New Physics Results (boosted signatures) from the LHC

Josh Xi

August 25, 2017

University of Michigan

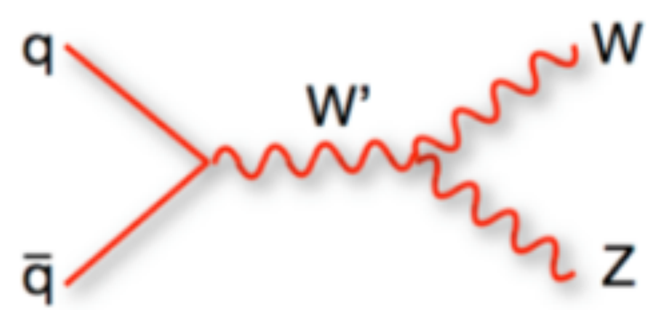
Introduction

- Many searches at LCH look for new physics with multiple bosons 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 multiple bosons in the final states; finding such new physics via multi-boson final states will be expedited in Run 2 of LHC with an increased center-of-mass energy.

Theoretical models

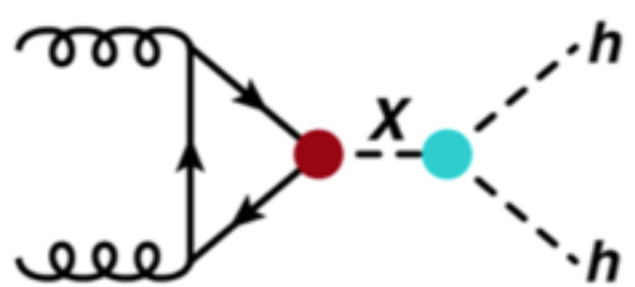
1. Heavy Vector Triplets (HVT)

- 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, $1 < g_V < 4\pi$, $c_H \approx c_F \approx 1$
- *WW, WZ* final states



2. Warped Extra Dimensions

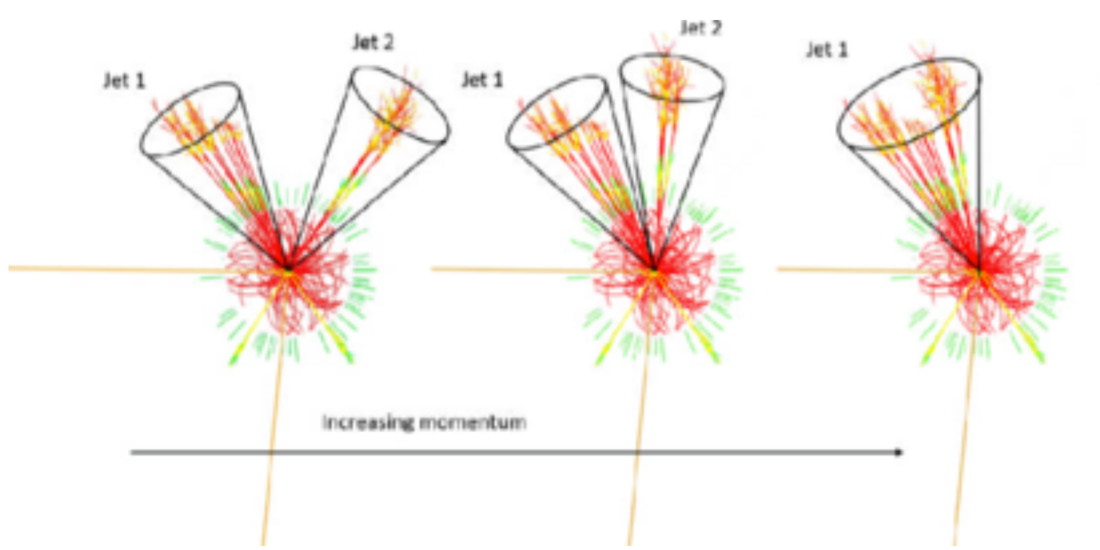
- Randall-Sundrum (RS) models
- Bulk graviton models allow SM particles into 5D-bulk
  - Production width dependent on $k/\bar{M}_{pl}$
- *WW, ZZ, hh* final states

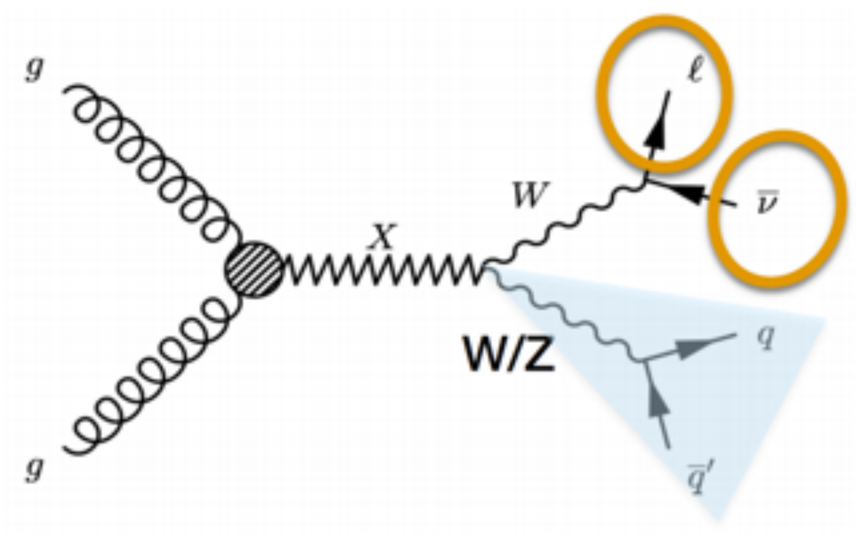


KK gravitons, heavy higgs, …

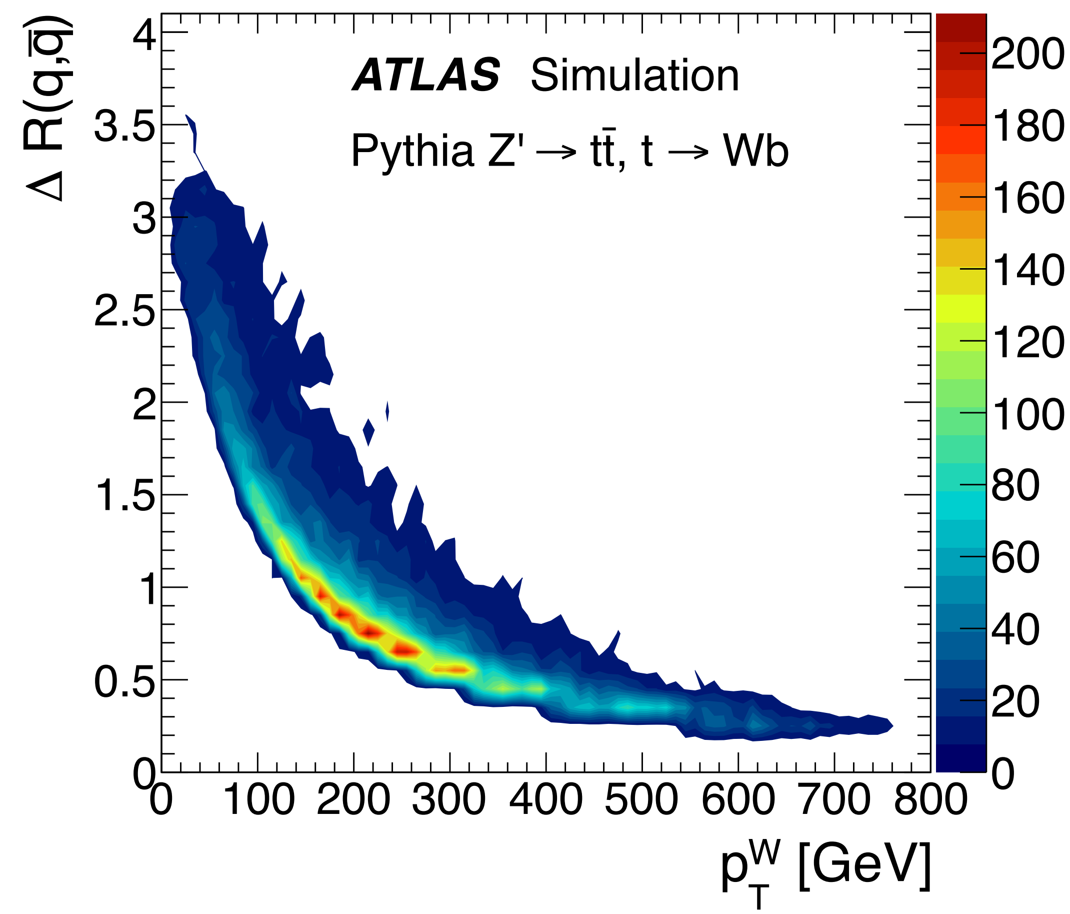
3. MSSM/2HDM etc.

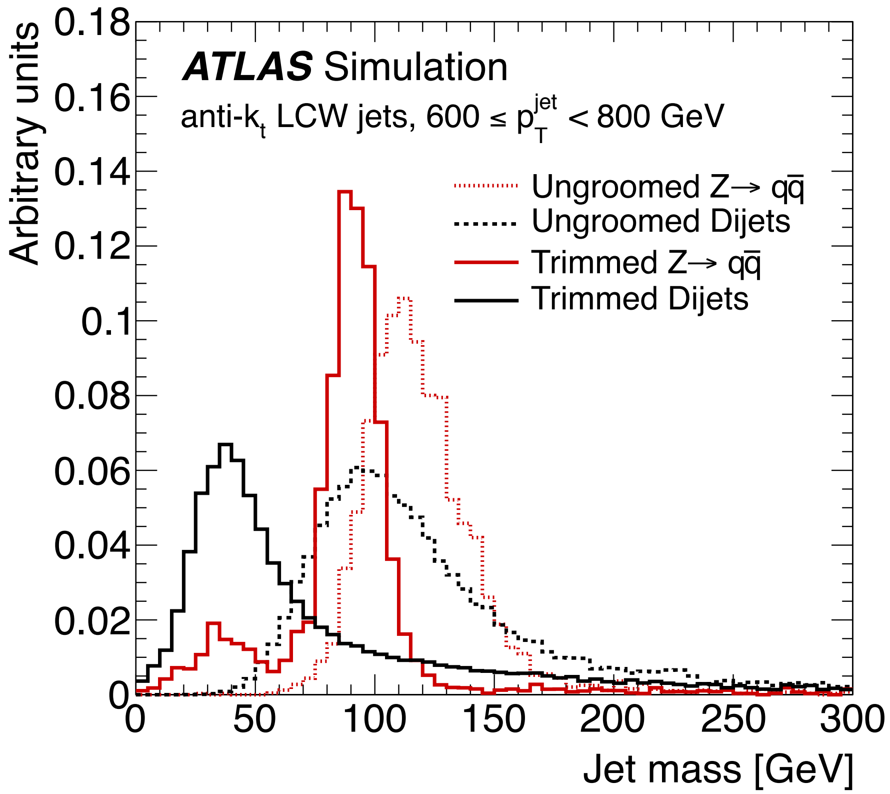
Identification of hadronic decays of boosted bosons



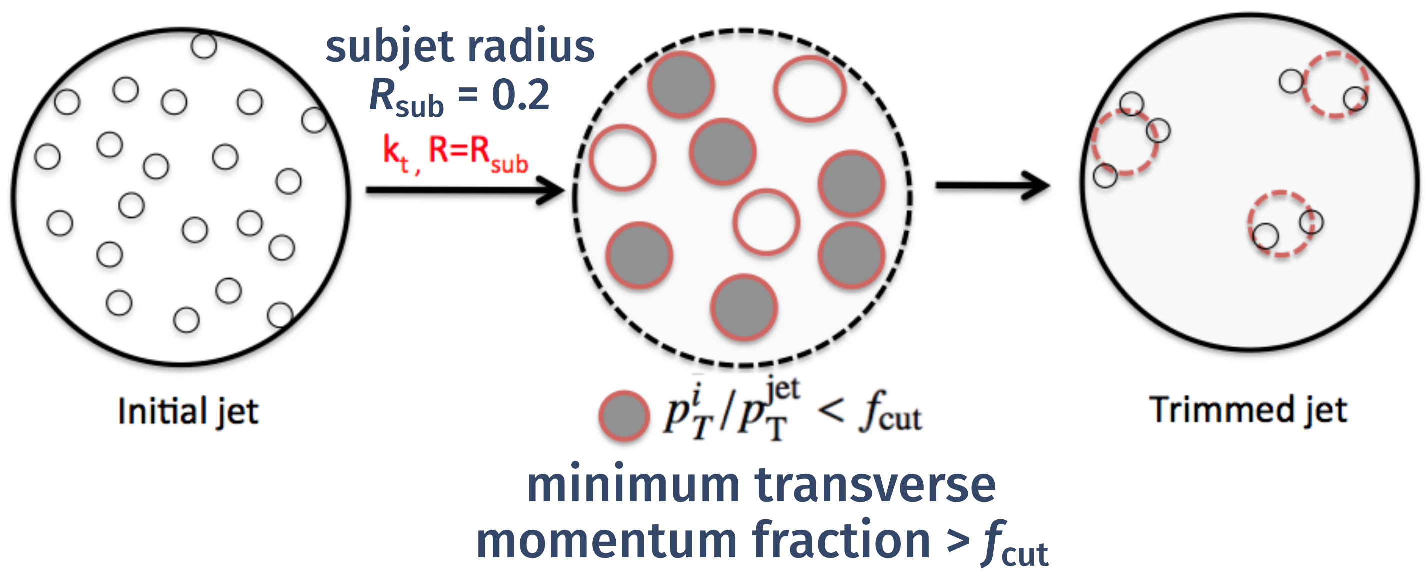


- Large-R jet: anti-k_T R = 1.0 trimmed jets
- Jet grooming technique: trimming
  - To remove the effects of pile-up and underlying event
  - Trimming parameters: R_{sub} = 0.2 and f_{cut} = 5%





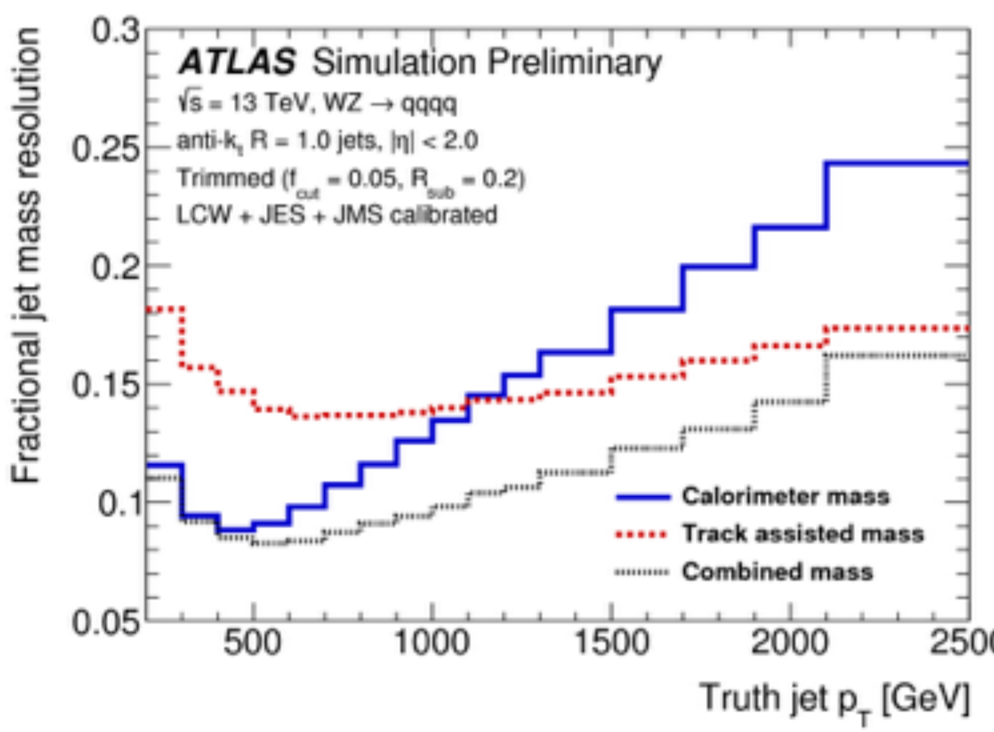
Jet trimming procedure

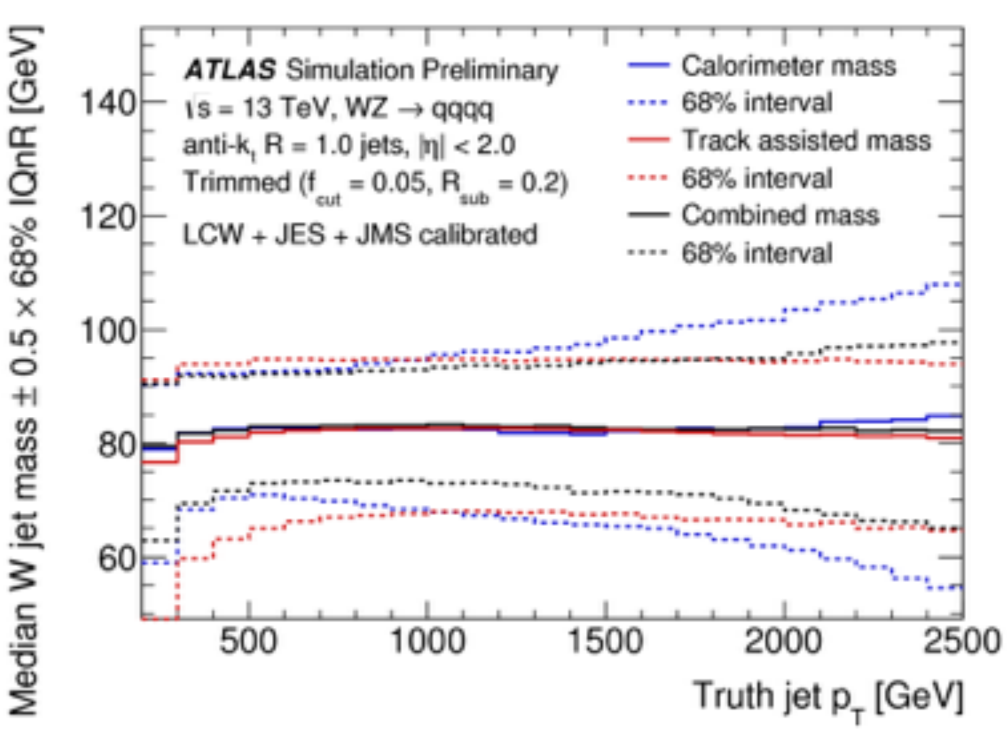


- Jet mass — combined mass
  - Track-assisted mass: $m^{\mathrm{TA}} = m^{\mathrm{track}} \times \frac{p_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{\mathrm{track}}}$
  - Spatial granularity of tracks can improve the mass resolution at high p_{T}
  - Combined mass based on both calorimeter and track:

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

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

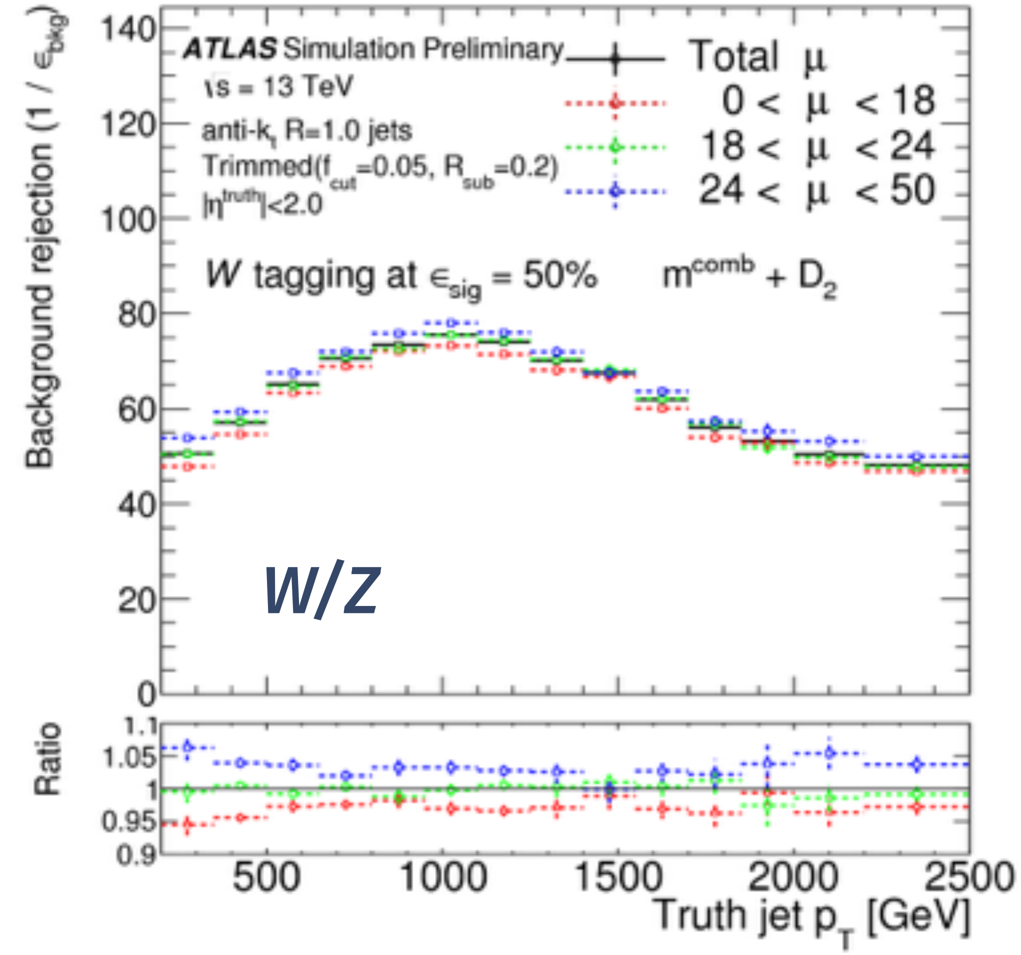


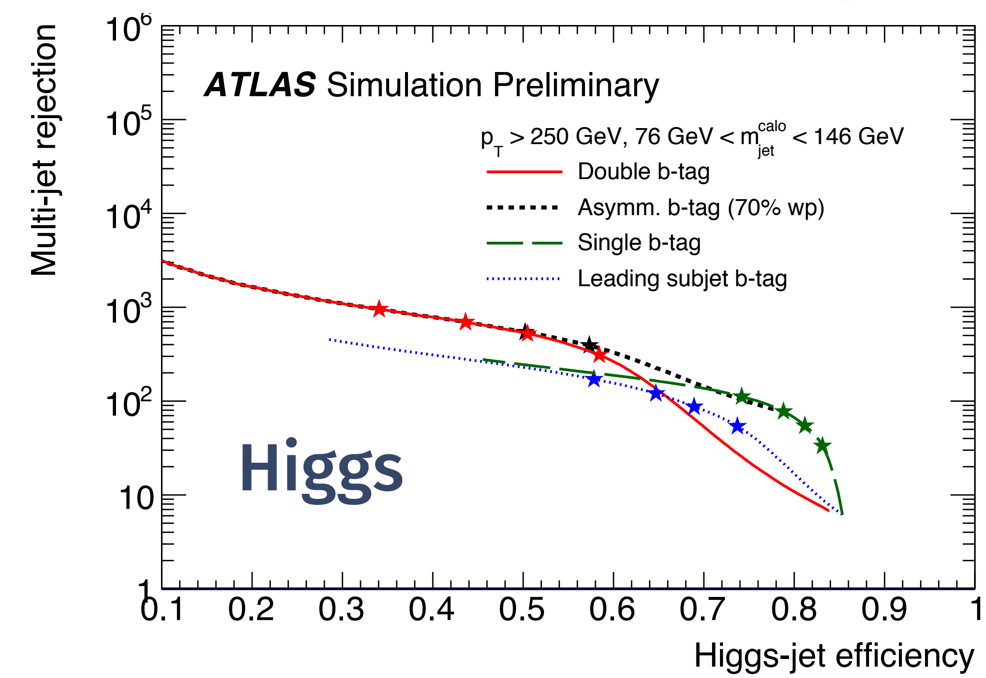


Boosted Tagging: ATLAS

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

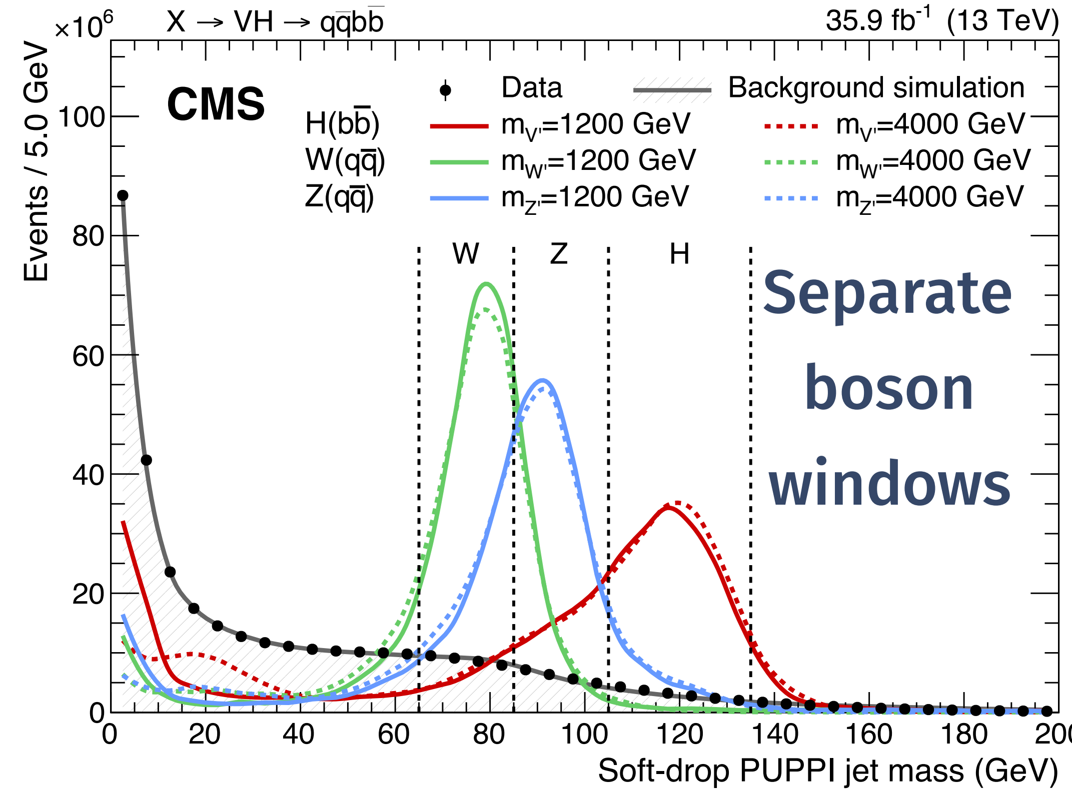
- *W*/*Z* tagger: 2-var optimized tagger which provides 50% and 80% signal efficiency working points. The two variables are:
  - Jet substructure $D_2^{(\beta=1)}$ (cut is p_T dependent)
  - Large-R jet mass window (cut is p_T dependent)
- Higgs-jet tagger:
  - *b*-tagging of ghost-associated track jet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

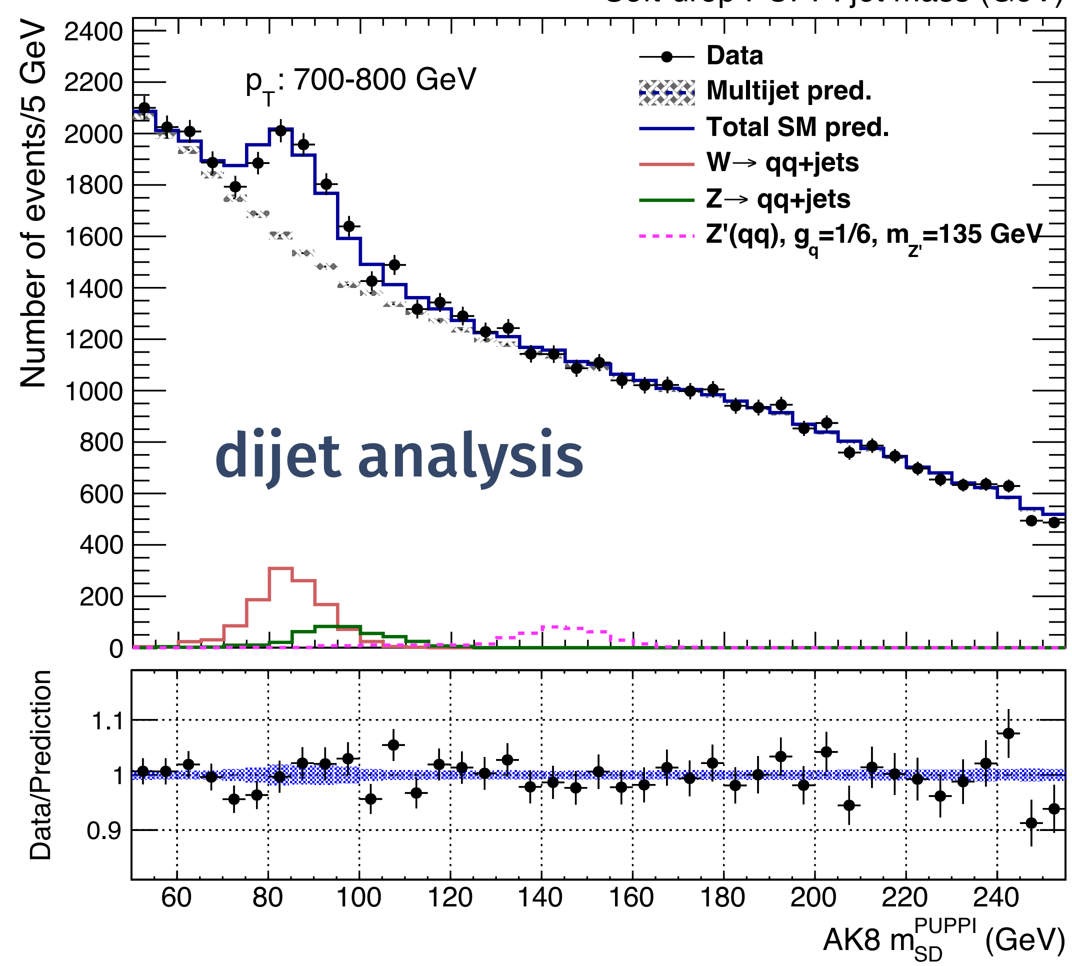




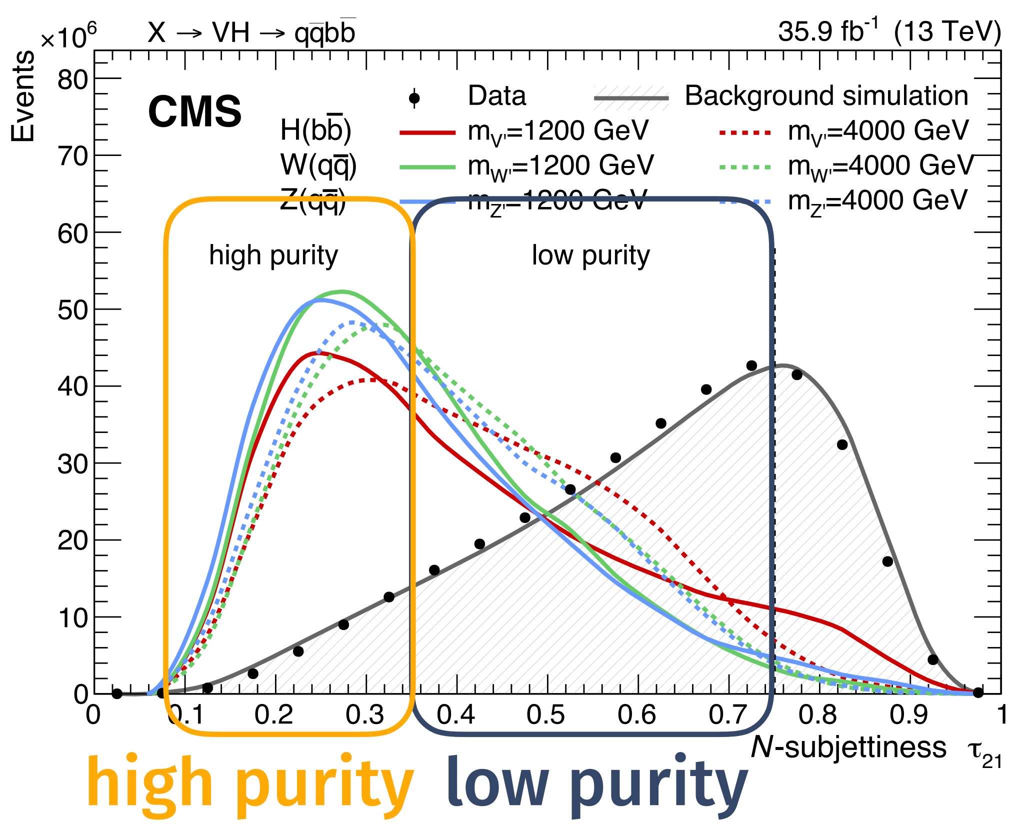
Stars: 60%, 70%, 77% and 80% WPs (left to right)

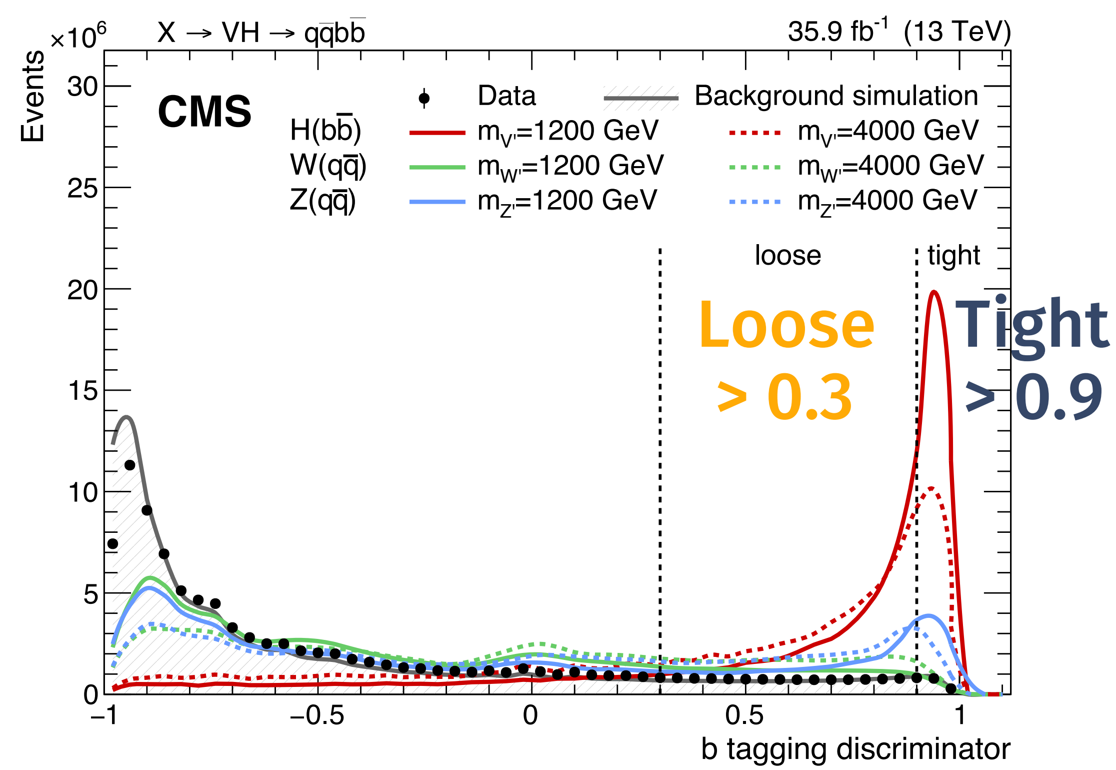
- PUPPI AK8 jets — Pile-up suppression:
  - Particles are assigned weights using the pileup per particle identification (PUPPI)
  - Four momenta of particles are rescaled based on the weights
  - Particles are subsequently clustered into AK8 jets (anti-k_T, R = 0.8)
- Jet mass — soft-drop algorithm: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





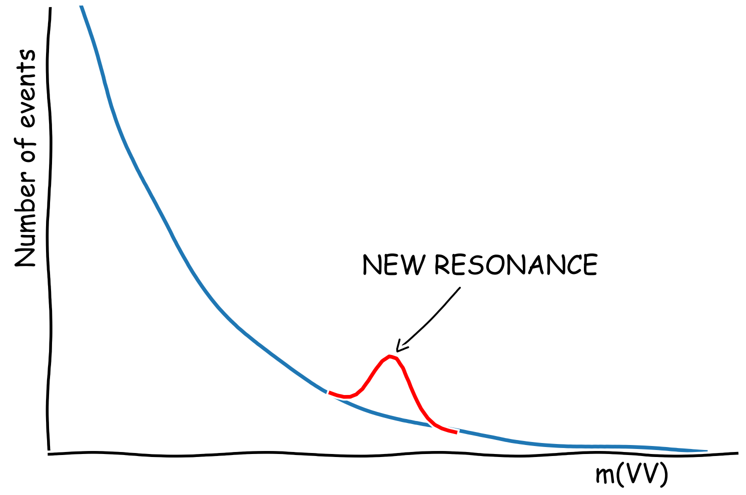
- Substructure variable — *N*-subjettiness τ_{21}:
  - τ_N describes the degree to which a jet is consistent with having ≤N sub-jets;
  - $\tau_{21} = \tau_2/\tau_1$ separating bosons jets from q/g jets; high- and low-purity regions based on the value of τ_{21}
- In addition to τ_{21}, **double-*b* tagger**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





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

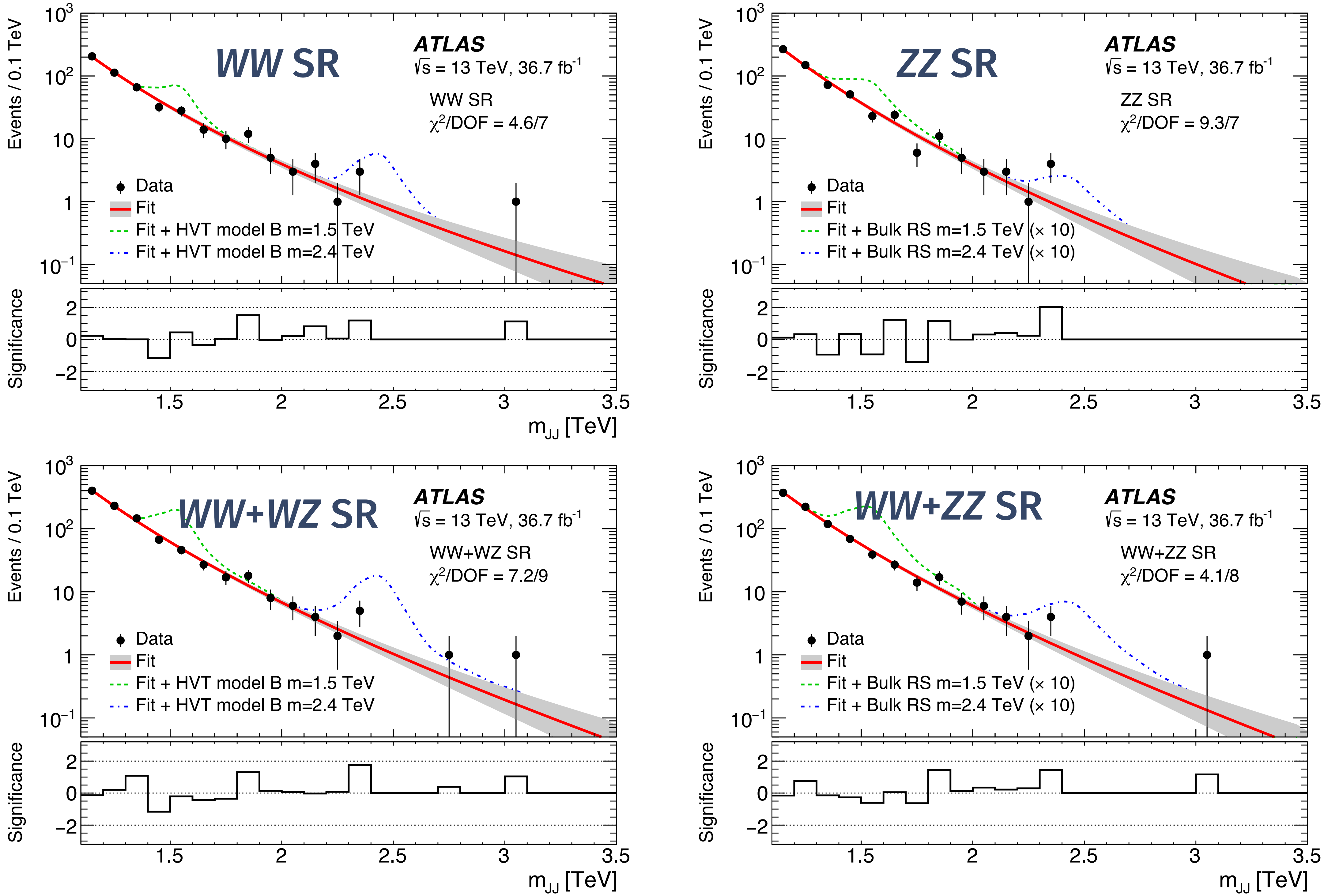
$X \rightarrow VV \rightarrow qqqq$



- 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
- Boosted *W* and *Z* mass windows partially overlap
- ATLAS: 50% efficiency *W/Z* tagger; *WW*+*WZ* or *WW*+*ZZ* for interpretation
- CMS: High-purity + low-purity signal regions. *WW*, *WZ* and *ZZ* interpreted separately.

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

EXOT-2016-19

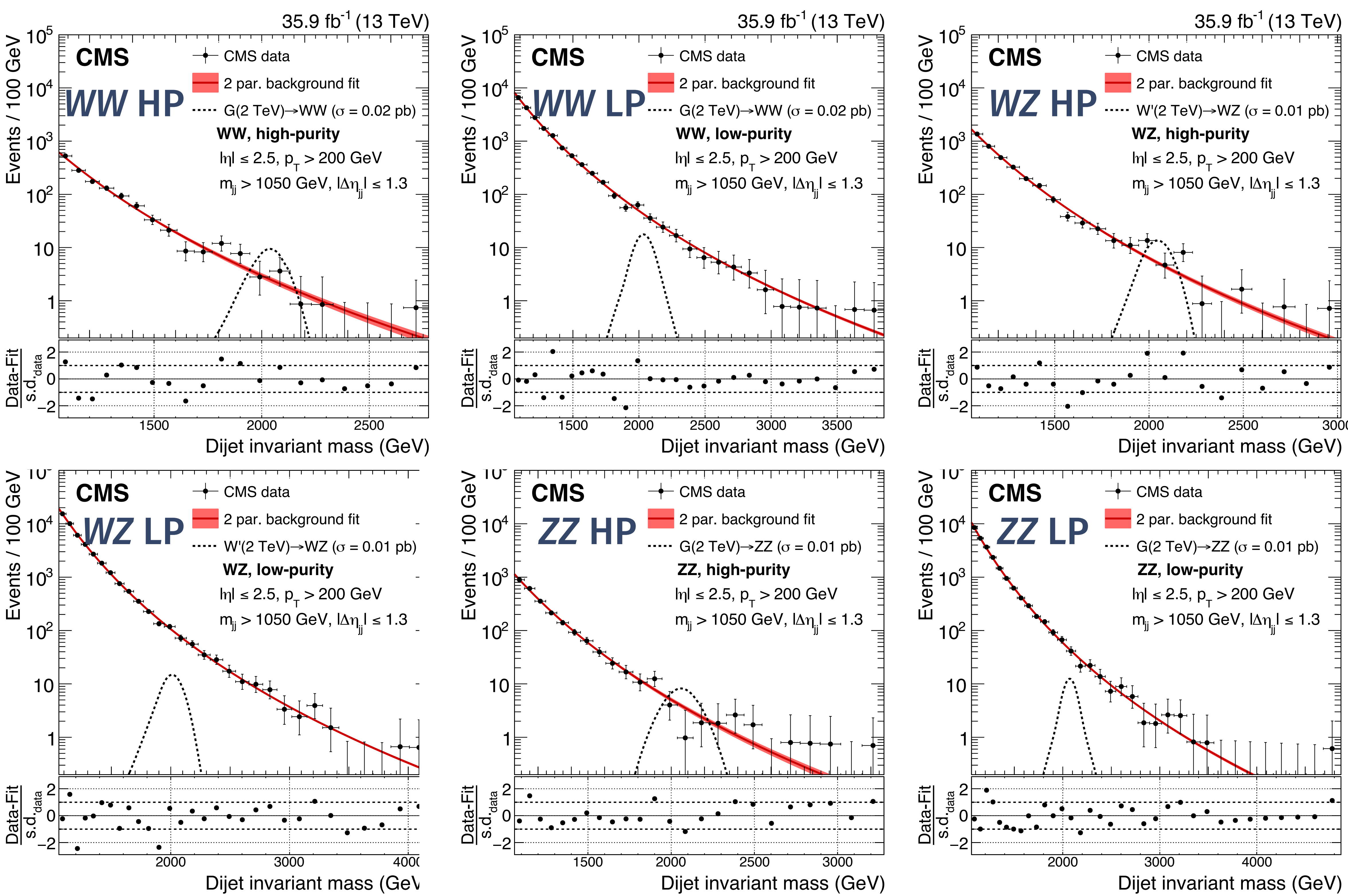


$W \to qq \to J$ and $Z \to qq \to J$ mass windows overlap; high-purity only

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

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

B2G-17-001

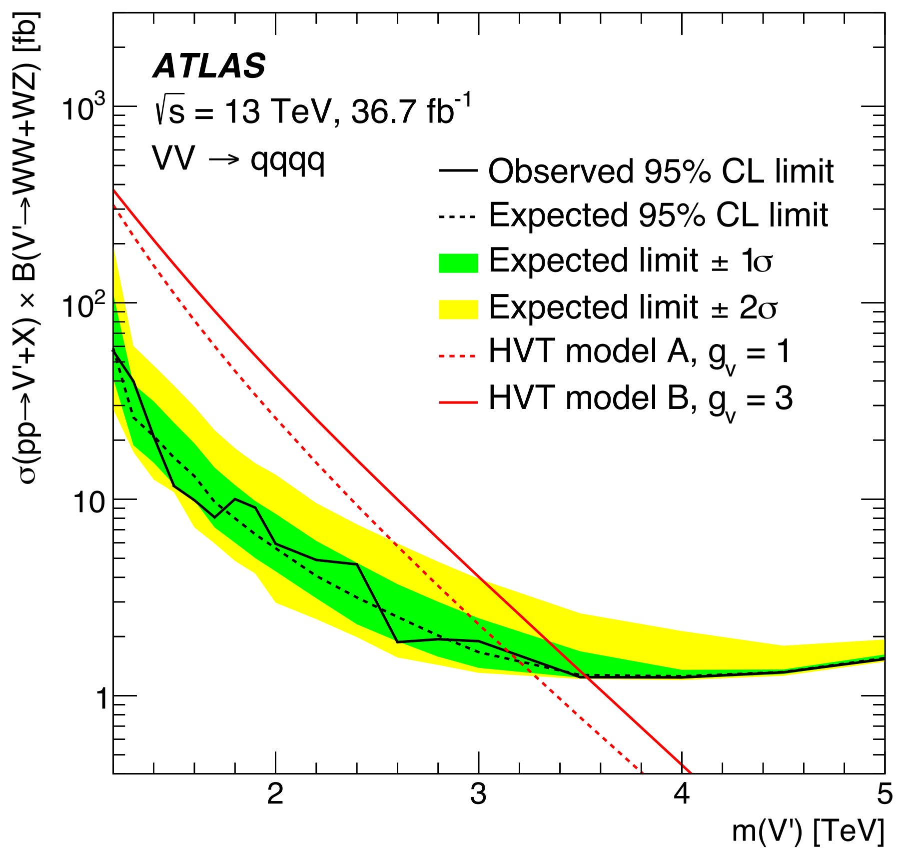


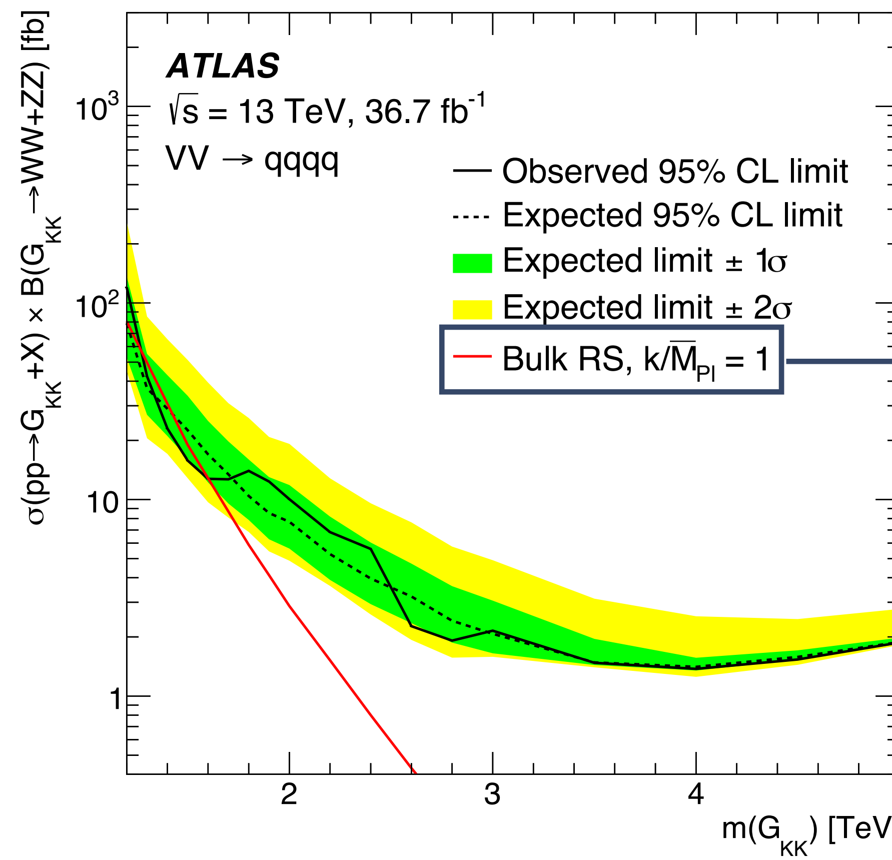
F-test: $$\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_1}} \text{ (2-par. form) or } \frac{dN}{dm_{jj}} = \frac{P_0(1-m_{jj}/\sqrt{s})^{P_2}}{(m_{jj}/\sqrt{s})^{P_1}} \text{ (3-par. form)}$$

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

EXOT-2016-19 B2G-17-001

Pseudo-experiment

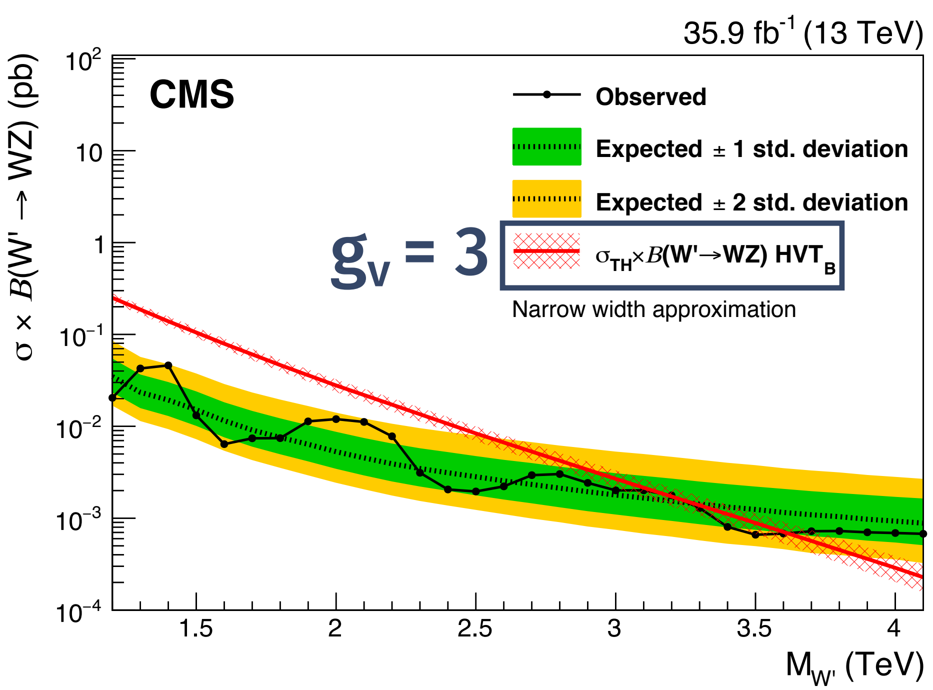


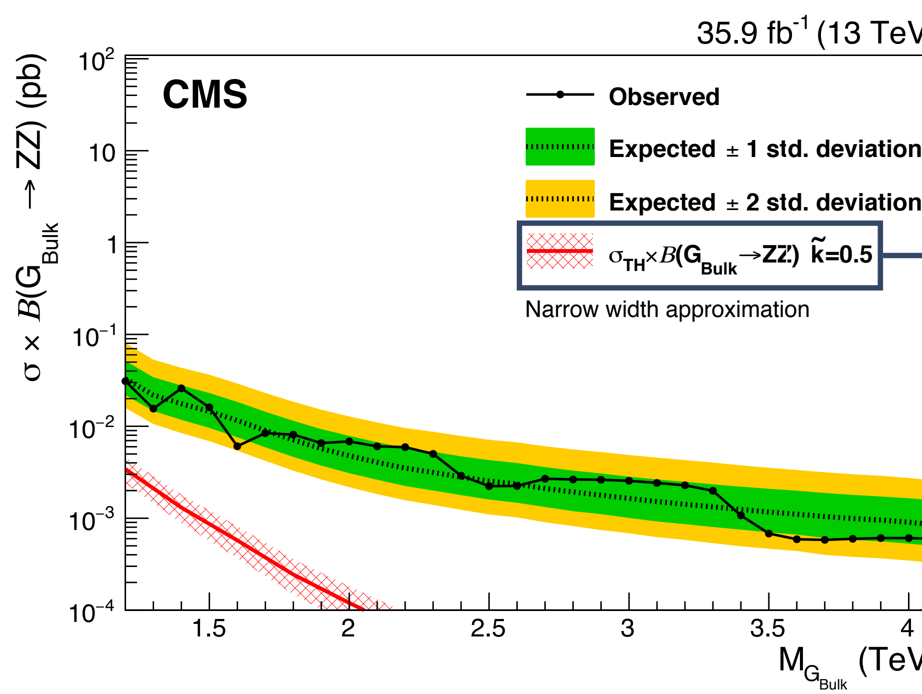


ATLAS: k = 1

CMS: k = 0.5

Asymptotic





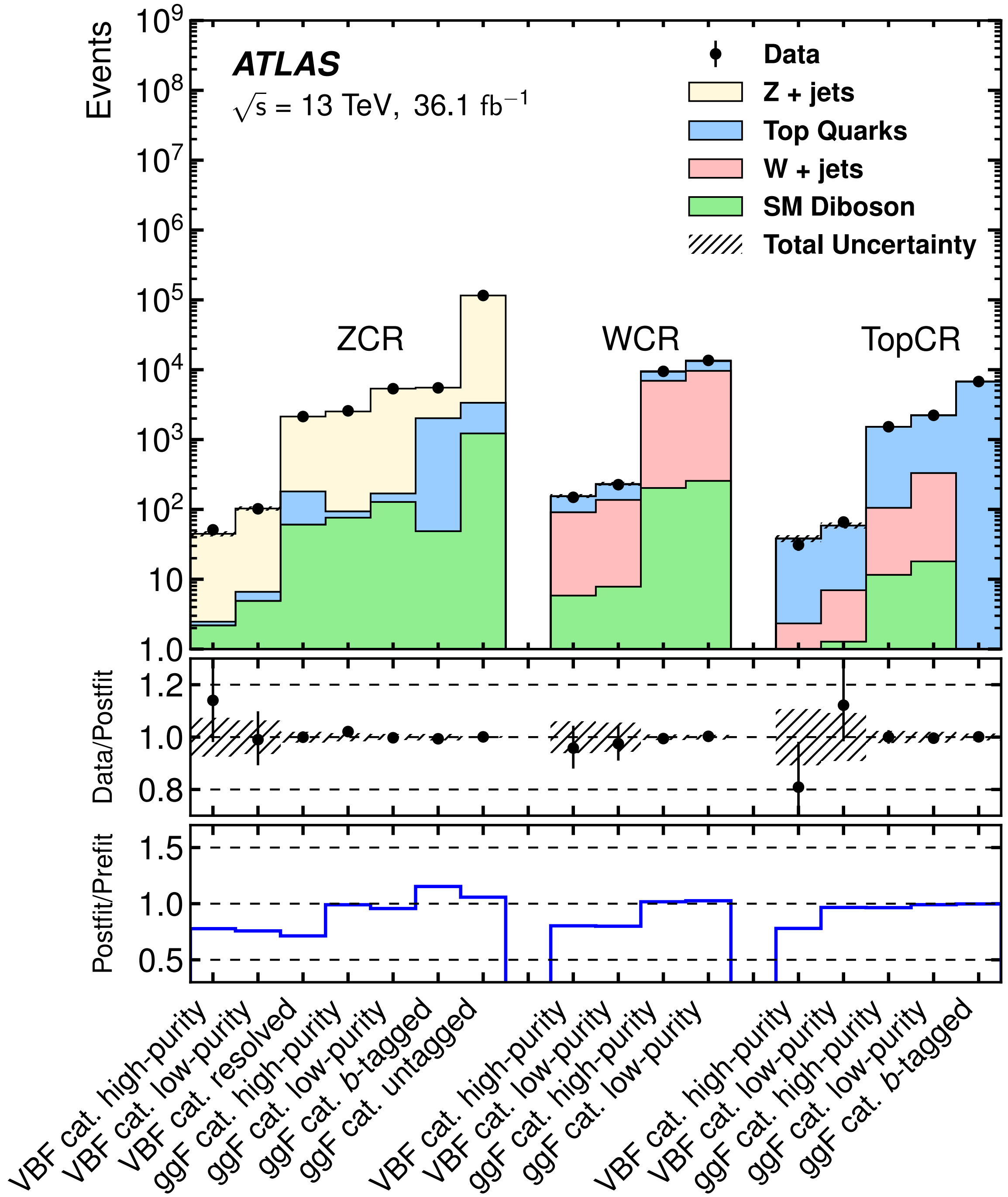
$X \to VV \to \ell^\pm\ell^\mp qq / \upsilon\upsilon qq$

- Semi-leptonic channel: $Z \to \ell^\pm\ell^\mp / \upsilon\upsilon$; $W/Z \to qq$
- 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 $\upsilon\upsilon qq$ 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 $\upsilon\upsilon qq$ results are public with the complete 2015+2016 dataset

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

To appear soon

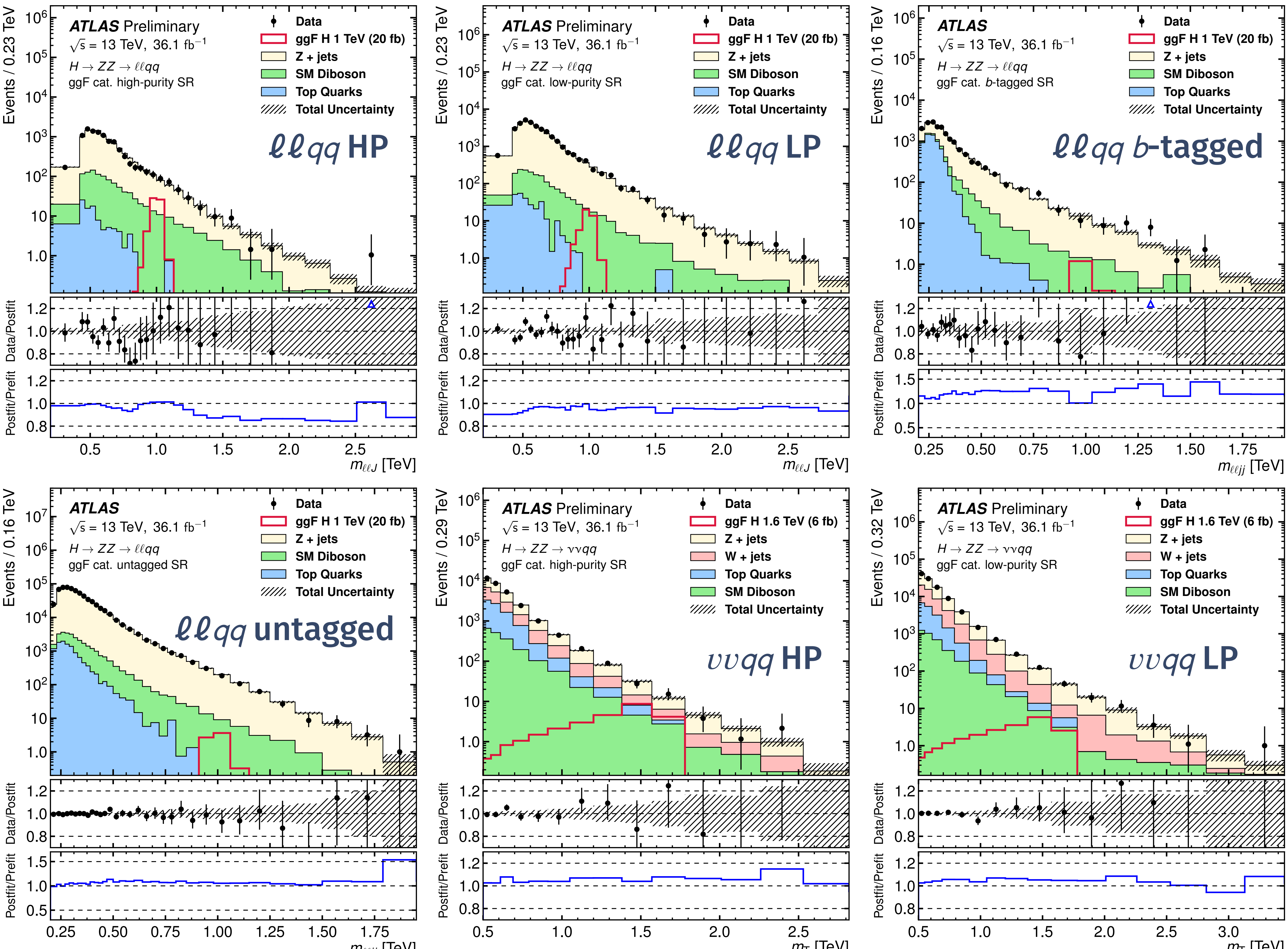
- $\ell\ell qq$ analysis:
  - $V \to qq \to J$: merged analysis first
  - $V \to qq \to jj$: resolved analysis next (untagged and b-tagged categories for $Z \to qq$)
- Dominant backgrounds for $\ell\ell qq$: Z+jets, $t\bar{t}$ (b-tagged category only)
- Dominant backgrounds for $\nu\nu qq$: Z+jets, W+jets,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



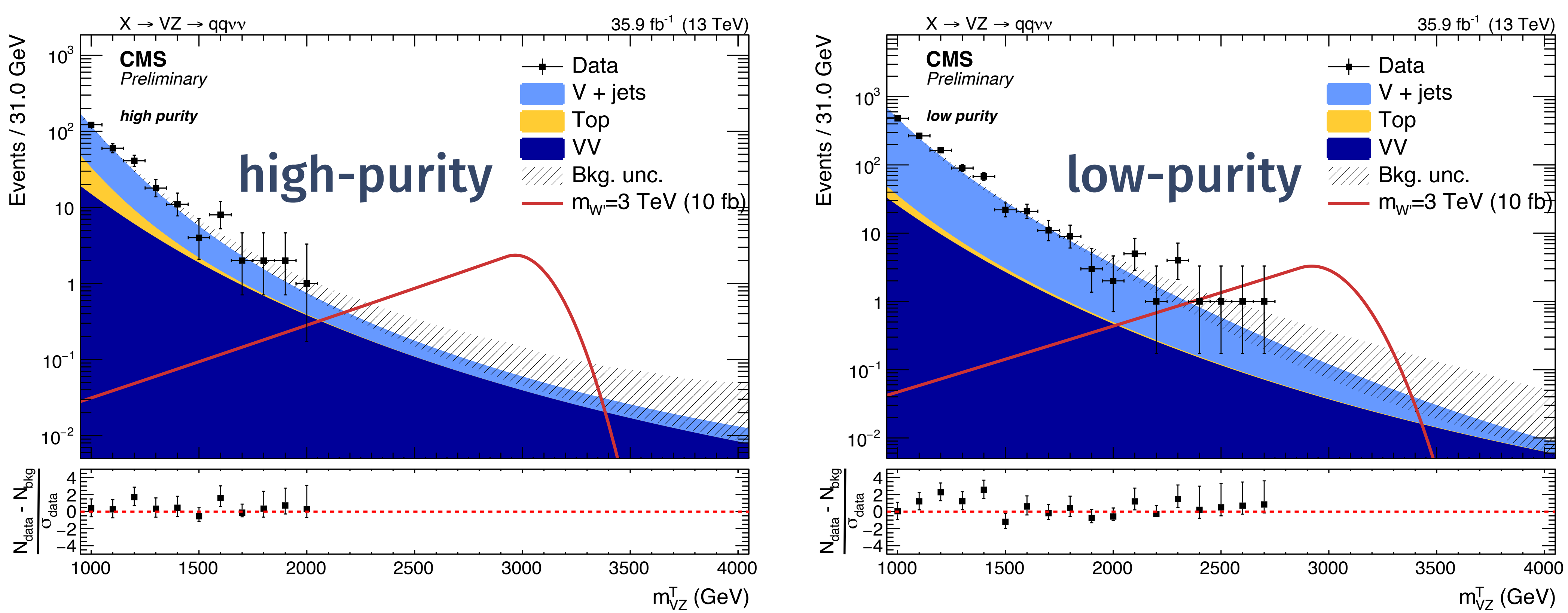
CR summary plot

$X \rightarrow VV \rightarrow \ell^{\pm}\ell^{\mp}qq/\nu\nu qq$: ATLAS Results

EXOT-2016-29



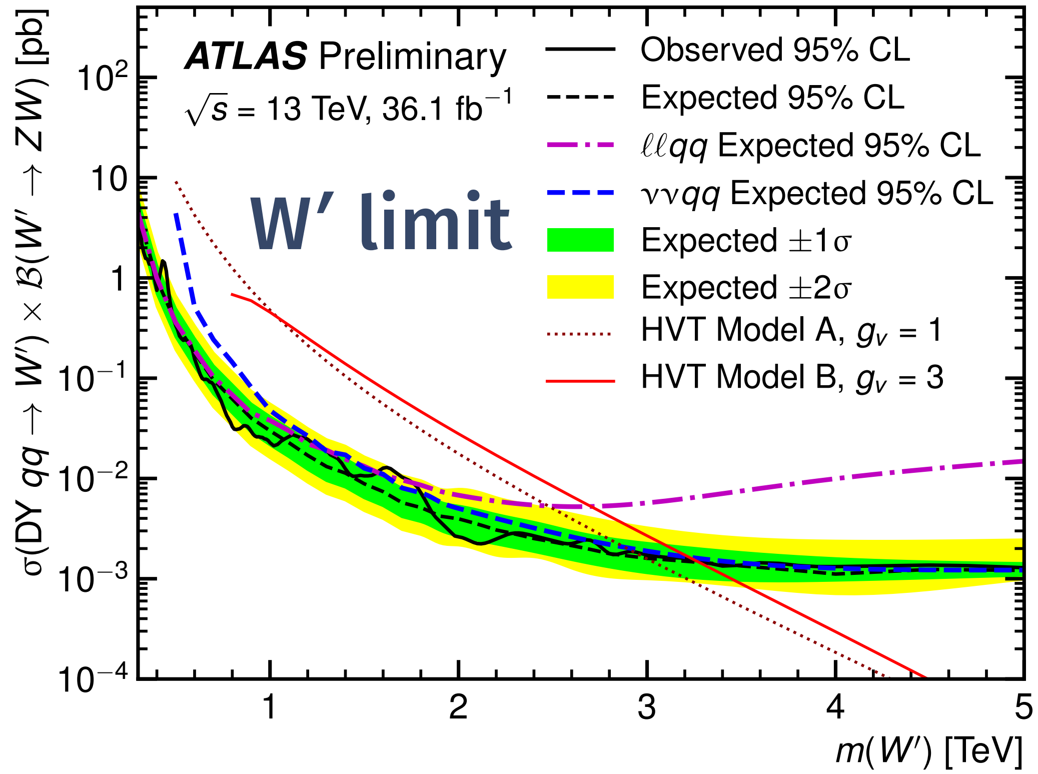
- Large-R jet mass window: 65 - 105 GeV
- Background estimation using simulation-assisted "alpha-ratio method"
  - Exploit the correlation between soft-drop jet mass and resonance mass.
  - Essentially, take ratio of simulation to data and extrapolate to signal region

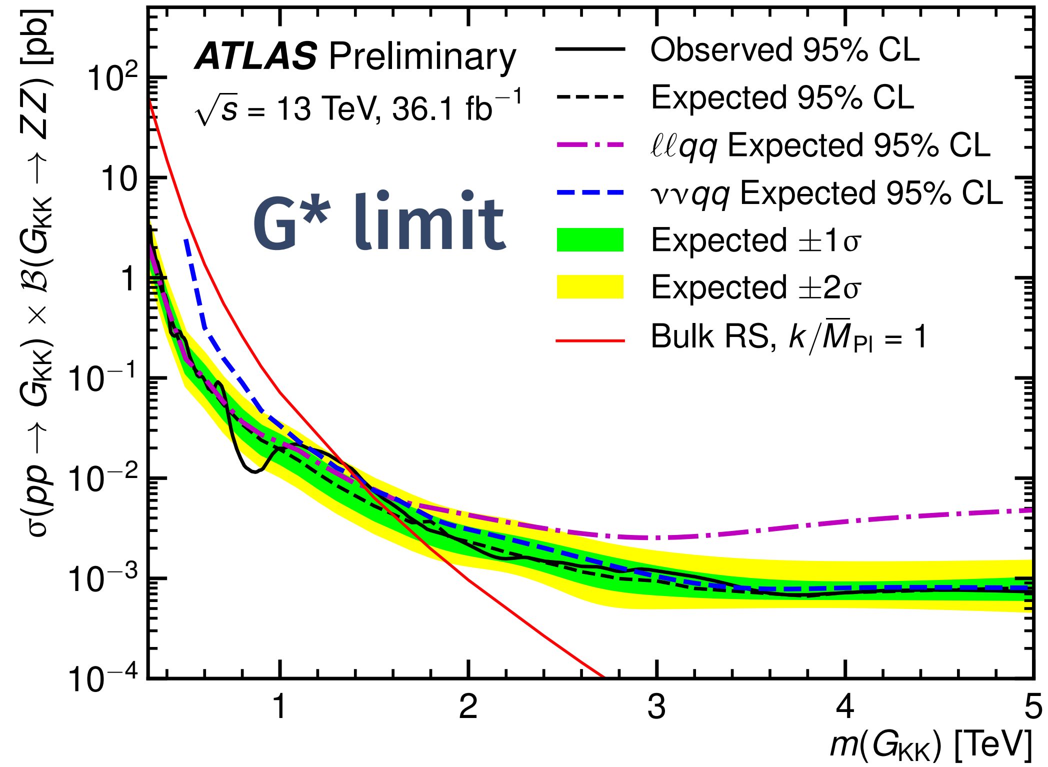


$X \to VV \to \ell^{\pm}\ell^{\mp}qq / \nu\nu qq$: Results

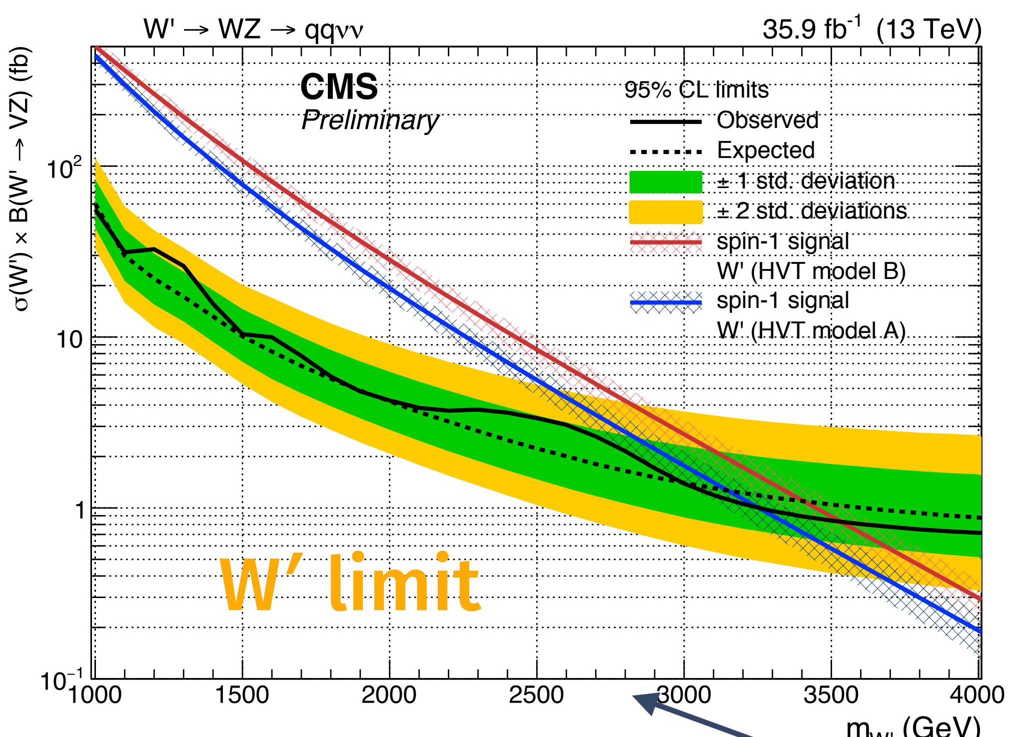
$\nu\nu qq$ dominates at high mass

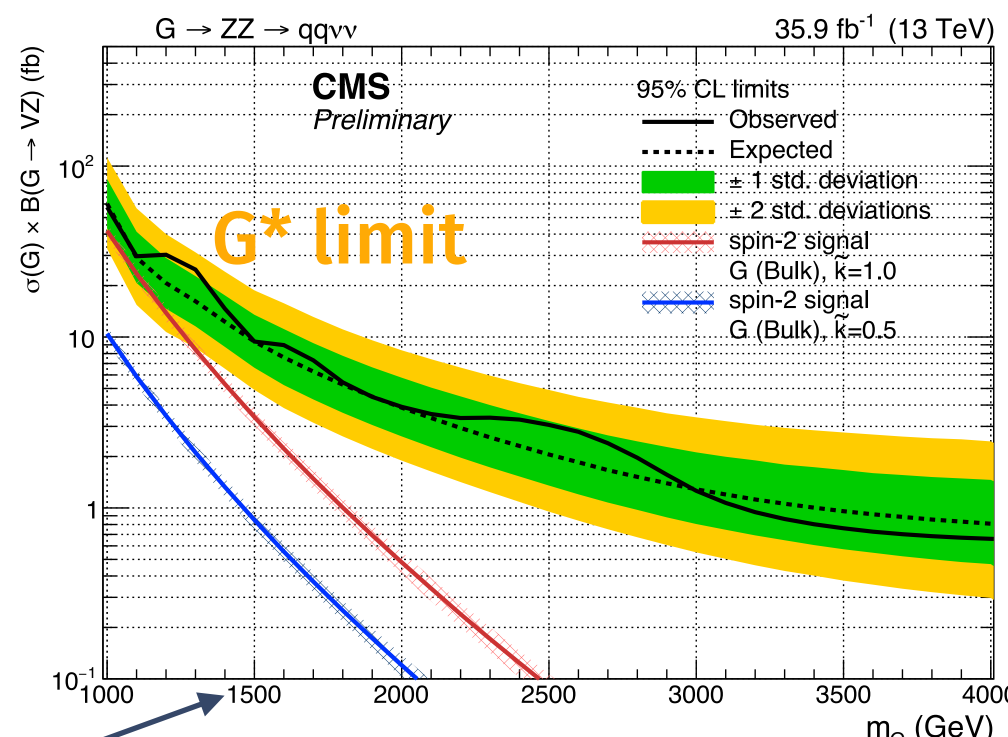
Asymptotic limits below 2 TeV
pseudo-experiments above 2 TeV





Asymptotic limits





same limits based on narrow-width approximation signal

$X \to VV \to \ell^{\pm}\upsilon qq$: ATLAS Results

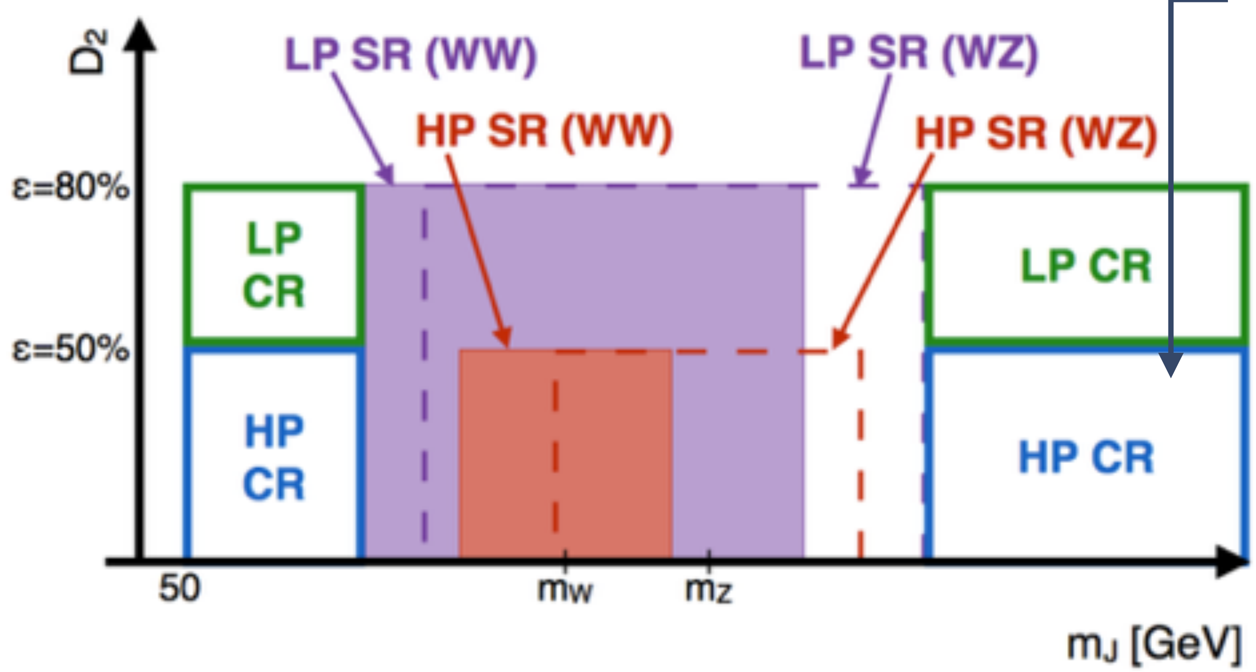
ATLAS-CONF-2017-051

- Semi-leptonic channel: $W \to \ell^{\pm}\upsilon$; $W/Z \to qq$
- 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.

CR: mass sideband of $V \to qq$

CR: presence of b-jets in addition to $V \to qq$

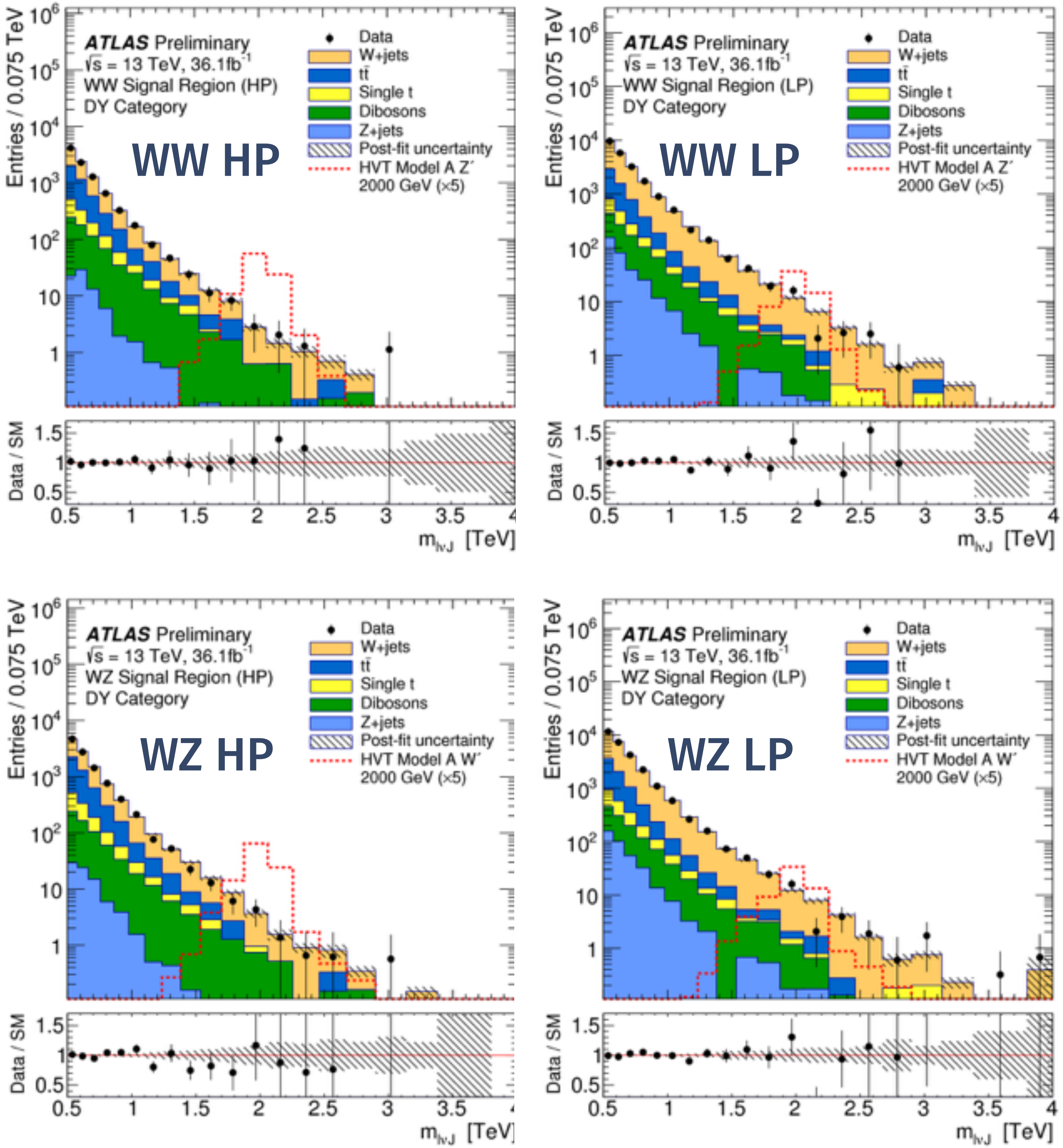
e.g. normalized to data in WCR

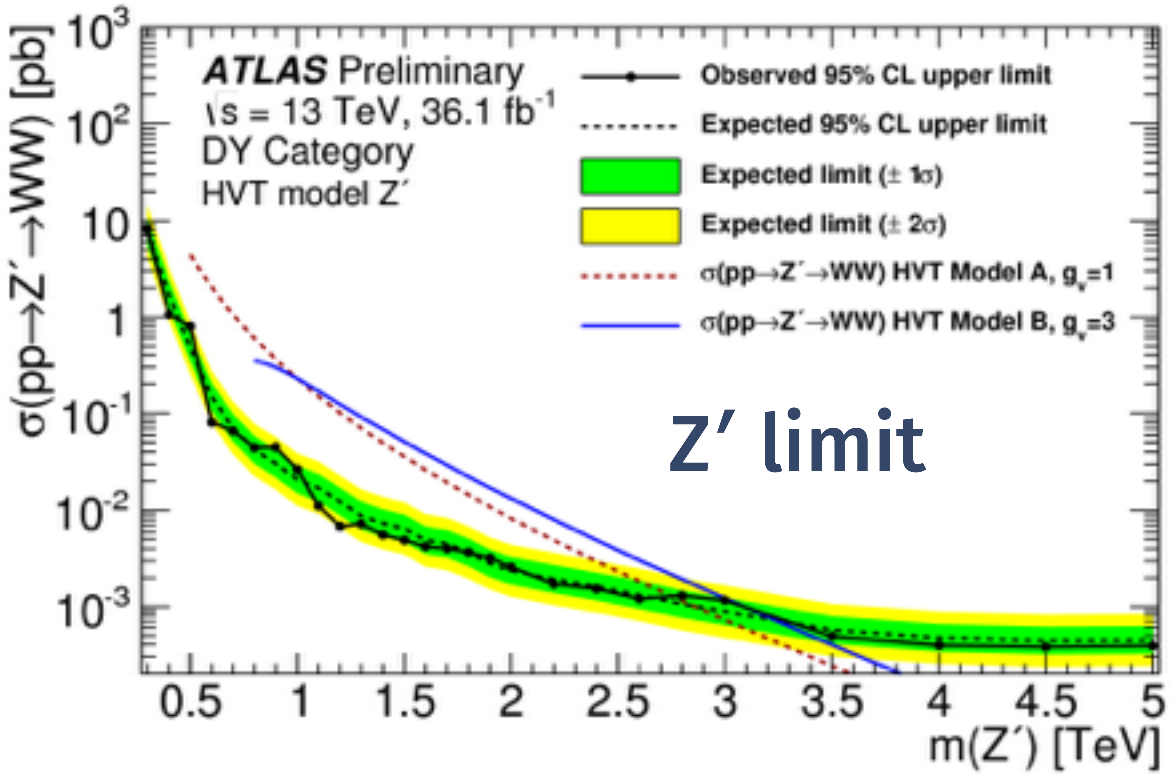


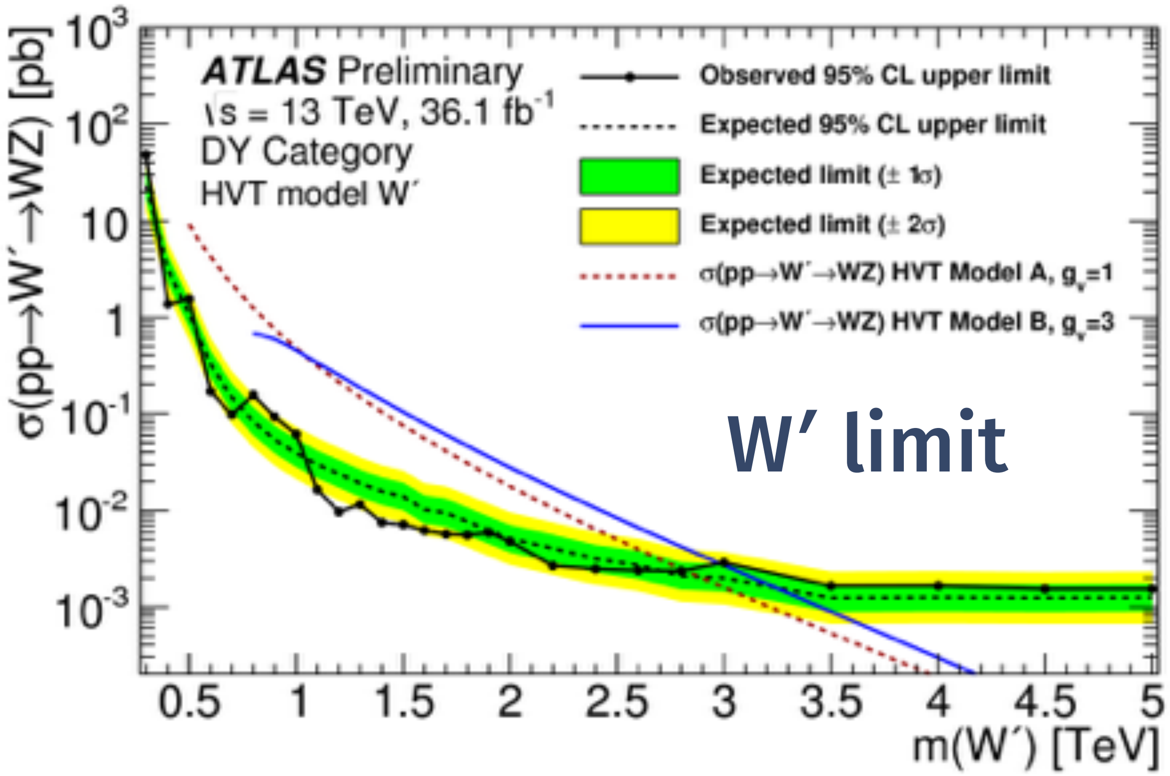
Latest CMS results: 12.9 fb^{-1}

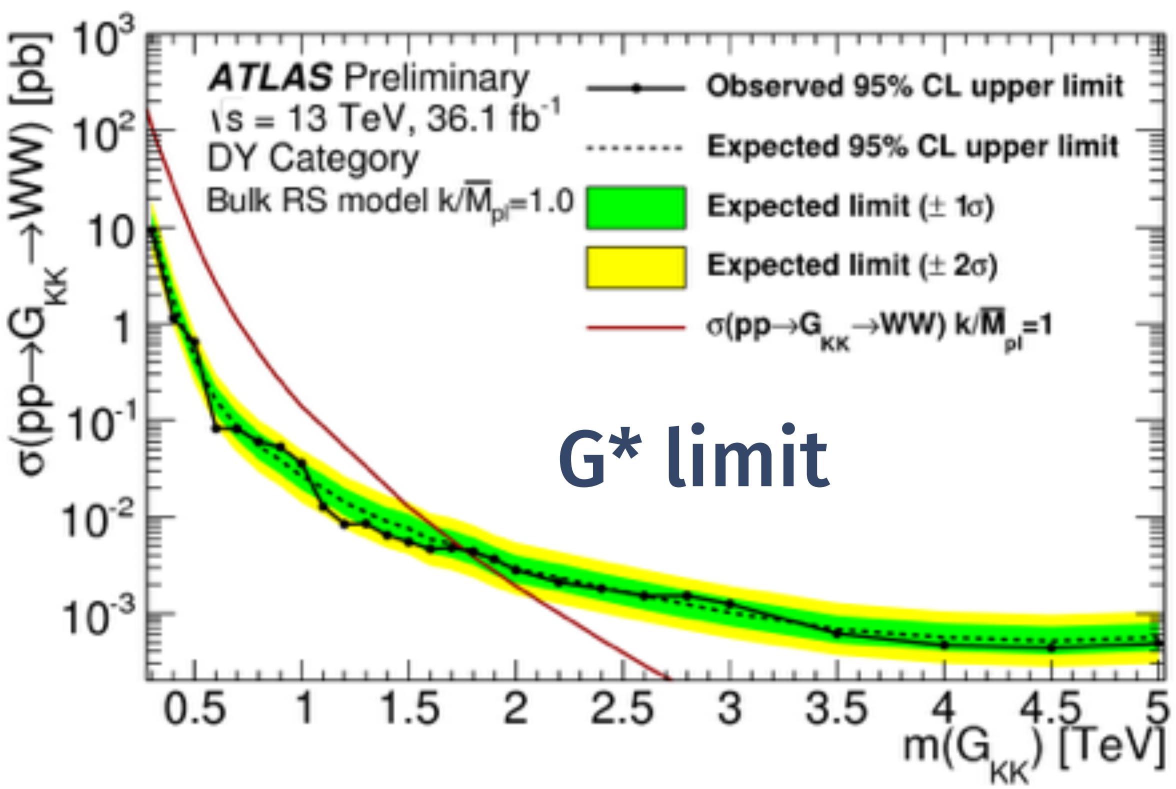
$X \to VV \to \ell^{\pm}\nu qq$: ATLAS Results

ATLAS-CONF-2017-051




ATLAS Preliminary
√s = 13 TeV, 36.1 fb⁻¹
DY Category
HVT model Z′
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit (± 1σ)
Expected limit (± 2σ)
σ(pp→Z′→WW) HVT Model A, g_v=1
σ(pp→Z′→WW) HVT Model B, g_v=3
Z′ limit
σ(pp→Z′→WW) [pb]
m(Z′) [TeV]


ATLAS Preliminary
√s = 13 TeV, 36.1 fb⁻¹
DY Category
HVT model W′
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit (± 1σ)
Expected limit (± 2σ)
σ(pp→W′→WZ) HVT Model A, g_v=1
σ(pp→W′→WZ) HVT Model B, g_v=3
W′ limit
σ(pp→W′→WZ) [pb]
m(W′) [TeV]

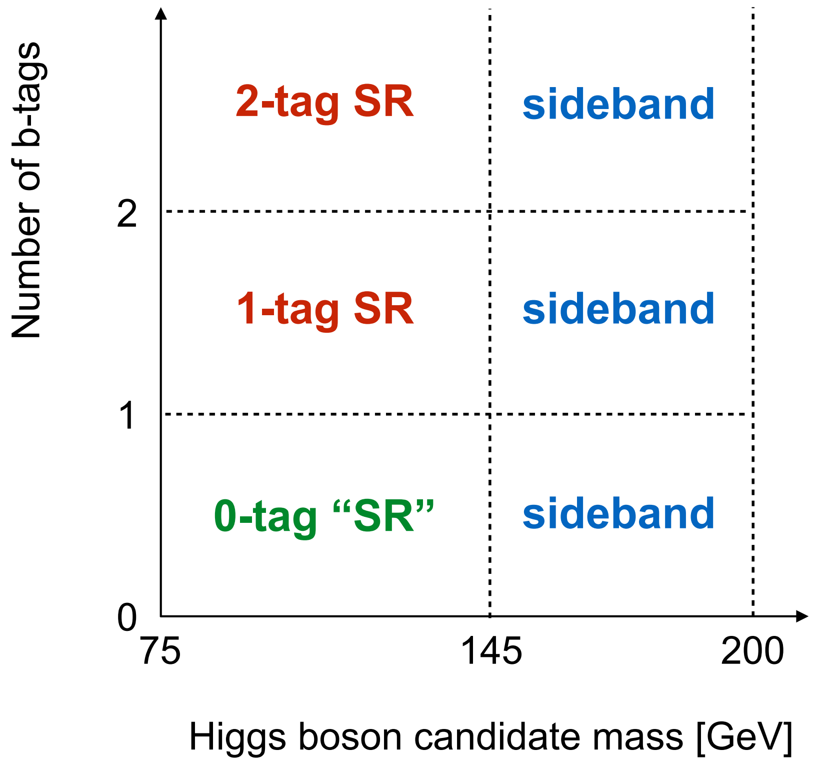

ATLAS Preliminary
√s = 13 TeV, 36.1 fb⁻¹
DY Category
Bulk RS model k/M̄_pl=1.0
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit (± 1σ)
Expected limit (± 2σ)
σ(pp→G_KK→WW) k/M̄_pl=1
G* limit
σ(pp→G_KK→WW) [pb]
m(G_KK) [TeV]

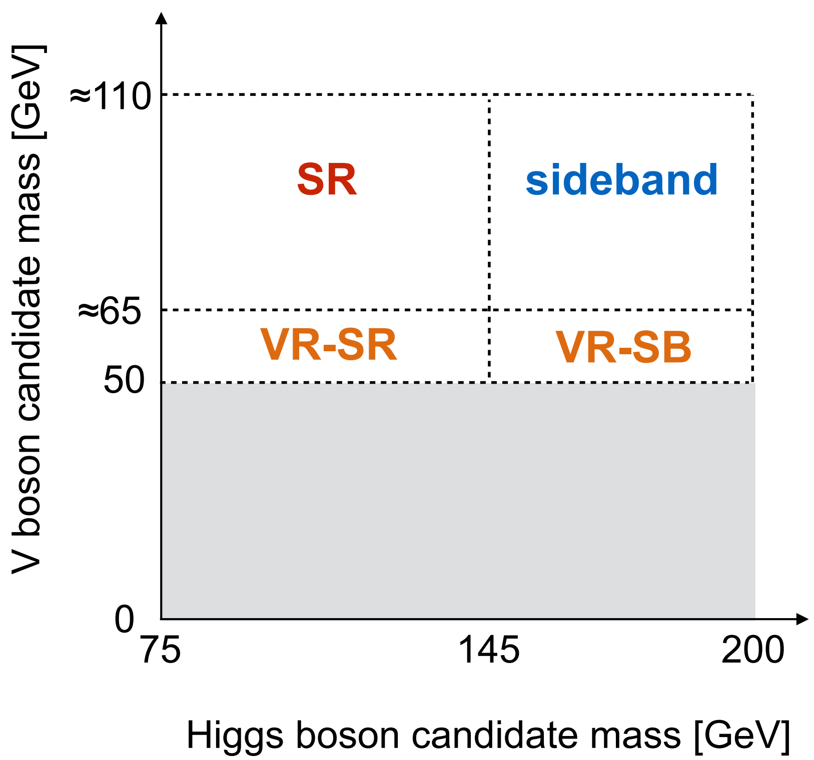
Search for resonances decaying into VH (V=W/Z)

$X \to VH \to qqbb$

- 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 2 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

- 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

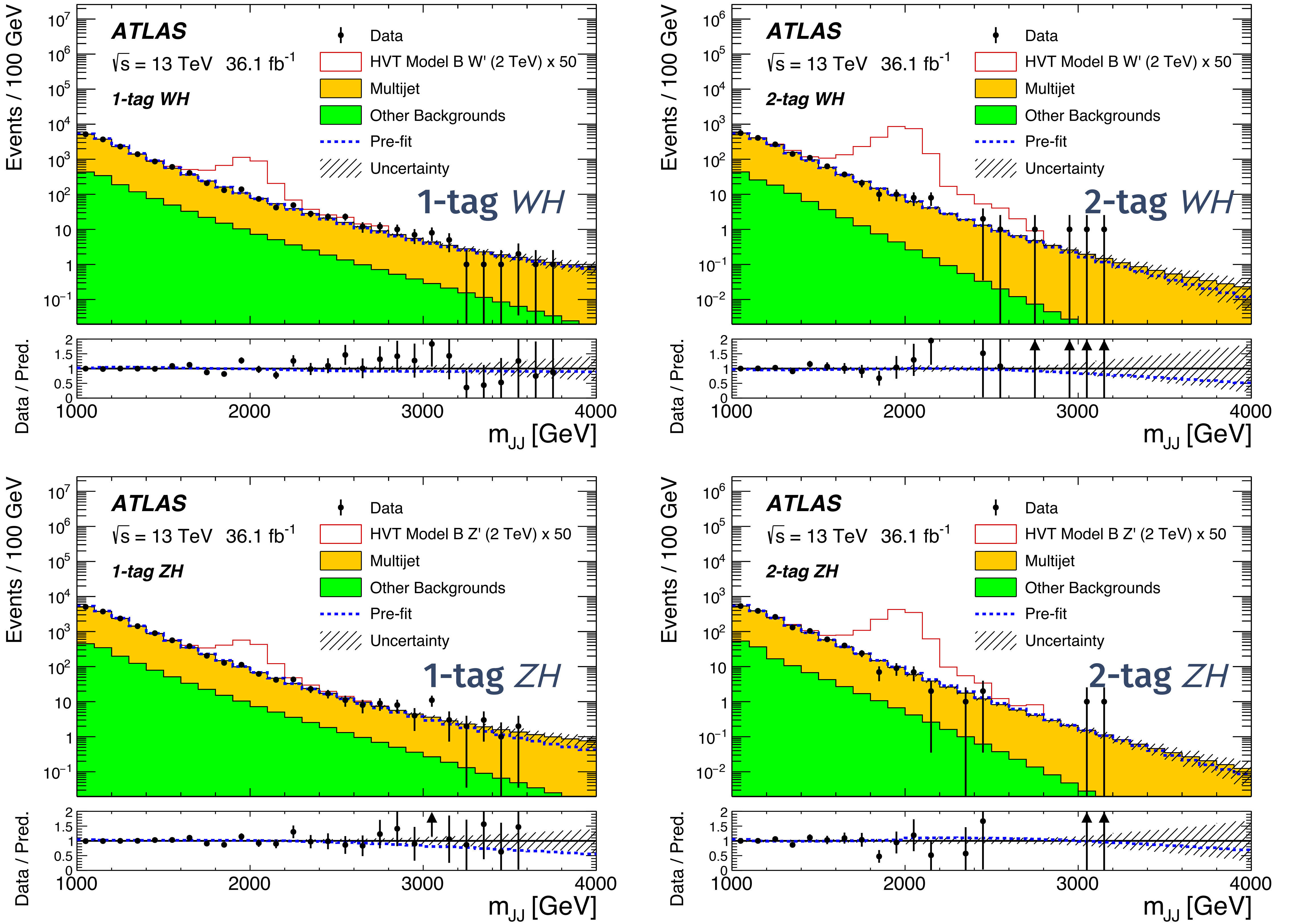




orthogonal regions

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

EXOT-2016-12

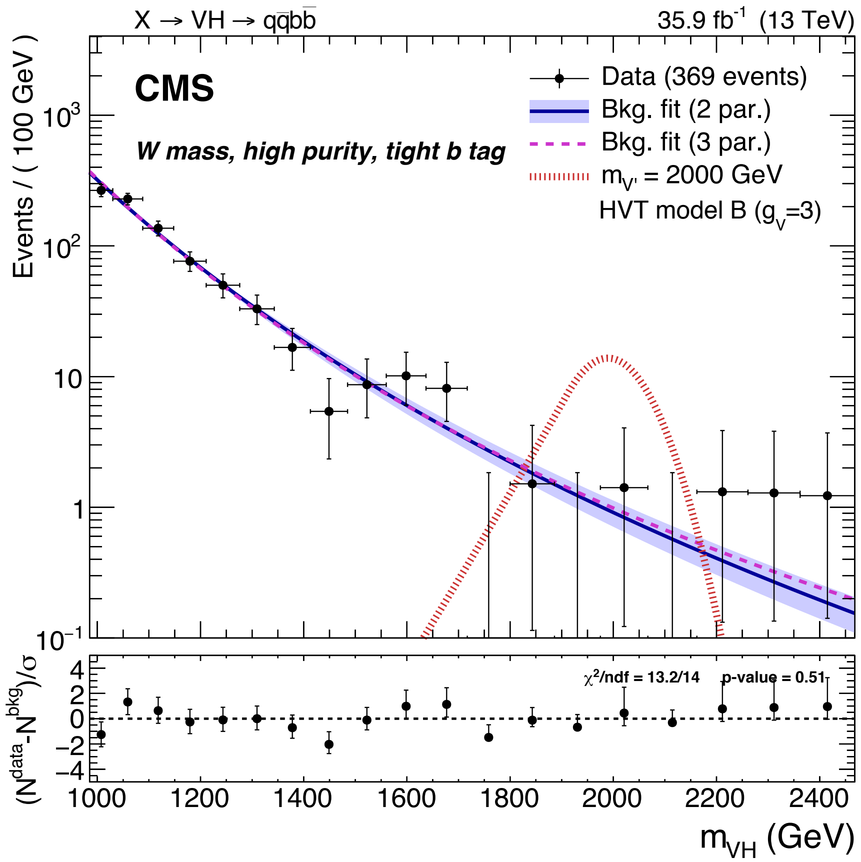


- Background largely dominated by multijet production (≳95%)
- Events are divided into eight exclusive categories:
  - b-tagging discriminator: tight and loose categories
  - τ_{21}: high-purity (HP) and low-purity (LP) categories
  - V jet mass: W mass and Z mass categories
- The background is estimated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

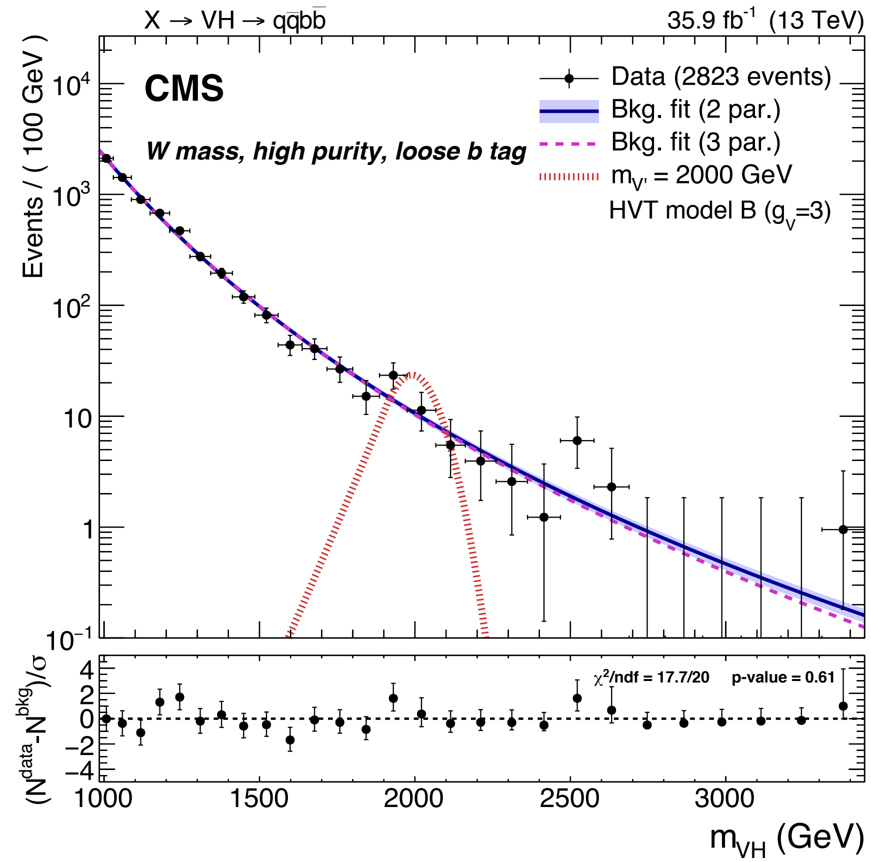
$X \to VH \to qqbb$: CMS Results

B2G-17-002

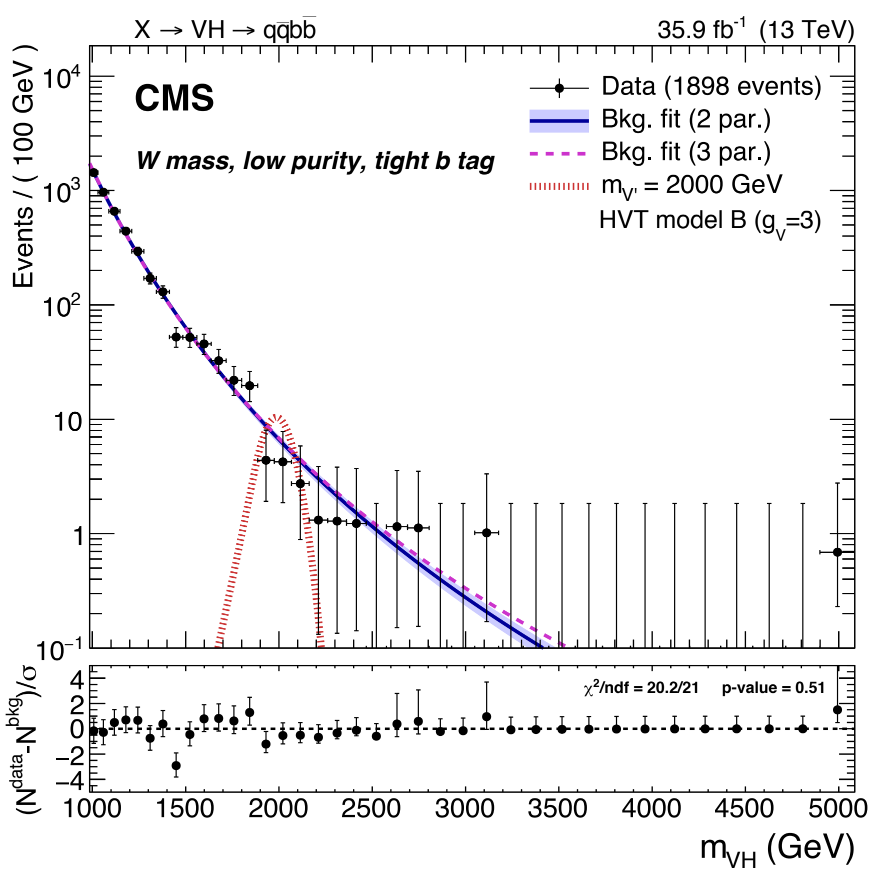
1-tag *WH* high-purity tight b-tag



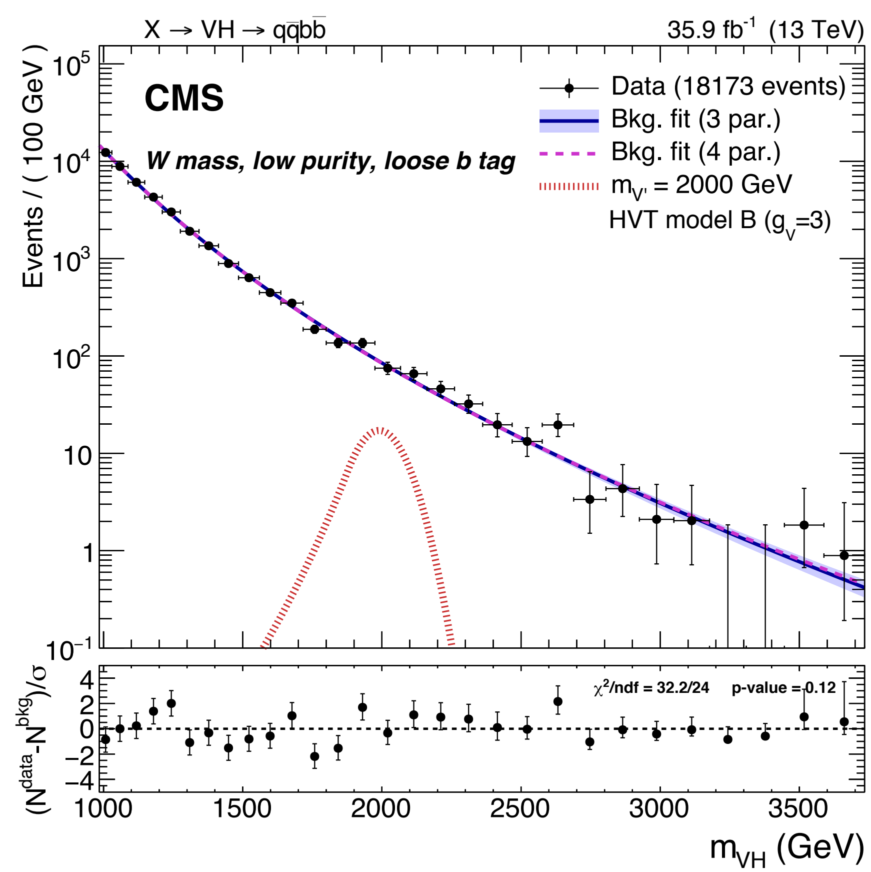
1-tag *WH* high-purity loose b-tag



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



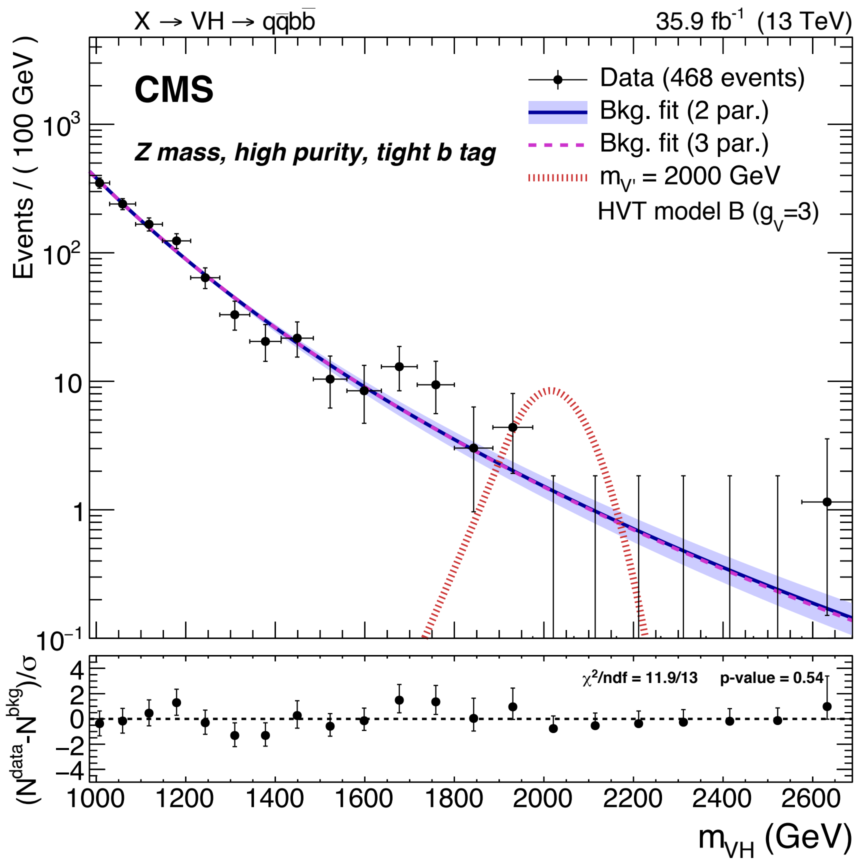
1-tag *WH* low-purity loose b-tag



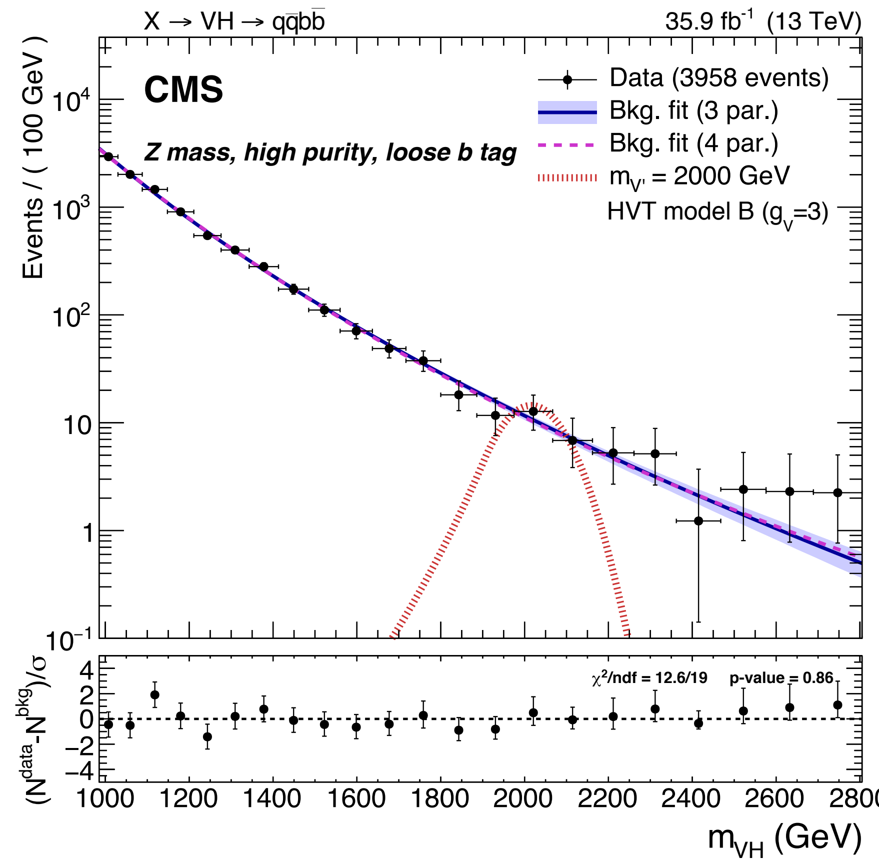
$X \rightarrow VH \rightarrow qqbb$: CMS Results

B2G-17-002

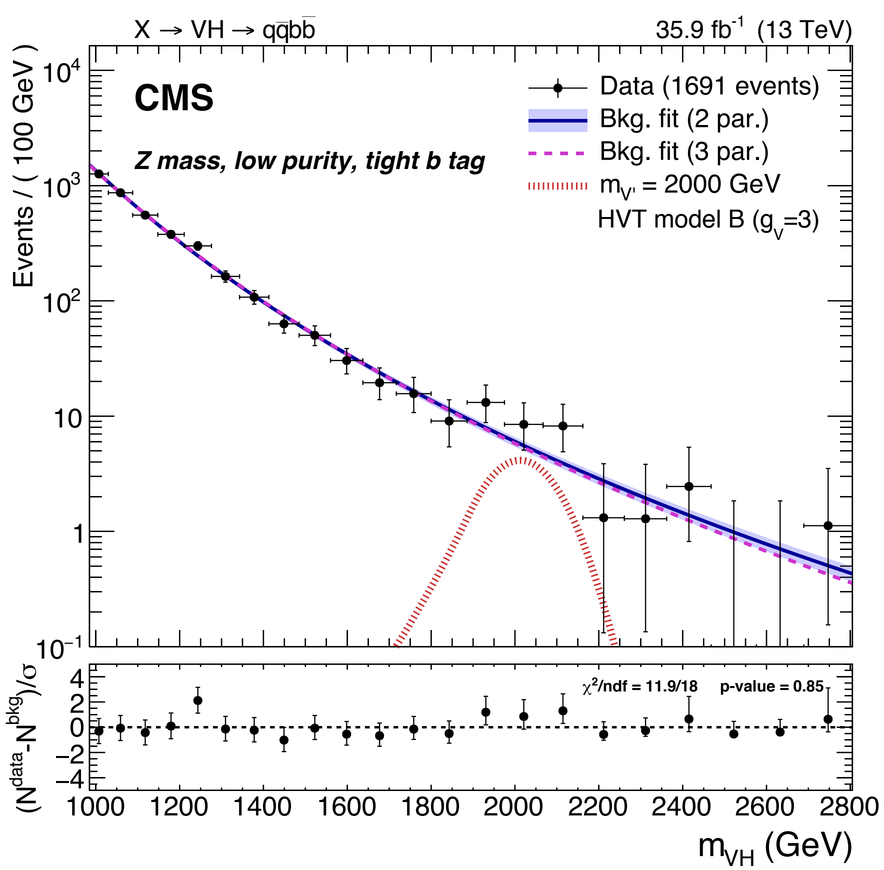
1-tag *ZH* high-purity tight b-tag



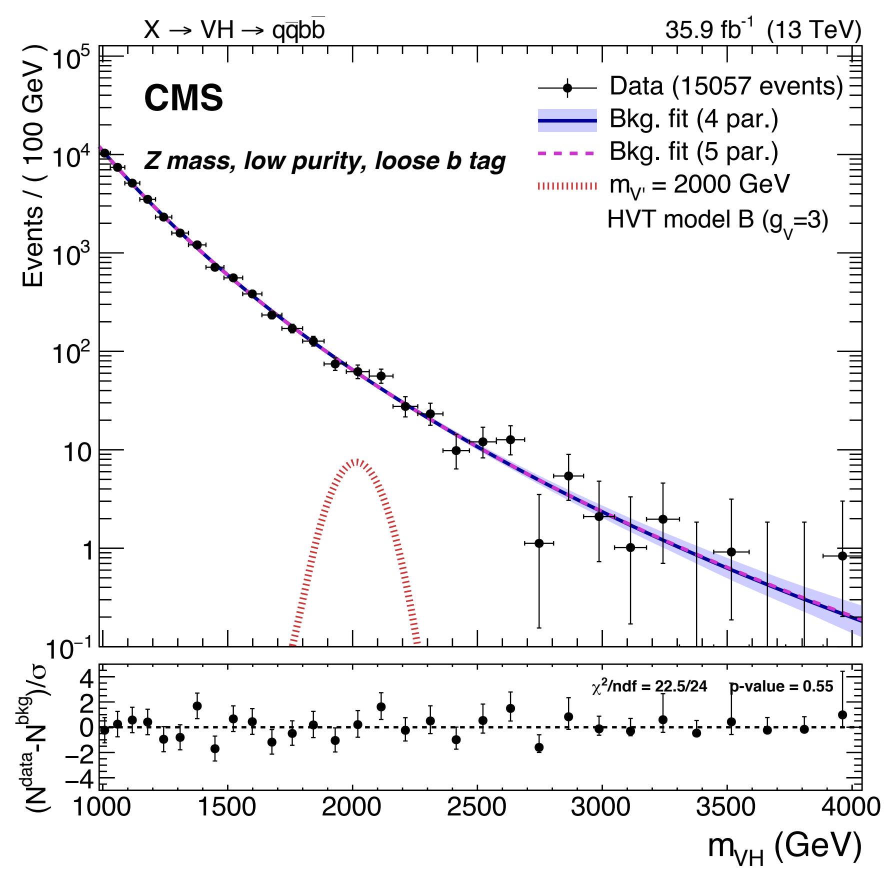
1-tag *ZH* high-purity loose b-tag



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

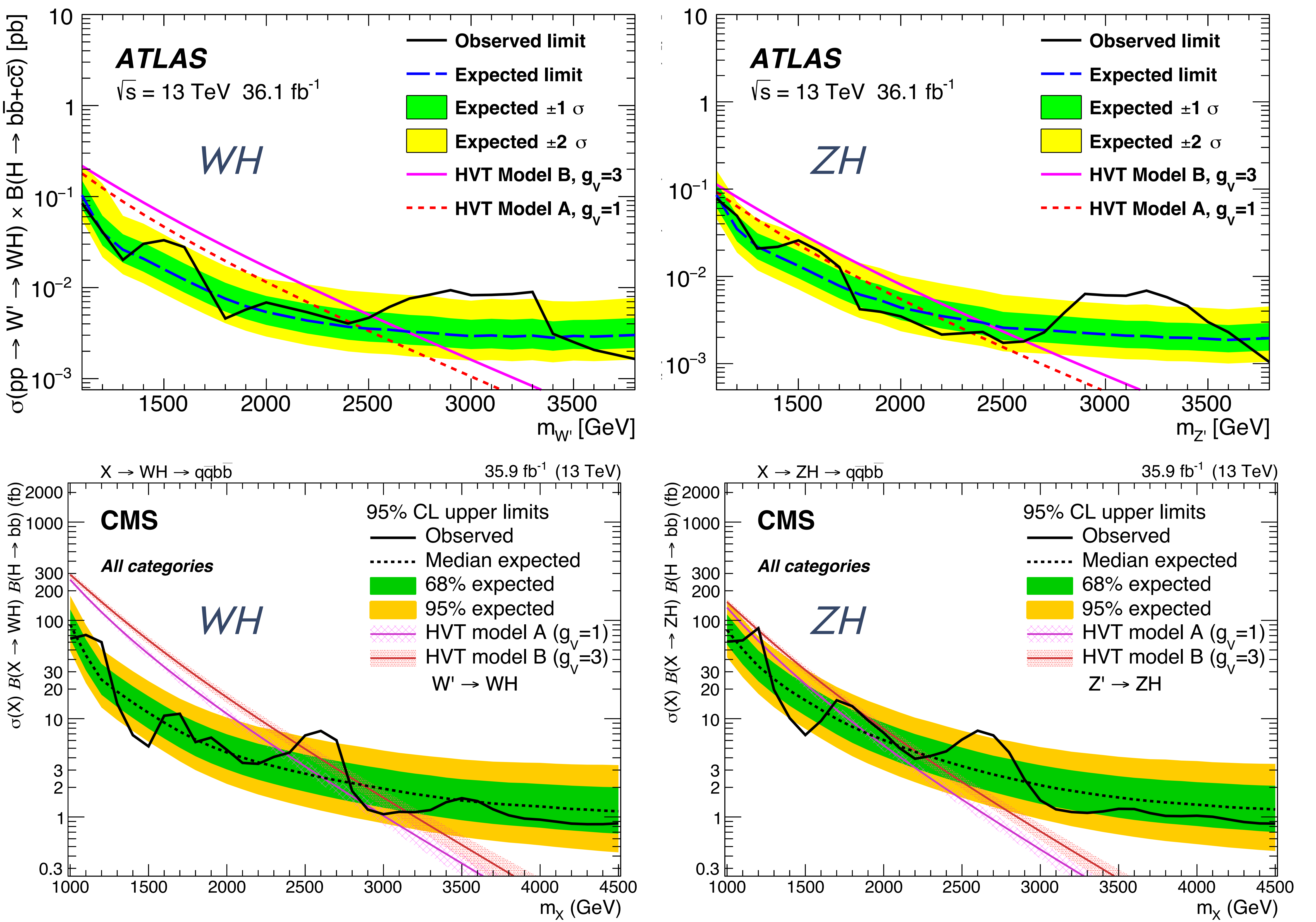


1-tag *ZH* low-purity loose b-tag



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

EXOT-2016-12 B2G-17-002



Semi-Leptonic VH: ATLAS

ATLAS-CONF-2017-055

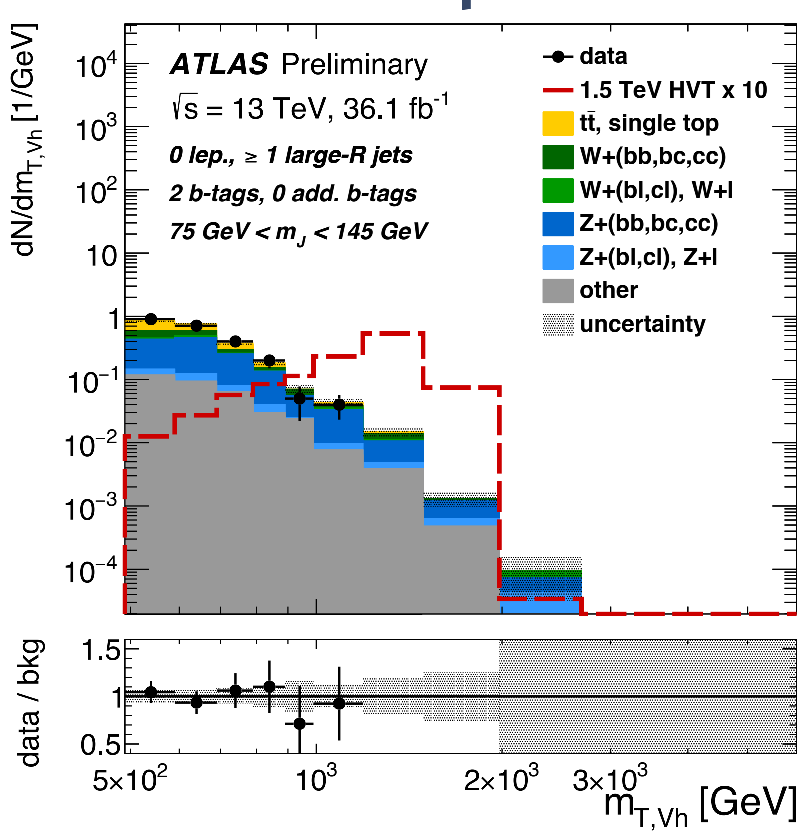
Latest CMS results: 2015 data

Resolved analysis is prioritized!

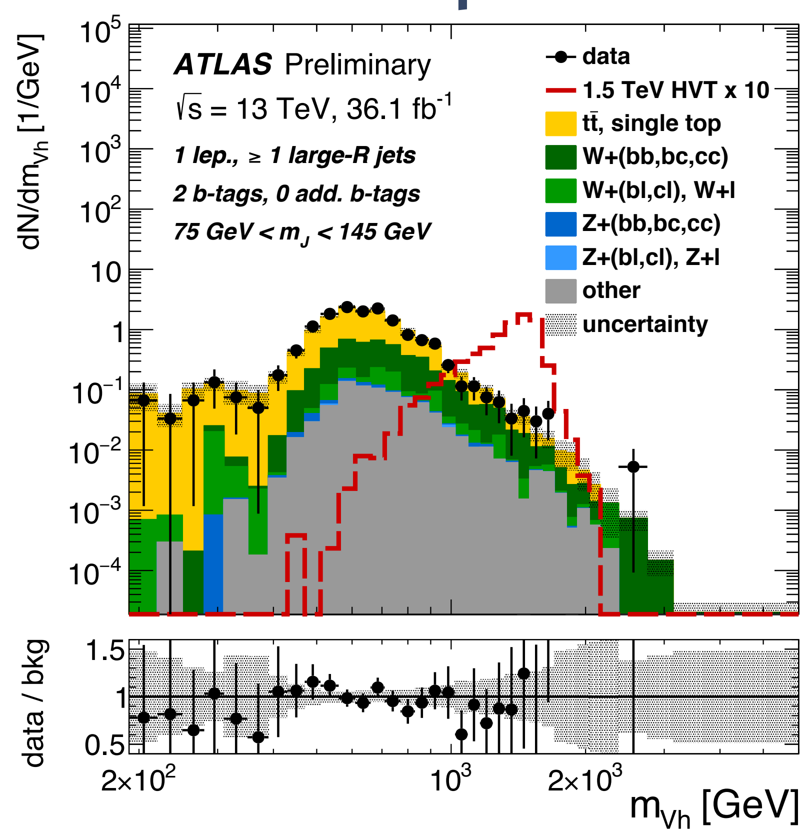
- Final states explored: $\nu\nu bb$, $\ell\nu bb$ and $\ell\ell bb$
- 3 channels based on V decays: 0-/2-lepton (A, Z'), 1-lepton (W')
- b-tag categories based on b-tagged track jets: 1-/2-tag used for A and V', 3+ tag used for A (sensitive to bbA).

Boosted 2-tag SRs

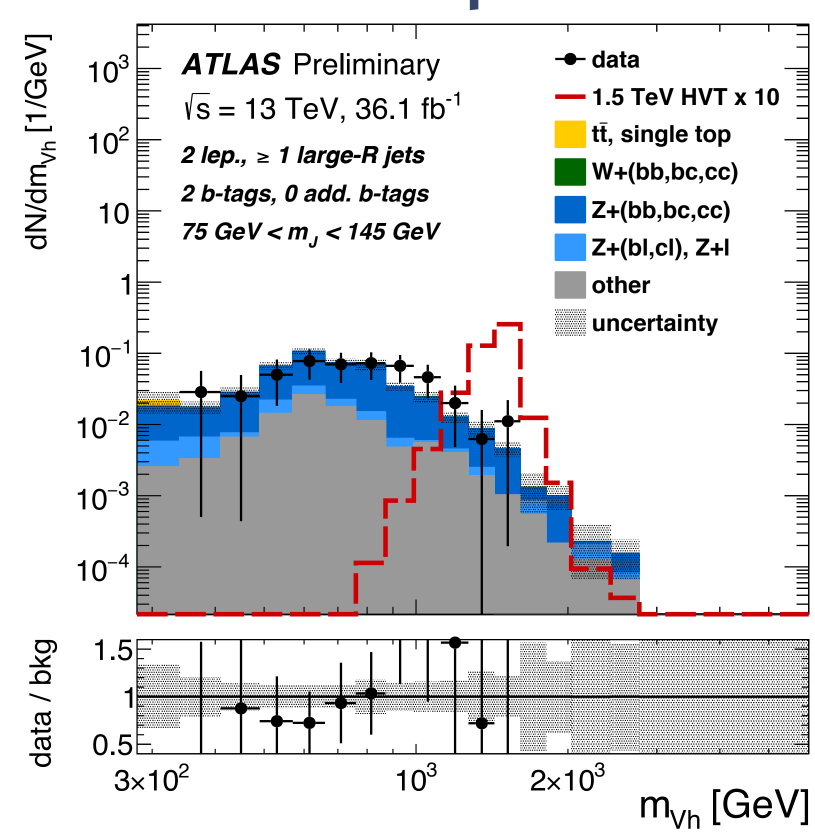
0lep



1lep

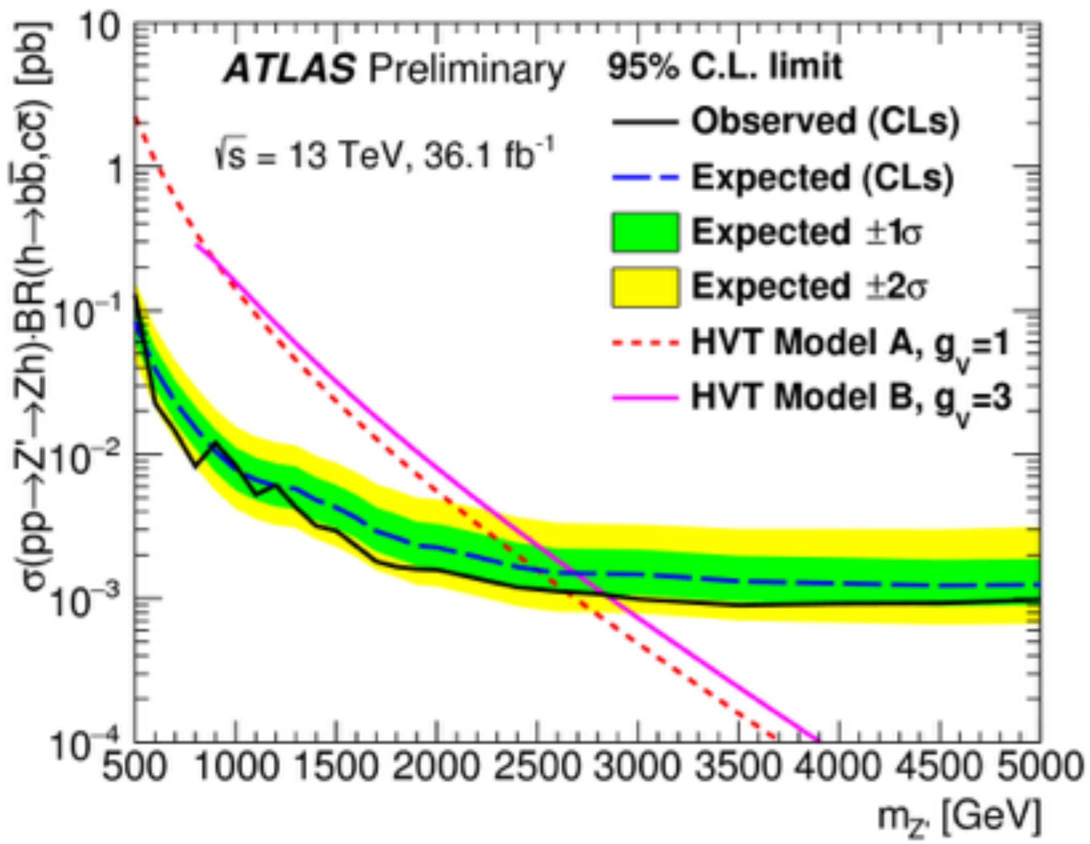


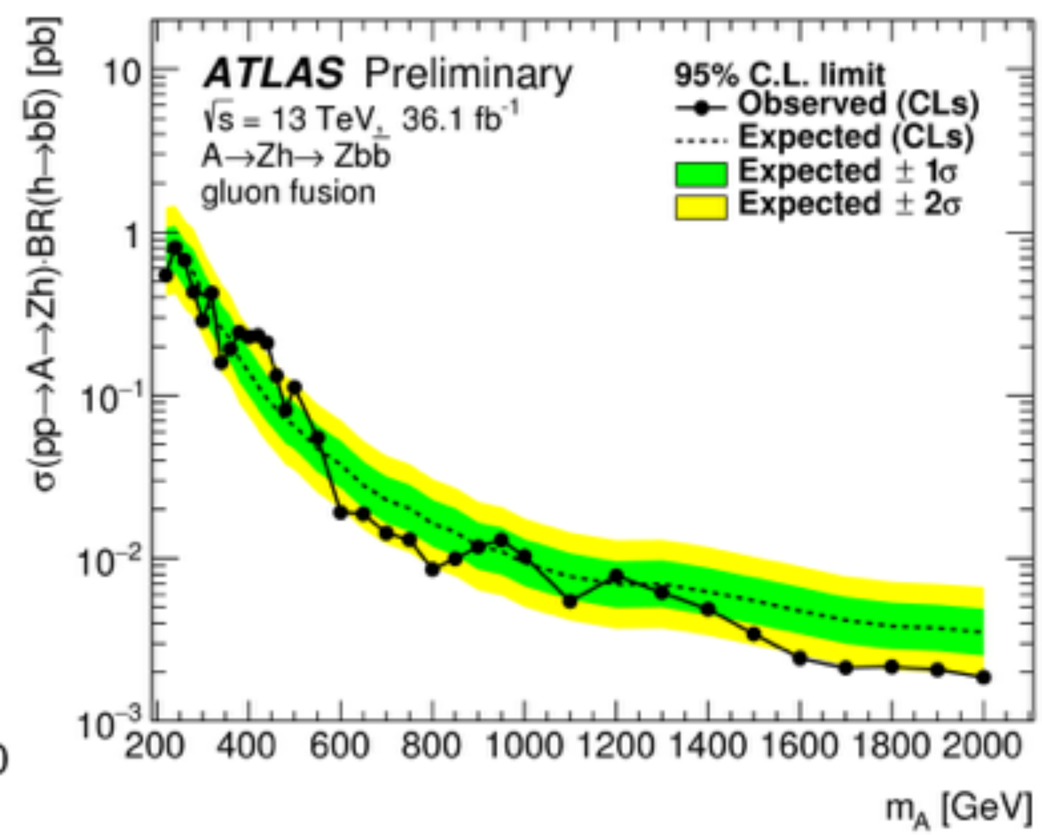
2lep

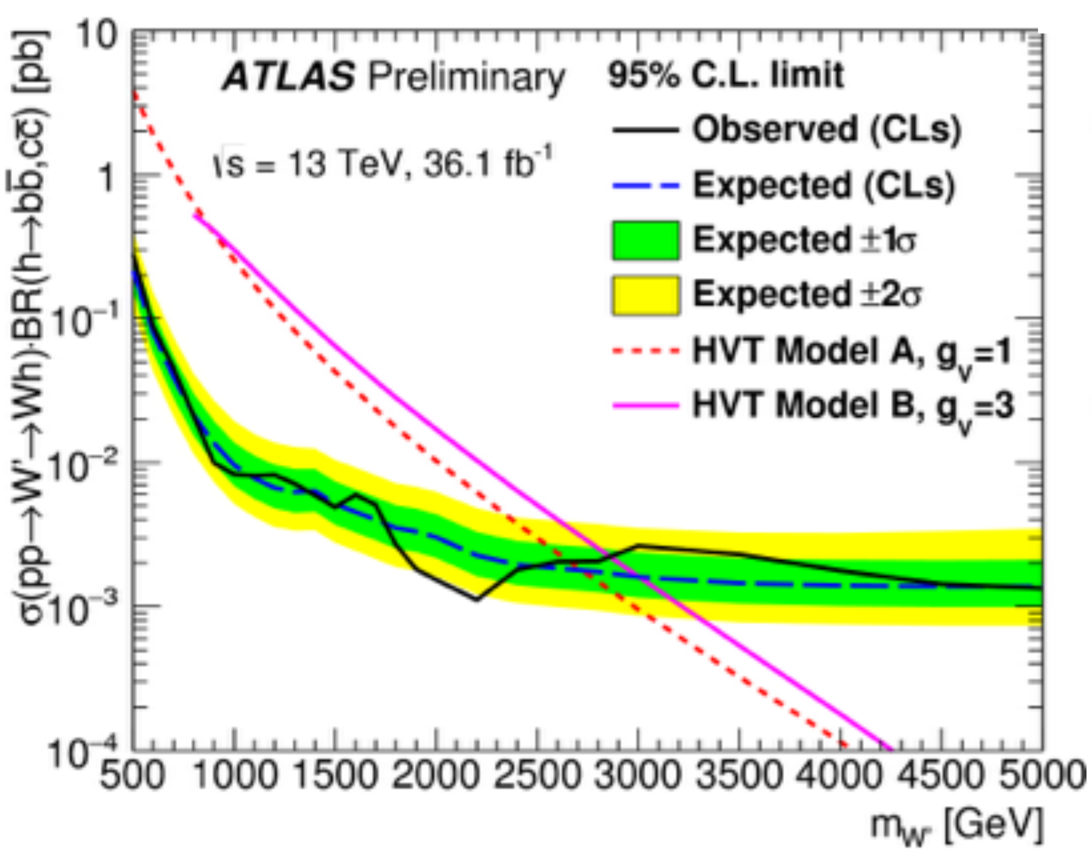


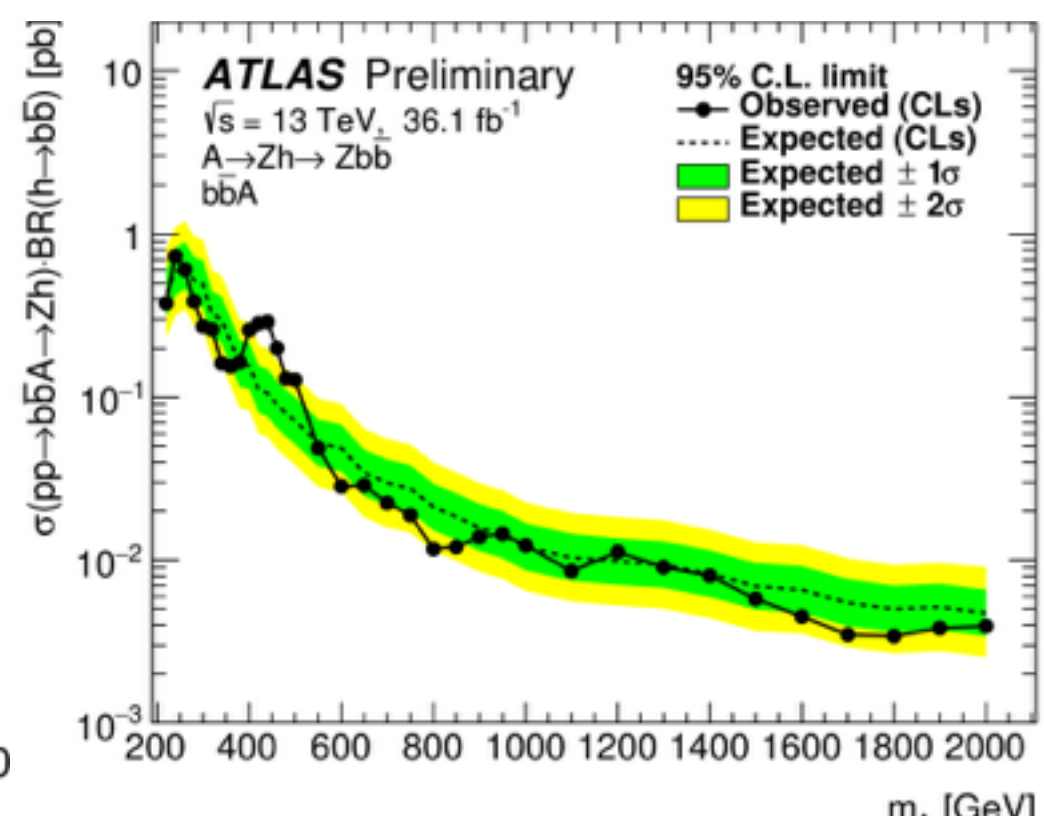
Semi-Leptonic VH: ATLAS Results

ATLAS-CONF-2017-055







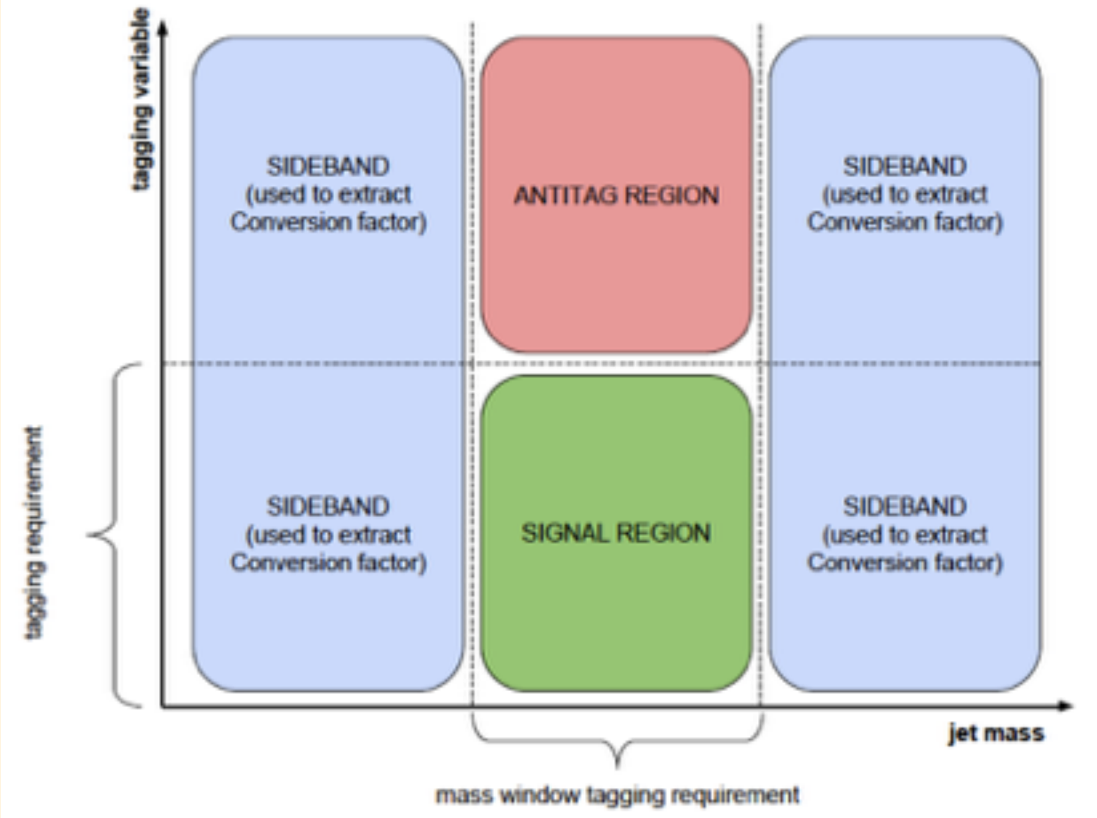


Search for resonances decaying into HH

$HH \to bbbb$: 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 $H \to bb$ is reconstructed as a large-R hadronic 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 Mj



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

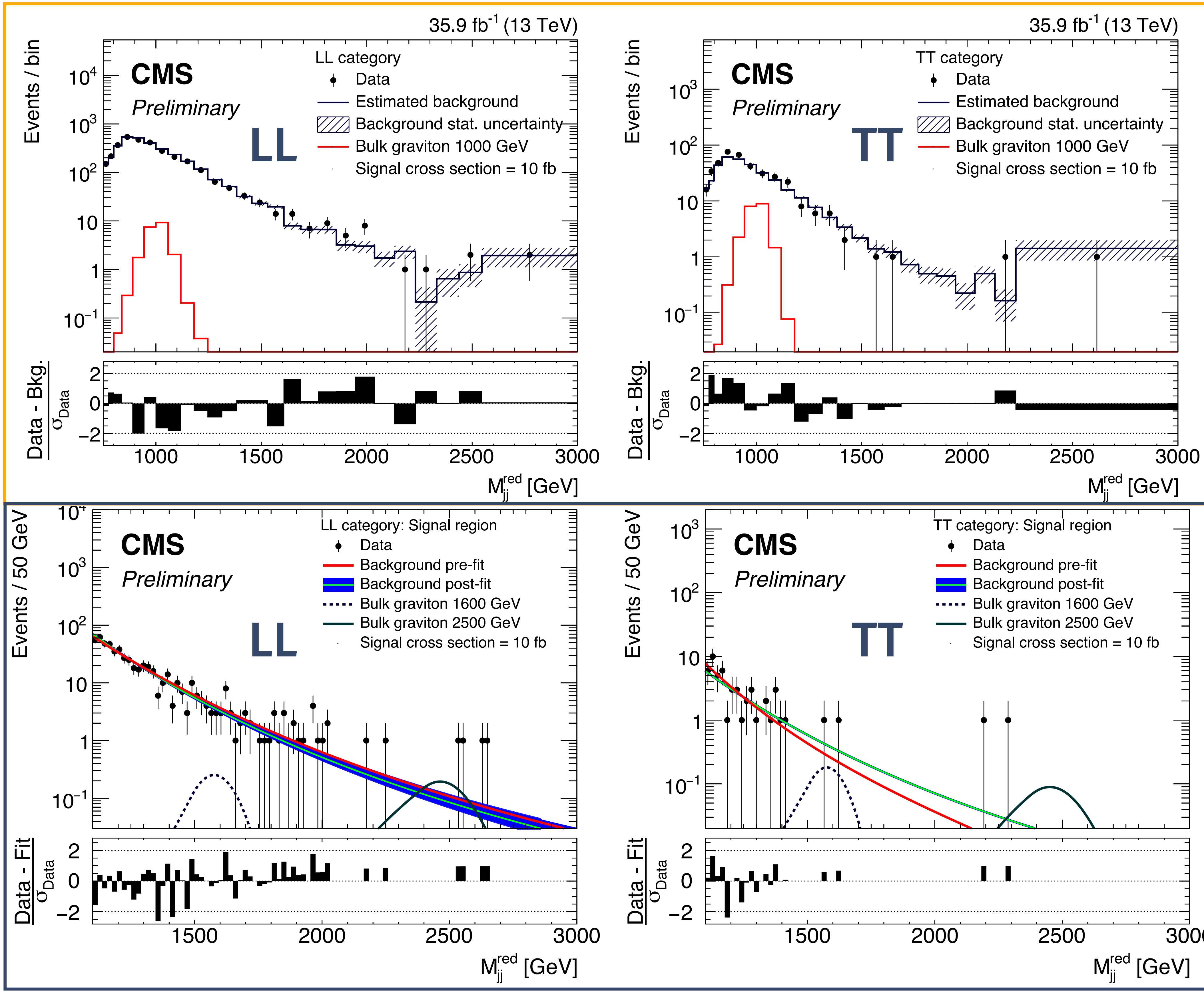
Latest ATLAS results: 13.3 fb^{-1}

$HH \to bbbb$: CMS Results

B2G-16-026

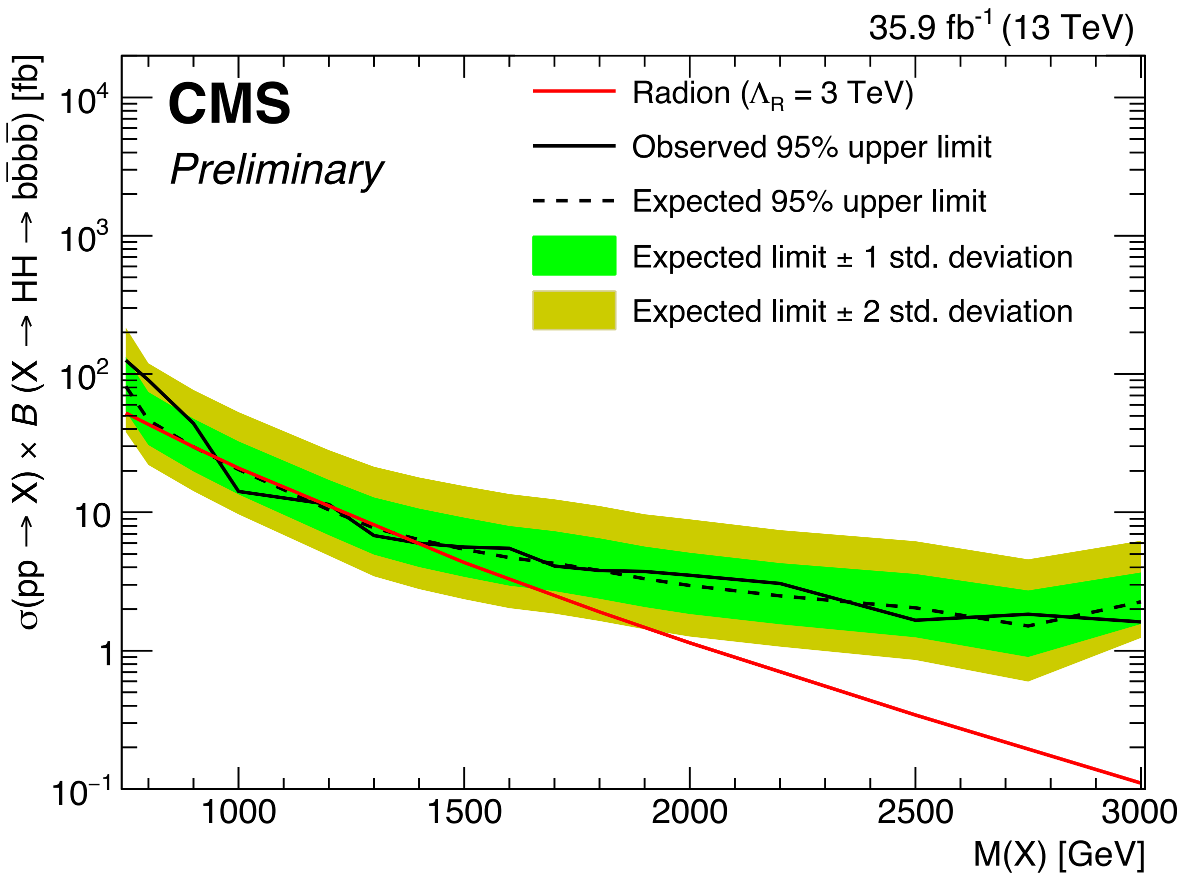
Alphabet

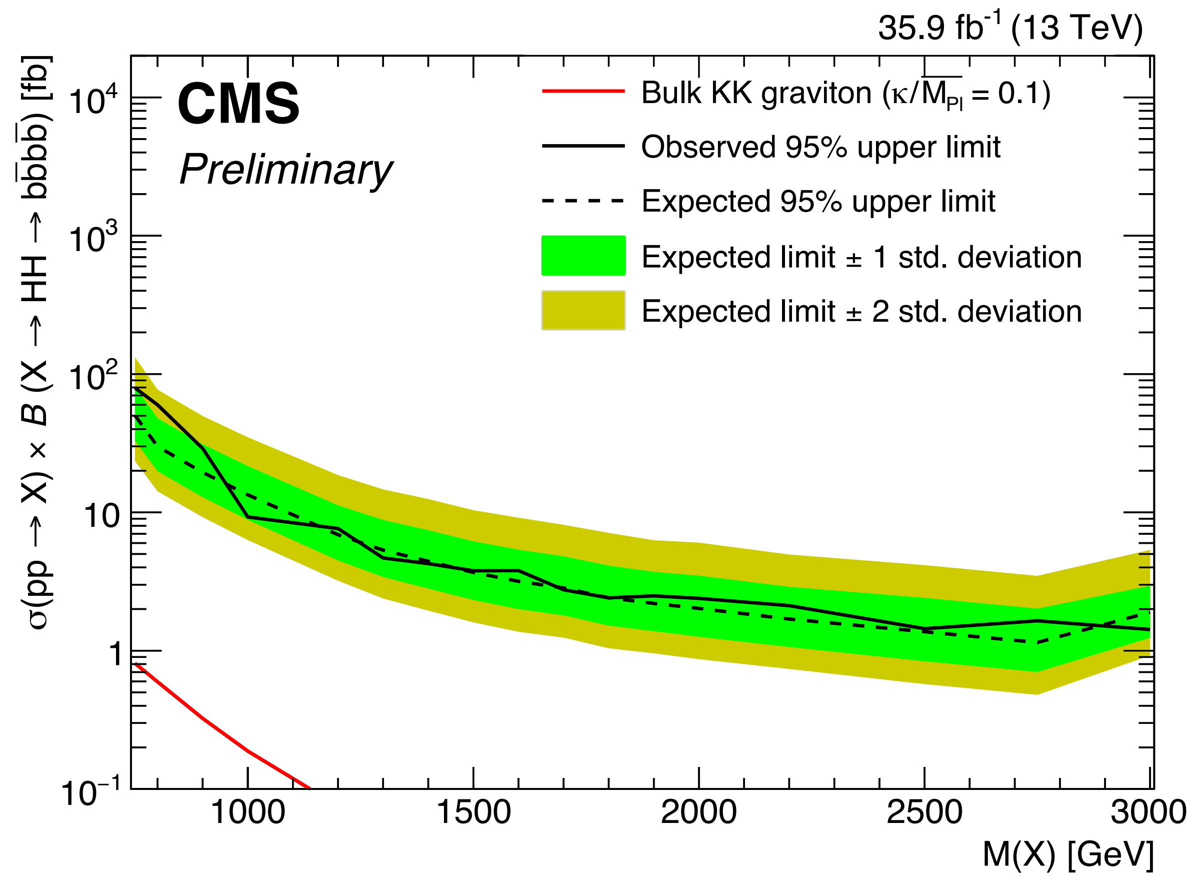
AABH



$HH \rightarrow bbbb$: CMS Results

B2G-16-026

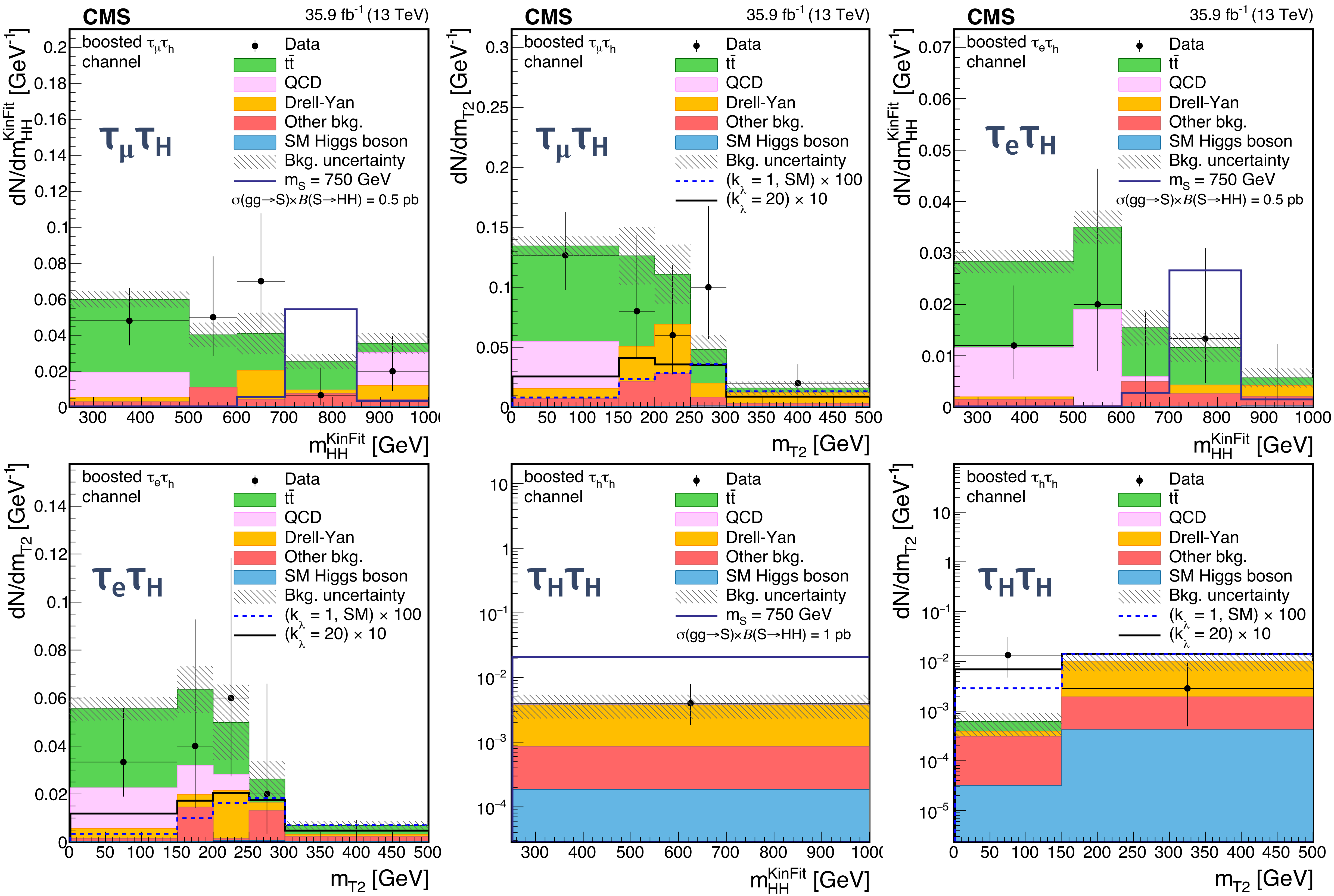




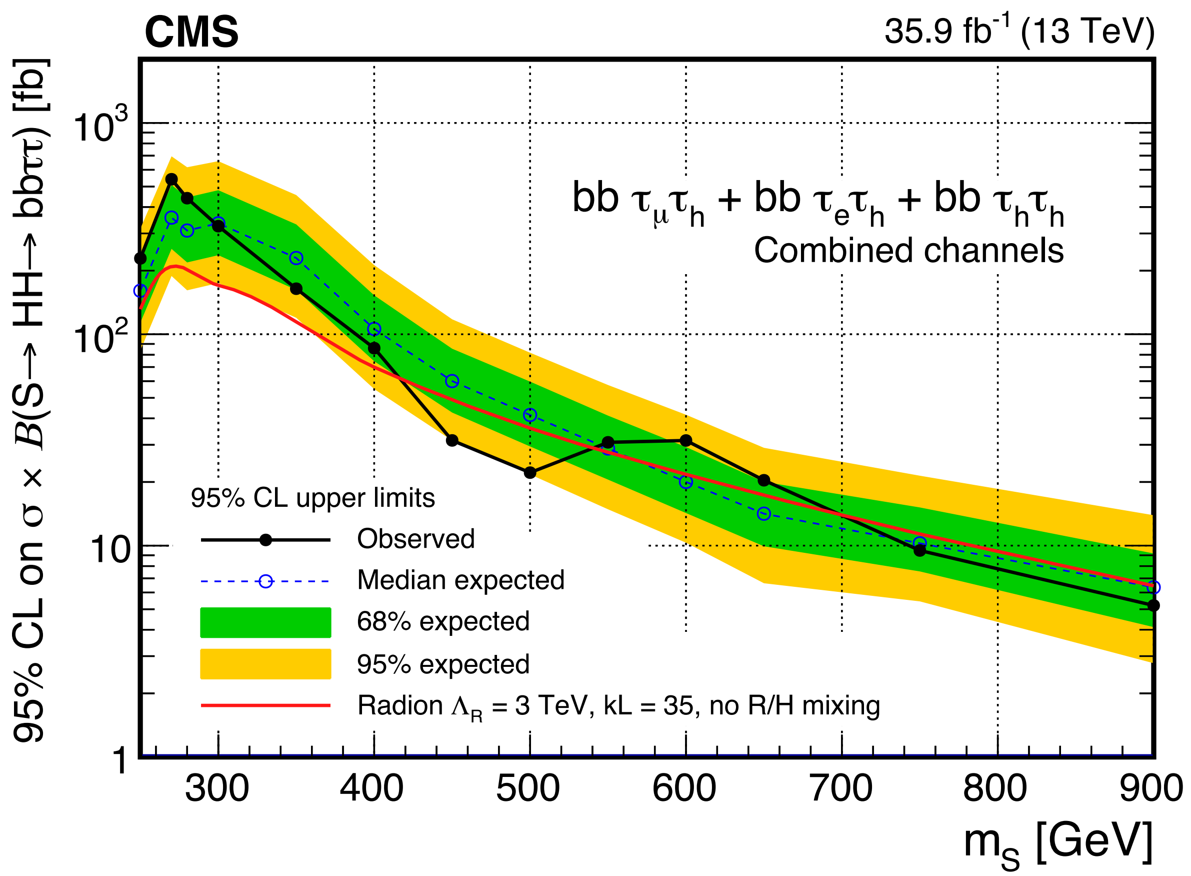
- Di-Higgs search in $\tau\tau$ final state to investigate both the resonant and non-resonant production mechanisms.
- 3 channels: $\tau_H\tau_H$, $\tau_H\tau_e$, $\tau_H\tau_\mu$, which cover 85% of $\tau\tau$ decays.
- 3 categories: 2 *b*-tags, 1 *b*-tag, ***high-mass boosted***.
- Main backgrounds: $t\bar{t}$, 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}.

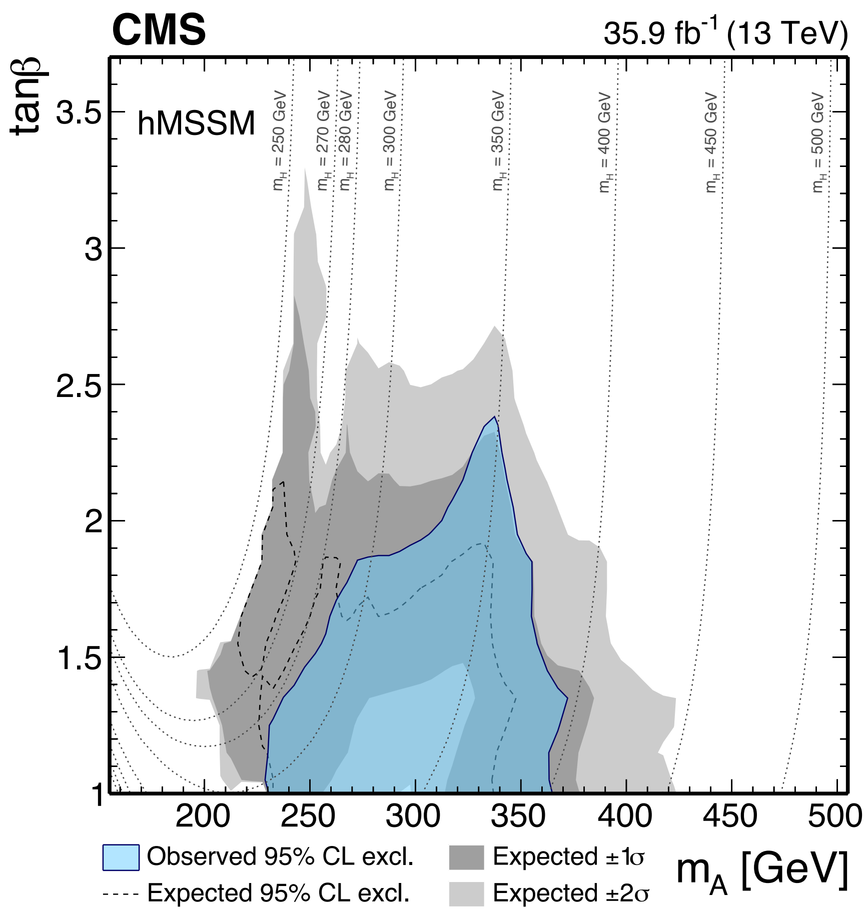
$HH \rightarrow bb\tau\tau$: CMS Results

HIG-17-002



Resonant results





Summary

Summary

- Latest ATLAS and CMS Run II searches with boosted topologies of multi-boson final states 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

Boosted analysis

Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
Production Category	VBF	$m^{\text{tag}}(j,j) > 770\,\text{GeV}$ and $\lvert\Delta\eta^{\text{tag}}(j,j)\rvert > 4.7$		
	DY	Fails VBF selection		
$W \to \ell\nu$ selection	Num. of signal leptons	1		
	Num. of veto leptons	0		
	$E_{\text{T}}^{\text{miss}}$	$> 100\,\text{GeV}$		
	$p_{\text{T}}(\ell\nu)$	$> 200\,\text{GeV}$		
	$E_{\text{T}}^{\text{miss}}/p_{\text{T}}(e\nu)$	> 0.2		
$V \to J$ selection	Num. of large-R jets	≥ 1		
	D_2 Eff. working point (%)	Pass 50 (80)	Pass 50 (80)	Pass 50 (80)
	Mass window Eff. working point (%)	Pass 50 (80)	Fail 80 (80)	Pass 50 (80)
Topology cuts	$p_{\text{T}}(\ell\nu)/m(WV)$ $p_{\text{T}}(J)/m(WV)$	> 0.3 for VBF and > 0.4 for DY category		
Num. of b-jets	$\Delta R(J,b) > 1.0$	0		≥ 1

Resolved analysis

Selection		WW (WZ) SR	W CR	$t\bar{t}$ CR
Production Category	VBF	$m^{\text{tag}}(j,j) > 770$ GeV and $\lvert\Delta\eta^{\text{tag}}(j,j)\rvert > 4.7$		
	DY	Fails VBF selection		
$W \to \ell\nu$ selection	Num. of signal leptons	1		
	Num. of veto leptons	0		
	$E_{\text{T}}^{\text{miss}}$	> 60 GeV		
	$p_{\text{T}}(\ell\nu)$	> 75 GeV		
	$E_{\text{T}}^{\text{miss}}/p_{\text{T}}(e\nu)$	> 0.2		
$V \to jj$ selection	Num. of small-R jets	≥ 2		
	$p_{\text{T}}(j_1)$	> 60 GeV		
	$p_{\text{T}}(j_2)$	> 45 GeV		
	$m(jj)$ [GeV]	[66, 94] ([82, 106])	< 66 or [106, 200]	[66, 106]
Topology cuts	$\Delta\phi(j,\ell)$	> 1.0		
	$\Delta\phi(j,E_{\text{T}}^{\text{miss}})$	> 1.0		
	$\Delta\phi(j,j)$	< 1.5		
	$\Delta\phi(\ell,E_{\text{T}}^{\text{miss}})$	< 1.5		
	$p_{\text{T}}(\ell\nu)/m(WV)$ $p_{\text{T}}(jj)/m(WV)$	> 0.3 for VBF and 0.35 for DY category		
Num. of b-jets	$b \equiv j_1$ or j_2 where $V \to j_1 j_2$	$\leq 1(2)$	≤ 1	> 2 or ≥ 1
	$b \neq j_1$ and $b \neq j_2$ where $V \to j_1 j_2$	0		