

# Constraints On New Theories with Precision Measurement

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# Introduction - What do we measure at the LHC?

- **Results** - What is the goal of the experimental programs at the LHC
  - Measure known phenomena as accurately as possible.
  - Search for something new!
- **Information**
  - What do we provide
  - What do people want
  - Will anyone actually use additional information
- **Tools**
  - Where/How do we best interface to theory

# Results - Searching for the unknown

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	$\ell, \gamma$	Jets†	$E_{miss}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/g$	$0, e, \mu$	1-4 J	Yes	$M_{KK}$ 7.75 TeV	$n=2$ ATLAS-CONF-2017-090
	ADD non-resonant $\gamma\gamma$	2 $\gamma$	-	-	$M_{KK}$ 8.6 TeV	$n=3$ HLZ NLO CERN-EP-2017-132
	ADD GBH	-	2 J	-	37.0	$n=6$ 1703.09217
	ADD BH High $\Sigma P_T$	$\geq 1, e, \mu$	$\geq 2 J$	-	3.2	$n=6, M_{D_2} = 3 \text{ TeV}$ cut BH 1606.02055
	ADD BH multiple	-	$\geq 3 J$	-	3.6	$n=6, M_{D_2} = 3 \text{ TeV}$ cut BH 1512.02656
	RS1 $G_{KK} - \gamma\gamma$	2 $\gamma$	-	-	36.7	$n=7, m_1 = 0.1$ CERN-EP-2017-132
Gauge bosons	Bulk RS $G_{KK} - WW \rightarrow \text{qq}^{\nu}$	1 $e, \mu$	1 J	Yes	36.1	$k/\Lambda_{UV} = 1.0$ ATLAS-CONF-2017-051
	2UED / RPP	1 $e, \mu$	$\geq 2, b, \geq 3 J$	Yes	13.2	ATLAS-CONF-2016-104
	SSM $Z' \rightarrow \ell\ell$	2 $e, \mu$	-	-	36.1	$\text{Tier}(1,1), \text{St}(A)^{1/2} - \text{st} = 1$ ATLAS-CONF-2017-027
Cl	SSM $Z' \rightarrow \tau\tau$	2 $\tau$	-	-	36.1	ATLAS-CONF-2017-050
	Leptophobic $Z' \rightarrow bb$	-	2 b	-	3.2	1603.08791
	Leptophobic $Z' \rightarrow \tau\tau$	1 $e, \mu$	$\geq 1, b, \geq 1, 2 J$	Yes	3.2	$f/m = 3\%$ ATLAS-CONF-2016-014
	SSM $W' \rightarrow \ell\nu$	1 $e, \mu$	-	Yes	36.1	1706.04786
	HVT $V' \rightarrow WW \rightarrow \text{qqqq}$ model B	0 $e, \mu$	2 J	-	36.7	$d_V = 3$ CERN-EP-2017-147
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$d_V = 3$ ATLAS-CONF-2017-055
DM	LRSM $W_2' \rightarrow \tau b$	1 $e, \mu$	2 b, 0-1 J	Yes	20.3	1410.4103
	LRSM $W_2' \rightarrow \tau b$	0 $e, \mu$	$\geq 1, b, 1 J$	-	20.3	1408.0886
CI	CI $\ell\ell\text{qq}$	-	2 J	-	37.0	1703.09217
	CI $\ell\ell\text{qq}$	2 $e, \mu$	-	-	36.1	ATLAS-CONF-2017-027
DM	CI $u\text{ttt}$	2(SB)/2(S $e, \mu$ )	$\geq 1, b, \geq 1 J$	Yes	20.3	1504.04605
	Axial-vector mediator (Dirac DM)	0 $e, \mu$	1-4 J	-	36.1	$d_V = 0.25, d_A = 1.0, m(\chi) < 400 \text{ GeV}$ ATLAS-CONF-2017-090
	Vector mediator (Dirac DM)	0 $e, \mu, 1 \gamma$	$\leq 1 J$	-	36.1	$d_V = 0.25, d_A = 1.0, m(\chi) < 480 \text{ GeV}$ 1704.03848
LO	$VV_{1/2}$ EFT (Dirac DM)	0 $e, \mu$	1 J, $\leq 1 J$	-	3.2	$m(\chi) < 150 \text{ GeV}$ 1606.02072
	Scalar LQ 1 <sup>st</sup> gen	2 $e$	$\geq 2 J$	-	3.2	$\beta = 1$ 1605.09035
	Scalar LQ 2 <sup>nd</sup> gen	2 $\mu$	$\geq 2 J$	-	3.2	$\beta = 1$ 1605.09035
Heavy quarks	Scalar LQ 3 <sup>rd</sup> gen	1 $e, \mu$	$\geq 1, b, \geq 3 J$	Yes	20.3	$\beta = 0$ 1506.04735
	VLQ TT $\rightarrow Hb + X$	0 or 1 $e, \mu$	$\geq 2, b, \geq 3 J$	Yes	13.2	$\text{St}(T \rightarrow Hb) = 1$ ATLAS-CONF-2016-104
	VLQ TT $\rightarrow Zb + X$	1 $e, \mu$	$\geq 1, b, \geq 3 J$	Yes	36.1	$\text{St}(T \rightarrow Zb) = 1$ 1705.10751
	VLQ TT $\rightarrow Wb + X$	1 $e, \mu$	$\geq 1, b, \geq 1, 2 J$	Yes	36.1	$\text{St}(T \rightarrow Wb) = 1$ CERN-EP-2017-094
	VLQ BB $\rightarrow Hb + X$	1 $e, \mu$	$\geq 2, b, \geq 3 J$	Yes	20.3	$\text{St}(B \rightarrow Hb) = 1$ 1505.04306
	VLQ BB $\rightarrow Zb + X$	2(SB) $e, \mu$	$\geq 2, b$	-	20.3	$\text{St}(B \rightarrow Zb) = 1$ 1409.3550
Excited fermions	VLQ BB $\rightarrow Wb + X$	1 $e, \mu$	$\geq 1, b, \geq 1, 2 J$	Yes	36.1	$\text{St}(B \rightarrow Wb) = 1$ CERN-EP-2017-094
	VLQ QQ $\rightarrow WqWq$	1 $e, \mu$	$\geq 4 J$	Yes	20.3	1509.04261
	Excited quark $q^* \rightarrow q\gamma$	-	2 J	-	37.0	only $u^*$ and $d^*, A = m(q^*)$ 1703.09127
	Excited quark $q^* \rightarrow q\gamma$	1 $\gamma$	1 J	-	36.7	only $u^*$ and $d^*, A = m(q^*)$ CERN-EP-2017-148
	Excited quark $b^* \rightarrow b\gamma$	1 b, 1 J	-	-	13.3	ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow W\tau$	1 or 2 $e, \mu$	1 b, 2-0 J	Yes	20.3	$f_b = f_s = f_c = 1$ 1510.02064
Other	Excited lepton $\ell^*$	3 $e, \mu, \tau$	-	-	20.3	$A = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton $\nu^*$	3 $e, \mu, \tau$	-	-	20.3	$A = 1.6 \text{ TeV}$ 1411.2921
	LRSM Majorana $\nu$	2 $e, \mu$	2 J	-	20.3	$m(W_2) = 2.4 \text{ TeV}$ , no mixing 1506.09020
	Higgs triplet $H^{**} \rightarrow \ell\ell$	2, 3, 4 $e, \mu$ (SB)	-	-	36.1	DV production ATLAS-CONF-2017-053
	Higgs triplet $H^{**} \rightarrow \ell\tau$	3 $e, \mu, \tau$	-	-	20.3	DV production, $\text{St}(H^{**} \rightarrow \ell\tau) = 1$ 1411.2921
	Monopole (non-res prod)	1 $e, \mu$	1 b	Yes	20.3	$d_{\text{min}} = 0.2$ 1410.3404
Multi-charged particles	-	-	-	20.3	DV production, $ q  = 5e$ 1504.04188	
Magnetic monopoles	-	-	-	7.0	DV production, $ q  = 1/2e, \text{spin } 1/2$ 1509.09059	

\*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).

- A huge array of analyses at ATLAS and CMS searching for new physics ([L] ATLAS exotics summary)
- A huge array of no observed excesses, can only constrain models
- How do we use this to comment on arbitrary new physics models not originally considered?
- What information do we provide to interpret these results?

# Results - Searching for the unknown

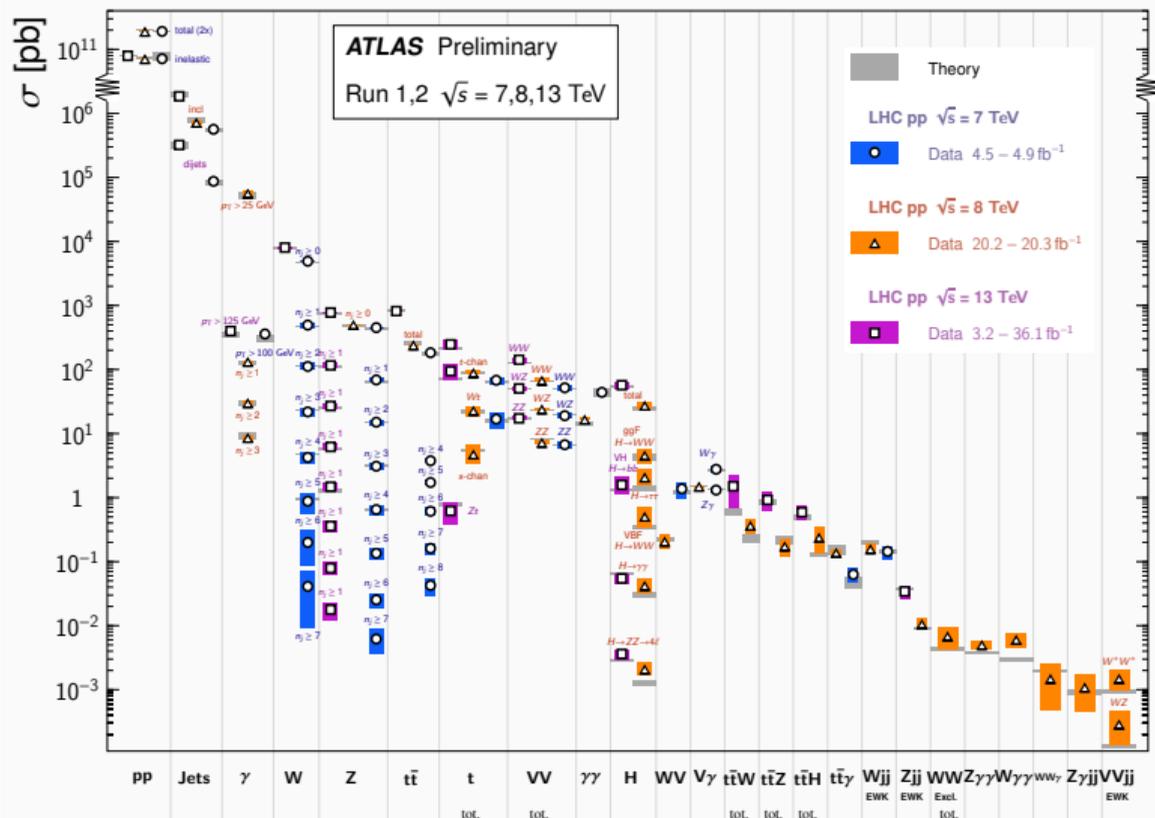
	Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	1-4 j	Yes	36.1	$M_D$
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$
	ADD QBH	-	2 j	-	37.0	$M_{\text{th}}$
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	36.7	$G_{KK}$ mass
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 e, \mu$	1 J	Yes	36.1	$G_{KK}$ mass
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	13.2	KK mass	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	36.1	$Z'$ mass
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z'$ mass
	Leptophobic $Z' \rightarrow bb$	-	2 b	-	3.2	$Z'$ mass
	Leptophobic $Z' \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	3.2	$Z'$ mass
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	36.1	$W'$ mass
	HVT $V' \rightarrow WV \rightarrow qq\bar{q}q$ model B	$0 e, \mu$	2 J	-	36.7	$V'$ mass
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V'$ mass
	LRSM $W'_R \rightarrow tb$	$1 e, \mu$	2 b, 0-1 j	Yes	20.3	$W'$ mass
LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	-	20.3	$W'$ mass	
CI	CI $qq\bar{q}q$	-	2 j	-	37.0	$\Lambda$
	CI $\ell\ell\bar{q}q$	$2 e, \mu$	-	-	36.1	$\Lambda$
	CI $uutt$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	20.3	$\Lambda$
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	1-4 j	Yes	36.1	$m_{\text{med}}$
	Vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	$\leq 1 j$	Yes	36.1	$m_{\text{med}}$
	$VV\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	1 J, $\leq 1 j$	Yes	3.2	$M_*$

- A huge array of analyses at ATLAS and CMS searching for **new physics** ([L] ATLAS exotics summary)
- A huge array of **no observed excesses**, can only **constrain** models
- How do we use this to comment on arbitrary new physics models **not originally considered**?
- What information do we provide to **interpret** these results?

# Results - Measuring the known

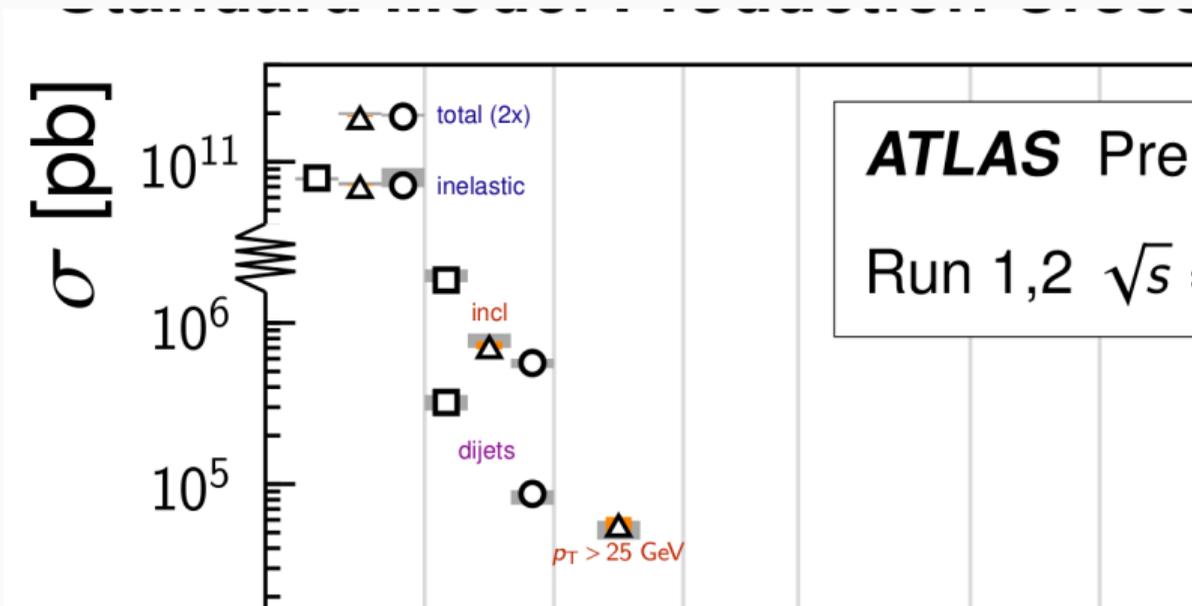
## Standard Model Production Cross Section Measurements

Status: March 2018



- An equally large array of unfolded **particle level** measurements
- This information can also be used to **constrain** new physics (important distinction: can't search here!)
- How do we go about this?

## Results - Measuring the known



- An equally large array of unfolded **particle level** measurements
- This information can also be used to **constrain** new physics (important distinction: can't search here!)
- How do we go about this?

HUGE development of tools for automated calculations of LHC physics, success depends on the toolchain!



## THE MODELS

- **Feynrules**, de facto language to describe new physics Lagrangians
- **Herwig7** (MG,Sherpa etc.) Generate full LHC simulations of these events

## THE DATA

- **Rivet(+HepData)**, plugin directly on generator output to replicate analysis definition
- Experimentally validated plugins, no question of ambiguity on acceptance

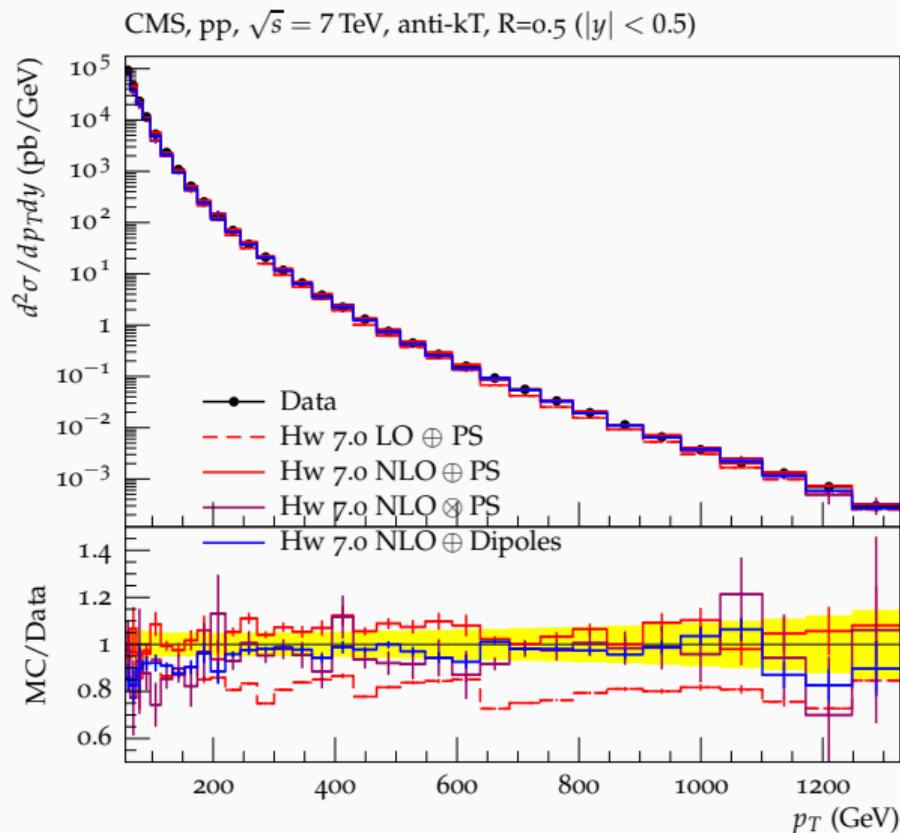


Logo pending...

## THE LIMITS

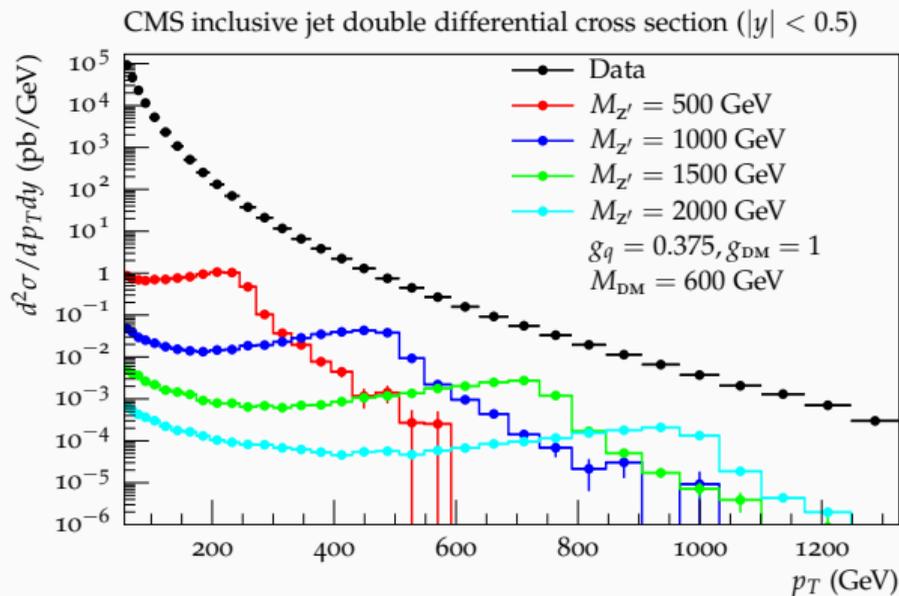
- **Contur**, Analysis framework plugin directly to Rivet output. Analyse deviations from data

# Contur - A Jetty Example



- Zoom in on one of those SM summary measurements, Inclusive Jets @ 7TeV CMS, [1406.0324](#)
- Rivet plugin used to replicate experimental definition for generator studies, here validation provided by Herwig authors, [Validation summary](#)
- We have a good understanding of the SM here
- We have a fast flexible way of reproducing the theory here

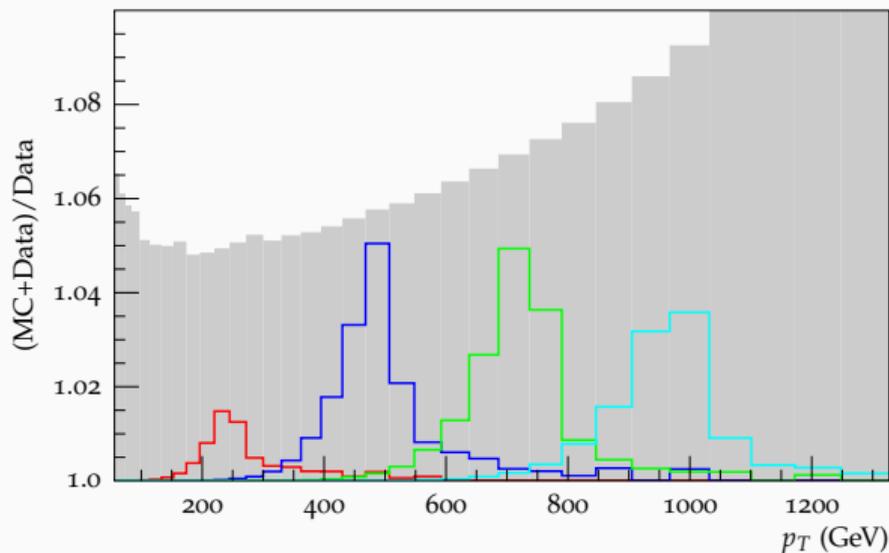
# Contur - A Jetty Example Back to data



BSM vs data cross section comparison for 1D parameter scan

- Again, Inclusive Jets @ 7TeV CMS, [1406.0324](#)
- This time apply analysis definition to BSM model, scan in 1 parameter dimension,  $M_{Z'}$
- BSM produces shapes with distinguishable kinematics, lead jet  $p_T \approx M_{Z'}/2$
- Stack reveals bump hunting idea

## Contur - A Jetty Example Back to data

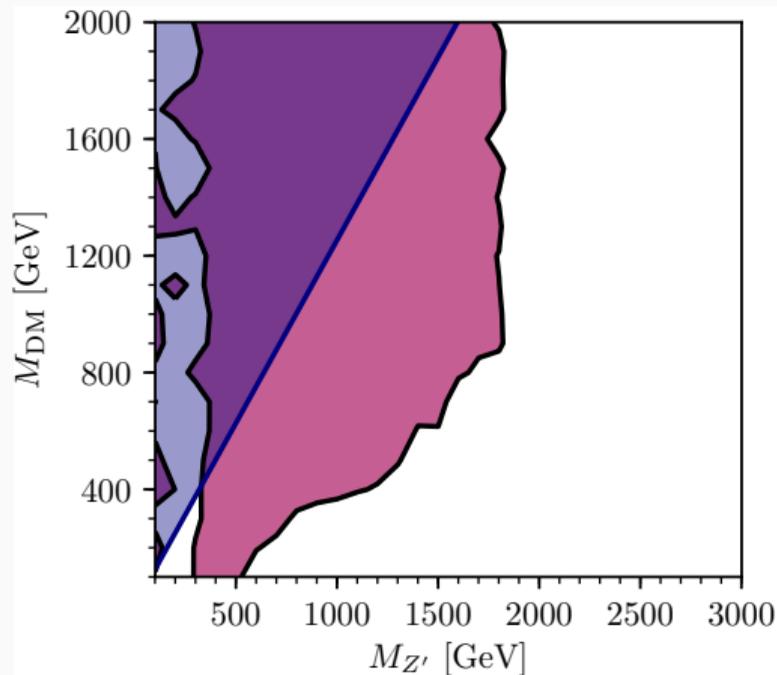


(BSM + data)/data cross section comparison for 1D parameter scan

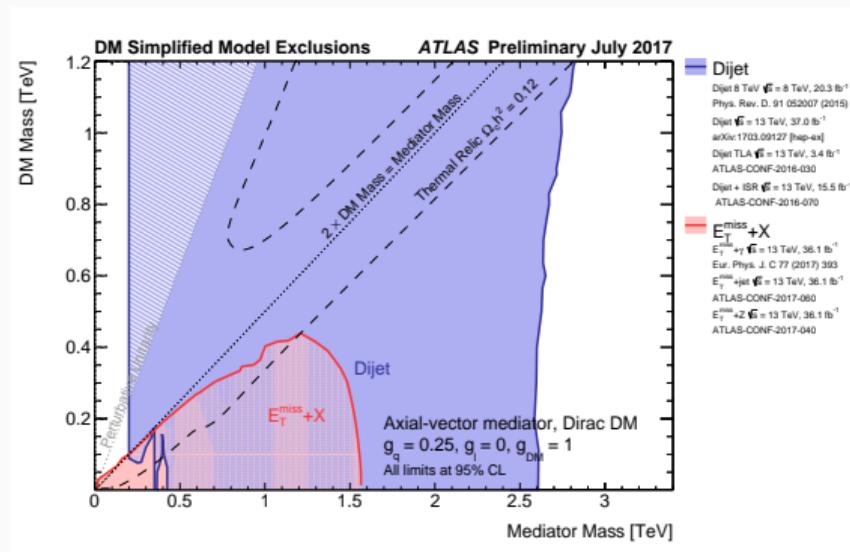
- Again, Inclusive Jets @ 7TeV CMS, [1406.0324](#)
- This time apply analysis definition to BSM model, scan in 1 parameter dimension,  $M_{Z'}$
- BSM produces shapes with distinguishable kinematics, lead jet  $p_T \approx M_{Z'}/2$
- Stack reveals bump hunting idea

# Contur - A Jetty Example

One of the simplest SM extensions, often discussed for the context of Dark Matter searches, [LHCDCMWG - 1603.04156](#)



95% CL contour (pink), for a simplified dark matter model.  
Theoretical bound from perturbative unitarity (blue)



The procedure gives comparable results to the official searches, differences are understood

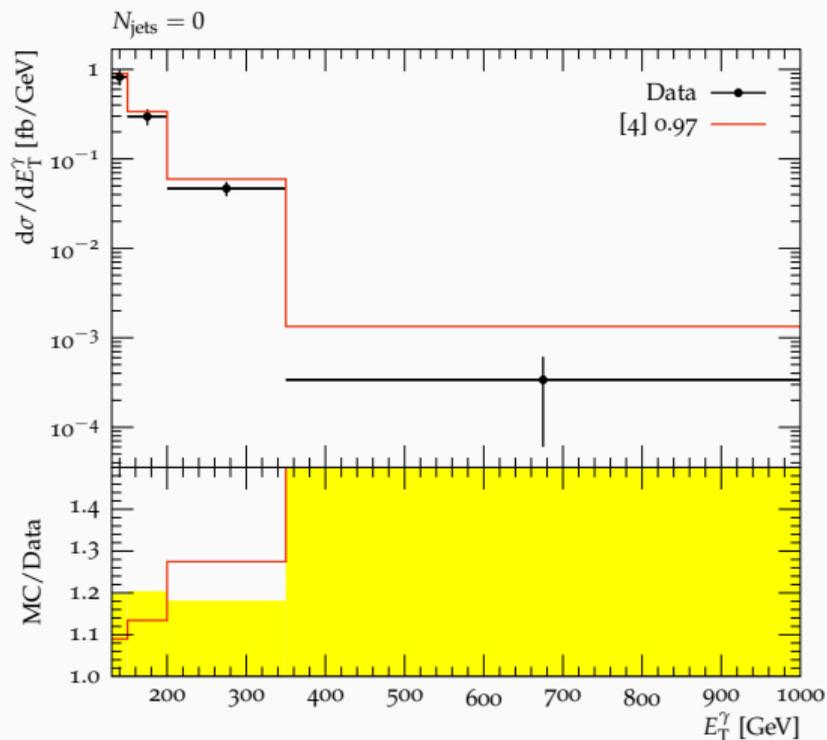
## **Contur - A recent example analysis**

A different model, Light Scalars at the LHC [1607.08653](#), contributions made to Les Houches proceedings (pending).

**Example:** CP-Even scalar has gauge sector interactions specified by the following Lagrangian:

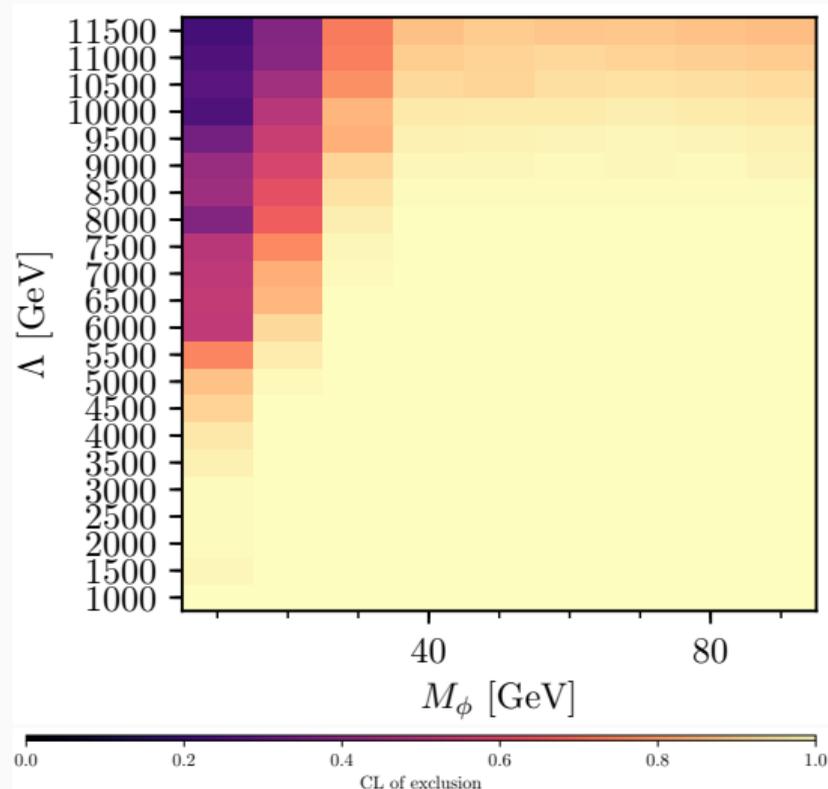
$$\mathcal{L}_{\text{eff}} \supset \phi \left( \frac{1}{\Lambda} G^{\mu\nu a} G_{\mu\nu}^a + \frac{1}{\Lambda} W^{\mu\nu I} W_{\mu\nu}^I + \frac{1}{\Lambda} B^{\mu\nu} B_{\mu\nu} + \frac{1}{\Lambda} |D^\mu H|^2 \right)$$

- EFT Model behaviour dictated by 2 parameters in this case, suppression scale  $\Lambda$ , scalar mass  $m_\phi$
- Well motivated extension of many BSM models is an [extended Higgs Sector](#) (e.g. 2HDM)
- Low mass scalars sector [not fully excluded](#) by low mass diphoton searches
- Decays to massive dibosons kinematically unfavoured in these mass ranges  $\rightarrow$  [predominant](#) decays to [diphoton](#)



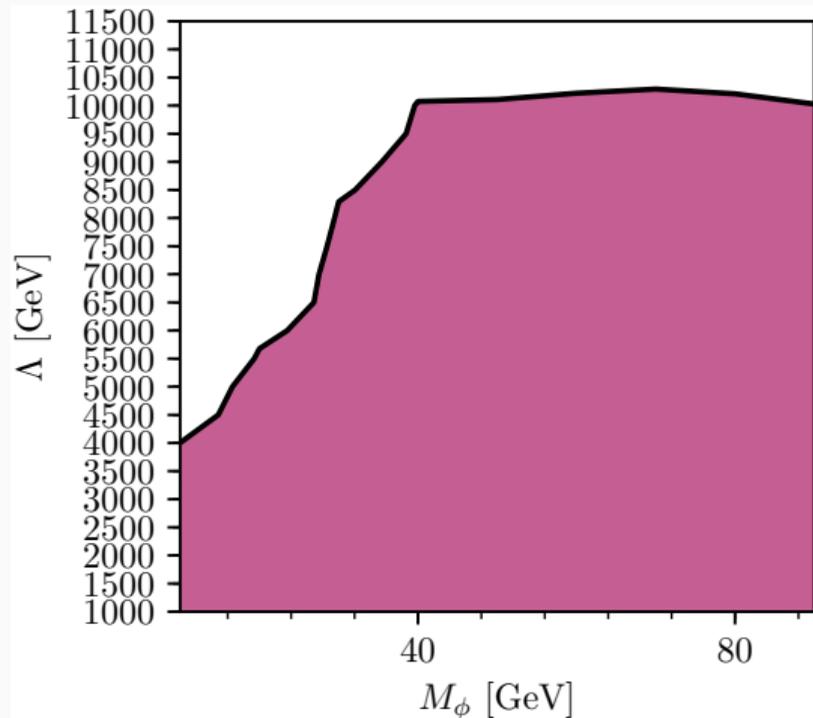
(BSM + data) vs data cross section comparison for 1 model point in 0 jet bin of ATLAS  $Z(\nu\nu)+\gamma$  as a function of  $E_T^\gamma$

- Gain exclusion limits from 7/8TeV gauge boson +  $\gamma(\gamma)$  measurements.
- Here show ATLAS 8TeV  $Z\gamma(\gamma)$ , [1604.05232](#)
- Perhaps less expected, typically would only consider diphoton measurements/searches
- The power of our approach relies on a huge breadth of complementary analyses, can catch atypical channels



$CL_s$  of a 2D scan of parameter space points

- Perform 2D Parameter scans (this case for CP-Even scalar) utilising as many Rivet plugins as possible
- Build orthogonal combinations of datasets
- Profile likelihood fit across all datasets
- Report exclusion of model in terms of  $CL_s$



95% CL contour (pink), for a CP even light scalar

- Perform 2D Parameter scans (this case for CP-Even scalar) utilising as many Rivet plugins as possible
- Build orthogonal combinations of datasets
- Profile likelihood fit across all datasets
- Report exclusion of model in terms of  $CL_s$
- Build 95% CL exclusion contour
- Maps out the low mass scalar landscape!

Hopefully this has demonstrated some interesting ideas:

- We have fast simulations of calculable theoretical quantities through SM measurements, this can form a robust net of measured parameters to confront BSM simulation with using [Contur](#) → the process is validated
- We can use these tools to demonstrate interesting phenomenological results → the process can tell us interesting/unexpected things about physics

**Thanks for Listening!**

**Backup**

# The Search Recasting Problem

Roughly speaking need to know two quantities to translate a particle level simulation to a count in a detector volume:

$$N_{\text{obs}} = L \cdot \sigma_{\text{Total}} \cdot A \cdot \epsilon \quad (1)$$

- A - Acceptance, effectively the analysis definition, can be simple
  - Do we provide code or ATLAS/CMS approved analysis description, Rivet?
  - More complicated analyses, BDTs etc, impossible?
- $\epsilon$  - Efficiency, detector simulation
  - Usually done by theorists with approx fast sims, e.g. Delphes
  - ATLAS approved fast sims? Not going to happen?
  - Other ways around this, Folding matrices?

The community as devised a variety of ways to provide additional information (Efficiency maps, generic resonance/cross section limits, etc.) But it is a difficult and pressing question to keep on top of

### PROS

- "Model Independent" - Very dependent on the SM, but this seems the best model to be dependent on!
- **Fast**, no expensive detector simulation
- Builds on independent, actively developed codes, Very little bespoke information needed.
- Builds on already established route to market for experimental data, and **feeds back** directly on this pipeline

### CONS

- Unfolded measurement data arrives **slower** than a search
- **Limited analysis coverage** (for now?) for some typical search regions (E.g. Large MET)
- Currently limited to profiling purely based on **Data and BSM** simulation, not entirely a con but a current internal limitation.