Measurements and searches with boosted techniques

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LHC Run-2 started last year

- Increase of energy 8 TeV → 13 TeV

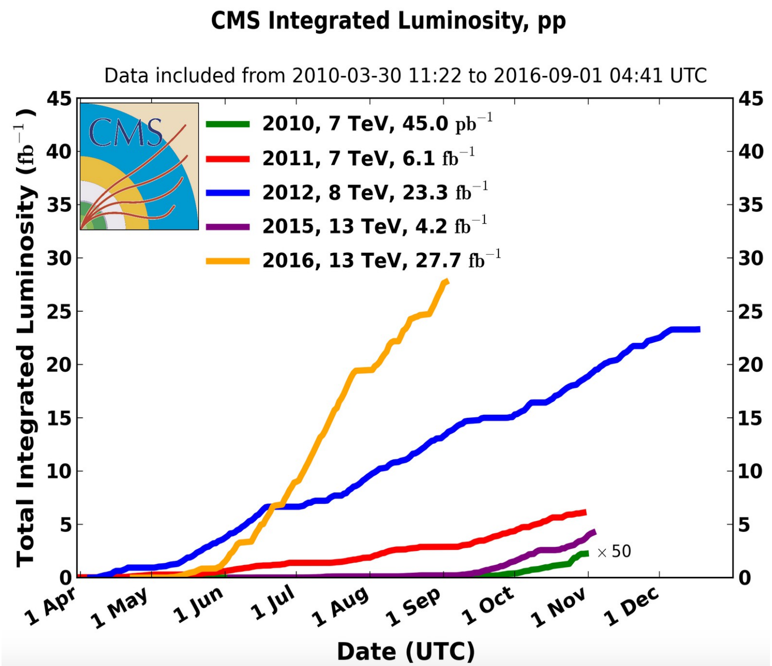
- Exceptional LHC, ATLAS and CMS performance in 2016
  - ATLAS (CMS) data taking eff. ~92 (91)%

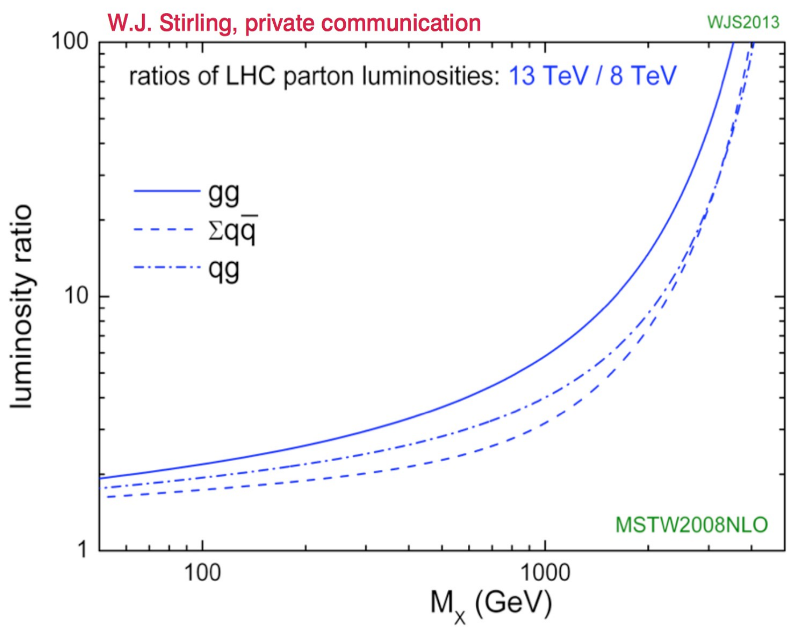
- Physics program for Run-2?

  - *Increase precision in SM measurements*
  - *Push BSM searches further*
    - Major new-physics sensitivity has opened up, specially at high masses

- Highly energetic particles in final state

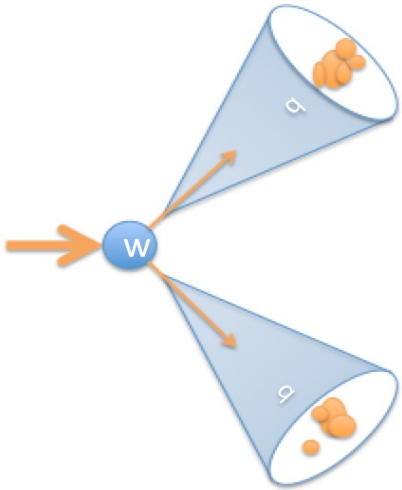
  - Unique boosted topologies
  - Require revisiting our object reconstruction and analysis techniques

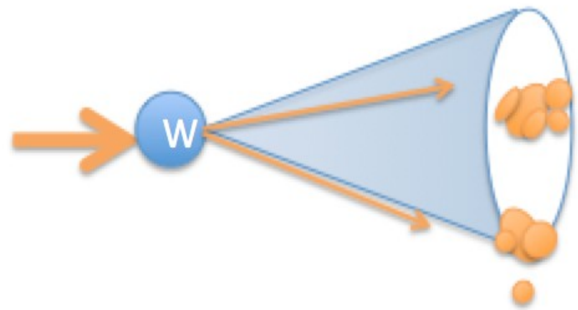




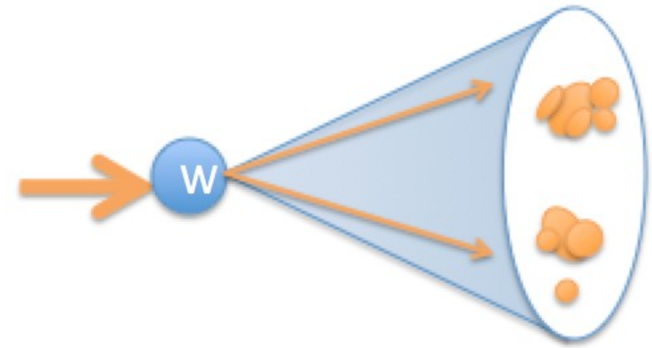
Reconstructing boosted bosons and tops

Resolved regime	Merged regime





Standard algorithms
Small-R jets (default R~0.4)



"New" algorithms
Large-R jets

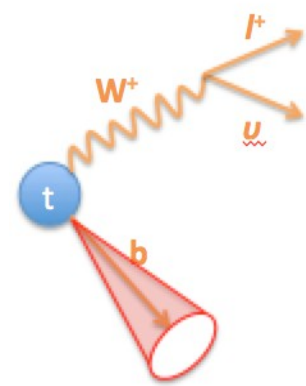
- In the boosted regime the decay products are collimated in the direction of the initial particle

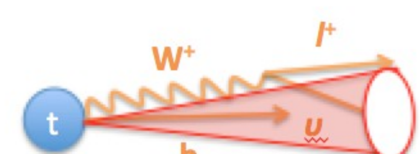
- Rule of thumb for angular separation of decay products

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \approx \frac{2m}{p_T}$$

A *W* boson with p_T~200 GeV, ΔR=0.8

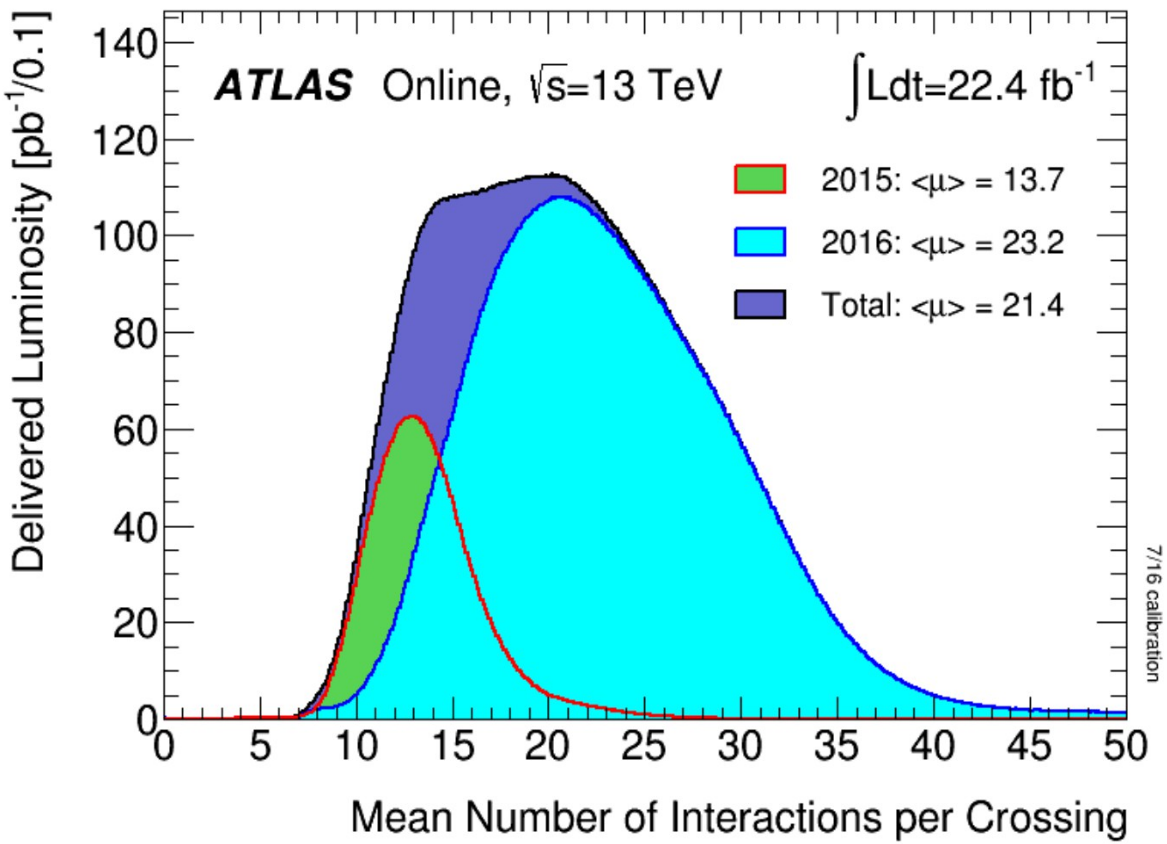
- From a practical point of view this means:
  - Hadronic decay products merge into a single jet
  - Leptons close to (or even) inside jets
    - (need to modify lepton isolation criteria)
  - At very high p_T the calorimeter granularity is a limitation

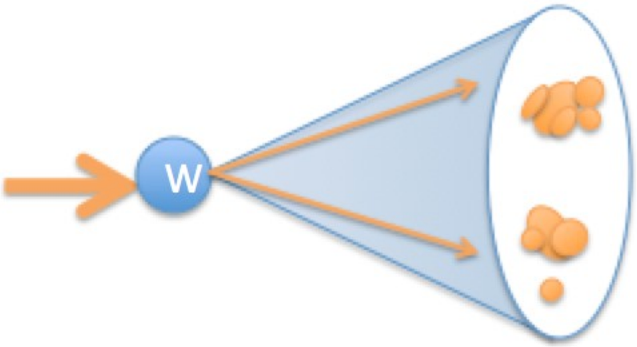




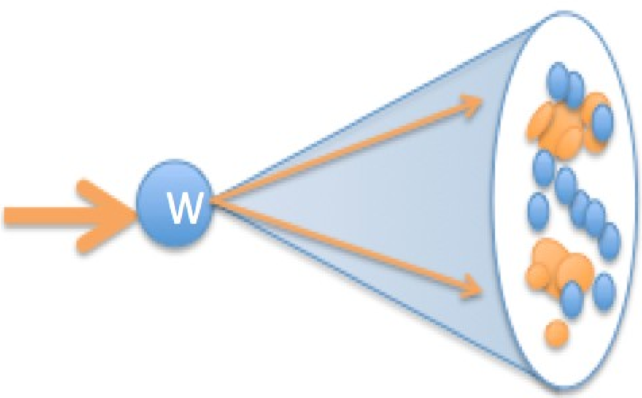
Reconstructing boosted bosons and tops

Pile-up conditions make this task more challenging





Without pile-up



With pile-up

Outline

- **Reconstruction techniques in the boosted regime**
- **Testing the SM at high p_T**
  - *Developing trust in these new techniques!*
  - Anomalous quartic gauge coupling
  - Boosted differential top pair cross-section
  - Boosted top pair charge asymmetry
- **Boosted Run-2 searches**
  - *Main customers of boosted techniques! Focus on latest results*
  - Dark matter searches
  - Top pair resonances
  - Diboson resonances
- *Disclaimer:*
  - *This selection reflects my personal biases*
  - *I apologize to the many great analyses I had to leave out*
  - *Excellent related talks (SUSY, Top)*

Boosted boson/top tagging: what do we need?

Fat jets

Large distance parameter to pick up all radiation from original decay

Grooming

Remove soft comp. PU+UE

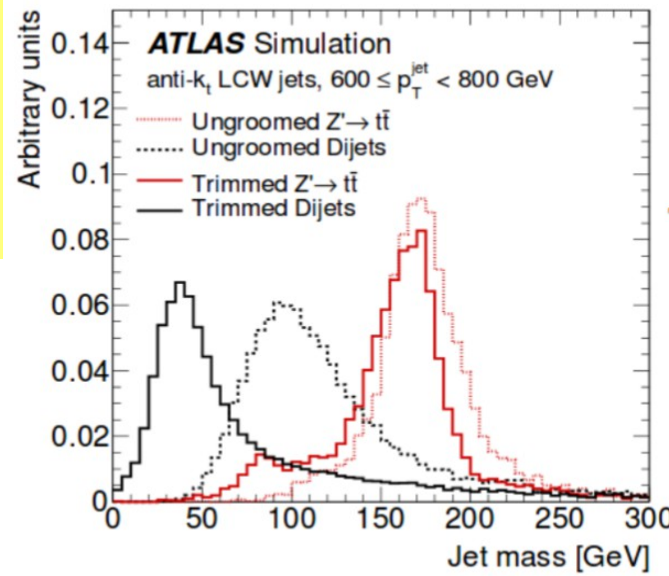
- Trimming [arXiv:0912.1342]
- Filtering [arXiv:0802.2470]
- Pruning [arXiv:0903.5081]
- Soft-drop [arXiv:1402.2657]

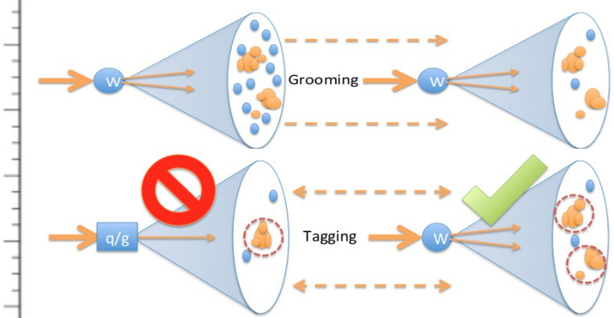
Tagger: substructure

Observables to characterize the underlying jet substructure, i.e. jet mass, momentum balance between subjets, track multiplicity

B-tagging ($H \to b\bar{b}$, $Z \to b\bar{b}$, $t \to Wb$)

ATLAS-CONF-2012-065





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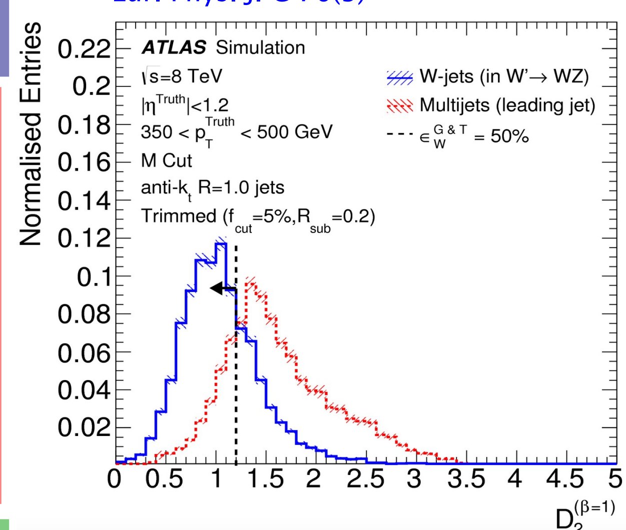
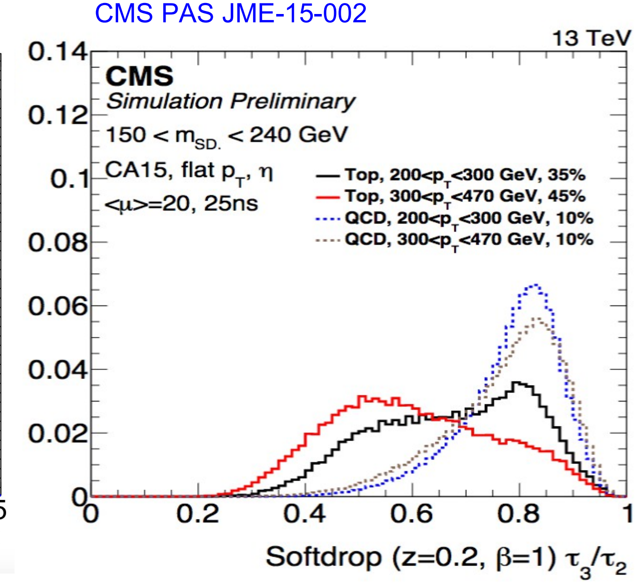


CMS PAS JME-15-002



Boosted boson/top tagging details

ATLAS

- Anti-k_T R=1.0 jets
- **Grooming**
  - Trimming, re-cluster with k_T R=0.2 and remove subjets with $p_T^{subjet}/p_T^{jet} < 5\%$
- **W/Z boson tagging** (ATL-PHYS-PUB-2015-033)
  - m_J consistent with m_W, m_Z within ±15 GeV
  - Substructure variable $D_2^{\beta=1}$ consistent with two prong decay. Used to define low and high purity categories
  - Efficiency 50%, QCD rejection factor ~50
- **Higgs boson tagging** (ATL-PHYS-PUB-2015-035)
  - Mass + anti-k_T R=0.2 b-tagged track jets
- **Top tagging** (ATL-PHYS-PUB-2015-053)
  - Mass + $\tau_{3/2}$ consistent with 3-prong decay

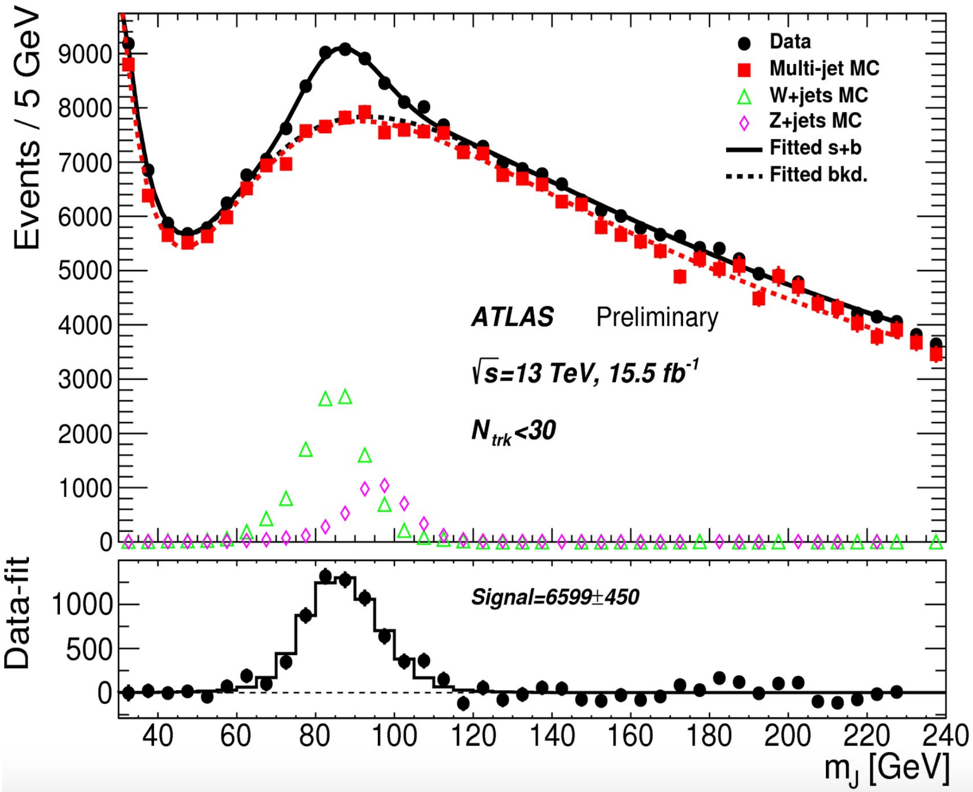
CMS

- Anti-k_T R=0.8 jets
- **Grooming:**
  - Top ID: Soft-drop (z_{cut}=0.1 and β=0)
  - Bosons ID: pruning, recluster with Cambridge-Aachen algorithm
- **W/Z boson tagging** (JME-14-002)
  - 65 < m_J < 105 GeV, pruned mass
  - $\tau_{2/1}$ consistent with two prong decay. Also used to define low and high purity categories
- **Higgs boson tagging** (BTV-15-001, BTV-15-002)
  - 110 < m_J < 135 GeV, pruned mass
  - b-tagged pruned subjets
- **Top tagging** (JME-15-002)
  - Soft-drop mass + $\tau_{3/1}$ + $\tau_{3/2}$

Criteria used in the analyses to be presented here, unless stated otherwise

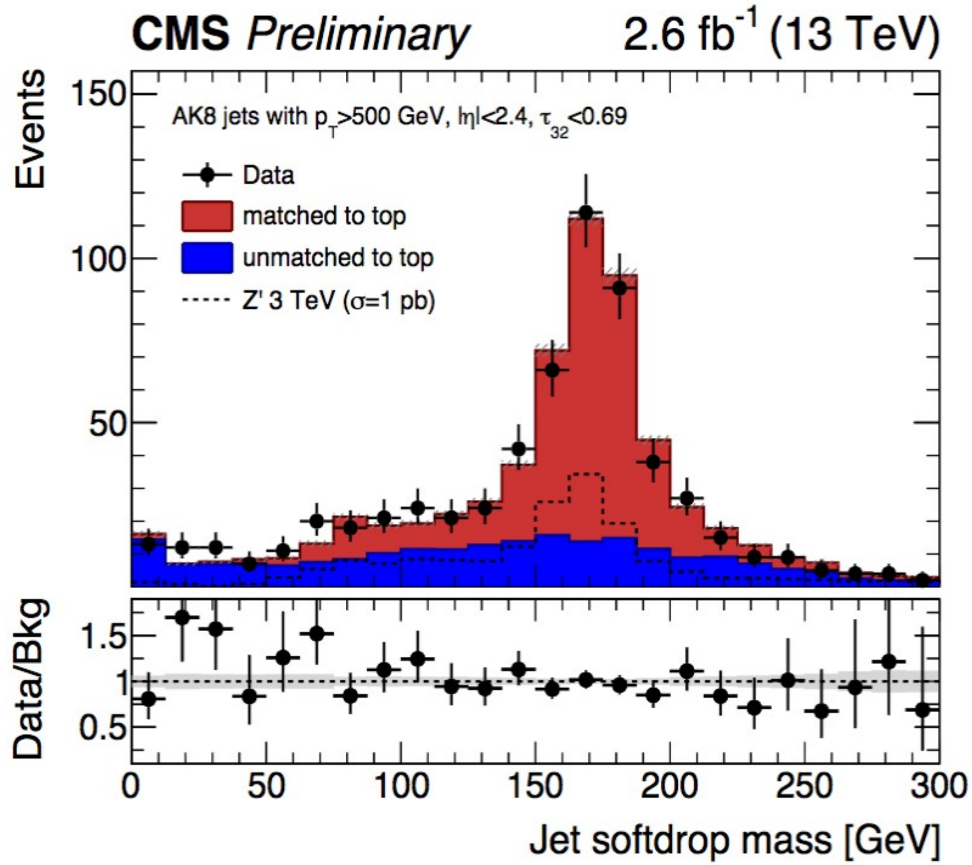
Do these techniques really work?

ATLAS-CONF-2016-055



Boson-tagging validation in W/Z+jets trimmed jets with D_2 requirement

TOP-16-013-pas

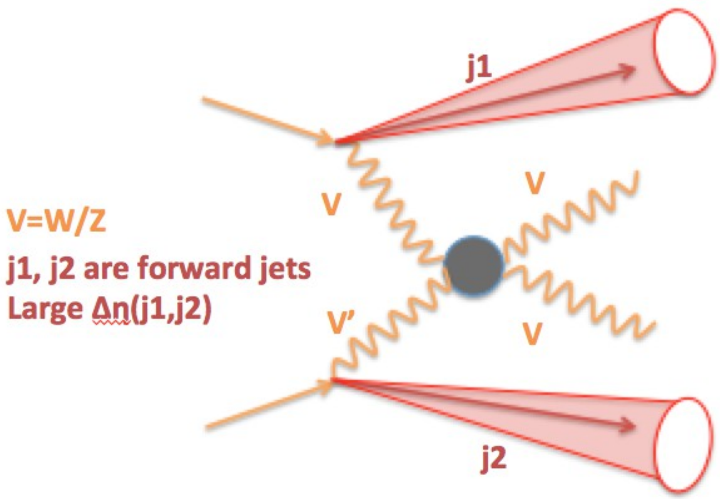


Top-tagging validation for Z'→$t\bar{t}$ search soft-drop mass with $\tau_{3/2}$ < 0.69

**Invite you to look at the hadronic W+Z cross-section measurement performed by ATLAS @7 TeV based on the invariant mass distribution (pT>320 GeV, |η|<1.9): arXiv:1407.0800*

Measurements

Anomalous quartic gauge couplings (aQGCs)

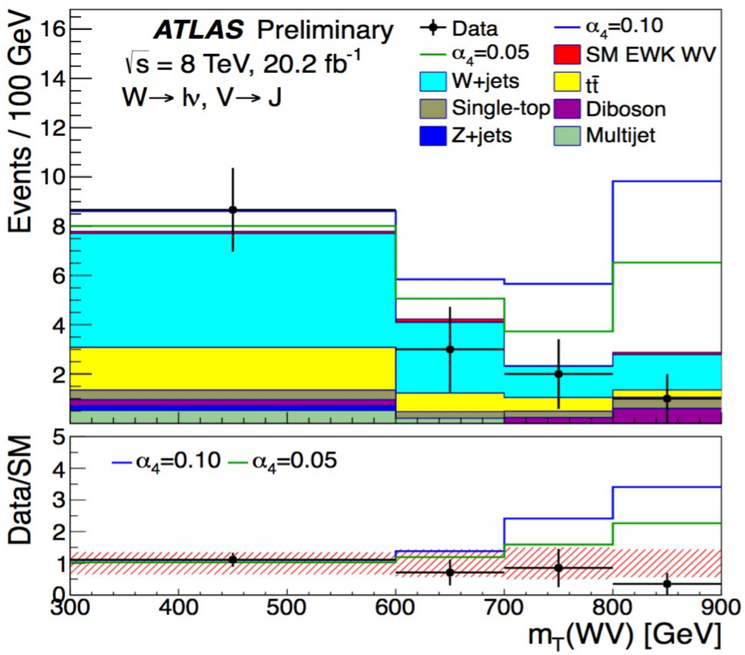


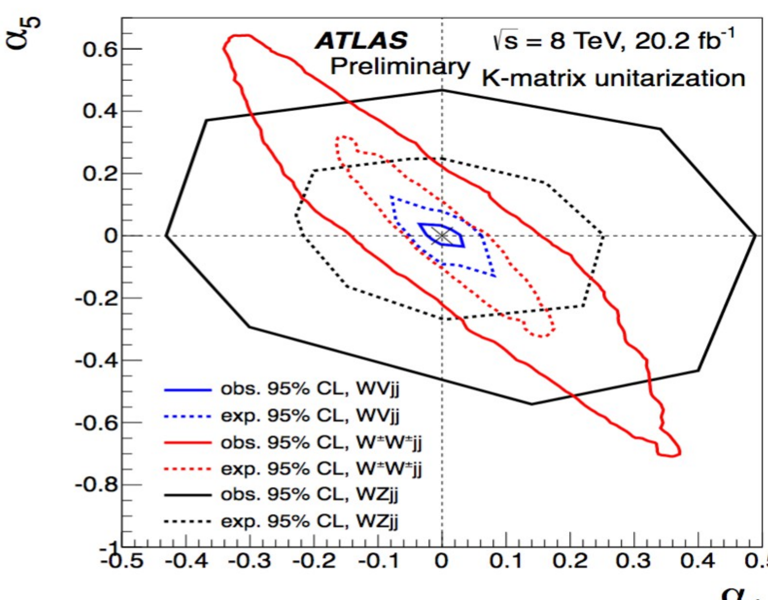
- Vector Boson Scattering (VBS) is key probe of EWSB

- WW/WZ identified as lepton plus MET and either two small-R jets or one large-R jet:
  - C/A R=1.2 split filtered with p_T>200 GeV and mass>40 GeV

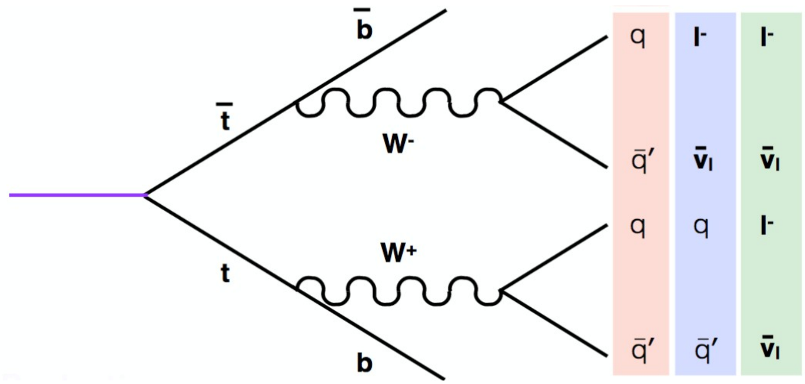
- Transverse mass of the WW/WZ system used to set limits on aQGCs

- Dominant systematic uncertainties are the jet energy scale and resolution and signal modeling





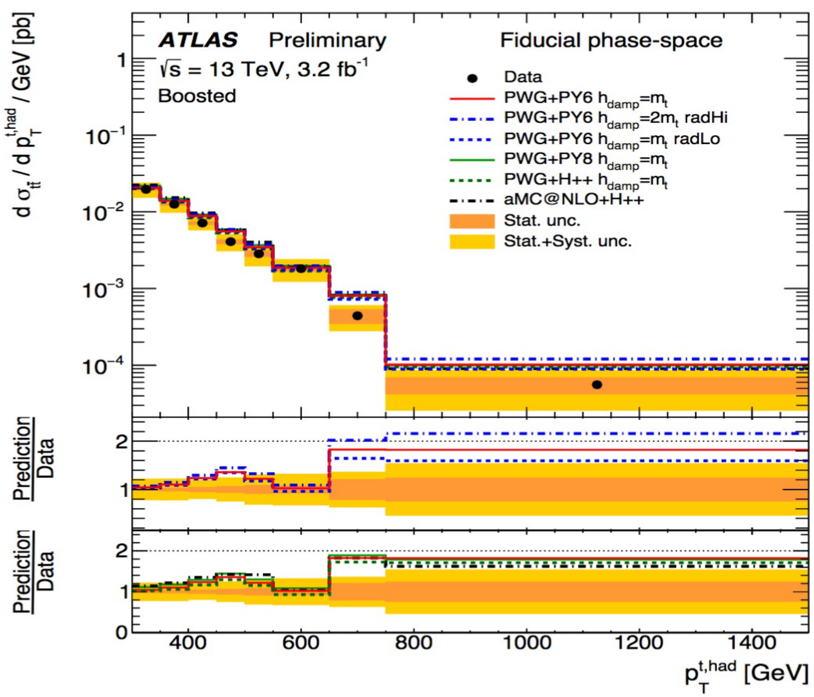
Boosted differential top pair XS

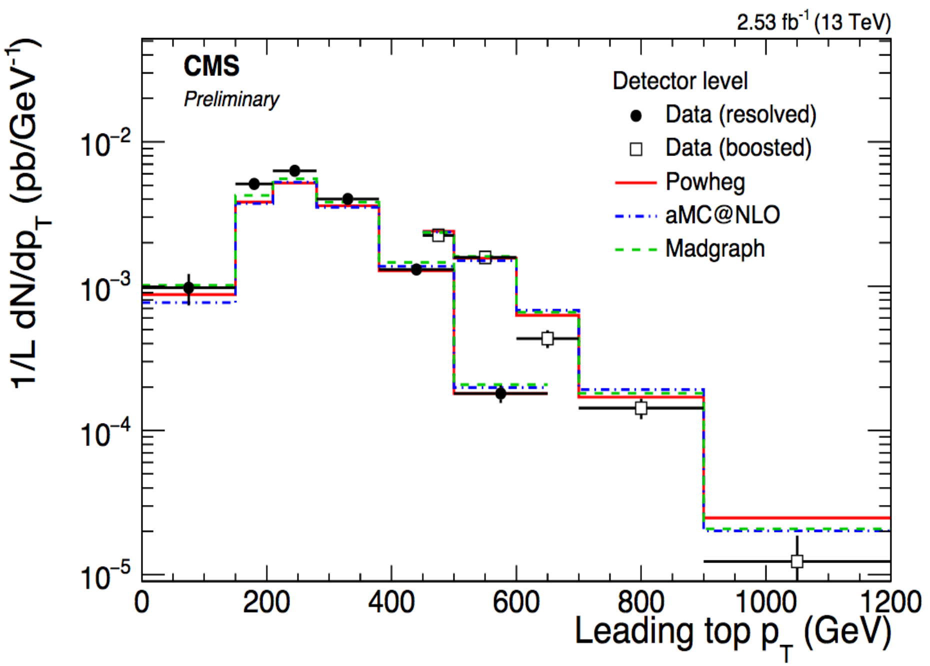


- Does top behave like the SM predicts?
- Why measure the top pair XS?
  - Precision test of QCD at high orders
  - Constrain new physics and background for searches
- Boosted regime allow us to test high p_T

ATLAS: semileptonic (ATLAS-CONF-2016-040)

CMS: full hadronic (TOP-16-013)



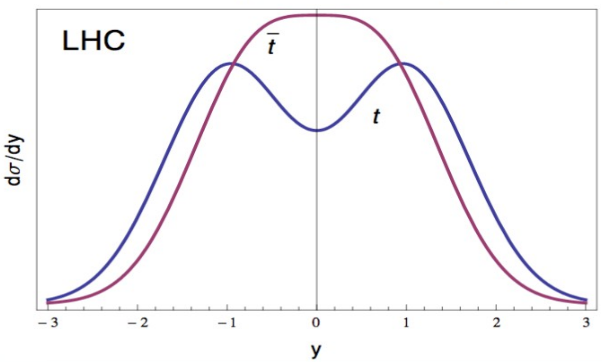


- Dominant uncertainties comes from the large-R jet energy scale and flavour tagging
- p_T in data softer than MC prediction across spectrum (similar results observed at 8 TeV)

Boosted top pair charge asymmetry

Physics Letters B (2016), Vol. 756, pp. 52-71

Kühn, Rodrigo, JHEP 1201 (2012) 063
Bernreuther, Si, Phys. Rev. Lett. D 86 (2012) 034026



$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

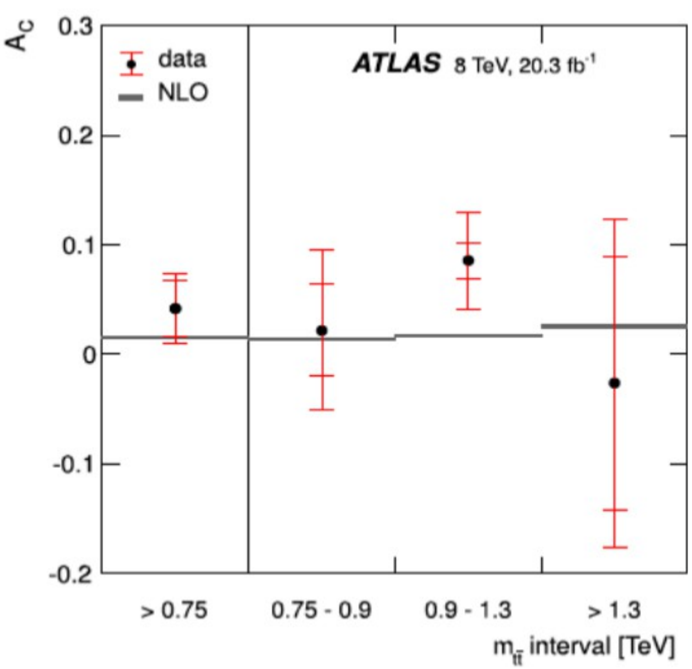
$$A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

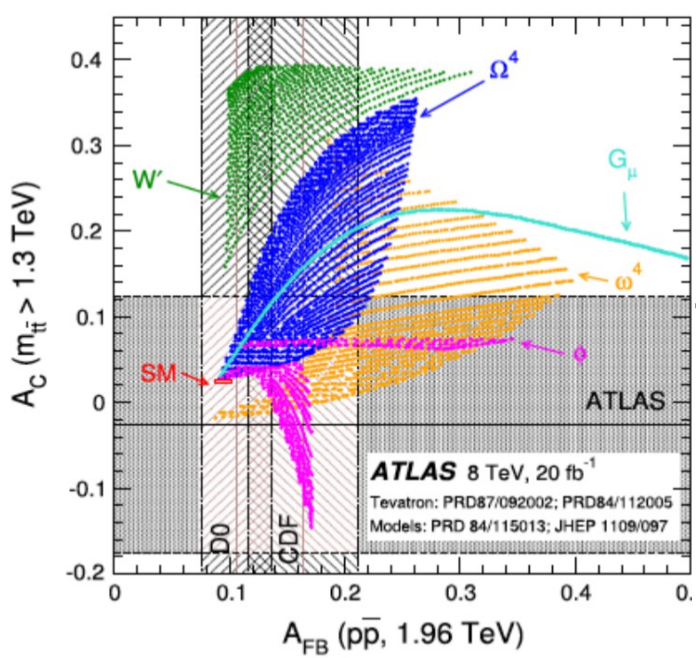
$$A_C^{t\bar{t}} = 0.0111 \pm 0.0004 \text{ (NLO QCD)}$$

- Why measure the top pair charge asymmetry?
  - $t\bar{t}$ production gives charge asymmetry at NLO due to interference: $q\bar{q}$ vs. gg
  - Differential distributions sensitive to new physics, such as axi-gluons, especially at high $m_{t\bar{t}}$ → Boosted ($m_{t\bar{t}}$>750 GeV)

- ATLAS boosted semileptonic analysis dominated by statistical uncertainties. Leading systematic is signal modeling

- Results compatible with SM predictions





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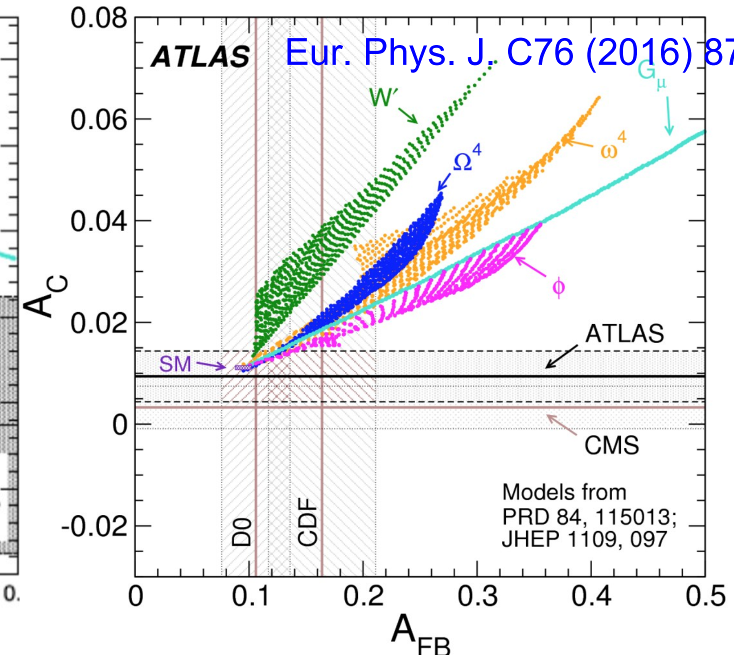
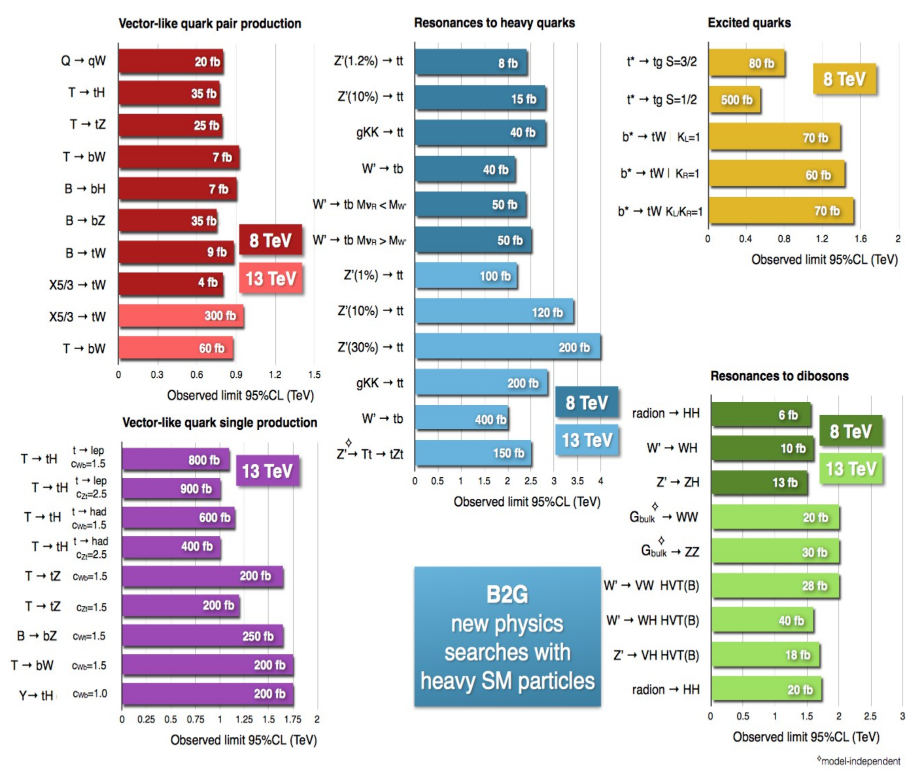


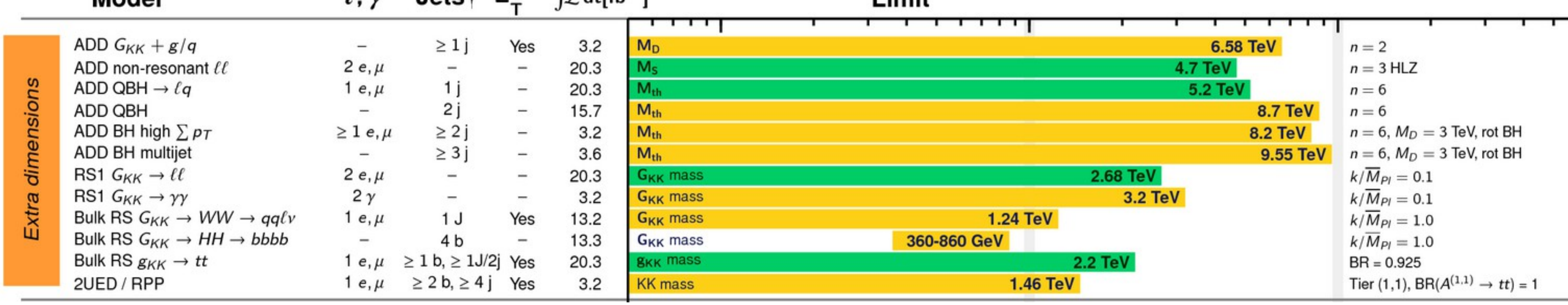
Searches: Searching as broad and general as possible

- Beyond SM searches consider many models trying to resolve different problems: hierarchy problem, Higgs mass stability, dark matter
- ATLAS and CMS searches are often signature driven. One signature probing various models
- Many beyond SM searches make use of boosted techniques
- I will present a biased selection of results
  - Decay of new resonances to heavy SM objects such as top, W, Z and Higgs bosons
  - Dark matter (DM) searches
  - SUSY searches using boosted techniques will be presented by M. Goblirsch-Kolb

https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsB2G/B2GSummary.pdf



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_Exotics_Summary/ATLAS_Exotics_Summary.png



ATLAS Exotics Searches* - 95% CL Exclusion

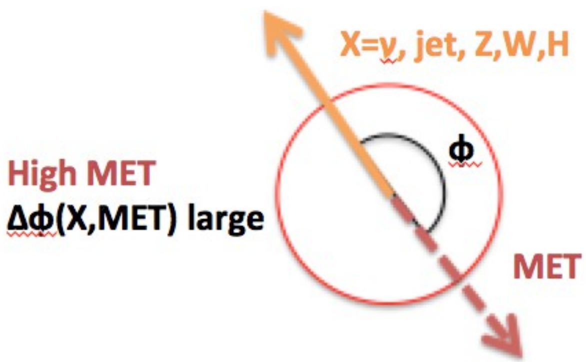
Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

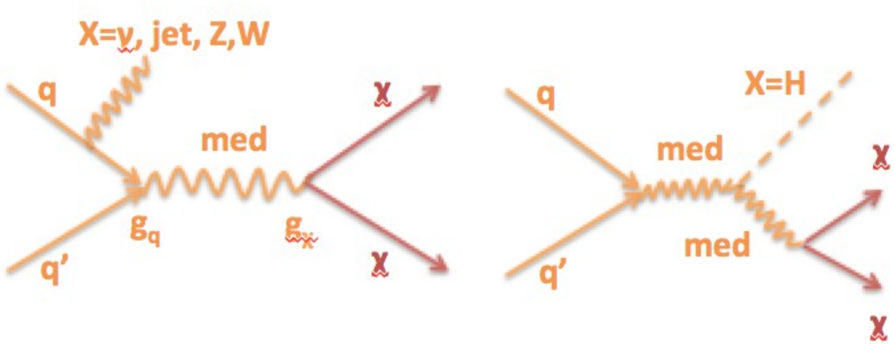
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D	6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S	4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	M_{th}	8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	G_{KK} mass	3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	13.2	G_{KK} mass	1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	G_{KK} mass	360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass	2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass	1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013

Dark matter searches using boosted techniques



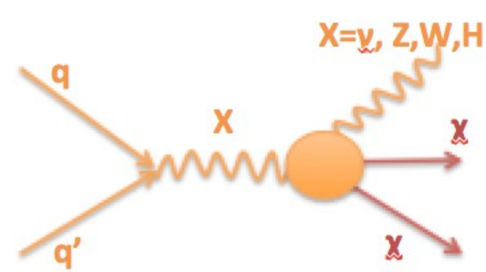
- The search for DM is an interdisciplinary effort
- Favorite collider dark matter candidate: WIMP
  - Weakly interacting, massive, stable and we should be able to produce them at the LHC
- Usual topology for dark matter searches: mono-X + MET
  - DM (χ) particles escape detection: MET
  - Radiation of a single SM object: mono-X
  - Powerful at low masses wrt direct detection
- Interpretations: ATLAS-CMS DM Forum (arXiv:1507.00966)

Simplified models



- *DM is a Dirac fermion*
- *X produced in ISR*
  - *If X=H, X is radiated by mediator*

EFT models



- *M_{med}>>momentum transfer at LHC*
- *Direct coupling DM and EW bosons*

Other models

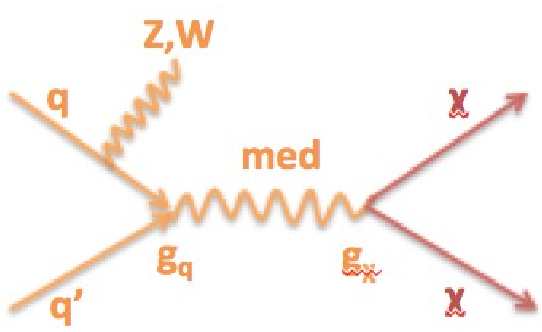
- *Type-2 two-Higgs-doublet model (H2DM)*
- *MFV models*

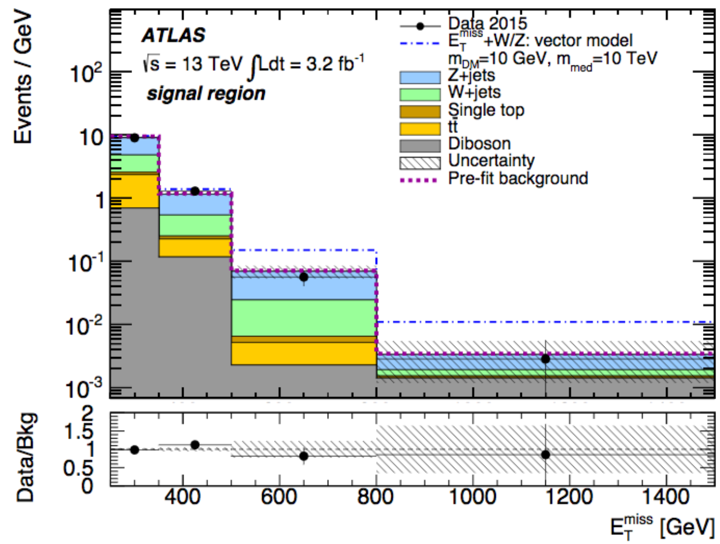
Let's review the latest 13 TeV results!

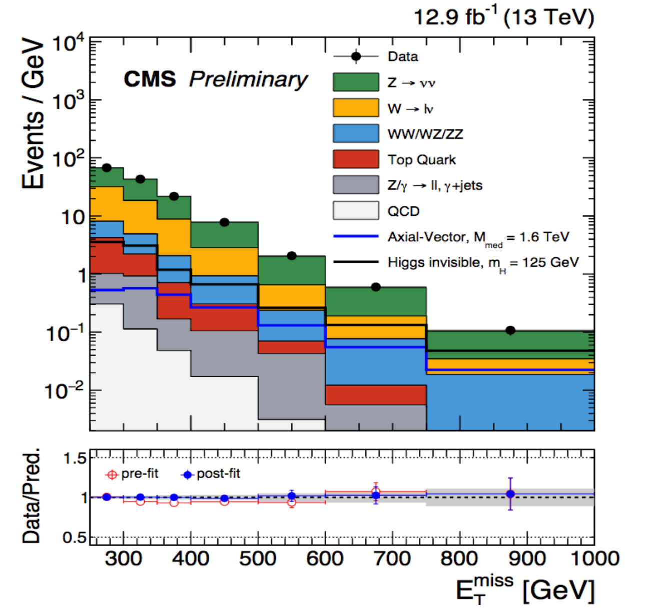
Dark matter searches using boosted techniques: W/Z + MET

arXiv:1608.02372

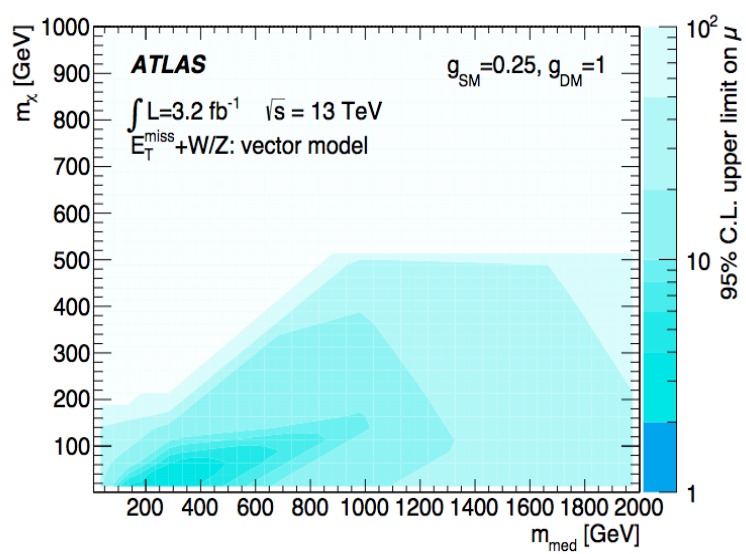
PAS EXO-16-037

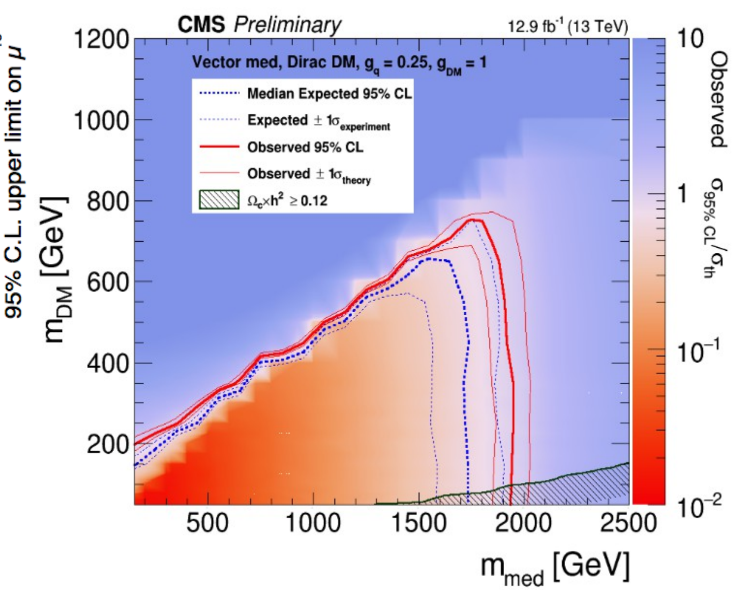




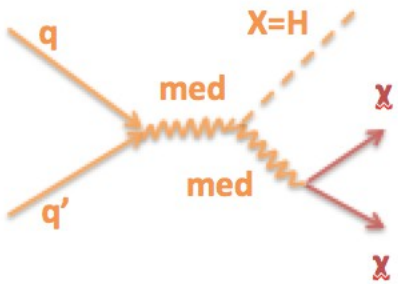


- Large R-jet plus MET
- Main backgrounds: Z/W+jets and tt̄
- Background in SR from simultaneous shape fit to MET distribution
- Good agreement with SM
- Simplified Model: exclusion limit on signal strengh μ, in (m_χ, m_{med}) plane

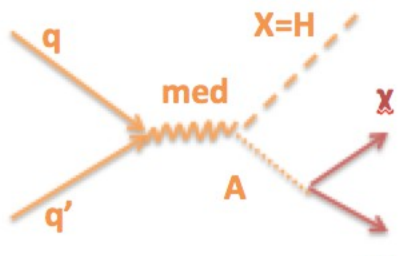




Dark matter searches using boosted techniques: H ($\to b\bar{b}$) + MET

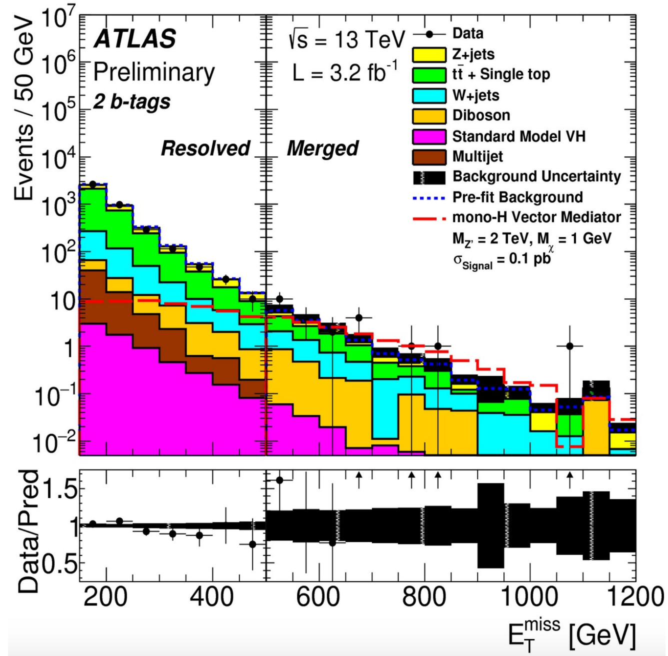


Simplified model

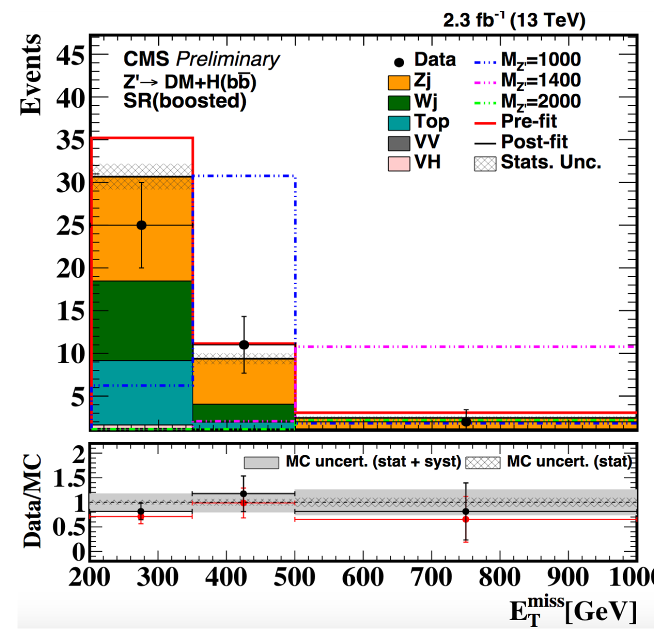


H2DM

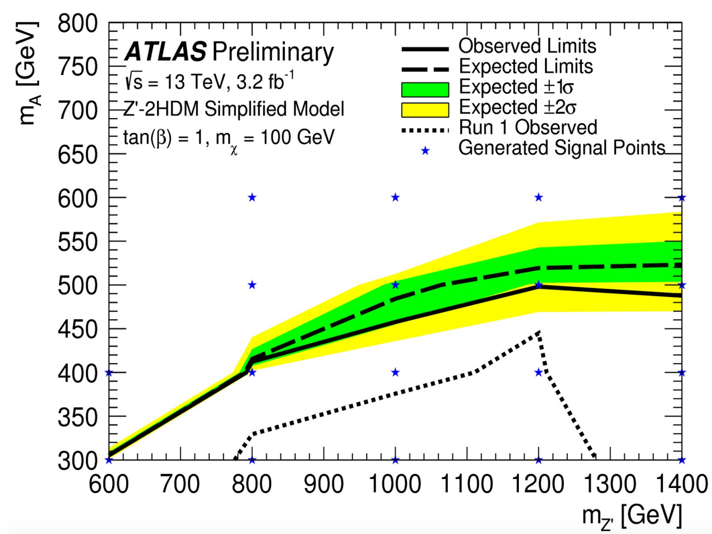
ATLAS-CONF-2016-019

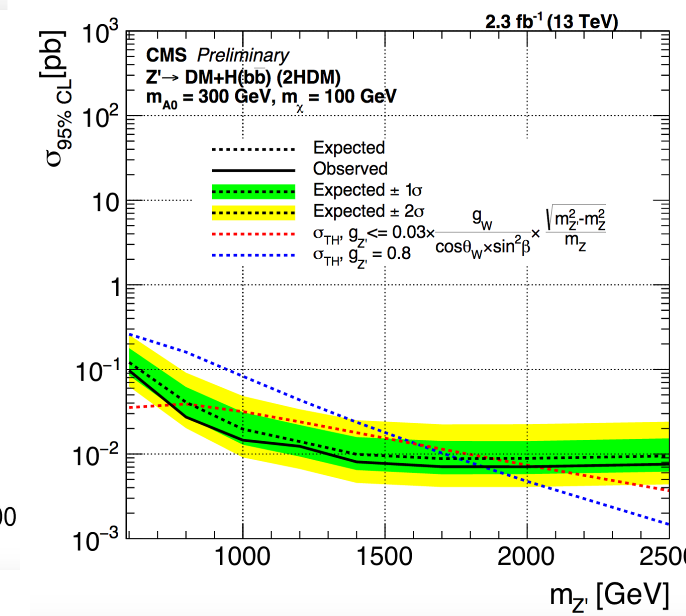


EXO-16-012



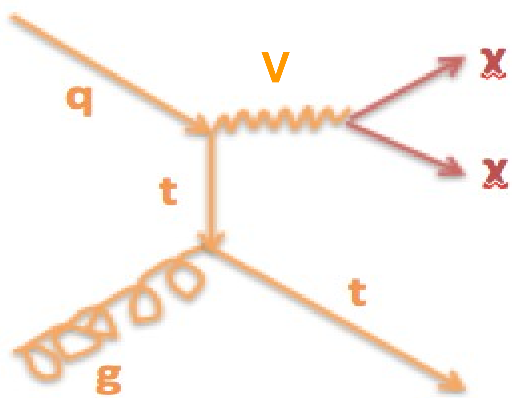
- Boosted and resolved
- Main backgrounds: Z/W+jets and $t\bar{t}$ (constrained by dedicated CRs)
- Good agreement with SM
- Limits on simplified and H2DM models



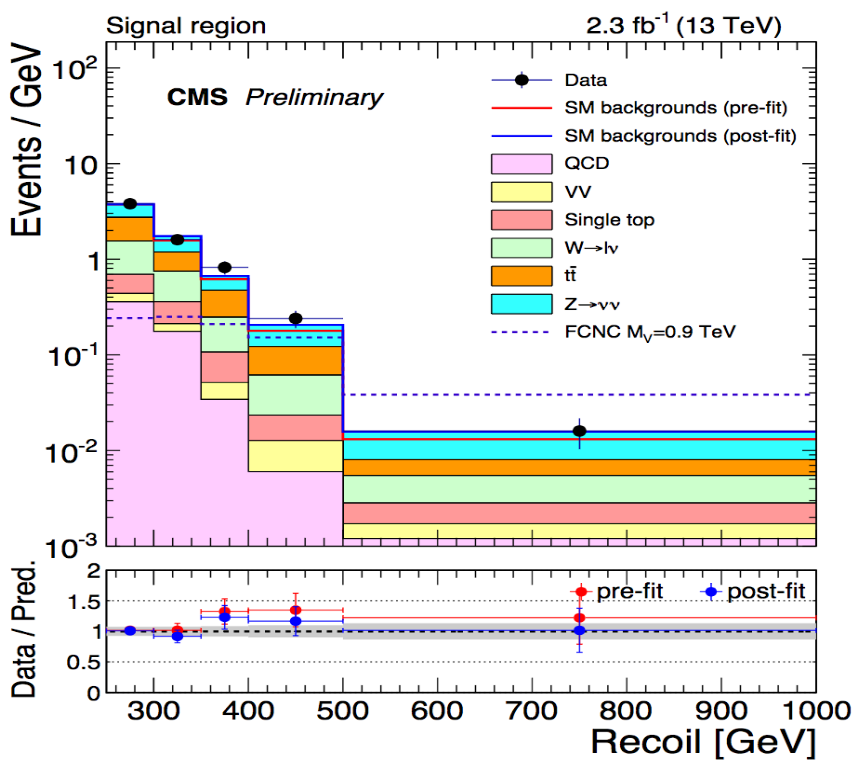


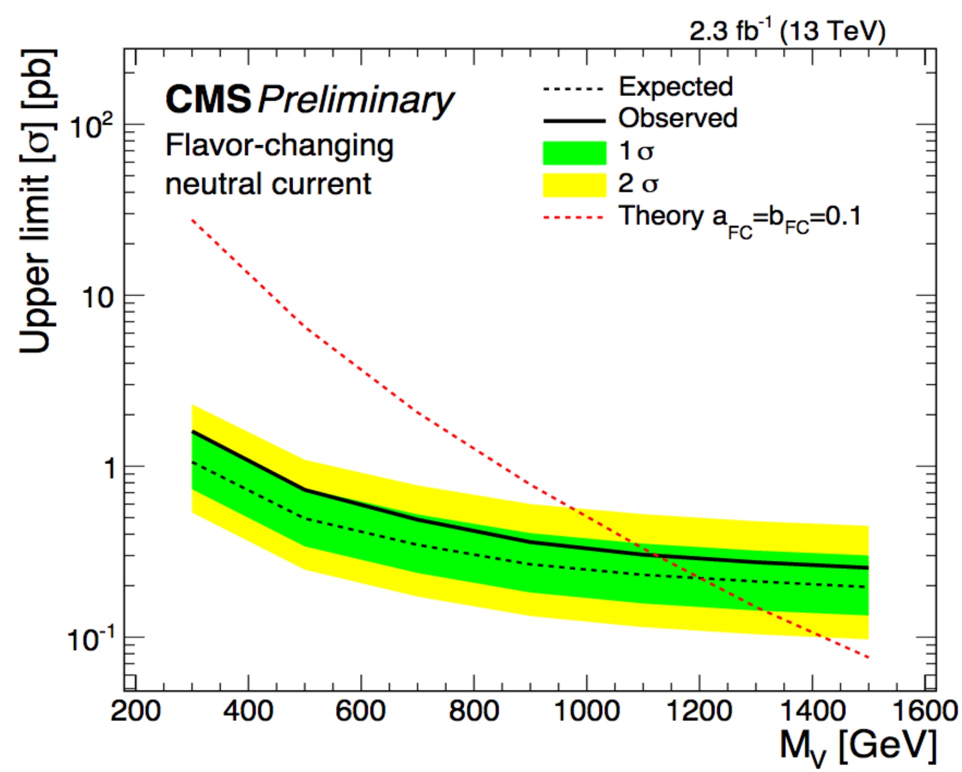
Dark matter searches using boosted techniques: boosted hadronic top + MET

EXO-16-017-pas



- Some models (e.g. MFV) enhance DM coupling to heavy quarks
- b-tagged fat jet with $110<m_{jet}<210$ GeV, $\tau_{3/2}$ and MET>250 GeV
- Veto extra b-tags, leptons
- Main backgrounds: $t\bar{t}$, Z(νν)+jets and W(lν)+jets → CRs: 1-2 e and μ, γ+jet regions
- No significant deviations. Limits on the production of invisible bosons (V) coupling to dark matter particles. Improving by 400 GeV the 8 TeV results

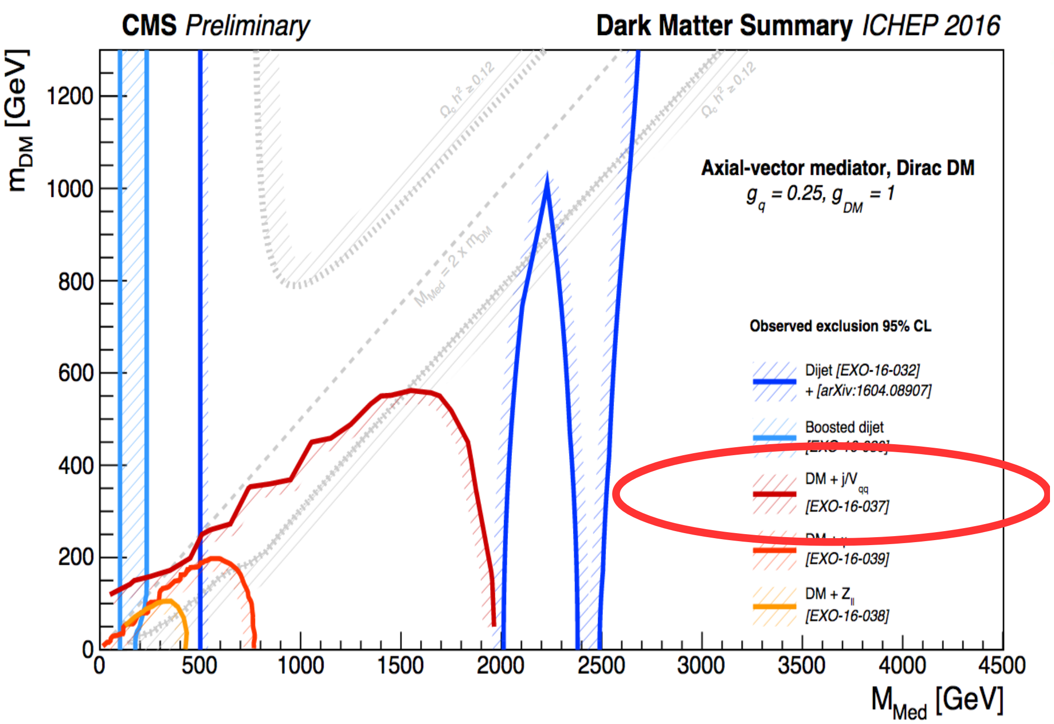


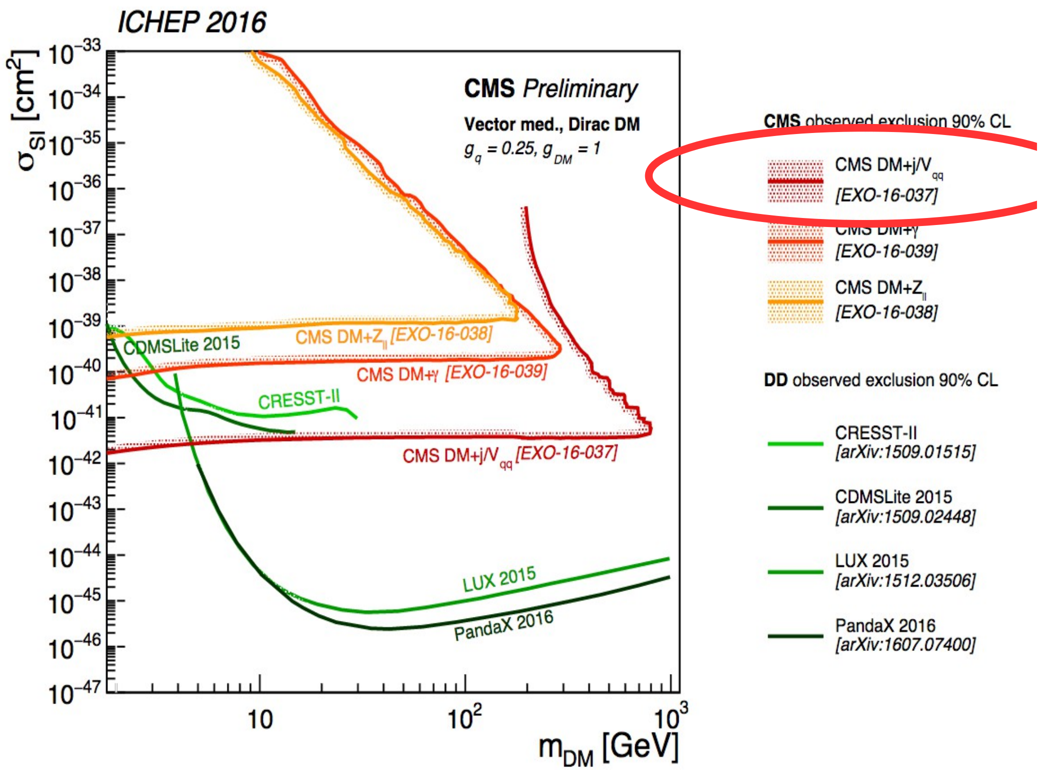


Dark matter searches using boosted techniques: A bit of perspective

Complementarity

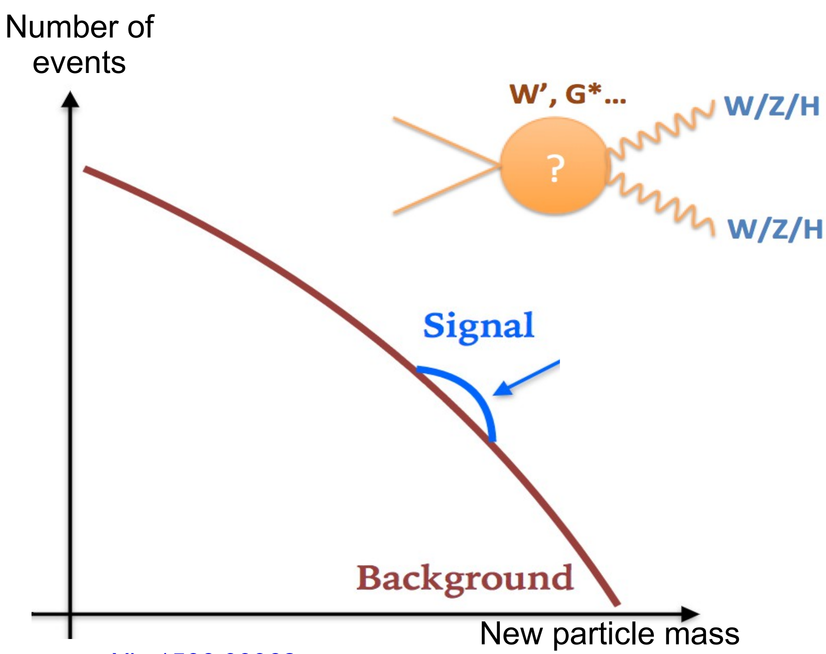
Caveat: results are model dependent



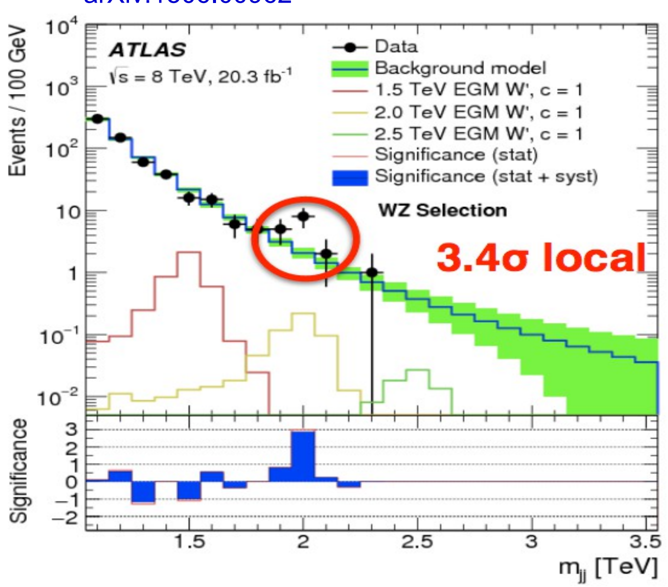


Looking for new heavy resonances

New particles: resonant excess (bump) over SM background

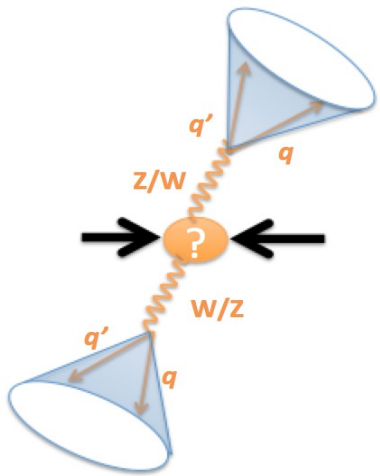


arXiv:1506.00962



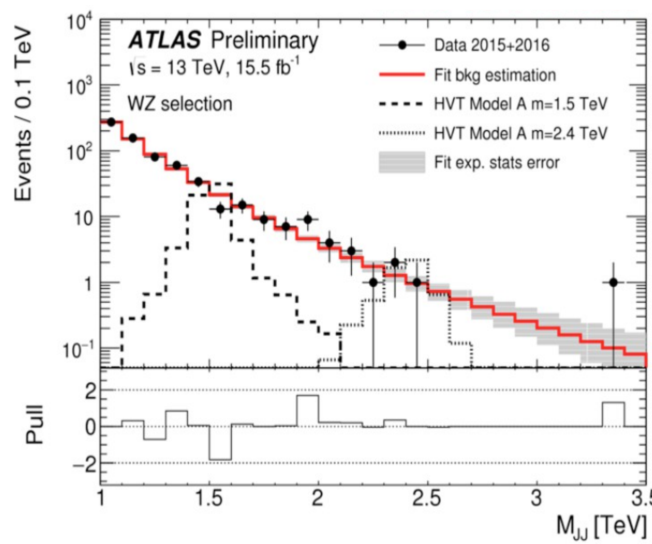
- Many final states using boosted techniques:
  - $VV \rightarrow llqq, l\nu qq, \nu\nu qq, qqqq$
  - $VH \rightarrow llbb, l\nu bb, \nu\nu bb, qqbb$
  - $HH \rightarrow bbbb$
  - $t\bar{t}$
- Interpreted in several scenarios
  - Dibosons connected to EWSB models
    - Spin 0: Heavy scalars in extended Higgs sector
    - Spin 1: Extended gauge models (W', Z' in HVT models)
    - Spin 2: Kaluza-Klein (KK) gravitons (Randall-Sundrum, RS)
  - $t\bar{t}$ interpretations:
    - Top-colour Z' narrow resonance (different models used by ATLAS and CMS)
    - Kaluza-Klein gluon wide resonance
- Excitement in Run-1 due to excess in $VV \rightarrow qqqq$
  - *Let's look at 13 TeV results!*

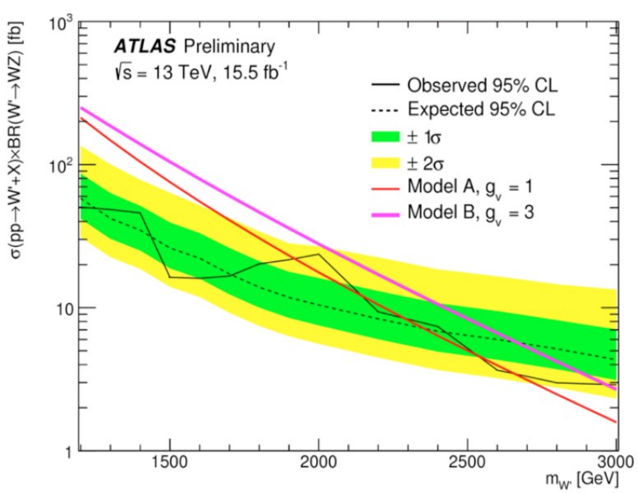
VV → qqqq



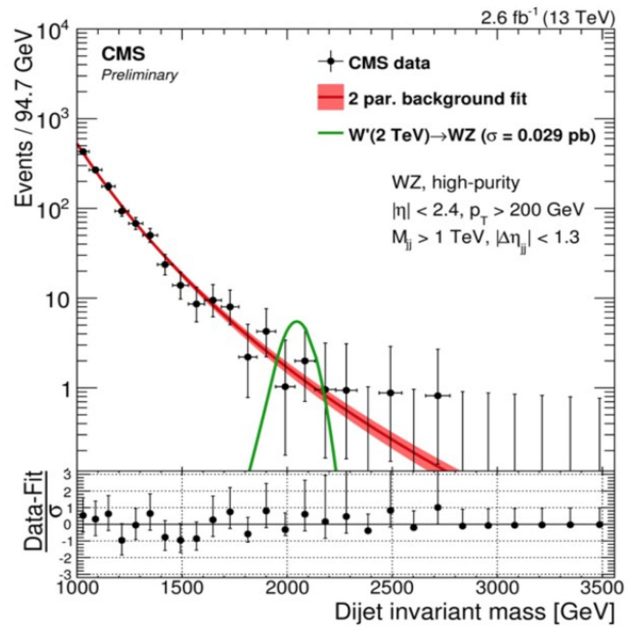
- Two high p_T jets boson tagged
  - ATLAS also includes a cut on the number of tracks in a jet < 30 selection (30% sensitivity improvement)
  - Similar kinematic selection to Run-1 analysis, but different large-R jet and grooming technique in the case of ATLAS
- Entirely dominated by multijet background (estimated from fit to the data)
- No significant deviation found in the WW/WZ/ZZ signal regions

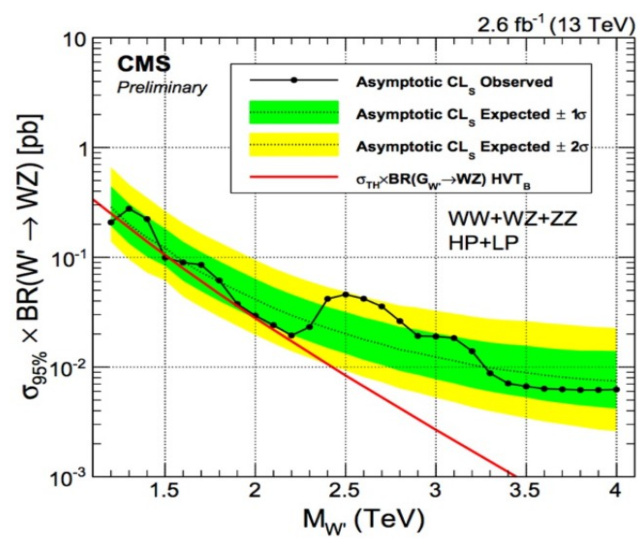
ATLAS-CONF-2016-055



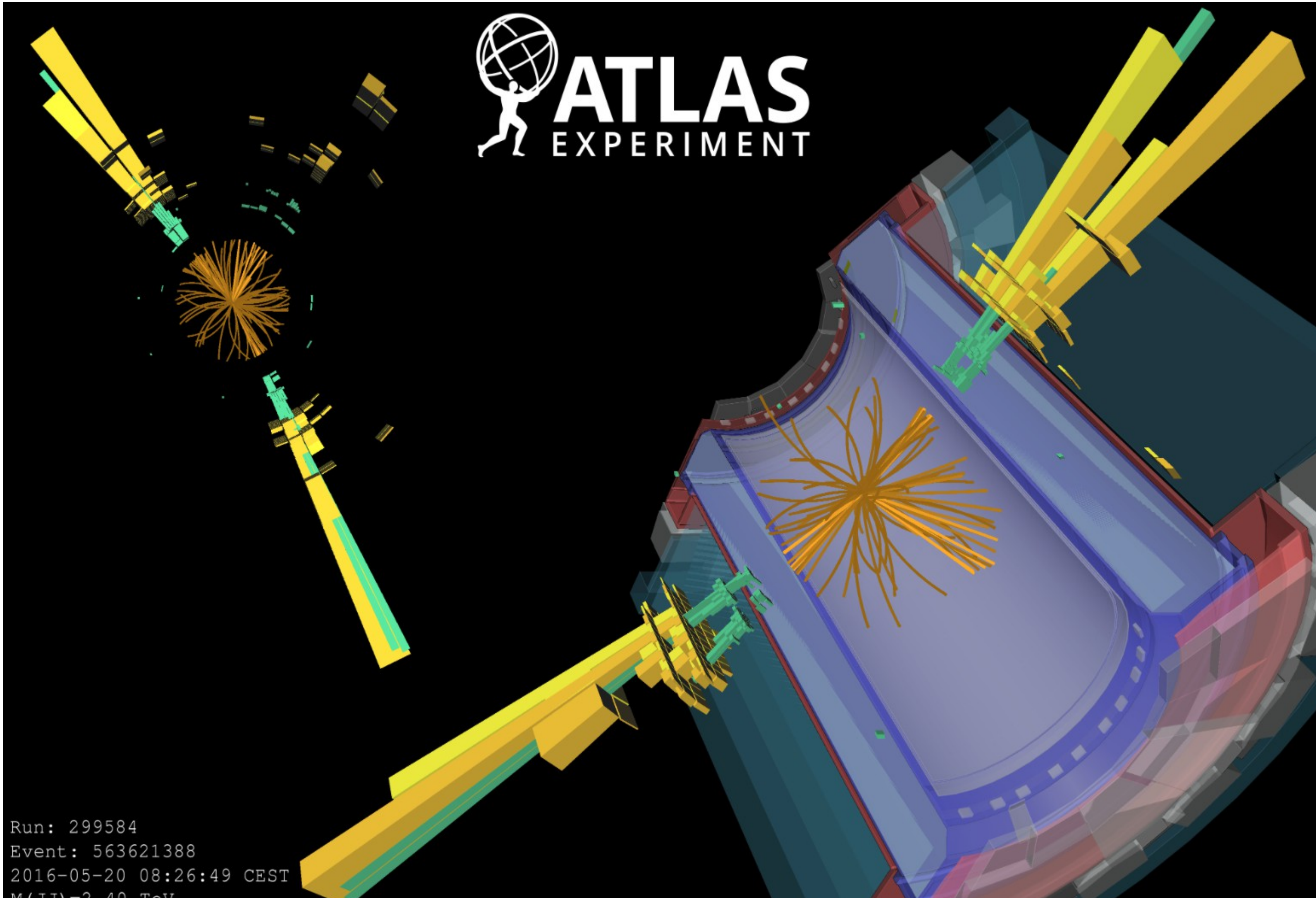


CMS PAS EXO-15-002

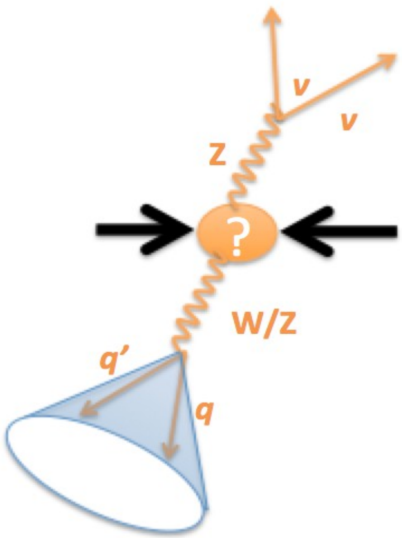




How these events look like?

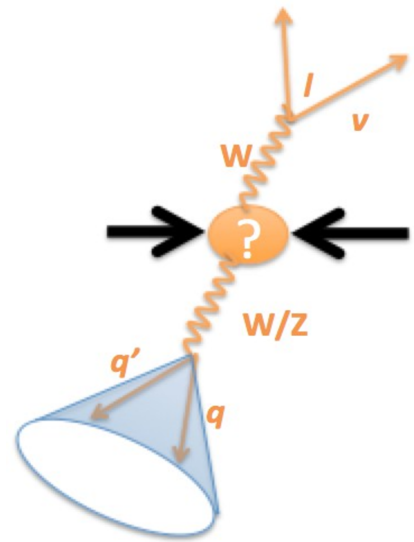


VV → lνqq/ννqq/llqq



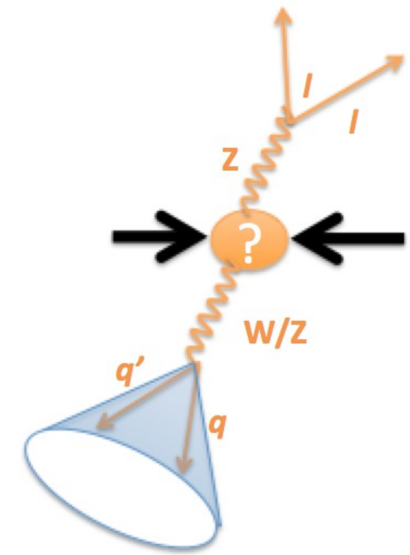
High MET

- ATLAS looked at boosted regime with 13 TeV 13.2/fb (ATLAS-CONF-2016-082)
- CMS results from 7 TeV in boosted regime (JHEP 02 (2013) 036)
- Main background: V+jets, $t\bar{t}$ and multijet



1 lepton + MET

- ATLAS looked at boosted regime with 13 TeV 13.2/fb (ATLAS-CONF-2016-062)
- CMS results from 13 TeV 2.2/fb boosted regime (EXO-15-002)
- Main background: W+jets, $t\bar{t}$ and multijet

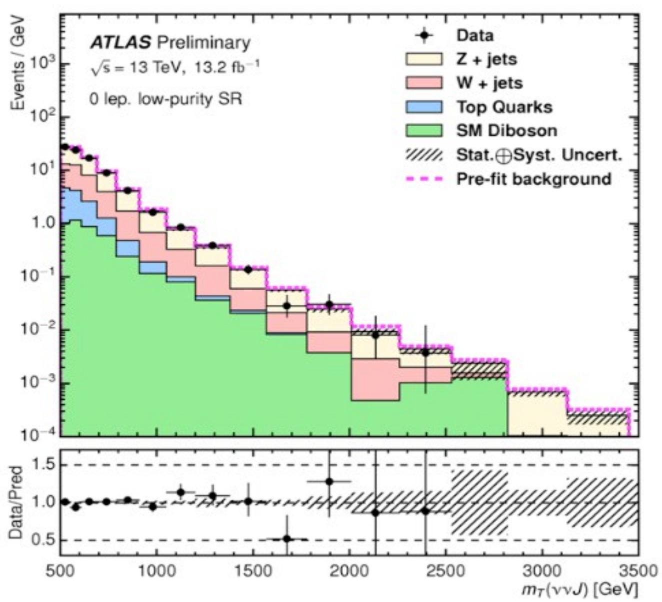


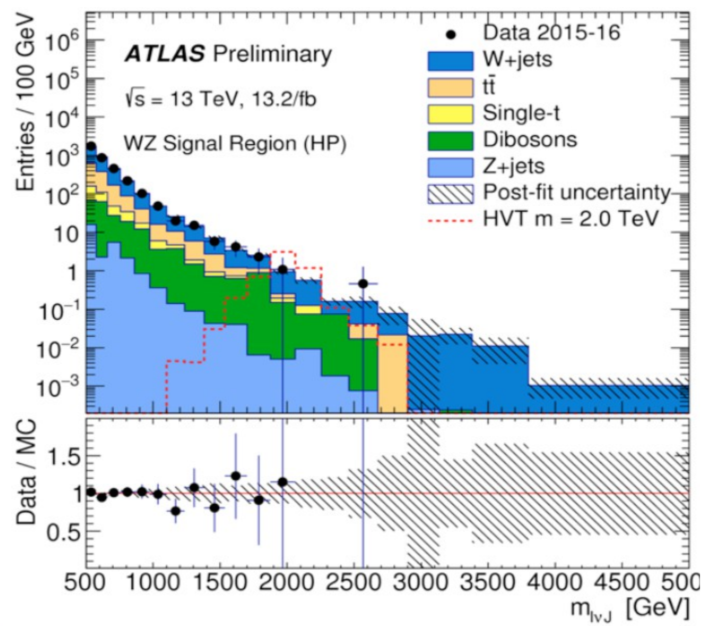
2 leptons and $m_{ll} \sim M_Z$

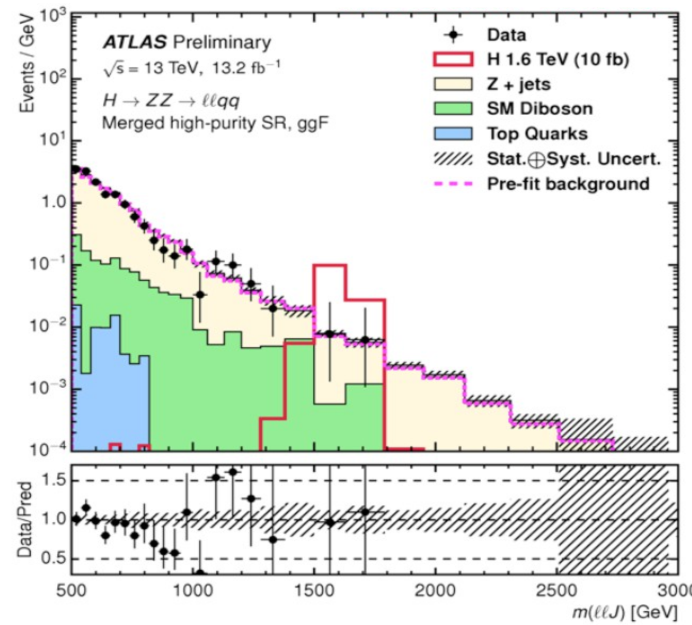
- ATLAS looked at boosted & resolved + VBF production with 13 TeV 13.2/fb (ATLAS-CONF-2016-082)
- CMS results from 13 TeV 2.2/fb boosted regime (B2G-16-010)
- Main background: Z+jets

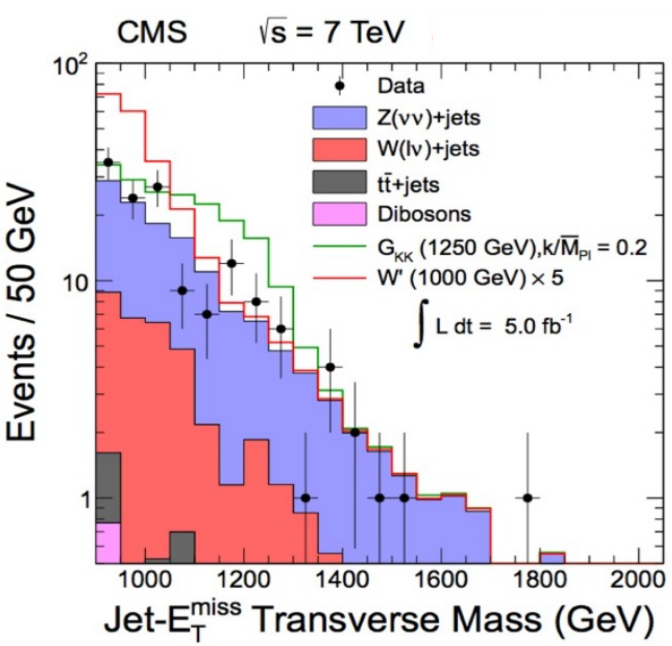
VV → lvqq/vvqq/llqq

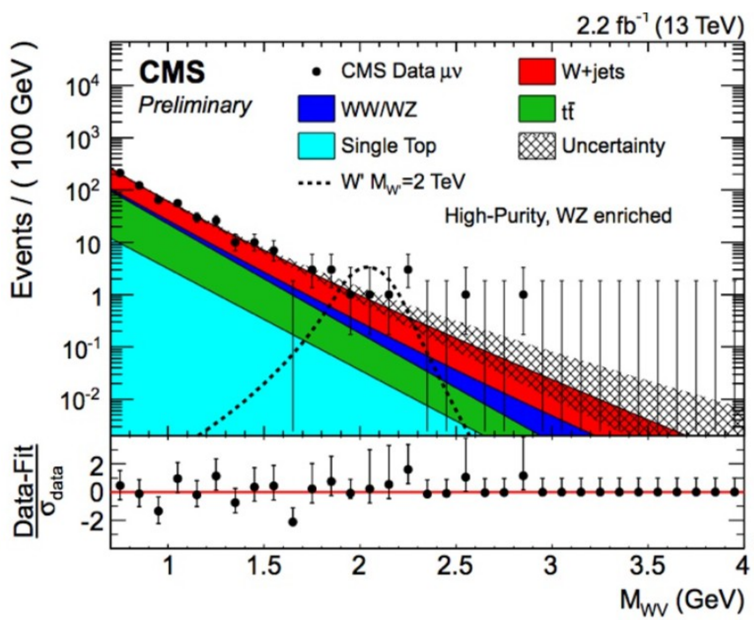
vvqq | lvqq | llqq

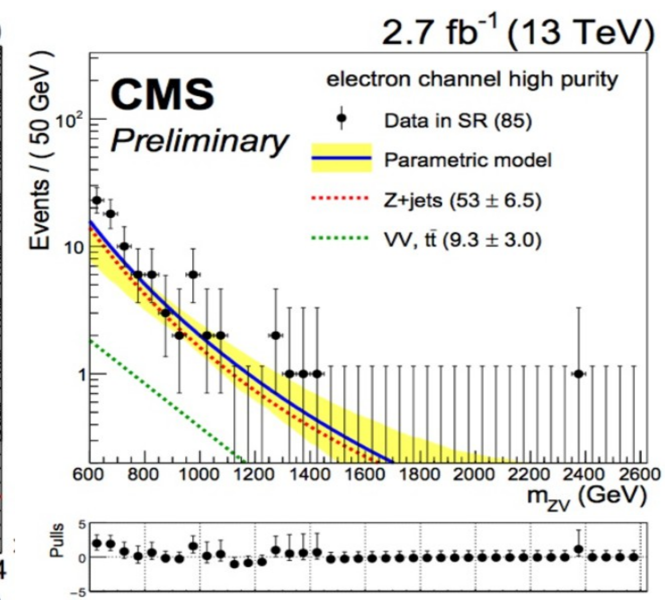






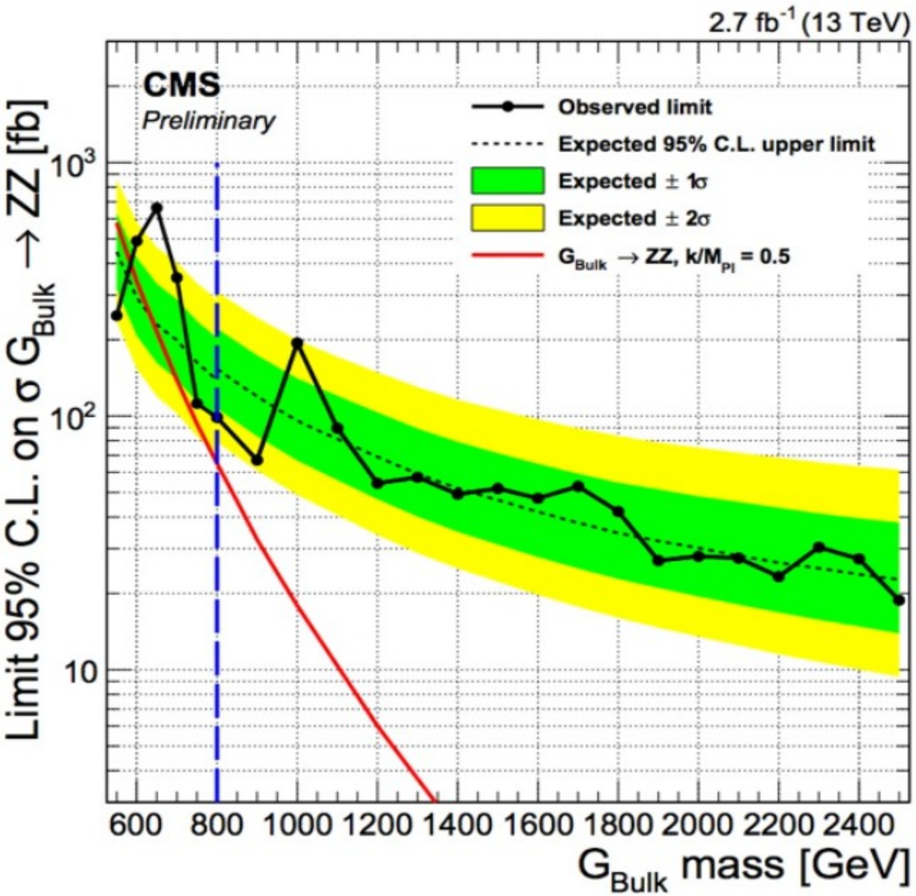


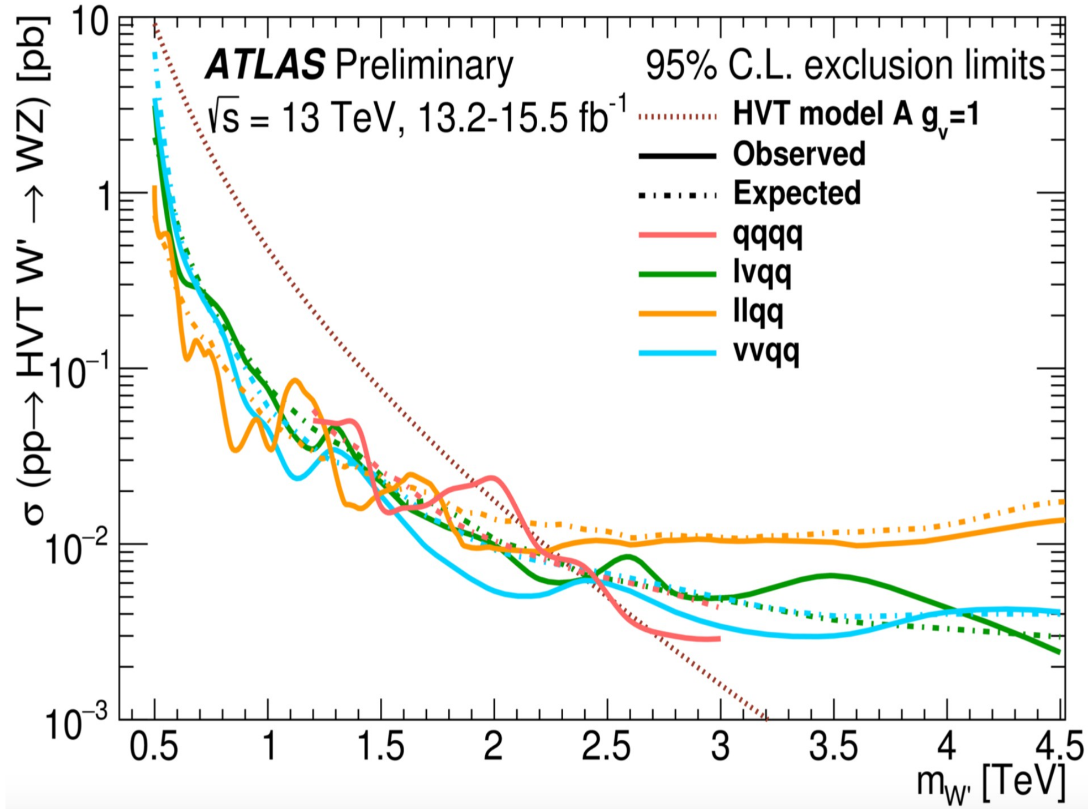




Dominated by statistical uncertainties at high masses. No significant deviation observed so far

VV resonances searches: A bit of perspective



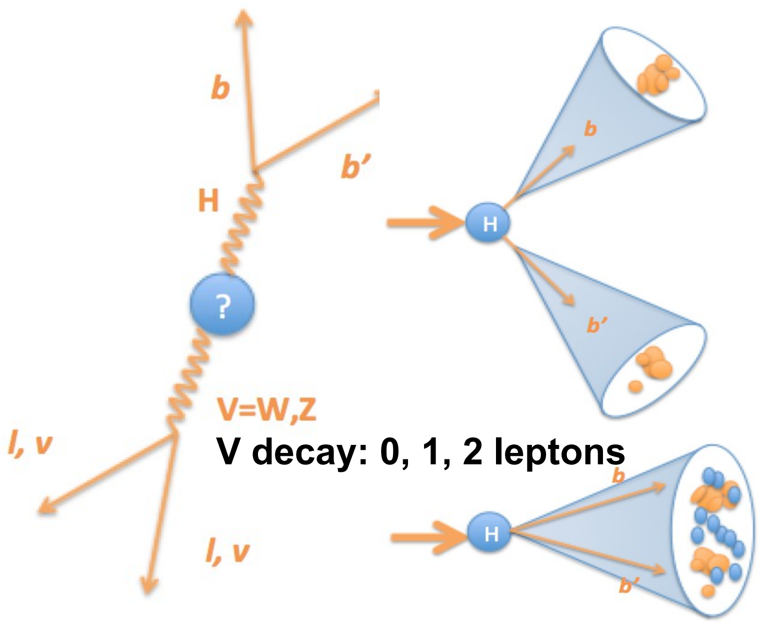


Most significant deviation in VV searches report by CMS at 650 GeV in the llqq channel

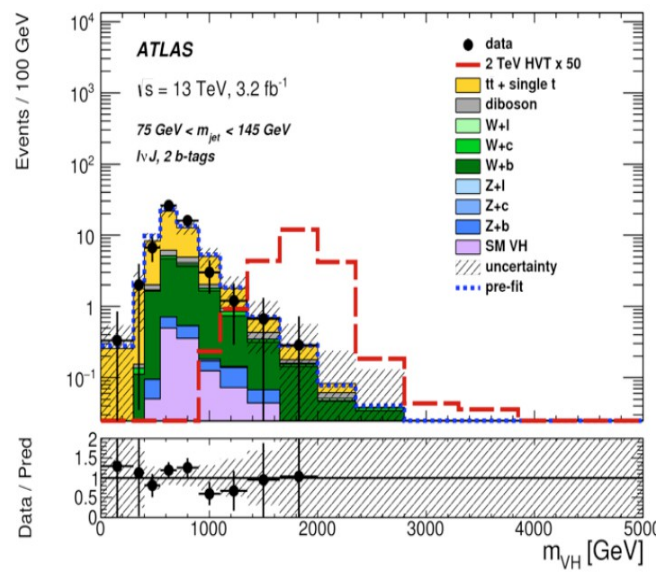
Here we can see which channel is more sensitive and where for the ATLAS searches

Current ATLAS Run-2 results highly disfavor the Run-1 2 TeV excess at its observed signal strength

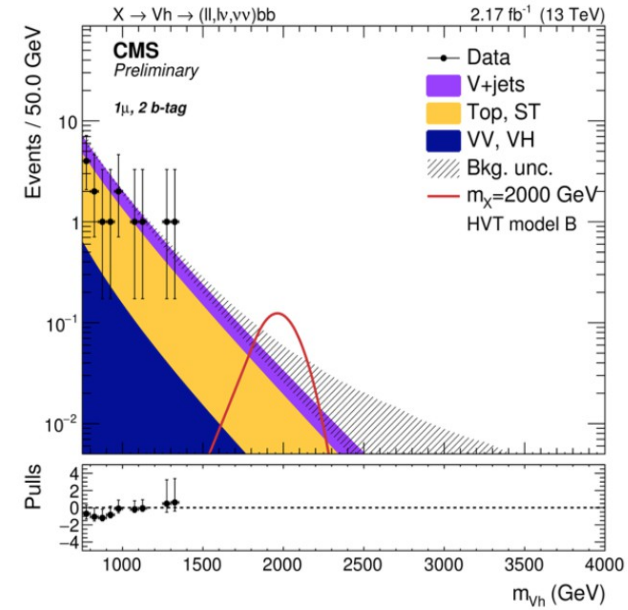
Search for VH, V→ ll/lν/νν and H→b$\bar{b}$



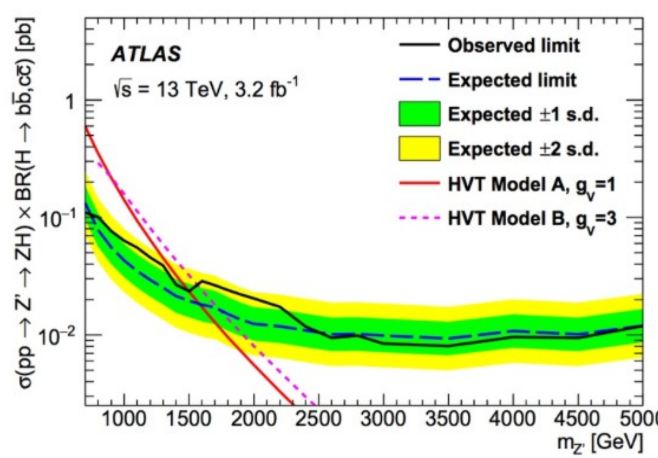
arXiv:1607.05621

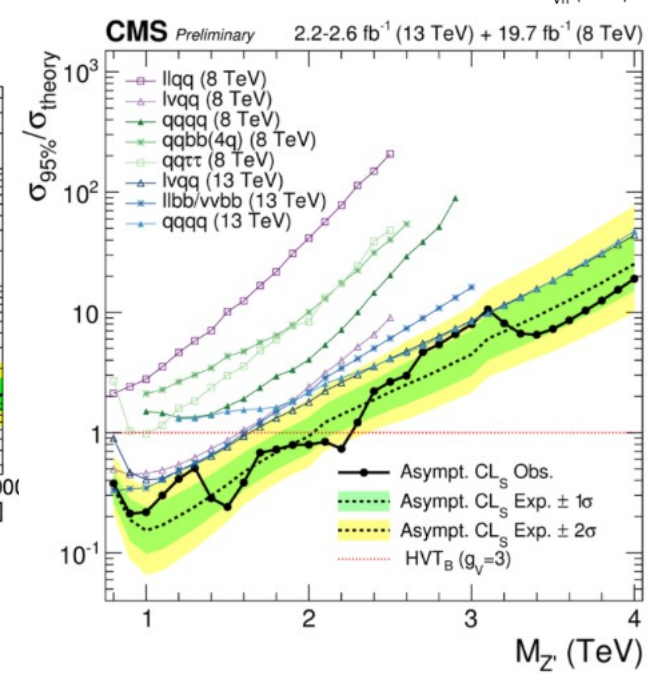


B2G-16-003
B2G-16-007

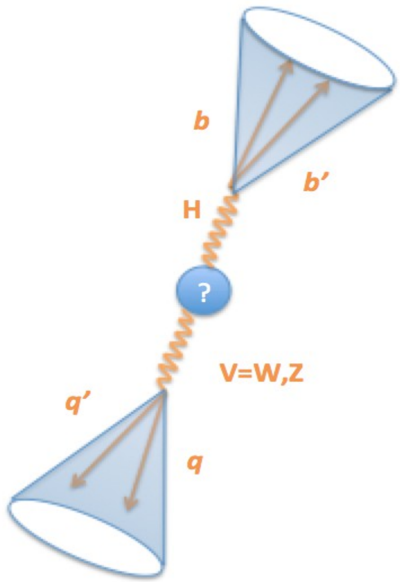


- Similar to VV searches except that we use Higgs tagging
- ATLAS results with 13 TeV 3.2/fb
- CMS results with 13 TeV 2.17-2.52/fb
- Final discriminant: invariant mass (1,2 leptons) and transverse mass m_T (0-lepton)
- No significant deviation found



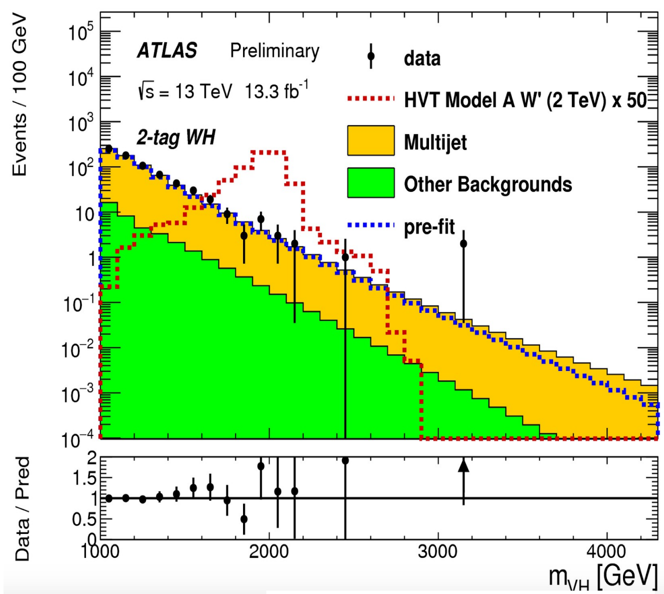


Search for VH, V→ qq and H→$b\bar{b}$

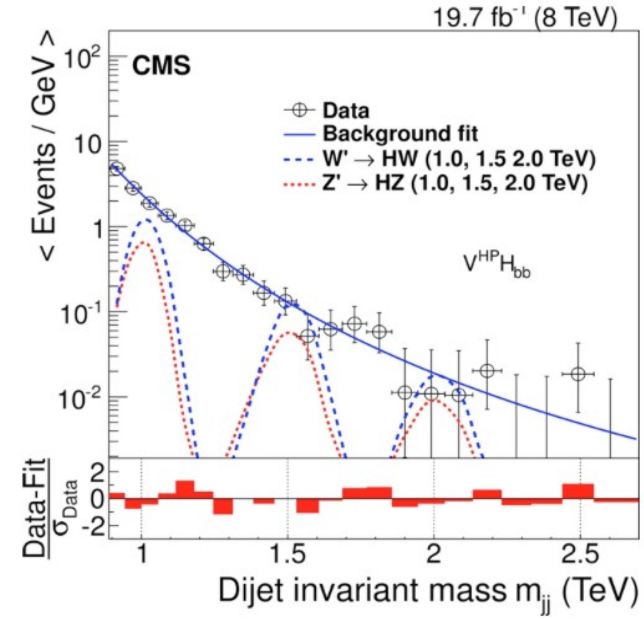


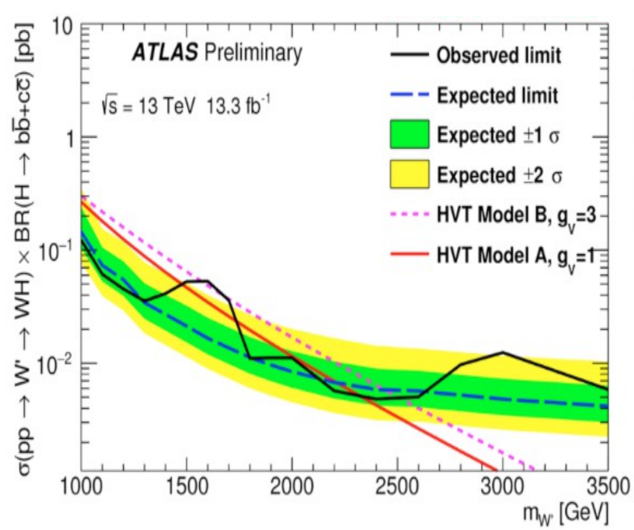
- Complementary to semi-leptonic VH searches at high masses
- Main backgrounds: multijet and $t\bar{t}$
- ATLAS results with 13 TeV 3.2/fb
- CMS results with 8 TeV
  - Combination of qqbb and VH → VWW → qqqqqq
- No significant deviation found
  - Largest deviation at 3 TeV reported by ATLAS (2.5σ global significance)

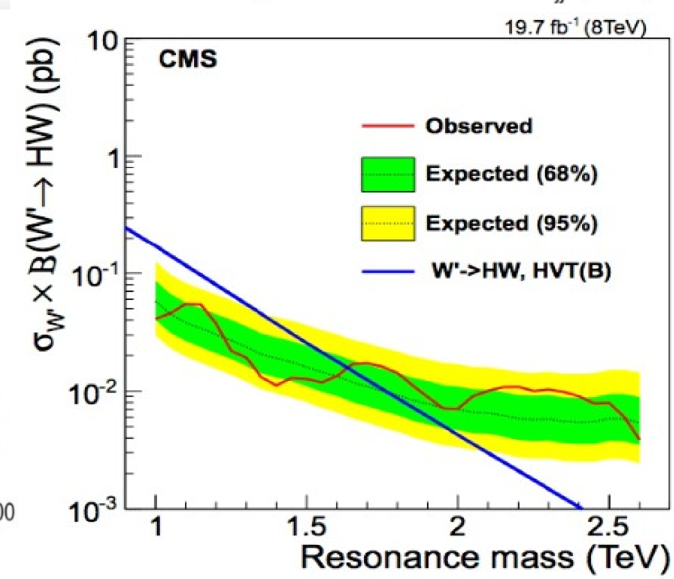
ATLAS-CONF-2016-083



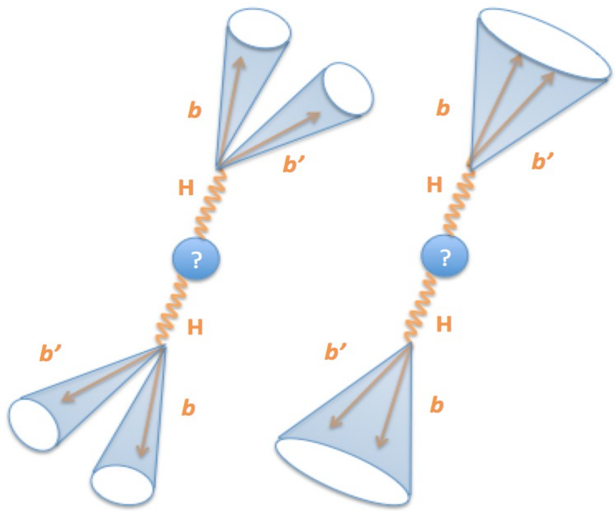
JHEP 02 (2016) 145



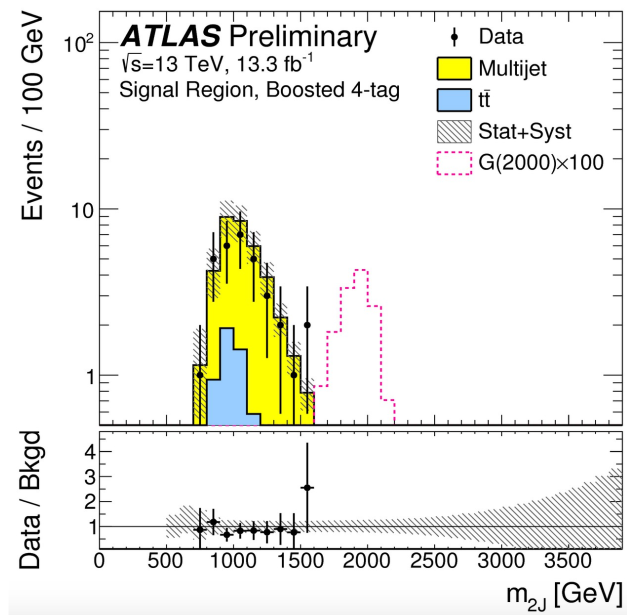




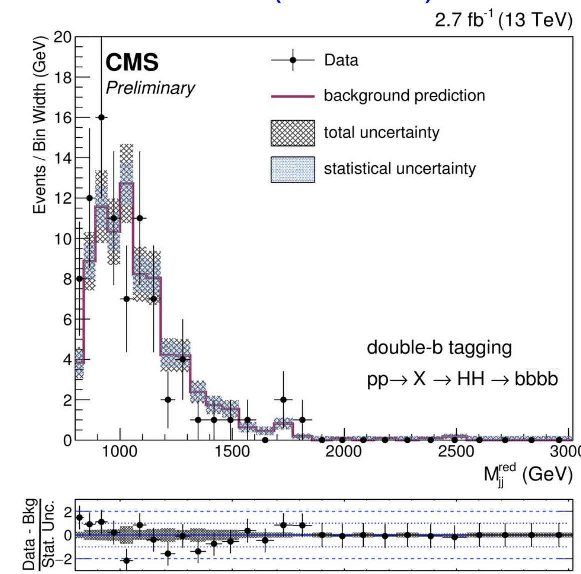
HH → bbbb



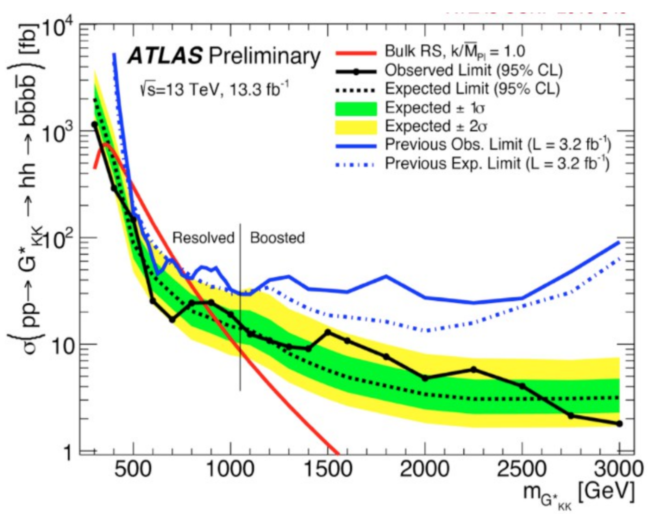
ATLAS-CONF-2016-049

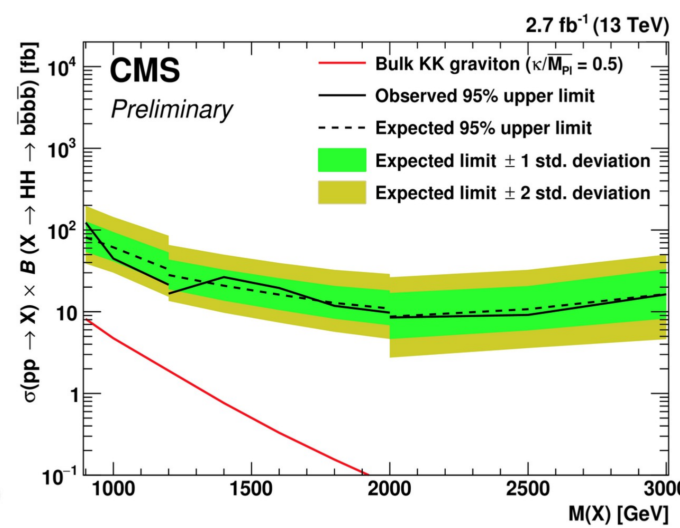


B2G-16-008 (boosted)
HIG-16-002 (resolved)



- Most sensitive HH final state across most of the search space
- Main backgrounds: multijet and $t\bar{t}$
- ATLAS results with 13 TeV 13.3/fb
- CMS results with 13 TeV 2.7/fb
- Resolved and boosted regimes studied
- No significant deviation found

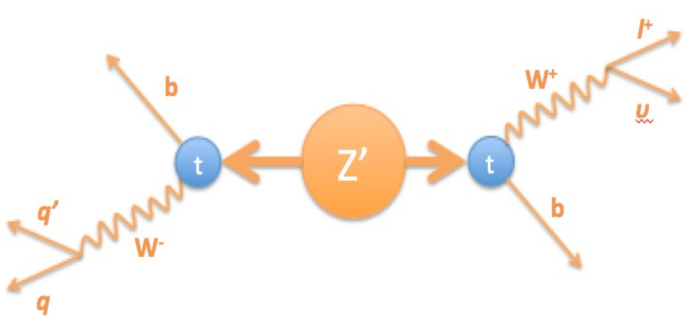


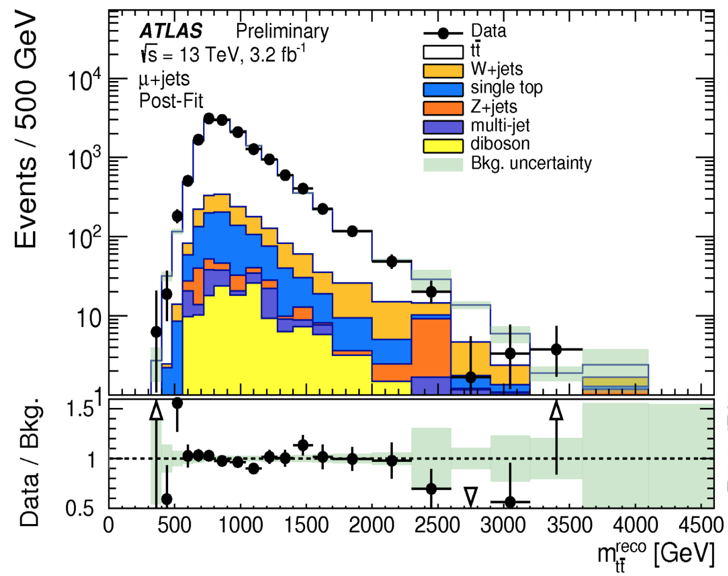


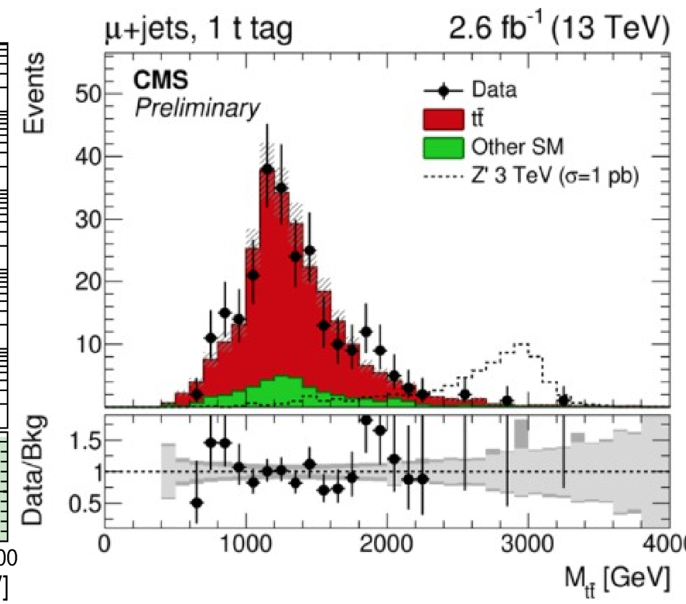
Boosted top-antitop resonances

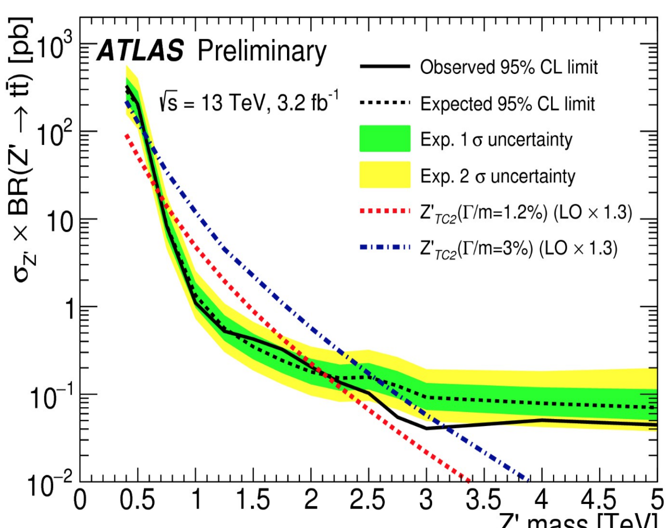
ATLAS-CONF-2016-014

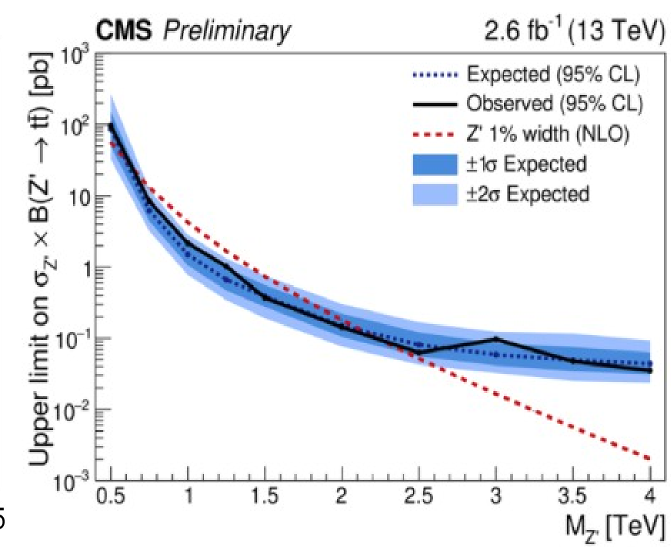
B2G-15-002











- Lepton+jets channel
- SM tt̄ is an irreducible background
- ATLAS results with 13 TeV 3.2/fb
- CMS results with 13 TeV 2.6/fb
- Resolved and boosted regimes
- No significant deviation found
- Cross section limits comparable but not the limits due to different models

Summarizing

- **LHC energy increase opened ways to explore the high p_T phase-space**

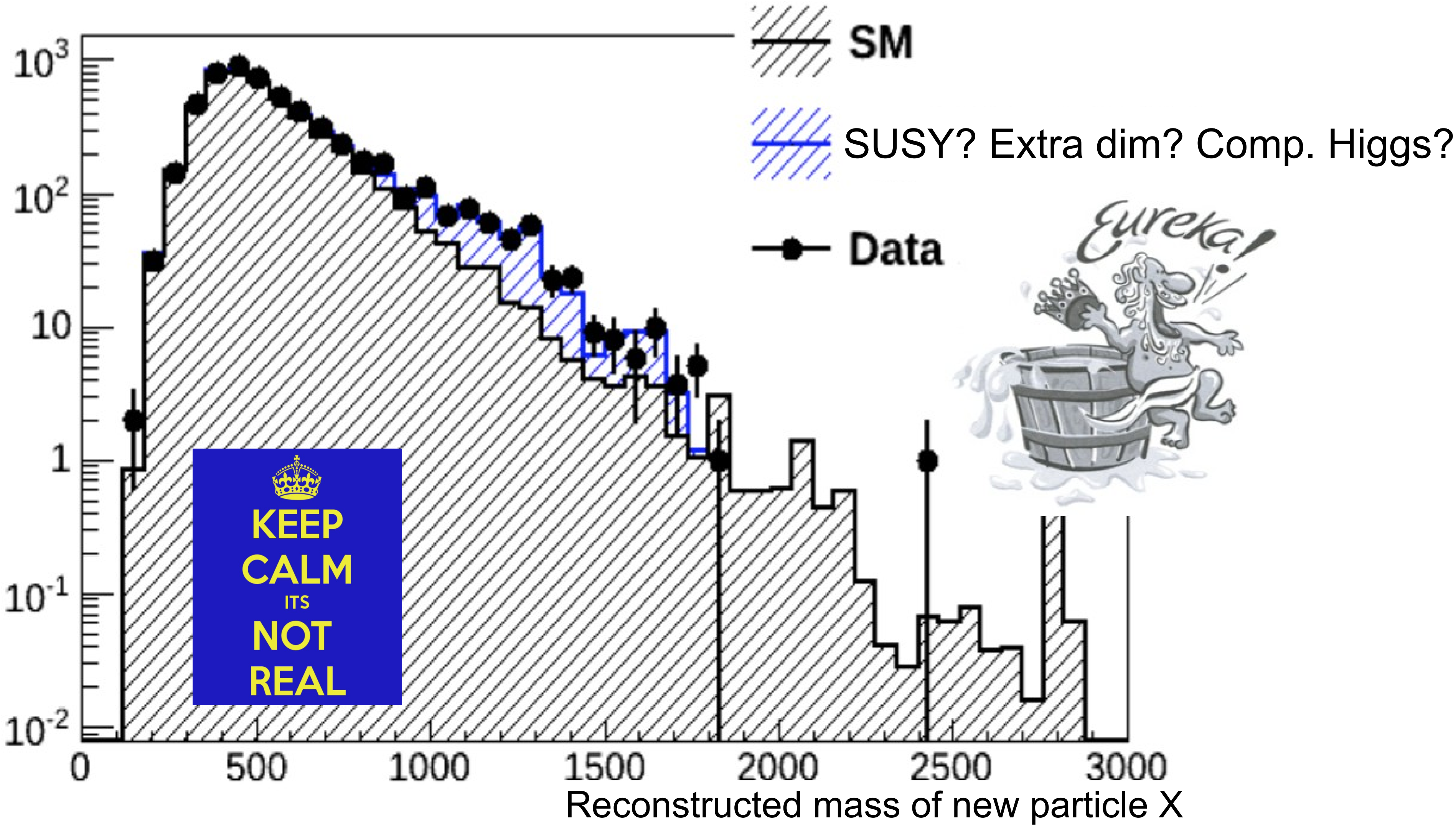
- Many Run-2 searches and measurements are now using these boosted techniques and many more are coming. **Wealth of physics encoded inside jets!**
  - A **very active field** in both collaborations
  - Important to build confidence in these tools through its use in more SM measurements
  - **Main challenges**: pile-up, detector granularity and simulation modeling

- **Exploring many boosted topologies looking for new physics**

- **No significant excess** observed so far but **lots of data is arriving now**!
  - Expecting > 30/fb by the end of the year
  - Data analyzed so far: a small fraction of total Run 2 (~100/fb)

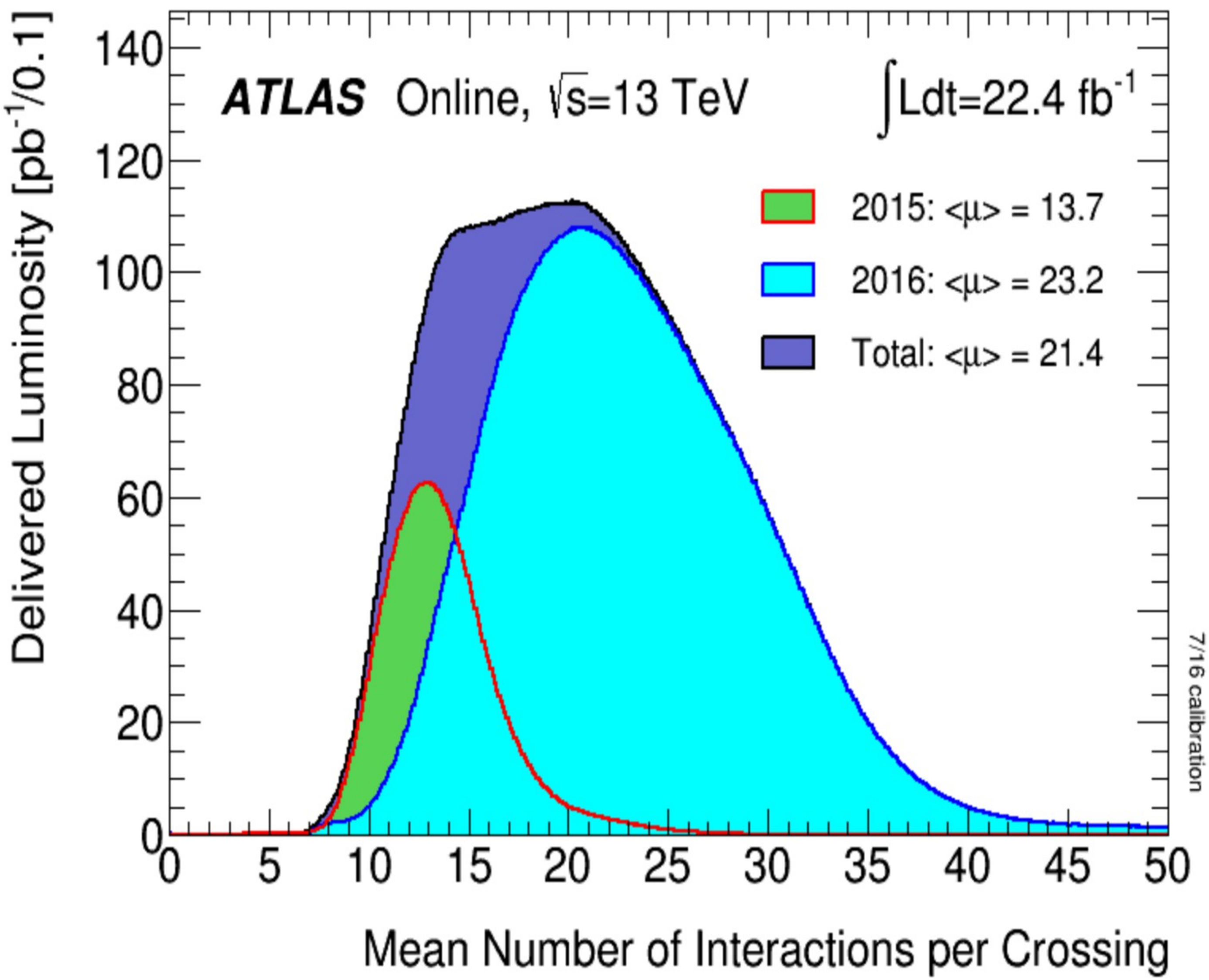
Thanks for your attention!

Will new physics appear in an analysis using boosted techniques?



BACKUP

Pile-up conditions



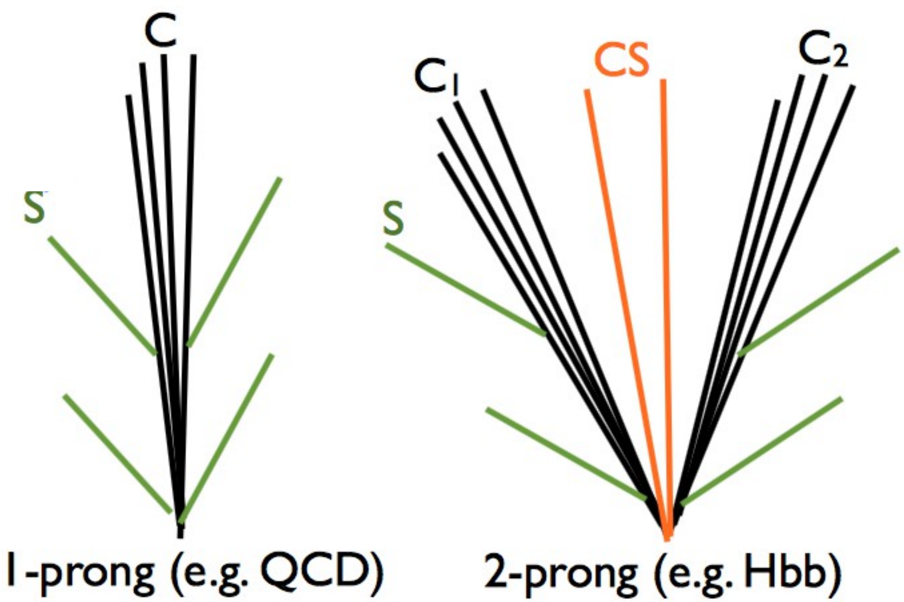
D_2 definition

$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \leq i < j \leq n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} ,$$

$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \leq i < j < k \leq n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta} ,$$

$$\boxed{D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}}$$

Larkoski et al,arXiV:1409.6298



Plots from R. Jacobs

D_2: large for 1-prong jet (e.g. QCD bkg.)

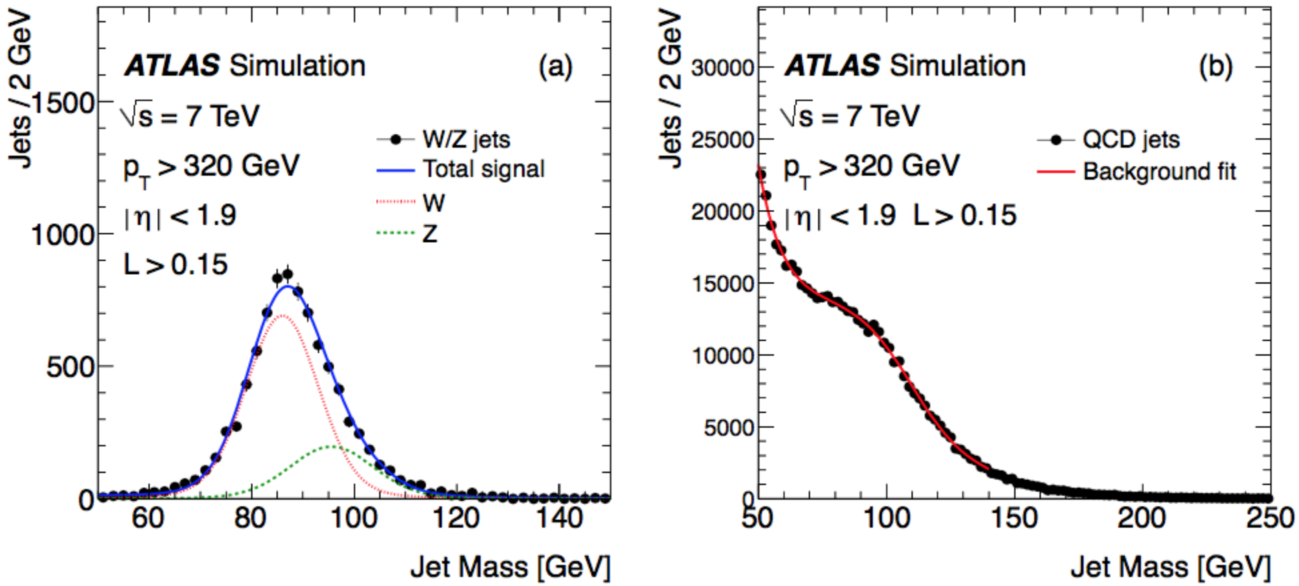
$$(e_2)^3 \lesssim e_3 \lesssim (e_2)^2$$

small for 2-prong jet (Higgs signal)

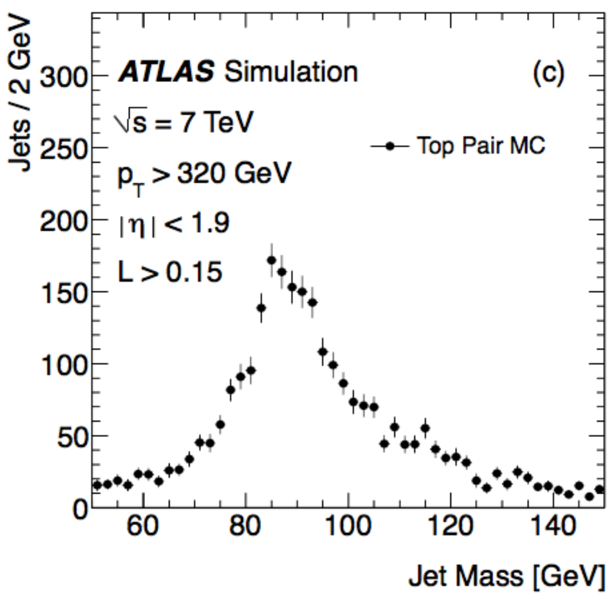
$$0 < e_3 \ll (e_2)^3$$

W+Z cross section measurement @7 TeV

arXiv: 1407.0800



- Using anti-k_T R=0.6 jets
- Likelihood discriminant using:
  - Thrust minor
  - Sphericity
  - Aplanarity
- Background from top-quark decays to W bosons are subtracted



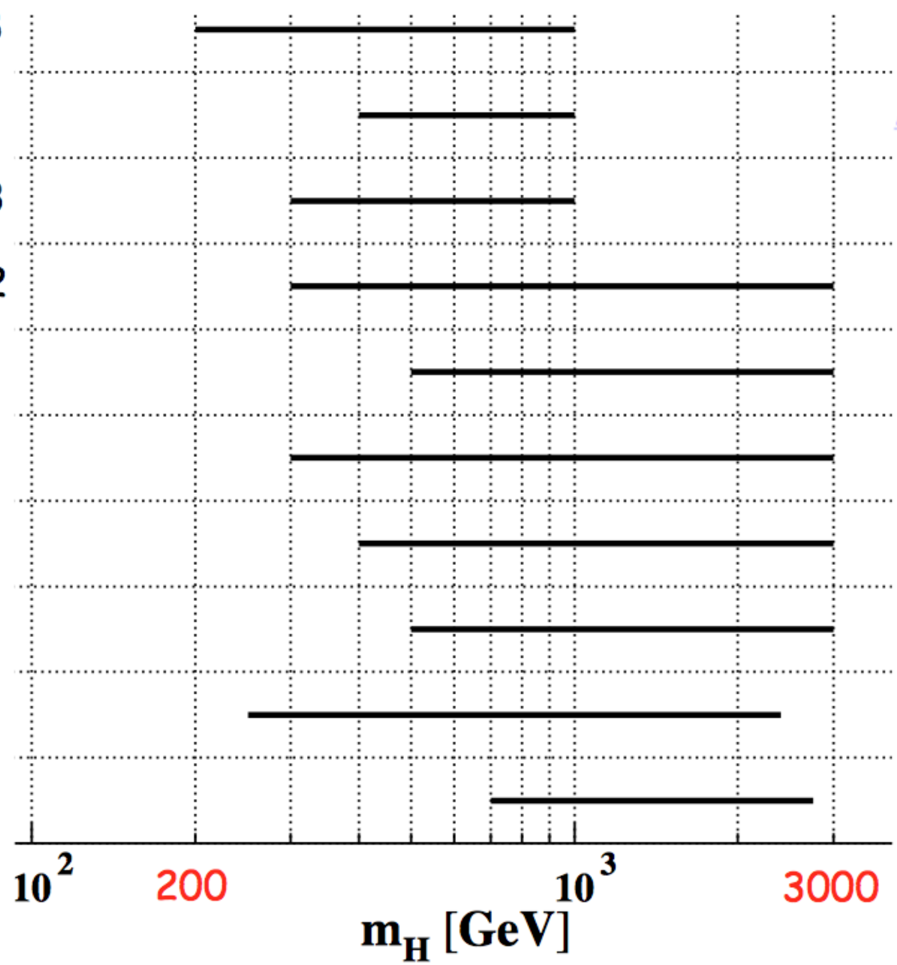
$$\sigma_{W+Z} = 8.5 \pm 0.8 \ \text{(stat.)} \pm 1.5 \ \text{(syst.)}\ \text{pb.}$$

Good agreement with NLO QCD theoretical prediction within 2σ

Overview of diboson modes & mass ranges

Channel	Lumi (fb^{-1})	Ref
ZZ→4l NWA	14.8	ATLAS-CONF-2016-079
LWA	14.8	ATLAS-CONF-2016-079
ZZ→llνν NWA	13.3	ATLAS-CONF-2016-056
ZZ→llqq NWA	13.2	ATLAS-CONF-2016-082
ZZ→ννqq NWA	13.2	ATLAS-CONF-2016-082
WW→lνlν NWA	13.2	ATLAS-CONF-2016-074
LWA	13.2	ATLAS-CONF-2016-074
WW→lνqq NWA	13.2	ATLAS-CONF-2016-062
Zγ→llγ NWA	13.3	ATLAS-CONF-2016-044
Zγ→qqγ NWA	3.2	arXiv:1607.06363

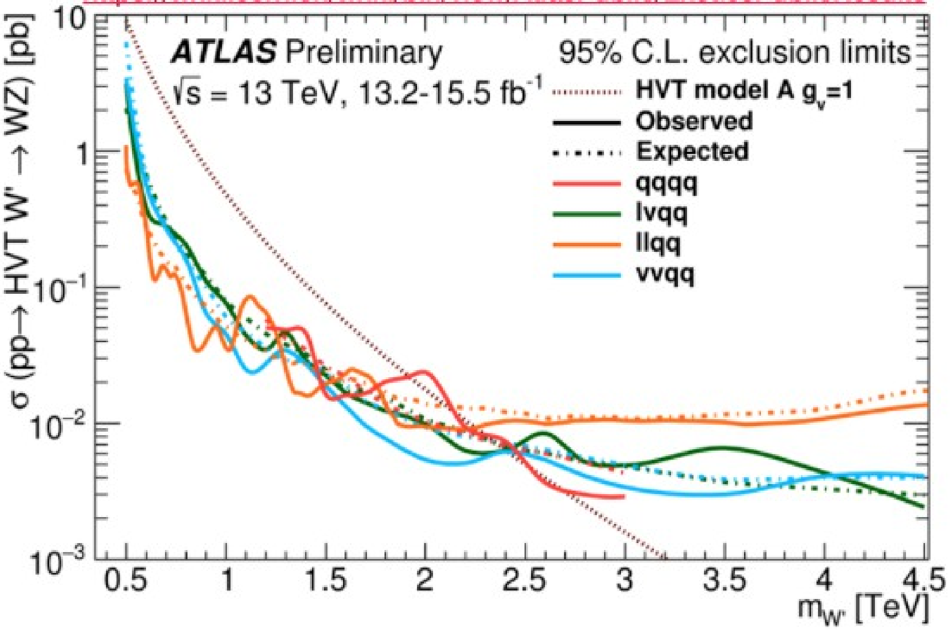
Mass range



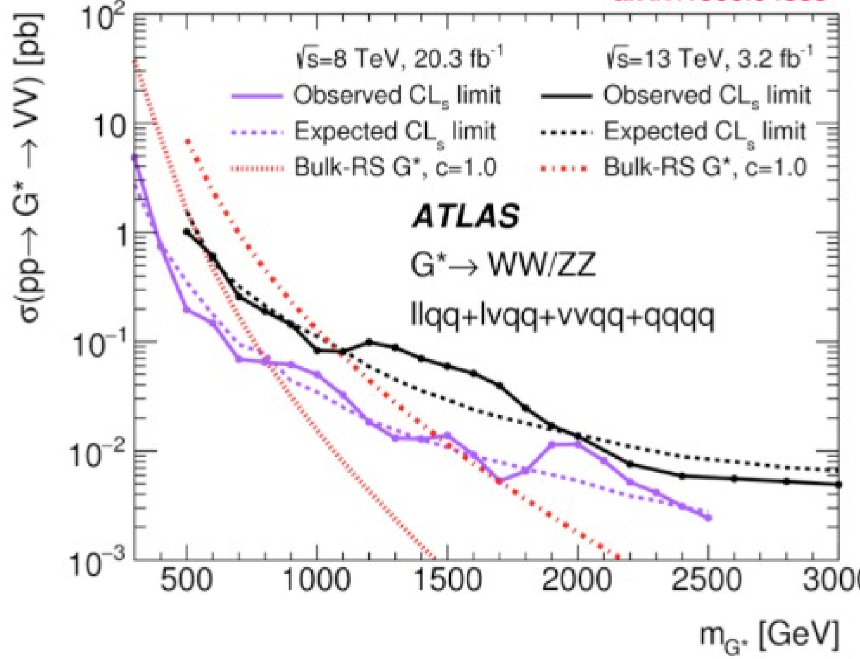
Courtesy of Z. Zhang

Summary of latest VV searches

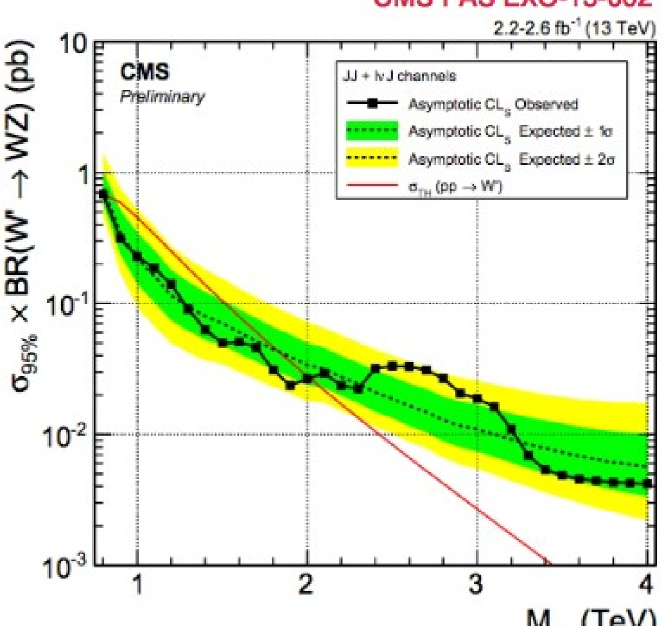
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults



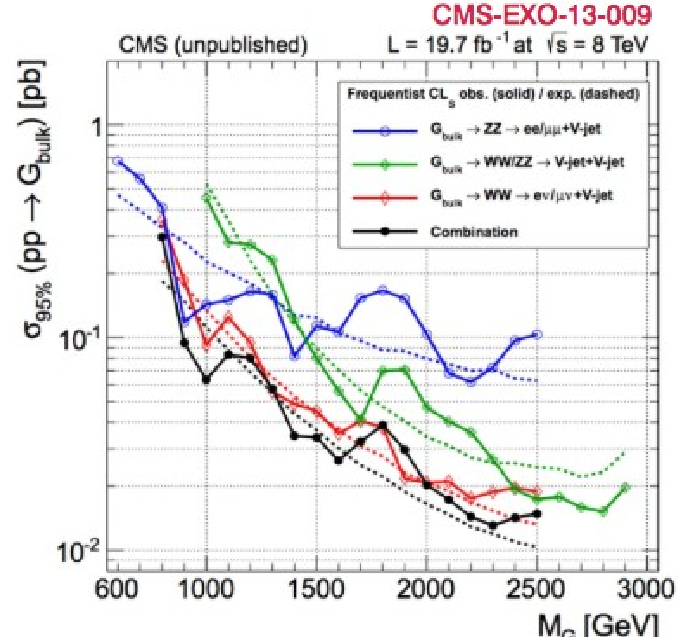
arXiv:1606.04833



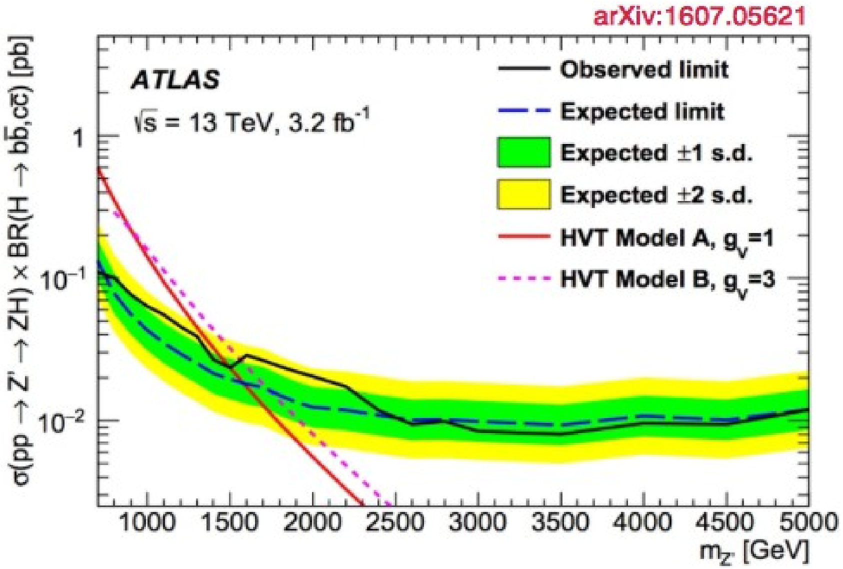
CMS PAS EXO-15-002

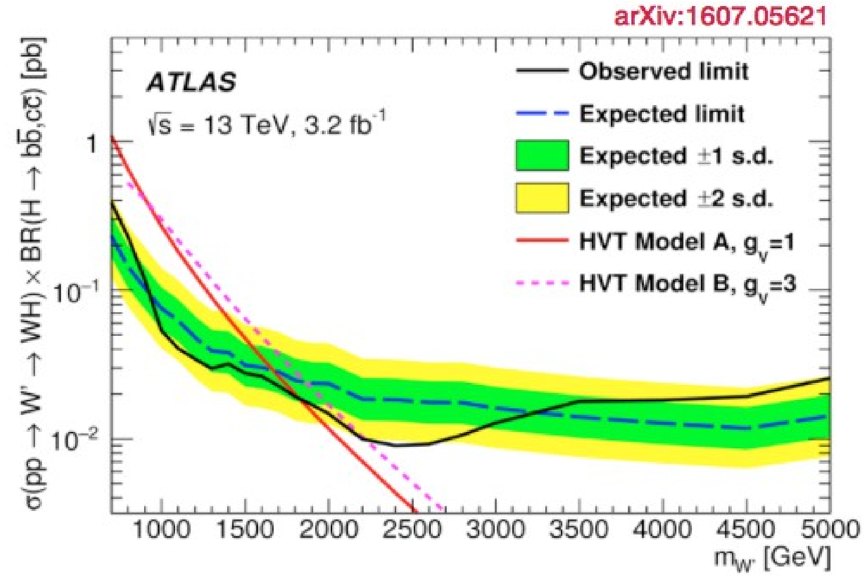


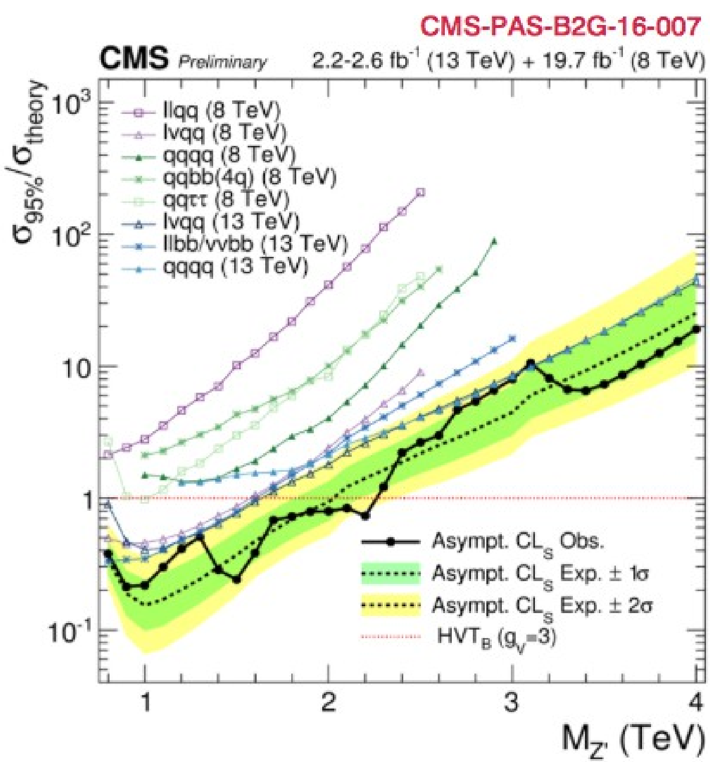
CMS-EXO-13-009

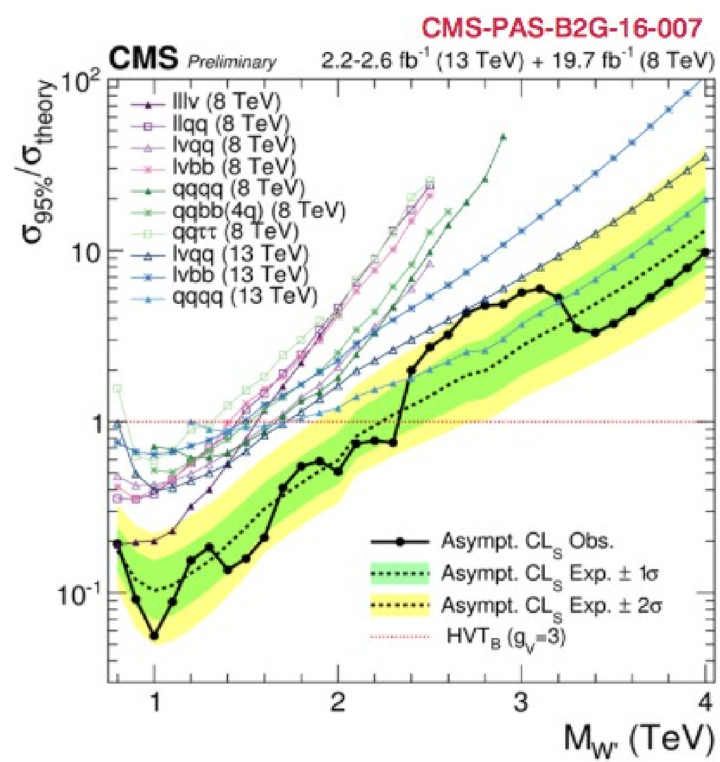


Summary of latest VH searches









Dark matter: complementarity of searches

Imperial College London

Complementarity of searches

	Interaction			
EWK style	Vector	low mass	high mass	
EWK style	Axial-Vector	low mass	high mass	
mass based	Scalar	low mass	high mass	
mass based	Pseudo-Scalar	low mass		large range

- Different types of DM searches probe different parameter space
- An eventual discovery has to be confirmed in more than one experiment and only a combination can truly identify and measure DM