

Constraining New Physics with Standard Model measurements

David Yallup

March 27, 2018

IOP Joint APP and HEP Conference 2018



Introduction - What do we measure at the LHC?

- **Results** - What is the goal of the experimental programs at the LHC (Specifically ATLAS and CMS)
 - 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	ℓ, γ	Jets†	E_{miss}^T	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/g$	$0, e, \mu$	1-4 J	Yes	36.1	M_{KK} 7.75 TeV	$n=2$ ATLAS-CONF-2017-090
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_{KK} 8.6 TeV	$n=3$ HLZ NLO CERN-EP-2017-132
	ADD GBH	-	2 J	-	37.0	M_{KK} 8.9 TeV	$n=6$ 1703.09217
	ADD BH $\Sigma \gamma$	$\geq 1, e, \mu$	≥ 2 J	-	3.2	M_{KK} 8.2 TeV	$n=6, M_{KK} = 3 \text{ TeV}$ cut BH 1606.02055
	ADD BH multiple	-	≥ 3 J	-	3.6	M_{KK} 9.55 TeV	$n=6, M_{KK} = 3 \text{ TeV}$ cut BH 1512.02656
	RS1 $G_{KK} - \gamma\gamma$	2 γ	-	-	36.7	See mass	$M_{KK} = 0.1$ CERN-EP-2017-132
Gauge bosons	Bulk RS $G_{KK} - WW \rightarrow \text{qq}^{\prime\prime}$	1 e, μ	1 J	Yes	36.1	See mass	$M_{KK} = 1.0$ ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	$\geq 2, b, \geq 3$ J	Yes	13.2	1.75 TeV 1.6 TeV	ATLAS-CONF-2016-104
	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	36.1	Z' mass 4.5 TeV	ATLAS-CONF-2017-027
Cl	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	Z' mass 2.4 TeV	ATLAS-CONF-2017-050
	Leptophobic $Z' \rightarrow bb$	-	2 b	-	3.2	Z' mass 1.5 TeV	1603.08791
	Leptophobic $Z' \rightarrow \tau\tau$	1 e, μ	$\geq 1, b, \geq 1, 2$ J	Yes	3.2	Z' mass 2.0 TeV	$f(m) = 3\%$ ATLAS-CONF-2016-014
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	Yes	36.1	W' mass 5.1 TeV	1706.04786
	HVT $V' \rightarrow WW \rightarrow \text{qqqq}$ model B	0 e, μ	2 J	-	36.7	W' mass 3.5 TeV	$d_V = 3$ CERN-EP-2017-147
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	W' mass 2.93 TeV	$d_V = 3$ ATLAS-CONF-2017-055
DM	LRSM $W_2' \rightarrow \tau b$	1 e, μ	2 b, 0-1 J	Yes	20.3	W' mass 1.32 TeV	1410.4103
	LRSM $W_2' \rightarrow \tau b$	0 e, μ	$\geq 1, b, 1, 2$ J	-	20.3	W' mass 1.76 TeV	1408.0886
LO	Cl qqqq	-	2 J	-	37.0	A 21.8 TeV κ_{Cl}	1703.09217
	Cl $\ell\ell\text{qq}$	2 e, μ	-	-	36.1	A 40.1 TeV κ_{Cl}	ATLAS-CONF-2017-027
	Cl uutt	2(SB)/2(S e, μ) $\geq 1, b, \geq 1$ J	Yes	20.3	A 4.8 TeV	$ K_{eff} = 1$ 1504.04605	
LC	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 J	Yes	36.1	M_{DM} 1.5 TeV	$d_V = 0.25, d_A = 1.0, m(\chi) < 400 \text{ GeV}$ ATLAS-CONF-2017-090
	Vector mediator (Dirac DM)	0 $e, \mu, 1, \gamma$	≤ 1 J	Yes	36.1	M_{DM} 1.2 TeV	$d_V = 0.25, d_A = 1.0, m(\chi) < 480 \text{ GeV}$ 1704.03848
	$VV_{1/2}$ EFT (Dirac DM)	0 $e, \mu, 1, \gamma$	≤ 1 J	Yes	3.2	M_{DM} 700 GeV	$m(\chi) < 150 \text{ GeV}$ 1606.02072
Heavy quarks	Scalar LQ 1 st gen	2 e	≥ 2 J	-	3.2	LQ mass 1.1 TeV	$\beta = 1$ 1605.09035
	Scalar LQ 2 nd gen	2 μ	≥ 2 J	-	3.2	LQ mass 1.05 TeV	$\beta = 1$ 1605.09035
	Scalar LQ 3 rd gen	1 e, μ	$\geq 1, b, \geq 3$ J	Yes	20.3	LQ mass 640 GeV	$\beta = 0$ 1506.04735
	VLQ TT $\rightarrow Hb + X$	0 or 1 e, μ	$\geq 2, b, \geq 3$ J	Yes	13.2	T mass 1.3 TeV	$\mathcal{B}(T \rightarrow Hb) = 1$ ATLAS-CONF-2016-104
	VLQ TT $\rightarrow Zb + X$	1 e, μ	$\geq 1, b, \geq 3$ J	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \rightarrow Zb) = 1$ 1705.10751
	VLQ TT $\rightarrow Wb + X$	1 e, μ	$\geq 1, b, \geq 1, 2$ J	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \rightarrow Wb) = 1$ CERN-EP-2017-094
Excited fermions	VLQ BB $\rightarrow Hb + X$	1 e, μ	$\geq 2, b, \geq 3$ J	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \rightarrow Hb) = 1$ 1505.04306
	VLQ BB $\rightarrow Zb + X$	2(SB) e, μ	$\geq 2, b$	-	20.3	B mass 790 GeV	$\mathcal{B}(B \rightarrow Zb) = 1$ 1409.3550
	VLQ BB $\rightarrow Wb + X$	1 e, μ	$\geq 1, b, \geq 1, 2$ J	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \rightarrow Wb) = 1$ CERN-EP-2017-094
	VLQ QQ $\rightarrow WqWq$	1 e, μ	≥ 4 J	Yes	20.3	Q mass 640 GeV	$\mathcal{B}(Q \rightarrow Wq) = 1$ 1509.04261
	Excited quark $q^* \rightarrow \text{qq}$	-	2 J	-	37.0	q^* mass 6.0 TeV	only u^* and $d^*, A = m(q^*)$ 1703.09127
	Excited quark $q^* \rightarrow \text{q}\gamma$	1 γ	1 J	-	36.7	q^* mass 5.3 TeV	only u^* and $d^*, A = m(q^*)$ CERN-EP-2017-148
Other	Excited quark $b^* \rightarrow \text{Ag}$	-	1 b, 1 J	-	13.3	b^* mass 2.3 TeV	ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow W\tau$	1 or 2 $e, \mu, 1, b, 2, 0$ J	Yes	20.3	b^* mass 1.5 TeV	$f_b = f_s = f_c = 1$ 1510.02064	
	Excited lepton ℓ^*	3 e, μ, τ	-	-	20.3	ℓ^* mass 3.0 TeV	$A = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV	$A = 1.6 \text{ TeV}$ 1411.2921
	LRSM Majorana ν	2 e, μ	2 J	-	20.3	$\nu\bar{\nu}$ mass 2.0 TeV	$m(W_2) = 2.4 \text{ TeV}$, no mixing 1506.09020
	Higgs triplet $H^{**} \rightarrow \ell\ell$	2, 3, 4 e, μ (SB)	-	-	36.1	H^{**} mass 870 GeV	DY production ATLAS-CONF-2017-053
Higgs triplet $H^{**} \rightarrow \ell\nu$	3 e, μ, τ	-	-	20.3	H^{**} mass 400 GeV	$\text{DY production, } \mathcal{B}(H^{**} \rightarrow \ell\nu) = 1$ 1411.2921	
Monopole (non-res prod)	1 e, μ	1 b	Yes	20.3	Spin 1 invisible particle mass 657 GeV	$f_{mon} = 0.2$ 1410.3404	
Multi-charged particles	-	-	-	20.3	Spin 0 invisible particle mass 785 GeV	$\text{DY production, } q = 5e$ 1504.04188	
Magnetic monopoles	-	-	-	7.0	Spin 0 invisible particle mass 2.24 TeV	$\text{DY production, } q = 1/2g_{EM}, \text{spin } 1/2$ 1509.09059	

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

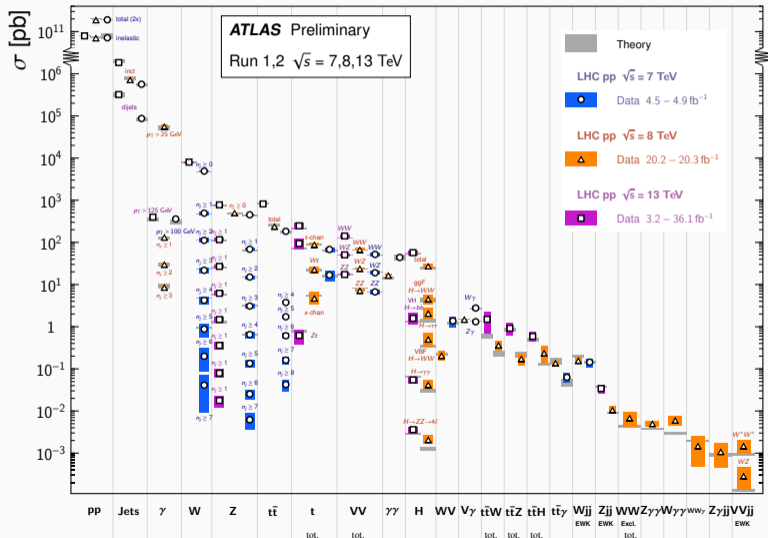
† Small-radius (large-radius) jets are denoted by the letter j (J).

- 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 - 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?

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

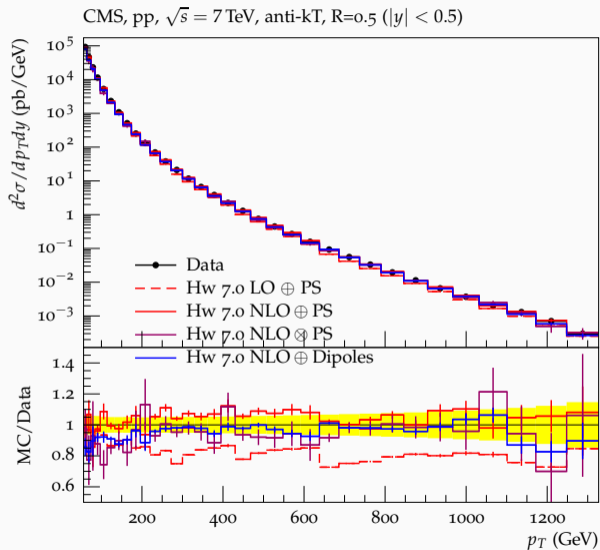


Logo pending...

THE LIMITS

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

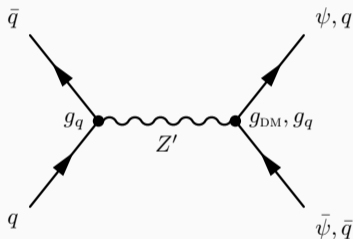
Contur - A Jetty Example



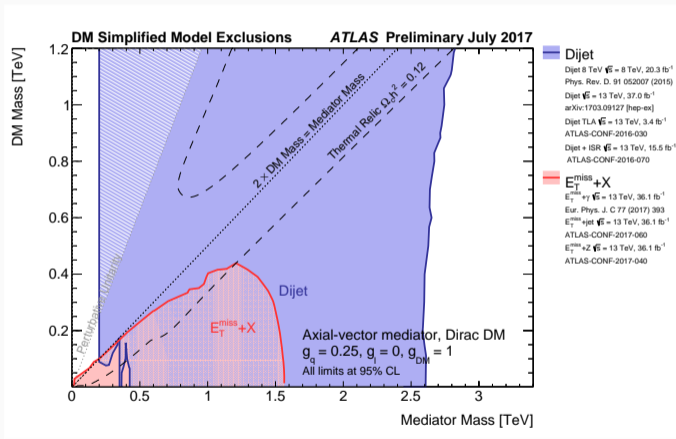
- Zoom in on one of those SM summary measurements, Inclusive Jets @ 7TeV CMS, [1406.0324](#)
- Rivet plugin used to replicate experimental definition for generator studies, here validation provided by Herwig authors, [Validation summary](#)
- We have a good understanding of the SM here
- We have a fast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

Contur - A Jetty Example Model

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

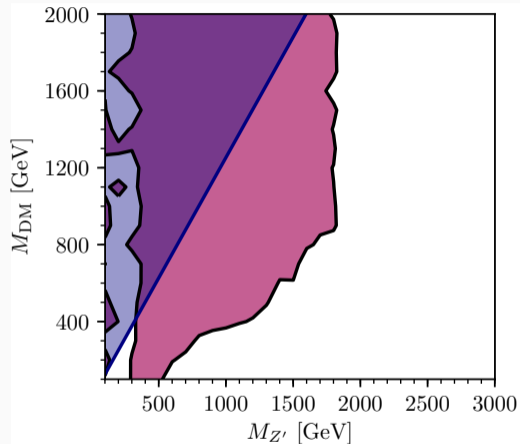


Simplified model forms 4D model parameter space: $g_q, g_{DM}, M_{DM}, M_{Z'}$. Easy to explore!



Searches in the collider context give MET-ey or Jet-ey signatures

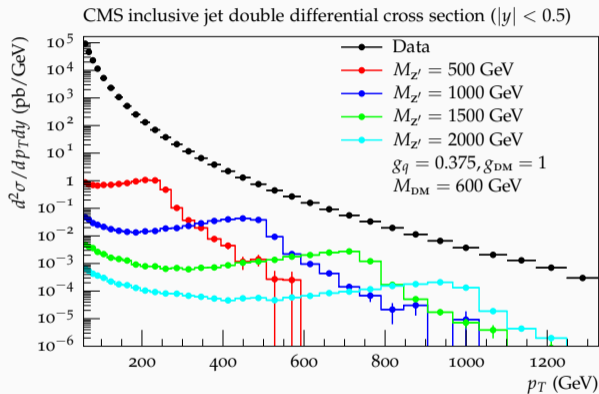
Contur - A Jetty Example, Mapping the parameter space



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

- Model studied in detail in the original Contur paper, [1606.05296](#)
- Rolling updates with expanded data shown here from the [Contur Webpage](#)
- Fix two parameters, $g_q = 0.25, g_{DM} = 1.0$, equivalent to the ATLAS/CMS benchmarks, 2D scan in $M_{DM}, M_{Z'}$
- [Profile likelihood fit](#) across all datasets
- Report exclusion of model in terms of CL_s
- Build 95% CL exclusion contour
- Maps out the collider DM landscape!

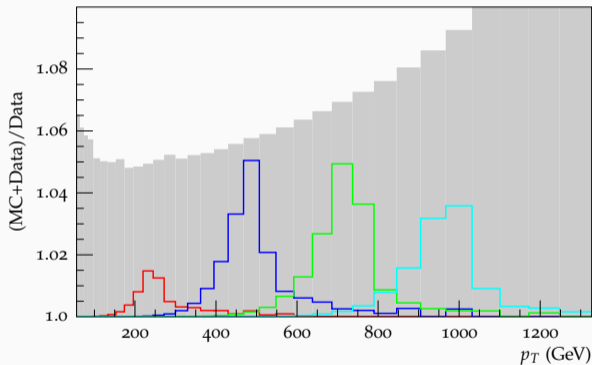
Contur - A Jetty Example Back to data



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

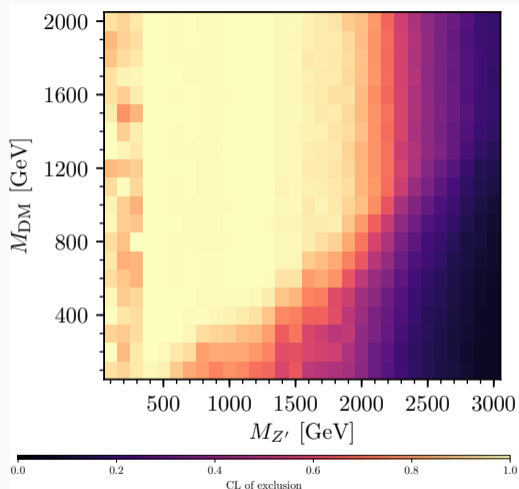
Contur - A Jetty Example Back to data



(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, Mapping the parameter space



CL_s of a 2D scan of parameter space points

- Model studied in detail in the original Contur paper, [1606.05296](#)
- Rolling updates with expanded data shown here from the [Contur Webpage](#)
- Fix two parameters, $g_q = 0.25$, $g_{DM} = 1.0$, equivalent to the ATLAS/CMS benchmarks, extend 1D scan shown previously to 2D scan in $M_{DM}, M_{Z'}$
- [Profile likelihood fit](#) across all datasets
- Report exclusion of model in terms of CL_s

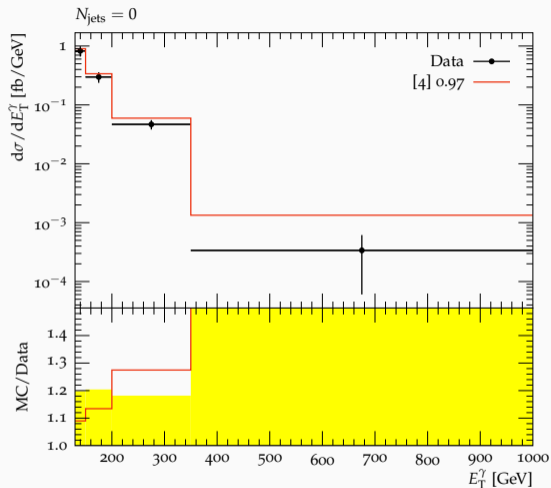
Contur - A recent example analysis

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:

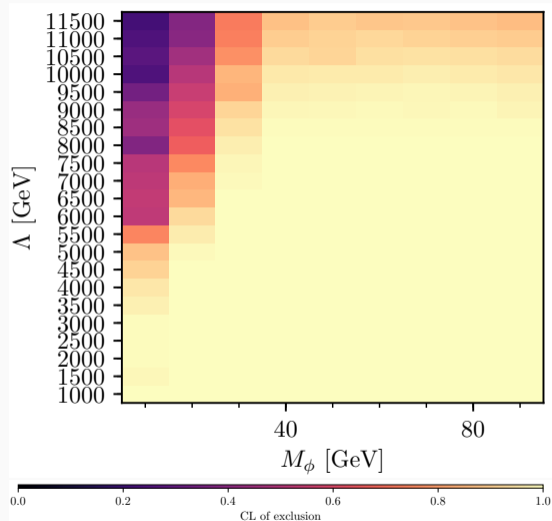
$$\mathcal{L}_{\text{eff}} \supset \phi \left(\frac{1}{\Lambda} G^{\mu\nu a} G_{\mu\nu}^a + \frac{1}{\Lambda} W^{\mu\nu I} W_{\mu\nu}^I + \frac{1}{\Lambda} B^{\mu\nu} B_{\mu\nu} + \frac{1}{\Lambda} |D^\mu H|^2 \right)$$

- EFT Model behaviour dictated by 2 parameters in this case, suppression scale Λ , scalar mass m_ϕ
- 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](#)



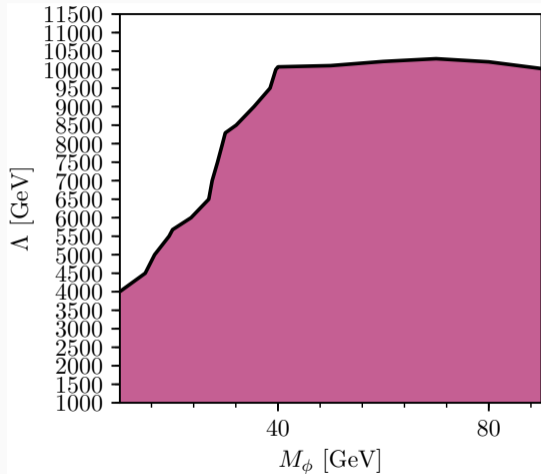
(BSM + data) vs data cross section comparison for 1 model point in 0 jet bin of ATLAS $Z(\nu\nu)+\gamma$ as a function of E_T^γ

- 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?
- ϵ - 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.