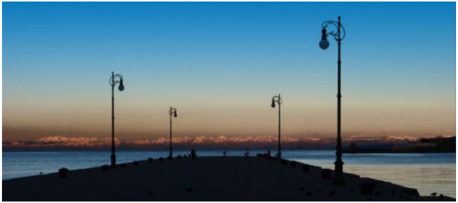
Search for heavy resonances decaying into W, Z, H bosons at CMS



Incontri di Fisica delle Alte Energie, Trieste, 19-21 aprile 2017

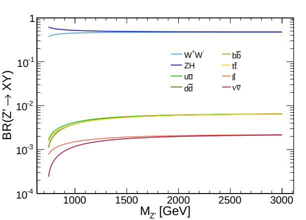
Lisa Benato on behalf of **CMS collaboration**

Theoretical motivations

- Beyond Standard Model theories: enlarging SM symmetry group → new heavy particles

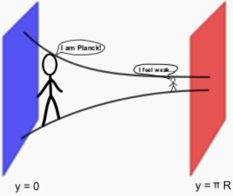
Heavy Vector Triplet

- General framework (including Little Higgs, Composite Higgs, Sequential Standard Model)
  - Introduction of (X^0, X^+, X^-)
  - Additional parameters: g_V (strength), c_H (coupling to bosons), c_F (coupling to fermions)
- HVT-A model: $BR(X \to f\bar{f})$ dominates
- HVT-B model: $BR(X \to f\bar{f}) << BR(X \to VV) \approx BR(X \to VH)$



Warped extra dimensions

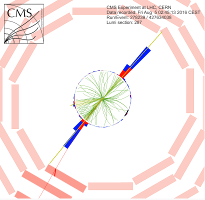
- Tentative solution of the hierarchy problem of the Higgs mass
- 5-dimensional bulk: Planck brane and TeV brane
- Spin-2 bulk gravitons and SM particles propagate among branes through warped extra dimension
  - Gravitons produced at TeV scale via gluon fusion, significant branching ratio into bosons



Overview of the analyses

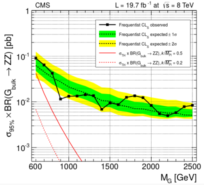
Searches for diboson resonances (W, Z, H)

- Most recent results with 2016 data provided by LHC p-p collisions ($\mathcal{L} \approx 36\ \text{fb}^{-1}$)
- "All-hadronic" final states:
  - $VV\ (V = W, Z) \rightarrow q\bar{q}q\bar{q}$
  - $VH \rightarrow q\bar{q}b\bar{b}\ (BR(H \rightarrow b\bar{b}) \approx 60\%)$
- Heavy ($m_X > 1$ TeV) resonances $\rightarrow$ decay products with large Lorentz boost
  - $q\bar{q}$ collimated $\rightarrow$ each boson reconstructed as large-cone jet
  - Jet substructure techniques to identify the V/H bosons

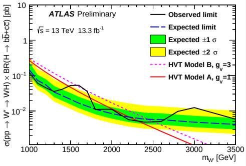


Highlights from previous searches

CMS EXO-13-009, 2012 data: local excess @ 1.8 TeV (2. σ)



ATLAS-CONF-2016-083, 2016 reduced dataset: local excess @ 1.6 TeV (2.5 σ), @ 3 TeV (3.5 σ)



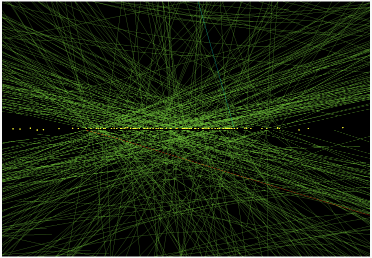
Event reconstruction

Di-jet event selection

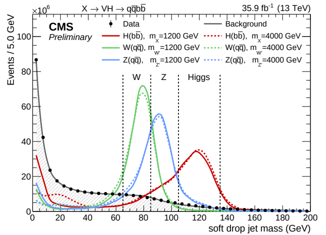
- Pair of large-cone jets:
  - clustered with anti-k_T in cone $\Delta R = 0.8$
  - high p_T (> 200 GeV)
- Veto on charged, isolated, well-identified leptons
- Small amount of E_T^{miss} (avoid $Z \to \nu\nu$)
- Dominant SM background: QCD multijet

Grooming algorithms

- Subtract pile-up (PUPPI algorithm) and soft radiation contributions (softdrop) from jet



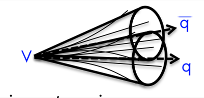
- Groomed jet mass tags the boson type:
  - W: $65 < m_j < 85$ GeV
  - Z: $85 < m_j < 105$ GeV
  - H: $105 < m_j < 135$ GeV



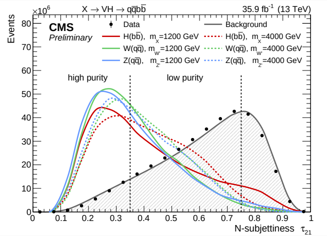
Boson tagging

V-tagging

- n-subjettiness: τ_{21} describes the 2-prong jet substructure hypotesis (typical of *W*,*Z*) vs the 1-prong (QCD)

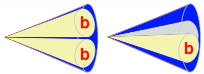


- 2 exclusive categories:
  - high purity: $0. < \tau_{21} < 0.35$
  - low purity: $0.35 < \tau_{21} < 0.75$

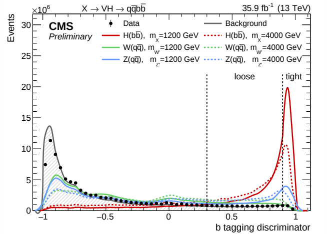


H-tagging

- Double b-tagger algorithm: pair of b-quarks in a large jet
- Information from displaced tracks, secondary vertices combined in MVA



- 2 exclusive categories:
  - loose operating point
  - tight operating point



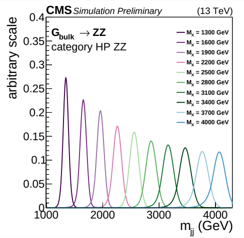
VV all hadronic [CMS PAS B2G-17-001]

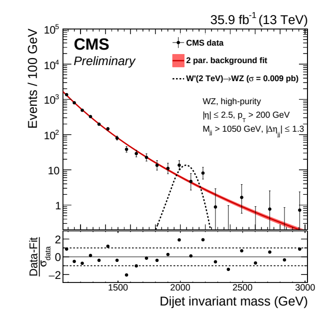
Event categorization

- 2 V-tagging (VV): 6 categories ($WW \times WZ \times ZZ$) $\times$ ($LP \times HP$)

Background modelling

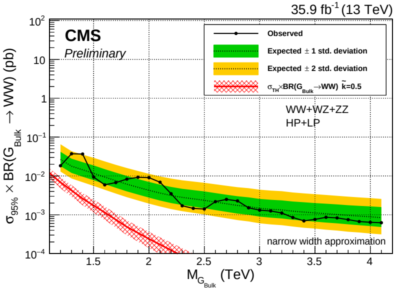
- "Bump hunt": fit to data with power law or exponential falling functions
- 10% CL Fisher test to determine the number of parameters (2-5)
- Signal modelled as Crystal Ball (narrow-width)

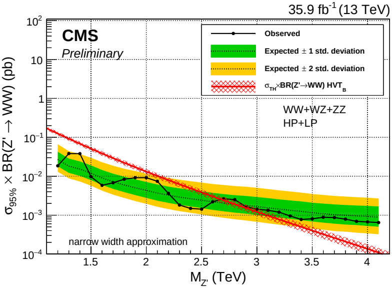


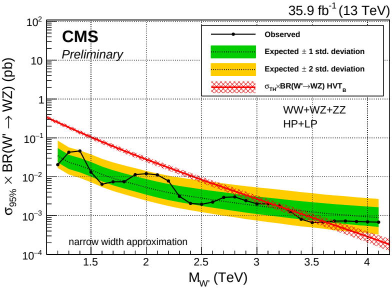


VV all hadronic results [CMS PAS B2G-17-001]

- No excess observed in data
- Best limits on HVT B-model
  $m_{Z'} < 2.7$ TeV and $m_{W'} < 3.6$ TeV







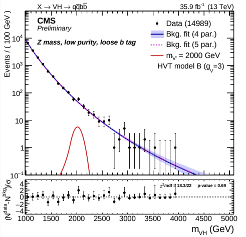
VH all hadronic [CMS PAS B2G-17-002]

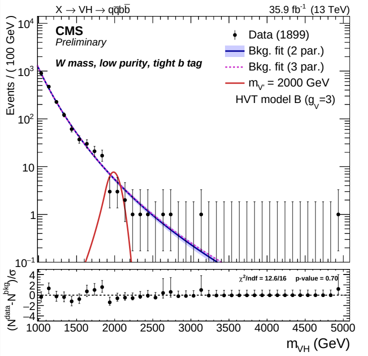
Event categorization

- 8 categories: $(W \times Z) \times (LP \times HP) \times (Loose \times Tight)$

Background modelling

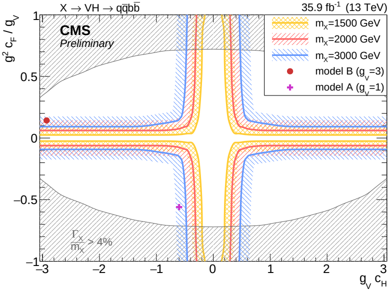
- ”Bump hunt”: fit to data with power law or exponential falling functions
- 10% CL Fisher test to determine the number of parameters (2-5)
- Signal modelled as Crystal Ball (narrow-width)

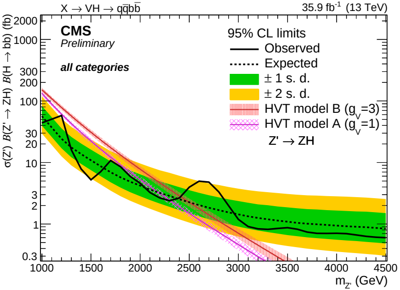


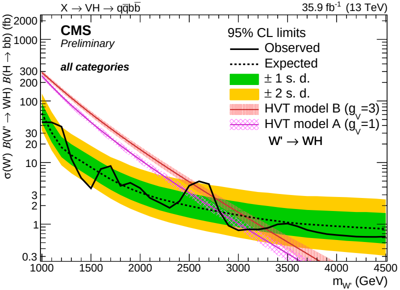


VH all hadronic results [CMS PAS B2G-17-002]

- No excess observed in data
- Limits on HVT A-B model
  $m_{Z'} < 2.4$ TeV and $m_{W'} < 3.3$ TeV
- Interpretation in model A and B in the HVT parameter space



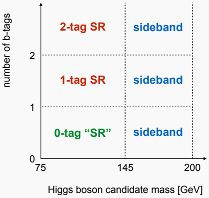




VH all hadronic [ATLAS-CONF-2017-018]

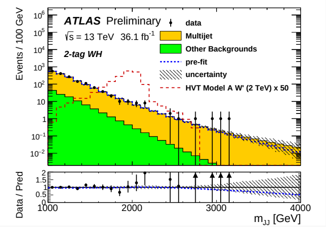
Analysis strategy

- Performed combining 2016-2015 datasets
- V-tagging:
  - jet mass categories (p_T-dependent, not orthogonal, $\approx 60 < m_V < 110$ GeV)
  - energy correlation functions D_2 to exploit 2-prong substructure
- H-tagging:
  - $75 < m_H < 145$ GeV
  - categorization in number of b-tagged track jets (1,2)



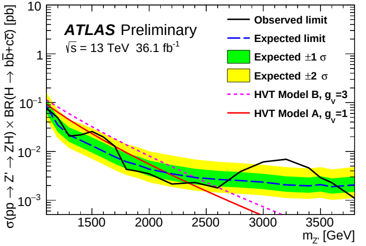
Background prediction

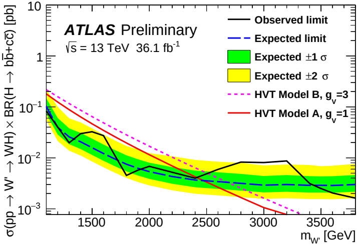
- Data-driven prediction of QCD multijet background
- Shape (power law) predicted from control region in data: 0-btag region
- Kinematical corrections extracted from data sidebands (outside m_H window)

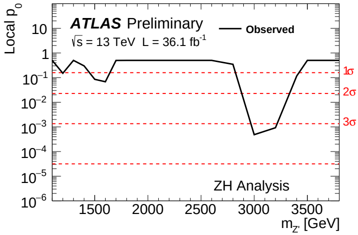


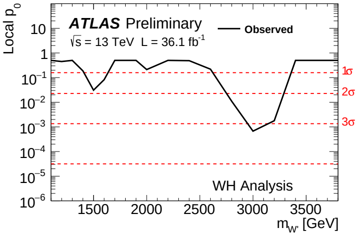
VH all hadronic results [ATLAS-CONF-2017-018]

- Limits on HVT A-B model, $m_{Z'} < 2.6$ TeV and $m_{W'} < 2.5$ TeV
- Local excess of 3.3σ (global 2.2σ) at ≈ 3 TeV









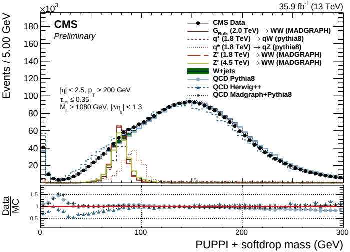
Conclusions

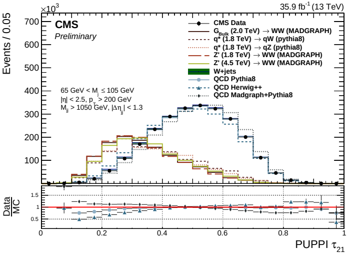
- Searches for heavy resonances decaying into dibosons (W, Z, H) with 2016 data produced by p-p collisions at LHC
  - VV hall adronic final state @ CMS: the best exclusion limits so far on HVT-B model
  - VH all hadronic final state @ CMS - ATLAS: local excess of 3.3σ observed by ATLAS at 3 TeV not confirmed by CMS
- New jet substructure algorithms and mass grooming techniques exploited in these analyses
- Common strategies in object definitions, jet substructure and background estimation methods allow smooth combinations within the same experiment, big improvement in the discovery reach
- Many other diboson searches are in a very advanced status, covering also leptonic final states $(\ell, \tau, \nu) \rightarrow$ new results are coming soon!
- CMS results with 2015 data - 2016 reduced dataset:
  - $VH \rightarrow (\ell\ell, \ell\nu, \nu\nu)b\bar{b}$ (2015 data): B2G-16-003
  - $VV \rightarrow \ell\nu q\bar{q}, q\bar{q}q\bar{q}$ (2015 data): B2G-16-004
  - Combination WW, WZ, ZZ, WH, ZH (2012 + 2015 data): B2G-16-007
  - $HH \rightarrow b\bar{b}b\bar{b}$ (2015 data): B2G-16-008
  - $VW \rightarrow q\bar{q}\ell\nu$ (2016 reduced dataset): B2G-16-020
  - $VZ \rightarrow q\bar{q}\ell\ell$ (2016 reduced dataset): B2G-16-022


Grazie dell'attenzione!

Backup slides

VV all hadronic [CMS PAS B2G-17-001]





Source	Relevant quantity	Uncertainty (%) 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	<0.7		<0.7	
Jet energy resolution	Signal yield	<0.5		<0.4	
Jet mass scale	Signal yield	<1.9		<0.9	
Jet mass resolution	Signal yield	<0.5–5.5		<0.2–7.4	
Pileup	Signal yield	2			
Integrated luminosity	Signal yield	2.6			
Jet mass scale	Migration	<35.8		<9.8	
Jet mass resolution	Migration	<25.0		<7.4	
V-tagging τ_{21}	Migration	22.2	33.4	11.1	22.3
V-tagging p_T-dependence	Migration	18.6–39.6	13.6–28.9	9.3–23.0	4.3–10.6
PDF and scales (W′ and Z′)	theory	2–18			
PDF and scales (G_{bulk})	theory	8–78			
PDF and scales (q*)	theory			1–61	

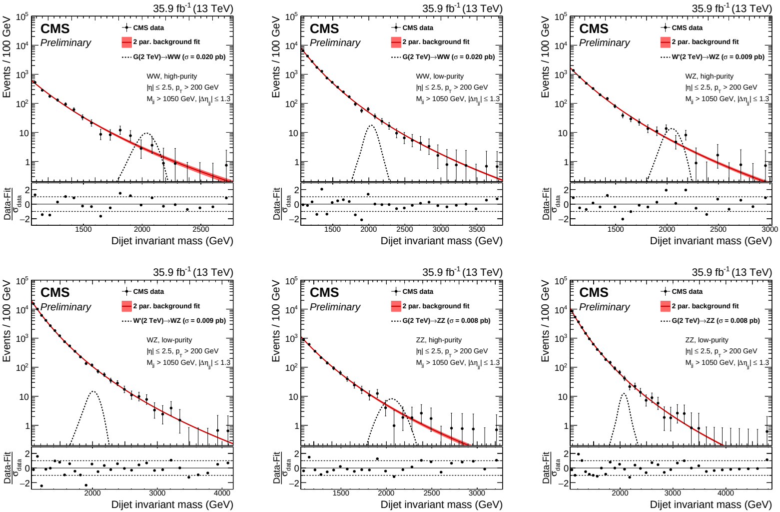
τ_{21} selection	Efficiency scale factor
$\tau_{21} < 0.35$	0.99 ± 0.1 (stat) ± 0.04 (sys)
$0.35 < \tau_{21} < 0.75$	1.03 ± 0.2 (stat) ± 0.11 (sys)

$$\frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2 + P_3 \times \log(m_{jj}/\sqrt{s}) + P_4 \times \log(m_{jj}/\sqrt{s})^2}} \text{ (5-par. form),}$$

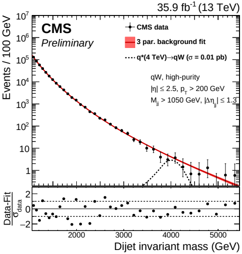
$$\frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}} \text{ (3-par. form),}$$

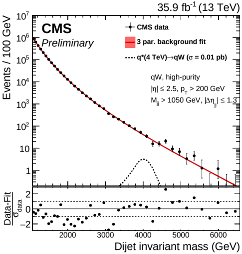
$$\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_2}} \text{ (2-par. form),}$$

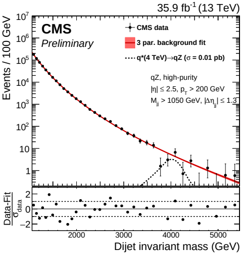
VV all hadronic [CMS PAS B2G-17-001]

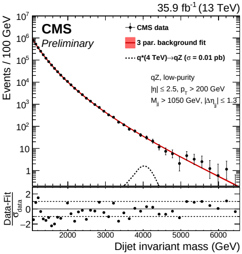


VV all hadronic [CMS PAS B2G-17-001]

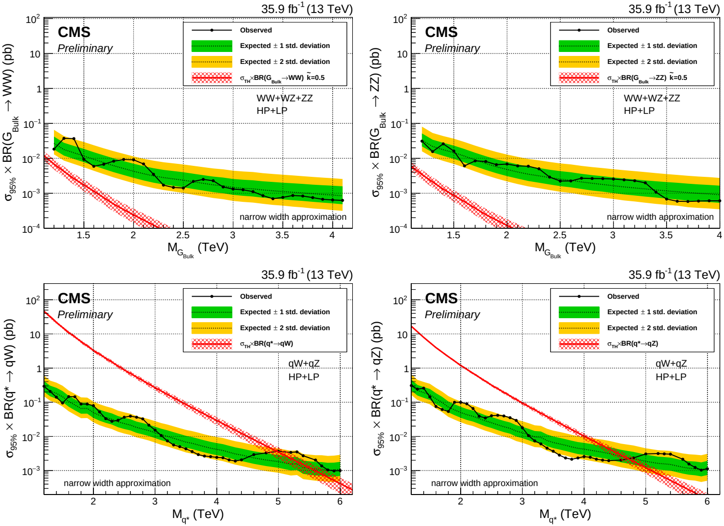








VV all hadronic [CMS PAS B2G-17-001]



VH all hadronic [CMS PAS B2G-17-002]

$$2\ parameters:\ p_0 \cdot \frac{1}{(x)^{p_1}}$$

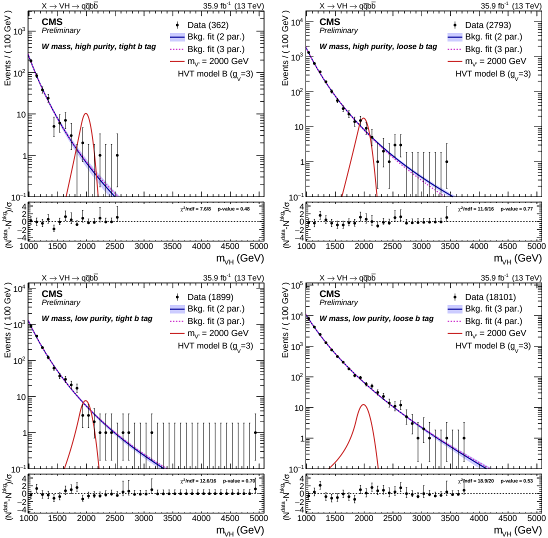
$$3\ parameters:\ p_0 \cdot \frac{(1-x)^{p_1}}{(x)^{p_2}}$$

$$4\ parameters:\ p_0 \cdot \frac{(1-x)^{p_1}}{(x)^{p_2+p_3 \cdot \log(x)}}$$

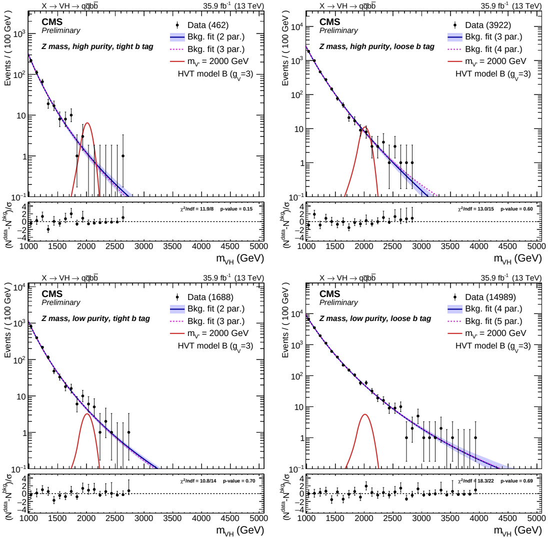
$$5\ parameters:\ p_0 \cdot \frac{(1-x)^{p_1}}{(x)^{p_2+p_3 \cdot \log(x)+p_4 \cdot \log^2(x)}}$$

$x = m_{VH}/\sqrt{s}$
$\sqrt{s} = 13$ TeV

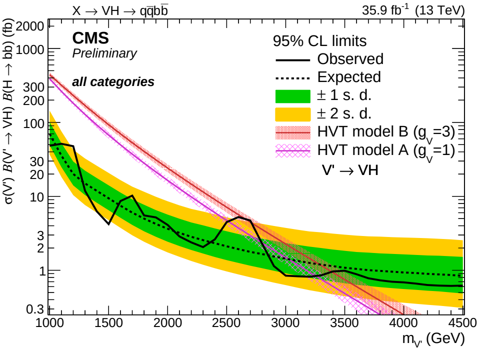
VH all hadronic [CMS PAS B2G-17-002]



VH all hadronic [CMS PAS B2G-17-002]



VH all hadronic [CMS PAS B2G-17-002]



VH all hadronic [ATLAS-CONF-2017-018]

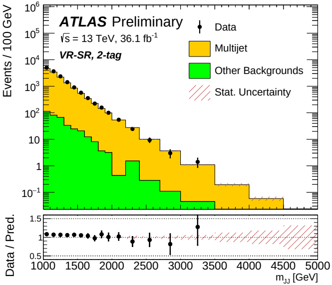
$$f_{\text{Multijet}}(x) = p_a(1-x)^{p_b}(1+x)^{p_c x}$$

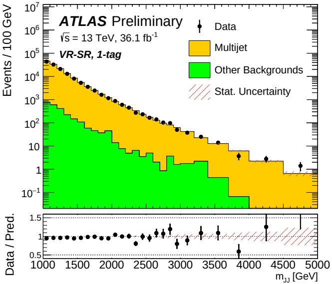
$$f_{t\bar{t}}^{\text{1-tag}}(x) = p_d(1-x)^{p_e} x^{p_f}$$

$$f_{t\bar{t}}^{\text{2-tag}}(x) = p_g e^{-p_h x}$$

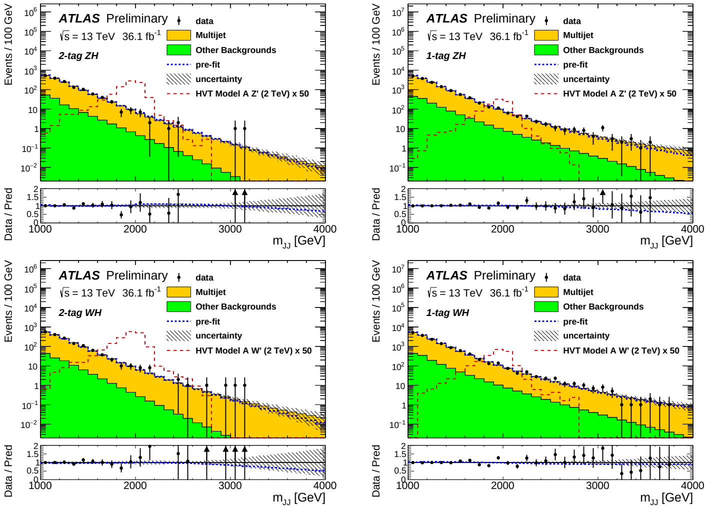
$x = m_{JJ}/\sqrt{s}$
$\sqrt{s} = 13$ TeV

VH all hadronic [ATLAS-CONF-2017-018]





VH all hadronic [ATLAS-CONF-2017-018]



Substructure variables

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

$$\mathrm{ECF}(0,\beta) = 1,$$

$$\mathrm{ECF}(1,\beta) = \sum_{i\in J} p_{T\,i},$$

$$\mathrm{ECF}(2,\beta) = \sum_{i<j\in J} p_{T\,i}\, p_{T\,j} (R_{ij})^\beta,$$

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in J} p_{T\,i}\, p_{T\,j}\, p_{T\,k} \left(R_{ij} R_{ik} R_{jk}\right)^\beta,$$

$$\mathrm{ECF}(4,\beta) = \sum_{i<j<k<\ell\in J} p_{T\,i}\, p_{T\,j}\, p_{T\,k}\, p_{T\,\ell} \left(R_{ij} R_{ik} R_{i\ell} R_{jk} R_{j\ell} R_{k\ell}\right)^\beta$$