Search for New Physics in Di-Boson Final States

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on behalf of the ATLAS and CMS collaborations

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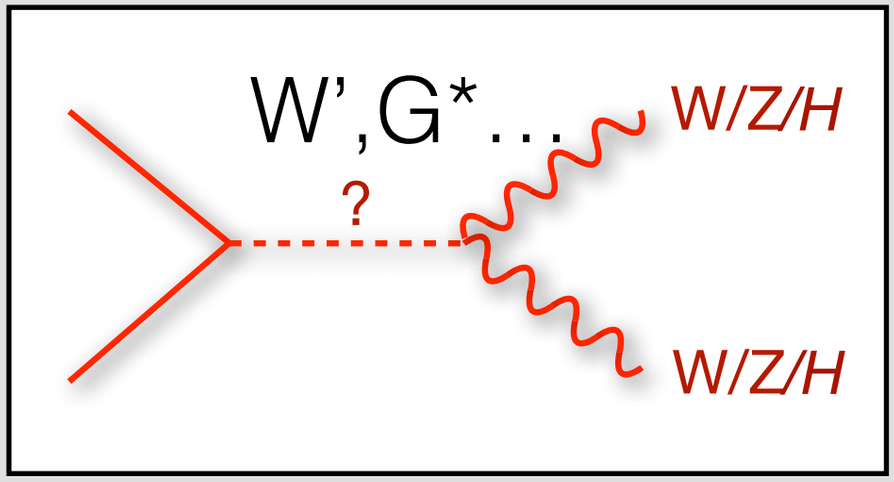
Why Di-Bosons at the LHC?

- Many well-motivated extensions to the SM predict new particles decaying into boson pairs (*W/Z/H/γ*)
  - Warped Extra Dimensions, GUTs, Technicolor, ...
  - Very rich phenomenology!



- 'Simple' analysis procedure: Look for excesses in the resonant mass spectrum, 'clean reconstruction' due to well-known boson properties and kinematics
- Main backgrounds come from SM continuum sources
- Final state decay products are often highly-boosted: *ideal grounds for use of innovative boosted-object tagging*

Results shown here using the full 2012 dataset!

Experimental Signatures Covered

- Analyses are logically separated in production channels and decay final states due to the experimental techniques used

Channel	Final States	ATLAS Reference	CMS Reference
WZ	*lνll*	arxiv.1406.4456	arxiv.1407.3476
Wγ & Zγ	*lνγ & llγ*	arxiv.1407.8150	
ZZ & ZW	*llqq*	arxiv.1409.6190	arxiv.1405.3447
WZ & WW	*lνqq*	arxiv.1503.04677	arxiv.1405.3447
WH & ZH	*[νν / lν / ll] + bb*	arxiv.1503.08089	CMS-EXO-14-010
HH	*$\gamma\gamma$bb*	arxiv.1406.5053	CMS-HIG-13-032
WW & WZ & ZZ	*qqqq*	arxiv.1506.00962	arxiv.1405.1994
WW & WZ & ZZ	*Combination*	ATLAS-CONF-2015-045	
WH & ZH	*qqbb*		arxiv.1506.01443
HH	*bbbb*	arxiv.1506.00285	CMS-EXO-12-053

See talk by O. Charaf dedicated to di-photons final states
See talk by A. Rizzi dedicated to di-Higgs final states

Will focus here on latest results!

The Decays Considered
Advantages and Disadvantages

- **Hadronic decays** (*qq, [bb: strongest H probe]*)
  - Larger branching ratios: performs best at high masses where the SM backgrounds fall off
  - Significant backgrounds from *X+jets* processes (can be mitigated through b-tagging, boosted jet techniques for merged decay products, etc.)
- **Leptonic decays** (*ll, lν, νν*)
  - Smaller branching ratios *(analyses ignore hadronic taus)*
  - Cleaner final states through lepton reconstruction: usually performs best at low masses
  - Need specific techniques to deal with final state kinematics being under-constrained (neutrinos)

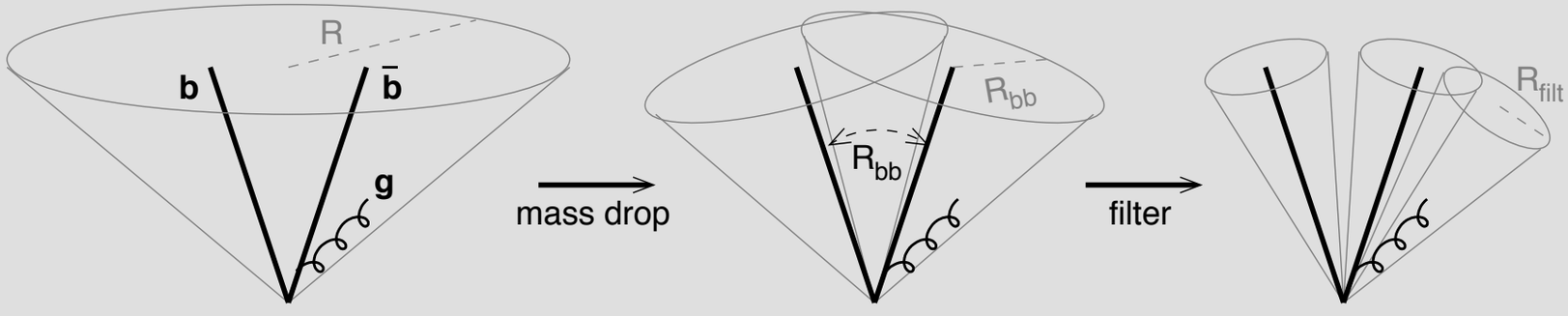
Dedicated Experimental Techniques

- Due to the high-mass regime investigated, the detector signature of the vector boson decay products often become entangled
- *Special treatment for leptons*
  - Nearby signal leptons need to be subtracted from each other's isolation cones
- *Special treatment for jets*
  - To increase the reconstruction efficiency, instead of attempting to directly resolve the individual decay products, combine them into a single object and inspect its properties
  - Reconstruction of these *large-R* jets is typically performed with the **Cambridge-Aachen** (CA) algorithm (*order of constituent merging is better suited to recognizing substructure*)
  - '**Grooming**' techniques are used to remove soft components of a jet, to increase robustness and sensitivity

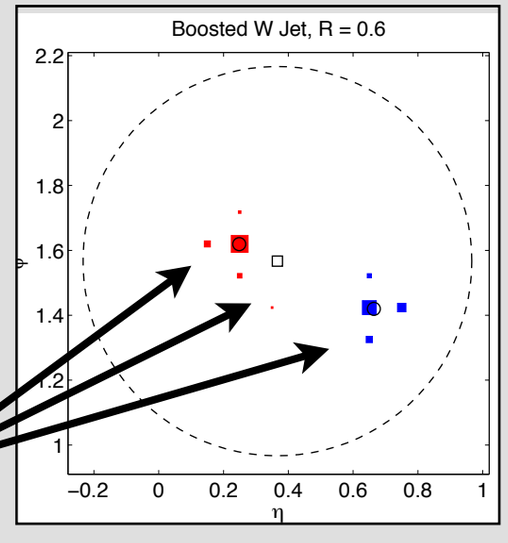
Boosted Tagging Techniques

See Talk by O. Zedin and Poster by T. Bristow

- **Re-clustering:** Run a different jet finding algorithm on the constituents of a jet
  - *Trimming*: Use a smaller radius algorithm, and reject sub-jets which do not carry a large enough fraction of the original jet's momentum
  - *Pruning*: Re-cluster the jet with extra requirements at every merging step (relative momentum and maximum distance)
- **De-clustering:** Reverse the clustering history, rejecting sub-jets if not compatible with the substructure hypothesis
  - *Momentum Balance:* Requirements on the k_T distance of the last splitting
  - *Mass-Drop:* De-clustered jet must carry a significant fraction of the mass



- **N-subjettiness**: p_T-weighted measure of the proximity of the jet constituents with the candidate sub-jet axes (typically use the ratio of 2 hypotheses)



ZZ & WZ → *llqq*

Both analyses require a dilepton pair compatible with the decay of a Z boson
Treatment of hadronic boson decay varies

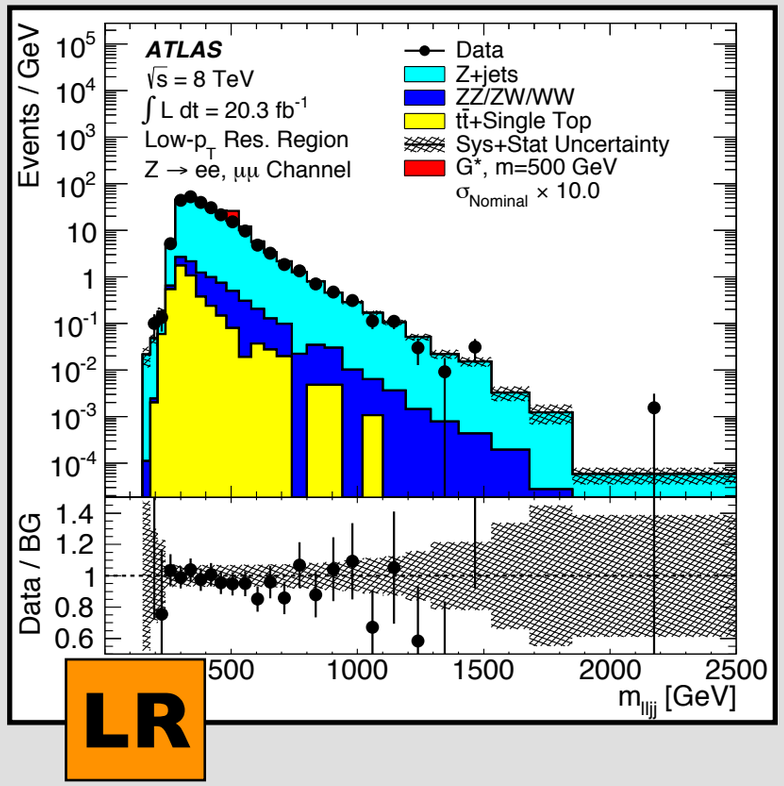
arxiv.1409.6190

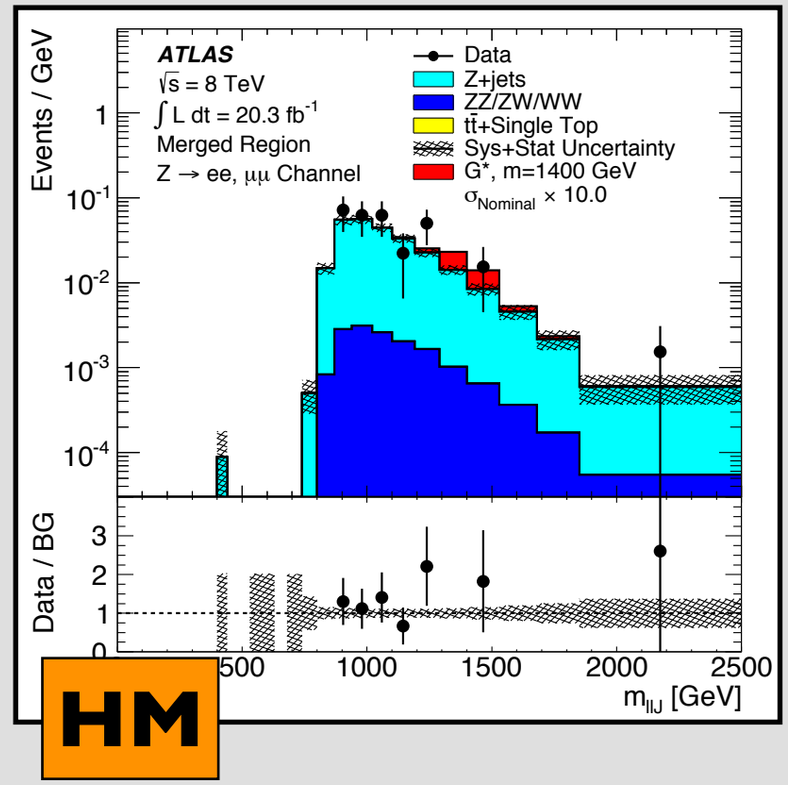
ATLAS

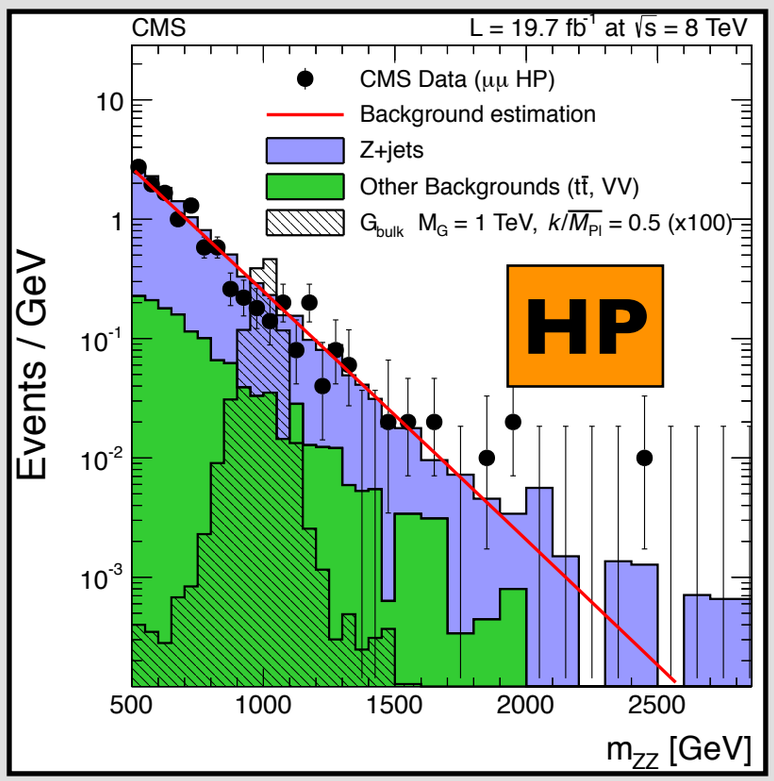
See also poster by E. Cheremushkina

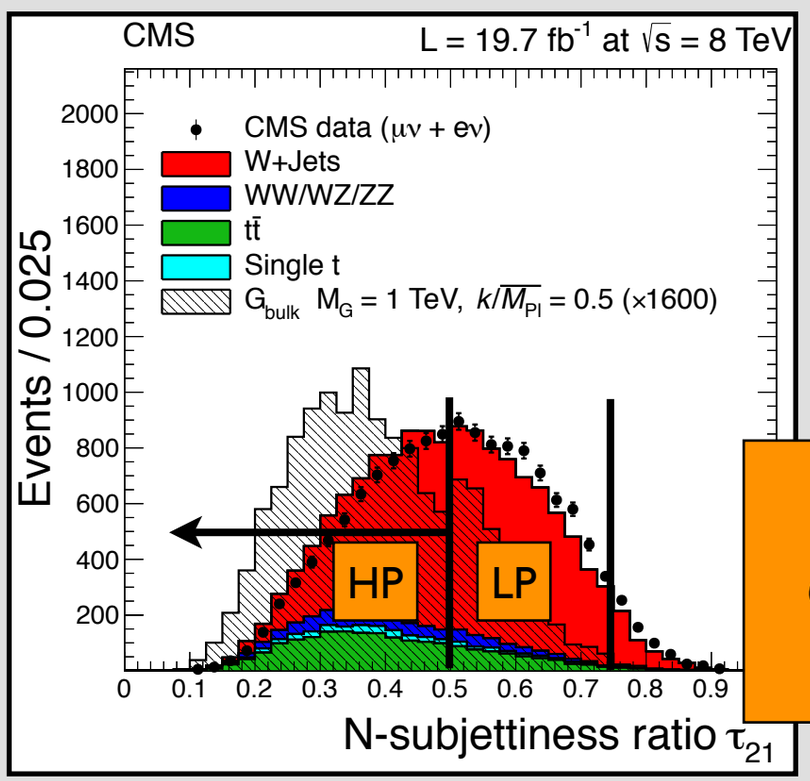
Symmetric p_T requirement on the dilepton / dijet pair used to split the analysis in 3 categories:

Low-Resolved: 100 GeV
High-Resolved: 250 GeV
High-Merged: R=1.2 large radius jet, 400 GeV









arxiv.1405.3447

CMS

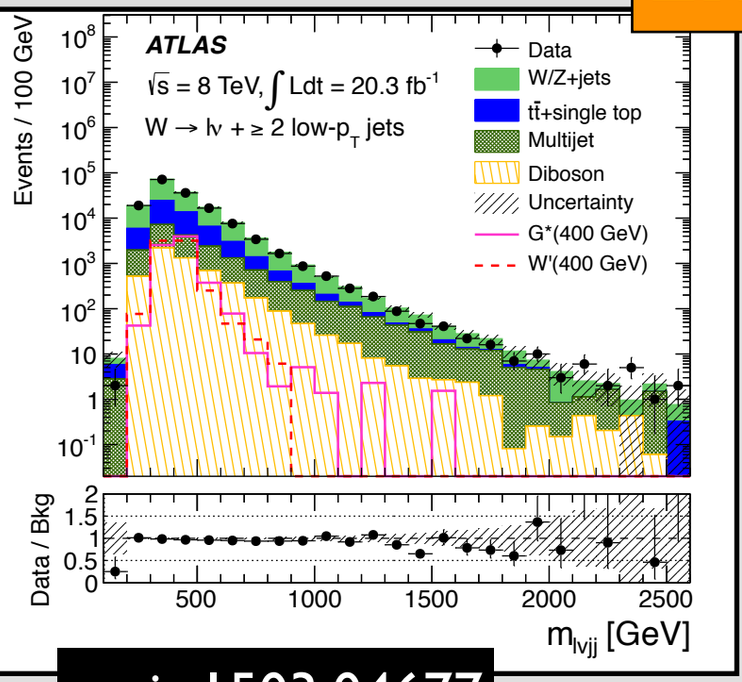
Two 'merged' selections based on subjettiness ratio to increase sensitivity in the low/high mass (high/low **purity**) regimes

In both cases, excellent agreement is found between SM predictions and data...

WW & WZ → *lνqq*

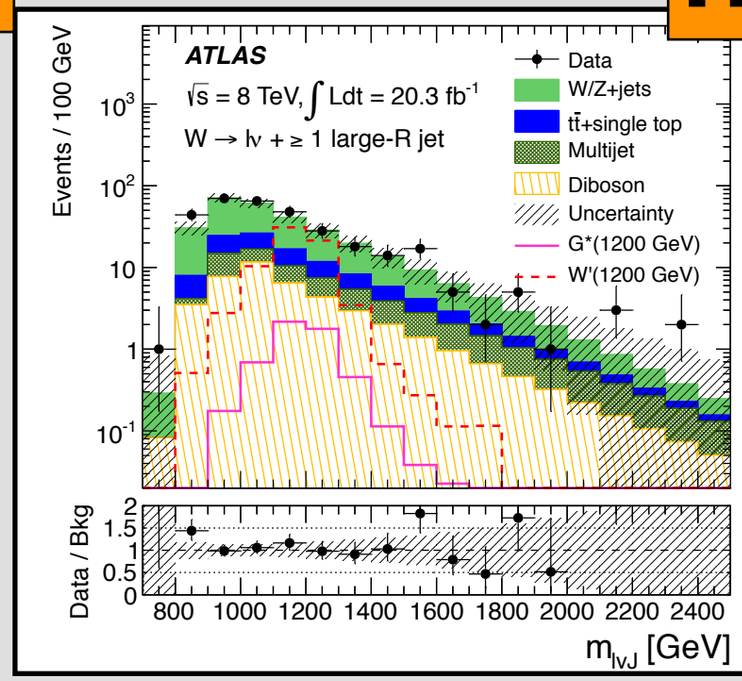
Hadronic boson decay system is treated in the same way as for the last analysis

LR



arxiv.1503.04677

HM

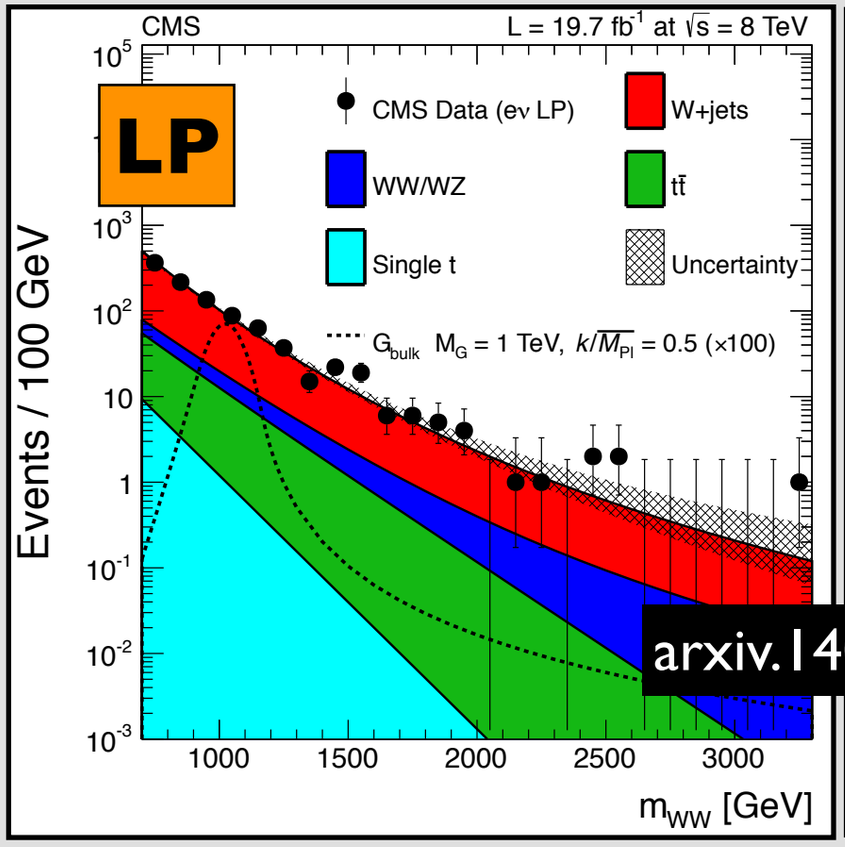


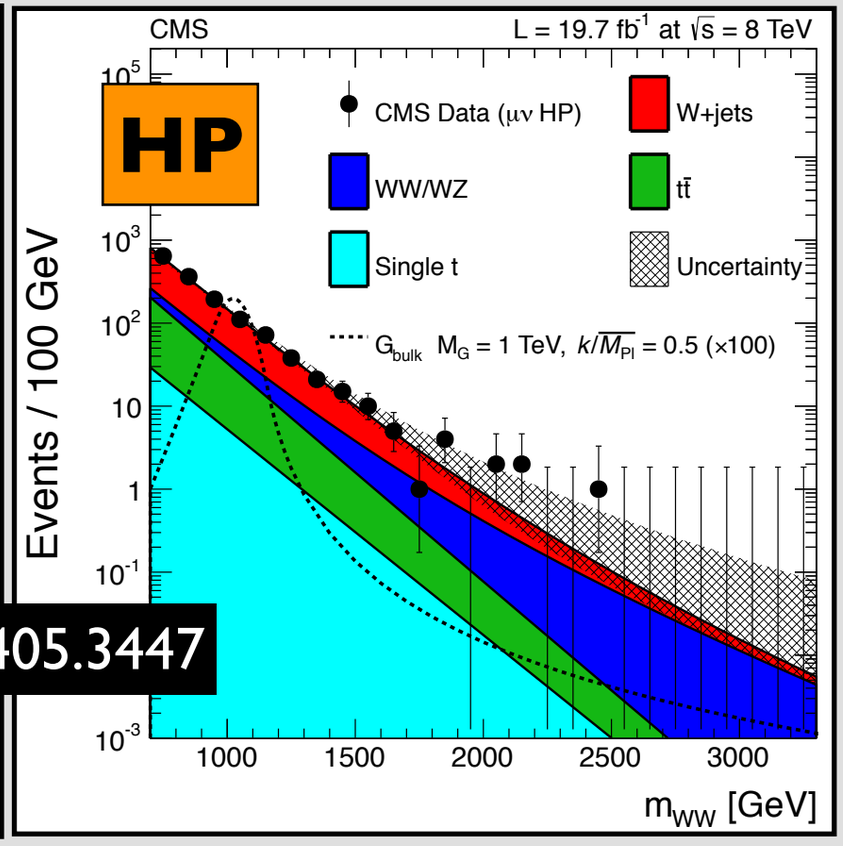
ATLAS & CMS

Leptonic W decay selected through requirements on E_T^{miss} and the presence of one lepton

Use E_T^{miss} and W mass constraint to reconstruct neutrino 4-mom

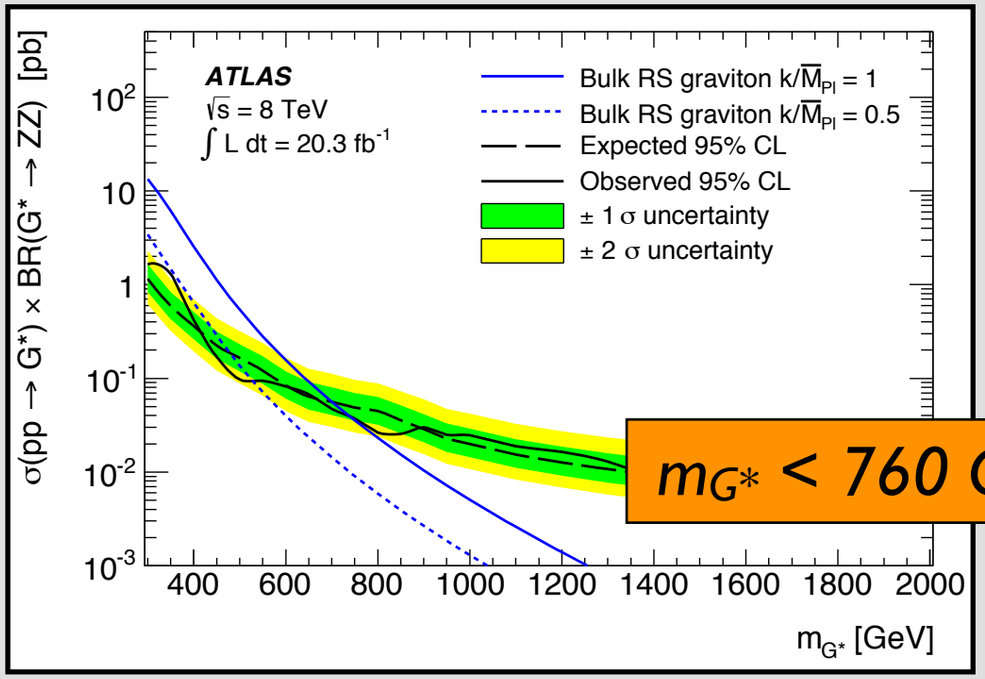
Once again, good agreement is found between SM predictions and data...

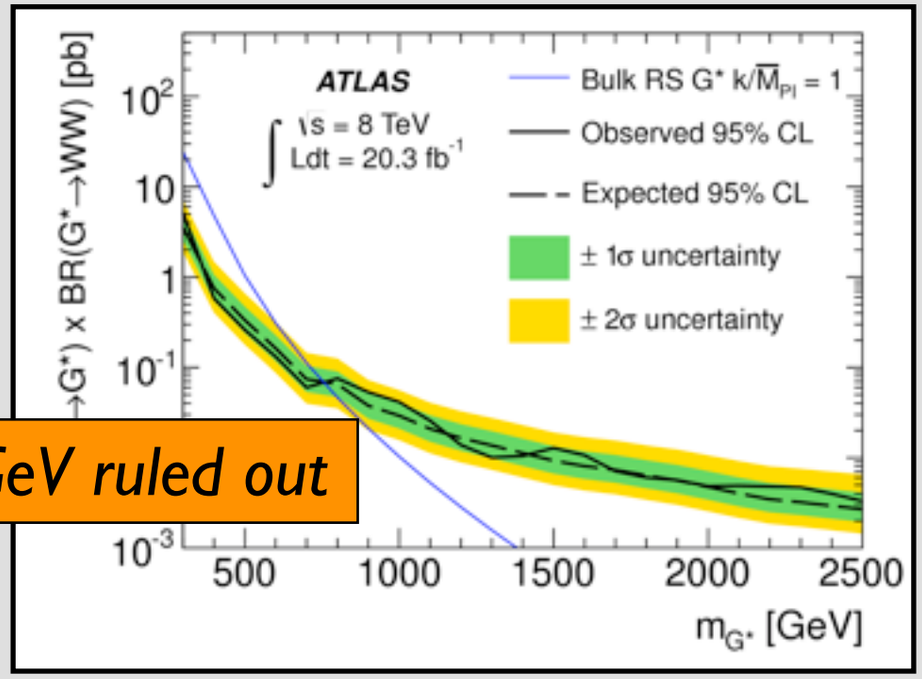




arxiv.1405.3447

VV → *llqq / lνqq* Limit Setting





m_{G^*} < 760 GeV ruled out

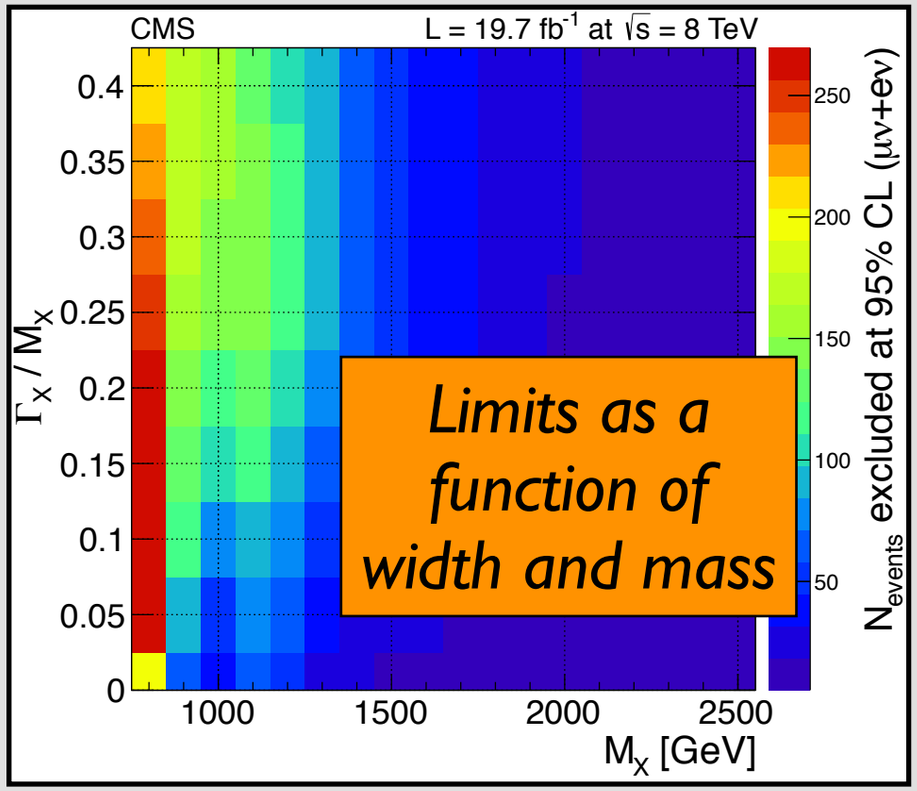
arxiv.1409.6190
arxiv.1503.04677

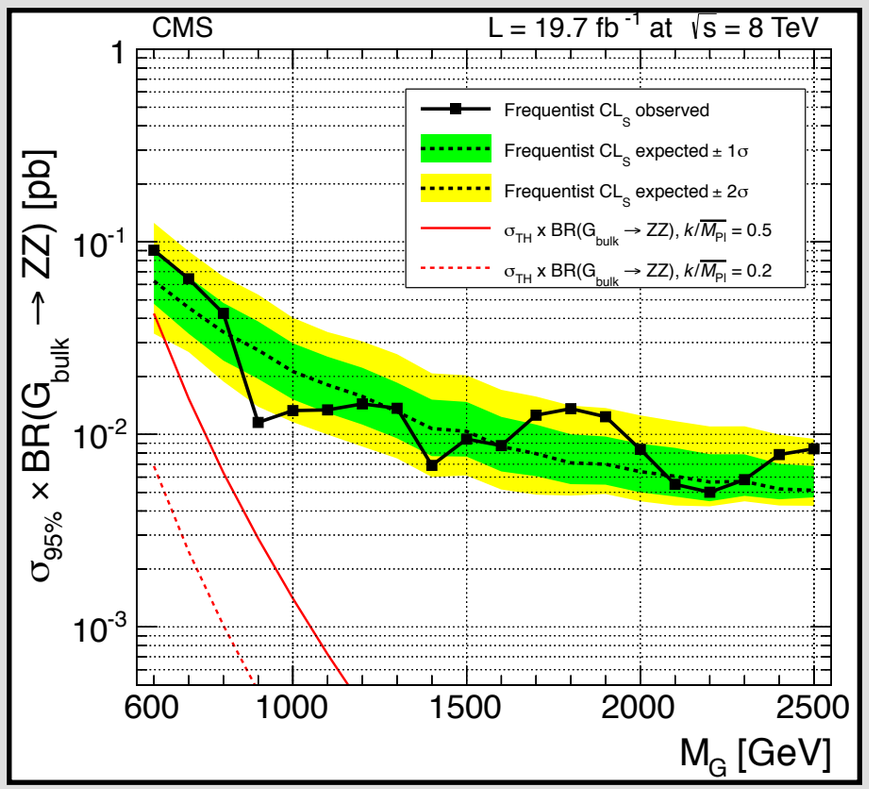
ATLAS

Limits on RS Gravitons and EGM W' as benchmarks

CMS arxiv.1405.3447

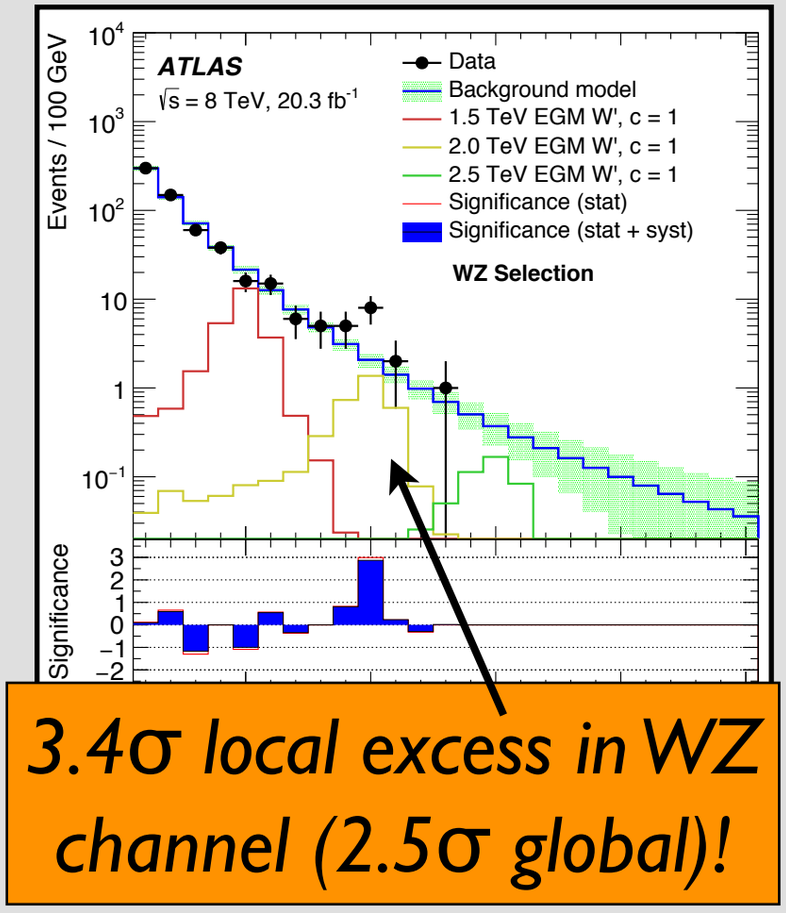
Limits on RS Gravitons and EGM W'
Also including framework for model-independent limit re-interpretation
(boson reconstruction efficiencies provided)



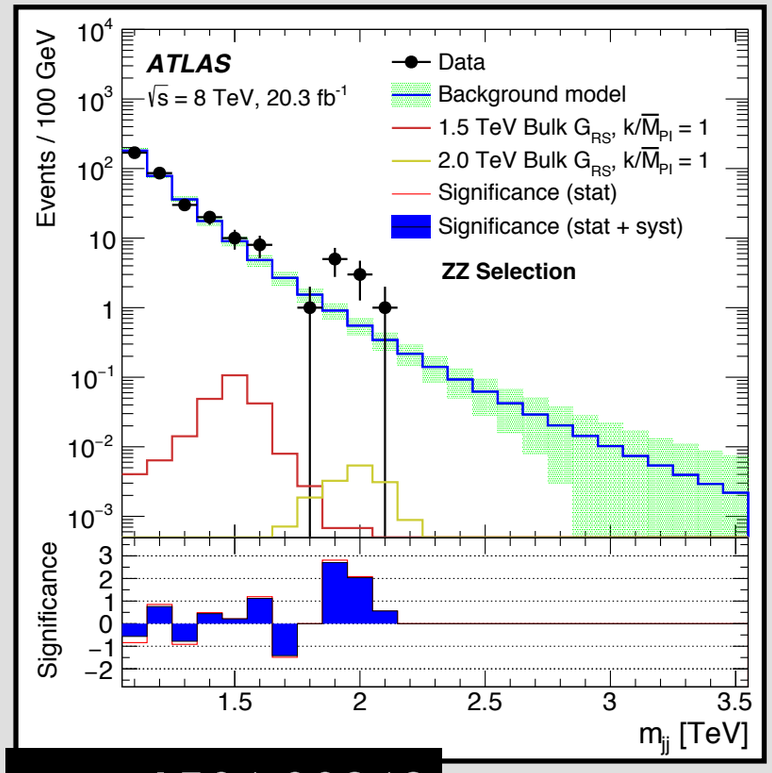


ZZ & WZ & WW → *qqqq*

Dijet boosted final state:
Identification of di-boson state is through the use of tagging techniques



3.4σ local excess in WZ channel (2.5σ global)!



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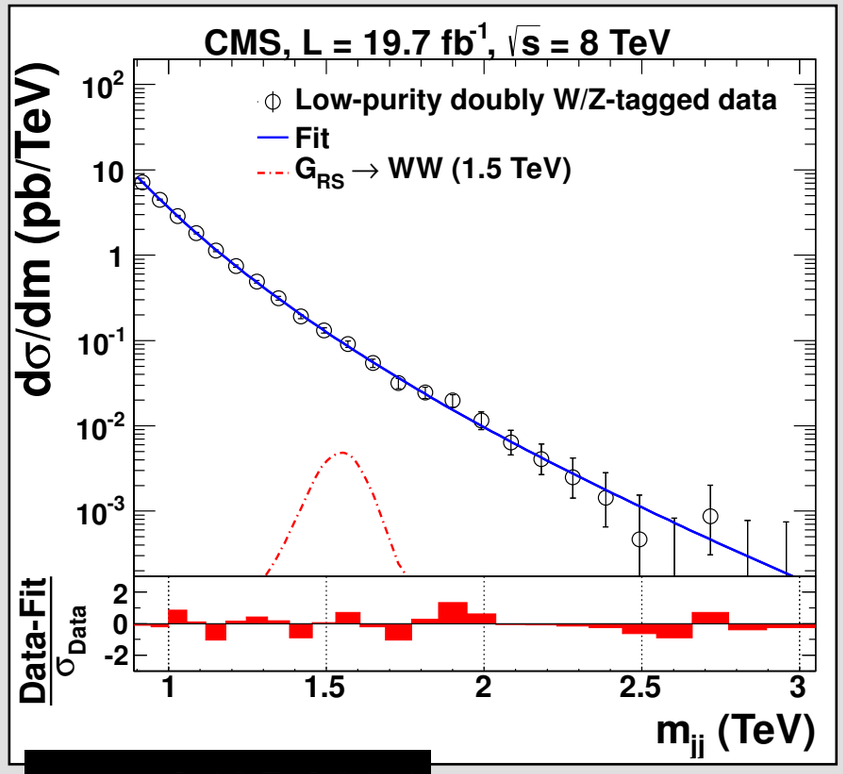


arxiv.1405.1994

ATLAS

Dedicated selection for all 3 channels based on W/Z jet mass requirements (26 GeV windows), implying **statistical overlap** between channels

2 large **CA** R=1.2 jets with $n_{trk} < 30$ are required in the events, satisfying boson tagging requirements (grooming & filtering). Extra topology requirements are used to reduce QCD backgrounds

CMS

Require 2 **CA** R=0.8 jets in the events along with topology requirements to reduce backgrounds

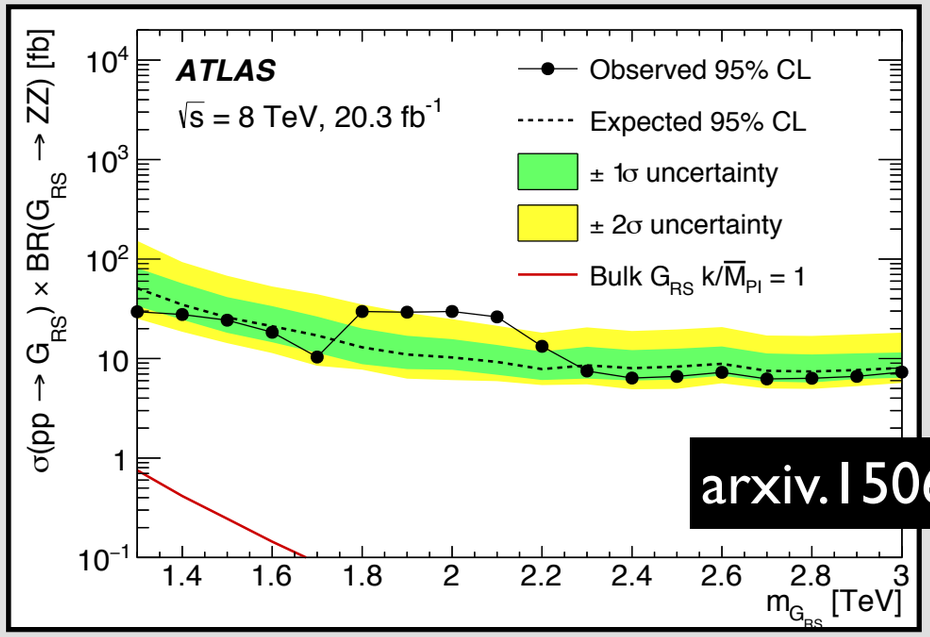
Jets are W/Z-tagged based on a combination of pruned mass and subjettiness requirements Separate events into 1/2 tag category, and use same **HP/LP** classification as in the *llqq* analysis

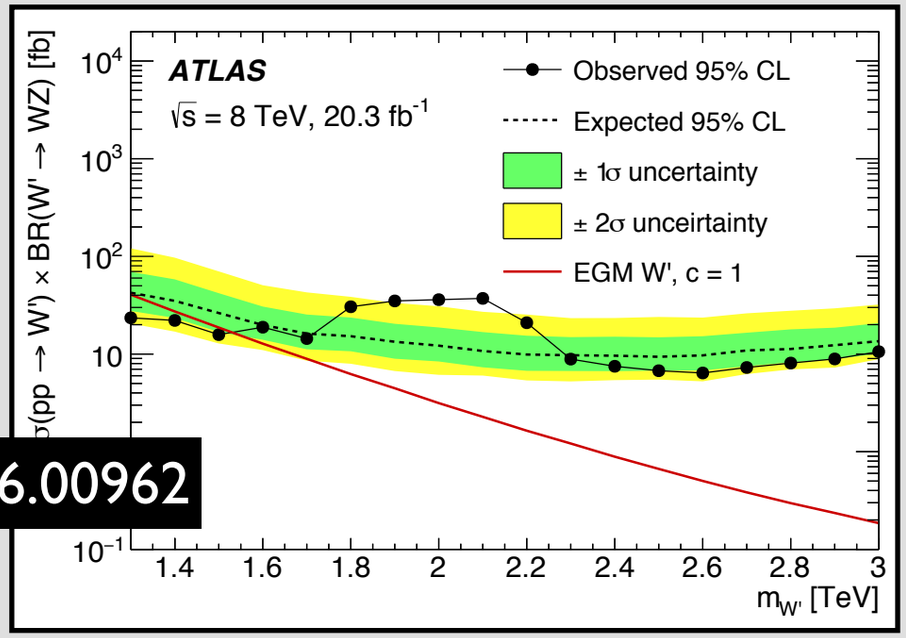
ZZ & WZ & WW → *qqqq* Limit Setting

ATLAS

Limits set on RS Gravitons and EGM W'

Excesses seen in all 3 channels (overlapping), at 3.4σ, 2.9σ and 2.4σ local significance





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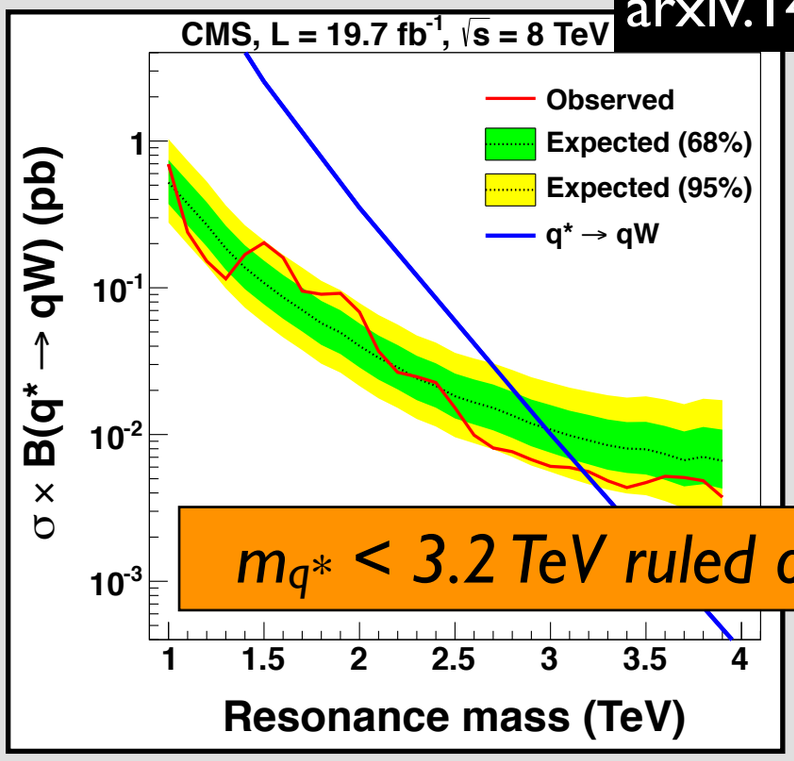
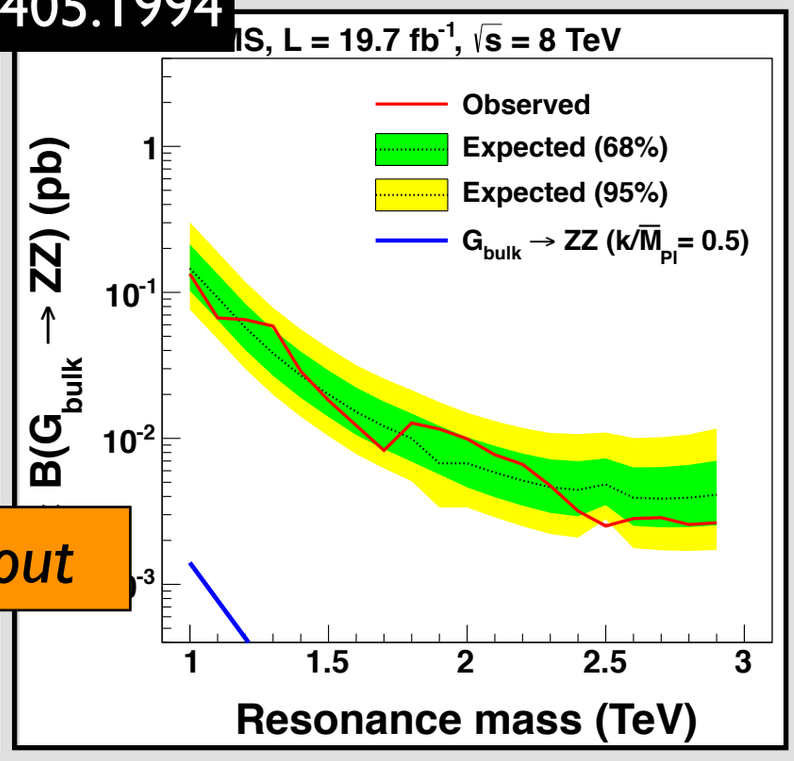




$m_{q^*} < 3.2$ TeV ruled out

CMS

Limits set on RS Gravitons and W'

Due to single tag category, unique sensitivity to excited quark scenarios (q*→qW/qZ)!

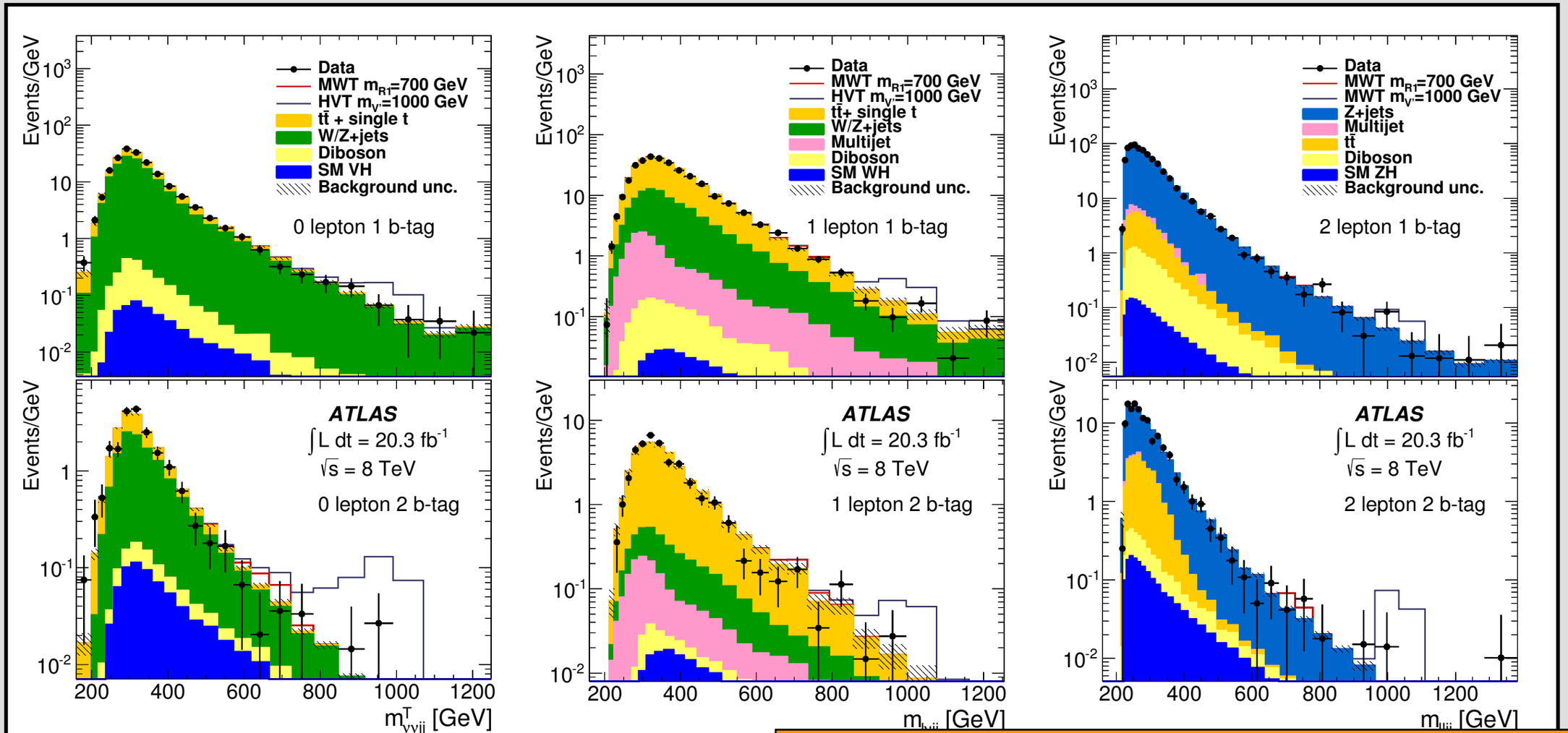
WH & ZH → [νν / lν / ll] + bb

ATLAS

arxiv.1503.08089

Define six exclusive signal regions to cover all final states through requirements on the number of leptons and b-tagged jets
Resolved scenarios only!

Additional event requirements are used to reduce backgrounds:
- 0 lep: Large E_T^{miss} and jet activity
- 1 lep: E_T^{miss} and transverse mass
- 2 lep: Compatibility with Z decay



(a) $\nu\nu b\bar{b}$ (b)

Limits are set on Minimal Walking Technicolor and Heavy Vector Triplet models

WH & ZH → [νν / lν / ll] + bb

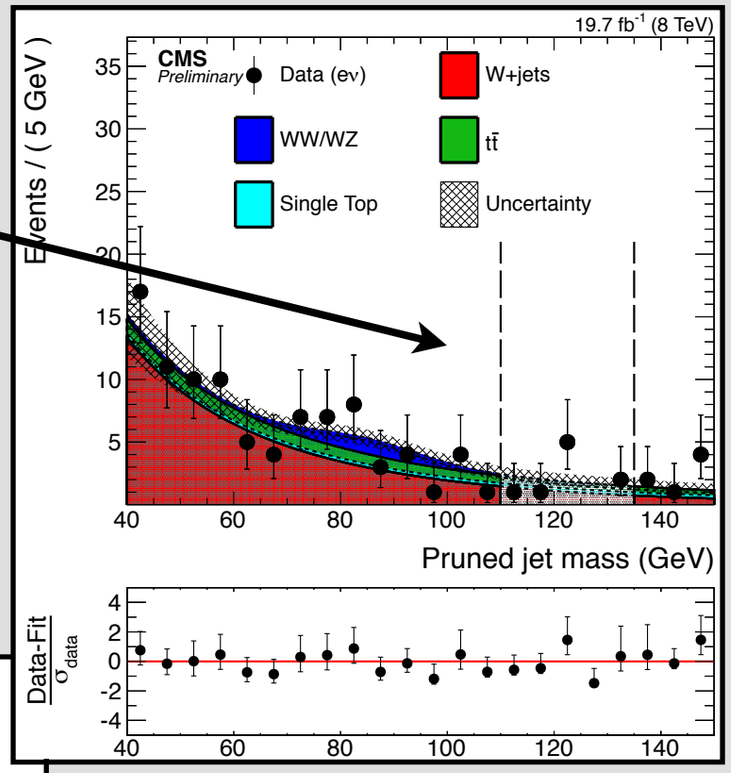
CMS

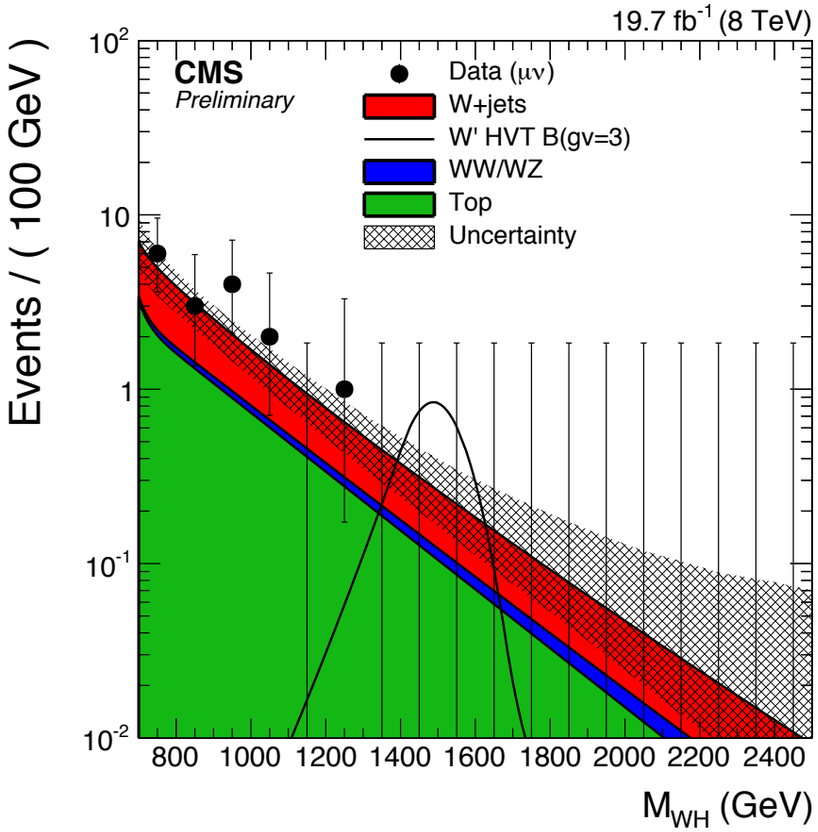
CMS-EXO-14-010

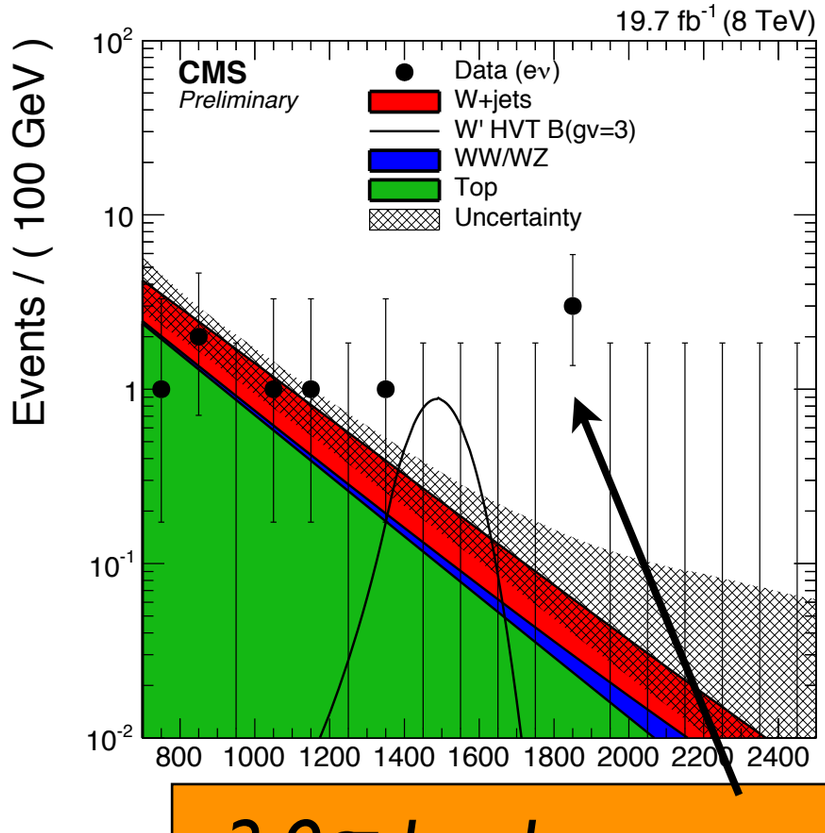
Using WH final state only for high-mass search
Identify final state via requirements on one lepton and E_T^{miss}

Large **CA** R=0.8 jet is used to identify Higgs candidates, through both requirements on its mass and on whether it is/its subjets are b-tagged (subjets are not/are well-separated)

Top events are veto'ed through requirements on the mass of the large jet and nearest lepton/jet







Limits are set on W' from Little Higgs model and Heavy Vector Triplet models

2.9σ local excess seen in electron channel!

WH & ZH → *qqbb & qqWW*

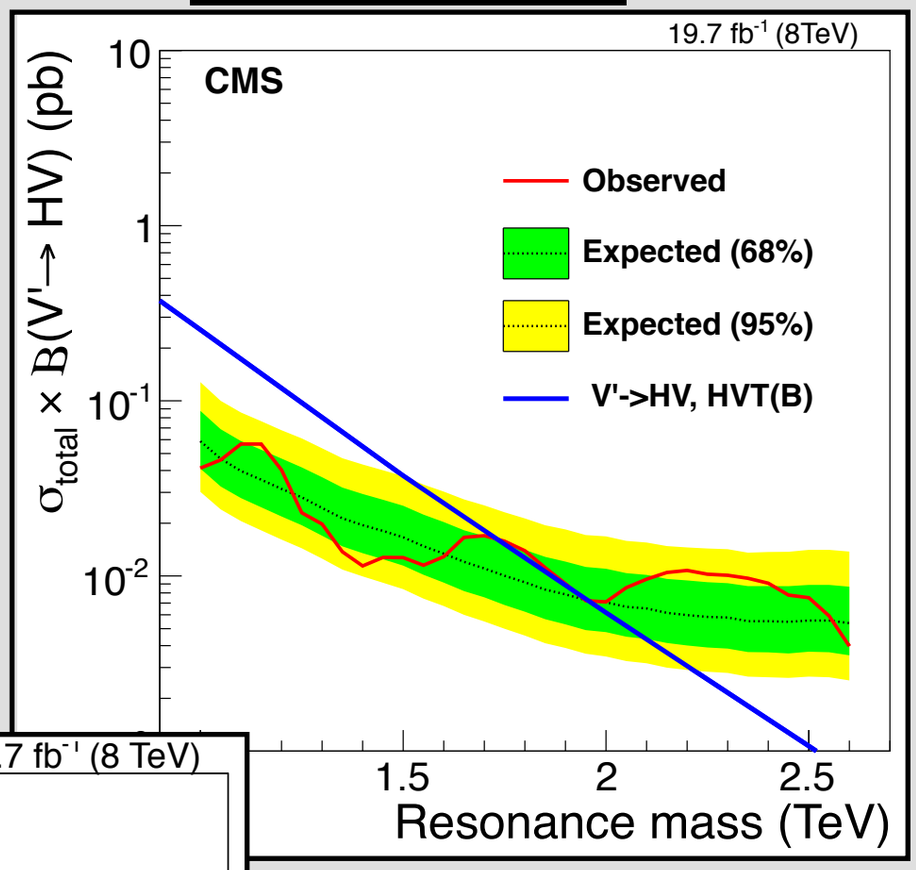
CMS only

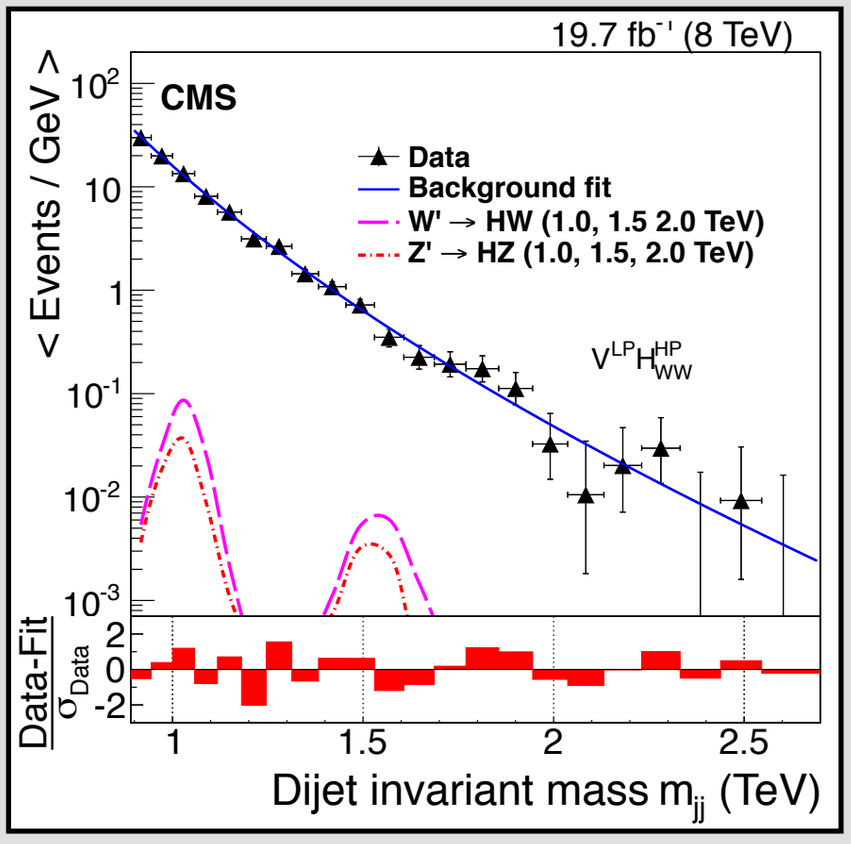
arxiv.1506.01443

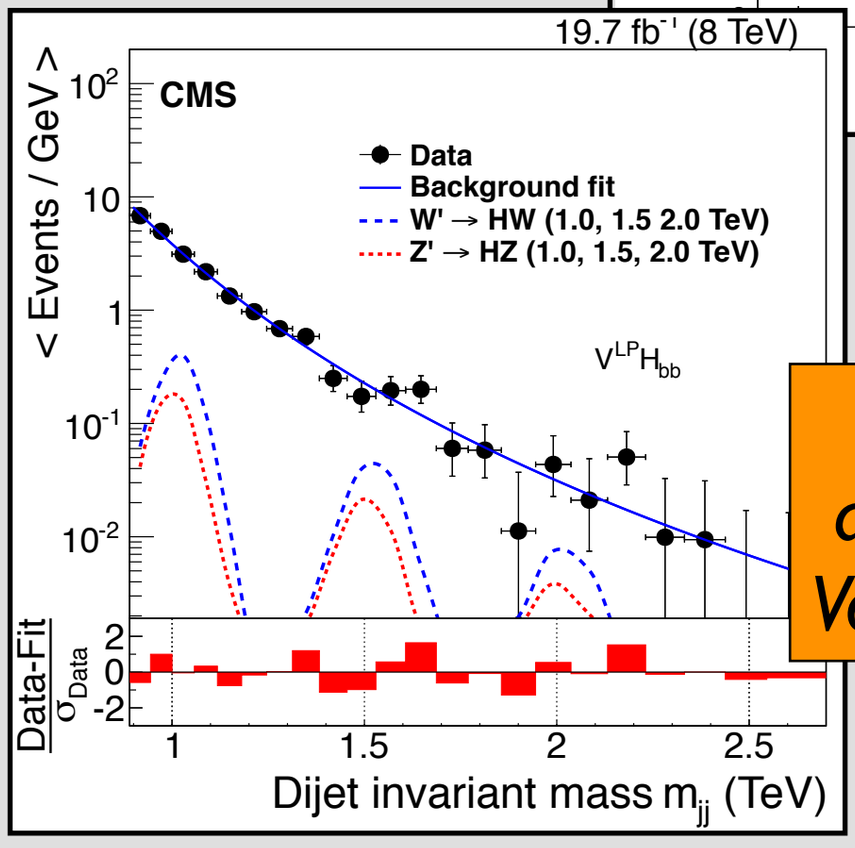
First search for VH in fully hadronic final state and first time inclusion of H→WW→qqqq decays via substructure techniques!

Separate analysis in 5 categories, through a combination of **HP**/**LP** boson-tagging (VH_{WW}) and b-tagging (VH_{bb})

Use same b-tagging and boson-tagging techniques as before; for WW→qqqq, use 4-2 subjettiness ratio







Limits are set on W' and Z' from the Heavy Vector Triplet framework

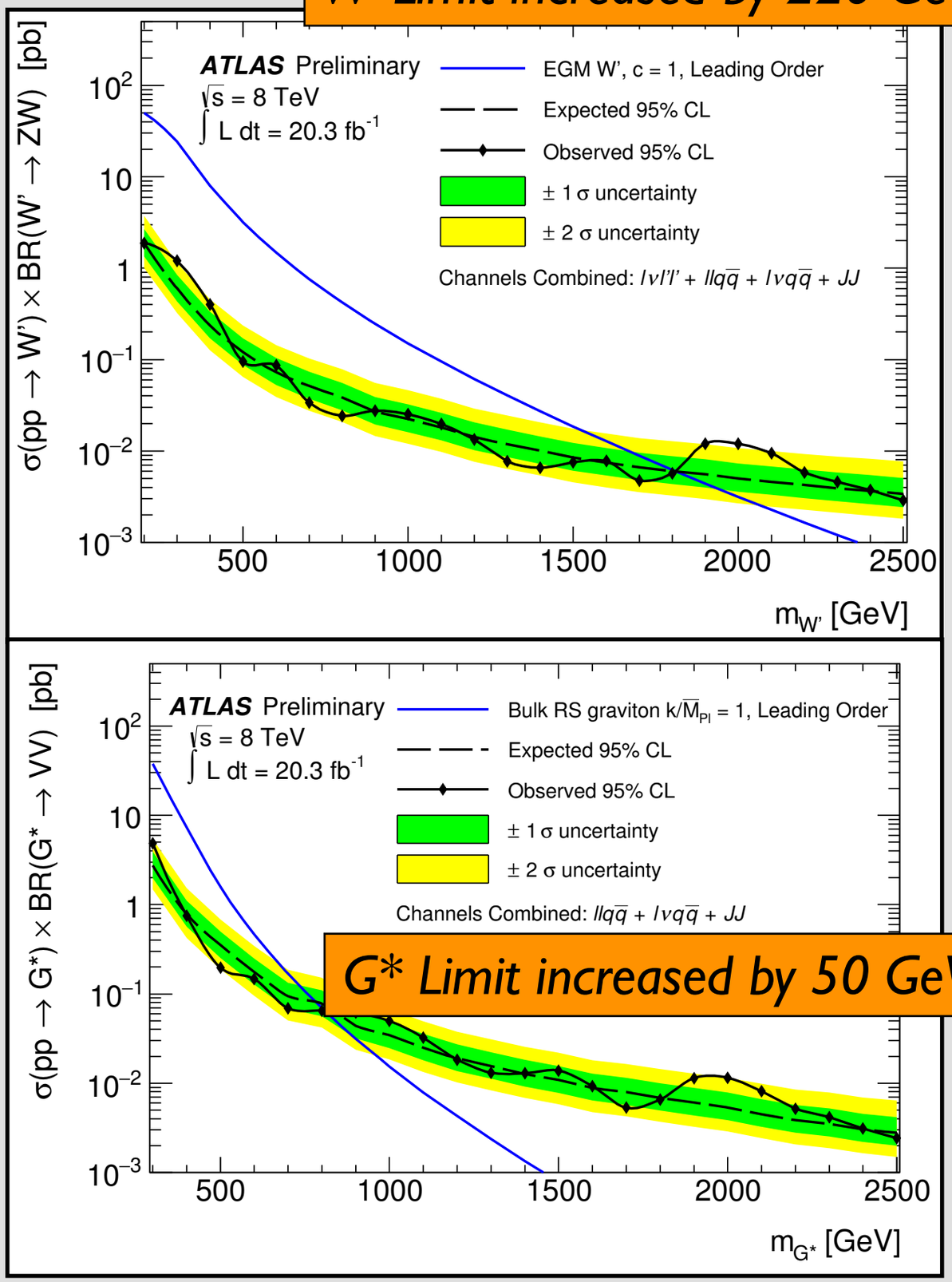
WW / WZ / ZZ Combination

ATLAS only

New!

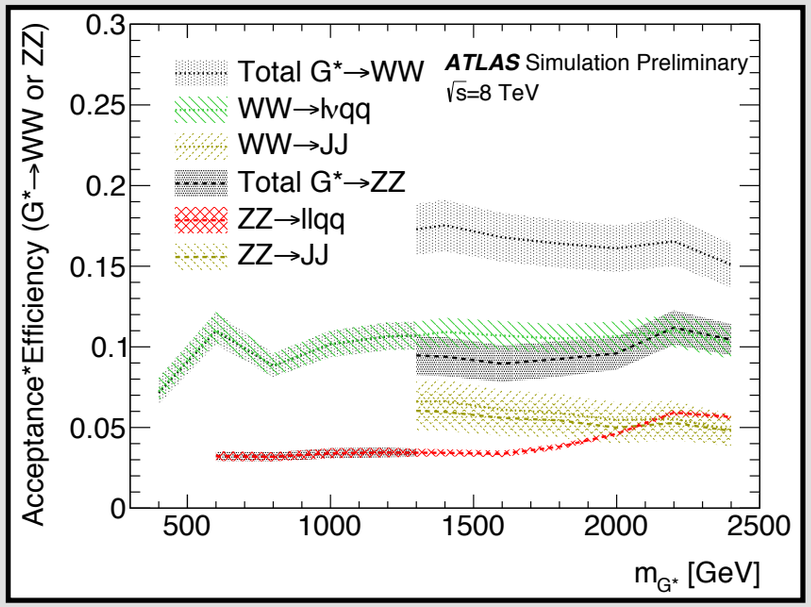
ATLAS-CONF-2015-045

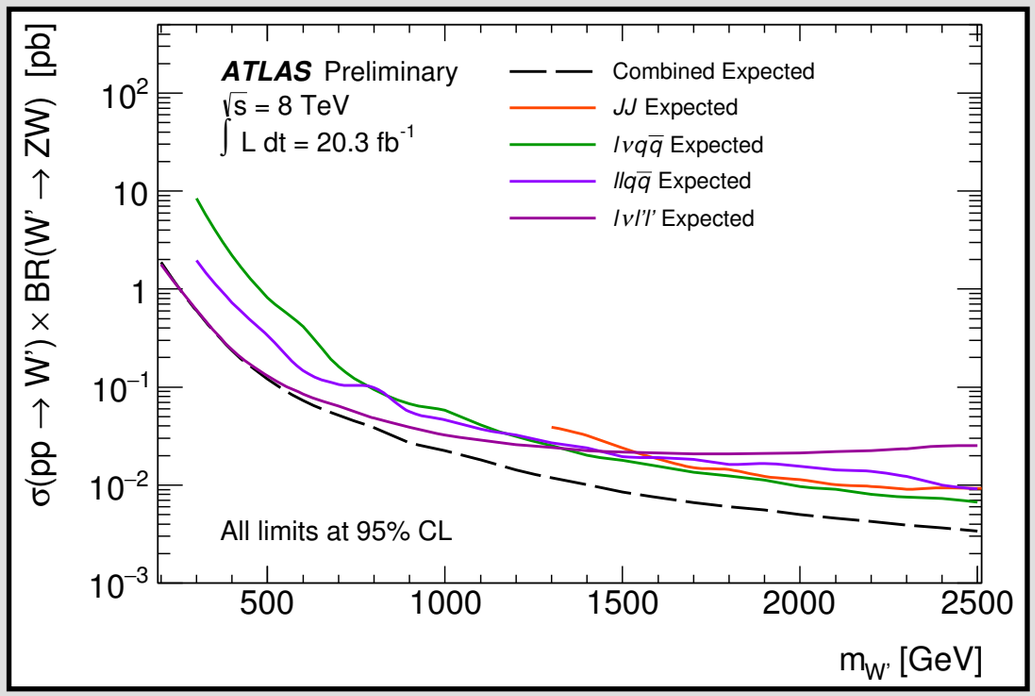
W' Limit increased by 220 GeV



G Limit increased by 50 GeV*

Combination of four statistically independent searches (of which *lνll* is the only one not shown in this talk, see arxiv:1406.4456)





Summary

- Searches for resonant di-boson production are a sensitive probe for new physics!
- The high-mass final states considered make them the perfect application for boosted-object reconstruction and tagging techniques - *Building confidence in their use!*
- Presented a summary of the most recent Run-I searches at both ATLAS & CMS
- Some interesting excesses seen - but are they here to stay?

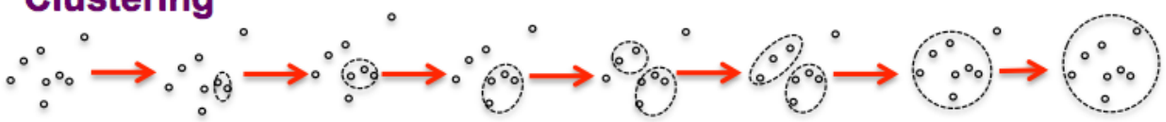
Run-II analyses are ramping up and awaiting the new data eagerly - could we be on the cusp of a discovery?

Thanks for your time!

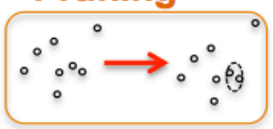
Bonus…

More on Substructure...

Clustering

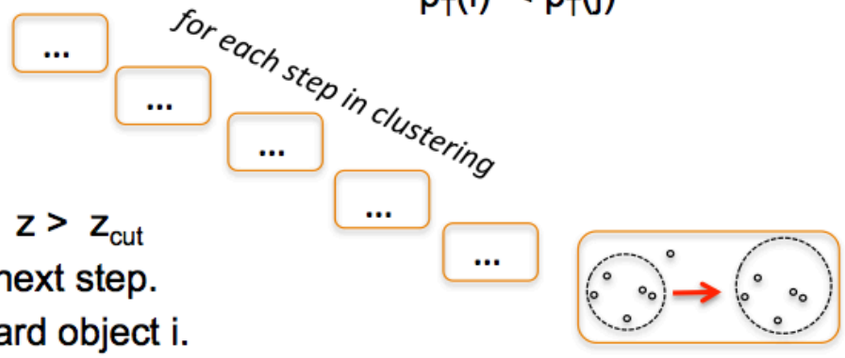


Pruning



$z = p_T(i) / p_T(i+j)$

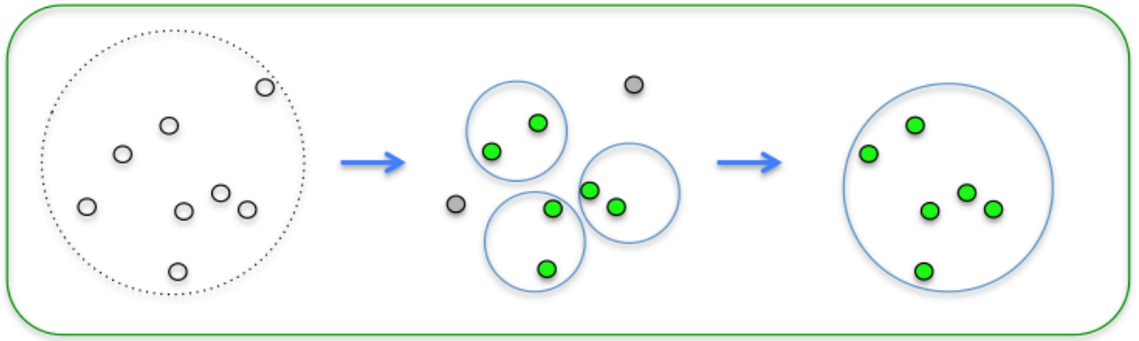
$p_T(i) < p_T(j)$



At each step:

If $\Delta R_{ij} < d_{cut}$ ***OR*** $z > z_{cut}$
continue to next step.
Otherwise, discard object i.

Filtering



Type 1 (Trimming) : If p_T (subjet i) / p_T (jet) < f_{cut} : discard subjet.

Type 2 : If $N_{subjets} \leq N_{min}$: discard jet.

Resulting jet is sum of subjets.

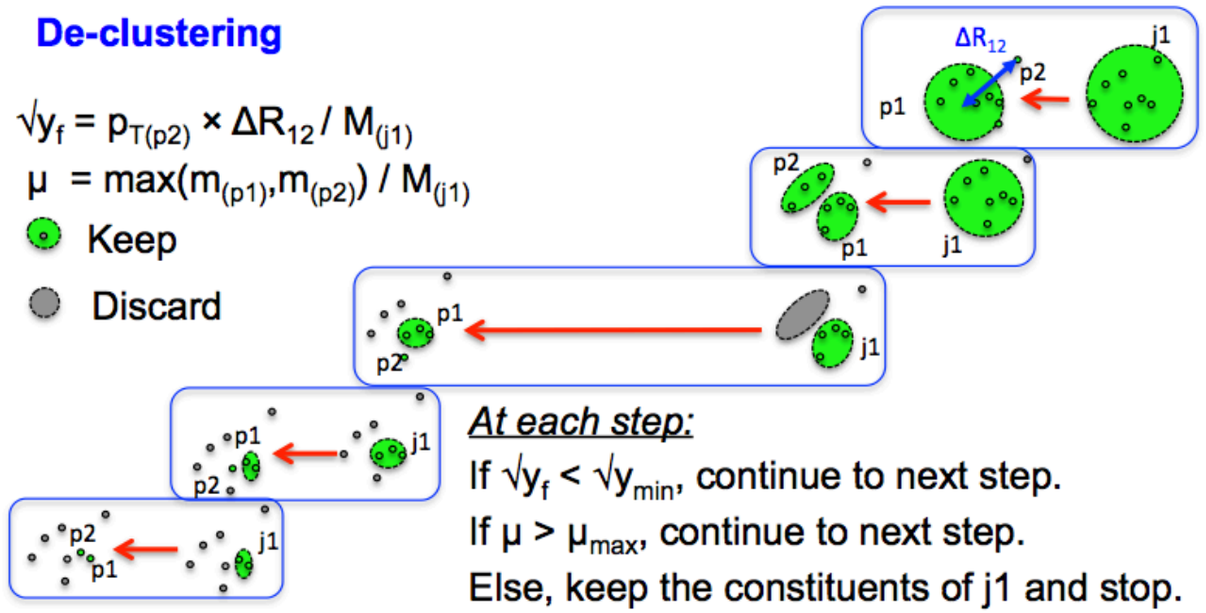
De-clustering

$\sqrt{y_f} = p_{T(p2)} \times \Delta R_{12} / M_{(j1)}$

$\mu = \max(m_{(p1)}, m_{(p2)}) / M_{(j1)}$

Keep

Discard



At each step:

If $\sqrt{y_f} < \sqrt{y_{min}}$, continue to next step.

If $\mu > \mu_{max}$, continue to next step.

Else, keep the constituents of j1 and stop.

See ATL-PHYS-PUB-2014-004 for a very in-depth review (many other references also!)

Average scale dR= $2m/p_T$

A bit about the models...

Charged (WZ)

Sequential Standard Model (W', spin-1)

✳ Trilinear W'WZ coupling set by Extended Gauge Model: ~ $(M_W/M_{W'})^2$

Neutral (WW,ZZ,HH)

Randall-Sundrum graviton (RS G*, spin-2)

✳ Traditional benchmark model with extra dimensions

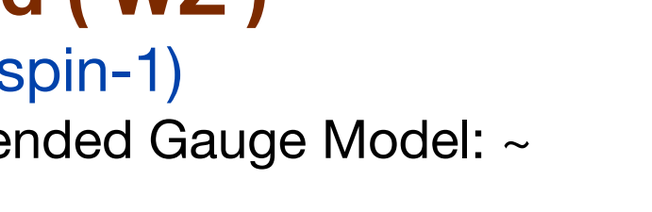
Bulk RS graviton (Bulk G*, spin-2)

✳ Graviton couples more with heavy particles (W, Z, t)

✳ Smaller σ, but larger branching ratio to WW, ZZ

Minimal Walking Technicolor (R_1,R_2, charged and neutral)

✳ Technicolor with minimal ingredients, can decay to ZH and WH



HVT (Simplified Lagrangian)

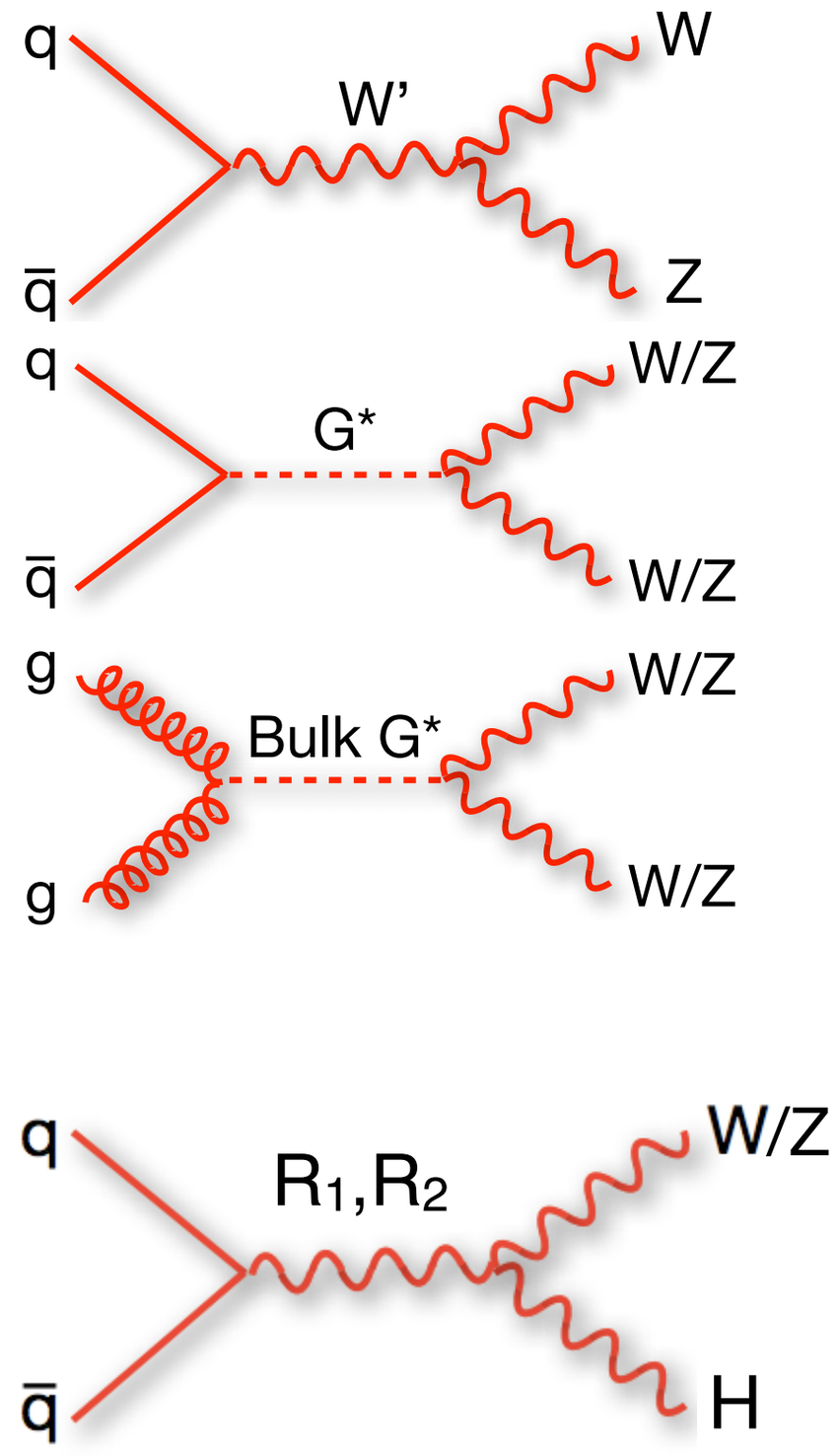
Model A

✳ weakly coupled vector resonances from extension of the gauge group

Model B

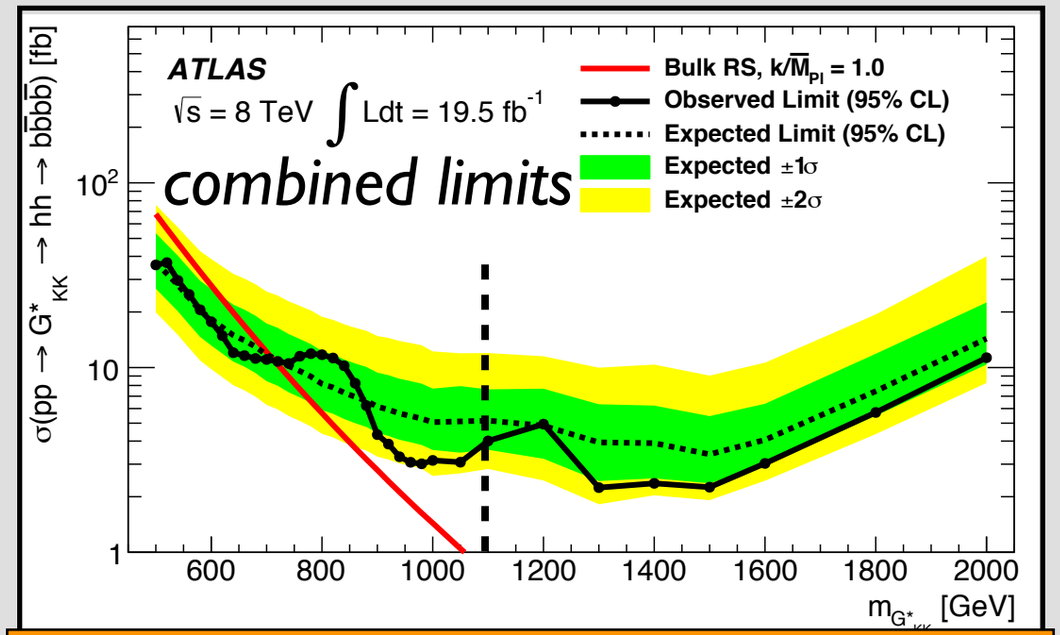
✳ produced in a strong scenario e.g. composite higgs model

Slide borrowed from V. Cavaliere...



HH → *bbbb*

arxiv.1506.00285 **ATLAS**

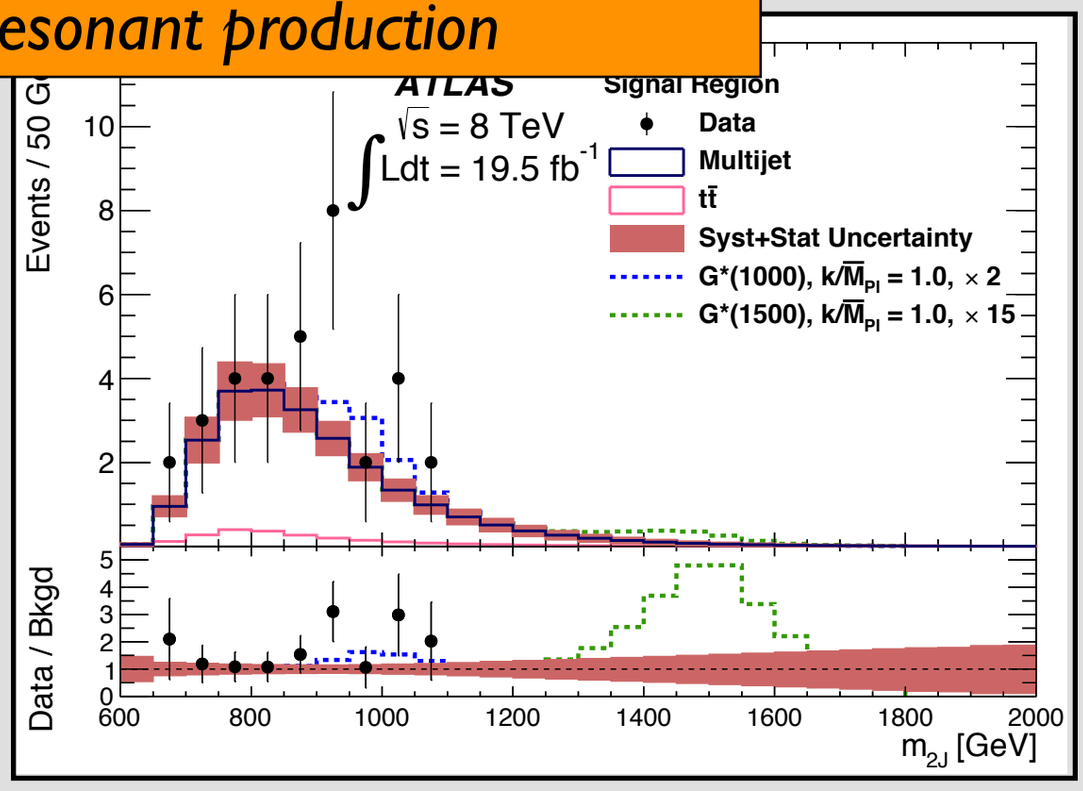


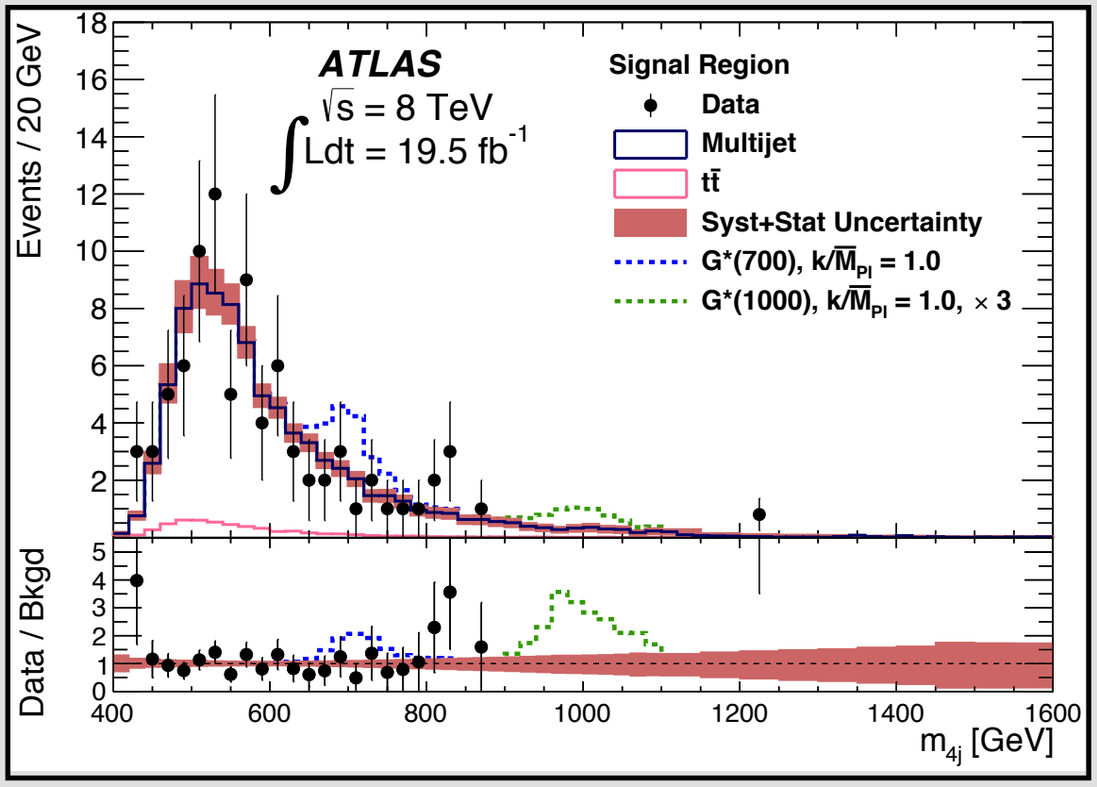
Limits are set on RS Gravitons, 2HDM models, narrow resonances and non-resonant production

Two complementary selections are used, targeting different mass ranges:

Resolved: 4 b-jets (2 separate dijet systems), use of complex ditop veto using jet kinematics
Boosted: 2 large R=1.0 anti-k_T jets, b-tagging applied to constituent small radius track jets

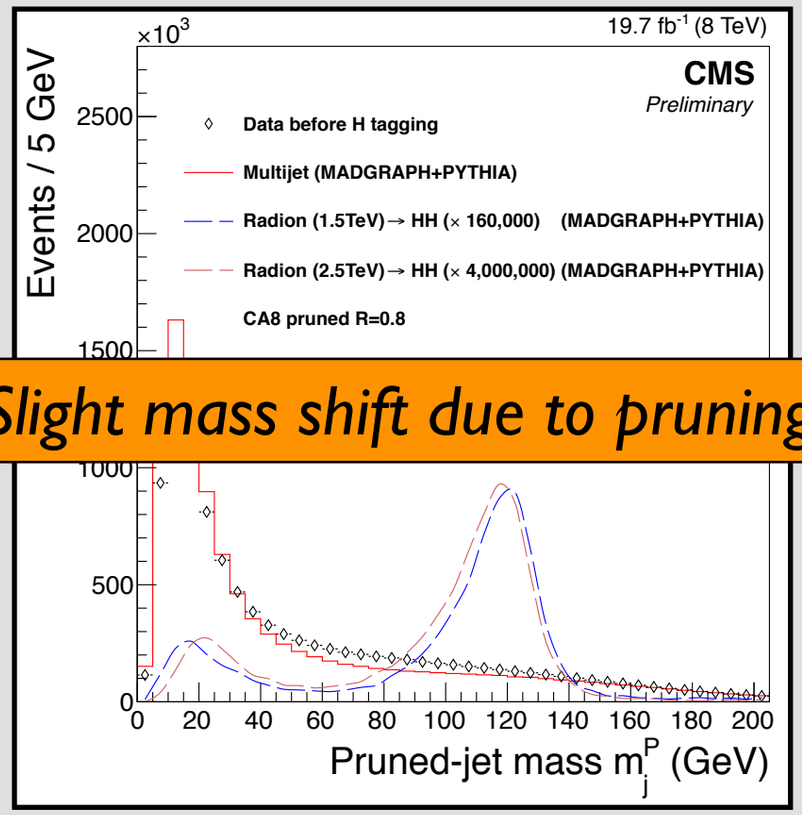
Mass requirements are applied to the large jets, and the dijet pairs





HH → *bbbb*

CMS-EXO-12-053 **CMS** *New!*

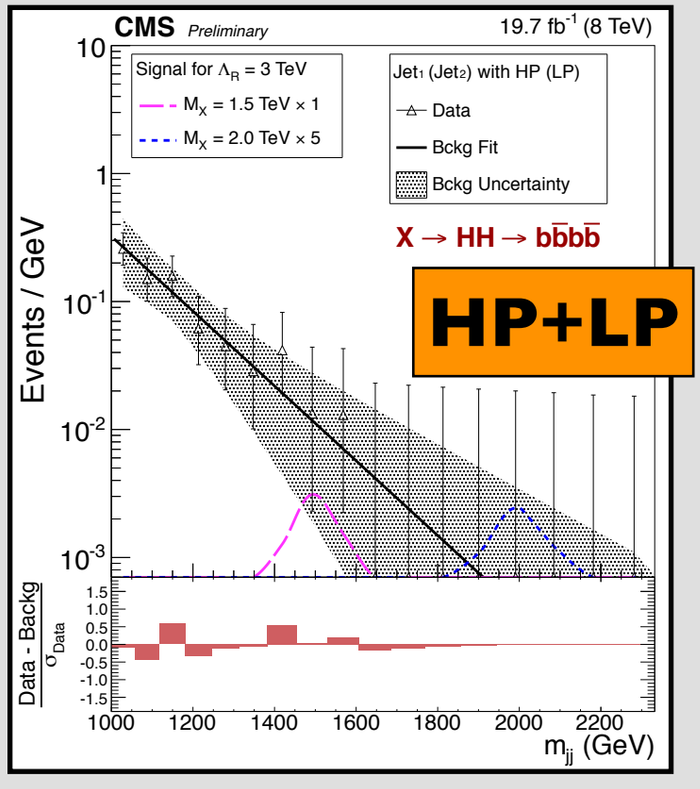


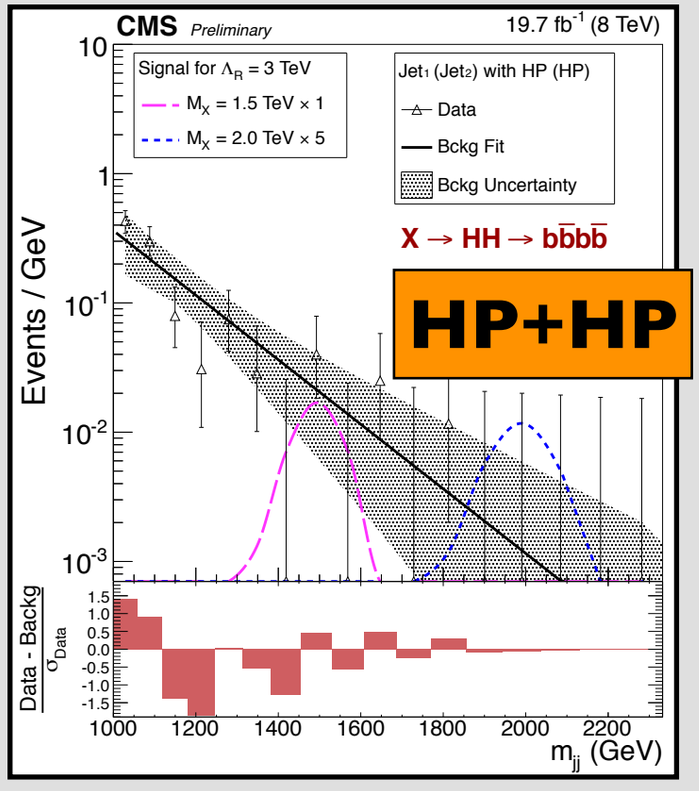
Slight mass shift due to pruning

Selecting 2 pruned **CA** R=0.8 jets with a 25 GeV mass window around m_H, with topology requirements to reduce multijet backgrounds (angular separation & invariant mass of jet pair)

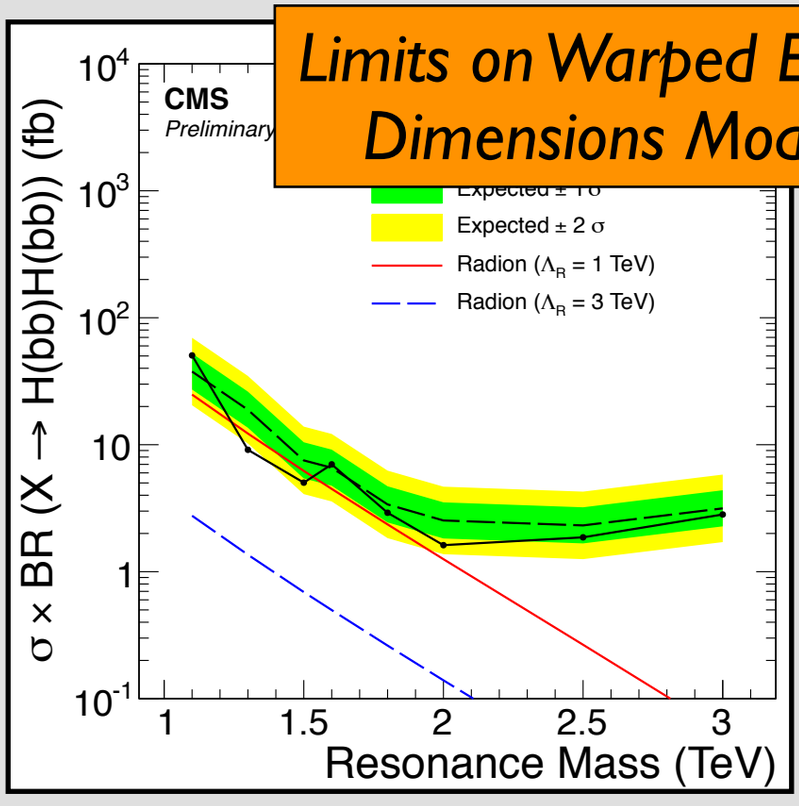
Define signal regions based on b-tagging properties:
Tight tag: Two R=0.3 subjets are b-tagged, or if the entire jet is tagged (subjets not sufficiently separated)
Tag: One R=0.3 subjet is b-tagged

Event Selection: 2 **tags**, at least one is **tight**, both jets satisfy subjettiness ratio (both at least **LP**, at least one is **HP**)





Limits on Warped Extra Dimensions Model



$VV \to \ell\ell qq$ / $\ell\nu qq$ Analysis Details

Sample	LR	HR	MR
Z + jets	9460 ± 40 ± 660	591 ± 4 ± 15	20.9 ± 0.3 ± 2.3
$WW/WZ/ZZ$	234 ± 4 ± 22	20.6 ± 0.3 ± 1.4	1.38 ± 0.02 ± 0.13
$t\bar{t}$ + Single t	175.3 ± 9.2 ± 9.9	-	-
Total (unconstrained)	9870 ± 690	612 ± 17	22.3 ± 2.5
Total (constrained)	9730 ± 98	608.8 ± 3.8	21.80 ± 0.46
Data	9728	619	25
G^* Signal	1097 ± 17 ± 63	14.27 ± 0.19 ± 0.76	0.0995 ± 0.0013 ± 0.0059
W' Signal	1950 ± 40 ± 140	145.0 ± 2.3 ± 8.1	3.64 ± 0.06 ± 0.31

Uncertainties < 10% in the resolved cases, 10-40% in the merged

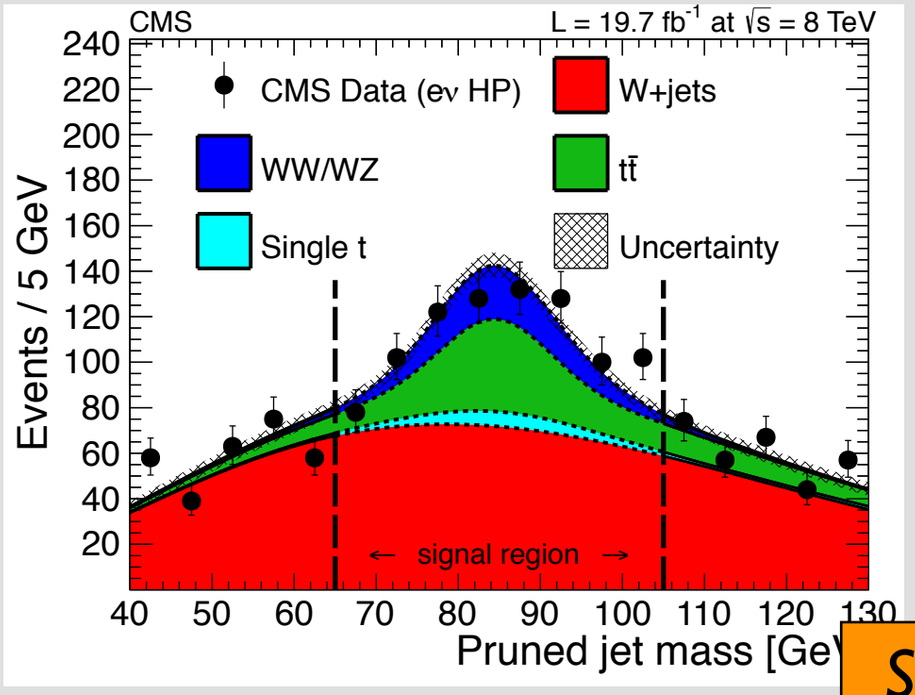
arxiv.1409.6190
arxiv.1503.04677

ATLAS

Control regions used to normalize W/Z+jets backgrounds with m_J/m_{jj} outside the cut window

CMS arxiv.1405.3447

Control regions used to normalize W/Z+jets backgrounds with m_J/m_{jj} outside the cut window, shape taken from low mass region



Source	Analysis $\ell\nu$+V-jet	Analysis $\ell\ell$+V-jet
Muons (trigger and ID)	2%	5%
Muon scale	1%	2%
Muon resolution	<0.1%	0.5%
Electrons (trigger and ID)	3%	3%
Electron scale	<0.5%	<0.5%
Electron resolution	<0.1%	<0.1%
Jet scale	1–3%	1%
Jet resolution	<0.5%	<0.1%
Unclustered energy scale	<0.5%	—
Pileup	0.5%	0.5%
V tagging	9% (HP) 24% (LP)	
PDF	<0.5%	
Luminosity	2.6%	

SFs/Uncertainties on boson-tagging taken from enriched samples

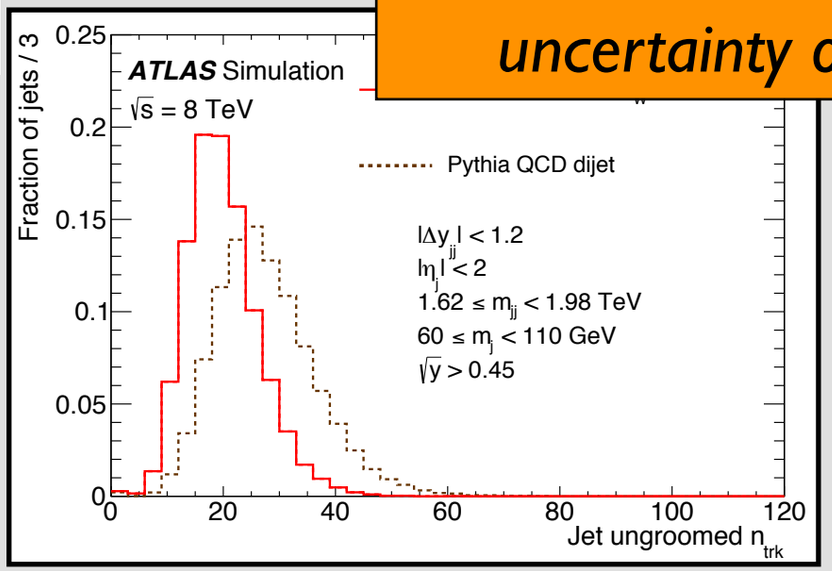
VV → *qqqq* Analysis Details

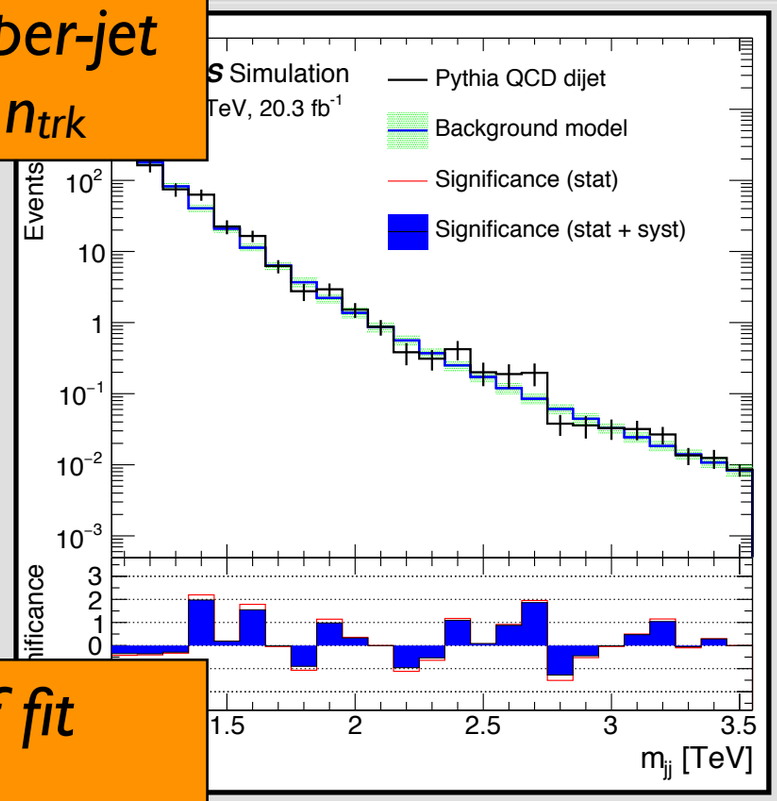
ATLAS arxiv.1506.00962

$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2-\xi p_3}\, x^{p_3}$$

Background estimate is a fit to the distribution, many checks for robustness (also repeated in mass windows around $m_{W/Z}$), generally <25% of the stat. error

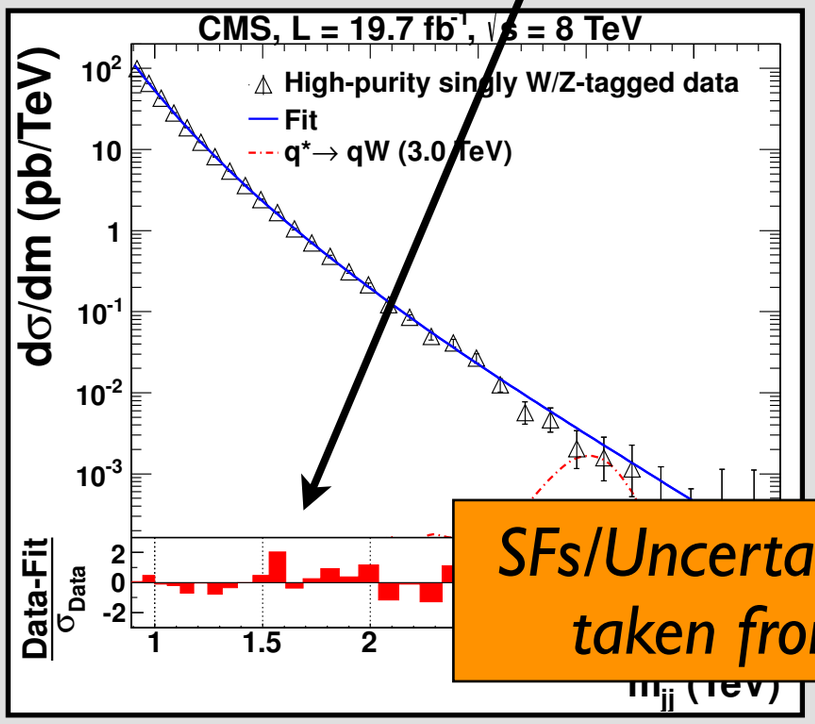
Data-driven 10% per-jet uncertainty on n_{trk}

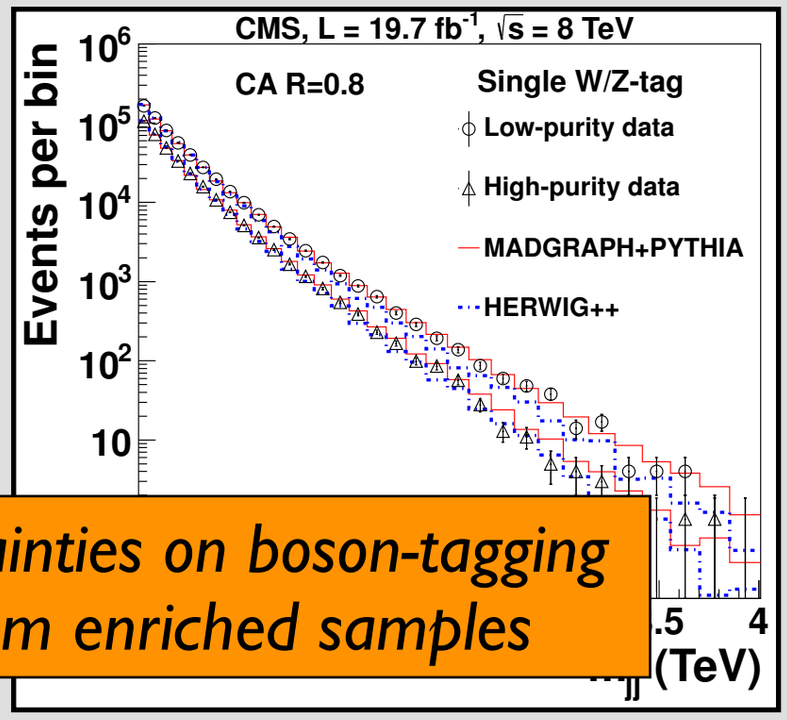




Largest excess at 1.5 TeV

Cross-check of fit robustness





SFs/Uncertainties on boson-tagging taken from enriched samples

CMS arxiv.1405.1994

$$P_D(m_{jj}) = \frac{P_0(1-m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}$$

Background estimate is a fit to the distribution, dependencies on the fit parameters are profiled away during interpretation

7.5% (54%) uncertainty on LP (HP) W-tagging...

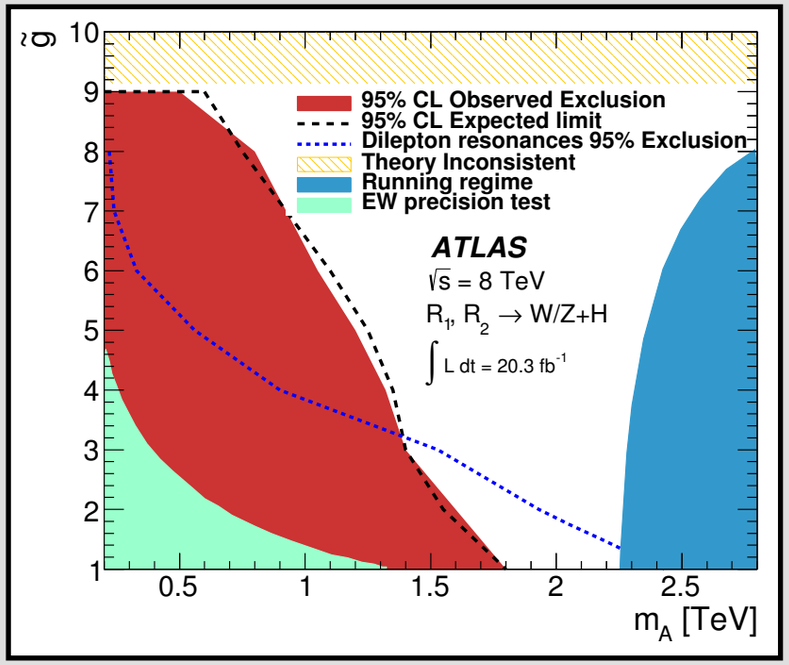
VH → [νν / lν / ll] + bb Analysis Details

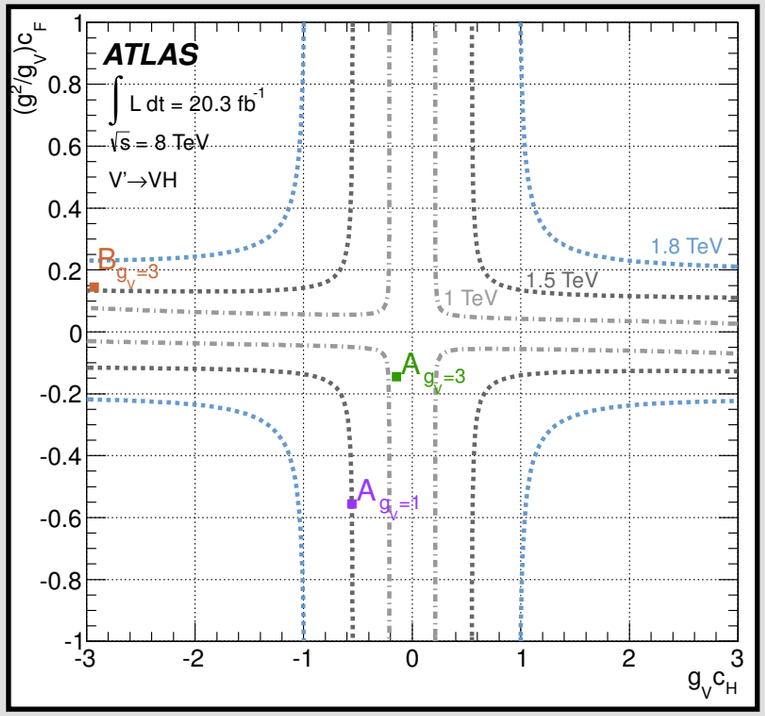
ATLAS arxiv.1503.08089

Background estimates are MC driven

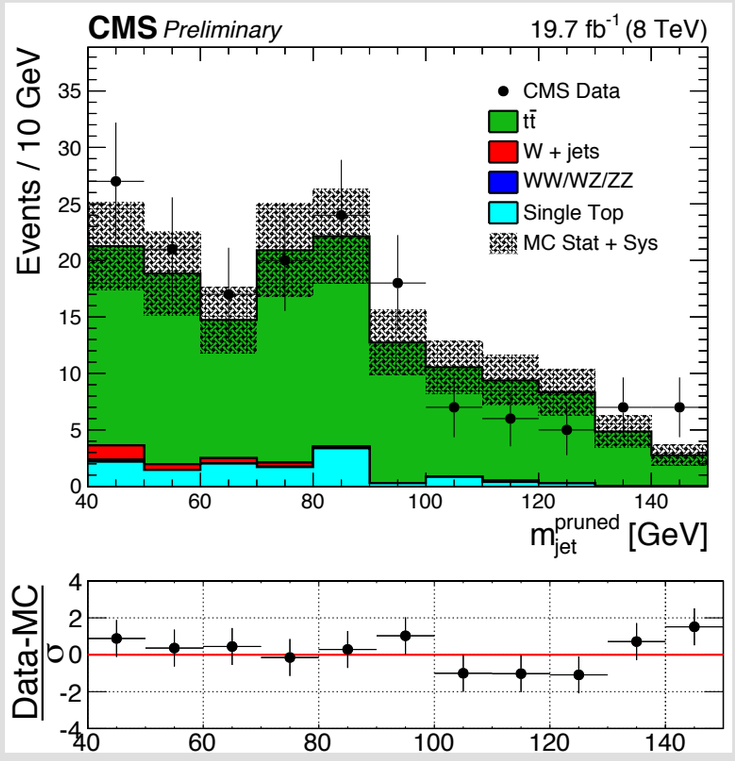
QCD obtained using ABCD method based on regions defined by dPhi (jet, E_T^{miss}) and dPhi (E_T^{miss}, p_T^{miss})

Largest uncertainties from b-tagging and JES





Source	Uncertainty eν+H-jet	Uncertainty μν+H-jet
Muons (trigger and ID)	–	2%
Muon scale	–	1%
Muon resolution	–	<0.1%
Electrons (trigger and ID)	3%	–
Electron scale	<0.5%	–
Electron resolution	<0.1%	–
Jet scale	1–3%	
Jet resolution	<0.5%	
Higgs mass tagging	2–10%	
Higgs b tagging	2–8%	
Unclustered energy scale	<0.5%	
Pileup	0.5%	
PDF	<0.5%	
Luminosity	2.6%	



CMS-EXO-14-010 CMS

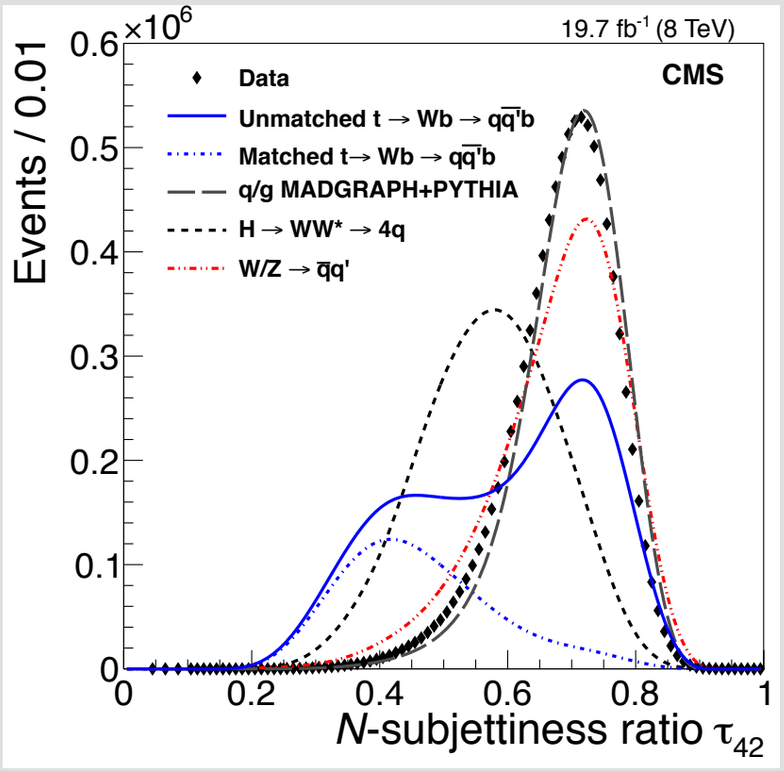
W+Jets background estimated using sideband regions in m_J to get the shape and normalization

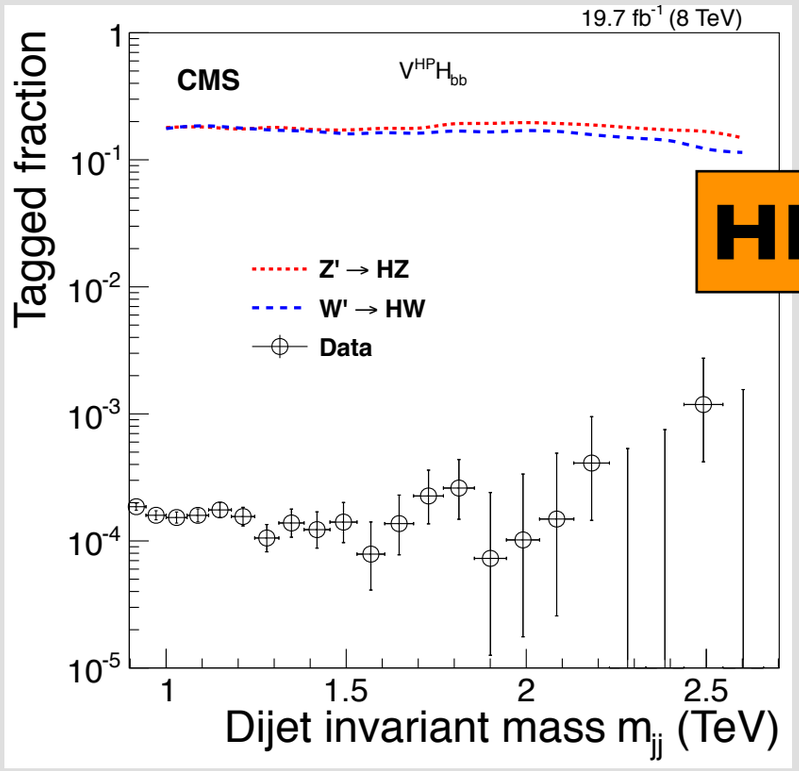
Ditop background normalized using a control region

WH & ZH → *qqbb & qqWW*

CMS only

arxiv.1506.01443





$$P_D(m_{jj}) = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}$$

Background estimate is a fit to the distribution separate for each channel, cross-checks with other functions performed - changes are negligible

Other Higgs decays (cross-talk) are eventually ignored (conservative - potentially 7-24% more sensitive)

Tagging efficiency uncertainty measured in a data-driven ttbar sample, extrapolation to high-p_T and 4*q* case done via comparison of MC generators

Source	HP uncertainties (%)	LP uncertainties (%)
JES	1	1
JER	10	10
Pileup	≤3.0	≤3.0
PDF	5–15	5–15
Integrated luminosity	2.6	2.6
W-tagging	7.5	54
W tag p_T dependence	4	12

Source	Final state		
	$H \to b\bar{b}$		$H \to WW^* \to 4q$
	VH_{bb}	VH_{WW}	VH_{WW}
$H \to b\bar{b}$ mass scale	2.6	—	—
H(4q)-tagging	—	7.5 (54)	7.5 (54)
H(4q)-tag τ_{42} extrapolation	—	7	7
Cross-talk	7	24	24
b-tagging	≤ 15	≤ 15	—