

# Exotics Searches at the LHC

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On behalf of the ATLAS, CMS and LHCb Collaborations

August 31, 2015



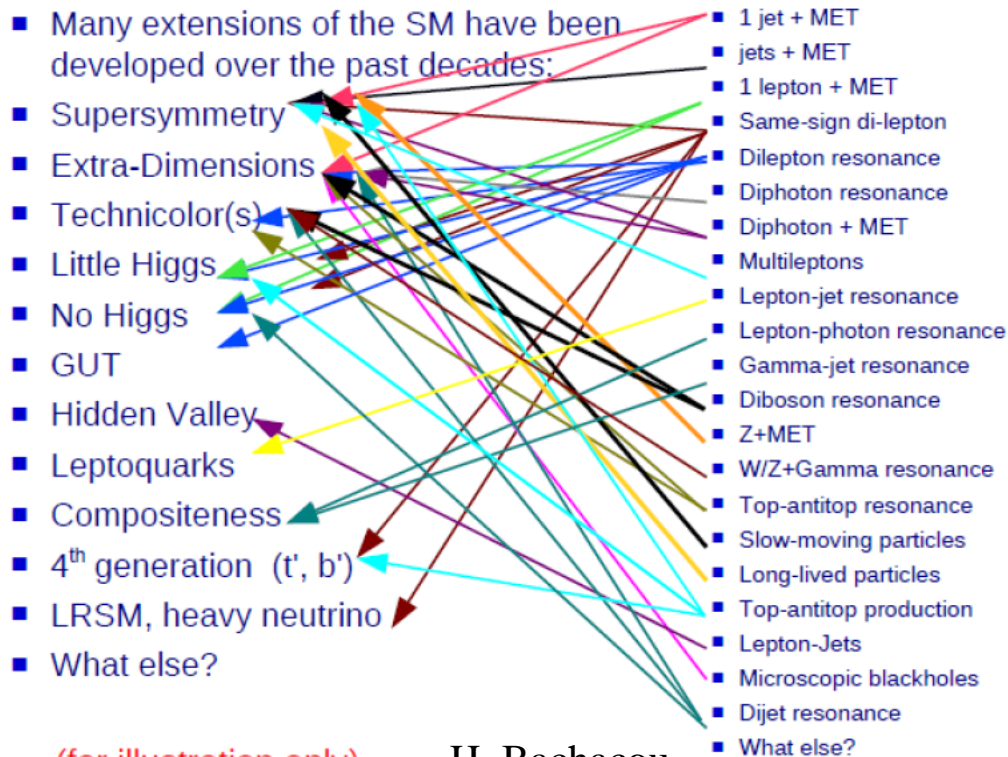
We are all reSearchers !

- A SM-like Higgs boson has been discovered
  - likely to be the only fundamental scalar particle found so far, its couplings are not dictated by any symmetries, receives quadratically divergent corrections to  $m_H^2$ 
$$m_H^2 = \mu^2 + \Delta m^2 \quad \text{with} \quad \mu = -2\lambda v^2 \quad \text{and} \quad \Delta m^2 \propto \Lambda^2$$
  - experimentally relatively low mass measured  $\rightarrow$  fine tuning
  - we have even more reasons to believe that BSM physics may well be in the reach of the LHC  $\rightarrow$  the Higgs discovery not only confirmed the anticipated answers but also the anticipated questions
  - an obvious lamppost to look under (See Pawel Renstrom's "BSM Higgs" talk this Thursday)

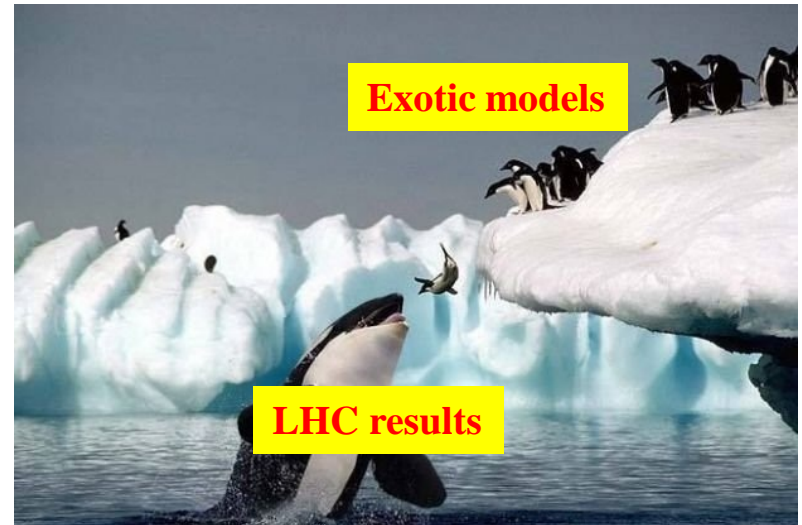
# LHC Run 1 Recap



- No other clear indications of new physics beyond the SM
  - cast a wide net to search for BSM physics
  - cover broad phase spaces: many different detector signatures, large span in production rates, wide range of masses
- Run 1 results have been extremely useful to kill some models or narrow down the allowed phase spaces



H. Bachacou



# Introduction

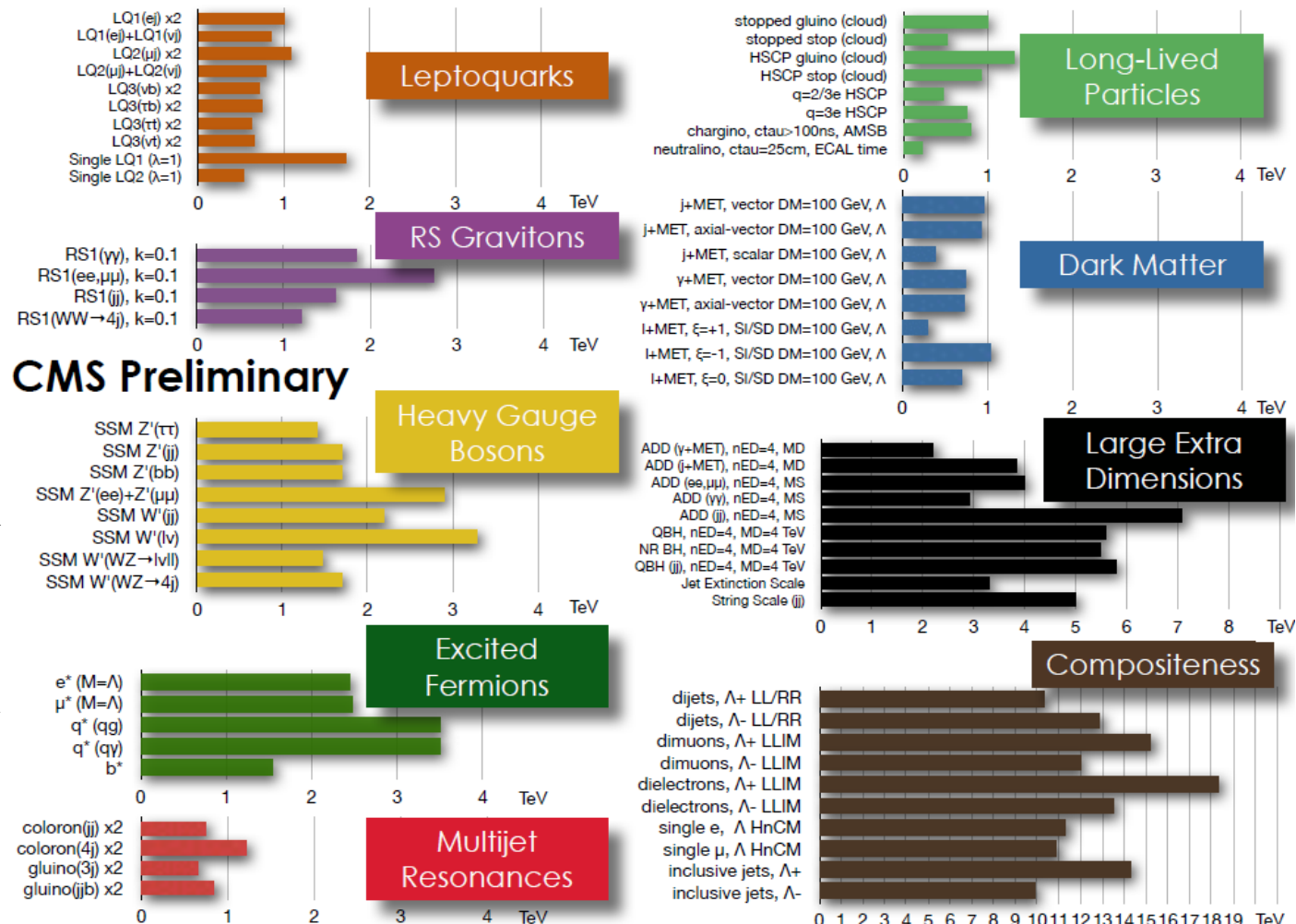


- Many old and new exotics search results from ATLAS, CMS and LHCb
- Impossible for me to cover all topics in 30 min., won't even try
- Only focus on a few Run 1 anomalies and related new results

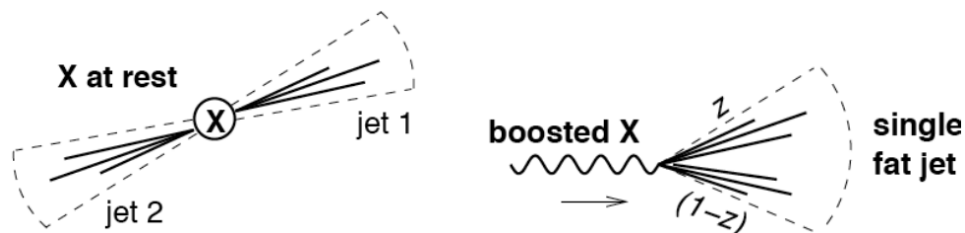
➤ **ATLAS exotics results:**  
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>

➤ **CMS exotics results:**  
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

➤ **LHCb results:**  
[http://lhcb.web.cern.ch/lhcb/lhcb\\_page/physics\\_results/recent\\_lhcb\\_results/](http://lhcb.web.cern.ch/lhcb/lhcb_page/physics_results/recent_lhcb_results/)



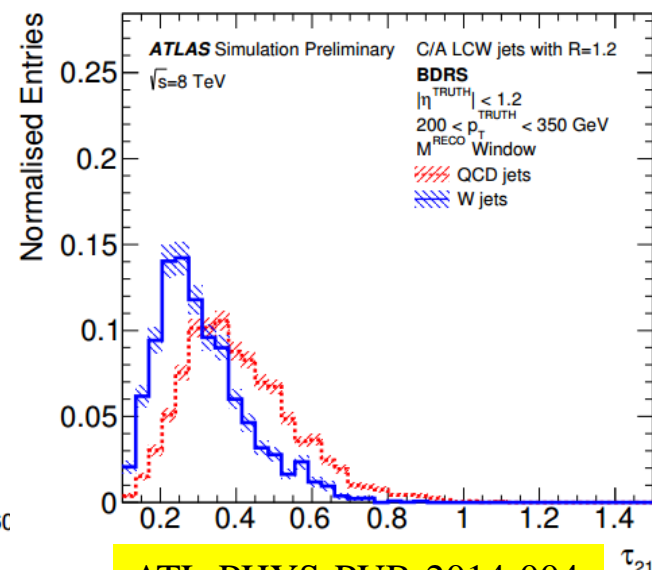
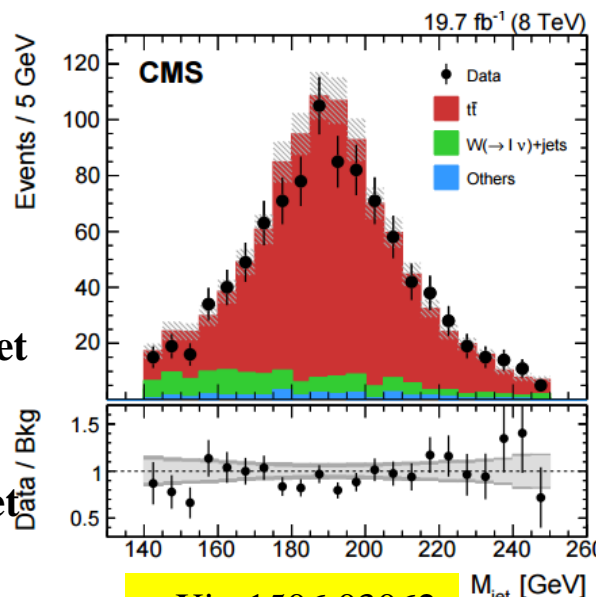
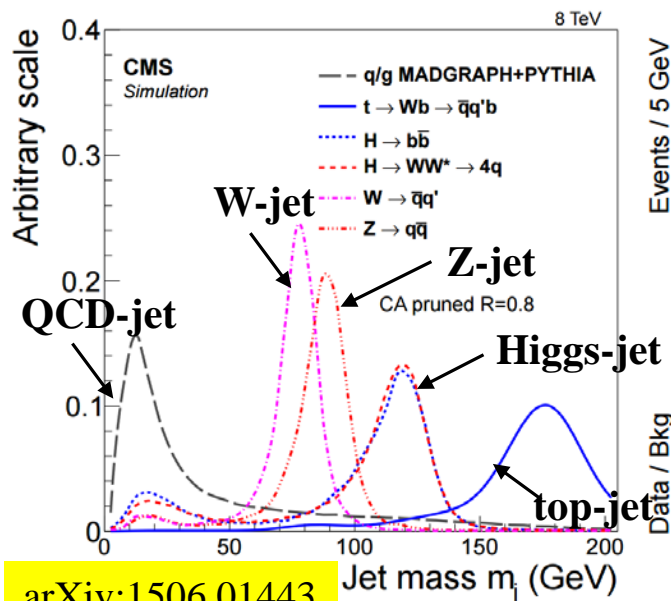
# A new frontier: jet substructure



Angular separation:  $\Delta R \sim 2m/p_T$   
 ( $\Delta R=0.36$  for  $m=90$  GeV and  $p_T=500$  GeV)  
 Resolved/merged jets

- Critical for heavy resonances decay to highly-boosted objects such as W, Z, H, t
- Jet filtering and pruning to reduce effects from soft radiation and pileup
- Identify jet types using mass, subjettiness, subjet momentum balance, tracks etc

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

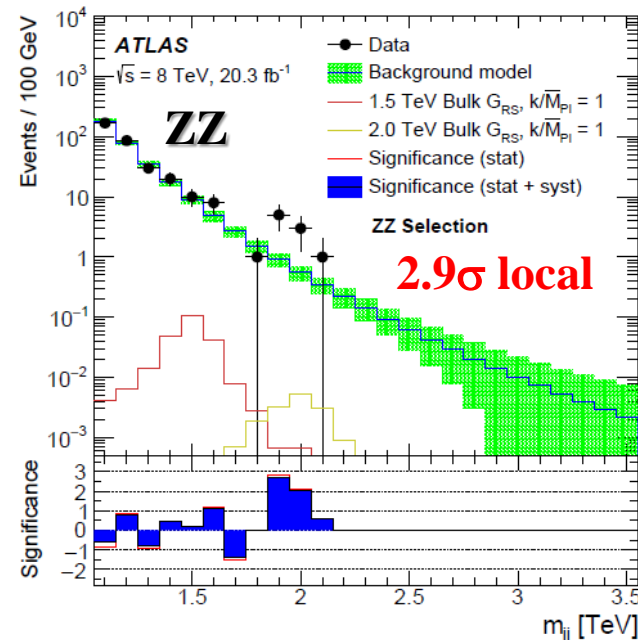
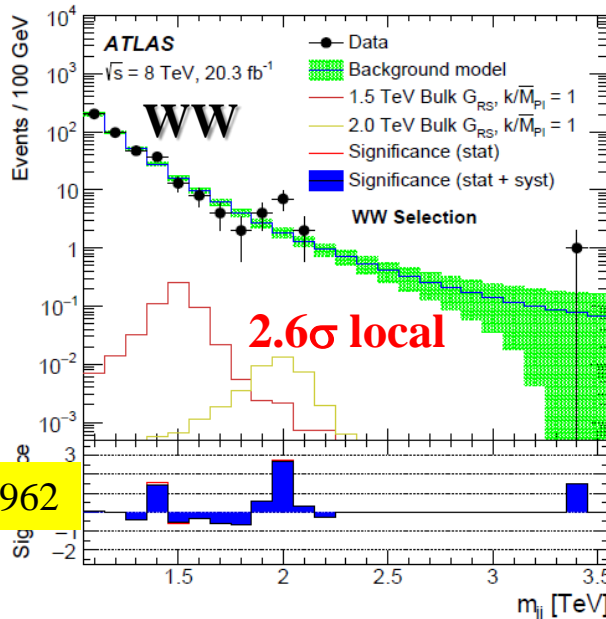
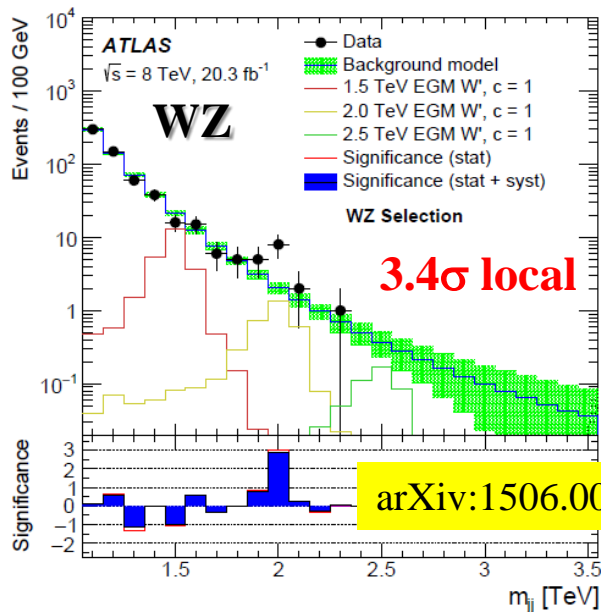
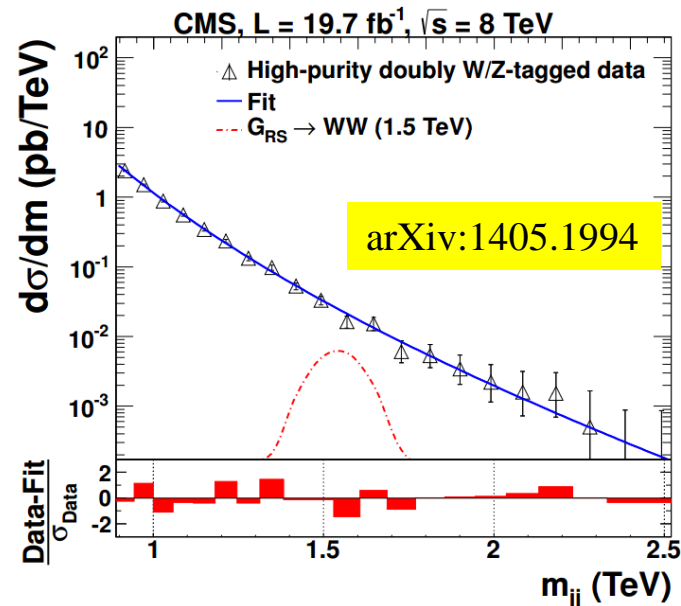


# X → VV → JJ Searches



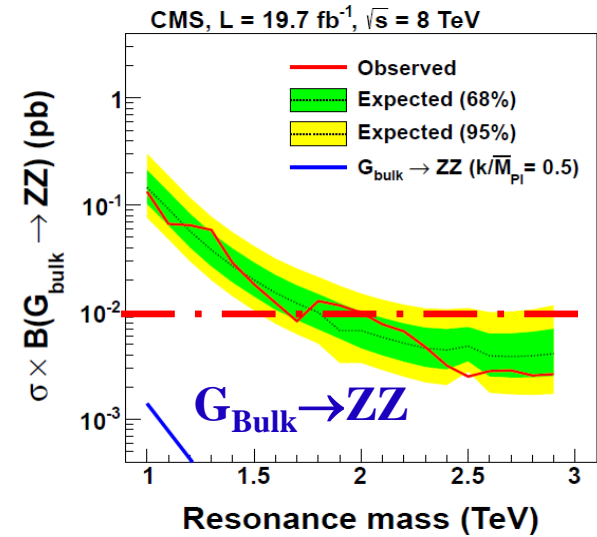
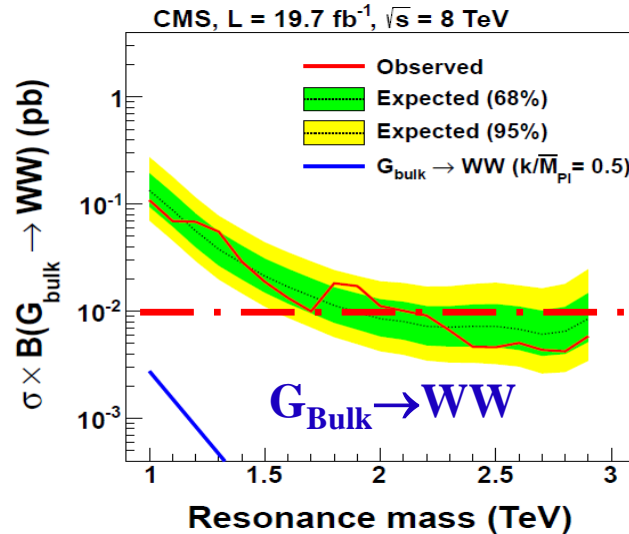
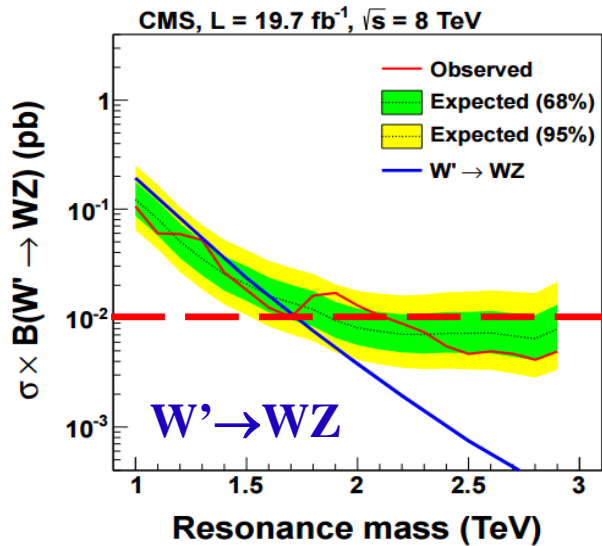
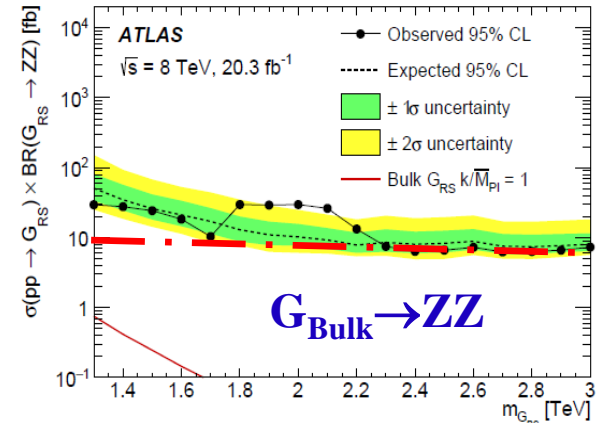
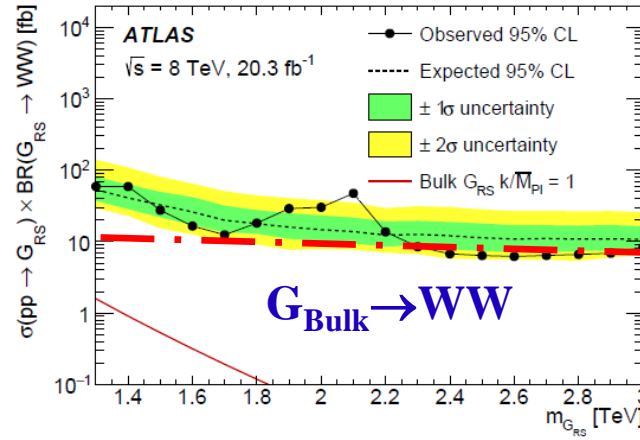
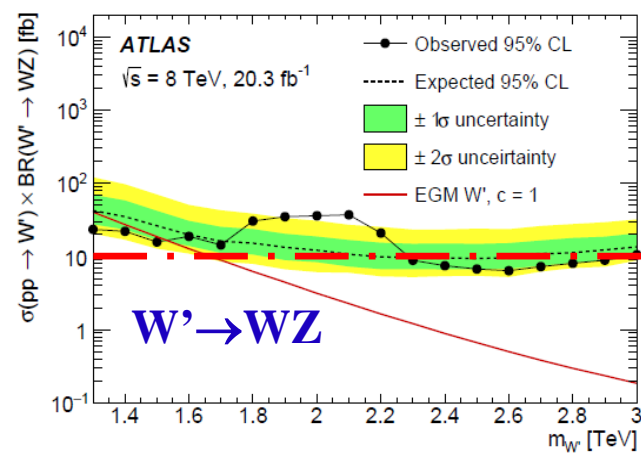
- Select events with two jets tagged as W/Z bosons
- CMS:  $|y_1 - y_2| < 1.3$ ,  $70 < m_J < 100$  GeV,  $\tau_{21} < 0.5$
- ATLAS:  $|y_1 - y_2| < 1.2$  and  $p_T$  asymmetry  $< 0.15$ , three signal regions ( $|m_J - m_V| < 13$  GeV) are not statistically independent
- QCD background estimated by fitting the data, functional form checked with MC dijet events

$$\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3} x^{p_3}$$





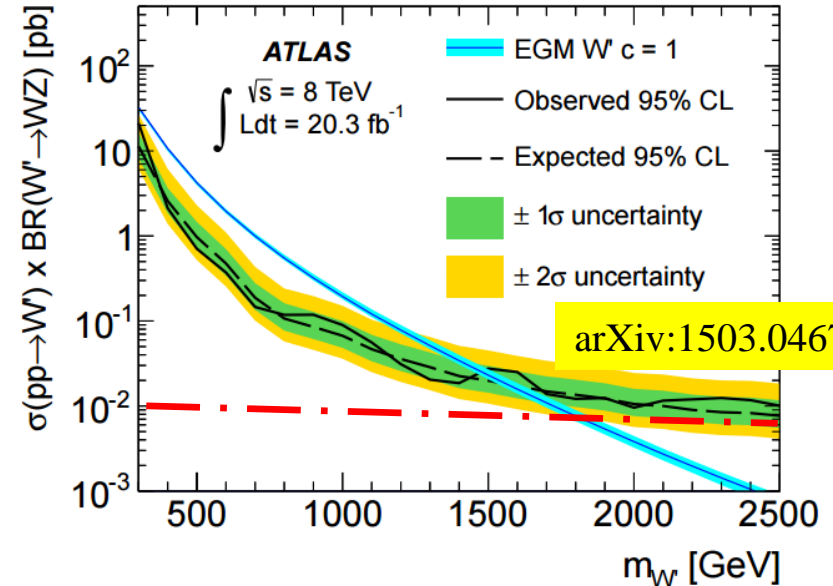
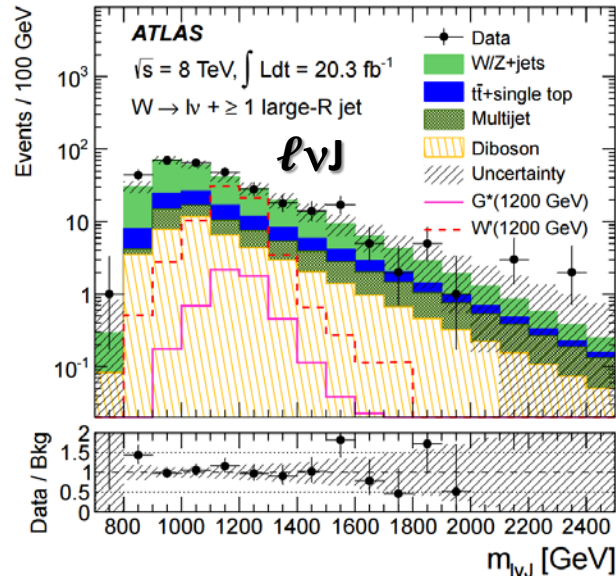
# X → VV → JJ Searches



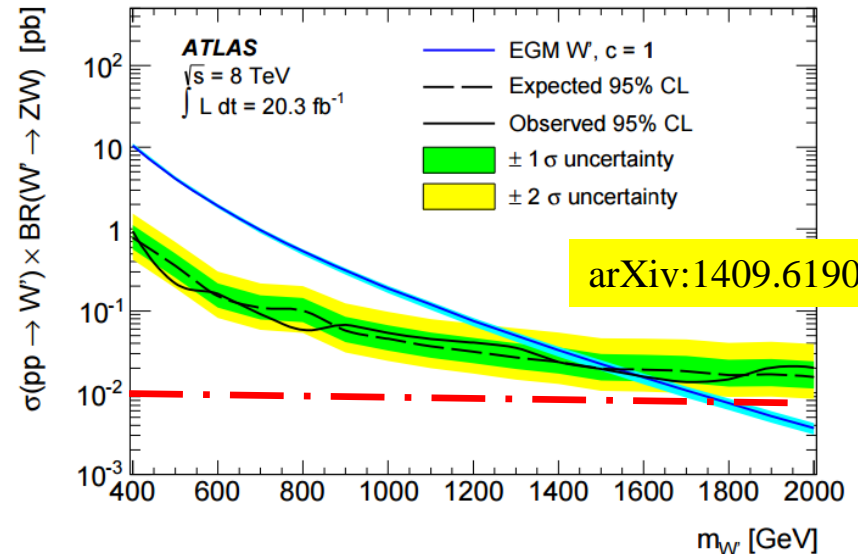
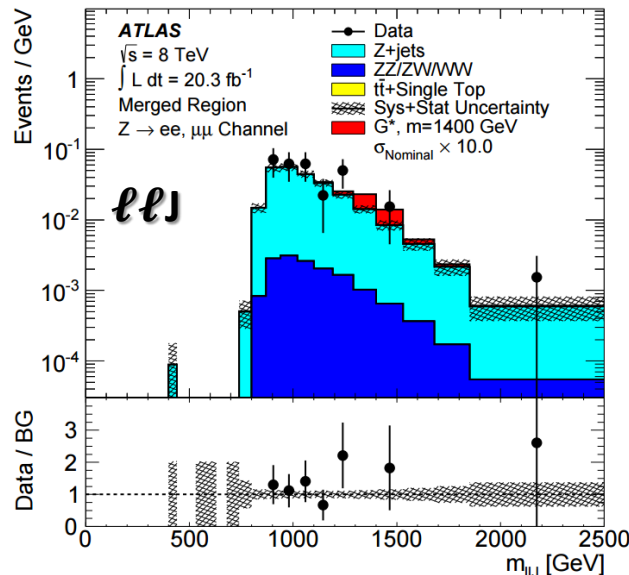
# $X \rightarrow VV \rightarrow \ell\nu(\ell\ell) + jj/J$ Searches



- Divide events into three categories: Low  $p_T$  resolved, High  $p_T$  resolved, High  $p_T$  merged



arXiv:1503.04677

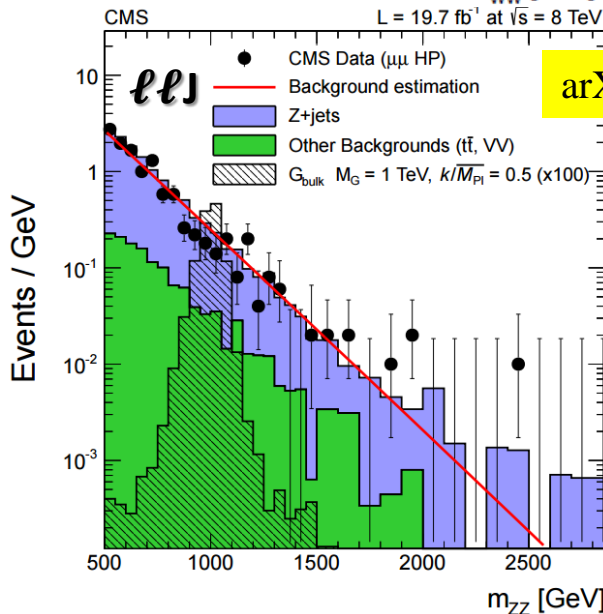
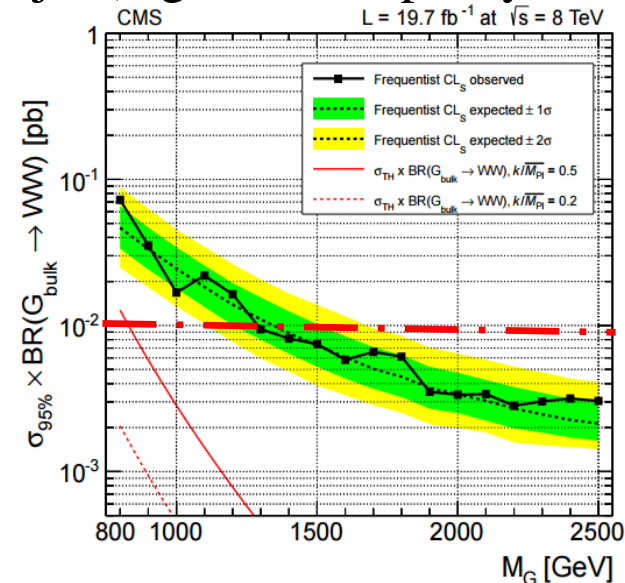
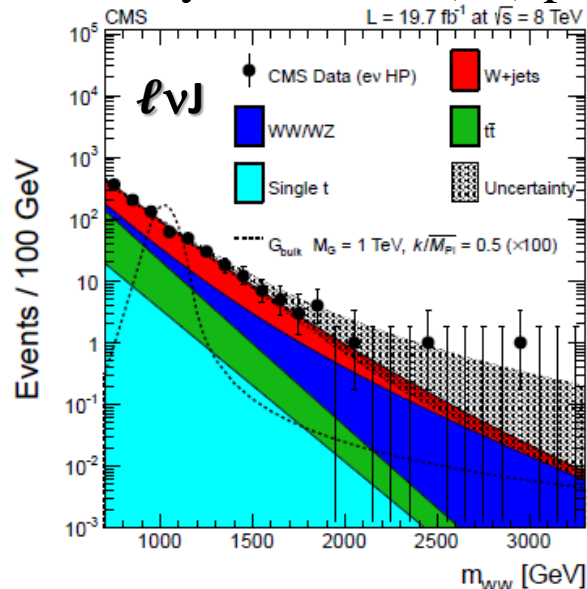


arXiv:1409.6190

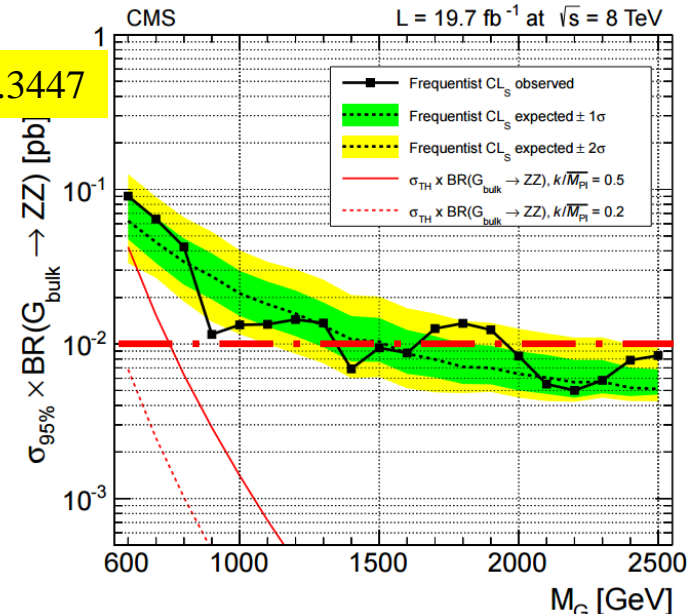


# $X \rightarrow VV \rightarrow \ell\nu(\ell\ell) + J$ Searches

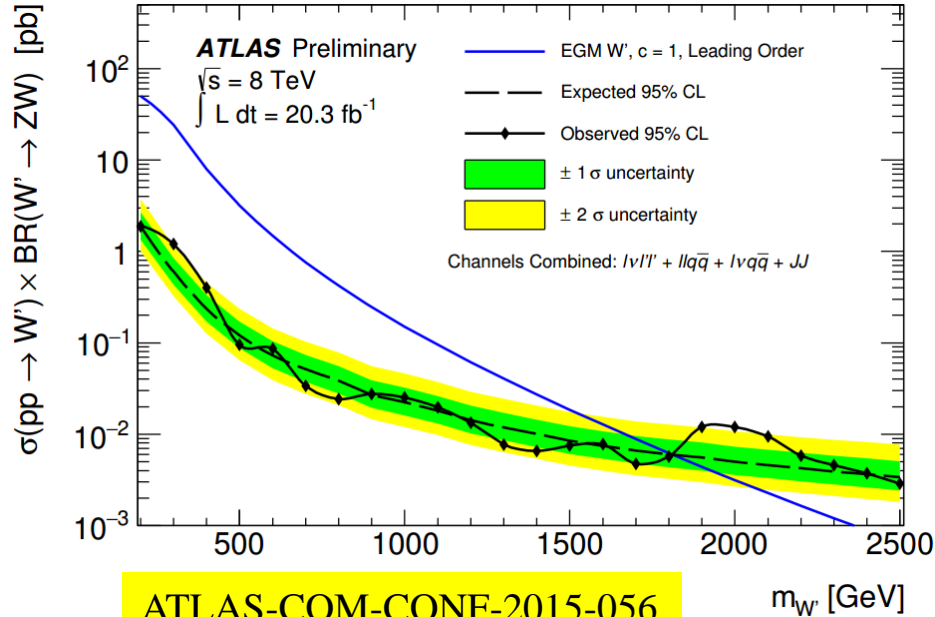
- Combined analysis with  $\ell\nu(\ell\ell)$  plus one V-jet (high- or low-purity based on  $\tau_{21}$ )



arXiv:1405.3447

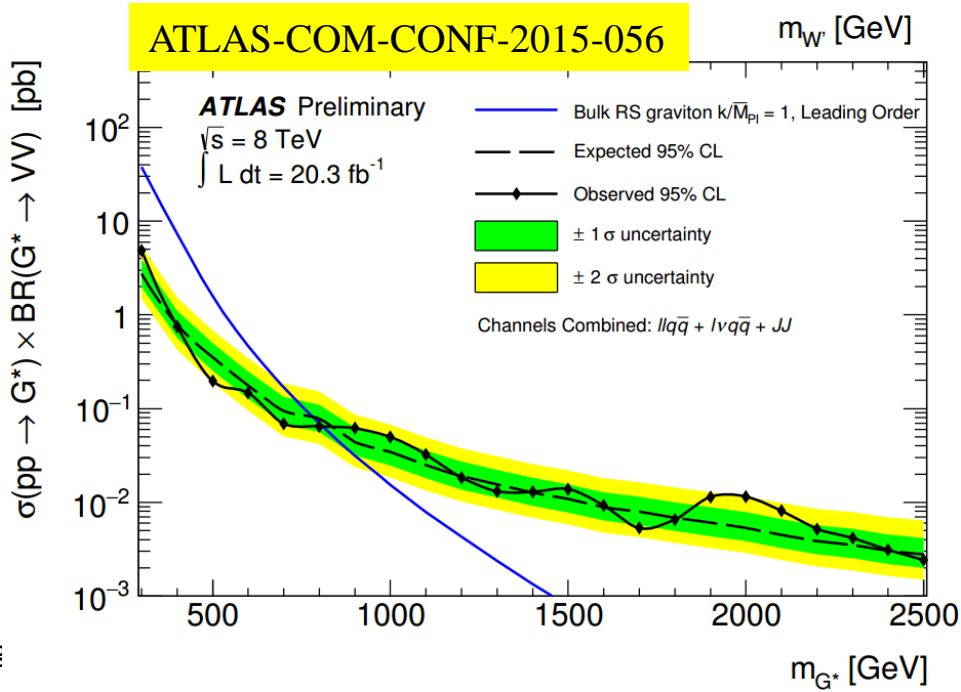


# ATLAS $X \rightarrow VV$ Combination



$W' \rightarrow WZ \rightarrow \ell \nu \ell \ell$   
 $W' \rightarrow WZ \rightarrow \ell \ell + jj/J$   
 $W' \rightarrow WZ \rightarrow \ell \nu + jj/J$   
 $W' \rightarrow WZ \rightarrow JJ$

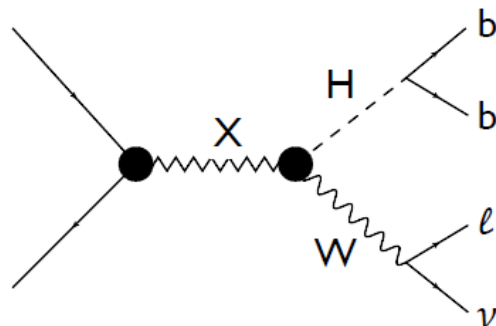
Exceeds previous limit by  $\sim 250 \text{ GeV}$



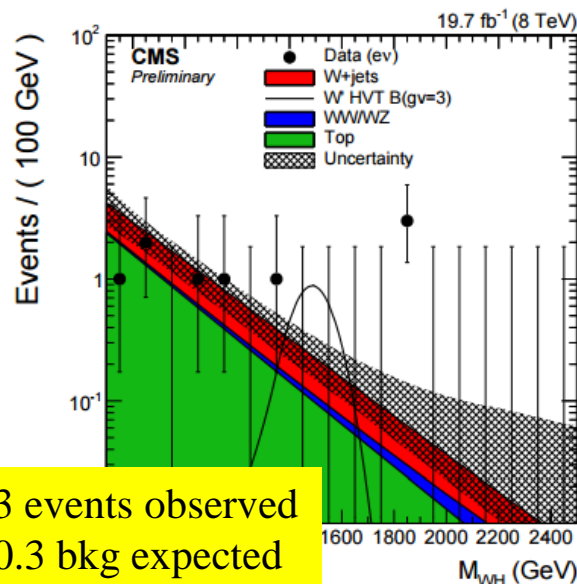
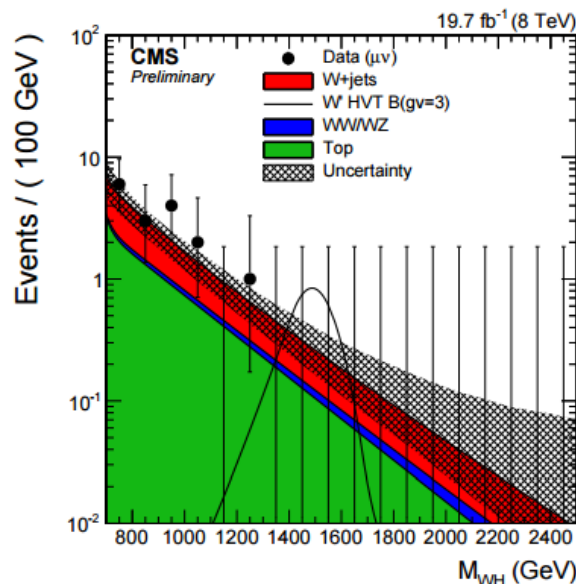
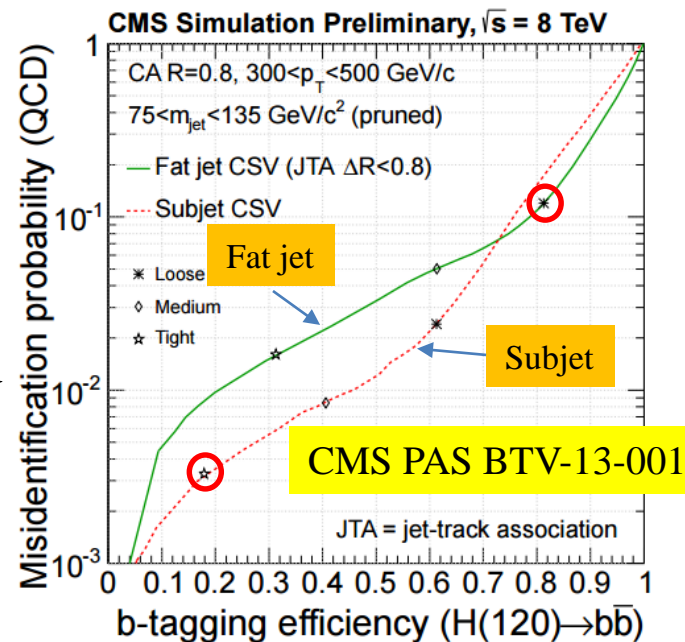
$G_{KK} \rightarrow ZZ \rightarrow \ell \ell + jj/J$   
 $G_{KK} \rightarrow WW \rightarrow \ell \nu + jj/J$   
 $G_{KK} \rightarrow WW/ZZ \rightarrow JJ$

Exceeds previous limit by  $\sim 50 \text{ GeV}$

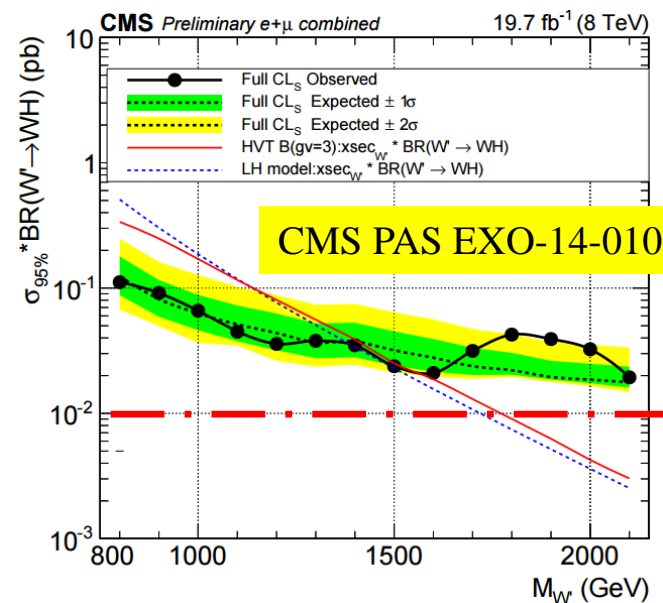
# $X \rightarrow WH \rightarrow \ell \nu b \bar{b} \rightarrow \ell \nu + b\text{-J}$ Searches



- C/A  $R=0.8$  jets with jet pruning algorithm applied and  $110 < m_{\text{jet}} < 135$  GeV
- Boosted  $H \rightarrow b\bar{b}$  tagging: tight b-tagging on two subjets if  $\Delta R > 0.3$ , otherwise loose b-tagging on the whole fat jet



3 events observed  
 0.3 bkg expected



# X→VH→JJ Searches

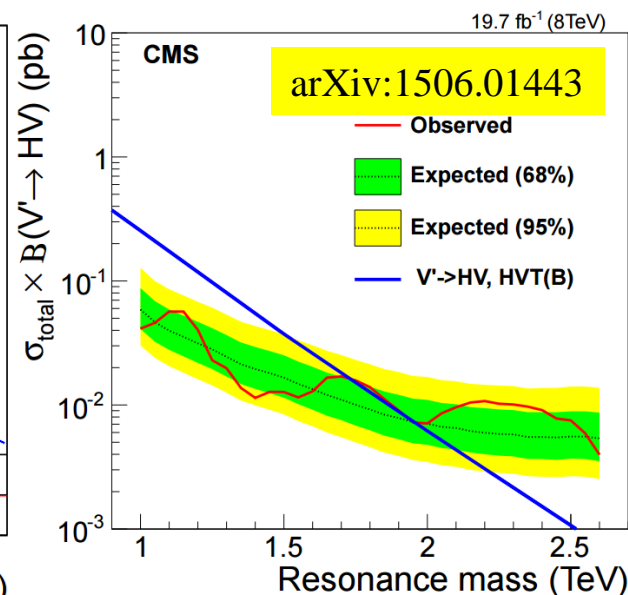
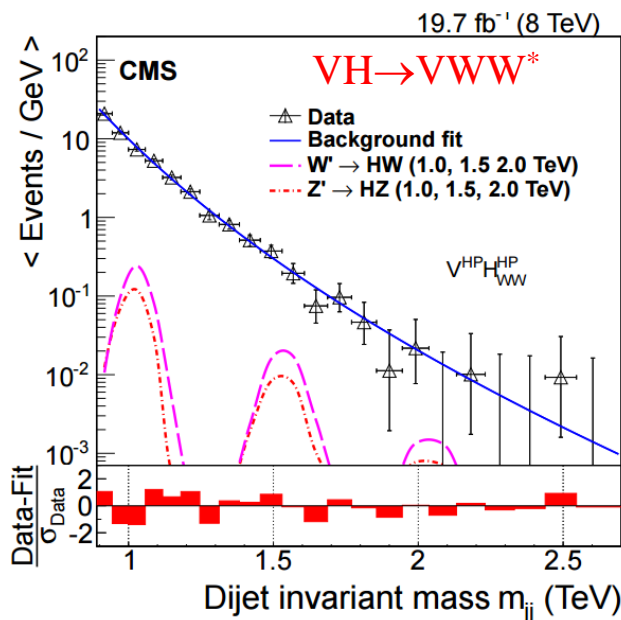
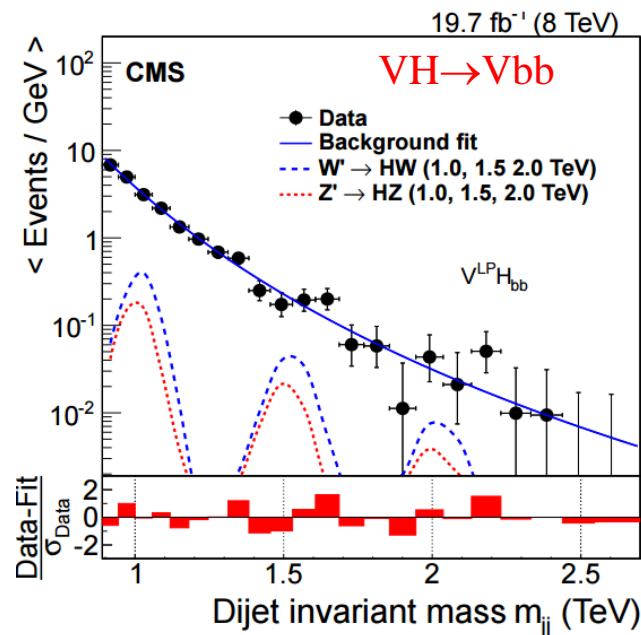
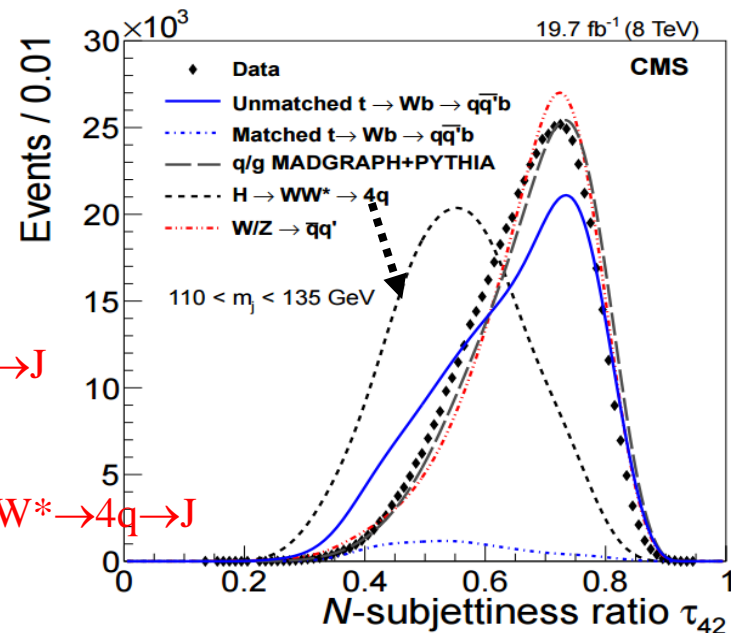


- $V \rightarrow qq \rightarrow J$  and  $H \rightarrow bb \rightarrow J$  or  $H \rightarrow WW^* \rightarrow 4q \rightarrow J$
- Use jet mass, N-subjettiness and subjet b-tagging to reduce multijet background

Categories	V tag	H tag
$V^{HP}H_{bb}$	$\tau_{21} \leq 0.5$	b tag
$V^{LP}H_{bb}$	$0.5 < \tau_{21} < 0.75$	b tag
$V^{HP}H_{WW}^{HP}$	$\tau_{21} \leq 0.5$	$\tau_{42} \leq 0.55$
$V^{LP}H_{WW}^{HP}$	$0.5 < \tau_{21} < 0.75$	$\tau_{42} \leq 0.55$
$V^{HP}H_{WW}^{LP}$	$\tau_{21} \leq 0.5$	$0.55 < \tau_{42} < 0.65$

$H \rightarrow bb \rightarrow J$

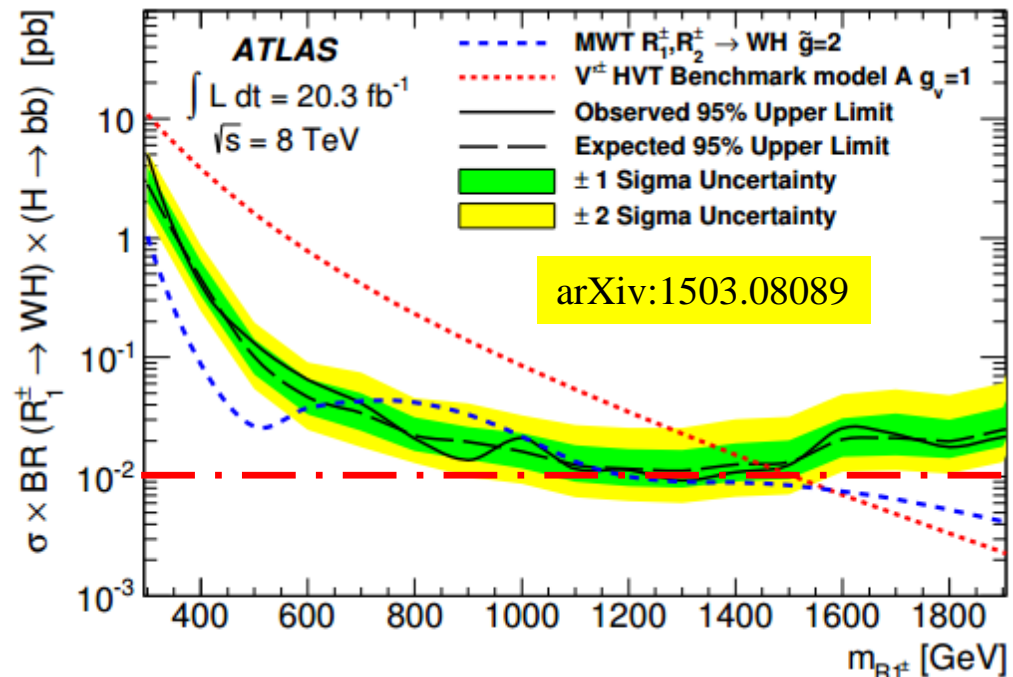
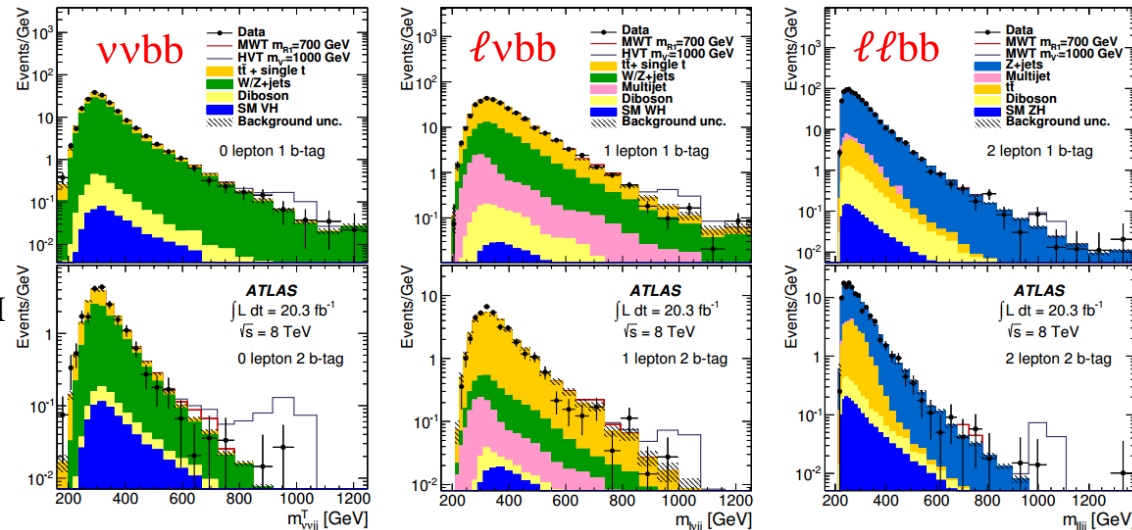
$H \rightarrow WW^* \rightarrow 4q \rightarrow J$



# $X \rightarrow VH \rightarrow \ell v / \ell\ell / vv + bb$ Searches



- Divide events into different categories based on numbers of leptons and b-jets
- Search for new resonances using  $m_{VH}^T$  for  $vvbb$  and  $m_{VH}$  for  $\ell vbb$  and  $\ell\ell bb$
- Set mass limits on MWT model used that predicts two triplets  $R_1^{\pm,0}$  and  $R_2^{\pm,0}$  and a simplified phenomenological model with HVT  $V'^{\pm,0}$

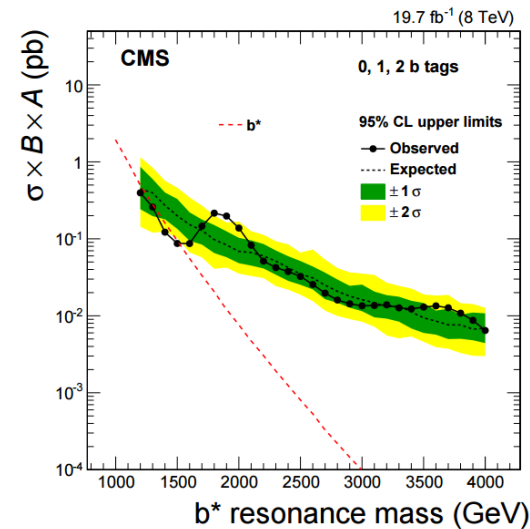
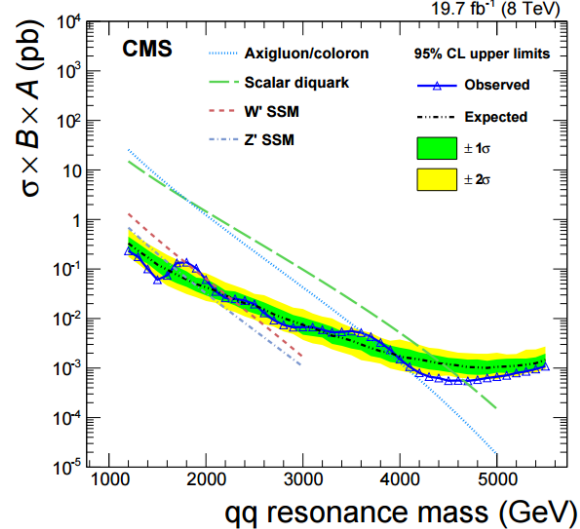
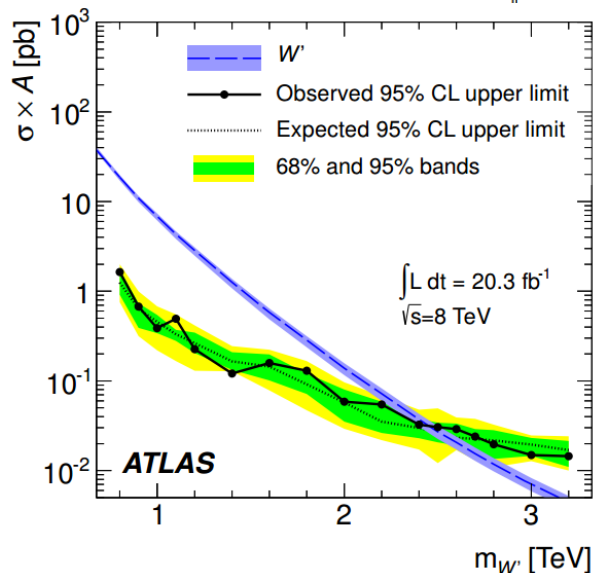
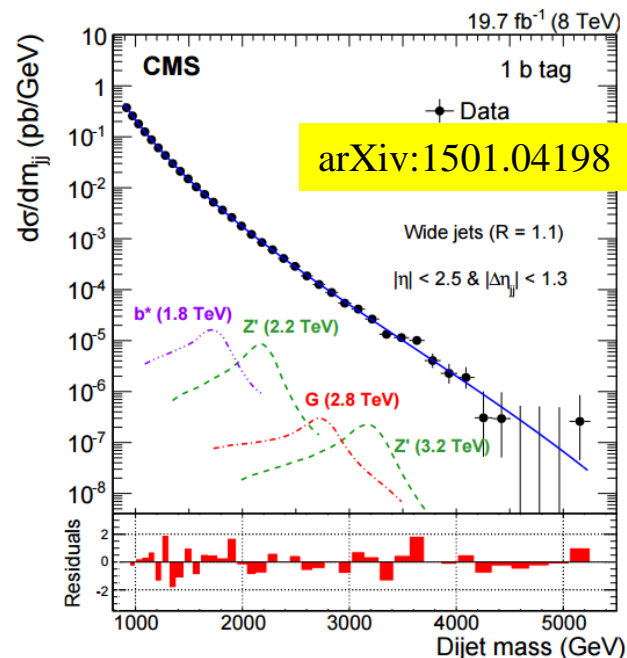
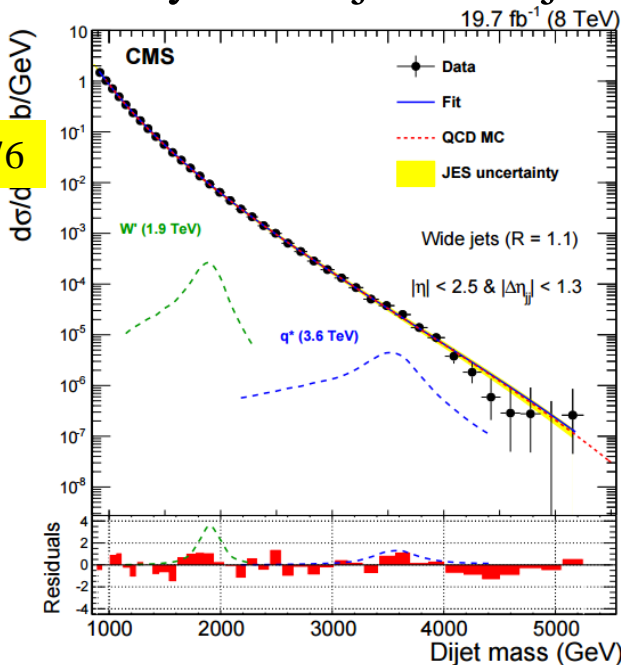
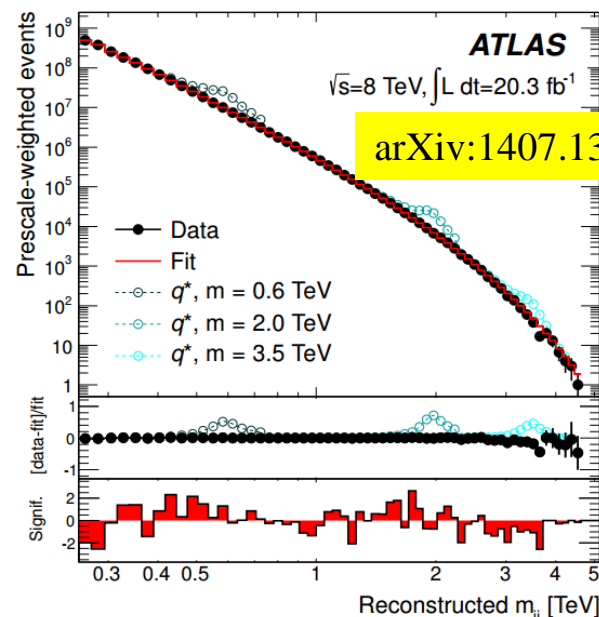




# X → jj Searches



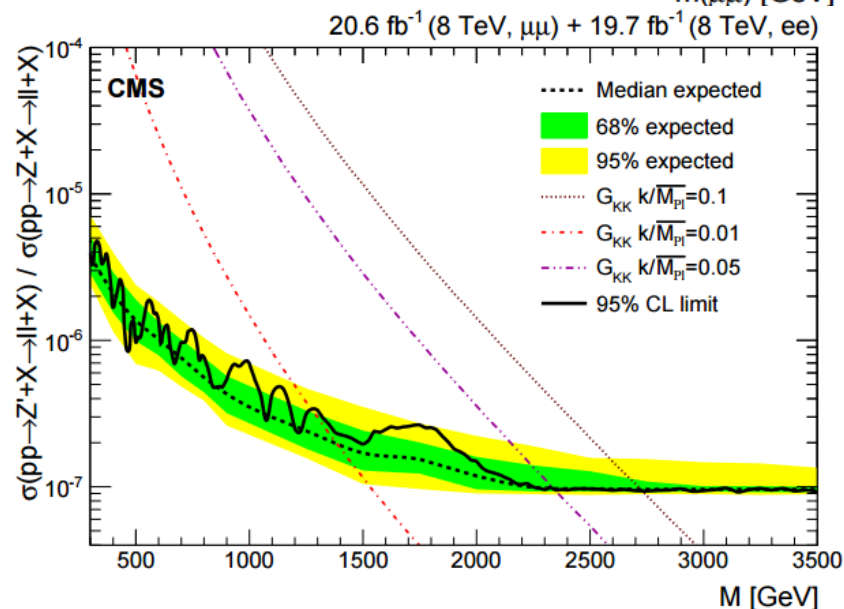
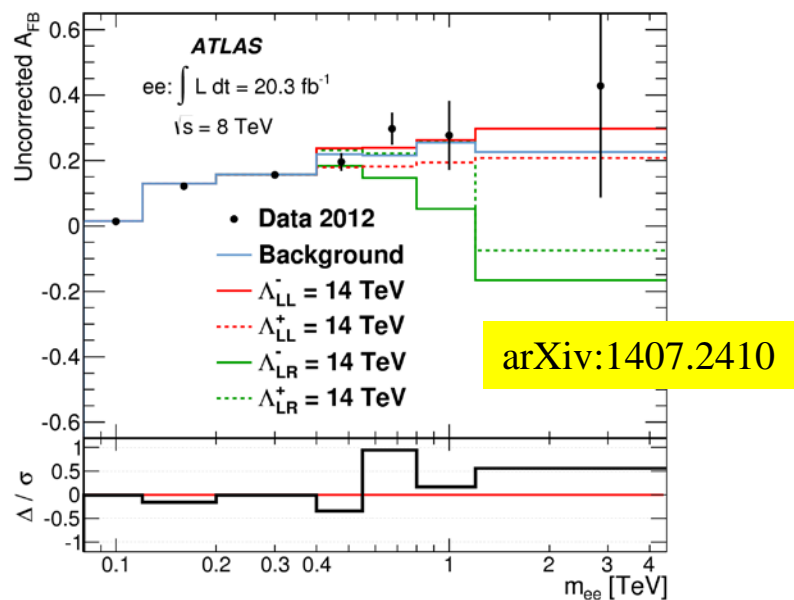
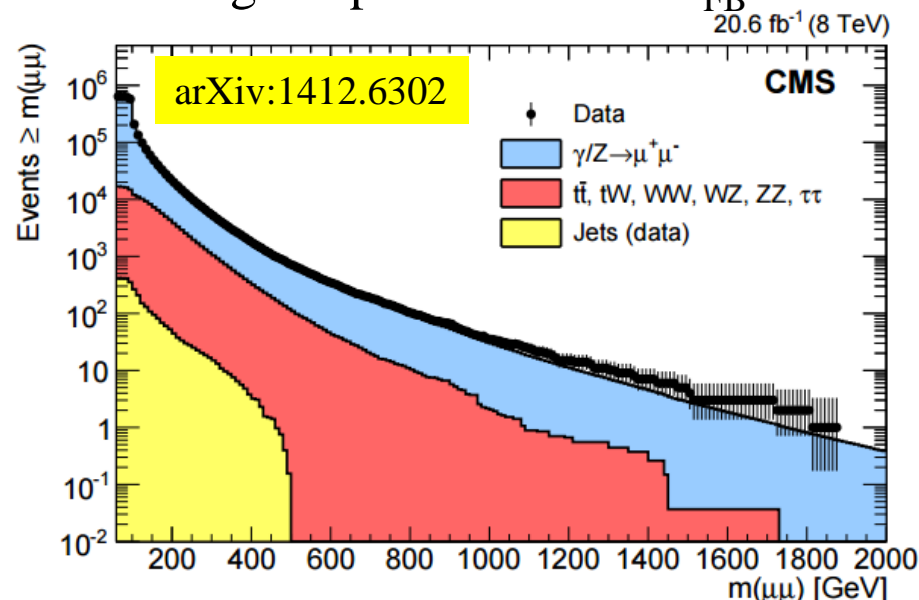
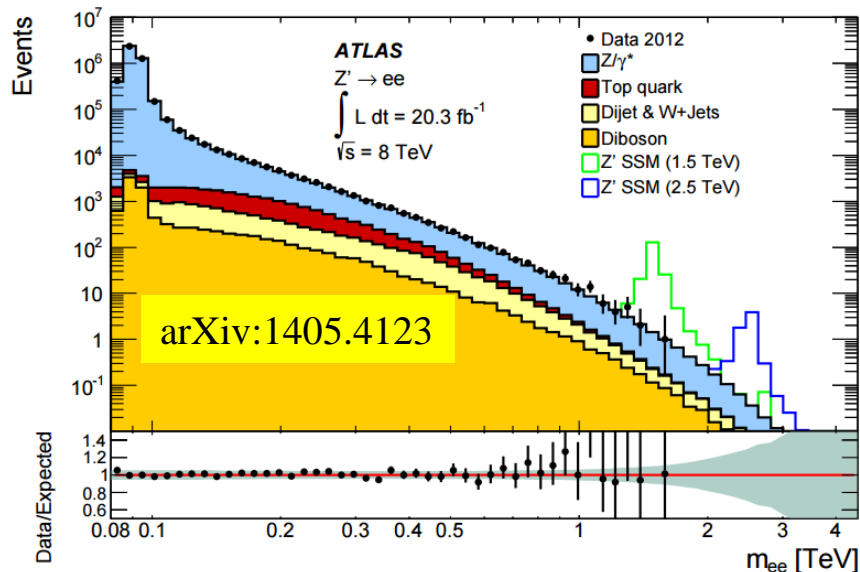
- new resonances may also decay to two jets or b-jets



# Dilepton Searches



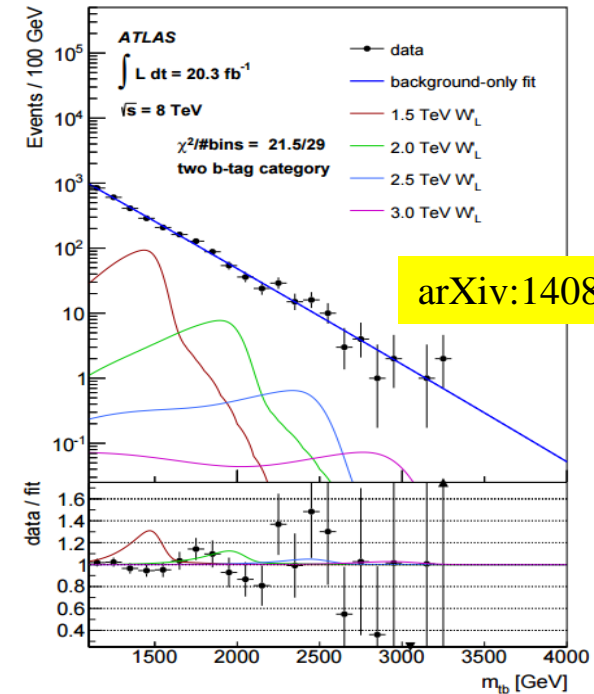
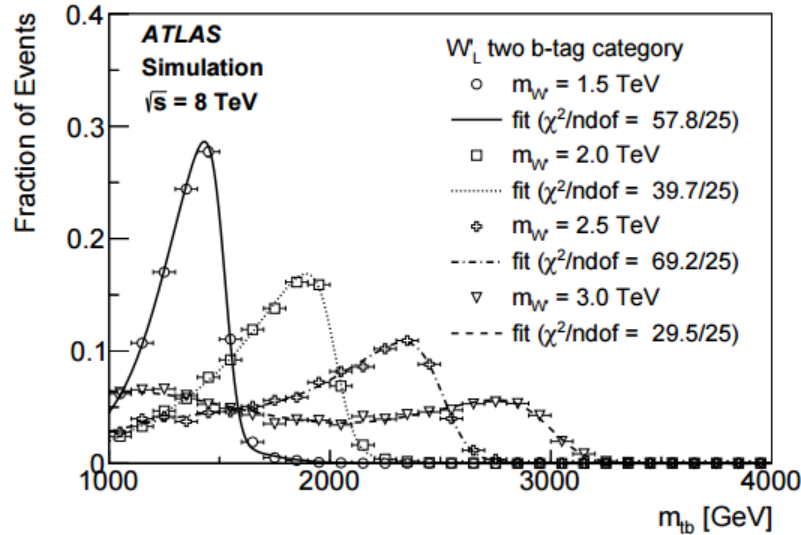
- We can also perform resonance/CI searches using dilepton mass and  $A_{FB}$



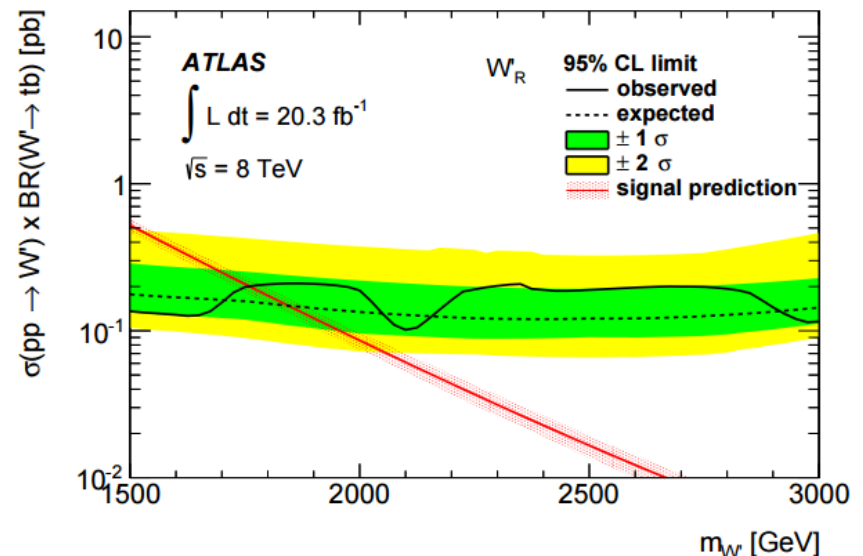
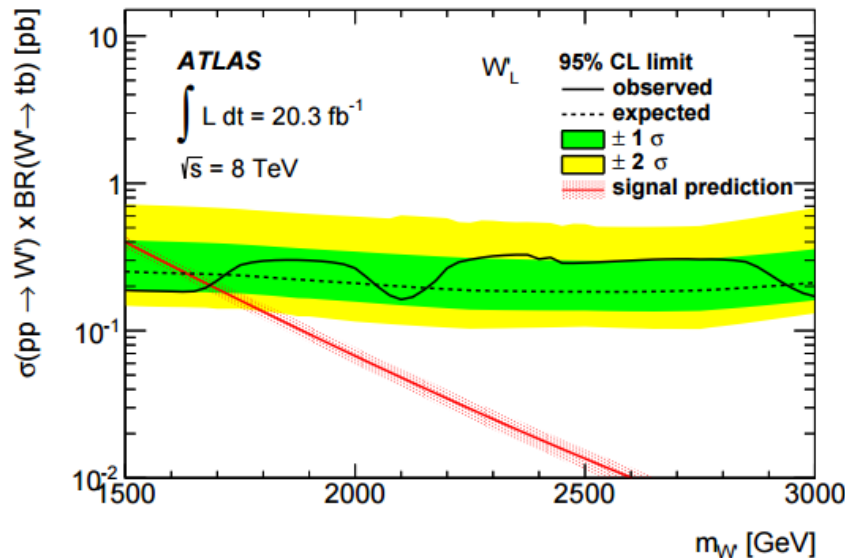
# $W' \rightarrow tb \rightarrow qqbb$ Searches



- New resonances may have different decays
- Hadronic channels rely on top-quark tagging



arXiv:1408.0886

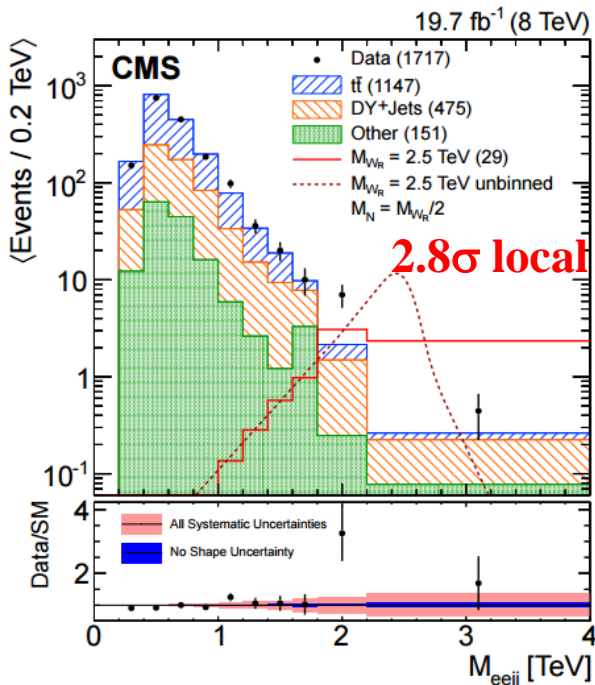


# $W_R \rightarrow \ell N \rightarrow \ell \ell qq$ Searches

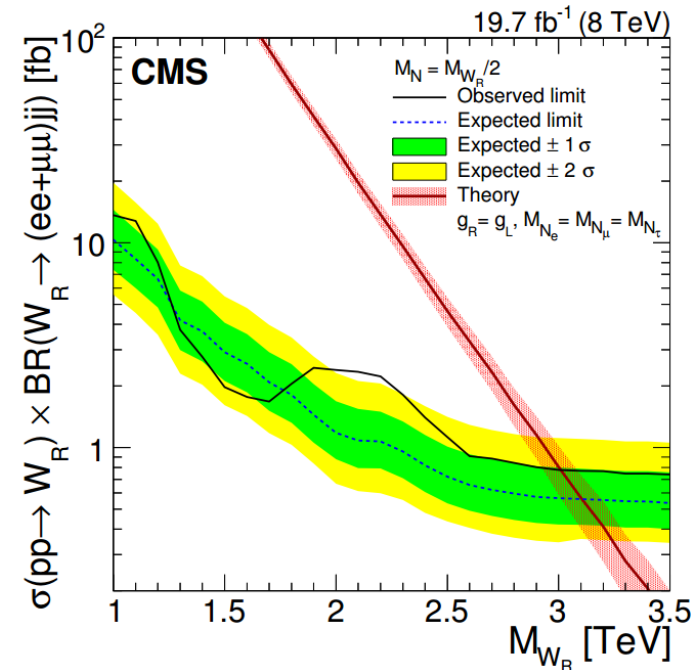
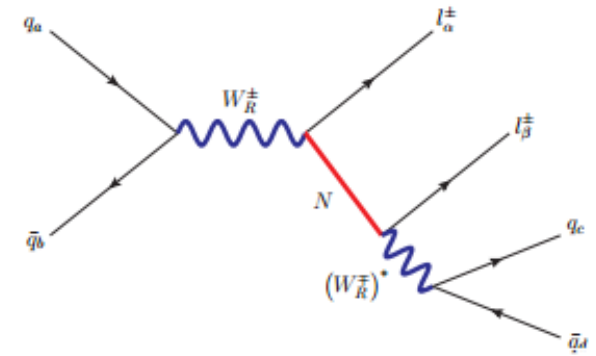
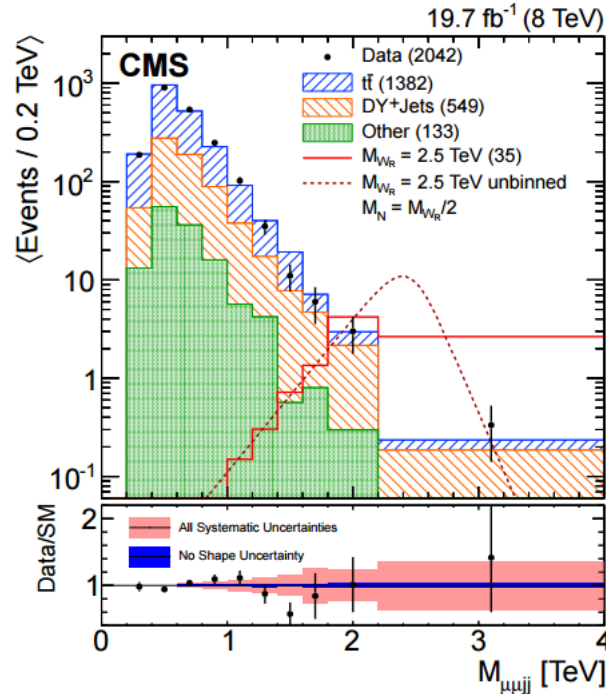


arXiv:1407.3683

- New resonances may have different decays
- Final state with two same-flavor leptons and two jets



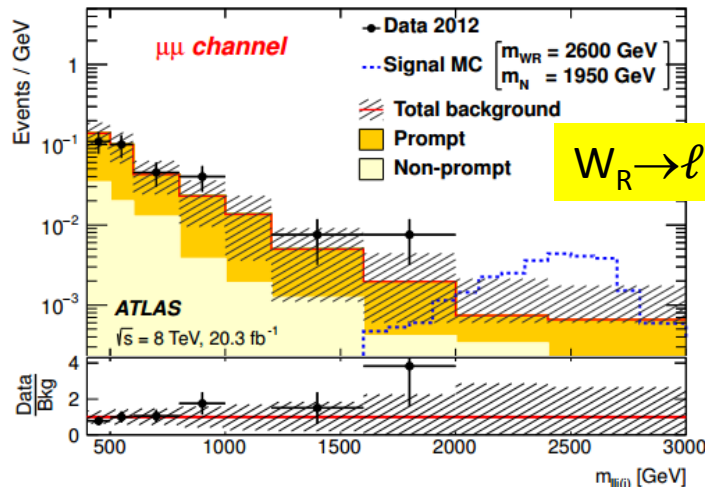
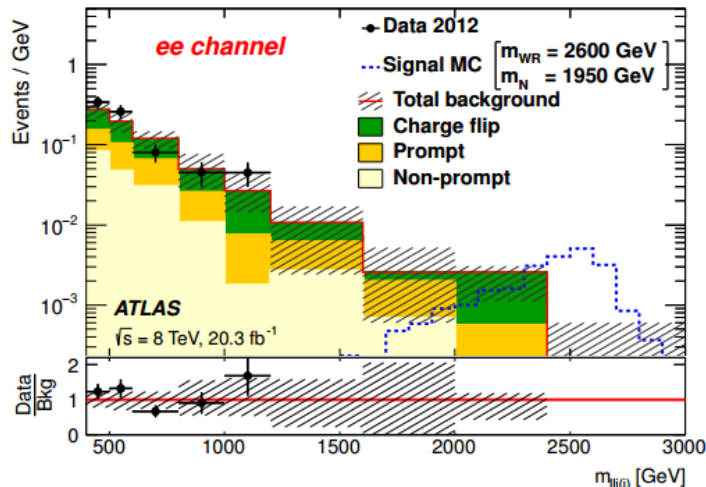
14 events observed  
4 bkg expected



# $W_R \rightarrow \ell N (LQLQ) \rightarrow \ell \ell qq$ Searches



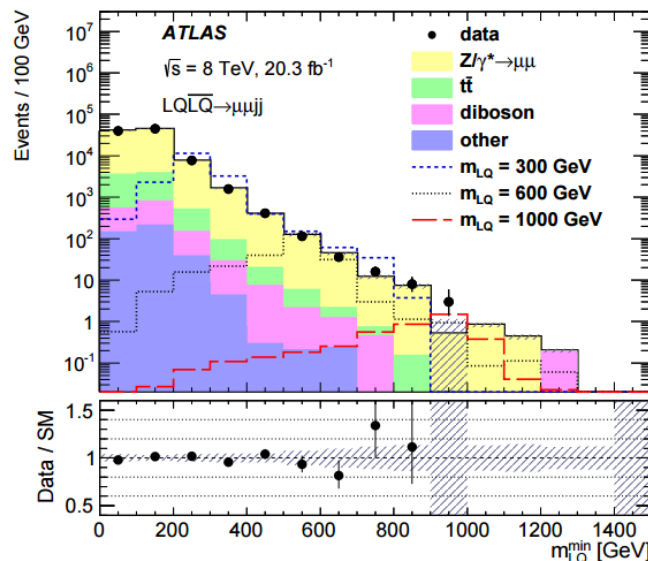
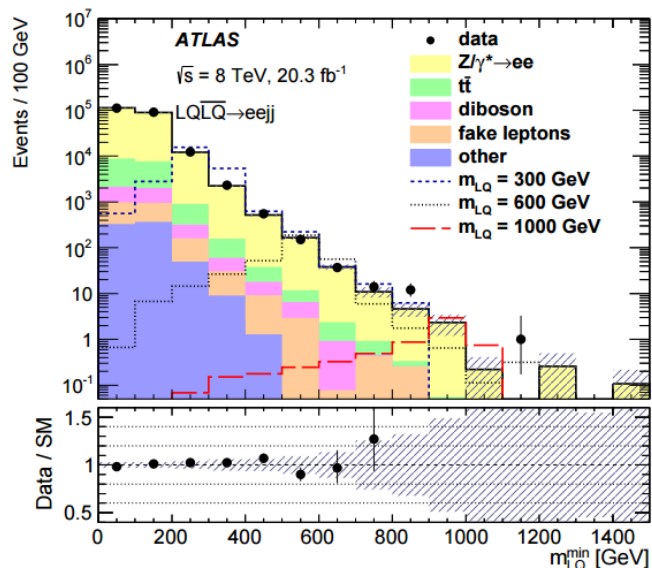
- Both  $W_R \rightarrow \ell N$  and scalar leptonquark models are considered



arXiv:1506.06020

$W_R \rightarrow \ell N$

Same-sign dilepton



arXiv:1508.04735

Opposite-sign dilepton

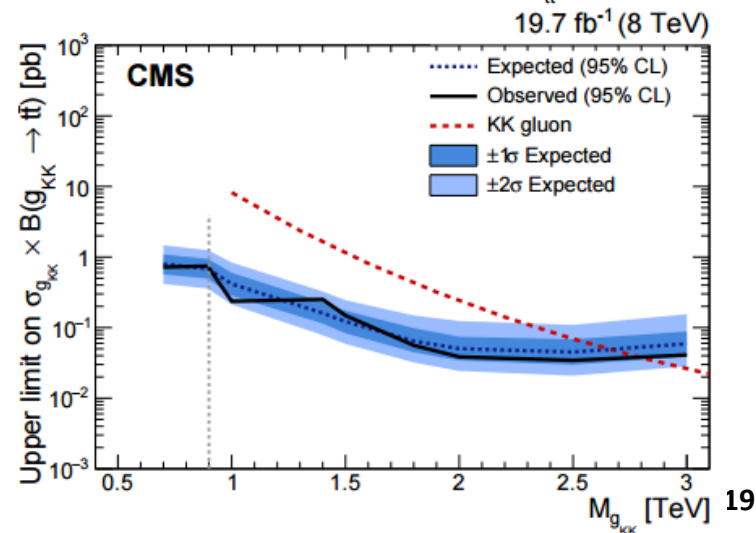
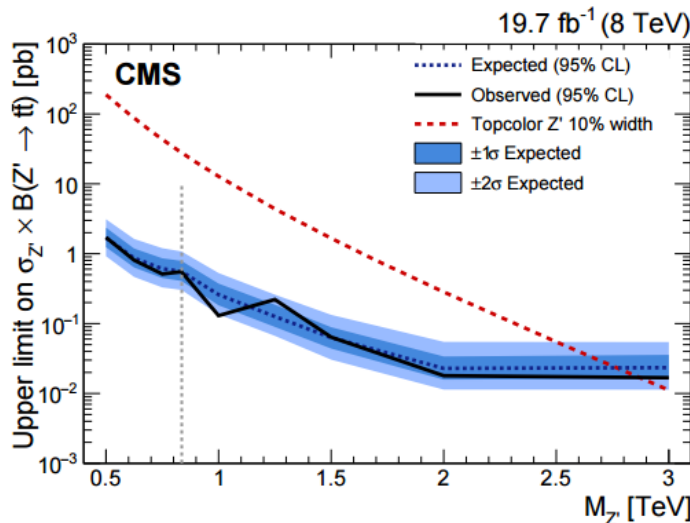
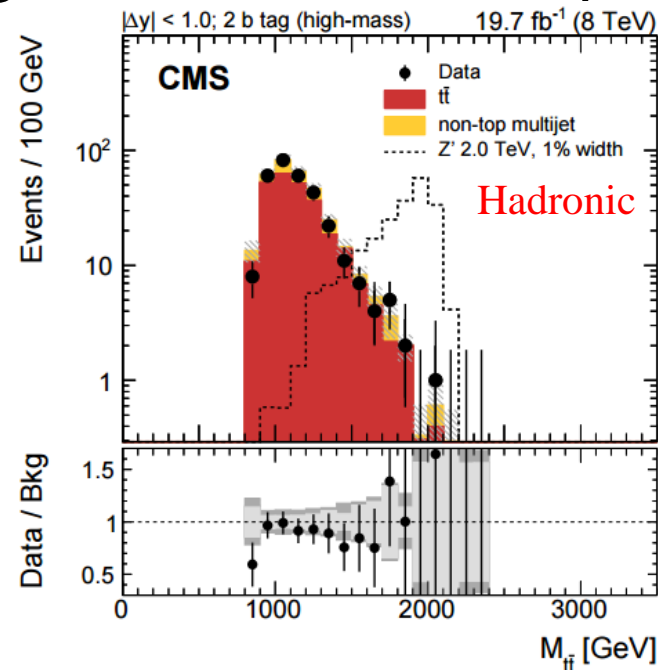
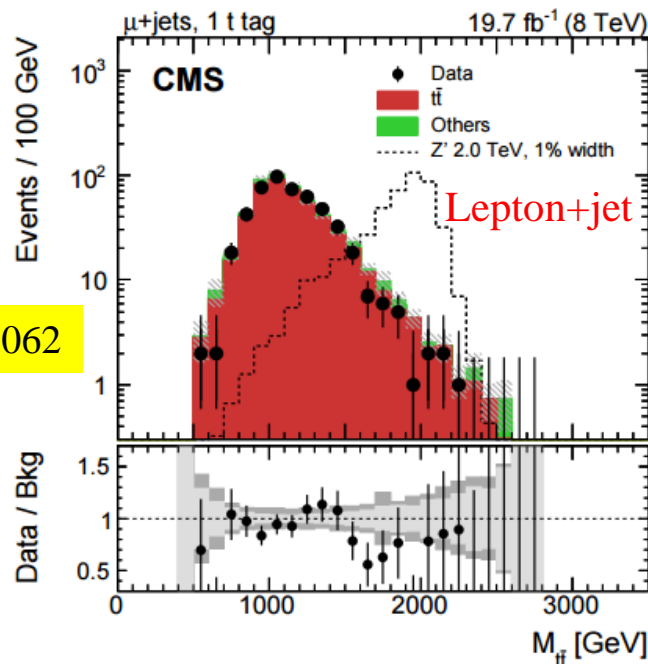


# Top Resonance Searches

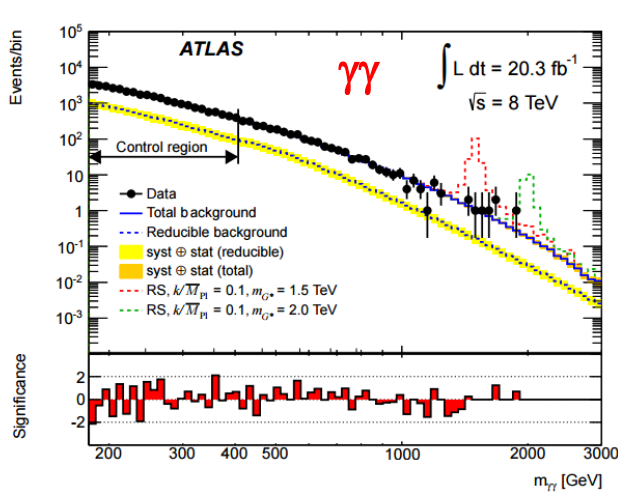


- Search for leptophobic  $Z'$ , RS gluon and graviton with enhanced couplings to  $t\bar{t}$

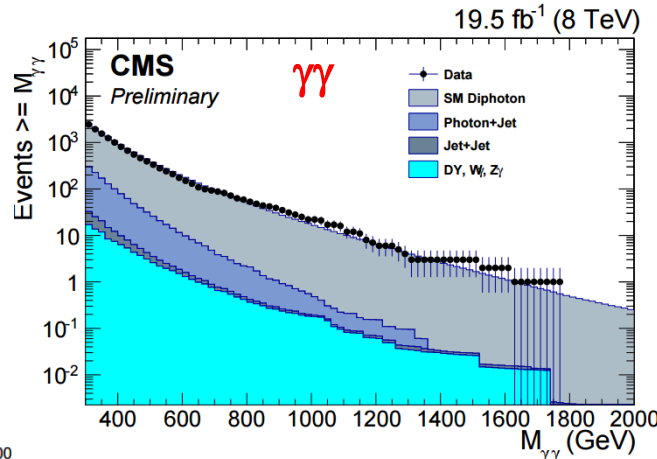
arXiv:1506.03062



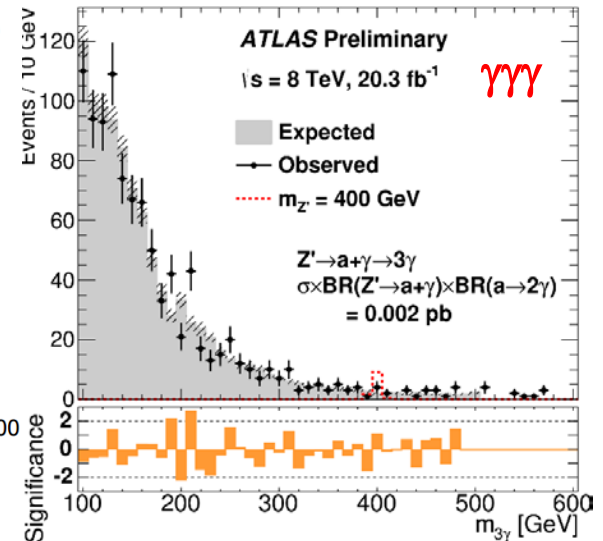
# Photon Resonance Searches



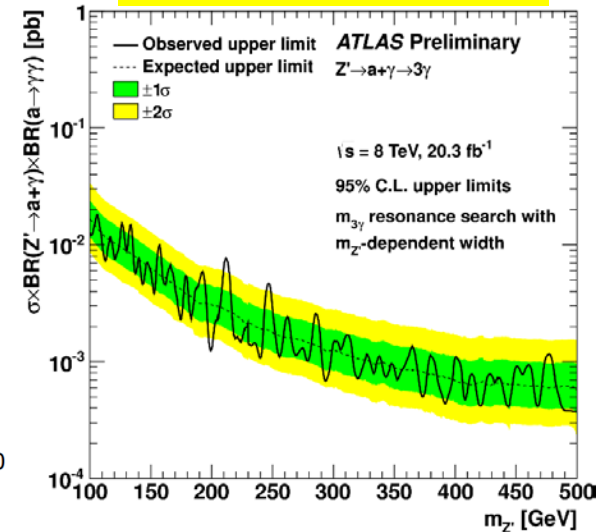
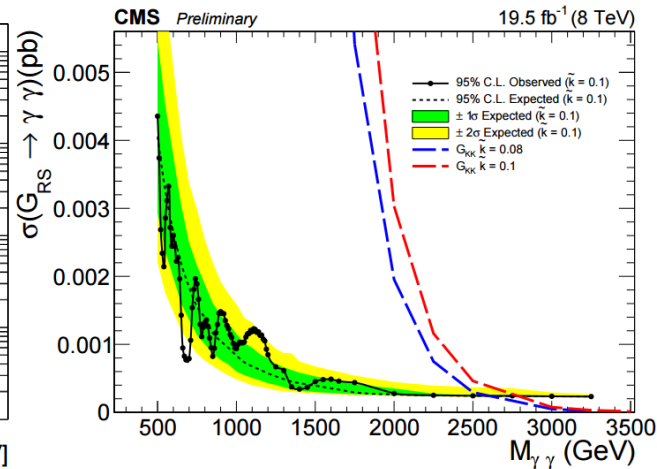
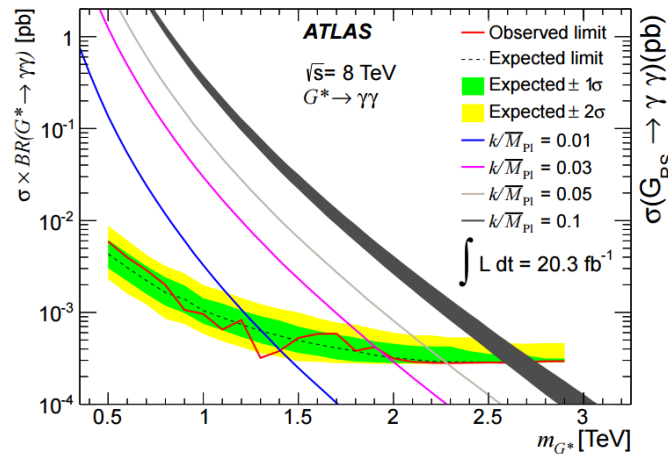
arXiv:1504.05511



CMS-EXO-12-045



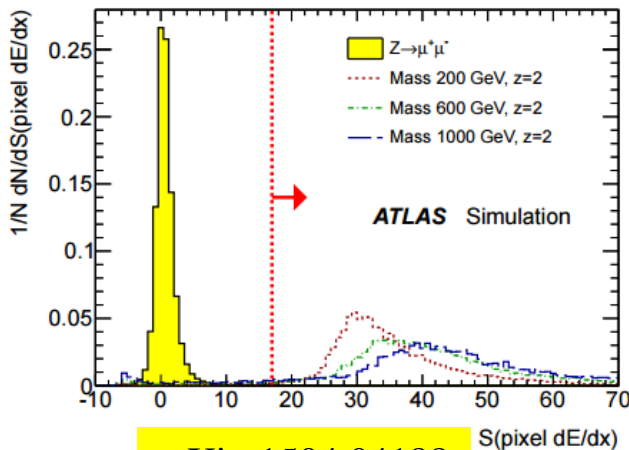
ATLAS-EXOT-2013-24



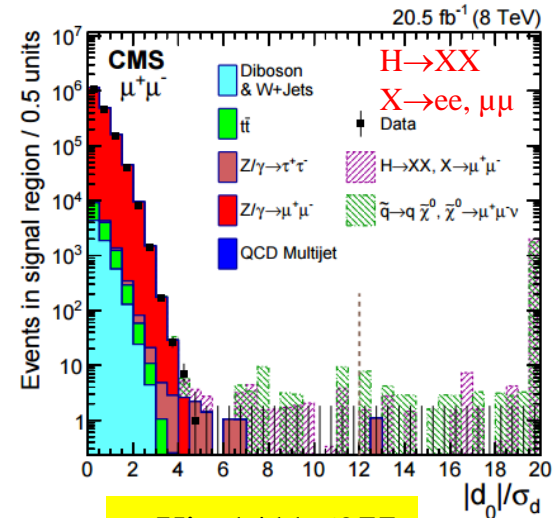
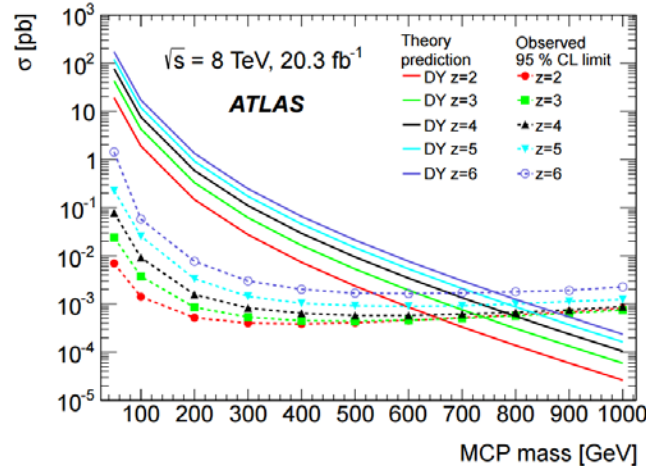
# Long-lived Particle Searches



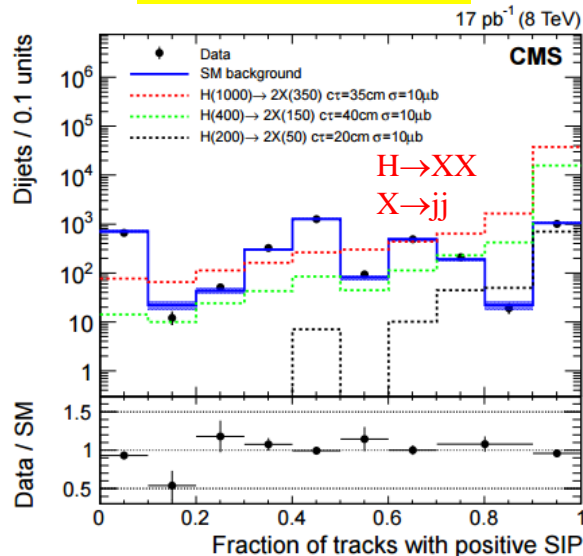
- Many models (such as hidden valley, SUSY etc) predict long-lived particles



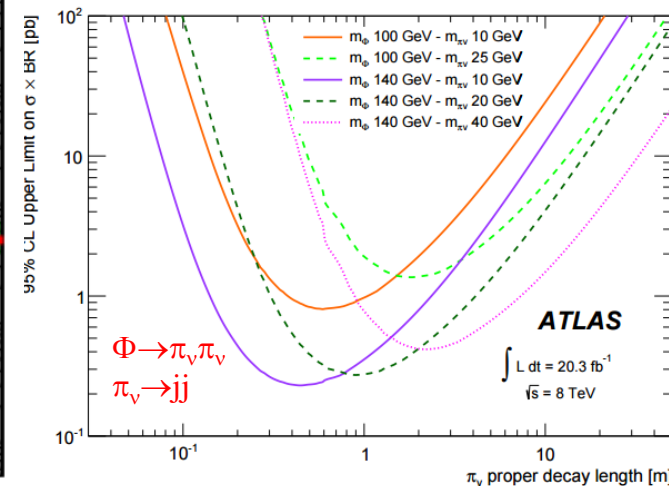
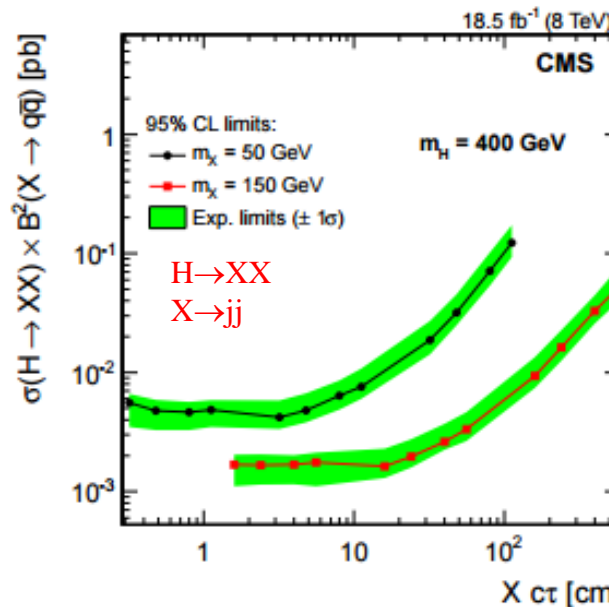
arXiv:1504.04188



arXiv:1411.6977

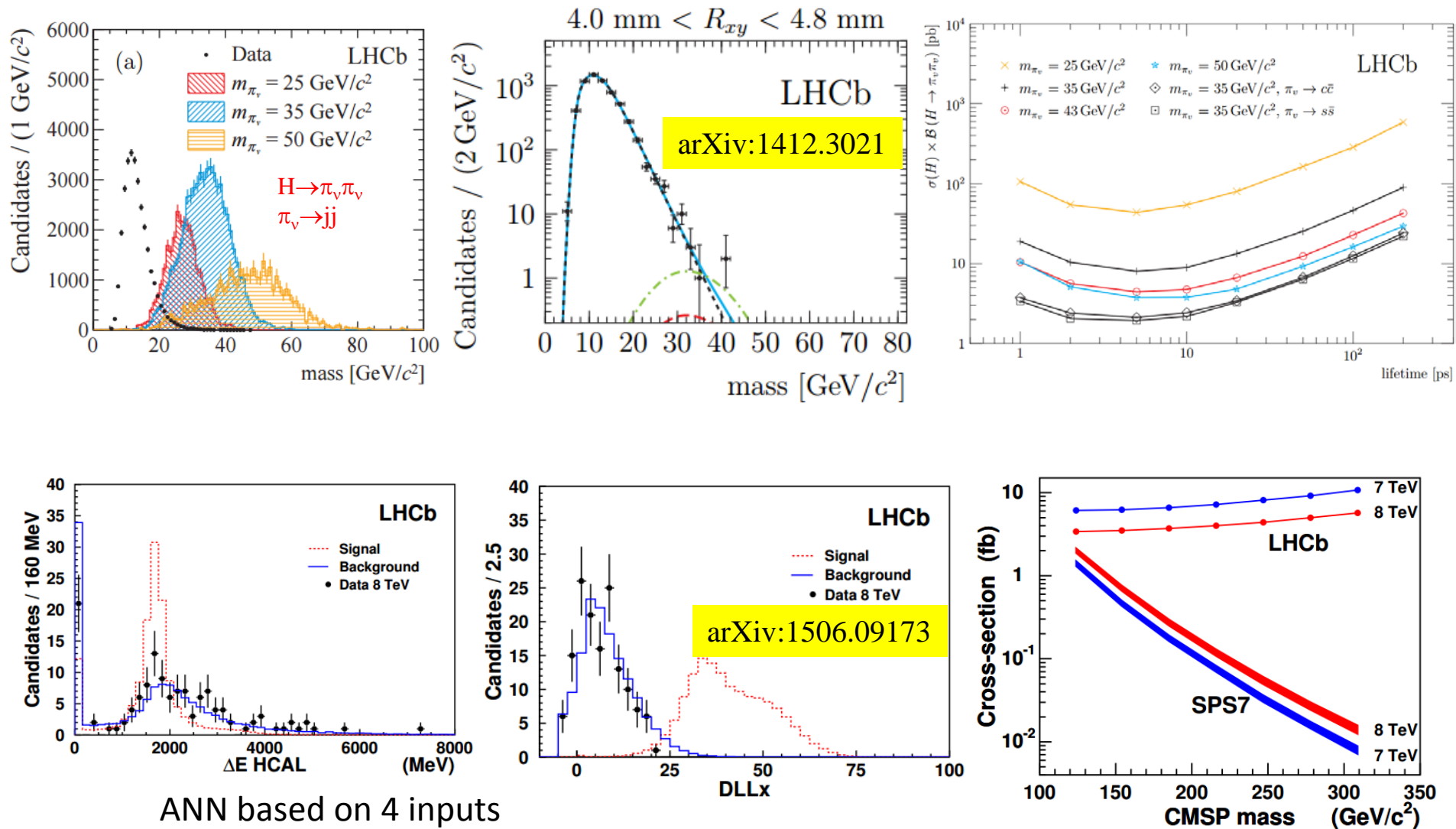


arXiv:1411.6530



arXiv:1501.04020

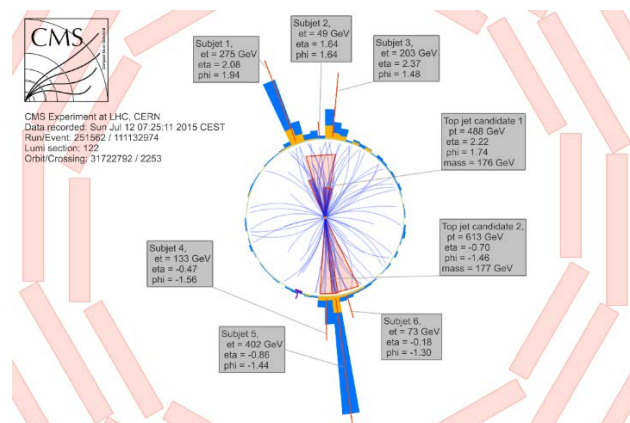
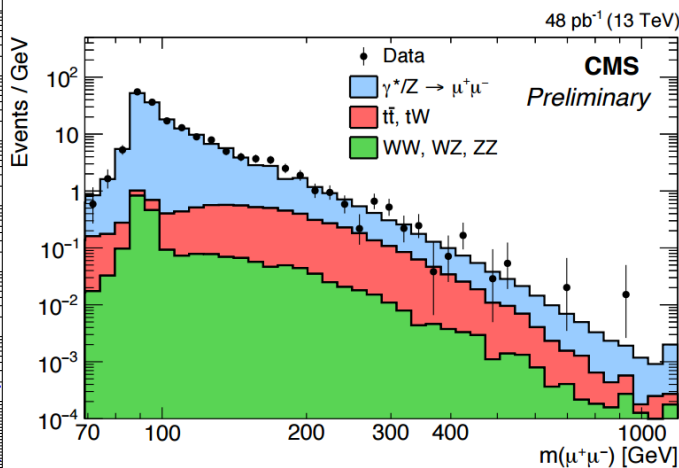
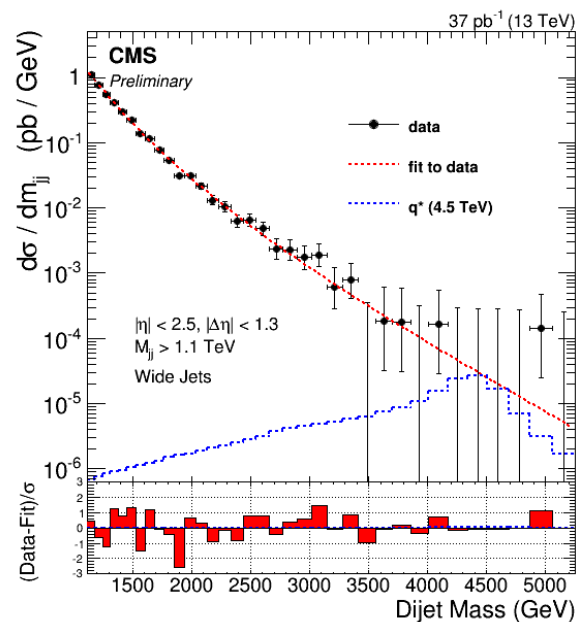
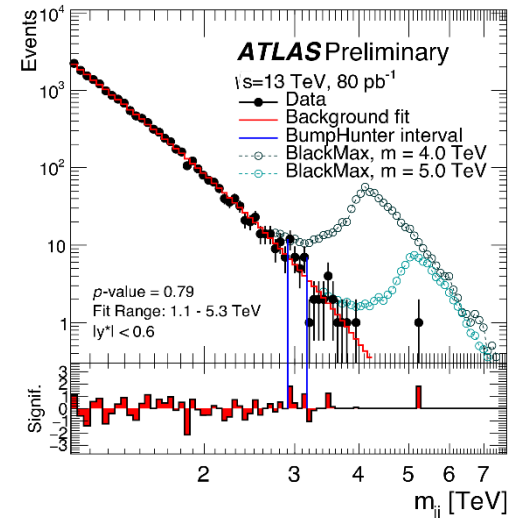
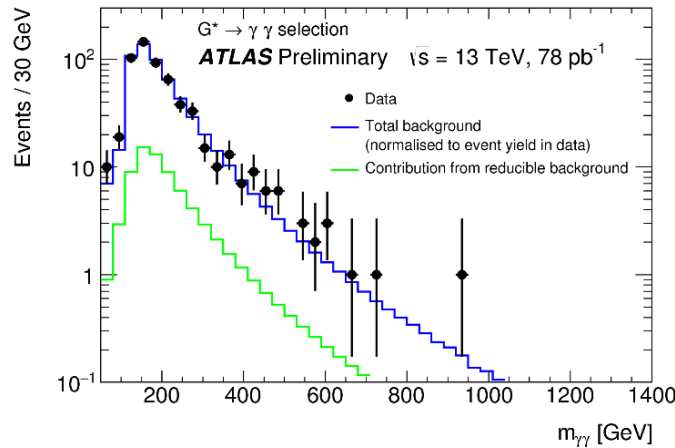
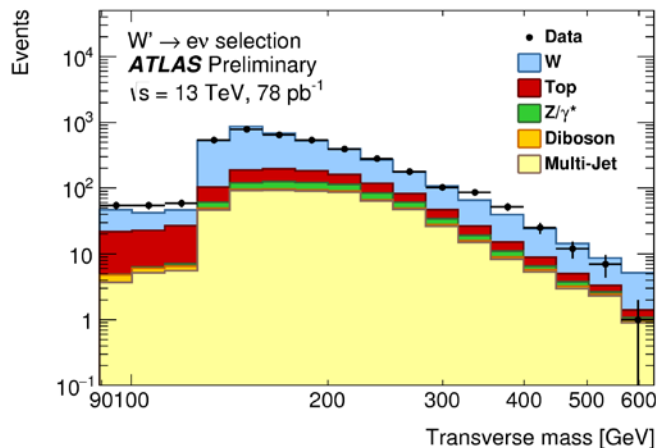
# Long-lived Particle Searches



ANN based on 4 inputs

DLLx: likelihood variable using ring Cherenkov detector information

# Run2 Physics Program is Underway

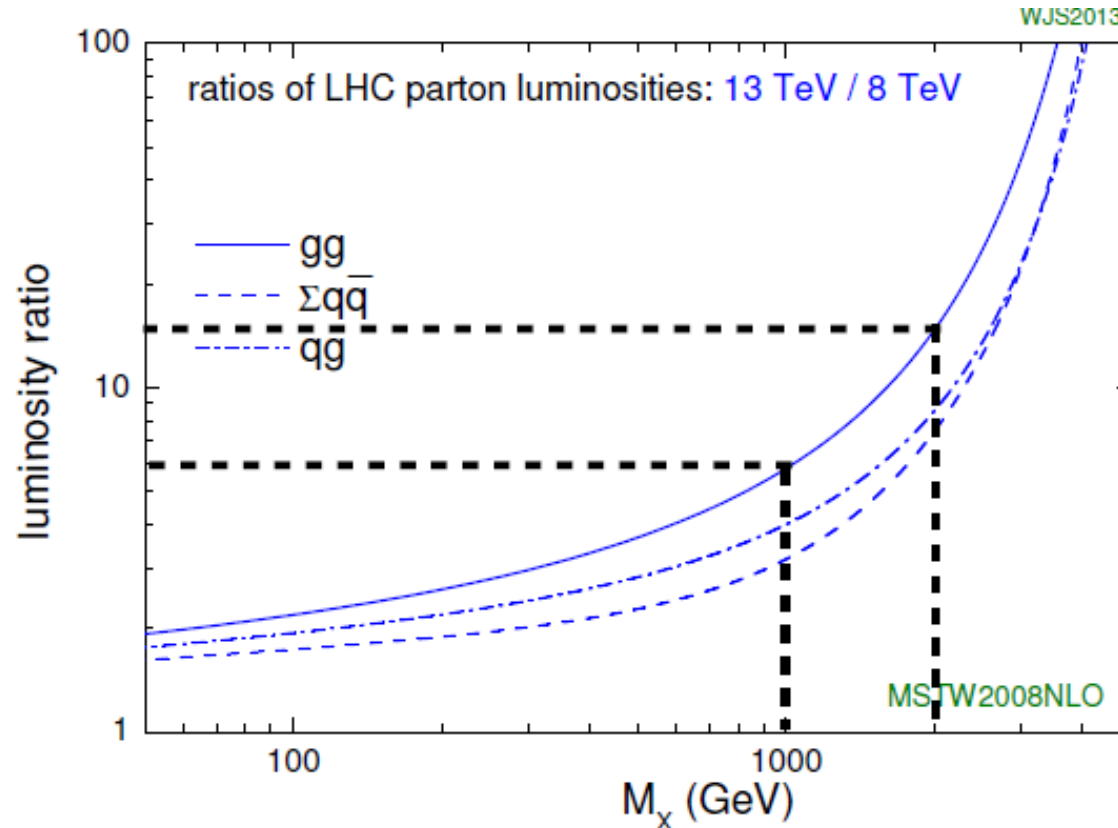


Boosted top candidate



# Run 2 Prospects

- Expected more data in Run 2 ( $\sim 100 \text{ fb}^{-1}$  vs  $20 \text{ fb}^{-1}$  for Run 1)
- Expect to have larger production cross sections due to increased  $\sqrt{s}$



- Run 2 is:  $\sim 6$  ( $\sigma$  ratio)  $\times 5$  (lumi ratio)  $\approx 30 \times$  Run 1 for gg production at 1 TeV  
 $\sim 15$  ( $\sigma$  ratio)  $\times 5$  (lumi ratio)  $\approx 75 \times$  Run 1 for gg production at 2 TeV

- The LHC Run 1 program is extremely successful
  - Discovered a Higgs boson that is EXOTIC compared to other fundamental particles that we know
  - Ruled out some models or narrowed down allowed phase spaces for others
  - No convincing evidences for BSM physics so far
- Presented results from a few ATLAS/CMS searches with data excess around 2 TeV, it still remains to be seen if they are due to BSM physics or fluctuations → more investigations will be performed using Run 2 data
- Presented a few other searches with W, Z, t, H,  $\gamma$  and long-lived particles
- Run 2 physics program is underway and we have great discovery potentials in the next few years, stay tuned!