Direct Searches for New Physics with Multiboson Final States

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On behalf of the ATLAS and CMS Collaborations

LPC Workshop: Multibosons at the Energy Frontier

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Resonant Diboson Publications

- Using data from 2016 onwards

CMS: 17 analyses

X→VH
B2G-17-002
B2G-17-004
B2G-17-006

X→VV
B2G-16-029
B2G-17-005
B2G-17-013
B2G-18-002

X→Hγ
EXO-17-019

X→ZZ
B2G-16-023
HIG-17-012

X→HH
B2G-16-026
B2G-17-019
HIG-17-006
HIG-17-008
HIG-17-009
B2G-18-008

X→WW
HIG-17-033

ATLAS: 19 analyses

X→VV
EXOT-2016-11
HIGG-2016-19
EXOT-2016-19
EXOT-2016-28
EXOT-2016-29
HIGG-2016-31
HDBS-2018-31

X→Vγ
EXOT-2016-30

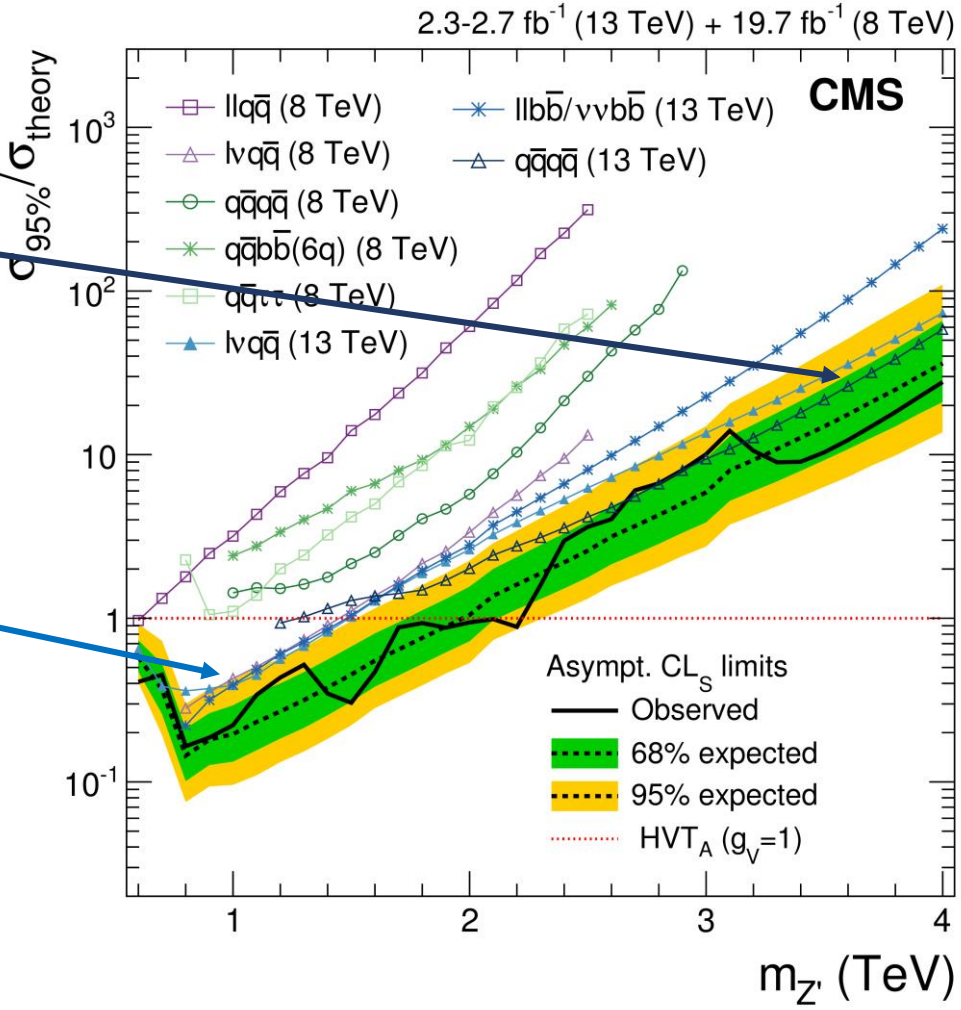
X→VH
EXOT-2016-10
EXOT-2016-12
EXOT-2016-34
EXOT-2017-31

X→HH
HIGG-2016-15
HIGG-2016-16
HIGG-2016-20
HIGG-2016-24
HIGG-2016-27
EXOT-2016-31
HDBS-2018-58

Complementary Search Channels

B2G-16-007

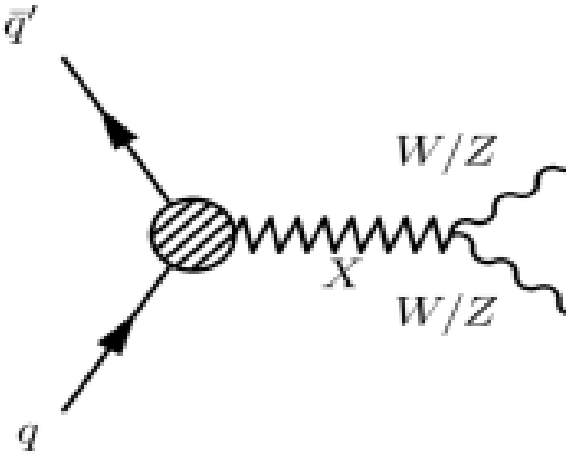
- Hadronic final state benefits from large BR → sensitive at high mass
- Leptonic states give more sensitivity at lower masses by reducing backgrounds

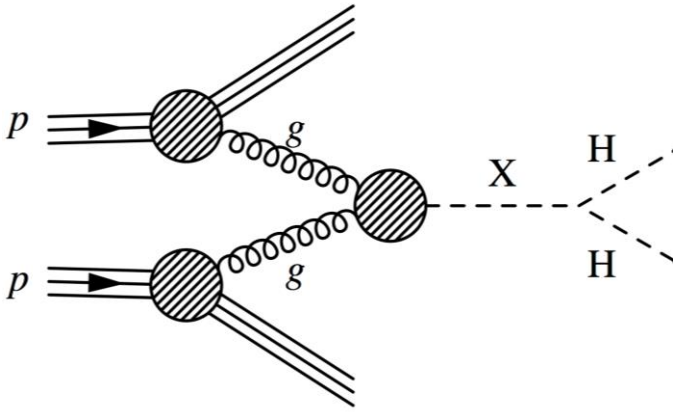


VV/VH combination

Motivation for Diboson Resonances

- General searches for new physics connected to the gauge sector
  - Couple to W, Z and H bosons
- Model independent analyses interpreted according to benchmark models
  - **Warped extra dimensions:** Integration of gravity in SM and solution to hierarchy problem
    - Prediction of a spin-0 radion and spin-2 graviton
  - **Heavy Vector Triplet model:** Hierarchy of the Higgs boson mass
    - Introduction of spin-1 massive bosons (X^0, X^+, X^-)

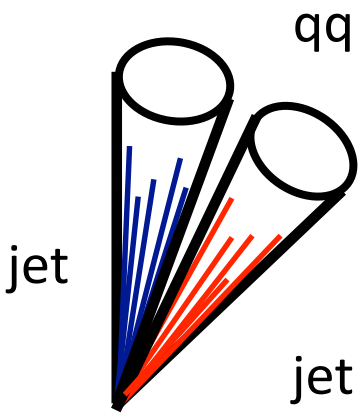


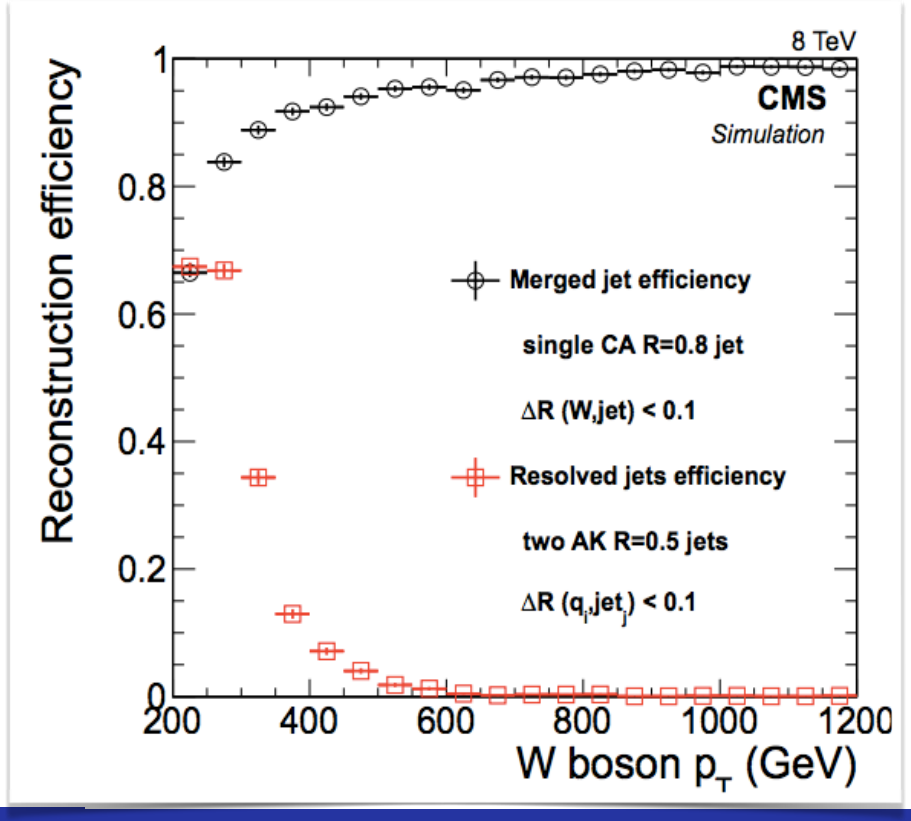


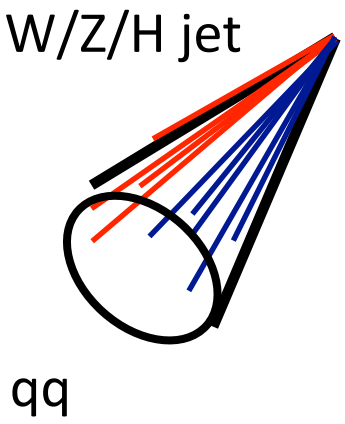
Reconstructing Bosons

Hadronically Decaying Bosons

- Bosons from high mass resonance have large Lorentz boost
  - Reconstructed as large-cone jets
- Lower mass resonance: use small cone size jets
  - Split searches into resolved and boosted categories

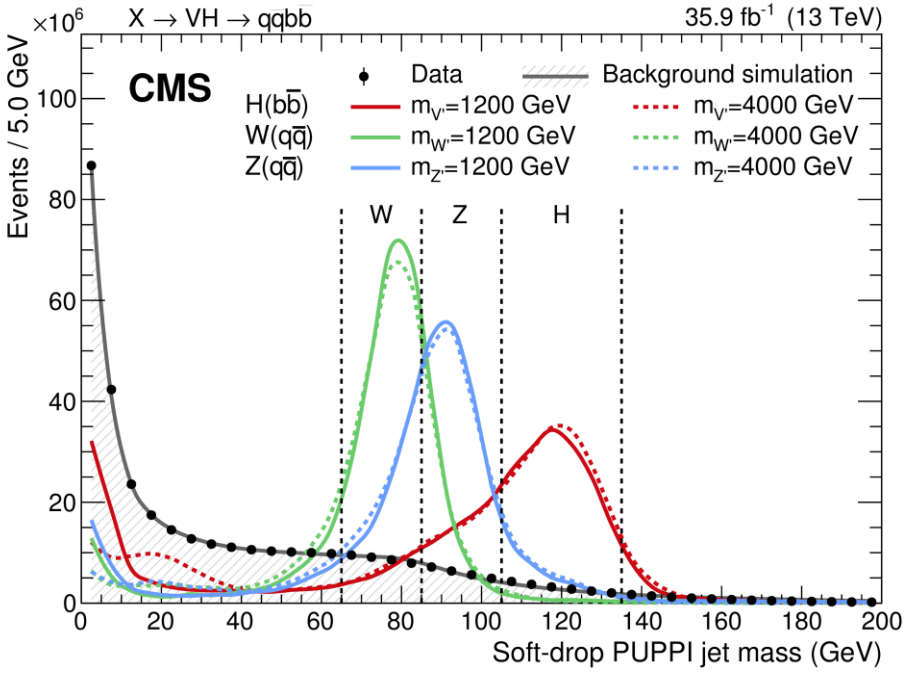


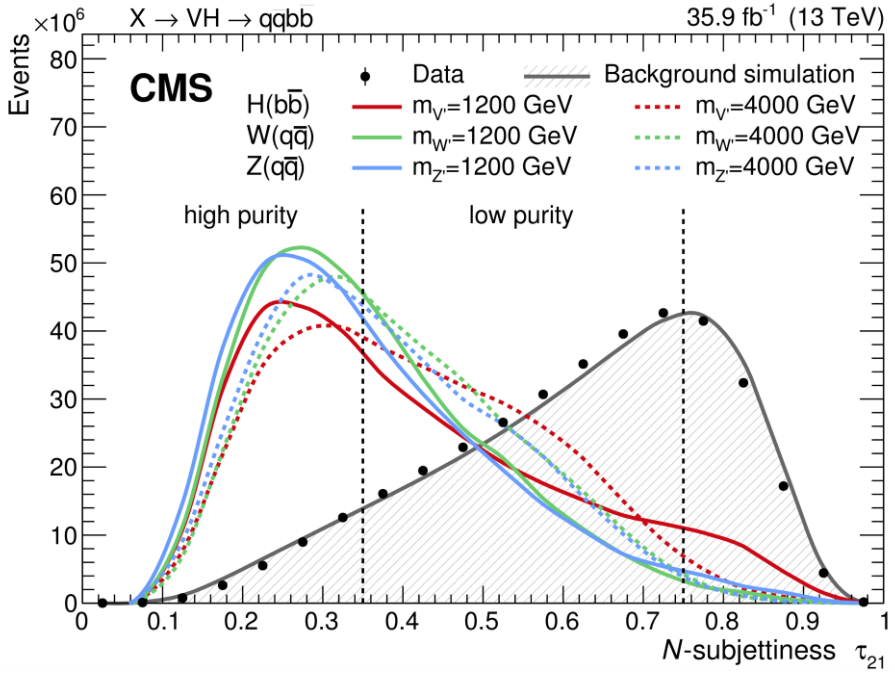




Boson Tagging Observables

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





Jet Mass After Grooming

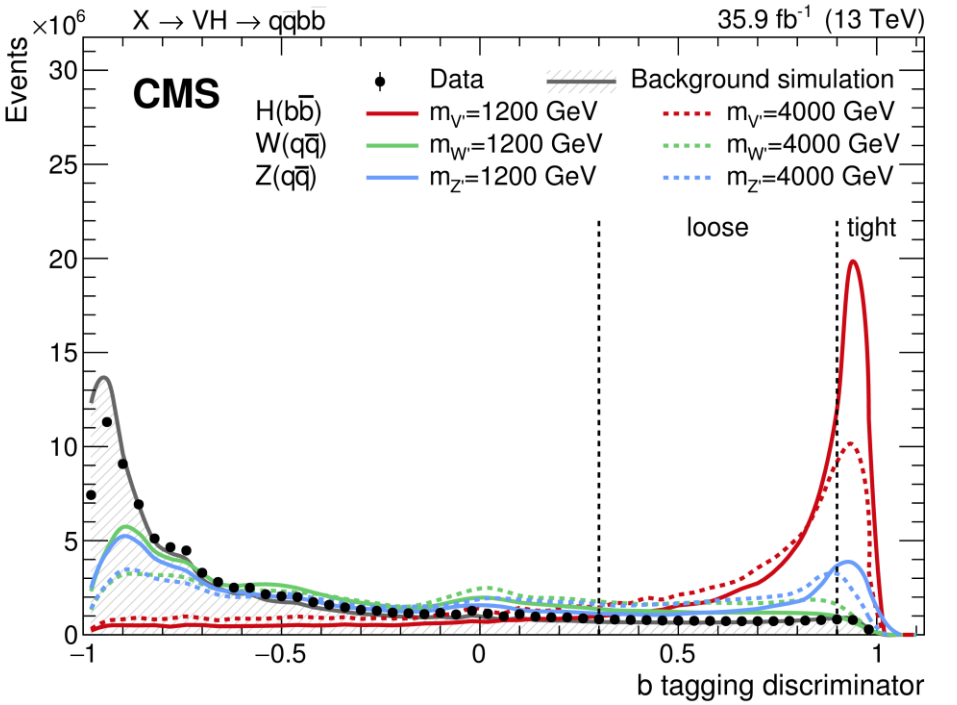
- Remove soft and wide-angle radiation (soft drop)
- Primarily aimed to separate W/Z/H-jets from q/g

Jet Substructure

- Measures the degree to which a jet can be considered as composed of N prongs

Boson Tagging Observables

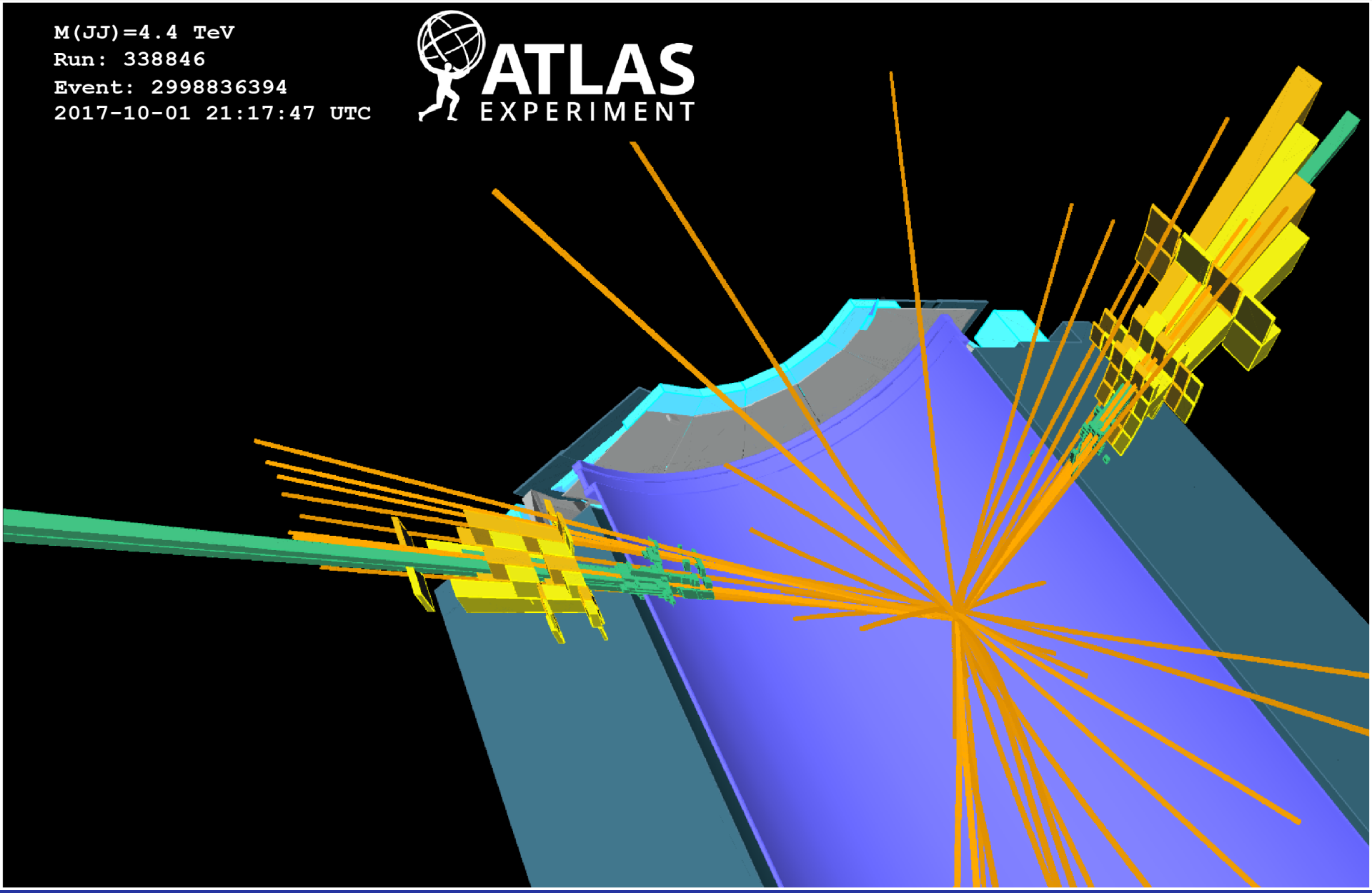
Eur. Phys. J. C 77 (2017) 636



Jet Flavor

- Discriminate jets originating from gluons and light-flavor quarks and b-quarks
- Multiple techniques
  - Subjet b-tagging
  - Double-b tagger at CMS holistically identifies the two B hadron decay chains within the same fat jet

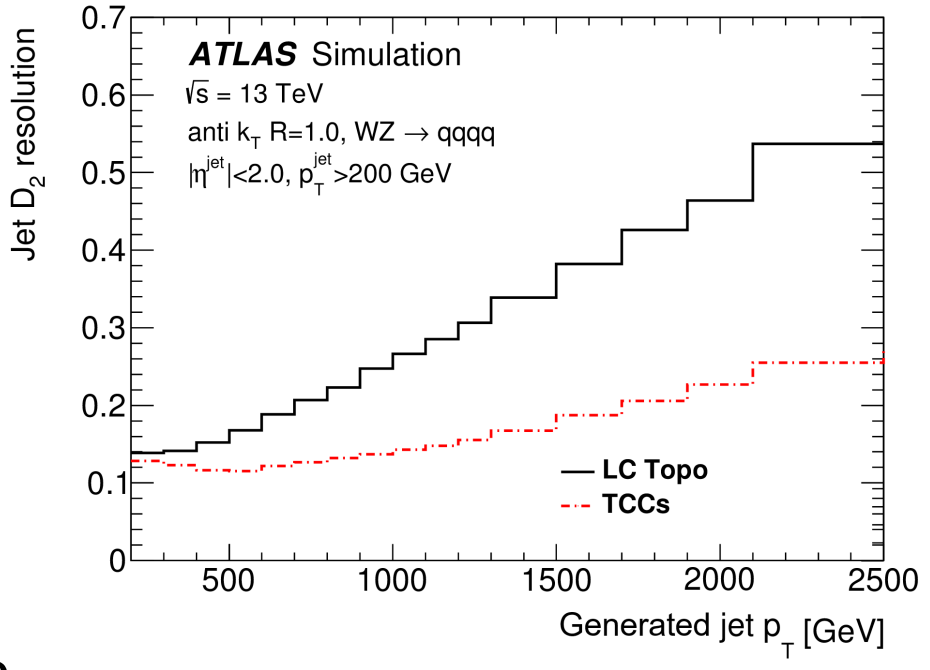
High Mass X→VV→Dijet



ATLAS X→VV → Dijet

Full Run2 dataset! HDBS-2018-31

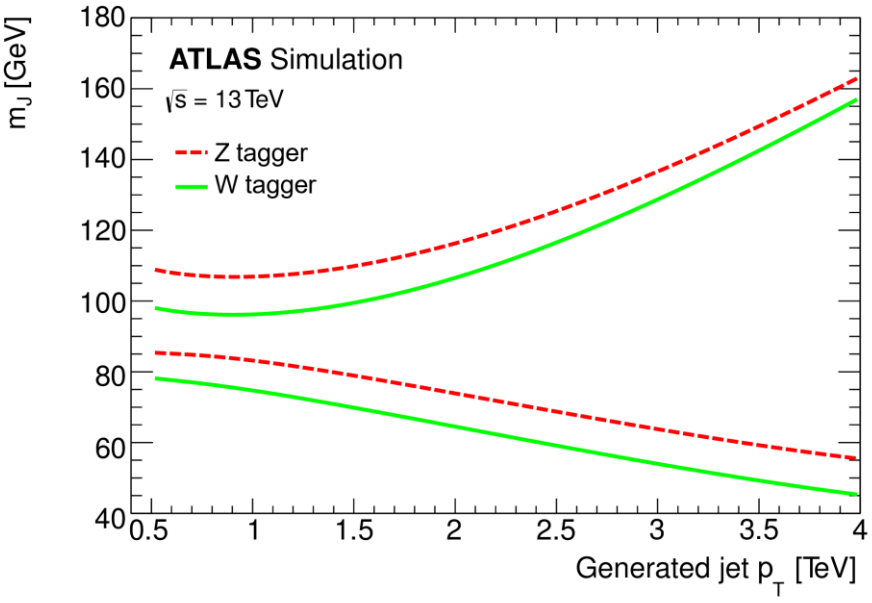
- Two high p_T merged W/Z→qq jets
- **New technique:** TrackCaloClusters(TCCs) algorithm improves V-jet reconstruction
  - Combine good calorimeter energy resolution with good tracker angular resolution to improve jet substructure resolution at high p_T

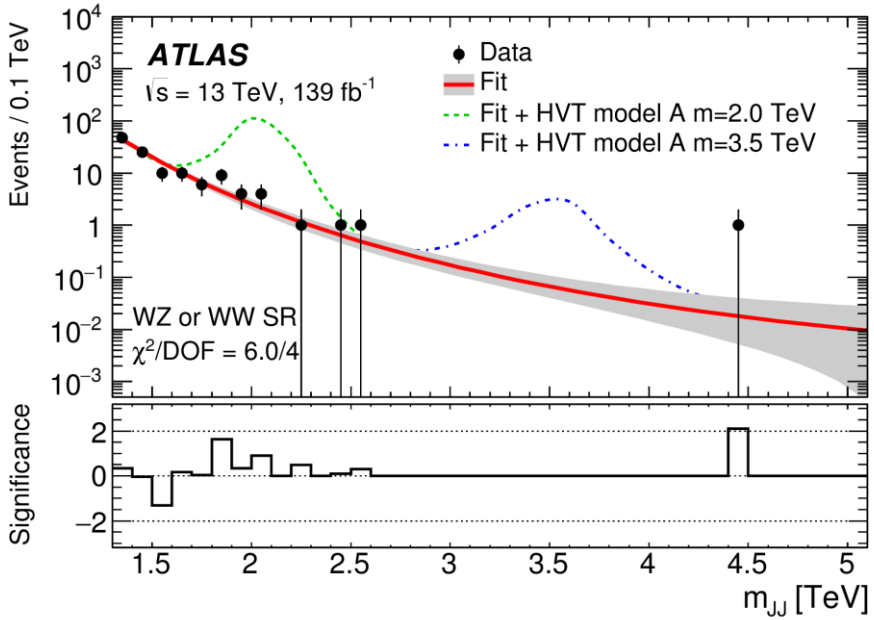


ATLAS X→VV → Dijet

Full Run2 dataset! HDBS-2018-31

- V-jet tagger
  - Simultaneously optimized the selection of 3 variables, mass, D_2, and n_{tk}, as a function of the jet p_T



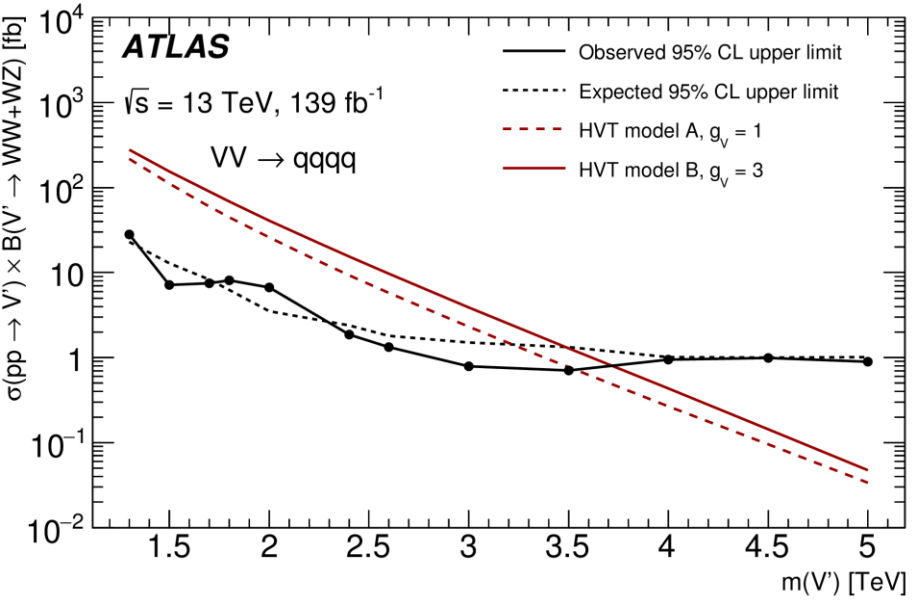


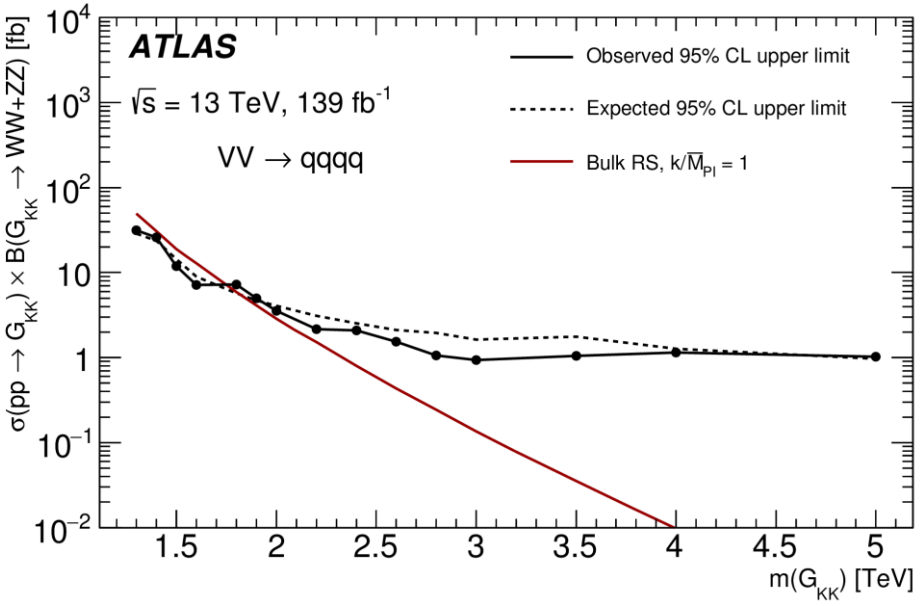
- Multijet background estimated by fitting the observed m_{jj} spectrum in the signal region using a parametric function (validated in CRs)

ATLAS X→VV → Dijet

Full Run2 dataset! HDBS-2018-31

- Most stringent limits on diboson resonances due to full Run2 luminosity and improved V-jet identification
  - Improvement 2-5 times larger than expected just from increase in luminosity



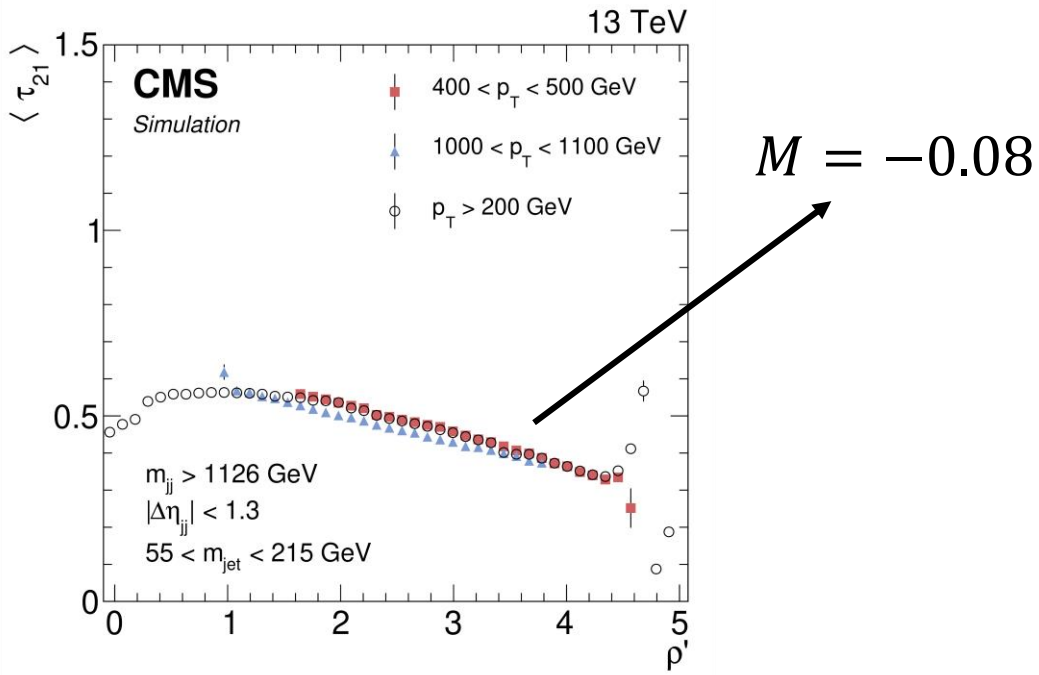


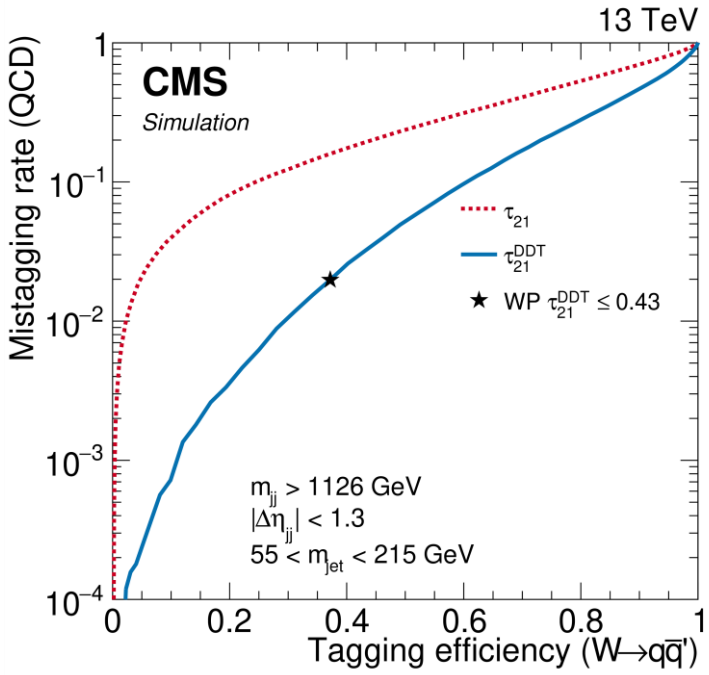
CMS X→VV → Dijet

2016+2017 data B2G-18-002

- CMS version based on 77fb^{-1}
- **New technique:** Decorrelated τ_{21} from jet mass and p_T through designed decorrelated tagger (DDT) method
  - Removes sculpting of monotonically falling background distribution
  - Improved V-jet identification

$$\tau_{21}^{DDT} = \tau_{21} - \mathrm{M} \cdot \rho$$
$$\rho = \log(m^2/p_T)$$

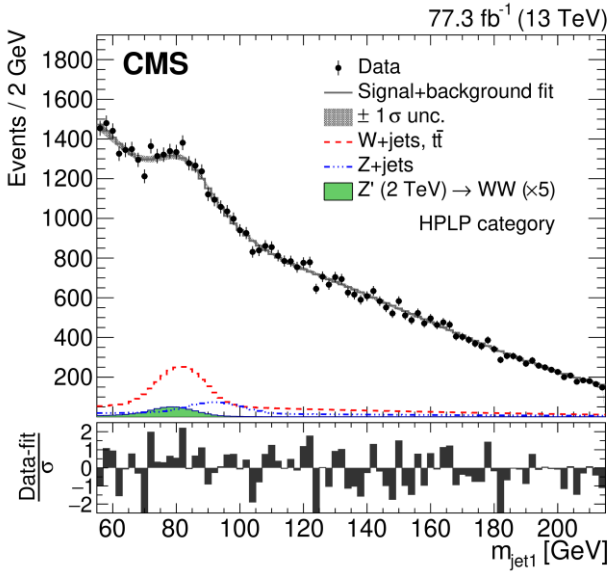


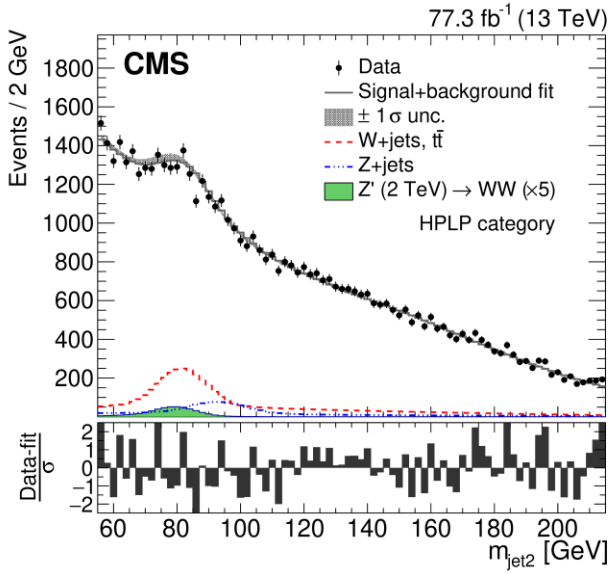


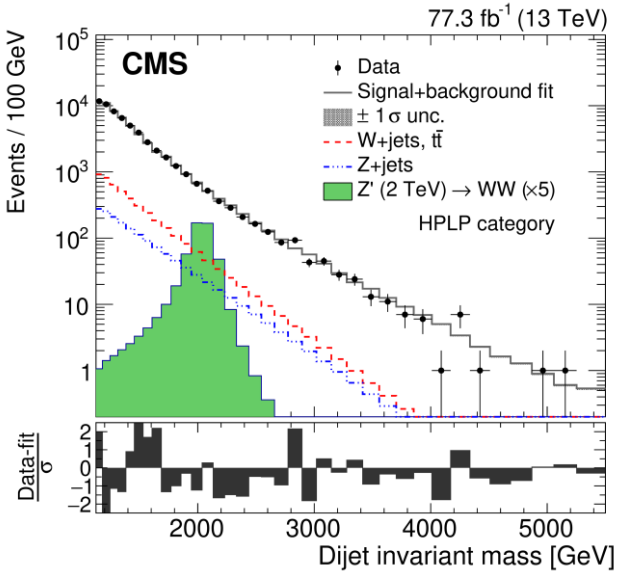
CMS X→VV → Dijet

2016+2017 data B2G-18-002

- Background estimation: 3D fit of m_{jet1}, m_{jet2}, and m_{jj}
  - Expands search for SM and non-SM bosons
  - Removes jet mass selections, which reduces statistical uncertainties in fitting procedure

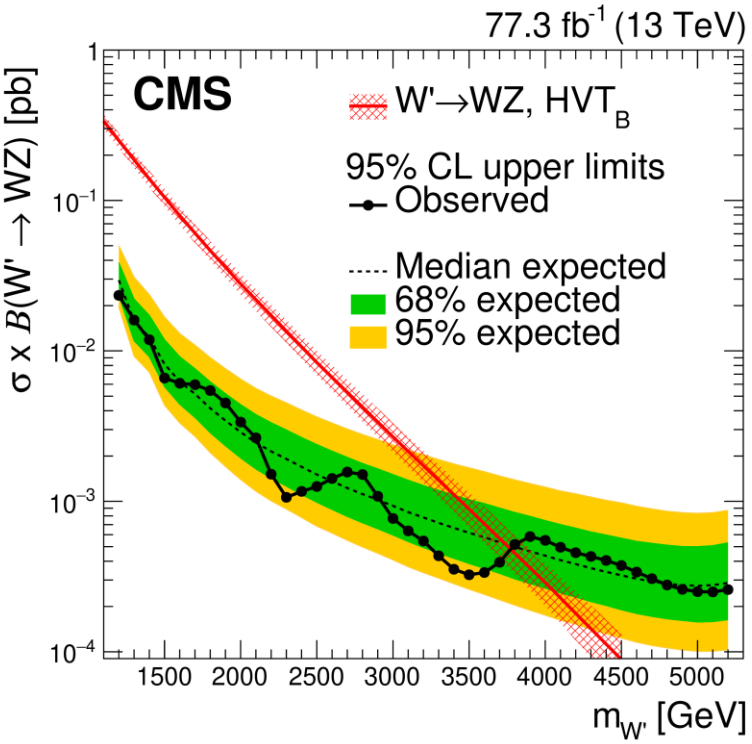


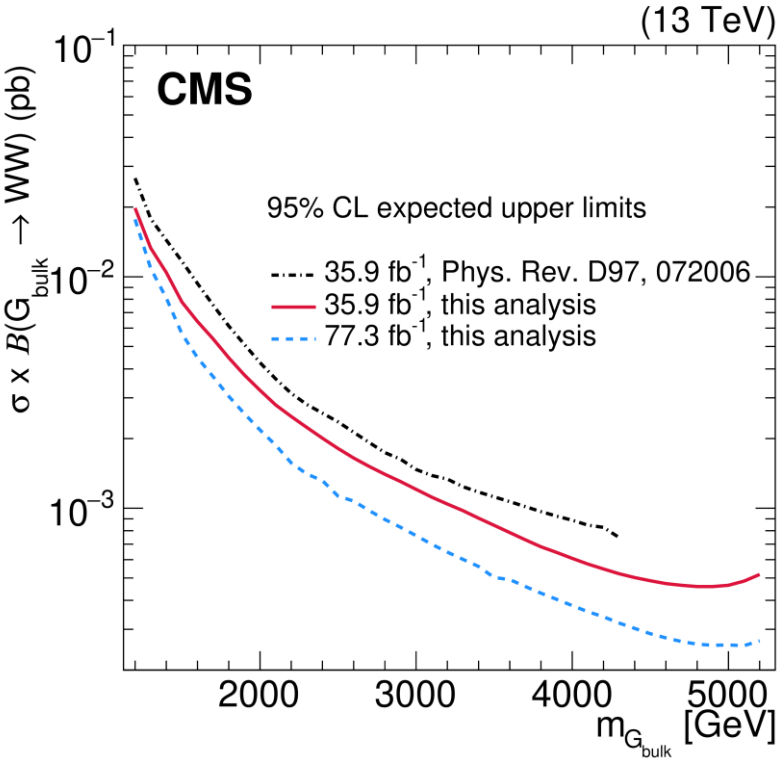




CMS X→VV → Dijet

2016+2017 data B2G-18-002

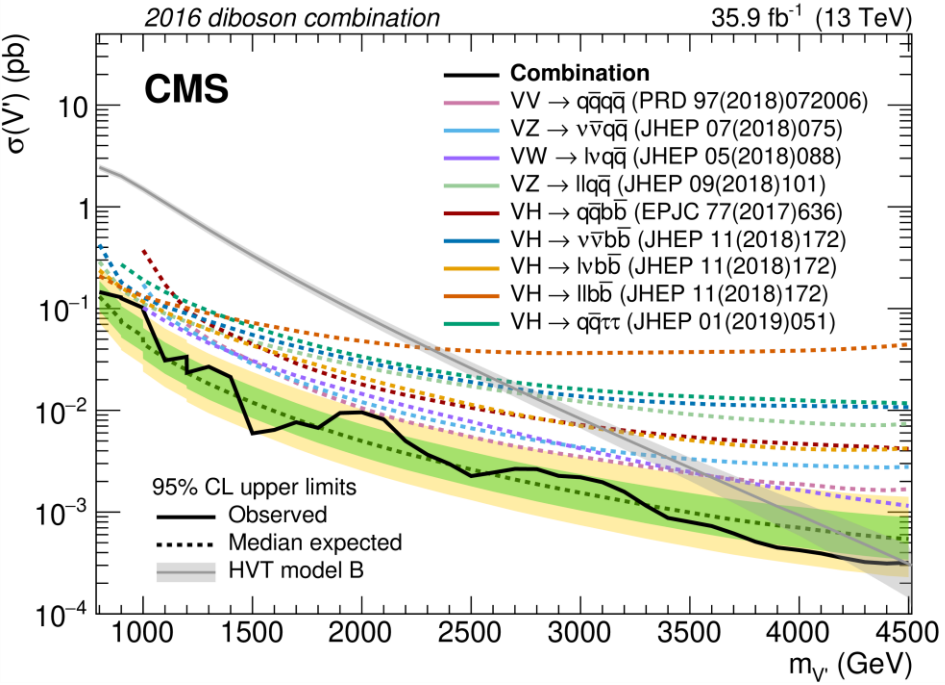


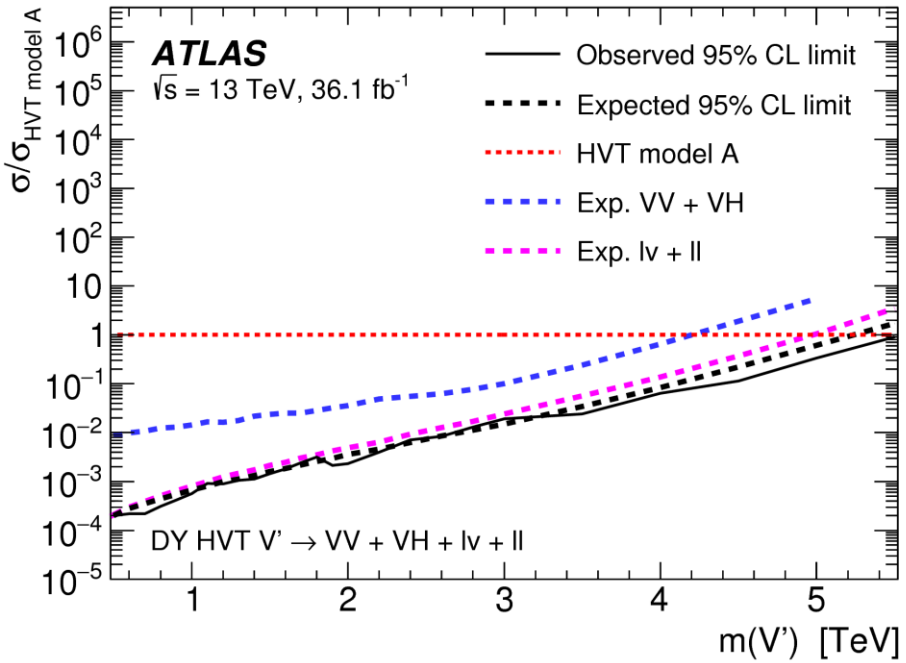


- Exclude spin-1 Z' and W' resonances below 3.5 and 3.8 TeV, respectively

X→VV/VH Combination

EXOT-2017-31
B2G-18-006





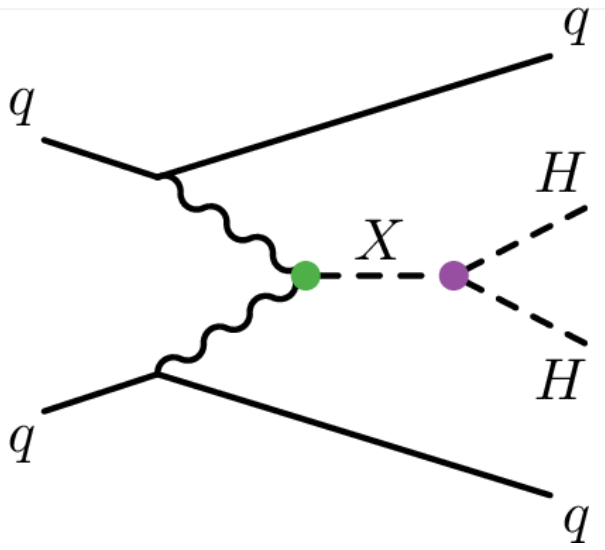
- Combination of all VV/VH analyses of 2016 data for spin-0, spin-1, and spin-2 interpretations
- Large improvement with respect to individual analysis


X→HH

X→HH → bbbb VBF

Full Run 2 data! CONF-2019-030

- First search in this production state

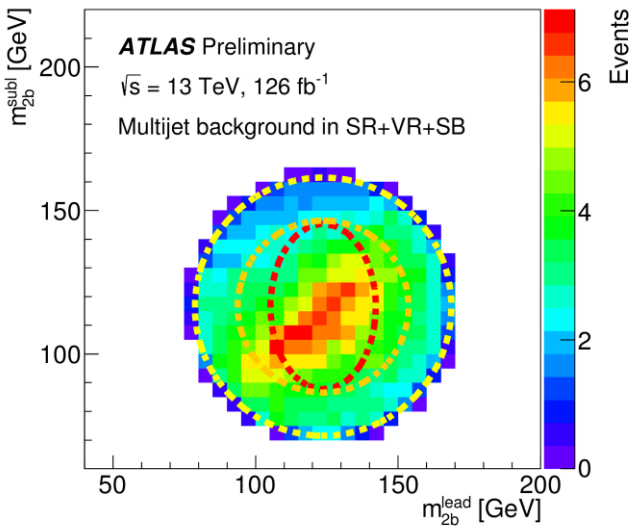


- Require 4 central b-tagged jets and 2 forward jets
  - Kinematic requirements between the jets optimized to S/B

$$\left.\begin{aligned} \frac{360\text{ GeV}}{m_{4b}} - 0.5 < \Delta R_{bb}^{\text{lead}} < \frac{653\text{ GeV}}{m_{4b}} + 0.475 \\ \frac{235\text{ GeV}}{m_{4b}} < \Delta R_{bb}^{\text{subl}} < \frac{875\text{ GeV}}{m_{4b}} + 0.35 \end{aligned}\right\} \text{if } m_{4b} < 1250\text{ GeV},$$

$$\left.\begin{aligned} \Delta R_{bb}^{\text{lead}} < 1 \\ \Delta R_{bb}^{\text{subl}} < 1 \end{aligned}\right\} \text{if } m_{4b} \geq 1250\text{ GeV},$$

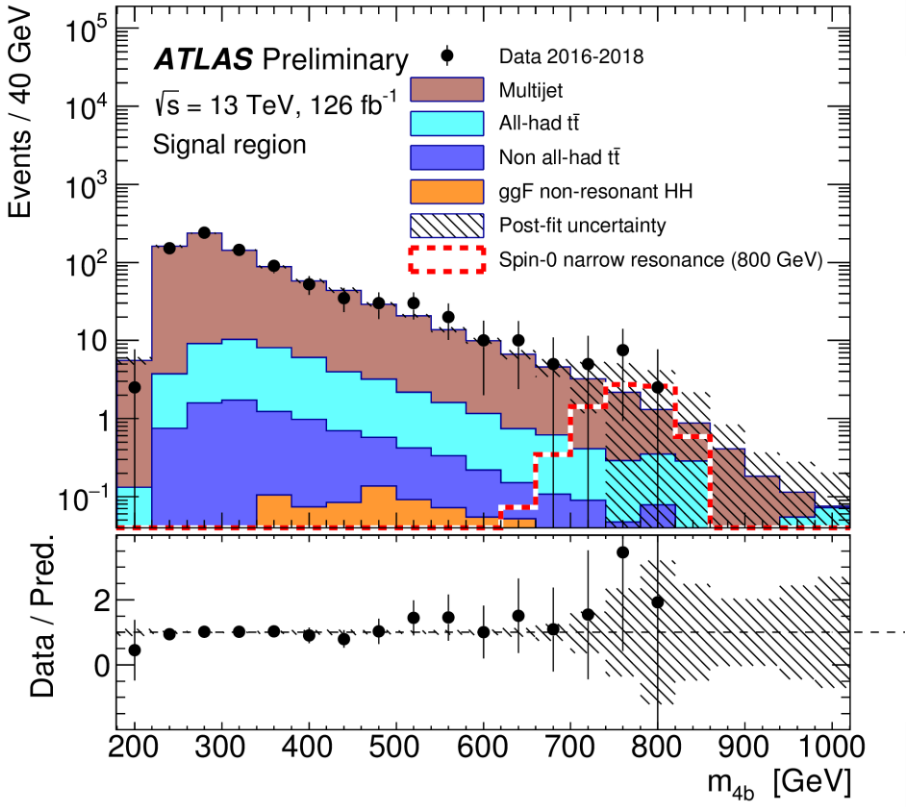
- 95% multijet and 5% $t\bar{t}$
  - Multijet background estimated from 2 b-jet and H candidate mass sidebands

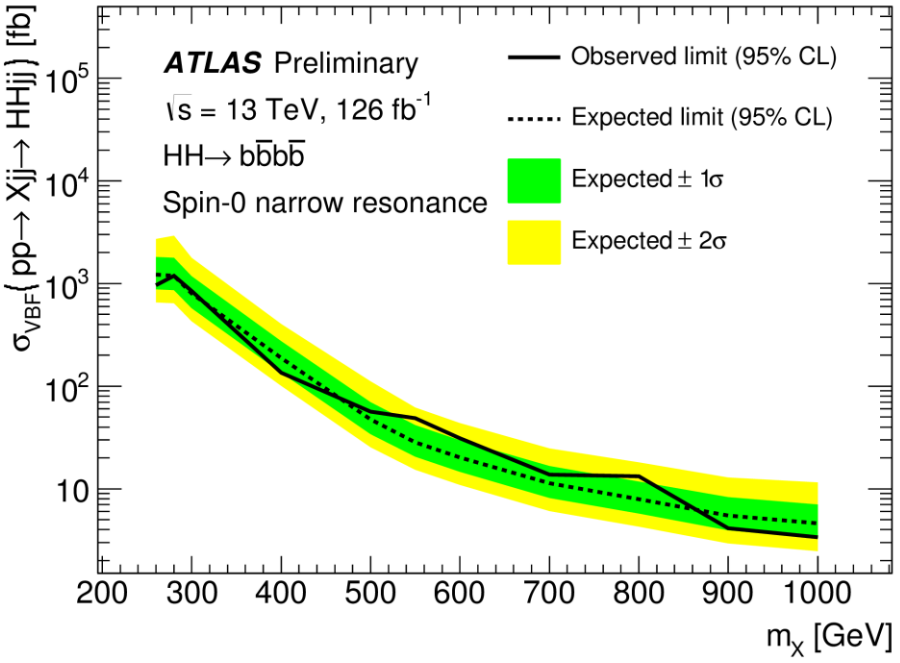


X→HH → bbbb VBF

Full Run 2 data! CONF-2019-030

- No excess found
  - Currently statistically limited at high masses

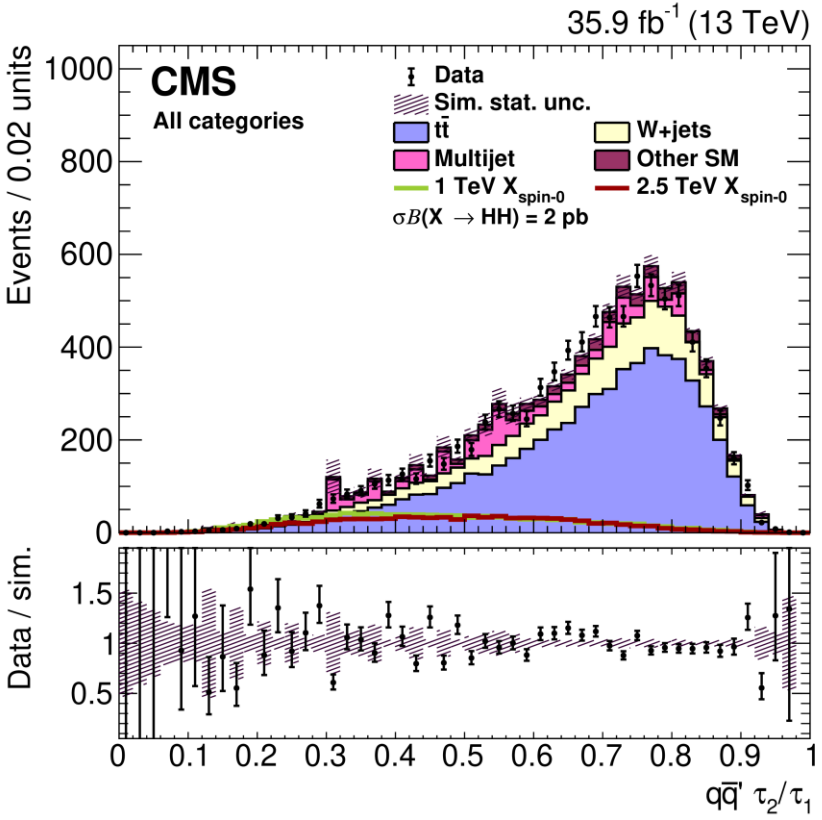




X→HH → bbWW

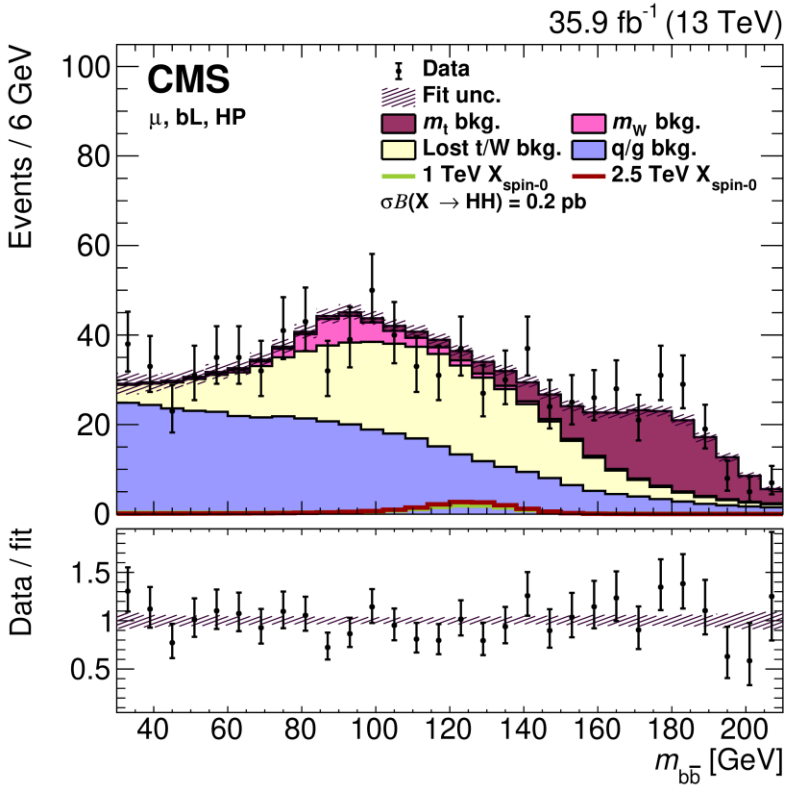
2016 data B2G-18-008

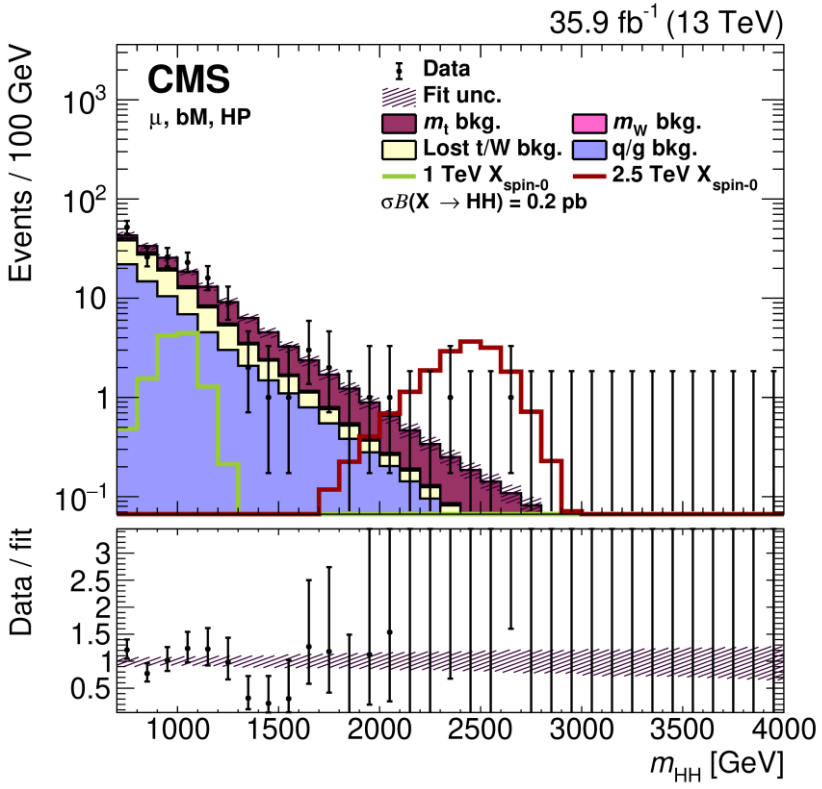
- WW→qqlν
- Use of jet substructure (τ_{21}) for V-jet tagging and b-tagging for the H(bb) jet
- **Challenge:** identification of boosted WW→qqlν with isolated lepton clustered inside the jet
  - Use p_T dependent isolation
  - Remove the lepton from PF candidates, then recluster jet and evaluate substructure



X→HH → bbWW

2016 data B2G-18-008



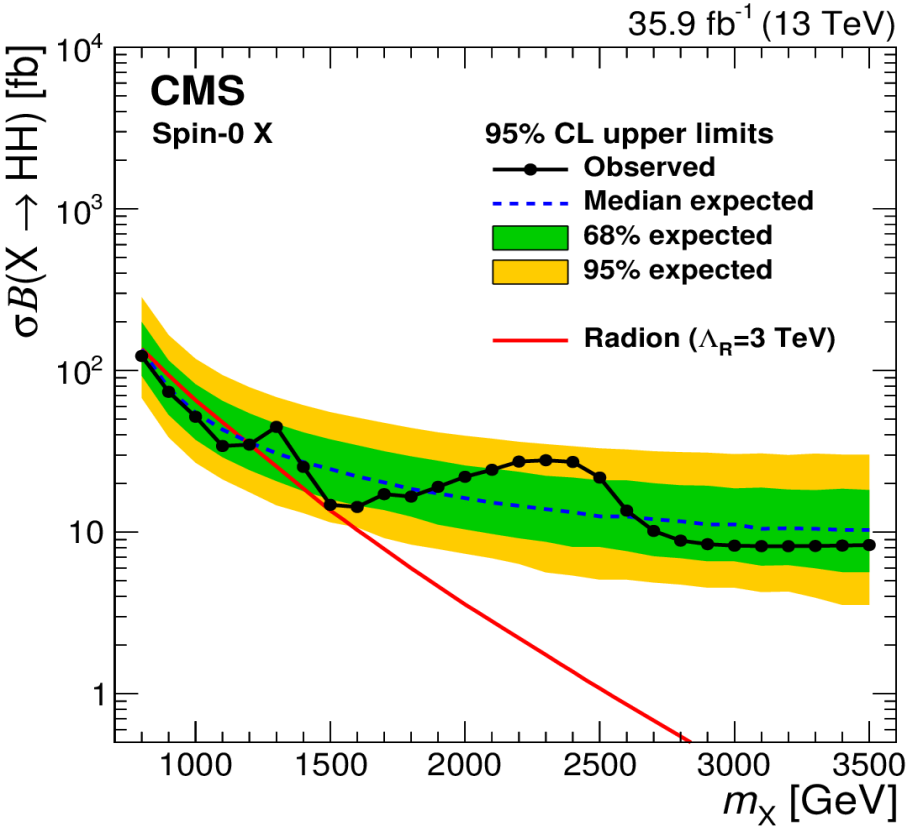


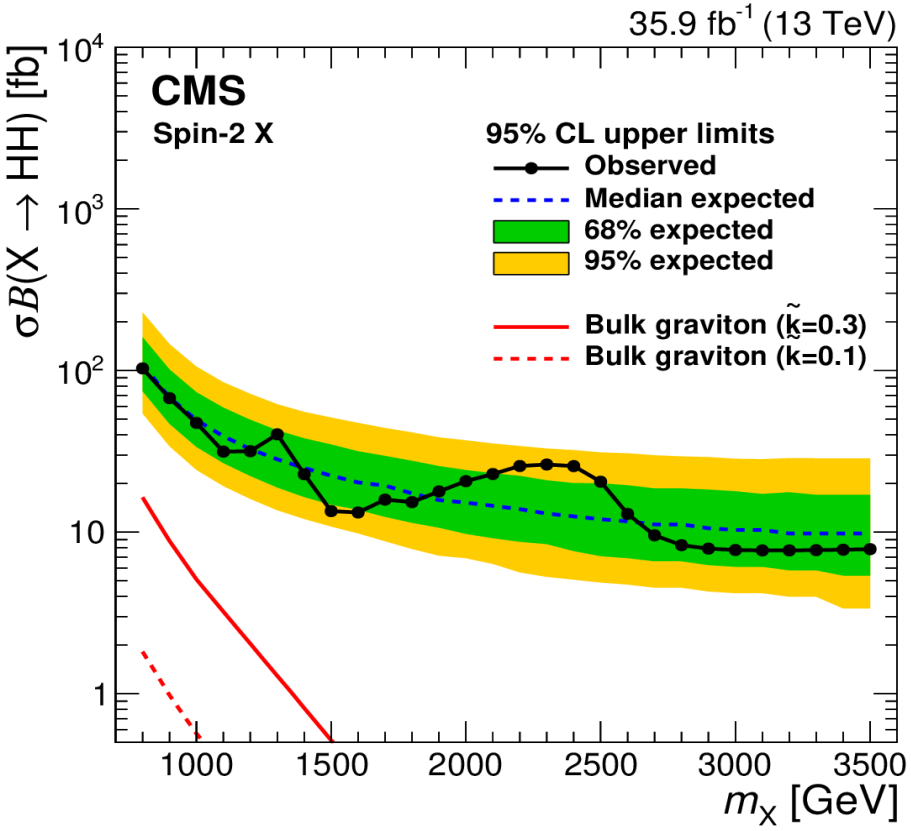
- Background Estimation: Perform a 2D fit in m_{HH} and m_{bb} in each category
  - Lepton flavor, subjet b-tagging, V-jet substructure

X→HH → bbWW

2016 data B2G-18-008

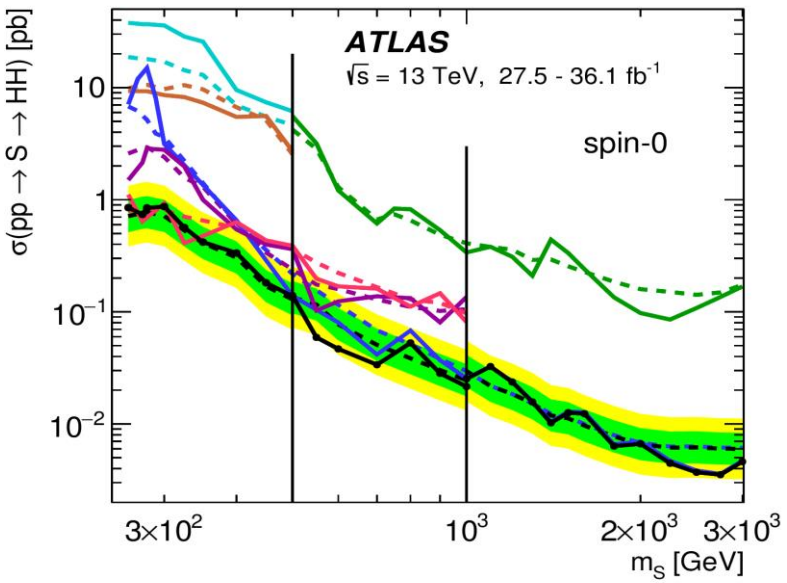
- Limits on spin-0 and spin-2 resonances have similar sensitivity to HH(4b) channel

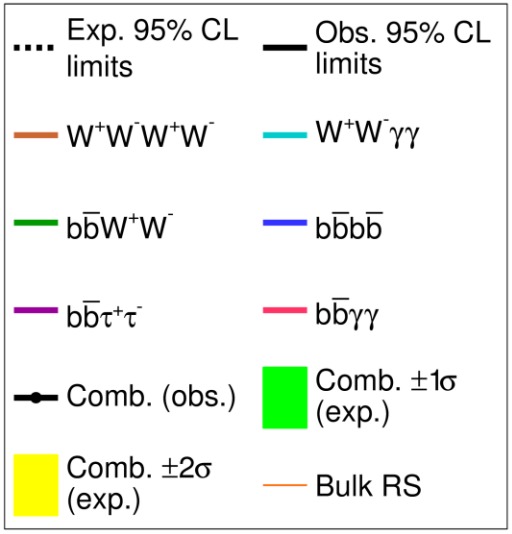


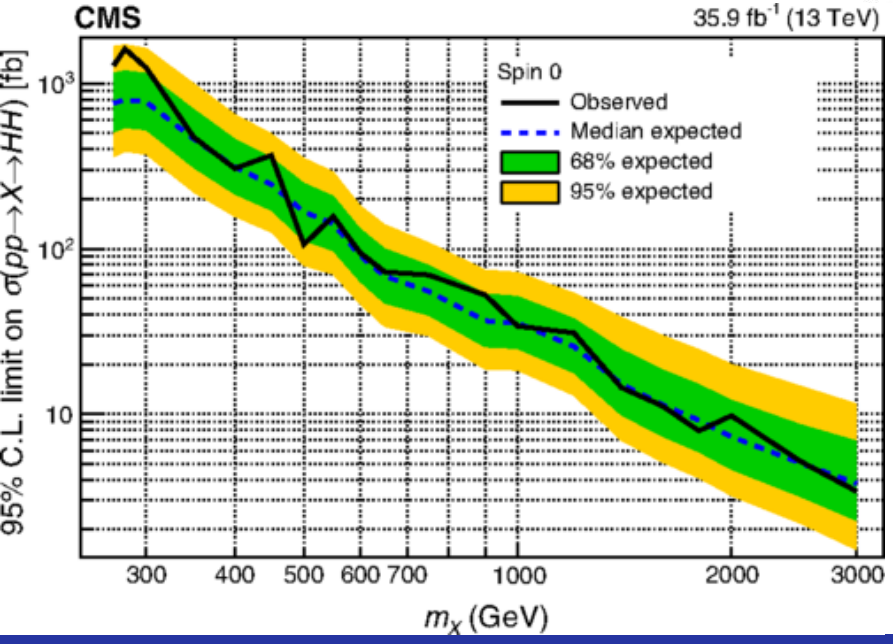


X→HH Combination

HDBS-2018-58
HIG-17-030







- Combination across 4 channels for CMS: bbbb, bbττ, bbγγ, bbVV

Summary

- CMS and ATLAS have large diboson search programs
  - No significant excess found so far

- ATLAS published first legacy analysis with complete Run2 data
  - Many more in the works from both experiments
  - Primary goal to improve sensitivity of 2016 only analyses from more than just adding luminiosity
    - More complex background estimation – multidimensional fits
    - Advanced boosted jet identification
  - New channels being searched for

- Expect substantial improvements in the upcoming year

Backup