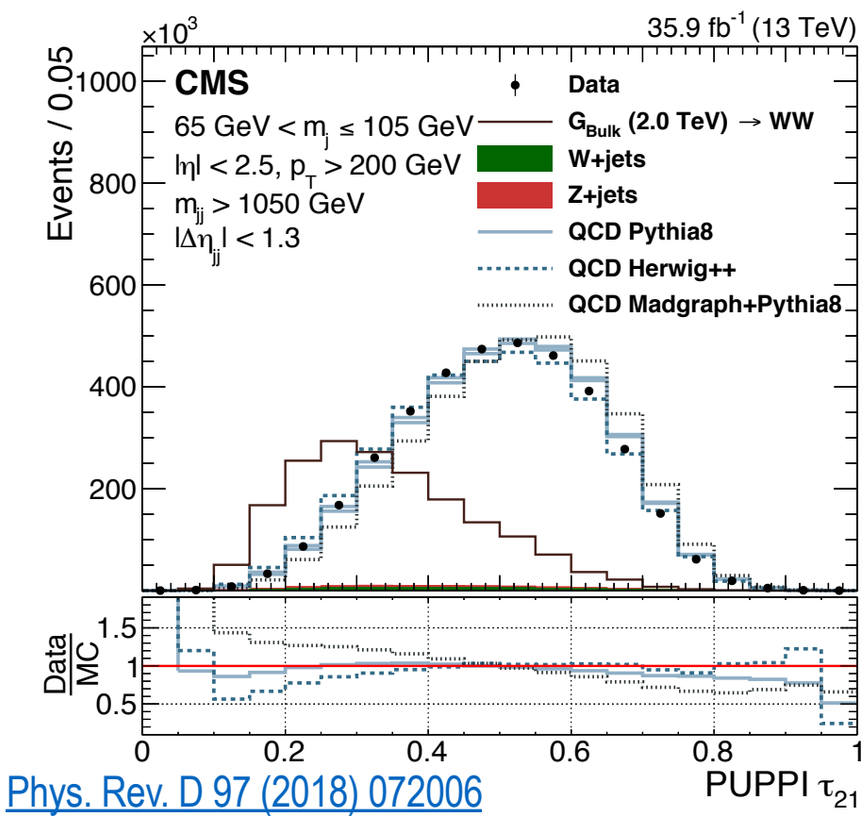
- Quantifies to what extent energy flow is aligned with N directions:

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

- Consistent use of the ratio $\tau_{21} = \tau_2/\tau_1$ in all analyses.
  - Lower values for 2-prong W/Z→qq than for quark- or gluon-initiated jets.
  - Key variable, carefully validated in data.
- Used to define event categories:
  - Split into high/low purity (HP/LP), τ_{21} thresholds depend on analysis.
  - LP categories recover signal efficiency at very high mass.



Eur. Phys. J. C 77 (2017) 636



Phys. Rev. D 97 (2018) 072006

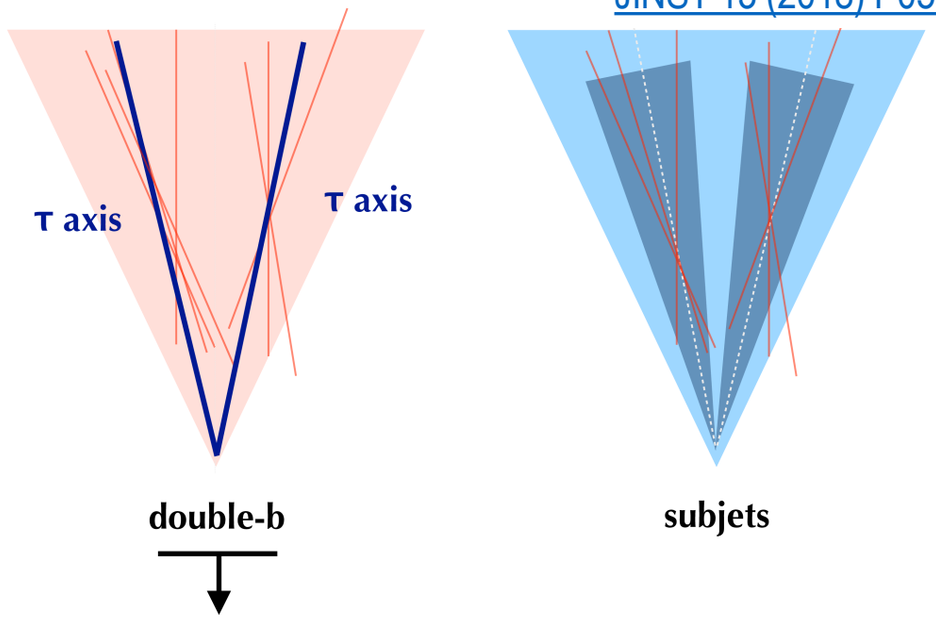
Jet substructure: H→bb tagging

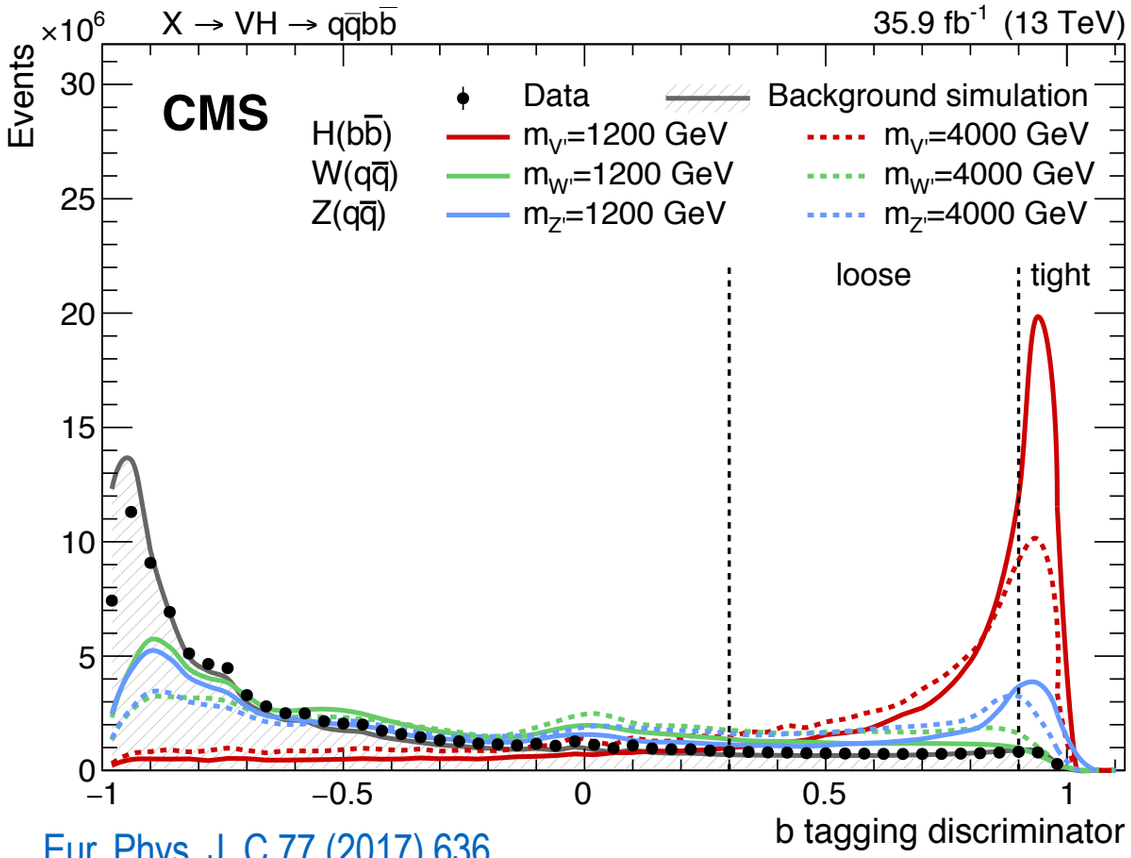
H→bb decays are tagged with 2 methods of similar performance:

- **Double-b tagger**, exploits the presence of 2 B hadrons in the fat jet.
  - Associates secondary vertices with the 2 directions of N-subjettiness axes.
  - Used in the VH→qqbb analysis (plot).
- Or apply the well-known **CSV tagger** to the two subjets.
  - Used in the VH→(2l/lν/2ν)bb analysis.

➔ Again define event categories (loose / tight).

JINST 13 (2018) P05011

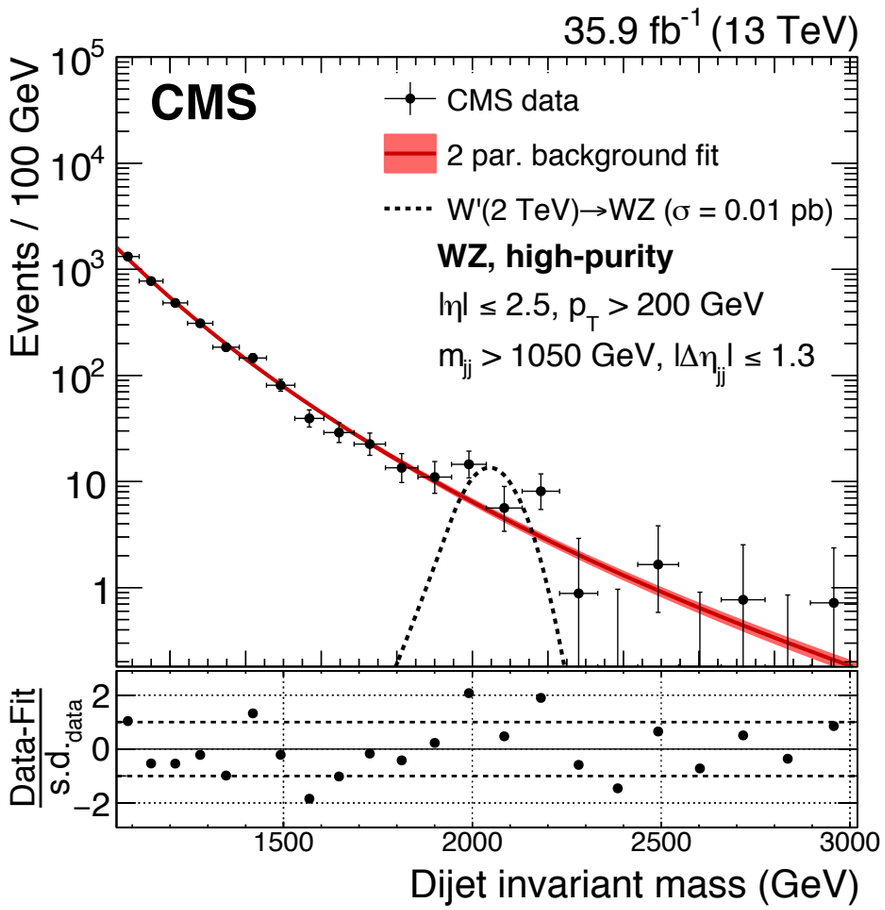




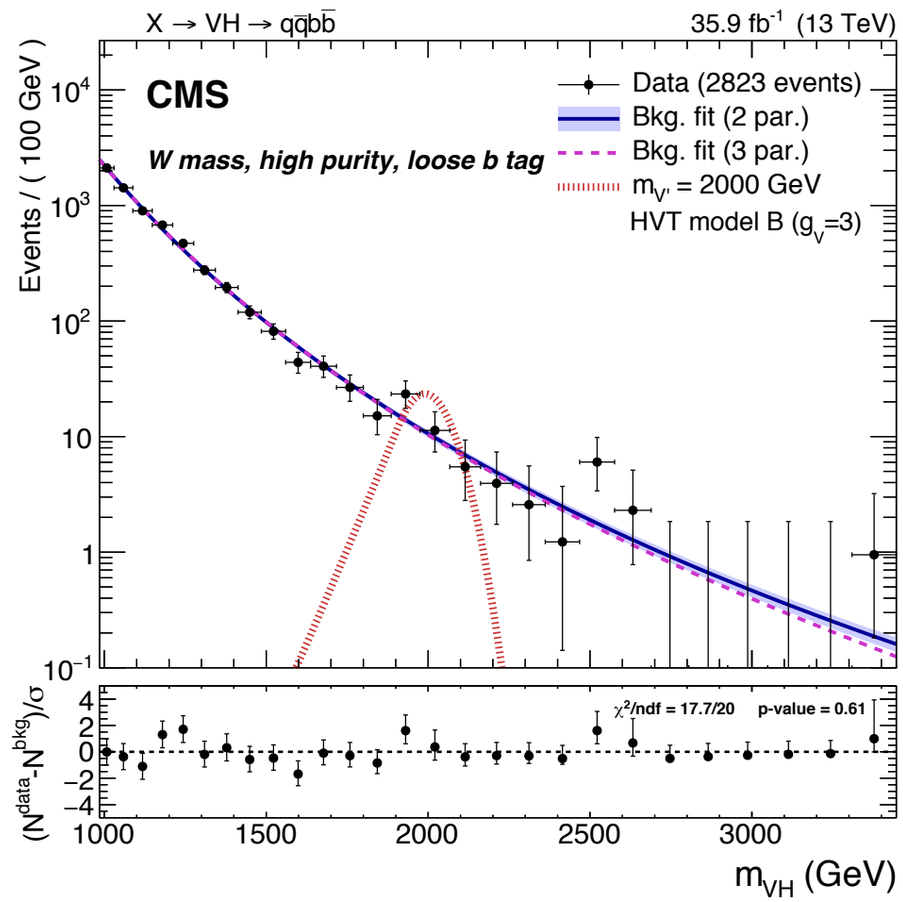
Eur. Phys. J. C 77 (2017) 636

All-hadronic searches

- Two analyses looking for a pair of large-radius jets:
  - **WW, WZ, or ZZ→4q**.
  - **WH or ZH→qqbb** (also illustrated in plots of p. 5–7).
- Main background (>95%) = QCD multijet.
  - Key role of cuts on soft-drop mass, τ_{21}, and (for qqbb) double-b tagger.
  - Monotonously falling spectrum, modelled with a **functional shape**:



Phys. Rev. D 97 (2018) 072006



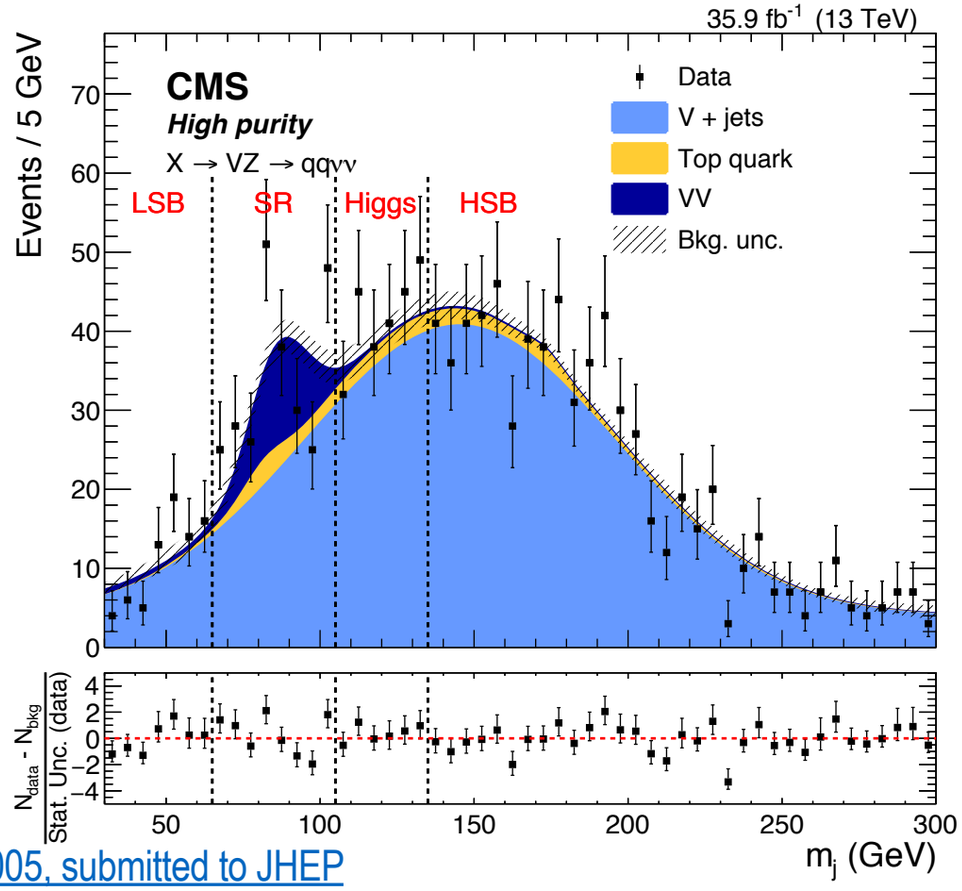
Eur. Phys. J. C 77 (2017) 636

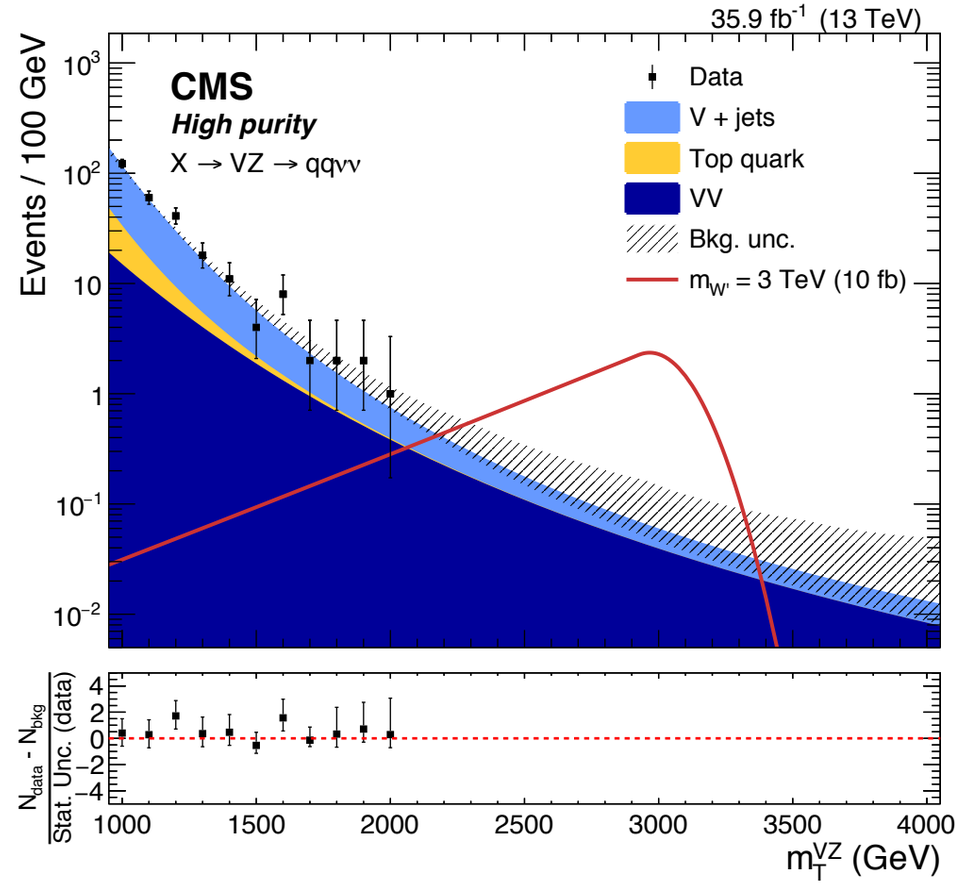
Semi-leptonic searches with α method

- Example of the analysis of the **ZV→ννqq channel**:
  - Main backgrounds = Z(νν)+jets and W(lν)+jets ➔ limited MC statistics.
  - Difficult region of the phase space (jet + large p_T^{miss}).

- Estimate this background with the **"α method"**:

  Use jet mass sidebands (40-65 GeV and >135 GeV, blind Higgs region) to exploit correlation between soft-drop jet mass and transverse ZV mass:
  - Determine normalization in SR from fit of jet mass pdfs to data in SB,
  - Extrapolate functional shape from SB to SR via transfer function $\alpha(m_T^{VZ})$.





CMS-B2G-17-005, submitted to JHEP

Semi-leptonic searches with α method

Similar method employed in 2 other semi-leptonic channels:

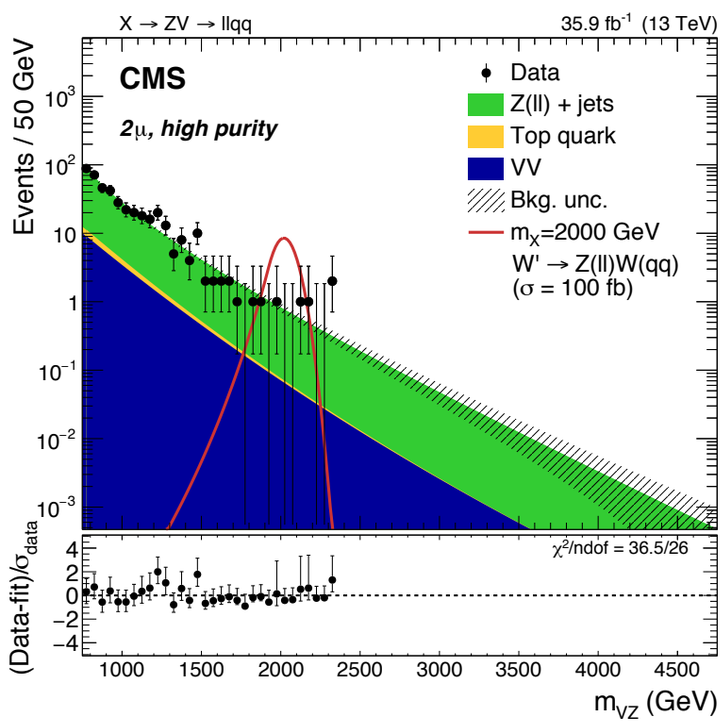
ZV → llqq:

- Dominant background = Z(ll) + jets.
- 2 complementary search strategies:
  - '**high-mass**' analysis (merged jet) using the α method,
  - '**low-mass**' analysis (merged or resolved), using simulation + shape correction from data.

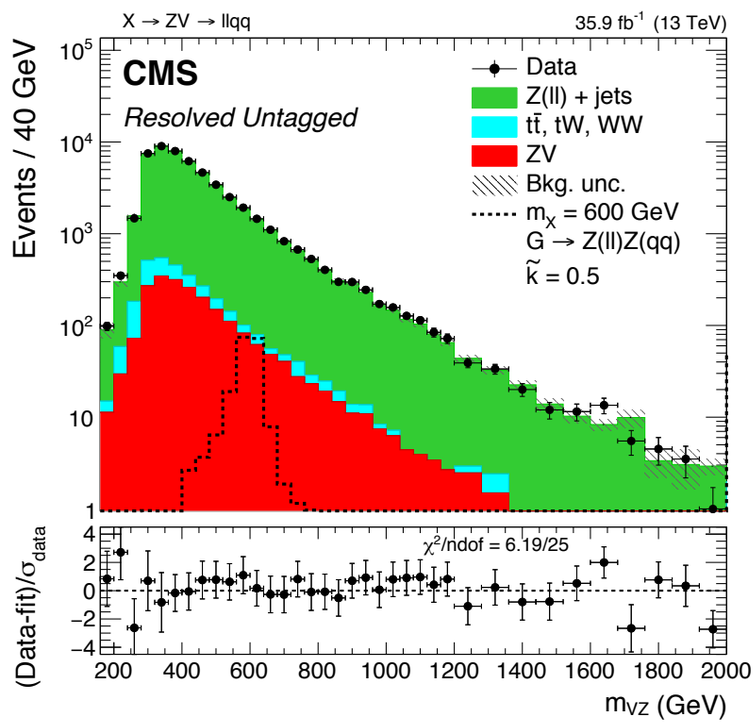
VH → ll/lν/νν bb:

- Main backgrounds = Z(ll/νν)/W(lν) + jets, and $t\bar{t}$ / t+X (notably in lν channels).
- α method for V+jets, this time applied keeping the 65–105 GeV soft-drop mass interval blind.

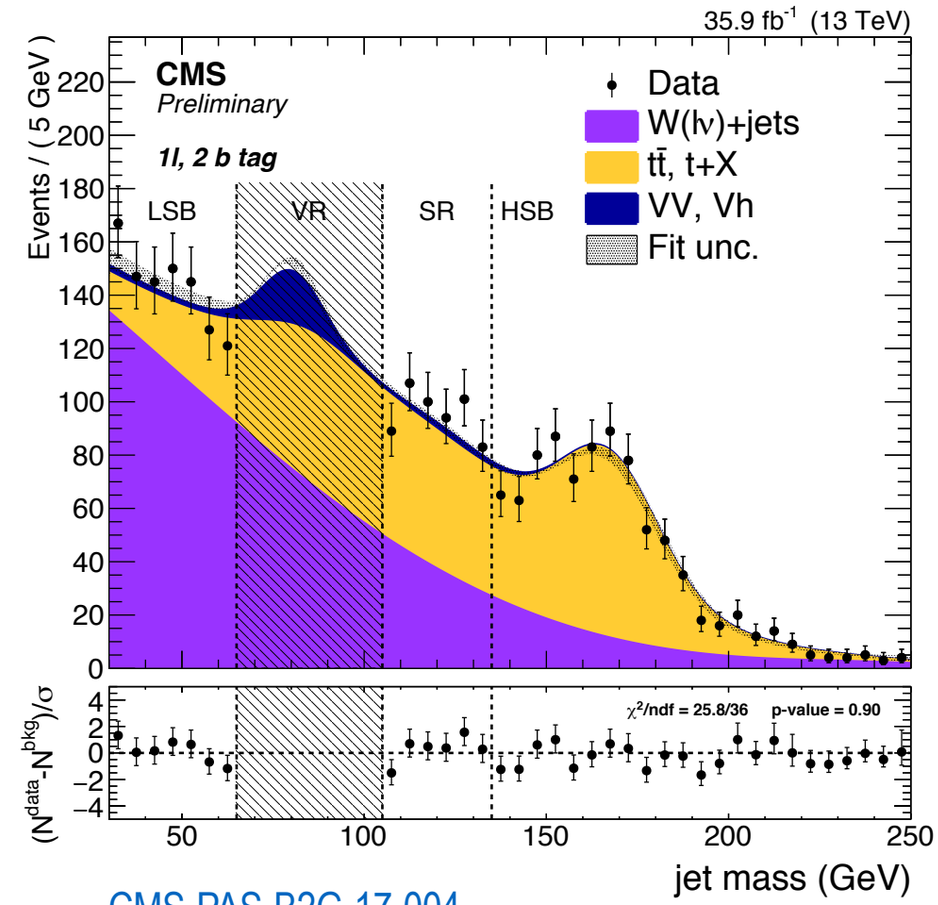
high-mass



low-mass, resolved



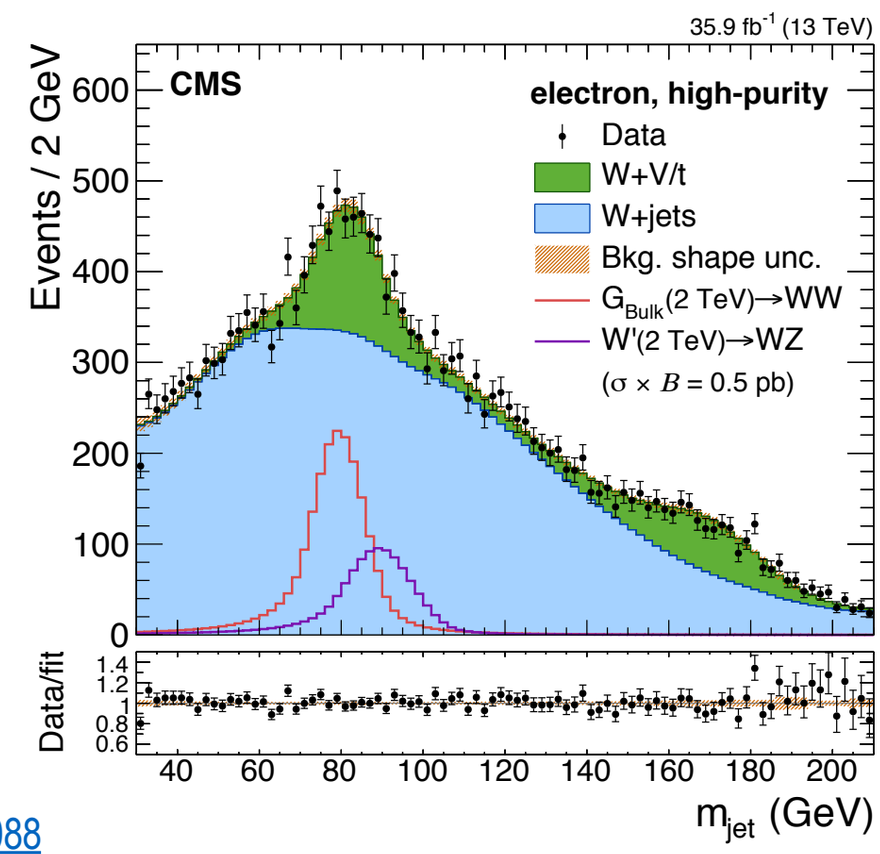
CMS-B2G-17-013, submitted to JHEP

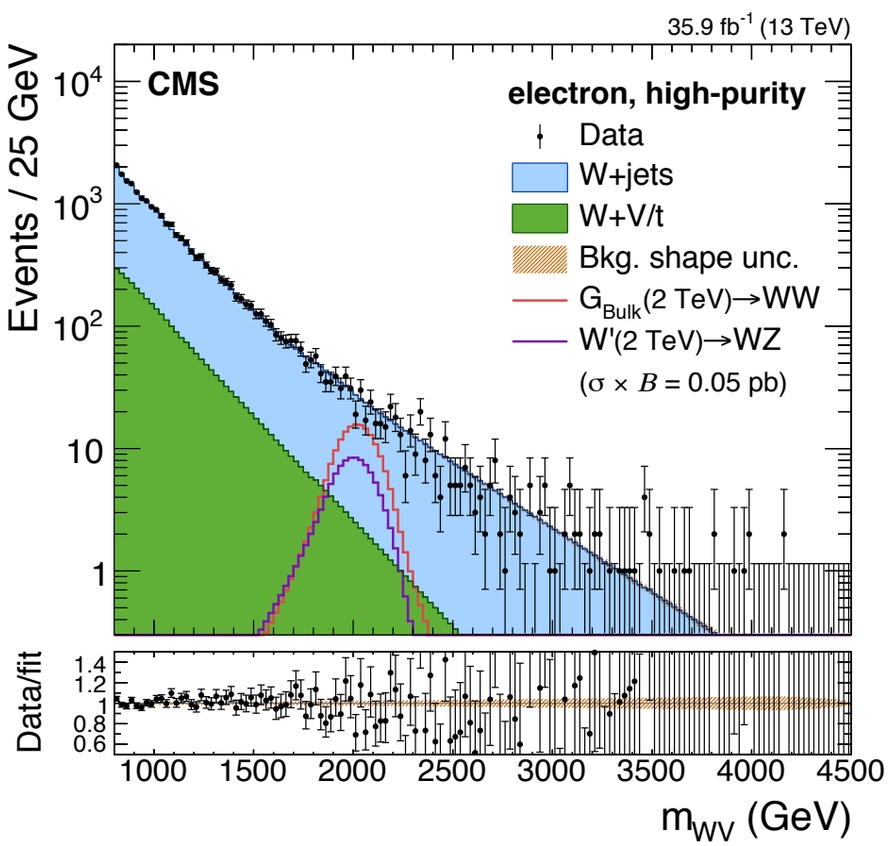


CMS-PAS-B2G-17-004

Semi-leptonic WV with 2D fit

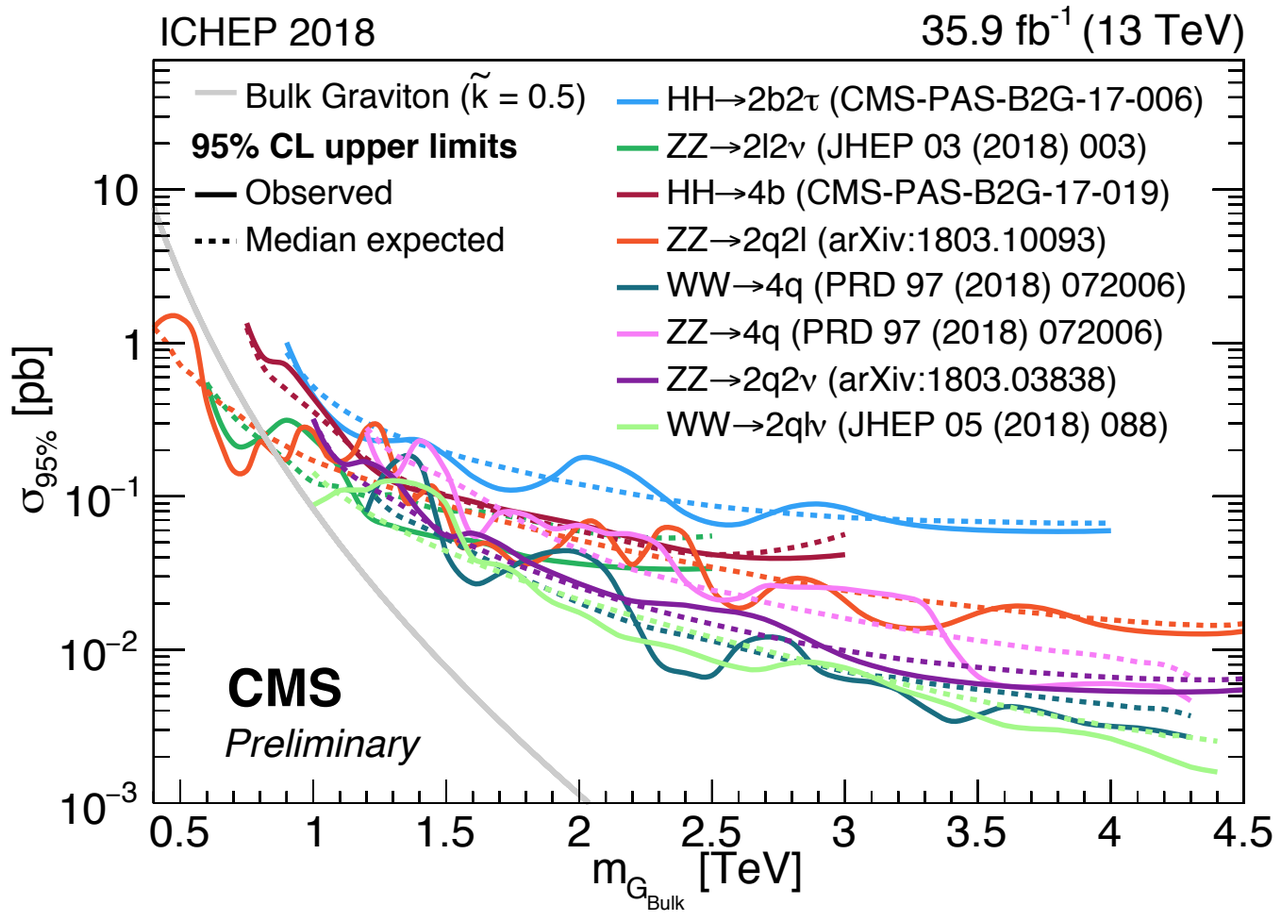
- $X \to WV \to l\nu qq$ search: pioneers a **2D bump hunt** in the (m_{WV}, m_{jet}) plane, where m_{jet} is the soft-drop jet mass.
- Takes full advantage of 2D sidebands to constraint 2 classes of backgrounds:
  - "**W+V/t**" ($t\bar{t}$-dominated), doubly **resonant** in m_{jet},
  - "**W+jets**" (W+jets, misassigned $t\bar{t}$), **non-resonant** in m_{jet}.
- Building of smooth 2D templates is based on a **kernel approach**.
  - Each gen.-level event contributes a gaussian, according to scale & resolution model.





JHEP 05 (2018) 088

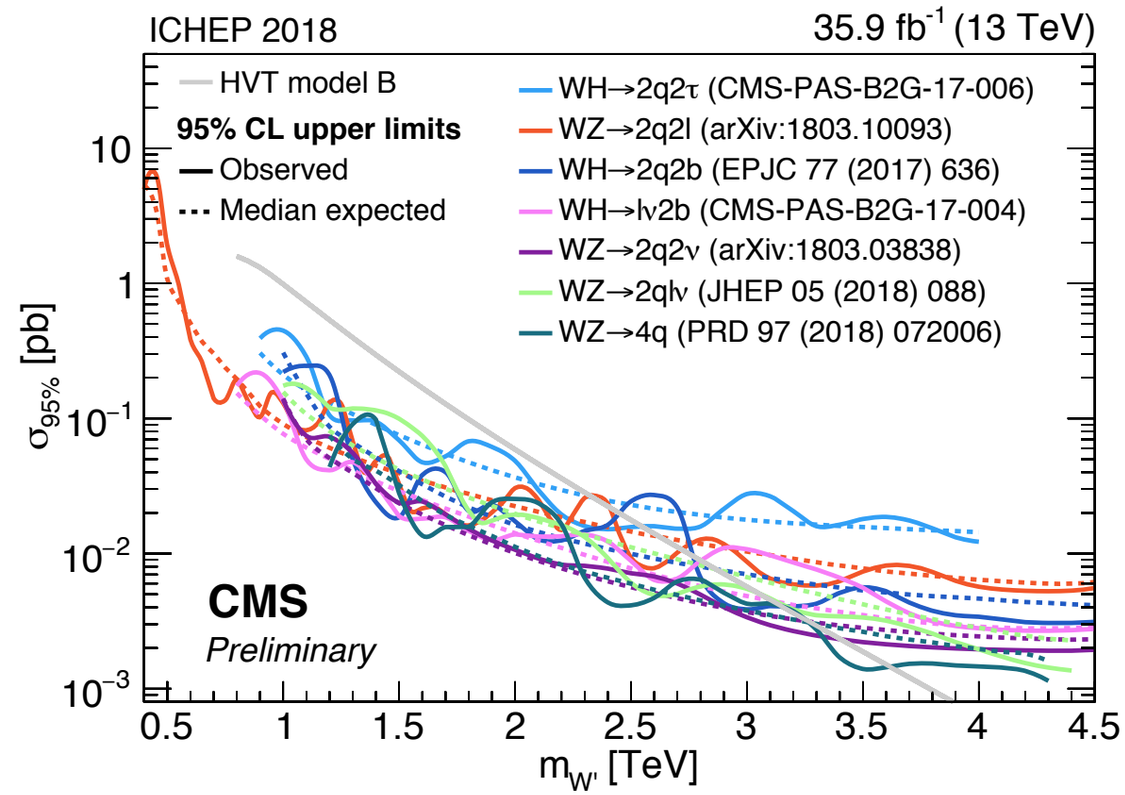
Results: bulk graviton model

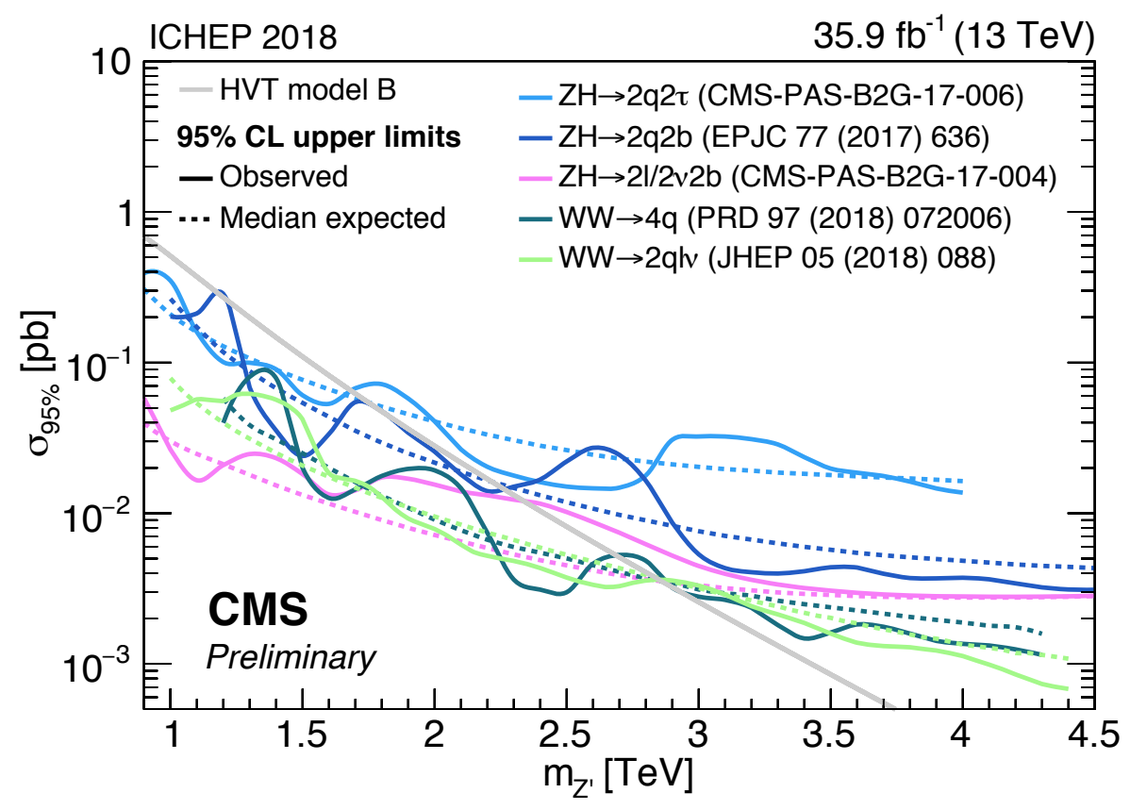


- All searches for WW, ZZ, and HH final states are interpreted as 95% CL upper limits on cross-section of spin-2 bulk graviton ($\tilde{k} = 0.5$).
- Data consistent with background expectations; masses below 800 GeV are excluded by ZZ→2l2ν.
- At high mass, most stringent limits come from WW→lνqq and WW→4q.
- Excess near 1.4 TeV: 2.4σ local significance in WW→lνqq, ~2σ in WW→4q.

Results: HVT model B

- 95% CL upper limits on cross sections of WZ, WH, and ZH resonances, here interpreted as the W' and Z' bosons of HVT model B.
- Several decay channels with comparable sensitivity ➔ will benefit from future combination.
- Data consistent with background expectations; no strong coincidence of local excesses.

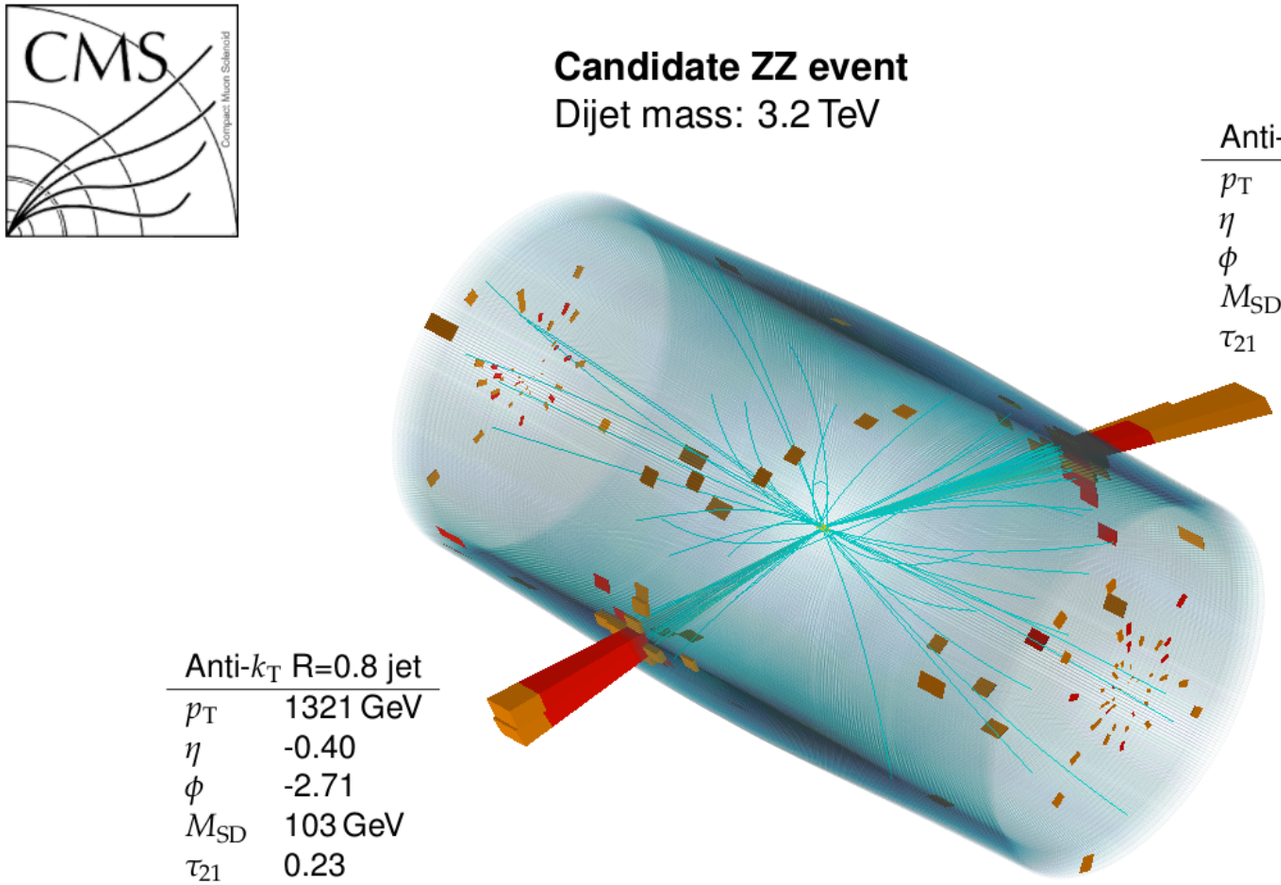




Conclusions

- Heavy diboson resonances were sought in the 2016 data sample in a **large set of final states**, using consistent analysis techniques.
- Data are **consistent with expectations from SM backgrounds**, upper limits are set on cross sections of spin-1 and spin-2 resonances in **HVT** and **Bulk graviton** models.
- Sensitivity will grow with the analysis of the **full LHC Run 2 data sample** (~ 4× larger) and the **combination** of decay channels.
- Steady progress in analysis strategies:
  - Catalyzing the fast development of **jet-related algorithms** (jet grooming, jet substructure and b tagging);
  - Introducing **multi-dimensional fits** to optimally constrain backgrounds.

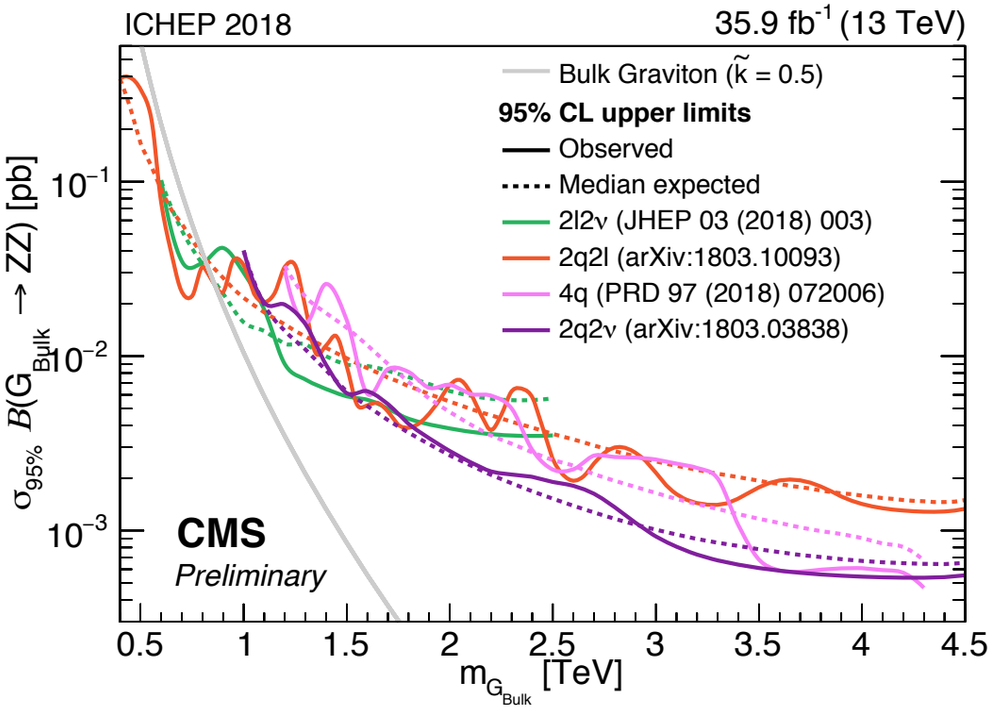
Thank you for your attention!

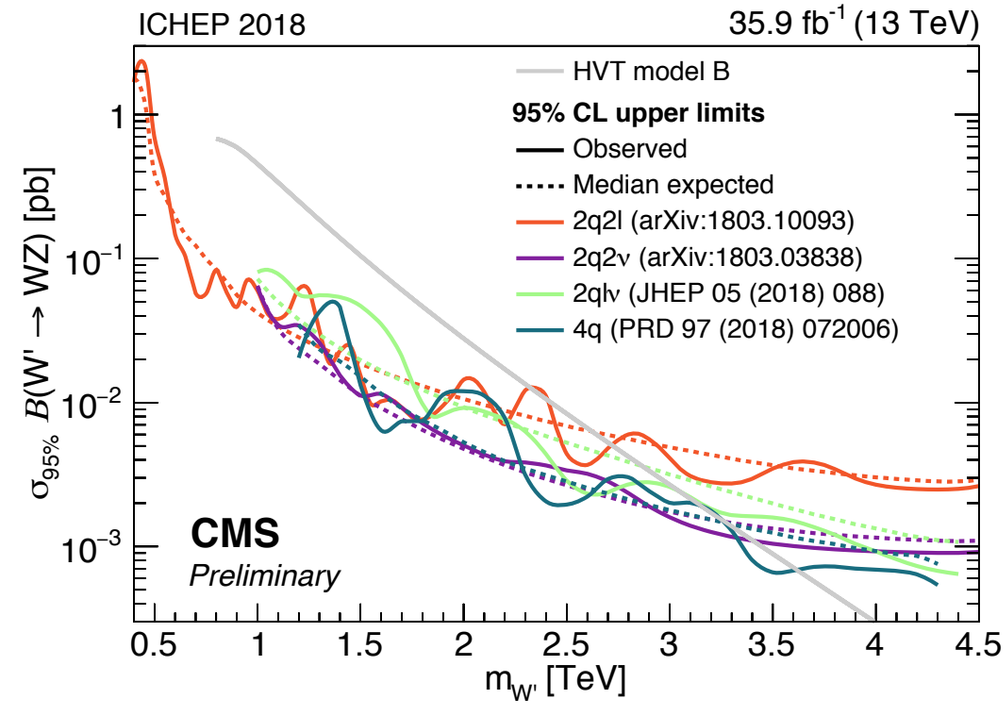


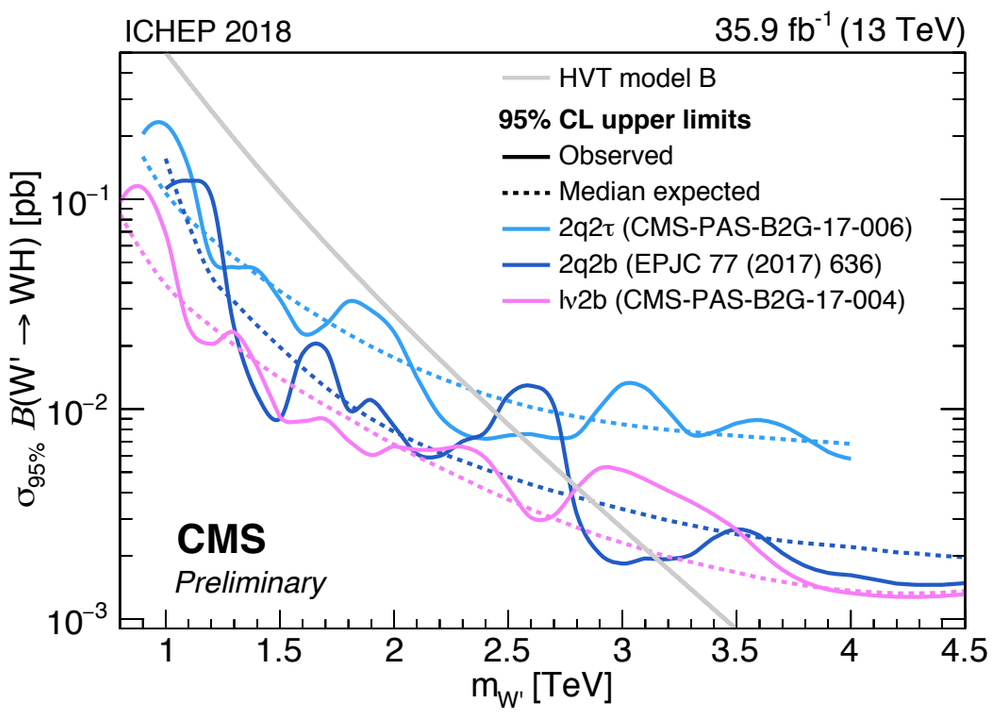
CMS Experiment at LHC, CERN
Data recorded: Mon Jul 18 19:59:10 2016 CEST
Run/Event: 276950 / 1080730125
Lumi section: 573

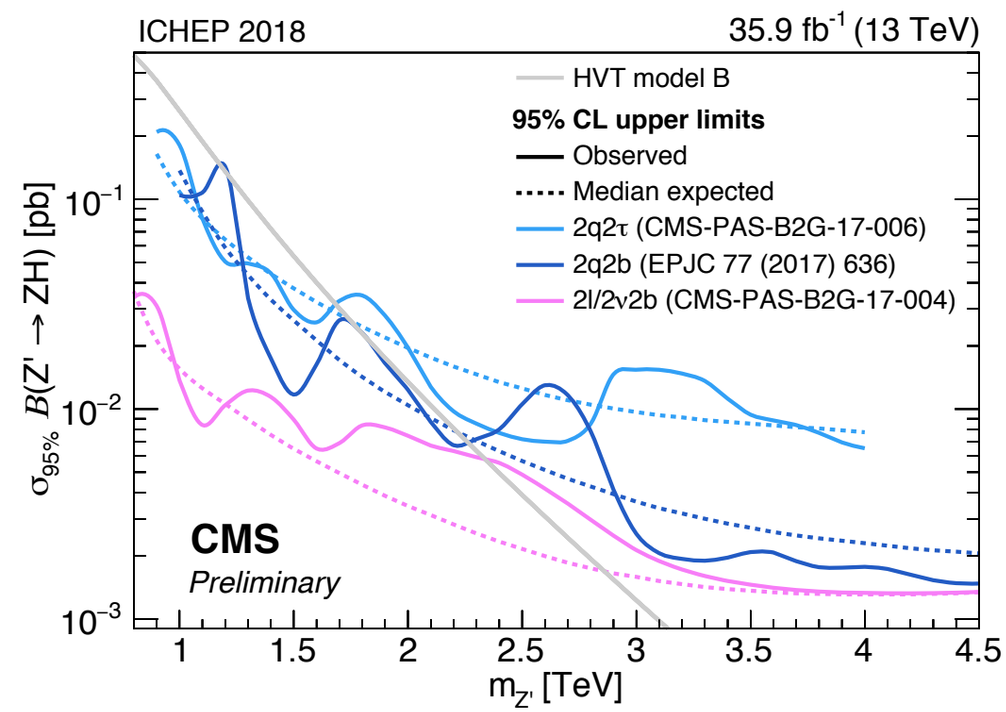
Additional material

Summary plots for ZZ, WZ, WH, and ZH









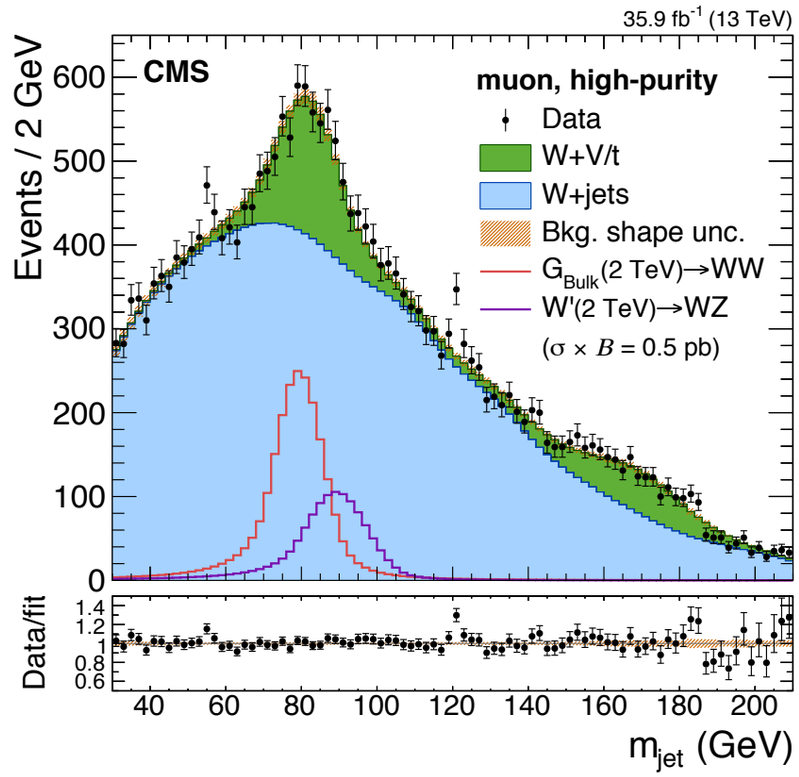
X→WV→lνqq search

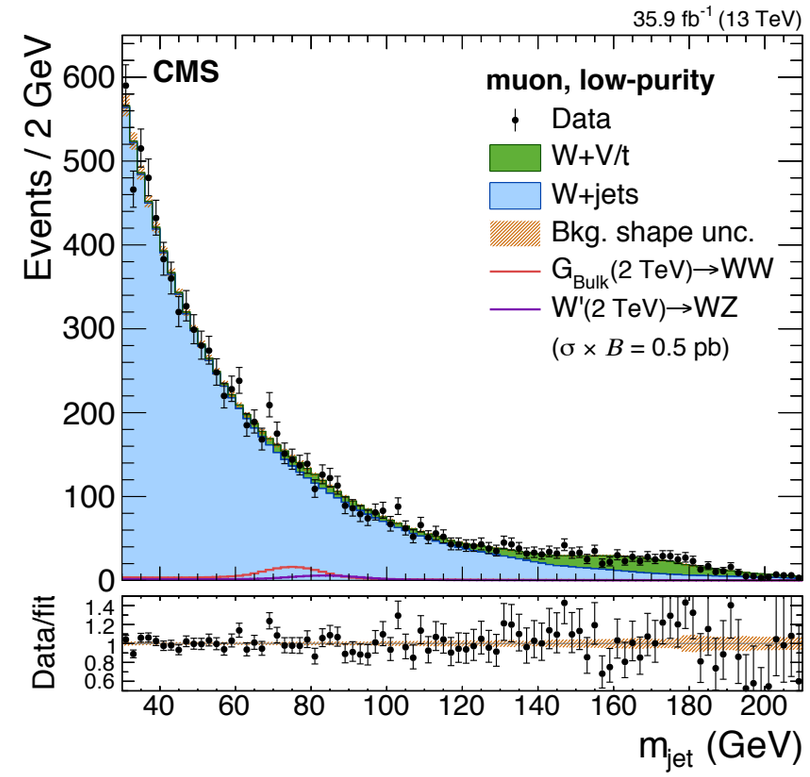
JHEP 05 (2018) 088
(CMS-B2G-16-029)

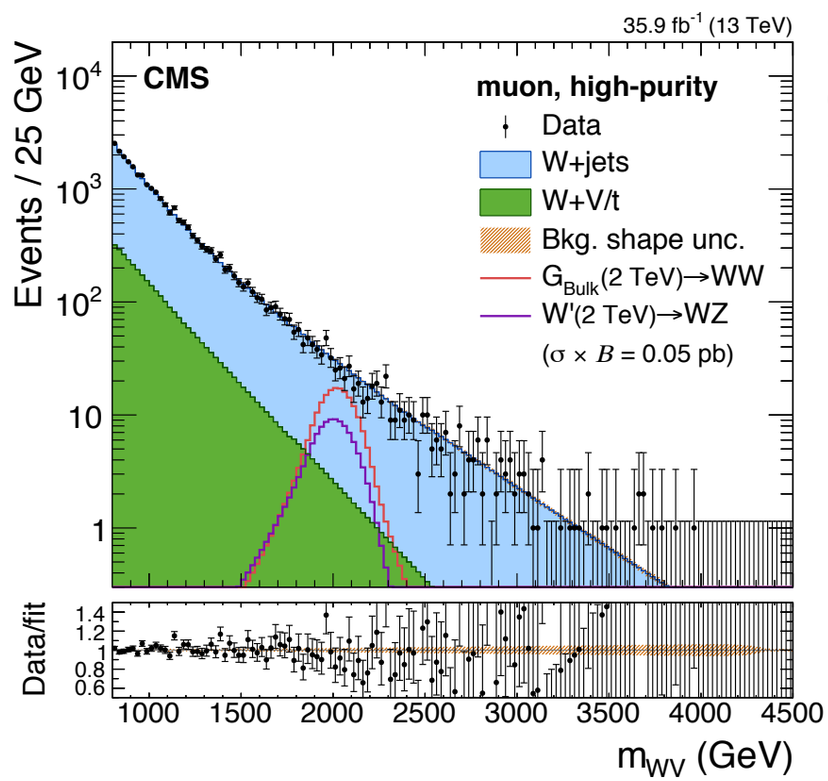
Kinematic selection:

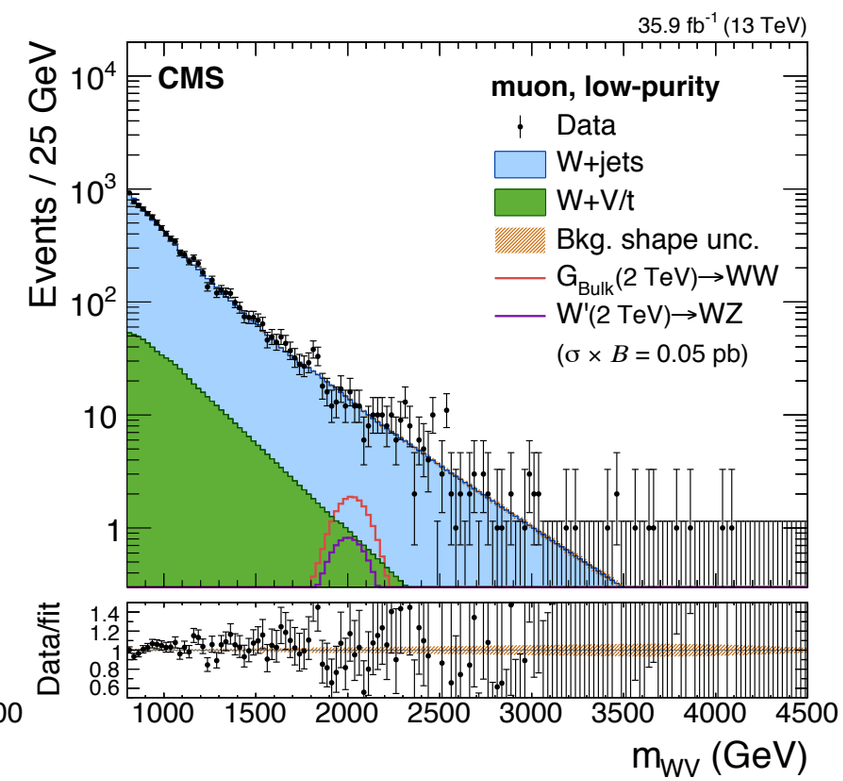
- $p_T(\mu/e) > 55$ GeV.
- $p_T^{miss} > 40/80$ GeV (μ/e channel).
- Leptonic W: reconstructed from m_W constraint, $p_T(W) > 200$ GeV.
- Hadronic V: most energetic large-radius (R=0.8) jet,
  $p_T > 200$ GeV, $|\eta| < 2.5$
  $\tau_{21} < 0.75$, $30 < m_{jet} < 210$ GeV.
- Require angular separation between V jet candidate and lepton, p_T^{miss}, and W candidate.
- Veto the event if a b tagged standard jet (R=0.4) is present.

4 search categories:
(e, μ) ×
(HP ($\tau_{21} < 0.55$), LP ($0.55 < \tau_{21} < 0.75$))









X→WV→lνqq search

JHEP 05 (2018) 088
(CMS-B2G-16-029)

Building 2D templates:

- **W+jets background** (plots):

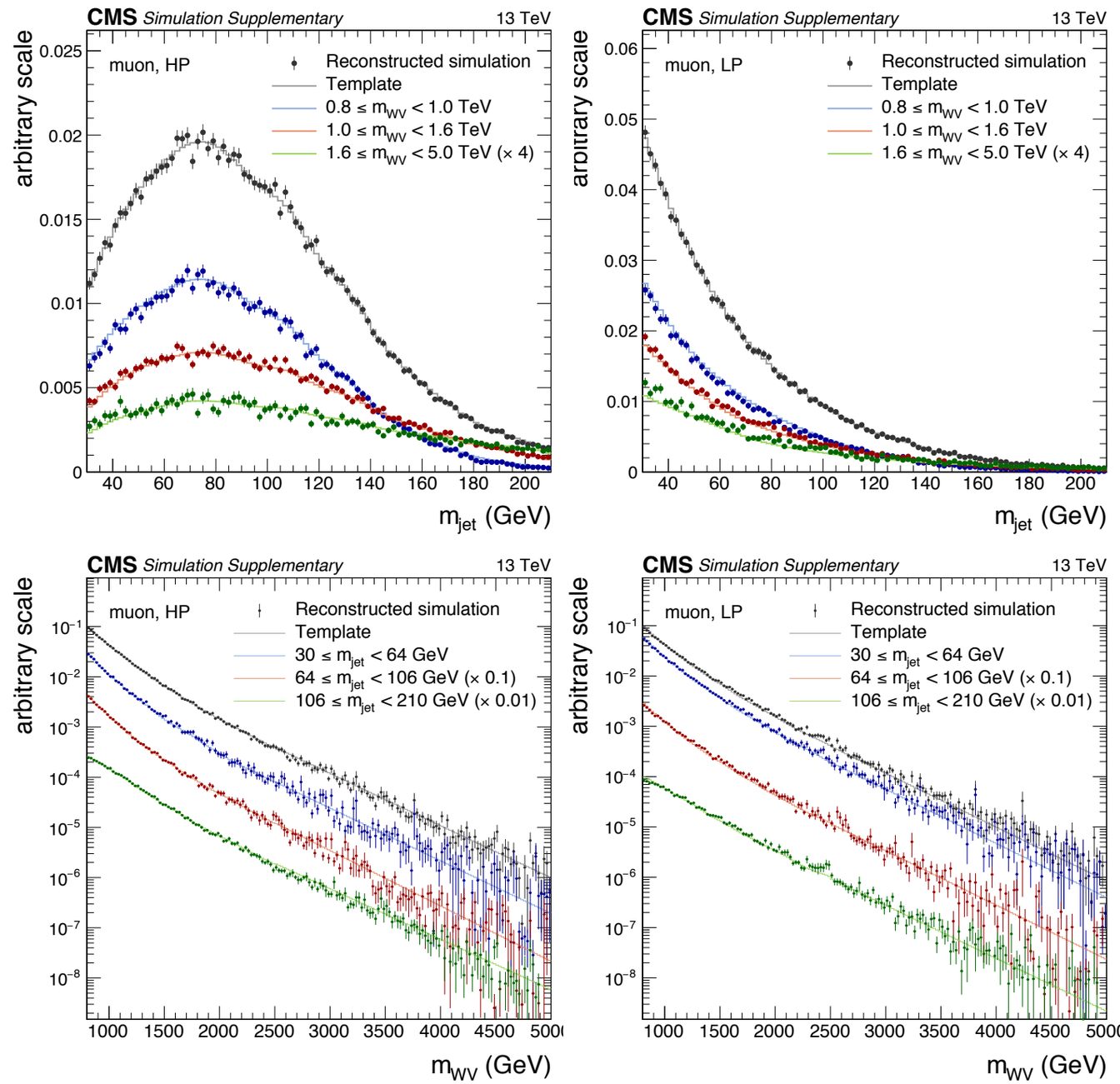
$$P_{\mathrm{W+jets}}(m_{\mathrm{WV}}, m_{\mathrm{jet}}) = P_{\mathrm{WV}}(m_{\mathrm{WV}}|m_{\mathrm{jet}}, \theta_1)\, P_j(m_{\mathrm{jet}}|\theta_2)$$

P_{WV} : each gen.-level event contributes a 2D gaussian according to scale/resolution model (exponential tail for $m_{\mathrm{WV}} > 2.5$ TeV).
P_{j} : 1D histogram.

- **W+V/t background:**

$$P_{\mathrm{W+V/t}}(m_{\mathrm{WV}}, m_{\mathrm{jet}}) = P_{\mathrm{WV}}(m_{\mathrm{WV}}|\theta_1)\, P_j(m_{\mathrm{jet}}|m_{\mathrm{WV}}, \theta_2)$$

P_{WV} : similar method as W+jets, in 1D (exponential tail for $m_{\mathrm{WV}} > 1.2$ TeV).
P_{j} : fit two double Crystal-Ball + exp., parameterize as a function of m_{WV}.



- **Signal:** $P_{\mathrm{sig}}(m_{\mathrm{WV}}, m_{\mathrm{jet}}|m_{\mathrm{X}}) = P_{\mathrm{WV}}(m_{\mathrm{WV}}|m_{\mathrm{X}}, \theta_1)\, P_j(m_{\mathrm{jet}}|m_{\mathrm{X}}, \theta_2)$
P_{WV} and P_{j} modelled by double CB functions (+ exponential for P_{j} in LP category), parameterize as a function of m_{X}.

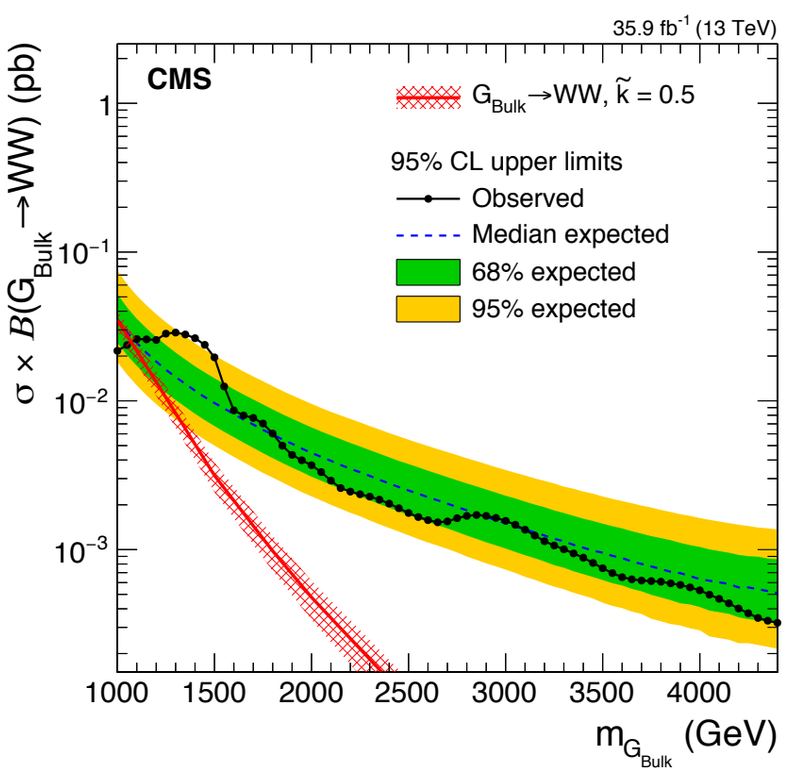
X→WV→lνqq search

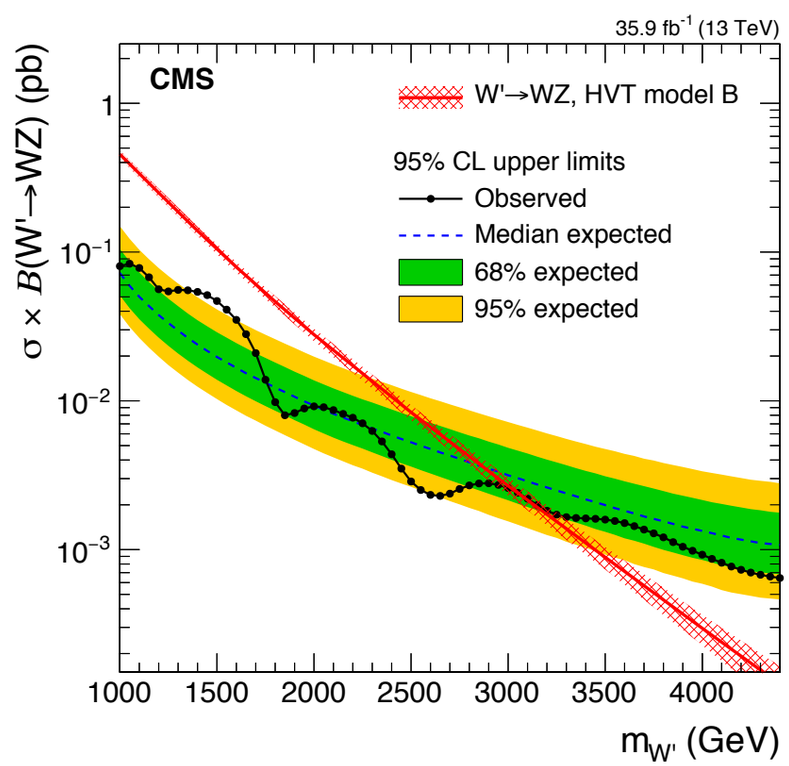
JHEP 05 (2018) 088
(CMS-B2G-16-029)

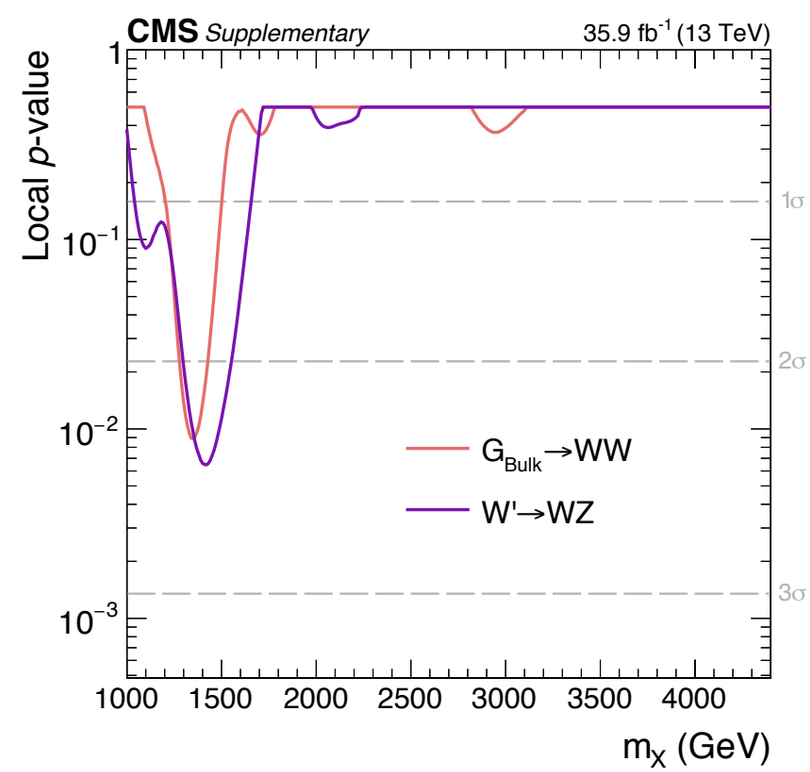
Main systematic uncertainties:

- Signal: efficiencies of lepton, τ_{21} (HP: 14%, LP: 33%), and b-tag;
  scale & resolution of jet p_T, soft-drop mass (corr. with W+V/t background), and p_T^{miss}
- Background uncertainties, uncorrelated across categories:
  - normalization uncertainties: 50% for W+jets, 20% for W+V/t
  - W+jets: alternative shapes $\propto m_{WV}$, $1/m_{WV}$ (p_T spectrum / mass scale) and $\propto m_{jet}$, $1/m_{jet}$ (hadronization/ substructure effects)
  - W+V/t: top peak fraction parameterized as $f = a + b/m_{WV}^2$; uncertainties a: ±20%, b: ±25000 GeV²

Results are interpreted as 95% CL limits on σ×*B* for bulk graviton (→WW) and W' of HVT model B (→WZ):







X→VV→qqqq search

Phys. Rev. D 97 (2018) 072006
(CMS-B2G-17-001)

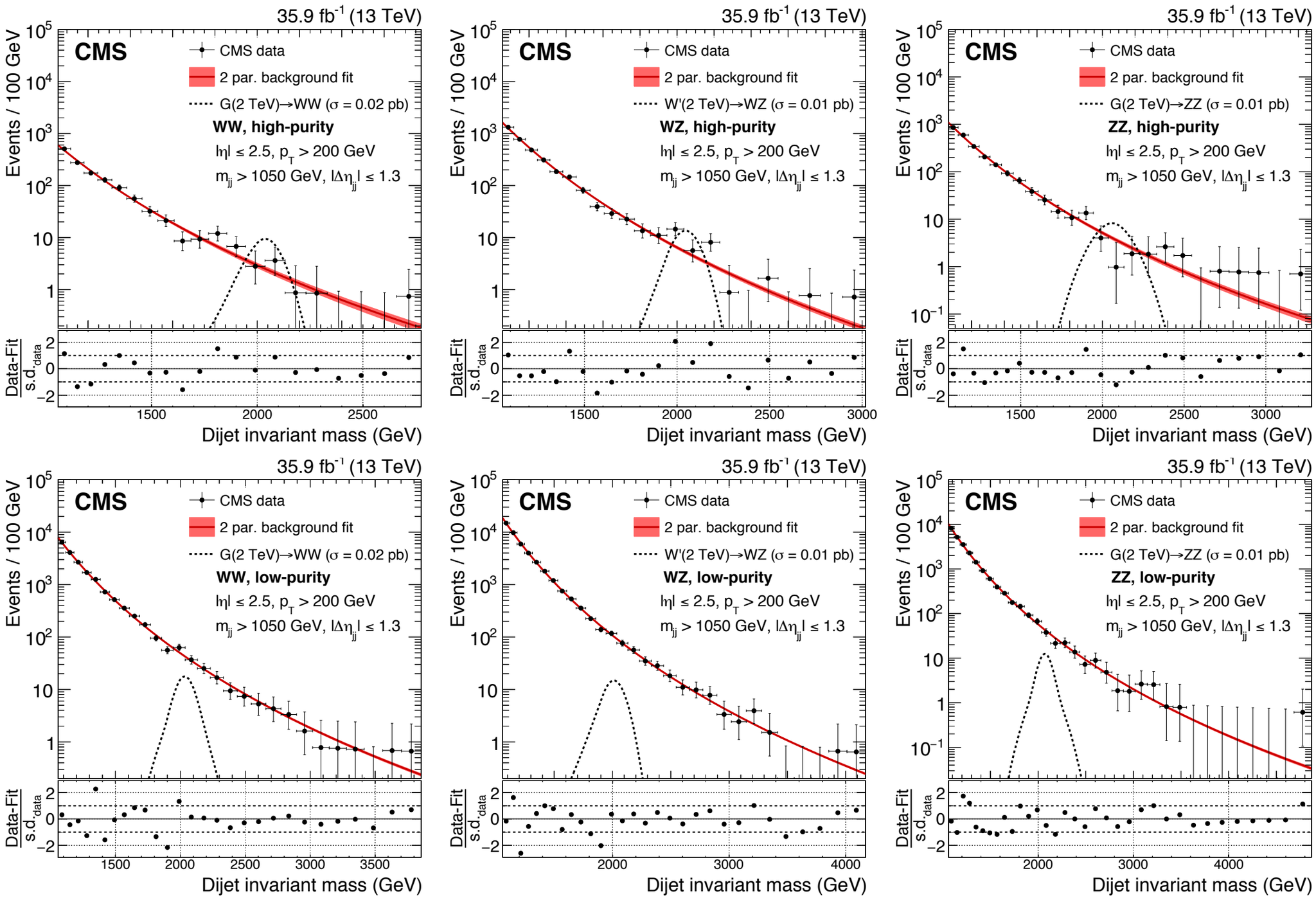
Dijet invariant mass distribution and background-only fit in the 6 search categories i.e. (WW, WZ, ZZ soft-drop mass windows) × (HP-HP, HP-LP):

HP: $\tau_{21} < 0.35$
LP: $0.35 < \tau_{21} < 0.75$

2-parameter function:

$$\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_1}}$$

(chosen over other N-parameter functions with Fisher F-test)



X→VV→qqqq search

Phys. Rev. D 97 (2018) 072006
(CMS-B2G-17-001)

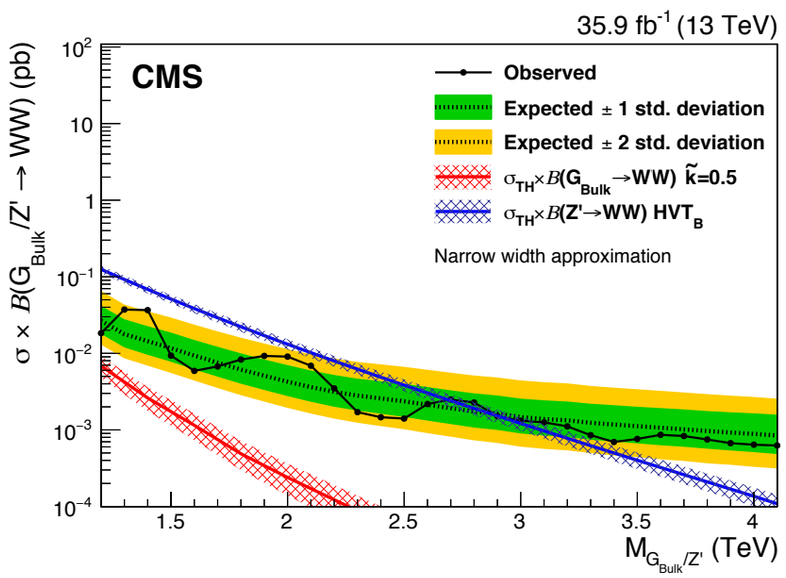
Summary of systematic uncertainties:

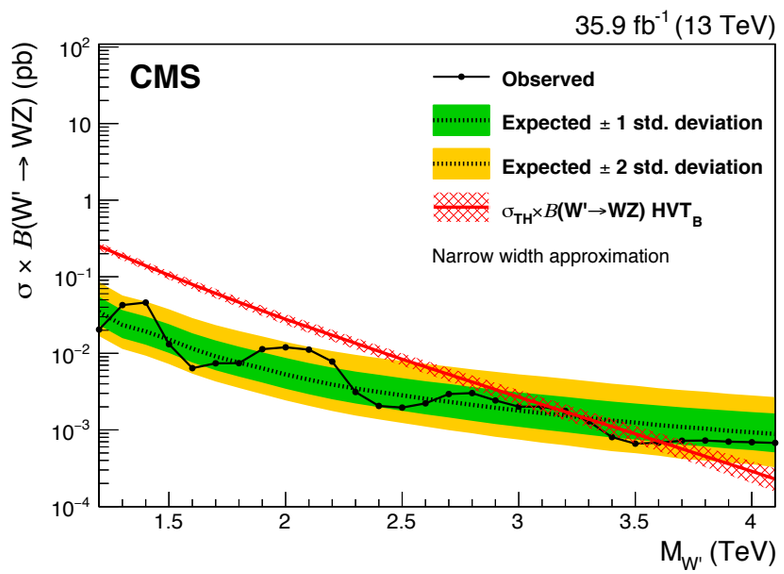
Source	Relevant quantity	Uncertainty (%)			
		Double-tag		Single-tag	
		HP+HP	HP+LP	HP+j	LP+j
Jet energy scale	Resonance shape	2	2	2	2
Jet energy resolution	Resonance shape	6	7	4	3
PDF	Resonance shape	5	7	13	8
Jet energy scale	Signal yield	<1		<1	
Jet energy resolution	Signal yield	<1		<1	
Jet mass scale	Signal yield	<2		<1	
Jet mass resolution	Signal yield	<6		<8	
Pileup	Signal yield	2			
PDF (acceptance)	Signal yield	2			
Integrated luminosity	Signal yield	2.5			
Jet mass scale	Migration	<36		<10	
Jet mass resolution	Migration	<25		<7	
V tagging τ_{21}	Migration	22	33	11	22
V tagging p_T-dependence	Migration	19–40	14–29	9–23	4–11
PDF and scales (W′ and Z′)	Theory	2–18			
PDF and scales (G_{bulk})	Theory	8–78			
PDF and scales (q*)	Theory			1–61	

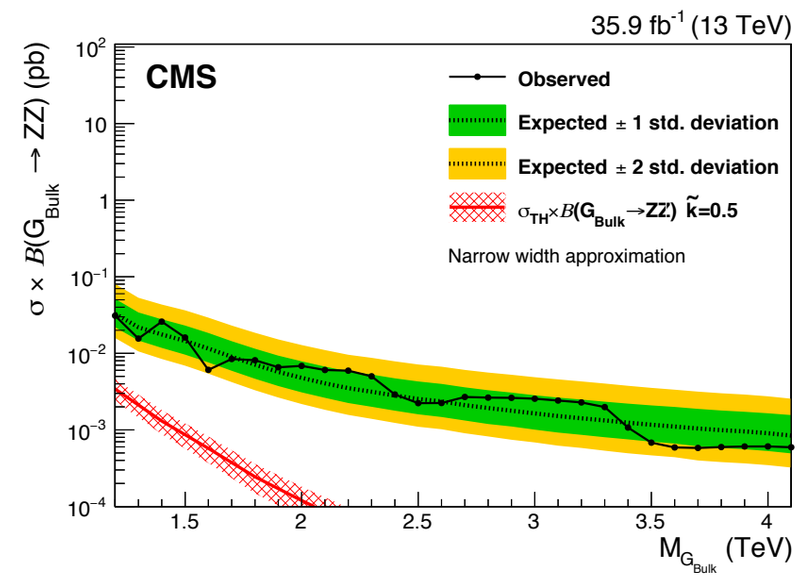
X→VV→qqqq search

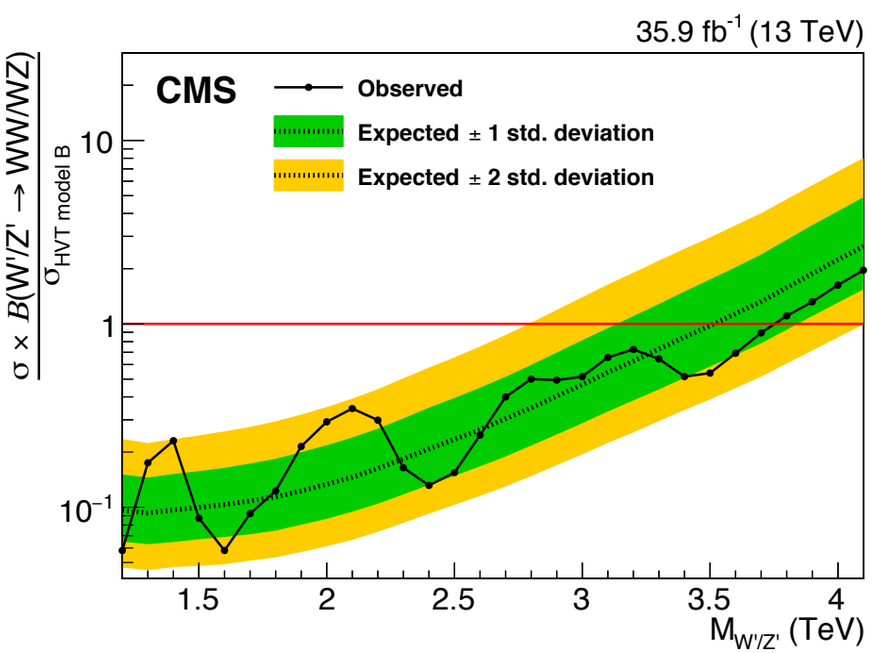
Phys. Rev. D 97 (2018) 072006
(CMS-B2G-17-001)

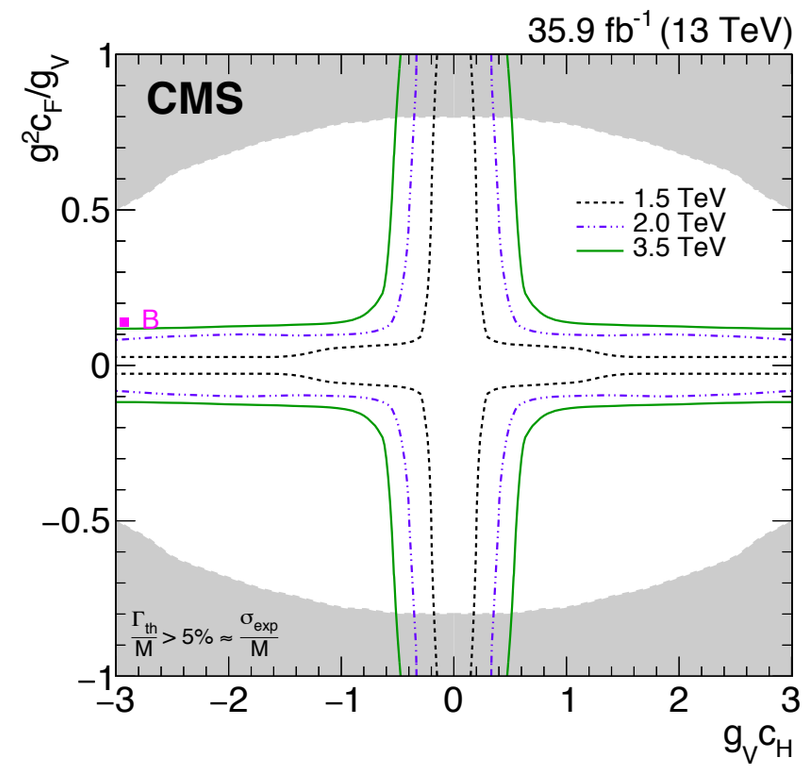
Results are interpreted as 95% CL limits on σ×*B* for bulk graviton (→WW, ZZ) and for W'→WZ, Z'→WW of HVT model B:











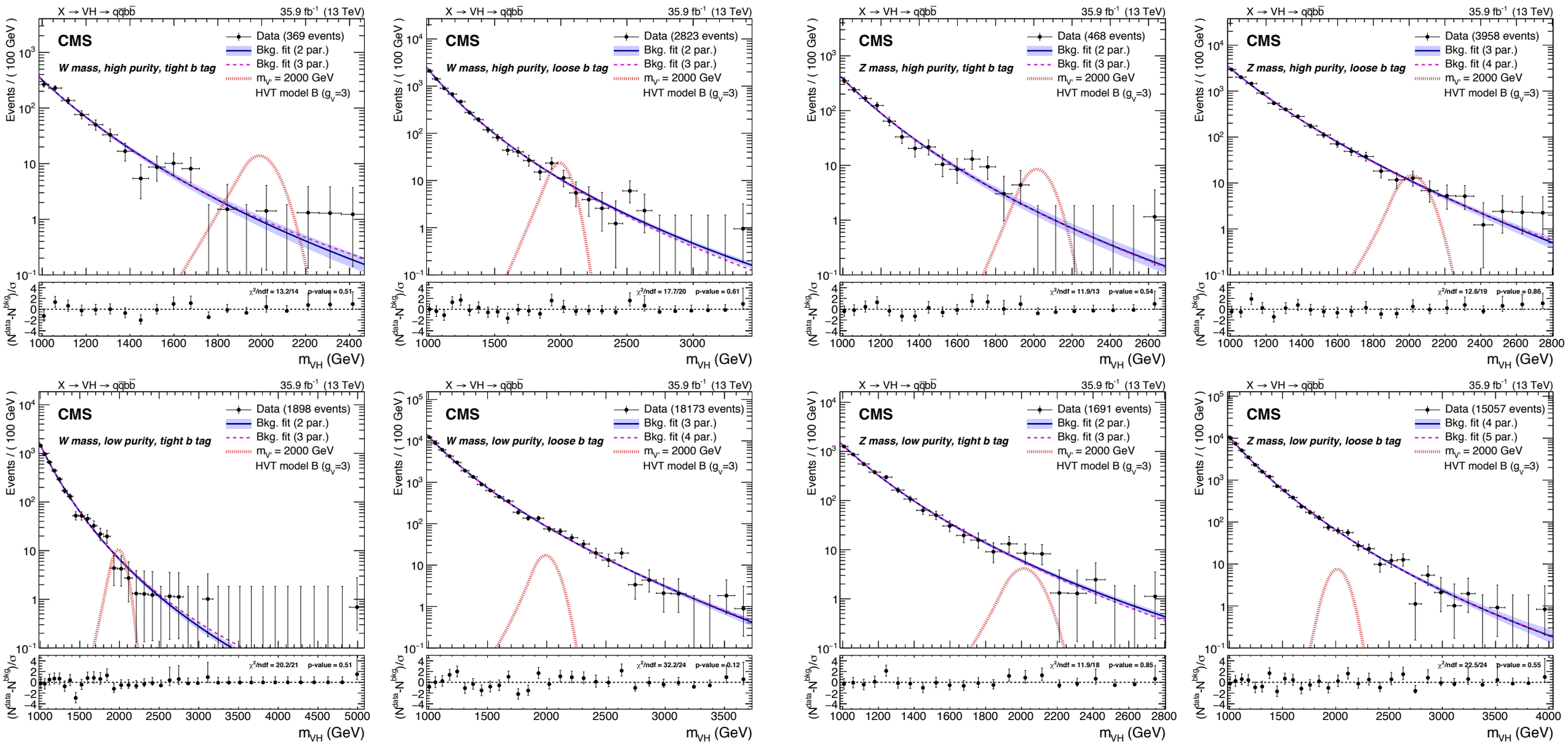
X→VH→qqbb search

Eur. Phys. J. C 77 (2017) 636
(CMS-B2G-17-002)

Background function: 2, 3, or 4 parameters, depending on category:

$$\frac{p_0}{x^{p_1}}, \quad \frac{p_0\,(1-x)^{p_1}}{x^{p_2}}, \quad \frac{p_0\,(1-x)^{p_1}}{x^{p_2+p_3\,\log(x)}}$$

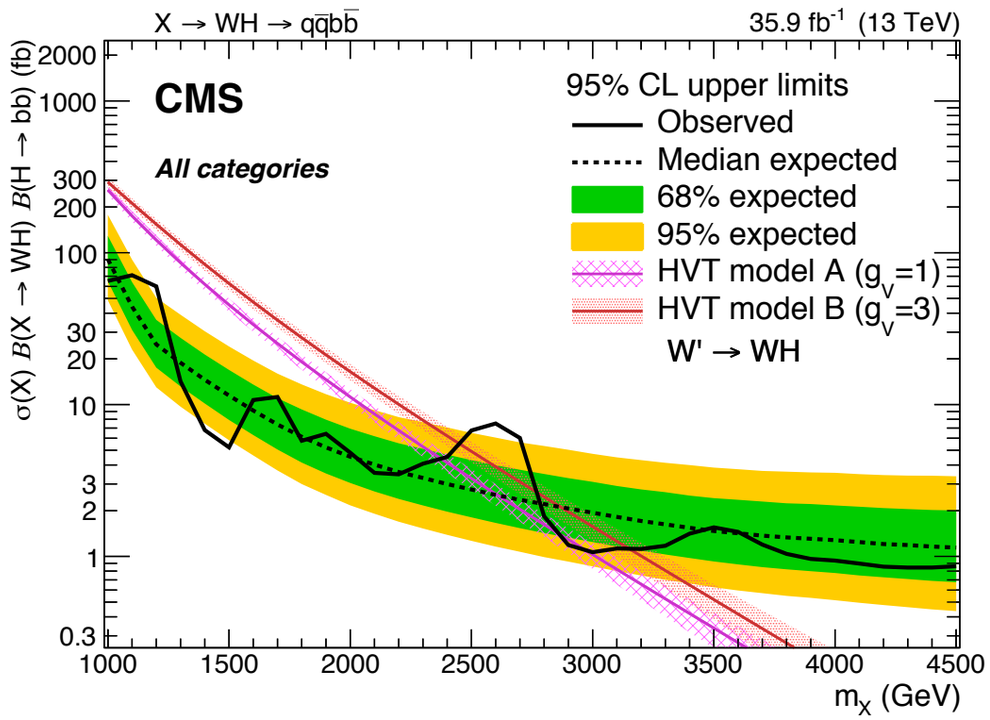
Dijet invariant mass distribution and background-only fit in the 8 search categories i.e. (W/Z mass window) × (HP/LP) × (loose/tight bb tag):

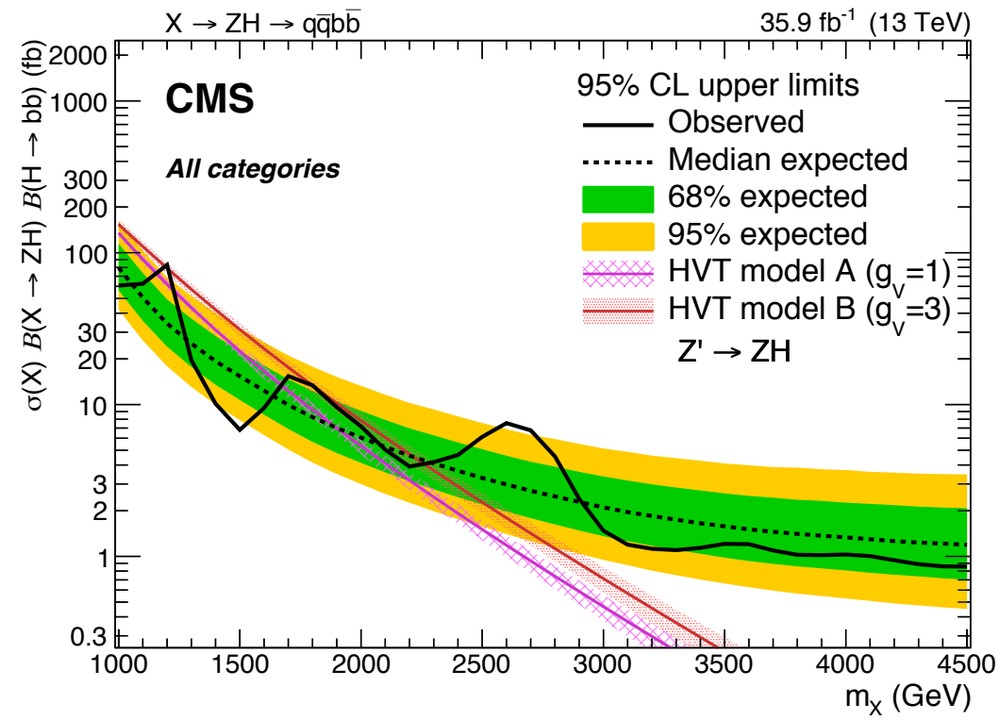


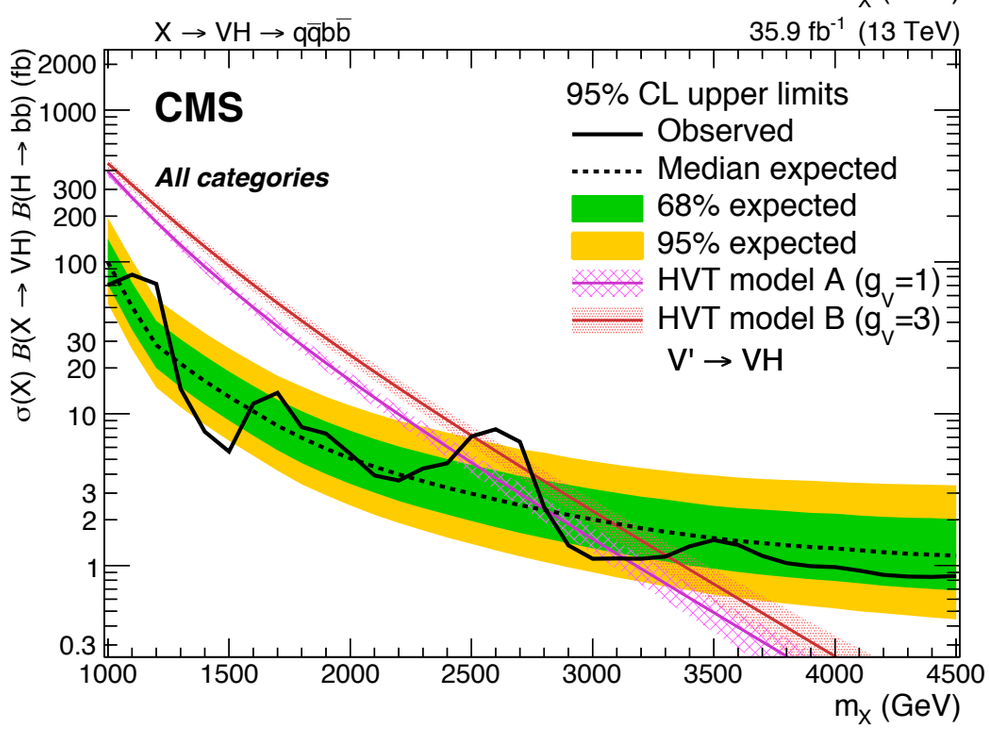
X→VH→qqbb search

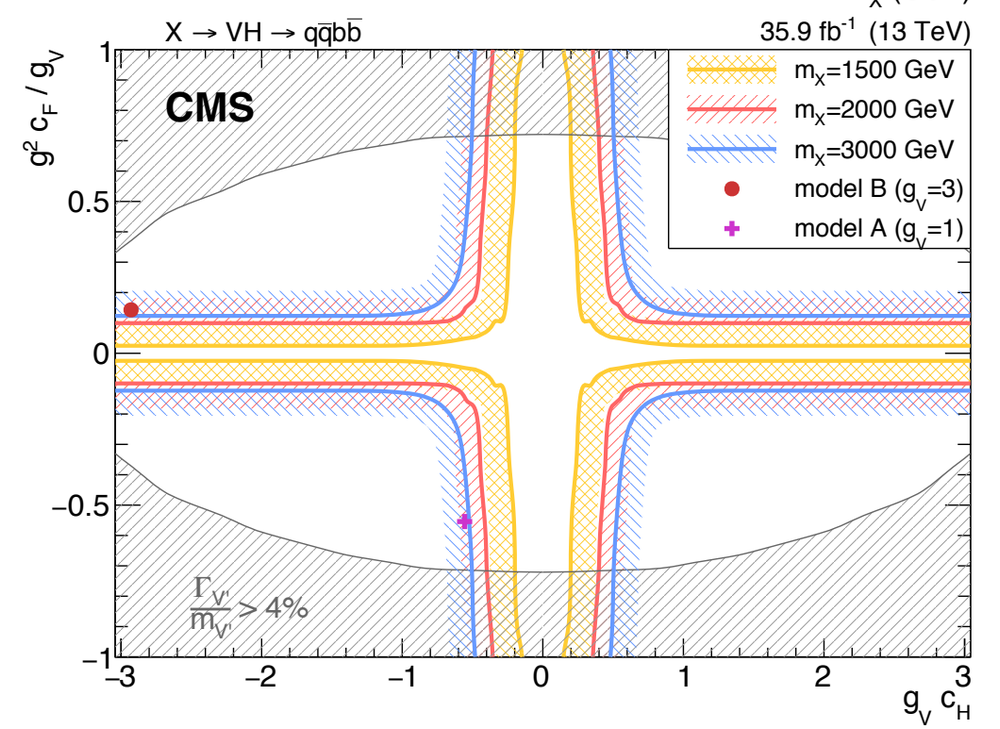
Eur. Phys. J. C 77 (2017) 636
(CMS-B2G-17-002)

Results are interpreted as 95% CL limits on σ×*B* for W'→WH, Z'→ZH, and V'→VH (summing the mass-degenerate W′ and Z′) for HVT models A and B:









X→ZV→ννqq search

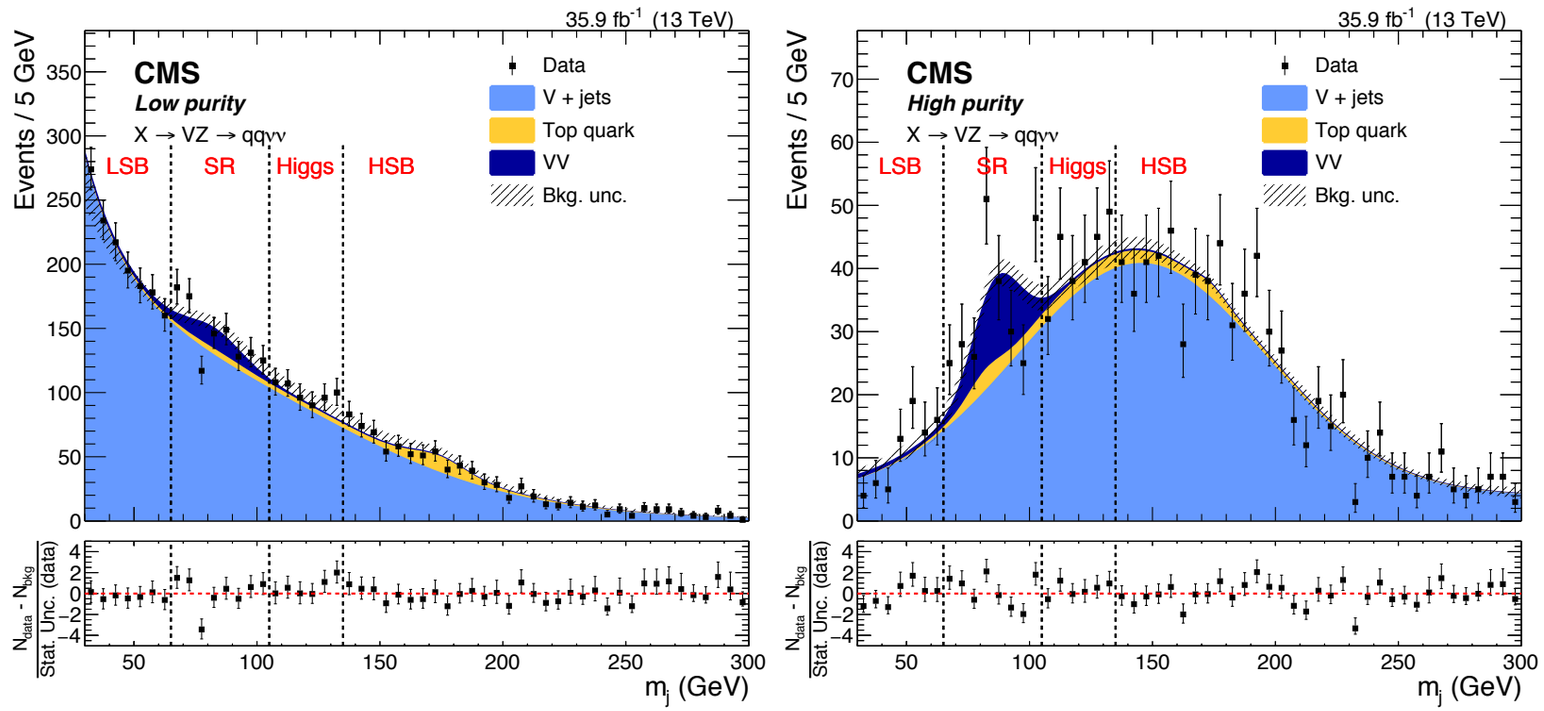
Submitted to JHEP
(CMS-B2G-17-005)

Kinematic selection:

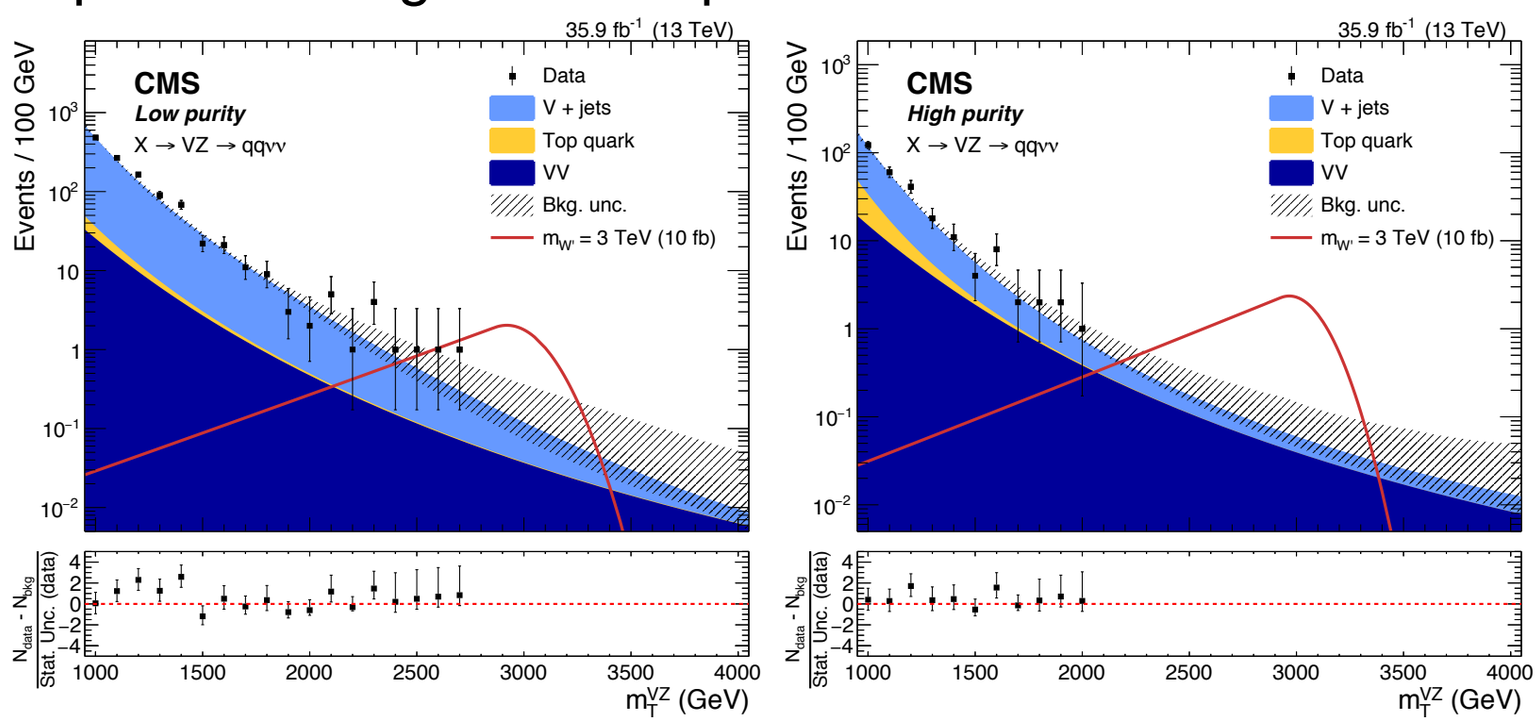
- $p_T^{miss} > 200$ GeV.
- V jet (R=0.8):
  $p_T > 200$ GeV, $|\eta| < 2.4$,
  soft-drop mass windows.
- Require angular separation between V jet and p_T^{miss}.
- Veto events with additional leptons, photons, b tagged standard jets (R=0.4).

2 search categories:
HP ($\tau_{21} < 0.35$)
LP ($0.35 < \tau_{21} < 0.75$)

Background yield prediction in SR from fit of m_{jet} in SB:



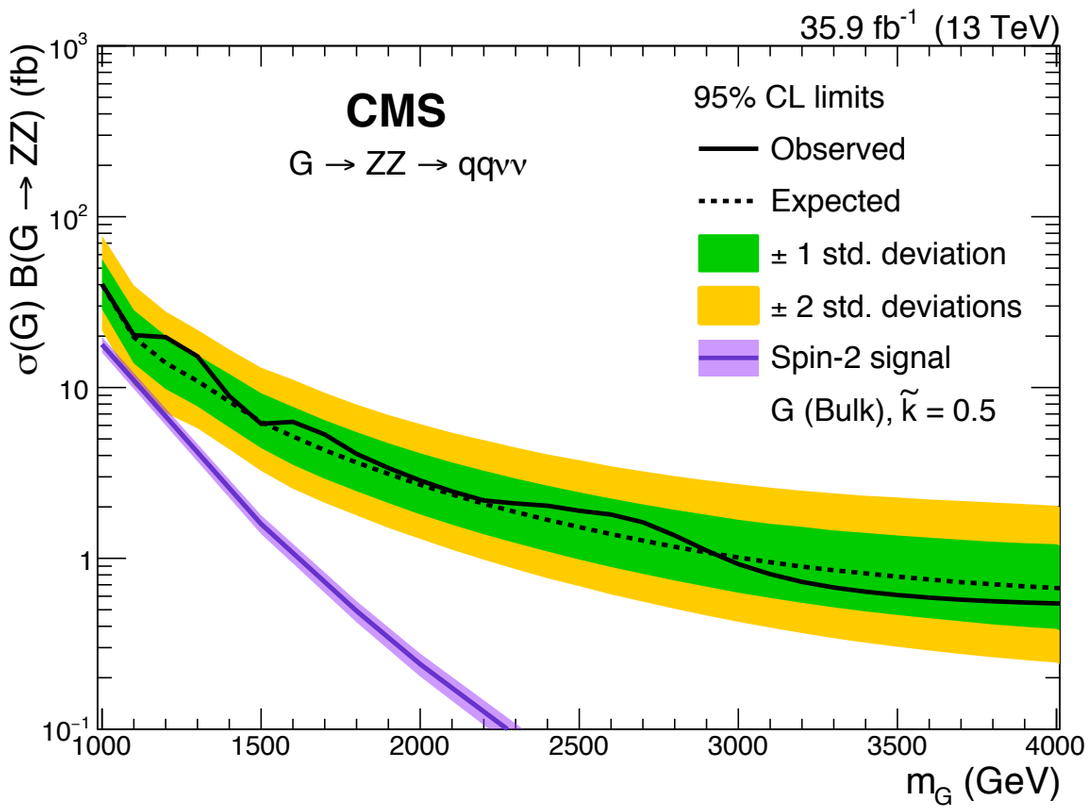
Expected background shapes vs. transverse mass:

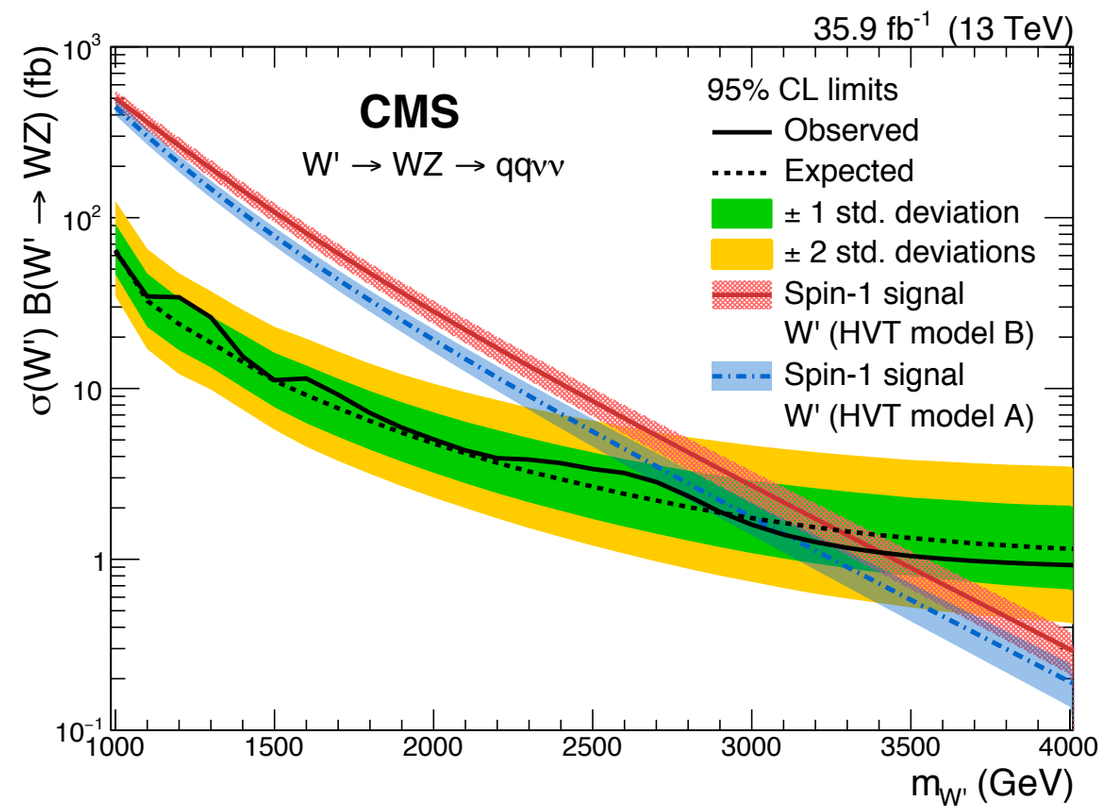


X→ZV→ννqq search

Submitted to JHEP
(CMS-B2G-17-005)

Results are interpreted as 95% CL limits on σ×*B* for bulk graviton → ZZ, and for W'→WZ in HVT models A and B:





X→ZV→llqq search

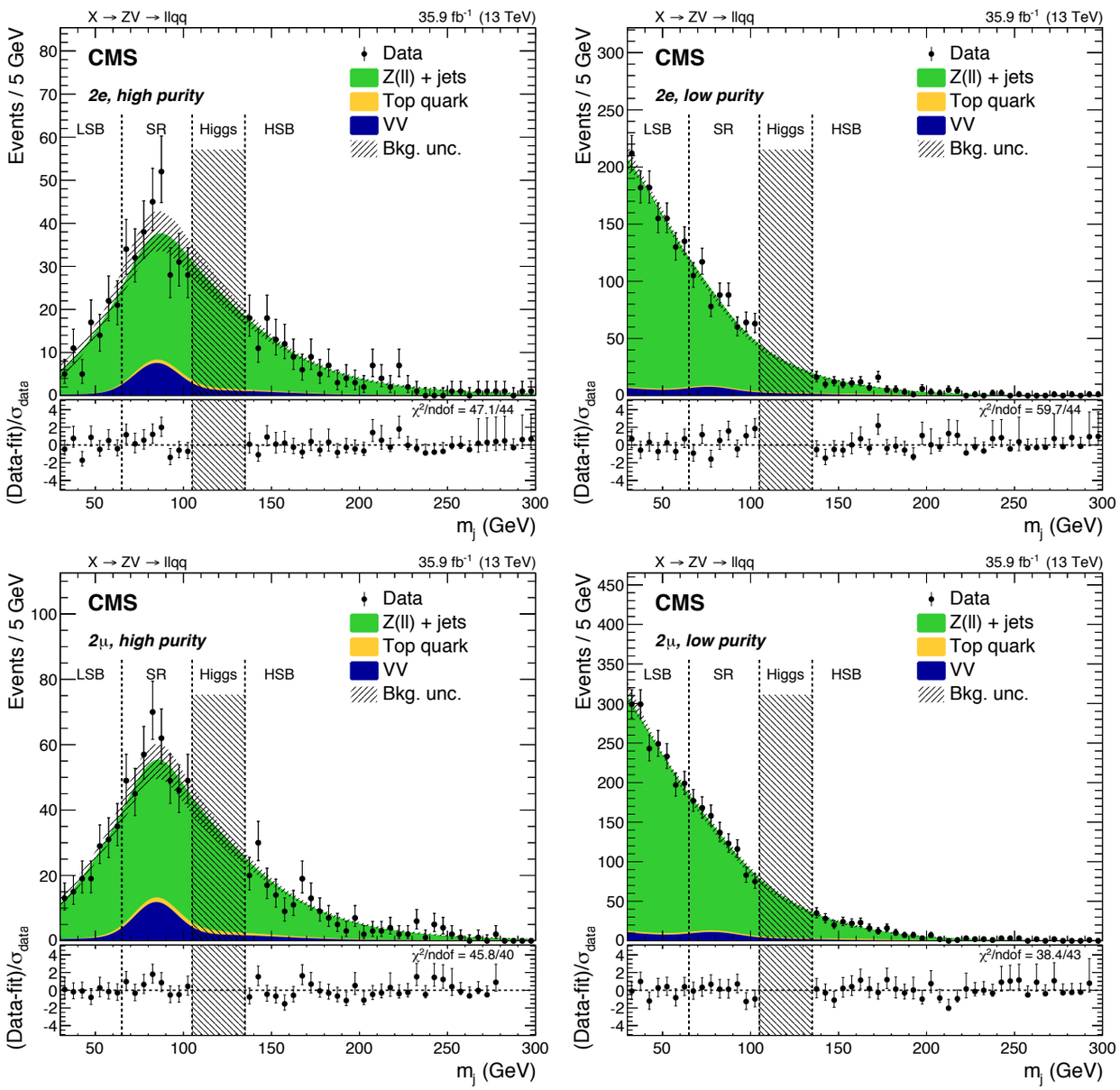
Submitted to JHEP
(CMS-B2G-17-013)

High-mass analysis

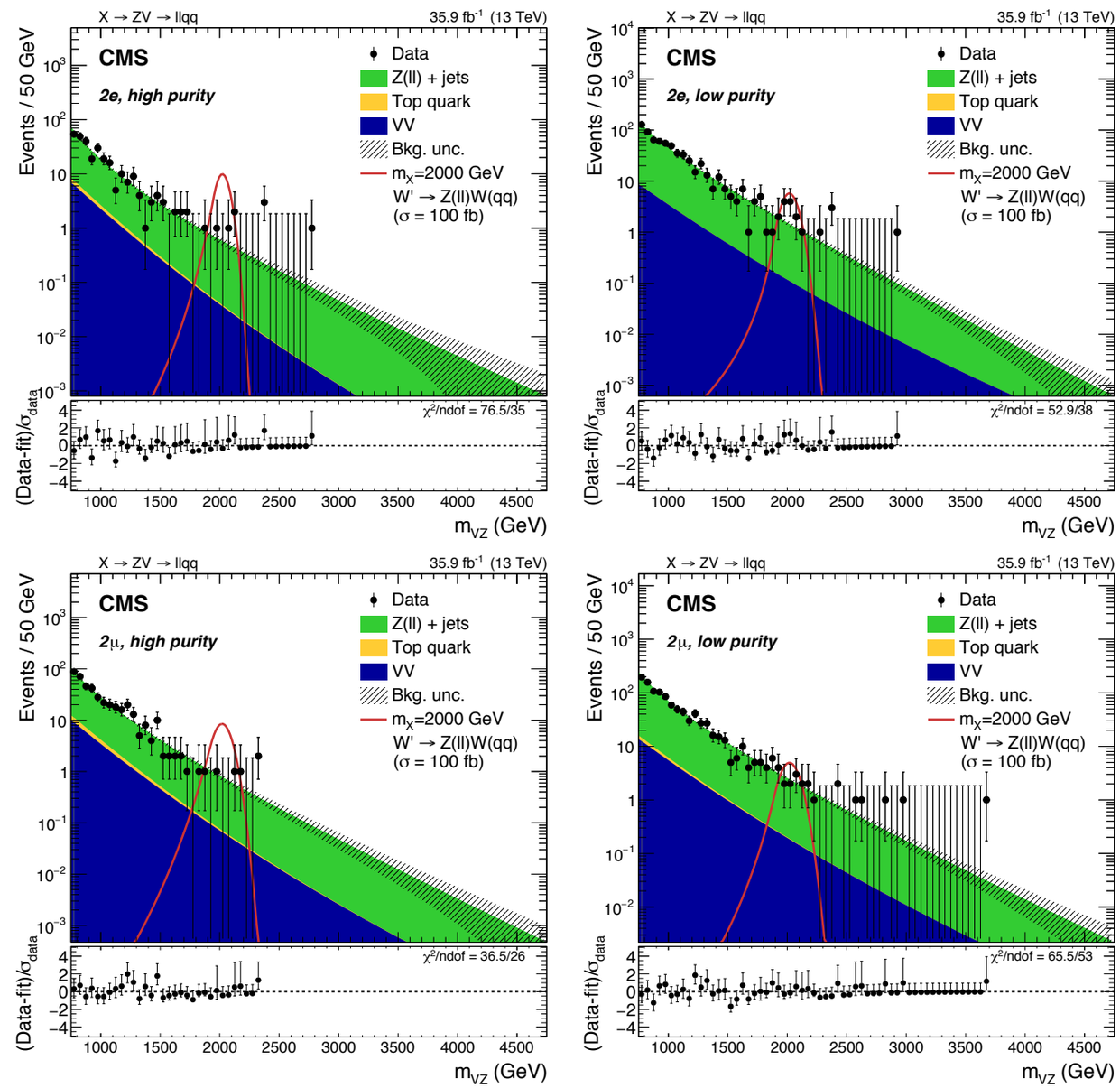
4 search categories: (e, μ) × (HP, LP)

Background estimated via α method:

fits of soft-drop mass distributions



expected background shapes of m_{VZ}



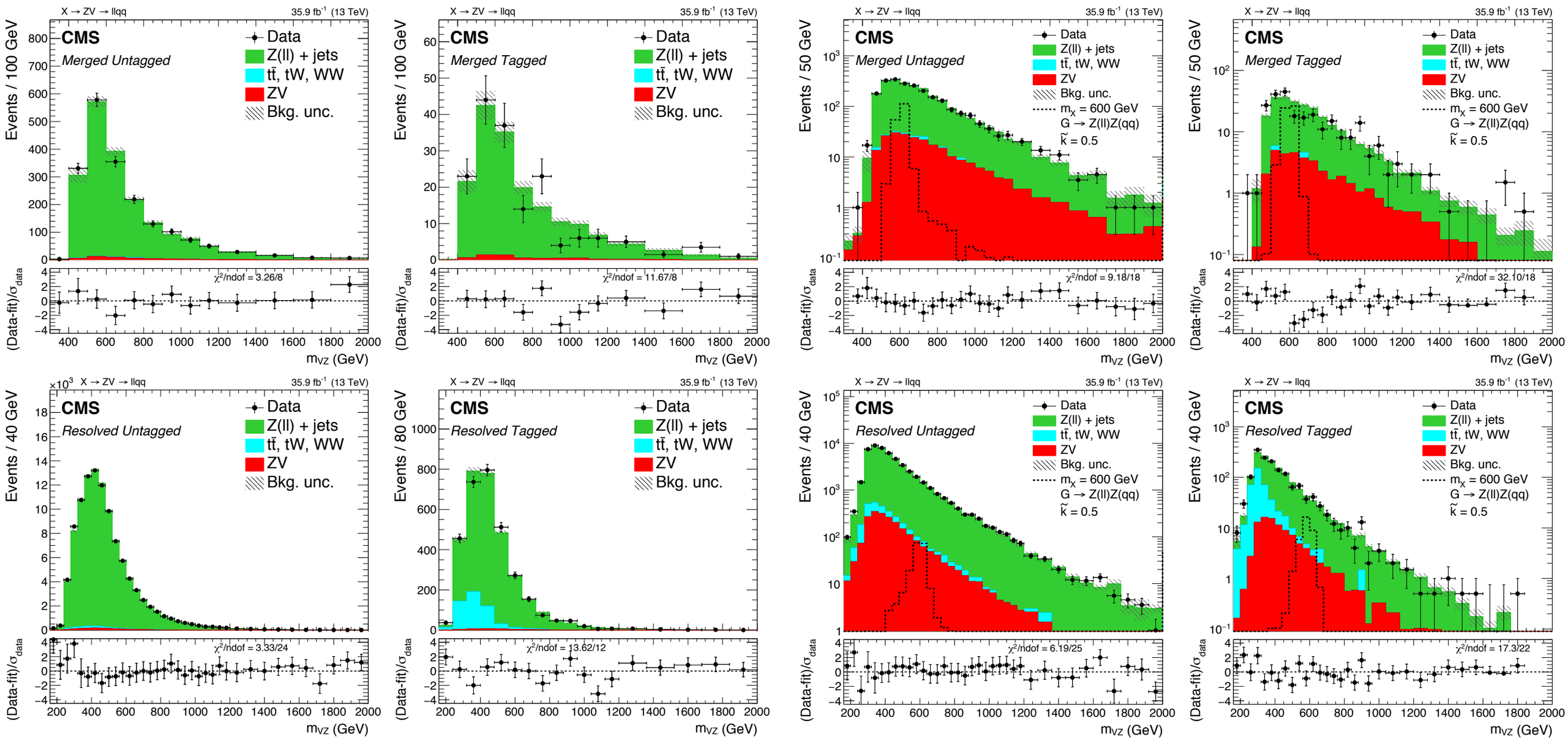
X→ZV→llqq search

Submitted to JHEP
(CMS-B2G-17-013)

Low-mass analysis

8 search categories: (e, μ) × (merged, resolved) × b tagging

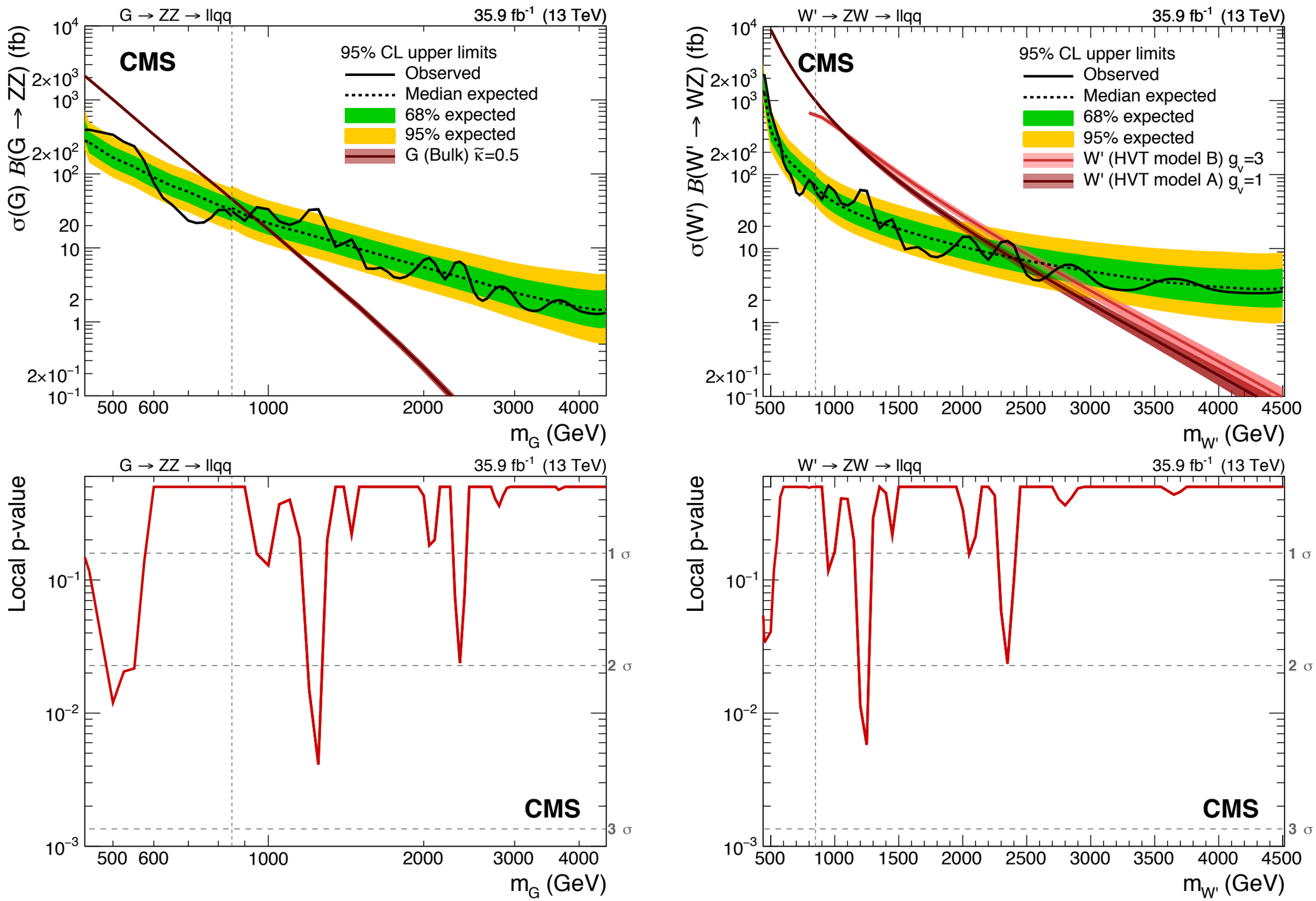
Background estimated from simulated events; normalization constrained by jet mass sidebands; shapes corrected with linear correction functions.



X→ZV→llqq search

Submitted to JHEP
(CMS-B2G-17-013)

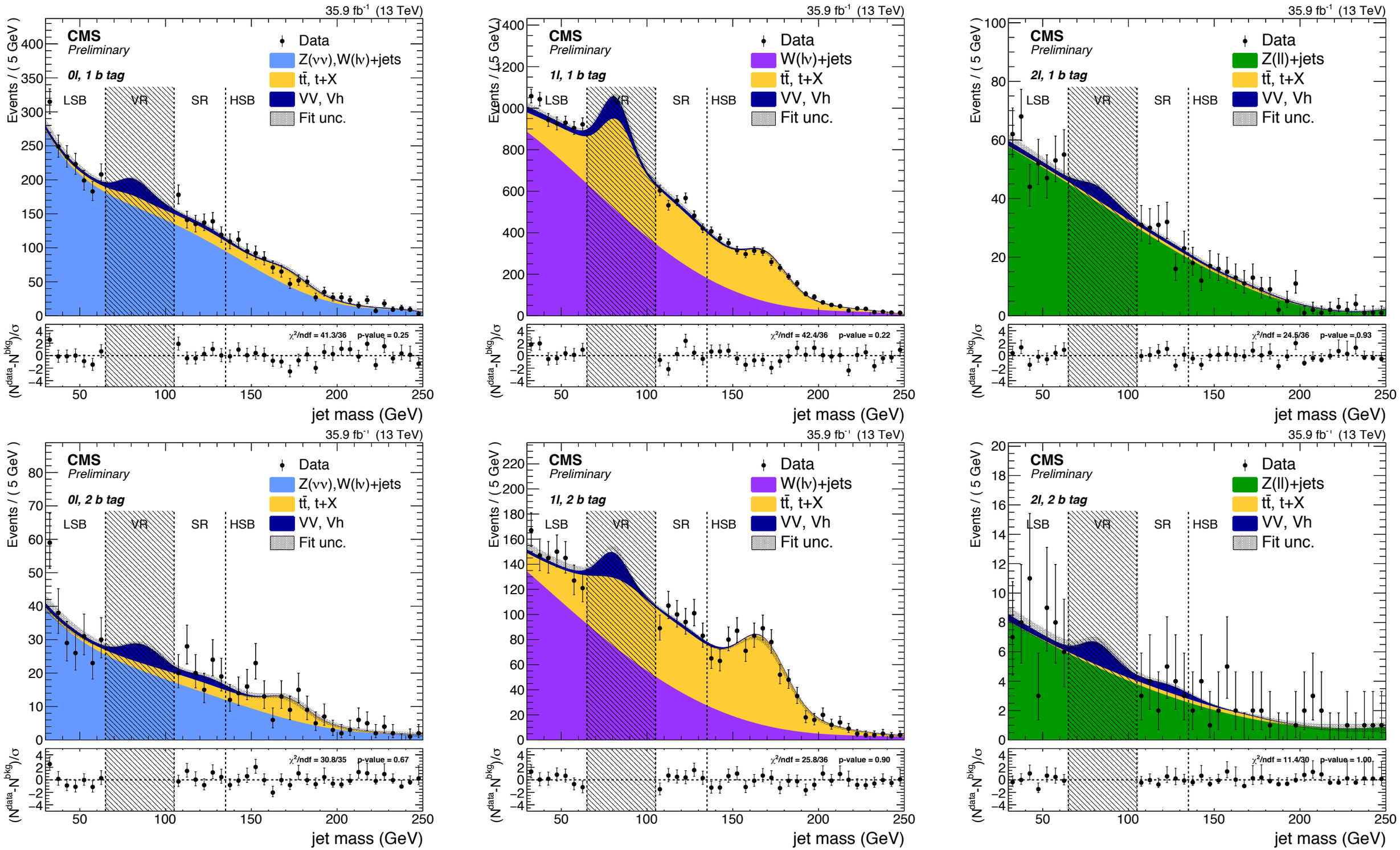
Results are interpreted as 95% CL limits on σ×*B* for bulk graviton → ZZ, and for W'→ZW in HVT models A and B:



X→VH→νν/lν/ll bb search

CMS-PAS-B2G-17-004

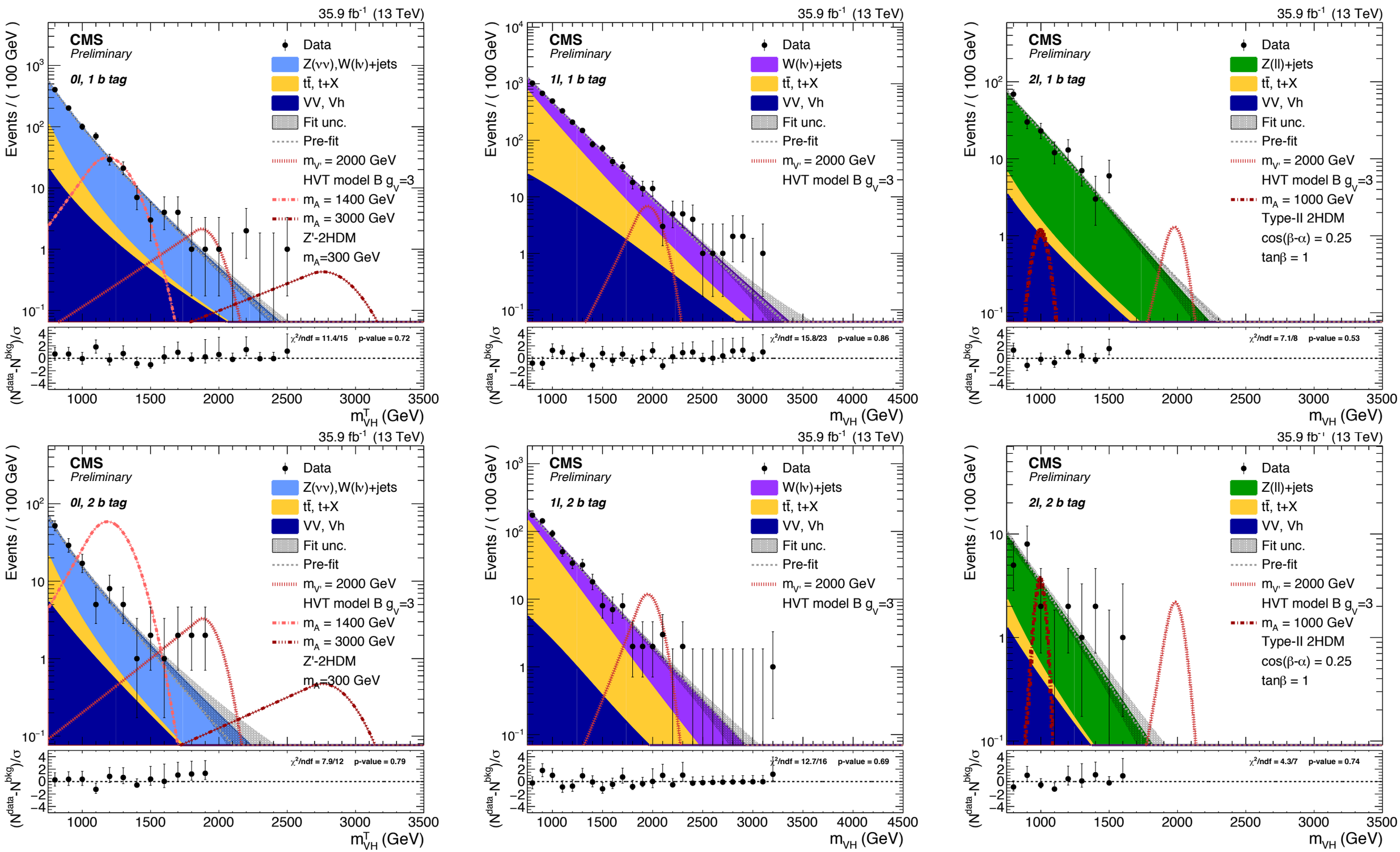
Soft-drop jet mass distributions:



X→VH→νν/lν/ll bb search

CMS-PAS-B2G-17-004

Resonance candidate mass and transverse mass distributions:



X→VH→νν/lν/ll bb search

CMS-PAS-B2G-17-004

10 search categories:
(0l, 1e, 1μ, 2e, 2μ)
× (1, 2) b-tagged subjets

Kinematic selection:

- H jet (R=0.8):
  $p_T > 200$ GeV, $|\eta| < 2.5$,
  $105 < m_j < 135$ GeV,
  ≥1 b-tagged subjet.
- **0l**: $p_T^{miss} > 200$ GeV, angular separation between jet and p_T^{miss}.
- **1l**: $p_T(e/\mu)>55$ GeV, $p_T^{miss}>80$GeV, W candidate from m_W constraint, $p_T(W) > 200$ GeV, angular separation from jet.
- **2l**: $70 < m_{ll} < 110$ GeV, $pT(Z) > 200$ GeV, angular separation from jet.

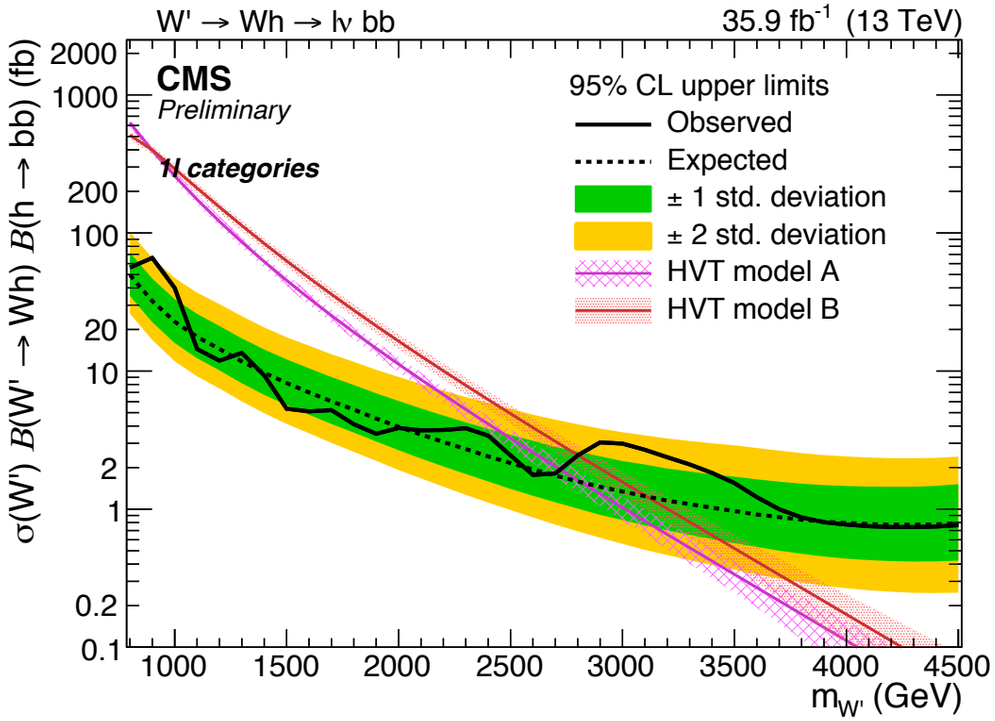
Summary of systematic uncertainties:

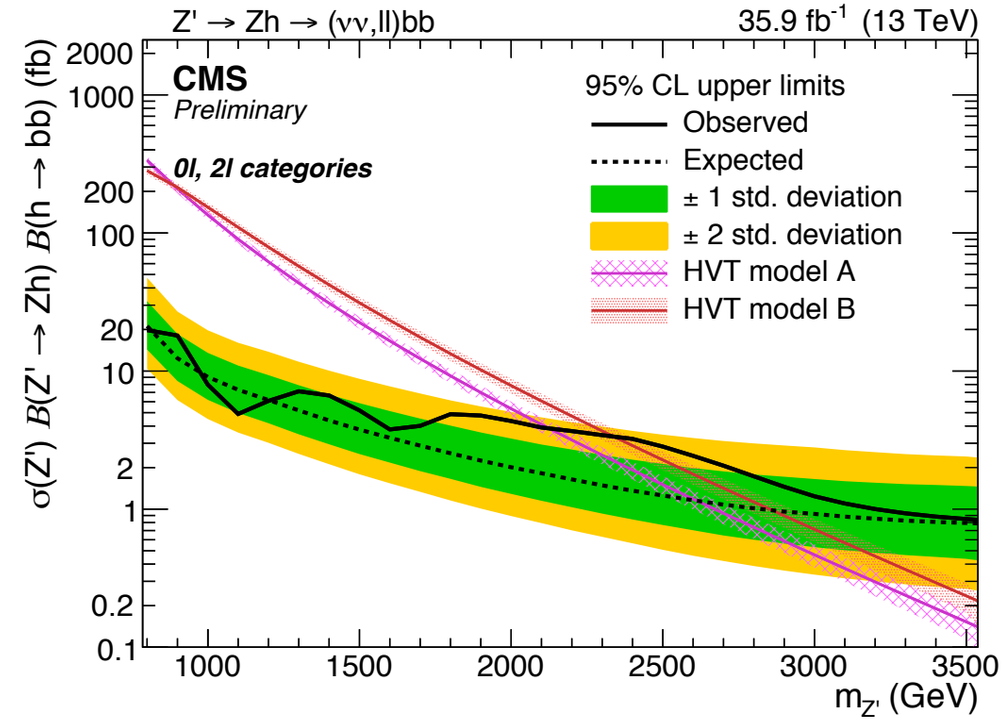
	V+jets	$t\bar{t}$, t+X	VV	Signal
bkg. normalization	2–15%	-	-	-
top scale factors	-	2–17%	-	-
jet energy scale §	-	-	3%	1%
jet energy resolution §	-	-	<1%	<1%
jet mass scale	-	-	6%	1%
jet mass resolution	-	-	6%	11%
lepton identification and isolation	-	1–3% †	2–4% (e), 4–5% (μ), 1% (0ℓ)	
lepton scale and res. §	-	-	-	1–5%
τ veto	-	-	3% (0ℓ)	
p_T^{miss} scale and res.	-	-	1%	1%
trigger	-	-	4% (e), 4% (μ), 3% (0ℓ)	
b tagging	-	3% (0ℓ, 1ℓ) 2–5% †	4% (1b) 5% (2b)	2–5% (1b) 3–7% (2b)
Higgs boson jet	-	-	-	6%
top quark p_T	-	6–14% †	-	-
pileup	-	<1% †	<1%	<1%
factorization and renormalization scales	-	21% †	19%	3–28% ‡
PDF normalization	-	5% †	5%	8–36% ‡
PDF acceptance	-	2% †	<2%	<1%
luminosity	-	-	2.5%	2.5%

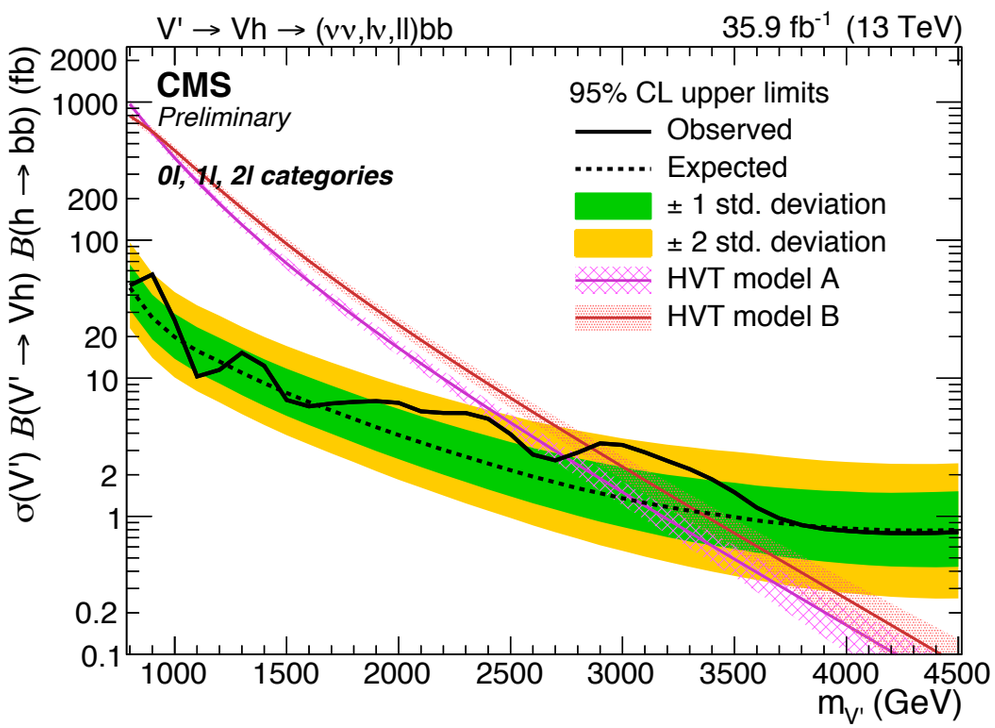
X→VH→νν/lν/ll bb search

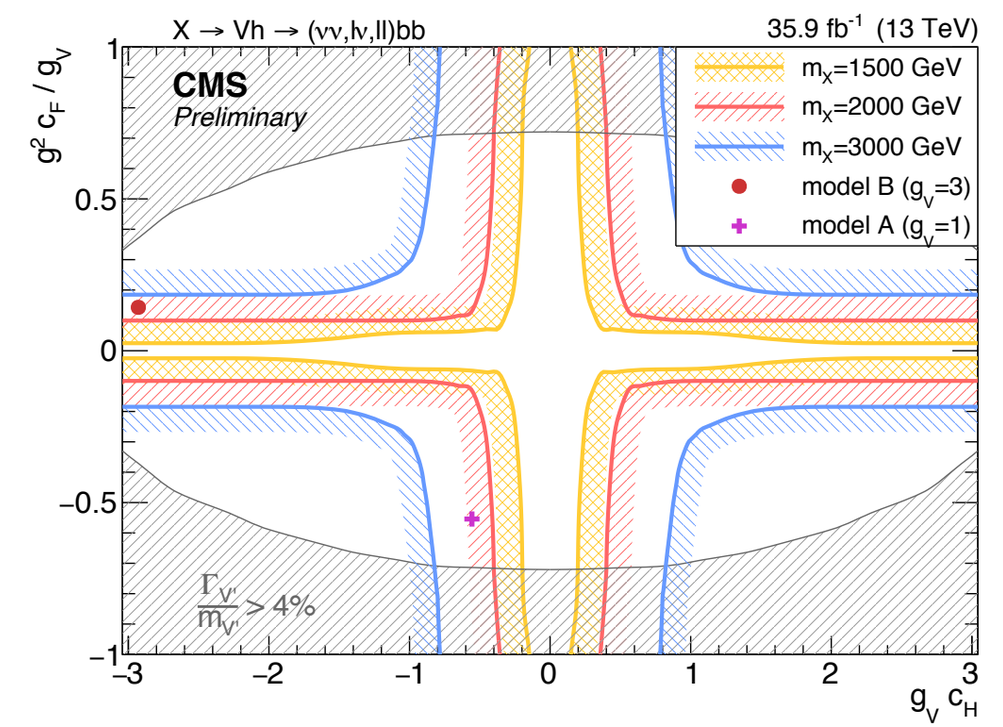
CMS-PAS-B2G-17-004

Results are interpreted as 95% CL limits on σ×*B* for W'→WH (1l), Z'→ZH (0l, 2l), and V'→VH (summing the mass-degenerate W′ and Z′) for HVT models A and B:







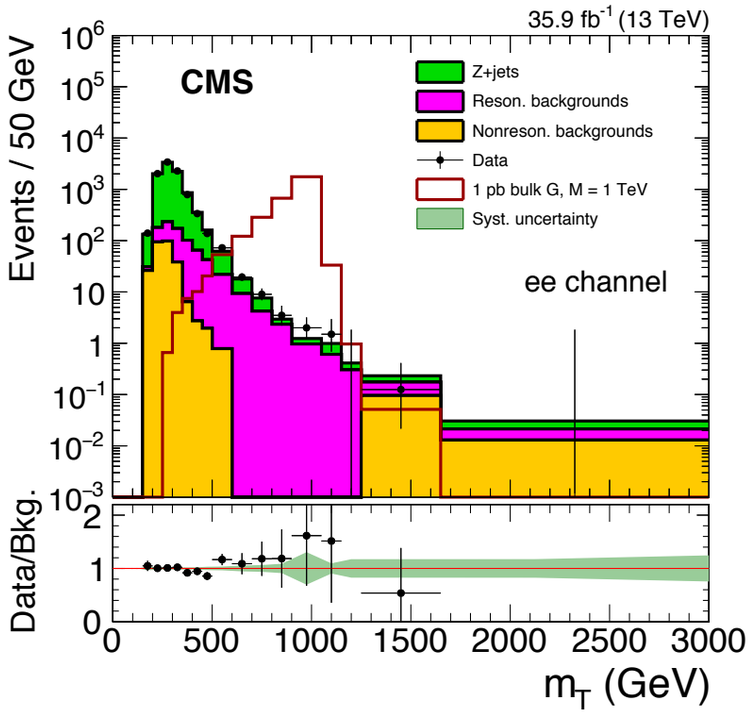


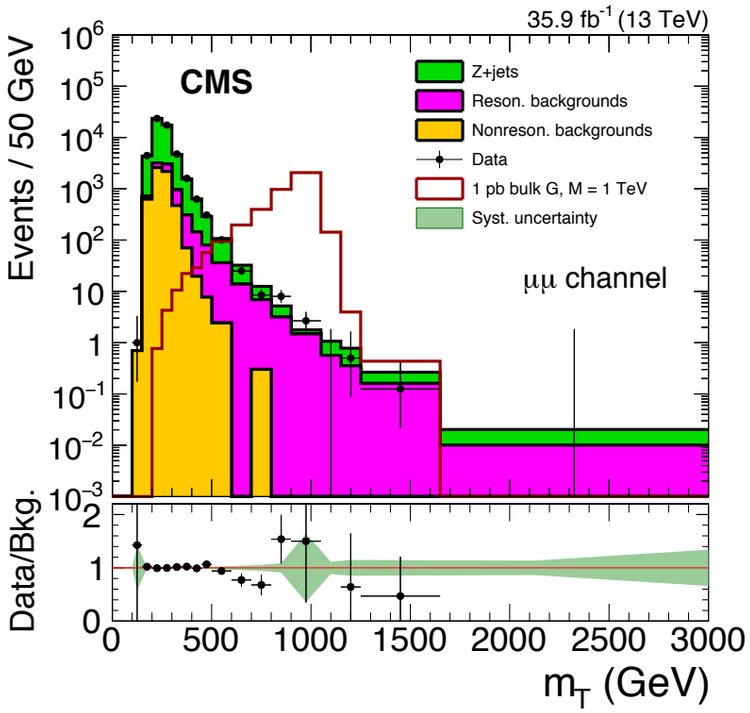
X→ZZ→llνν search

JHEP 03 (2018) 003
(CMS-B2G-16-023)

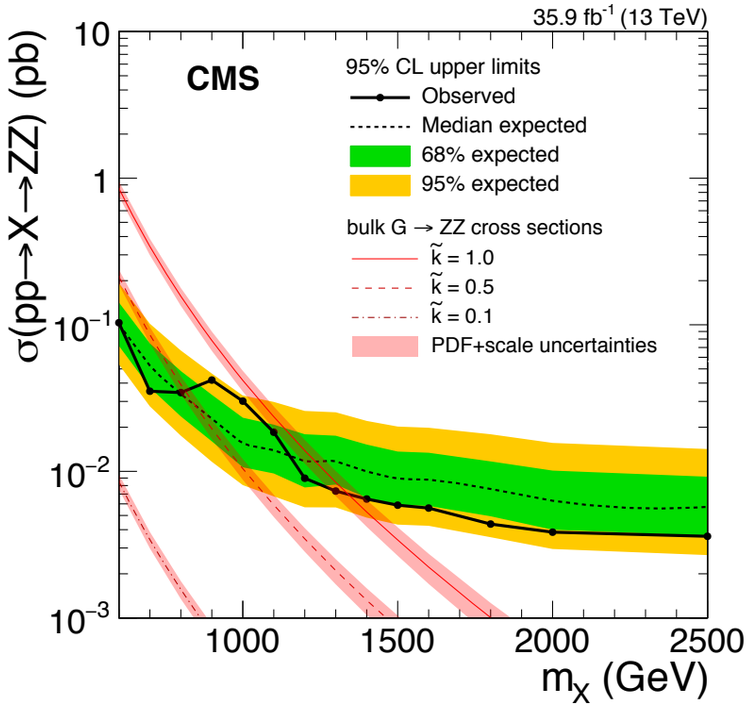
2 oppositely charged leptons ($70 < m_{ll} < 110$ GeV) and large missing transverse momentum.

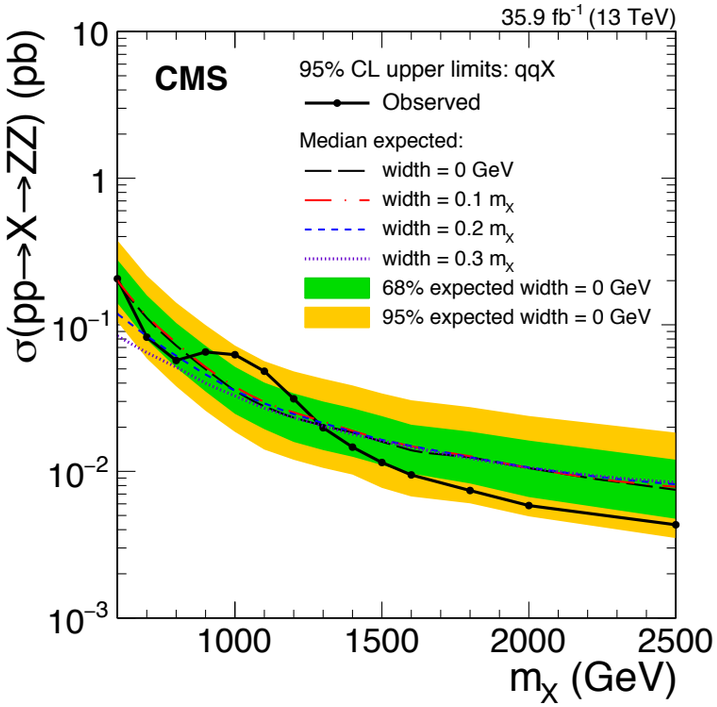
Dominant Z+jets background: estimated using a data control sample of γ+jets events (reweighted to reproduce the kinematics of Z in Z+jets events).

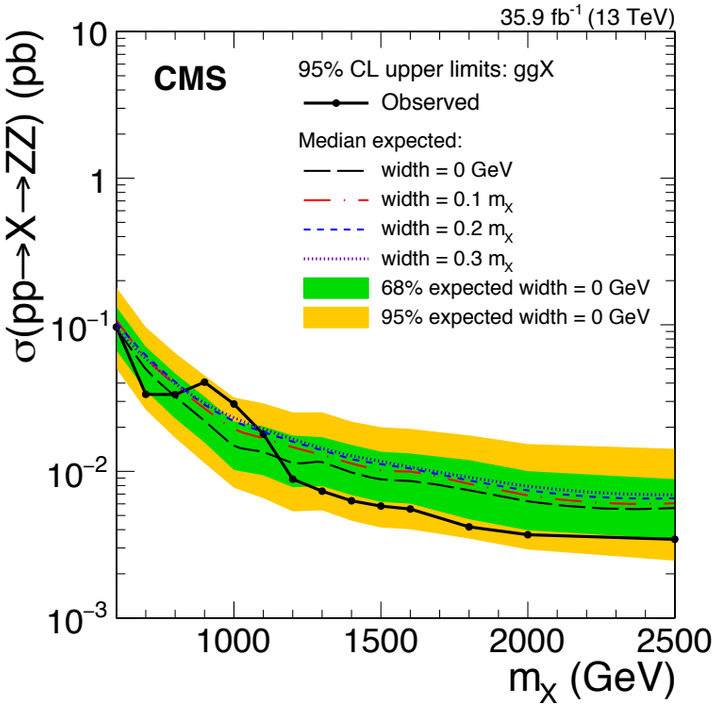




Results are interpreted as 95% CL limits on σ×*B* for bulk graviton → ZZ, either zero-width and various $\tilde{k}$, or wide widths :



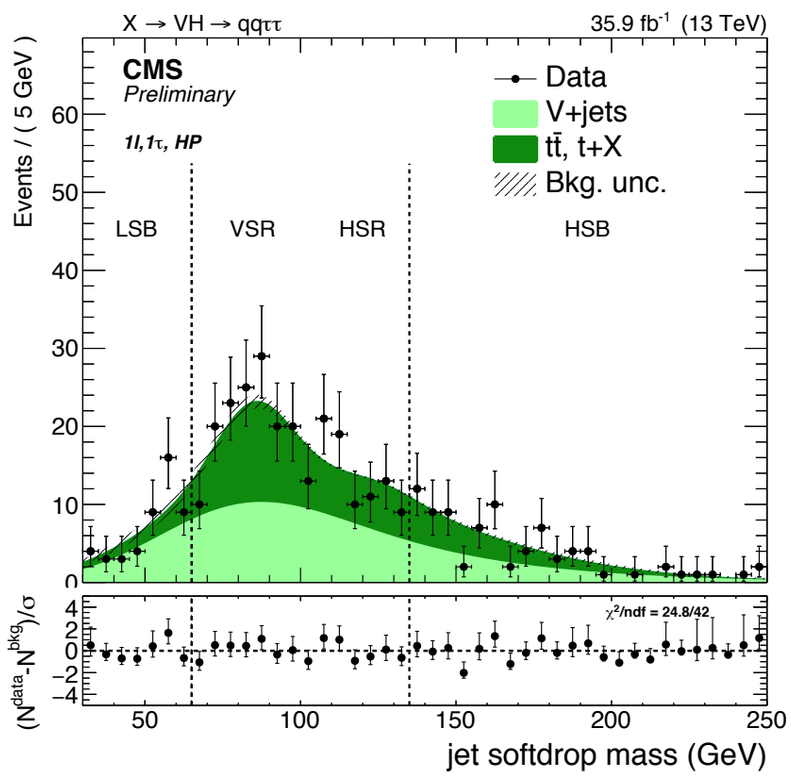


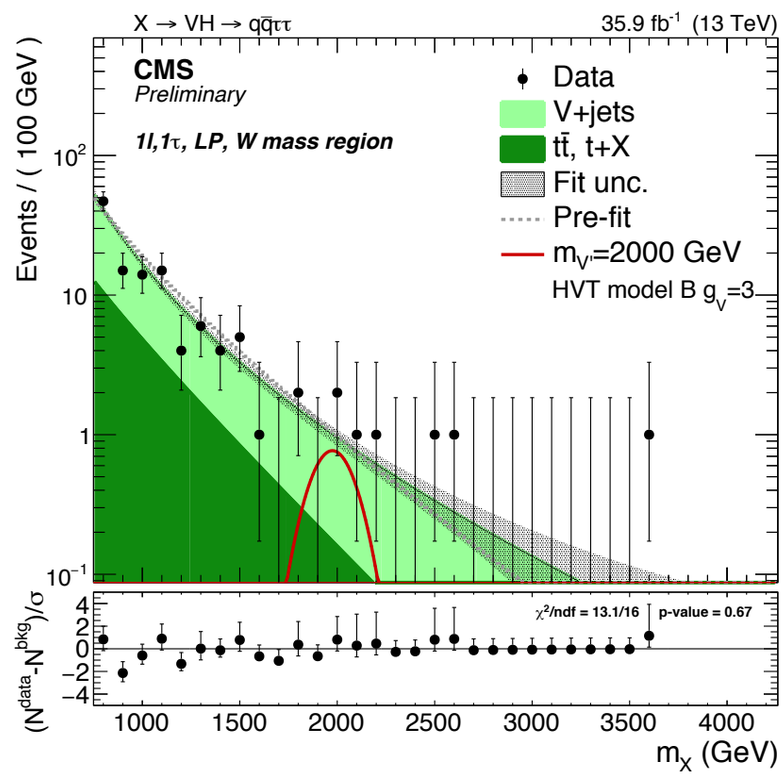


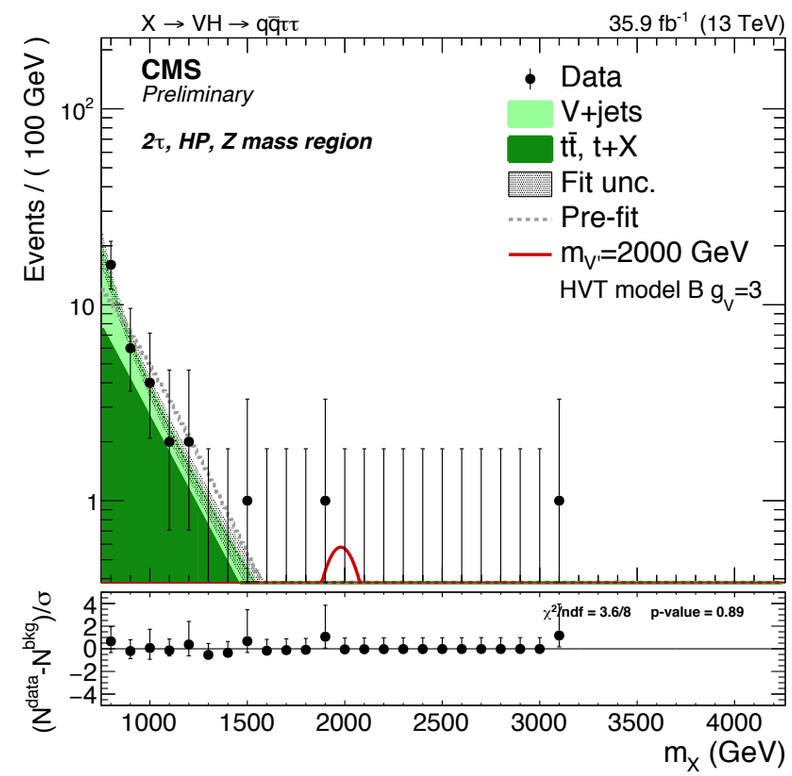
X→VH→qqττ

CMS-PAS-B2G-17-006

- Part of a larger analysis including HH → bbττ
- 8 search categories: ($\tau_l\tau_h$, $\tau_h\tau_h$) × (HP, LP) × (W/Z mass window)
- V+jets background handled by α method;
  tt from a control region with b tagged jet.
- Examples of distributions of soft-drop mass and m_{VH} in some categories:







X→VH→qqττ

CMS-PAS-B2G-17-006

Results are interpreted as 95% CL limits on σ×*B* for W'→WH, Z'→ZH, and V'→VH (summing the mass-degenerate W′ and Z′) for HVT models A and B: