Searches for high-mass resonances at the LHC

A First Glance Beyond the Energy Frontier

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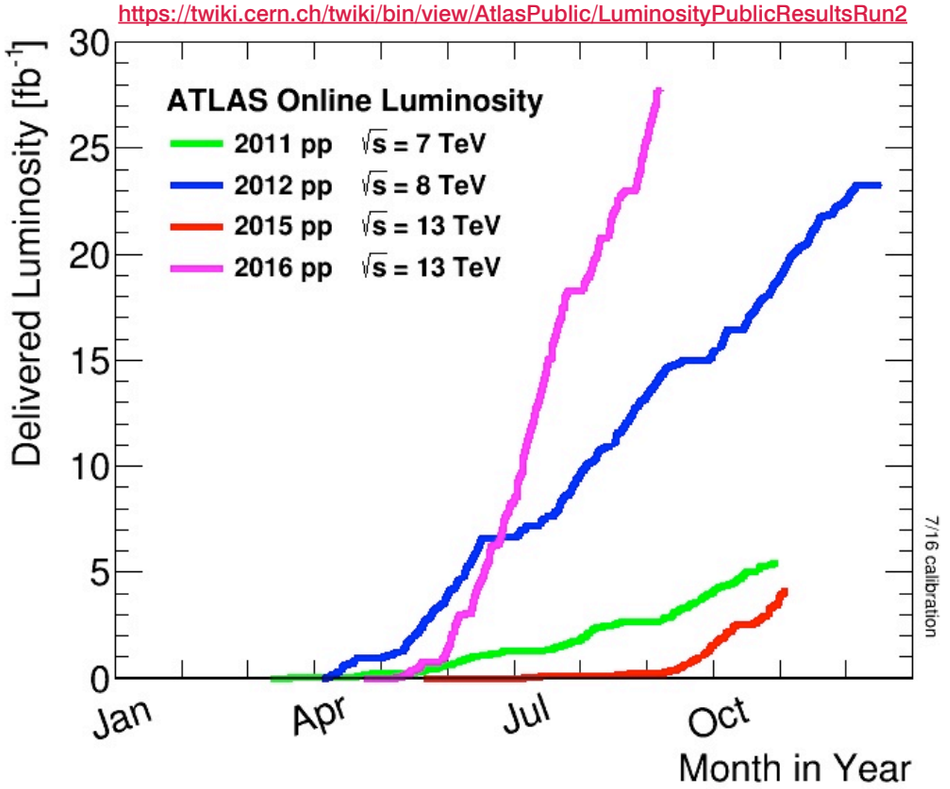
on behalf of the ATLAS and CMS Collaboration

07 - September - 2016

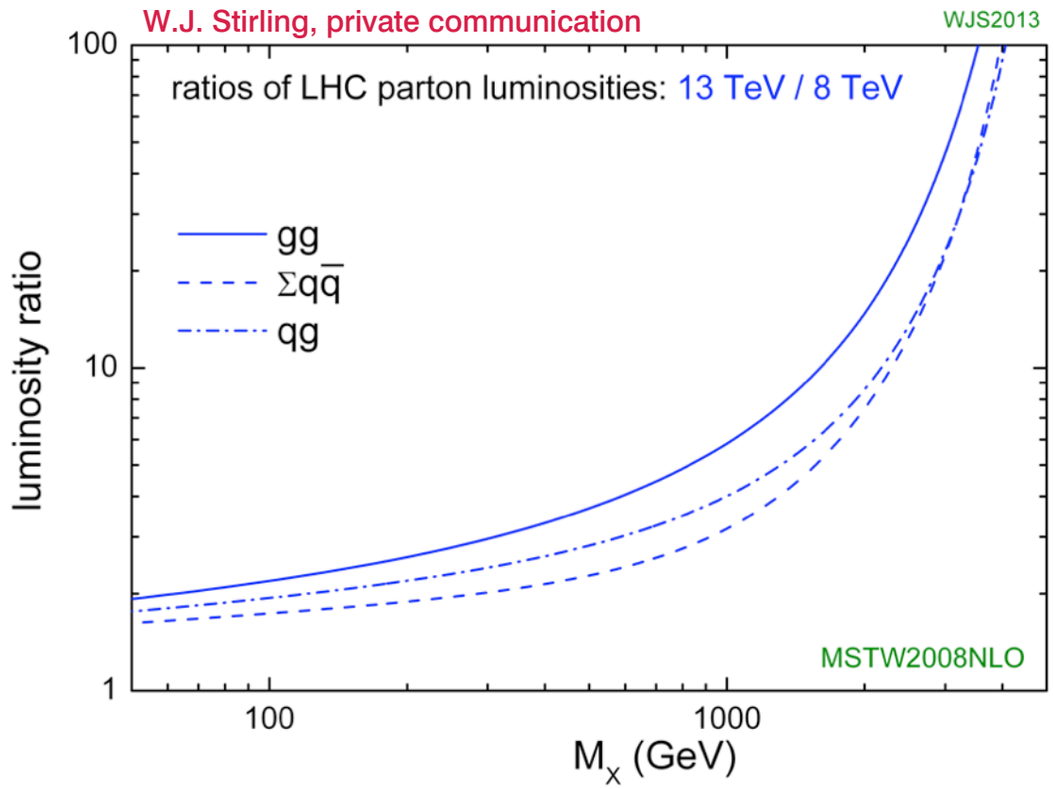
LHC Run 2

- Increase in energy from 8 → 13 TeV
- Major new-physics sensitivity has opened up, specially at high masses
- Exceptional LHC performance in 2016 following 13 TeV commissioning in 2015
- Integrated luminosity delivered (so far) in 2016: ~27.6 fb^{-1}
  - ➡ Most analysis with ICHEP dataset: 12 - 15 fb^{-1} of 13 TeV data

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

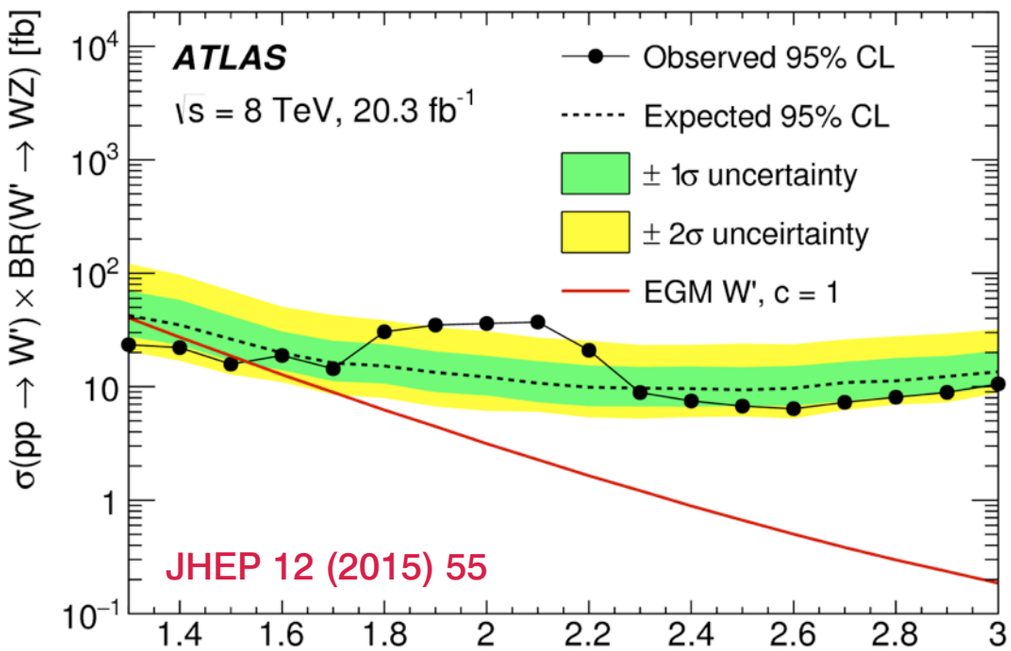


W.J. Stirling, private communication

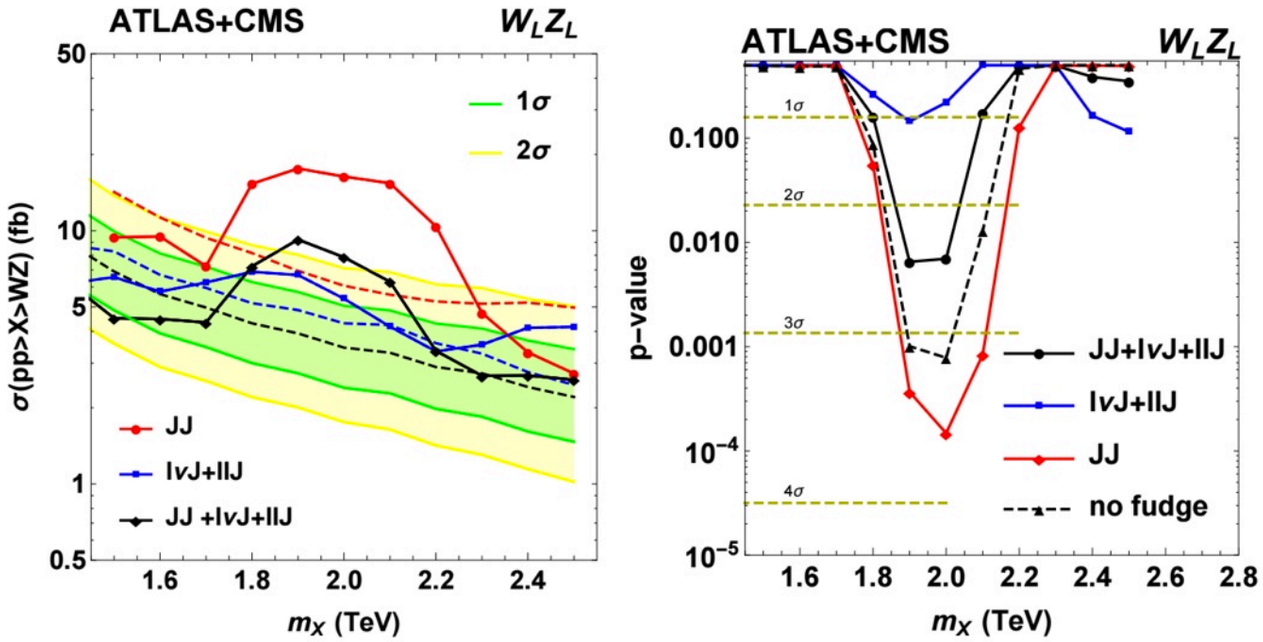


Exotic Diboson Searches

- Historically connected to electroweak symmetry breaking models
  - ➡ Not excluded with SM Higgs $m_H \sim 125$ GeV
- Several scenarios
  - ➡ **Spin 0**: Heavy scalars in extended Higgs sector
  - ➡ **Spin 1**: Extended gauge models (W', Z' in SSM/HVT models)
  - ➡ **Spin 2**: Kaluza-Klein gravitons (bulk Randall-Sundrum)
- Excitement from Run-1 searches in VV→ JJ channels



Phenomenology paper combination



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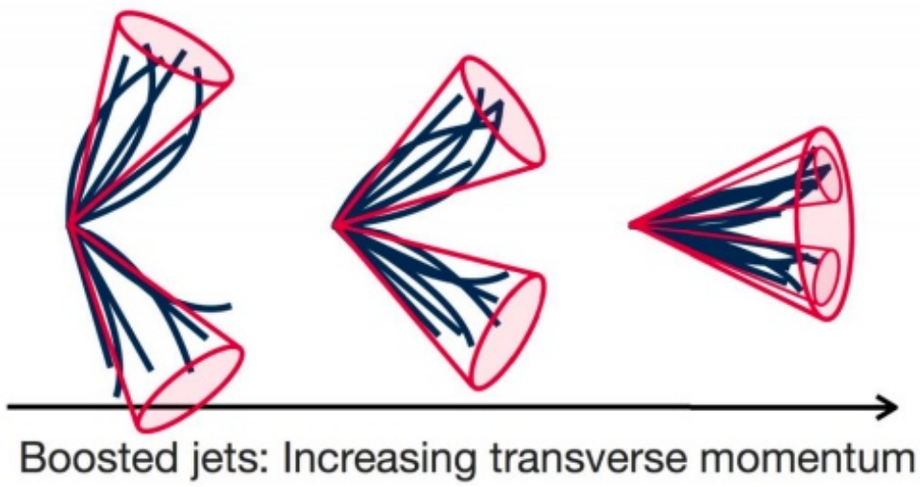
Di-boson Final States

- Look into many final states:
  - VV → $\ell\ell$qq, $\ell\nu$qq, $\nu\nu$qq, qqqq
  - VH → $\ell\ell$bb, $\ell\nu$bb, $\nu\nu$bb, qqbb
  - HH → bbbb



- Wide range of boson p_T: distinct topologies for hadronic decays
  - Resolved: 2 small R jets (jj)
  - Boosted: single large R jets (J)
- Addition of VBF production mode in some channels

Large-R Jets - Grooming

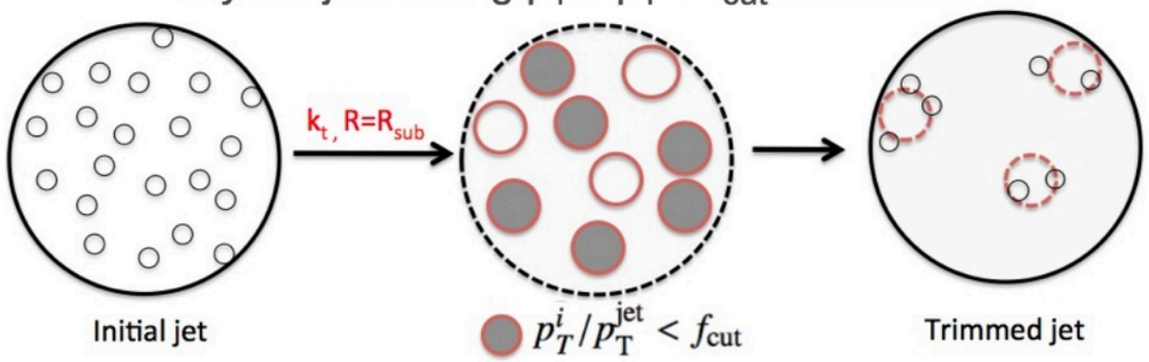
- Get rid of softer components in a jet from UE or pileup and leave constituents from the hard scatter behind

➡ Better mass resolution expected after grooming

➡ Specially important in high pileup environment

"Trimming" http://arxiv.org/abs/0912.1342
(D. Krohn, J. Thaler, L. Wang)

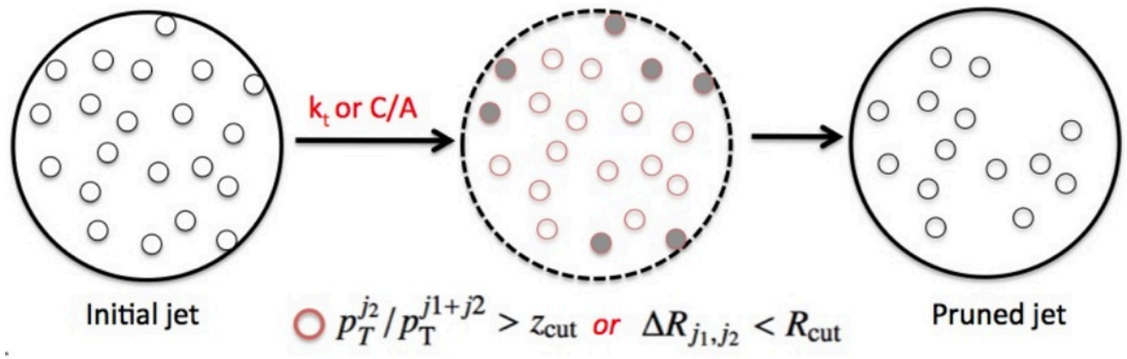
- uses k_t algorithm to create subjets of size R_{sub} from the constituents of the large-R jet: any subjets failing $p_T i / p_T < f_{cut}$ are removed



Tuned parameters:
f_{cut} and R_{sub}

"Pruning" http://arxiv.org/abs/0912.0033 (S. Ellis, C. Vermilion, J. Walsh)

- Recombine jet constituents with C/A or kt while vetoing wide angle (R_{cut}) and softer (z_{cut}) constituents. Does not recreate subjets but prunes at each point in jet reconstruction



Tuned parameters:
R_{cut} and z_{cut}

Large-R Jets - Boson Tagging

EPJC 76(3), 1-47

CMS PAS JME-14-002

ATLAS

- Anti-k_T R = 1.0 jets
- Grooming:
  - ➡ Trimming, re-cluster with k_T R_{sub}=0.2 and remove sub-jets with $f_{cut} < 0.05$
- W / Z boson tagging:
  - ➡ m_J consistent with m_W, m_Z within ±15 GeV
  - ➡ Substructure variable $D_2^{\beta=1}$ consistent with two prong decay
  - ➡ High and Low purity (HP, LP) categories based on $D_2^{\beta=1}$
- Higgs boson tagging:
  - ➡ Match to anti-k_T R=0.2 b-tagged track jets

CMS

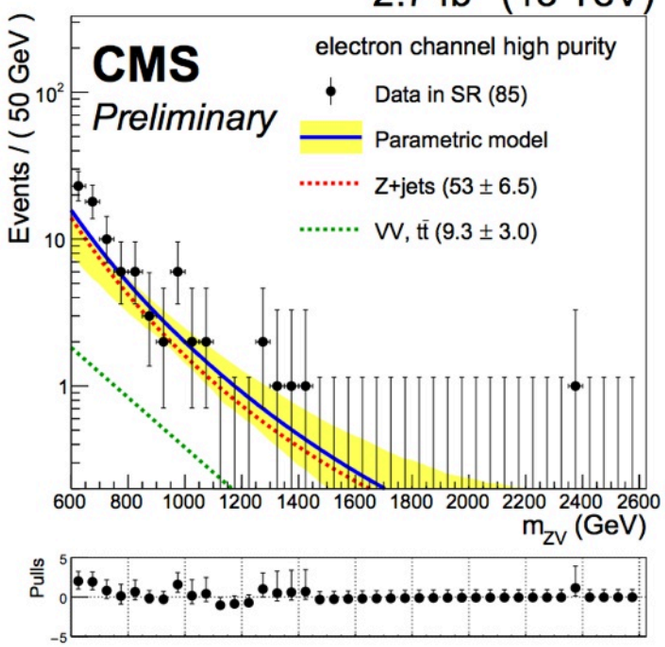
- Anti-k_T R = 0.8
- Grooming:
  - ➡ Pruning, re-cluster with CA algorithm, $R_{cut} < 0.5$, $Z_{cut} > 0.1$
- W / Z boson tagging:
  - ➡ $65 < m_J < 105$ GeV, pruned mass
  - ➡ Substructure variable τ_N consistent with two prong decay
  - ➡ High and Low purity (HP, LP) categories based on τ_N
- Higgs boson tagging:
  - ➡ $110 < m_J < 135$ GeV, pruned mass
  - ➡ b-tag pruned subjets

VV Results

ZV → ℓℓqq

- Look into a Z boson leptonic (ee, μμ) decay in association with a hadronic vector boson (W,Z)
  - ➡ Dominant background: Z+jets. Contributions from diboson, top processes
- ATLAS
  - ➡ 13 TeV, 13.2 fb^{-1} results
  - ➡ Analysis includes both resolved and boosted regime, looking for new resonances from 500 - 5000 GeV
- CMS
  - ➡ Latest public results with 13 TeV, 2.7 fb^{-1}, boosted and resolved regime

CMS PAS B2G-16-010



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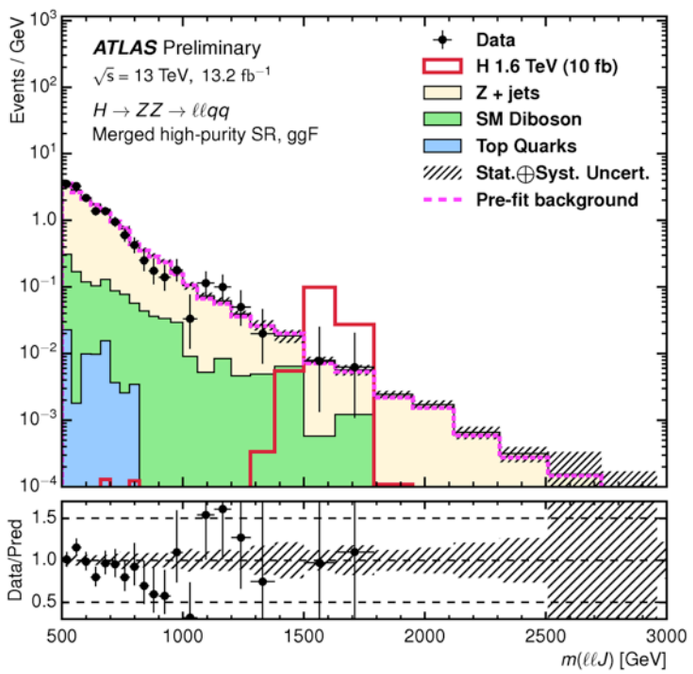

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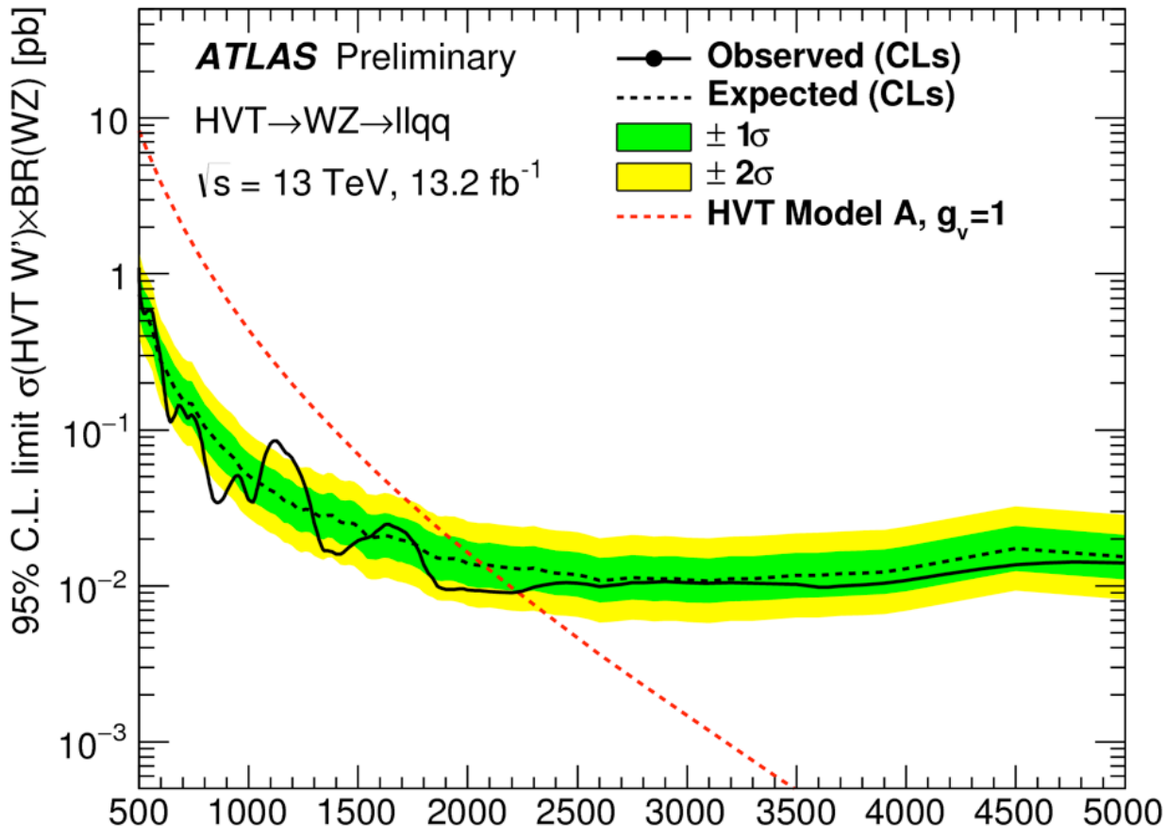
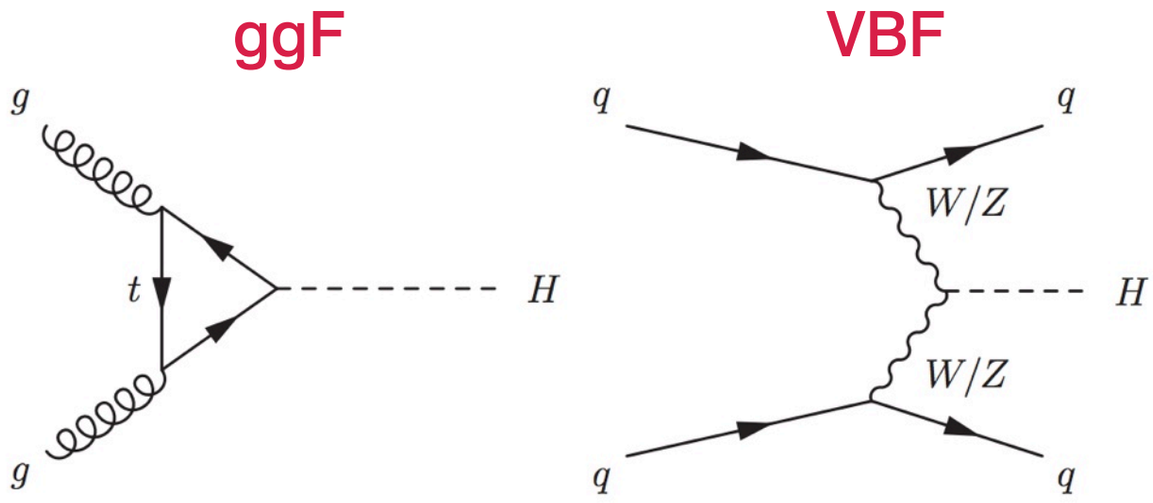


ZZ → ℓℓqq - VBF

- VBF production channel important for scalar interpretations
  - ➡ In the SM, ~10% of the production cross section
- VBF selection
  - ➡ 2 additional jets j_1, j_2
  - ➡ $|\Delta\eta(j_1,j_2)| > 3.1$
  - ➡ $m(j_1,j_2) > 600$ GeV



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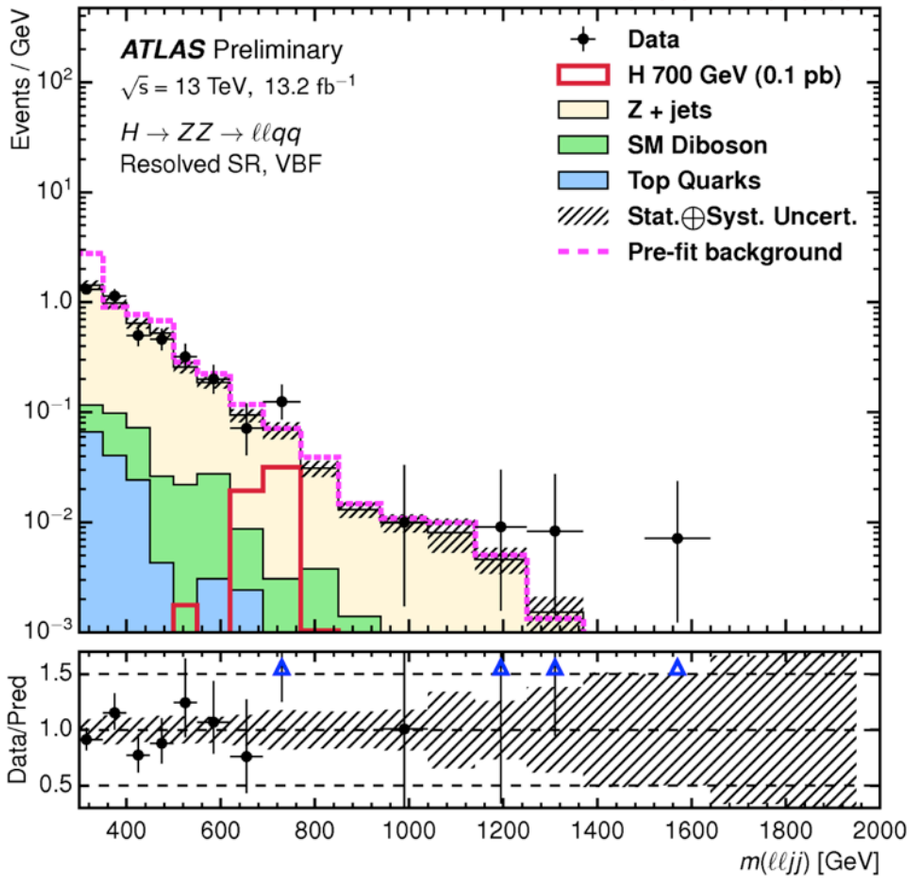

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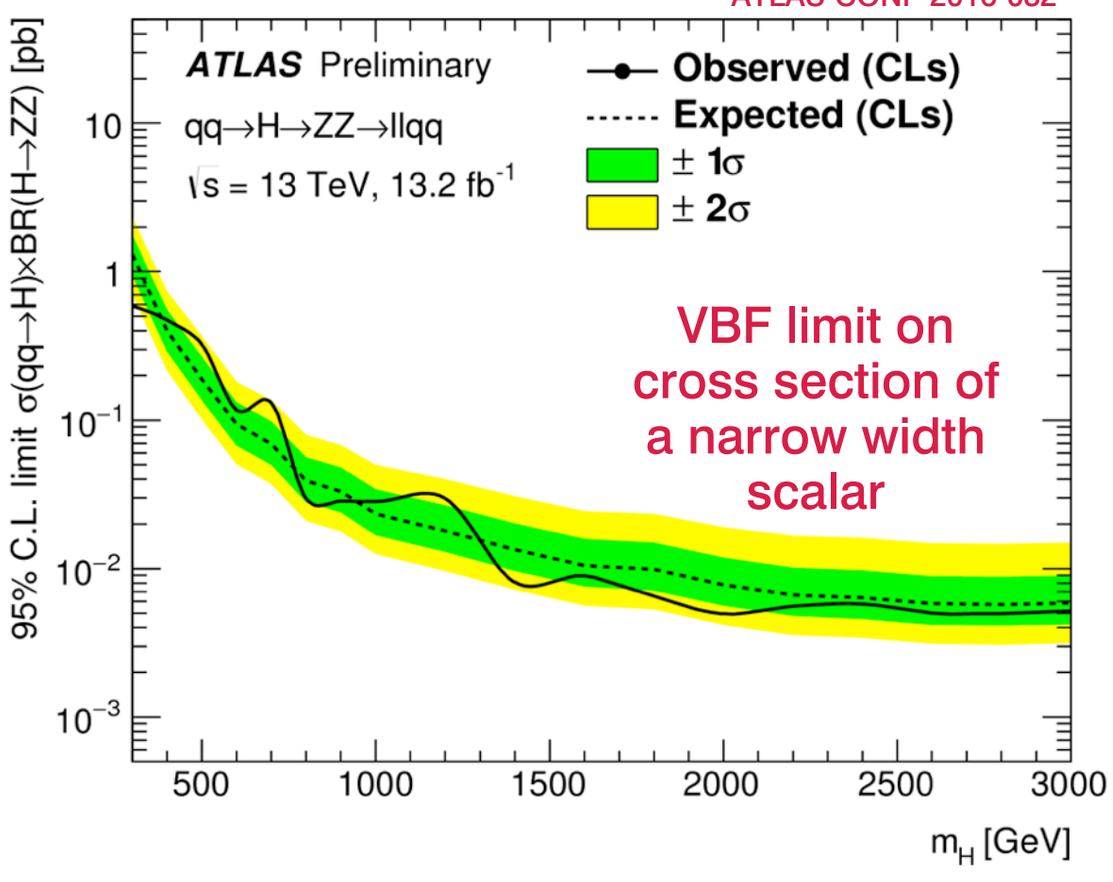
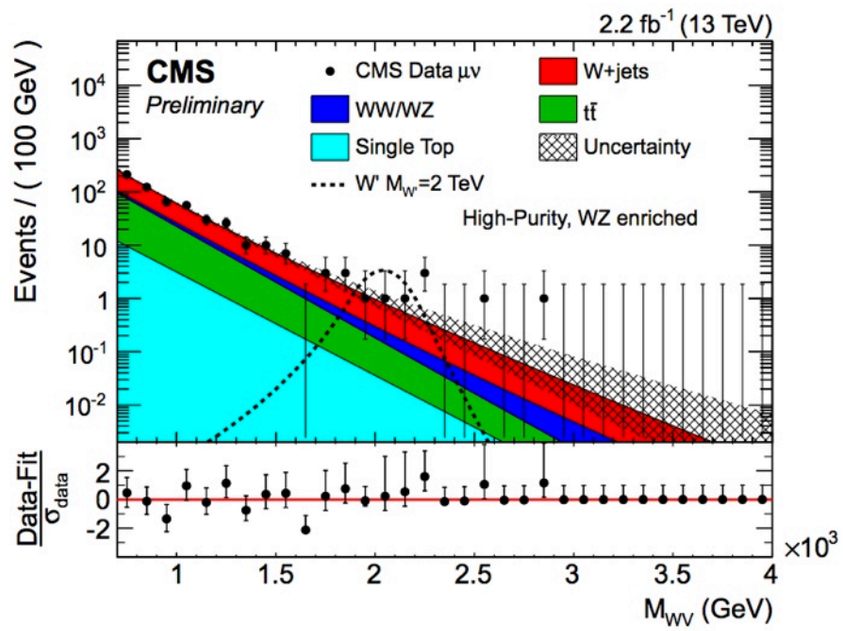


VV → ℓνqq

- Look into a W boson leptonic (eν, μν) decay in association with a hadronic vector boson (W,Z)
  - ➡ Backgrounds: W+jets, top, diboson, Z+jets
- ATLAS
  - ➡ 13 TeV, 13.2 fb^{-1} results , boosted regime
- CMS
  - ➡ Latest public results with 13 TeV, 2.2 fb^{-1}, boosted regime

CMS PAS EXO-15-002



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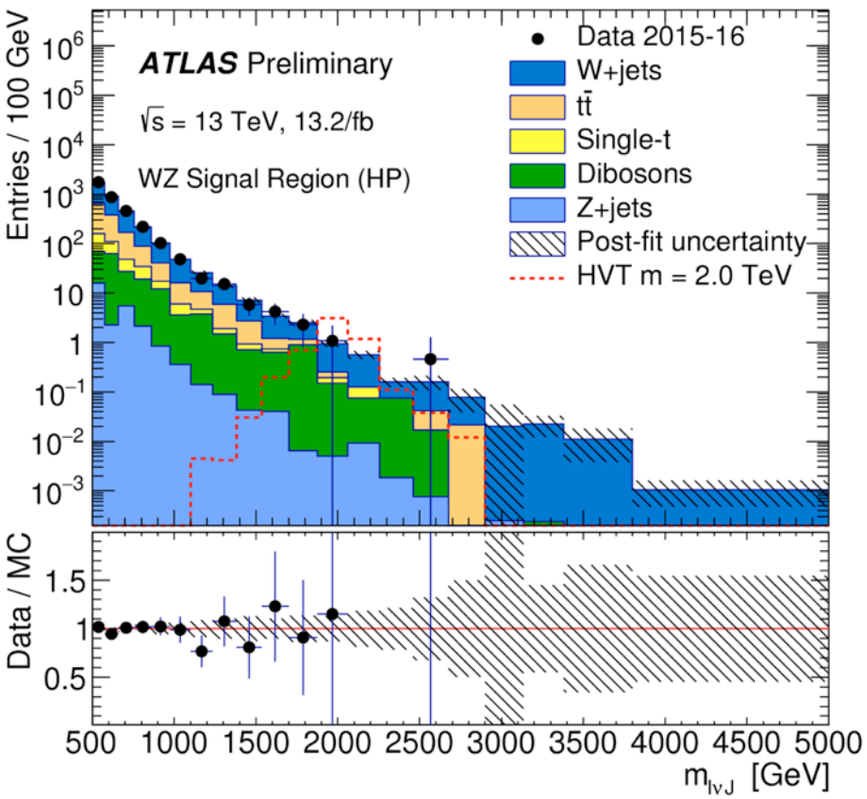

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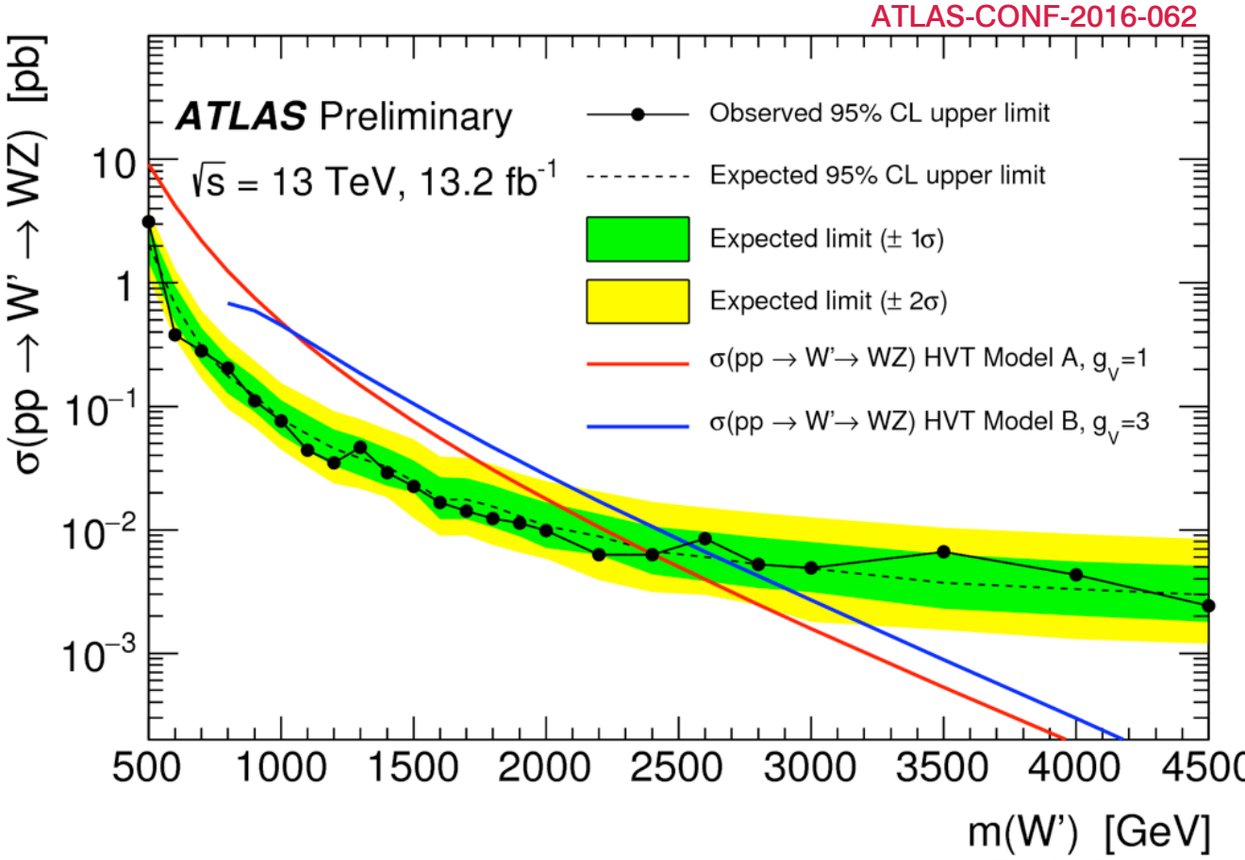
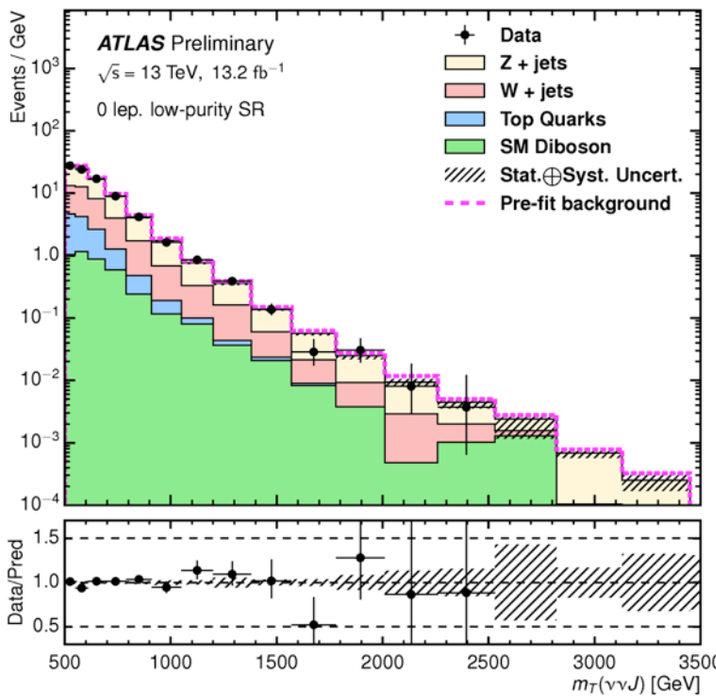


VV → ννqq

- Look into a Z boson invisible (νν) decay in association with a hadronic vector boson (W,Z)
- ATLAS
  - ➡ 13 TeV, 13.2 fb^{-1} results
  - ➡ Boosted regime
- CMS
  - ➡ Latest public results in diboson context with 7 TeV, 5 fb^{-1}
    - Similar final state in DM searches, i.e. CMS PAS EXO-16-037
  - ➡ Boosted regime

ATLAS-CONF-2016-082



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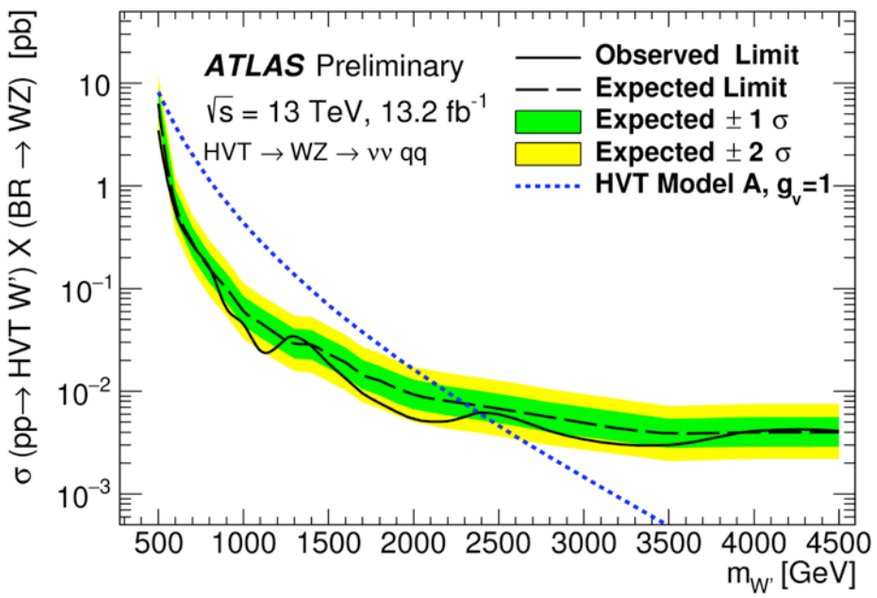
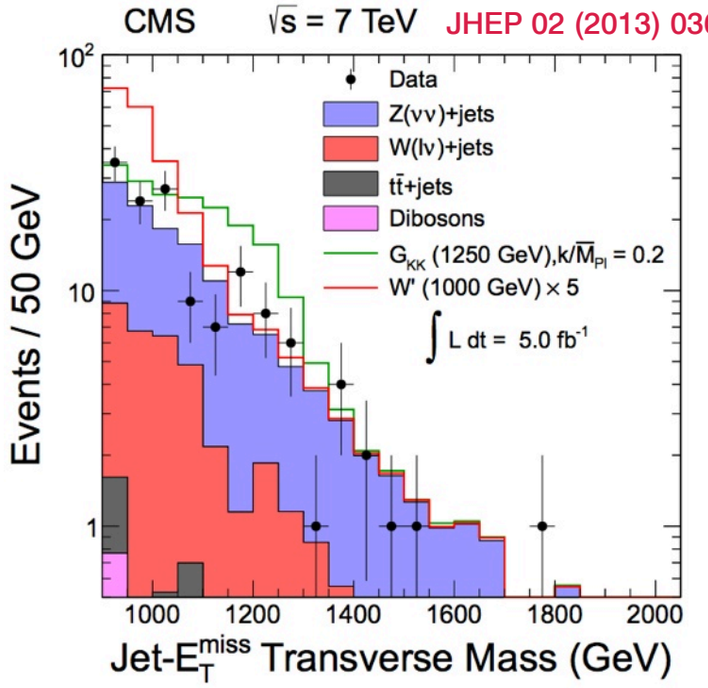


JHEP 02 (2013) 036



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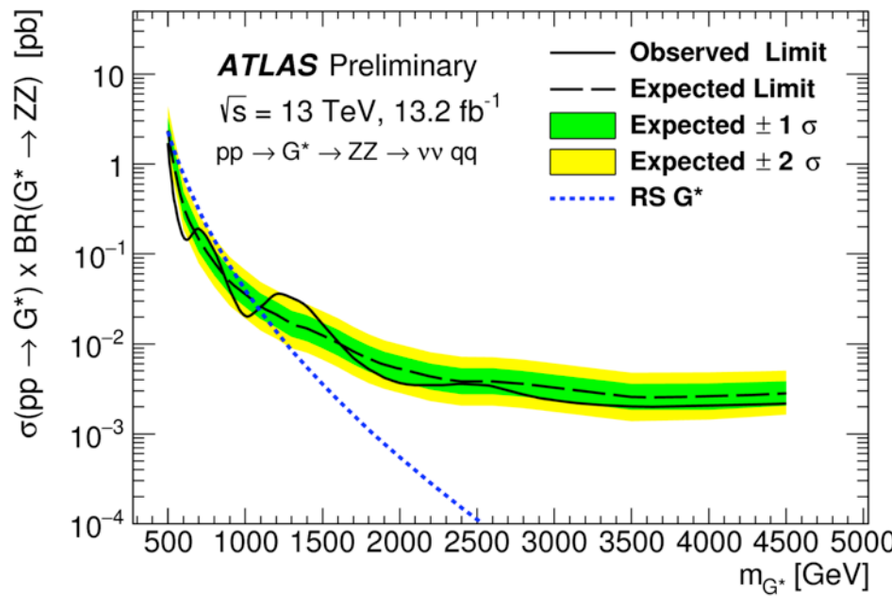
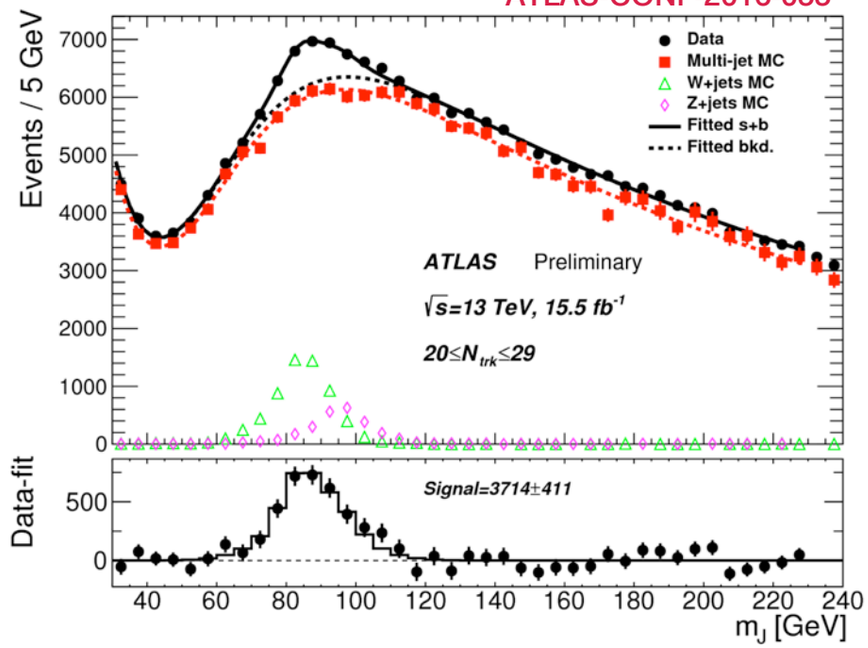


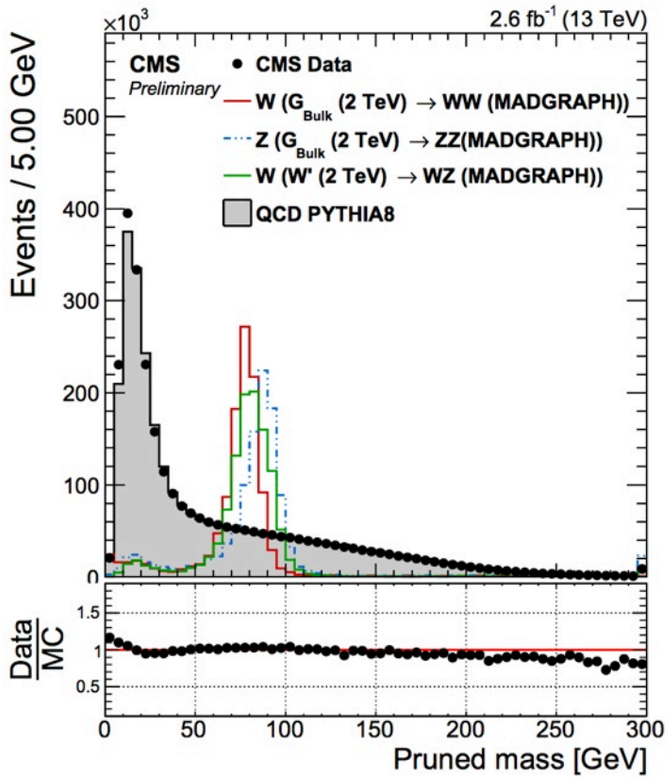
VV → qqqq

- Boosted regime only: both vector bosons decaying into a large-R jet
  - ➡ Two jets with very high p_T (> 200 GeV), boson tagged
  - ➡ Background dominated by multijet, estimated by data-driven fit in the signal region
- ATLAS
  - ➡ 13 TeV, 15.5 fb^{-1}
  - ➡ Similar kinematic selection to the Run-1 analysis with the excess at 2 TeV
  - ➡ Different large-R jet algorithm and grooming techniques
  - ➡ Includes the number of tracks in a jet < 30 selection (30% sensitivity improvement)
- CMS
  - ➡ 13 TeV, 2.6 fb^{-1}
  - ➡ Same jet algorithm, grooming and substructure selection as Run-1 analysis

ATLAS-CONF-2016-055

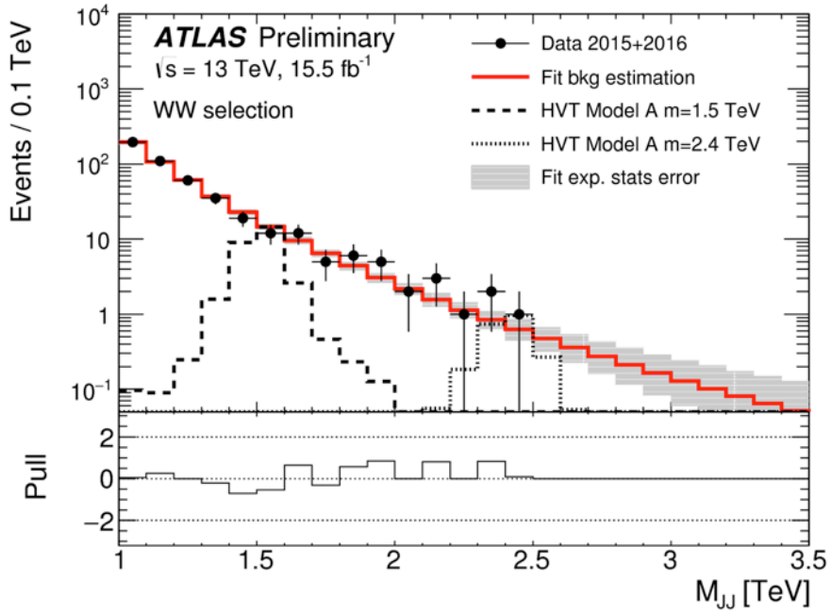


CMS PAS EXO-15-002



VV → qqqq (II)

ATLAS-CONF-2016-055



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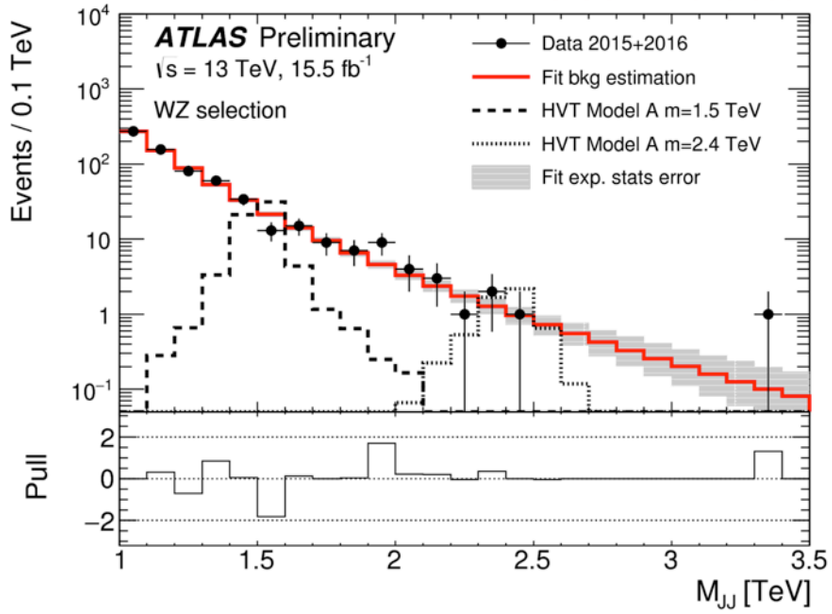

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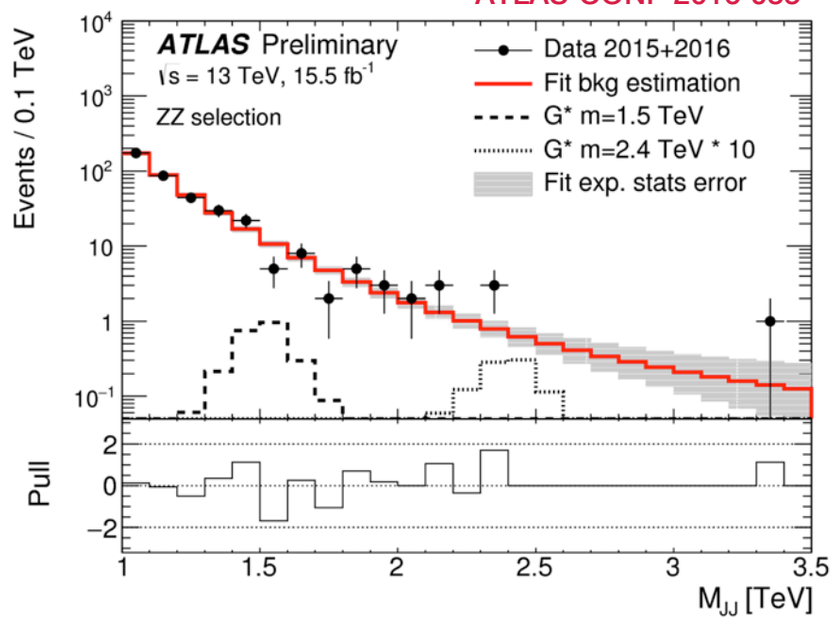
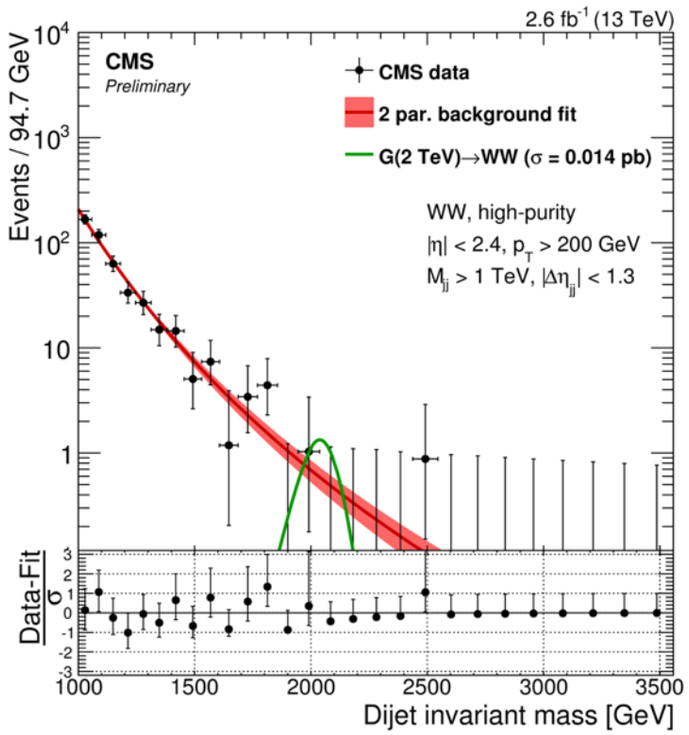
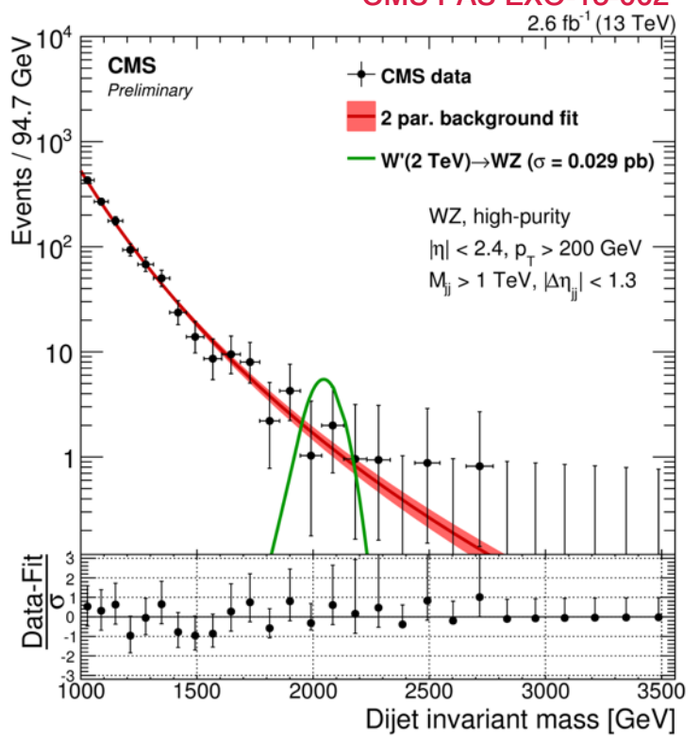


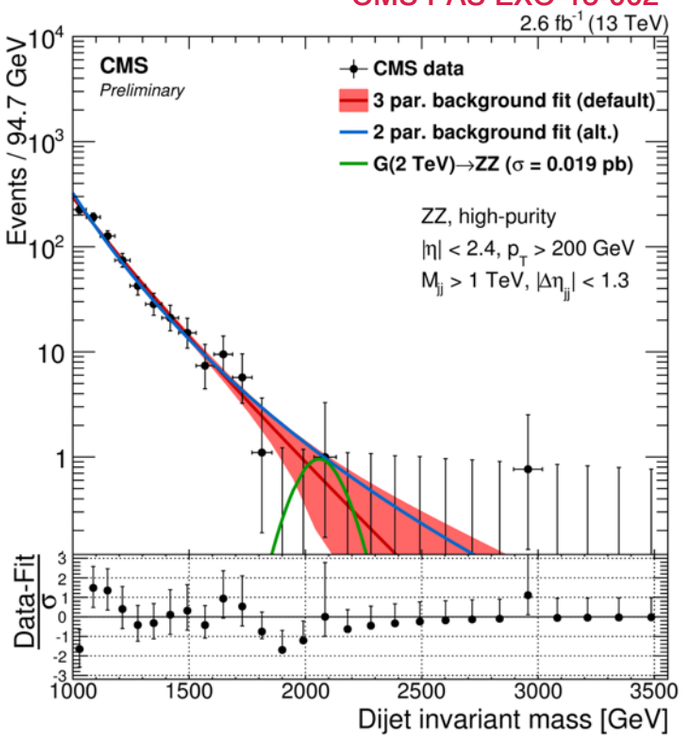
CMS PAS EXO-15-002



CMS PAS EXO-15-002



CMS PAS EXO-15-002



VV → qqqq (lll)

- No significant excess found in any of the different signal regions (WW, WZ, ZZ)

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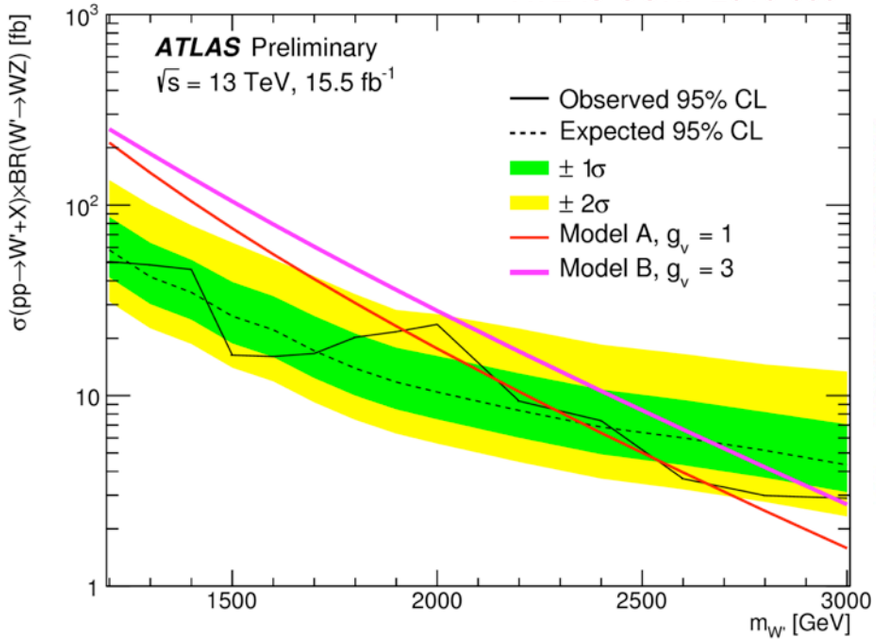
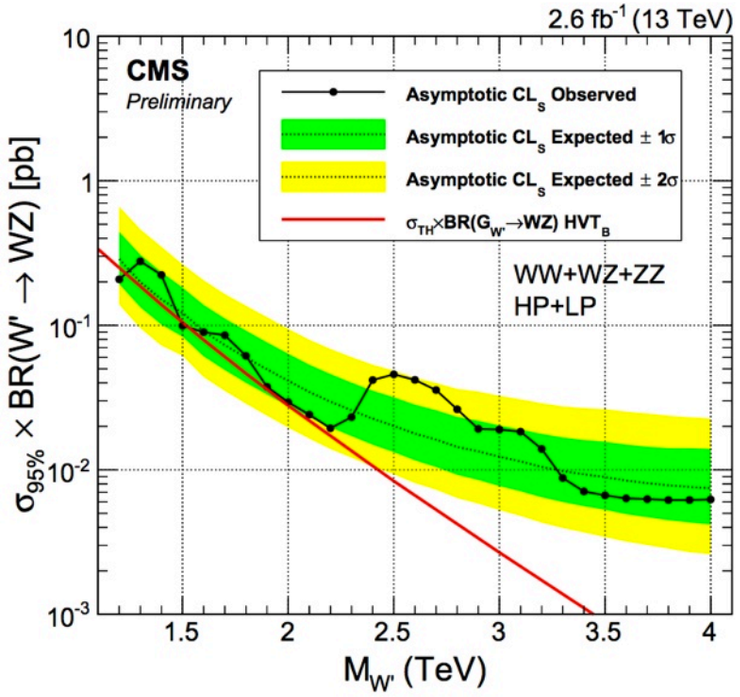


CMS PAS EXO-15-002



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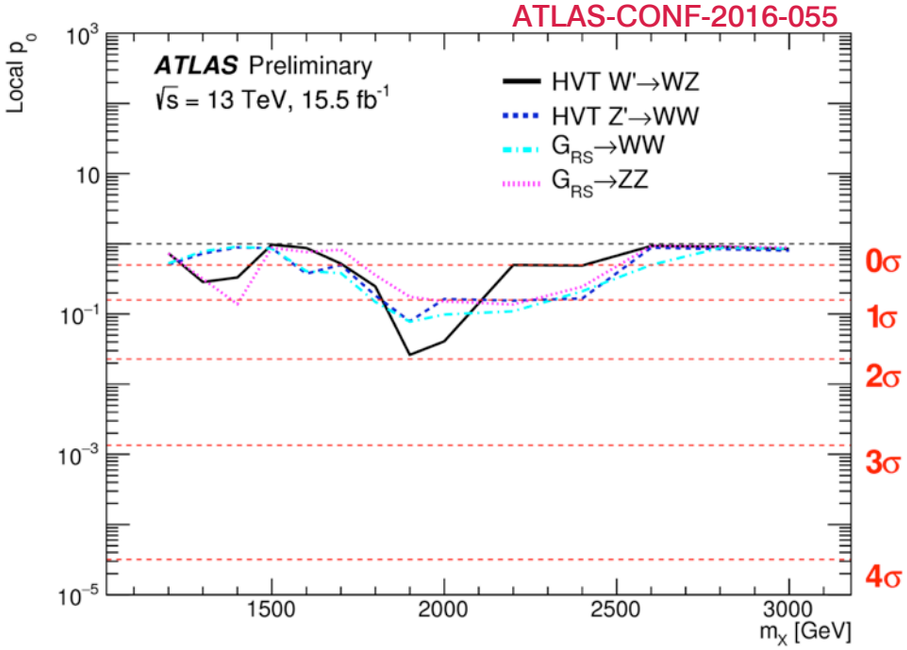

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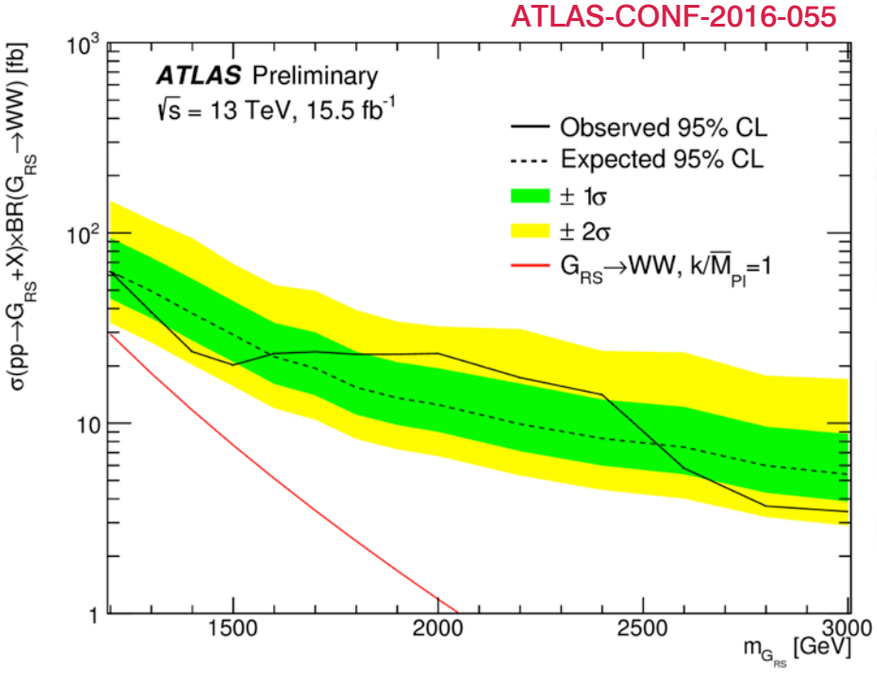
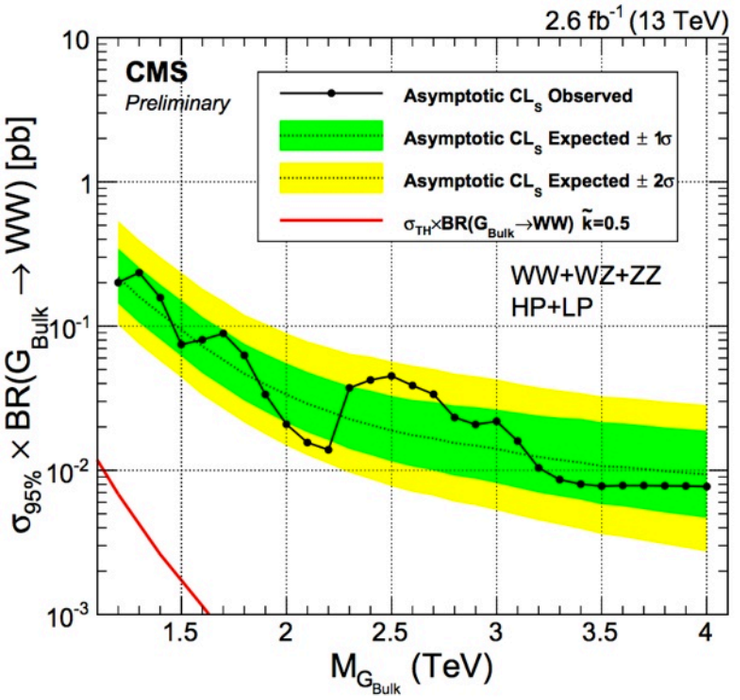
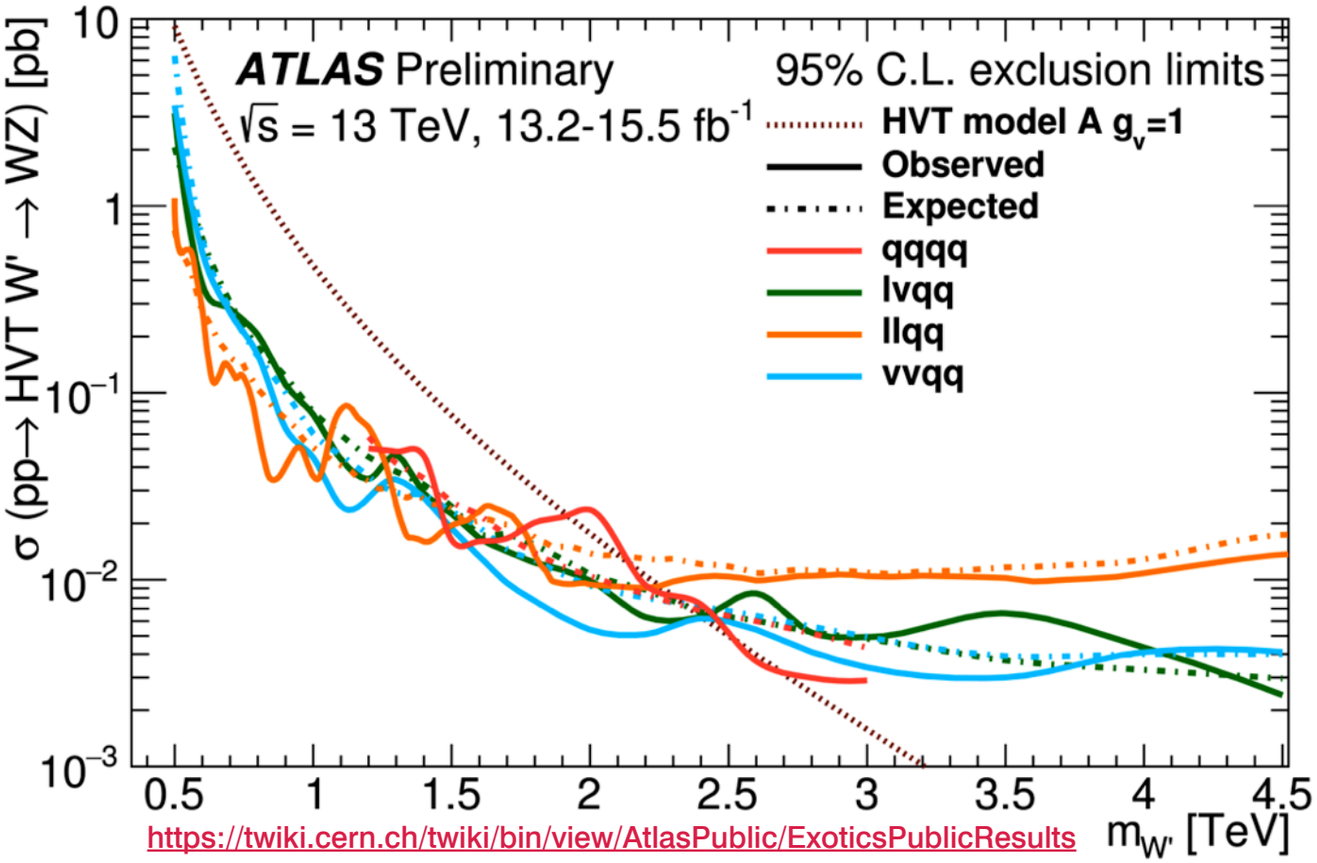


CMS PAS EXO-15-002

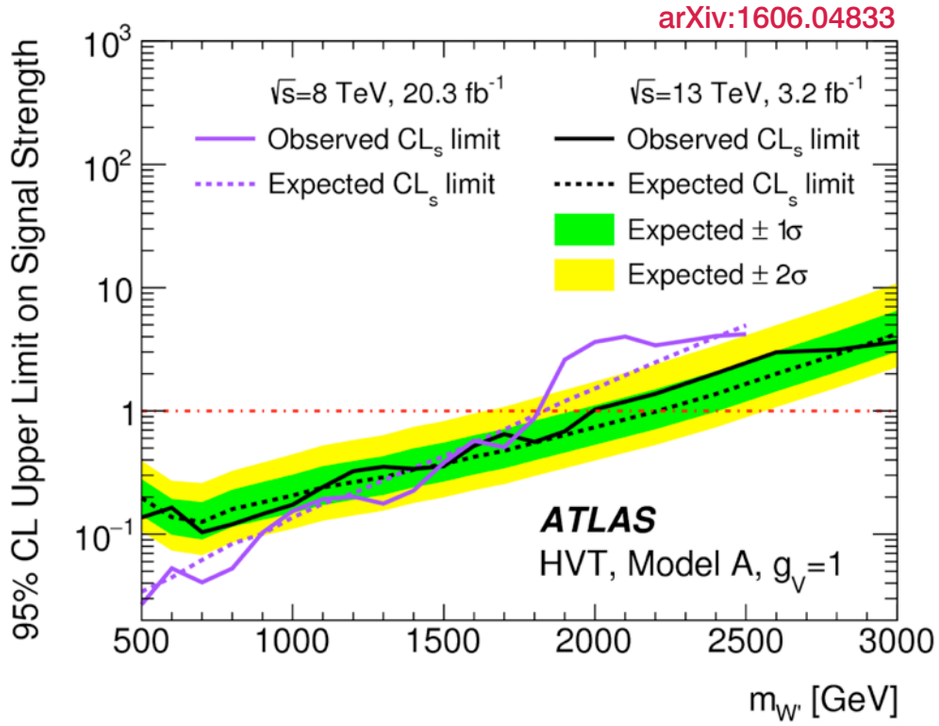


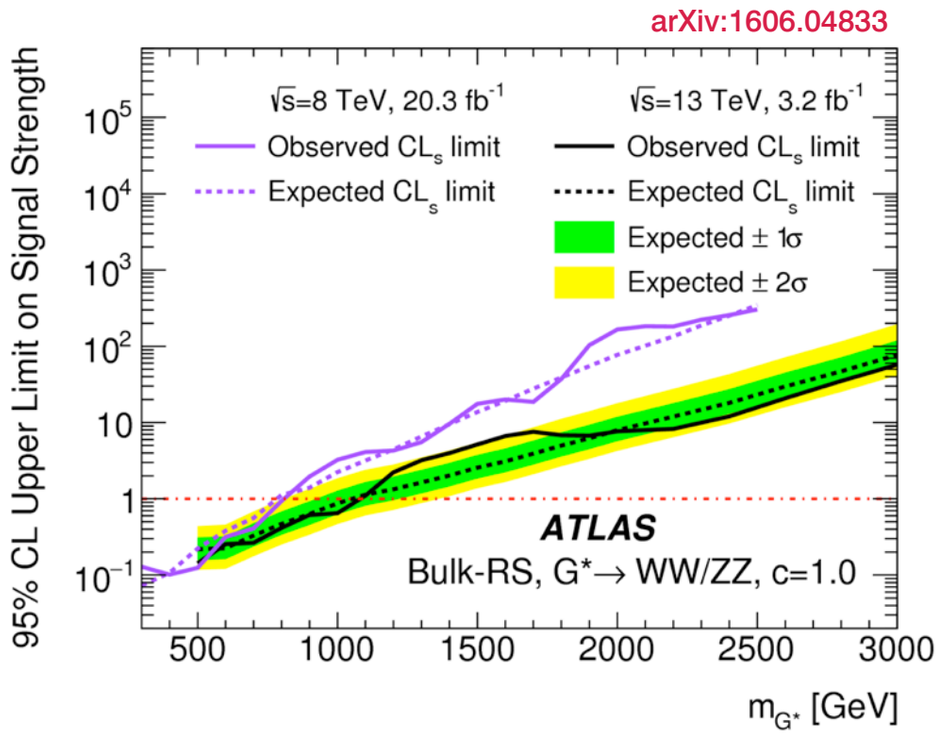
Summary of Latest VV Searches

ICHEP2016 results - superimposed (not combined)



- Comparison between VV combination in Run-1 (8 TeV, 20.3 fb^{-1}) and Run-2 winter (13 TeV, 3.2 fb^{-1})
  - ➡ At m = 2 TeV, even with just the winter dataset, the analysis had more sensitivity than the Run-1 dataset



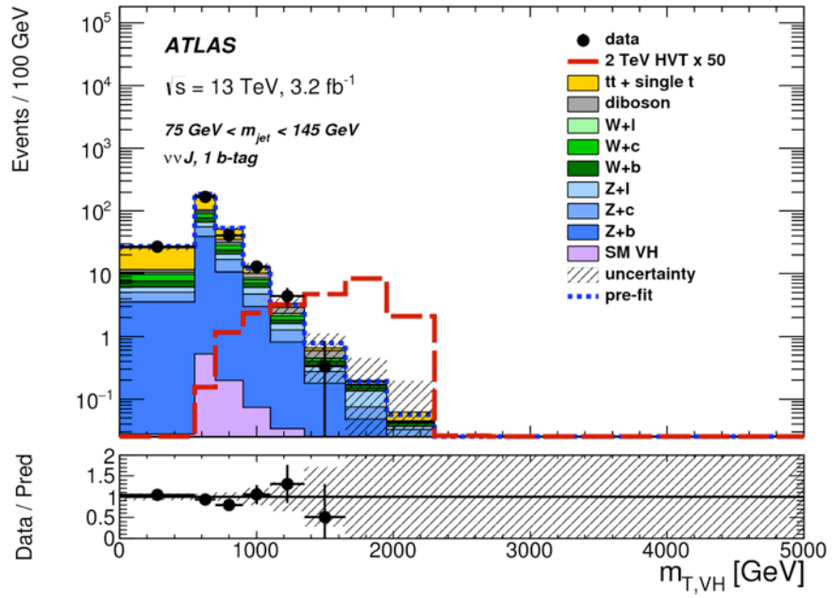


VH Results

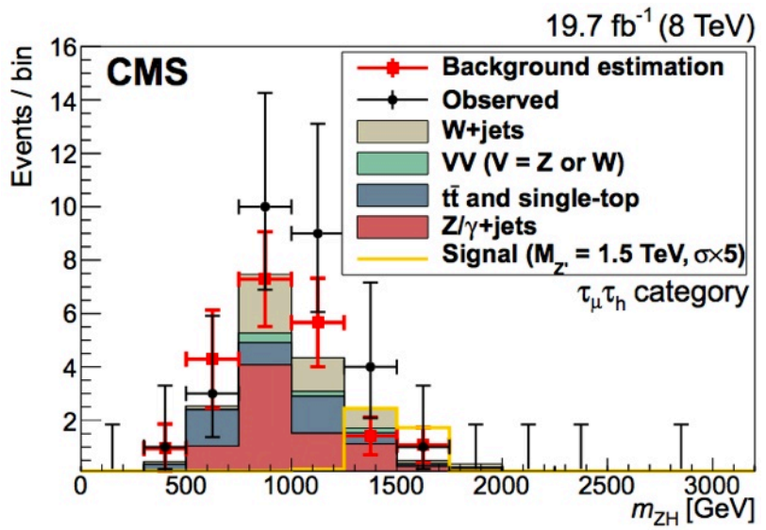
Exotic VH - Semi-Leptonic

- Exotic VH searches in the context of Heavy Vector Triplet models
  - ➡ Complementary to the VV searches
- Both collaborations looking into boosted topologies, with merged jets
  - ➡ ATLAS
    - VH→ $\ell\ell$bb, $\ell\nu$bb, $\nu\nu$bb channels
    - 13 TeV, 3.2 fb^{-1}
  - ➡ CMS
    - VH→ $\ell\ell$bb, $\ell\nu$bb, $\nu\nu$bb channels with 13 TeV, 2.17-2.52 fb^{-1}
    - VH→ qq$\tau\tau$, $\ell\nu$bb channels with 8 TeV, 19.7 fb^{-1}

arXiv:1607.05621



Phys. Lett. B 748 (2015) 255



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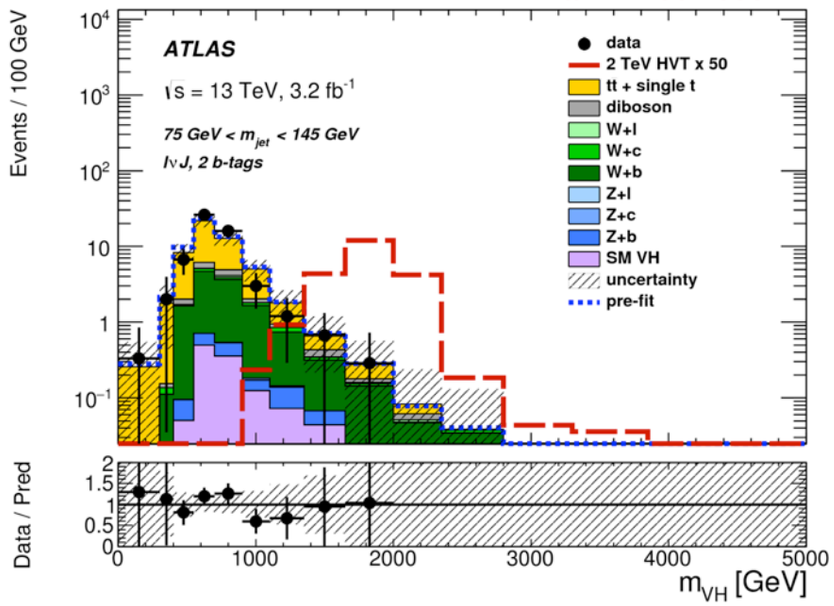
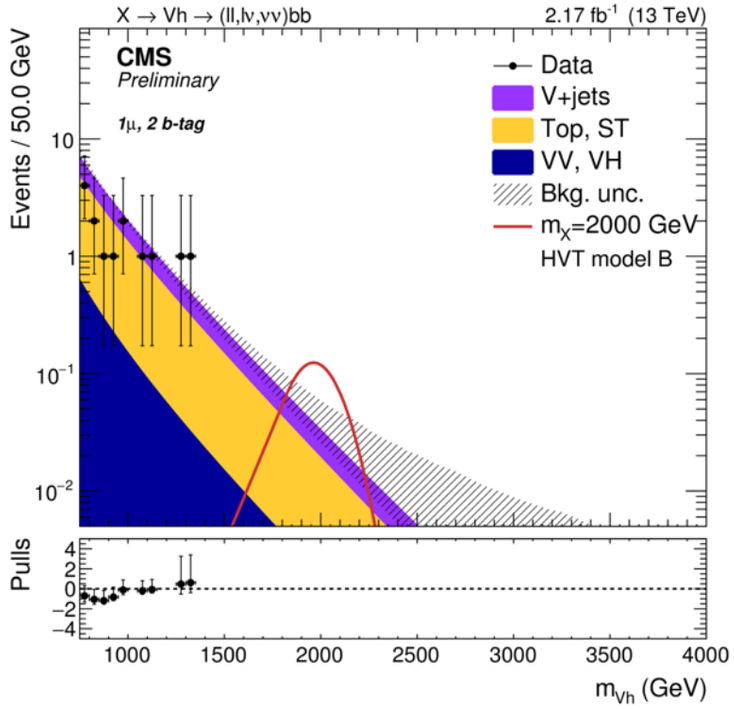
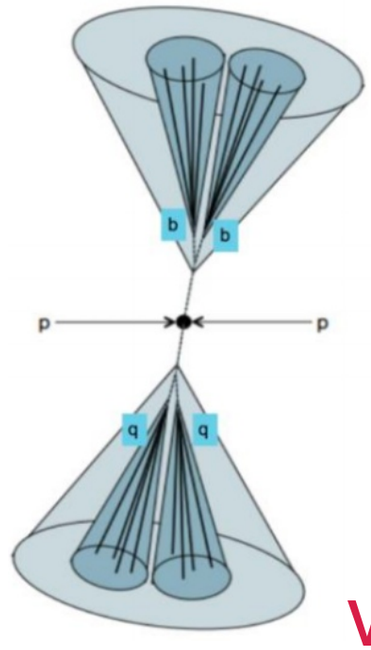


CMS-PAS-B2G-16-003



VH → qqbb

- Complementary to semi-leptonic VH searches
  - ➡ Benefits from W,Z → qq high BR (67%, 70%)
- Competitive at high m_X, where multi-jet background diminishes
- 1 boson tagged large-R jet, one Higgs tagged large-R jet
- ATLAS: 13 TeV, 13.3 fb^{-1}
- CMS: latest results with Run-1



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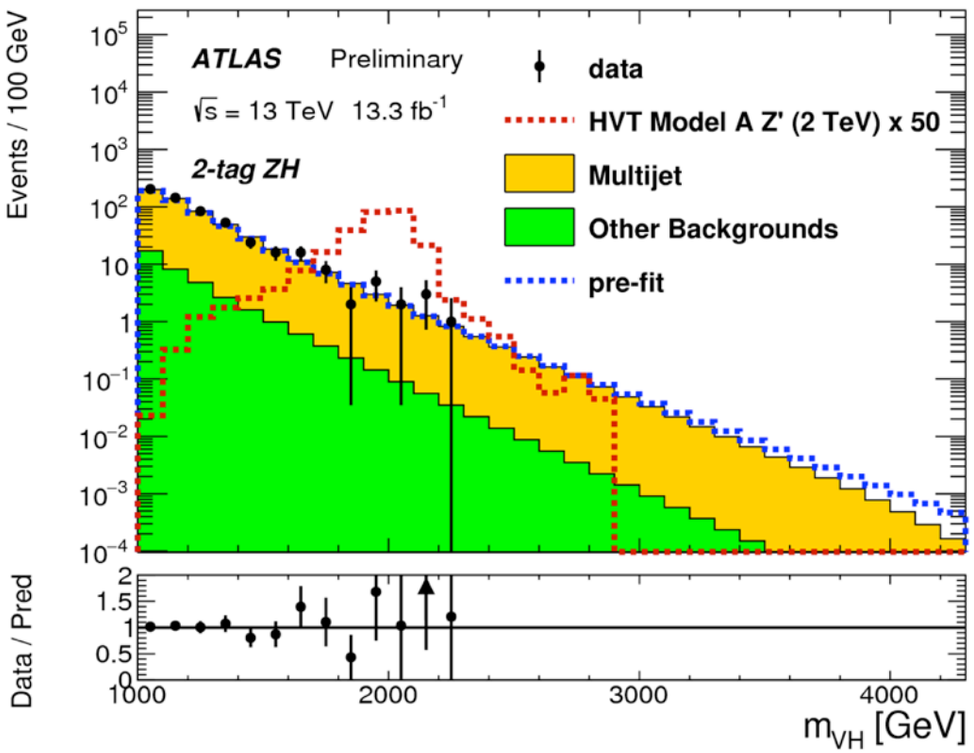

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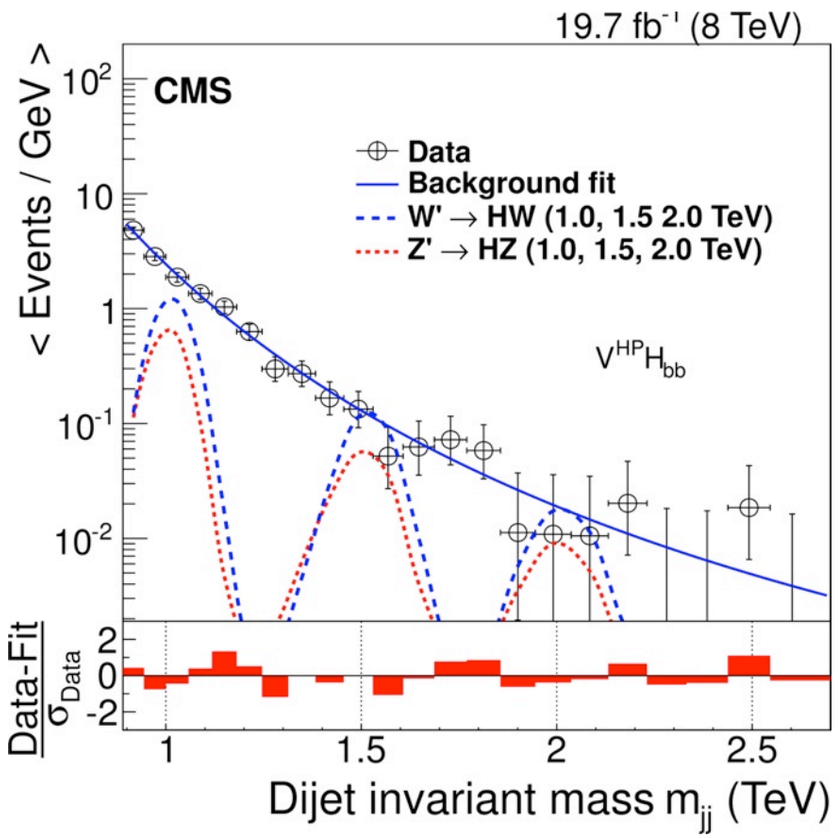
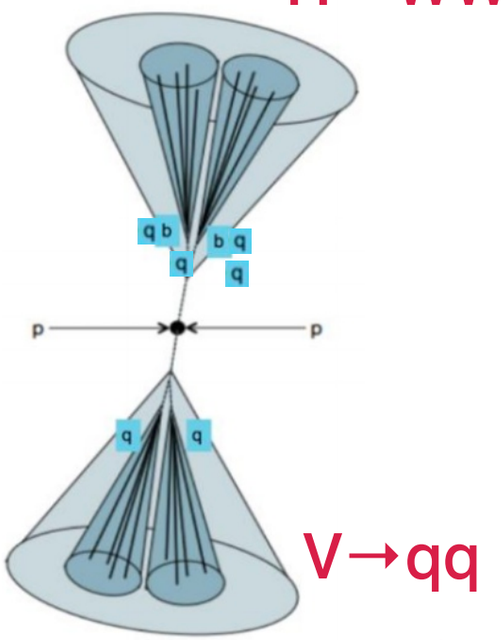
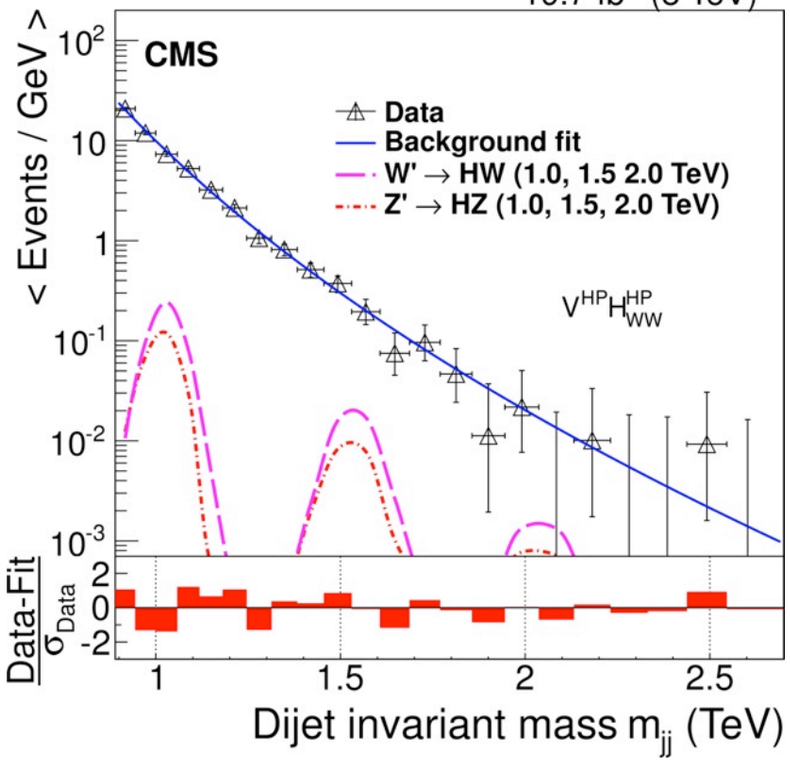


VH→ qq WW*(→qqqq)

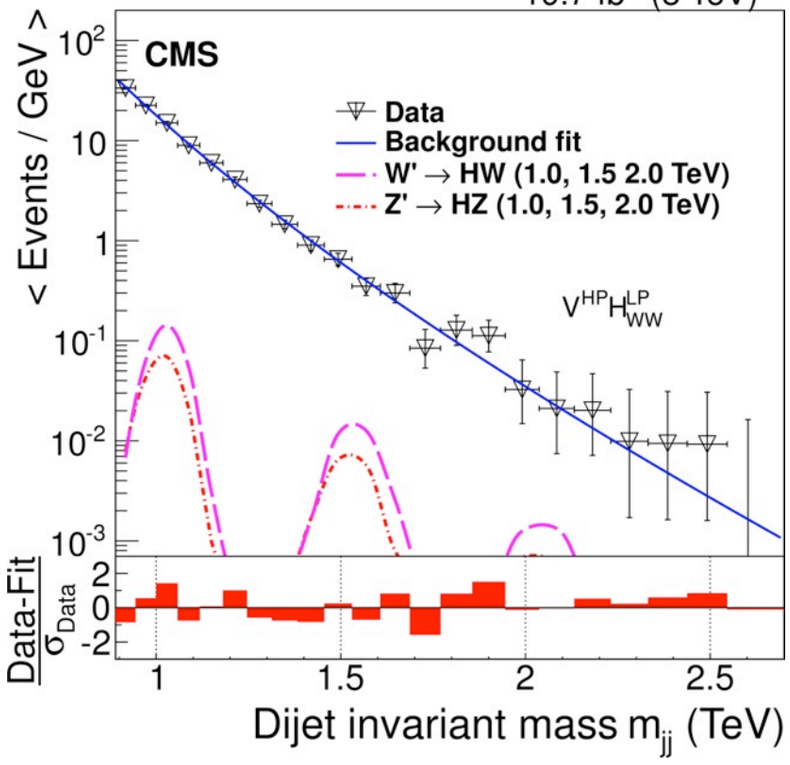
- Look into VH, H→WW* fully hadronic decays
- First application of jet substructure techniques to identify H→WW*→qqqq decays at high Lorentz boost



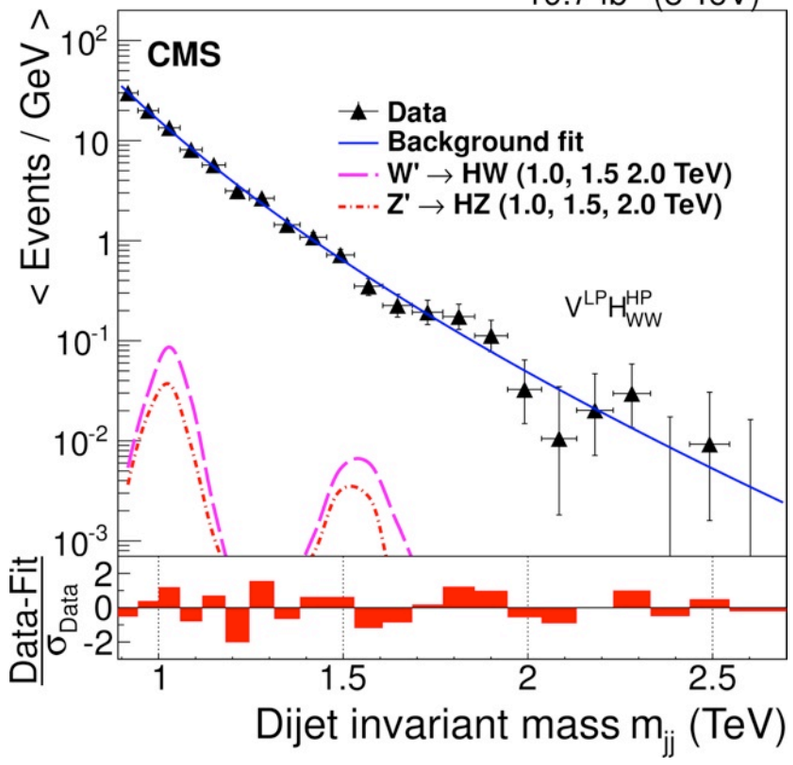
JHEP 02 (2016) 145
19.7 fb^{-1} (8 TeV)



JHEP 02 (2016) 145
19.7 fb^{-1} (8 TeV)



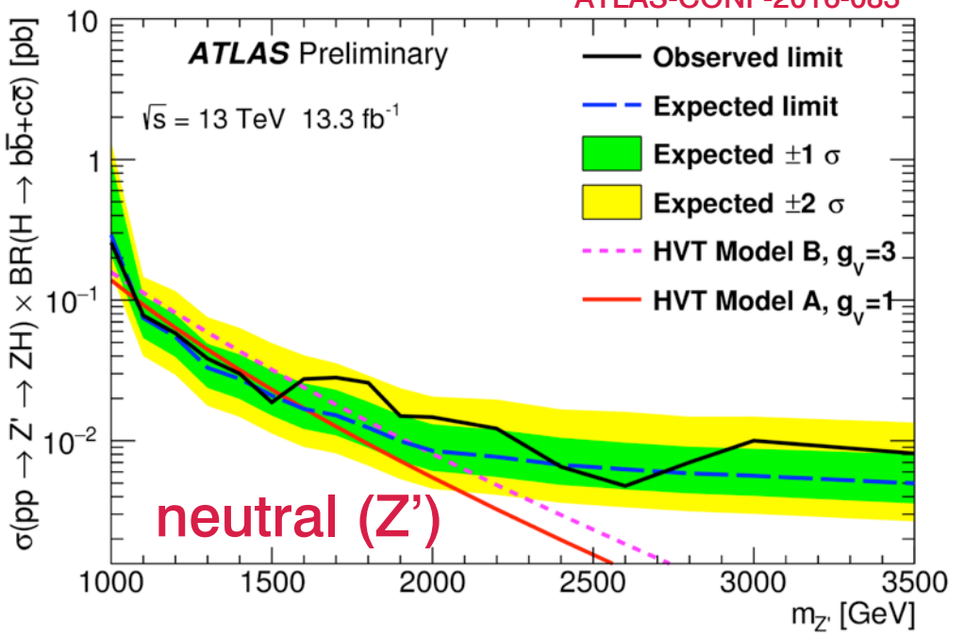
JHEP 02 (2016) 145
19.7 fb^{-1} (8 TeV)



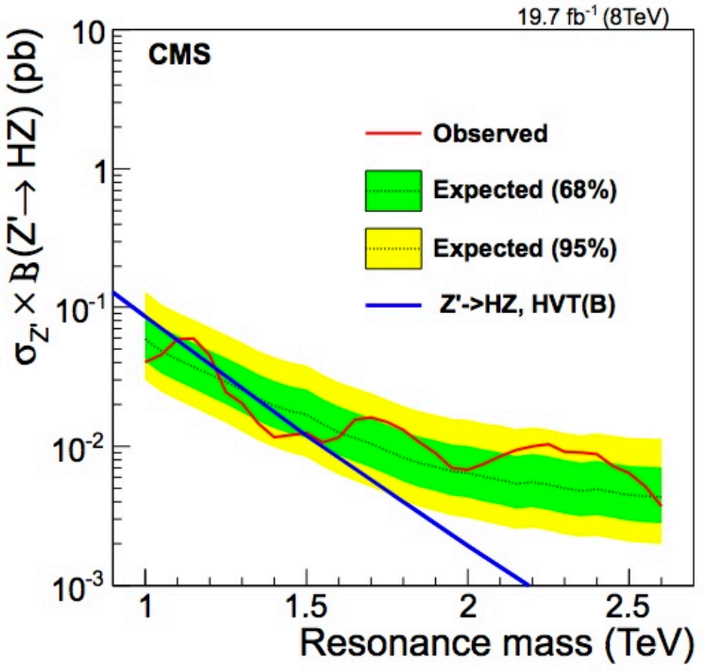
VH → qqbb, qqWW(→ qqqq)

- ATLAS results
  - ➡ 13 TeV, 13.3 fb^{-1} qqbb only
- CMS results
  - ➡ Run-1 combination of qqbb and qqqqqq
- No significant excess above expectations found
  - ➡ biggest fluctuation at 1.6 TeV in ATLAS W′→qqbb channel

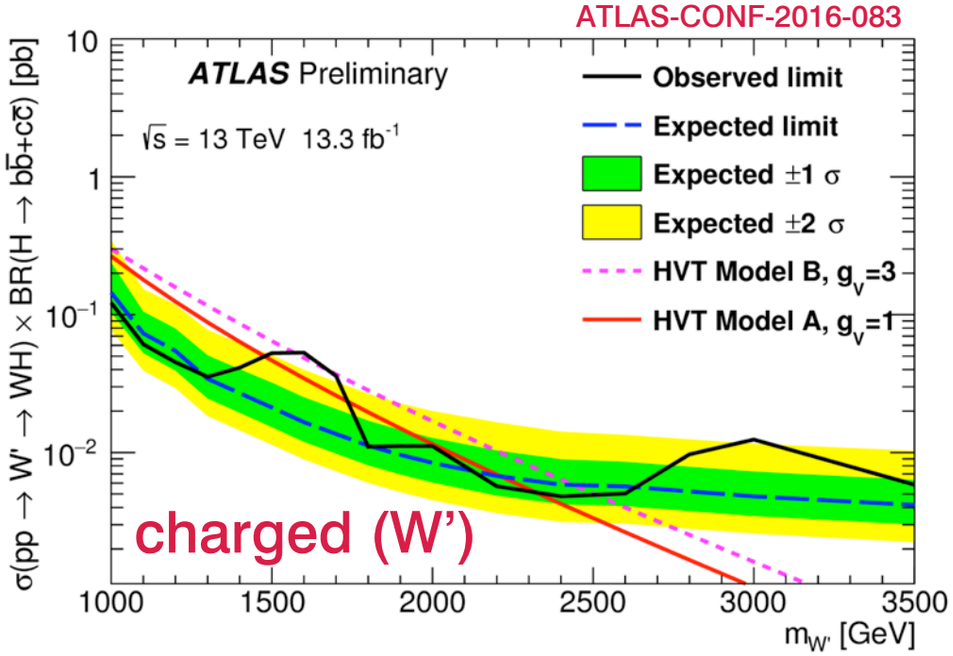
ATLAS-CONF-2016-083



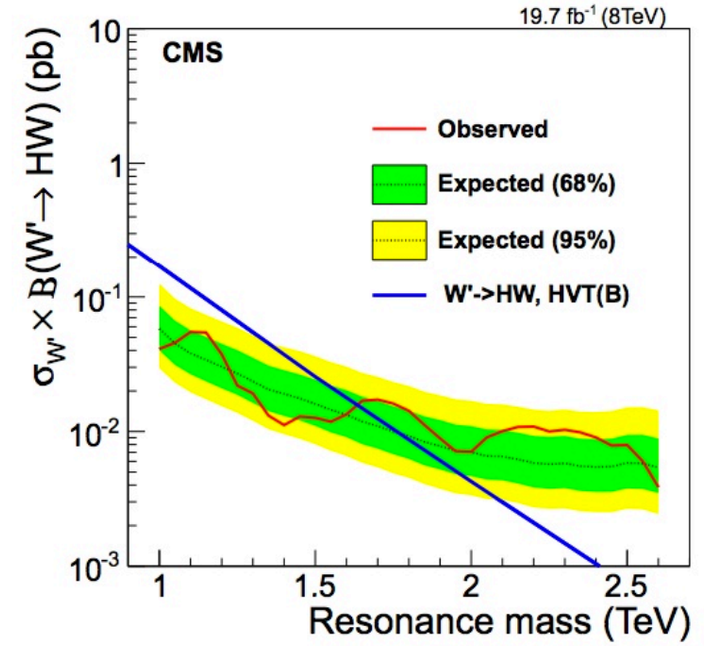
JHEP 02 (2016) 145



ATLAS-CONF-2016-083



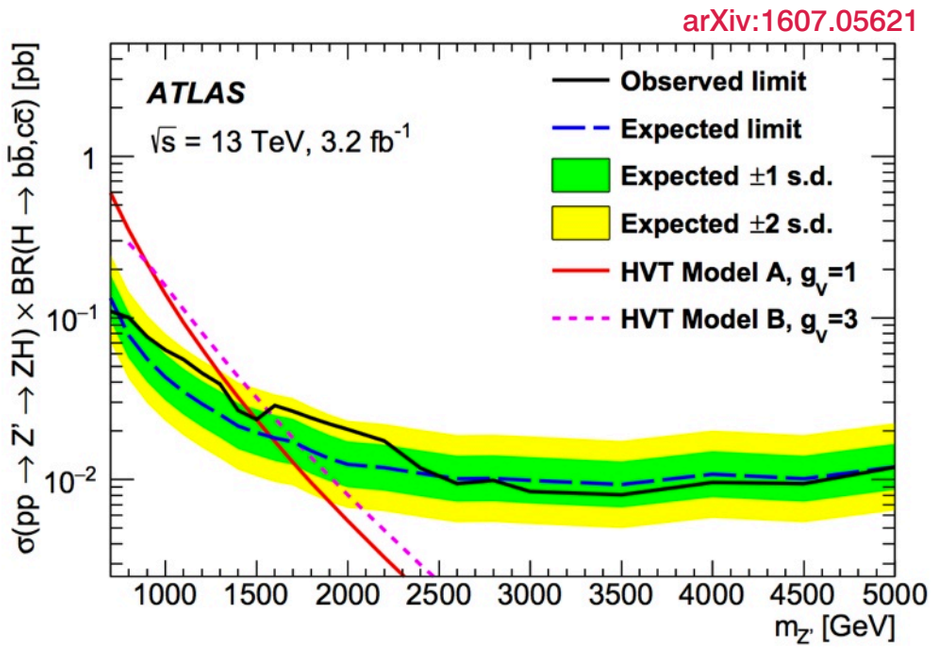
JHEP 02 (2016) 145

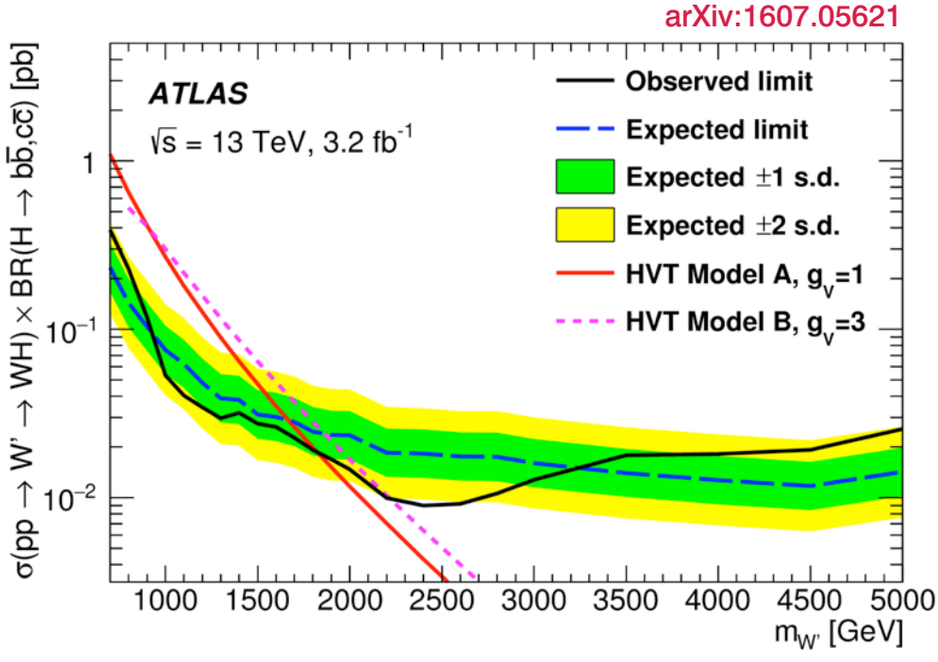


Summary of Latest VH Searches

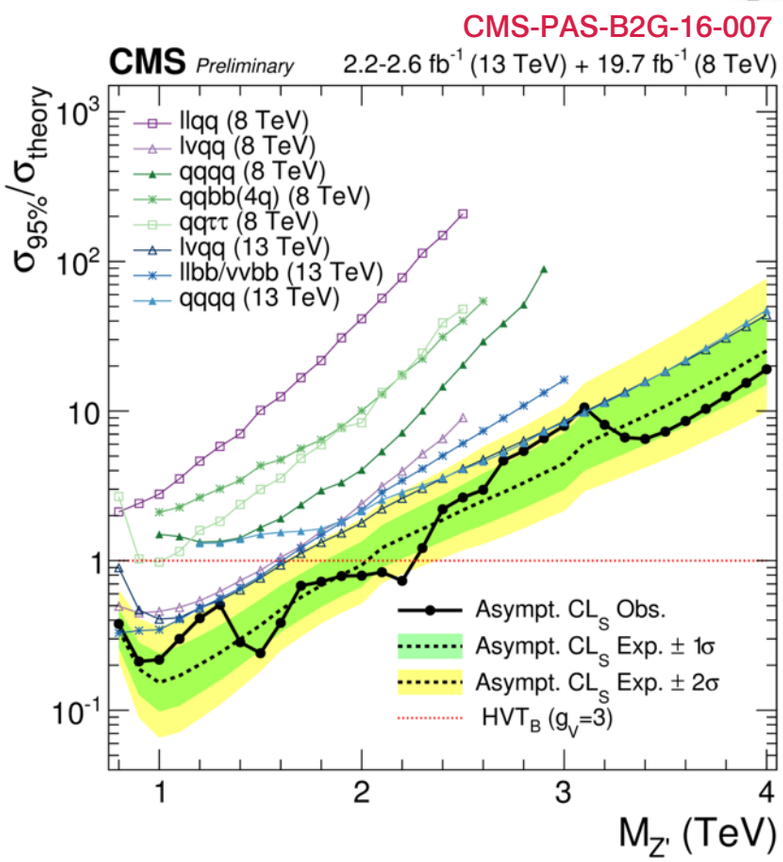
- All using HVT models A and B as benchmarks

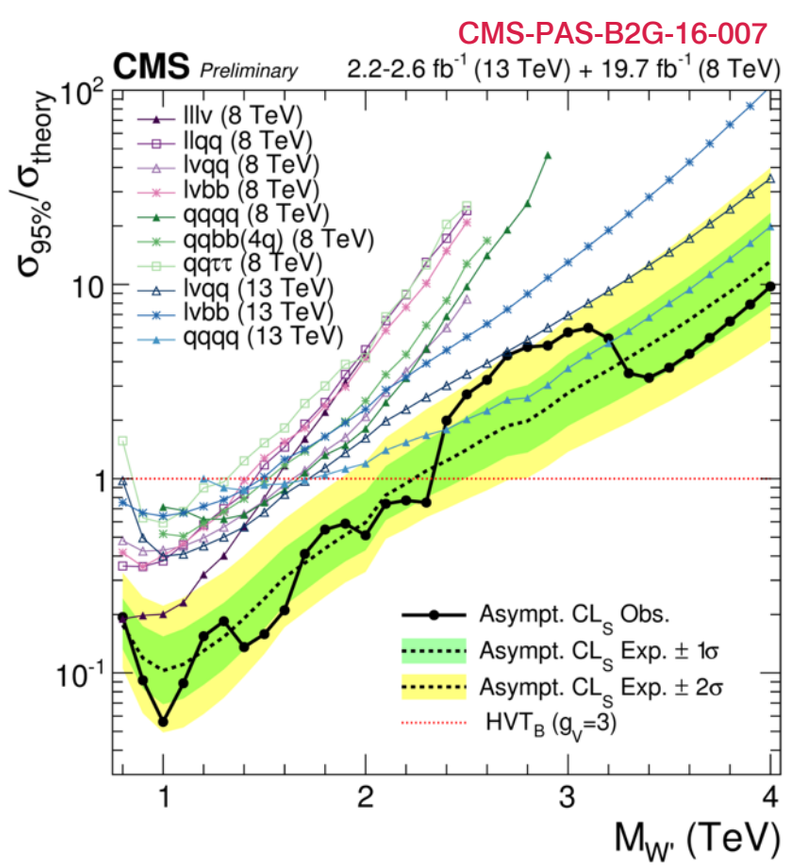
- ATLAS combination of semi-leptonic channels at 13 TeV, 3.2 fb^{-1}





- CMS combination of:
  - ➡ semi-leptonic and fully hadronic VH at 8 TeV
  - ➡ semi-leptonic VV at 13 TeV, 2.2-2.6 fb^{-1}

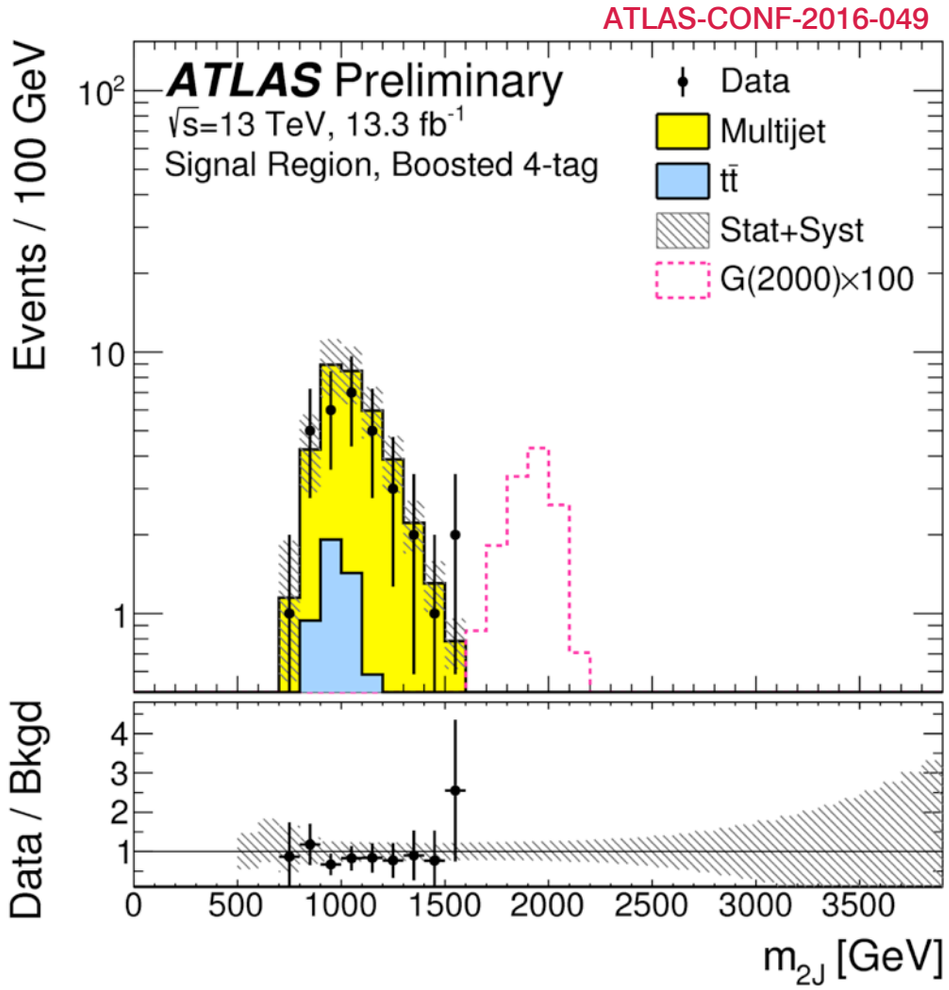




HH Results

HH → bbbb

- BR (HH→bbbb) ~ 33%
  - ➡ Most sensitive HH final state across most of the search space
- Topologies
  - ➡ Resolved: 4 b-tagged small-R jets
  - ➡ Boosted: 2 trimmed large-R jets, matched to b-tagged small-R track jets
- Background:
  - ➡ QCD multijet, dominant
  - ➡ ttbar, ~10%



HH → bbbb (II)

- ATLAS:
  - 13 TeV, 13.3 fb^{-1}
  - Excludes bulk RS gravitons ($K/M_{Pl} = 1.0$) below 850 GeV
- CMS:
  - 8 TeV, 19.7 fb^{-1}
  - Excludes radions ($\Lambda_R = 1$ TeV) below 1.6 TeV

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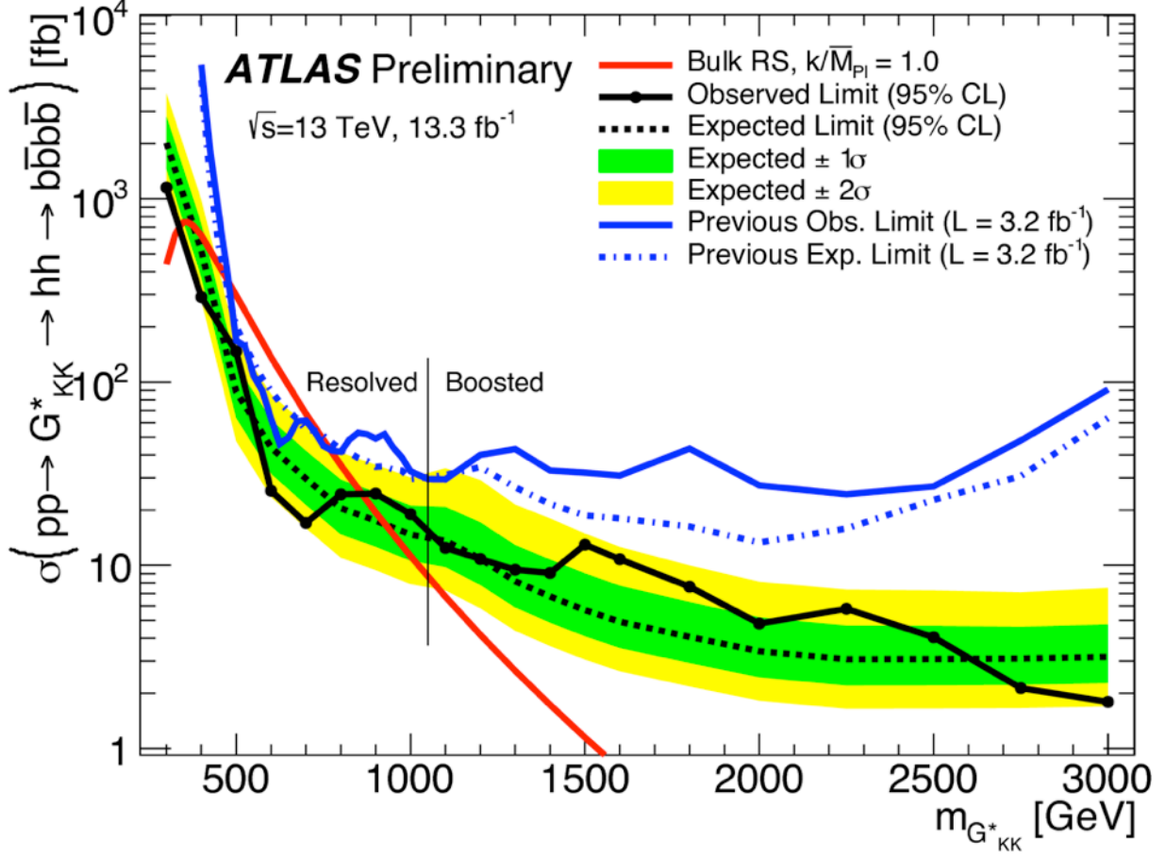
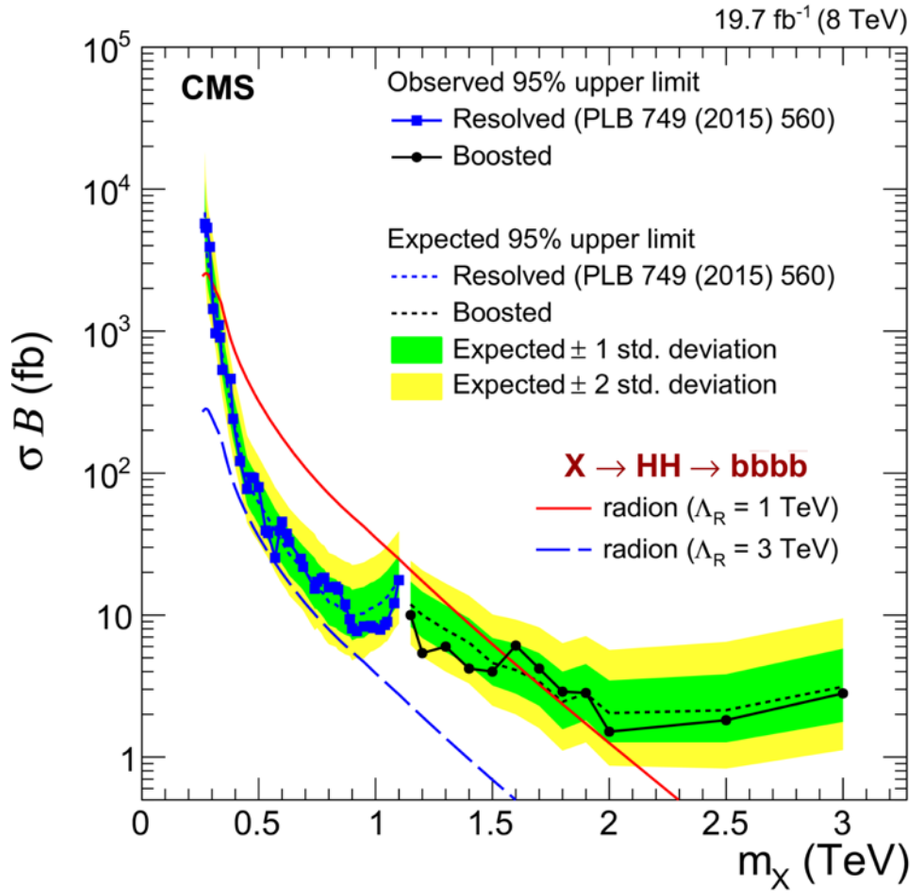
ATLAS-CONF-2016-049



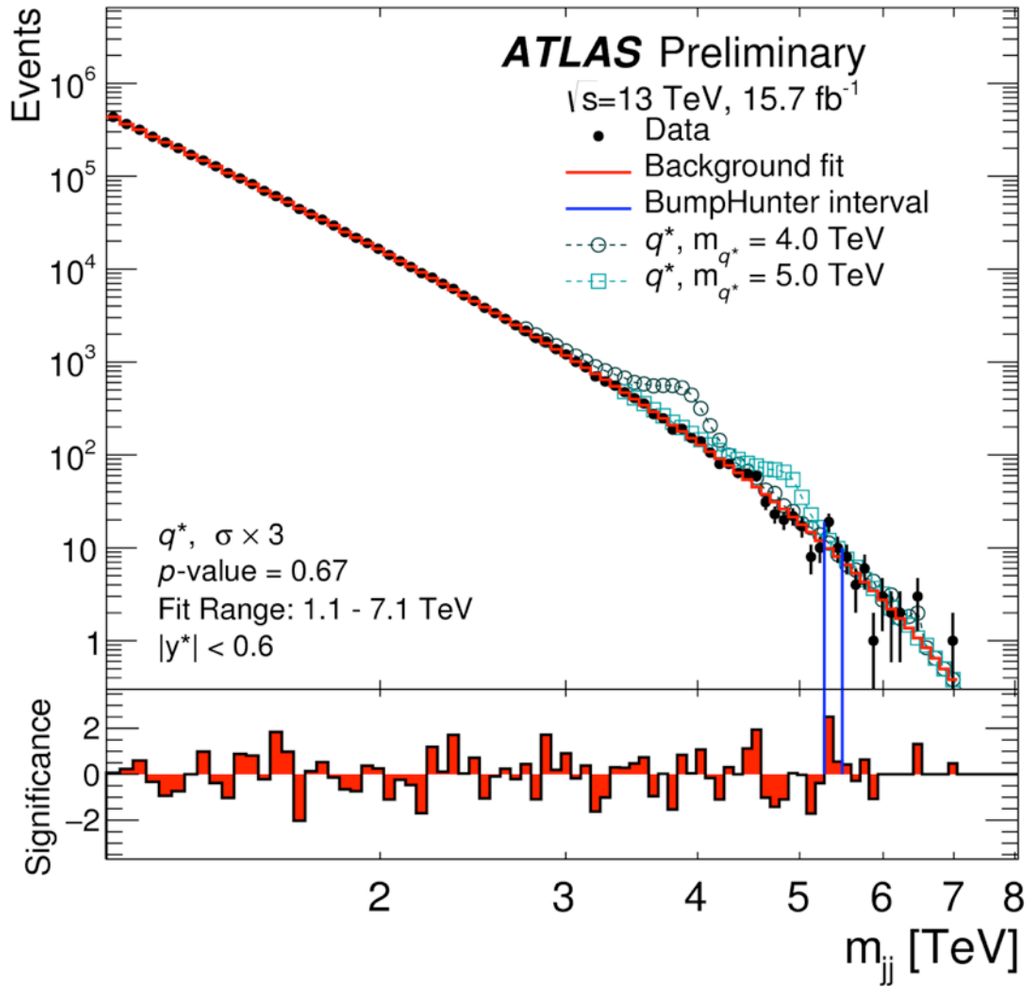


Other Interesting High Mass Searches

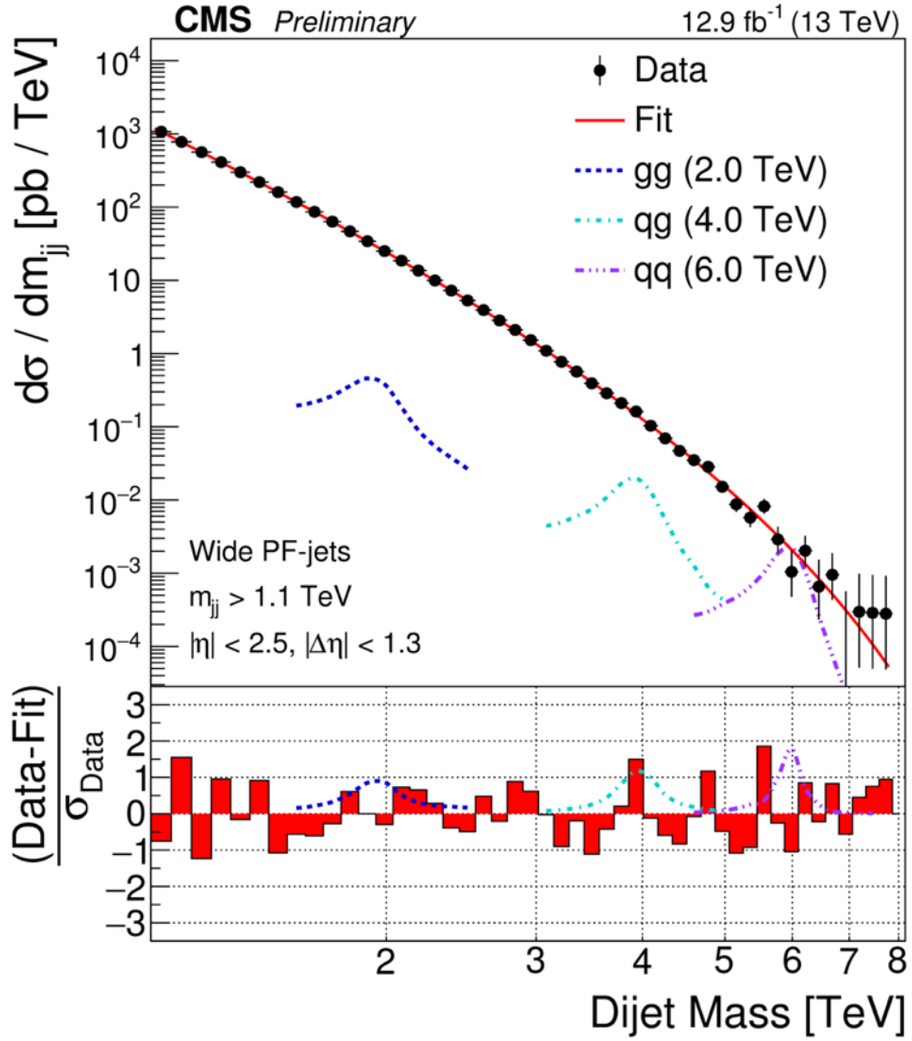
Exotic Di-jet Resonances

- $2 \rightarrow 2$ scattering processes are described well by QCD in the Standard Model (SM). Departure from SM implies New Physics (NP).
- Useful variables: Dijet invariant mass (mjj), dijet angular distribution.

ATLAS-CONF-2016-069



CMS-PAS-EXO-16-032

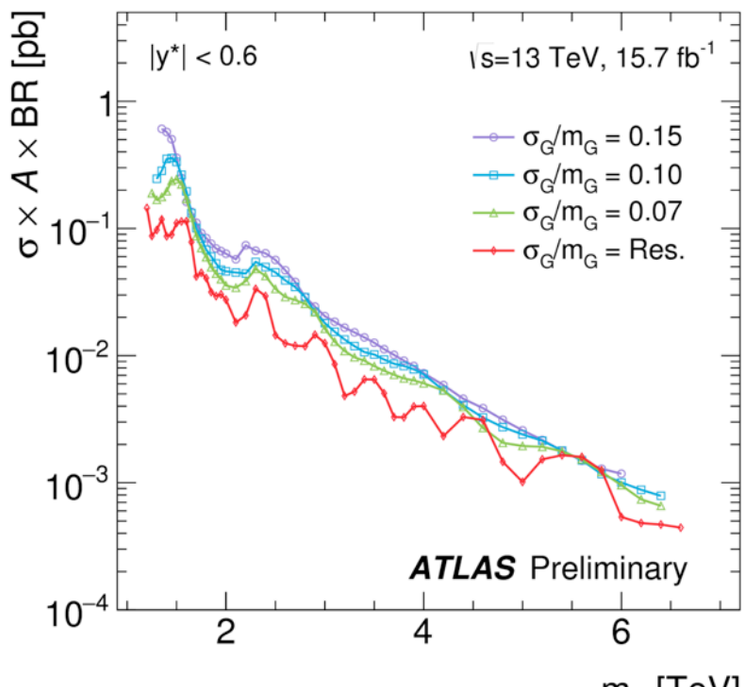


Di-jet (II)

ATLAS-CONF-2016-069

Model	95% CL exclusion limit	
	Observed	Expected
Quantum black holes, ADD (BlackMax generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
W'	2.9 TeV	3.3 TeV
W^*	3.3 TeV	3.3 TeV

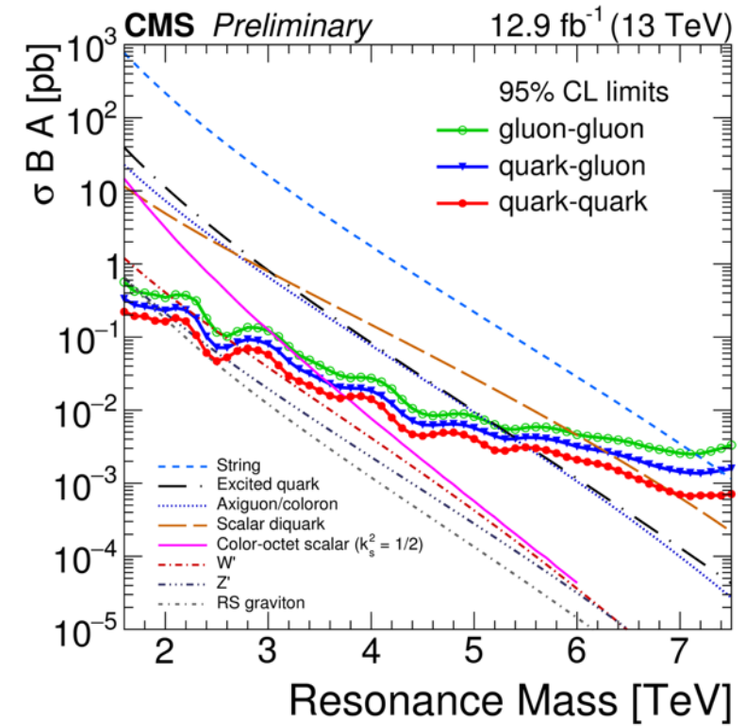
ATLAS-CONF-2016-069



CMS-PAS-EXO-16-032

Model	Final State	Observed (expected) mass limit [TeV] 12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0 (3.3)	—	—
W′	$q\bar{q}$	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	$q\bar{q}$, gg	1.9 (1.8)	—	1.6 (1.3)

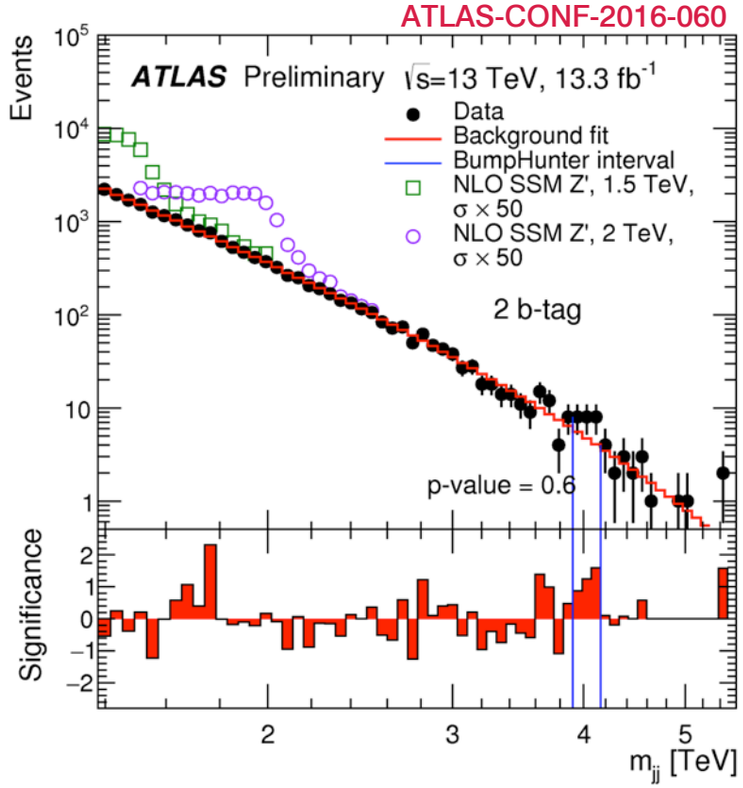
CMS-PAS-EXO-16-032



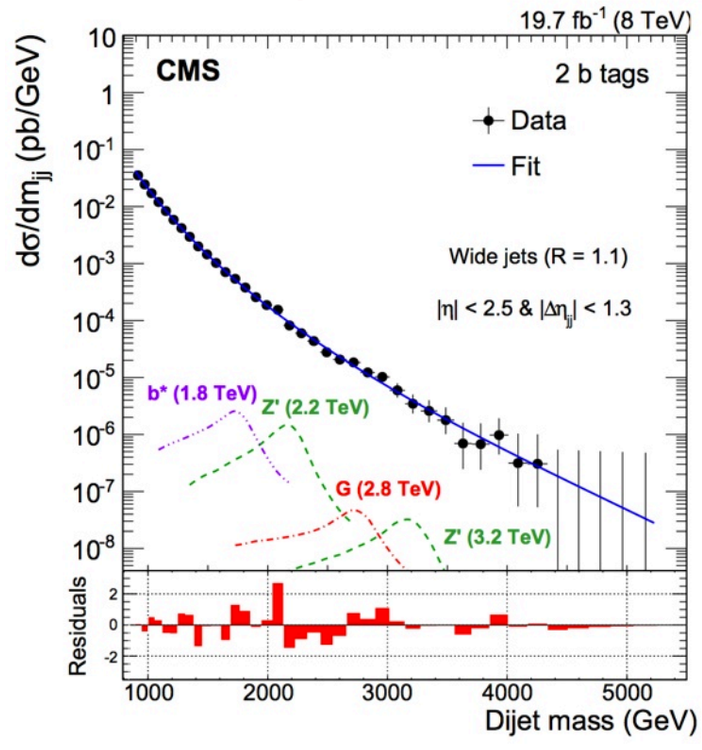
Di-jet with 1 or 2 b-tags

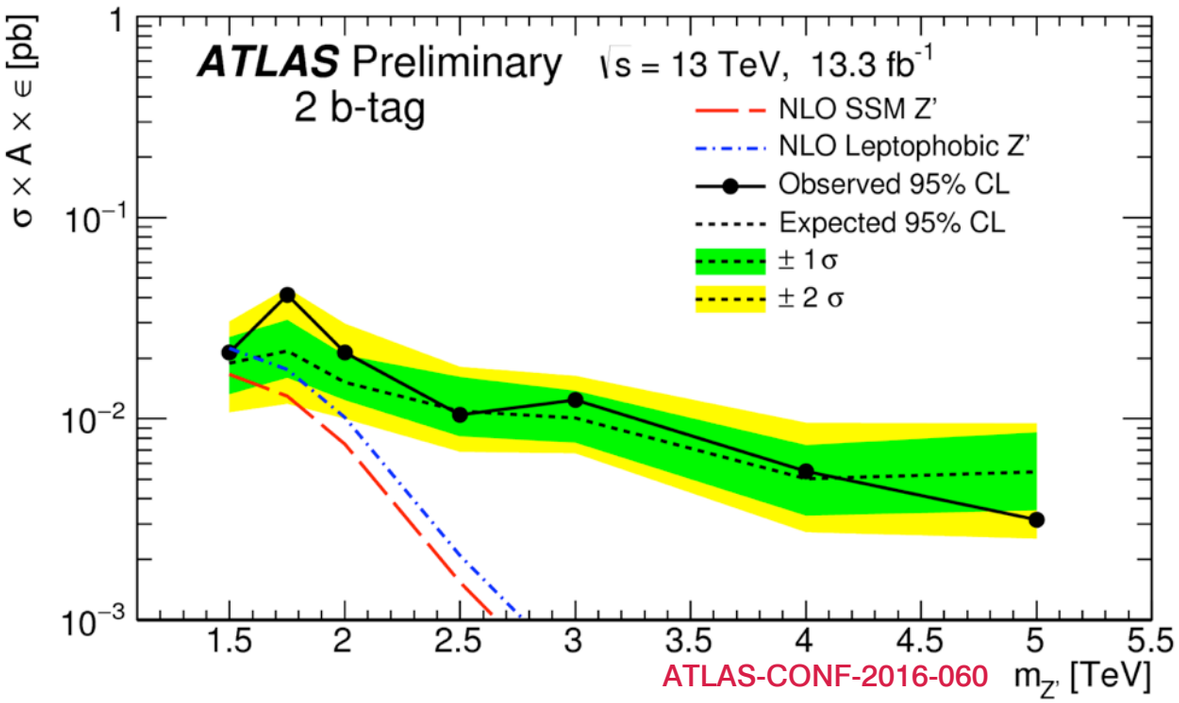
- Increase sensitivity in scenarios where a new particle couples to b-quarks
  - ➡ b-tag reduces QCD background
- ATLAS
  - ➡ 13 TeV, 13.3 fb^{-1} results
- CMS
  - ➡ 8 TeV, 19.7 fb^{-1} results

ATLAS-CONF-2016-060



Phys. Rev. D 91, 052009 (2015)

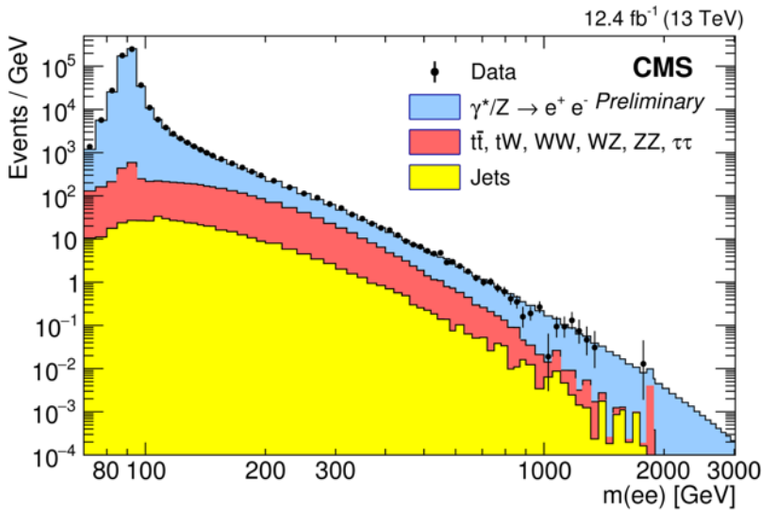


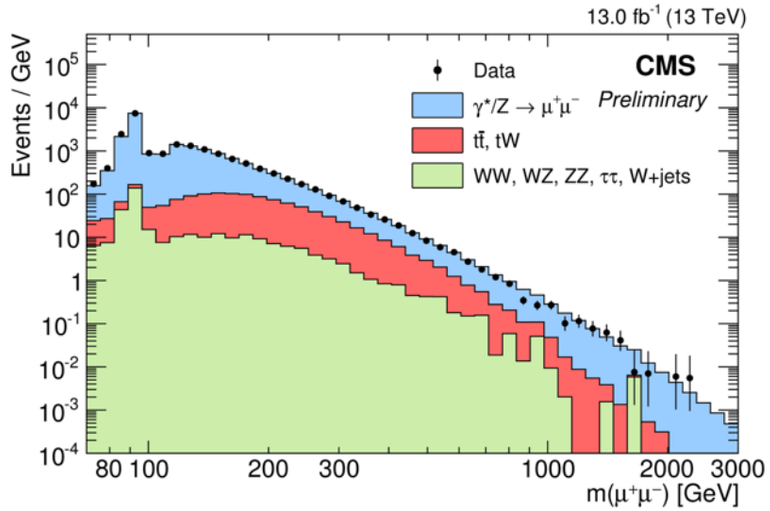


$Z' \rightarrow \ell\ell$

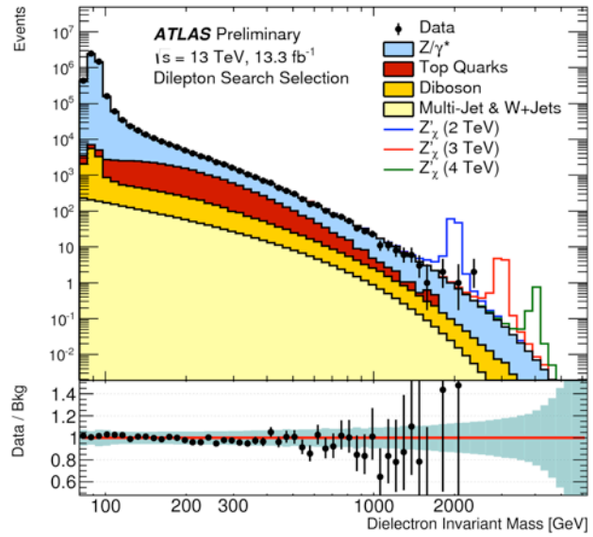
- Straightforward analysis, looking for a di-lepton pairs
- Very similar sensitivity for ATLAS and CMS
- Limits, excluding at 95% C.L.:
  - ➡ $Z'_{\Psi} < 3.5$ TeV (GUT inspired E6 gauge group)
  - ➡ $Z'_{SSM} < 4.0$ TeV (Sequential Standard Model)

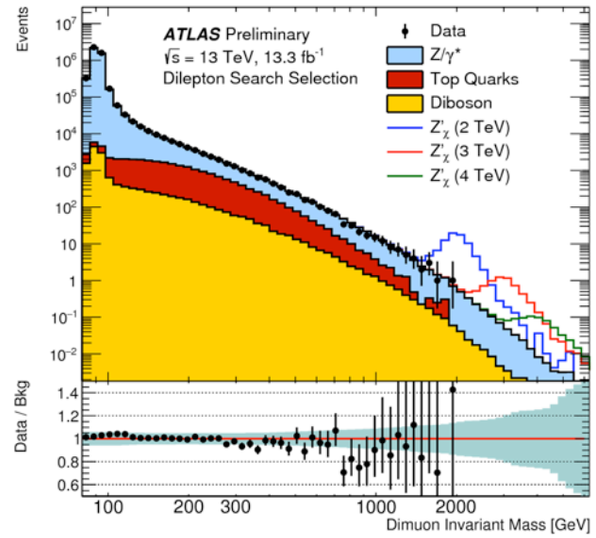
CMS-PAS-EXO-16-031

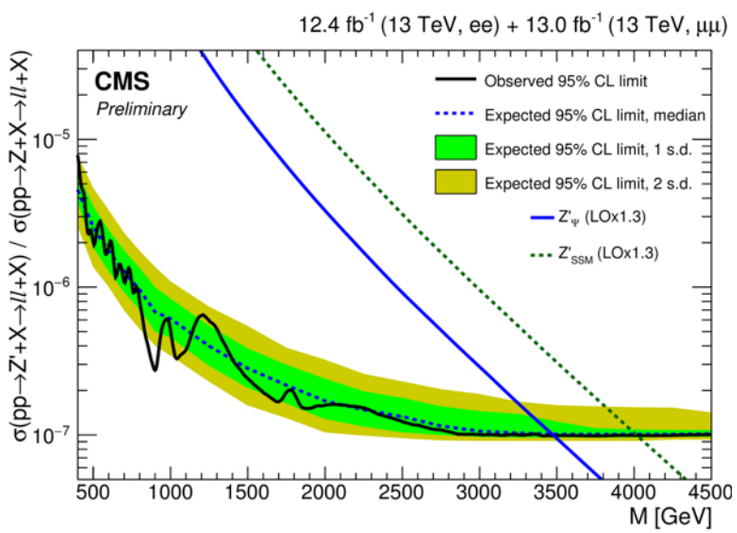


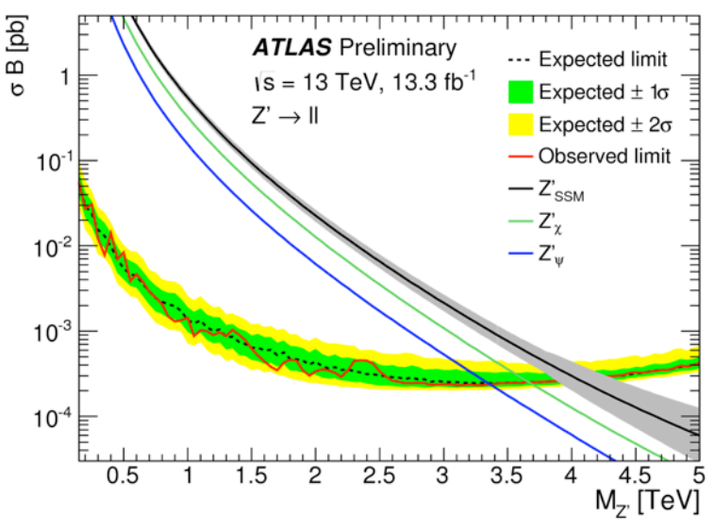


ATLAS-CONF-2016-045





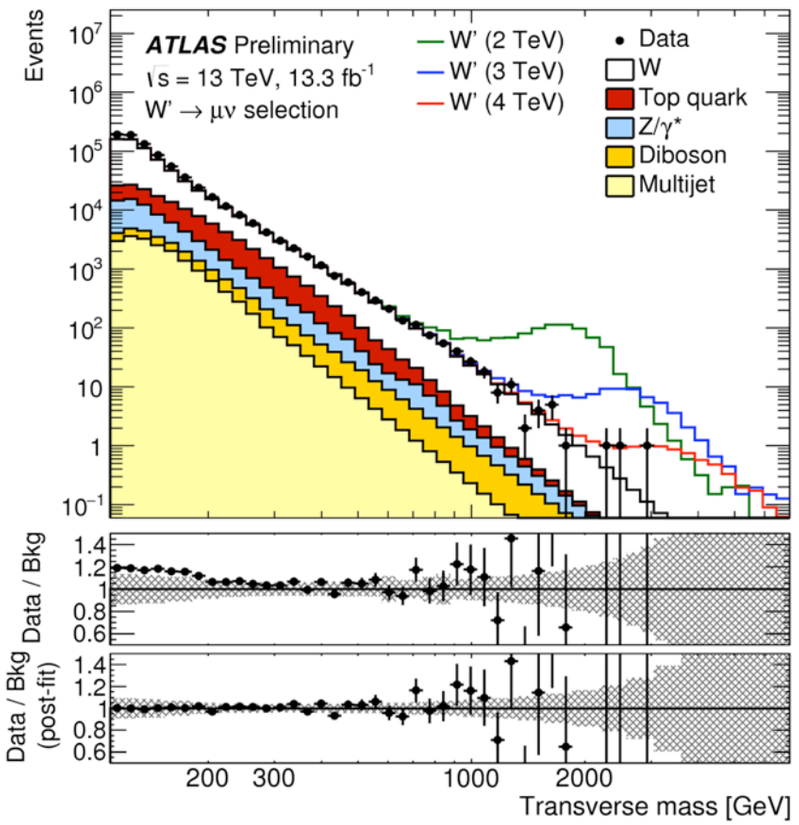




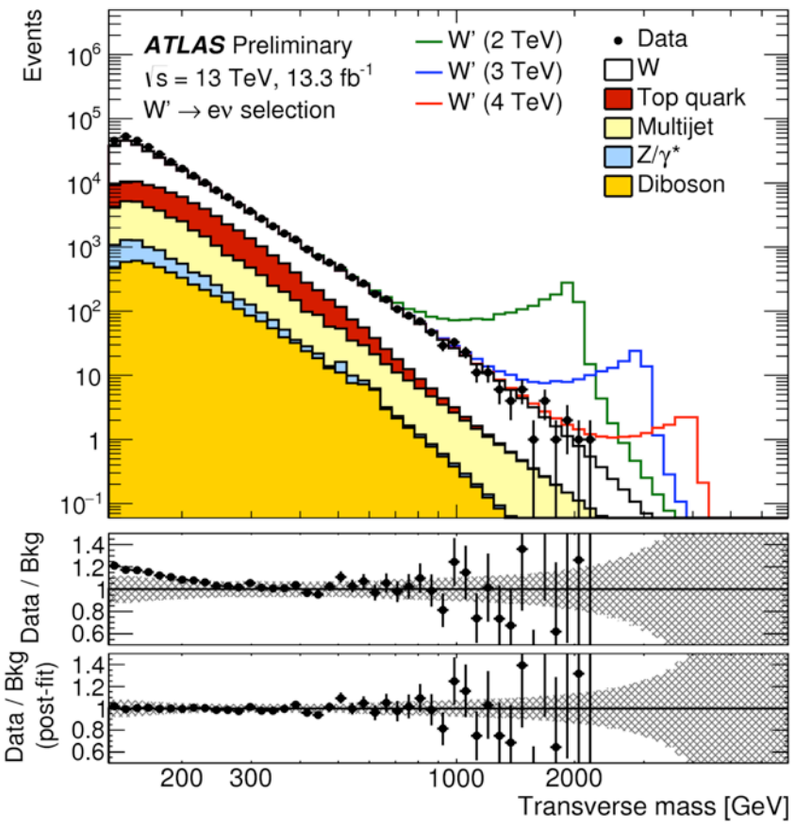
$W' \rightarrow \ell\nu$

- Looking for a lepton and MET
- ATLAS:
  - ➡ Results with 13 TeV, 13.3 fb^{-1}
  - ➡ Excludes $W'_{SSM} < 4.9$ TeV
- CMS:
  - ➡ Results with 13 TeV, 2.2 fb^{-1}
  - ➡ Excludes $W'_{SSM} < 4.3$ TeV

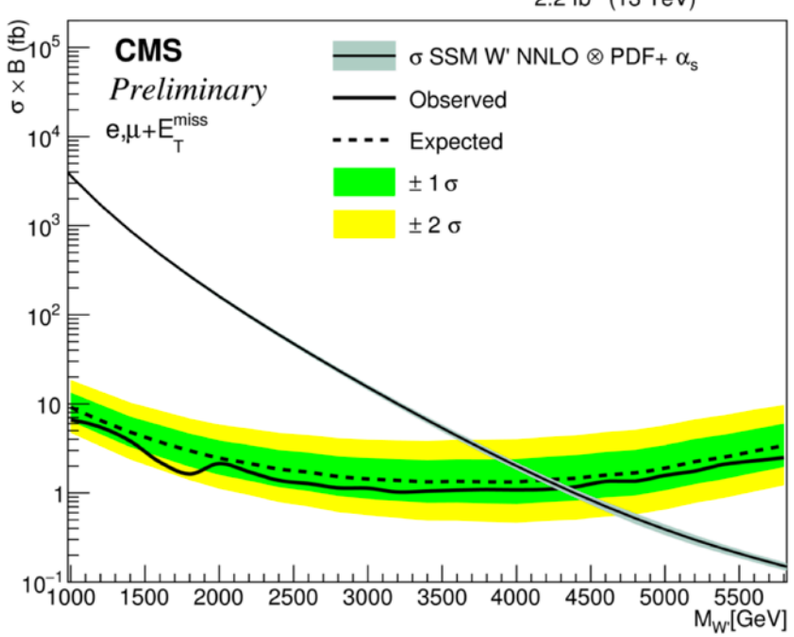
ATLAS-CONF-2016-061



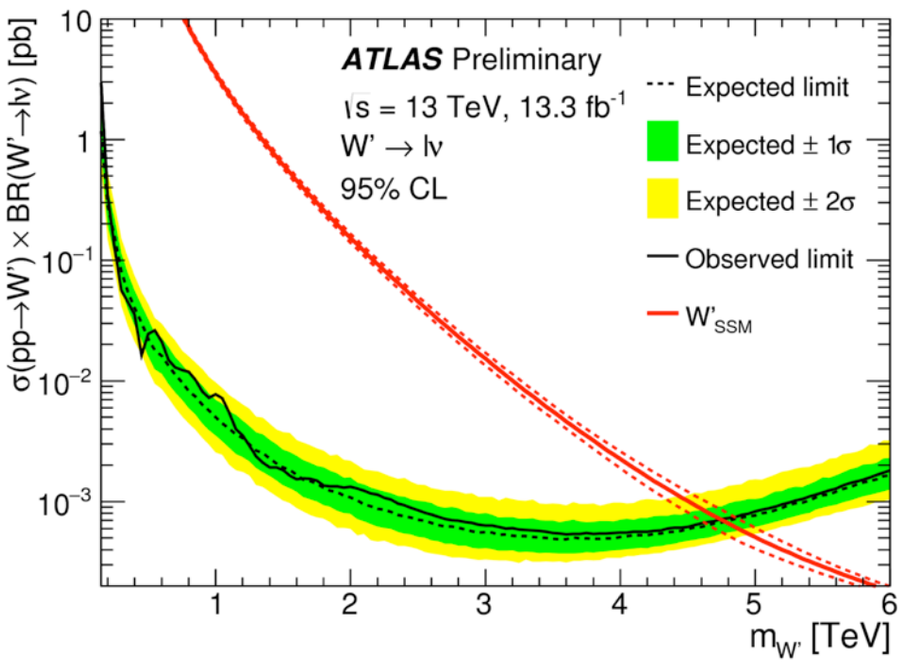
ATLAS-CONF-2016-061



CMS-PAS-EXO-15-006

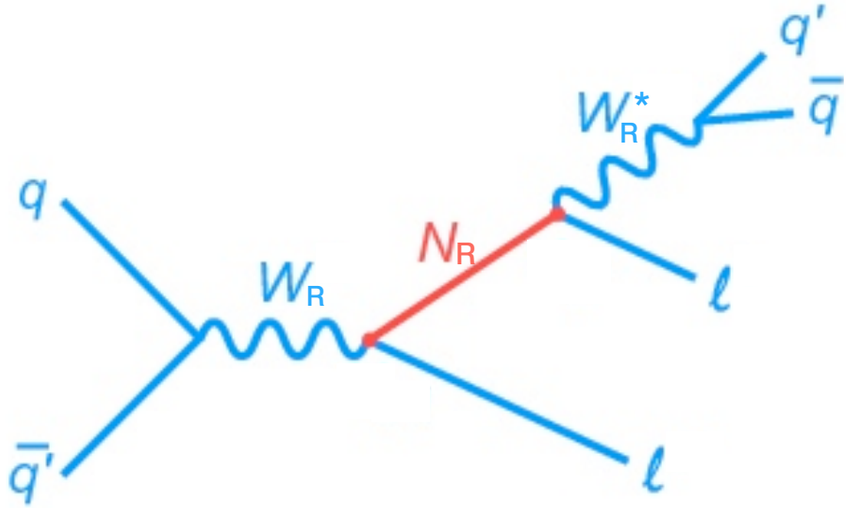


ATLAS-CONF-2016-061



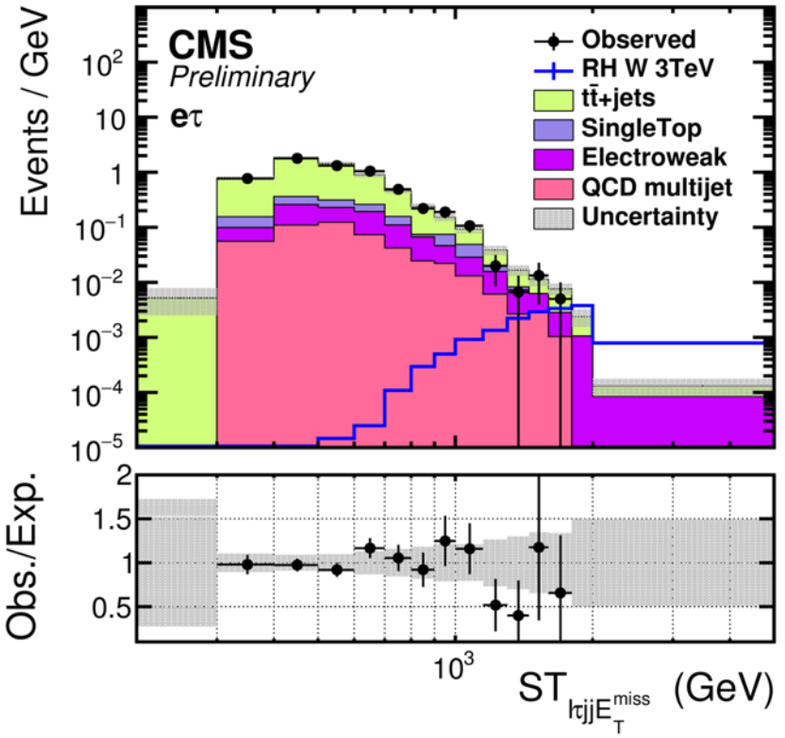
Right Handed W and Heavy Neutrinos

- Left-right symmetric models: right handed W_R and a heavy neutrino (N_R)
  - ➡ Majorana N_R: Opposite Sign (OS) + Same Sign (SS)
  - ➡ Dirac N_R: OS
- Run-1
  - ➡ Excess on CMS OS eejj analysis (not in μμjj)
- CMS
  - ➡ 13 TeV, 12.9 fb^{-1} results in the ℓτjj channel (OS)
  - ➡ 13 TeV, 2.3 fb^{-1} results in the ℓℓJ channel (OS)
- ATLAS
  - ➡ 8 TeV, 20.3 fb^{-1} results in the ℓℓjj channel for SS cases



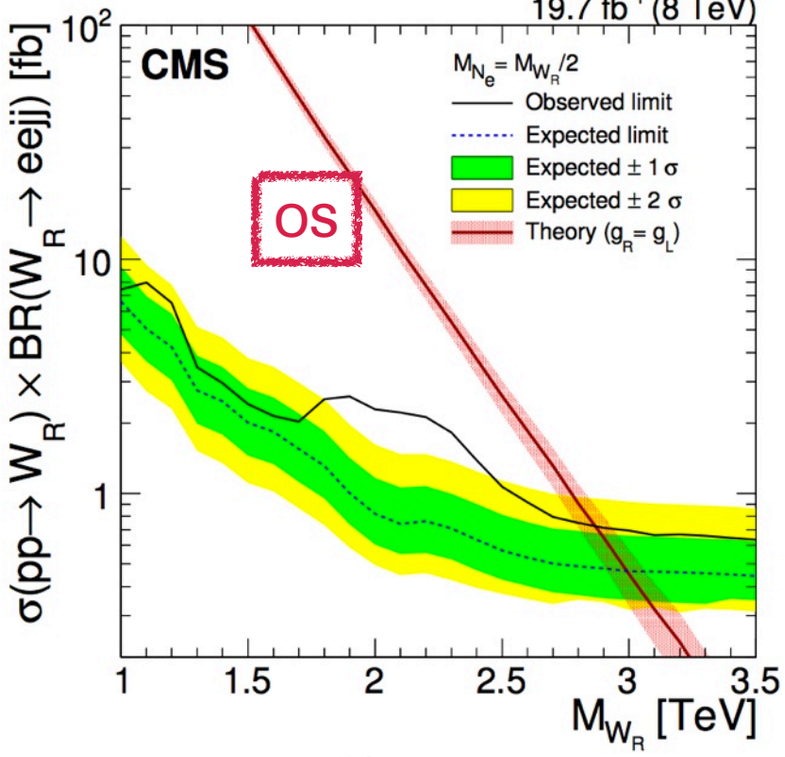
CMS-PAS-EXO-16-023

12.9 fb^{-1} (13 TeV)

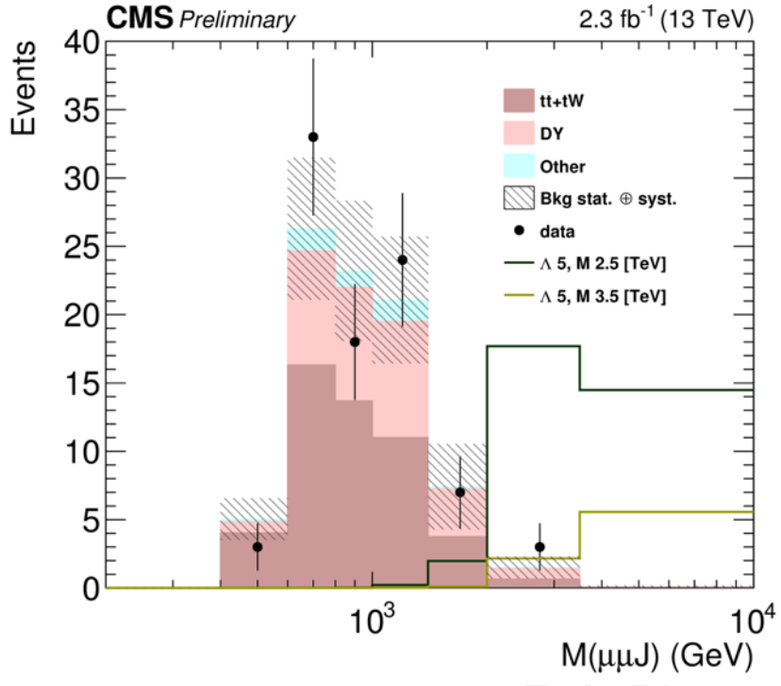


Eur. Phys. J. C 74 (2014) 3149

19.7 fb^{-1} (8 TeV)



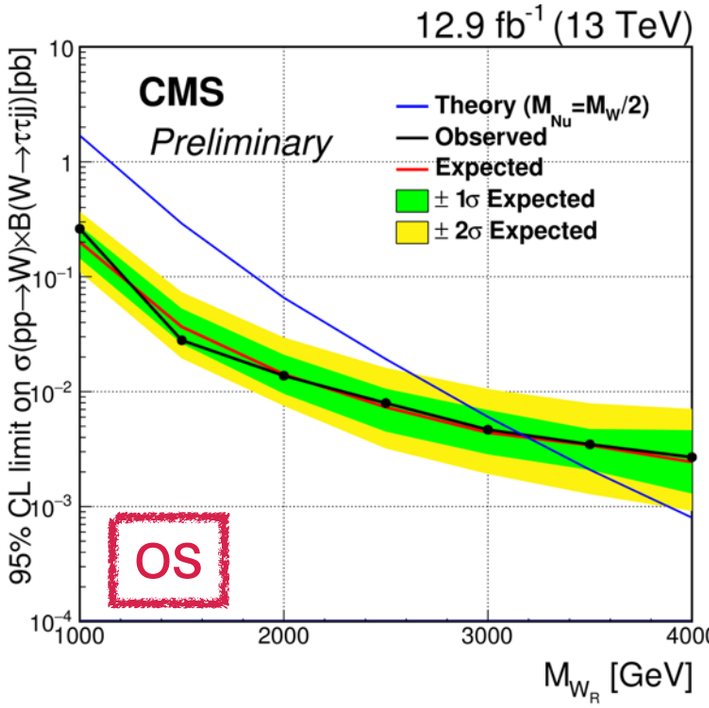
CMS-PAS-EXO-16-026



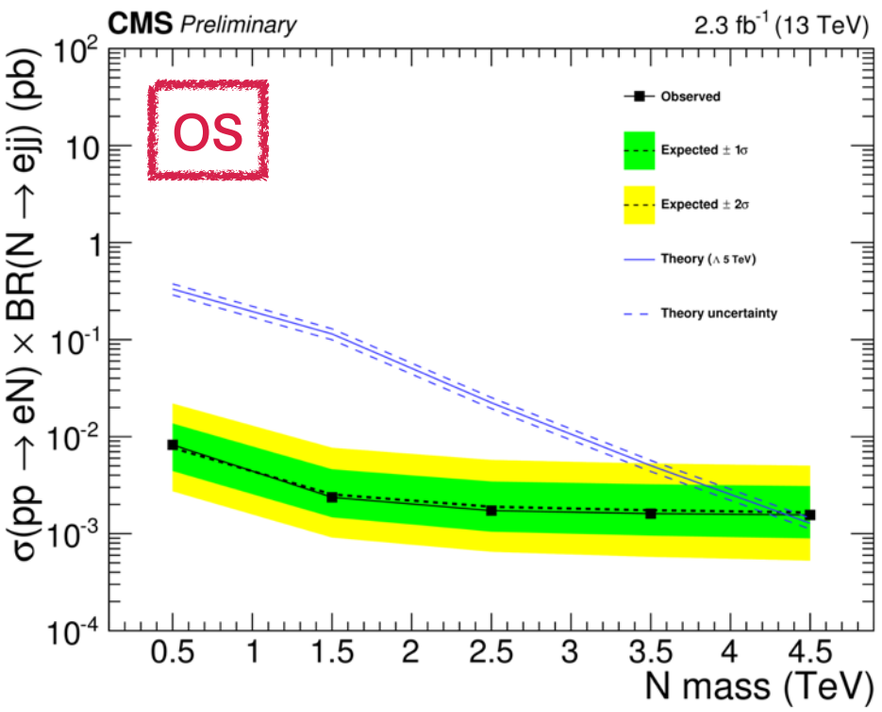
Right Handed W and Heavy Neutrinos (II)

- No significant excess observed in any of the analysis currently public
  - ➡ CMS: limits on $m(W_R) < 3.2$ TeV for $m(W_R) = 2 * m(N_R)$
- ATLAS and CMS do not have results which can be directly compared due to different parameter space coverage (OS vs SS) in the searches
  - ➡ Ongoing analysis in both collaborations will address both OS and SS signatures with full 2015+2016 data
- The analysis equivalent to the $\ell\ell$qq Run-1 excess is not yet public with 13 TeV data in either collaboration

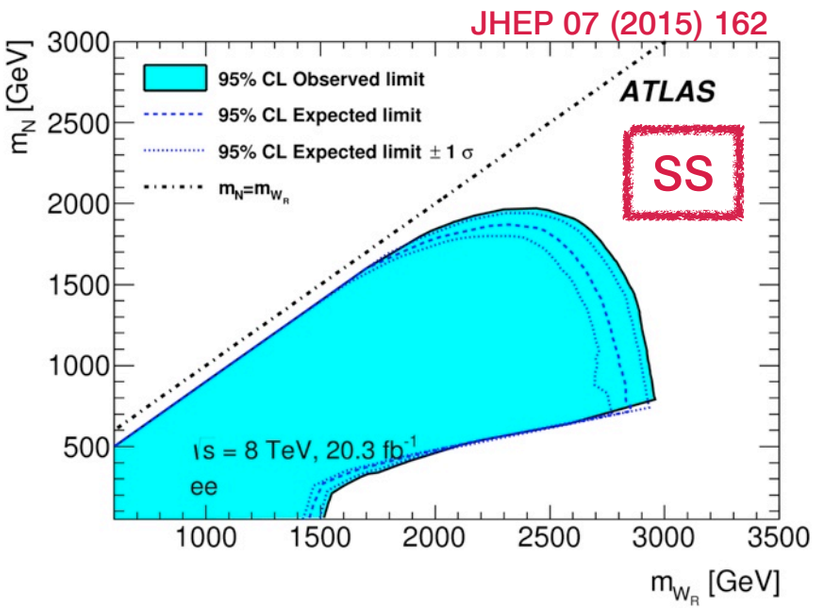
CMS-PAS-EXO-16-023



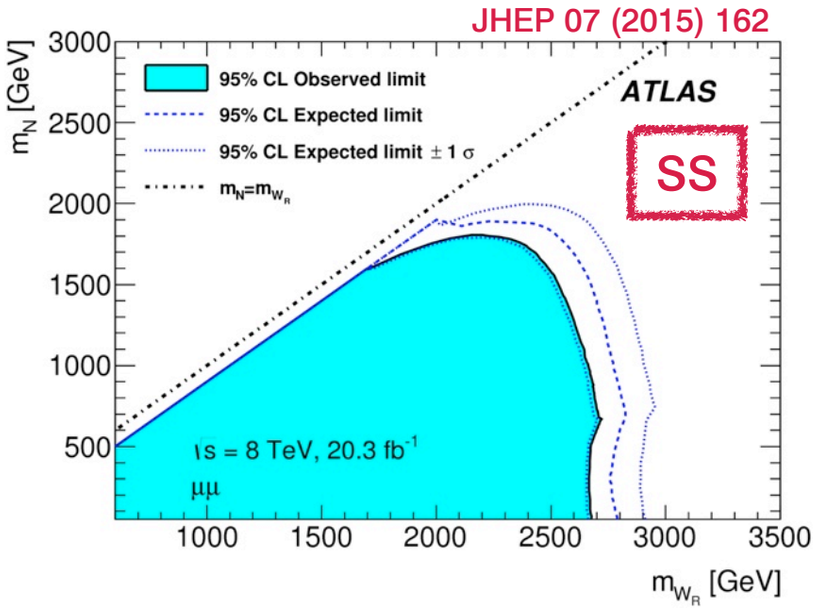
CMS-PAS-EXO-16-026



JHEP 07 (2015) 162



JHEP 07 (2015) 162



Summary

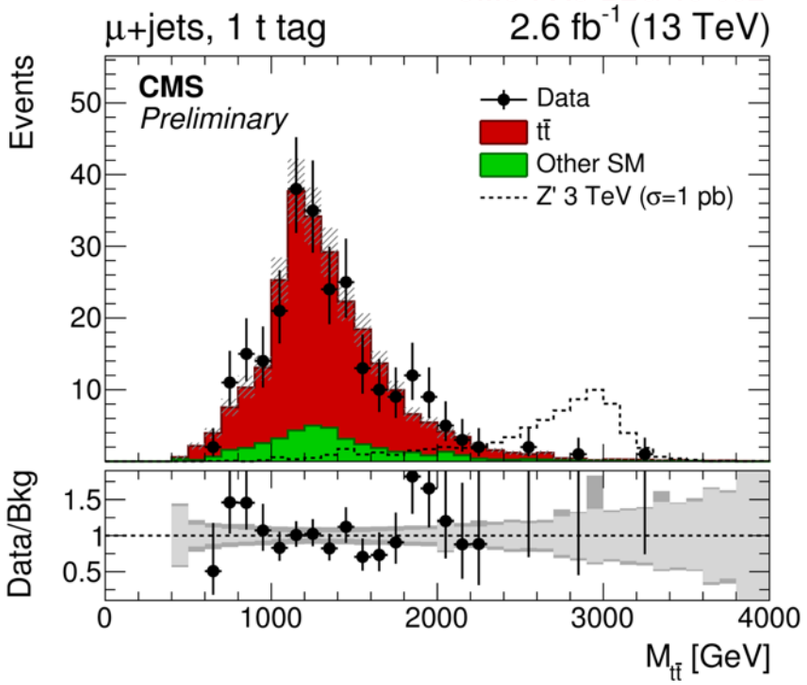
- LHC Run-2 is producing a lot of data in 2016
- Exploring the data in many topologies
  - ➡ Many complex searches with multiple signal regions probed
  - ➡ No significant excesses, only some ~2-3 σ effects (as expected when looking into that many signal regions)
    - More data will tell which, if any, will remain
  - ➡ Many more exciting analysis not covered here, please check the collaborations public pages
- The fantastic performance of the LHC promises a very exciting journey ahead! Stay tuned!

Backup Slides

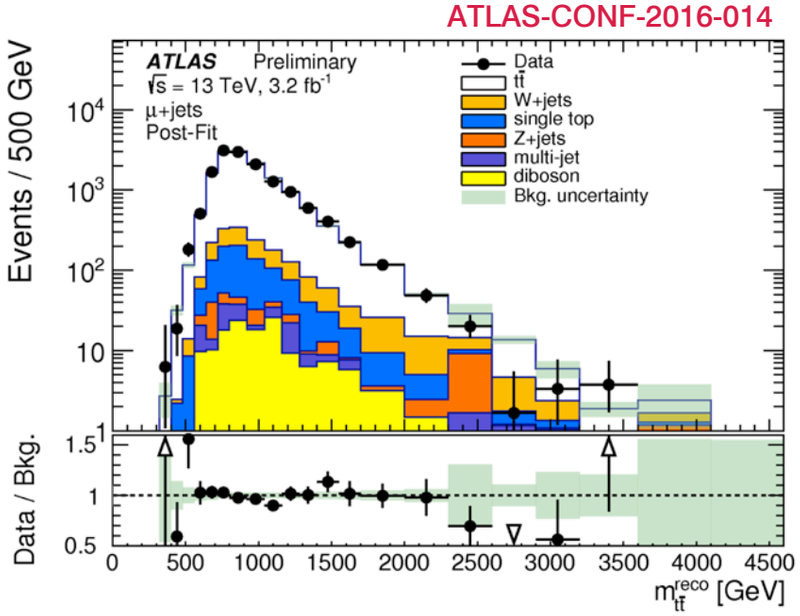
Boosted $t\bar{t}$ Resonances

- Lepton+jets channel
  - ➡ Hadronic top reconstructed as a single jet
- ATLAS:
  - ➡ Results with 13 TeV, 3.2 fb^{-1}
  - ➡ Excludes $Z'_{TC2(1.2\%\ w)} < 2.0$ TeV
- CMS:
  - ➡ Results with 13 TeV, 2.6 fb^{-1}
  - ➡ Excludes $Z'_{SSM\ (1\%\ w)} < 2.2$ TeV
- Note that the mass limits are not comparable due to different models
  - ➡ Cross section limits comparable, slightly better with ATLAS (expected with more luminosity)

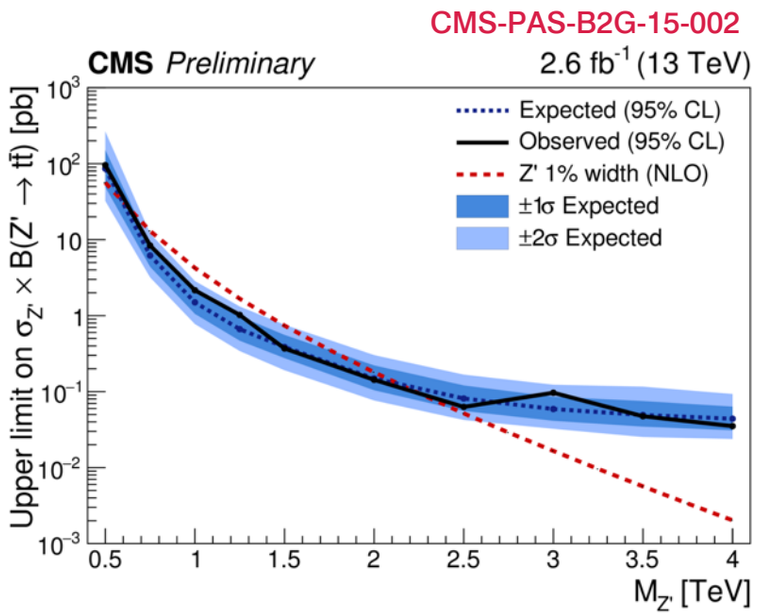
CMS-PAS-B2G-15-002



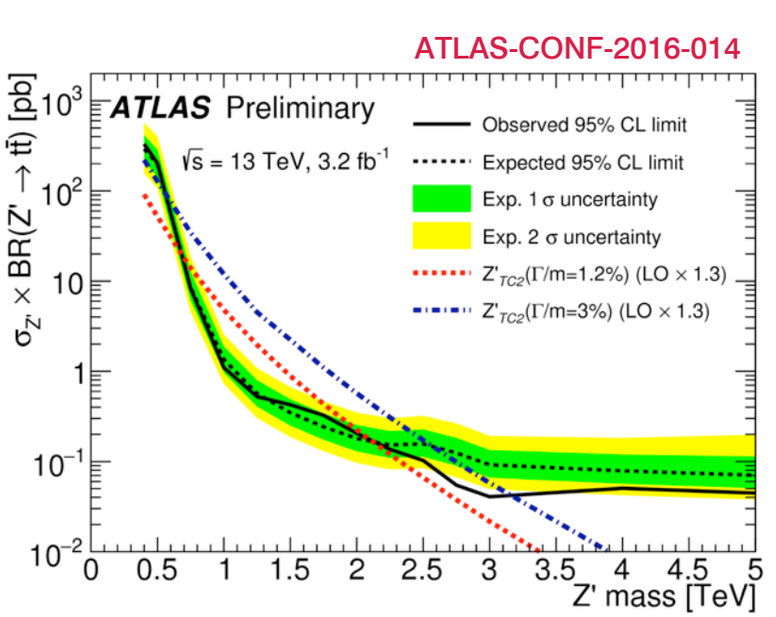
ATLAS-CONF-2016-014



CMS-PAS-B2G-15-002



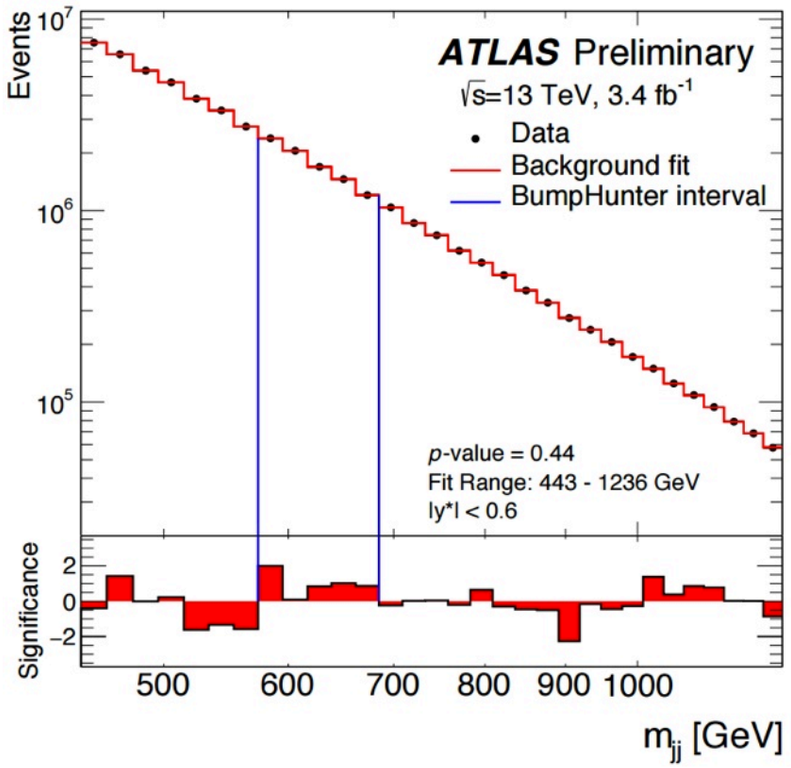
ATLAS-CONF-2016-014



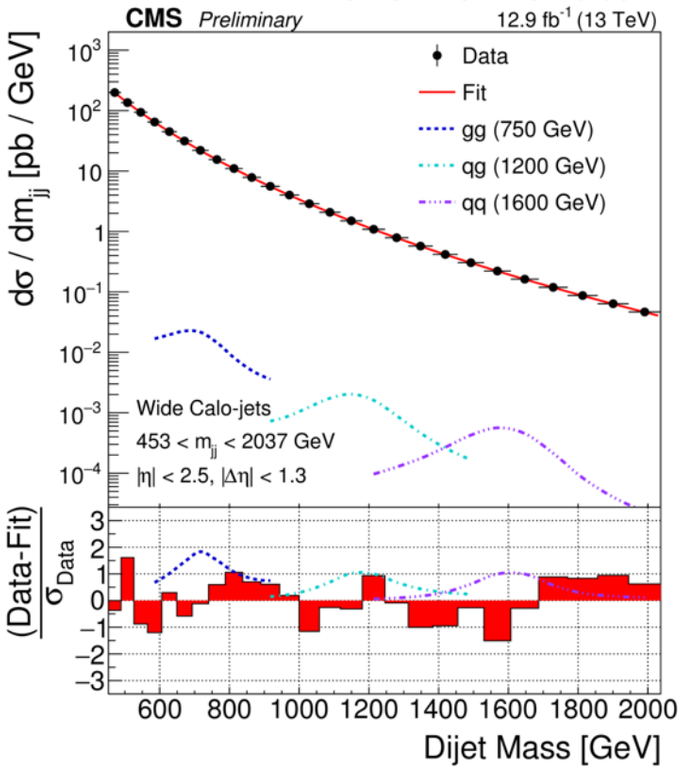
Low Mass Di-jet Resonances

- ATLAS
  - ➡ 13 TeV, 3.4 fb^{-1}
  - ➡ Low mass search uses Trigger-object level analysis
  - ➡ Use partial information events with single jet HLT
- CMS
  - ➡ 13 TeV, 12.9 fb^{-1}
  - ➡ Low mass search uses data scouting from HLT
  - ➡ Calorimeter jets instead of particle flow jets

ATLAS-CONF-2016-030



CMS-PAS-EXO-16-032



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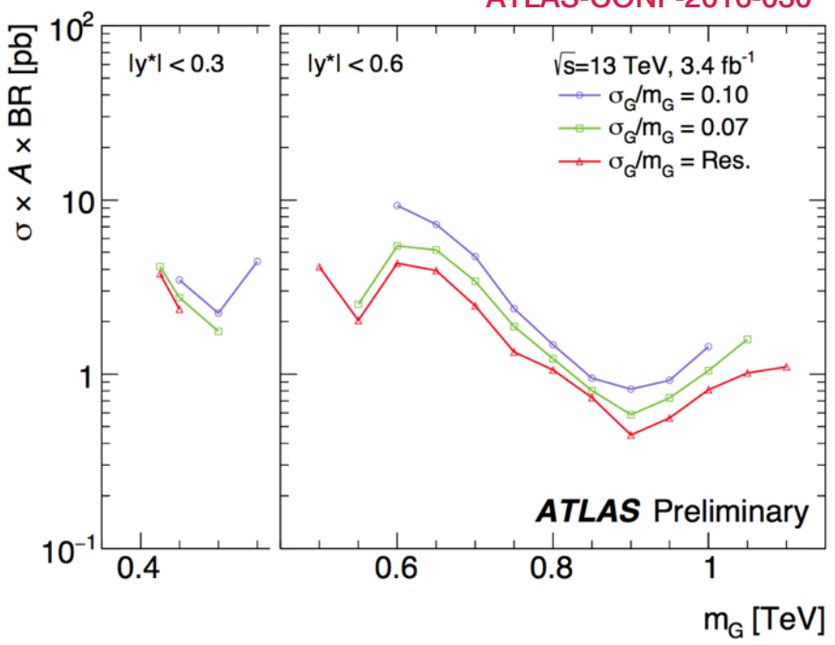

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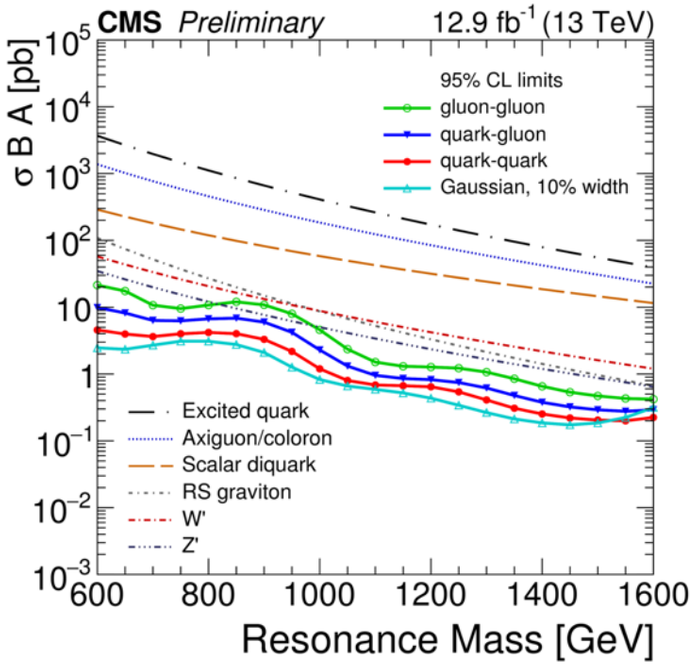
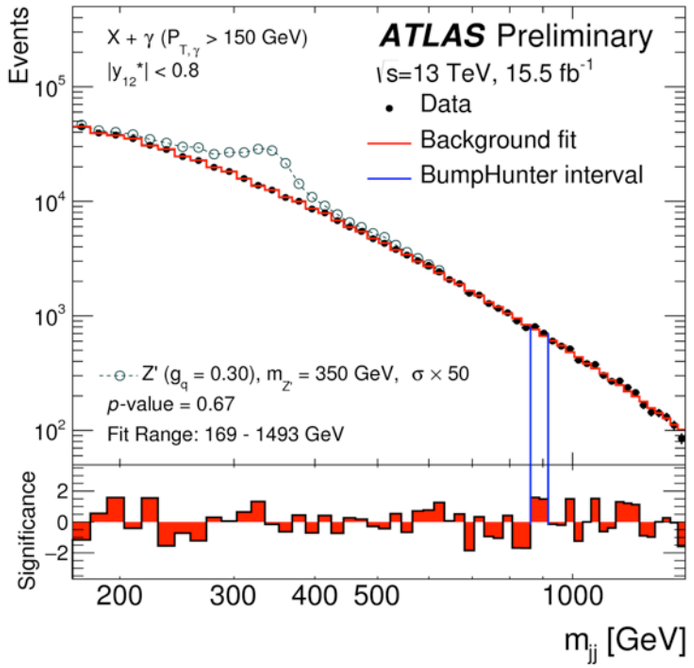
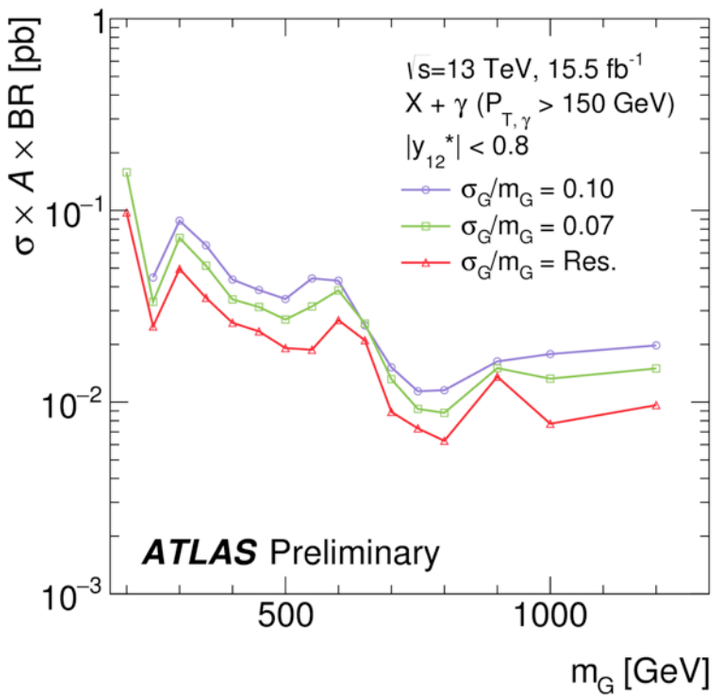


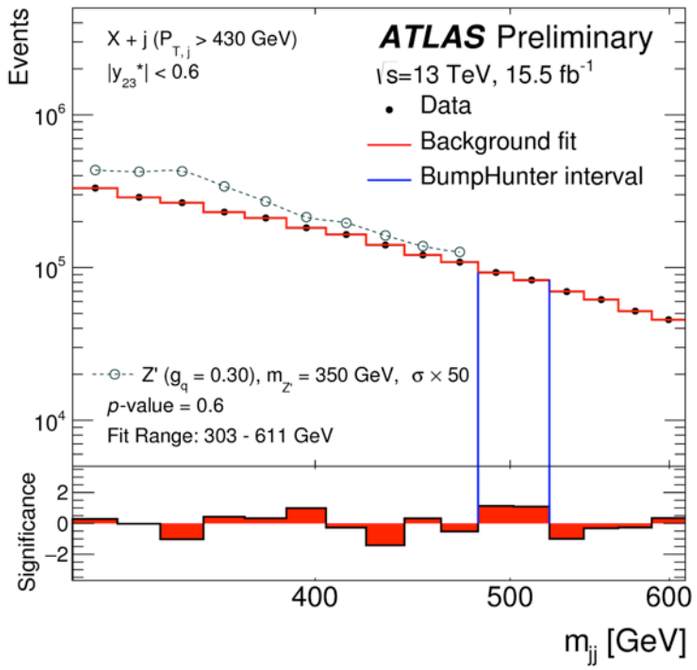
Low Mass Di-jet+ISR Resonances

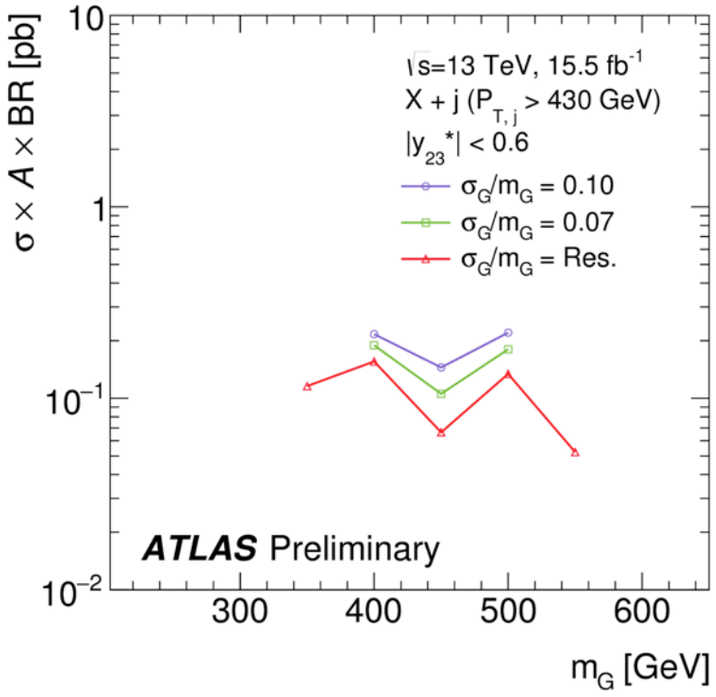
ATLAS-CONF-2016-070

- ATLAS
  - ➡ 13 TeV, 5.5 fb^{-1}
  - ➡ ISR photon or jet used to trigger events at low mass
  - ➡ No excess observed. Cross section limits for gaussian resonances with different width hypothesis



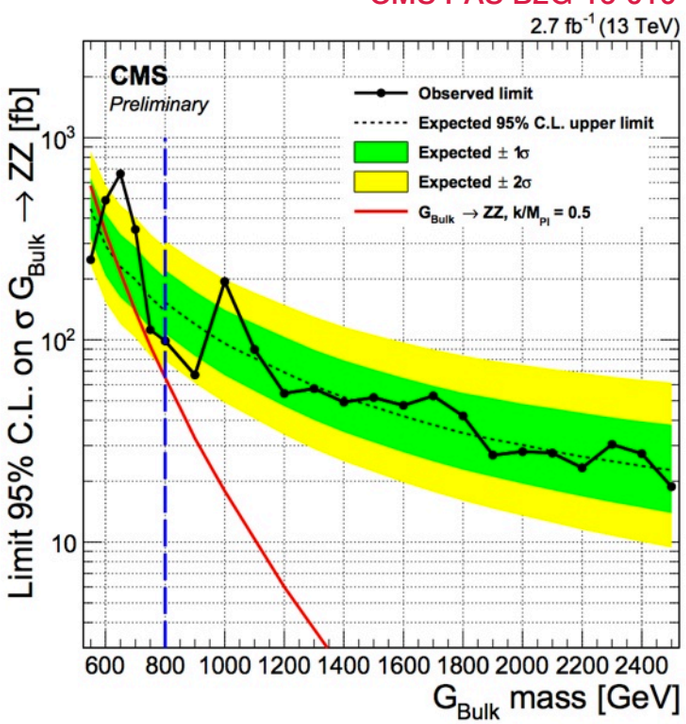




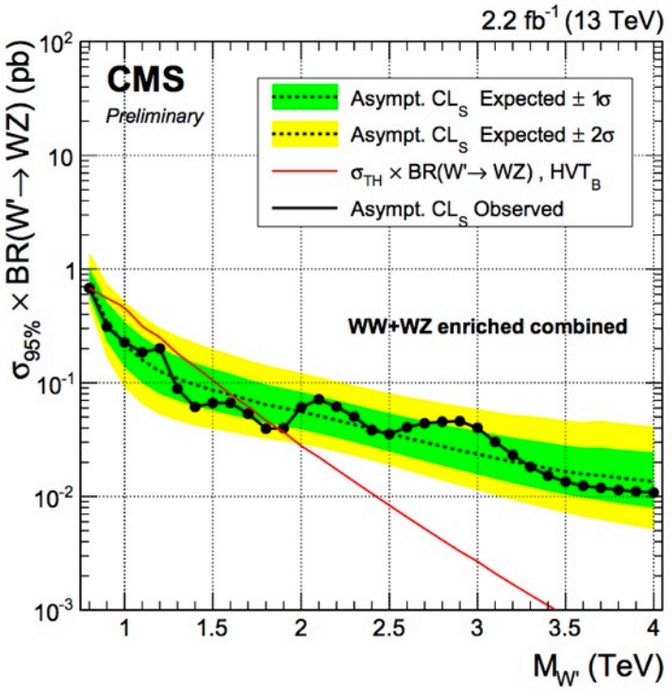


Extra plots - VV

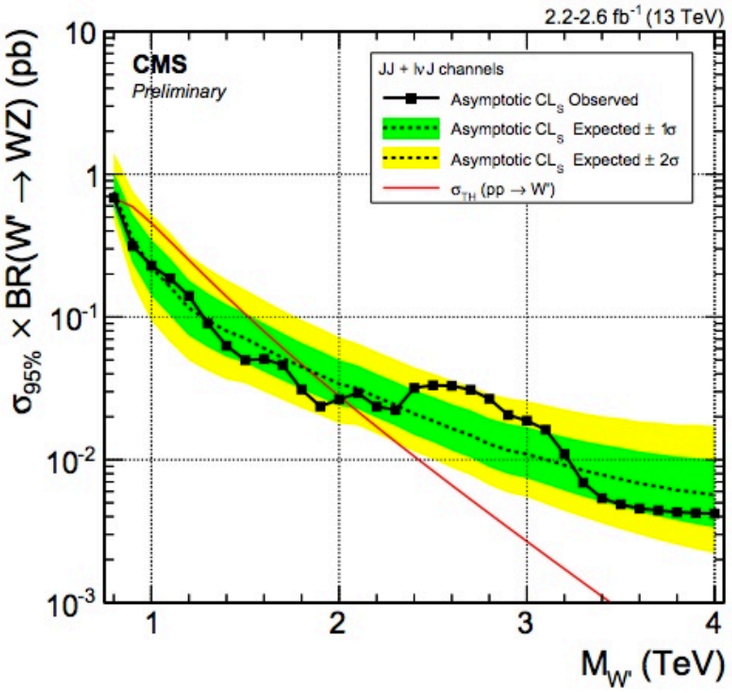
CMS PAS B2G-16-010



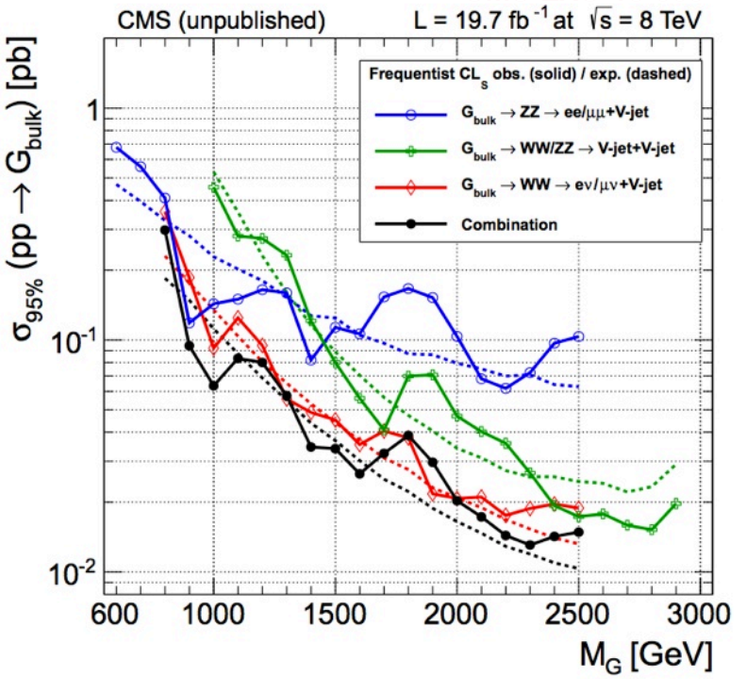
CMS PAS EXO-15-002



CMS PAS EXO-15-002

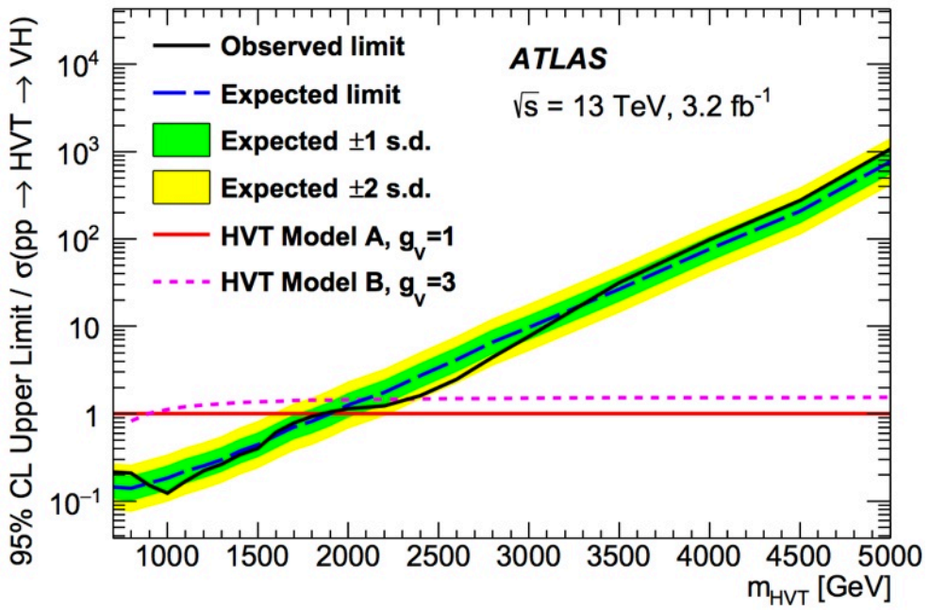


CMS-EXO-13-009



Extra plots - VH

arXiv:1607.05621



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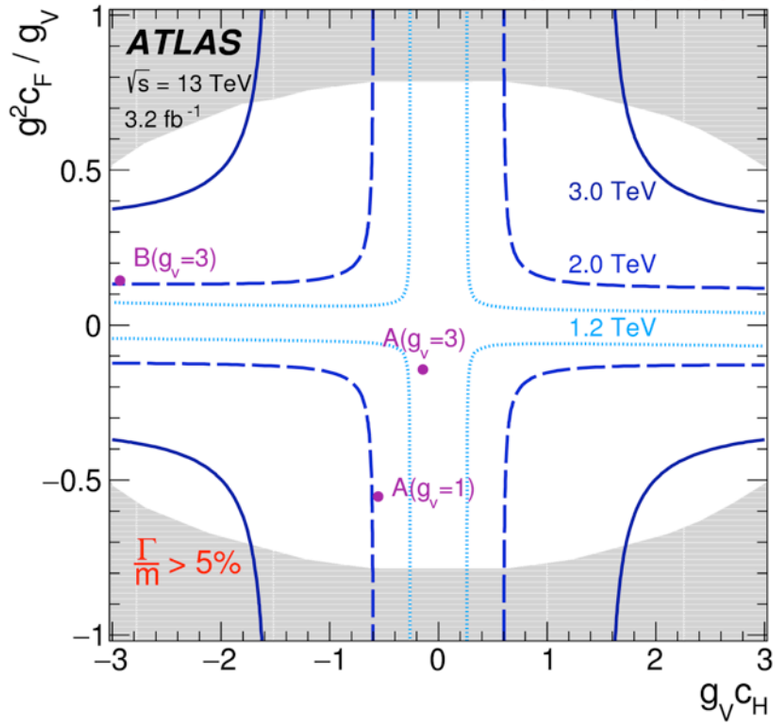
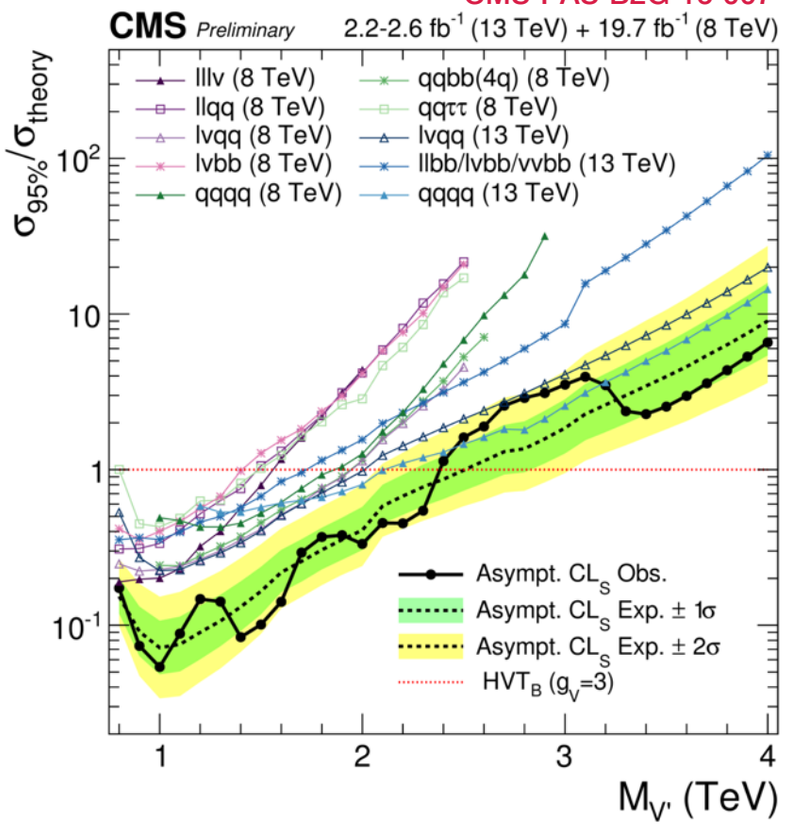
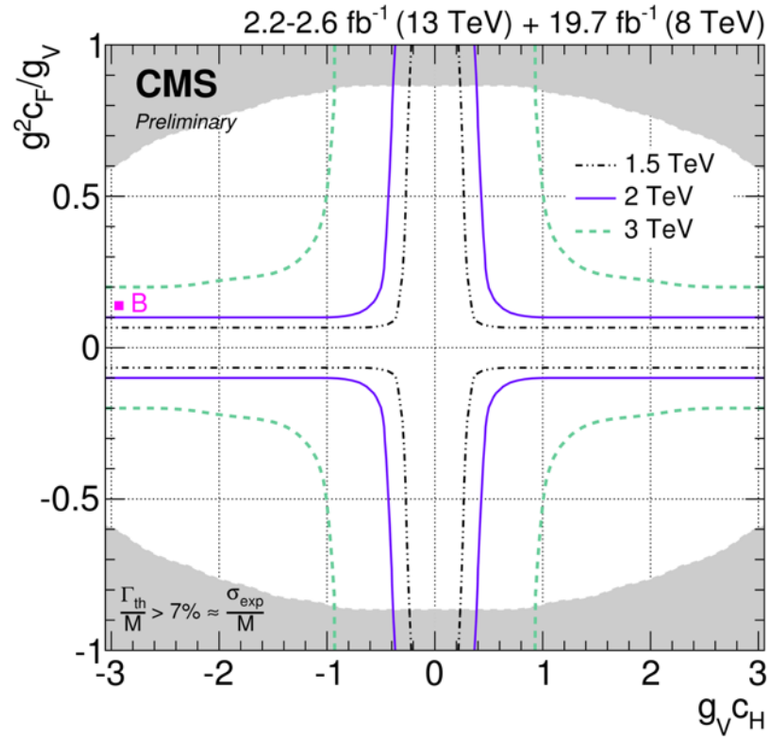


CMS-PAS-B2G-16-007



CMS-PAS-B2G-16-007



Extra plots - Dijet (b-tagged)

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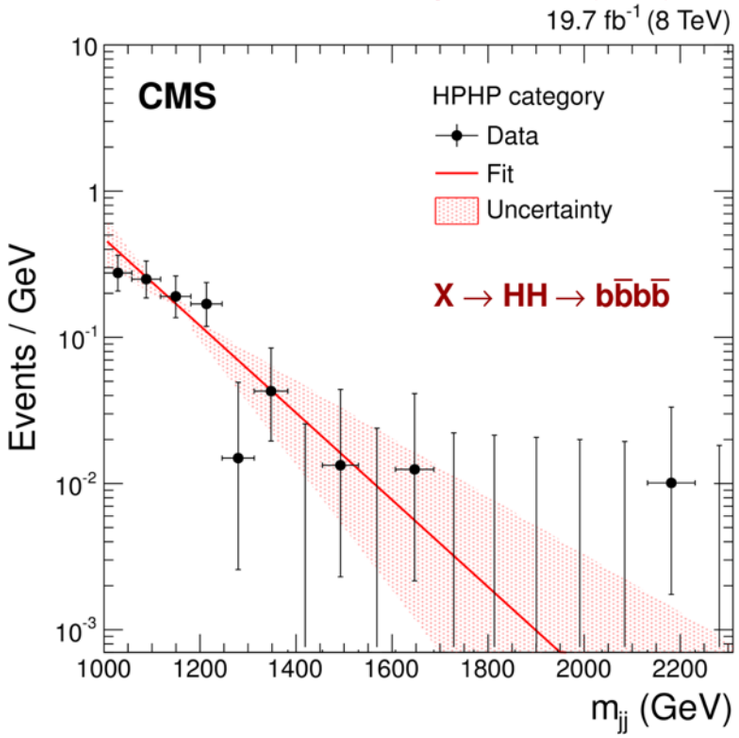
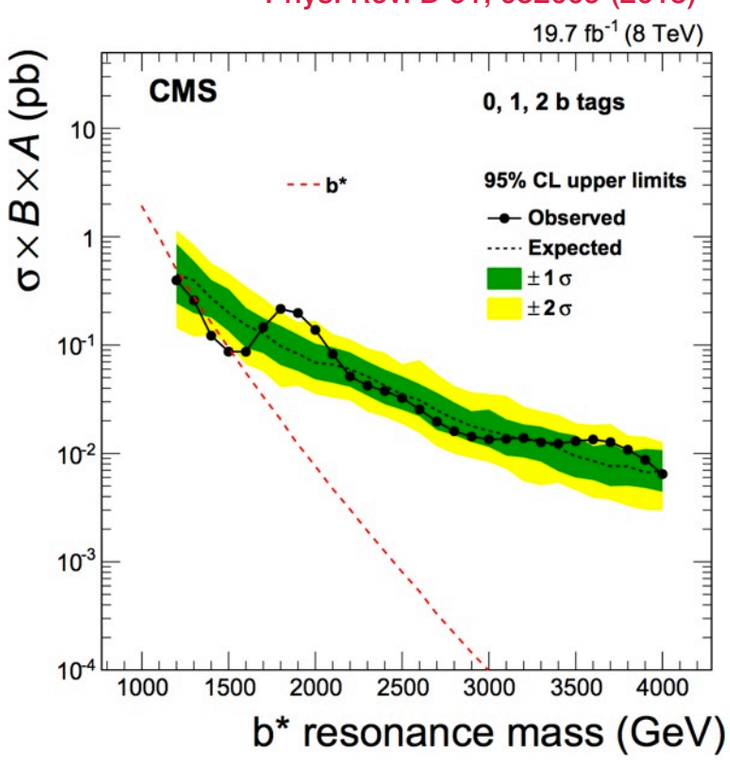
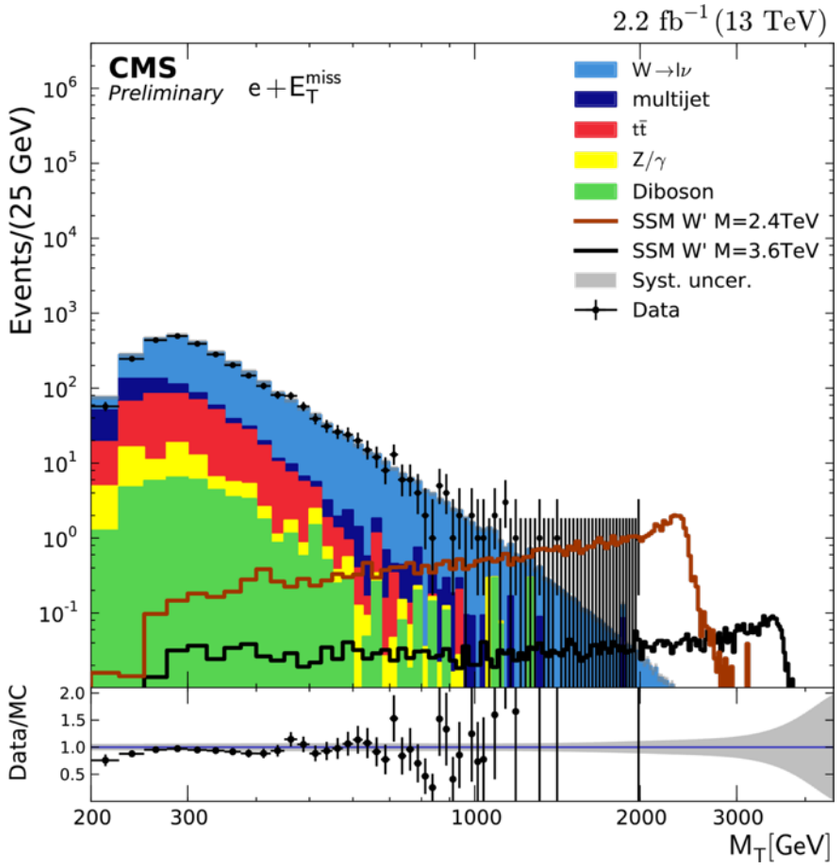


Phys. Rev. D 91, 052009 (2015)



Extra plots - W'→$\ell\nu$

CMS-PAS-EXO-15-006



CMS-PAS-EXO-15-006