New Physics Results (boosted signatures) from the LHC

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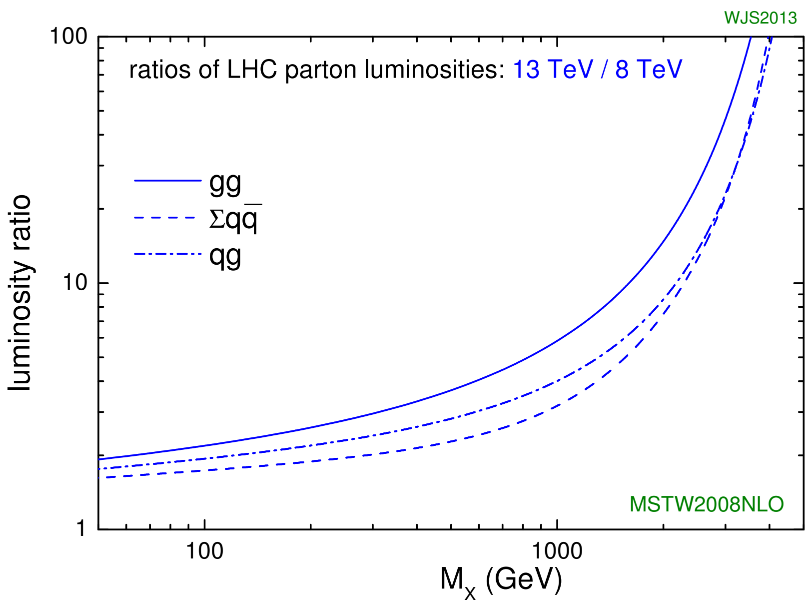
Introduction

- Many searches at LHC look for new physics with diboson in the final sates.
- Data collected at LHC so far have been found to be in good agreement with the predictions from the Standard Model
- However, many questions remain unanswered:
    - Baryogenesis: imbalance of matter and anti-matter
    - The Hierarchy problem
    - Dark matter and gravity

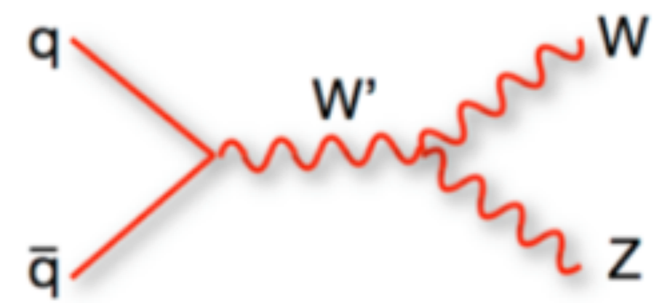


- Many theories attempting to address these issues predict new physics with diboson in the final states
- Finding such new physics via diboson final states will be expedited in Run 2 of LHC with an increased center-of-mass energy.

Theoretical models

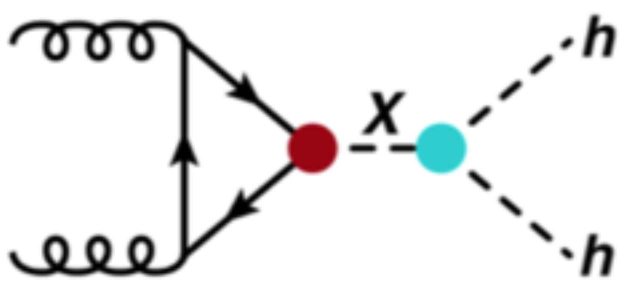
1. Heavy Vector Triplets (HVT)

- A simplified phenomenological Lagrangian:
  - Model A: coupling to fermions dominating; weakly coupled vector resonances from extension of the gauge group, $g_V \sim 1$, $c_H \sim -g^2/g_V^2$
  - Model B: coupling to fermions suppressed; produced in a strong scenario (composite Higgs models), $1 < g_V < 4\pi$, $c_H \sim c_F \sim 1$
- *WW, WZ, Vh* final states



2. Warped Extra Dimension

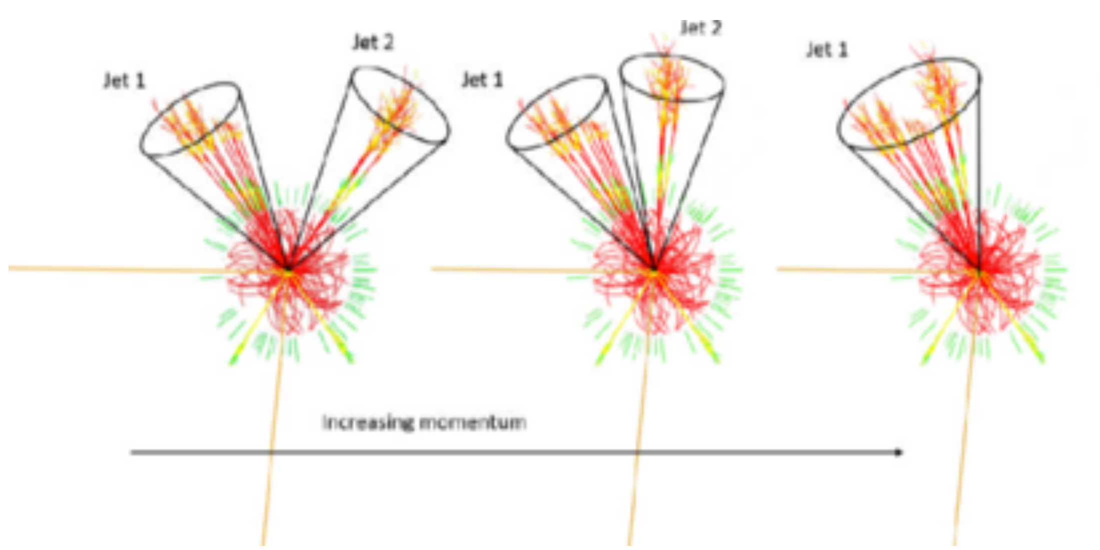
- Randall-Sundrum (RS) model
- Existence of spin-2 Kaluza-Klein (KK) gravitons at TeV scale
  - Cross section and intrinsic width scale as the square of $k/\bar{M}_{pl}$
- *WW, ZZ, hh* final states

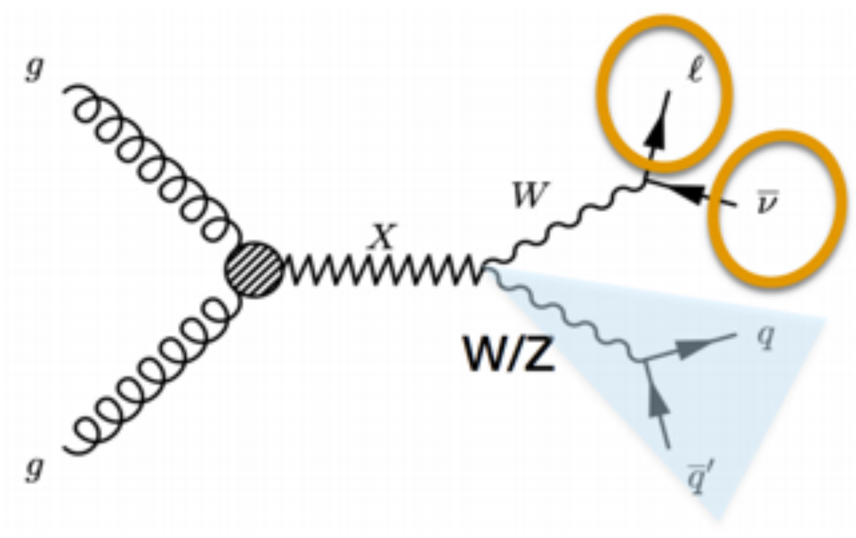


KK gravitons, heavy higgs, …

3. MSSM/2HDM etc.

Identification of hadronic decays of boosted bosons

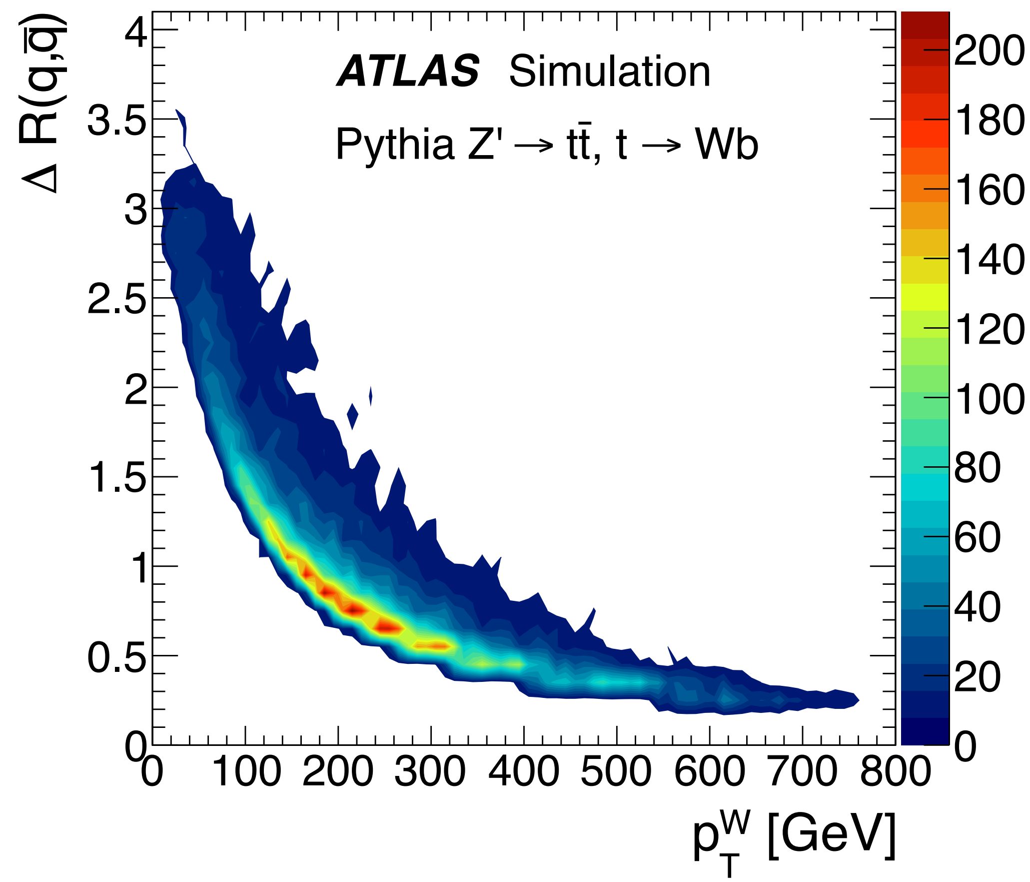




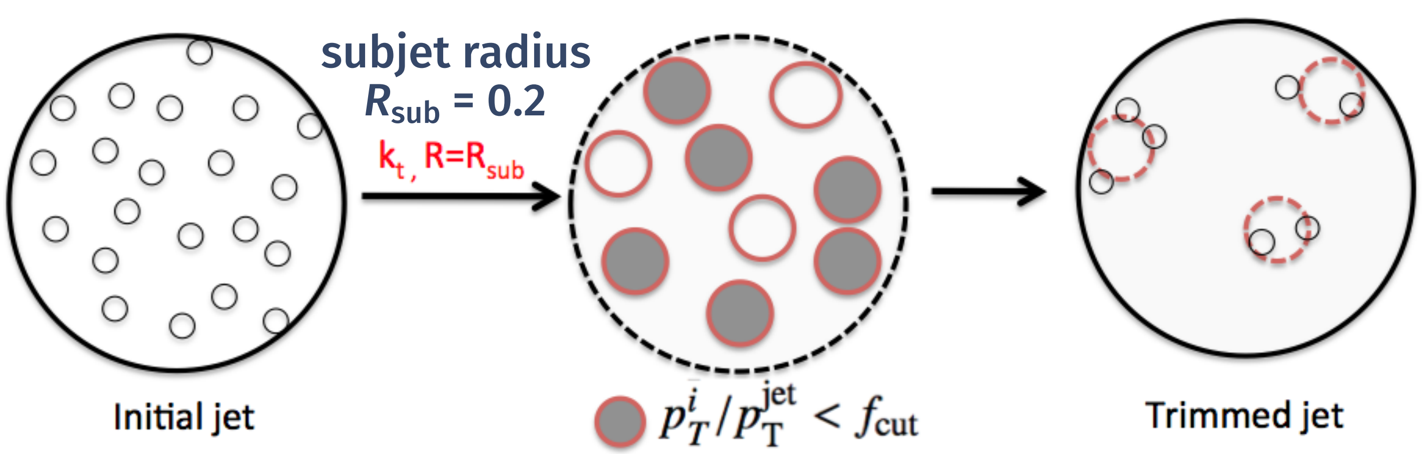
Boosted Tagging: ATLAS

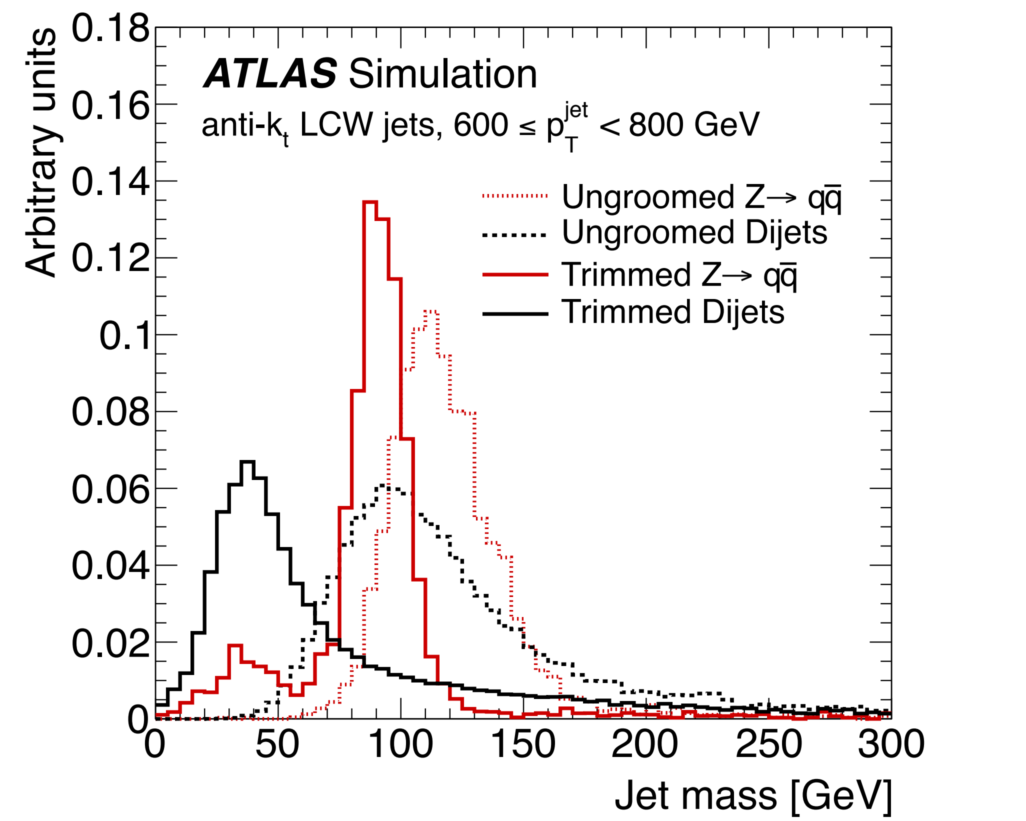
JHEP09 (2013) 076

- Large-R jet: anti-k_T R = 1.0 trimmed jets
- Jet grooming technique: trimming
  - To remove the effects of pile-up and underlying event
  - Trimming parameters: R_{sub} = 0.2 and f_{cut} = 5%



Jet trimming procedure

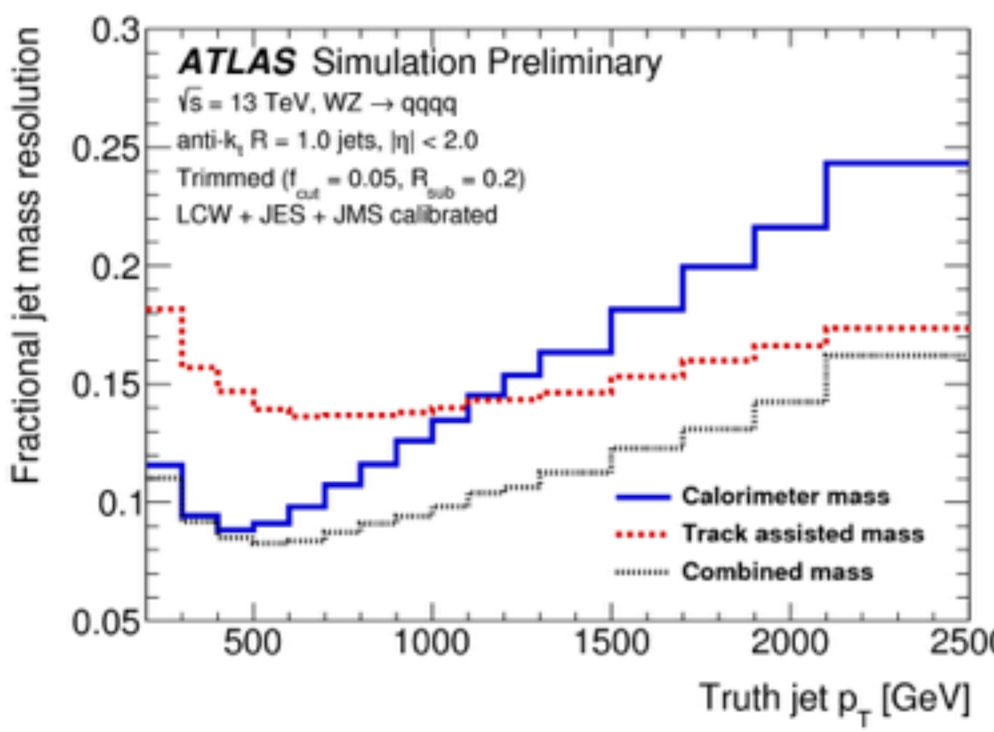


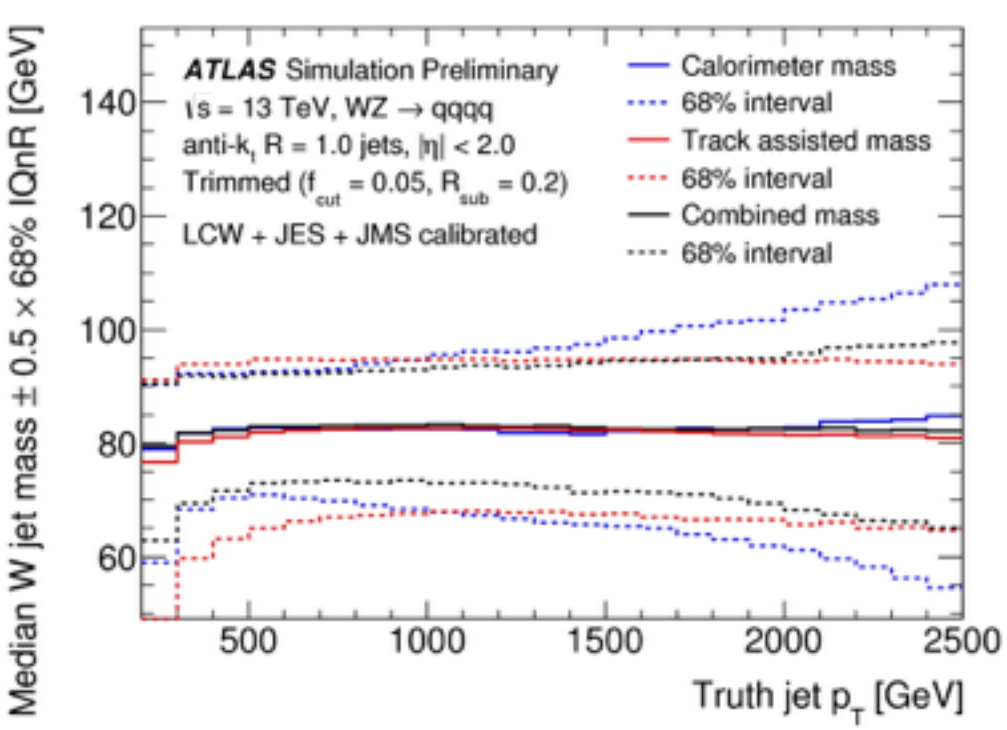


- Jet mass — combined mass
  - Track-assisted mass: $m^{\mathrm{TA}} = m^{\mathrm{track}} \times \frac{p_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{\mathrm{track}}}$
  - Spatial granularity of tracks can improve the mass resolution at high p_{T}
  - Combined mass based on both calorimeter and track:

$$m^{\mathrm{comb}} = \frac{\sigma_{\mathrm{calo}}^{-2} m^{\mathrm{calo}} + \sigma_{\mathrm{TA}}^{-2} m^{\mathrm{TA}}}{\sigma_{\mathrm{calo}}^{-2} + \sigma_{\mathrm{TA}}^{-2}}$$

  - where σ_{calo} and σ_{TA} are the calorimeter and track-assisted mass resolutions

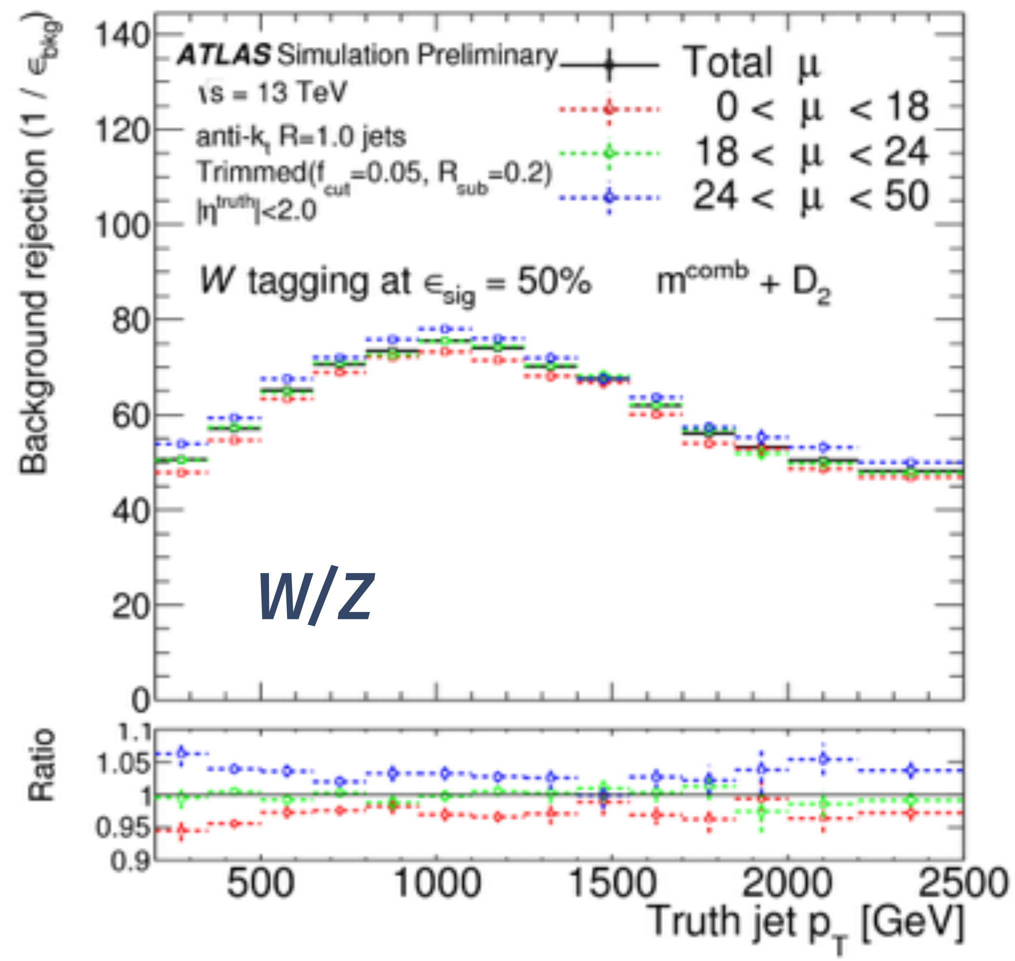


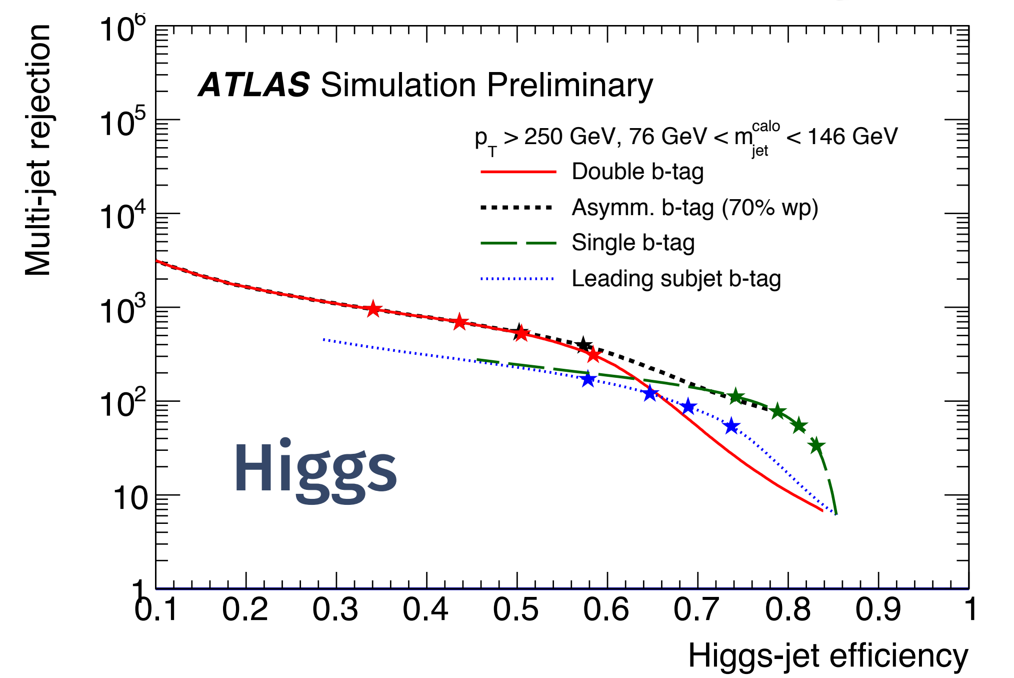


Boosted Tagging: ATLAS

ATLAS-CONF-2016-039 ATLAS-CONF-2017-064

- *W/Z* tagger: 2-var optimized tagger which provides 50% and 80% signal efficiency working points. The two variables are:
  - Jet substructure $D_2^{(\beta=1)}$ (cut is p_T dependent) **"two-prong"**
  - Large-R jet mass window (cut is p_T dependent)
- Higgs-jet tagger:
  - *b*-tagging of ghost-associated track jet (R=0.2)
    - MV2c10 algorithm for *b*-jet ID
  - A fixed large-*R* jet mass window cut



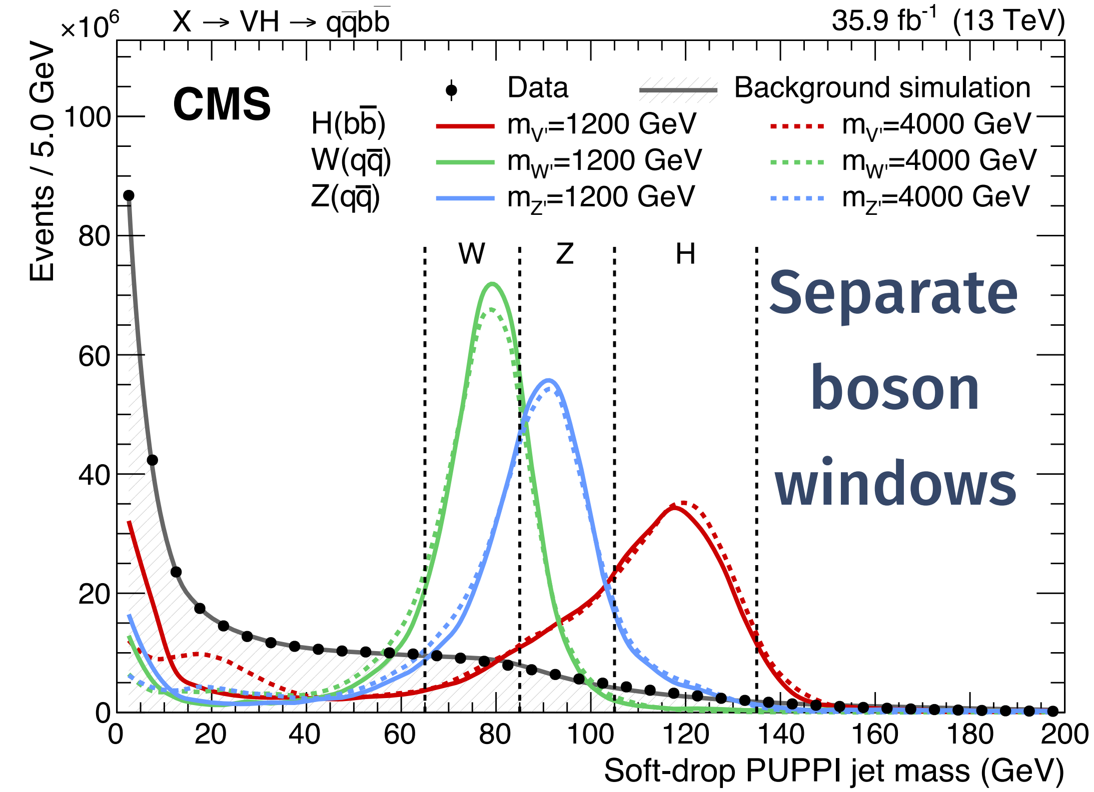


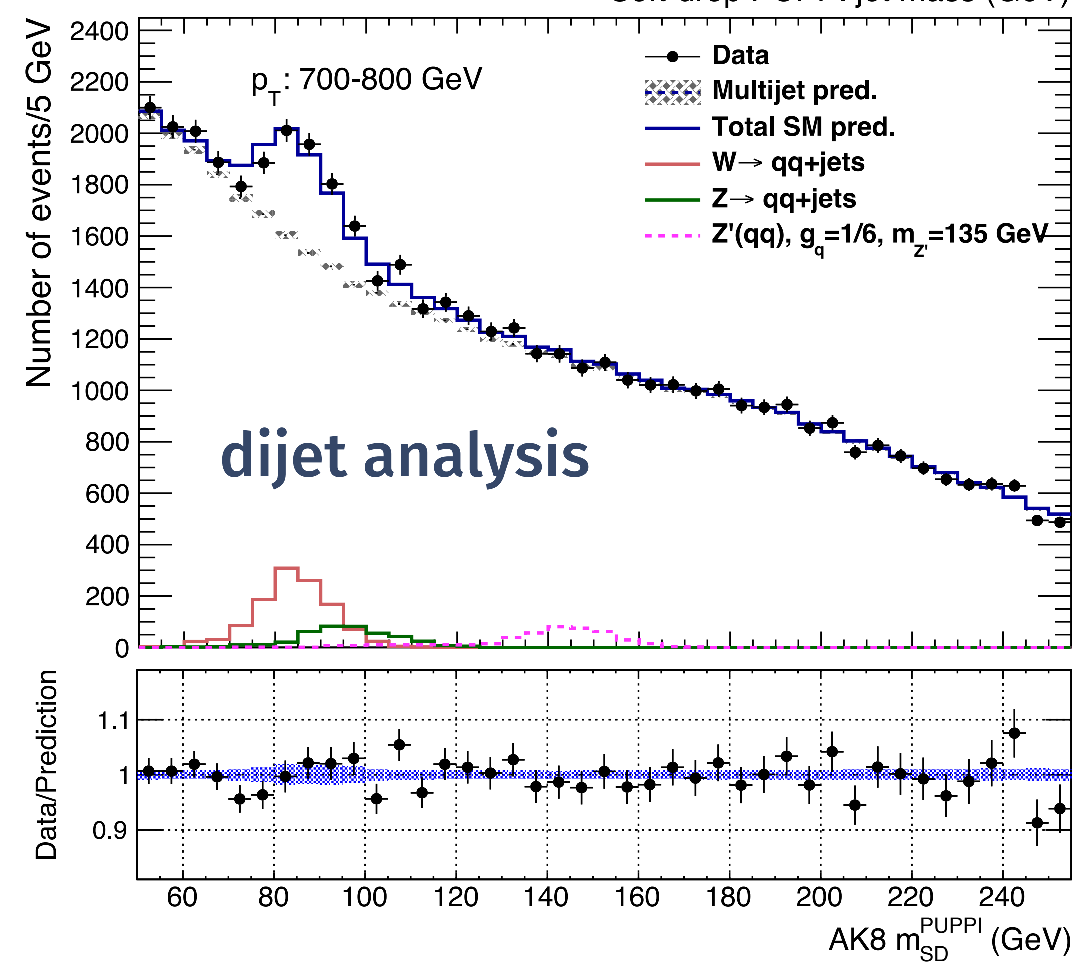
Stars: 60%, 70%, 77% and 80% WPs (left to right)

Boosted Tagging: CMS

EXO-17-001 B2G-17-002

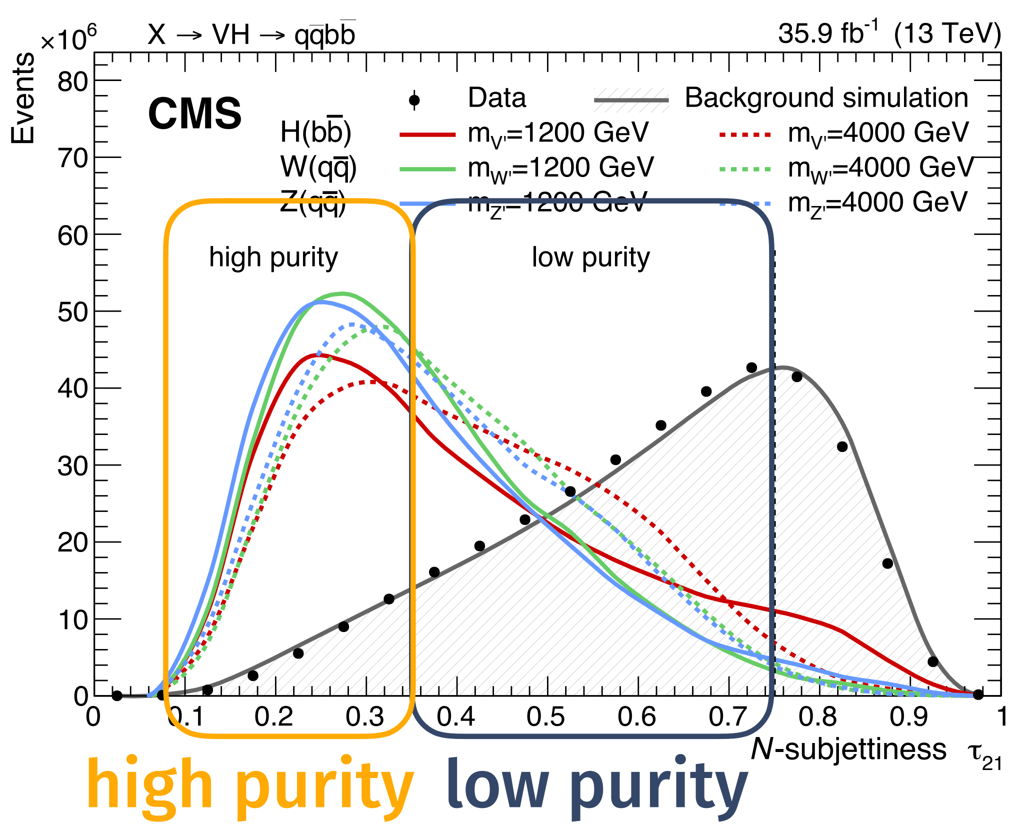
- PUPPI AK8 jets — Pileup suppression:
  - Each PF particle is assigned a weight using the pileup per particle identification (PUPPI), which describes the likelihood that the particle originates from a pileup interaction
  - Four momenta of particles are rescaled based on the weights
  - Particles are subsequently clustered into AK8 jets (anti-k_T, R = 0.8)
- Jet mass — soft-drop algorithm:
  - Applied to PUPPI AK8 jets
  - Recursively removes soft wide-angle radiation from a jet
  - Infrared and collinear safe

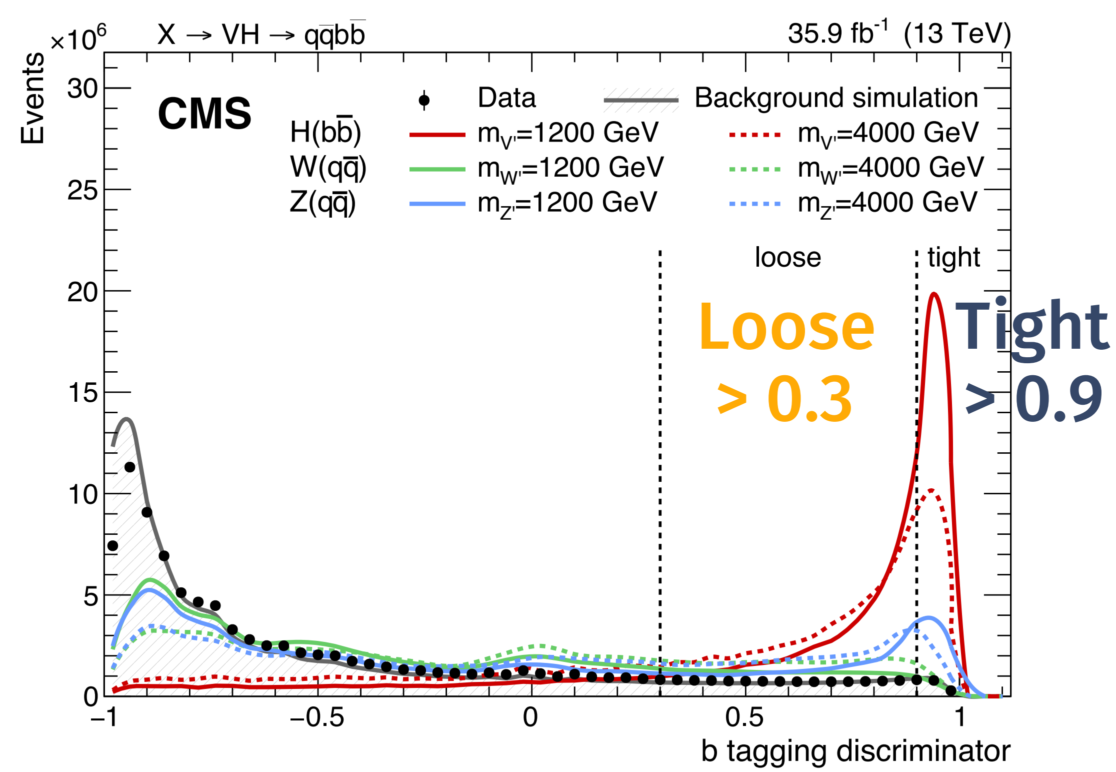




Boosted Tagging: CMS

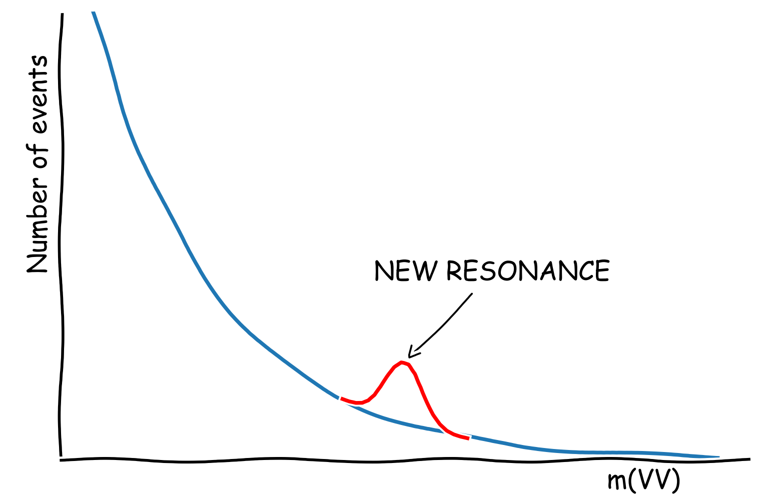
- Substructure variable — τ_{21}:
  - τ_N (*N*-subjettiness) describes the degree to which a jet is consistent with having ≤N sub-jets;
  - $\tau_{21} = \tau_2/\tau_1$ separating bosons jets from *q*/*g* jets; high- and low-purity regions based on the value of τ_{21}
- In addition to τ_{21}, **double-*b* tagger** for boosted Higgs candidates:
  - MVA to discriminate between $H \to bb$ and background multi-jet production
  - "Loose" requirement: > 0.3; "tight" requirement: > 0.9





Search for resonances decaying into *VV* (*V*=*W*/*Z*)

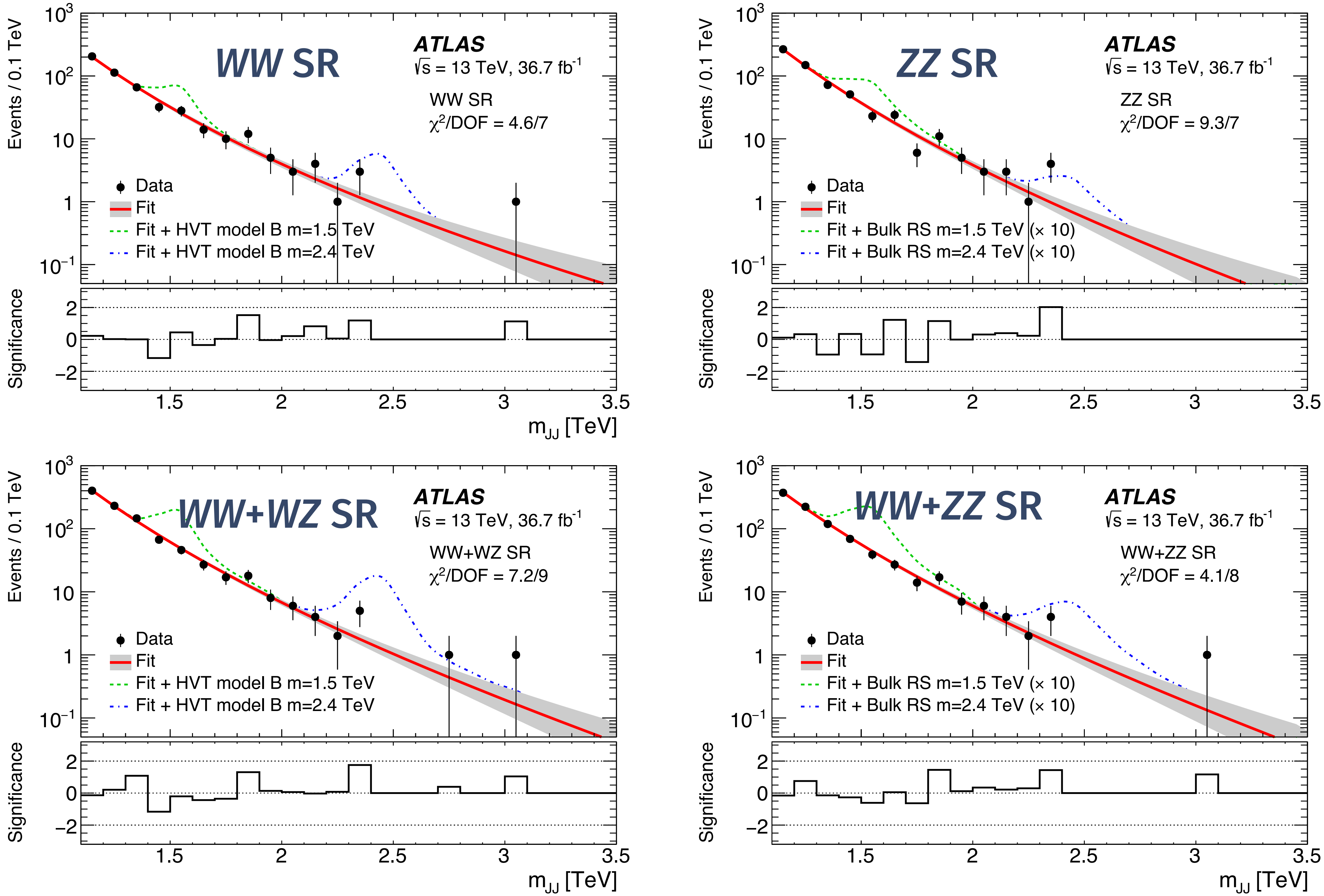
X→*VV*→*qqqq*



- Dijet final state: *WW*, *WZ*, *ZZ*
- SM multi-jet background dominates
- Background estimation using functional shape:
  - Di-jet function to model the monotonously falling spectrum
- ATLAS: 50% efficiency *W*/*Z* tagger; *WW*+*WZ* or *WW*+*ZZ* for interpretation
  - Boosted *W* and *Z* mass windows partially overlap
- CMS: High-purity + low-purity signal regions. *WW*, *WZ* and *ZZ* interpreted separately.

$X \to VV \to qqqq$: ATLAS Results

EXOT-2016-19

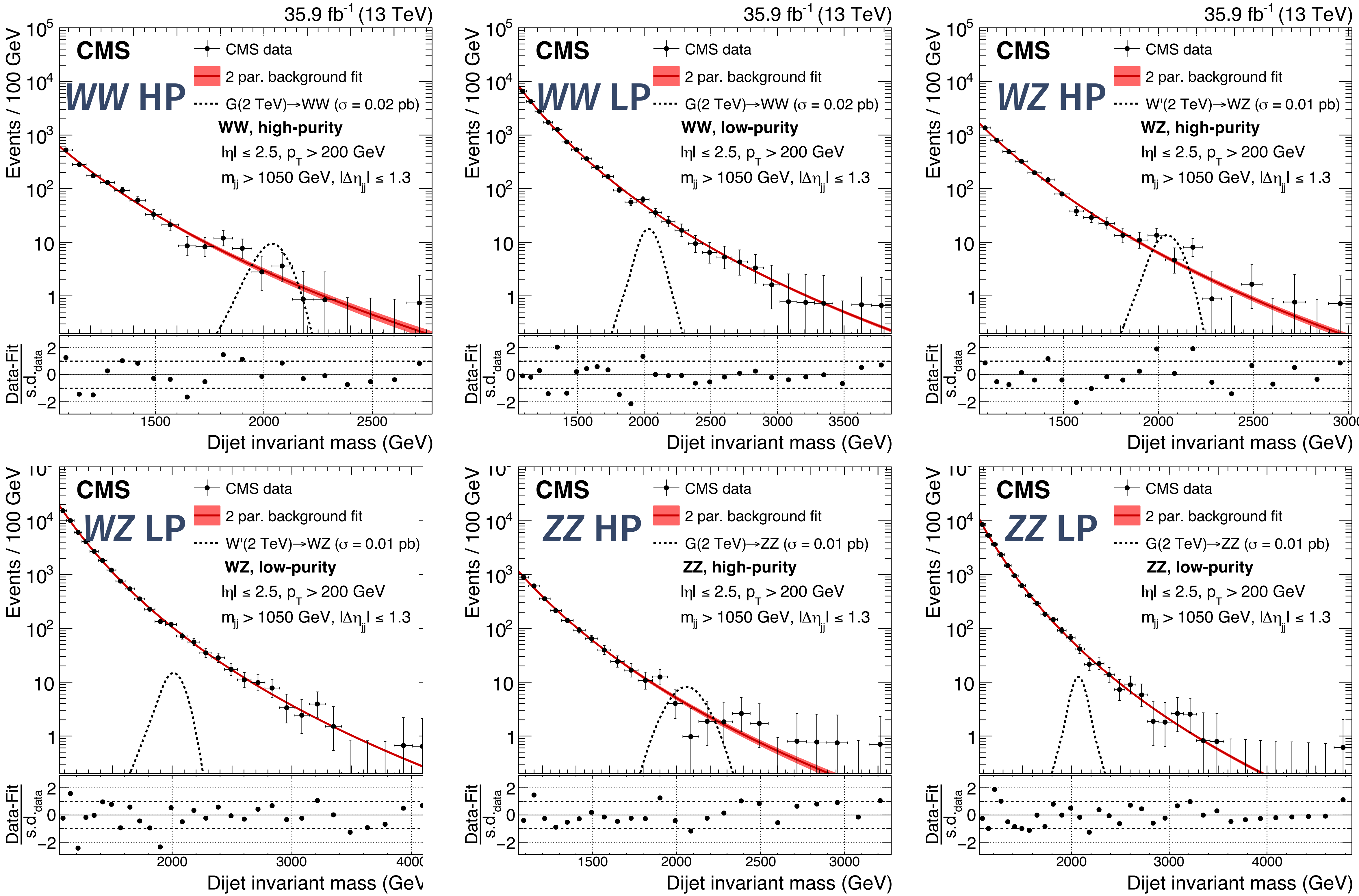


$W \to qq \to J$ and $Z \to qq \to J$ mass windows overlap; 50% efficiency WP

Background: $\frac{dn}{dx} = p_1 \cdot (1 - x)^{p_2 - \xi p_3} \cdot x^{-p_3},\ x = m_{JJ}/\sqrt{s}$

$X \to VV \to qqqq$: CMS Results

B2G-17-001



F-test: $$\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_1}} \text{ (2-par. form) or } \frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_2}}{(m_{jj}/\sqrt{s})^{P_1}} \text{ (3-par. form)}$$

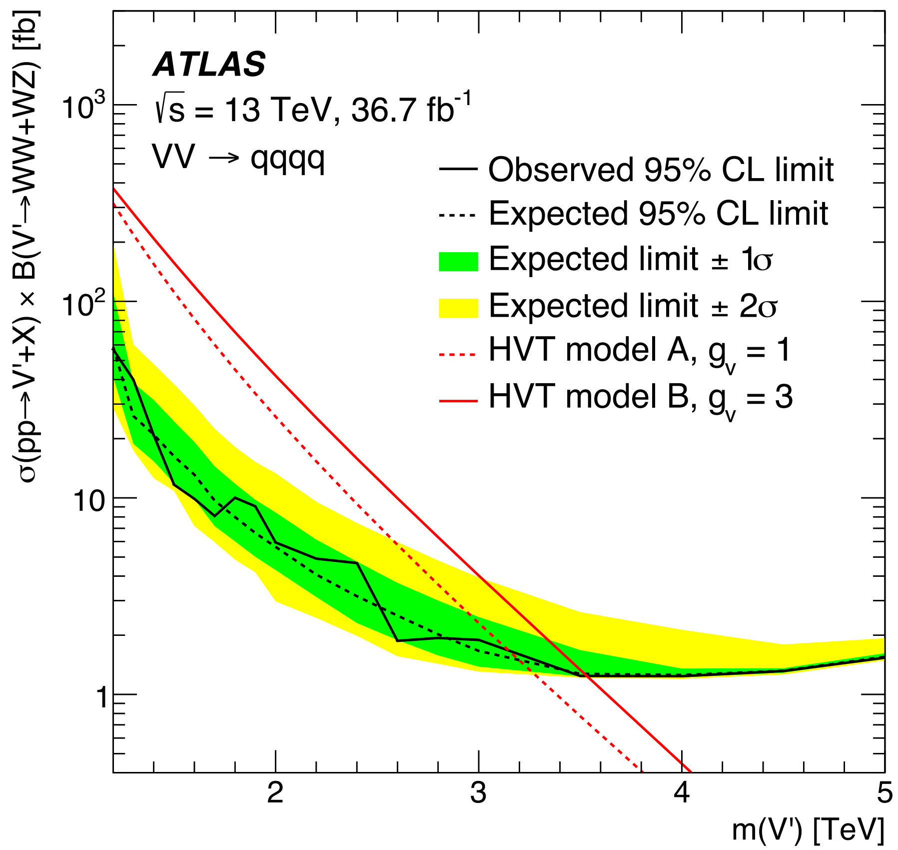
$X \to VV \to qqqq$: ATLAS and CMS Results

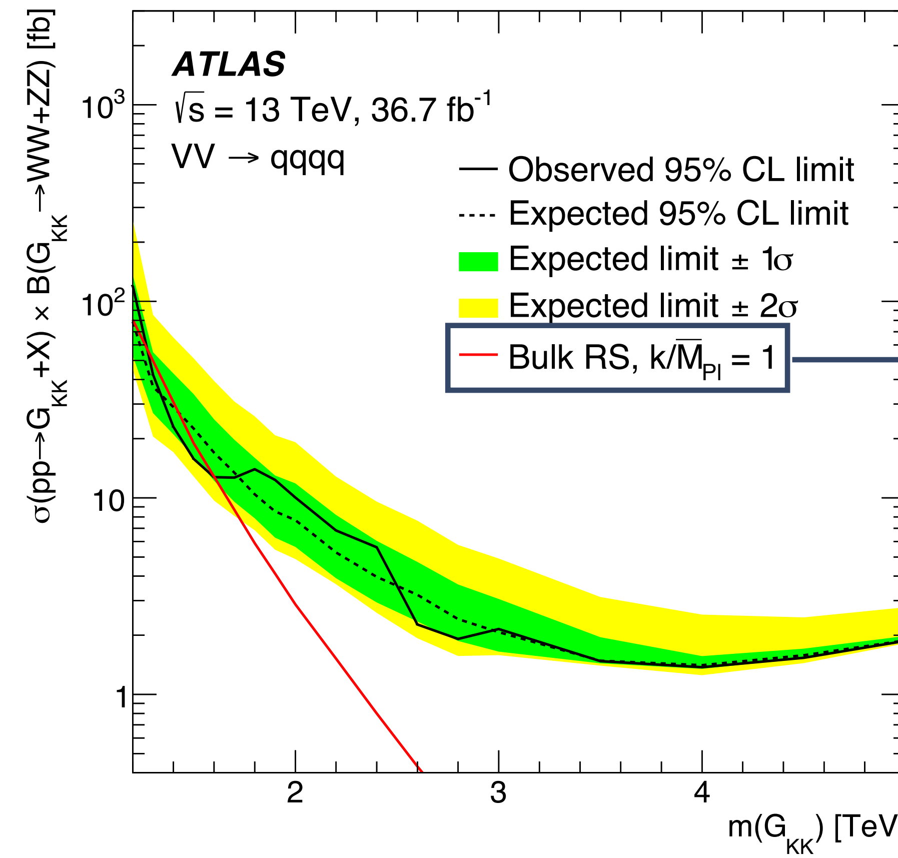
EXOT-2016-19 B2G-17-001

HVT with degenerate W′ and Z′

$G_{KK} \to WW$ or ZZ

Pseudo-experiment



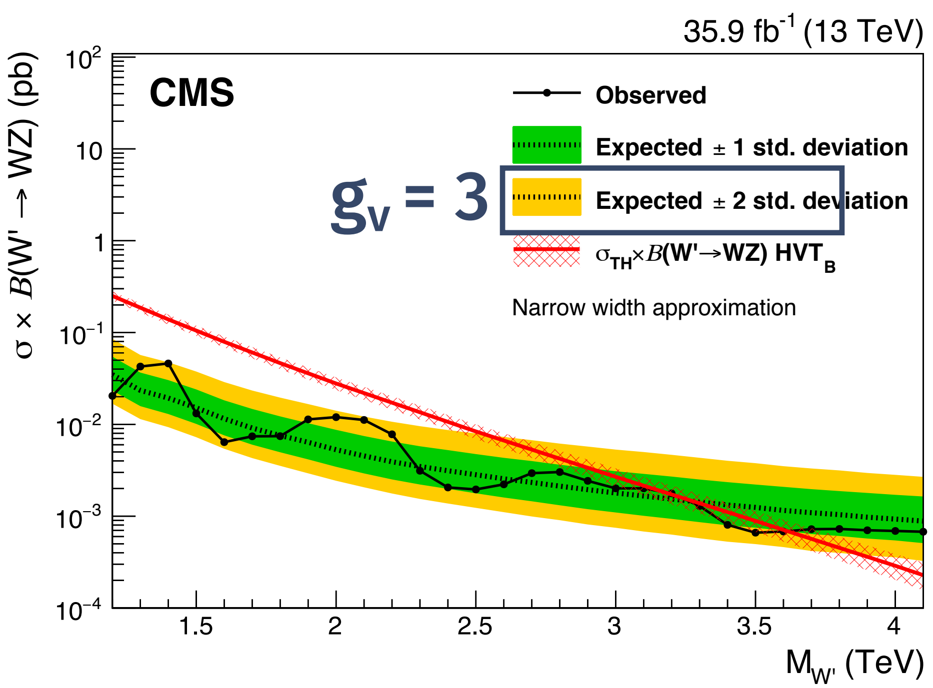


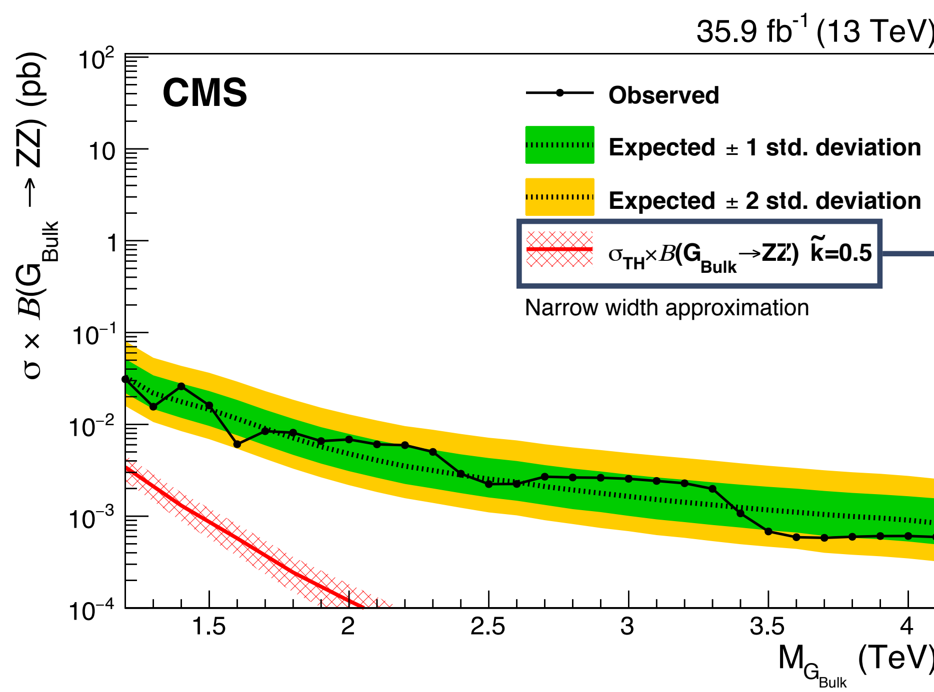
ATLAS: k = 1

CMS: k = 0.5

Asymptotic

$g_V = 3$





$X \to ZV \to \ell^{\pm}\ell^{\mp} qq / \nu\nu qq$

- Semi-leptonic channel: $Z \to \ell^{\pm}\ell^{\mp} / \nu\nu$; $W/Z \to qq$
- Both high-purity and low-purity regions are present to enhance the sensitivity
- ATLAS
  - High purity: 50% W/Z tagger WP; low purity: 80% W/Z tagger WP
  - Results of $\ell^{\pm}\ell^{\mp} qq$ and $\nu\nu qq$ are combined; merged analysis is prioritized, followed by resolved analysis
- CMS
  - High purity: $\tau_{21} < 0.35$; low purity: $0.35 < \tau_{21} < 0.75$
  - Only $\nu\nu qq$ results are public with the complete 2015+2016 dataset

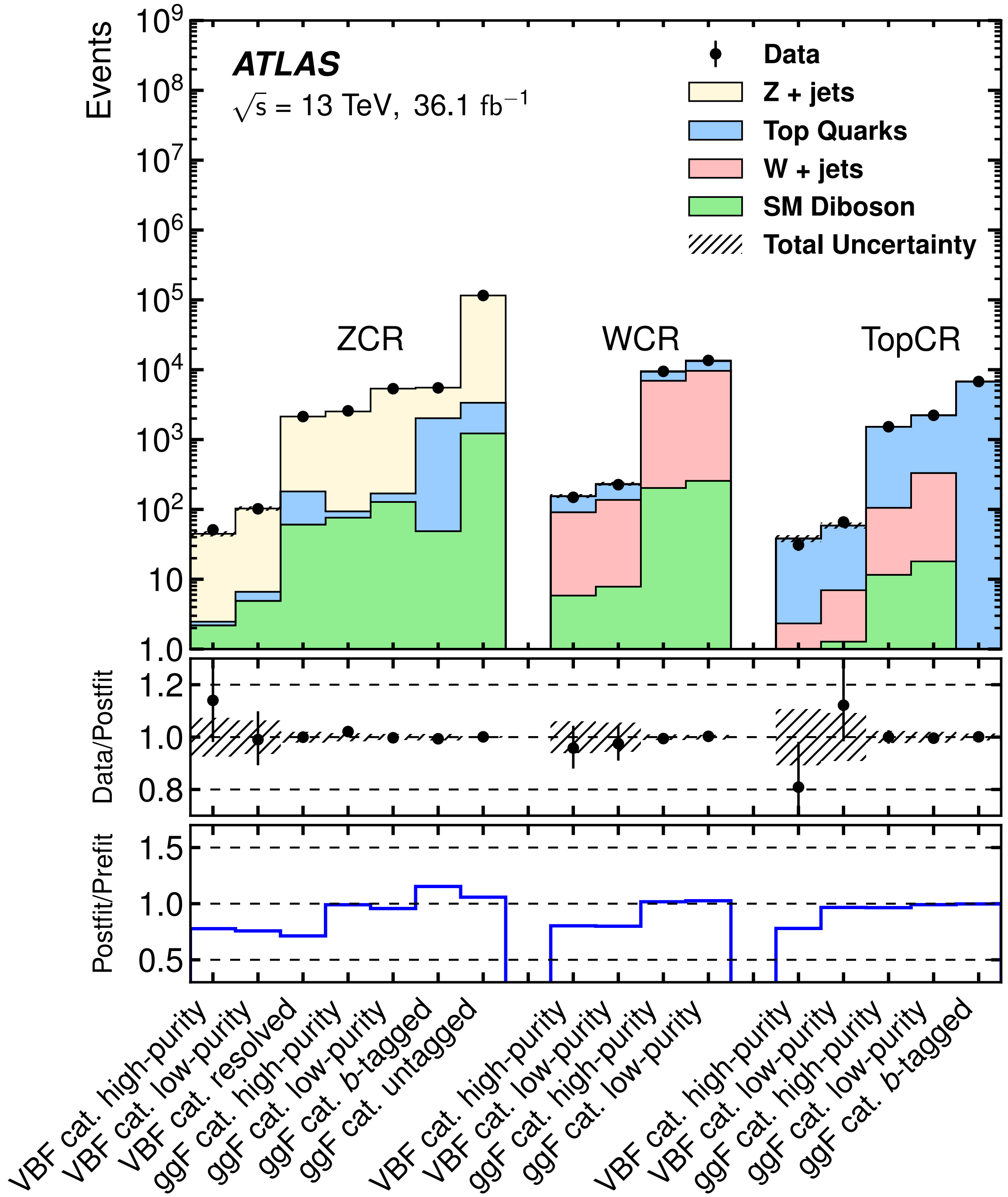
Latest CMS $\ell\ell qq$ results:
12.9 fb^{-1}

$X \to ZV \to \ell^{\pm}\ell^{\mp}qq/\nu\nu qq$: ATLAS Results

EXOT-2016-29

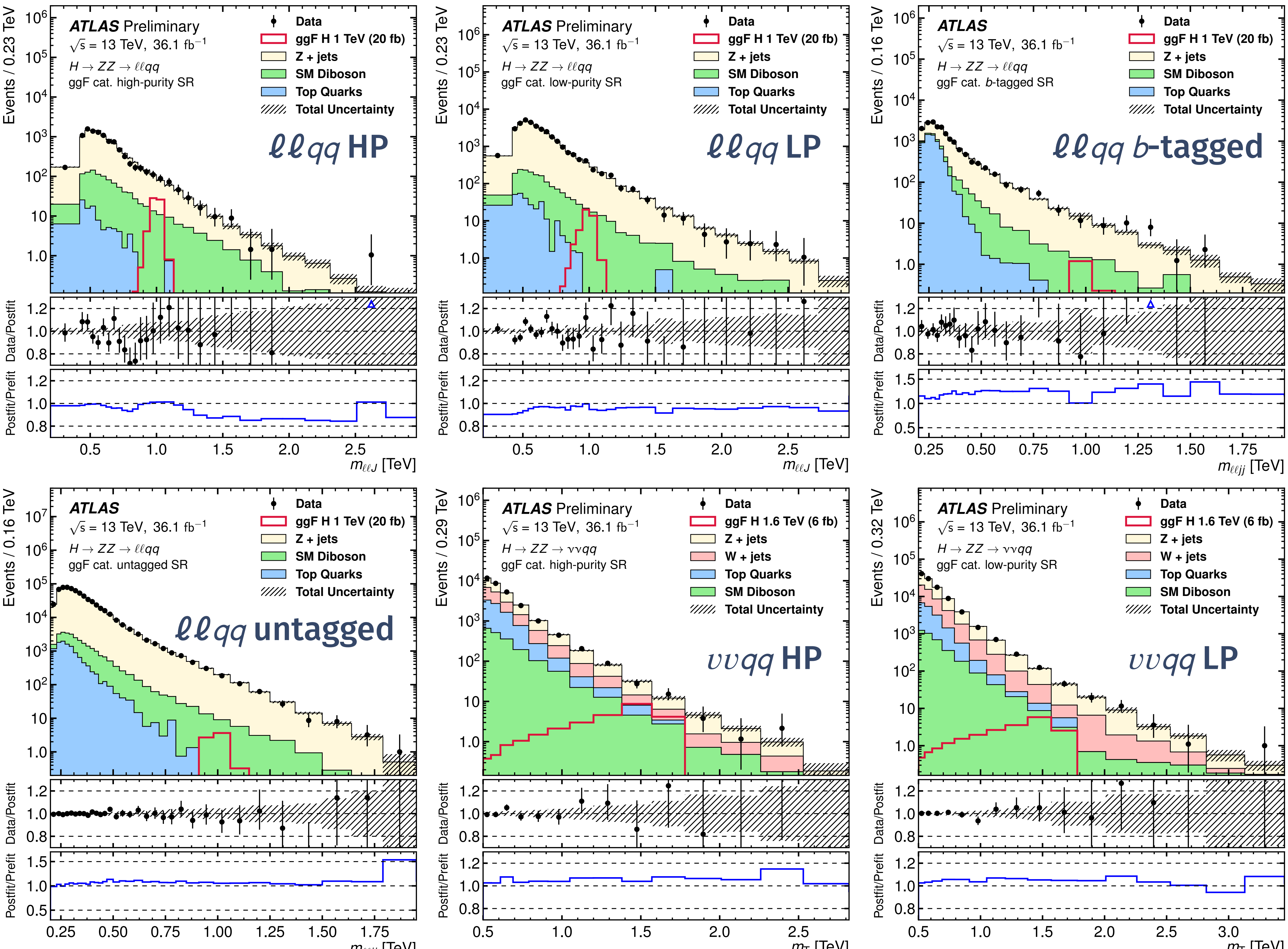
To appear soon

- $\ell\ell qq$ analysis:
  - $V \to qq \to J$: merged analysis first
  - $V \to qq \to jj$: resolved analysis next (untagged and b-tagged categories for $Z \to qq$)
- Dominant backgrounds for $\ell\ell qq$: Z+jets, $t\bar{t}$ (b-tagged category only)
- Dominant backgrounds for $\nu\nu qq$: Z+jets, W+jets, $t\bar{t}$
- Background templates taken from MC; normalized to data in control regions
- **Binned maximum-likelihood fit**



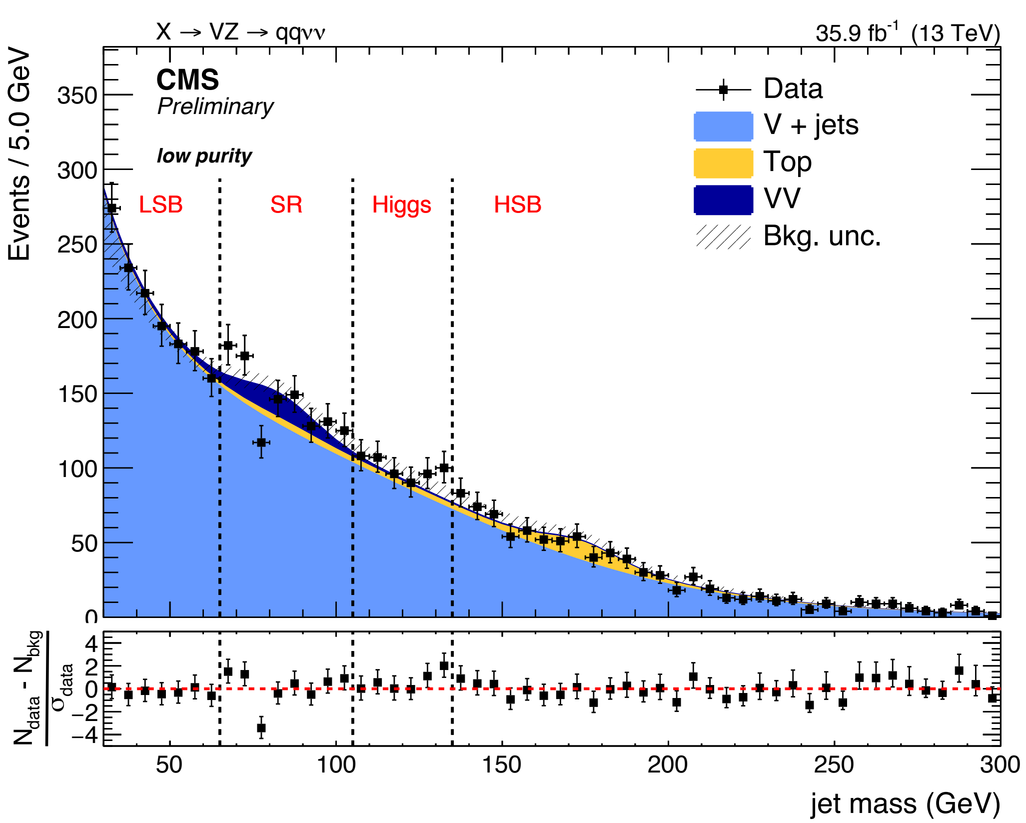
CR summary plot

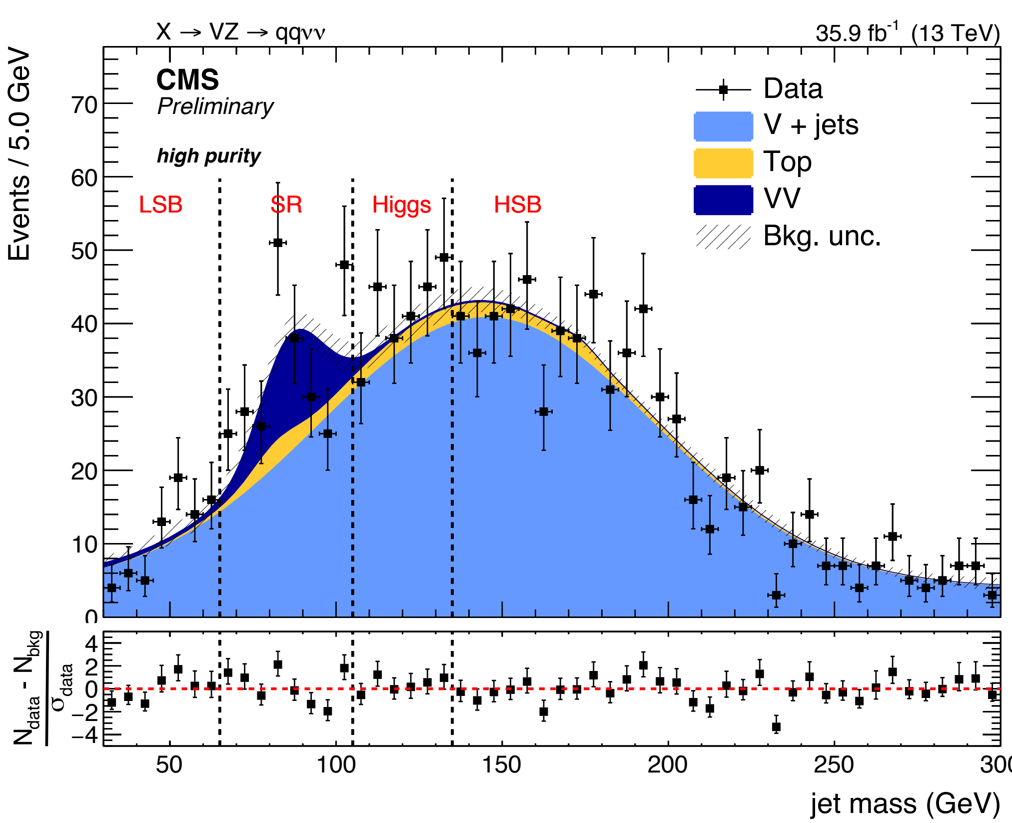
$X \to ZV \to \ell^{\pm}\ell^{\mp}qq/\nu\nu qq$: ATLAS Results



$X \to ZV \to \nu\nu qq$: CMS Results

- Large-*R* jet mass window: 65 - 105 GeV
- Background estimation using simulation-assisted “alpha-ratio method”
  - Exploit the correlation between soft-drop jet mass and resonance mass.
  - Calculate ratio of simulation to data and extrapolate to signal region
  - Normalization obtained from m_J, shape from transverse mass
- **Unbinned maximum-likelihood fit**

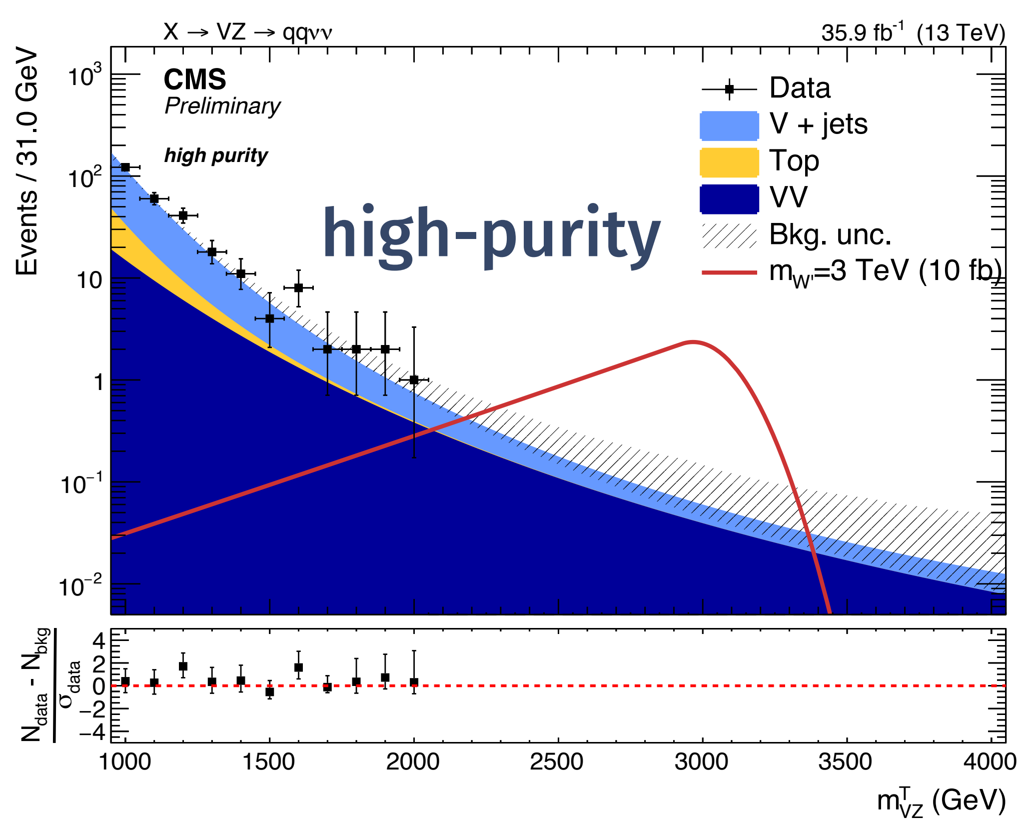


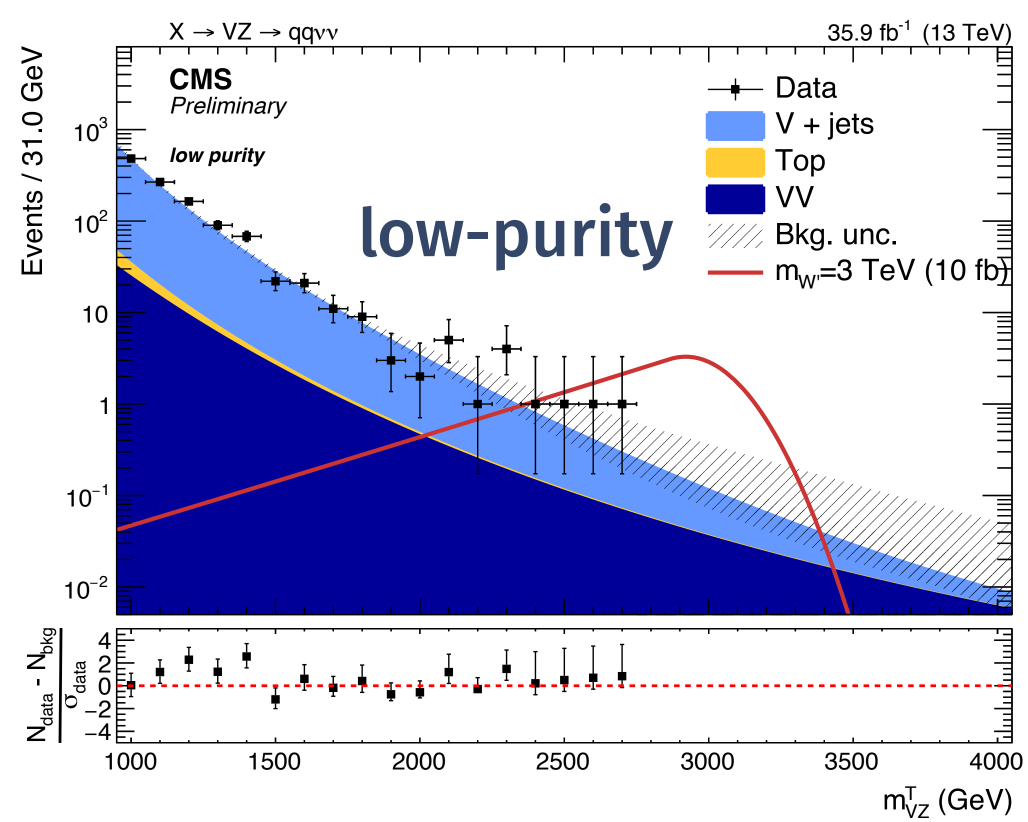


$X \to ZV \to \nu\nu qq$: CMS Results

B2G-17-005

- Large-*R* jet mass window: 65 - 105 GeV
- Background estimation using simulation-assisted “alpha-ratio method”
  - Exploit the correlation between soft-drop jet mass and resonance mass.
  - Calculate ratio of simulation to data and extrapolate to signal region
  - Normalization obtained from m_J, shape from transverse mass
- Unbinned maximum-likelihood fit



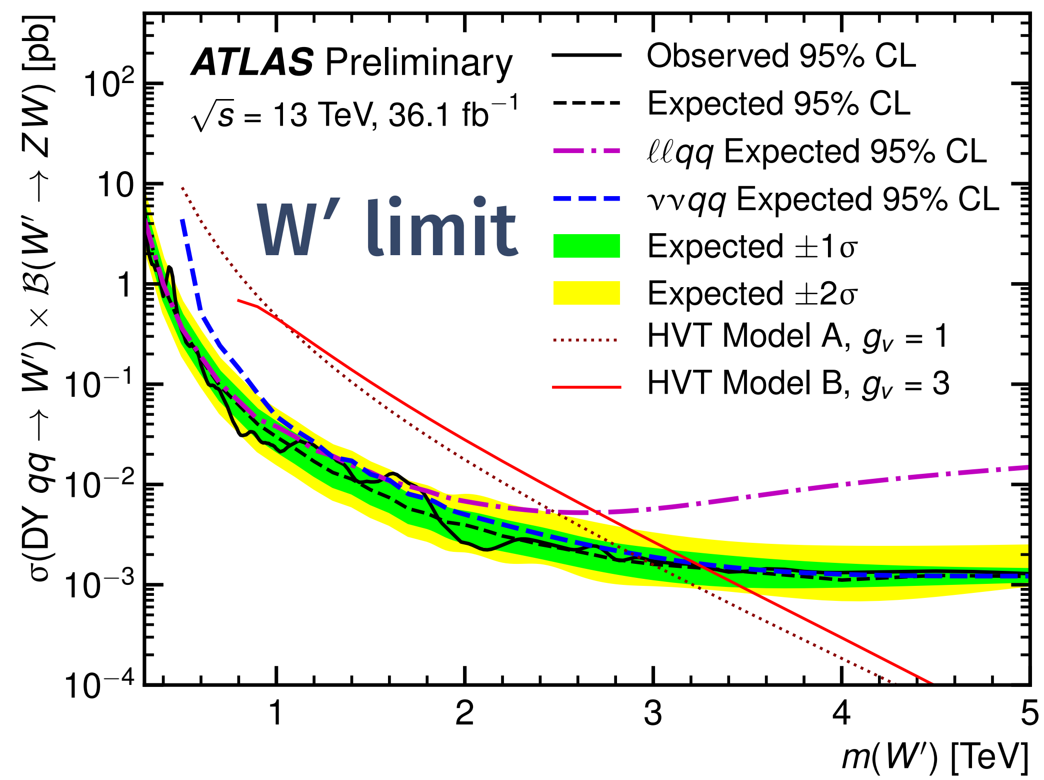


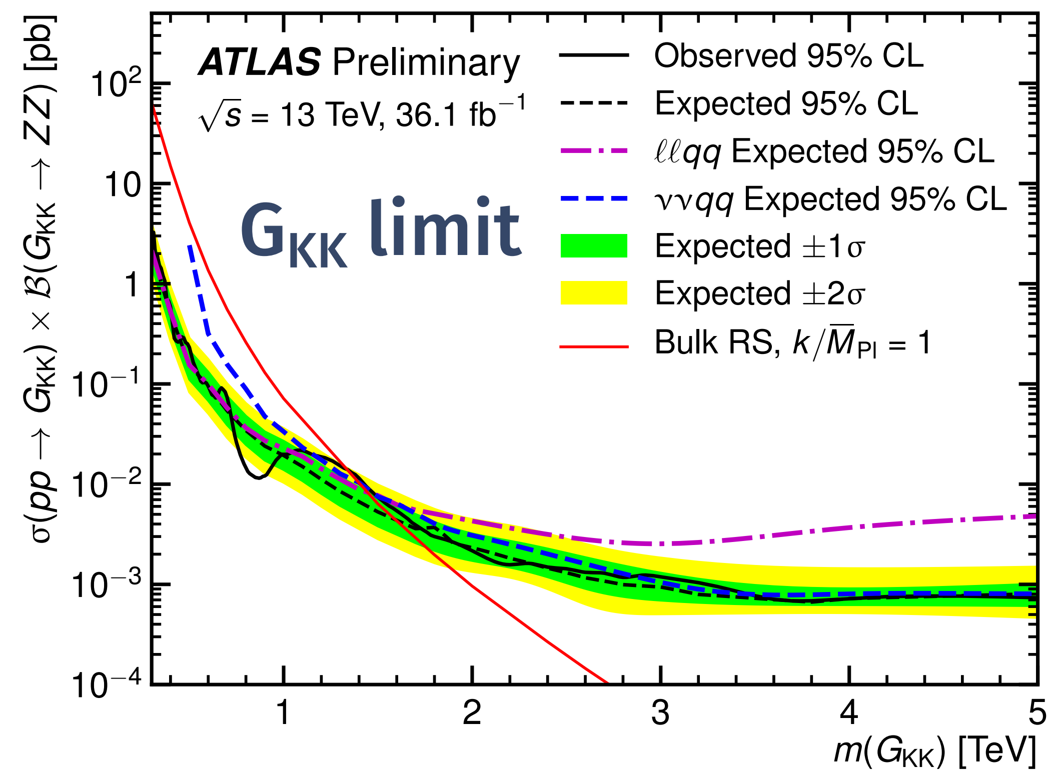
$X \to ZV \to \ell^{\pm}\ell^{\mp}qq / \nu\nu qq$: Results

EXOT-2016-29 B2G-17-005

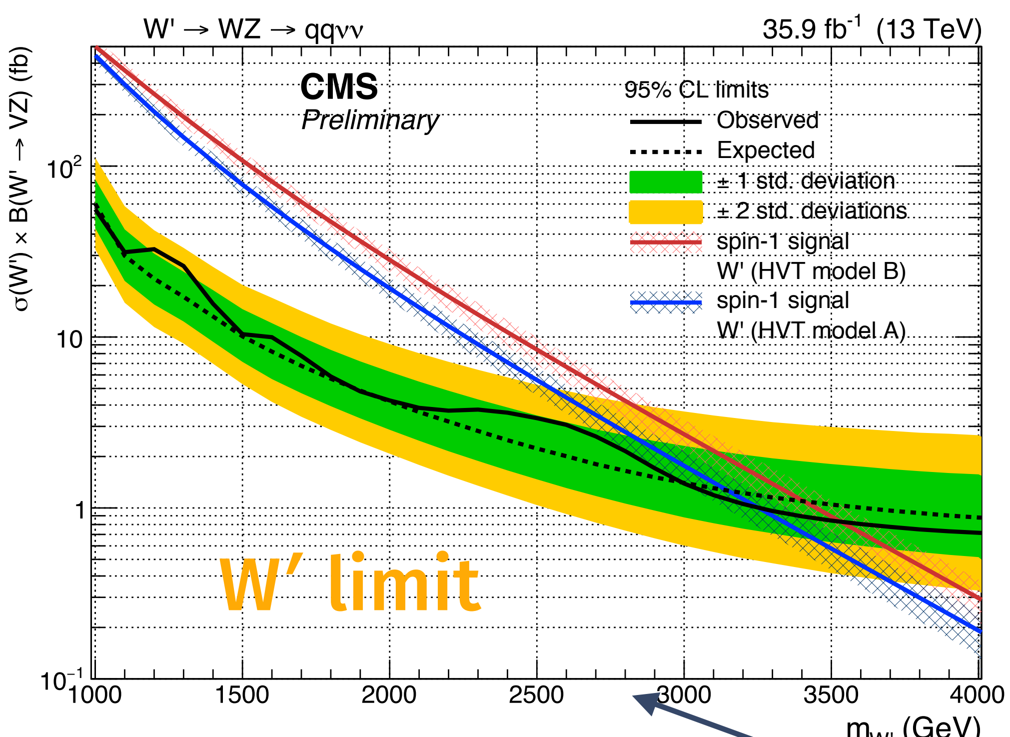
$\nu\nu qq$ dominates at high mass

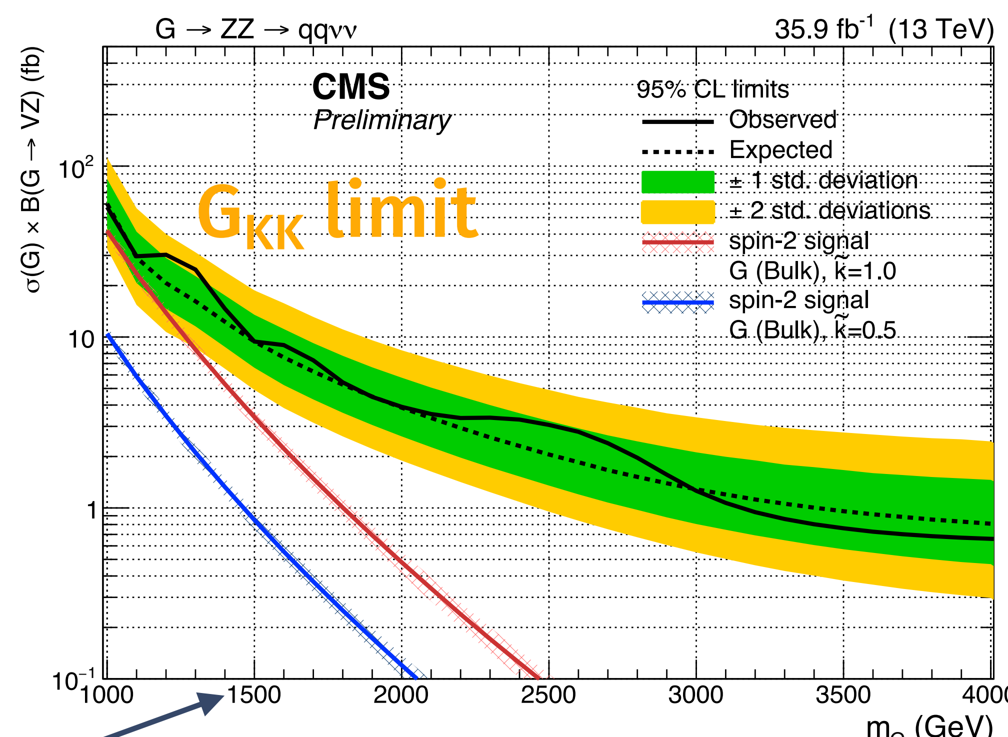
Asymptotic limits below 2 TeV
pseudo-experiments above 2 TeV





Asymptotic limits





limits based on narrow-width approximation signal

$X \to WV \to \ell^{\pm}\nu qq$: ATLAS Results

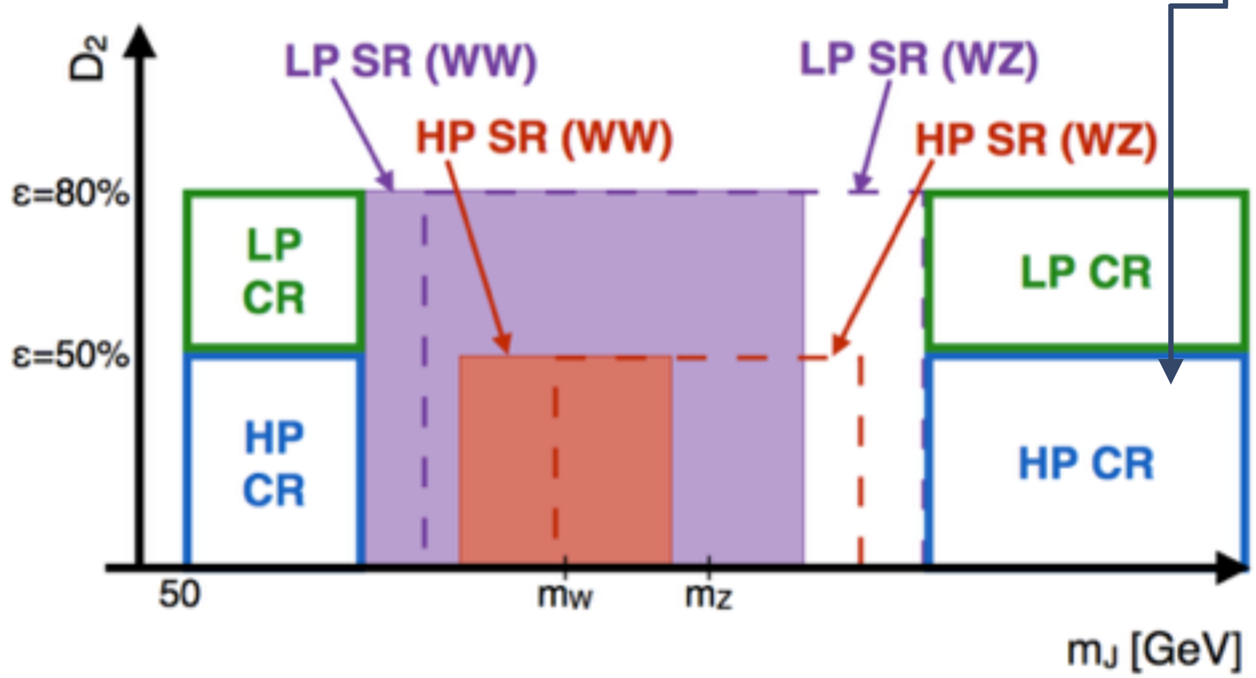
ATLAS-CONF-2017-051

- Semi-leptonic channel: $W \to \ell^{\pm}\nu$; $W/Z \to qq$
- Merged analysis is prioritized, followed by resolved analysis
- Both high-purity (50% WP) and low-purity (80% WP) regions are present to enhance the sensitivity
- Dominant background processes: W+jets, $t\bar{t}$
  - Templates from MC simulations
  - Normalizations obtained from W+jets and $t\bar{t}$ control regions correspondingly.

W+jets → CR: mass sidebands of $V \to qq$

$t\bar{t}$ → CR: presence of b-jets in addition to $V \to qq$

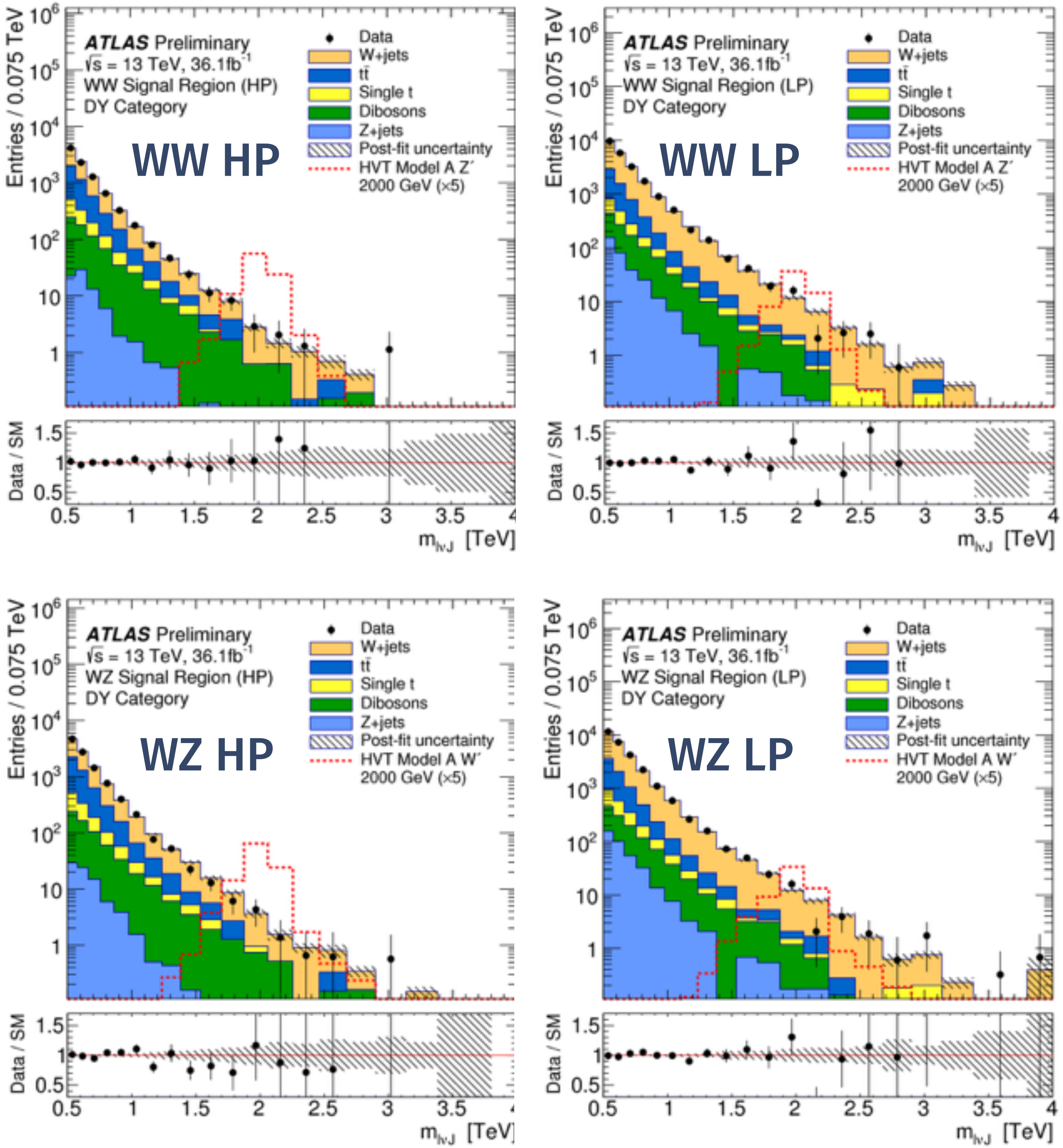
e.g. normalized to data in WCR

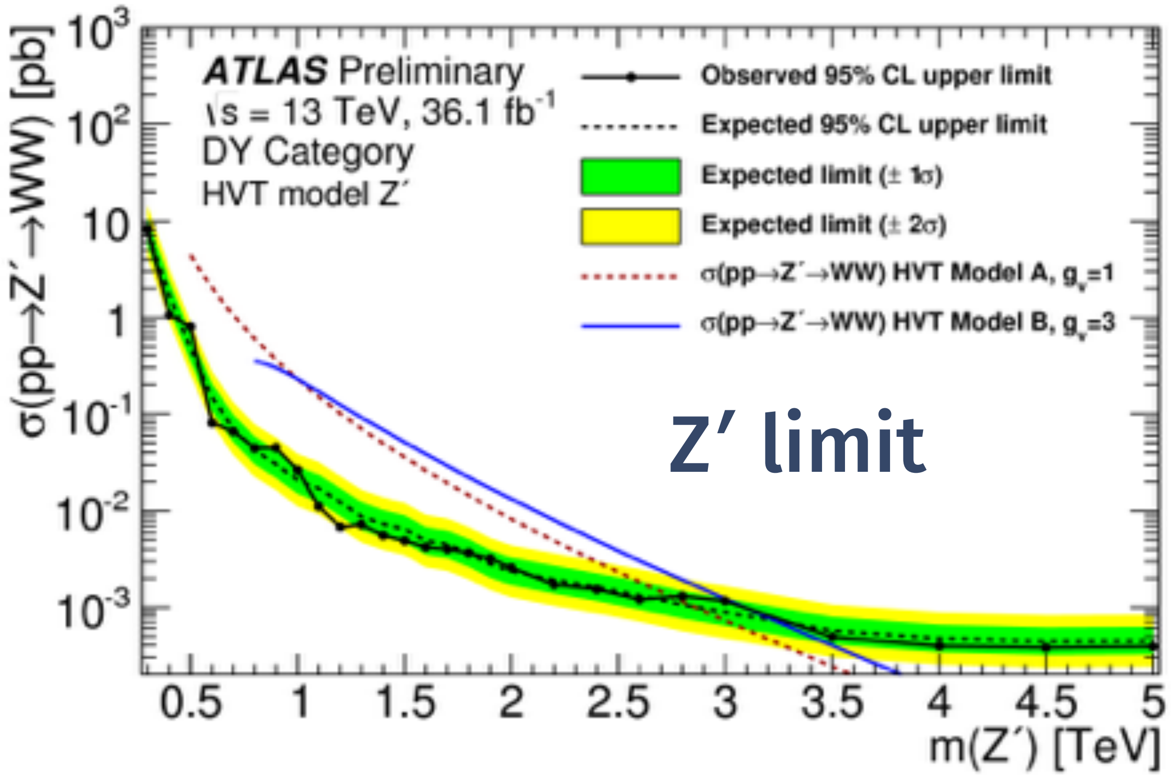


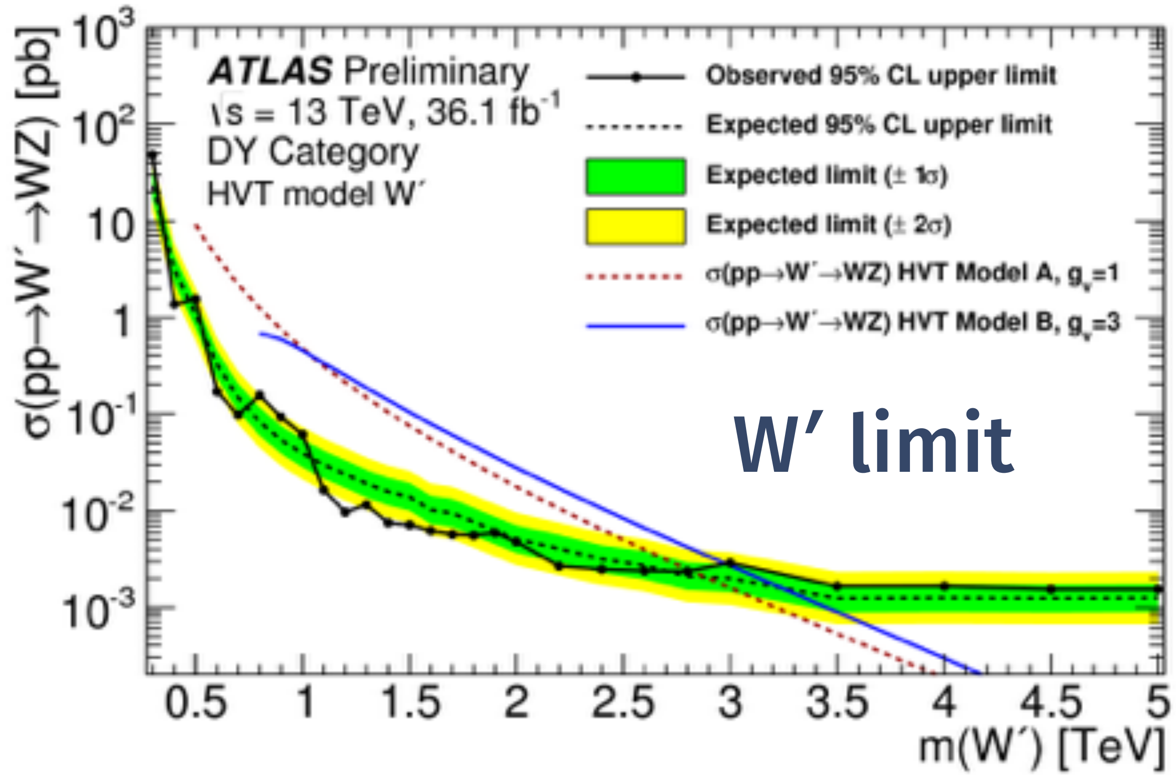
Latest CMS results: 12.9 fb^{-1}

$X \rightarrow WV \rightarrow \ell^{\pm}\nu qq$: ATLAS Results

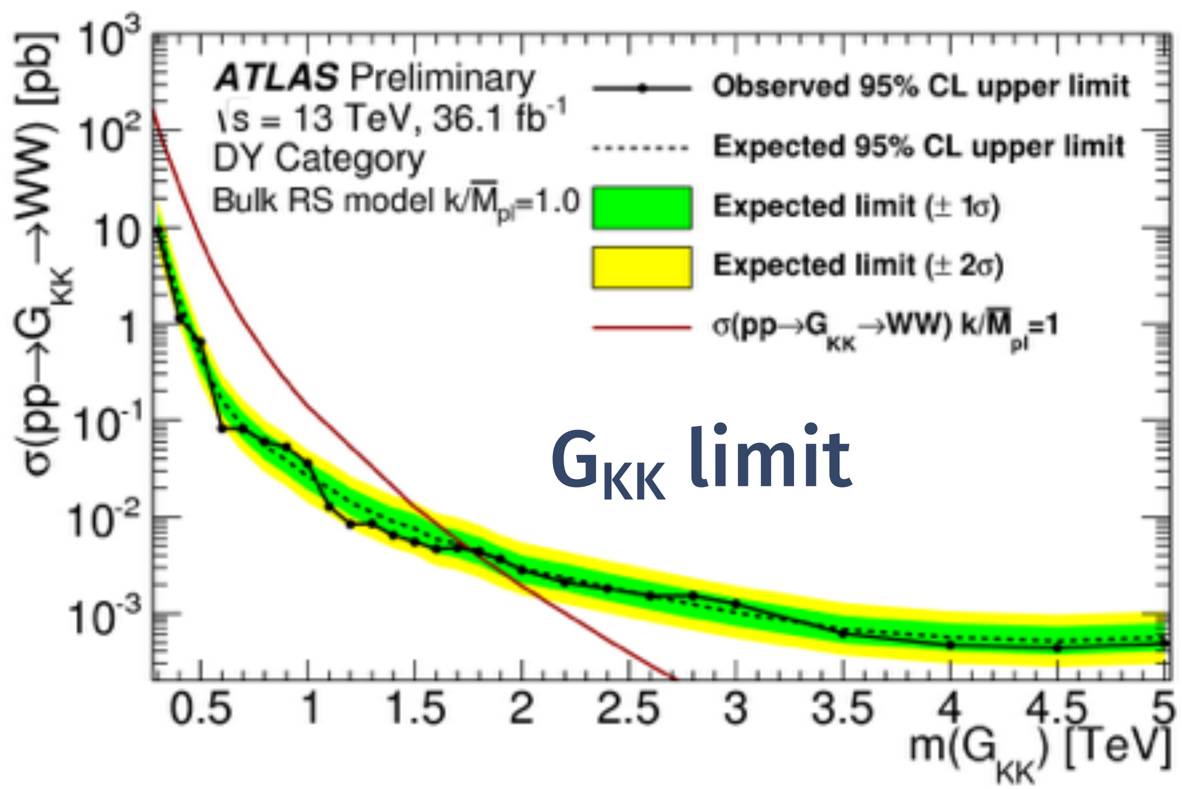
ATLAS-CONF-2017-051







Asymptotic limits



Search for resonances decaying into VH (V=W/Z)

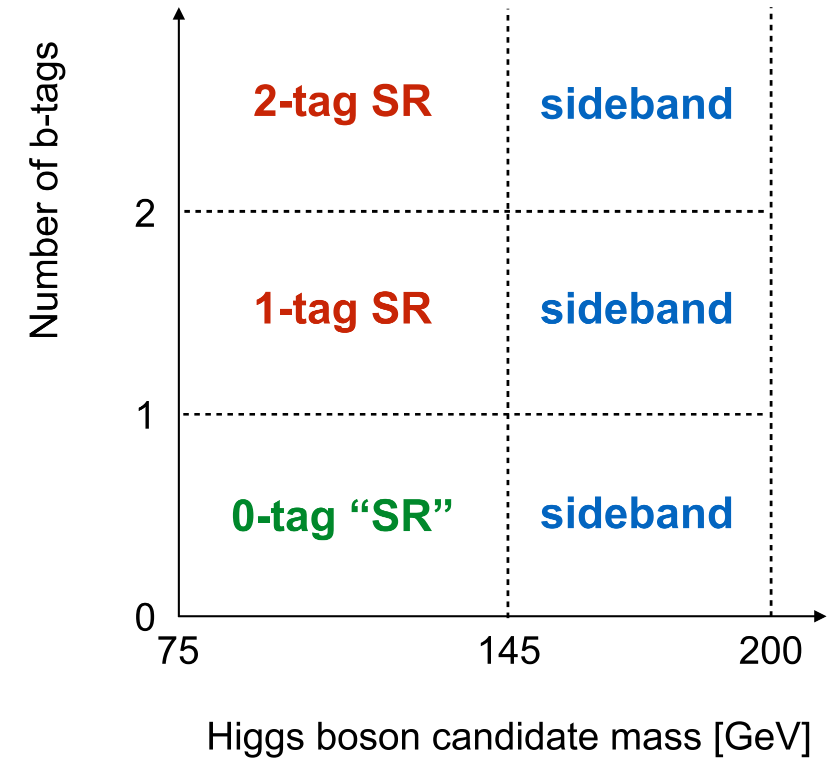
$X \rightarrow VH \rightarrow qqbb$

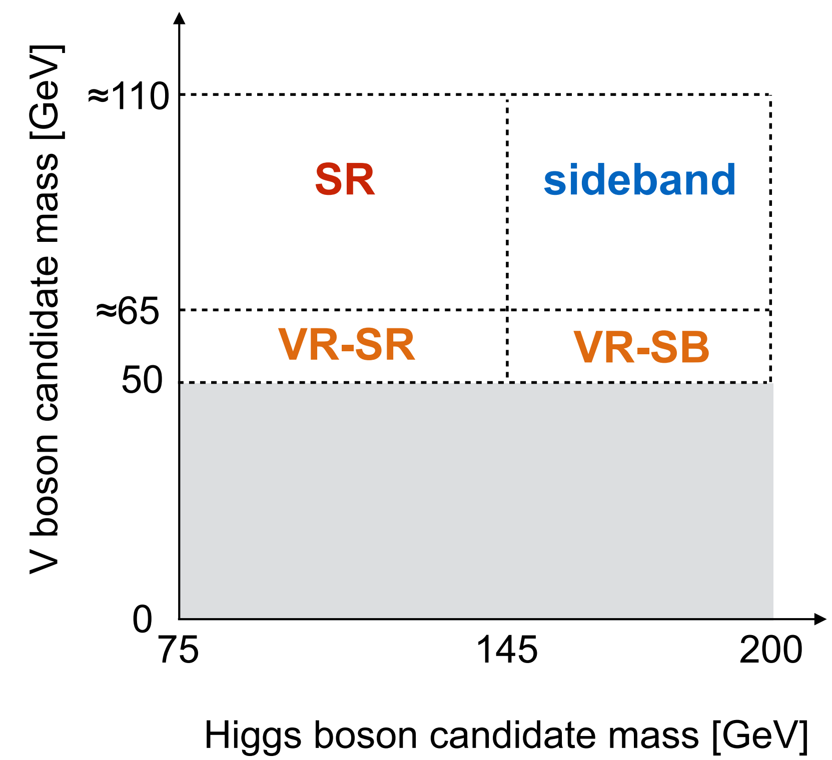
- Vector boson and Higgs decays selected as large-R jets
- Dominant background: multijet
- ATLAS
  - 1-tag and 2-tag signal regions based on the number of *b*-tagged track jets associated to the *H* candidate
  - 2-tag SR prevails < 2.5 TeV and 1-tag SR becomes more sensitive > 2.5 TeV when the two track jets merge into a single one
- CMS
  - High-purity and low-purity signal regions, in which both loose and tight *b*-tagging are done on the *H* candidate using the double-*b* tagger

$X \rightarrow VH \rightarrow qqbb$: ATLAS

EXOT-2016-12

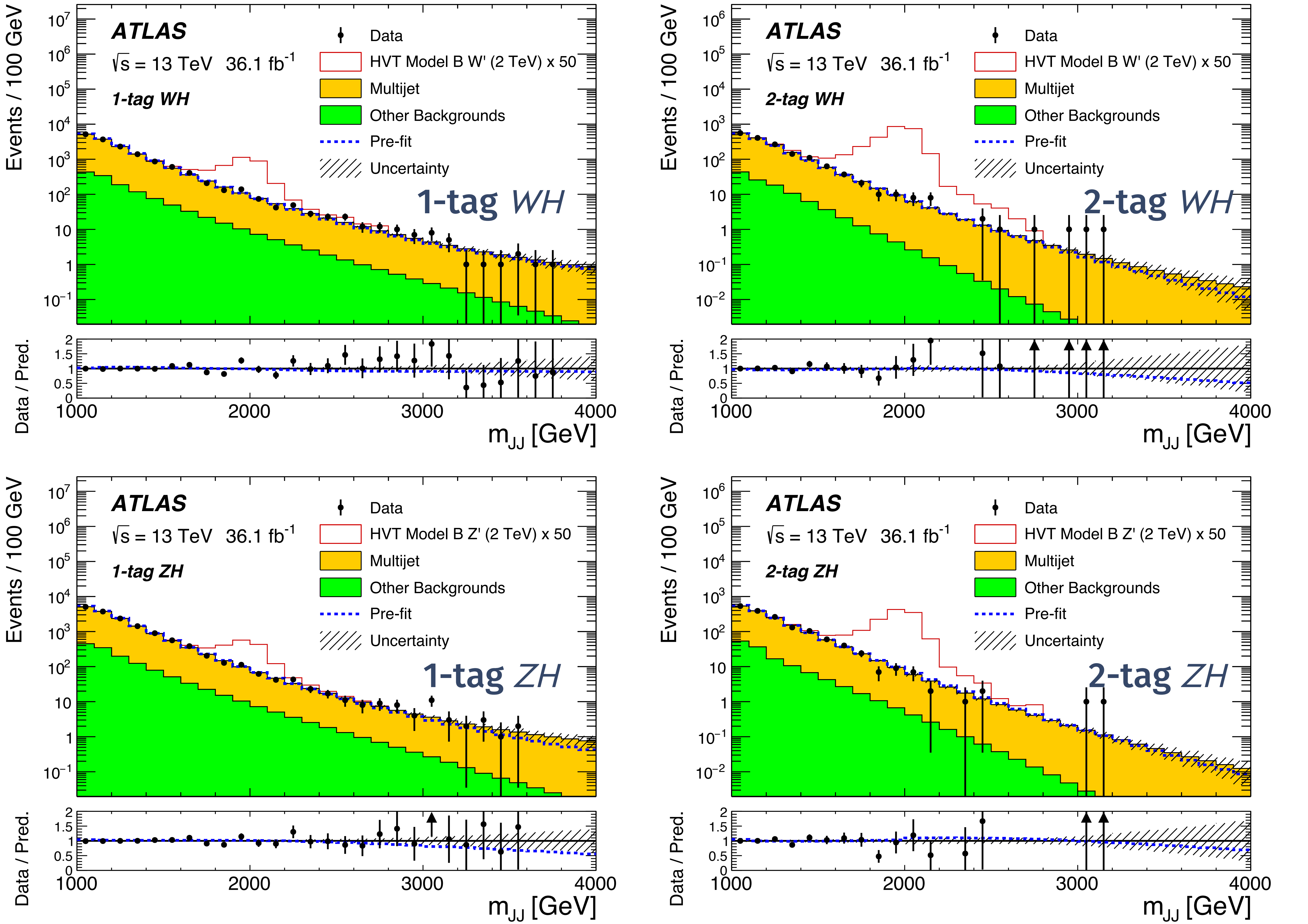
- Multijet (~90%) modeled directly from data, other minor backgrounds (~10% $t\bar{t}$, ≲1% V+jets) from simulation
- 0-tag sample (99% multijet) is used to model the kinematics of the multijet background in the 1-tag and 2-tag SRs:
  - Kinematic corrections to multijet template are applied by reweighting events from the 0-tag sample
  - Normalization uncertainties assessed from the validation regions
  - Shape uncertainties assigned by fitting a variety of empirical functions and by varying the fit range
- Binned maximum-likelihood fit





orthogonal regions

$X \rightarrow VH \rightarrow qqbb$: ATLAS Results

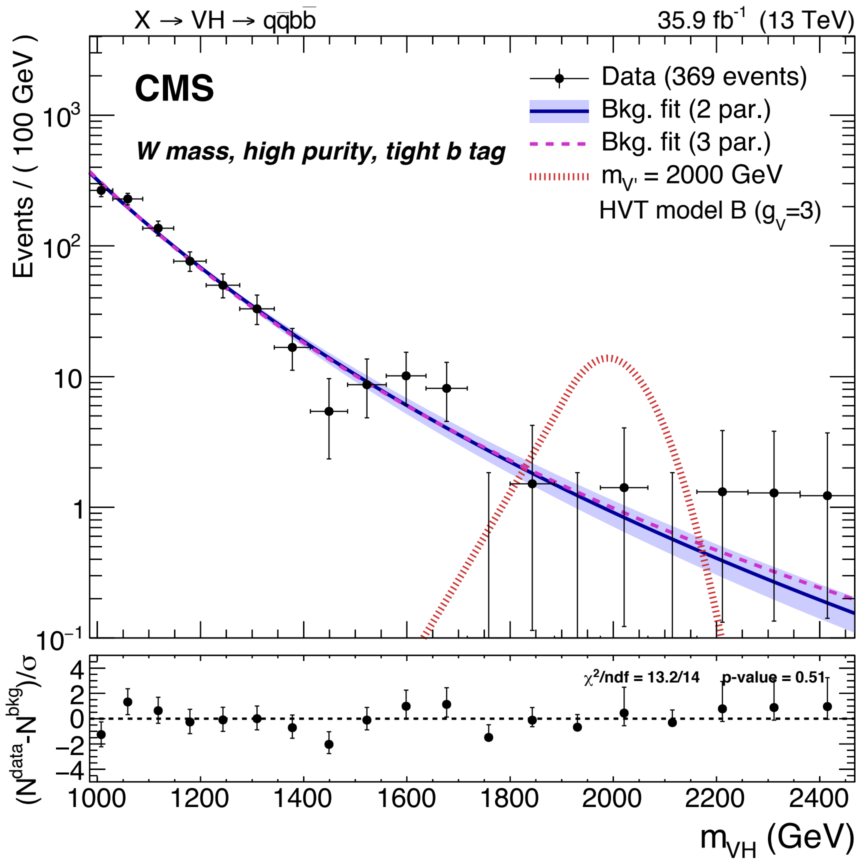


- Background largely dominated by multijet production (≳95%)
- Events are divided into eight exclusive categories:
  - b-tagging discriminator: tight and loose categories
  - τ_{21}: high-purity (HP) and low-purity (LP) categories
  - V jet mass: W mass and Z mass categories
- The background is estimated directly from data by a smooth and monotonically decreasing parametric function
- F-test employed to identify the “best” function:
  - $\frac{p_0}{x^{p_1}}, \quad \frac{p_0(1-x)^{p_1}}{x^{p_2}}, \quad \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)}}, \quad \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)+p_4\log^2(x)}}$

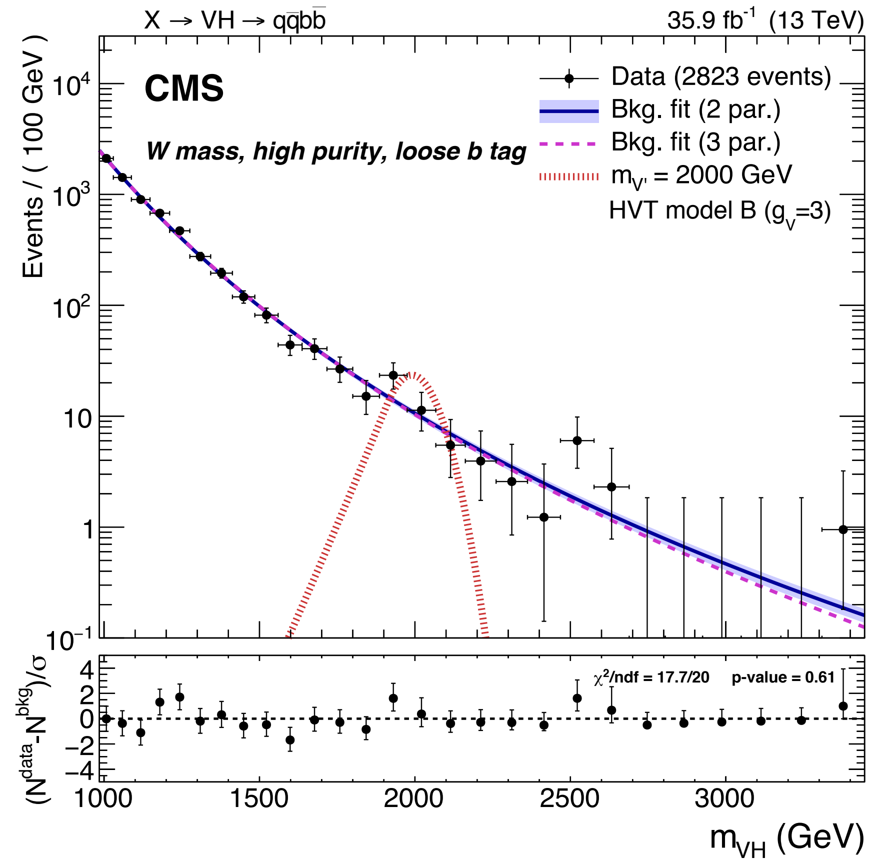
$X \rightarrow VH \rightarrow qqbb$: CMS Results

B2G-17-002

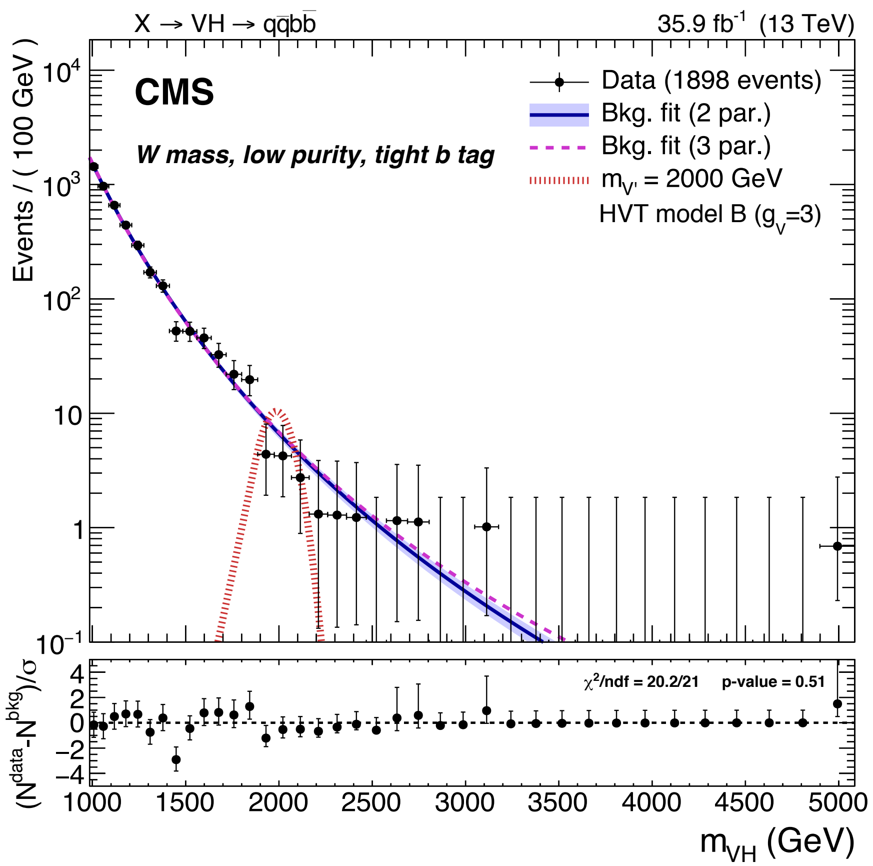
1-tag *WH* high-purity tight b-tag



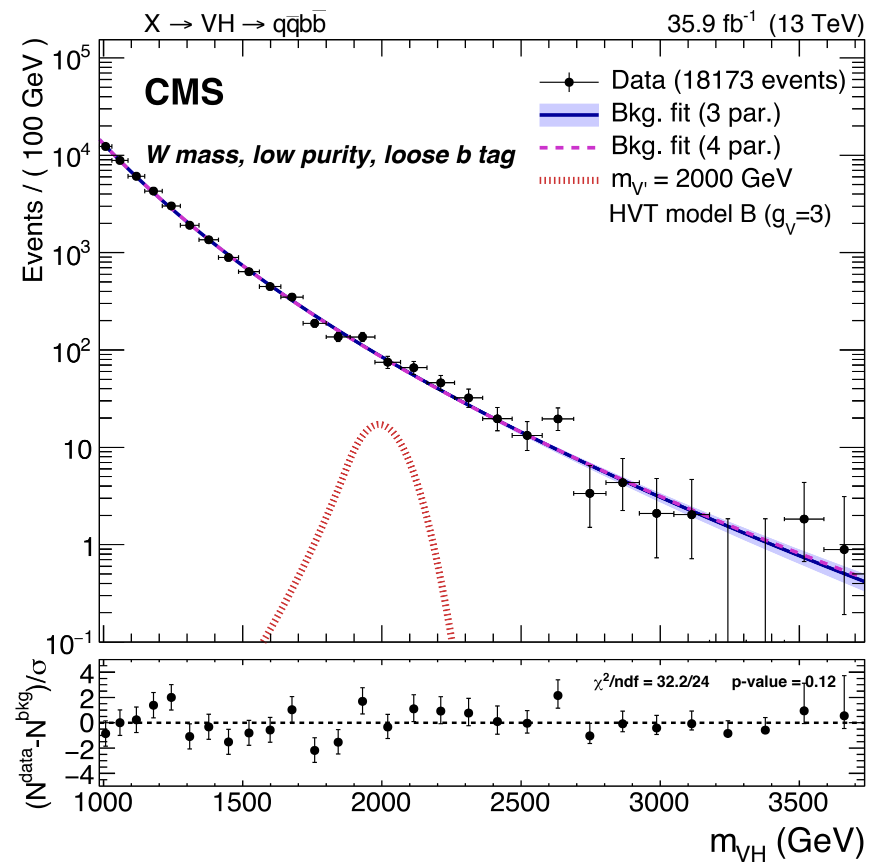
1-tag *WH* high-purity loose b-tag



1-tag *WH* low-purity tight b-tag



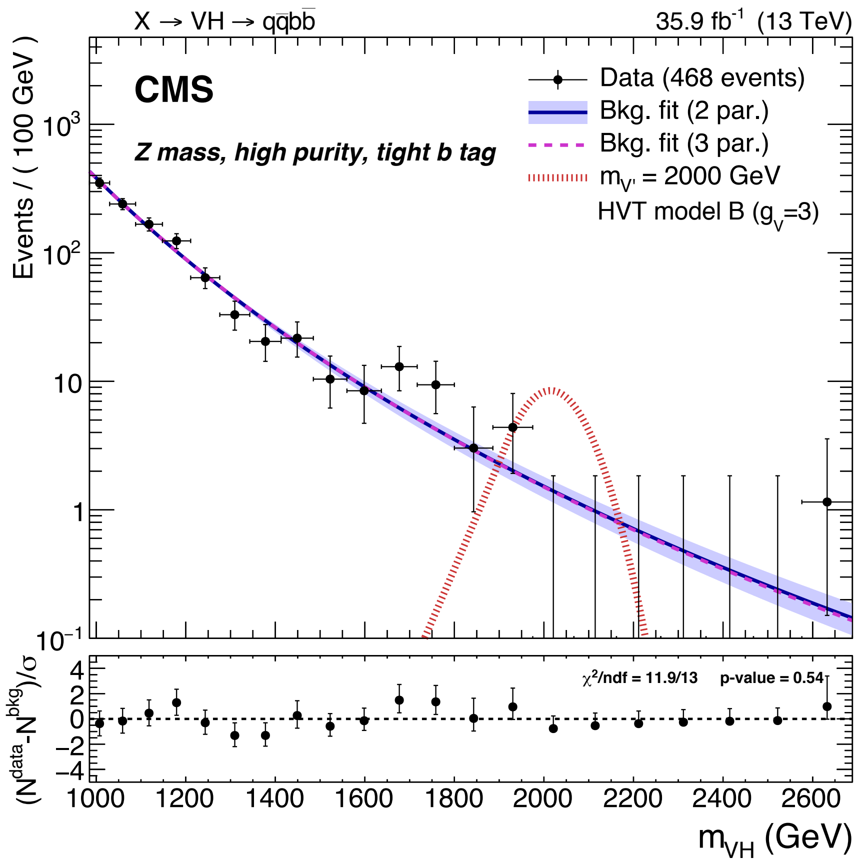
1-tag *WH* low-purity loose b-tag



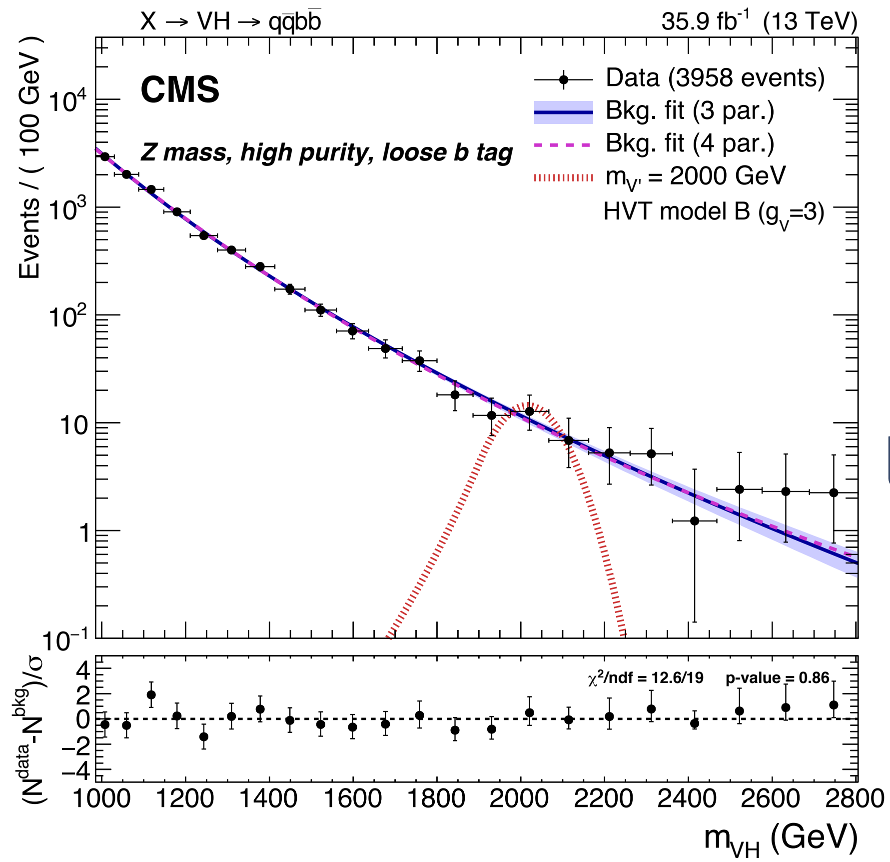
$X \to VH \to qqbb$: CMS Results

B2G-17-002

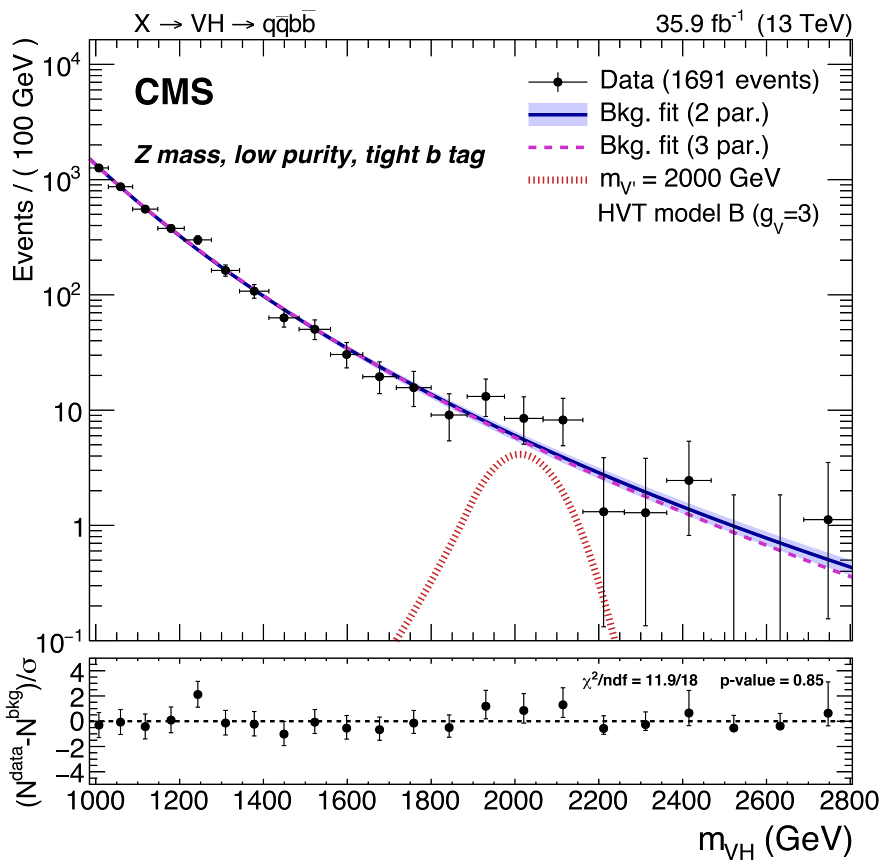
1-tag *ZH* high-purity tight b-tag



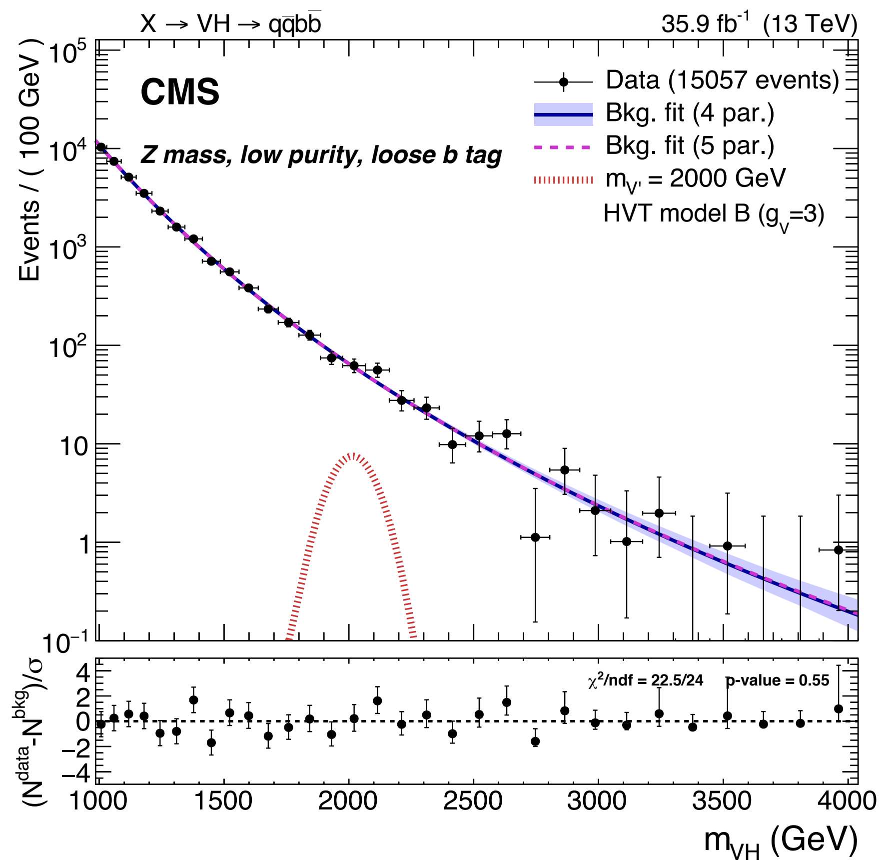
1-tag *ZH* high-purity loose b-tag



1-tag *ZH* low-purity tight b-tag

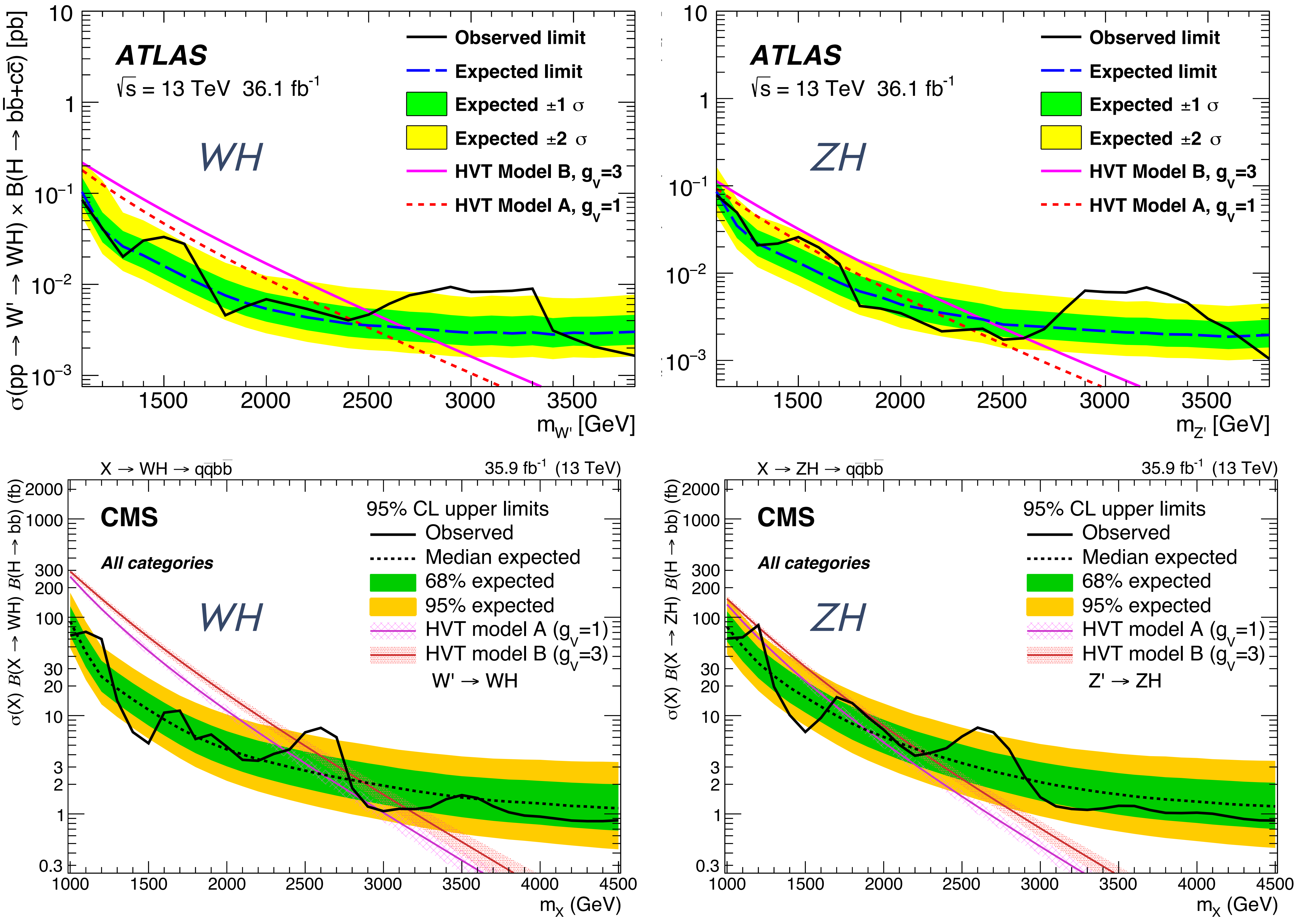


1-tag *ZH* low-purity loose b-tag



$X \to VH \to qqbb$: ATLAS and CMS Results

EXOT-2016-12 B2G-17-002



Semi-Leptonic VH: ATLAS

ATLAS-CONF-2017-055

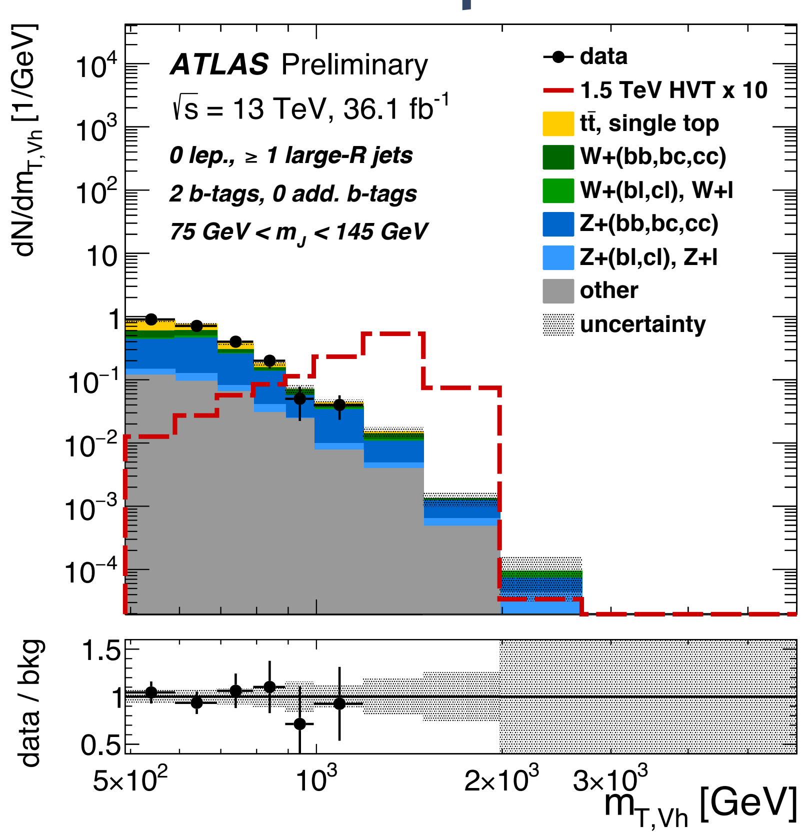
Latest CMS results: 2015 data

Resolved analysis is prioritized!

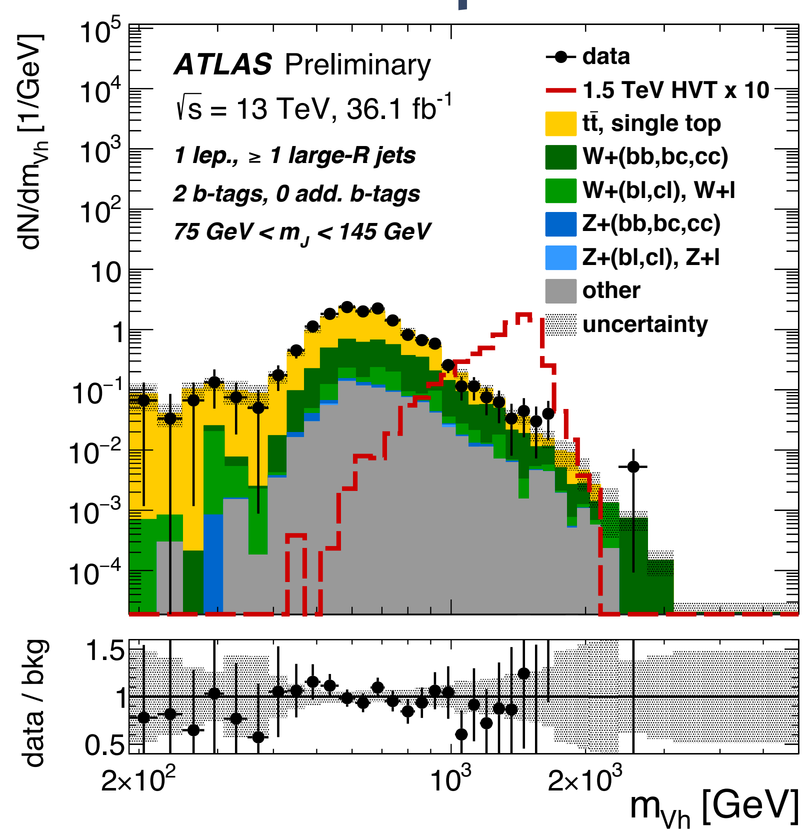
- Final states explored: $\nu\nu bb$, $\ell\nu bb$ and $\ell\ell bb$
- 3 channels based on V decays: 0-/2-lepton (A, Z'), 1-lepton (Z')
- b-tag categories based on b-tagged track jets: 1-/2-tag used for A and V', 3+ tag used for A (sensitive to bbA)

Boosted 2-tag SRs

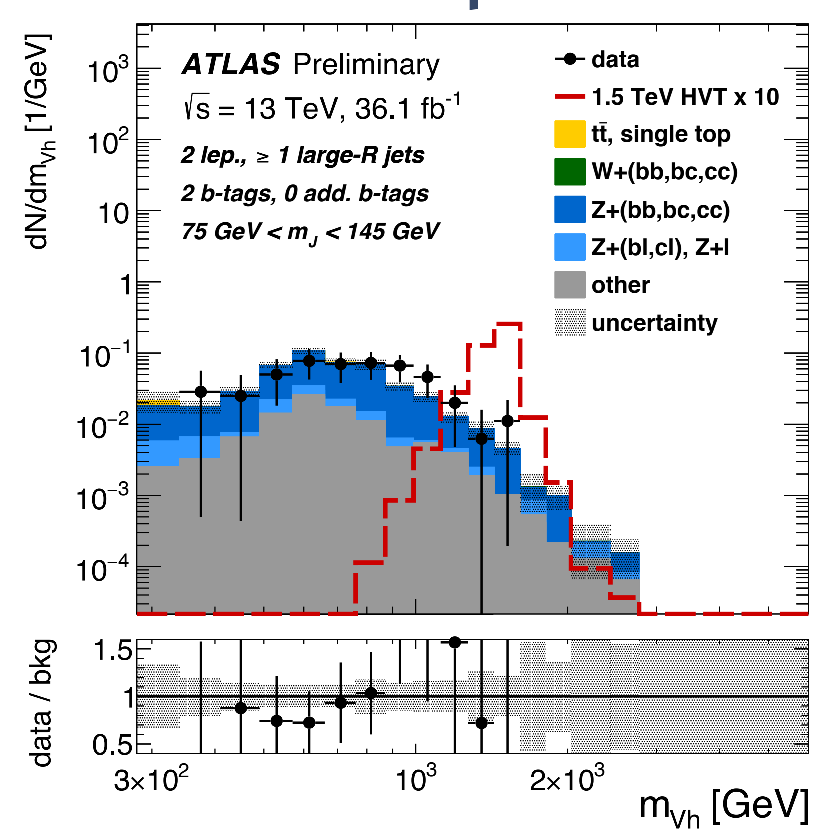
0lep



1lep

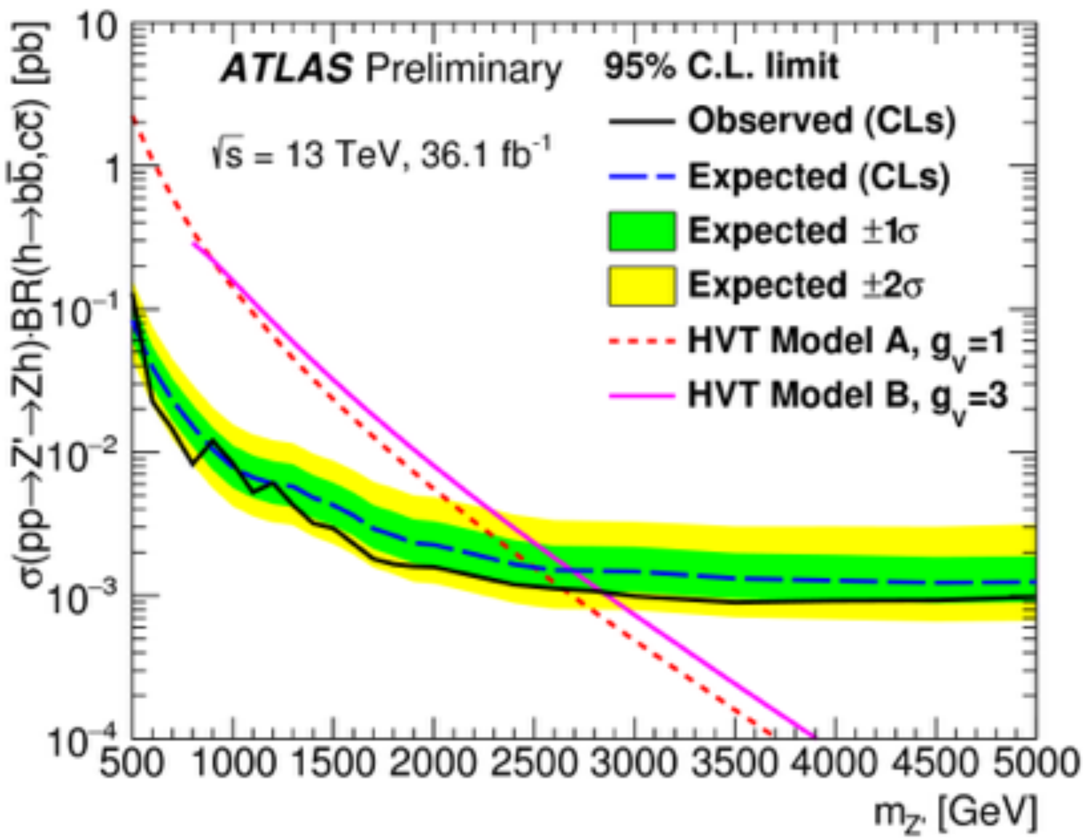


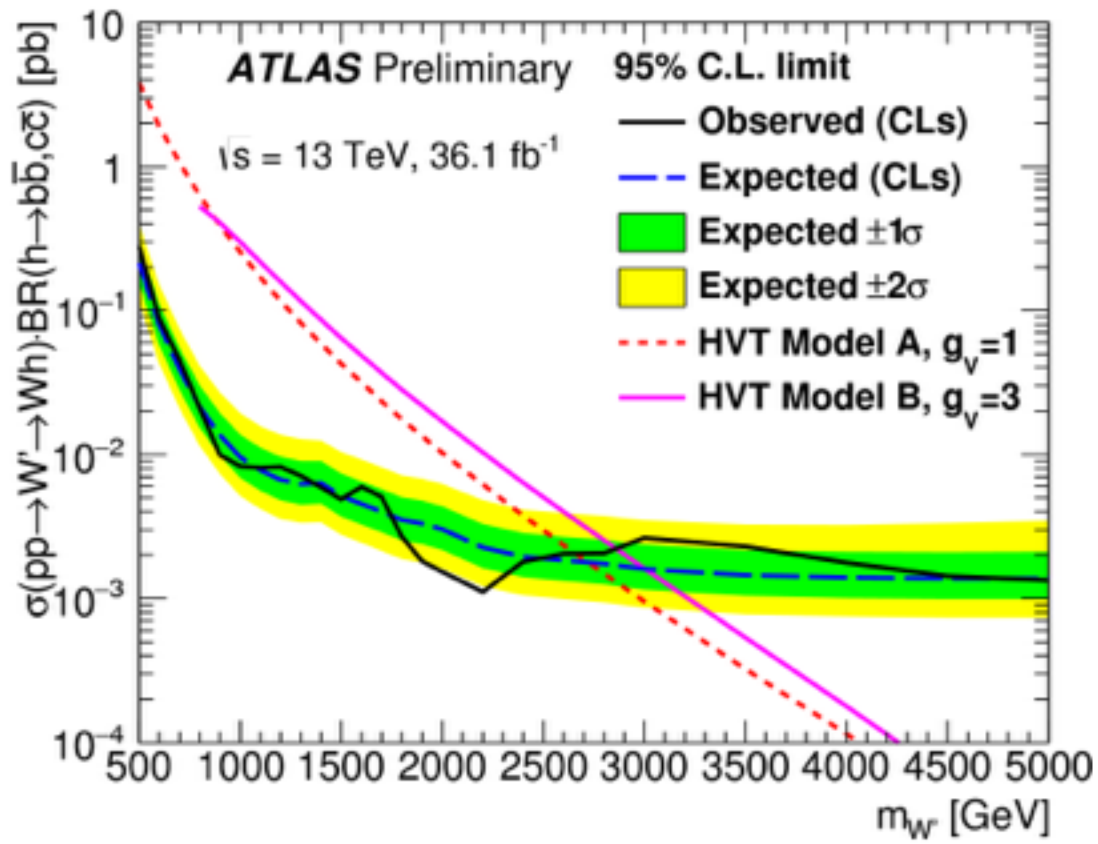
2lep

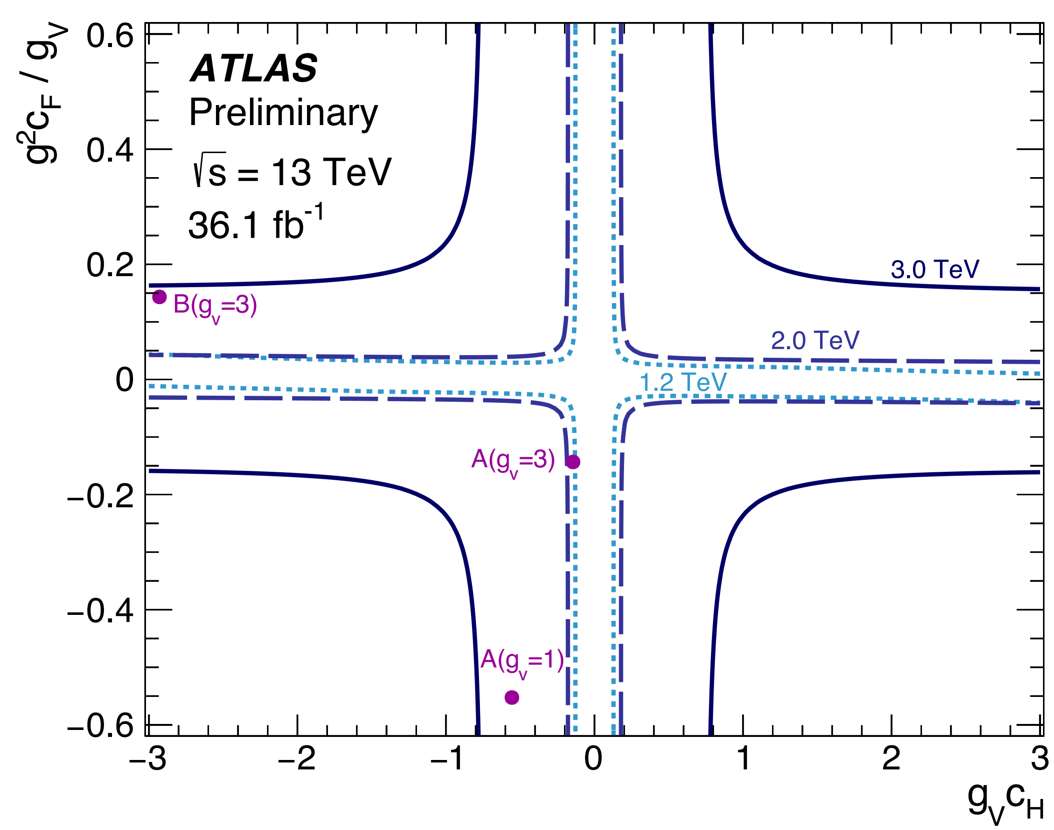


Semi-Leptonic VH: ATLAS Results

ATLAS-CONF-2017-055







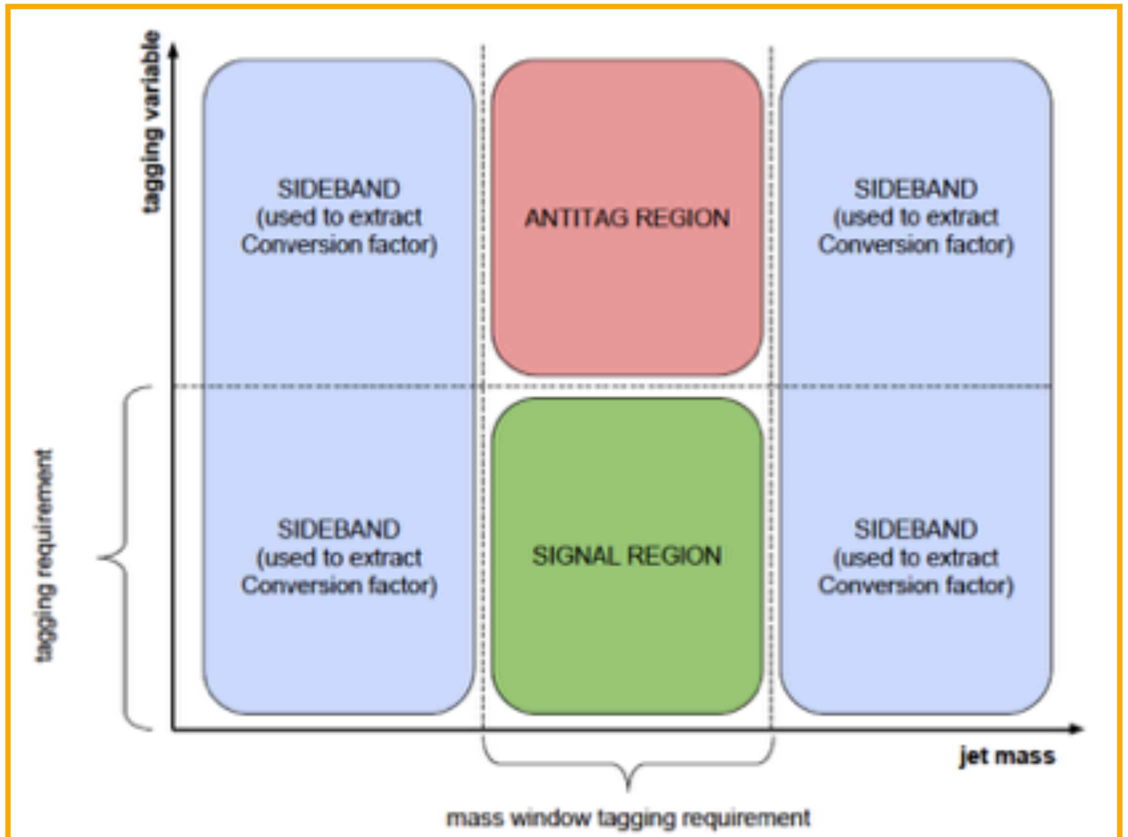
Search for resonances decaying into HH

HH→bbbb: CMS

B2G-16-026

- Search for new physics with a pair of SM Higgs bosons. Only boosted resonant search updated with 35.9 fb^{-1}.
- In high-mass resonance searches, each *H→bb* is reconstructed as a large-R jet.
- Multi-jet background estimation:
  - m_X < 1200 GeV, data-driven "Alphabet" method
  - m_X > 1200 GeV, Alphabet Assisted Bump Hunt (AABH) with leveled exponential function
  - Normalization extracted from sidebands in *b*-tag and M_j

Generalized ABCD method: pass-fail ratio measured as a function of M_{j1} in several sidebands



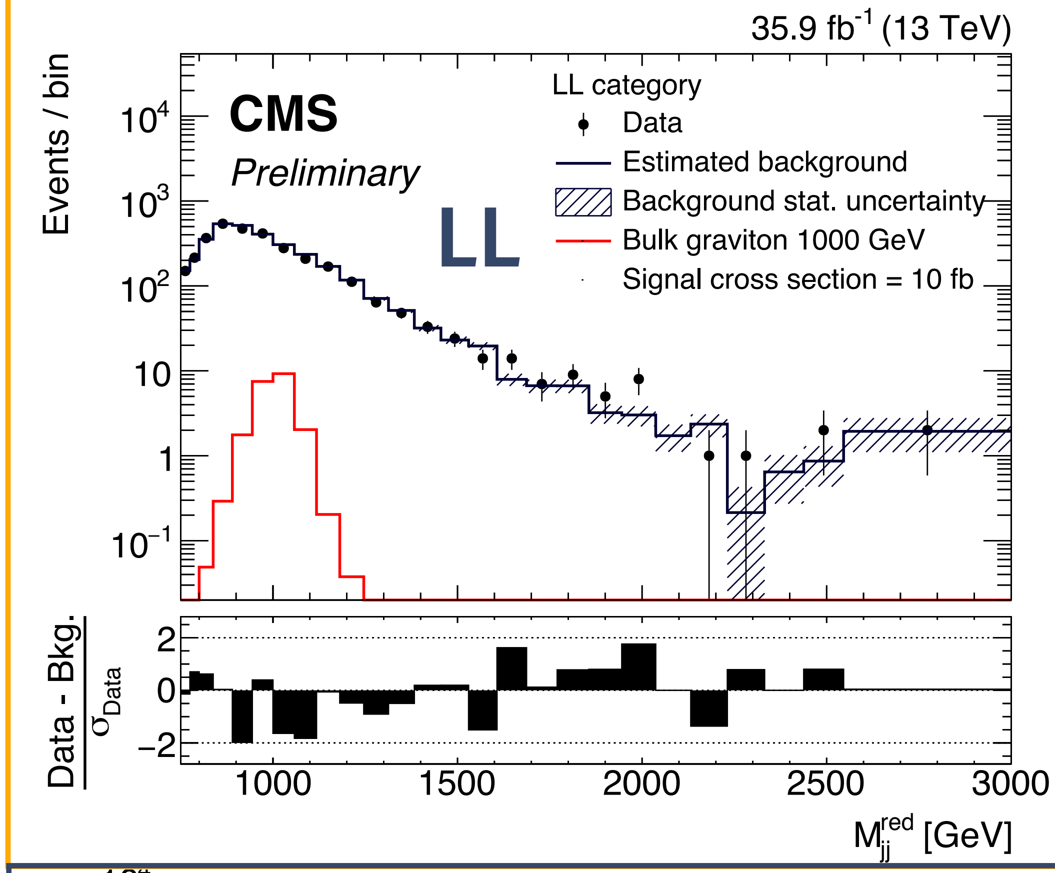
$$f(x) = N \cdot e^{-ax/(1+a \cdot b \cdot x)}$$

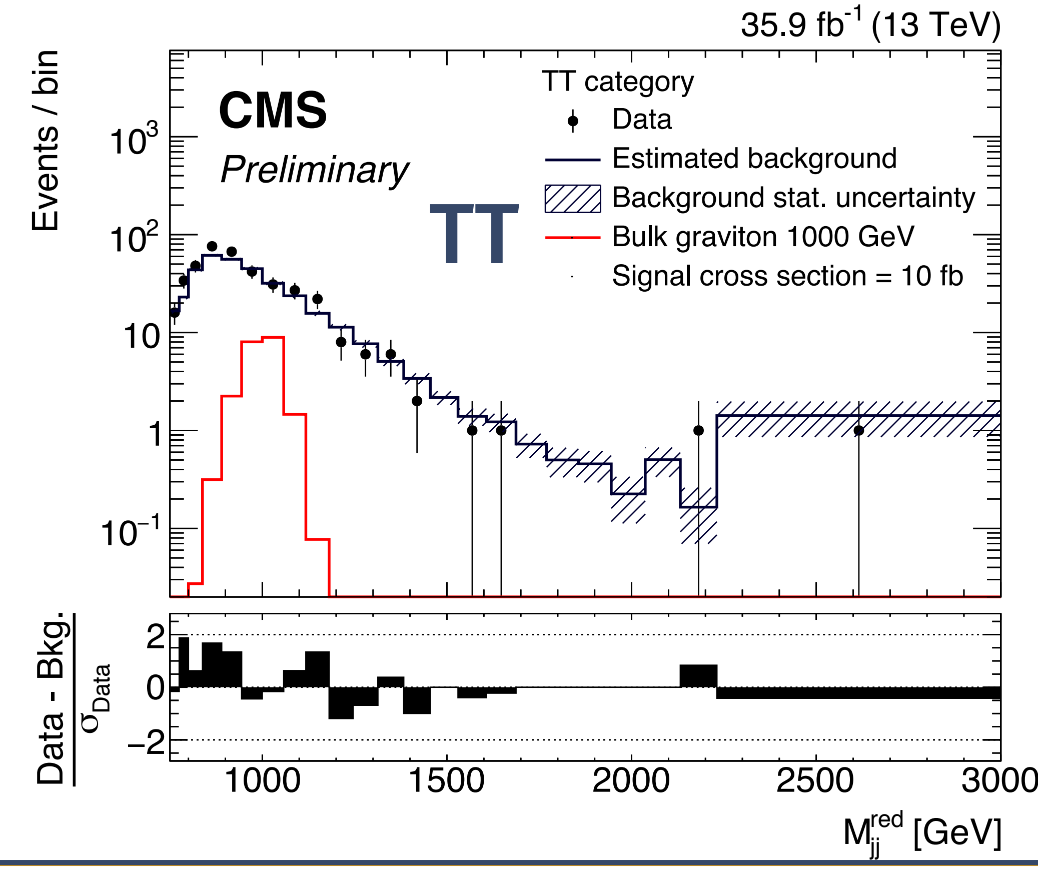
Latest ATLAS results: 13.3 fb^{-1}

HH→*bbbb*: CMS Results

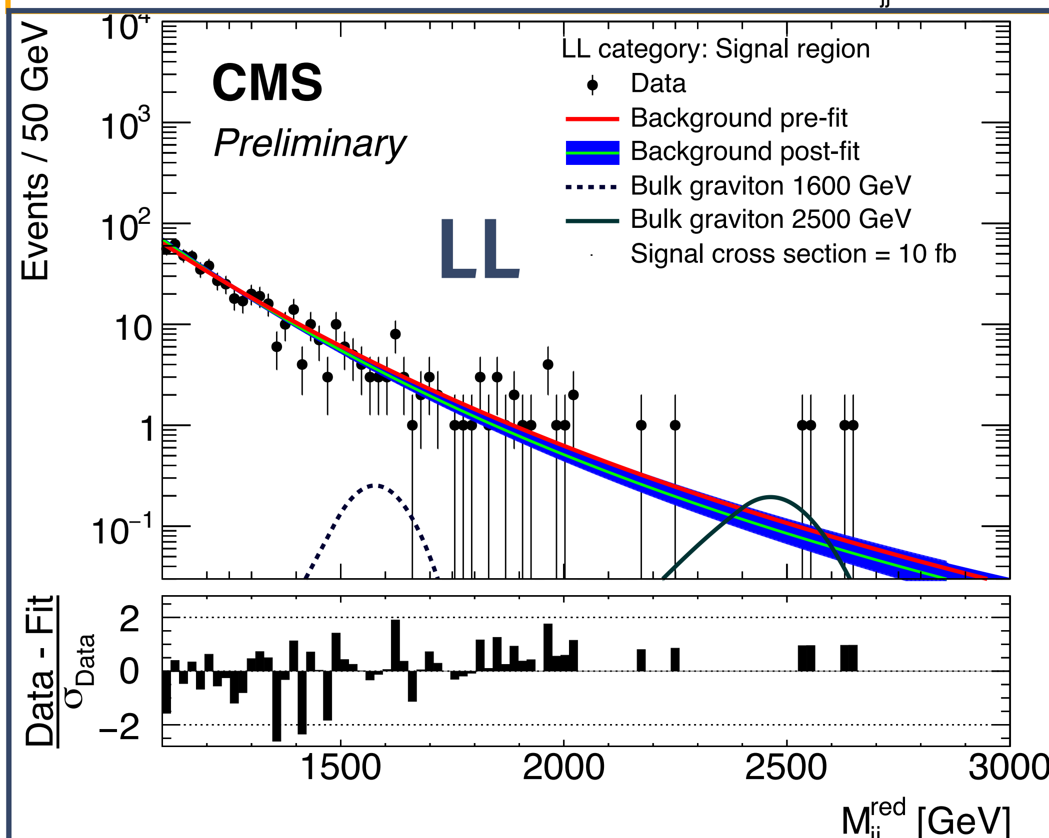
B2G-16-026

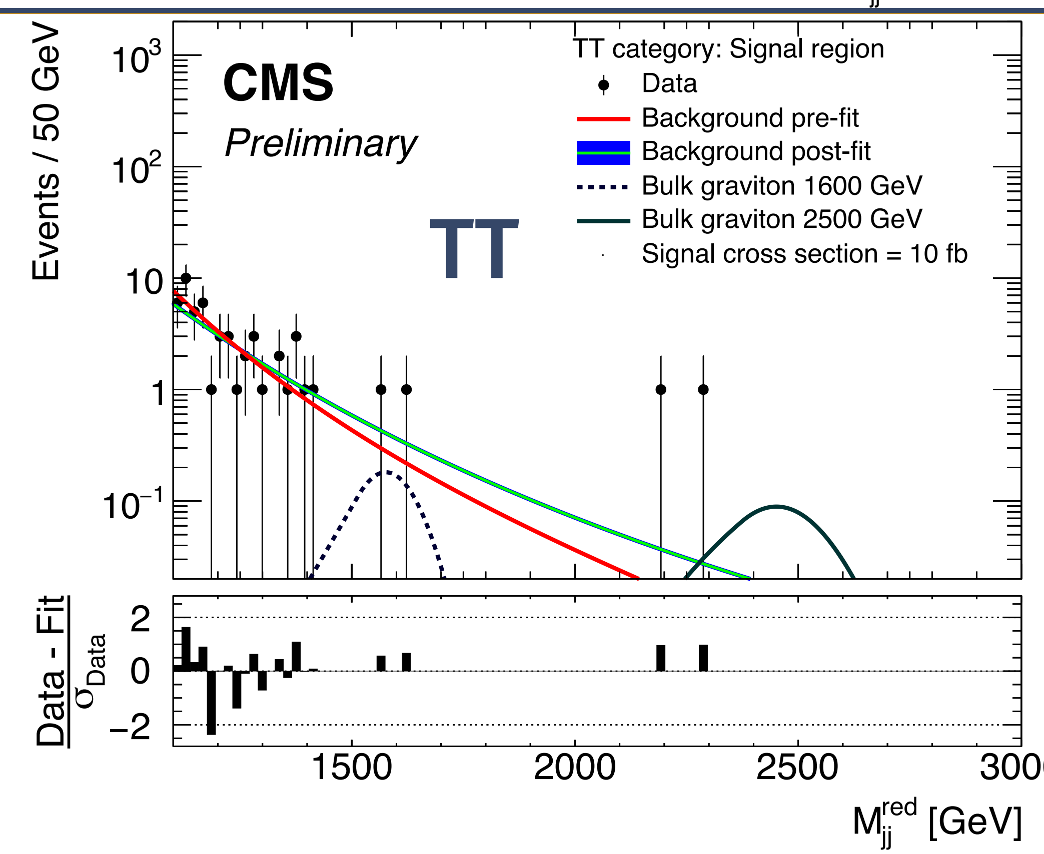
Alphabet

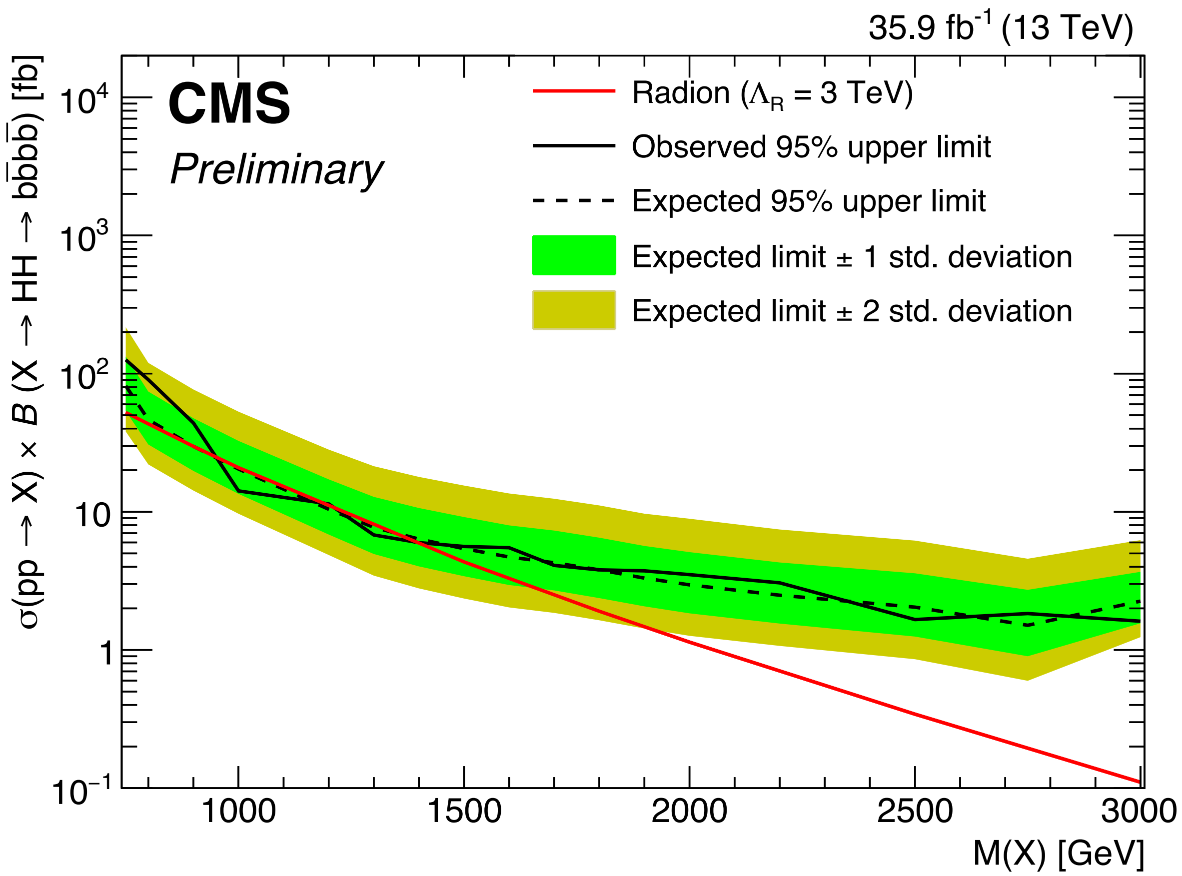




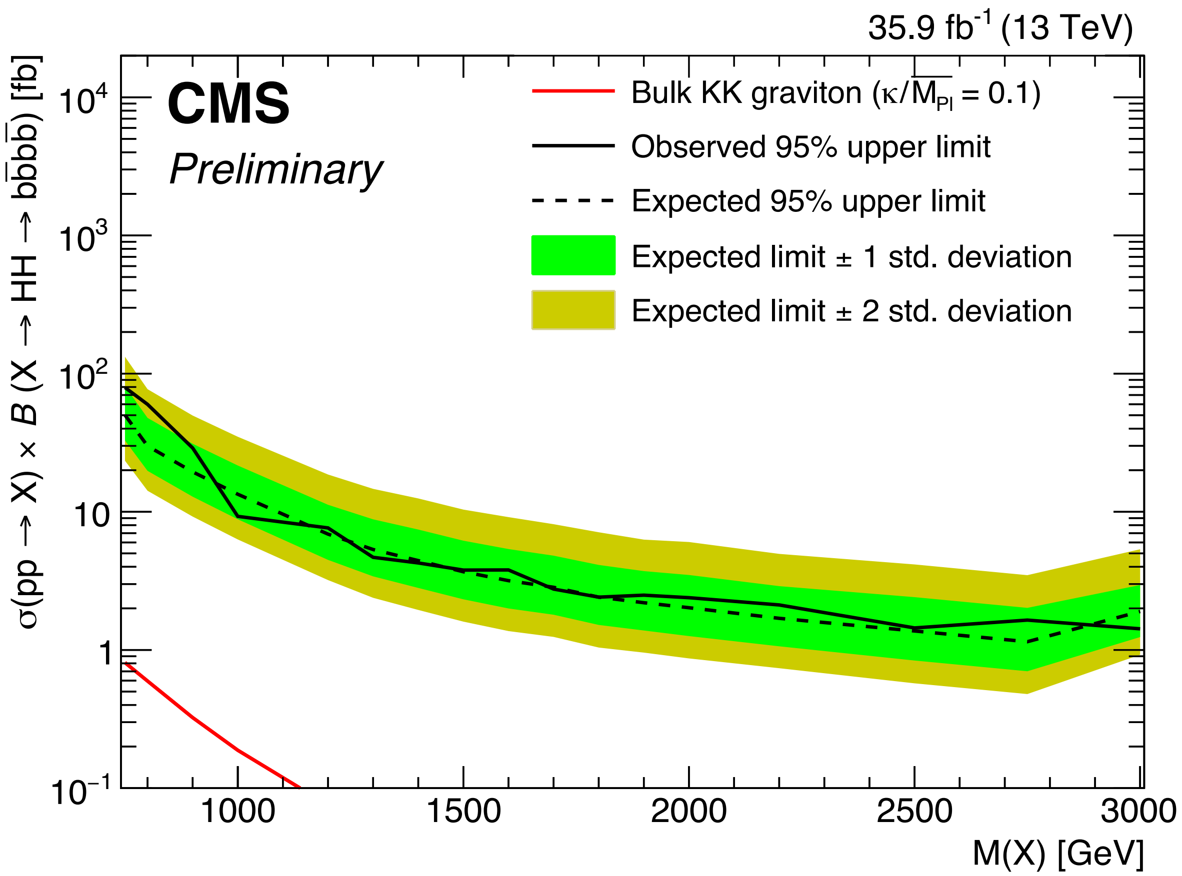
AABH







35.9 fb-1 (13 TeV)
CMS
Preliminary
Radion (ΛR = 3 TeV)
Observed 95% upper limit
Expected 95% upper limit
Expected limit ± 1 std. deviation
Expected limit ± 2 std. deviation
σ(pp → X) × B (X → HH → bb̄bb̄) [fb]
M(X) [GeV]

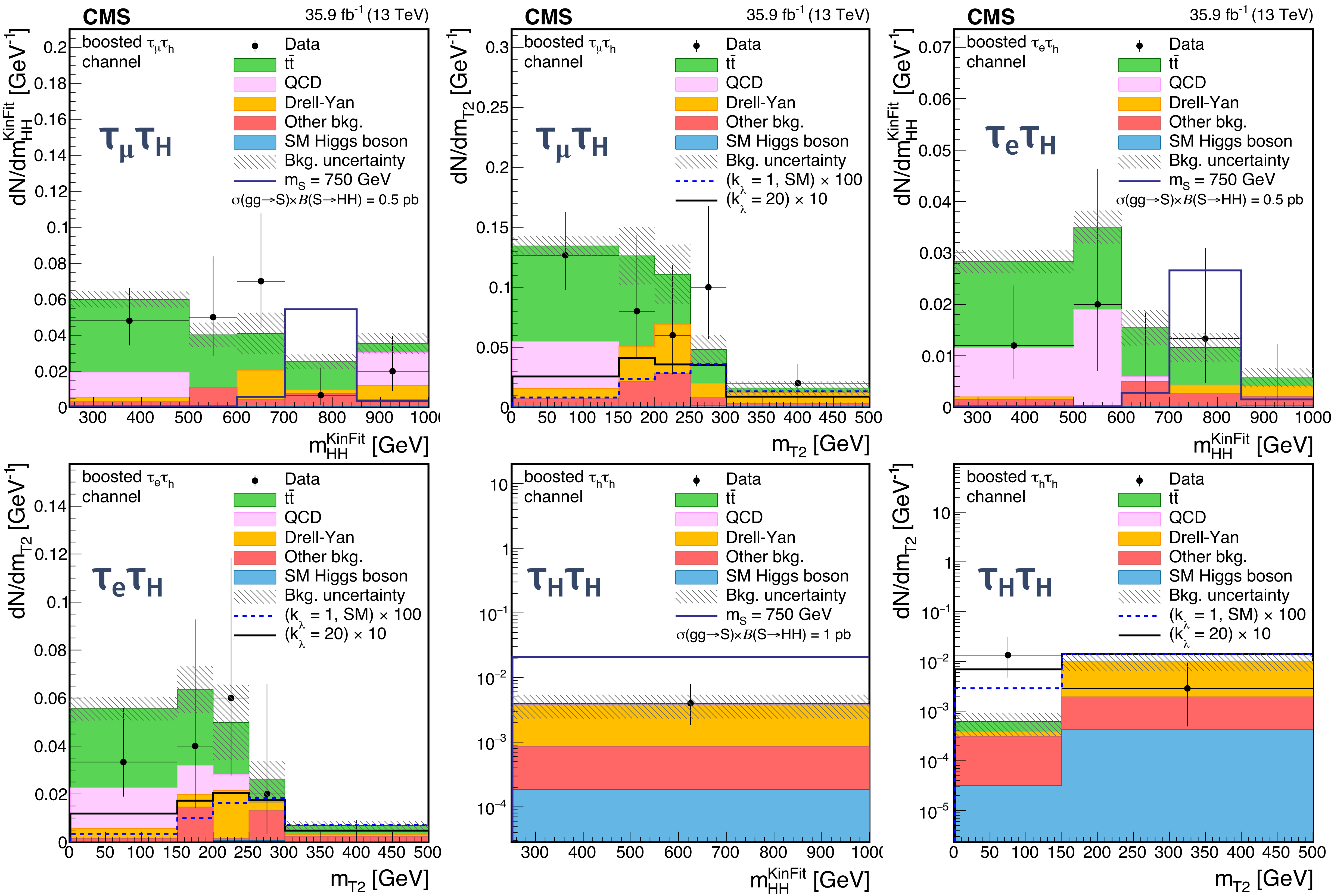


35.9 fb-1 (13 TeV)
CMS
Preliminary
Bulk KK graviton (κ/M̄Pl = 0.1)
Observed 95% upper limit
Expected 95% upper limit
Expected limit ± 1 std. deviation
Expected limit ± 2 std. deviation
σ(pp → X) × B (X → HH → bb̄bb̄) [fb]
M(X) [GeV]

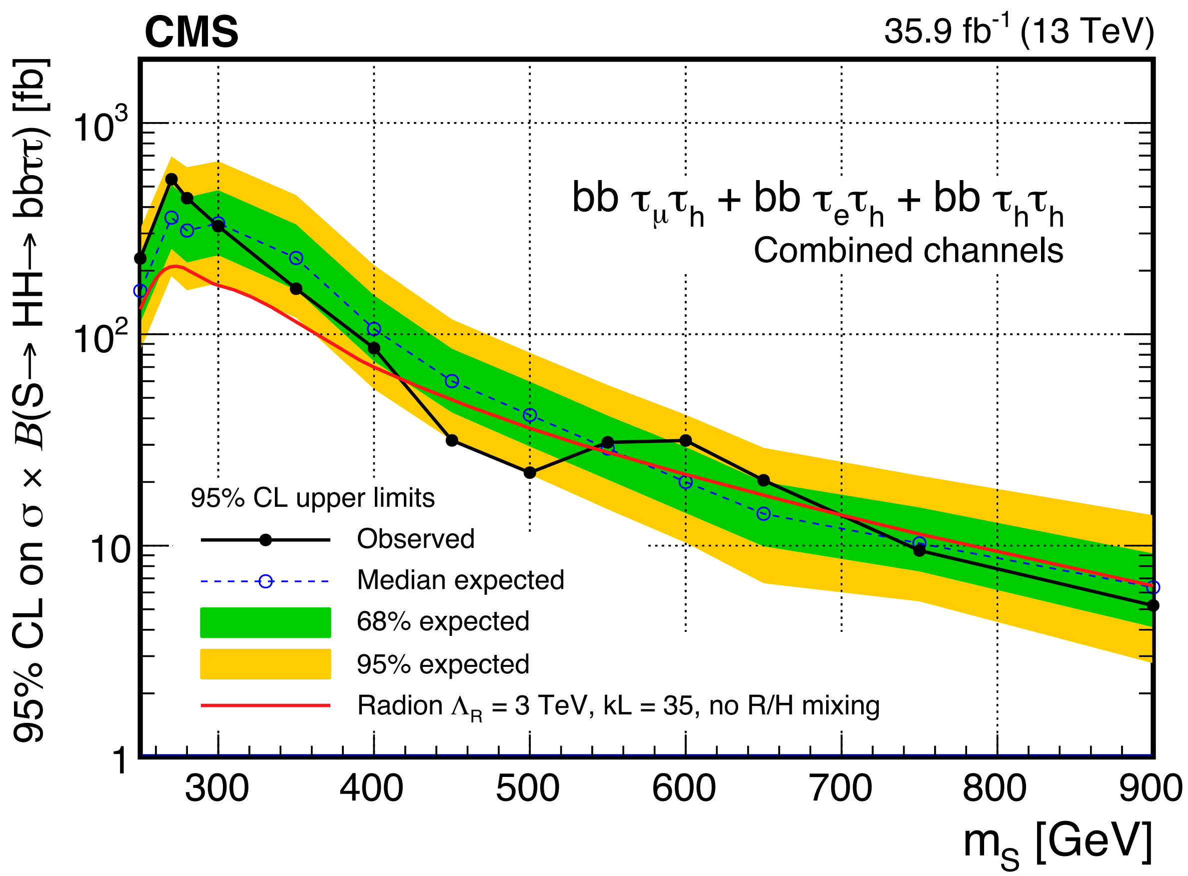
- Di-Higgs search in $\tau\tau$ final state to investigate both the resonant and non-resonant production mechanisms.
- 3 channels: $\tau_H\tau_H$, $\tau_H\tau_e$, $\tau_H\tau_\mu$, which cover 85% of $\tau\tau$ decays.
- 3 categories: 2 *b*-tags, 1 *b*-tag, ***high-mass boosted***.
- Main backgrounds: $t\bar{t}$, Drell-Yan, QCD (data-driven estimates).
- 2 BDTs to reject $t\bar{t}$ process in $\tau_H\tau_e$, $\tau_H\tau_\mu$ channels.
- Signal extraction from:
  - resonant: $m_{\mathrm{HH}}^{\mathrm{KinFit}}$
  - non-resonant: ‘stransverse’ mass m_{T2}.

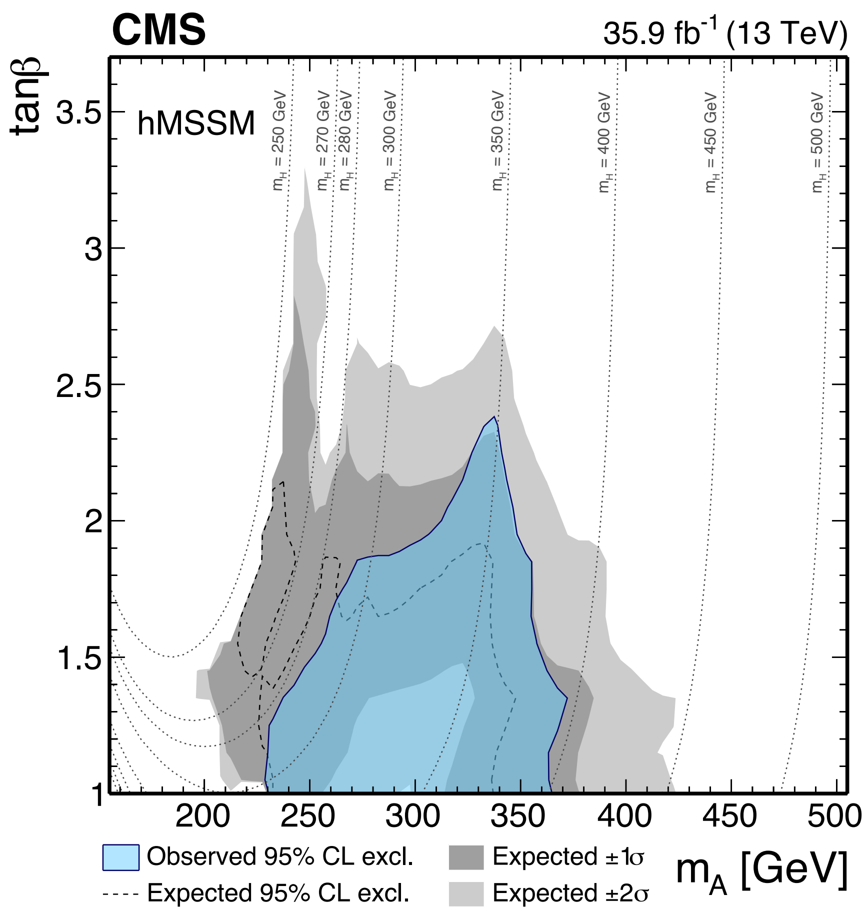
$HH \rightarrow bb\tau\tau$: CMS Results

HIG-17-002



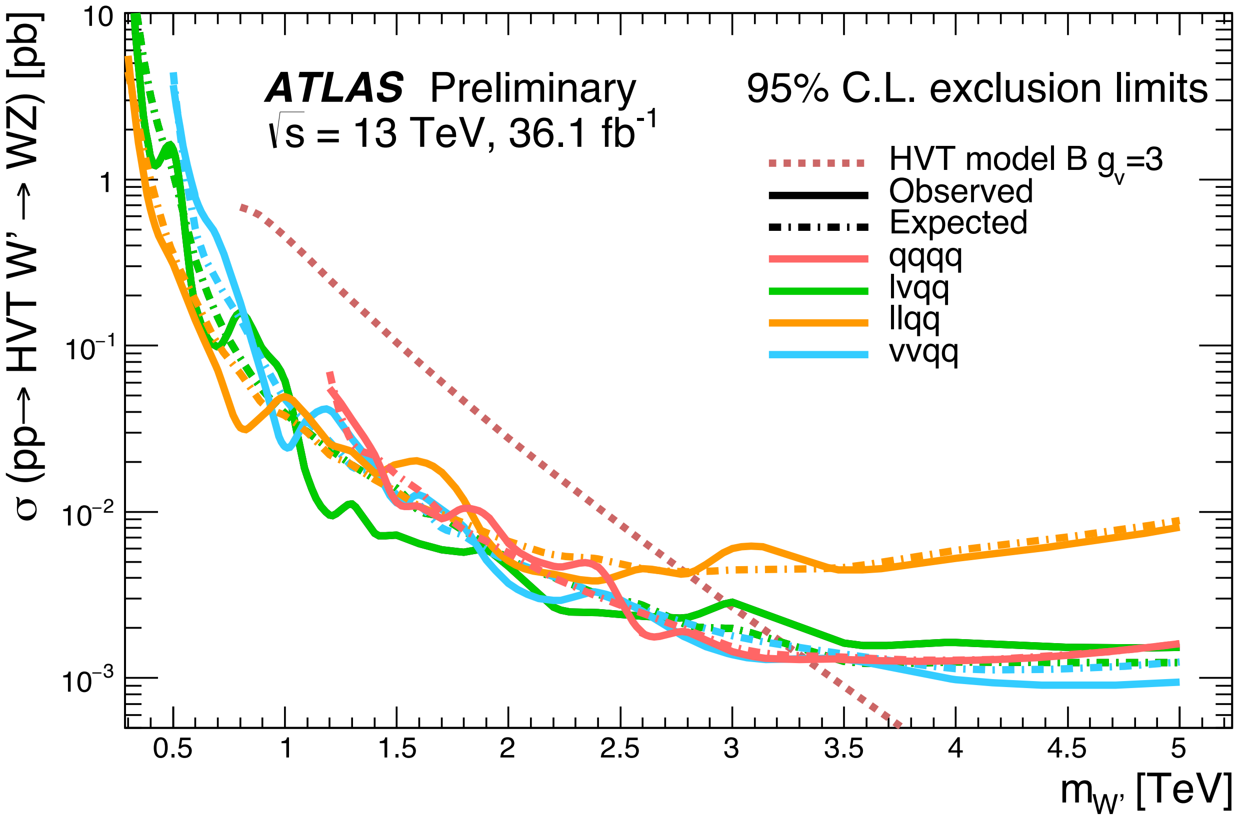
Resonant results

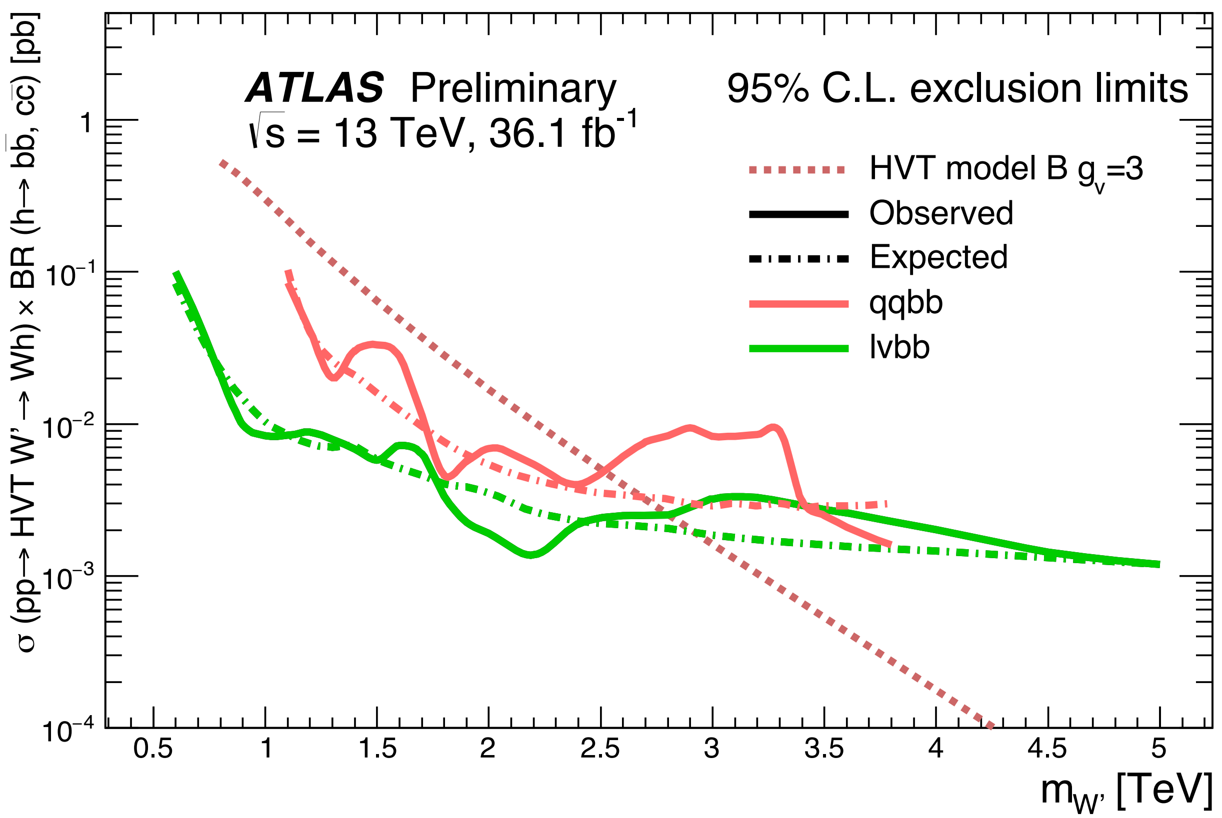


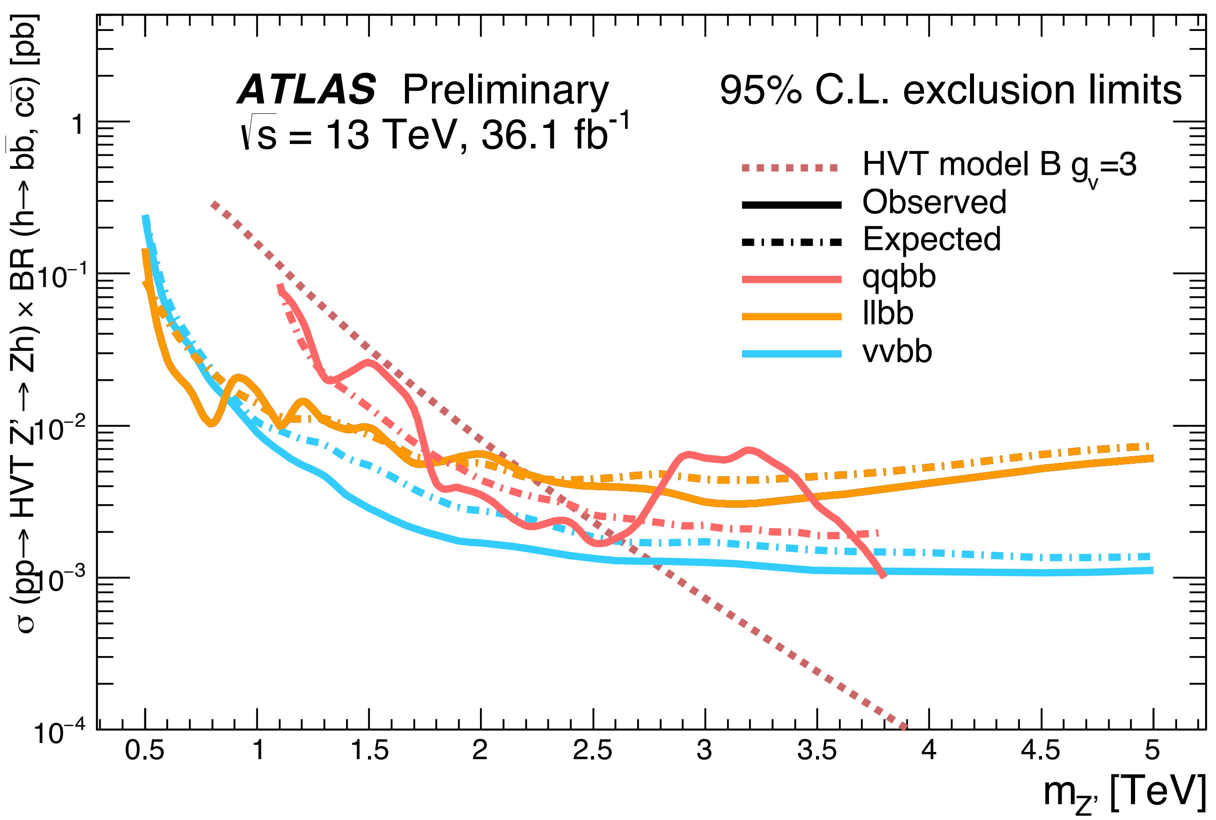


Summary

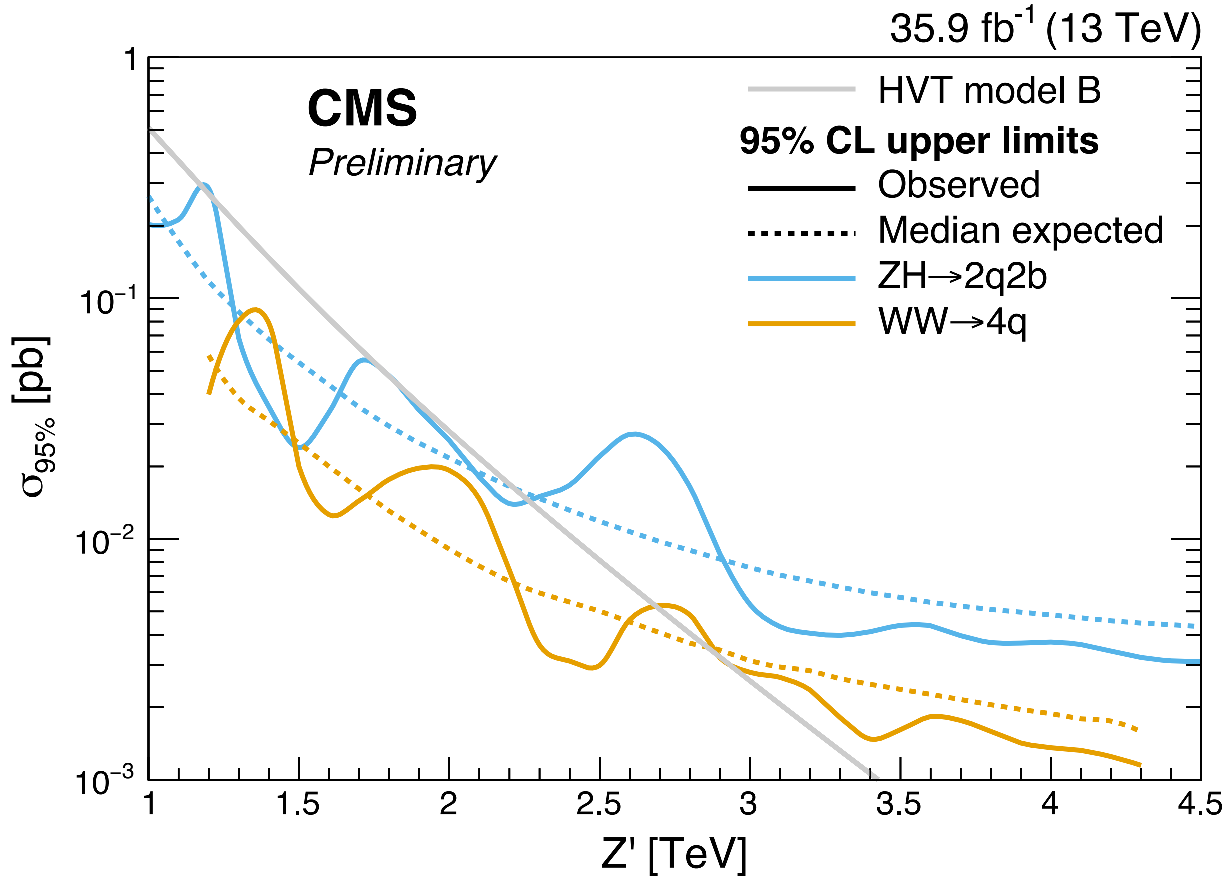
ATLAS Diboson Summary

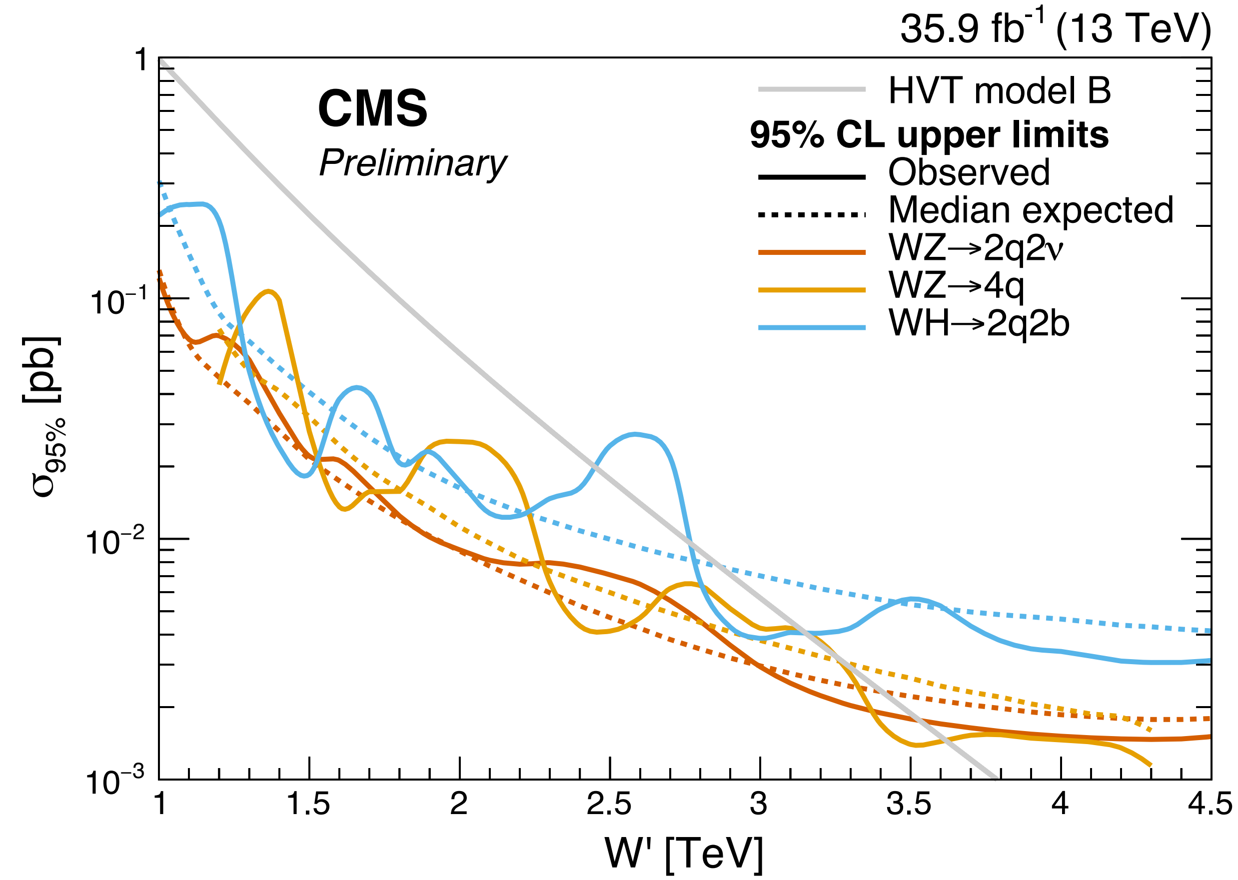


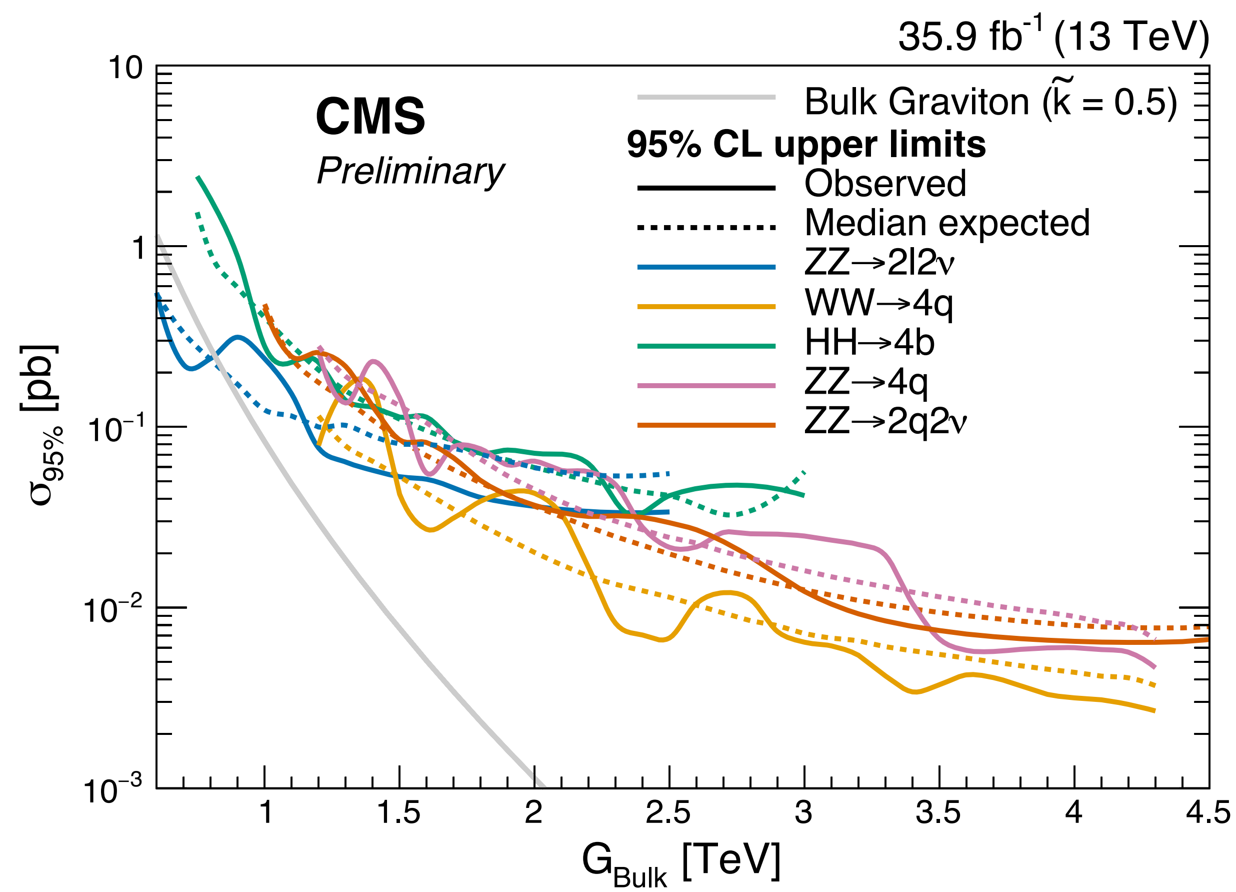




CMS Diboson Summary







Summary

- Latest ATLAS and CMS Run II searches for diboson resonances with boosted topologies are presented.
- No significant deviations from Standard Model observed .
- Looking towards the full Run 2 dataset:
  - Refine and improve the methods for the incoming data.
  - Benefit from more advanced boosted tagging techniques.
  - Exploring other ideas open-mindedly.

Backup

ATLAS Exotics Summary

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η^-_{LL}		1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV η^-_{LL}		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm}_L \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1 g_D$, spin 1/2	1509.08059

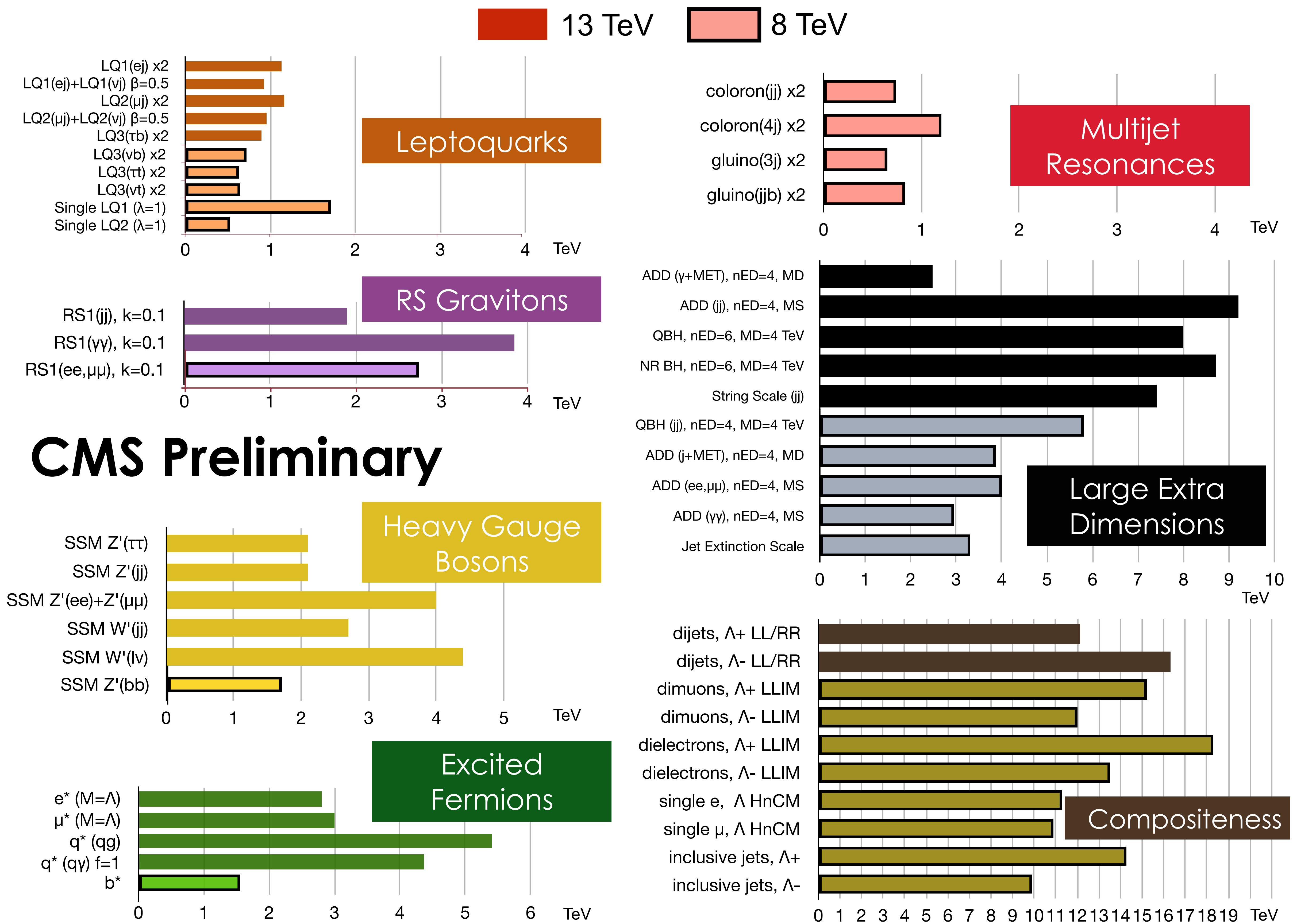
$\sqrt{s} = 8$ TeV $\sqrt{s} = 13$ TeV

Mass scale [TeV]: 10^{-1}, 1, 10

*Only a selection of the available mass limits on new states or phenomena is shown.

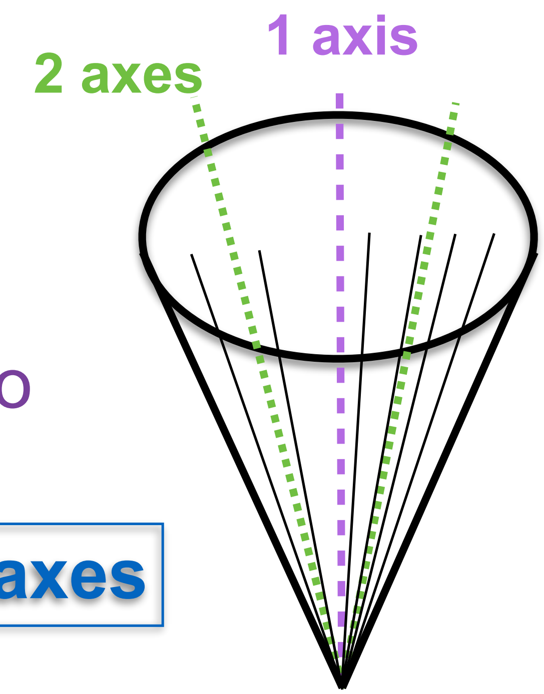
†Small-radius (large-radius) jets are denoted by the letter j (J).

CMS Exotica Summary



- for **boson-tagging**: want to quantify how **2-subjetty** a jet is
- ➜ to what extent is energy flow aligned along 2 momentum directions (N=2)?

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

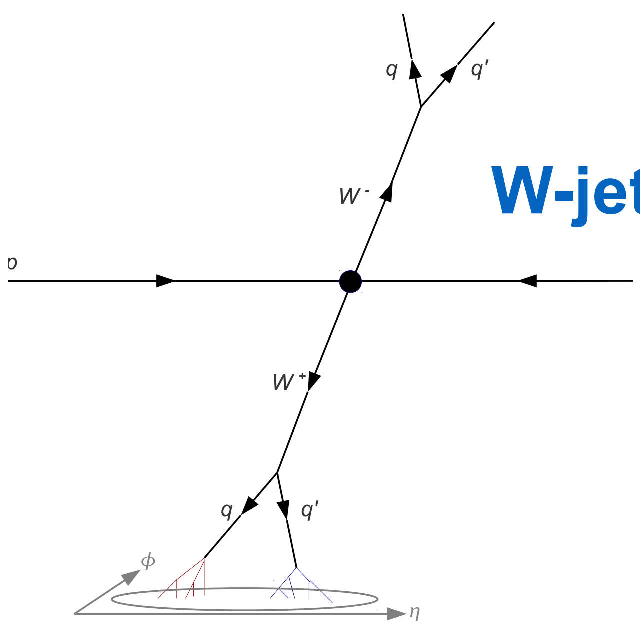


normalisation

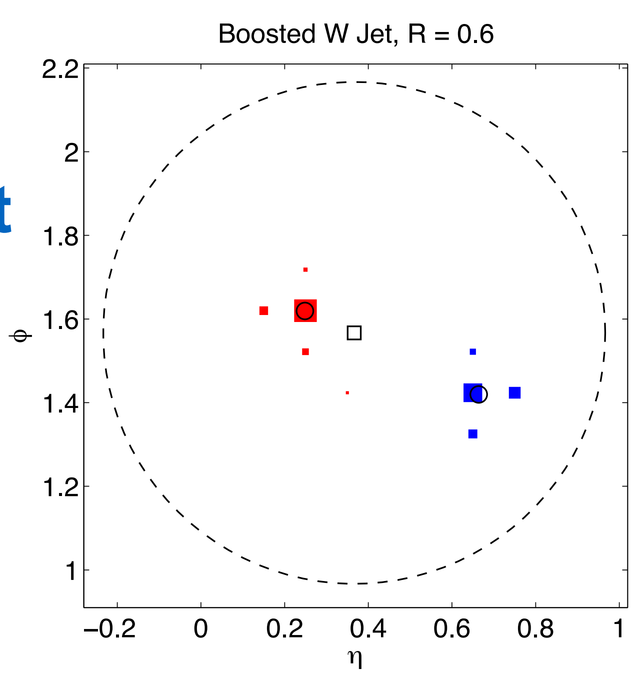
sum over particles

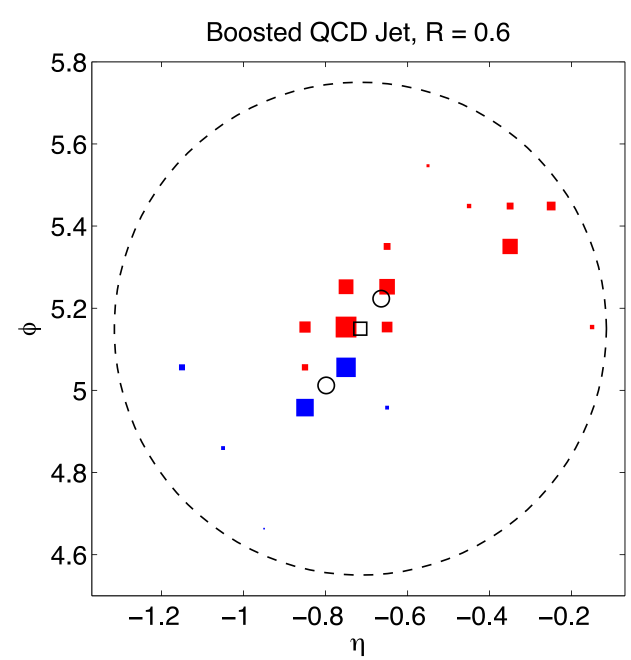
minimise distance to candidate subjets

low values of τ_N ➜ compatibility with the hypothesis of N axes

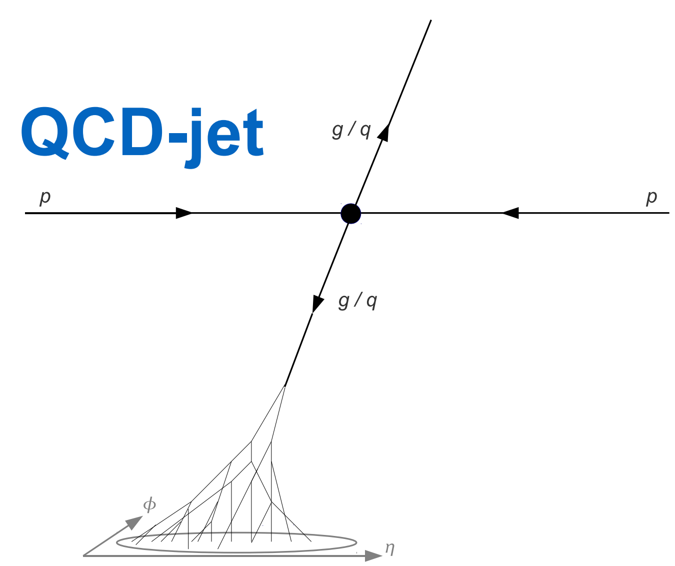


W-jet





QCD-jet



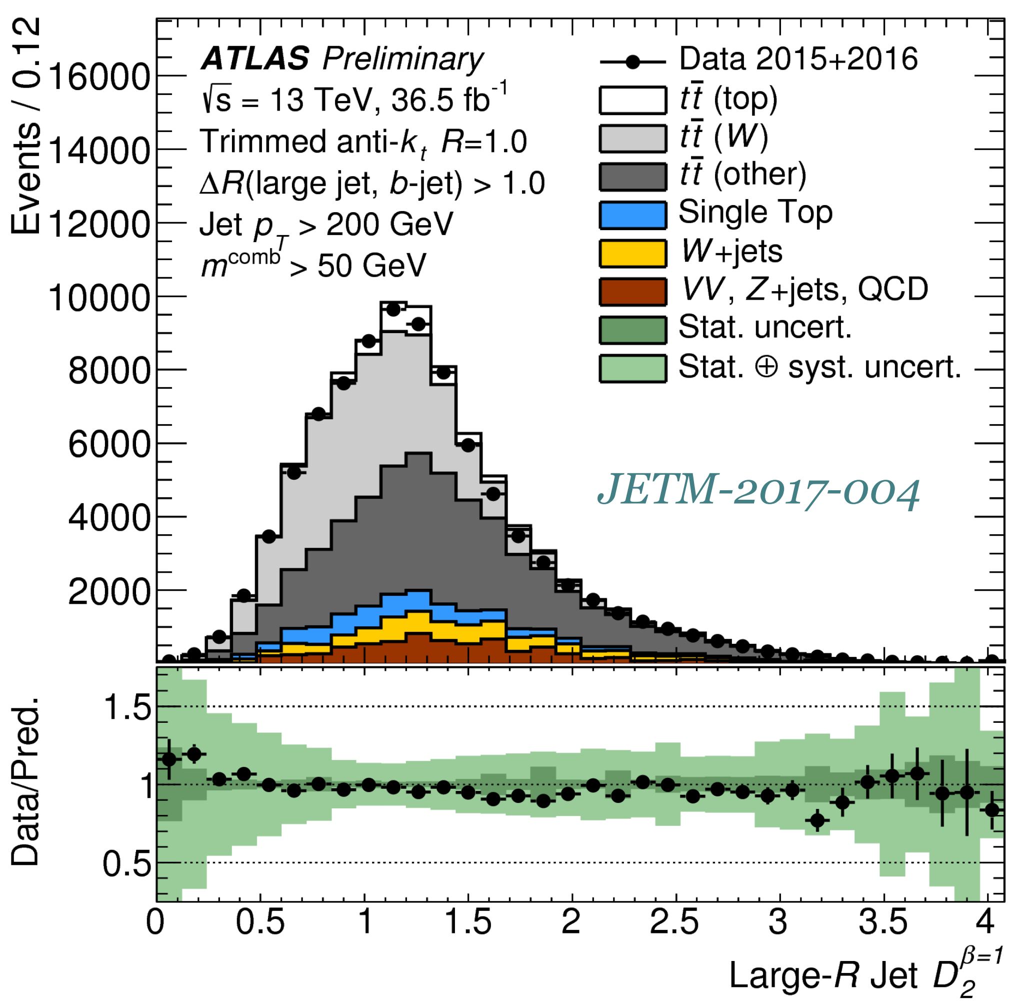
Substructure Variable: $D_2^{(\beta=1)}$

- Energy Correlation Functions (ECF)

$$E_{\mathrm{CF1}} = \sum_i p_{\mathrm{T},i}$$

$$E_{\mathrm{CF2}} = \sum_{ij} p_{\mathrm{T},i} p_{\mathrm{T},j} \Delta R_{ij}$$

$$E_{\mathrm{CF3}} = \sum_{ijk} p_{\mathrm{T},i} p_{\mathrm{T},j} p_{\mathrm{T},k} \Delta R_{ij} \Delta R_{jk} \Delta R_{ki}$$



- Substructure Variable:

$$D_2^{\beta=1} = E_{\mathrm{CF3}} \left(\frac{E_{\mathrm{CF1}}}{E_{\mathrm{CF2}}} \right)^3$$

- *Different working points (w.p.): providing different signal efficiency, e.g. 50%, 80%*
- *Variable cuts: according to the jet p_T*