Diboson and Triboson Resonant and Nonresonant Production

Tracey Berry on behalf of the ATLAS and CMS collaboration

HEFT October 28th 2016, Copenhagen

ROYAL HOLLOWAY UNIVERSITY OF LONDON

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Troels C. Petersen on behalf of…
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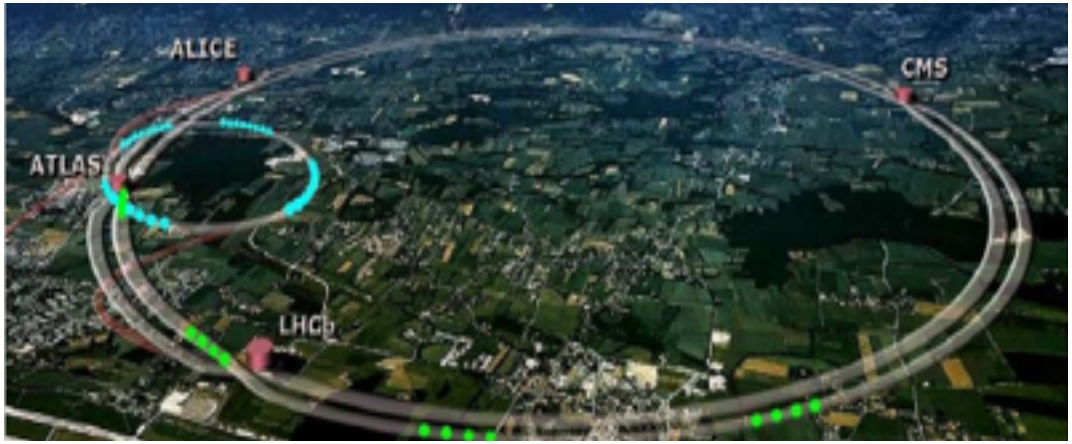
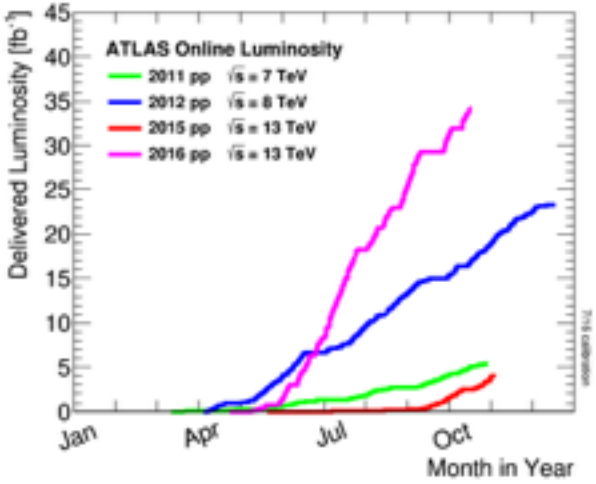
LHC

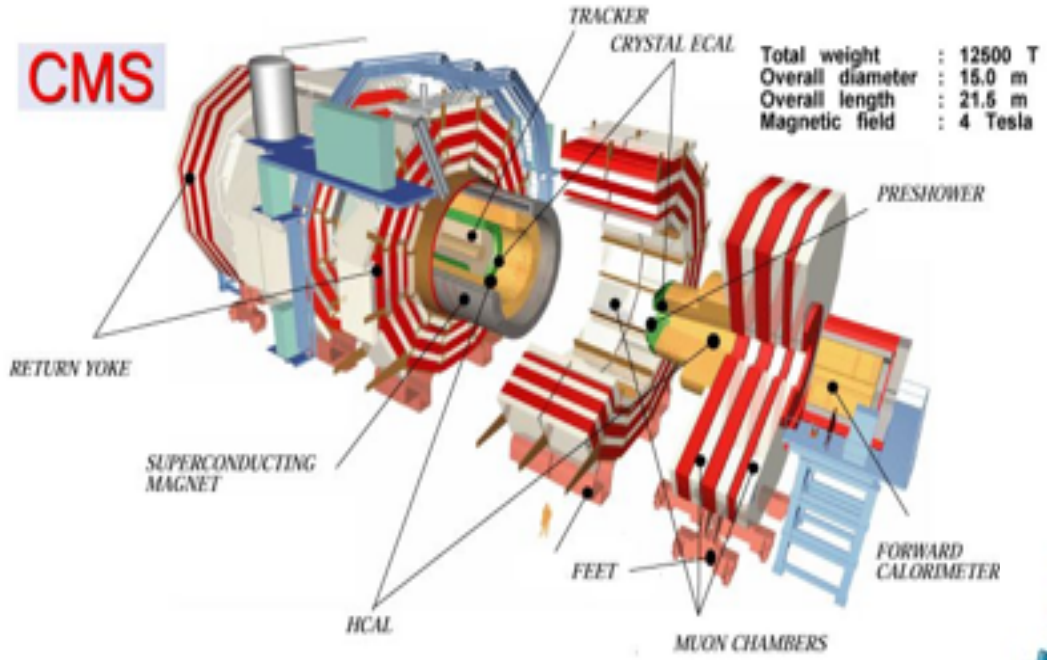


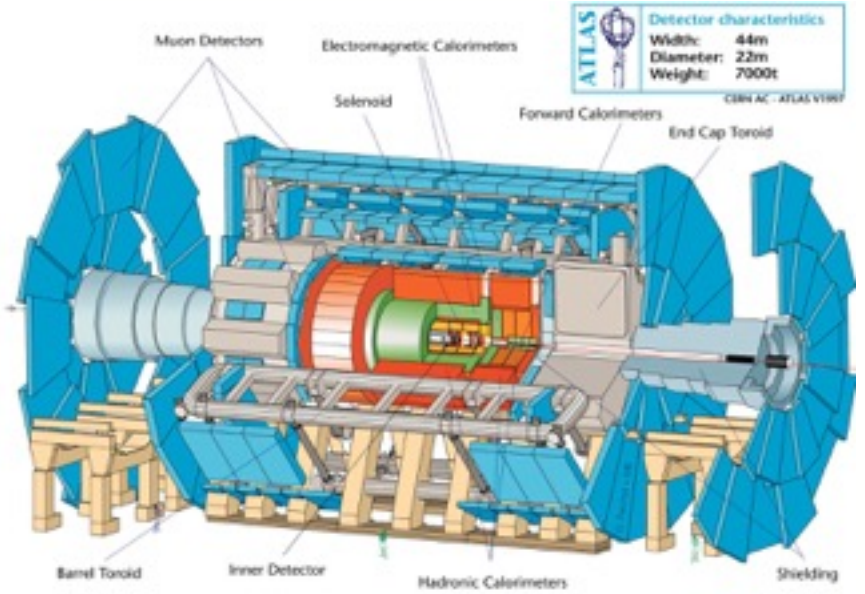


LHC performance impressive

Run 1 : **5** fb^{-1} delivered @ 7 TeV in 2011, and **20** fb^{-1} @ 8 TeV in 2012

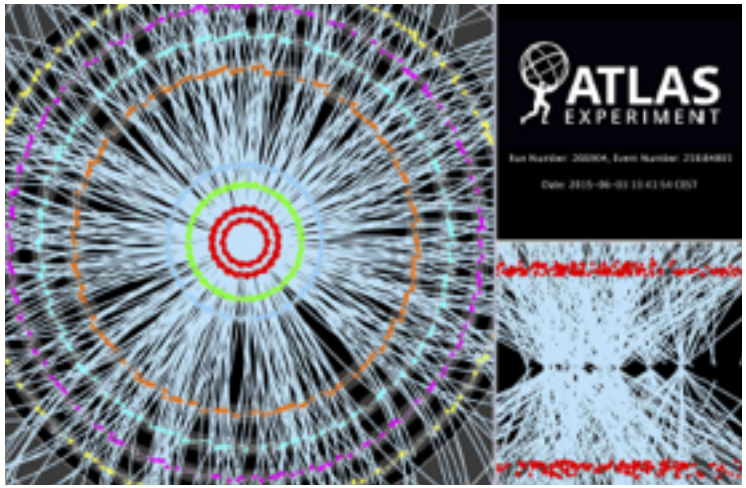
Run 2 @ 13 TeV started in 2015 with **3** fb^{-1}, and already > **40** fb^{-1} this year


CMS
TRACKER
CRYSTAL ECAL
Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla
PRESHOWER
RETURN YOKE
SUPERCONDUCTING MAGNET
FEET
FORWARD CALORIMETER
HCAL
MUON CHAMBERS

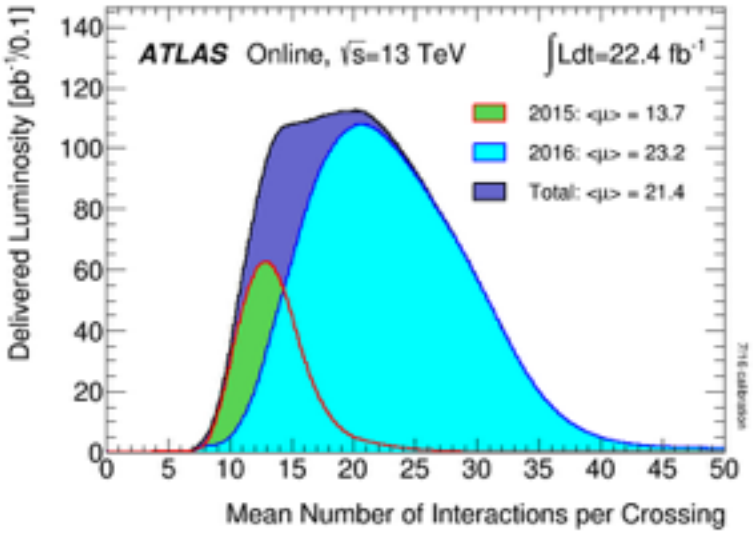

ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
Muon Detectors
Electromagnetic Calorimeters
Selenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

LHC Data

LHC: already > 40 fb^{-1} this year, but ...



2015 Atlas event with
17 reconstructed vertices



- high number of collisions per crossing (despite switch to 25 ns for run 2)
- Challenge for Jets (energy scale, resolution) and Missing Et
- Simulated in MC

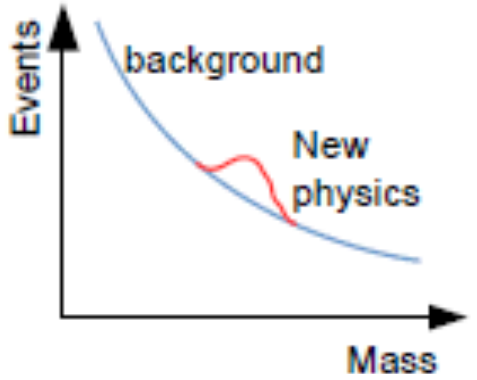
Overview:

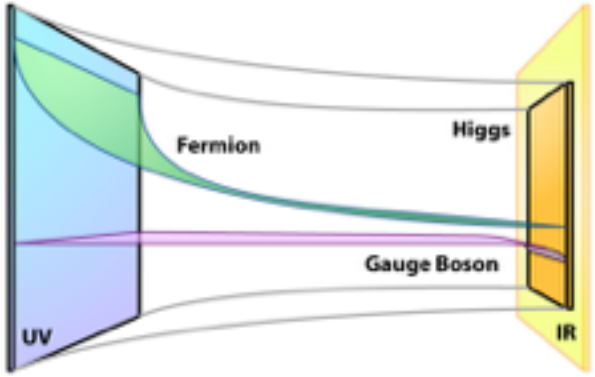
Exotics Diboson Searches

Reconstruct decay product of resonance X for a **peak** on a **smooth background**.

- ***Benchmark*** *models*
- Spin-0 : Heavy scalars in extended Higgs sector
- Spin-1 : Extended gauge models

  W', Z' in SSM/ Heavy Vector Triplet models:
  - Model A : stronger constraints from leptonic searches
  - Model B : enhanced couplings to dibosons
- Spin-2 : Randall-Sundrum Gravitons (RS G)





Excitement from Run-1 searches in VV→ JJ channels

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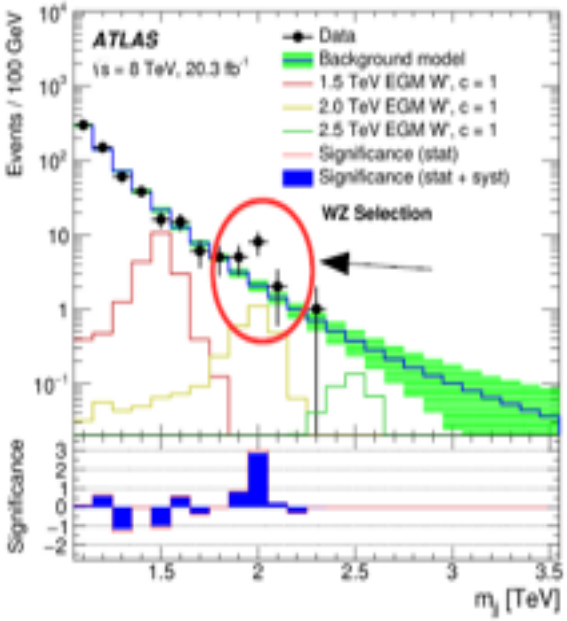
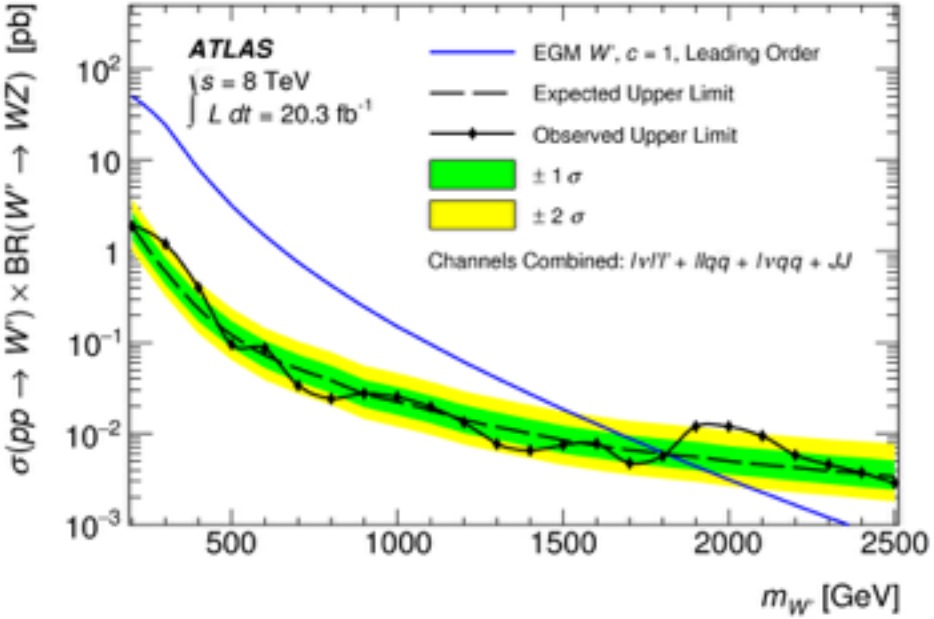
Reminder of Run 1 excesses in diboson searches

- ATLAS : **2.5σ excess** (*MV'* = 2 TeV) for fully hadronic W' → WZ [arXiv:1506.00962]
- significance decreases in combination with semileptonic channels [arXiv:1512.05099]
- CMS : **1.9σ excess** (*MV'* = 1.8 TeV) for W' → WH → lvbb [arXiv:1601.0643]
- ATLAS : **no excess** in W' → WH → lvbb [arXiv:1503.08089]
- Less sensitive to high mass resonances with resolved jet analysis
- For Run 2: Use **boosted jet selection** (large-R jets)

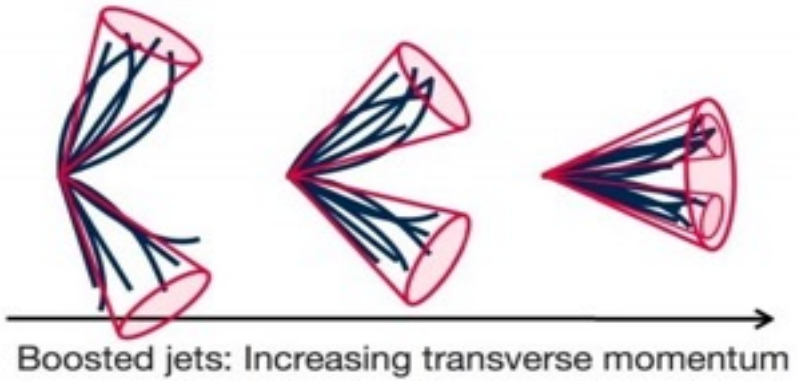




Di-boson FinalStates

Diboson *searches in this talk: many final states*

- *VV → qqqq*
- *VV → vvqq , lvqq , llqq*
- *VH → vvbb , lvbb , llbb*
- *HH → bbbb*
- γγ



Wide range of boson p_T's leading to distinct topologies for their hadronic decays:

- **Resolved**: 2 small R jets (jj) for boson p_T up to a few hundred GeV
- **Boosted**: single large R jets (J) for higher boson p_T

(Notation: "j" for akt4 jets, "J" for akt10 jets)

Jet Cleaning

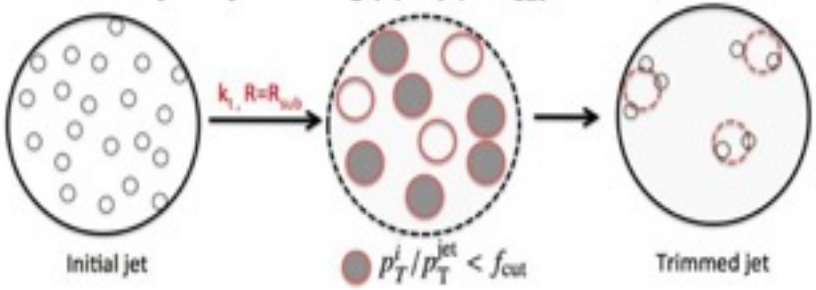
Get rid of softer components in a jet from UE or pileup and leave constituents from the hard scatter behind

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)

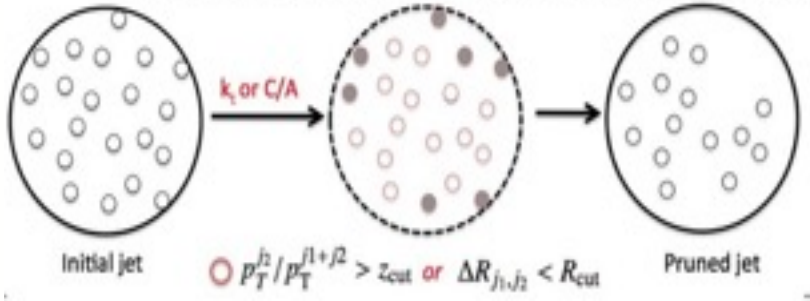
- uses k_t algorithm to create subjets of size R_{sub} from the constituents of the large-R jet: any subjets failing $p_T i / p_T < f_{cut}$ are removed



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

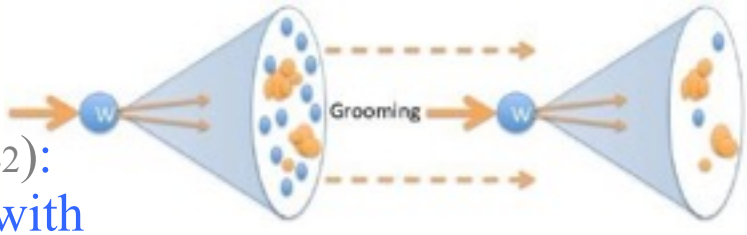


Tuned parameters: R_{cut} and z_{cut}

Event Selection

- **Grooming:** to minimize impact of energy deposits from pile-up interactions
  - ATLAS mainly uses "Trimming" (arXiv:0912.1342): re-cluster with k_t R=0.2 and remove sub-jets with

$$p_{\mathrm{T}}^{\mathrm{subjet}} / p_{\mathrm{T}}^{\mathrm{jet}} < 0.05$$



- **W/Z boson tagging:** ATL-PHYS-PUB-2015-033
  - m_J consistent with m_W/m_Z within ±15GeV
    - W and Z windows overlap
  - Sub-structure consistent with two-prong decay
    - Most popular variable: $D_2^{(\beta=1)}$ (arXiv: 1409.6298, 1507.03018)
    - Typical WP: ε=50%, QCD rejection factor ~50

- **Higgs boson (b-) tagging:** ATL-CONF-2016-039
  - Match to anti-k_t R=0.2, b-tagged track-jets

Large-R Jets - Boson Tagging

EPJC 76(3), 1-47

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 $D_2^{B=1}$ consistent with two prong decay
  - High and Low purity (HP, LP) categories based on $D_2^{B=1}$
- Higgs boson tagging:
  - Match to anti-k_T R=0.2 b-tagged track jets

CMS PAS JME-14-002

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

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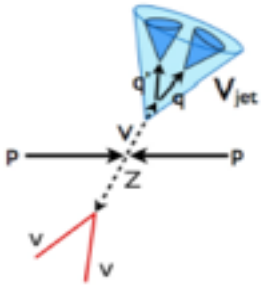
VV → ννqq , lνqq , llqq : selection

- *One large-R (R = 1.0) anti-kt jet (groomed)*
  - pT > 200 GeV
  - W/Z boson tagged
    - 50% efficiency working point
    - QCD rejection factor of 40-70 per jet
- *Three lepton channels :*

One V decays hadronically
→ Reconstructed as large-R jet, boson tagged, p_J^T >200 GeV

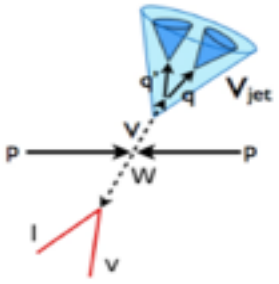
Other V decays leptonically (either 0, 1, or 2 charged leptons).

- **0 lepton channel**
- veto on leptons
- E_T^{miss} > 250 GeV
- E_T^{miss}, p_T^{miss}, jet angular cuts
- b-jet veto
- Bkgs: V+jets, tt, Diboson



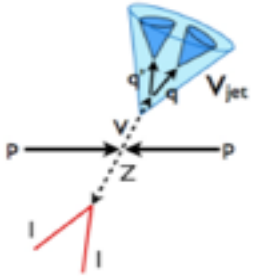
Can be: ZW, ZZ

- **1 lepton channel**
- exactly 1 lepton
- E_T^{miss} > 100 GeV
- $p_T^{lv\,J} > 0.4m_{lvJ}$
- b-jet veto
- Bkgs: W+jet, tt, Diboson



ZW, ZZ

- **2 lepton channel**
- exactly 2 leptons
- $p_T^{ll\,J} > 0.4m_{llJ}$
- b-jet veto
- Bkgs: Z+jets, Diboson



WW, WZ

WW, ZW, ZZ

ZV→ llqq

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- Look into a Z boson leptonic (ee, μ μ) decay in association with a hadronic vector boson (W,Z)

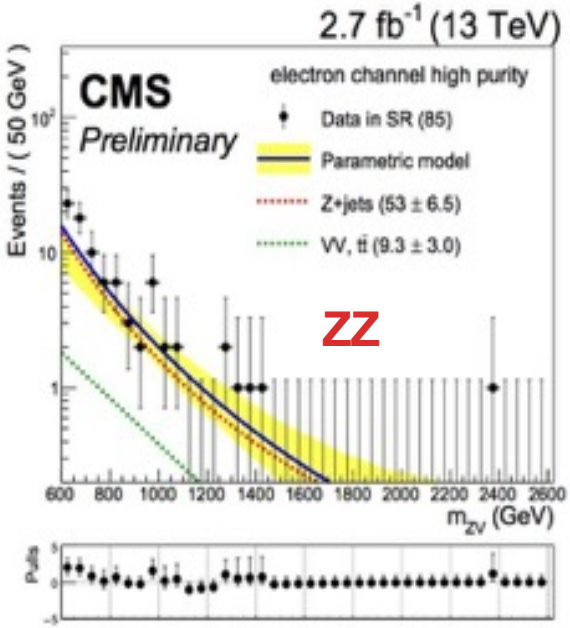
  Dominant background: Z+jets. Contributions from diboson, top processes

CMS: Latest public results with 13 TeV, 2.7 fb^{-1}, boosted and resolved regime

ATLAS: 13 TeV, 13.2 fb^{-1} results

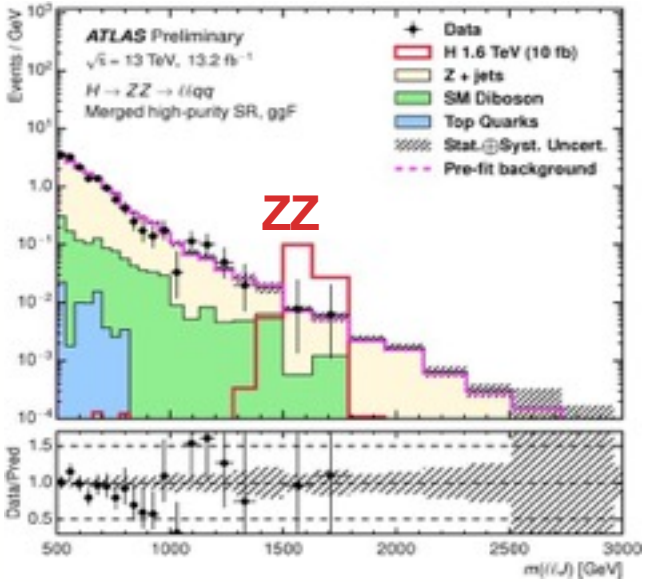
Analysis includes both resolved and boosted regime, looking for new resonances from 500 - 5000 GeV

CMS PAS B2G-16-010



y,

ATLAS-CONF-2016-082



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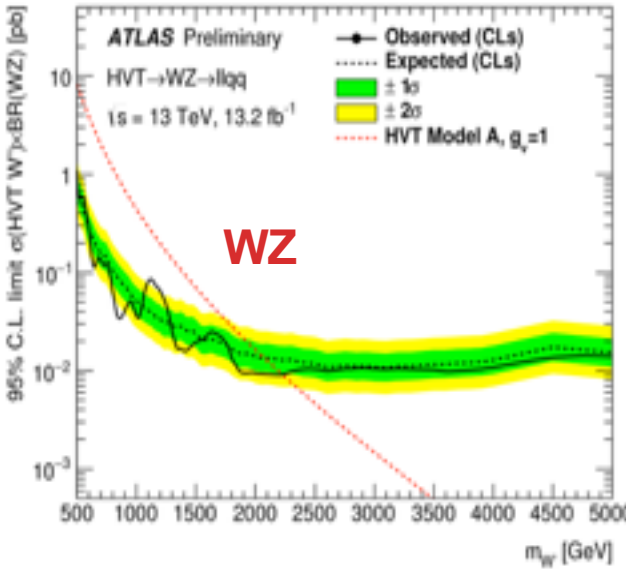


X→WV→ lνqq

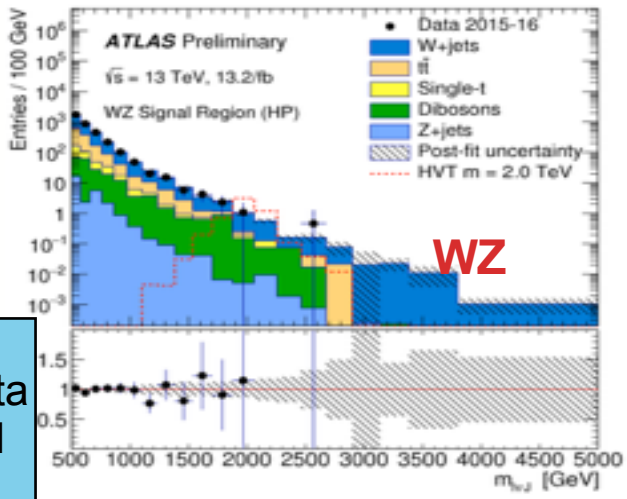
Look into a W boson leptonic (e, μ) decay in association with a hadronic vector boson (W,Z)

Backgrounds: W+jets, top, diboson, Z+jets

ATLAS 13 TeV, 13.2 fb^{-1} results , boosted regime

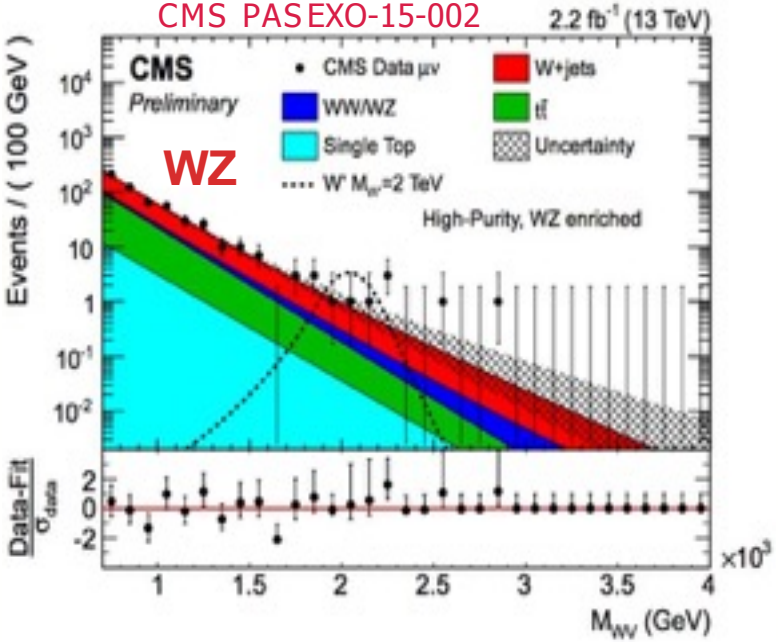
CMS Latest public results with 13 TeV, 2.2 fb^{-1}, boosted regime

ATLAS-CONF-2016-062

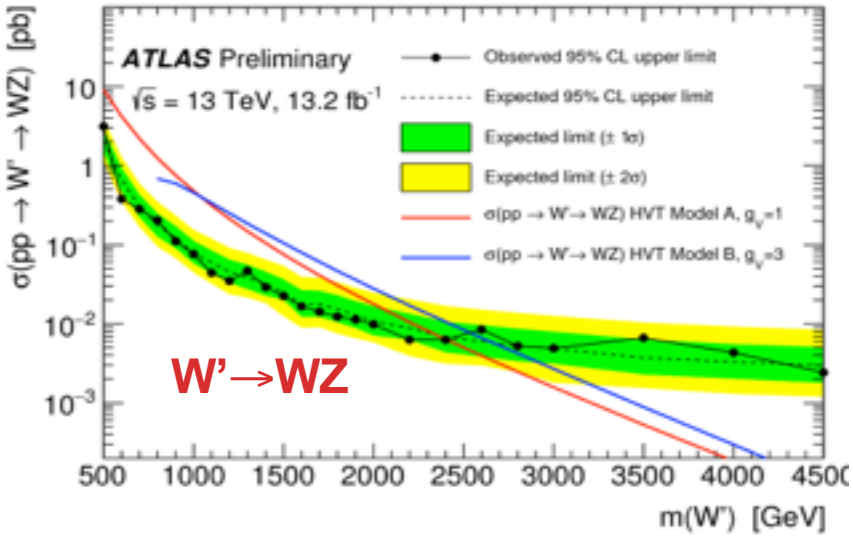


No excess observed in data over predicted background…

CMS PAS EXO-15-002



ATLAS-CONF-2016-062



WV→ lvqq

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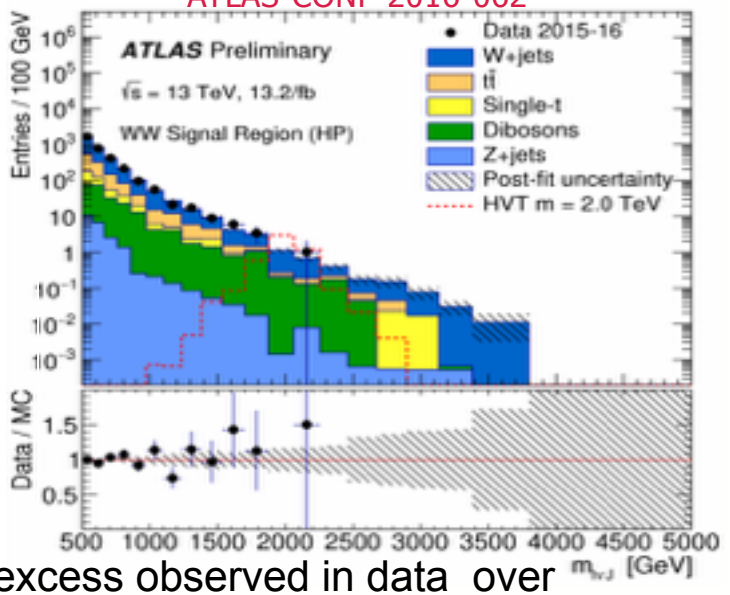
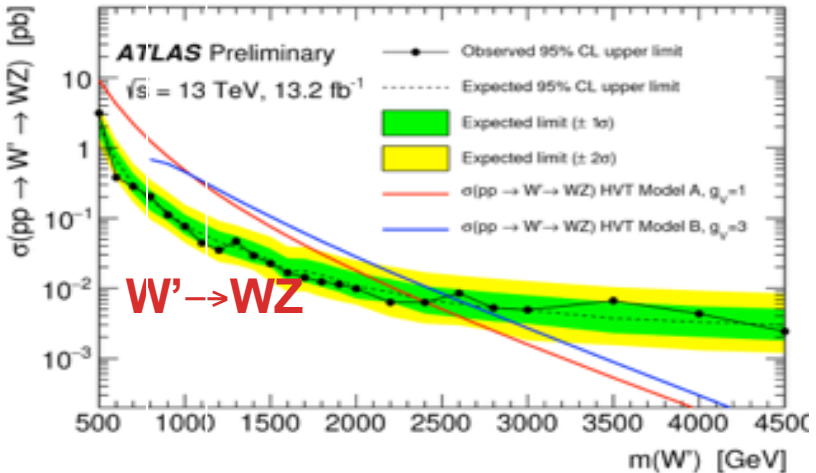
- W → lν: E_T > 100 GeV, p_T(lν) > 200 GeV
- V→qq with large-R jet boson-tagging
  - large-R jet with pT>200GeV
  - High/low purity regions (wrt. $D_2^{(\beta=1)}$ cut)

ATLAS-CONF-2016-062



No excess observed in data over predicted background…

- Dominant bkgs: W+jets and ttbar
  - Estimated using control regions in data, which are included in the combined fit
    - W+jets CR: m_J sidebands
    - Top CR: at least one b-tagged akt4 jet
- Discriminant: transverse mass m_{lvJ}



X→ZV→ ννqq

Look into a Z boson invisible ("") decay in association with a hadronic vector boson (W,Z)

ATLAS

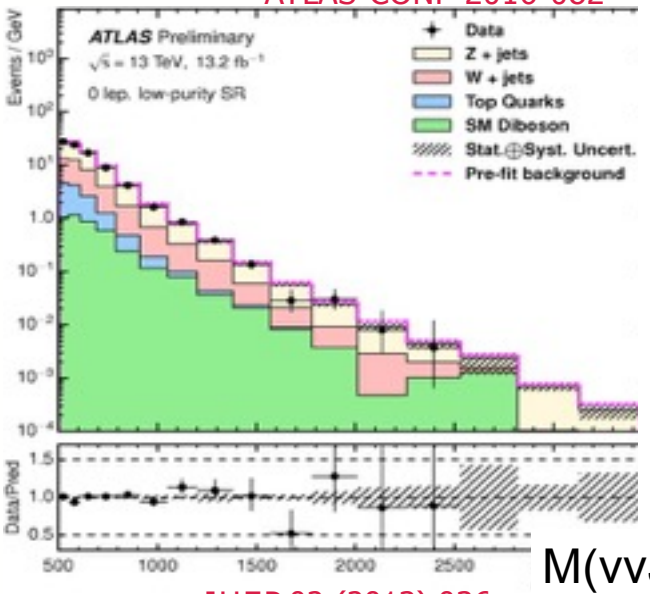
13 TeV, 13.2 fb^{-1} results

Boosted regime

CMS

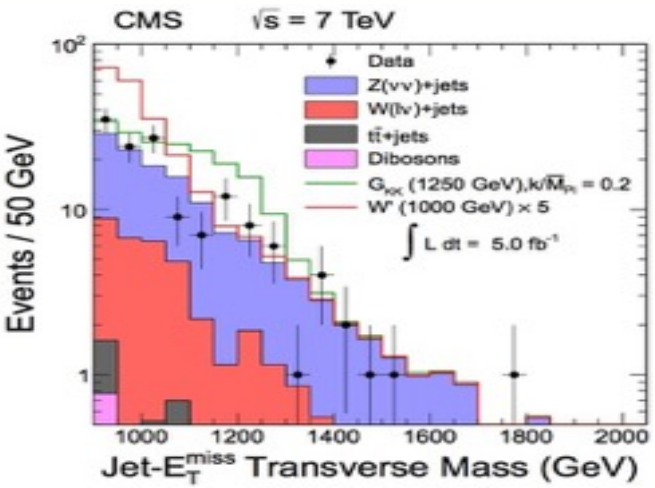
Latest public results in diboson context with 7 TeV, 5 fb^{-1}

ATLAS-CONF-2016-082



M(νvJ)

JHEP 02 (2013) 036



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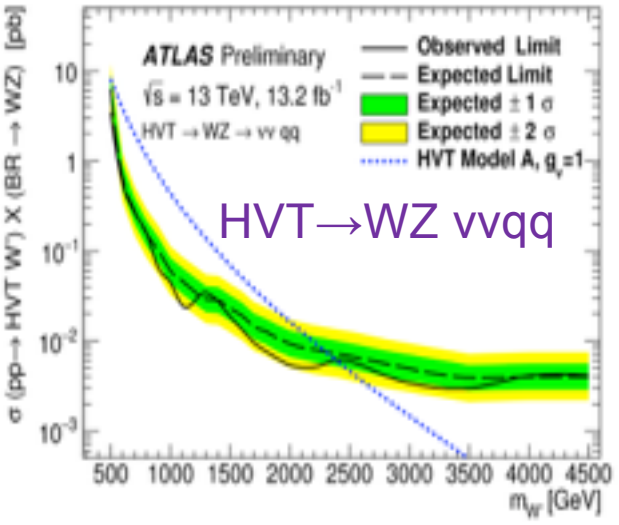

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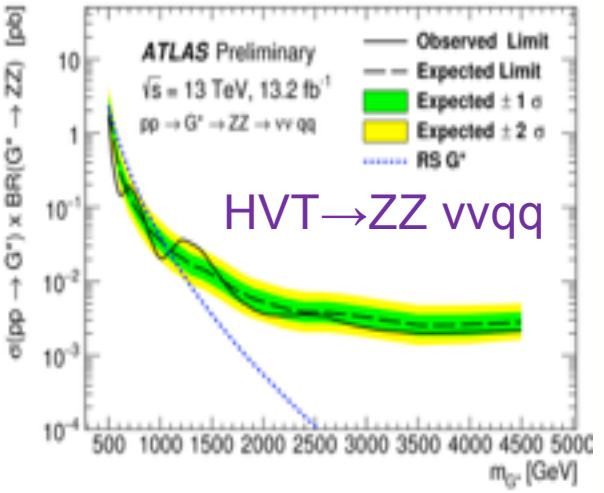


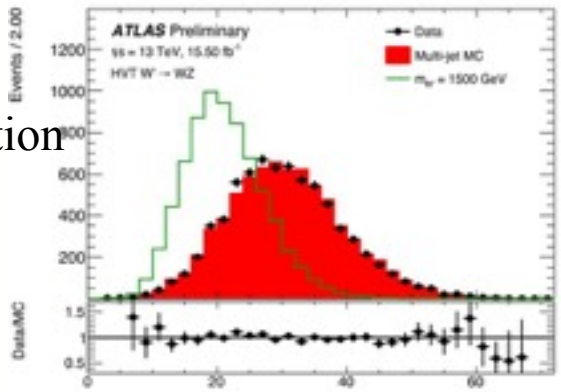
X→VV→ qqqq

- Slight excess @~2TeV in Run-1 result…

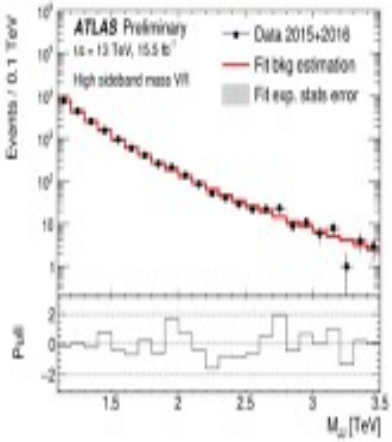
- Run-2 analysis has similar kinematic selection but uses trimmed akt10 jets
  - Two very high jets: p_T>450/200GeV
  - Standard boson tagging ($D_2^{\beta=1}$)
  - Number of tracks in a jet < 30
    - ~30% improvement in sensitivity
- Multijet bkg dominant (others negligible)
  - Data-driven estimate, modeled with

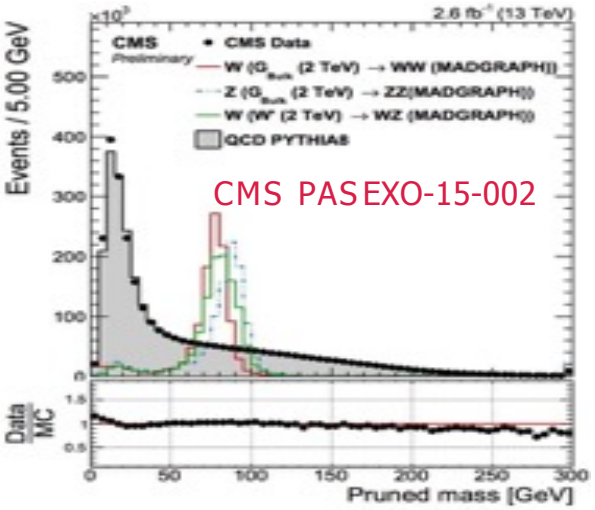
$$\frac{dn}{dx} = p_1(1-x)^{p_2+\xi p_3}x^{p_3} \qquad x = m_{JJ}/\sqrt{s}$$

  - Tested in several control regions in data, e.g.
    - Both jets in boson mass sidebands (low, high, mixed)
    - Only one of the two jets satisfies boson-tagging cuts



ATL-CONF-2016-055





CMS PAS EXO-15-002

➡ CMS 13 TeV, 2.6 fb^{-1}

➡ Same jet algorithm, grooming and substructure selection as Run-1 analysis

X→VV→ qqqq results

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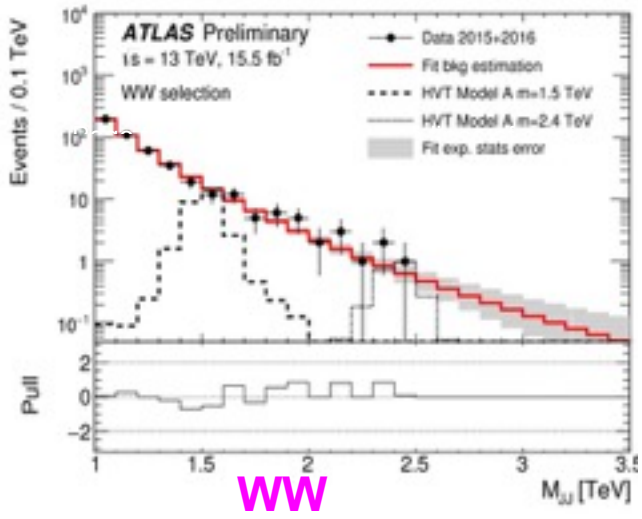
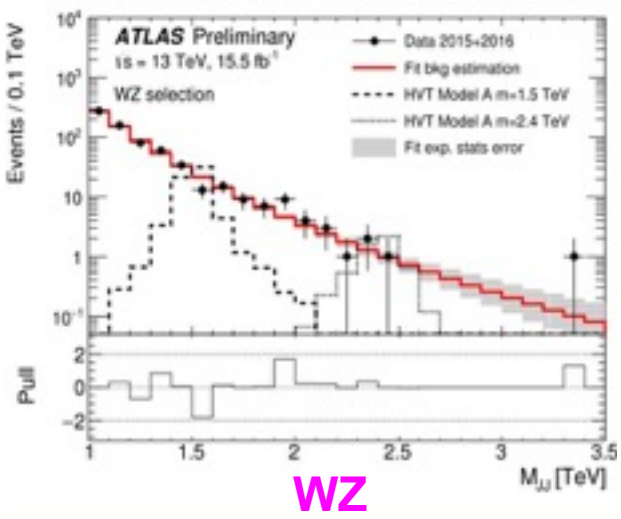
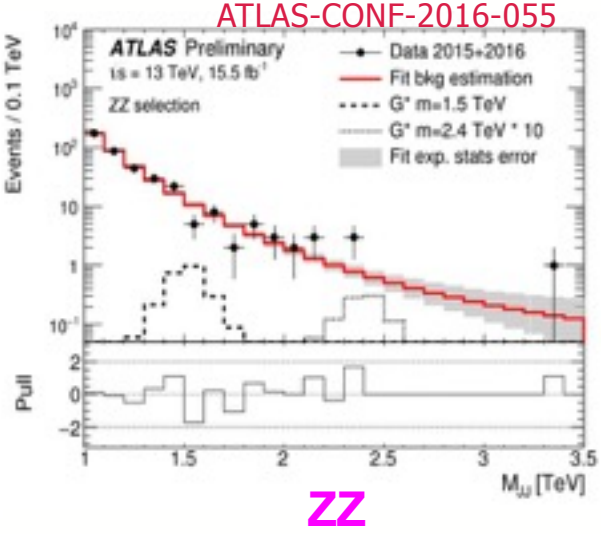
ATLAS-CONF-2016-055



WW

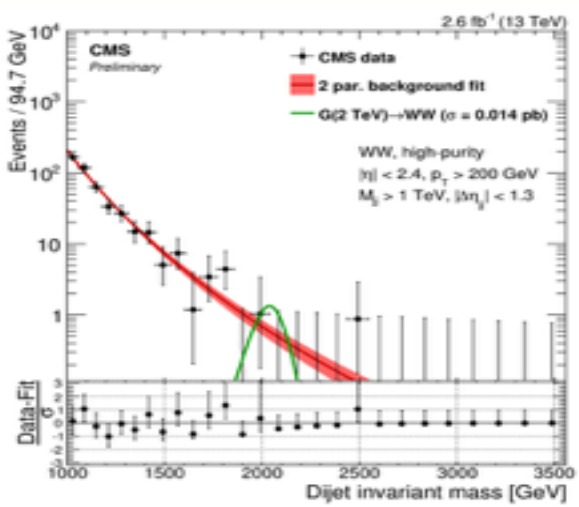


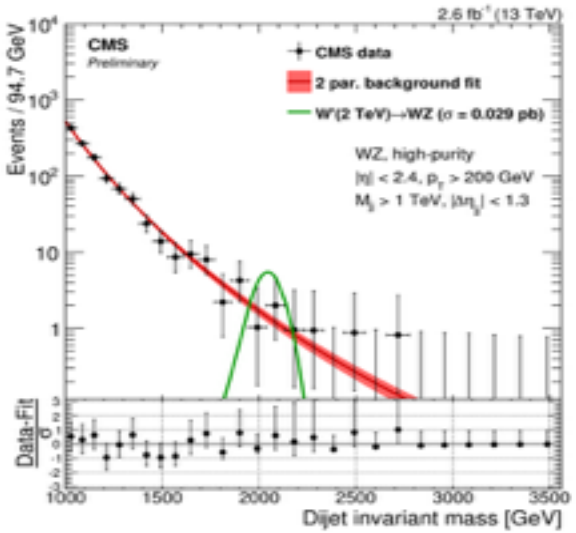
WZ

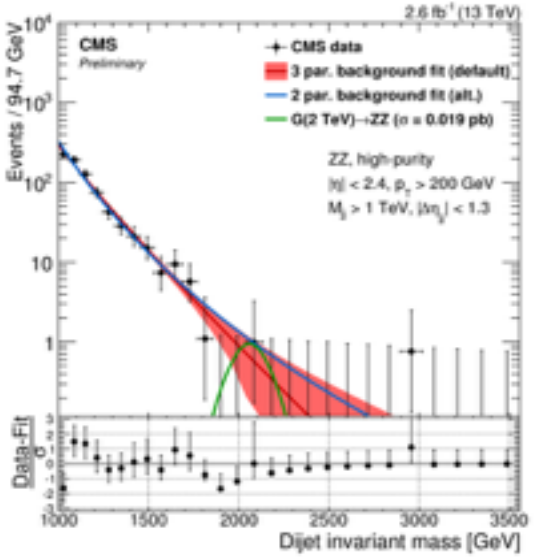


ZZ

CMS PAS EXO-15-002



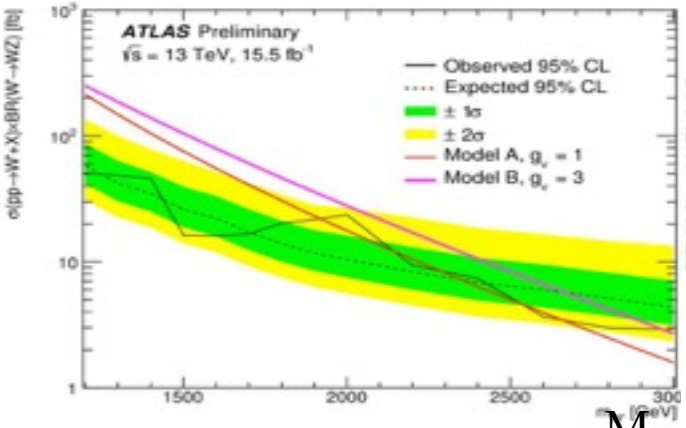




VV → qqqq

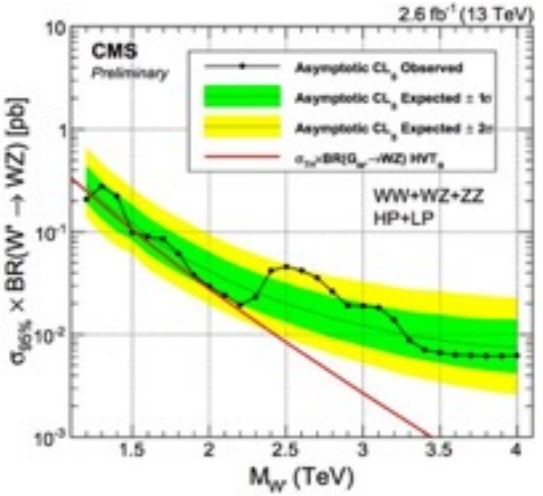
- No significant excess found in any of the different signal regions (WW, WZ, ZZ)

ATLAS-CONF-2016-055

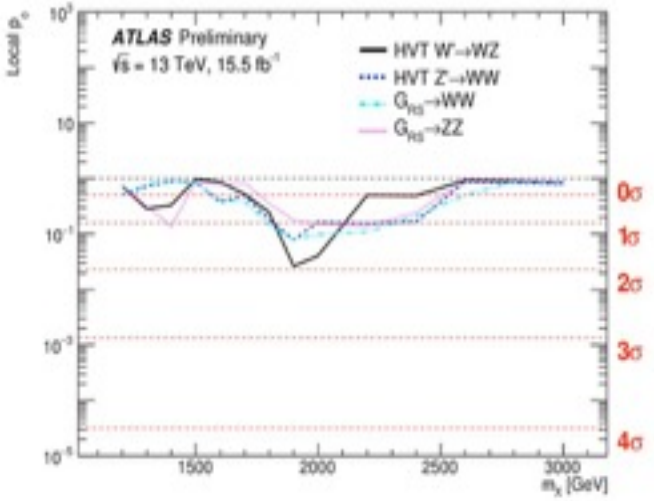


M_W

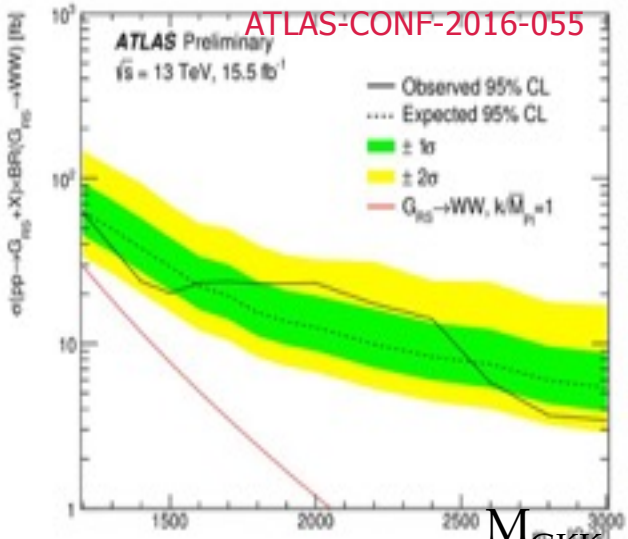
CMS PAS EXO-15-002



ATLAS-CONF-2016-055

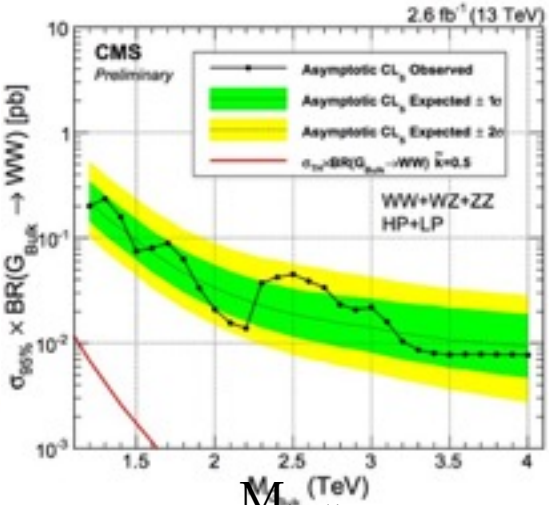


ATLAS-CONF-2016-055



M_{GKK}

CMS PAS EXO-15-002



M_{bulk}

Summary of Latest VV Searches

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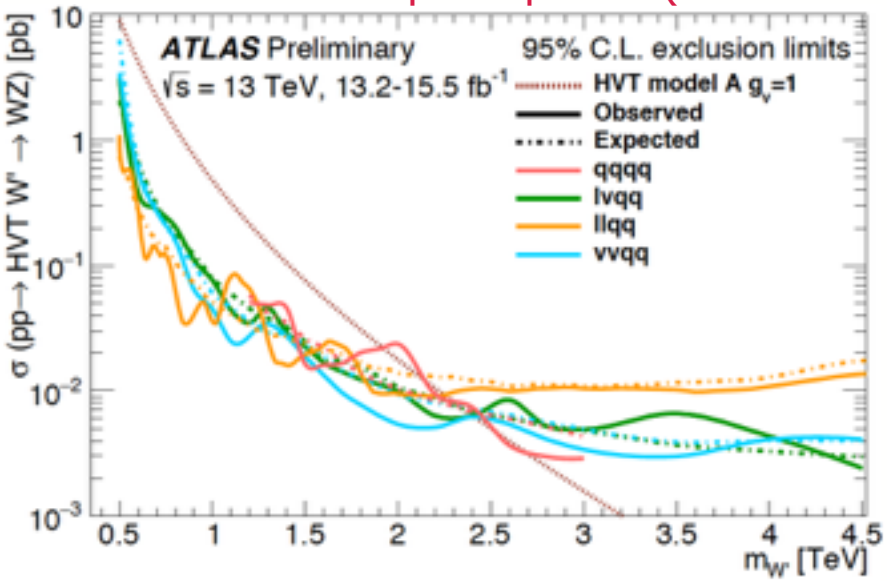
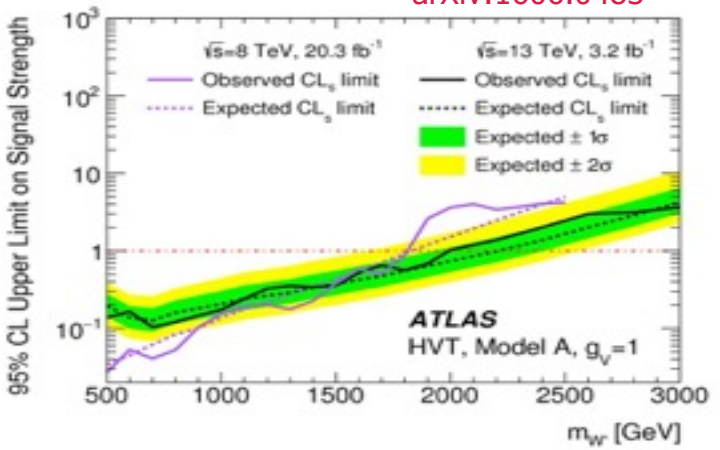
ICHEP2016 results - superimposed (not combined)

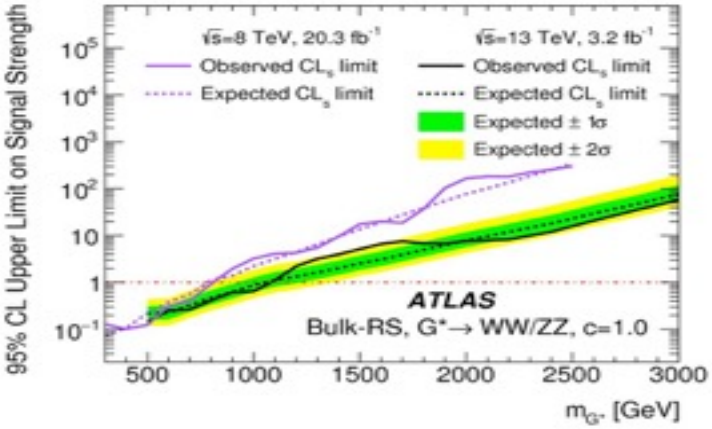


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

arXiv:1606.0483



arXiv:1606.04833



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

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Exotic VH Semi-Leptonic

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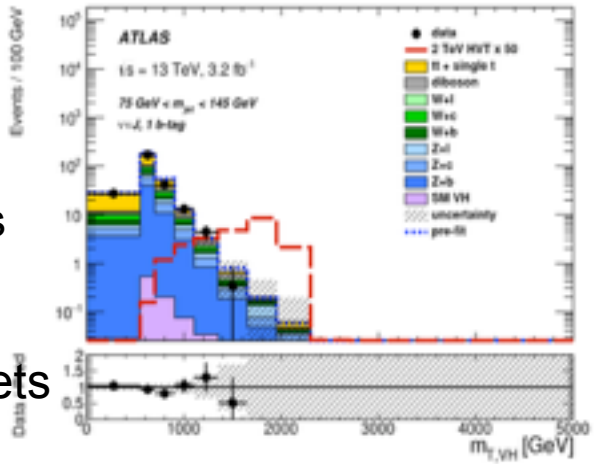
Exotic VH searches in the context of Heavy Vector Triplet models

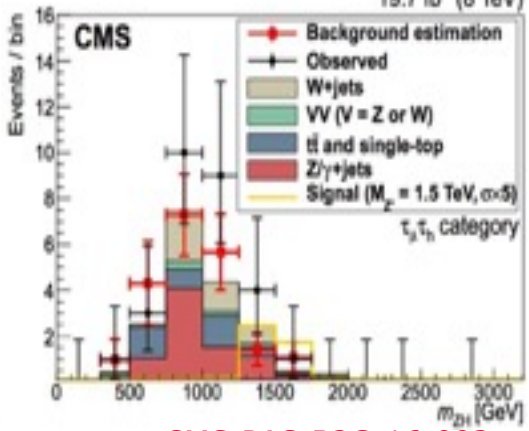
Complementary to the VV searches

Both collaborations looking into boosted topologies, with merged jets

arXiv:1607.05621

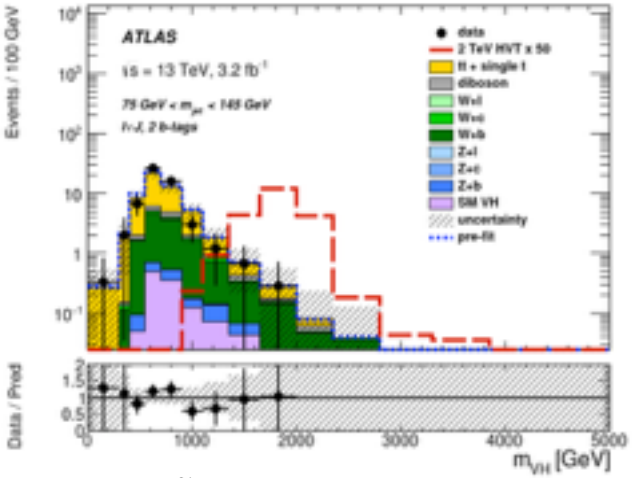


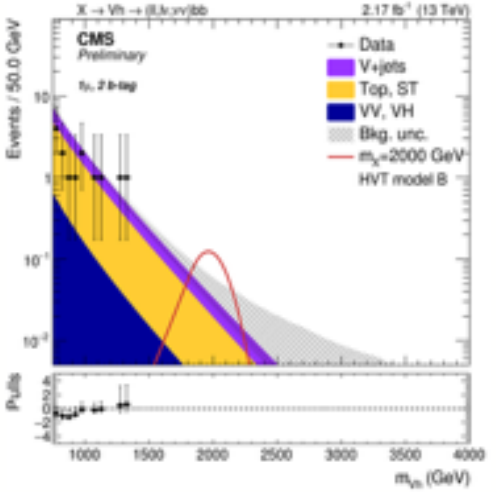
Phys. Lett. B 748 (2015) 255



CMS-PAS-B2G-16-003

arXiv:1607.05621





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}

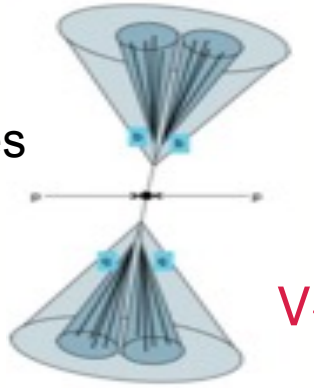
VH→ qqbb, $\ell\nu$bb channels with 8 TeV, 19.7, 9 fb^{-1}

VH →qqbb

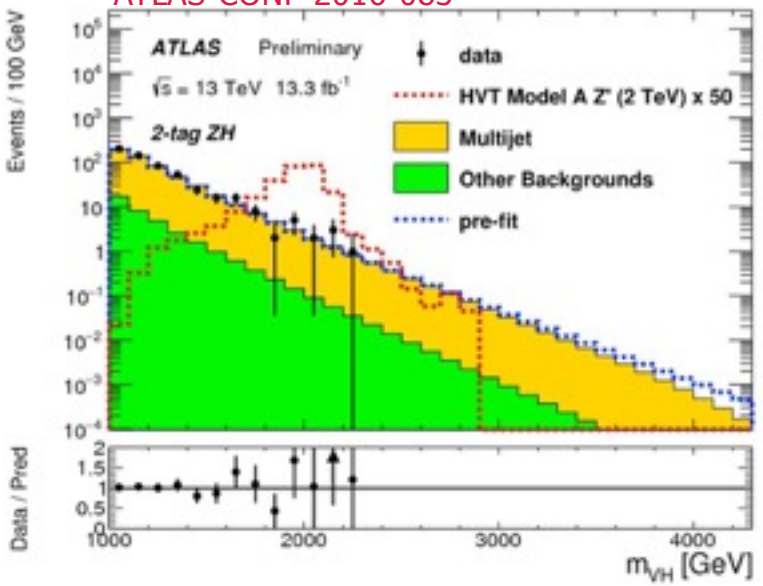
- Complementary to semi-leptonic VH searches

  Benefits from W,Z → qq high BR (67%, 70%)

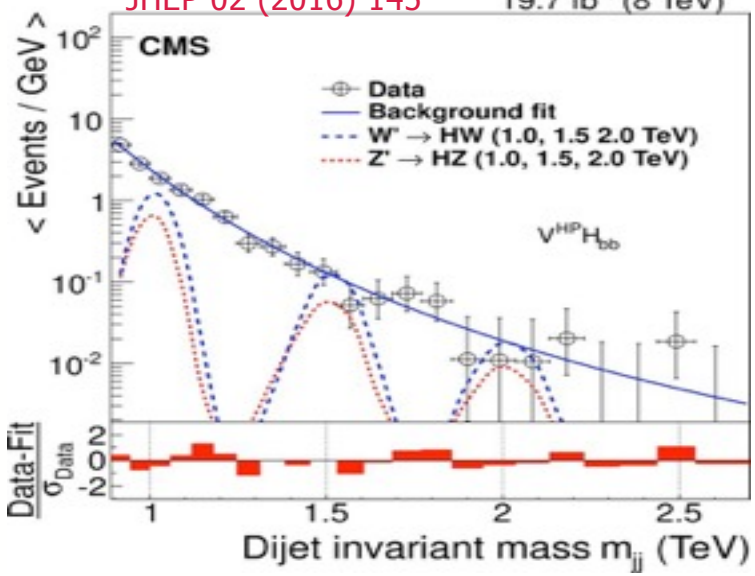
  - Competitive at high m_X, where multi-jet background diminishes
  - 1 boson tagged large-R jet, one Higgs tagged large-R jet
  - Data-driven multijet bkg estimation from 0-b-tag sample
  - ATLAS: 13 TeV, 13.3 fb^{-1} , CMS: latest results with Run-1



ATLAS-CONF-2016-083



JHEP 02 (2016) 145

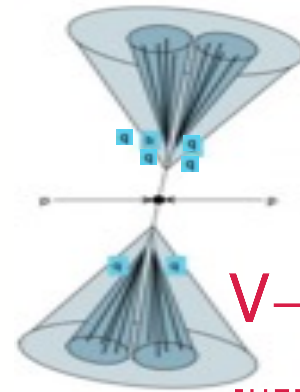


VH→ qq WW*(→qqqq)

Look into VH, H→WW* fully hadronic decays

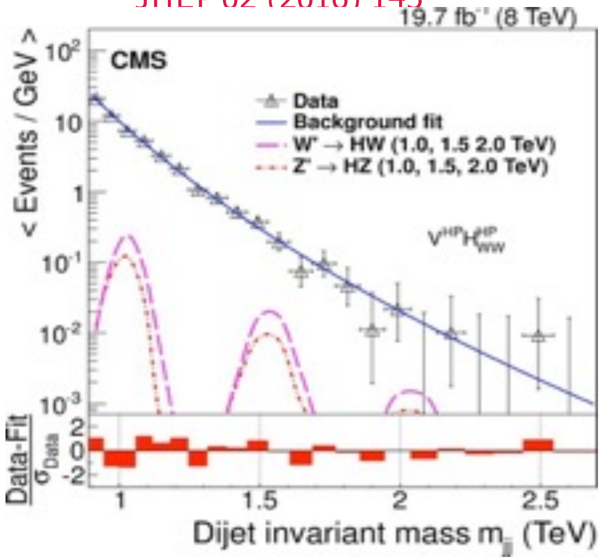
First application of jet substructure techniques to identify H→WW*→qqqq decays at high Lorentz boost

H→WW*

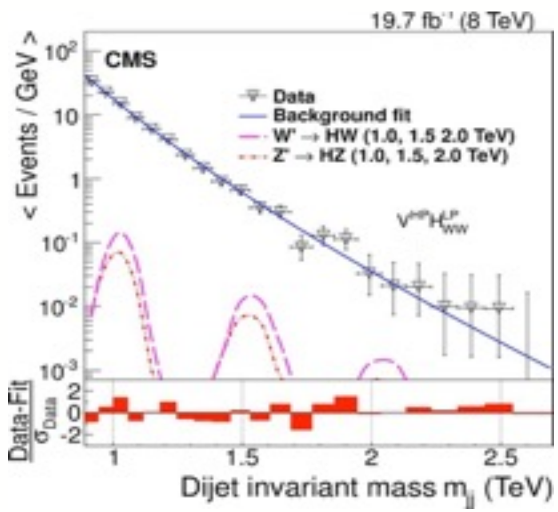


V→qq

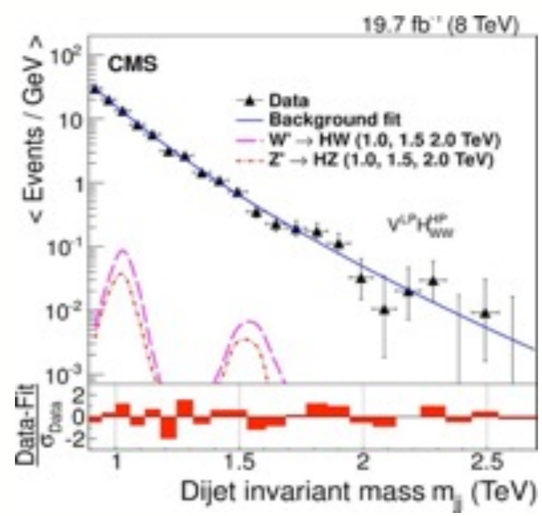
JHEP 02 (2016) 145



JHEP 02 (2016) 145



JHEP 02 (2016) 145



VH → qqbb, qqWW(→ qqqq)

- ATLAS results

➡ 13 TeV, 13.3 fb^{-1} qqbb only

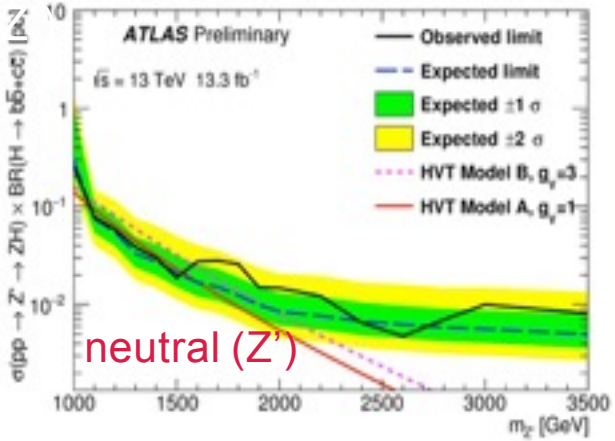
- CMS results

➡ Run-1 combination of qqbb and qqqq

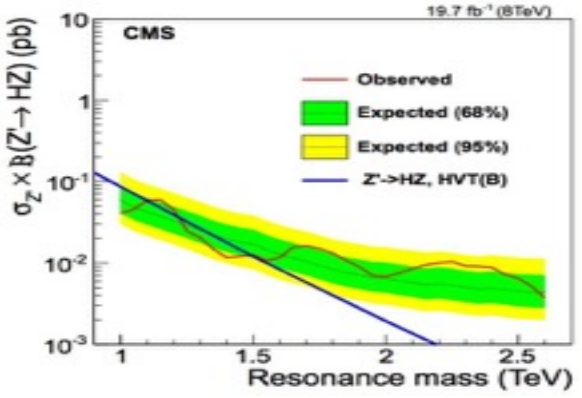
No significant excess above expectations found

➡ biggest fluctuation at 1.6 TeV in ATLAS W'→qqbb channel

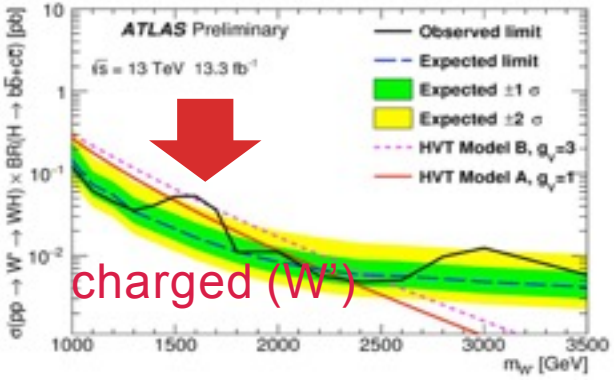
ATLAS-CONF-2016-083



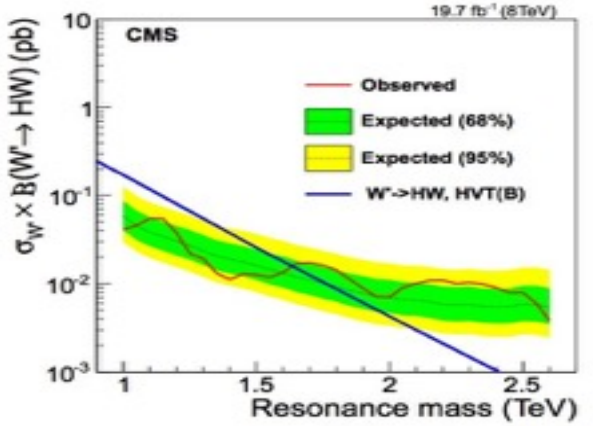
JHEP 02 (2016) 145



ATLAS-CONF-2016-083



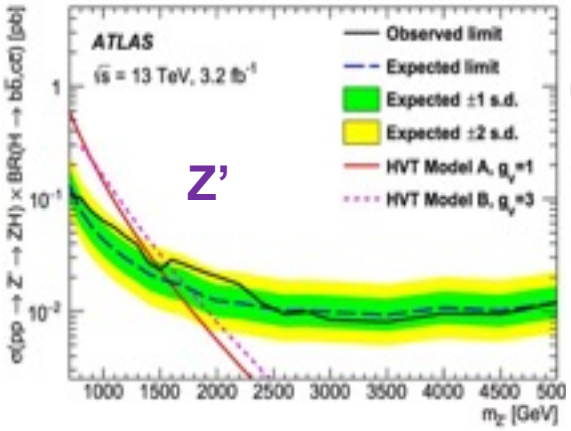
JHEP 02 (2016) 145

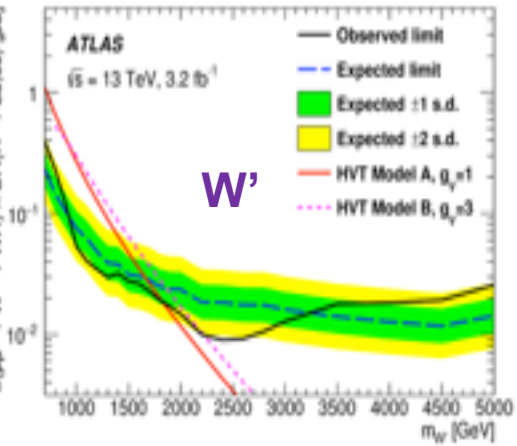


Summary of Latest VH Searches

- All using HVT models A and B as benchmarks
- ATLAS combination of semi-leptonic channels at 13 TeV, 3.2 fb^{-1}

arXiv:1607.05621

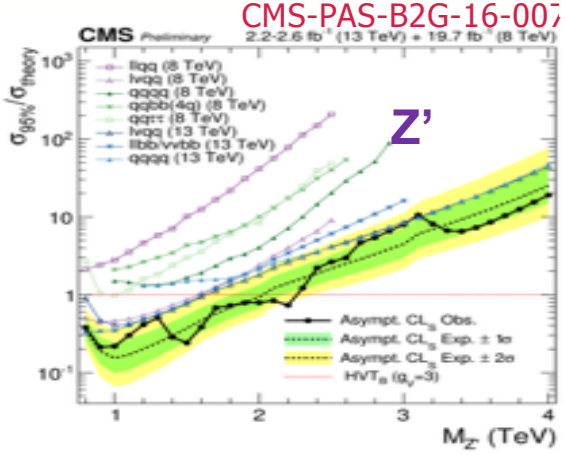


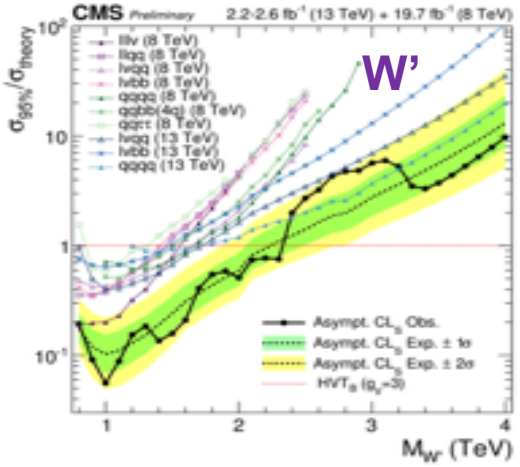


CMS combination of:

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

CMS-PAS-B2G-16-007





HH

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HH→bbbb

- BR (HH→bbbb) ~ 33%

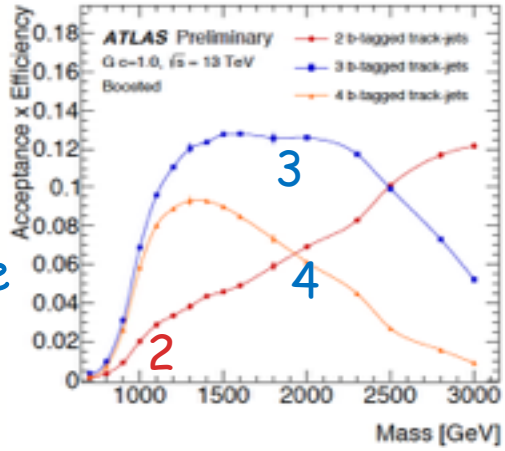
➡ Most sensitive HH final state across most of the search space

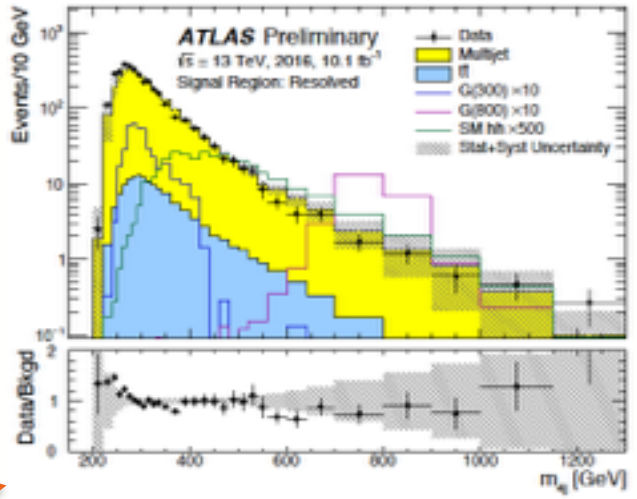
Topologies

➡ **Resolved**: 4 b-tagged small-R jets forming two Higgs candidates

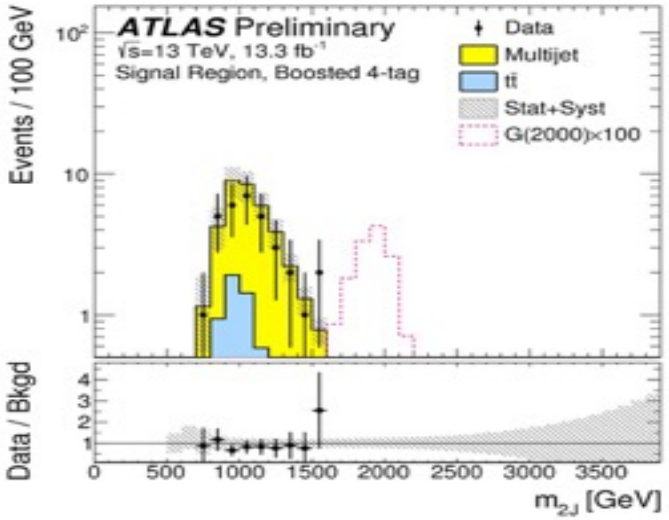
➡ **Boosted**: 2 trimmed large-R jets, masses consistent with m_H and to b-tagged small-R track subjets

- Background:
  - ➡ QCD multijet, dominant
  - ➡ ttbar, ~10%





ATLAS-CONF-2016-049

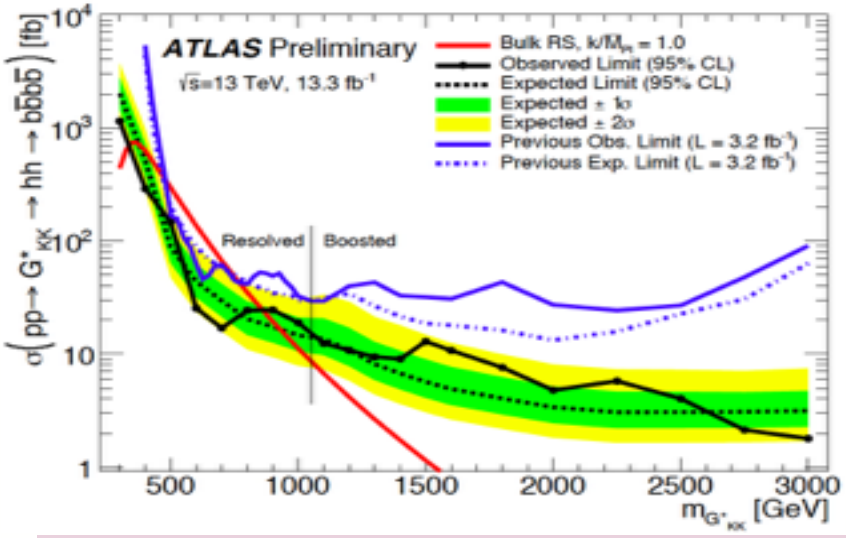


HH → bbbb

ATLAS:

➡ 13 TeV, 13.3 fb-1

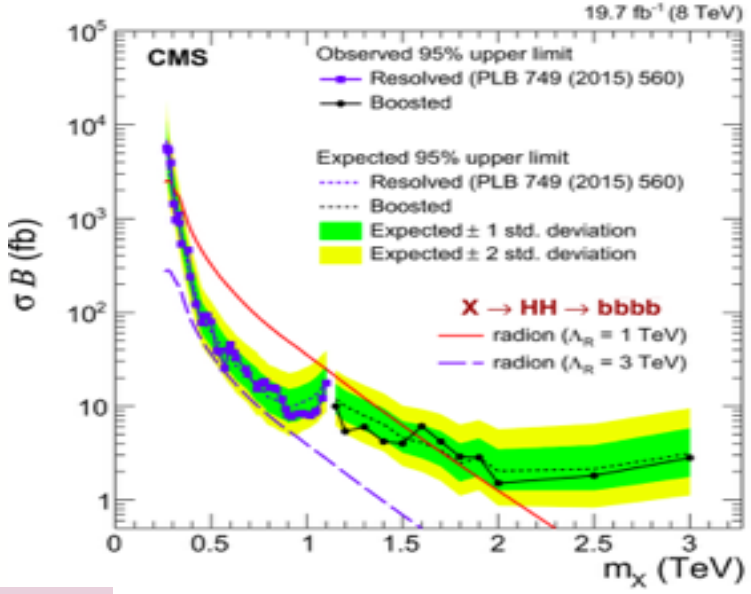
➡ Excludes bulk RS gravitons (K/M_{Pl} = 1.0) below 850 GeV



CMS:

➡ 8 TeV, 19.7 fb-1

➡ Excludes radions (Λ_R = 1 TeV) below 1.6 TeV

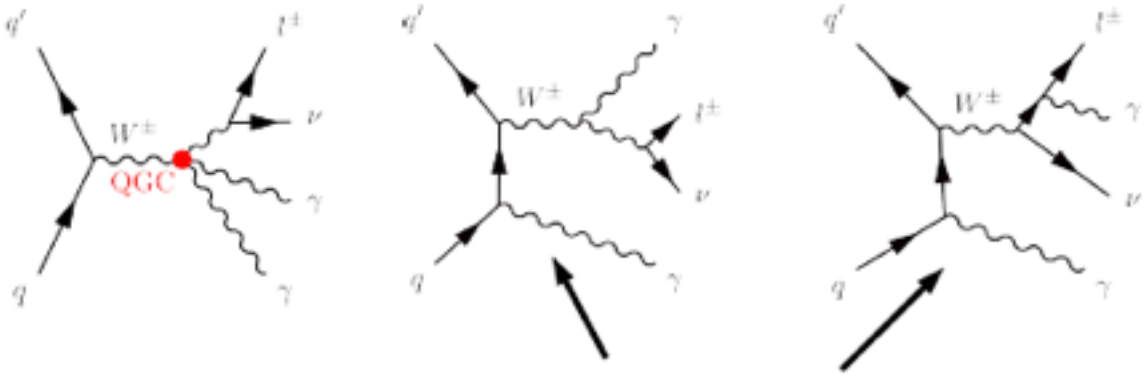


Resolved analysis also sets world's best limit on non-resonant HH production:

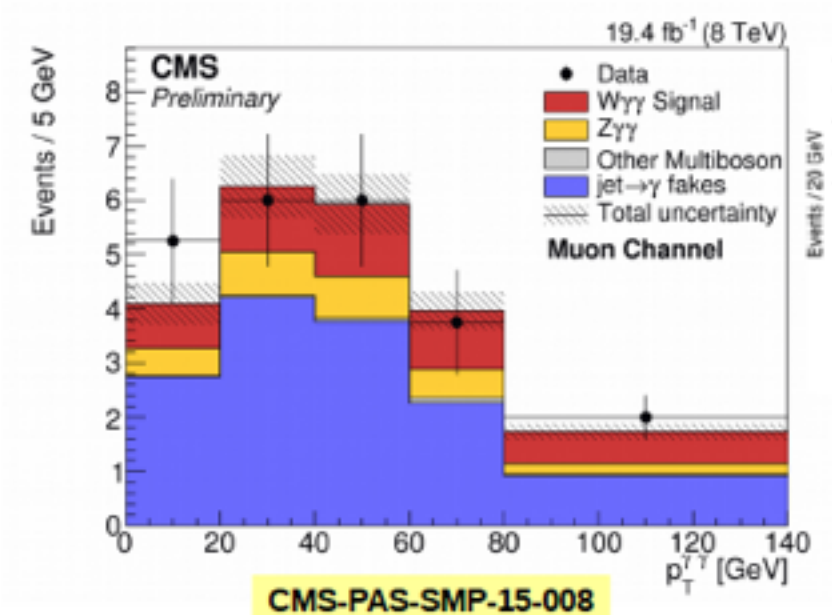
$$\sigma(pp \to hh \to b\bar{b}b\bar{b}) < 330 \text{ fb}$$

(~30x the SM cross section)

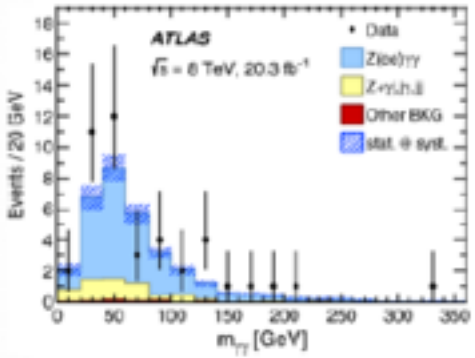
Triboson: Wγγ and Zγγ

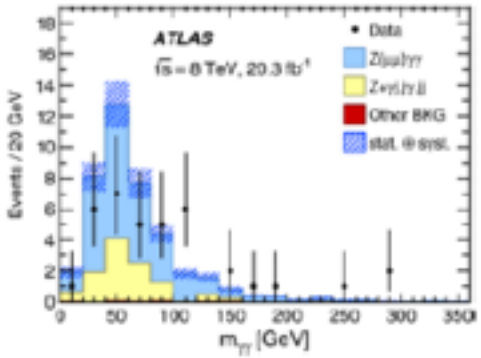


TGC and ISR/FSR contribute



CMS-PAS-SMP-15-008





ArXiv:1604.05232

Diphoton Search

Simultaneous search for **spin-0** and **spin-2** resonances:

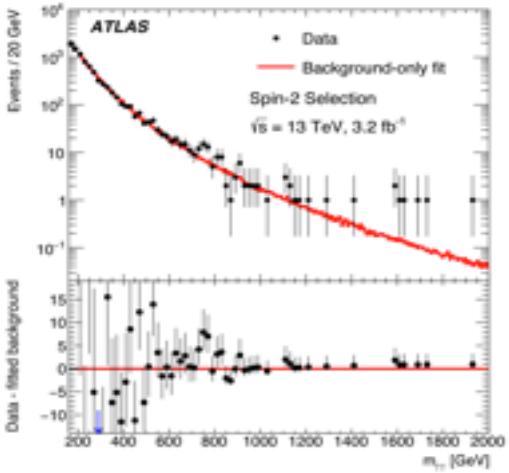
• spin-0 (extended Higgs sector) - 200 GeV - 2 TeV and widths up to 10% of hypothesised m_X ($\Gamma_X/m_X < 0.1$)

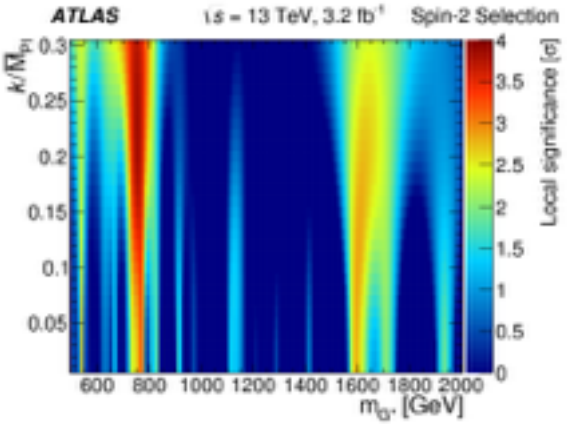
• spin-2 (Randall-Sundrum model with graviton excitation G* and dimensionless coupling k/M_{Pl}) - 500 GeV - 5 TeV and k/M_{Pl} ranging from 0.01 to 0.3

ATLAS Simple selection:

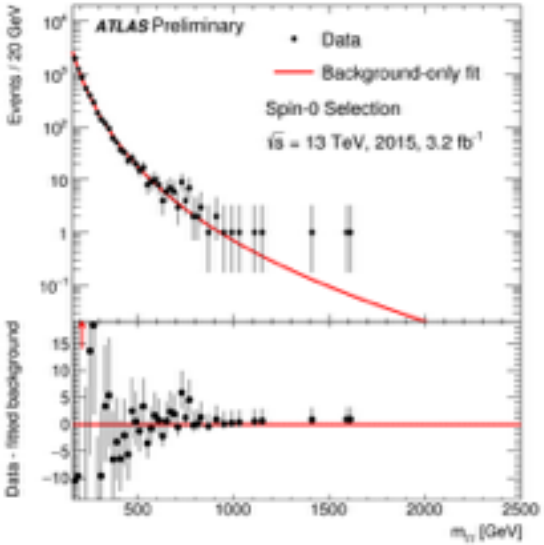
1. Diphoton trigger (35/25 GeV E_T thresholds)
2. Two well identified and isolated photons with $|\eta|<2.37$ (excl. crack region):
1. $E_T > 55$ GeV for spin-2
2. $E_T > 0.4(0.3)*m_{\gamma\gamma}$ for spin-0 leading (subleading) γ
3. tight calorimeter and track isolation criteria
3. Primary vertex selected using NN based on photon pointing

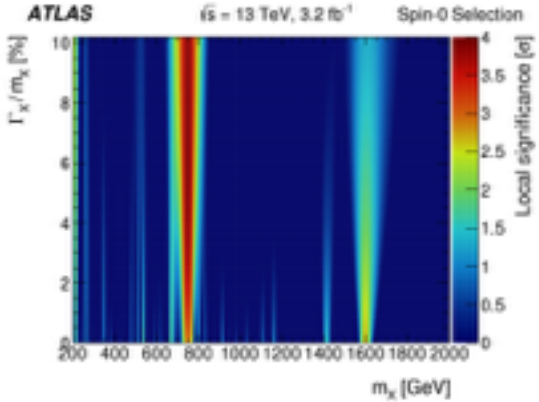
H→ γγ Results - spin-0 and spin-2





Best-fit @ 750 GeV and k/MPl=0.23 (57 GeV):
local **3.8σ** and global **2.1σ**

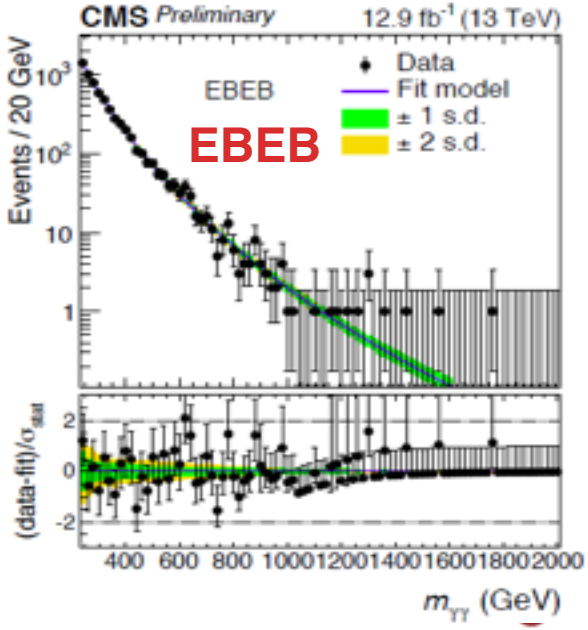


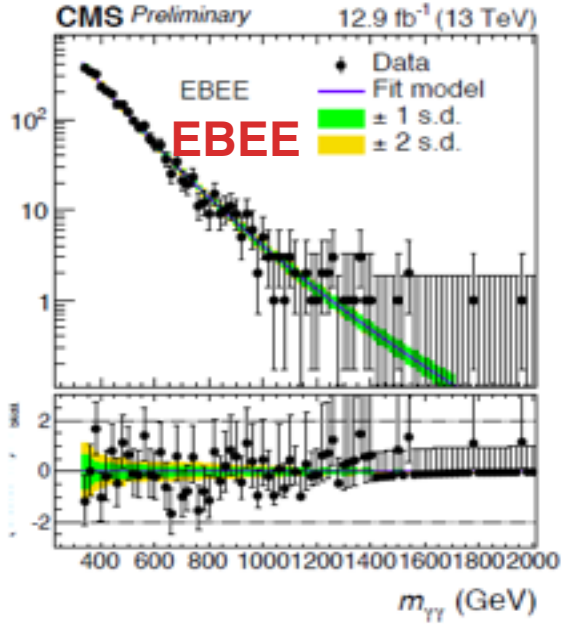


Best-fit @ 750 GeV and ΓX/mX=6% (45 GeV):
local **3.9σ** and global **2.1σ**

CMS diphoton

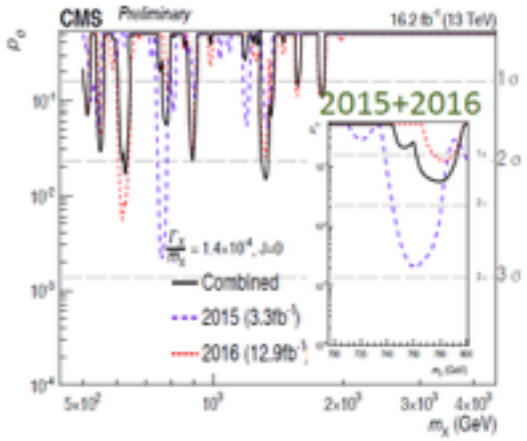
8878 events

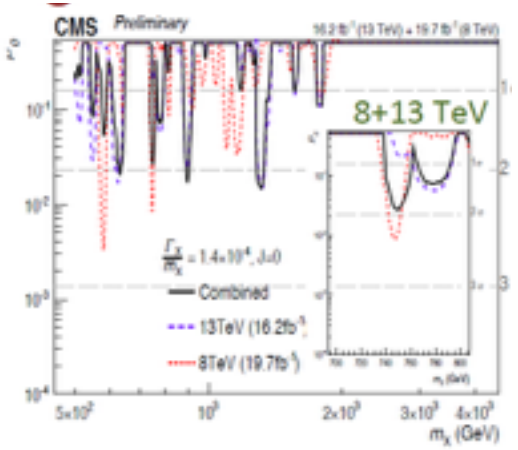




2016 Data consistent With Standard Model expectations

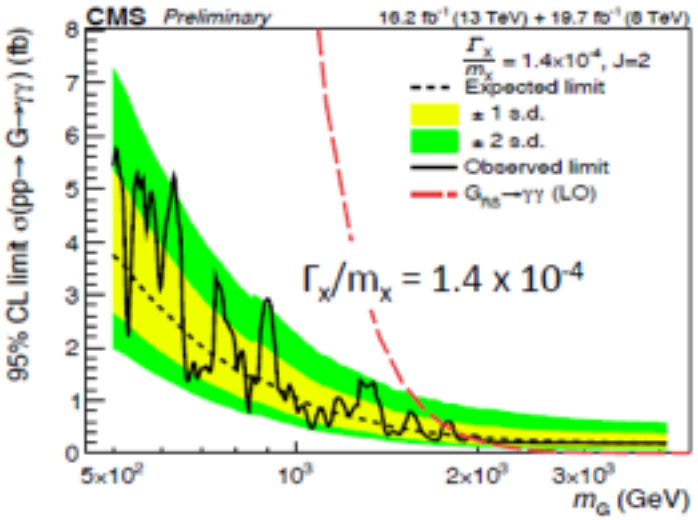
Excess based on 2015 data around 750 GeV not confirmed by the new data

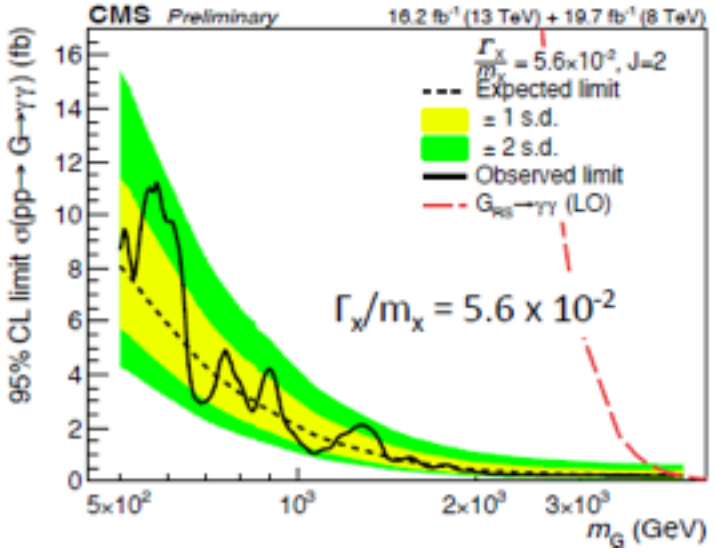




Local excesses around 750 GeV:
ATLAS: 2015 only: 3.8σ →
2015+2016: <1σ
CMS: 8TeV+2015: 3.4σ →
8TeV+2015+2016:<2σ

Diphoton Results





Sensitivity driven by 2016 dataset

13TeV

Coupling	Exclusion
0.01	$m_G < 1.95$TeV except for [1.75, 1.85]
0.1	$m_G < 3.85$ TeV
0.2	$m_G < 4.45$ TeV

8TeV contribution:

~10% at low mass, negligible at high mass

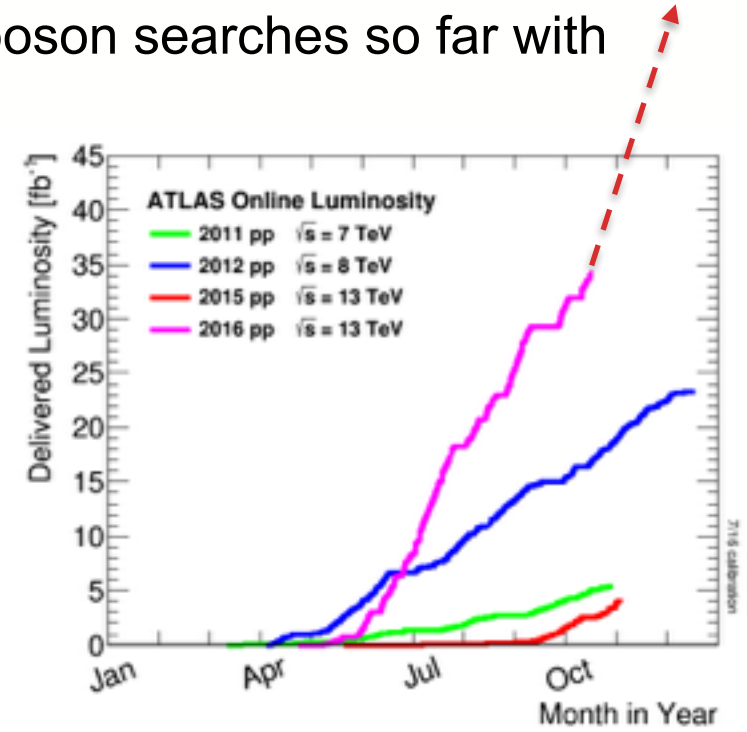
Summary

8878 events

- LHC is providing high quality data, with impressive integrated luminosity

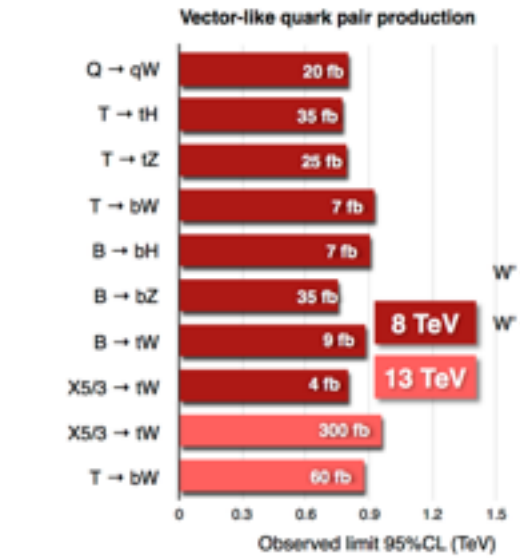
- No significant excesses observed in diboson searches so far with 13 fb^{-1} at 13 TeV

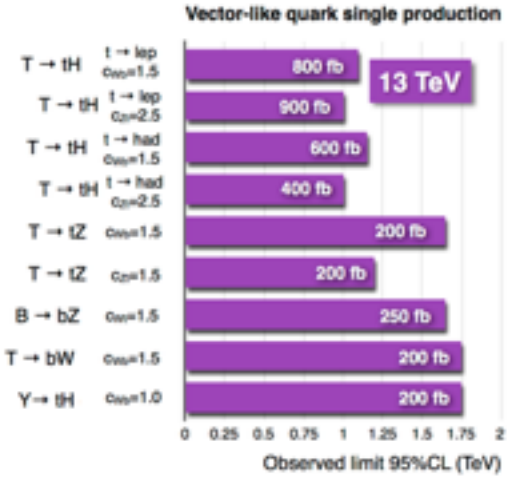
- Lots of the LHC data @ 13 TeV still to be analysed … more results expected soon!

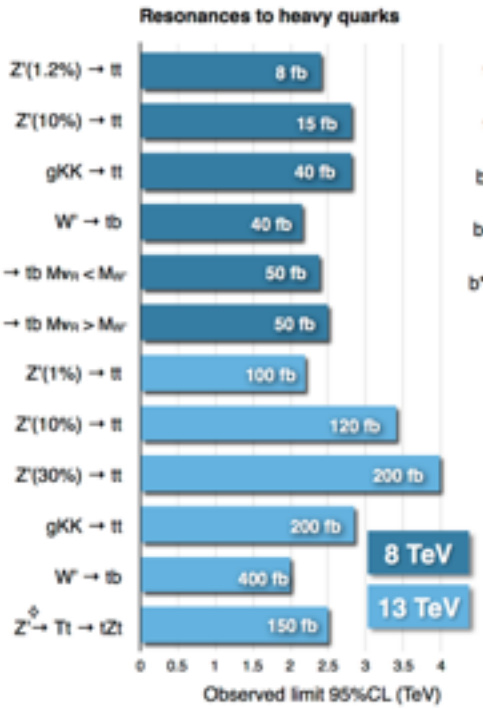


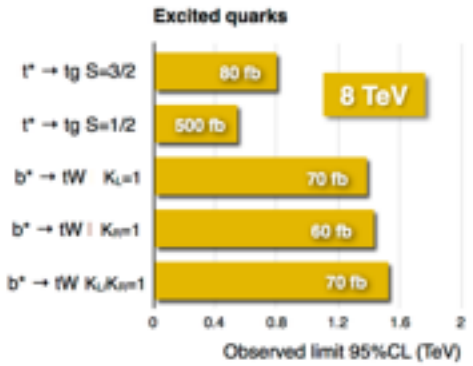
Summary

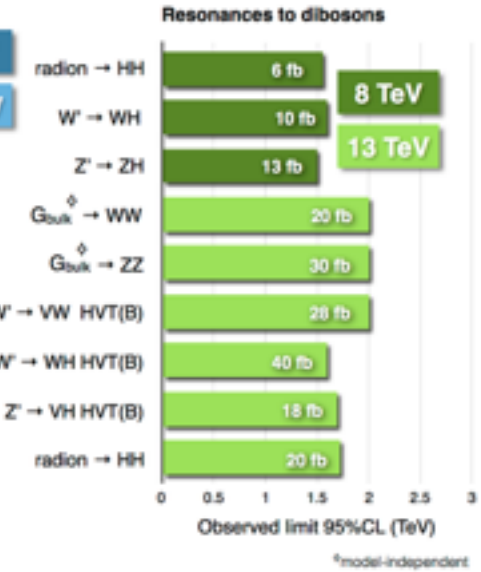
8878 events











B2G
new physics searches with heavy SM particles